Neutrino physics

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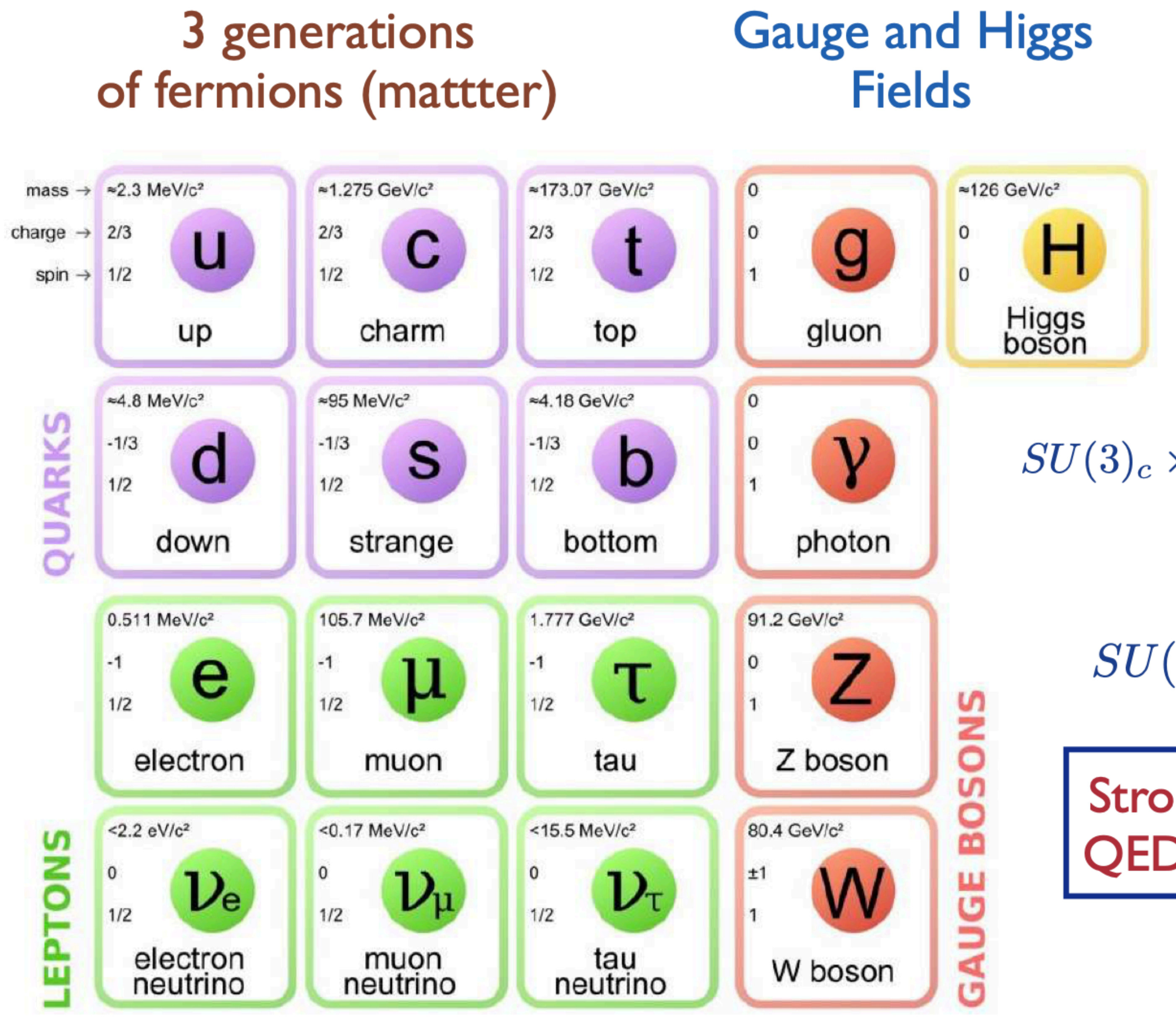
IDPASC School, July 2025

The Standard Model

- Nature is governed by four fondamental interactions: ElectroMagnetic (EM), Weak, Strong and Gravitational forces
- Gravitation is not in the SM framework
- EM and Weak interactions are unified in the Electroweak theory
- SM is an incredibly successful theory that describes the physics of elementary particles
  - The discovery of the Higgs boson, responsible for the mechanism giving masses to the particles, completed the SM framework !
- But …



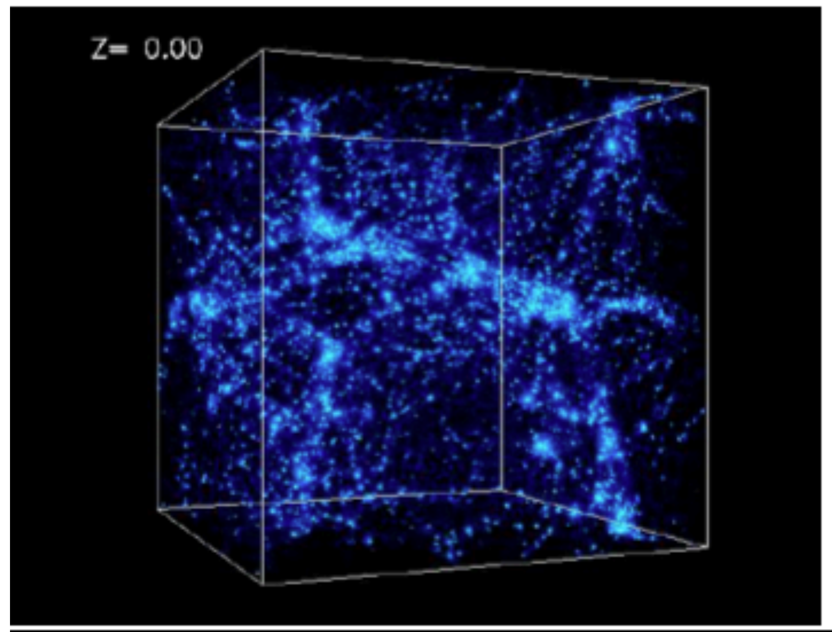
$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

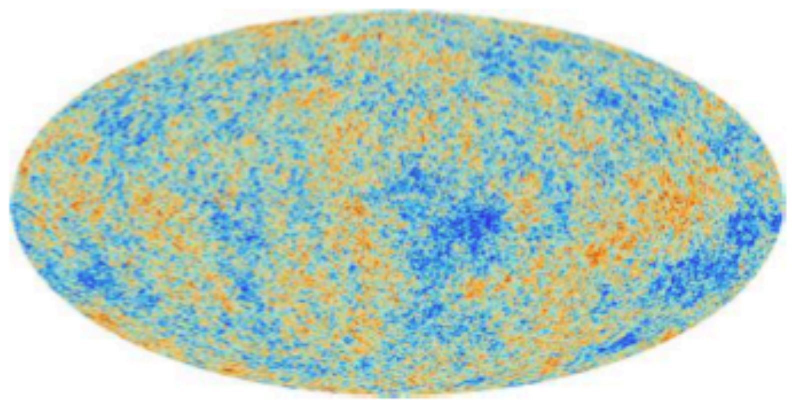
$$\downarrow \quad <H> = \frac{v}{\sqrt{2}}$$

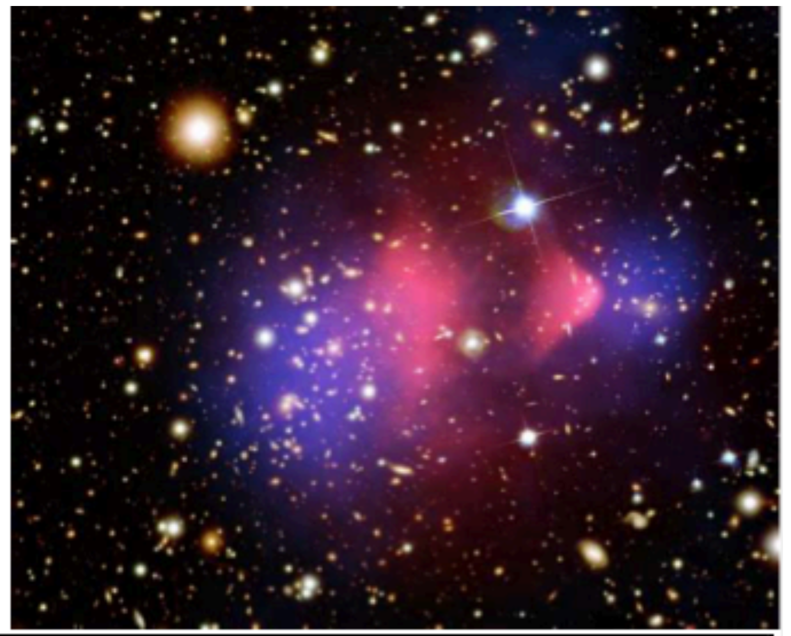
$$SU(3)_c \times U(1)_{em}$$

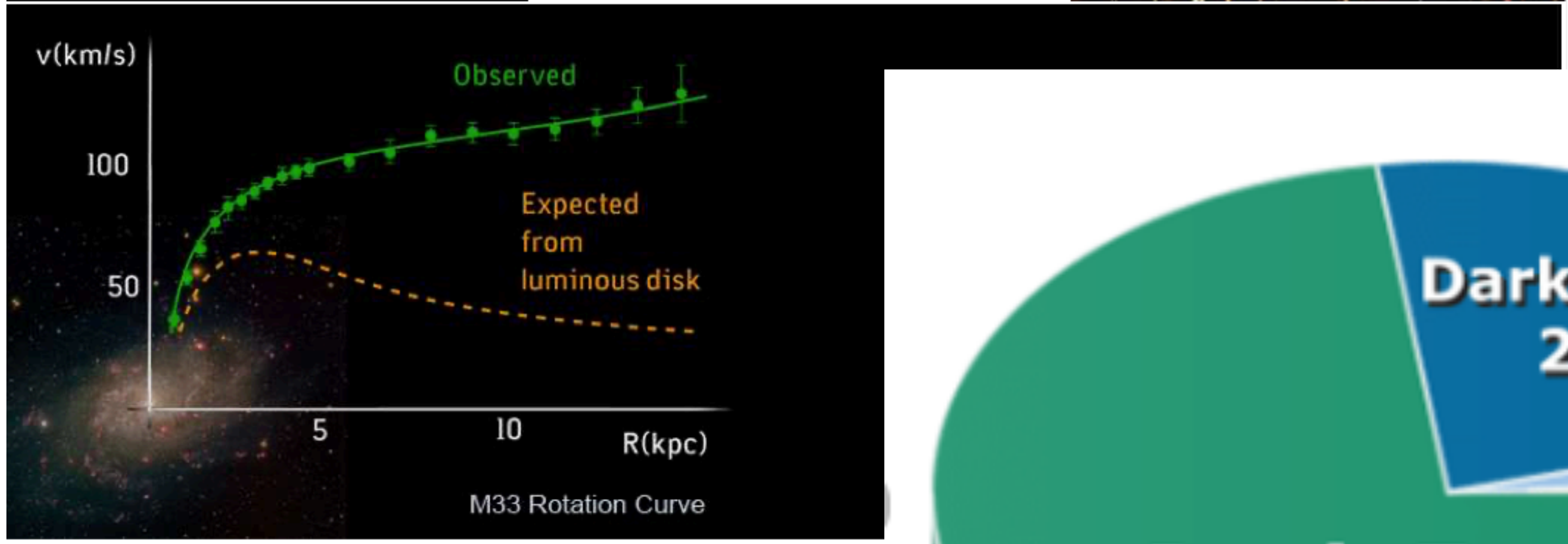
Strong, Weak and QED Interactions

Few unknowns

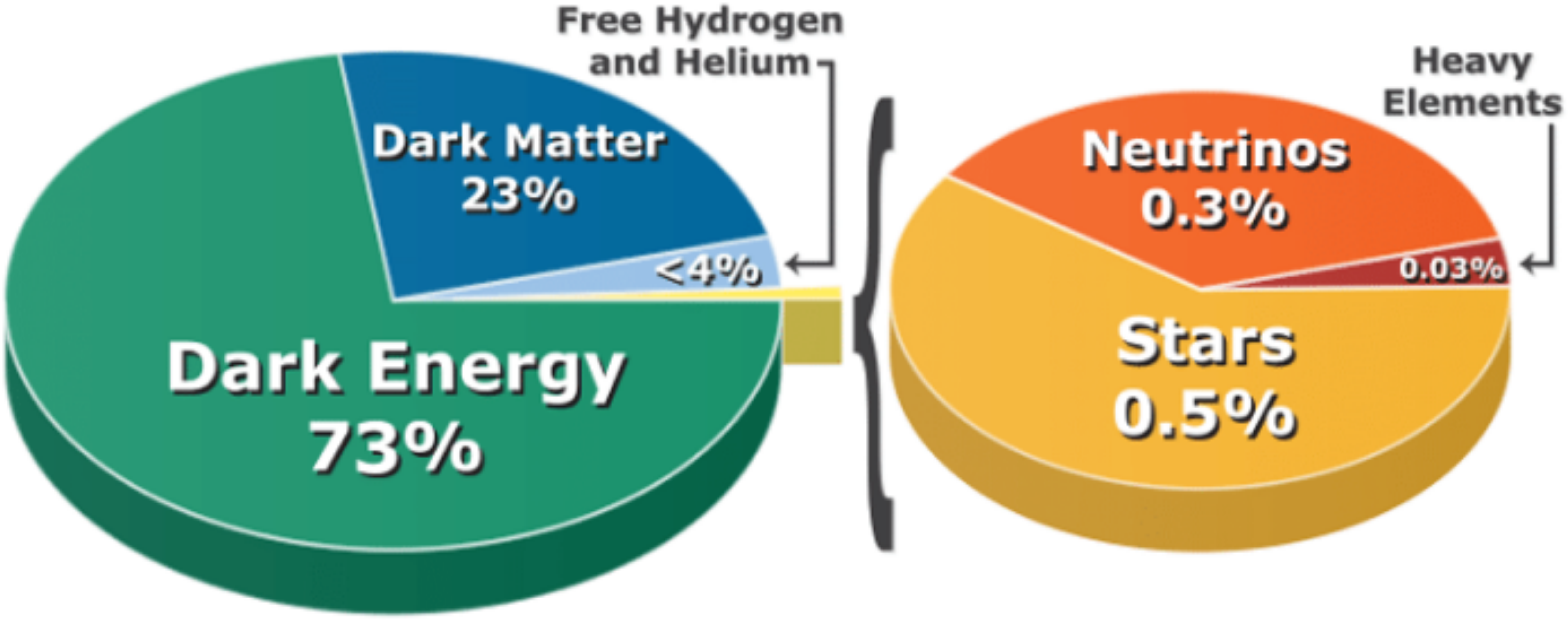




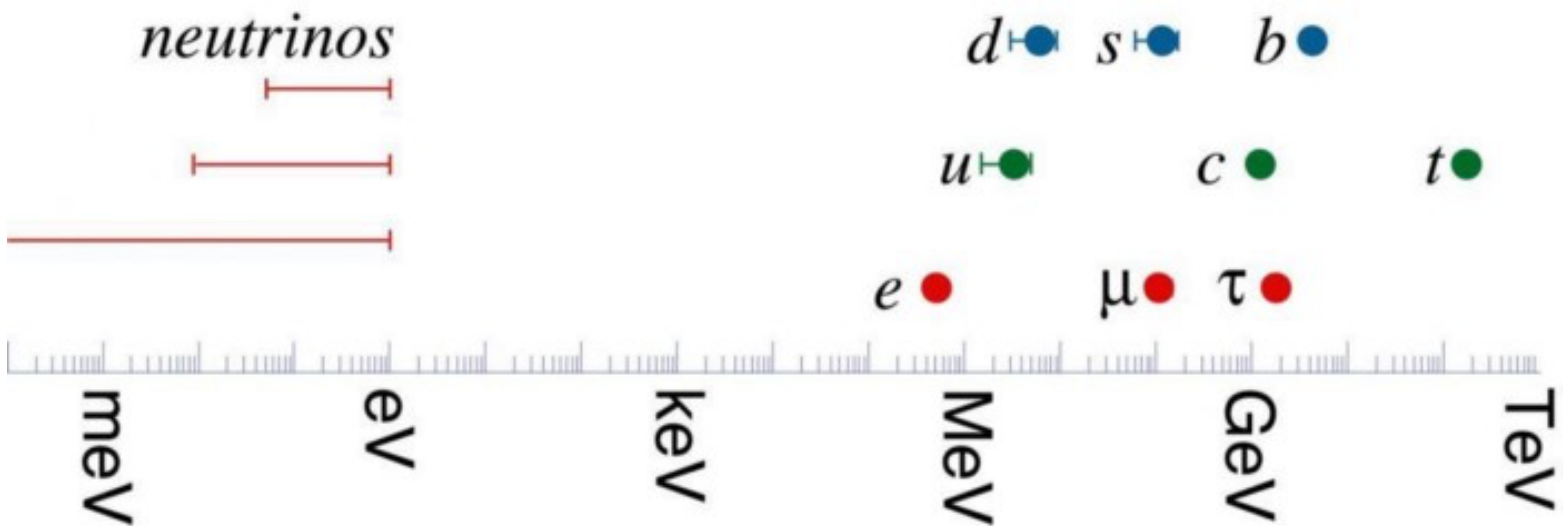




- Standard Model only explains ~5% of the content of the Universe!



Masses of elementary particles

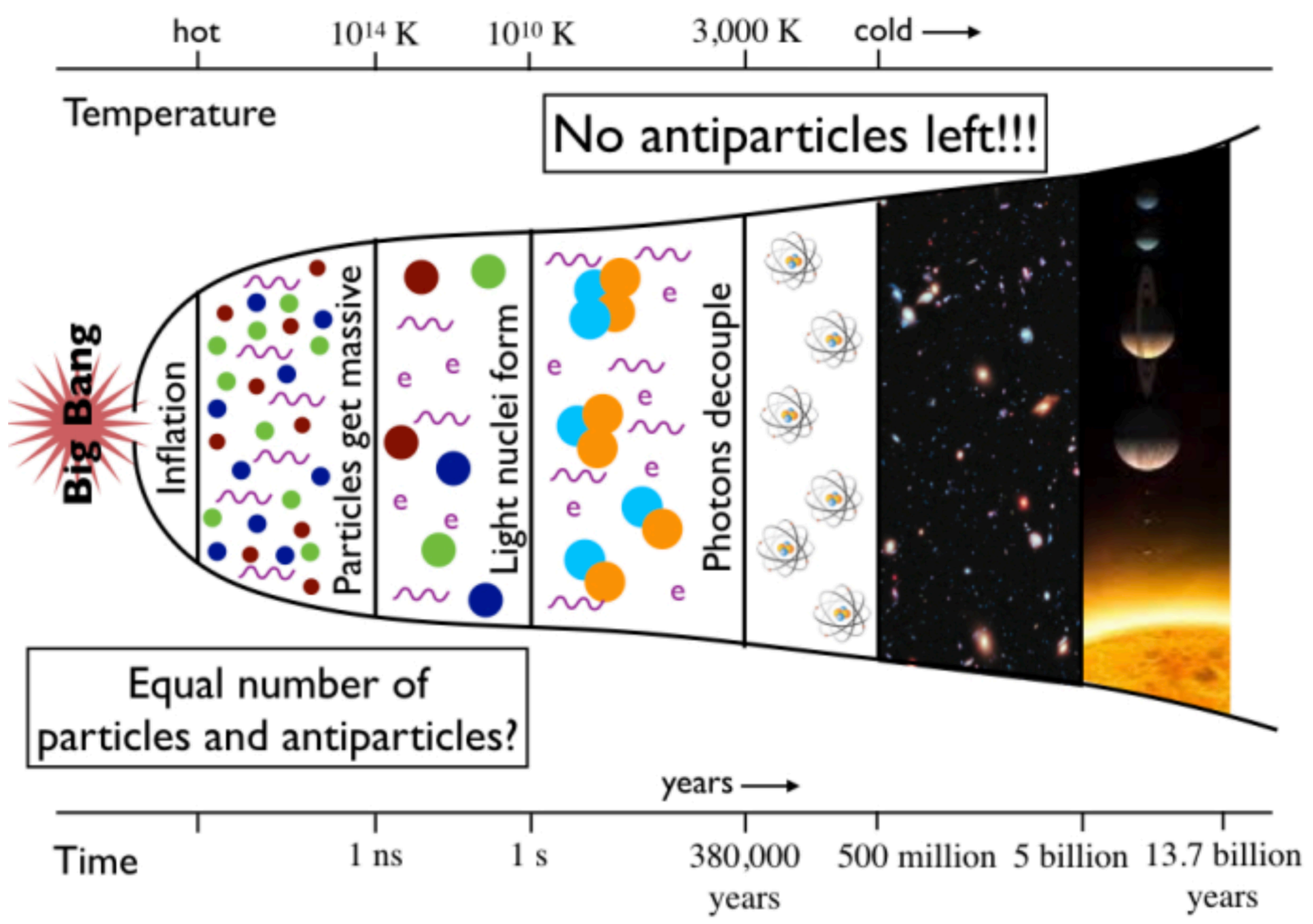


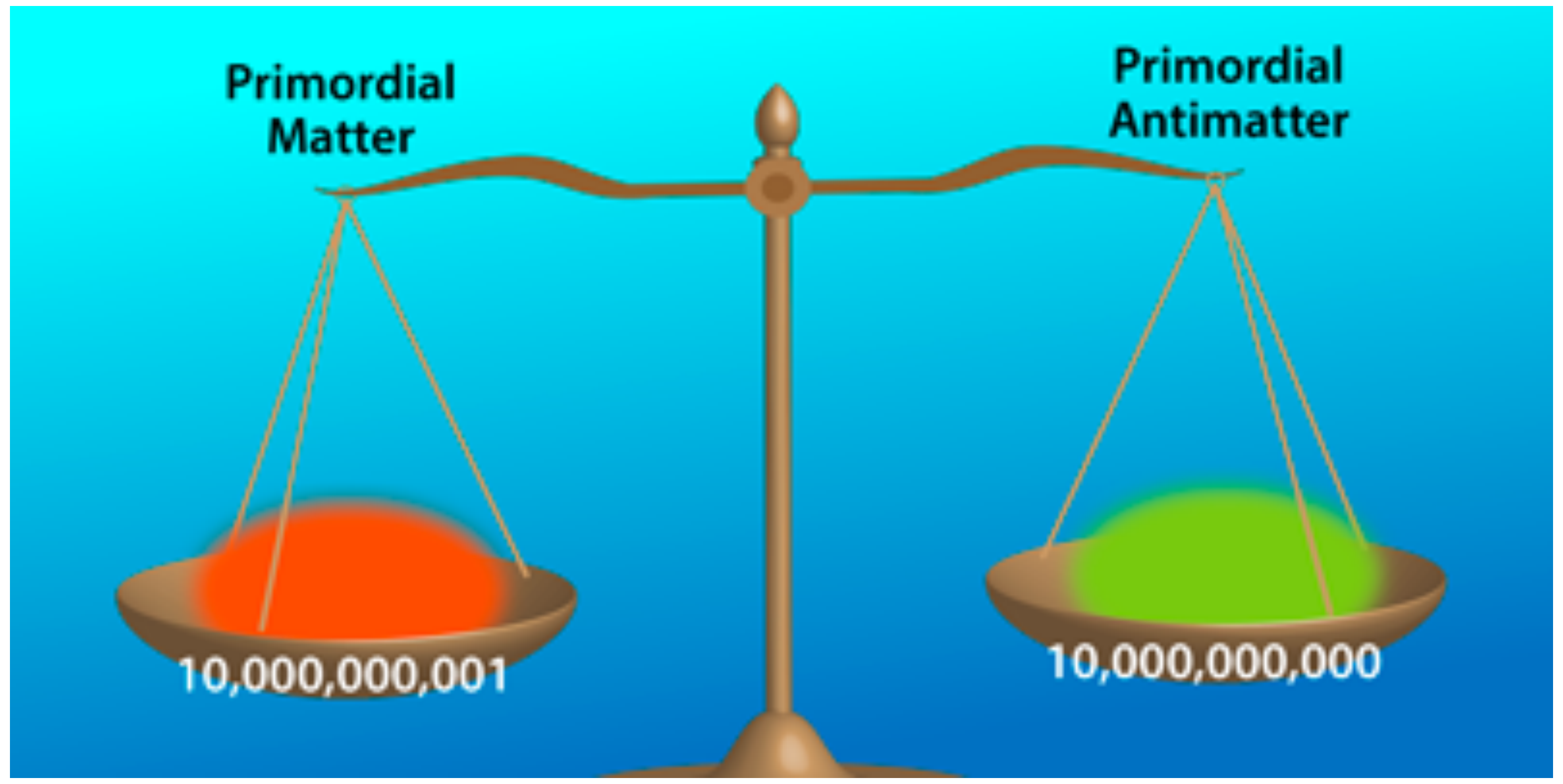
- Mass of elementary particles span over a huge range of values
- For neutrinos we only have upper limits and they were supposed massless in the SM → as such they are the only confirmed DM candidate!
- Standard model provides a mechanism for mass generation but do not explain why

Matter-Antimatter asymmetry

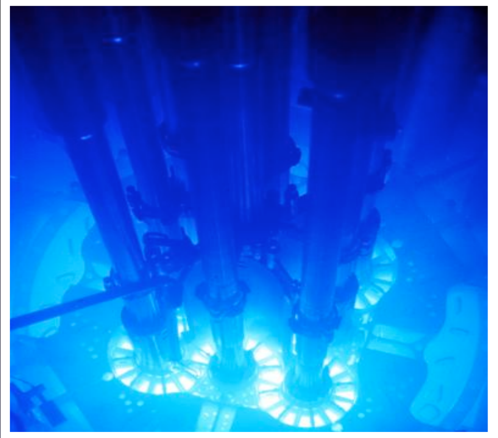
- Evolution of the Universe do not explain why we live in a matter-dominated Universe
- 1 second after Big Bang → Cosmic neutrino background (CνB) → 340 ν per cm^3
- Lepton asymmetry few minutes after Big Bang would affect primordial nucleosynthesis
- 400 ky after Big Bang → Cosmic Microwave Background (CMB)

- How the evolution of the Universe changed from the initial matter-antimatter equilibrium to a matter dominated Universe?





Neutrino sources



Neutrinos from reactors.

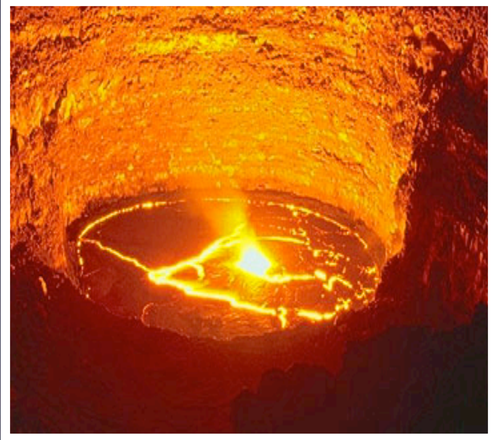
Detected (1950s)

Neutrinos from supernovae.

Detected (1980s)

Neutrinos from the sun.

Detected (1960s)

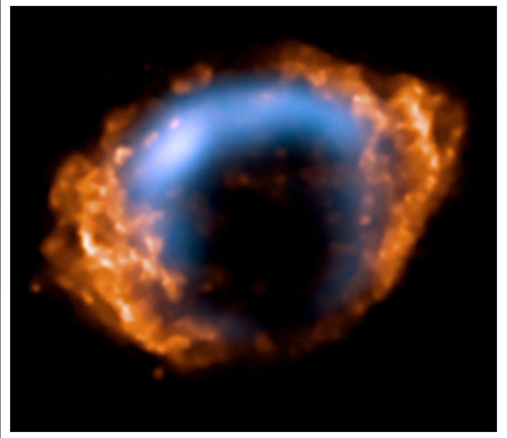


Neutrinos from the Earth.

Detected (2000s)

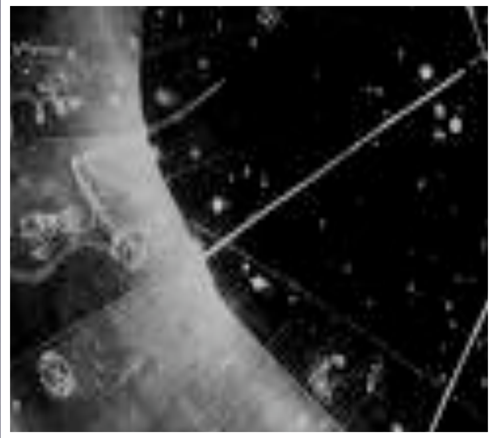
Neutrinos from the atmosphere.

Detected (1960s)



Neutrinos from galactic sources.
(e.g. remnant SN's, other?)

Not yet (but close!)



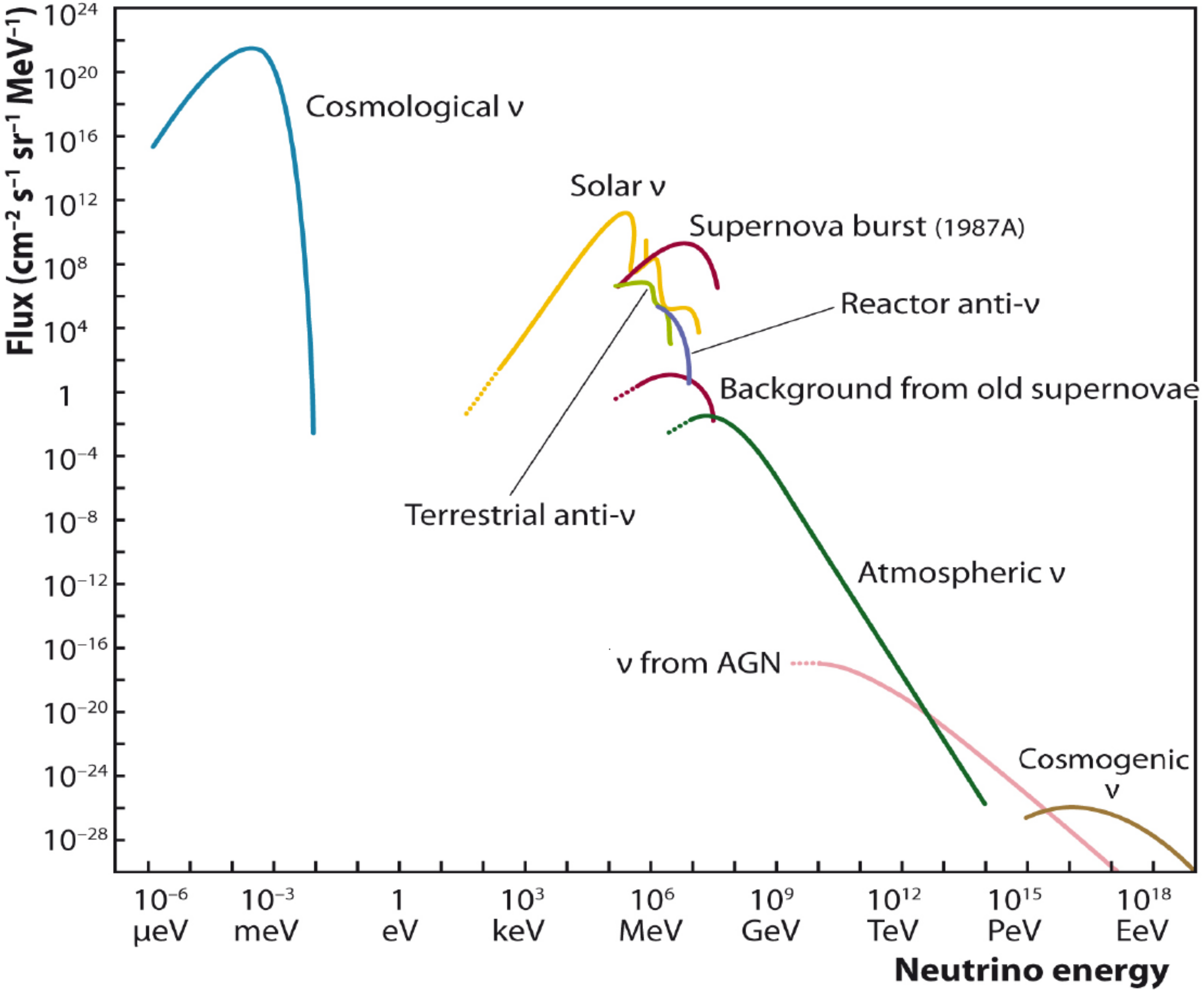
Neutrinos from accelerators.

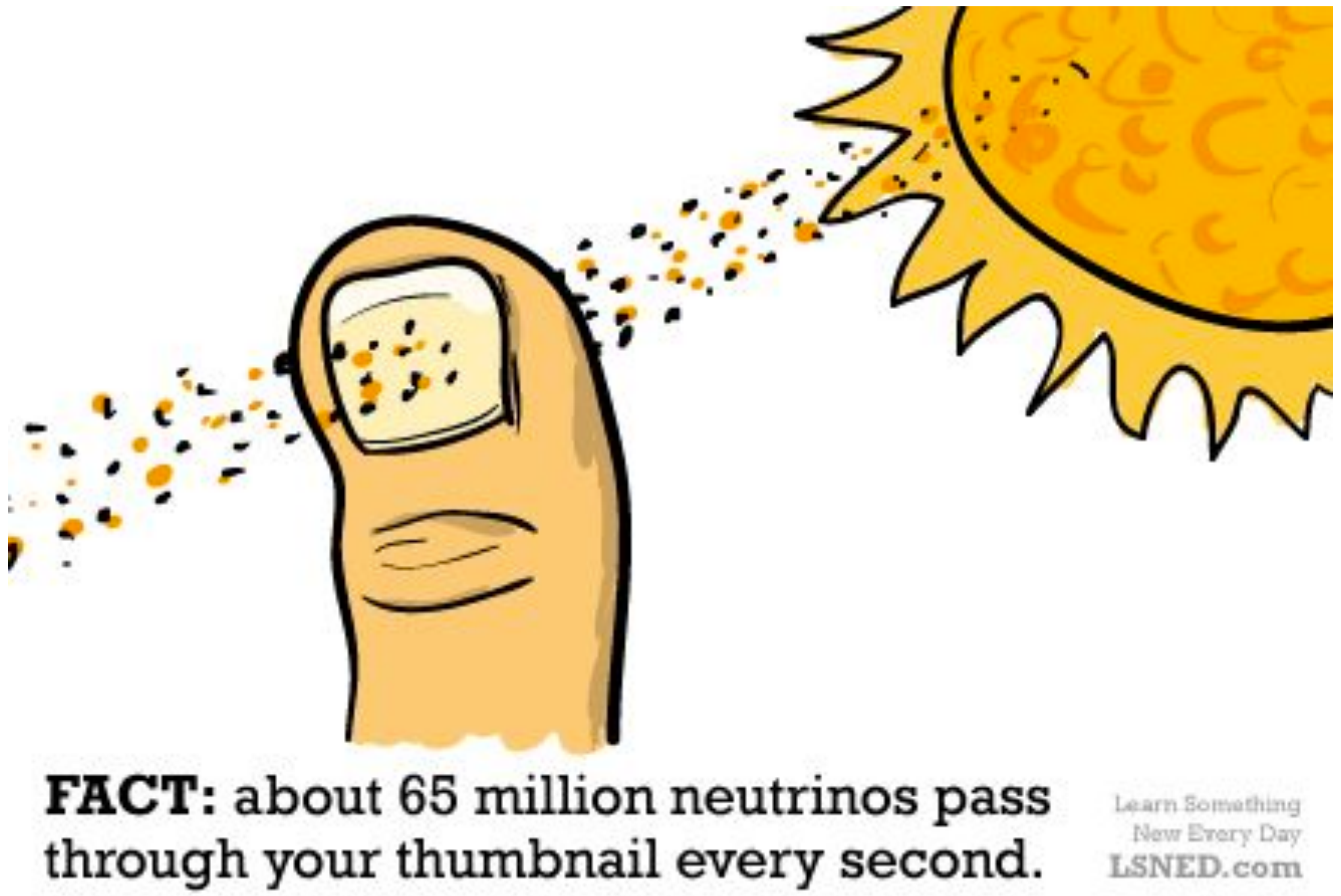
Created & detected (1960s)

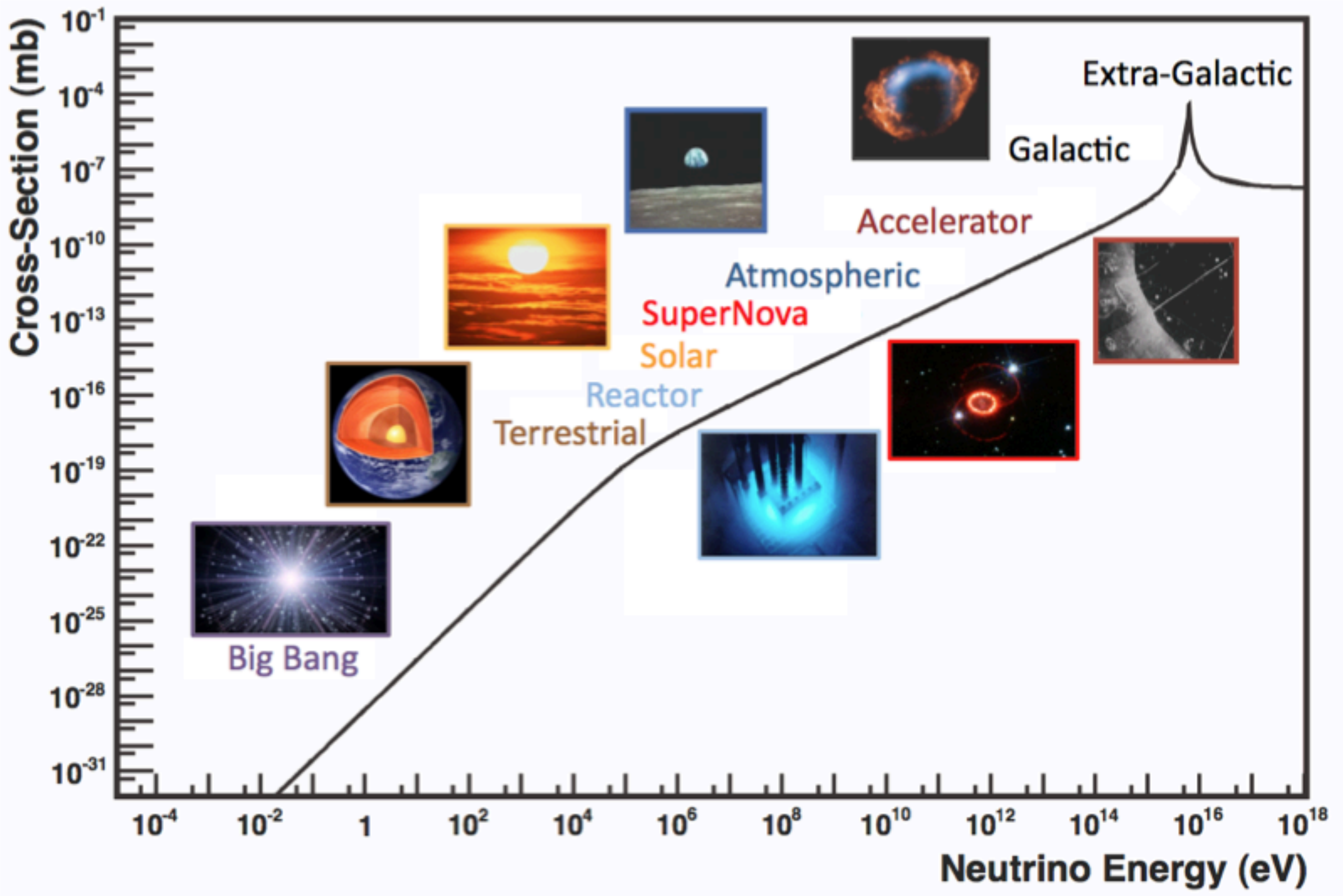
Neutrinos from the Big Bang.

Not even close...

Neutrino fluxes






Cross-Section (mb)
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
10^{-31}
Extra-Galactic
Galactic
Accelerator
Atmospheric
SuperNova
Solar
Reactor
Terrestrial
Big Bang
10^{-4} 10^{-2} 1 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12} 10^{14} 10^{16} 10^{18}
Neutrino Energy (eV)

Put in some perspective

- What does it mean a cross-section of $\sigma = 10^{-43} cm^2$?
- Let's look at the mean free path $\lambda = \dfrac{u}{n\sigma}$
  - Where u is the atomic mass unit $u = 1.67 \times 10^{-27}\ kg$
  - n is the density of the medium
  - σ the ν cross-section
- Two examples: water (n=1000 kg/m³) and lead (n = 11400 kg/m³)

$$\lambda_{H_2O} = \frac{u}{n_{H_20}\sigma_\nu} = \frac{1.67 \times 10^{-27}\ kg}{1000\ kg/m^3 \times 10^{-47}\ m^2} \sim 1.7 \times 10^{17}\ m$$

$$\lambda_{Lead} = \frac{u}{n_{Lead}\sigma_\nu} = \frac{1.67 \times 10^{-27}\ kg}{11400\ kg/m^3 \times 10^{-47}\ m^2} \sim 1.5 \times 10^{16}\ m$$

- One light-year is $9.5\text{x}10^{15}$ m !

How to detect neutrinos?

Nuclear explosions?

1995 F. Reines
Nobel Lecture

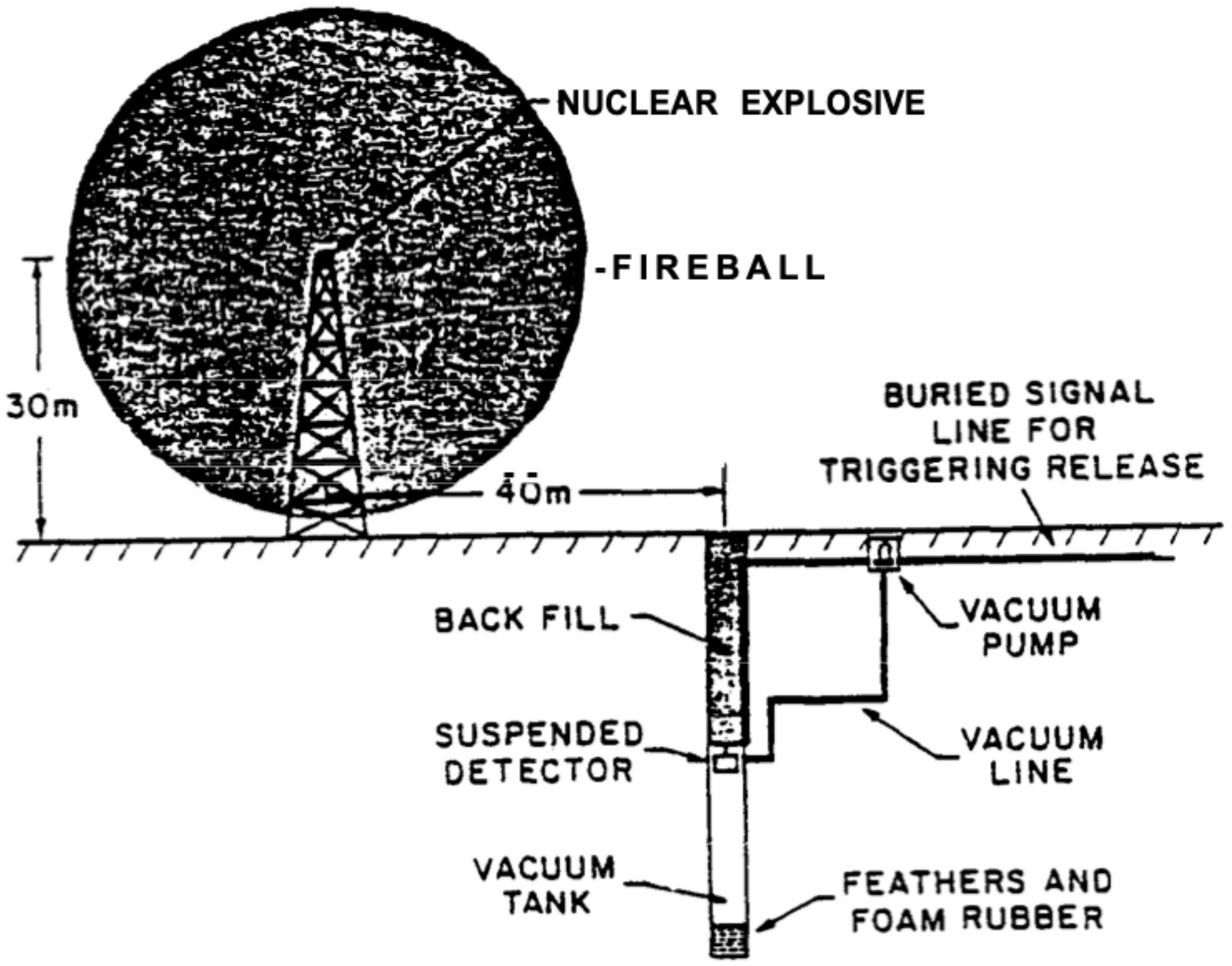


Figure 1. Sketch of the originally proposed experimental setup to detect the neutrino using a nuclear bomb. This experiment was approved by the authorities at Los Alamos but was superceded by the approach which used a fission reactor.

- The first proposal from Cowan and Reines was to detect neutrinos from nuclear explosions
- Plan to use a Liquid Scintillator detector but only looking at the positron signal from IBD
  - $\nu + p \rightarrow e^+ + n$
- Large backgrounds..

ment neutrino source ascended skyward. We anticipated a signal consisting of a few counts assuming the predicted (~ 10^{43} c m^2/proton) cross section, but background estimates suggested that our sensitivity could not be guaranteed for cross sections < 10^{-39} cm^2/proton, four orders of magnitude short! It is a tribute to the wisdom of Los Alamos Director, Norris Bradbury, that he approved the attempt on the grounds that it would nevertheless be ~ 1000 times as sensitive as the then existing limits.

Better ideas

Reines letter to Fermi

Dear Enrico.

We thought that you might be interested in the latest version of our experiment to detect the free neutrino, hence this letter. As you recall, we planned to use a nuclear explosion for the source because of background difficulties. Only last week it occurred to us that background problems could be reduced to the point where a Hanford pile would suffice by counting only delayed coincidences between the positron pulse and neutron capture pulse. You will remember that the reaction we plan

Dr. Fred Reines
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico

Dear Fred:

Thank you for your letter of October 4th by Clyde Cowan and yourself. I was very much interested in your new plan for the detection of the neutrino. Certainly your new method should be much simpler to carry out and have the great advantage that the measurement can be repeated any number of times. I shall be very interested in seeing how your 10 cubic foot scintillation counter is going to work, but I do not know of any reason why it should not.

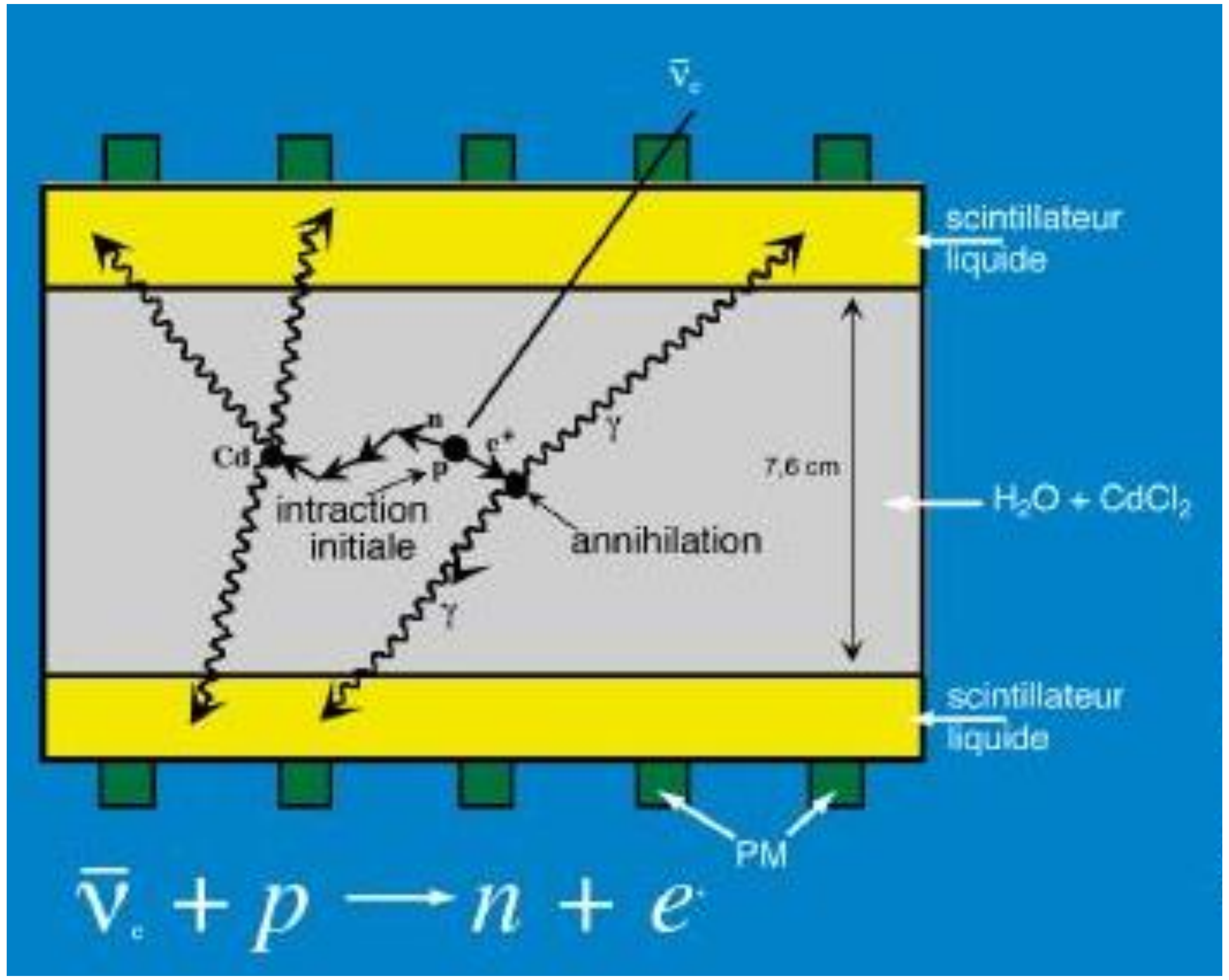
Good luck.

Sincerely yours,

Enrico

Enrico Fermi

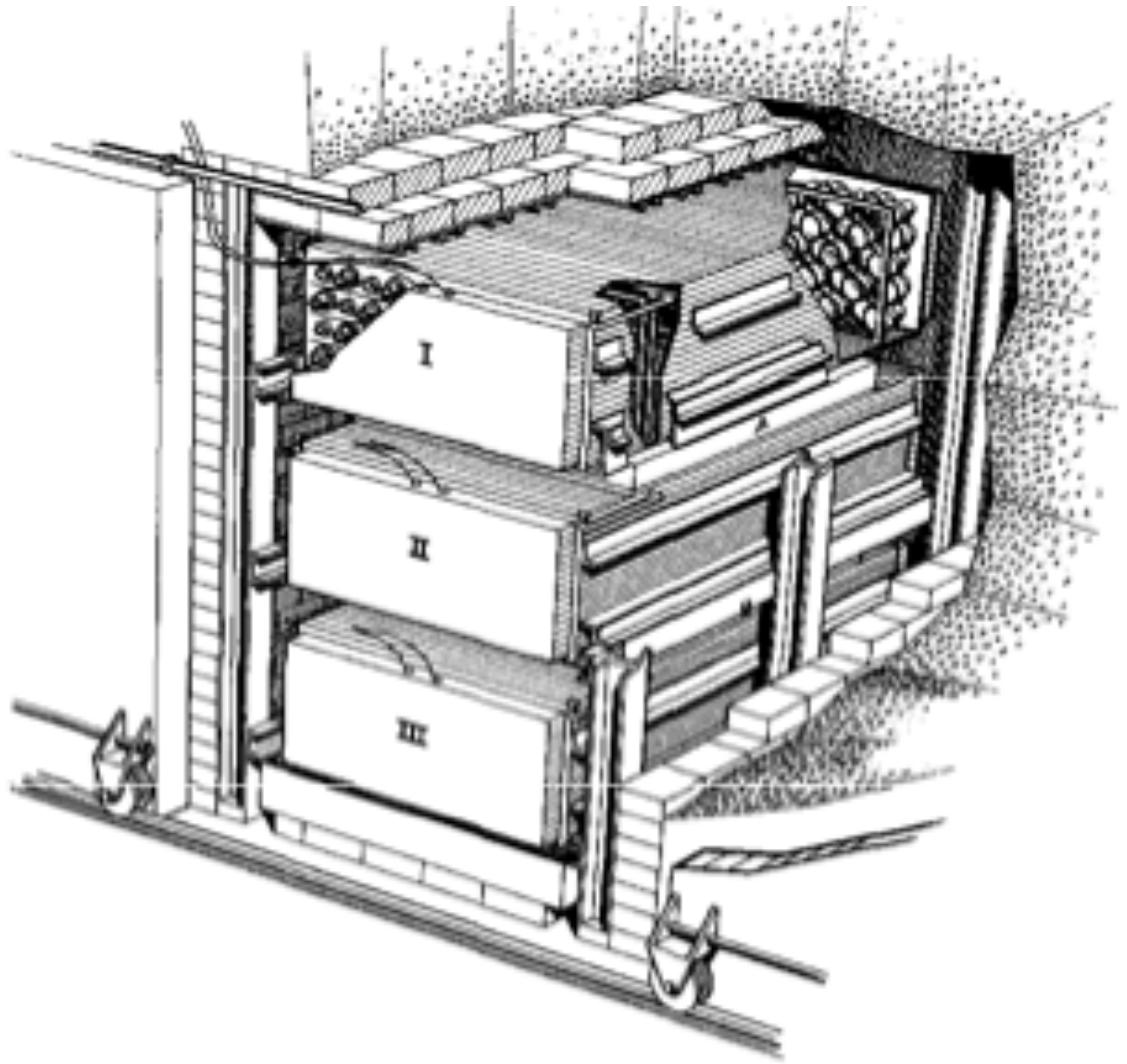
Savannah River experiment (1955)



$$\bar{\nu}_e + p \rightarrow n + e^+$$
$$n + {}^{108}Cd \rightarrow {}^{109}Cd + \gamma$$

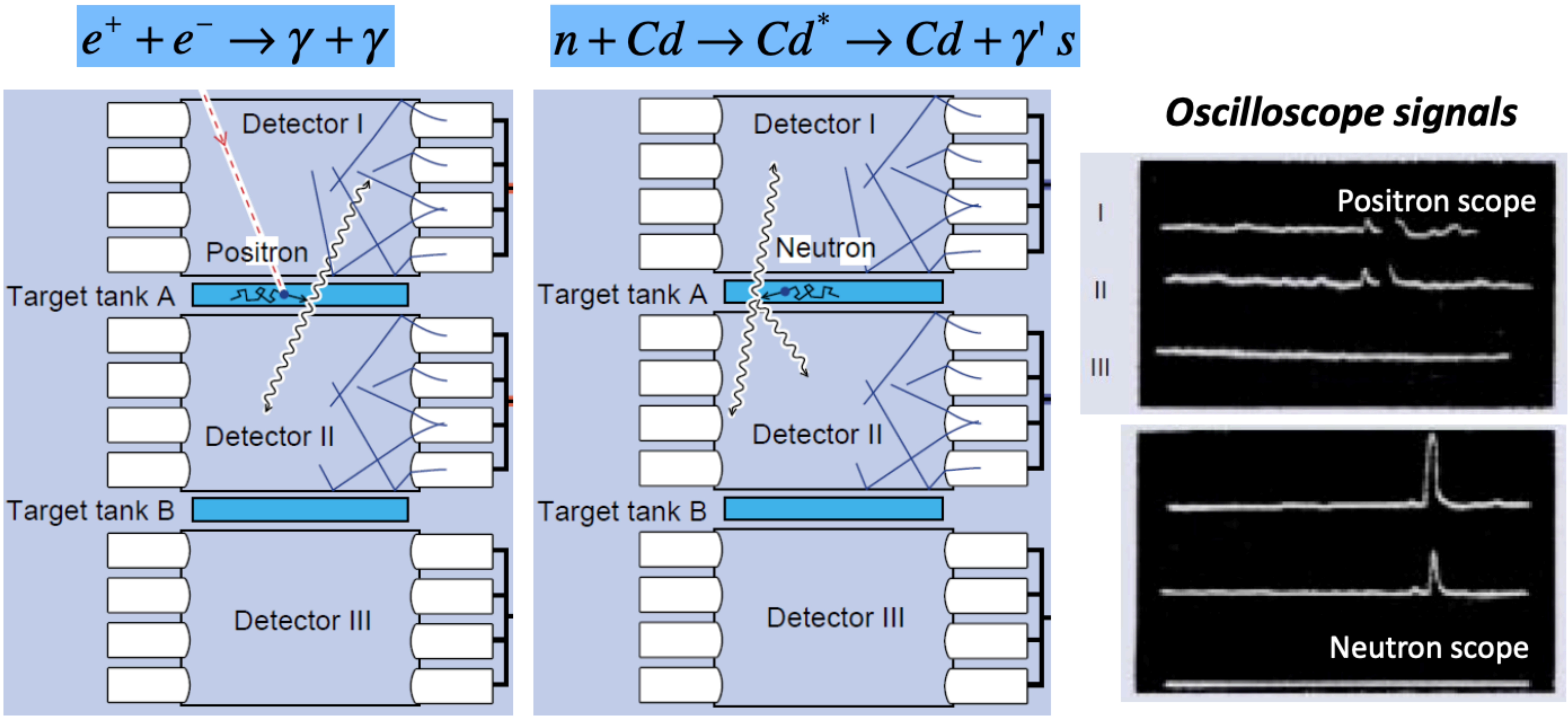
e^+ slow down and annihilates with an e^- producing two 0.5 MeV γ → exit water target and are detected by LS detector

The neutron is slowed down by water and captured by Cd → 3 γ are produced and detected in the LS



- Use coincidence detection technique
- Go underground (12 m shielding)
- 700 MW reactor at 11 m distance → 1.2×10^{13} /cm^{2}s

Savannah River experiment

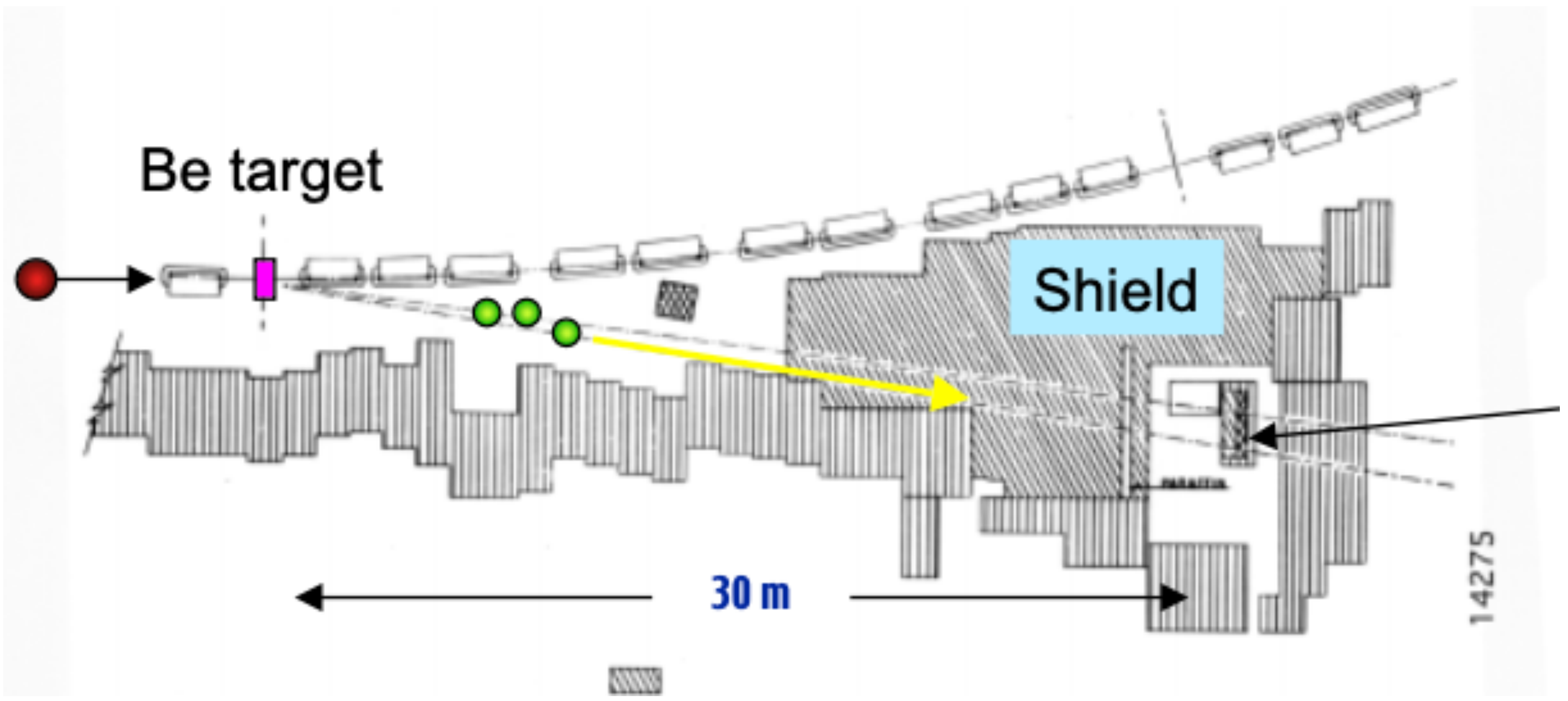


- Rate consistent with expectations
  - Observed a signal rate of 3.0±0.2 ev/h
  - Determined positron and neutron detection efficiency with radioactive sources
  - Use reactor flux of $\phi = 1.2 \cdot 10^{13}/(cm^2 s)$
    - $\sigma_{exp} = (12^{+7}_{-4}) \cdot 10^{-44}\ cm^2$
    - $\sigma_{th} = (5 \pm 1) \cdot 10^{-44}\ cm^2$

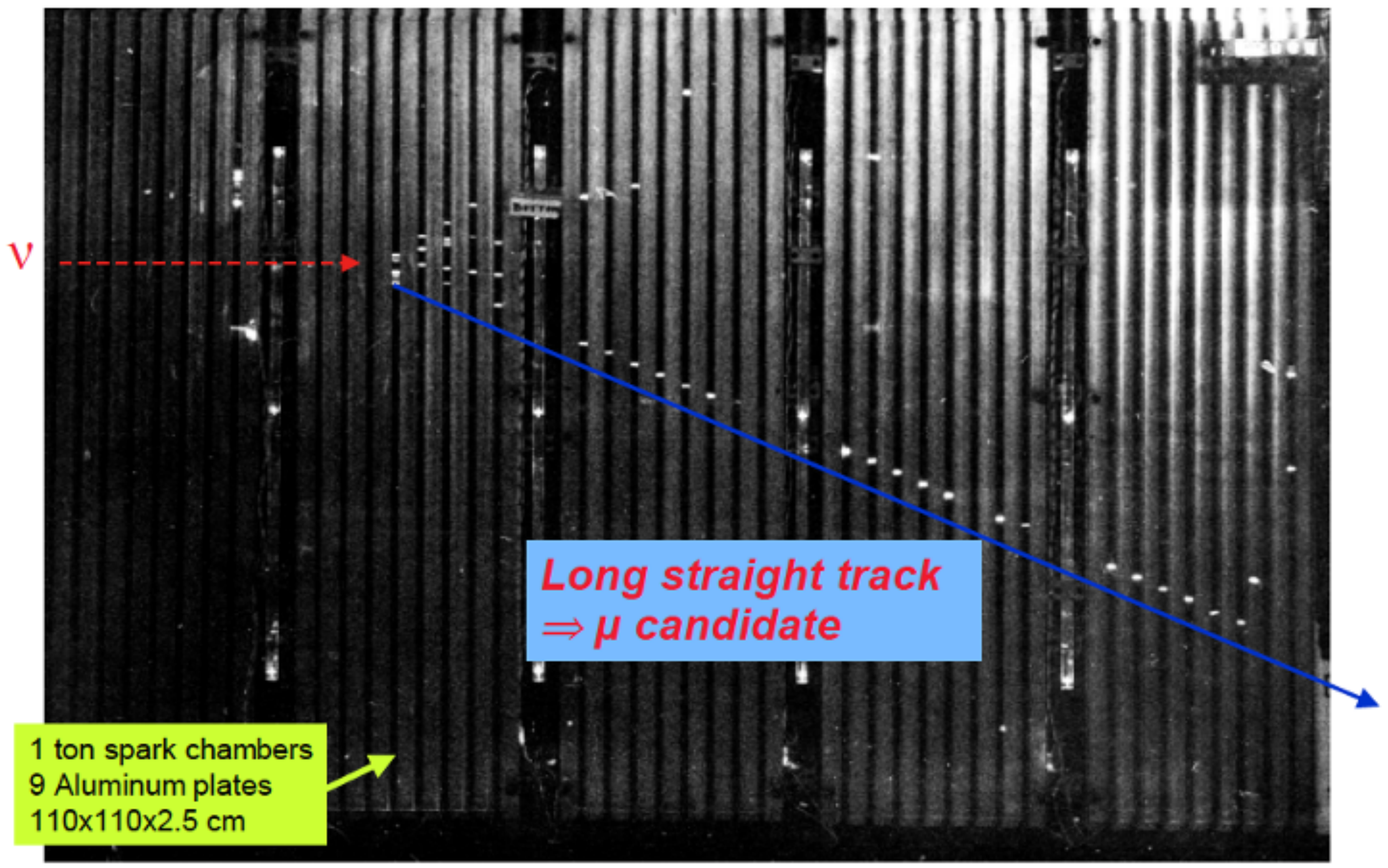
- Each “detector” tank contained 1400 liters of liquid scintillator, viewed on each end by 55 PMTs
- “Target” tank contained 200 liters of water and 40 kg of dissolved $CdCl_2$ for neutron capture
- Lead separating detector and tank

The first accelerator neutrino beam (1962)

- If ν from π-decay and ν from β-decay are the same particles then, by detecting neutrino interactions from neutrinos produced by π-decay, one should observe the same number of
  - $\nu + n \rightarrow e + p$ and $\nu + n \rightarrow \mu + p$
- Need an accelerator able to produce enough neutrinos → Brookhaven AGS accelerator (1962)
  - Proton energy 15 GeV
  - Proton intensity 4×10^{11} p/pulse with 3000 pulse/hour



Need a detector with large mass and able to distinguish e from μ



The Standard Model of neutrinos

- 1914: The electron spectrum in β-decay is continuous → crisis of energy conservation
- 1930: Desperate remedy from Pauli: a new undetectable particle is emitted
- 1933: Fermi introduce the first theory of weak interactions (four-fermion interaction) and names the new particle “neutrino”
- 1956: Reines and Cowan first detection of neutrinos
- 1958: Goldhaber → neutrinos are left-handed particles and anti-neutrinos right-handed
- 1962: Lederman, Schwartz and Steinberger found that $\nu_\mu \neq \nu_e$
- 1966: Davis - observation of ν from the Sun
- 1973: Discovery of neutral currents (Gargamelle @ CERN)
- 1983: Discovery of W and Z at CERN
- 1989: Measurement of Z width at CERN → N_ν=3
- 2000: Direct observation of τ neutrino

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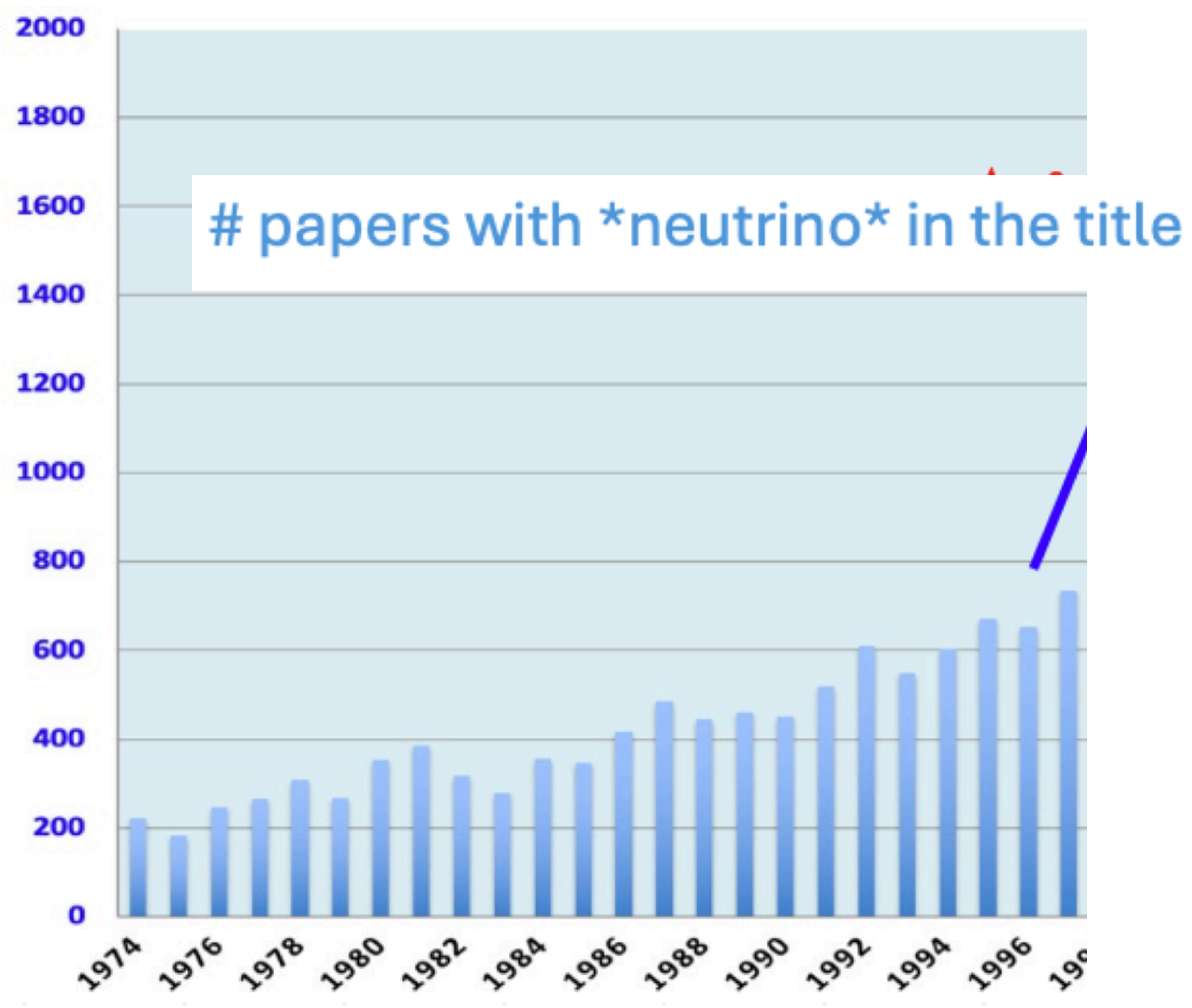


That's it!

Merci et à la prochaine!

Neutrino oscillates!

The New York Times

NEW YORK, FRIDAY, JUNE 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, Friday, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that a significant part of the mass of the universe might be in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter, the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

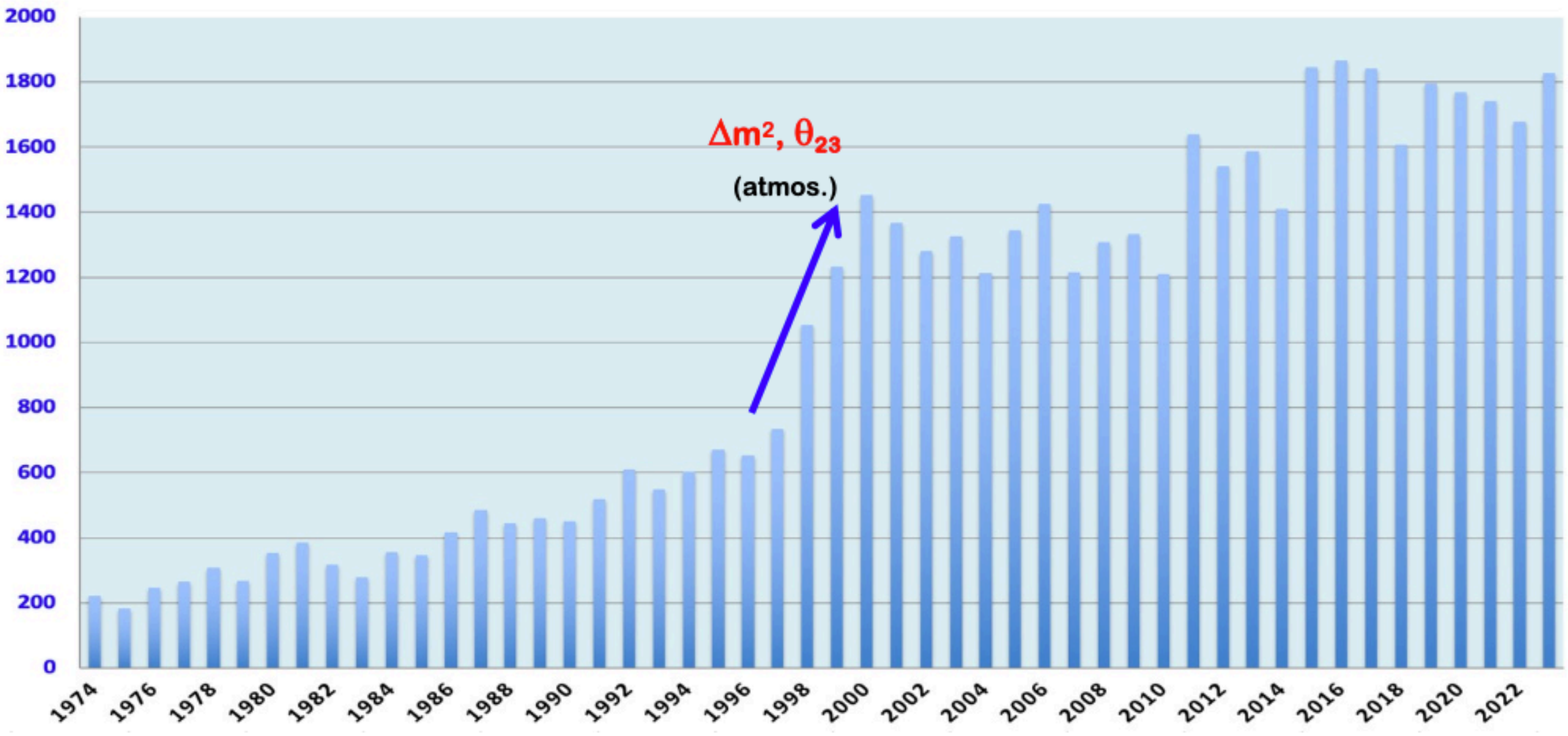
Detecting Neutrinos

And Detecting Their Mass

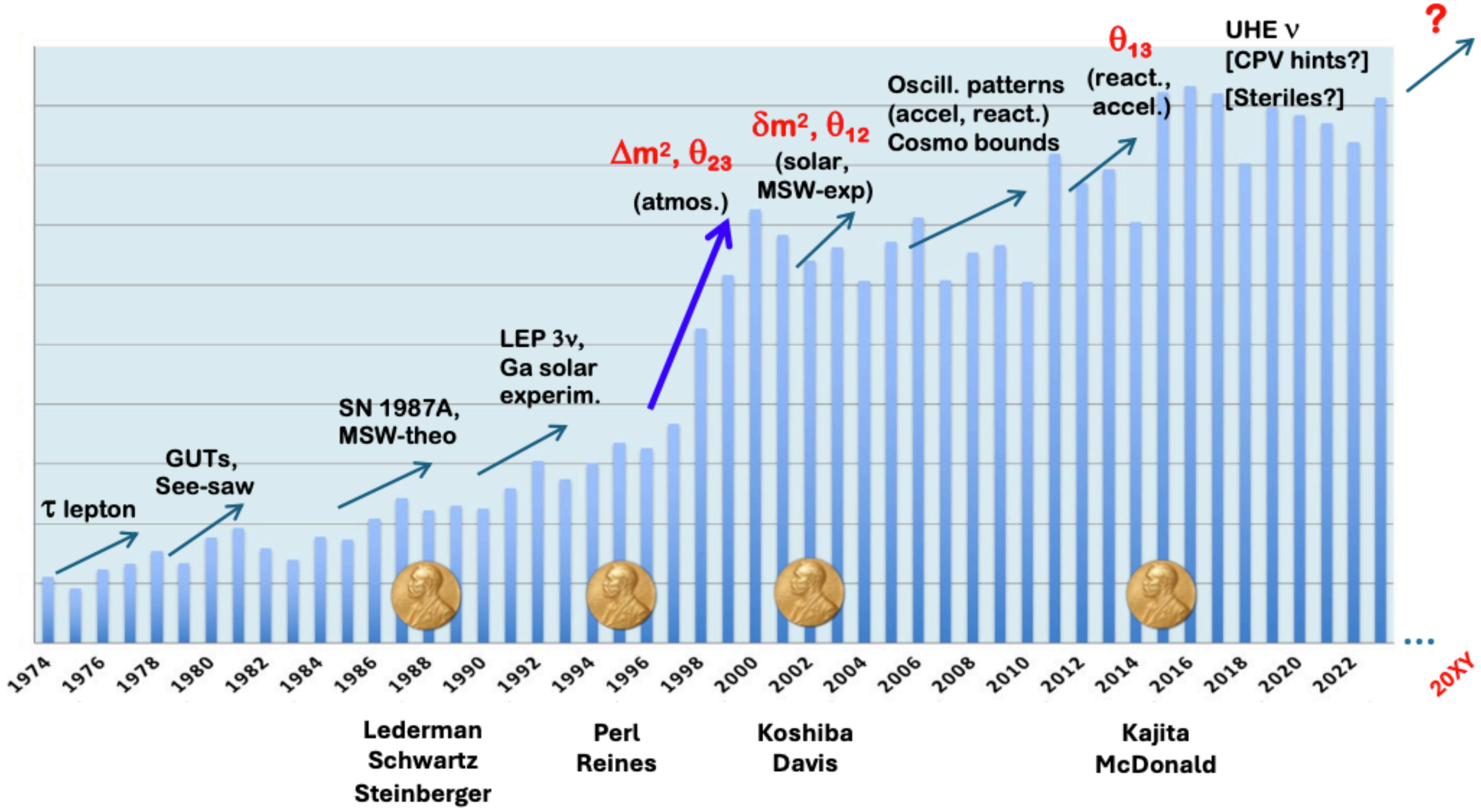
By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

papers with *neutrino* in the title, 50-yr trend from iNSPIRE HEP



Discovery of ν oscillations



τ lepton
GUTs,
See-saw
SN 1987A,
MSW-theo
LEP 3ν,
Ga solar
experim.
Δm², θ23
(atmos.)
δm², θ12
(solar,
MSW-exp)
Oscill. patterns
(accel, react.)
Cosmo bounds
θ13
(react.,
accel.)
UHE ν
[CPV hints?]
[Steriles?]
?
1974
1976
1978
1980
1982
1984
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2002
2004
2006
2008
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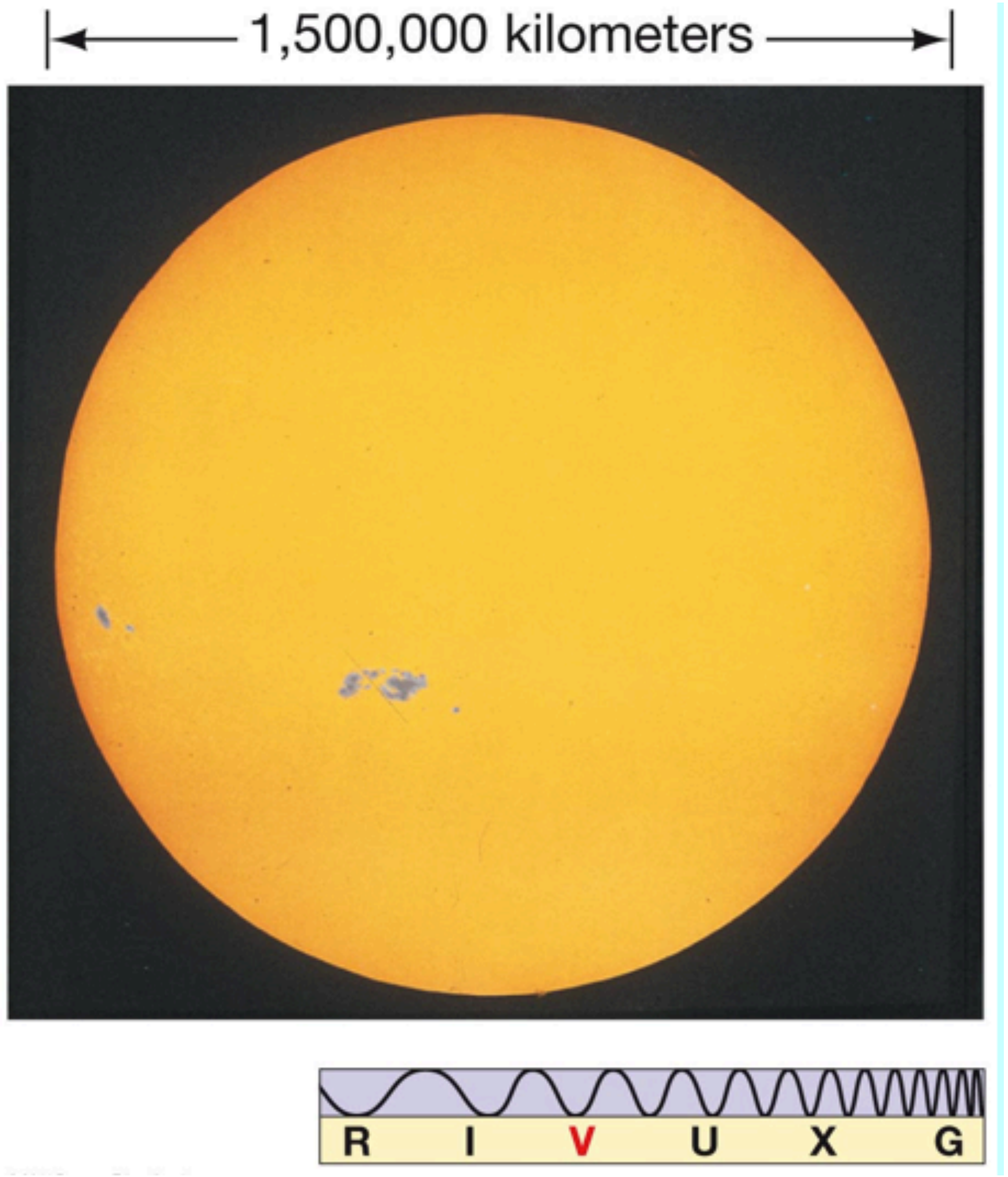
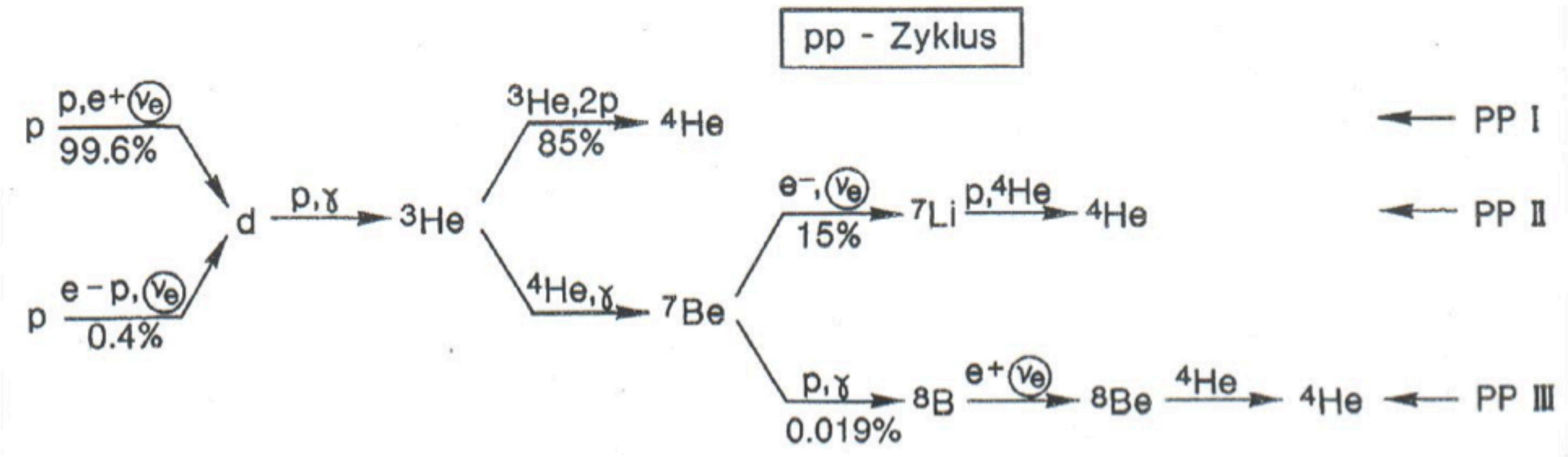
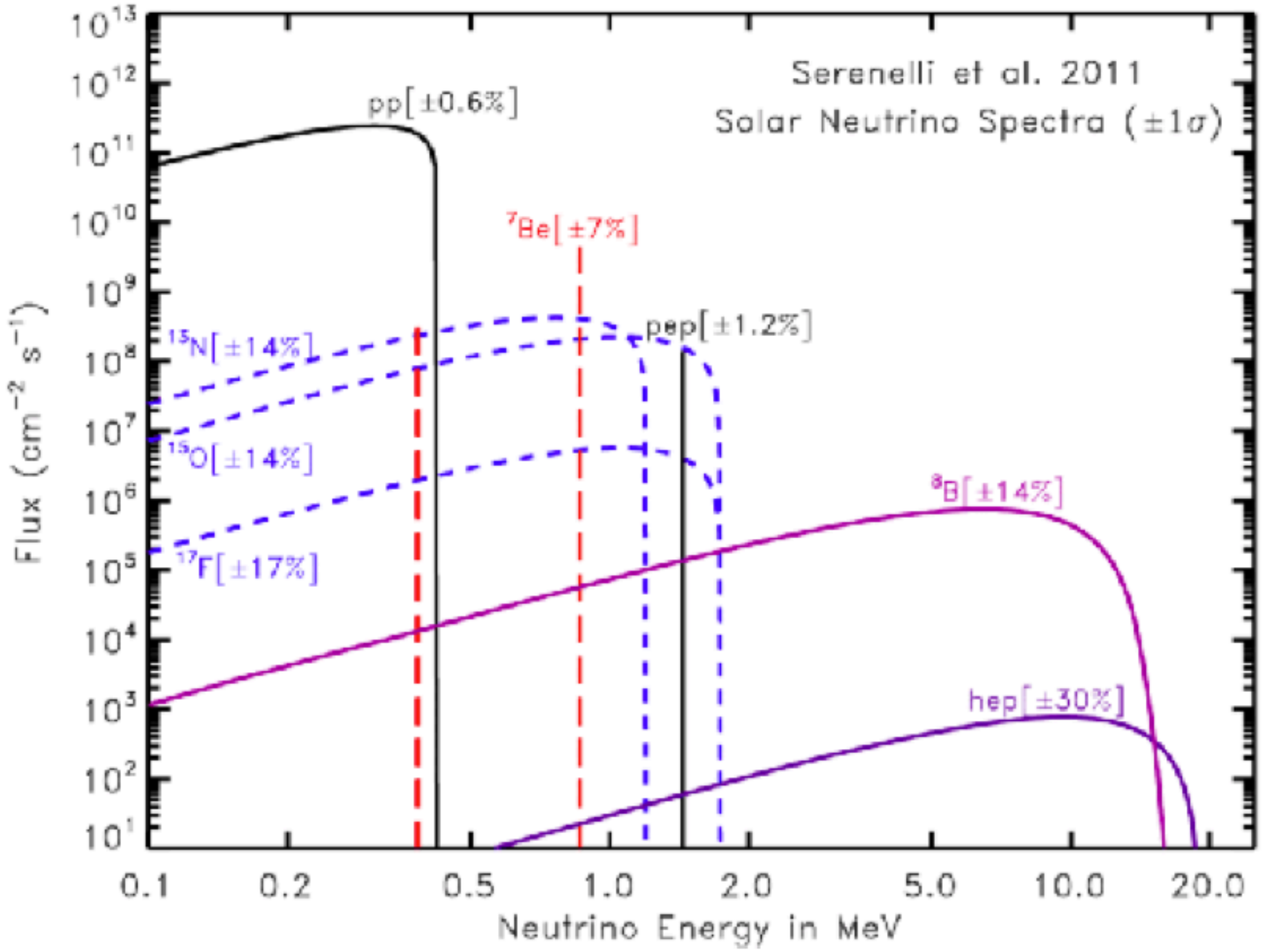
2012
2014
2016
2018
2020
2022
20XY
...
Lederman
Schwartz
Steinberger
Perl
Reines
Koshiba
Davis
Kajita
McDonald

Solar Neutrinos

$$4\,H^+ + 2e^- \rightarrow {}^4He^{++} + 2\,\nu_e + 26.73\text{ MeV}$$
$$\langle E(2\nu_e)\rangle = 0.59\text{ MeV}$$

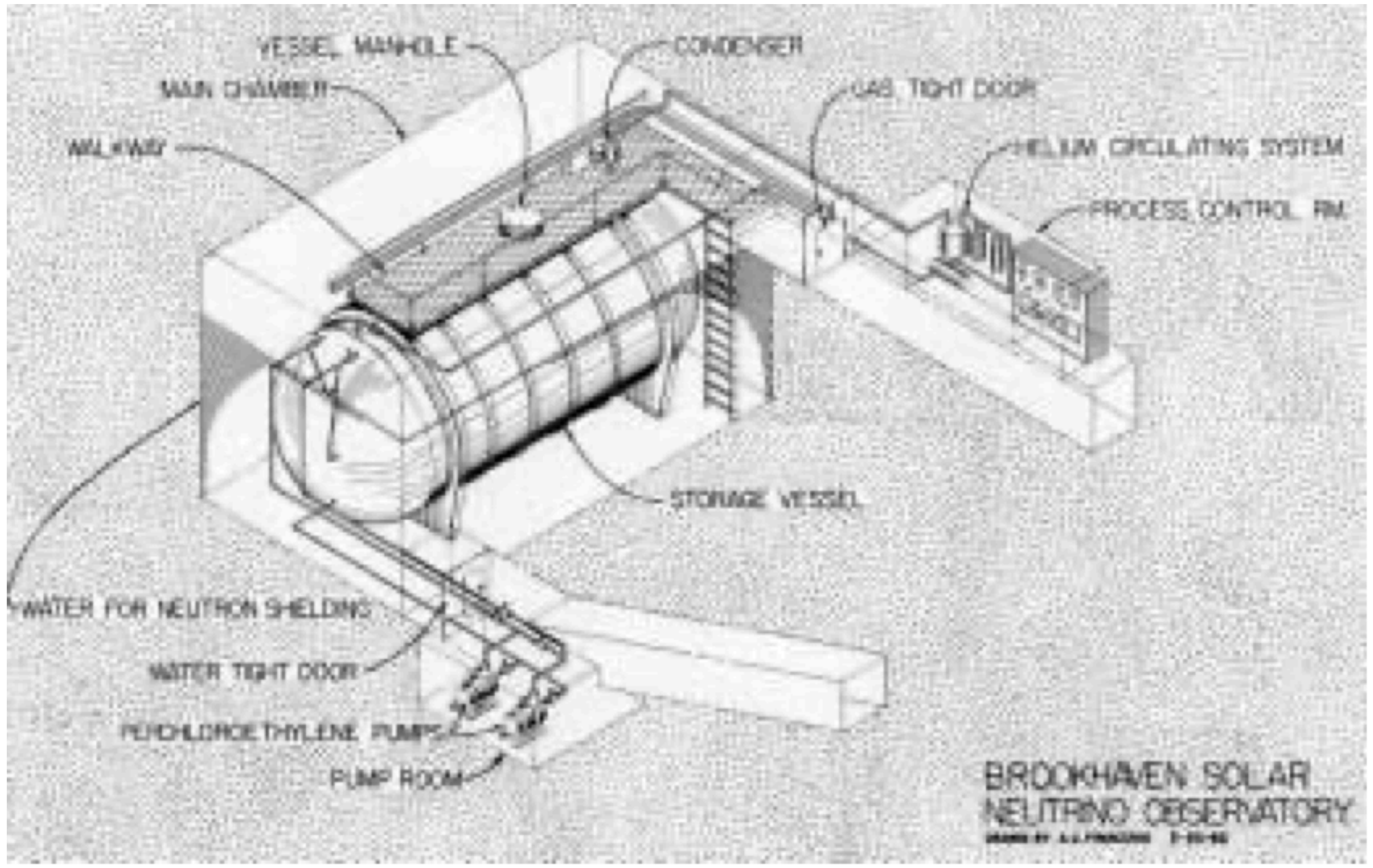






Homestake experiment

- 0.61 kton of perchloroethylene
- 1500 m undergound
- Argon extracted chemically every few months and decays counted in a counting station (35 days of half-life)



Very first run (letter from Davis to Willy Flowler)

Argon from 10^5 gal tank = 16 ± 4 counts (tot. 39.7 d)

Background = 4 × (39.7/11.5) = 14 ± 4 counts (for 39.7 d)

Increase = 2 ± 5 counts

Using: 2.1×10^{30} Cl^{37} atoms in tank

Counter efficiency ≈ 0.50

Then, $\Sigma\phi\sigma = (0.2 \pm 0.4) \times 10^{-35}\ \mathrm{sec}^{-1}$

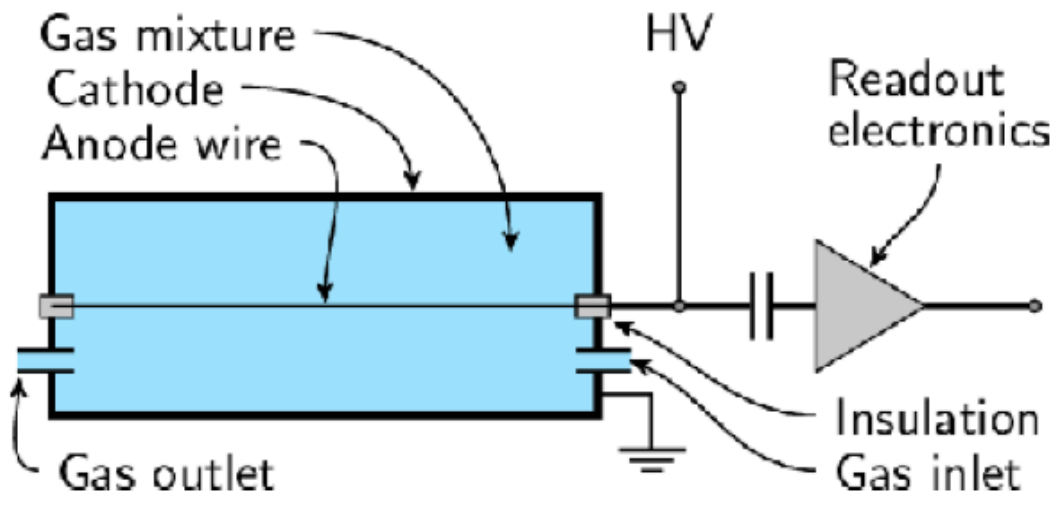
$\leq 0.6 \times 10^{-35}\ \mathrm{sec}^{-1}$

Using $\phi(B^8) = 1.35 \times 10^{-42}$ (Bahcall)

$\phi B^8 \leq 0.5 \times 10^7\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$

Please regard these results as very preliminary. There are several points that must be checked before we are certain this is a bonafide observation. I will collect another sample in September–we are ready now, turn on the sun.

Counting. The purified argon is loaded into a small **proportional counter** along with tritium-free methane, which serves as a counting gas. Signal: 2.82 keV Auger electron from electron capture decay of ^{37}Ar. The counting of the gas typically continues for about one year (~10 half lives).



$$_{18}Ar^{37} + e^- \rightarrow {}_{17}Cl^{37} + \nu + 3\ \text{keV x-ray}$$

Homestake results

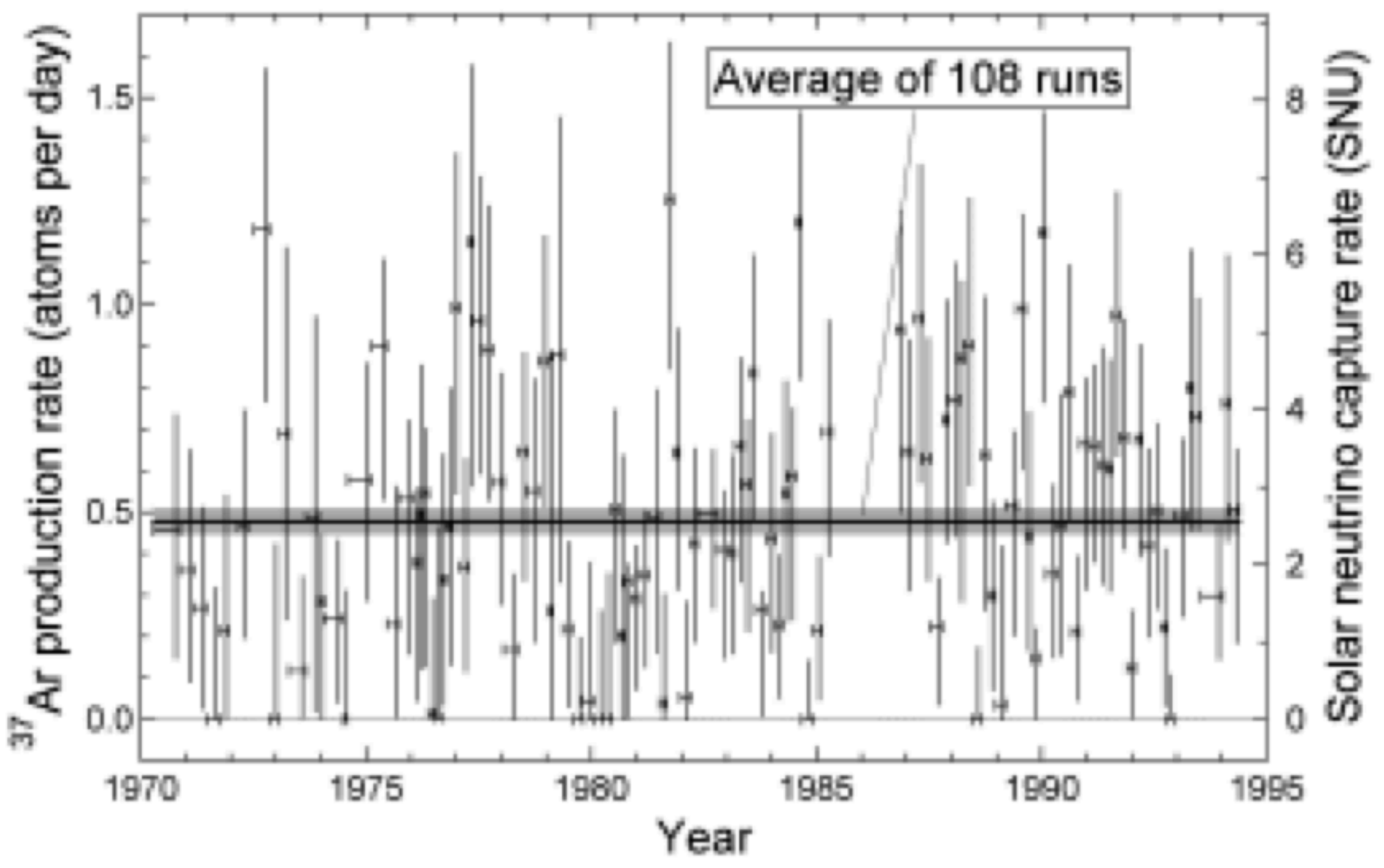
- Homestake experiment run for more than 20 years and found a flux of ν from sun
  1/3 of the expected flux

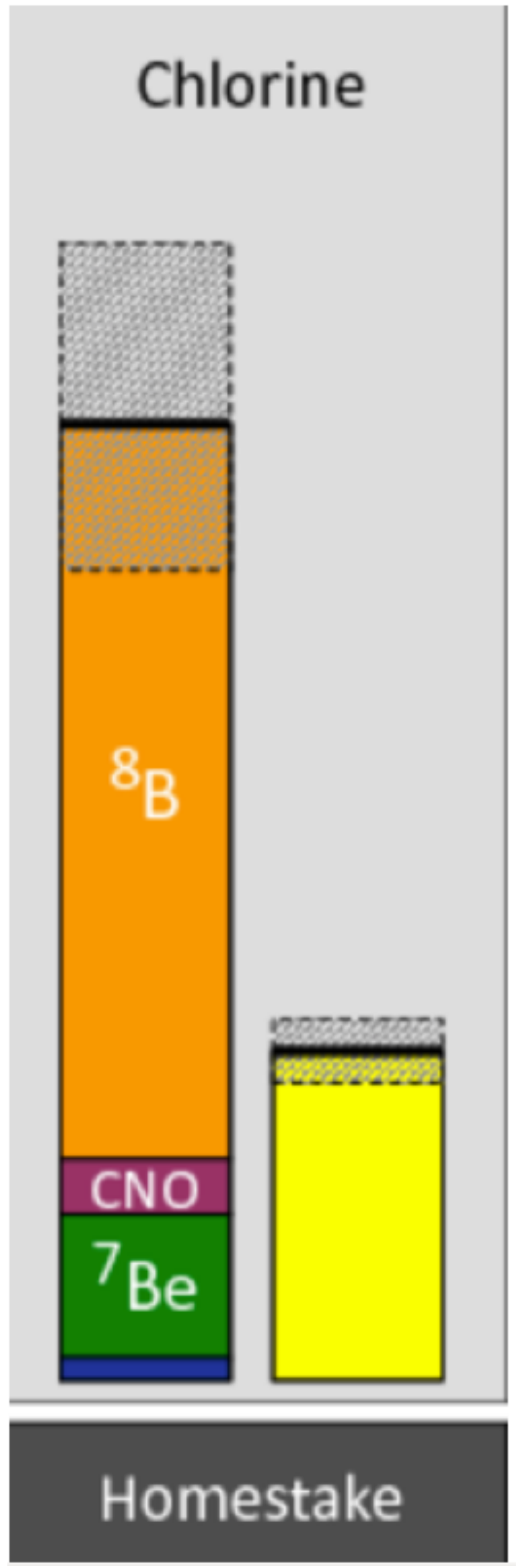
$$\langle \sigma\phi \rangle_{^{37}Cl} = (2.55 \pm 0.17 \pm 0.18)\ SNU$$

$$\langle \sigma\phi \rangle_{th} = (8.0 \pm 0.1)\ SNU\ or\ (6.4 \pm 1.4)\ SNU$$

Solar Neutrino problem is born and Homestake has been the only running experiment for > 20 years!

At first, the scientific community thought the experiment must be wrong, but Davis insisted he was right. "The solar neutrino problem caused great consternation among physicists and astrophysicists", Davis wrote. "My opinion in the early years was that something was wrong with the standard solar model; many physicists thought there was something wrong with my experiment."

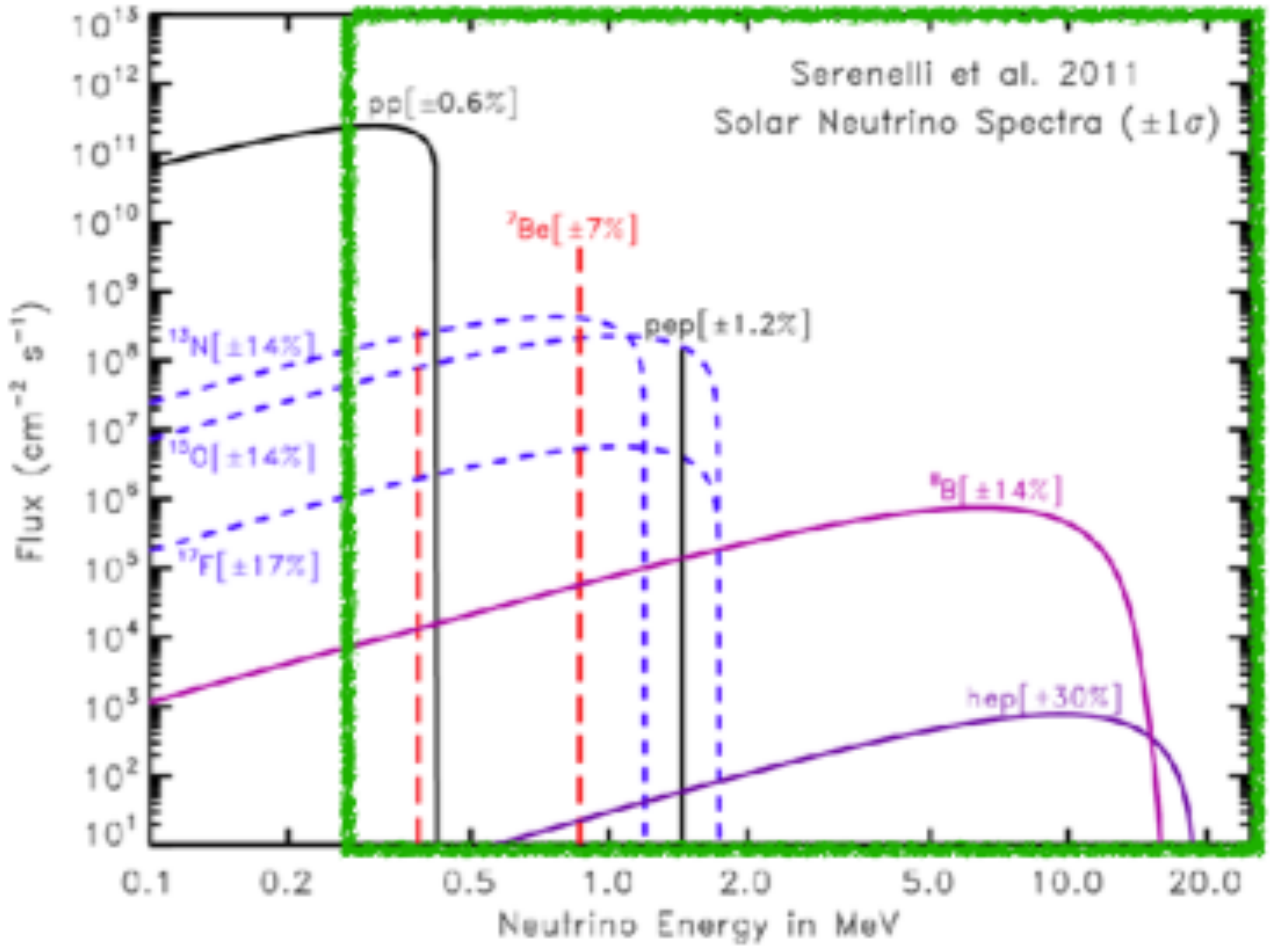




1 SNU = the neutrino flux producing 10^{-36} captures per target atom per second

Gallium experiments

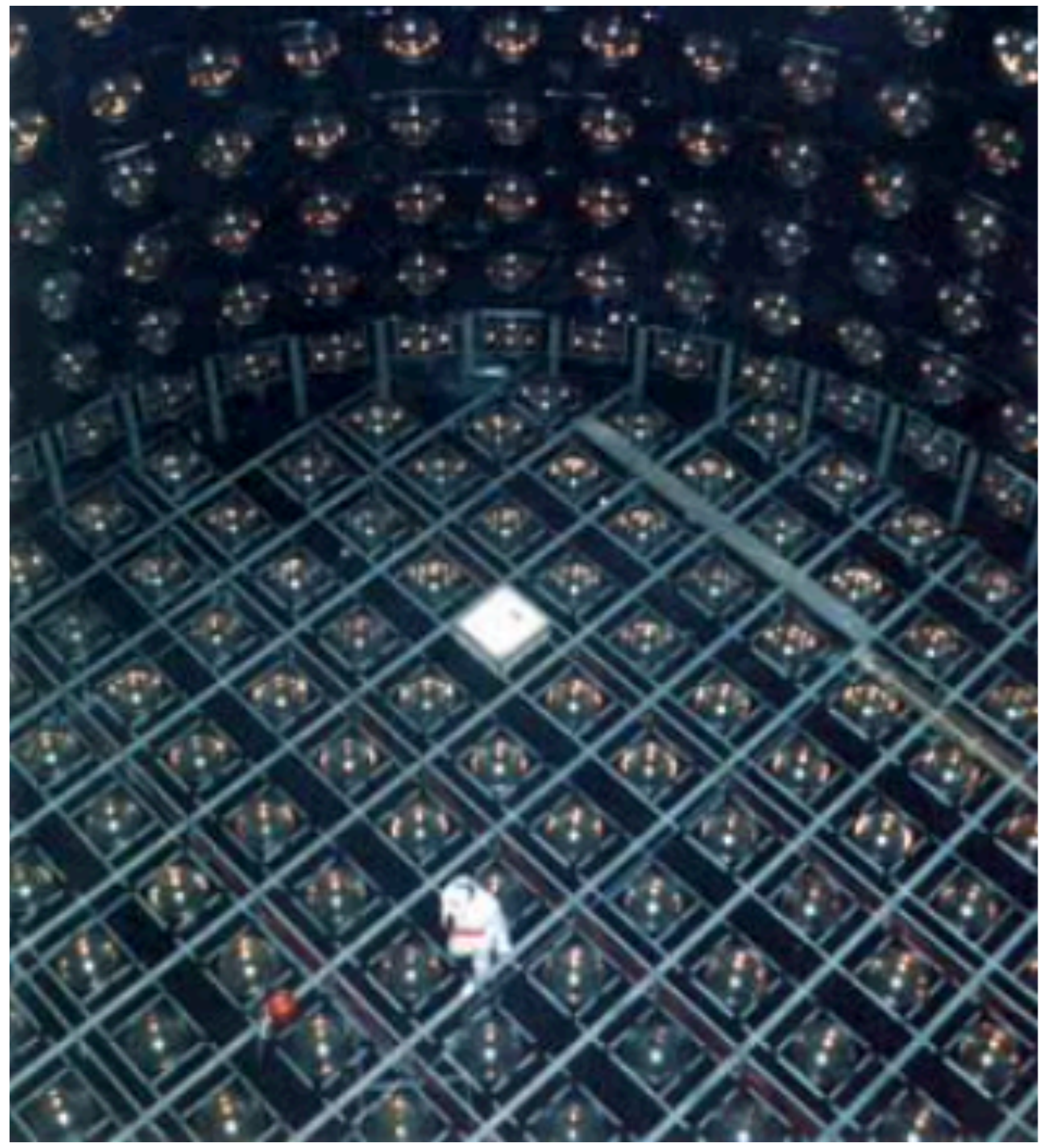
- Another target for radiochemical experiments are capture on Gallium
- $\nu_e + ^{71}Ga \rightarrow ^{71}Ge + e^-$ and then $^{71}Ge \rightarrow ^{71}Ga + \nu_e + \gamma$ with τ_d~11.4 days
- The threshold is much lower than 37Cl → 233 keV instead of 0.8 MeV → sensitive to pp-neutrinos
- Lower threshold require particular care for the backgrounds!



SAGE: Soviet-American Gallium Experiment
- Baksan Neutrino Observatory, northern Caucasus
- 50 tons of metallic 71Ga
- 2000 m deep, 4700 m.w.e. => $\Phi\mu$ ~ 2.6 m^{-2} day^{-1}

GALLEX / G.N.O. : GALLium EXperiment
- Gran Sasso Underground Laboratory, Italy,
- 30.3 tons of gallium in 101 tons of gallium chloride ($GaCl_3$ -HCl) solution
- 1400 m deep, 3300 m.w.e.=> $\Phi\mu$ ~ 30 m^{-2} day^{-1}

KamiokaNDE



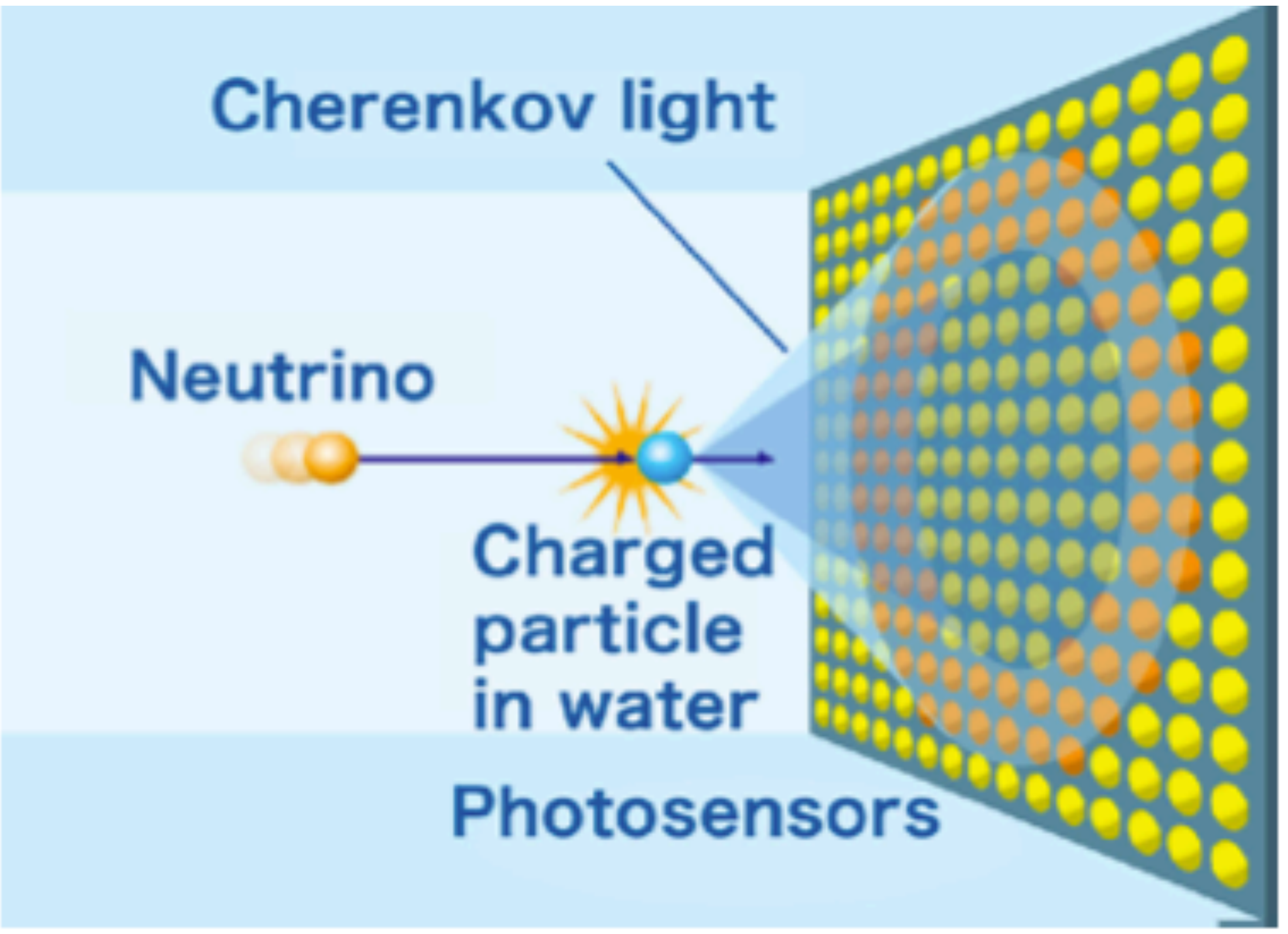
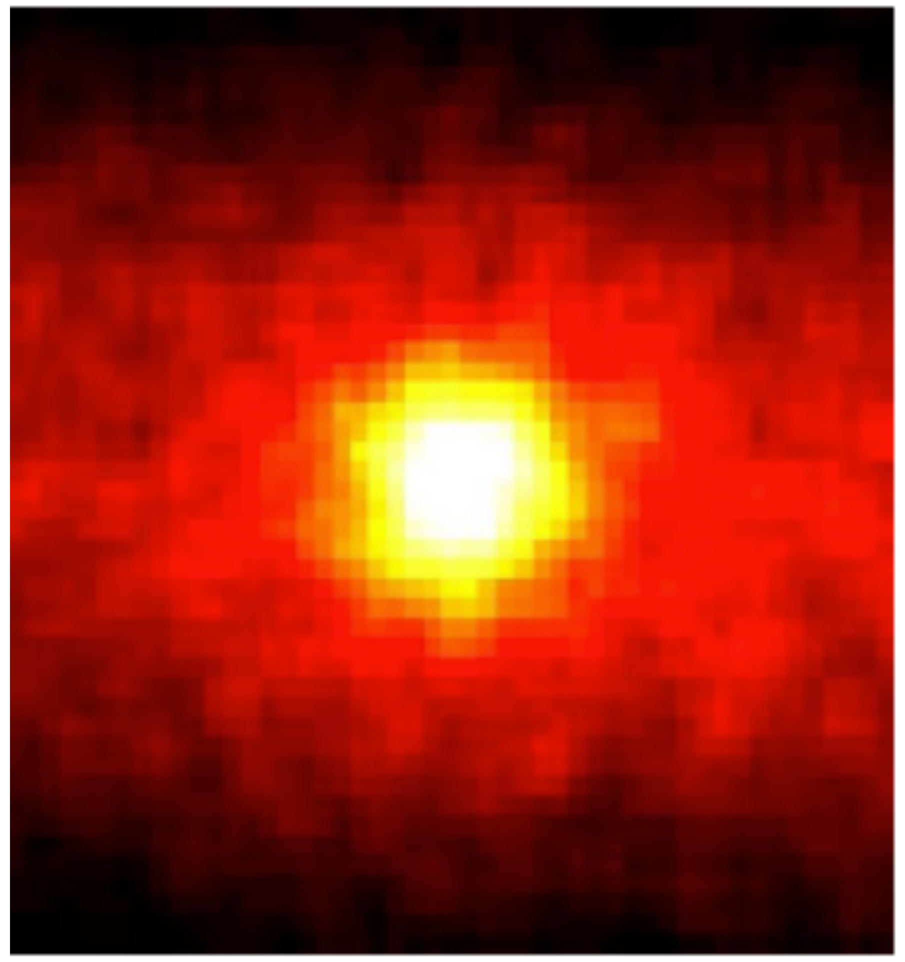
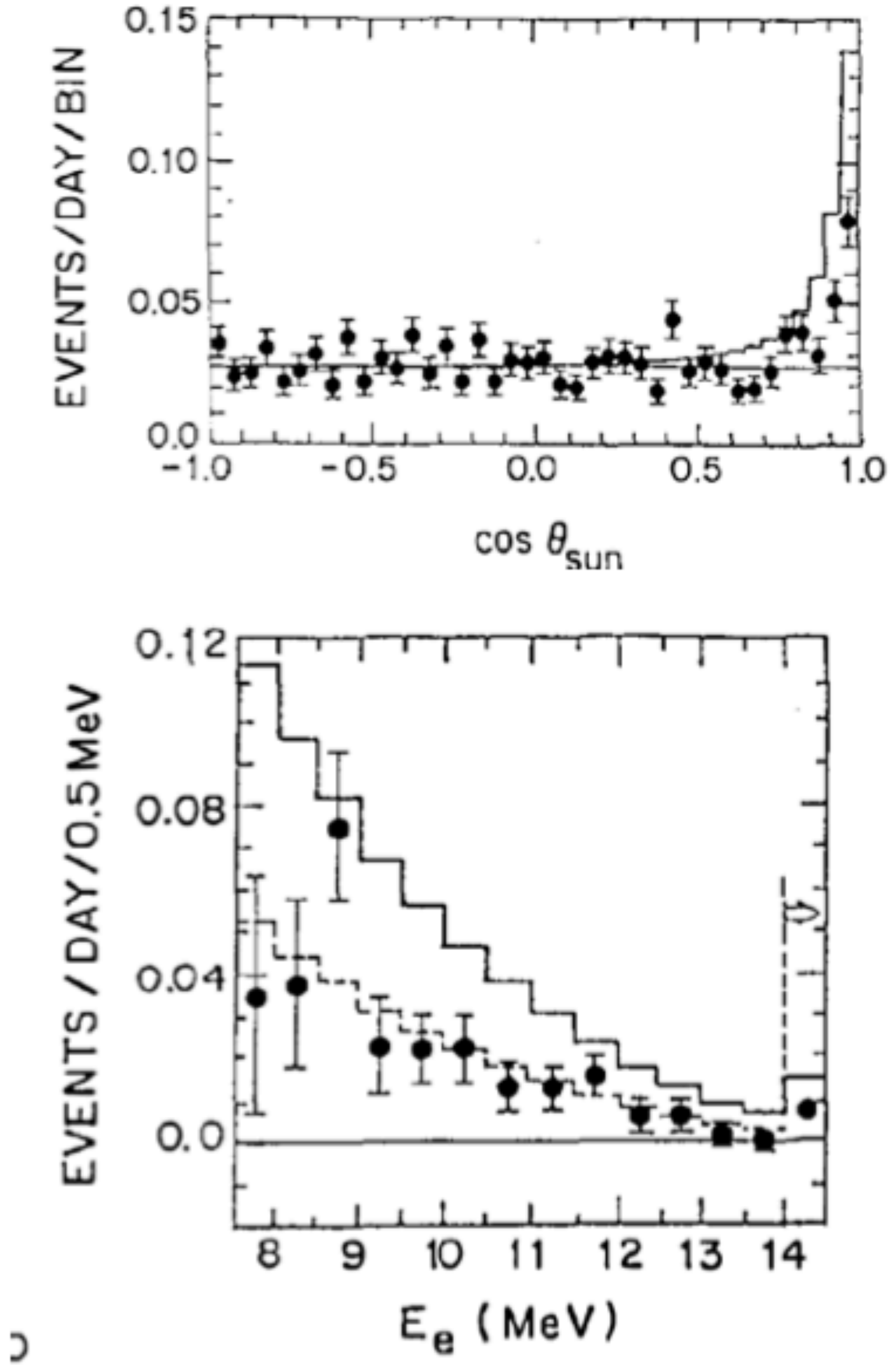
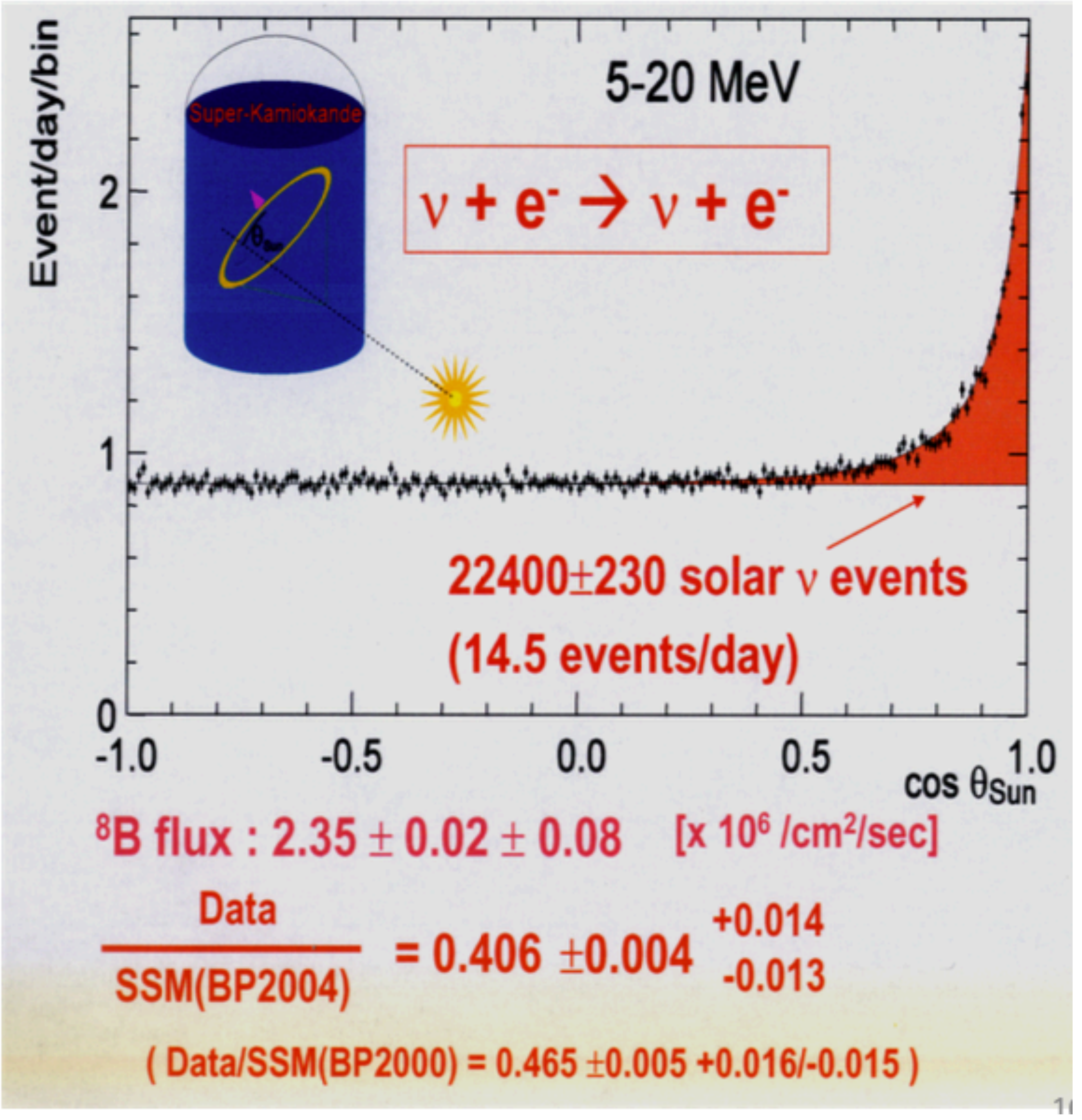


Image of the Sun from 1000 m Underground!

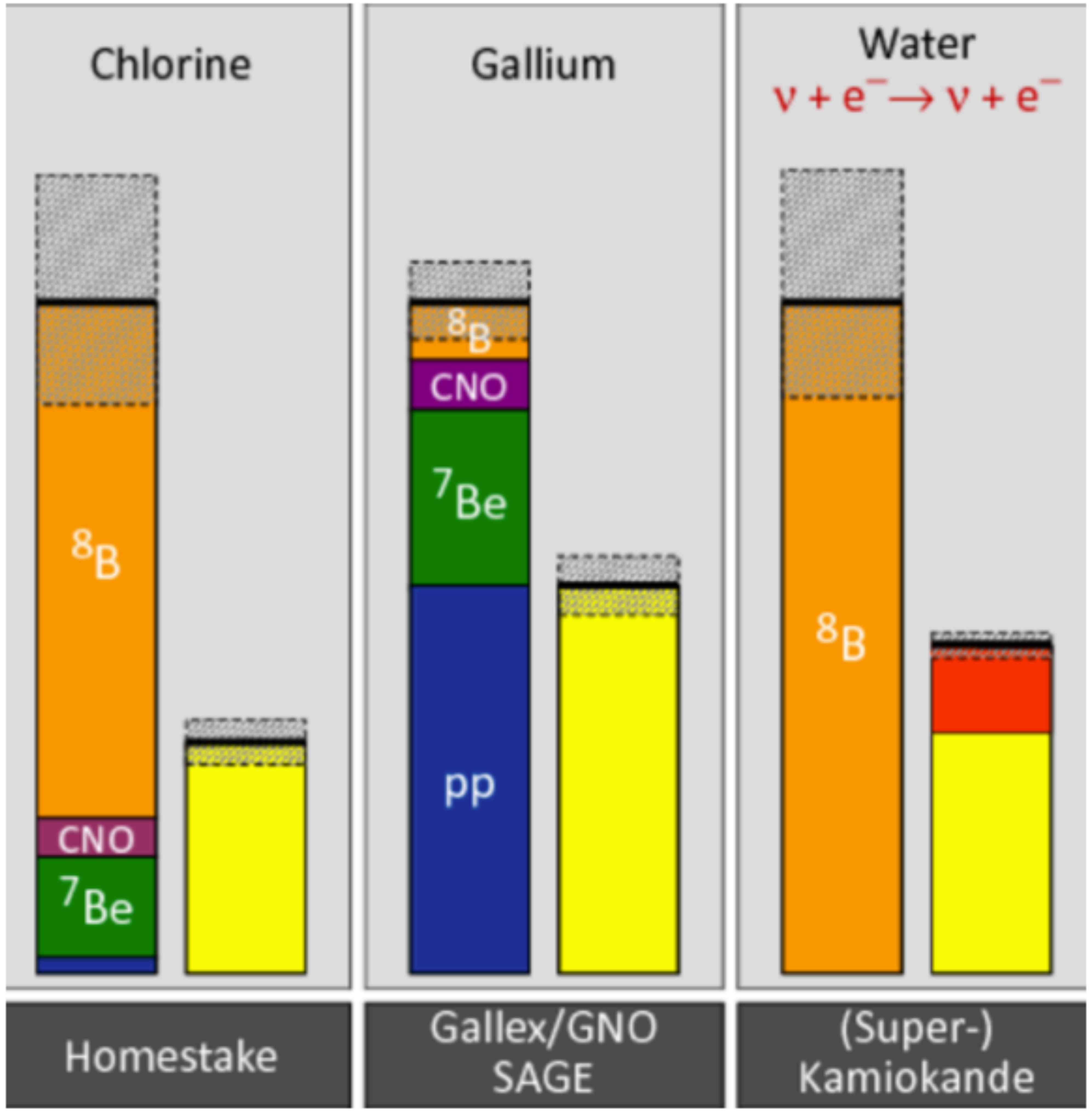






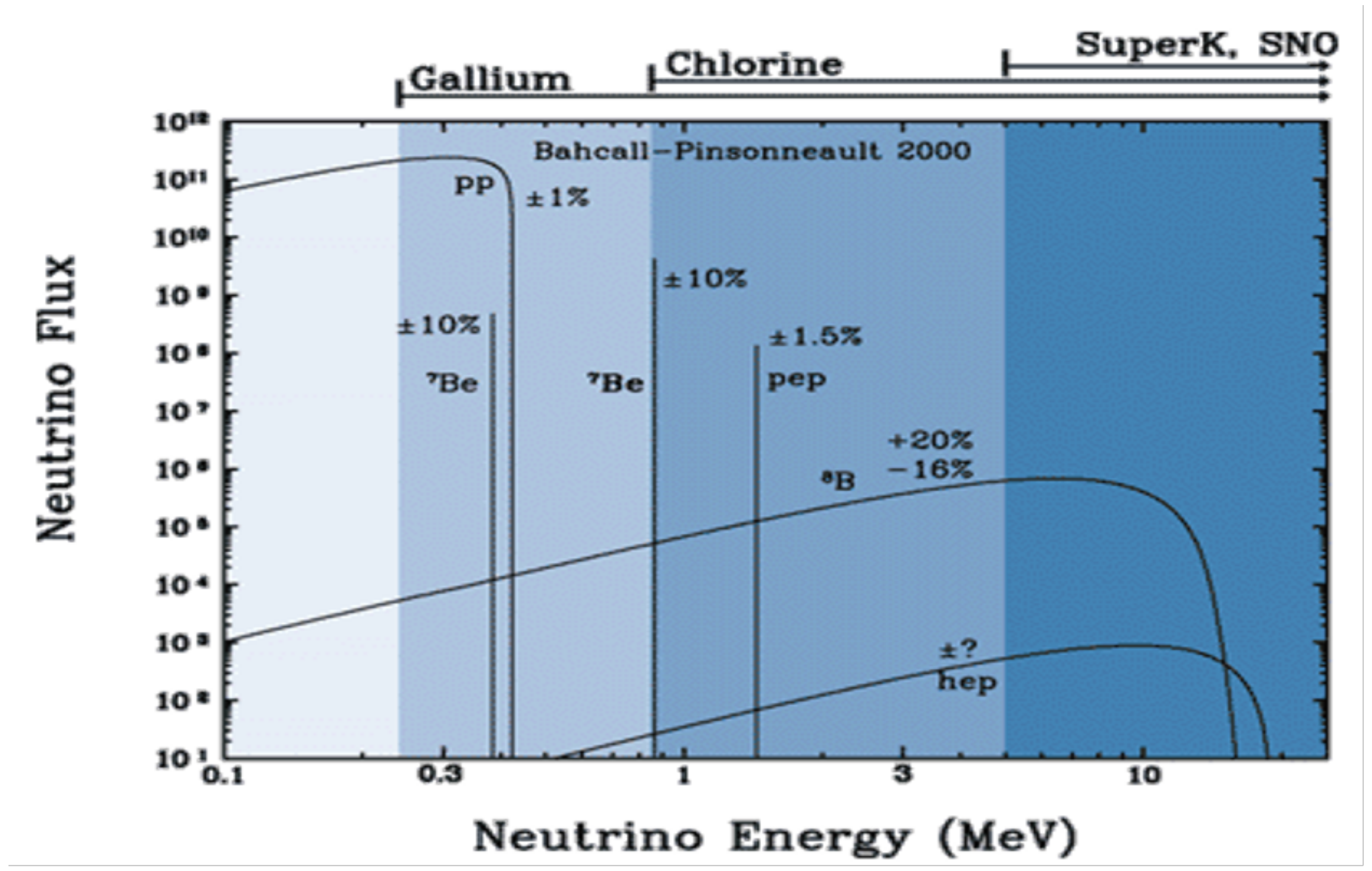
- Measure neutrinos in real time
- Angle information allow to separate solar neutrinos from backgrounds
- Direct demonstration that the Sun produce neutrinos!
- Recoil spectrum is reduced in amplitude but not distorted in shape

Solar Neutrino Anomaly



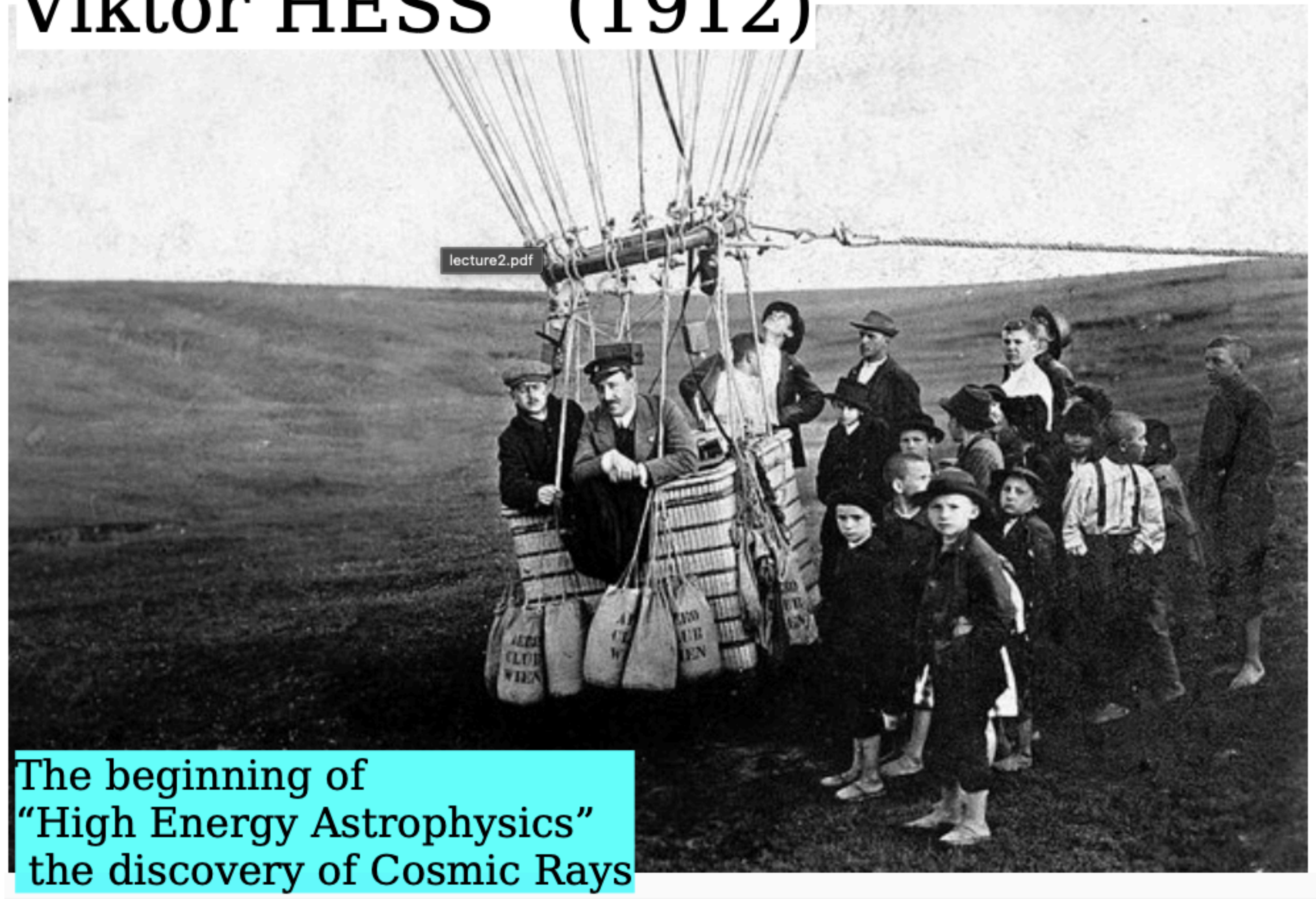
- 3 different types of experiment
  - Different energy threshold
  - Observing different components of the solar ν flux

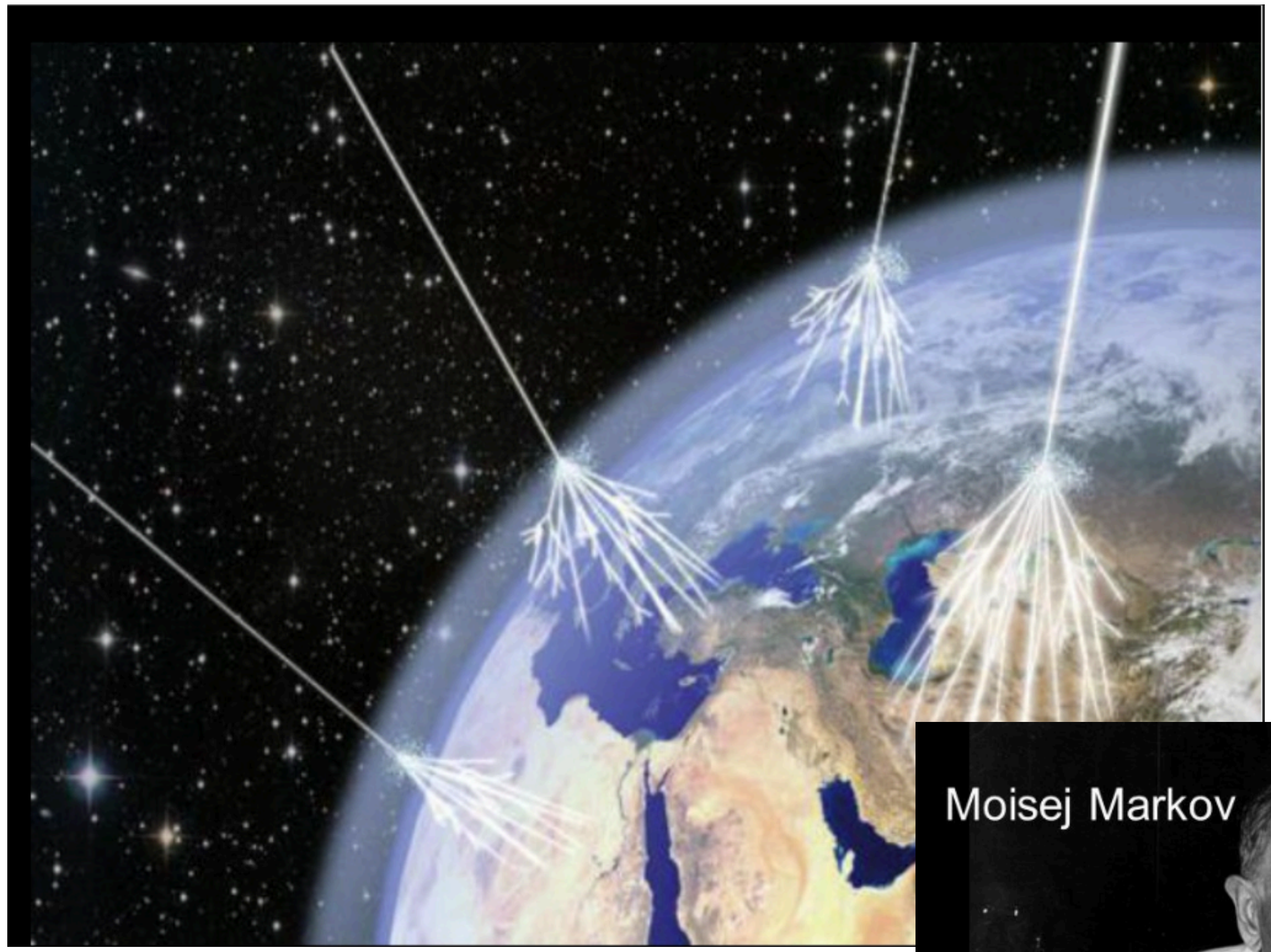
- They all observe a deficit with respect to the Standard Solar Model

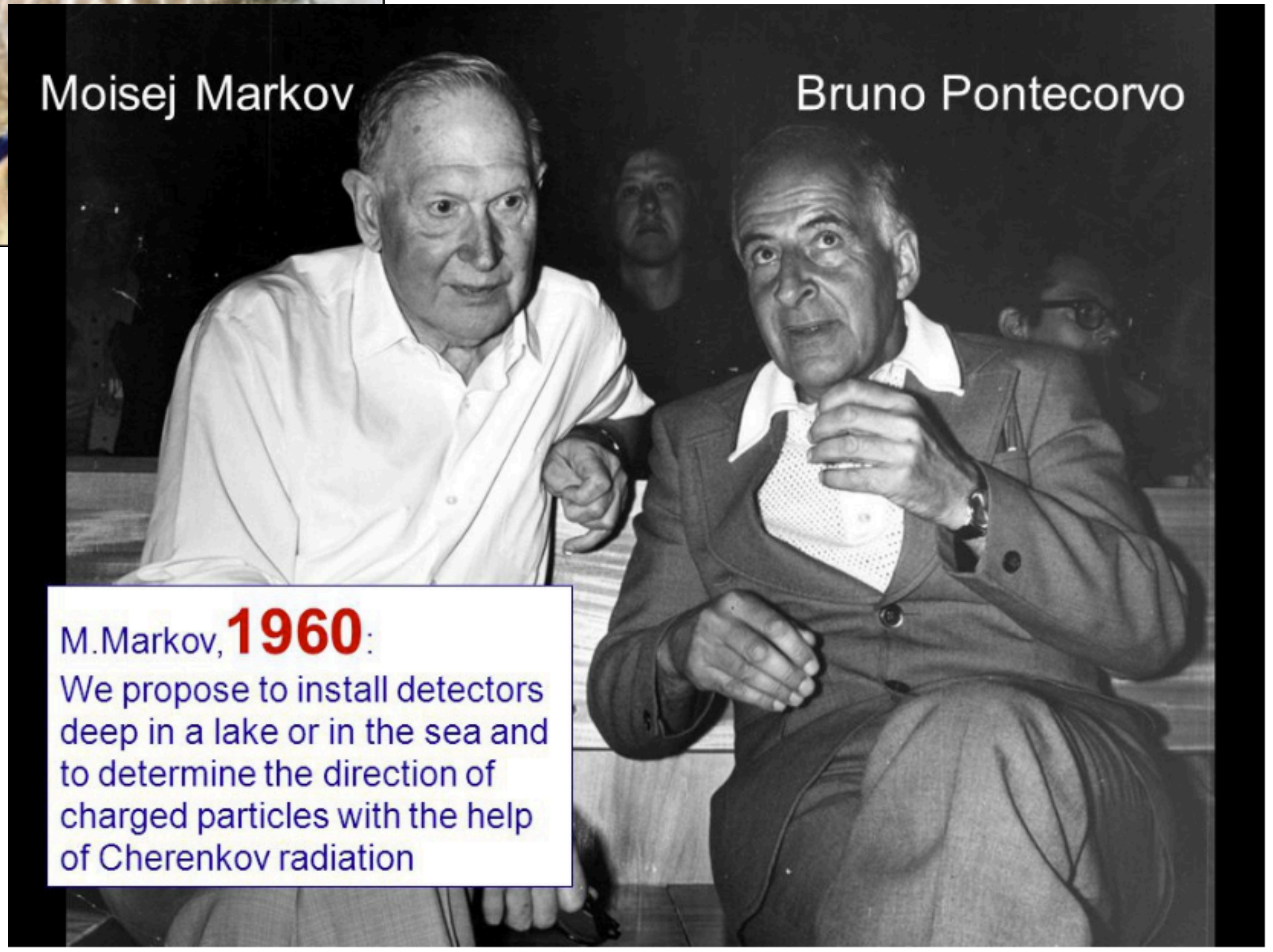


Atmospheric Neutrinos

Viktor HESS (1912)





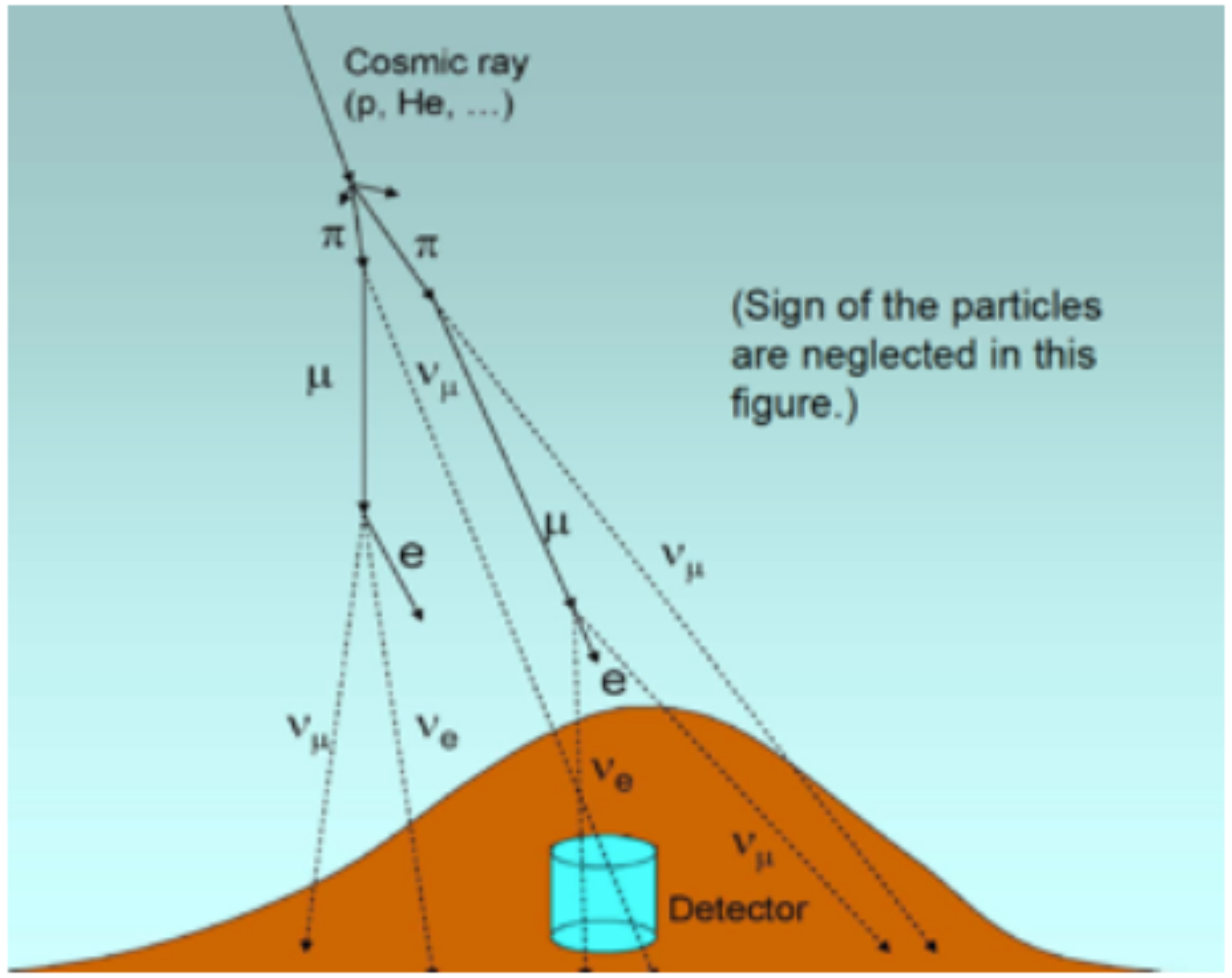


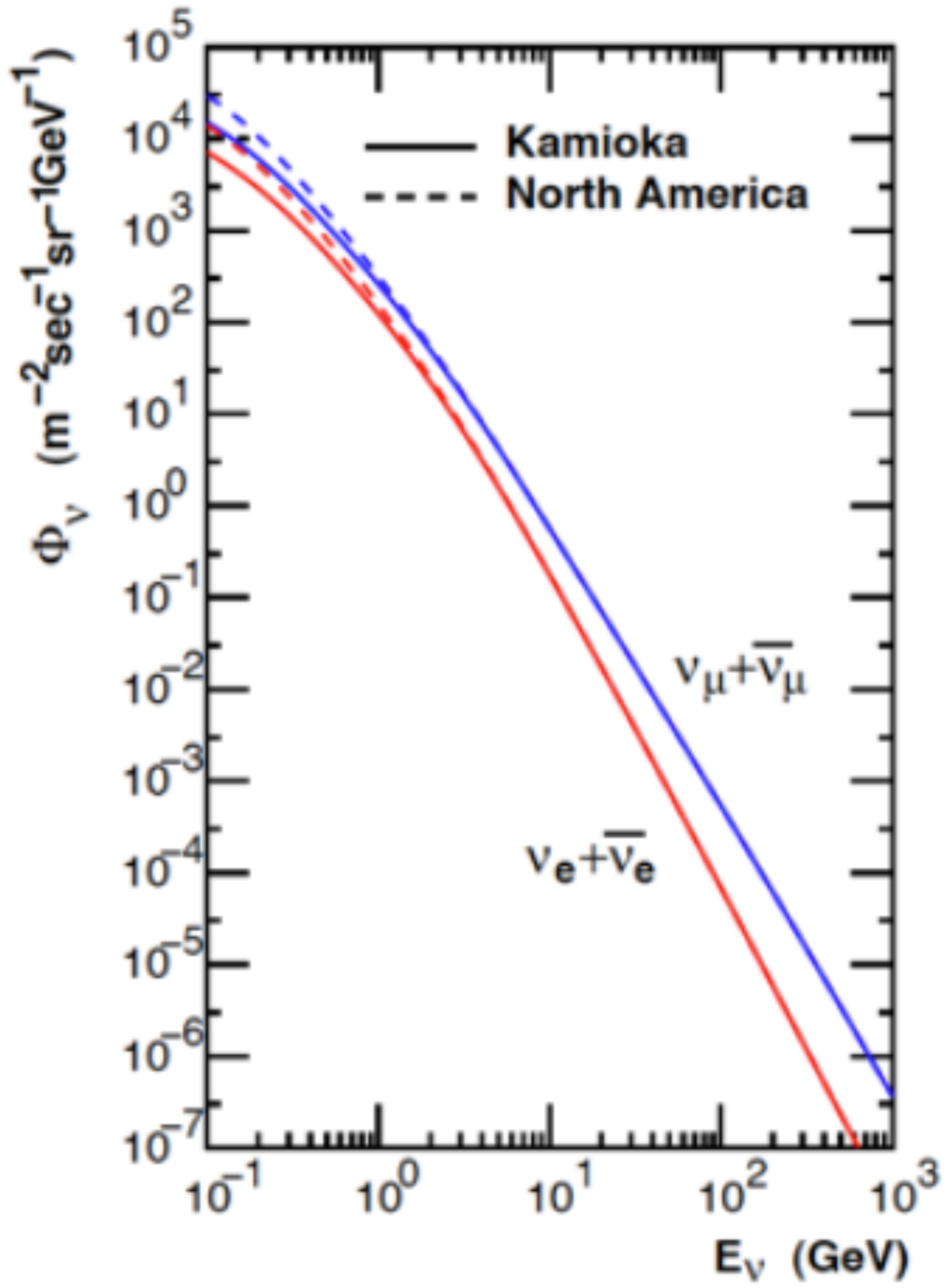
- Cosmic ray showers in Earth Atmosphere

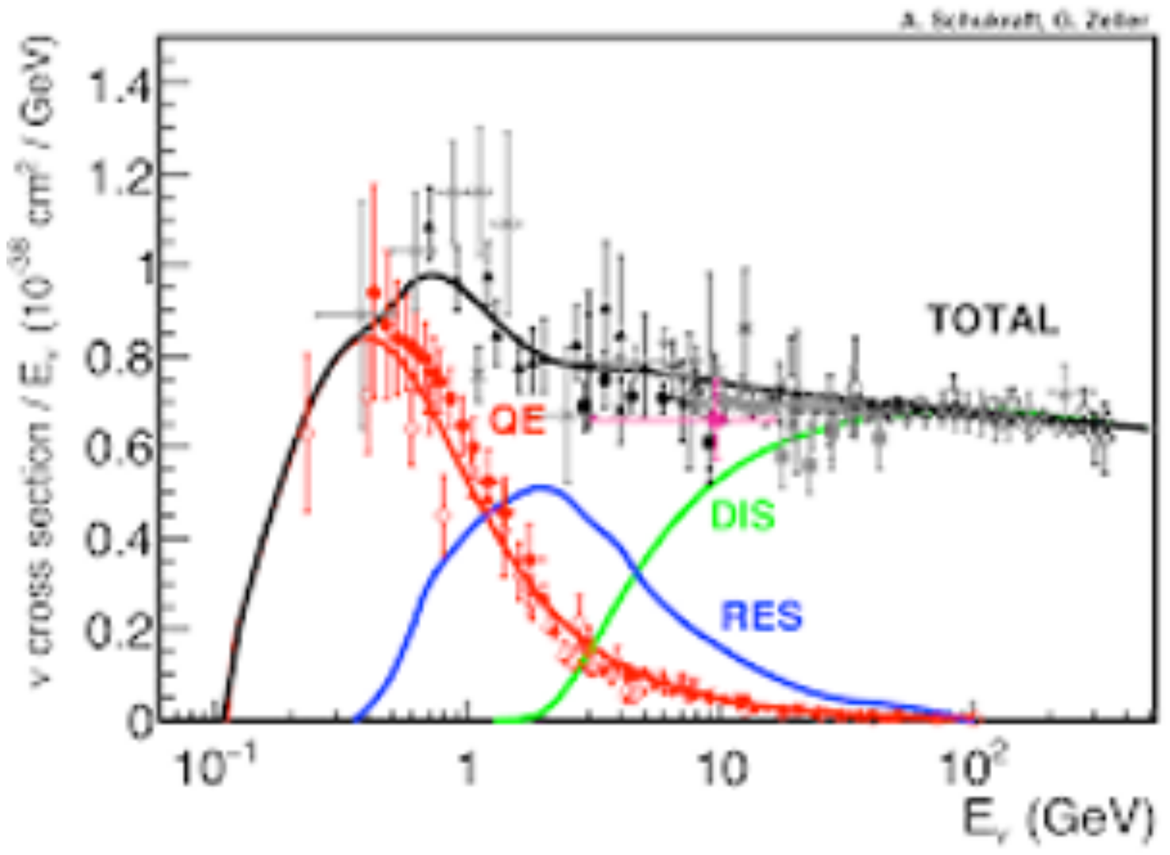
  $p + Air \rightarrow p, \pi^+, \pi^-, \pi^0, K, \ldots$

- These mesons will decay producing neutrinos → can we detect them?
- $\pi^+ \rightarrow \mu^+ \nu_\mu \qquad \mu^+ \rightarrow \bar{\nu}_\mu e^+ \nu_e$ → Expected ratio of ν_μ/ν_e ~ 2/1

Atmospheric neutrino fluxes







~1 $cm^{-2}s^{-1}$

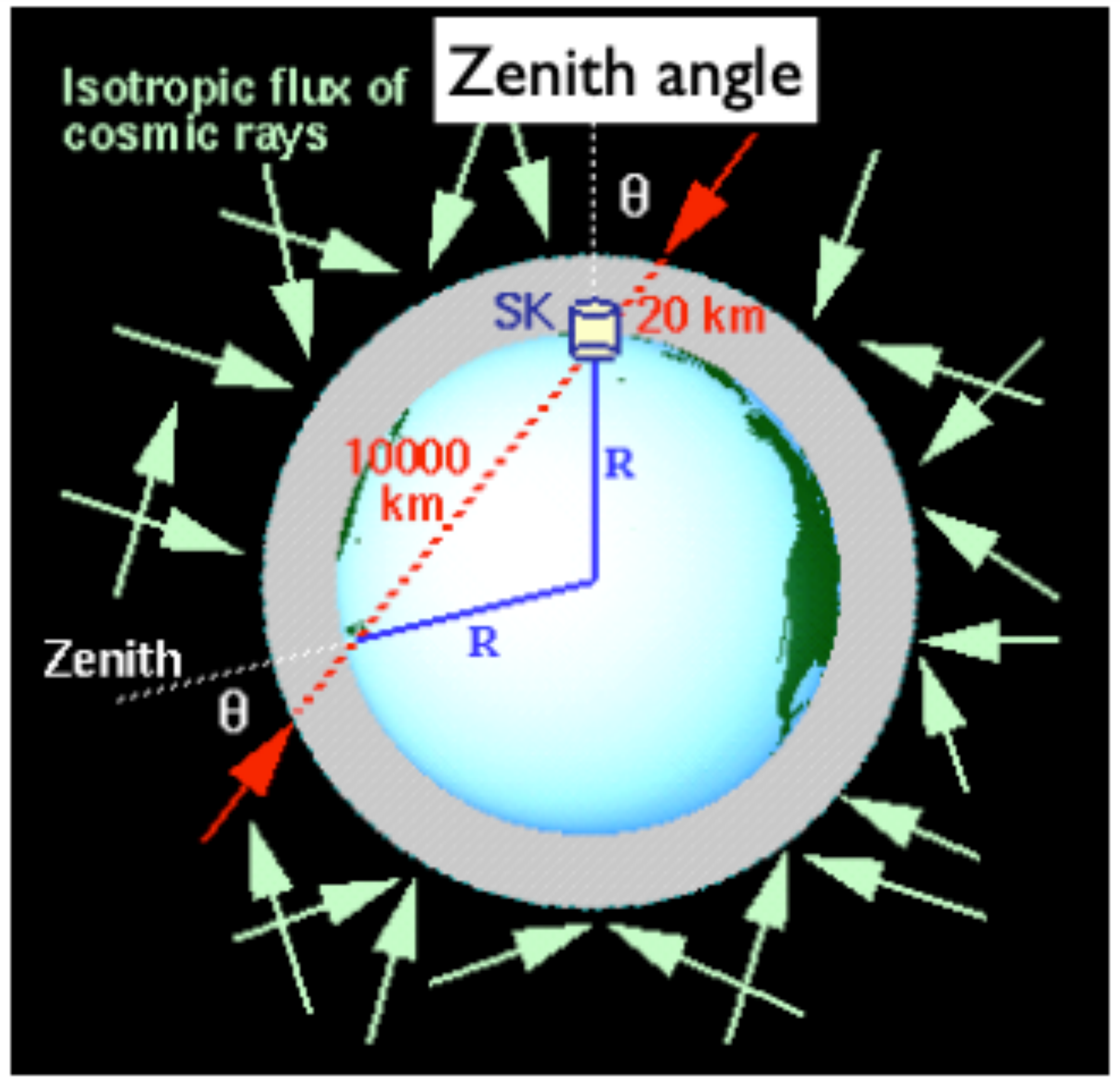
$$R = N_T \times \phi_\nu \times \sigma_\nu$$

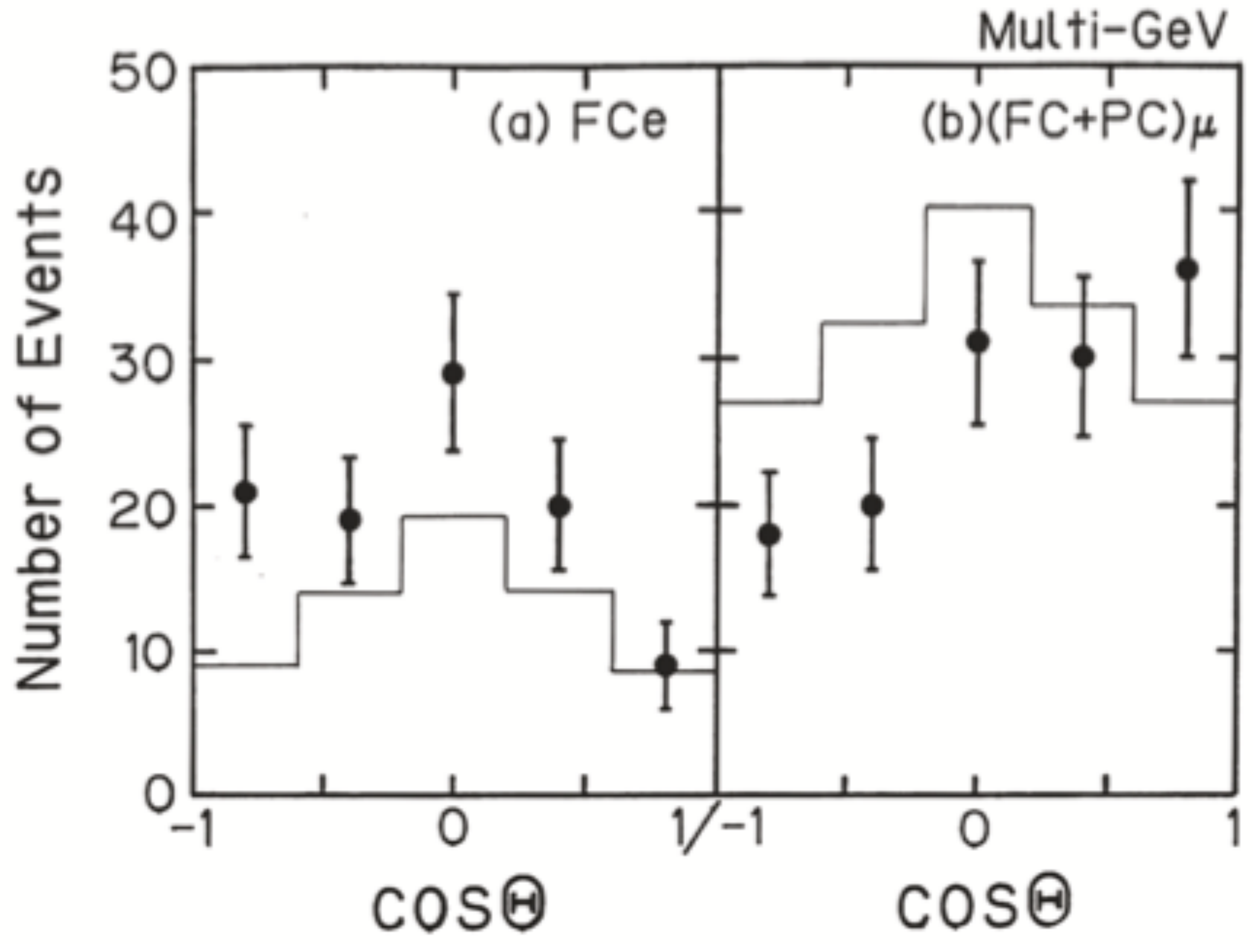
~6*10^{32} kton ~10^{-38} cm^2

R ~130 interactions / yr / kton

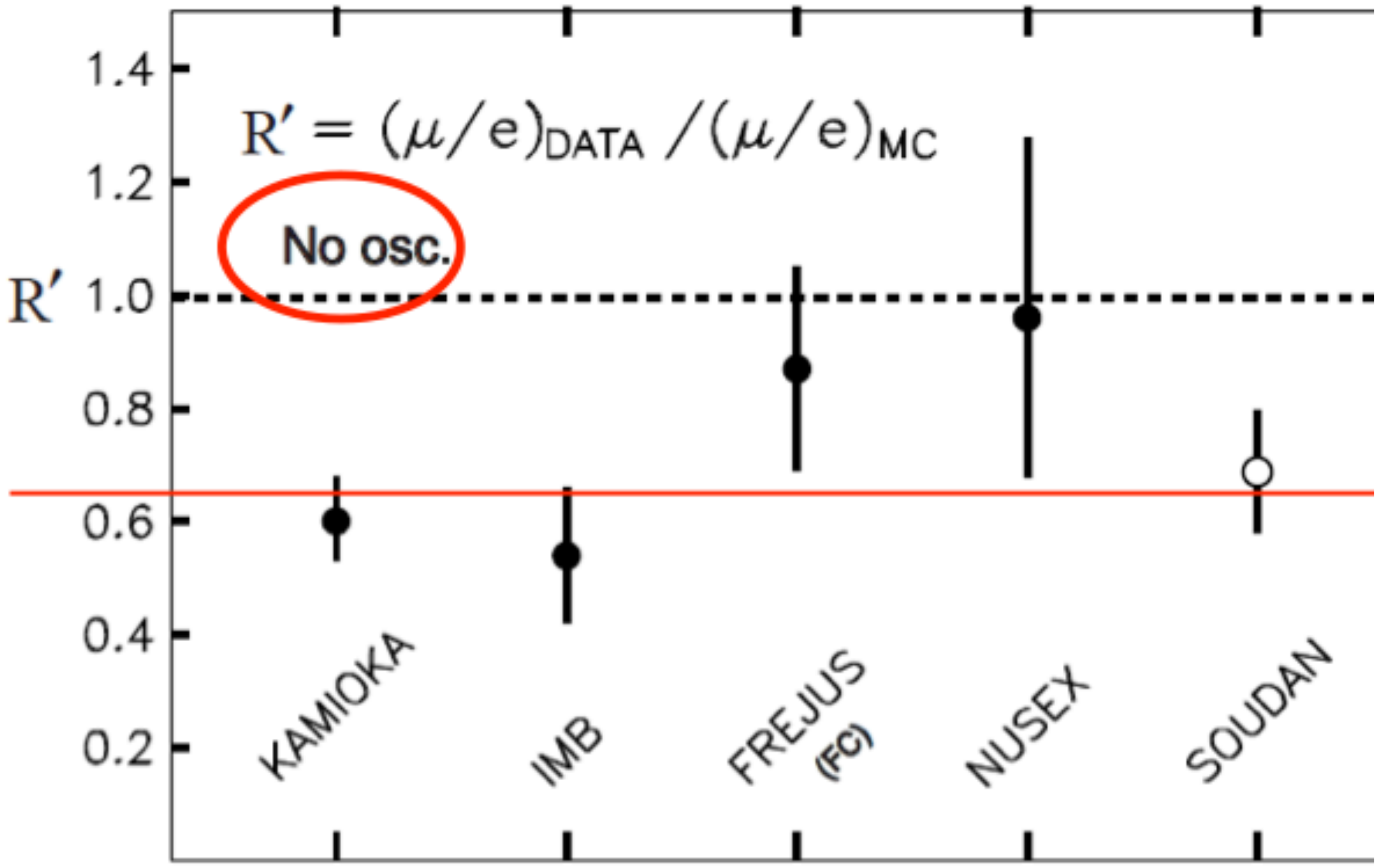
- Need to build a large detector.. is the physics case of atmospheric neutrinos good enough?
- Luckily theorists were claiming proton-decay was just around the corner → GUT theories predicted τ_p~10^{32} y
  - Today limit is $\tau_p > 10^{34}$ y
- For that you need many protons → large detectors

Atmospheric neutrino anomaly





- Until 1998 confusing situation → many experiments see deficit but no smoking gun for neutrino oscillations
- Some experiments saw ratio compatible with expectations
- Many possible reasons invoked to explain the results → one of them was $\nu_\mu \to \nu_\tau$ oscillation
- All these reason except for $\nu_\mu \to \nu_\tau$ will be ruled out by Super-Kamiokande 1998 results!



Evidence / Hypothesis	Pre 1998: R E < 1 GeV	Pre 1998: μ dk Frac	Pre 1998: Vol Frac	From SK: R E > 1 GeV	From SK: A_e ~0	From SK: A_μ > 0	From SK: R(L/E) ~0.5
Atm. Flux Calc.	xx			x		x	x
Cross Sections	xx			x		x	
Particle Ident.		xx	xx				
Entering Bkgrd.			xx			x	
Detector Asym.			xx				
X-Ter. ν_e						x	x
Proton Decay				x		x	
ν_μ Decay							x
ν_μ Abs.							x
ν_μ - ν_e osc					x		
Nonstandard Osc							x
$\nu_\mu - \nu_s$ osc							x
$\nu_\mu - \nu_\tau$ osc							

A=Down/Up

SuperK rules out all except μ <-> τ
But small violations ever allowed

Neutrino oscillations

- First idea from B. Pontecorvo in 1958 → at that time only $\bar{\nu}$ from reactors had been observed
    - Davis tried to detect from reactors $\nu +^{37} Cl \rightarrow e^{-} +^{37} Ar$
    - This would have violated the conservation of the lepton number but Pontecorvo suggested this reaction could be seen if $\bar{\nu}$ → ν oscillations
- In 1962 Maki, Nakagawa and Sakata (MNS) proposed a mechanism for mixing of different flavors
- In 1967 (after the discovery of ν_μ neutrinos) Pontecorvo proposed ν_e → ν_μ oscillations → could explain deficit seen by Homestake
- Initially the oscillation probability was estimated in analogy with Kaon oscillations
- Mixing can be introduced in analogy with the quark sector

Quark and leptons

Quarks: $\begin{pmatrix} u \\ d' \end{pmatrix}; \begin{pmatrix} c \\ s' \end{pmatrix}; \begin{pmatrix} t \\ b' \end{pmatrix}$ $\mathcal{L}^{CC}_{quarks} = -\frac{g}{\sqrt{2}}\left(\bar{u}, \bar{c}, \bar{t}\right)\gamma^{\mu}\frac{1}{2}(1-\gamma^5) V_{\text{CKM}} \begin{pmatrix} a \\ s \\ b \end{pmatrix} + h.c.$

Quark weak eigenstates are linear combinations of the mass eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

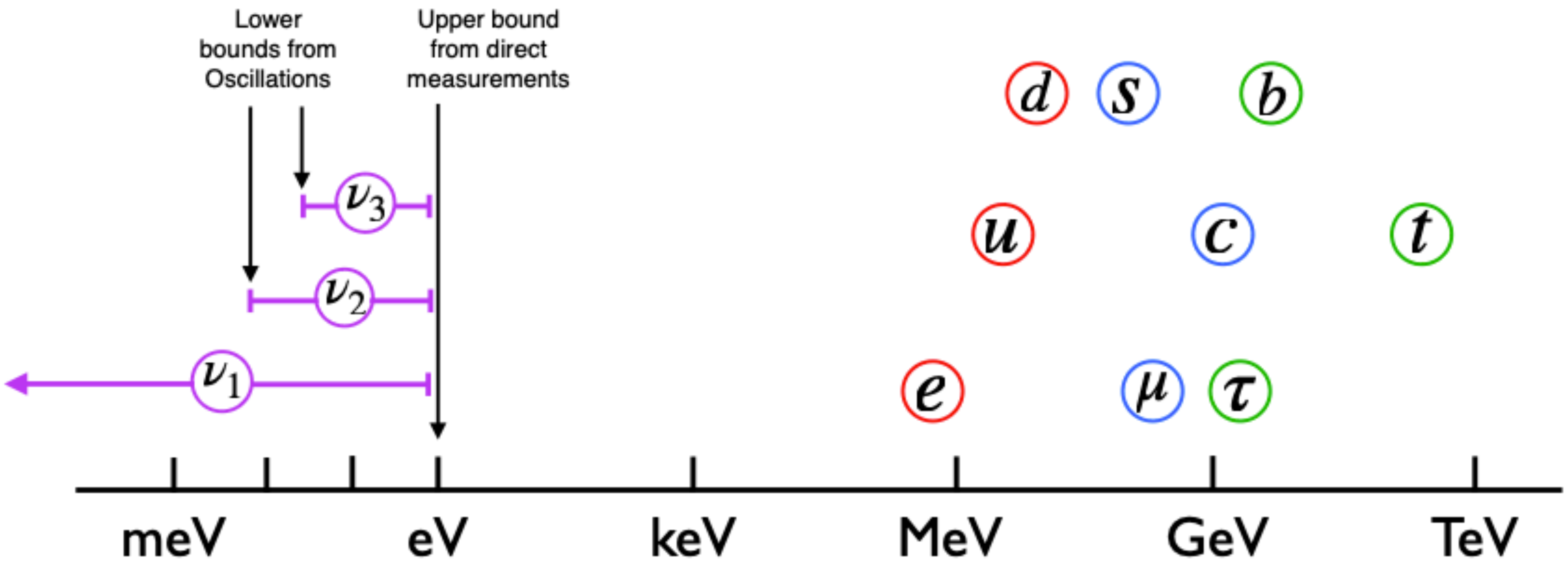
Leptons: $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}; \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}; \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$ $\mathcal{L}^{CC}_{leptons} = -\frac{g}{\sqrt{2}}\left(\bar{e}, \bar{\mu}, \bar{\tau}\right)\gamma^{\mu}\frac{1}{2}(1-\gamma^5) U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_2 \end{pmatrix} + h.c.$

Neutrino weak eigenstates in SM are massless ($m_{\nu_e} = m_{\nu_\mu} = m_{\nu_\tau} = 0$)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- CKM is a unitary 3x3 matrix that describe the mixing in the quark sector
- A similar matrix can be written in the leptonic sector
- In the SM neutrinos are massless meaning that $U_{PMNS} = I$ → no distinction between weak and mass eigenstates
- If neutrino are massive with $m_{\nu_e} \neq m_{\nu_\mu} \neq m_{\nu_\tau} > 0$ → weak eigenstates can be linear combination of mass eigenstates

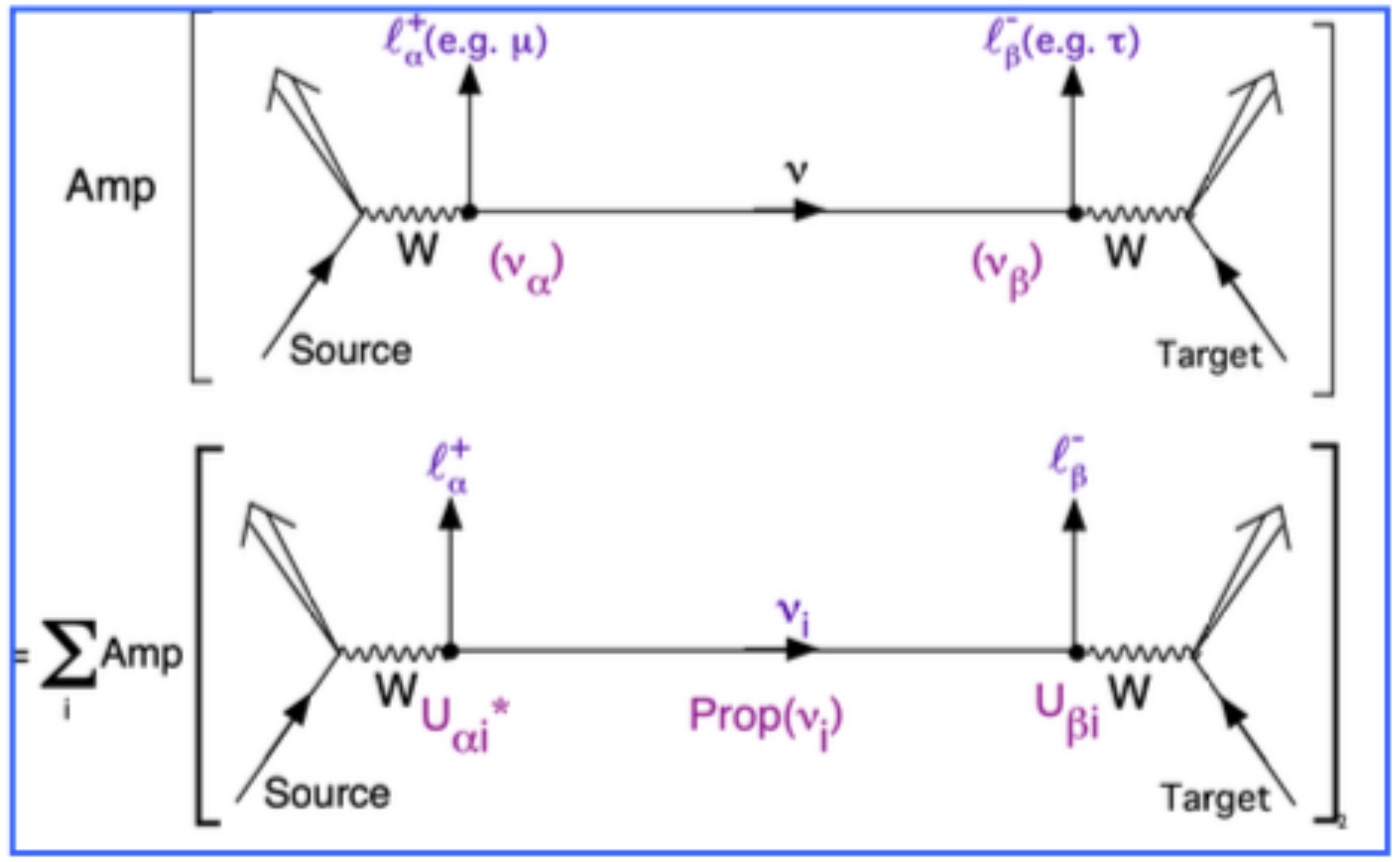
Neutrino masses



- Neutrino masses are predicted to be zero in the SM → No ν_R state means no mass through Yukawa coupling mechanism
- Upper bound from end-point of the β-decay spectrum
- But what happens if neutrinos have masses → they can be subject to mixing similarly to the quarks!

Time evolution in vacuum

- Neutrinos are produced at t=0 as weak eigenstates $|\nu_\alpha(t=0)\rangle, \alpha = e, \mu, \tau$ via charged current interaction and propagates as mass eigenstates $|\nu_i\rangle, i = 1,2,3$



As in the case of the quark, the weak eigenstates can be written as linear combination of mass eigenstates

$$|\nu_\alpha\rangle = \sum_j U^{*\,PMNS}_{\alpha j} |\nu_j\rangle$$

U^{PMNS} must be unitarity to conserve the probability
$U^{+}U = I \rightarrow U^{-}1 = U^{+} = (U^{*})^{T}$

The time evolution in vacuum gives $|\nu(t)\rangle = \sum_j U^{*}_{\alpha j} e^{-iE_j t} |\nu_j\rangle$

- If masses are different then states with different energies have different phases that interfere each other
- The probability of observing a state α at time t is $P_\alpha = P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\alpha | \nu(t) \rangle|^2$

Time evolution in vacuum

Using the notation $\vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$ the time evolution is $i\frac{d\vec{\nu}}{dt} = U^* H U^T \vec{\nu}$ where the Hamiltonian is $H = \begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix}$

The eigenvalues are $E_i = \sqrt{p^2 + m_i^2} \sim p + m_i^2/2p \sim p + m_i^2/2E$ where we use the smallness of neutrino masses giving $E \sim p$

$$i\frac{d\vec{\nu}}{dt} = \frac{1}{2E} U^* \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^T \vec{\nu}$$

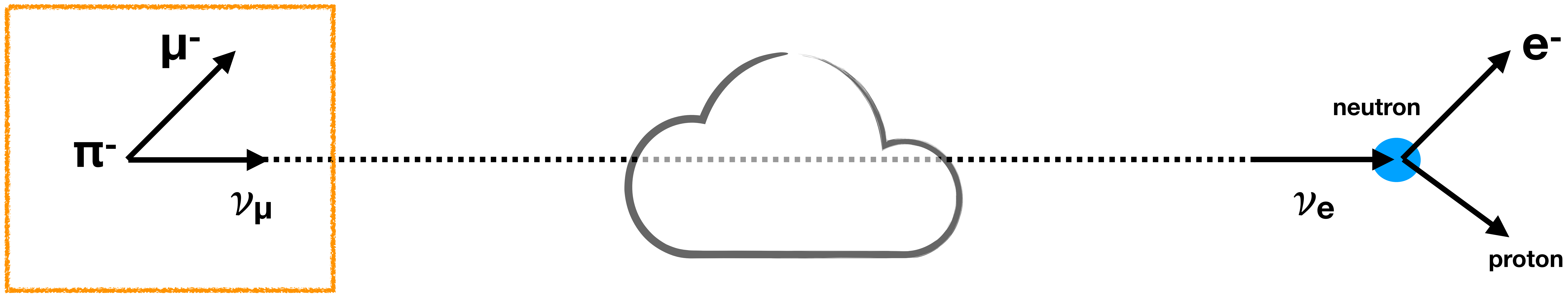
$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

p can be ignored because it is the same for all the mass eigenstates and does not contribute to the interference

Subtracting a constant phase m_i^2

The time evolution of weak eigenstates is affected by the quantum interference between mass eigenstates

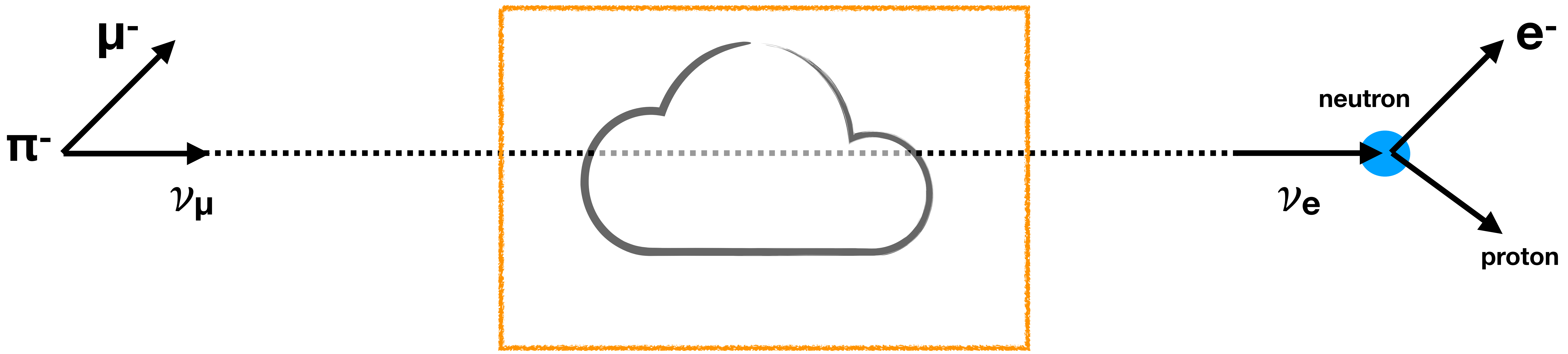
ν production



- At the production neutrinos are produced in flavour eigenstates defined by their accompanying lepton → example ν_μ

$$\begin{pmatrix}\nu_e \\ e\end{pmatrix} \quad \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix} \quad \begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}$$

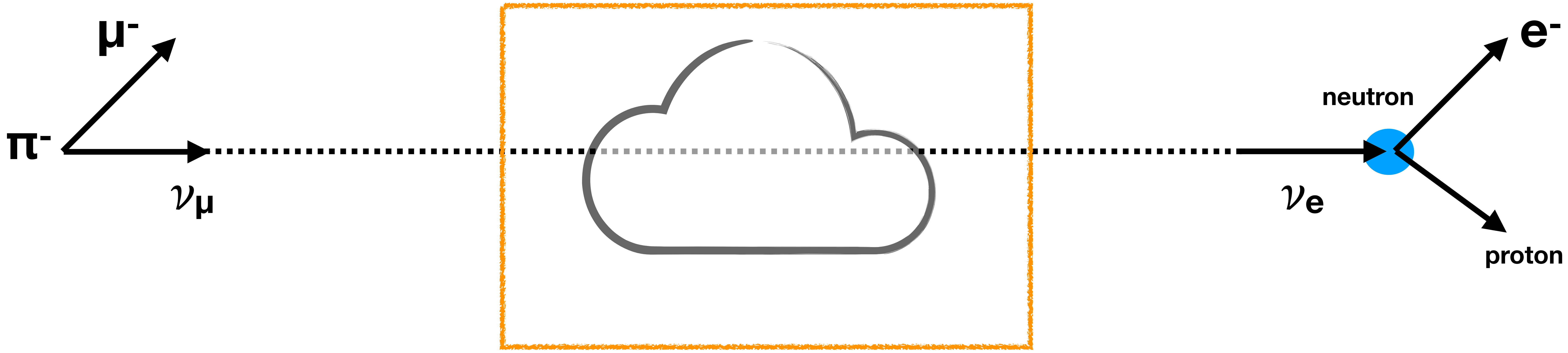
ν propagation in vacuum



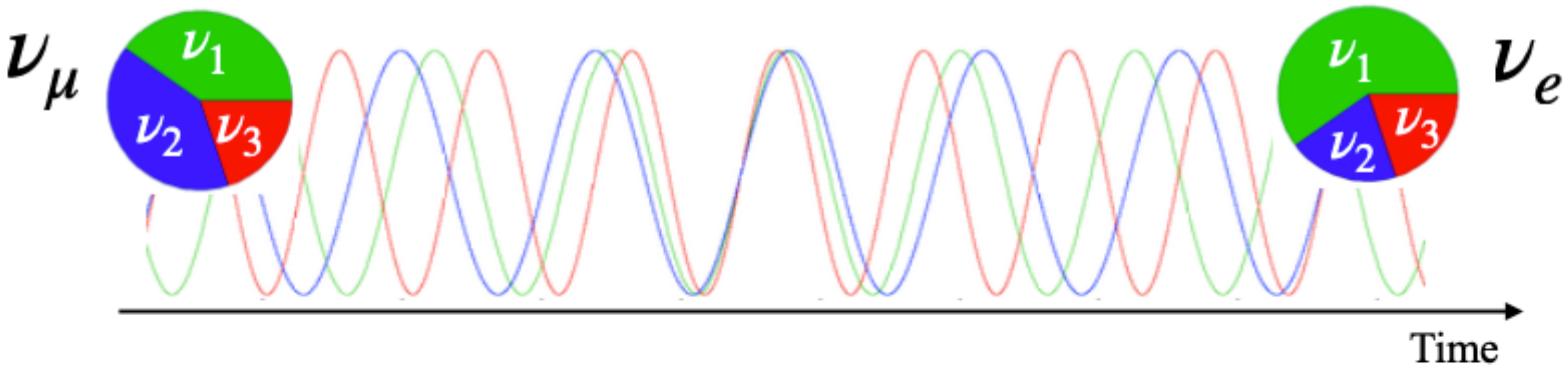
- During the evolution in time ν is a superposition of mass states evolving in time with different velocities e^{-iE_jt} due to the different masses $m_1 \neq m_2 \neq m_3$ → neutrino oscillations implies that neutrino have masses

$$|\nu_\mu\rangle = U^*_{\mu 1} e^{-iE_1 t} |\nu_1\rangle + U^*_{\mu 2} e^{-iE_2 t} |\nu_2\rangle + U^*_{\mu 3} e^{-iE_3 t} |\nu_3\rangle$$

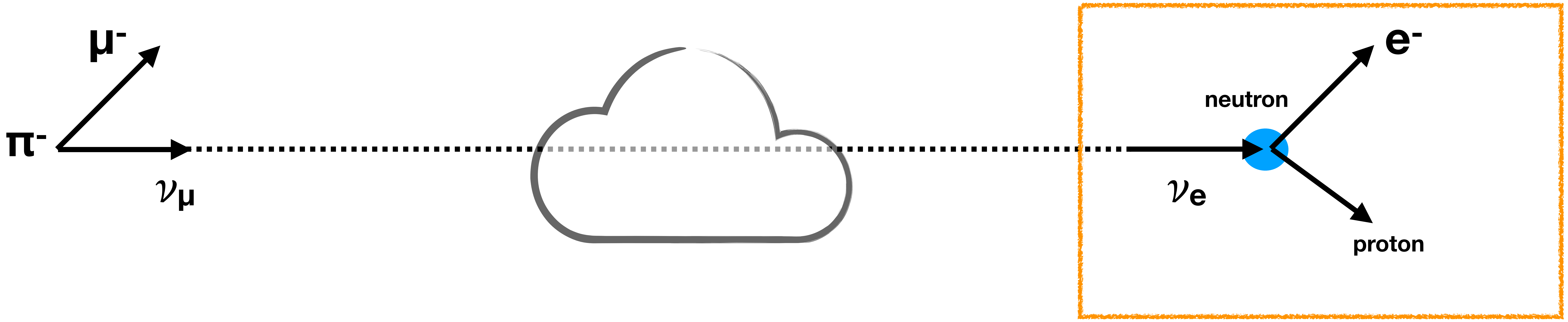
ν propagation in vacuum



- Fraction of ν_1, ν_2 and ν_3 change over time



ν propagation in vacuum



- At detection the neutrinos has a different fraction of $\nu1$, $\nu2$ and $\nu3$
- It is detected in a flavour eigenstate → defined by the lepton emitted in the neutrino interaction

$$P(\nu_\mu \rightarrow \nu_\mu) \neq 1$$

$$P(\nu_\mu \rightarrow \nu_e) \neq 0$$

$$P(\nu_\mu \rightarrow \nu_\tau) \neq 0$$

Neutrino oscillations is a quantum interference phenomenon implying neutrinos have non-degenerate masses

Parametrization of the PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

CP-violation → all mixing angles and δ different from 0

$$\Im m(U_{\alpha i}U^*_{\alpha j}U^*_{\beta i}U_{\beta j}) = c_{12}s_{12}c_{23}s_{23}c^2_{13}s_{13}sin\delta$$

2-flavour approximation

- We introduced U_{PMNS} as a 3x3 unitary matrix but to start with a simpler case we can start assuming only two massive neutrinos
- This is useful because oscillation formula are much simpler
- Many experimental data can be analyzed by using a simple effective model with two neutrinos
- In this case the matrix is only given by one mixing angle

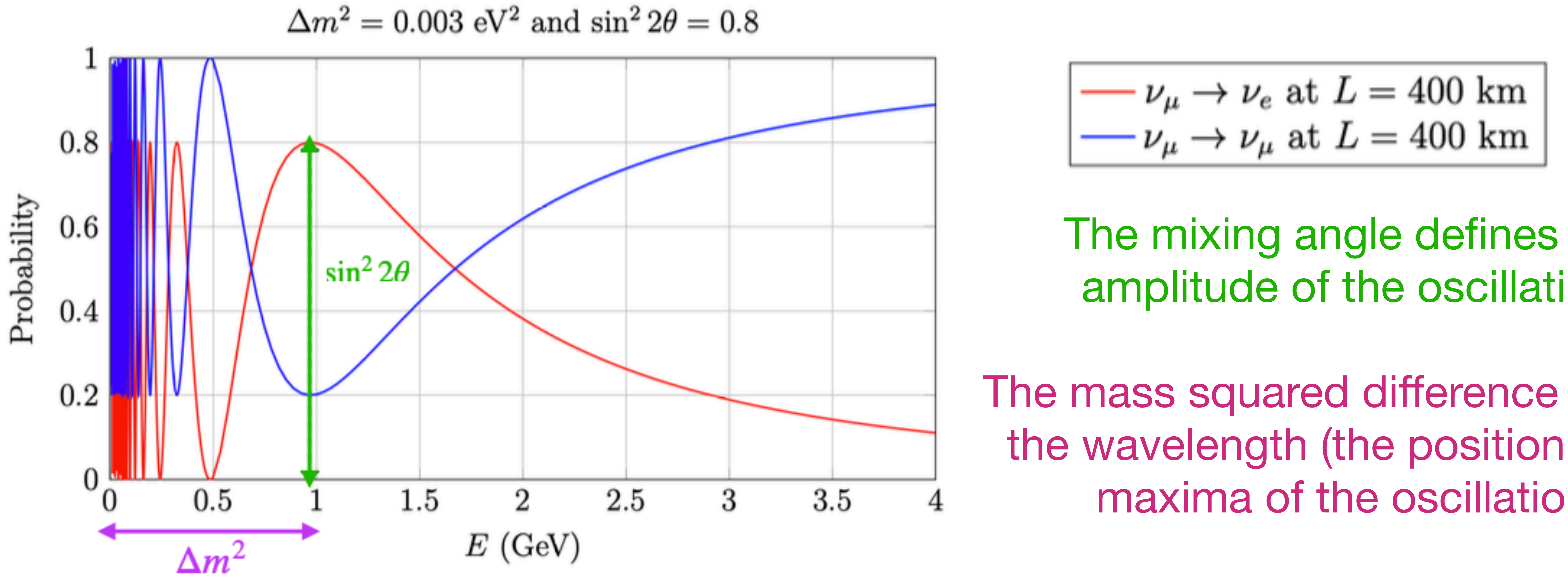
$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$ and one mass-squared difference $\Delta m_{21}^2 = m_2^2 - m_1^2$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$ and

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Phenomenology of 2-flavour approximation

- Oscillation probability for a fixed distance

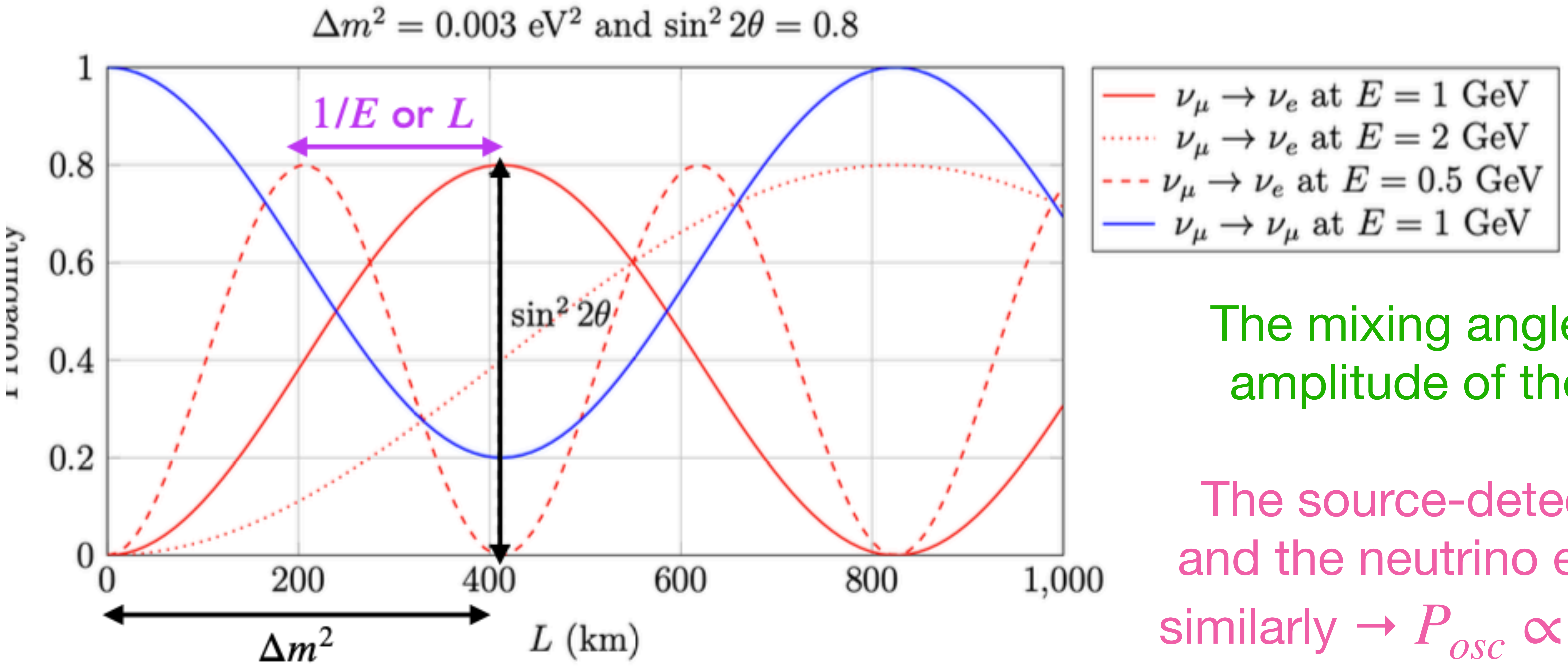


The mixing angle defines the amplitude of the oscillation

The mass squared difference defines the wavelength (the position of the maxima of the oscillation)

Phenomenology of 2-flavour approximation

- Oscillation probability for a fixed energy

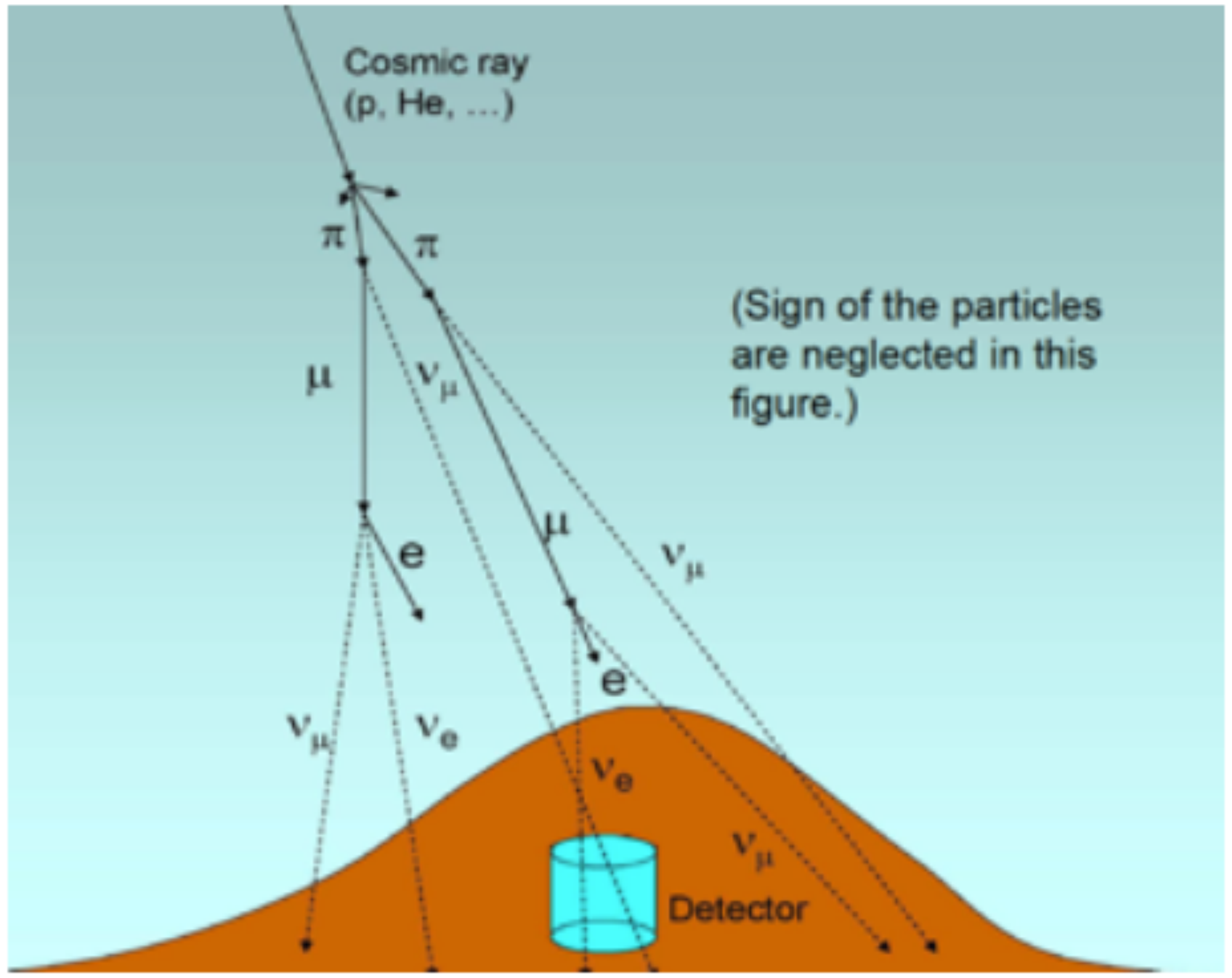


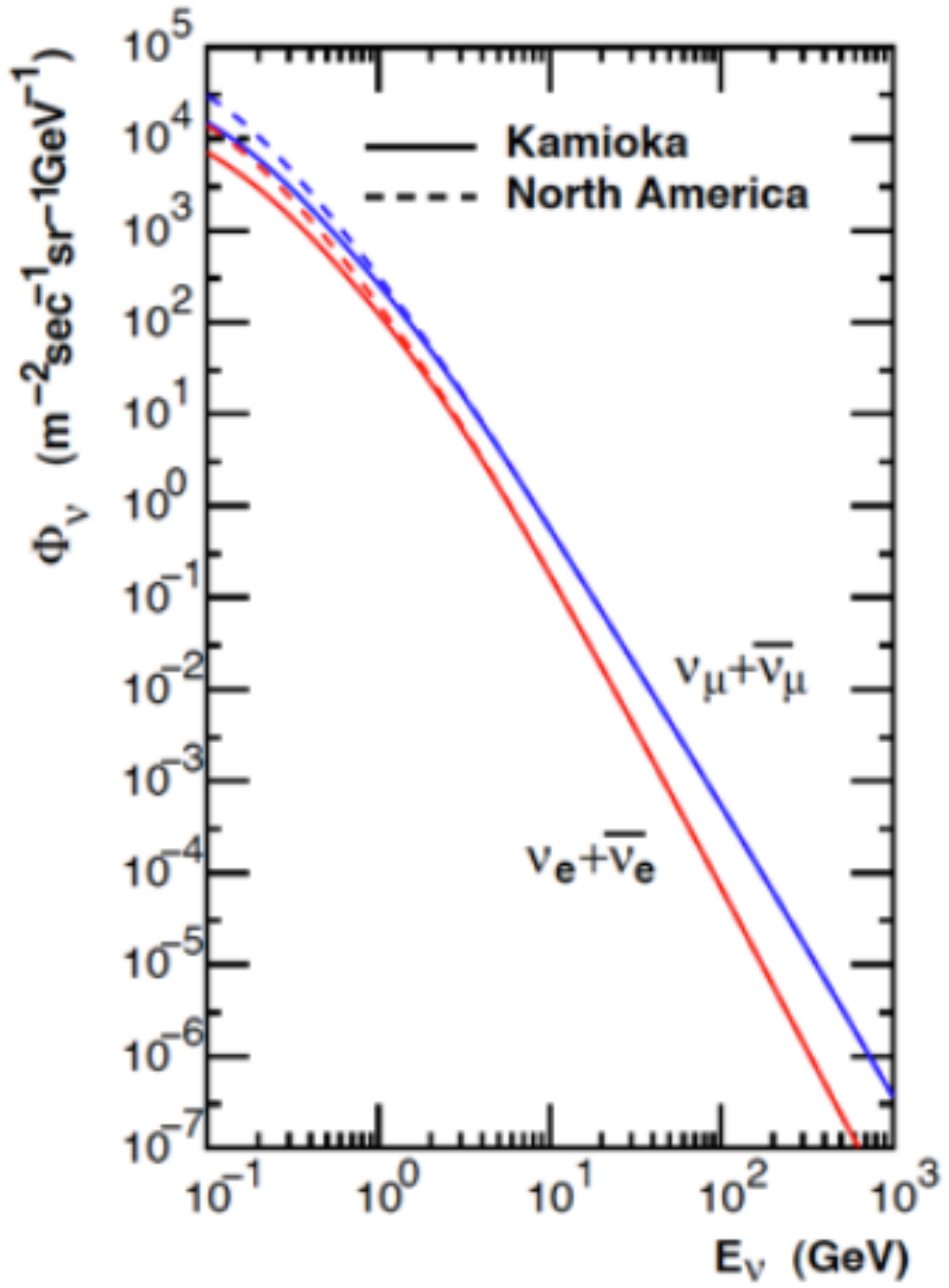
The mixing angle defines the amplitude of the oscillation

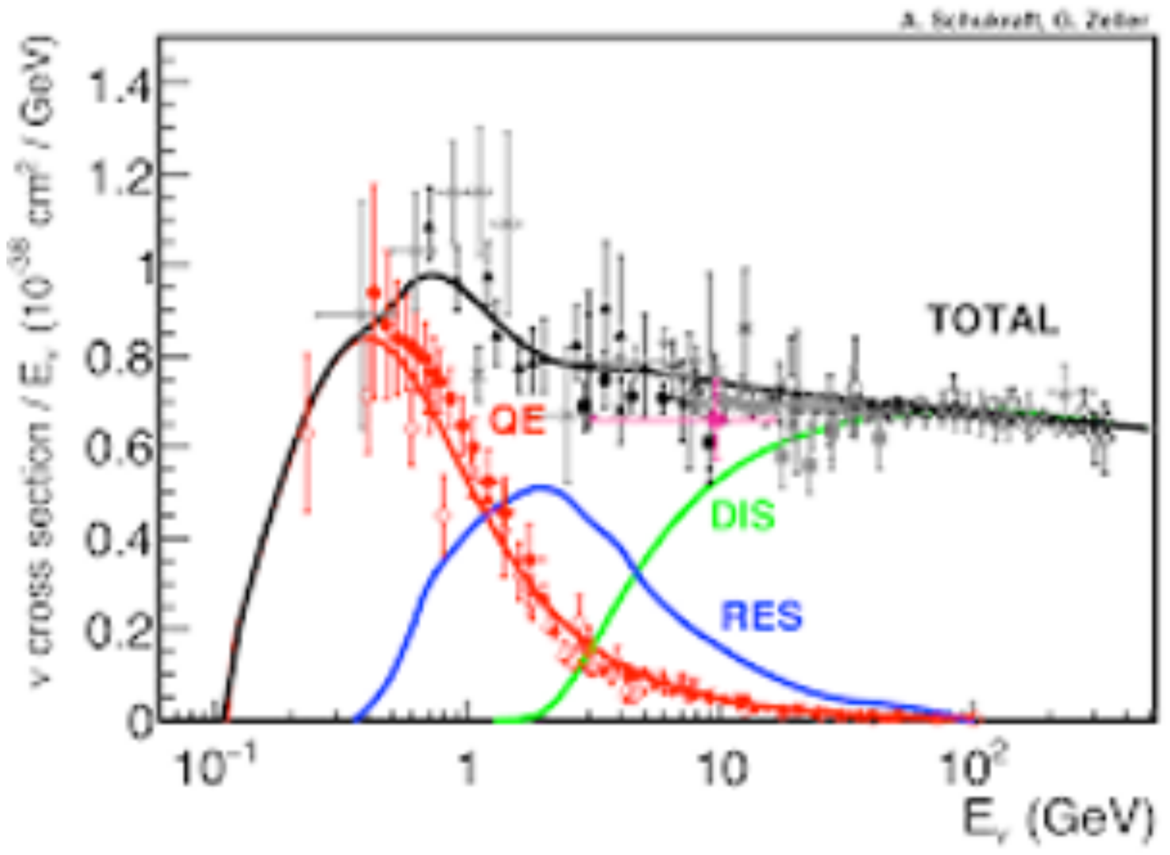
The source-detector distance and the neutrino energy behave similarly → $P_{osc} \propto \sin(\Delta m^2 L/E)$

Discovery of neutrino oscillations

Atmospheric neutrino fluxes







- Need to build a large detector.. is the physics case of atmospheric neutrinos good enough?
- Luckily theorists were claiming proton-decay was just around the corner → GUT theories predicted τ_p~10^{32} y
  - Today limit is $\tau_p > 10^{34}$ y
- For that you need many protons → large detectors

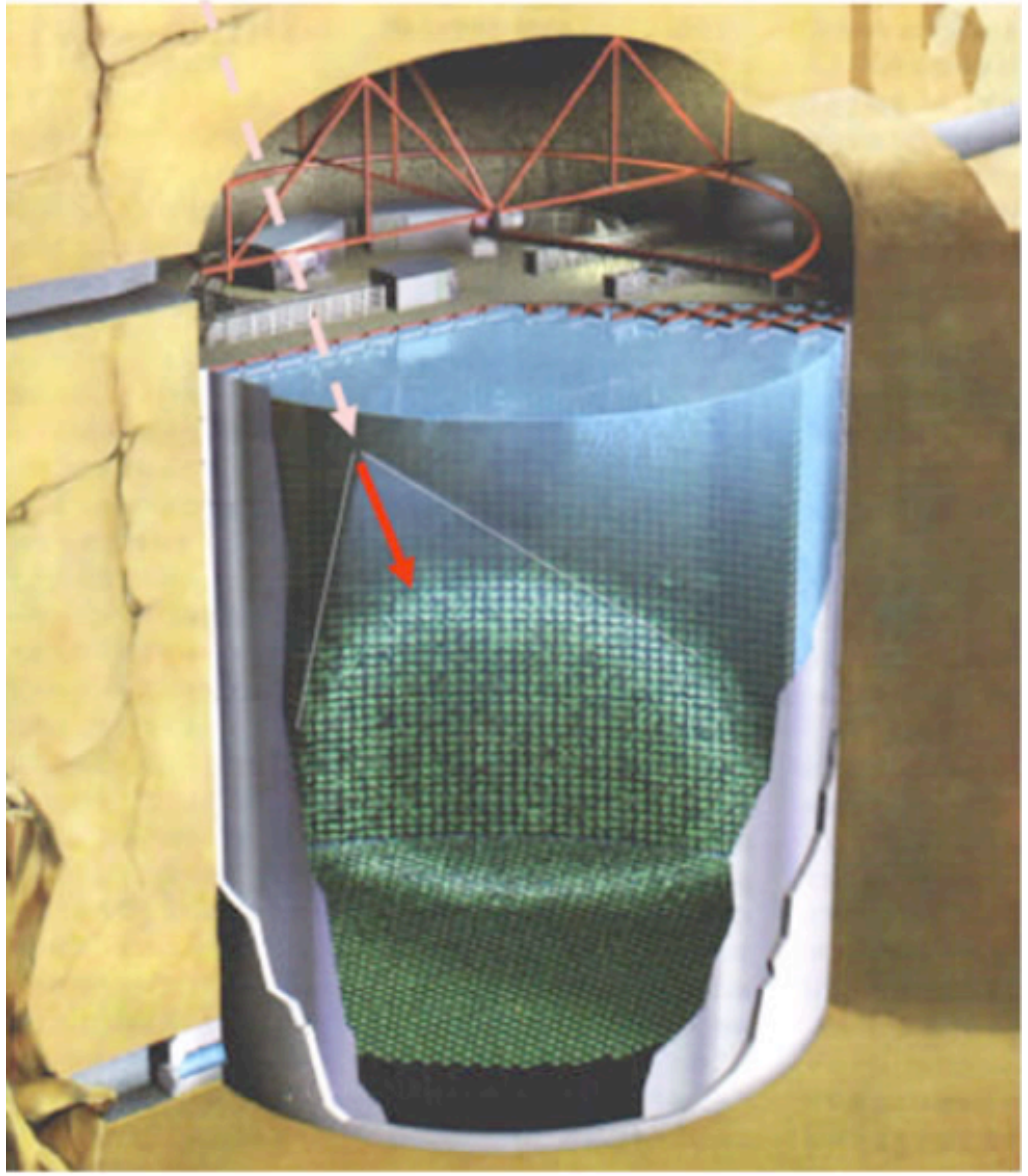
~1 cm^{-2}s^{-1}

$$R = N_T \times \phi_\nu \times \sigma_\nu$$

~6*10^{32} kton **~10^{-38} cm^2**

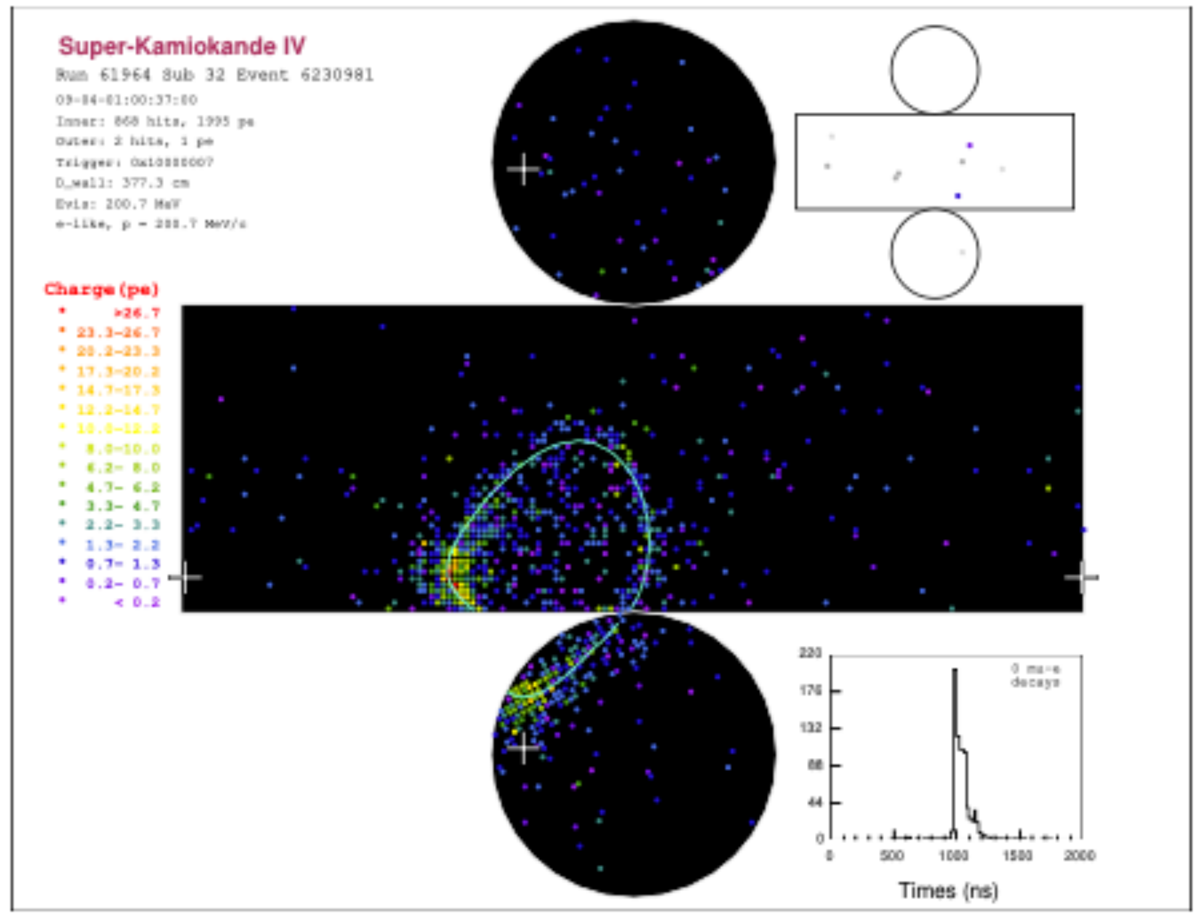
R ~130 interactions / yr / kton

Super-Kamiokande

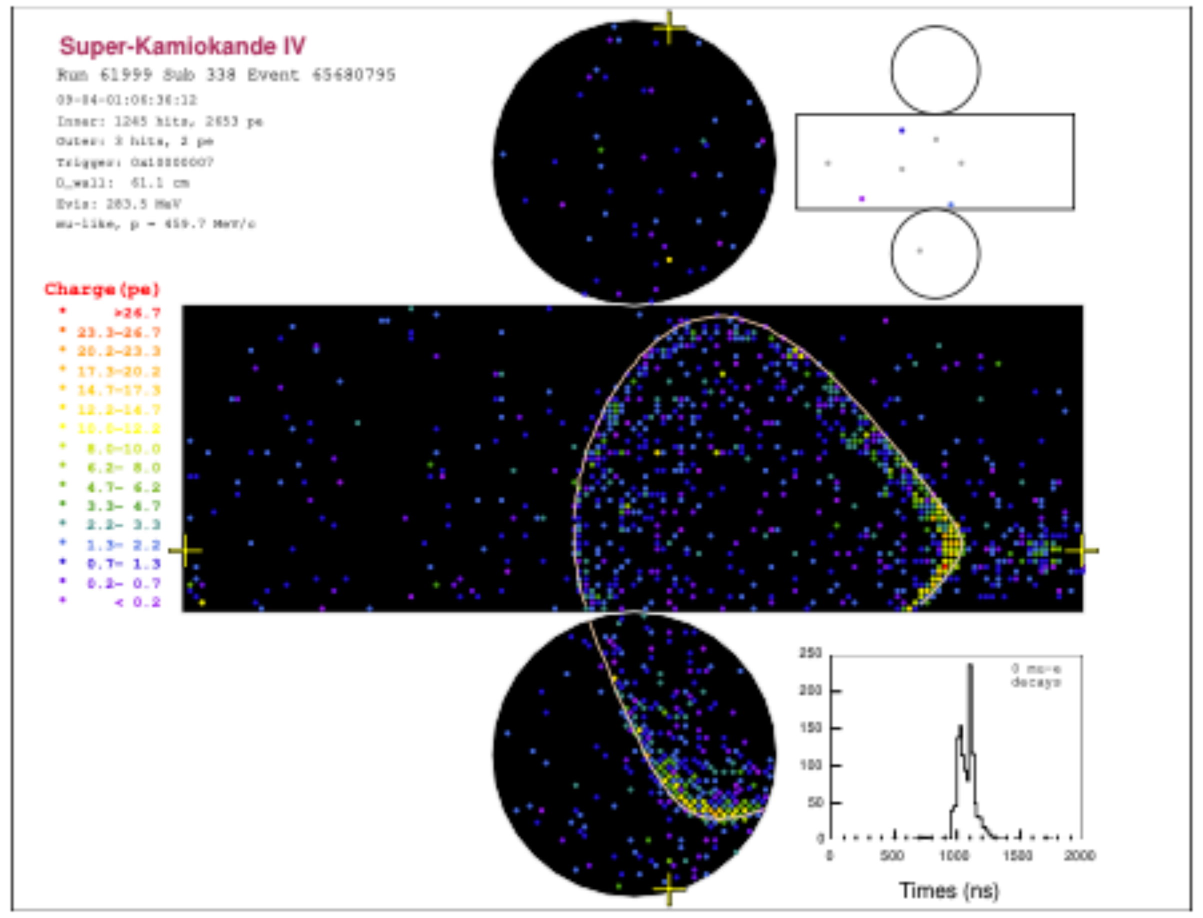


- 50 kton Water Cherenov detector located in the Kamioka mine
- In operation since 1996
- Two concentric optically separated detectors
    - Inner detector instrumented with 11146 PMTs (40% coverage)

e-like ring

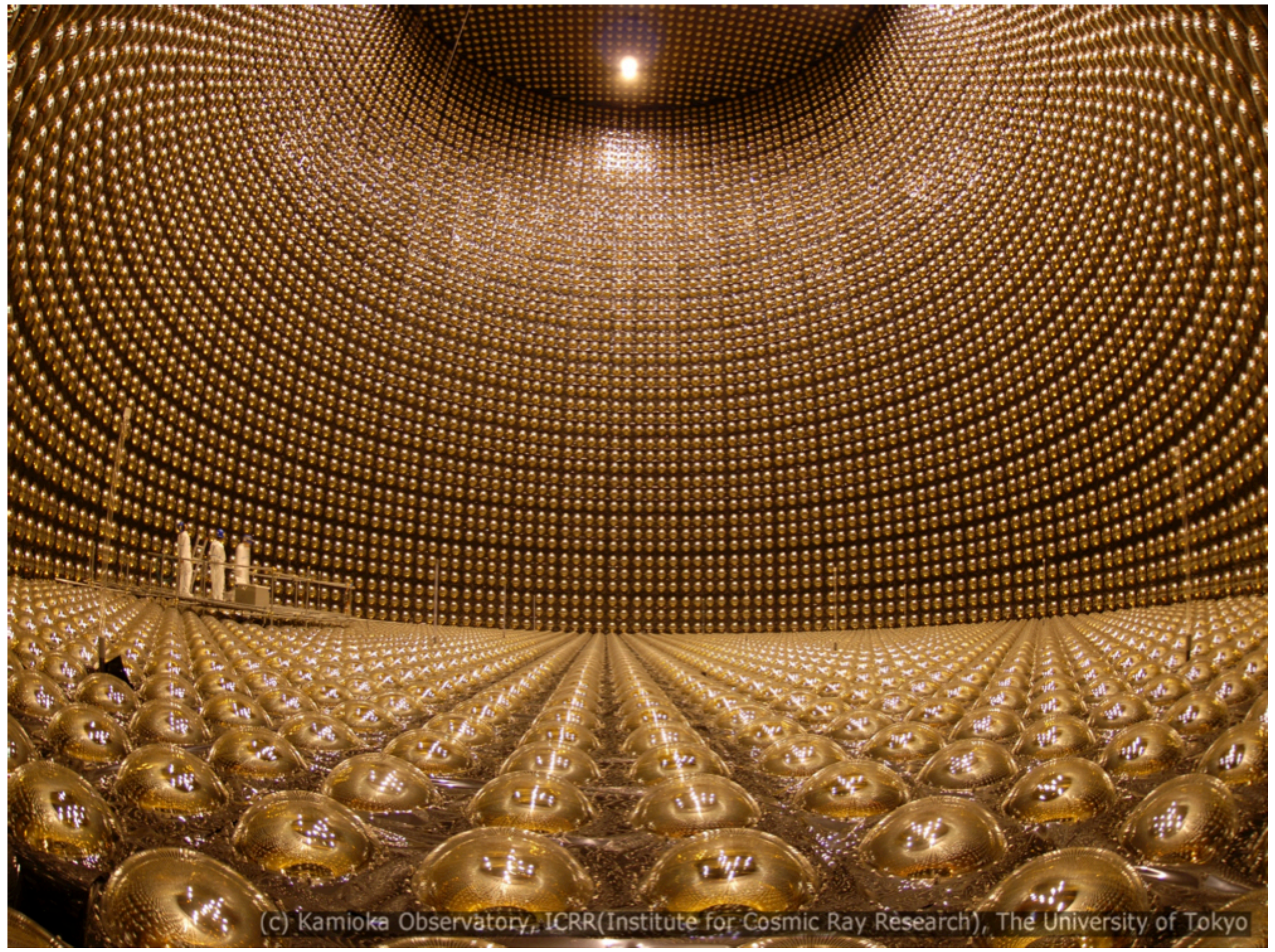


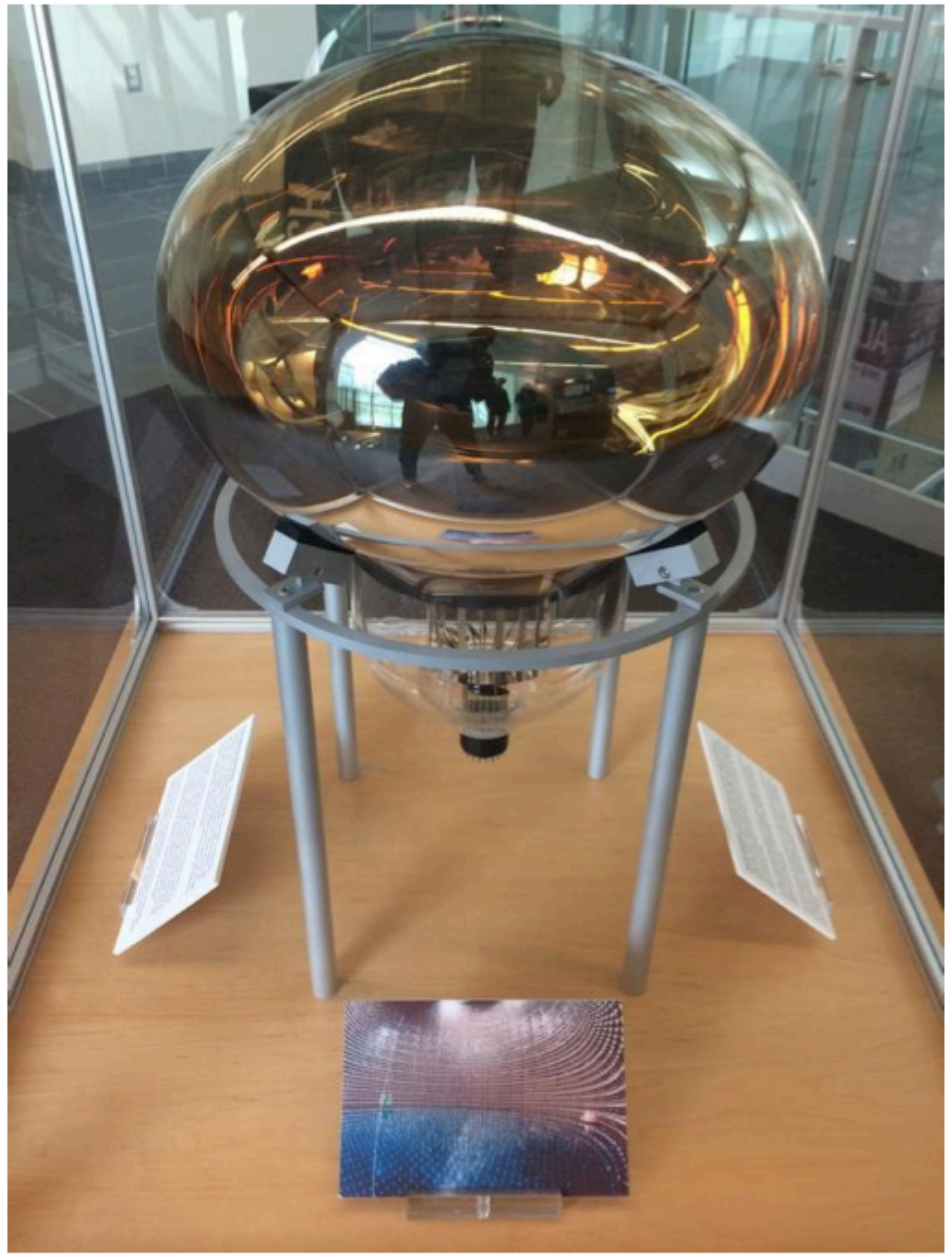
μ-like ring



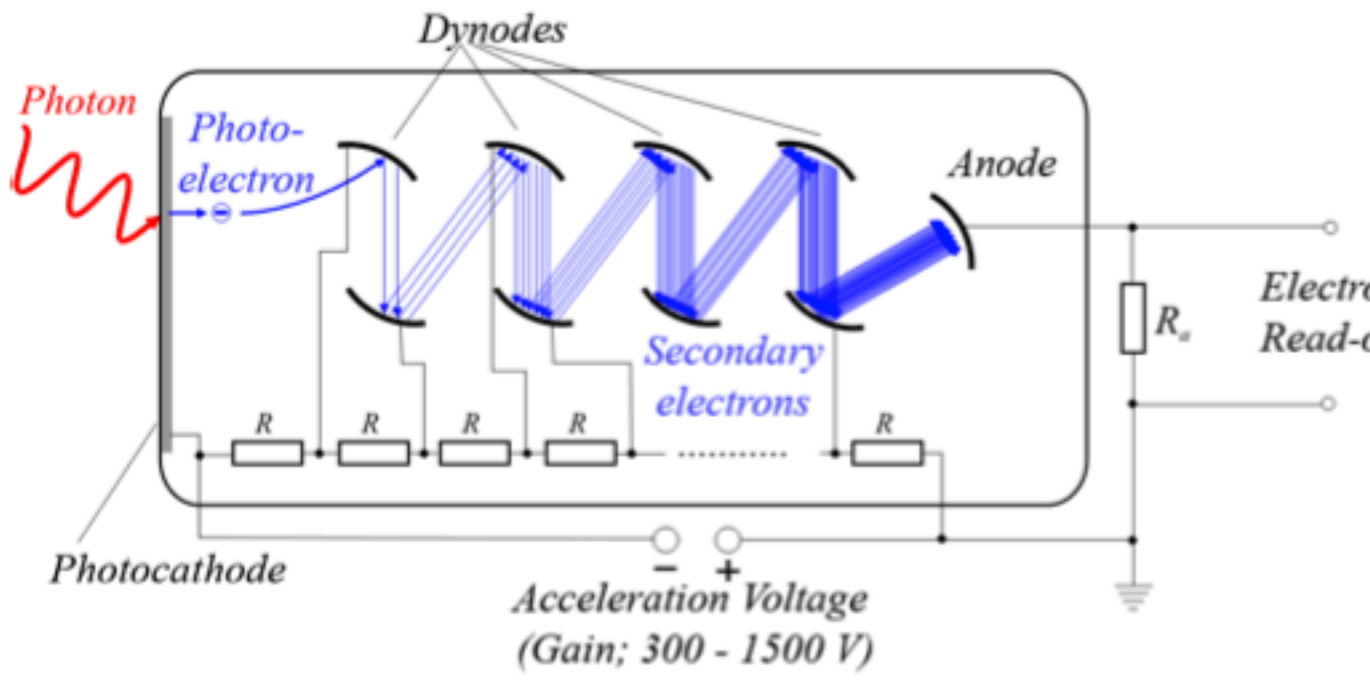
Courtesy of SK collaboration

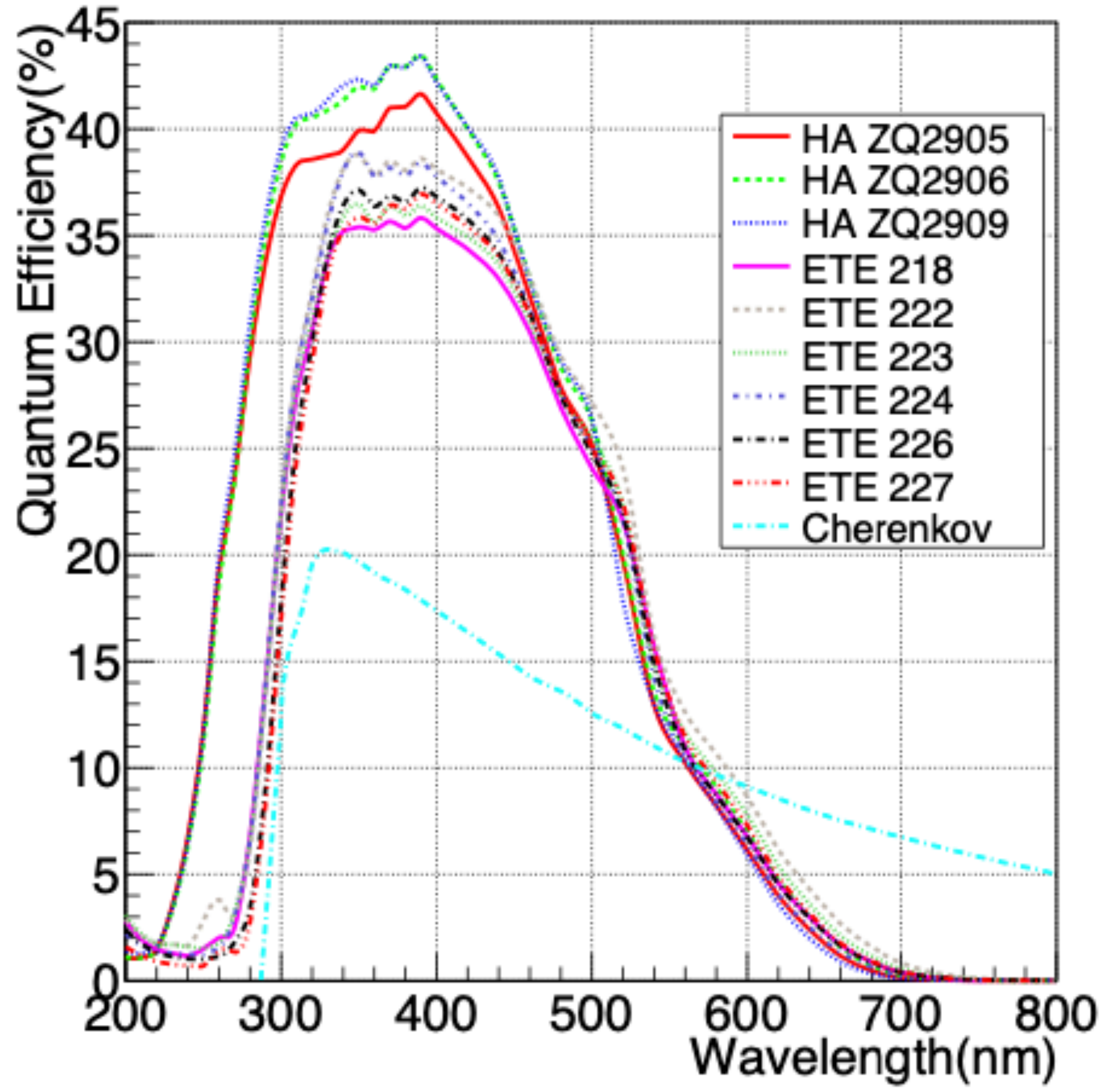
Super-Kamiokande PMTs



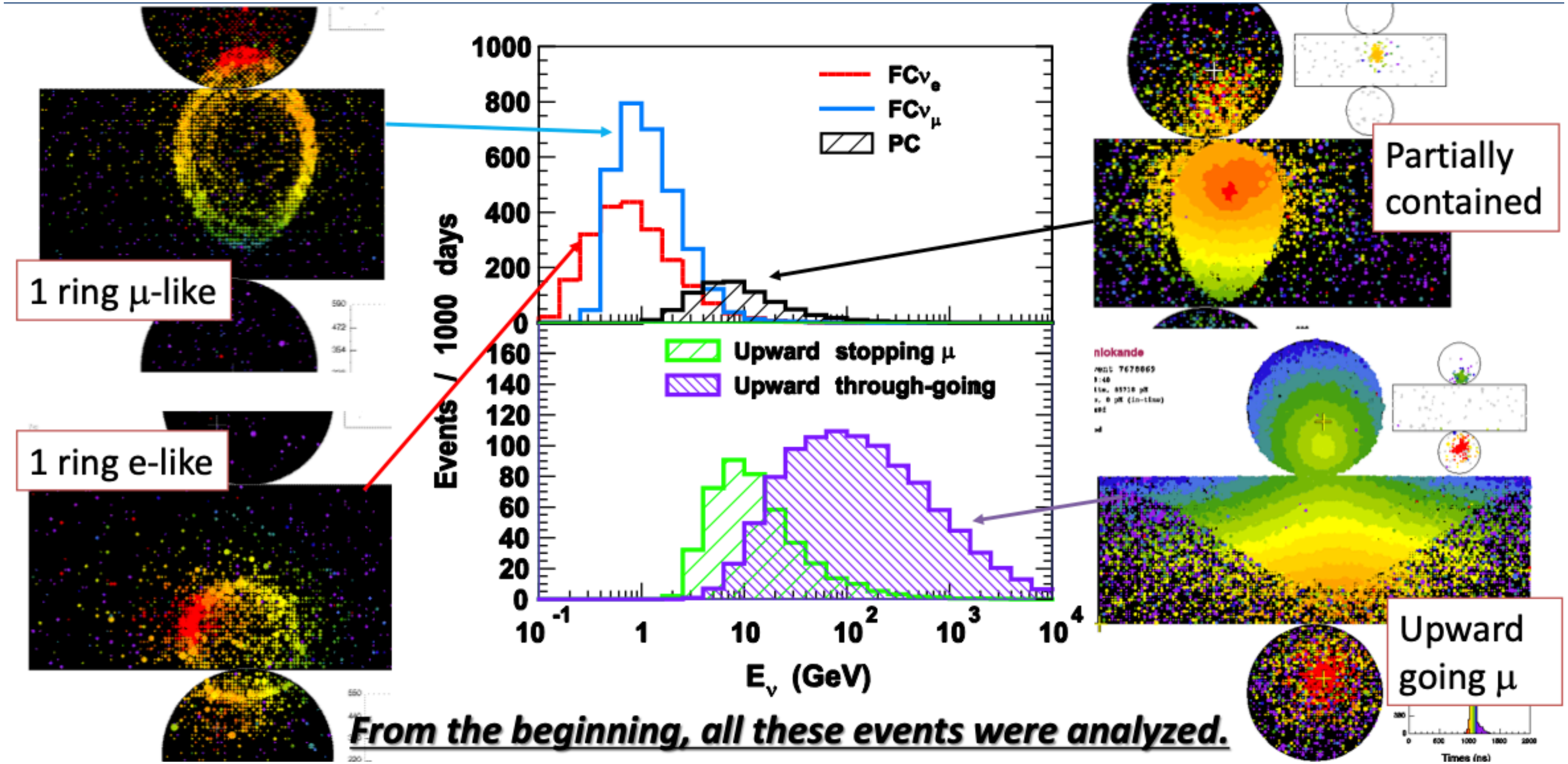


Courtesy of SK collaboration





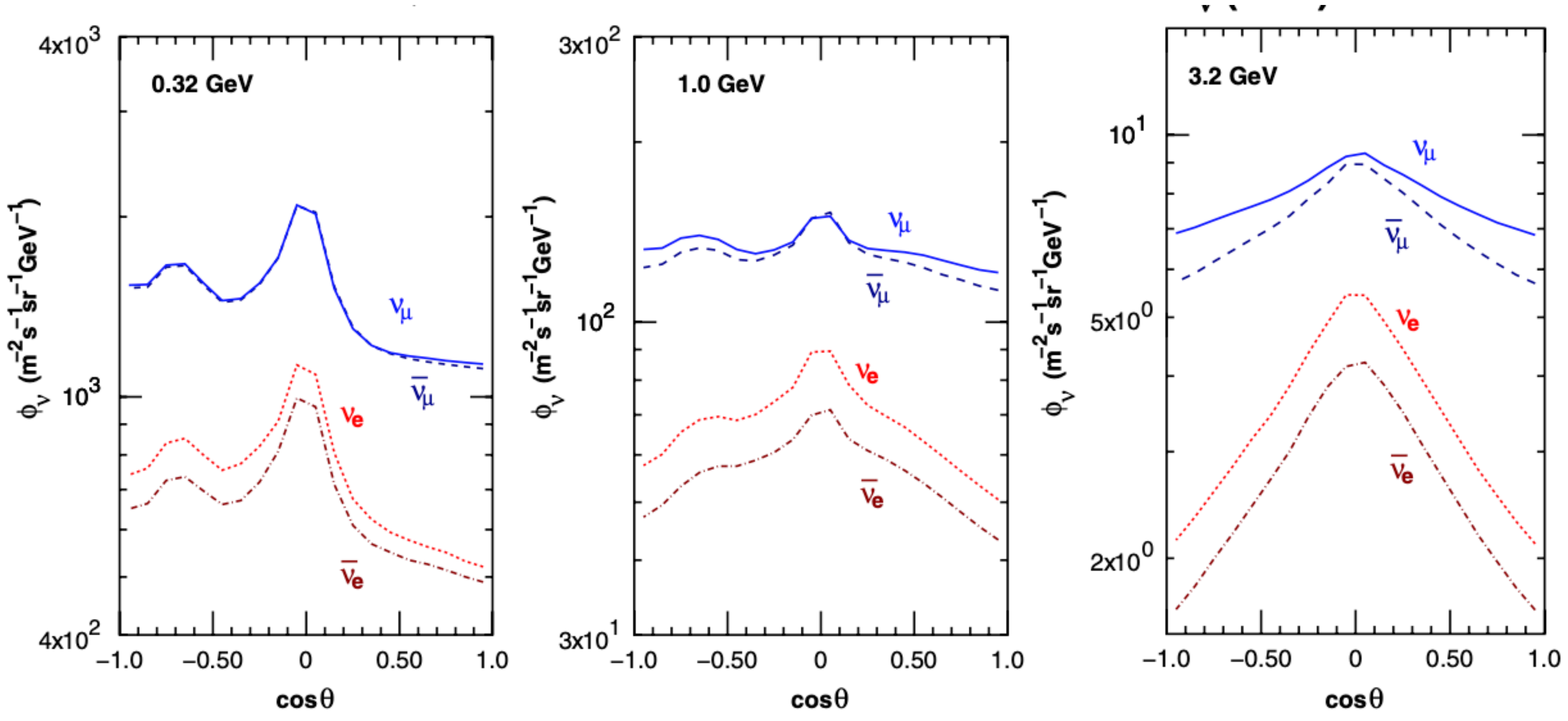
T. Toyama *et al.* (CTA consort.) arXiv:1307.5463 [astro-ph.IM] (2013)



From the beginning, all these events were analyzed.

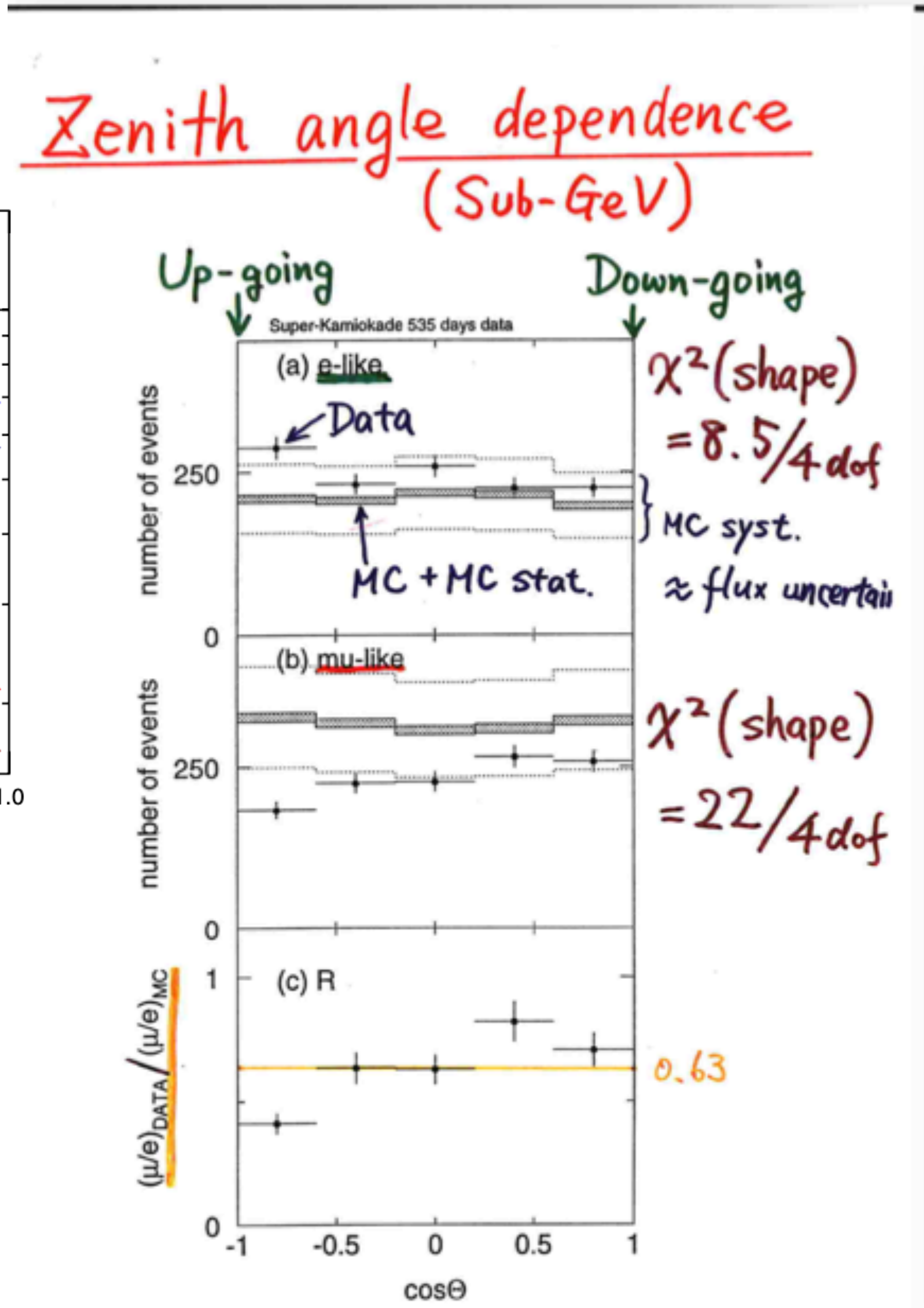
Super-Kamiokande 1998 results

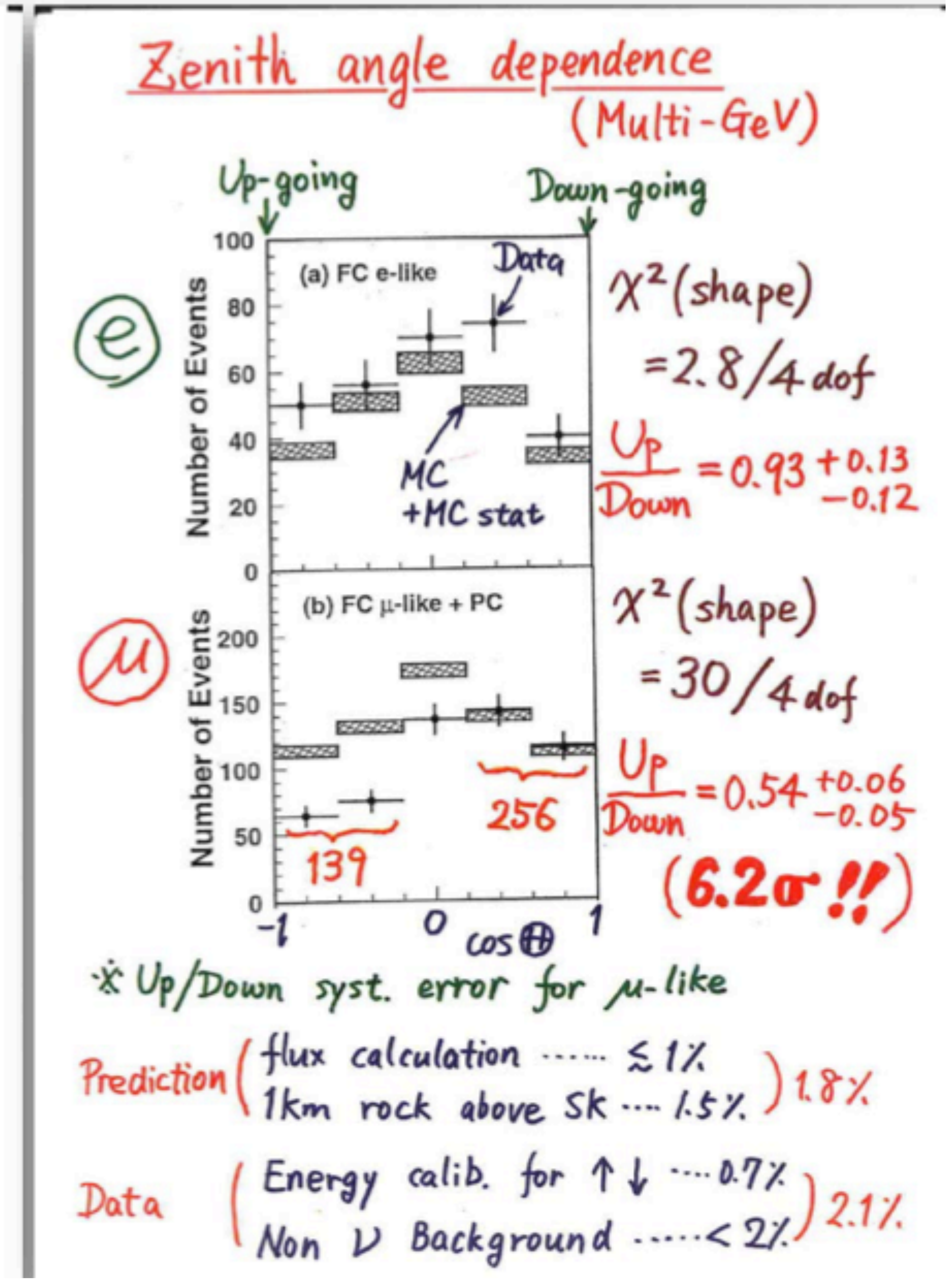
$$N_l(\cos\theta) = N_l(-\cos\theta)$$



$$Up/Down = 0.54^{+0.06}_{-0.05} \rightarrow 6.2\sigma$$
$$\Delta\chi^2(no\ osc) = 70$$

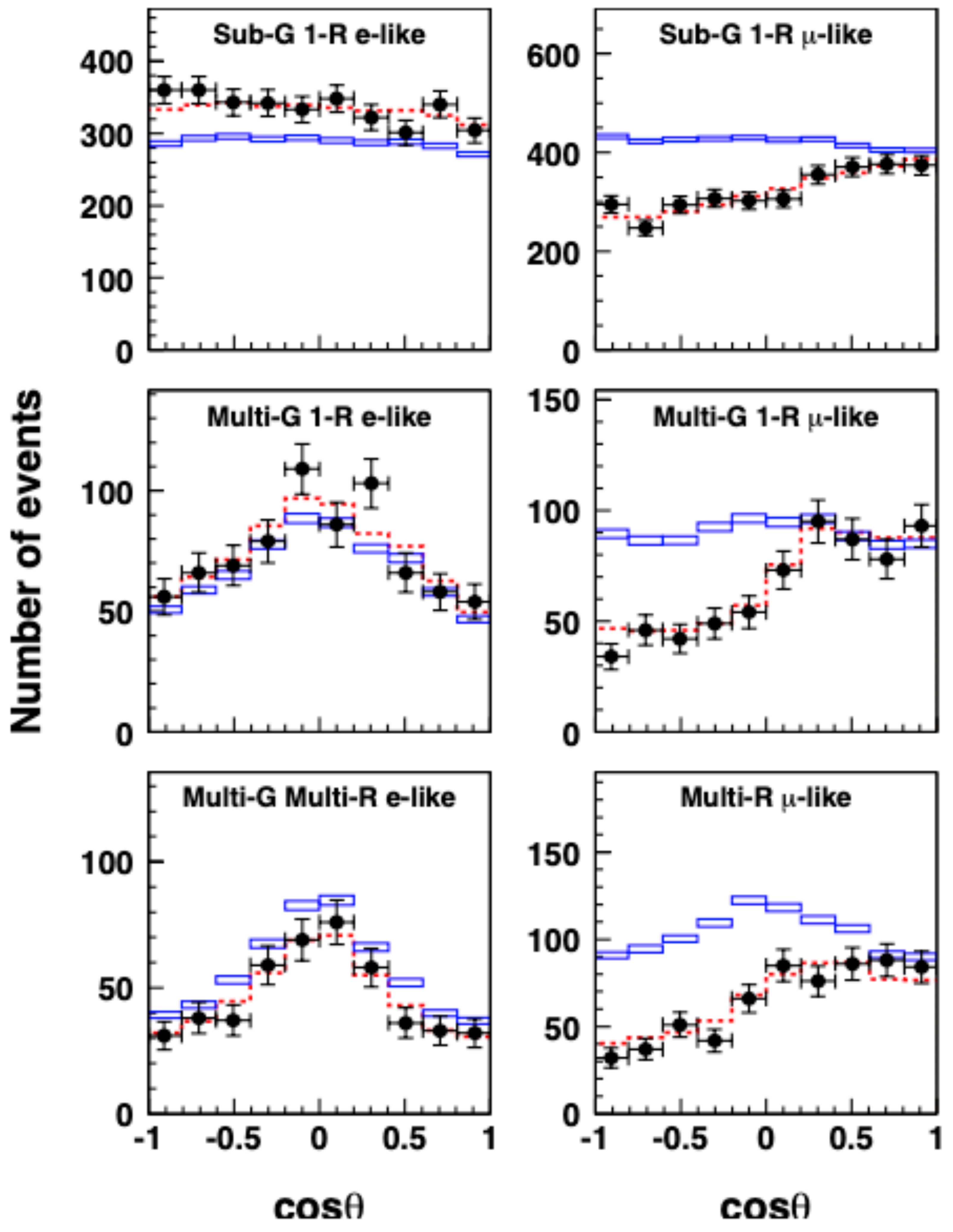
Discovery of neutrino oscillations!



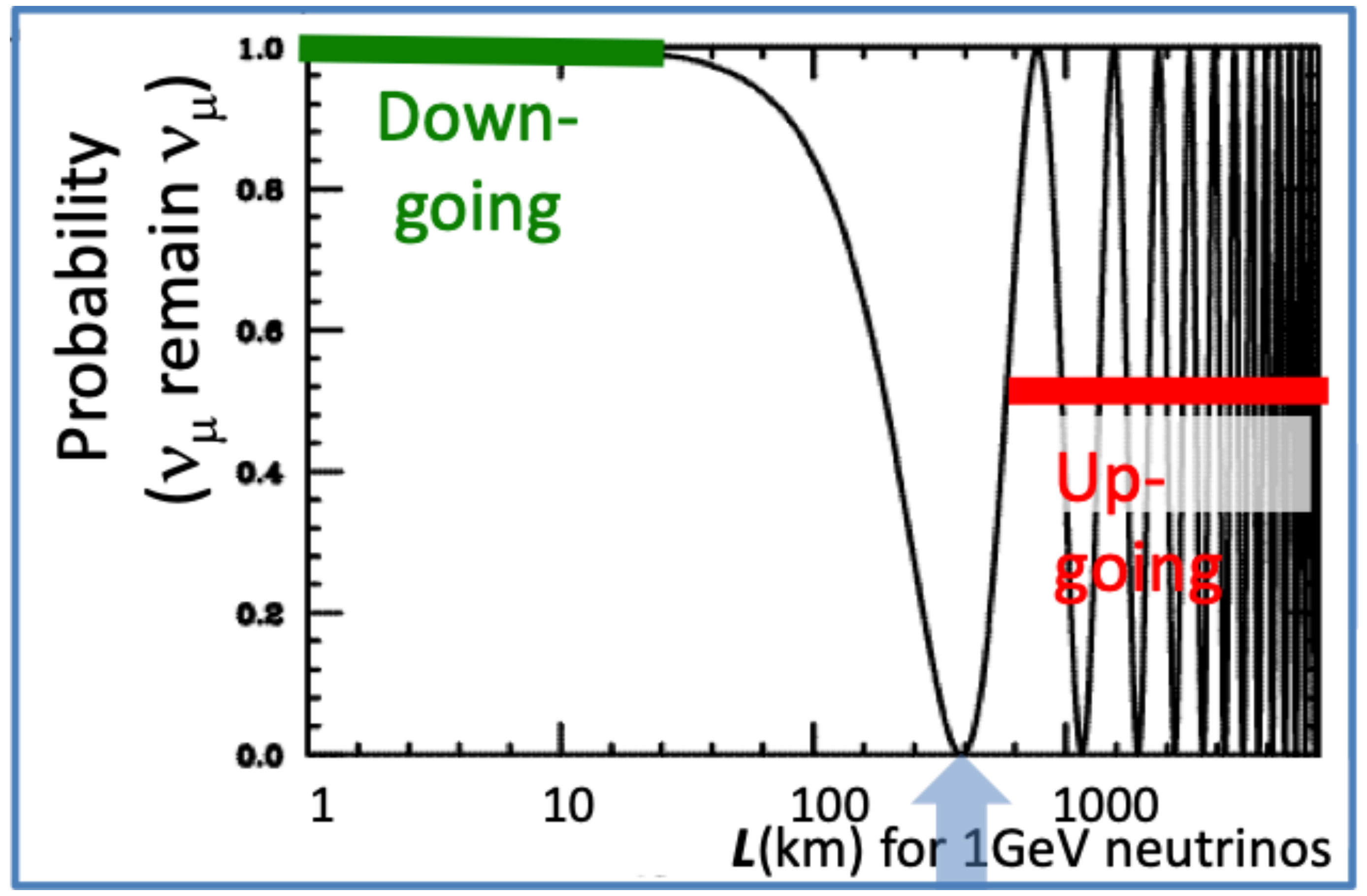


Oscillations

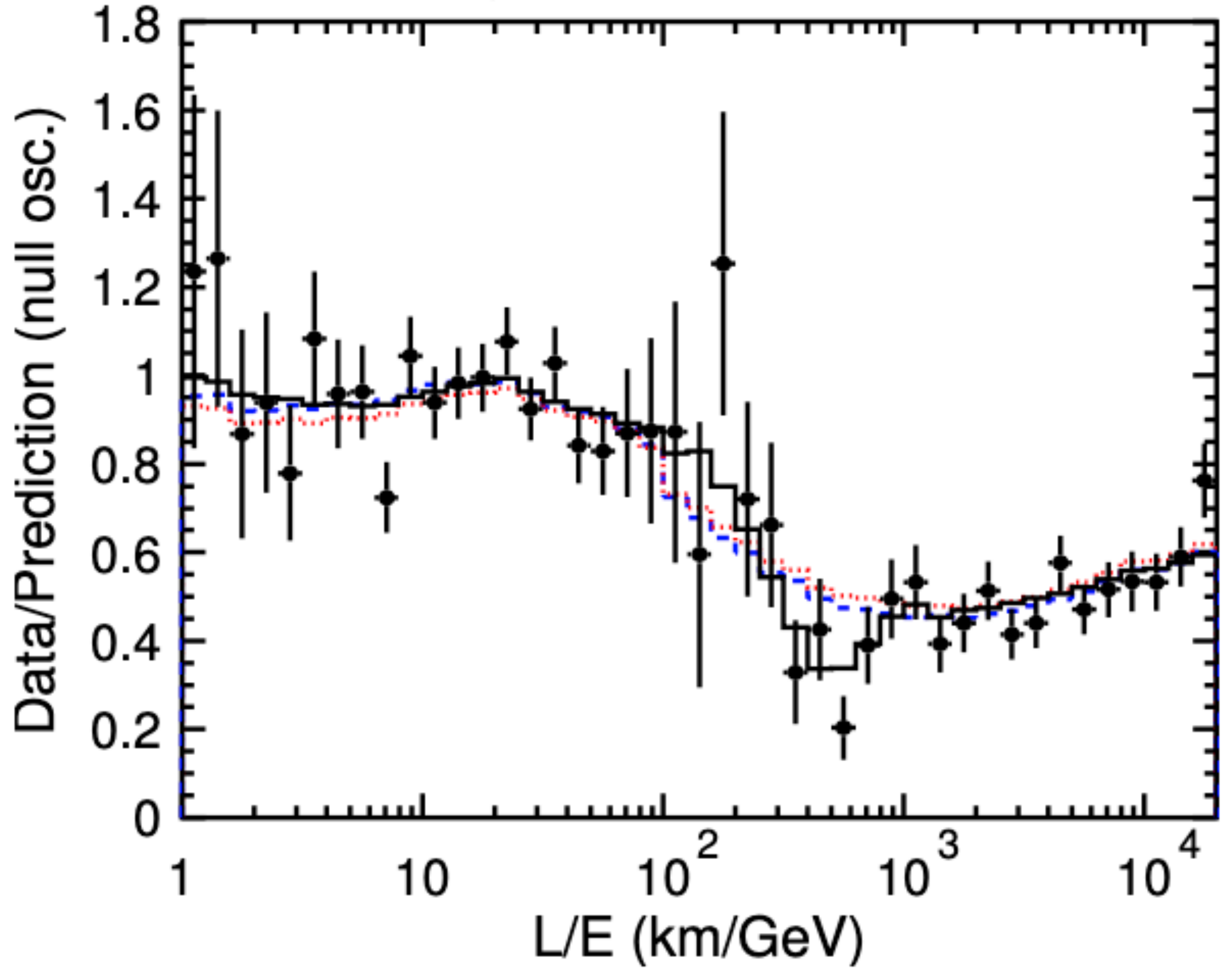
Y. Ashie et al. *Phys. Rev.* D71, 2005



- Clear deficit of ν_μ
- No apperance of ν_e
- L/E behaviour observed!



Y. Ashie et al. *Phys. Rev. Lett.* 93, 101801, 2004

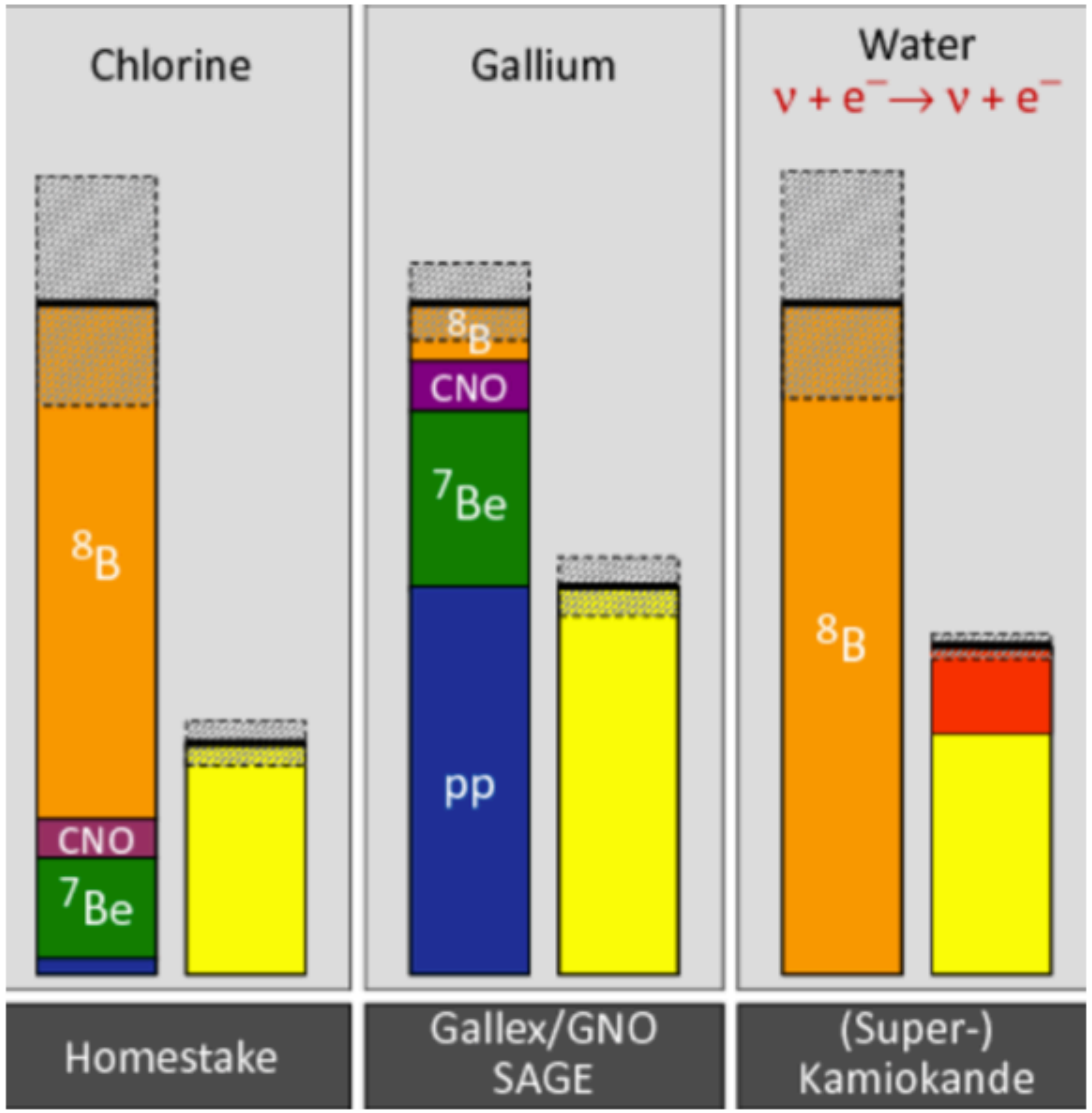


Discovery of neutrino oscillations

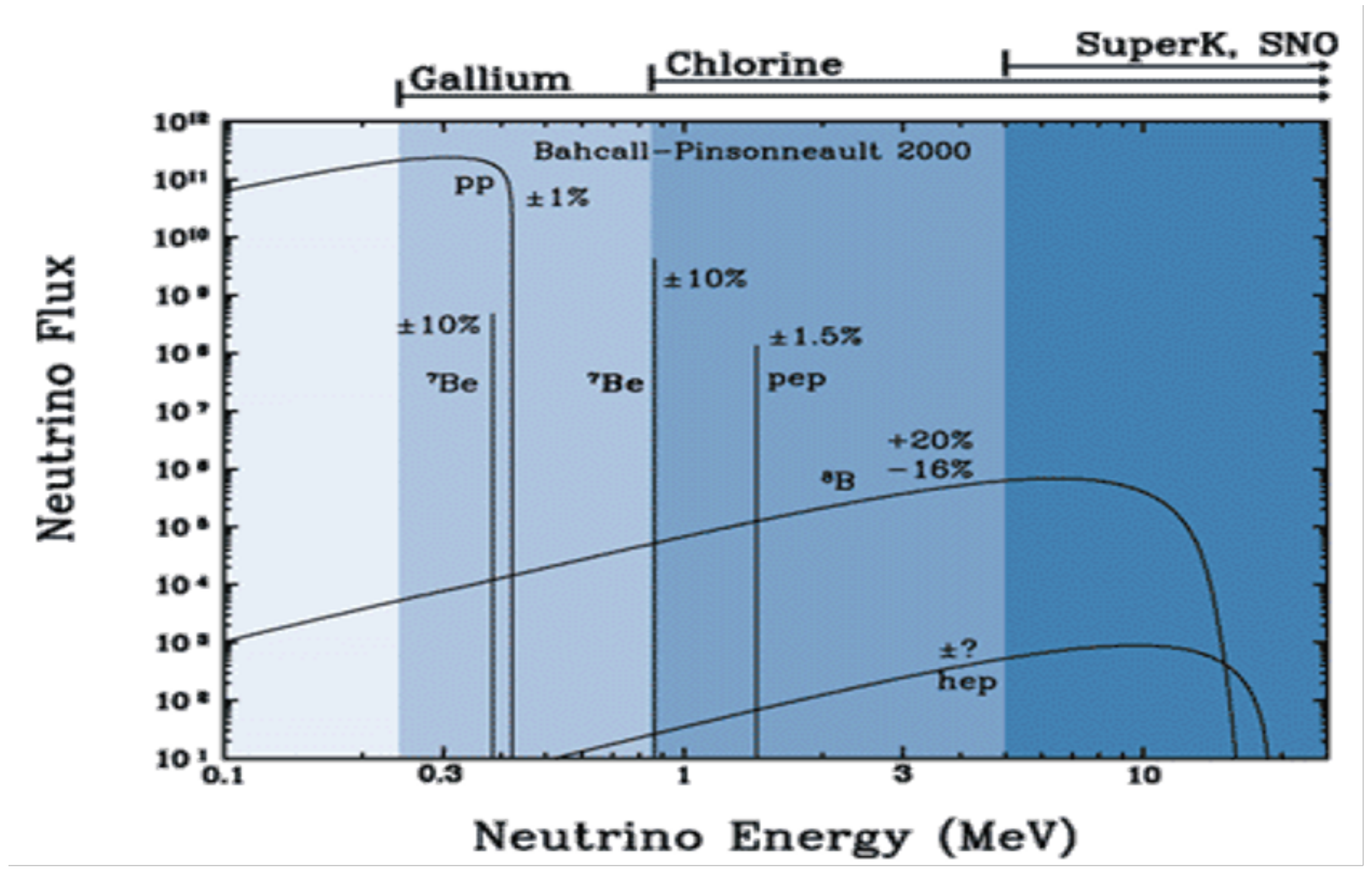
- The 1998 SK results marked a revolution in the history of neutrino physics
- Neutrino anomaly became the discovery of neutrino oscillations
    - Neutrino oscillations implies that neutrino are massive particles!
    - Physics beyond Standard Model!
    - Many new foundamental parameters to measure with experiments!
- What about the other long-standing problem of solar neutrinos?

Solar neutrinos

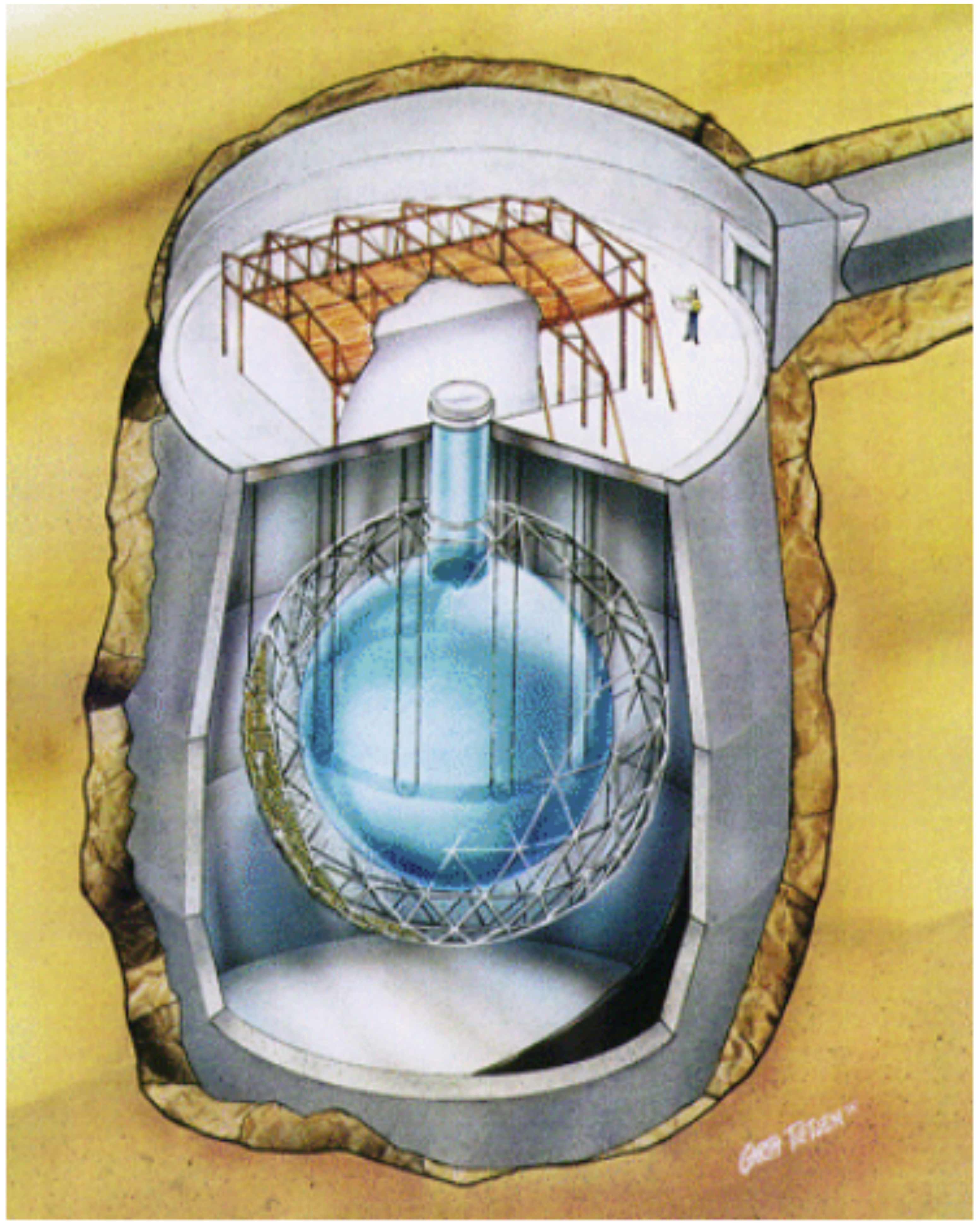
Solar Neutrino Anomaly



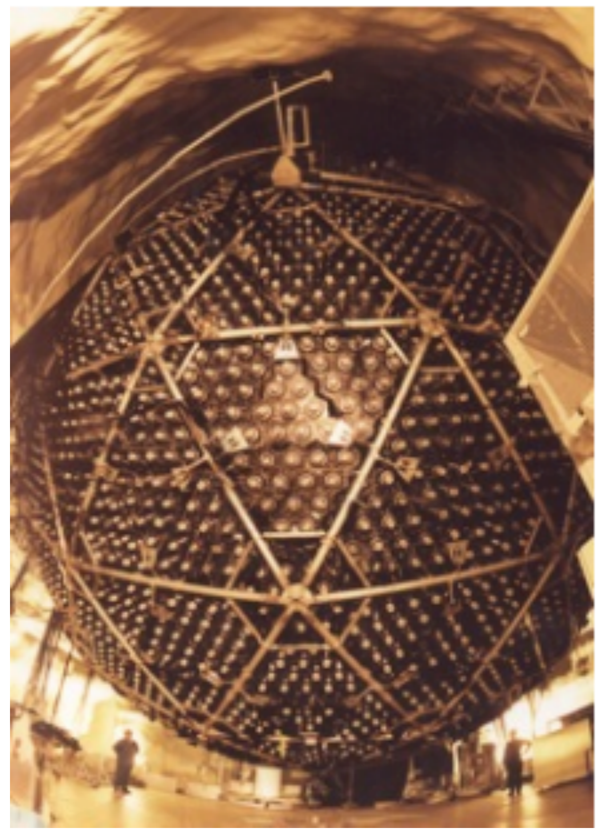
- 3 different types of experiment
  - Different energy threshold
  - Observing different components of the solar ν flux
- They all observe a deficit with respect to the Standard Solar Model
- Is it the solar model that is wrong? Or neutrino mixing?

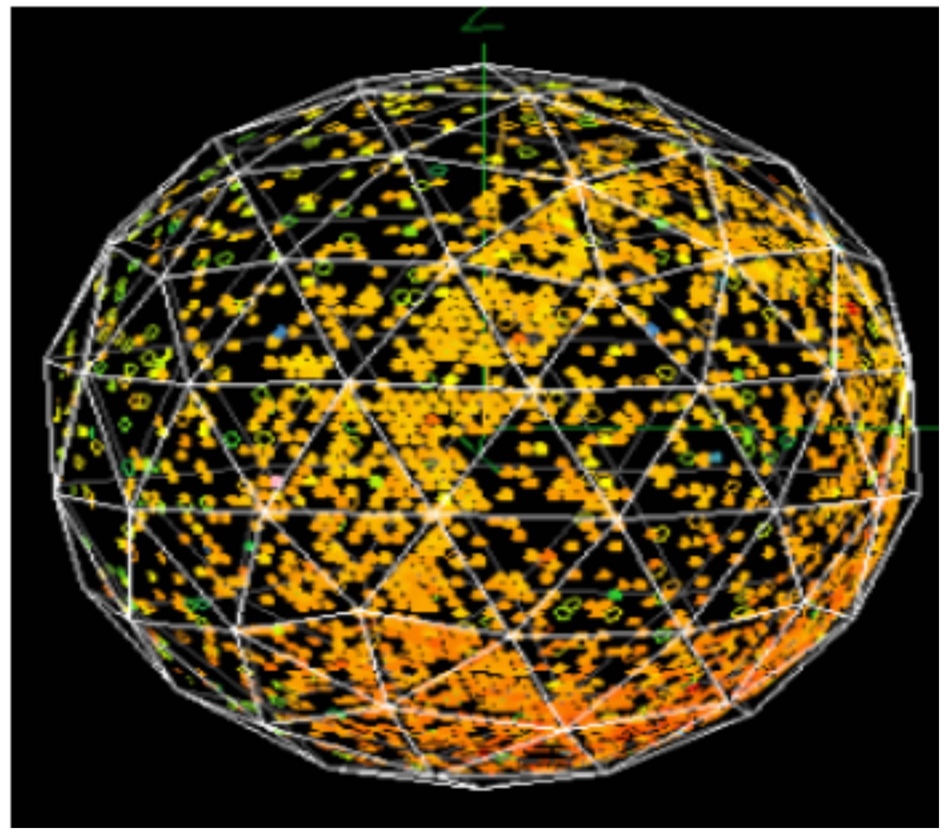


SNO experiment



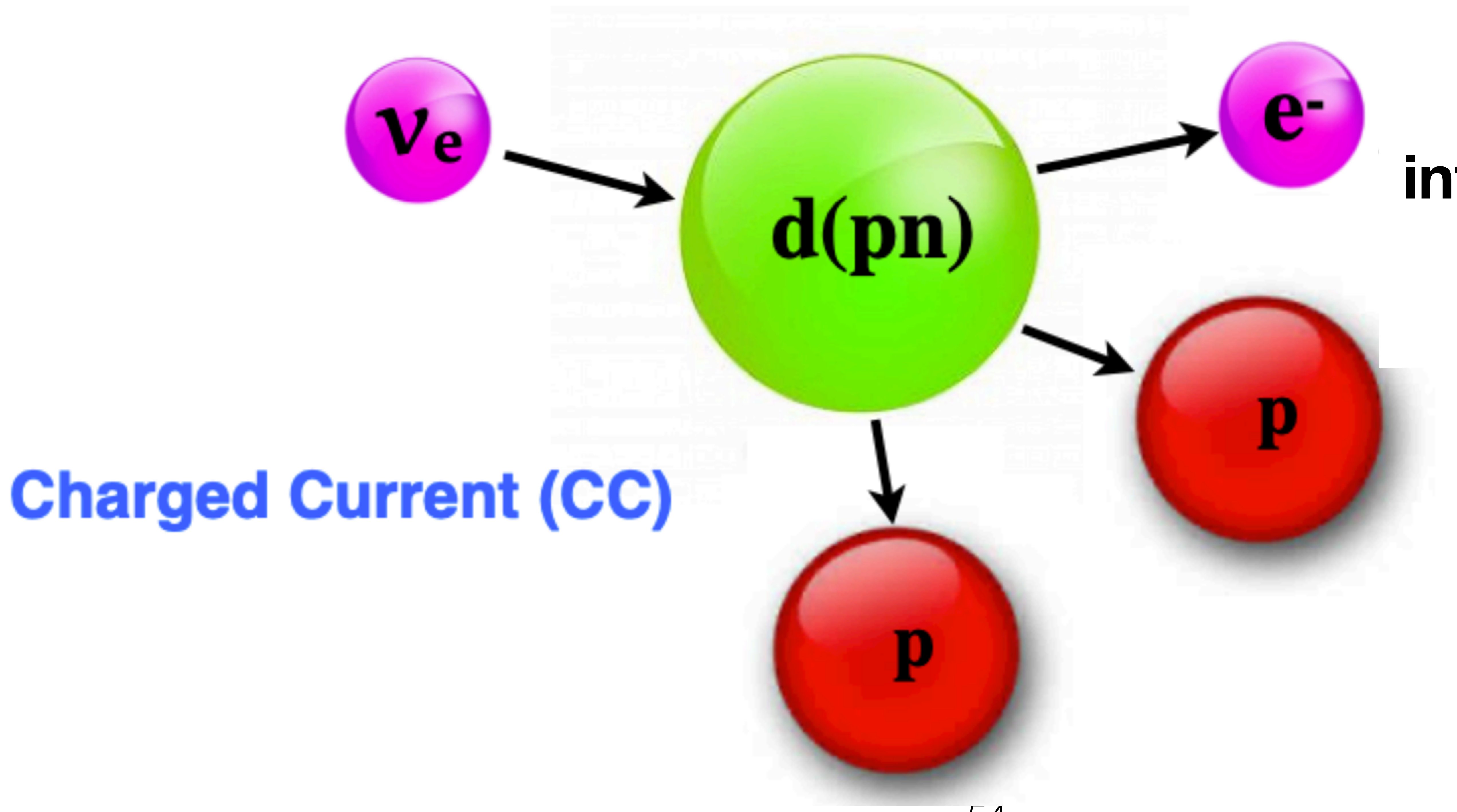
- 1 kton of heavy water (D20)
    - 12 m diameter acrylic vessel
    - 9500 PMTs
- Unique feature: sensitive to Neutral Currents!





SNO detection - Charged Current

$$CC: \ \nu_e + D(p,n) \rightarrow p + p + e^-$$
$$ES: \ \nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$$
$$NC: \ \nu_\alpha + D(p,n) \rightarrow \nu_\alpha + p + n$$



An e- is produced thanks to the interaction on n in the deuterium (not possible at SK)

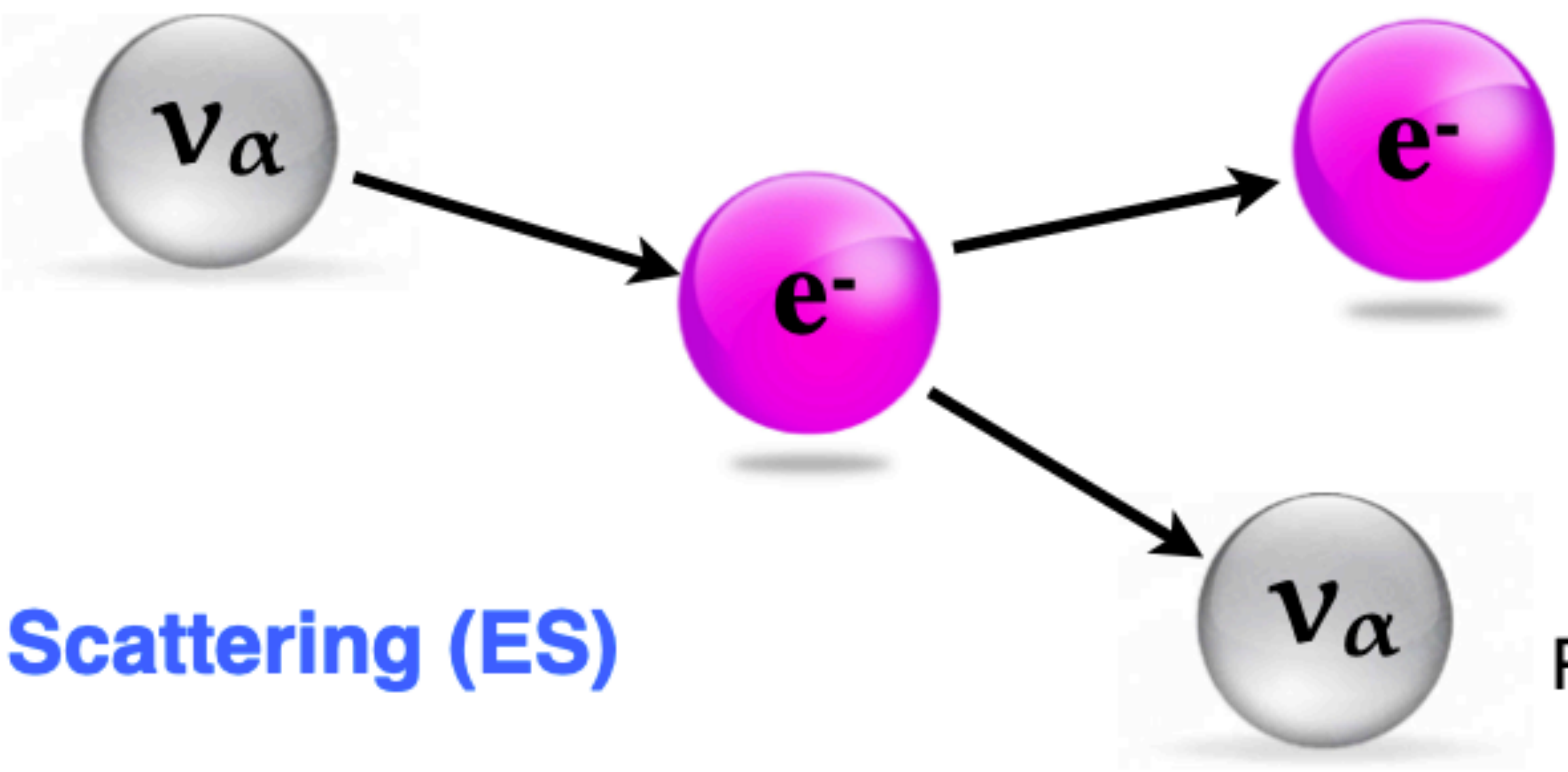
SNO detection - Elastic Scattering

$$CC: \ \nu_e + D(p,n) \rightarrow p + p + e^-$$

$$ES: \ \nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$$

$$NC: \ \nu_\alpha + D(p,n) \rightarrow \nu_\alpha + p + n$$

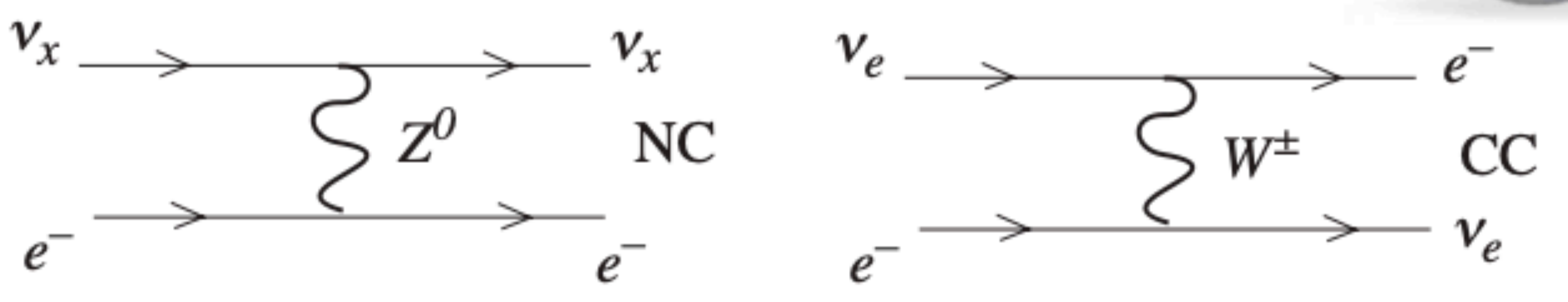
Sensitive to ν_e (NC+CC) and to (ν_μ,ν_τ) (only NC) ~ $\sigma_{\nu e}$x0.15



Detected

Probability to have this interaction is smaller than CC
⇒ a fewer neutrino interactions

Elastic Scattering (ES)



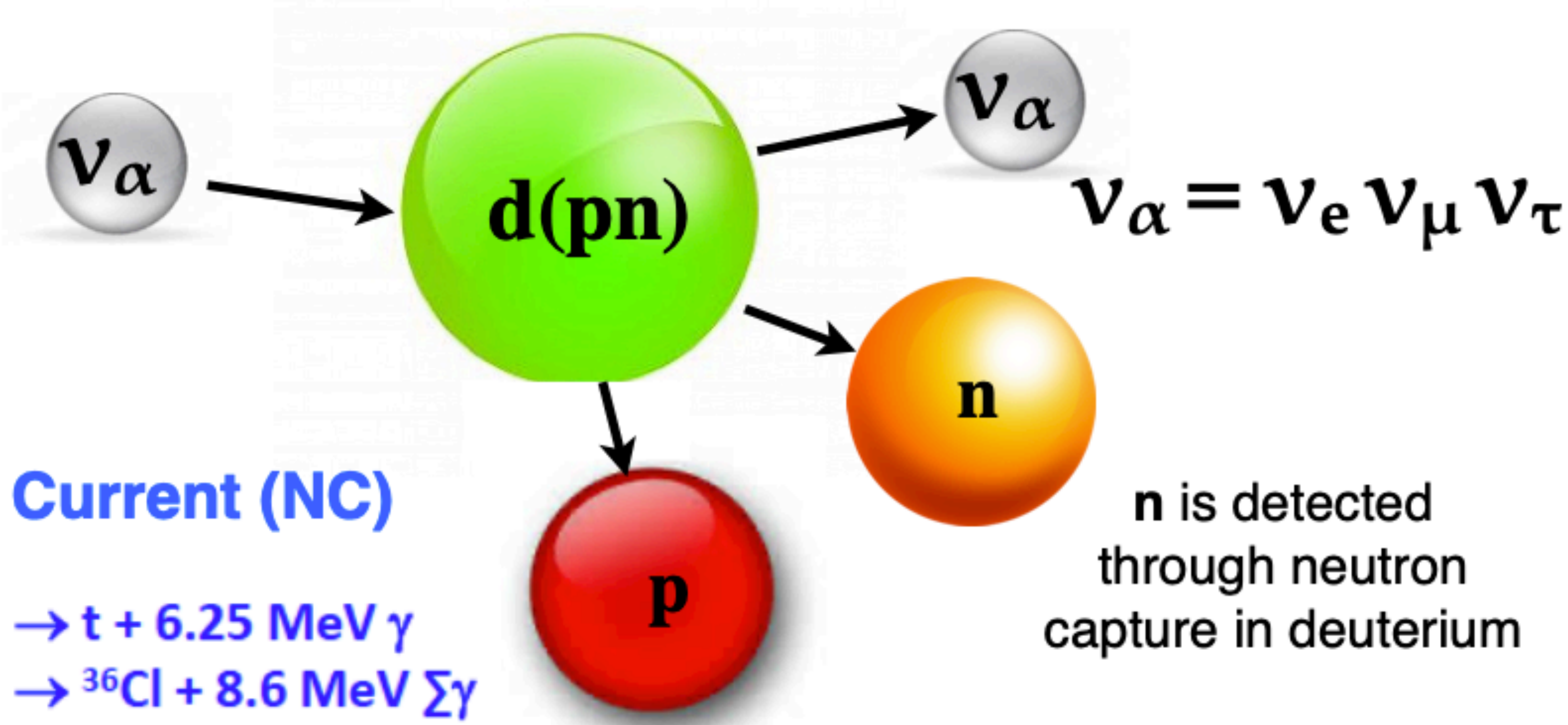
SNO detection - Neutral Current

$$CC: \ \nu_e + D(p,n) \rightarrow p + p + e^-$$

$$ES: \ \nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$$

$$NC: \ \nu_\alpha + D(p,n) \rightarrow \nu_\alpha + p + n$$

Sensitive to the total ν flux from the Sun !



n is detected through neutron capture in deuterium

Neutral Current (NC)

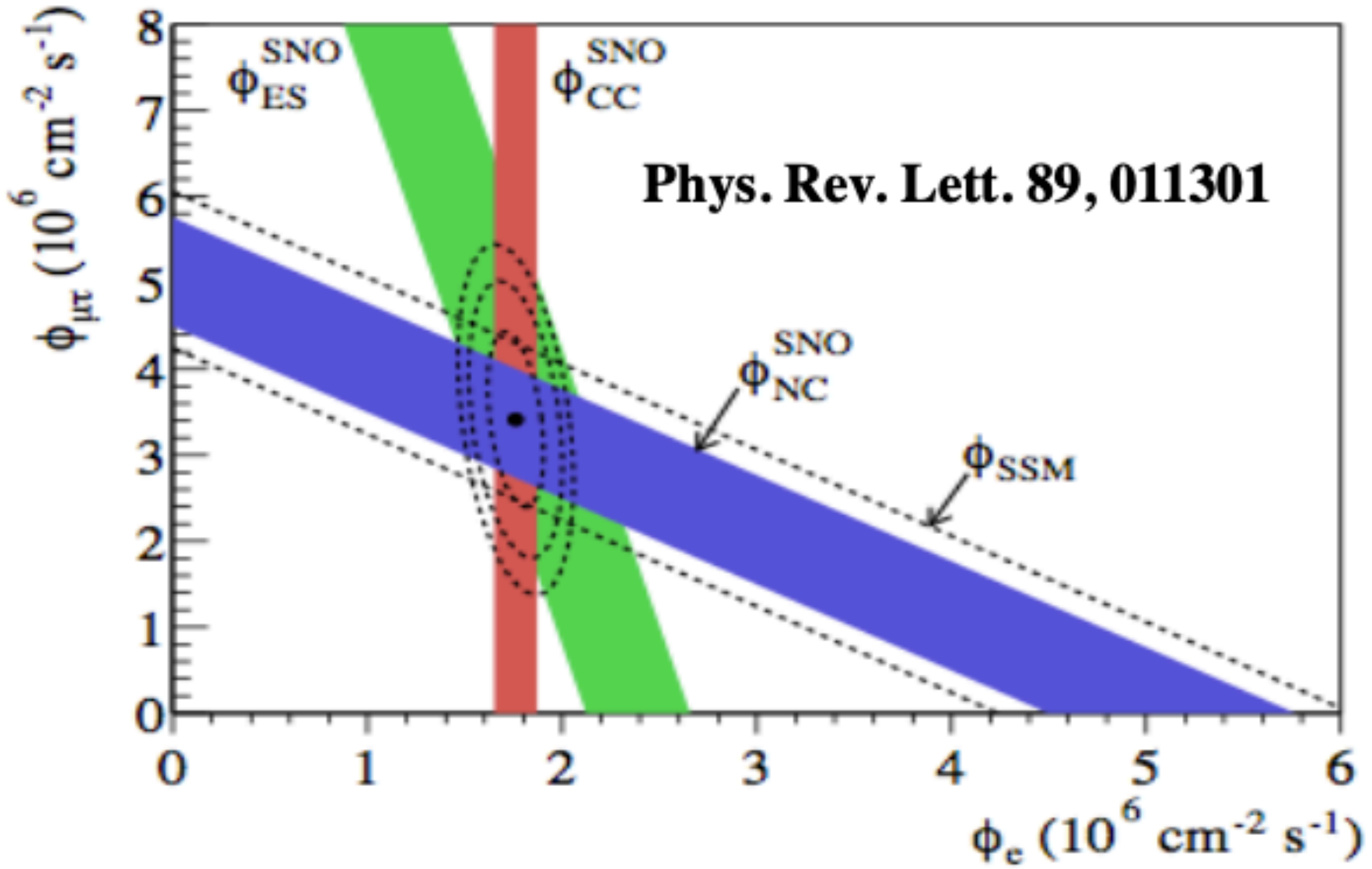
1) $n + d \rightarrow t + 6.25$ MeV γ
2) $n + {}^{35}Cl \rightarrow {}^{36}Cl + 8.6$ MeV $\Sigma\gamma$
3) $n + {}^{3}He \rightarrow p + t + 0.76$ MeV

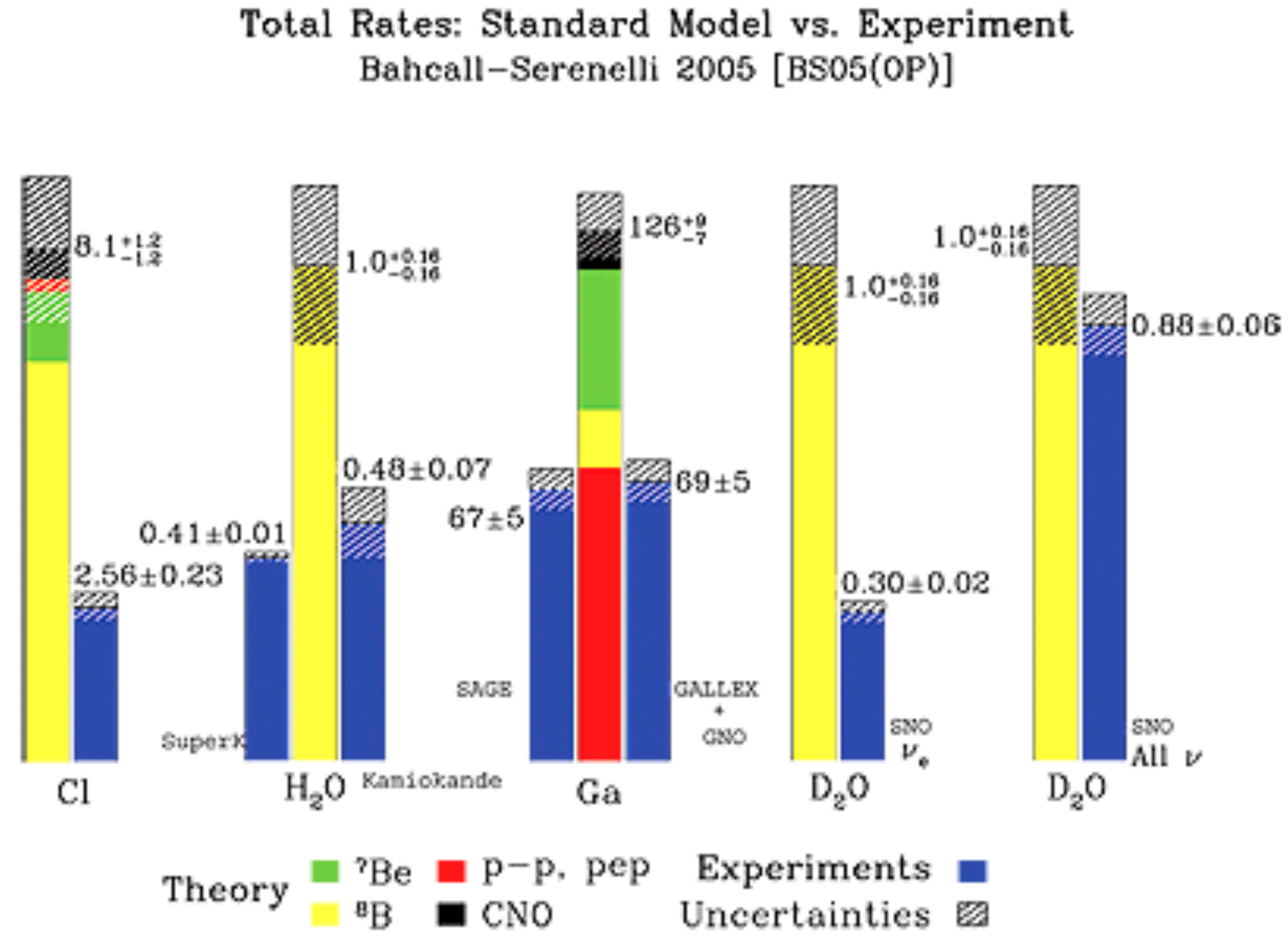
SNO results

$$CC: \ \nu_e + D(p,n) \rightarrow p + p + e^- \qquad \phi_{CC} = 1.76 \pm 0.06(stat.) \pm 0.09(syst)$$

$$ES: \ \nu_\alpha + e^- \rightarrow \nu_\alpha + e^- \qquad \phi_{ES} = 2.39 \pm 0.24(stat.) \pm 0.12(syst)$$

$$NC: \ \nu_\alpha + D(p,n) \rightarrow \nu_\alpha + p + n \qquad \phi_{NC} = 5.09 \pm 0.44(stat.) \pm 0.45(syst)$$



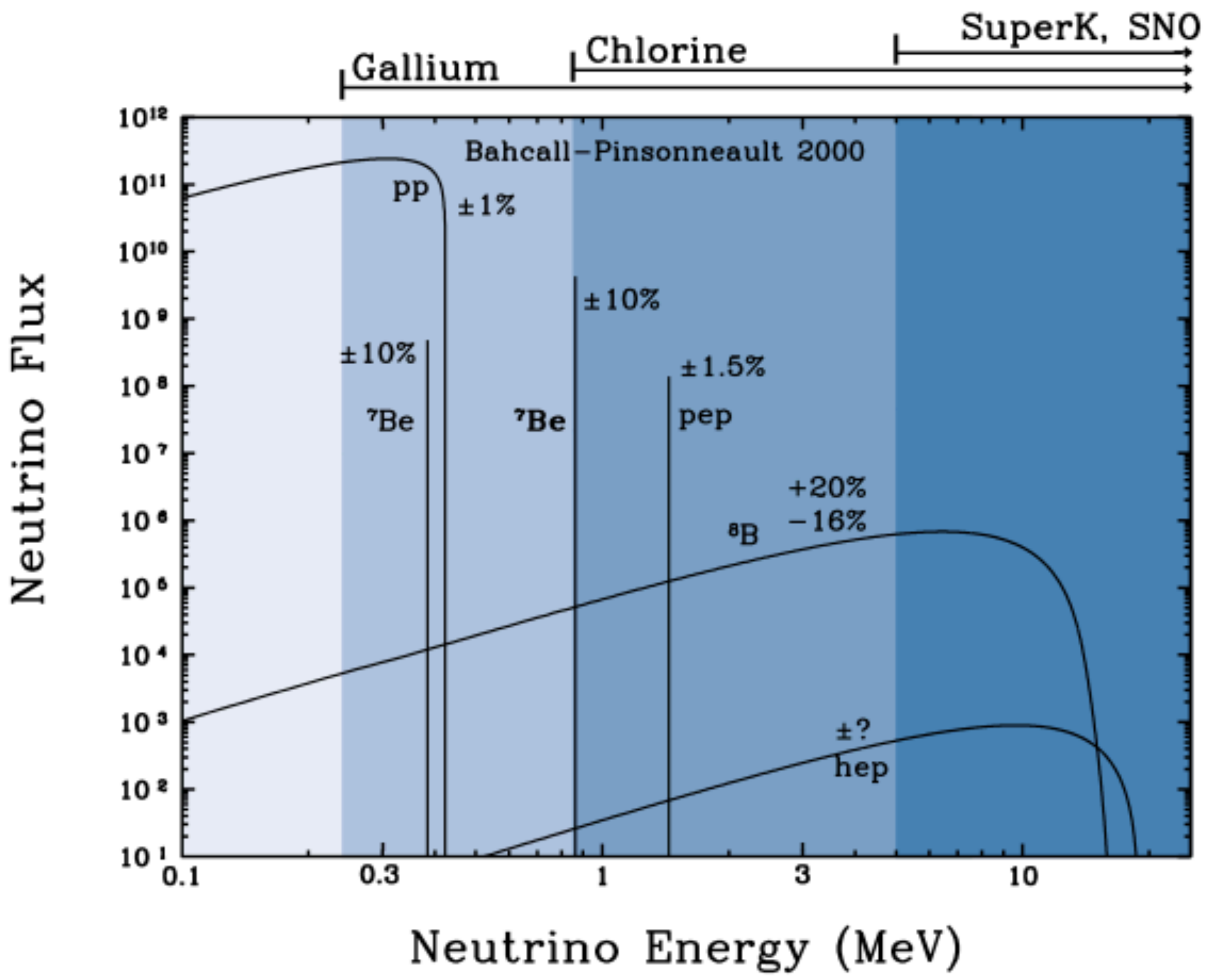


Solar neutrinos "oscillations"

MSW resonance

$$P(\nu_e \to \nu_e) = |\langle \nu_e | \nu_2 \rangle|^2 = \sin^2\theta$$

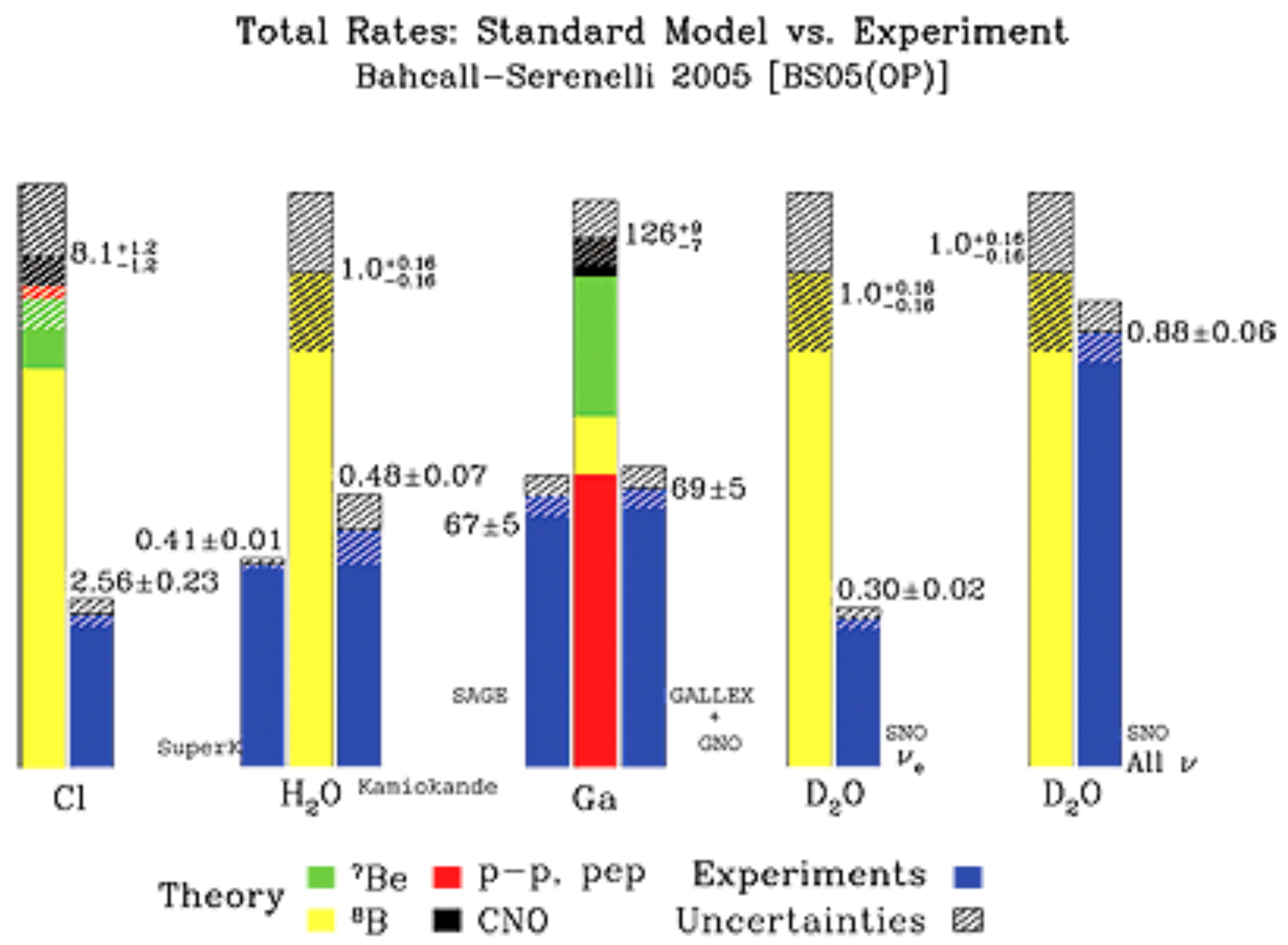
Homestake, SNO CC and SK
→ ^{8}B neutrinos → $P_{osc} \sim 0.3$



Vacuum oscillations

$$\langle P(\nu_e \to \nu_e) \rangle = 1 - \frac{1}{2}\sin^2 2\theta > 0.5$$

Gallium Experiments
→ pp-neutrinos, vacuum regime → $P_{osc} \geq 0.5$



Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

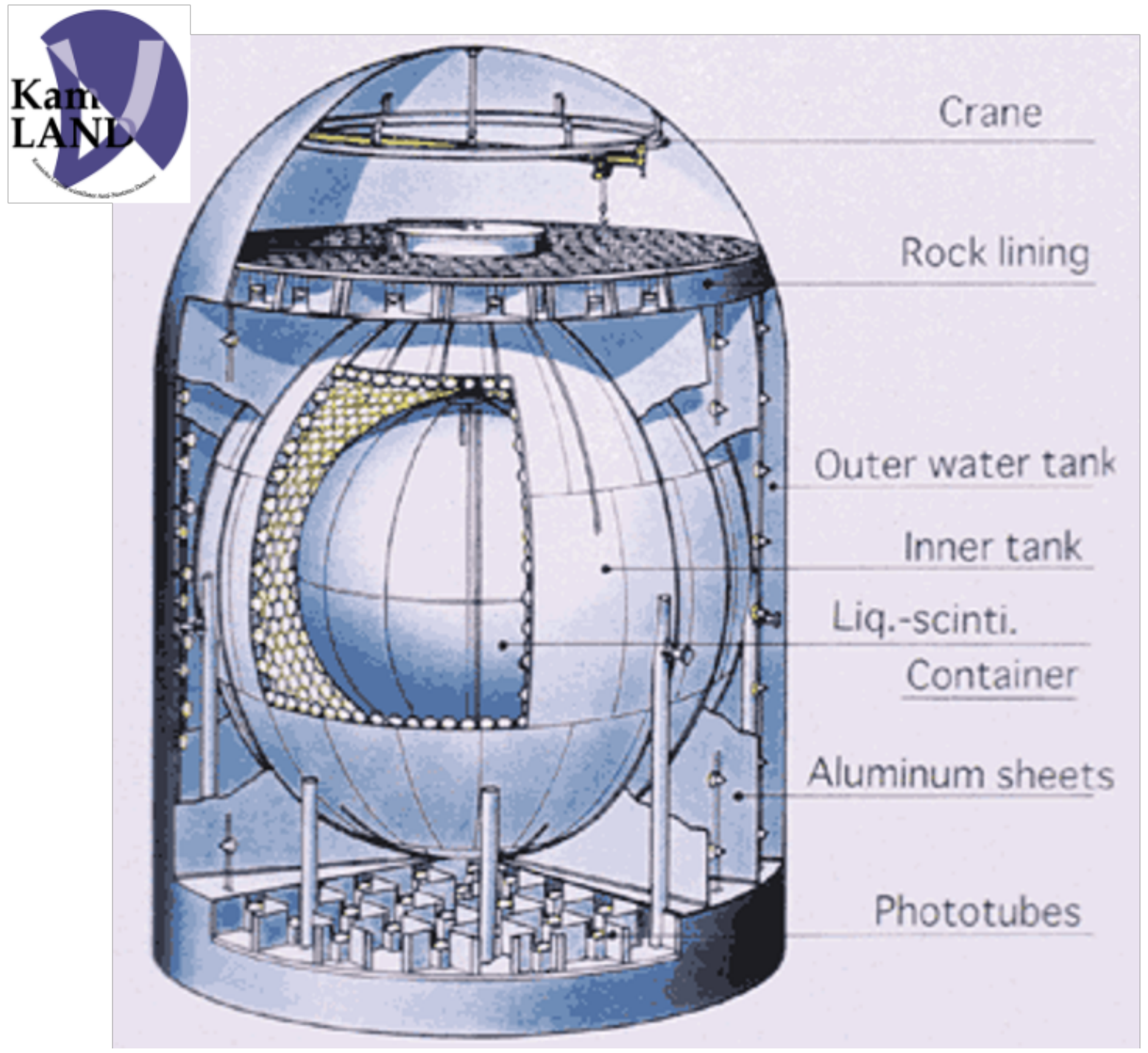
Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

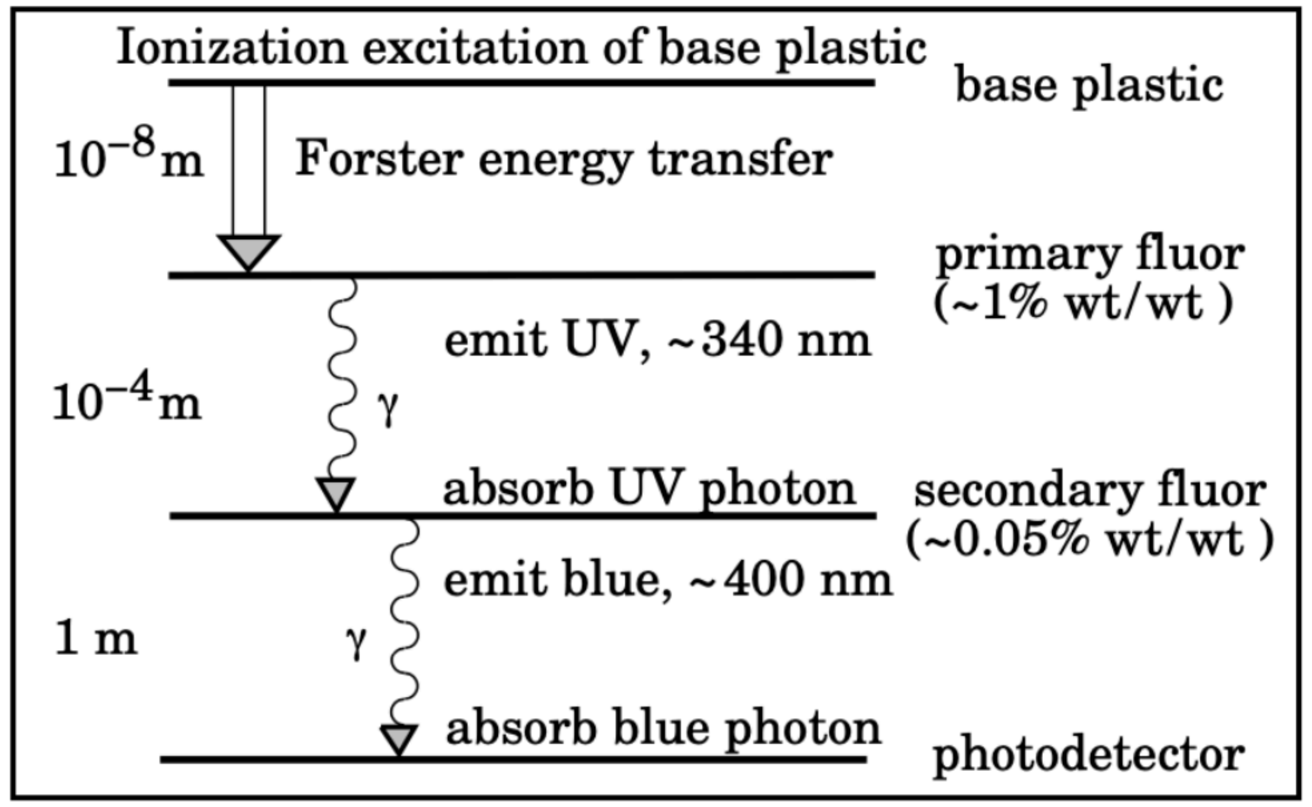
Prize motivation:
"for the discovery of neutrino oscillations,
which show that neutrinos have mass"

KamLAND Experiment

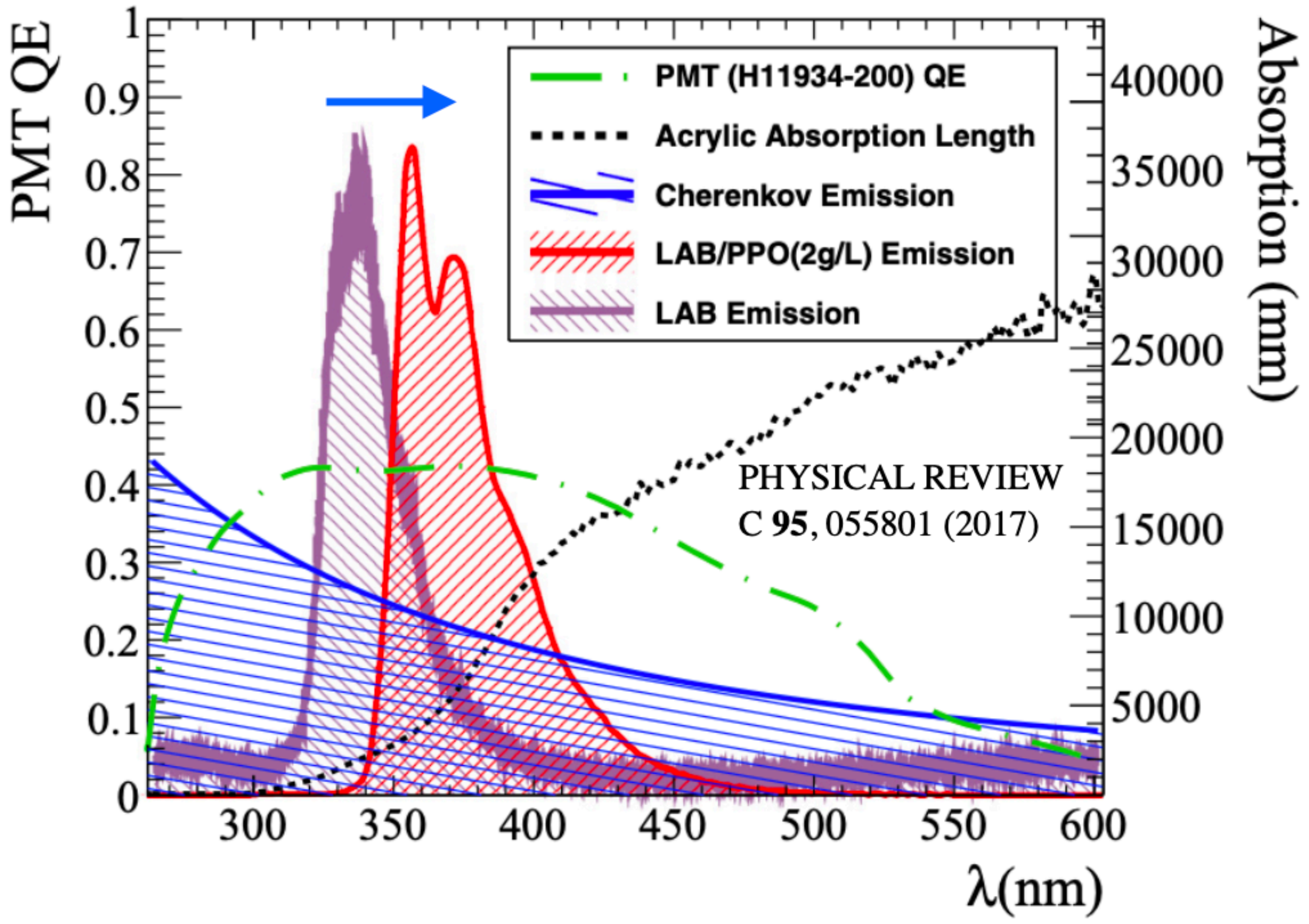
- Unsegmented detector
- 1 kton ultrapure Liquid Scintillator
- Detect $\bar{\nu}e$ through IBD from nearby reactors (55 reactors contributing to KamLAND signal)
  - Average distance 180 km

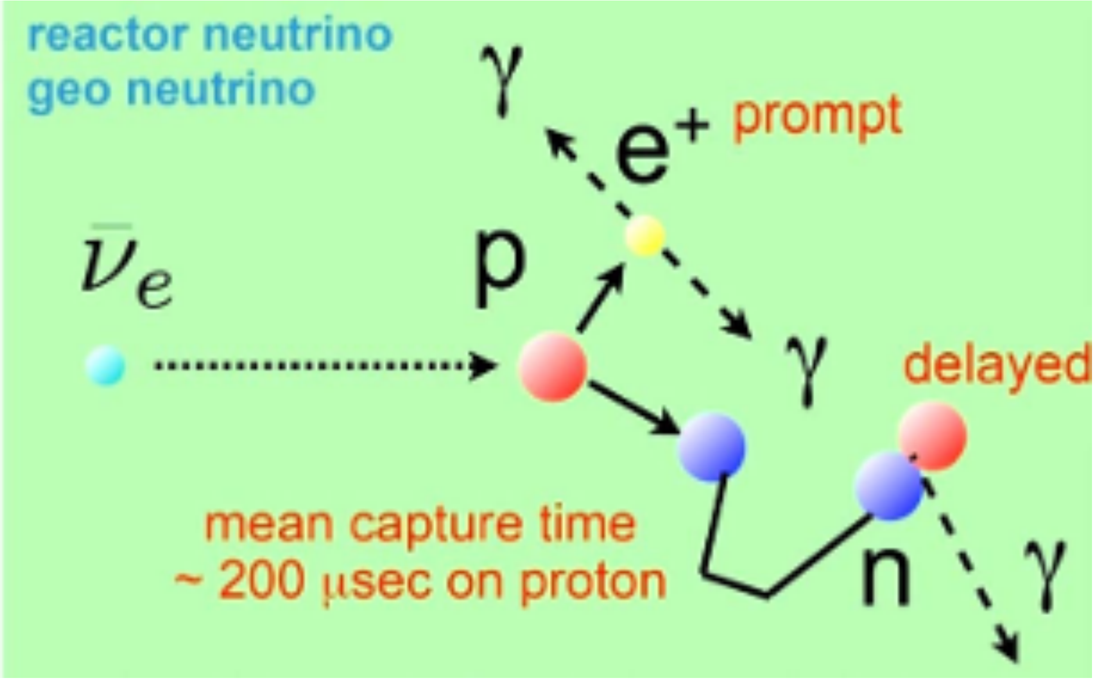
.





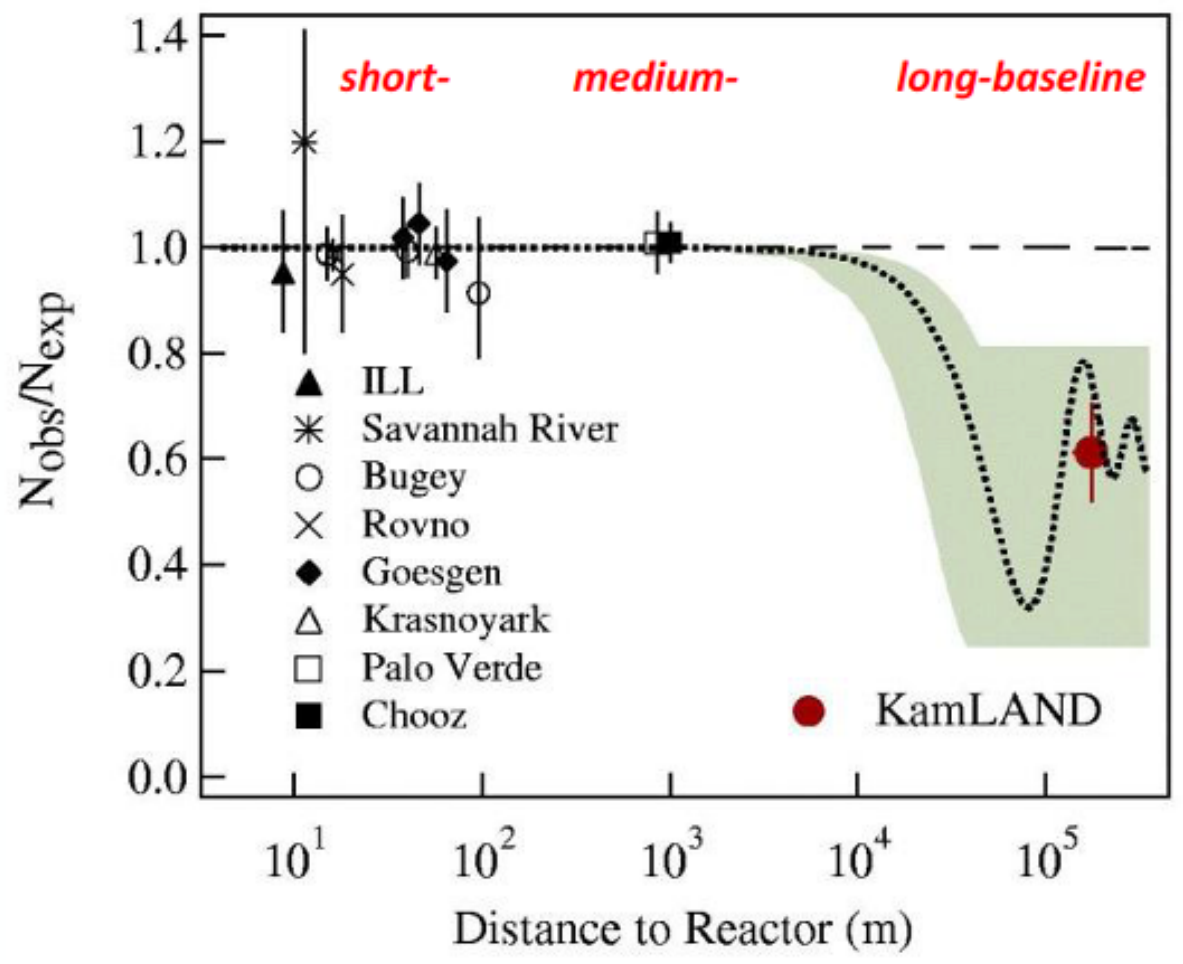
Fluors shift to wavelength where scintillator is more transparent

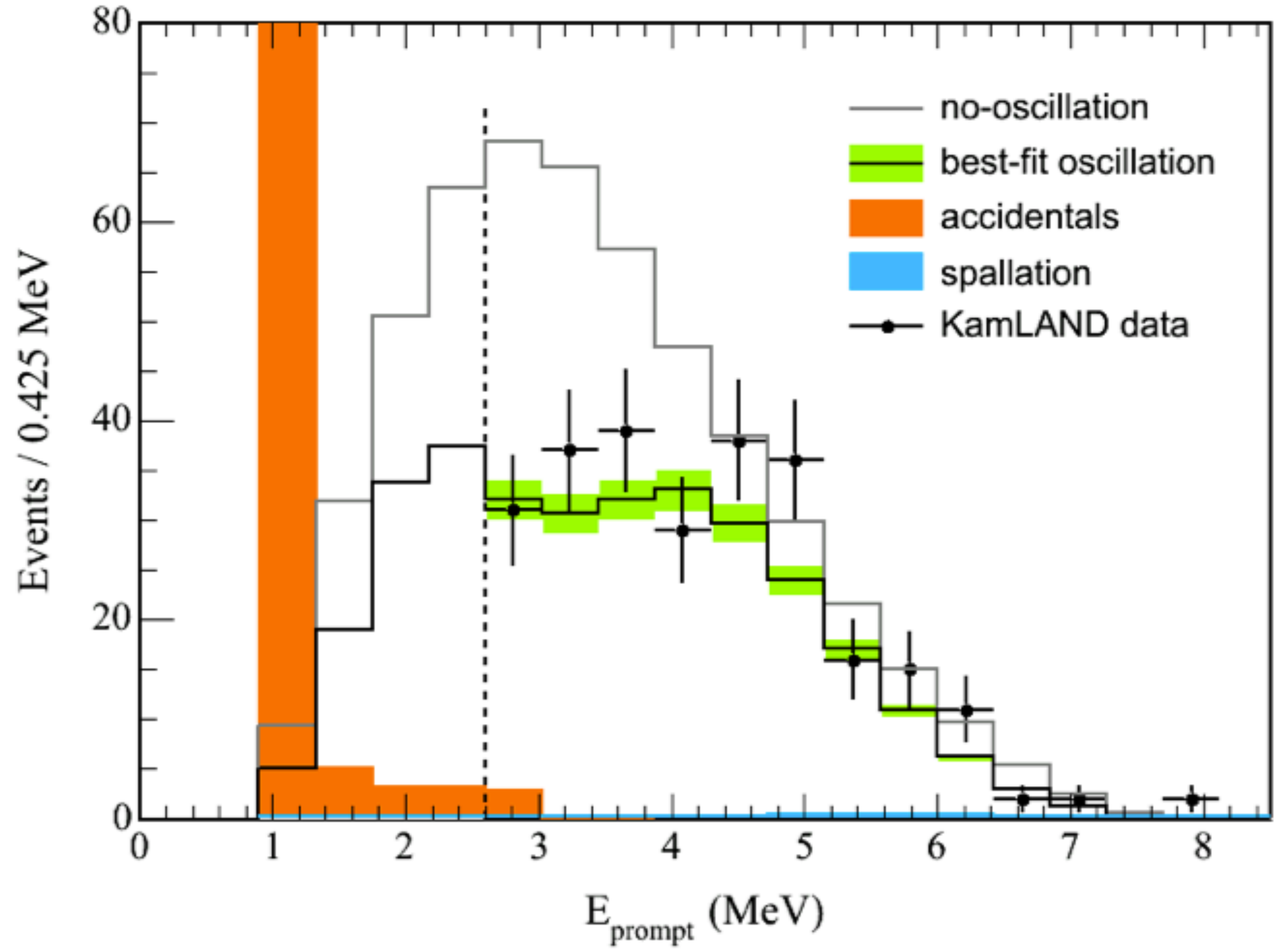


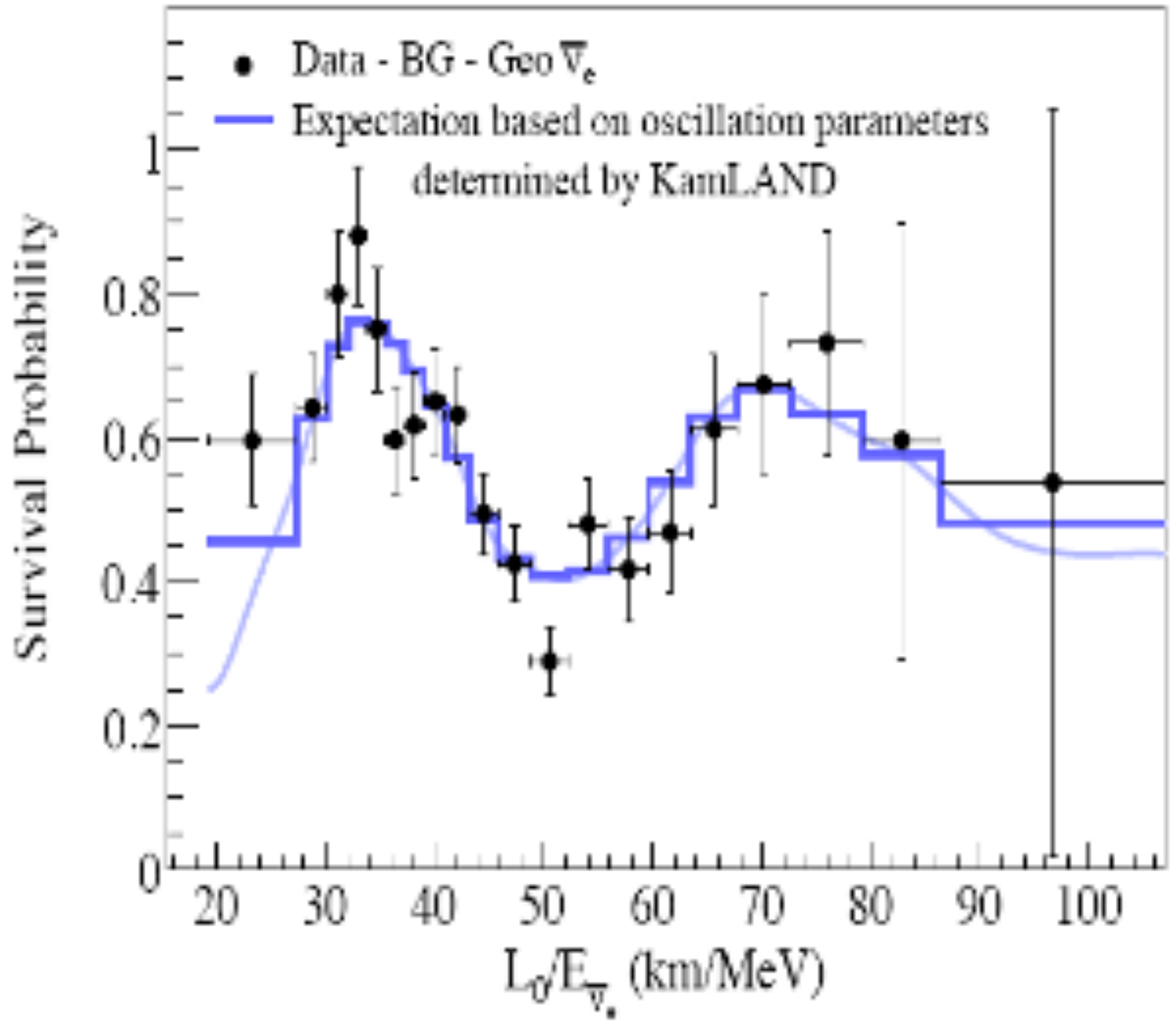


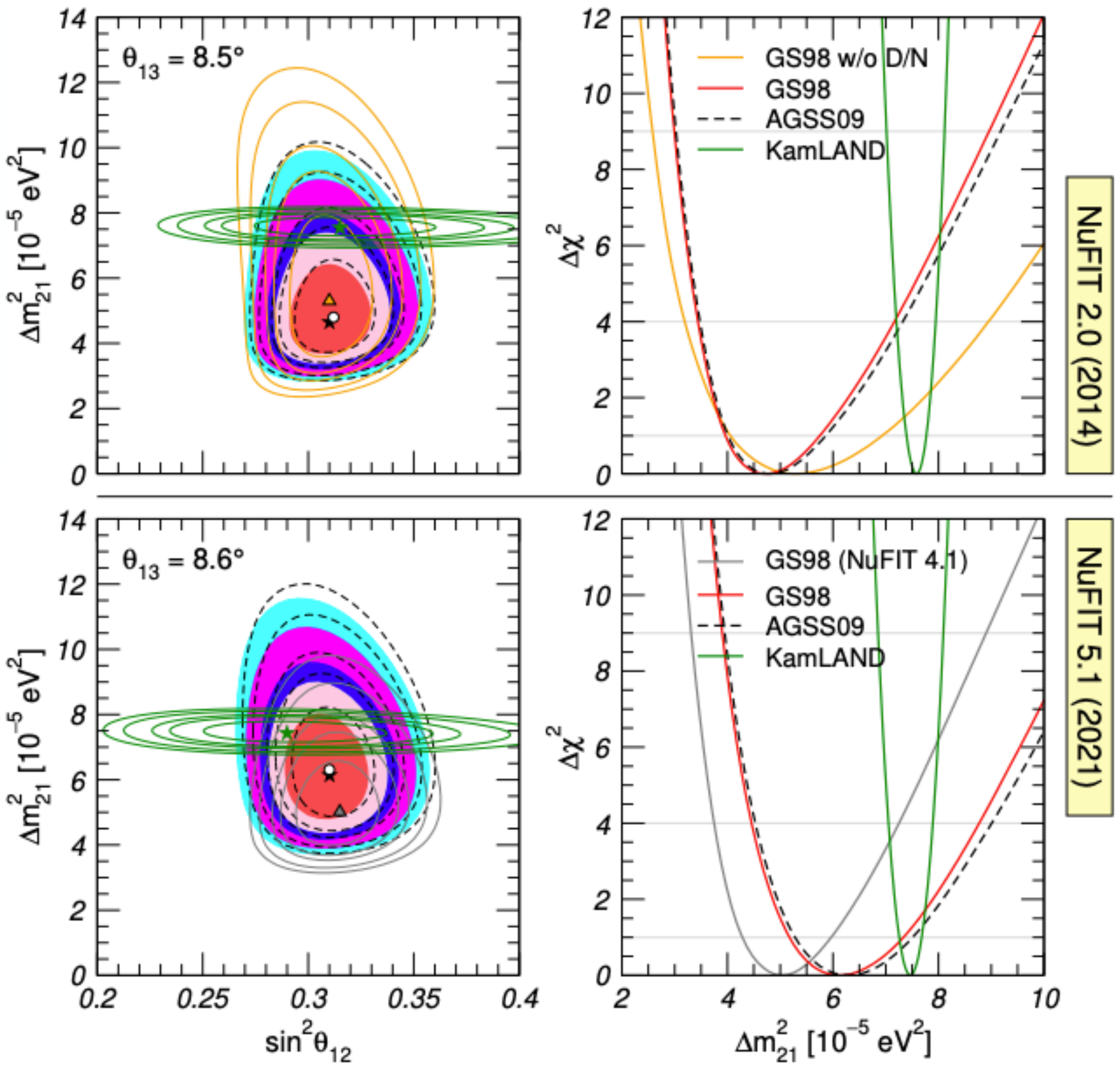
KamLAND results (2002)

- Very precise measurement of the oscillation peak → Δm^2_{12}
- Larger uncertainties on θ12 → combination with solar experiments give consistent picture if MSW resonance with LMA
- Notice that KamLAND was built before Borexino results → whether LMA was the right solution was not sure… it could have missed oscillations if $\Delta m^2_{12} > 2\times10^{-4} eV^2$



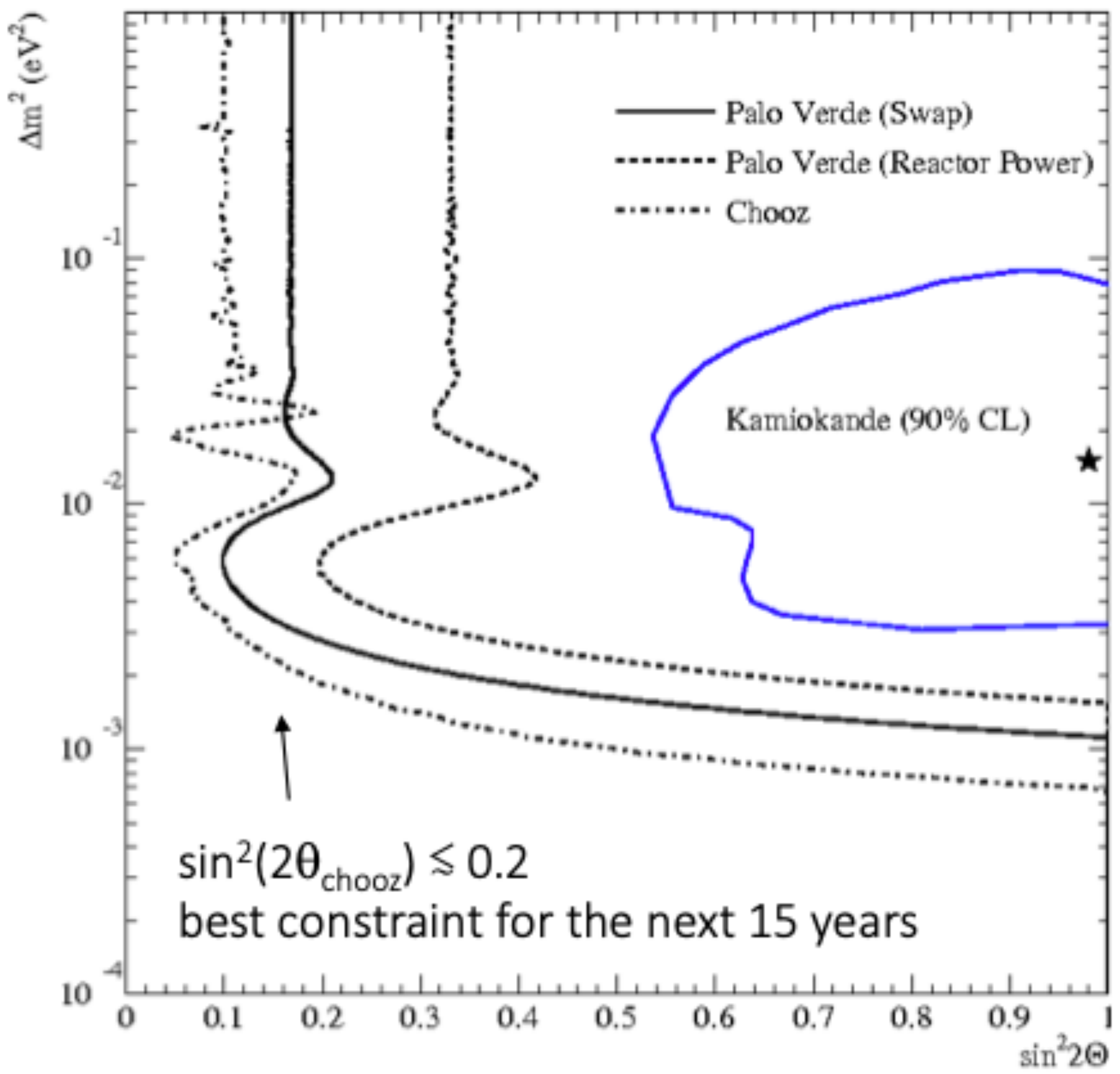




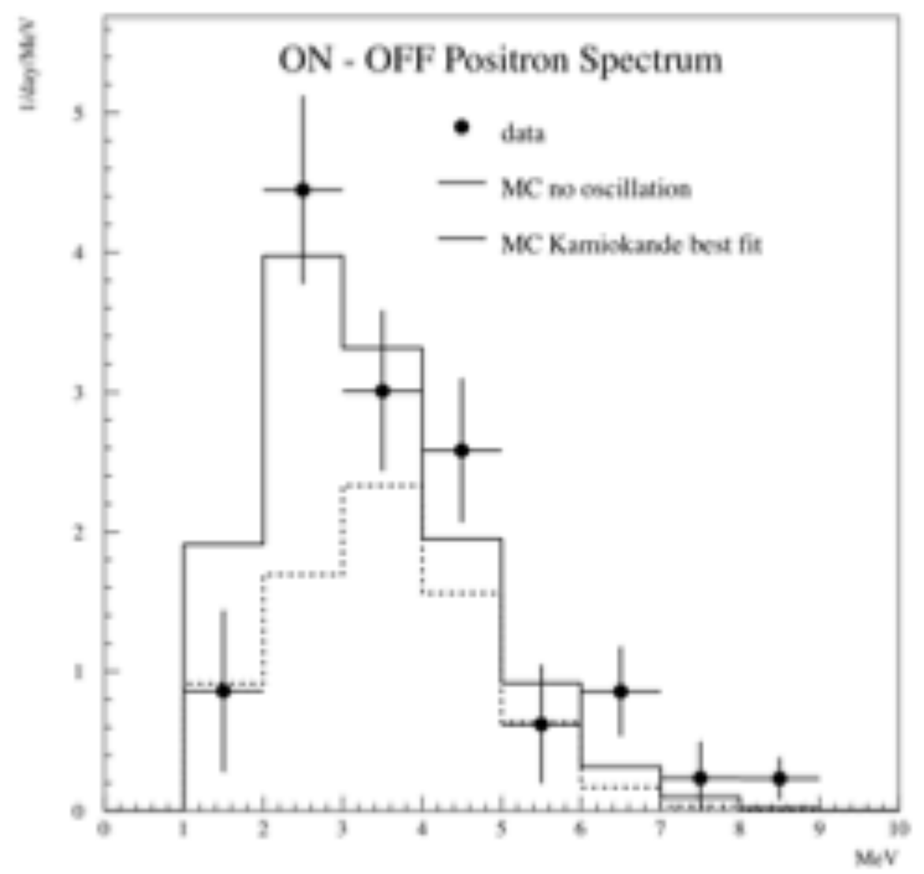


What else with reactors?

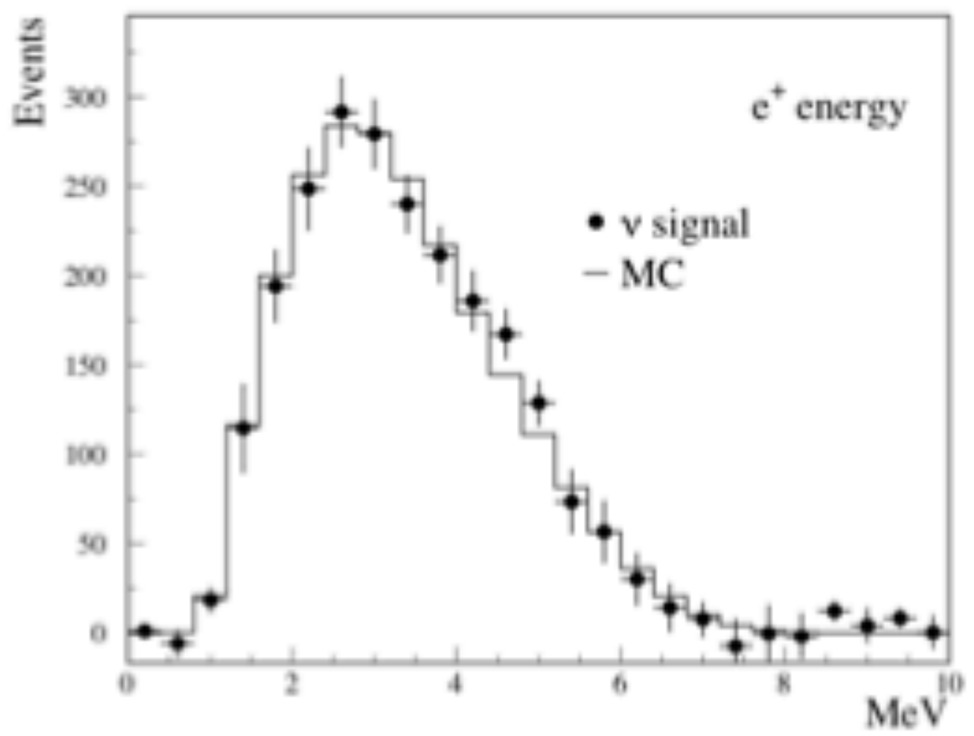
- Can we observe neutrino oscillations close to the reactor source?
- $P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27 \cdot \Delta m^2 L[km]}{E[GeV]}\right)$
- $\sin^2\left(\frac{1.27 \cdot \Delta m^2 L}{E}\right) \sim 1 \to \Delta_m^2 = \frac{\pi/2 \cdot E}{1.27 \cdot L} \sim 3 \times 10^{-3}\ eV^2$ for E~0.003 GeV, L = 1 km
- Same Δm2 as the atmospheric neutrinos → no oscillation observed confirm that $\nu_\mu \to \nu_\tau$ and not ν_e → $\sin^2 2\theta_{13} < 0.2$



Palo-Verde
1000 evts



Chooz
1000 evts



Mixing parameters

$$U^{\mathrm{D}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

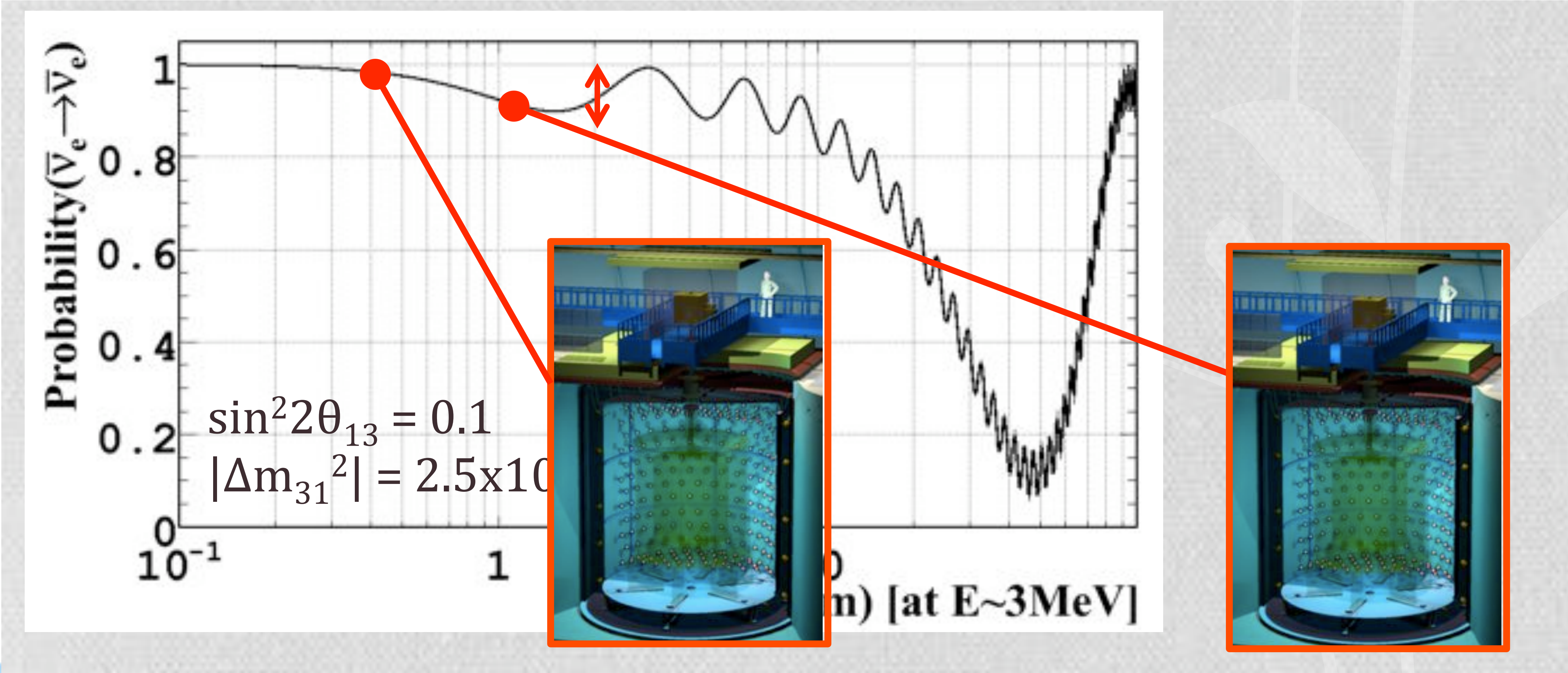
SOL →

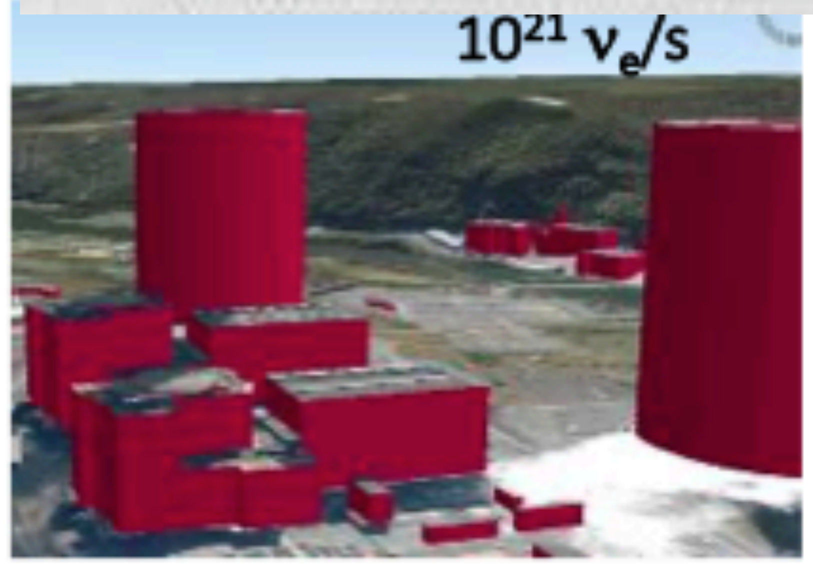
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

↑ ATM

- U_{e3} is the only element affecting both solar and atmospheric sectors
- Solar ν depends on U_{e1}, U_{e2}, U_{e3}
- Atmospheric neutrinos depends only on the third component because $\Delta m^2_{21} << \Delta m^2_{31}$
- $\sin\theta_{23} = \dfrac{|U_{\mu 3}|^2}{\sqrt{(1-|U_{e3}|^2)}}$ and $\sin\theta_{13} = |U_{e3}|^2$
- Chooz measured $sin^2 2\theta_{13} = 4|U_{e3}|^2(1-|U_{e3}|^2) < 0.2 \ \rightarrow |U_{e3}|^2 = \dfrac{1}{2}\left(1 \pm \sqrt{(1-\sin^2 2\theta_{13})}\right) < 0.05$
- How can we measure $\sin^2 2\theta_{13}$ → reactor or long baseline experiments
- We will discuss today reactor measurements

Near/Far ratio

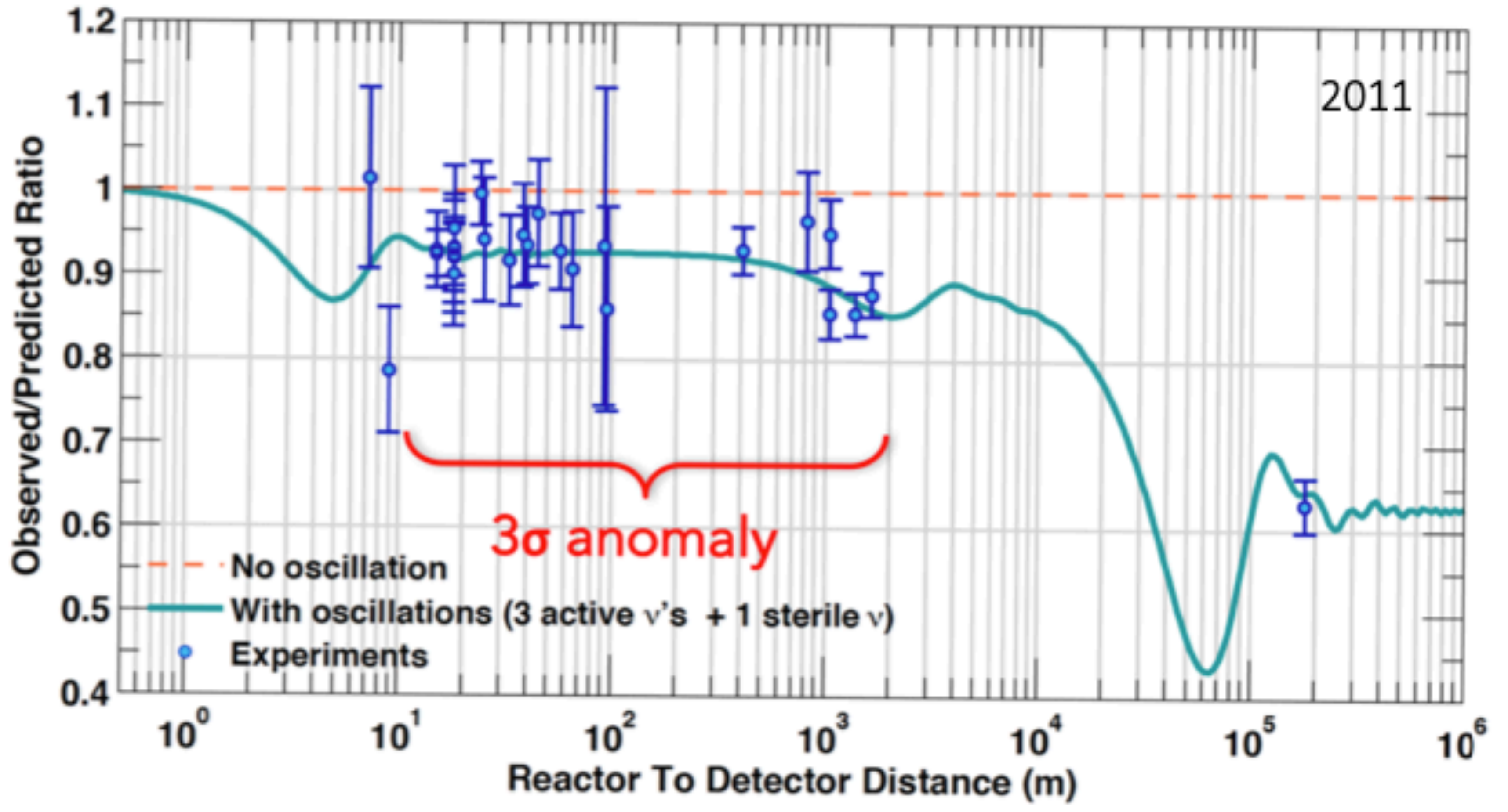




Nuclear Power Station

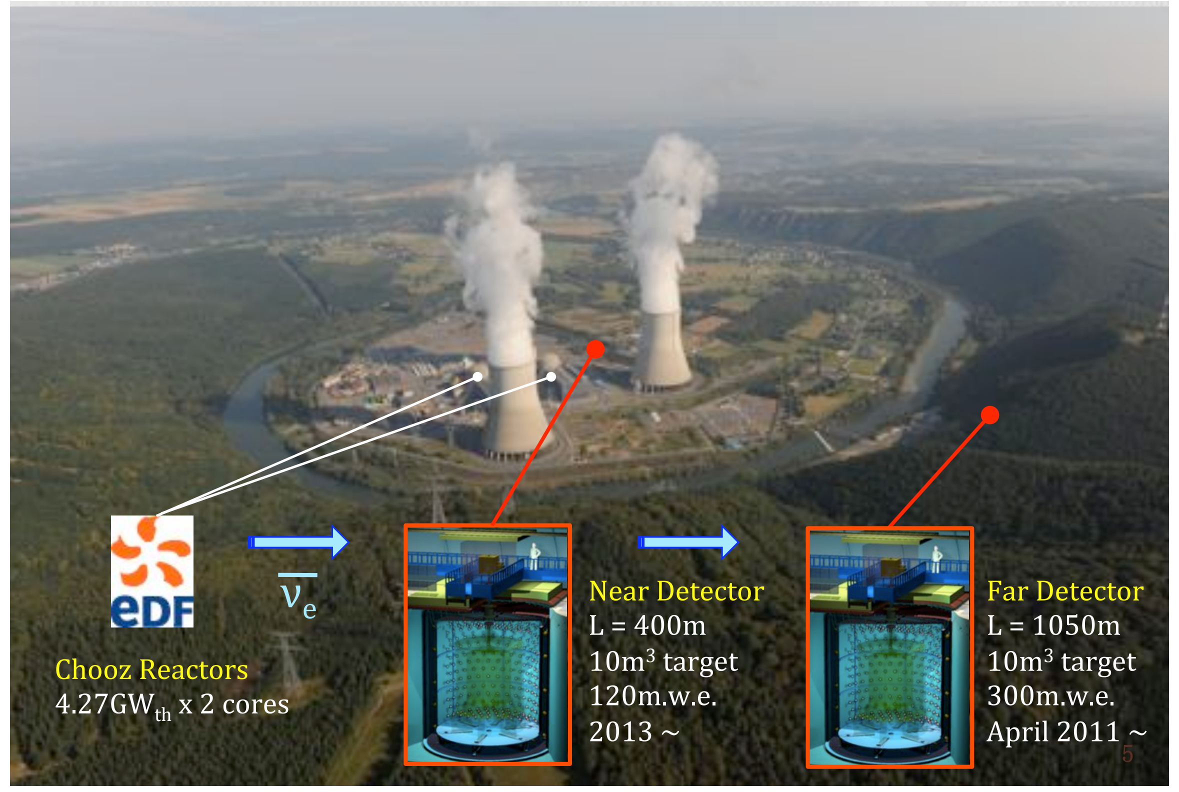
- Knowing U_{e3} is small we are looking for a small signal of $\bar{\nu}_e$ disappearance
- Main systematics uncertainties is the flux of neutrinos from reactors
- Measure $\bar{\nu}$e before the oscillations at a near detector and after the oscillations at a far detector!

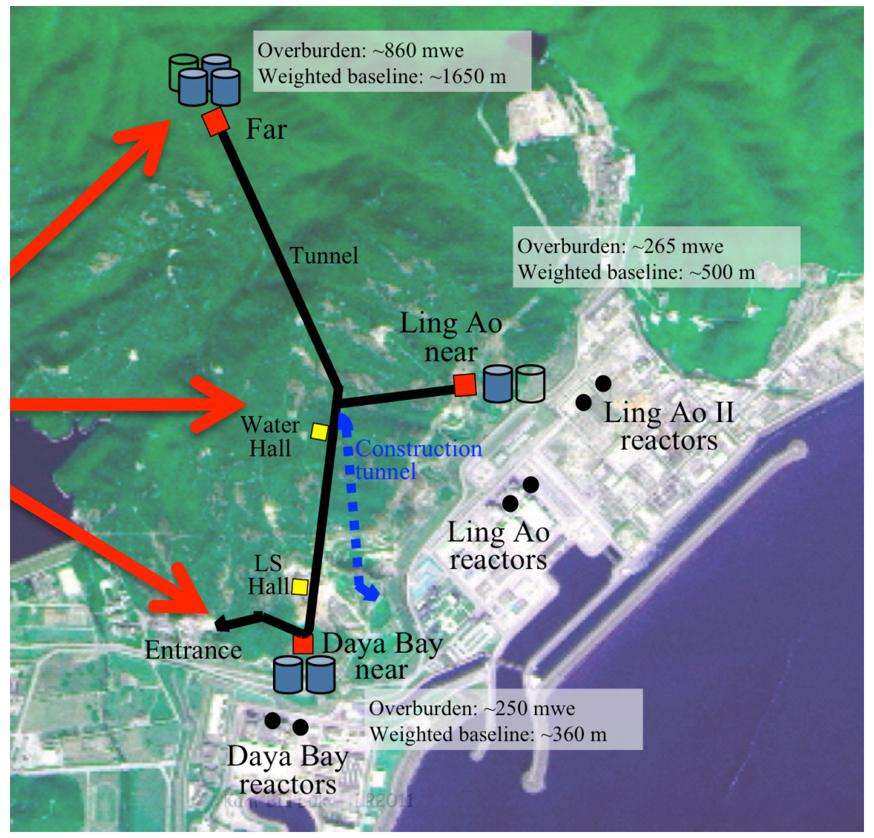
2011 reactor anomaly → sterile neutrinos?
Now ~solved and due to reactor fluxes

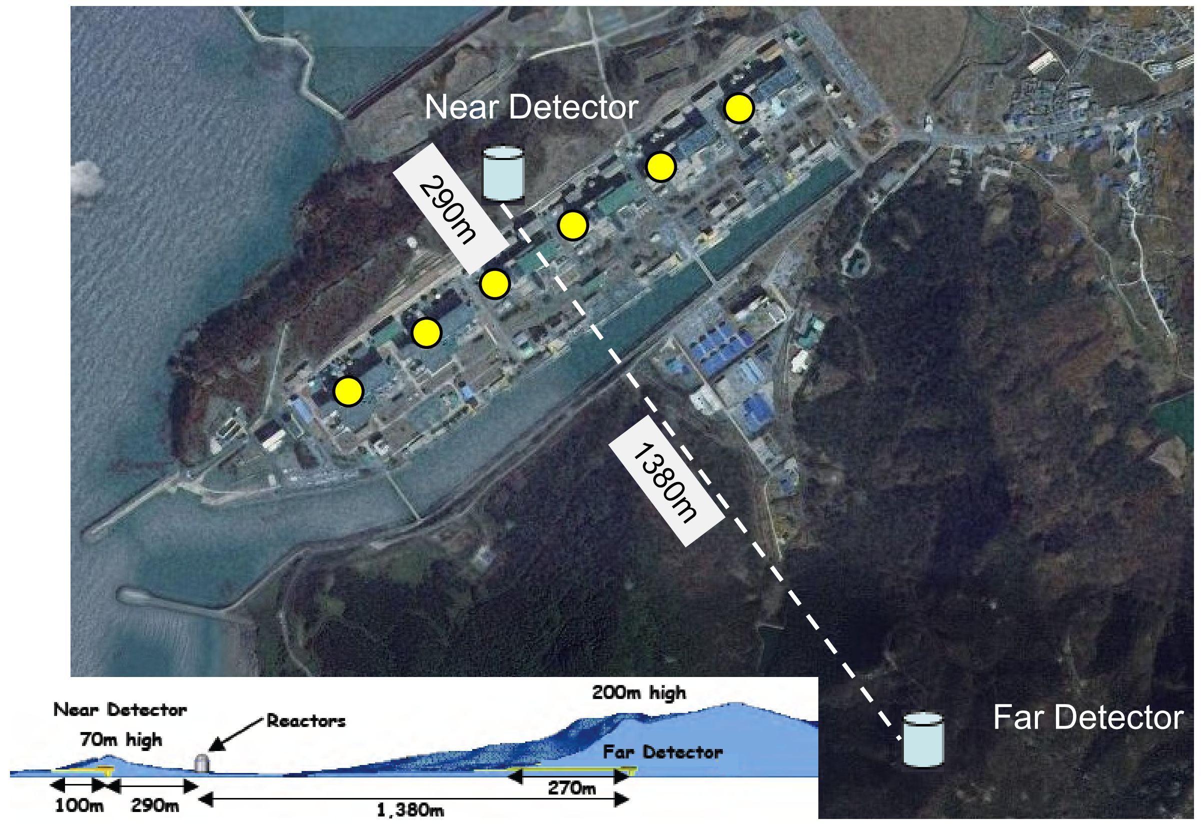


θ_{13} at the reactors

- 3 experiments searching for θ_{13} at the reactors → distance from reactor core ~ 1 km
  - Double-Chooz (France), Daya Bay (China), Reno (Korea)
- θ_{13} small → small disappearance → need a precise knowledge of the neutrino flux from the reactor
- Use Near detector(s) to constrain the reactor flux
- Far detector(s) to measure the ν_e disappearance due to θ_{13}

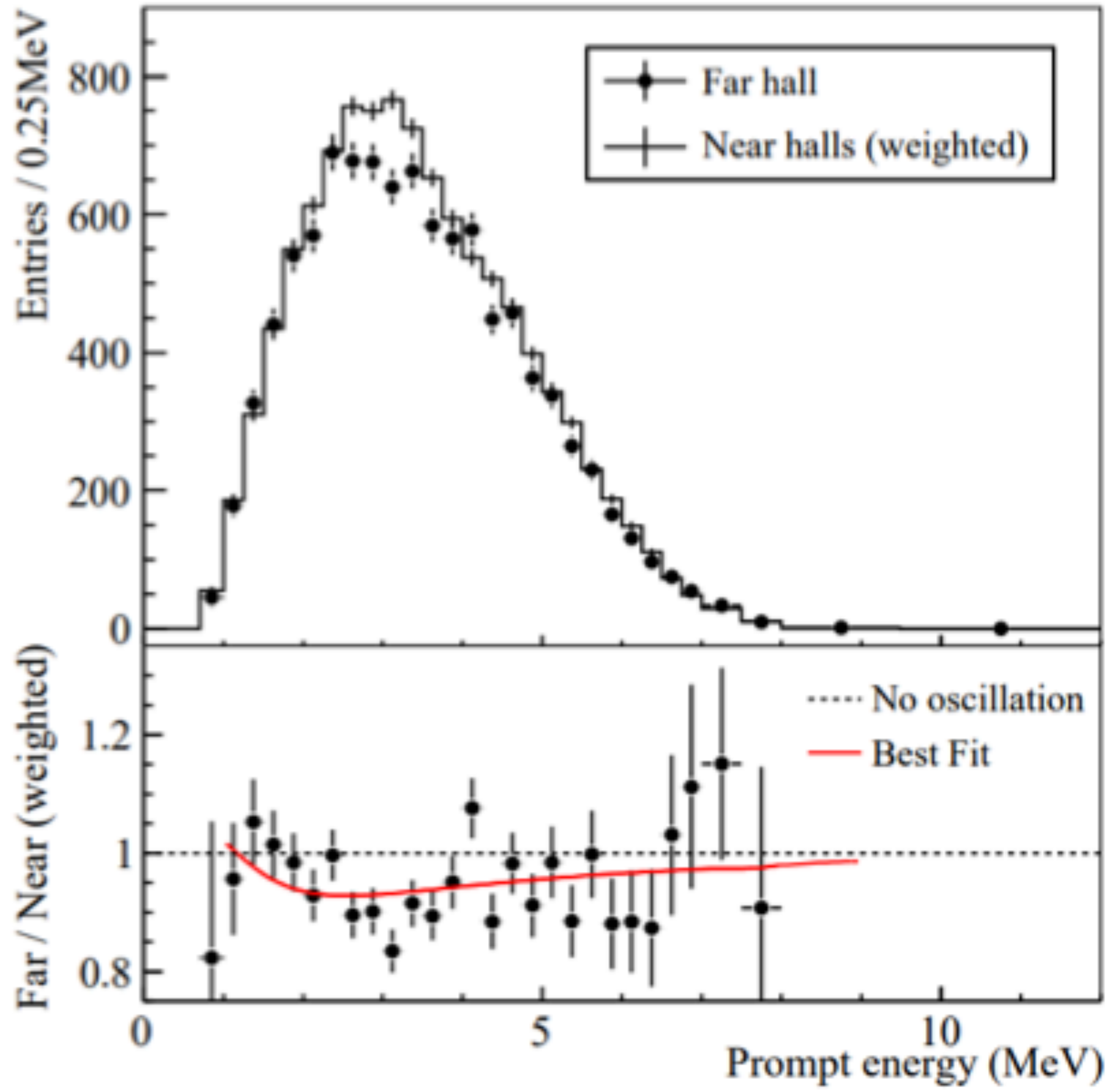




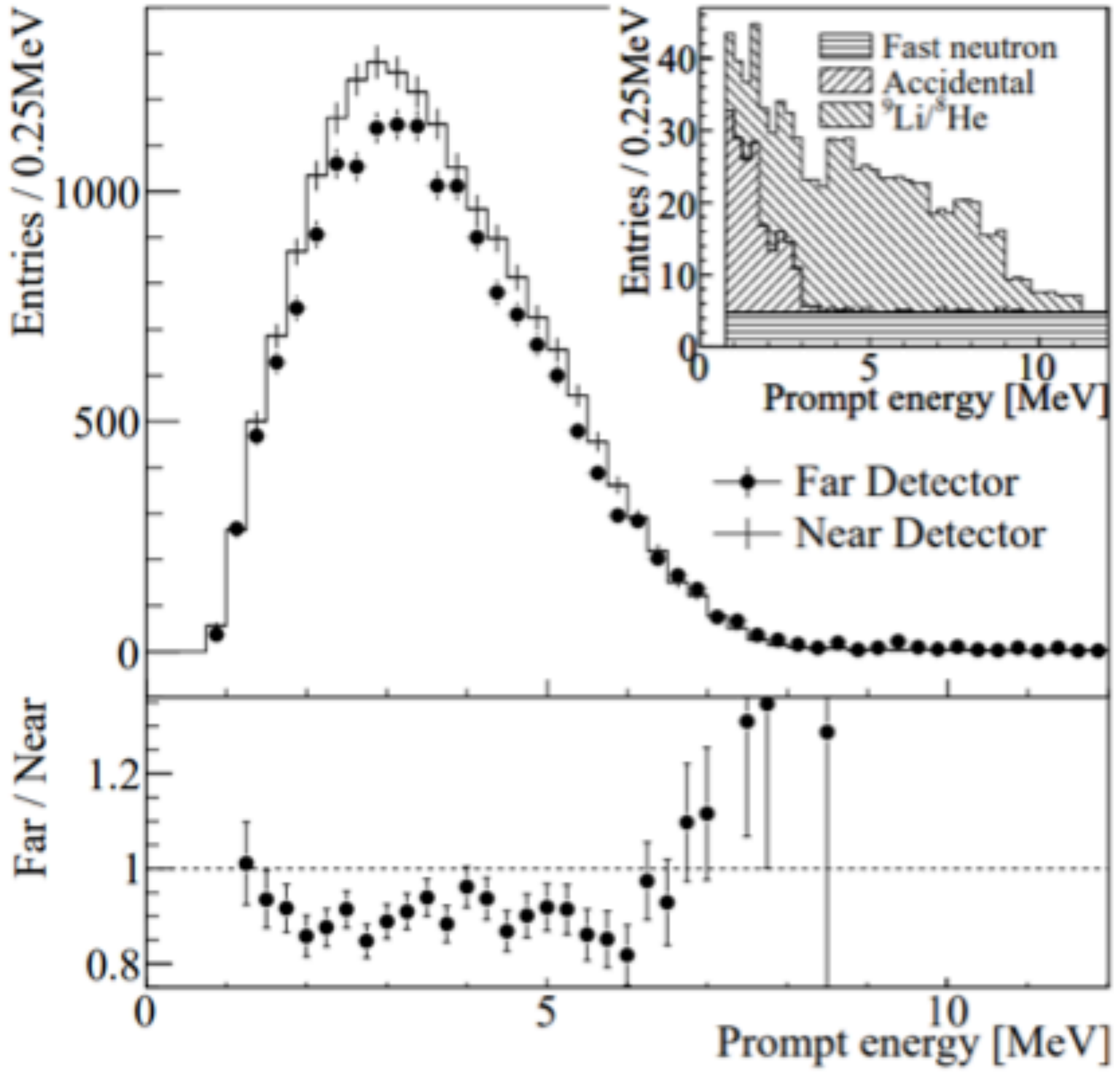


Reactor measurements in 2012

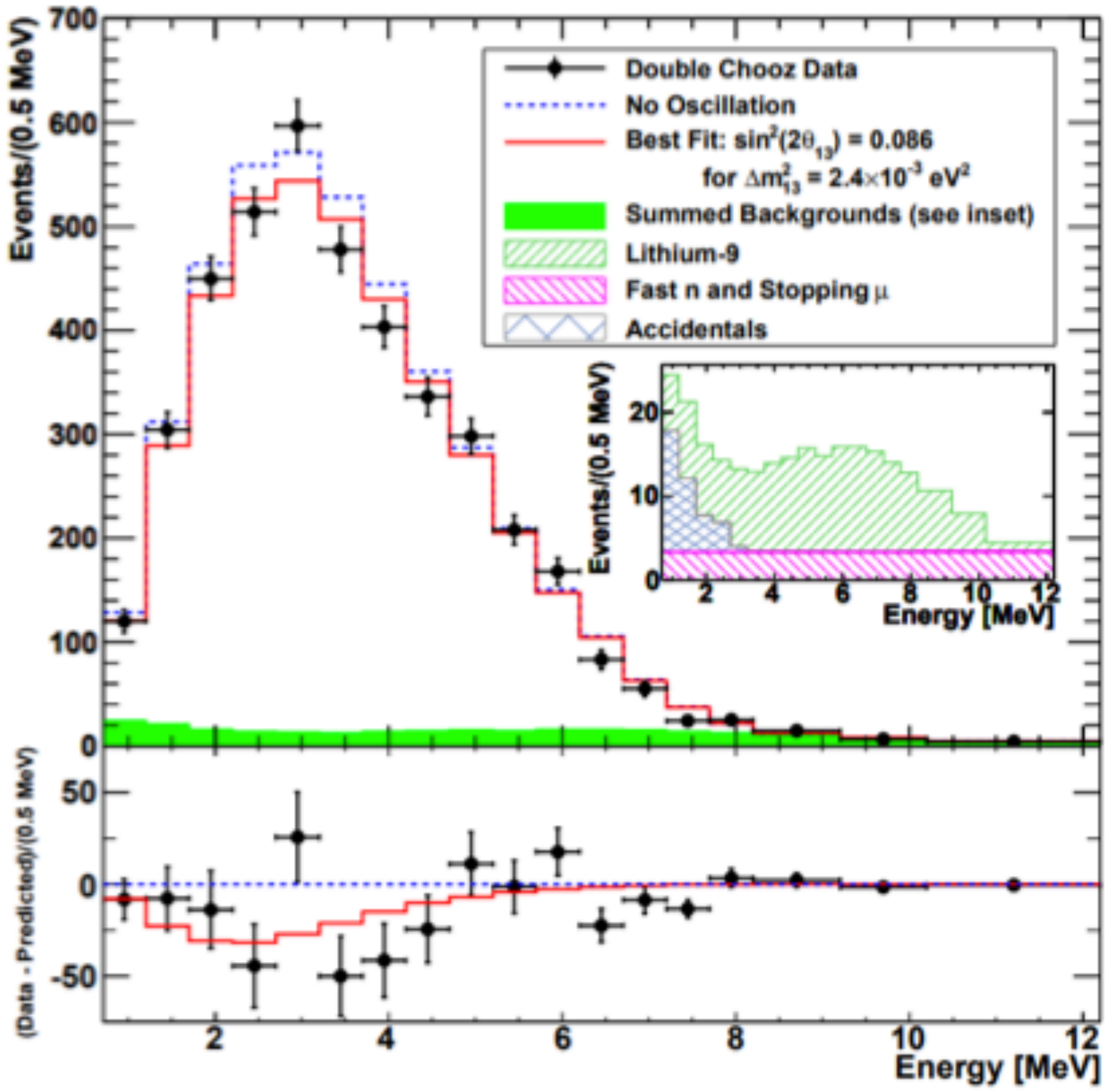
- First measurements in 2012
- θ_{13} is ~ large (close to Chooz limit)



Daya Bay, March 2012
Phys.Rev.Lett. 108 (2012) 171803

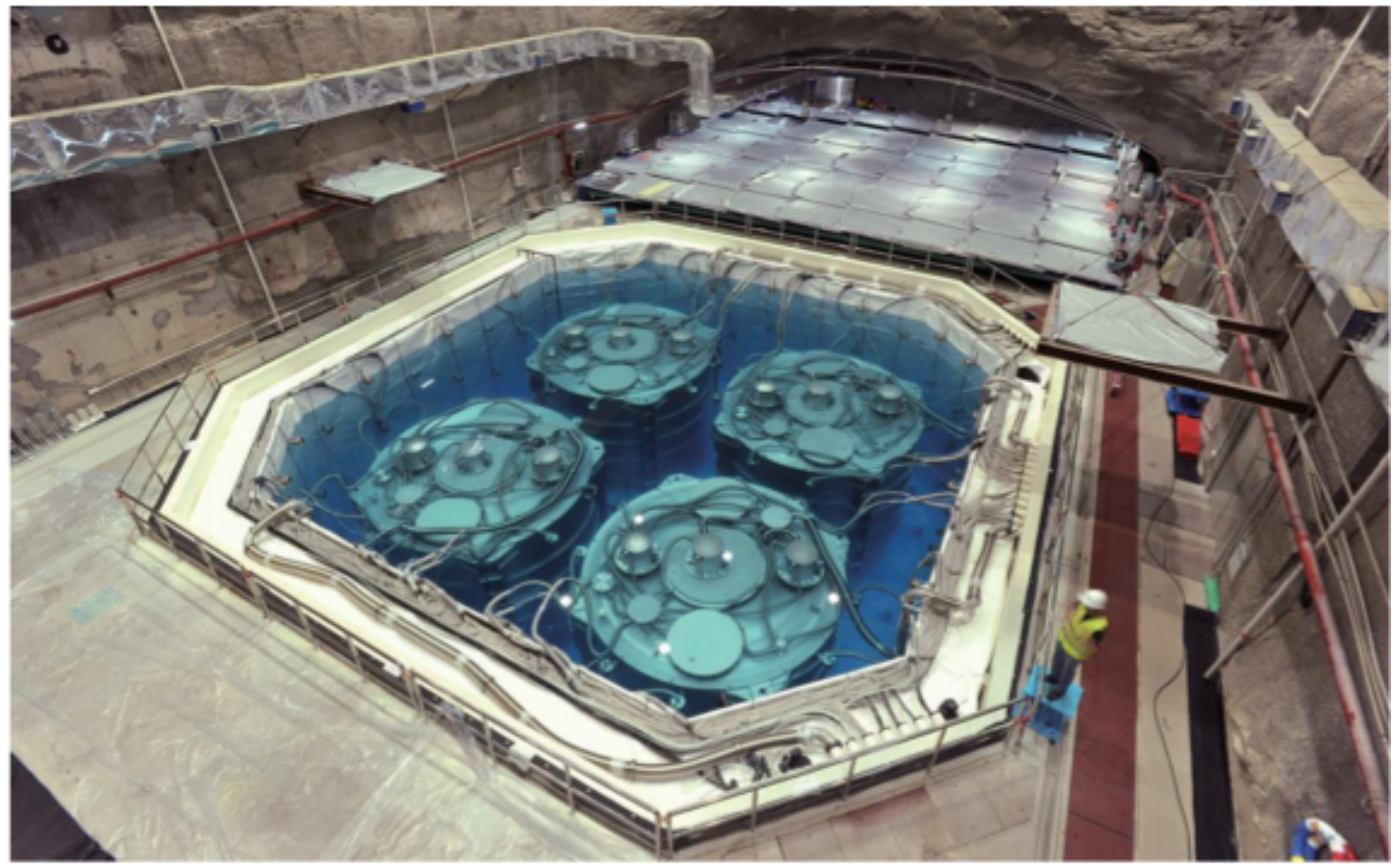


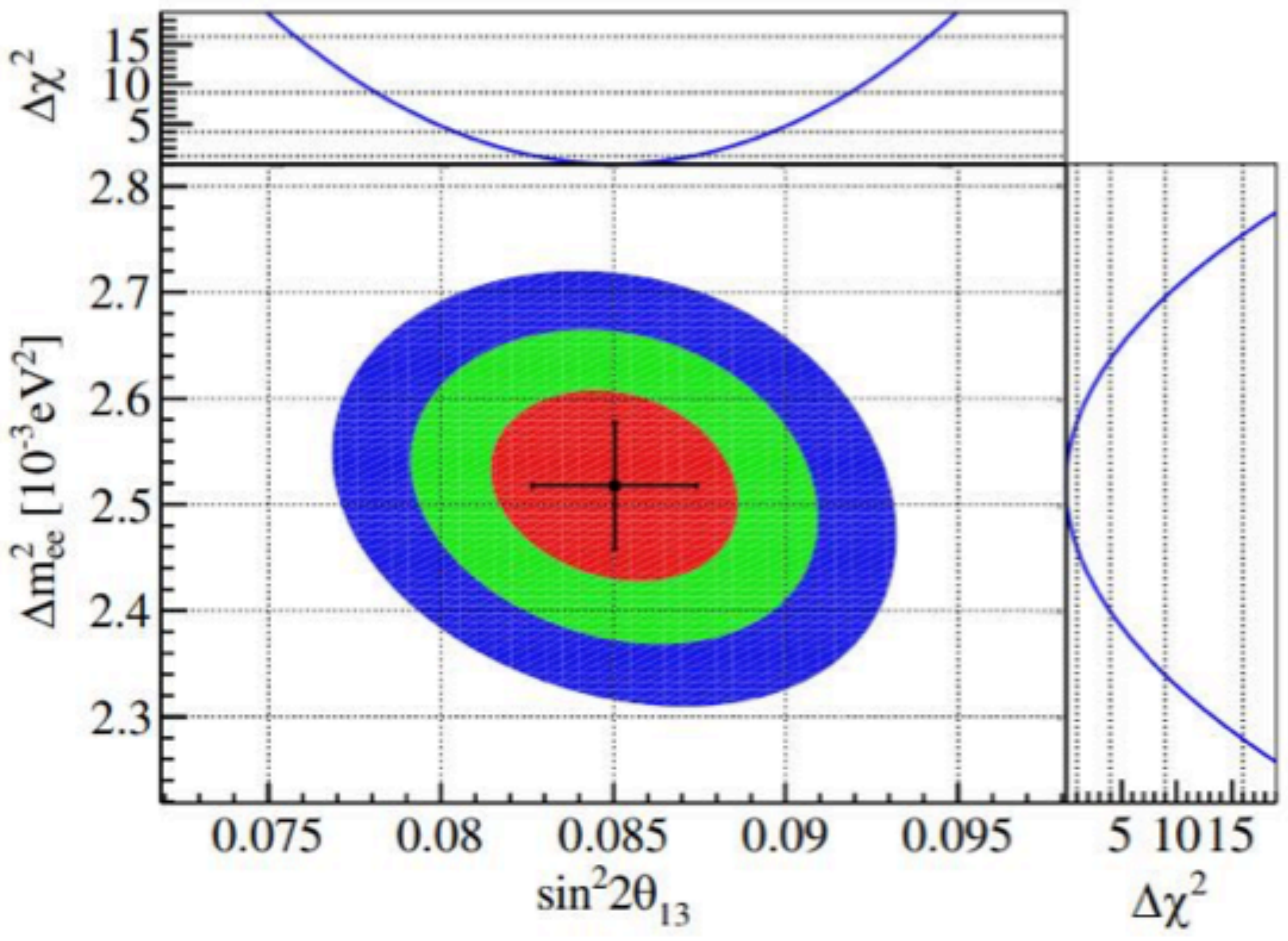
RENO, April 2012
Phys.Rev.Lett. 108 (2012) 191802

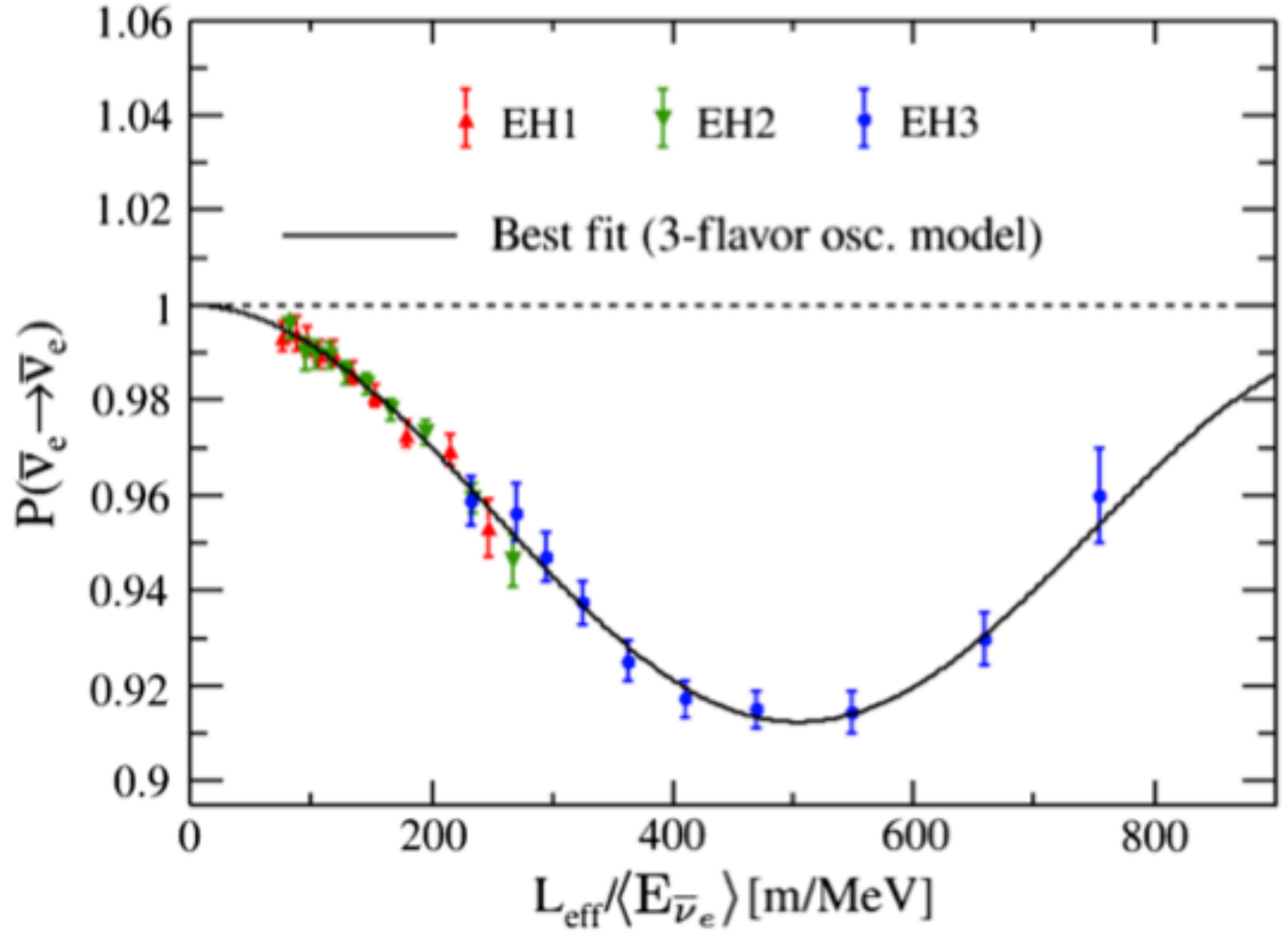


Double Chooz far detector
Phys.Rev.Lett. 108 (2012) 131801

New results from reactors







- Daya Bay has several identical detector close to nuclear reactors in China and at ~ 1 km distance → ideal place to detect oscillations driven by Δm^2 and measure θ_{13}
- θ_{13} value was unknown until 2012 and it is now the most precisely measured mixing angle

2. Daya Bay leads the precision measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{32}|$ in reactor side

2.1 Reactor experiments average: $\sin^2 2\theta_{13}$ = 0.0839 ± 0.0021, 2.5% precision

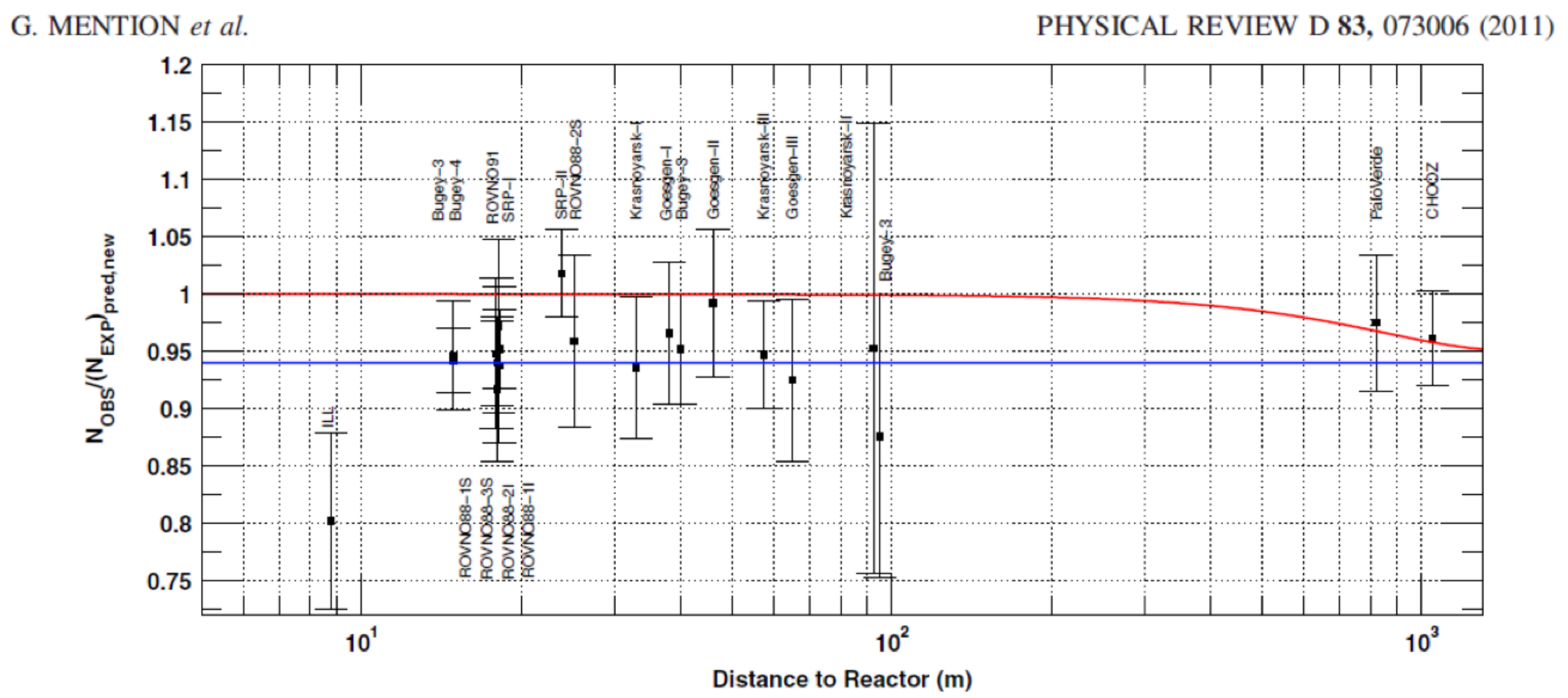
→ The most precisely measured mixing angle up to Nu-2024

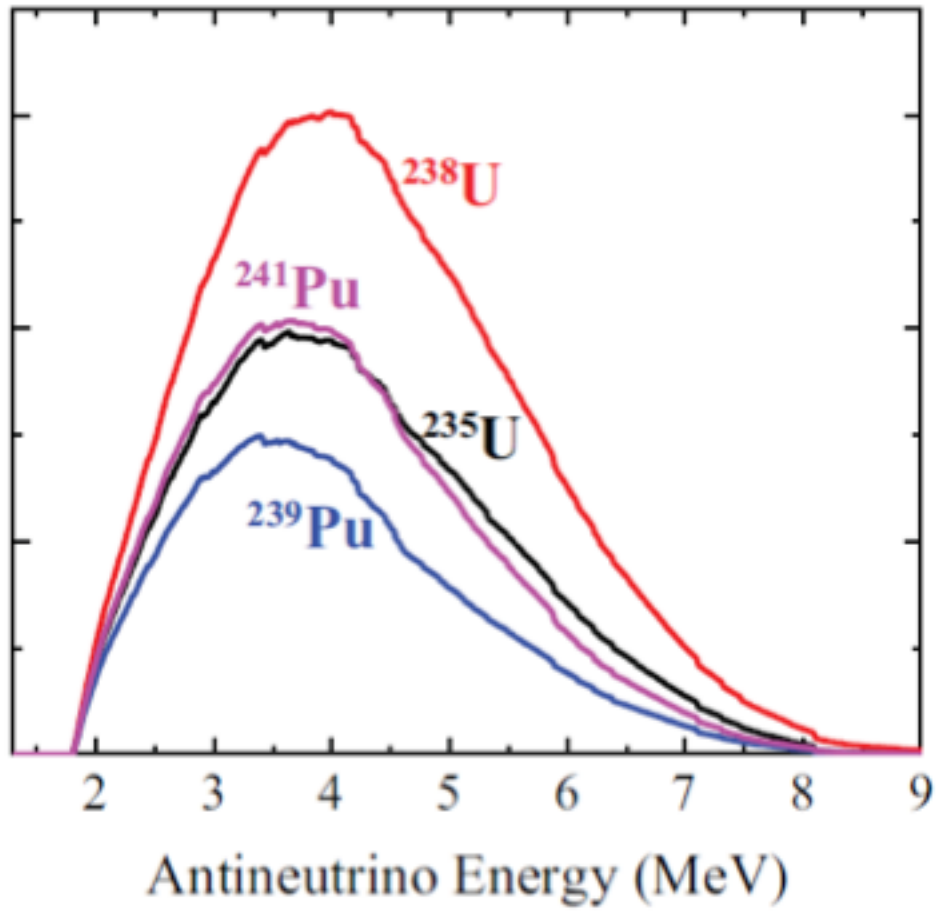
2.2 Reactor experiments average: Δm^2_{32}=(2.51[-2.61] ± 0.05)*10^{-3} eV^2 , 2% precision

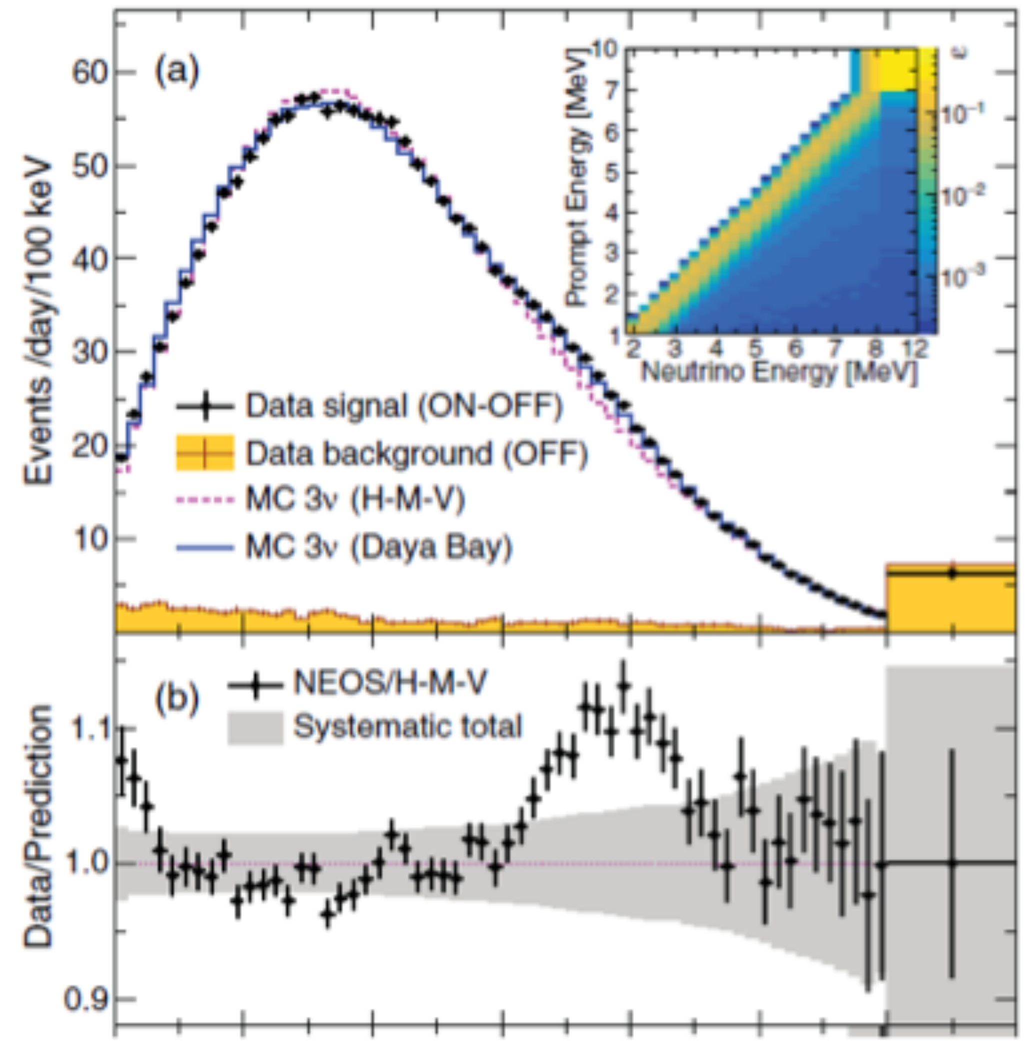
→ Slightly prefer normal mass ordering by comparing with accelerator results

$\bar{\nu}$ fluxes and reactor anomaly

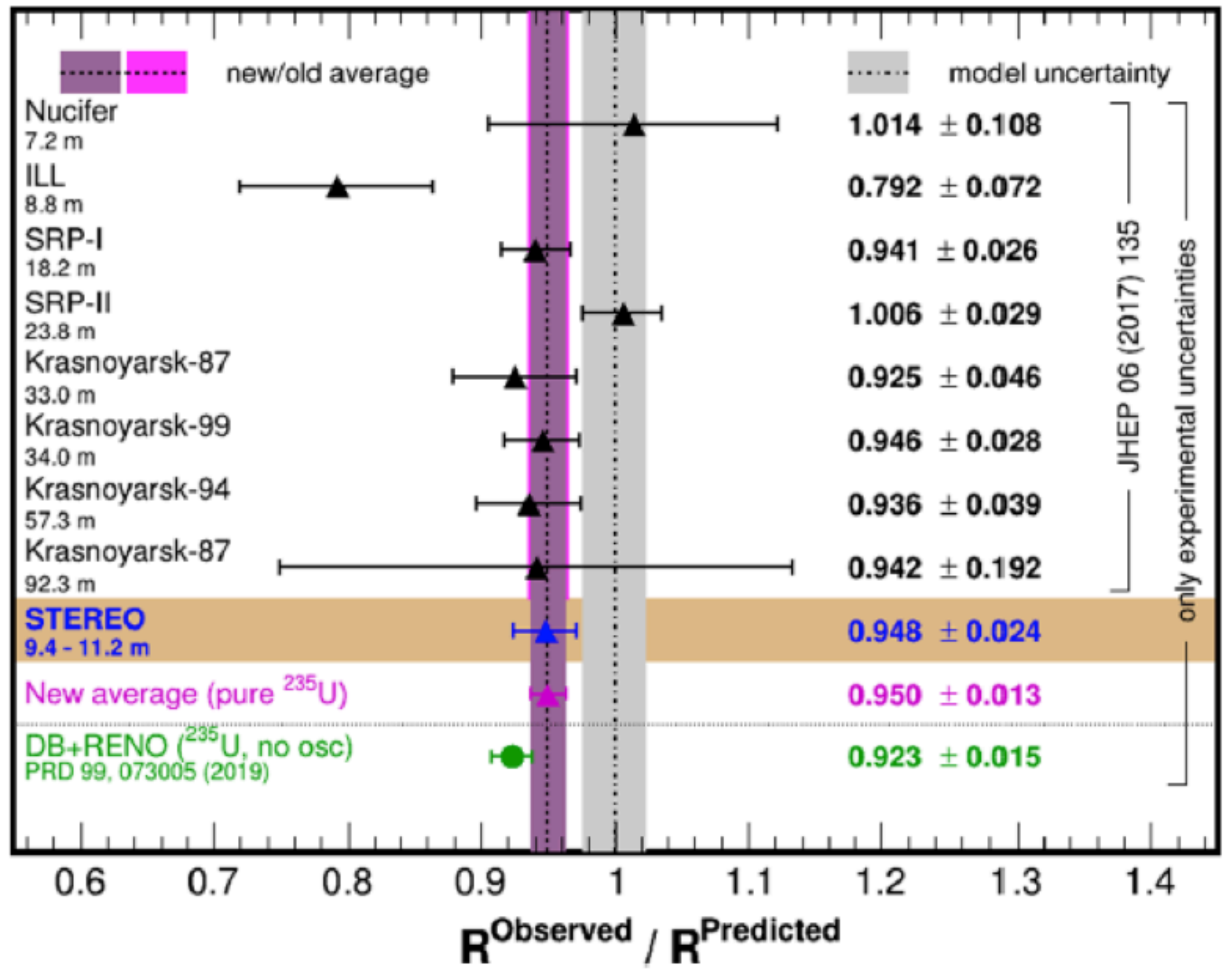
An analysis of earlier experiments with the updated antineutrino spectra reveal a ~6% deficit at short distances.
The term **Reactor Antineutrino Anomaly (RAA)** has been coined to refer to this deficit.







- Reactor anomaly : deficit of $\bar{\nu}$ flux with respect to expectation → sterile neutrinos?
- Neutrino emitted from reactors come from a combination of fission from different isotopes
- The modeling is not simple → bump in the spectrum of neutrinos
- Measurements from STEREO (very close to the reactor so no sterile neutrinos) confirm the deficit
- There are no exciting anomalies (new physics) → we just need more precise measurements of neutrinos emitted from reactors



Neutrino oscillations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospherics and LBL
$\theta_{23} \sim 45°$
$|\Delta m^2_{32}| \sim 2.5\mathrm{x}10^{-3}$ eV^2

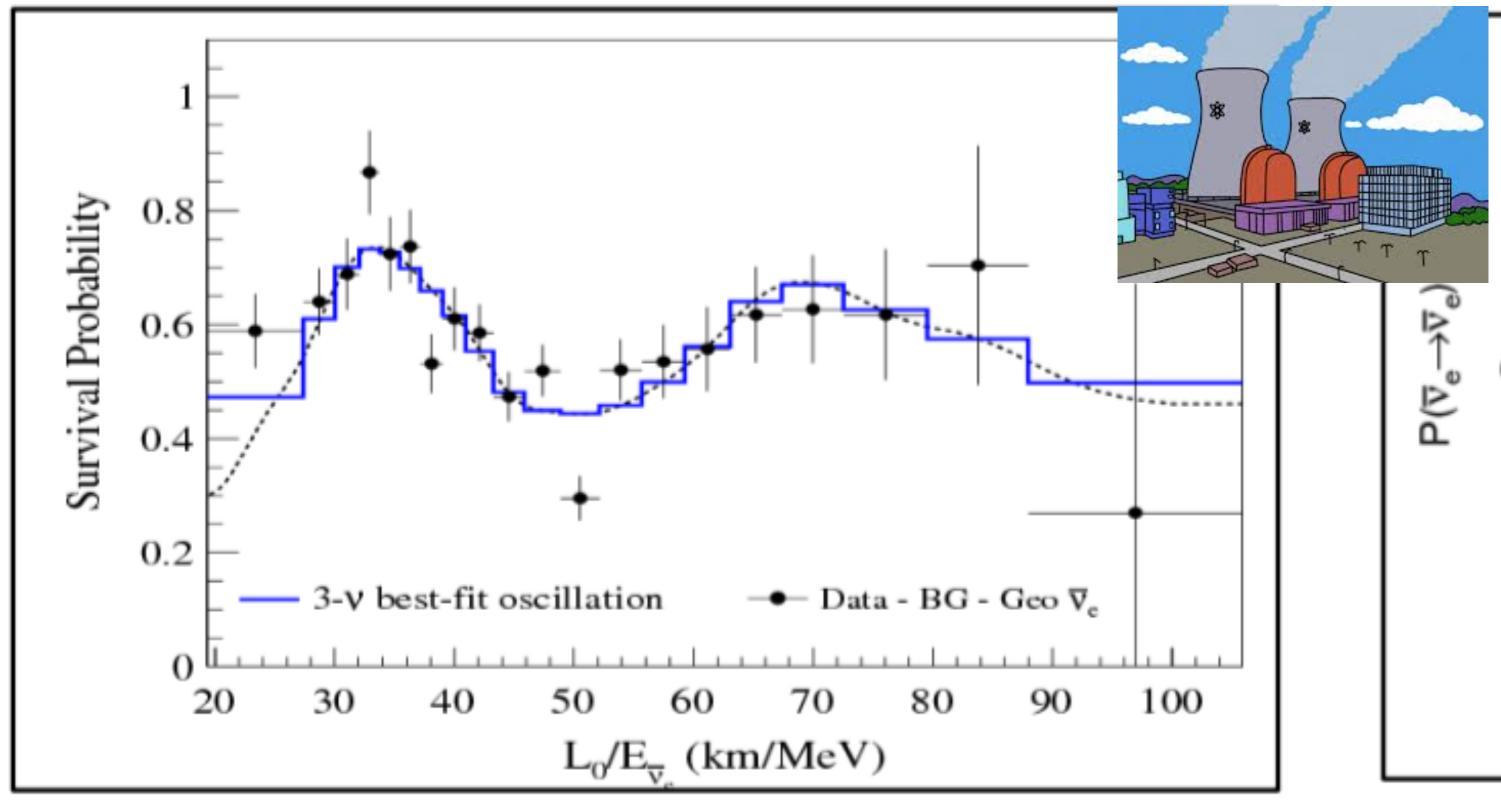
Reactors
$\theta_{13} \sim 10°$
LBL
θ_{13} and δ_{CP}

Solar and reactors
$\theta_{12} \sim 35°$
$\Delta m^2_{21} \sim 7.5\mathrm{x}10^{-5}$ eV^2

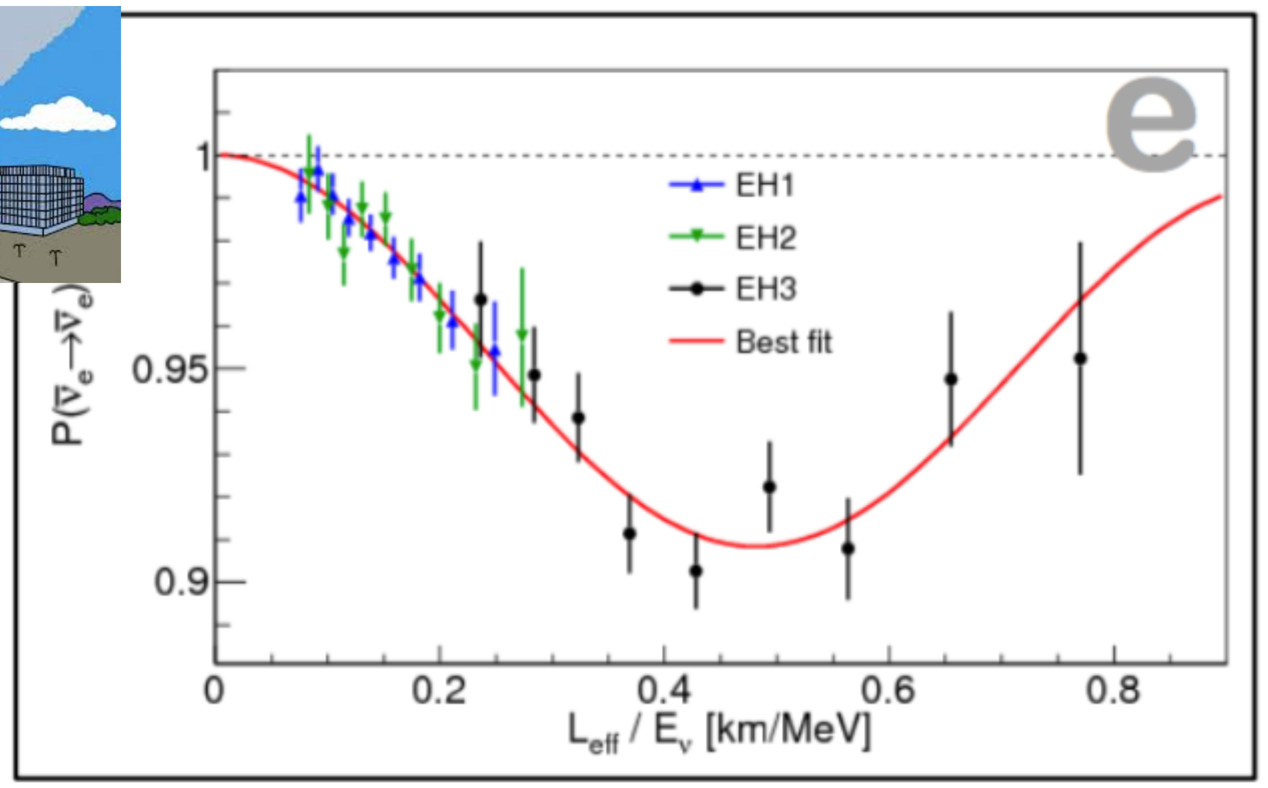
- Neutrinos come in 3 flavours but propagate as 3 mass eigenstate
- 3 mixing angles, 2 mass squared differences, 1 CPV phase
- Neutrino oscillations observed in solar neutrinos, reactor (anti-)neutrinos, atmospheric neutrinos and long-baseline experiments
- We don't know yet wether CP is violated in the leptonic sector and the mass ordering → Normal ordering $\nu_3 > \nu_2 > \nu_1$ or Inverted ordering $\nu_2 > \nu_1 > \nu_3$

Neutrino oscillations

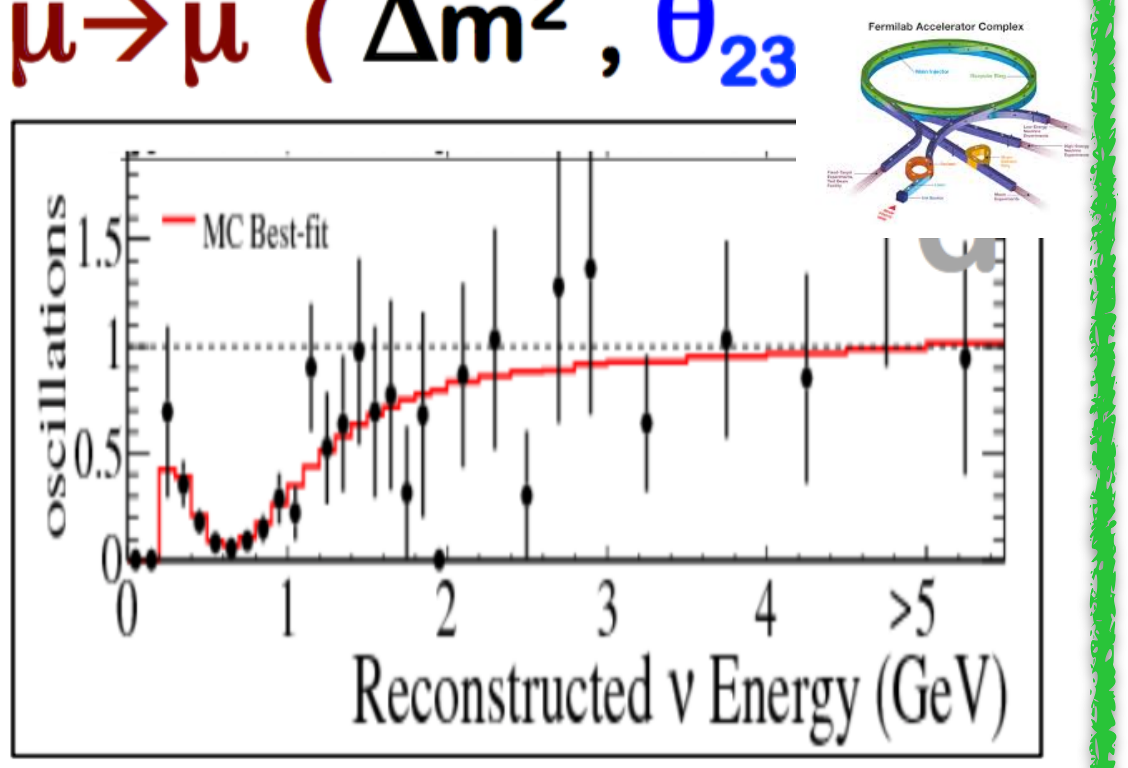
e→e (δm² , θ_{12})



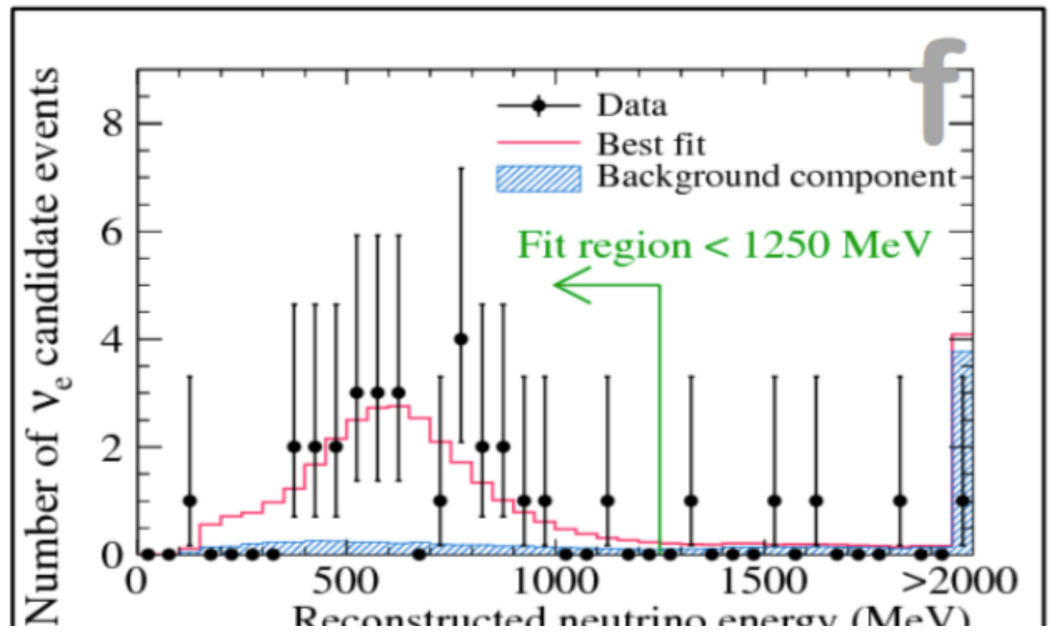
e→e (Δm² , θ_{13})



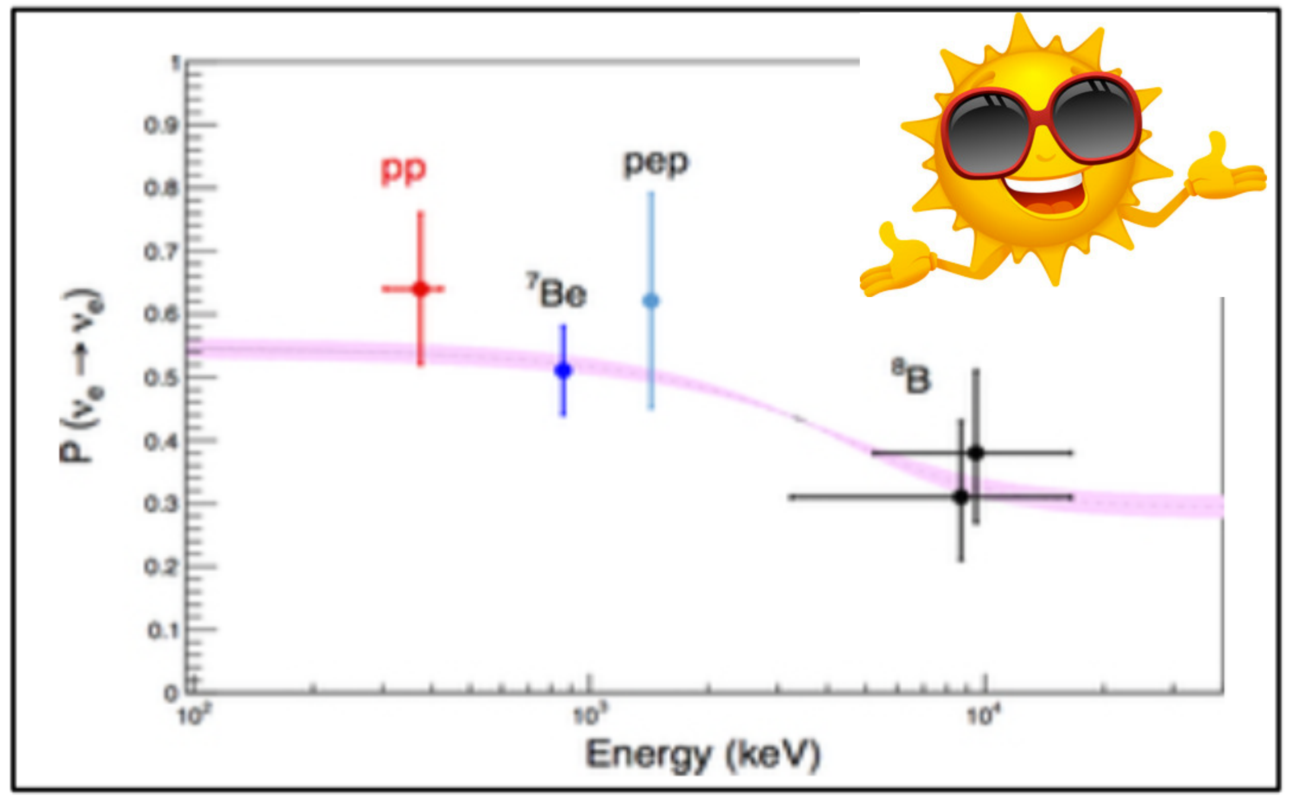
μ→μ (Δm² , θ_{23})



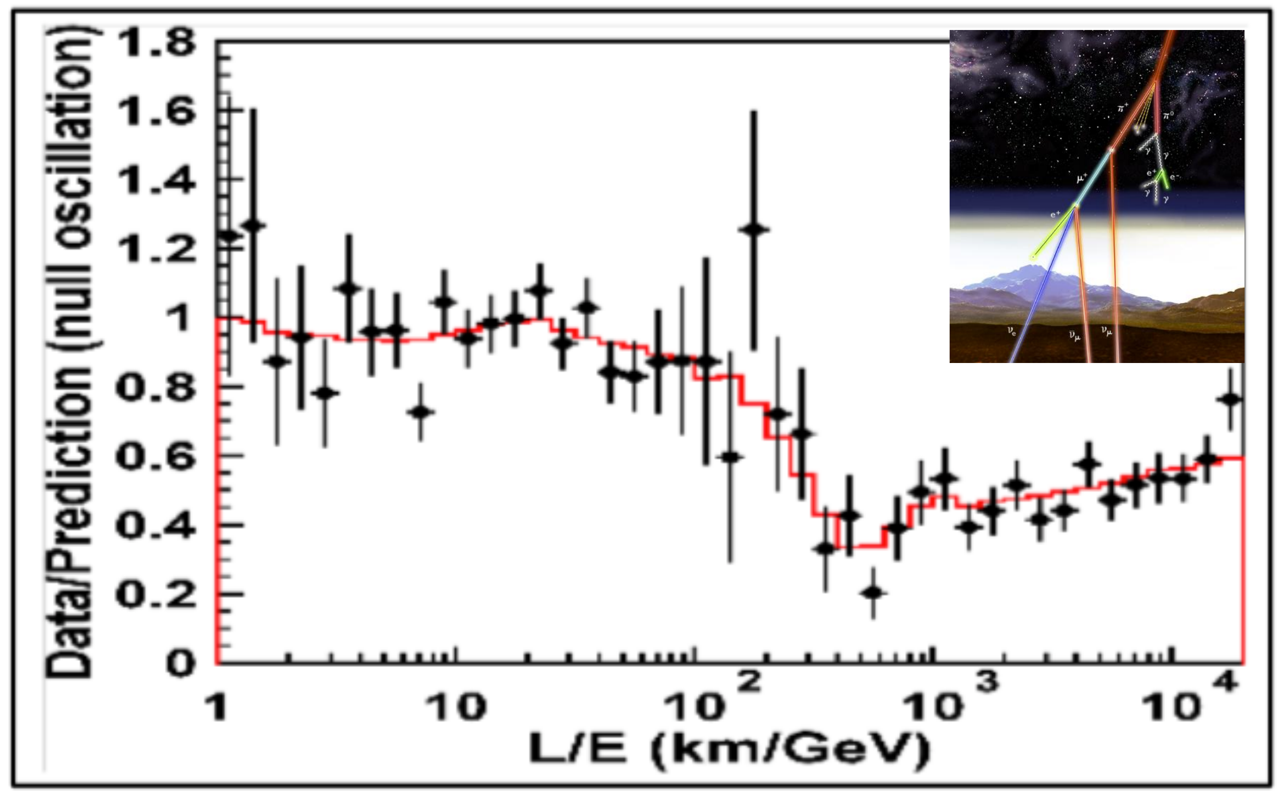
μ→e (Δm² , θ_{13} , θ_{23})



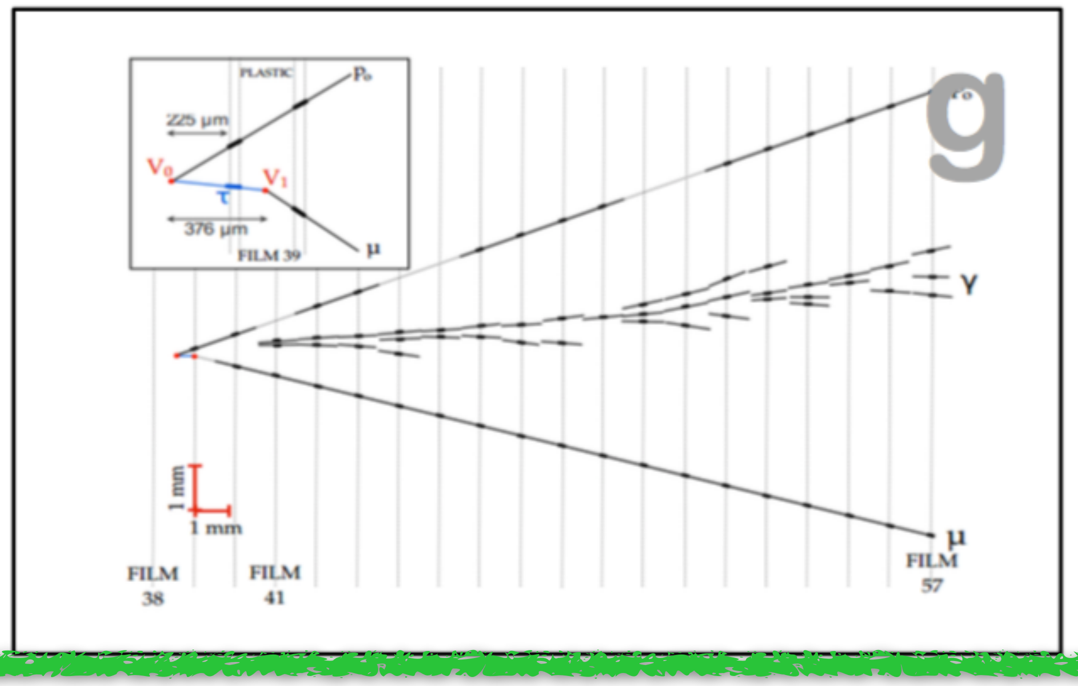
e→e (δm² , θ_{12})



μ→μ (Δm² , θ_{23})

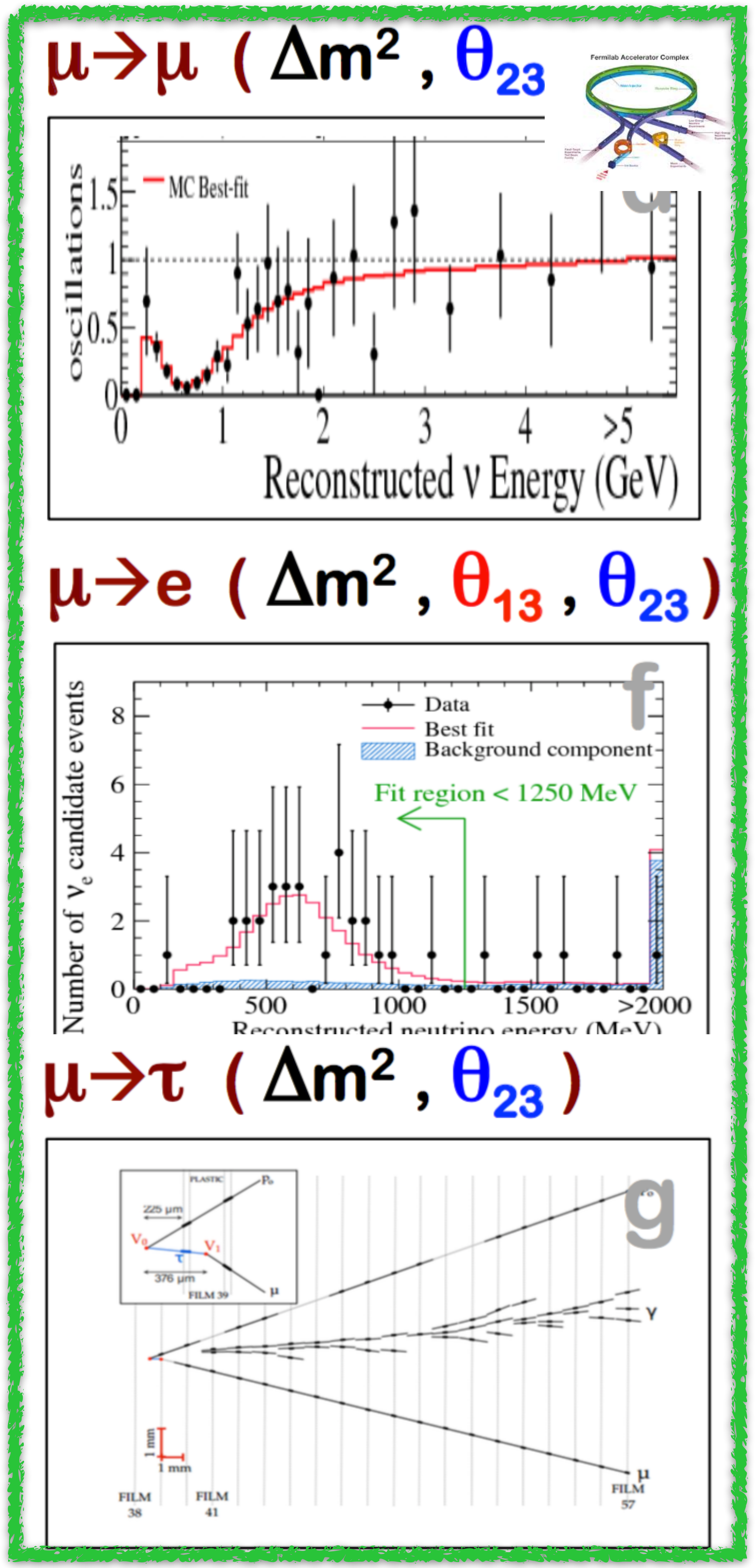


μ→τ (Δm² , θ_{23})



Summary

- Neutrinos oscillations have been definitely established by :
  - Super-Kamiokande (1998) : observation of neutrino oscillations in the atmospheric neutrinos
  - SNO (2002): observation of neutrino transitions in the Sun $\Phi_{NC} > \Phi_{CC}$
  - KamLAND (2003): observation of neutrino oscillations from nuclear reactors at O(100 km) distance
  - More recently Daya Bay, Double Chooz and RENO measured θ_{13} from reactors at O(1 km) distance
- In this discussion we didn't include (yet…) Long Baseline Neutrino Oscillation experiments that will be the main subject of the next lecture
  - Confirmed disappearance of ν_μ (K2K and MINOS)
  - Observed ν_e apperance (T2K and NOvA) and ν_τ appearance (OPERA)
  - Looking for CP violation in the leptonic sector (T2K→HK, DUNE)

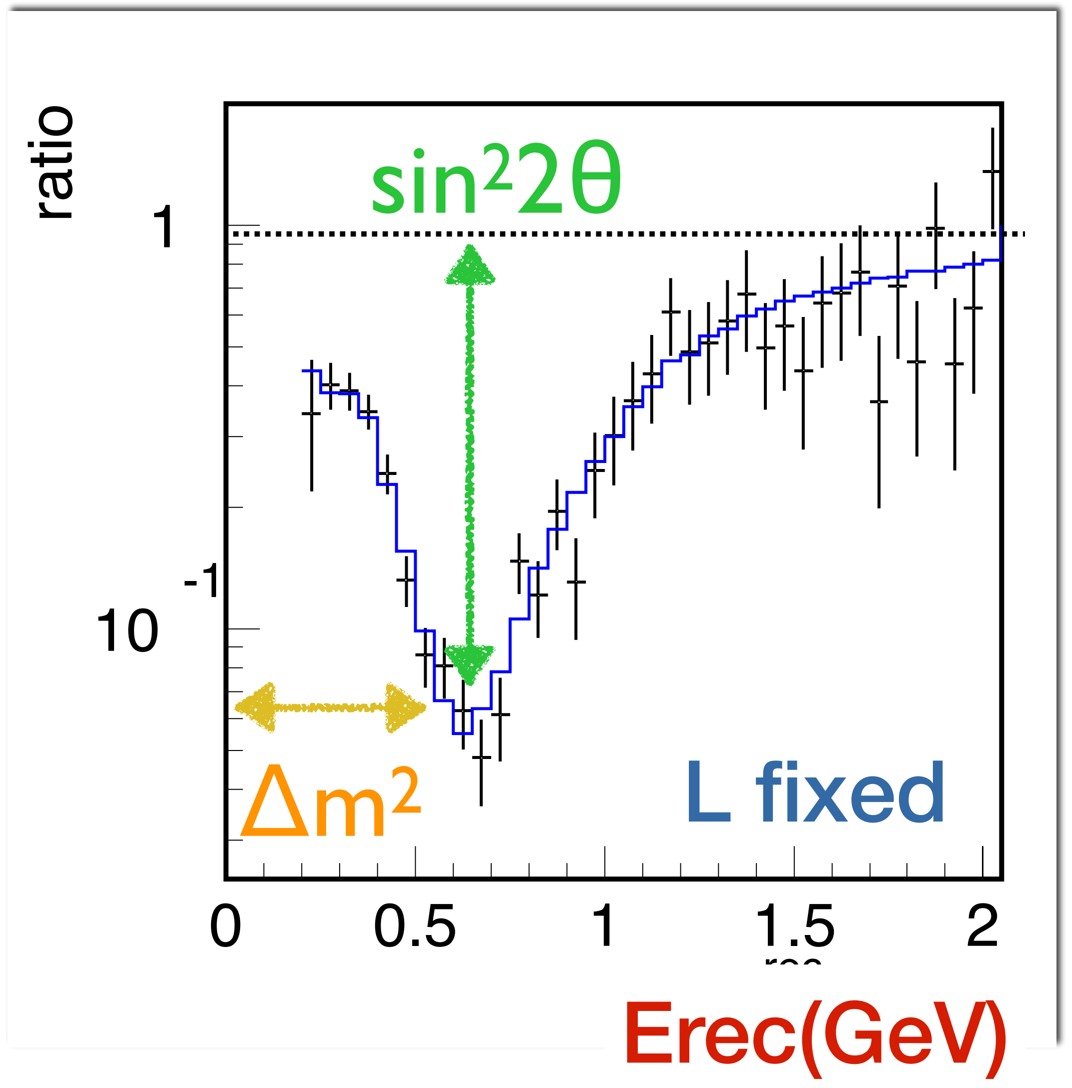


Artificial sources of neutrinos

- Oscillations were discovered with solar and and atmospheric neutrinos
- Great sources of neutrinos → they come for free, just need to build a detector
  - Ideal for discoveries (span several ranges of L/E -> Δm^2)
  - Cannot be tuned → not the best sources for precision measurements
- Reactors → reactor spectrum is fixed but the distance can be tuned (KamLAND for θ_{12}, DB/DC/RENO for θ_{13}, Juno for mass ordering)
- Accelerators → can tune both energy and distance
  - Well defined L/E → maximize oscillation probability knowing Δm^2
  - Can produce beam of ν_μ and $\bar{\nu}_\mu$

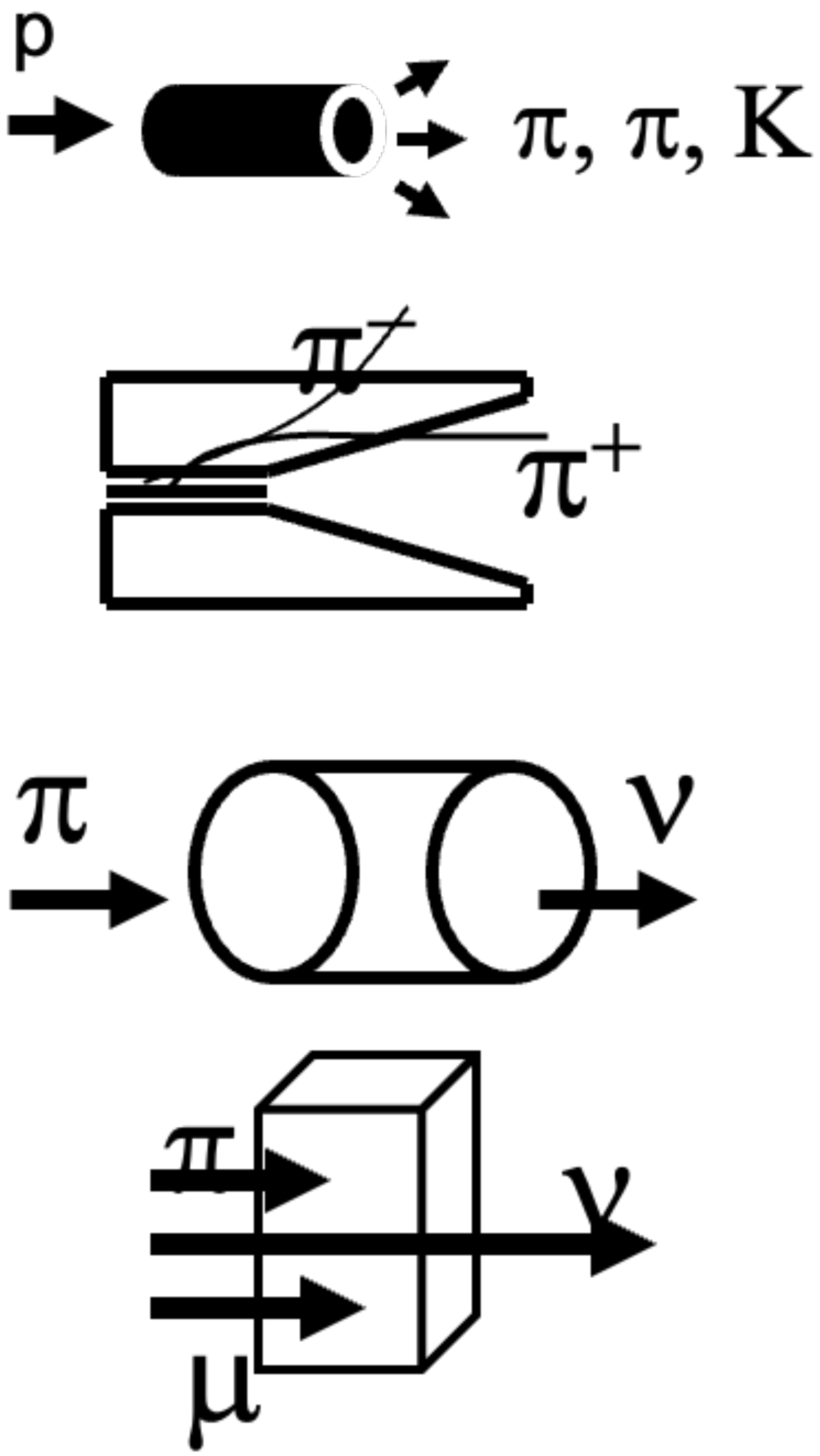
→ 5 oscillation parameters (θ_{23}, θ_{13}, Δm^2_{23}, δ_{CP}, and mass ordering)

$$P(\nu_\mu \to \nu_\mu) = \sin^2(2\theta)\sin^2(\Delta m^2 L/E)$$



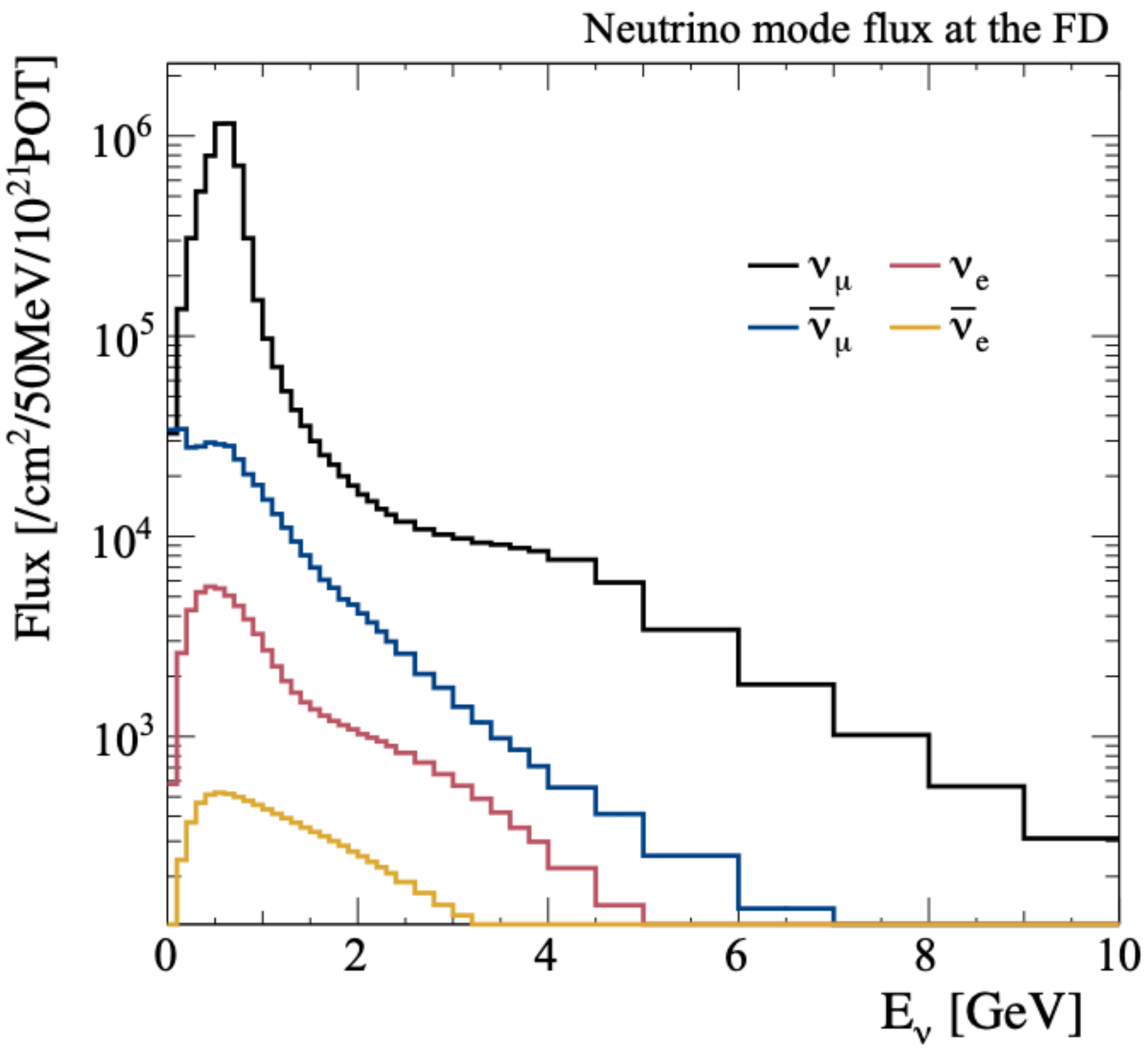
How to do a neutrino beam

- Accelerate protons in a particle accelerator and strike a target $p + N \rightarrow \pi^+, \pi^-, \pi^0, K, \ldots$
- A system of magnetic horns focus adn select in charge the hadrons $\pi^+ \ or \ \pi^-$
- The pions enter a decay tunnel of ~100 m length in which they decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$
    - What happens if you focus π^-?
- A beam dump stops all particles that are not neutrinos!



ν_μ beam

- Most of neutrinos produced by $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- Some negative pions manage to enter the decay tunnels producing $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- Some Kaons are produced and decay into $K^+ \rightarrow \mu^+ + \nu_\mu$ but also $K^+ \rightarrow \pi^0 + e^+ + \nu_e$
- The muons can also decay into $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- In the end we produce a beam with >90% of ν_μ but some contamination from $\bar{\nu}_\mu$ and ν_e

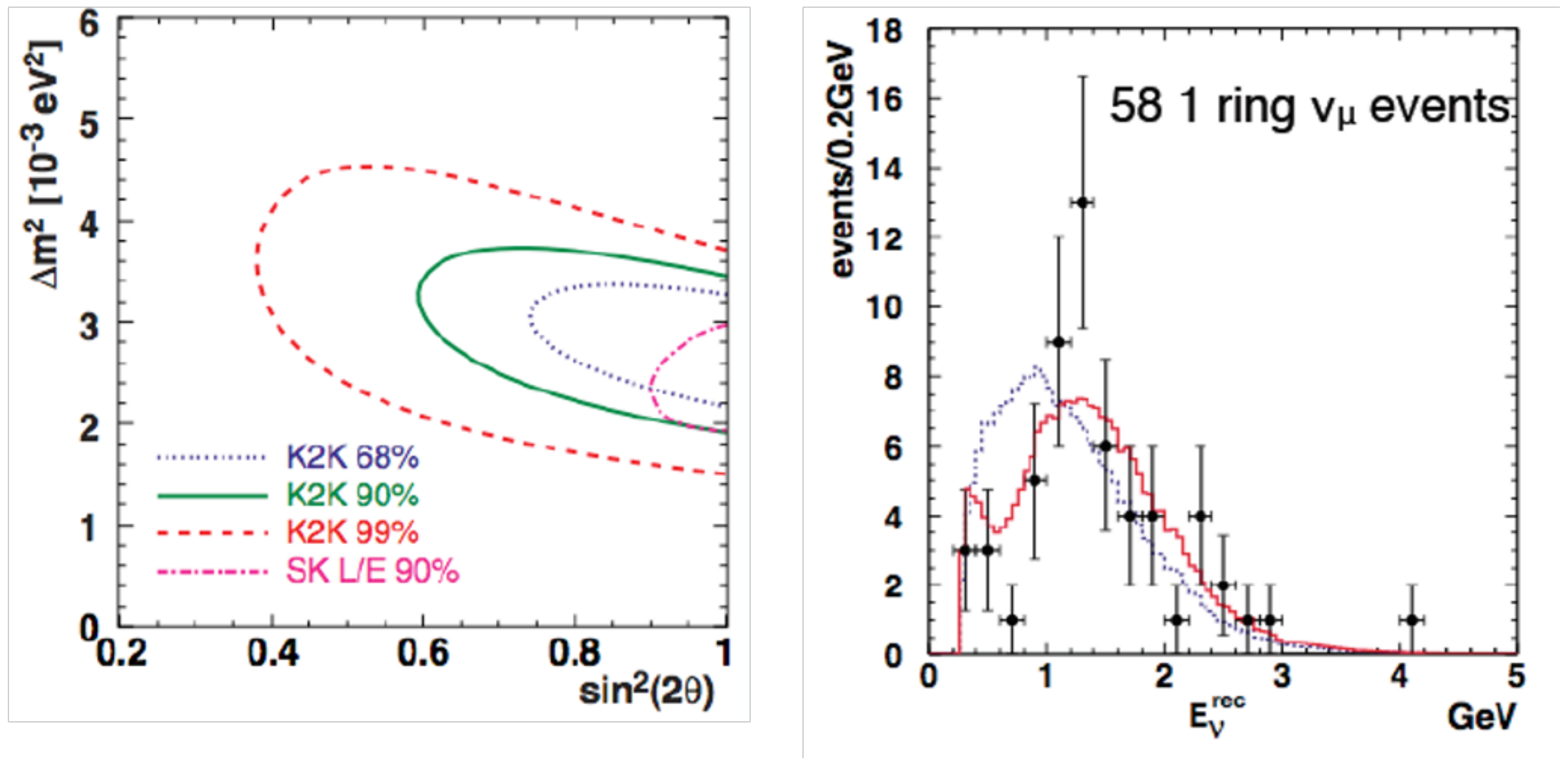


K2K experiment

- $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27 \cdot \Delta m^2_{23} \cdot L[km]}{E[GeV]}\right)$
- $\sin^2\left(\frac{1.27 \cdot \Delta m^2_{23} L}{E}\right) \sim 1 \rightarrow L/E = \frac{\pi/2}{1.27 \cdot \Delta m^2_{23}} \sim 500\ km * GeV^{-1}$

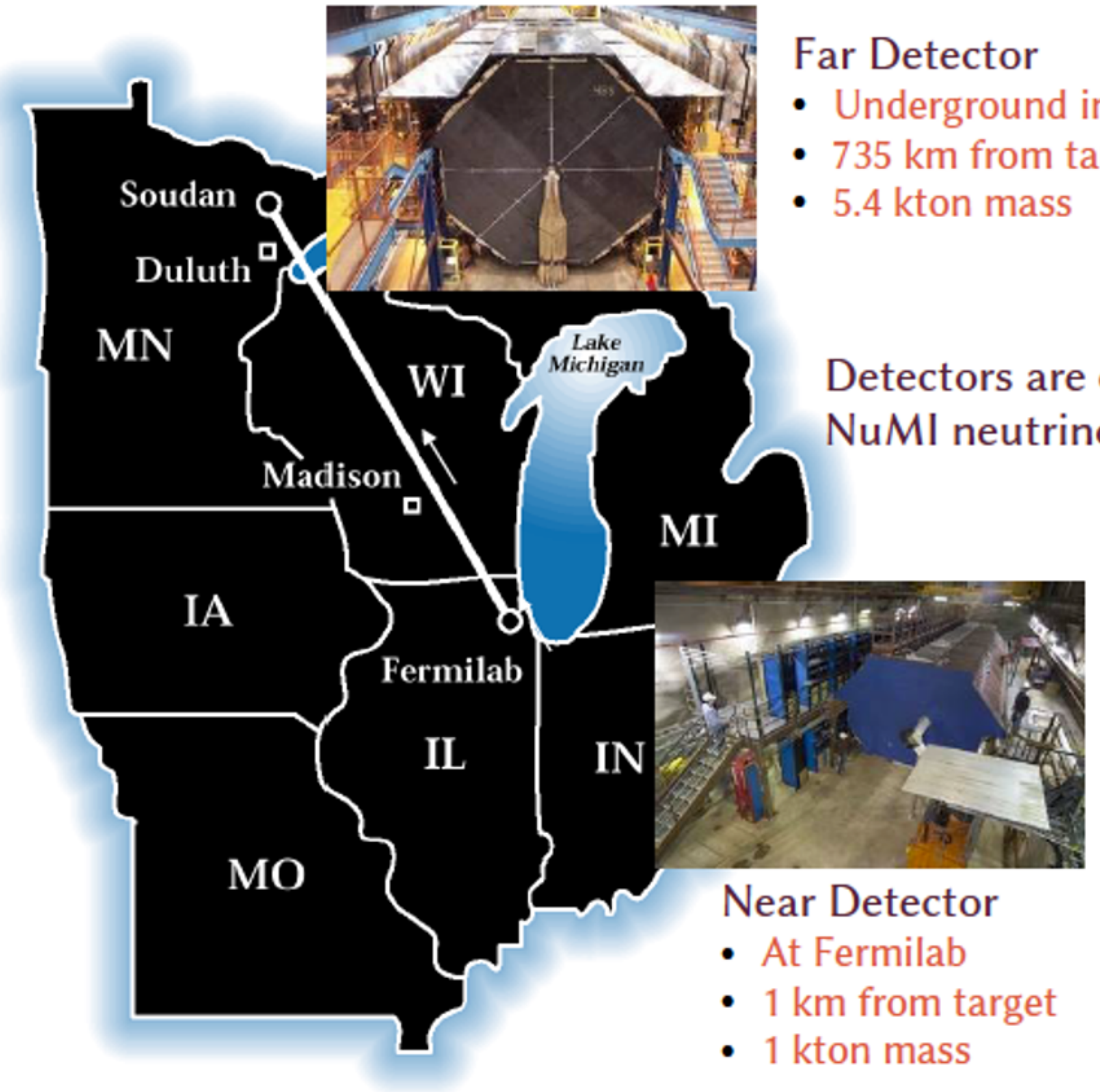
- K2K used Super-Kamiokande as far detector with beam produced at KEK (250 km distance)
- Measured spectrum at the near detector, compare with the one at the far detector to extract oscillation parameters
- Compatible with SK results and observe νμ disappearance at ~[0.5-1] GeV

ν_μ disappearance measurement



MINOS experiment

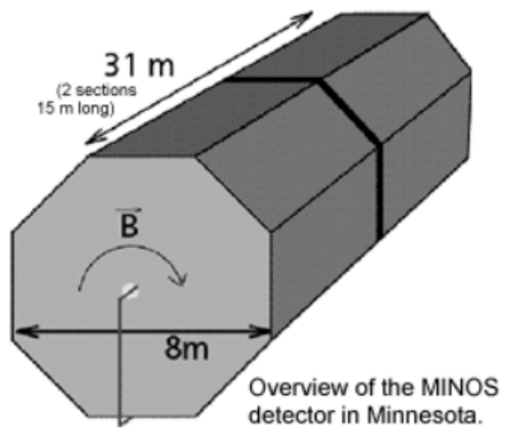
- MINOS and MINOS+ were designed to study neutrino oscillations over long baselines using two detectors that are:
  - Iron-scintillator tracking calorimeters to contain muons
  - Functionally identical for systematic uncertainty reduction
  - Magnetized for sign selection and energy estimation



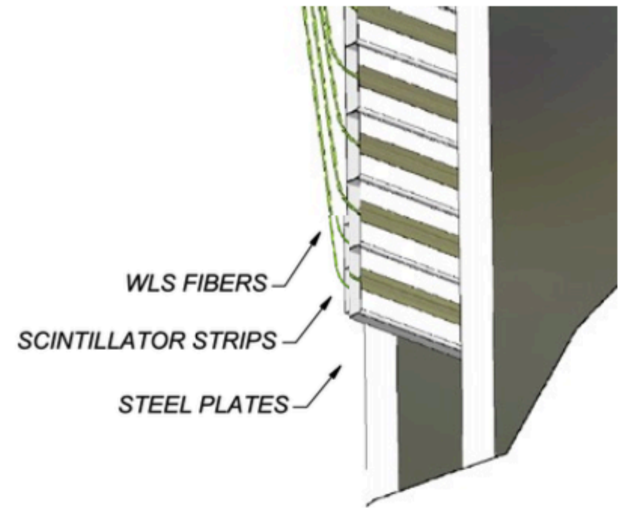
Far Detector
- Underground in Soudan mine
- 735 km from target
- 5.4 kton mass

Detectors are on-axis for NuMI neutrino beam

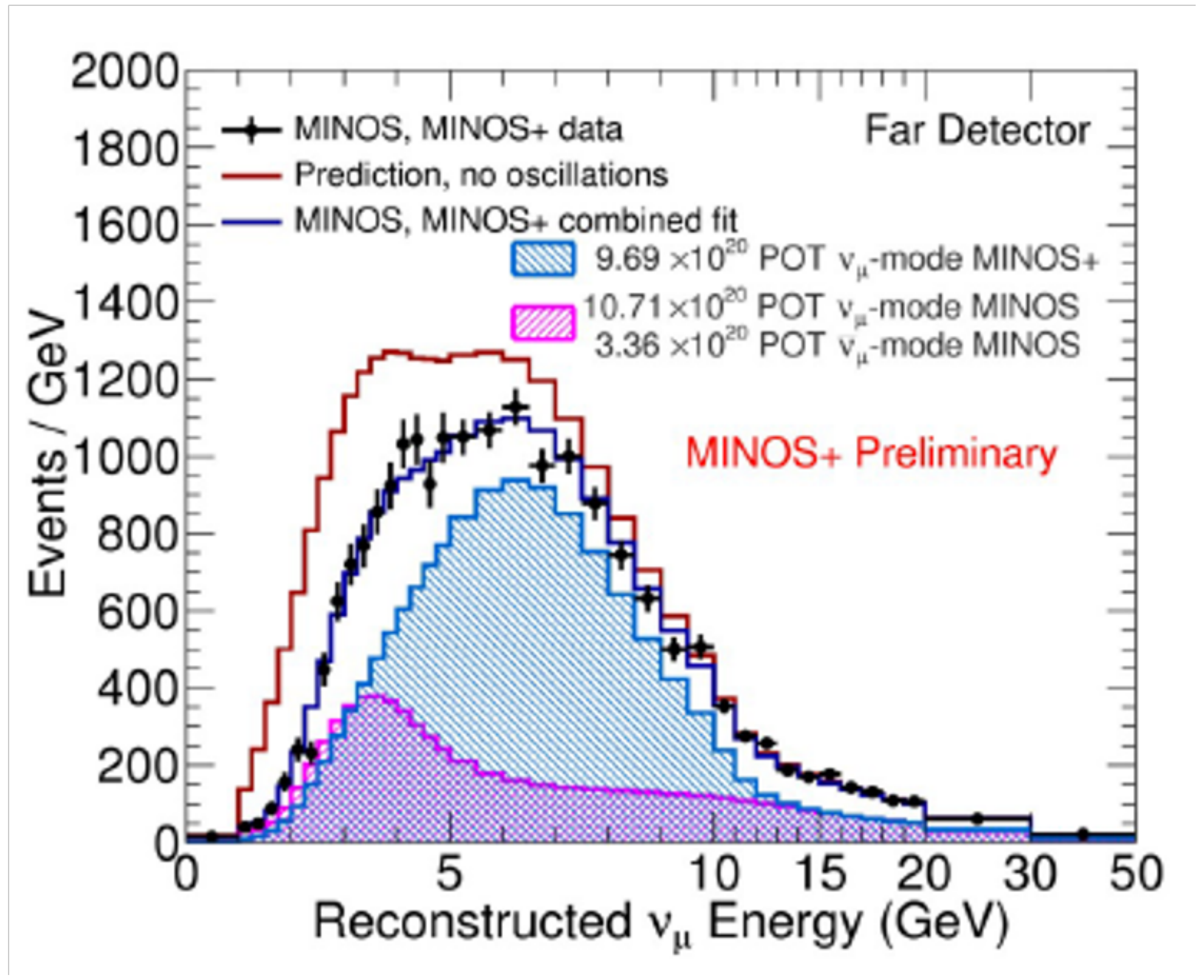
Near Detector
- At Fermilab
- 1 km from target
- 1 kton mass



Magnetized (1.3T) tracking sampling calorimeter
- Muon energy (~1GeV) from range or curvature
- Distinguish μ^+ from μ^-
- Plastic scintillator (C_nH_n) as detection medium

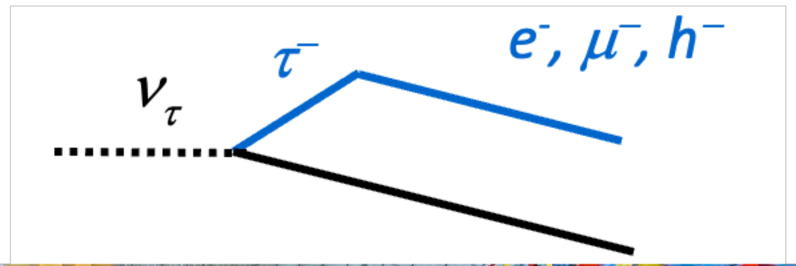


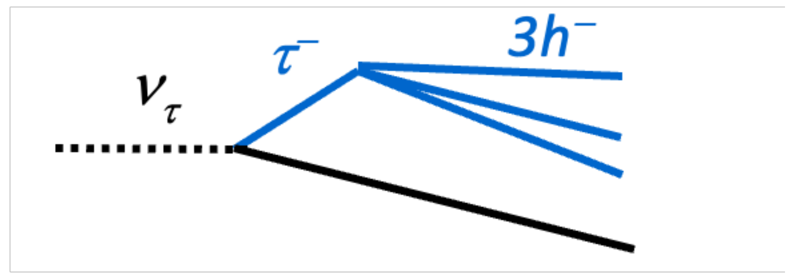
- Observe ν_μ disappearance at larger energies than K2K (longer baseline!)
- Data consistent with 3-flavour neutrino oscillation → rule out many alternative scenarios

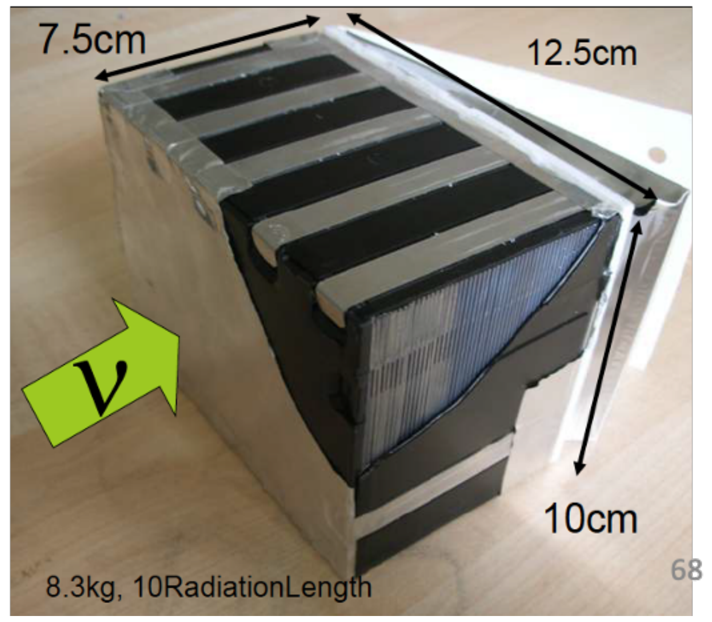


OPERA experiment

- SK, K2K and MINOS experiments all observed ν_μ disappearance
  - No indication of ν_e appearance
  - In a 3-ν framework $\nu_\mu \rightarrow \nu_\tau$
  - Why they didn't observe ν_τ appearance?



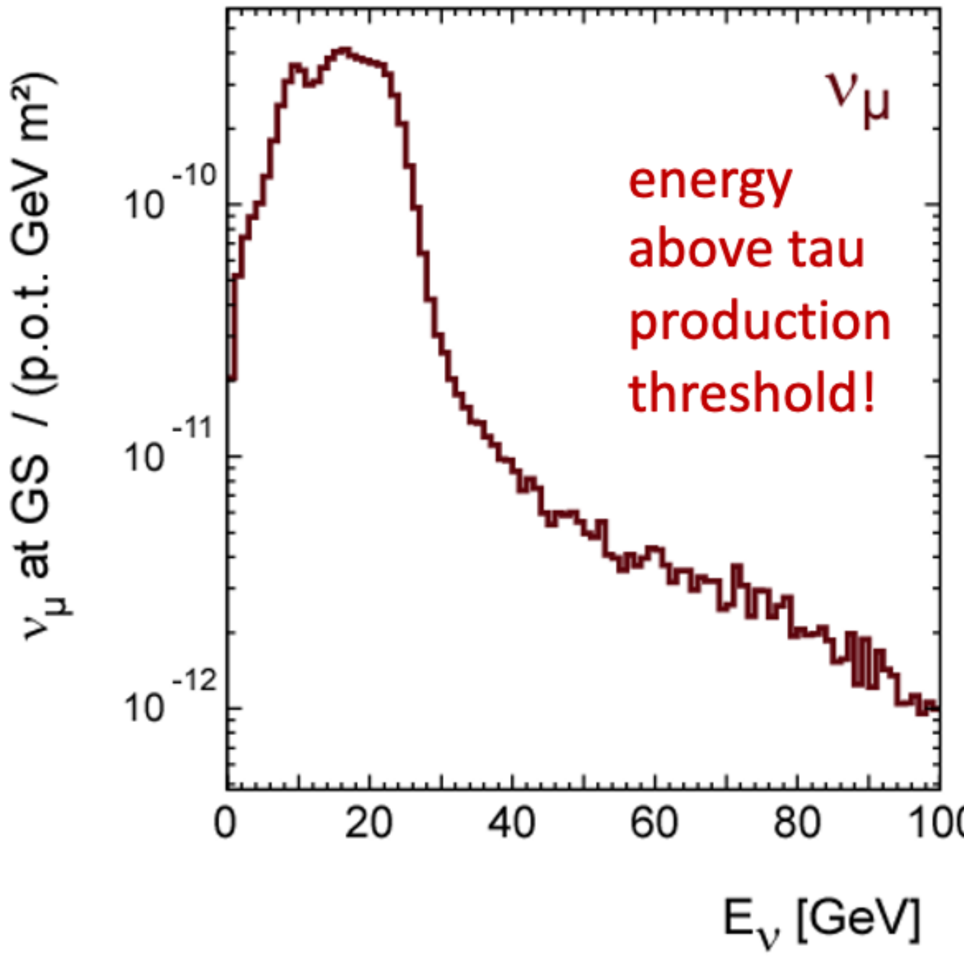


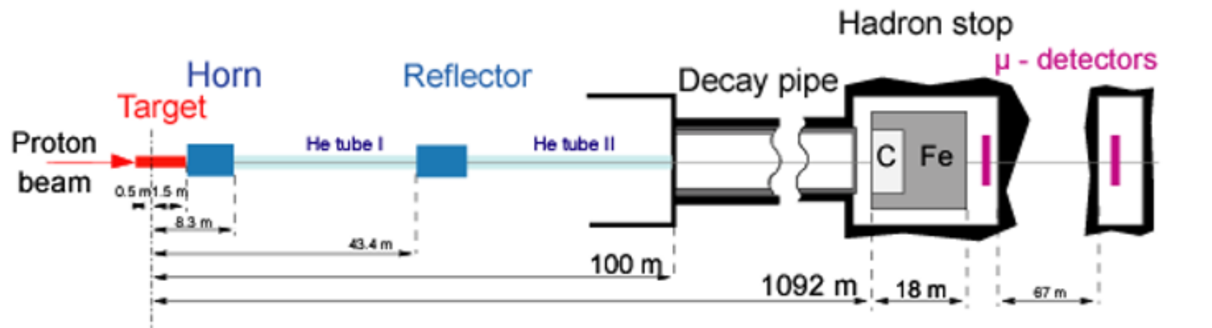


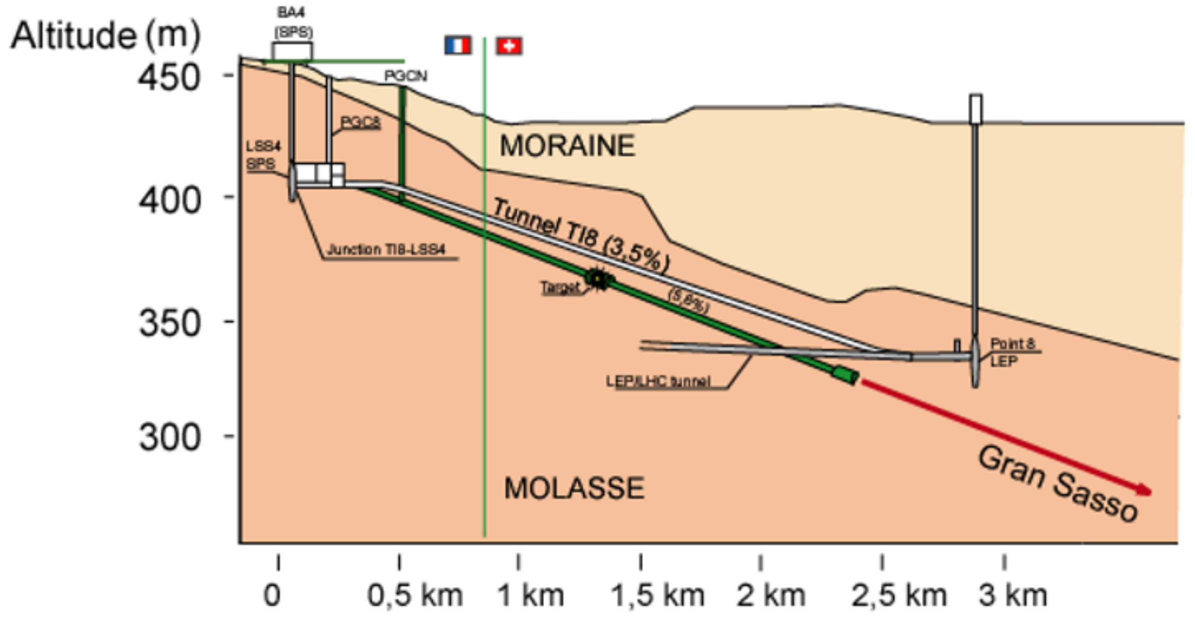
CNGS (**C**ERN **N**eutrino beam to **G**ran **S**asso)

L= 732 km E_ν= 10-30 GeV

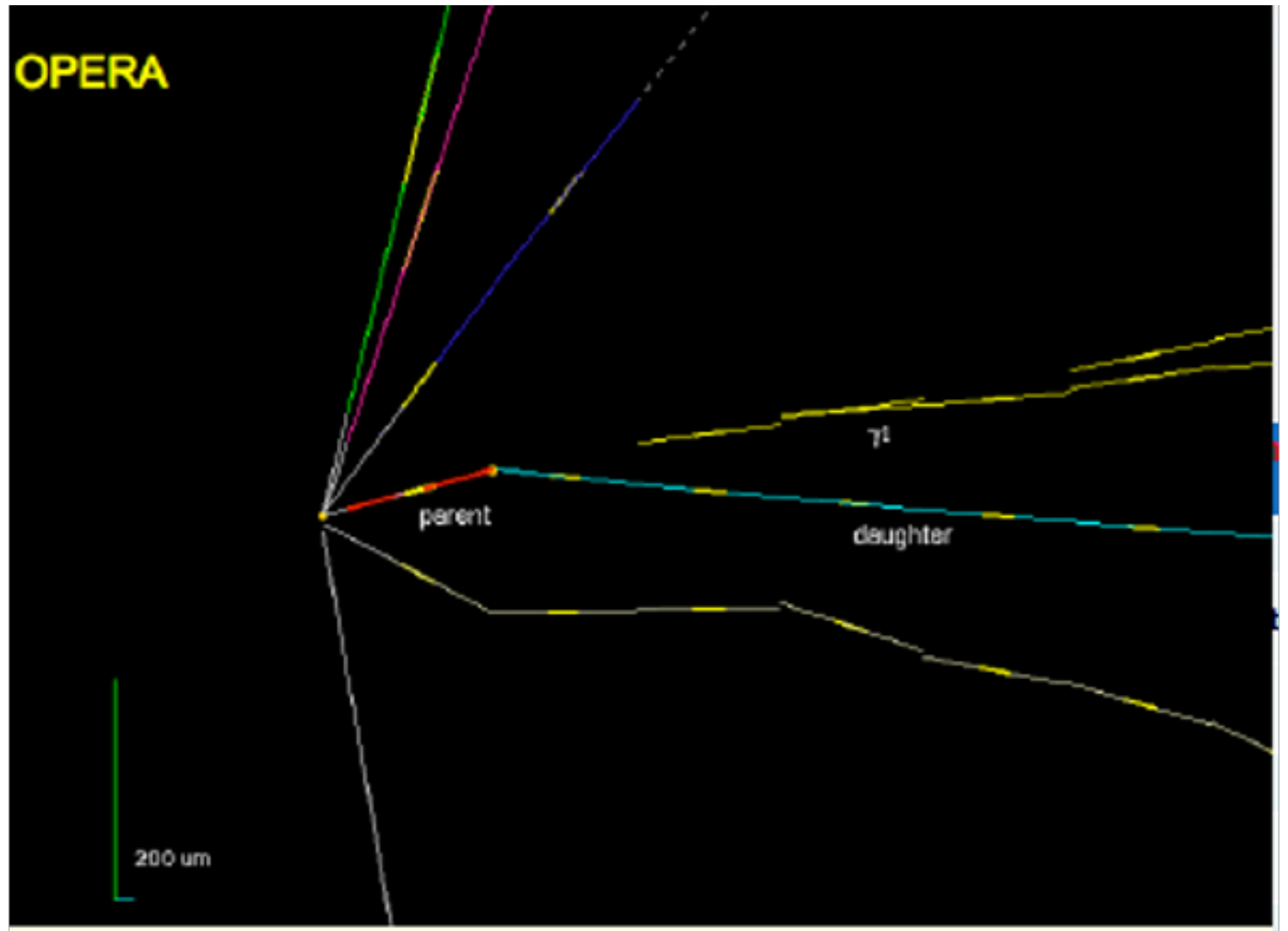
400 GeV p from CERN-SPS on C-target horn + reflector : sign selected pions for WBB
decay tunnel : 992 m , near detector @ 1850 m from target



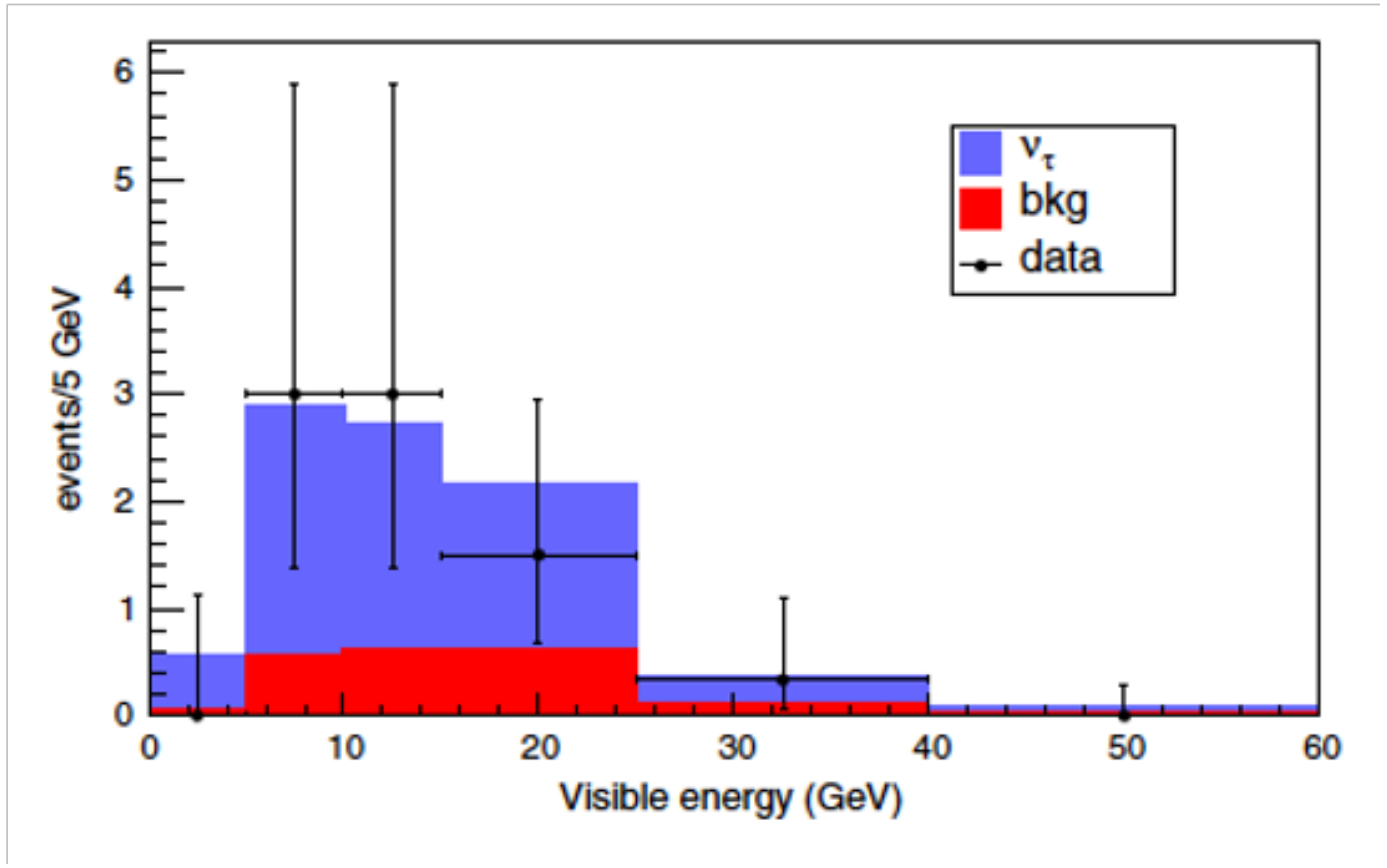




OPERA results



First candidate $\nu_\mu \to \nu_\tau$ $\tau^- \to \pi^- + \pi^0$

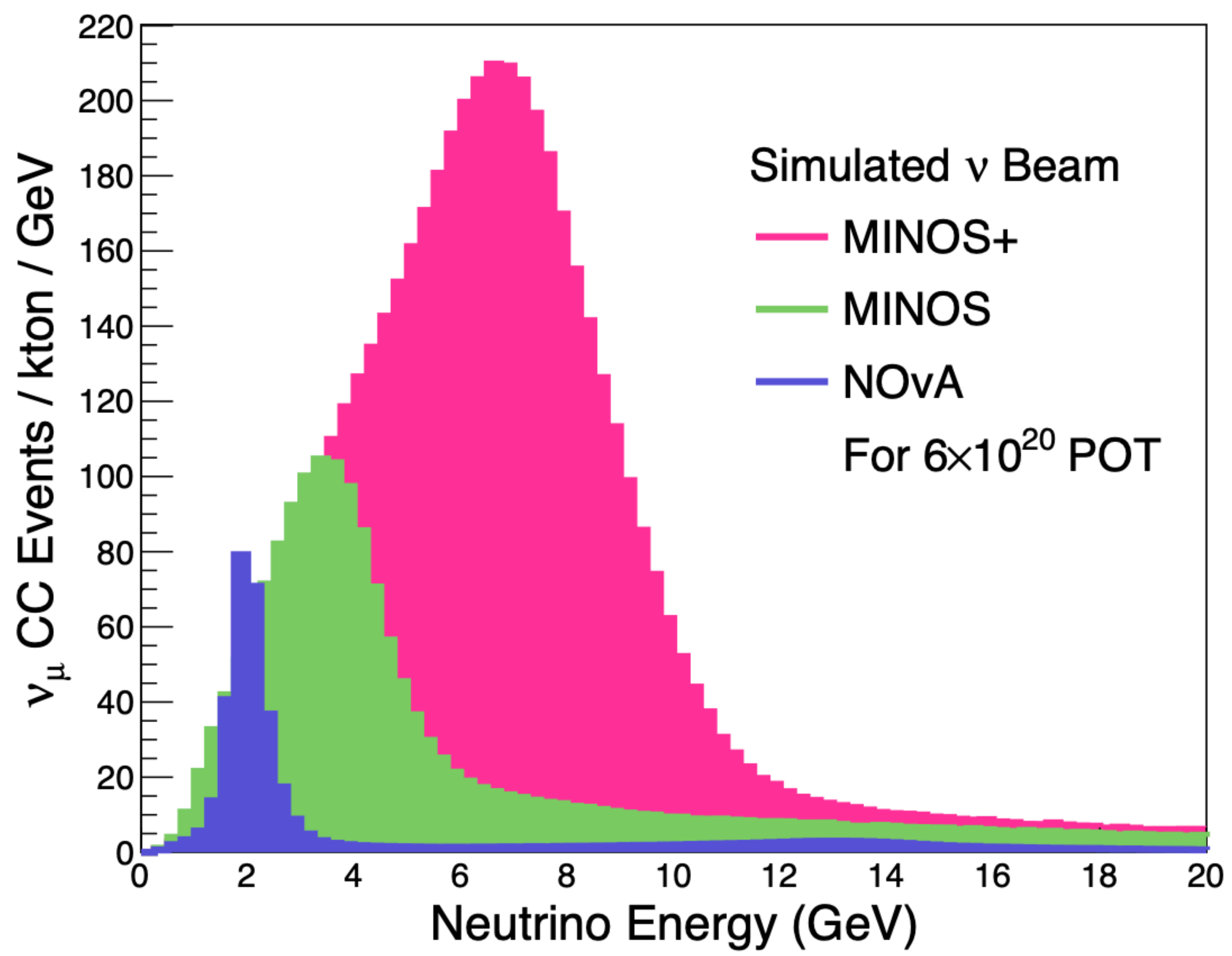


- 10 neutrino candidates observed with an expected background of 2.0±0.4
- 6.1σ significance of ν_τ appearance
- As we will see tomorrow this is not the first observation of ν appearance!

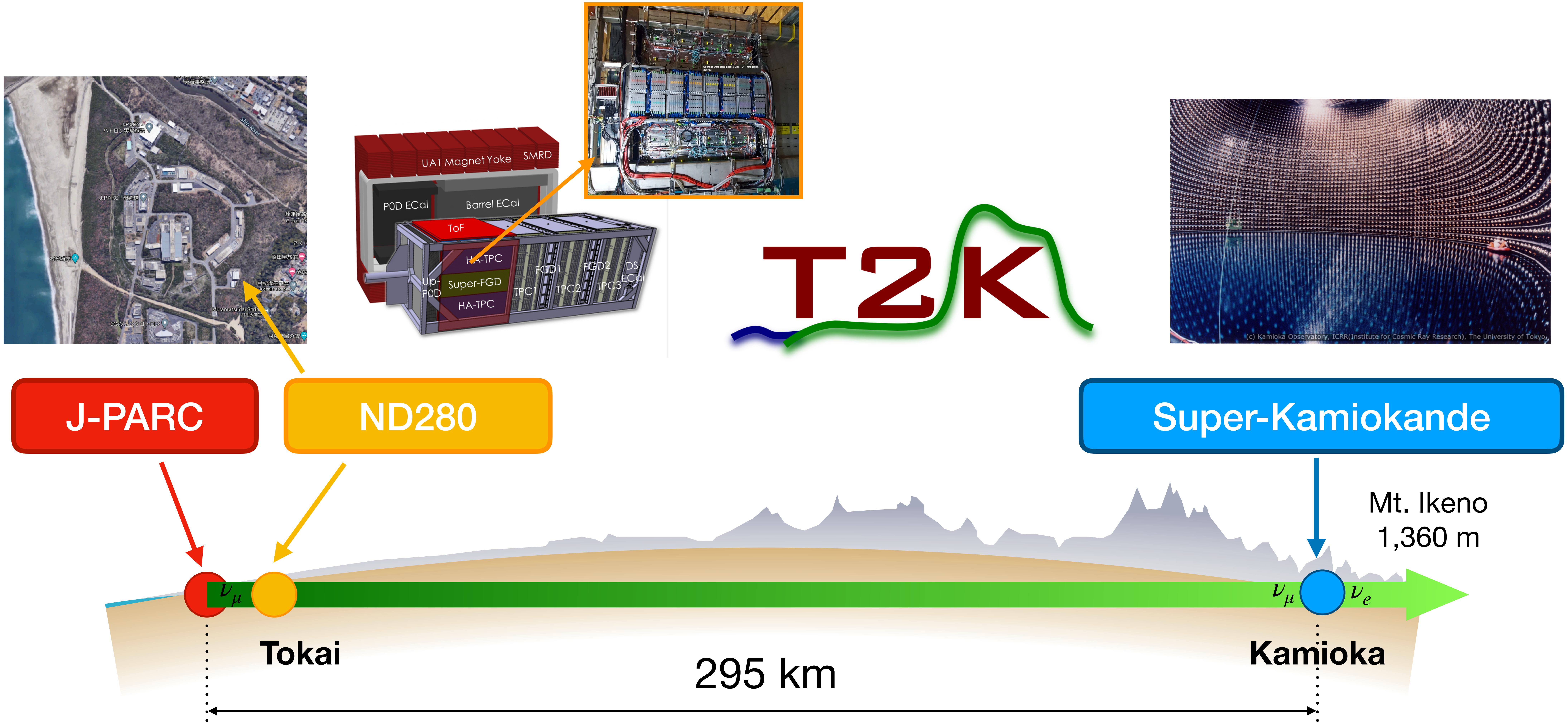
Second generation of LBL experiments

- With the precise measurements of the “atmospheric” squared mass difference $\Delta m^2 \simeq 2.5 \times 10^{-3} eV^2$ it was possible to design experiments optimized for the precise measurement of neutrino oscillations
    - $P(\nu_\mu \to \nu_\mu) = \sin^2(2\theta)\sin^2(1.27 \cdot \Delta m^2[eV^2]L[km]/E[GeV])$
    - Probability maximal for $1.27 \cdot \Delta m^2[eV^2]L[km]/E[GeV] = \pi/2$
- First generation experiments (K2K and MINOS) used wide-band beam to span large ranges of Δm^2
- Second generation experiments (T2K and NOvA) use narrow band beam

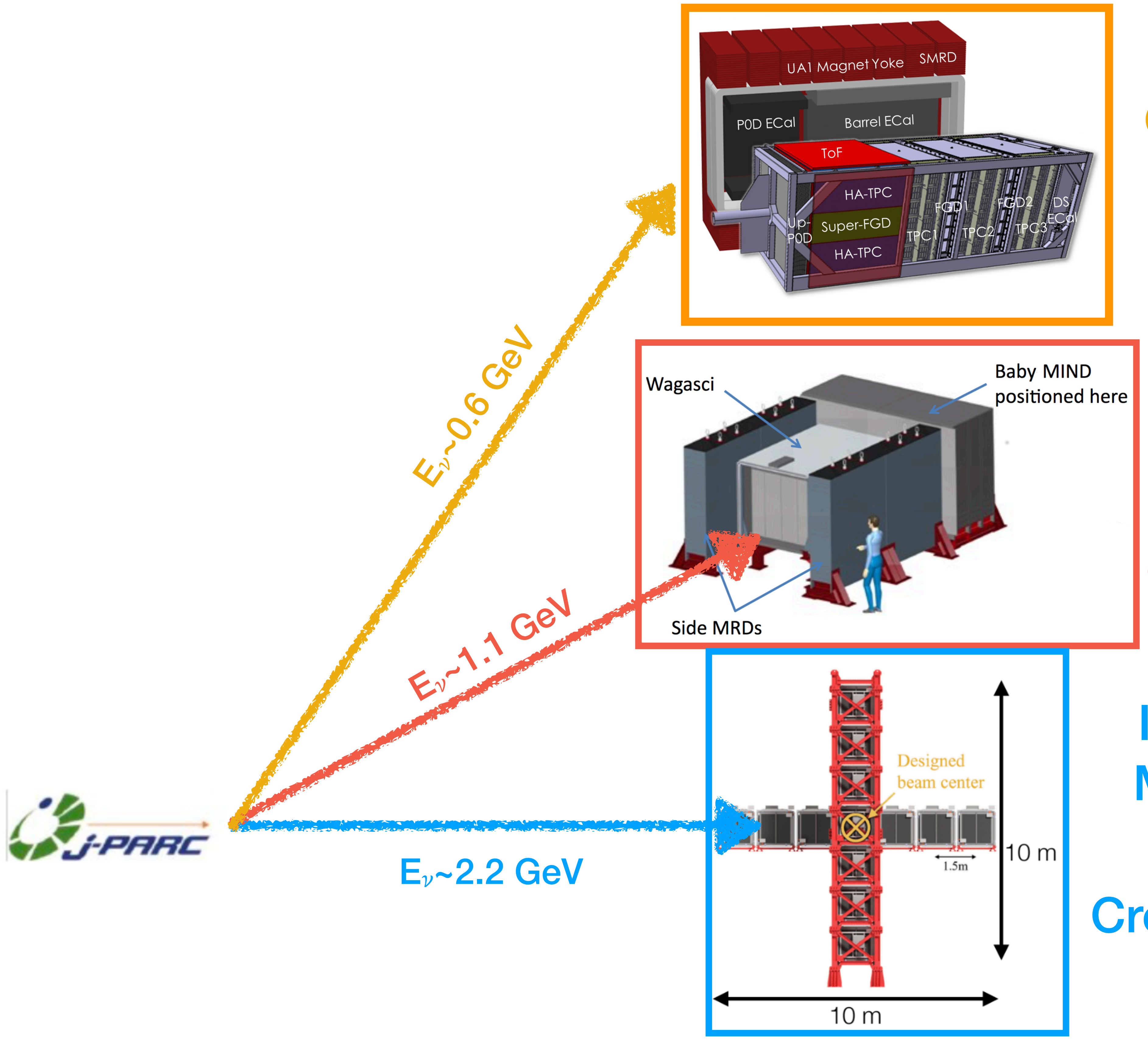
	E	L	1.27Δm²L/E
MINOS	~3 GeV	750 km	~0.7
T2K	0.6 GeV	295 km	~1.5
NOνA	2 GeV	810 km	~1.2



T2K experiment



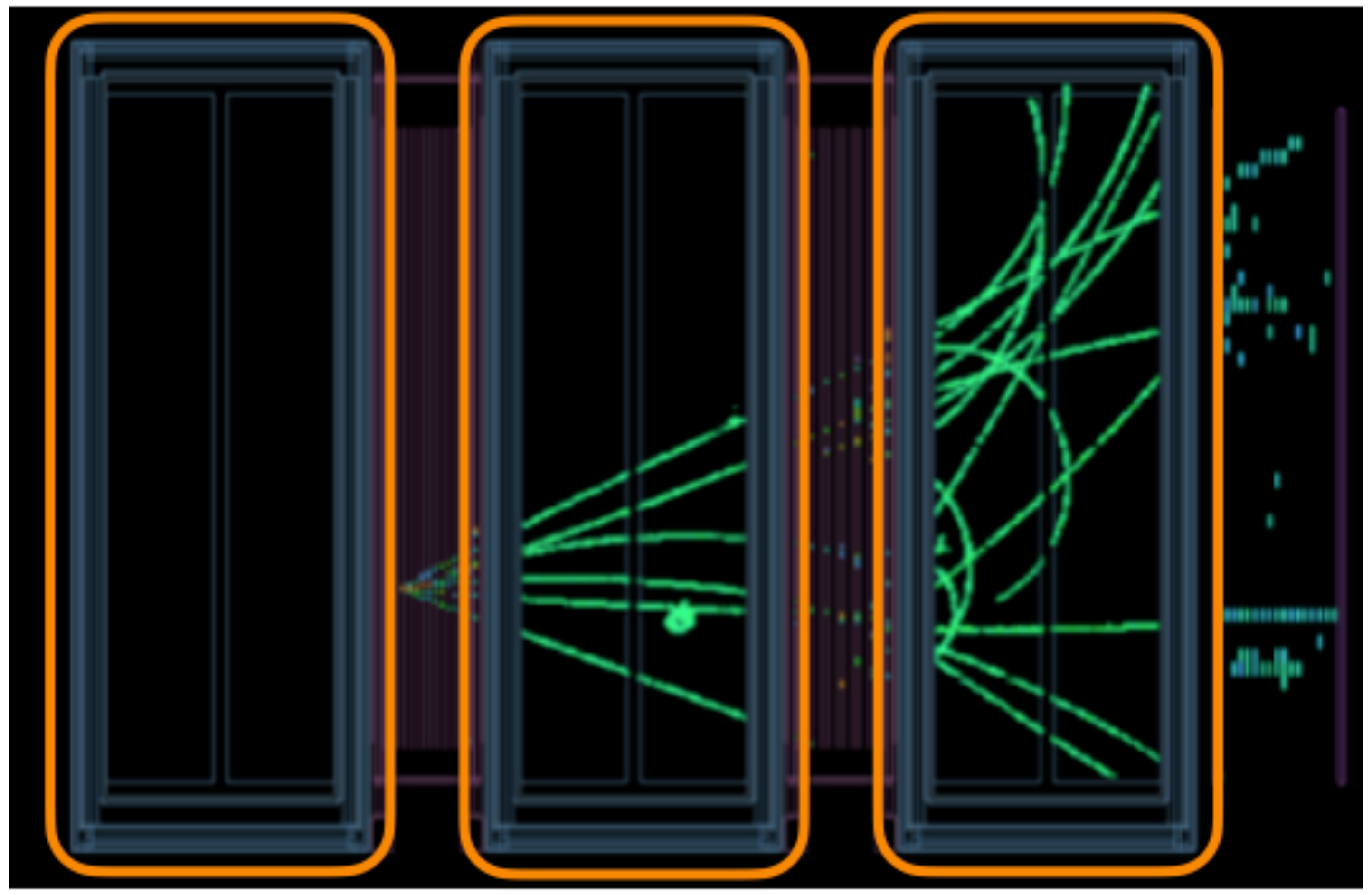
T2K Near/Far detector



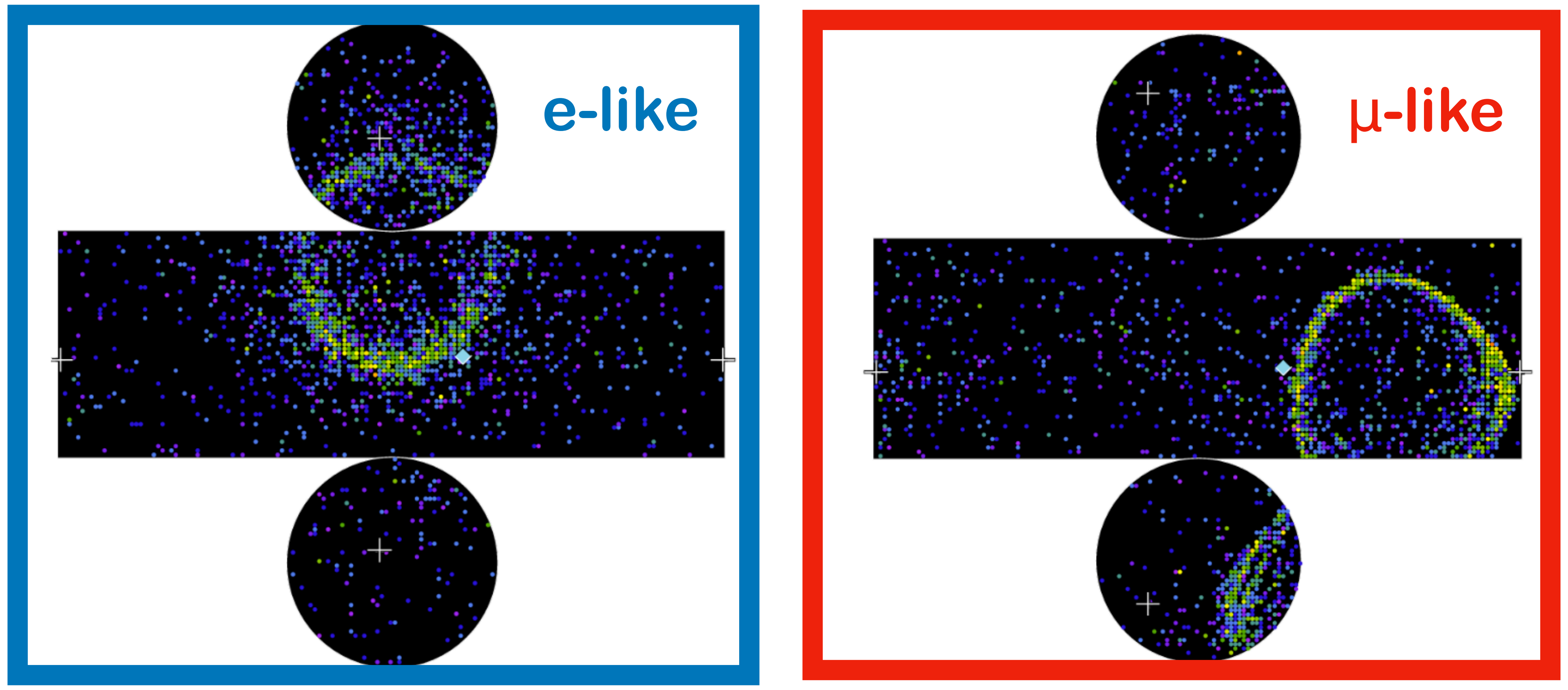
Off-Axis ND280
Constrain systematics in T2K oscillation analyses
Measure neutrino cross-sections

WAGASCI/BabyMIND
Installed in 2019
Cross-sections on water

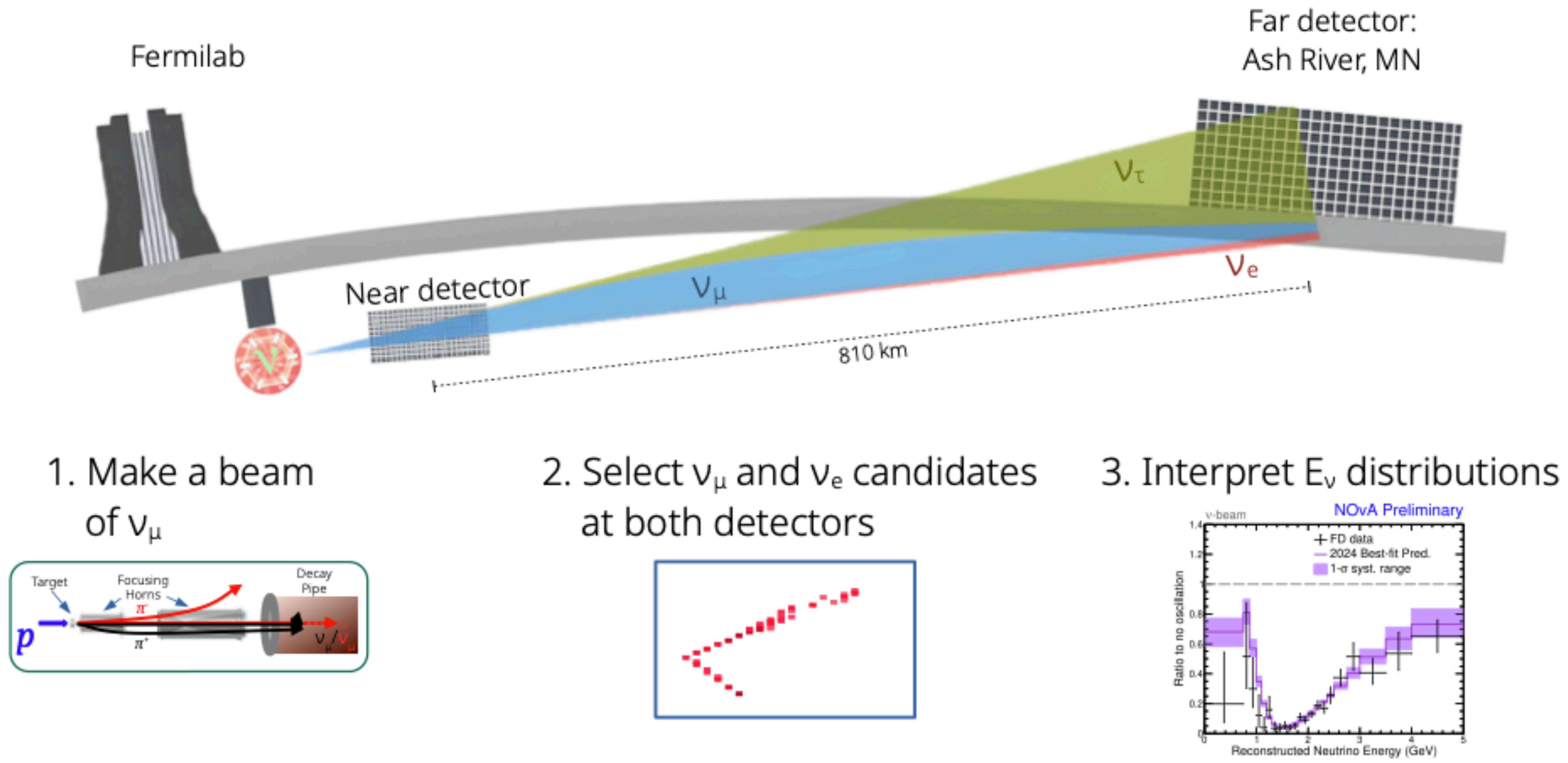
INGRID: on-axis detector
Monitoring ν beam profile day-by-day
Cross-section measurements
In operation since 2009

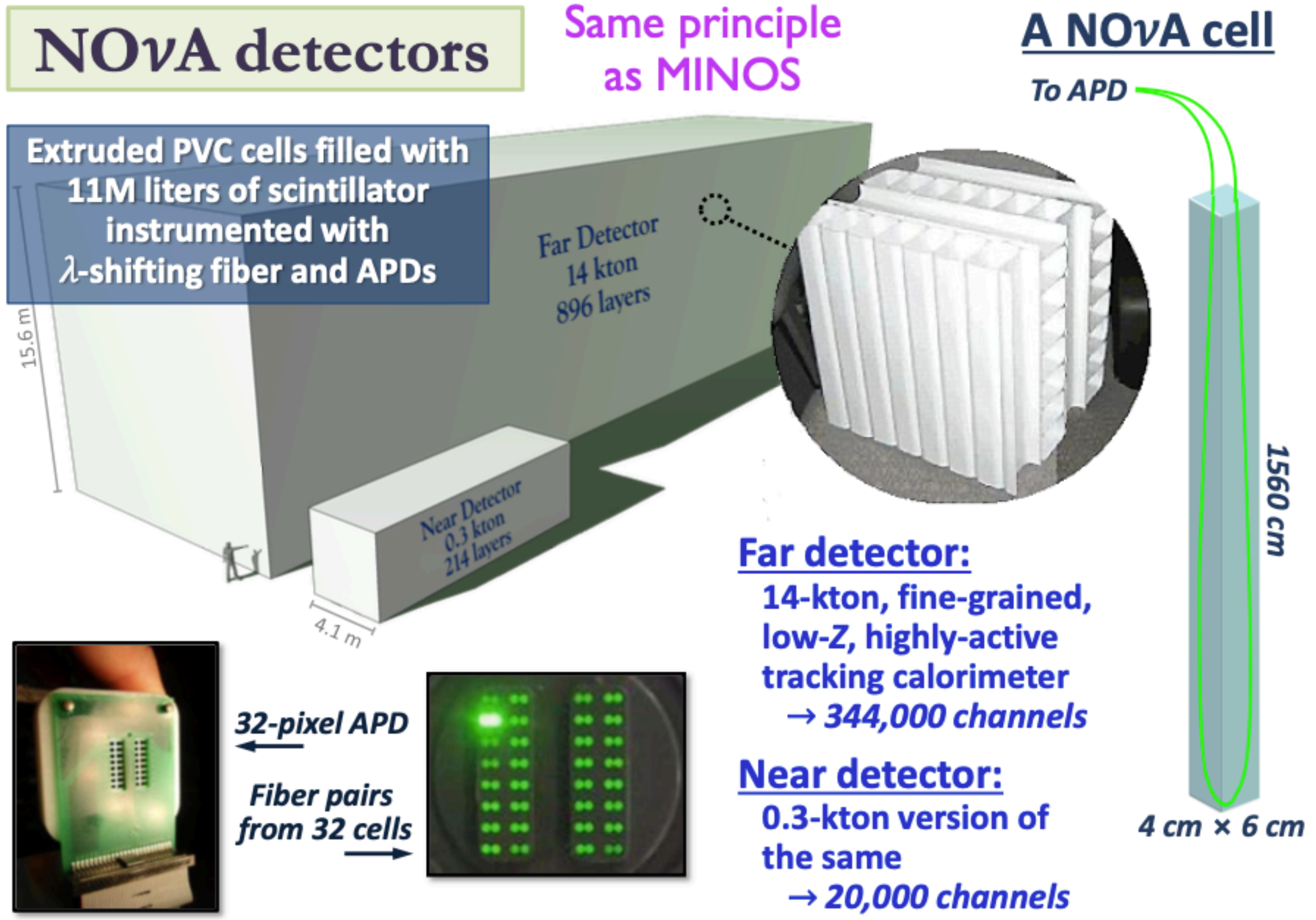


Far Detector: Super-Kamiokande



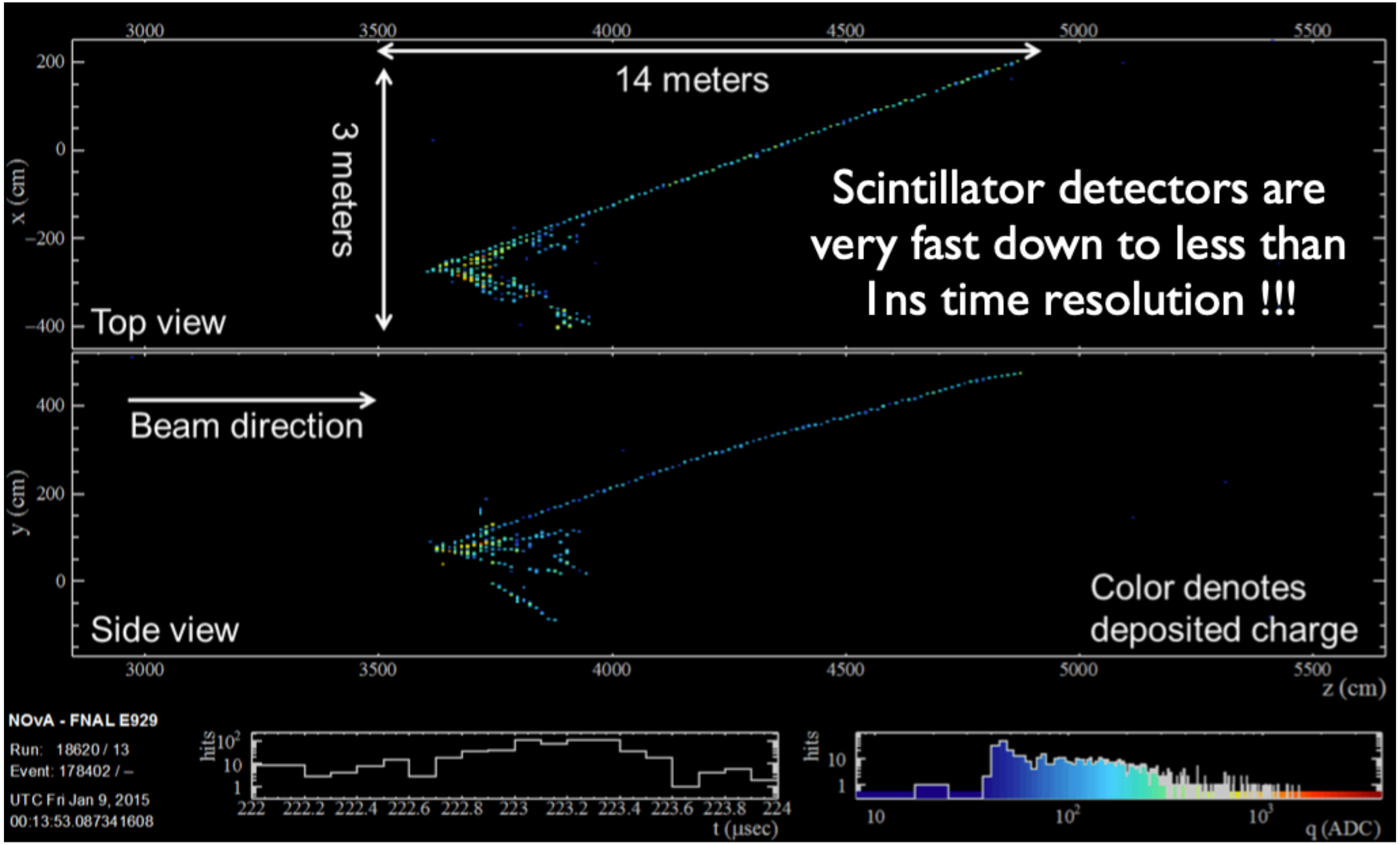
NOvA experiment





- Identical near and far detector

NOvA neutrino interaction

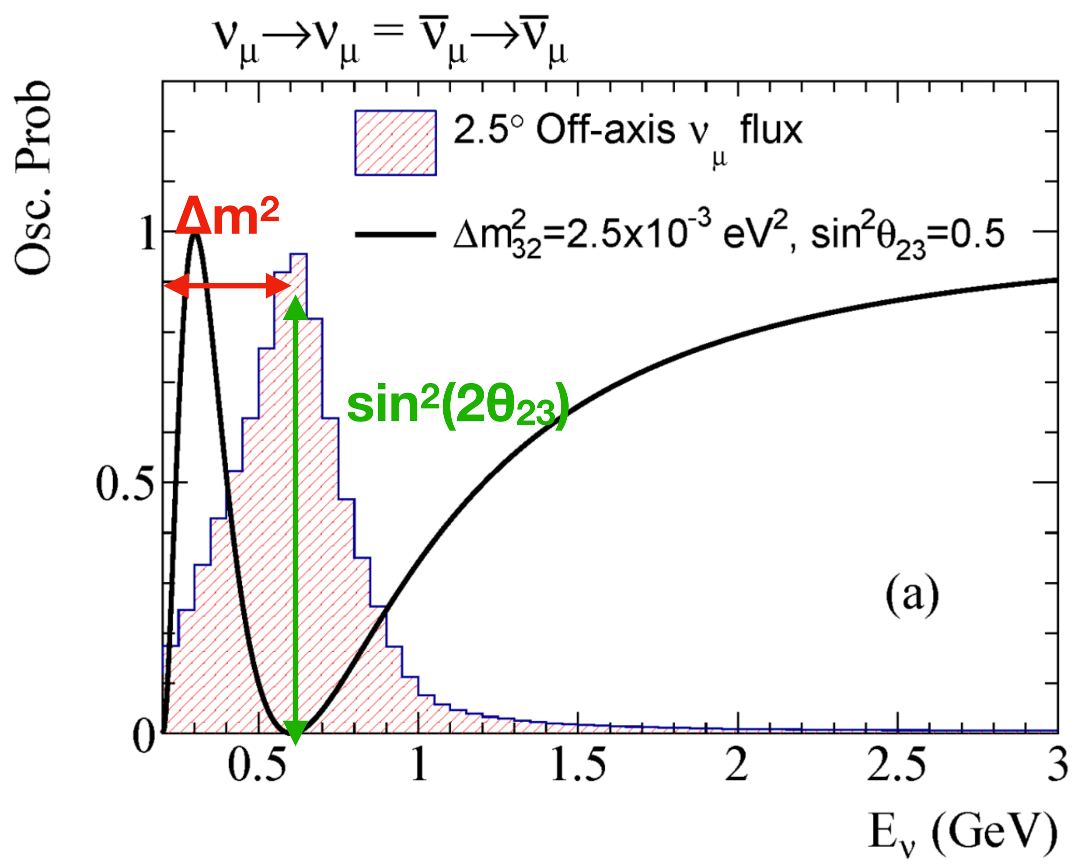


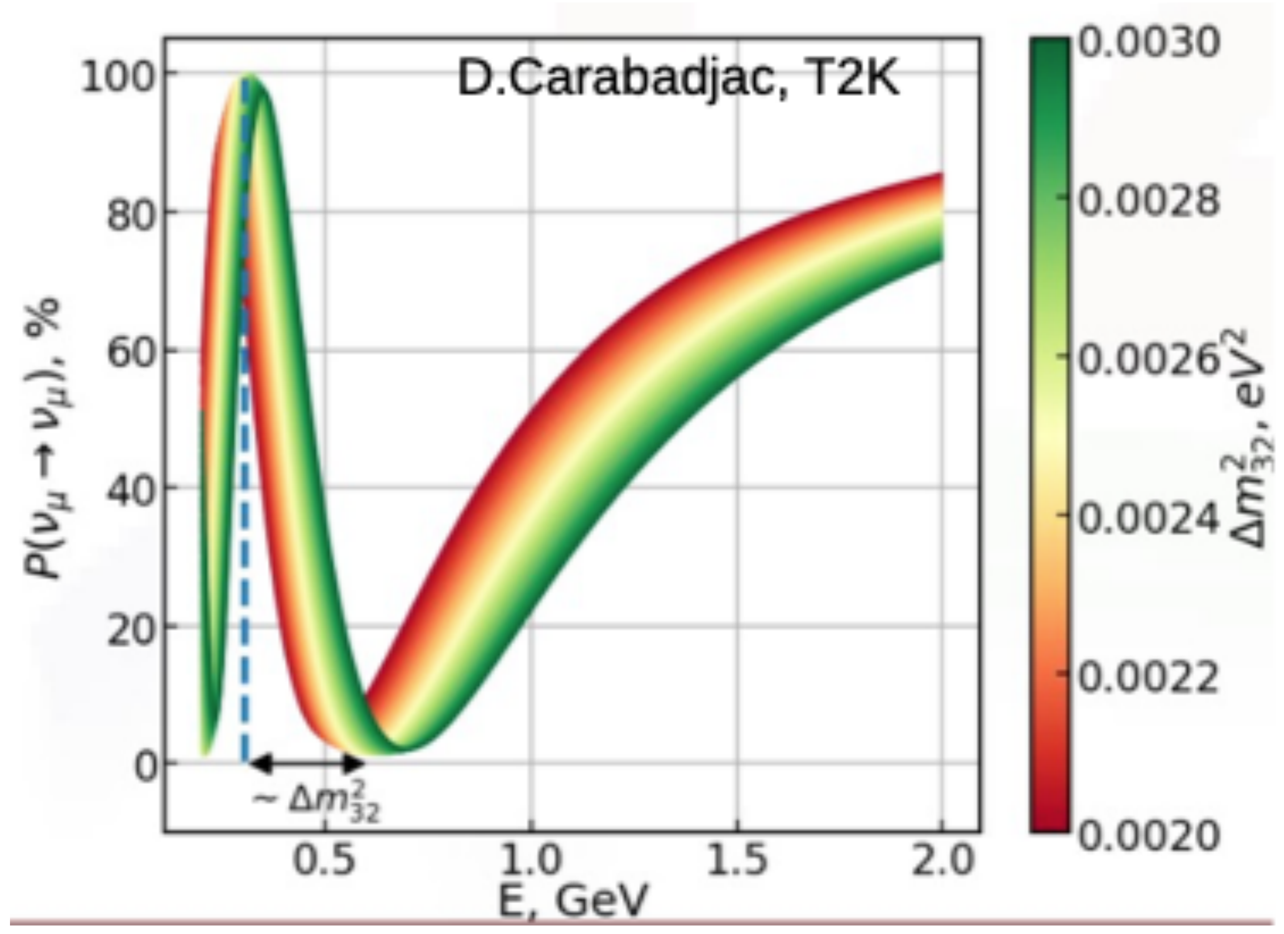
ν_μ disappearance

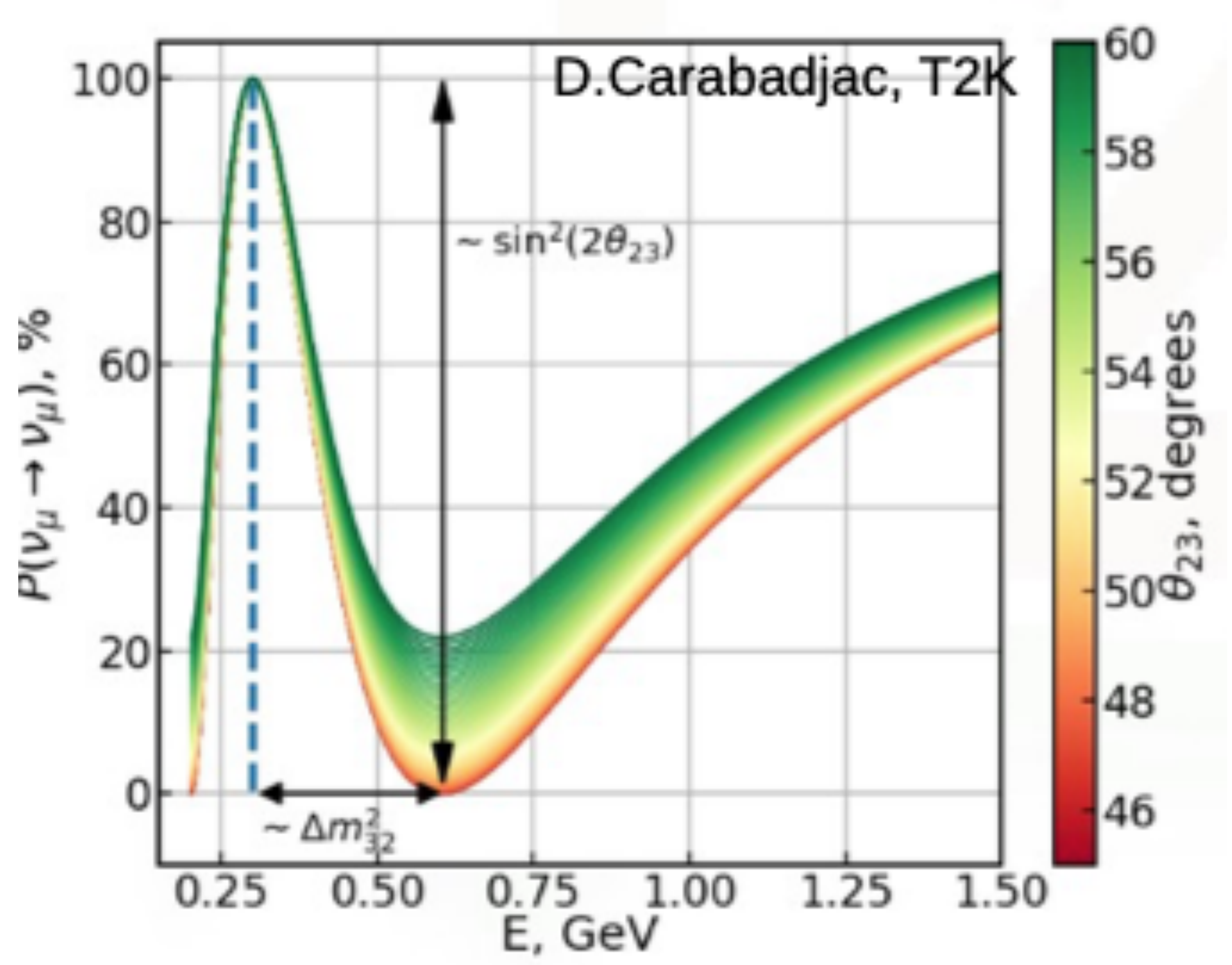
$$P(\nu_\alpha \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha) = 1 - 4\sum_{i<j} |U_{\alpha i}U_{\alpha j}|^2 \sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

$$P(\nu_\mu \to \nu_\mu) = 1 - (c^4_{13}\sin^2 2\theta_{23} + s^2_{23}\sin^2 2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

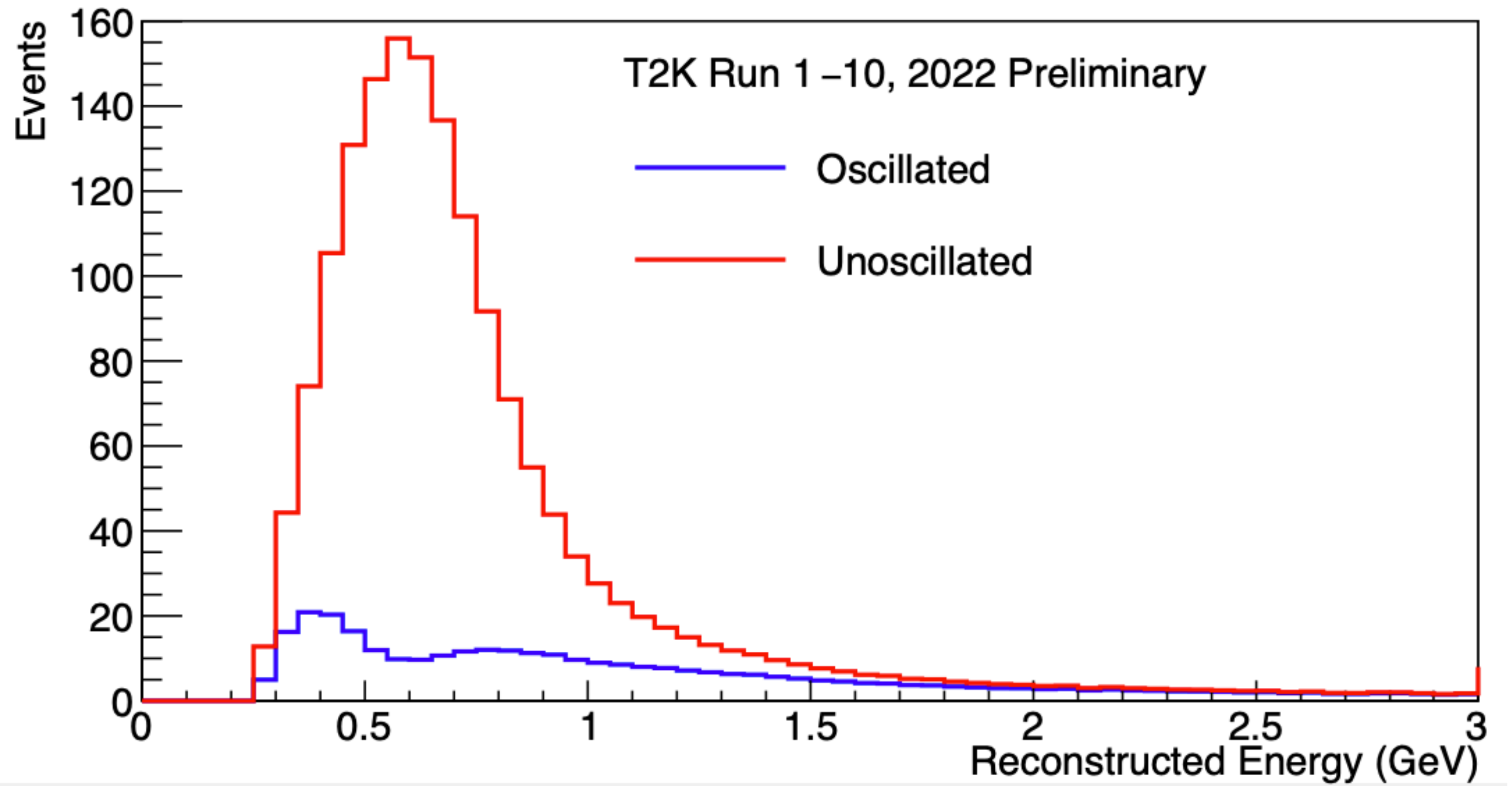
- In order to measure precisely Δm2 a good reconstruction of the neutrino energy is crucial → good resolution and no biases!

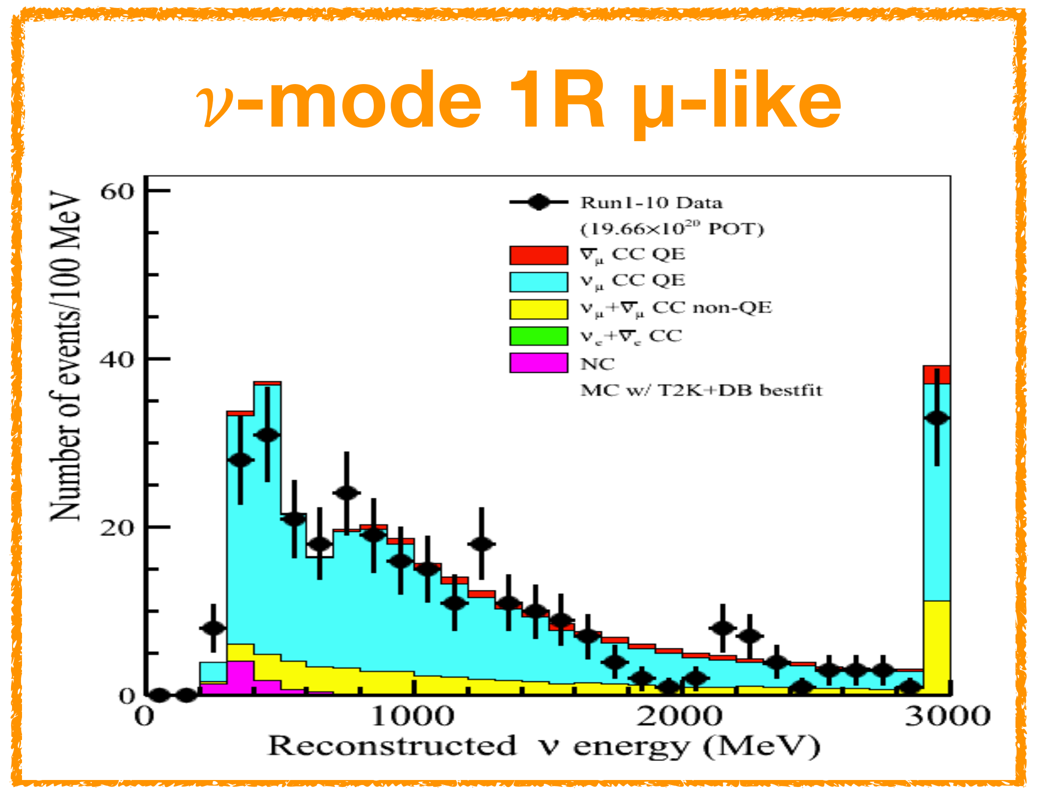


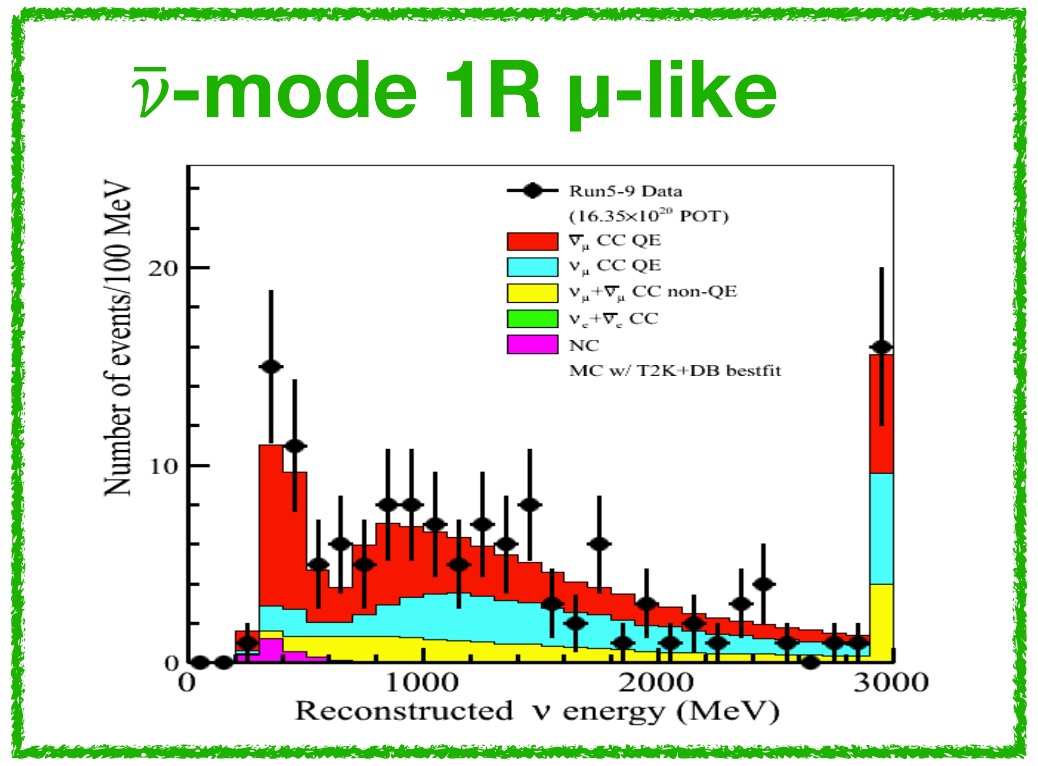


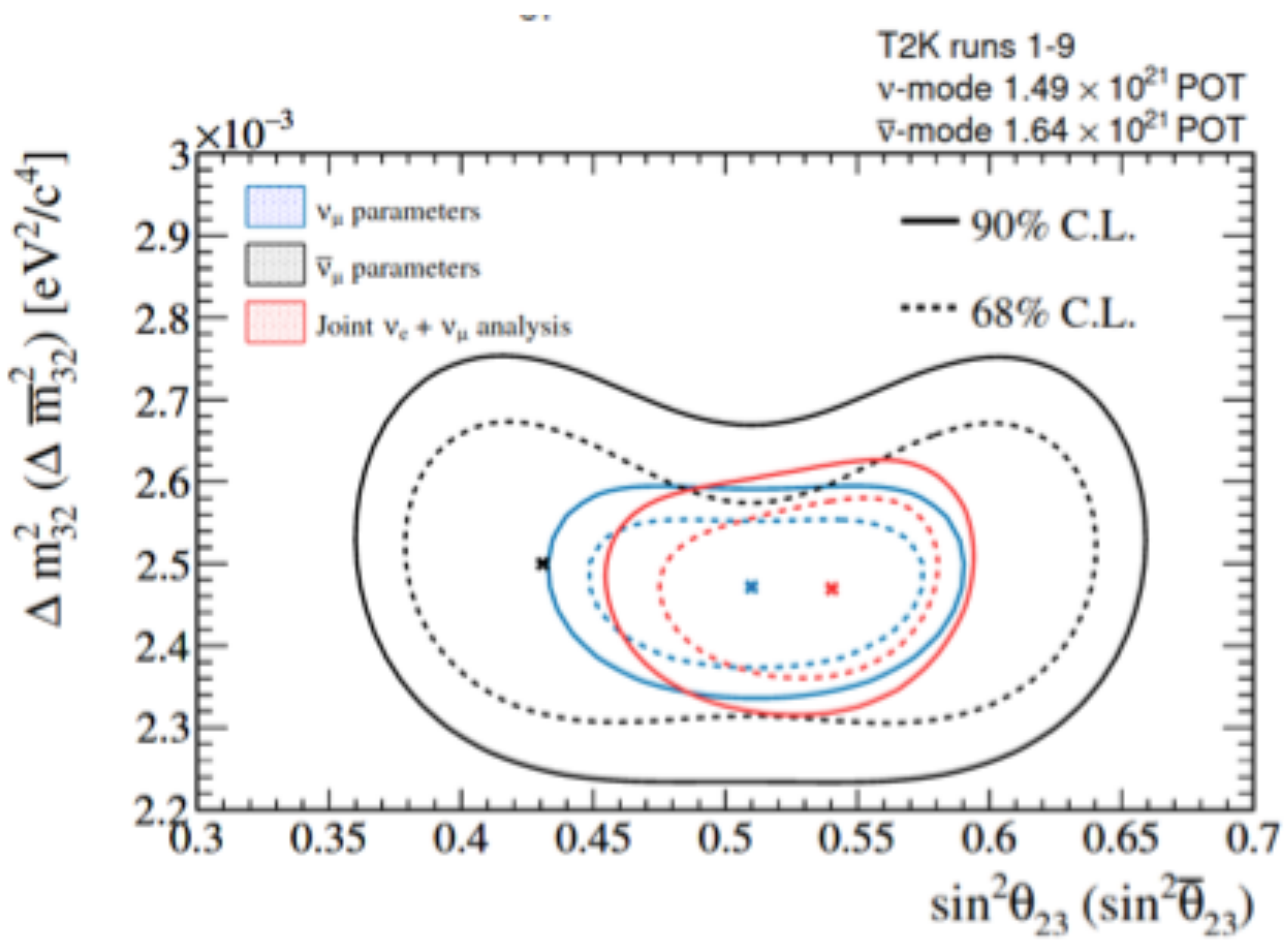


CPT invariance







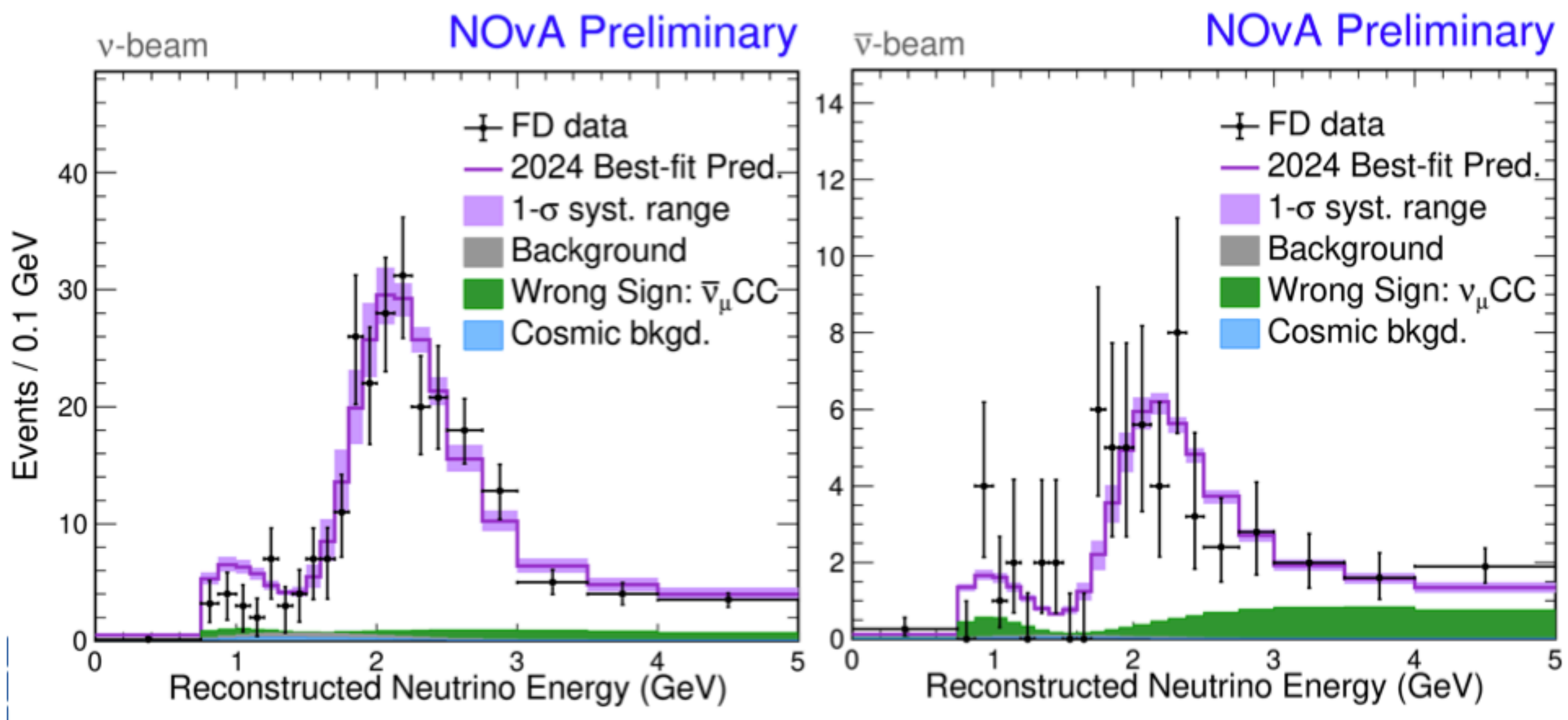


- In disappearance channel ν_μ and $\bar{\nu}_\mu$ have same oscillation probabilities
- A difference in the mixing angles would mean CPT violation!

$$P(\nu_\mu \to \nu_\mu) = 1 - (c_{13}^4 \sin^2 2\theta_{23} + s_{23}^2 \sin^2 2\theta_{13})\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

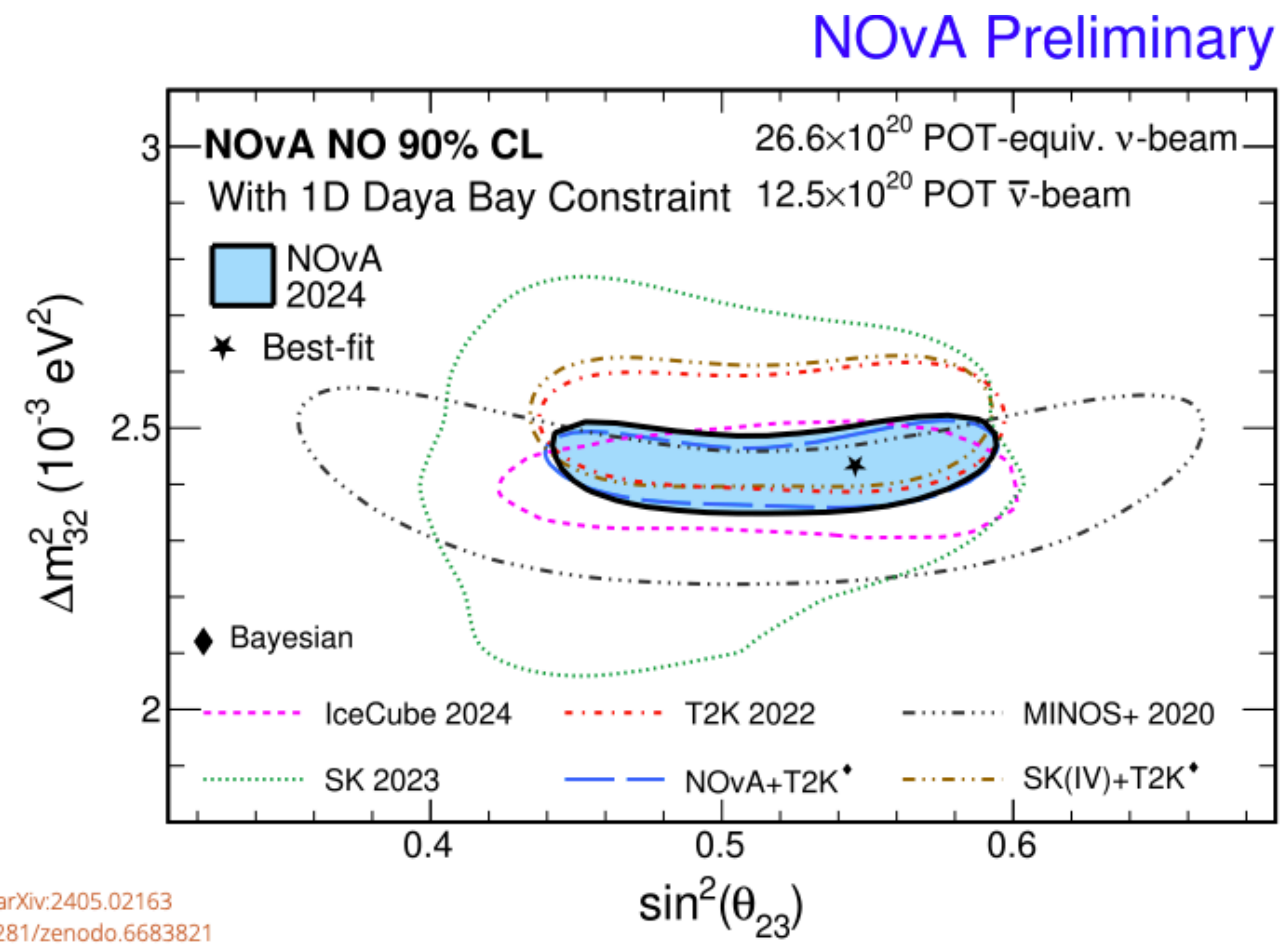
- Small sensitivity to the octant from disappearance alone ($\sin^2 2\theta_{13}$ is small)

Global Picture Atmospheric sector



384 ν_μ data candidates
(11.3 background)

106 $\bar{\nu}_\mu$ data candidates
(1.7 background)

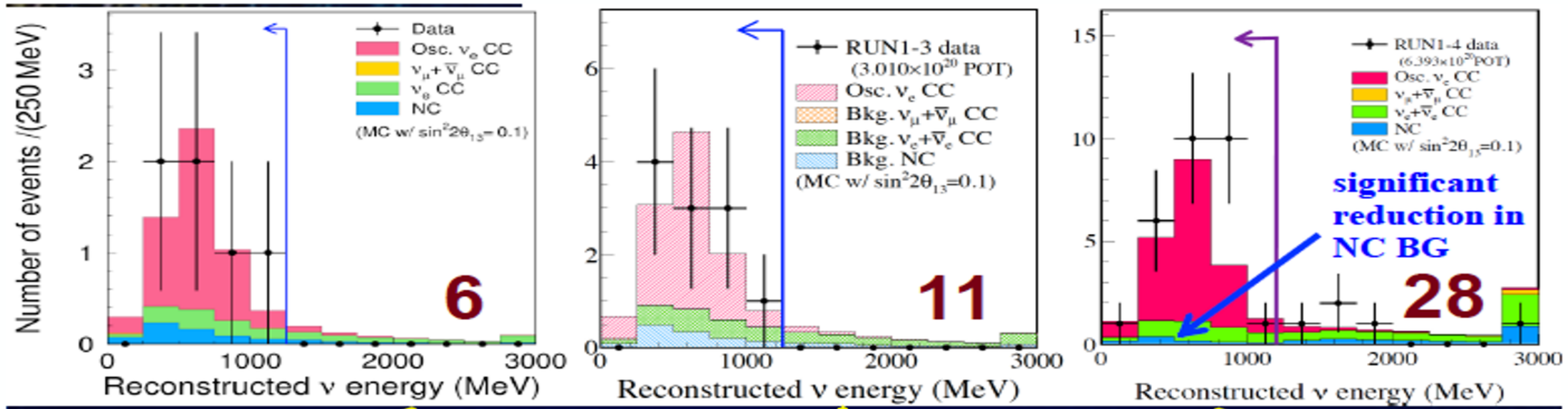


24: arXiv:2405.02163
).5281/zenodo.6683821

- Long-Baseline experiments dominate precision for Δm^2 and θ_{23}
- Results in good agreement and fully consistent with an interpretation in the 3ν framework

ν_e appearance

- At first order (neglecting matter effects and CP violation!)
  - $P(\nu_\mu \to \nu_e) \sim s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$
- Observation of ν_e appearance → θ_{13} different from zero
- 2012: measurement of θ_{13} from Daya Bay



Year	2011	2012	2013
POT (10^{20})	1.43	3.01	6.57
$N_{\nu_e}^{obs.}$	6	11	28
N_{BG}^{exp}	1.5 ± 0.3	3.3 ± 0.4	4.92 ± 0.55
$\sin^2 2\theta_{13}$(T2K)	0.11	$0.088^{+0.049}_{-0.033}$	$0.140^{+0.038}_{-0.032}$
Significance	2.5σ	3.1σ	7.3σ
Systematic Error (%) on N_{tot}^{exp}	17.5	9.9	8.8

- θ_{13}= 0 is excluded at 7.3σ level of significance

ν_e and $\bar{\nu}_e$ appearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta_{31}$$

$$(\mp)\alpha\frac{J_0 \sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}]$$

$$+\alpha\frac{J_0 \cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}] + O(\alpha^2)$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30$$

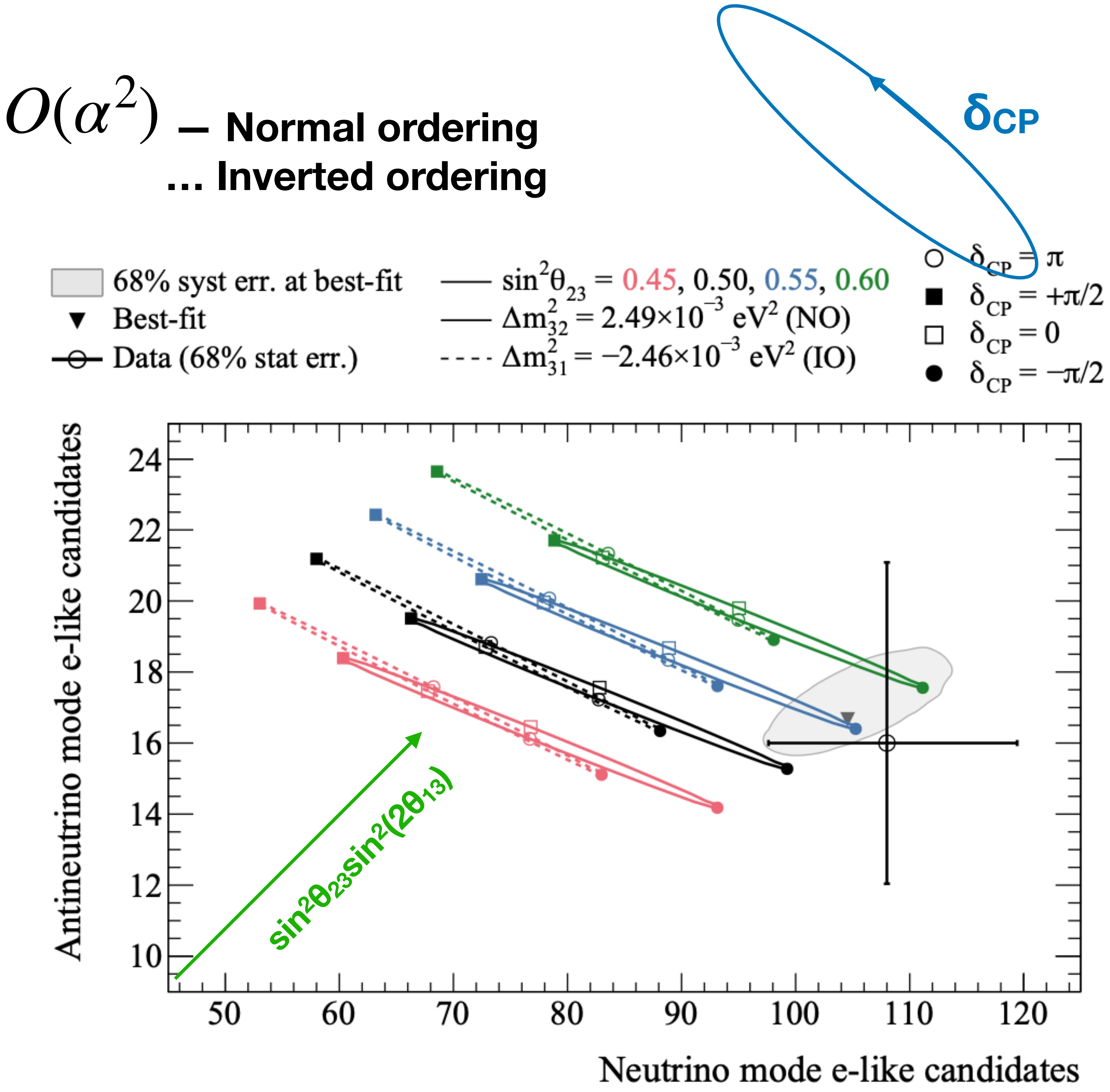
$$J_0 = \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$

$$A = (\mp)2\sqrt{2}G_F n_e E/\Delta m^2_{31}$$

— Normal ordering

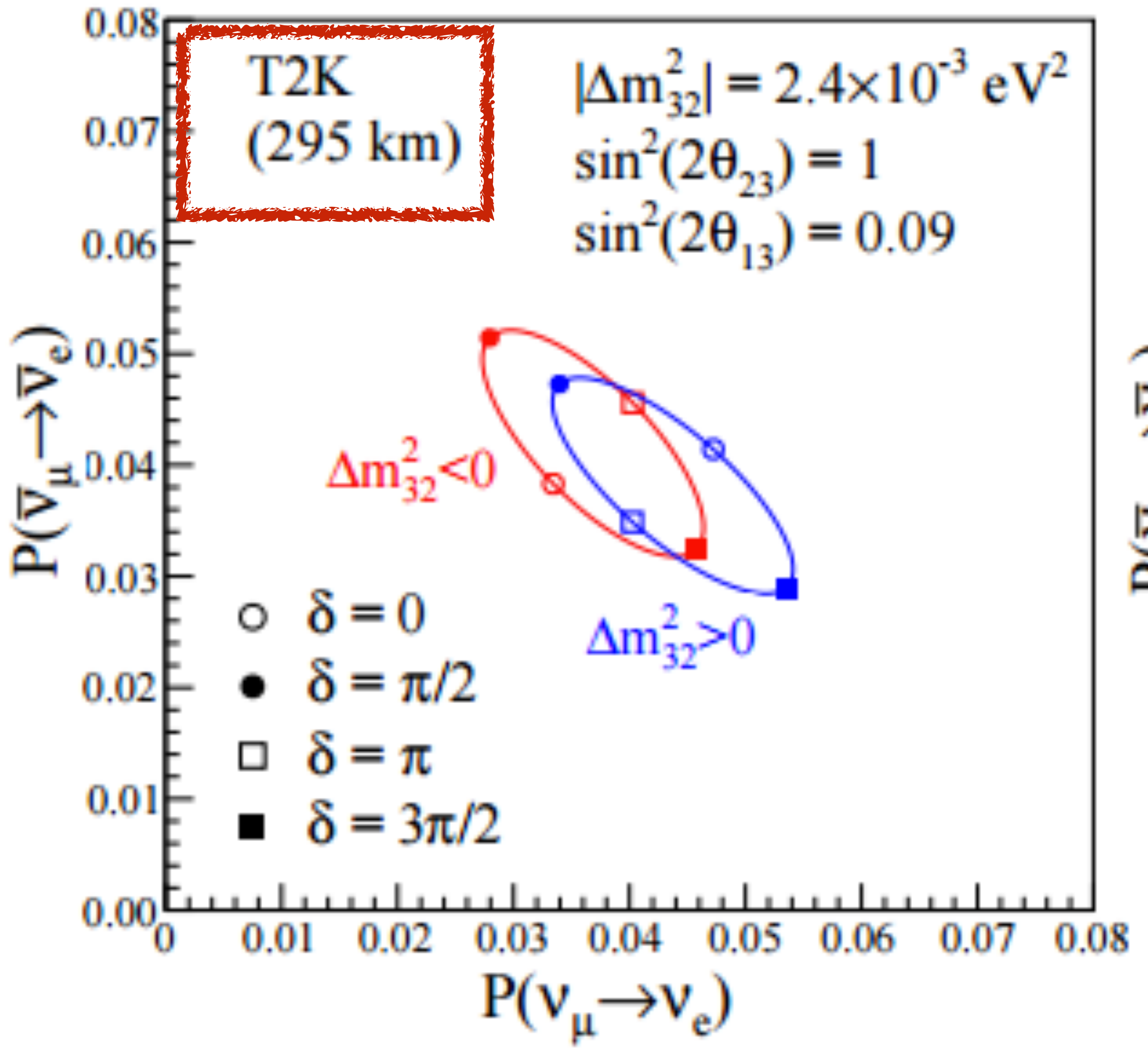
… Inverted ordering

Sensitivity to δ_{CP}, to the mass ordering and to the octant of θ_{23}

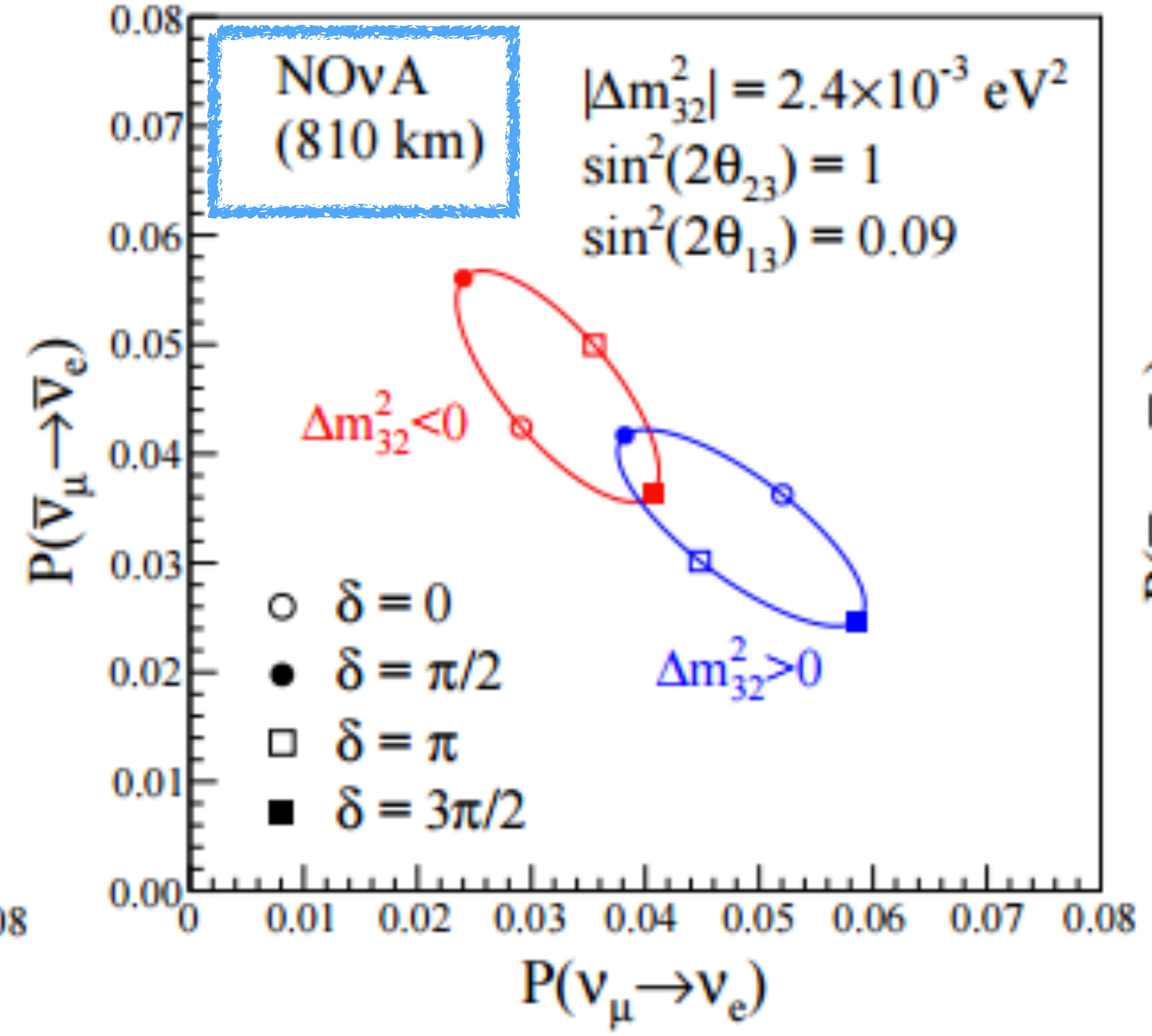


Increasing baselines (and energy!)

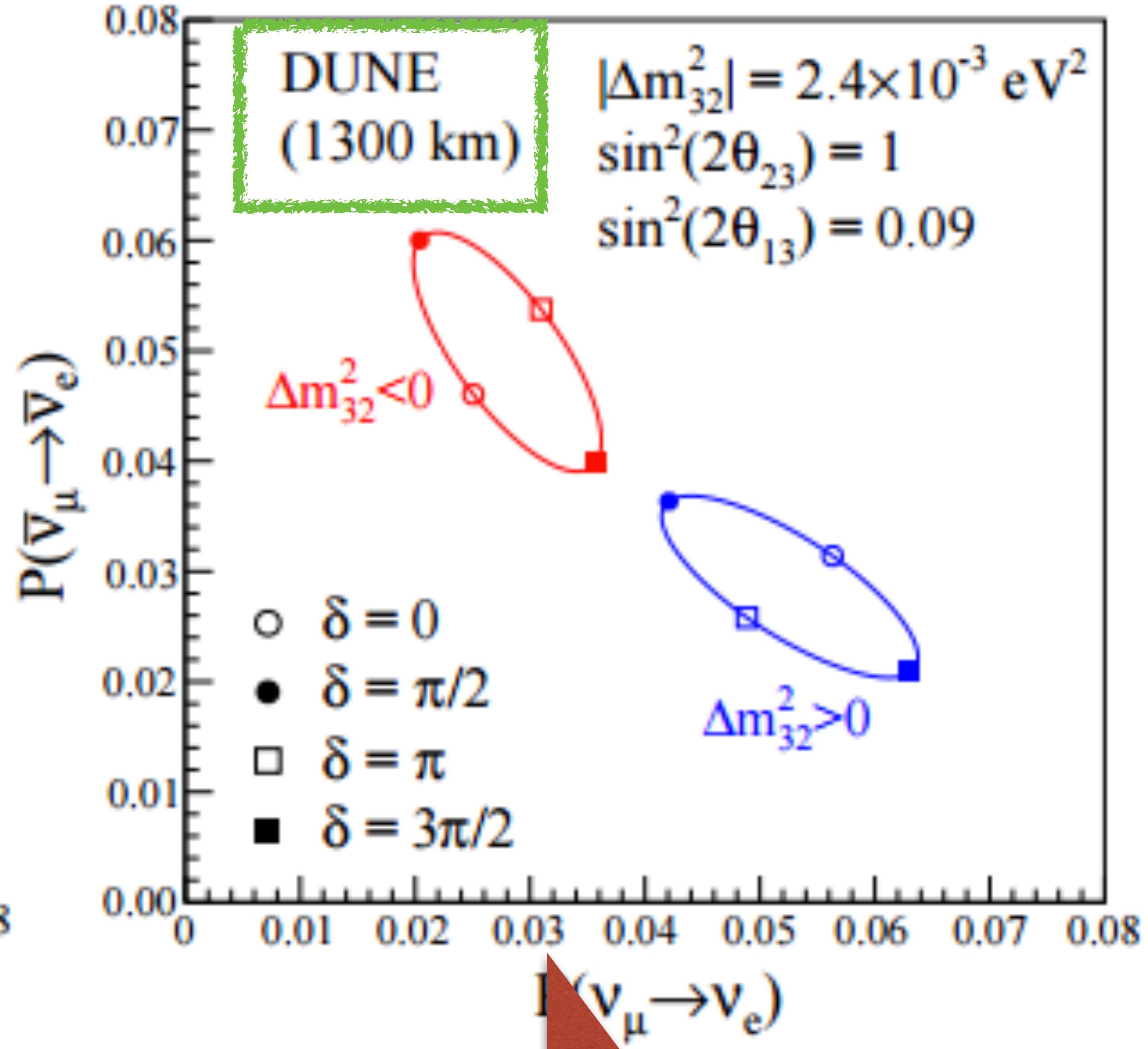
T2K almost no MH —>
~ clean measurement of CPV



NOVA sensitive to MH and CPV
but with some degeneracies

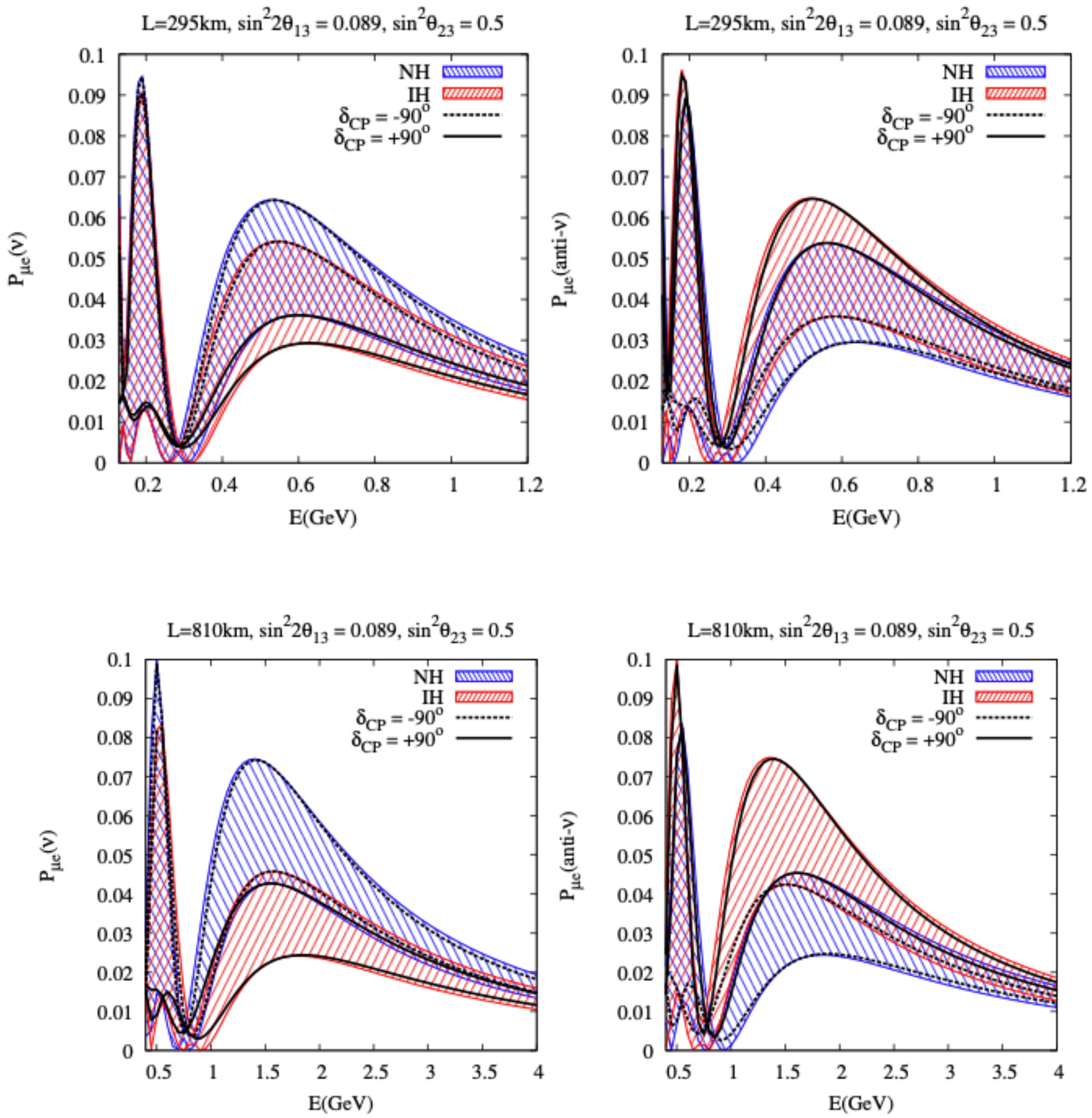


DUNE breaks the degeneracy
between MH and CPV

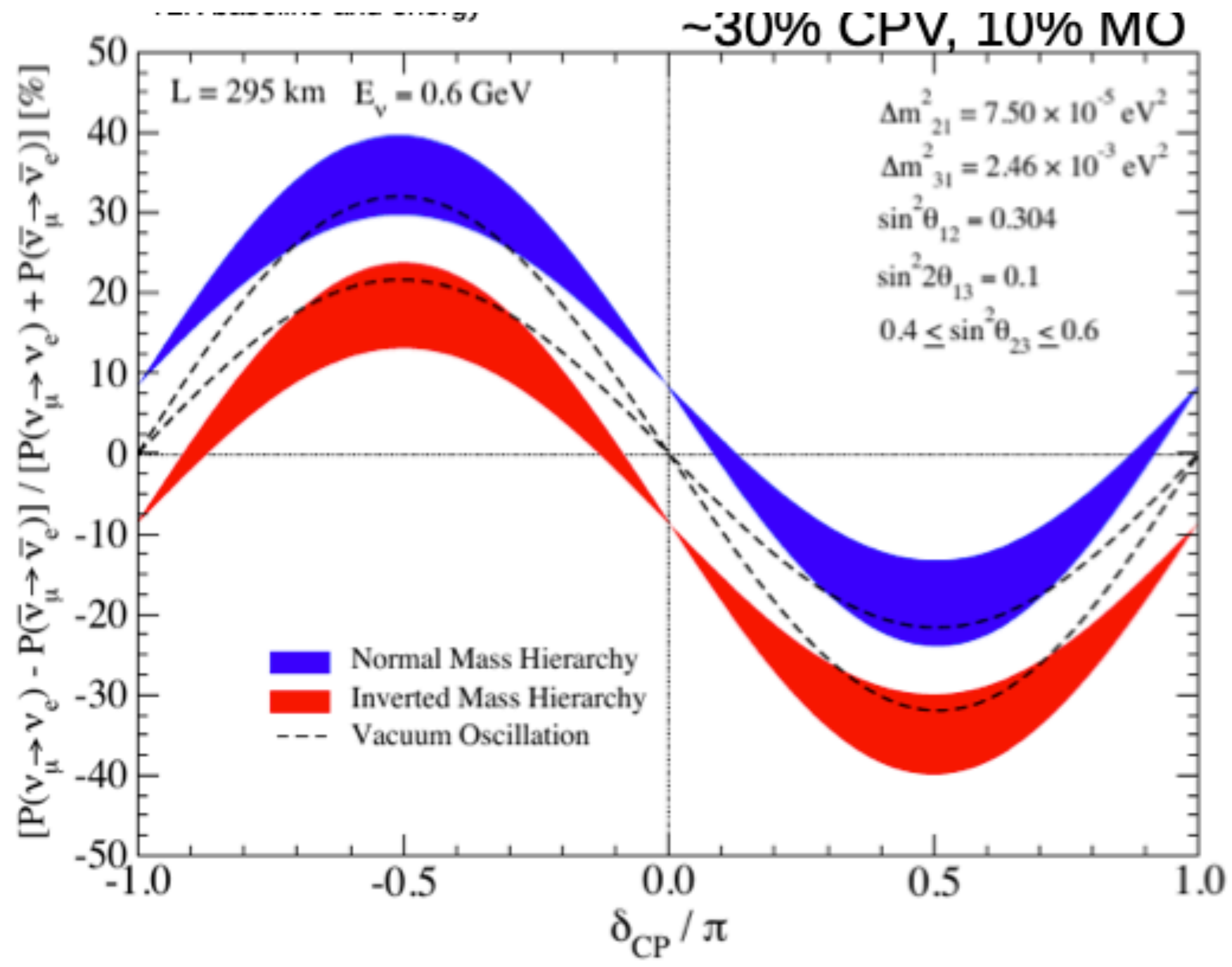


L/E → increasing baseline and energy → larger matter effects

Asymmetry and CP violation

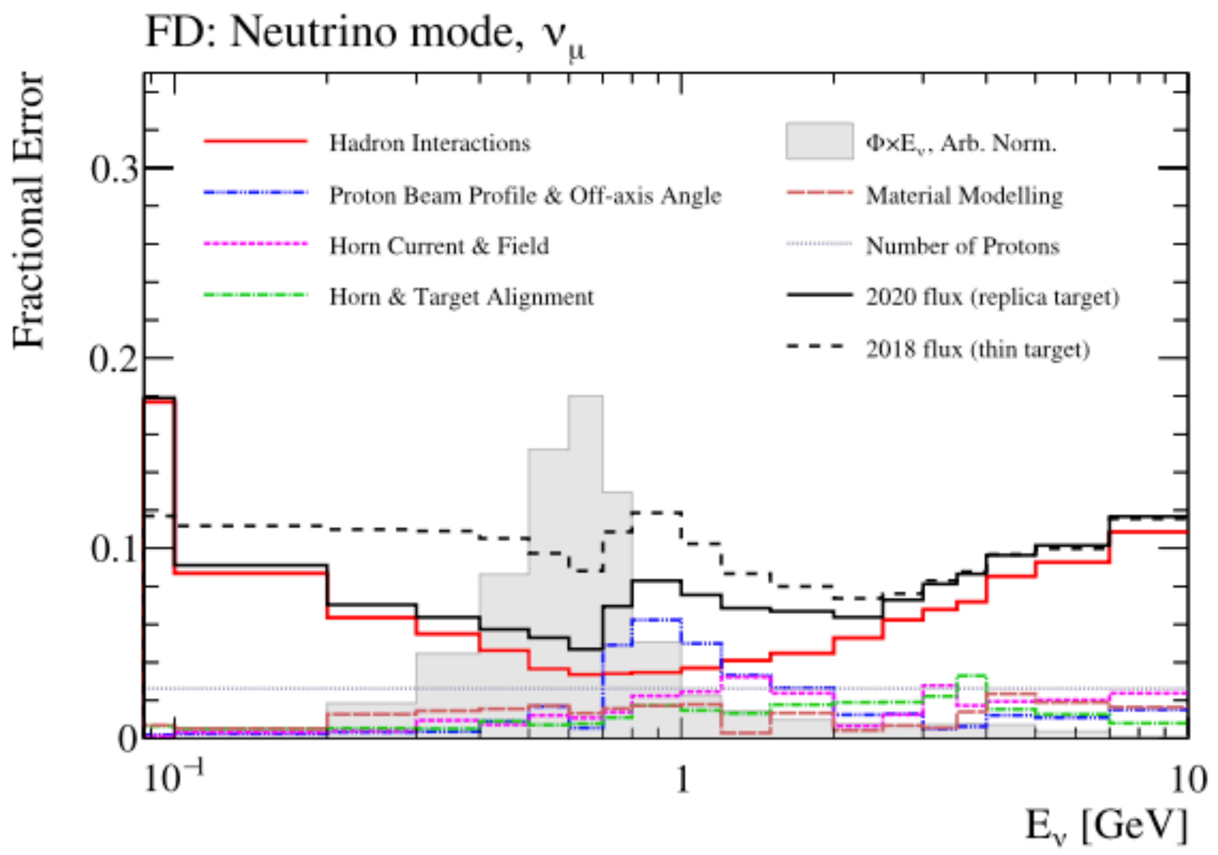


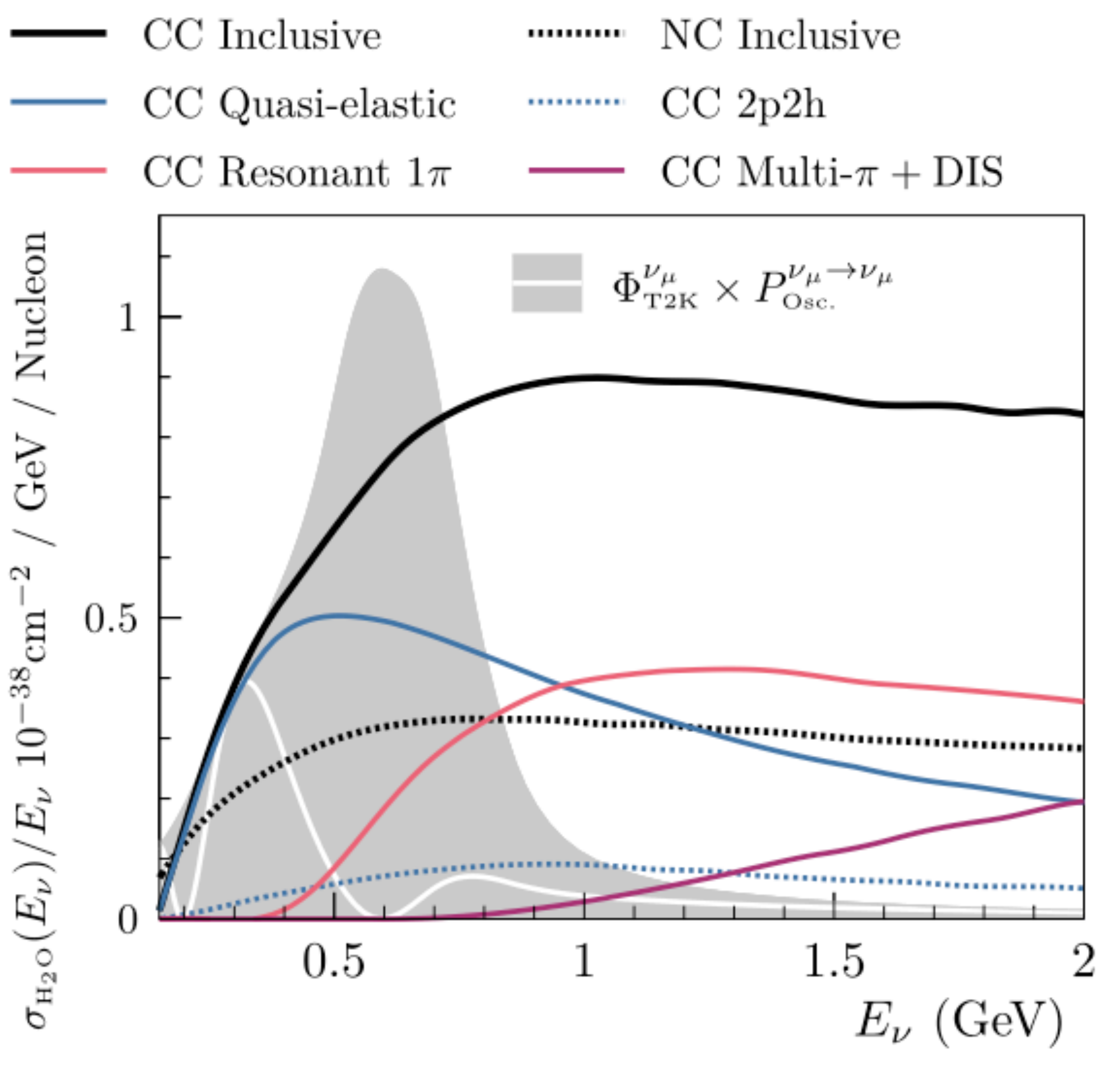
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \sim -\frac{\cos\theta_{23}\sin 2\theta_{12}}{\sin\theta_{23}\sin\theta_{13}} sin\left(\frac{\Delta m^2_{21} L}{4E}\right)\sin\delta_{CP}$$

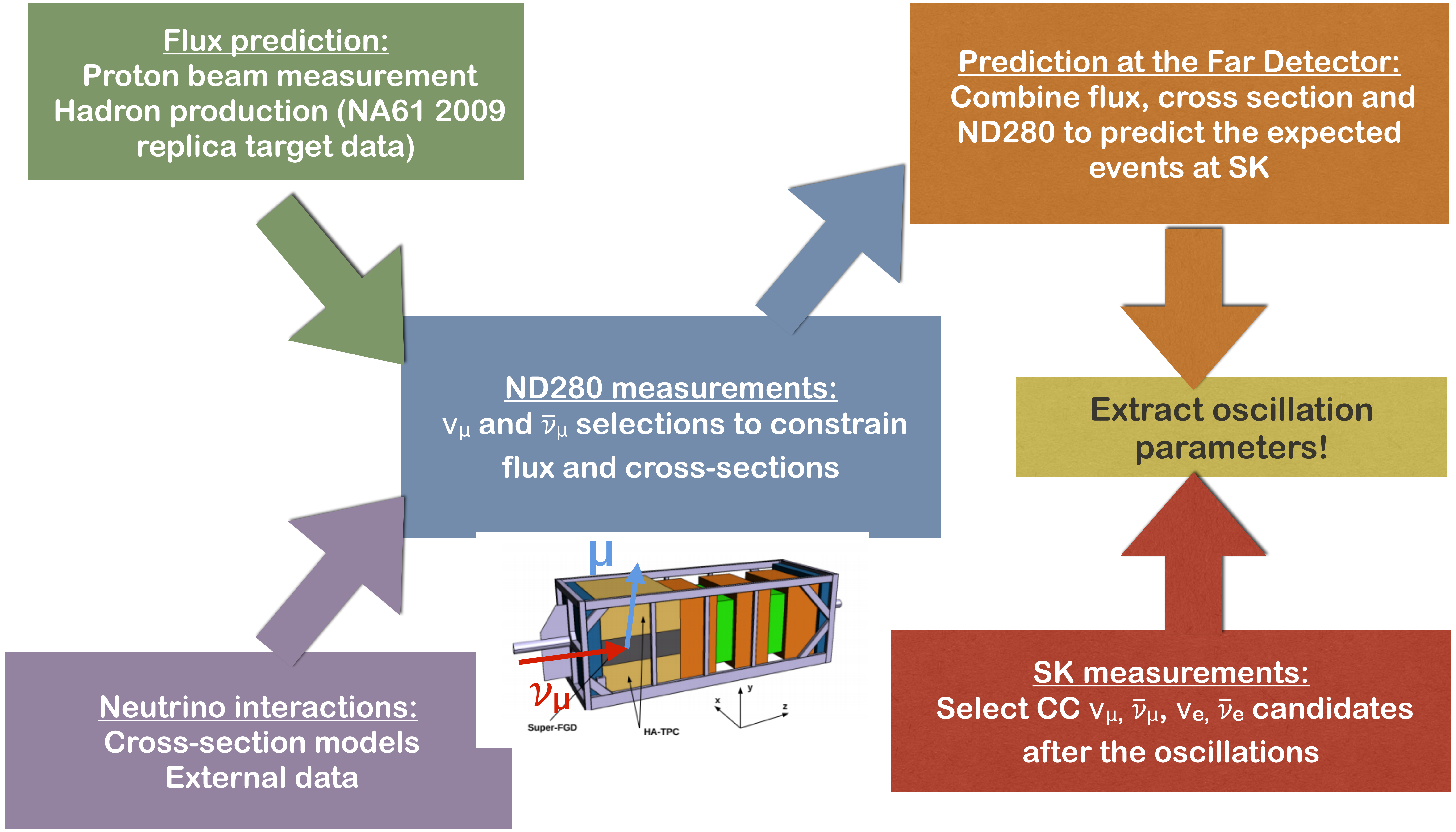


Steps towards oscillation analyses

T2K oscillation analysis



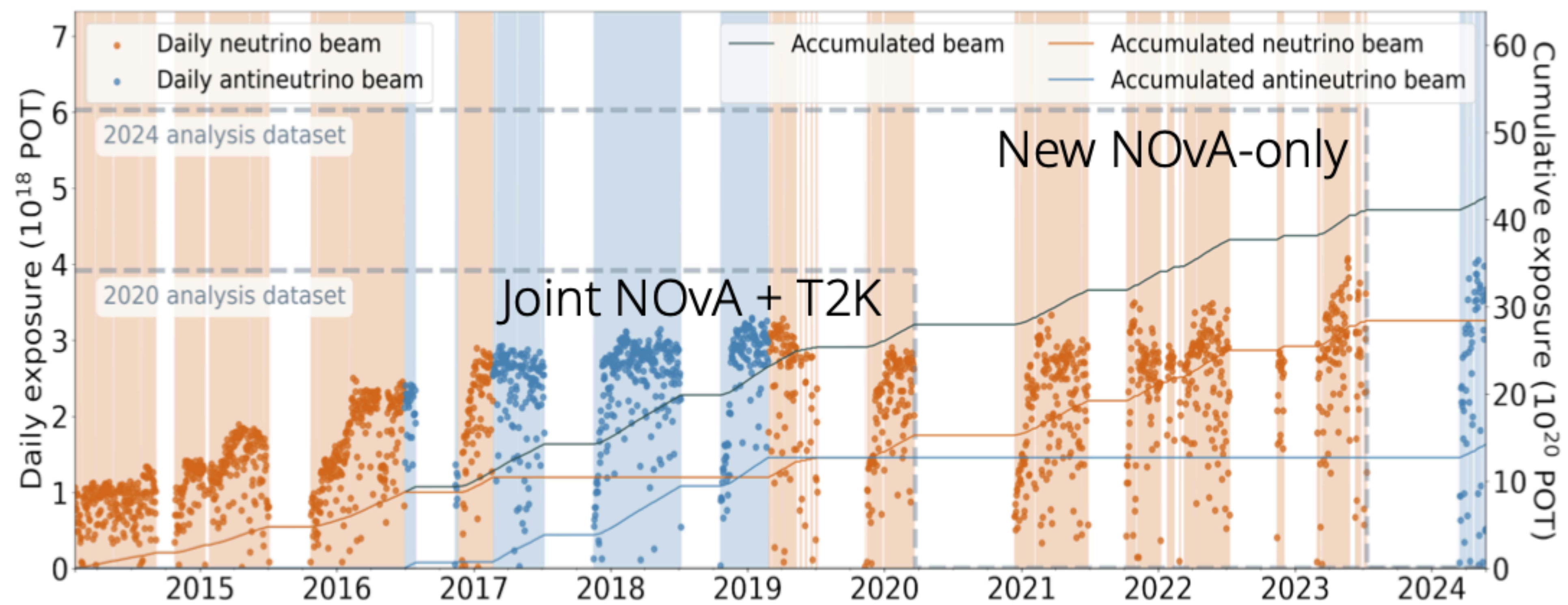


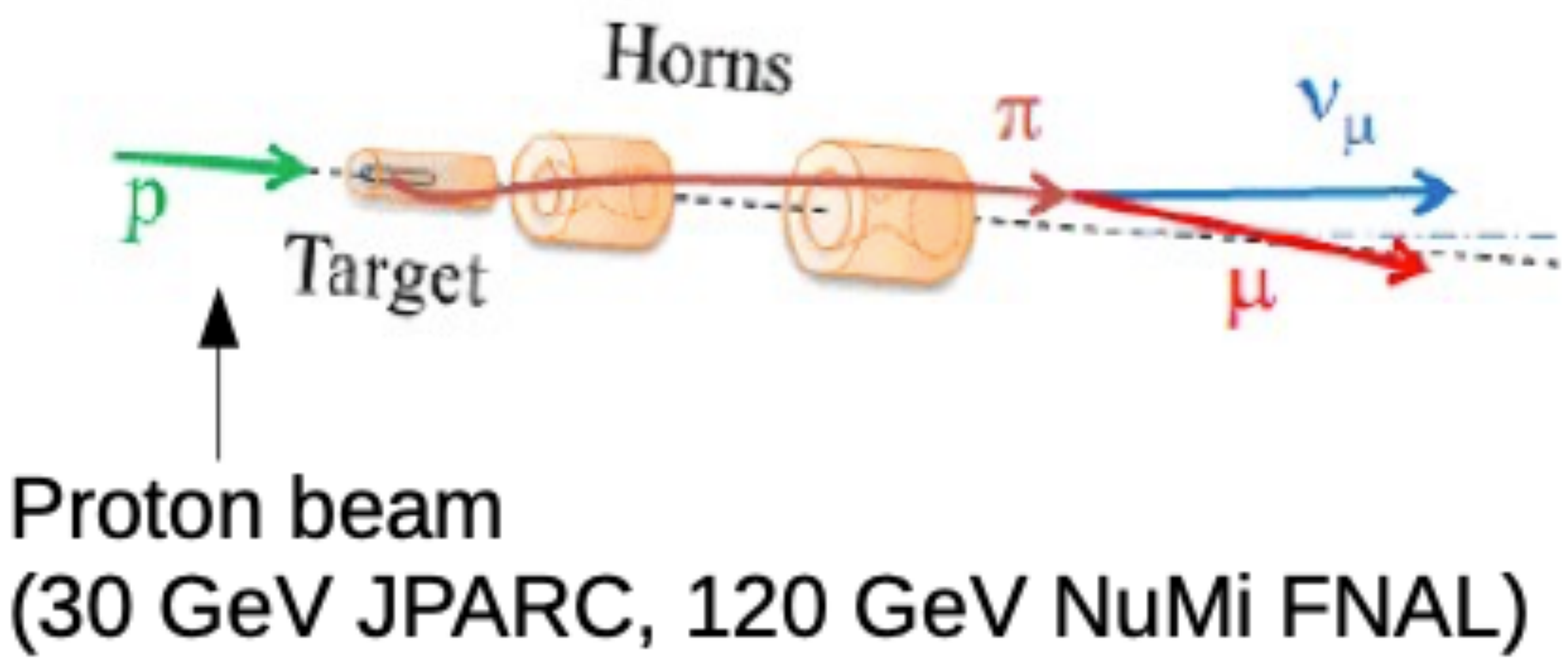


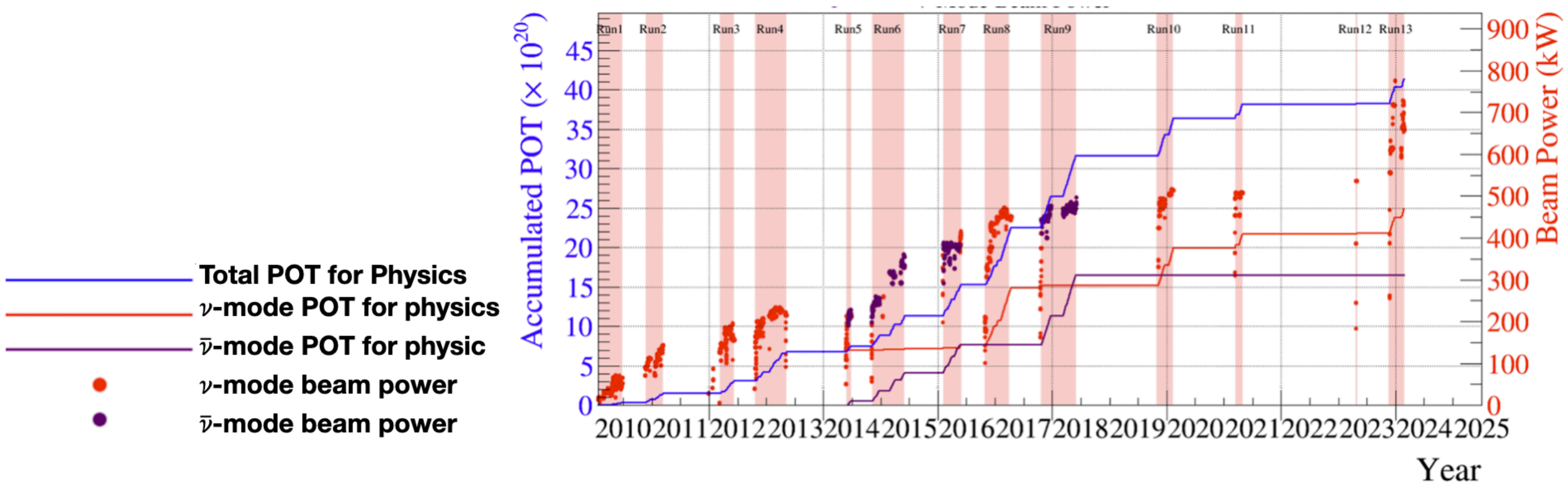
Neutrino beam

- In order to collect statistics we need to produce enough neutrinos
- The number of neutrinos is given by the beam power
- Not easy to increase → T2K took > 10y to go from 50 kW to 800 kW
- Hyper-K and DUNE plan to run at more than 1 MW!

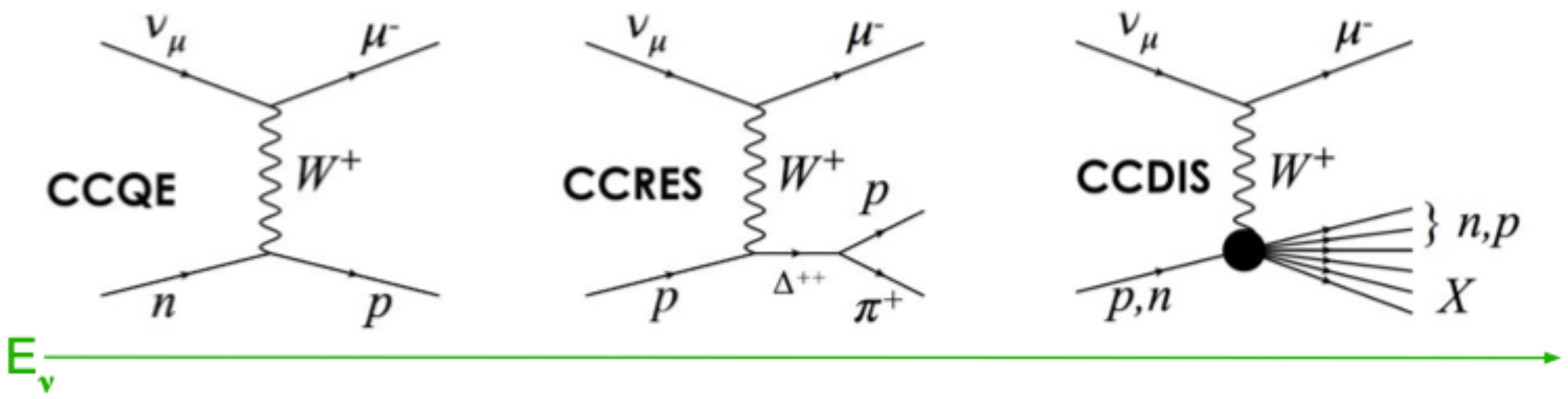
$$P(kW) \propto POT(10^{20}) \times E_p\ (GeV)/T\ (10^7 s)$$

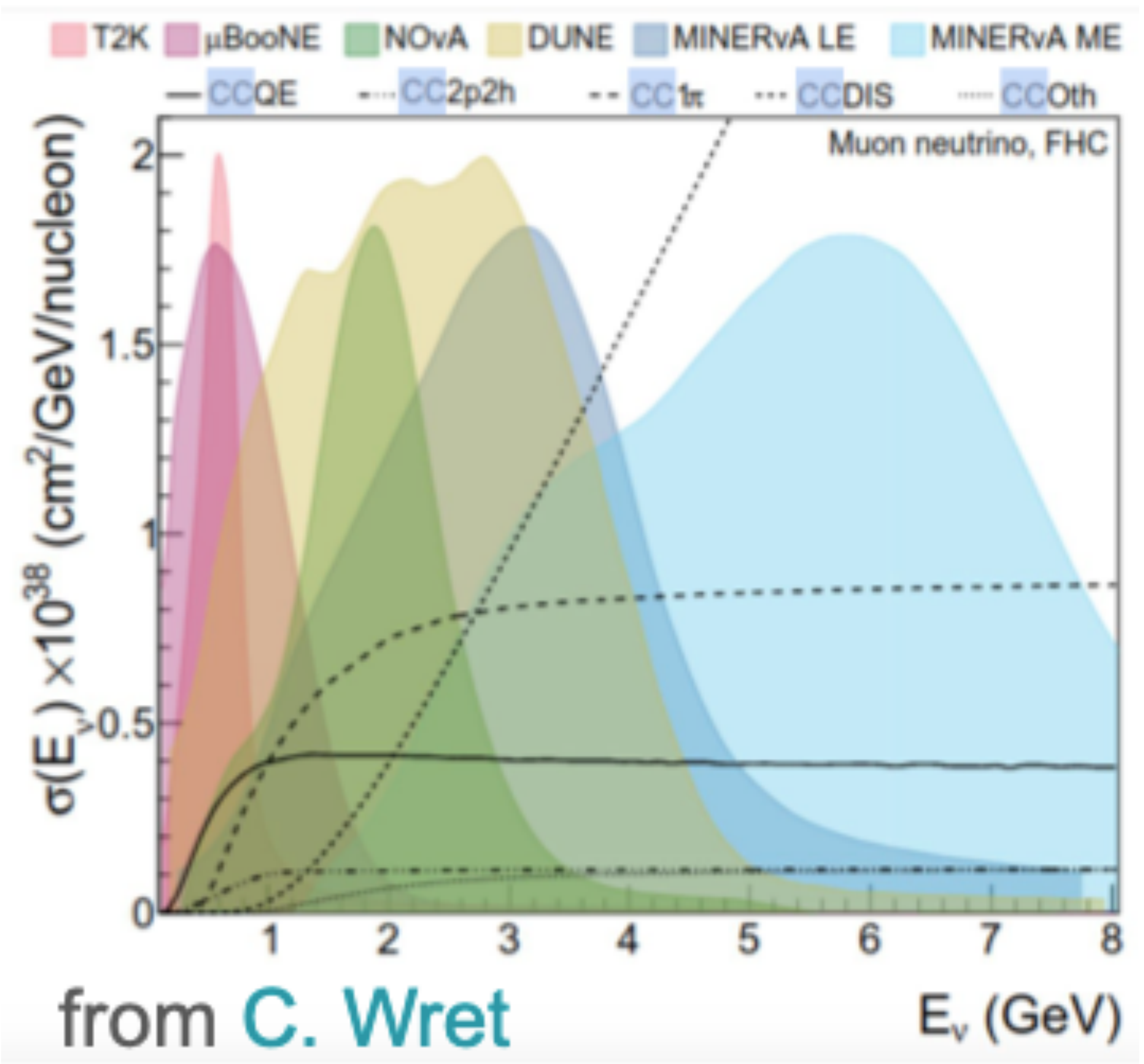




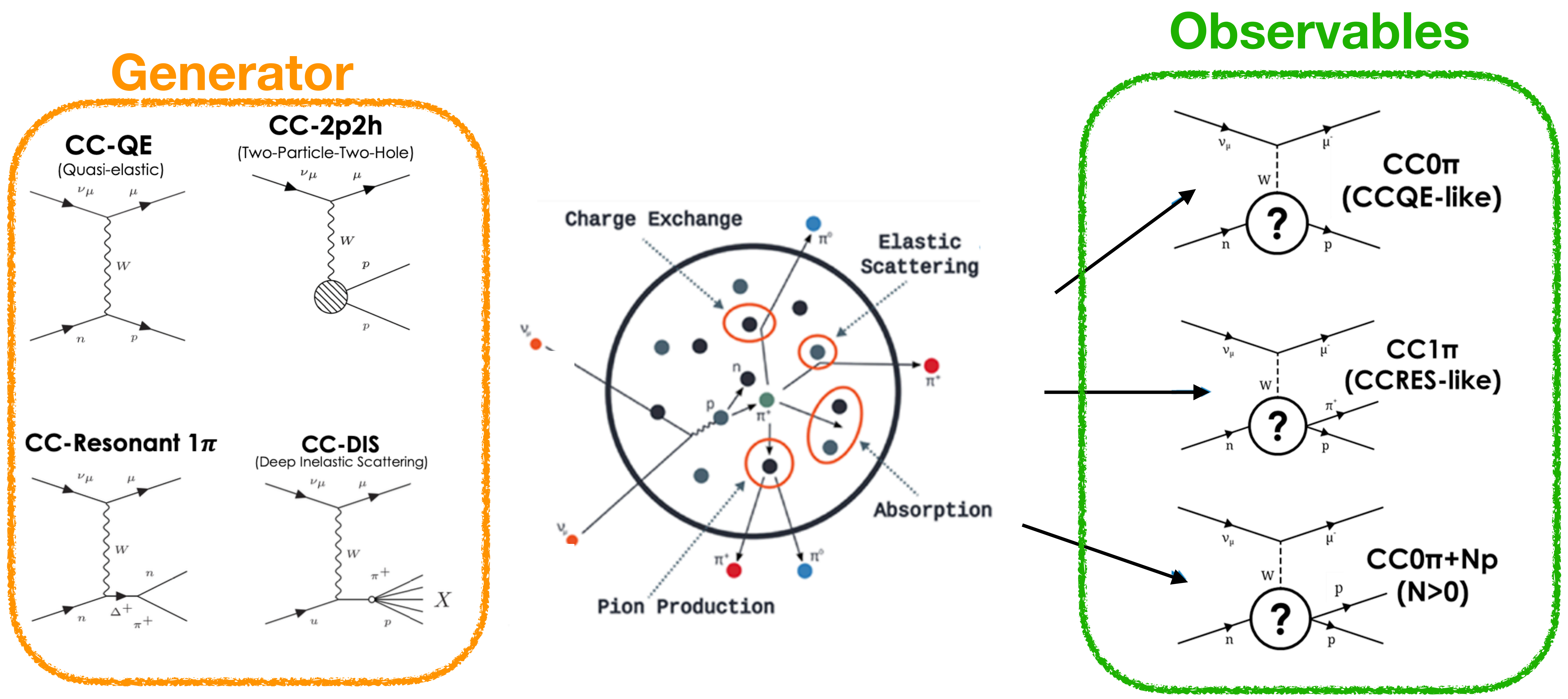


Neutrino cross-sections

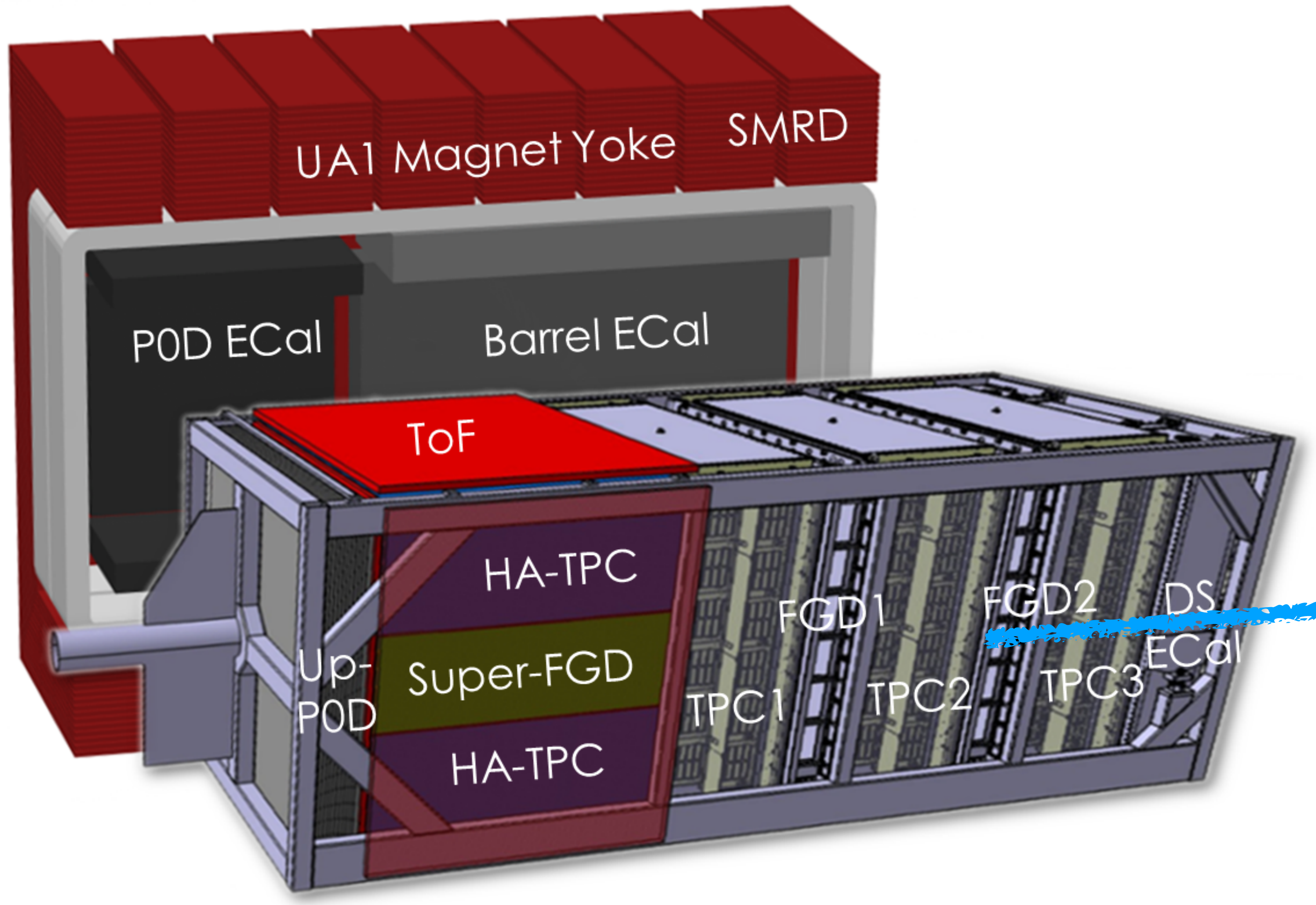


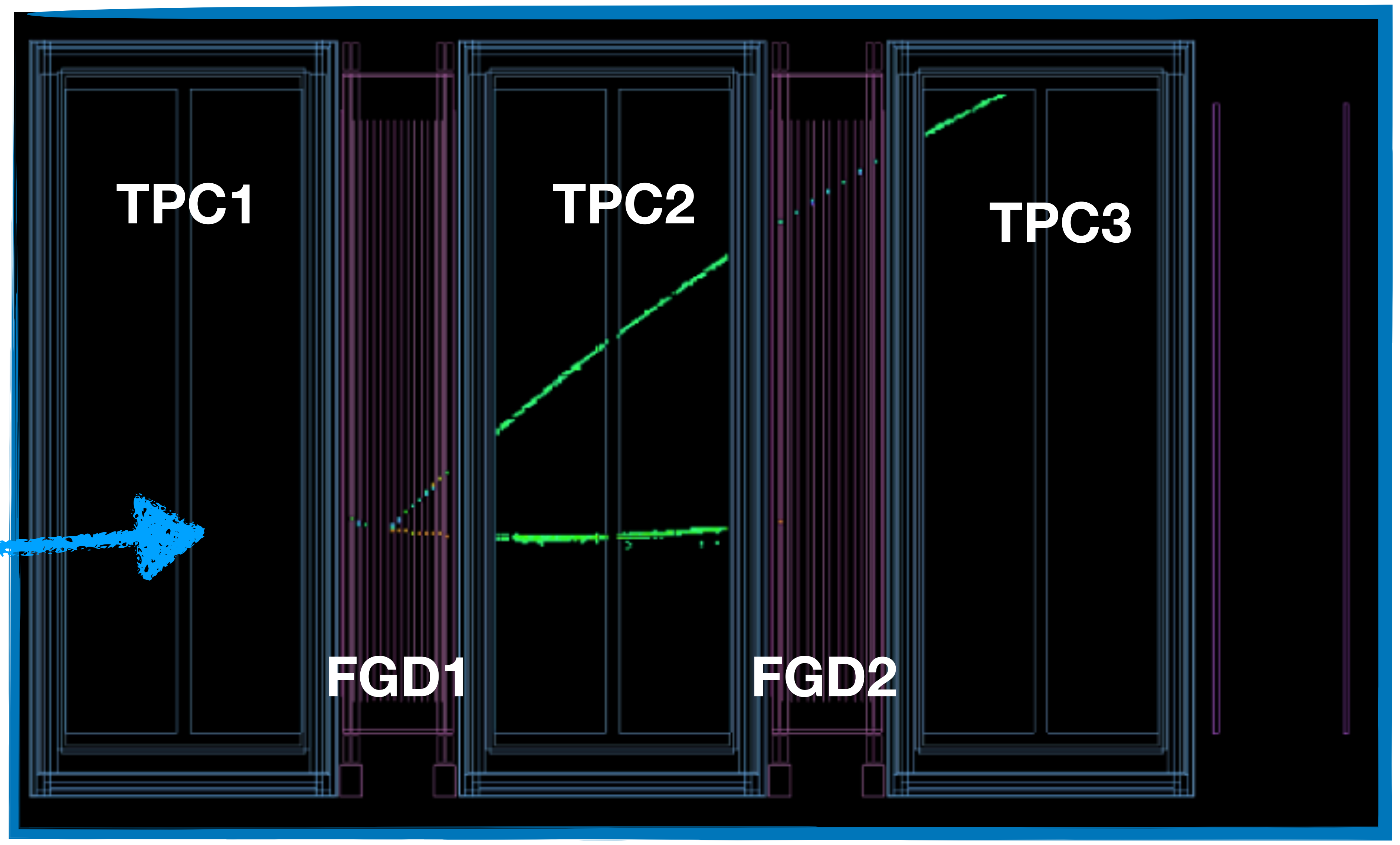


- Model for ν (and $\bar{\nu}$) cross-sections → each type of interaction has different models / processes
- Compare with what we observe in the detector → not the same, particle below thresholds, not reconstructed, not emitted from nuclei, …
- Work to try to unfold from observed topology to the underlying model!



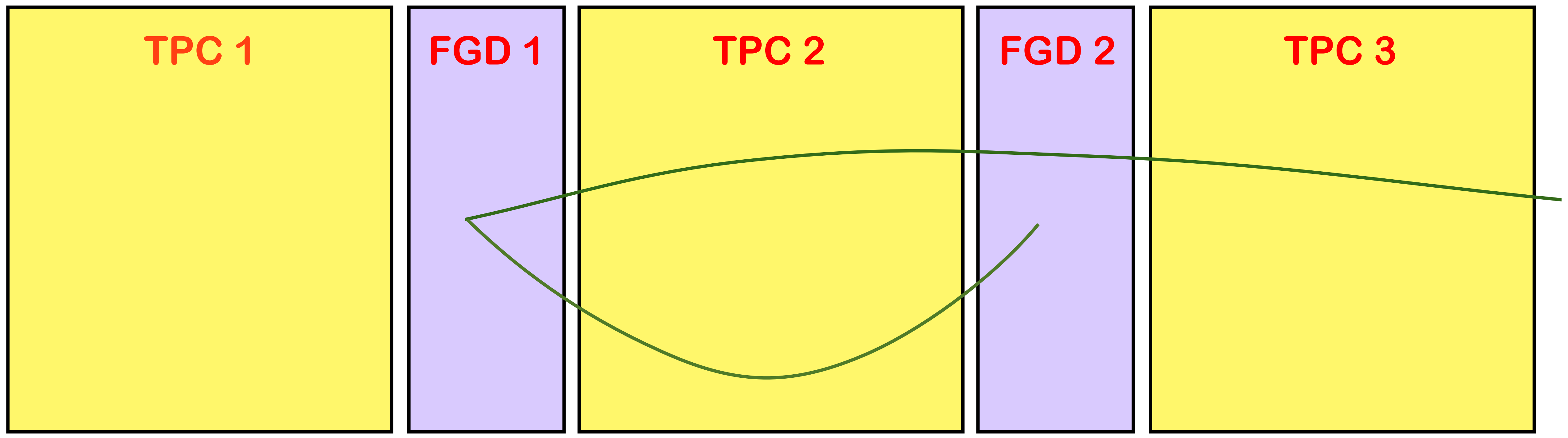
Off-axis ND280

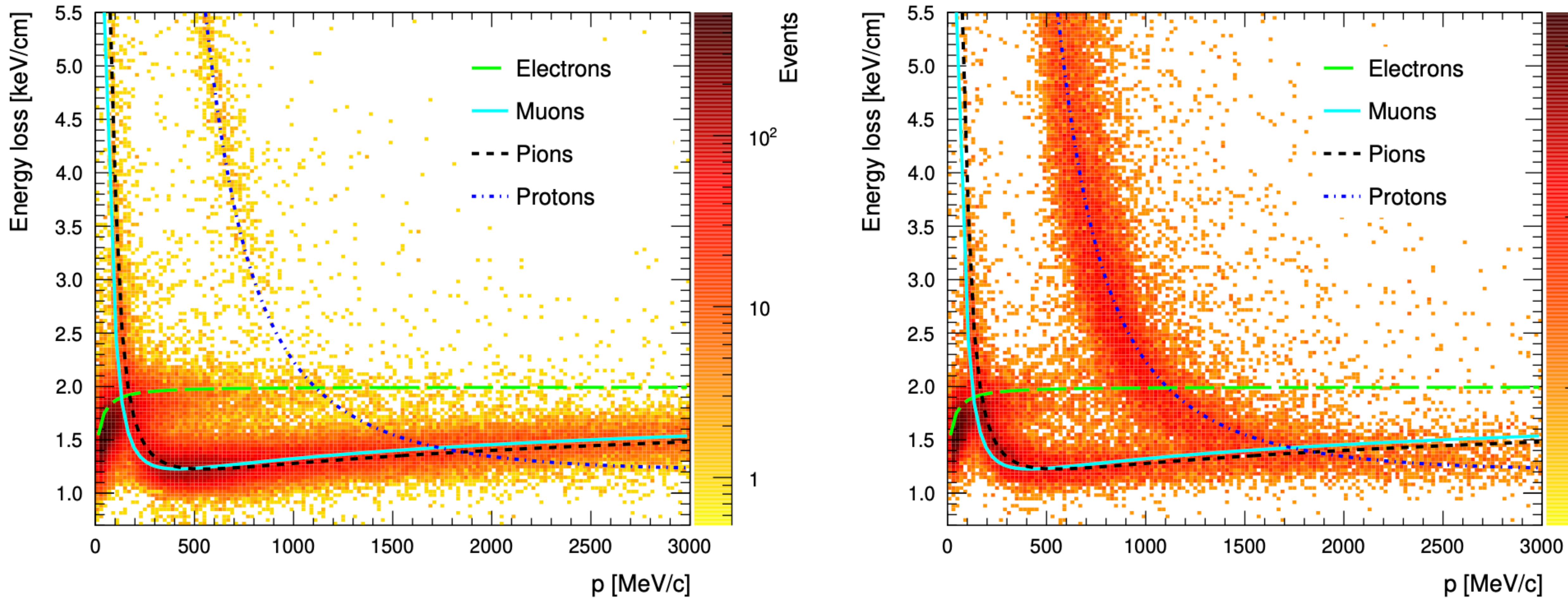




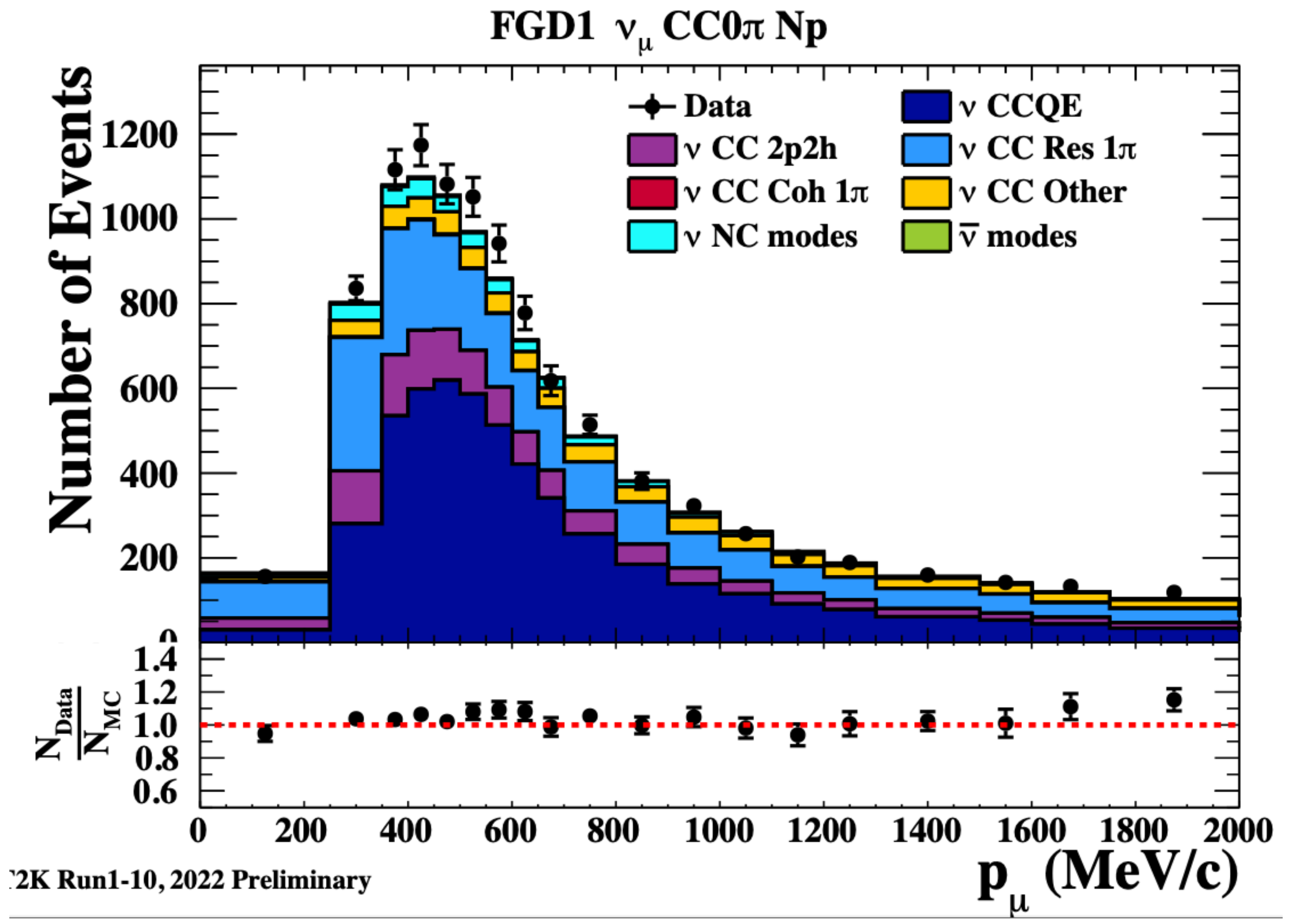
- Measure beam spectrum and flavor composition before the oscillations
- Detector installed inside the UA1/NOMAD magnet (0.2 T)
- An electromagnetic calorimeter to distinguish tracks from showers
- Upgraded in 2023 but for the analyses shown here the original tracker system is used:
  - 2 Fine Grained Detectors (target for ν interactions). FGD1 is pure scintillator, FGD2 has water layers interleaved with scintillator
  - 3 Time Projection Chambers: reconstruct momentum and charge of particles, PID based on measurement of ionization

ν_μ selections at ND280

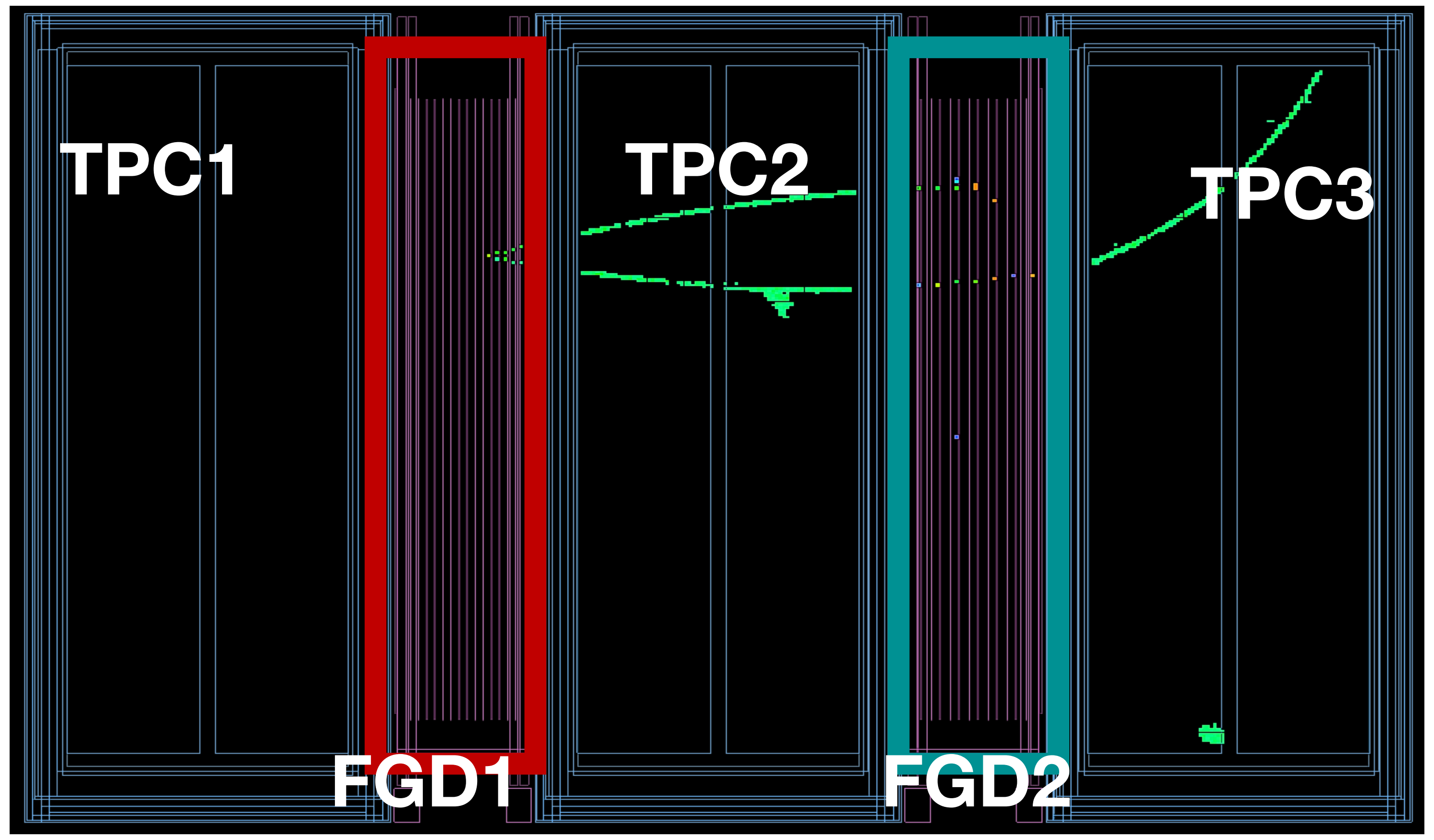




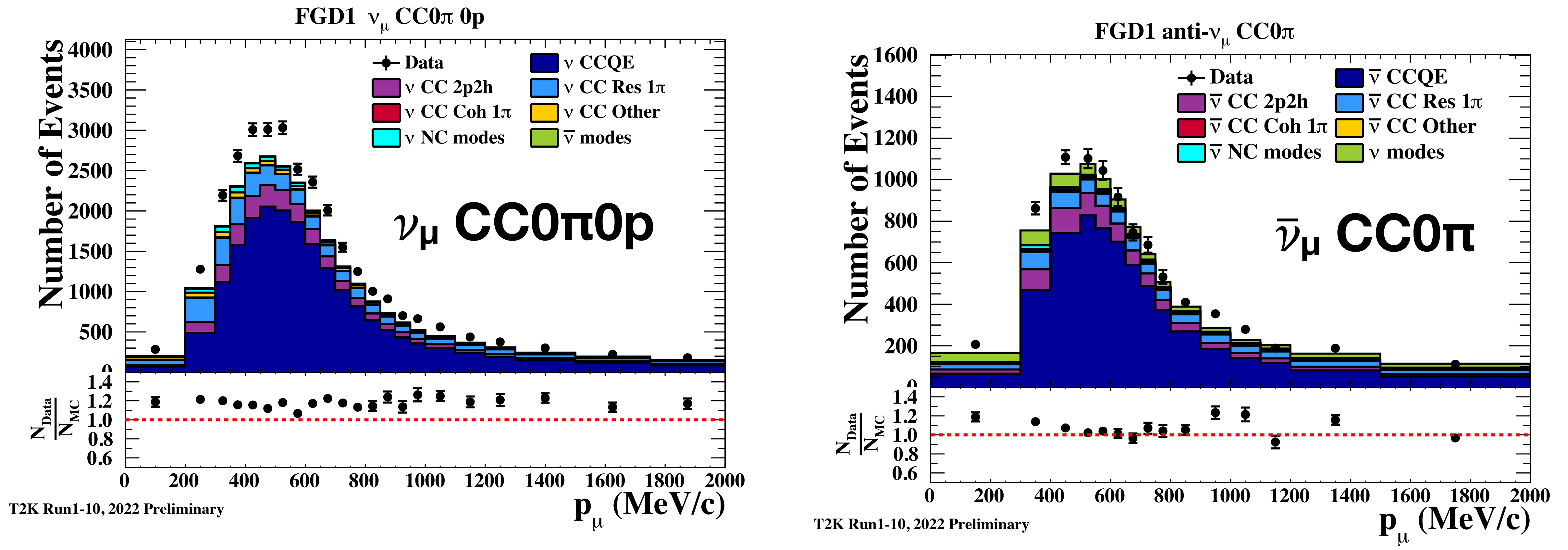
- ND280 is a magnetized detector
- Select neutrino and anti-neutrinos interactions by reconstructing muon charge
  - $\nu_\mu + n \rightarrow \mu^- + p$ while $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
- TPC PID (dE/dx vs P) is also used to select muons
- Reconstruct momentum and angle of the leptons in the TPCs

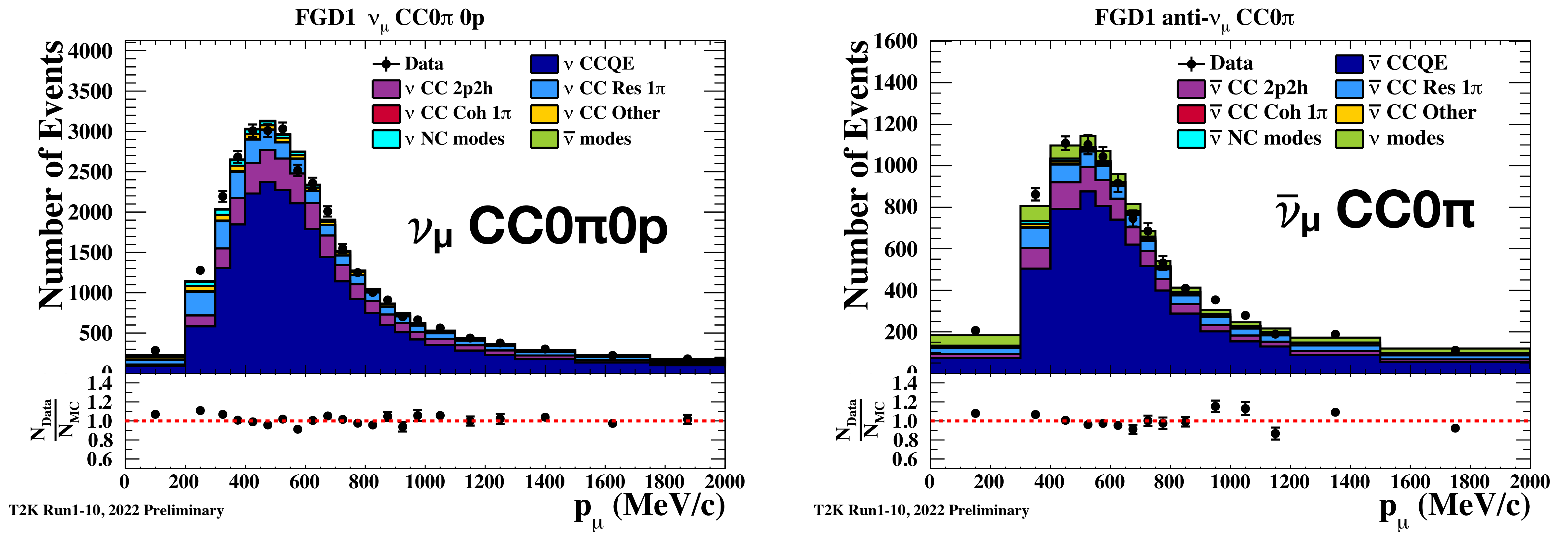


ND280 selections



Before the fit



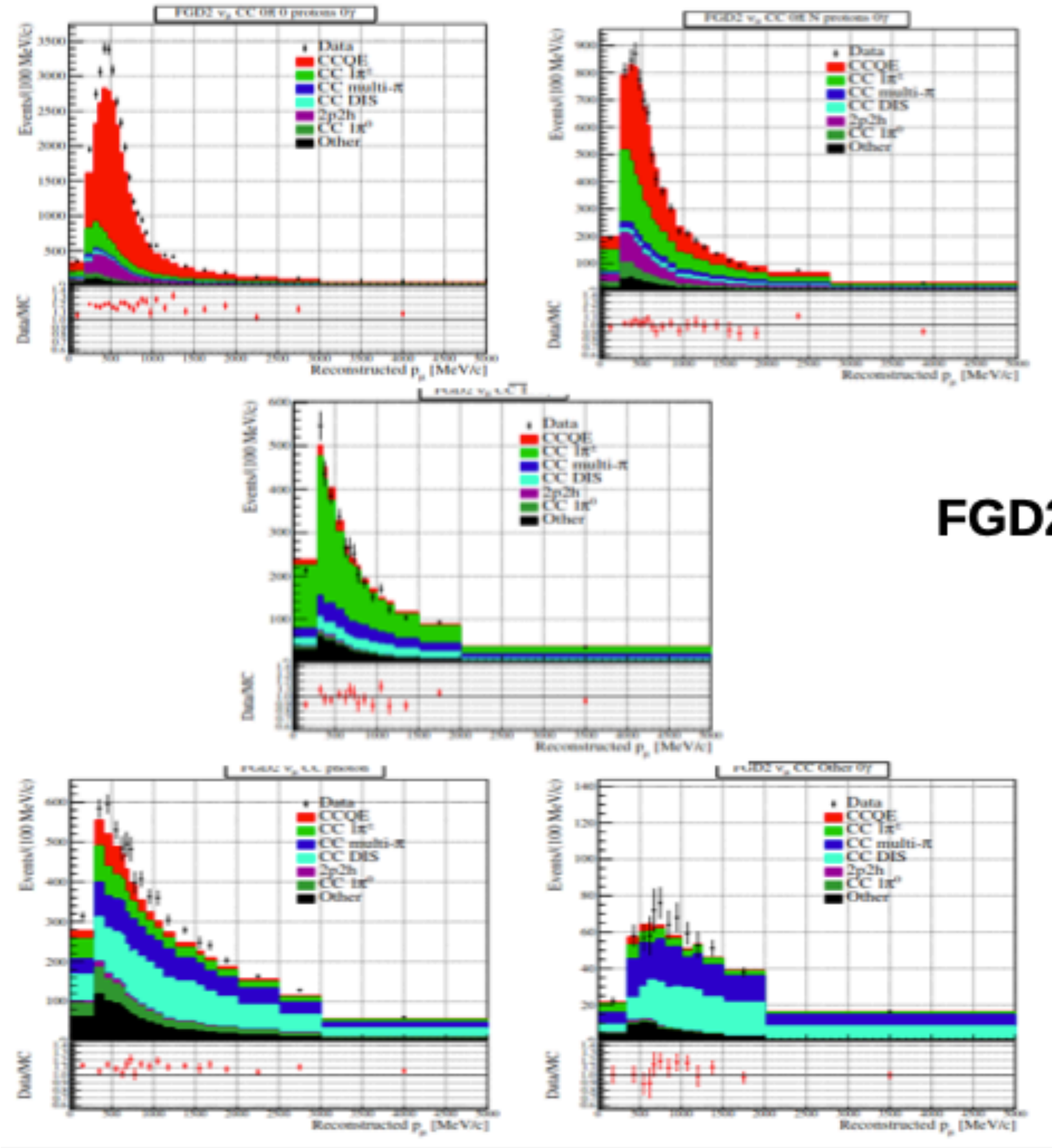


After the ND280 fit

Constraint flux and cross-section model

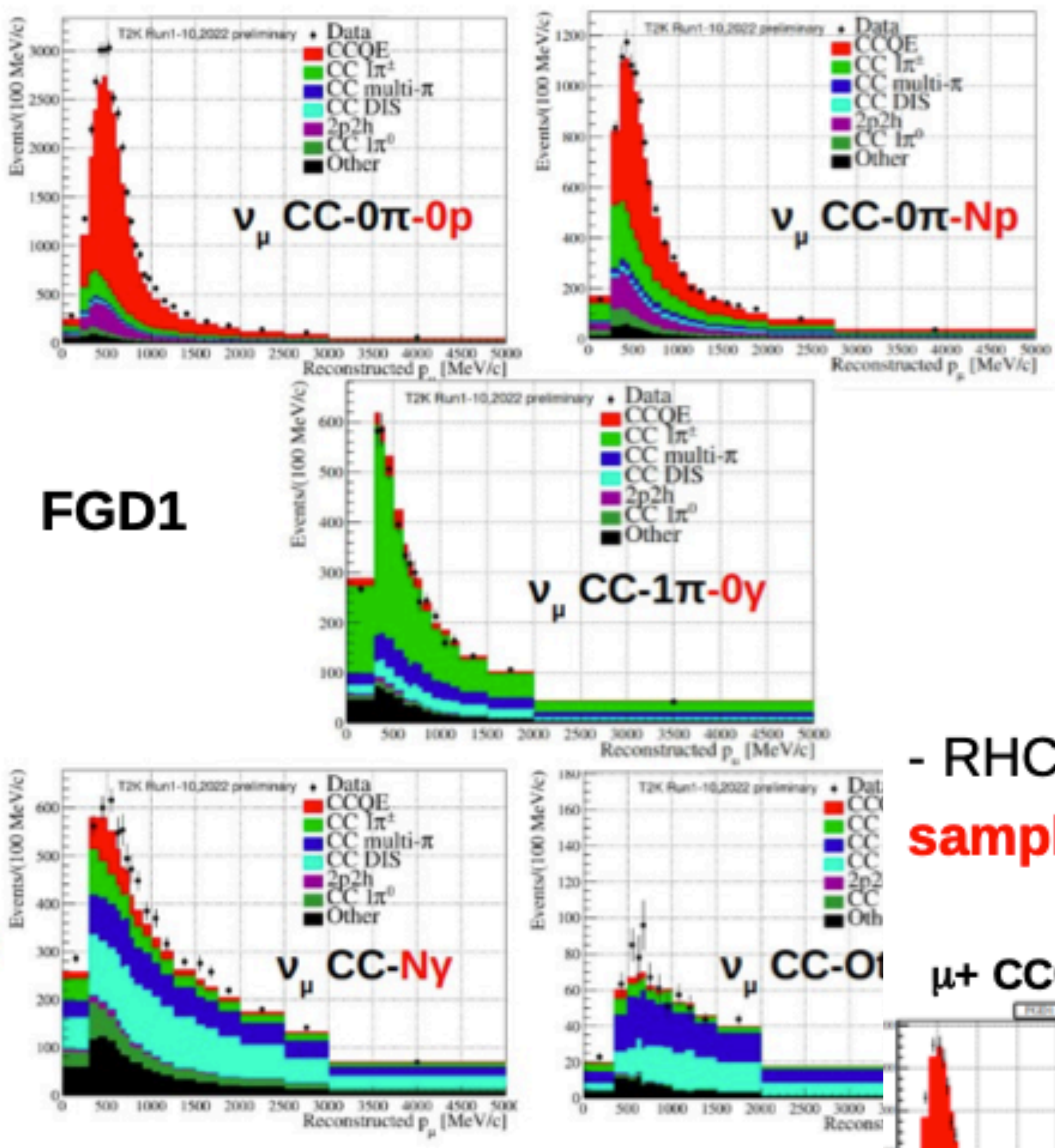
- ND280 magnetized detector
- Select interactions on CH (FGD1) and CH/Water (FGD2)
- Precise measurement of P_μ and θ_μ with the TPCs
- Distinguish ν from $\bar{\nu}$ interactions thanks to the reconstruction of the charge of the lepton
- Separate samples based on number of reconstructed pions (CC0π, CC1π, CCNπ), protons, photons, etc → 22 samples in total are used in the fit

ND280 samples



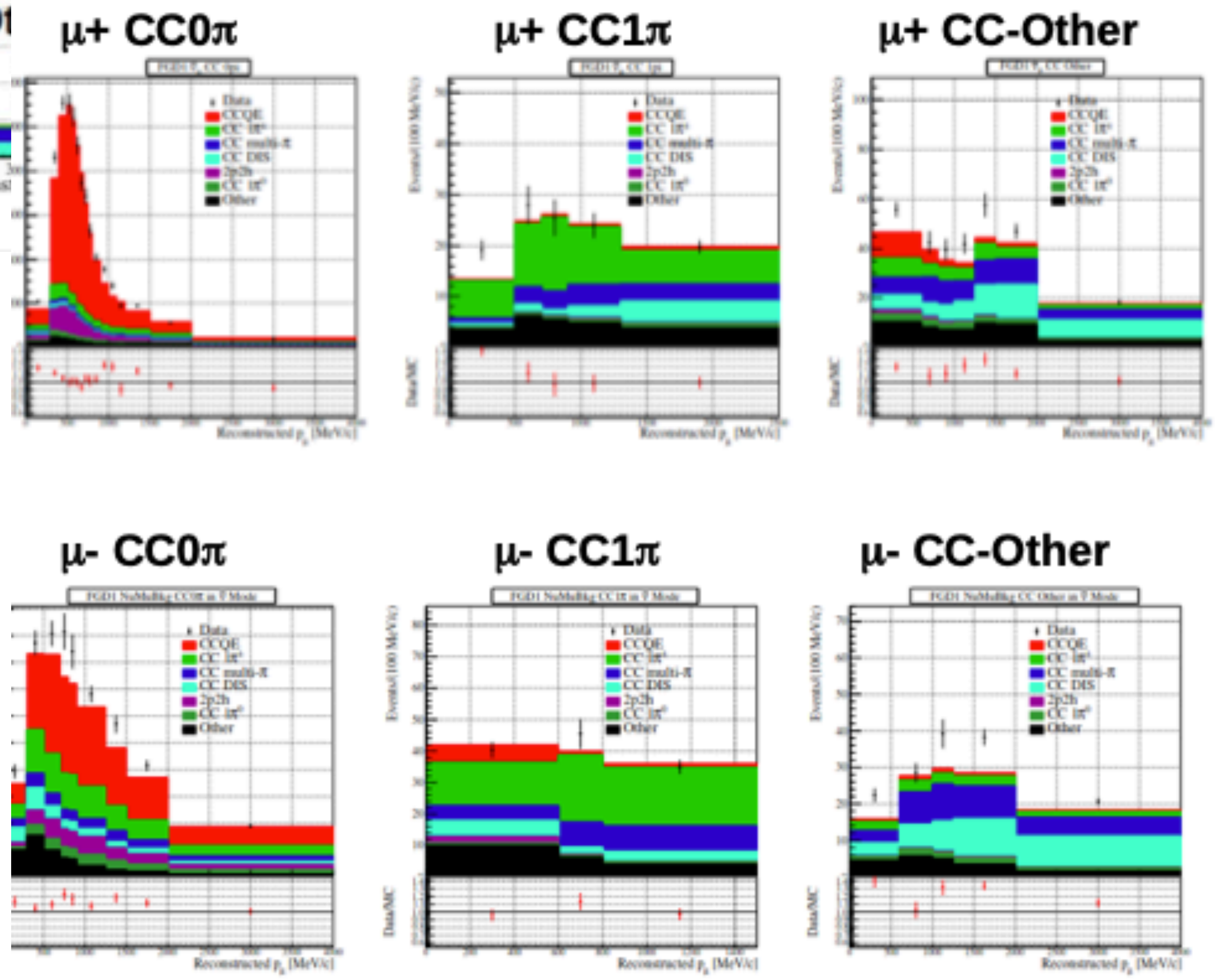
FGD2

FGD1

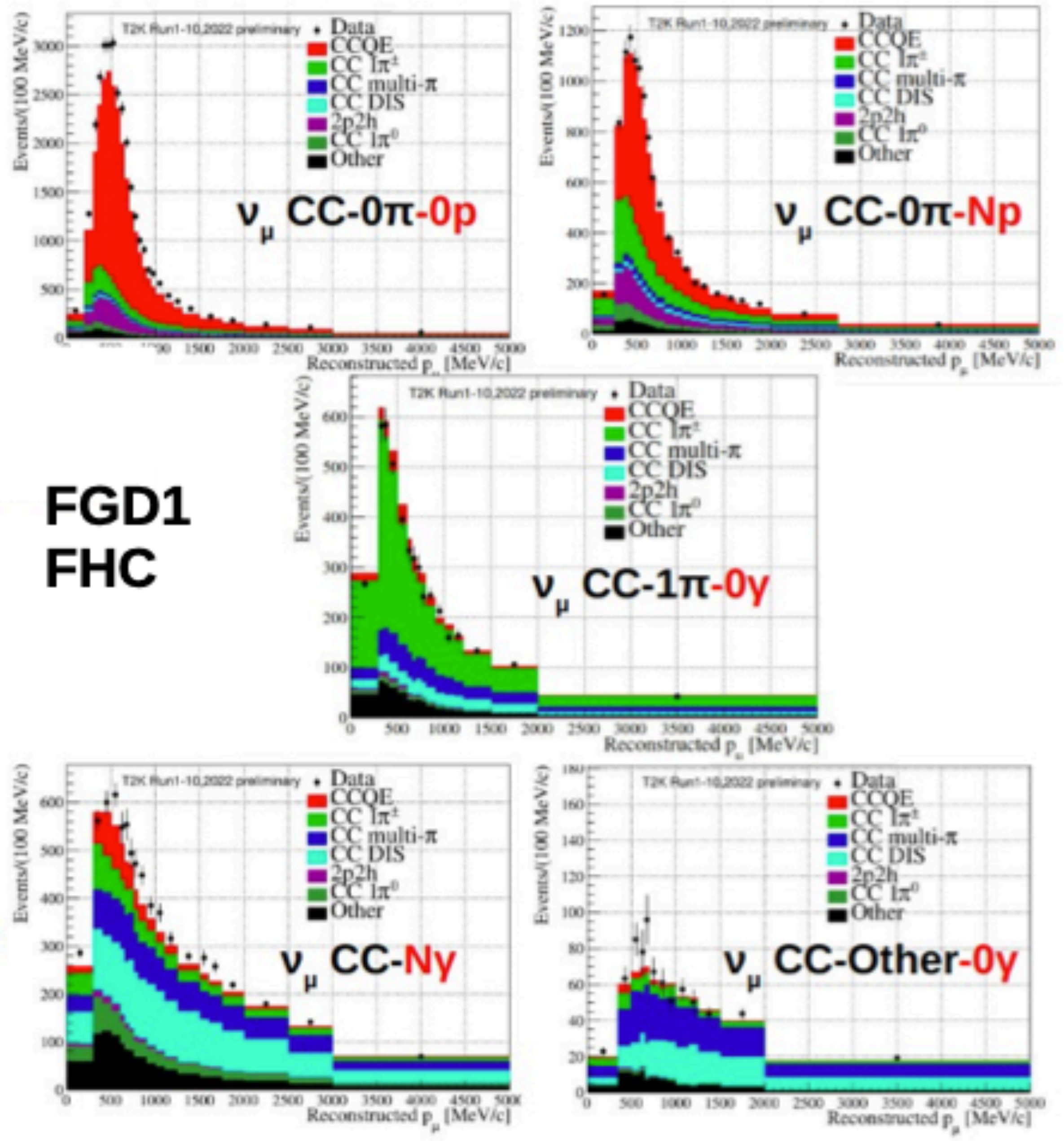


- RHC mode: μ+ ($\bar{\nu}_\mu$) and μ- (ν_μ) separate samples

FGD1 RHC



FGD1 FHC



Oscillation analyses

$$R_{ND} = \int \phi_\nu(E_\nu)^{ND} \frac{d\sigma_\nu}{dE_\nu} dE_\nu$$

$$R_{FD} = \int \phi_\nu(E_\nu)^{FD} P_{osc}^{\nu \to \nu'}(E_\nu) \frac{d\sigma_\nu}{dE_\nu} dE_\nu$$

$$\phi^{FD} \sim \phi^{ND}/L^2$$

FD has to be much larger than the ND
to compensate for the reduction in the flux!

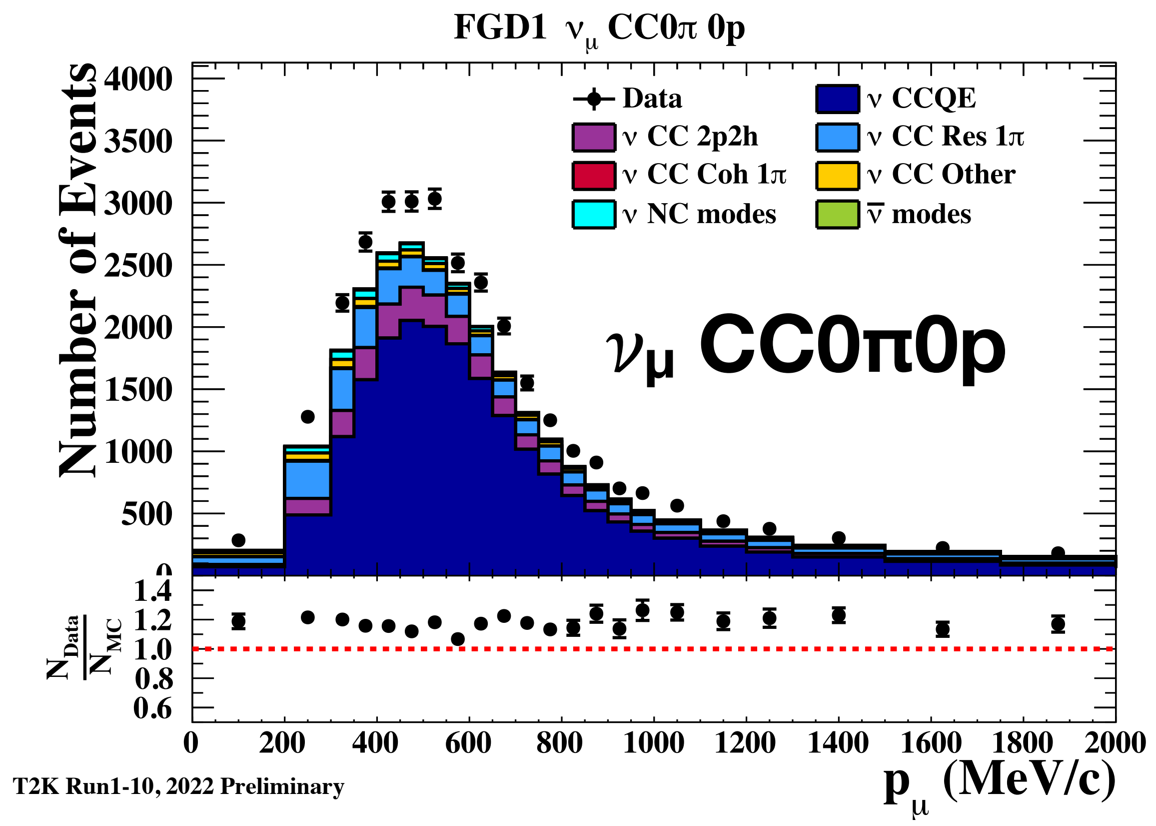
ND280 ~ 2 ton active mass
SK ~ 50 kton of active mass

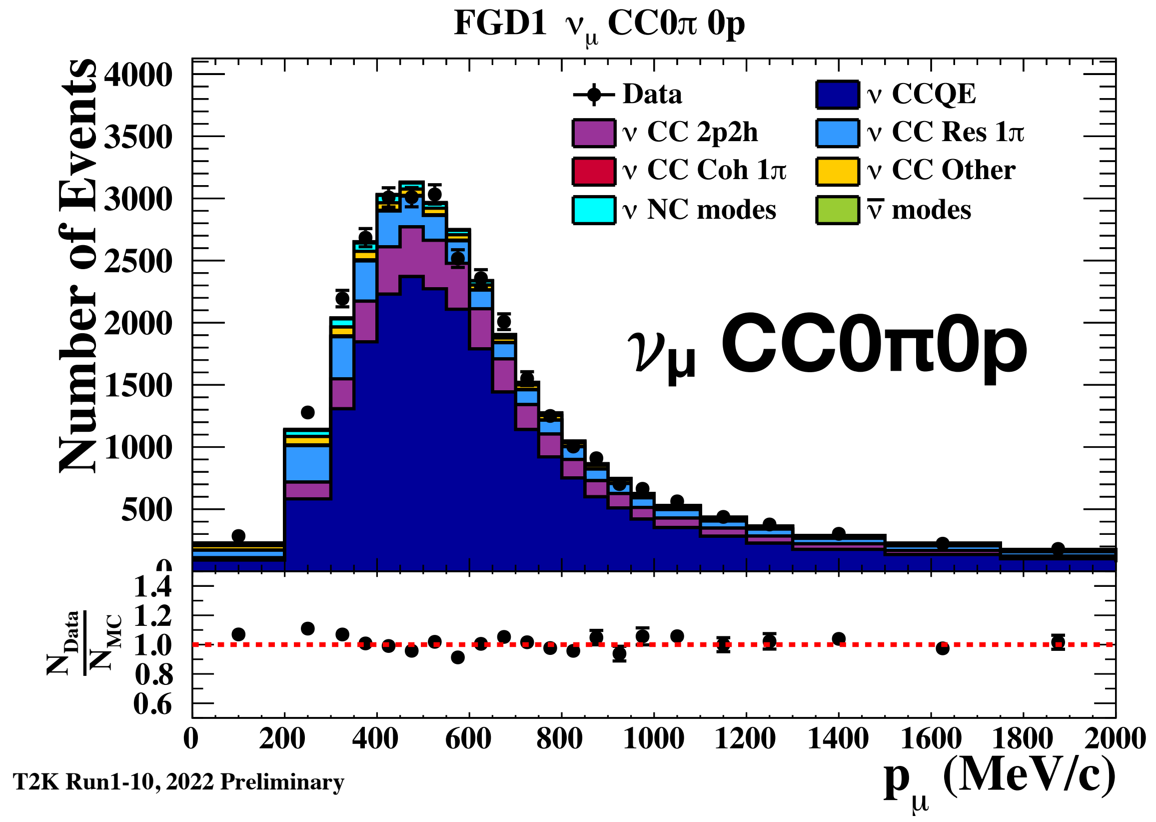
$$R_{ND} = \phi_\nu(E_\nu) \frac{d\sigma_\nu}{dE_\nu} dE_\nu = F(p_\mu, \cos\theta_\mu; \alpha_{ND}, \alpha_{model})$$

p_μ, θ_μ are the observables at the Near Detector
α_{ND} are the syst. uncertainties on the detector
α_{model} are the syst. uncertainties on flux and x-sec

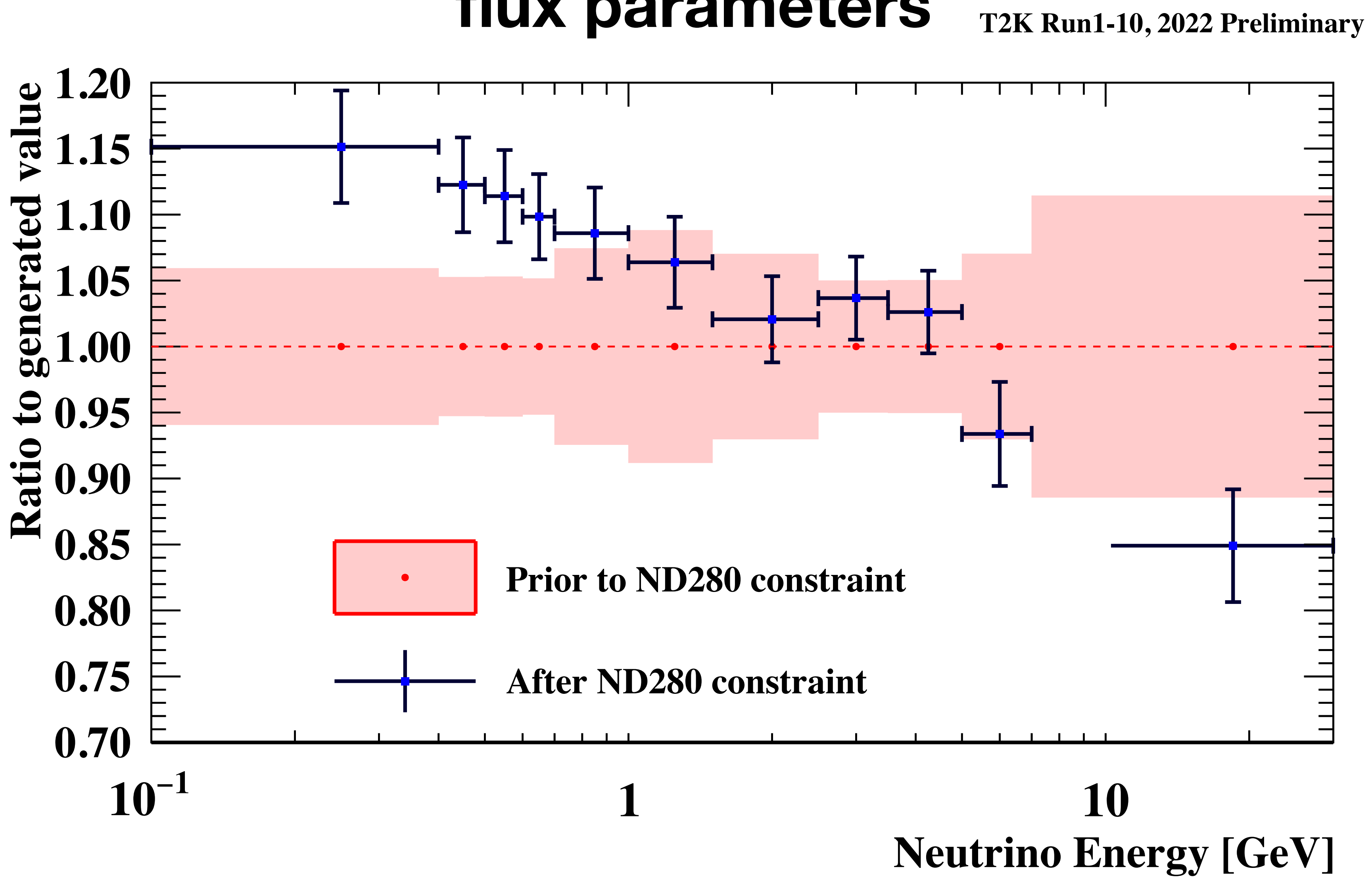
Distributions are the far detector are fitted with the model obtained by ND fit + P_{osc} **to extract the oscillation parametres**

ND280 fit

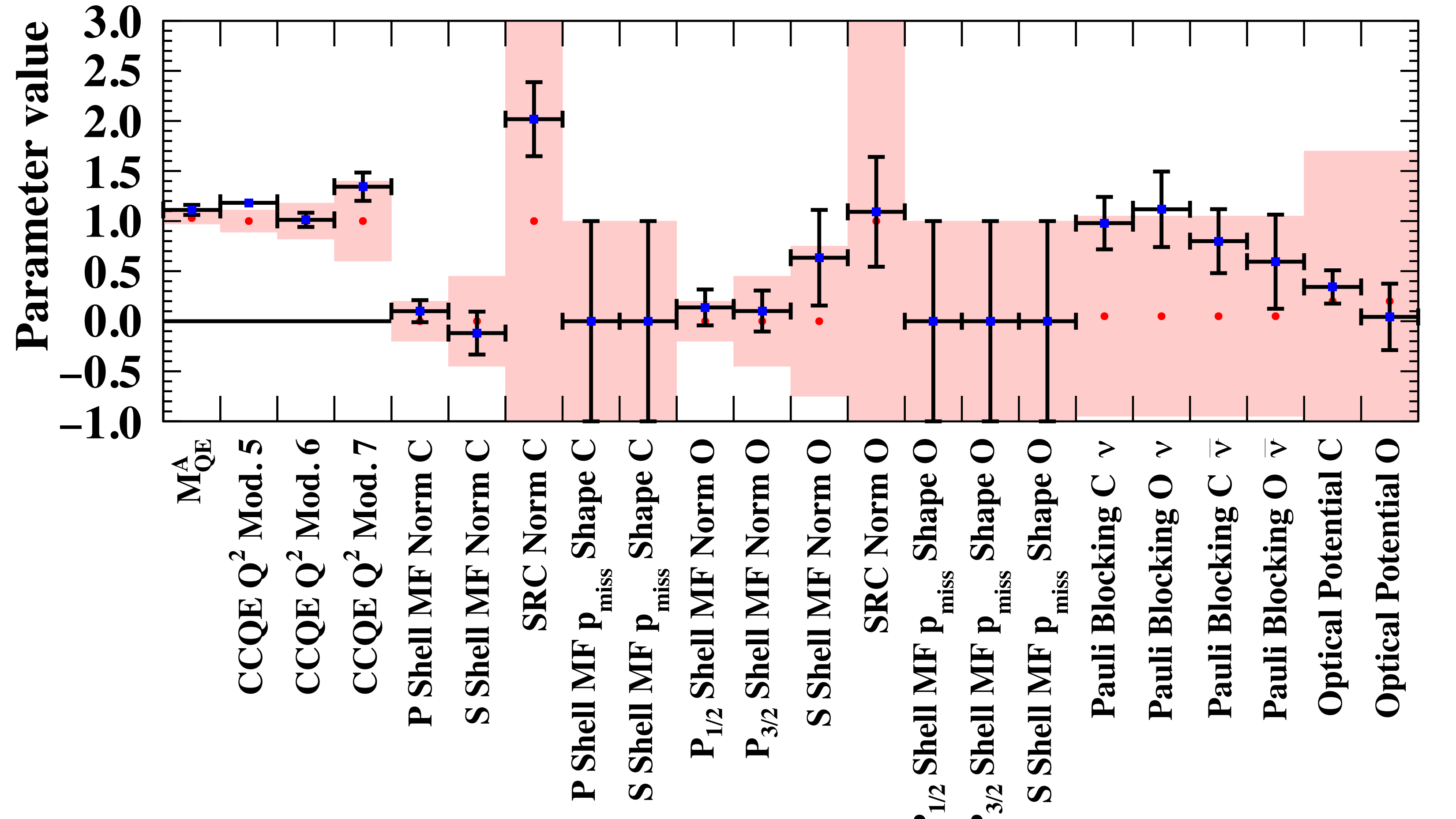


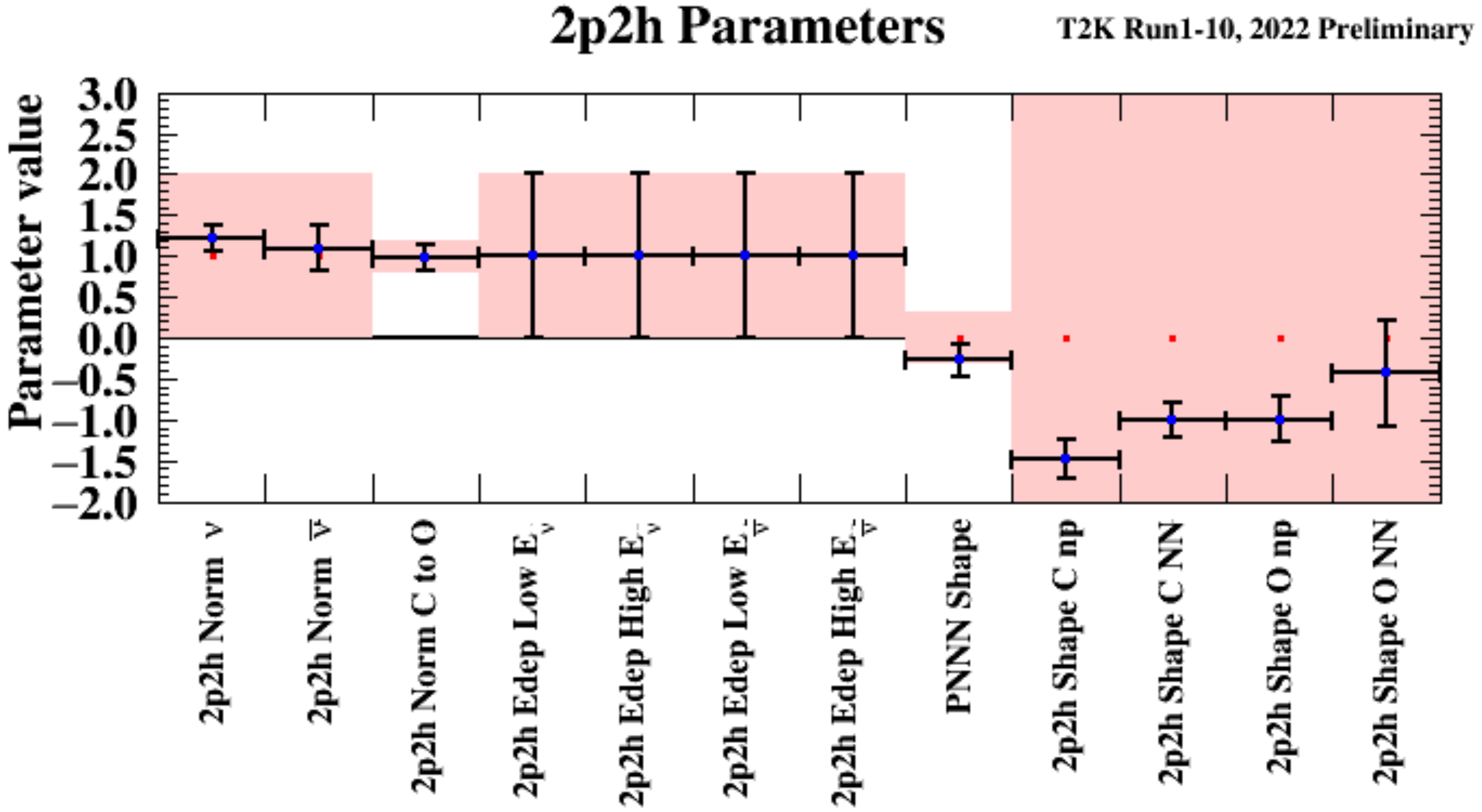


ND280 ν-mode flux parameters



CCQE x-sec parameters





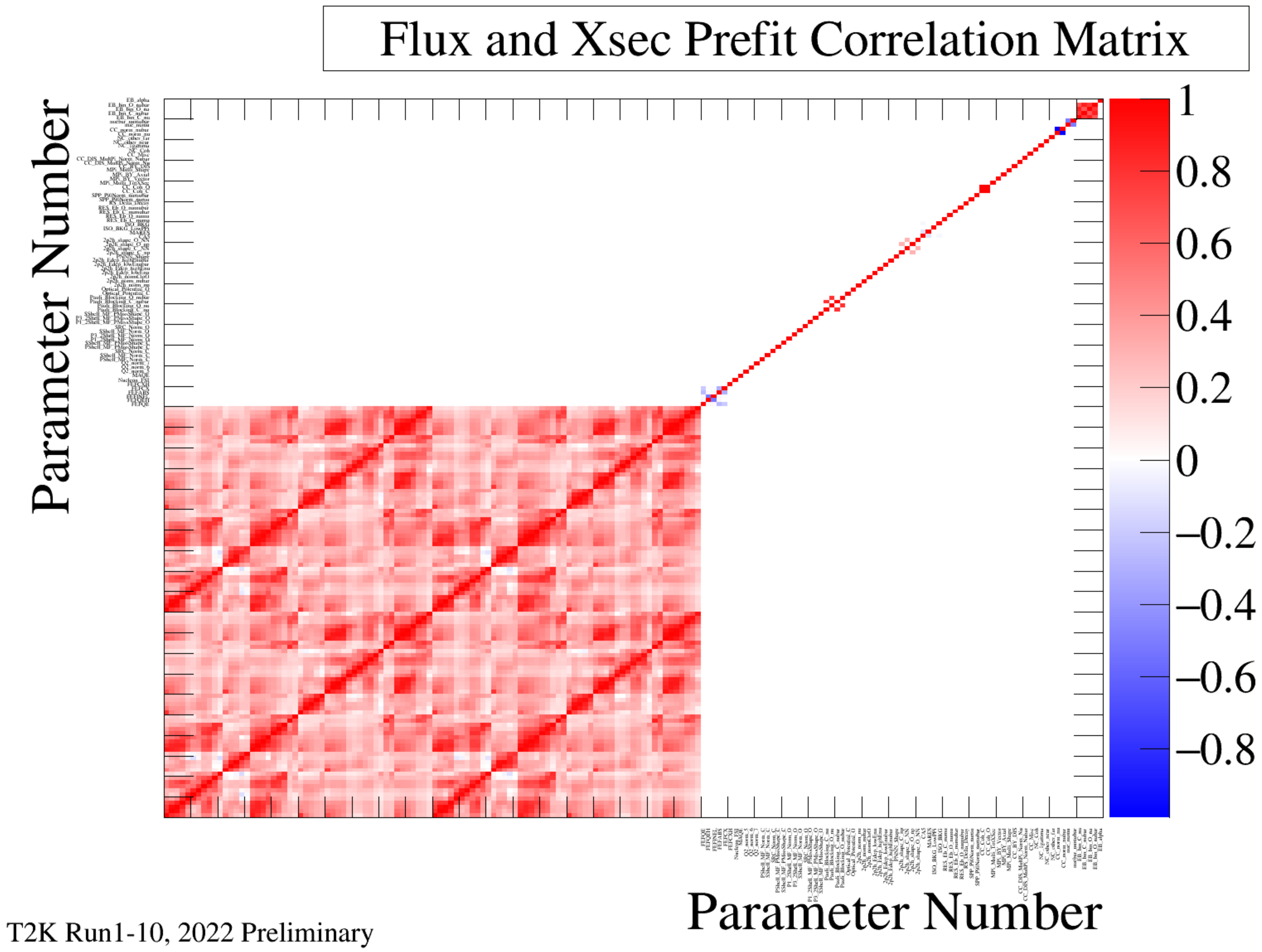
More events than predicted → increase flux parameters

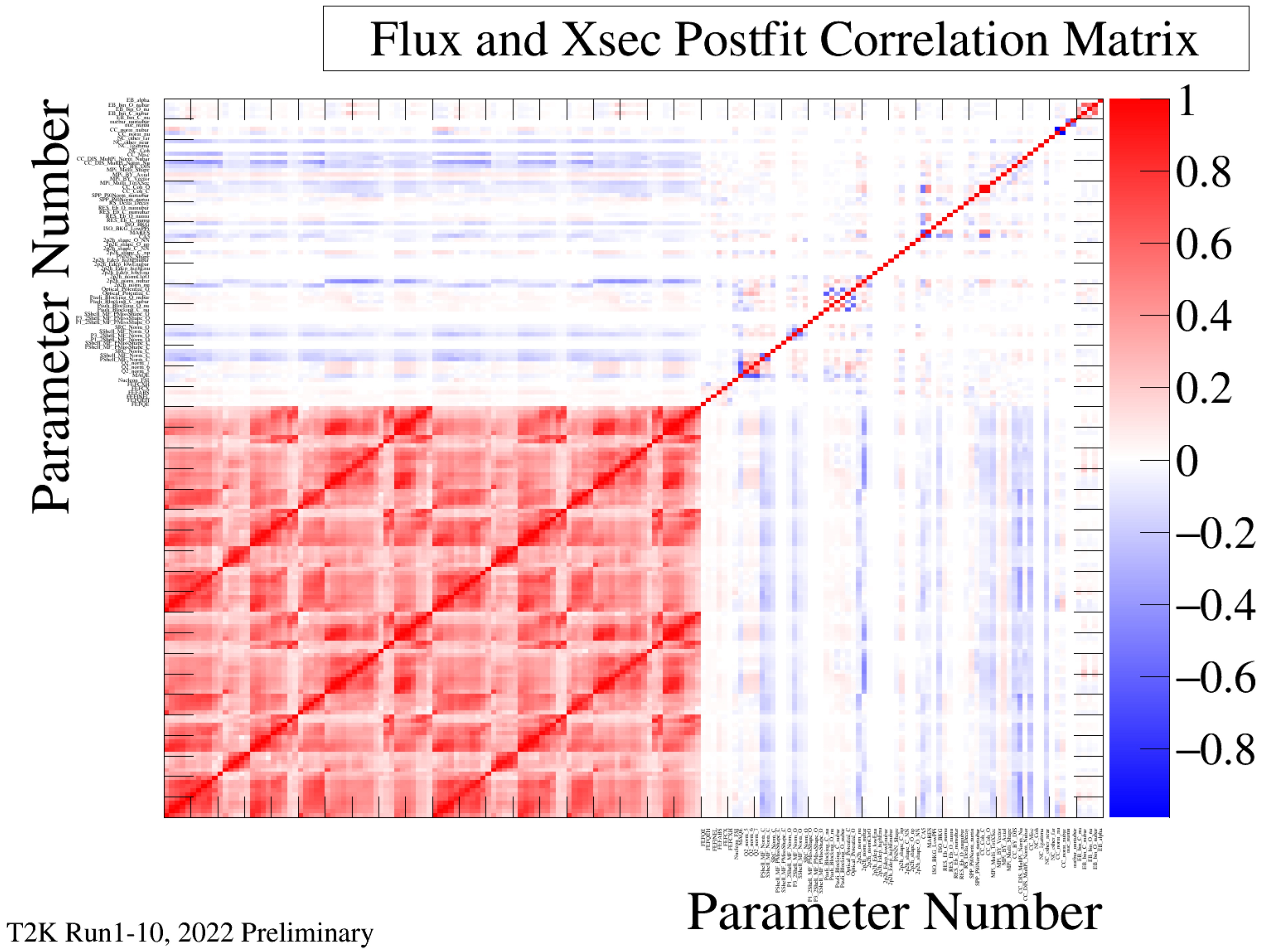
Changes also for the cross-sectic parameters → correlated betweer flux and cross-section

Flux - cross-section correlation

- Anti-correlation between flux and cross-section parameters

$$N_{ND} = \phi_\nu \cdot \sigma_\nu \cdot \epsilon_{ND}$$

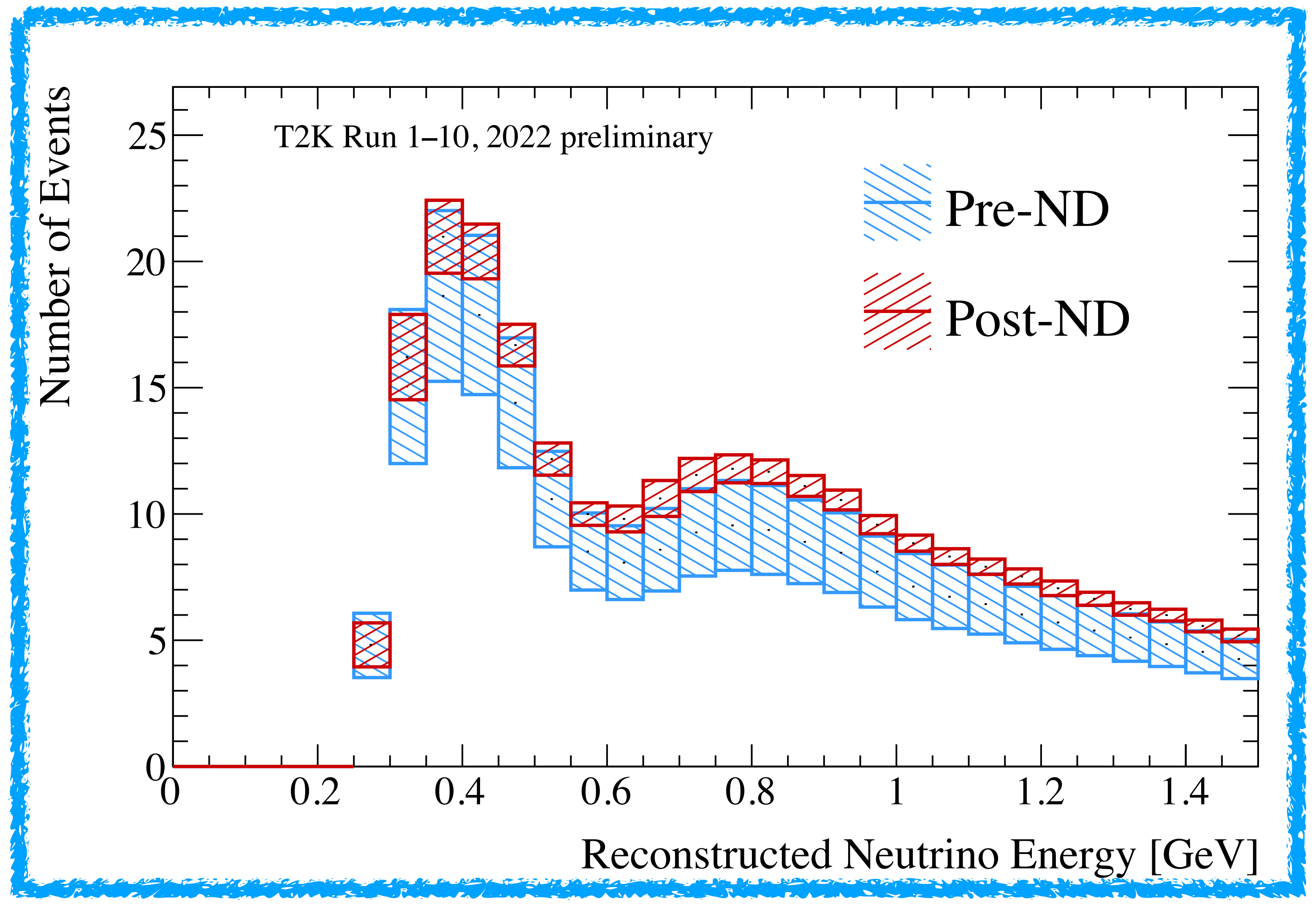




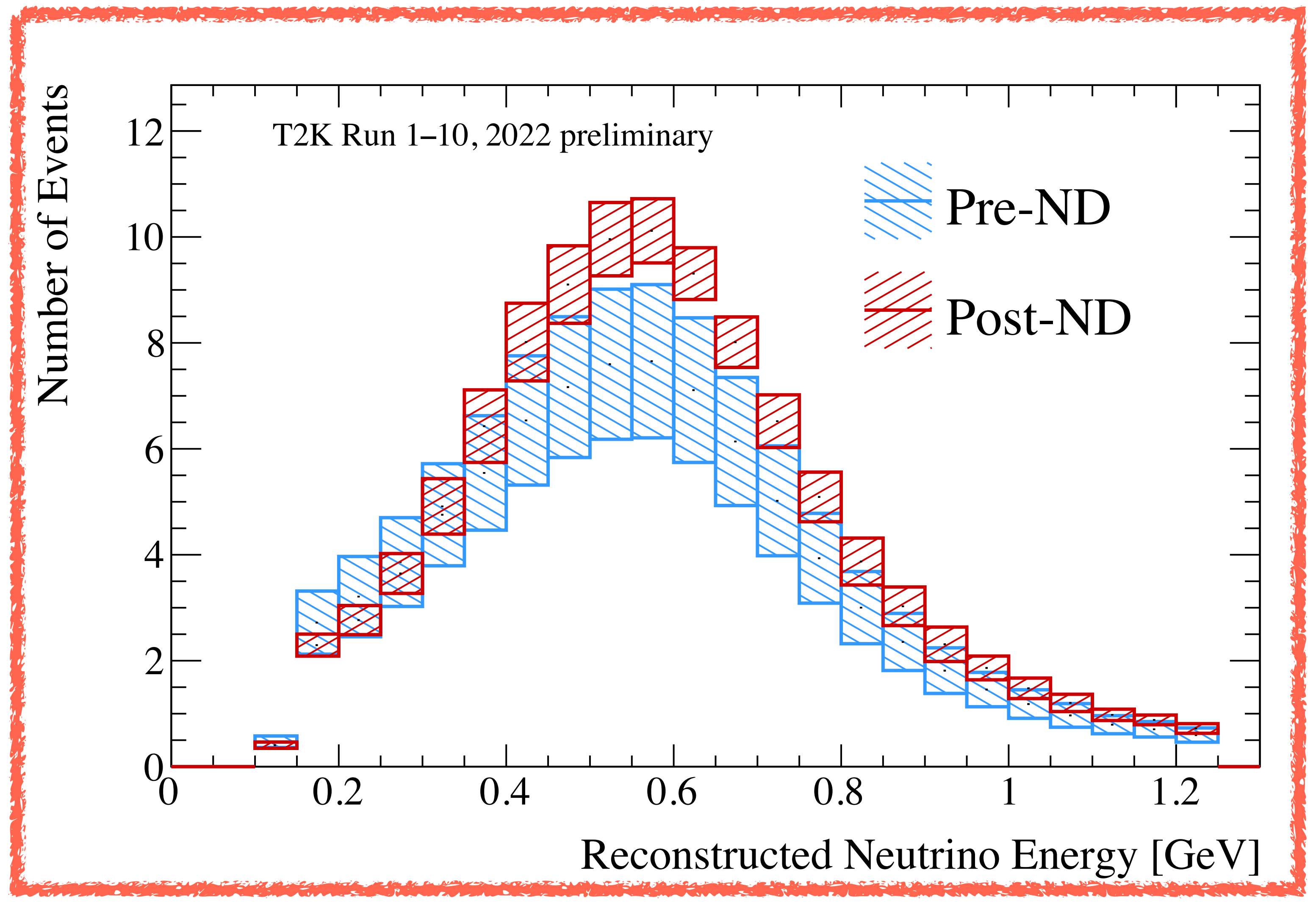
Impact on FD predictions

Sample	Pre-ND fit	Post-ND fit
ν-mode 1Rμ	16.7%	3.4%
ν-mode 1Re	17.3%	5.2%
ν-mode MR	12.5%	4.9%
ν-mode 1Re+d.e.	20.9%	14.3%
$\bar{\nu}$-mode 1Rμ	14.6%	3.9%
$\bar{\nu}$-mode 1Re	14.4%	5.8%

SK Single ring μ-like sample

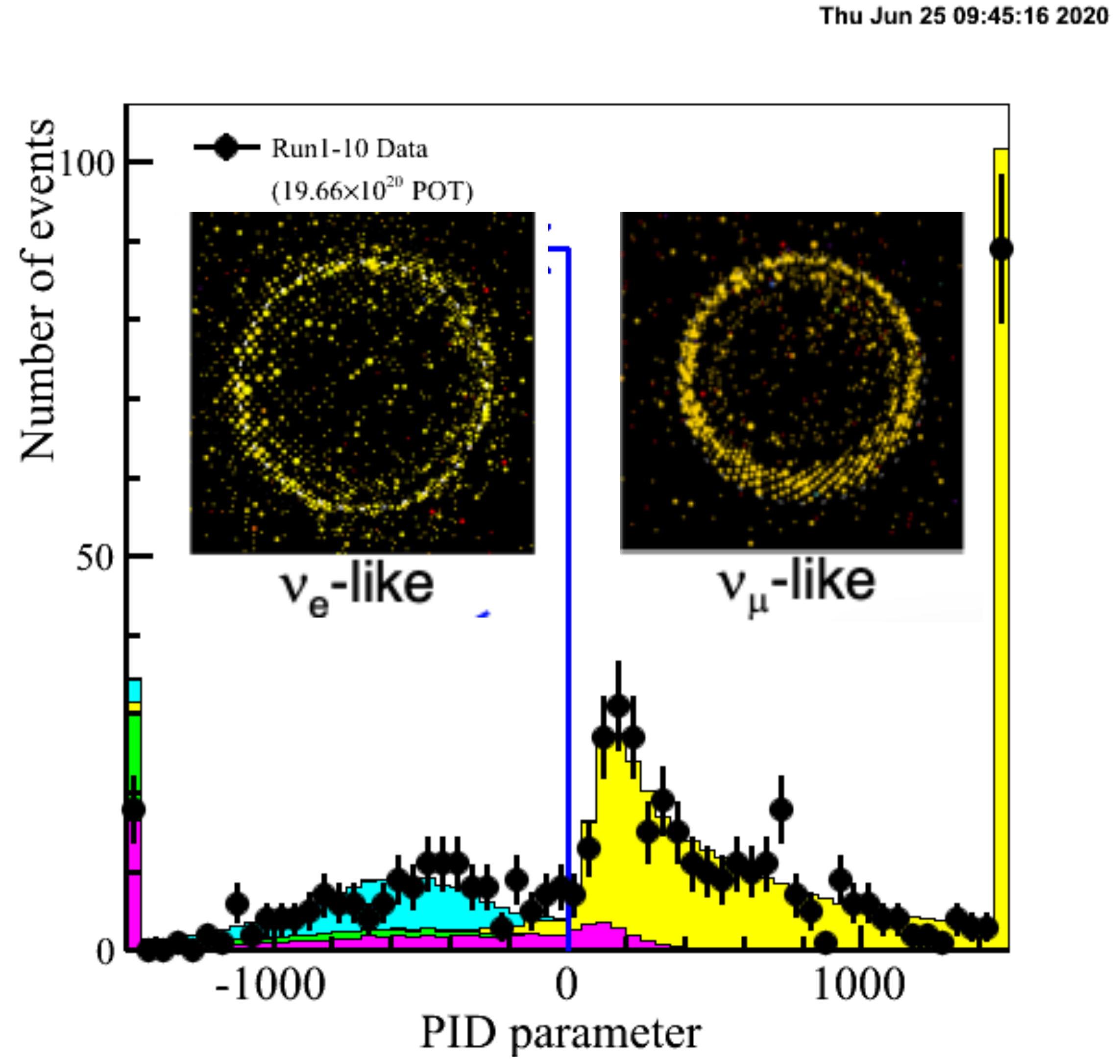


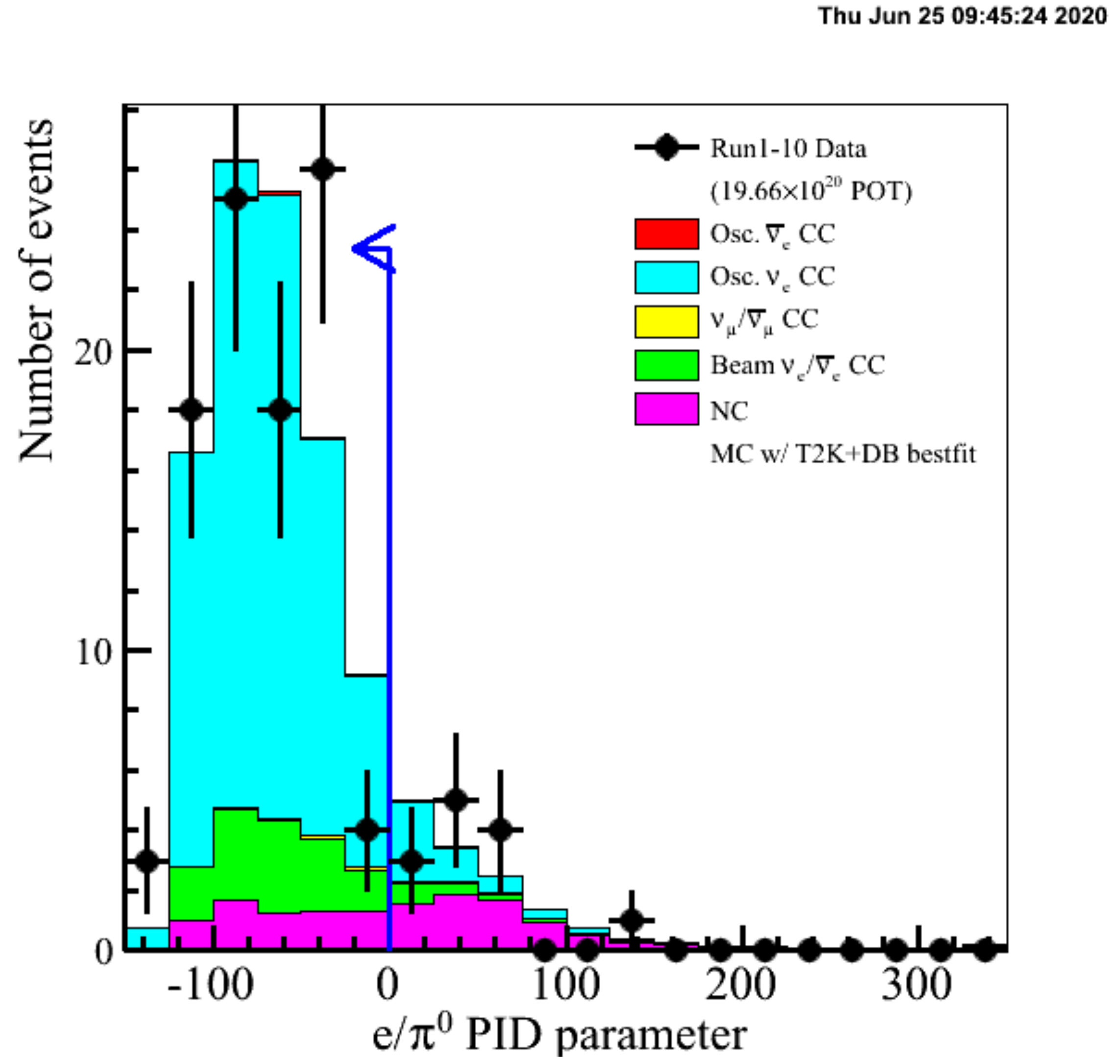
SK single ring e-like sample

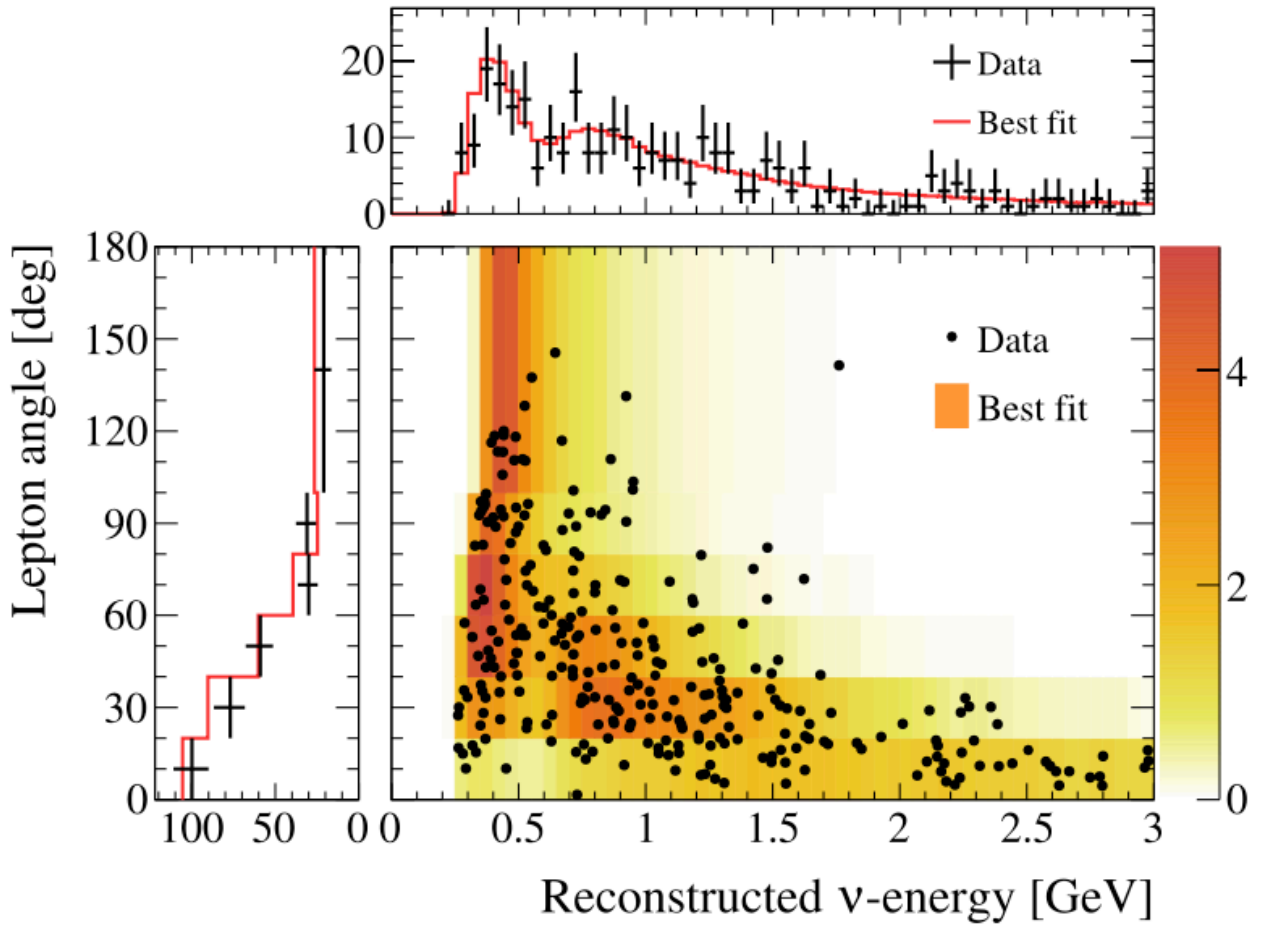


SK selections

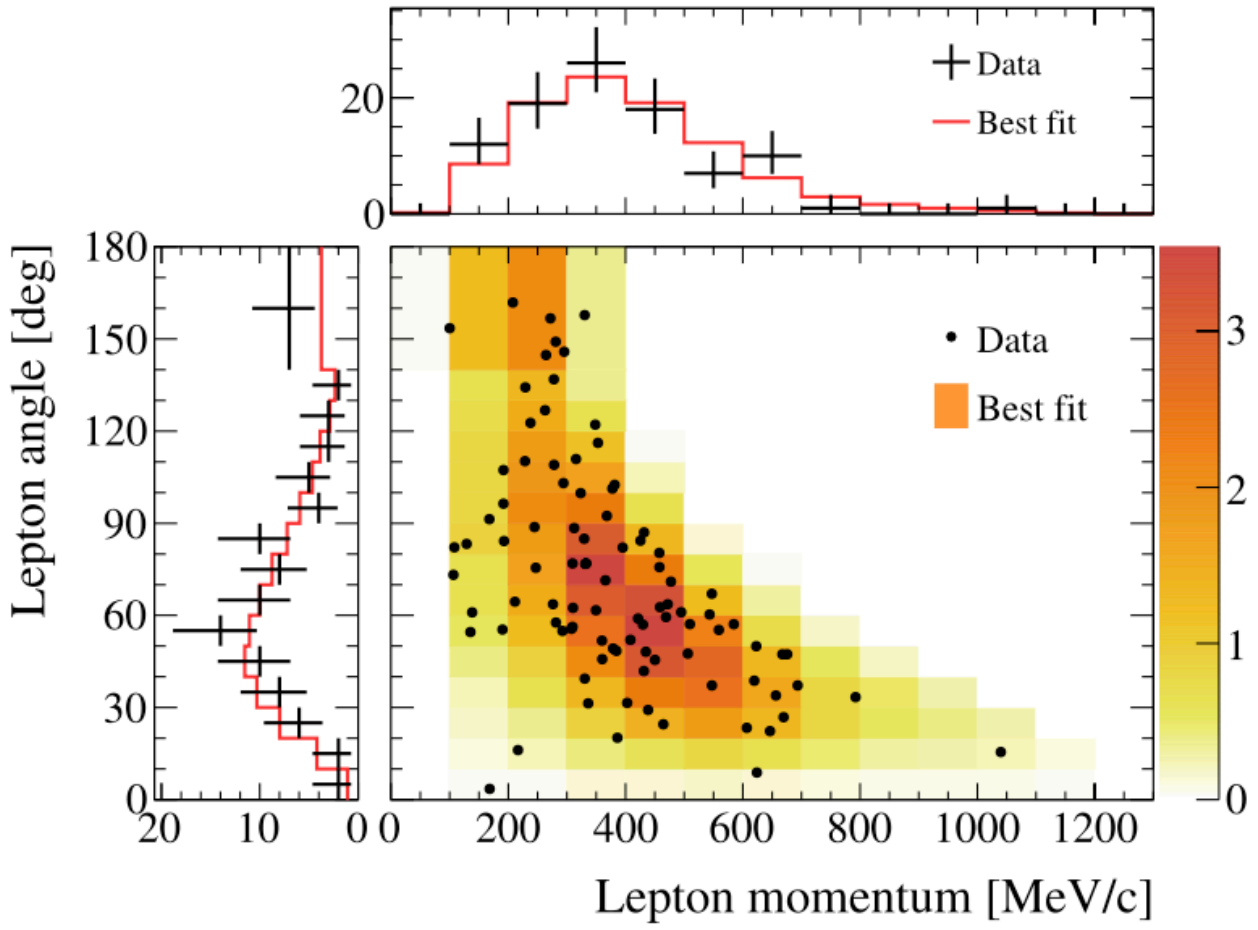
- Single ring (mostly CCQE)
- PID to distinguish e from μ and e from π^0
- Reconstruct momentum and angle of the lepton → neutrino energy through QE formula



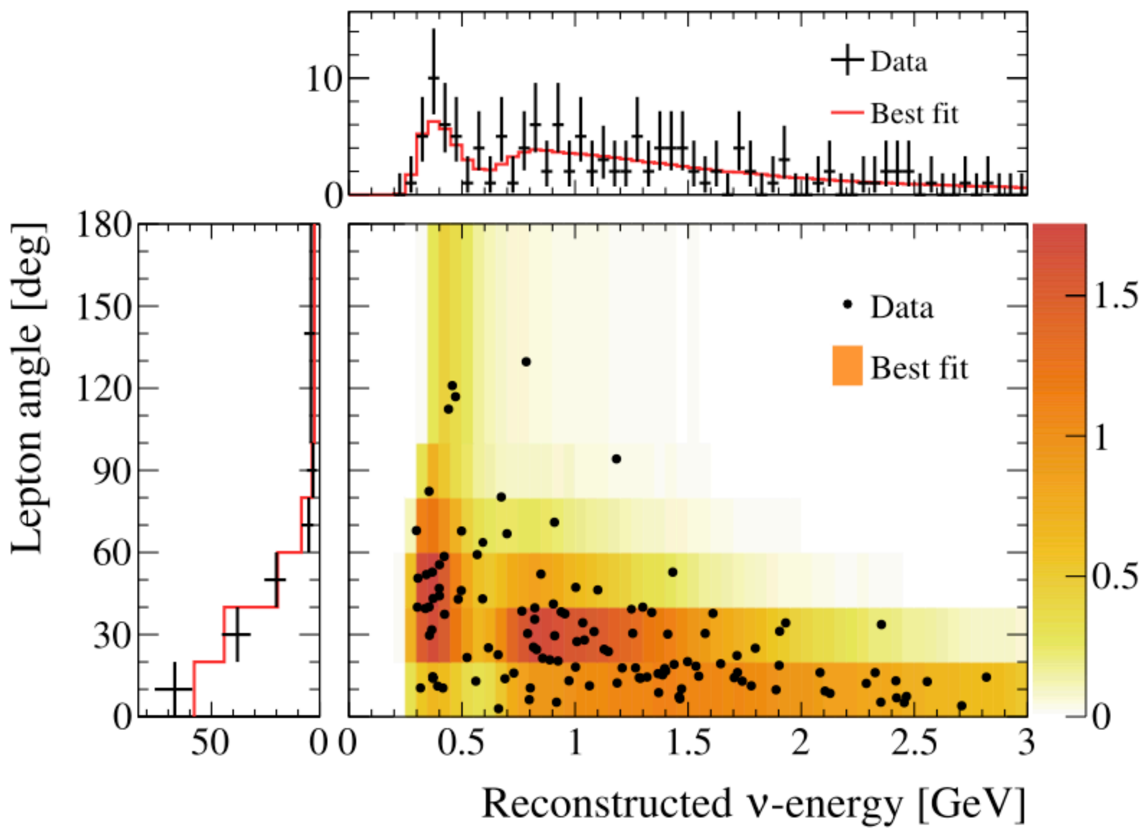




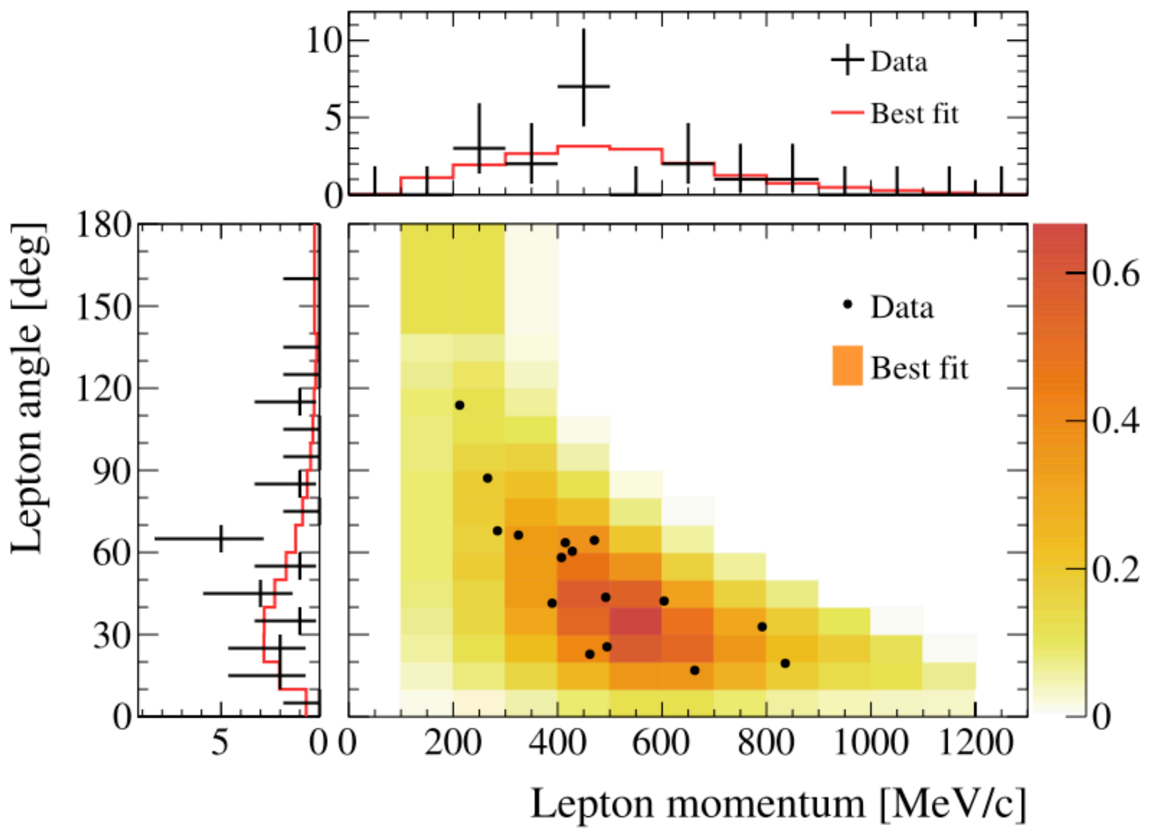
ν-mode 1 Rμ



ν-mode 1 Re



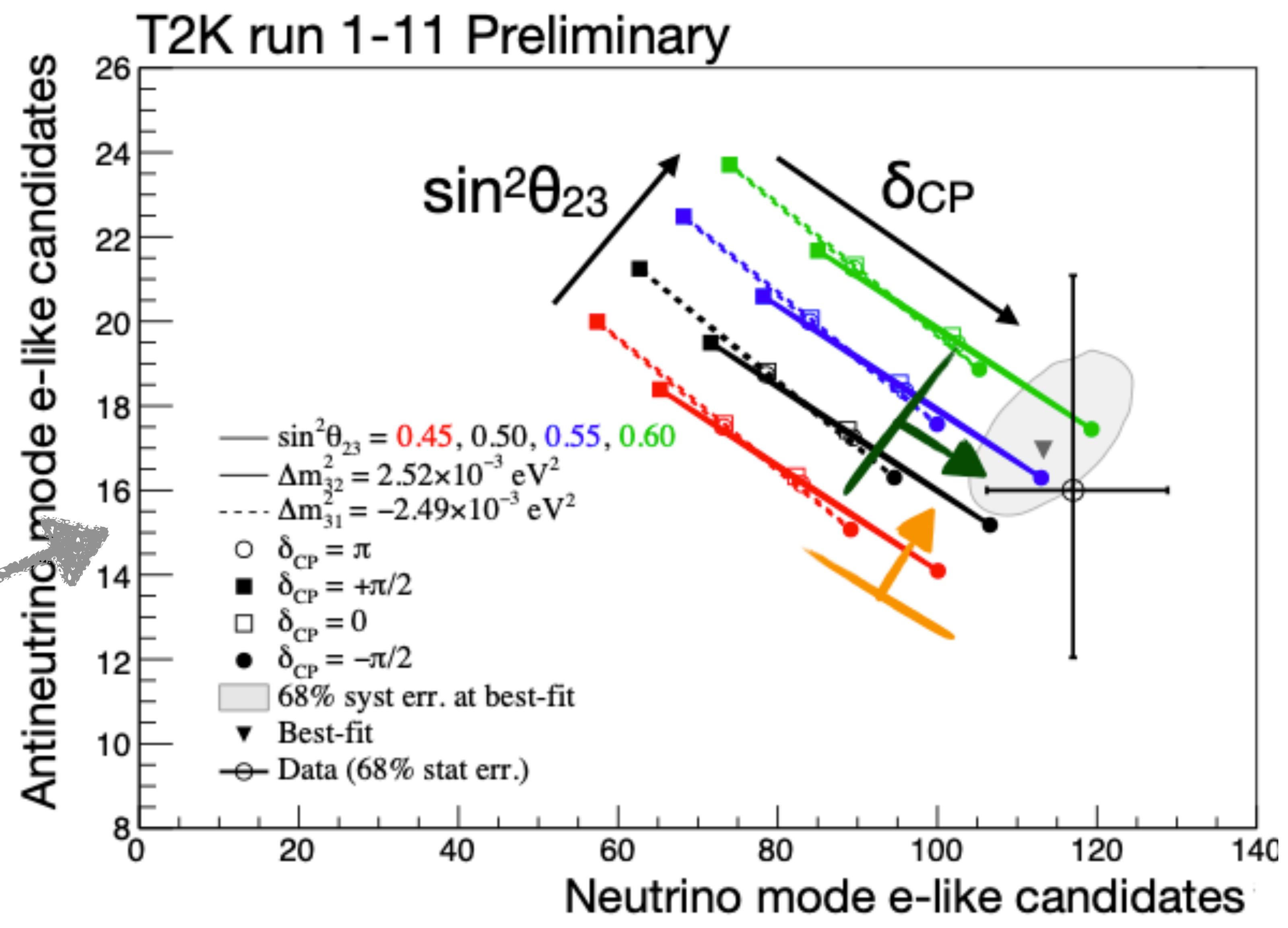
$\bar{\nu}$-mode 1 Rμ



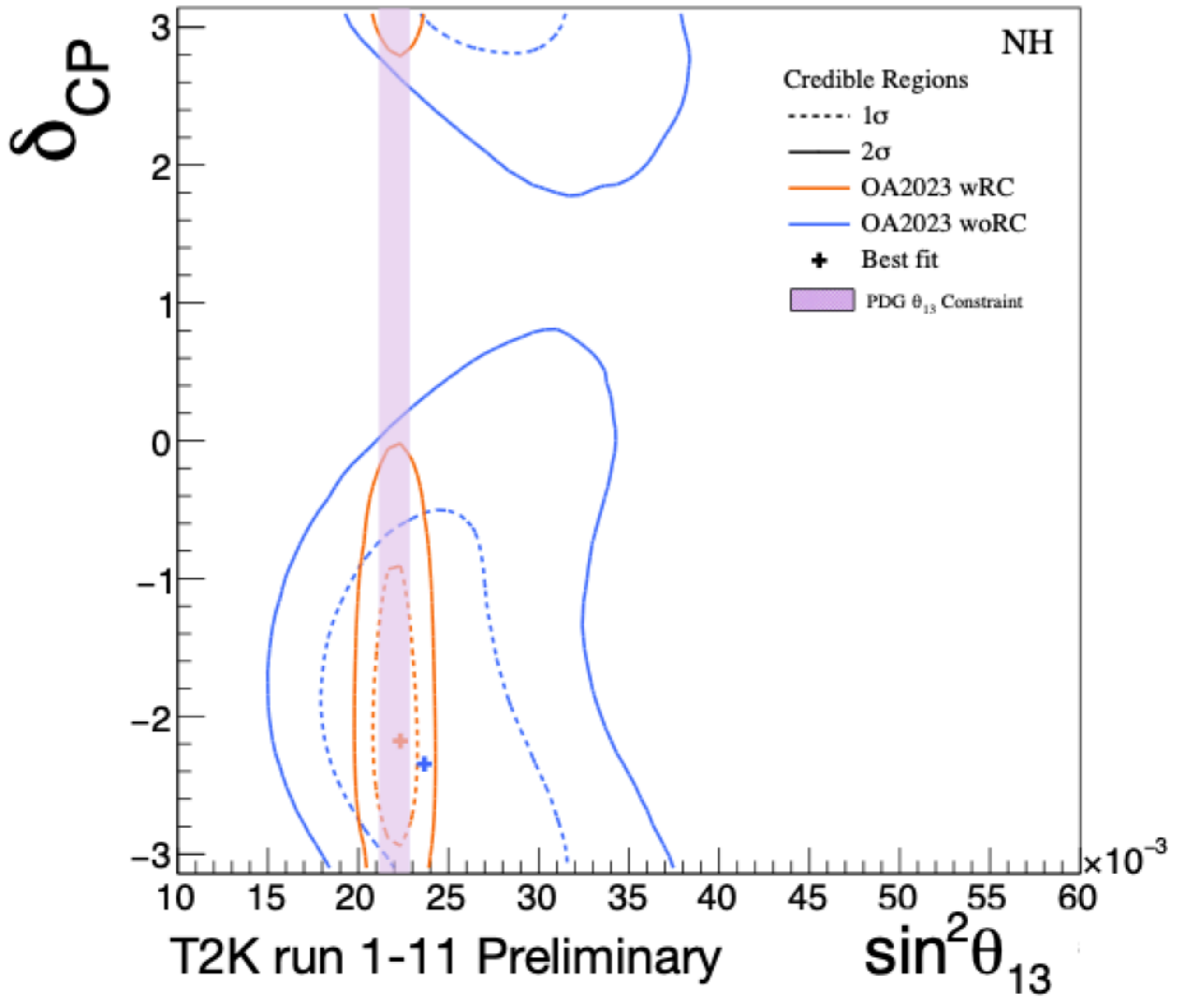
$\bar{\nu}$-mode 1 Re

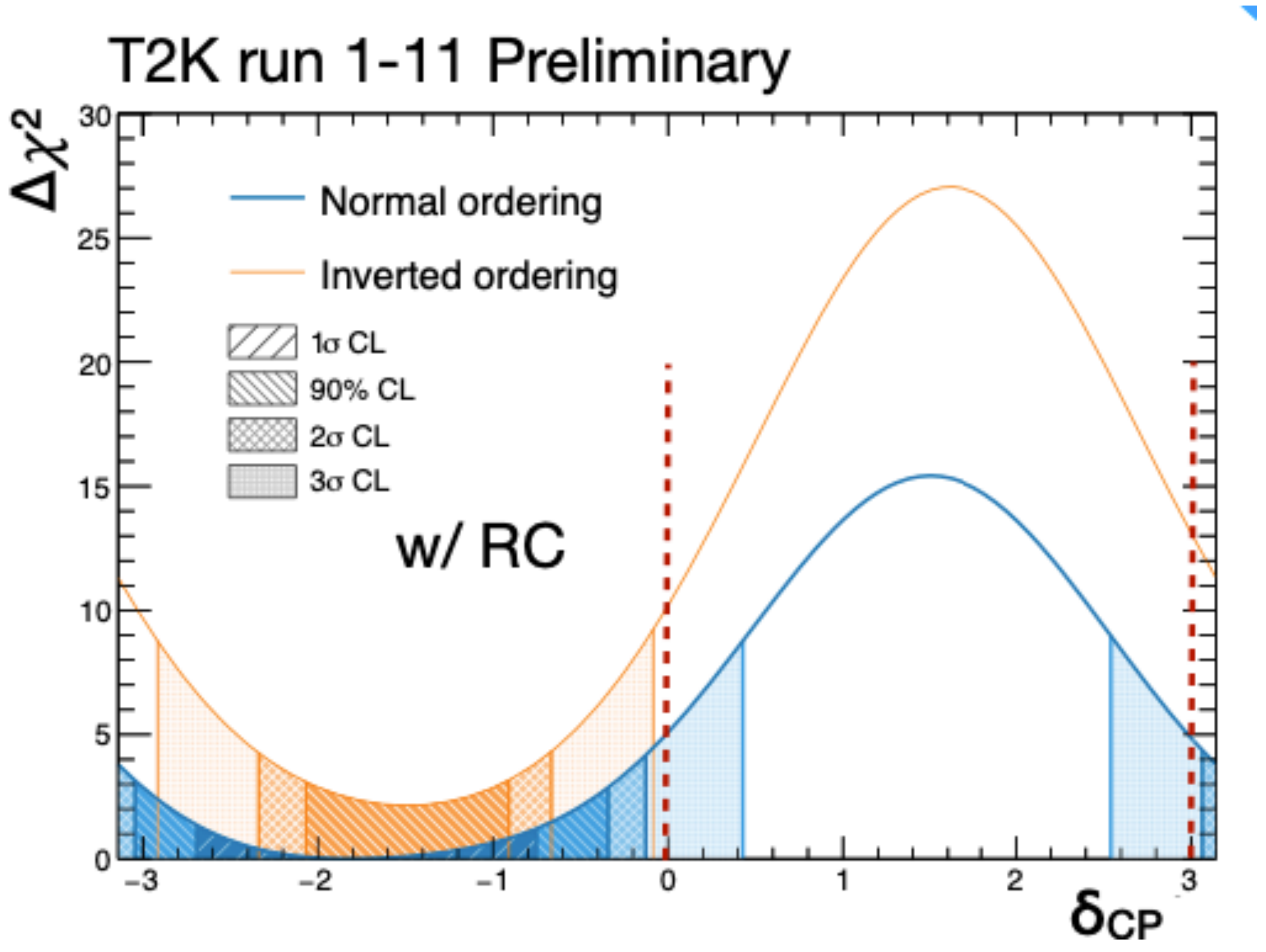
Oscillation analysis results

Sample	δ_{CP}=-π/2	δ_{CP}=0	δ_{CP}=π/2	δ_{CP}=π	Data
ν-mode 1Rμ	417.2	416.3	417.1	418.2	357
ν-mode MR	123.9	123.3	123.9	124.4	140
$\bar{\nu}$-mode 1Rμ	146.6	146.3	146.6	147.0	137
ν-mode 1Re	113.2	95.5	78.3	96.0	102
$\bar{\nu}$-mode 1Re+d.e.	10.0	8.8	7.2	8.4	15
$\bar{\nu}$-mode 1Re	17.6	20.0	22.2	19.7	16

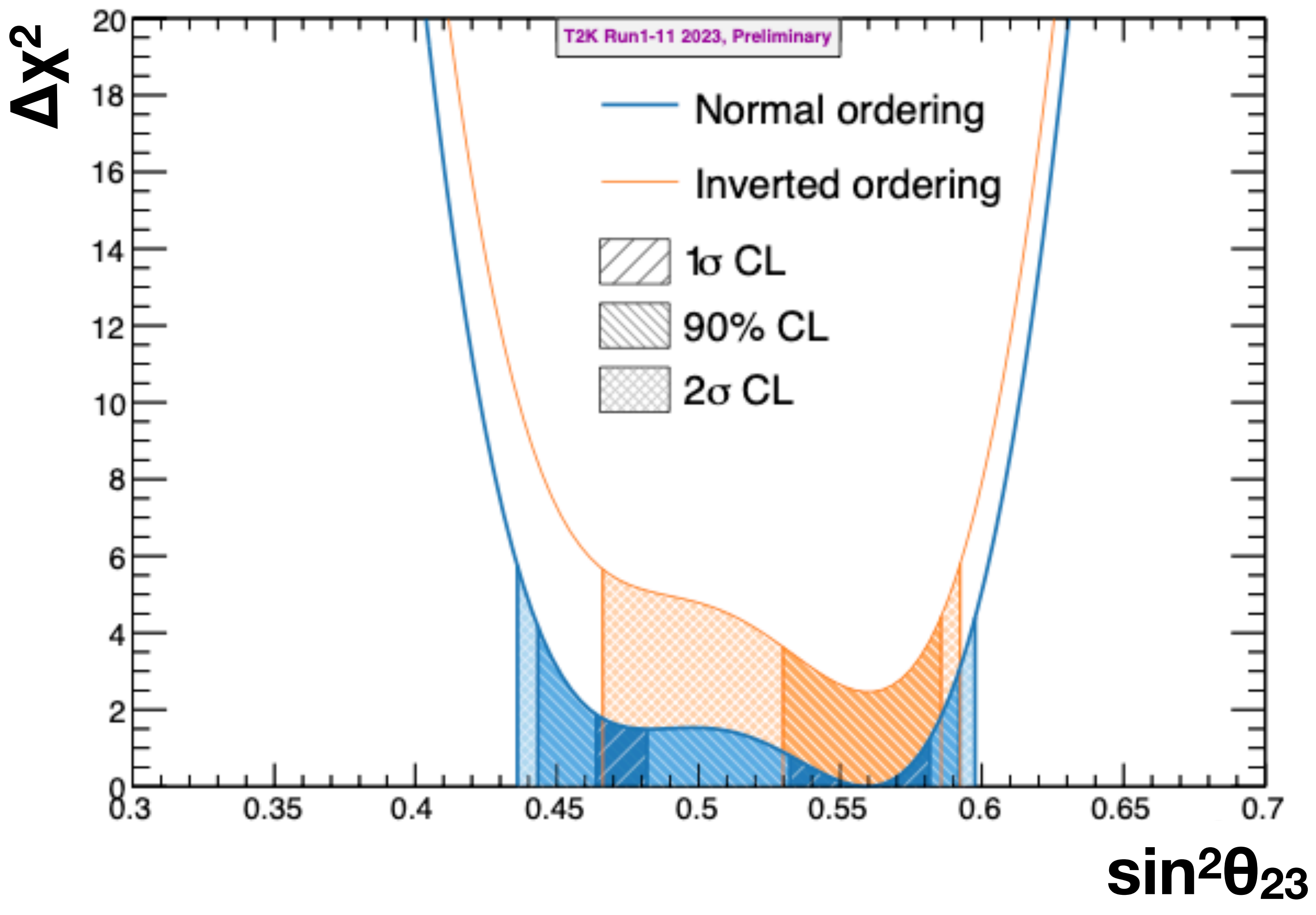


- Preference for δ_{CP}~-π/2 but CP conserving values are within the 2σ interval



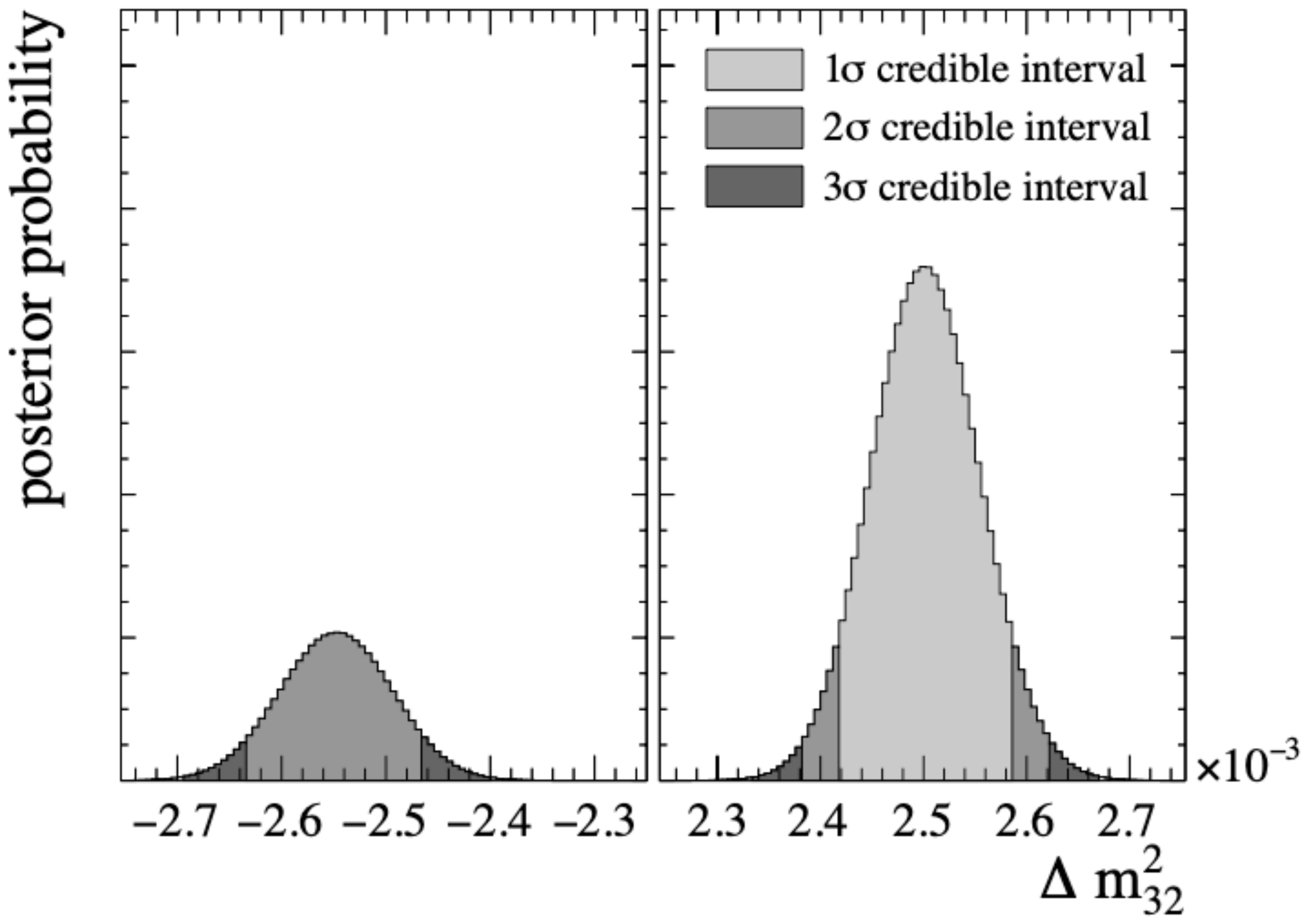


Mass ordering and θ_{23} octant

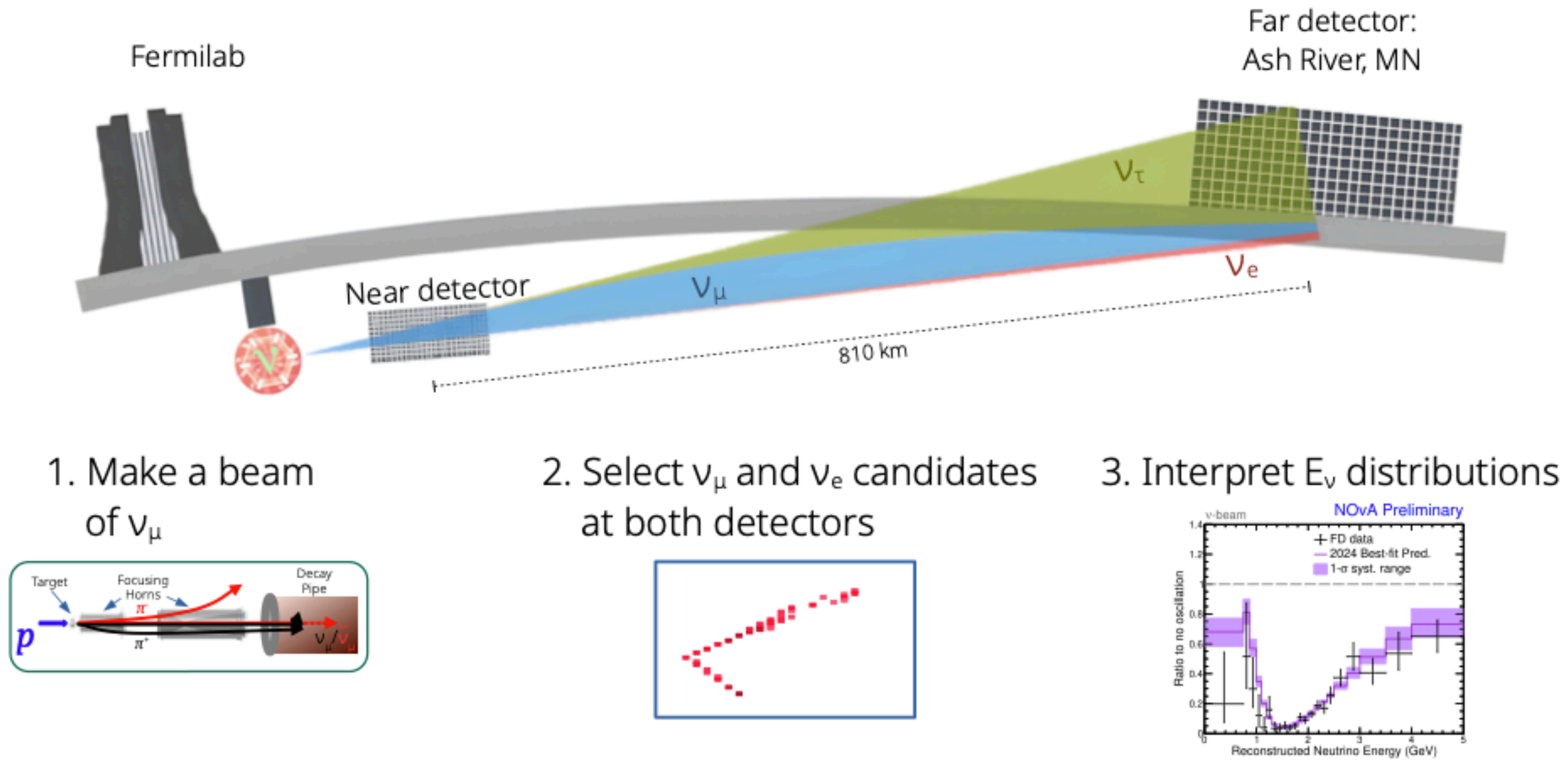


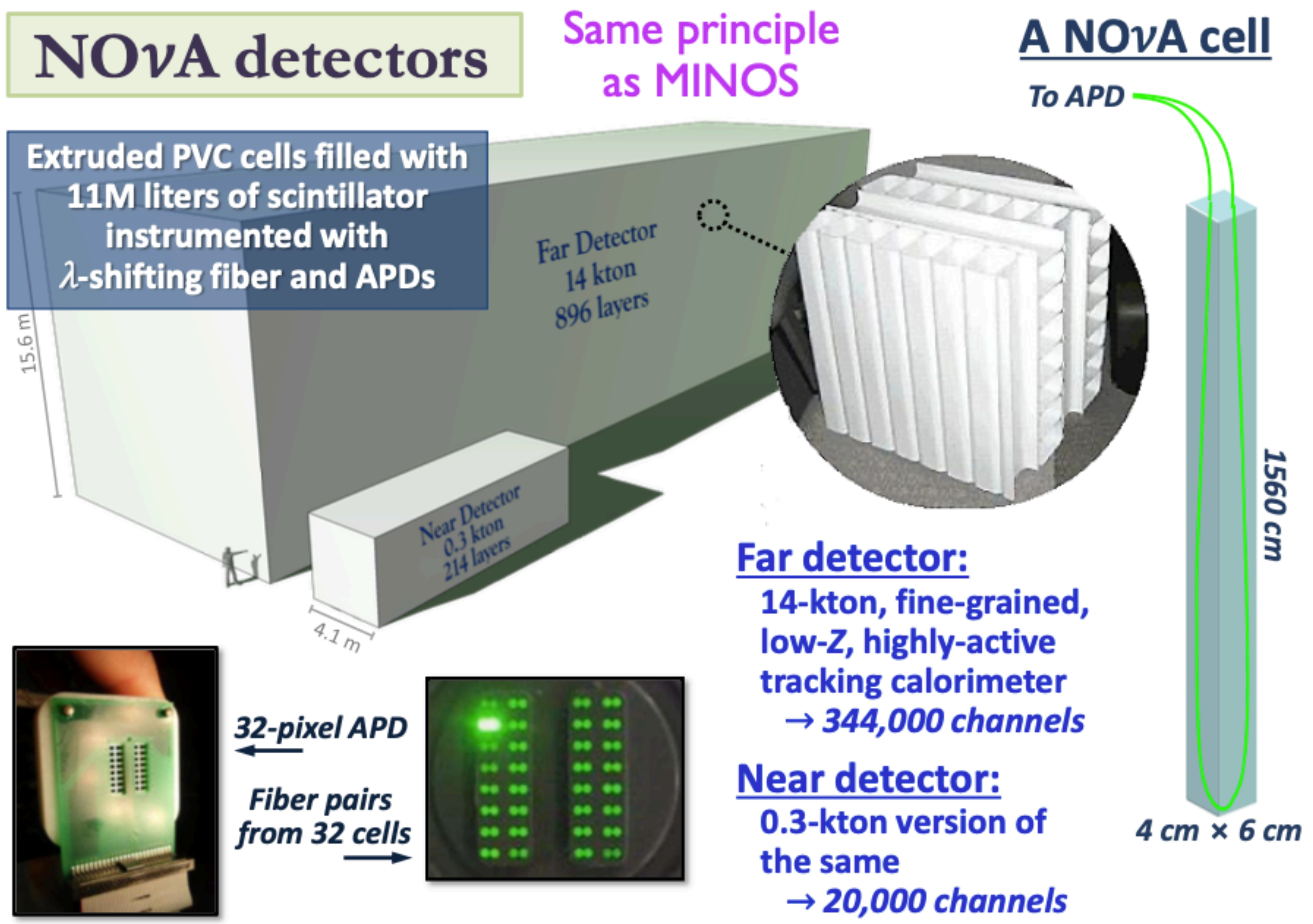
- Slight preference for normal ordering and upper octant but none of them is significant

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.23	0.54	0.77
IH ($\Delta m^2_{32} < 0$)	0.05	0.18	0.23
Sum	0.28	0.72	1.00



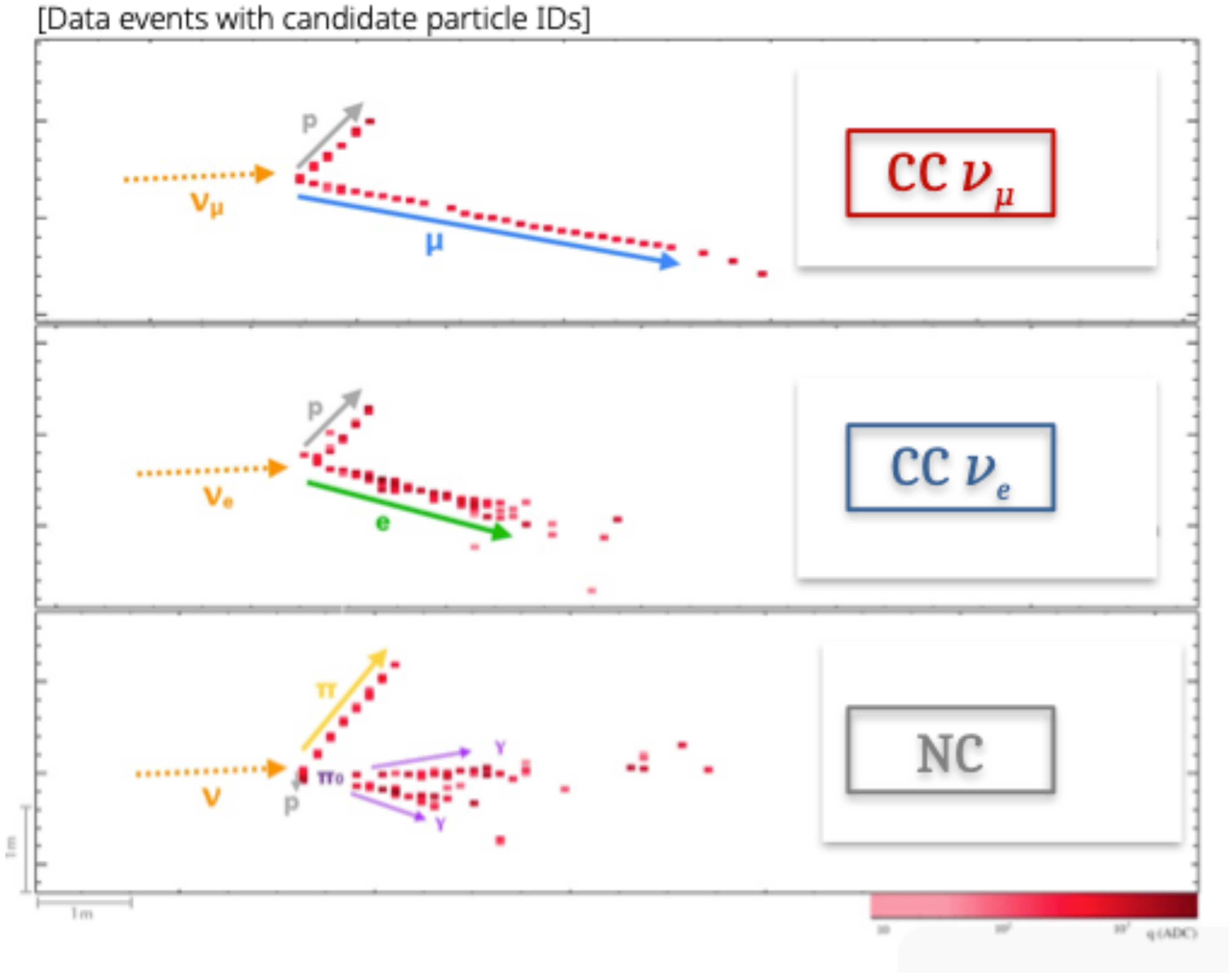
NOvA experiment

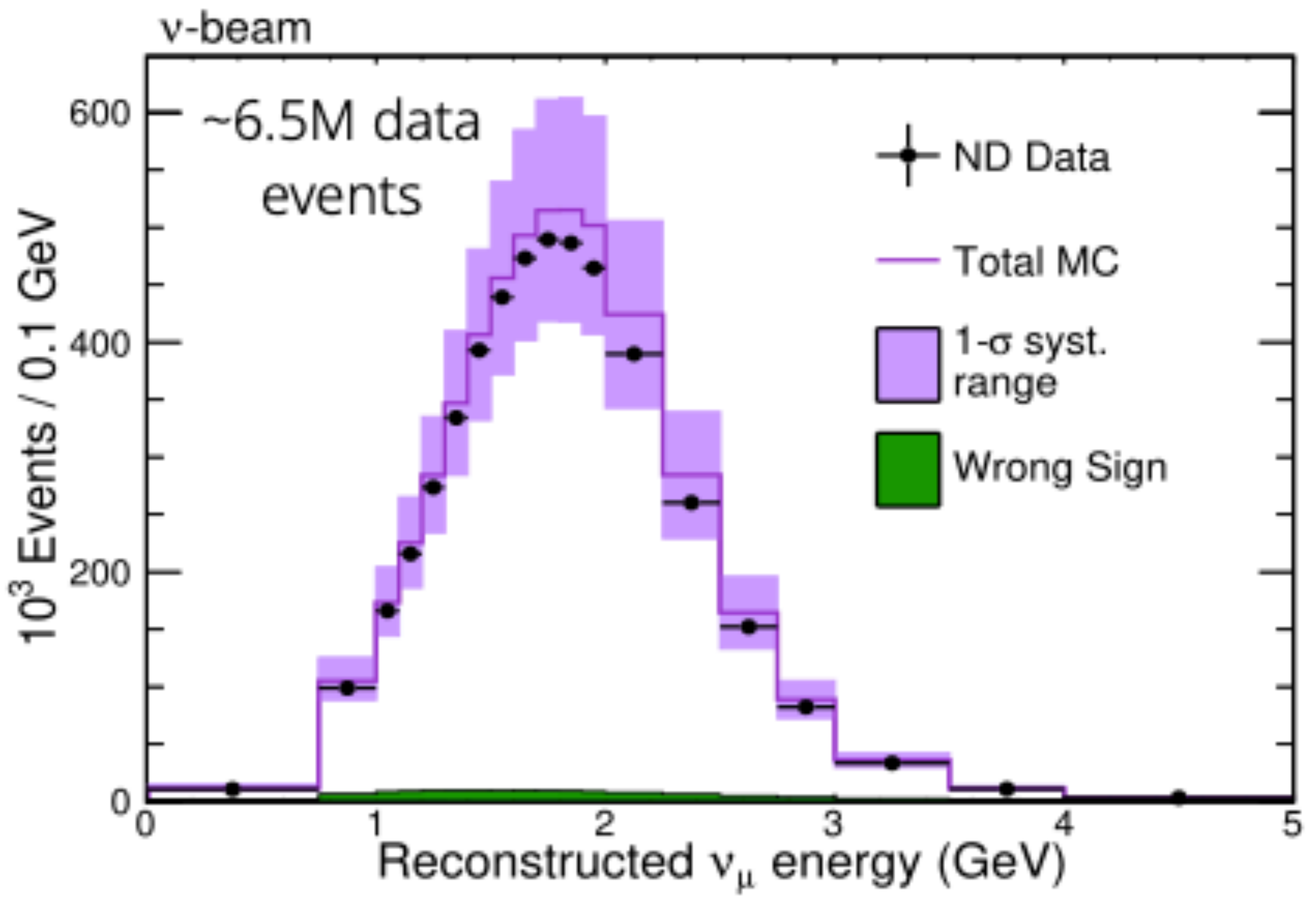


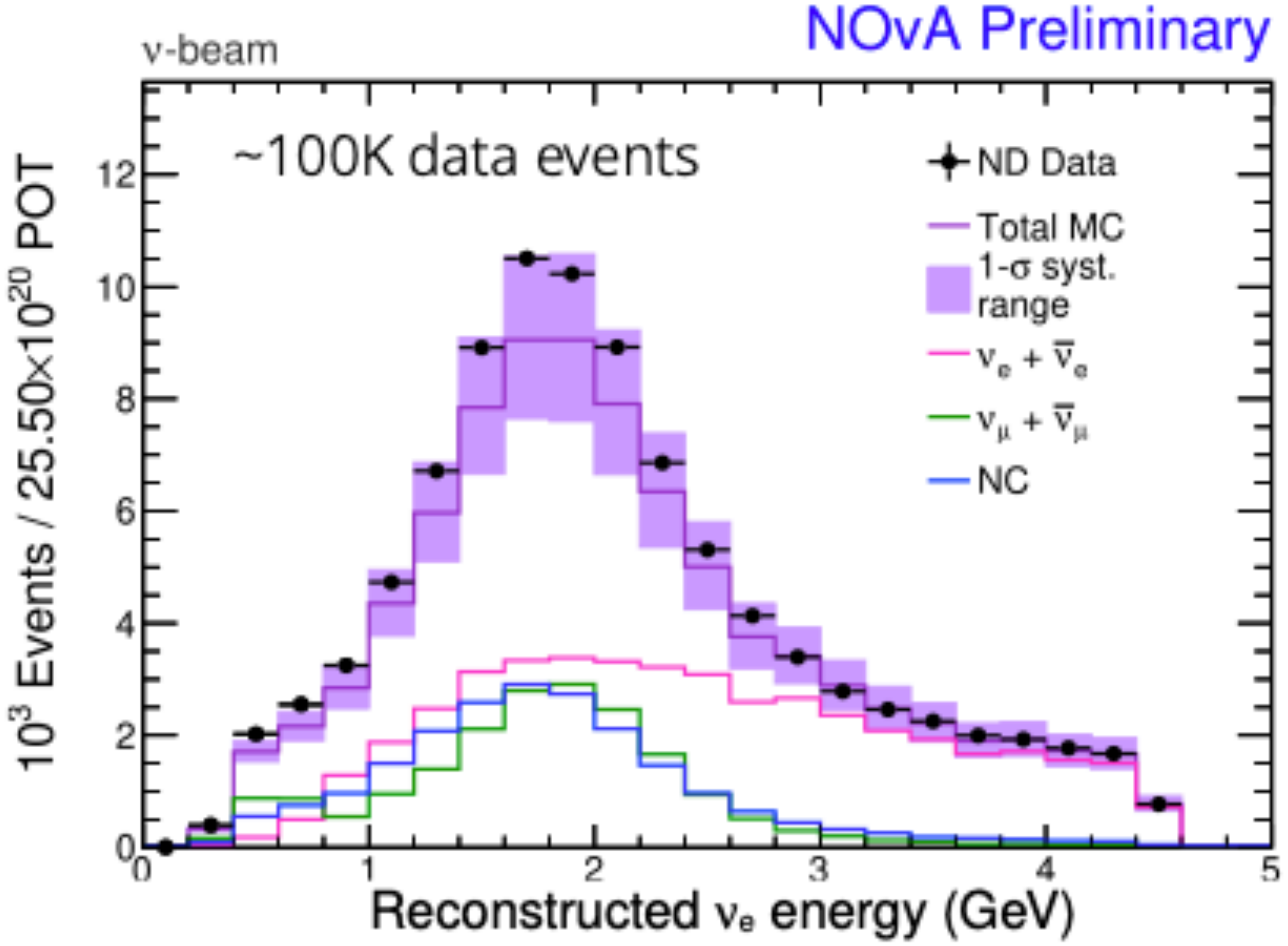


- Identical near (300 ton) and far detector (14 kTon)

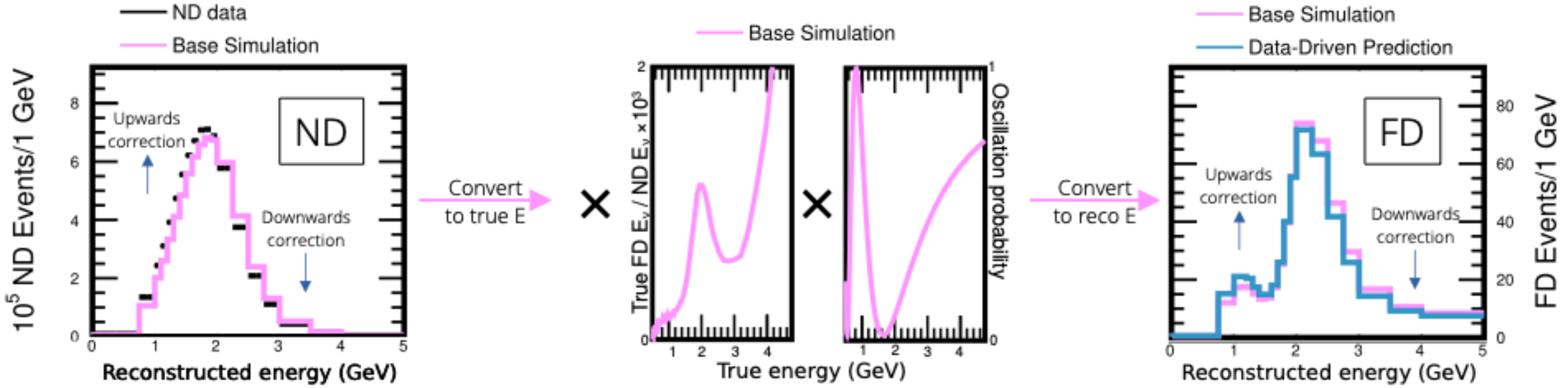
NOvA ND samples







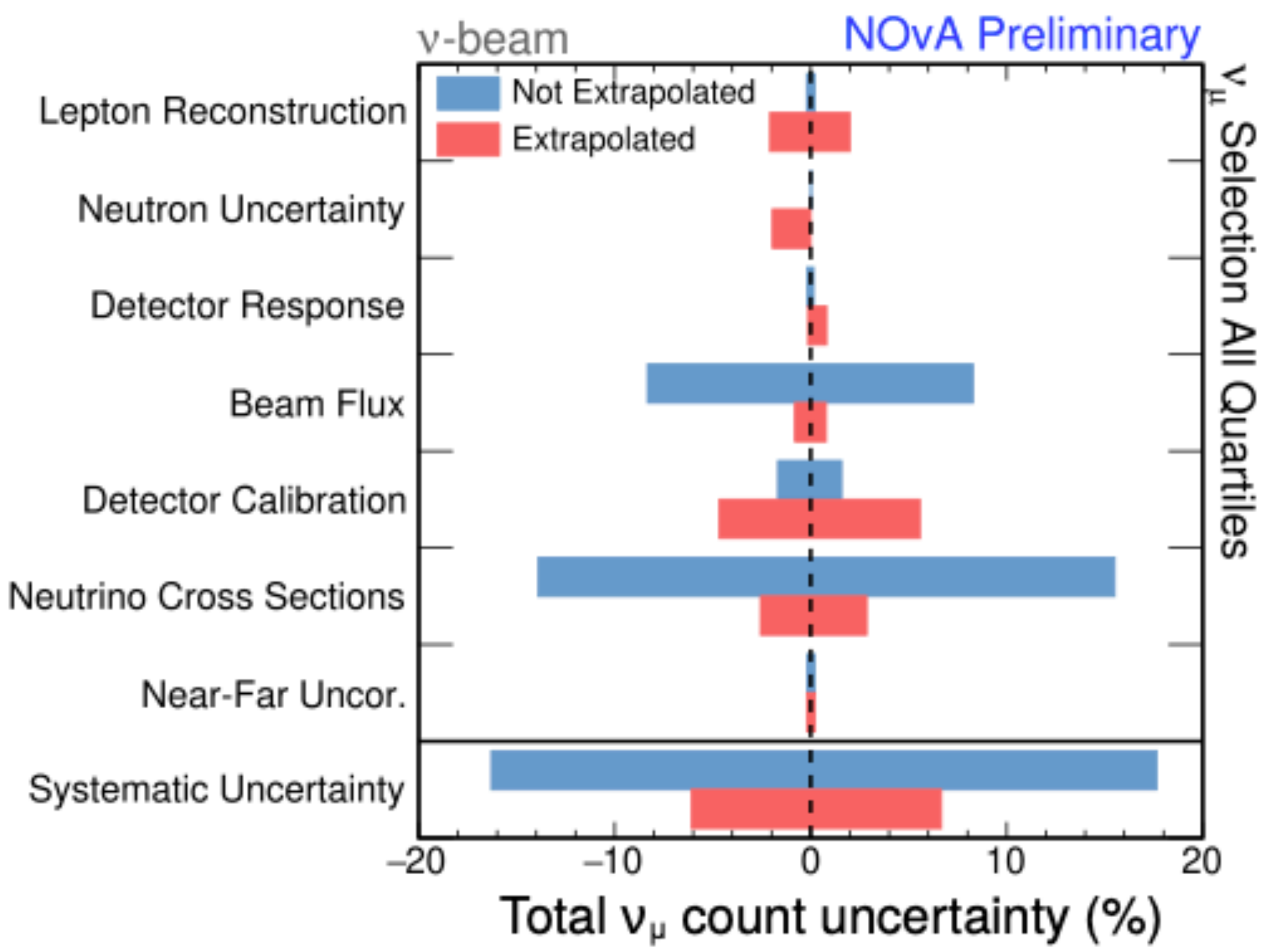
Extrapolation Near/Far

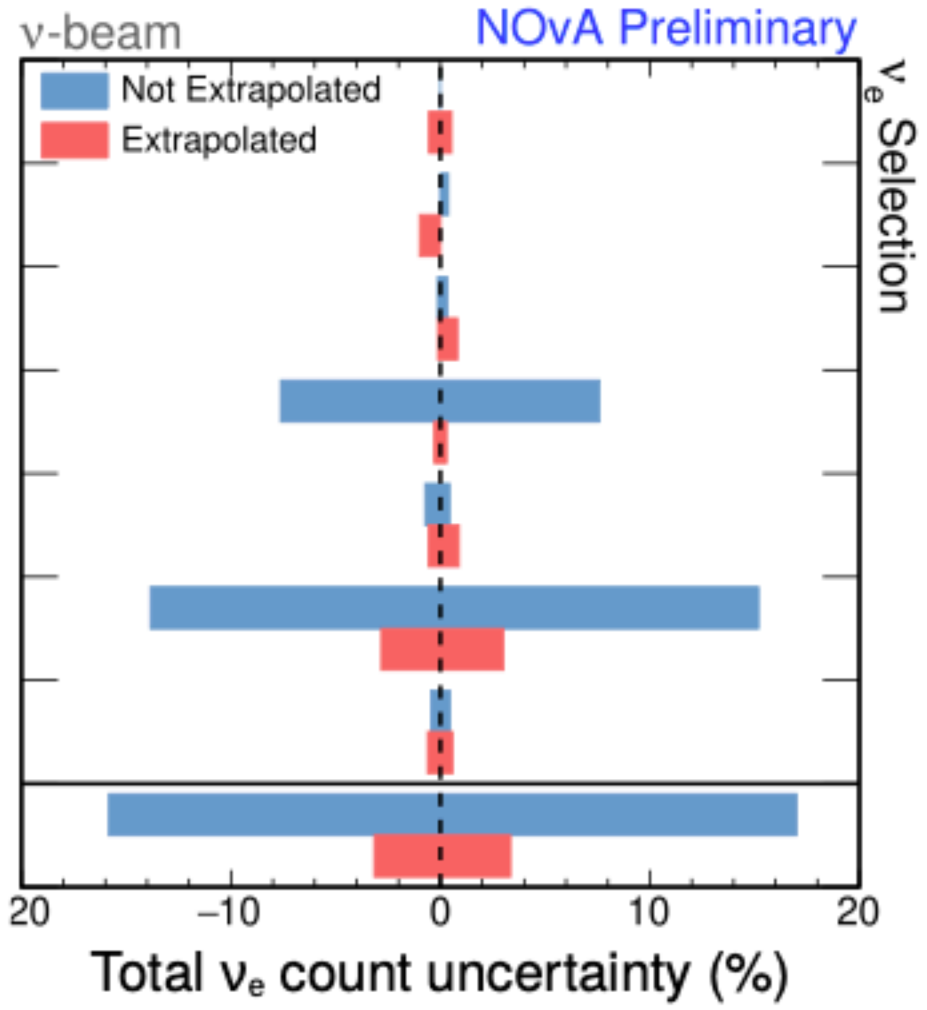


Correcting ND simulation to agree with data in reco E_ν...

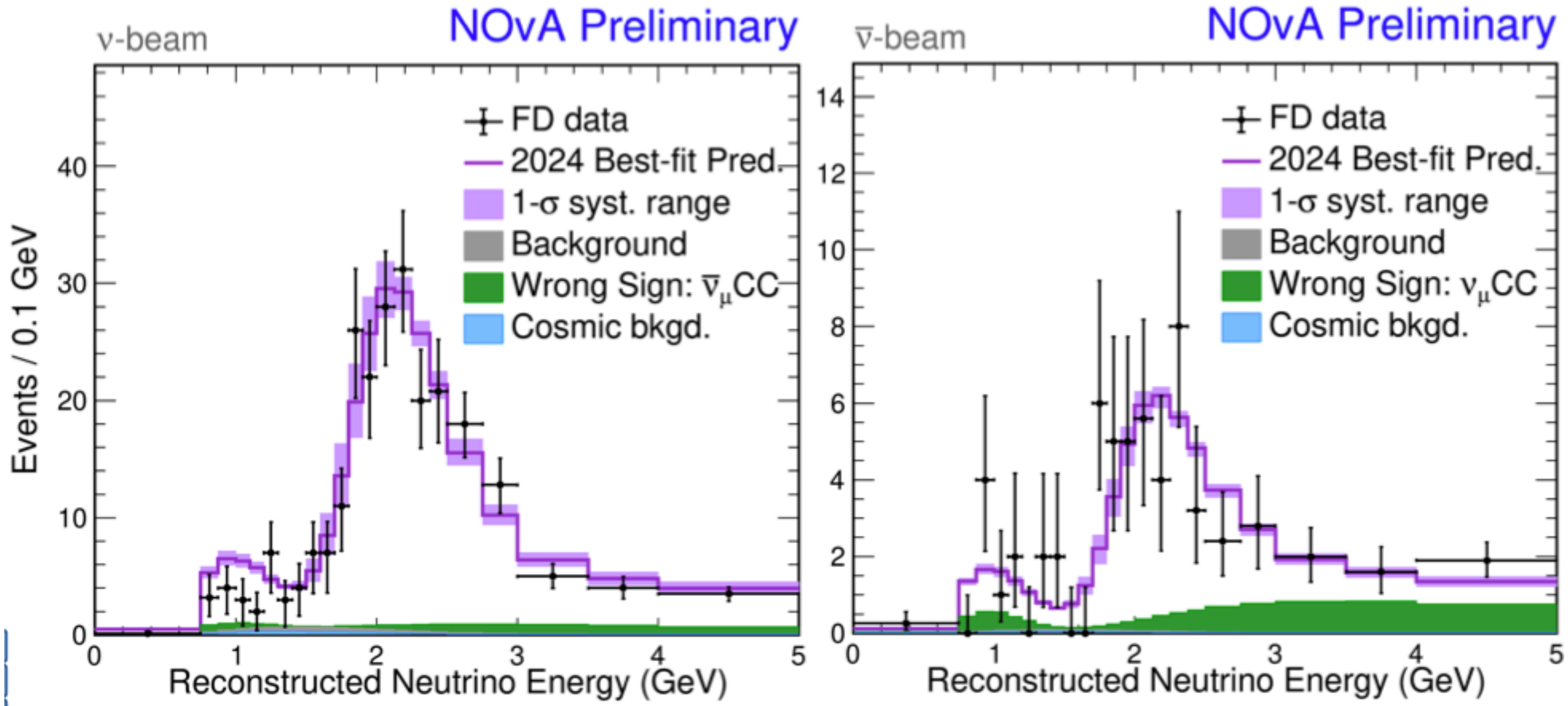
... via **Far/Near transformation** that comprises **well understood effects** (beam divergence, detector acceptance) **+ oscillations**

... results in **constrained FD E_ν prediction** highly correlated with ND correction





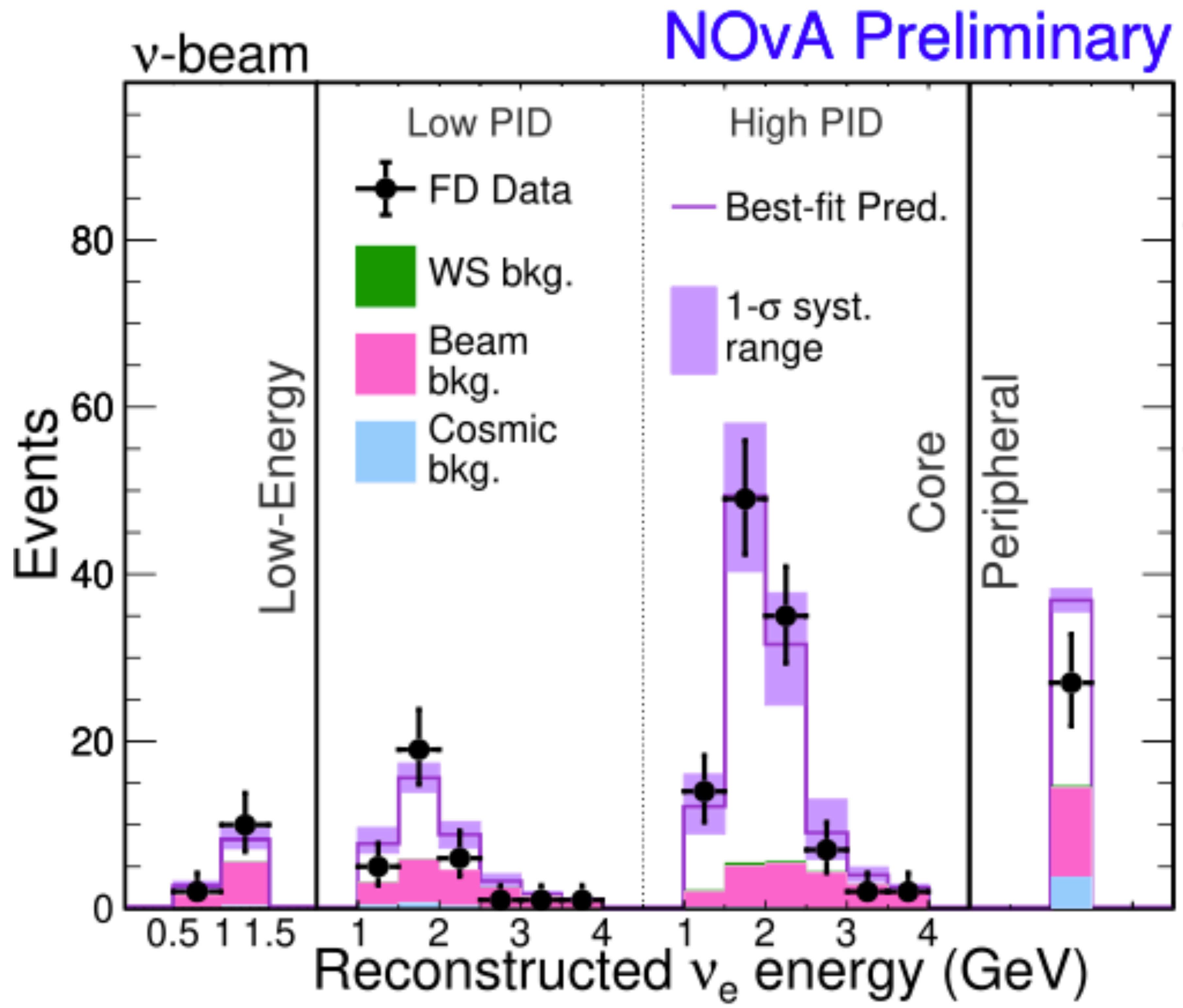
Far Detector ν_μ and $\bar{\nu}_\mu$ samples

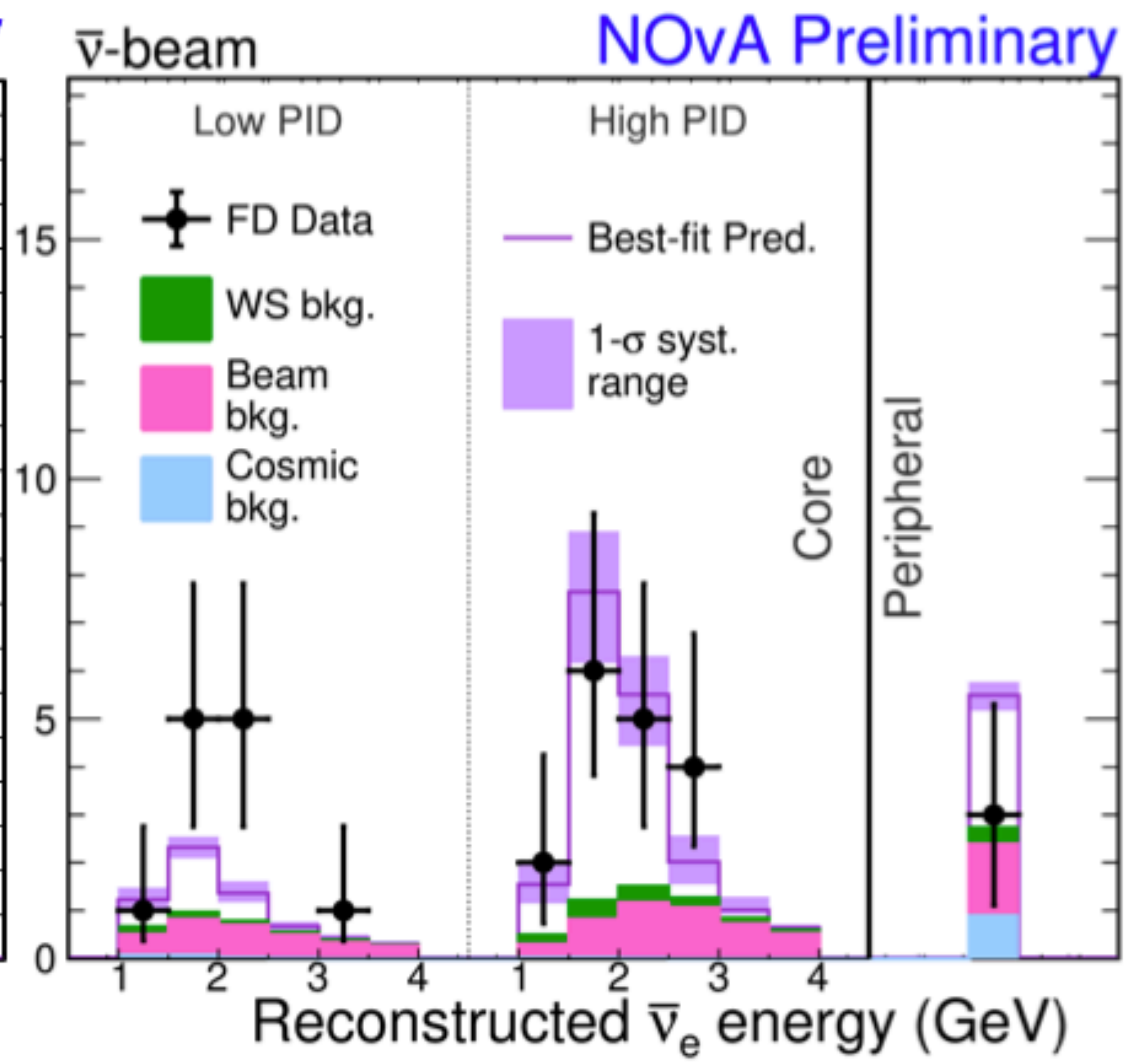


384 ν_μ data candidates
(11.3 background)

106 $\bar{\nu}_\mu$ data candidates
(1.7 background)

Far Detector ν_e and $\bar{\nu}_e$ samples





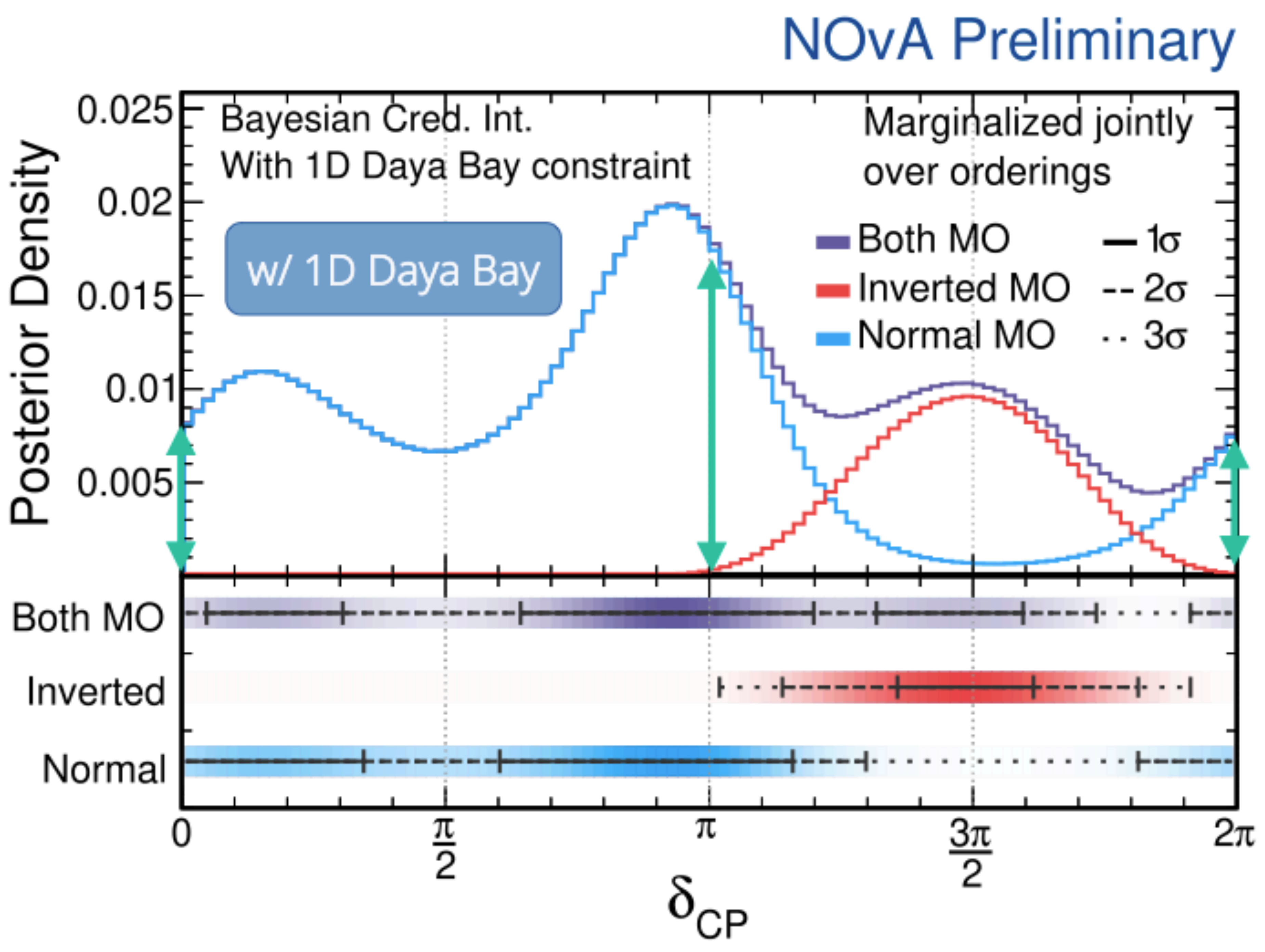
181 ν_e data candidates

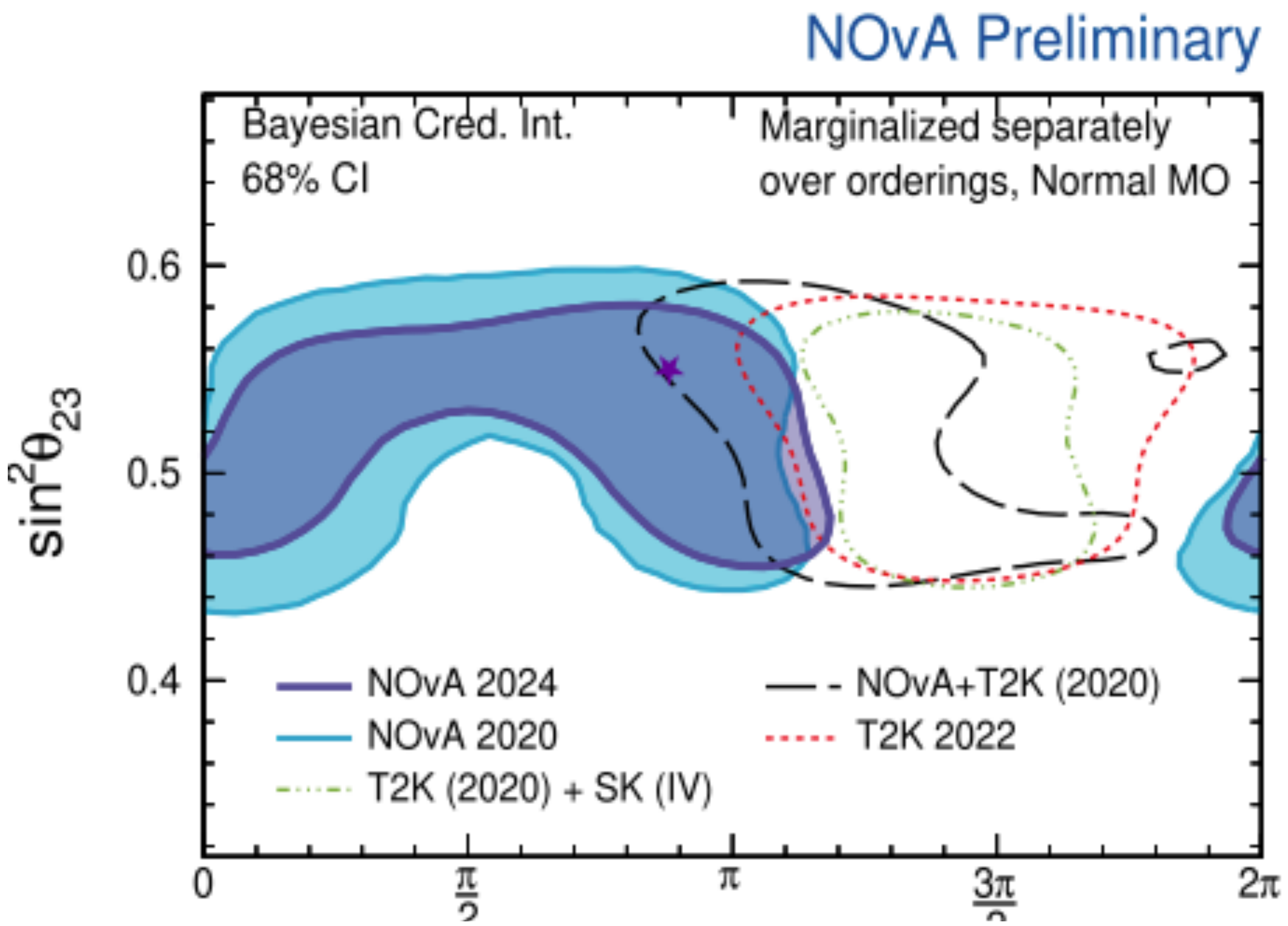
	Best fit	Range
Total pred	186.2	119 – 250
Wrong-sign	1.8	1.6 – 2.8
Beam bknd.	53.7	
Cosmic bknd.	6.2	
Total bknd	61.7	61 – 63

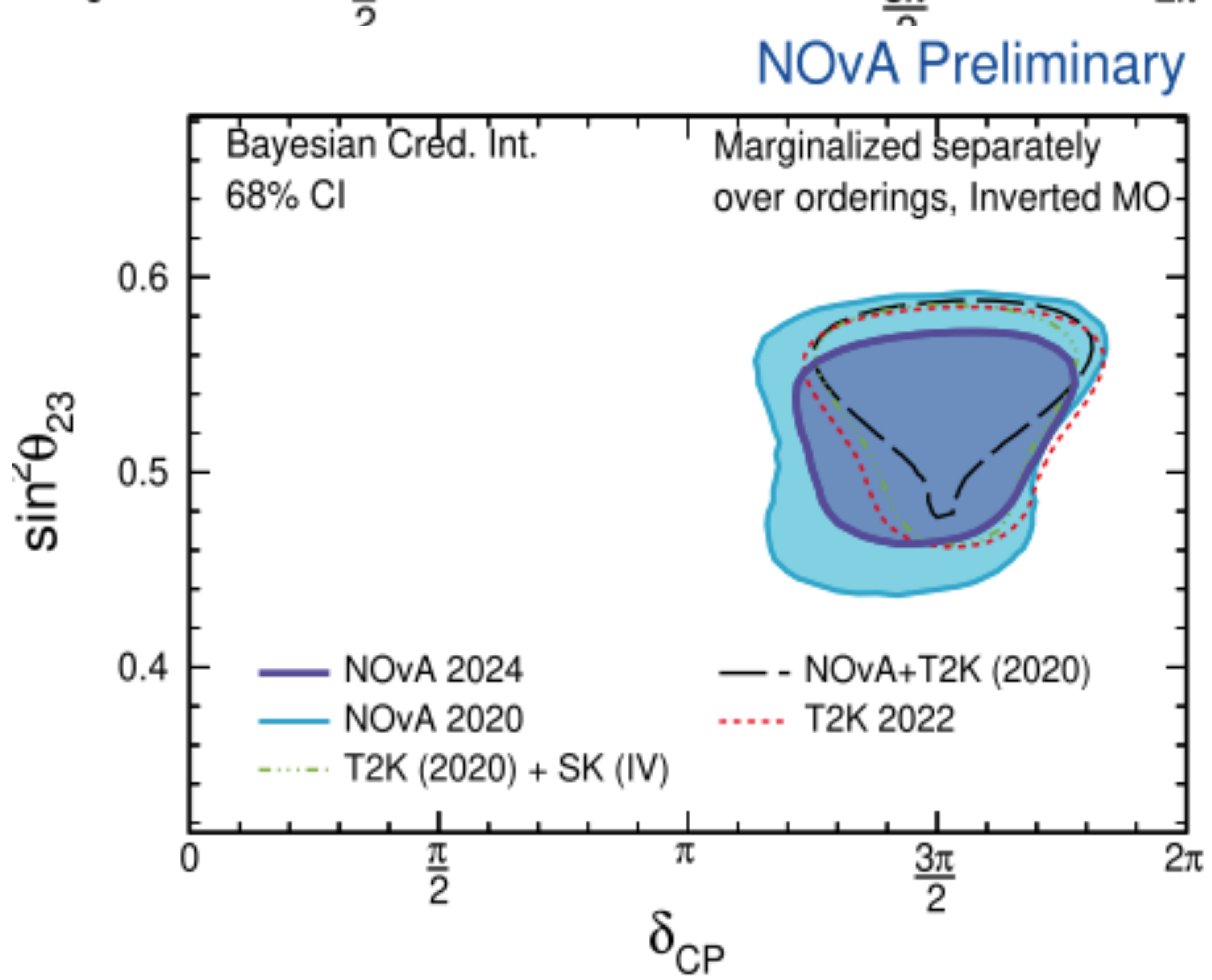
32 $\bar{\nu}_e$ data candidates

	Best fit	Range
Total pred	30.4	28 – 38
Wrong-sign	2.1	1.0 – 3.2
Beam bknd.	9.0	
Cosmic bknd.	1.1	
Total bknd	12.2	11 – 13

Mass Ordering and CPV



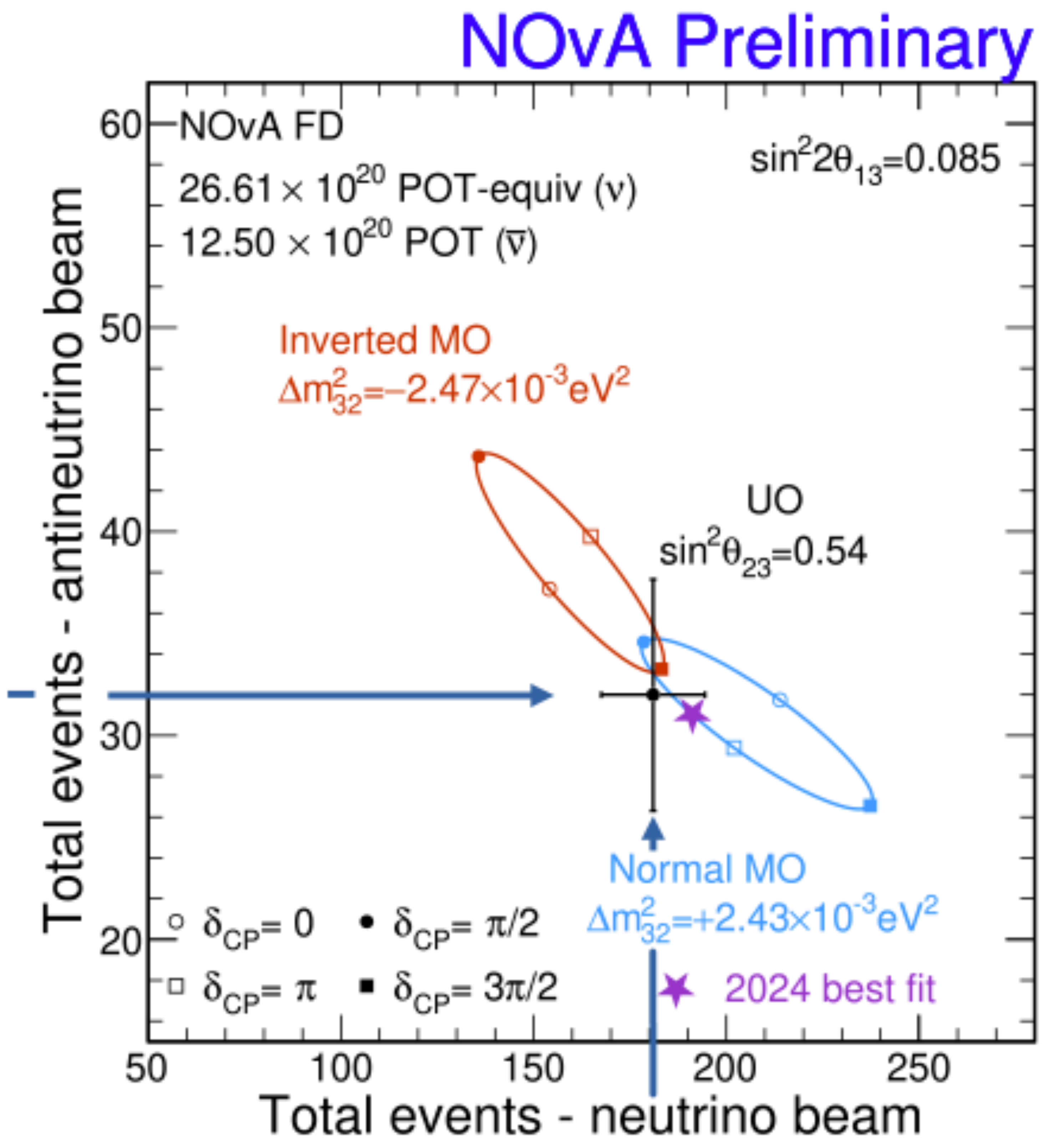




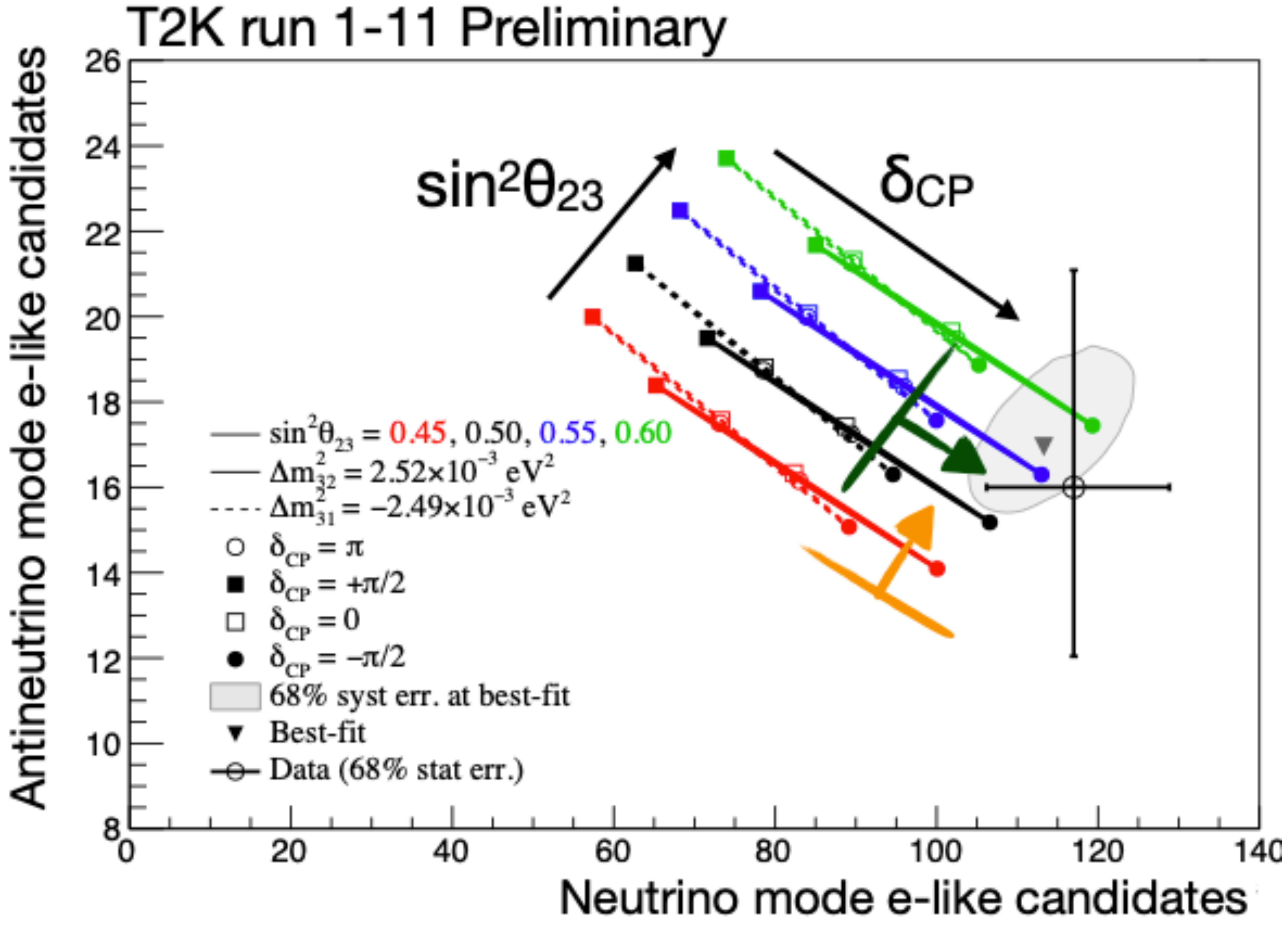
- Mass Ordering and CP violation heavily entangled
- Answer on δ_{CP} change completelychange if the ordering is swapped

NOvA and T2K

32 $\bar{\nu}_e$ data candidates



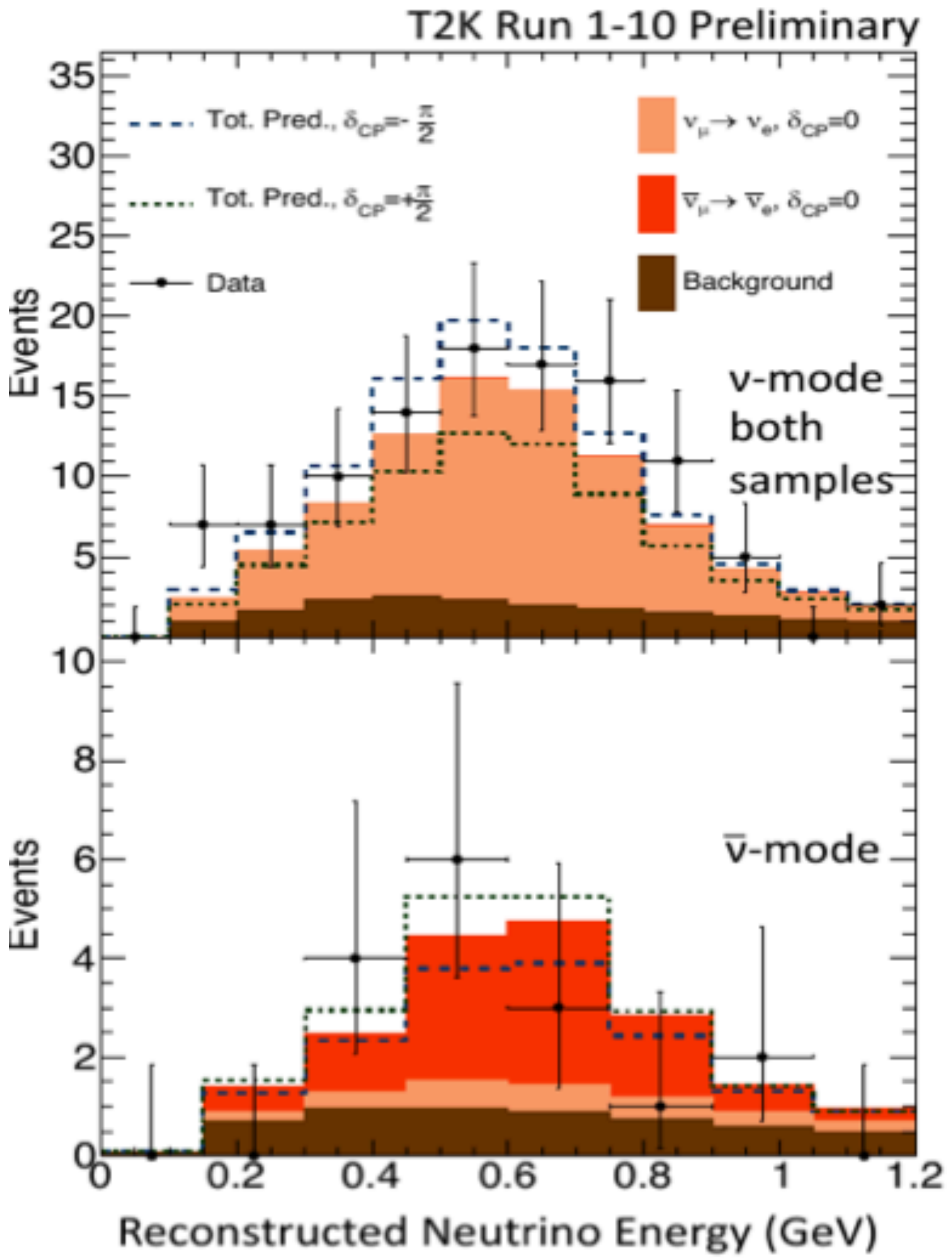
181 ν_e data candidates

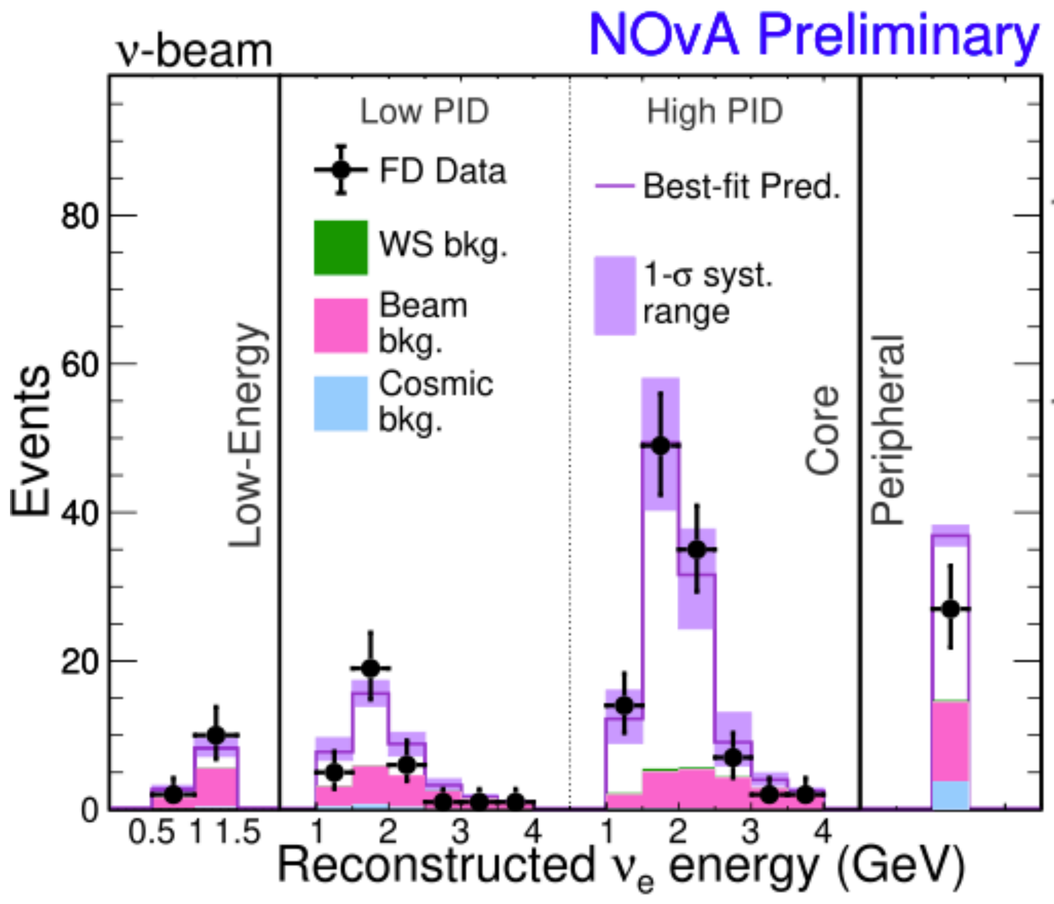


What’s next?

Next generation LBL

- On-going experiments (T2K and NOvA) proved that systematic uncertainties in LBL experiments can be reduced to <5%
- Unfortunately these experiments are still limited by statistics (~300 appearance events in $\nu+\bar{\nu}$ mode combining T2K and NOvA)
- Luckily two new experiments will come online soon
  - Hyper-Kamiokande → Water Cherenkov detector 8 times larger than SK (will collect 4000 appearance events in $\nu+\bar{\nu}$ mode) using same beam and ND complex as T2K
  - DUNE → 40 kton Liquid Argon detector with great tracking capabilities
- These larger detectors require even better understanding of the systematic uncertainties





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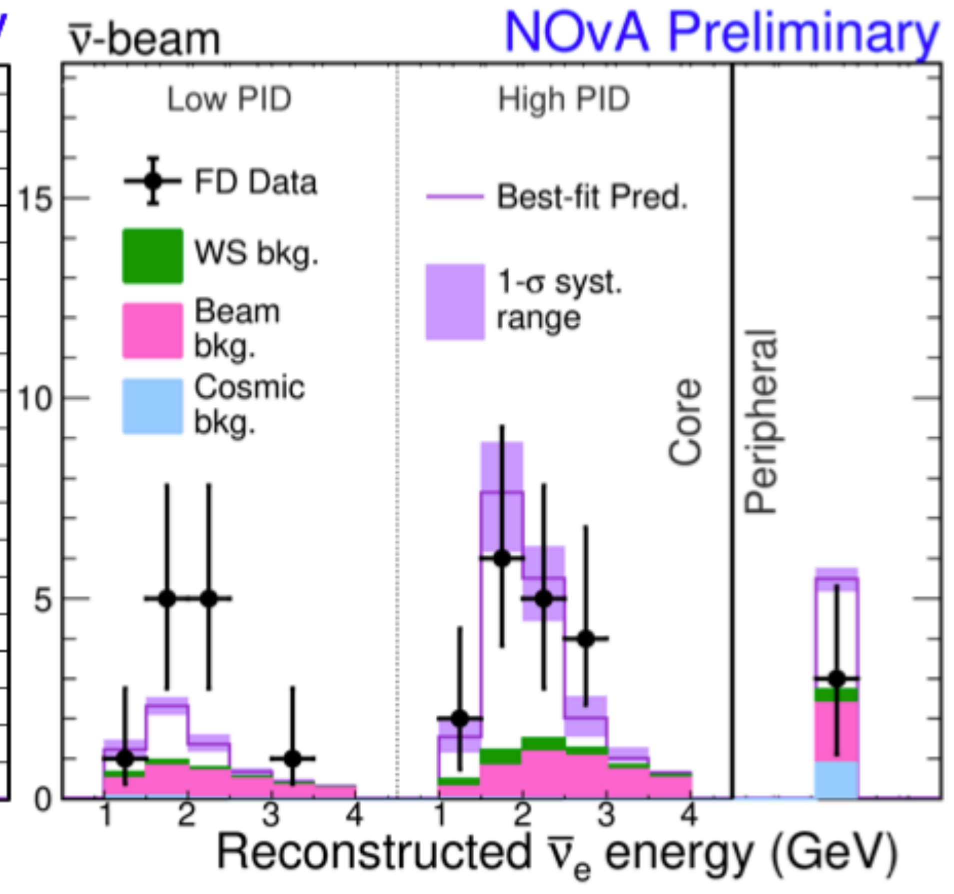

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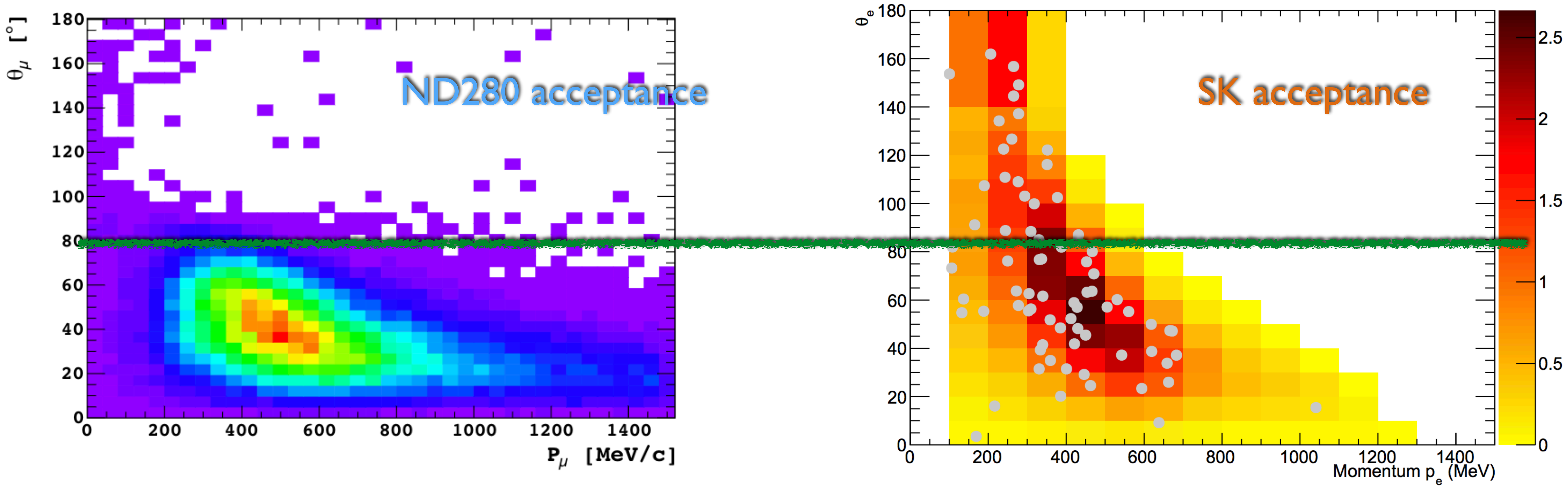
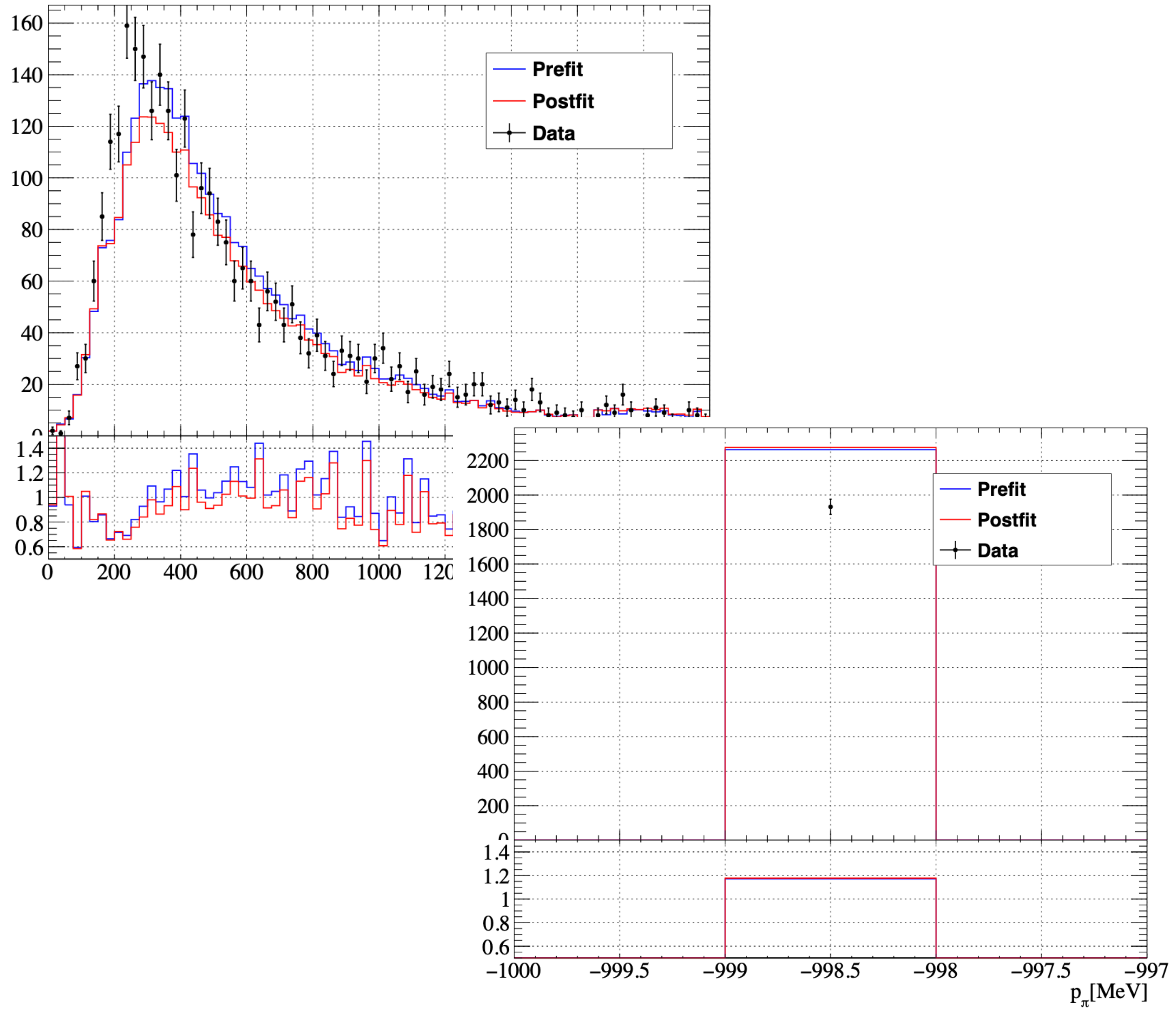
Cosmic bknd.	1.1	
Total bknd	12.2	11 – 13

ND280 Upgrade for T2K and HK





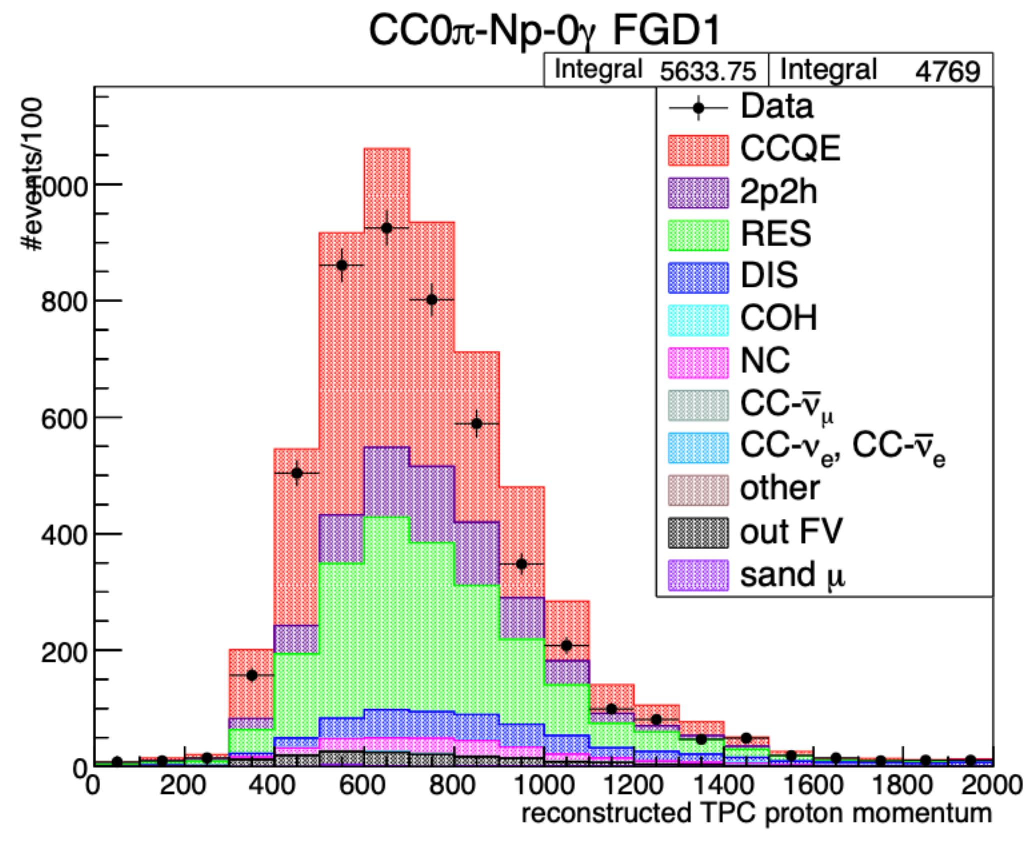
- Improve angular acceptance ν

- But also better reconstruction and usage of the hadronic part of the interactions!

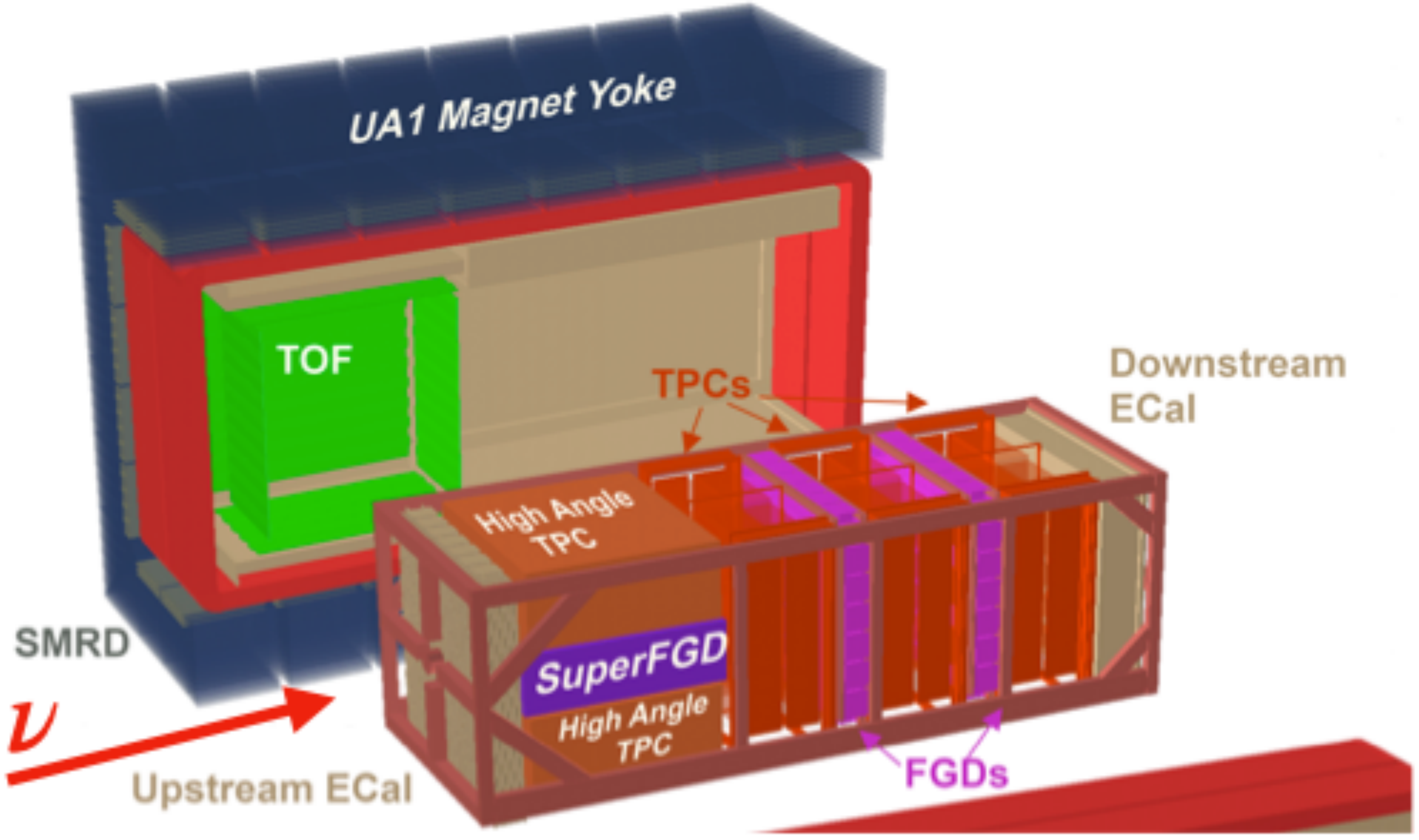
  - Currently samples are selected according to their topology (0π, 1π, 1p, Nπ, …) but the kinematics of the hadrons is not used in any way in the constraint on flux and x-sec systematics → plenty of additional information to be exploited

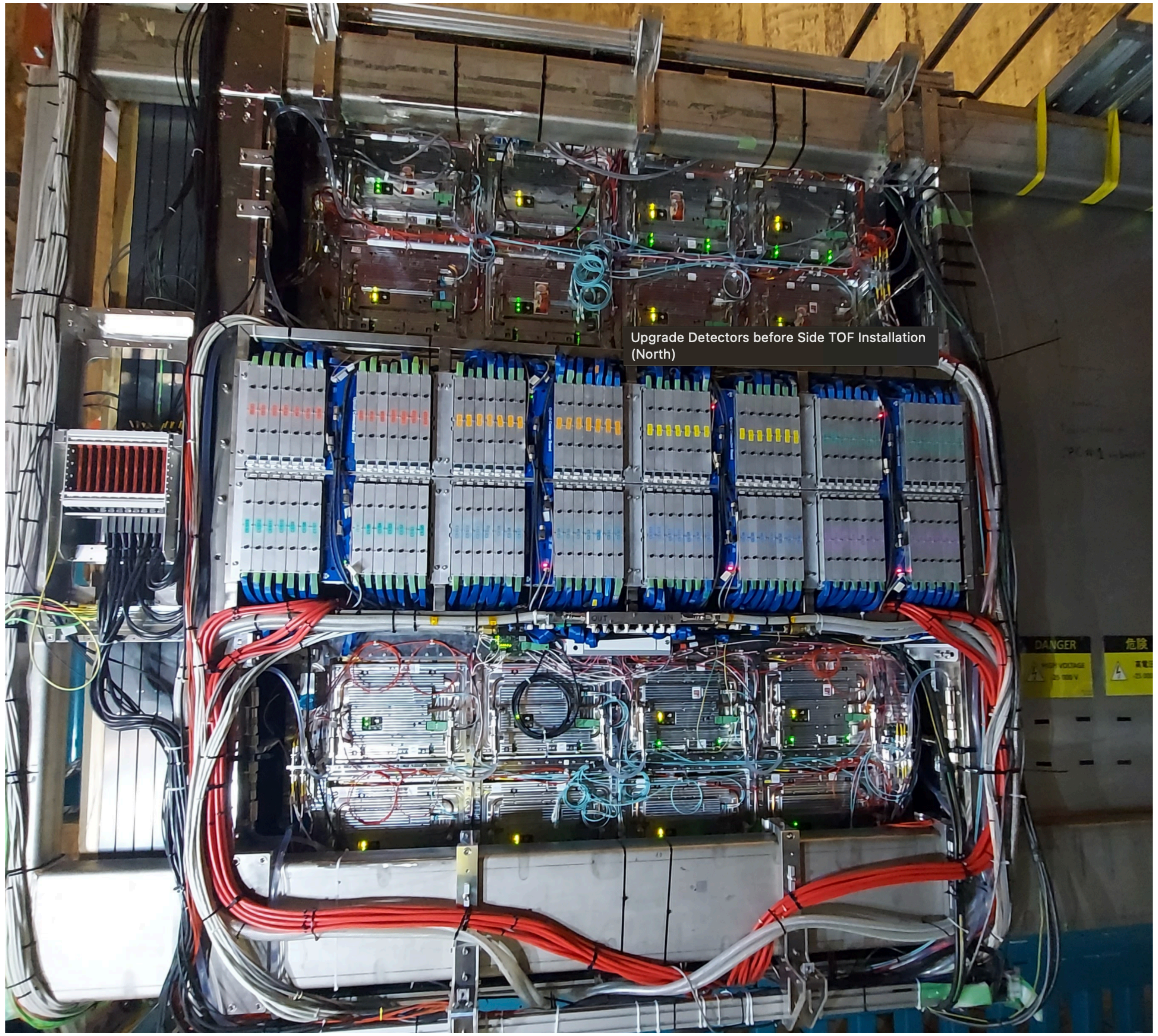
  - This is due to both, a low efficiency from ND280 to reconstruct hadrons and the diffucties in modeling the x-sec systematics for the hadronic part

    - With the upgrade we plan to improve the efficiency to reconstruct hadronic part

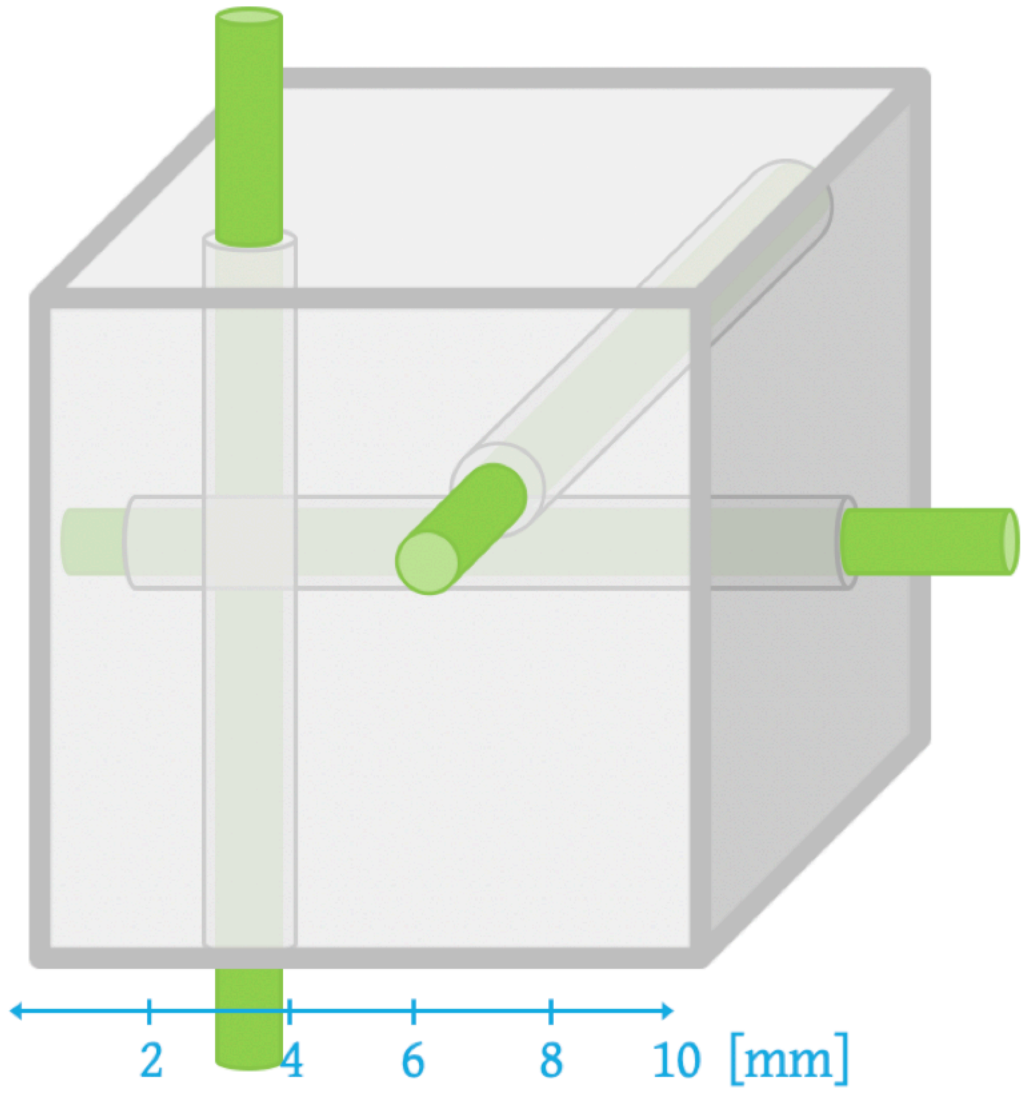


The Near Detector upgrade





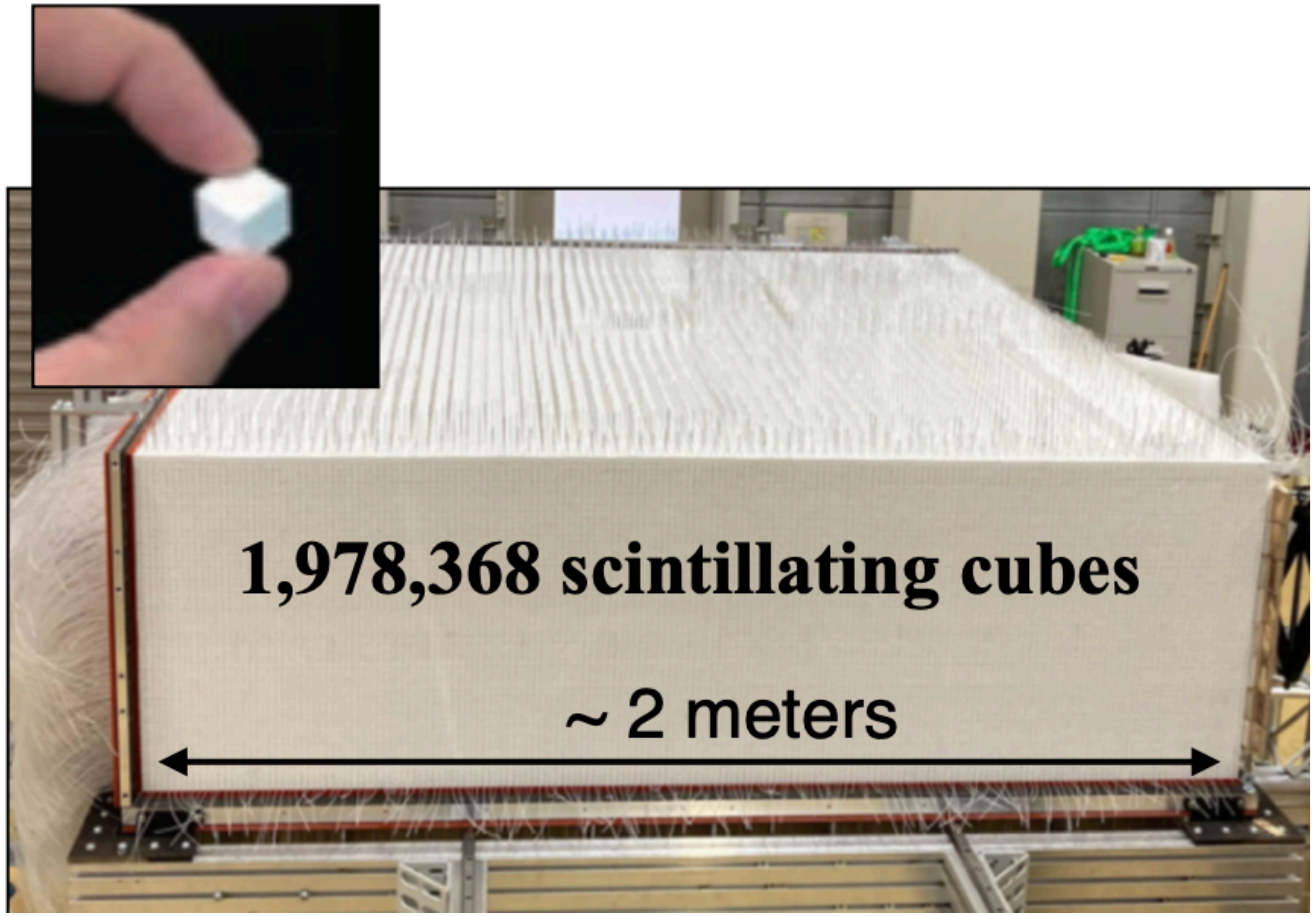
Super-FGD



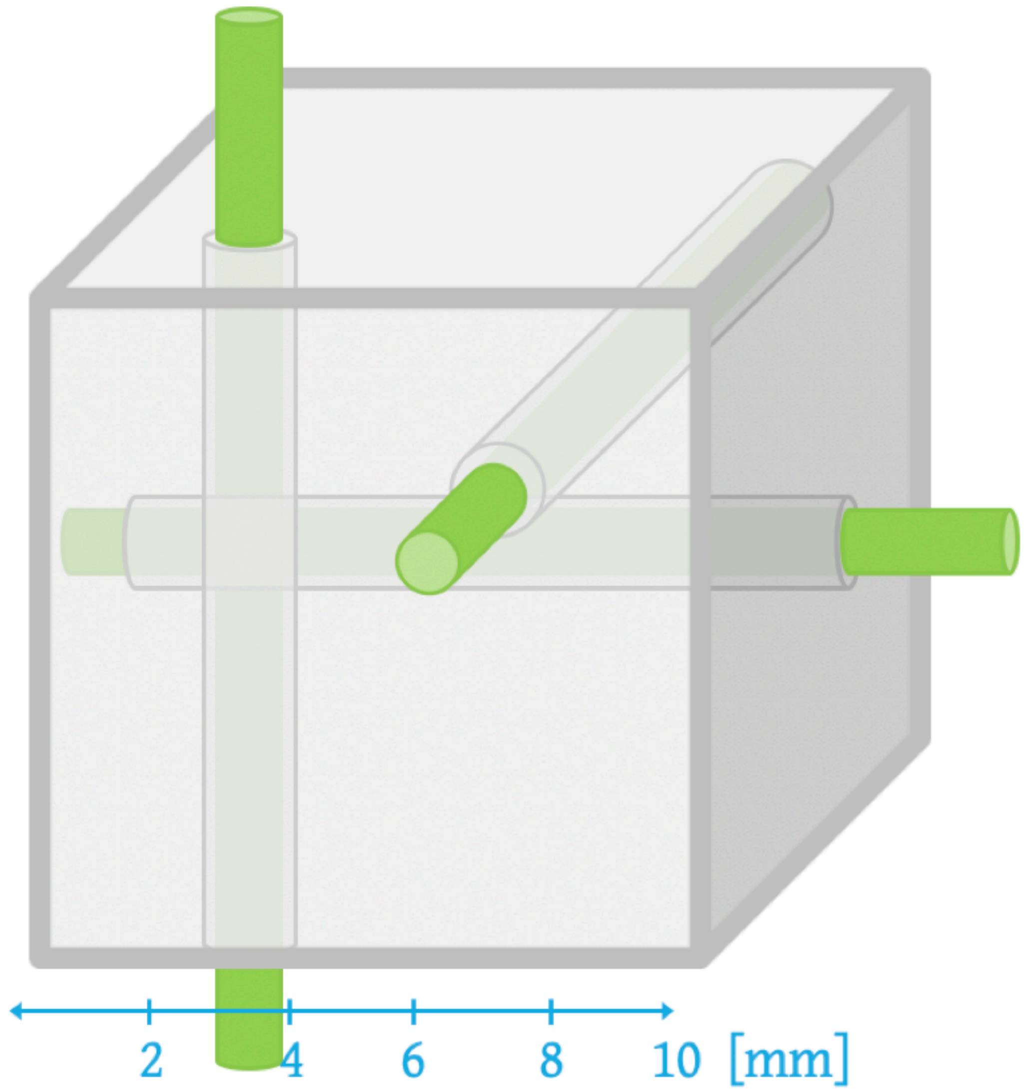
- 2 millions plastic scintillator cubes made of polystyrene and doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP.

- Each cube is optically independent

- Cubes production was done at UNIPLAST (Russia)

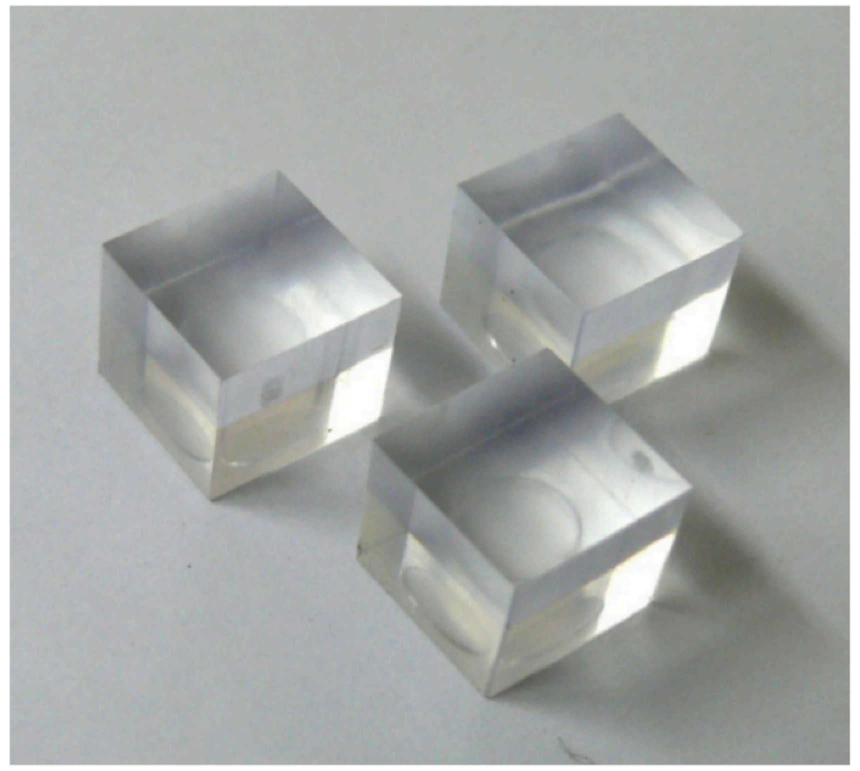


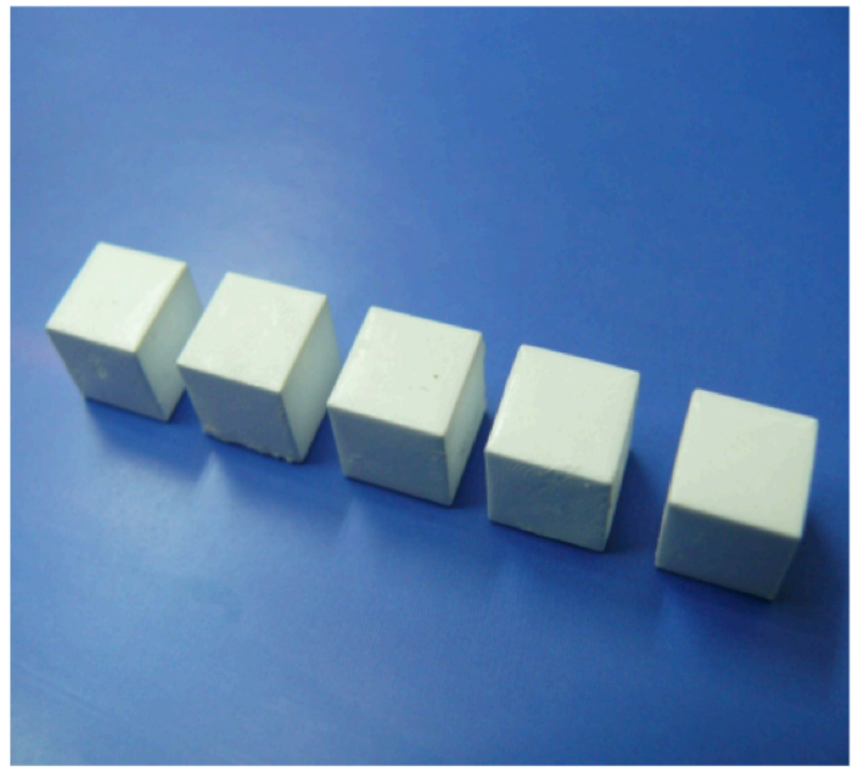
Super-FGD

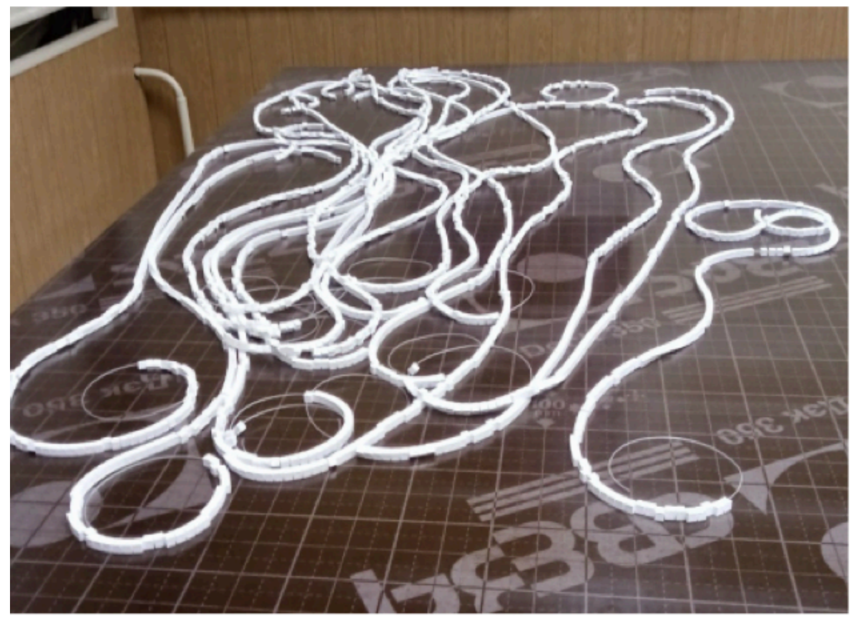


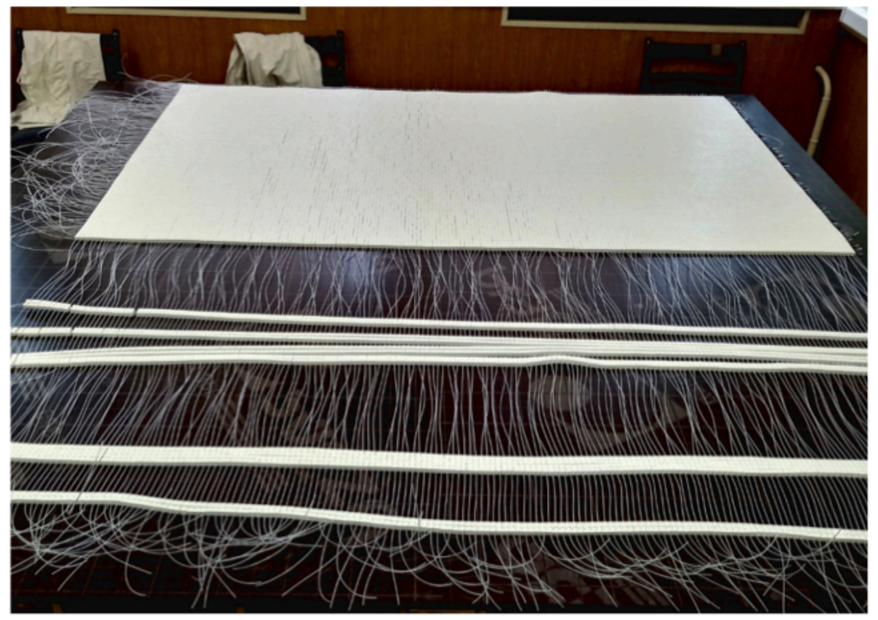
- 2 millions plastic scintillator cubes made of polystyrene and doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP.
- Each cube is optically independent
- Cubes production was done at UNIPLAST (Russia)

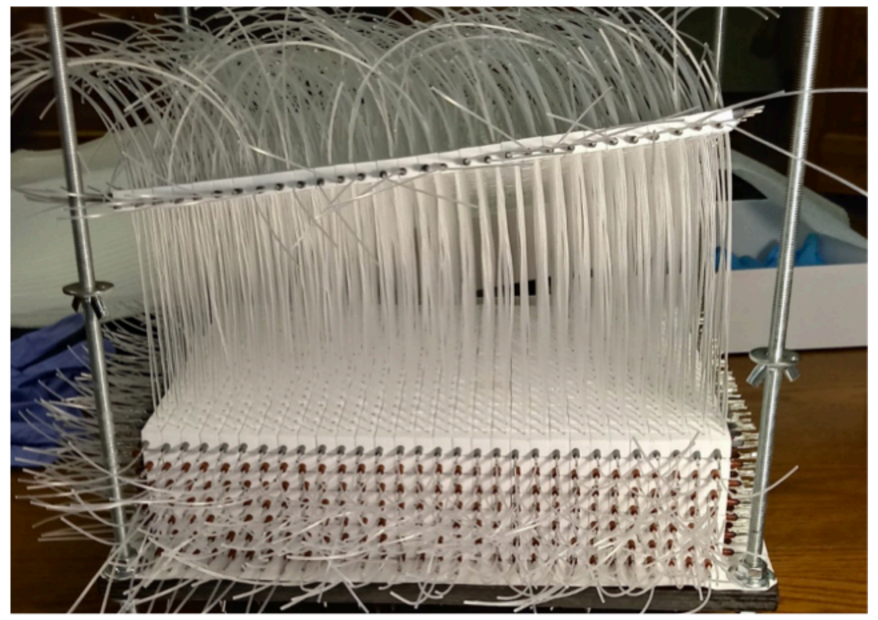
Produce cubes by injection molding → **Etched in a chemical to deposit a reflective layer** → **3 orthogonal holes are drilled**







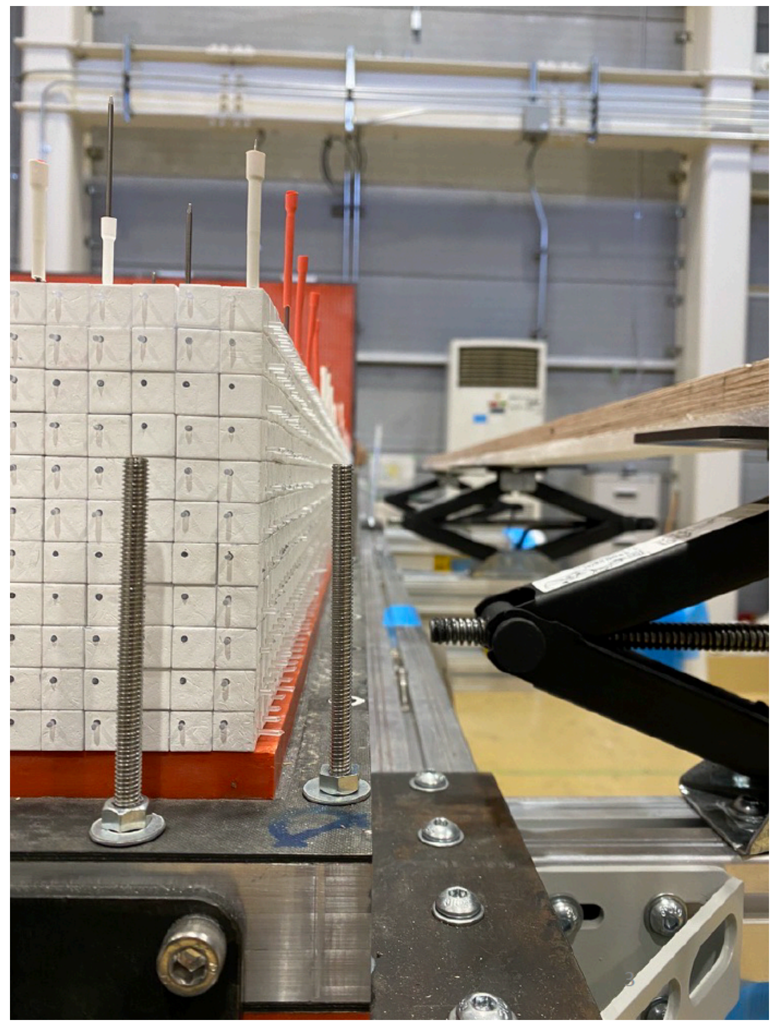




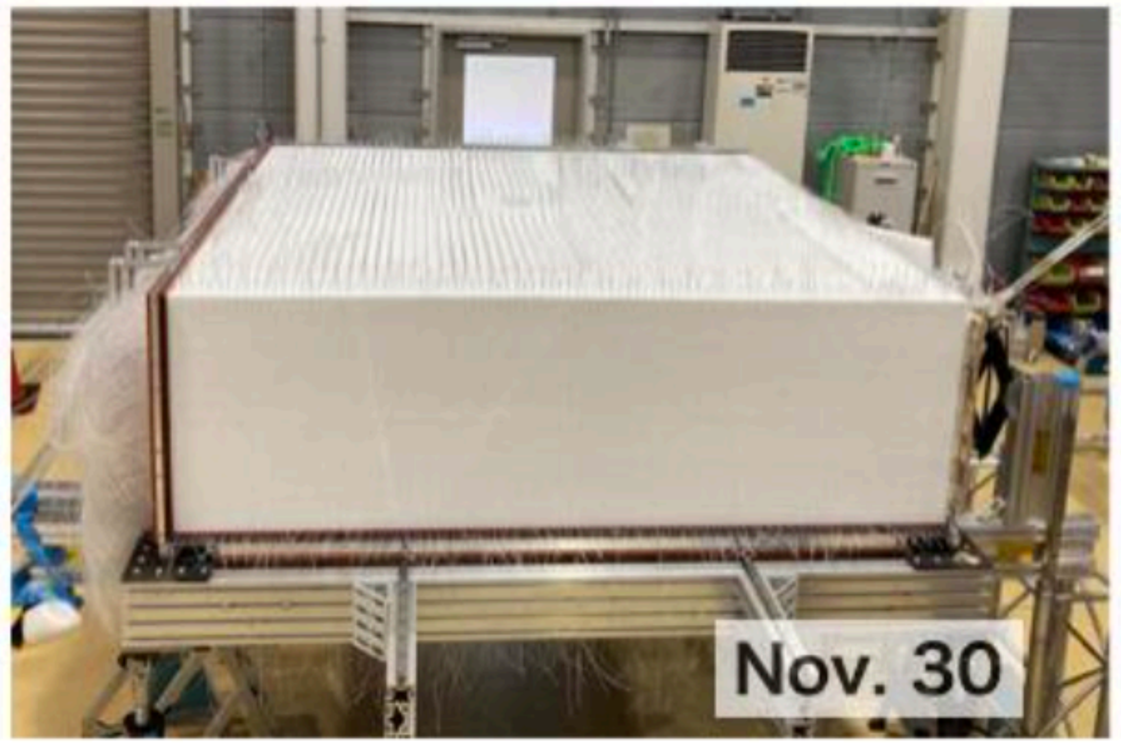
Assembled in 56 X-Y layers with fishing lines before shipment to Japan

SuperFGD assembly at J-PARC

First cube layer assembly



Stop panels removed

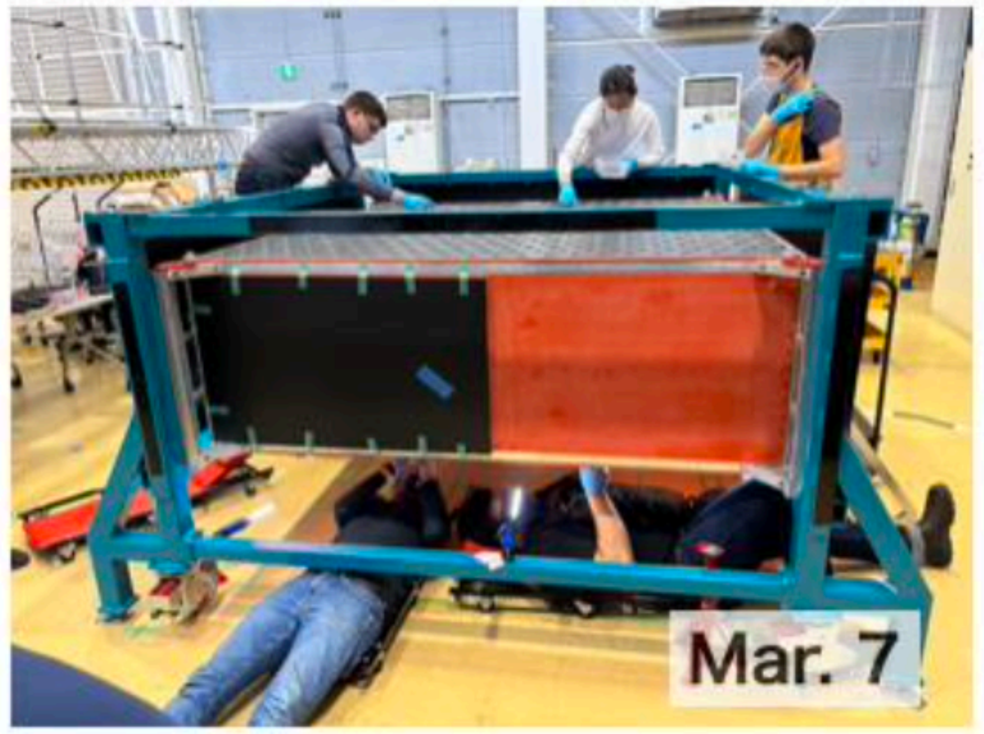


Box closure

Horizontal fibers assembly

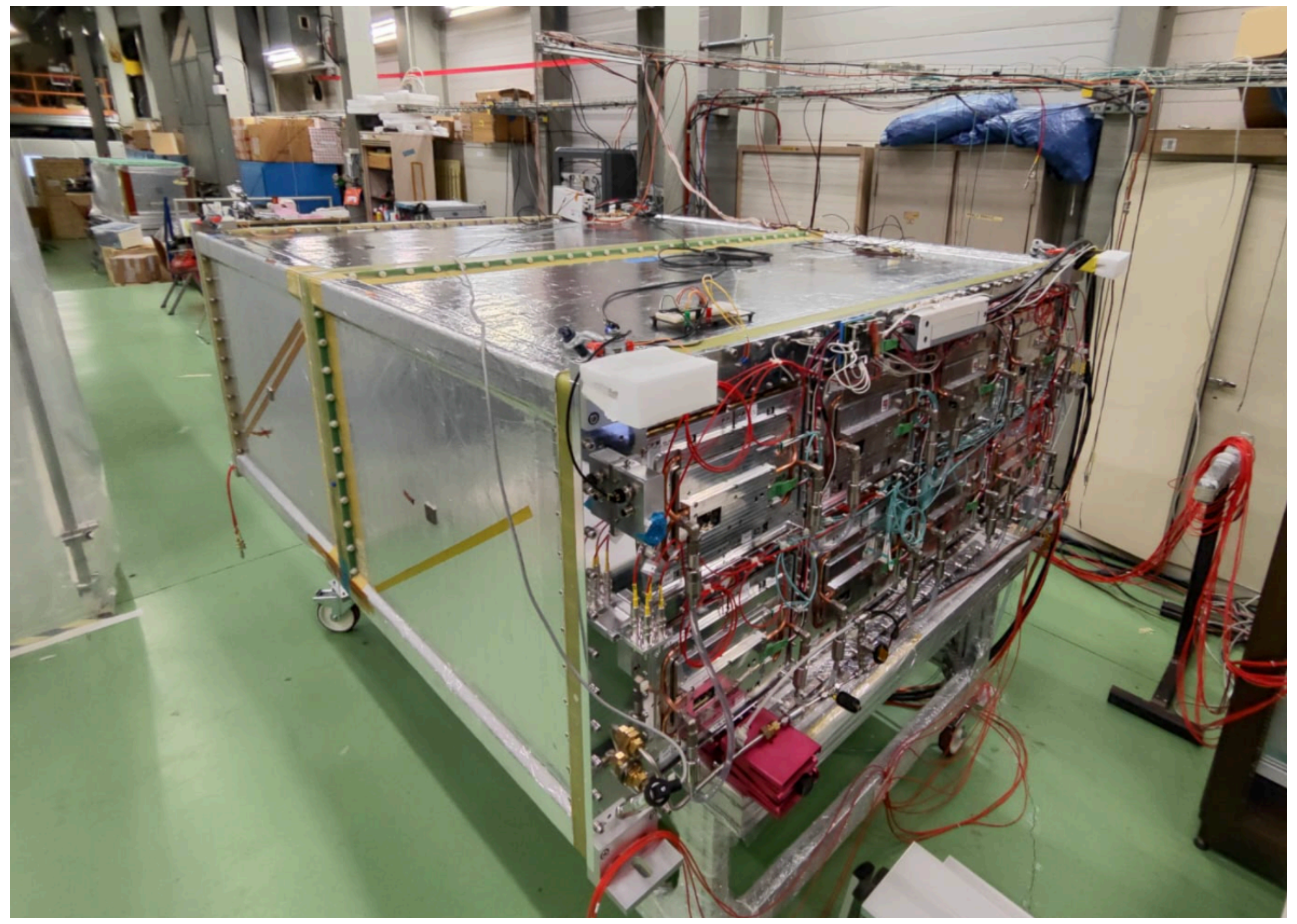
Vertical fibers assembly

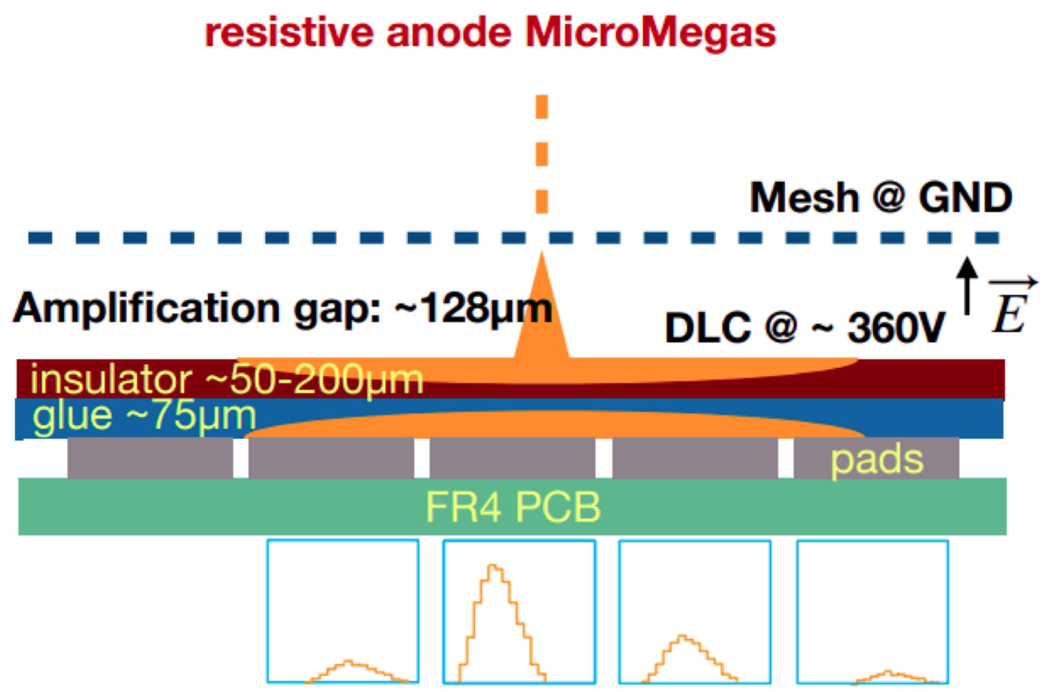
Top MPPCs assembly



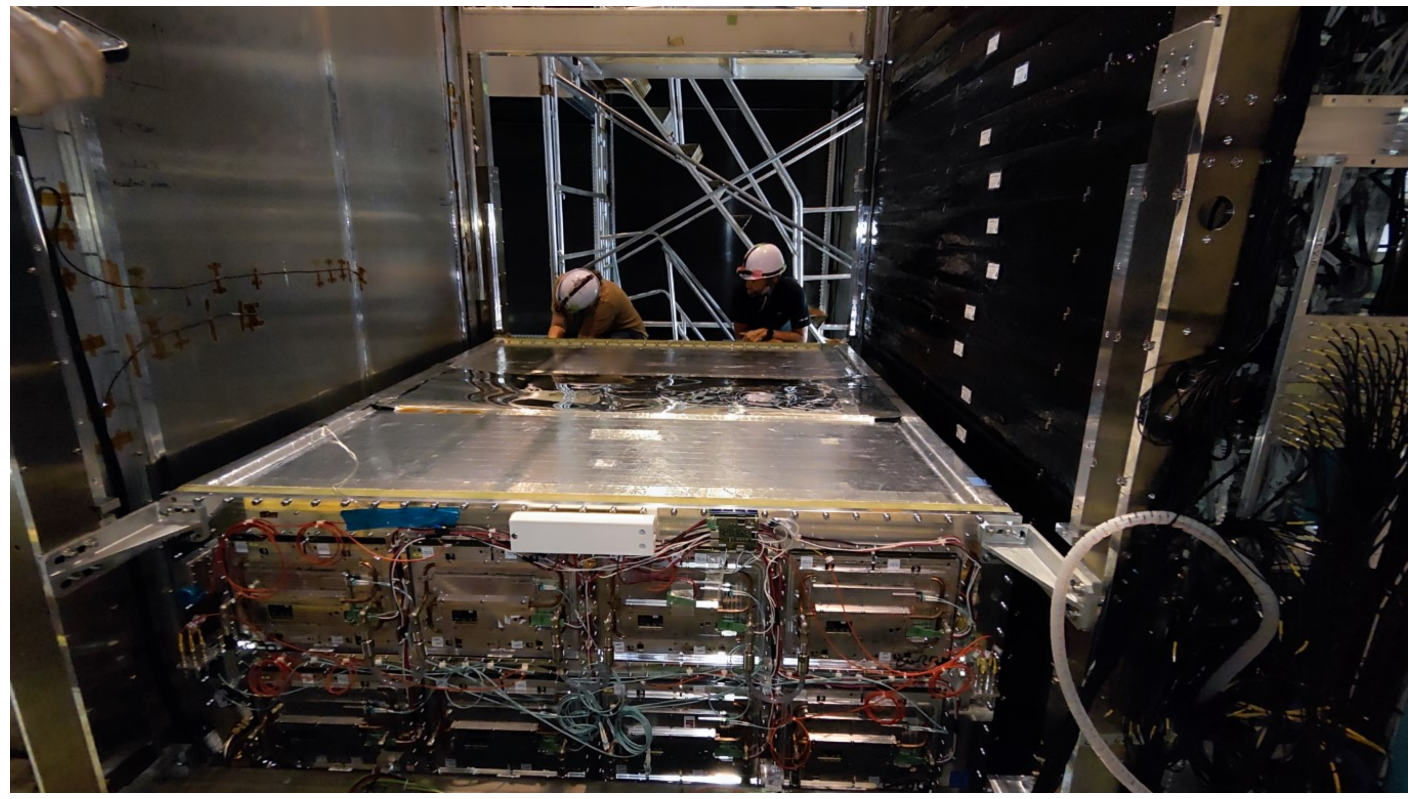
Light barrier/cables asse

High-Angle TPCs

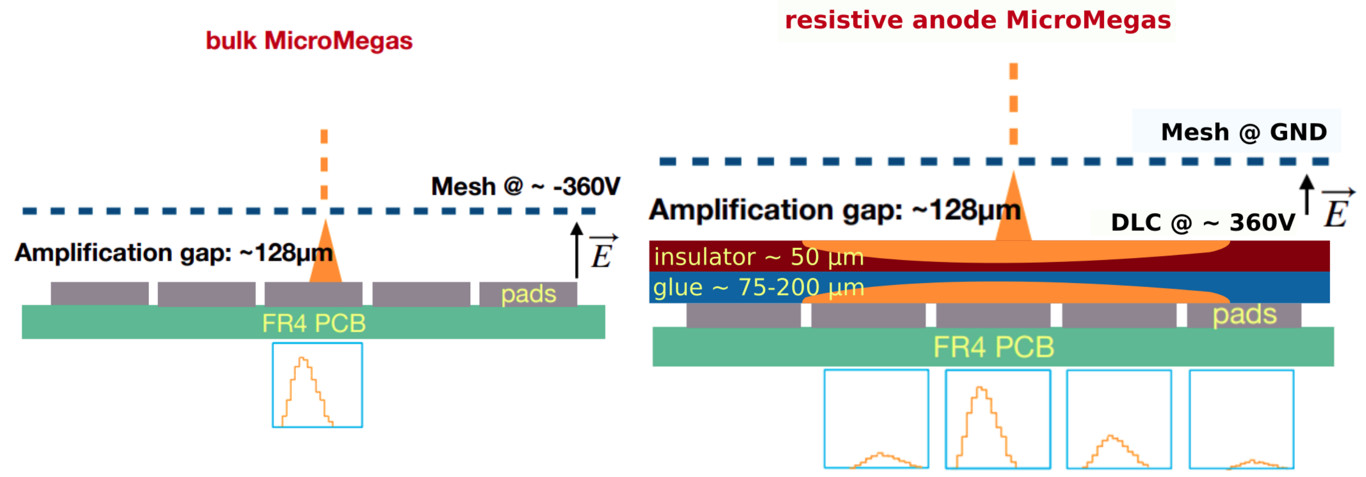


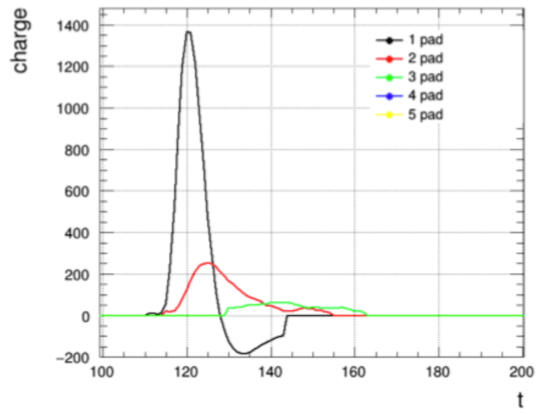


- Reconstruct leptons emitted at high angle with respect to the beam
- TPC instrumented with resistive MicroMegas modules
- Chambers have been assembled and tested at CERN before shipment



HATPC performances



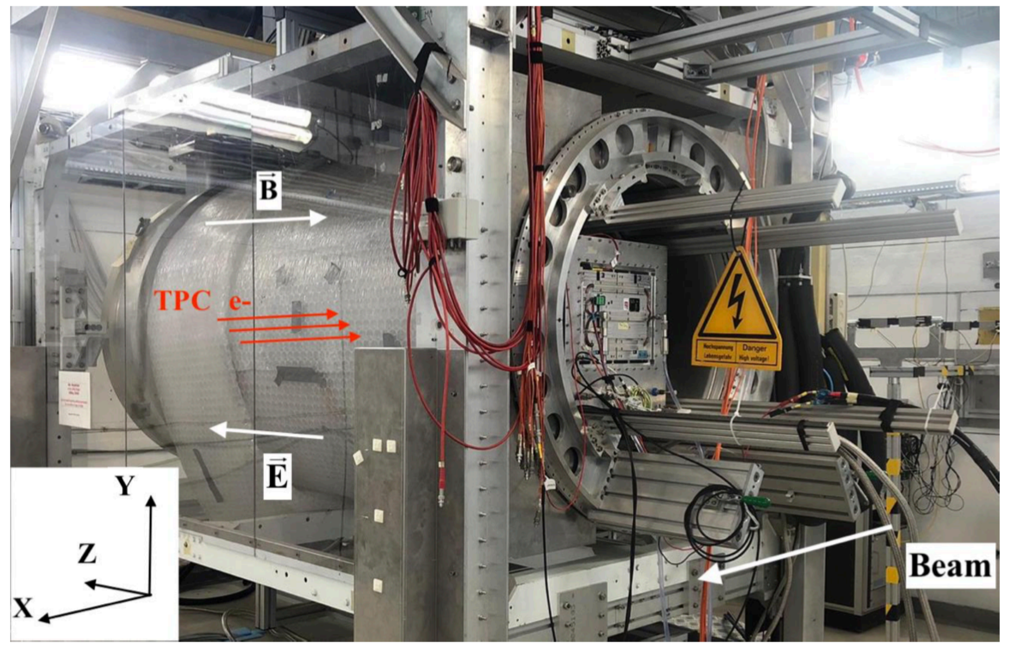


$$\rho(r,t) = \frac{RC}{2t}\exp\left[-\frac{r^2 RC}{4t}\right]$$

R- surface resistivity
C- capacitance/unit area

Gaussian spreading as a function of time with :

$$\sigma_r = \sqrt{\frac{2t}{RC}} \quad \begin{cases} t \approx shaping\ time\ (few\ 100\ ns) \\ RC_{[ns/mm^2]} = \dfrac{180\, R_{[M\Omega/\blacksquare]}}{d_{[\mu m]}/175} \end{cases}$$



- 3 test beam campaigns to characterise ERAM detectors
- Spatial resolution between 200 and 600 µm (w.r.t. 600 to 1000 for vertical TPCs)
- dE/dx resolution below 10%

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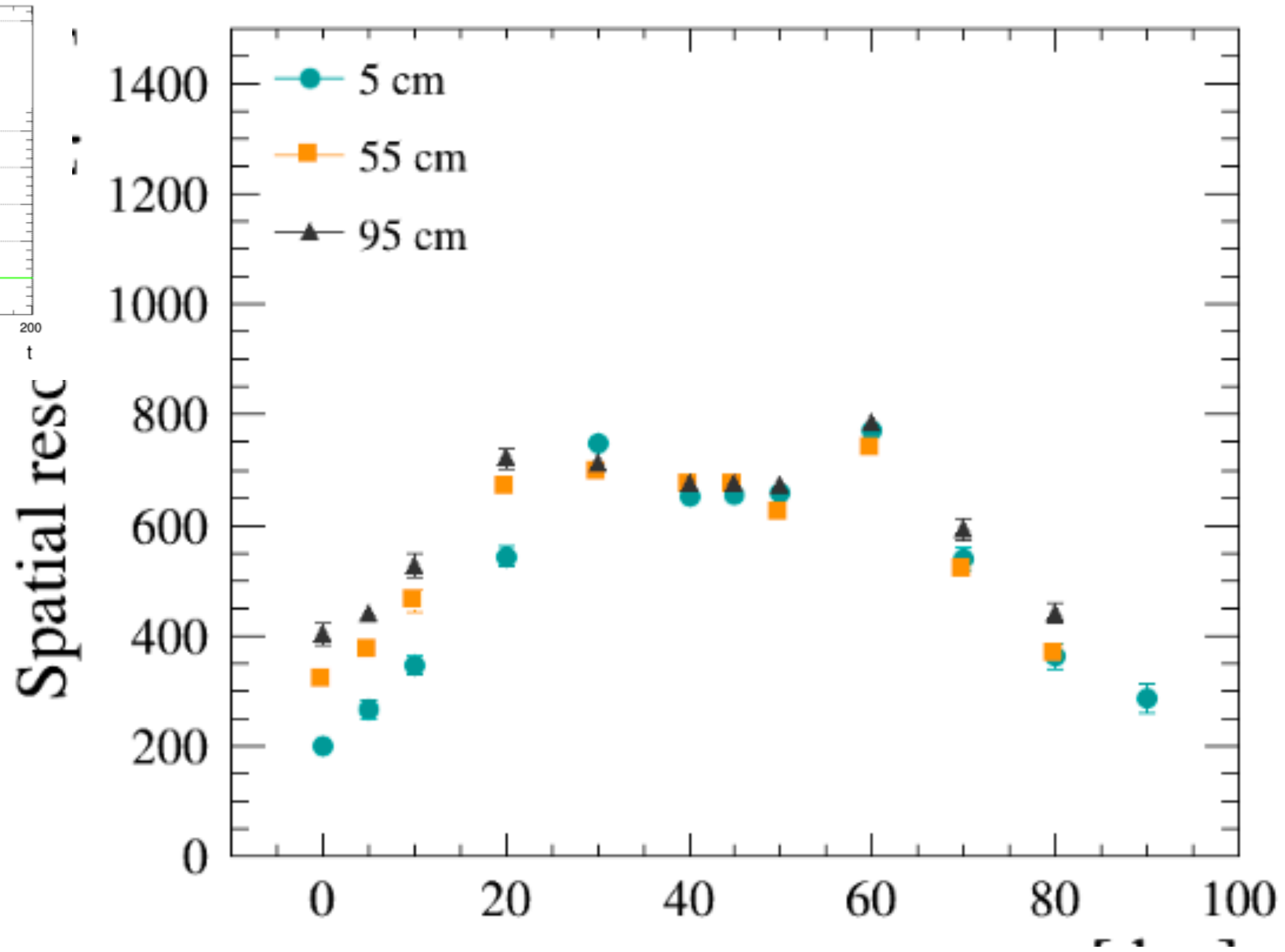
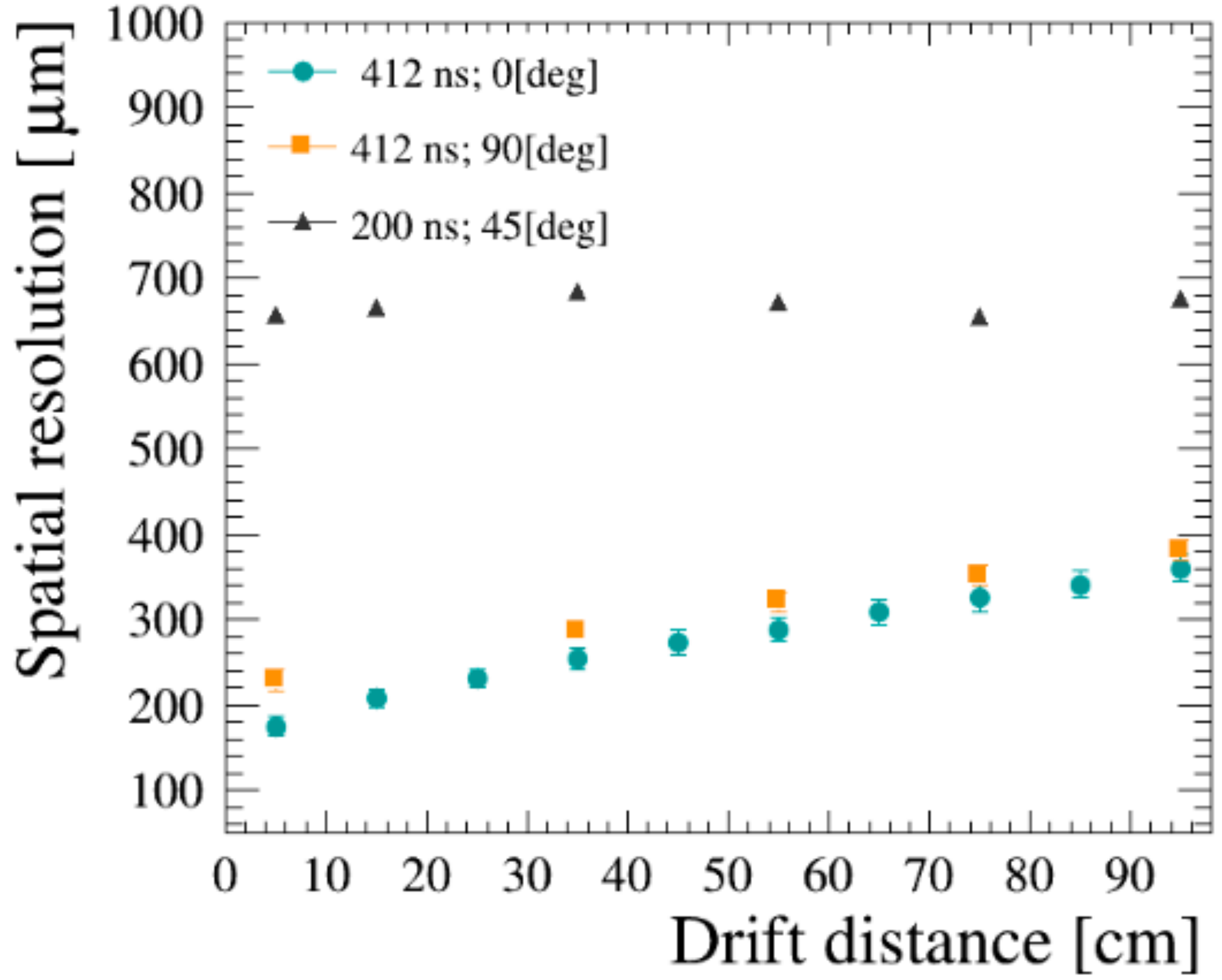
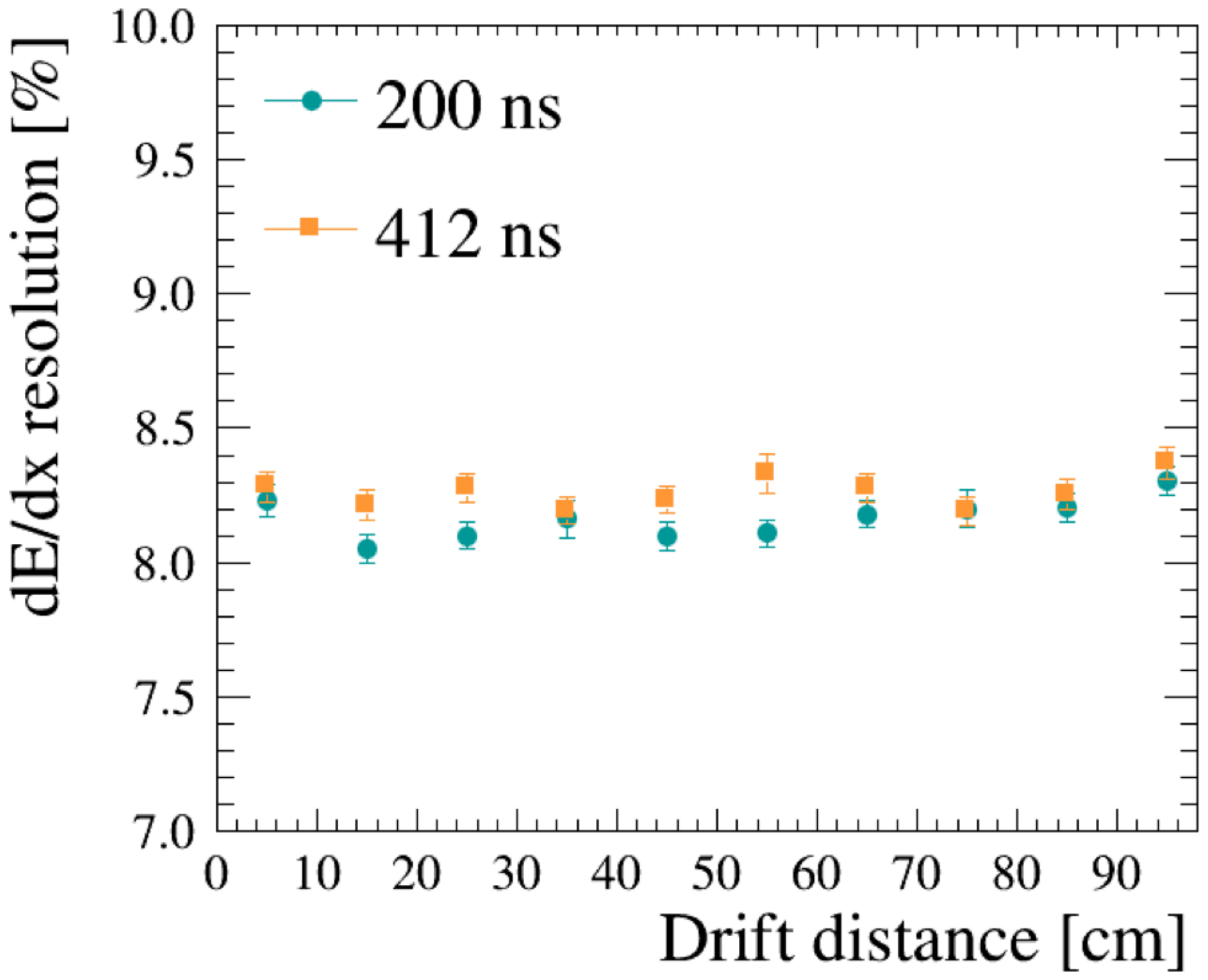
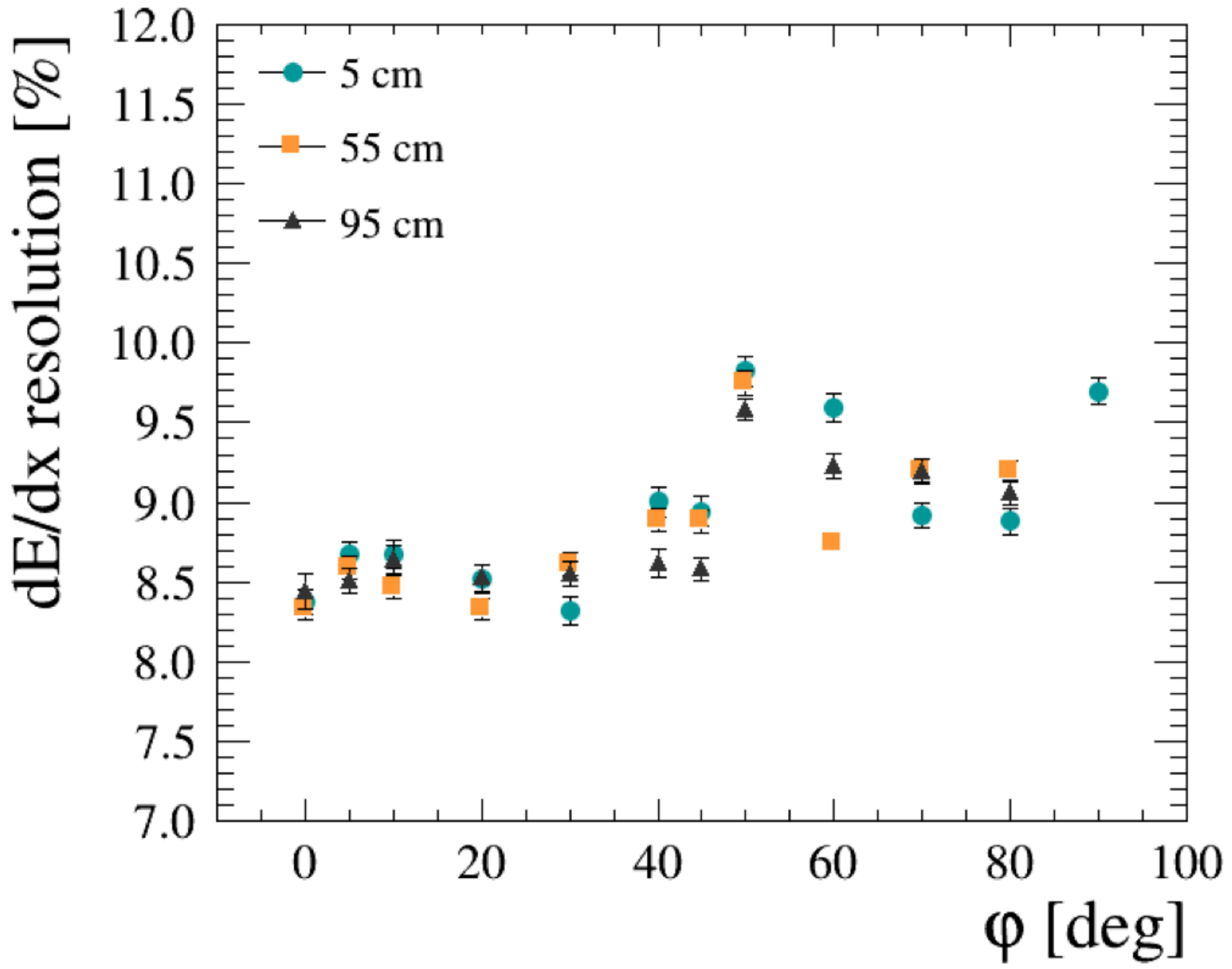
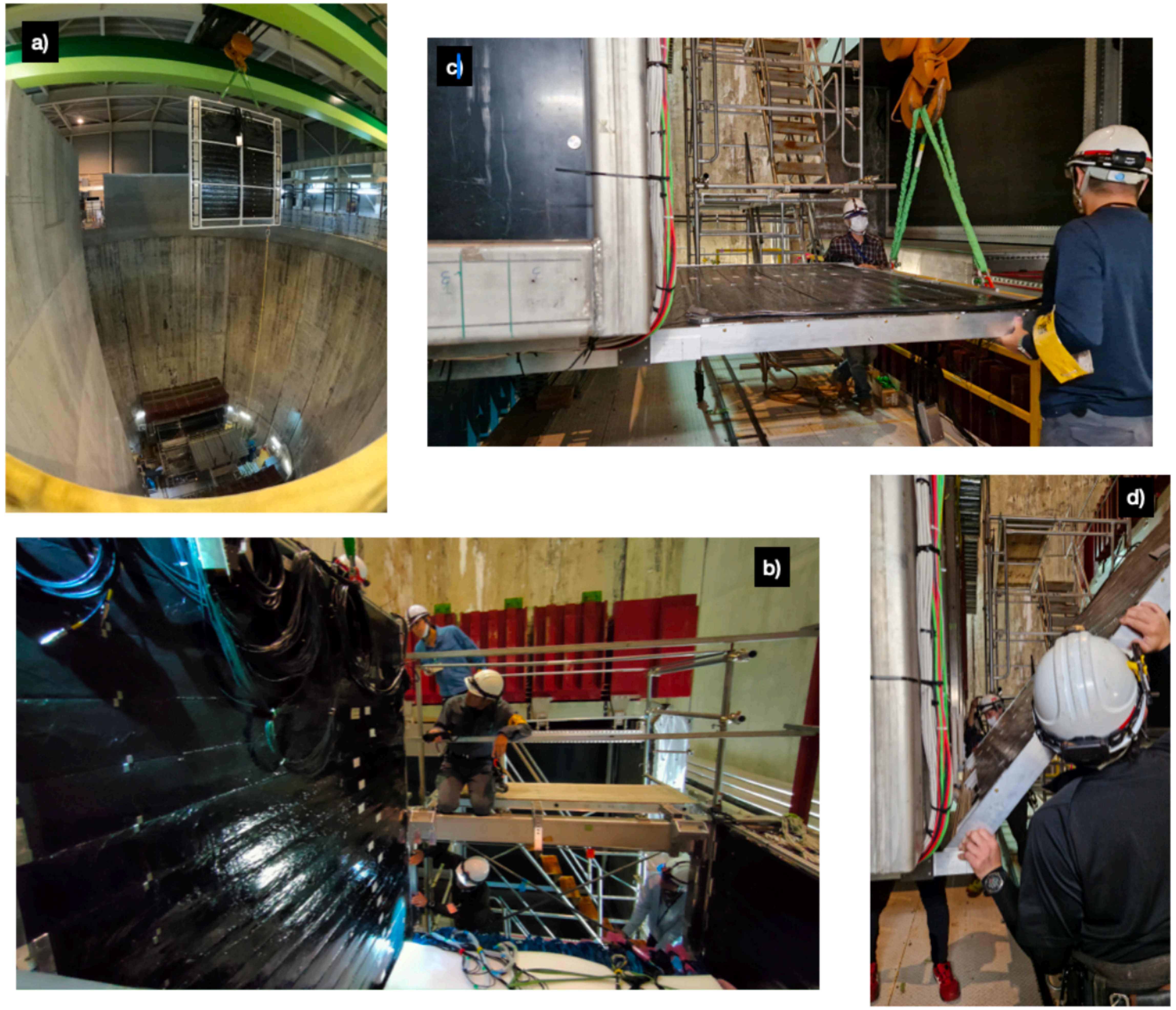




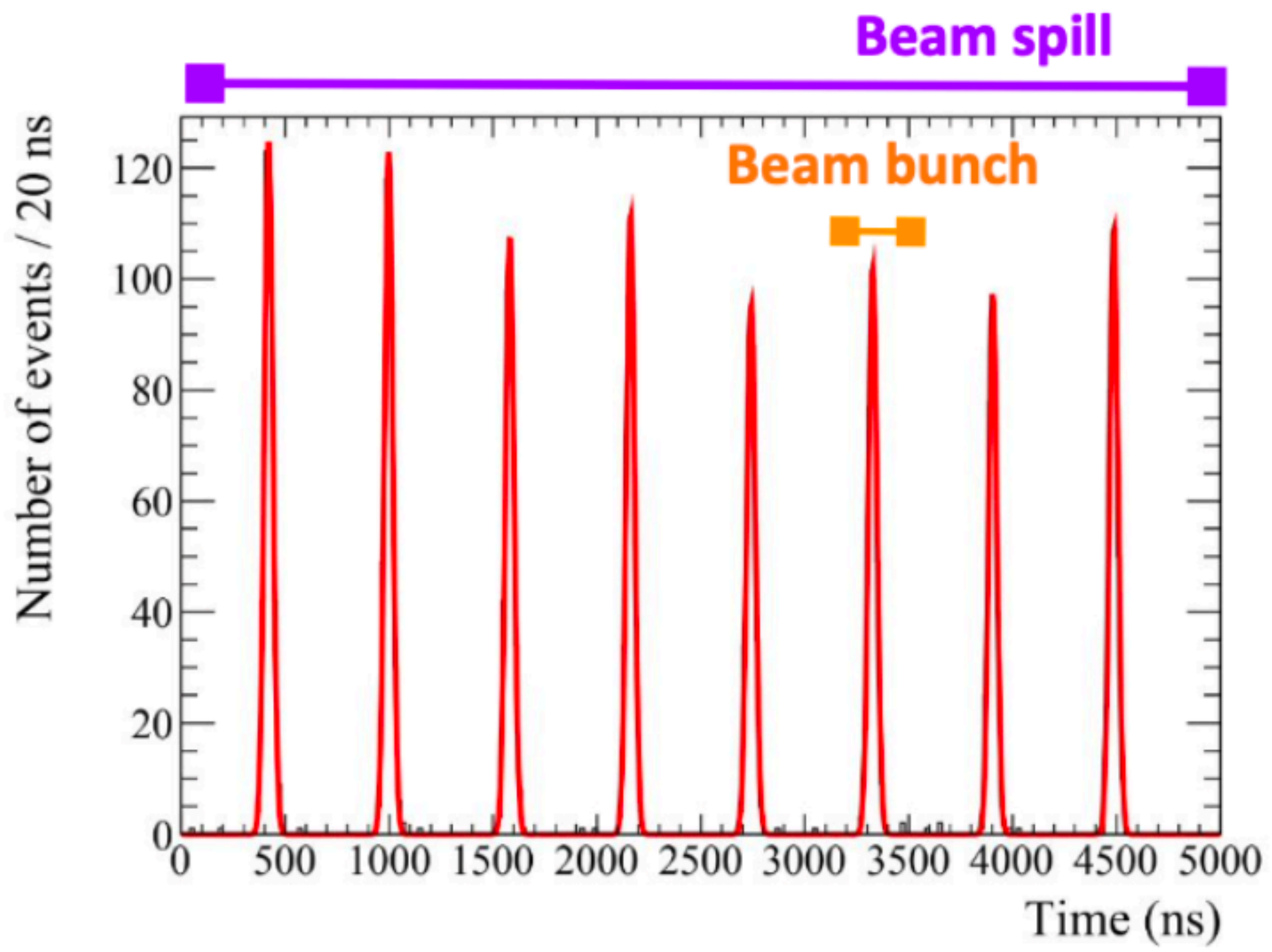




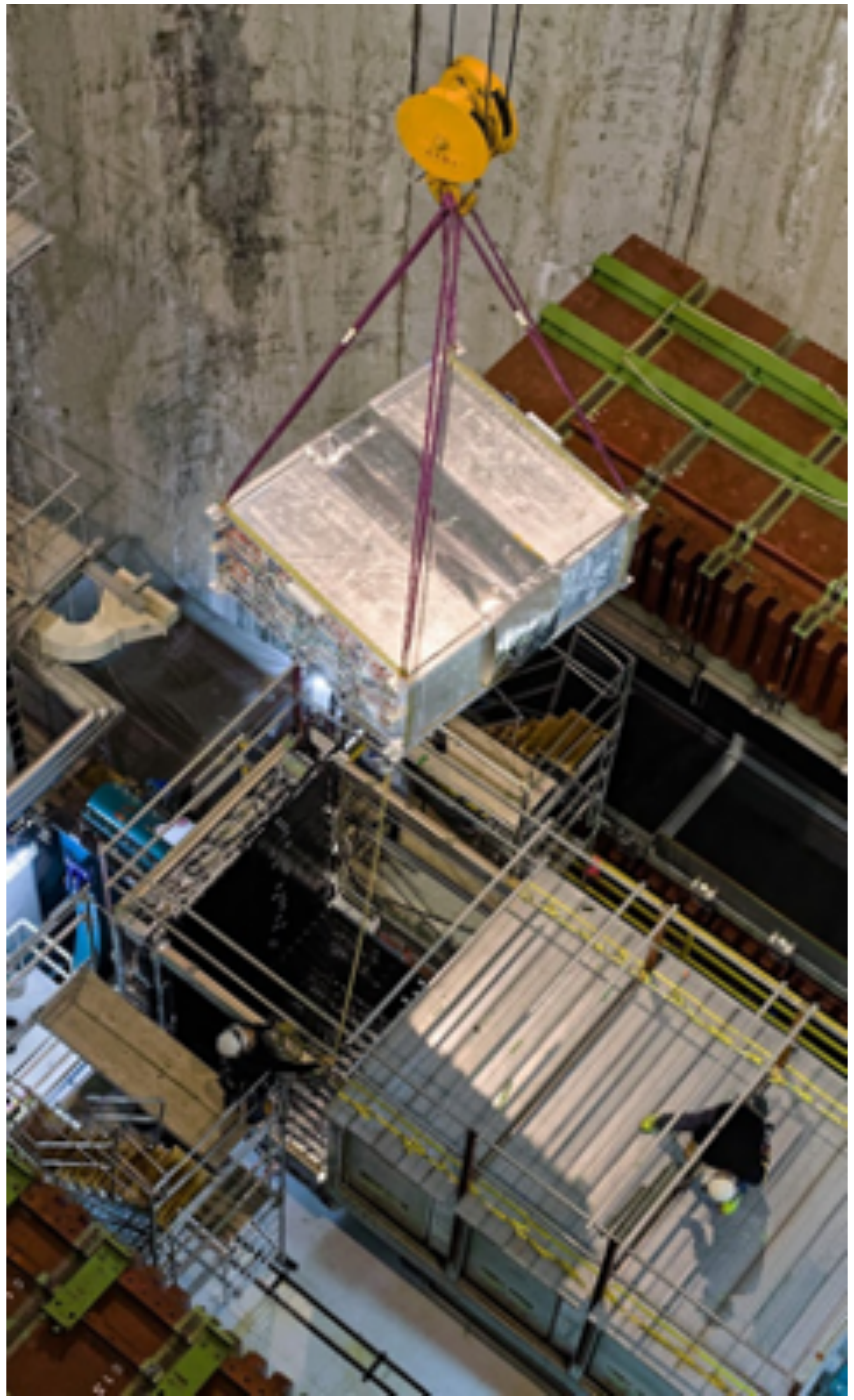
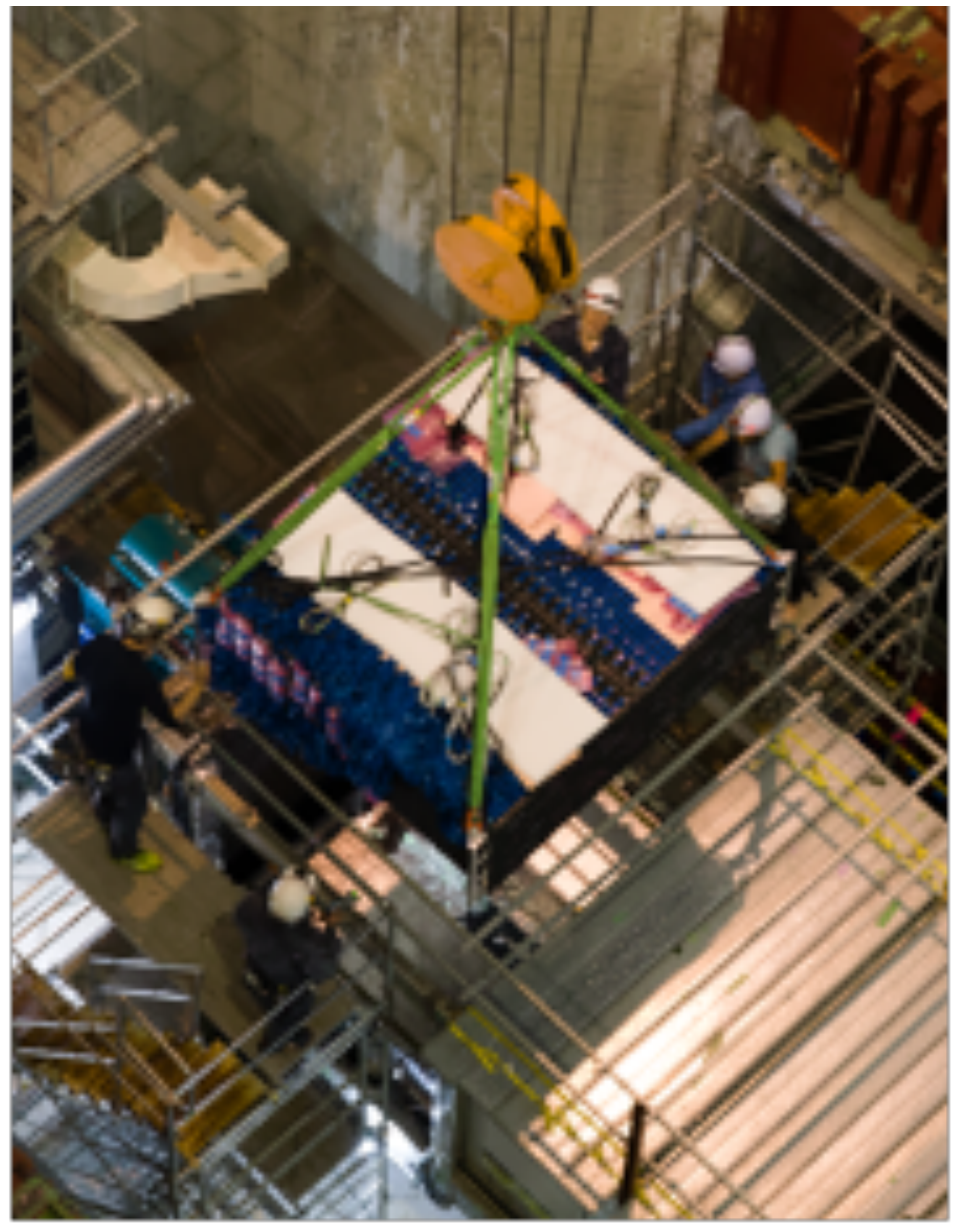
Time-Of-Flight

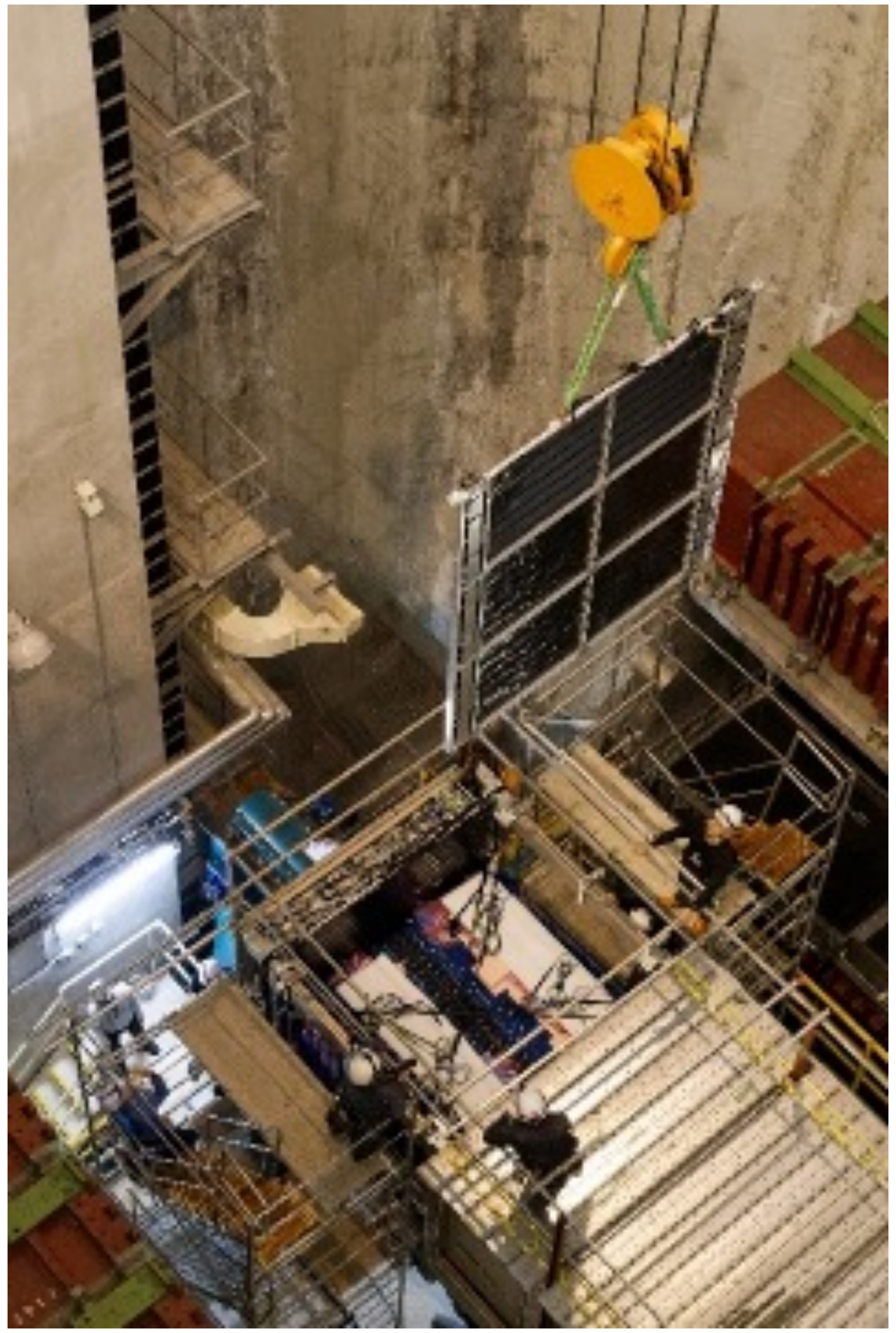


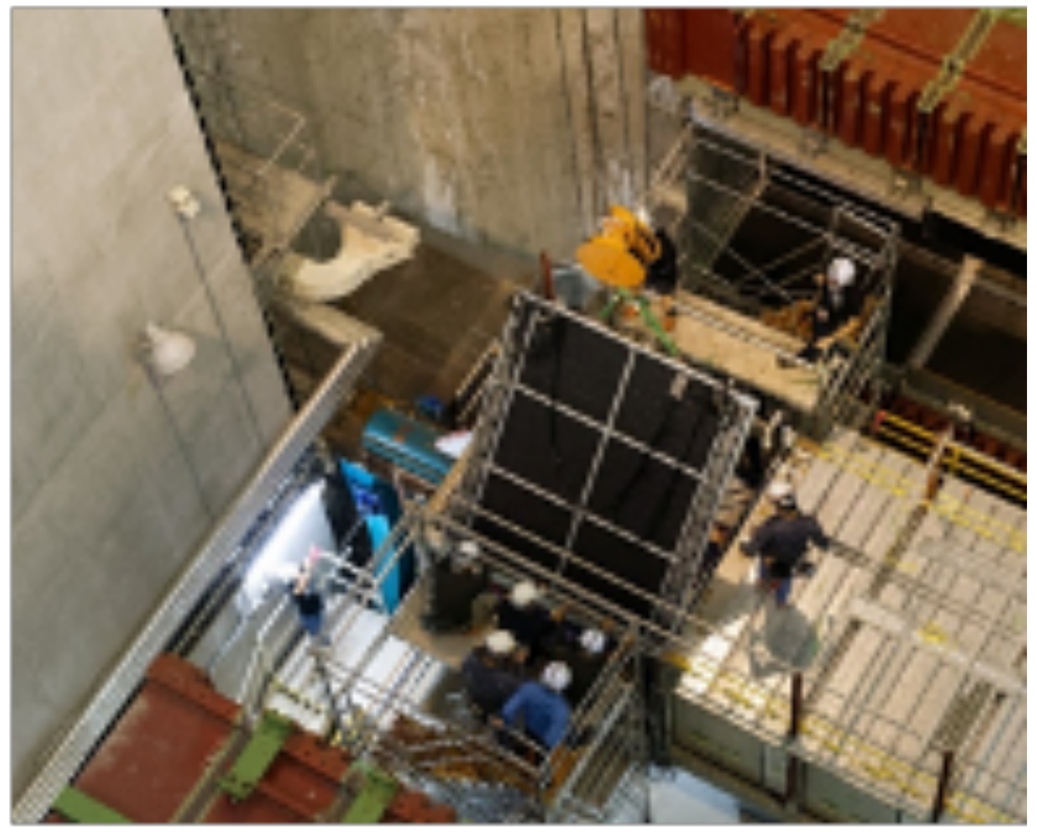
- Reconstruct track direction to reject tracks entering the new tracker region
- All 6 TOF modules assembled and tested at CERN and shipped to J-PARC
- Time resolution ~ 150 ps observed during tests at CERN
- 8 bunches neutrino beam structure clearly visible



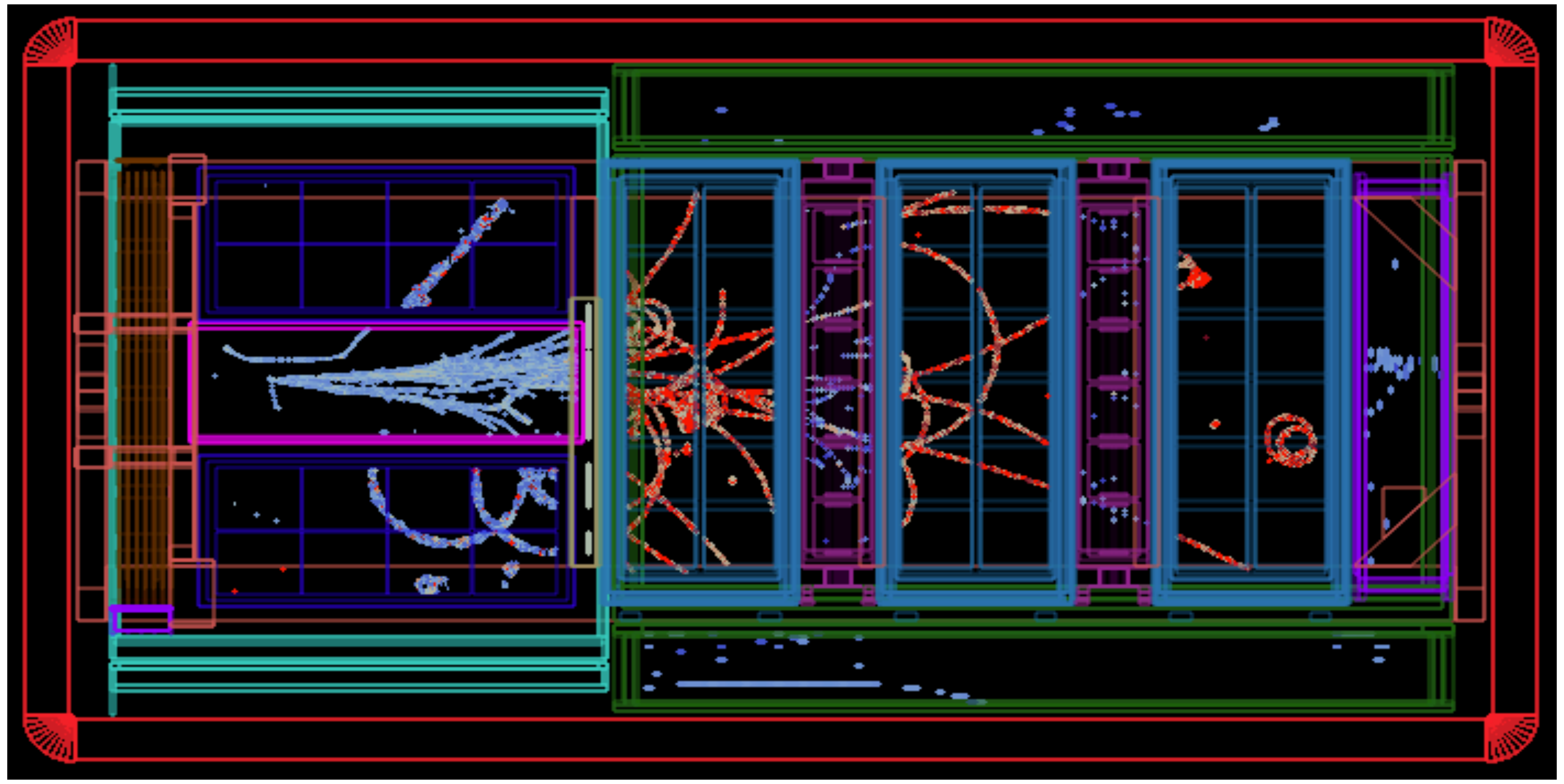
Installation at J-PARC

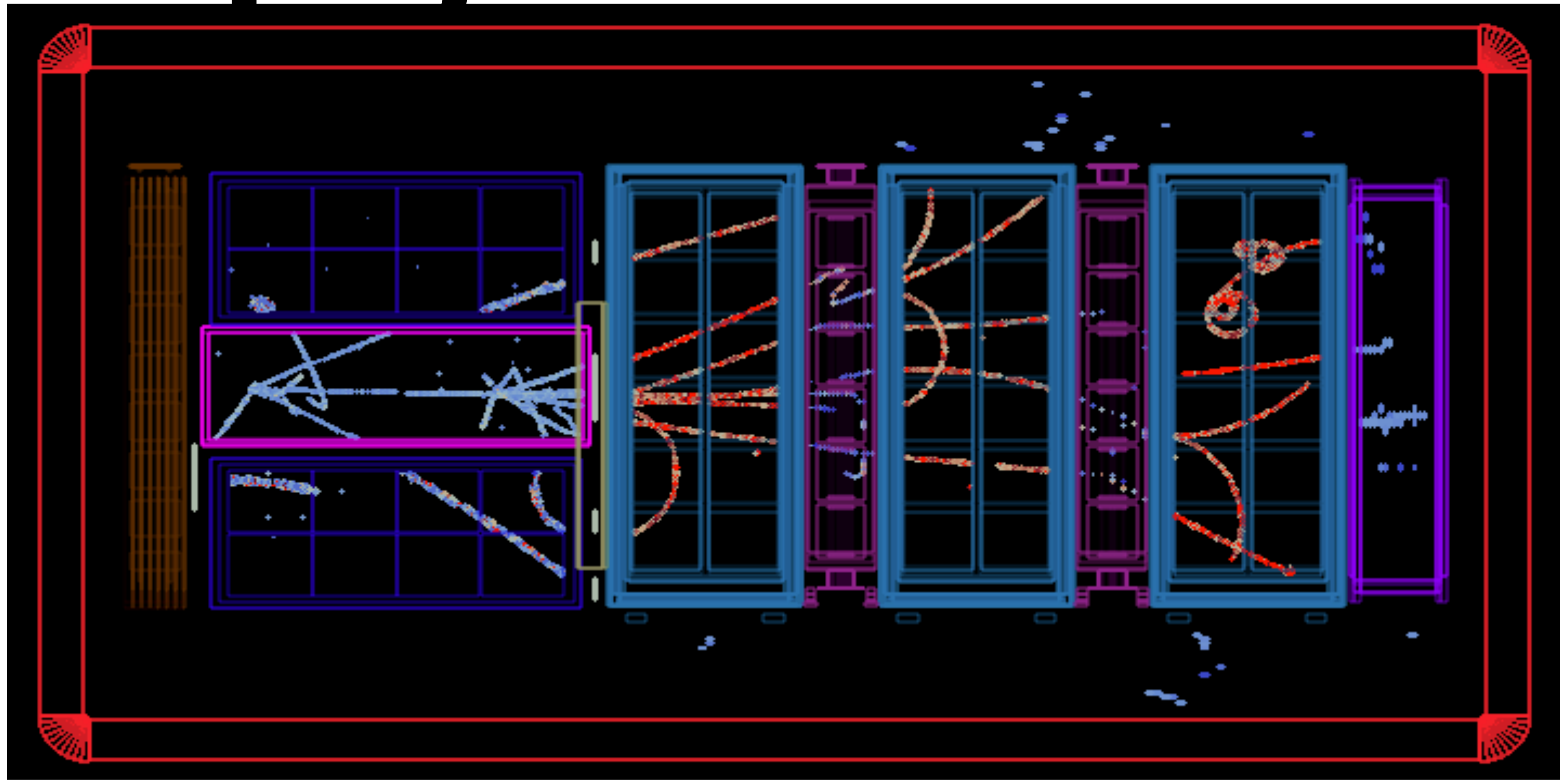



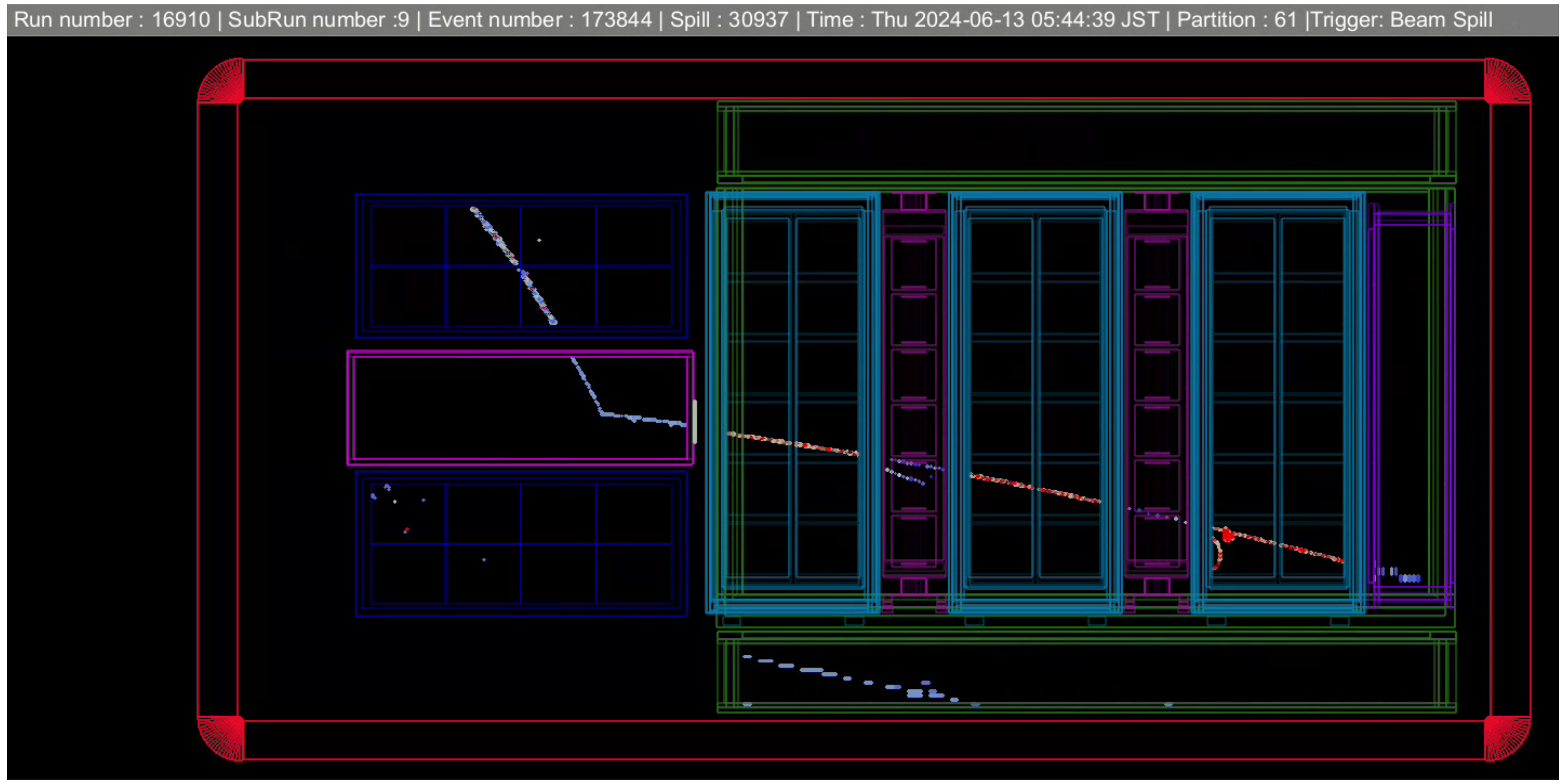


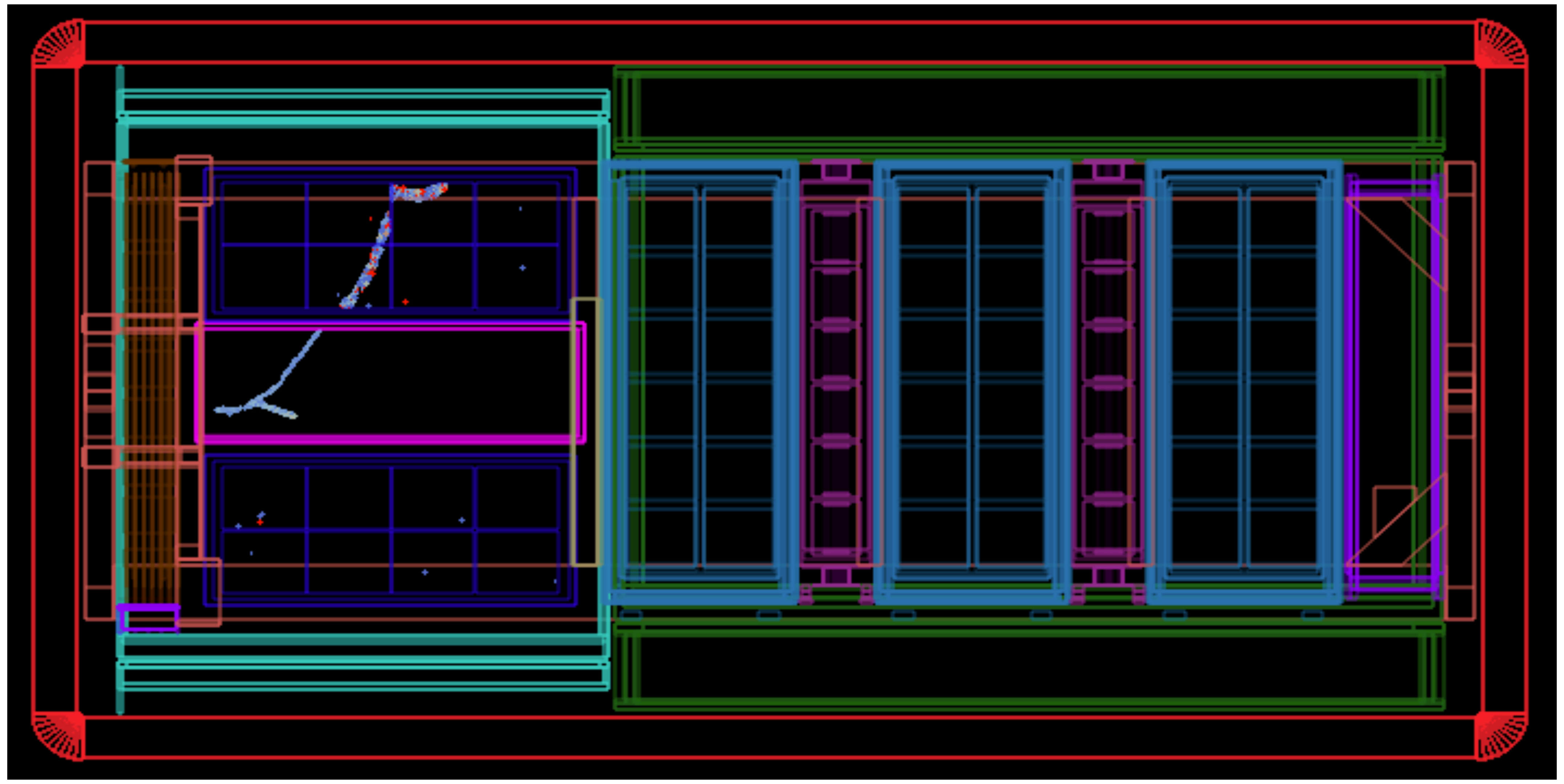


June 2024: Full upgrade

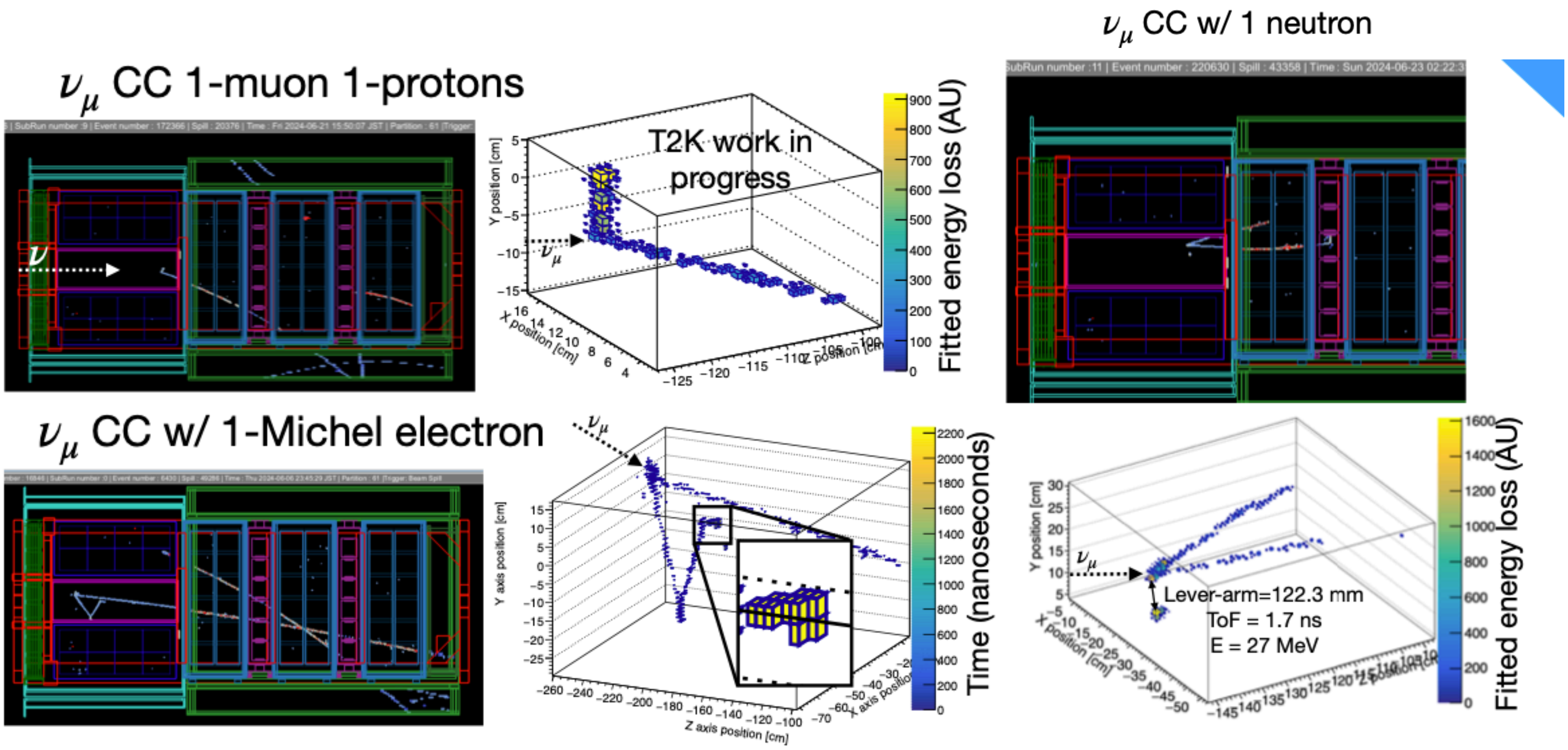








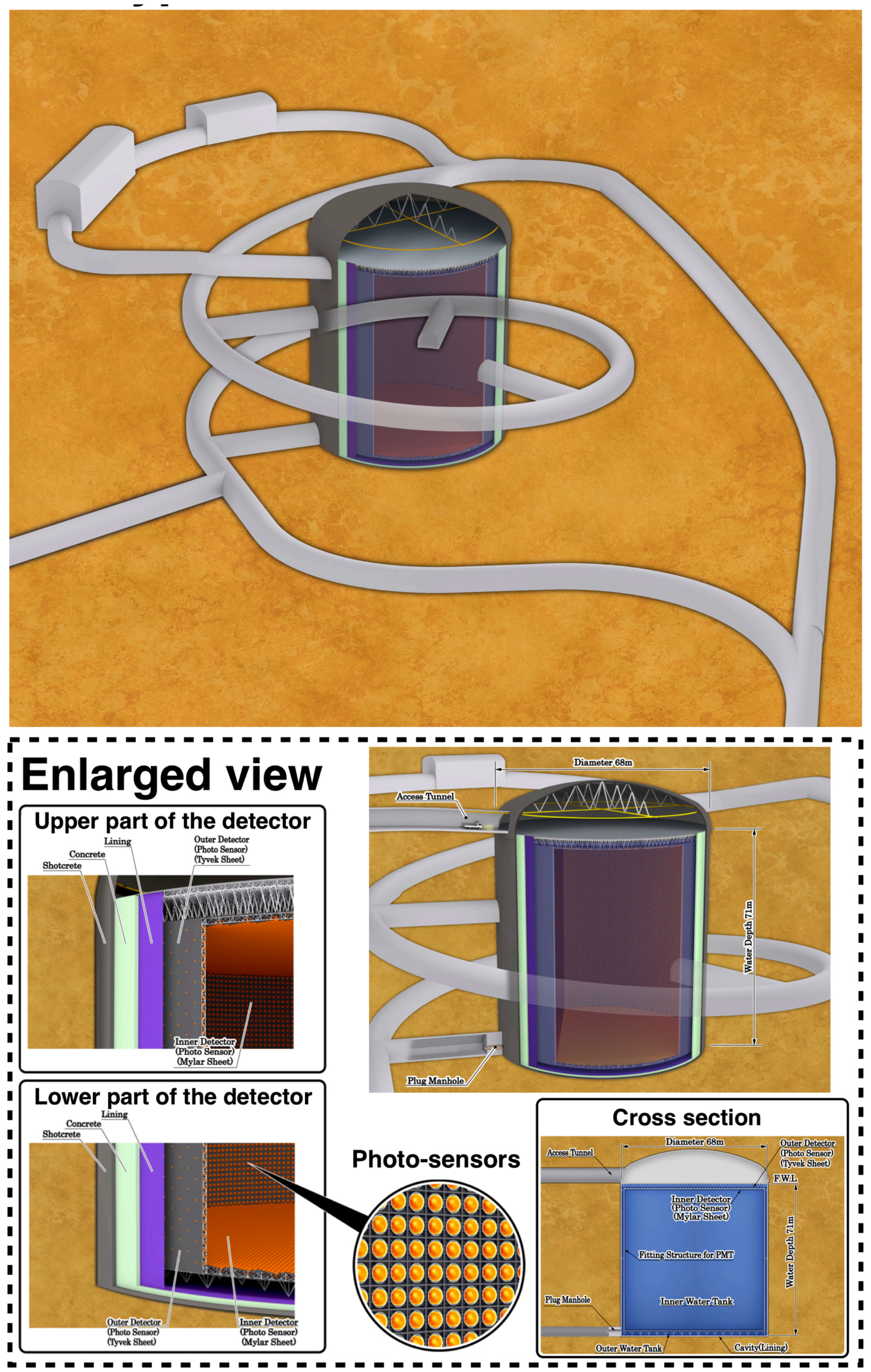
ND280 Upgrade event displays



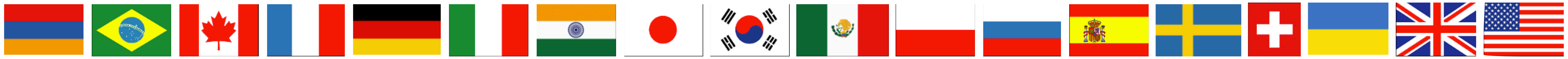
Hyper-Kamiokande

- Extremely well established Water Cherenkov technology
  - 190 kton FV (SK 22.5), instrumented with up to 40k PMTs
- HK will be the most sensitive observatory for rare events (proton decay, SN neutrinos, …)
- Search for CP violation in lepton sector
  - Upgrade of J-PARC neutrino beam (1.3 MW)
  - Near and Intermediate detector complex
- Construction started in April 2020 → start operation in 2027


Excavation reached center of cavern dome in July

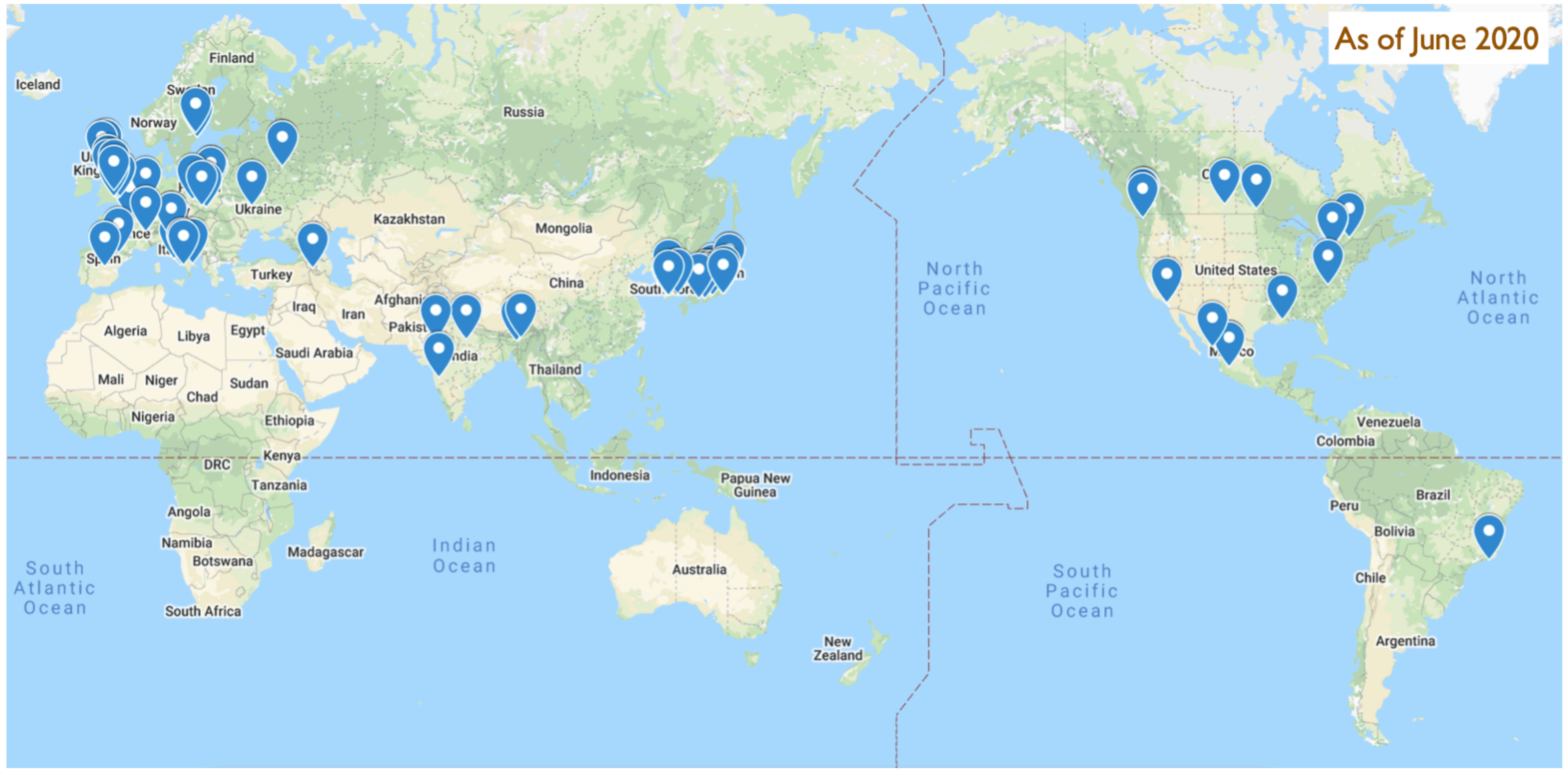


Hyper-Kamiokande collaboration

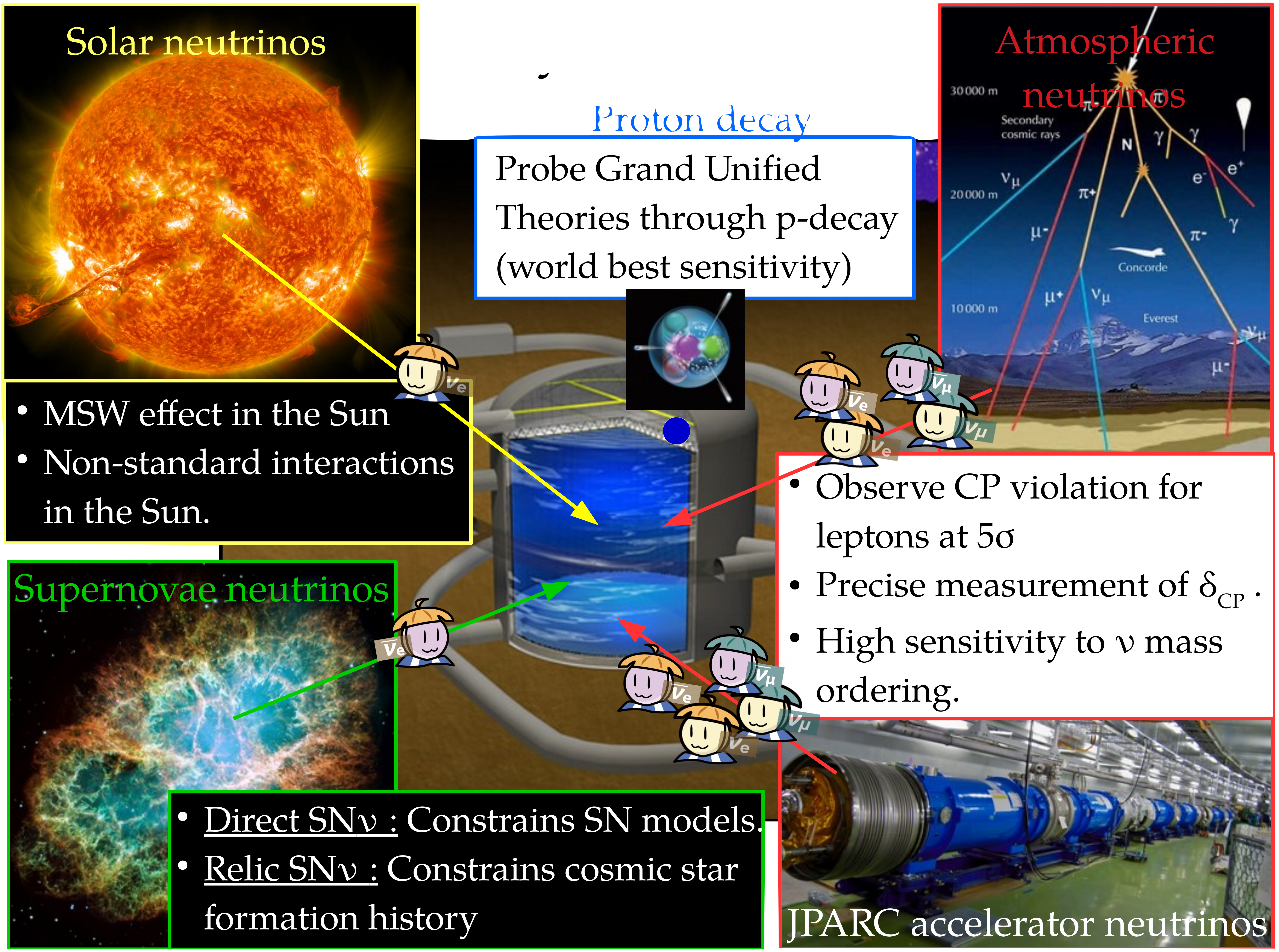


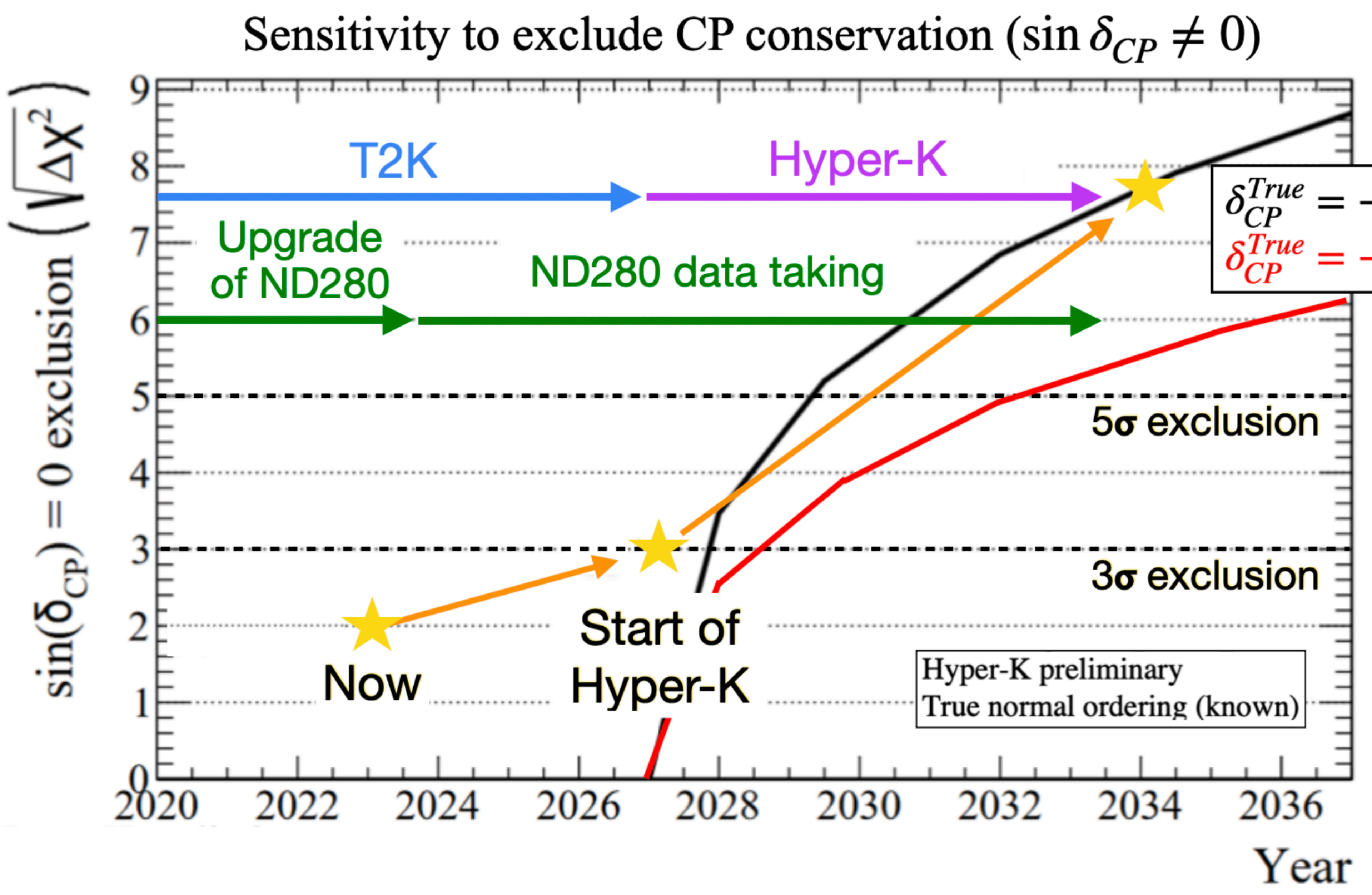
18 countries, 82 institutes, ~390 people

Hyper-Kamiokande



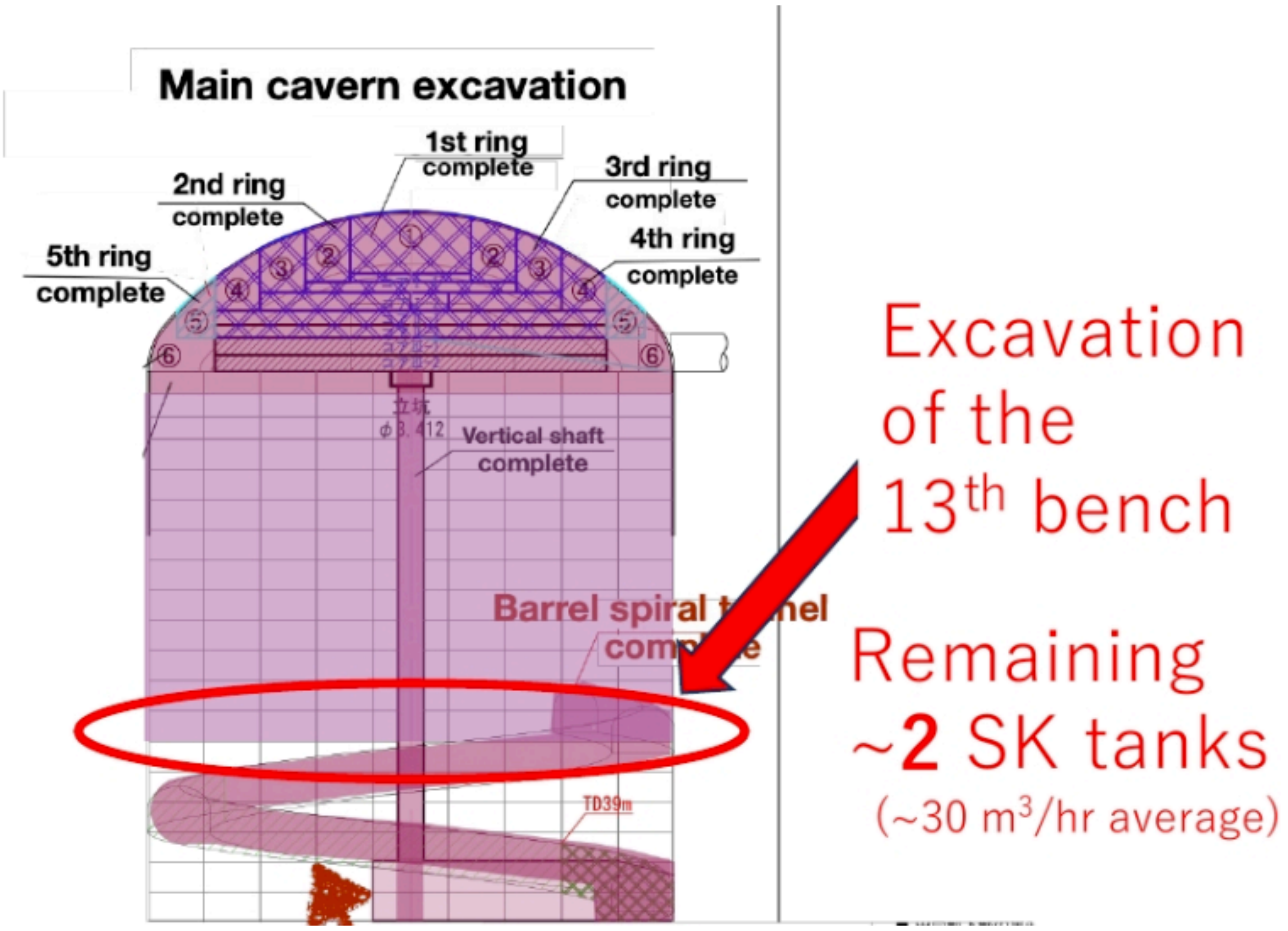
Physics case





HK construction status

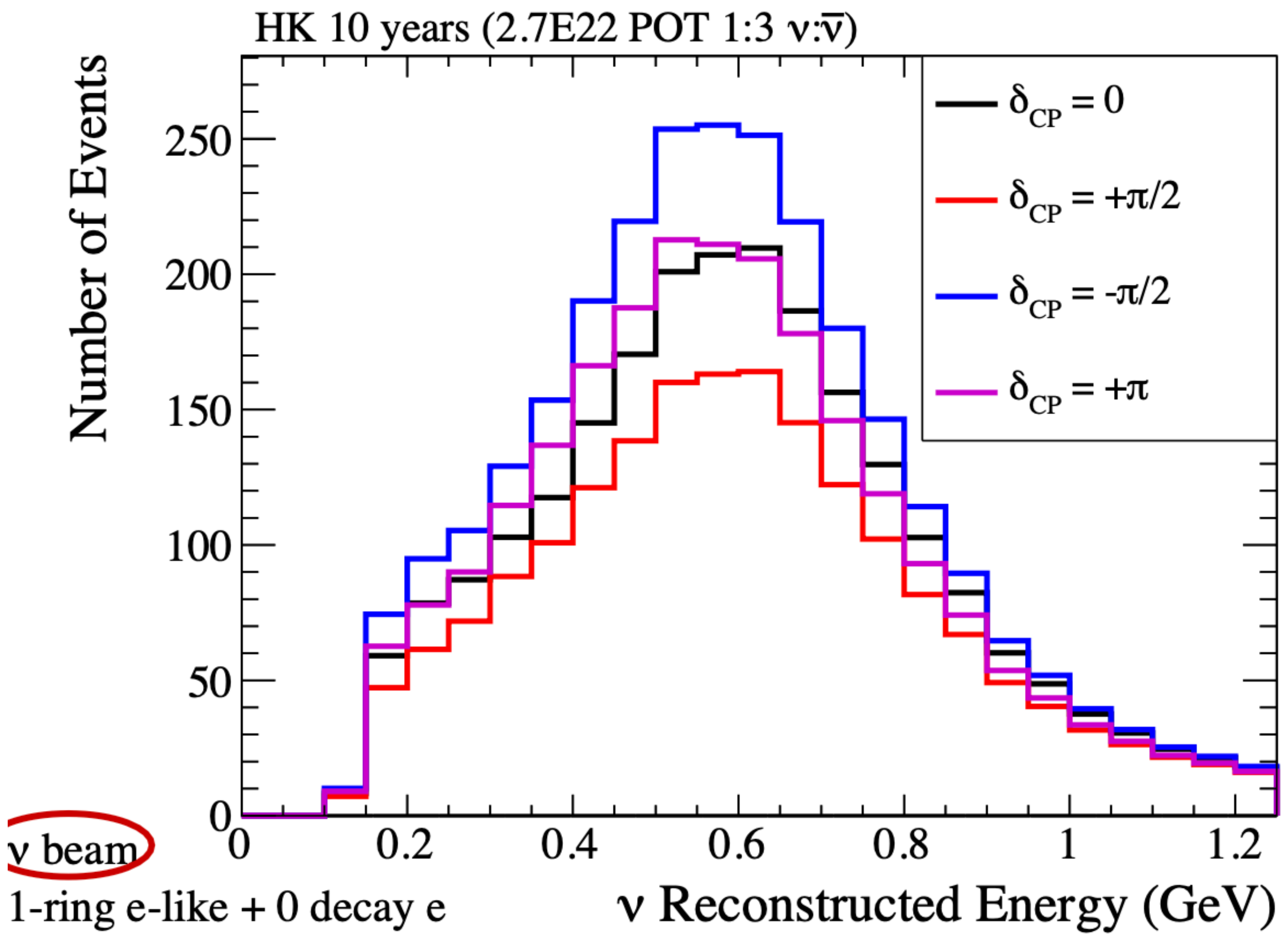
Excavating world largest human-made cavern

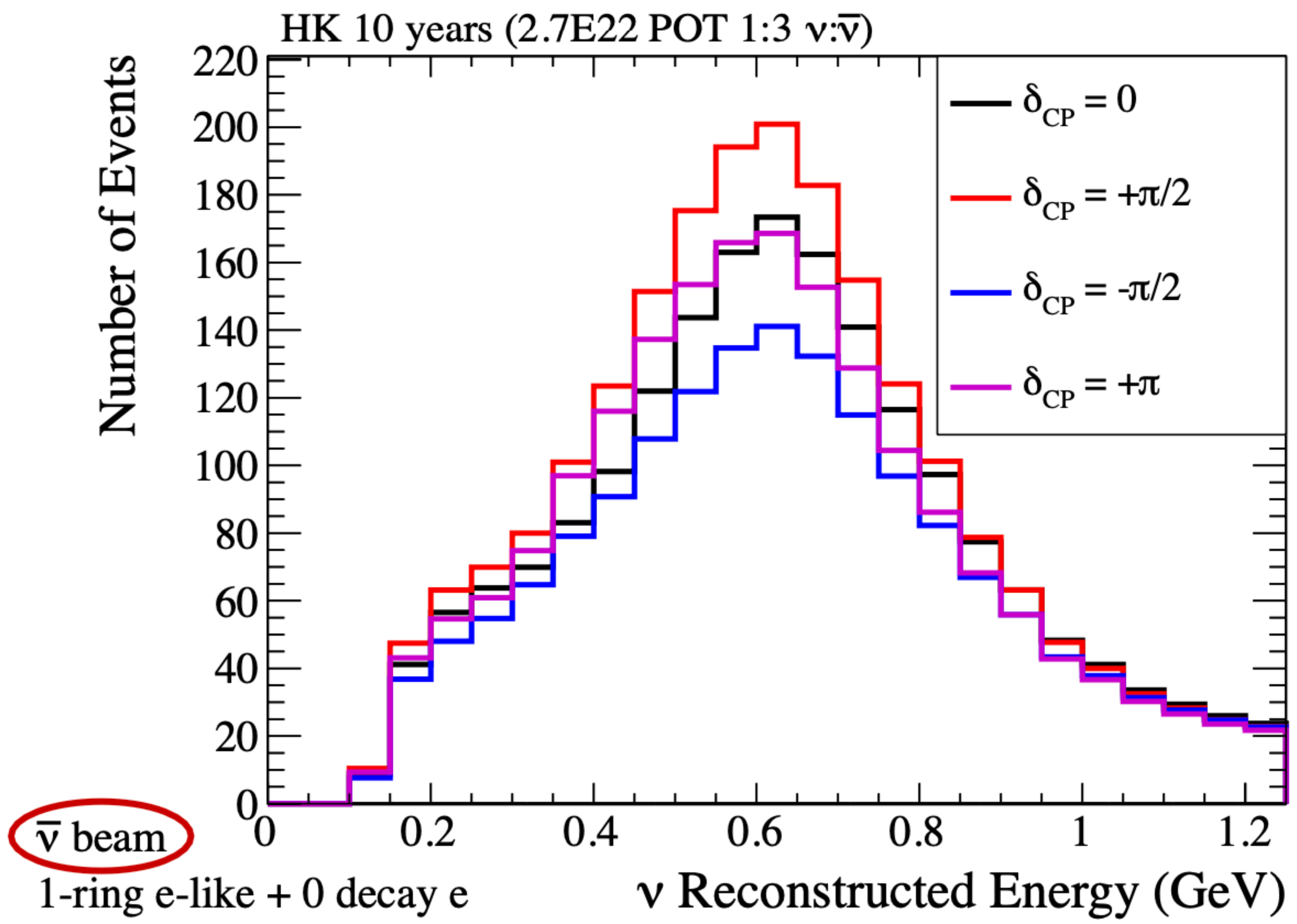


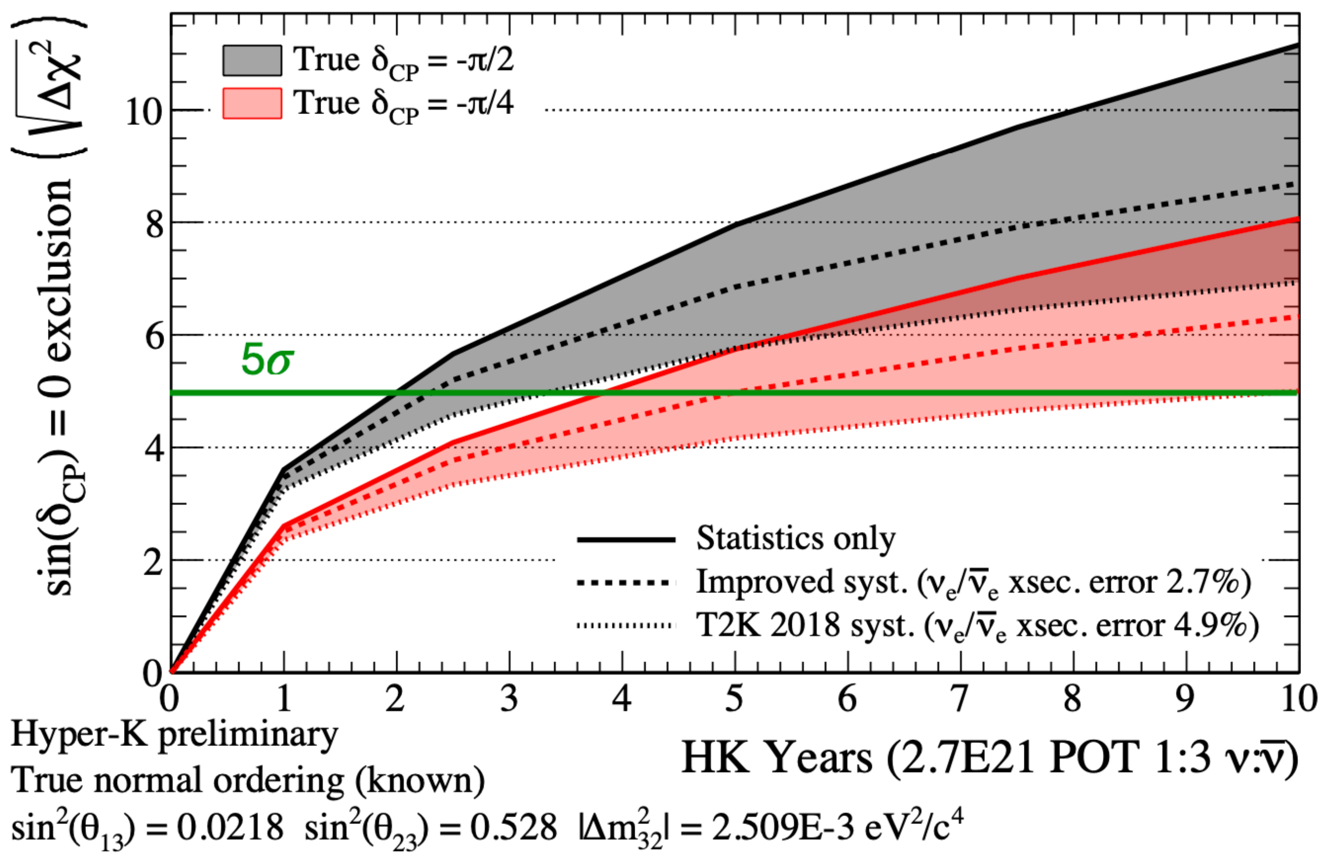
- Excavation on-going → expect to complete by the end of the year
- 20” PMTs being produced by Hamamatsu
- Assembly of the electronics modules on-going at CERN (next slide)
- Goal to start HK operation in 2027

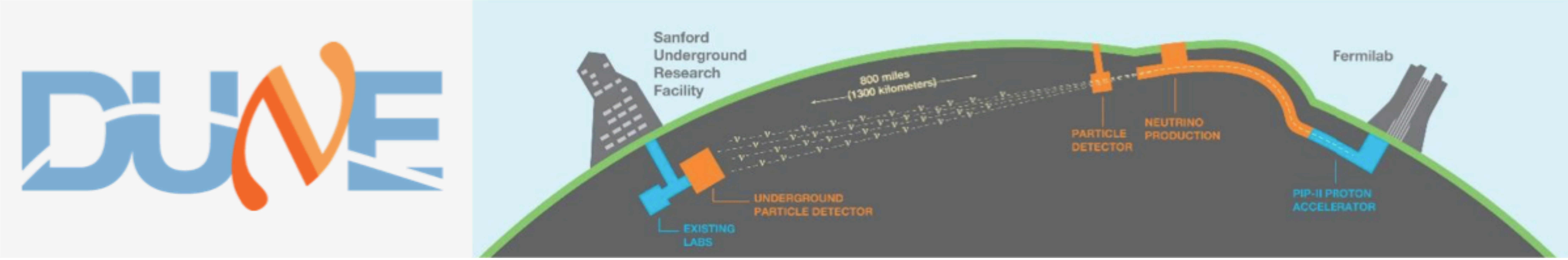
LBL physics at HK

- ~2000 ν_e and 2000 $\bar{\nu}_e$ interactions selected at HK after 10 years of data taking → to be compared with ~100 ν_e and ~20 $\bar{\nu}_e$ in T2K
- Also ~20000 ν_μ and $\bar{\nu}_\mu$ interactions will be selected
- Plan to re-use ND280 to constraint flux and x-sec systematics
  - Intermediate Water Cherenkov detector will be built for HK → only sensitive to lepton kinematics + off-axis spanning
  - Do we need more from ND280? → ND280++

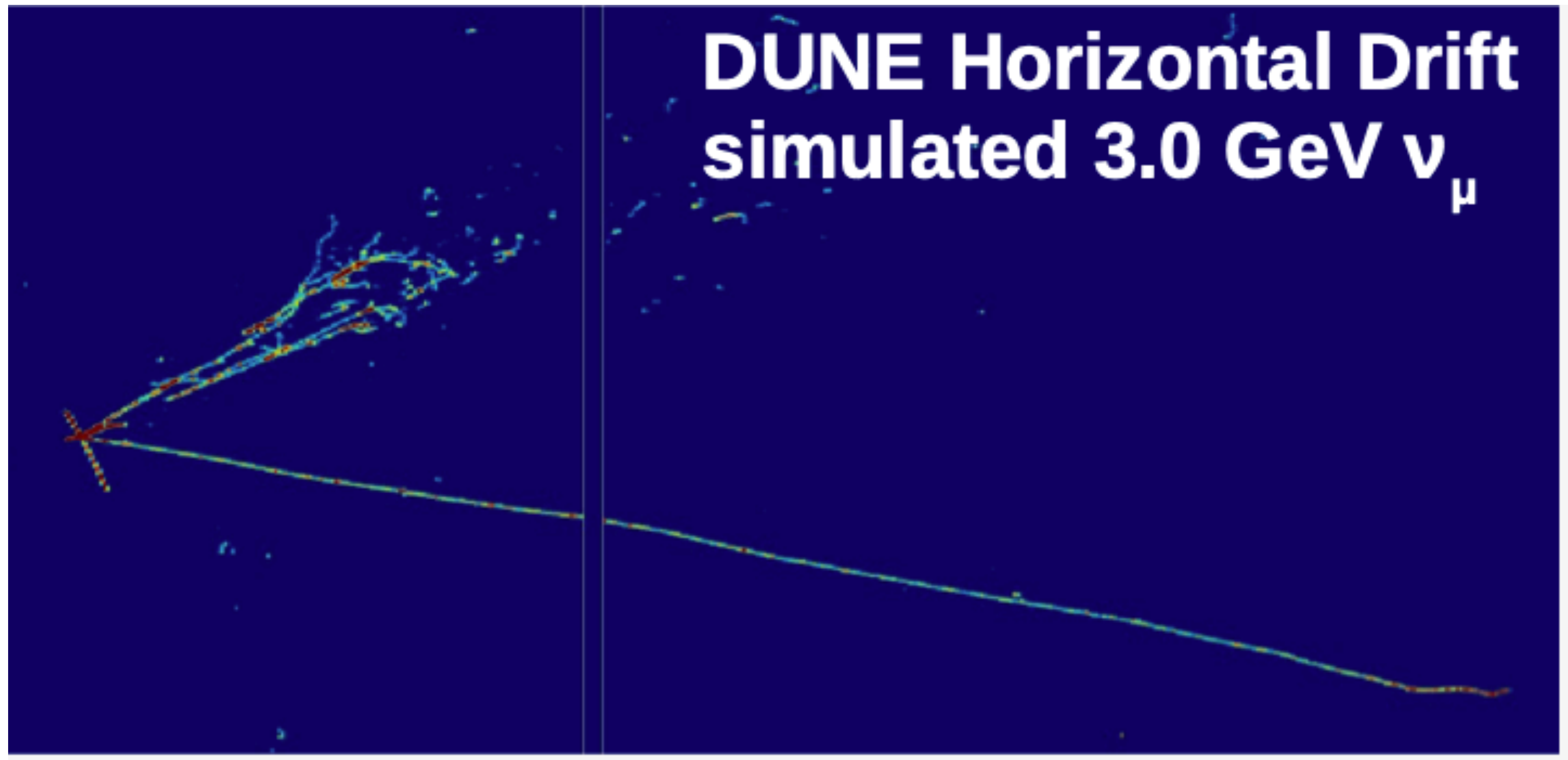


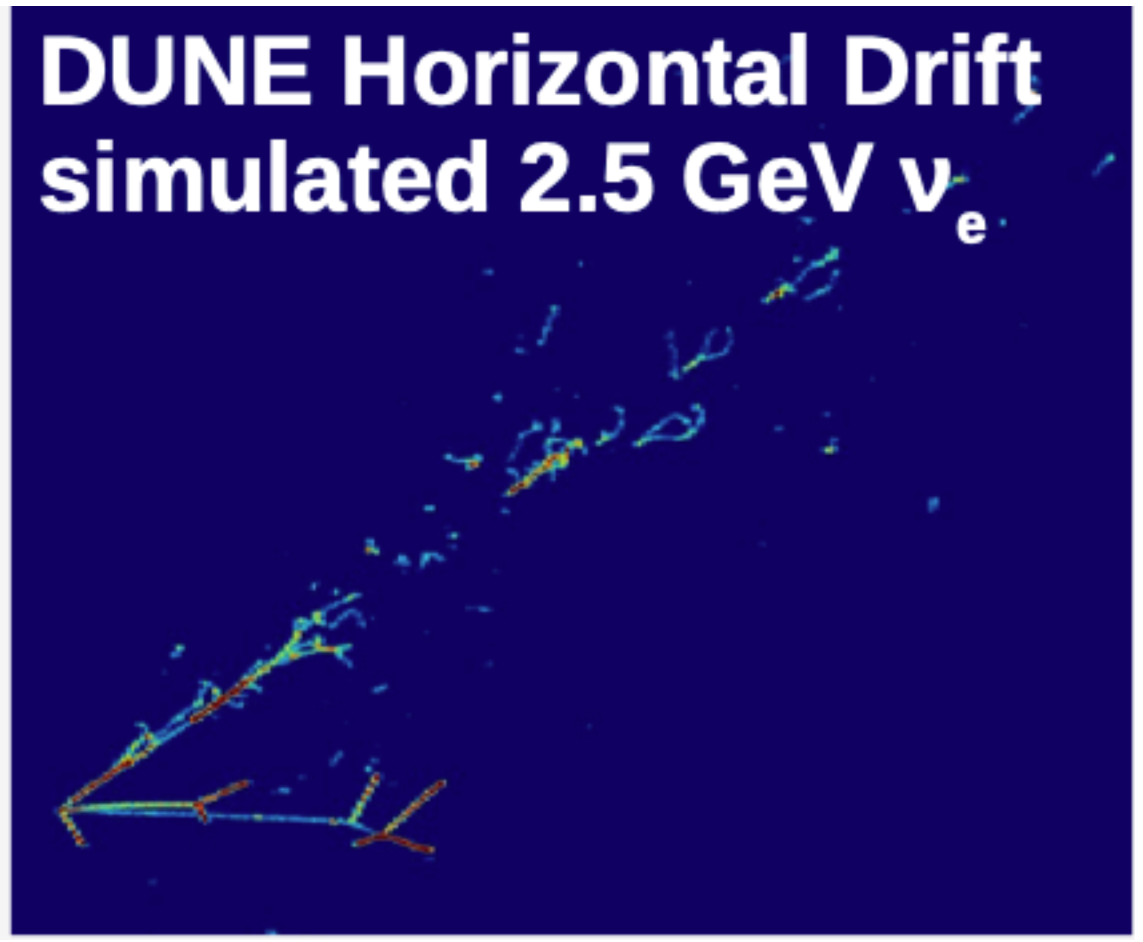


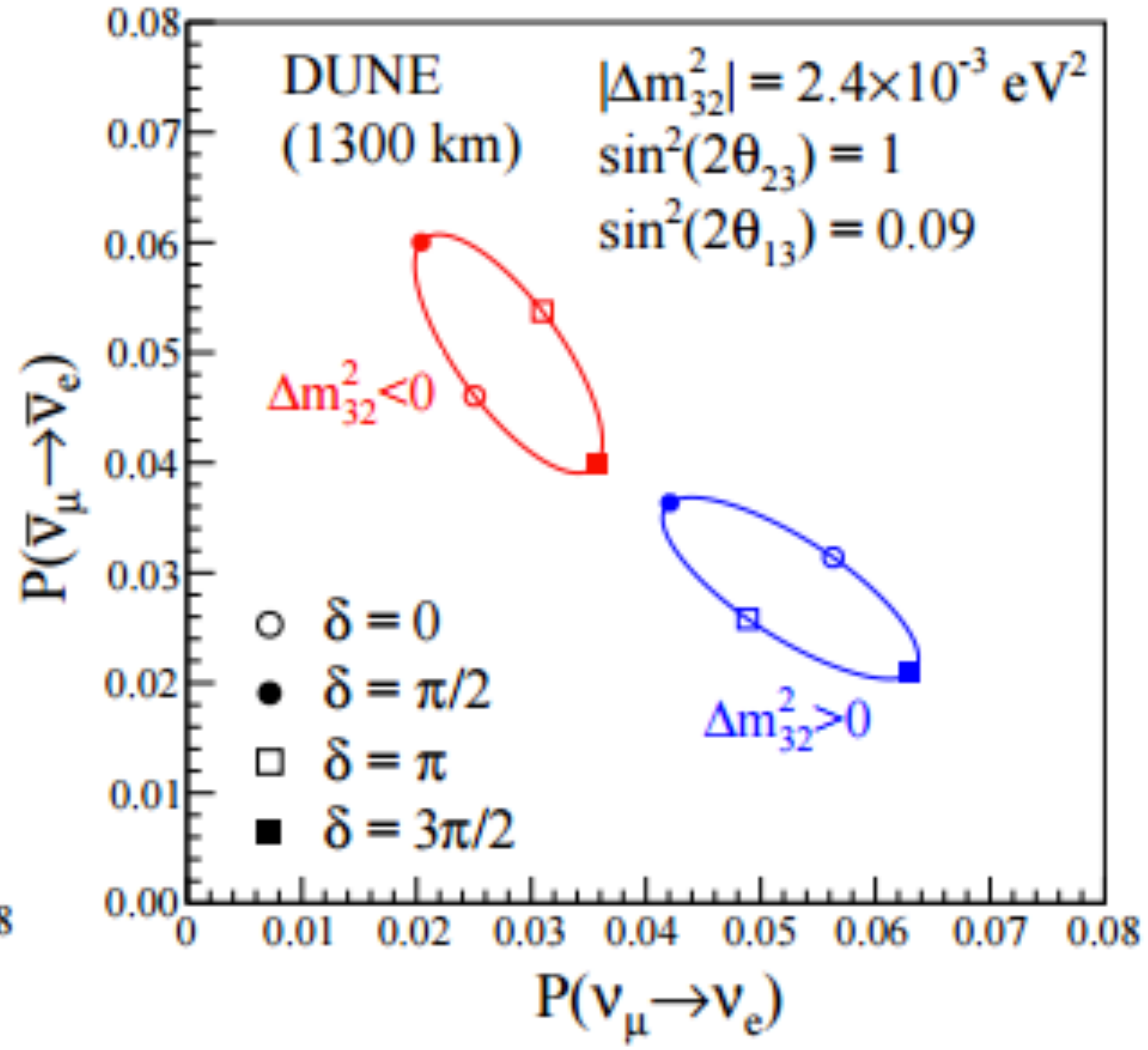




- Wideband beam with >2 MW intensity
- 4 modules of Liquid Argon (2 in the first phase) with more than 20 kton Fiducial mass
- Brand new near detector complex to be built at Fermilab
- Very long baseline and higher beam energy → no degeneracies between



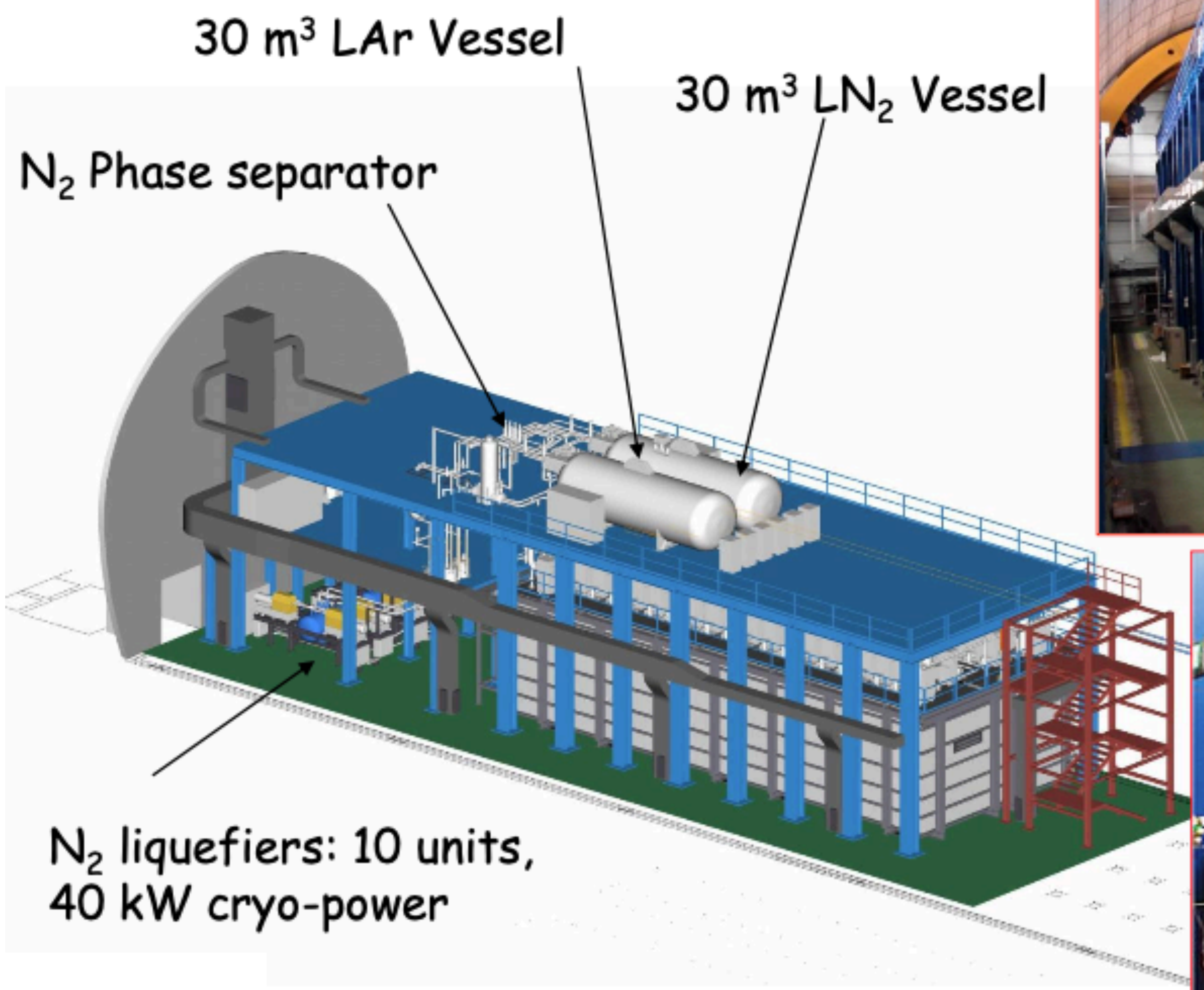


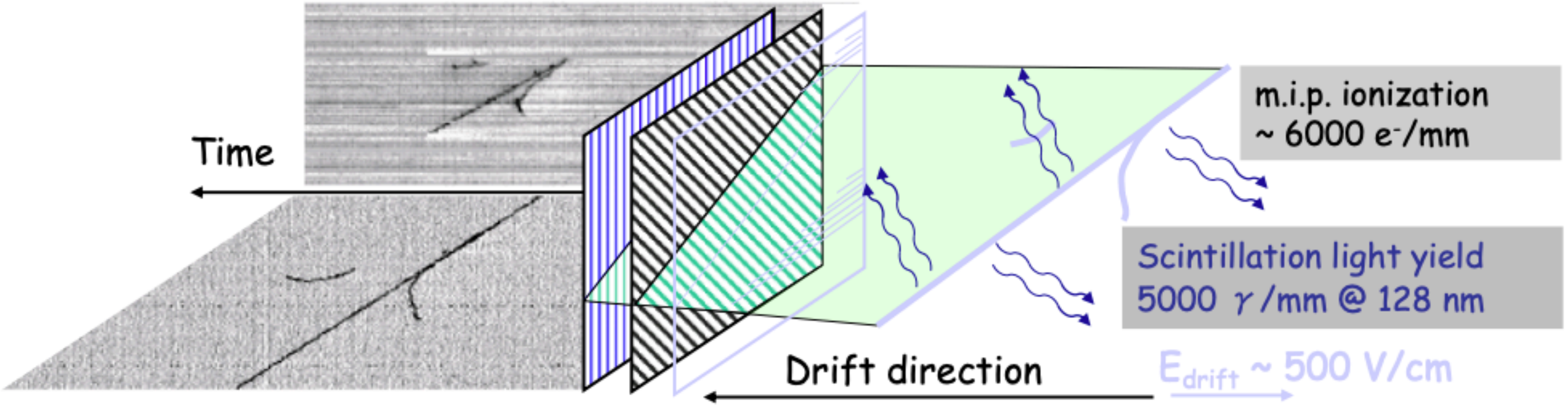


Liquid Argon TPC

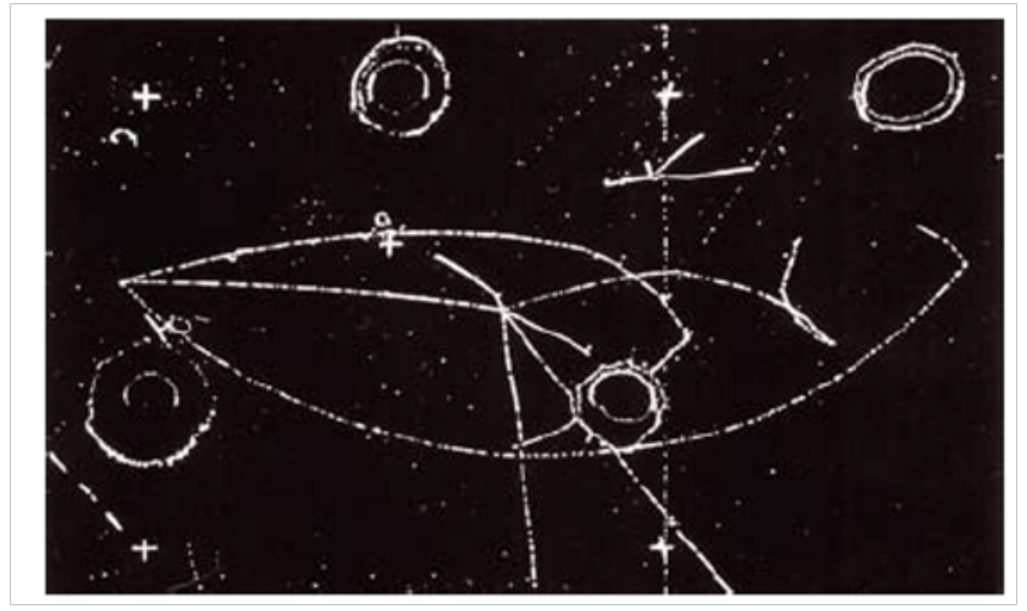
- Cool argon down to 87 K to obtain liquid Argon
  - High granularity in dense material
  - Excellent calorimetric properties
  - Particle Identification through dE/dx vs range
  - Scalable to kTon scale

ICARUS T600 in LNGS Hall B

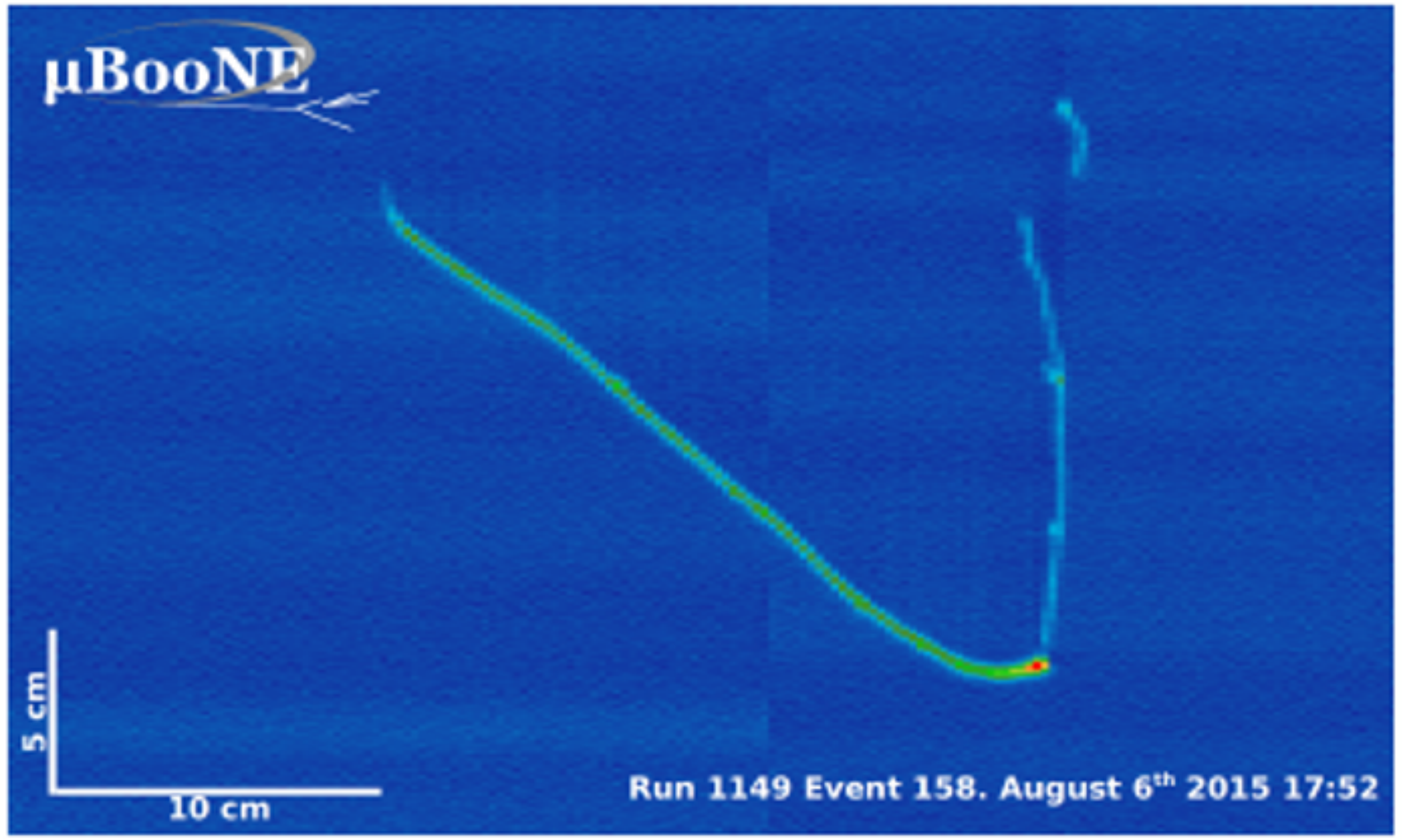




Inspired by bubble chamber philosophy



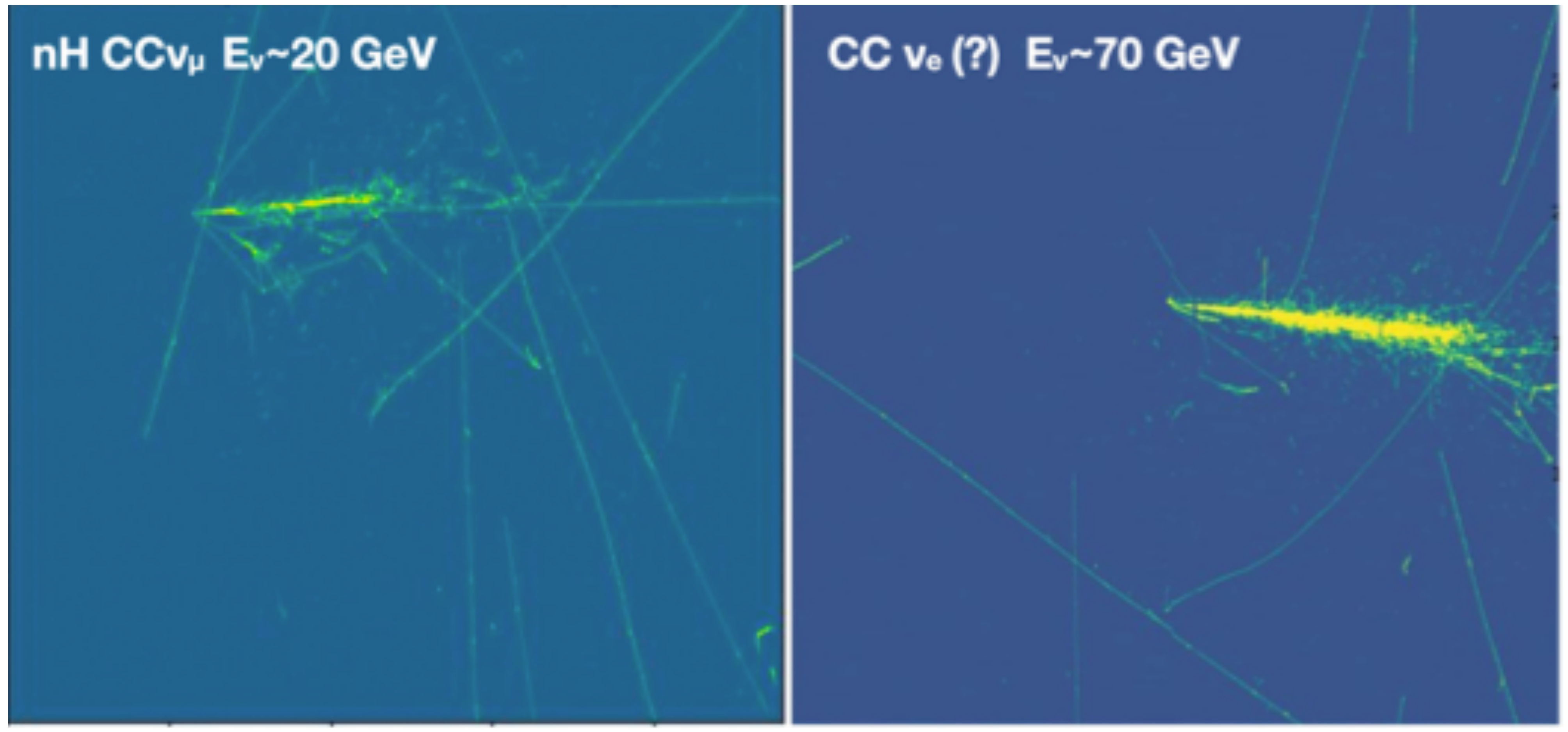
MicroBooNE example



- Detailed and precise tracking information to relatively low thresholds
  - allows precise vertexing
  - matching/separation of distinct objects (e.g. cosmic ray overlaid on neutrino interaction)
- Topological information such as showering
  - track, electromagnetic shower, hadronic shower separation
  - delta rays from tracks
- Ionization pattern, such as Bragg peak from stopping track

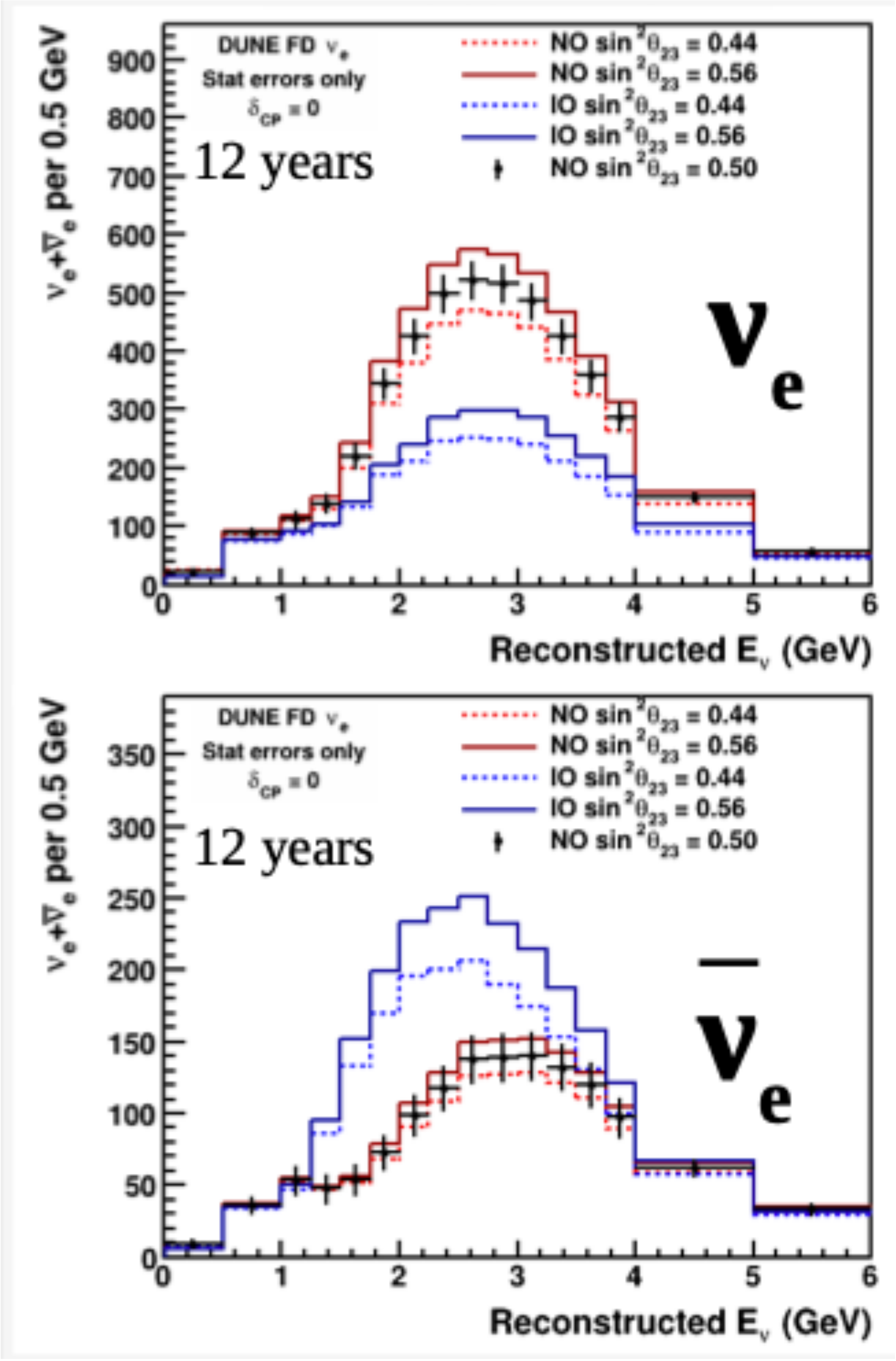
ProtoDUNE at CERN

- 2 prototypes built at CERN → each ~600 ton Liquid Argon
- 2 technologies: vertical and horizontal drifts
- Allow to prove the technologies need to built 10 kton detectors



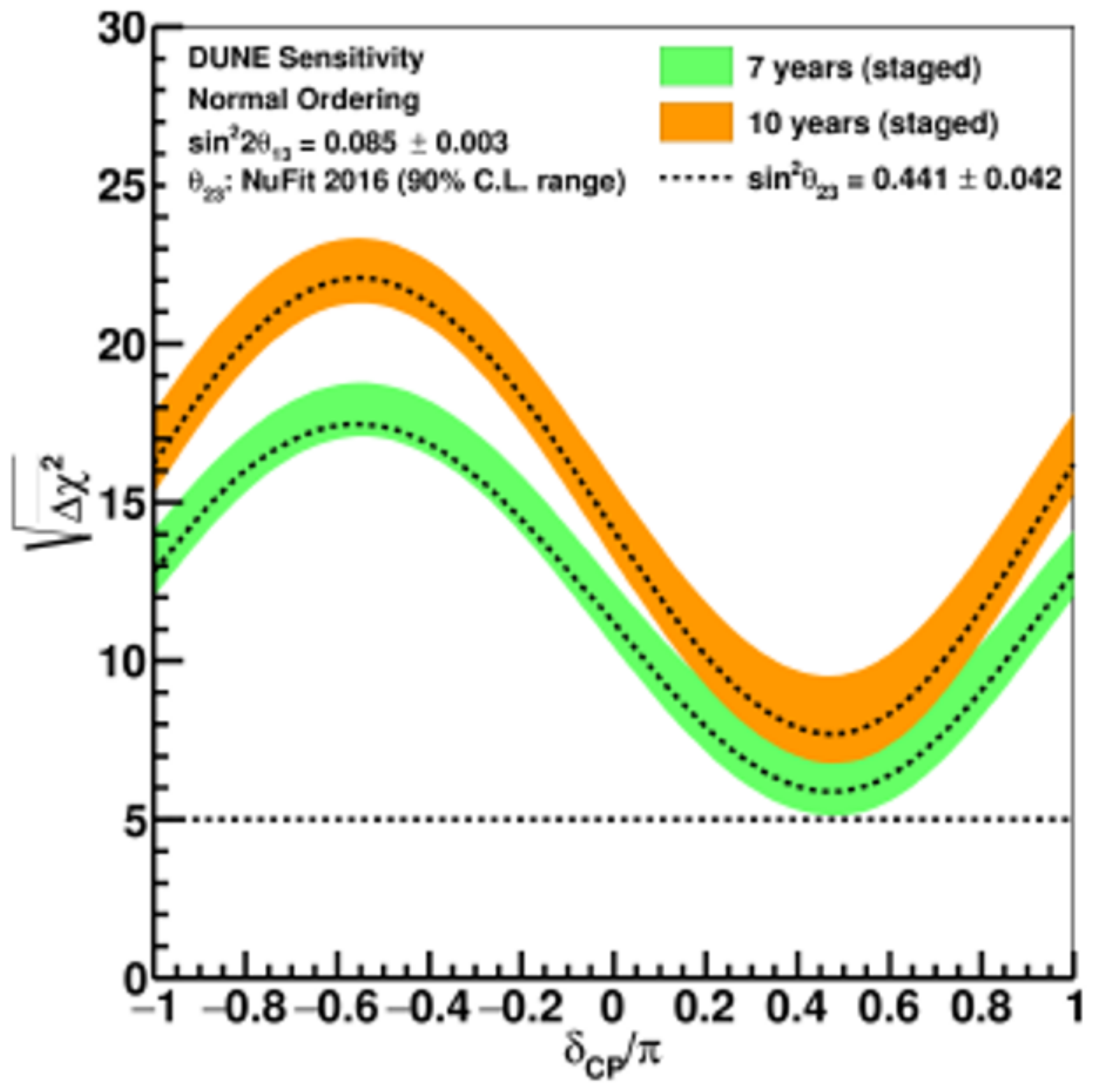
DUNE prospects

- The different unknown parameters (mass ordering, δCP and θ23) affect the spectra with different shapes
  - This allow to solve the degeneracies between these parameters
- Thanks to its high energy beam DUNE can quickly determine mass ordering
- Expect to have 2 Far Detectors installed in 2029 and start operations with beam in 2031



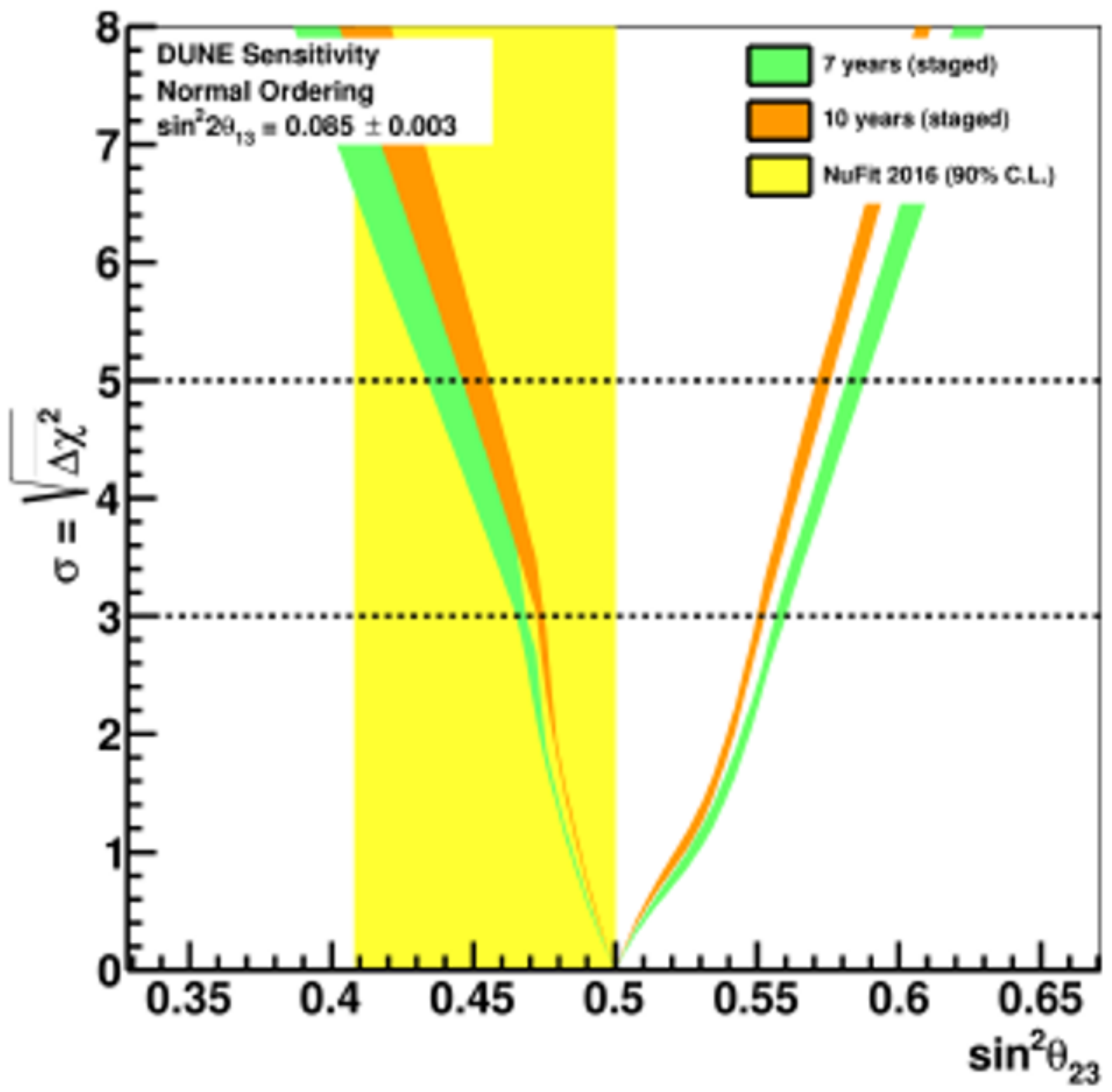
DUNE sensitivity

Mass Ordering

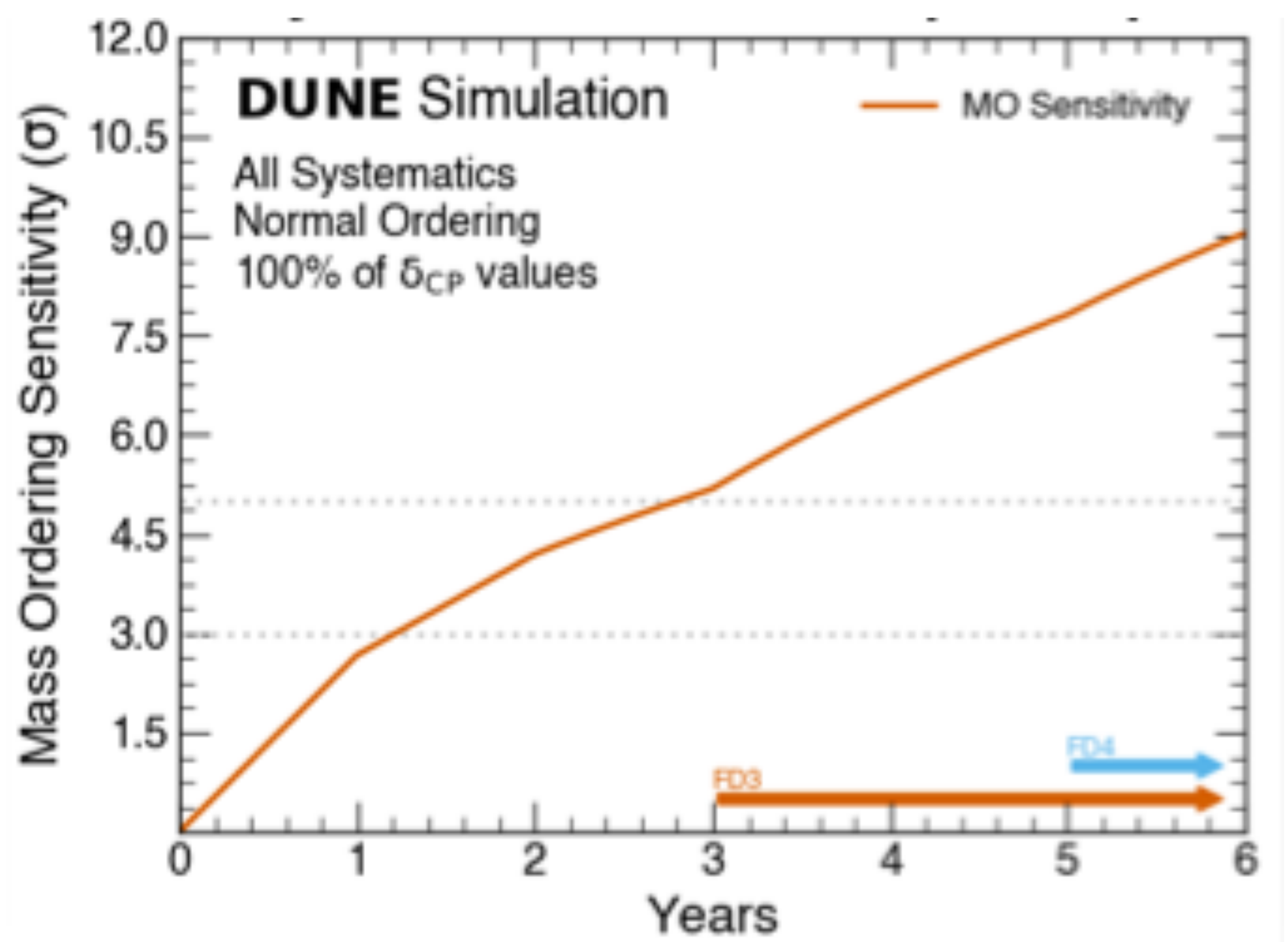


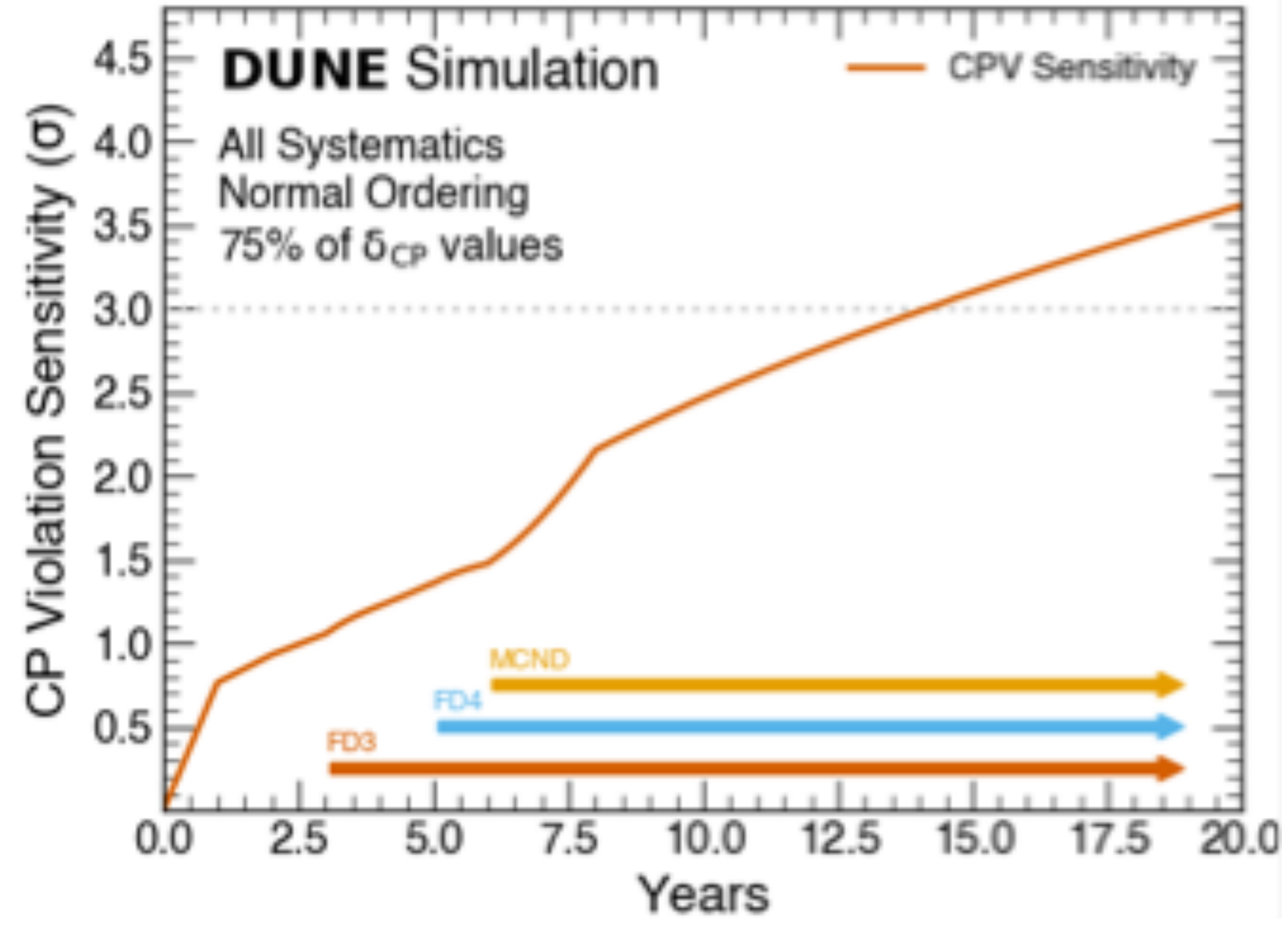
Width of band indicates variation in possible central values of θ_{23}

Octant



Width of band indicates variation in possible true value of δ_{CP}

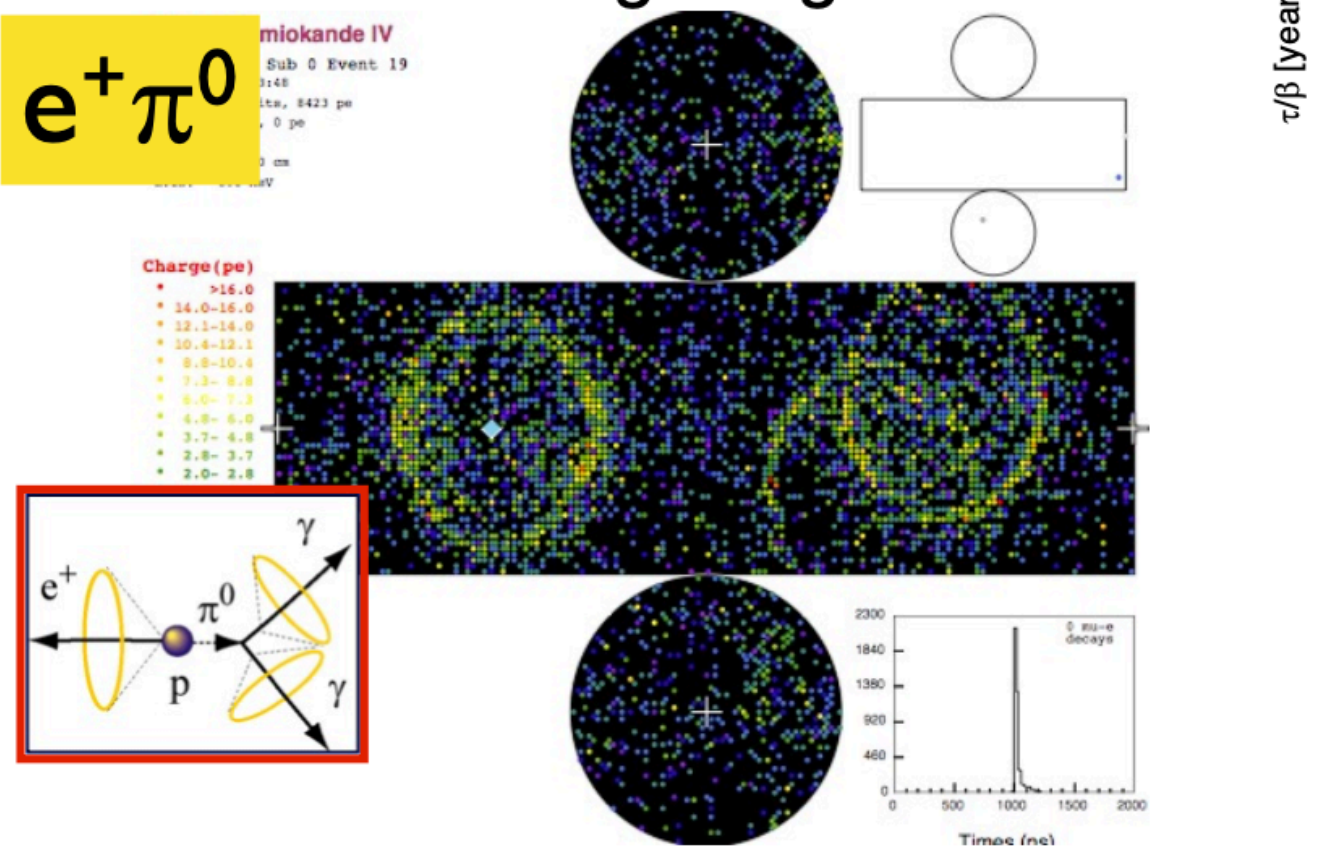




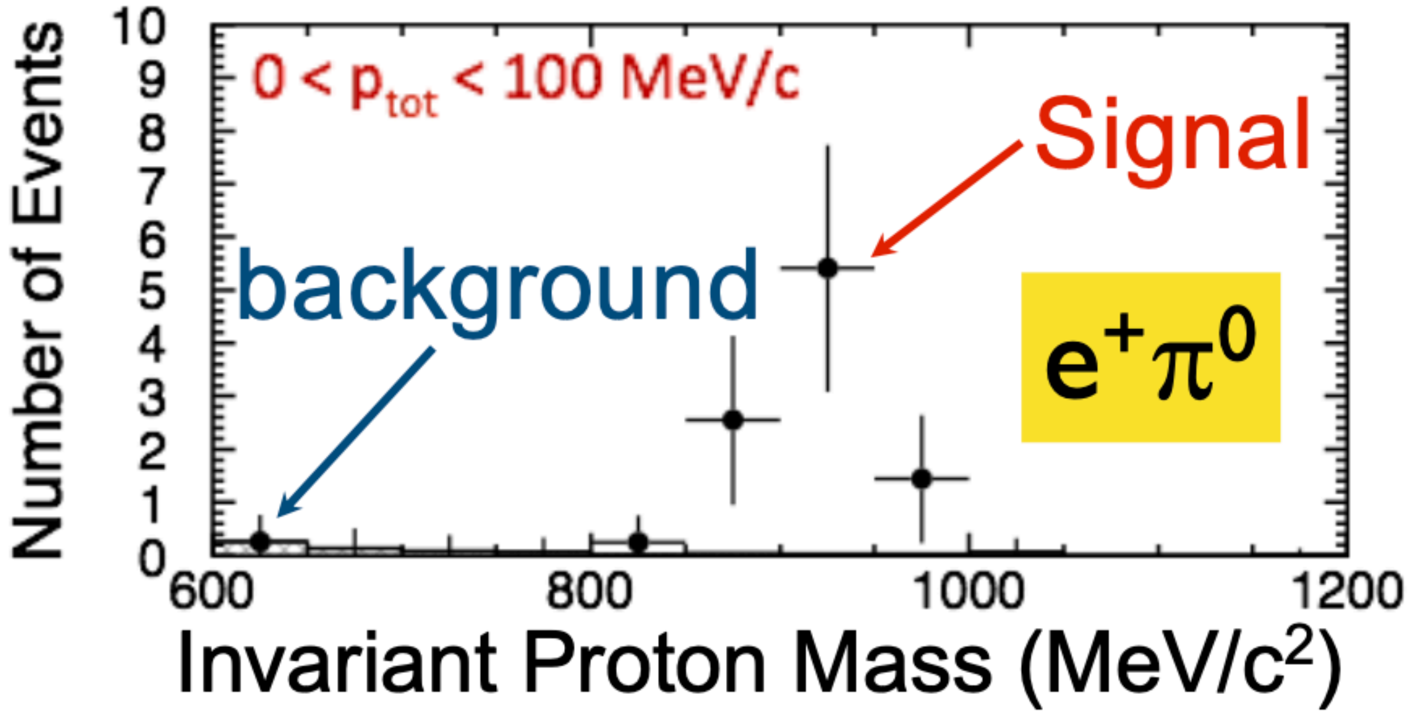
Beyond PMNS measurements

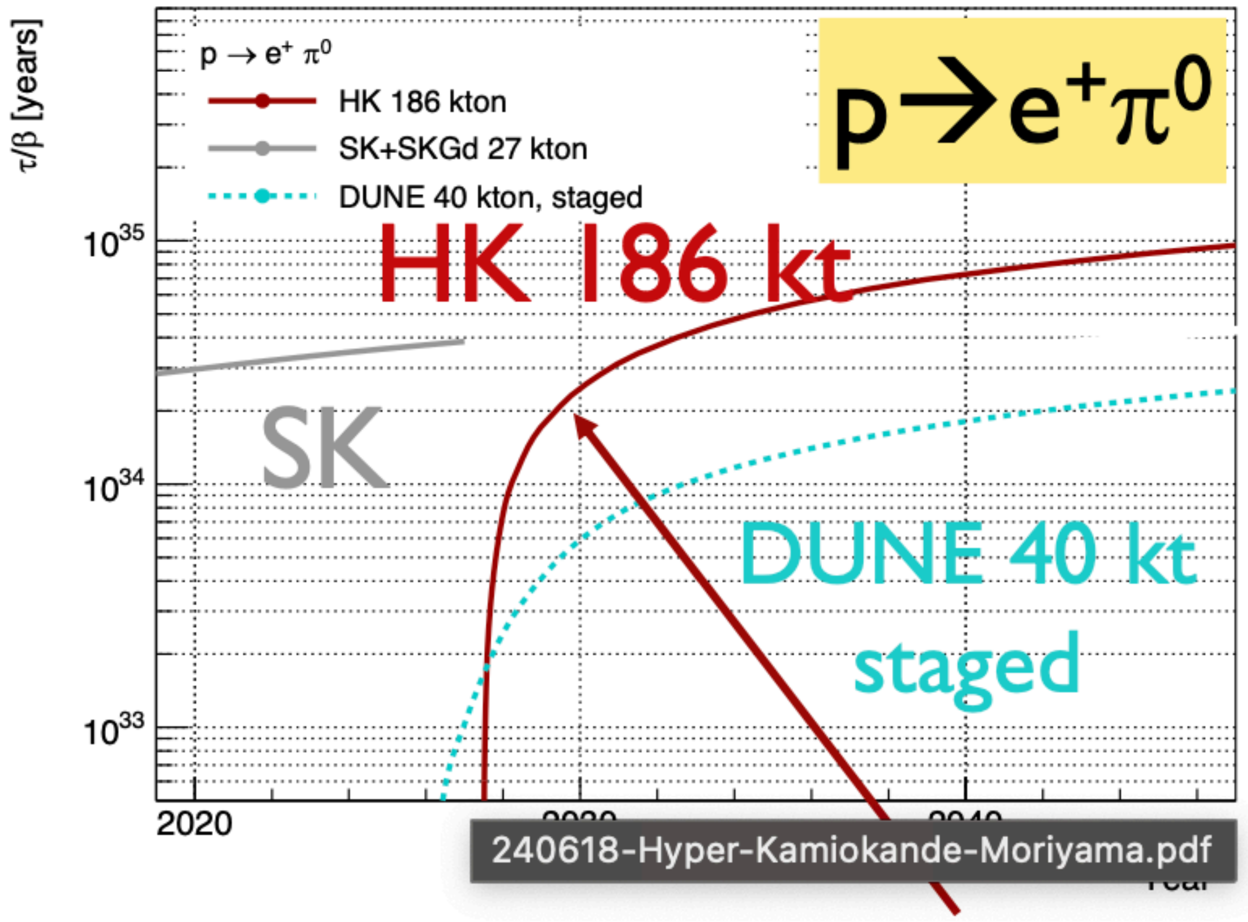
Proton decay searches (note: FV ~8 x Super-K)

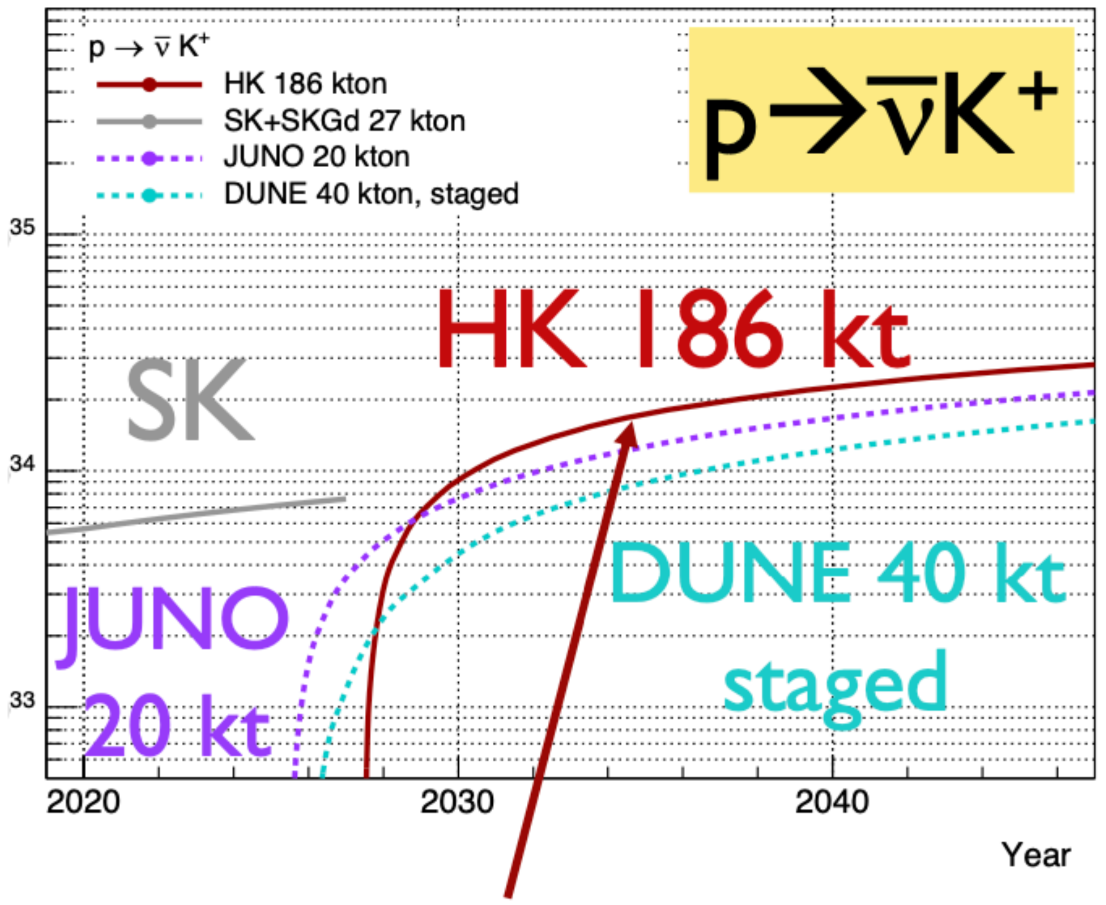
Cherenkov ring image $e^+\pi^0$ in SK



Hyper-K 10 years operation assuming $\tau_{proton}=1.7\times10^{34}$ years (~Super-K limit)







3σ discovery potential

HK 10 years

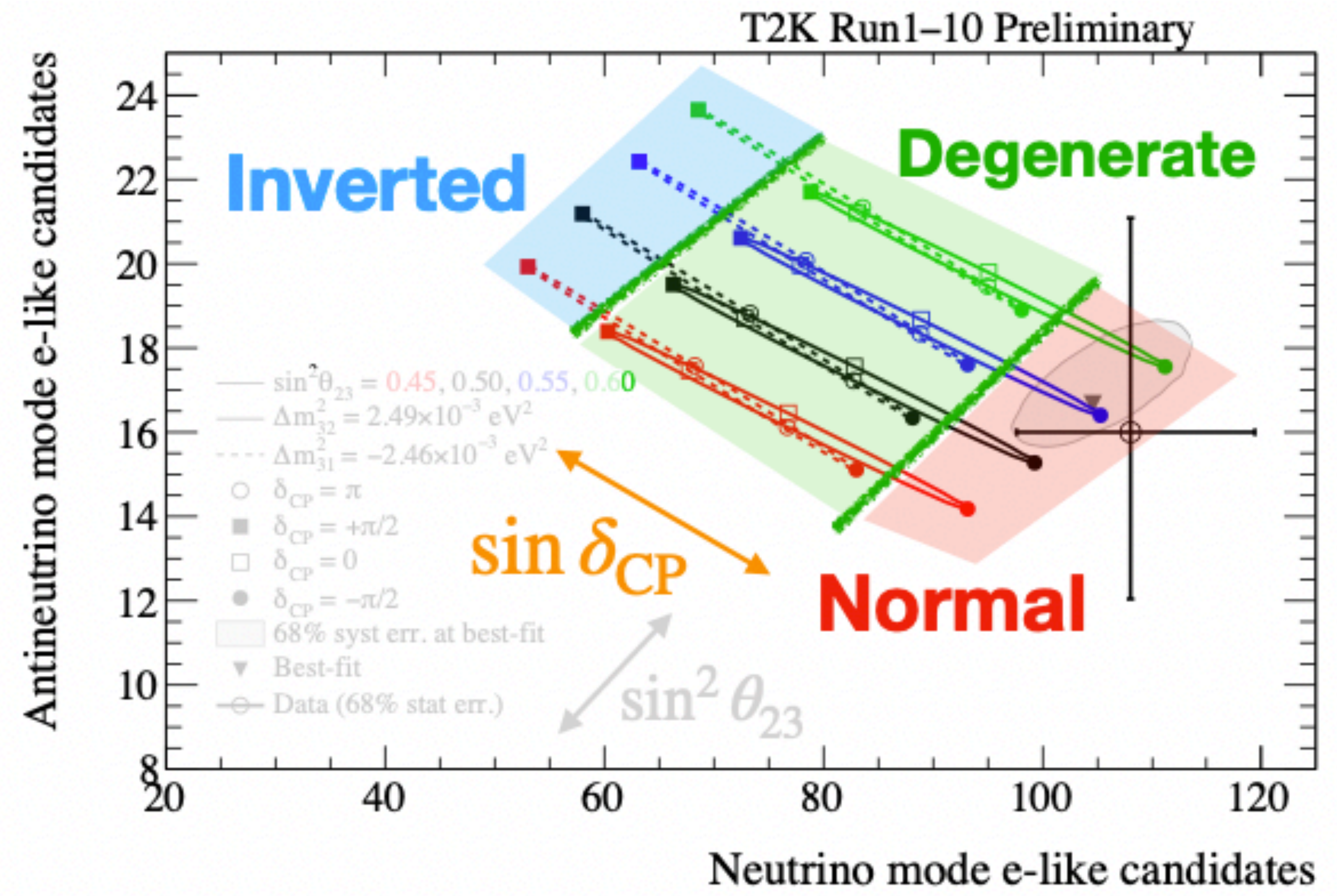
- $p \to e^+\pi^0$: ~6×10^{34} yrs
- $p \to \nu K^+$: ~2×10^{34} yrs
- …

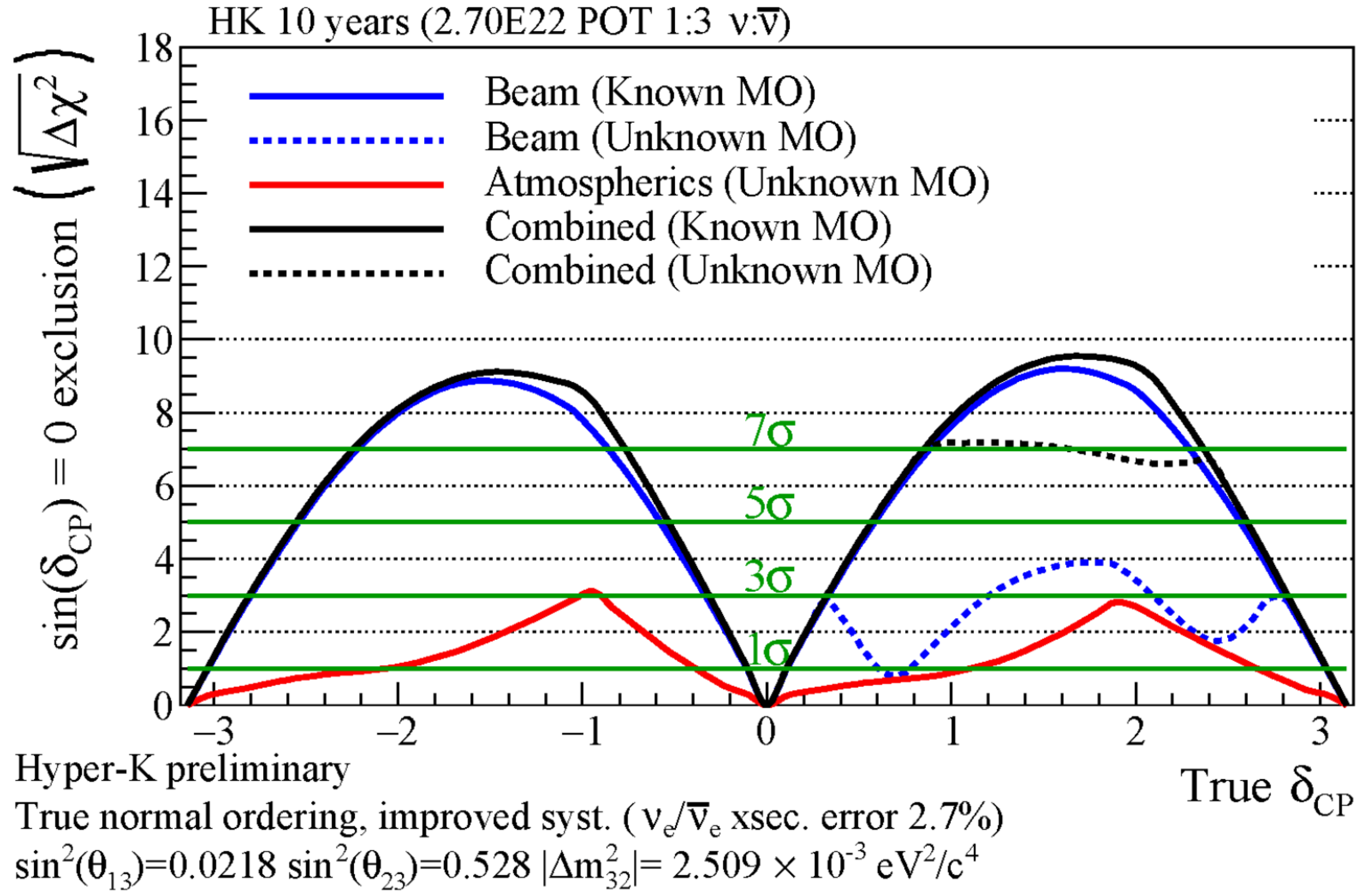
Hyper-K will play a leading role in the next-generation proton decay search

8

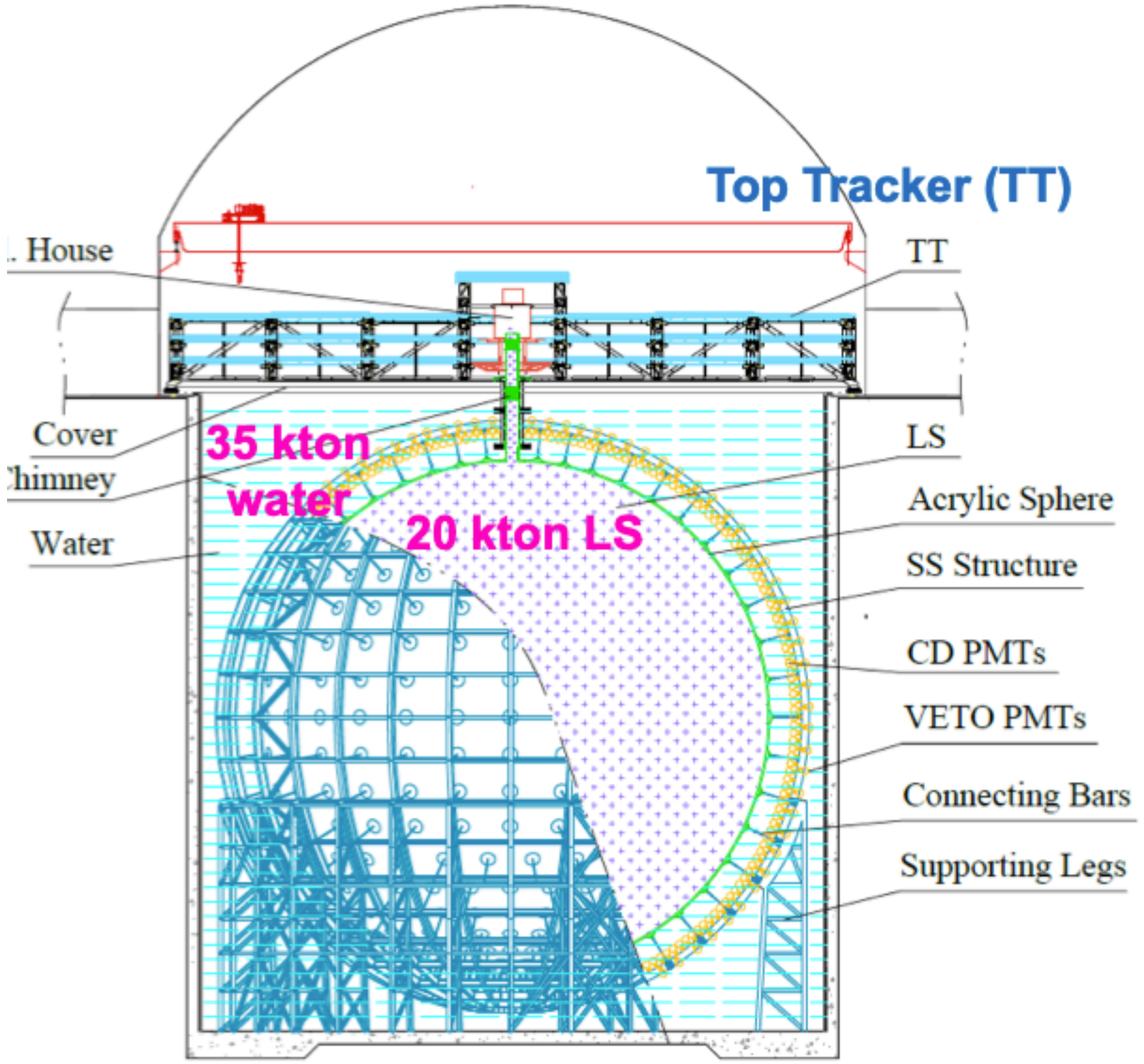
Prospects

- Long-Baseline experiments are the only proposed experiments able to measure δ_{CP} → HK and DUNE will discover CPV in the leptonic sector for 80% of the values of δ_{CP}
    - Of course if δ_{CP}=0 there is no CPV!
- DUNE will be able to quickly measure mass ordering once it starts data taking (say before 2035)
- HK will be able to quickly measure CPV for large values of CPV if MO is known or not degenerate with CPV
    - If MO is unknown and degenerate Hyper-K can still measure CP by combining beam and atmospheric neutrinos
- But can we measure MO before next generation LBL?

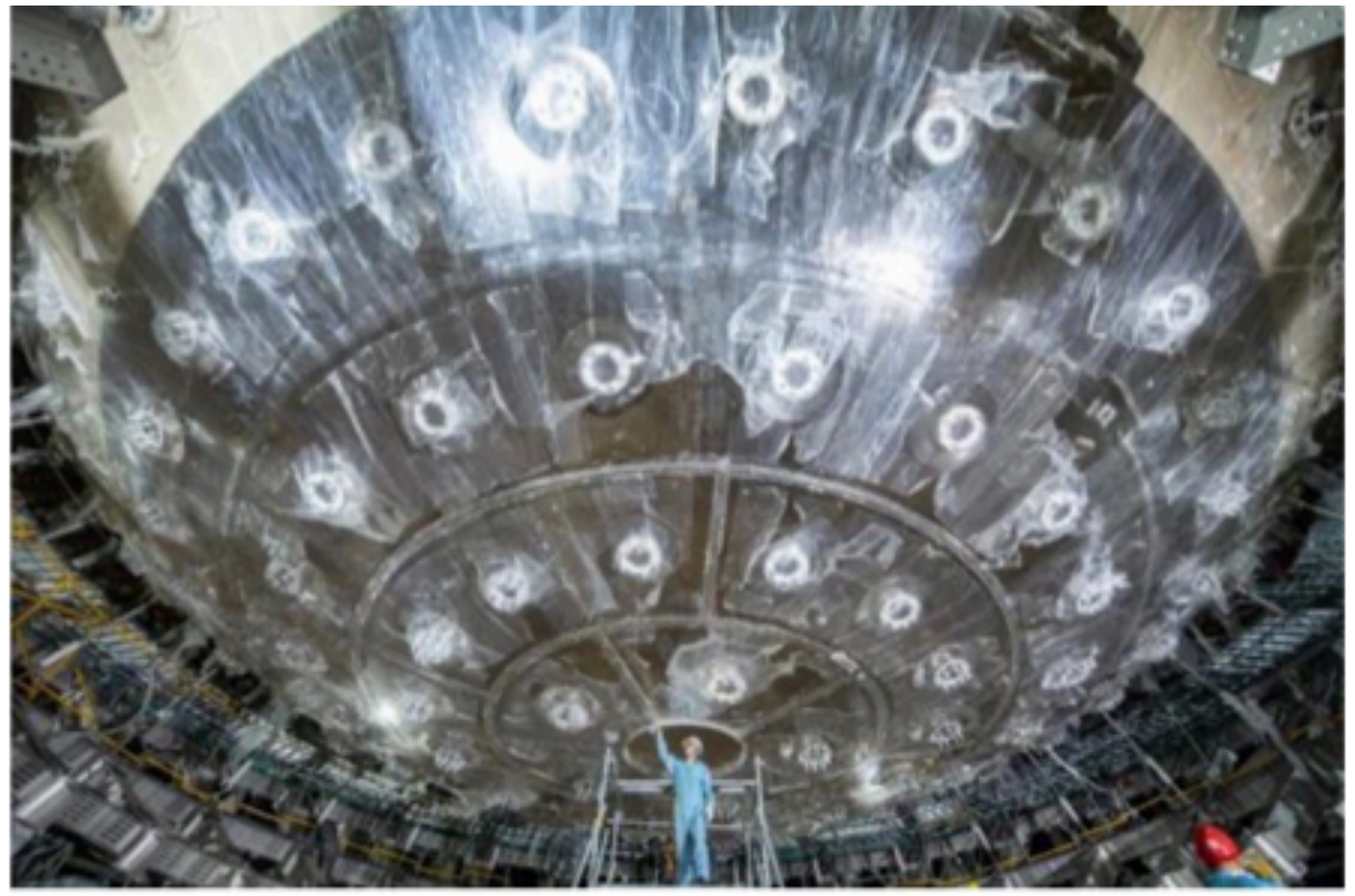




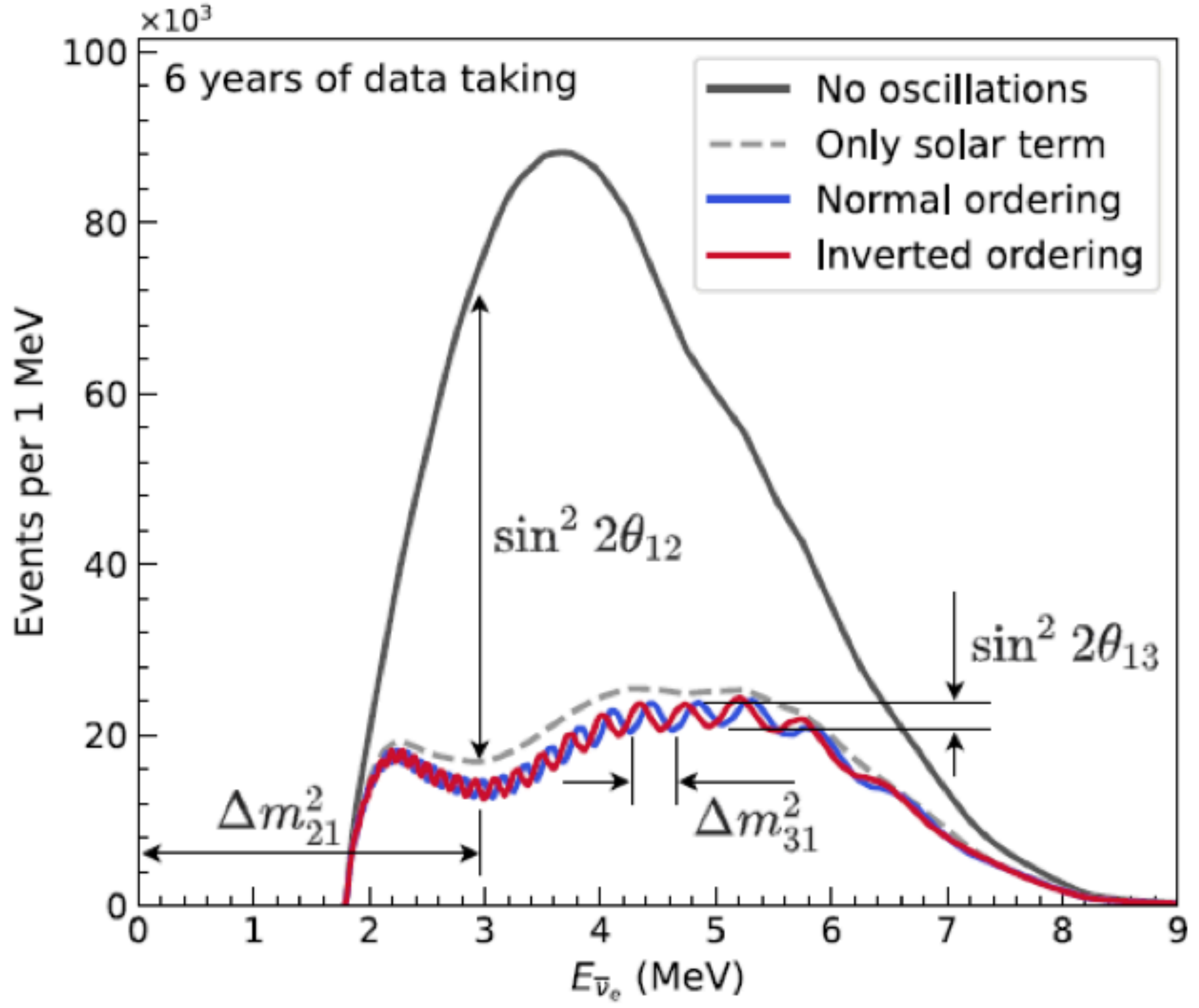
JUNO

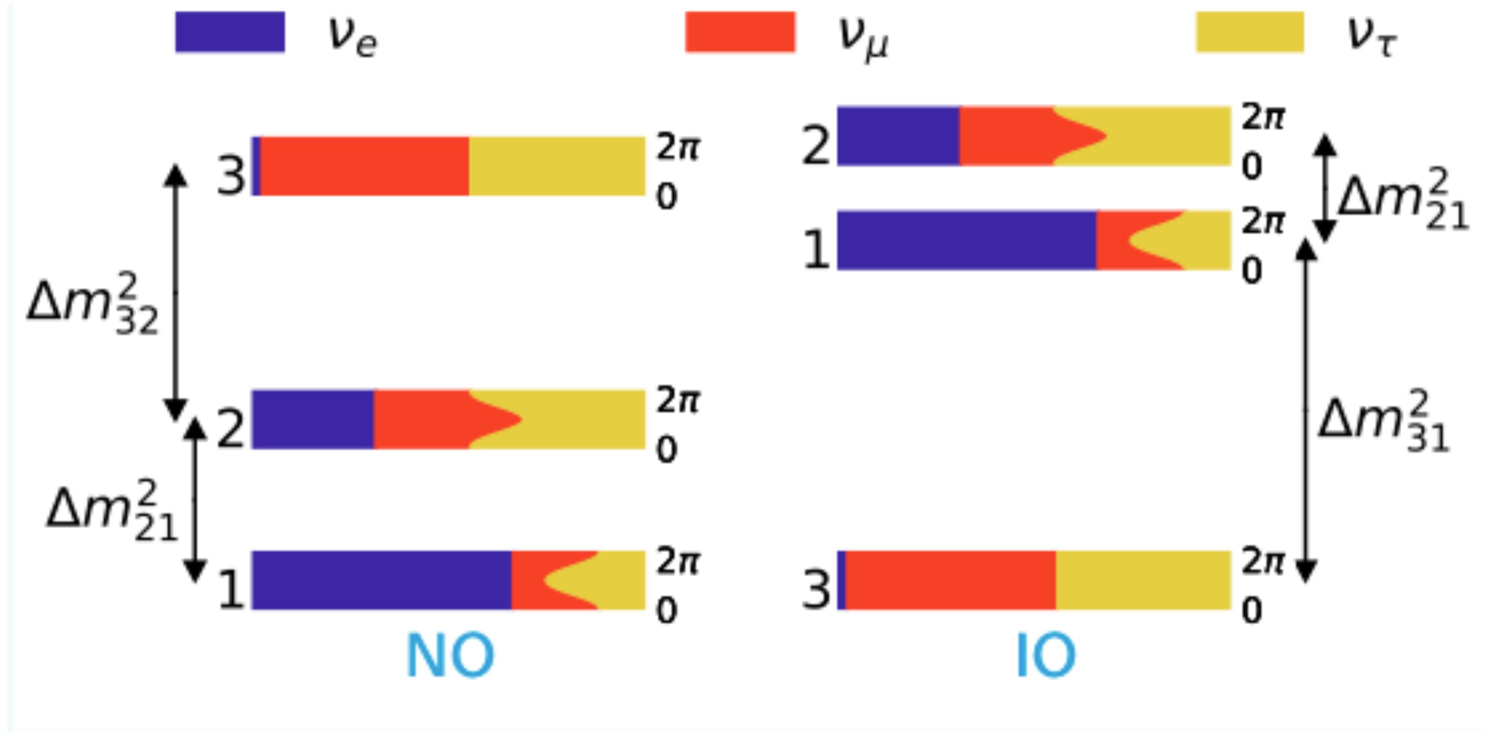


- 20 kTon Liquid Scintillator detector
- Detect $\bar{\nu}_e$ from reactors at 53 km distance via inverse beta decay
- Construction almost completed → start data taking in 2025!



JUNO physics potential





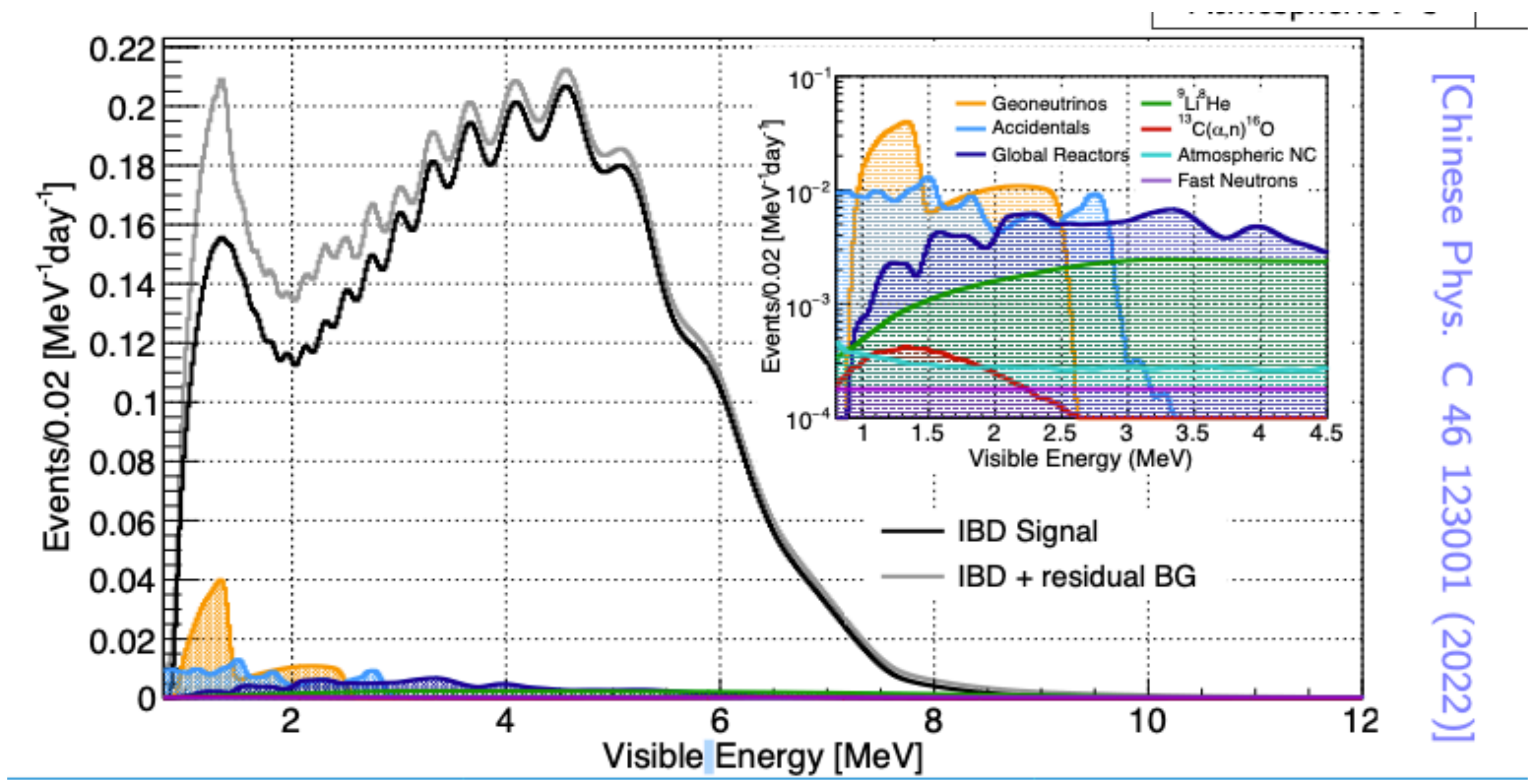
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$-\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + sin^2\theta_{12}\sin^2\Delta_{32})$$

- Observe two oscillation modes : slow oscillations (like KamLAND) driven by Δm^2_{21} and a fast oscillation driven by Δm^2_{31}

- NO both Δm^2 are positive while in IO they are both negative
  $|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}| \sim 2.5 \times 10^{-3} eV^2$
  $|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}| \sim 2.4 \times 10^{-3} eV^2$

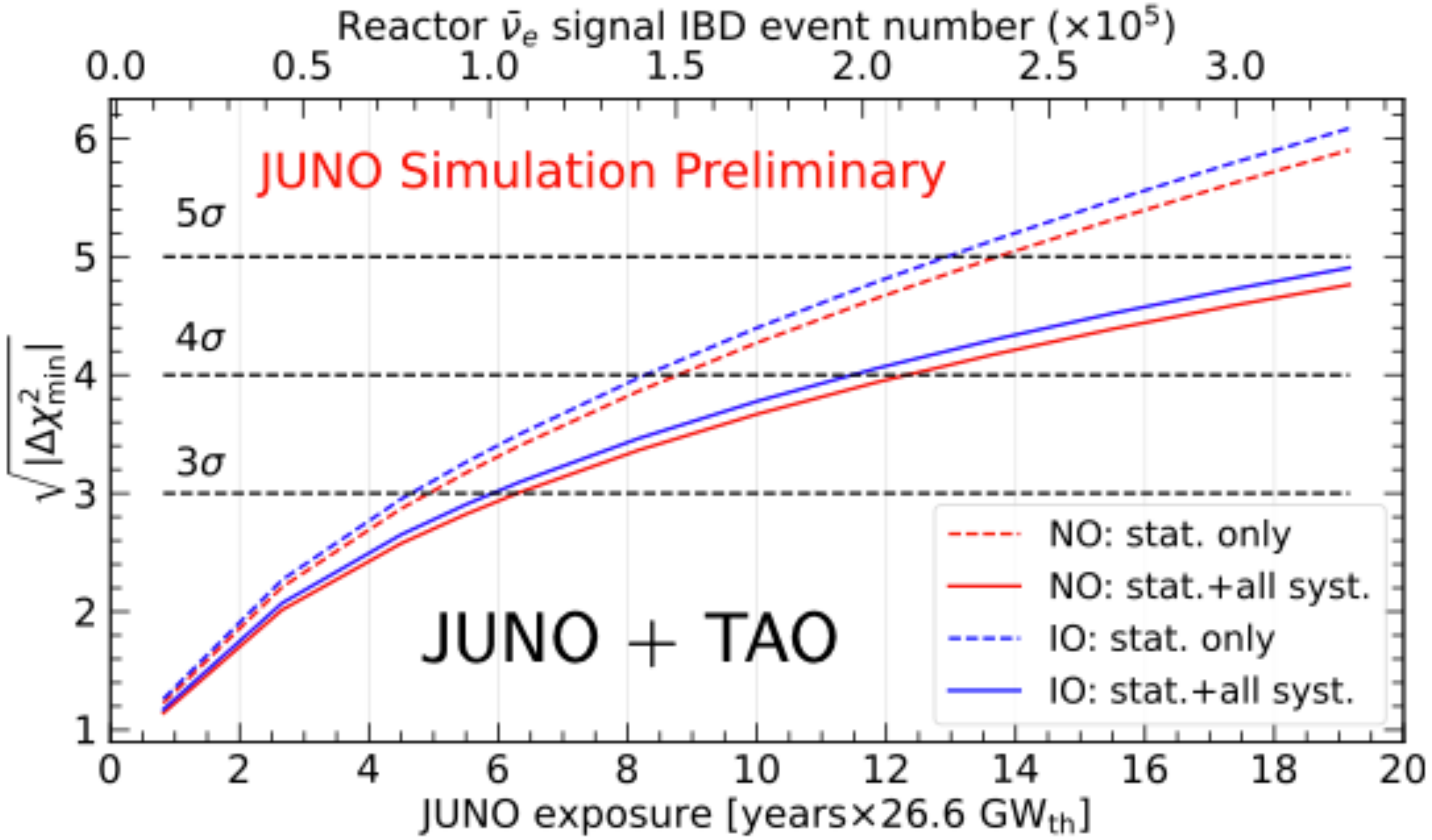
- This difference allow to distinguish the two cases if the oscillation can be measured with enough precision → critical parameter for JUNO is the energy resolution

Energy resolution in JUNO



- Assuming energy resolution of $3\,\%/\sqrt{E}$

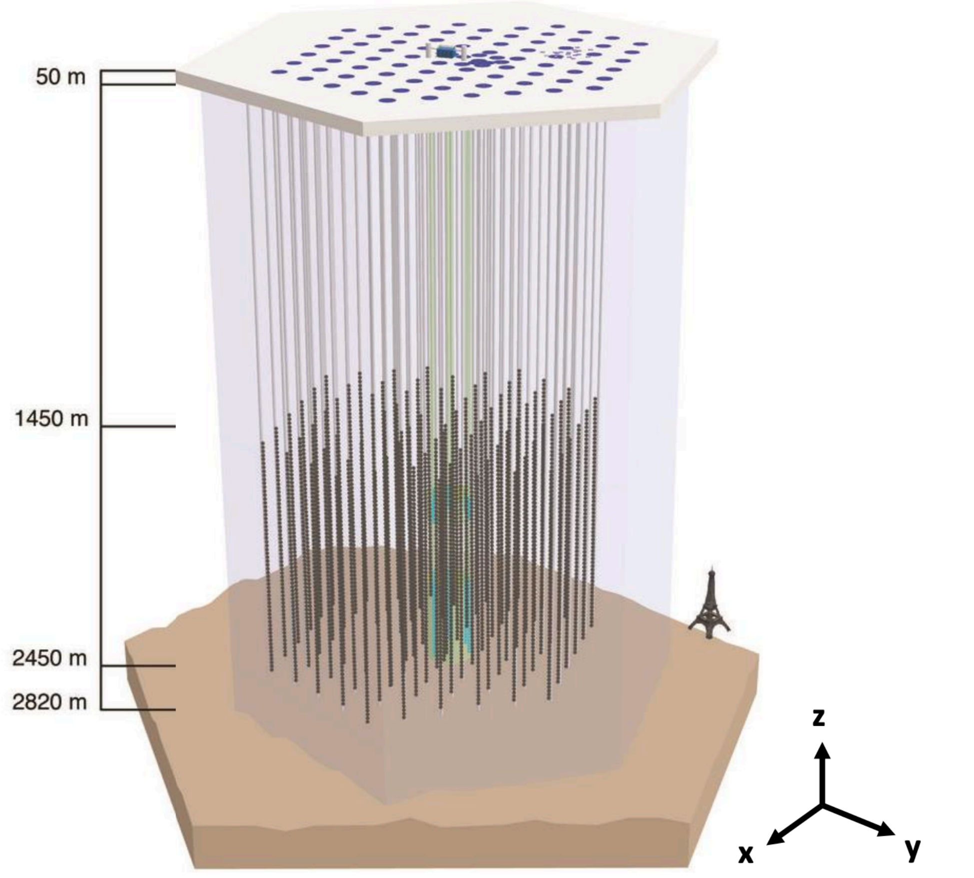
- Statistics is 100k interactions in 6 y (60 evts/day)



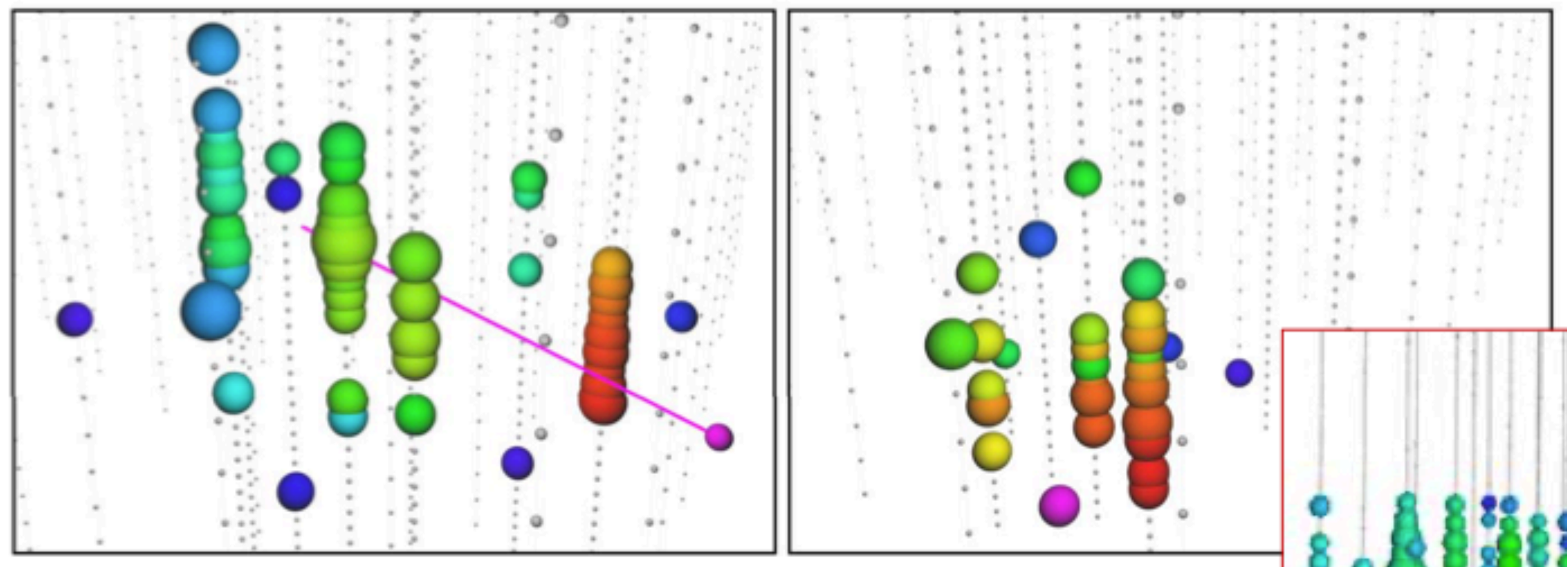
IceCUBE

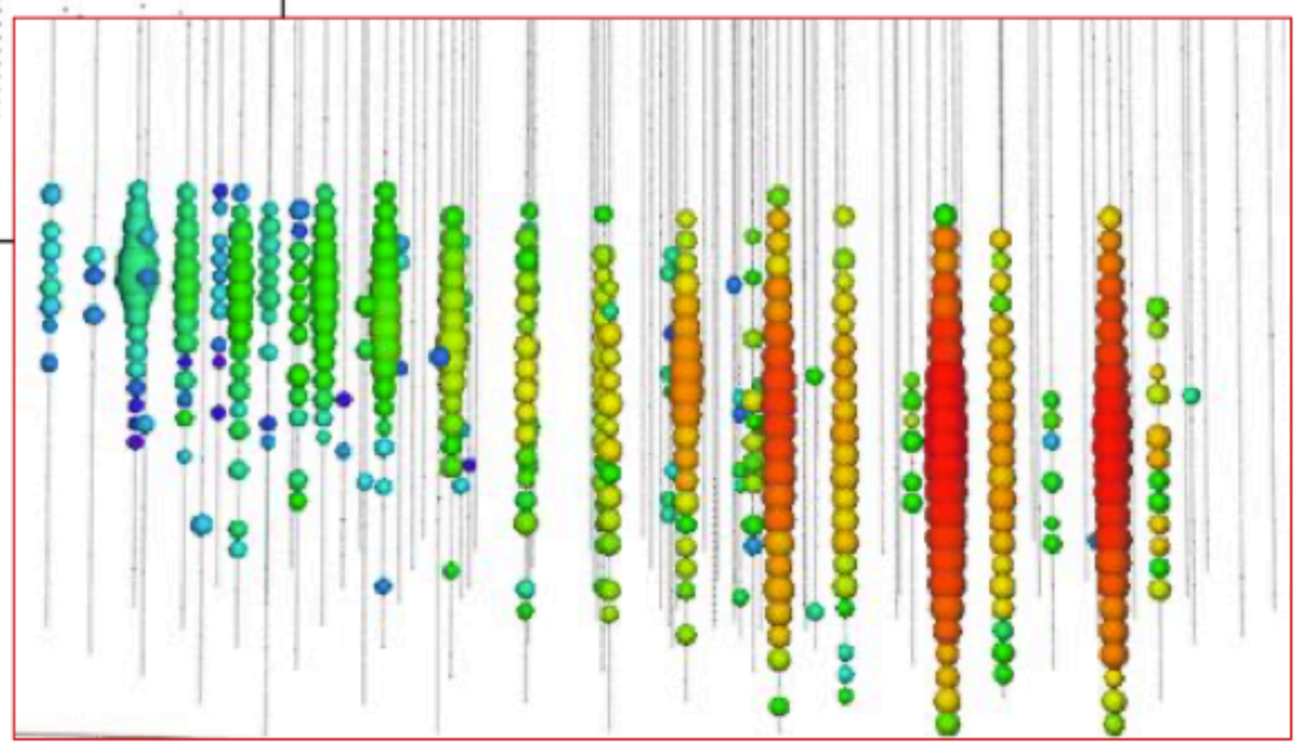
- Neutrino telescope installed in the ice in Antarctica
- Huge volumes (km3 size) optimized for astrophysics
- But if the telescope is dense enough one can also detect atmospheric neutrinos and measure them well enough to measure oscillations!
- Separate ν_e from ν_μ from the shape of the Cherenkov track/shower

- Ice **Cherenkov ν** detector
- 1.5 – 2.5 km under ice
- 5,160 DOMs on 86 strings
- 1 km^3 volume
- High energy array spacing
  - Δz=17m
  - $\Delta(x, y)$=125m
- LE extension: DeepCore
  - Δz=7m
  - $\Delta(x, y)$=40-70m



GeV events in DeepCore for ν oscillations



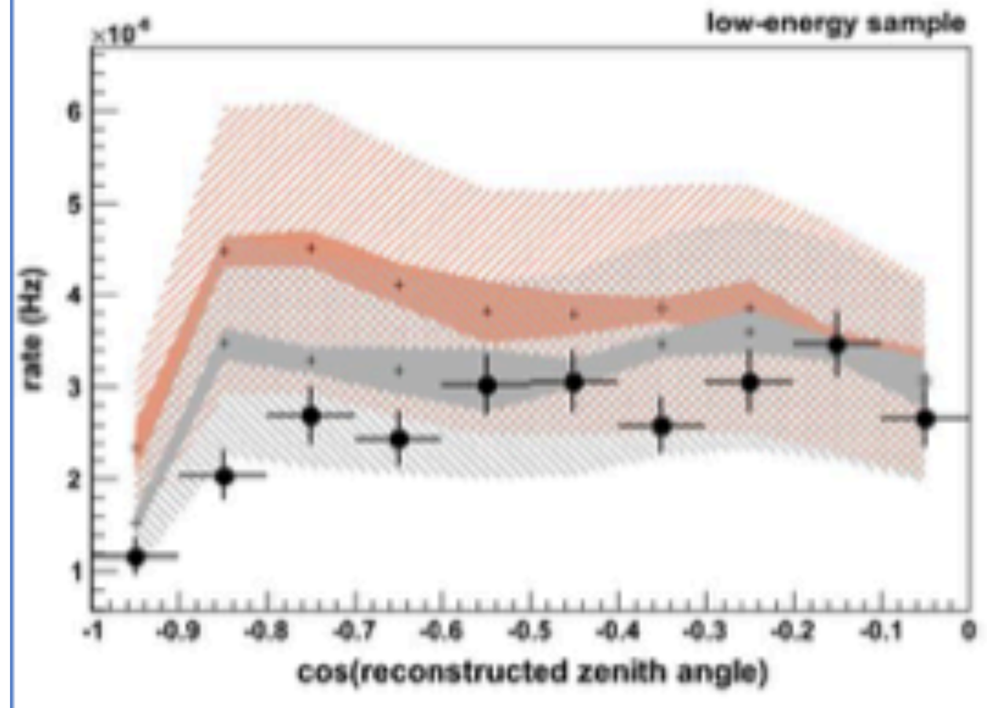


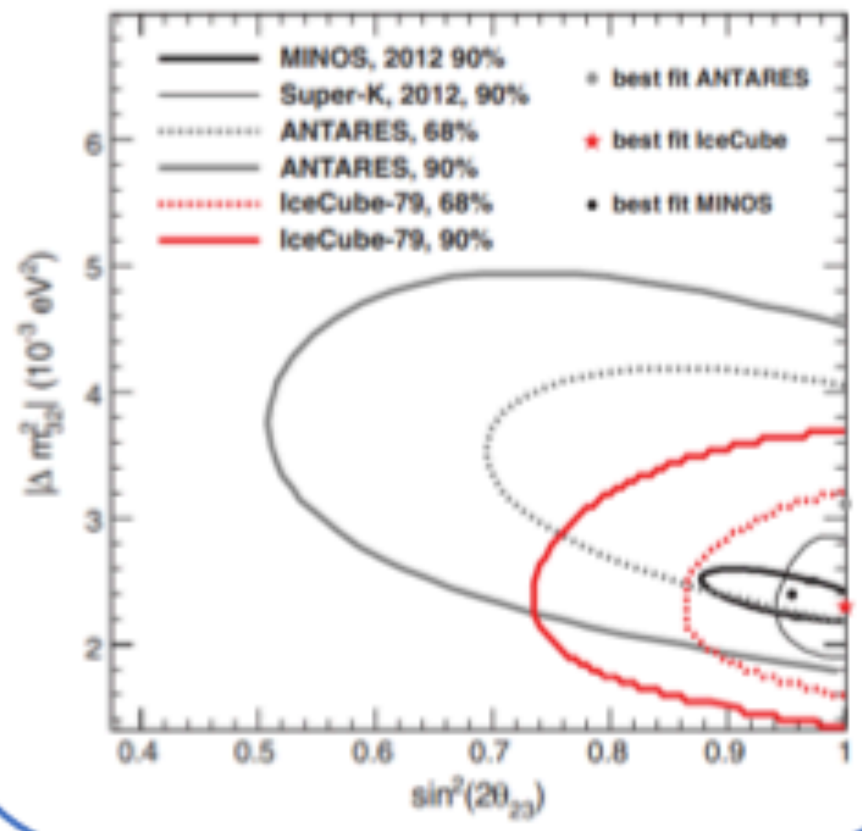
Color indicates time (red=early, blue=late).
Sphere size is proportional to number of photons observed.

TeV event in IceCube for sterile ν searches

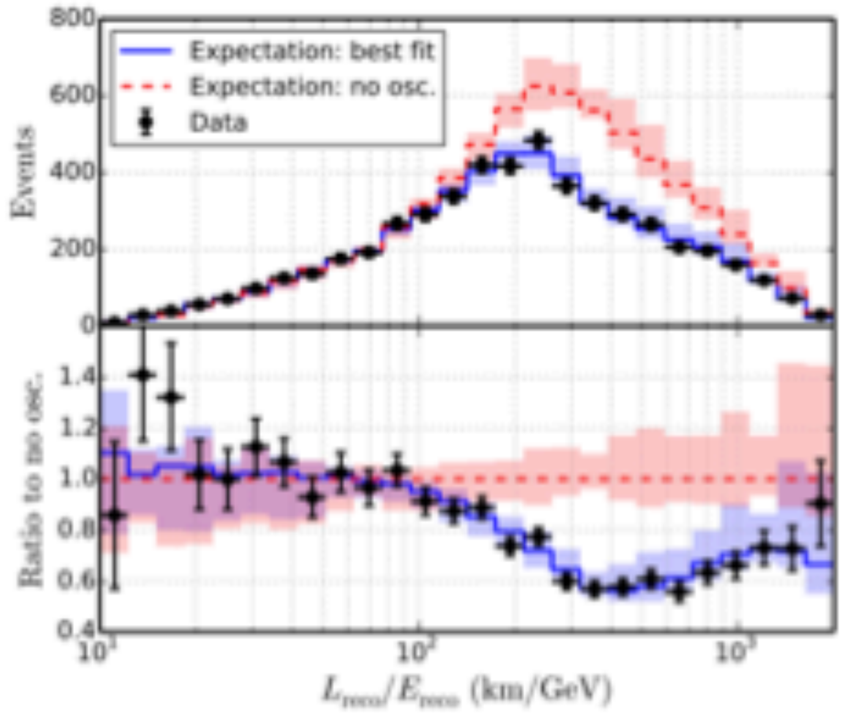
Atmospheric neutrinos

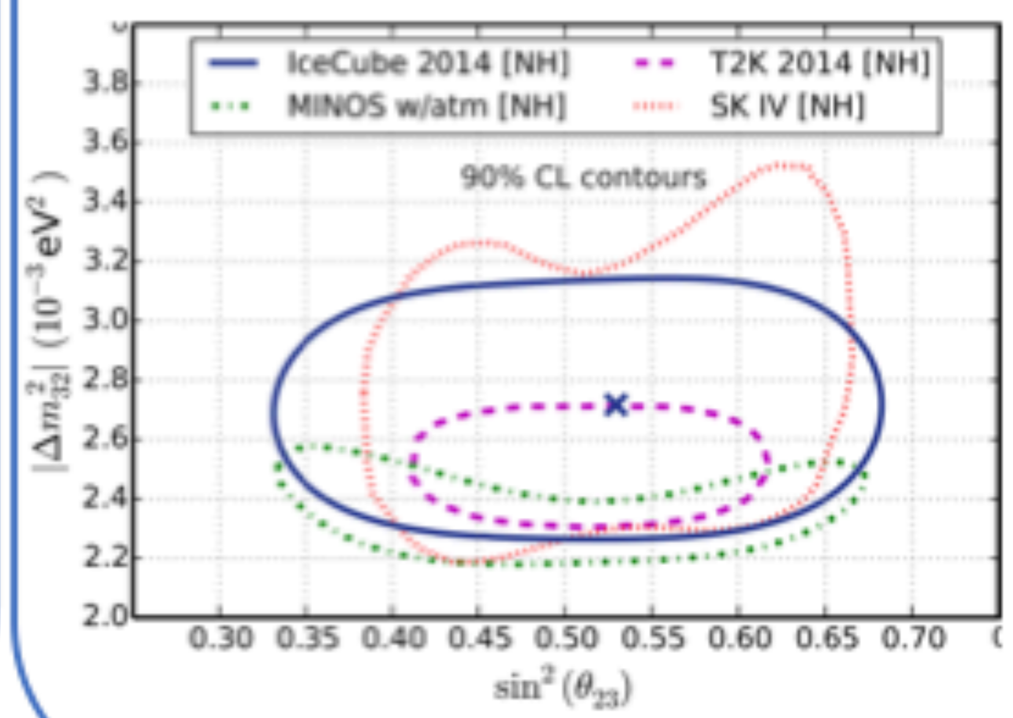
IceCube, PRL 111, 081801 **(2013)**
700 events



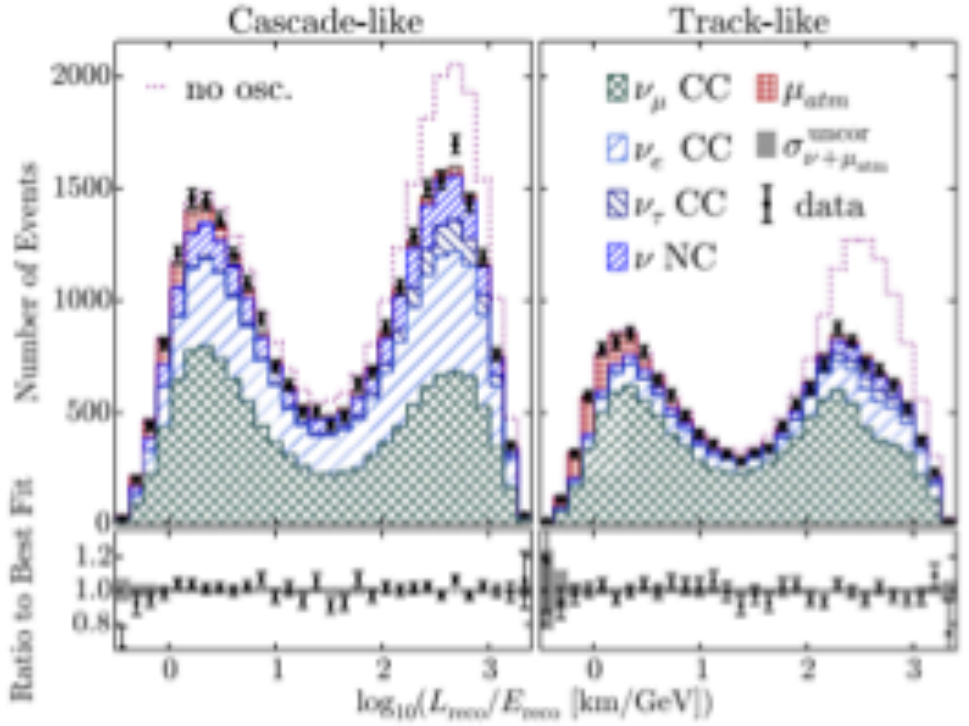


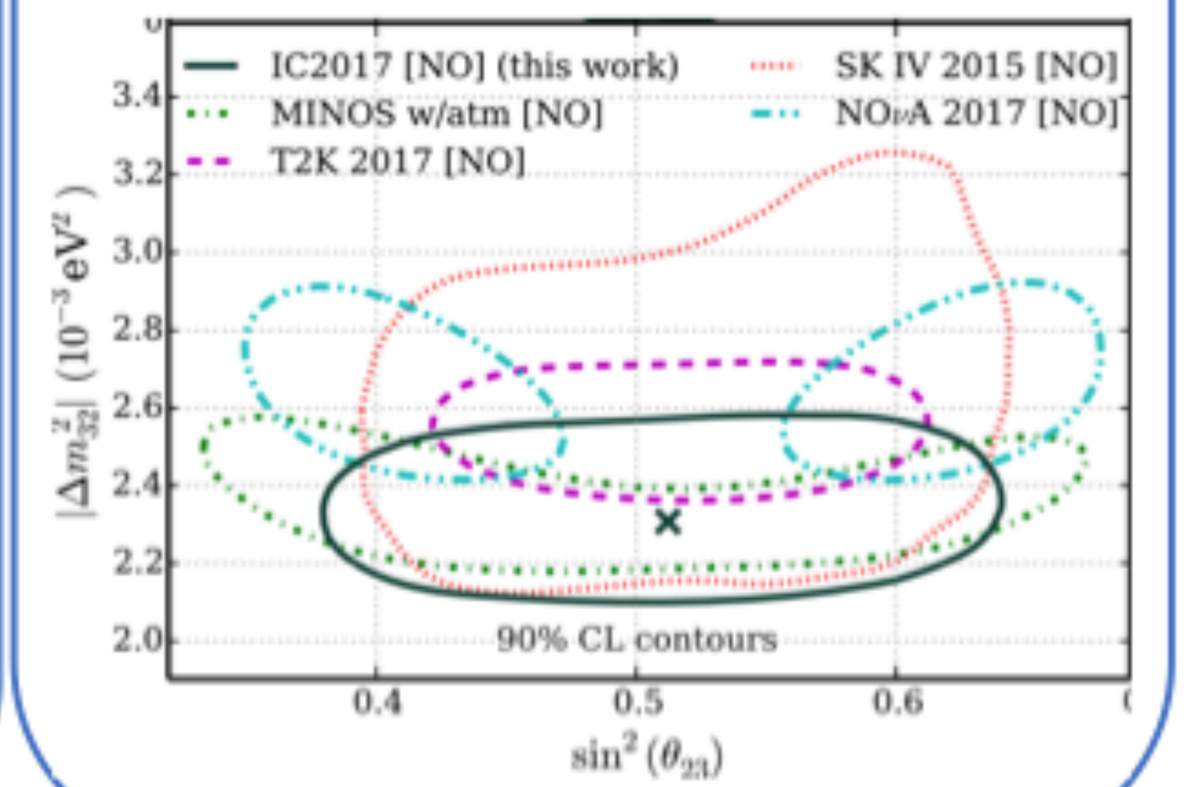
IceCube, PRD 91, 072004 **(2015)**
~5k events, "golden events"



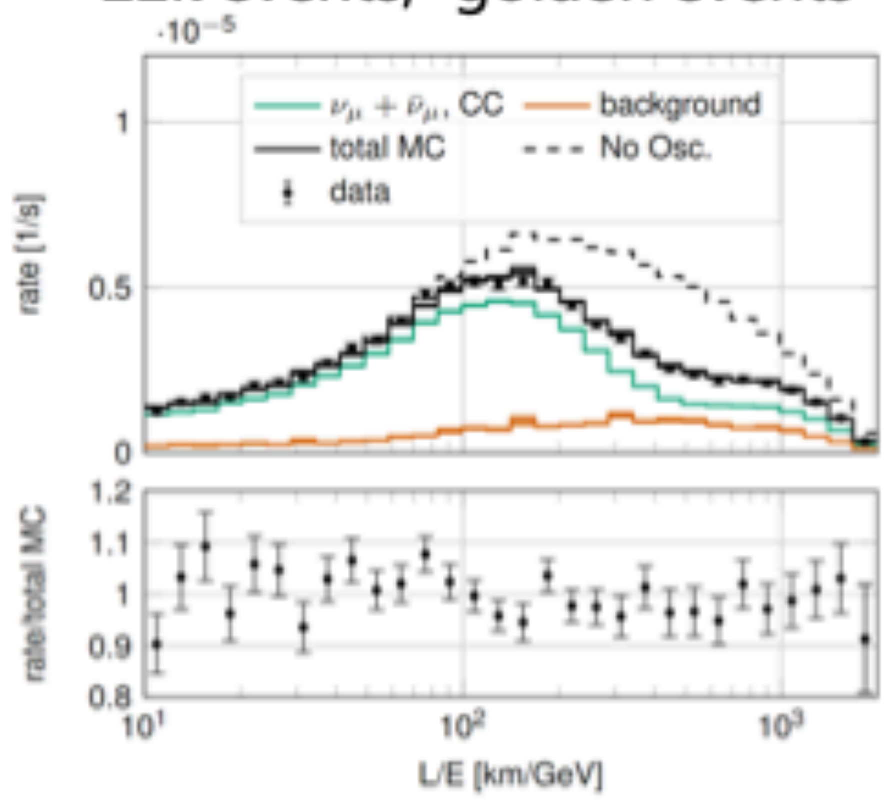


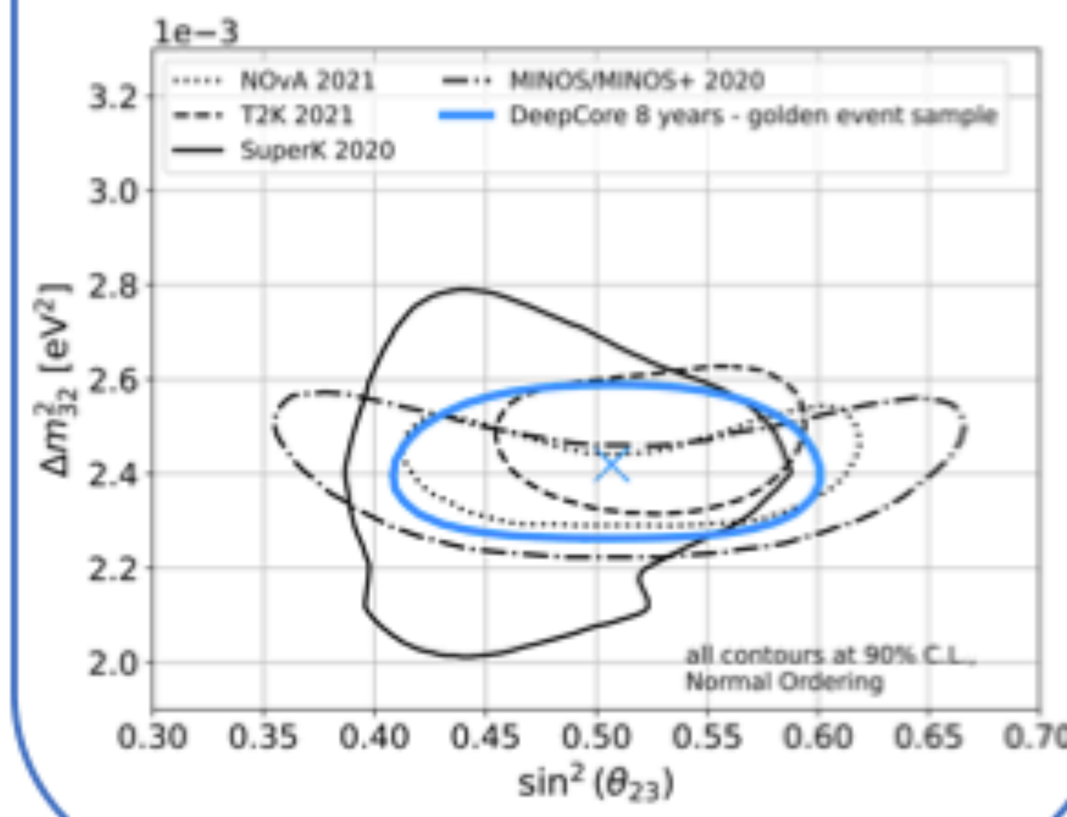
IceCube, PRL 120, 071801 **(2018)**
~35k events, inclusive sample





IceCube, PRD 108, 012014 **(2023)**
~22k events, "golden events"





12

Most recent results

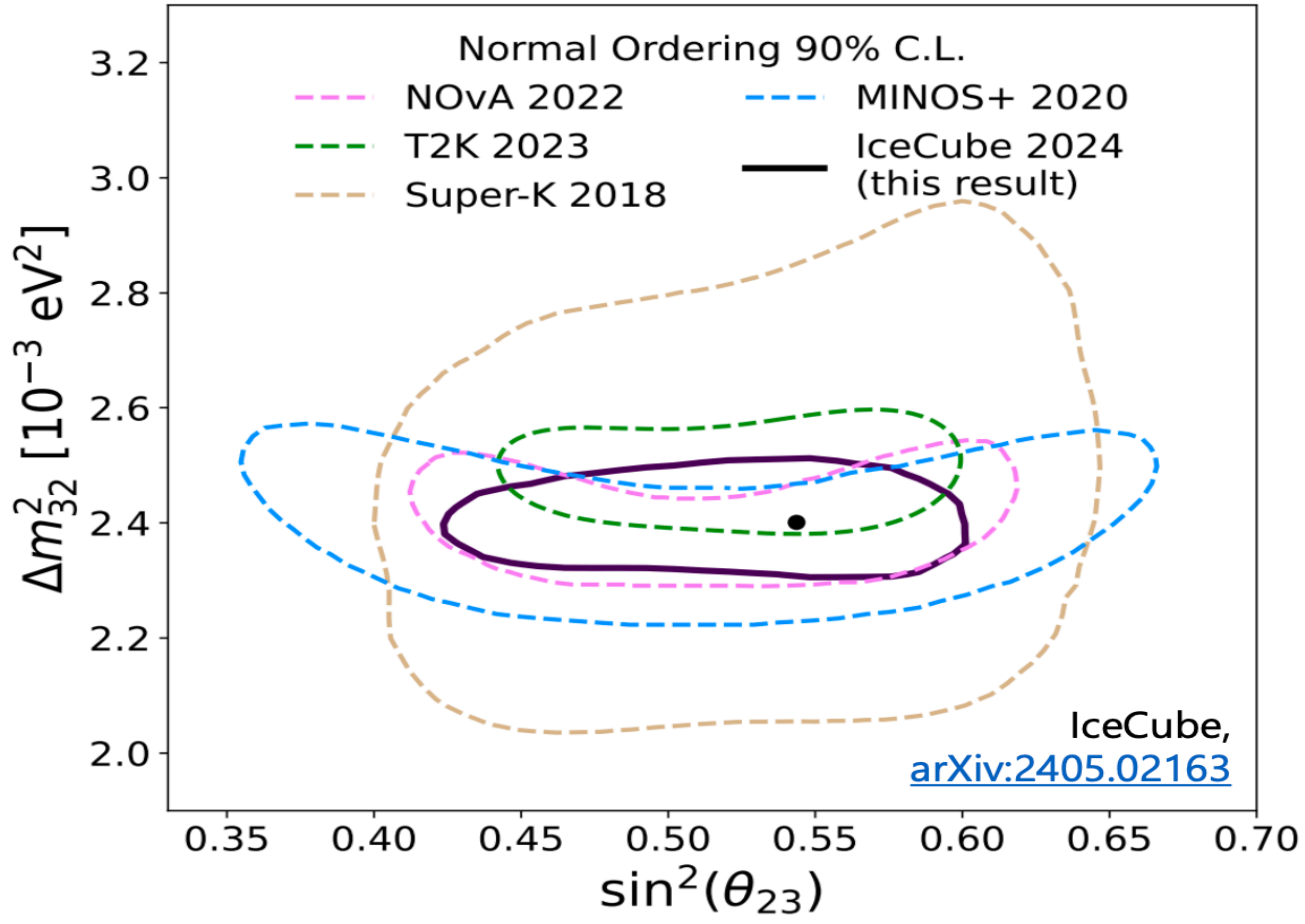
Atm. Osc. - **Newest result**

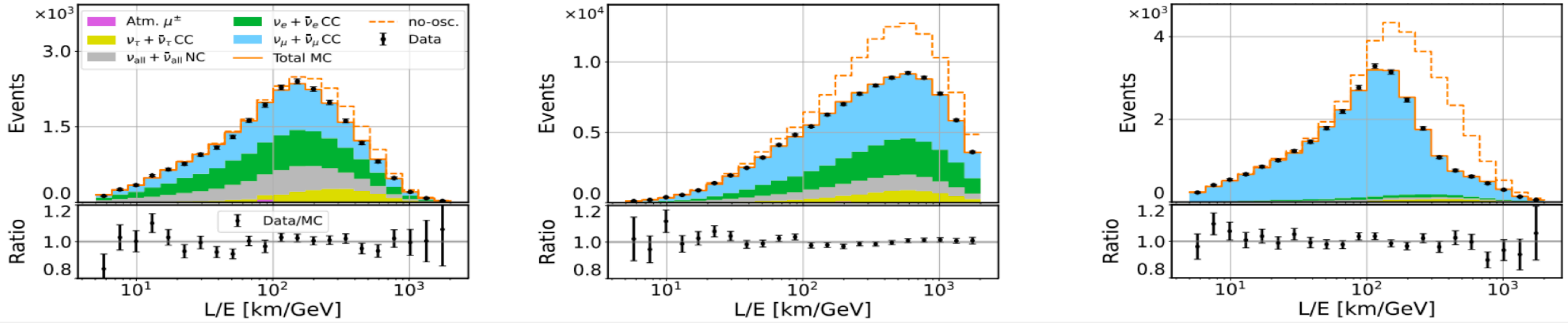
- CNN-based classification and reco
  - Uses inputs that our MC describes well
  - Recovers events that are hard to handle
  - 150,000 ν candidates in 9 years of data
- Best fit

  $\sin^2\theta_{23} = 0.54^{+0.04}_{-0.03}$

  $\Delta m^2_{32} = 2.40^{+0.05}_{-0.04} \times 10^{-3}$ eV²

  GoF p-value: 19%

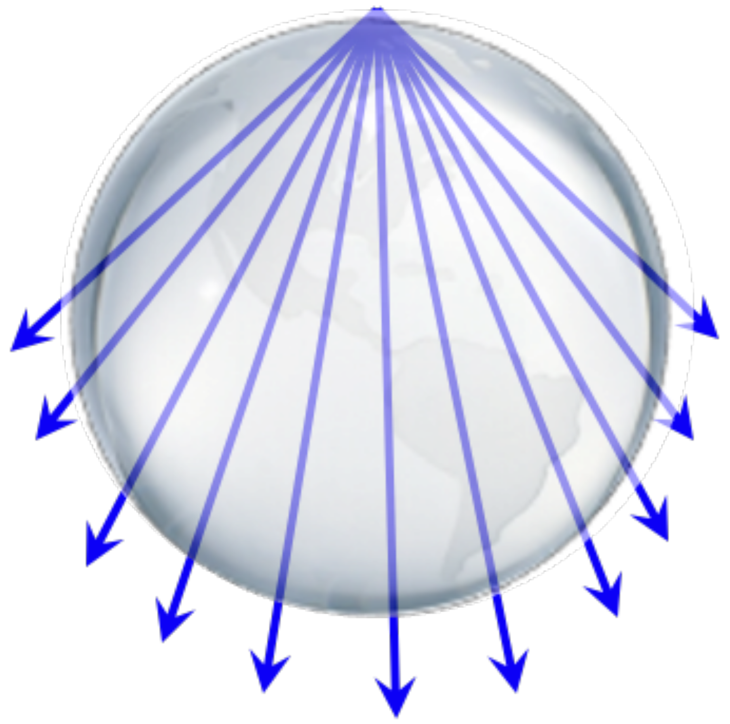




Can we do more? MSW!

Earth is transparent to ν's with a "refractive index" ⇒ Effective mass states and mixing

⇒ Modified oscillation probabilities



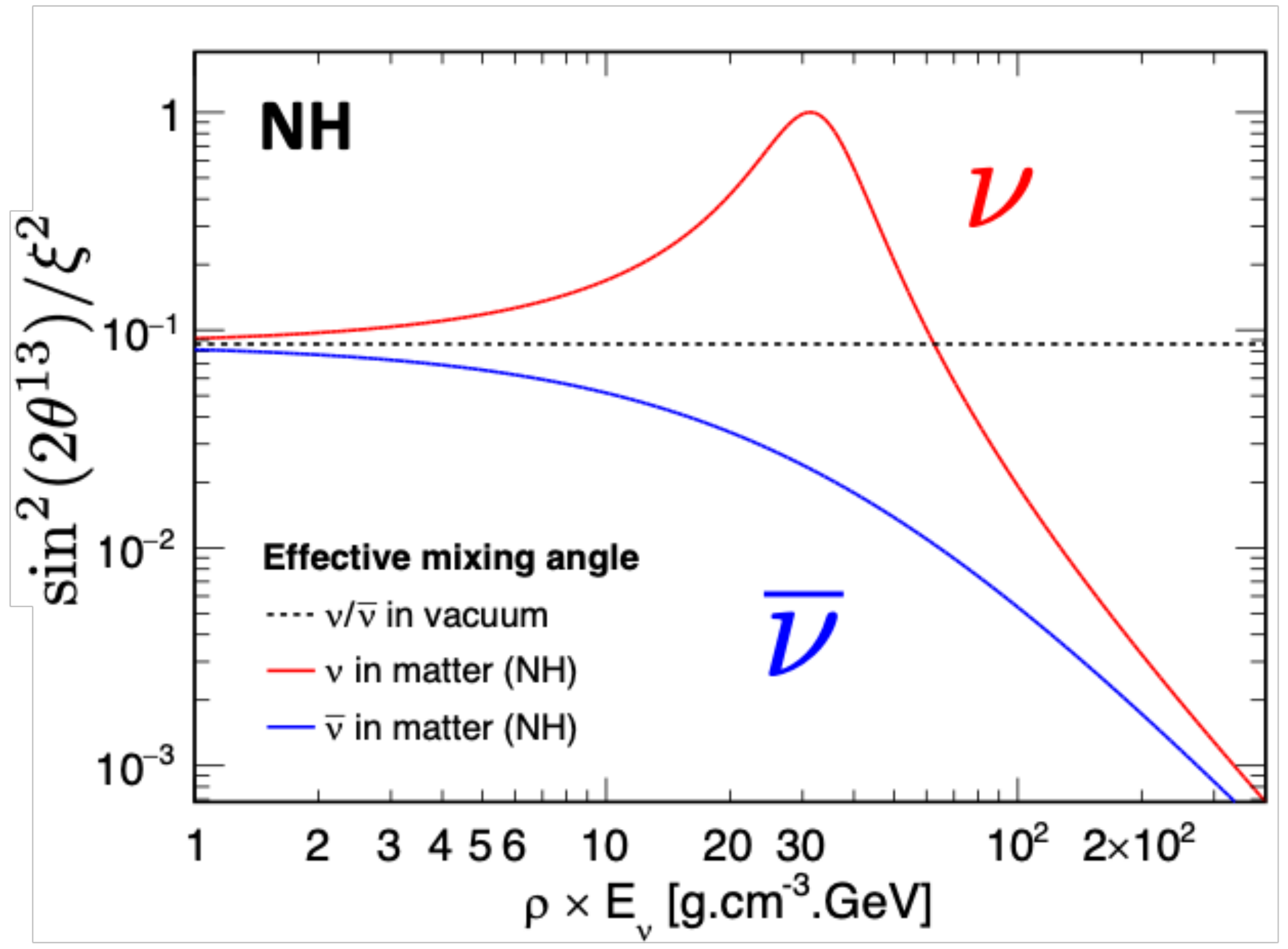
In a 2-neutrino scheme:

$$P_{\alpha\to\beta}(L,E) = \frac{\sin^2(2\theta)}{\xi^2}\sin^2\left[\frac{\xi\cdot\Delta m^2 L}{4E}\right]$$

$$\xi = \sqrt{\sin^2 2\theta + \left(\cos 2\theta \pm 2\sqrt{2}G_F\frac{E\cdot N_e(x)}{\Delta m^2}\right)^2}$$

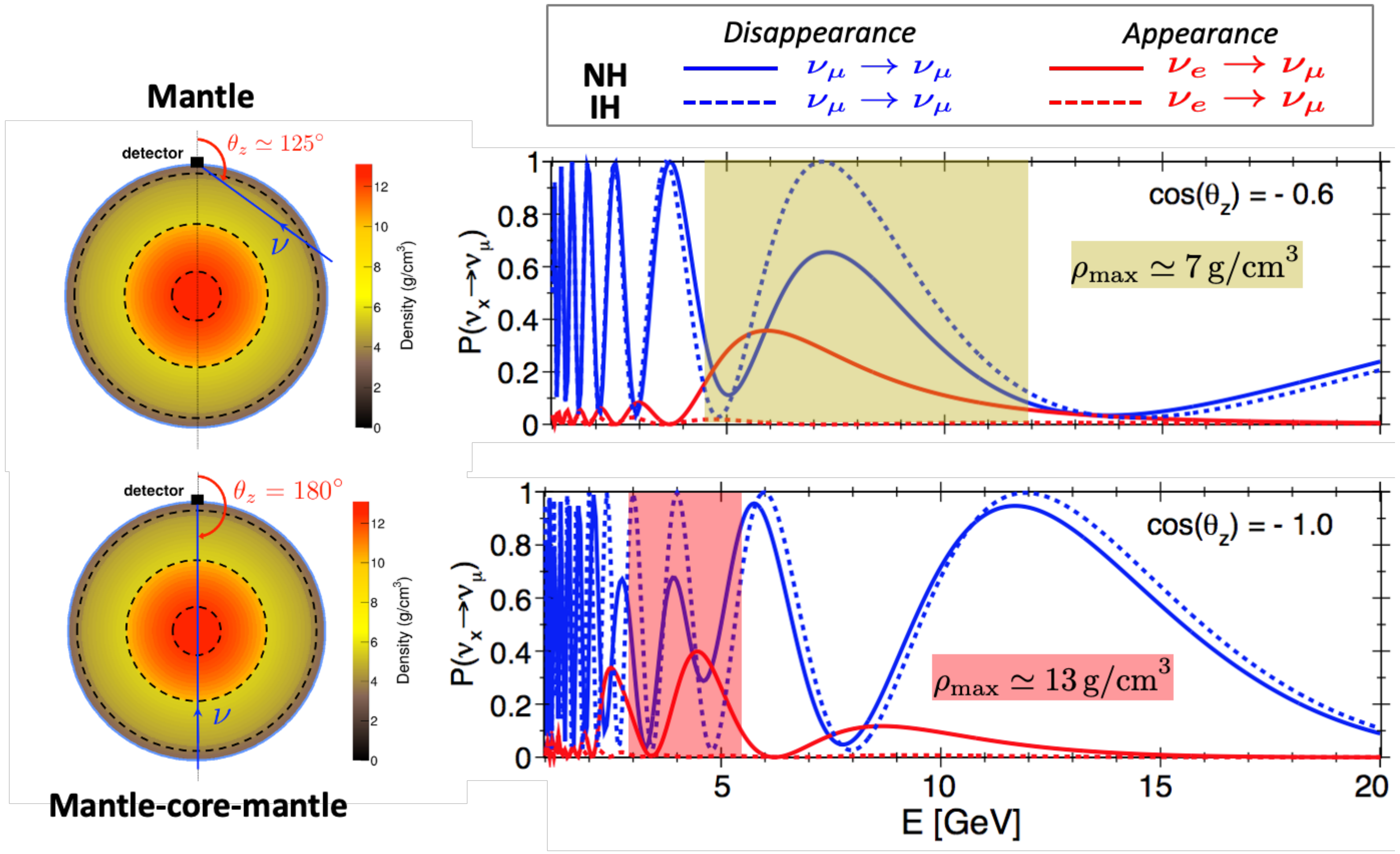
$-$ for ν
$+$ for $\overline{\nu}$

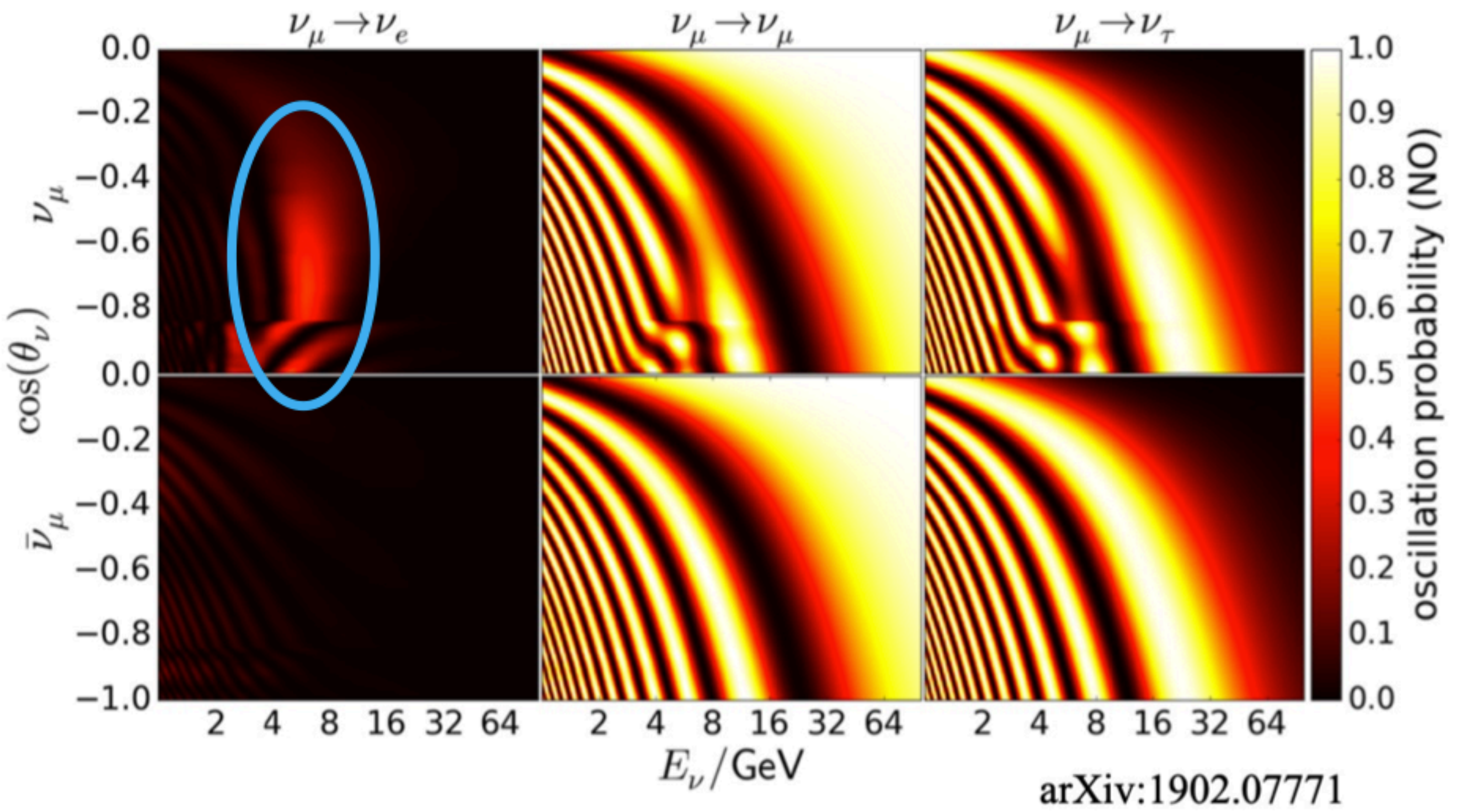
> 0 for NH
< 0 for IH



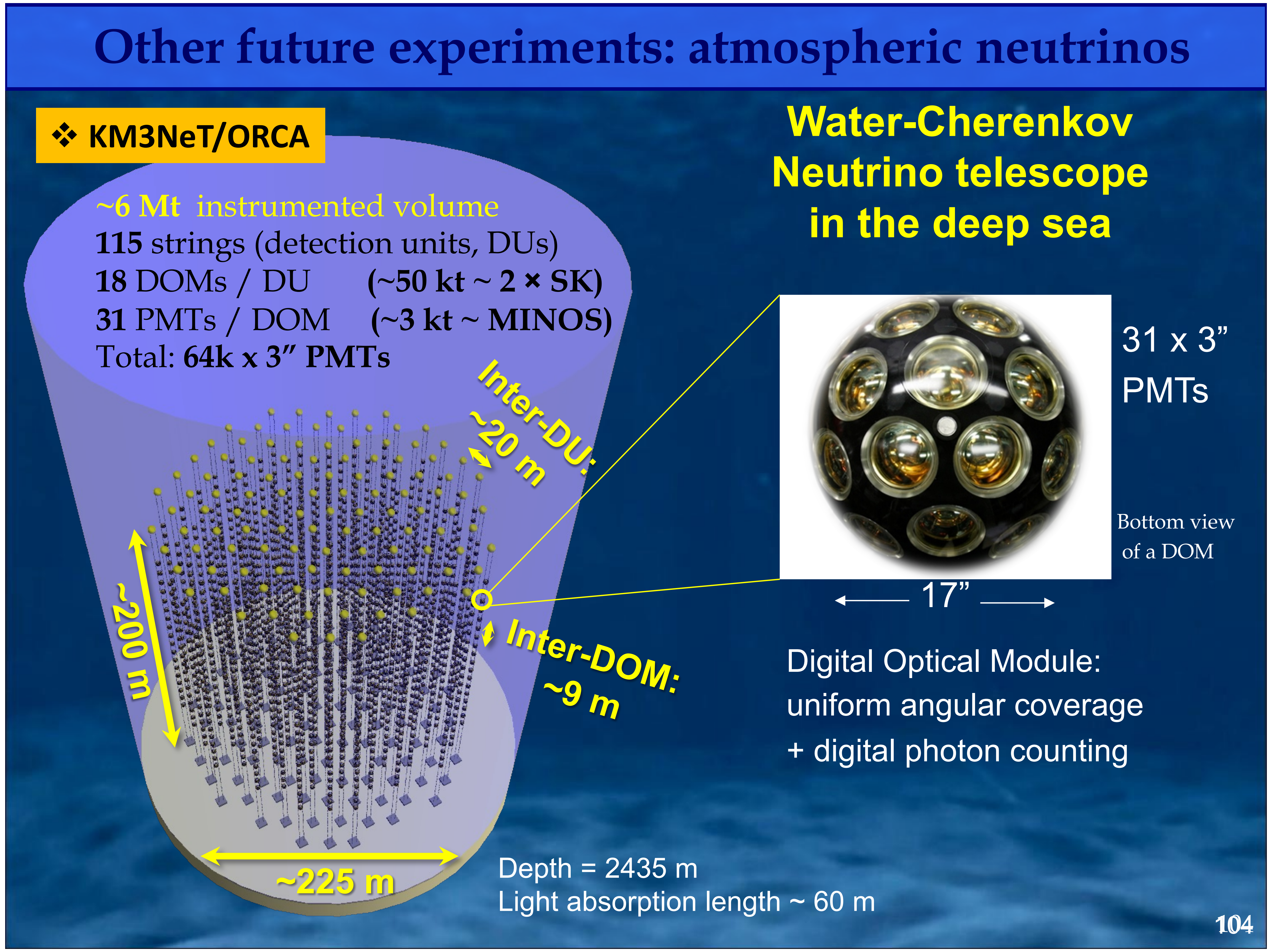
⇒ MSW resonant enhancement of the oscillation **for neutrinos in NH and antineutrinos in IH**

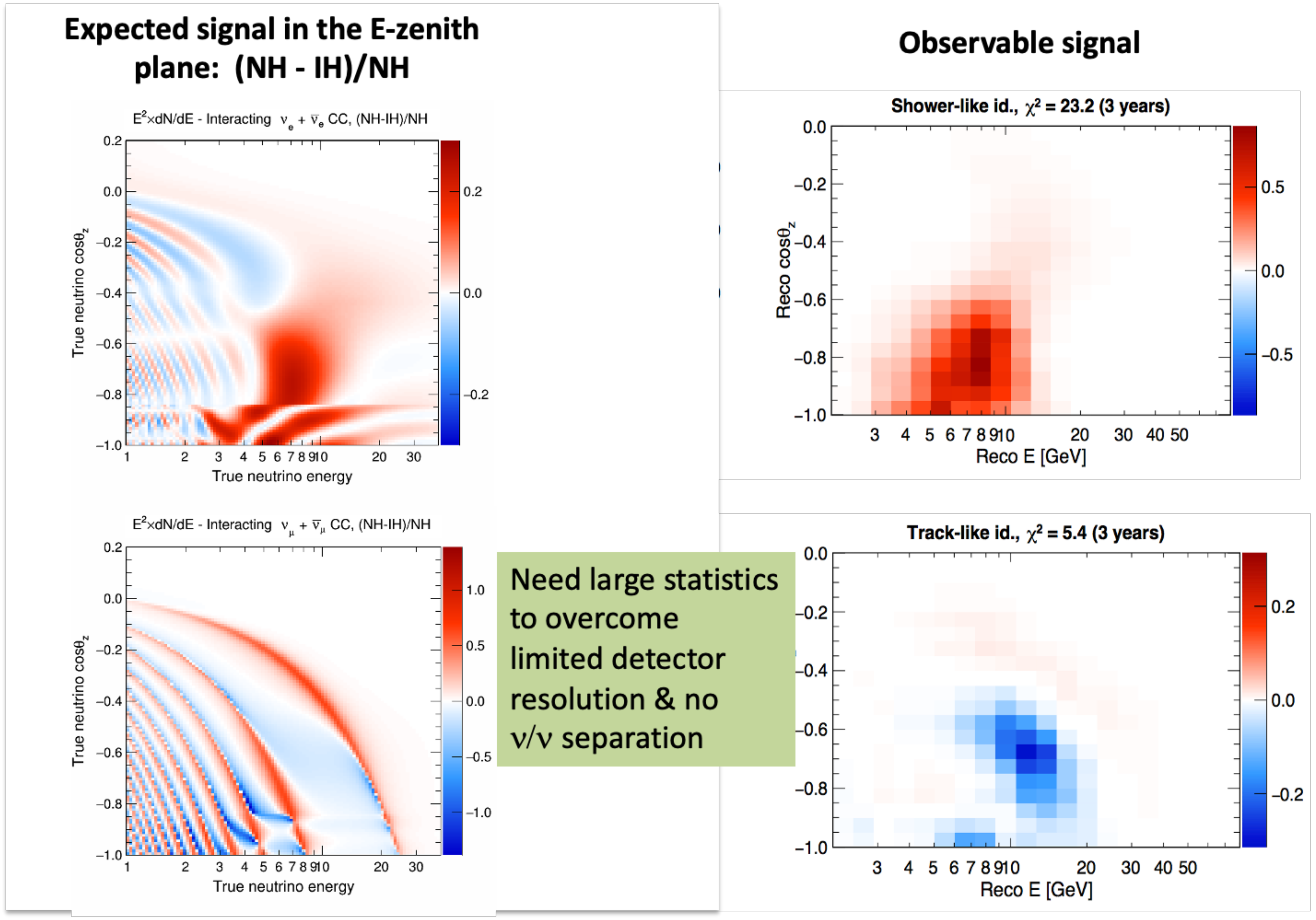
MSW effect in the Earth





ORCA experiment

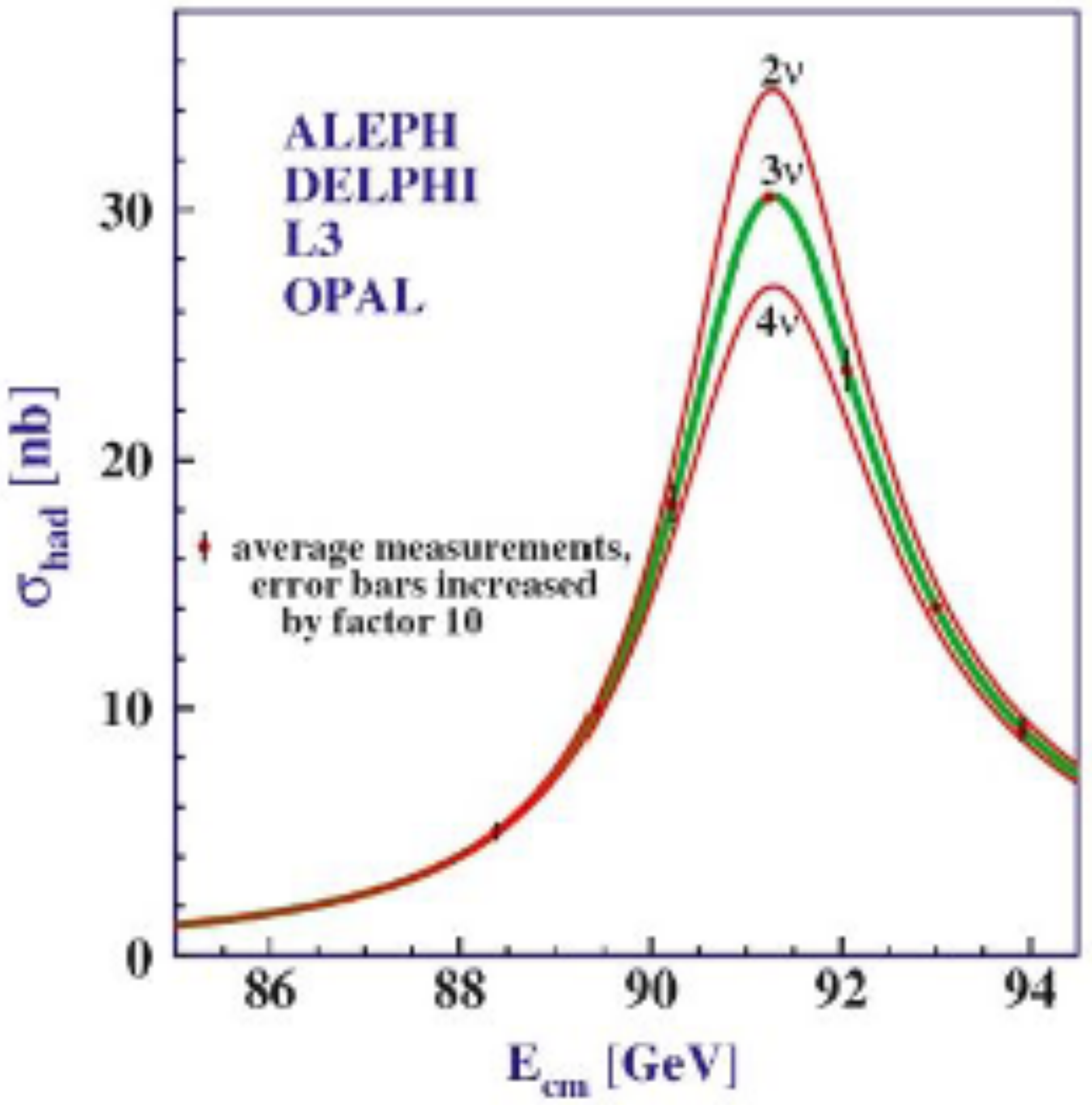




The sterile neutrino saga

Sterile neutrinos

- Number of light active neutrinos is 3
  - Light means $M_\nu < M_Z/2$
  - And what about non-active (sterile) Neutrinos?
- What is a sterile neutrino: neutrino that do not couple with Z so do not interact via weak interactions
  - But affect the ν mixing through their coupling with active neutrinos



Final LEP average $N_\nu = 2.984 \pm 0.008$

3+1 phenomenology

$$\begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \\ \nu_s(x) \end{pmatrix}_L = U \begin{pmatrix} \nu_1(x) \\ \nu_2(x) \\ \nu_3(x) \\ \nu_4(x) \end{pmatrix}_L = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1(x) \\ \nu_2(x) \\ \nu_3(x) \\ \nu_4(x) \end{pmatrix}_L$$

- In the simpler scenario we can add one sterile neutrino family : 3+1 model
- $U_{e4} = s_{14}, \quad U_{\mu 4} = c_{14}s_{24}, \quad U_{\tau 4} = c_{14}c_{24}s_{34}$
- One additional mass eigenstate.
- In the simplest scenario $m_4 \gg m_{1,2,3}$ and we can use a 2-ν framework approach
  - $\Delta m^2_{SBL} = \Delta m^2_{41} \sim \Delta m^2_{42} \sim \Delta m^2_{43} \gg |\Delta m^2_{31}|$

Sterile Neutrinos oscillations

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta^{SBL} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta^{SBL} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\theta^{SBL}_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2) = \sin^2 2\theta_{14}$$

$$\sin^2 2\theta^{SBL}_{\mu\mu} = 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) = \cos^2\theta_{14} \sin^2 2\theta_{24} + \sin^4\theta_{24} \sin^2 2\theta_{14}$$

$$\sin^2 2\theta^{SBL}_{\mu e} = 4|U_{\mu 4}U_{34}|^2 = \sin^2\theta_{24} \sin^2 2\theta_{14}$$

$$\sin^2 2\theta^{SBL}_{\mu e} = \frac{1}{4} \sin^2 2\theta^{SBL}_{ee} \sin^2 2\theta^{SBL}_{\mu\mu}$$

- A sterile neutrino means that one should observe 2 disappearance signals when looking at ν_μ and ν_e and 1 appearance signal $\nu_\mu \to \nu_e$

2018 MiniBooNE results

Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment

A. A. Aguilar-Arevalo[13], B. C. Brown[6], L. Bugel[12], G. Cheng[5], J. M. Conrad[12], R. L. Cooper[10,15], R. Dharmapalan[1,2], A. Diaz[12], Z. Djurcic[2], D. A. Finley[6], R. Ford[6], F. G. Garcia[6], G. T. Garvey[10], J. Grange[7], E.-C. Huang[10], W. Huelsnitz[10], C. Ignarra[12], R. A. Johnson[3], G. Karagiorgi[5], T. Katori[12,16], T. Kobilarcik[6], W. C. Louis[10], C. Mariani[19], W. Marsh[6], G. B. Mills[10,†], J. Mirabal[10], J. Monroe[18], C. D. Moore[6], J. Mousseau[14], P. Nienaber[17], J. Nowak[9], B. Osmanov[7], Z. Pavlovic[6], D. Perevalov[6], H. Ray[7], B. P. Roe[14], A. D. Russell[6], M. H. Shaevitz[5], J. Spitz[14], I. Stancu[1], R. Tayloe[8], R. T. Thornton[10], M. Tzanov[4,11], R. G. Van de Water[10], D. H. White[10], D. A. Wickremasinghe[3], E. D. Zimmerman[4]

(The MiniBooNE Collaboration)


Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment
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Intriguing news from MiniBooNE
New research results have potentially identified a fourth type of neutrino: the sterile neutrino.
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Evidence Found for a New Fundamental Particle
PARTICLES AND INTERACTIONS | RESEARCH UPDATE
Evidence for sterile neutrinos claimed by Fermilab experiment
04 Jun 2018
Mysterious neutrino surplus hints at the existence of new particles
Science & Environment
Has US physics lab found a new particle?
By Paul Rincon
Science editor, BBC News website
Science
Boffins quietly cheering possible discovery of new fundamental particle: Sterile neutrino
Champagne on ice, but MiniBooNE's 15-year hunt has produced promising results
LIVESCIENCE
NEWS TECH HEALTH
Live Science › Strange News
A Major Physics Experiment Just Detected a Particle That Shouldn't Exist
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Evidence Found for a New Fundamental Particle
PARTICLES AND INTERACTIONS | RESEARCH UPDATE
Evidence for sterile neutrinos claimed by Fermilab
The reports of my death have been greatly exaggerated.
~ Mark Twain
Standard Model
Science & Environment
Has US physics lab
By Paul Rincon
Science editor, BBC News website
Science
Boffins quietly cheering possible discovery of new fundamental particle: Sterile neutrino
Champagne on ice, but MiniBooNE's 15-year hunt has produced promising results
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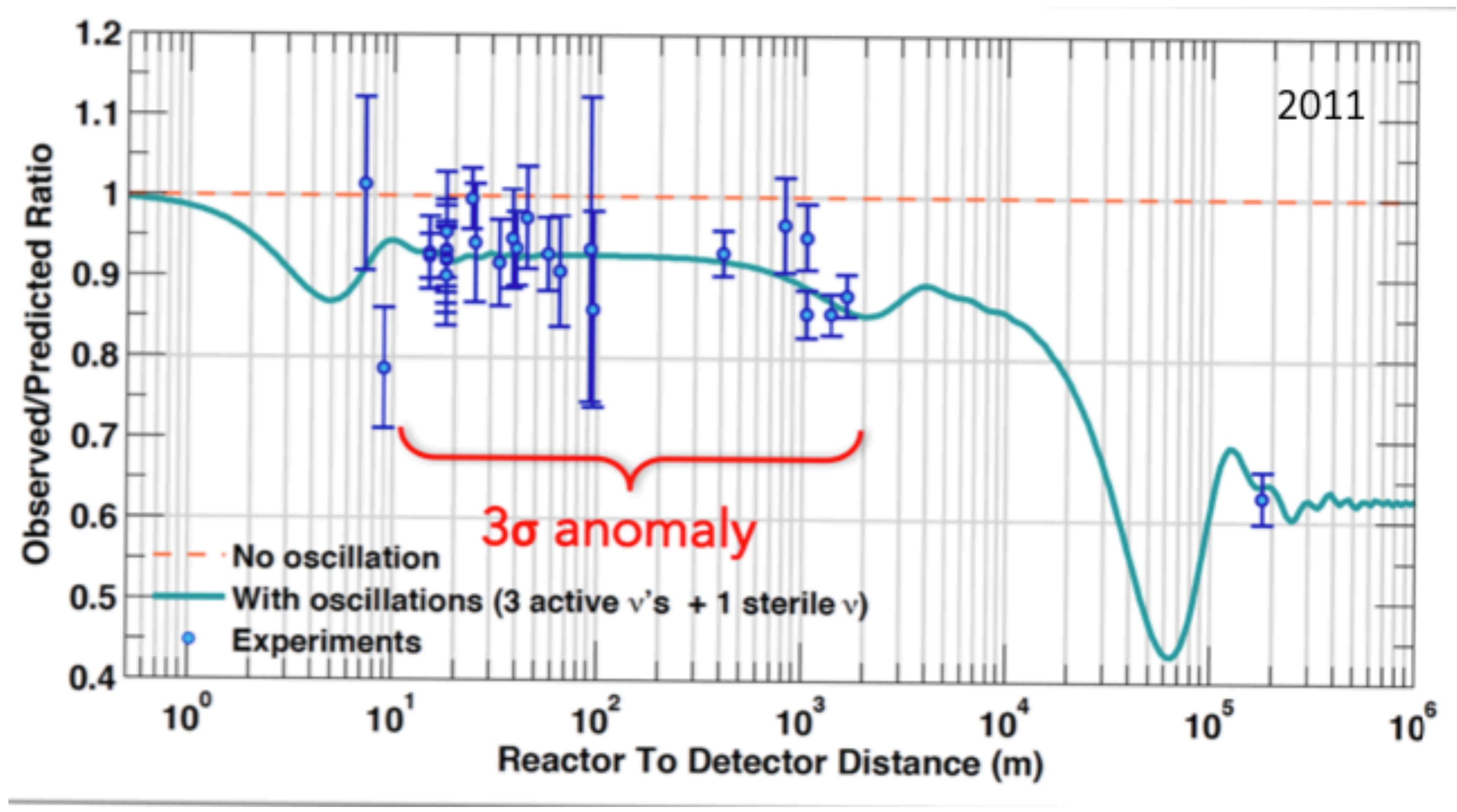
3

Anomalies can be everywhere

- Atmospheric anomaly → Neutrino oscillations
- Solar Anomaly → Neutrino flavor transition

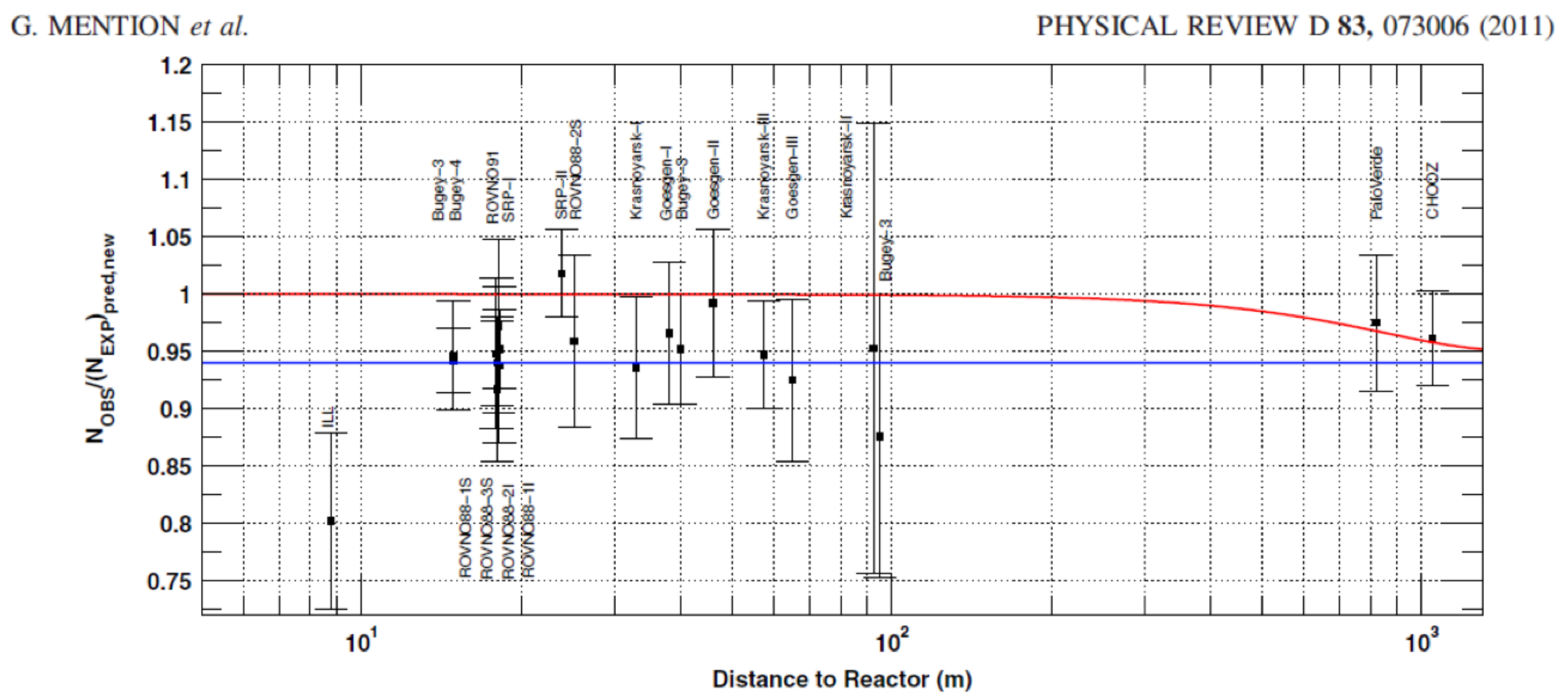
2011 reactor anomaly → sterile neutrinos?

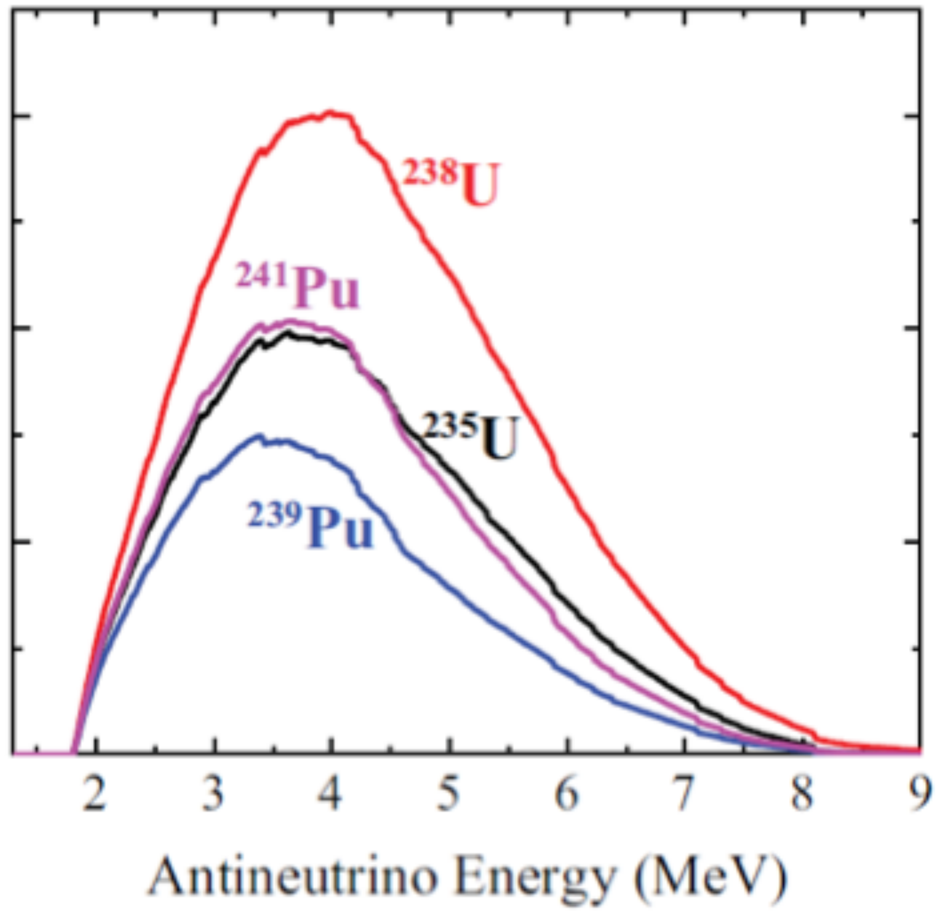


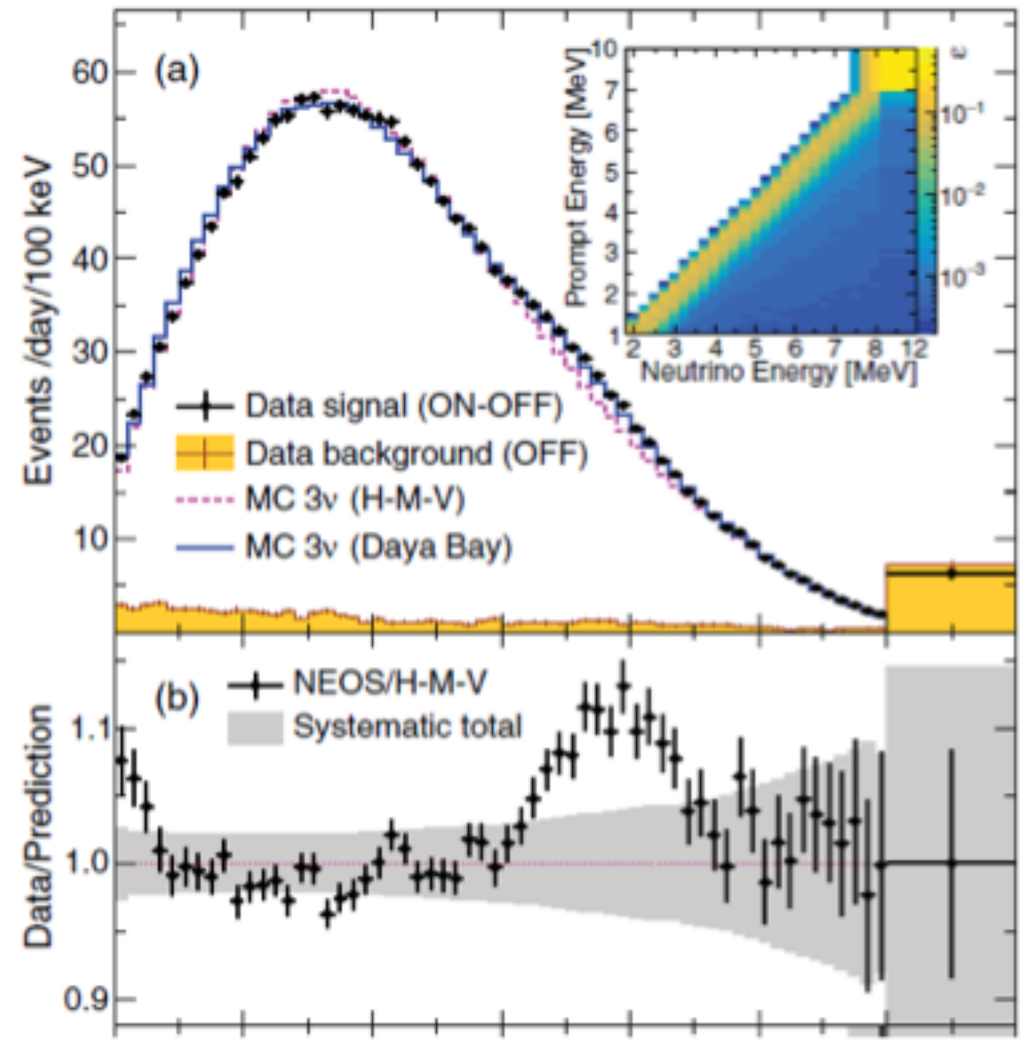
- All experiments close to reactors observed a deficit of $\bar{\nu}e$ neutrinos
- This would be compatible with $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ on a very short baseline → $\Delta m^2 \geq 1eV^2$
- Or with some systematics effects

$\bar{\nu}$ fluxes and reactor anomaly

An analysis of earlier experiments with the updated antineutrino spectra reveal a ~6% deficit at short distances.
The term **Reactor Antineutrino Anomaly (RAA)** has been coined to refer to this deficit.







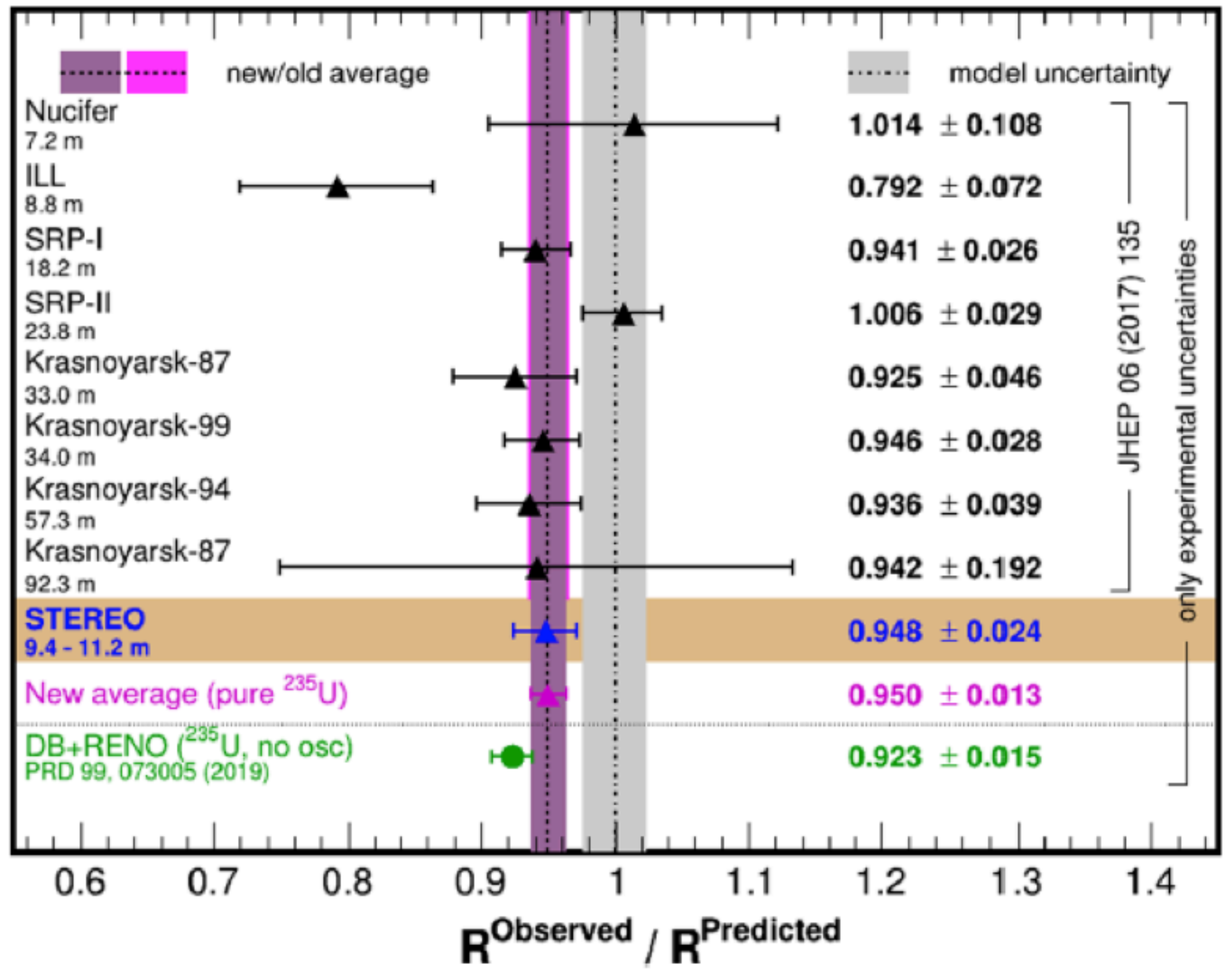
- Reactor anomaly : deficit of $\bar{\nu}$ flux with respect to expectation → sterile neutrinos?

- Neutrino emitted from reactors come from a combination of fission from different isotopes

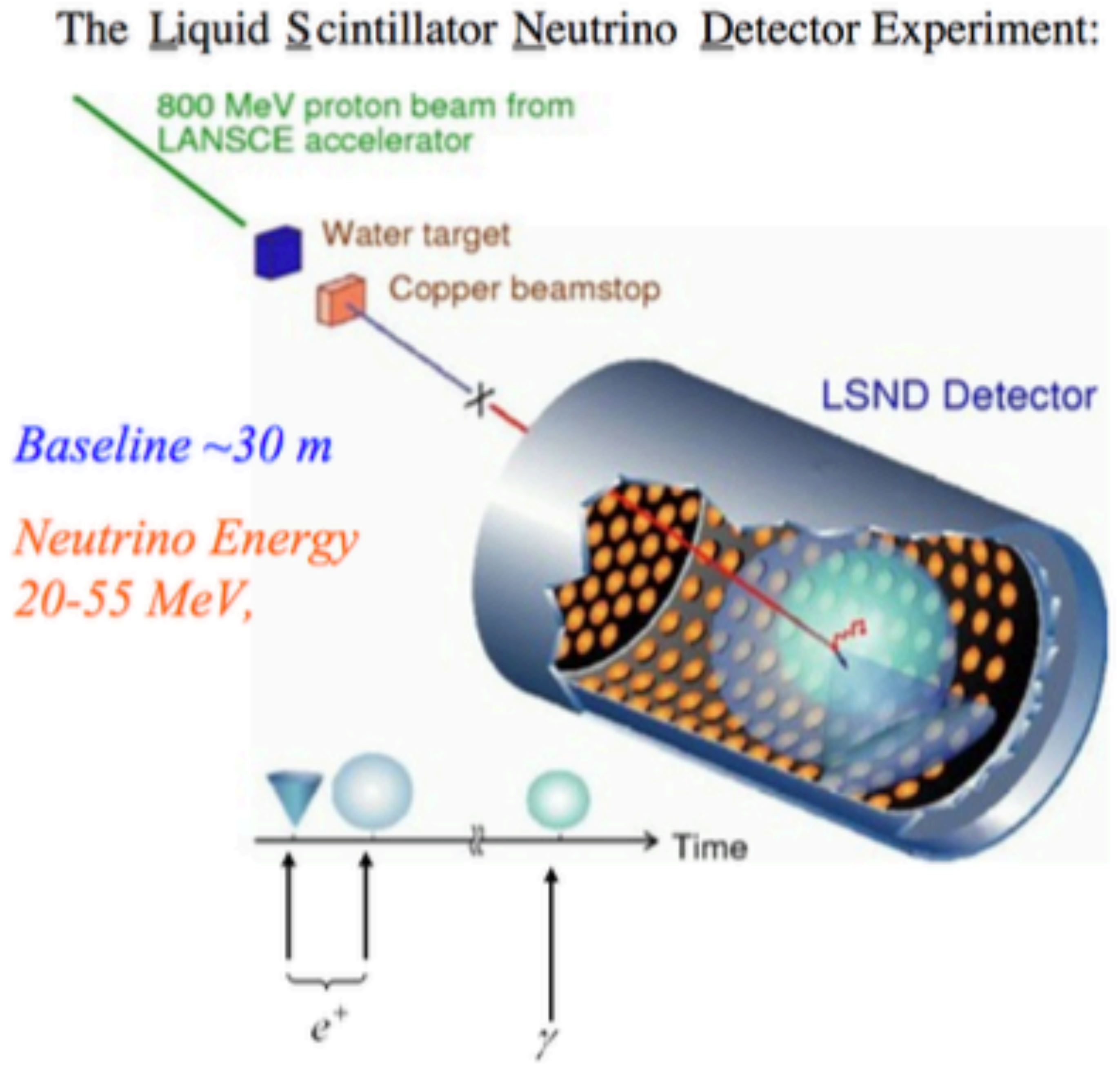
- The modeling is not simple → bump in the spectrum of neutrinos

- Measurements from STEREO (very close to the reactor so no sterile neutrinos) confirm the deficit

- There are no exciting anomalies (new physics) → we just need more precise measurements of neutrinos emitted from reactors



The LSND results (1995)



- *Beam of protons on water produces π^+ mainly*

$\pi^+ \to \mu^+ \nu_\mu$

Stop at Cu target $\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

Oscillations? $\hookrightarrow \bar{\nu}_e$

- *Search for $\bar{\nu}_e$ through*

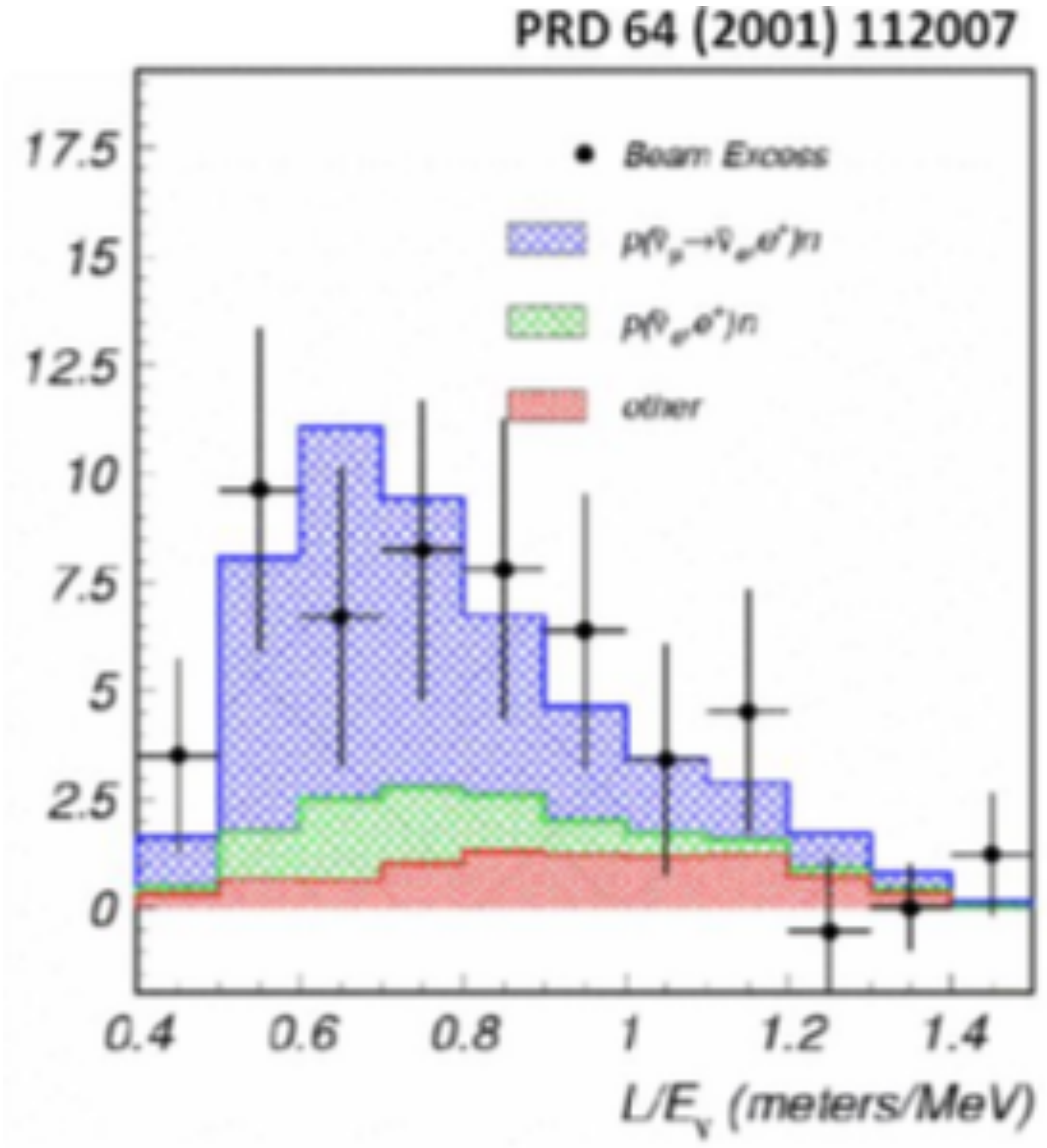
$\bar{\nu}_e p \to e^+ n$

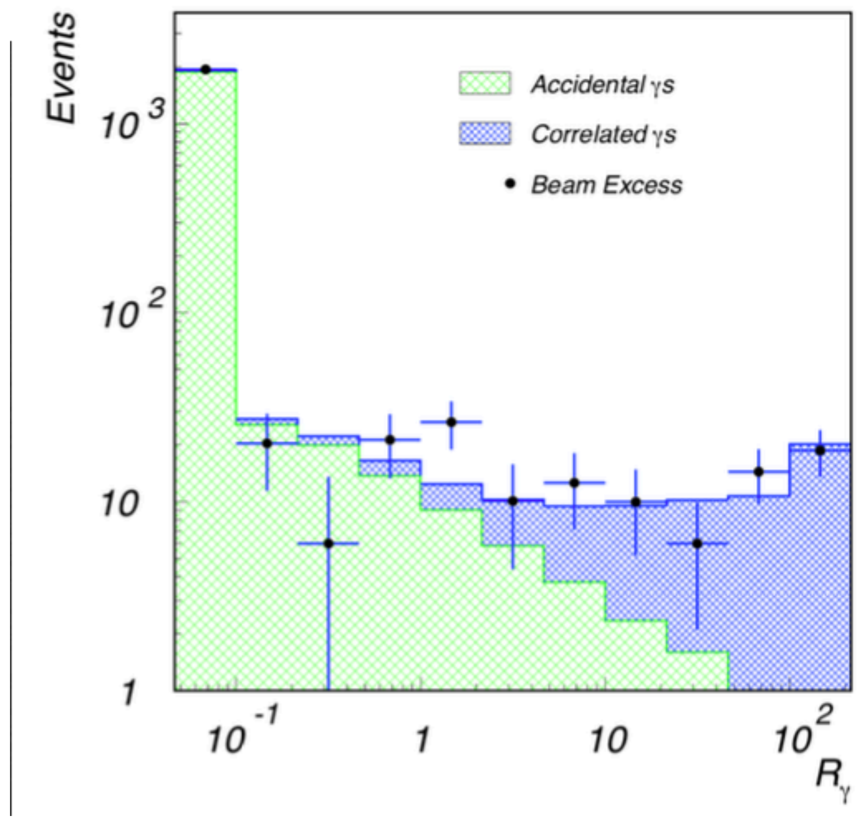
detect prompt e track, $20 < E_e < 60$ MeV (+ scintillation)

- *neutron capture:*

$np \to d\gamma$

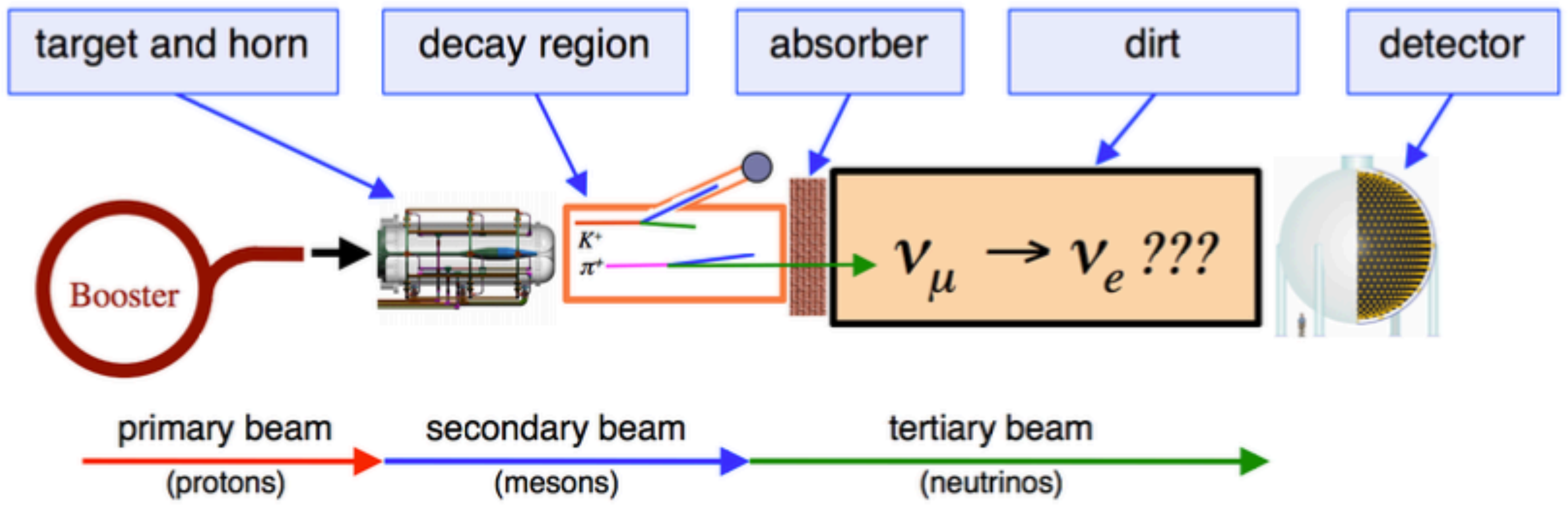
2.2 MeV scintillation signal, 186 μs later

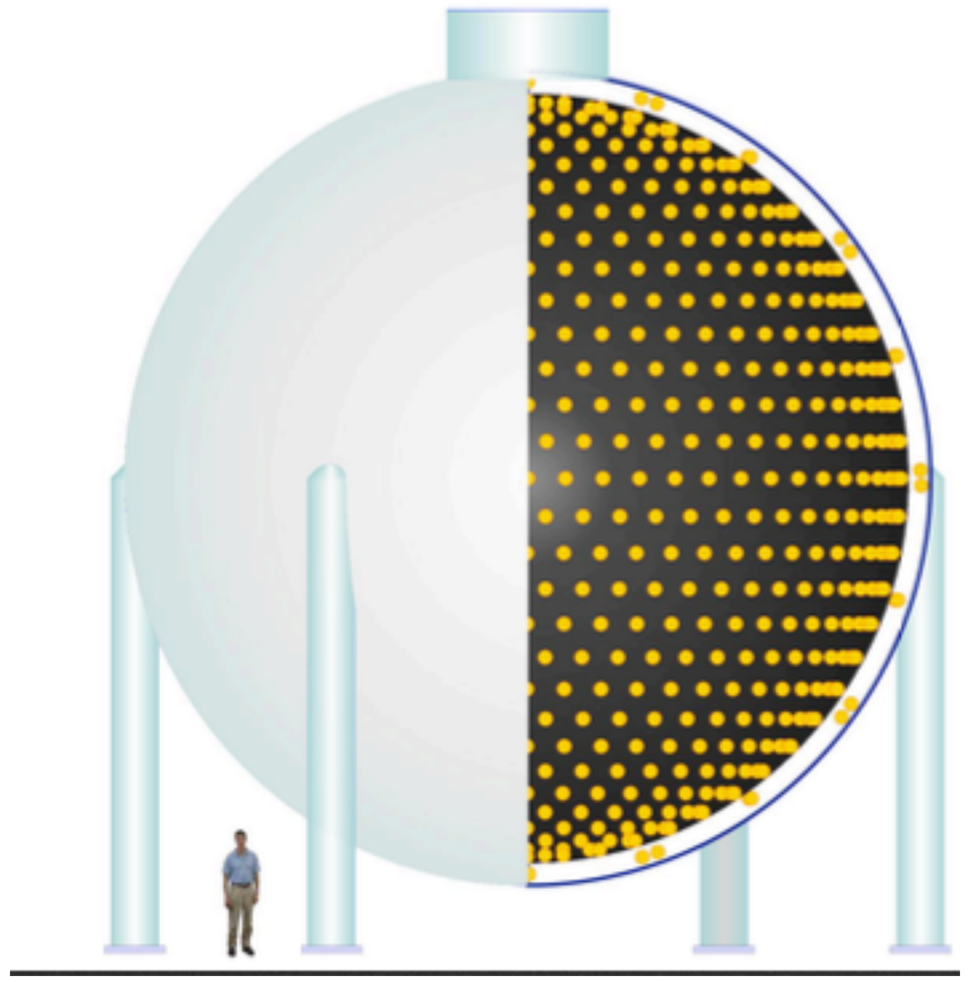


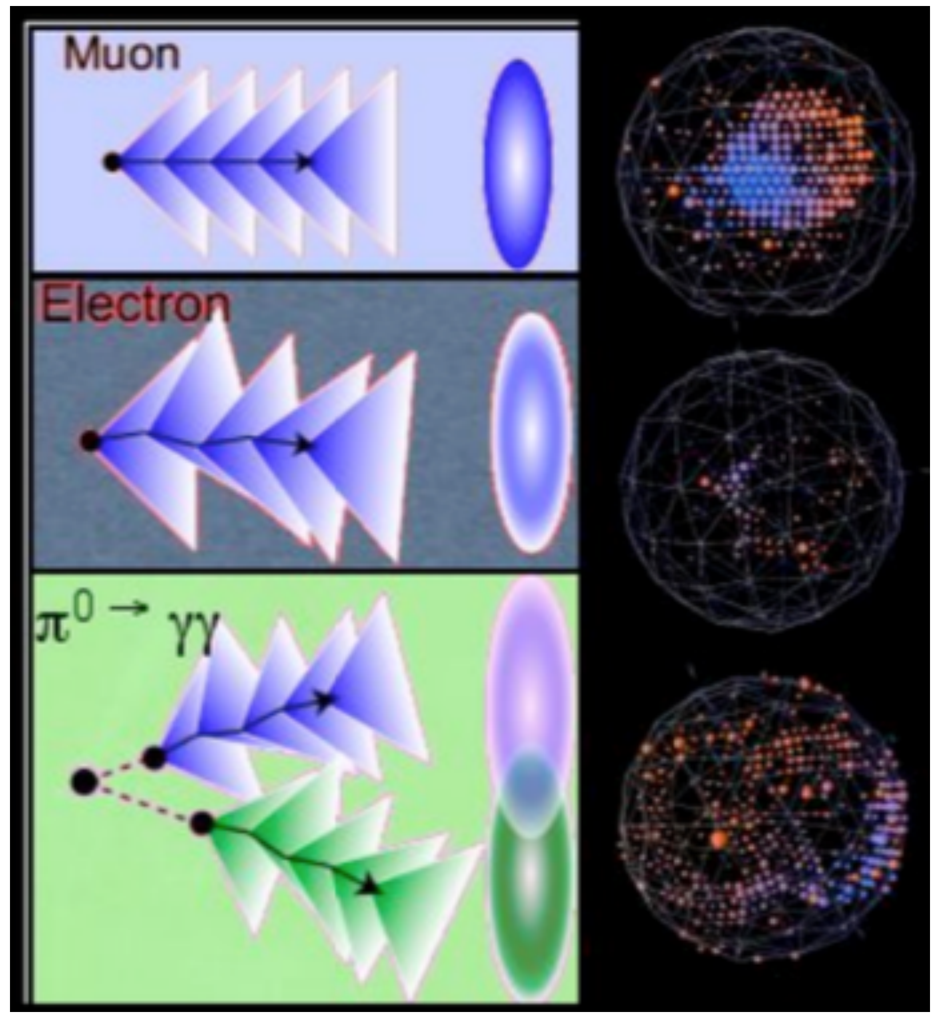


- Short baseline and small ν energy ($\bar{\nu}_\mu$ produced by pion decay at rest)
- Search for Inverse Beta Decay only possible for $\bar{\nu}_e$ so need $\bar{\nu}_\mu$ to oscillate to $\bar{\nu}_e$
- Excess of signal induced by $\bar{\nu}_e$?
- Excess is quite significant $87.9 \pm 22.4 \pm 6.0$
- But events are selected after removing huge accidental backgrounds

MiniBooNE

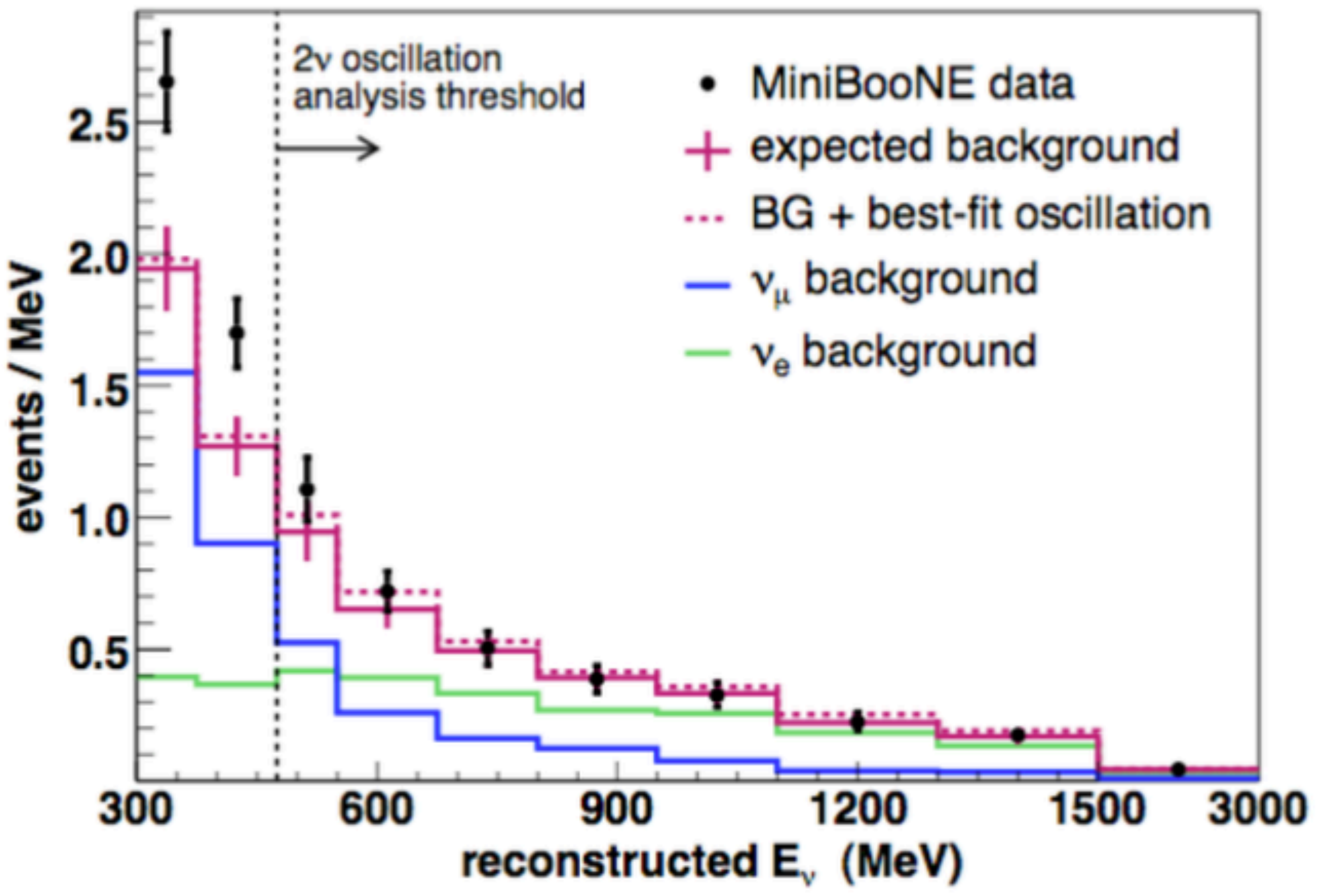


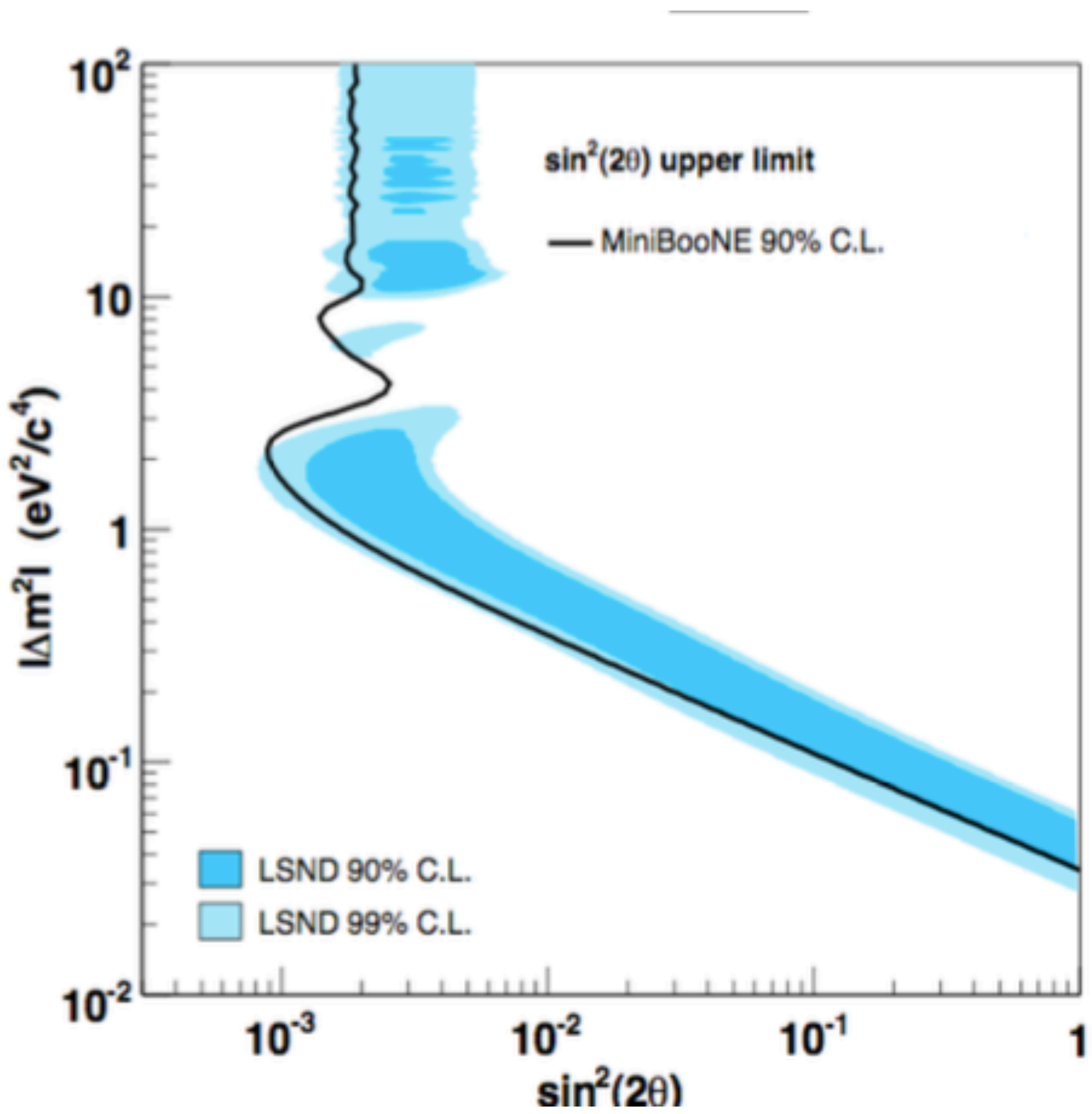




- Distance L = 500 m
- Neutrino energy Eν = 600 MeV
- L/E same as LSND
- Possibility of producing $\nu\mu$ and $\bar{\nu}\mu$
- Test LSND anomaly with different baseline, neutrino energy and ν vs $\bar{\nu}$
- One limitation.. no near detector!

First MiniBooNe results (2007)

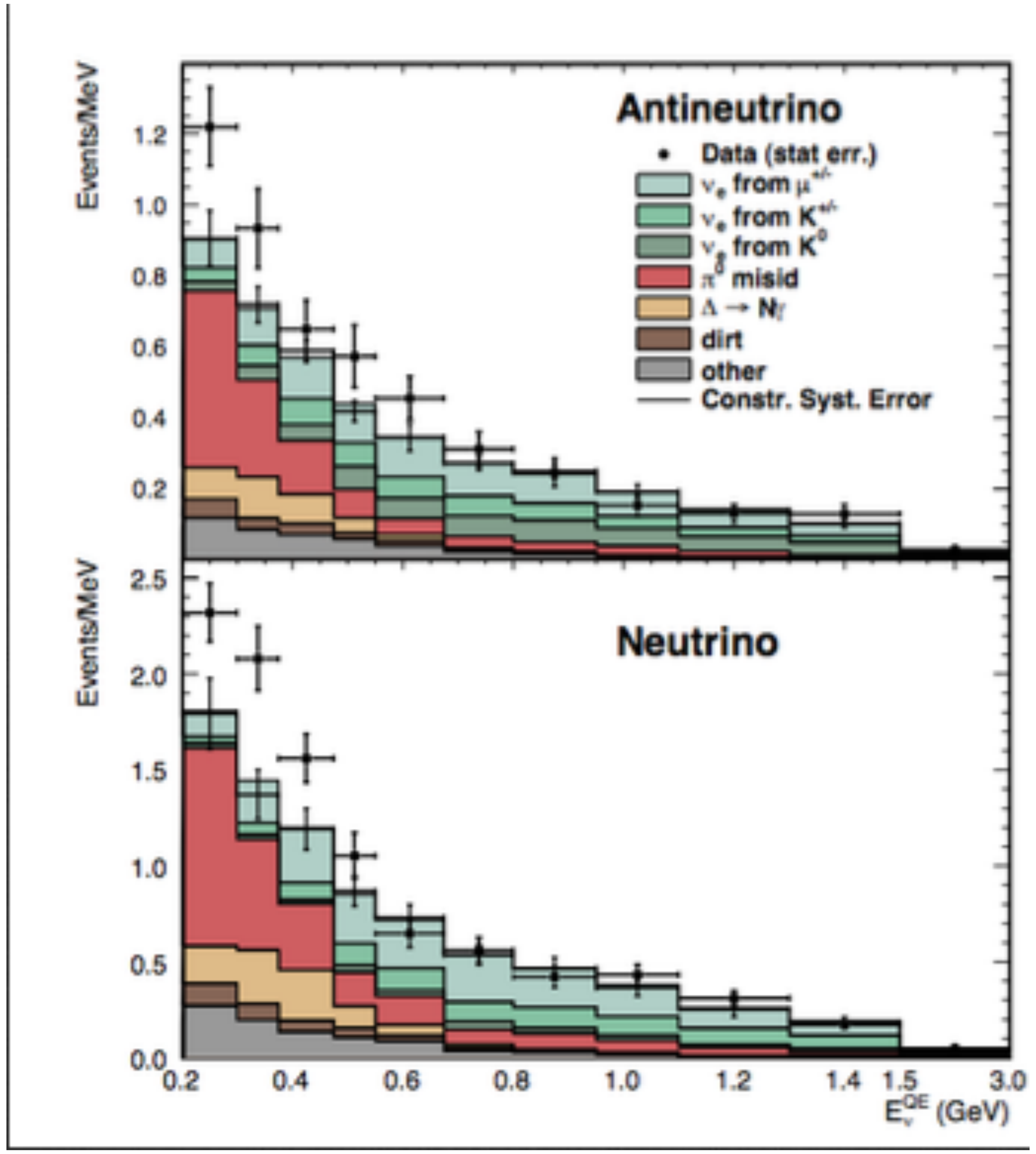


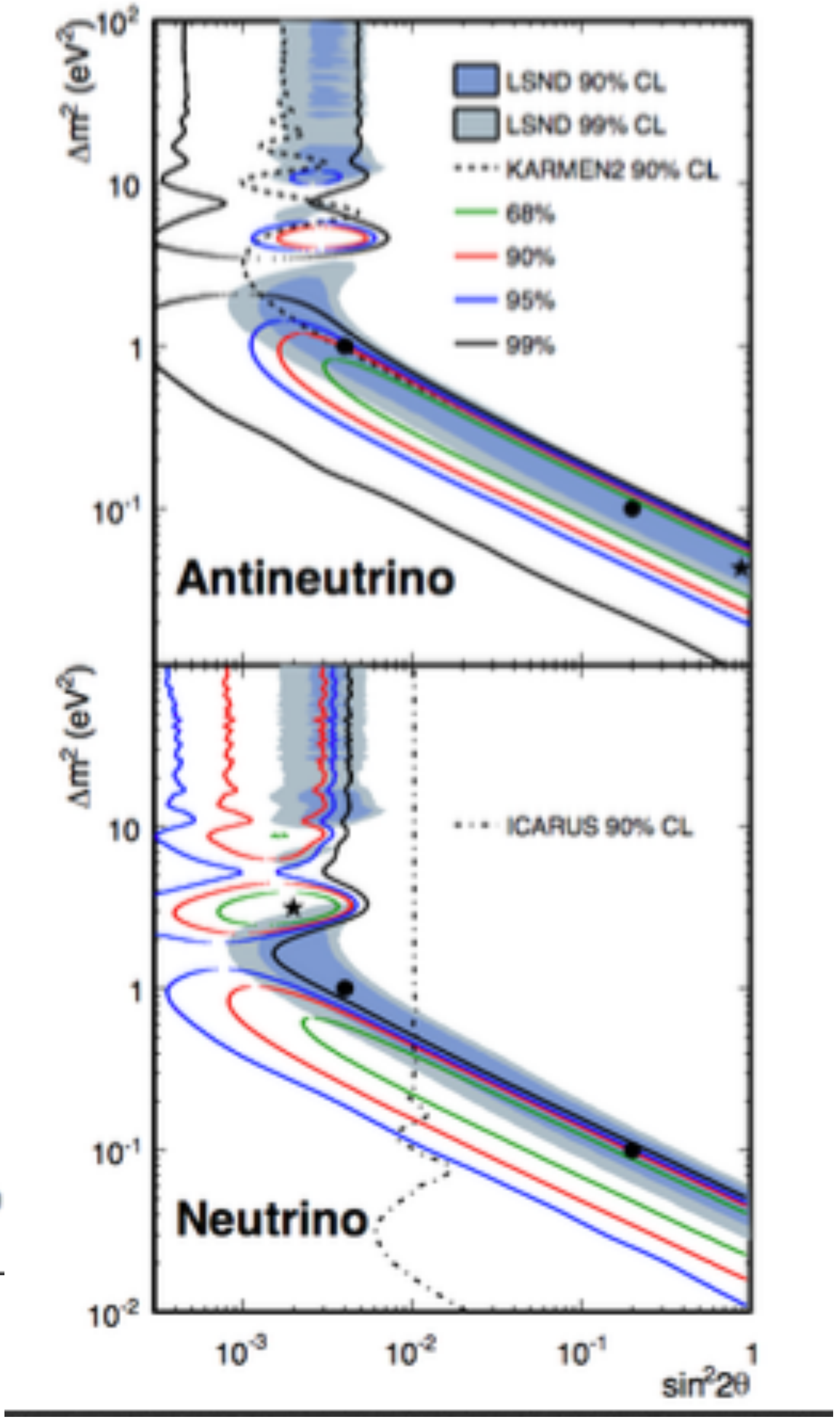


- Blind analysis
- Energy range from 475 MeV to 3 GeV (where LSND signal is expected)
- No excess observed → set limit that exclude LSND
- But low energy excess…

MiniBooNE 2013 results

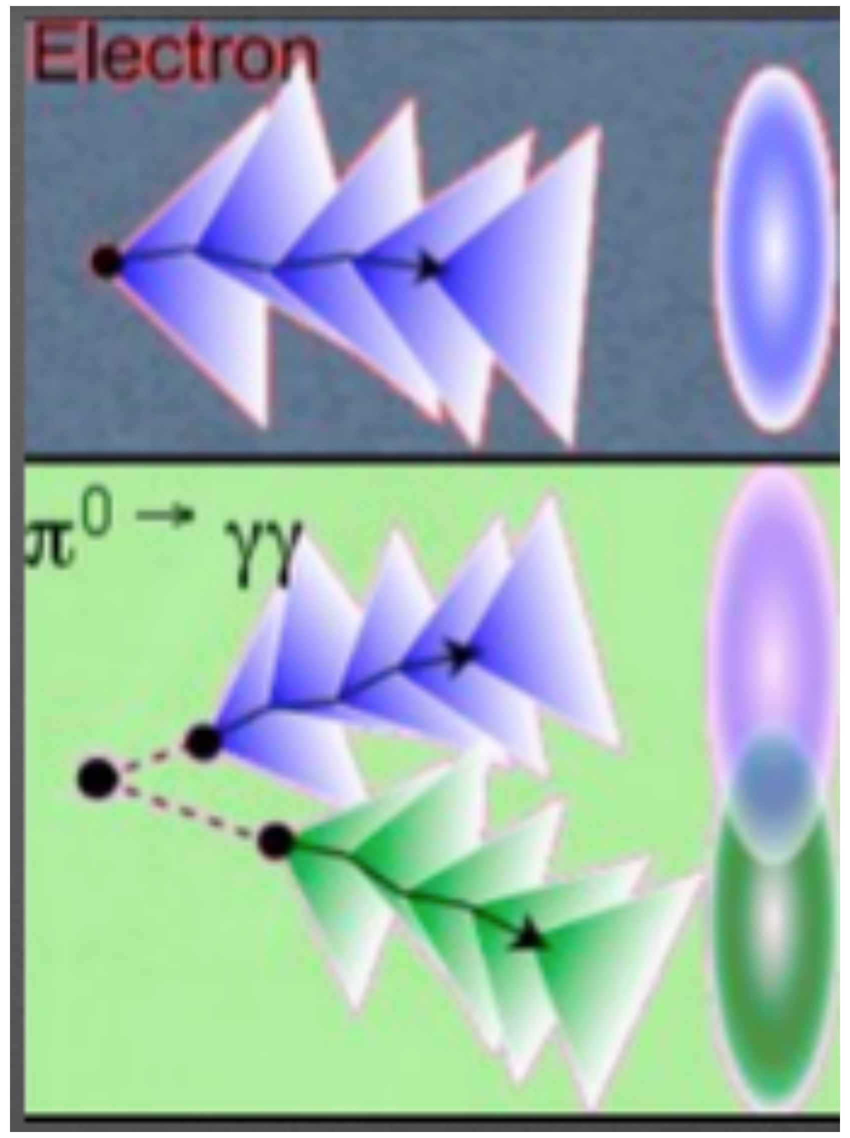
- Added data in antineutrino mode
- Also in this channel they observed an excess below 475 MeV
- Include in the fit all data from 200 MeV
- Excess at the level of 2.8σ for $\bar{\nu}$ and 3.4σ for ν!
- Compatible with LSND

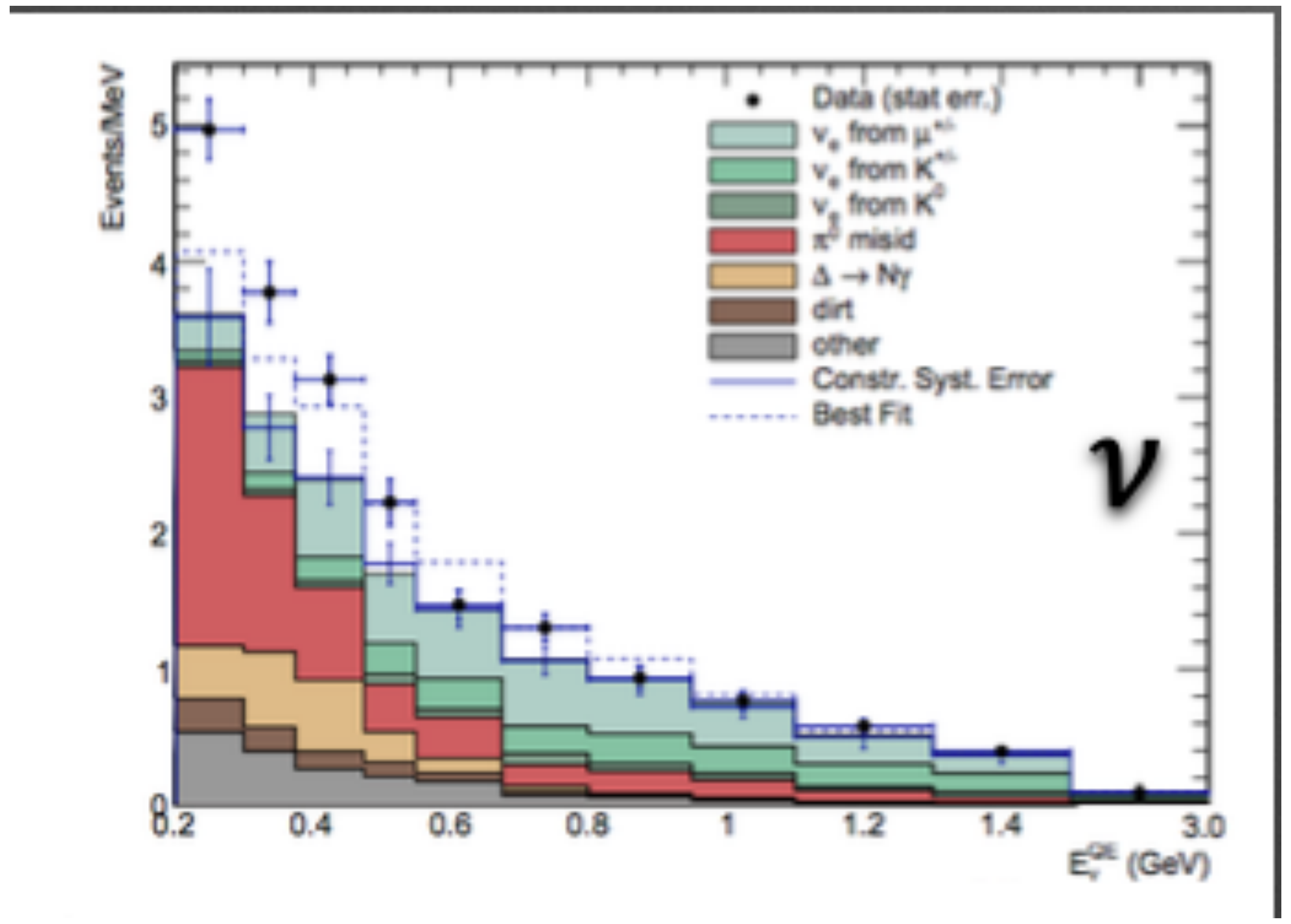


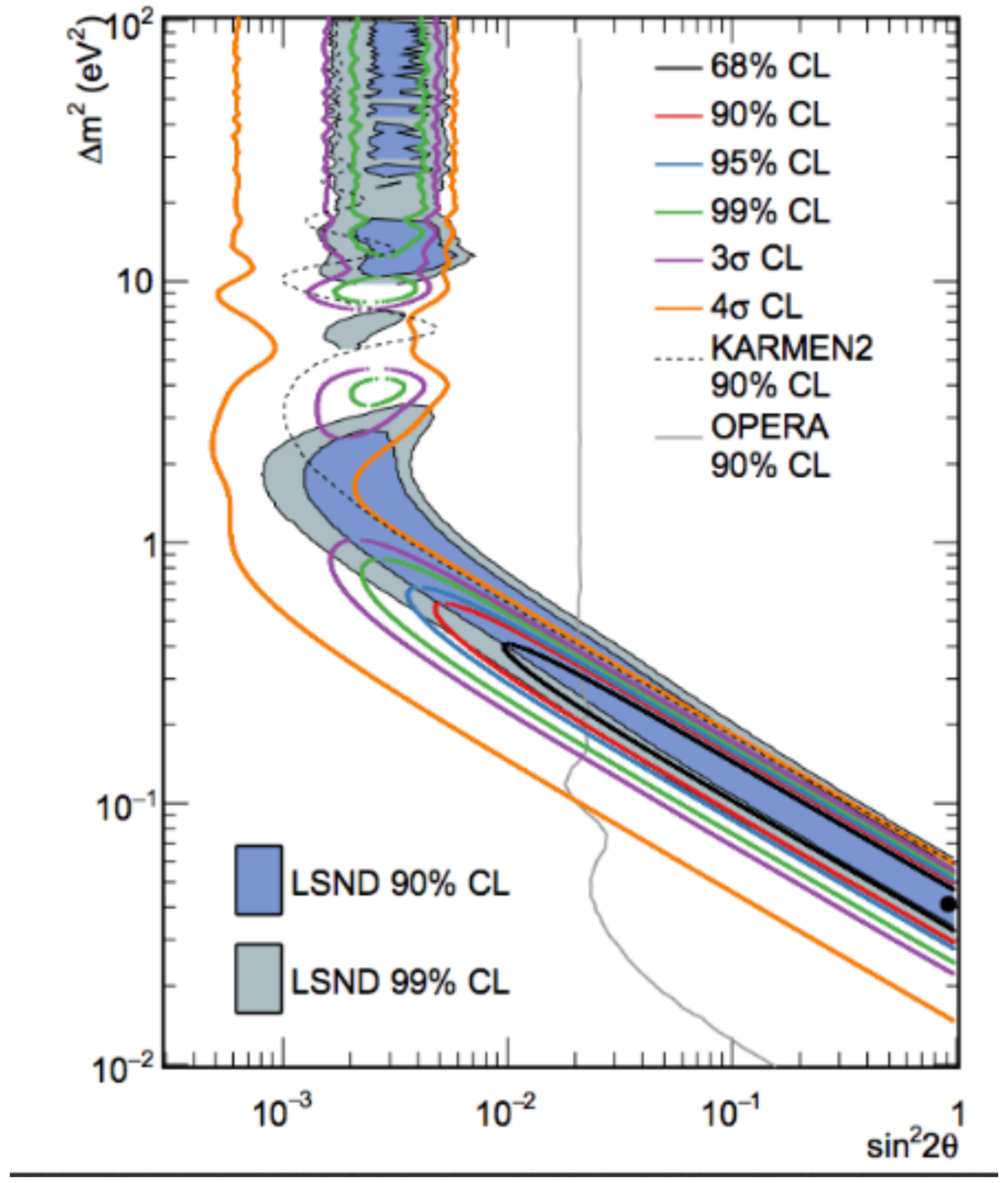


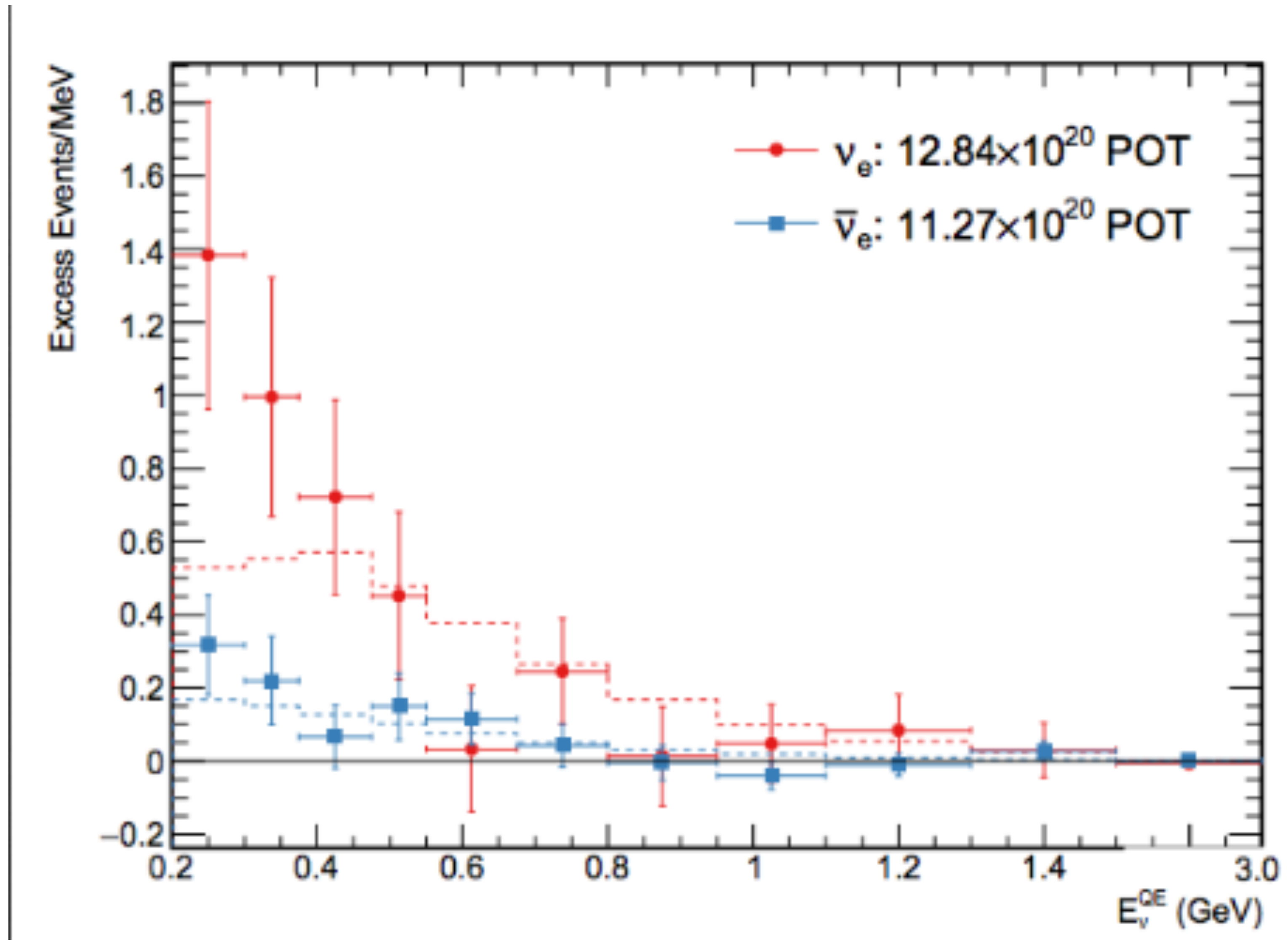
MiniBooNE 2018 results

- Double stat in ν mode
- Excess in the low energy region confirmed → but this region is dominated by background!
- To explain it with sterile neutrino a very large mixing angle is needed (and still the oscillation do not fit the excess even at the best fit
- 6.1 σ excess … is it a discovery of sterile neutrinos?? No!!

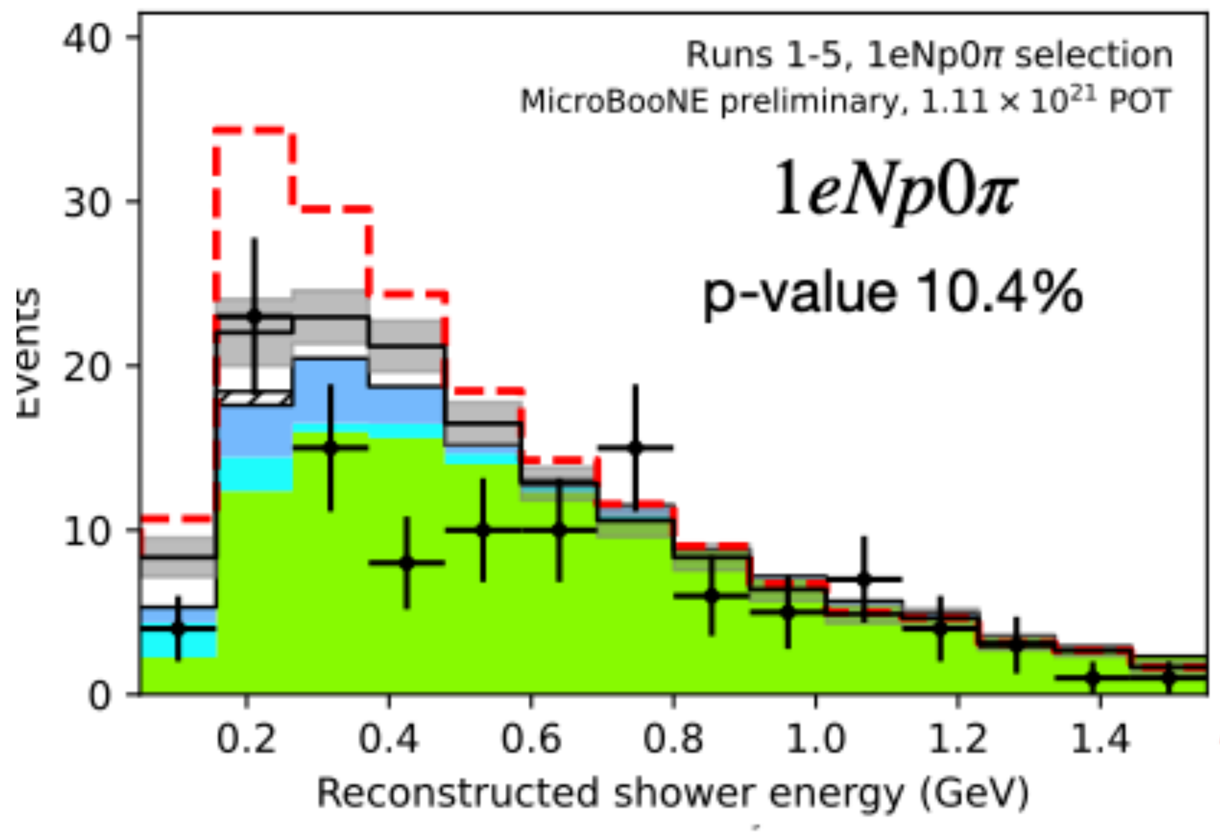


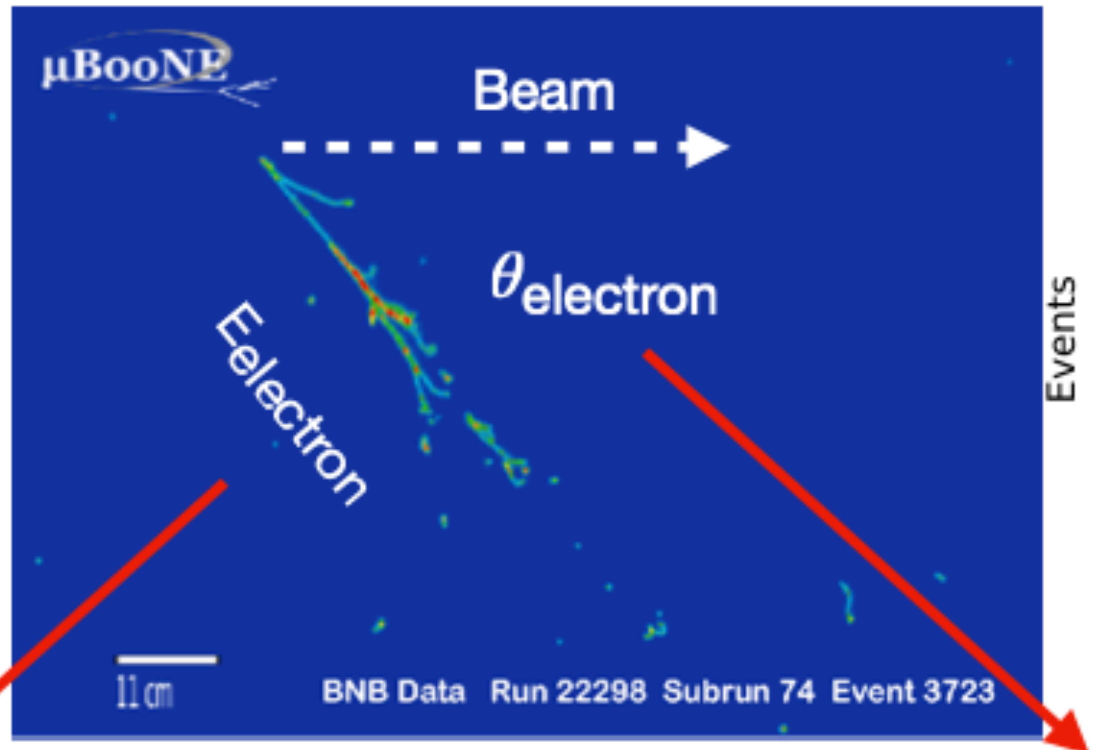


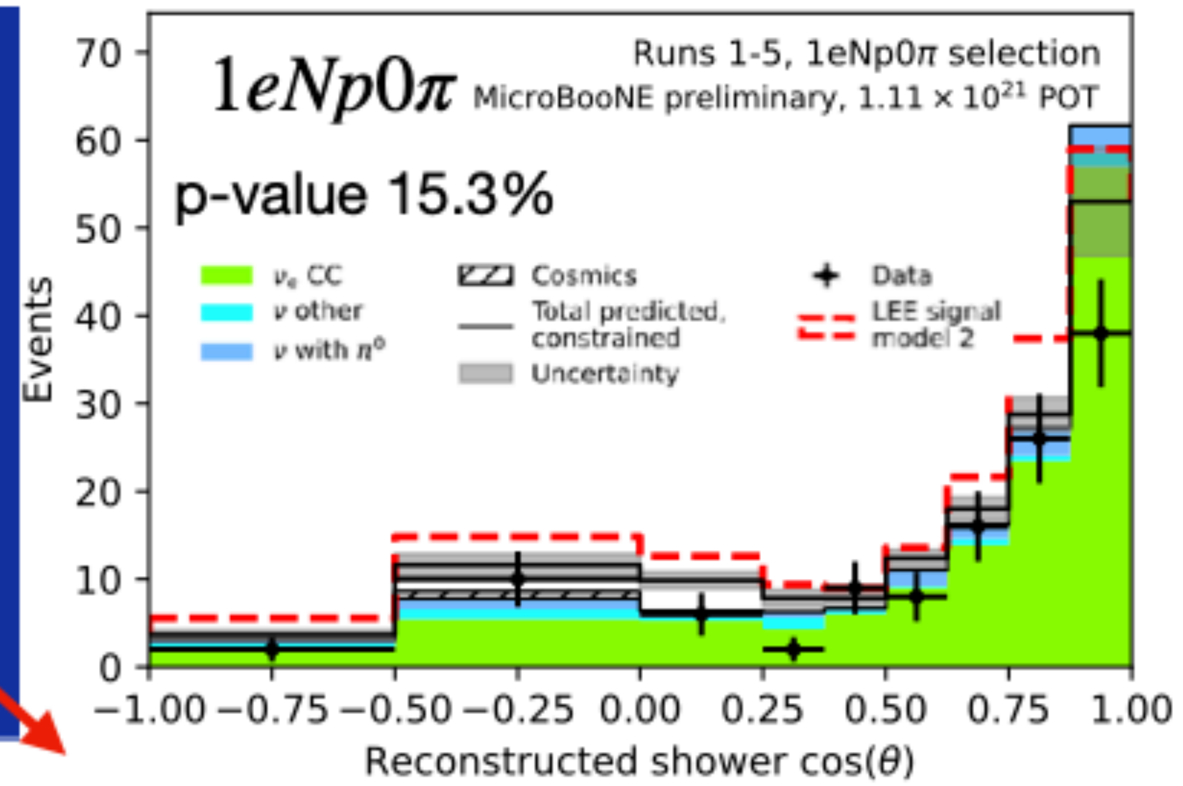


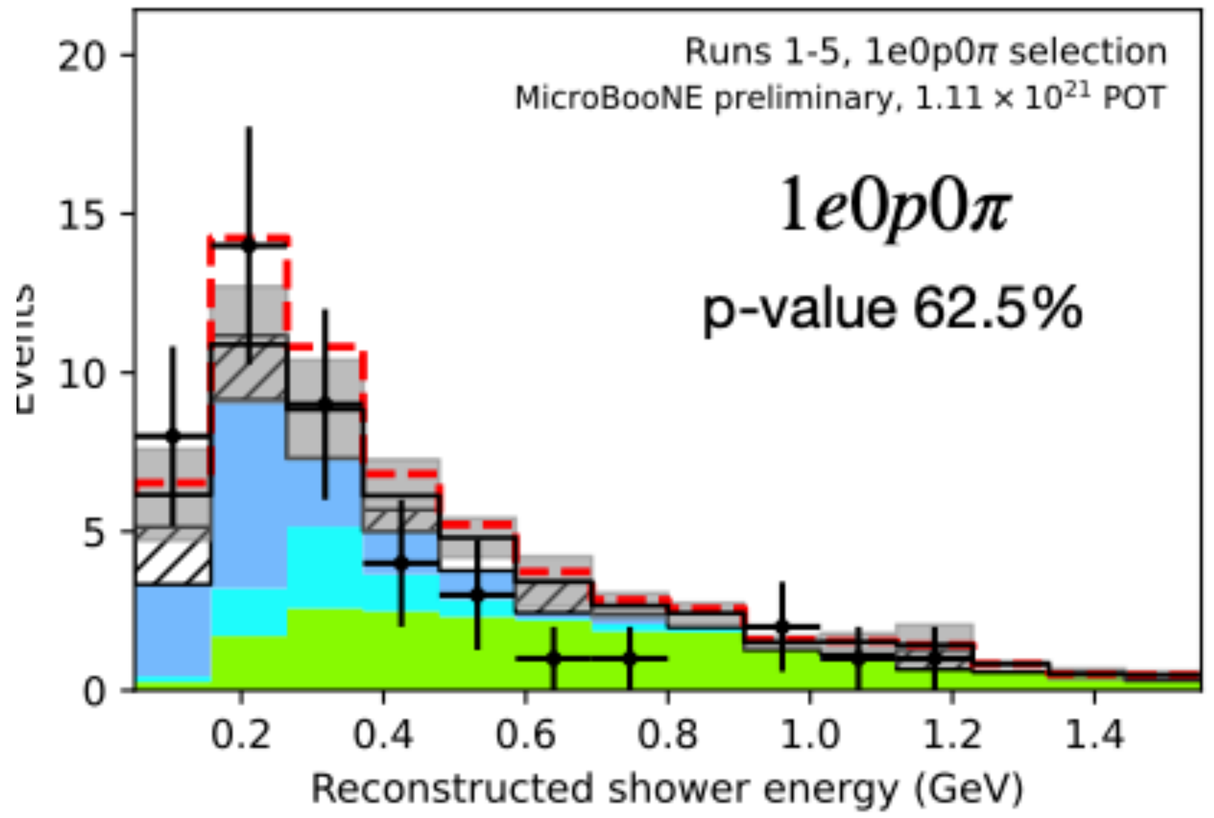


New MicroBooNE results (2024)







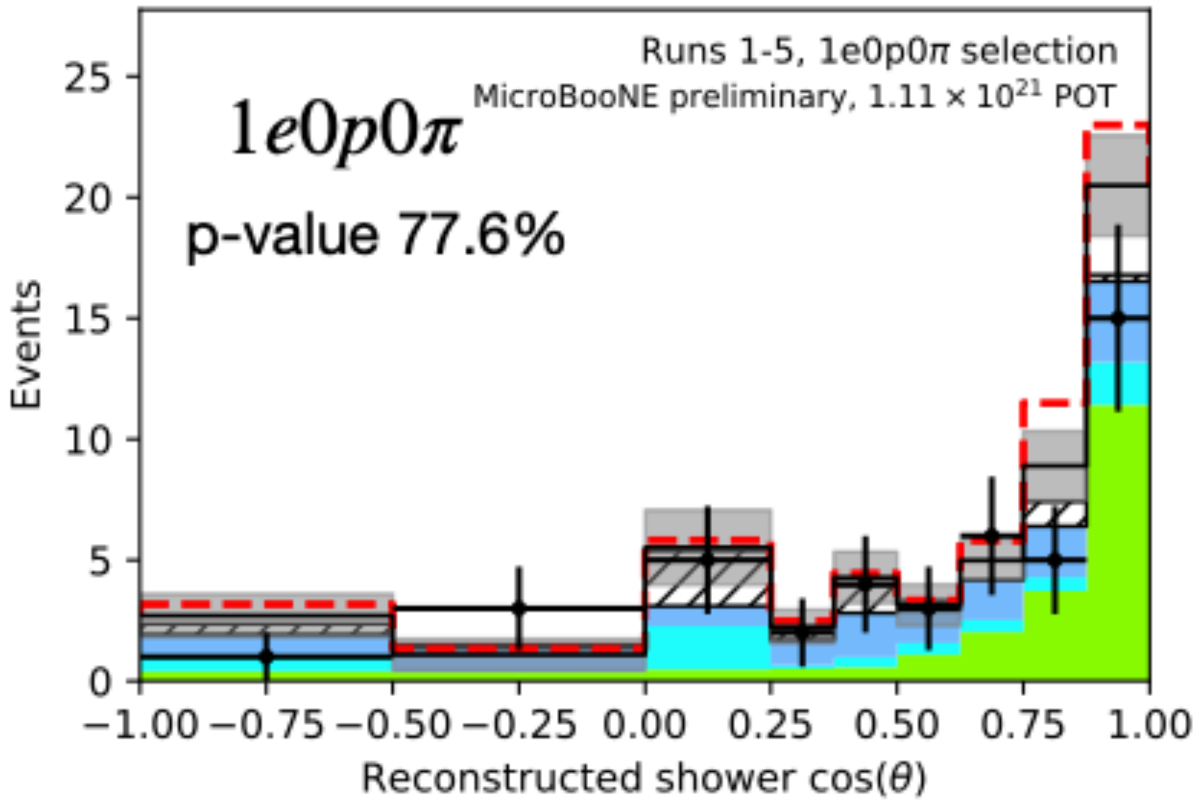


Shower kinematics-based model:

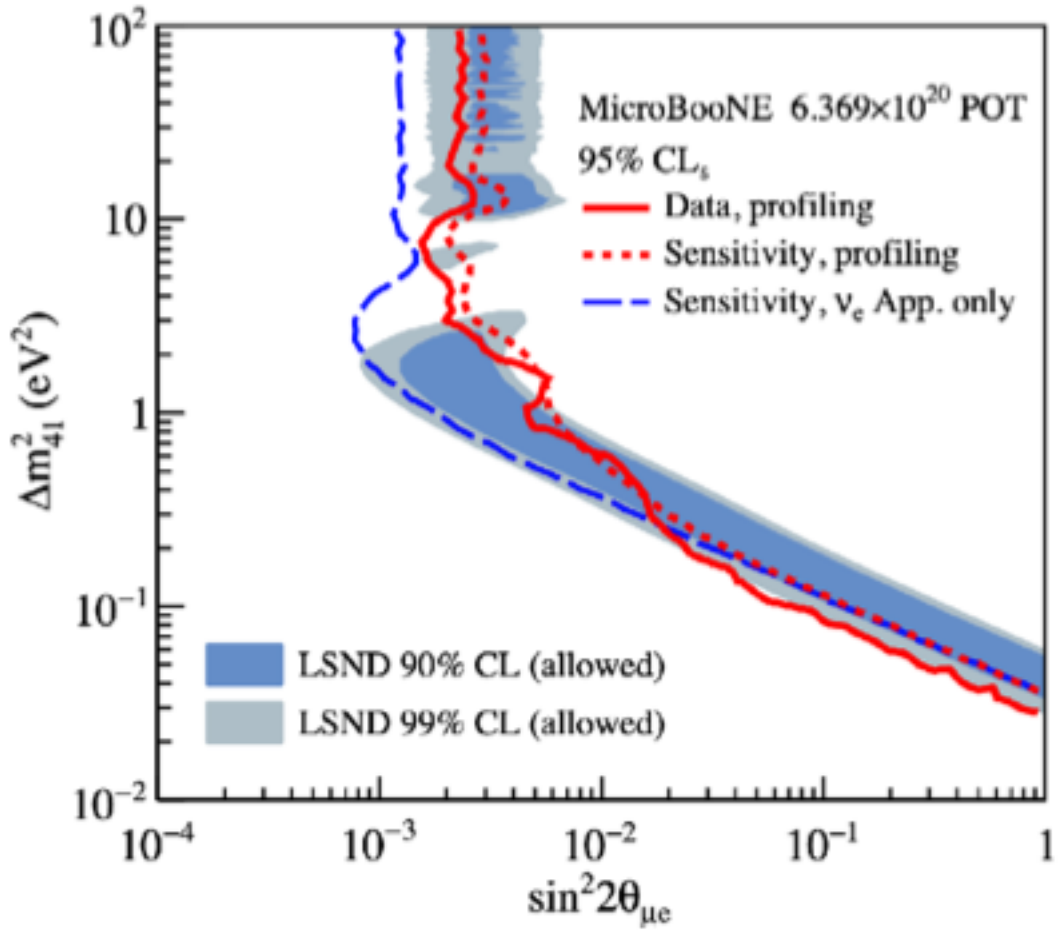
combined Np & 0p channels:

exclude model at > 99.9% CL

18

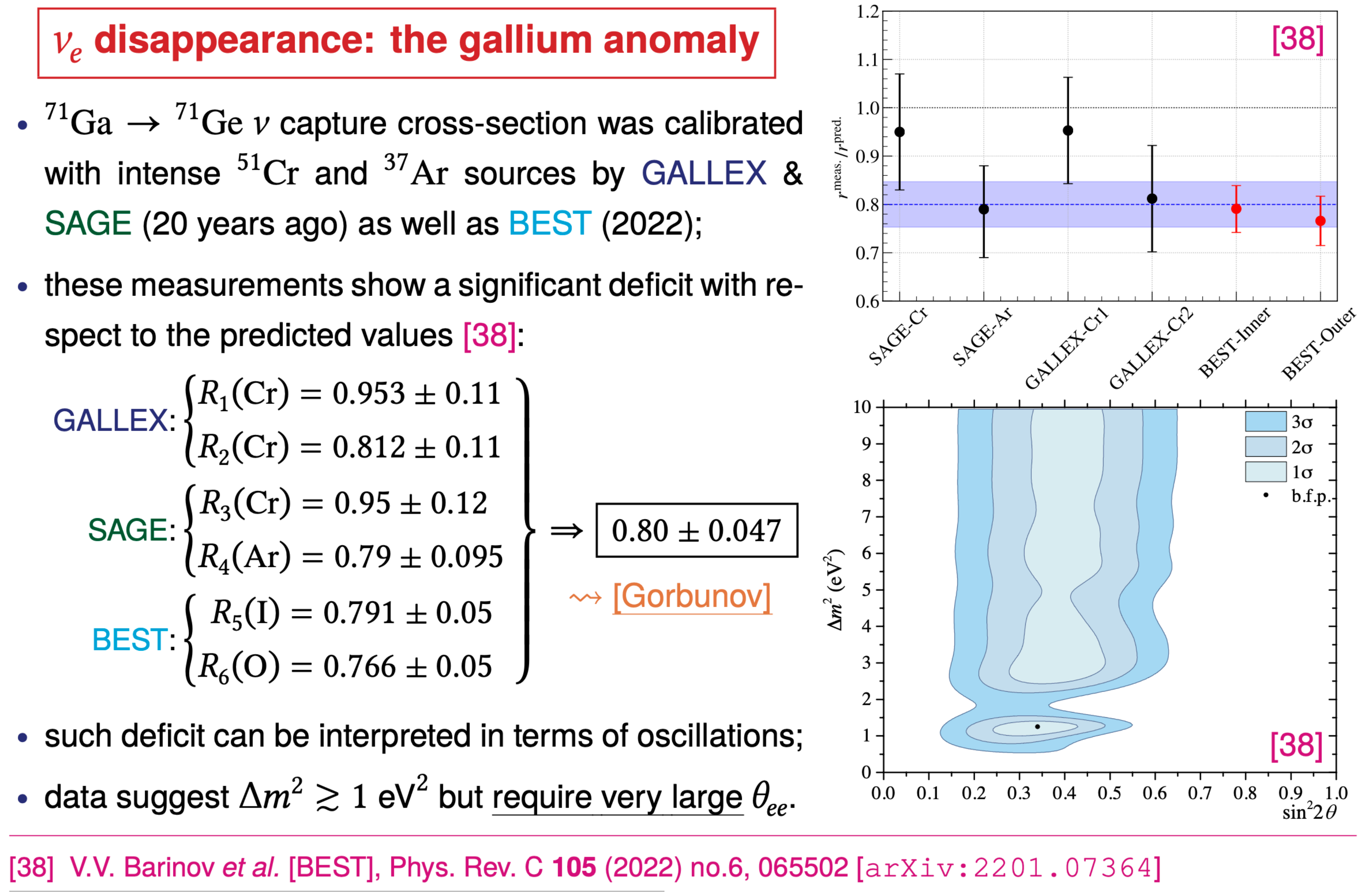


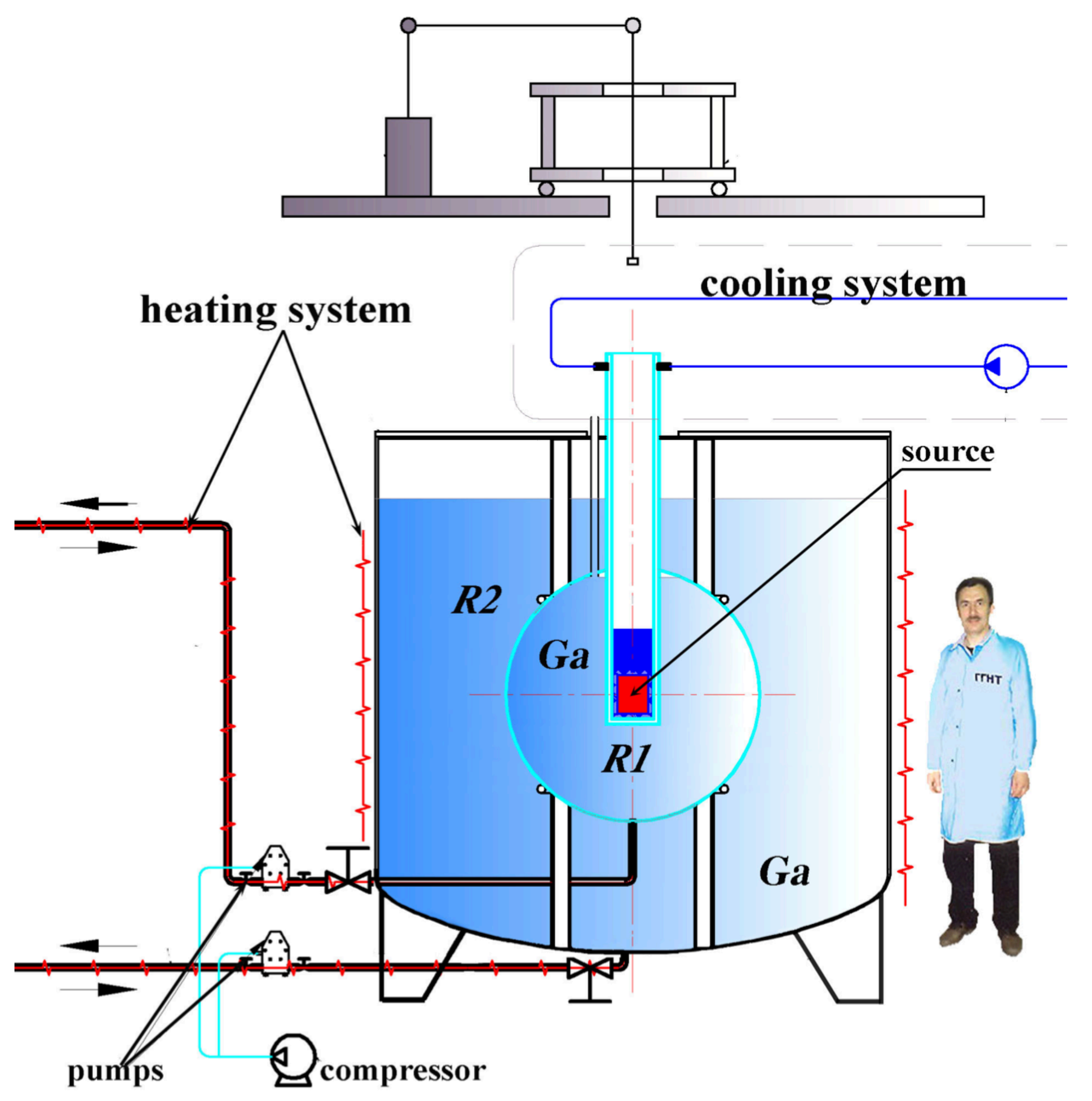
- Liquid Argon detector
- Same baseline and beam as MiniBooNE
- Better performances to distinguish electron from gamma
- ICARUS and SBND currently taking data at FNAL

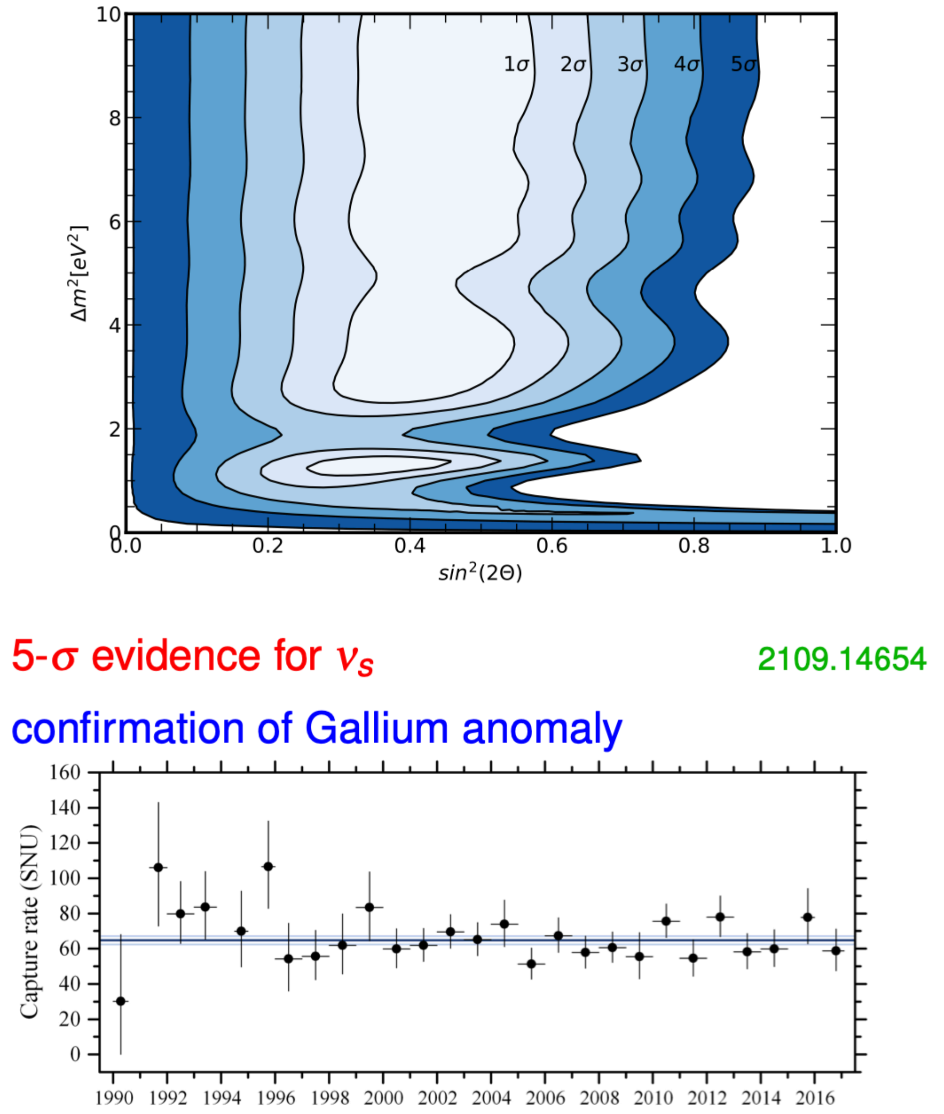


Sterile neutrinos → ν_e disappearance

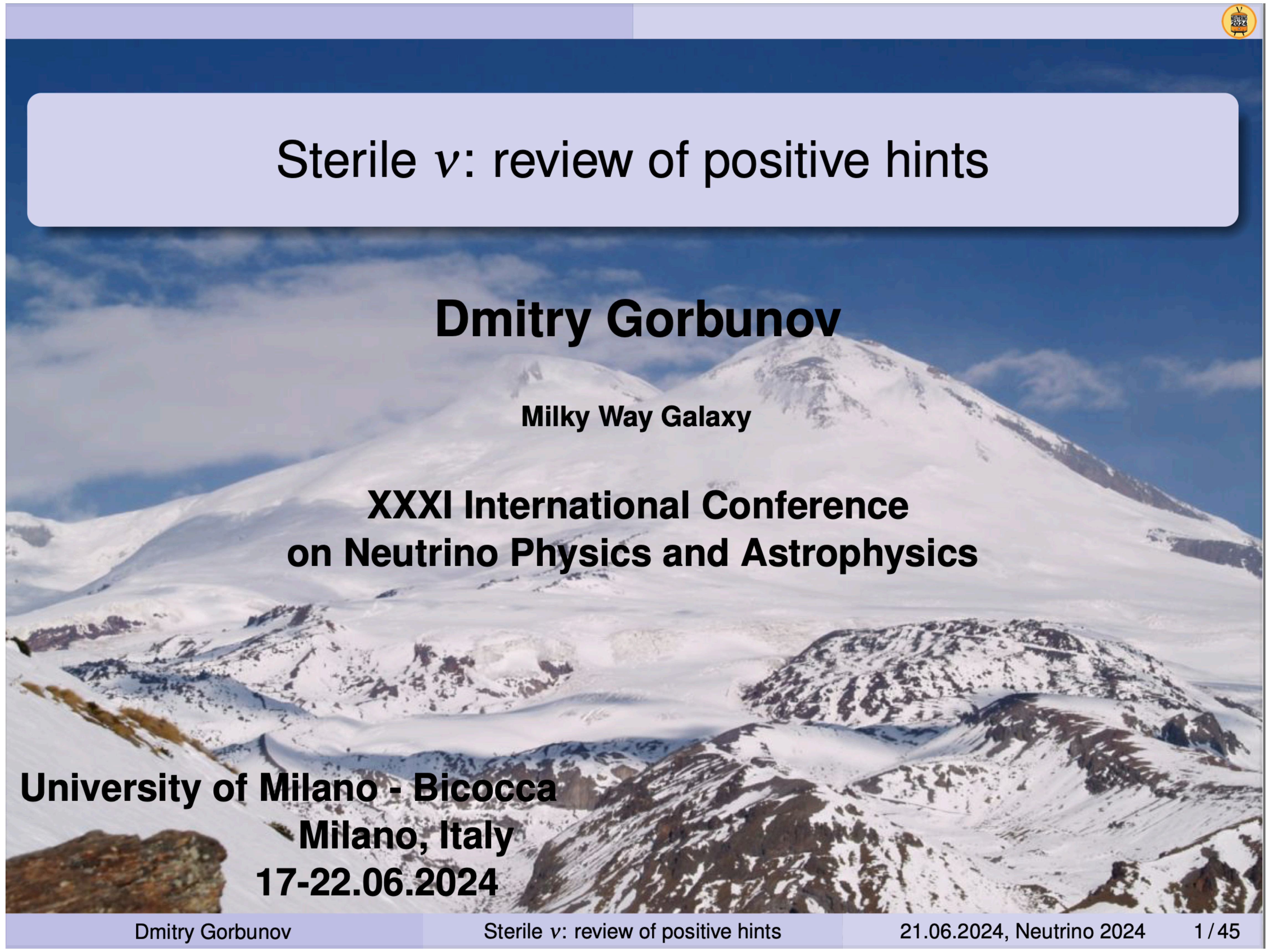
- 2 sources of possible ν_e disappearance
  - Reactor anomaly → solved by more recent calculations of reactor fluxes and by the STEREO measurement
  - Gallium anomaly → new measurements from BEST confirm this anomaly







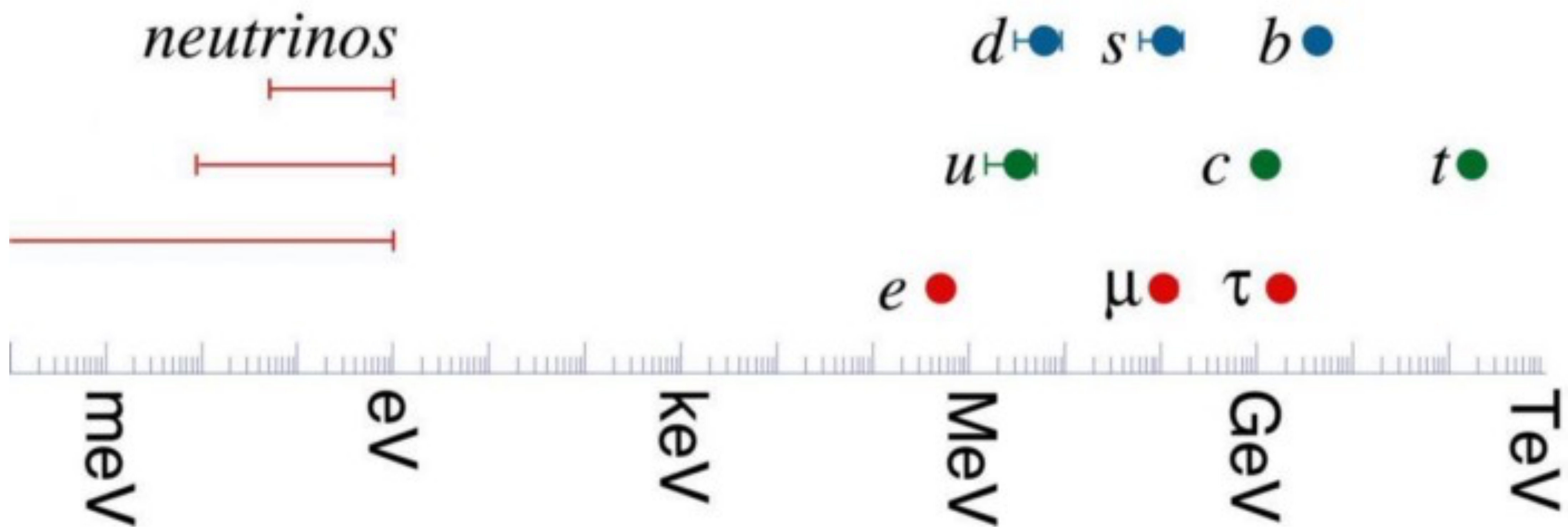
Pick your favorite talk



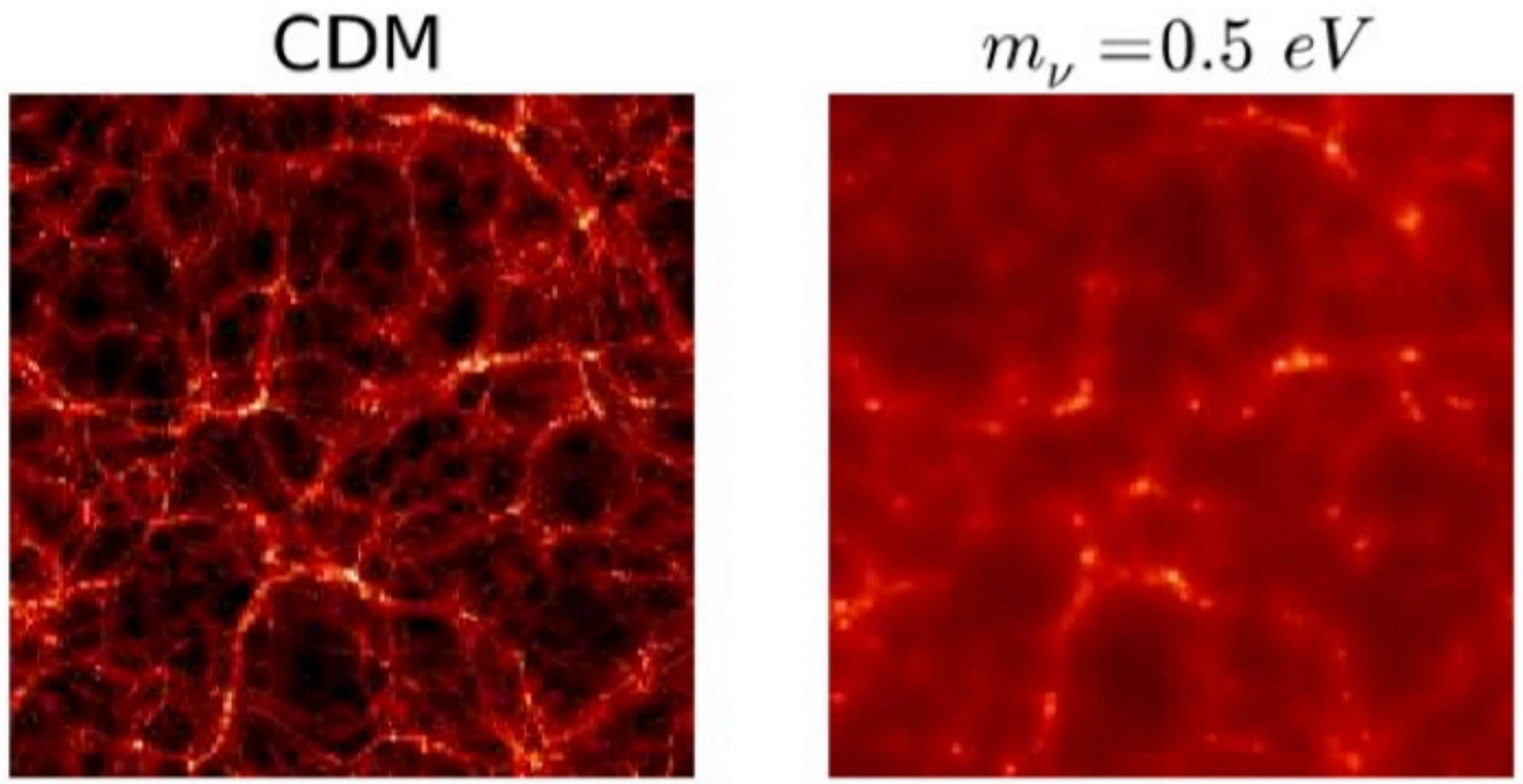
The mass of neutrinos

How to measure neutrino mass?

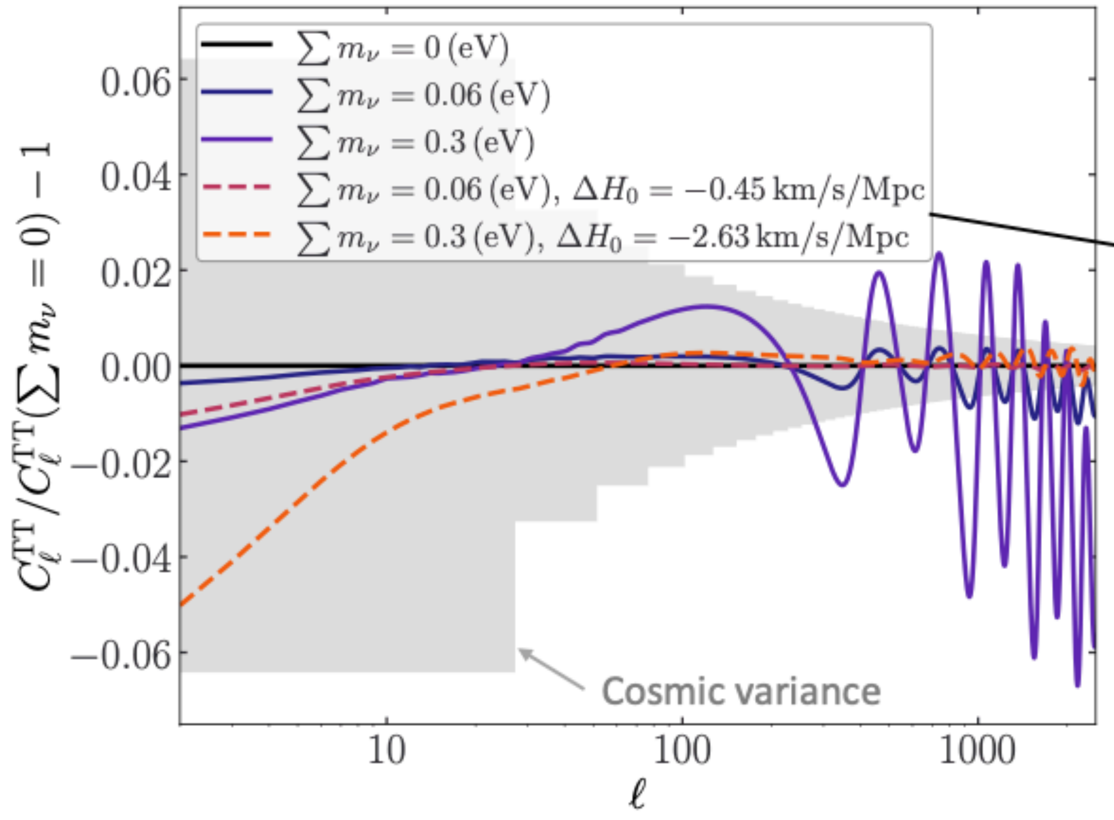
- Neutrino oscillations provides measurement of mass differences between mass eigenstates
- Lower limit on the neutrino masses:
  - Normal Ordering: $m_1 = 0 \rightarrow m_2 = 8 \times 10^{-3}\ eV(\sqrt{\Delta m^2_{21}}) \rightarrow m_3 = 0.058\ eV^2\ (\sqrt{\Delta m^2_{32}} + m_1)$
  - Inverted Ordering: $m_3 = 0 \rightarrow m_2 = 0.05\ eV \rightarrow m_3 = 0.058\ eV$
- The sum of the neutrino masses is different in the two cases → total mass content of neutrinos in the Universe change



Cosmology

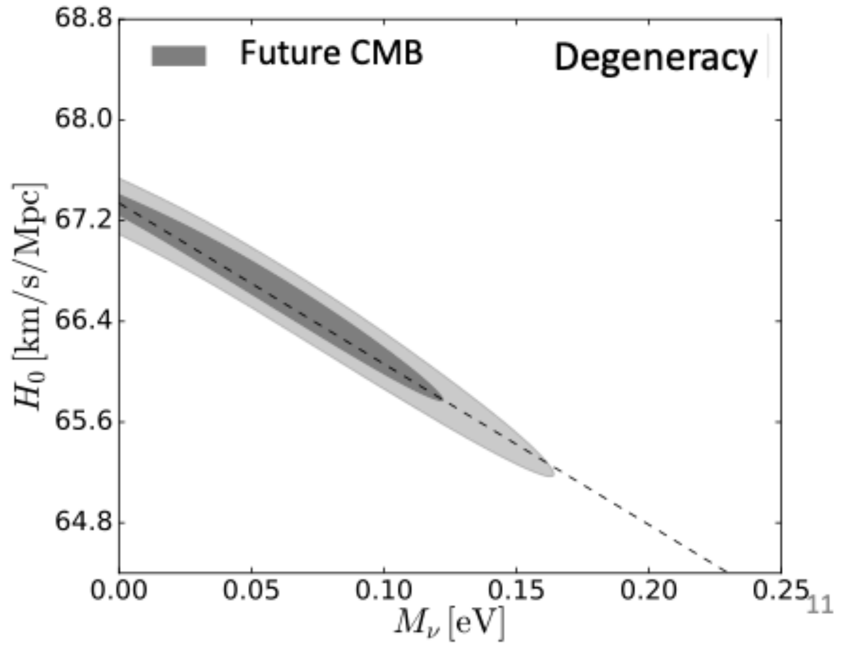


Villaescusa Navarro et al. (2013)

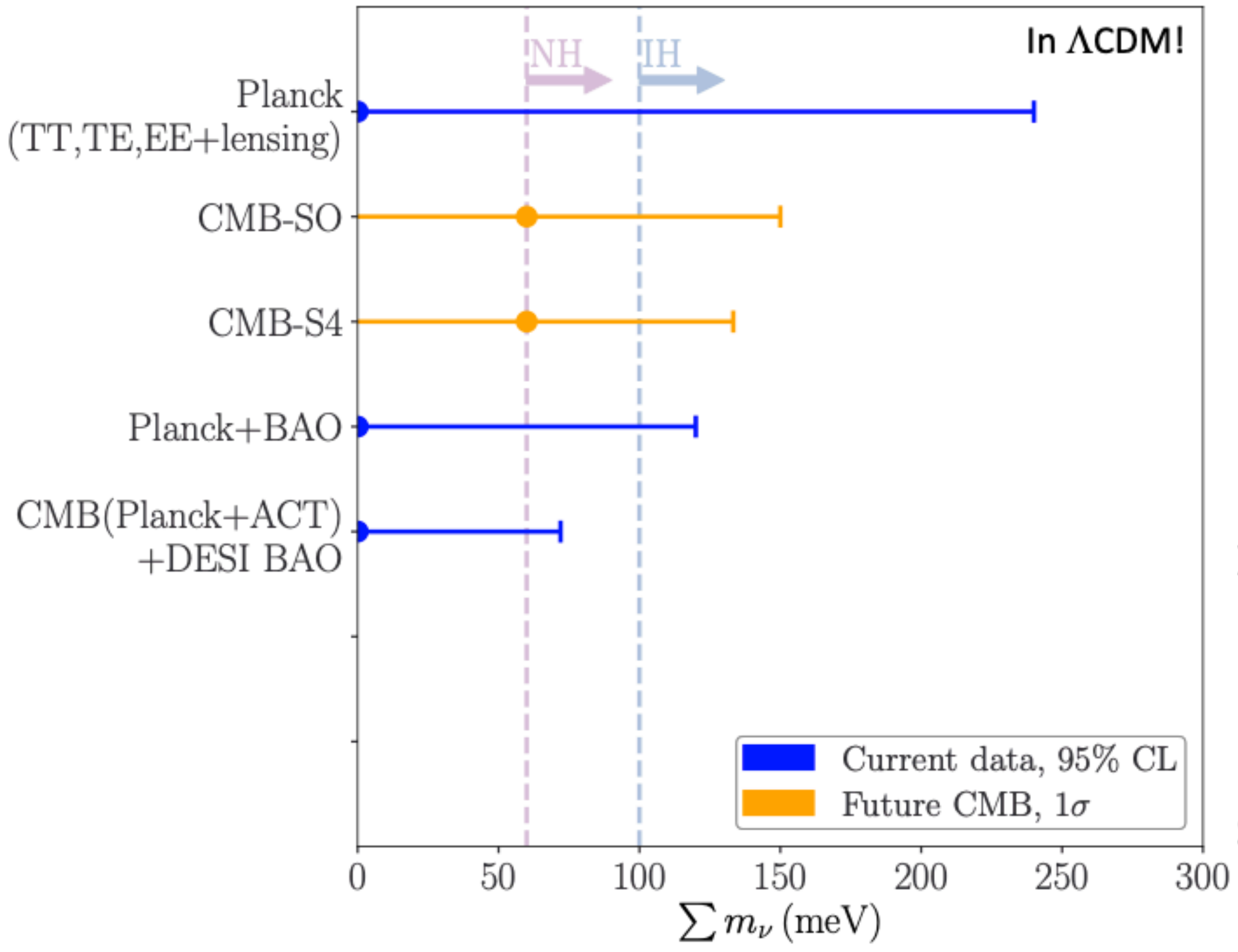


- Background effects
- Perturbation effects

Varying the Hubble constant H_0 compensates for the variation of the neutrino mass.



- Neutrinos masses have impact on the structure formation in the Universe
- Experiments measuring cosmological properties are sensitive to neutrino masses
  - Their limits are valid in the Λ_{CDM} model
- No detection yet but limits start to be in mild contrast with the Inverted Ordering scenario



Σm_ν < 72 meV, 95% CL
[DESI Collaboration (2024)]
Talk by Willem Elbers

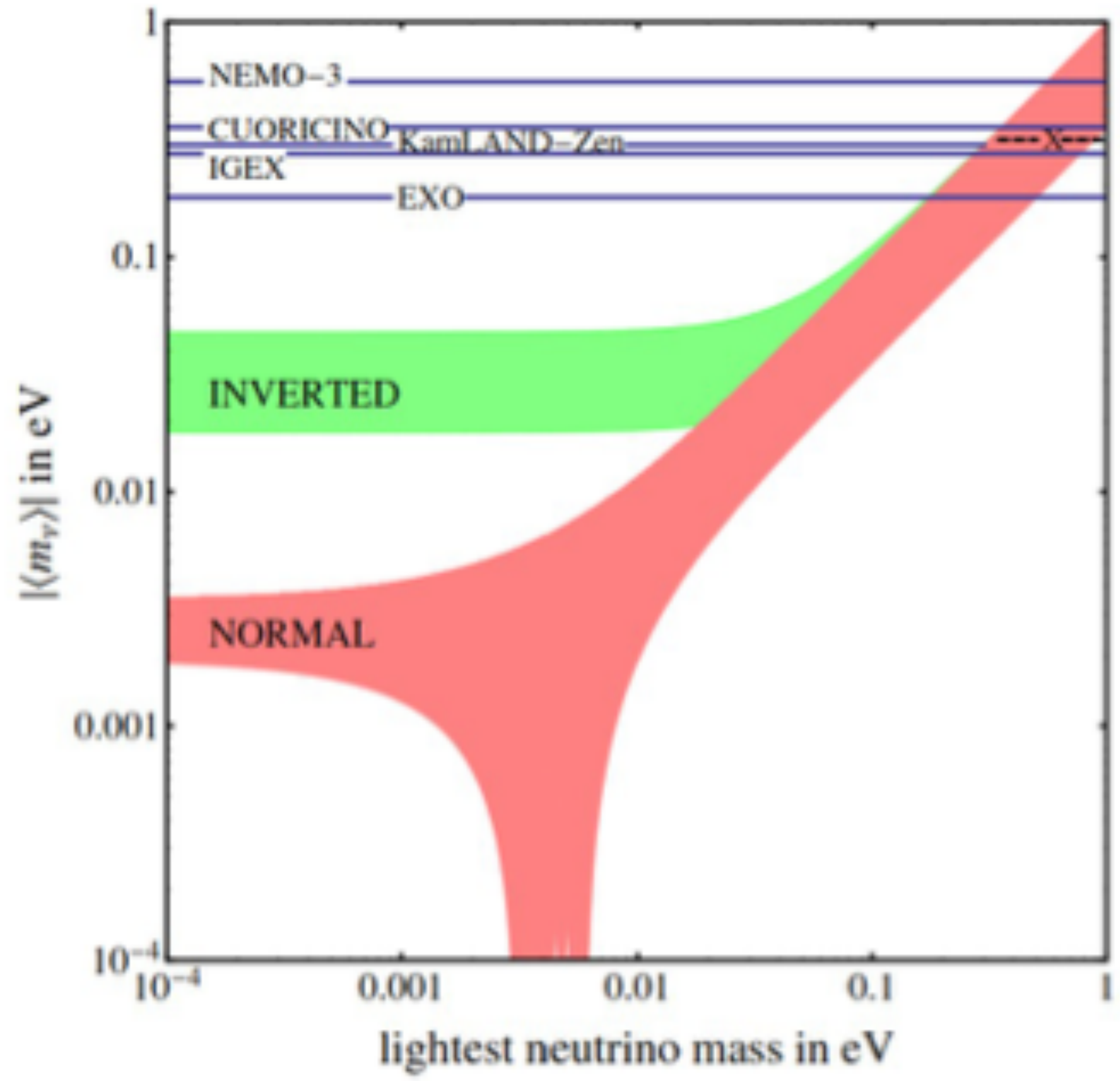
Still no evidence/detection!

Direct measurements of ν mass

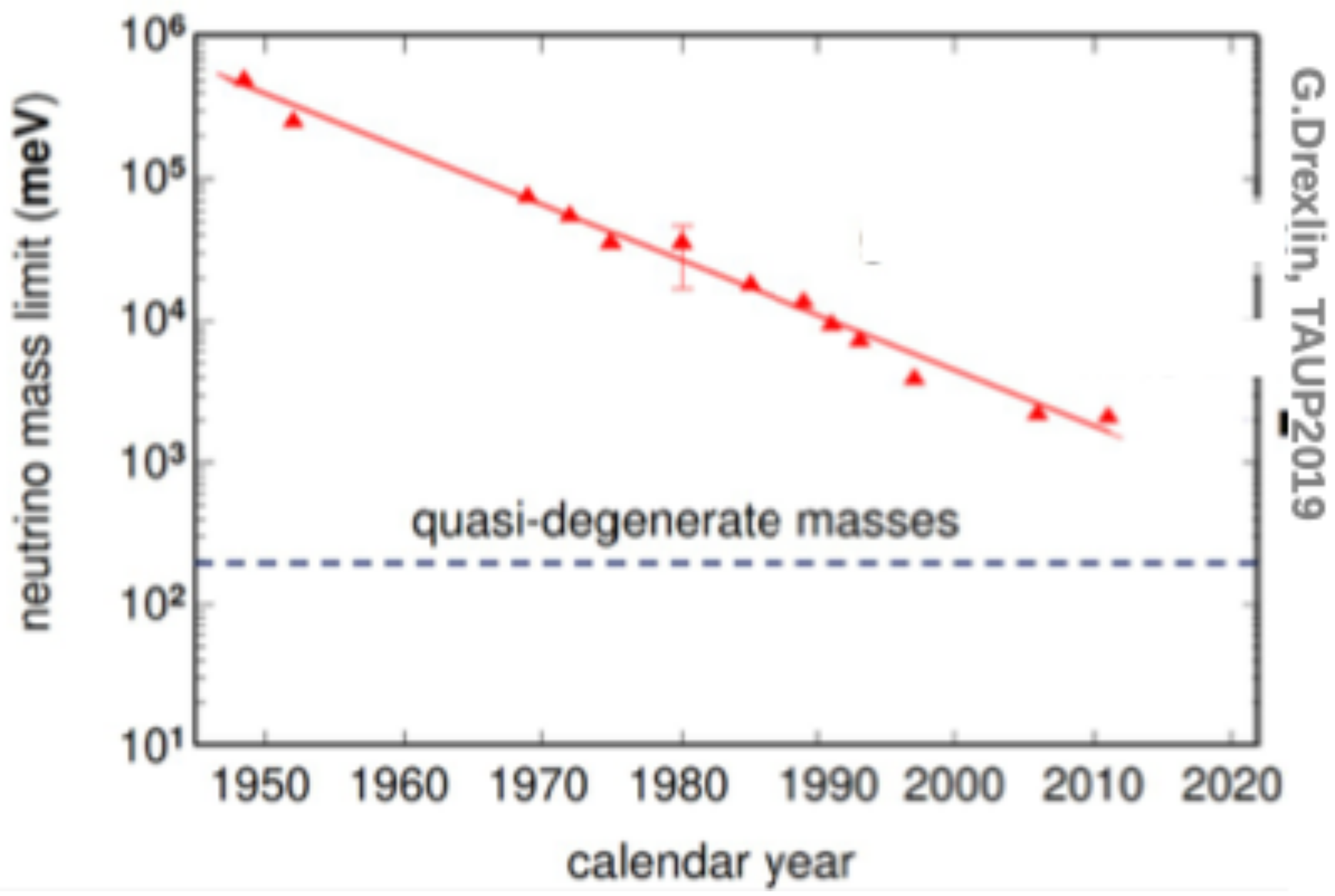
- Two possible methods of measuring neutrino masses "in laboratory"

$0\nu\beta\beta$ → can only happen if
Neutrinos are Majorana particles
$m_{\beta\beta}$~100 meV

kinematics of the β spectrum →
m_e~50-200 meV



J. Barea et al. PRL 109, 042501 - (2012)



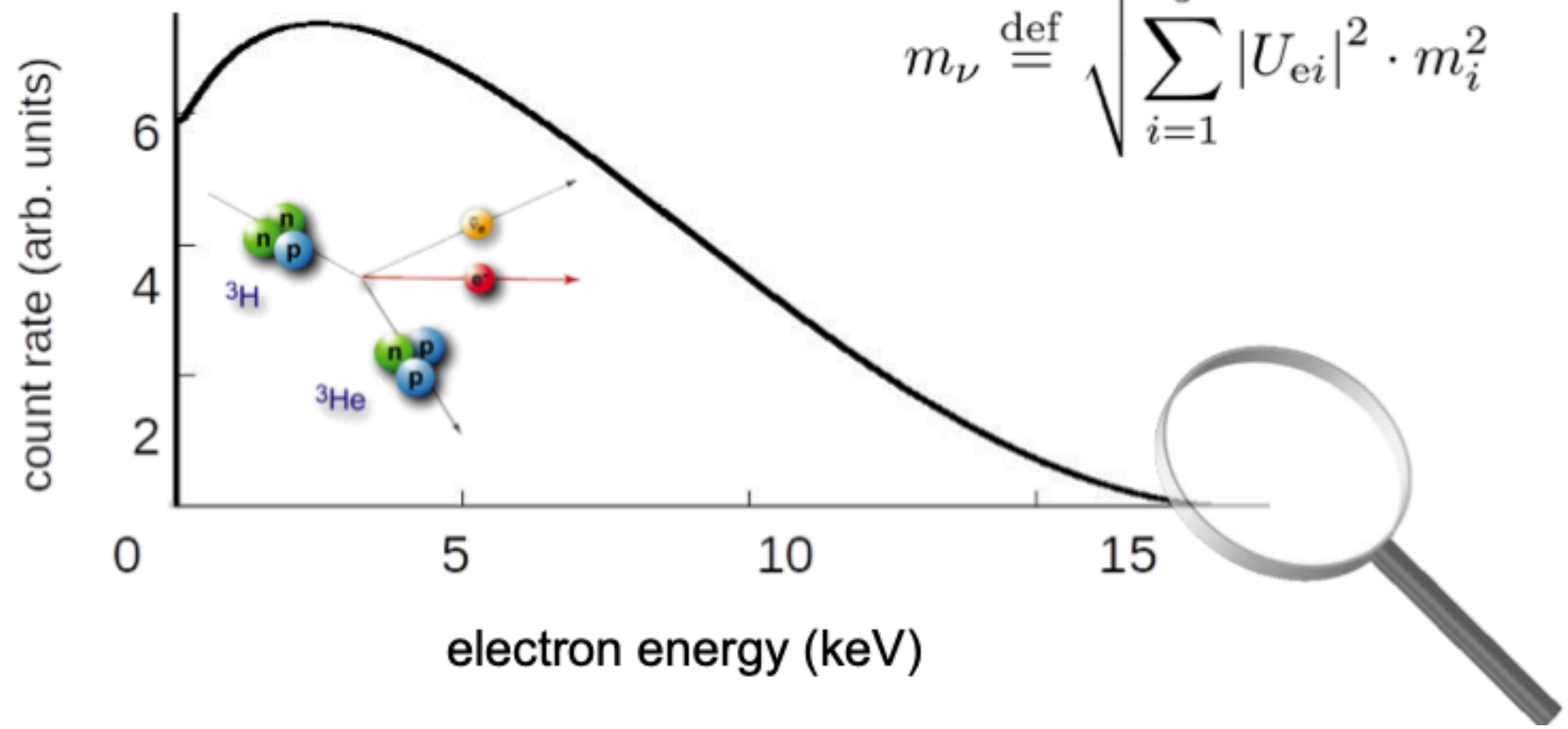
G.Drexlin, TAUP2019

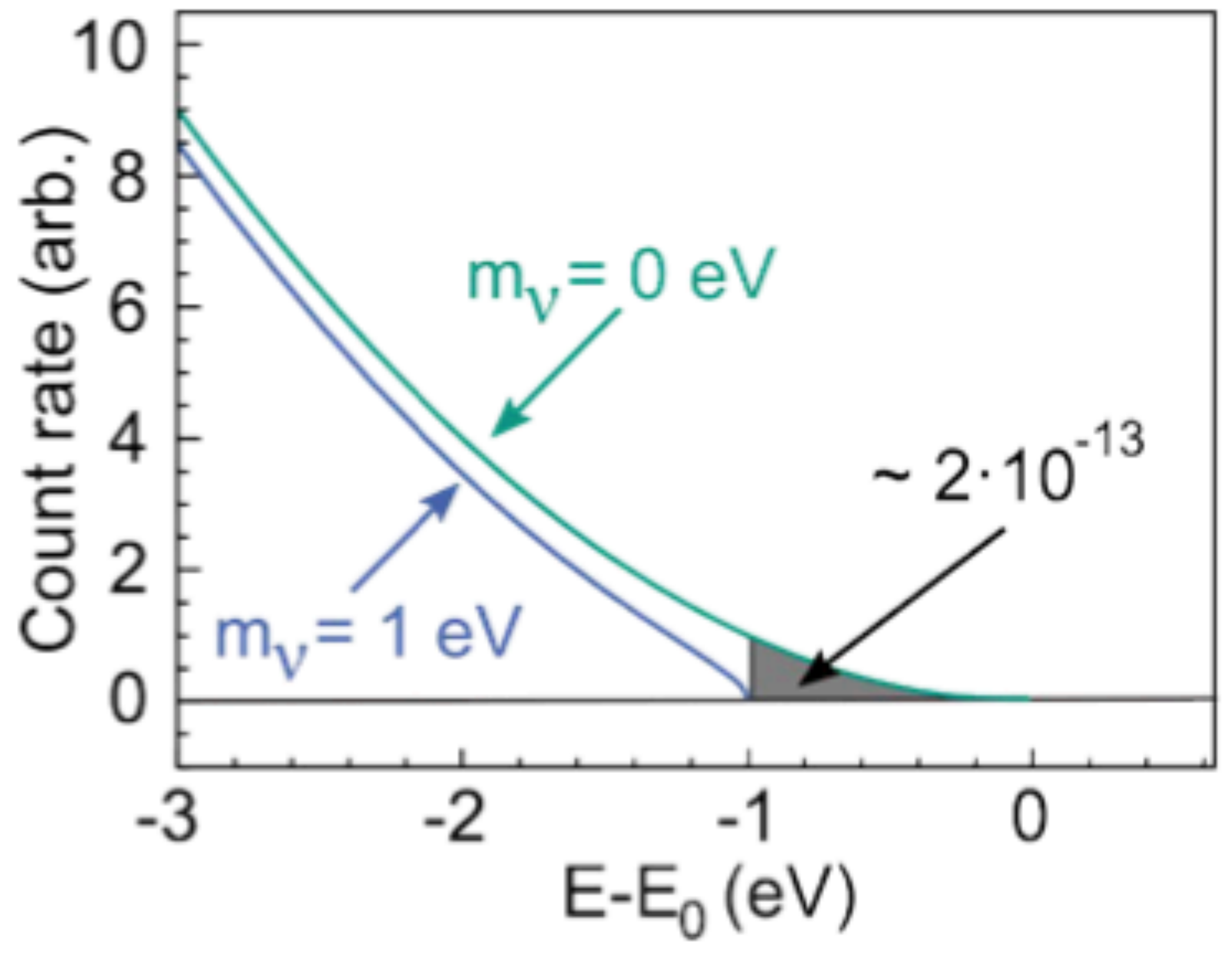
End-point of the β decay spectrum

- Measurement of the mass based on kinematic parameters and energy conservation
- Look for Tritium decay ${}^3H(n,n,p) \rightarrow {}^3He(n,p,p) + e^- + \bar{\nu}_e$

$$R_\beta(E) \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$

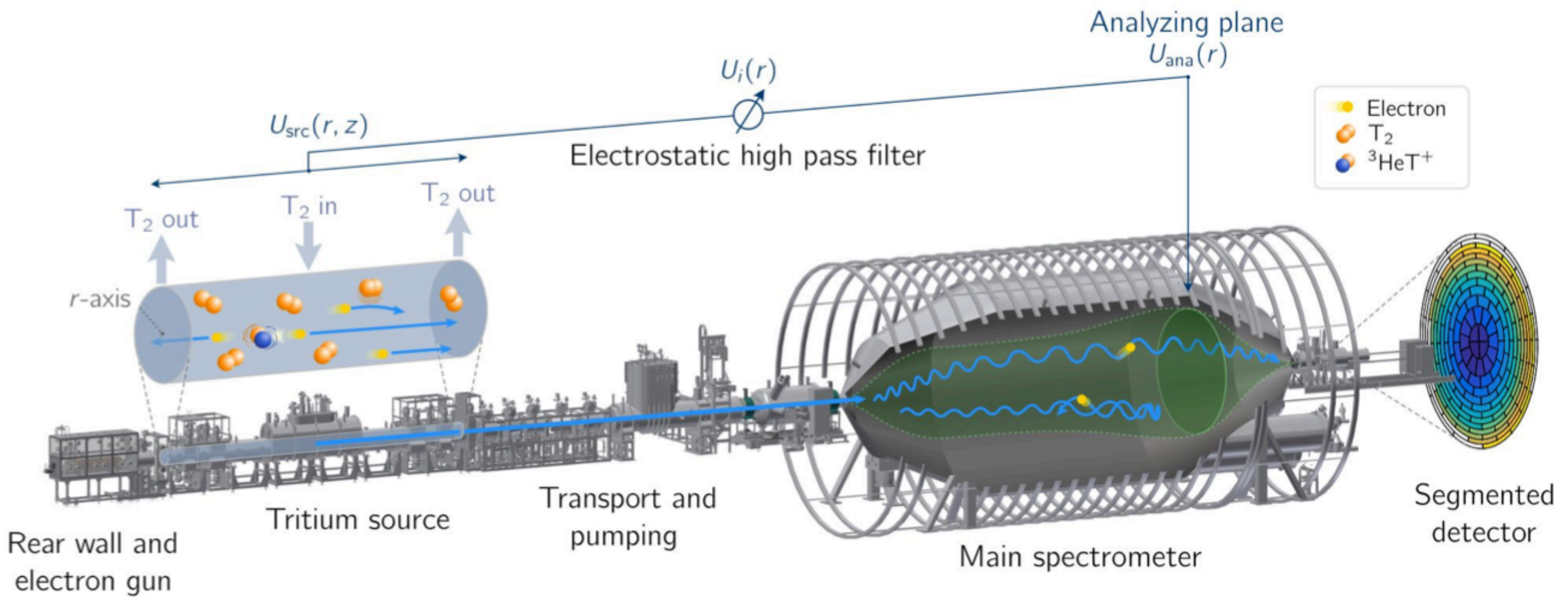
$$m_\nu \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$





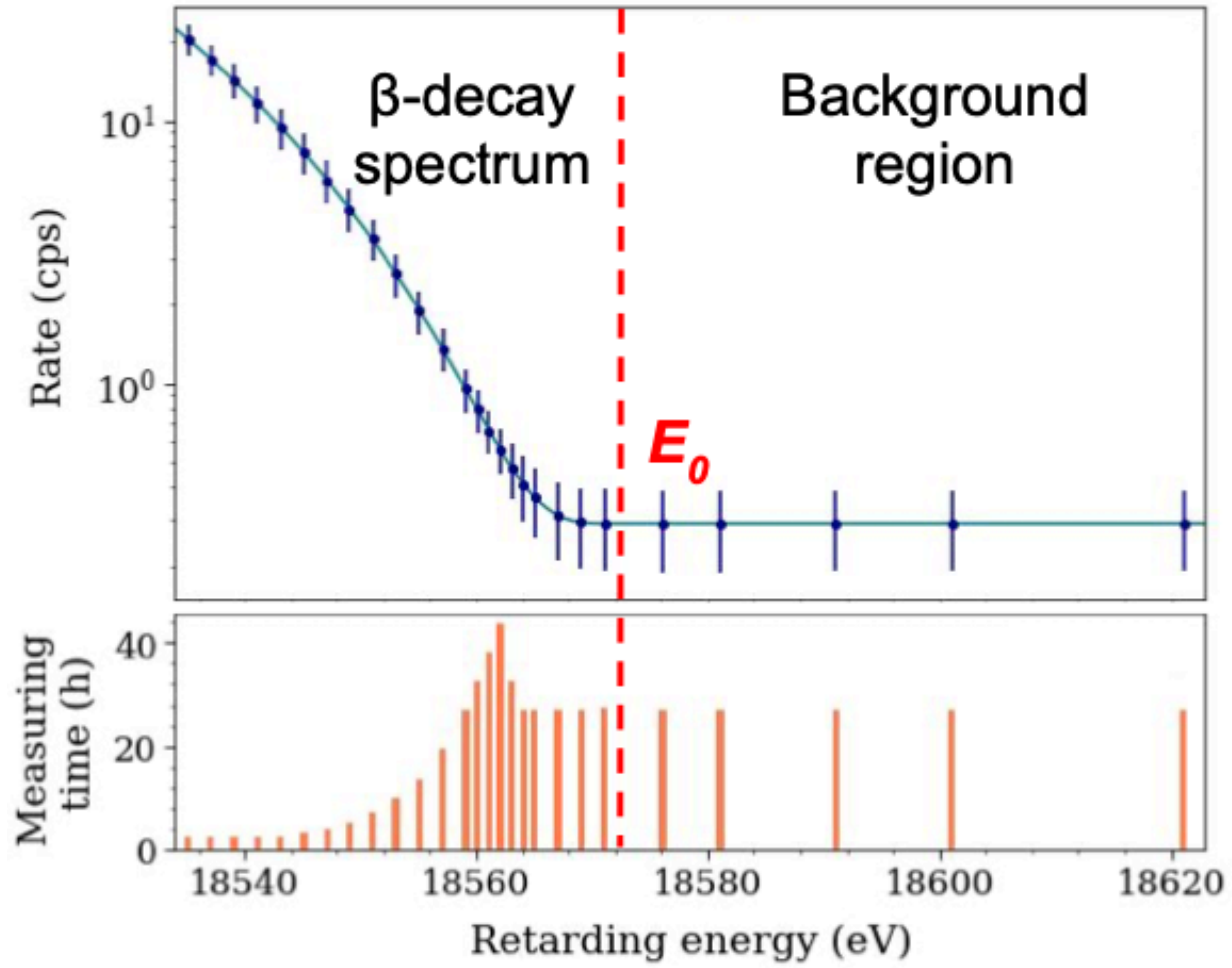
KATRIN:
Karlsruhe
Tritium
Neutrino
Experiment

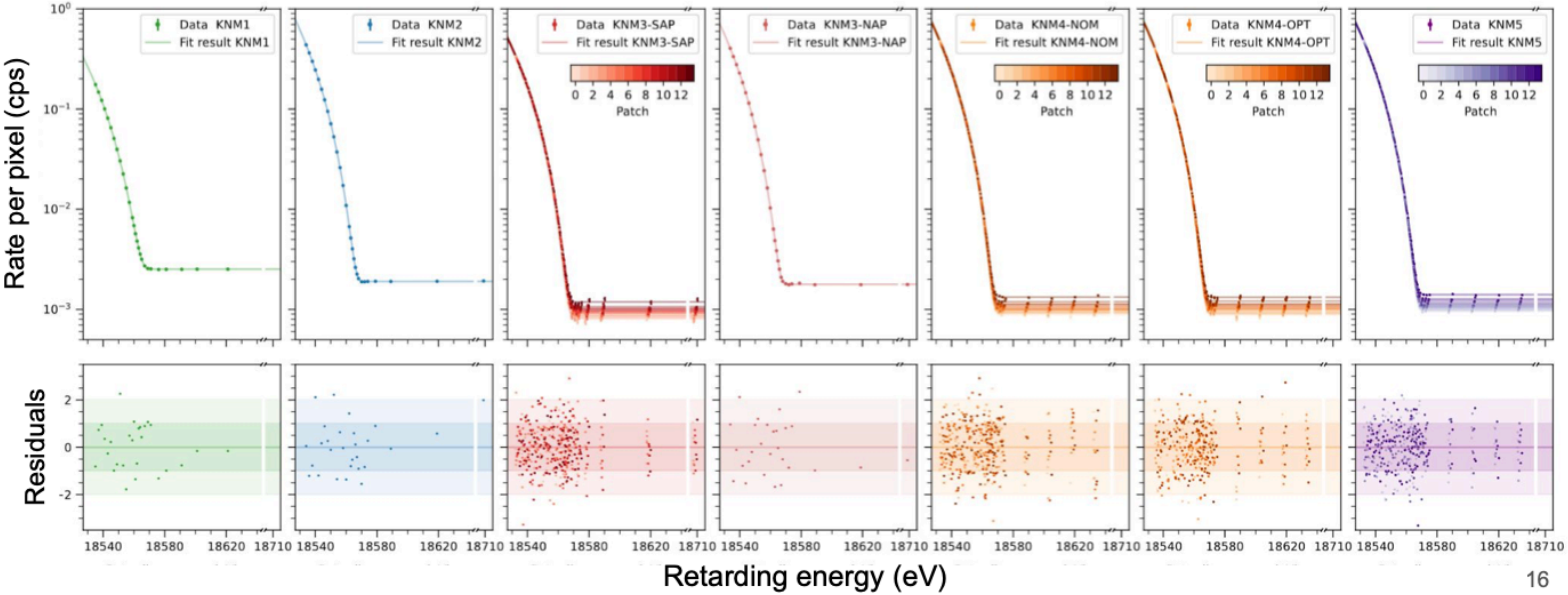
The KATRIN experiment

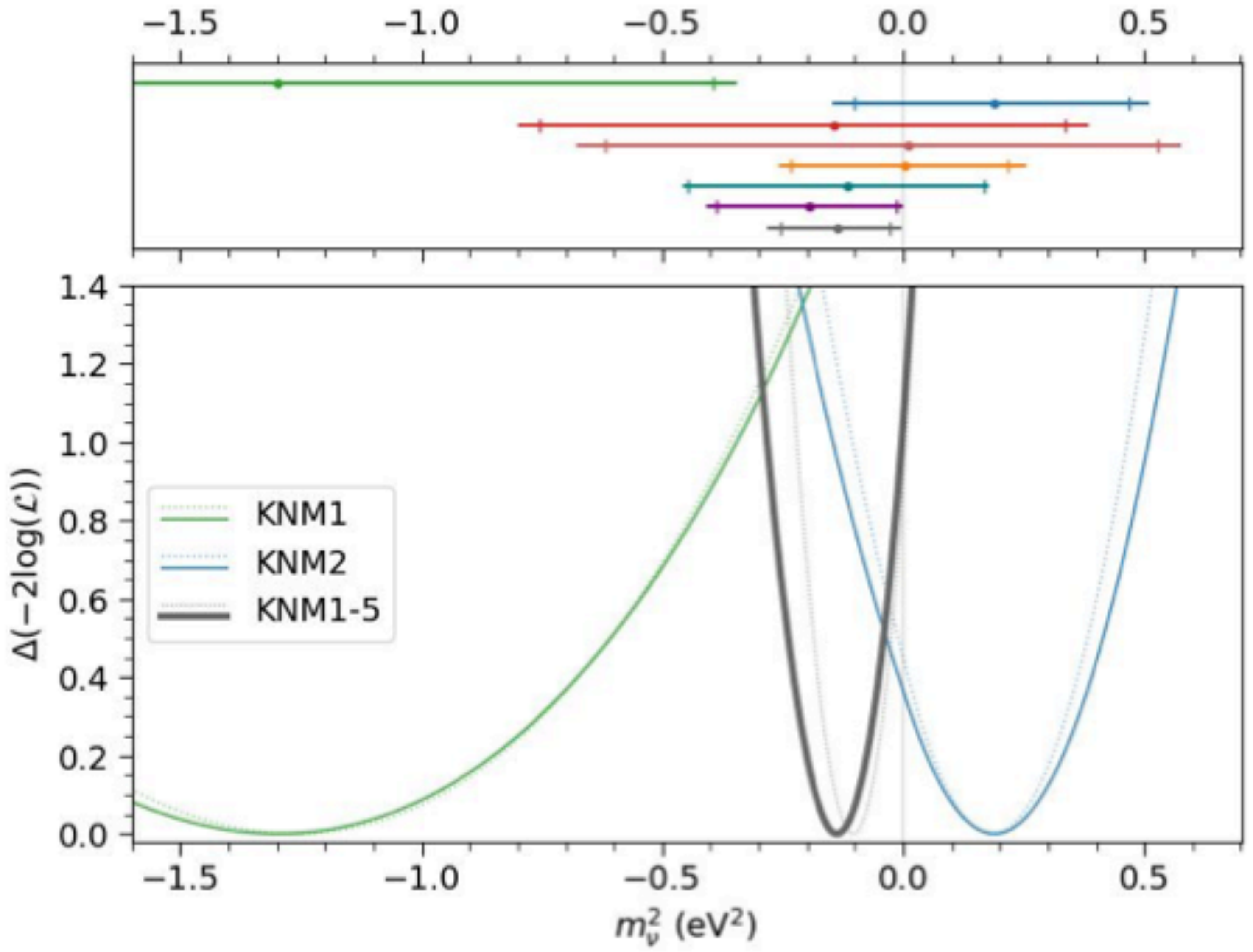


Full system description & commissioning: KATRIN, JINST 16 (2021) T08015

- Spectrometer with high resolution (1 eV)
- 2-3 hour scan for each energy

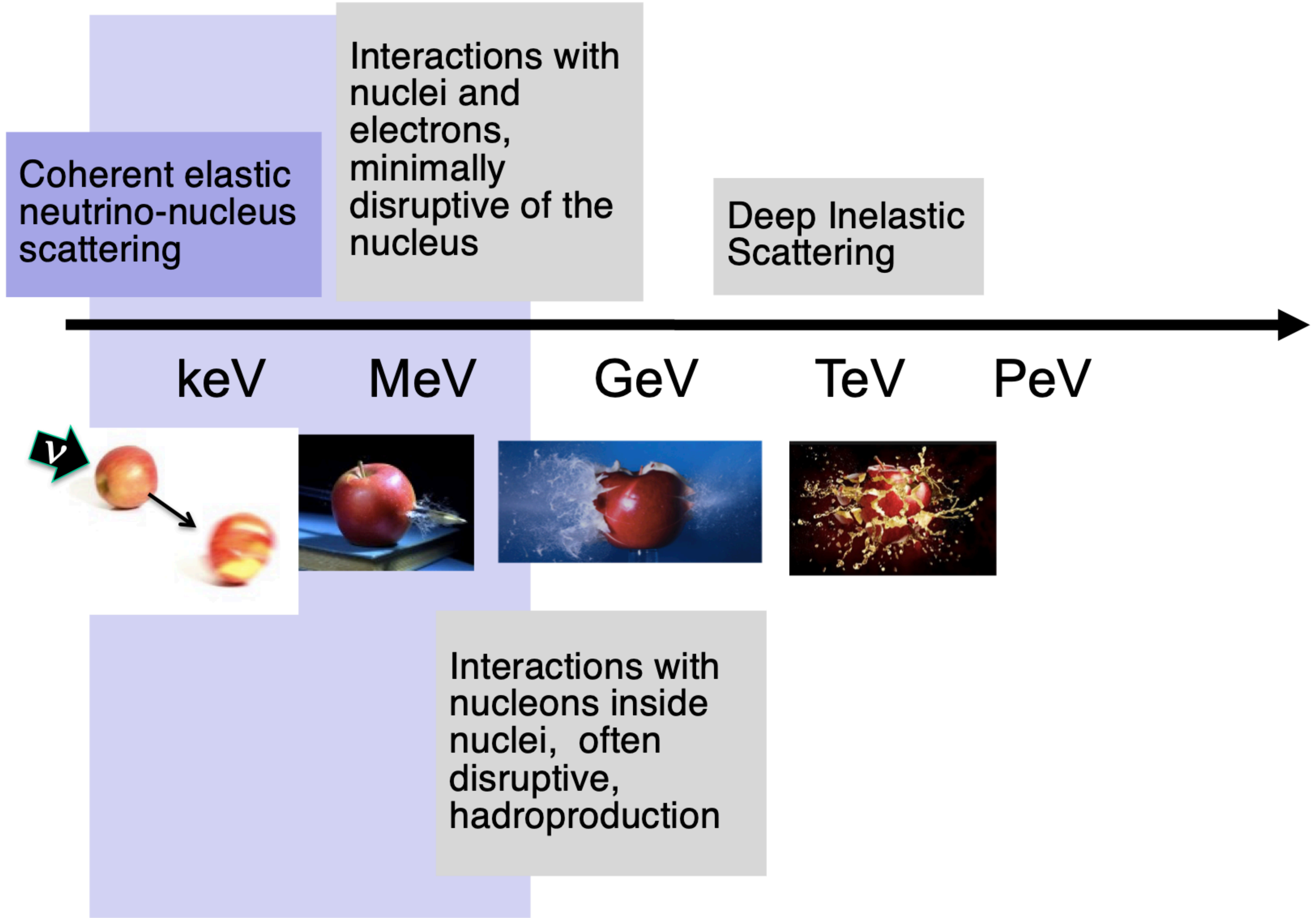






- Best fit $m_\nu^2 = -0.14^{+0.13}_{-0.15}\ eV^2$
- $Q - value : (18575.0 \pm 0.3) eV$
- Upper limit: $m_\nu < 0.45\ eV^2\ (90\,\%\ CL)$

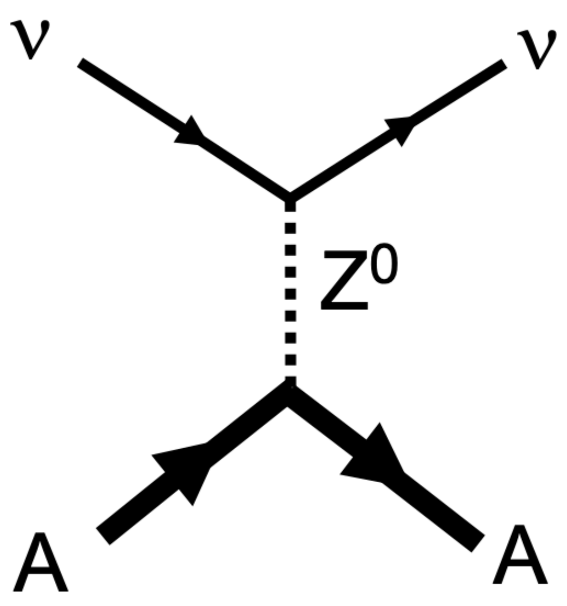
Coherent elastic scattering

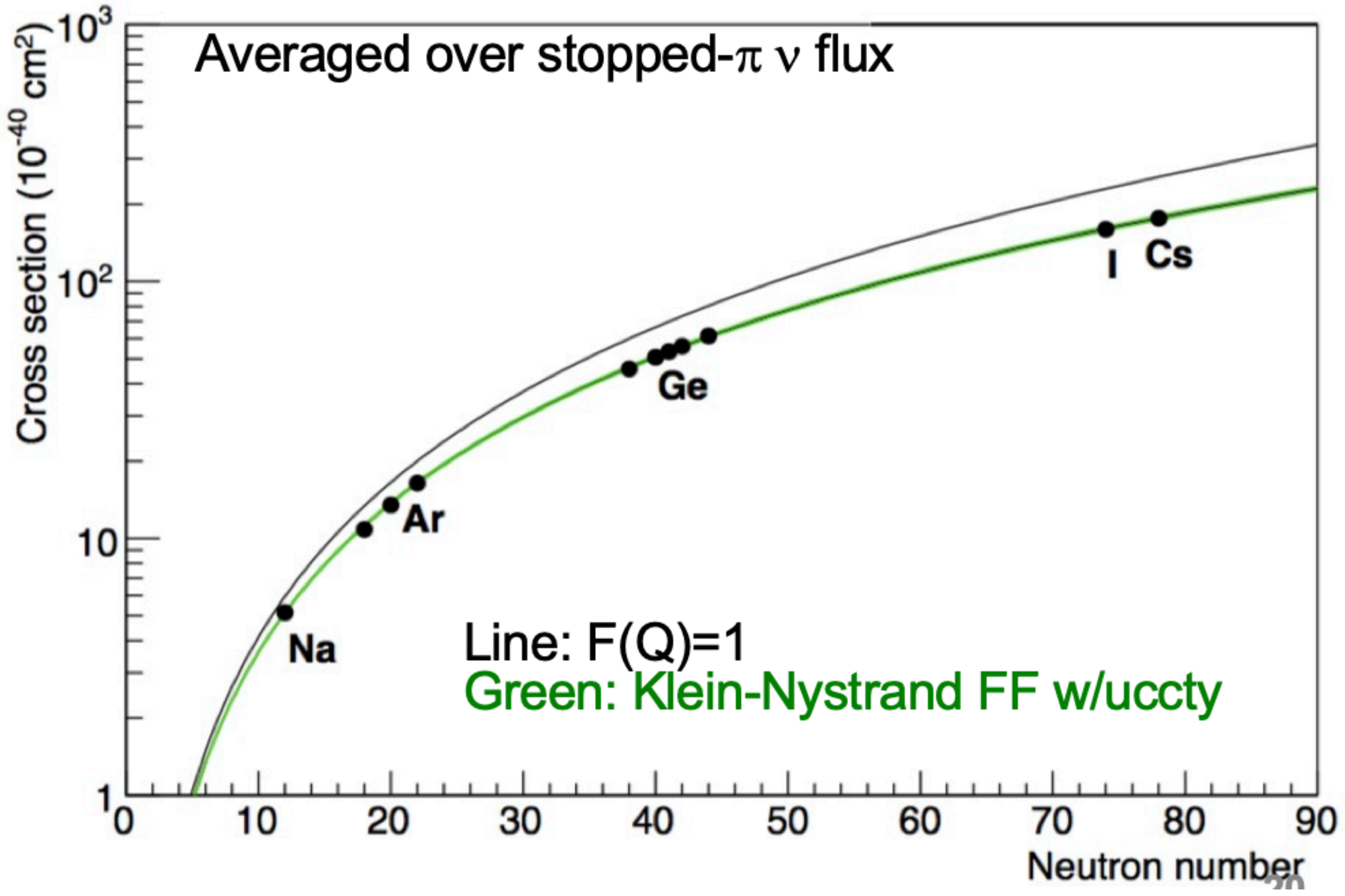


- $\sigma \propto N^2$

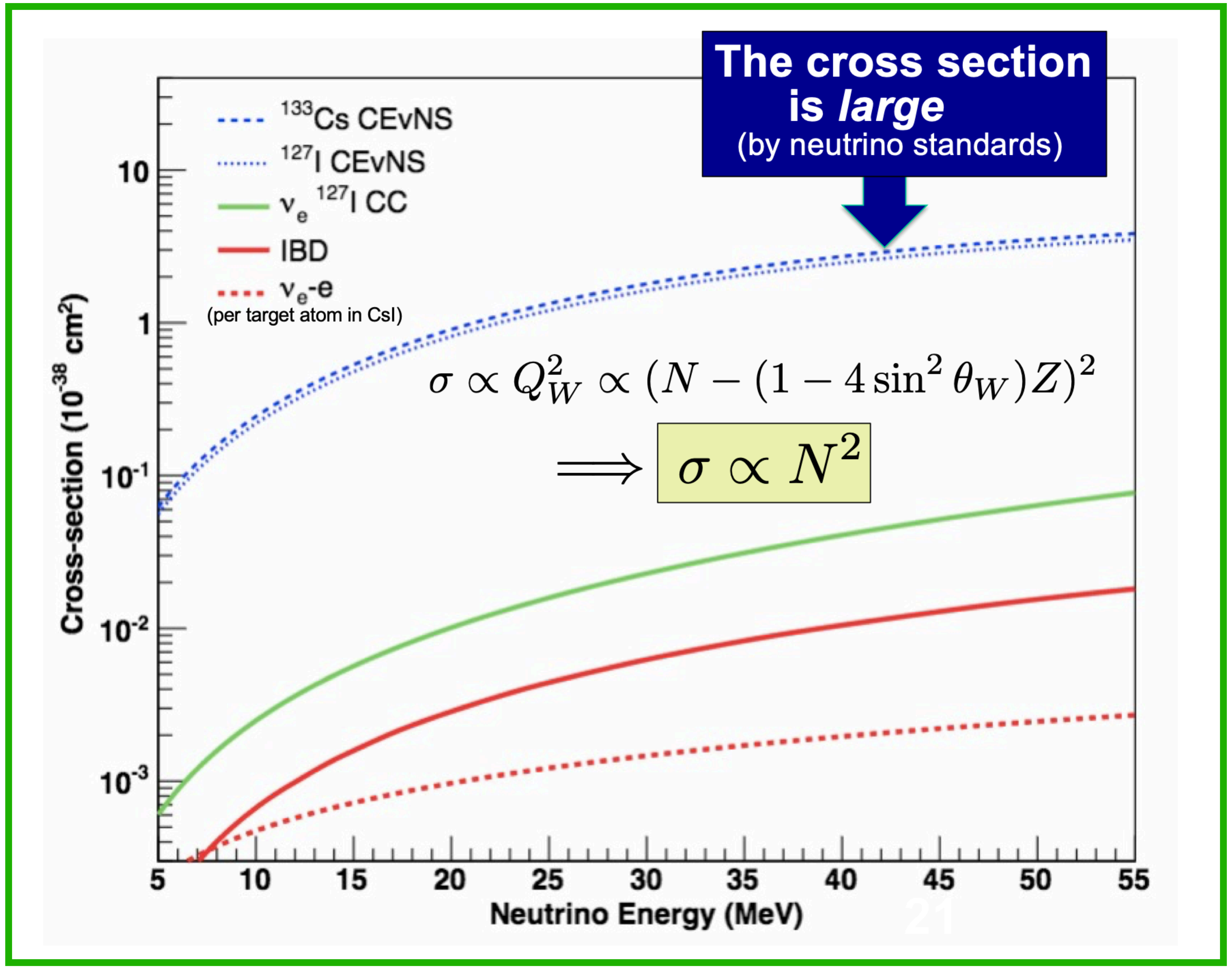
ν + A → ν + A

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV



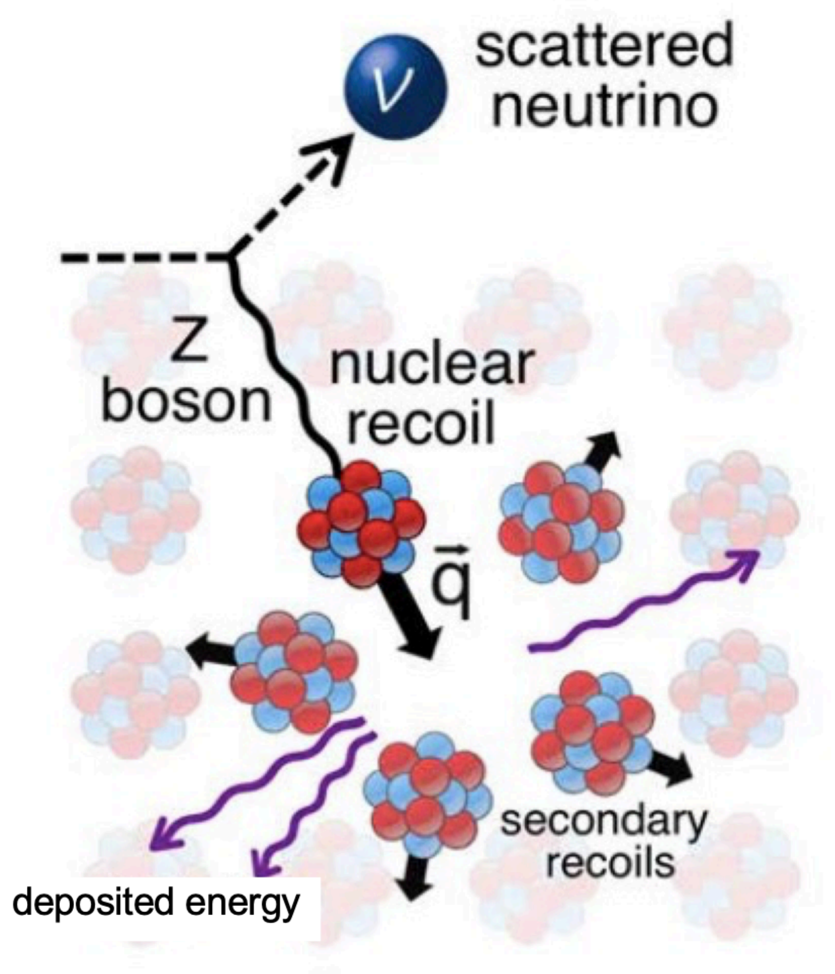


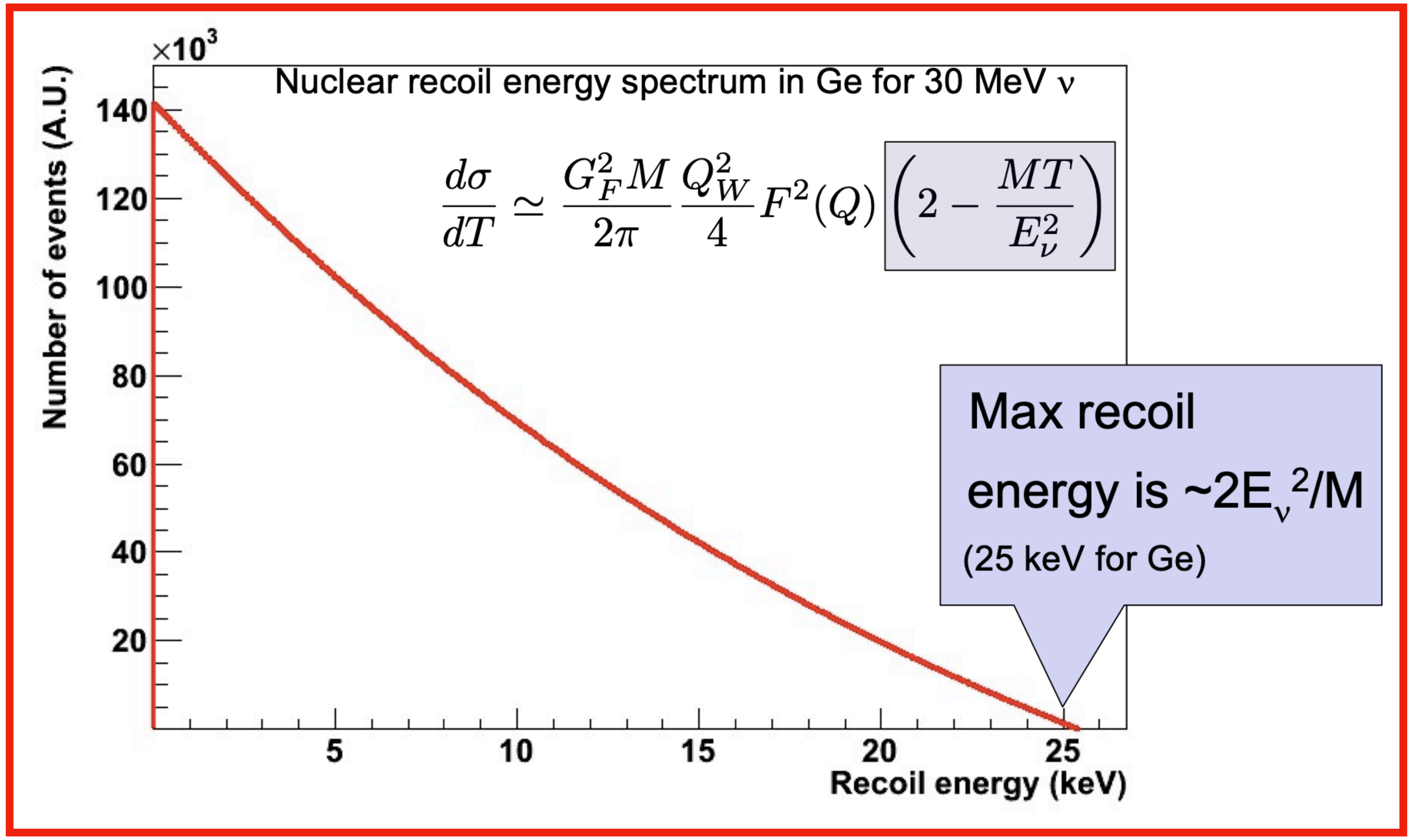
Signals



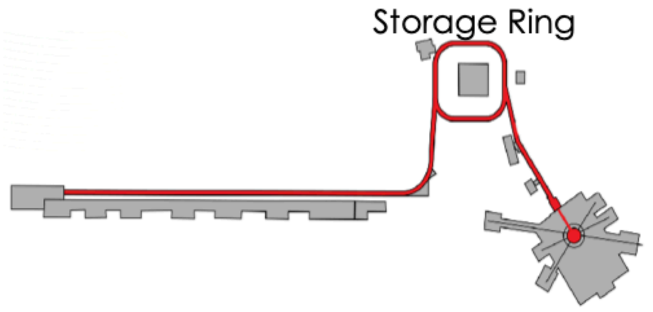
The only experimental signature:

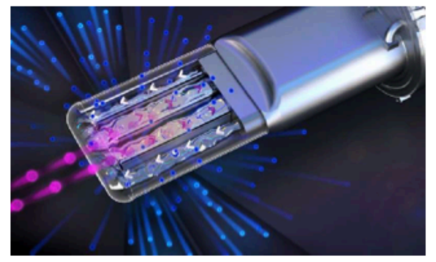
tiny energy deposited by nuclear recoils in the target material

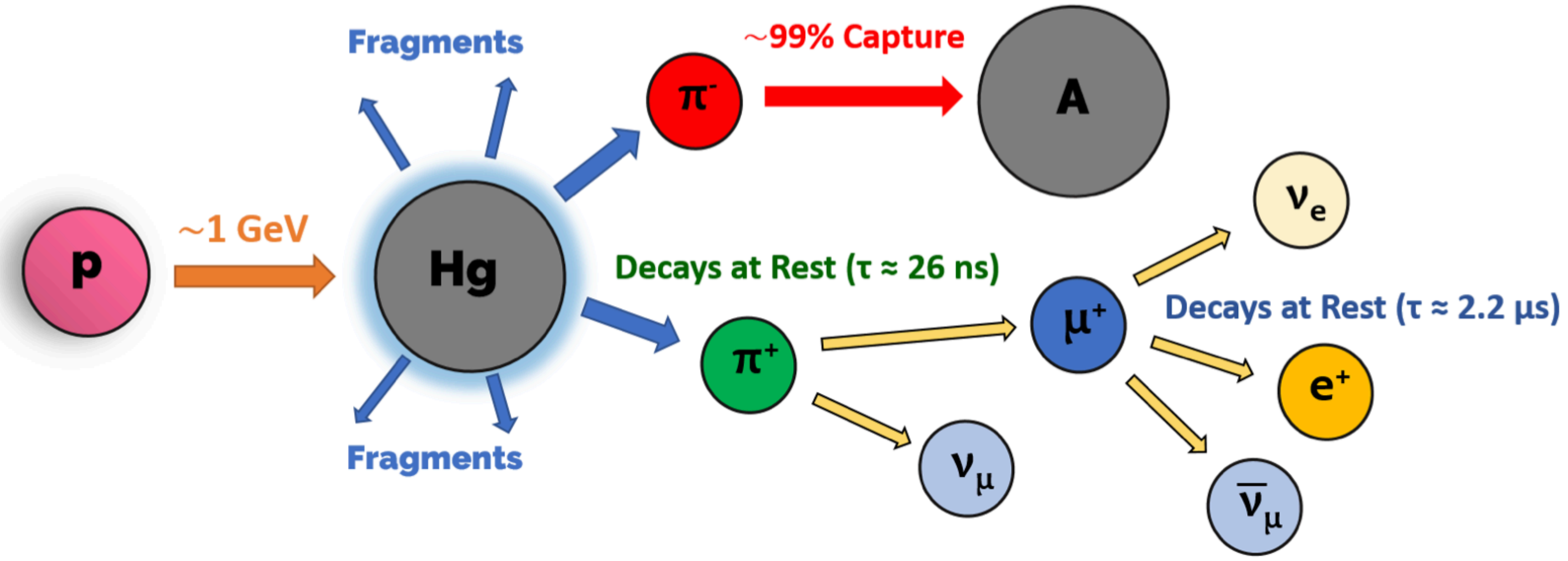




Neutrinos from Spallation Neutron Source







- Proton Beam:
  - 0.9-1.3GeV
  - 0.9-1.7MW, **soon 2MW (PPU)**.
- Total ν flux: ~4.3 x 10^7 cm^{-2} s^{-1} at 20m
- Beam timing & duty cycle (60Hz, 380ns FWHM) allow for powerful reduction of steady-state backgrounds (~10^{-4})

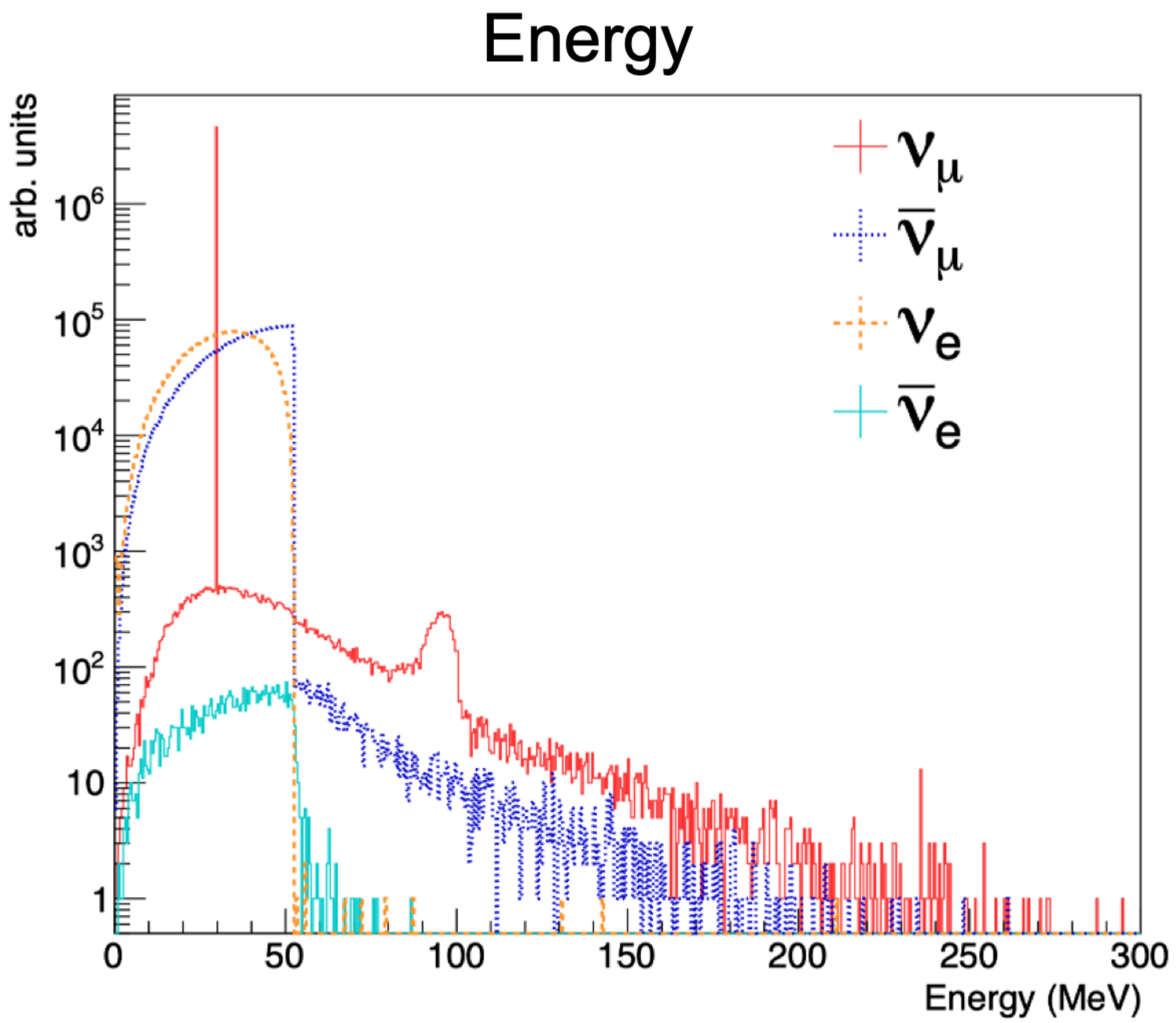
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

2-body π⁺-decay: Prompt (26nsec)
Monochromatic: 29.9MeV ν_μ

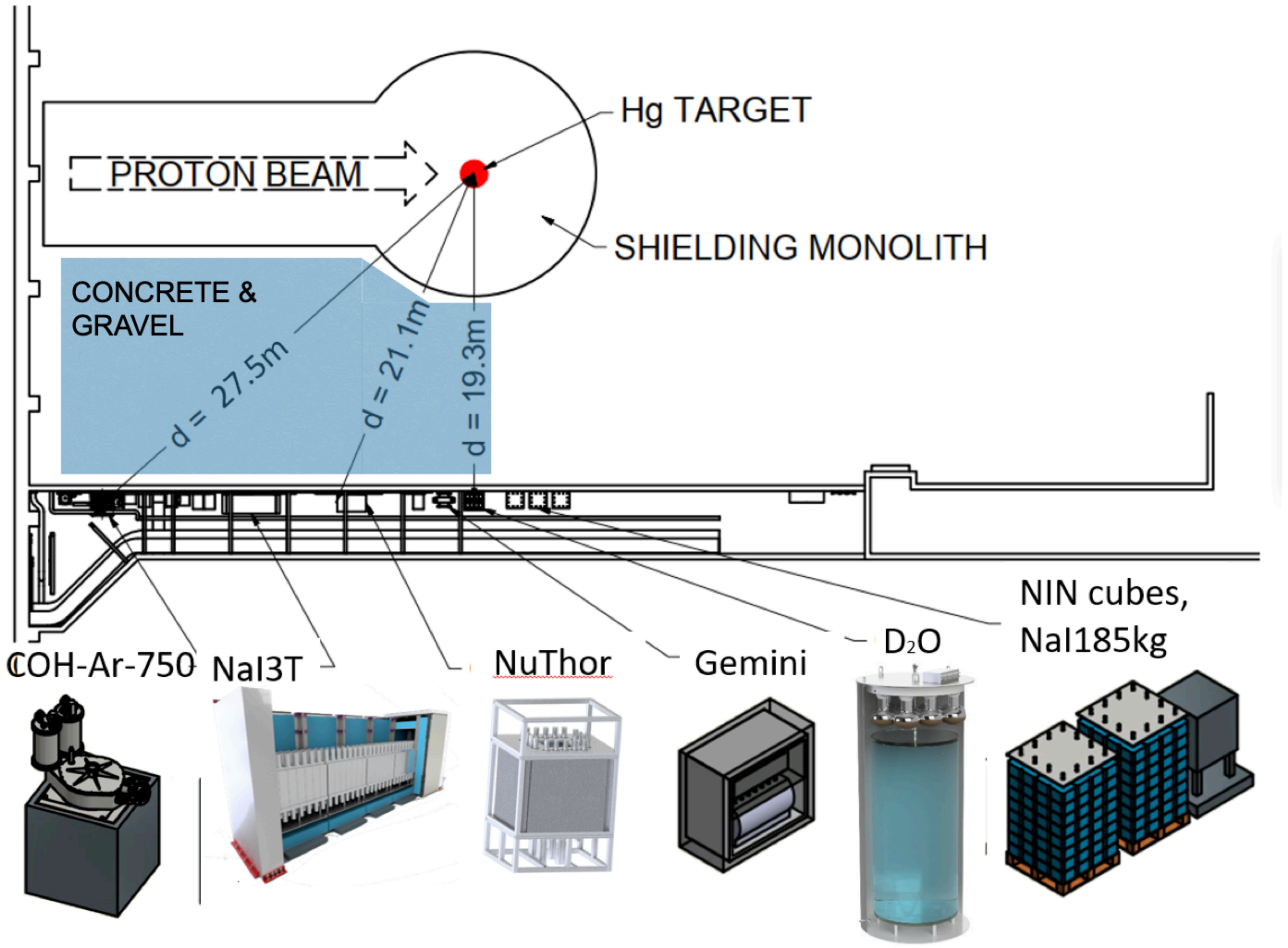
$$\downarrow$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

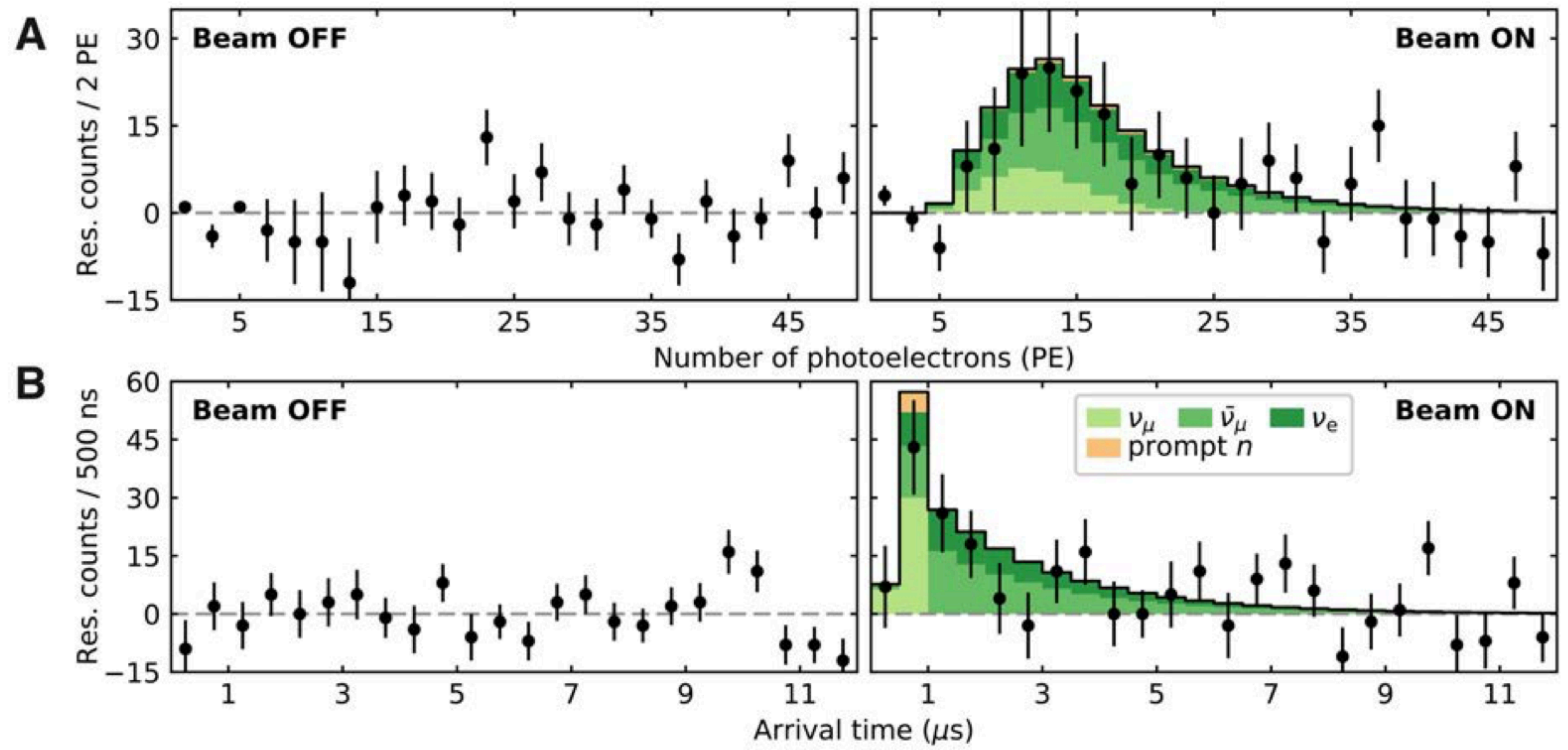
3-body μ⁻-decay:
Delayed (2.2μsec)
0-53MeV $\bar{\nu}_\mu$, ν_e



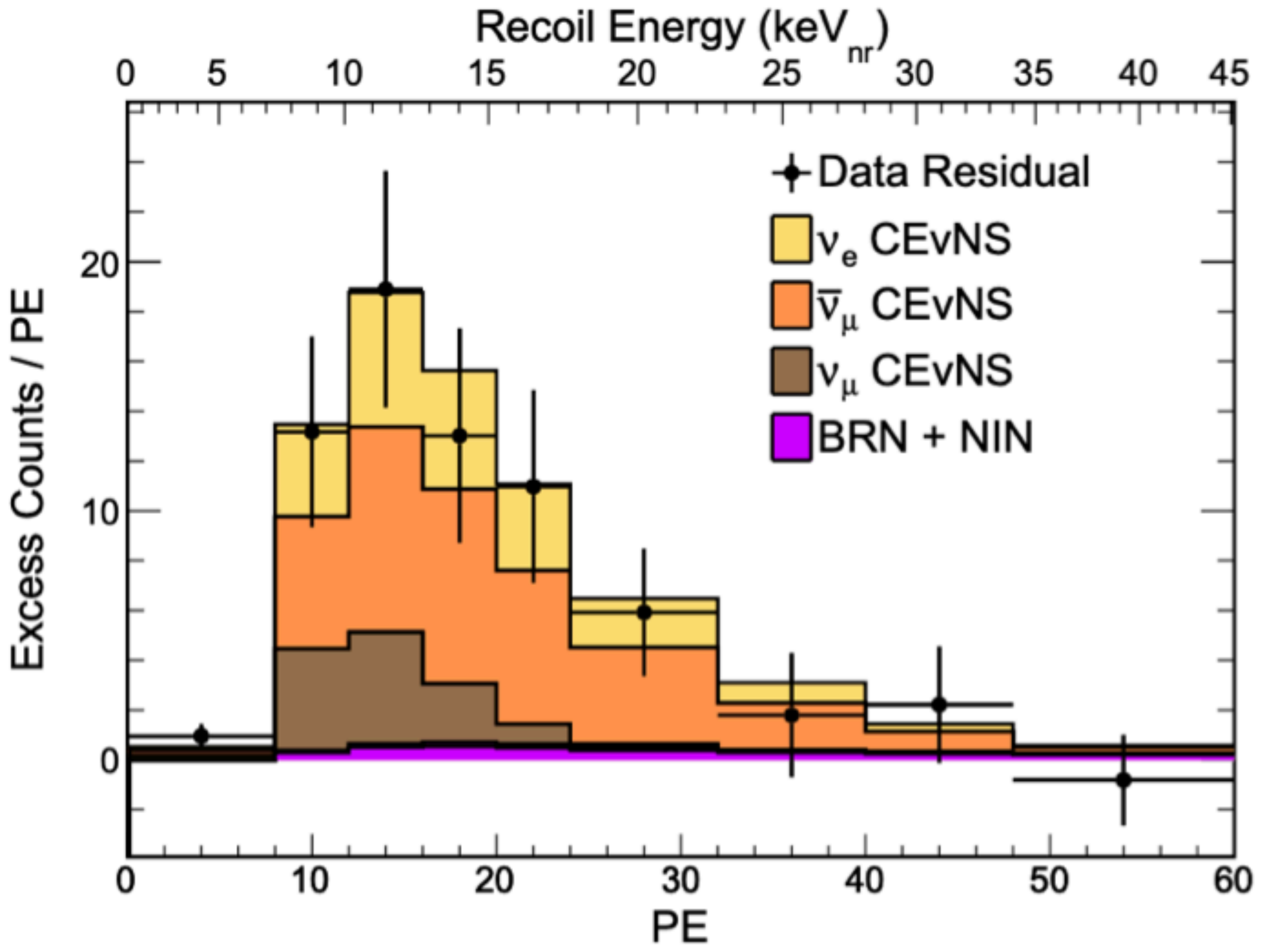
Several small-scale experiments

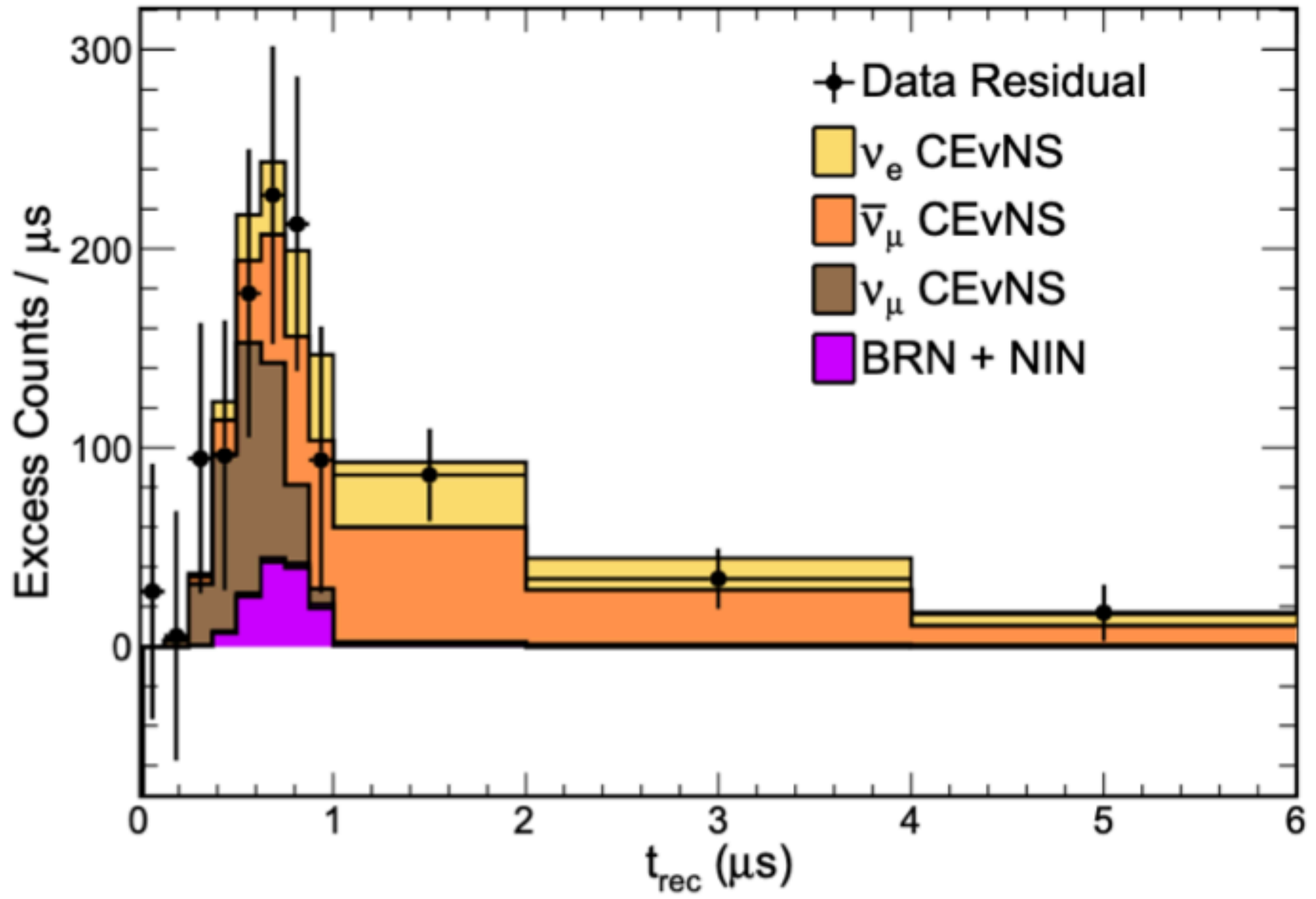


Neutrino Alley



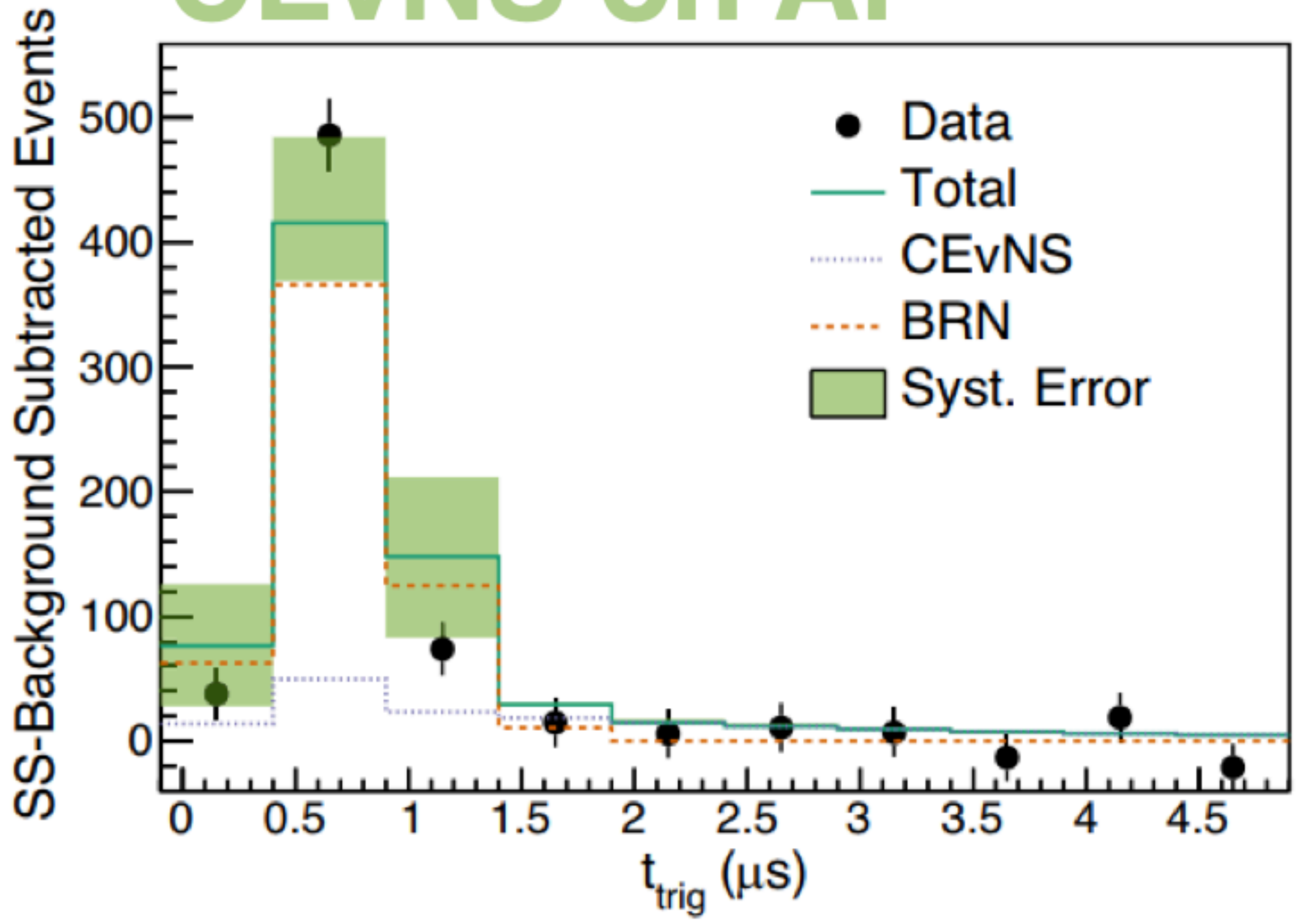
CEvNS on CsI

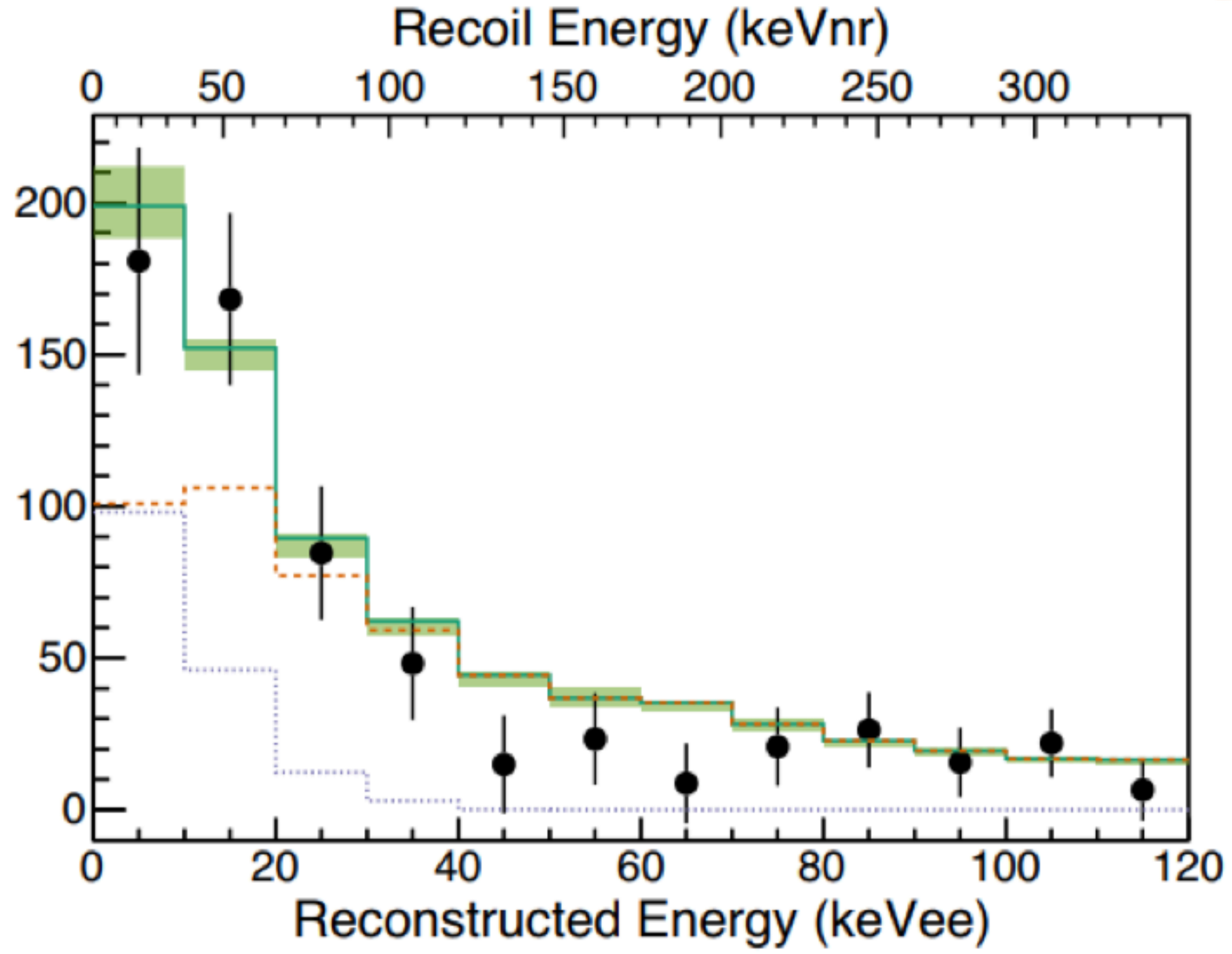


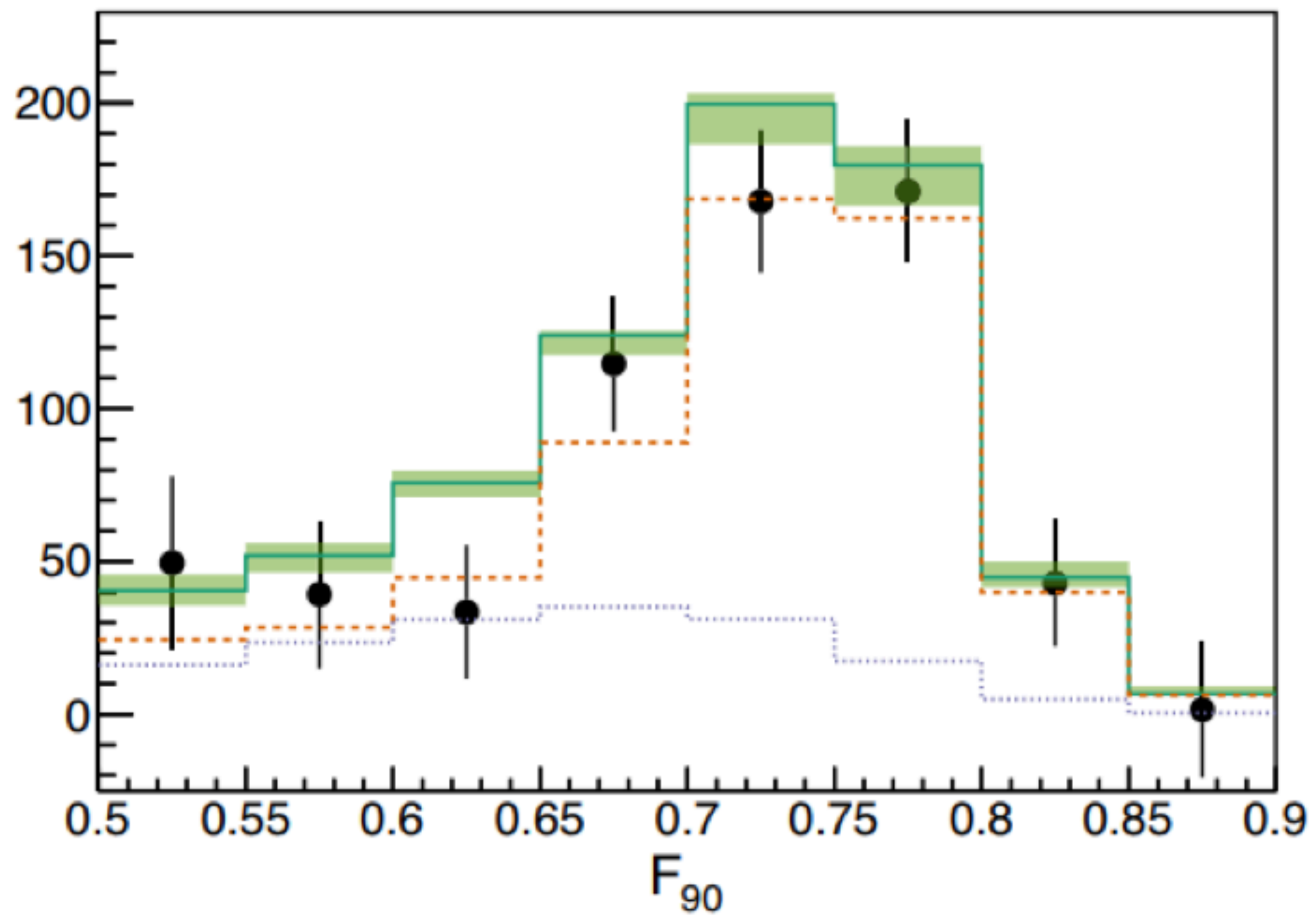


COHERENT, PRL 129 081801 (2022)

CEvNS on Ar

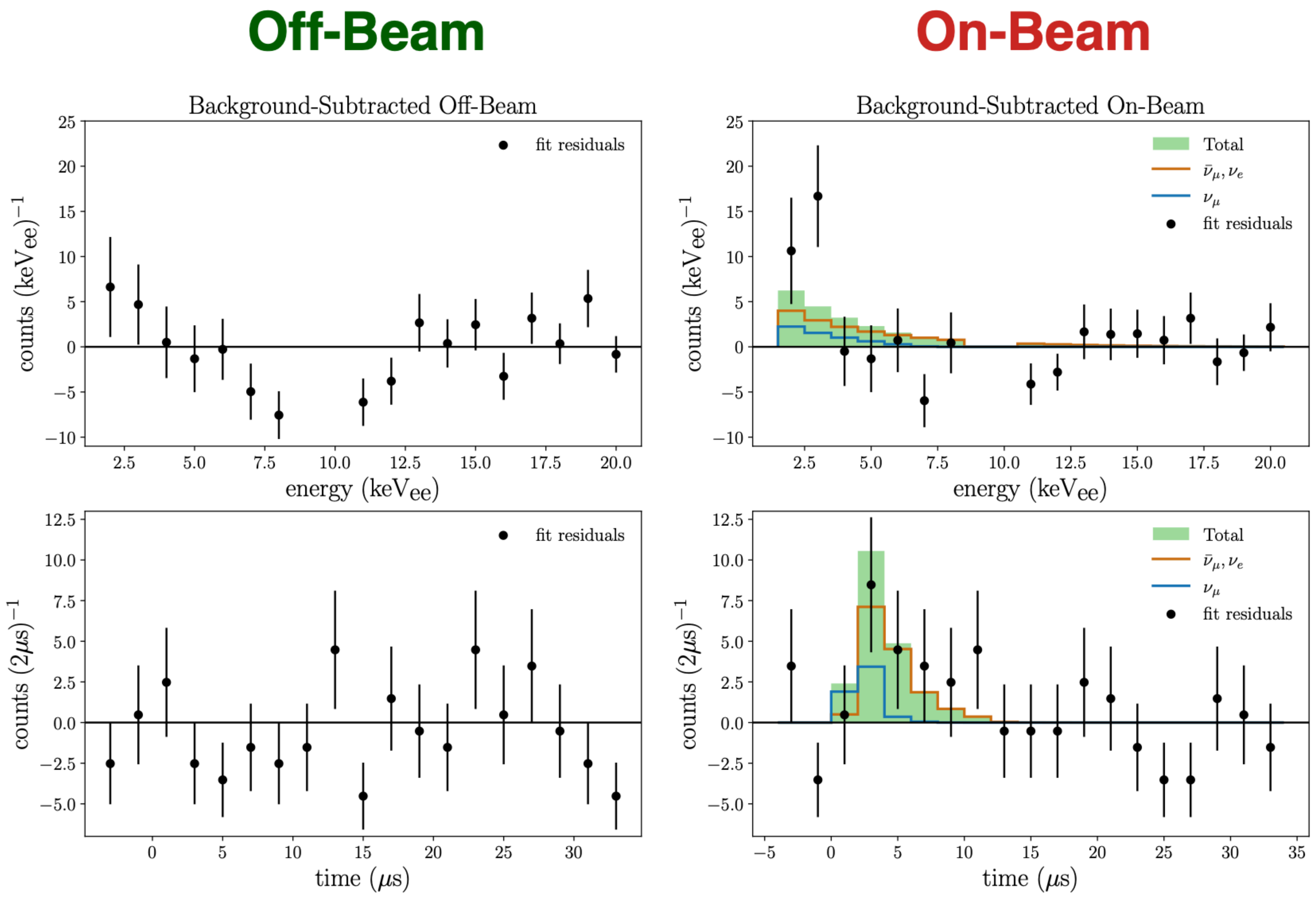




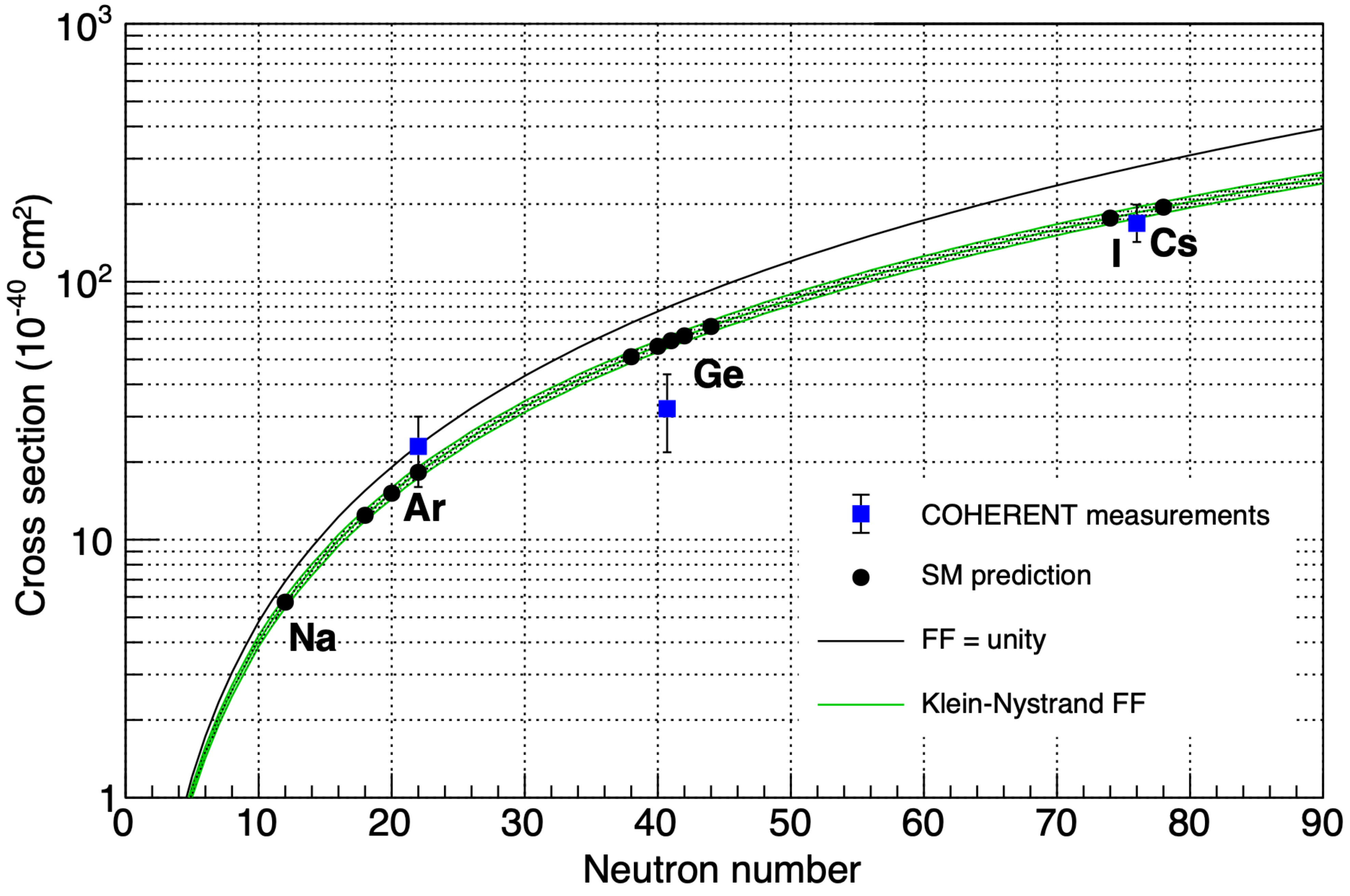


COHERENT, PRL 126 012002 (2021)

Germanium detector



arXiv:2406.13806



Coherent scattering in DM experiments