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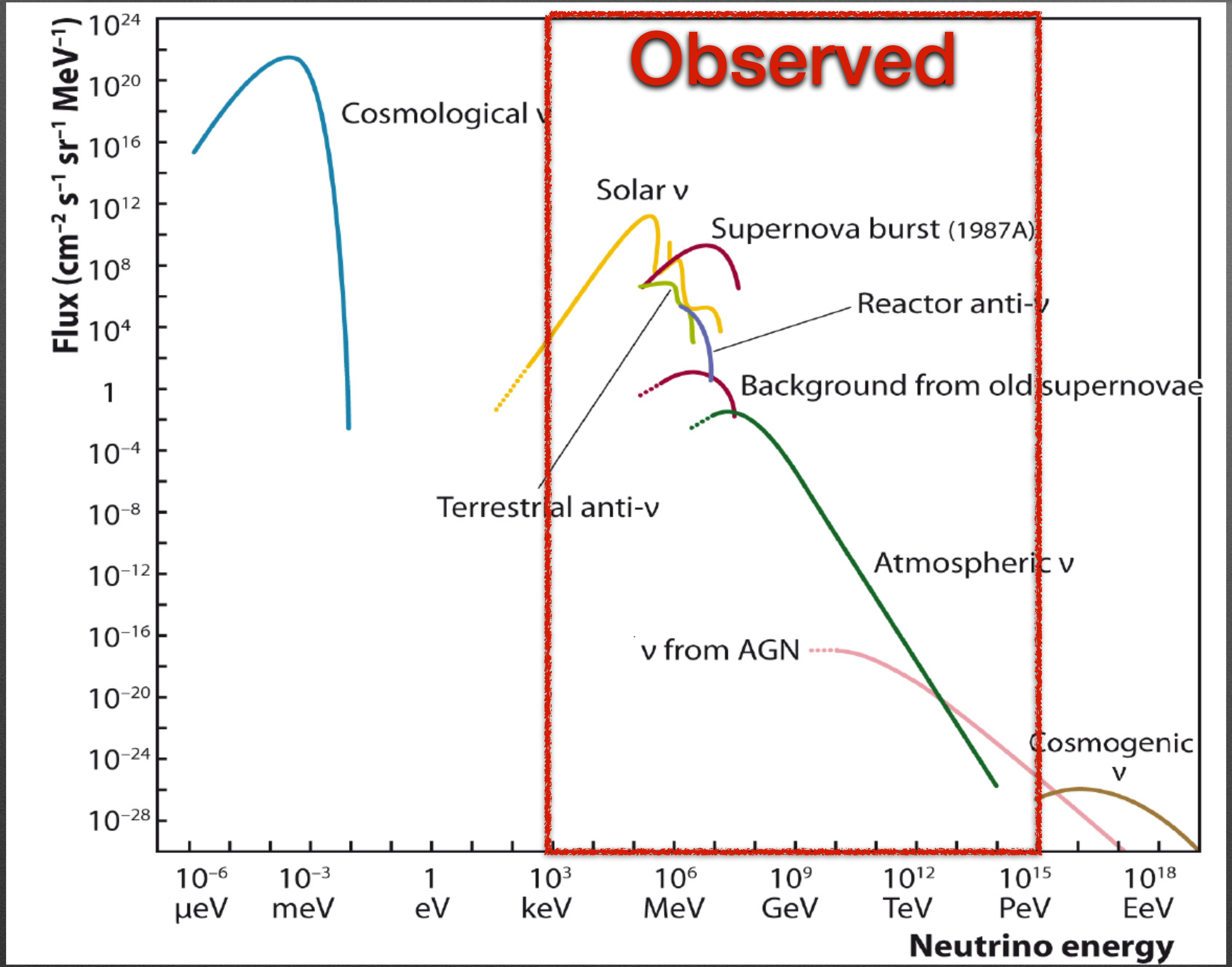
Experimental review of Neutrino Physics

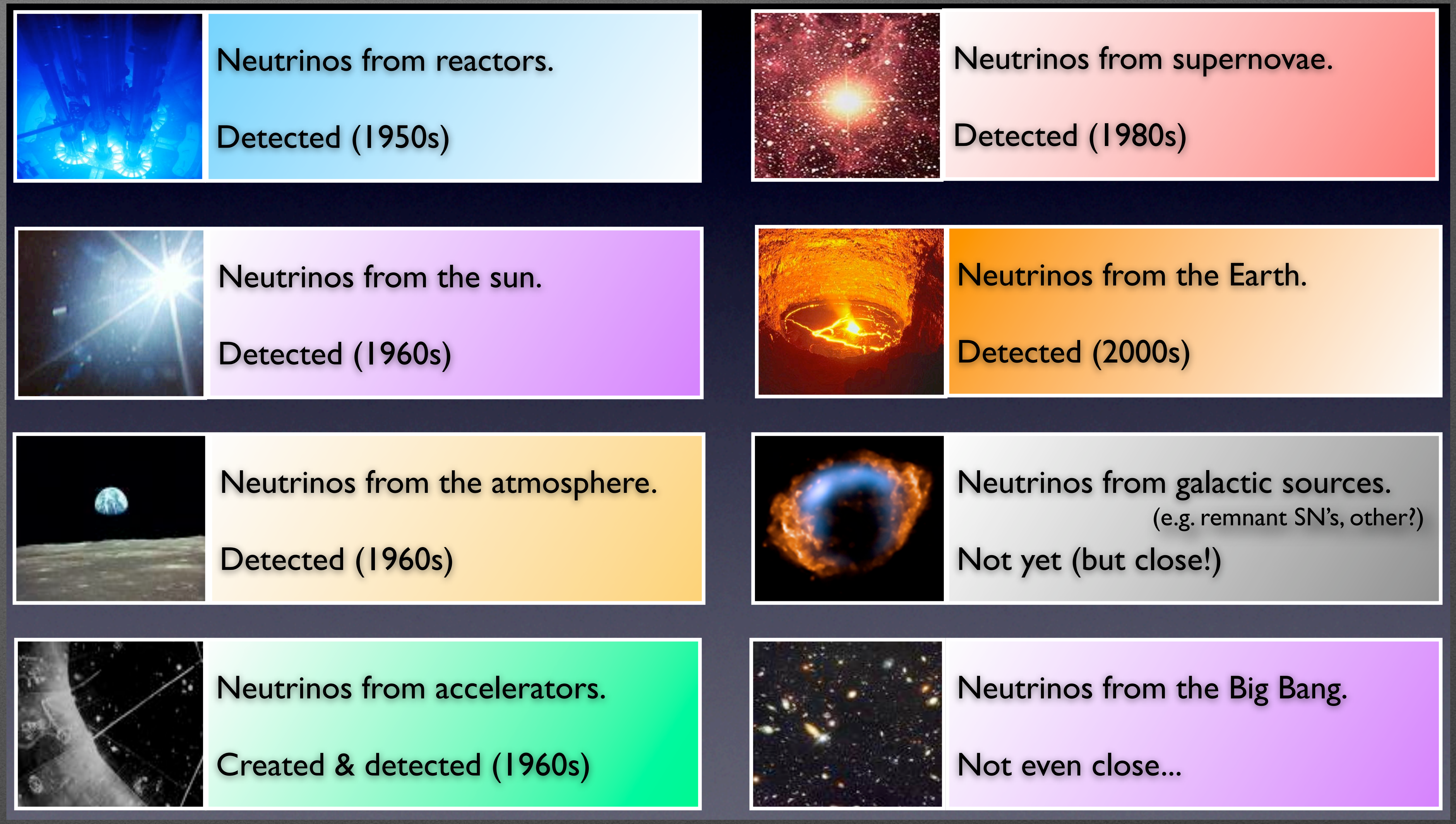
Claudio Giganti - LPNHE Paris

INVISIBLES' 22 WORKSHOP 20-24 JUNE 2022 University Paris-Saclay / Orsay Campus IJCLab ORSAY France

Neutrinos



Observed
Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy



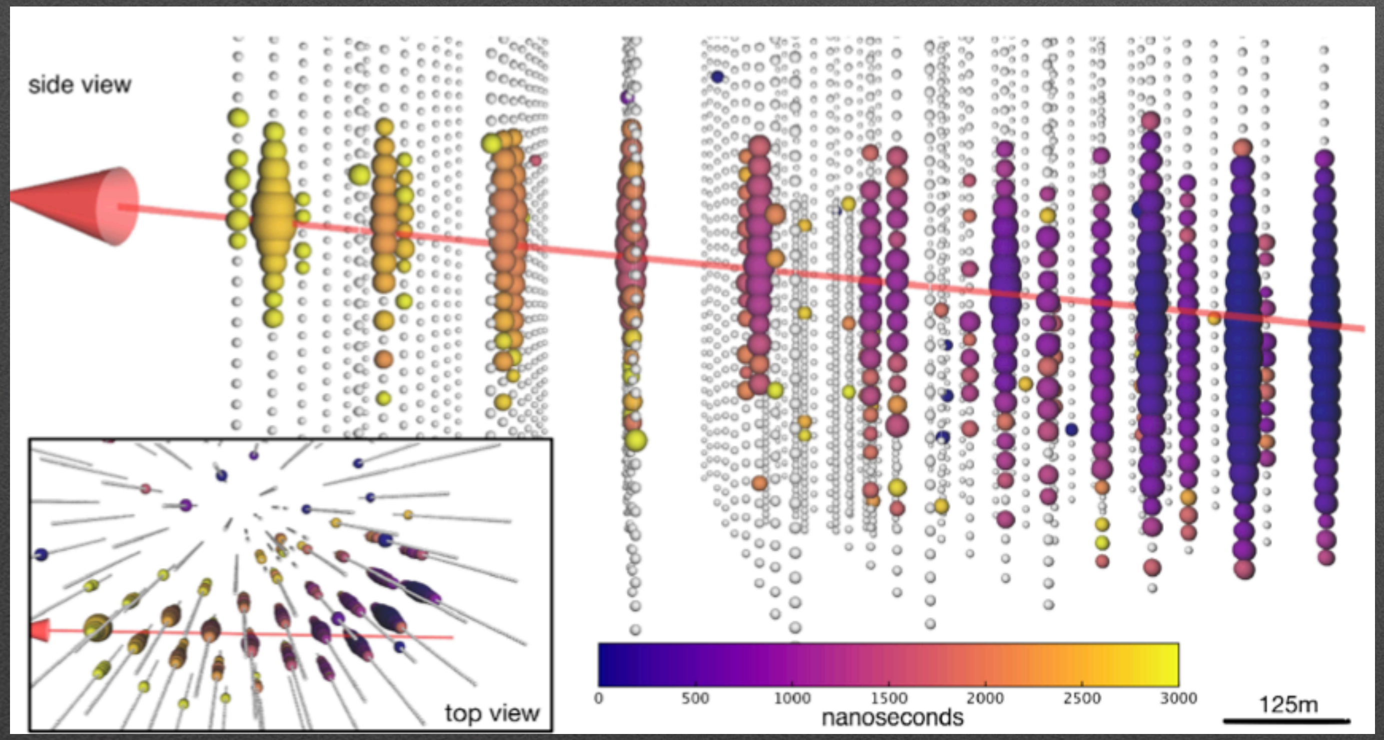
Neutrinos from reactors.
Detected (1950s)
Neutrinos from supernovae.
Detected (1980s)
Neutrinos from the sun.
Detected (1960s)
Neutrinos from the Earth.
Detected (2000s)
Neutrinos from the atmosphere.
Detected (1960s)
Neutrinos from galactic sources.
(e.g. remnant SN's, other?)
Not yet (but close!)
Neutrinos from accelerators.
Created & detected (1960s)
Neutrinos from the Big Bang.
Not even close...

Wot U mean
vu sur YATAHONGA.com
Neutrinos goin THRU me!?
ICANHASCHEEZBURGER.COM

How a neutrino looks like in an experiment

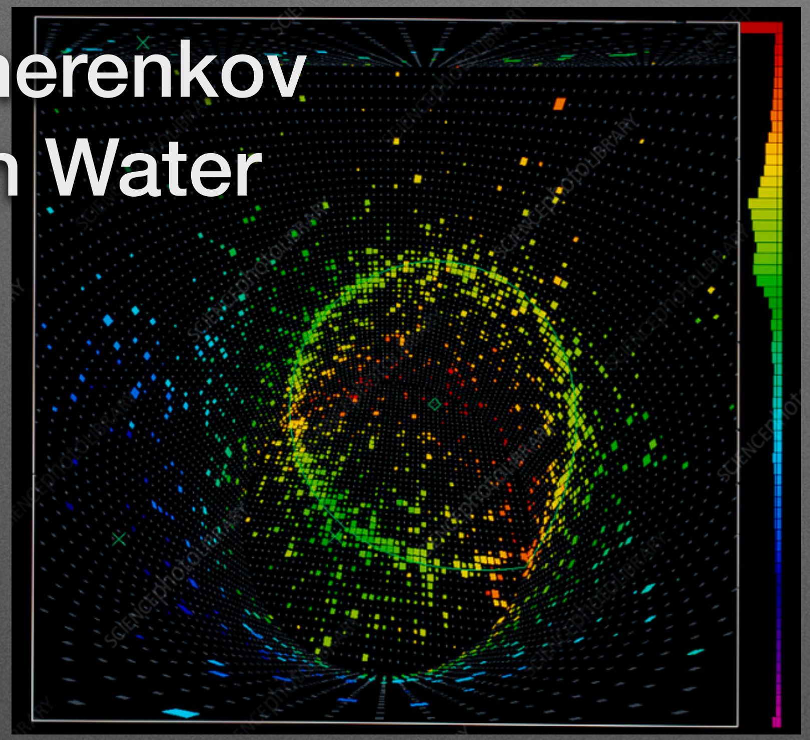
High energy ν (TeV, PeV)
>>Mton detectors

Cherenkov in Ice or in Water

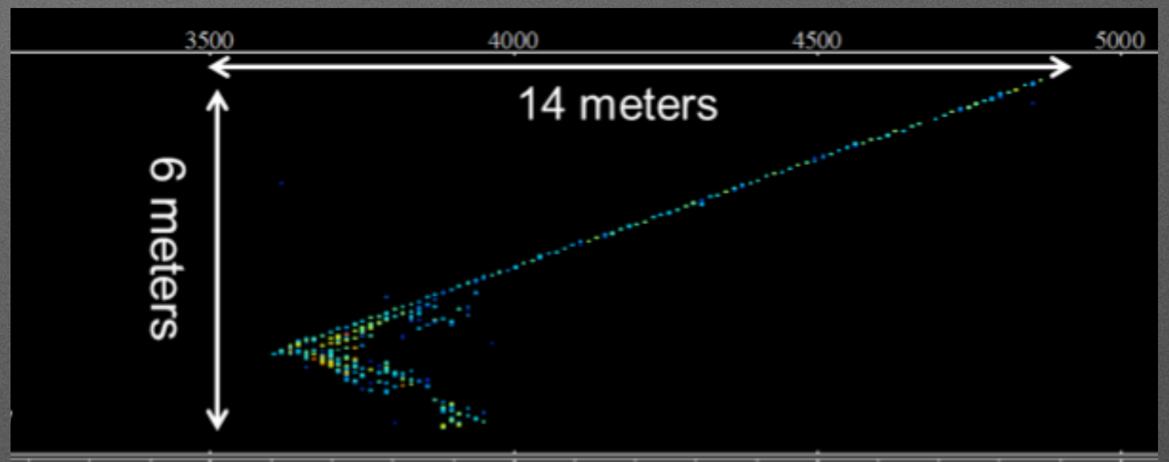


Atmospheric and accelerators (~GeV)
~ 10-100 kton detectors

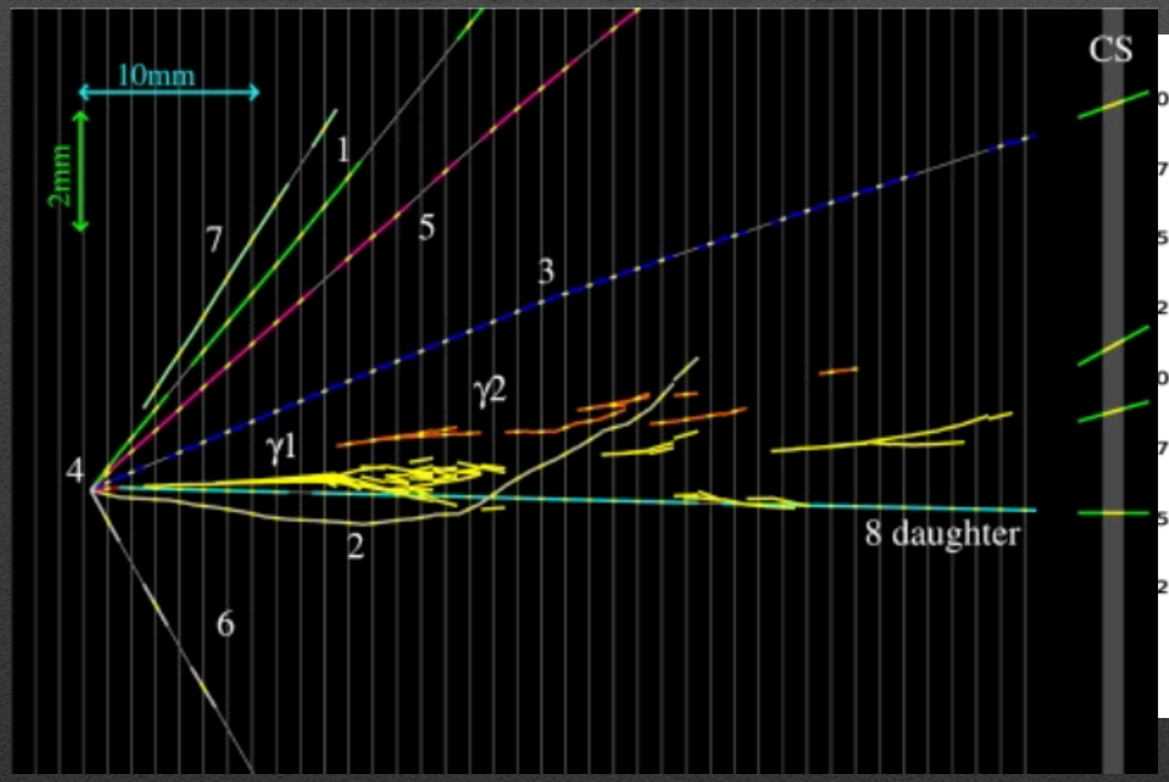
Cherenkov in Water



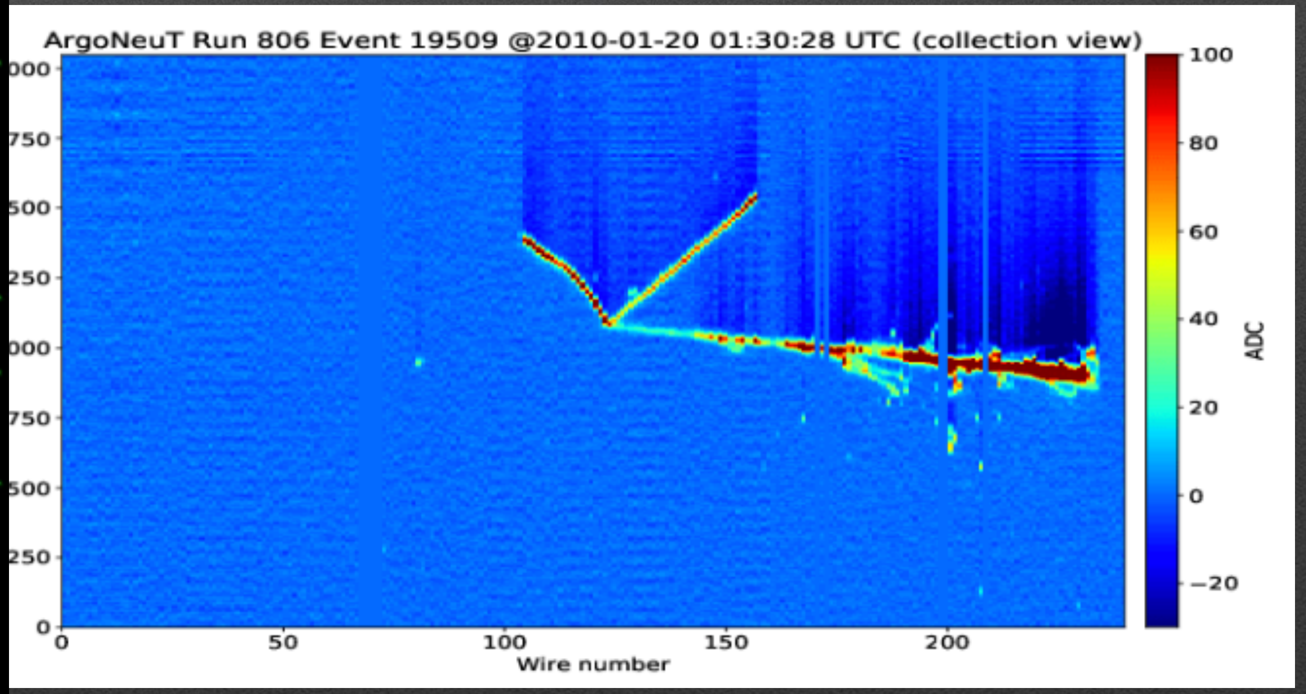
Plastic Scintillator



Nuclear emulsions

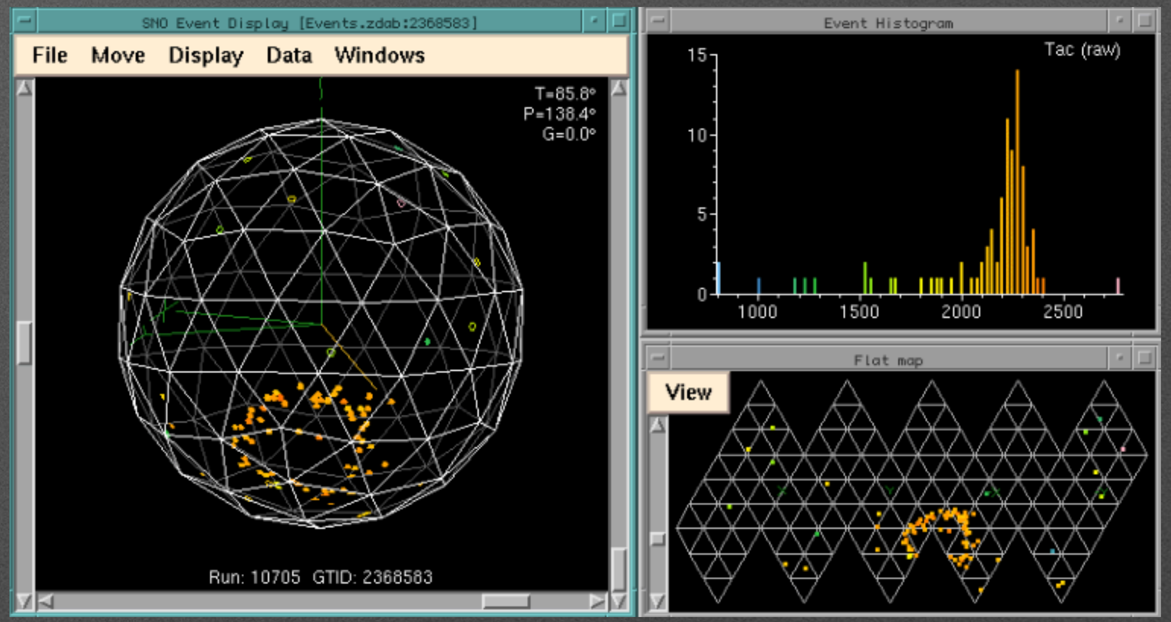


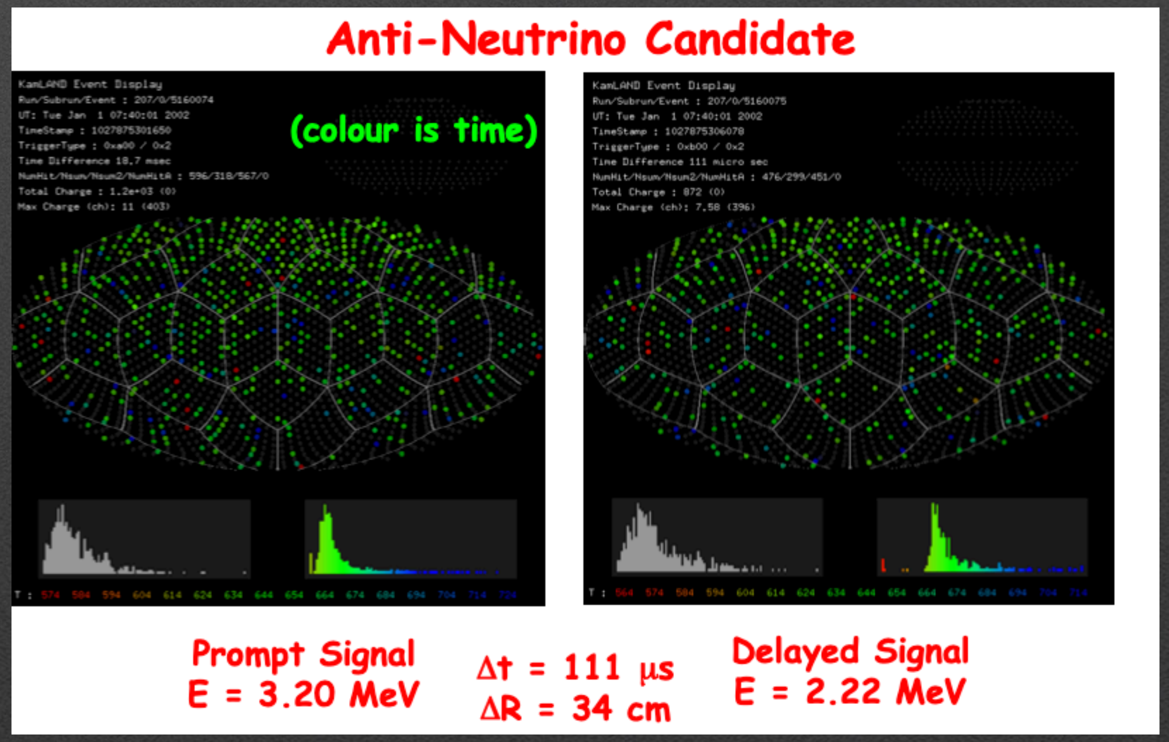
Liquid Argon



Solar and reactors (~MeV)
~ 100 ton detectors

Cherenkov in Water





Liquid Scintillators with
Delayed neutron capture

Experimental review of Neutrino ~~Physics~~ Oscillations

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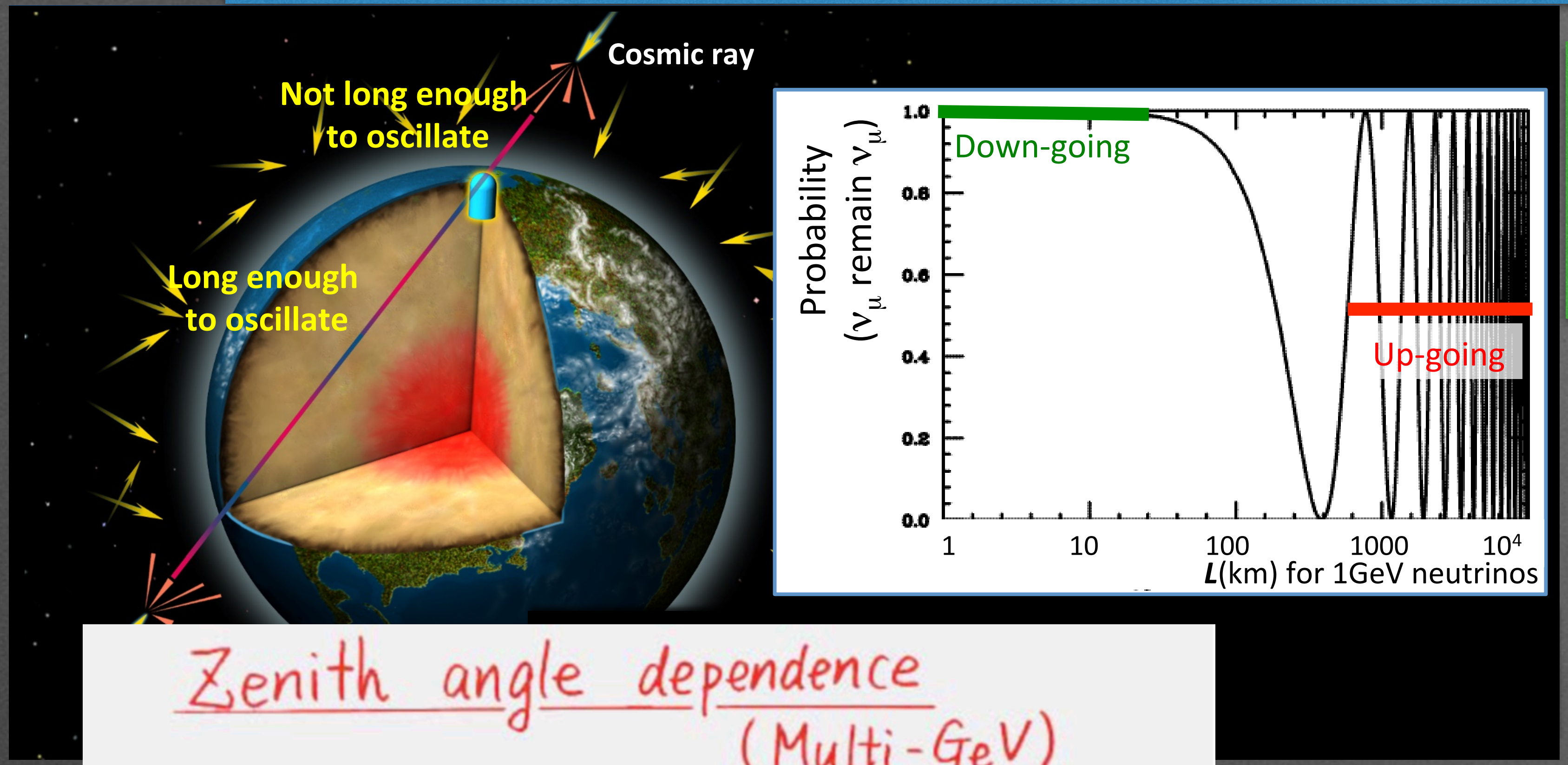
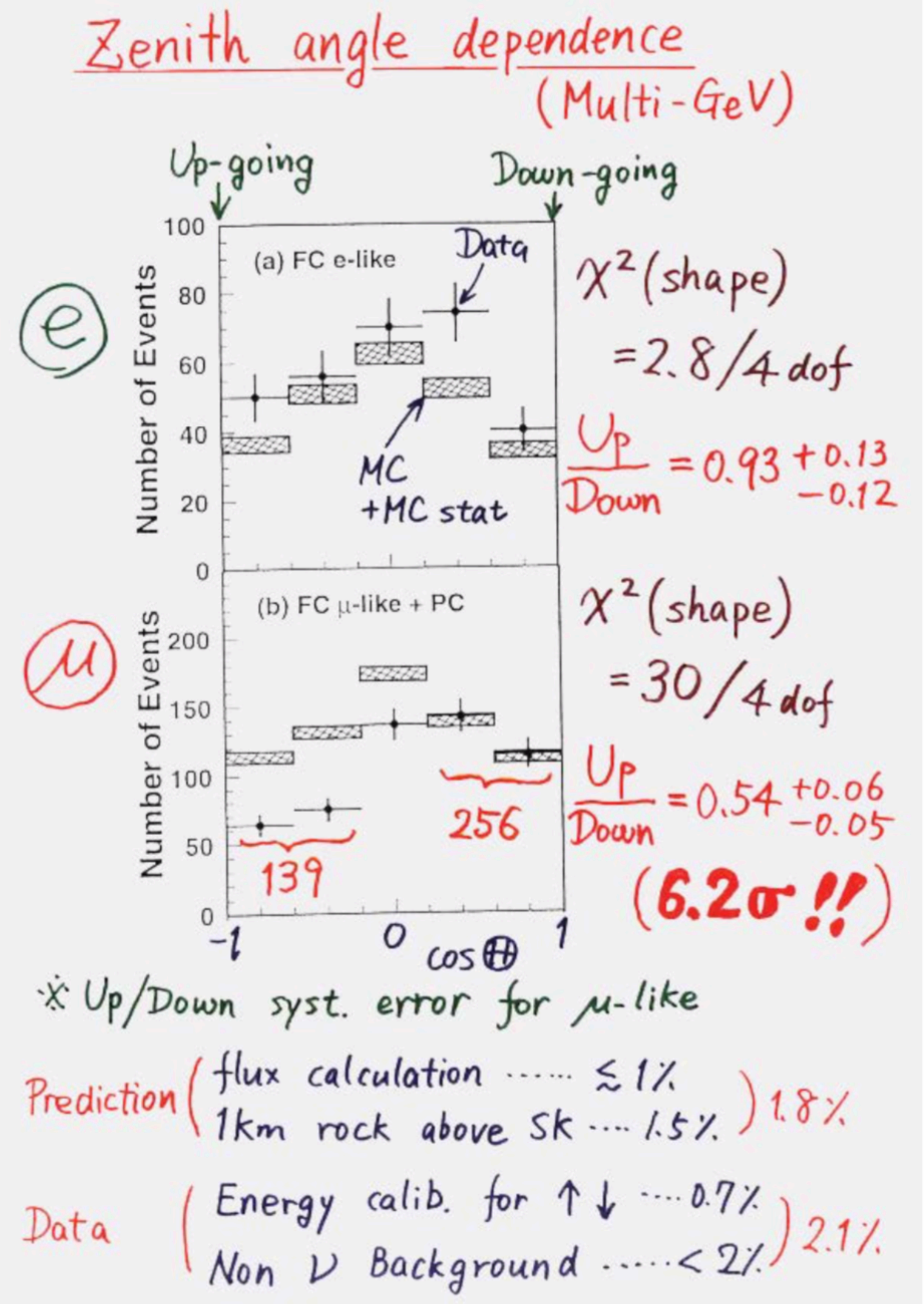
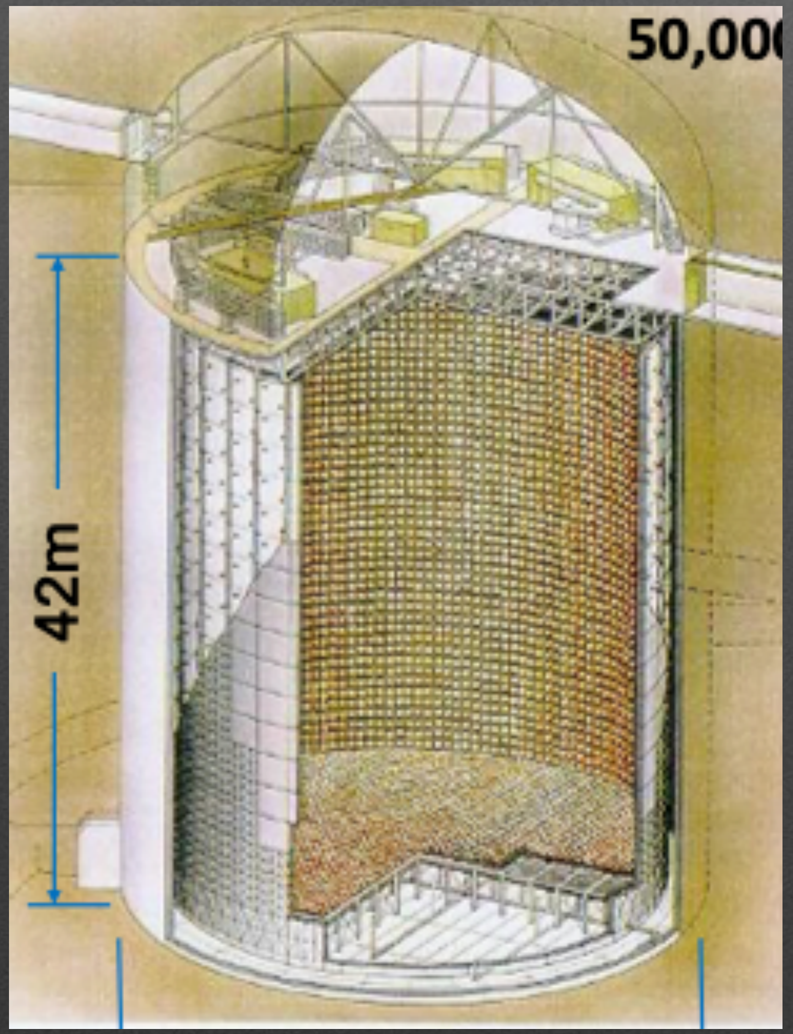
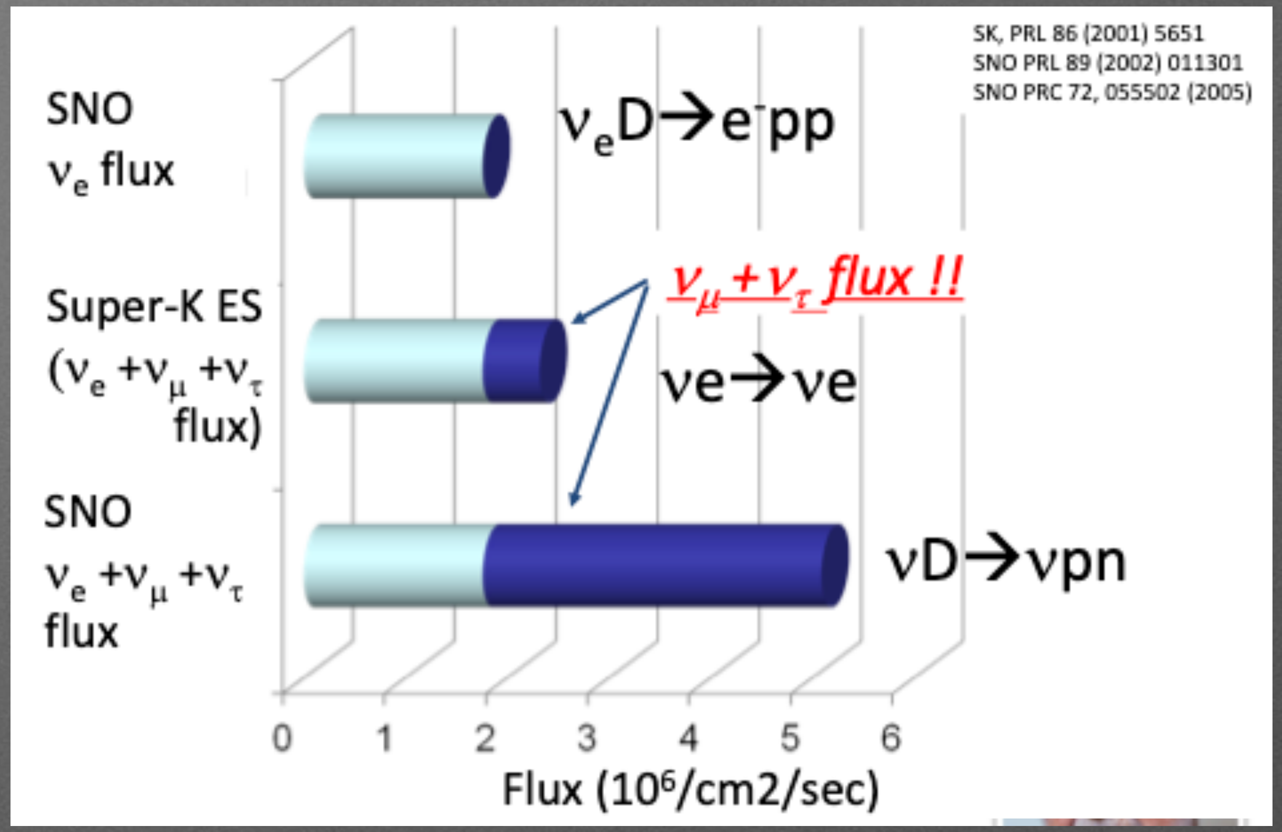
Discovery of ν oscillations



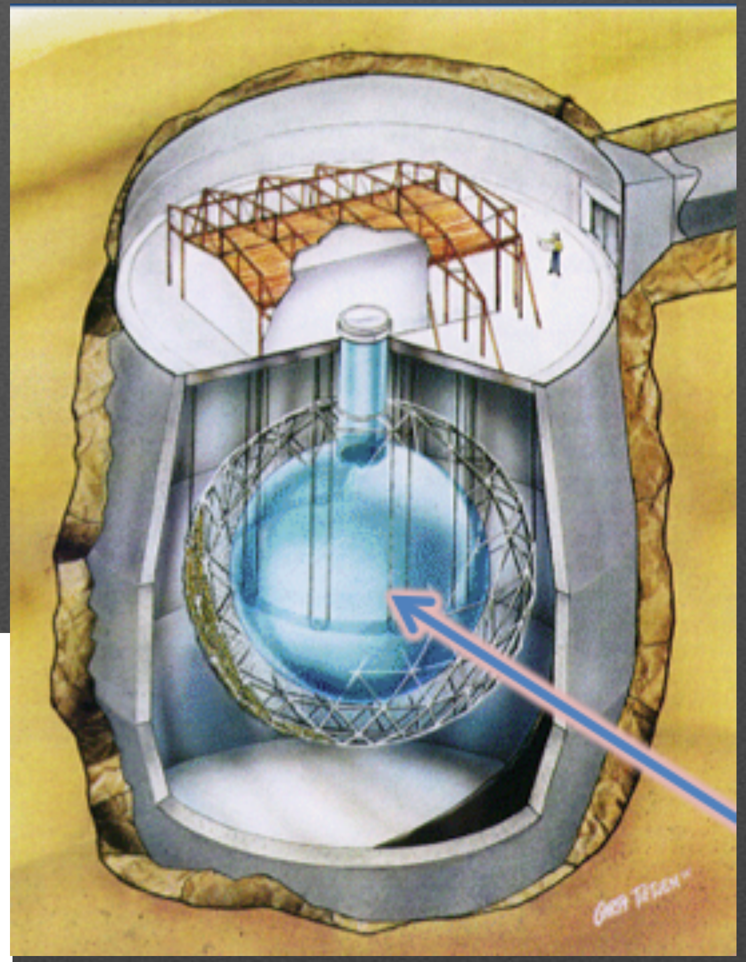
Super-K 1998

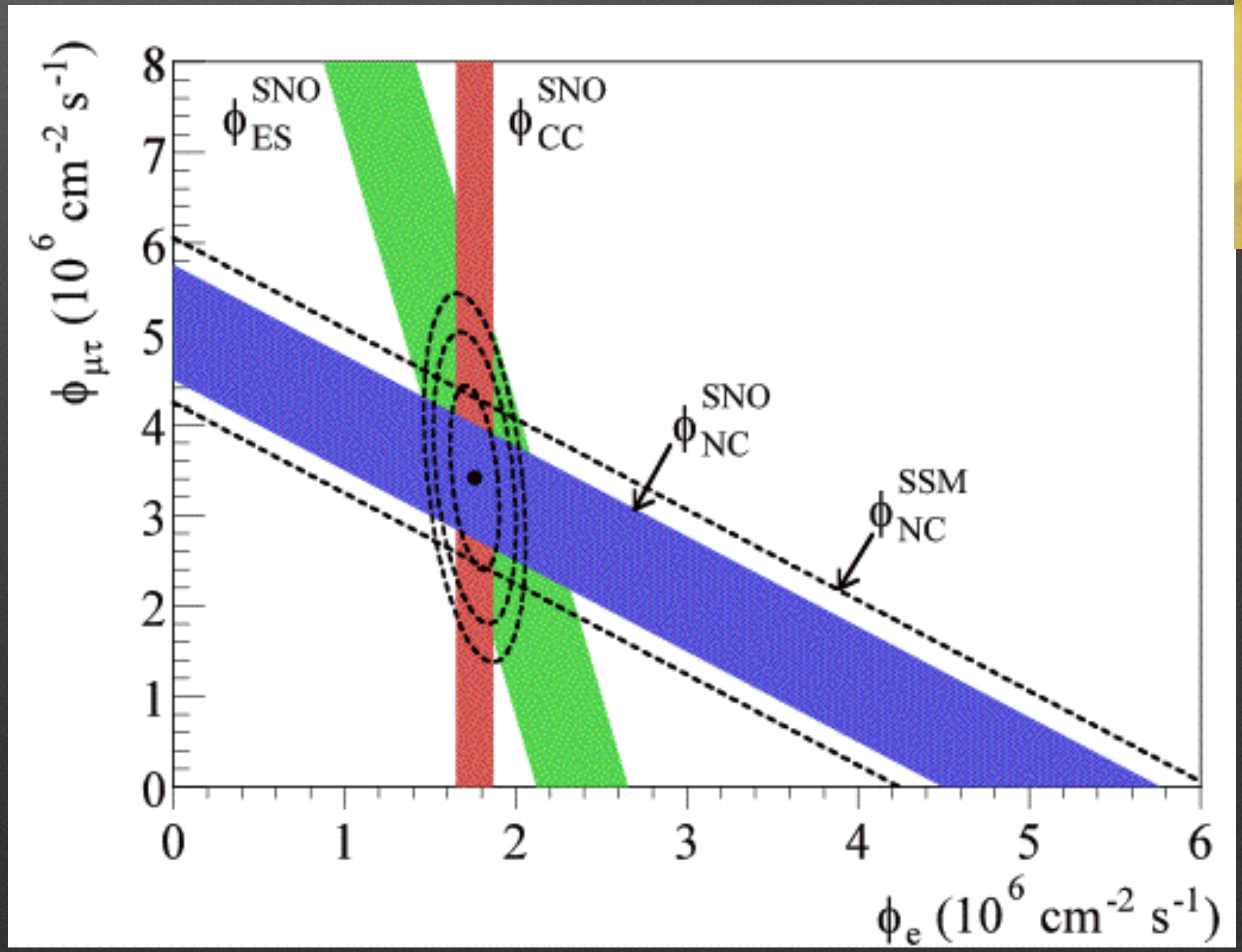






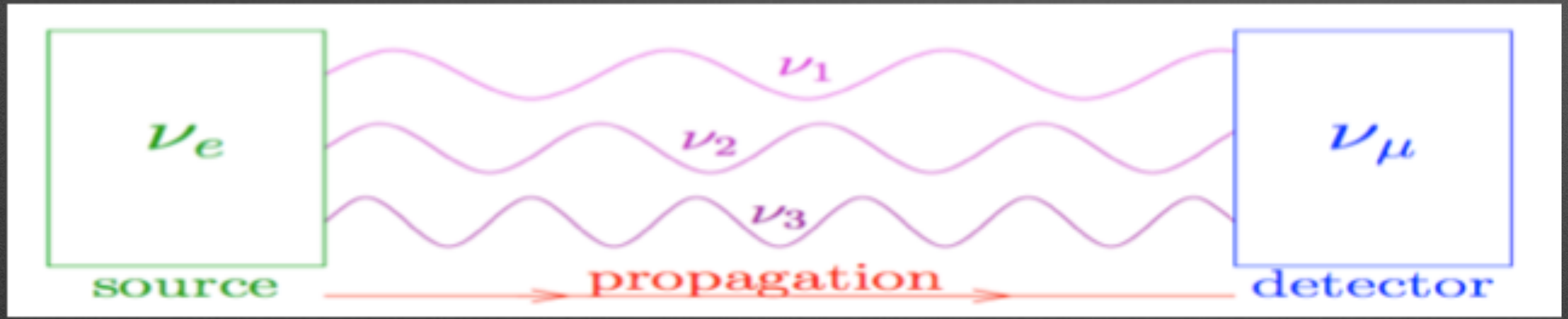
SNO 2002





Neutrino oscillations

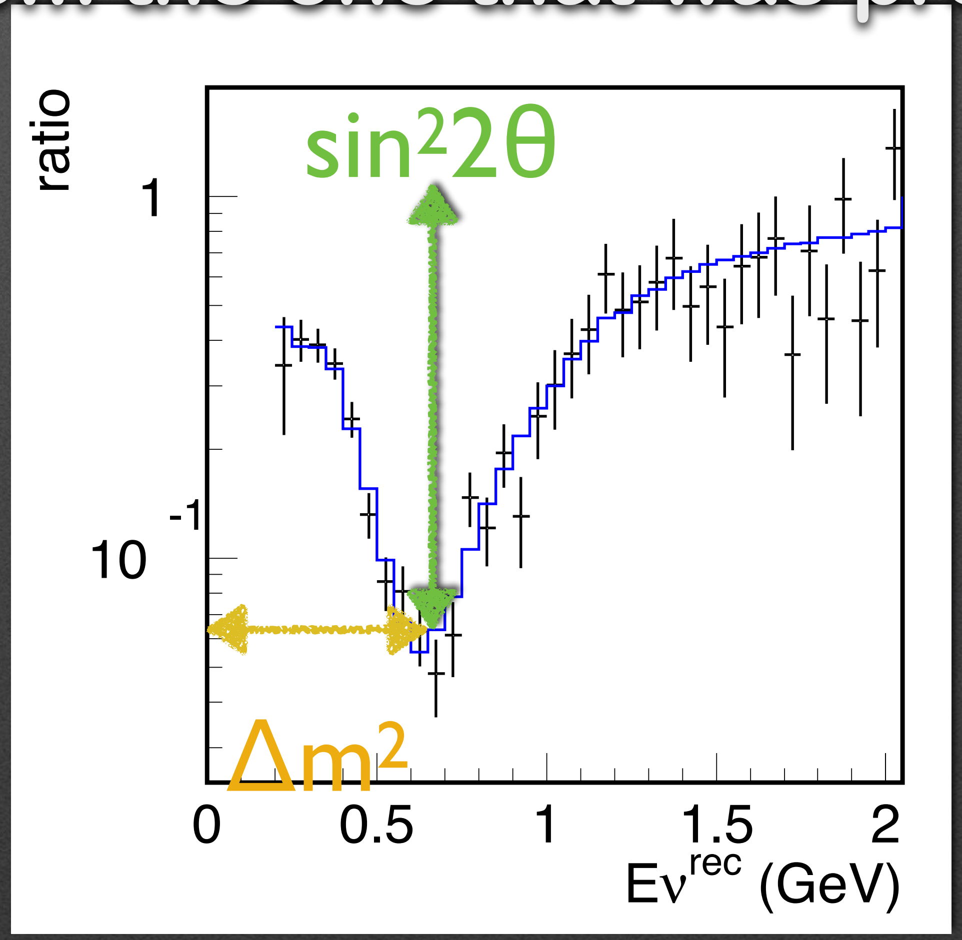
- First introduced by Bruno Pontecorvo in 1957
- Neutrinos are produced in flavor eigenstates (ν_μ, ν_e, ν_τ) that are linear combination of mass eigenstates (ν_1, ν_2, ν_3)
- Neutrino propagate as mass eigenstates
- At the detection a flavor eigenstate is detected → it can be different from the one that was produced



ν_e produced in a mixture of ν_1, ν_2, ν_3

ν_1, ν_2, ν_3 travel at different speed because they have different masses → interference

Different mixture of ν_1, ν_2, ν_3 → ν_μ is detected

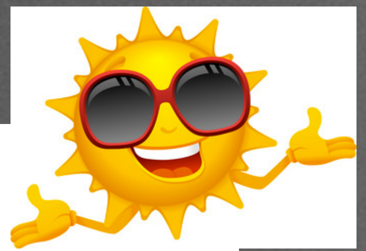


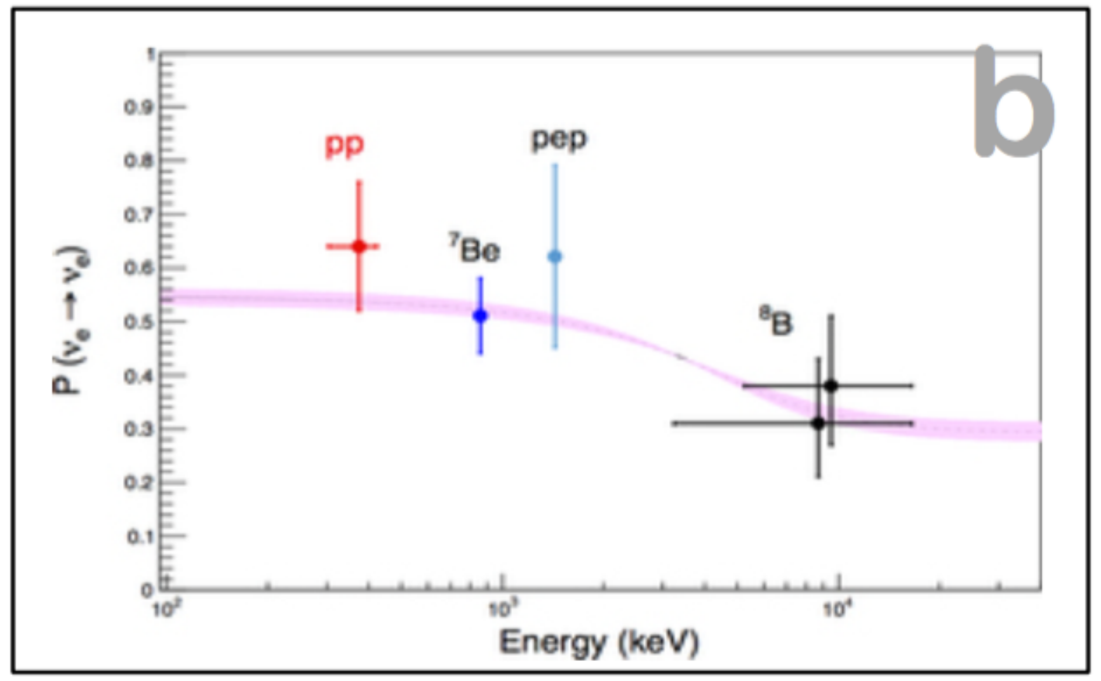
Neutrino oscillation implies massive neutrinos

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2(\Delta m^2_{12} L/E)$$

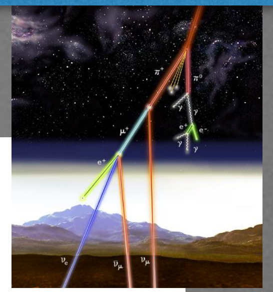
How neutrino oscillations looks like in an experiment

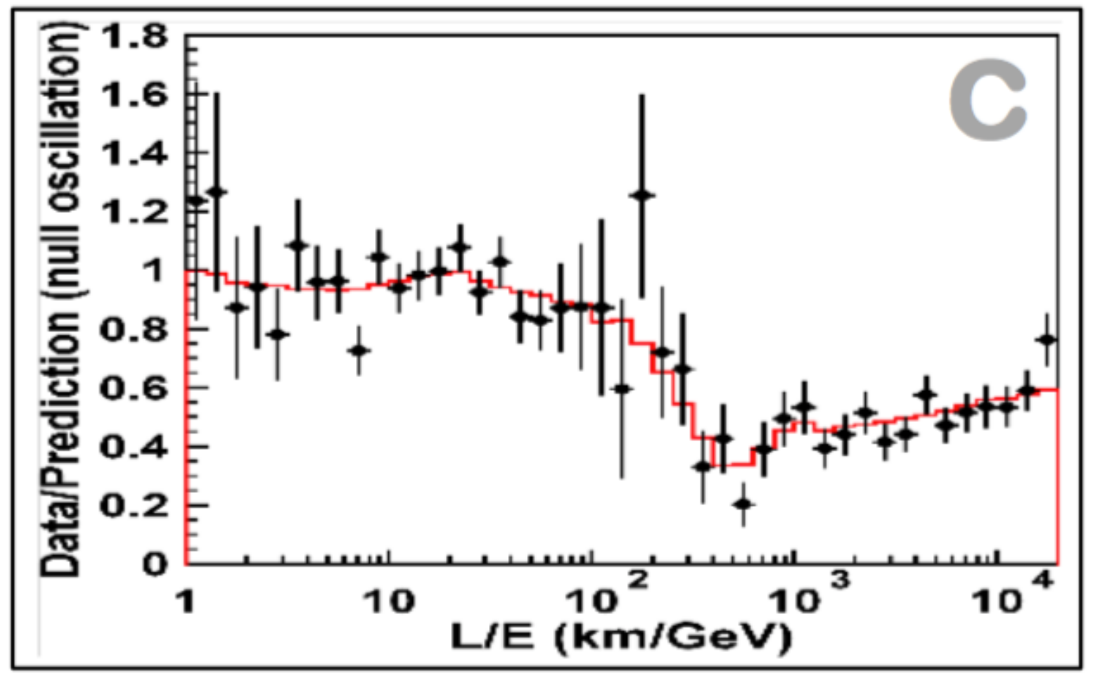
$e \rightarrow e$ (δm^2 , θ_{12})

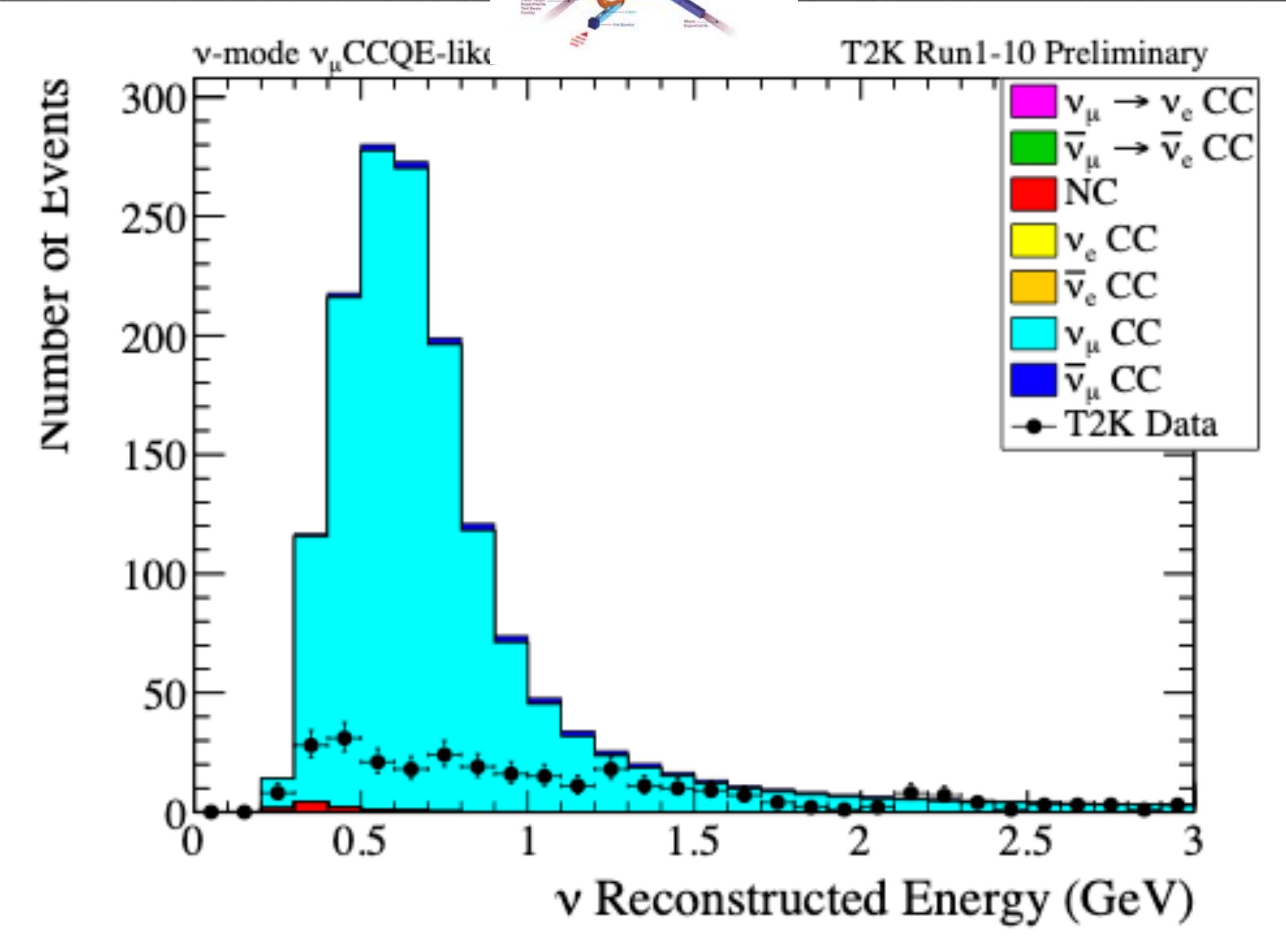




$\mu \rightarrow \mu$ (Δm^2 , θ_{23})







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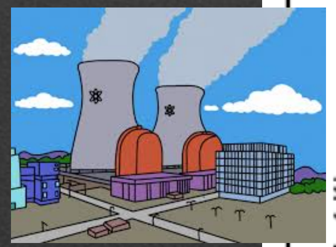
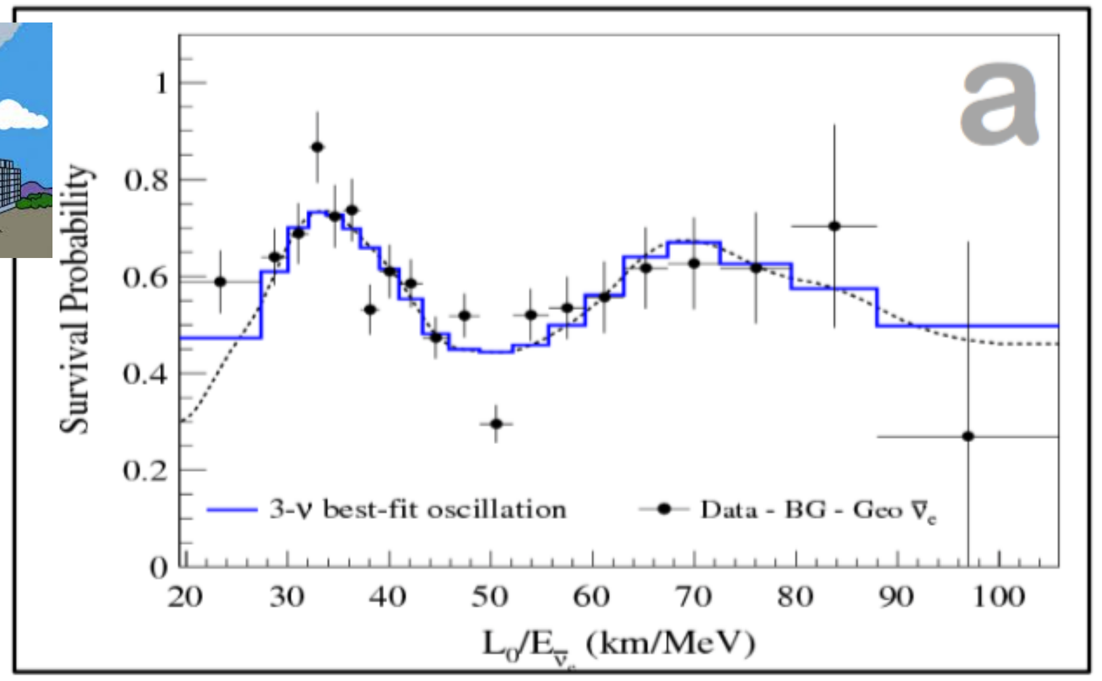
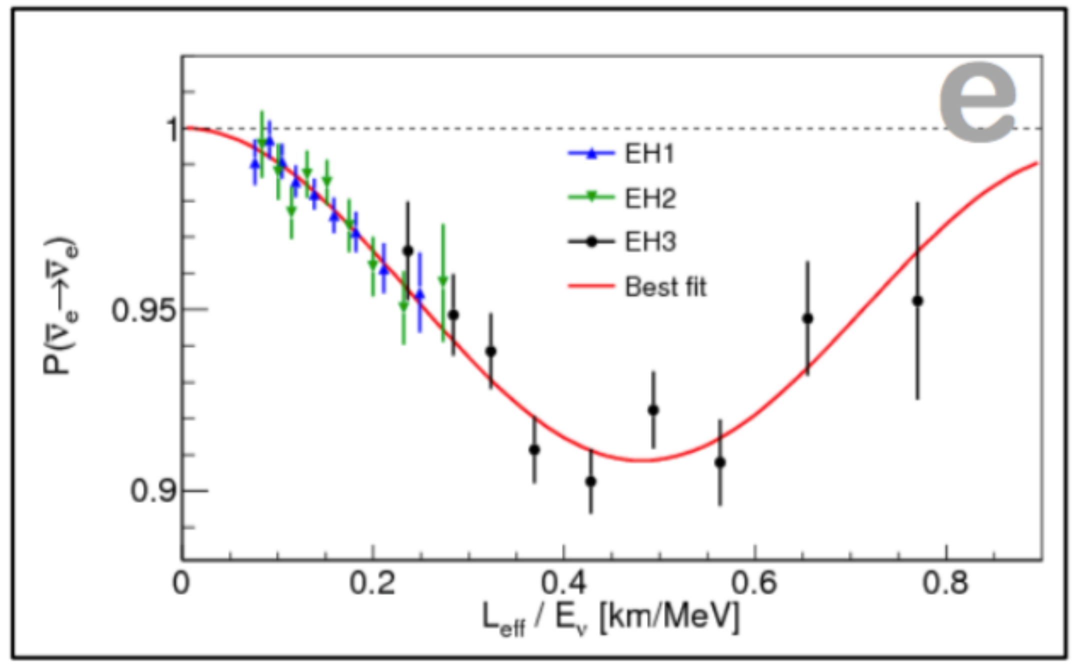
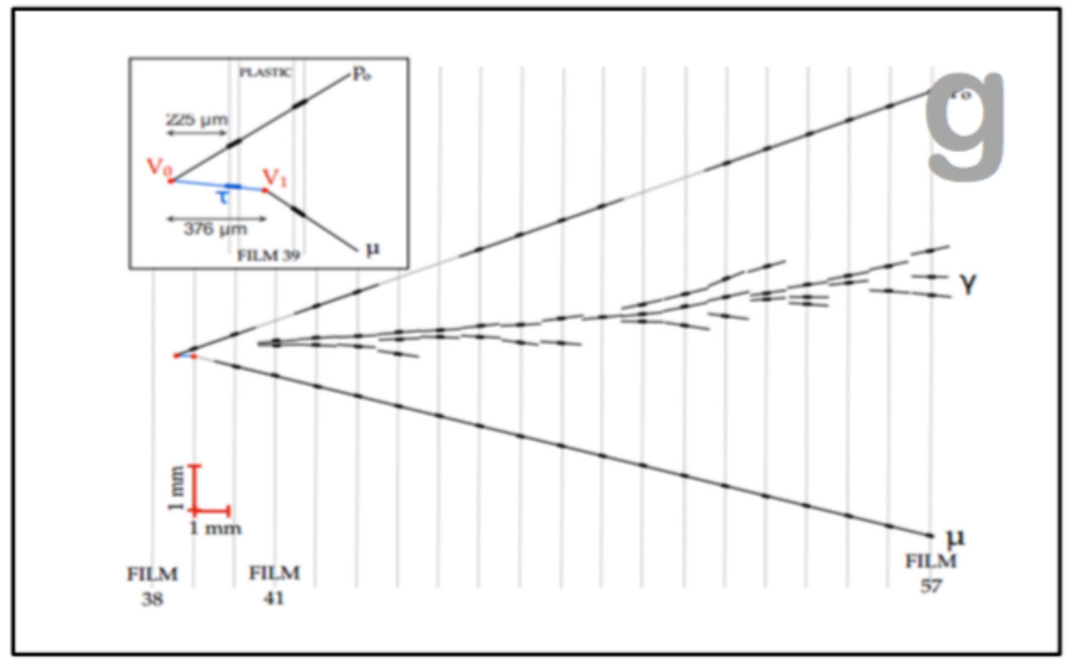




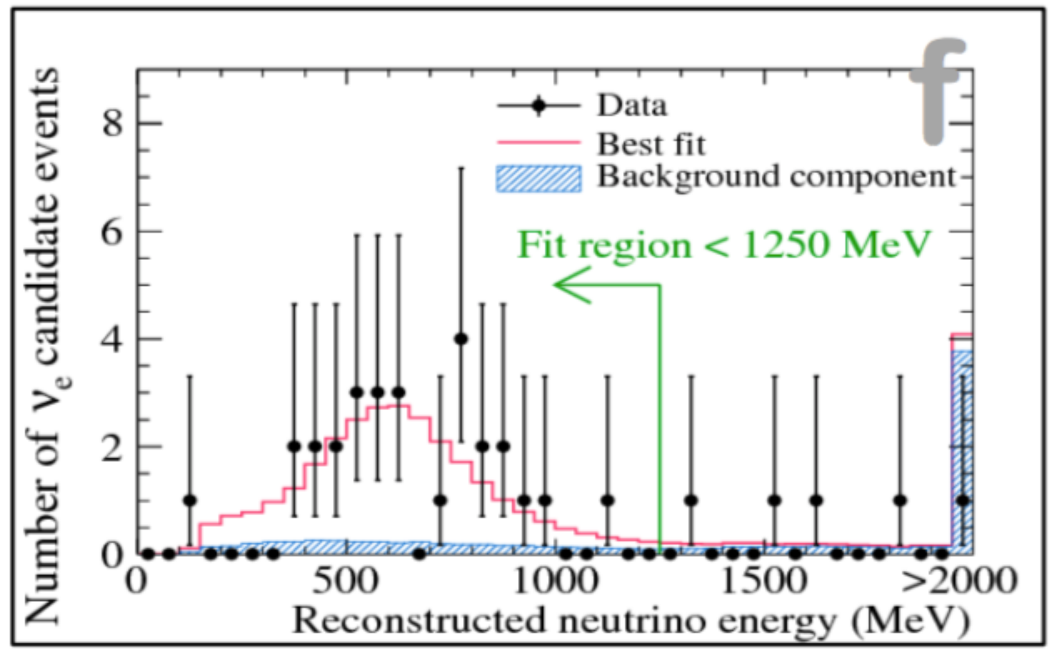
$e \rightarrow e$ (Δm^2 , θ_{13})



$\mu \rightarrow \tau$ (Δm^2 , θ_{23})

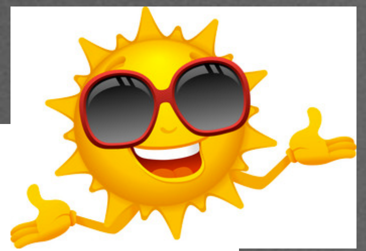


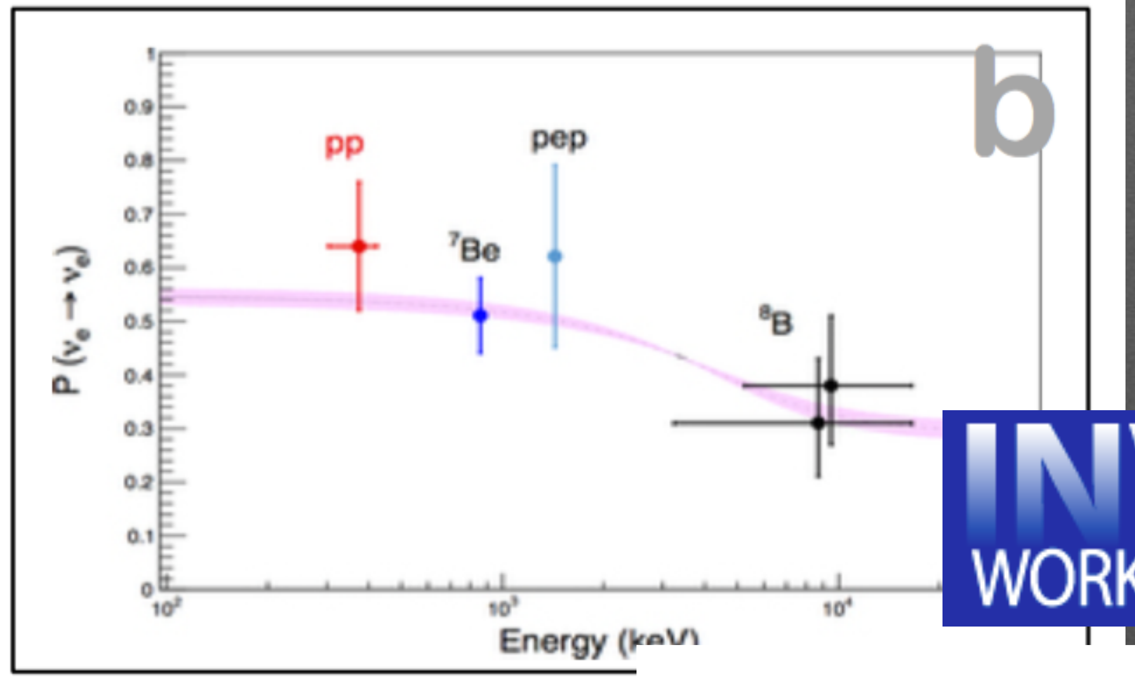
$\mu \rightarrow e$ (Δm^2 , θ_{13} , θ_{23})



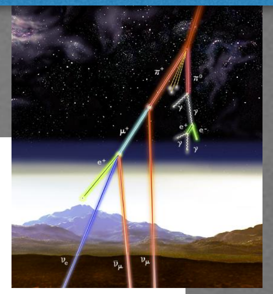
How neutrino oscillations looks like in an experiment

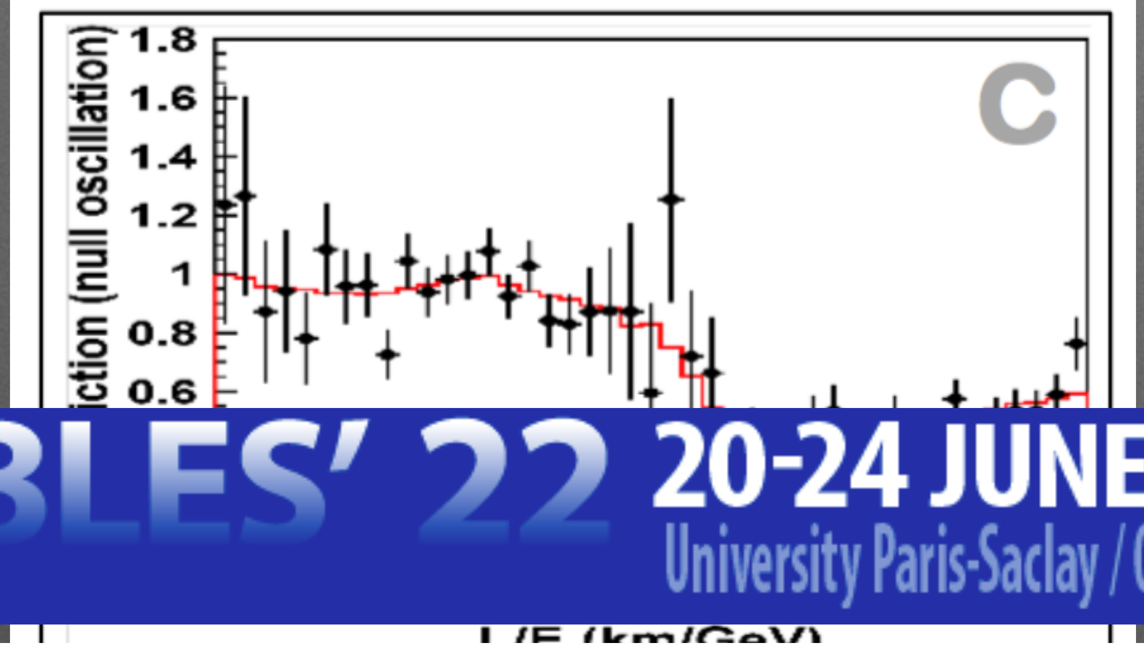
$e \to e$ (δm^2 , θ_{12})

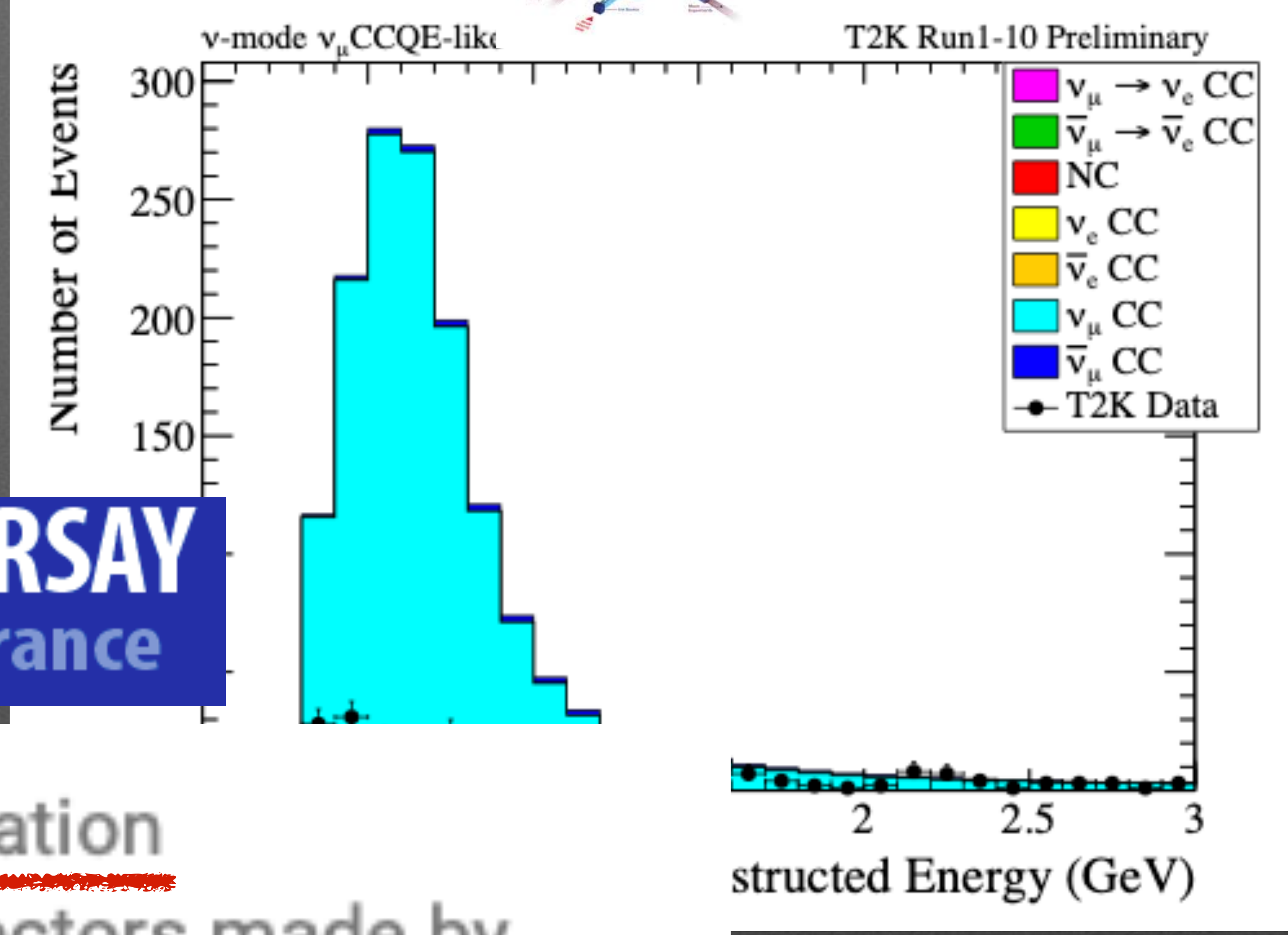




$\mu \to \mu$ (Δm^2 , θ_{23})







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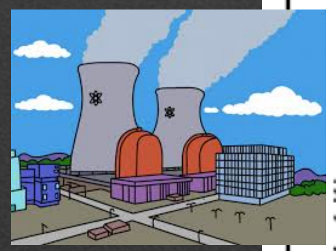
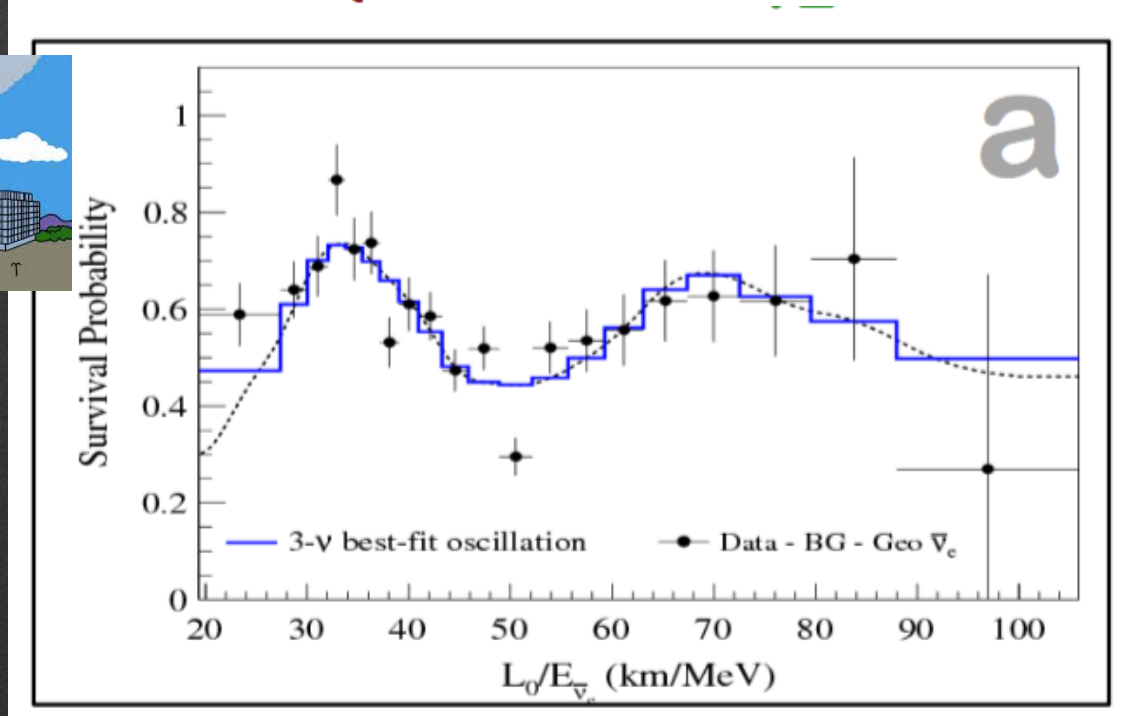
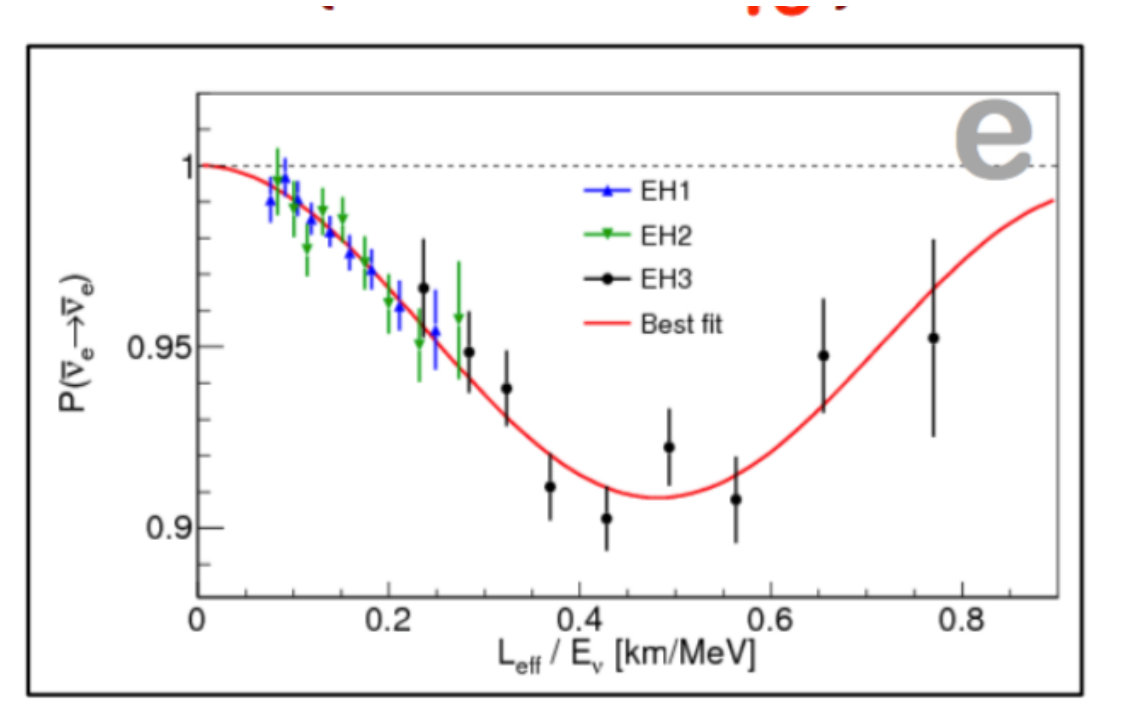
The focus of the workshop will be on revealing new sources of CP-violation and (a)symmetries yet to be discovered, in particular, in the invisible sectors made by neutrinos, dark matter and other hidden particles. The interplay with cosmological and

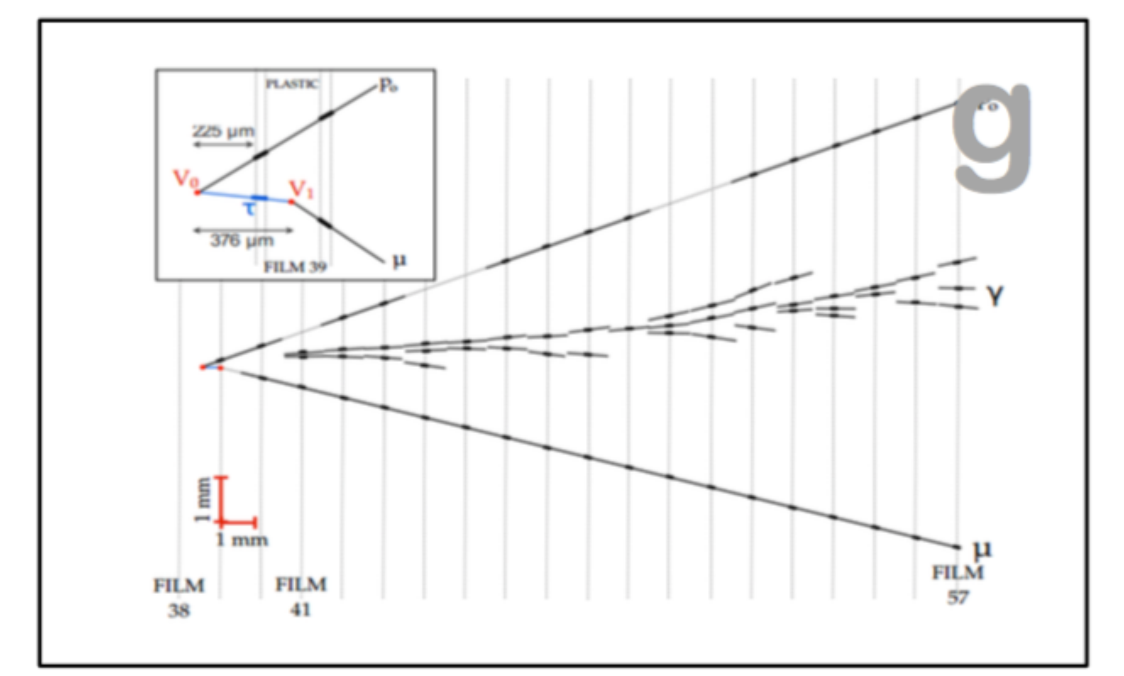
$e \to e$ (δm



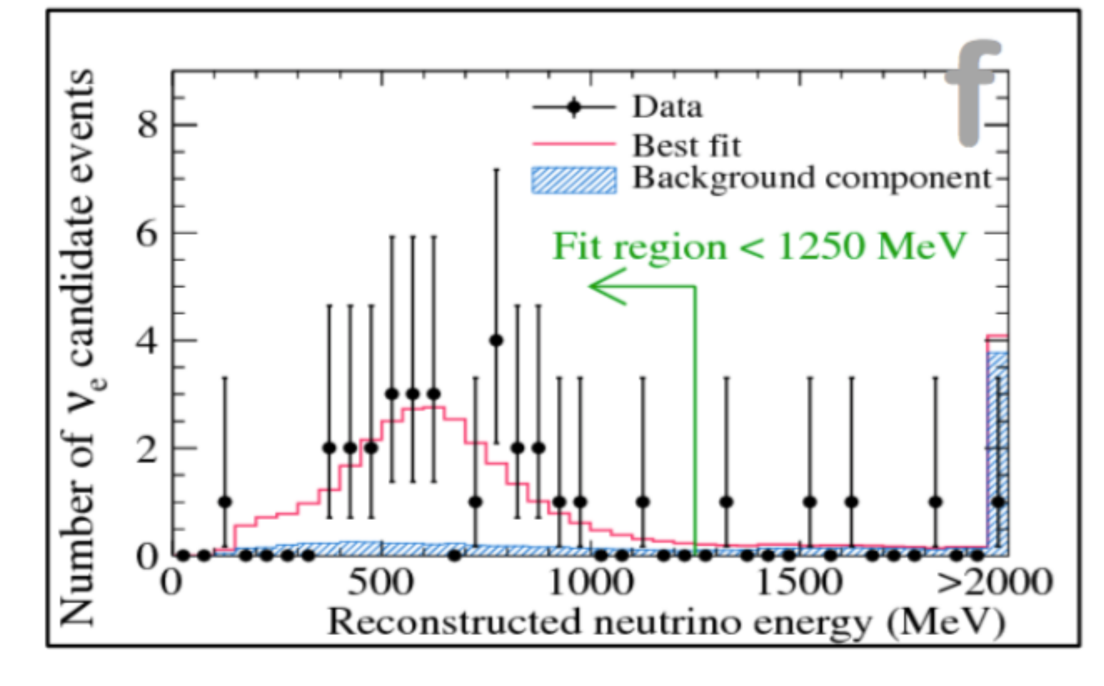




$\mu \to \tau$ (Δm^2 , θ_{23})



$\mu \to e$ (Δm^2 , θ_{13} , θ_{23})



Neutrino oscillations and the quest for CP violation

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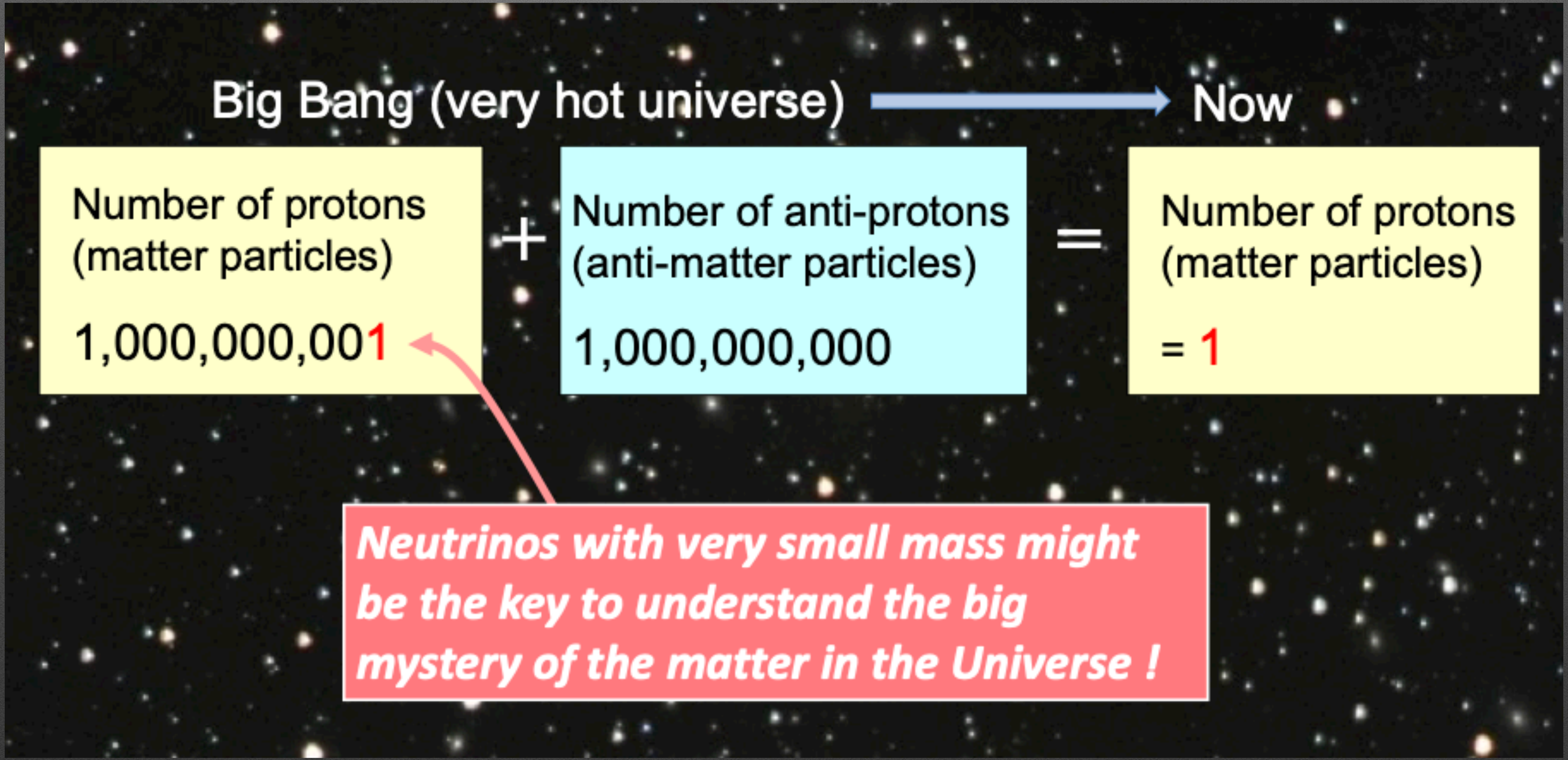
Why CP violation in neutrinos ?

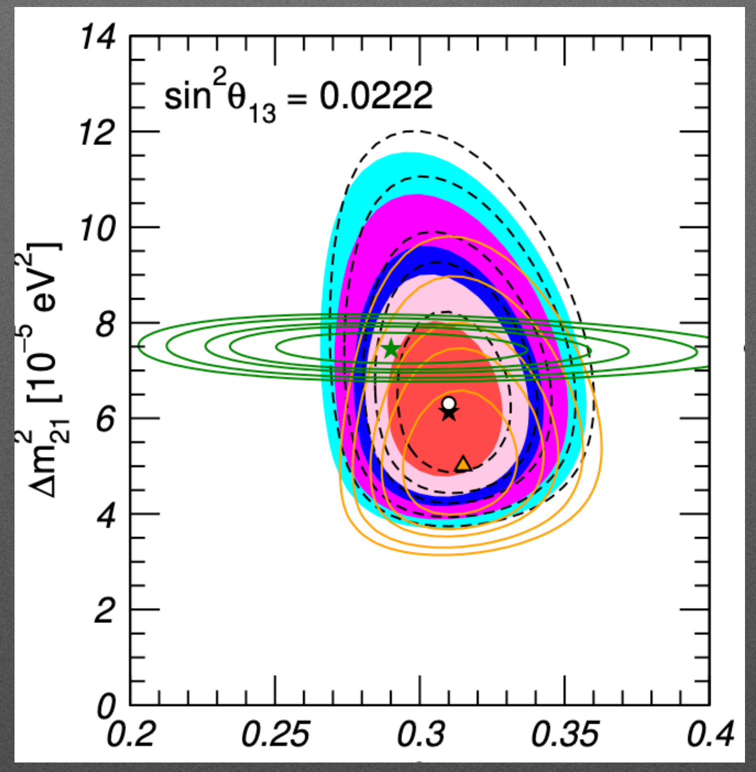


- δ_{CP} is one of the few unknown parameters in the SM (together with the values of the neutrino masses)
- CP violation in the leptonic sector would be an indication in favor of the leptogenesis
    - In some models of the leptogenesis the baryon asymmetry in the Universe could be produced by large values of δ_{CP}

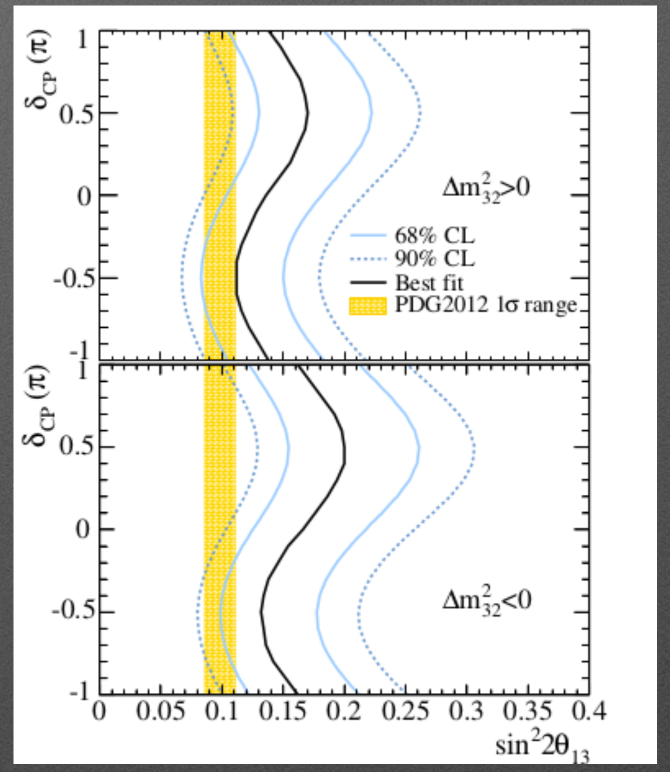
What do we need?

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

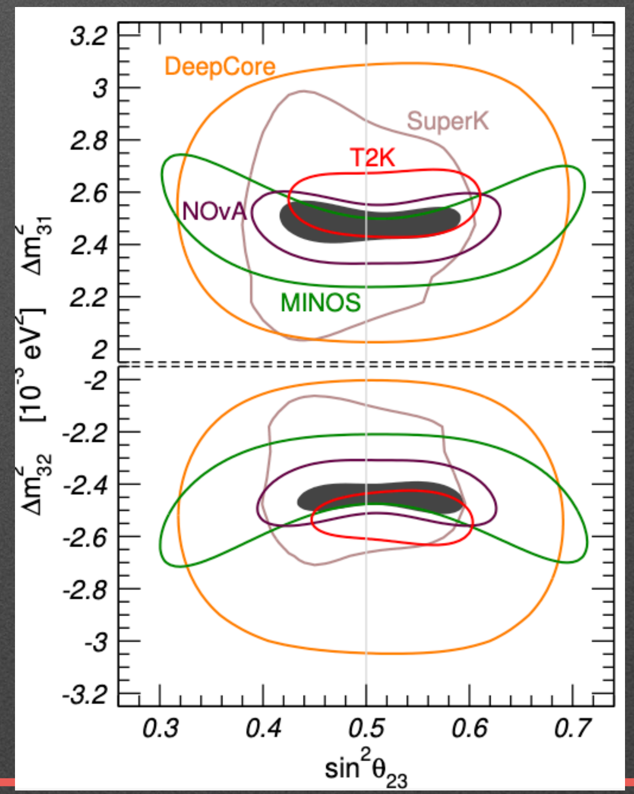
Solar and accelerators → θ_{12}, Δm_{12}



Reactors and accelerators → θ_{13}, δ_{CP}

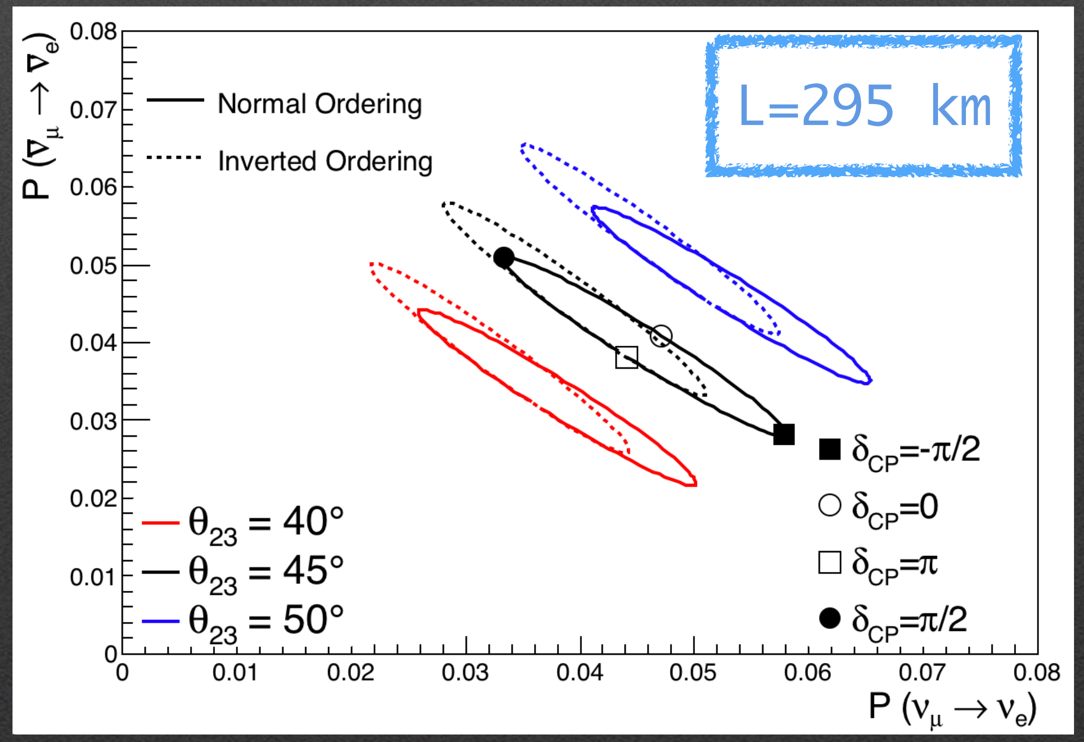


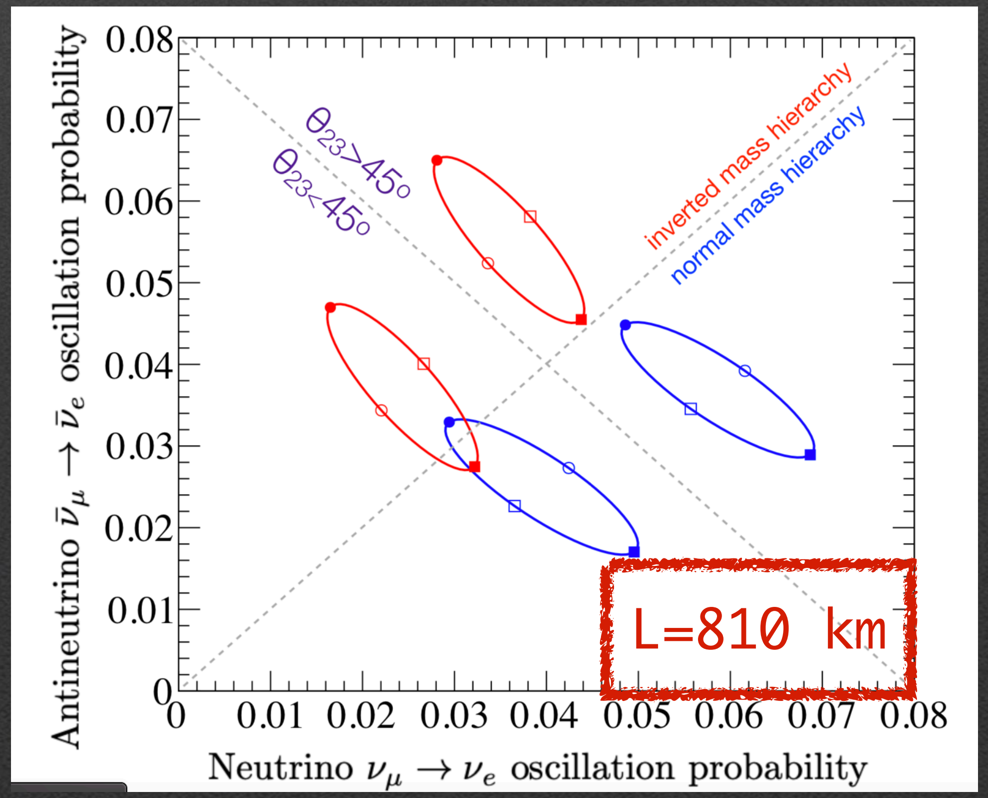
Atmospheric and accelerators → θ_{23}, Δm_{32}



- 3 mixing angles different from zero ☑
- Measure oscillation in appearance mode to access 3 flavor effects ☑
- Compare oscillation probabilities between neutrinos and antineutrinos ☑

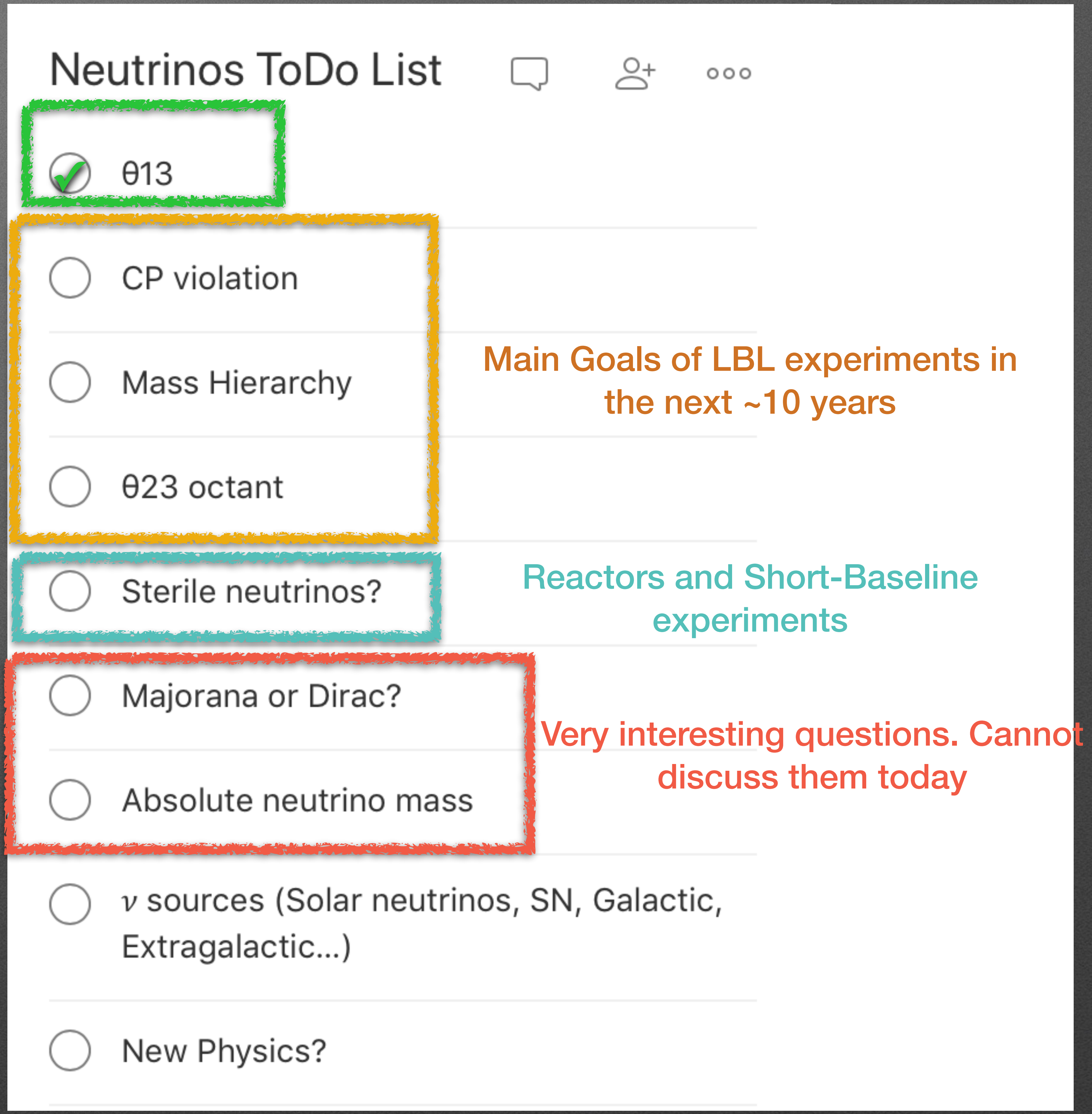
(Just need more precision..)

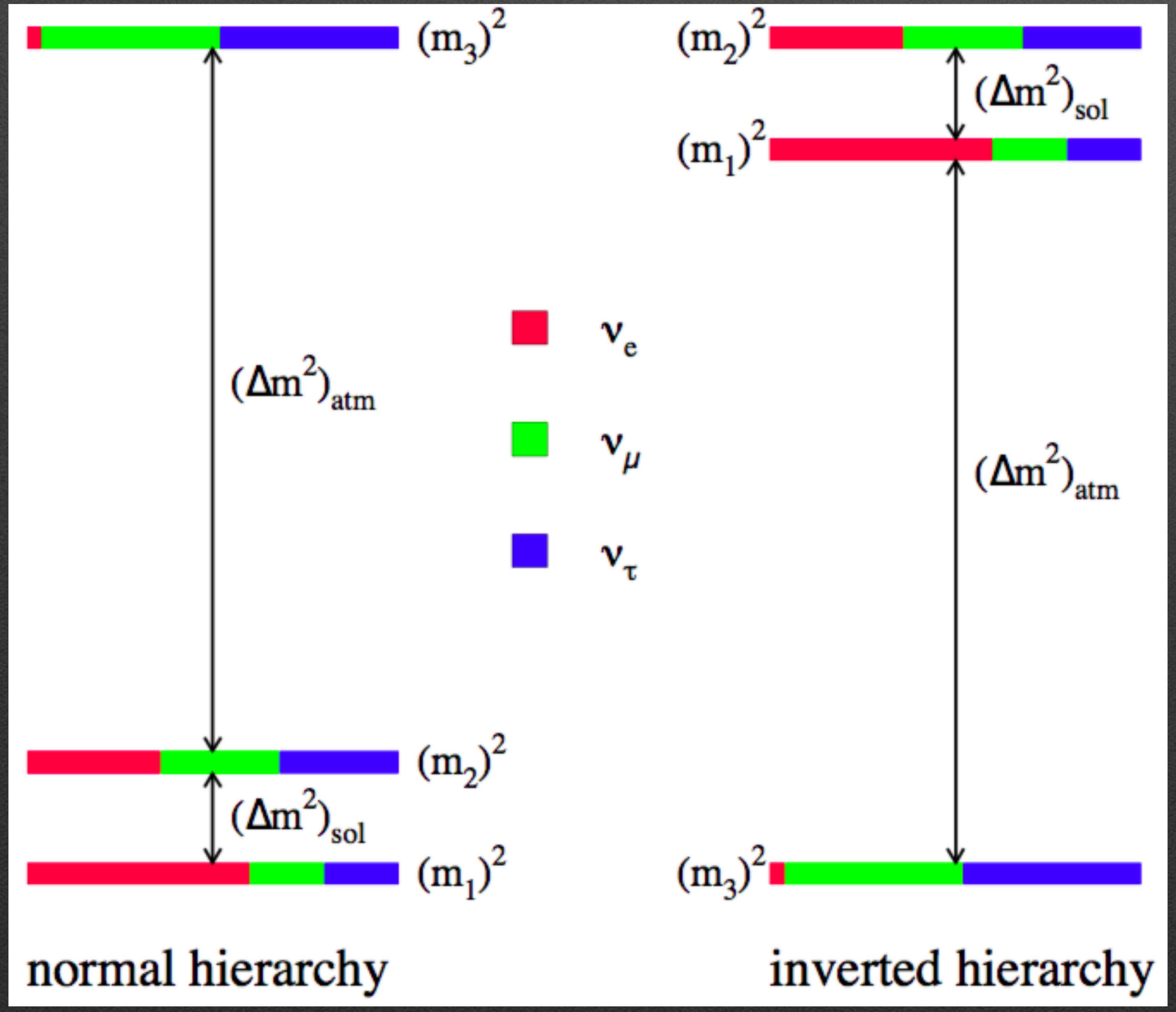


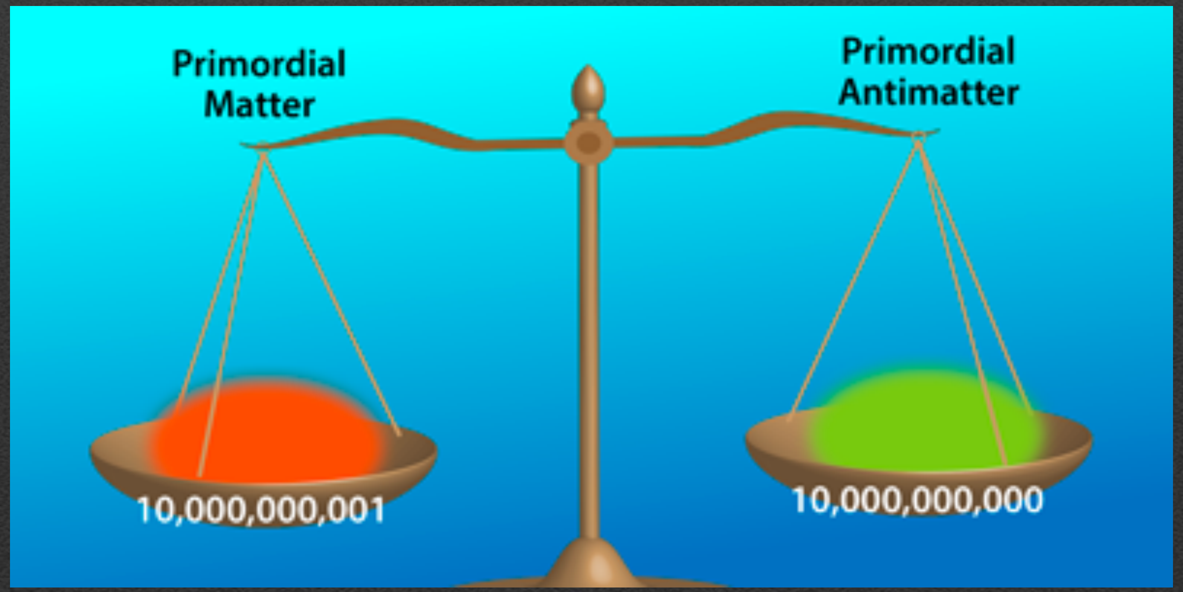


What are we looking for

- Still many open questions related to neutrino oscillations → "guaranteed" measurements
- We also don't know the nature of neutrinos (Dirac or Majorana) and their absolute mass
- Multi-messenger astronomy with neutrinos has started
- New physics (or surprises) and sterile neutrinos?



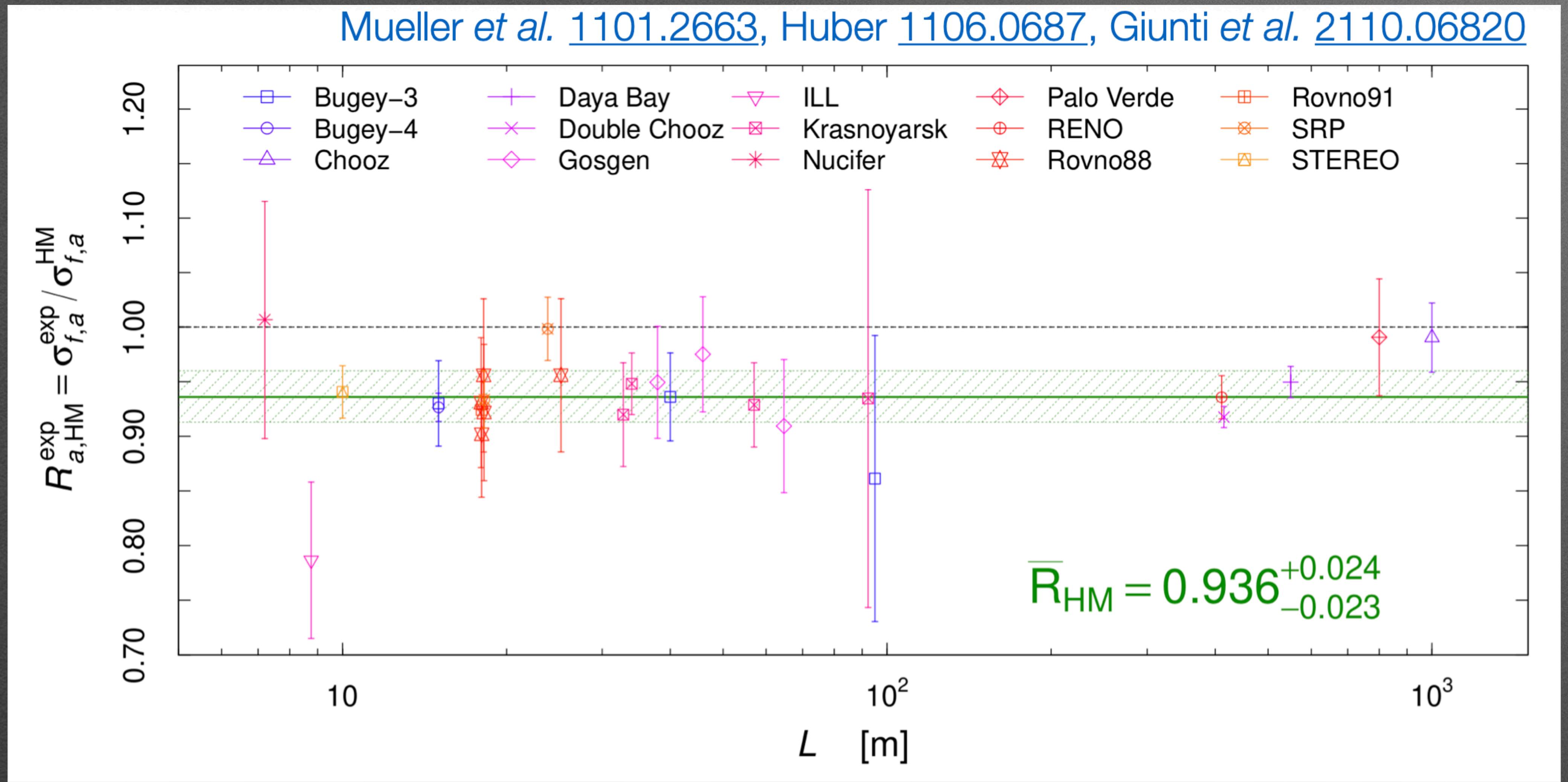




Sterile neutrinos

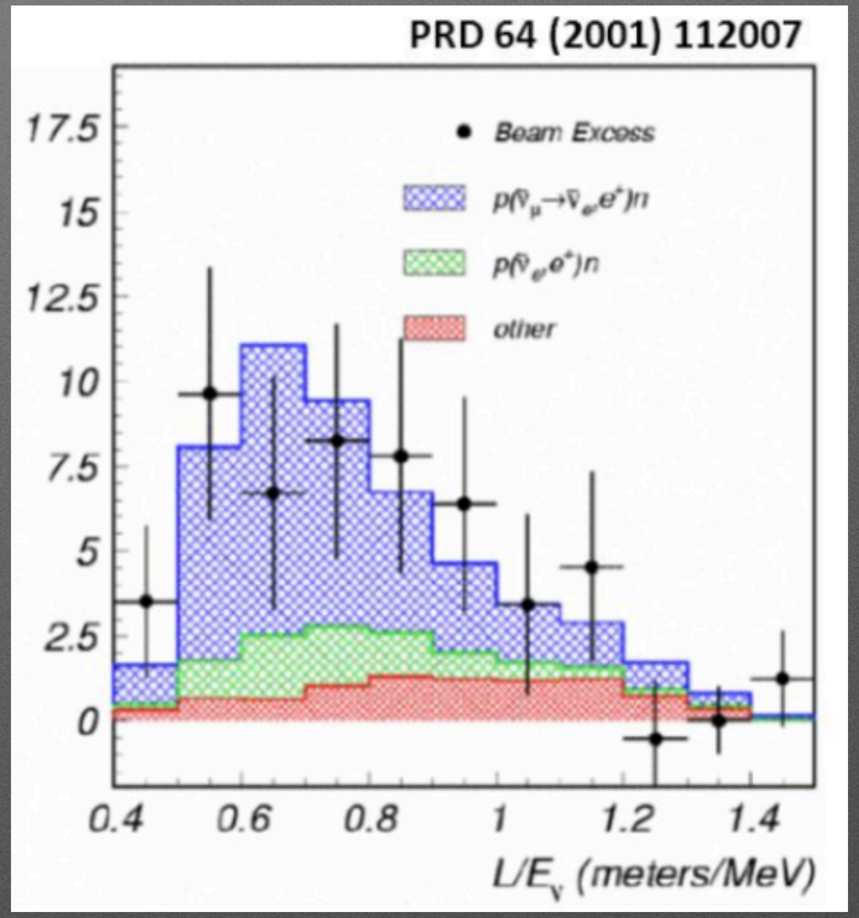
Reactor anomaly

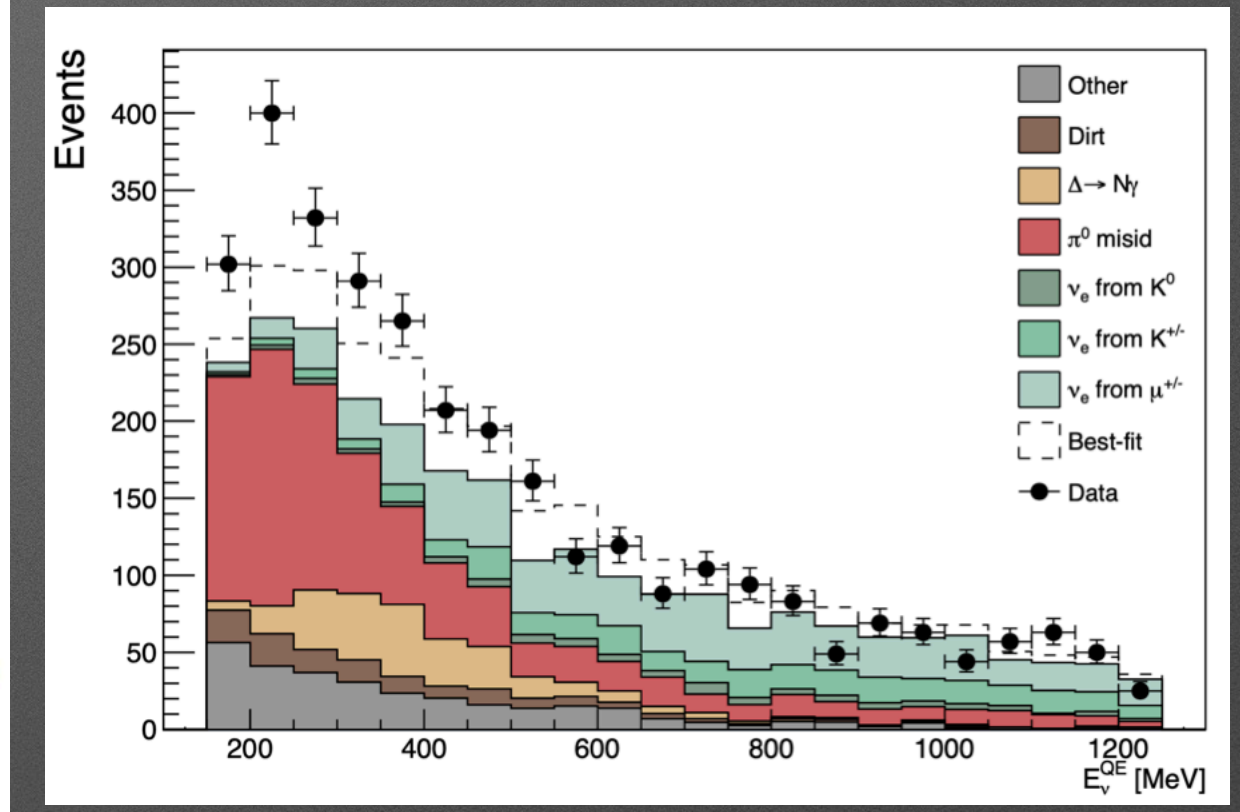
νe disappearance
$\Delta m^2 \sim 1$ eV^2



LSND/MiniBooNE

$\nu\mu \rightarrow \nu e$ appearance
$\Delta m^2 \sim 1$ eV^2



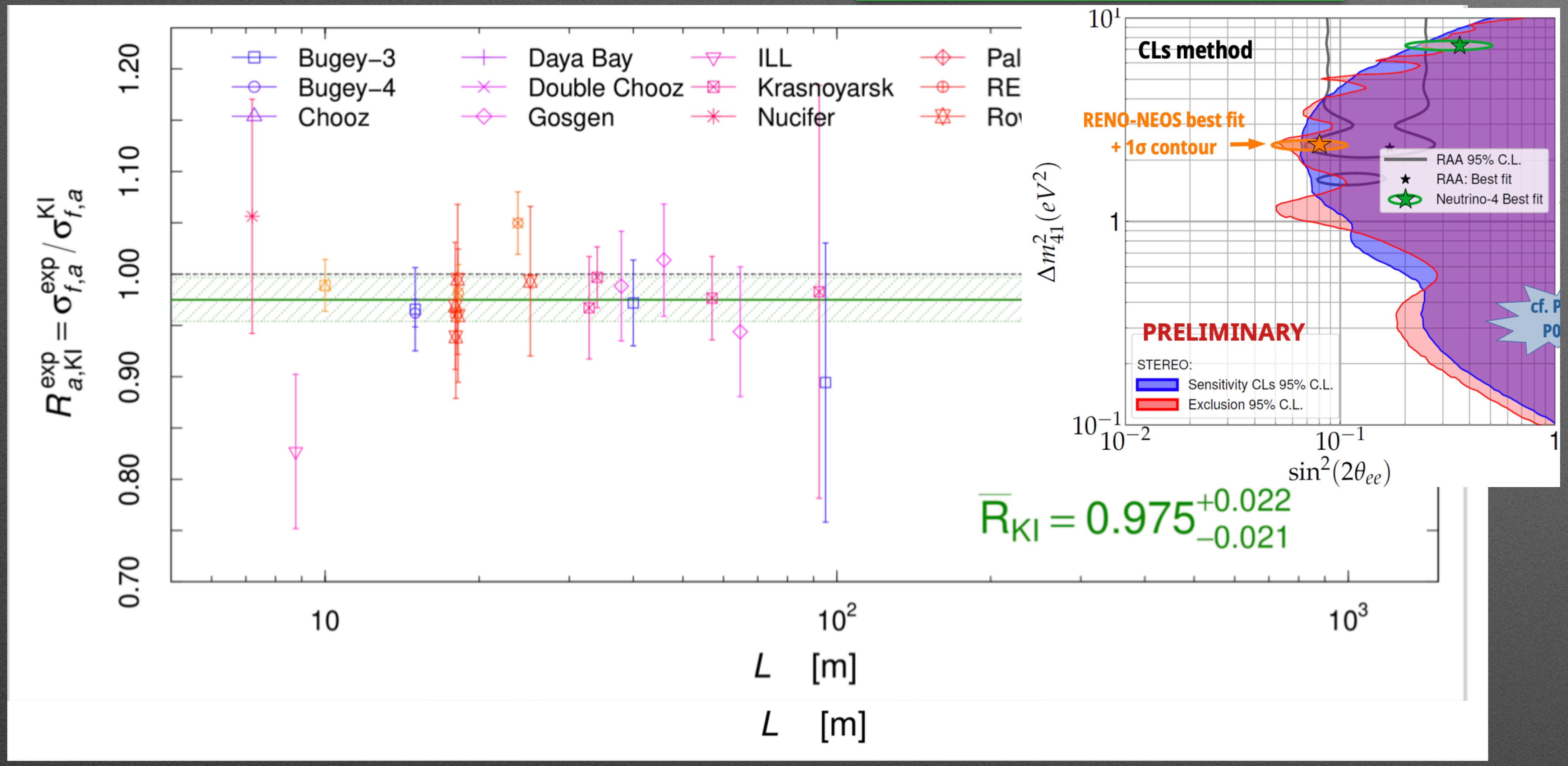


- We know since LEP that it exists 3 families of active neutrinos with mass < Z/2
- 3 flavor framework of ν oscillations is well established with multiple observations using different neutrino sources and detection technology
- It exists however few anomalies that could be explained adding additional “sterile” states

Sterile neutrinos

Reactor anomaly

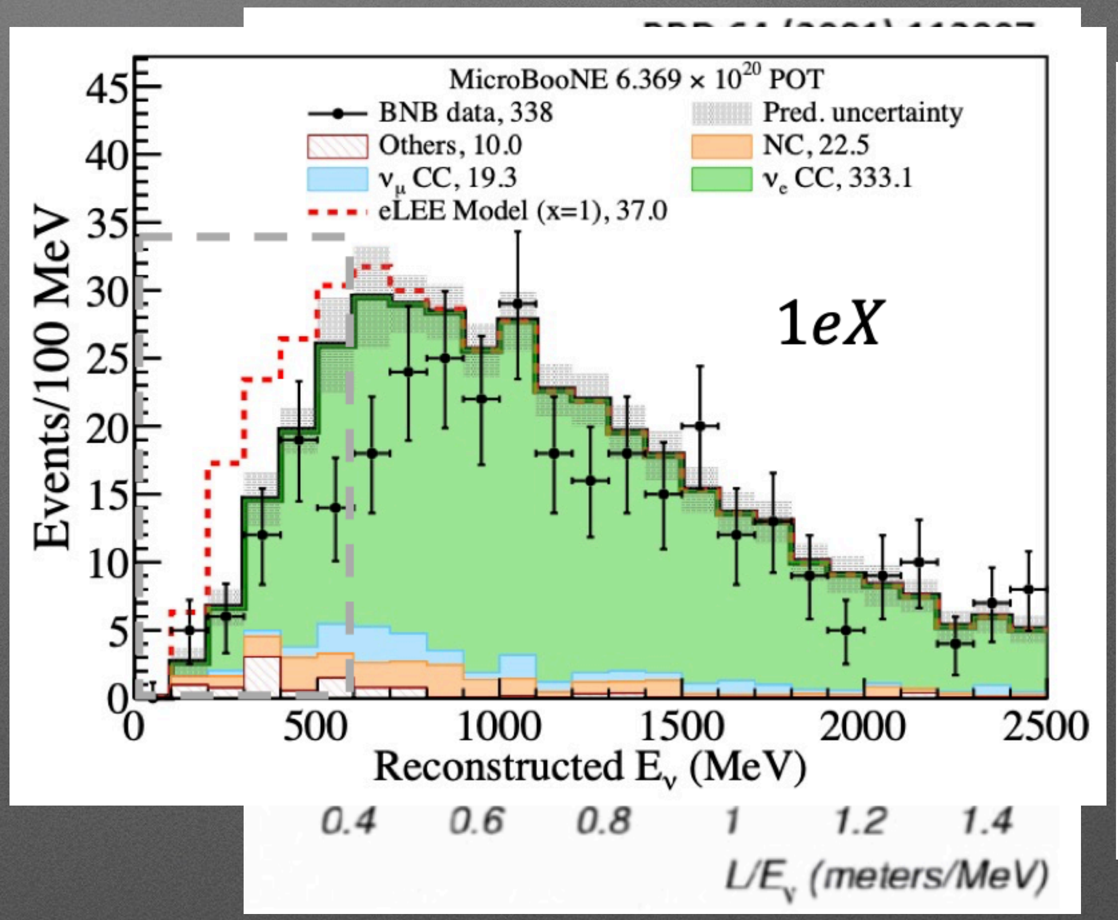
νe disappearance
$\Delta m^2 \sim 1\ eV^2$

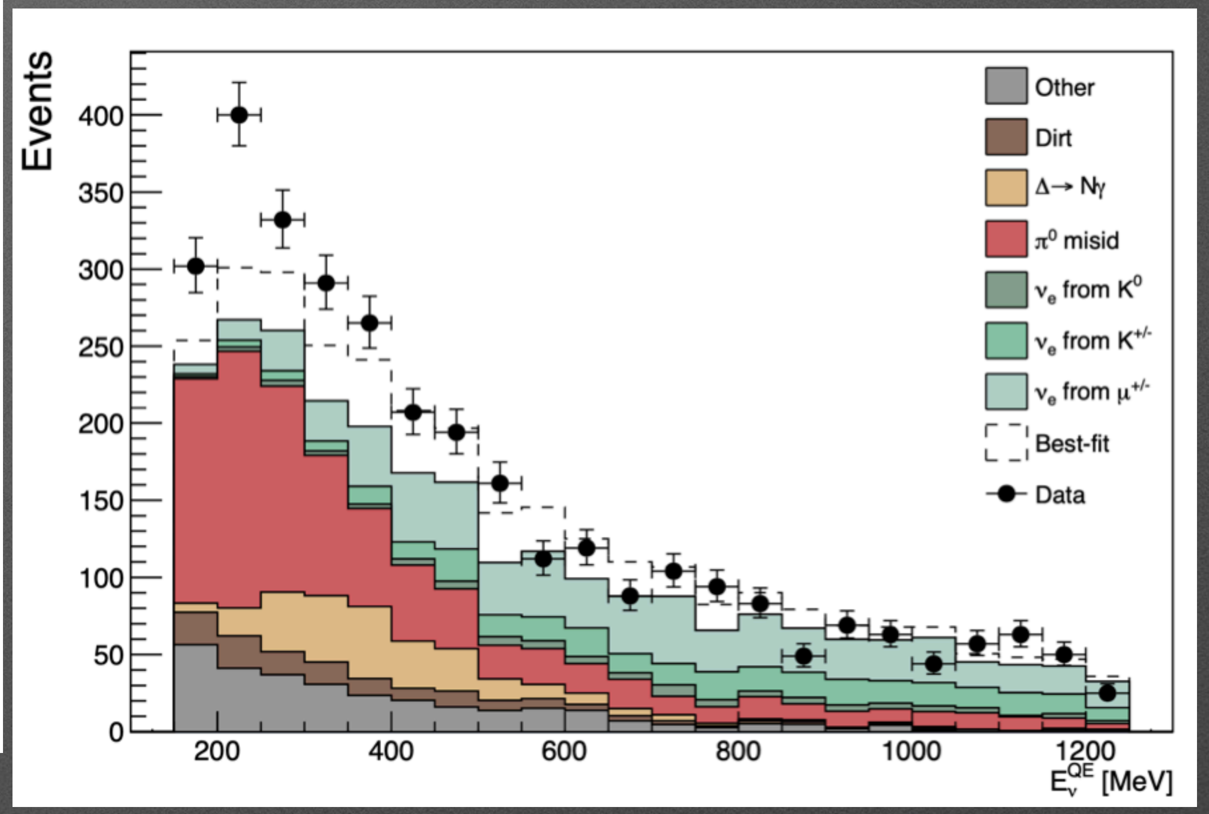


New flux calculation (β spectrum from 235U)
Results from very short baseline experiments (STEREO, Prospect, …)

LSND/MiniBooNE

$\nu\mu \rightarrow \nu e$ appearance
$\Delta m^2 \sim 1\ eV^2$



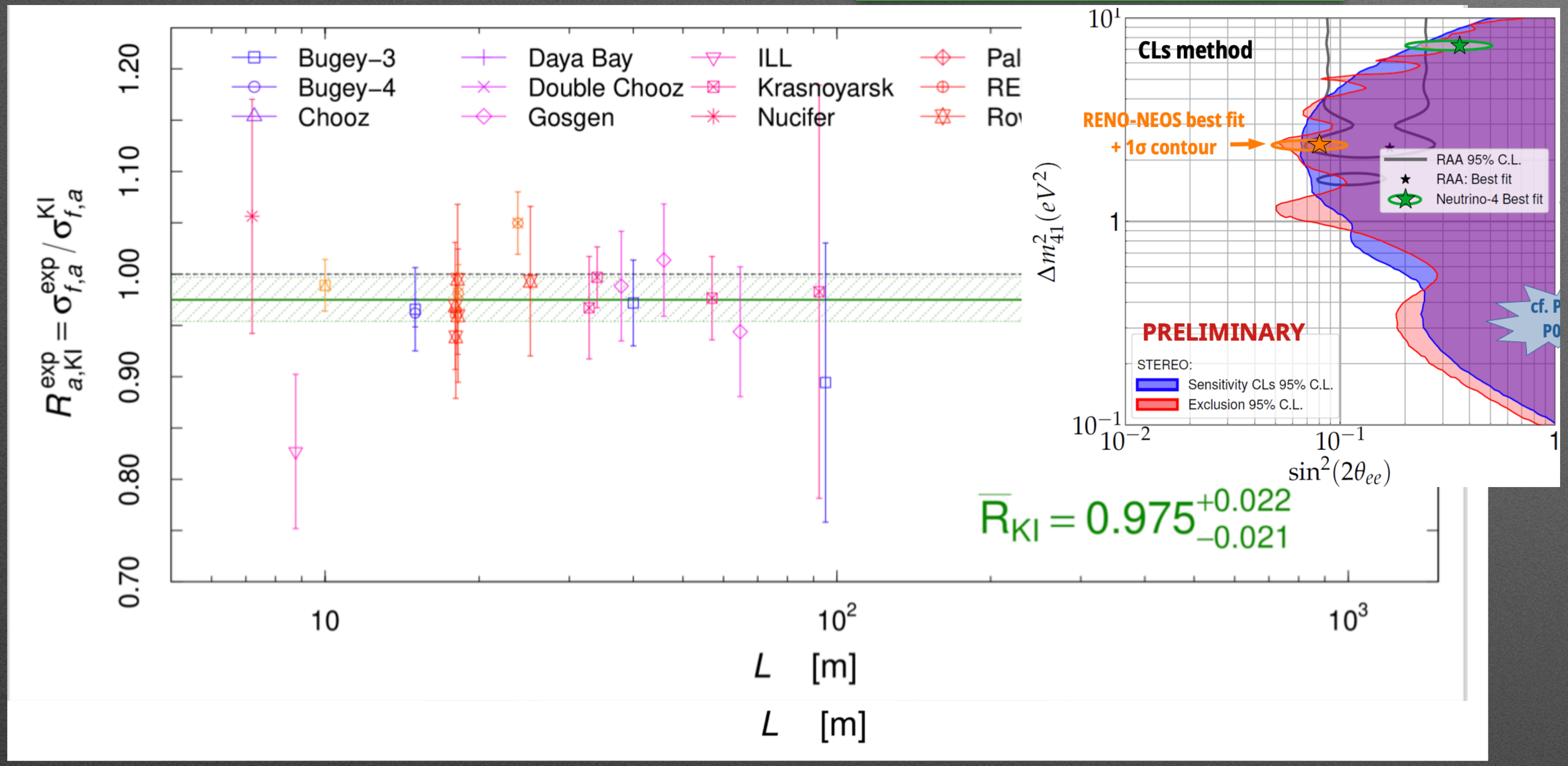


MicroBooNE → same beam as MiniBooNE but better separation between νe and γ thanks to Liquid Argon
No excess in the νe channel

Sterile neutrinos

Reactor anomaly

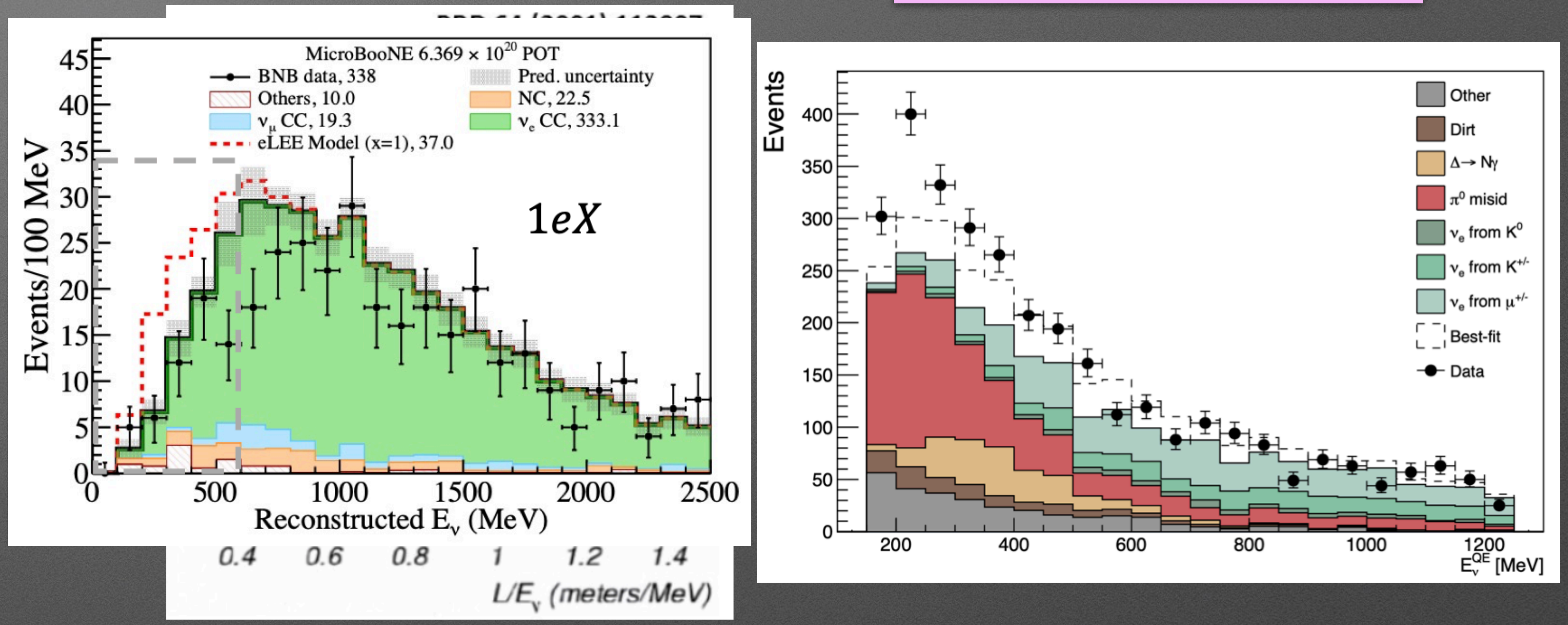
νe disappearance
$\Delta m^2 \sim 1$ eV²



New flux calculation (β spectrum from 235U)
Results from very short baseline experiments (STEREO, Prospect, …)

LSND/MiniBooNE

$\nu\mu \rightarrow \nu e$ appearance
$\Delta m^2 \sim 1$ eV²



MicroBooNE → same beam as MiniBooNE but better separation between νe and γ thanks to Liquid Argon
No excess in the νe channel

- Few anomalies still exist and we will never be able to exclude the presence of sterile neutrinos somewhere (for example for very small mixing angles)
- But, in my opinion, experimental results currently available show no hints of sterile neutrinos
- Existing anomalies fails when we try to combine together in a single consistent picture

2012: measurement of θ_{13}

✱Last measured mixing angle → smaller than θ_{23} and θ_{12}

Reactors (DChooz, RENO, Daya Bay)

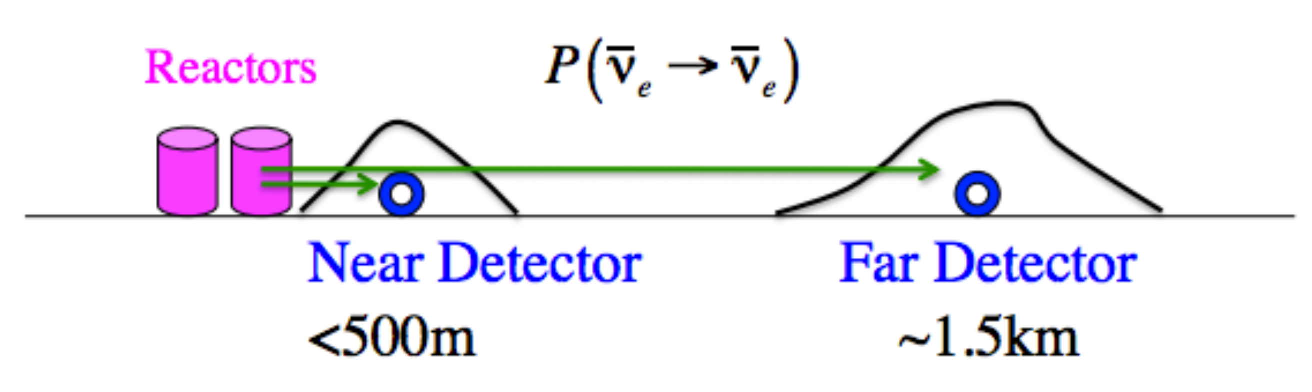
✓ Disappearance of $\overline{\nu}_e$ $P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$

✓ $\overline{\nu}_e$ produced in nuclear reactors

  ✓Neutrino energy few MeV

  ✓Distance L ~ 1 km

✓ Signature: disappearance of the $\overline{\nu}_e$ produced in the reactor → depends only on θ_{13}



Accelerators (T2K, Nova):

✓ Appearance experiment: $P(\nu_\mu \rightarrow \nu_e)$

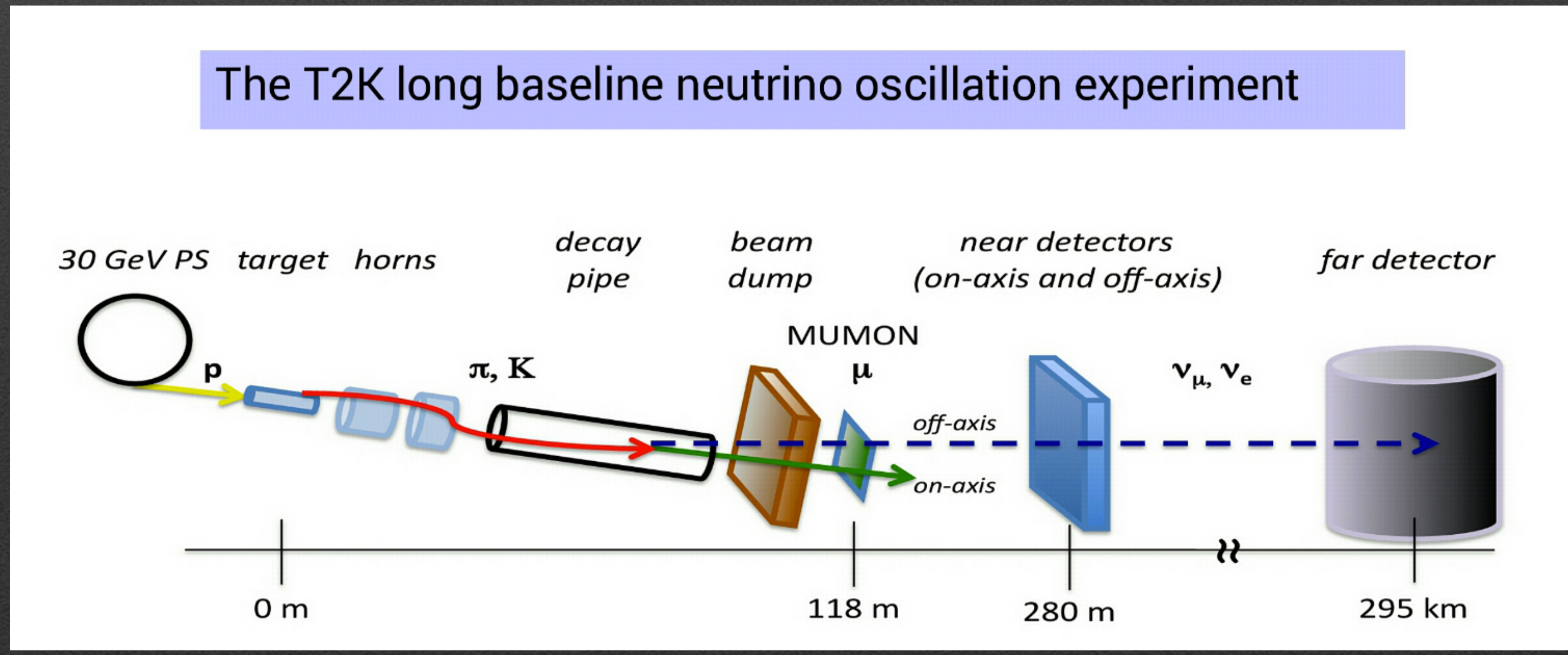
✓ ν_μ neutrino beam

  ✓ Neutrino energy ~1 GeV

  ✓ Distance L >~ 300 km

✓Signature: ν_e appearance in ν_μ beam

✓Degeneracies of θ_{13}, δ_{CP}, sign of Δm^2

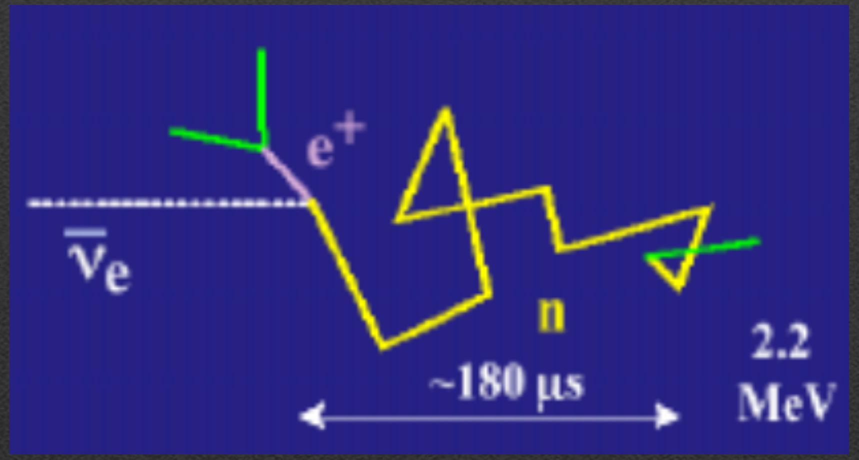


Inverse β decay at reactors

* Reactor antineutrino spectrum ~ 4 MeV

* $\Delta m^2_{12}, \theta_{12}$ → distance of 200 km (KamLAND)

* $\Delta m^2_{13}, \theta_{13}$ → distance of ~1 km (Daya Bay, RENO, Double Chooz)

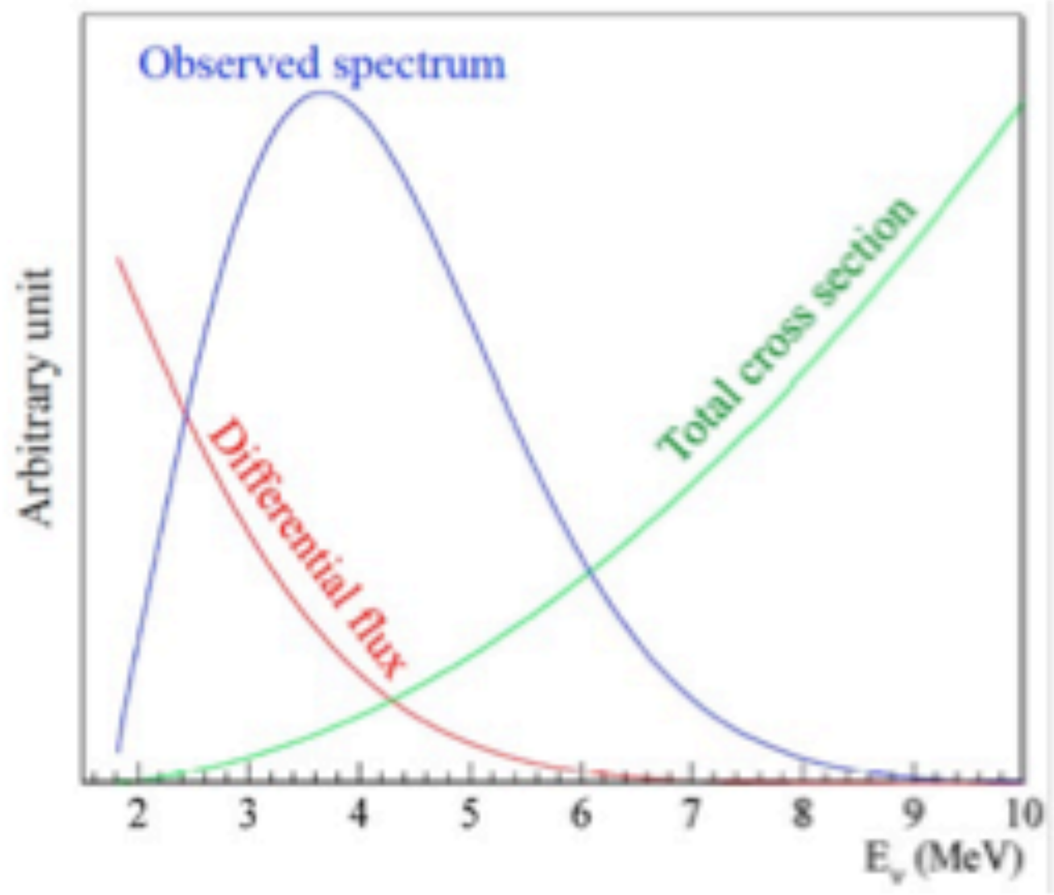


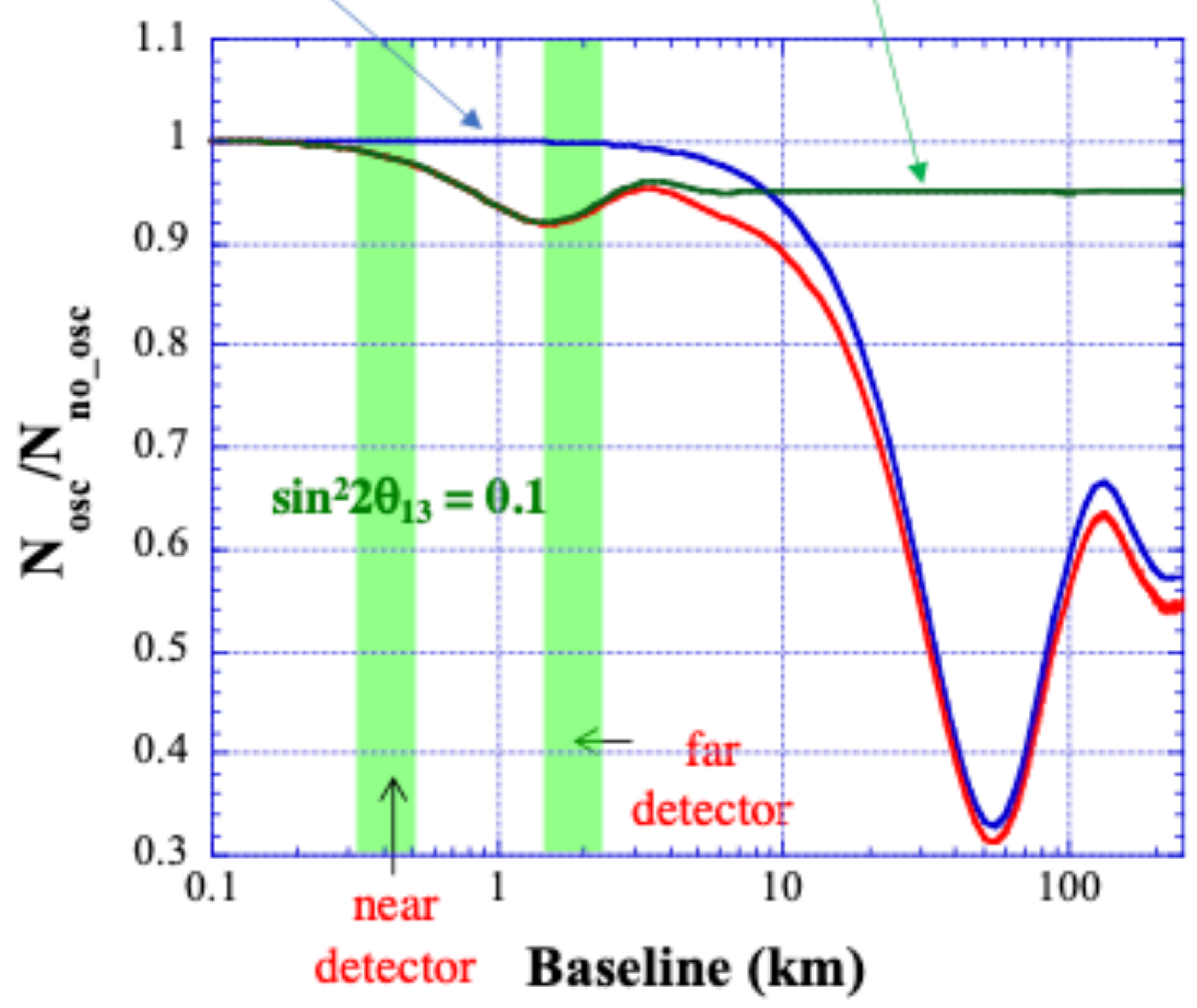
$\bar{\nu}_e + p \rightarrow e^+ + n$

$n + p \rightarrow d + \gamma$ (2.2 MeV)

$n + Gd \rightarrow Gd^* + \gamma$ (8 MeV)

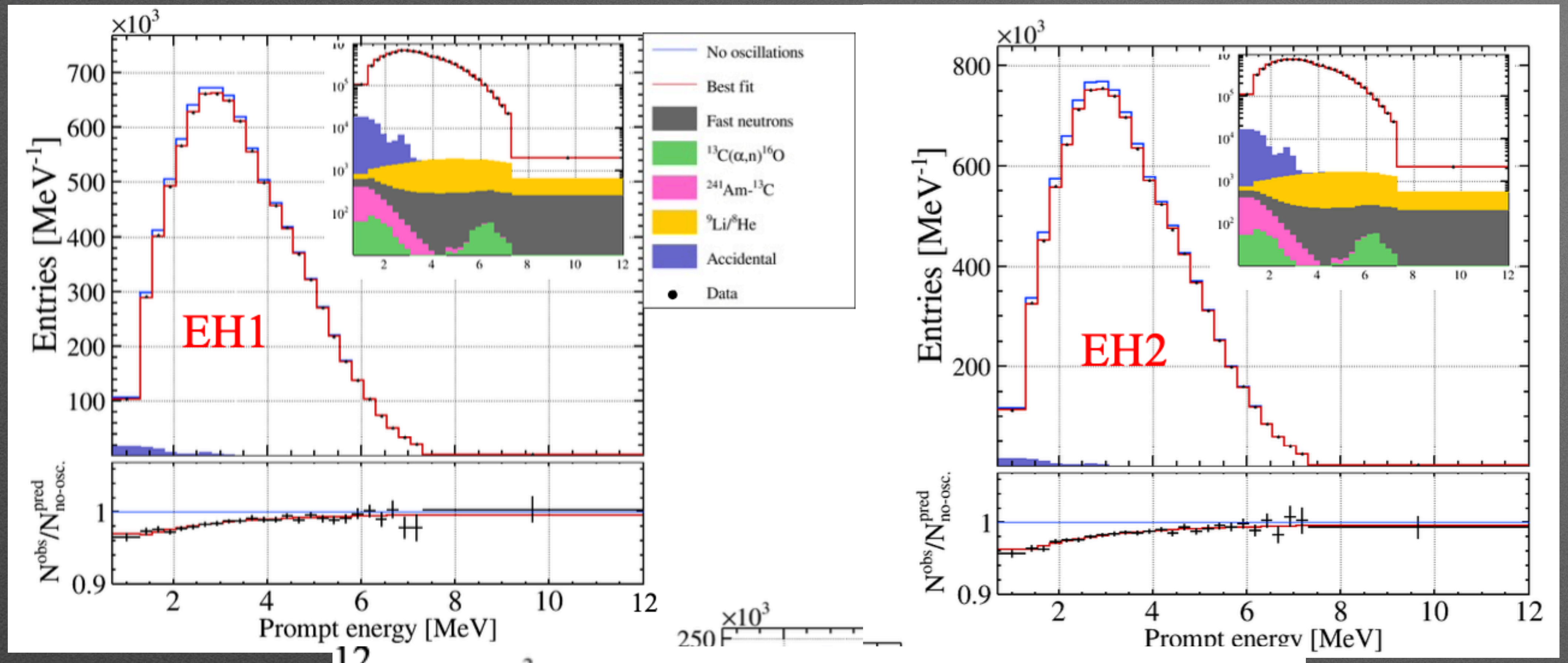
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \boxed{sin^2 2\theta_{13}\left[cos^2\theta_{12} sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + sin^2\theta_{12} sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right]}$$
$$- \boxed{cos^4\theta_{13} sin^2 2\theta_{12} sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)}$$

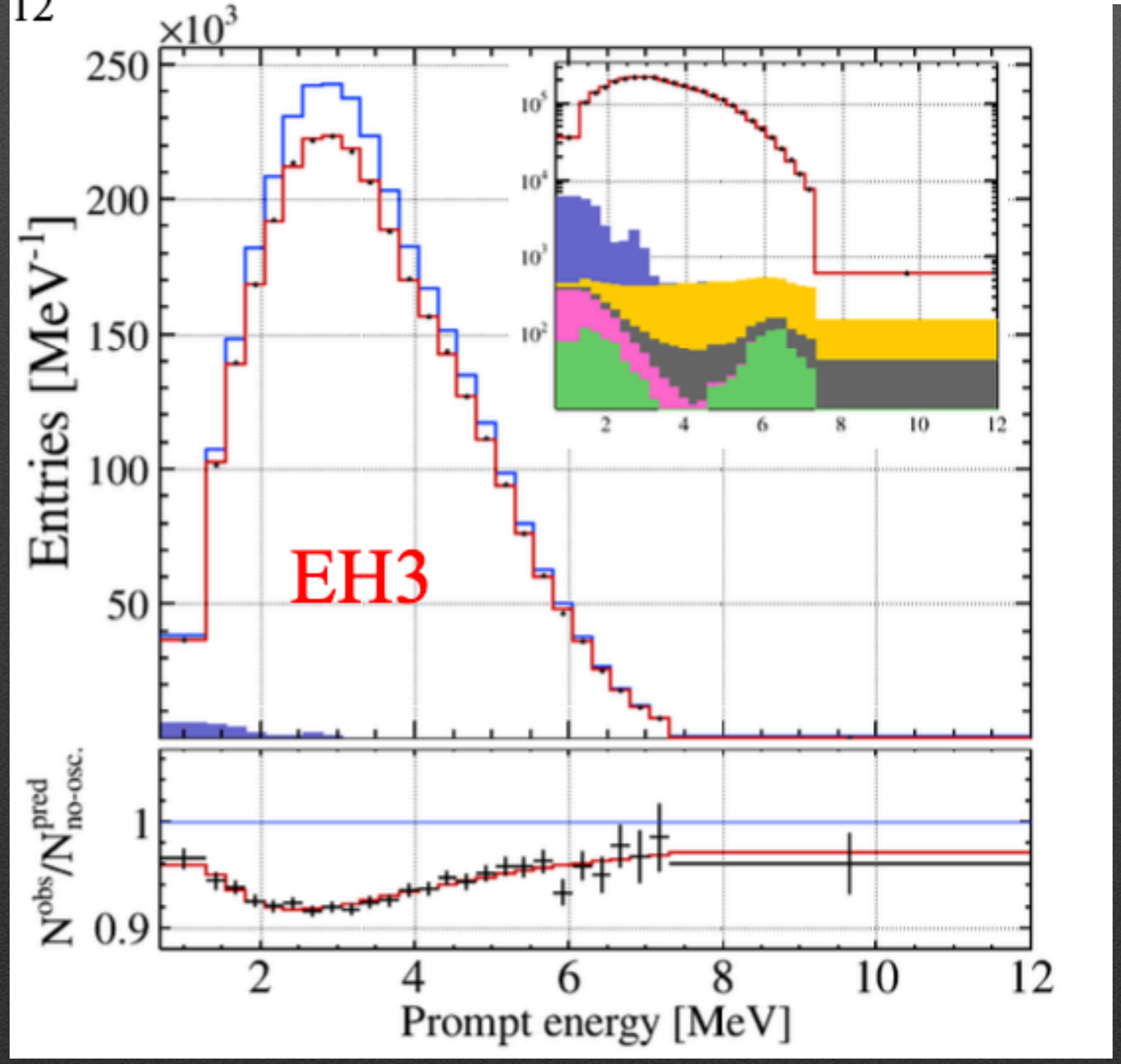


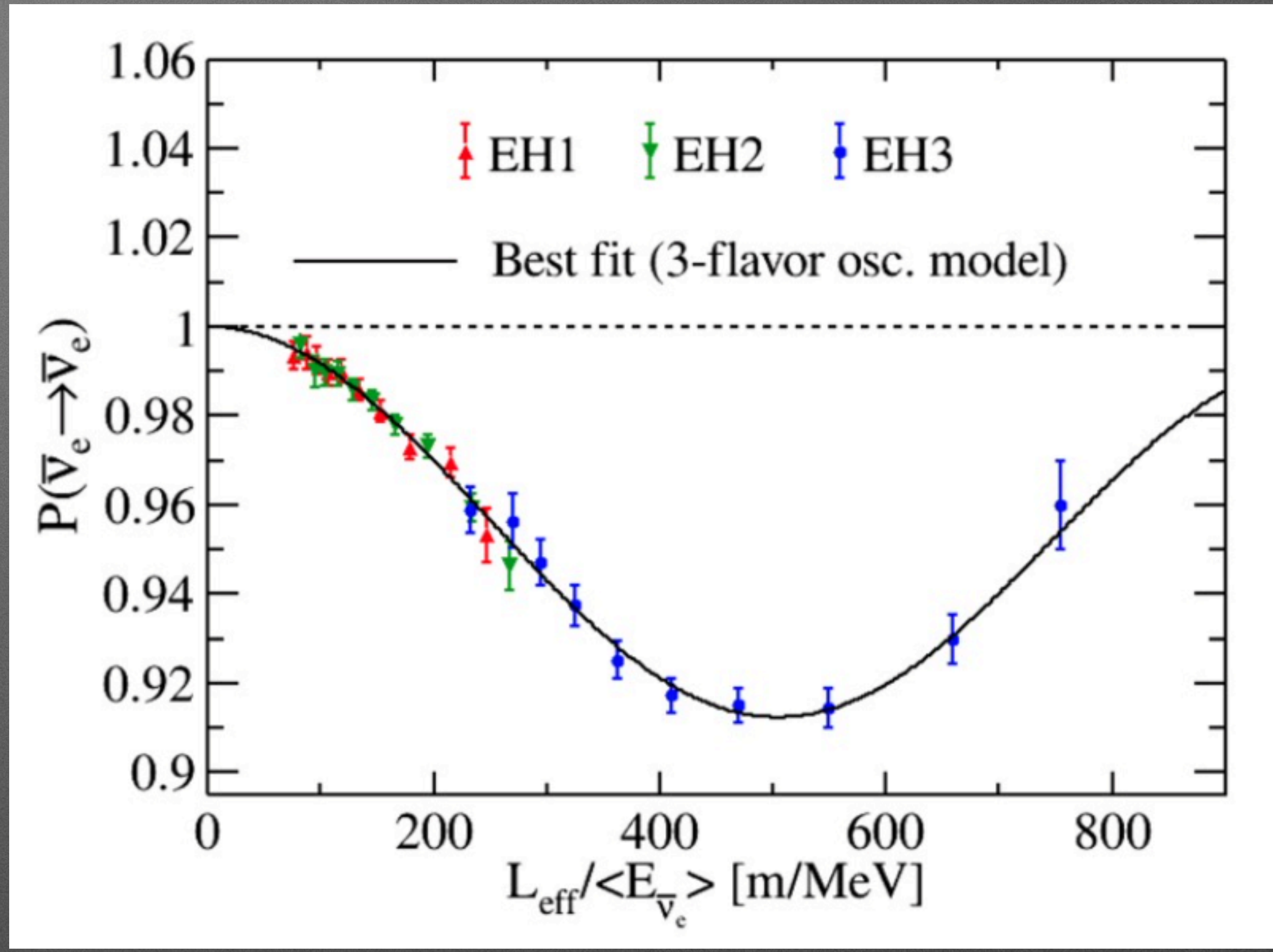


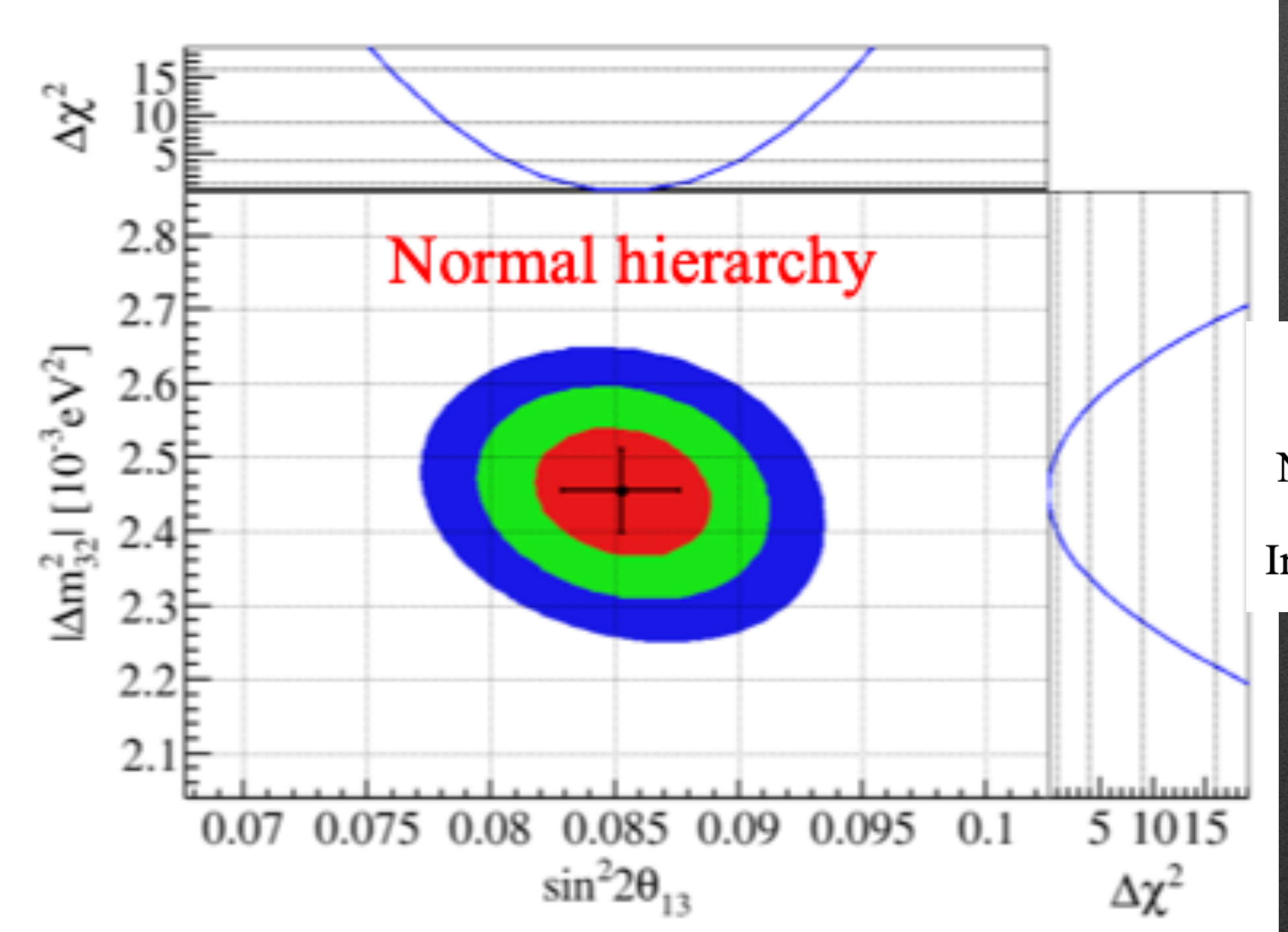
- Reduce systematic issues by performing relative measurement with Far/Near ratio

θ_{13} measurement









$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$ (2.8% precision)

Normal hierarchy: $\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}$ eV^2

Inverted hierarchy: $\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}$ eV^2

(2.3% precision)

From the last unknown mixing angle to the most precisely known!

Accelerator experiments

- Accelerate protons and strike them on a target
- This produce pions that are focused and selected in charge by electromagnetic horns
- Pions enter a decay tunnel where they decay into ν_μ or $\bar{\nu}_\mu$
- Neutrinos are then detected in a Near Detector (before oscillations) and at a far detector (after oscillations)

T2K
L = 295 km
$E_\nu \sim 0.7$ GeV

NOνA
L = 810 km
$E_\nu \sim 2$ GeV

Sensitive to 5 oscillation parameters
ν_μ disappearance → θ_{23} and Δm^2_{32}
ν_e appearance → θ_{13},
ν_e vs $\bar{\nu}_e$ appearnce → δCP and mass ordering

Mass ordering and CPV

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4\boxed{C_{13}^2 S_{13}^2 S_{23}^2} \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \boxed{\sin\delta} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& -8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},
\end{aligned}
$$

Leading term ➔ θ_{13}

CPV term

Matter effects

∝ distance

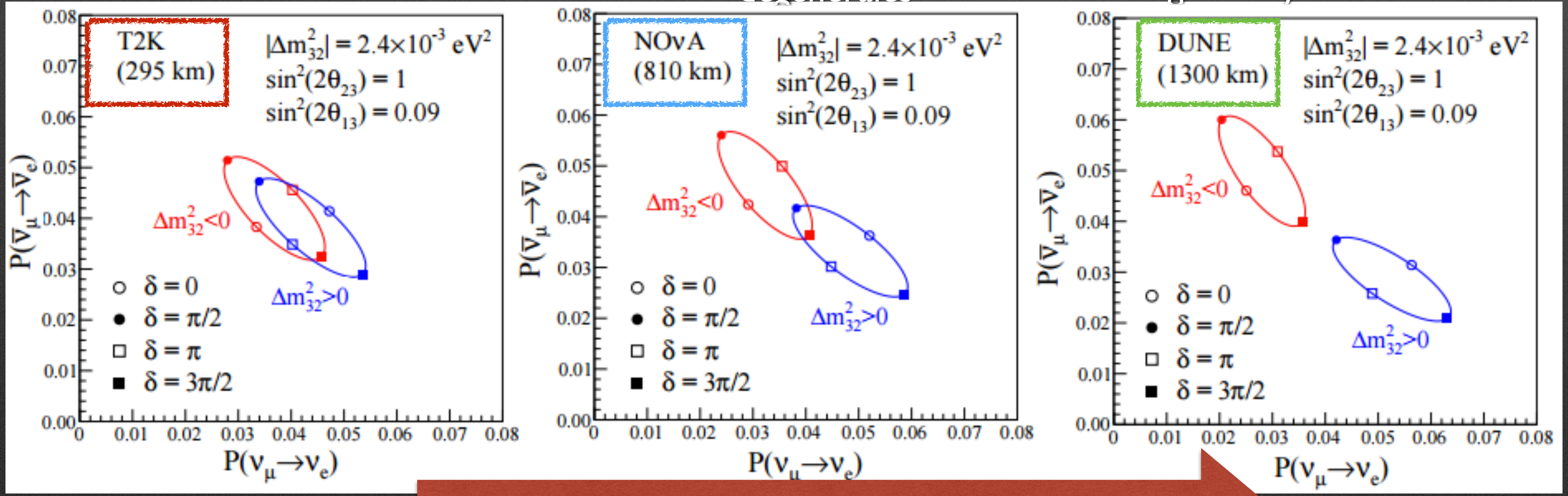
Experimentally we measure an appearance probability

sinδ and **a** change sign from neutrino to antineutrino

T2K/HK almost no matter effect → ~clean measurement of CPV

NOVA sensitive to mass Ordering and CPV with some degeneraies

DUNE breaks the degeneracy between MH and

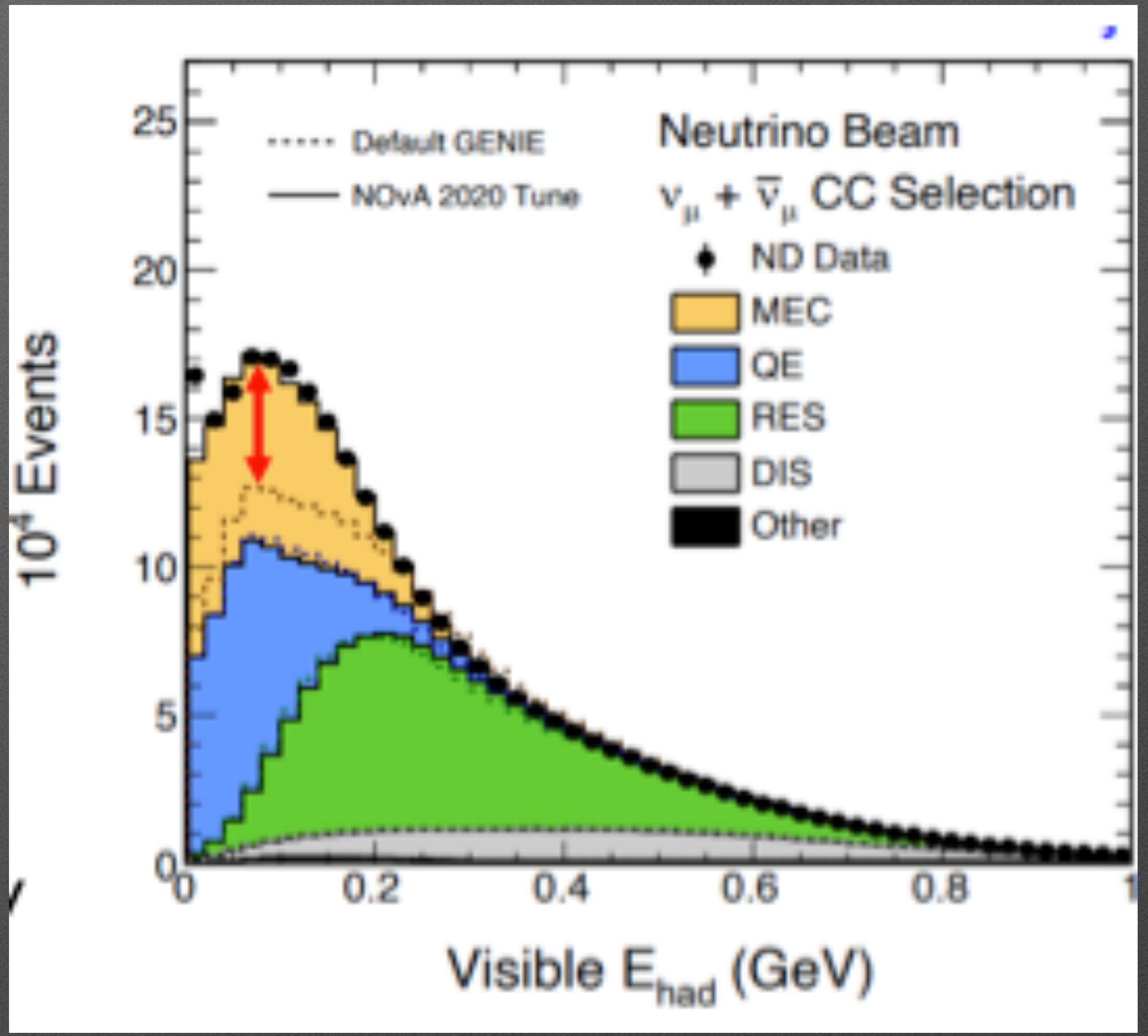


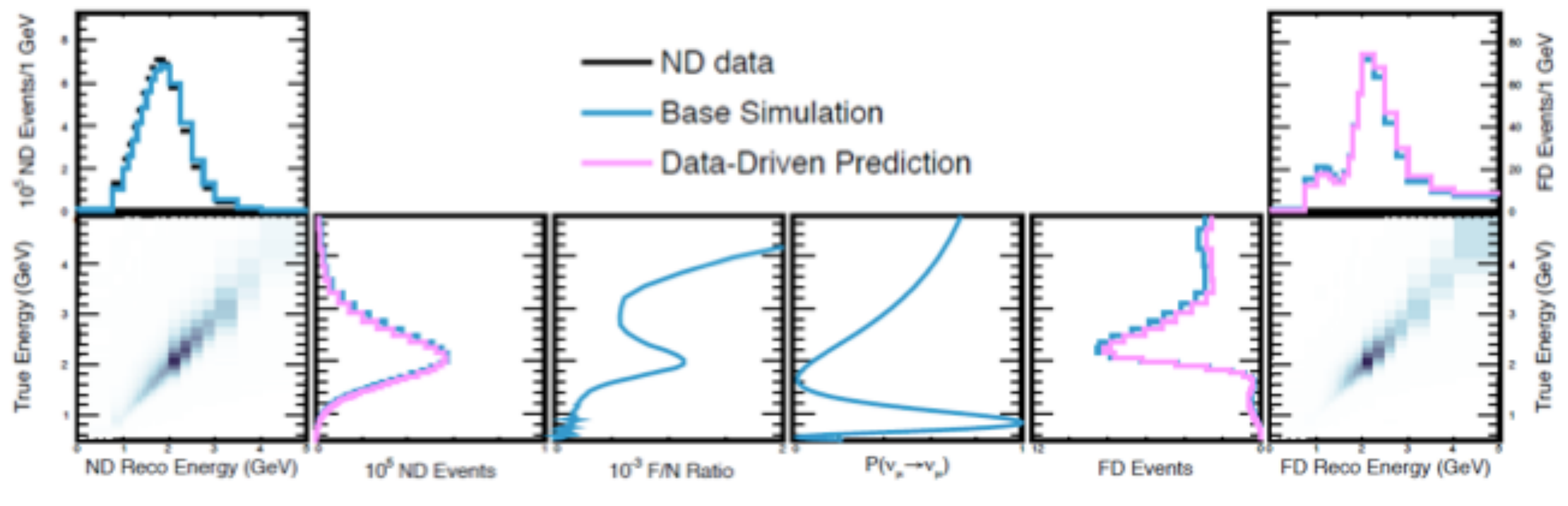
increasing baseline

CPV is a small effect → need good control of systematics → Near Detectors!

NOvA oscillation analysis and Near Detector

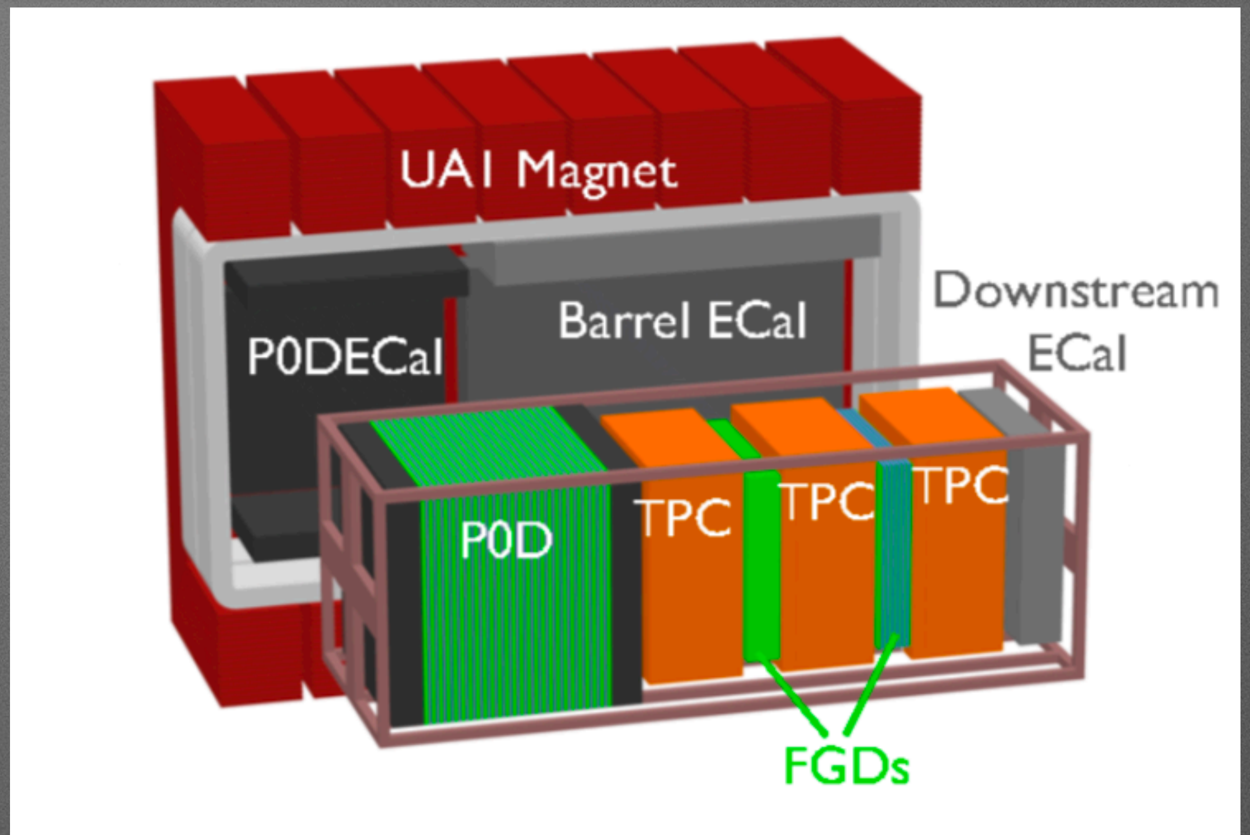
- Very different strategy between NOvA and T2K about Near Detectors
- NOvA : identical Near and Far detector
- Take ND data and unfold into true energy
  - Samples split according to the hadronic energy
- Propagate to the Far Detector applying oscillation probabilities
- Profit of the fact that ND and FD are identical but need a good modeling to unfold from reconstructed to true energy

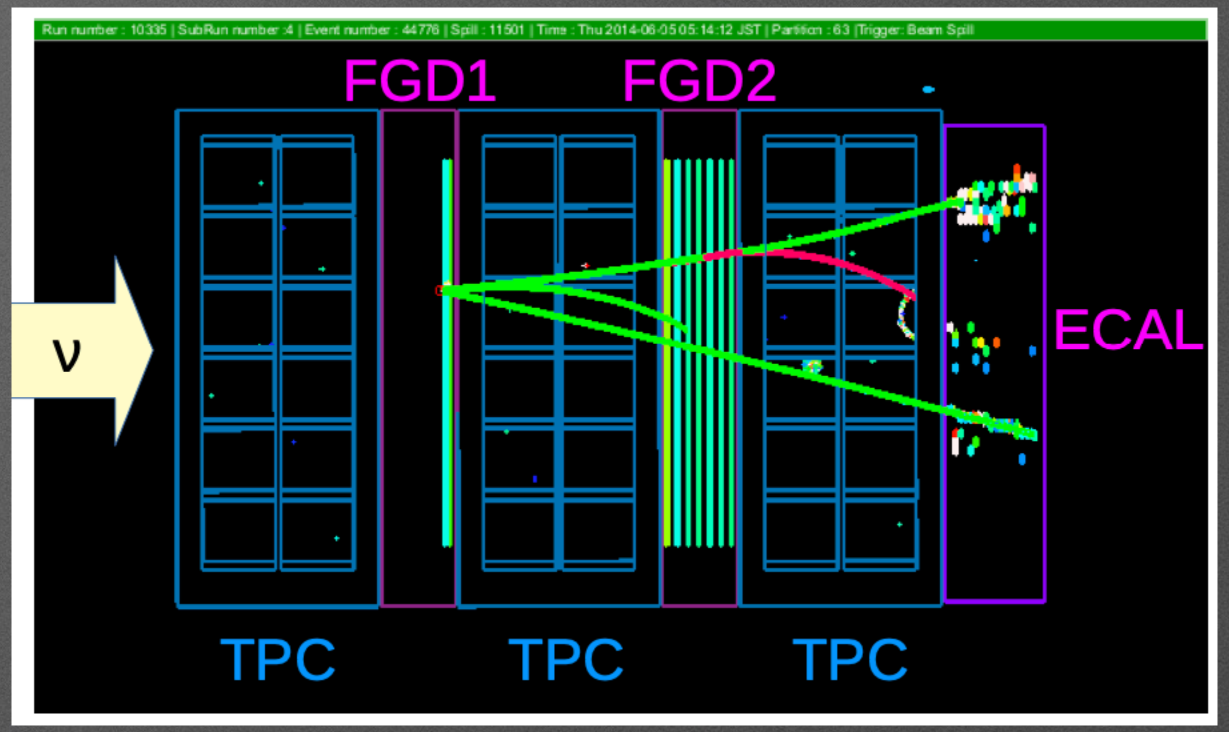


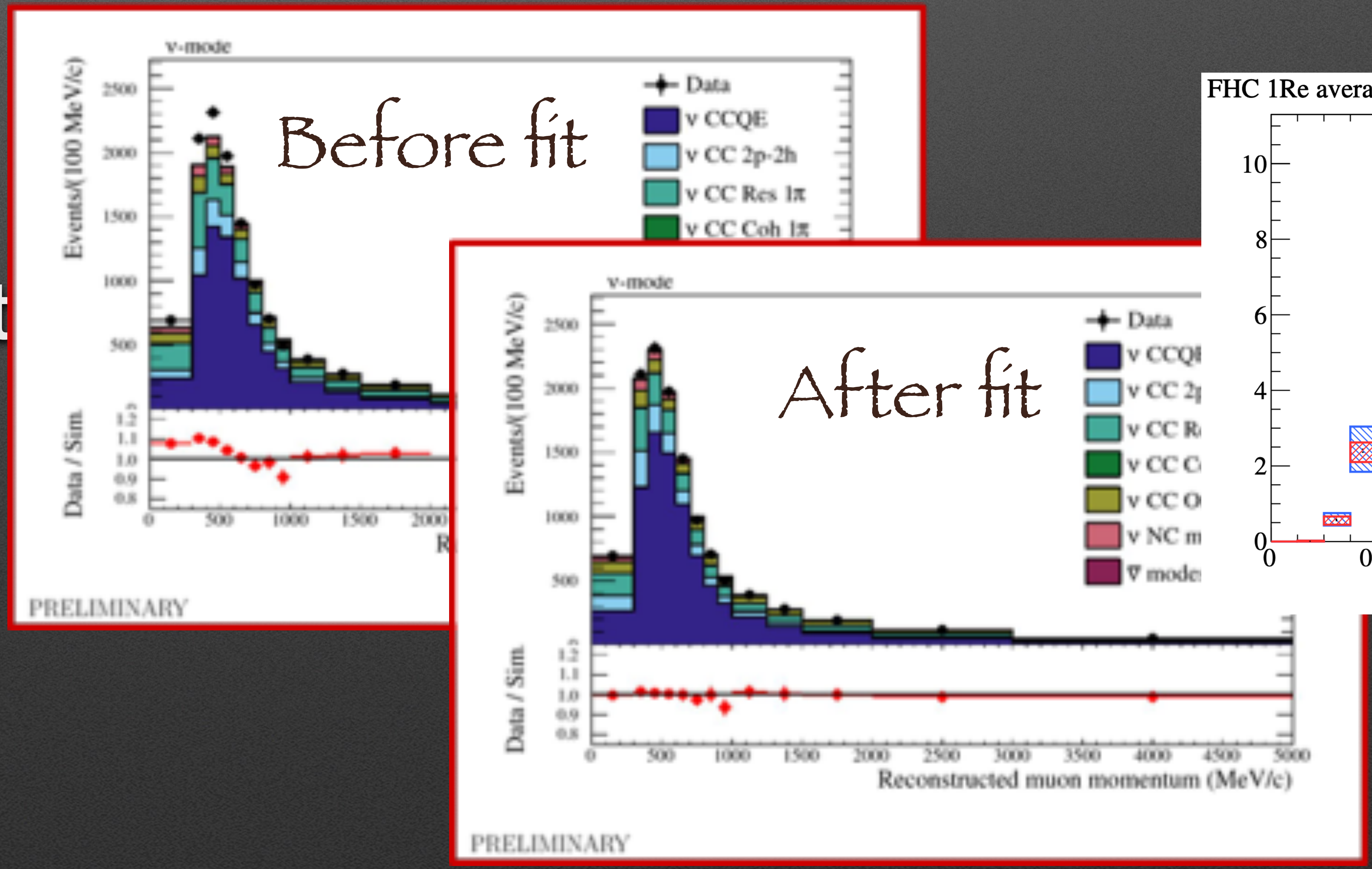


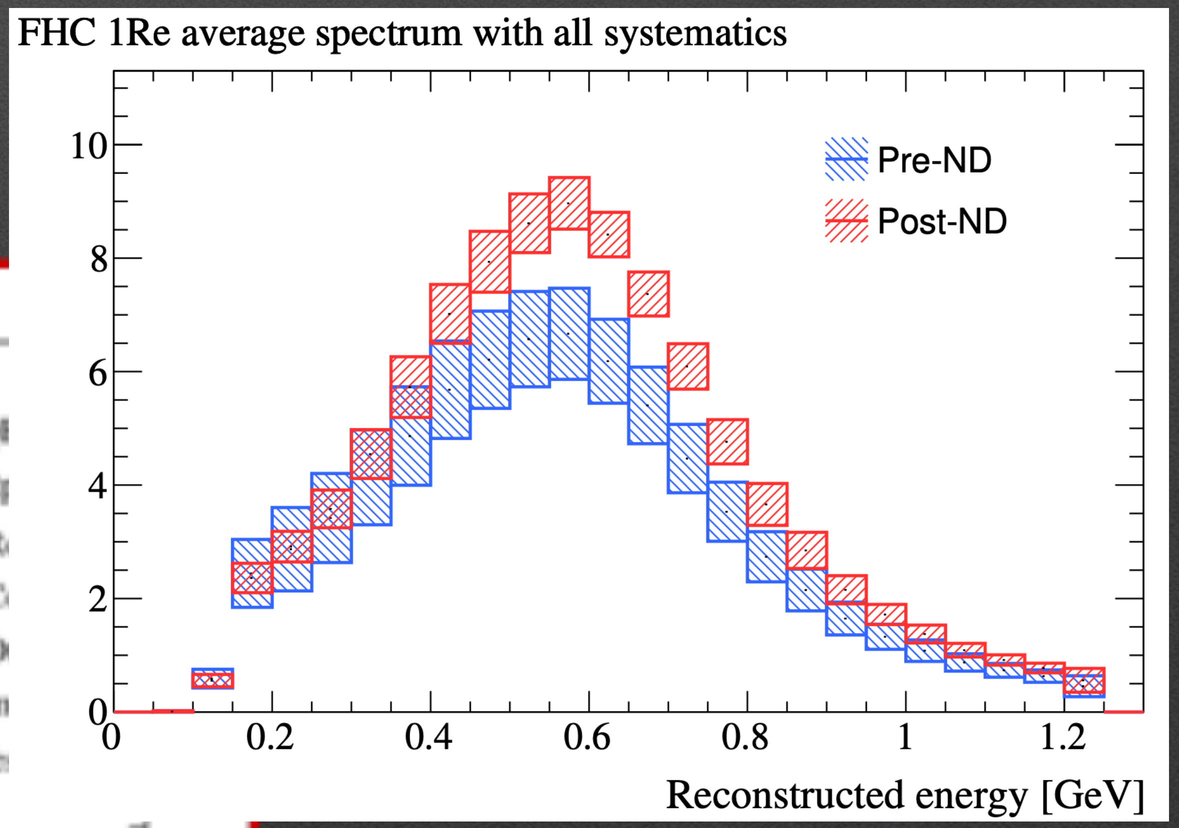
T2K Near Detector

- In T2K Near and Far detector are different
- ND280 is a magnetized near detector in which charged particles are reconstructed
- Build a model of flux and cross-section systematics and use it to fit ND data
- The obtained model is then propagated to the far detector

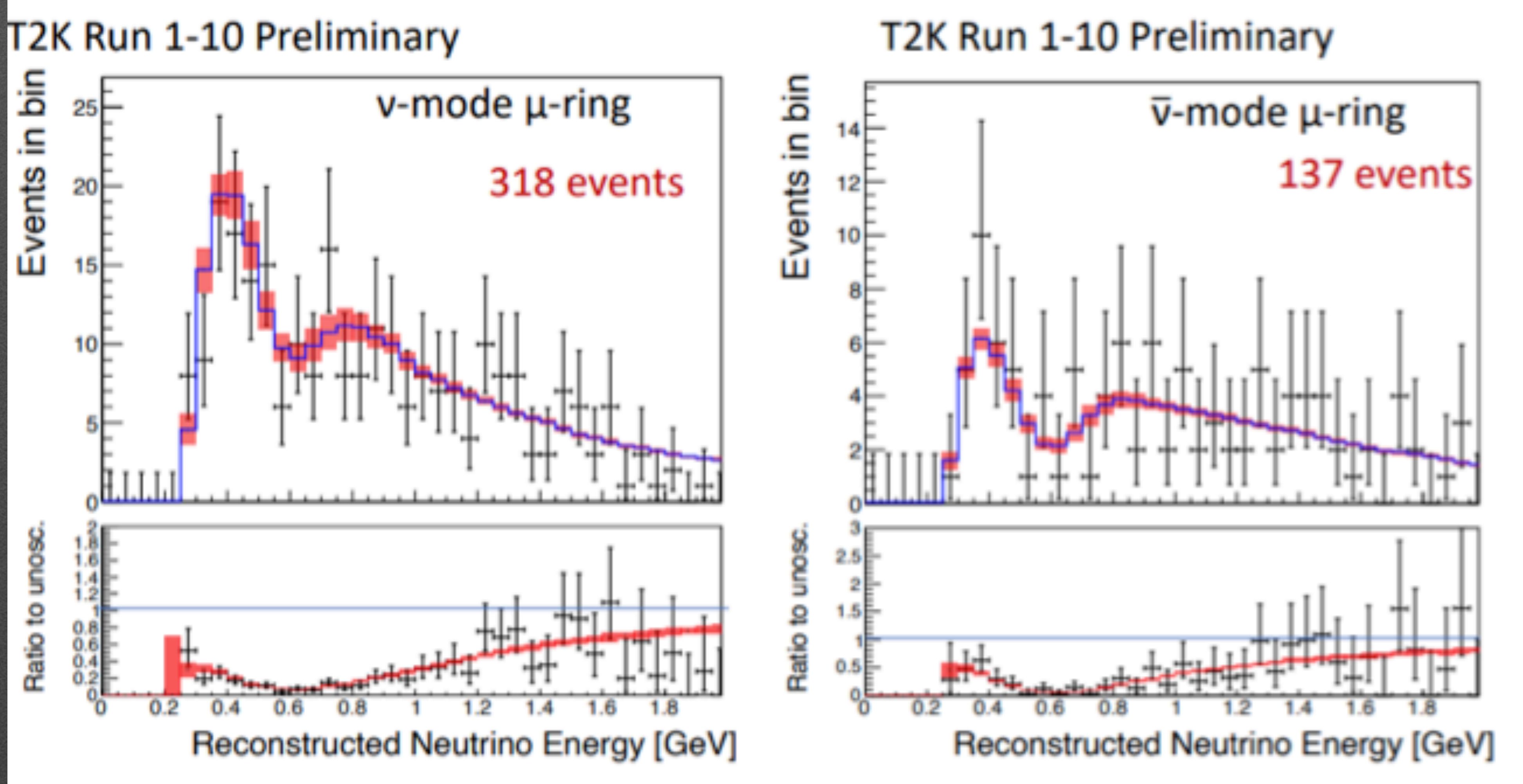


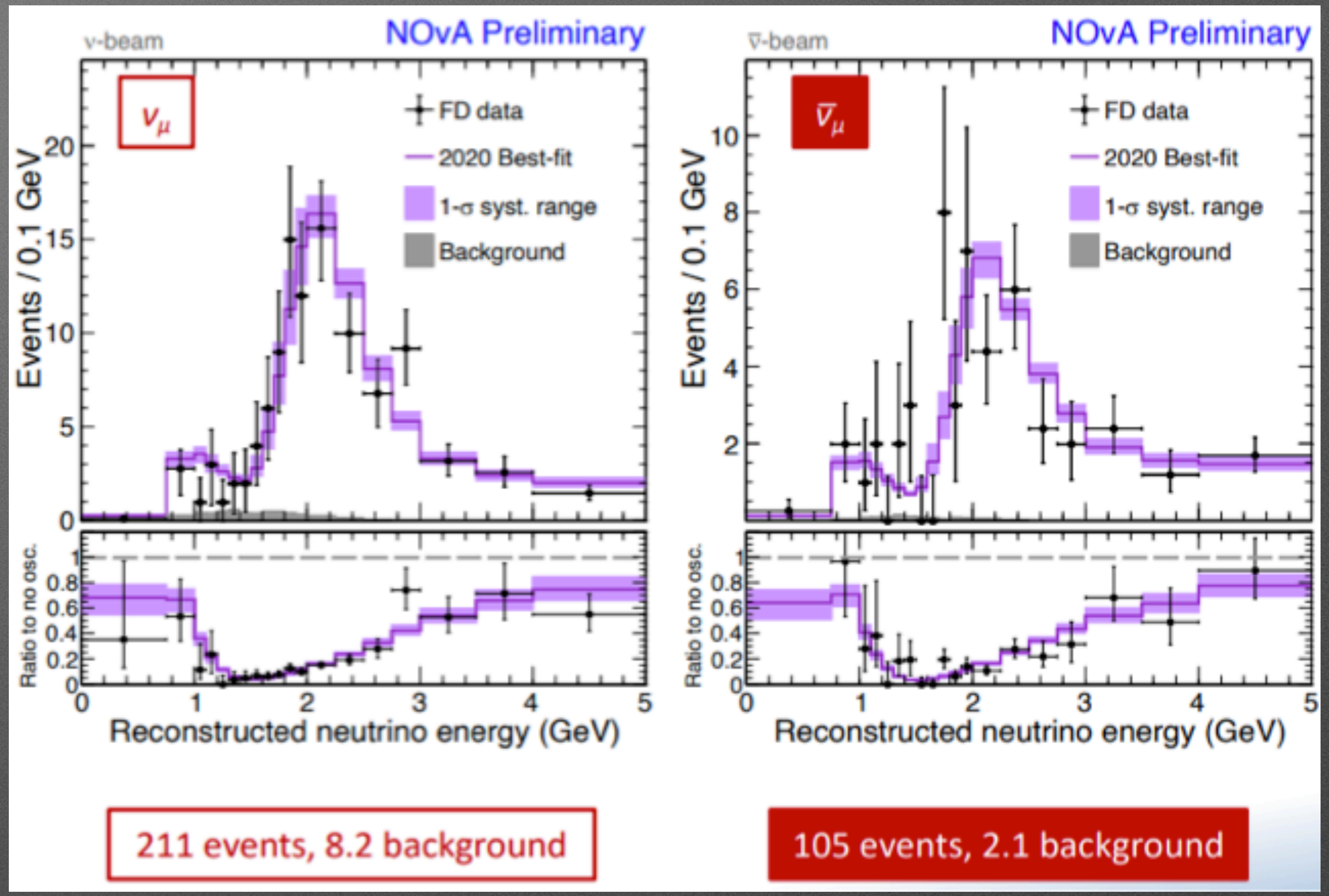


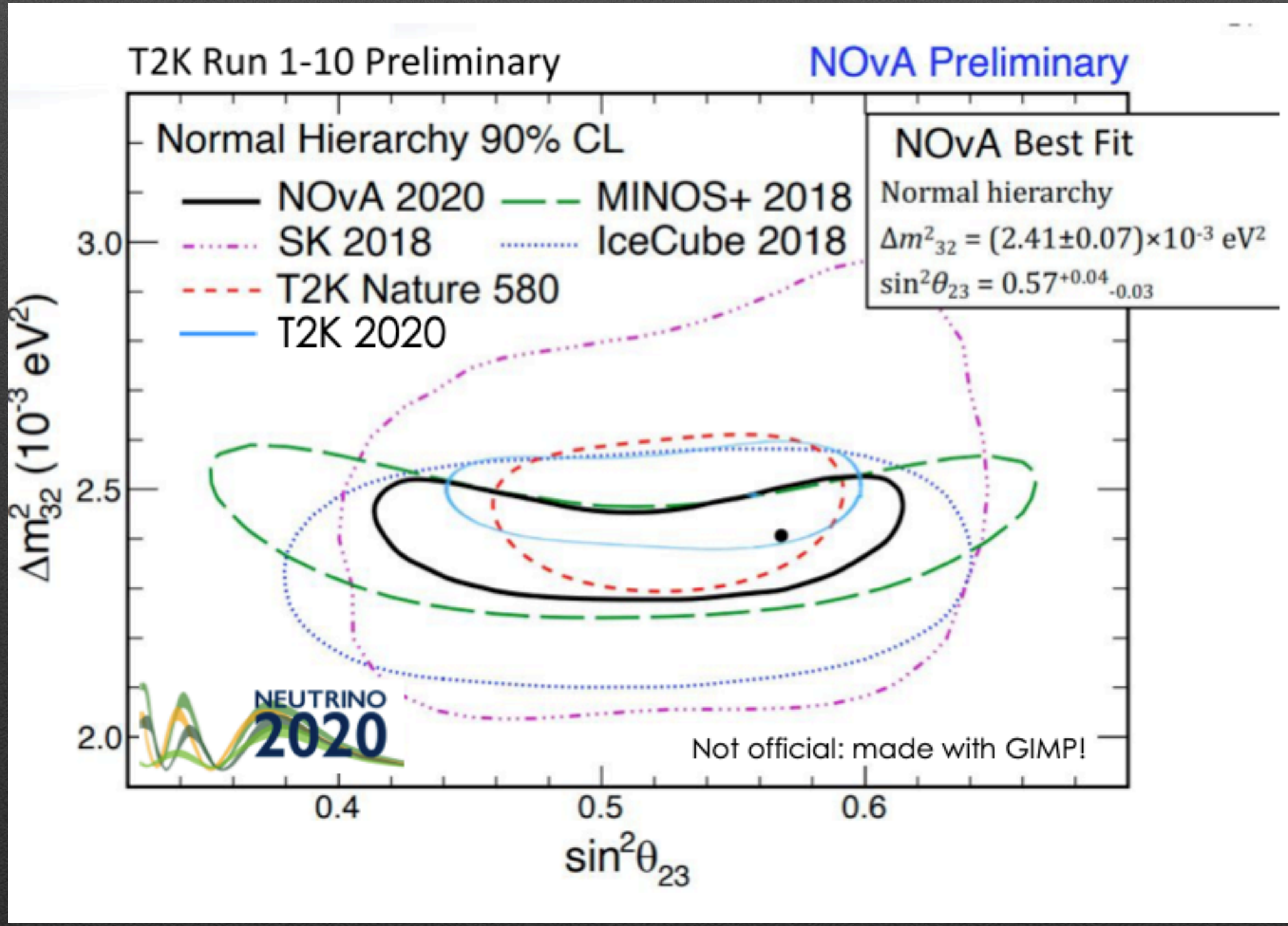




ν_μ disappearance

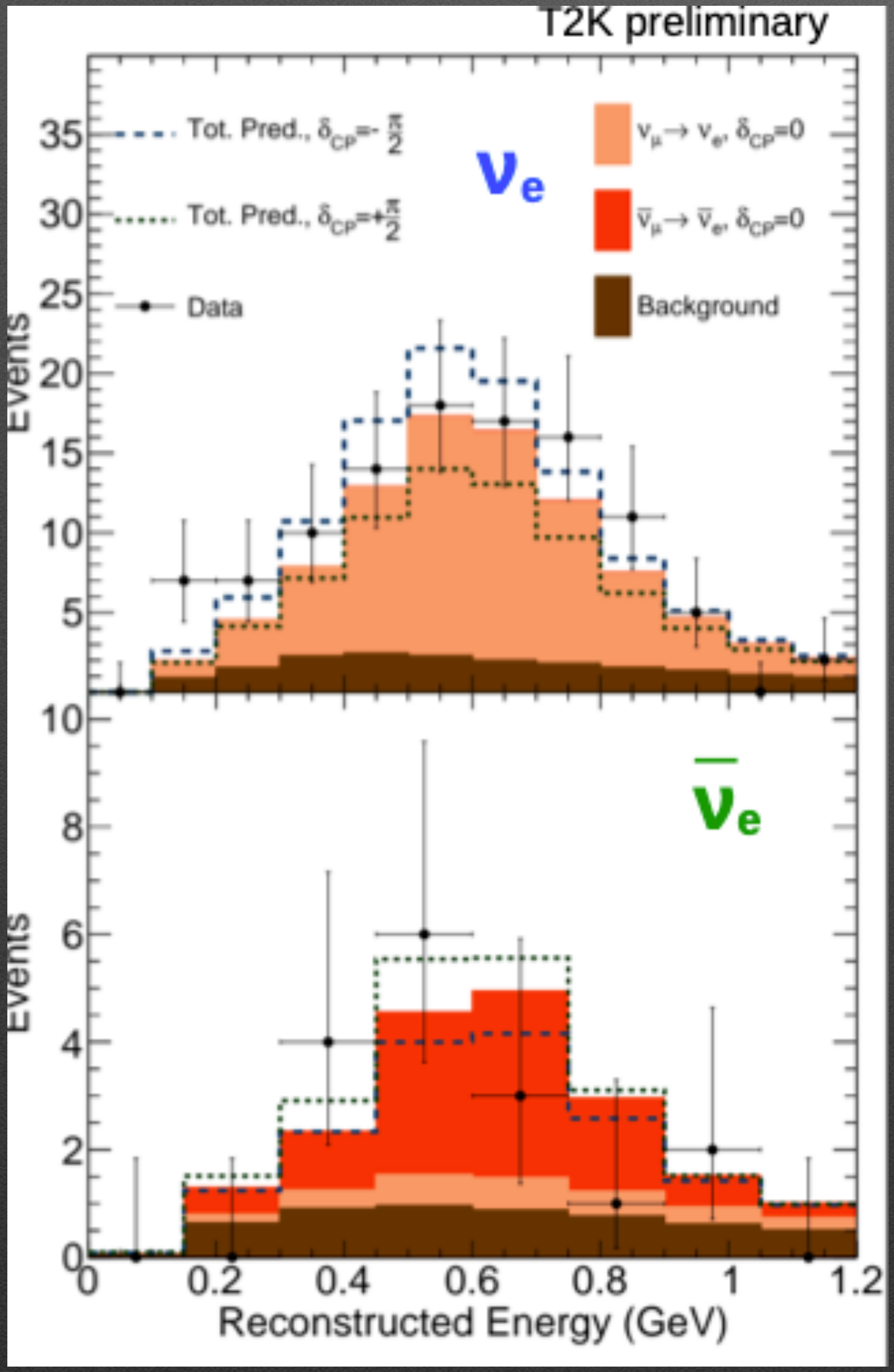




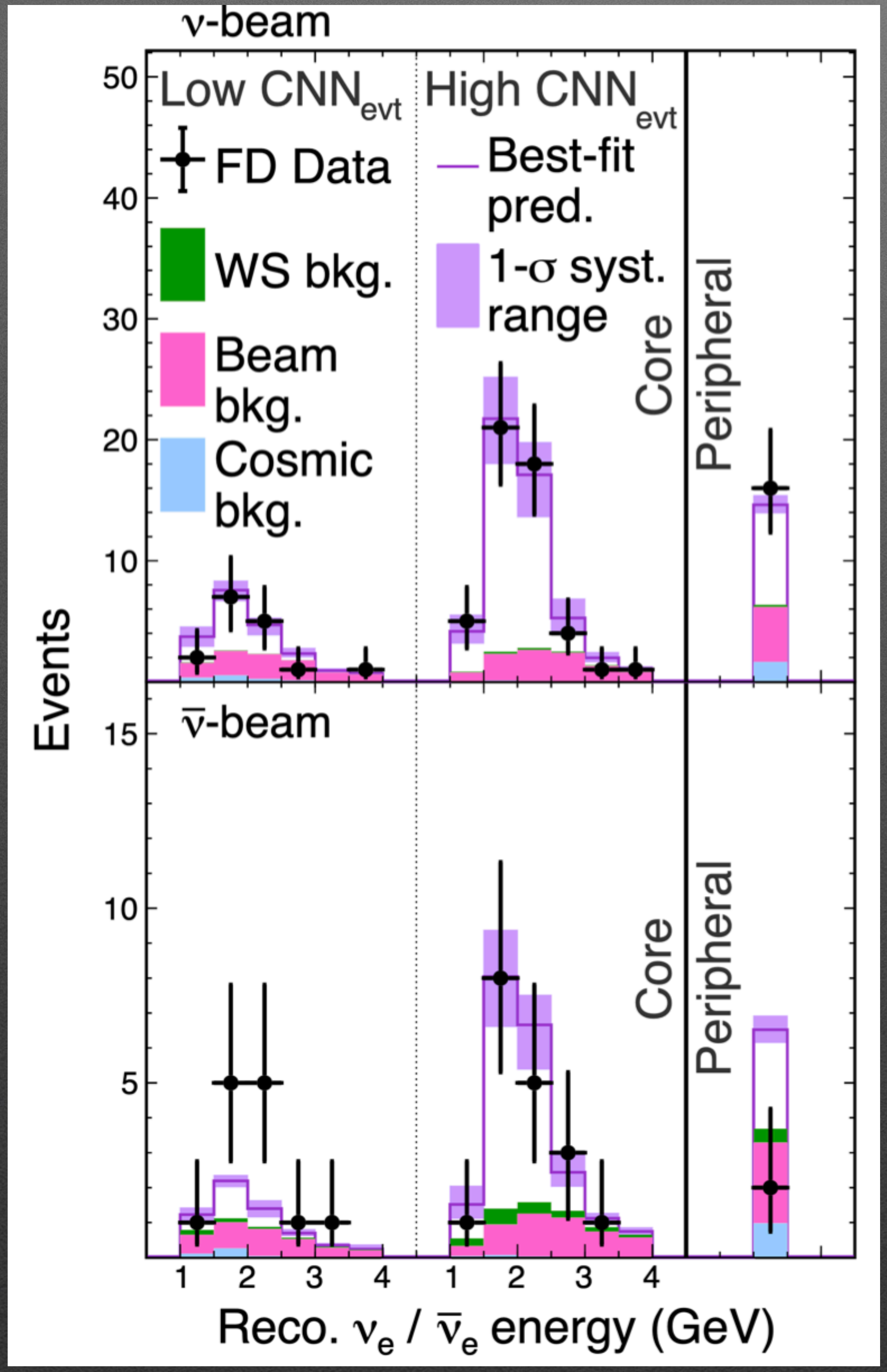


T2K - NOvA ν_e appearance

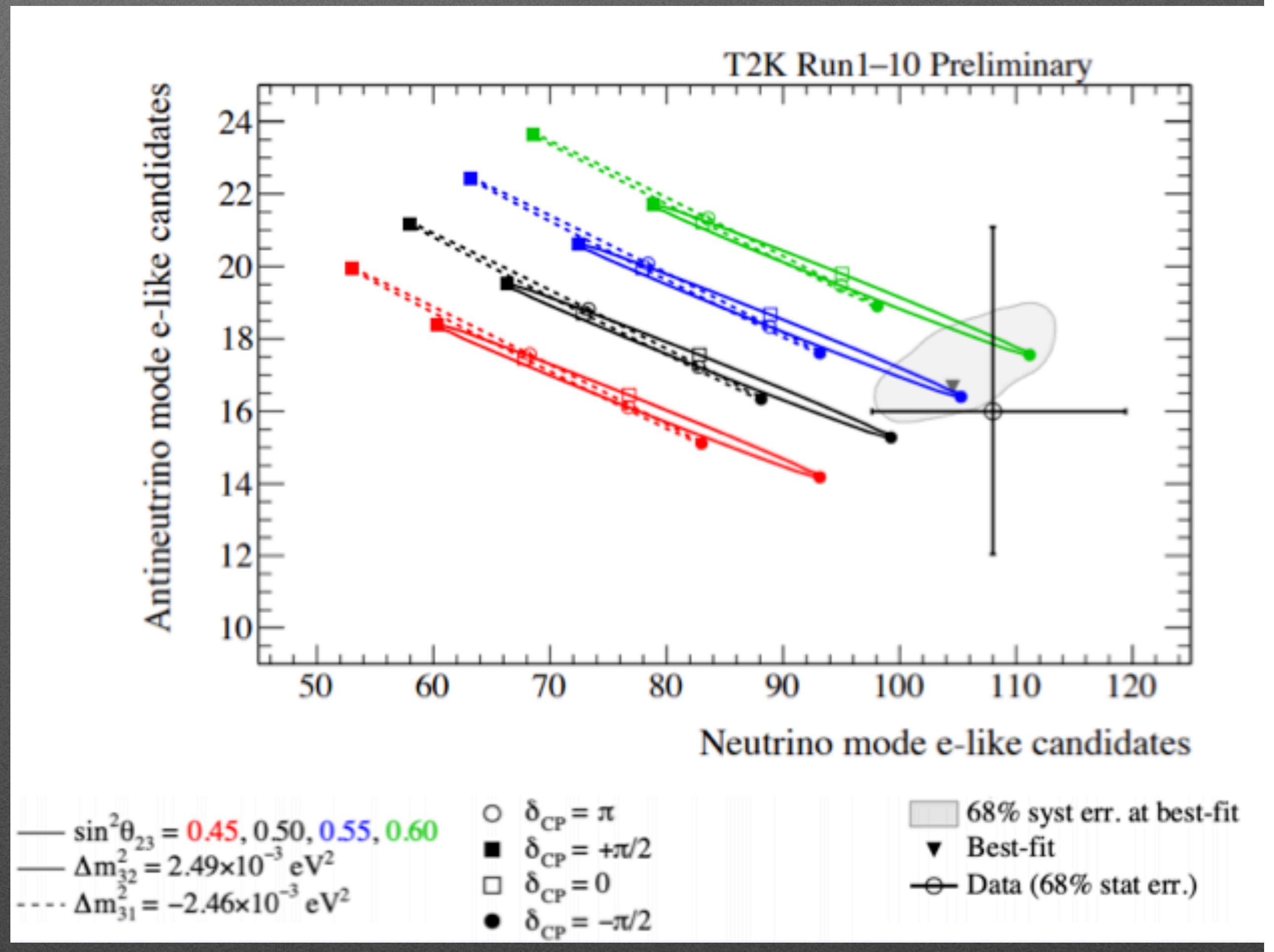
T2K



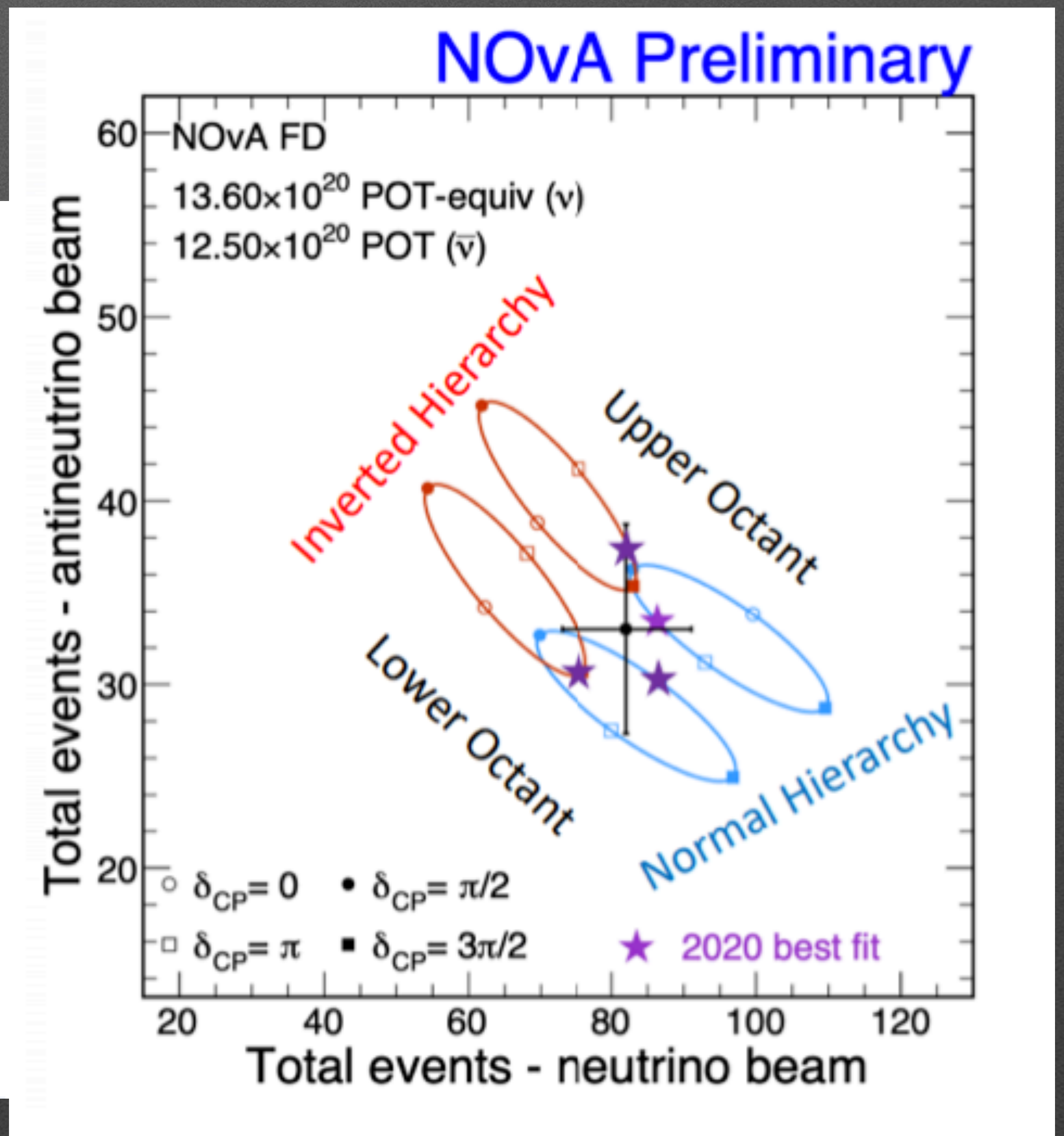
NOvA



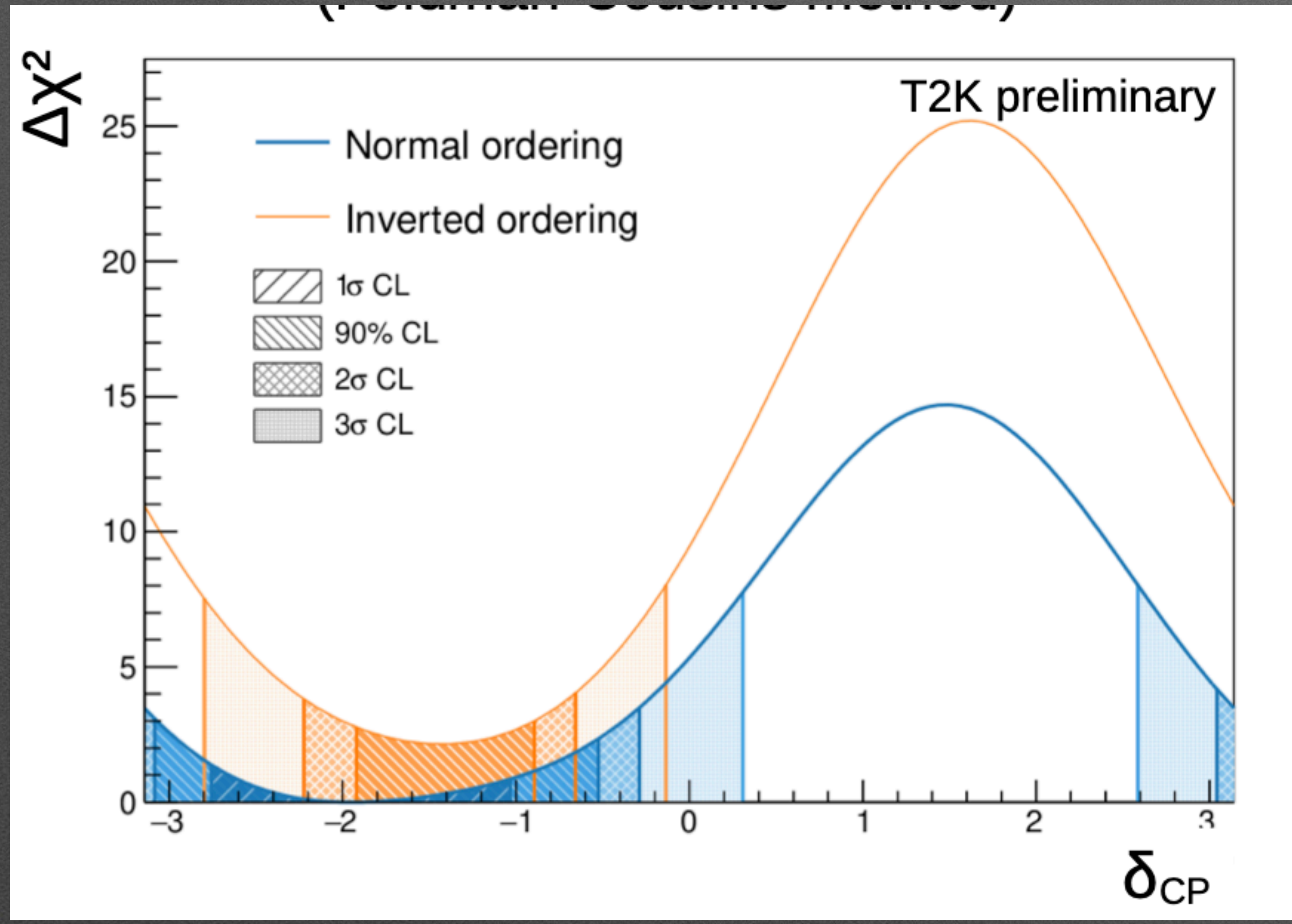
T2K

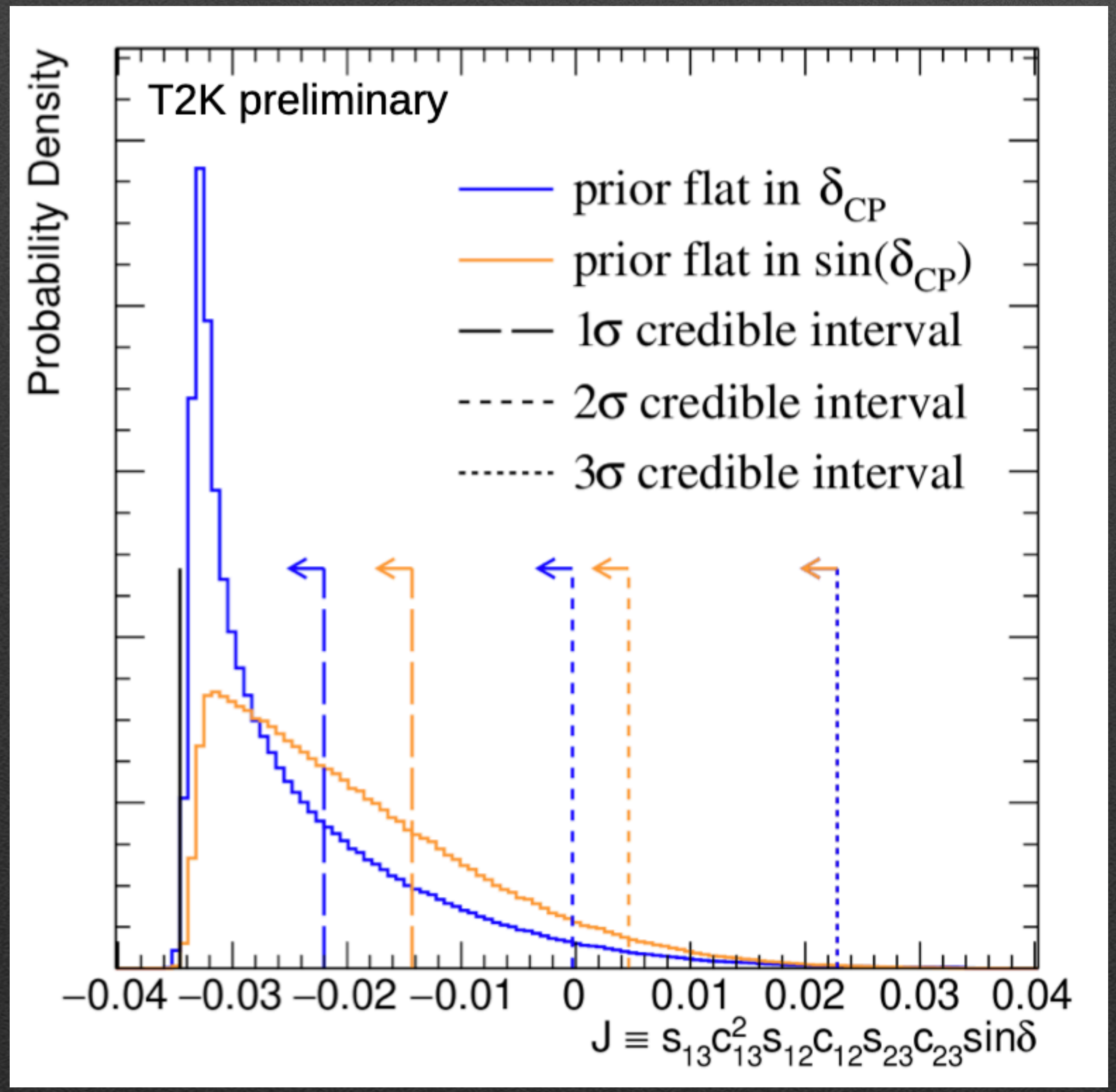


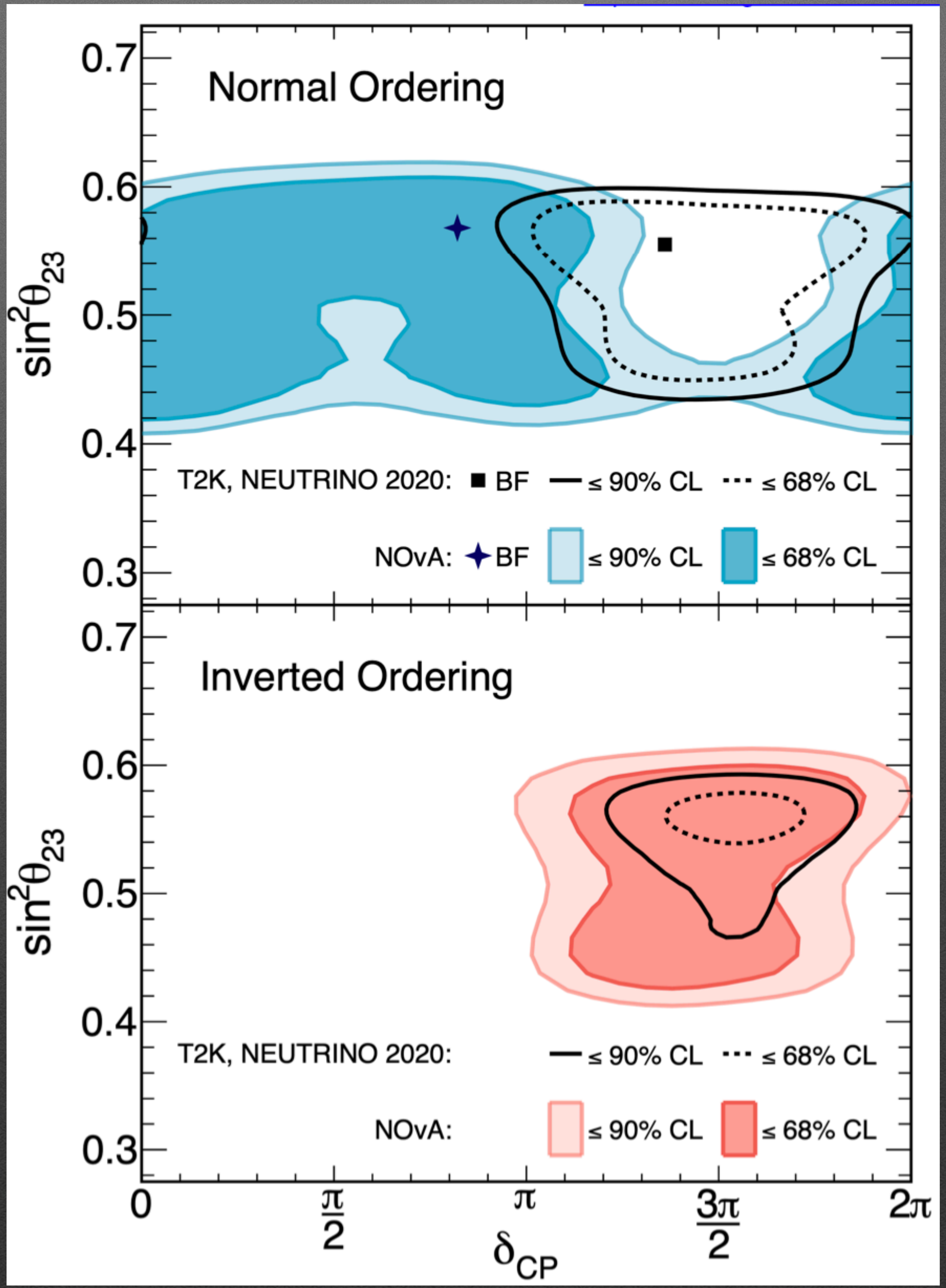
NOvA

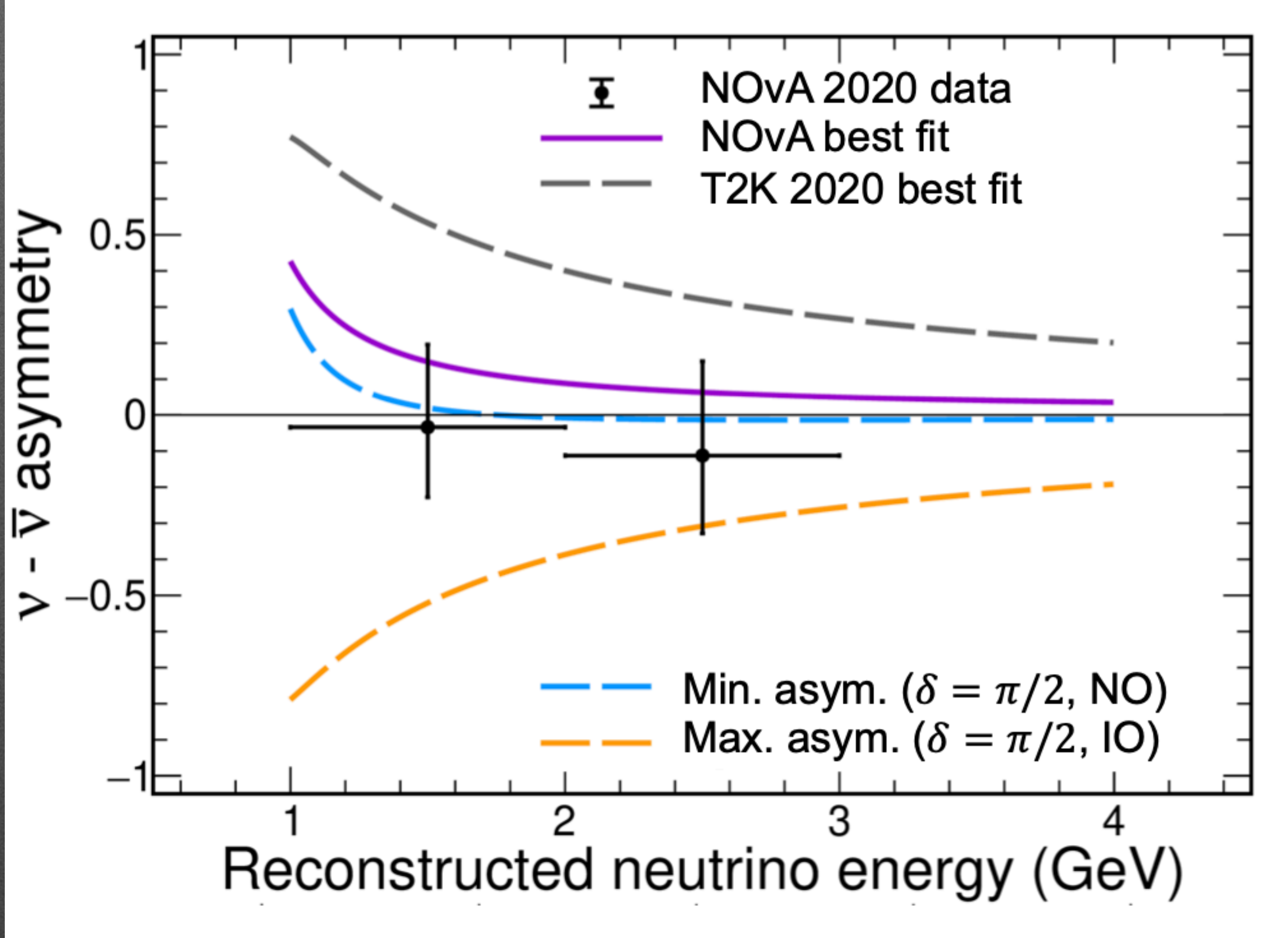


T2K-NOvA “mild tensions”





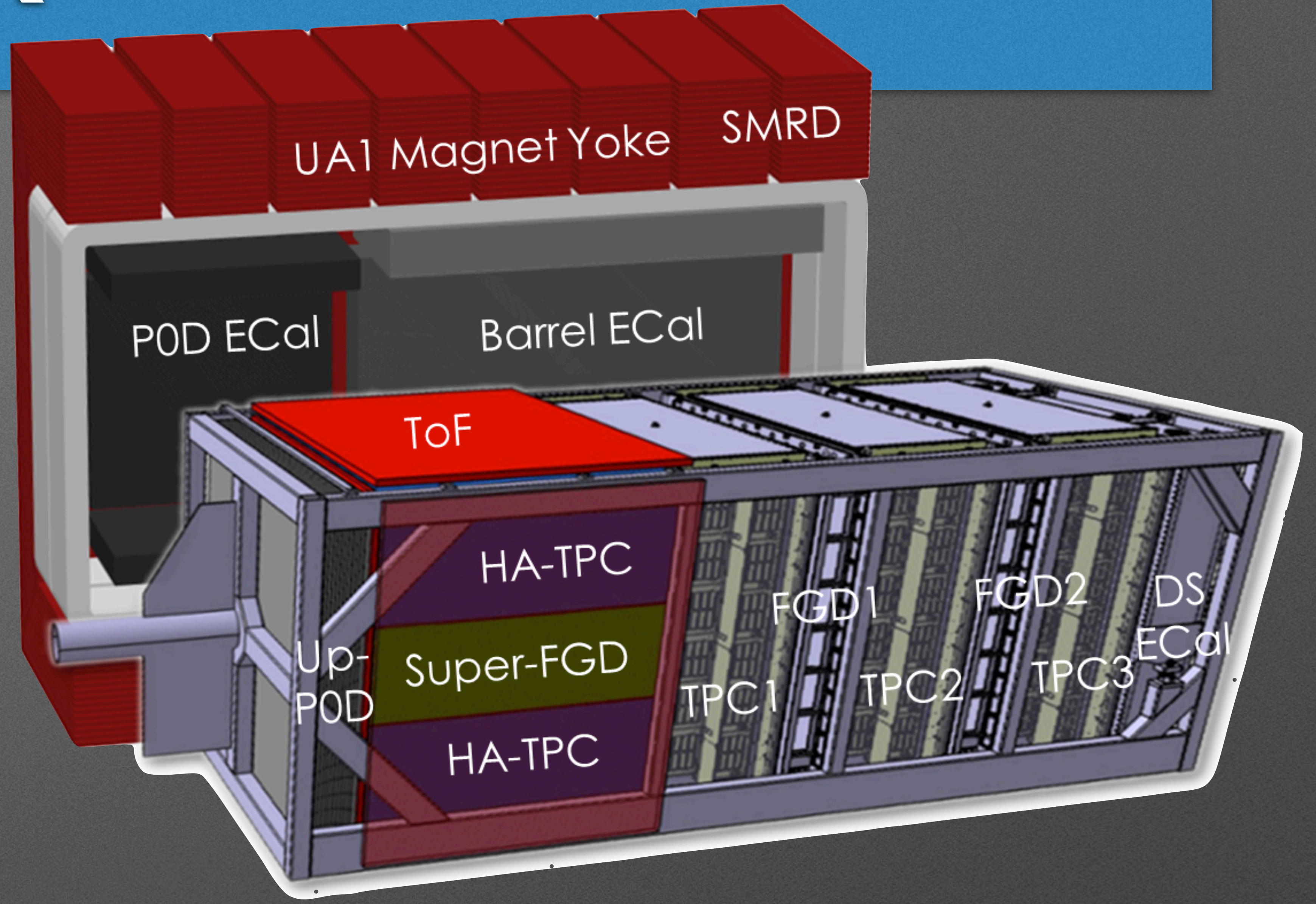


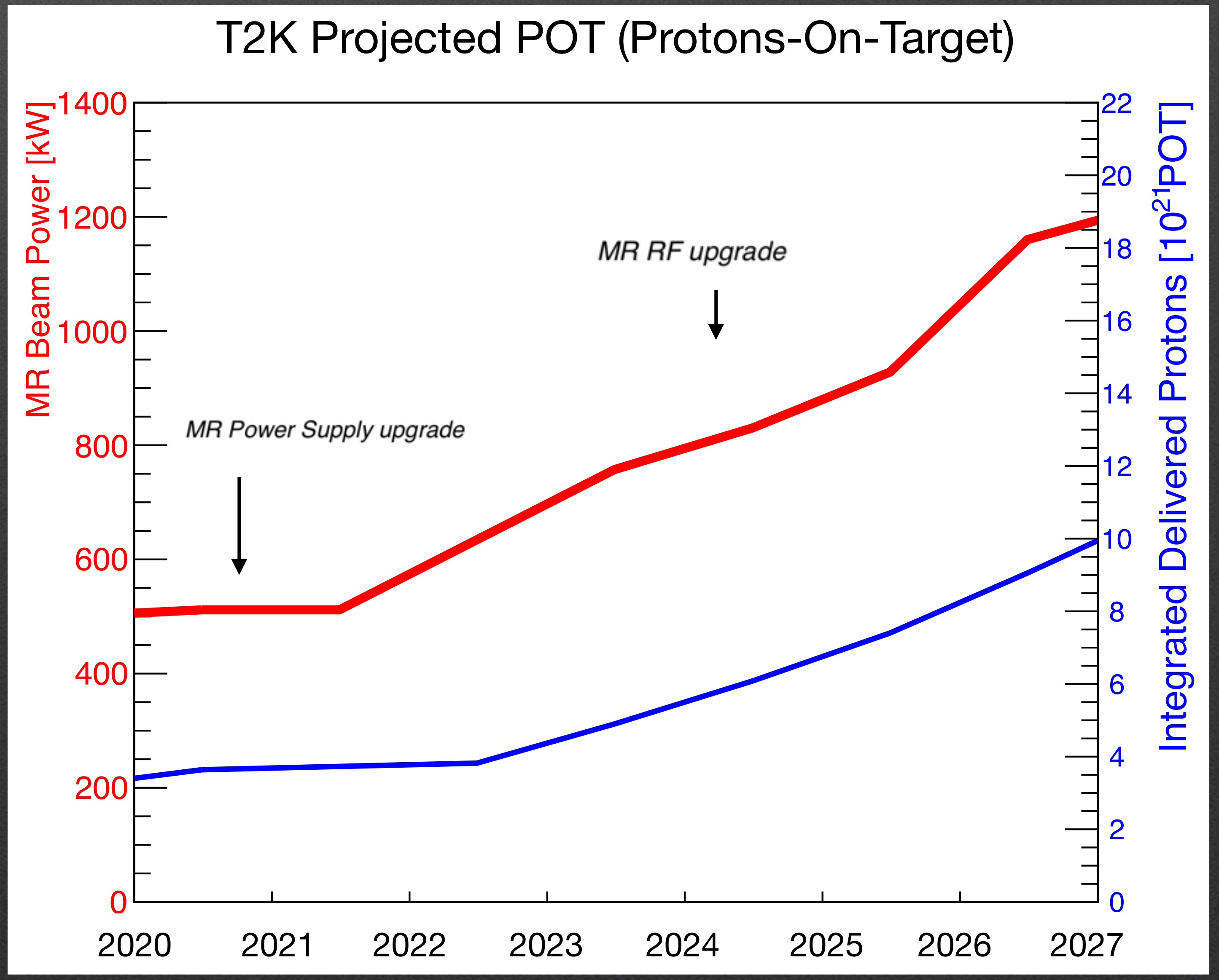


The two collaborations are working on a combined fit → goal to release results this year

Future outlook

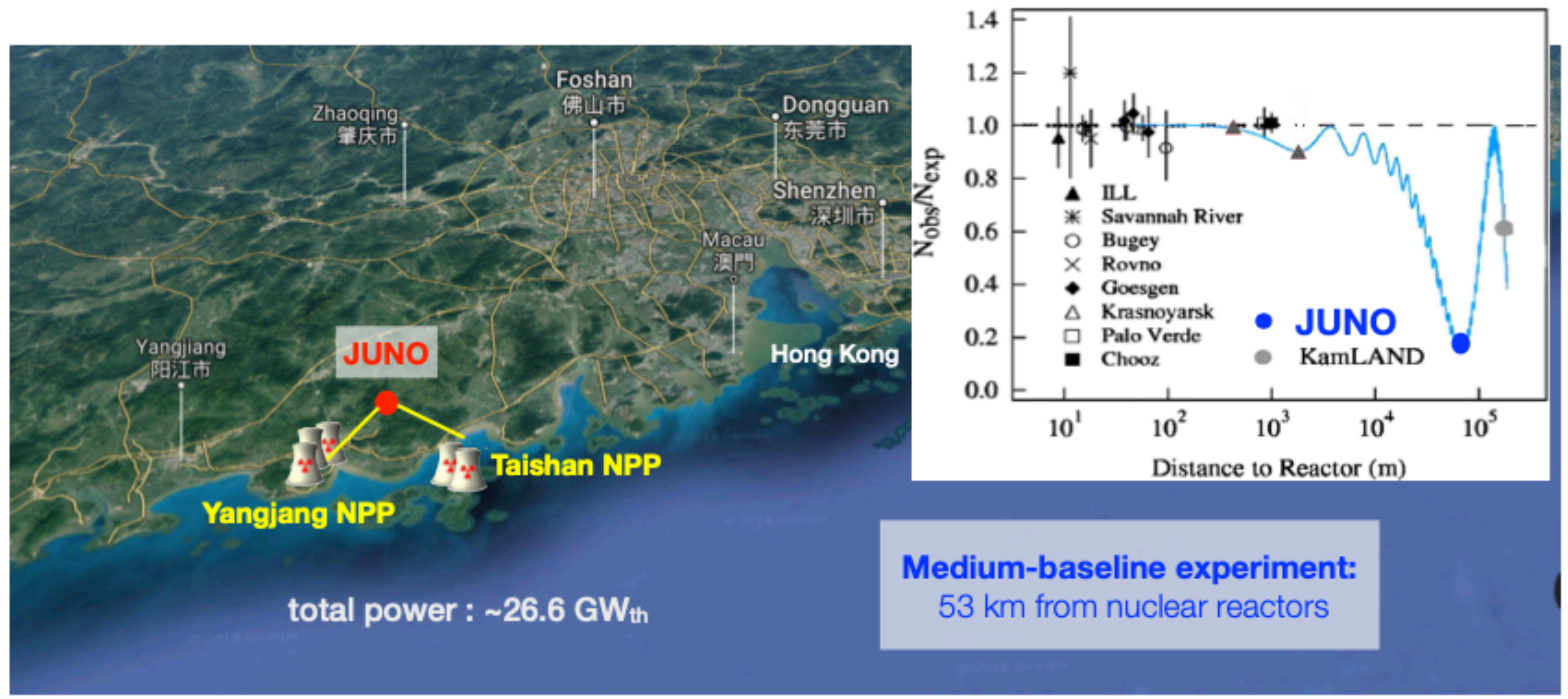
- Running experiments (T2K and NOvA) are both statistically limited
- Will take data in the next few years → T2K-II with Near Detector upgrade!
- T2K and NOvA could reach 3σ indications of CPV and mass ordering for favorable values of δ_{CP}
- To reach 5σ for mass ordering and CPV we need next generation of experiments
- Mass Ordering → reactors (JUNO) & atmospheric (ORCA) and later DUNE
- CPV → only accelerators (Hyper-Kamiokande and DUNE)



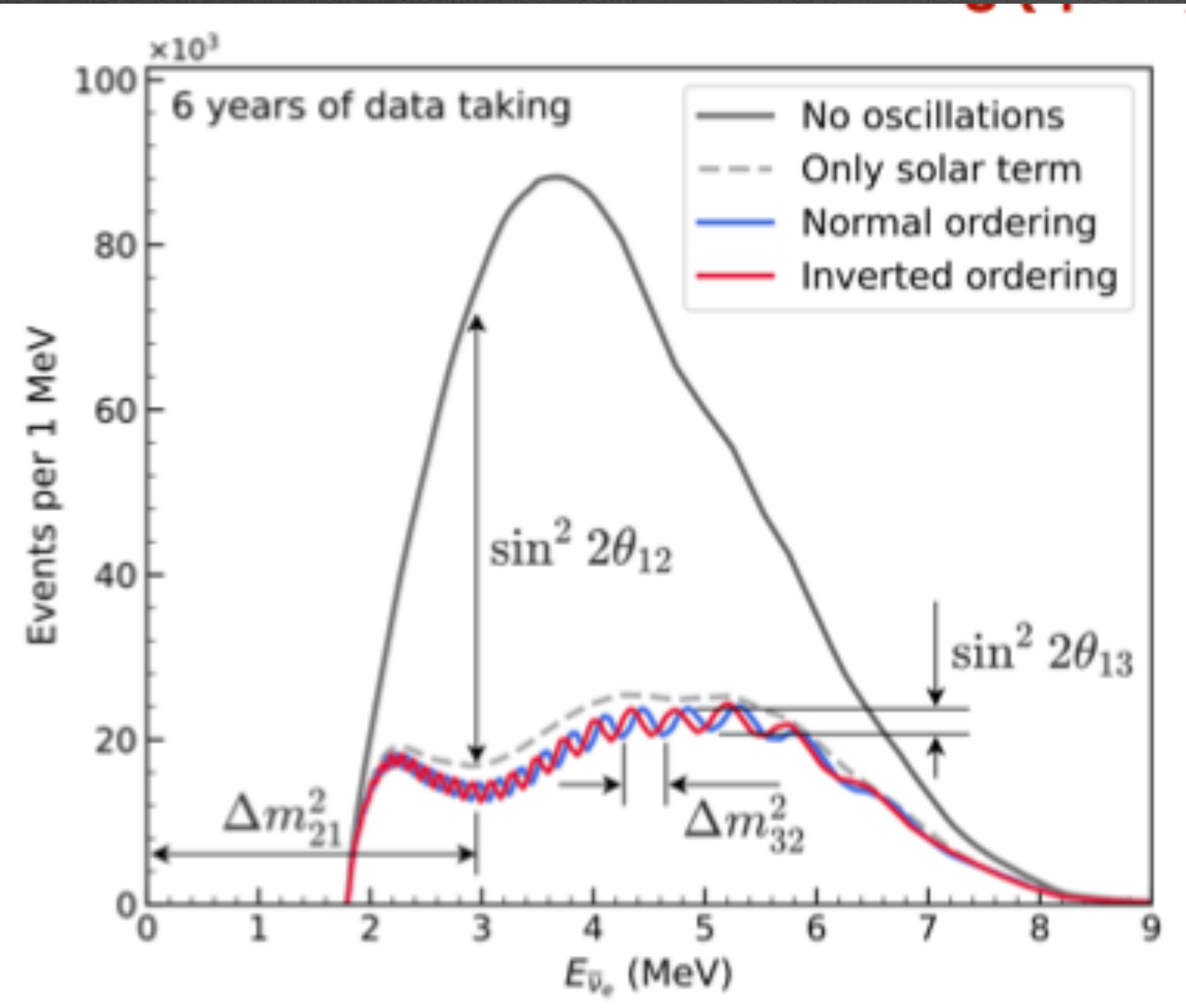


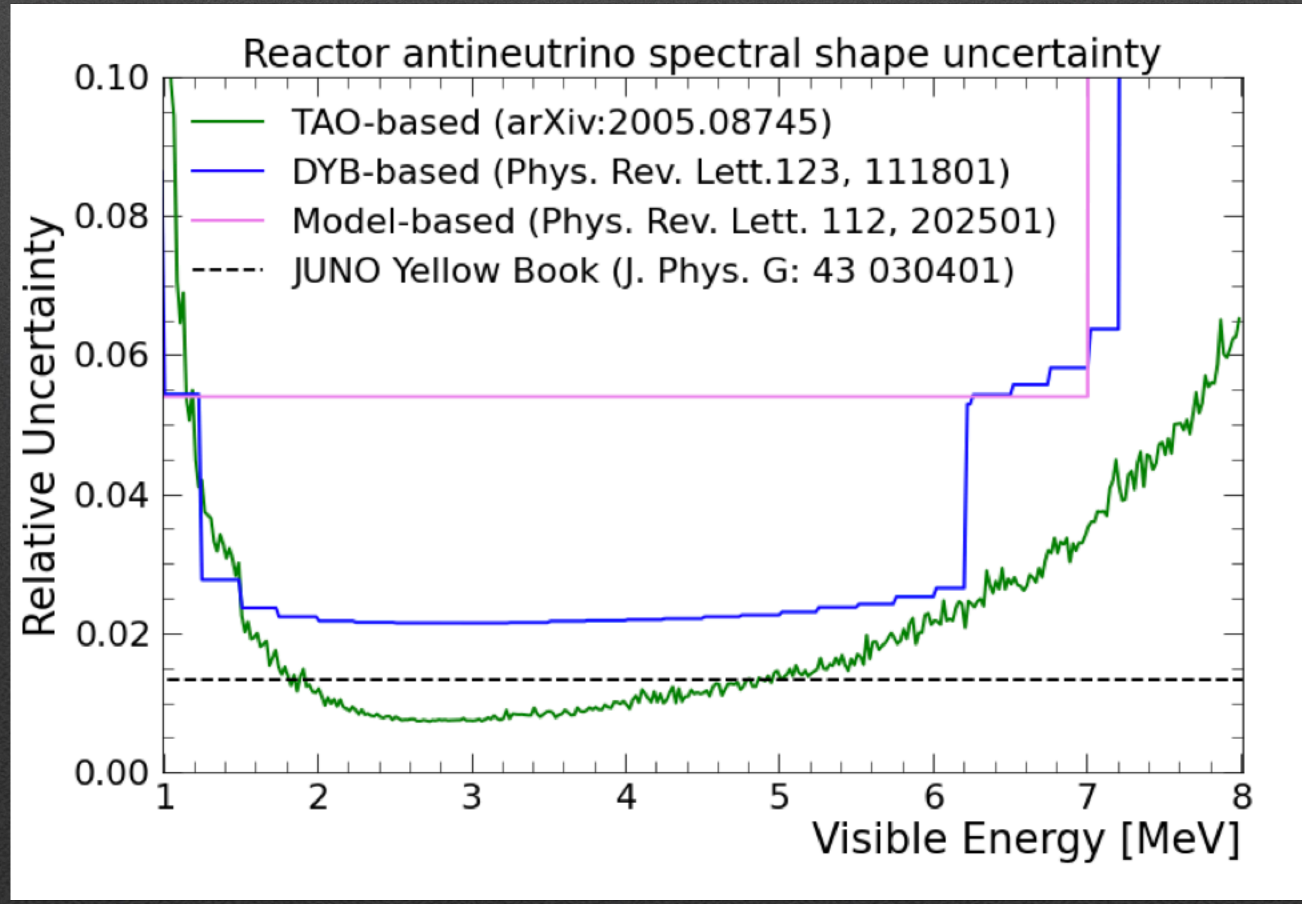
JUNO

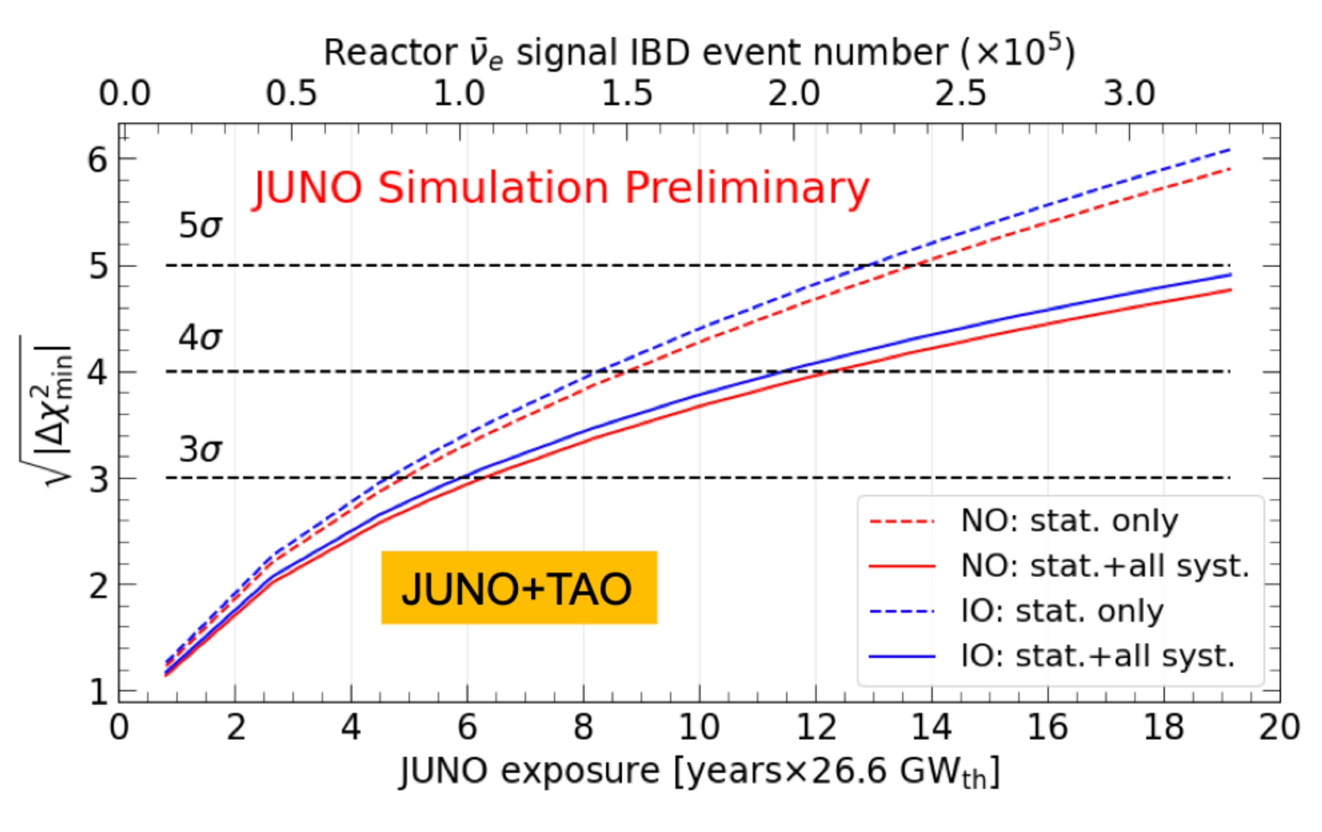
- ✱20 kton Liquid Scintillator detector
- ✱Detector construction will be completed in 2023
- ✱Installed at 53 km from nuclear reactor in China ("solar" oscillations) → very precise measurement of Δm^2_{21} and $\sin^2\theta_{12}$
- ✱~3σ sensitivity to the mass ordering after 6 years of data taking → main challenge is to keep energy resolution <3%



$\bar{\nu}_e$ interaction: Inverse Beta Decay (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$



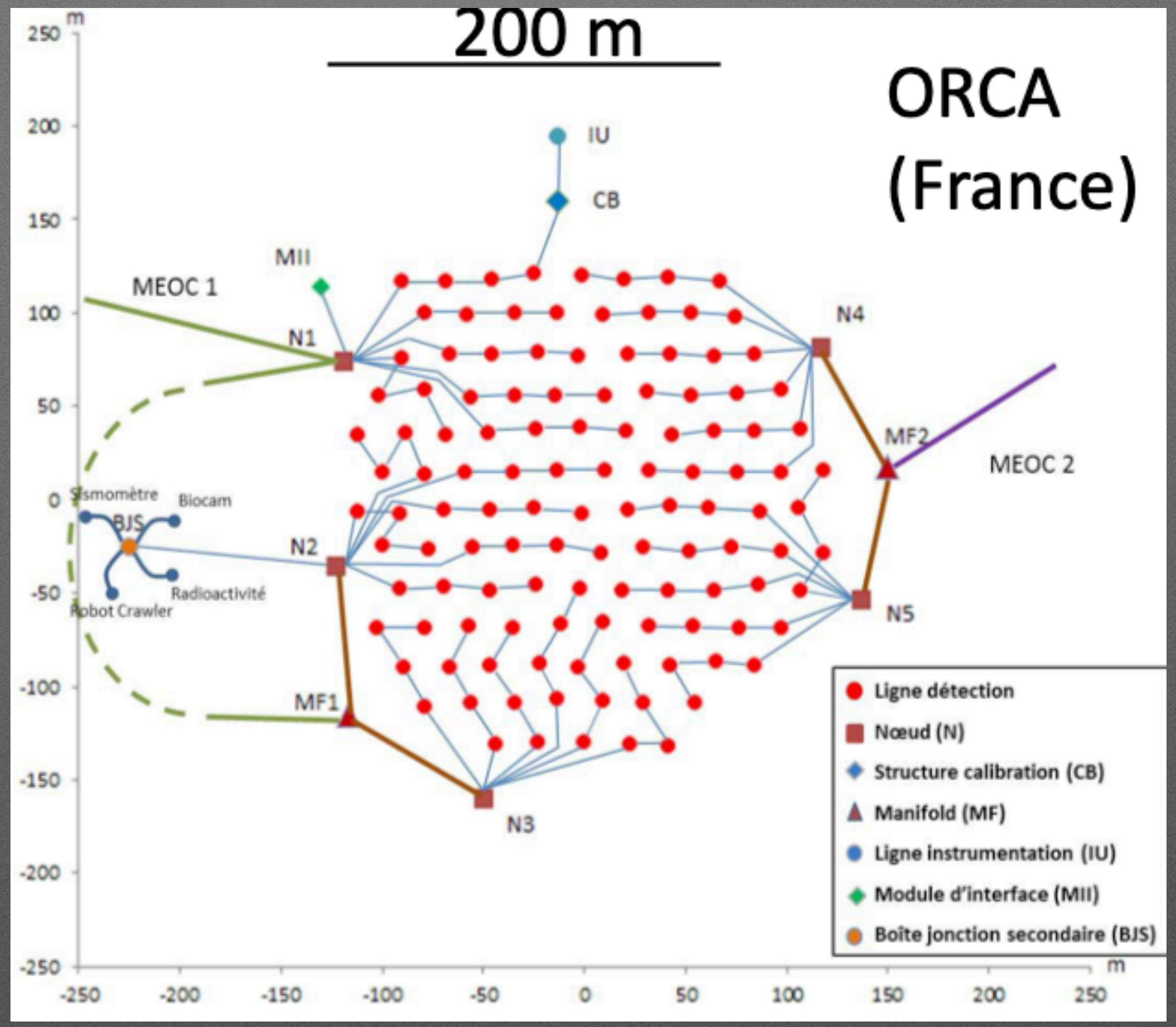


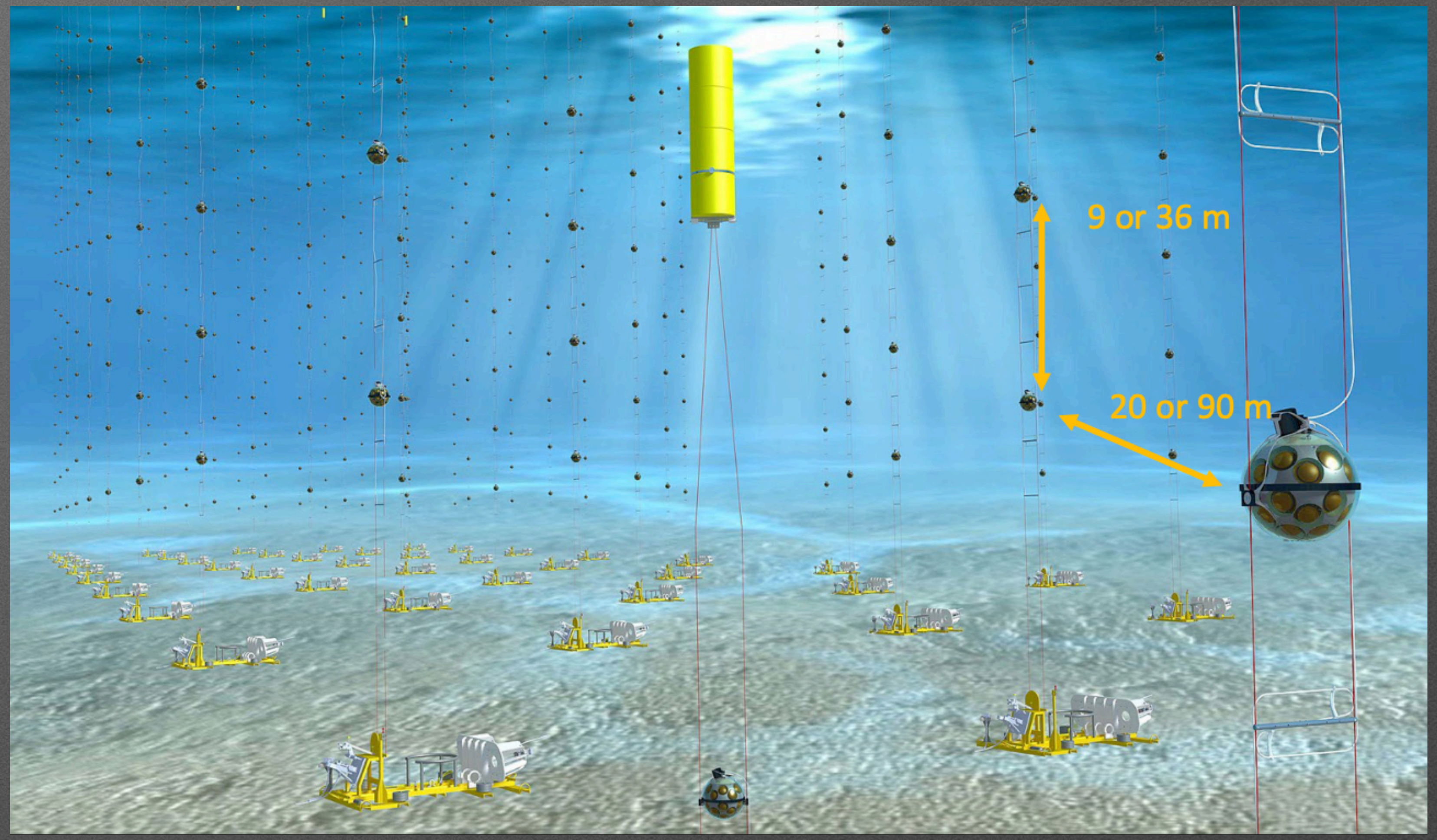


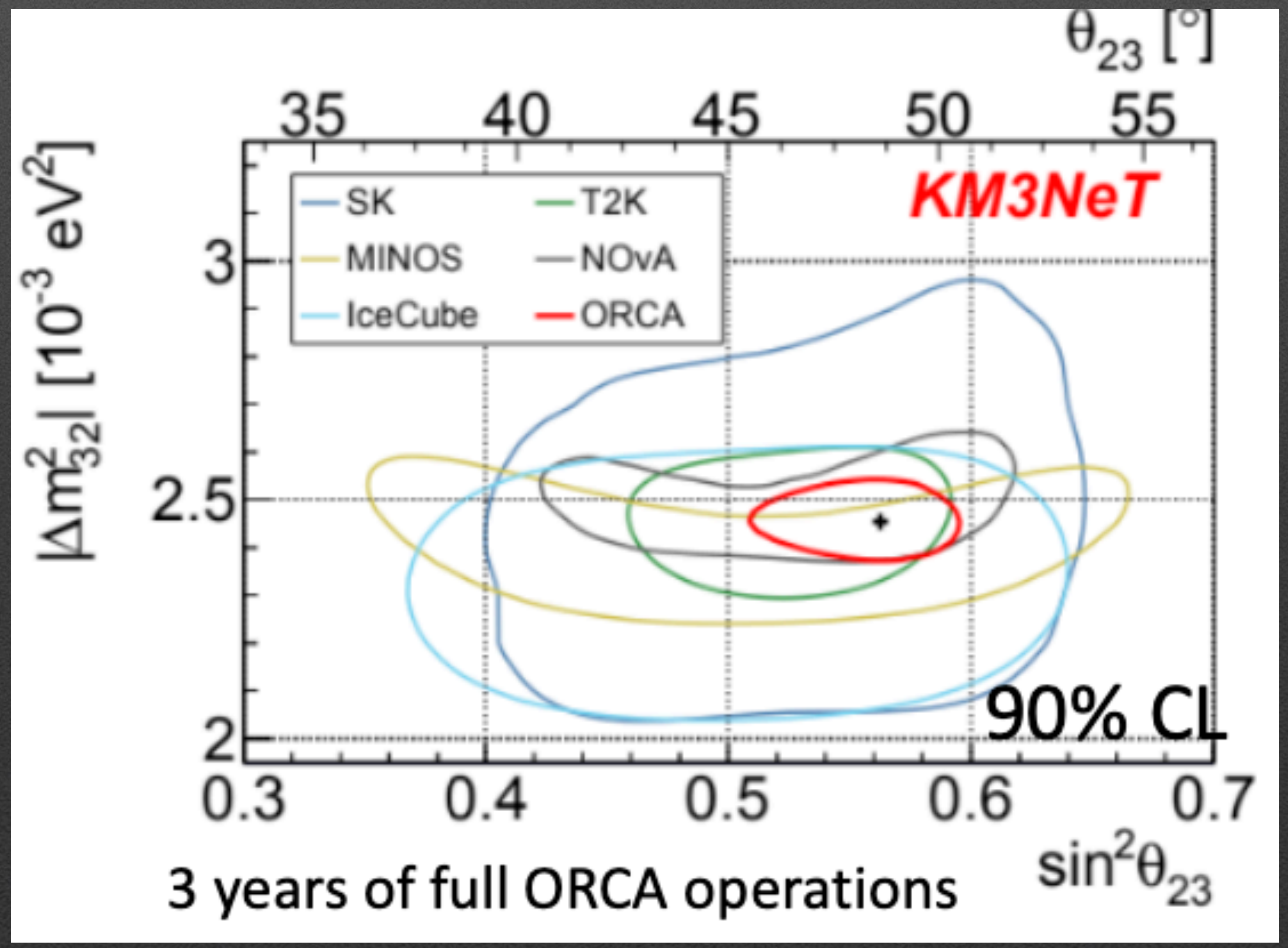
ORCA / KM3NET

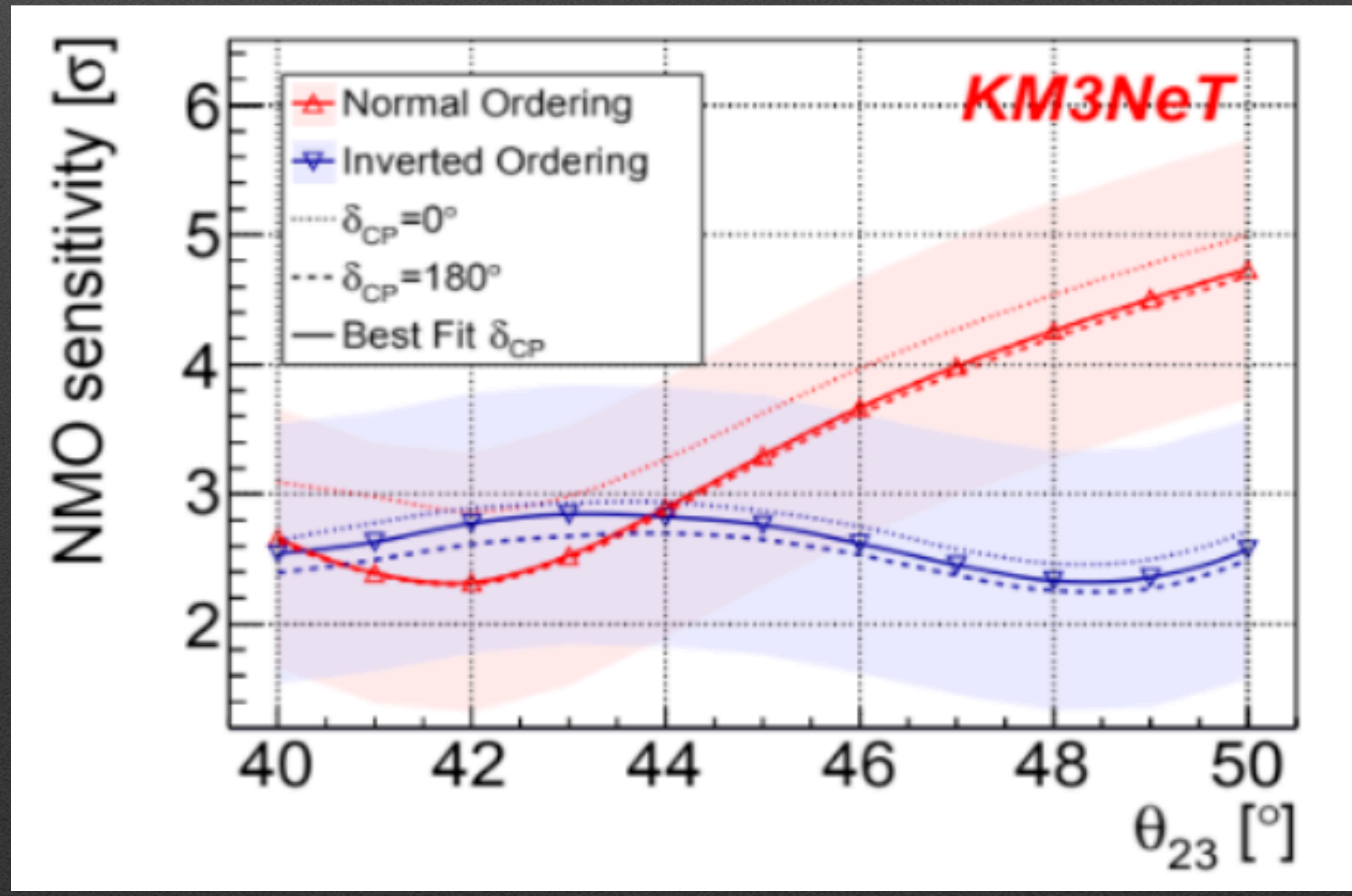
	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Instrumented mass	7 Mton	500*2 Mton

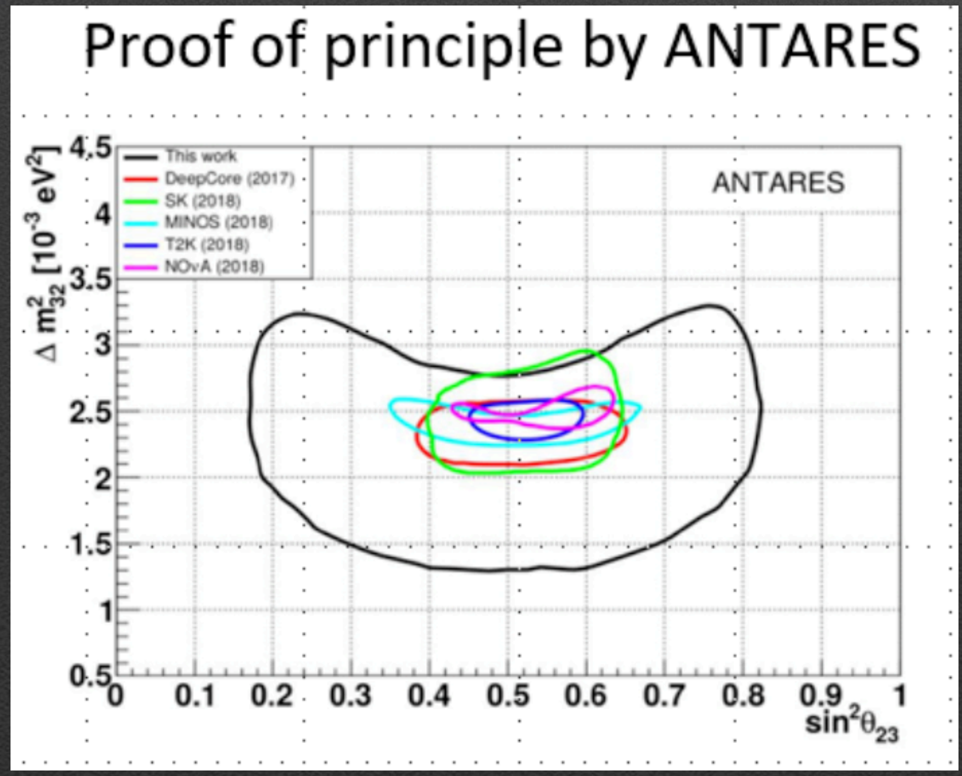
- KM3NET is un undersea neutrino telescope in the Mediterranean Sea
- 2 sites : ARCA mainly for astrophysics and ORCA for neutrino oscillation physics
- Sensitivity to mass ordering by looking for resonant effects in the Earth











The future: Mass Ordering

- When Δm231 is measured in the correct hierarchy the measuremnt from JUNO and ORCA coincide

JUNO
ORCA

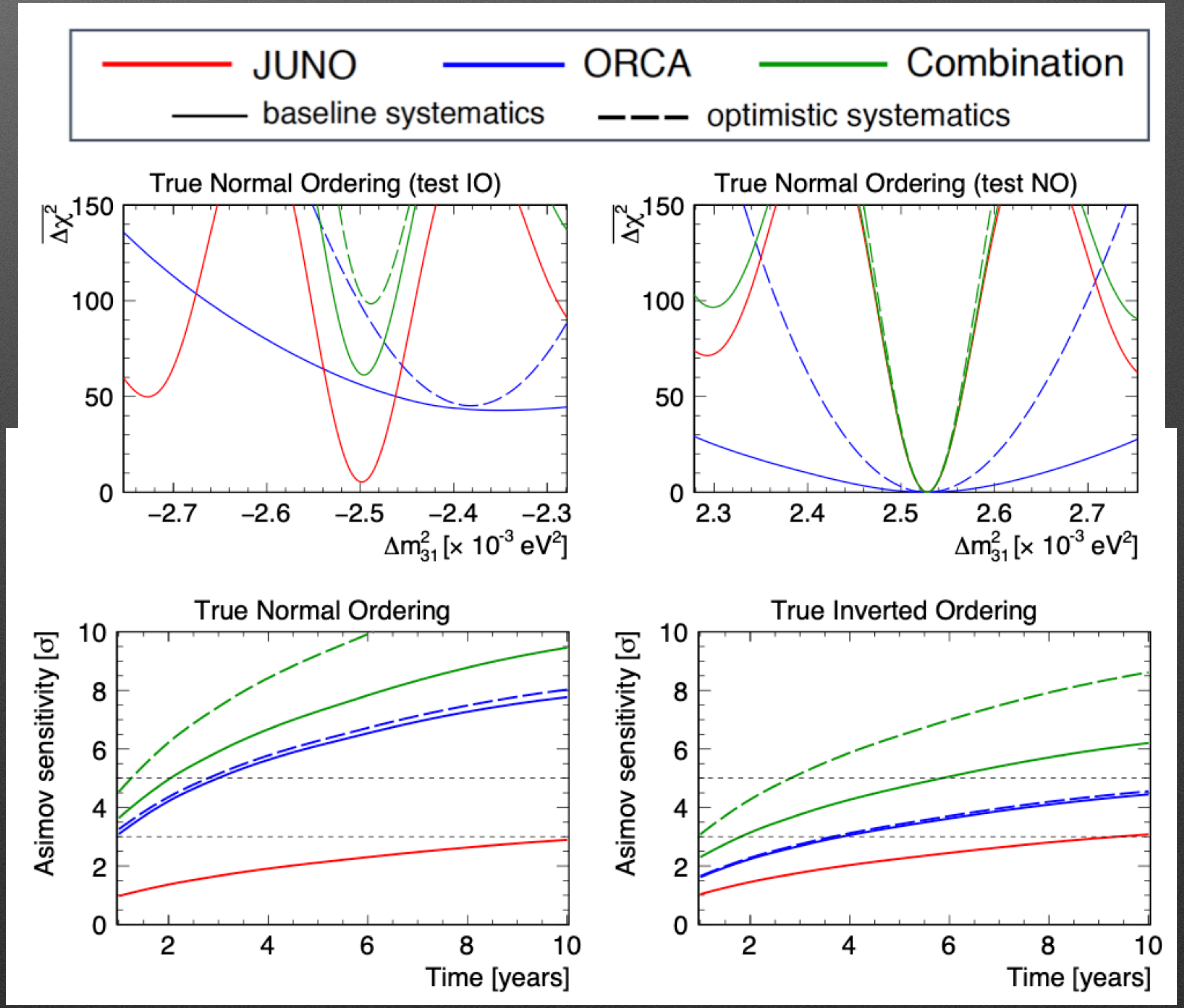
$$\Delta m^2_{ee} = c^2_{12}\Delta m^2_{31} + s^2_{12}\Delta m^2_{32}$$
$$\Delta m^2_{\mu\mu} = s^2_{12}\Delta m^2_{31} + c^2_{12}\Delta m^2_{32} + \mathcal{O}(s_{13}\Delta m^2_{21})$$

Differ by $\pm \sim 1.5\%$ in each mass ordering

- When it is done in the wrong hierarchy the minimum is found at different values and the combination boost the sensitivity to mass ordering

- Possibility of measuring Mass Ordering at more than 5σ for all values of θ_{23} and ordering

- Definite measurement of Mass Ordering in one single experiment will be done by DUNE thanks to its longer baseline



Next generation LBL experiments

- Combinations of reactor and atmospheric neutrinos will help answering the question about Mass Ordering

- But to observe CP violation in the leptonic sector we need a next generation of Long Baseline experiments!

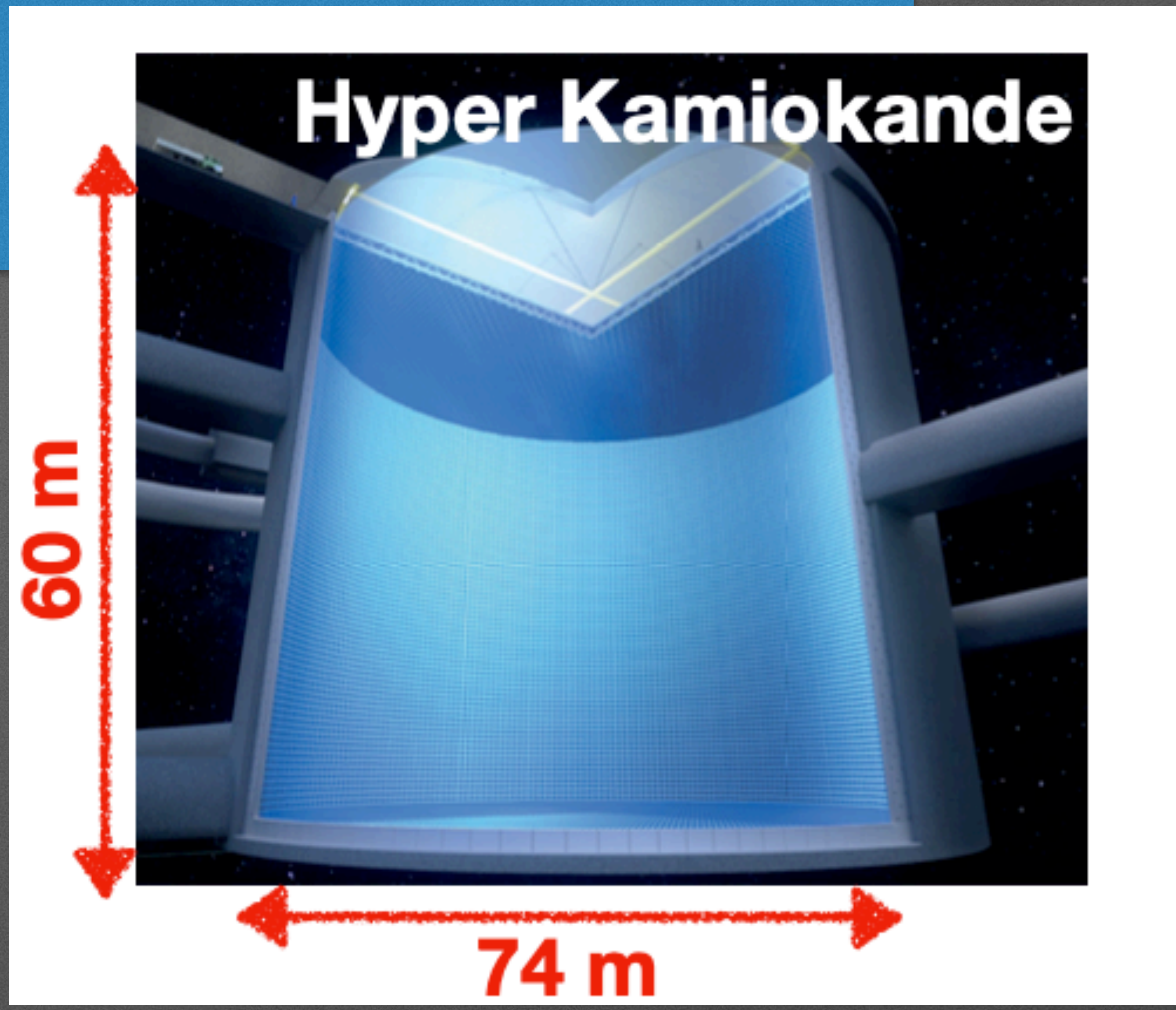
- These experiments have a guaranteed measurement → δCP will be measured with precision of 10-20 degrees depending on its value

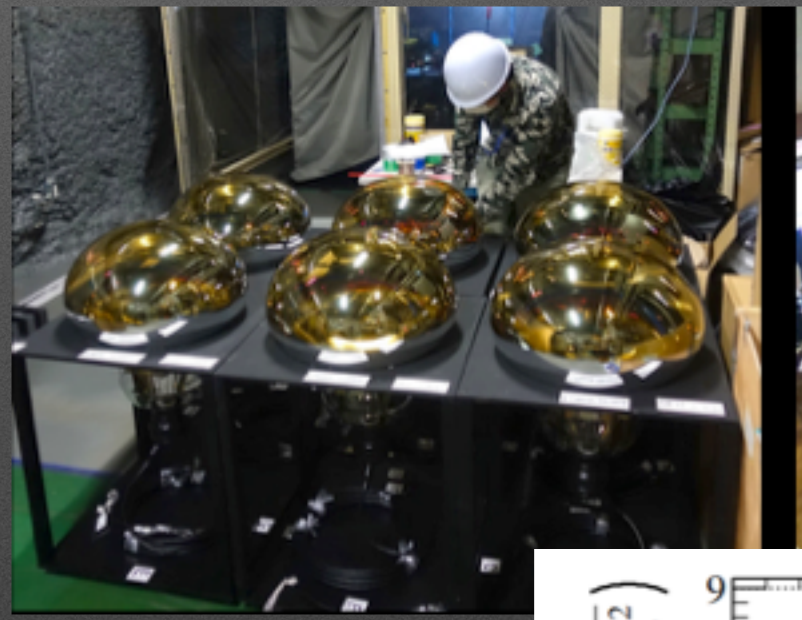
- They will also be an unprecedented observatory for astrophysics neutrinos (especially SN neutrinos) and for seraches of proton decay!

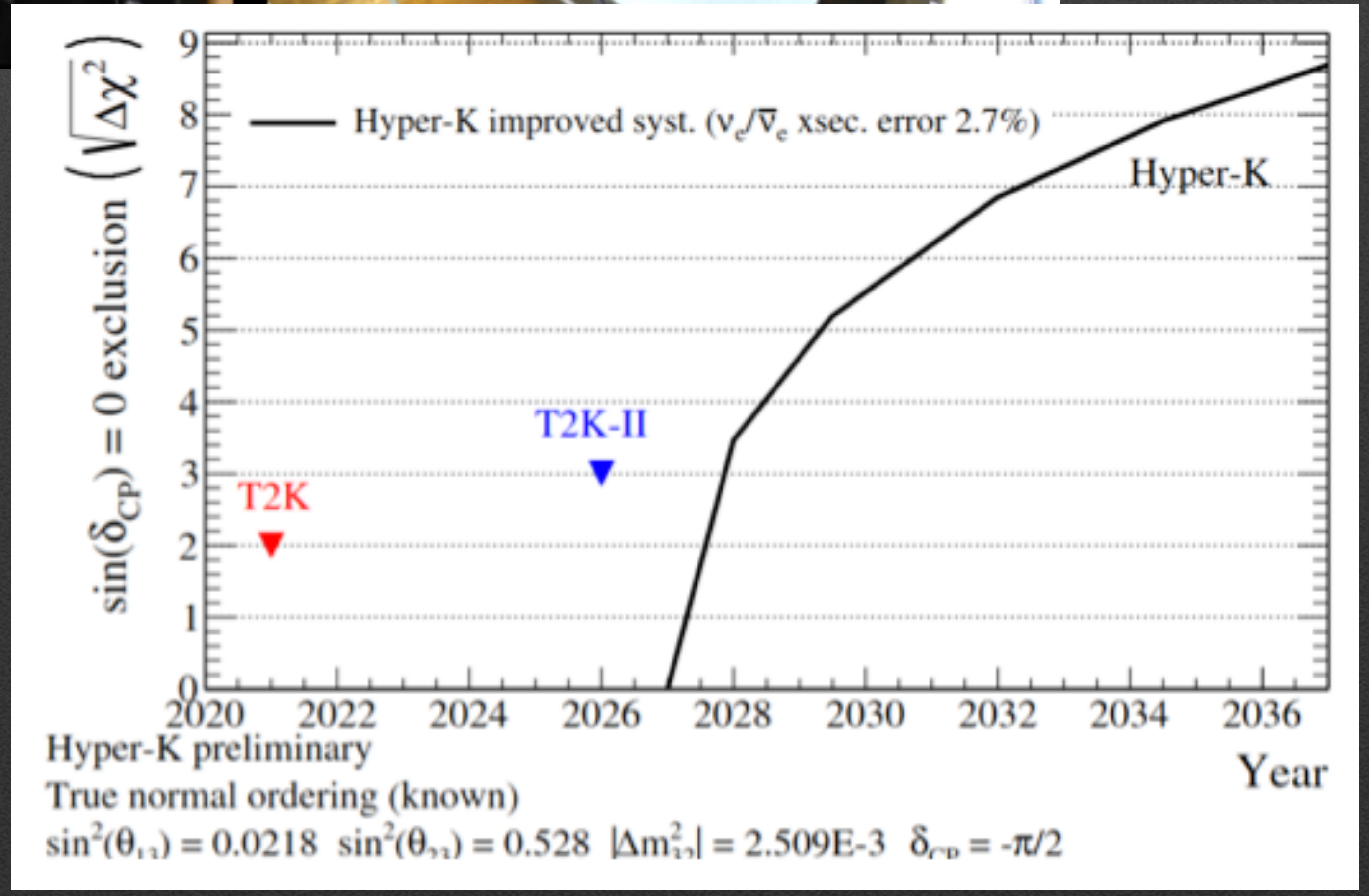
- Two such experiments will start in this decade: Hyper-Kamiokande and DUNE

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 detector composed by T2K ND280 and a new Intermediate detector
- 1 year of HK → > 20 years of T2K!
- Construction started in April 2020 → start operation in 2027

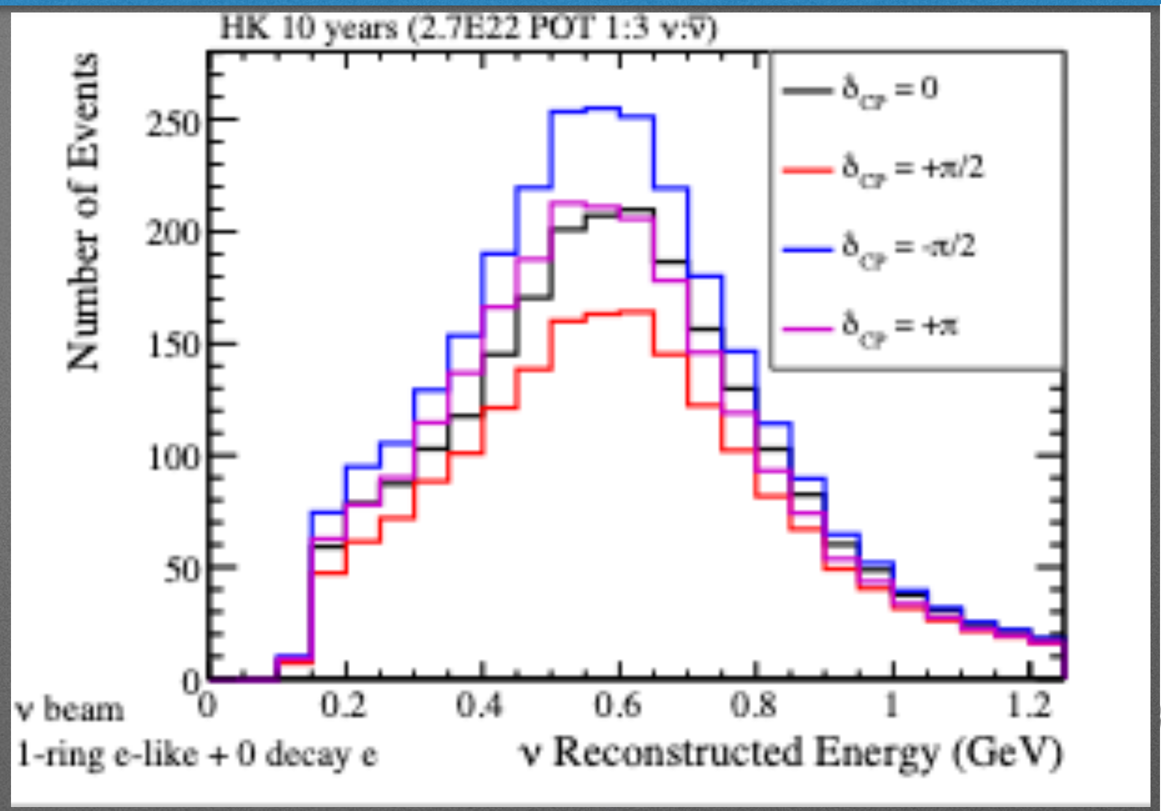


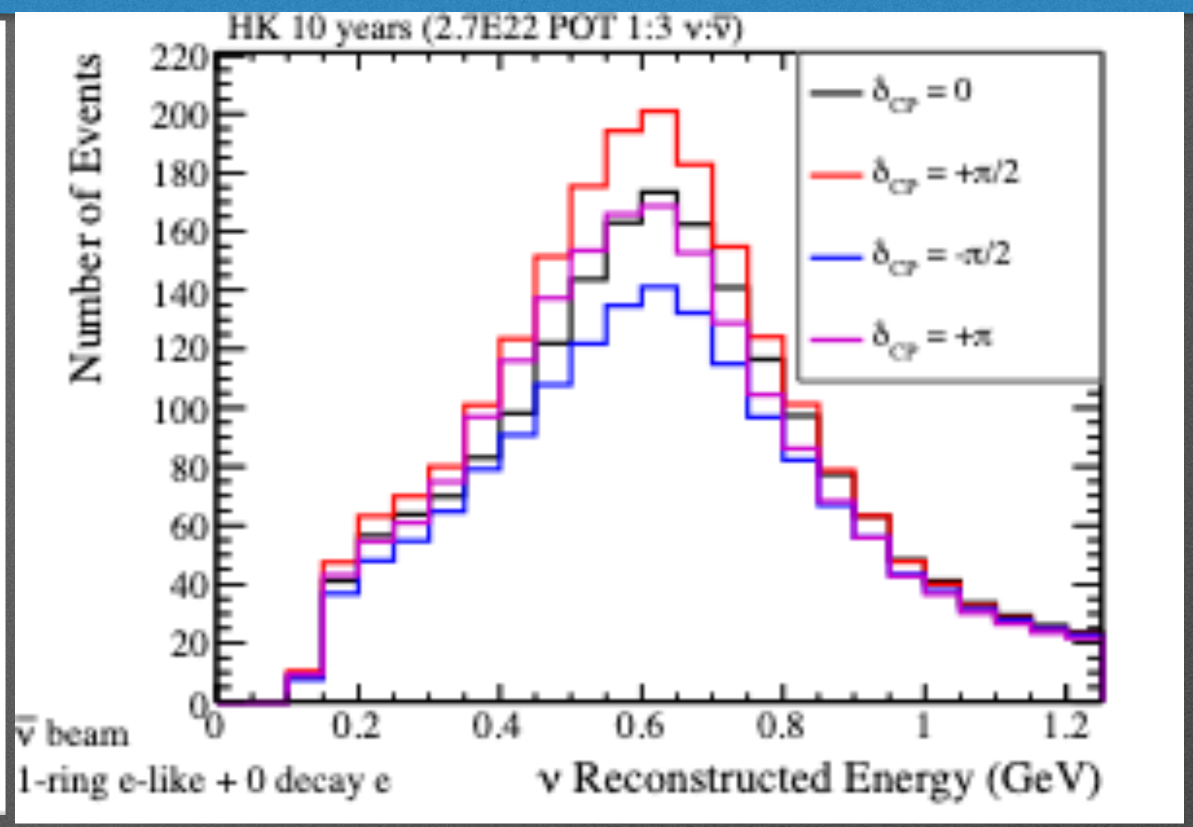


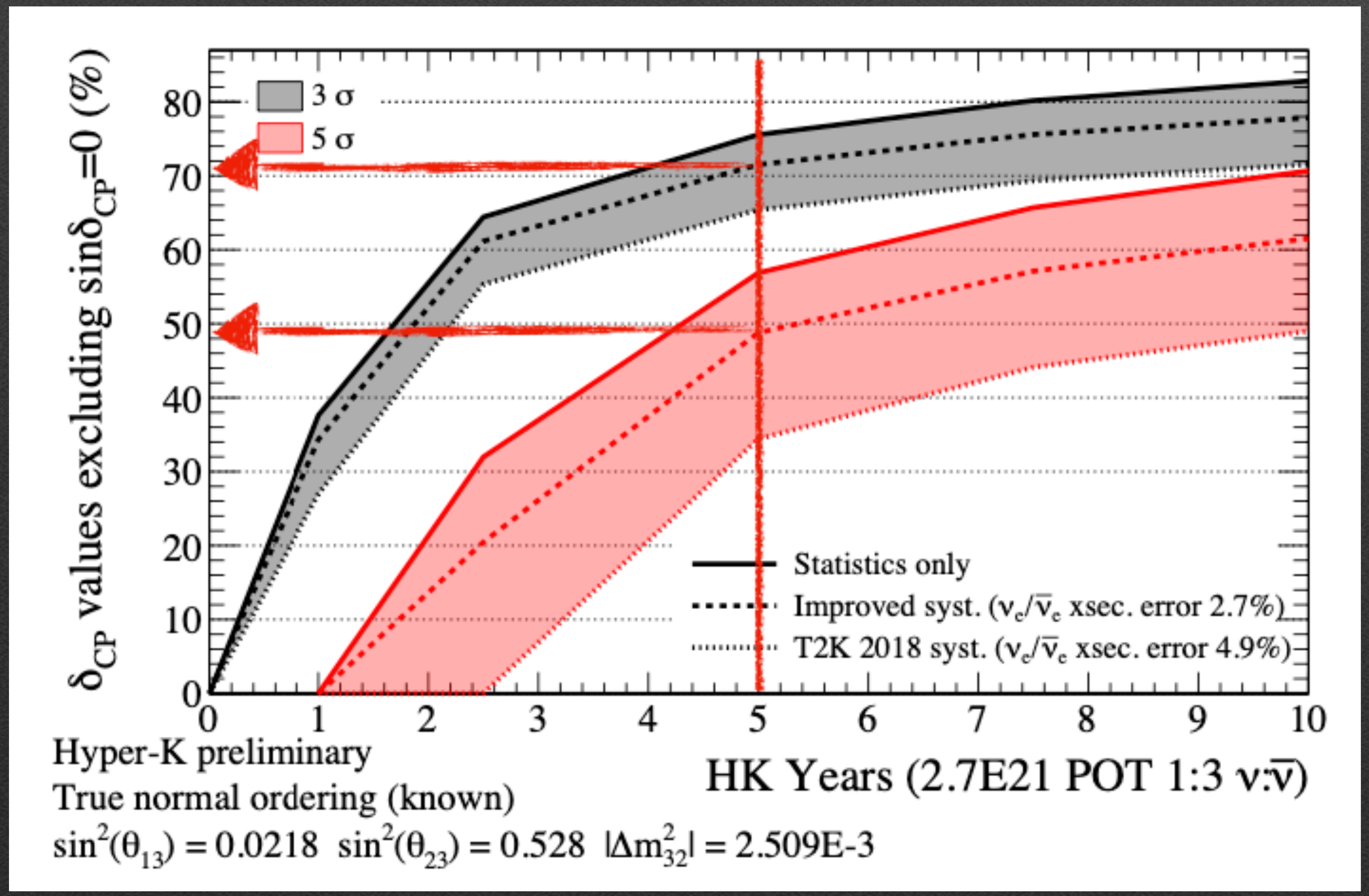


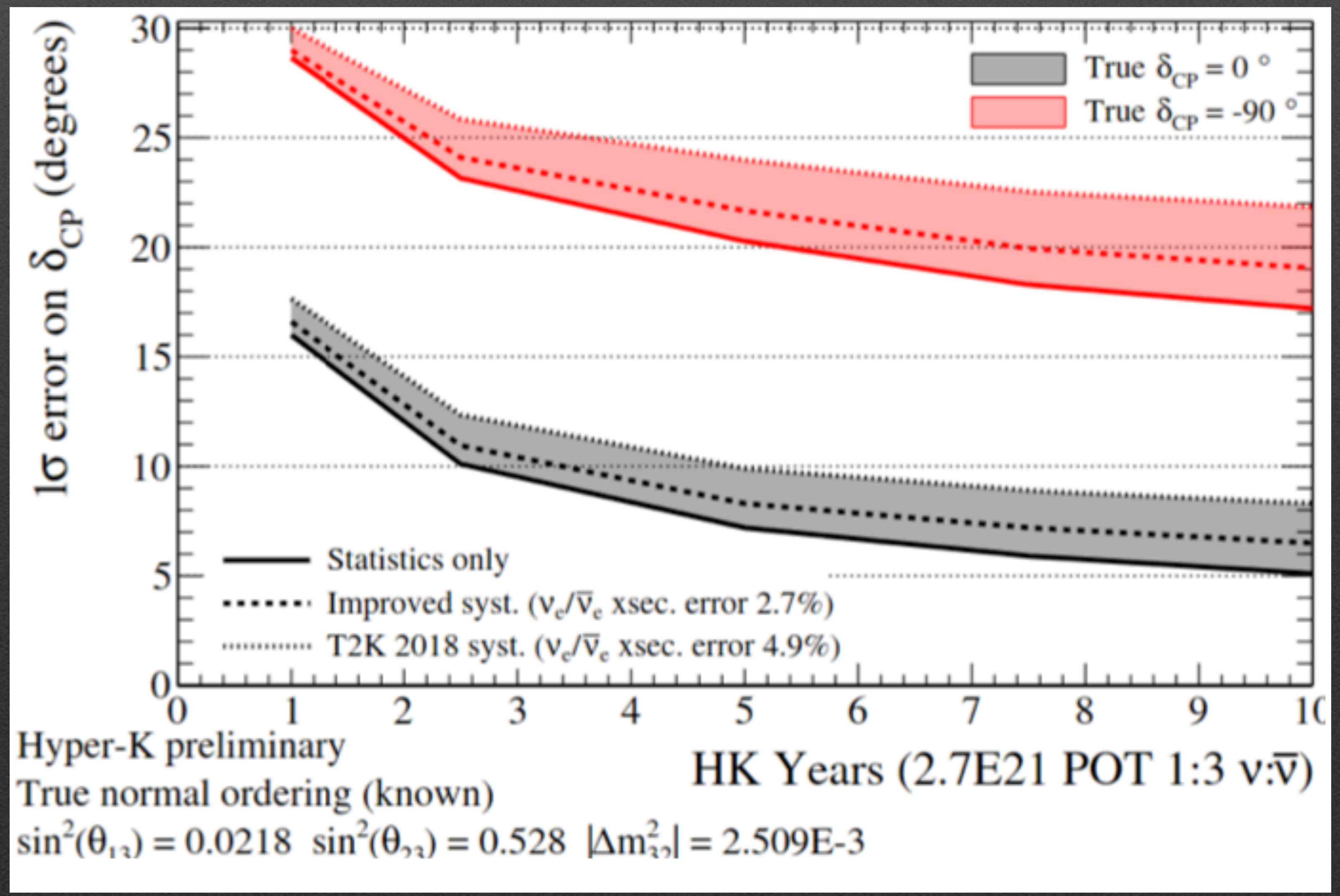
HK sensitivity to CP violation

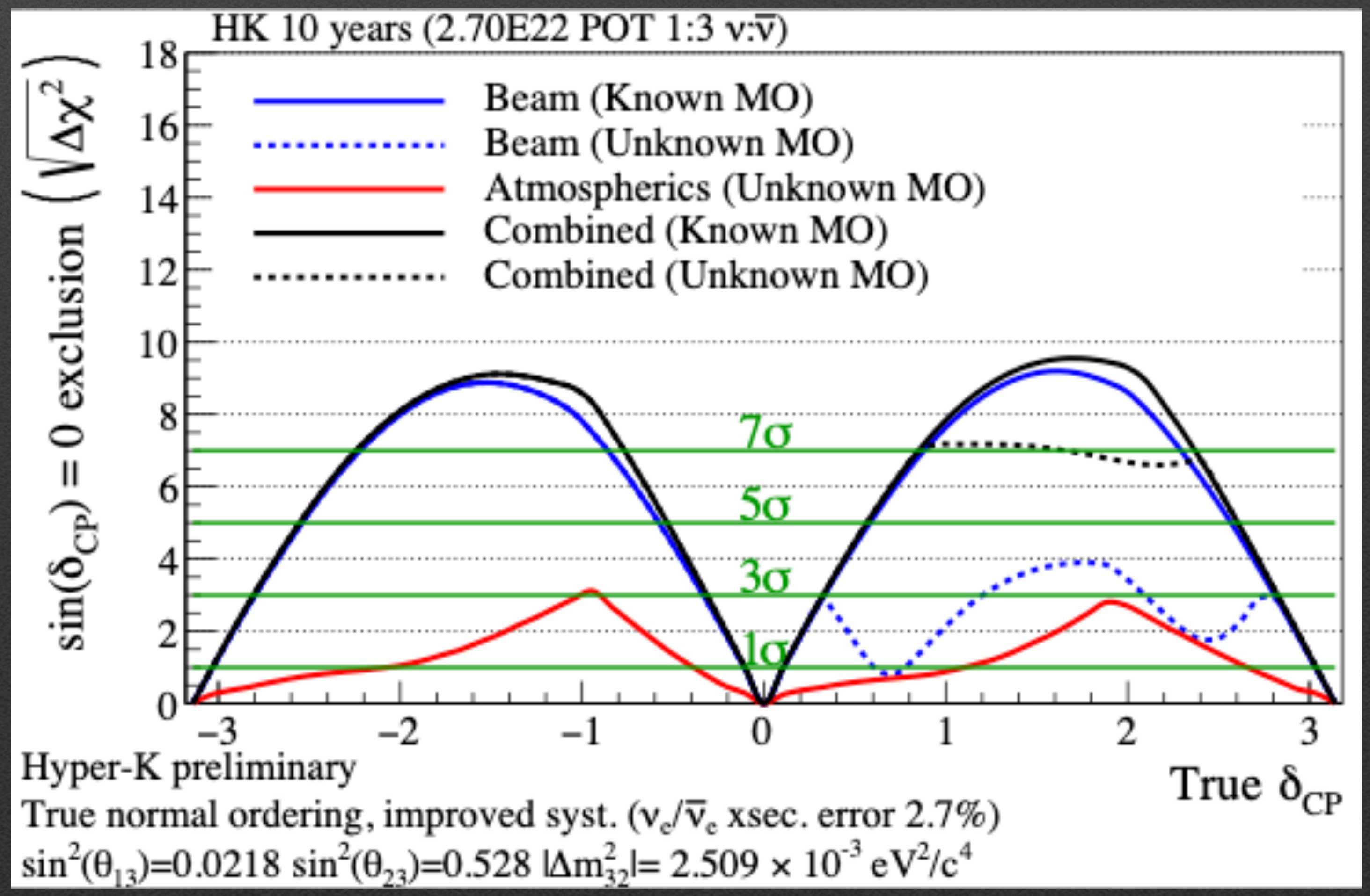
- ~2000 signal events for ν and $\bar{\nu}$ in 10 years
- CPV at 5 σ in 2 years for δ_{CP}=-π/2
- After 5 years observe CPV at 5σ for 50% of the values of δCP and at 3σ for 70% of the values
- If MO unknown, HK will break degeneracies between MO and CPV by combining beam and atmospheric neutrinos





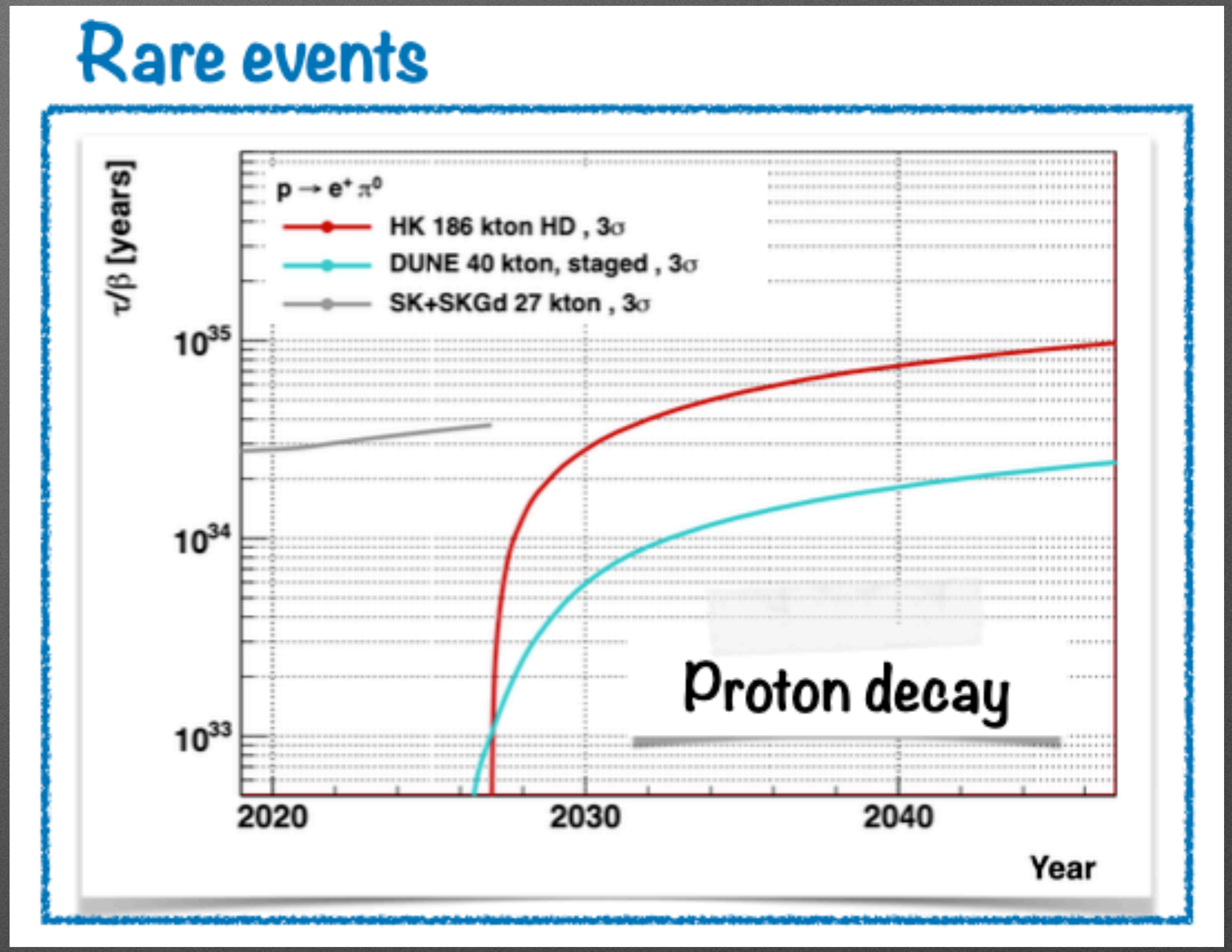




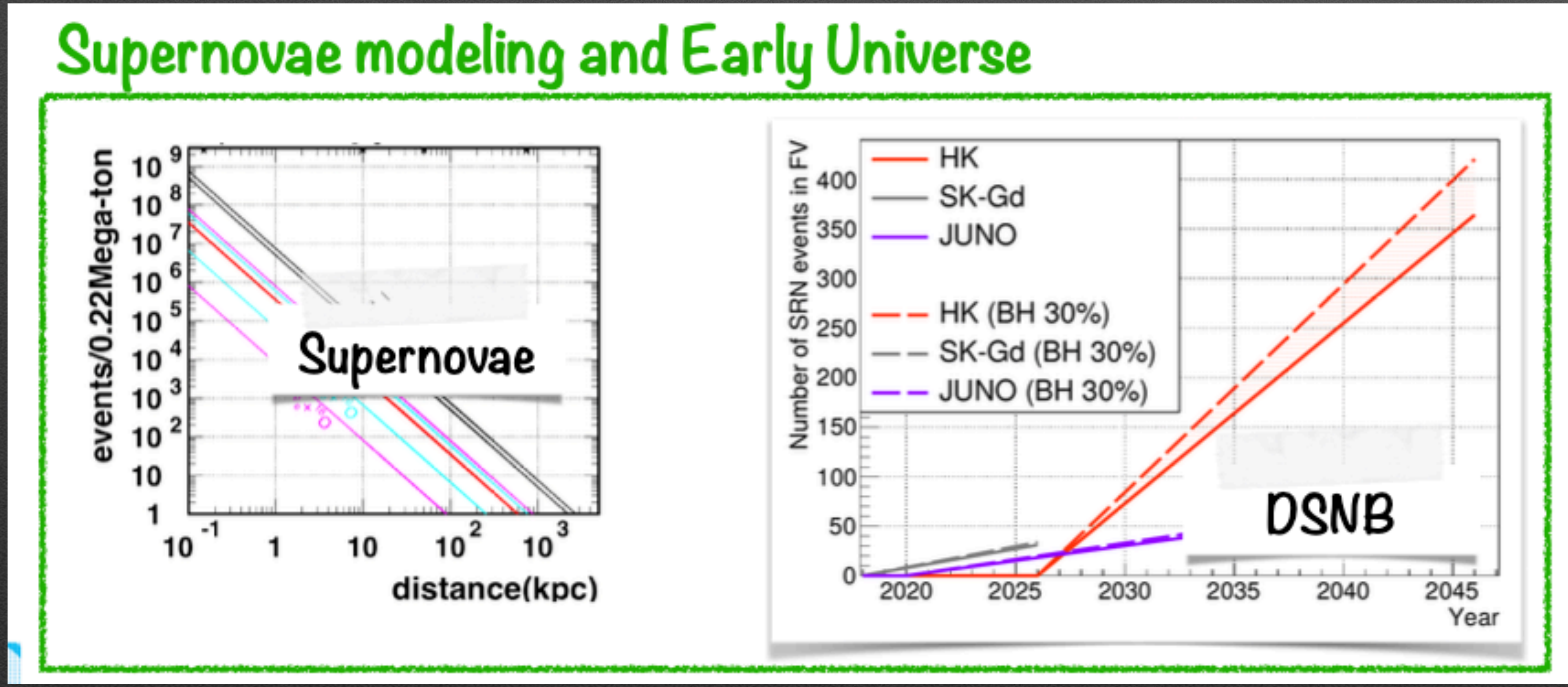


HK → Not only CP violation!

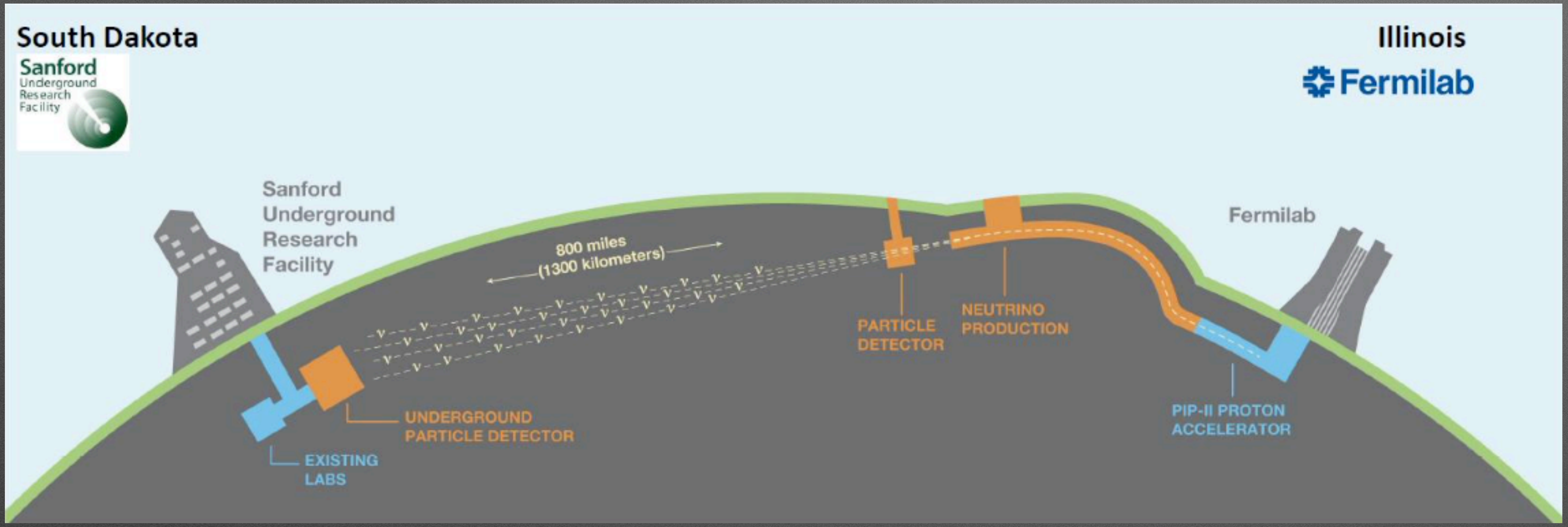
- HK will be the largest detector sensitive to MeV neutrinos → surpass Super-K sensitivity
- Sensitive to neutrinos from SuperNovae bursts at 1 Mpc → except 1 SN every 3 years
  - >1000 events in few seconds for explosions in our galaxy!
- Sensitive to neutrinos from Diffuse SN background

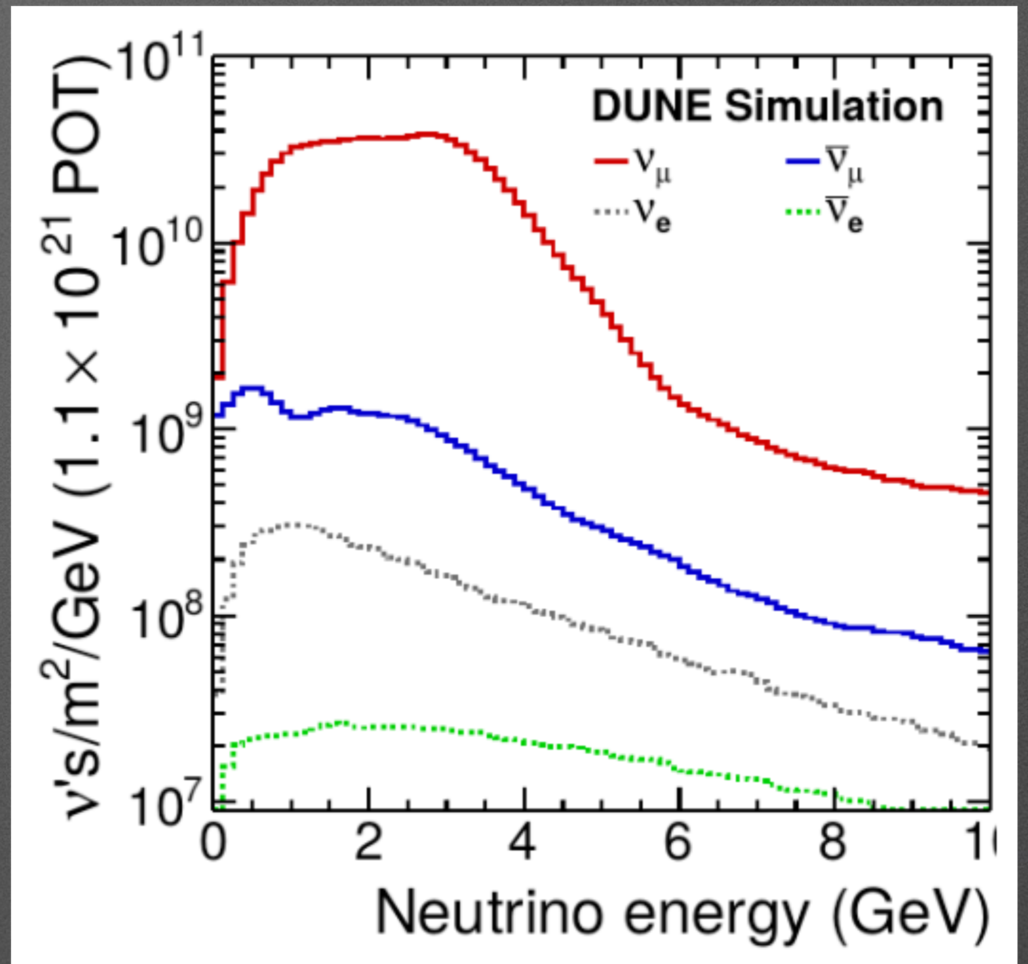


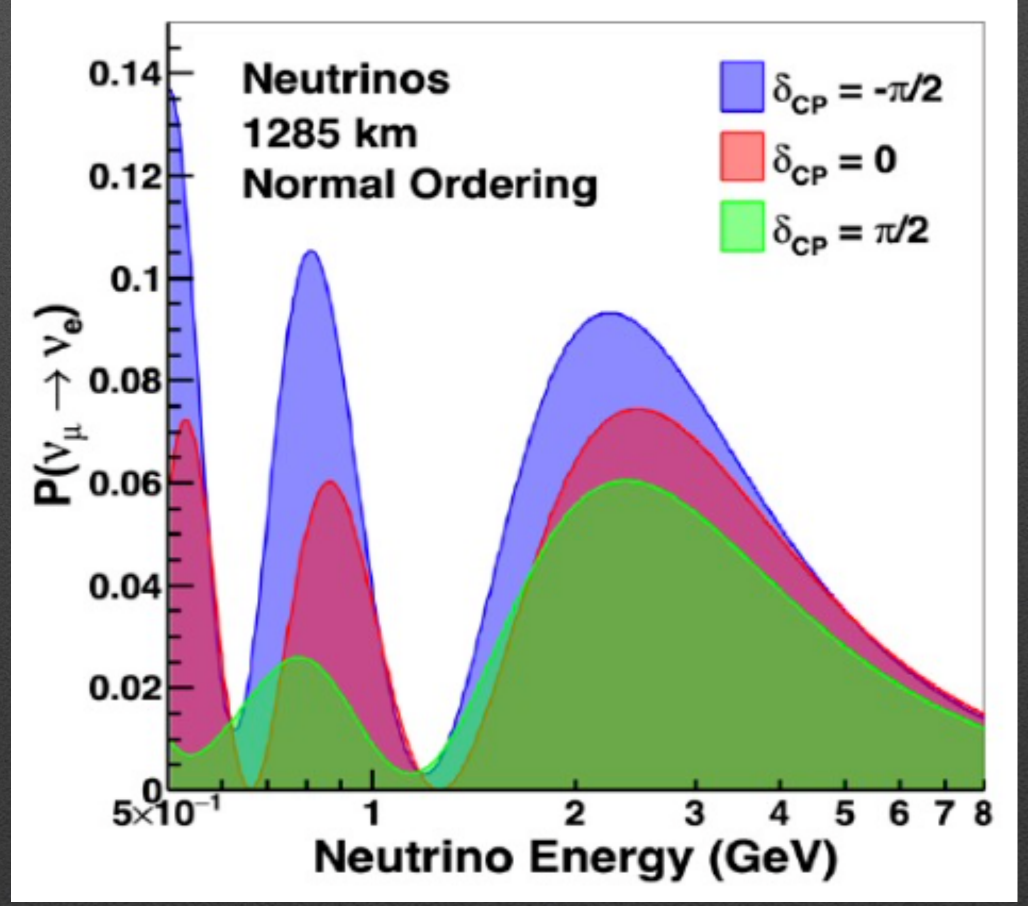
- Improve limits on proton decay by ~1 order of magnitude



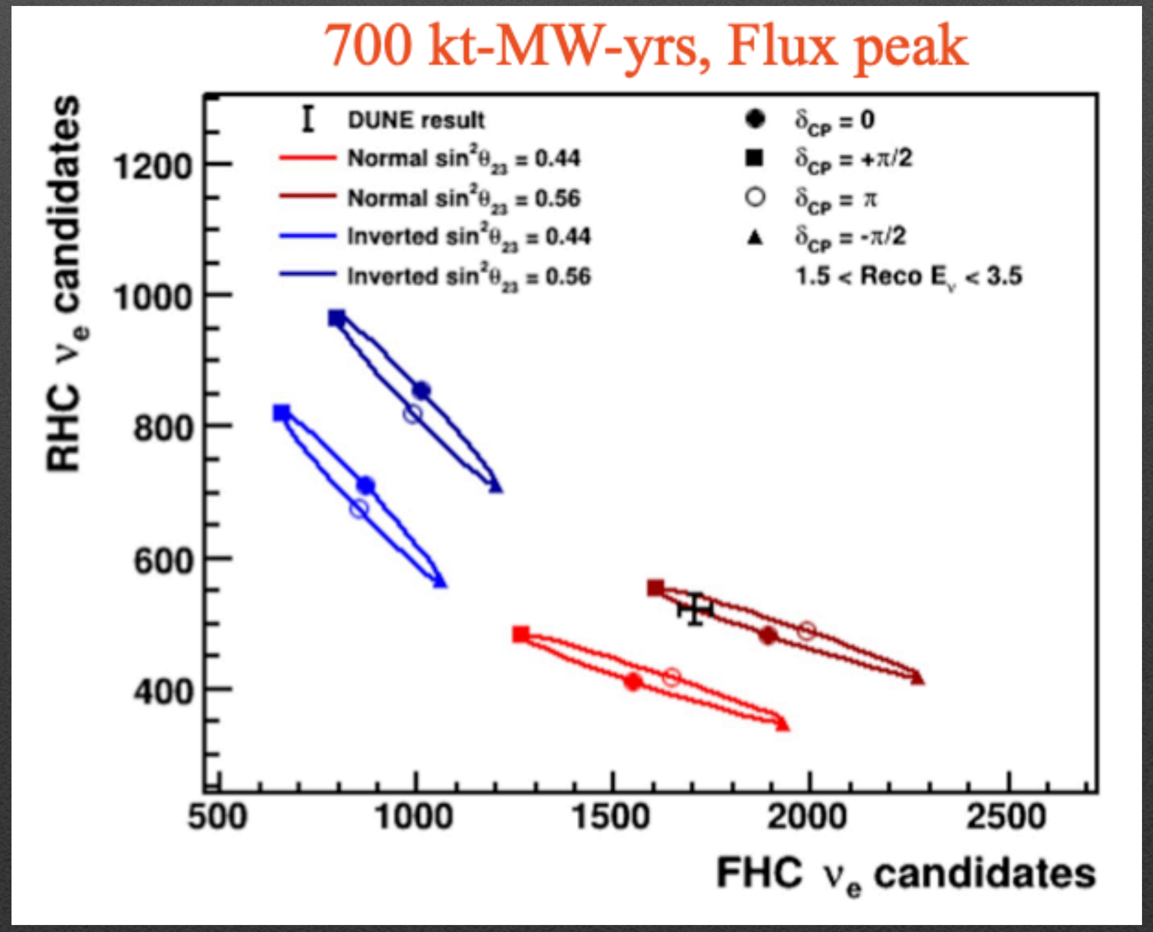
DUNE



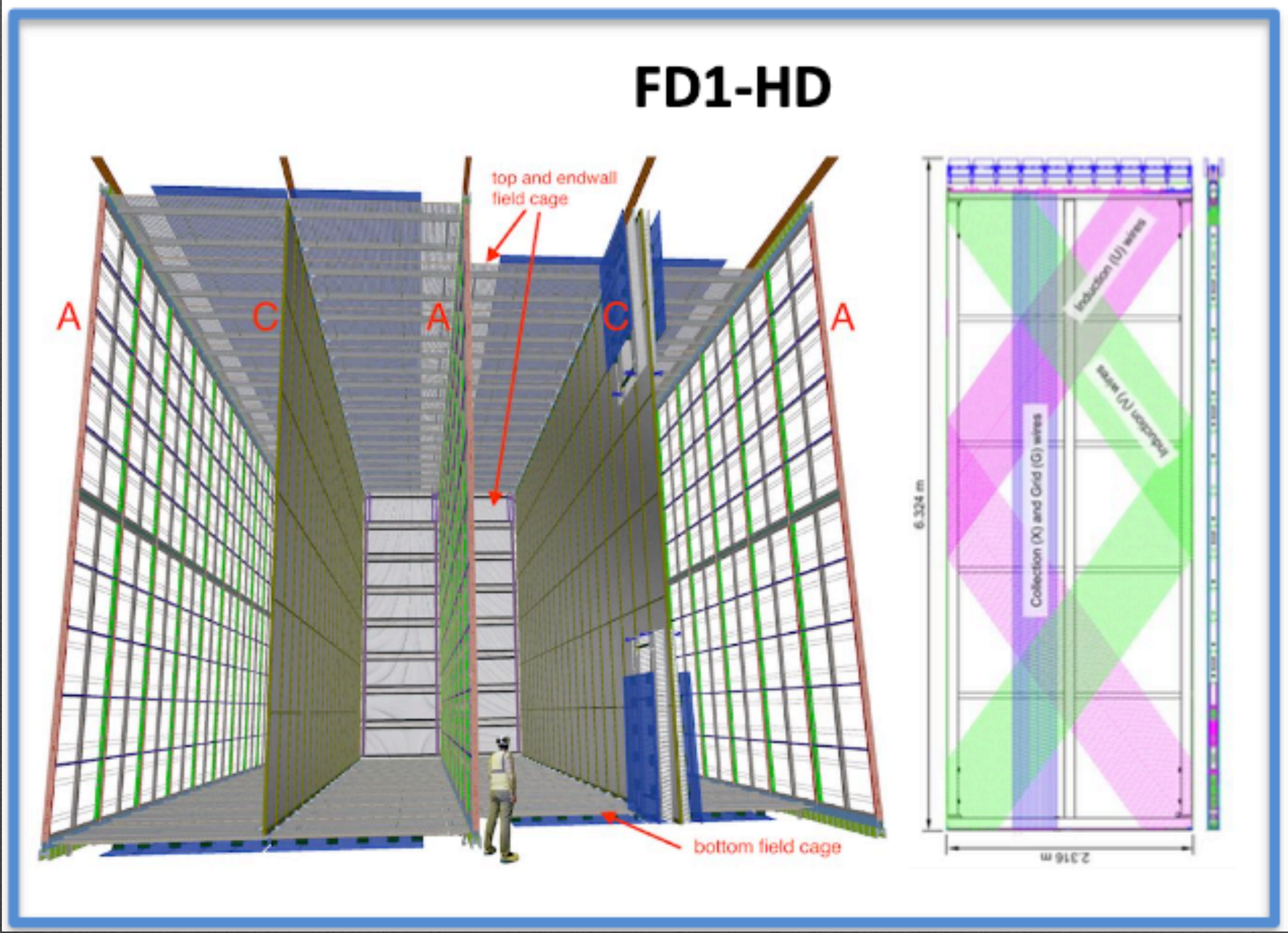


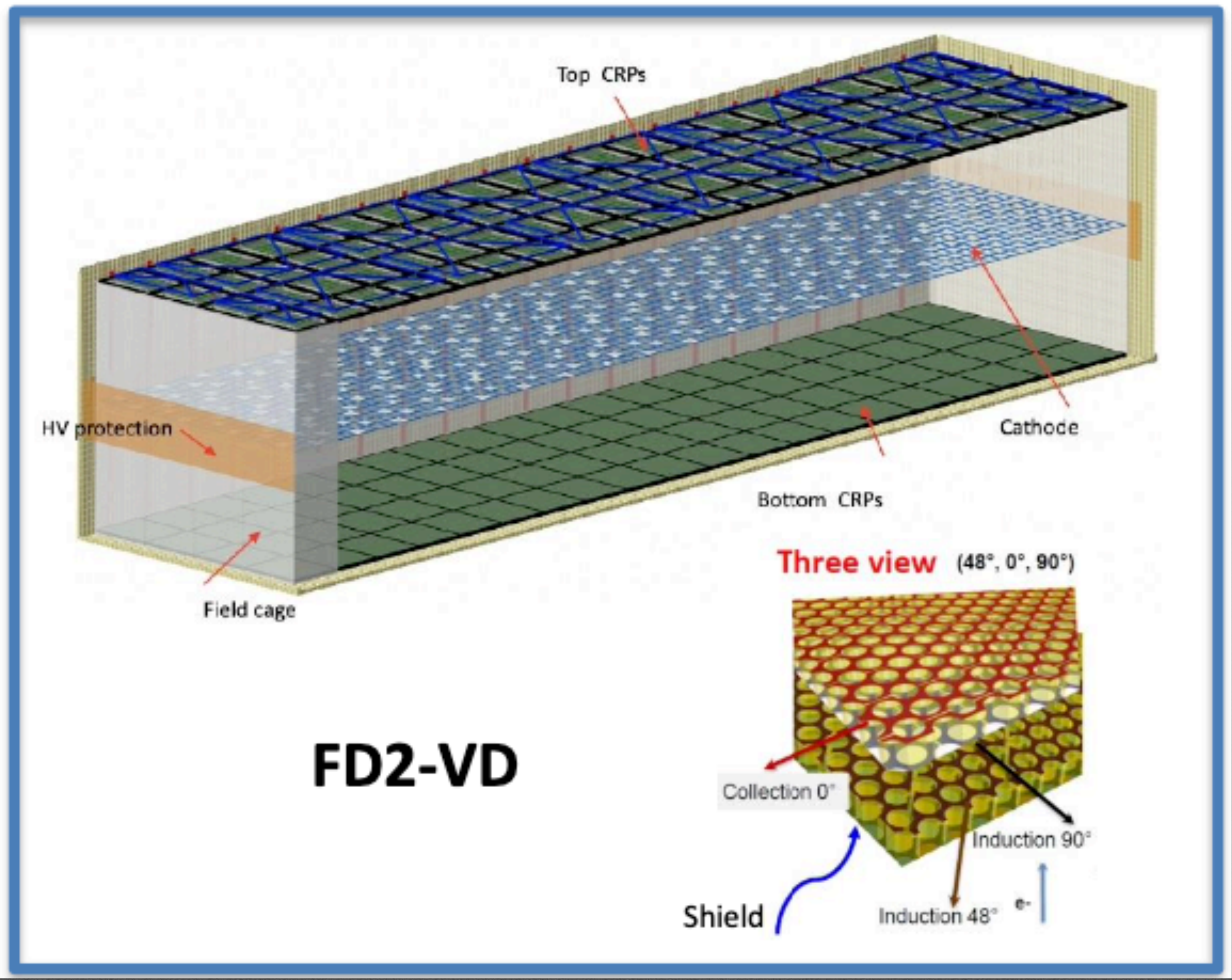


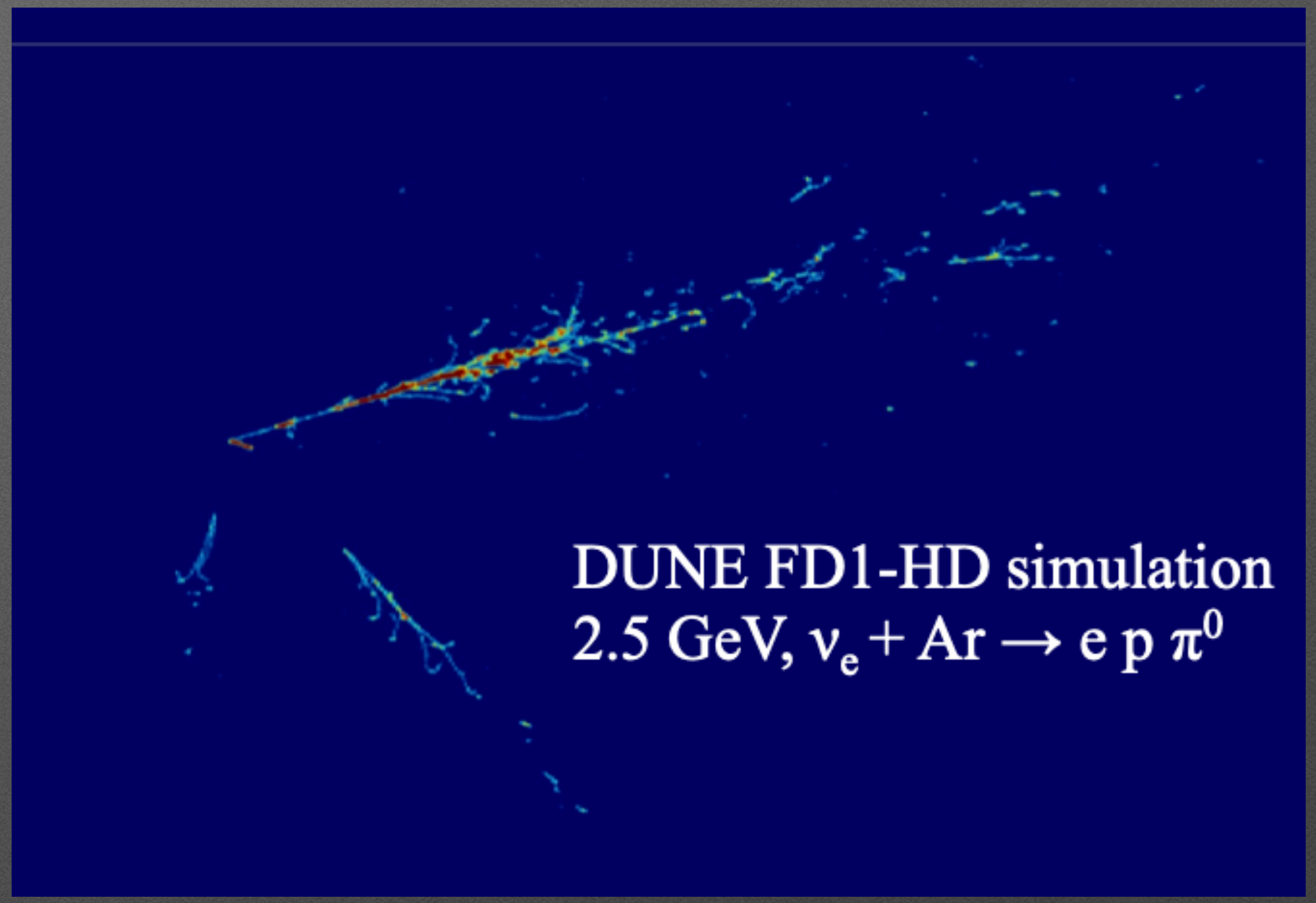
- Longer baseline (1300 km) → excellent sensitivity to Mass Ordering
- Wide beam covering two oscillation maxima → shape information
- Use Liquid Argon technology at an unprecedented scale (4 modules, 10 kton each)
- Installation of first two modules in 2029, start of beam data in 2031



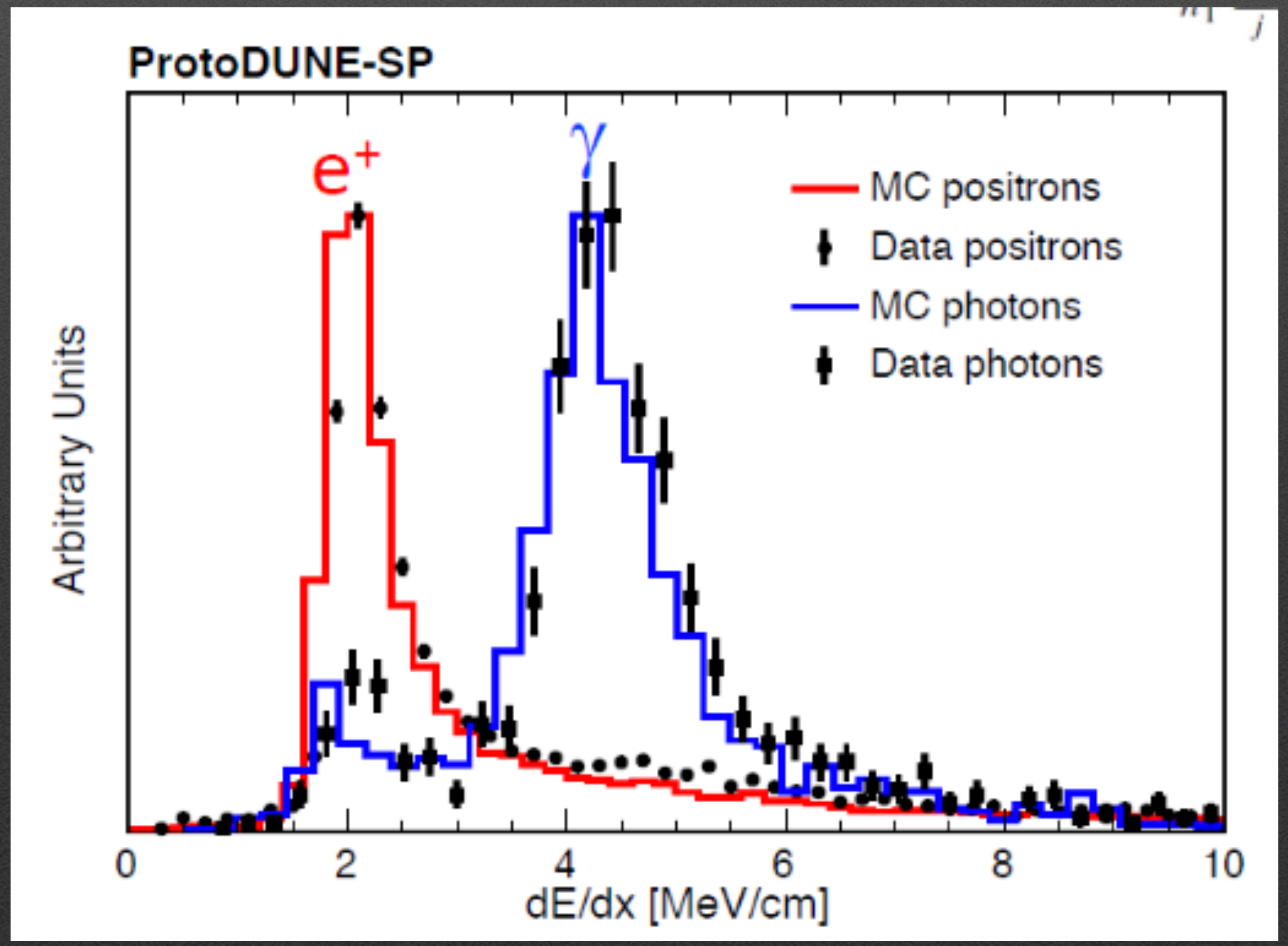
Liquid Argon technology

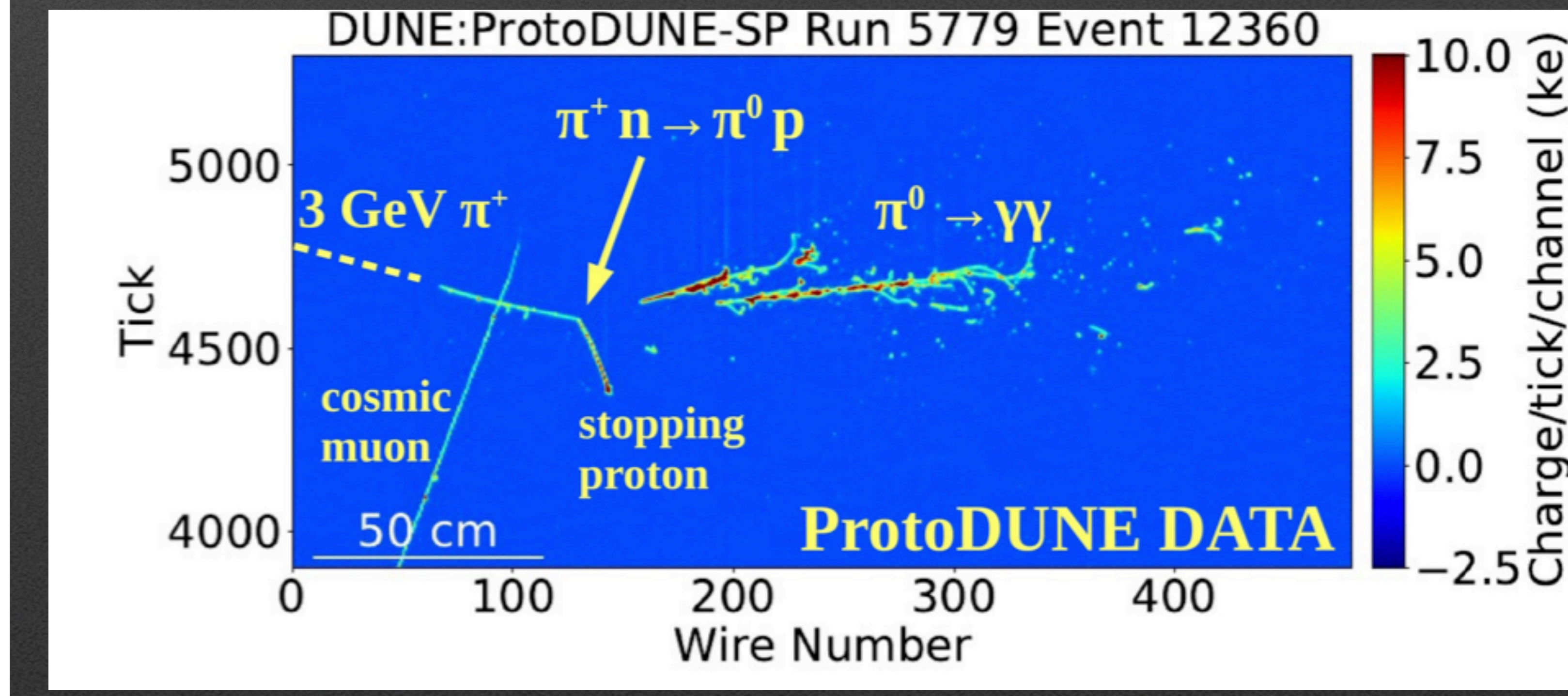






- ✱Full calorimetric reconstruction thanks to the Liquid Argon
- ✱Two technologies are being developed and tested at CERN→ Horizontal drift and Vertical drift
- ✱First two modules will be installed by 2029



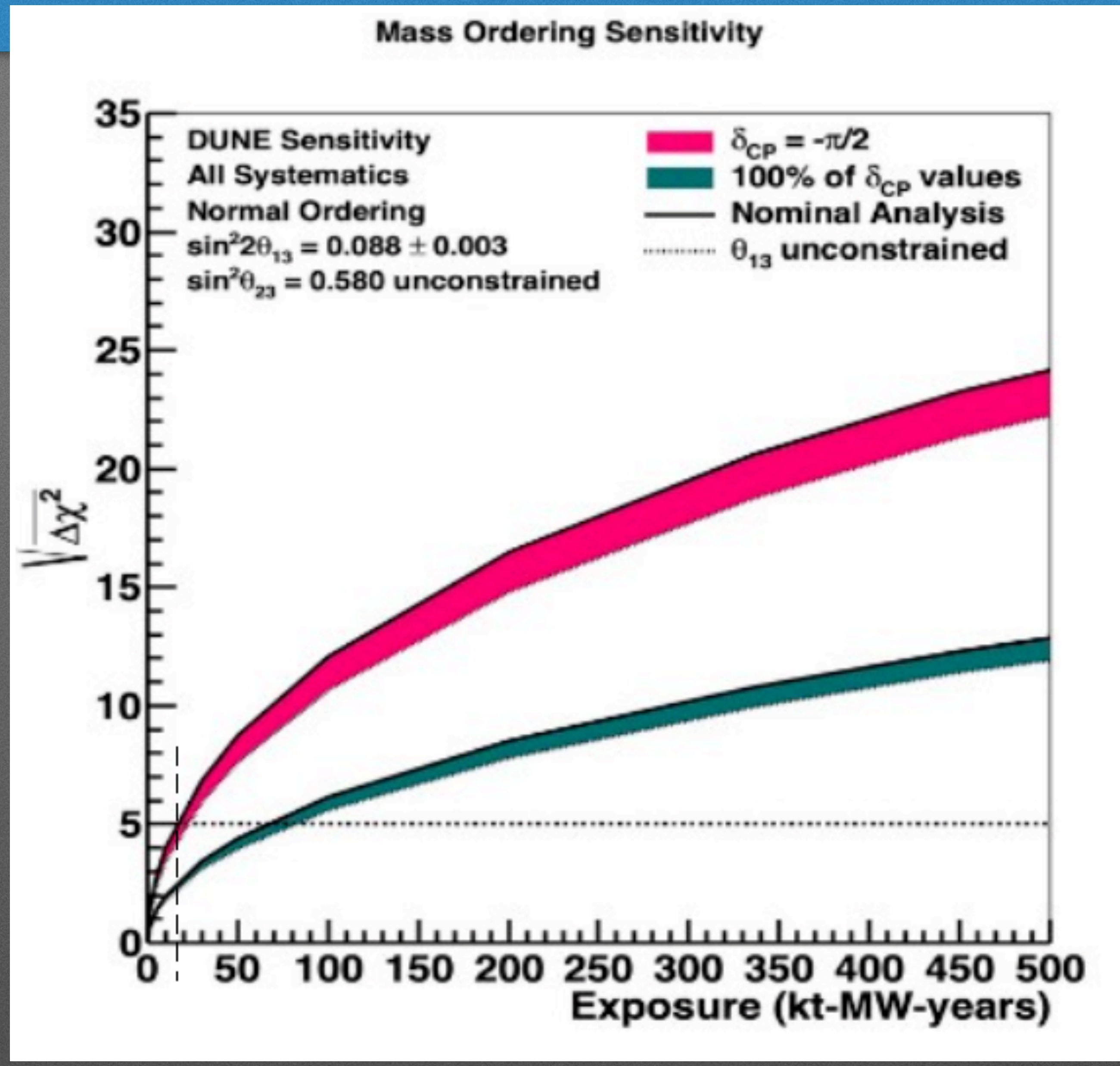


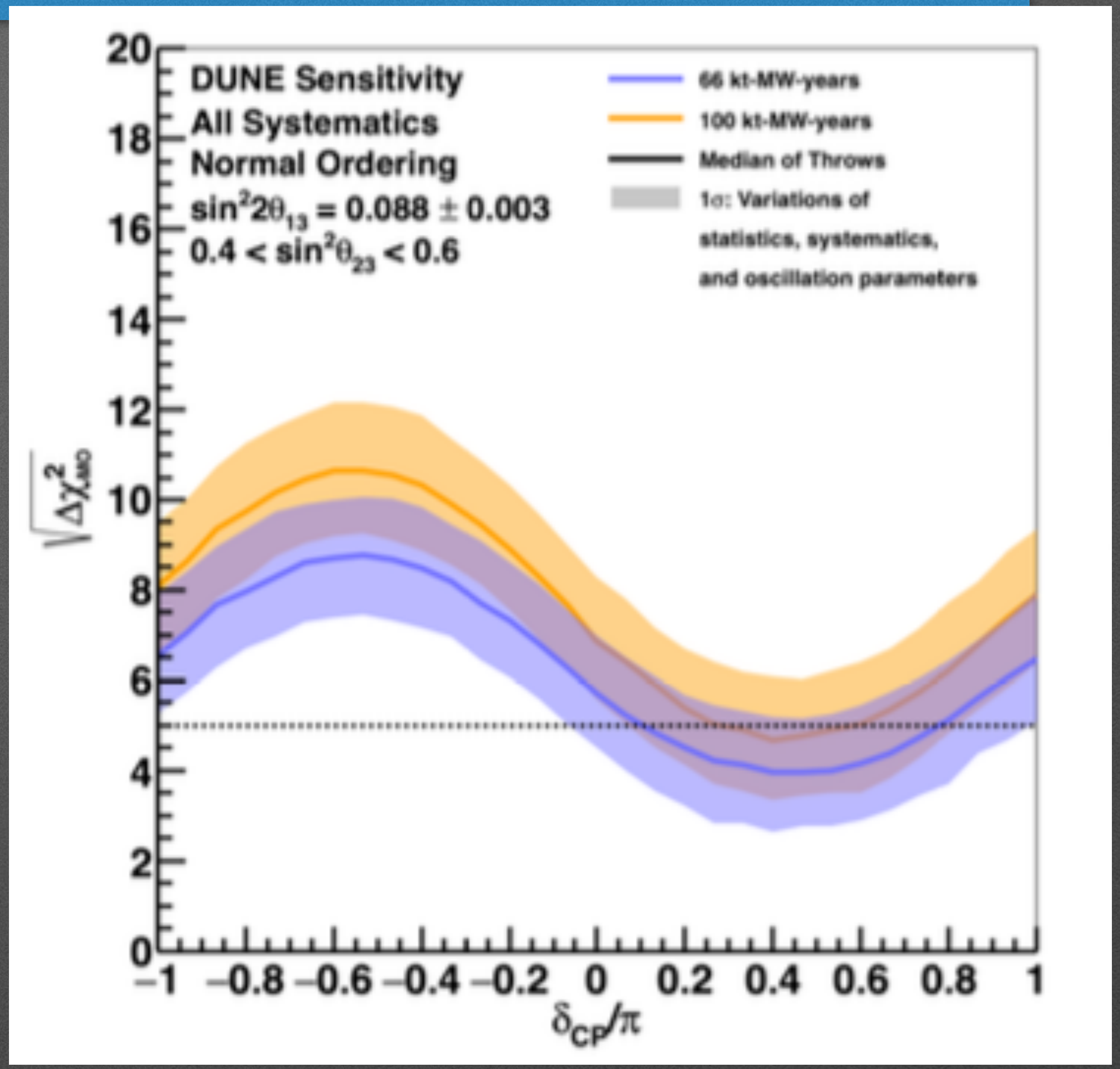
DUNE sensitivity

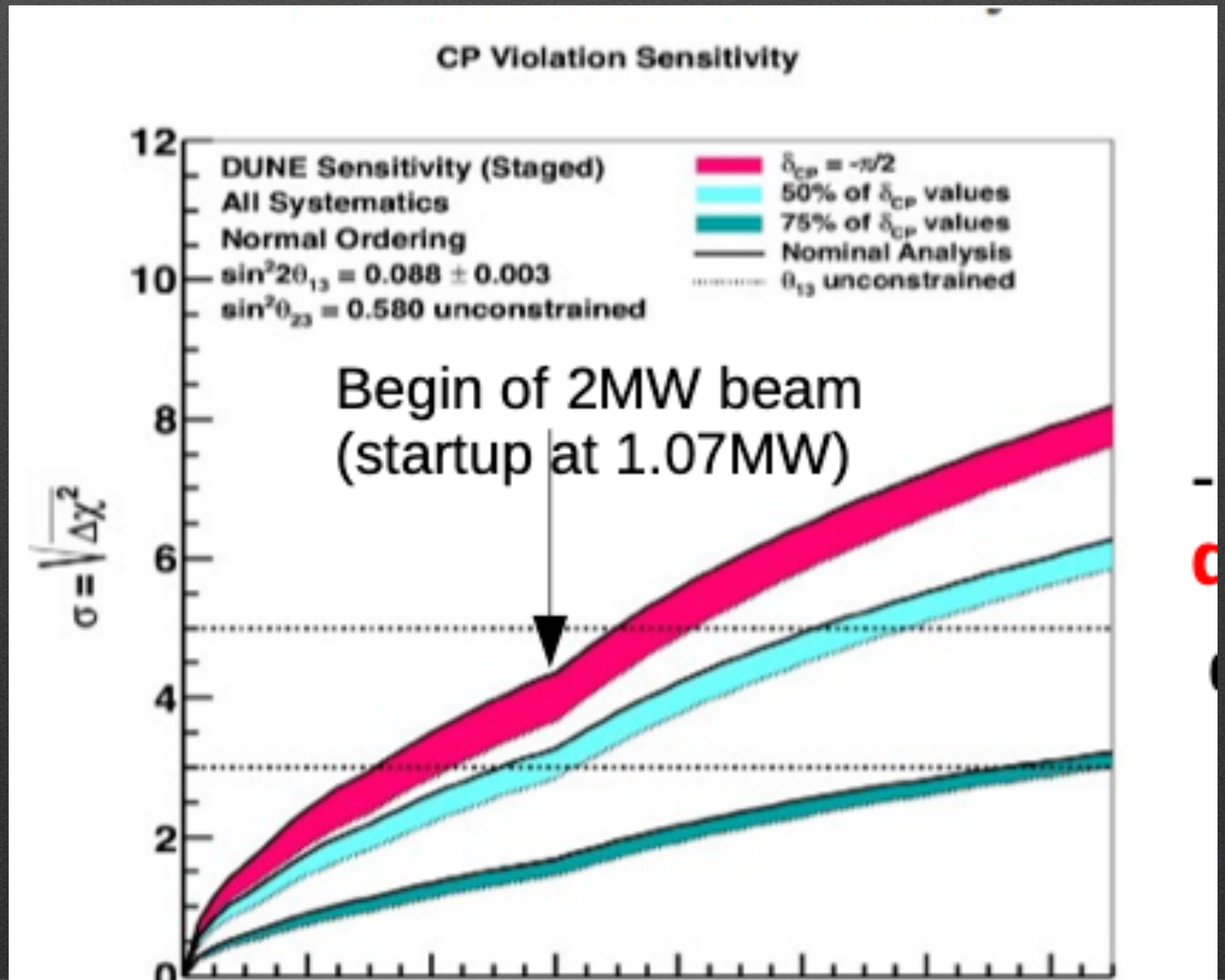
- DUNE phase I (2 modules and a 1.2 MW beam) will be enough to measure MO at > 5 σ for any value of CPV

- Measure CPV for some cases of large asymmetry

- Phase II will follow (4 modules and 2.4 MW beam) and will perform precise measurement of CPV → strong synergies with Hyper-Kamiokandde







Conclusions

- In the last 20 years there have been huge progresses in neutrino oscillations physics → we now know that all mixing angles are different from zero
- The next 10 years will answer many of the remaining outstanding questions with a well defined accelerator-based program
  - Is CP violated?
  - Which is the mass ordering?
  - Is θ_{23} maximal?
  - Sterile neutrinos?
- Two new experiments with unprecedented sensitivities will start in the next decade
  - Very interesting physics in front of us
  - Some guaranteed measurements (δCP) but also a lot of space for surprises!
    - Still waiting for the next SuperNova!
    - And maybe proton decay?