Neutrinos on Earth and in the sky

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IJCLab - 4 October 2024

cfp CIEMAT física de partículas
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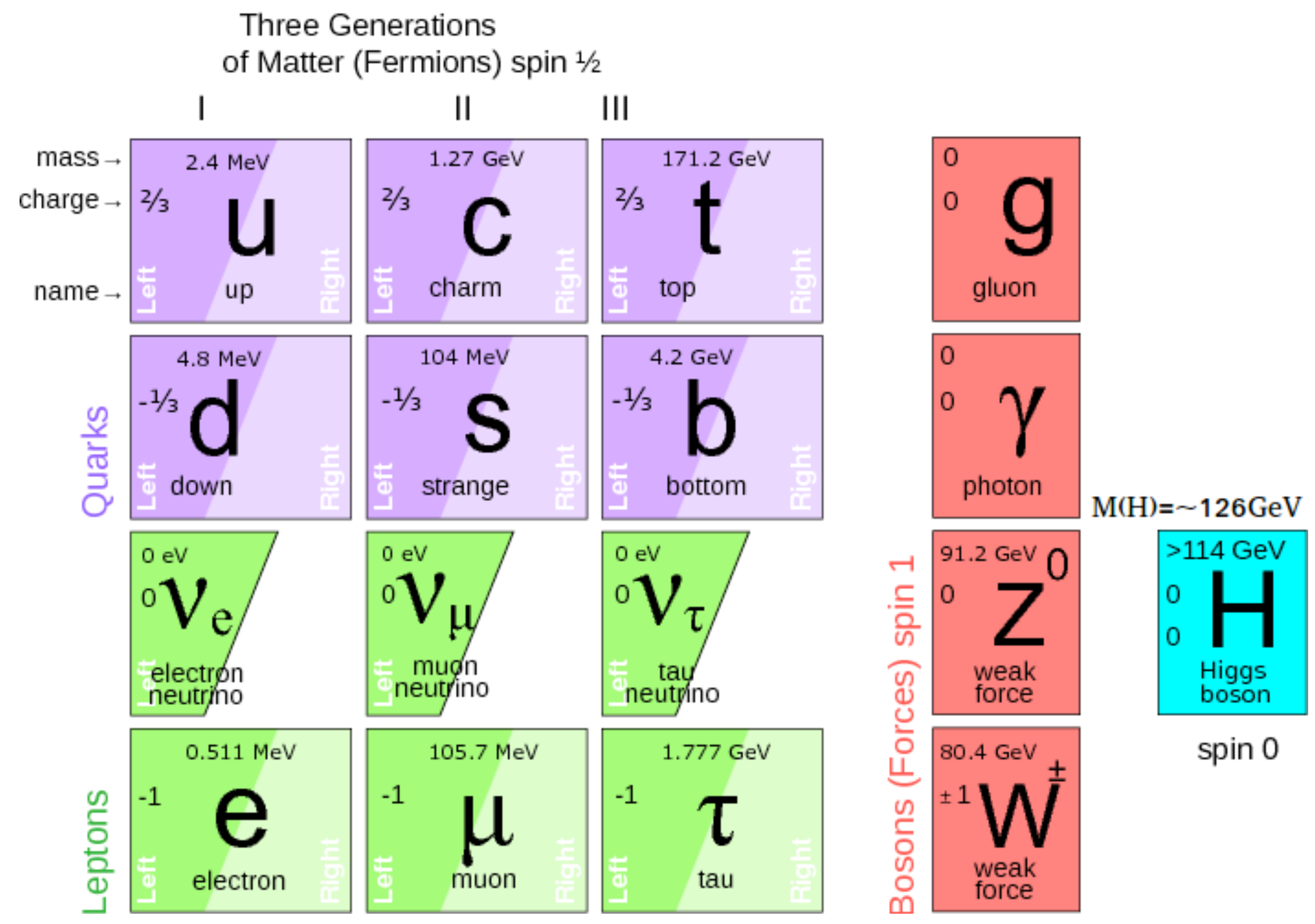
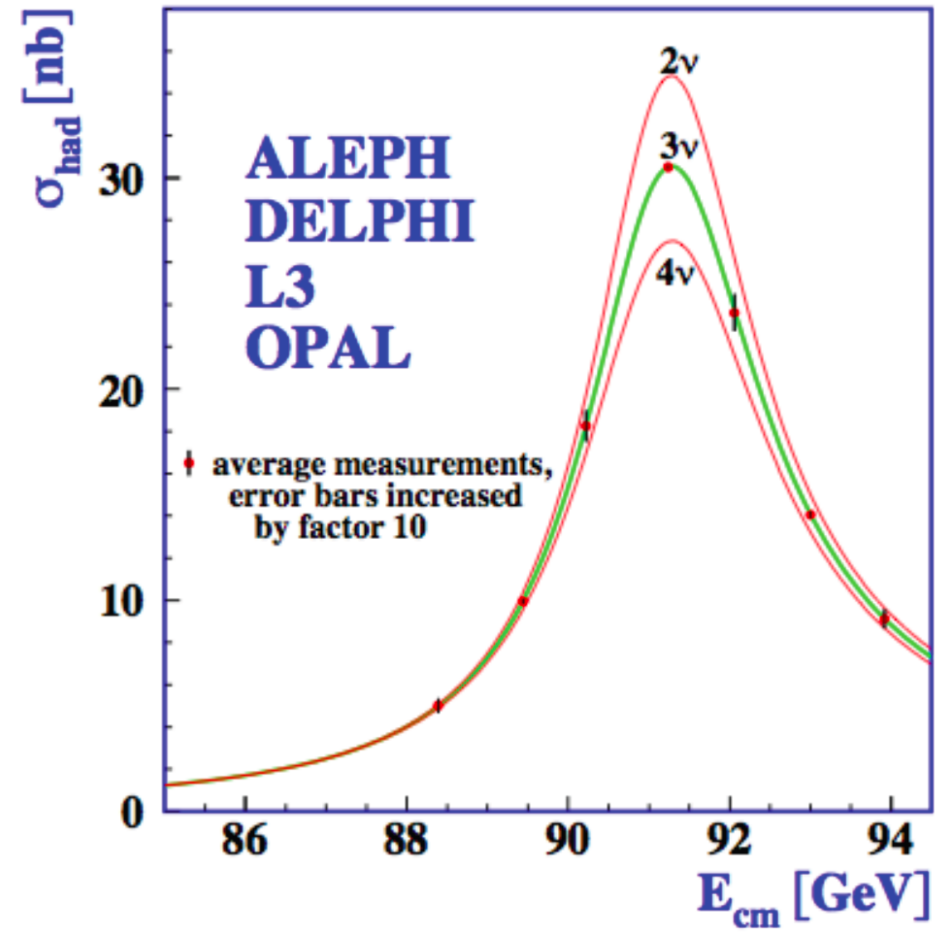
Outline

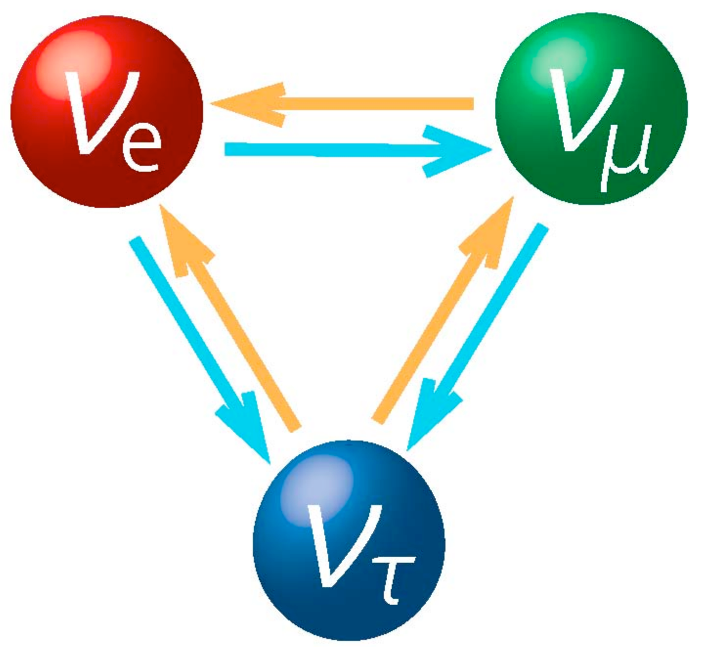
- Neutrinos and the Standard Model of Particle Physics
- Neutrino detection
- Neutrino oscillation: measurements, anomalies, and prospects
- Neutrino mass
- Astrophysical neutrinos
- Conclusions

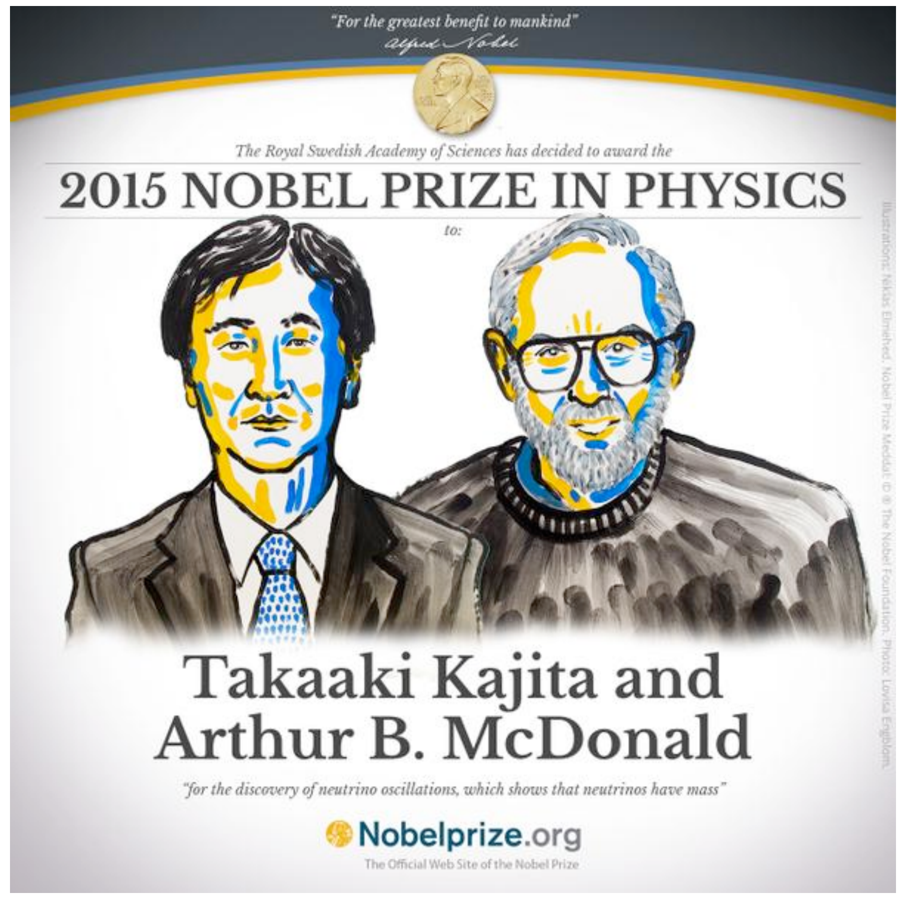
Neutrinos beyond the Standard Model

- The last 20 years have been a **revolution for neutrino physics**







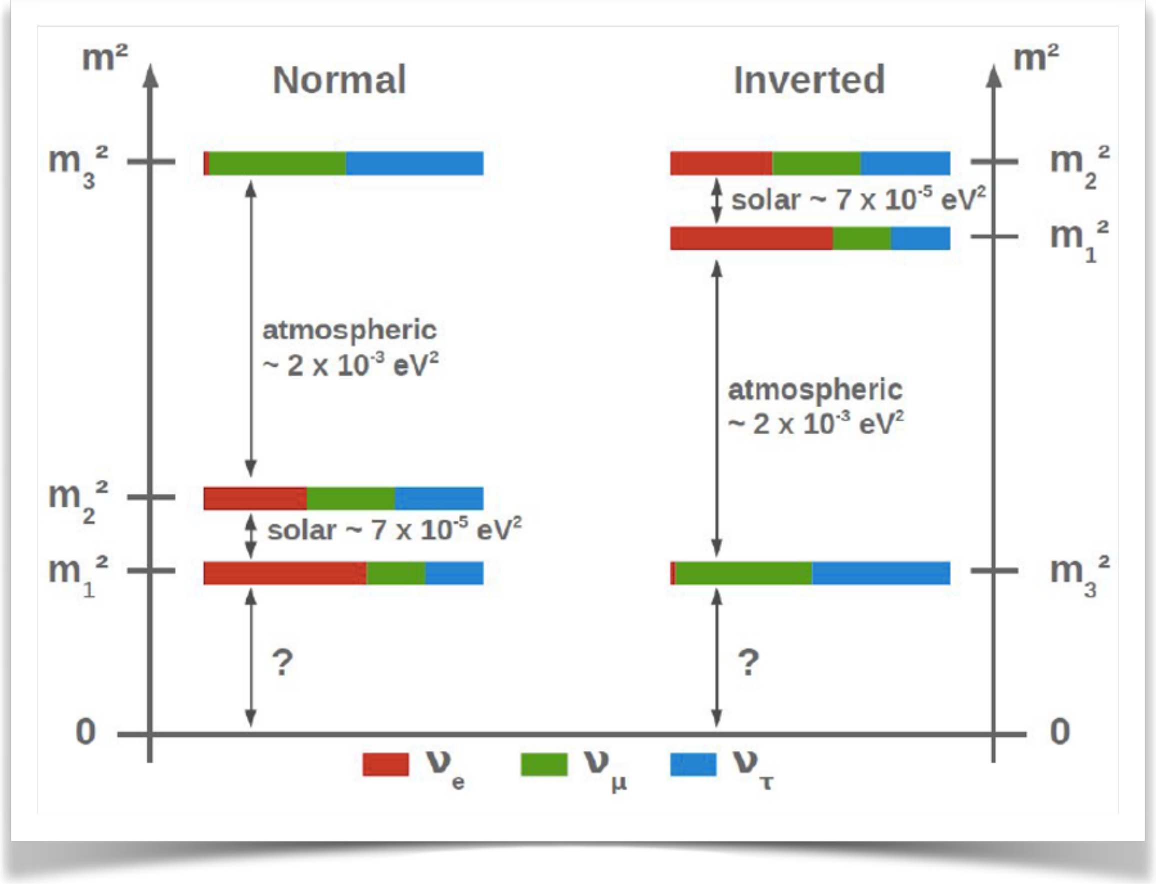


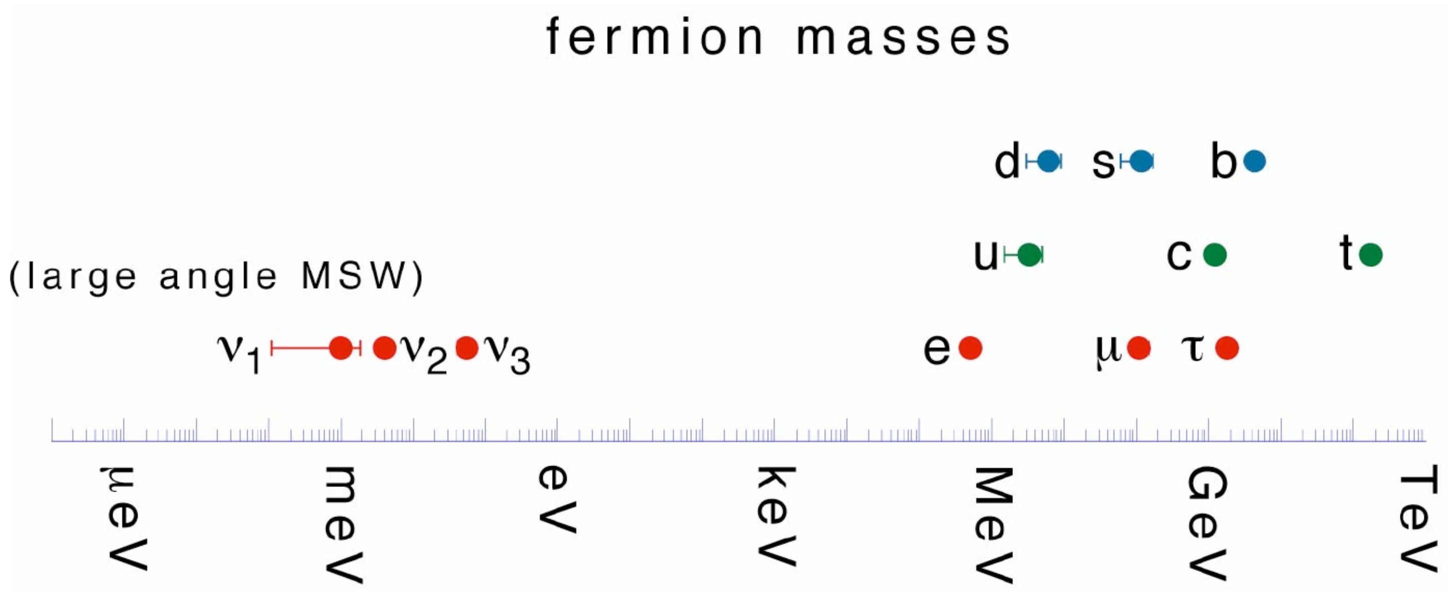
- Observation of neutrino oscillations → **non-vanishing neutrino mass** (flavor mixing)
- First evidence of **physics beyond the Standard Model**

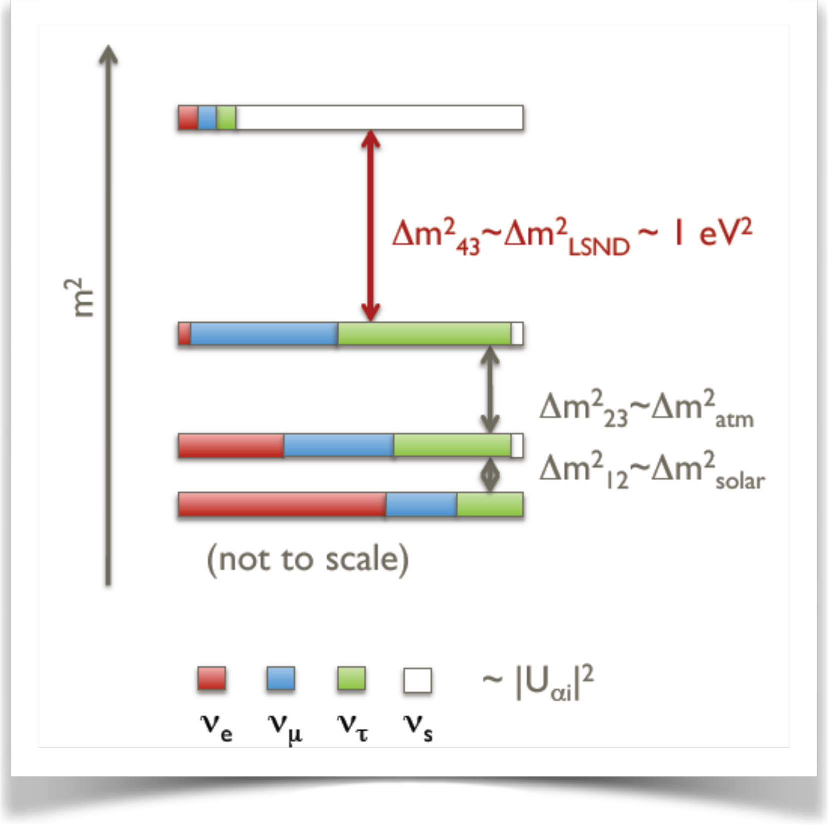
Main open questions

However, there are **fundamental unanswered questions**:

- ✦ What is the mass of neutrinos?
- ✦ Are neutrinos their own antiparticle? Dirac or Majorana?
- ✦ Why are neutrinos much lighter than the other fermions?
- ✦ What is the neutrino mass ordering?
- ✦ Is there CP violation in the lepton sector? CP-phase value?
- ✦ Are there any sterile neutrino states? If so, what are their masses?
- ✦ Deviations from unitarity of the PMNS matrix?



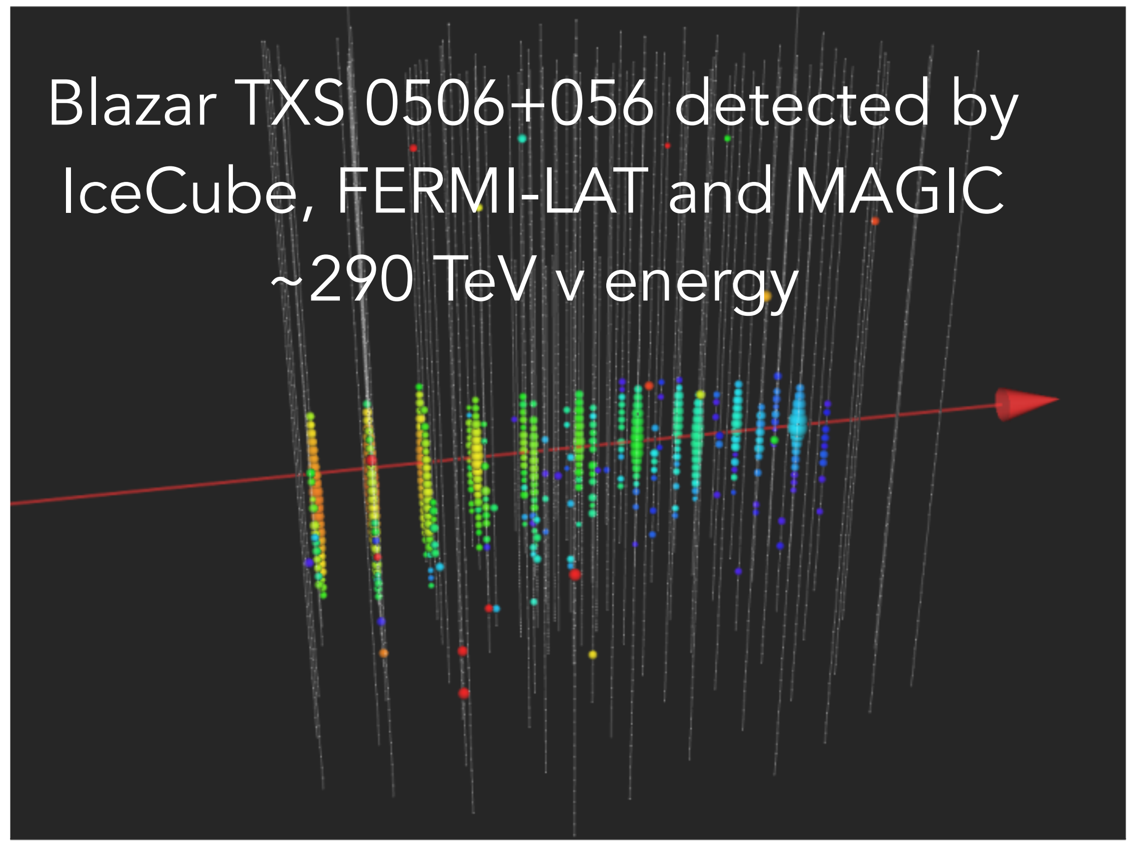


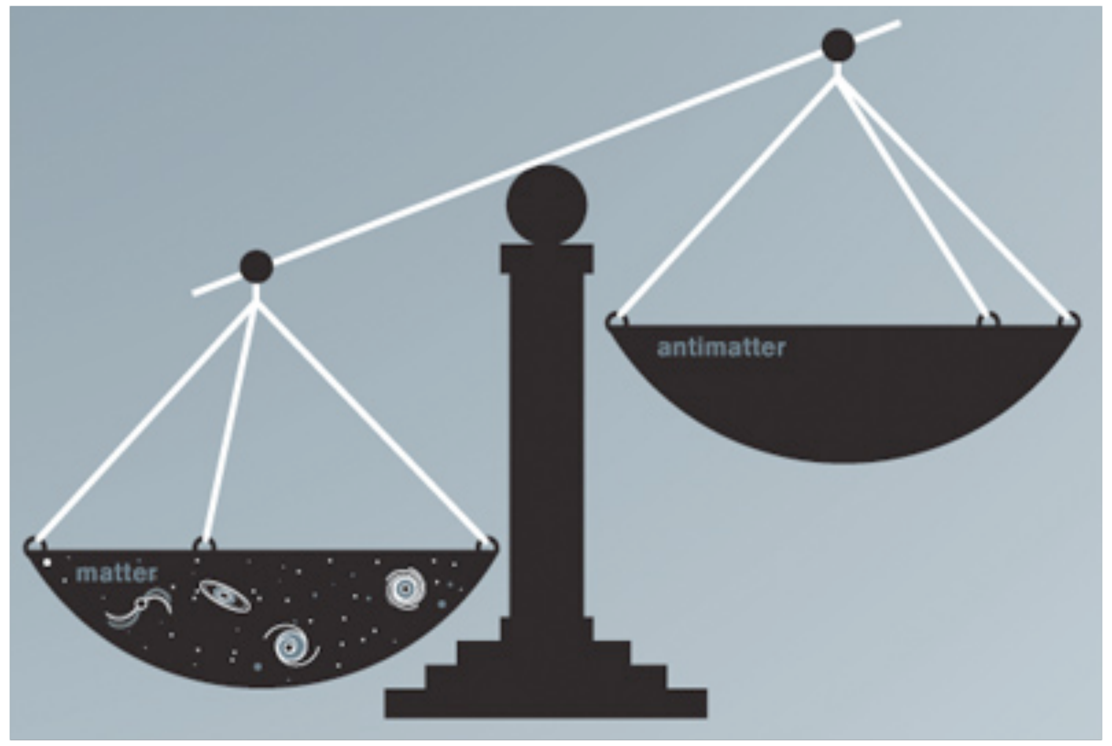


Connection with astrophysics and cosmology

Neutrinos as **probes of the Universe**:

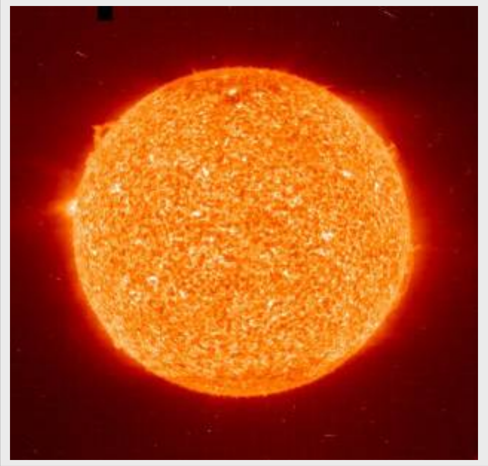
- ✦ High-energy neutrino physics
- ✦ New astrophysical sources
- ✦ Core-collapse supernova and diffuse SN neutrino background
- ✦ Relic neutrinos from early Universe
- ✦ Matter-antimatter asymmetry relation
- ✦ Sterile neutrinos as dark matter?





Neutrino sources

NATURAL

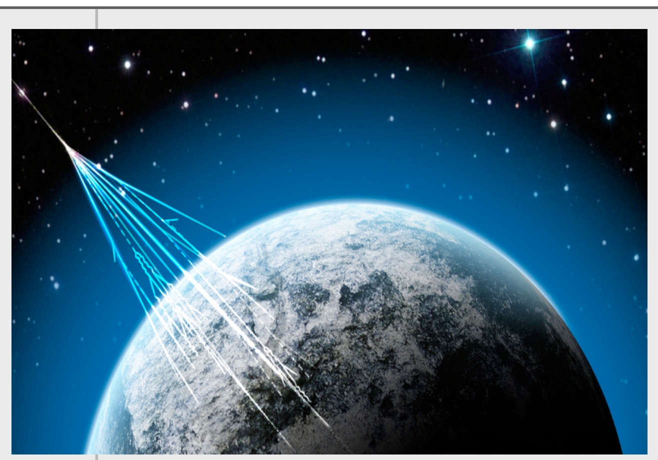


ϕ_ν ~65 x 10^9 /cm^2 s

E ~ MeV

Sun

L ~ 10^8 km

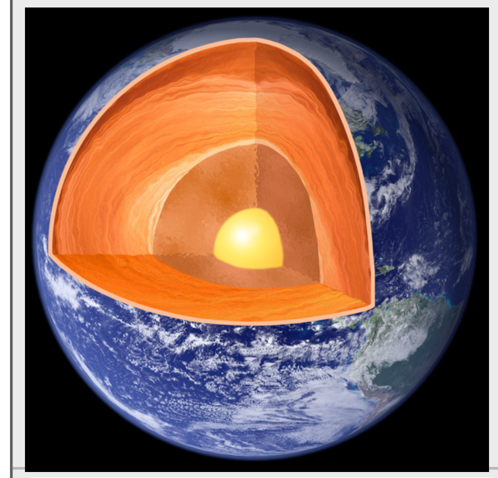


ϕ_ν ~10^2 - 10^9 /GeV cm^2 sr s

E ~ GeV-TeV

Atmosphere

L ~ 10 - 10^4 km



ϕ_ν ~10^6 /cm^2 s

E ~ MeV

Earth

L ~ 10 - 10^3 km

E ~ MeV

Supernovae

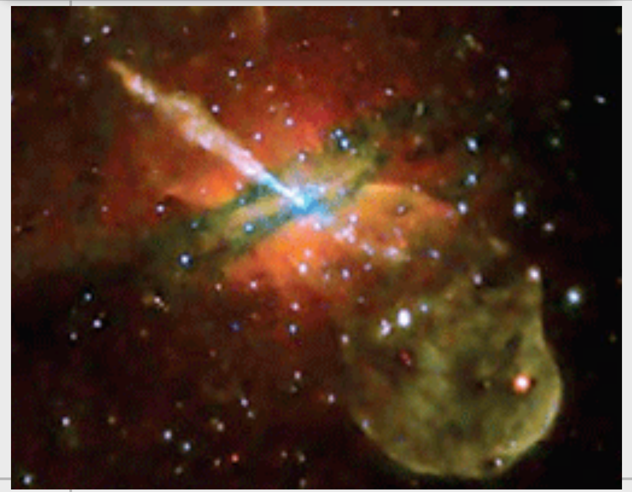
L ~ kpc- Mpc

ϕ_ν ~300 /cm^3

E $\lesssim$ meV

Big Bang

L ~ Mpc

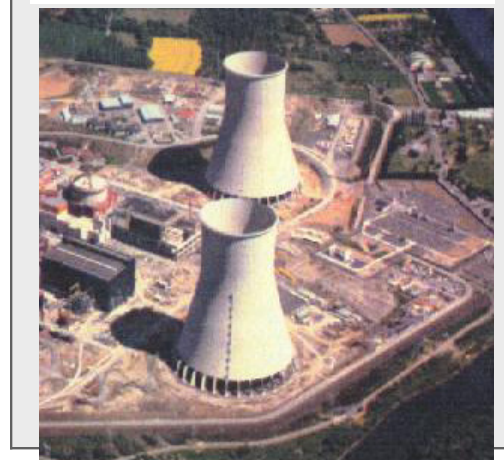


E ~ TeV-PeV

Astrophysics Accelerators

L ~ kpc- Mpc

ARTIFICIAL



ϕ_ν ~2 x 10^{20} /s GW_{th}

E ~ MeV

Nuclear Reactors

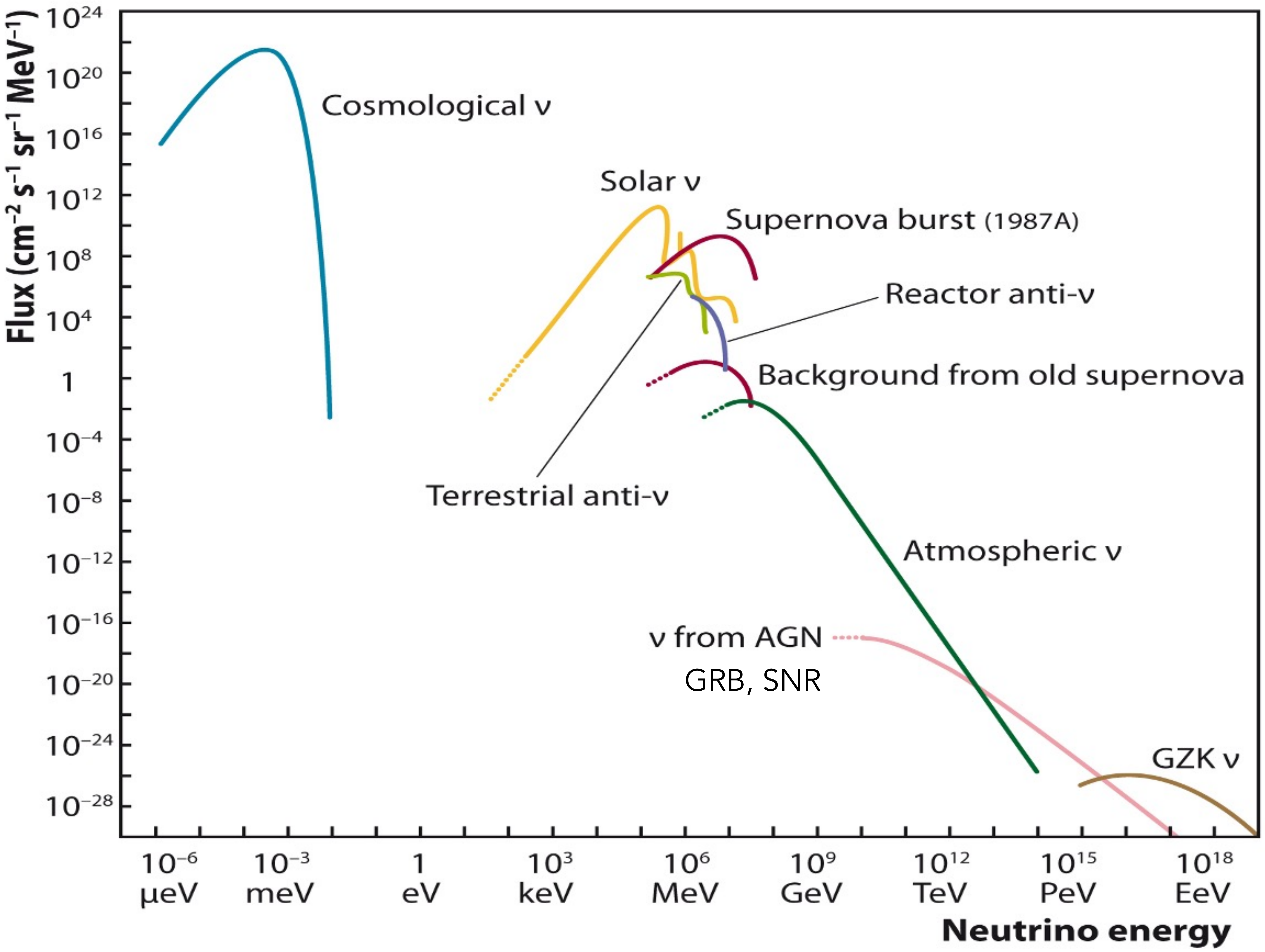
L ~ 1-100 km

E ~ GeV

Particle Accelerators

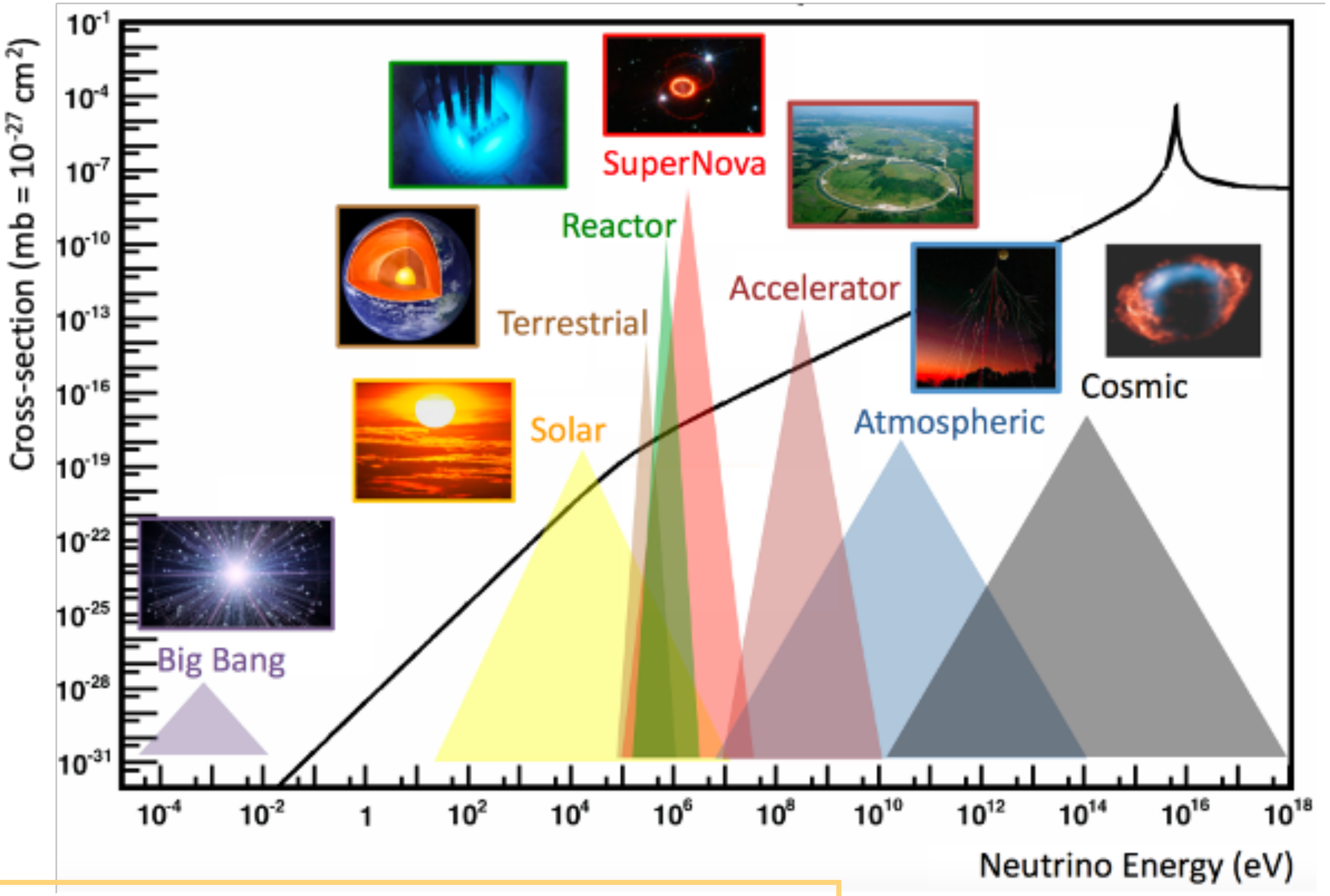
L ~ 100-1000 km

Neutrino fluxes at Earth



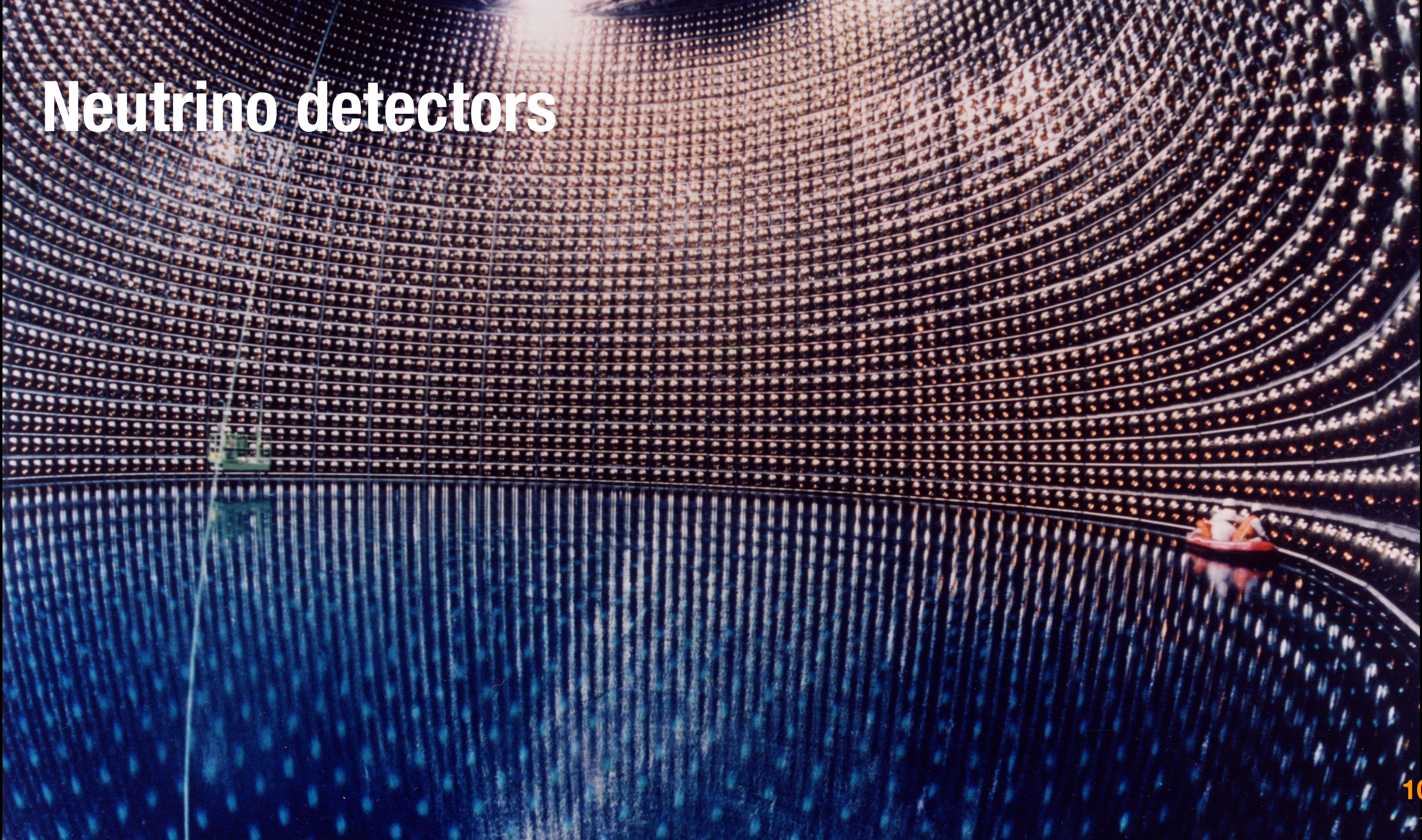
Neutrino detection

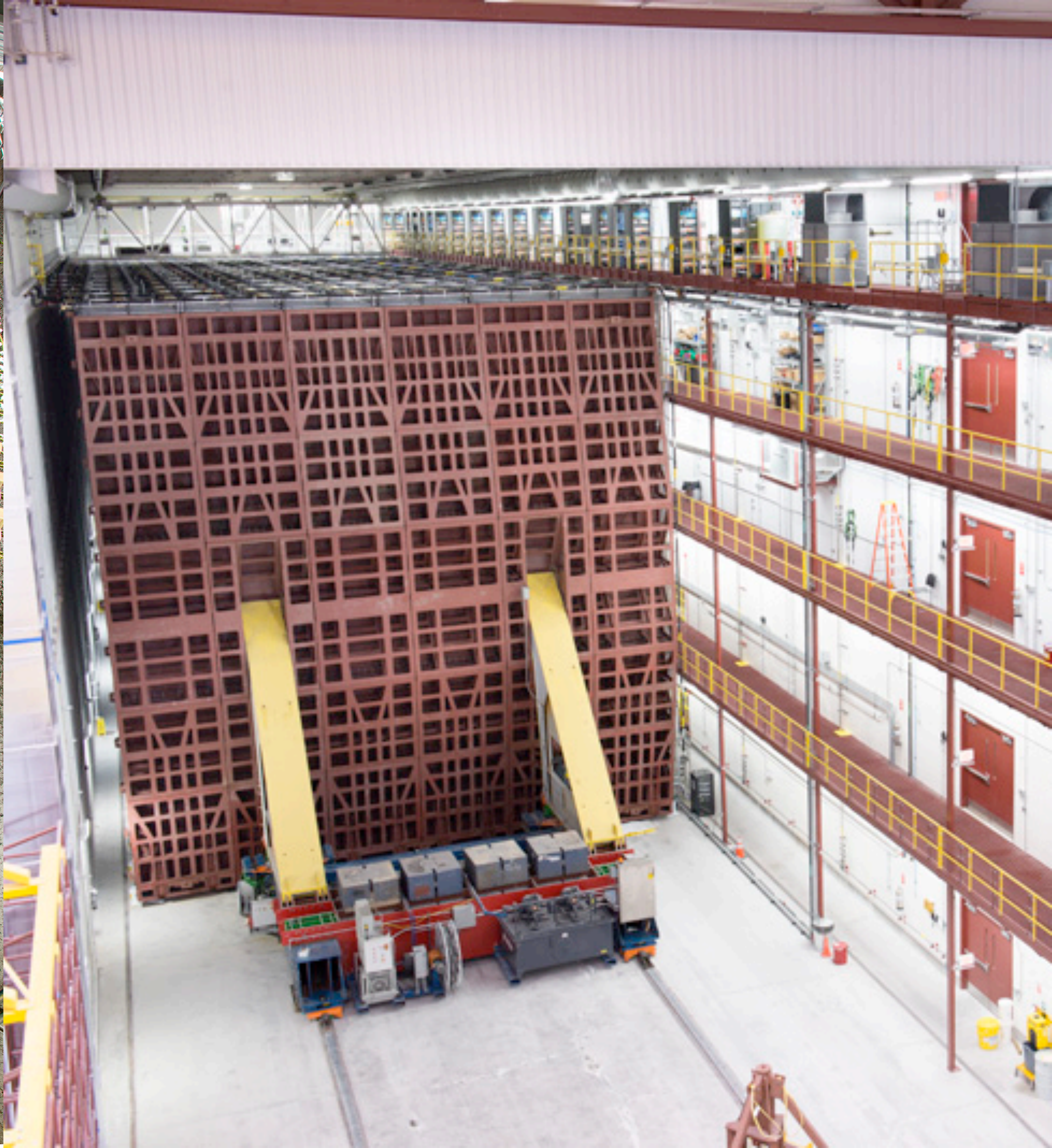
Neutrino interaction cross-section

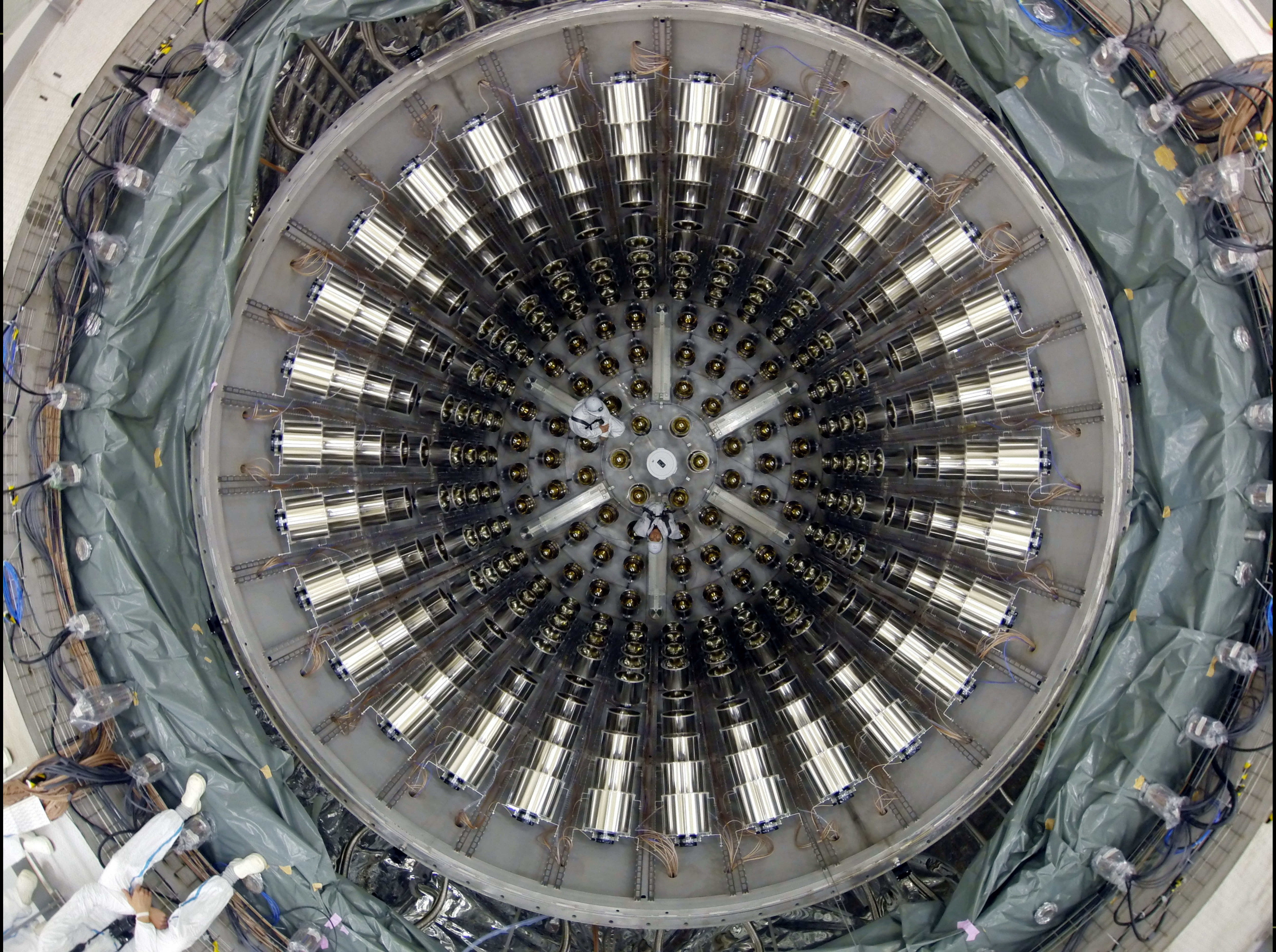


For comparison: inelastic pp cross-section at 13 TeV ~75 mb

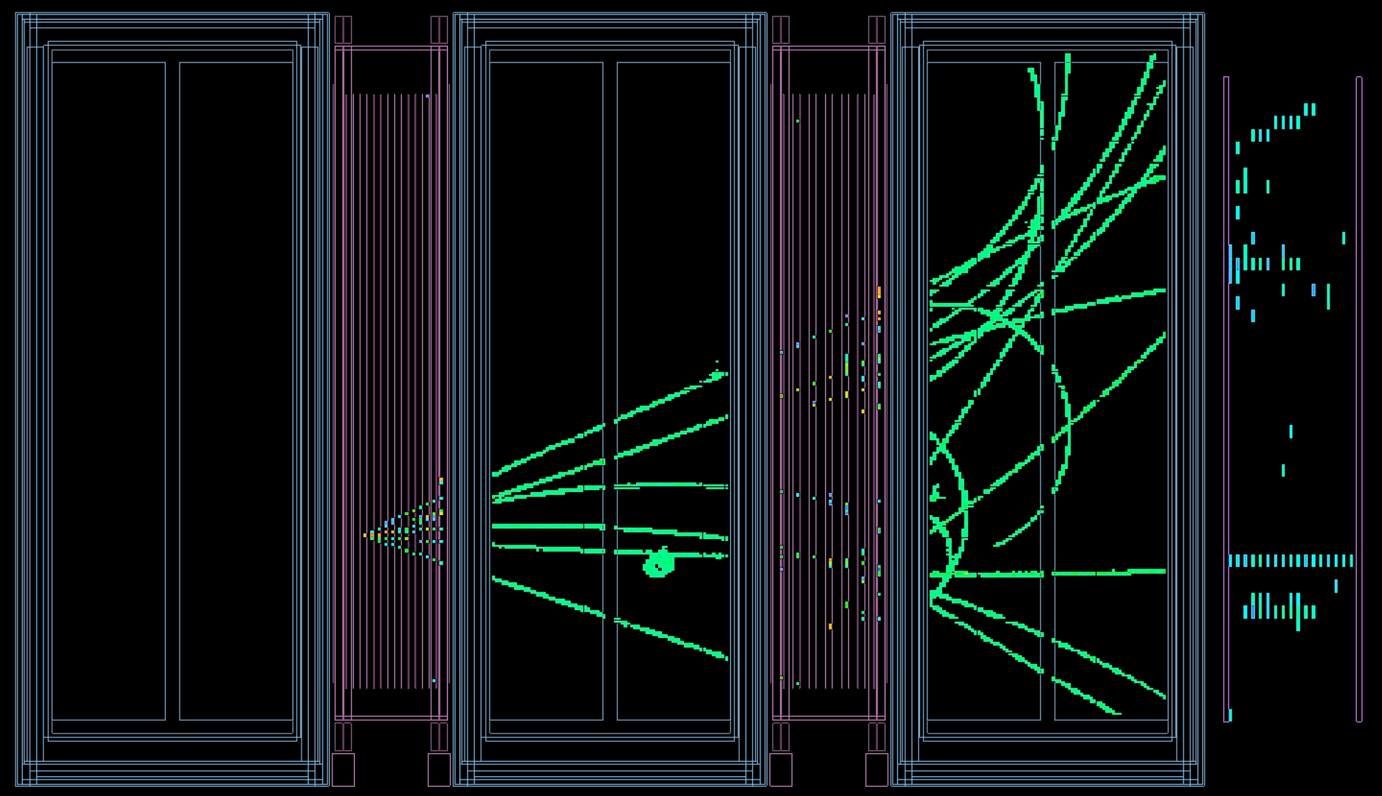
Neutrino detectors

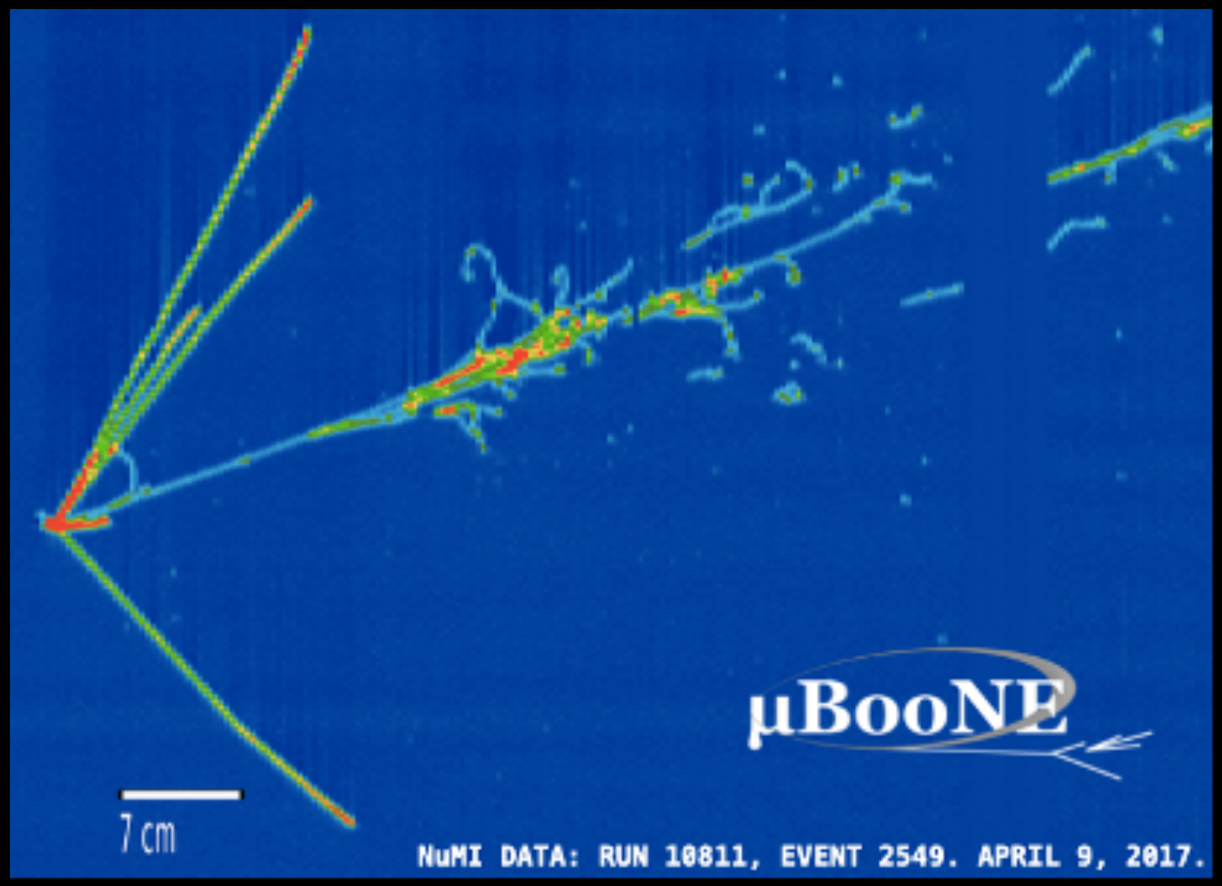


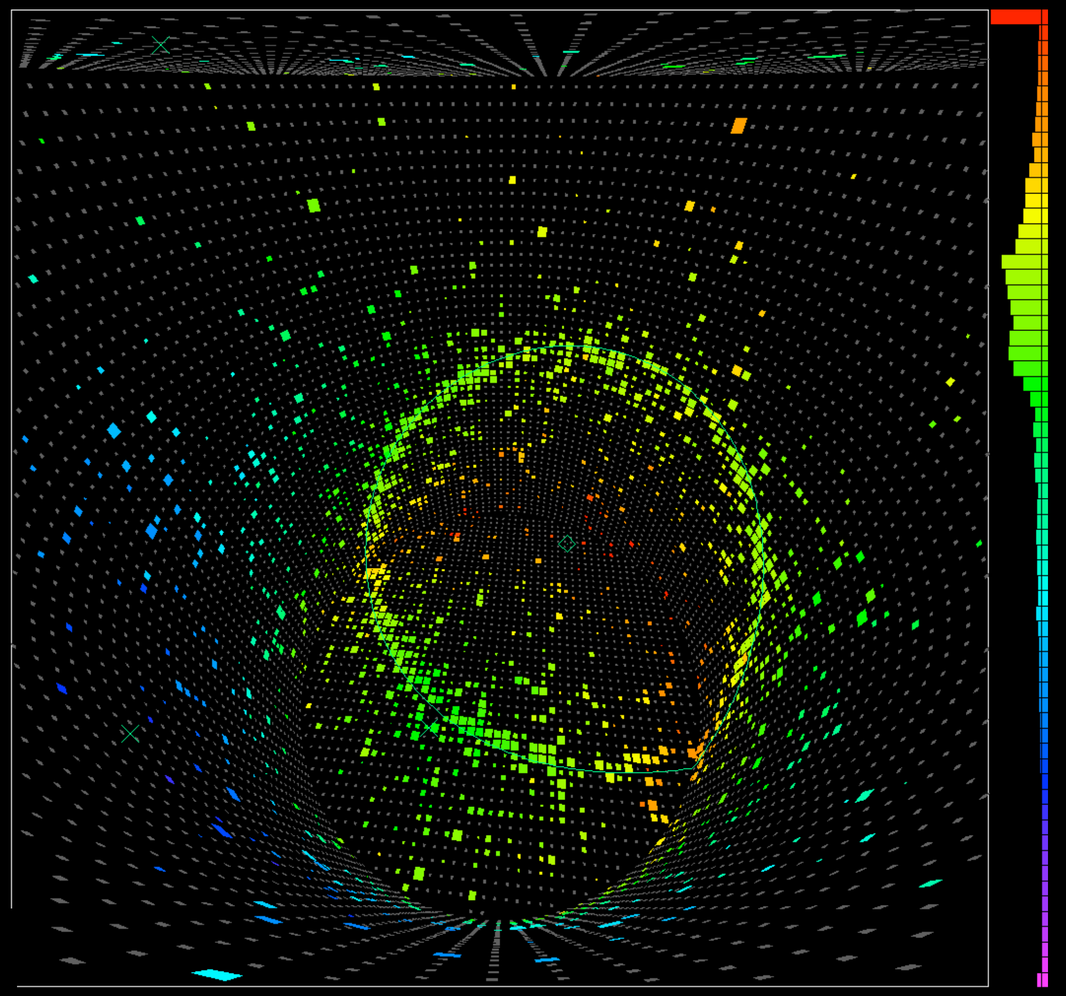



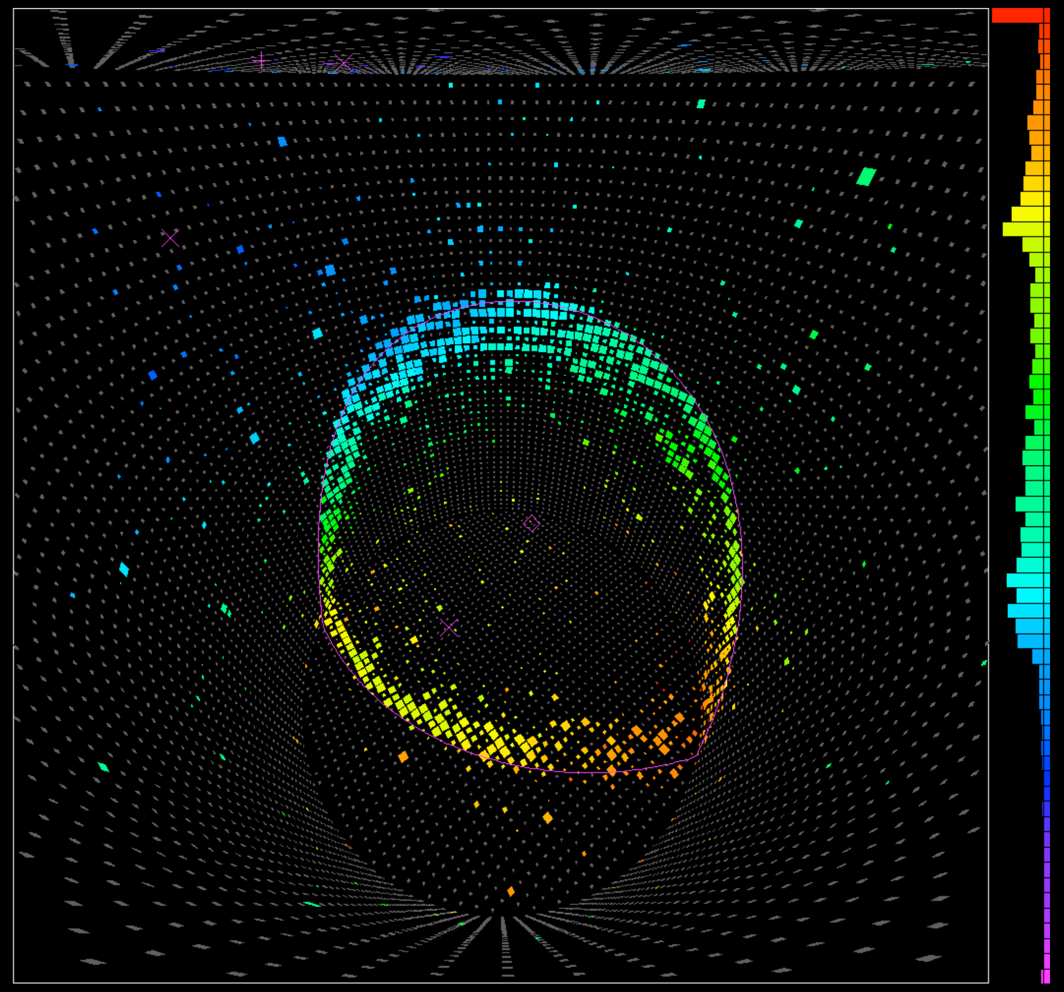


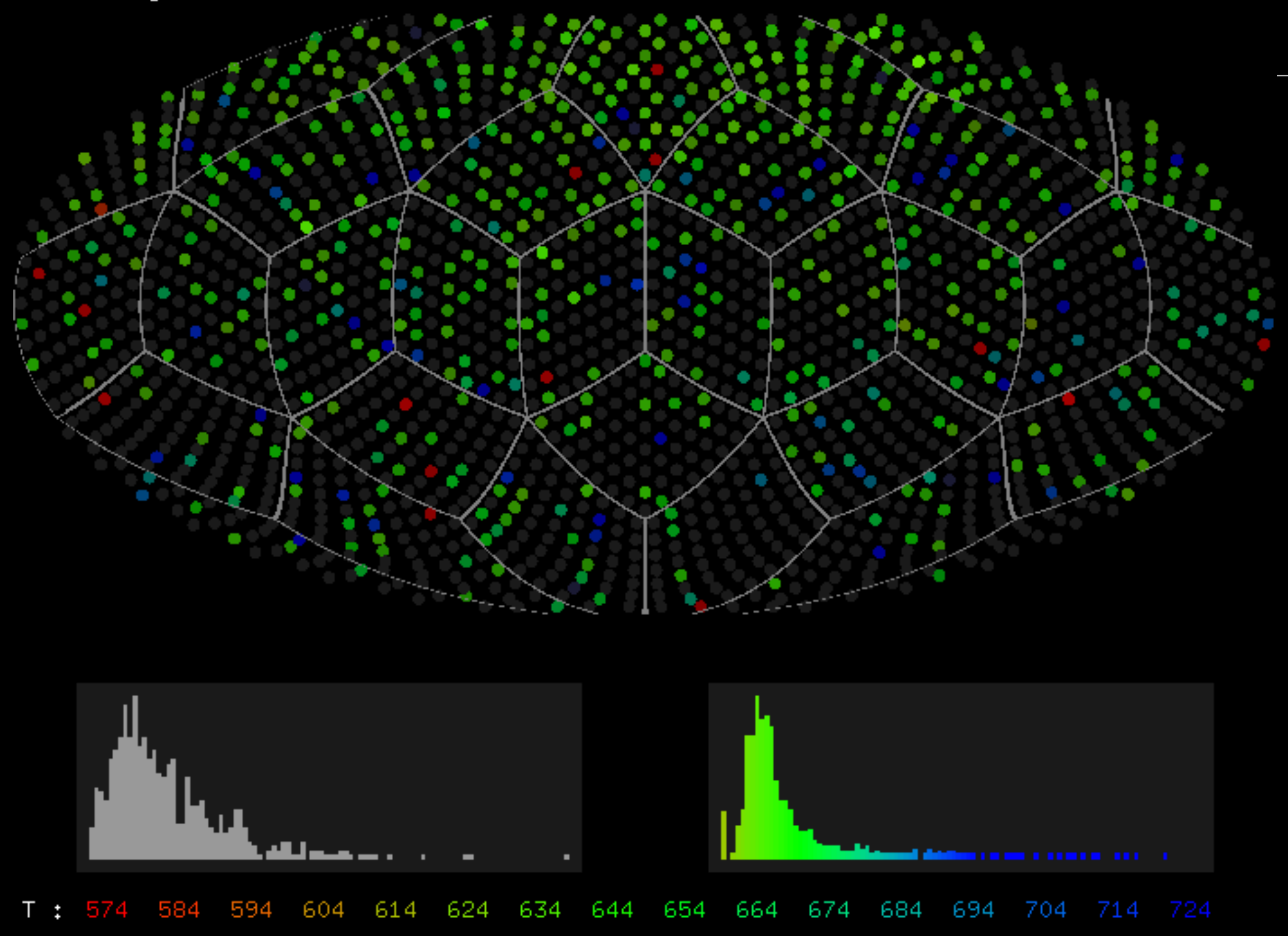
Neutrinos

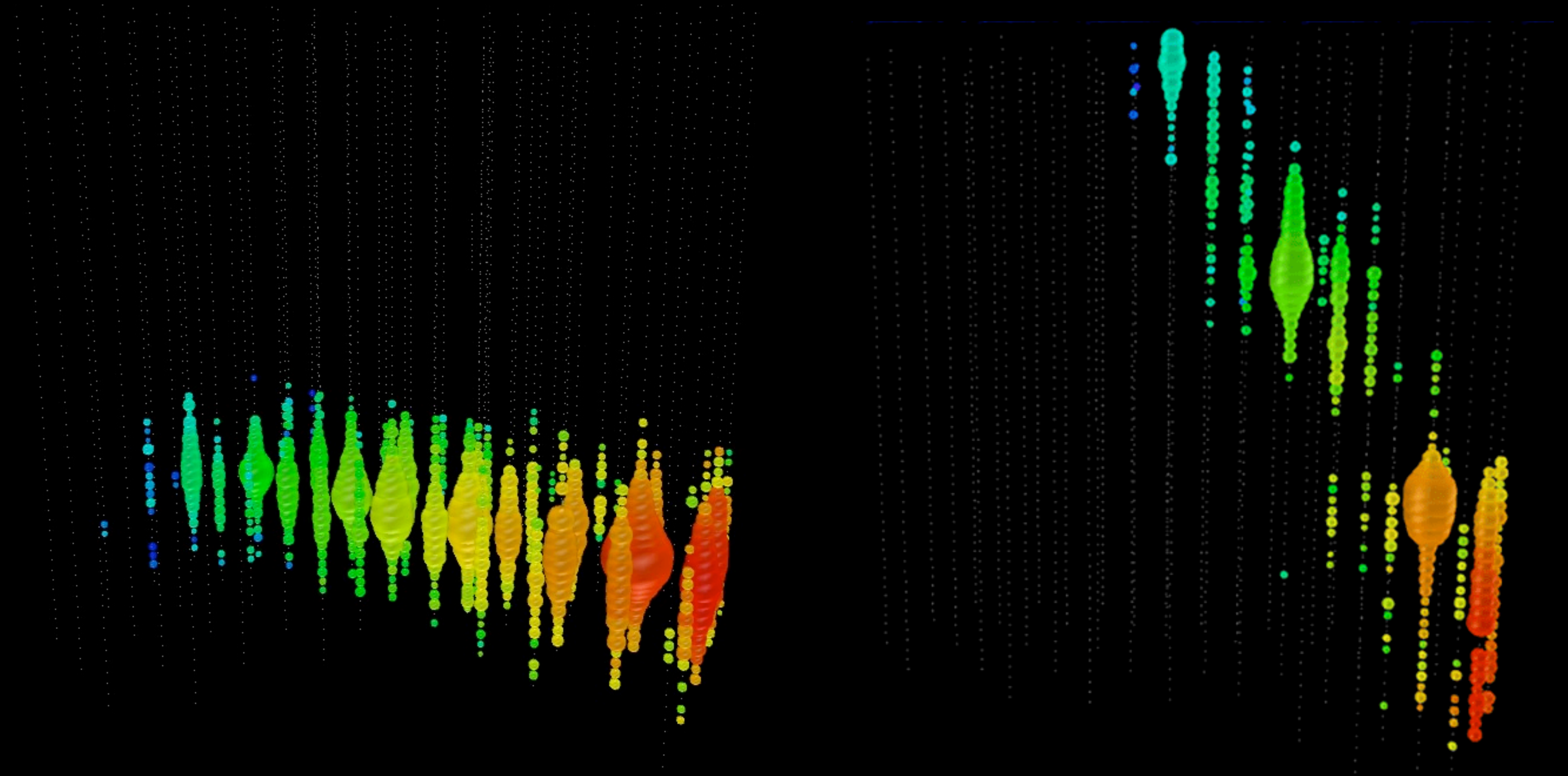


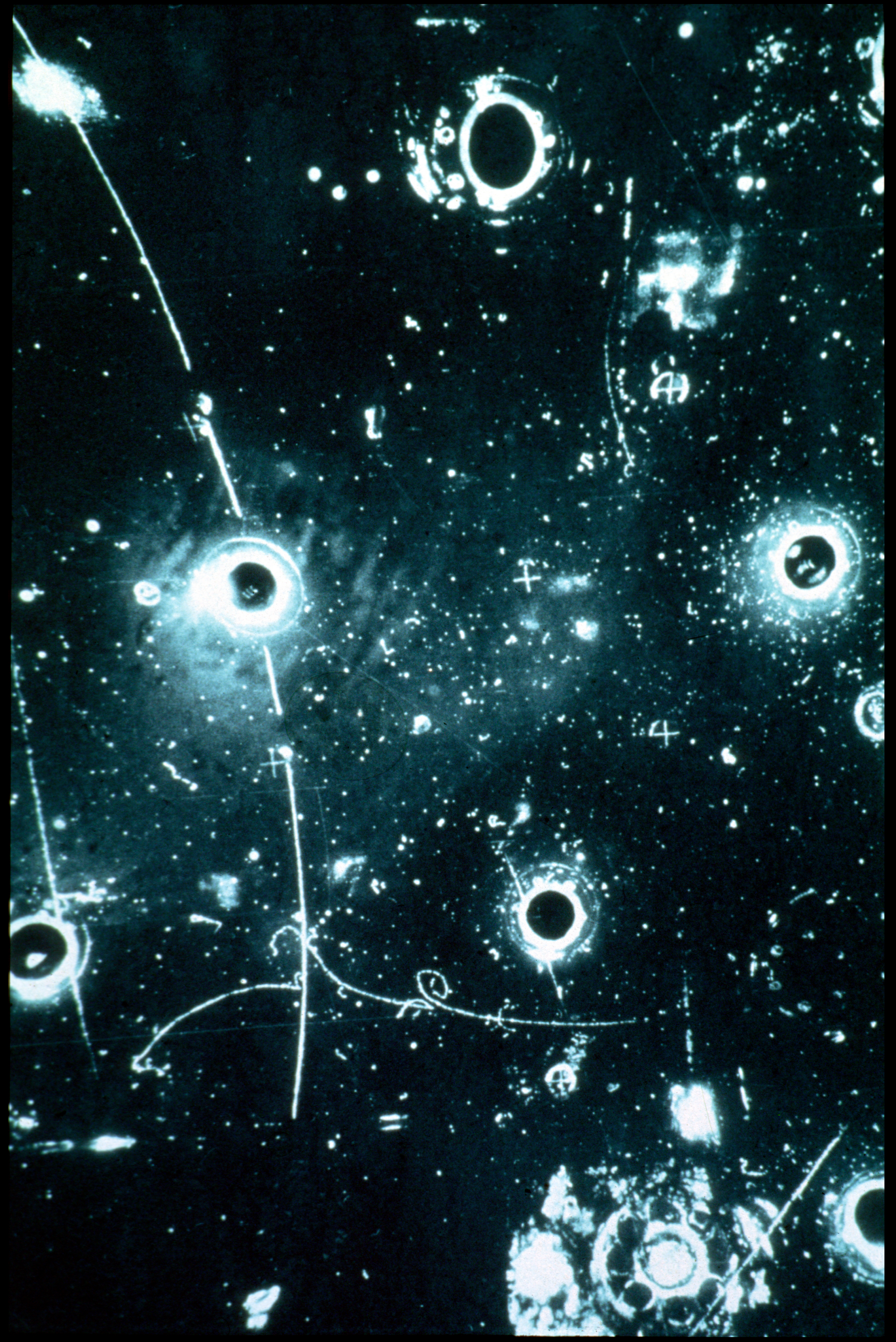

µBooNE
7 cm
NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.

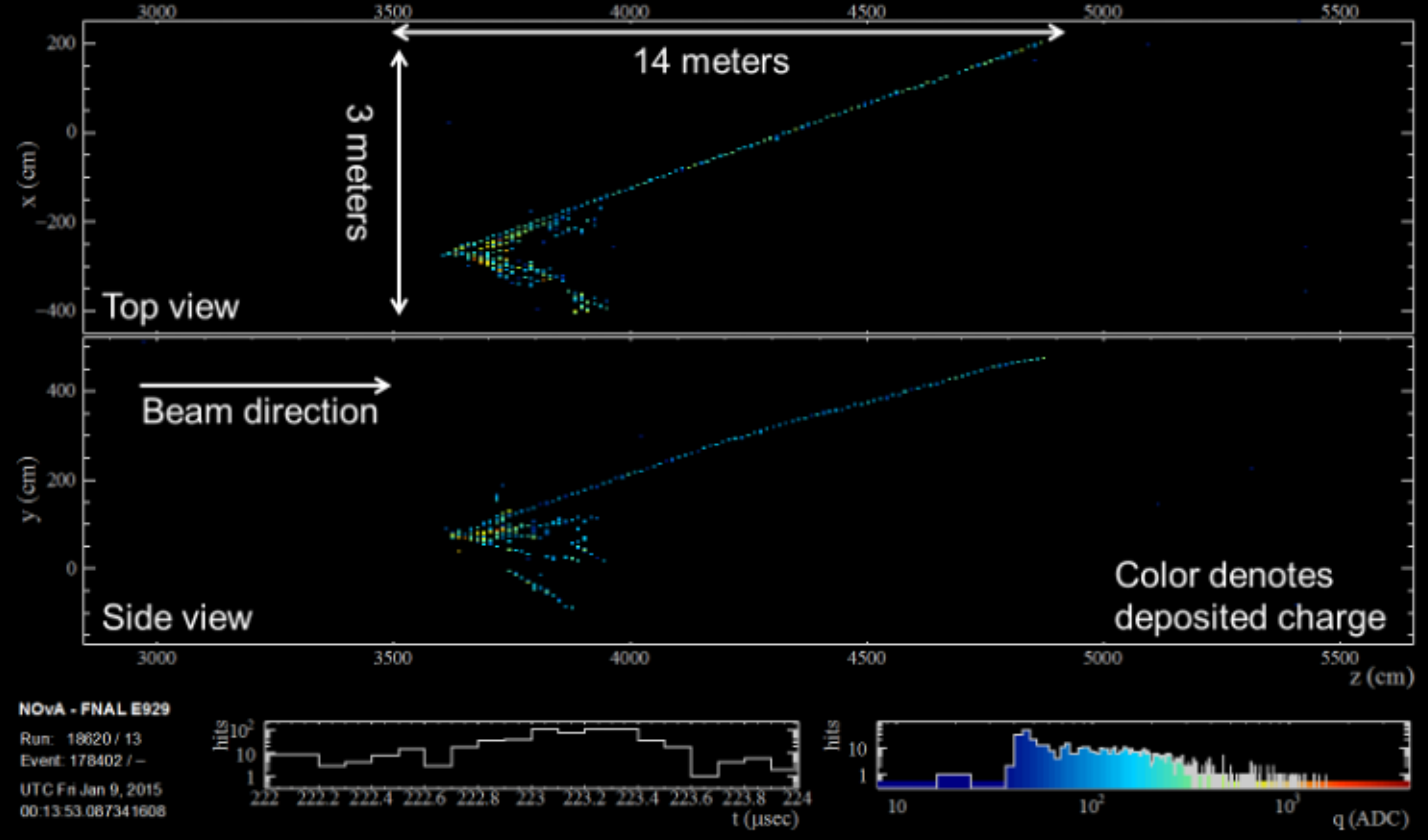





T : 574 584 594 604 614 624 634 644 654 664 674 684 694 704 714 724

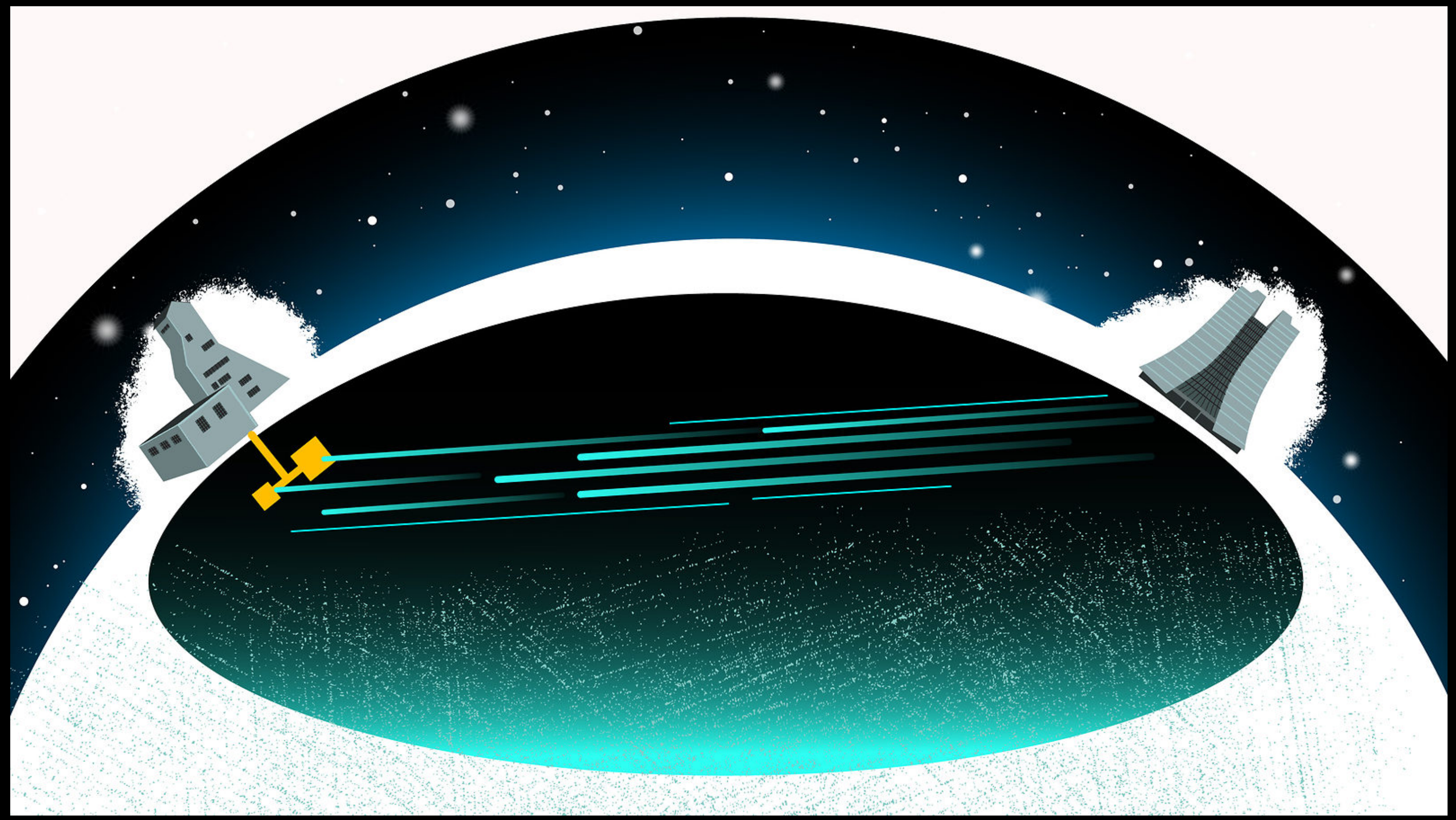
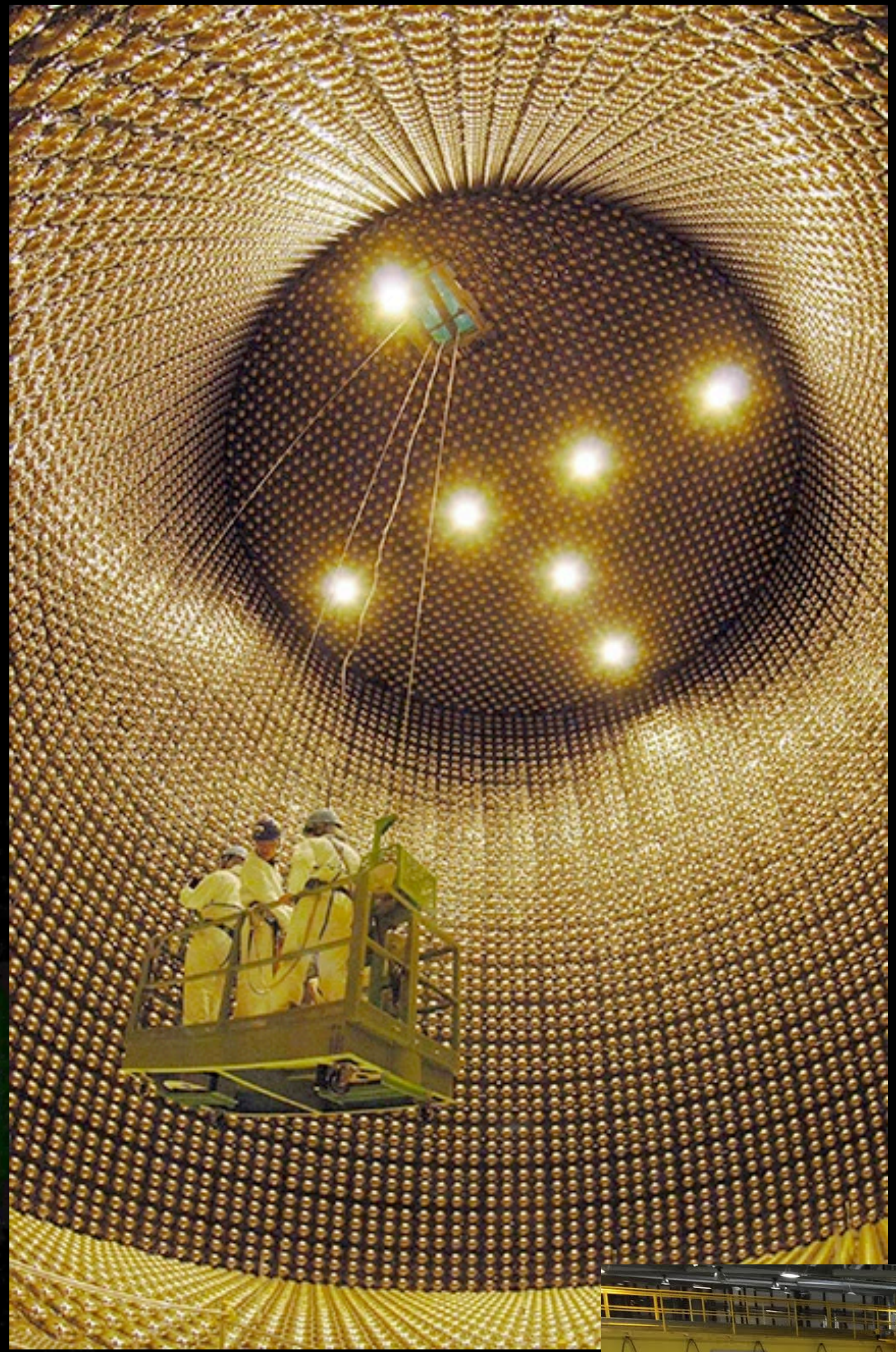
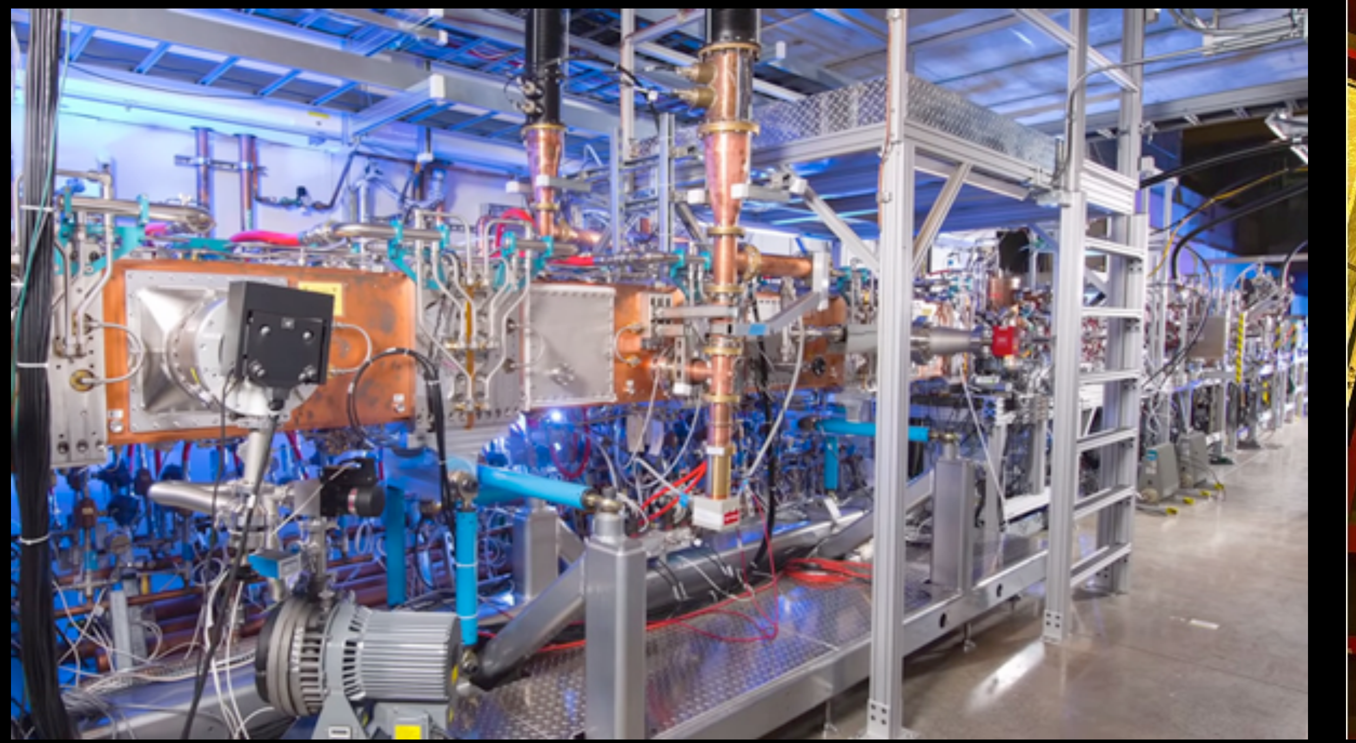


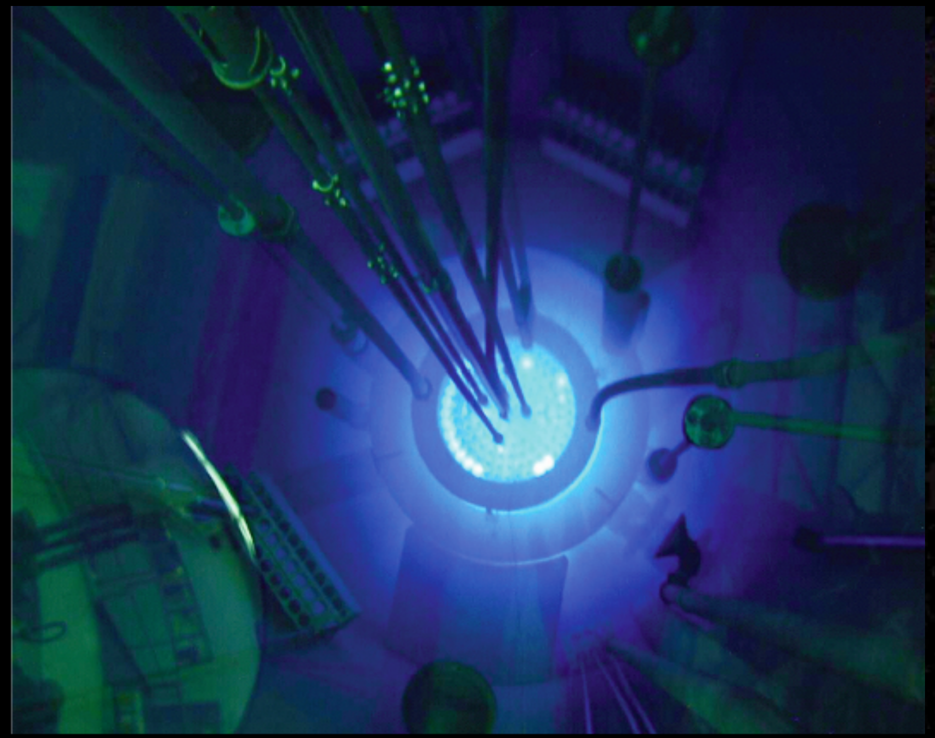
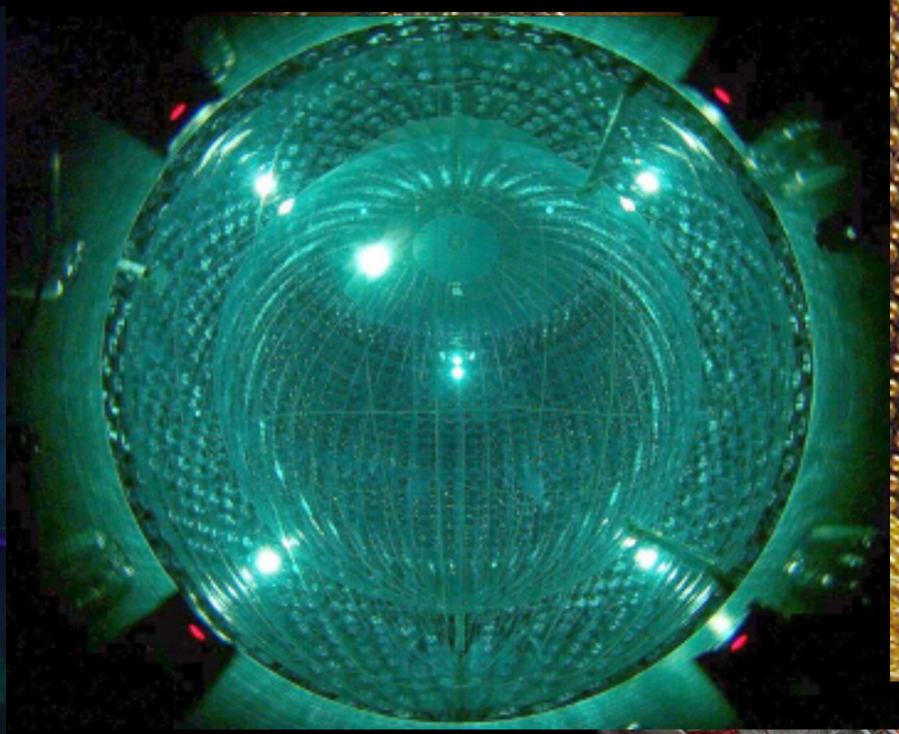


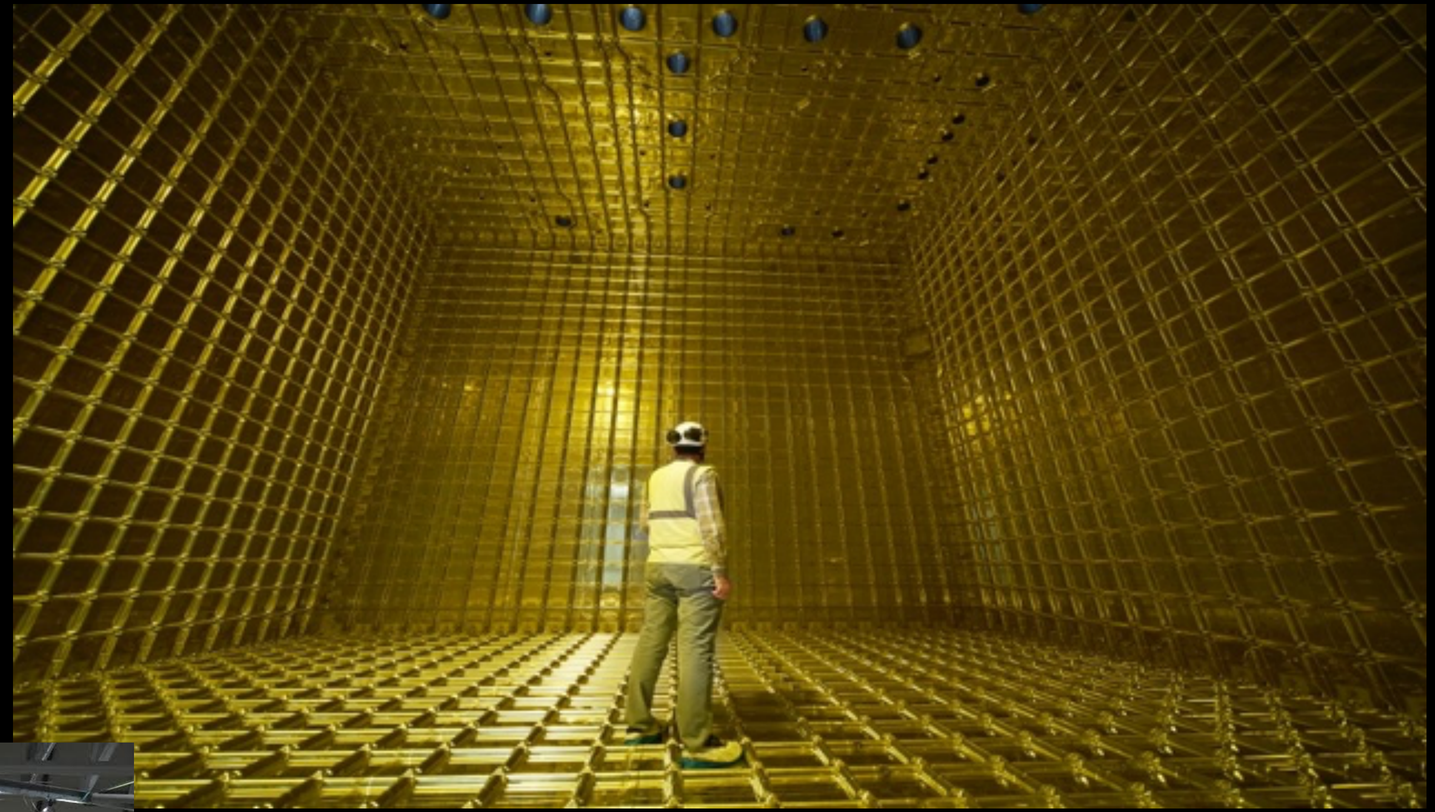
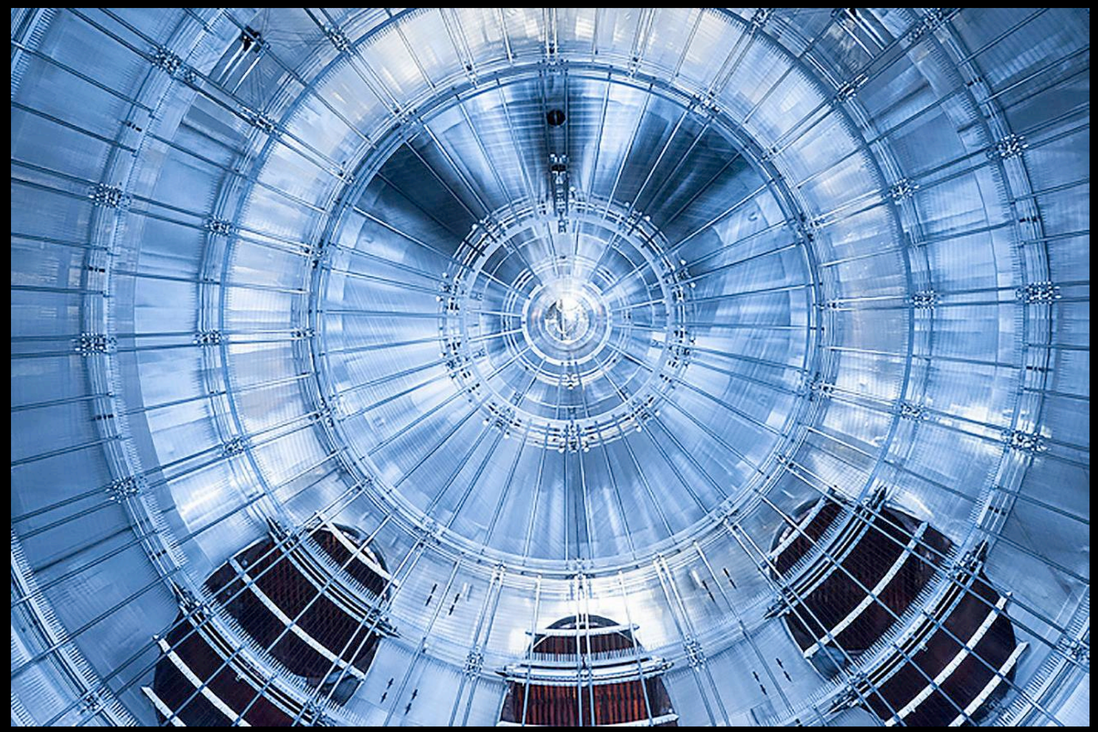
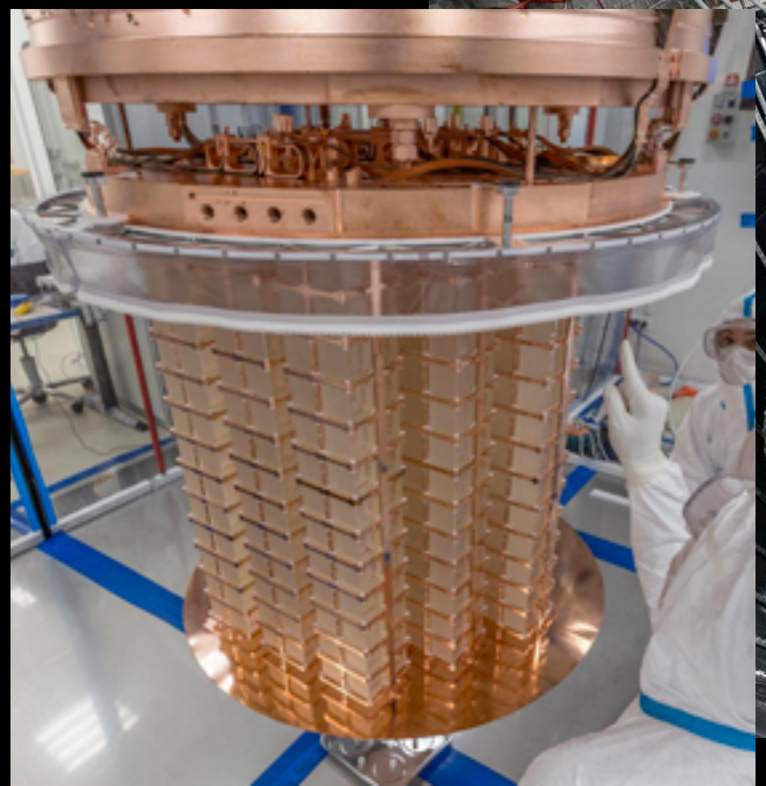

14 meters
3 meters
Top view
Beam direction
Side view
Color denotes
deposited charge
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
t (µsec)
q (ADC)
hits

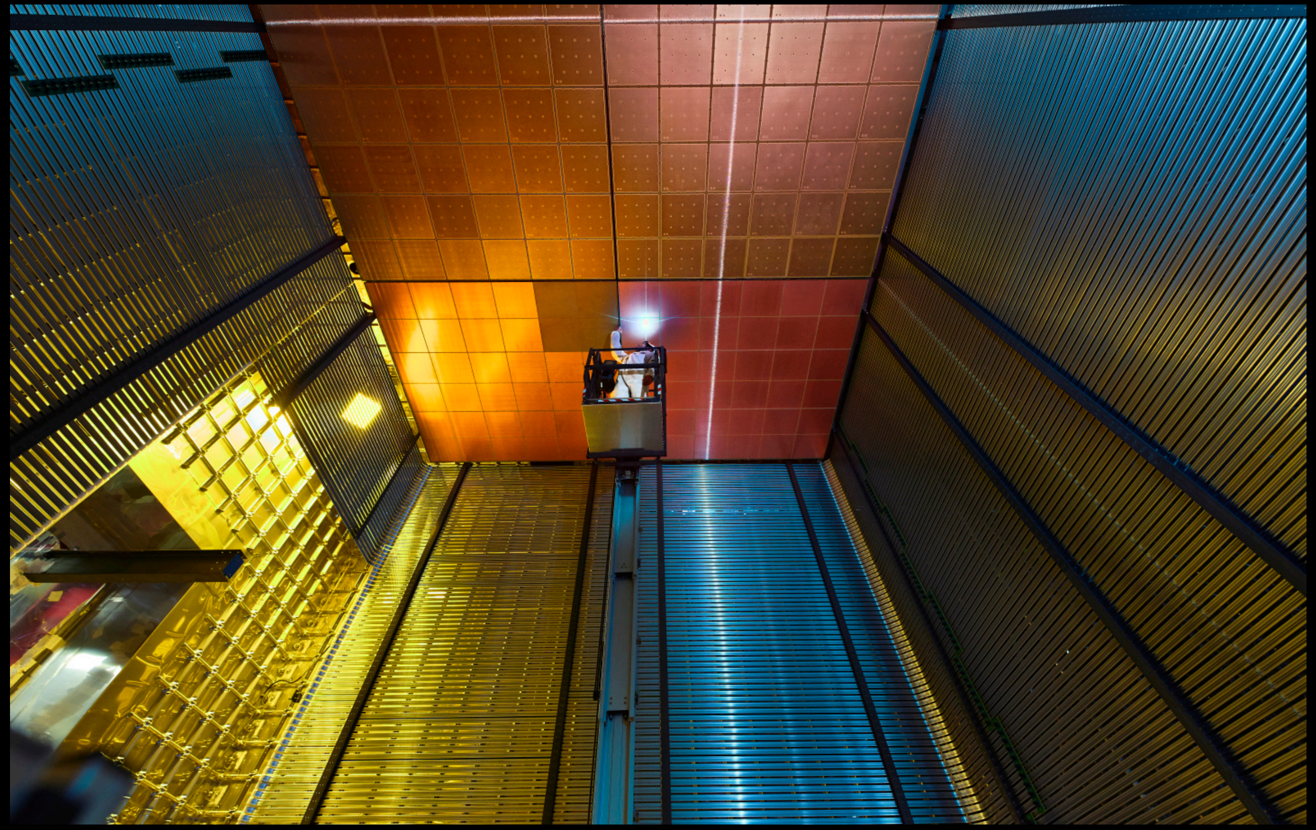

µBooNE
10 cm
BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016

Intense experimental program

Neutrino oscillations

Neutrino oscillations

3 neutrino mixing: $|\nu_\alpha> = \sum_{i=1}^{3} U_{\alpha i} |\nu_i>$

Pontecorvo, Maki, Nakagawa, Sakata (PMNS) 3x3 mixing matrix

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

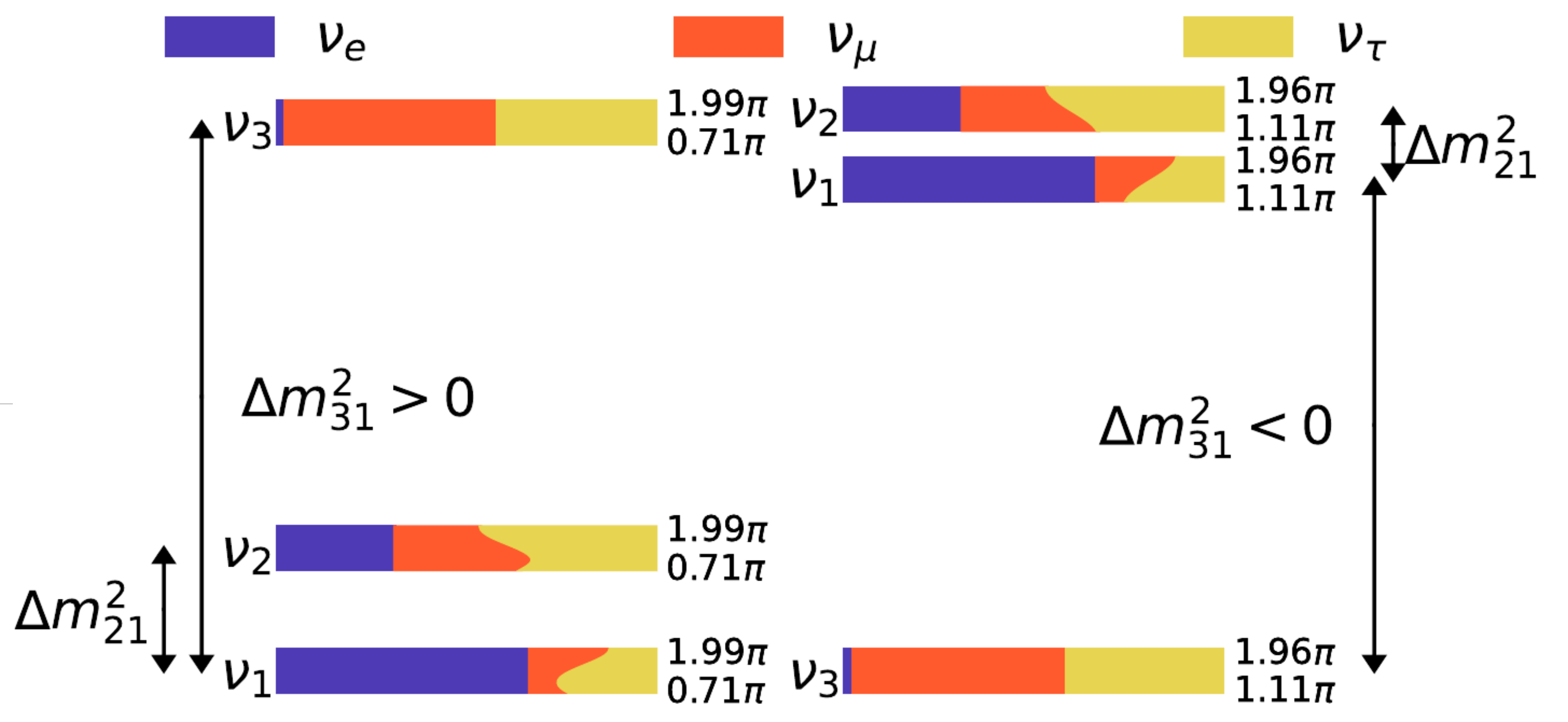
θ_{23}	θ_{13}, δ_{CP}	θ_{12}
Atmospheric + LBL acc.	SBL reactors + LBL acc.	Solar + KamLAND

Oscillation probability

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \delta_{\alpha\beta} - 4 \sum_{i>j} Re\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) - 2 \sum_{i>j} Im\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

Neutrino mass spectrum

$\Delta m^2_{ij} = m^2_i - m^2_j$



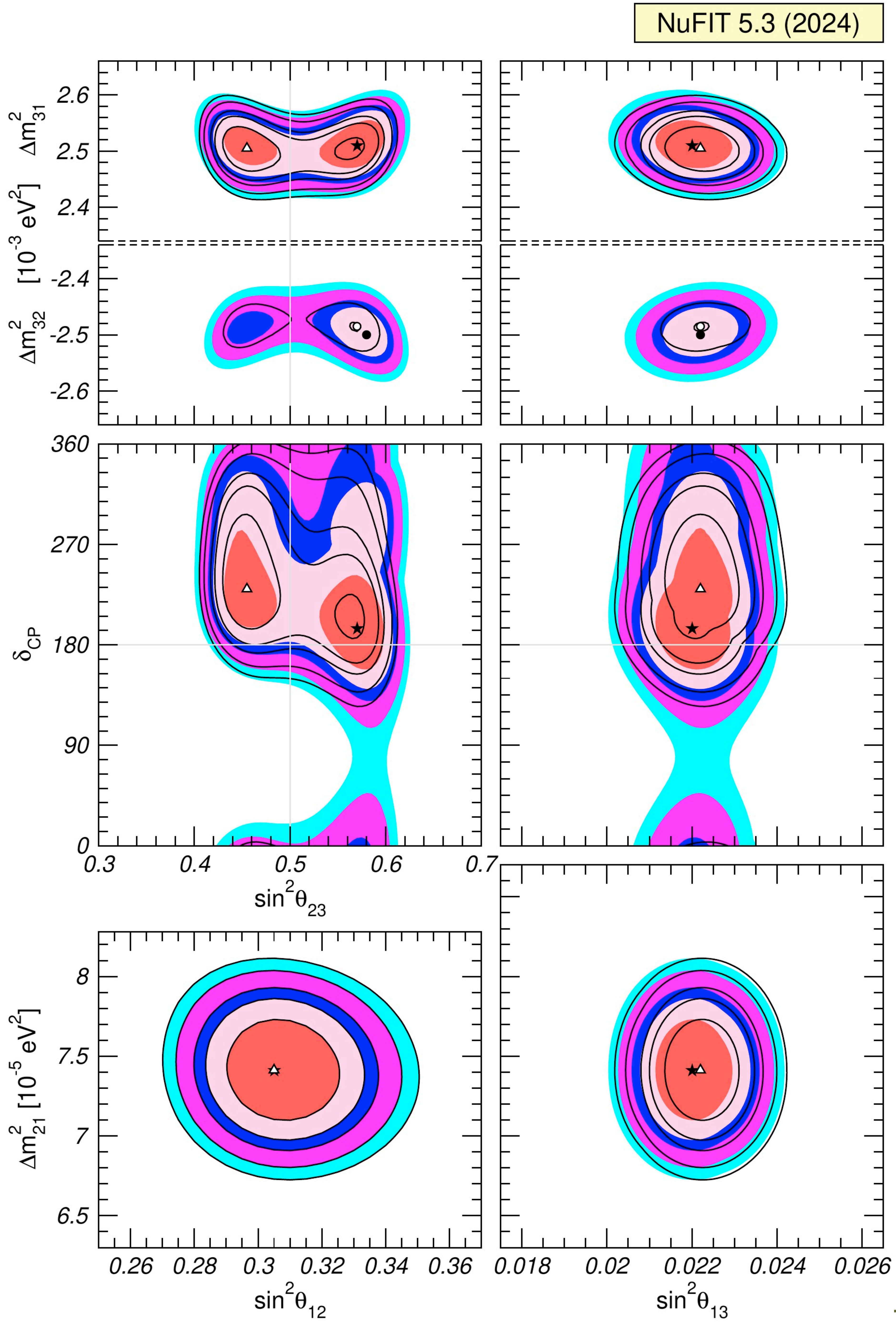
Normal Ordering　　Inverted Ordering

Unknown parameters: mass ordering (sign of Δm^2_{31}), δ_{CP}, octant of θ_{23}

Global fit information

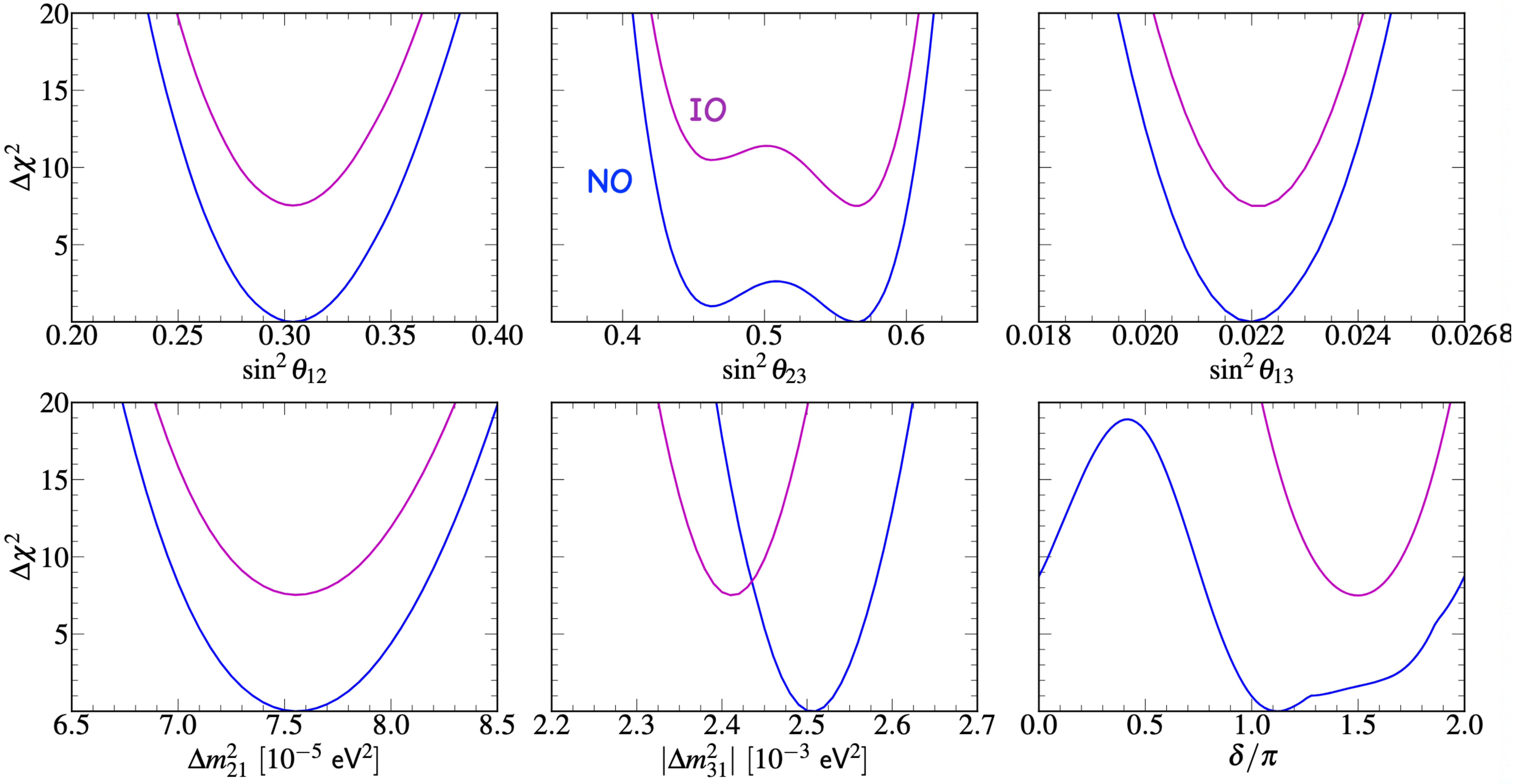
- Global 6-parameter fit (including δ_{CP}):
  - **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + BX(1–3);
  - **Atmospheric**: SK(1–4) + DeepCore;
  - **Reactor**: KamLAND + Dbl-Chooz + Daya-Bay + Reno;
  - **Accelerator**: Minos + T2K + NOvA;

- **θ_{23} octant** is **not resolved** yet (slight preference for the second octant)
- The sign of **Δm^2_{32}** is **unknown** (Normal Ordering is preferred)
- **δ_{CP} unknown**: Tension between T2K and NOvA experiments for NO. CP-violation for IO at ~3σ



Global fit results

Mariam Tórtola, Neutrino2024



Global fit results

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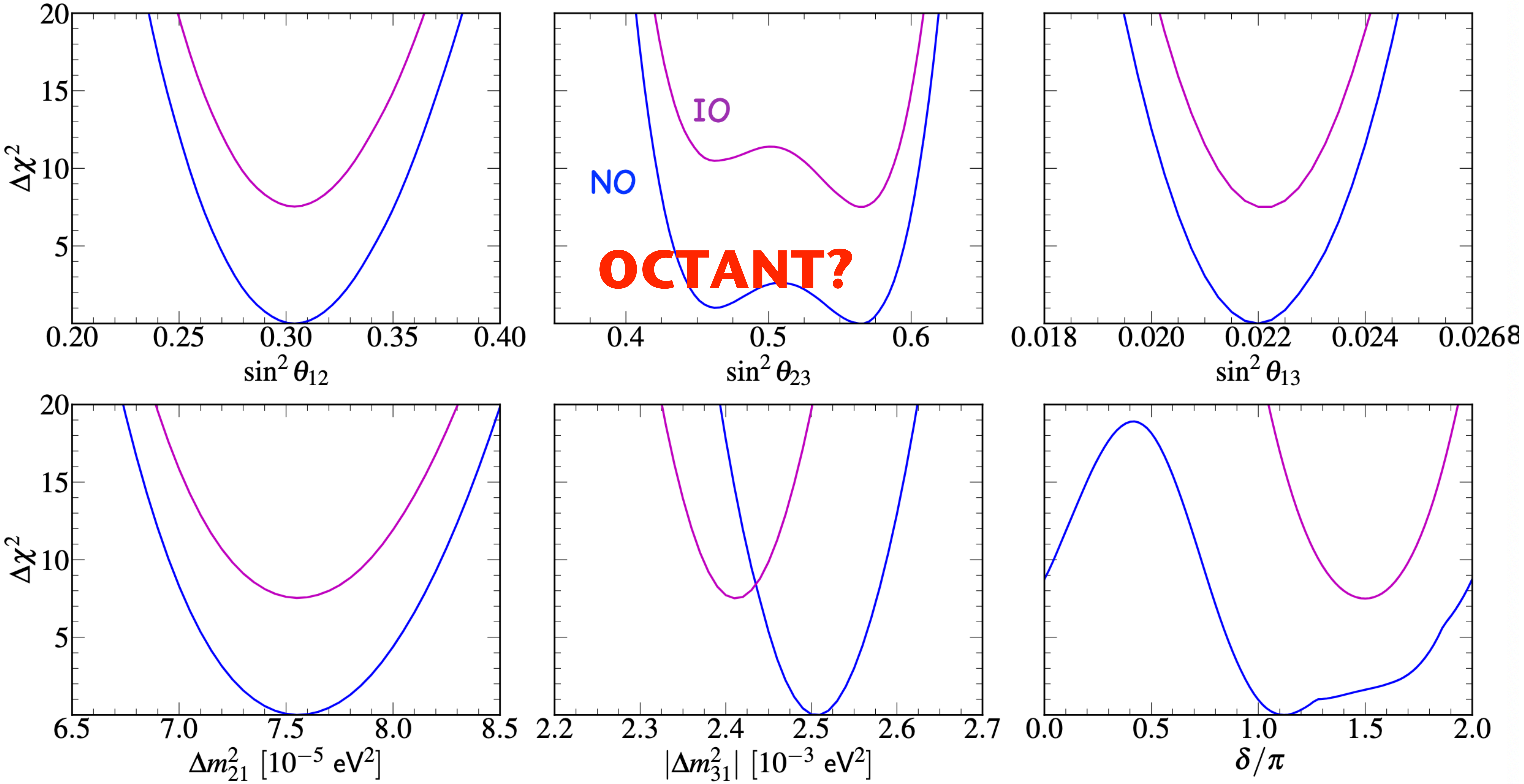
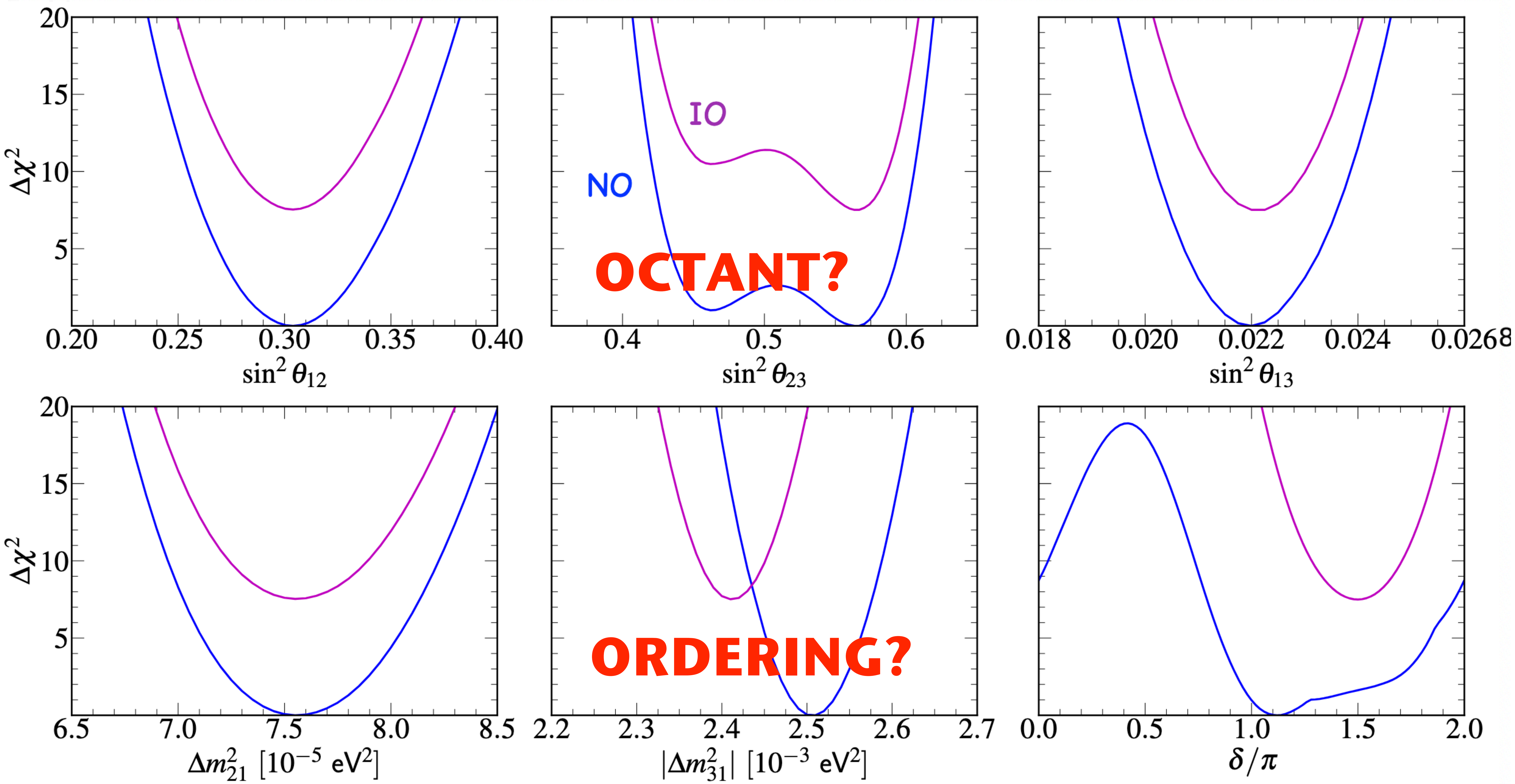


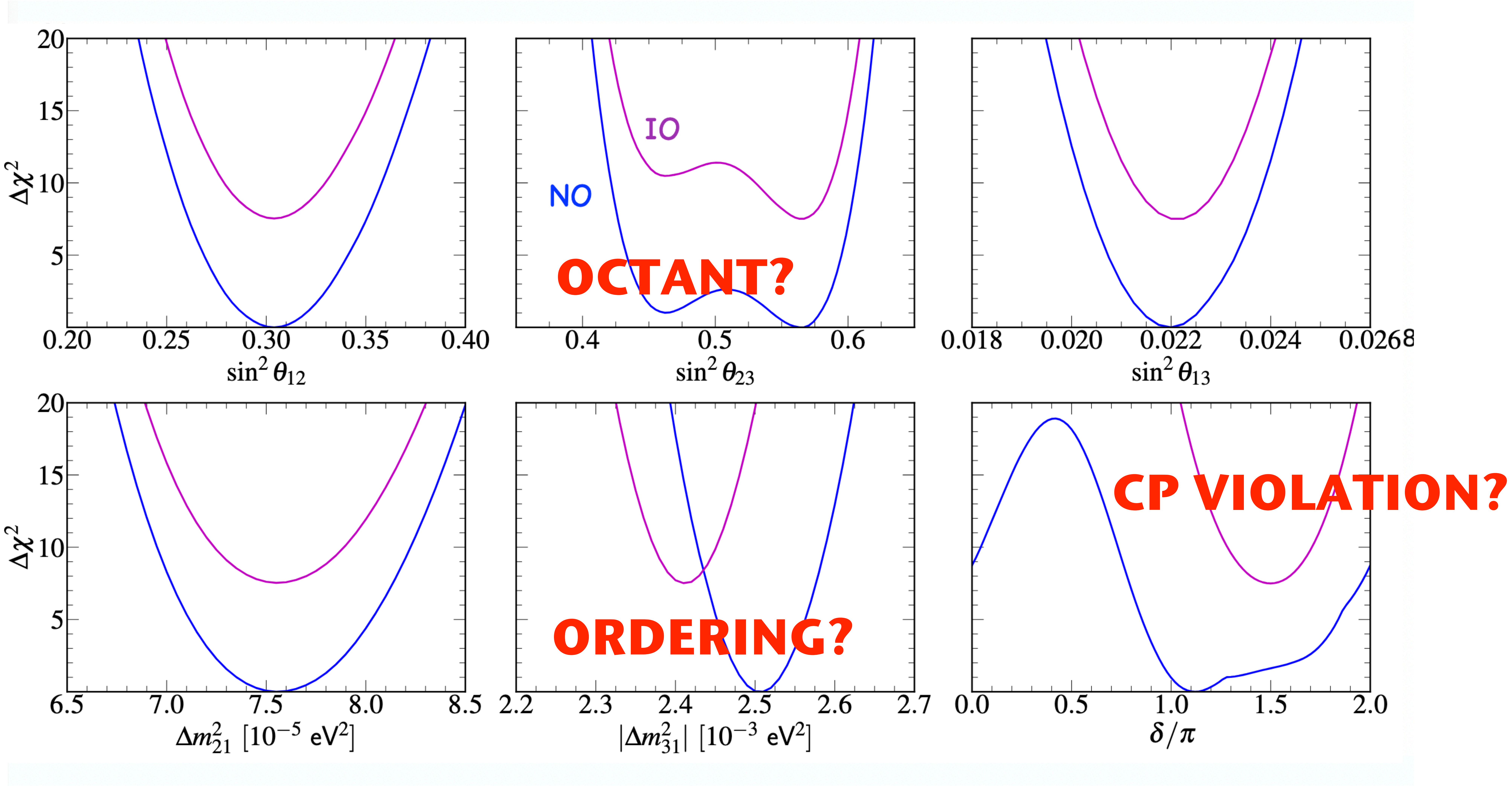
Global fit results

Mariam Tórtola, Neutrino2024



Global fit results

Mariam Tórtola, Neutrino2024



Oscillation Parameters

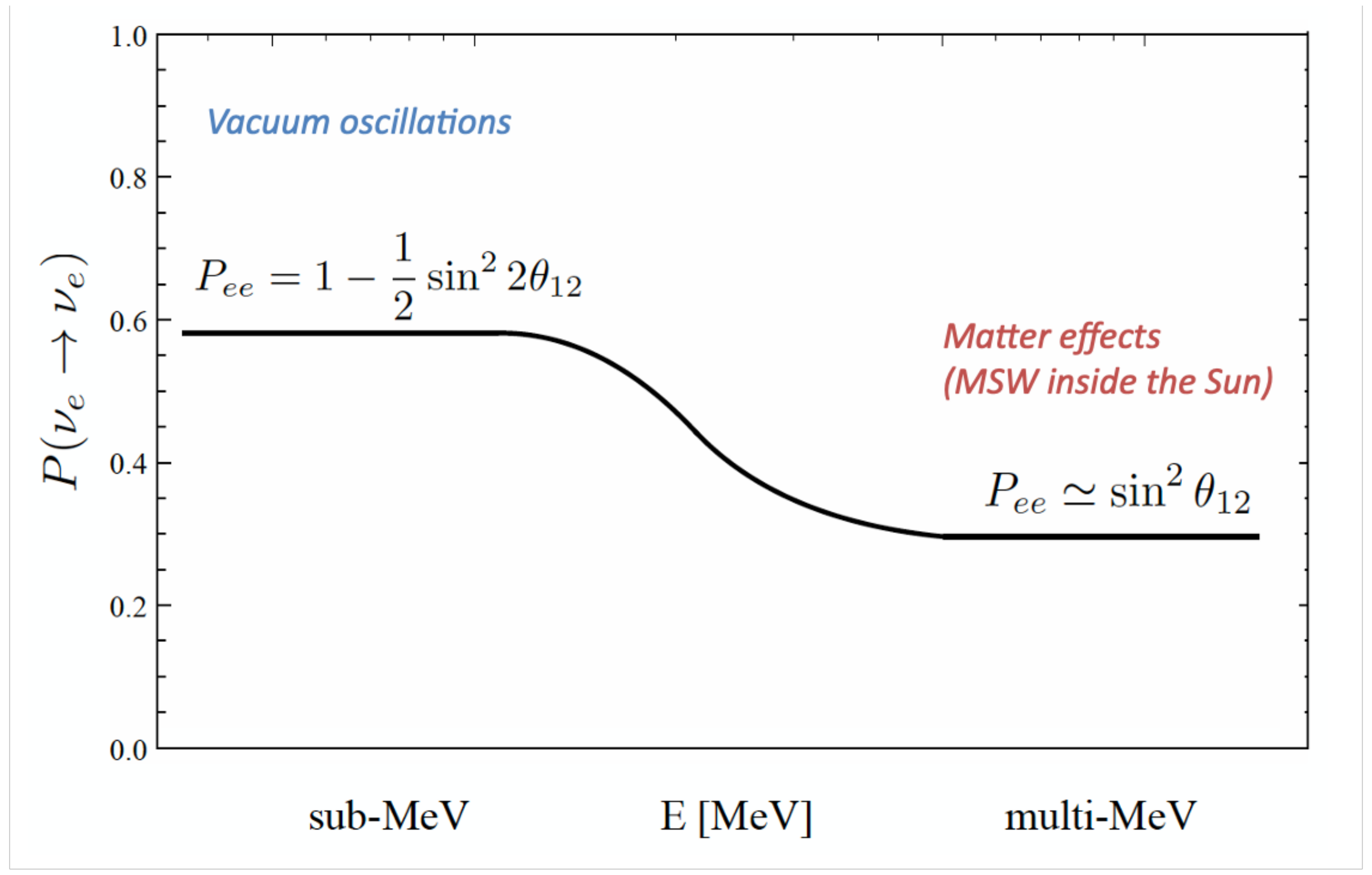
parameter	best fit $\pm\ 1\sigma$	3σ range	*Relative precision at 1σ*	
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	$7.55^{+0.22}_{-0.20}$	6.98–8.19	2.7 %	Precision
$\lvert\Delta m^2_{31}\rvert\ [10^{-3}\mathrm{eV}^2]$ (NO)	$2.51^{+0.02}_{-0.03}$	2.43–2.58	1.0 %	**SIGN UNKNOWN**
$\lvert\Delta m^2_{31}\rvert\ [10^{-3}\mathrm{eV}^2]$ (IO)	$2.41^{+0.03}_{-0.02}$	2.34-2.49		
$\sin^2\theta_{12}/10^{-1}$	$3.04^{\pm}0.16$	2.57–3.55	5.4 %	Precision
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.64^{+0.15}_{-0.21}$	4.23–6.04	3-4 %	**OCTANT UNKNOWN**
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.64^{+0.15}_{-0.18}$	4.27–6.03		
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.20^{+0.05}_{-0.06}$	2.03–2.38	2.6 %	Precision
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.20^{+0.07}_{-0.04}$	2.04–2.38		
δ/π (NO)	$1.12^{+0.16}_{-0.12}$	0.76–2.00		**CP VIOLATION?**
δ/π (IO)	$1.50^{+0.13}_{-0.14}$	1.11–1.87		

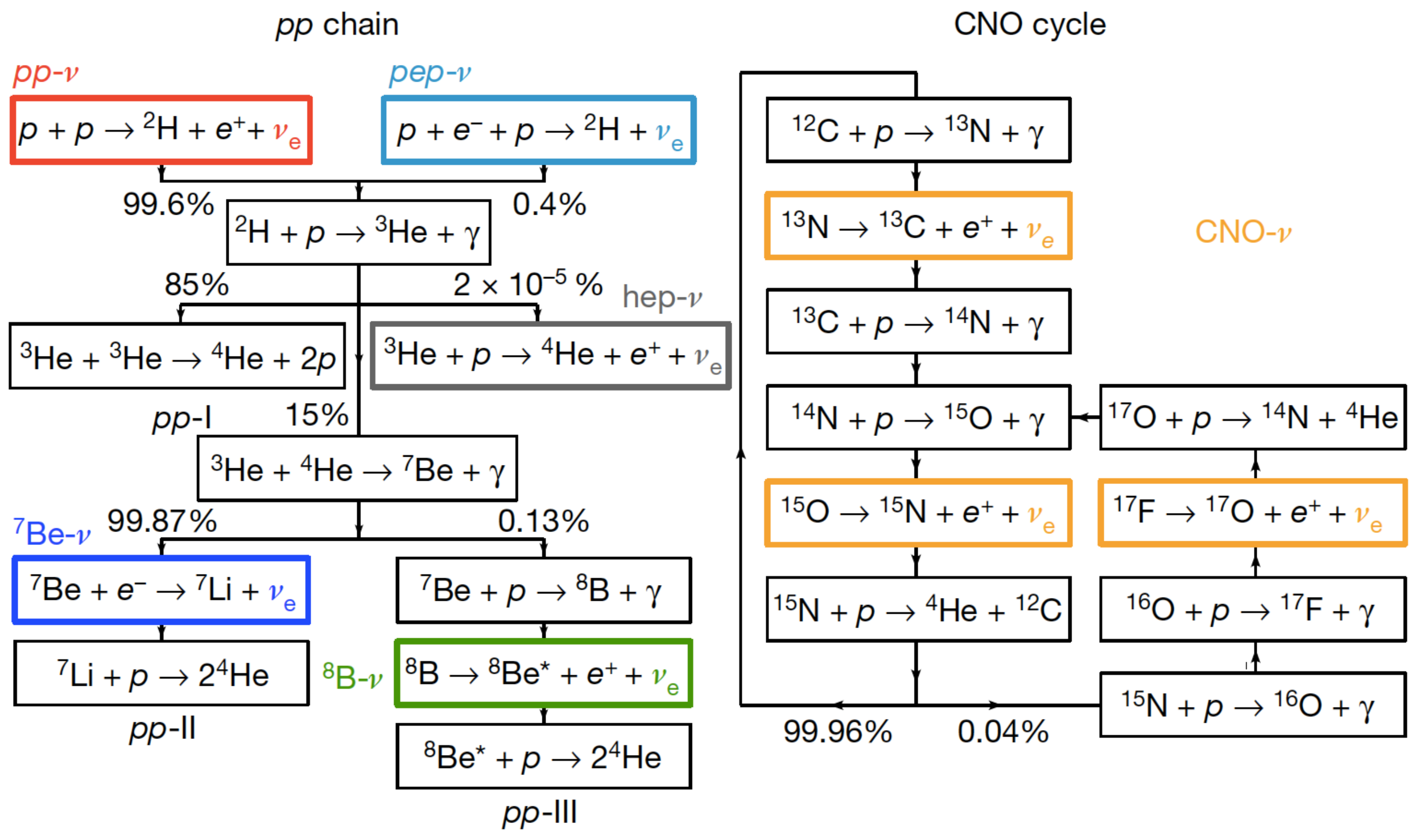
Mariam Tórtola, Neutrino2024

Solar and reactor neutrino oscillations

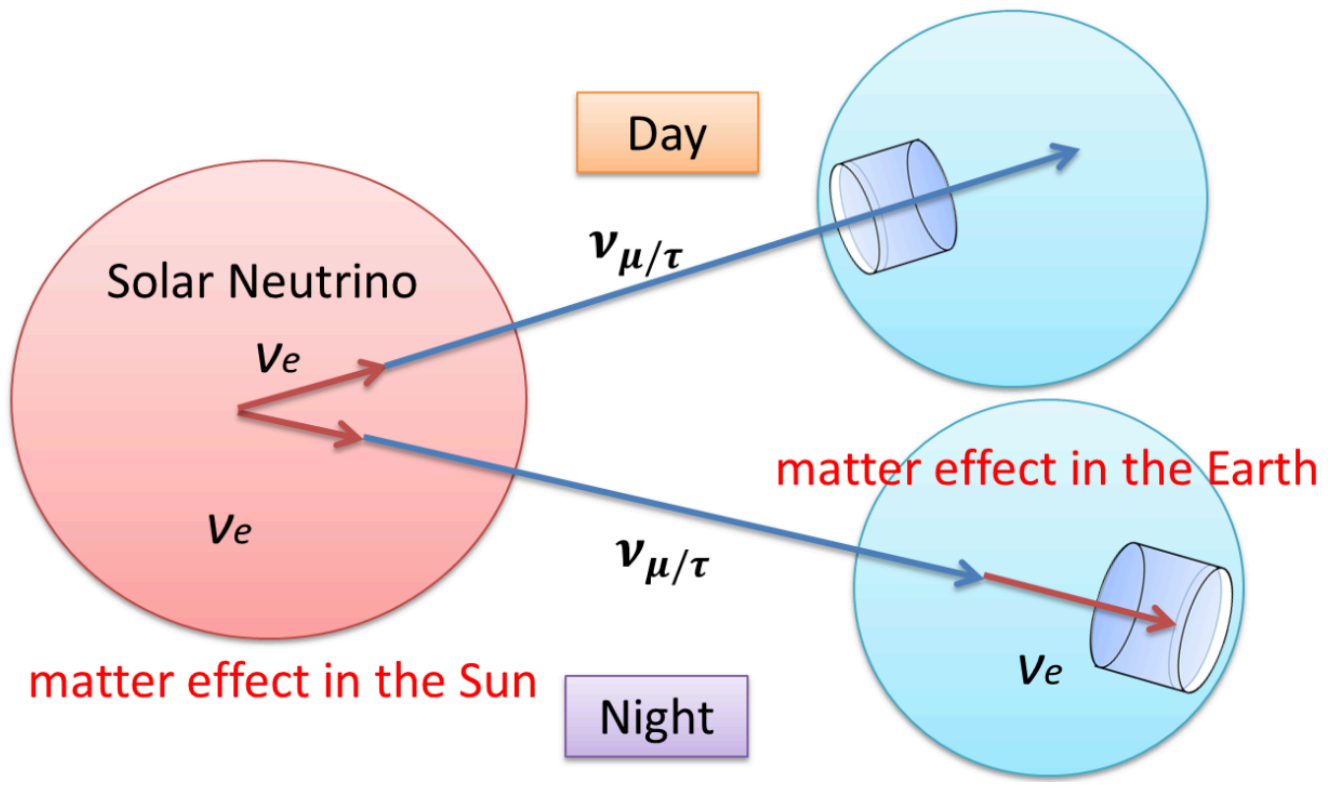
Solar neutrinos

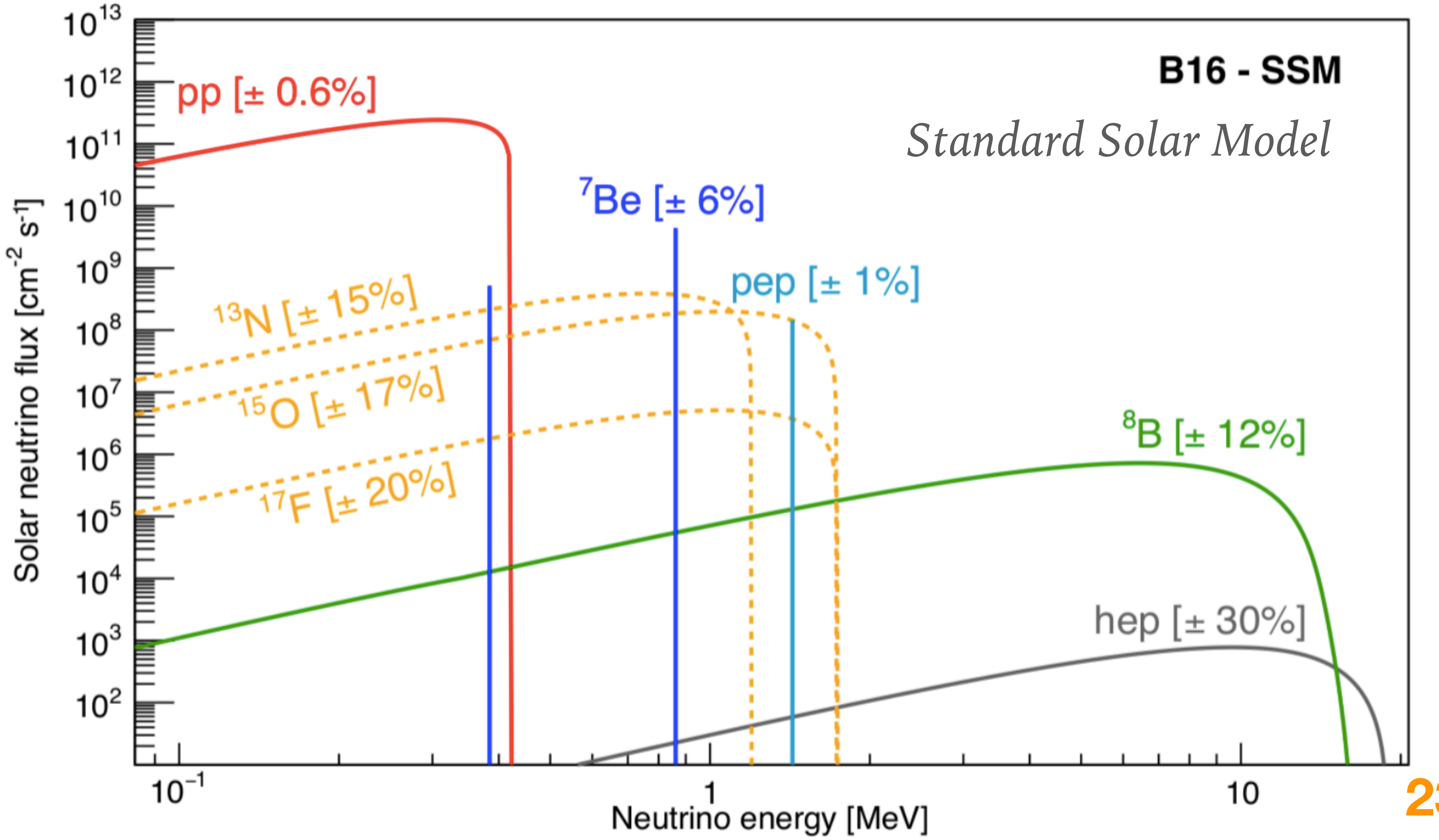
Neutrino spectrum





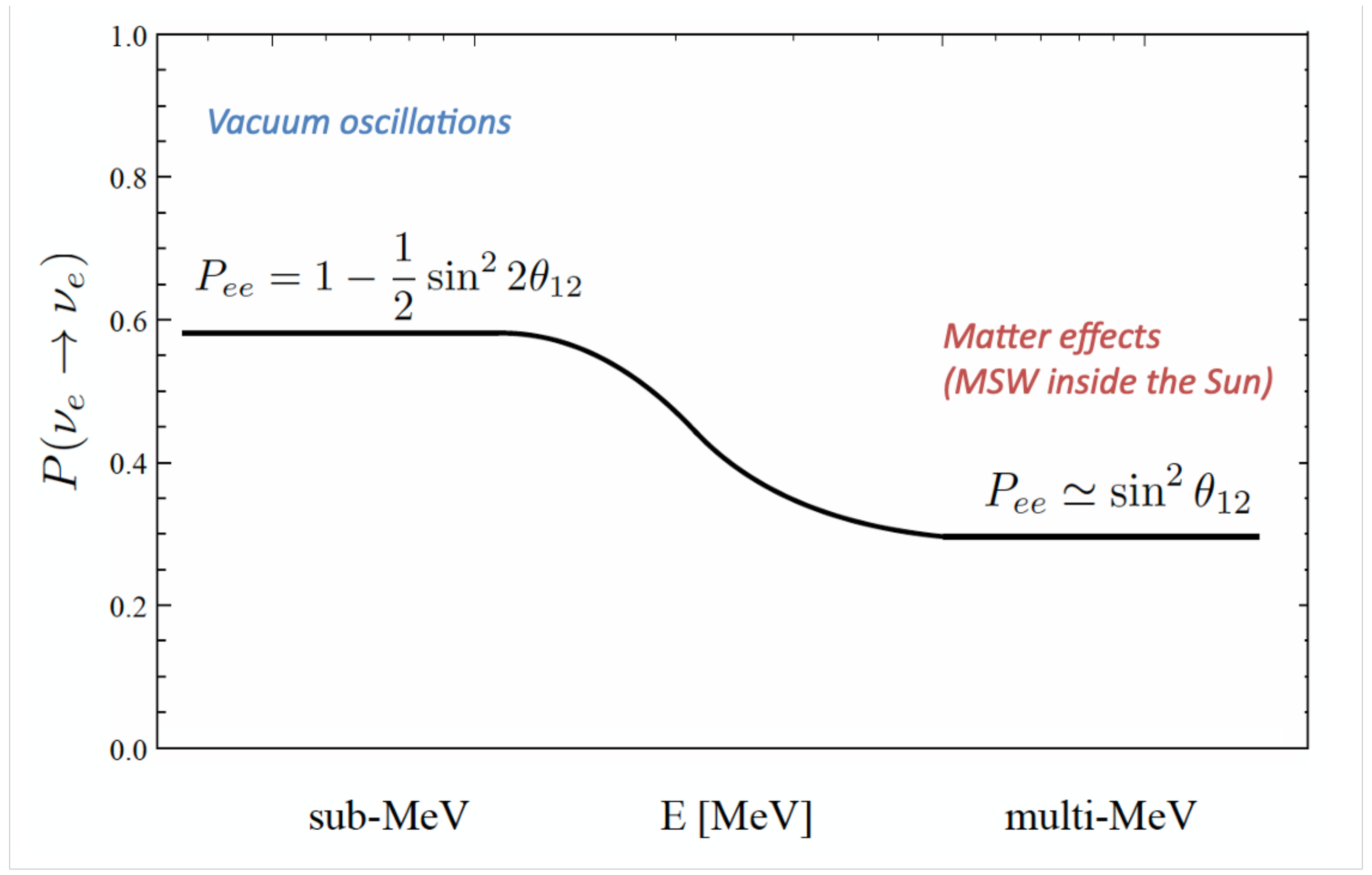
Day-night flux asymmetry 2(D-N)/(D+N)



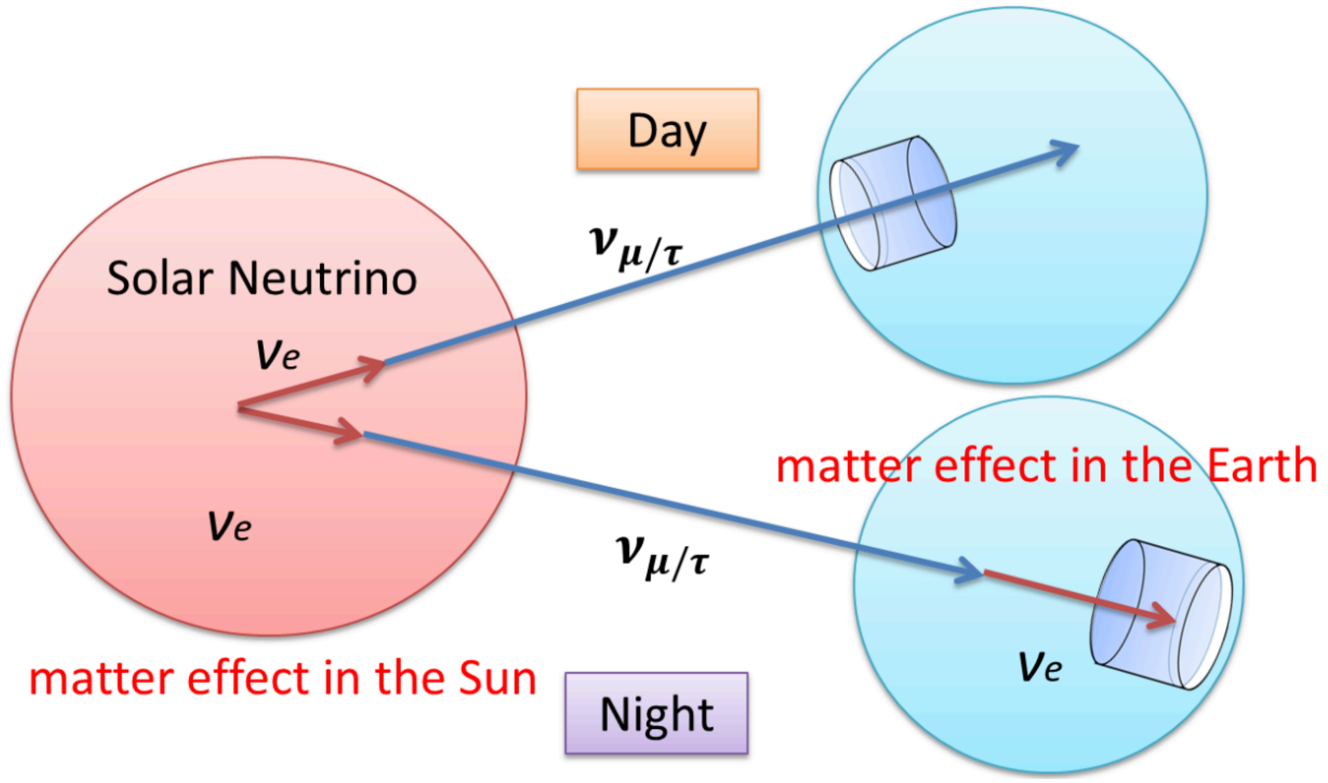


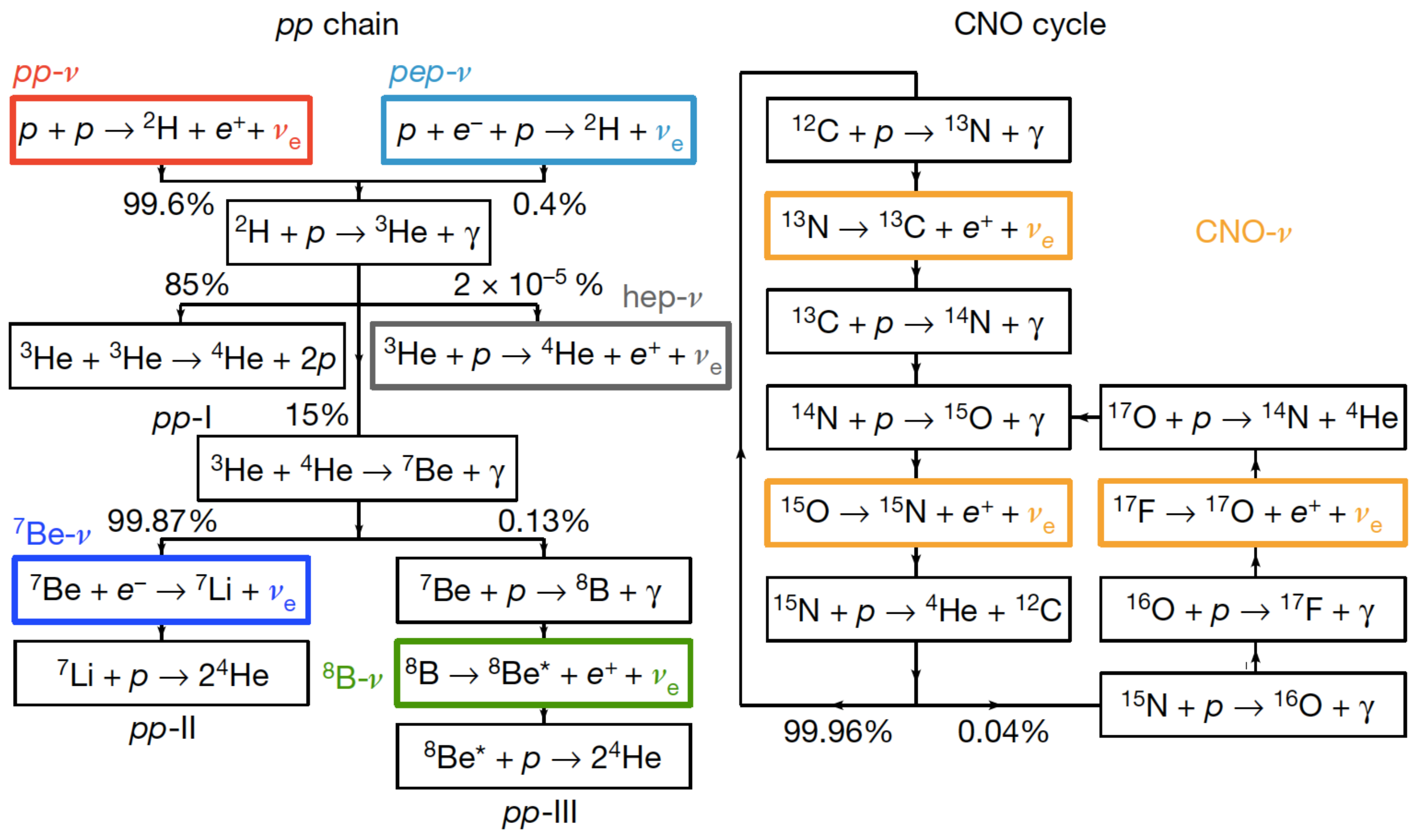
Solar neutrinos

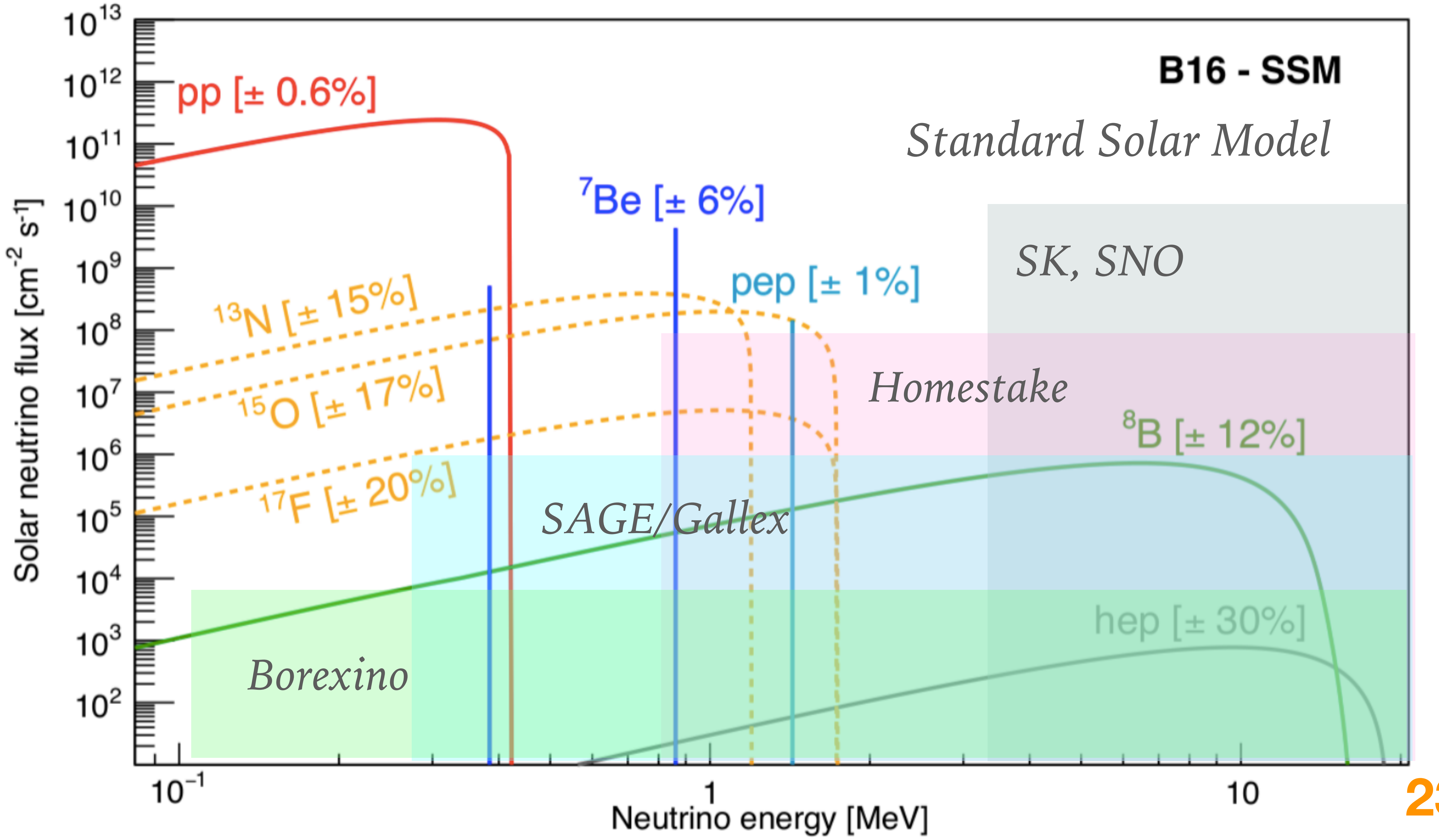
Neutrino spectrum



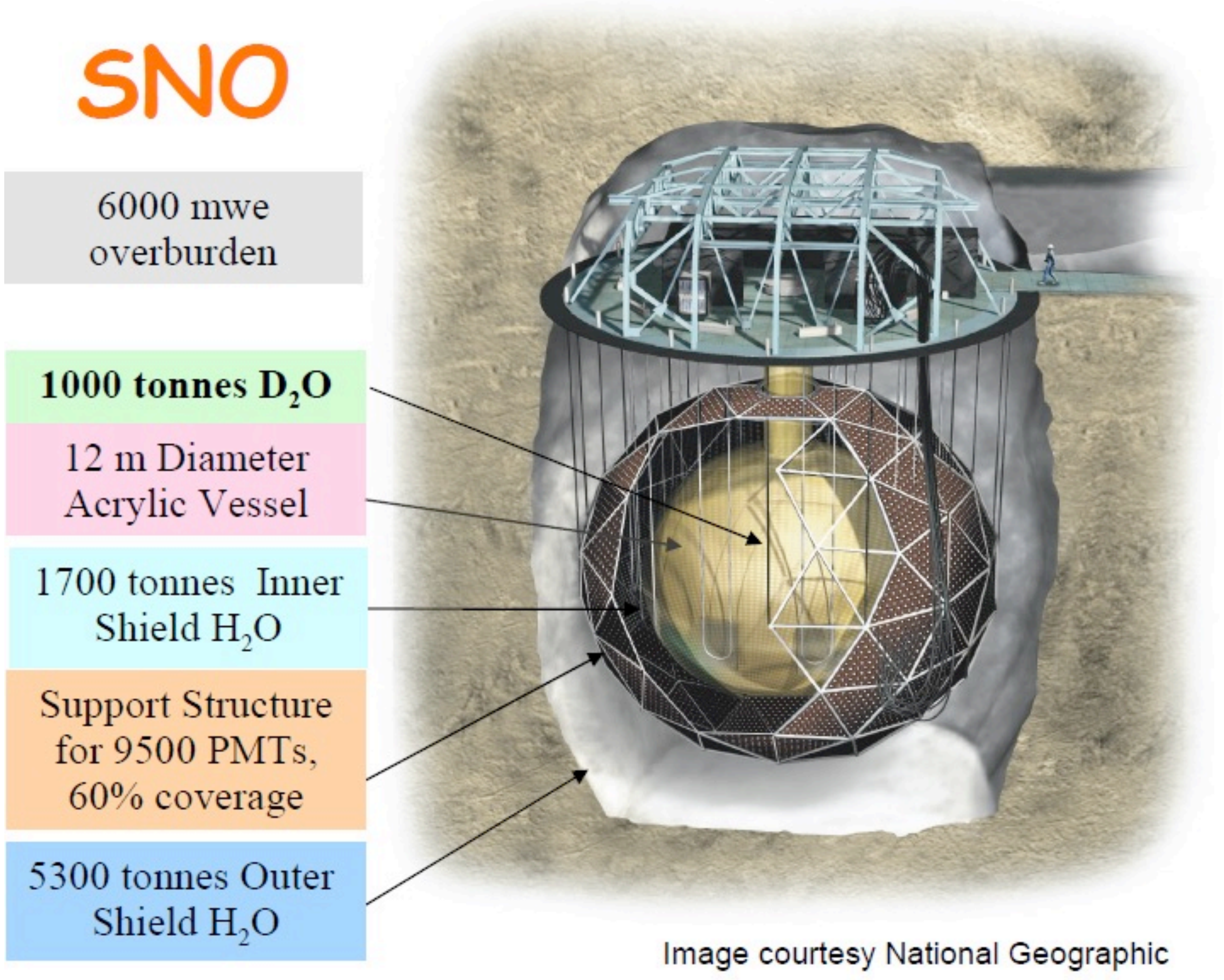
Day-night flux asymmetry 2(D-N)/(D+N)







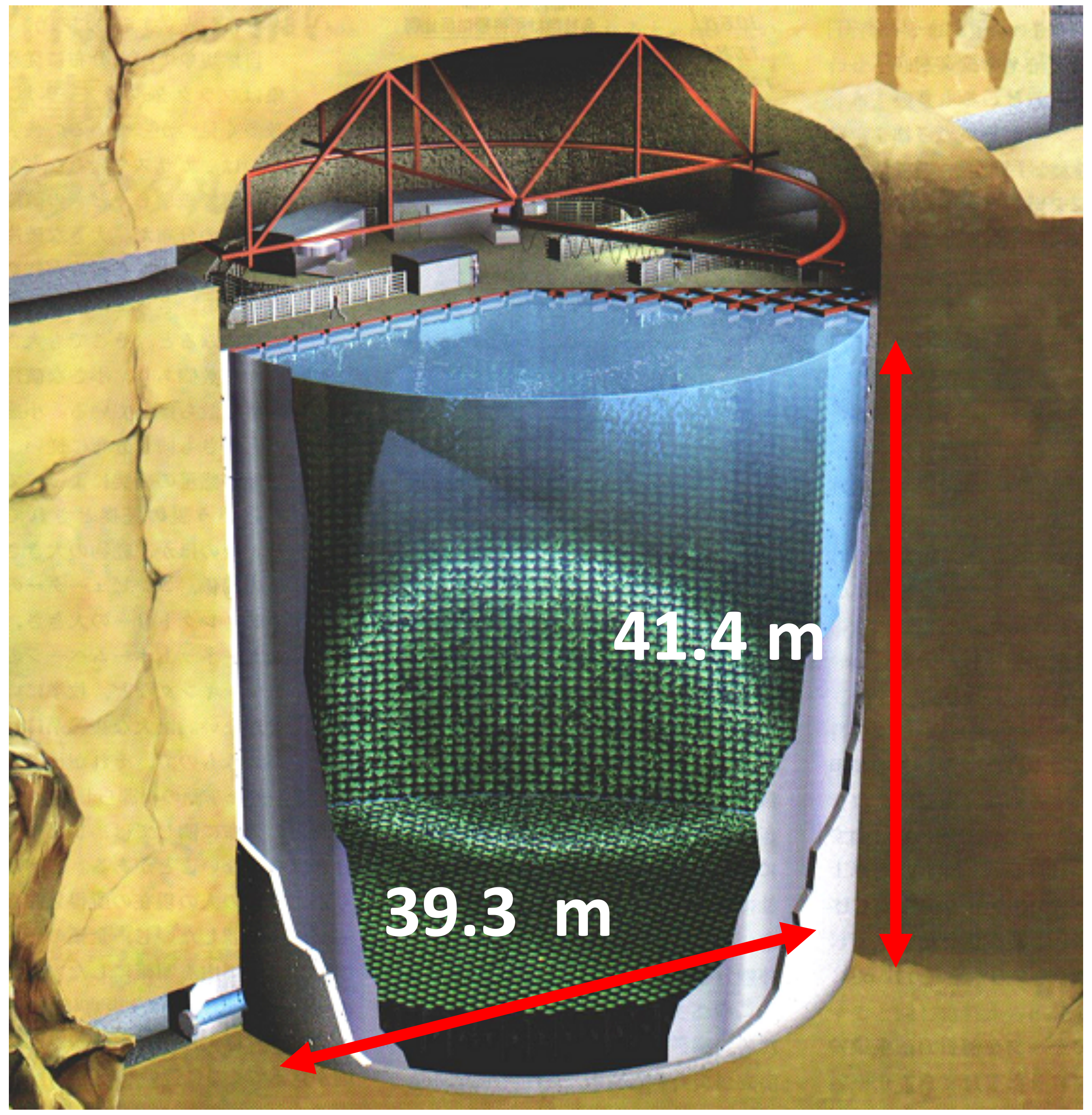
SNO / Super-K detectors



Super-K

ES $\nu_x + e^- \rightarrow \nu_x + e^-$

(solar channel)



$$CC \quad \nu_e + d \Rightarrow p + p + e^-$$
$$ES \quad \nu_x + e^- \Rightarrow \nu_x + e^-$$
$$NC \quad \nu_x + d \Rightarrow p + n + \nu_x$$

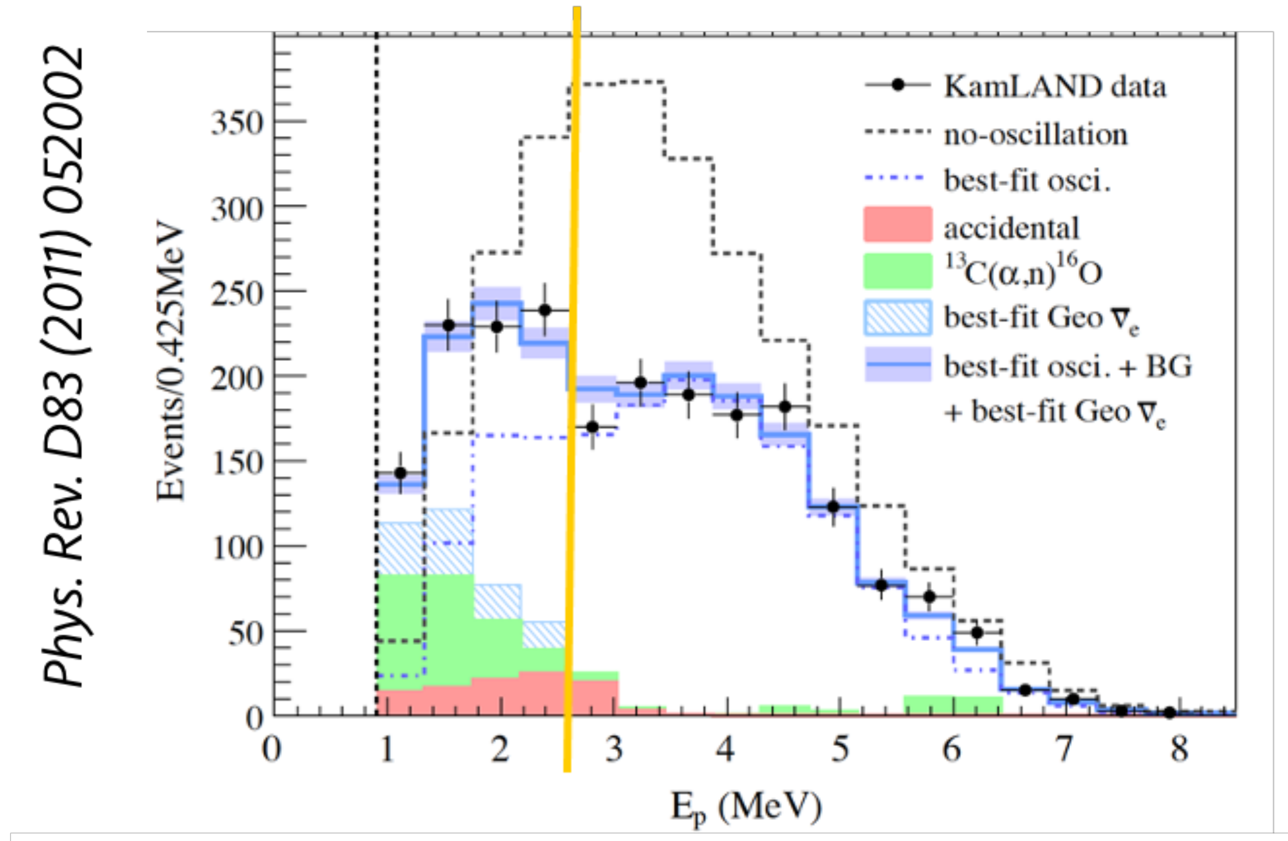
- 1 kt heavy water Cerenkov detector in Sudbury mine (Canada)
- Nobel prize in physics (2015) by the solar neutrino oscillations thanks to 3 detection channels (Solar Neutrino Problem solved)
- SNO finished in 2006: SNO+ devoted to neutrinoless double beta decay searches

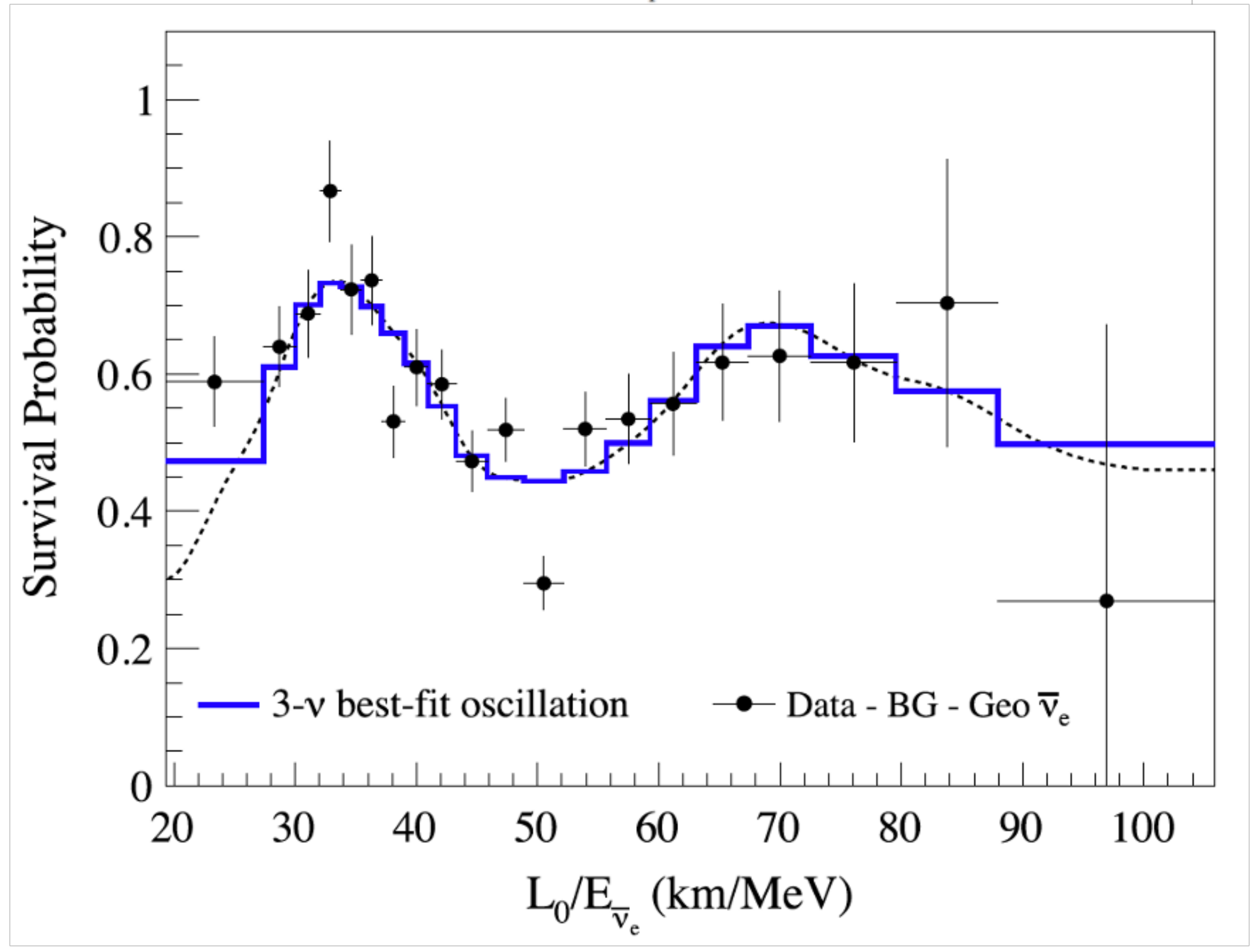
- 50 kt (22.5 kt fid) Water Cerenkov detector (taking data since 1996) in Kamioka mine (Japan)
- Provides direction and energy of solar neutrinos

Solar + KamLAND (LBL reactor) oscillation results

- **KamLAND** (2002-2011): 1 kt liquid scintillator reactor neutrino experiments in Japan (L~180 km from nuclear power plants) → antineutrino oscillations
  - ✦ Now KamLAND-Zen: neutrinoless double beta decay

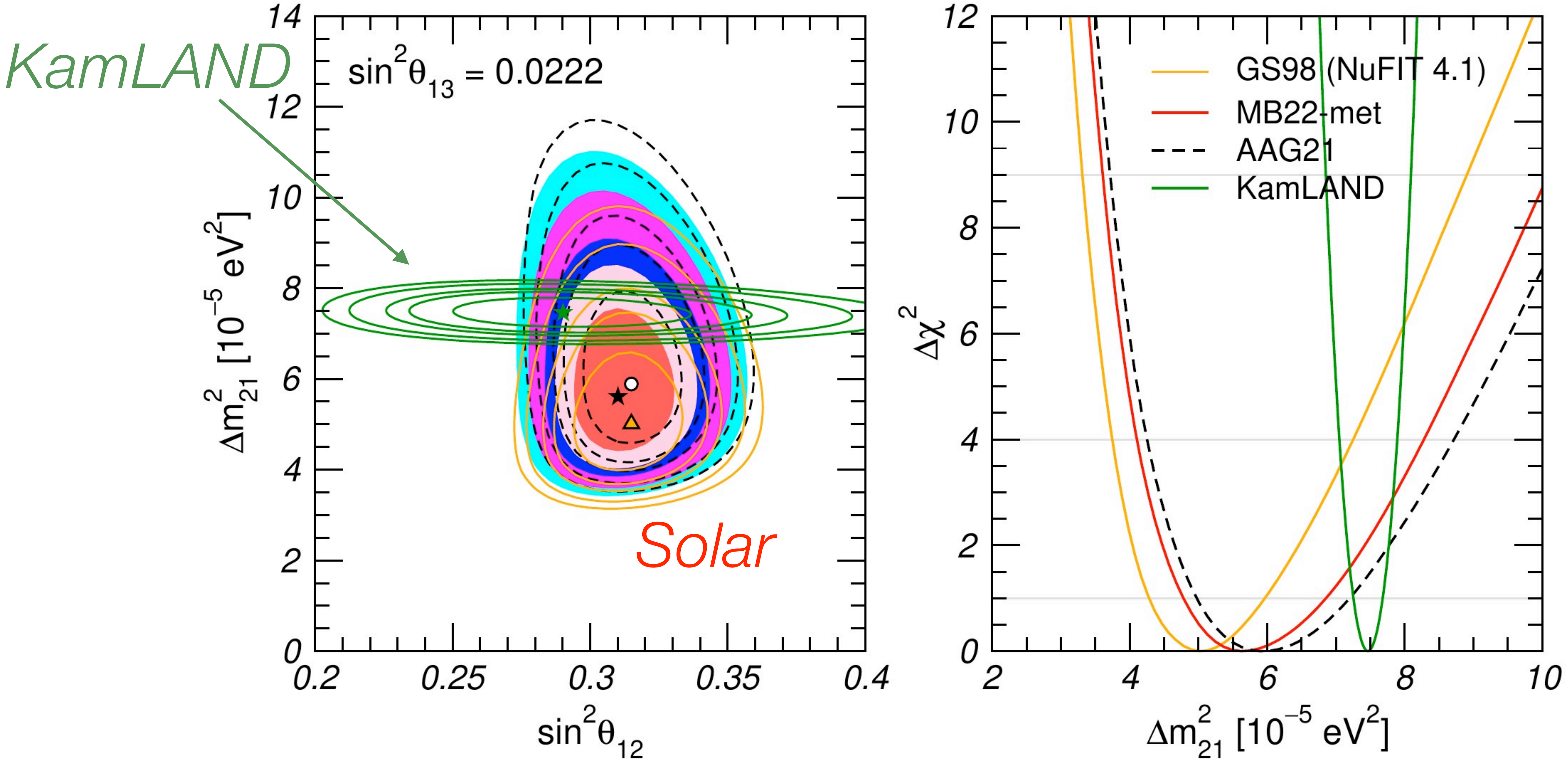
$$P_{ee} \approx 1-\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{13}{}^2 L}{4E_\nu}\right)-\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$





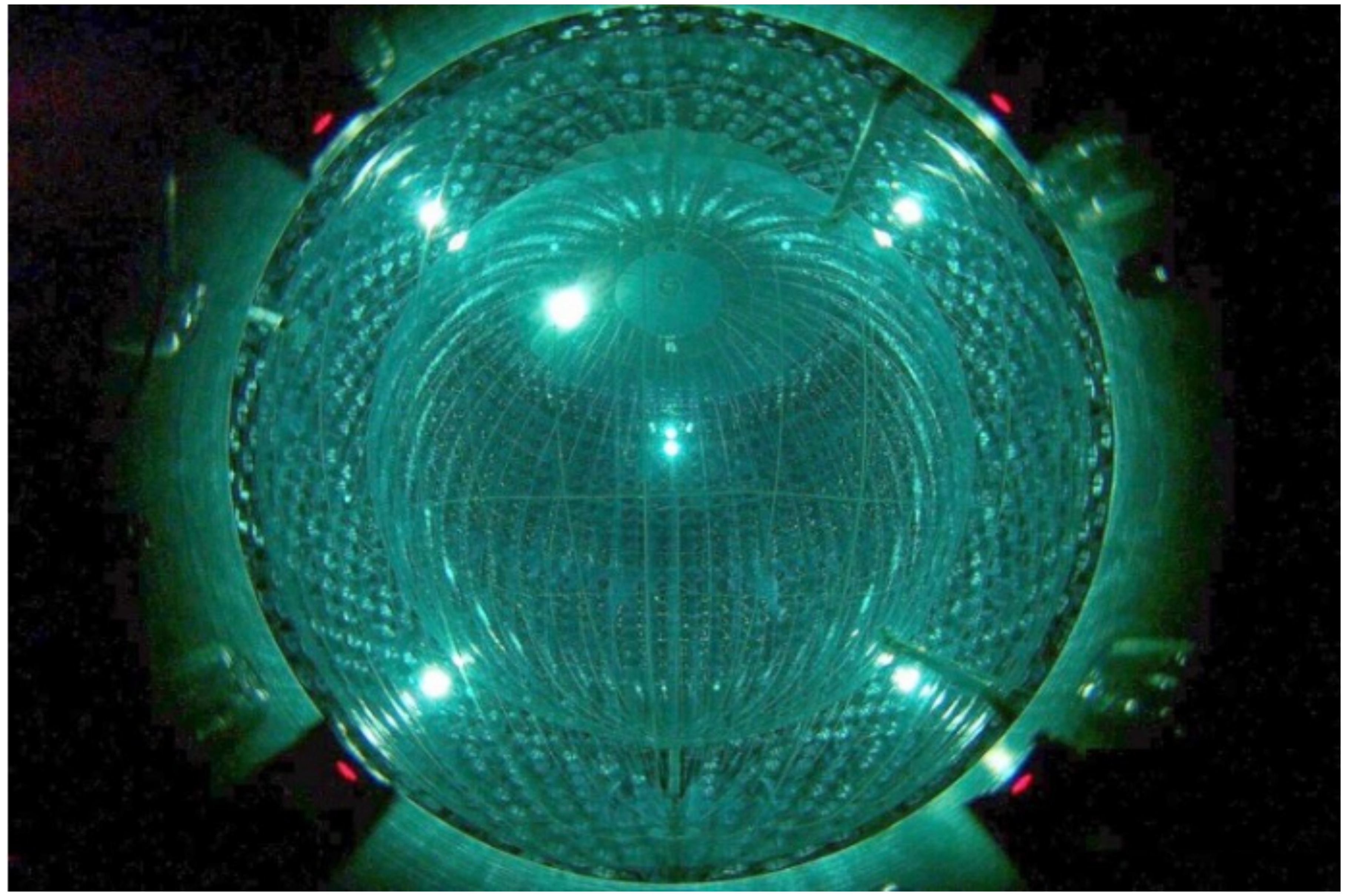
Slight disagreement between solar (electron neutrino oscillation) and KamLAND (electron antineutrino oscillation) at ~1.5σ

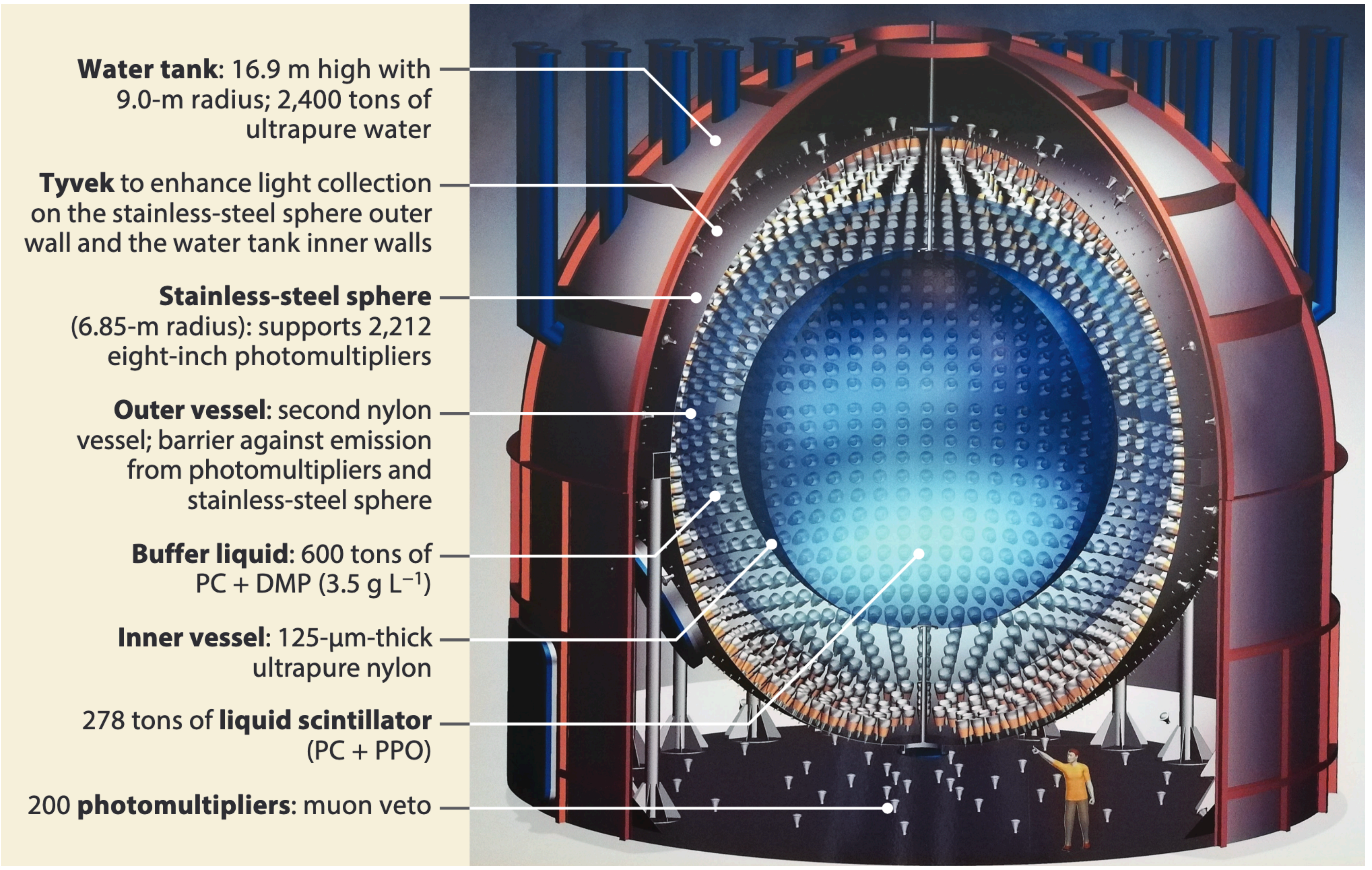
NuFIT 5.3 (2024)



Borexino

- 278 ton liquid scintillator ν-e scattering (Gran Sasso Laboratory - Italy)
- Real time measurements of the MeV-subMeV flux and spectrum of solar neutrinos:
  - ✦ Monochromatic ^{7}Be ν (0.86 MeV) & ^{8}B , pep, CNO, pp measurements
  - ✦ High radiopurity requirements
- 200 keV energy threshold
- Excellent energy resolution (5% at 1 MeV)
- Very low background level
- Data taking from 2007 to 2021

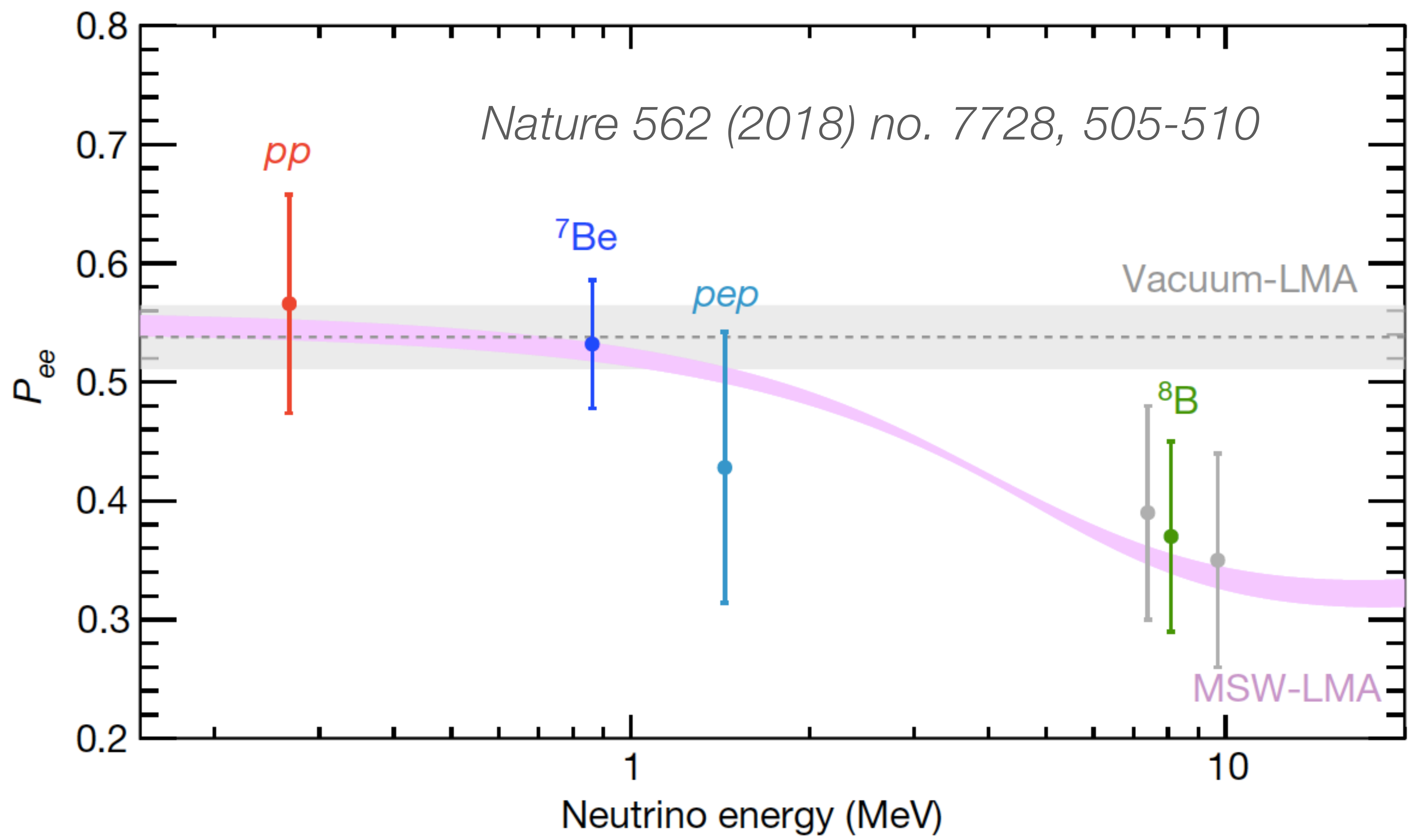


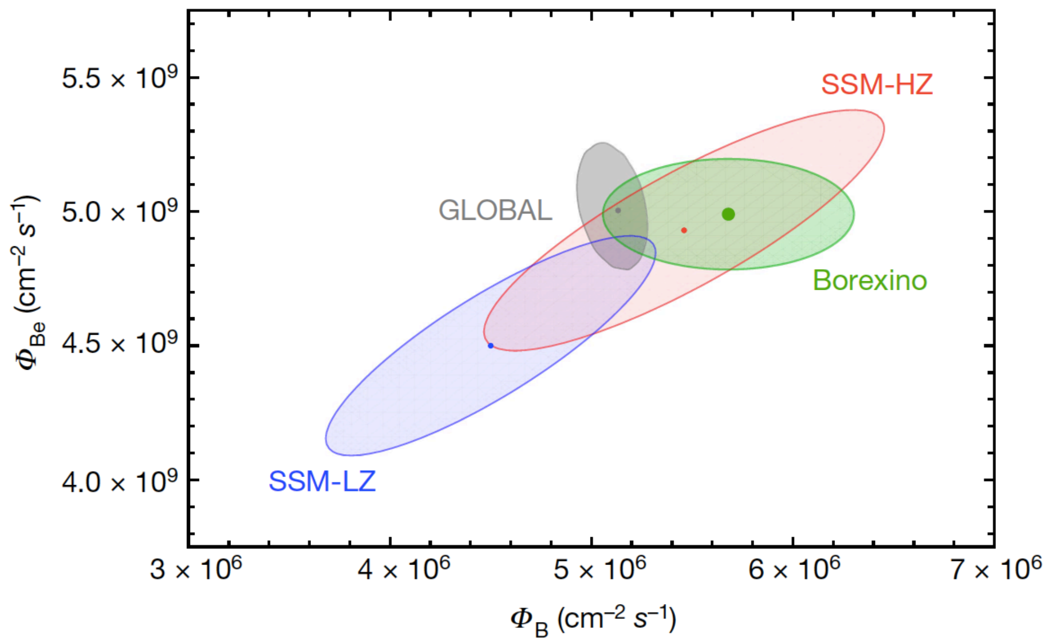


Borexino - pp & CNO ν measurements

Nature 587 (2020) 577-582

- The only experiment simultaneously testing neutrino flavor conversion in vacuum and matter-dominated regimes
- The most precise **pp-chain** measurement

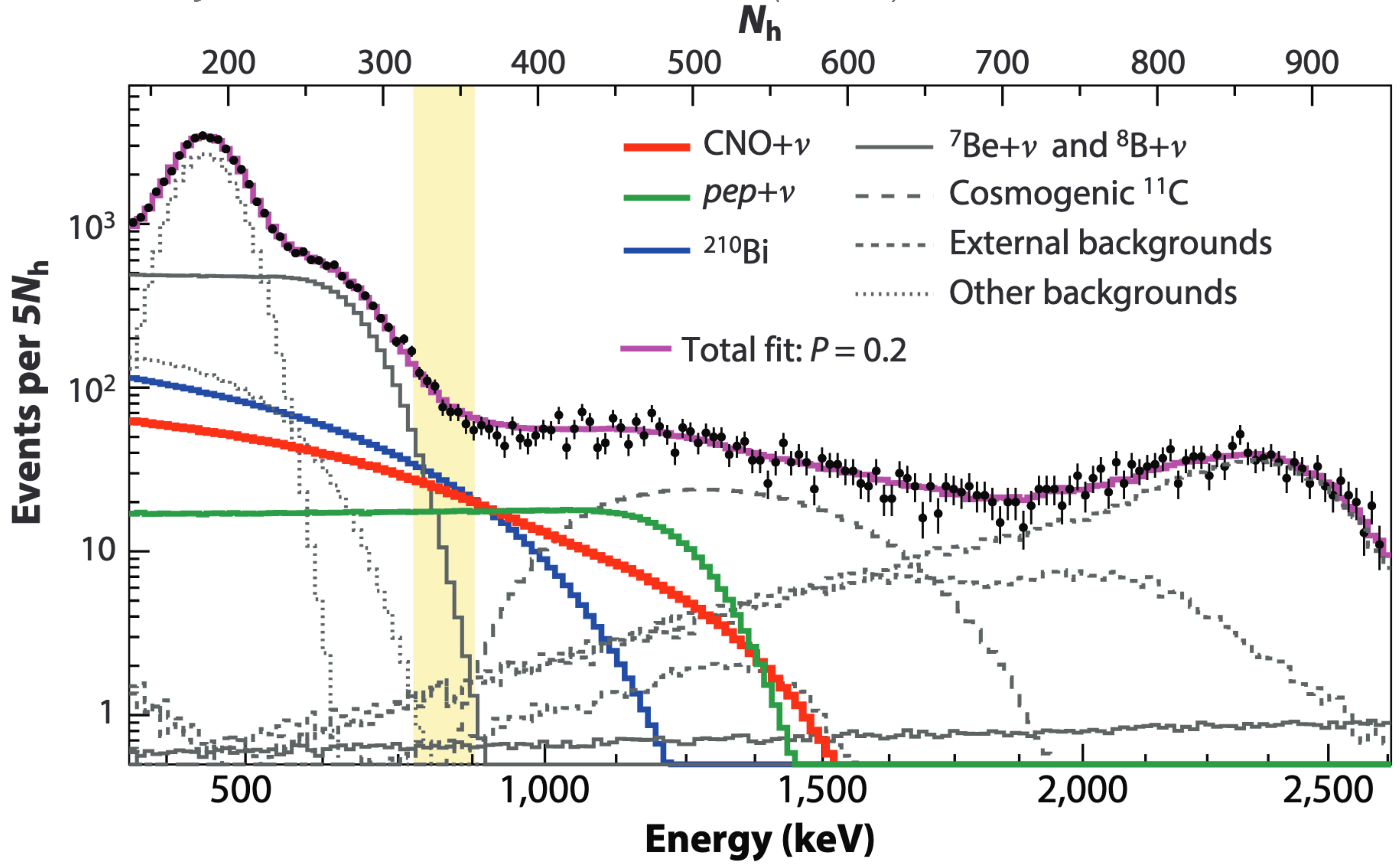




Test of solar metallicity: hint favoring SSM-HZ prediction

- **CNO** was never directly observed before
- Small expected signal: 5 cpd/100t
- Main backgrounds: pep-ν and ^{210}Bi

Phys. Rev. Lett. 129:252701 (2022)

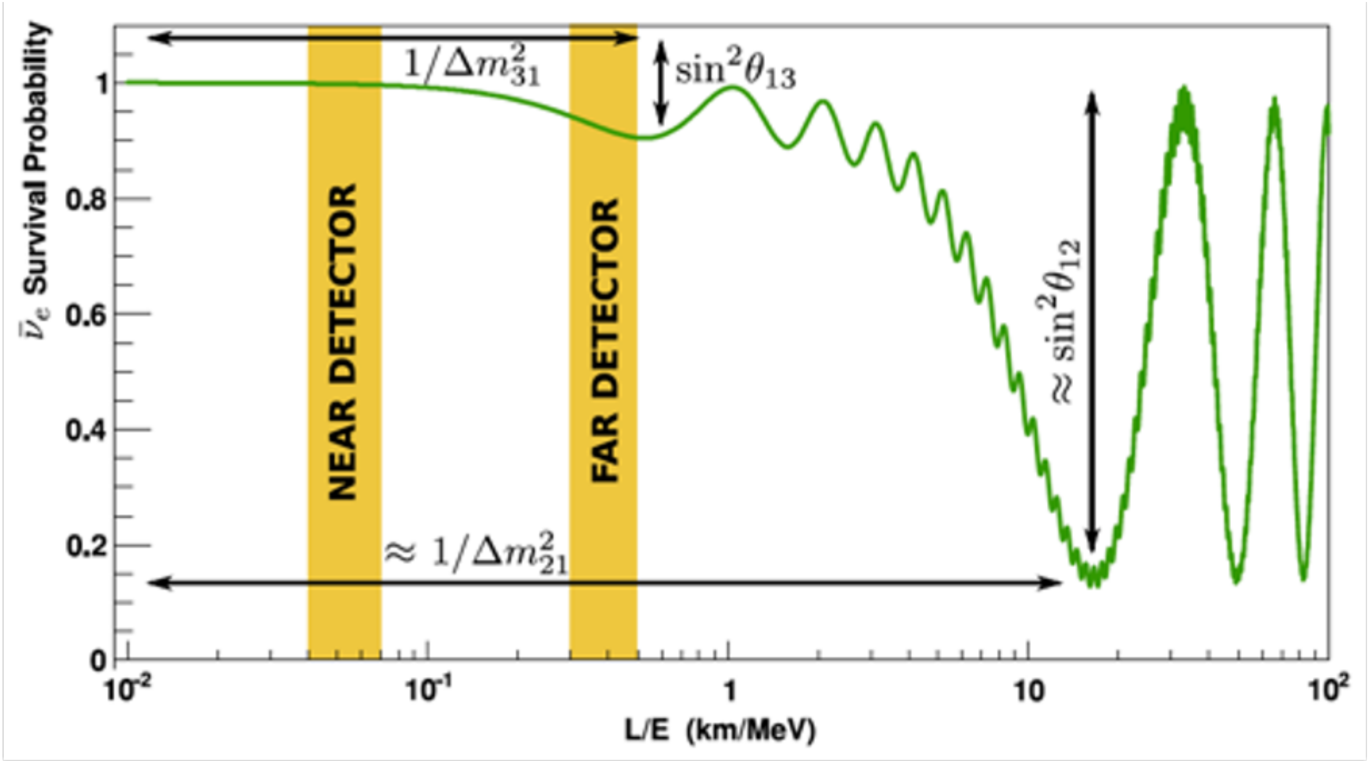


CNO result (68% CL stat+sys) = 6.7 +2.0 -0.8 cpd/100t

No CNO hypothesis excluded at 7σ

(Short-baseline) Reactor neutrino experiments

Pure θ13 measurement from electron antineutrino disappearance

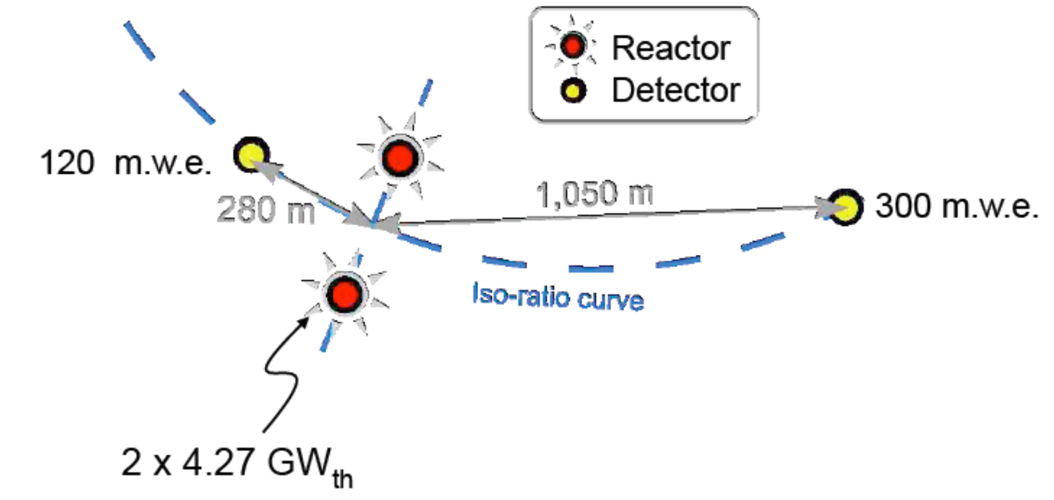


$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}{}^2 L}{4E_\nu}\right)$$

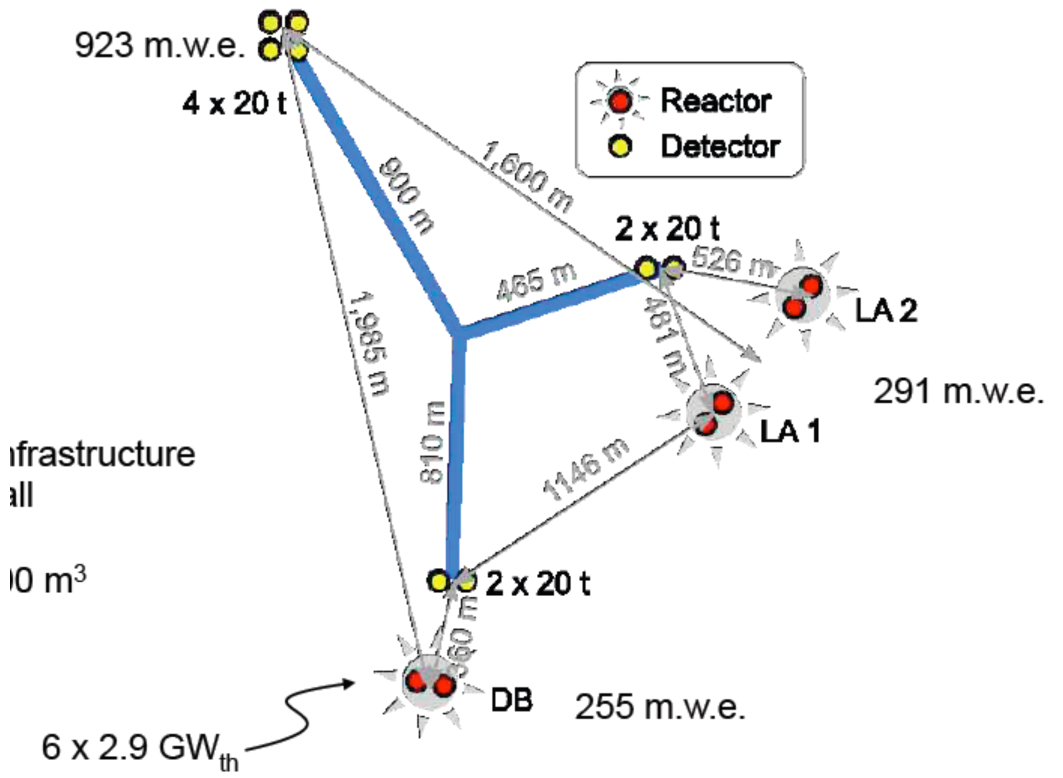
Liquid scintillators doped with Gd

Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

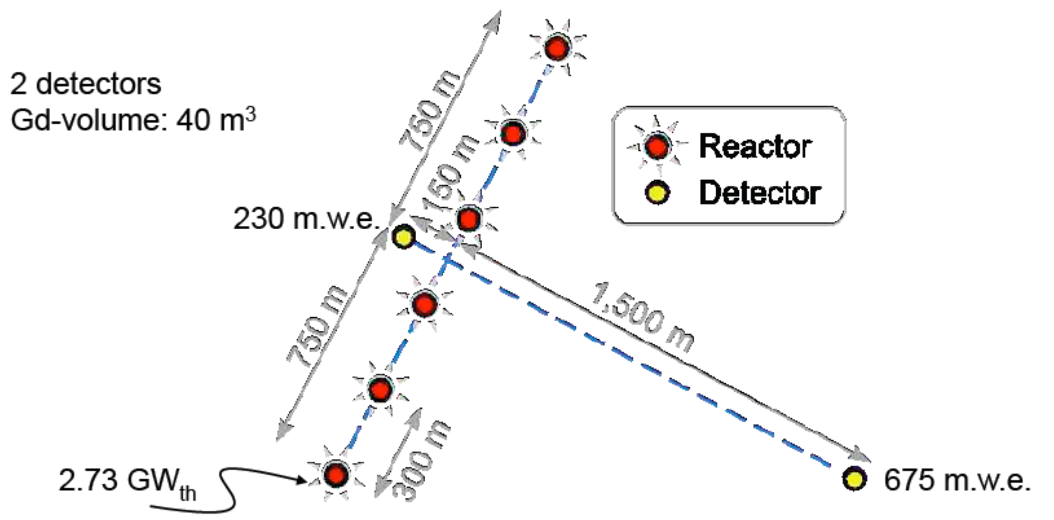
Double Chooz



Daya Bay



RENO

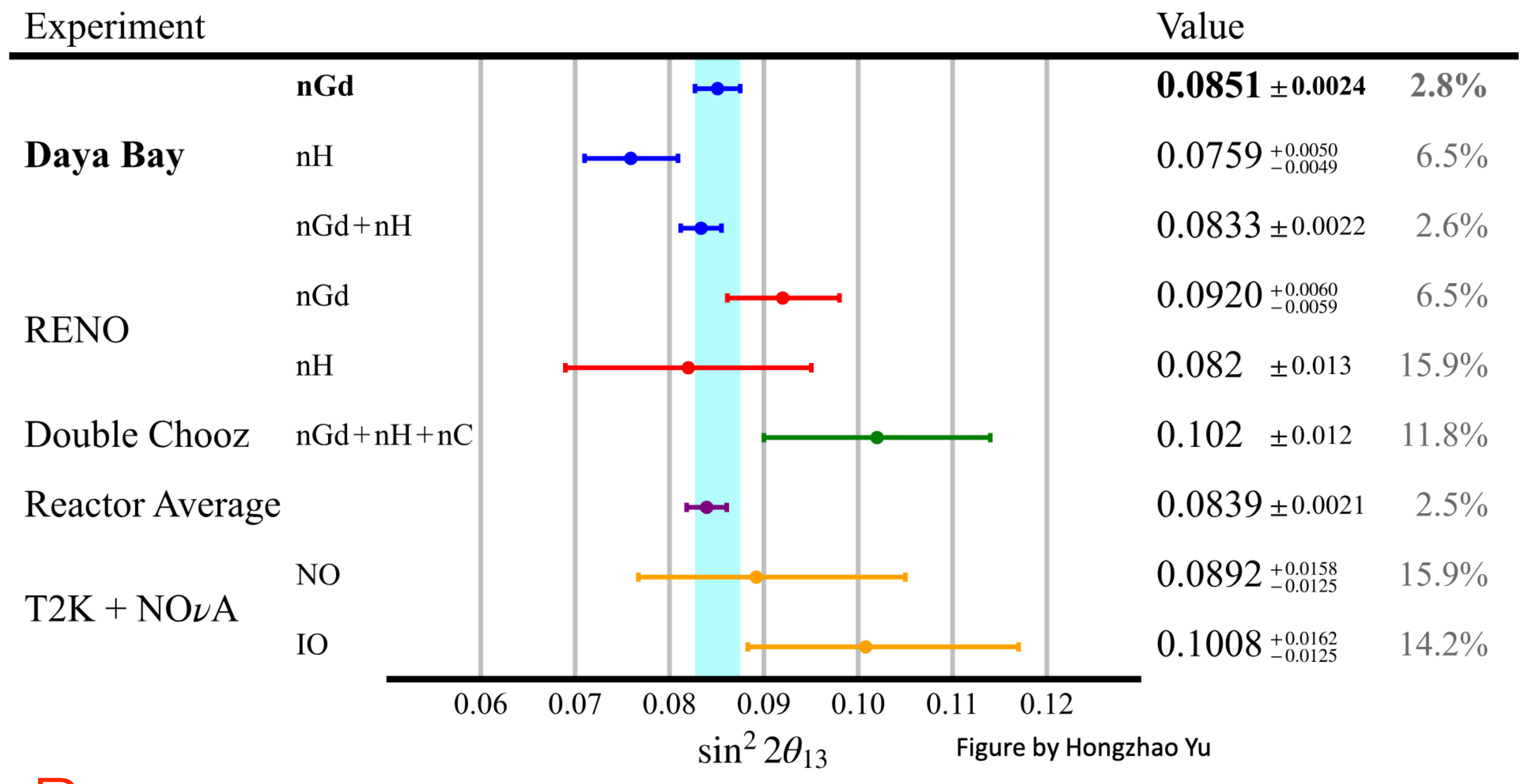


France

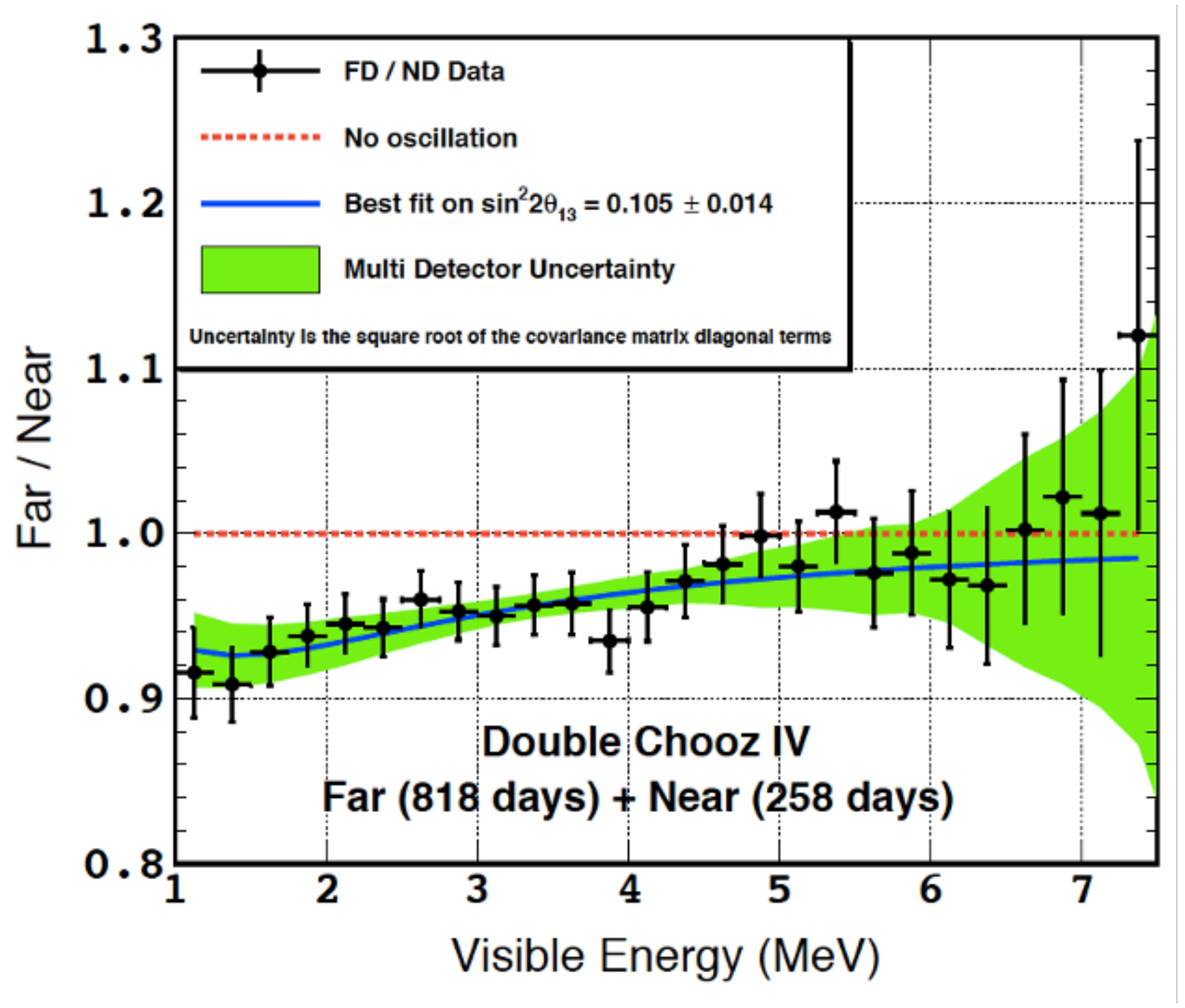
China

Korea

Reactor neutrino status



Double Chooz *Nature Physics 16 (2020) 558-564*

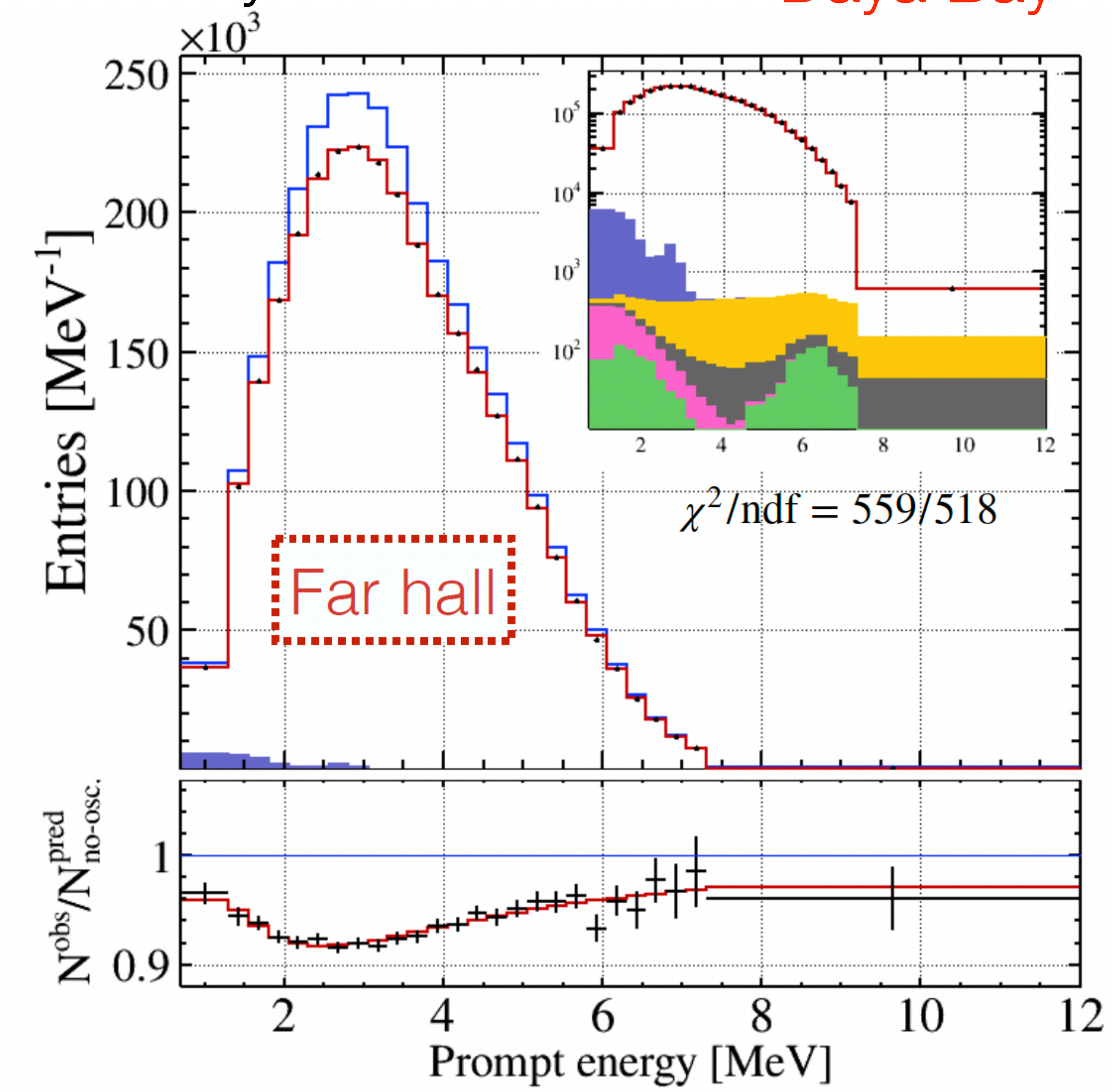


$\sin^2(2\theta_{13}) = 0.105 \pm 0.014$ (stat + sys)

$\chi^2/\mathrm{dof} = 182/112$ (D2MC result)

3158 days Daya Bay

PRL 130, 161802 (2023)

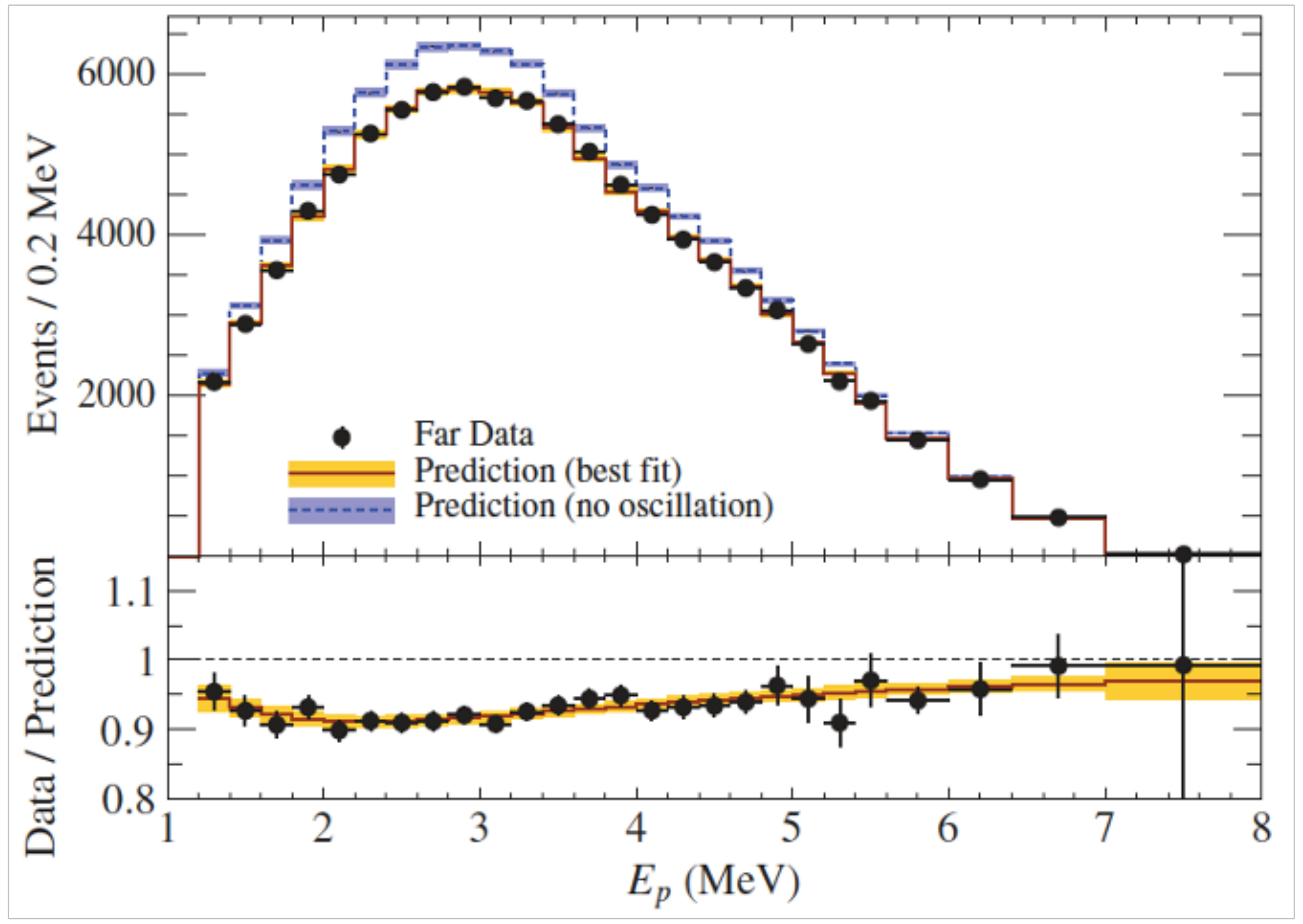


$$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024,$$

$$\Delta m^2_{32} = (2.466 \pm 0.060) \times 10^{-3}\ \mathrm{eV}^2 \quad \text{NO}$$

$$\Delta m^2_{32} = -(2.571 \pm 0.060) \times 10^{-3}\ \mathrm{eV}^2 \quad \text{IO}$$

RENO 2200 days



Phys.Rev.Lett. 121 (2018) no.20, 201801

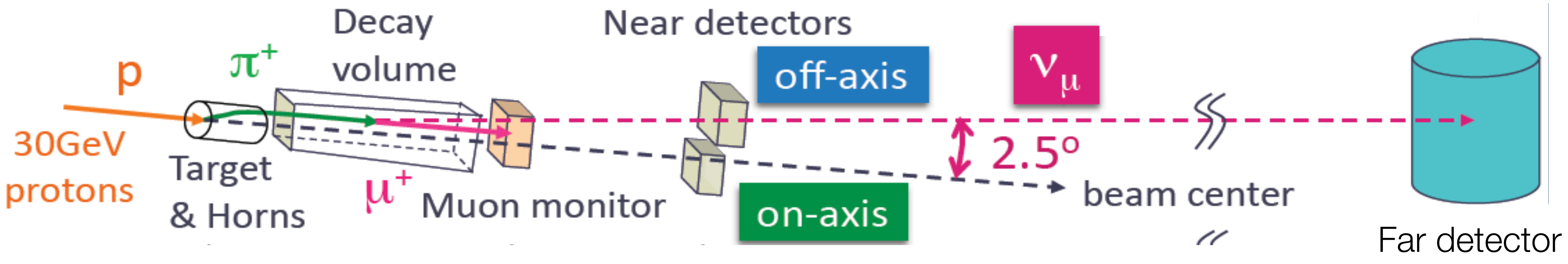
$$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\mathrm{stat}) \pm 0.0047(\mathrm{syst})$$

$$|\Delta m^2_{32}| = (2.63 \pm 0.14) \times 10^{-3}\ \mathrm{eV}^2$$

$$(2.73 \pm 0.14) \times 10^{-3}\ \mathrm{eV}^2$$

Long-baseline and atmospheric neutrino oscillations

Long-baseline accelerator neutrinos



Survival probability

$$P_{\mu\mu} \approx 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E_\nu}$$

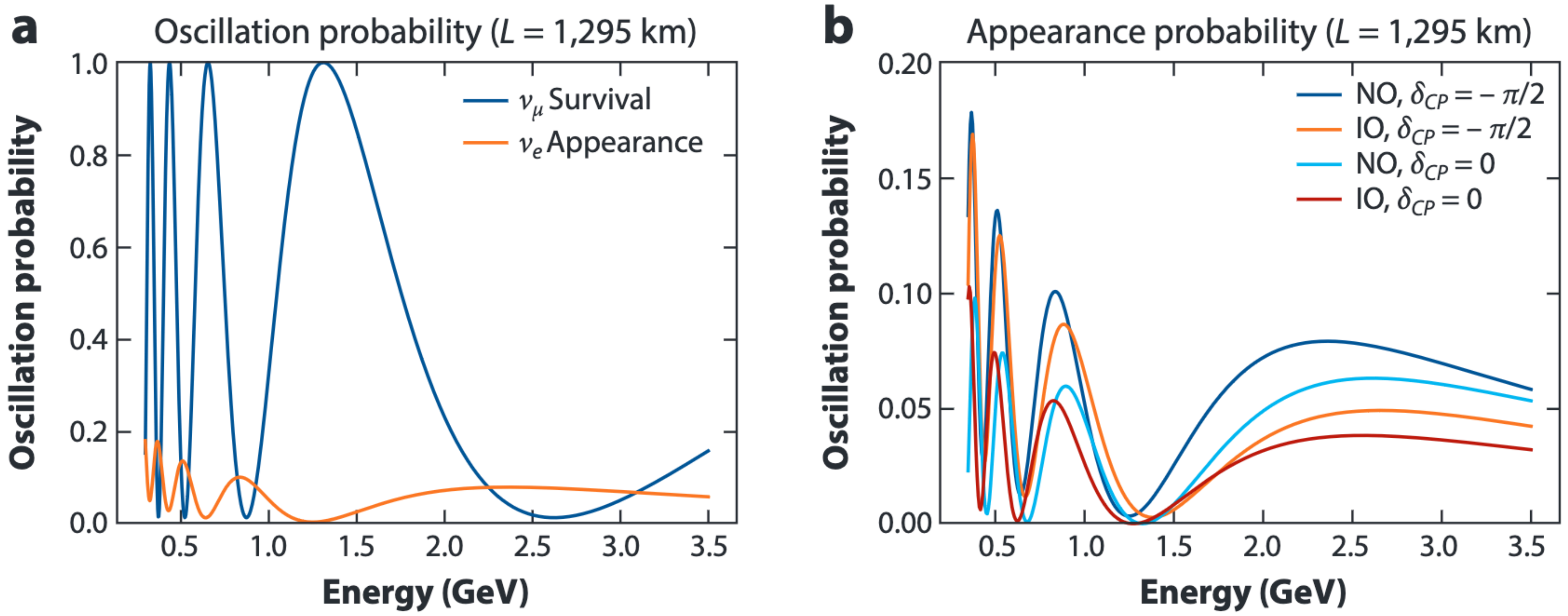
$$\approx 1 - \cos^2\theta_{13}\sin^2(2\theta_{23})\sin^2\frac{\Delta m^2_{32} L}{4E_\nu} + \mathcal{O}(\alpha, s^2_{13})$$

$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$$

Appearance probability

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta^2_{31}$$
$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\Delta_{31}$$
$$\times \frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31} \pm \delta_{\mathrm{CP}})$$
$$+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta^2_{21},$$

$$a = \pm\frac{G_F N_e}{\sqrt{2}} \approx \pm\frac{1}{3500\ \mathrm{km}}\left(\frac{\rho}{3.0\ \mathrm{g/cm^3}}\right)$$



- SIGNAL
  - CCQE

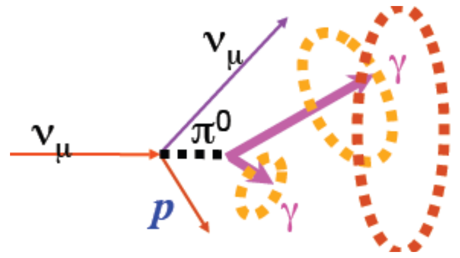
ν_μ signal

$\nu_\mu + n \to p + \mu^-$

ν_e signal

$\nu_e + n \to p + e^-$

- BACKGROUNDS
  - ν_e contamination in the beam
  - π^0 production in neutral currents



- Dependencies on θ_{13}, θ_{23} octant, sign of Δm^2_{31} and δ_{CP} phase
  - ✦ Parameter correlations and degeneracies
- Matter effects sensitive
- Possibility to measure δ_{CP} using ν_μ, $\bar{\nu}_\mu$ beams
- Experimental challenges: ν beam intensity, flavor contamination, flux properties, ν-N interactions

T2K (Tokai to Kamioka) in Japan

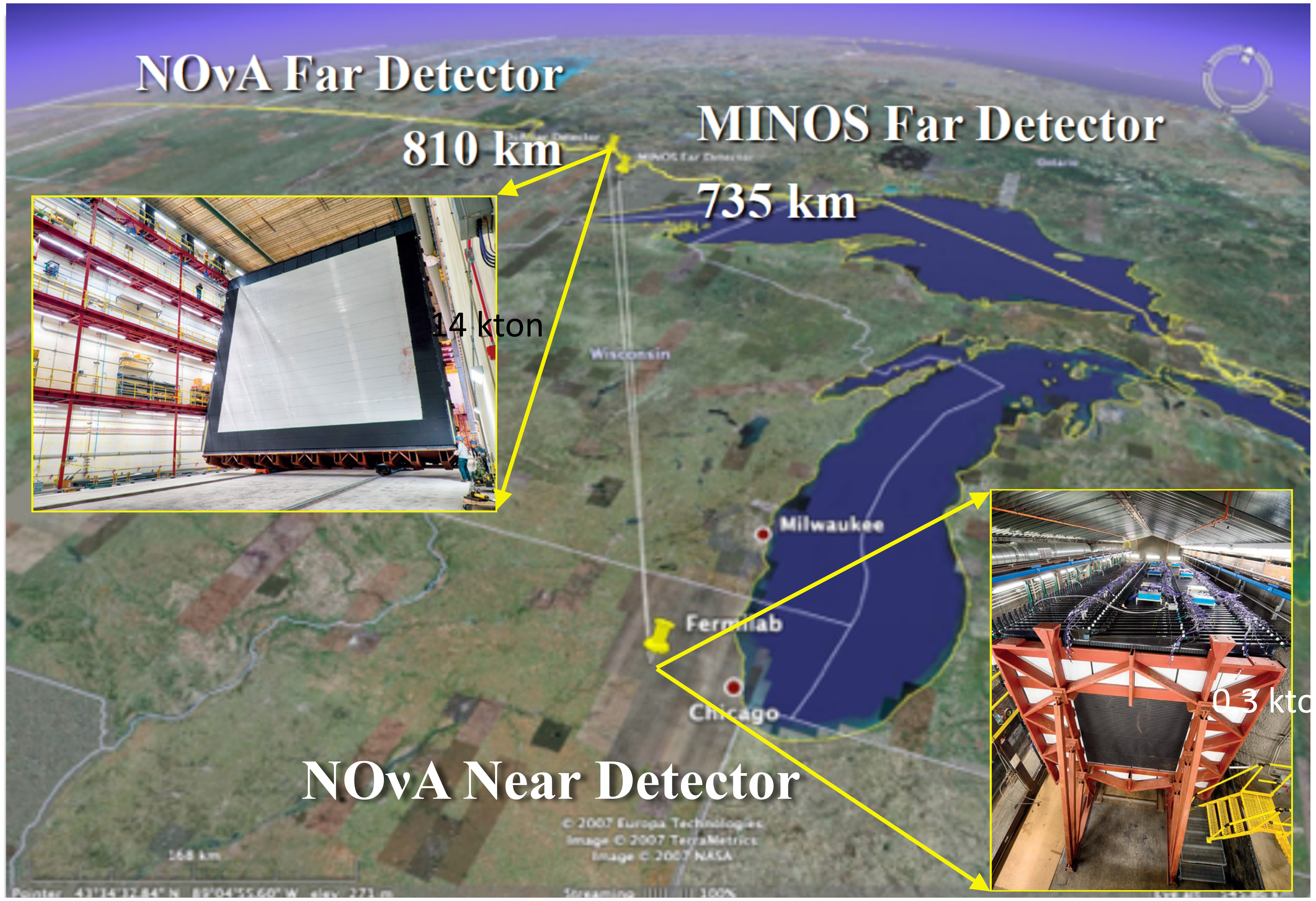
Proton beam, ~500 kW

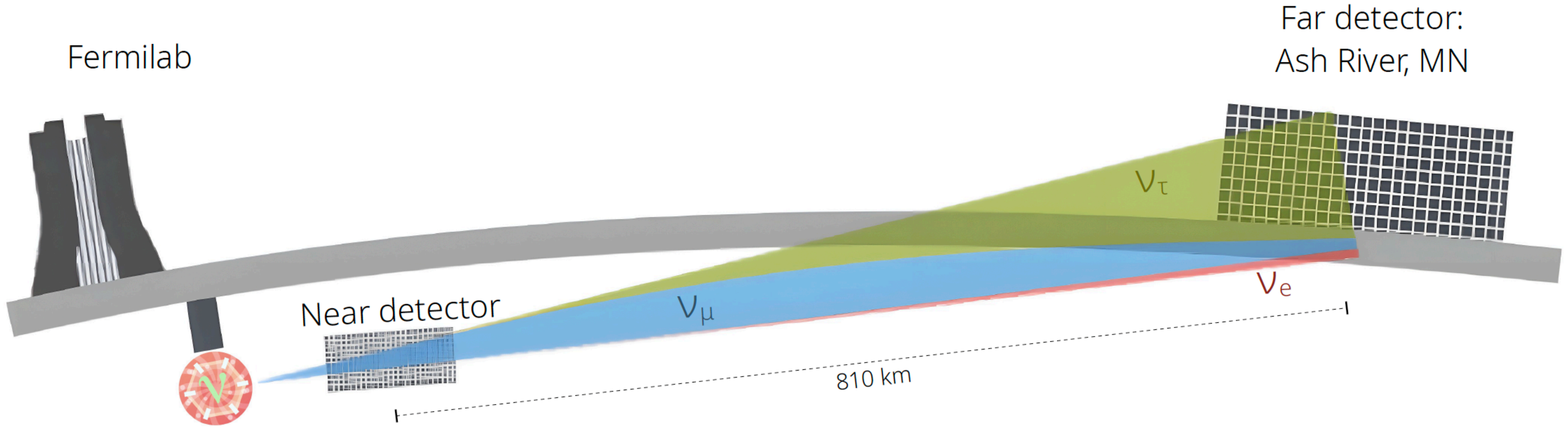
50 kton, 22.5 kton fiducial

- Long-baseline experiment: near (ND280) and far (SK) detectors
- Neutrino beam travels 295 km across Japan
- T2K beam is 95% ν_μ, 4% $\bar{\nu}_\mu$, <1% ν_e ~500 kW → 800 kW reached in June 2024
- Both detectors are 2.5° off ν beam axis ($E_{peak} \approx 600$ MeV)

NOvA (NuMI Off-Axis Nue Appearance) in USA

- 810 km baseline from Fermilab to Ash River, MN
- 900 kW NuMI neutrino beam at Fermilab
- Near and Far Detectors placed 14 mrad off the NuMI beam axis
- Measure $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ to:
  - Determine ν mass hierarchy
  - Determine the θ_{23} octant
  - Constrain δ_{CP}
- Use $\nu_\mu \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ to:
  - make precise measurements of θ_{23} and Δm^2_{32}
- Many other physics topics:
  - ν cross sections at the ND
  - Sterile neutrinos
  - Supernova neutrinos
  - …

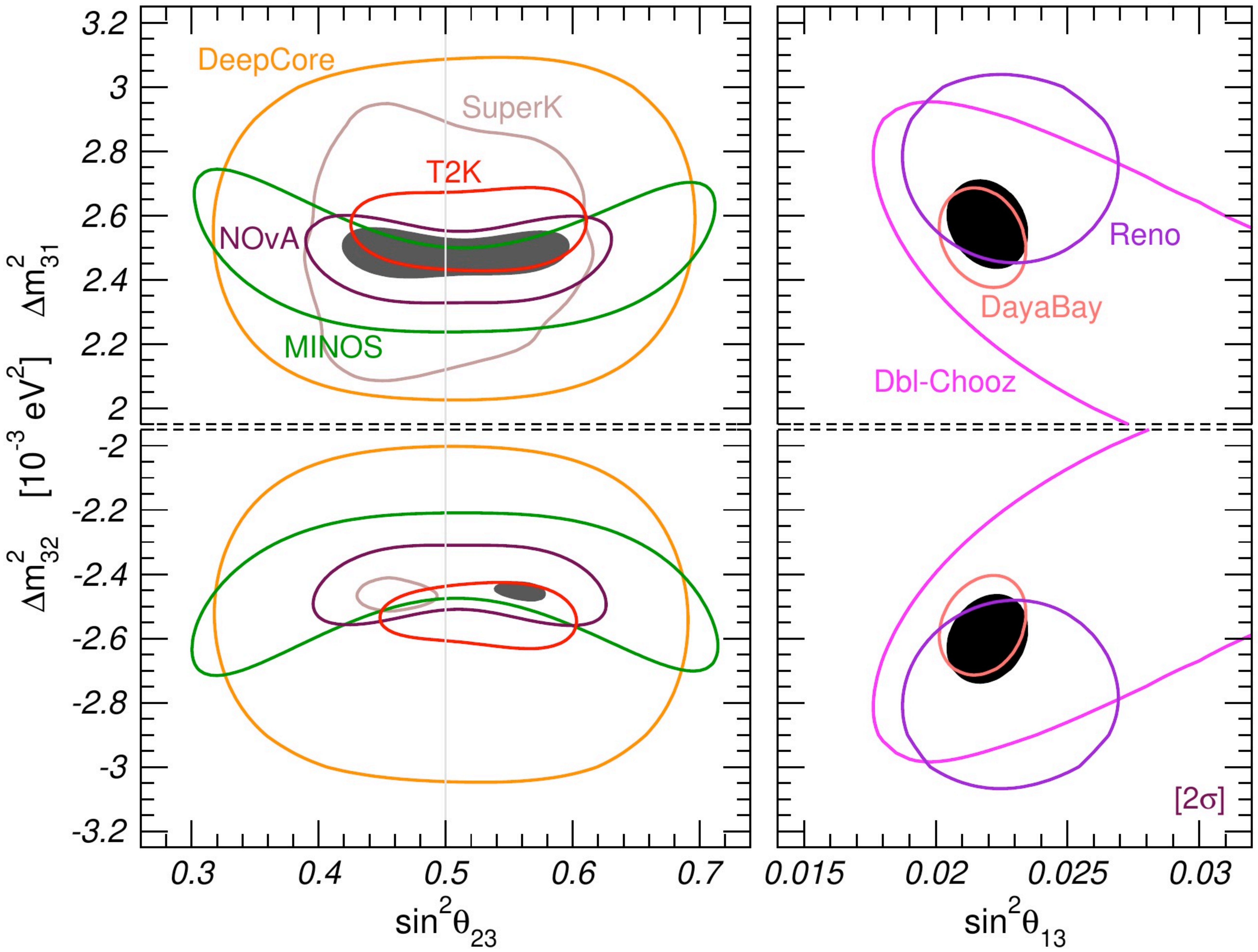




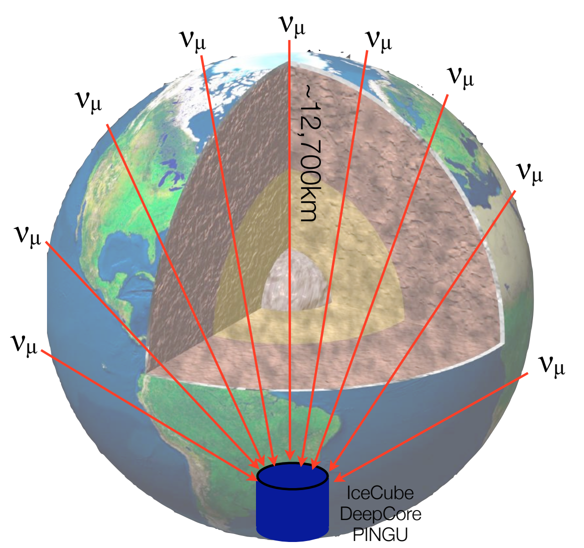
Octant of θ_{23} and mass ordering from LBL

NuFIT 5.3 (2024)

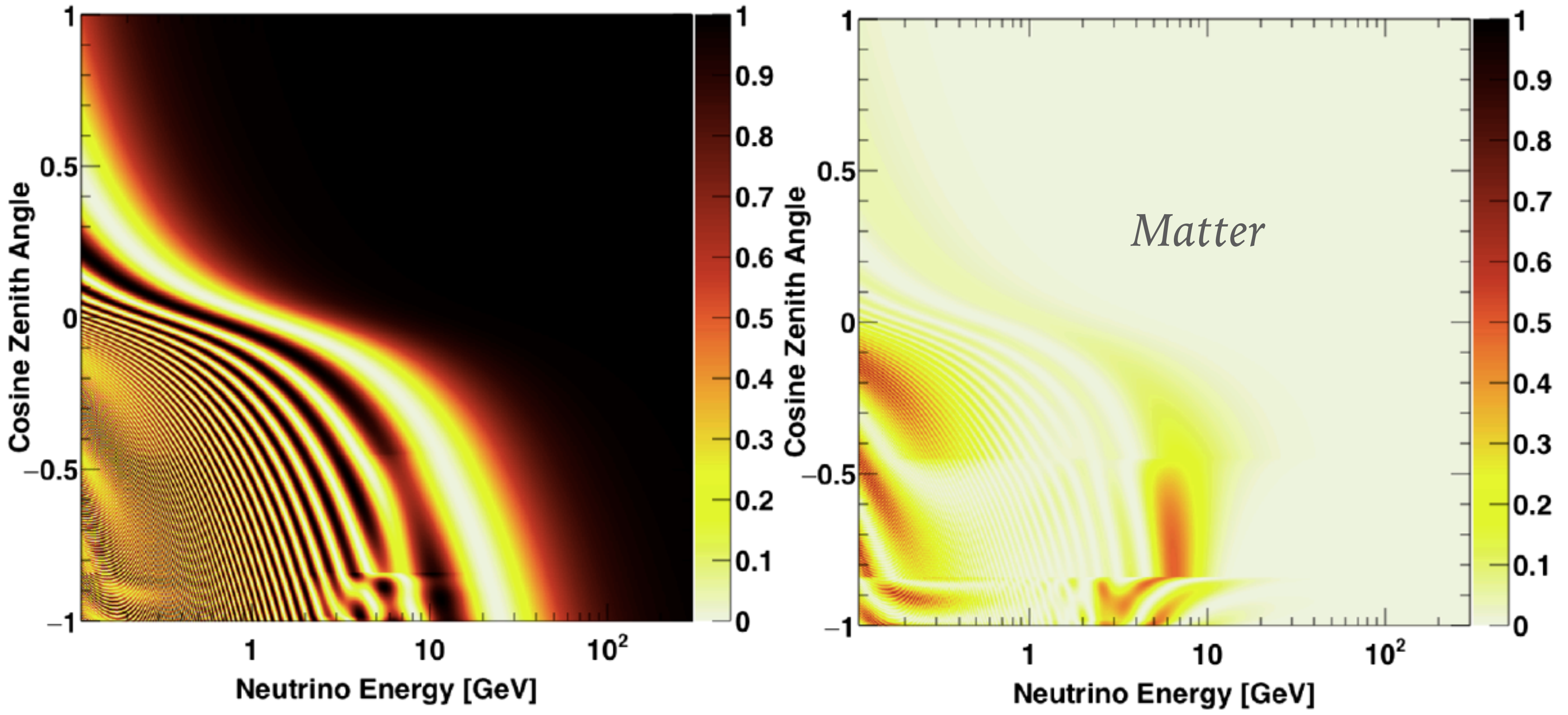
- Maximal mixing disfavored
- T2K and NOvA have mild preference for the upper octant and NO
- Δm^2_{32} measurement dominated by NOvA
- $\sin^2\theta_{23}$ measurement dominated by T2K



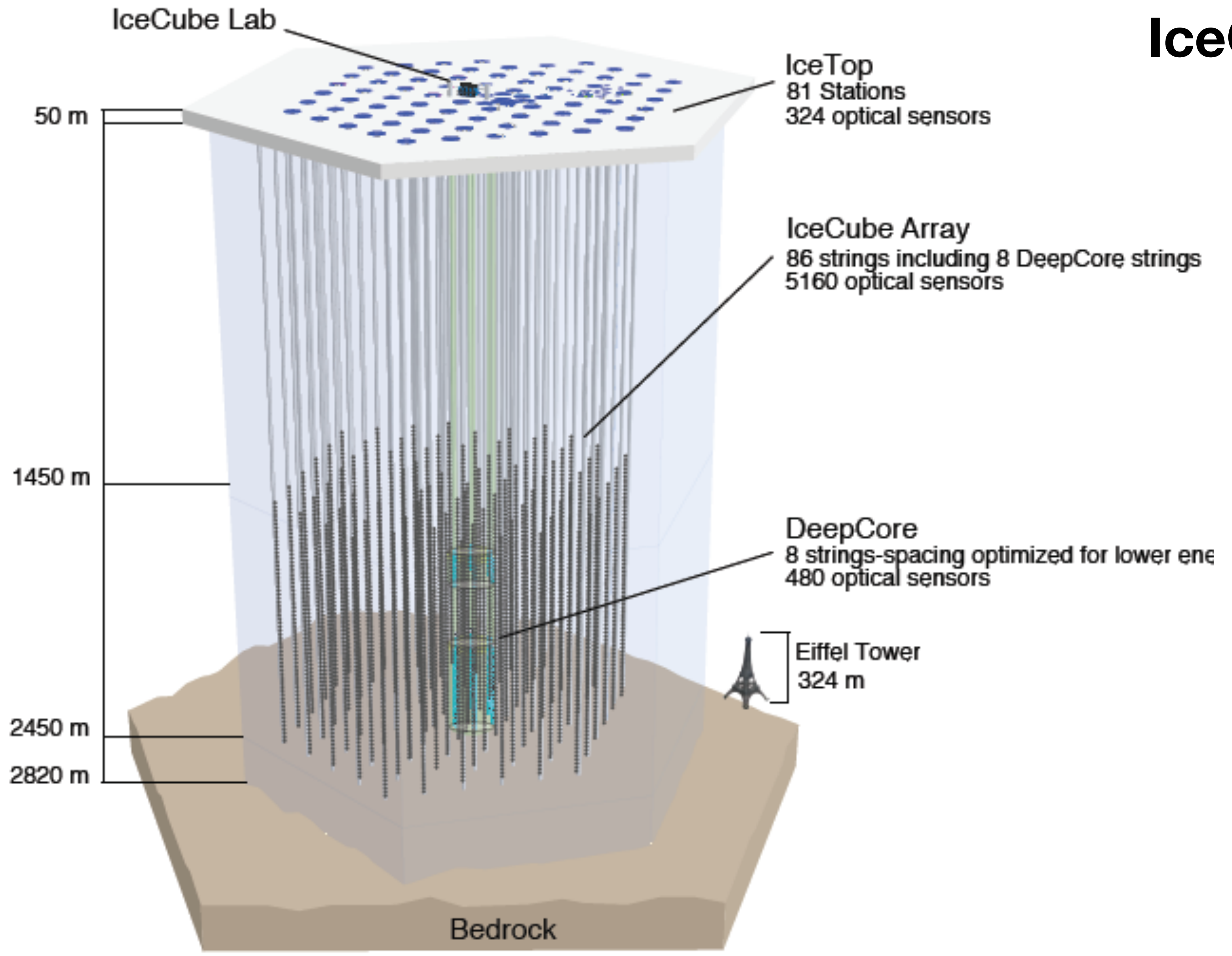
Atmospheric neutrinos with SK and IceCube



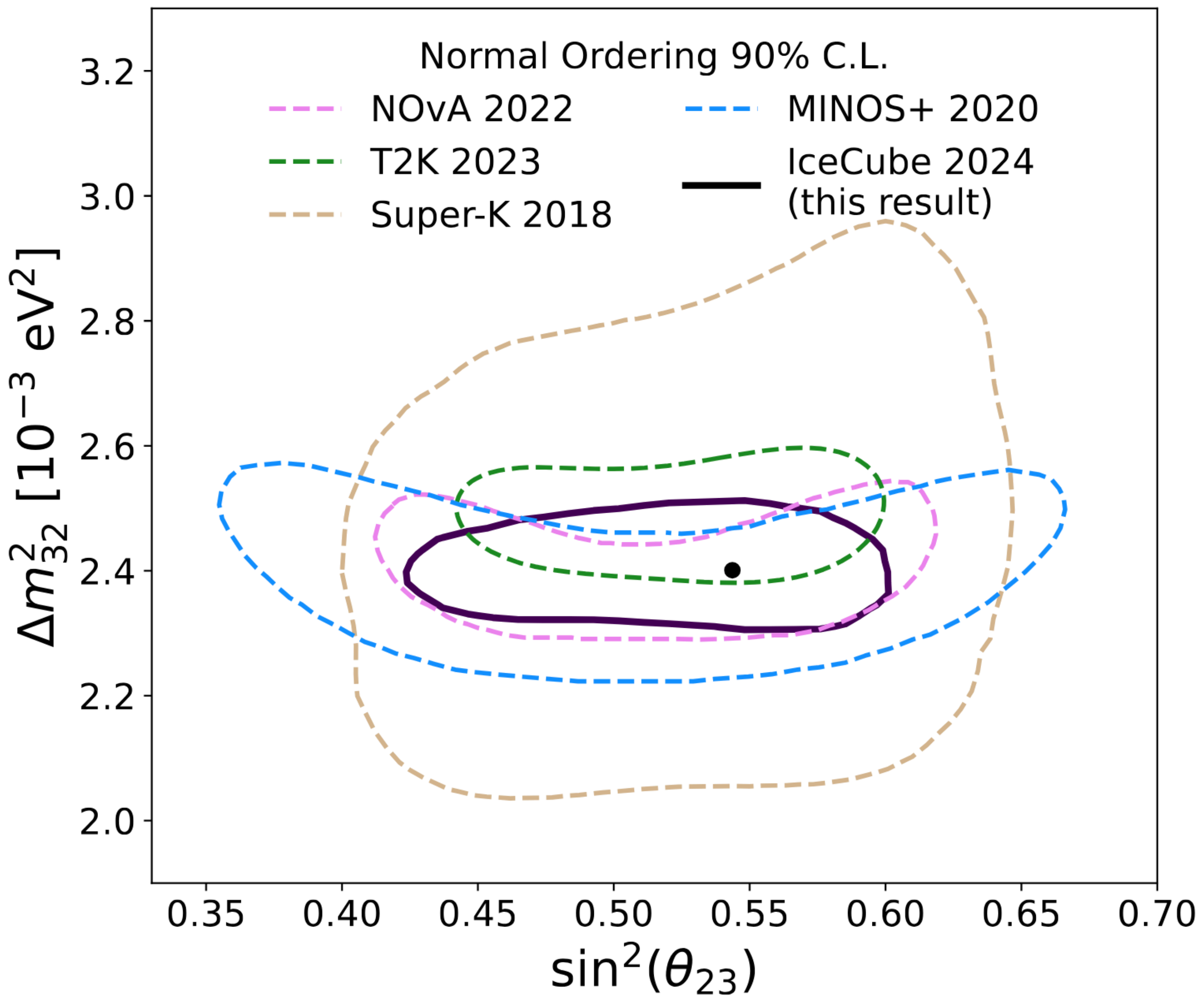
Matter effects in Earth modify the oscillation pattern and arise in neutrinos (for NO) or antineutrinos (for IO) for energies < 15 GeV



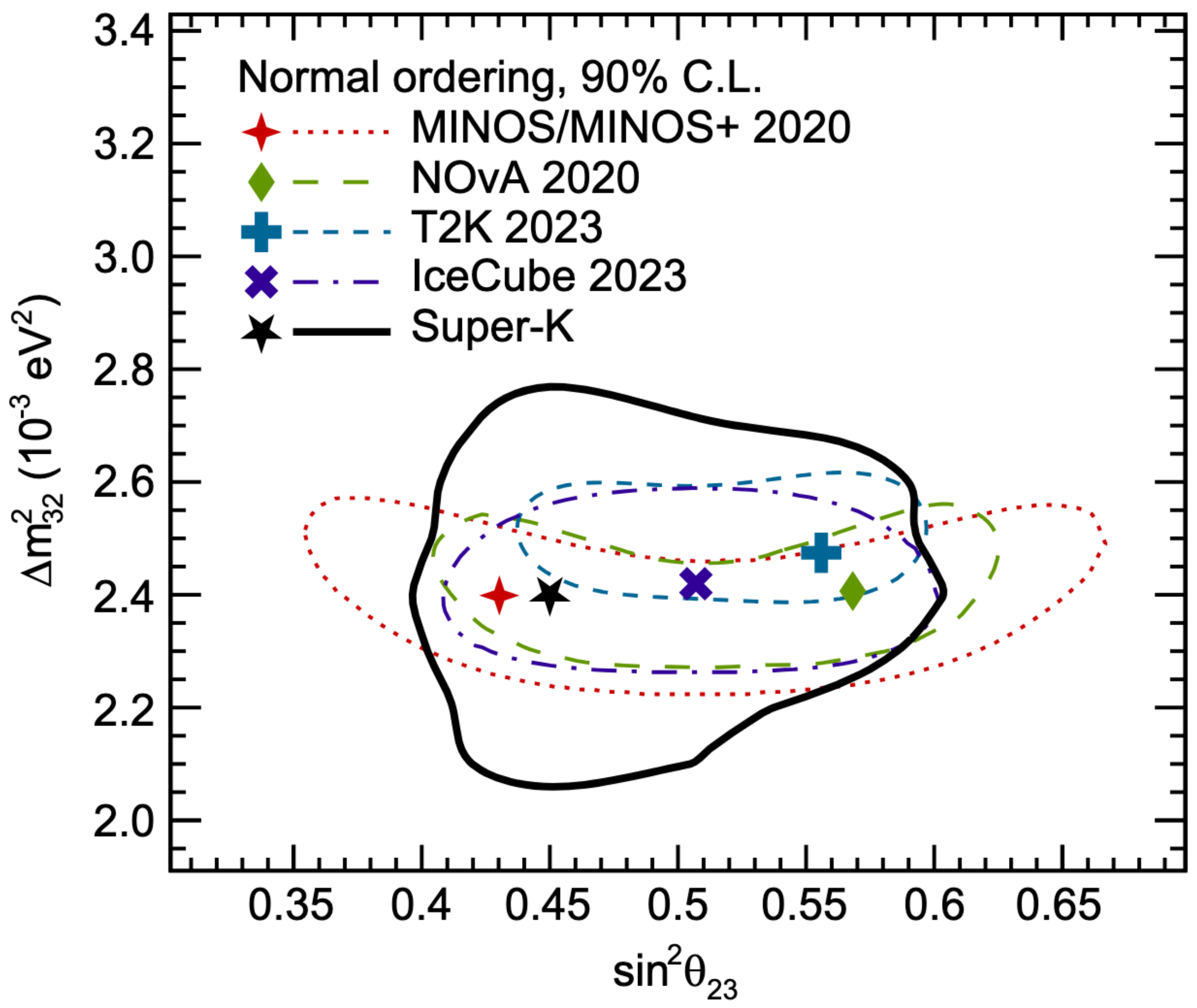
(a) $P(\nu_\mu \to \nu_\mu)$ (b) $P(\nu_\mu \to \nu_e)$



IceCube DeepCore: arXiv:2405.02163 (9.3 y)

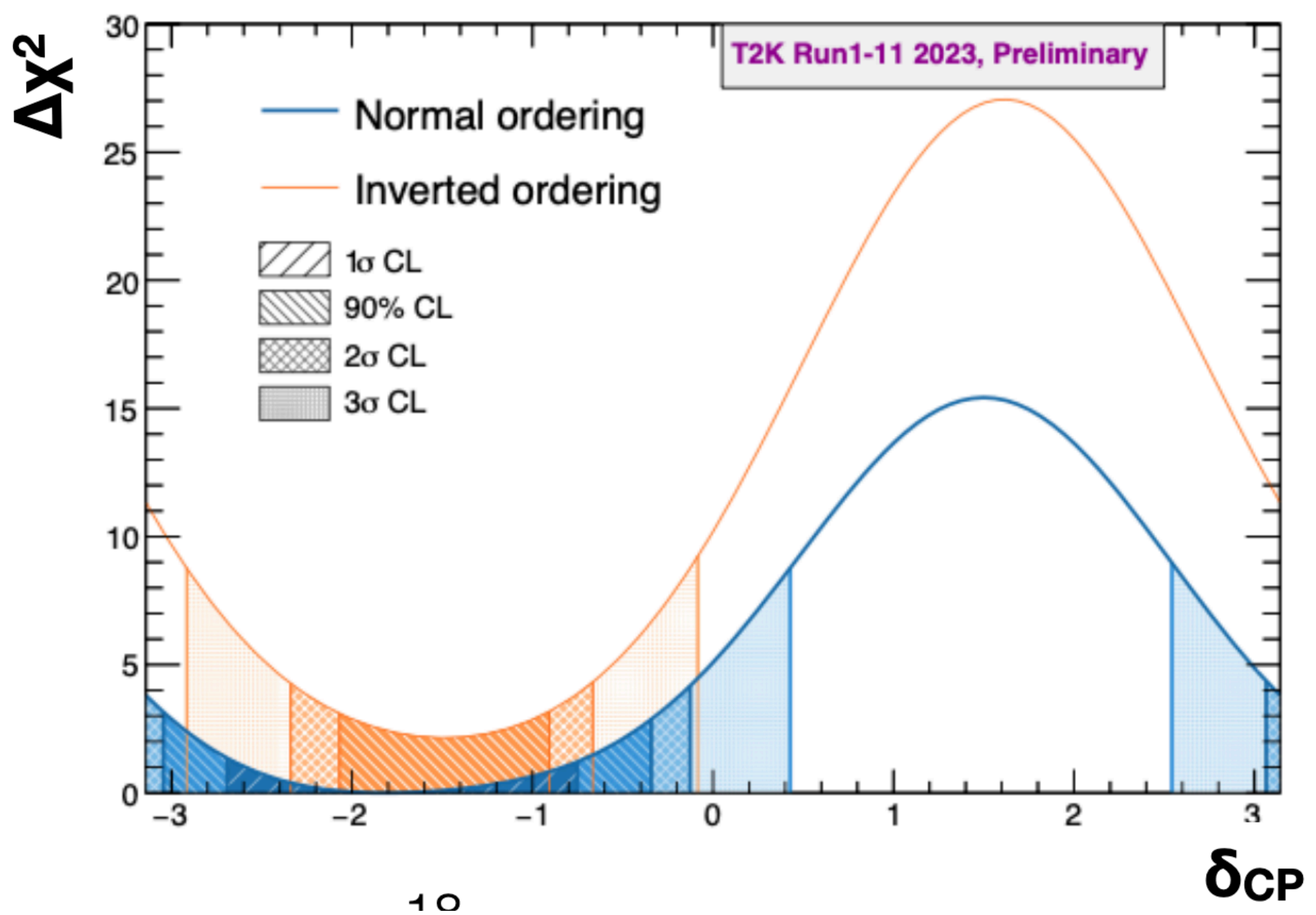


SuperK: PRD 109 (2024) 072014 (6511.3 live days)



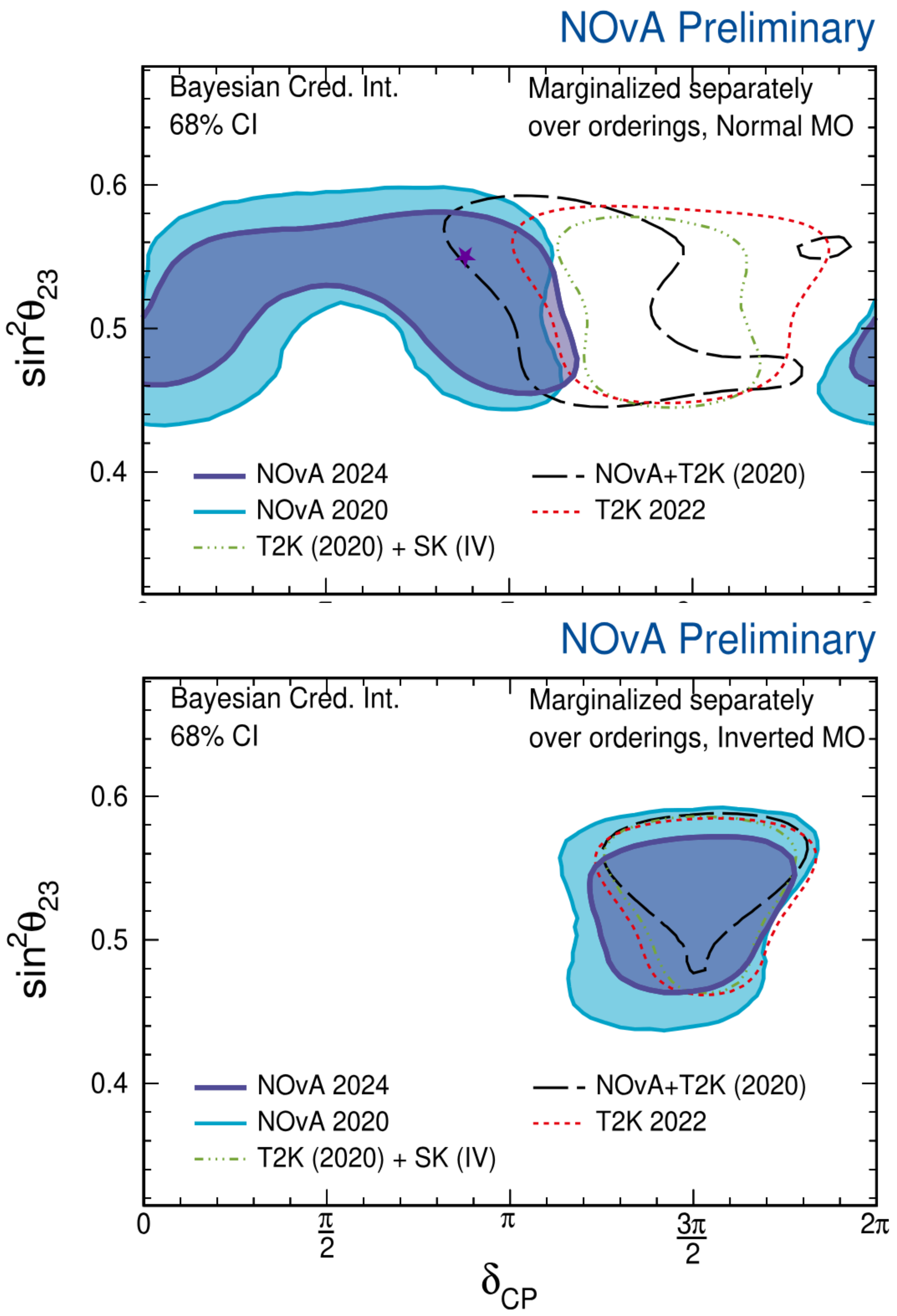
Tension between T2K & NOvA in δ_{CP} results

T2K



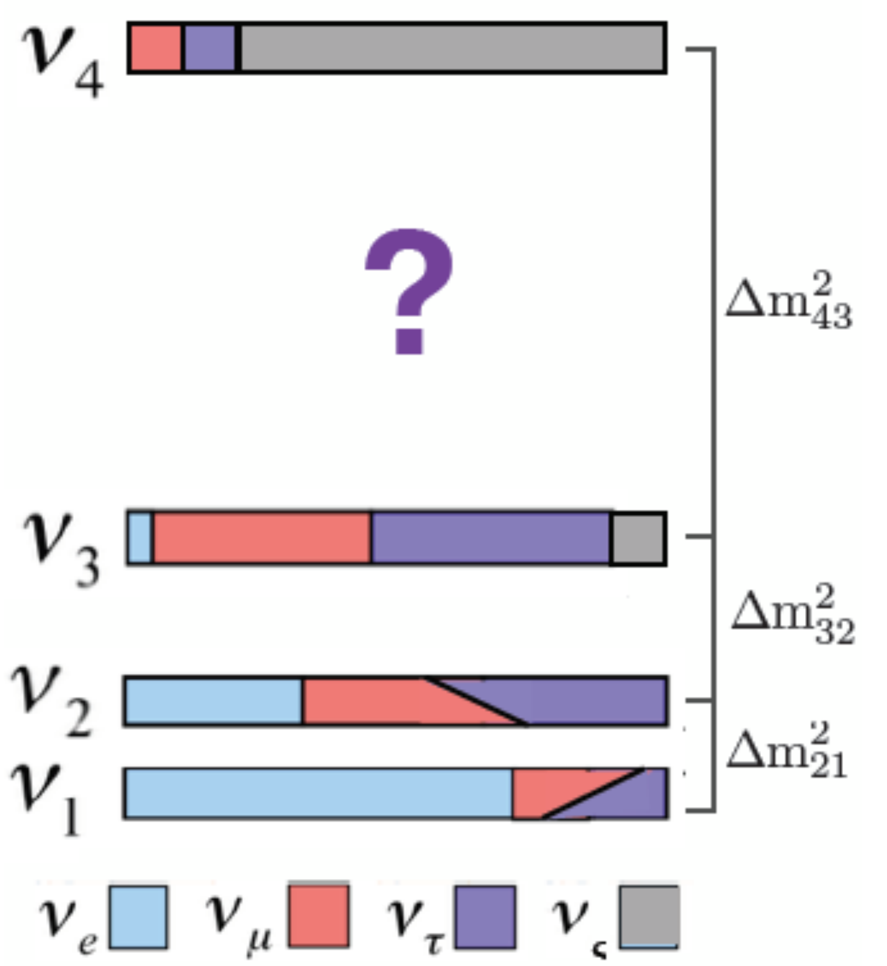
Preference for δ_{CP} ~$-\pi/2$

CP conserving values excluded at 90% CL



NOvA data favor different regions in NO

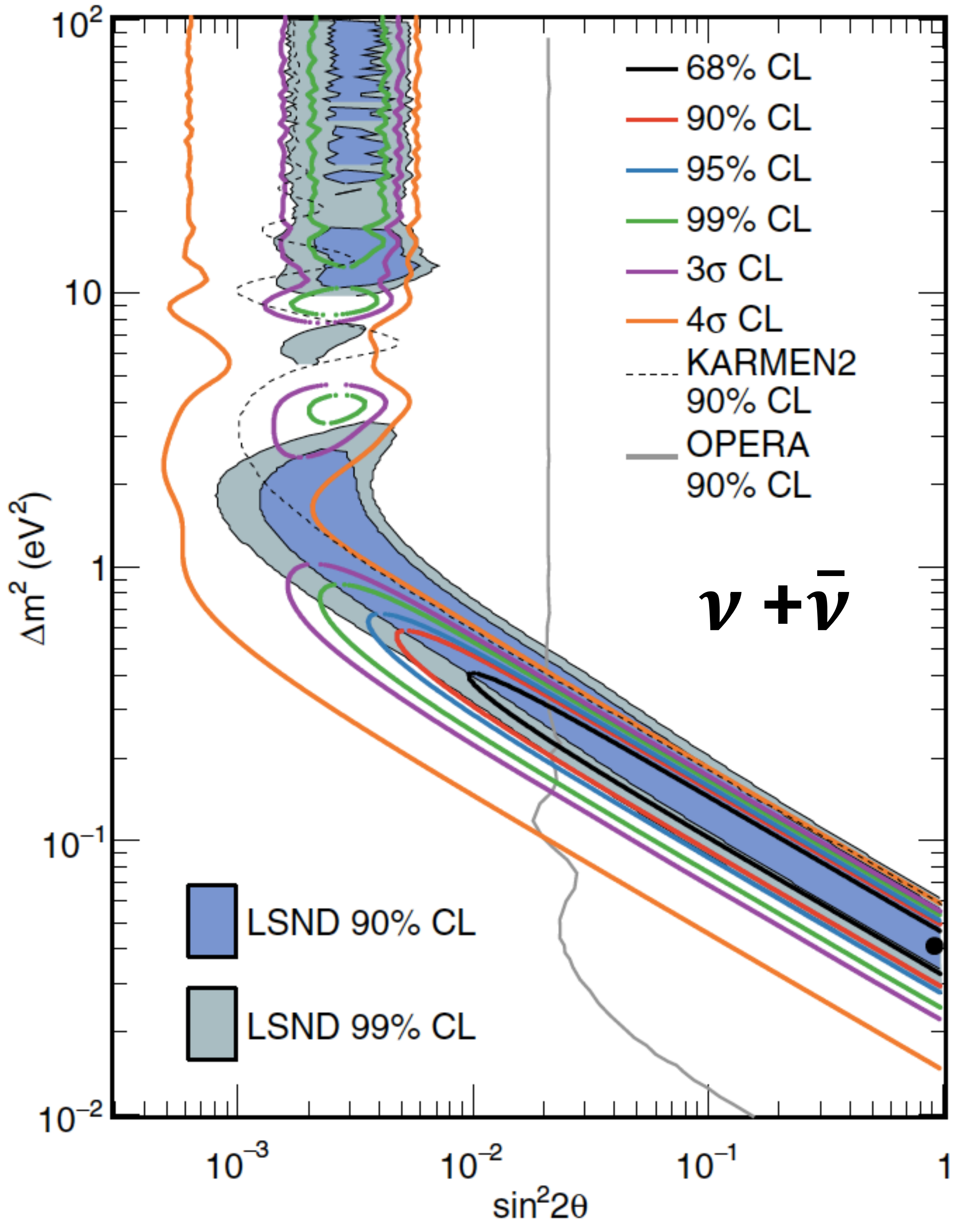
Neutrino oscillation anomalies



- Anomalies pointing to **~1 eV scale in mass difference**
- Evidence for sterile neutrinos is **inconclusive**. Big tension between appearance and disappearance measurements

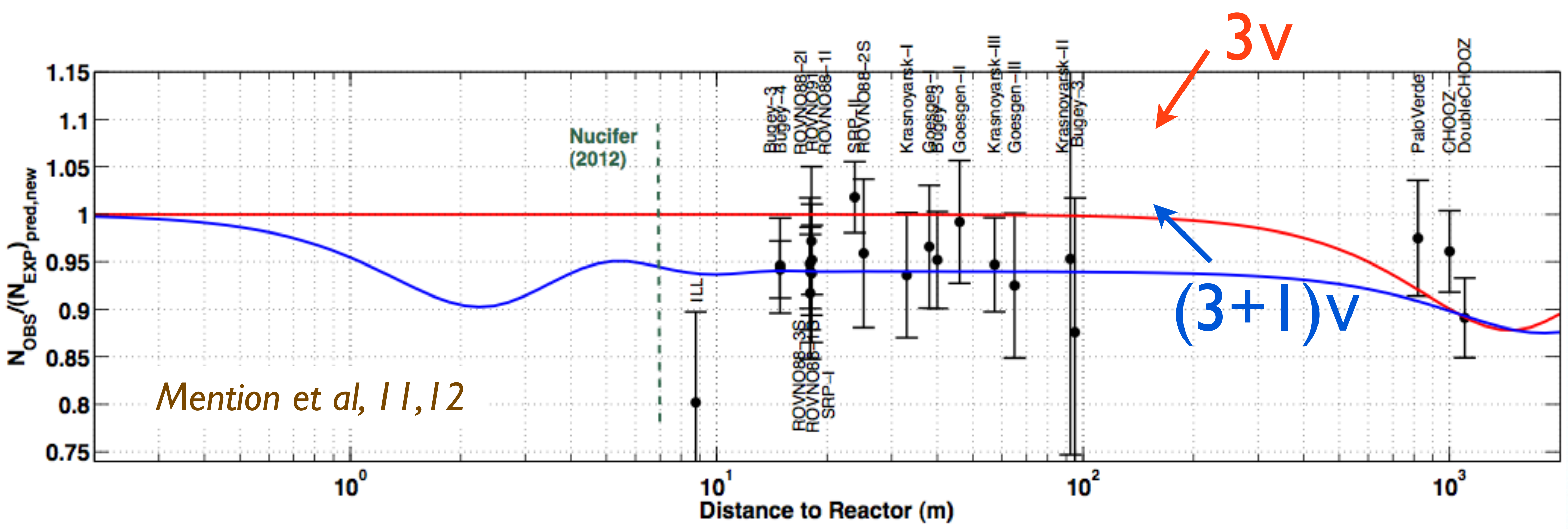
LSND + MiniBooNE

$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.918)$
$\chi^2/ndf = 19.4/15.6$ (prob = 21.1%)



Phys. Rev. Lett. 121 (2018) 221801

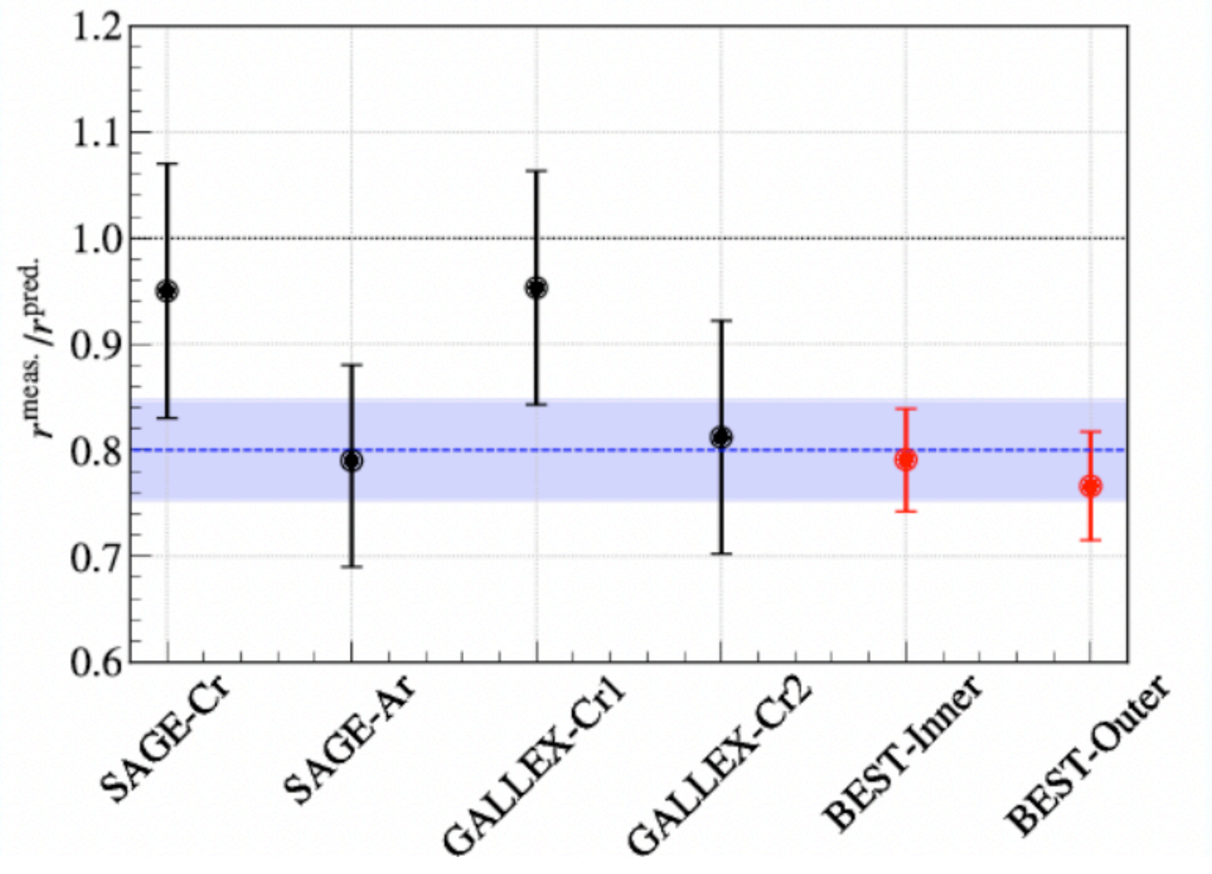
Reactor neutrino anomaly



Disagreements with predictions. ^{235}U may be incorrect in the flux model

MicroBooNE does not support the interpretation of the LE excess in terms of ν_e

Ga anomaly

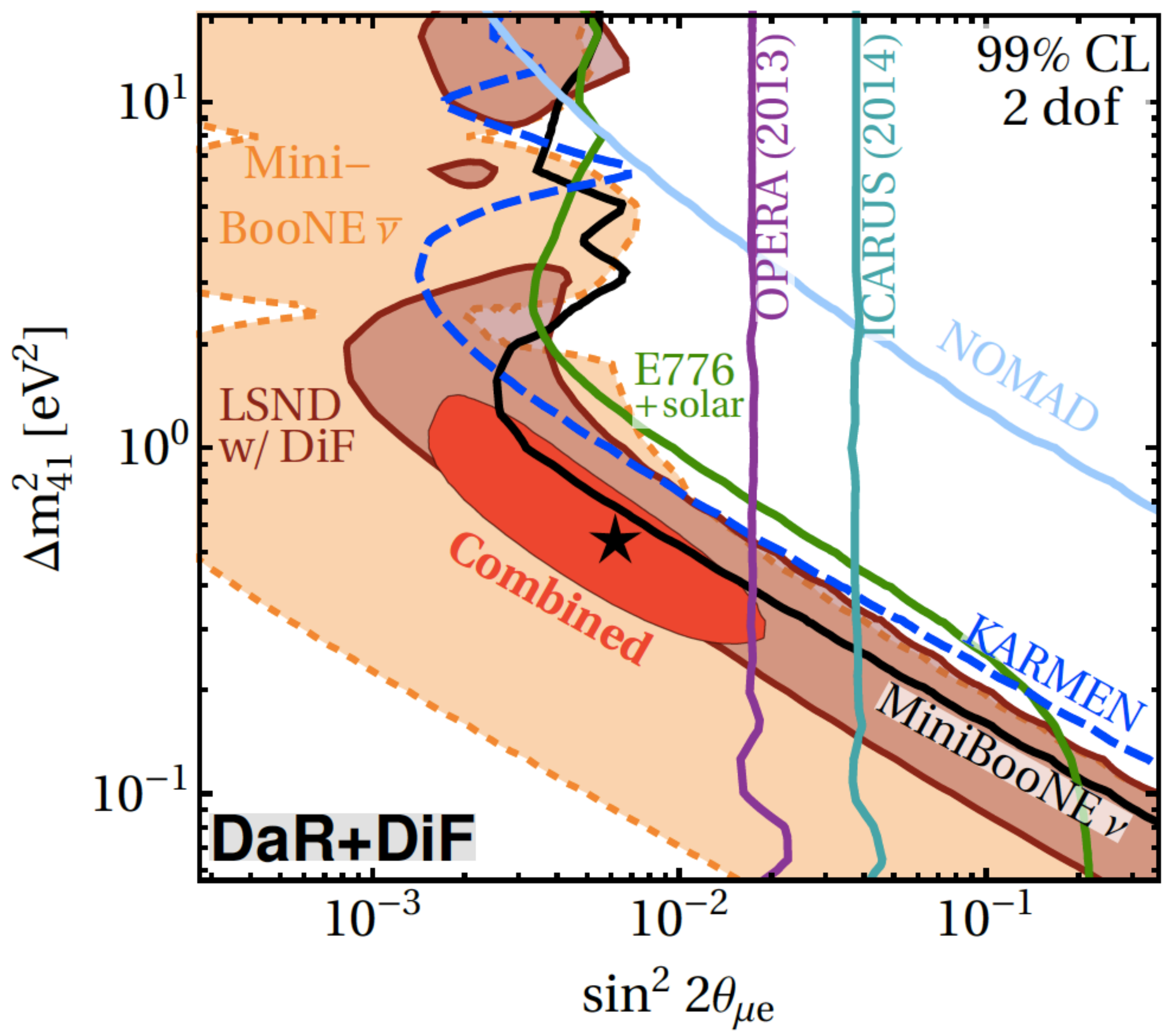


Intense ^{51}Cr and ^{37}Ar neutrino sources show deficit wrt predictions. Recently confirmed by BEST

Global sterile results

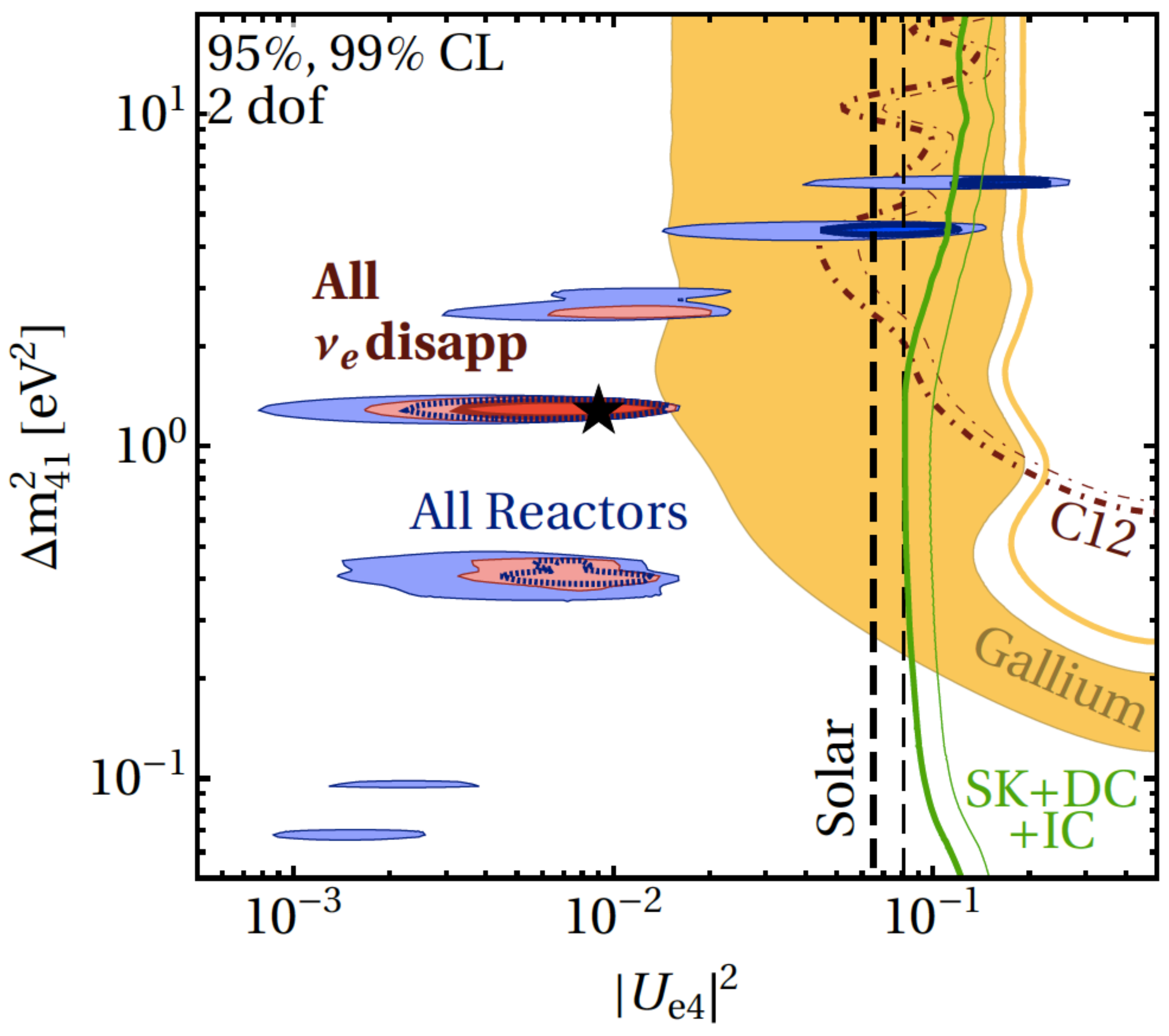
- Tension between the three results
- Sterile neutrino models fail to simultaneously account for all experimental data (strong tension between appearance and disappearance experiments)

$\overset{(-)}{\nu}_e$ appearance



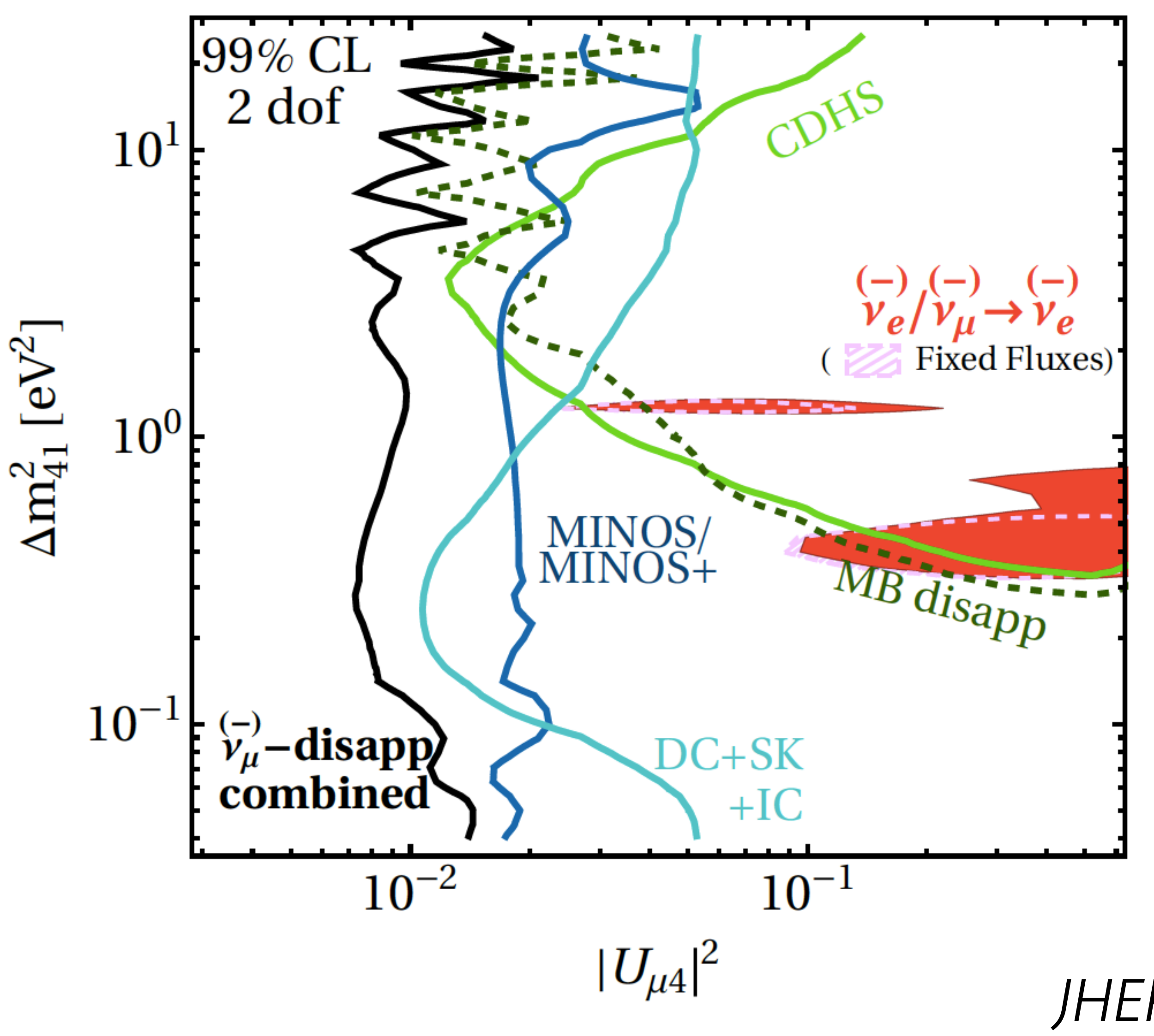
Observation by LSND & MiniBooNE

$\overset{(-)}{\nu}_e$ disappearance



Observation by reactors & radioactive sources

ν_μ disappearance



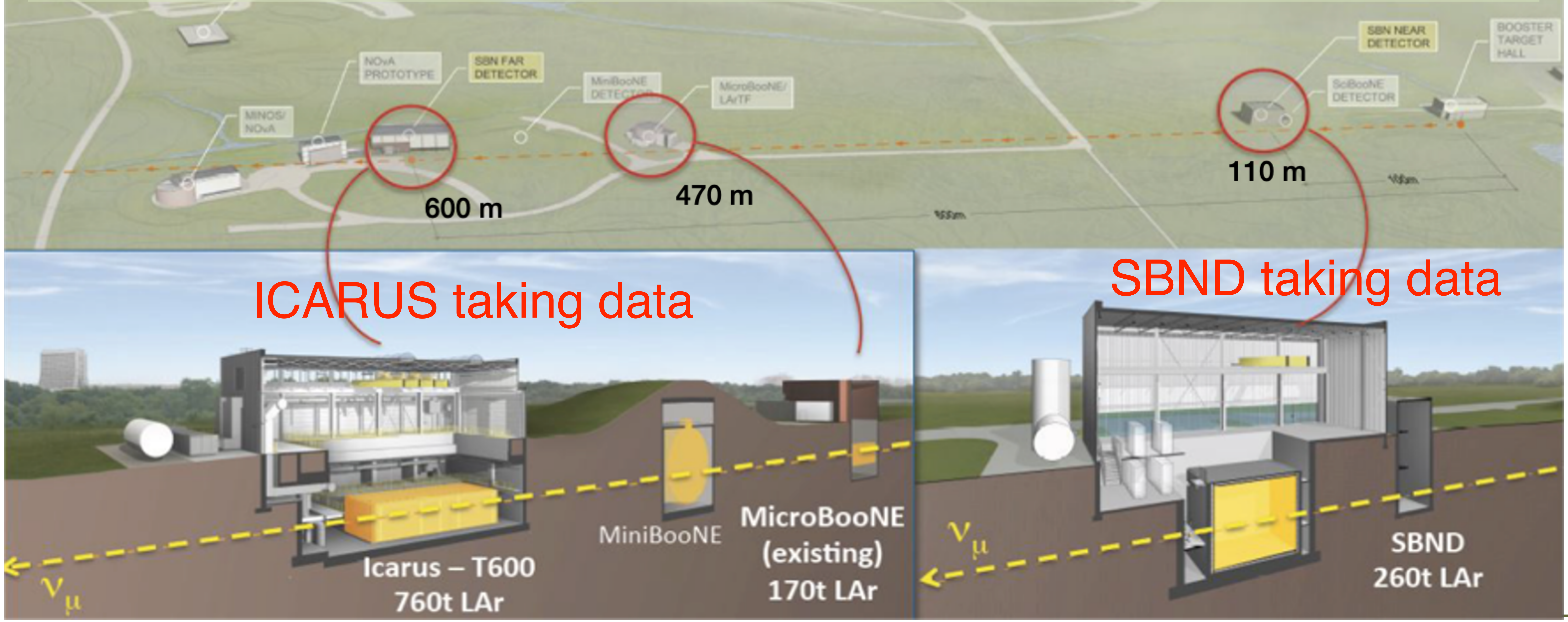
Non observation

JHEP 08 (2018) 010

Short-Baseline Neutrino Program at Fermilab

3 LAr TPC detectors in the ν beam from the 8 GeV Booster E_ν^{peak} ~800 MeV to

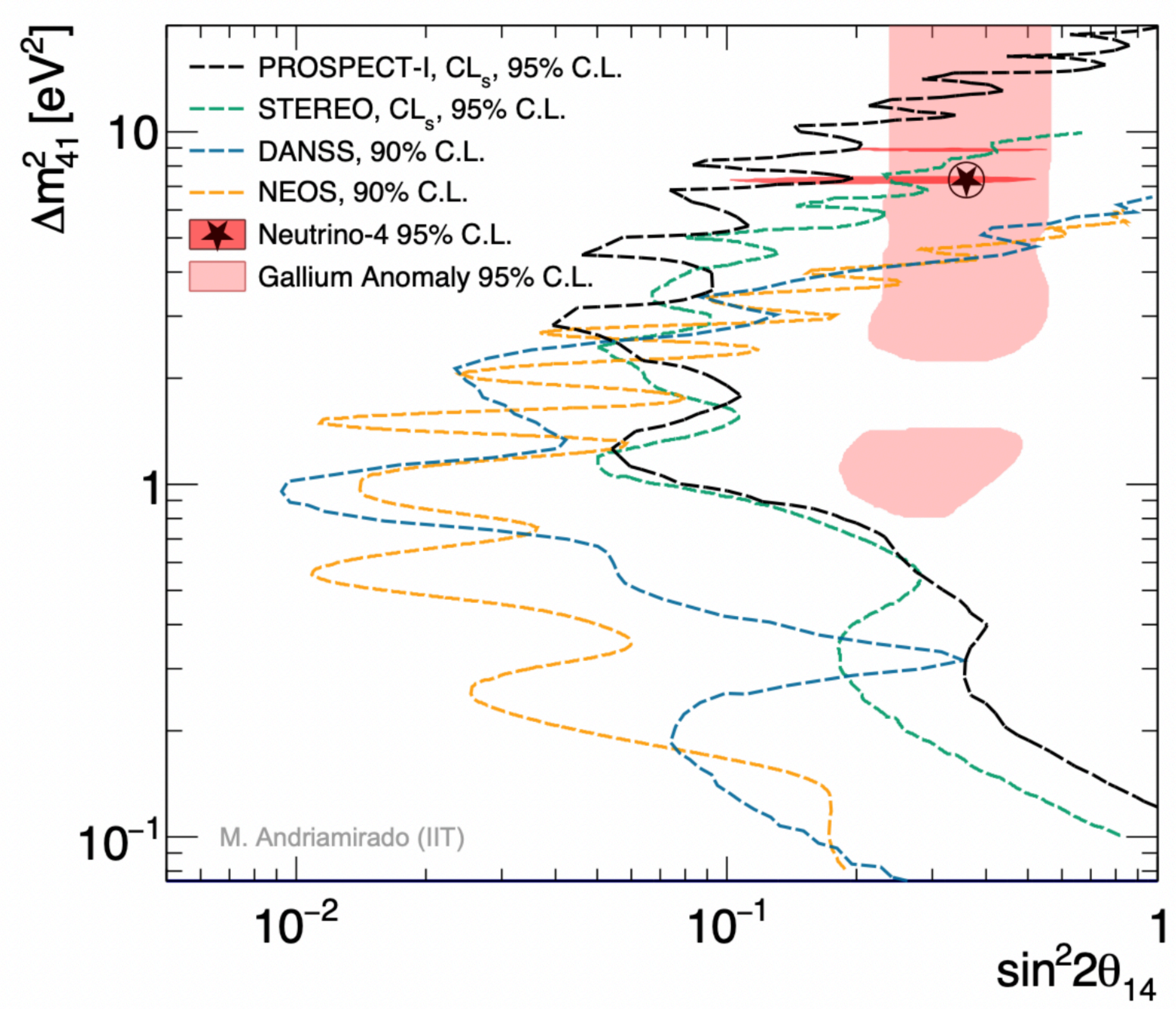
- Investigate eV-scale **sterile neutrino** oscillations (anomalies to the three-neutrino paradigm reported by reactor and accelerator based experiments)
- ν-Ar cross sections, BSM searches, R&D for future LAr detectors



Very short-baseline reactor experiments

- DANSS, NEOS, Neutrino-4, PROSPECT, SoLid, STEREO
  - ✦ Experiments searching for sterile neutrino oscillations at a O(10m) baseline from a nuclear reactor
- Only one of these experiments has claimed an observation: Neutrino-4
  PRD 104, 032003 (2021)
- Controversial Neutrino-4 claim at 2.7σ, strong tension with null results from other experiments, consistent with the Ga anomaly

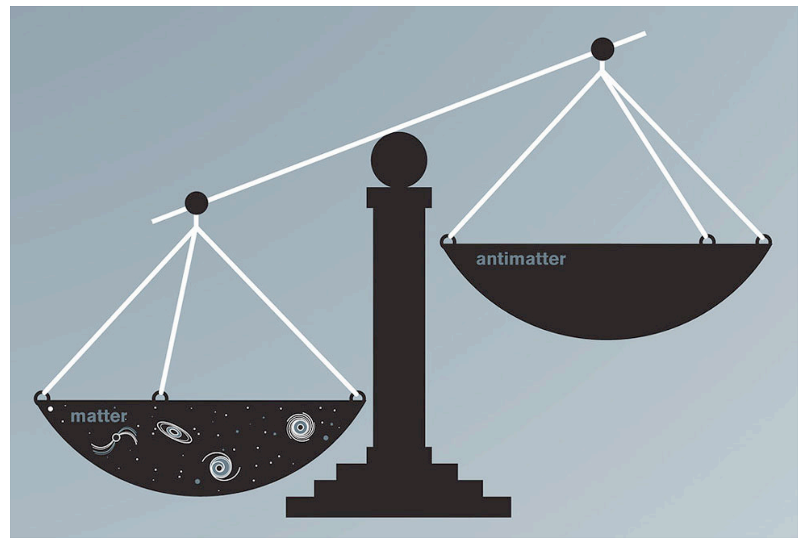
D. L'huillier Neutrino 2024

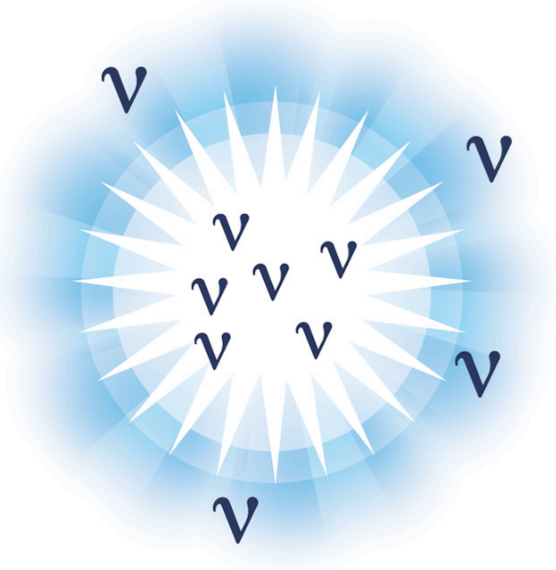


Prospects in neutrino oscillations

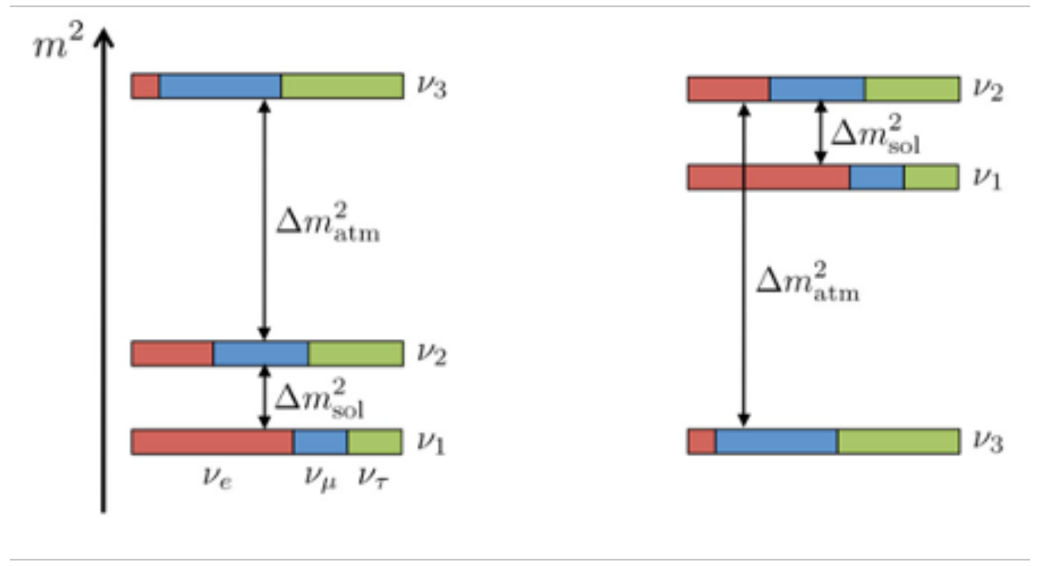
Discovery opportunities

- **CP violation**
  - ✦ T2K and NOvA could reach 3σ sensitivity to CPV over the next years
  - ✦ To reach discovery and precise measurement, larger detectors and (upgraded or new) beams are needed

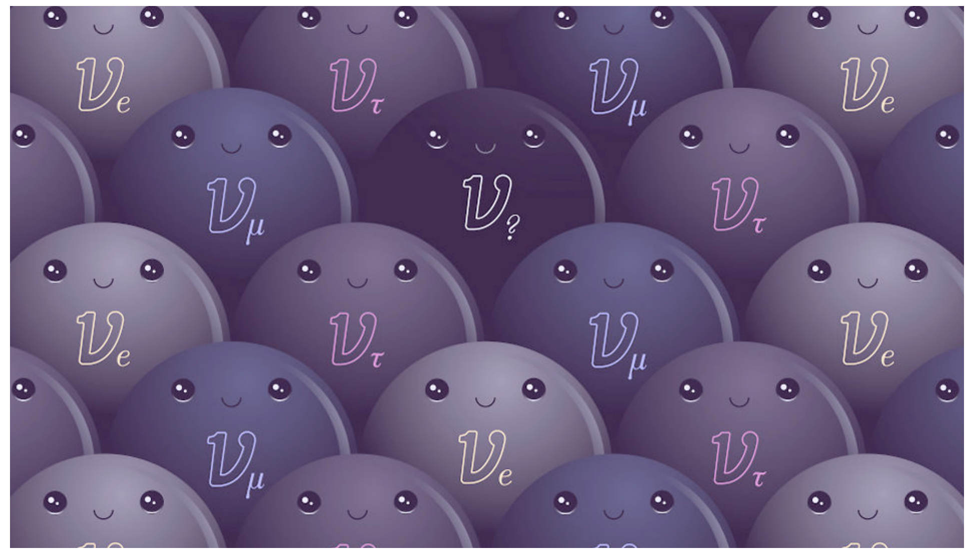


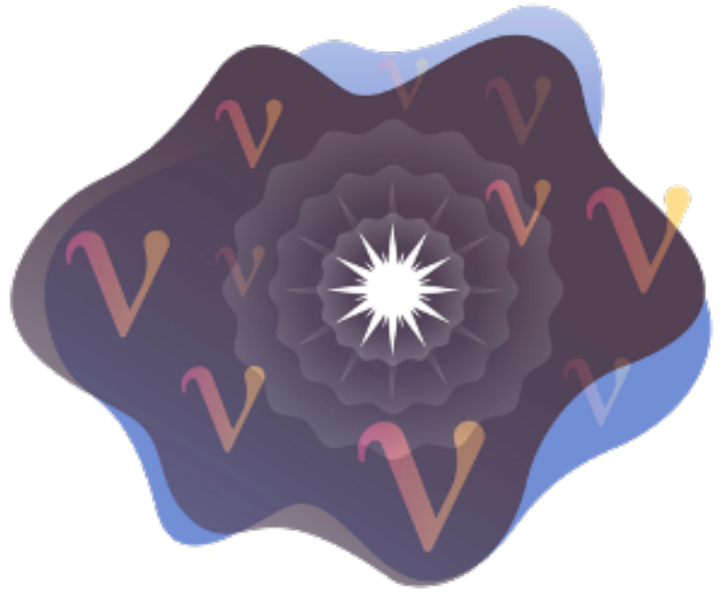


- Neutrino **mass ordering**
  - ✦ Small preference for NO with current data (not conclusive)



- **Octant** of θ_{23}
  - ✦ Maximal? $\nu_\mu \leftrightarrow \nu_\tau$ mixing symmetric? If so, why?





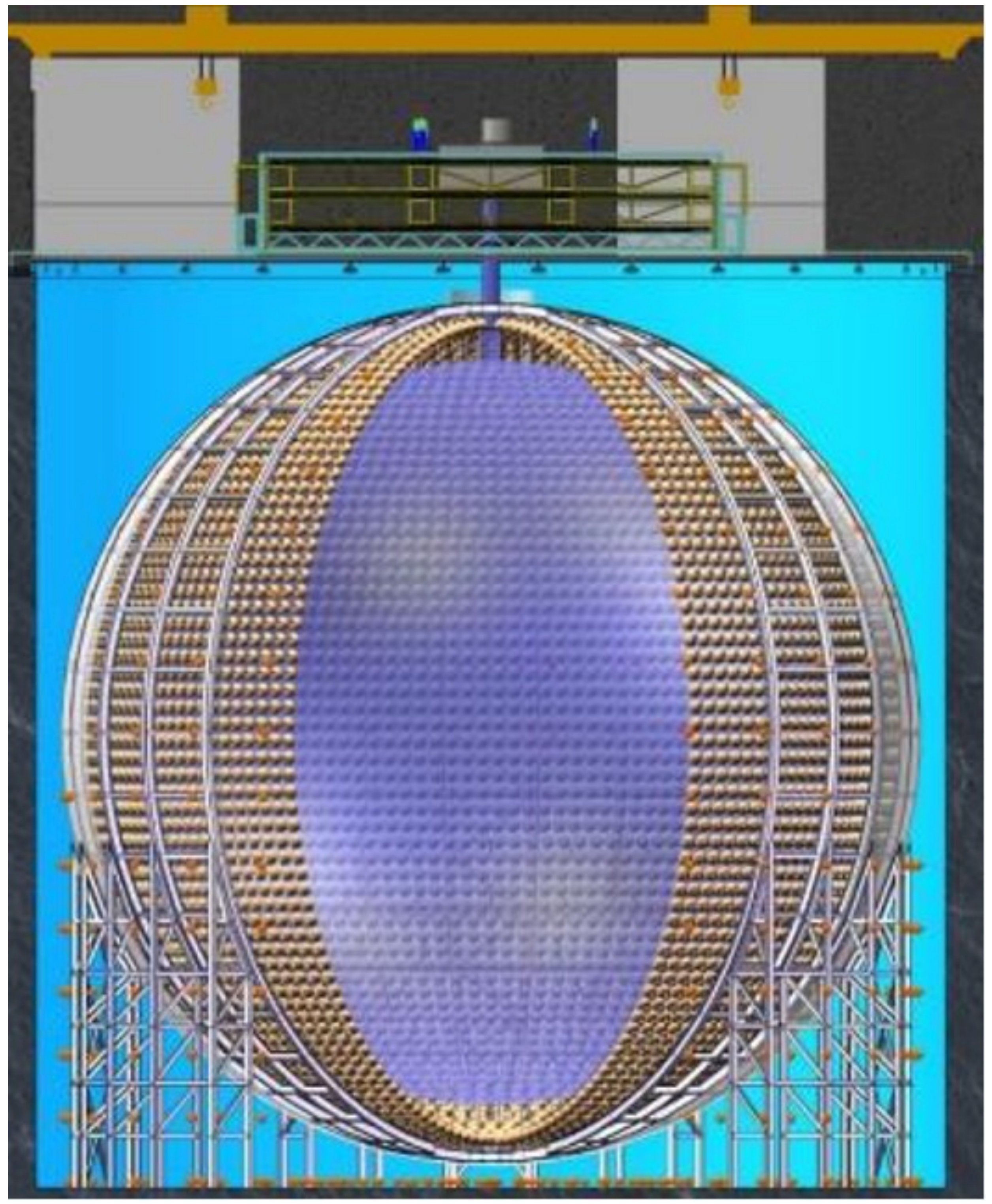
- Neutrino anomalies: **sterile neutrinos**?
- **Solar** neutrinos: hep neutrino flux
- **Supernova** burst and Diffuse SN Neutrino Background detection
- **Beyond the Standard Model**: nucleon-decay, testing the 3-neutrino flavor paradigm

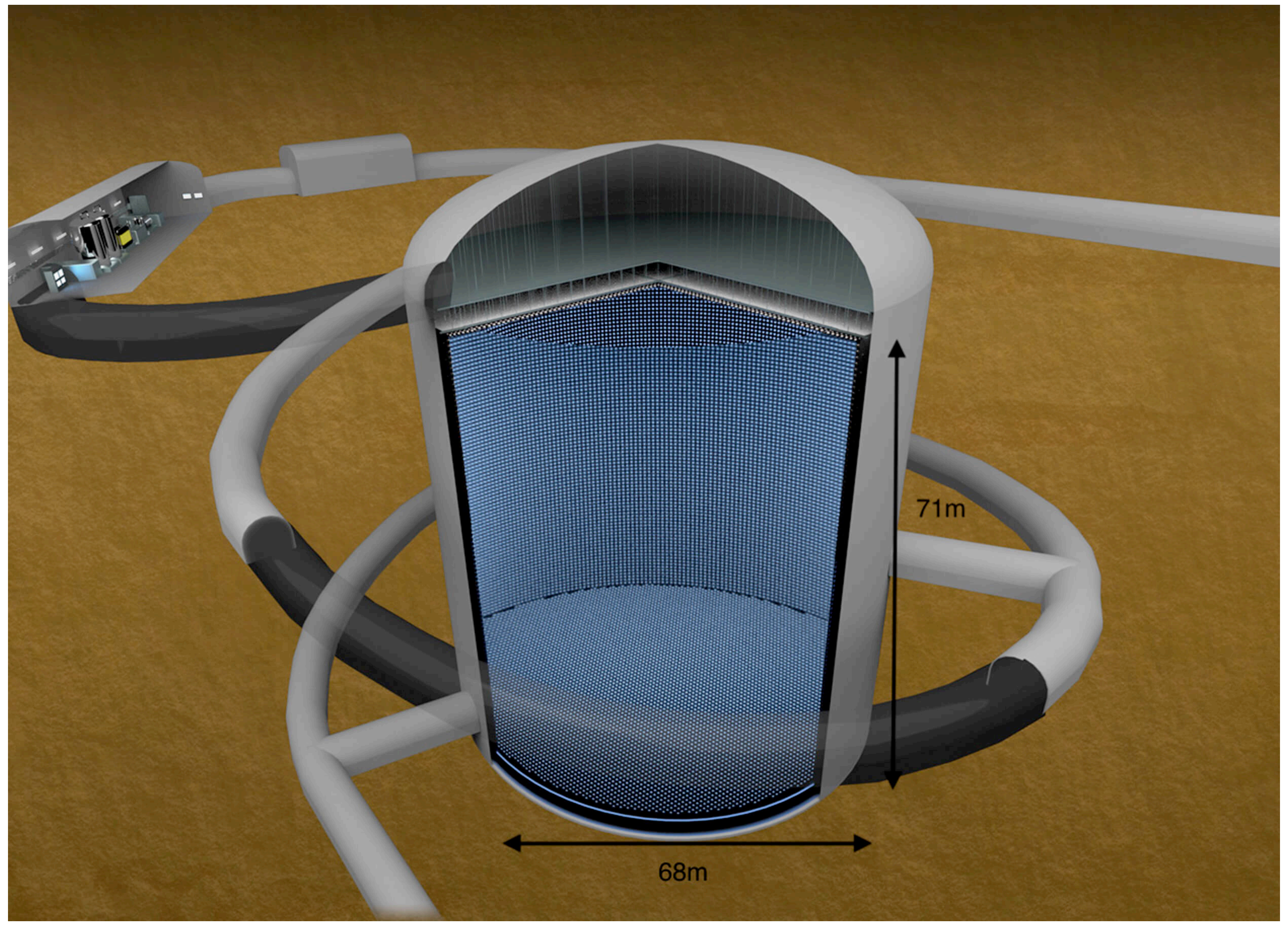
Three large-scale projects under construction

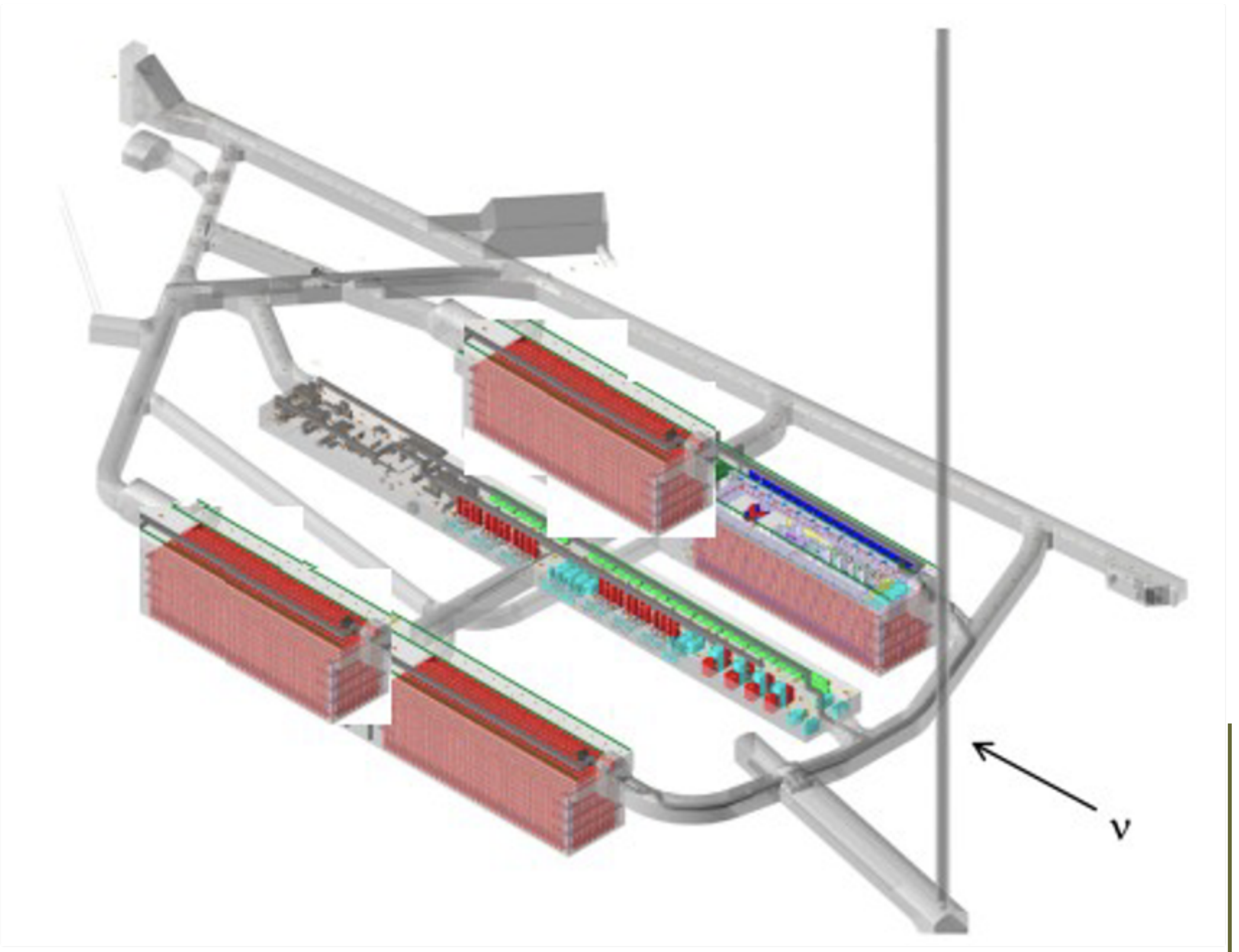
JUNO

Hyper-K

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

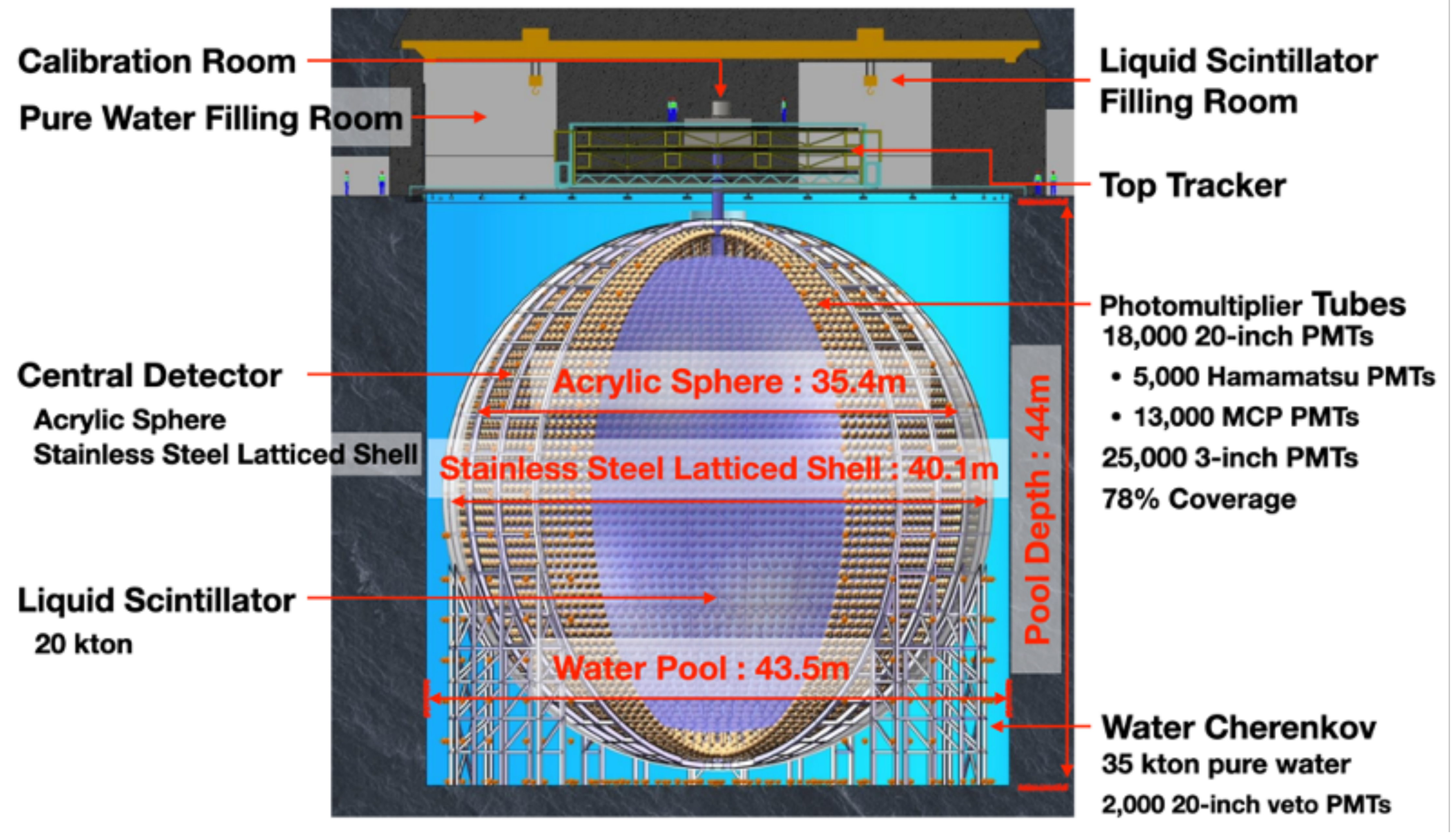


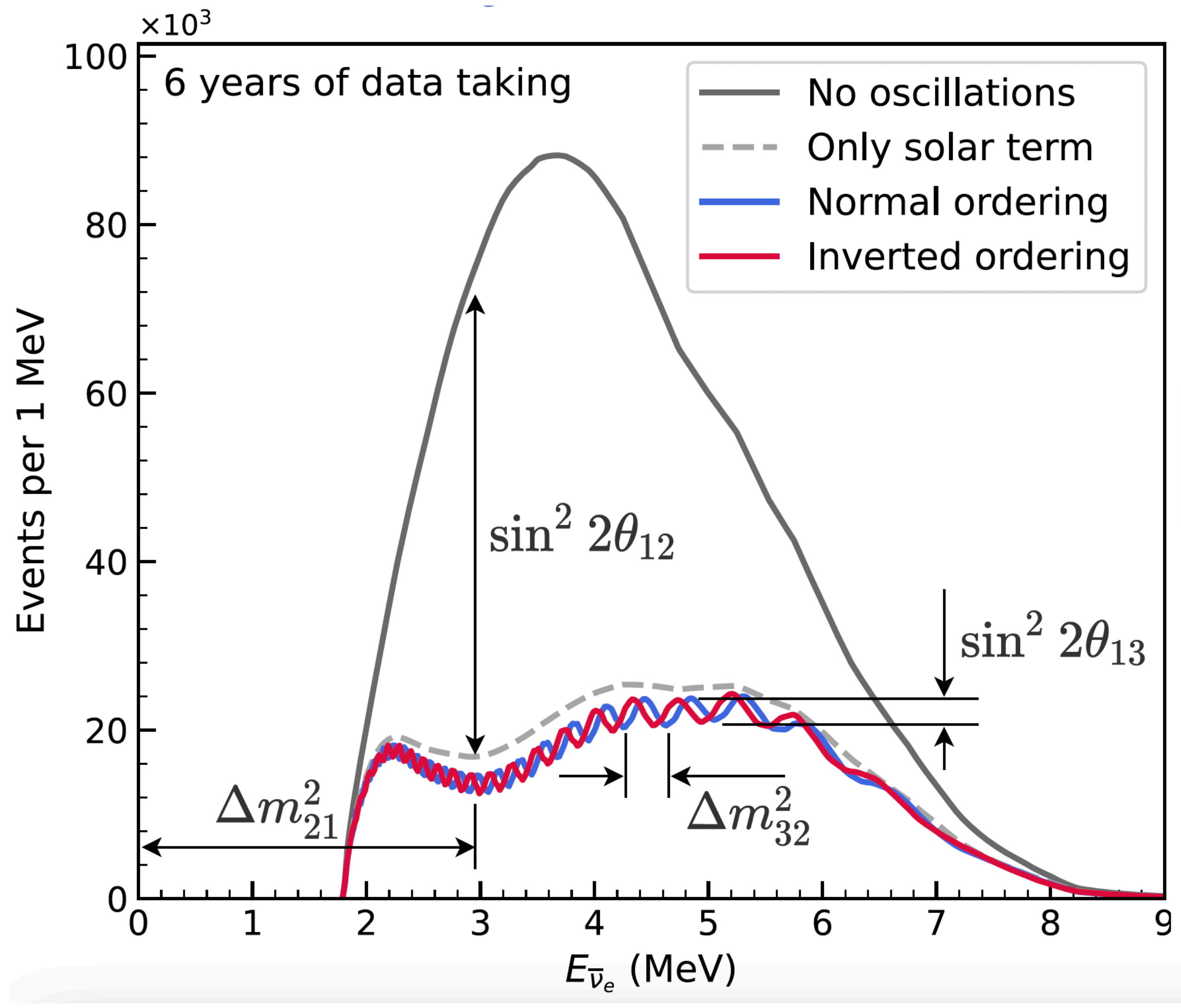




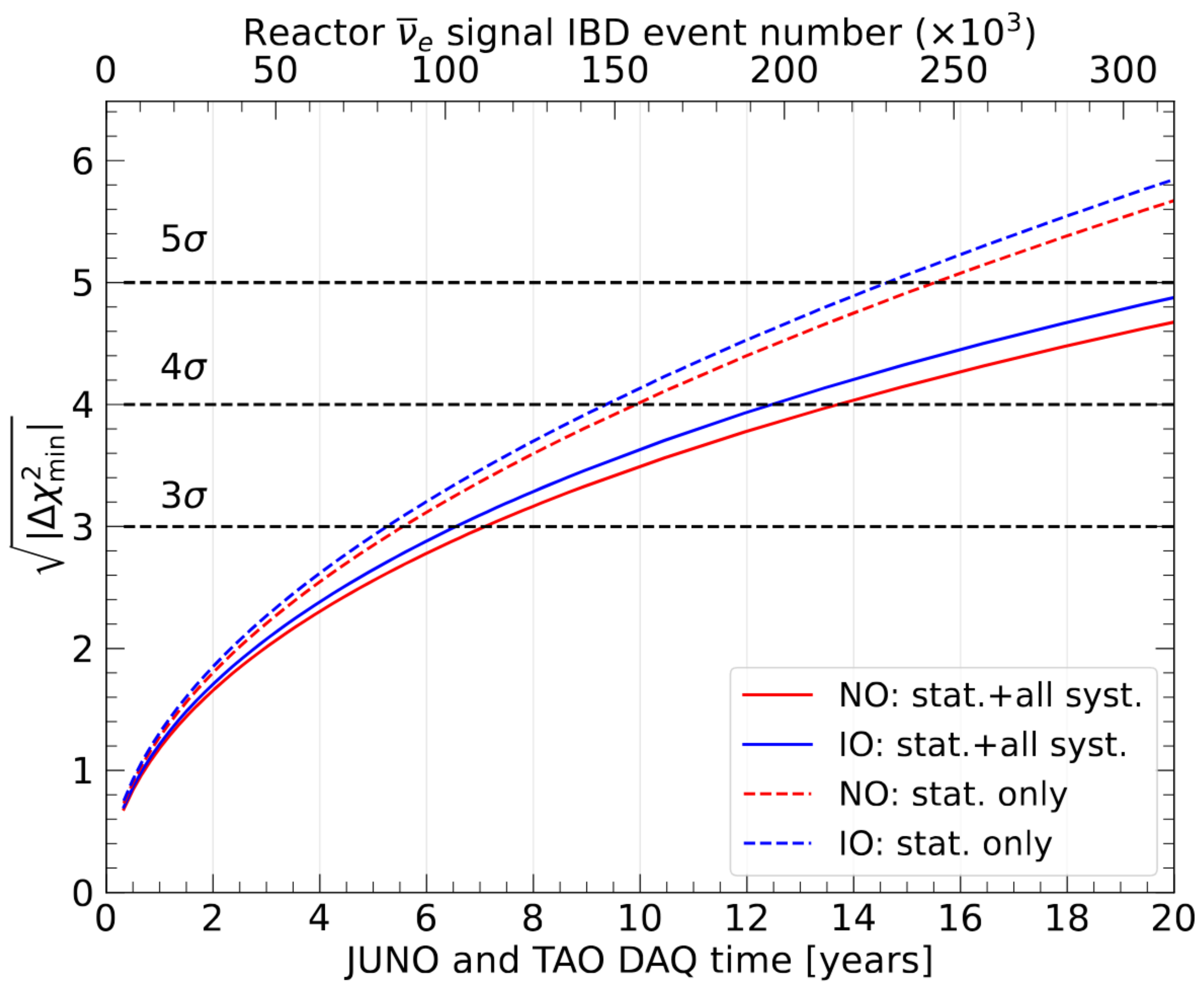
JUNO (Jiangmen Underground Neutrino Observatory)

- Next-generation Large Liquid Scintillator detector (20 kton)
  - ✦ Medium baseline **reactor experiment** (<L>=50 km) in China
  - ✦ Aim at much improved light yield and energy resolution ≈3%/√E(MeV)
  - ✦ Relatively shallow depth (700m overburden)
  - ✦ Expect to start data taking in 2025!
- Design to reach 3σ precision on **mass ordering** determination after 6y + precise **solar oscillation parameters** (<0.5%) in 7y + other low-E physics





Reactor antineutrino spectrum

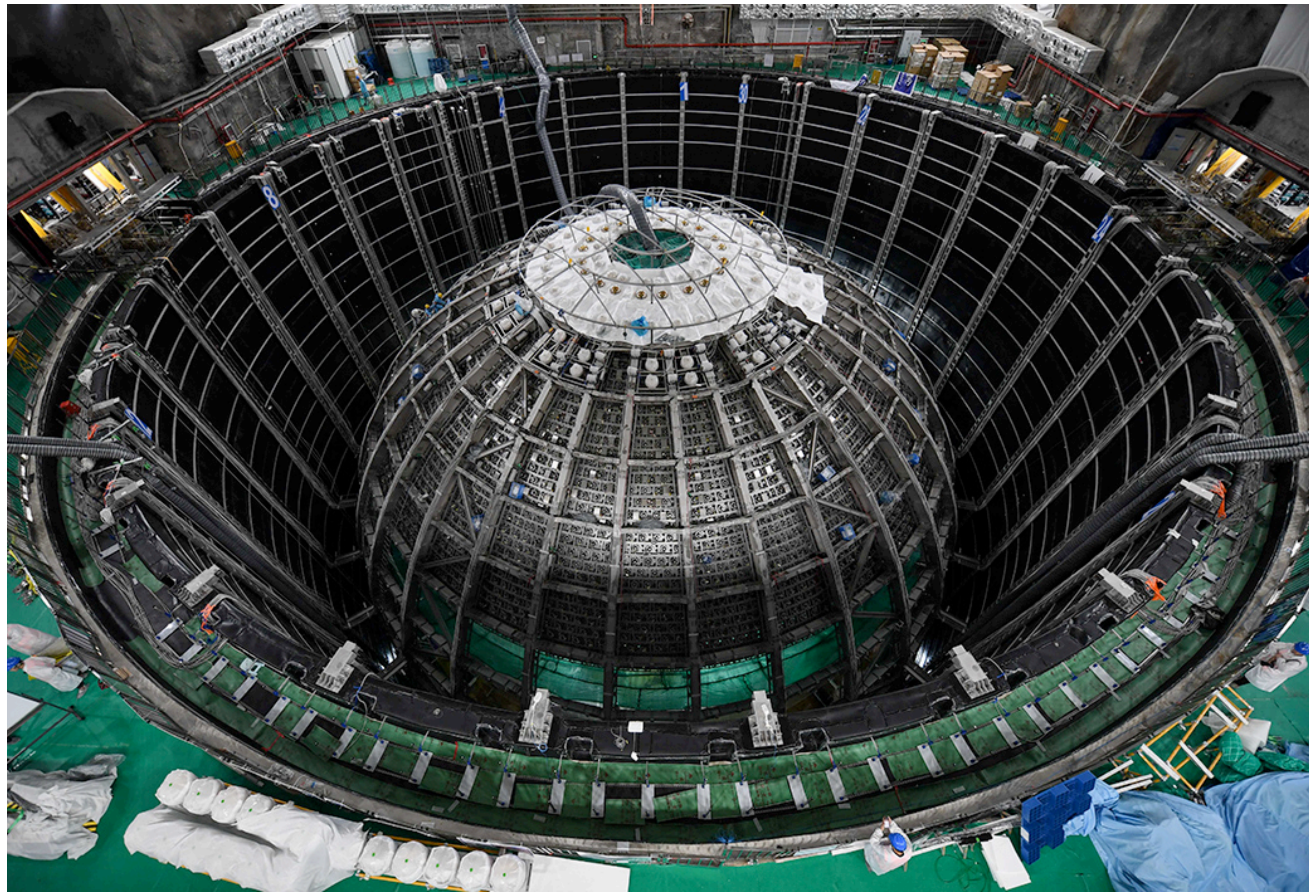


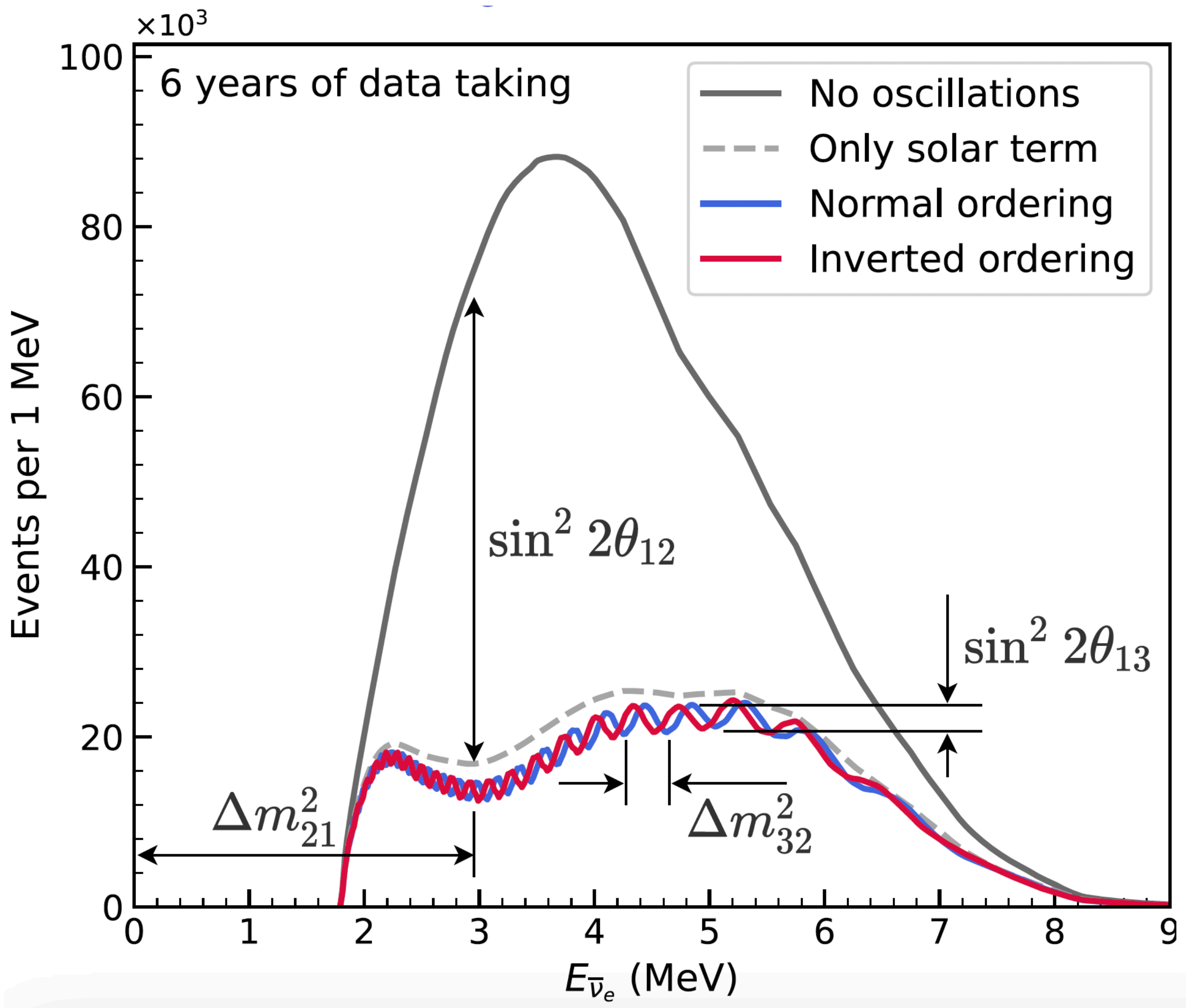
Mass ordering sensitivity

arXiv:2405.18008

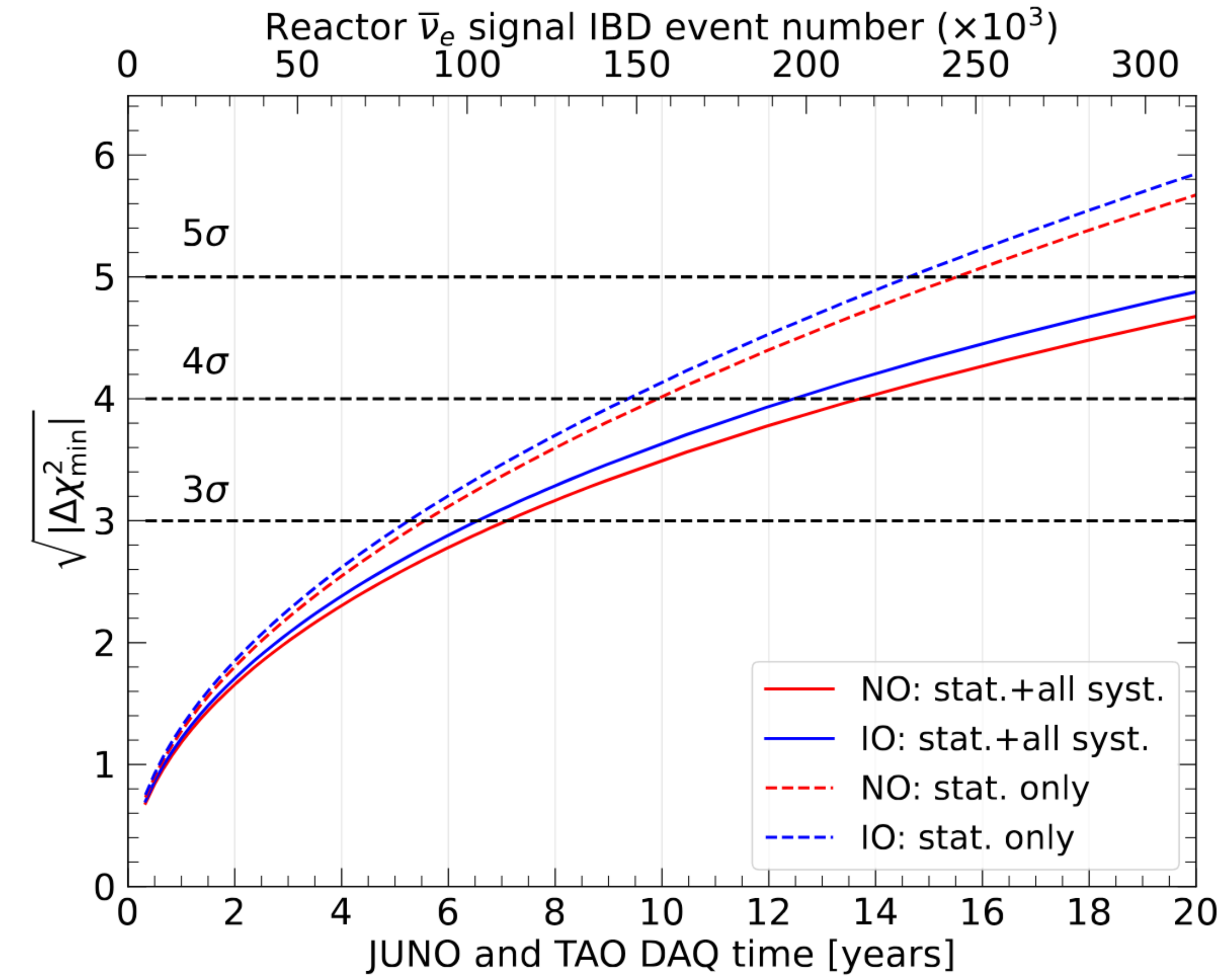
JUNO (Jiangmen Underground Neutrino Observatory)

- Next-generation Large Liquid Scintillator detector (20 kton)
  - ✦ Medium baseline **reactor experiment** (<L>=50 km) in China
  - ✦ Aim at much improved light yield and energy resolution ≈3%/√E(MeV)
  - ✦ Relatively shallow depth (700m overburden)
  - ✦ Expect to start data taking in 2025!
- Design to reach 3σ precision on **mass ordering** determination after 6y + precise **solar oscillation parameters** (<0.5%) in 7y + other low-E physics





Reactor antineutrino spectrum



Mass ordering sensitivity

arXiv:2405.18008

Long-baseline neutrino accelerator experiments

Oscillation probability in matter

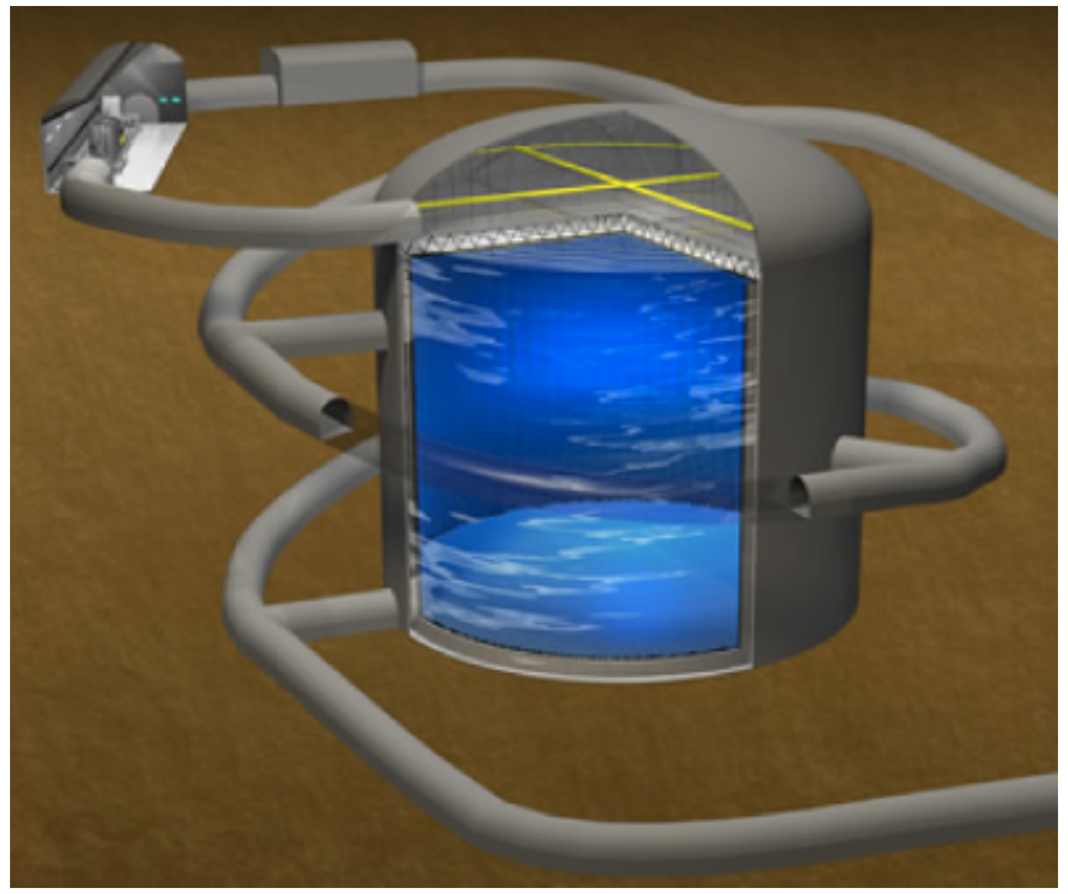
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{CP})$$
$$+\ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

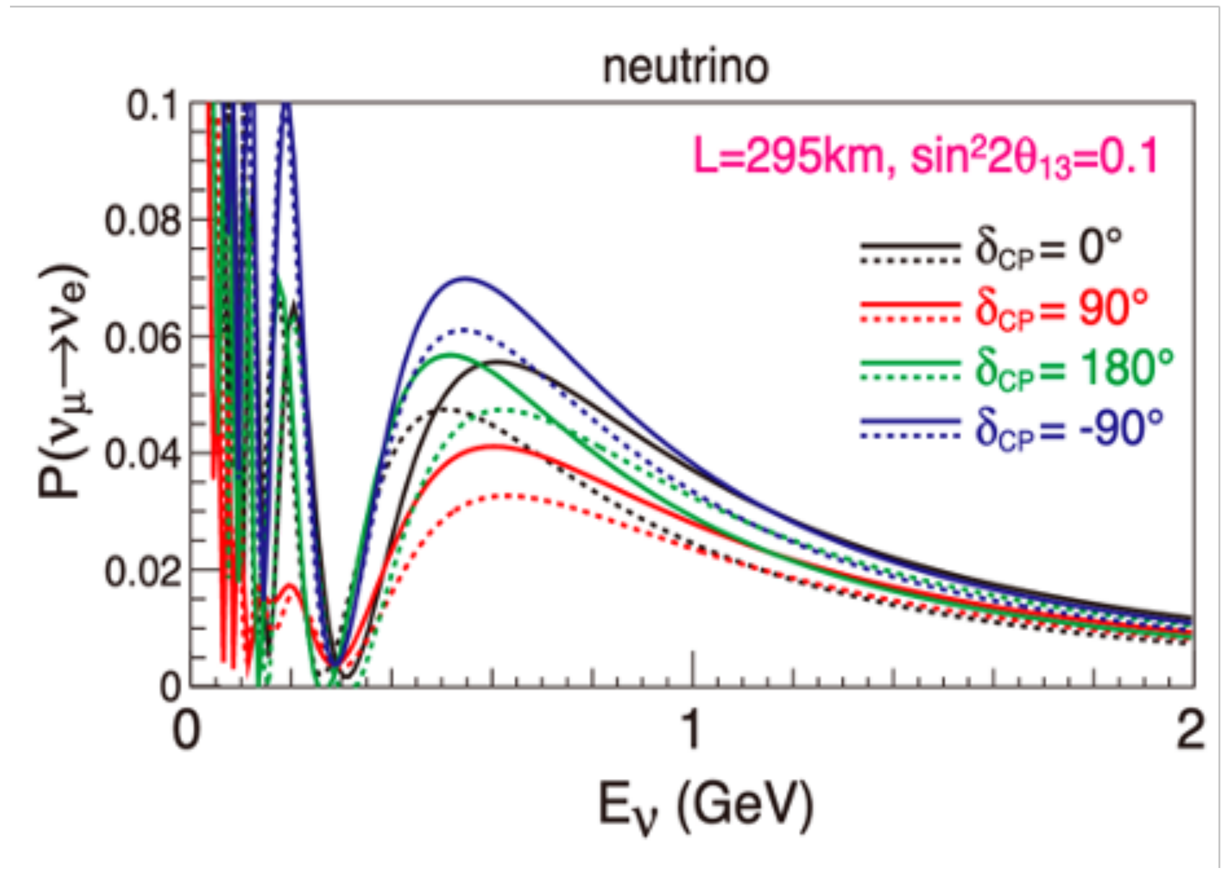
$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$$
$$a = \pm G_F N_e/\sqrt{2}$$

T2HK: Tokai to HyperK

✦ Minimize matter effects and maximize statistics to focus on CPV discovery (MO and other parameters must be known by other means) + non-beam physics program

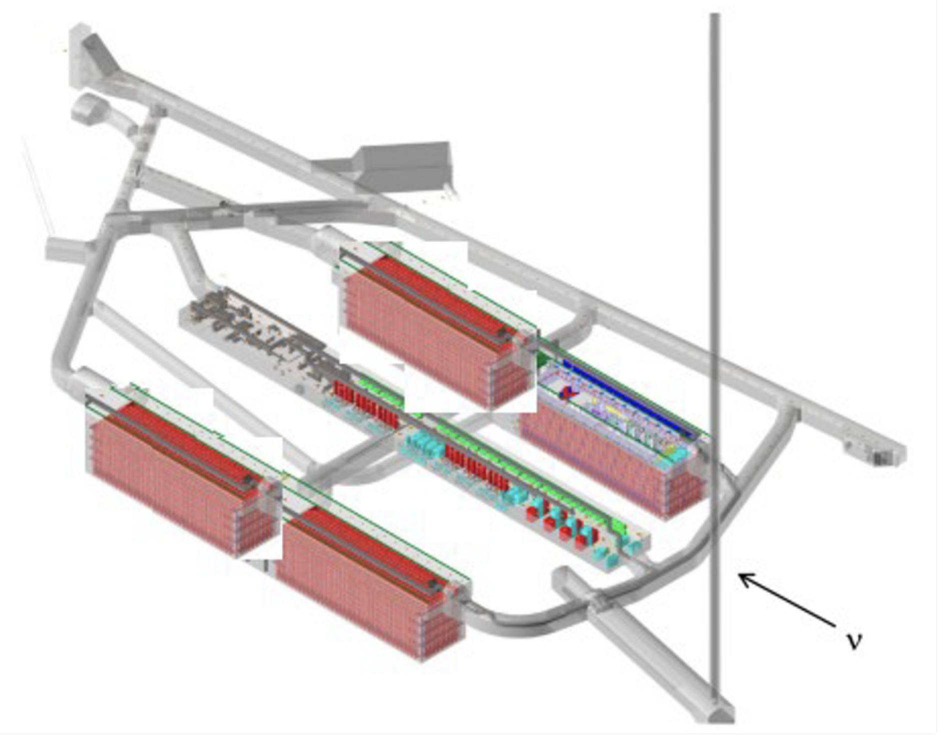
✦ Narrow-band beam (~0.6 GeV; 500 kW → 1.3 MW) and Water-Cerenkov detector (190 kt fiducial)

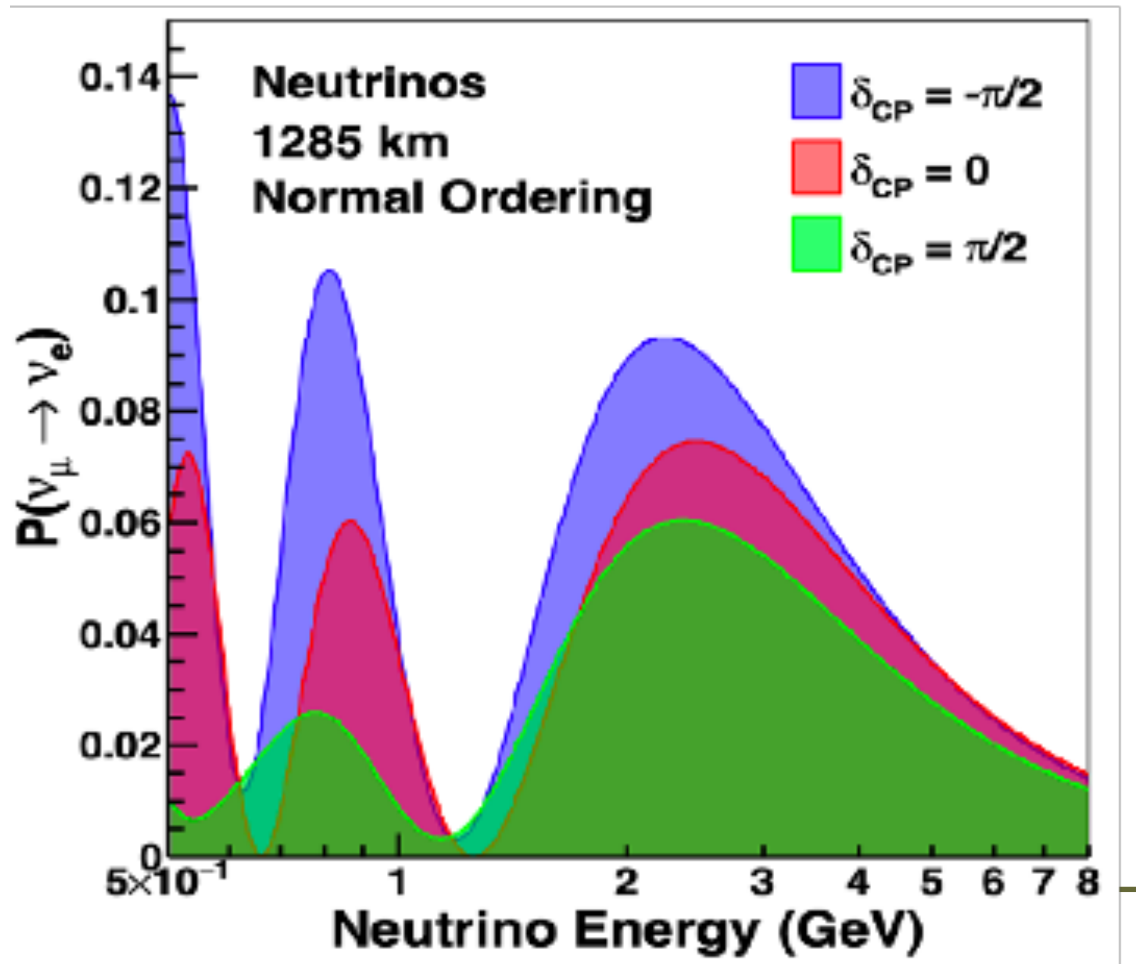




DUNE: FNAL to SURF

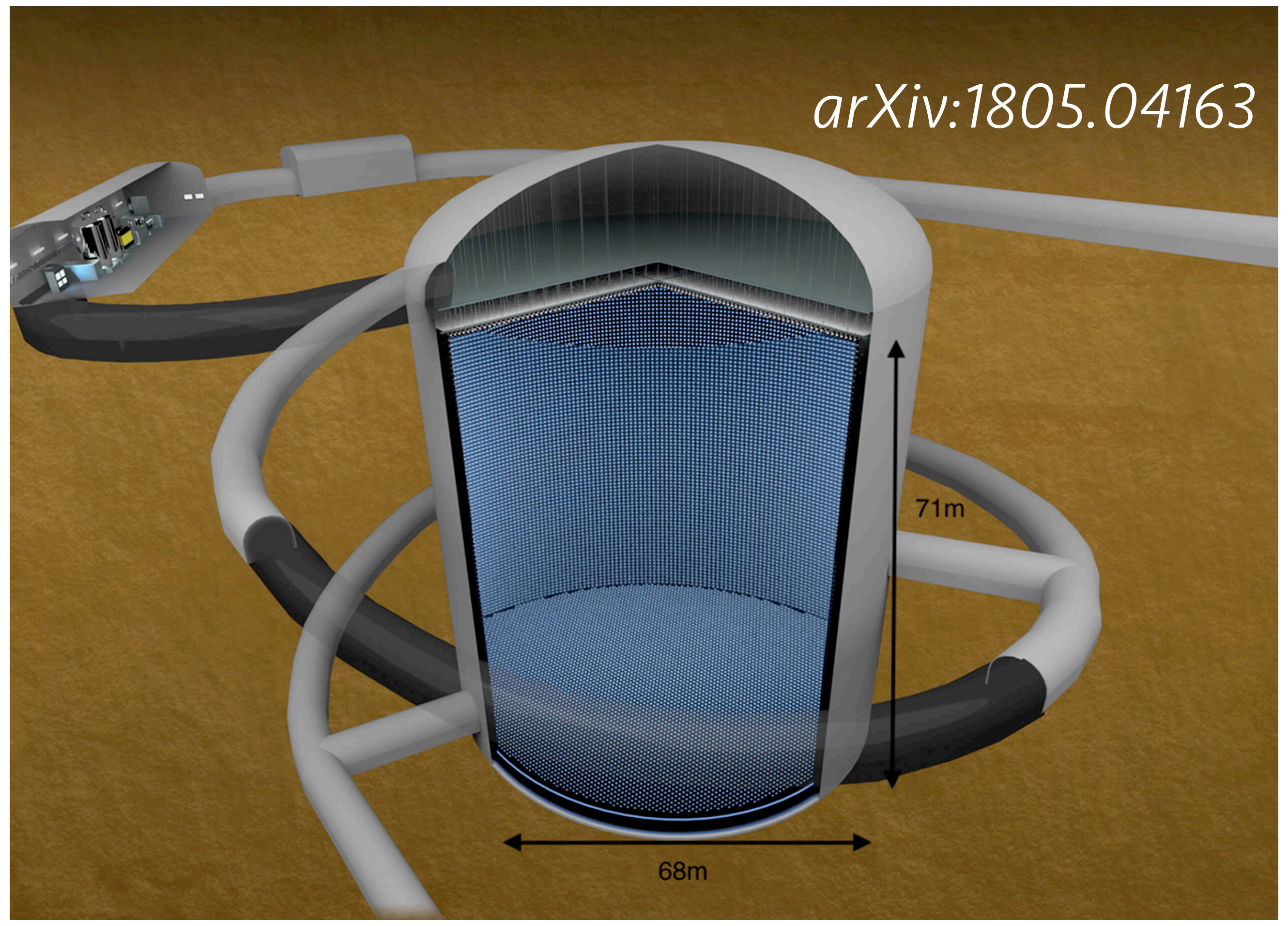
- Measure first and second oscillation maxima to disentangle CPV and matter effects and access to all neutrino oscillation parameters + non-beam physics program
- Wide-band beam (0.5-5 GeV; 1.2 → >2 MW) and liquid Argon TPC (>40 kt fiducial)





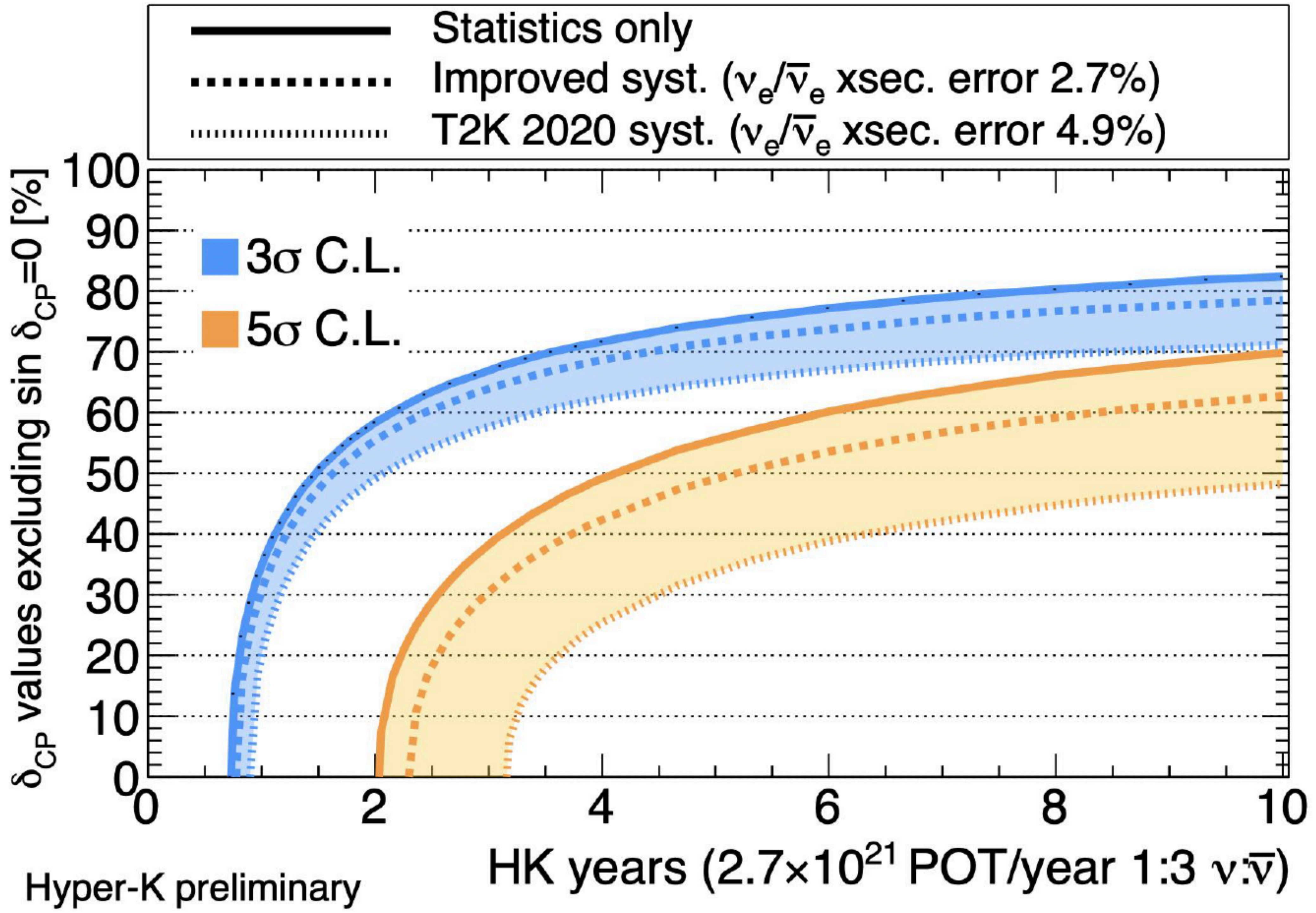
Hyper-Kamiokande

- Upgrade J-PARC neutrino beam with expected power 1.3 MW, 2.5^{o} off-axis angle
- Baseline: 295 km
- WC Total mass: 260 kton pure water, Inner detector: 216 kton, Fiducial mass: **~200 kton (x 8 SK)**
- Between 20-40% photocathode coverage
- New cavern in a different part of Kamioka mine under construction (600 m rock overburden)
- Aiming to start operation in 2027



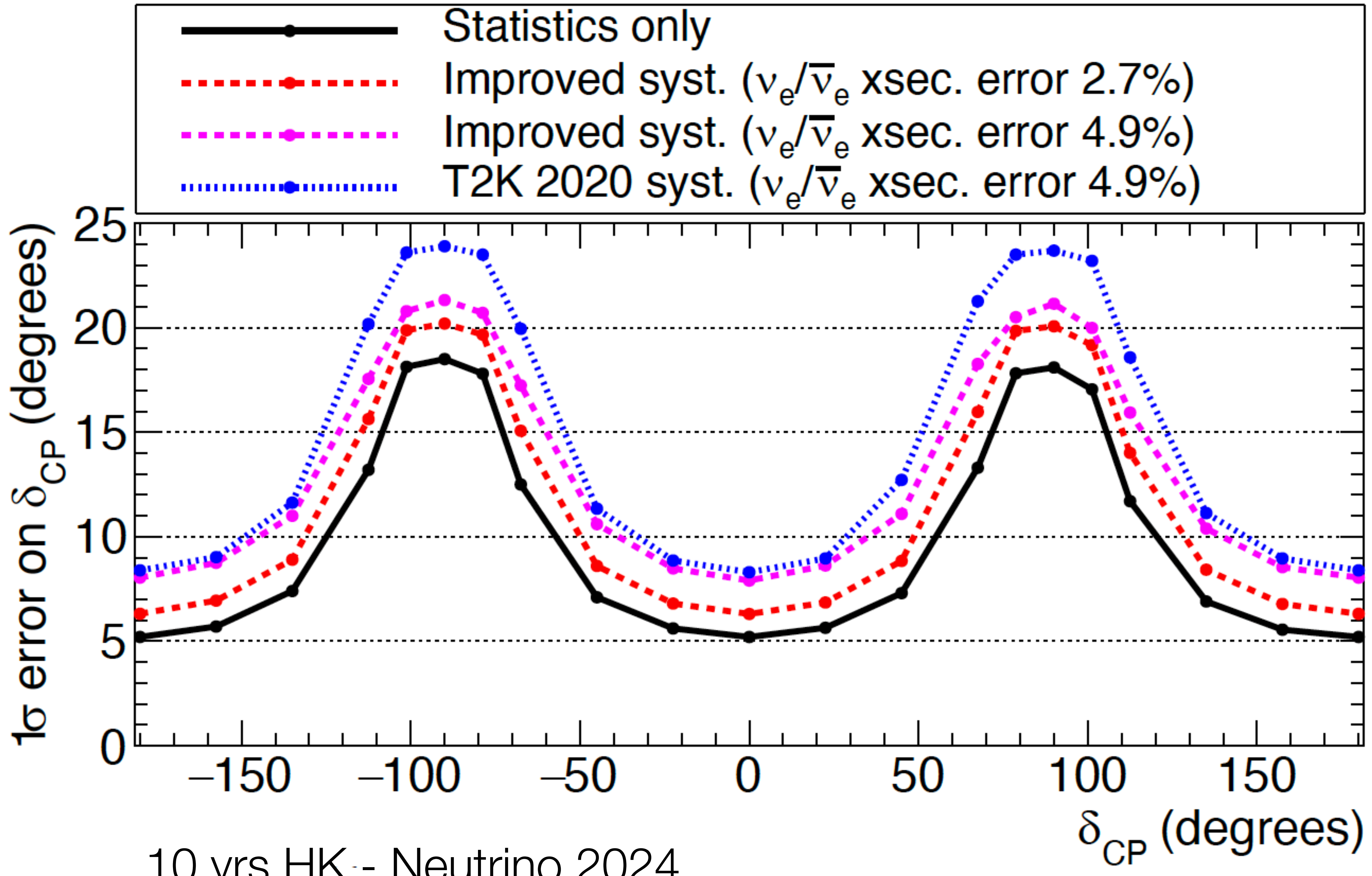
Hyper-Kamiokande sensitivity

- Able to exclude **CP** conservation at 5σ for 60% of δ_{CP} values (if MO known) in 10 years for nominal power
- 1σ resolution of δ_{CP} in 10 yrs ~20° (6°) for δ_{CP} = -90° (0°)
- 4-6σ **MO** determination depending on $\sin^2\theta_{23}$ for 10y of data taking combining beam and atmospheric neutrinos



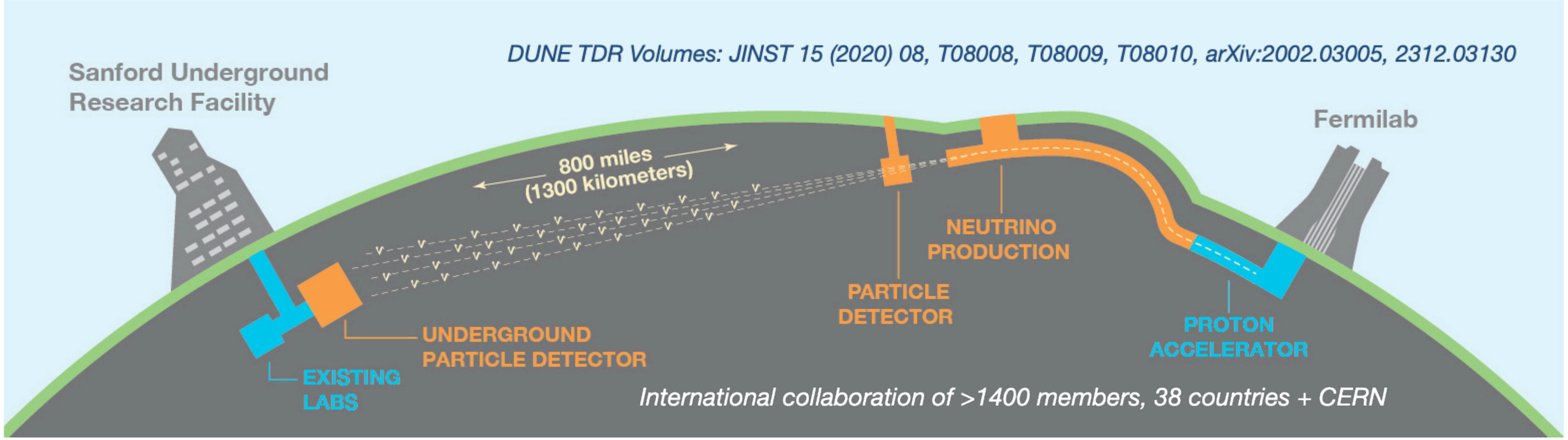
Hyper-K preliminary

Neutrino 2024



10 yrs HK - Neutrino 2024

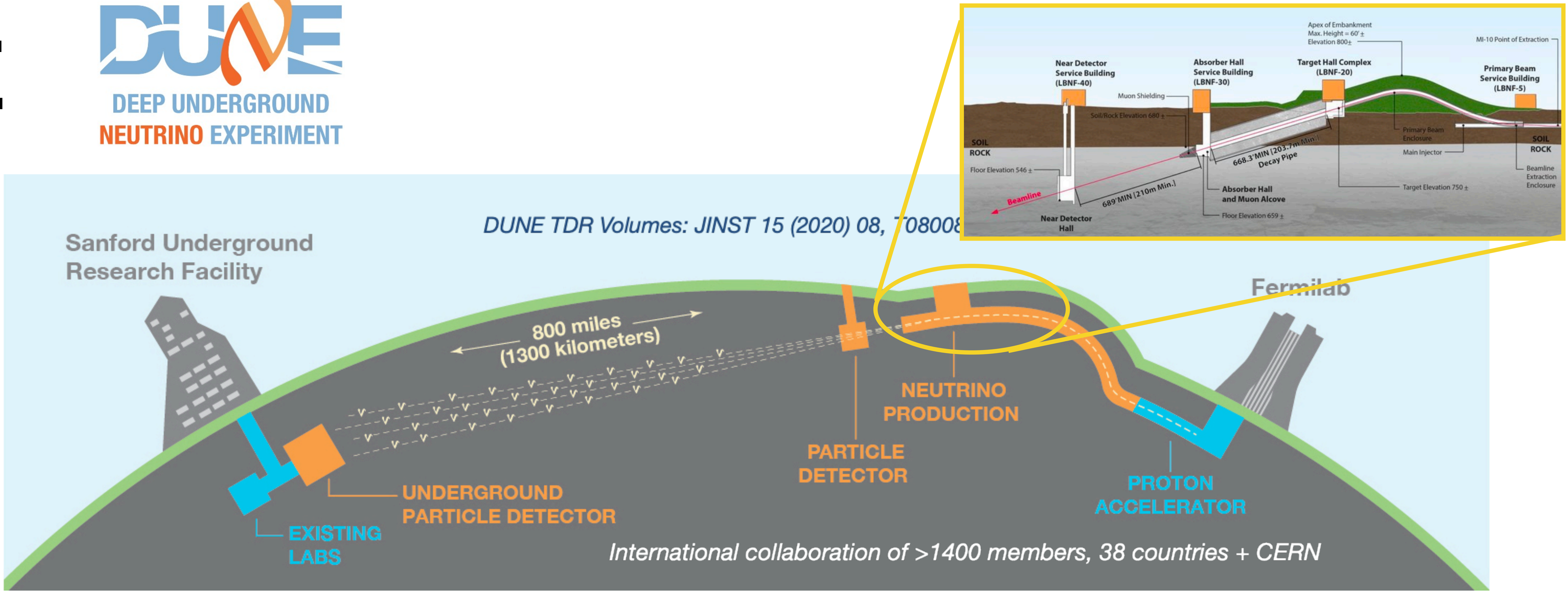
DUNE



- 70 kton (4 x 10 kt fiducial) **LAr TPC far detectors** at 1480 m depth (4300 mwe) at SURF measuring neutrino spectra at 1300 km in a wide-band high purity ν_μ beam with peak flux at 2.5 GeV operating at ~1.2 MW and upgradeable to >2 MW
- **Near detector** (*CDR: arXiv:2103.13910*) at 560 m from the neutrino source: LArTPC, TMS/magnetized GAr TPC & magnetized beam monitor
- **Physics goals**: LBL oscillations (MO and CP violation), precise osc. measurements, SN burst neutrinos, solar neutrinos, nucleon decay, Beyond Standard Model searches, non-standard interactions…

DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT



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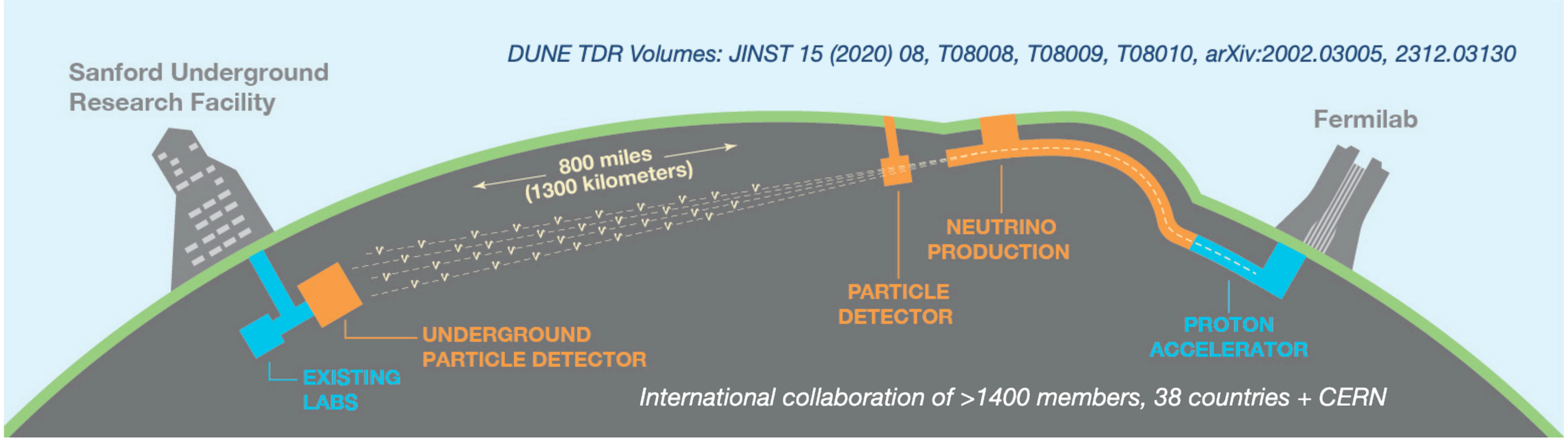

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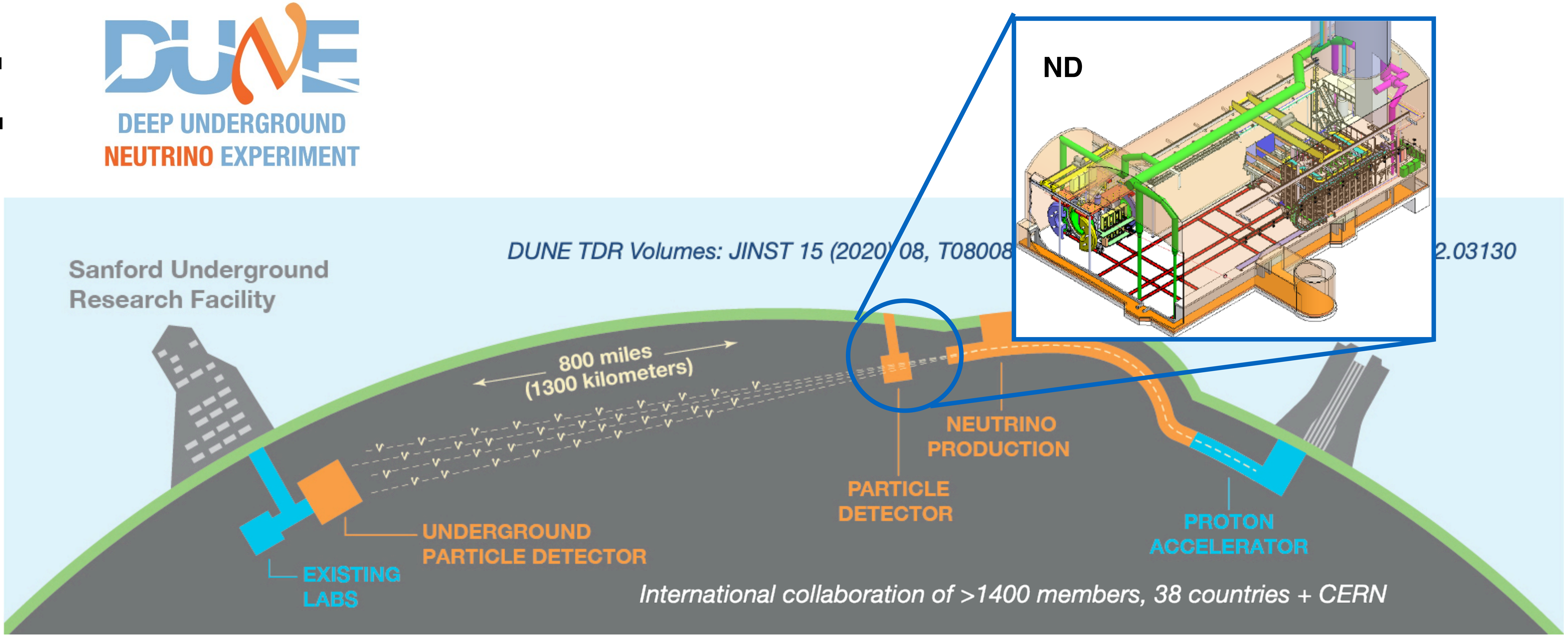

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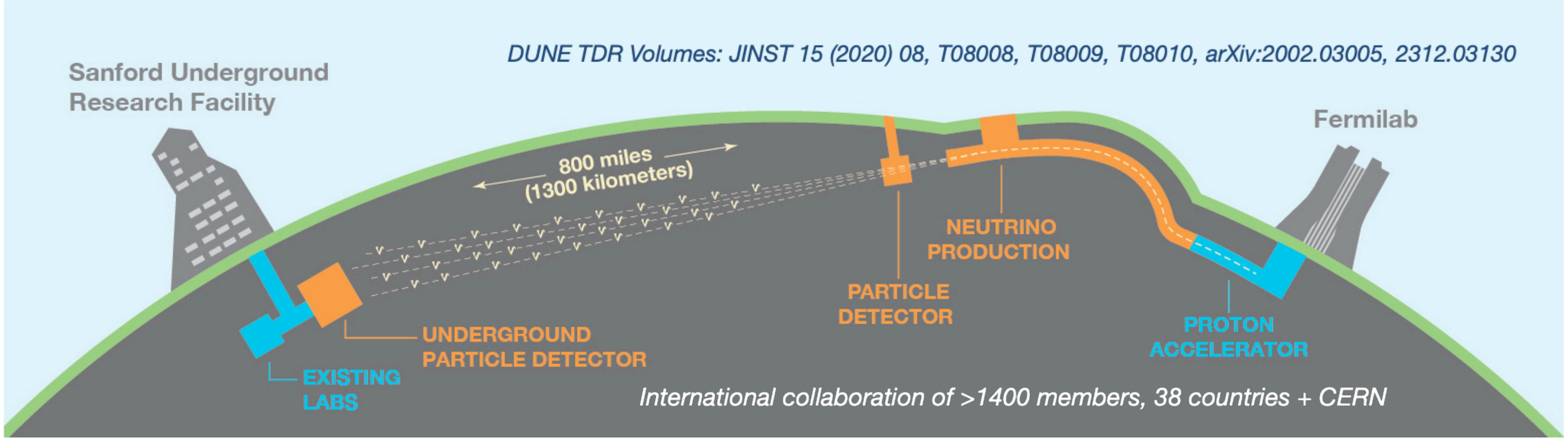

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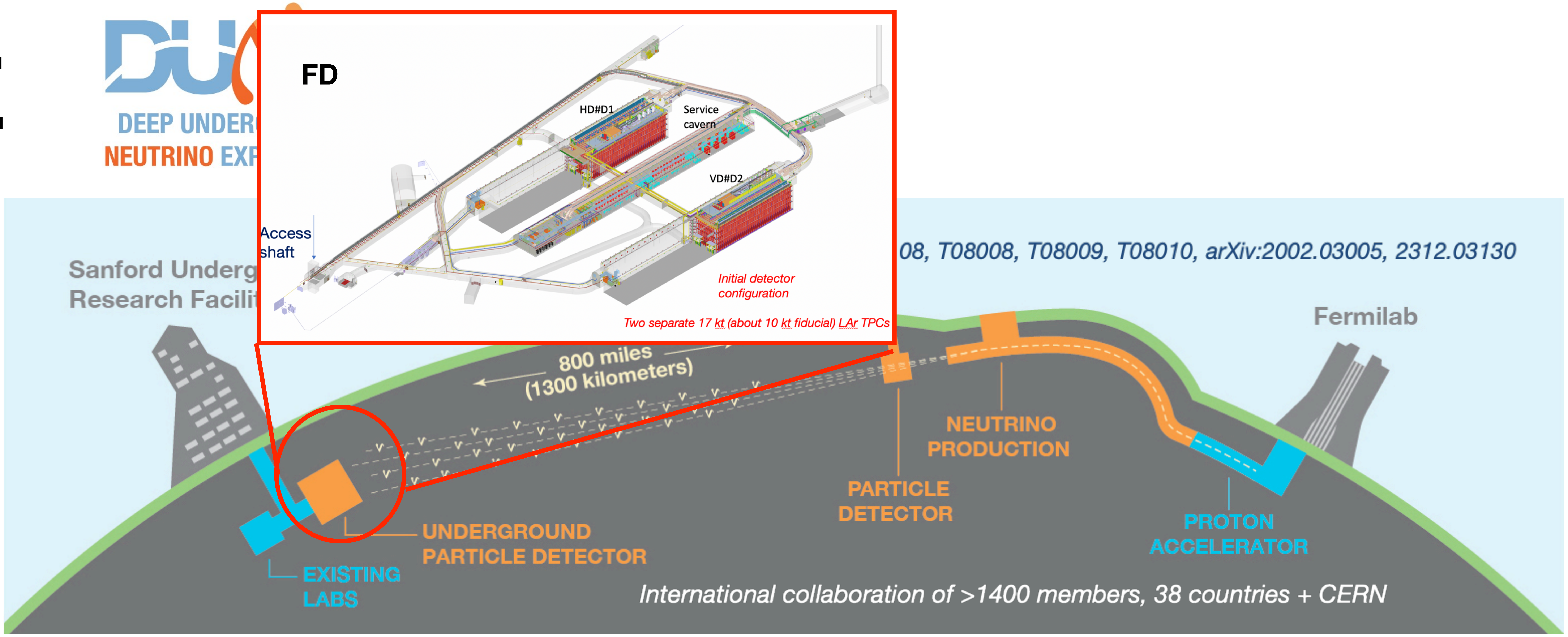
DUNE



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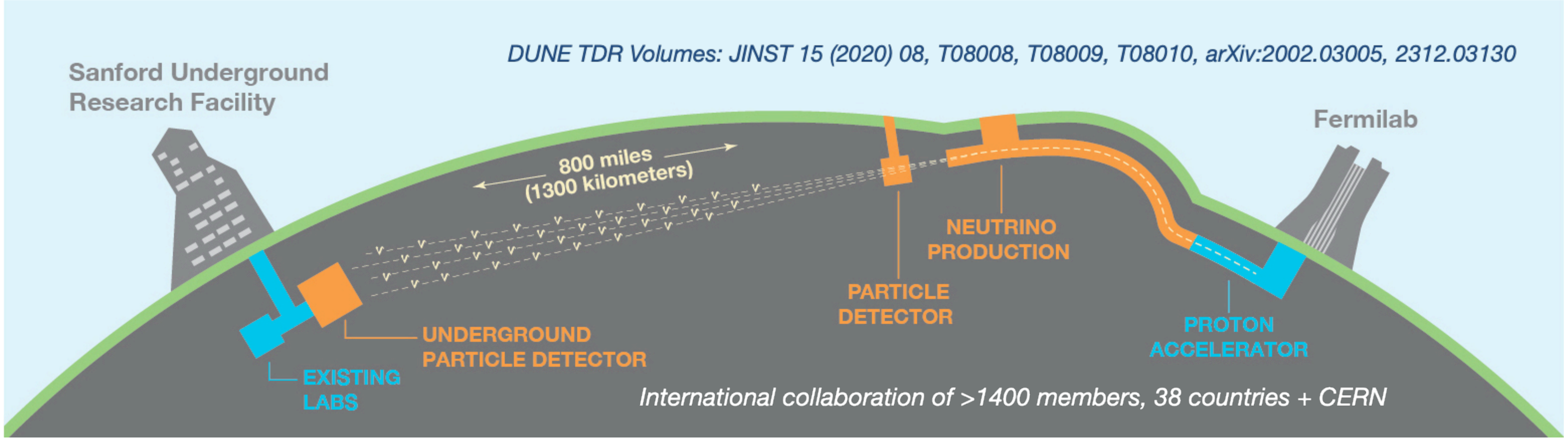

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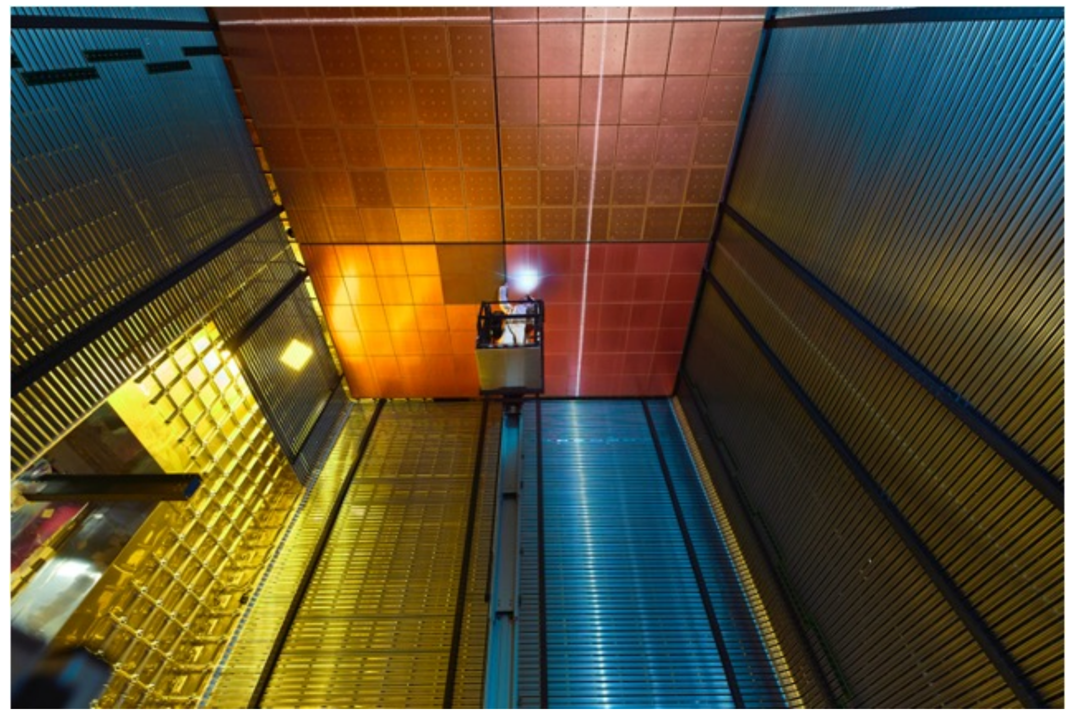
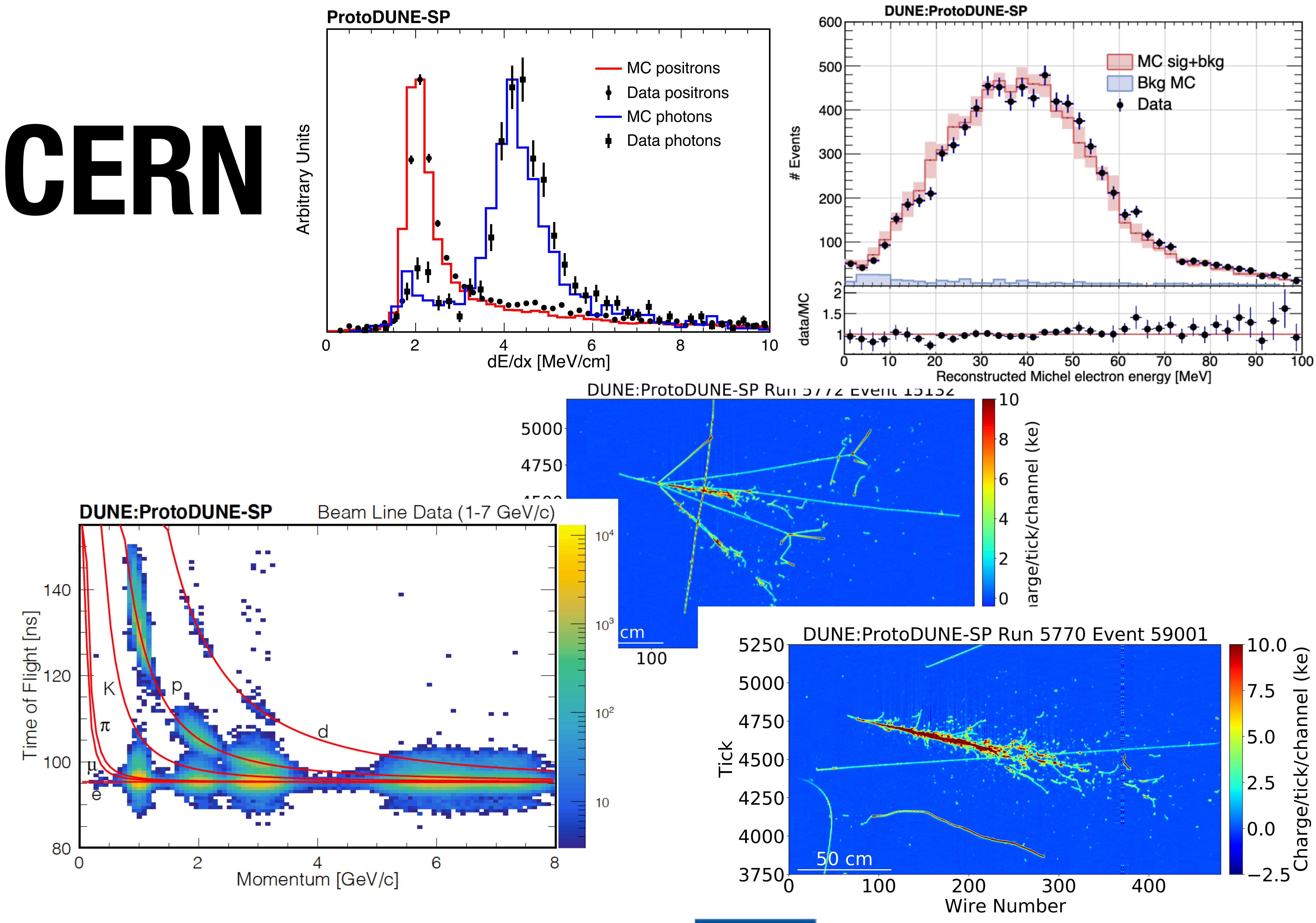
CERN Neutrino Platform

ProtoDUNEs operation at CERN

FIRST PHASE PROTODUNEs

- Construction and operation of ProtoDUNEs at CERN (2018 - 2020)
- Successful demonstration of the DUNE LAr TPC performance
- Several ongoing analyses (hadron-Ar cross sections…)





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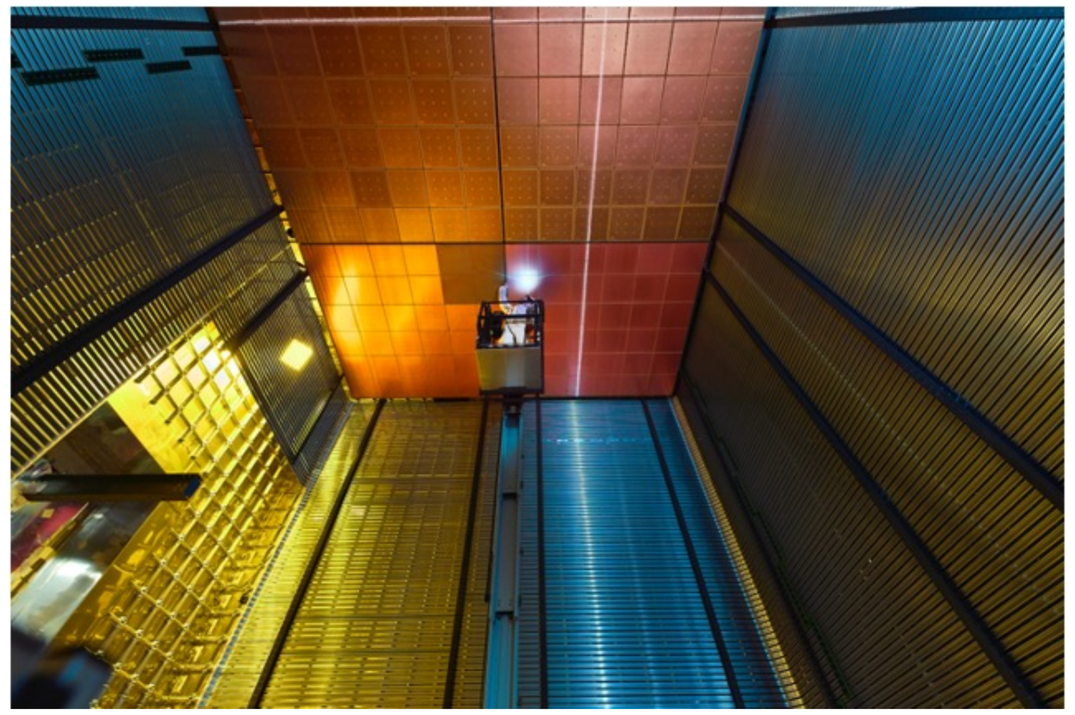
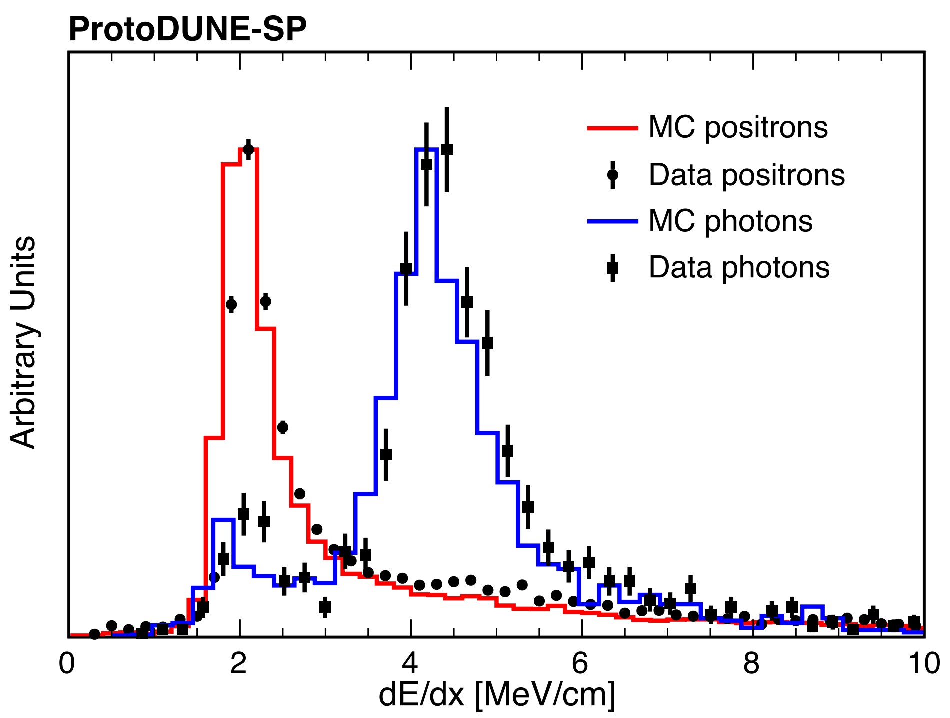
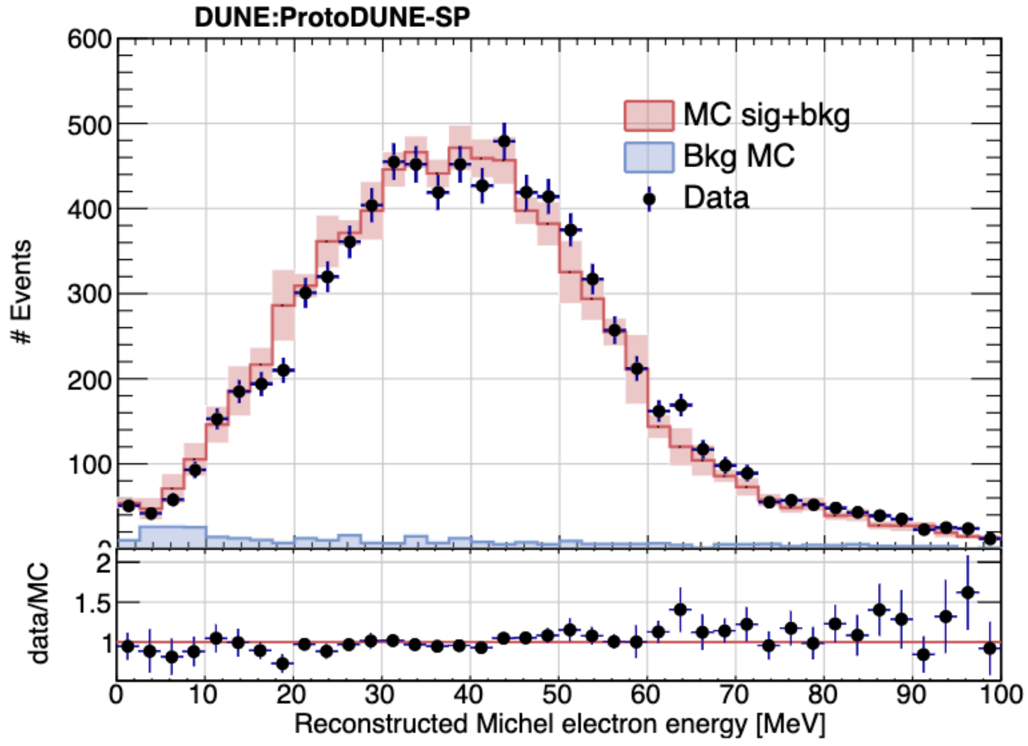
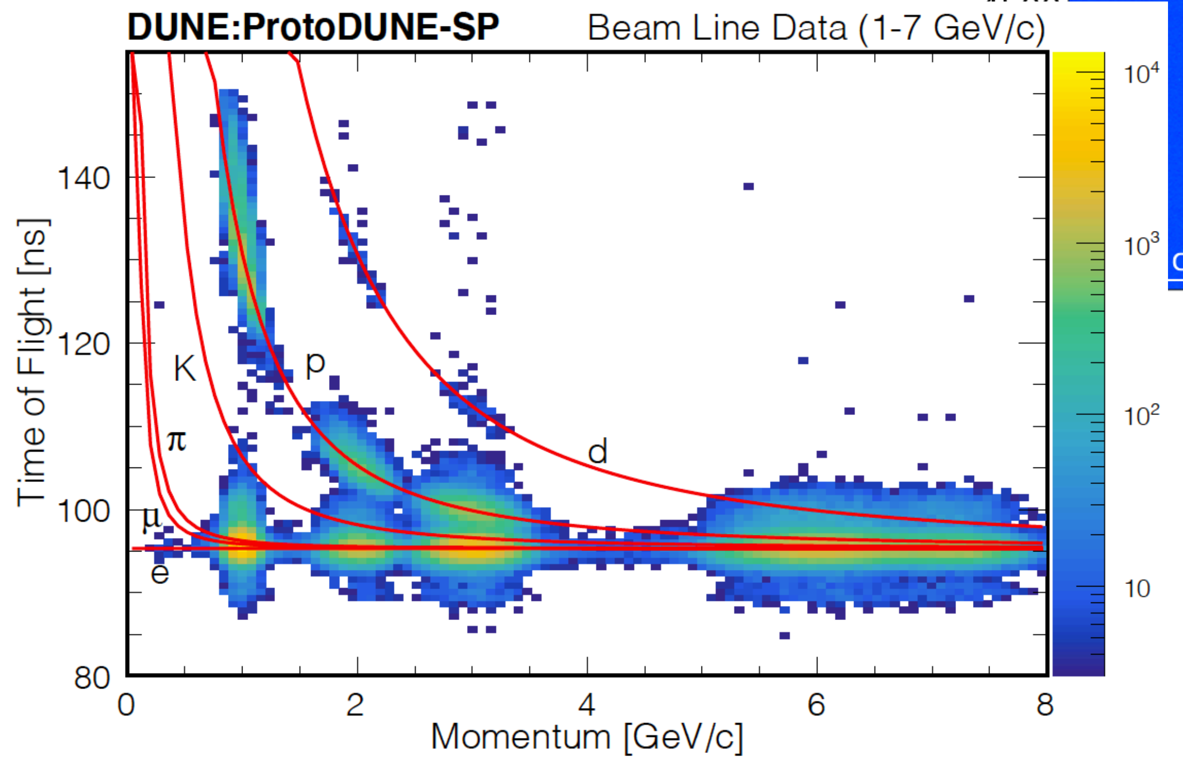
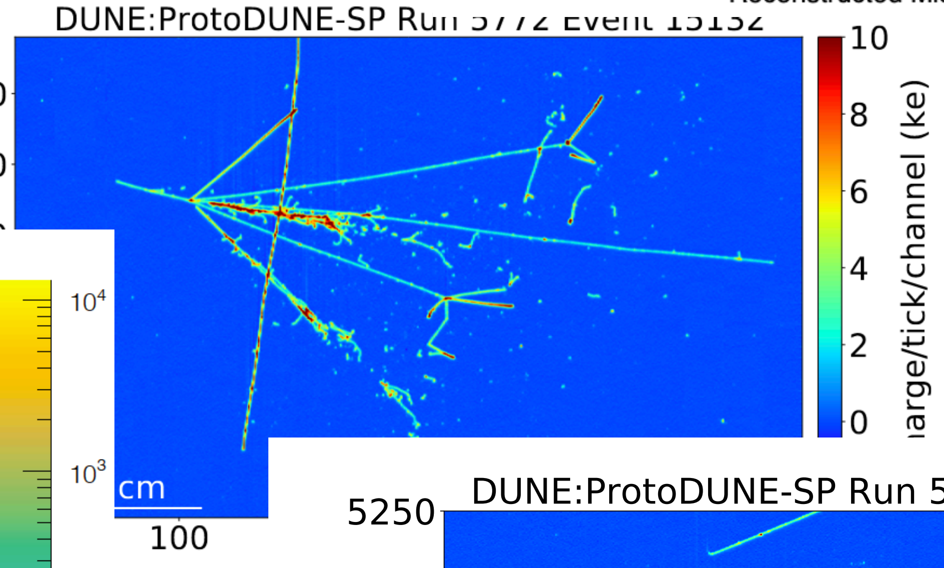
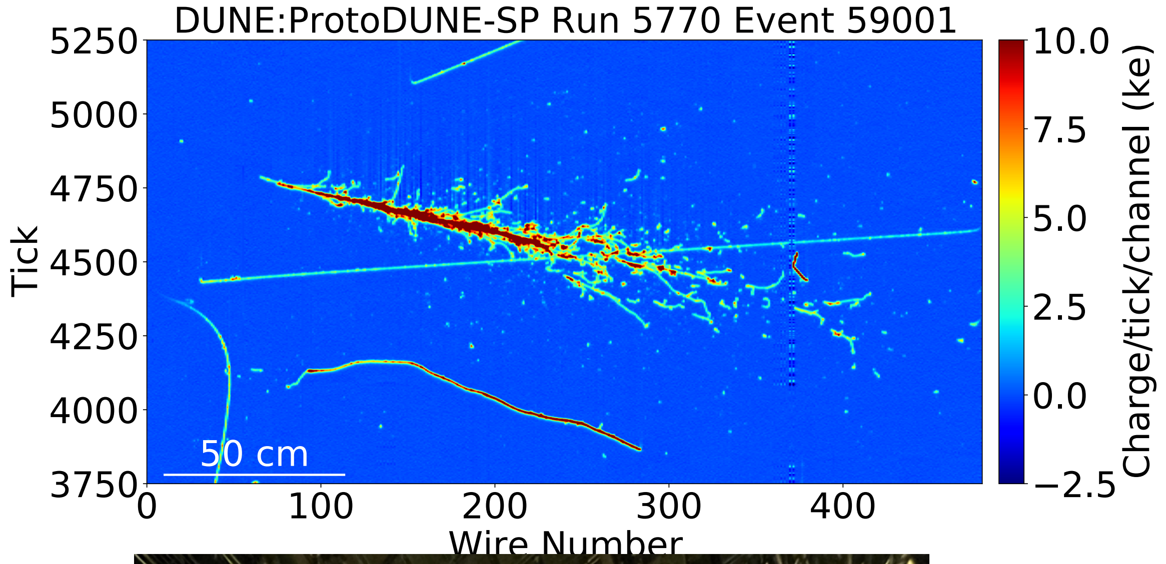






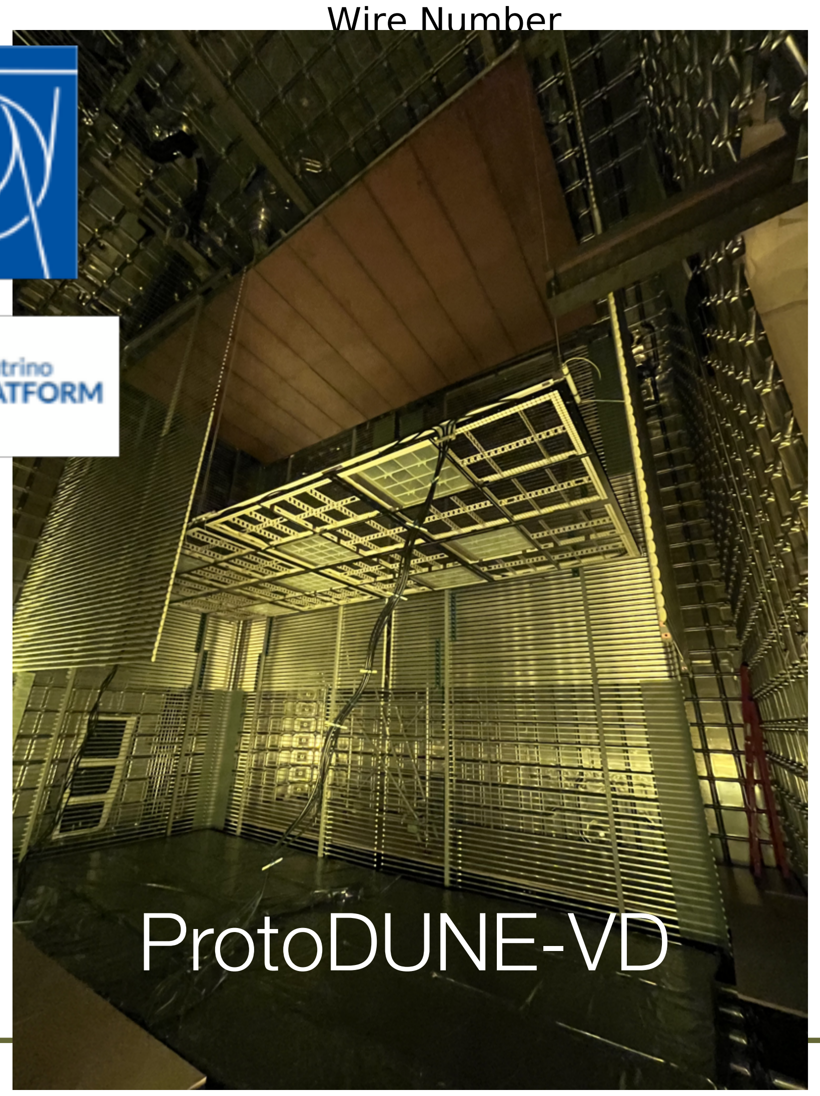






SECOND PHASE PROTODUNEs (2020-2023 construction + operation ≥2024)

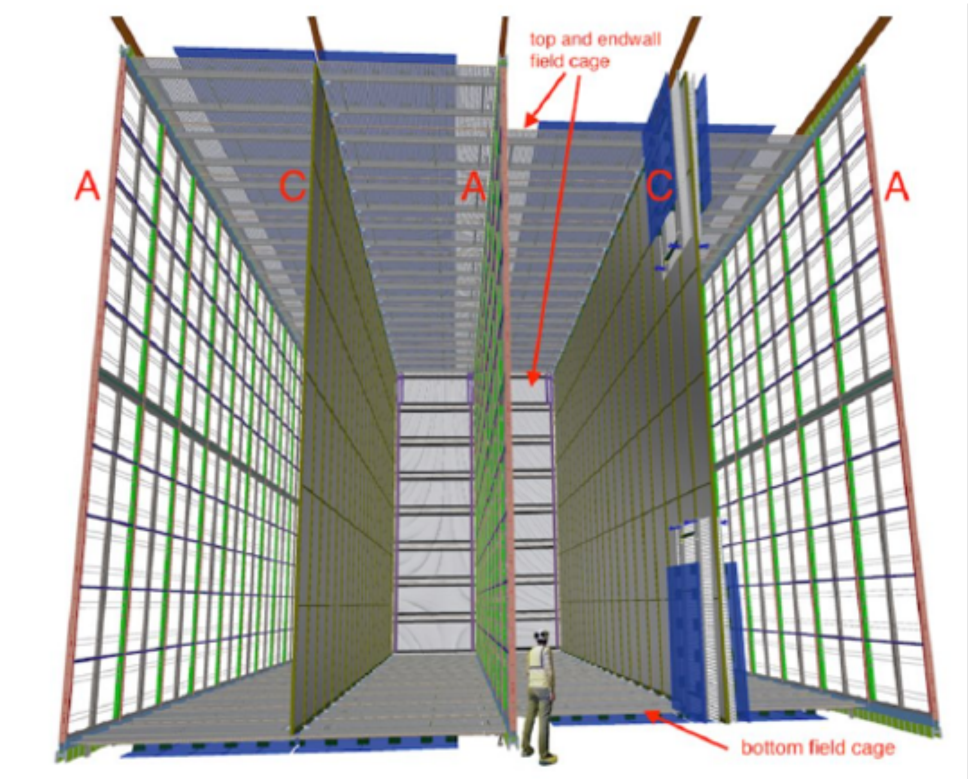
- ProtoDUNE-HD
  - ✦ Final technical solutions for all FD-HD subdetectors
  - ✦ Detector filled and currently taking data with charged-particle test-beam and cosmic muons at CERN
- ProtoDUNE-VD
  - ✦ Realization of a Module-0 detector in 2022-2023; LAr will be transferred to ProtoDUNE-VD in October for running starting in early 2025



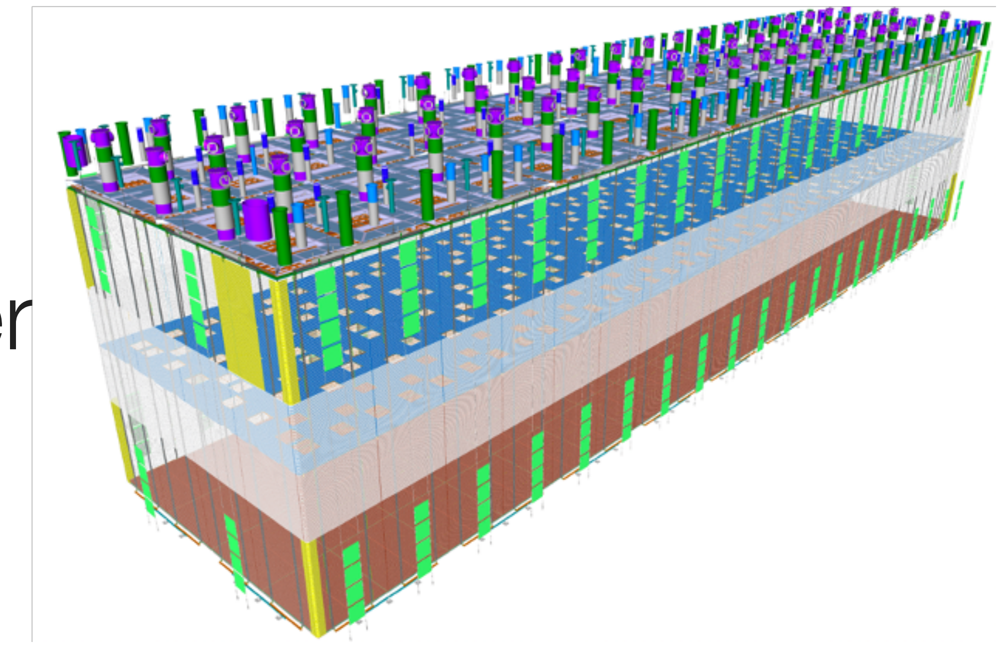
DUNE Phases

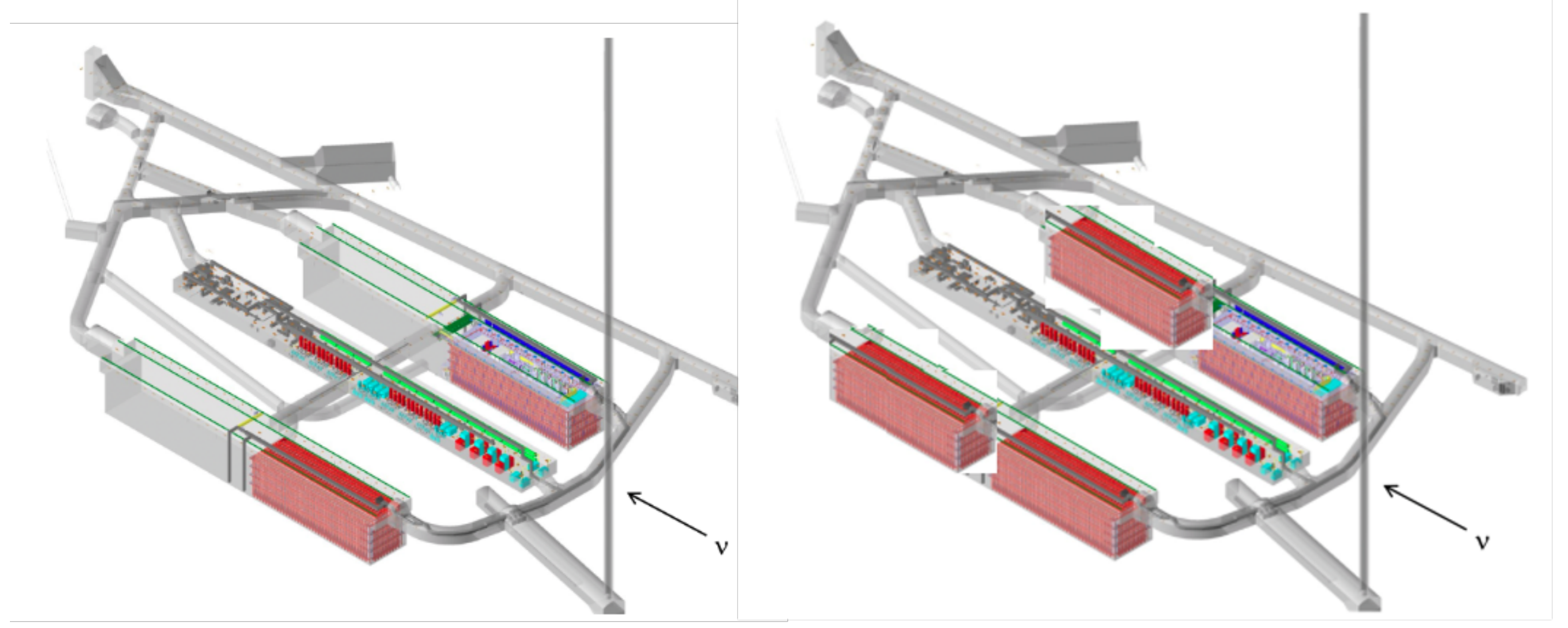
- **DUNE Phase I** (2026 start inst; 2029 physics; 2031 beam+ND)
  - ✦ Full near + far site facility and infrastructure
  - ✦ Two 17 kt LArTPC modules
  - ✦ Upgradeable 1.2 MW neutrino beamline
  - ✦ Movable LArTPC near detector with muon catcher
  - ✦ On-axis near detector
- **DUNE Phase II**:
  - ✦ Two additional FD modules (≥40 kt fiducial in total)
  - ✦ Beamline upgrade to >2 MW
  - ✦ More capable Near Detector (ND-GAr)

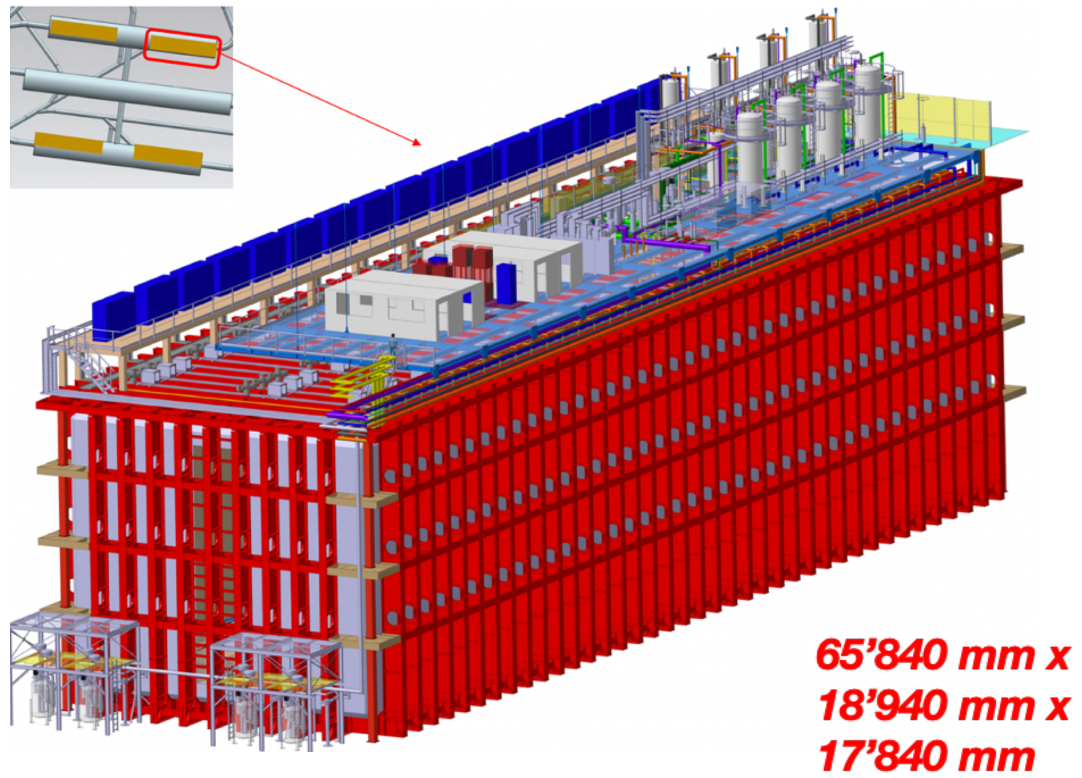
***FD-HD**: JINST 15 T08010 (2020)*



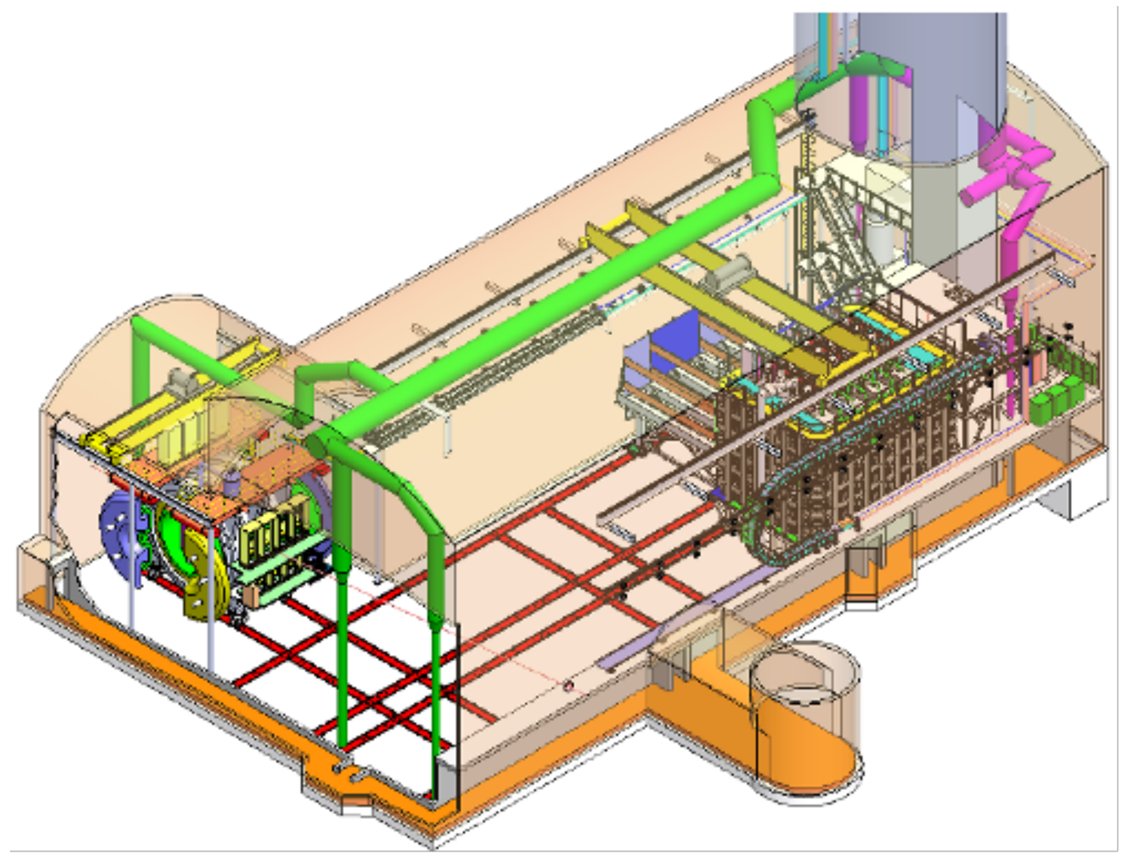
***FD-VD**: arXiv:2312.03130 (2023)*





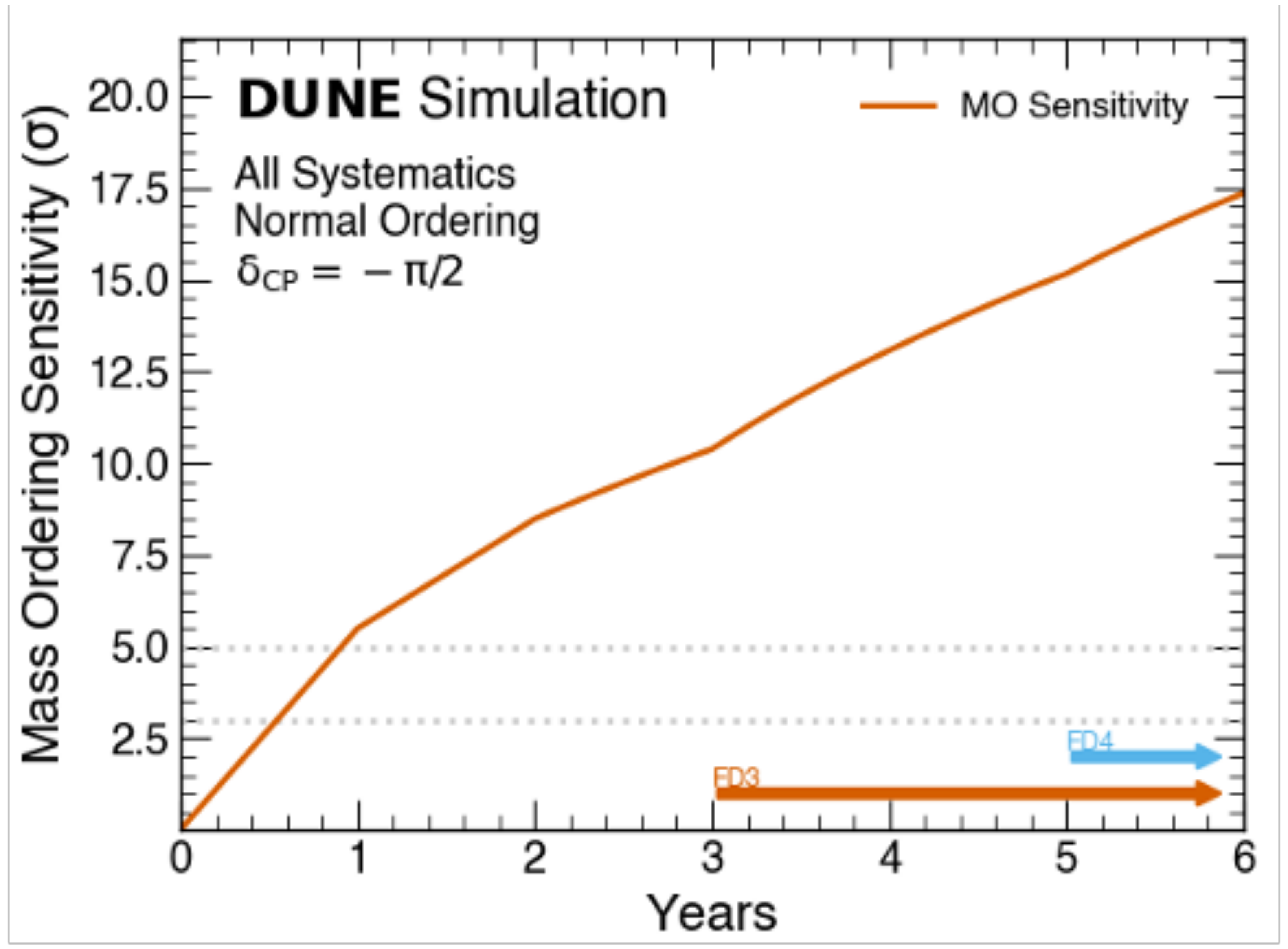


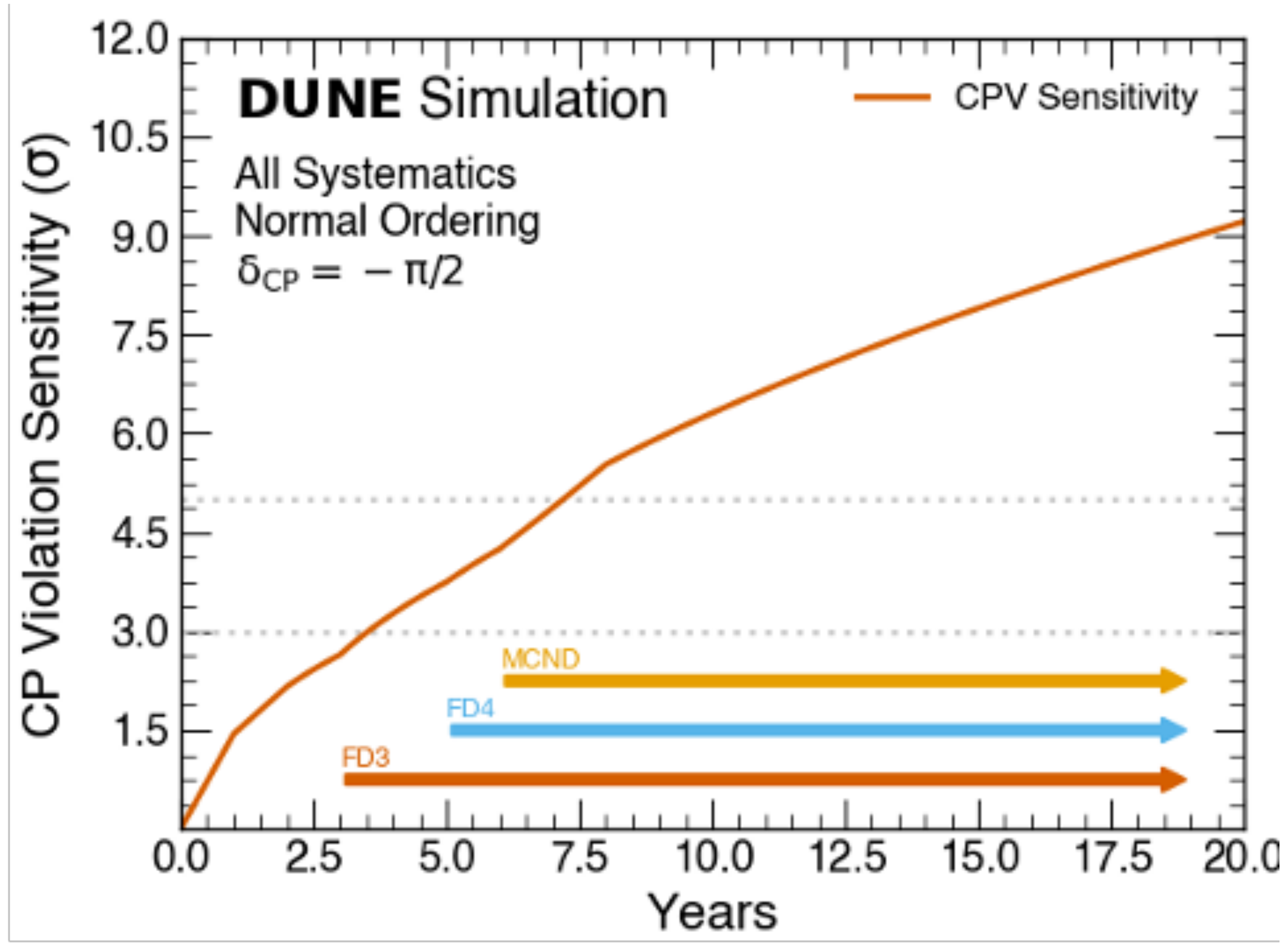
65'840 mm x 18'940 mm x 17'840 mm (L x W x H)

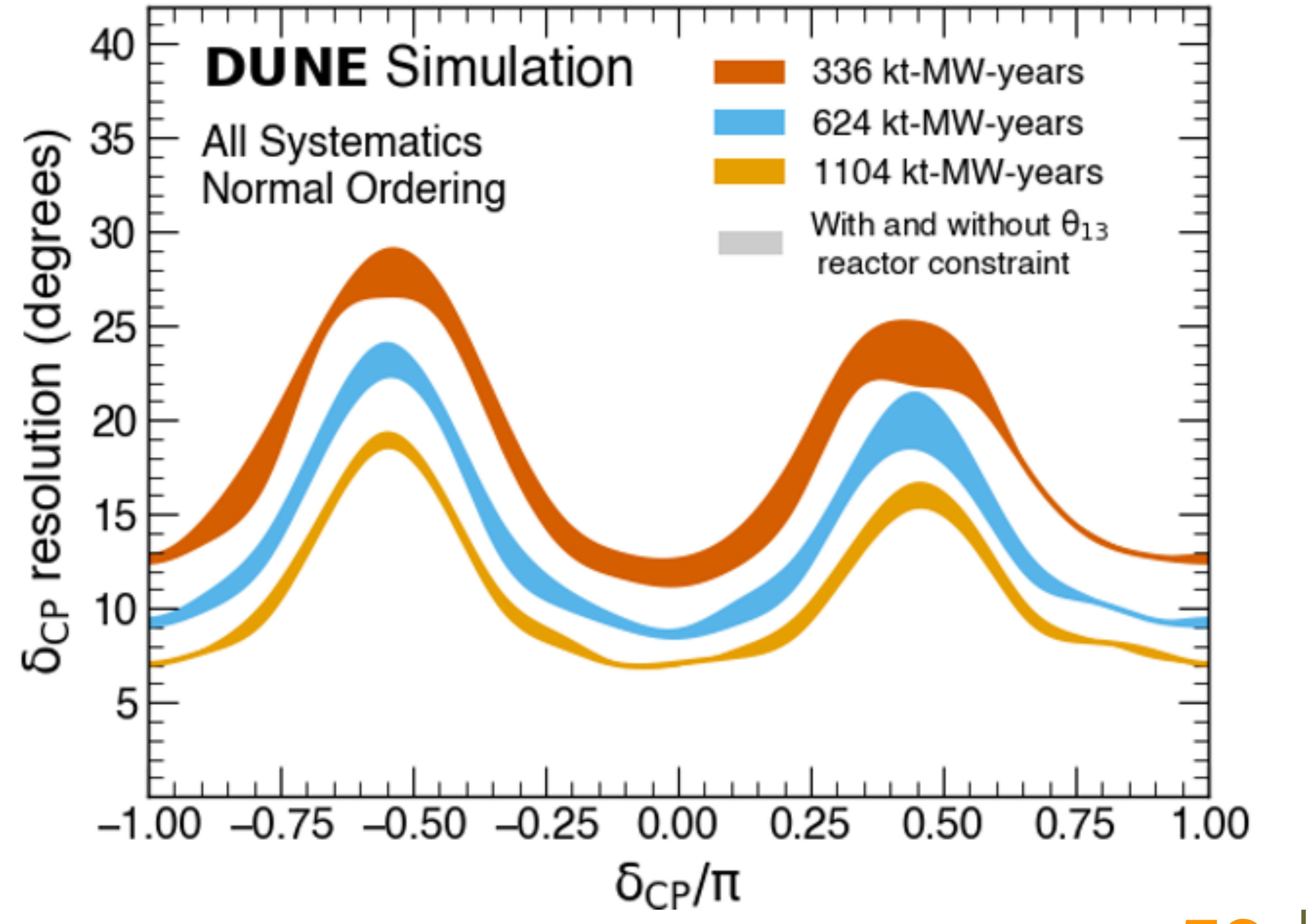


DUNE Physics Program

- DUNE can determine the neutrino **mass ordering** at 5σ in 1-3 years of data (depending on δ_{CP} value)
- Excellent resolution to θ_{23}
- **CP violation**: if maximal, 3σ (5σ) observation in 3.5y (7.5y); in long-term >3σ CPV for 75% of δ_{CP}; 6º-16º resolution
- Precise measurement of all oscillation parameters
- Supernova and solar neutrinos + BSM (NSI, non-unitary mixing, dark matter, sterile neutrinos, nucleon decay,…)







Neutrino mass

Neutrino mass measurements

From oscillations: $m_\nu > 0.05$ eV

- **Direct measurements**:

  Tritium beta decay experiments:

  - ✦ KATRIN 2022: **m < 0.8 eV (90% CL)**
  - ✦ KATRIN (goal): m < 0.3 eV (90% CL) in 2026

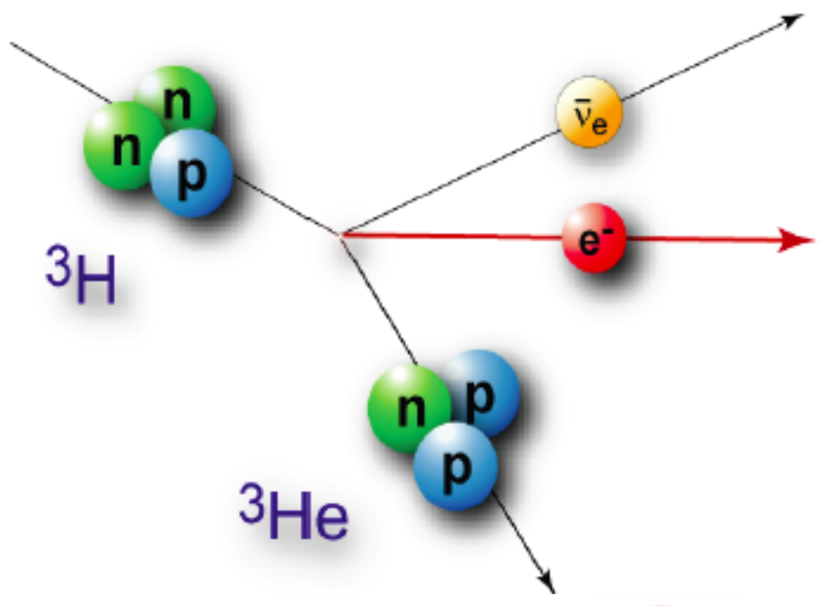
- **Neutrinoless double beta decay**:

  - ✦ If measured, neutrinos are Majorana particles
  - ✦ GERDA, EXO, CUORE, CUPID, NEMO-3, KamLAND-Zen: **$m_{\beta\beta}$ < 28-122 meV (90% CL)**
  - ✦ Future ton scale: $m_{\beta\beta}$ < 10 meV (only IO)

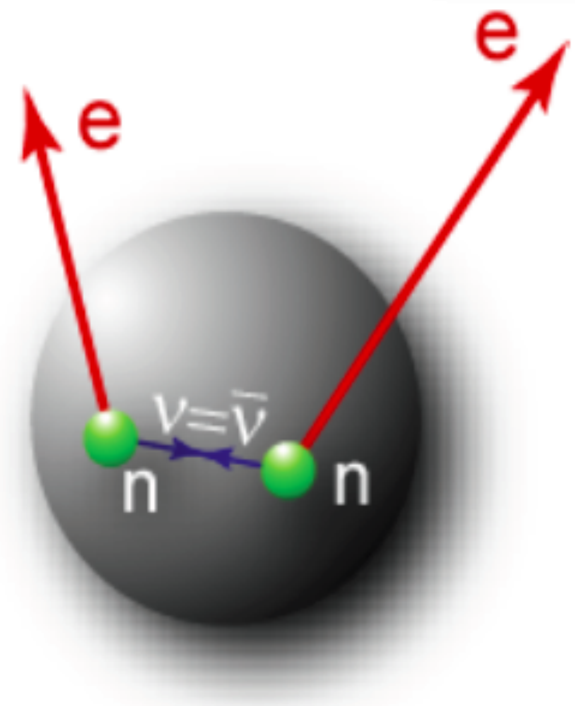
- **Indirect measurements (Cosmology)**:

  PLANCK 2018: A&A 641 (2020) A6

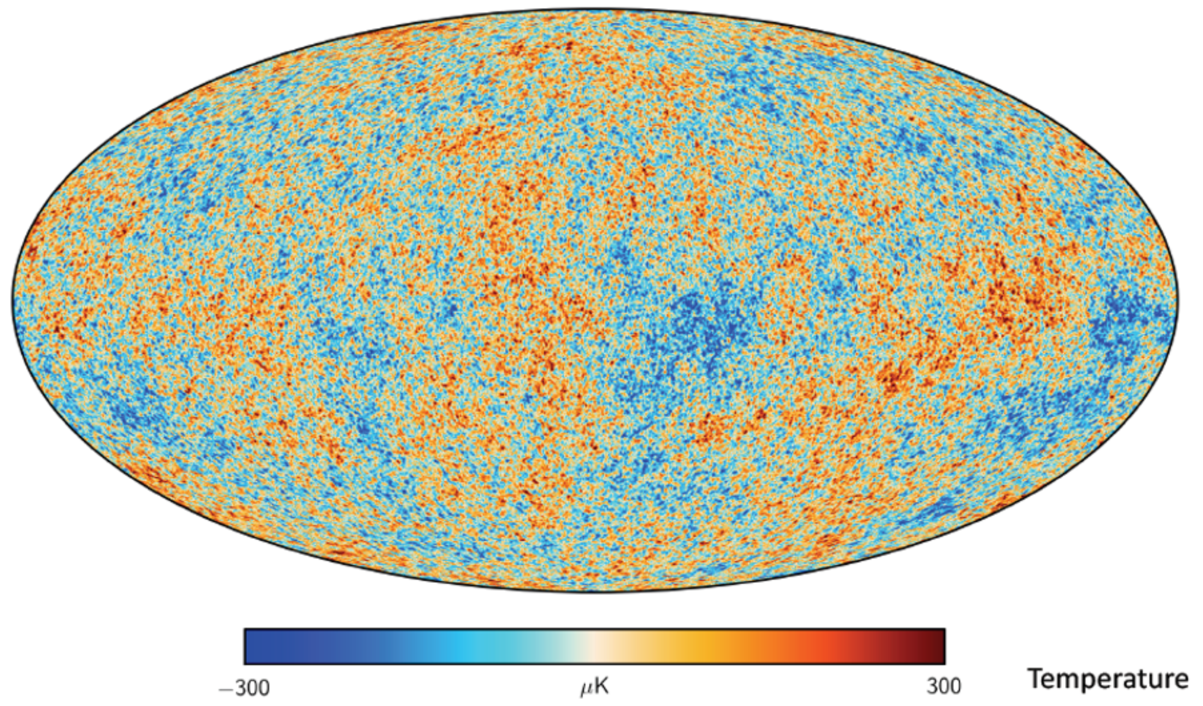
  - ✦ **$\sum m_\nu$ < 0.12 eV** (Planck TT,TE,EE +low E +lensing +BAO)
  - ✦ $N_{eff} = 2.99^{+0.34}_{-0.33}$ (Planck TT,TE,EE +low E +lensing +BAO)



$$m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$$

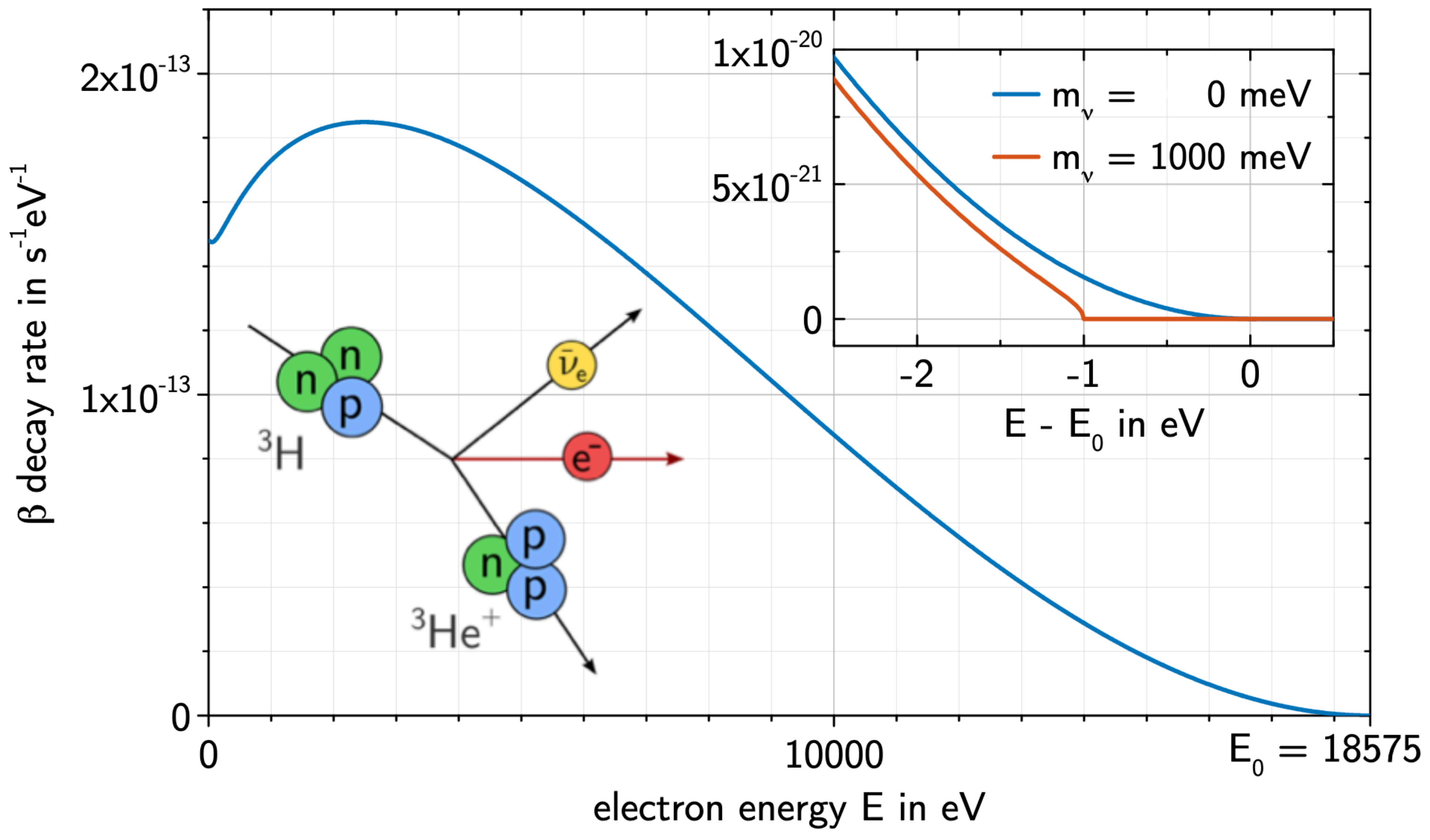


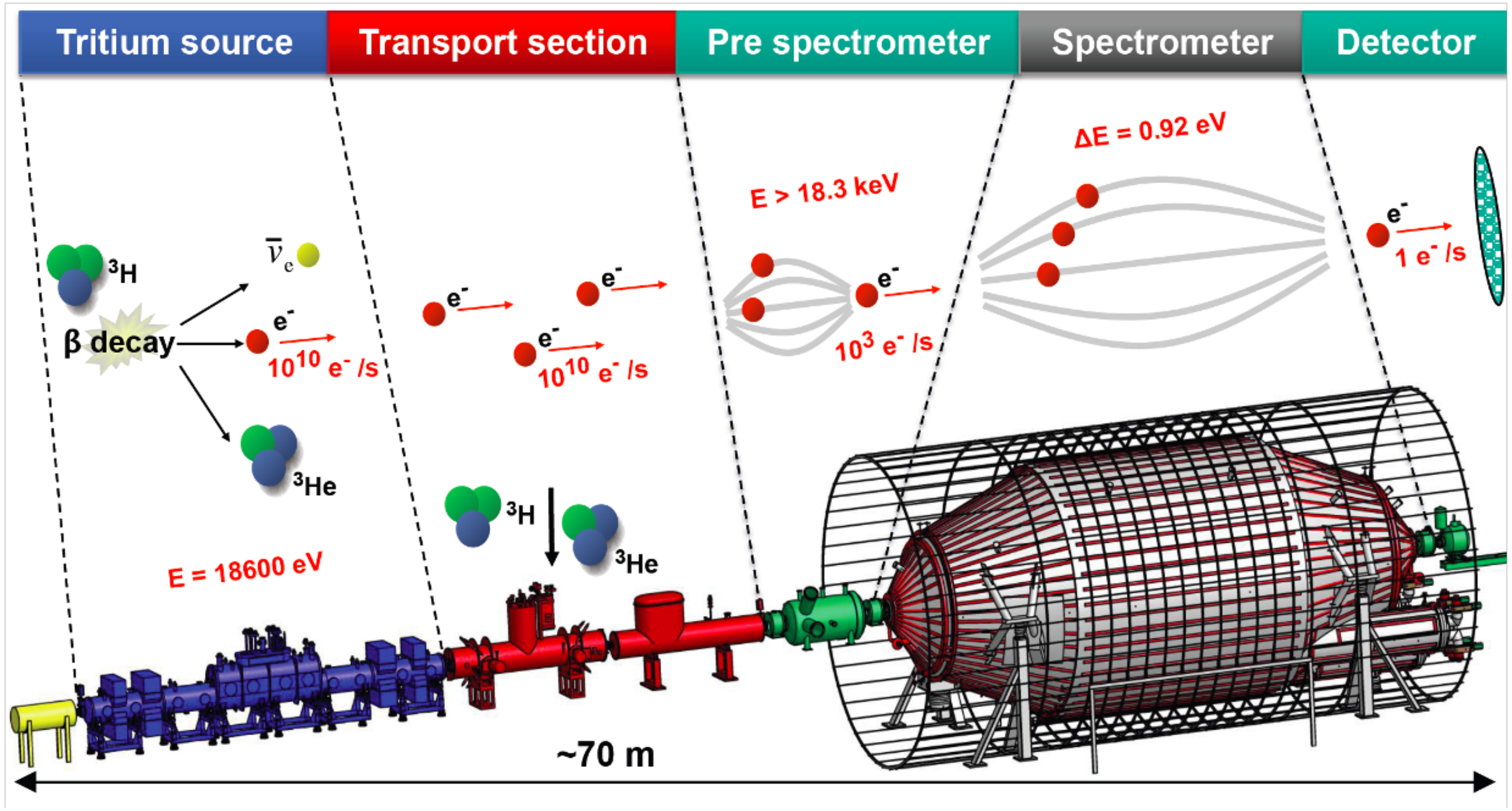
$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \cdot m_{\nu_i} \right|$$



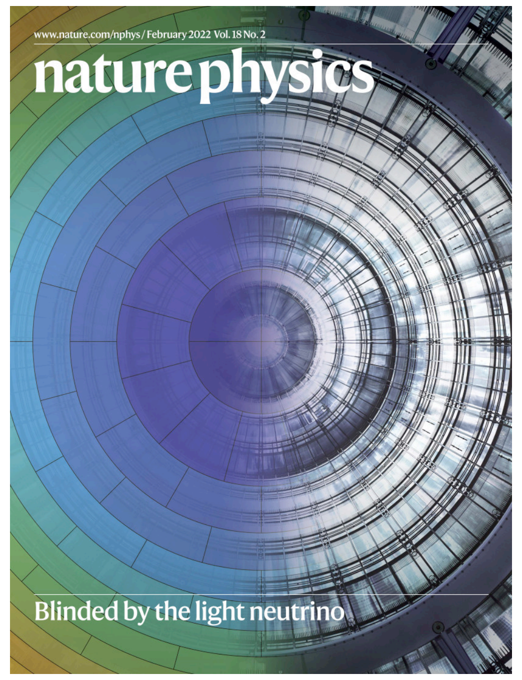
$$m = \sum_i m_{\nu_i}$$

Status of KATRIN



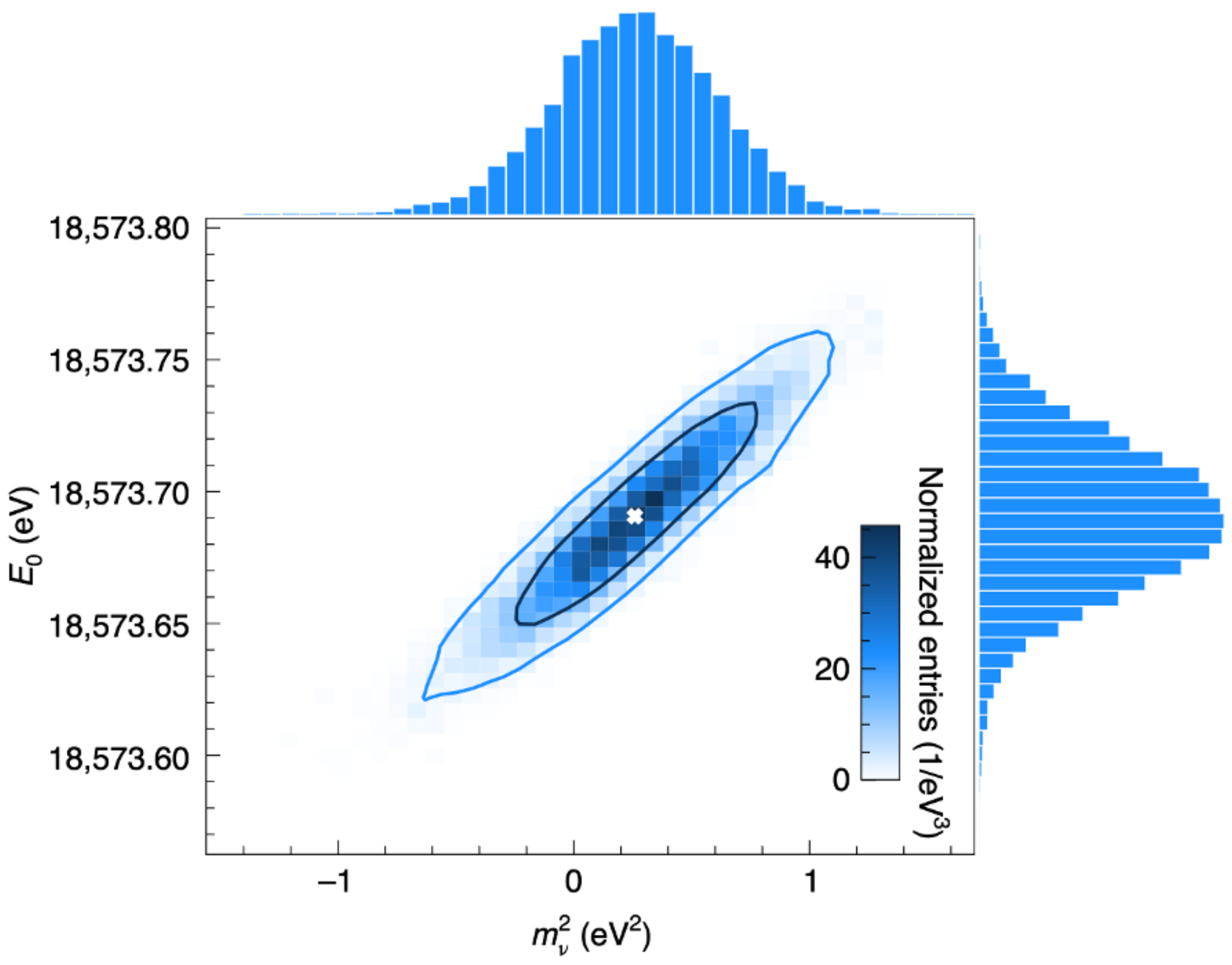


New KATRIN result (2024)

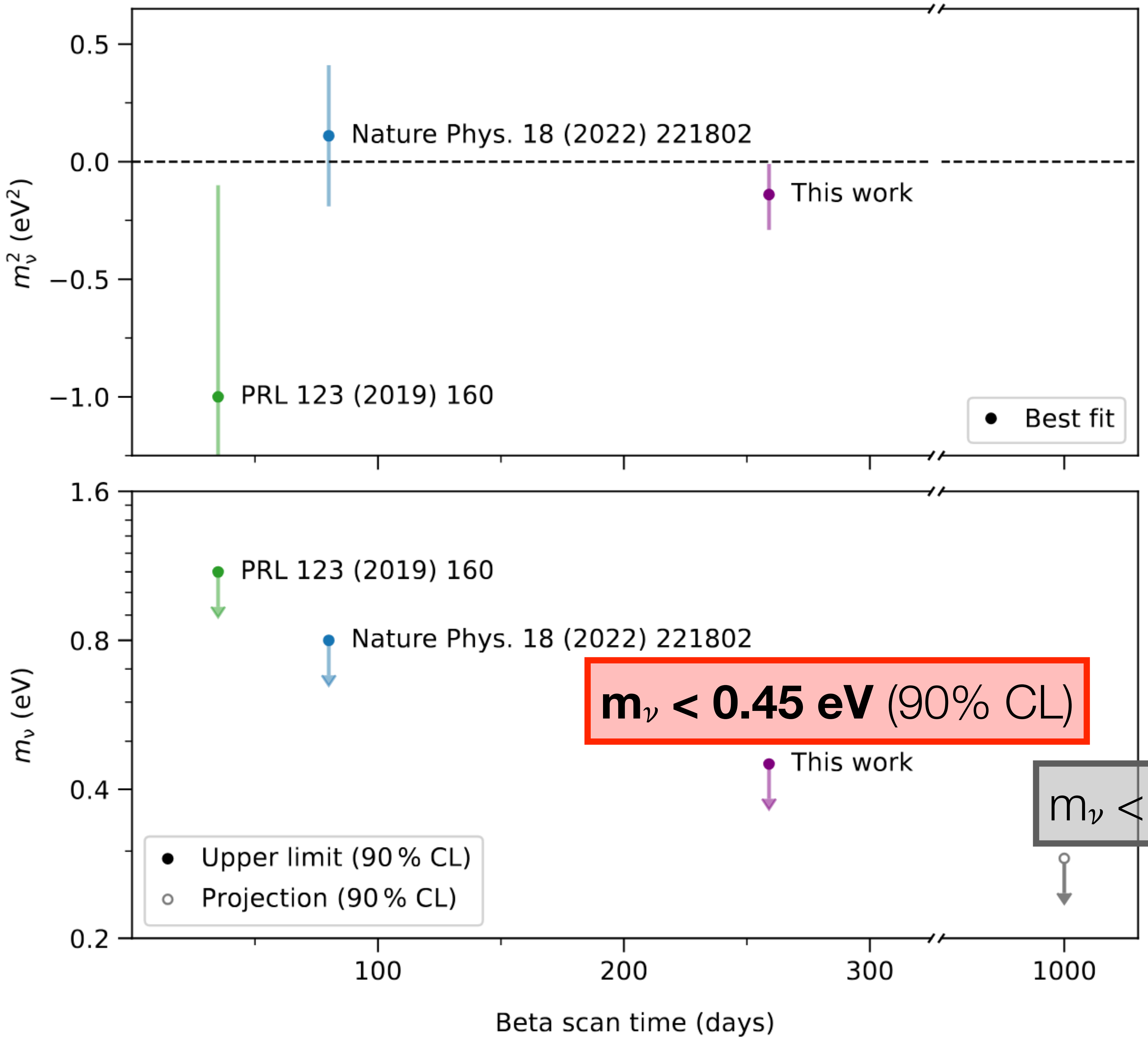


Nature Physics 18, 160-166 (2022)

$m_\nu < 0.8$ eV (90% CL)



KATRIN arXiv:2406.13516 (2024)



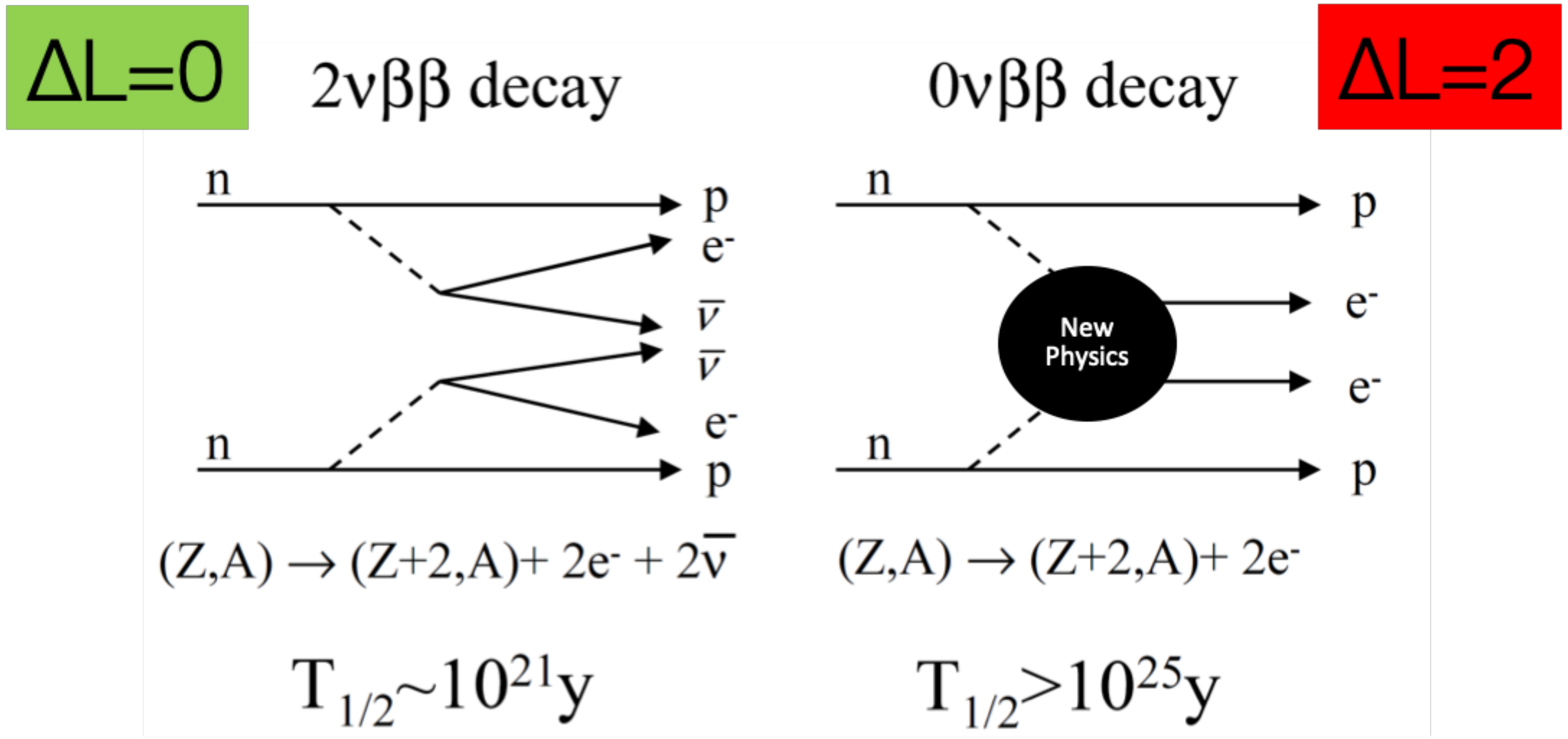
m_ν < 0.45 eV (90% CL)

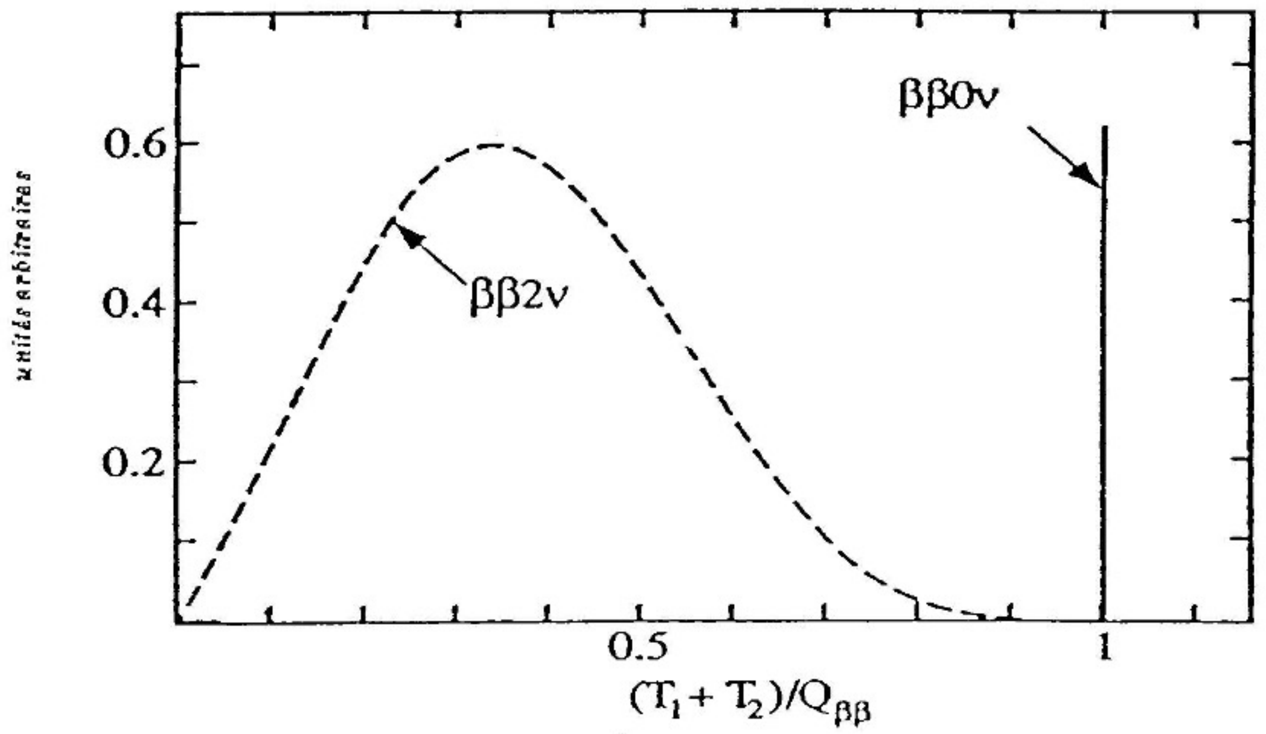
Final goal

$m_\nu < 0.3$ eV (90% CL)

Other technologies (cyclotron radiation: Project-8; micro-calorimetry with holmium: ECHo, Holmes) **under development**

Neutrinoless double beta decay





In the light-neutrino exchange model, $0\nu\beta\beta$ decay half-life:

$$T_{1/2}^{0\nu} = \left(G\,|\mathcal{M}|^2\,\langle m_{\beta\beta}\rangle^2\right)^{-1}$$

Phase space

Nuclear matrix elements

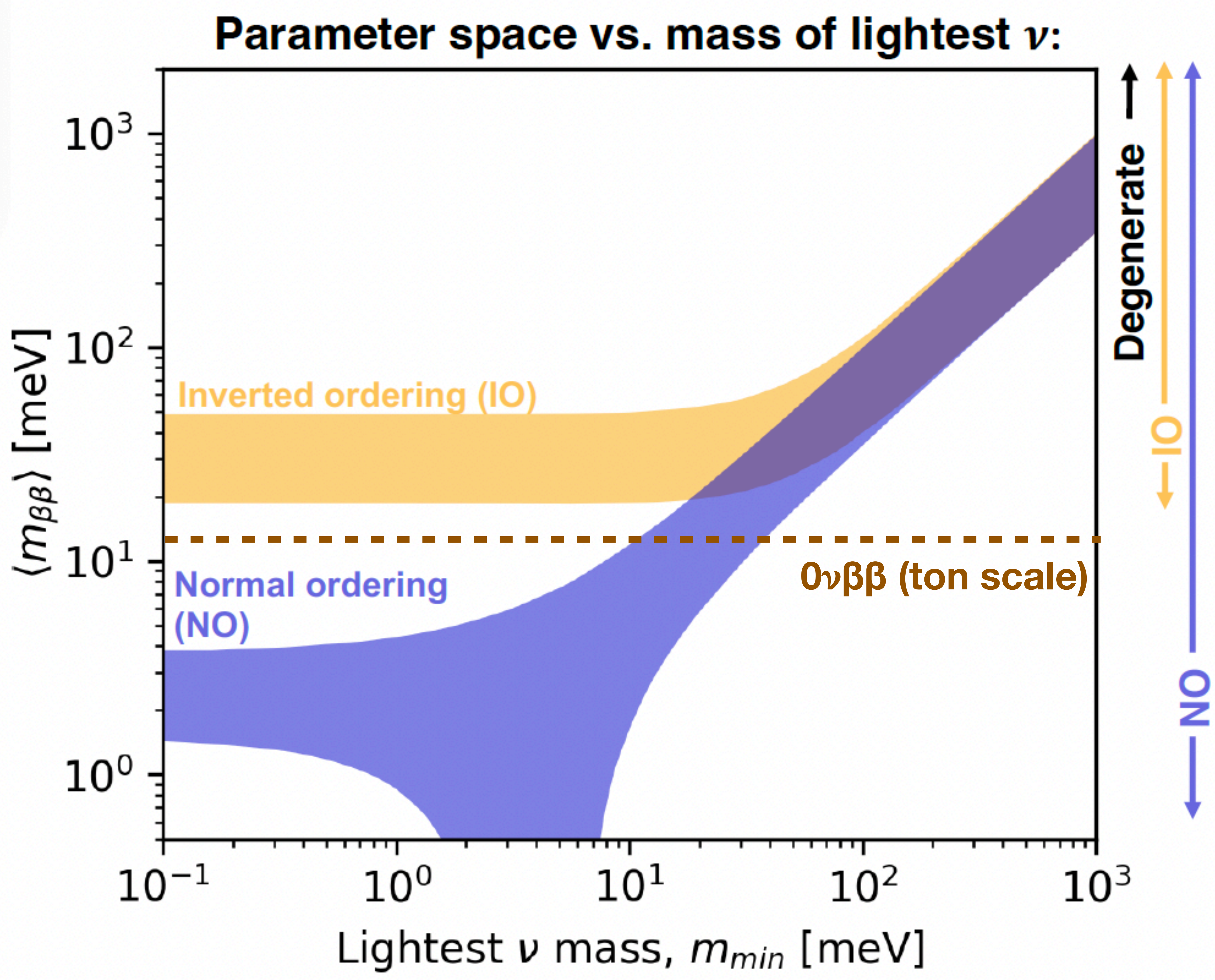
Effective Majorana neutrino mass

$$m_{\beta\beta} = \left|\sum_i U_{ei}^{\ 2} \cdot m_{\nu_i}\right|$$

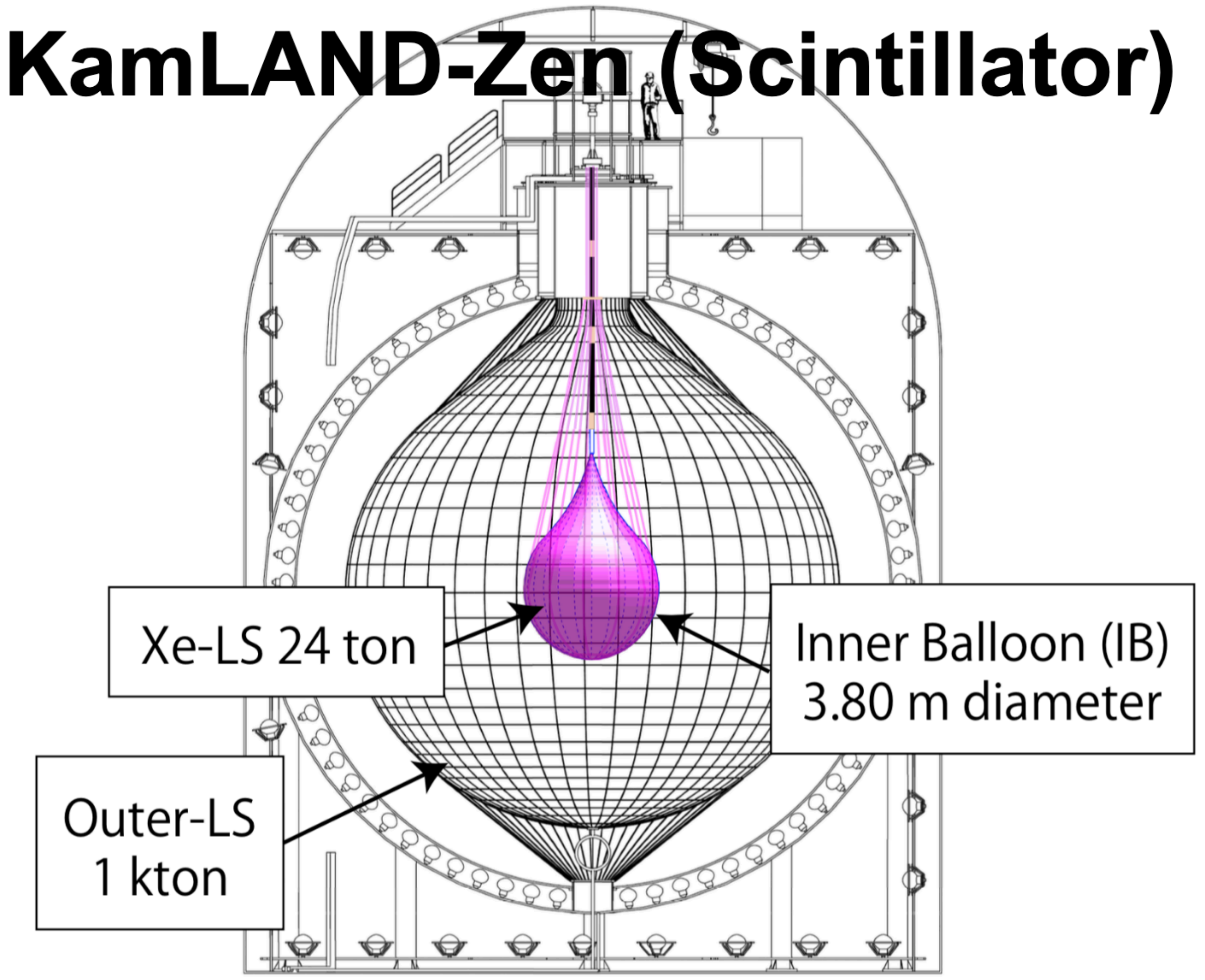
$$\boxed{m_{\beta\beta} \equiv \left|m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-\delta)}\right|}$$

- **2νββ** has been observed in more than 10 isotopes (lifetimes $10^{18} - 10^{21}$ y)
- **0νββ** has not been observed yet (lifetimes > $10^{25} - 10^{26}$ y):
    - ✦ It would imply **total lepton number violation** (LNV) and **neutrino Majorana mass**
    - ✦ Different mechanisms are possible: SUSY, leptoquarks, extradimensions, Majorons, …
    - ✦ Most discussed mechanism: **light Majorana neutrino exchange**

Current status of $0\nu\beta\beta$ searches



KamLAND-Zen (Scintillator)



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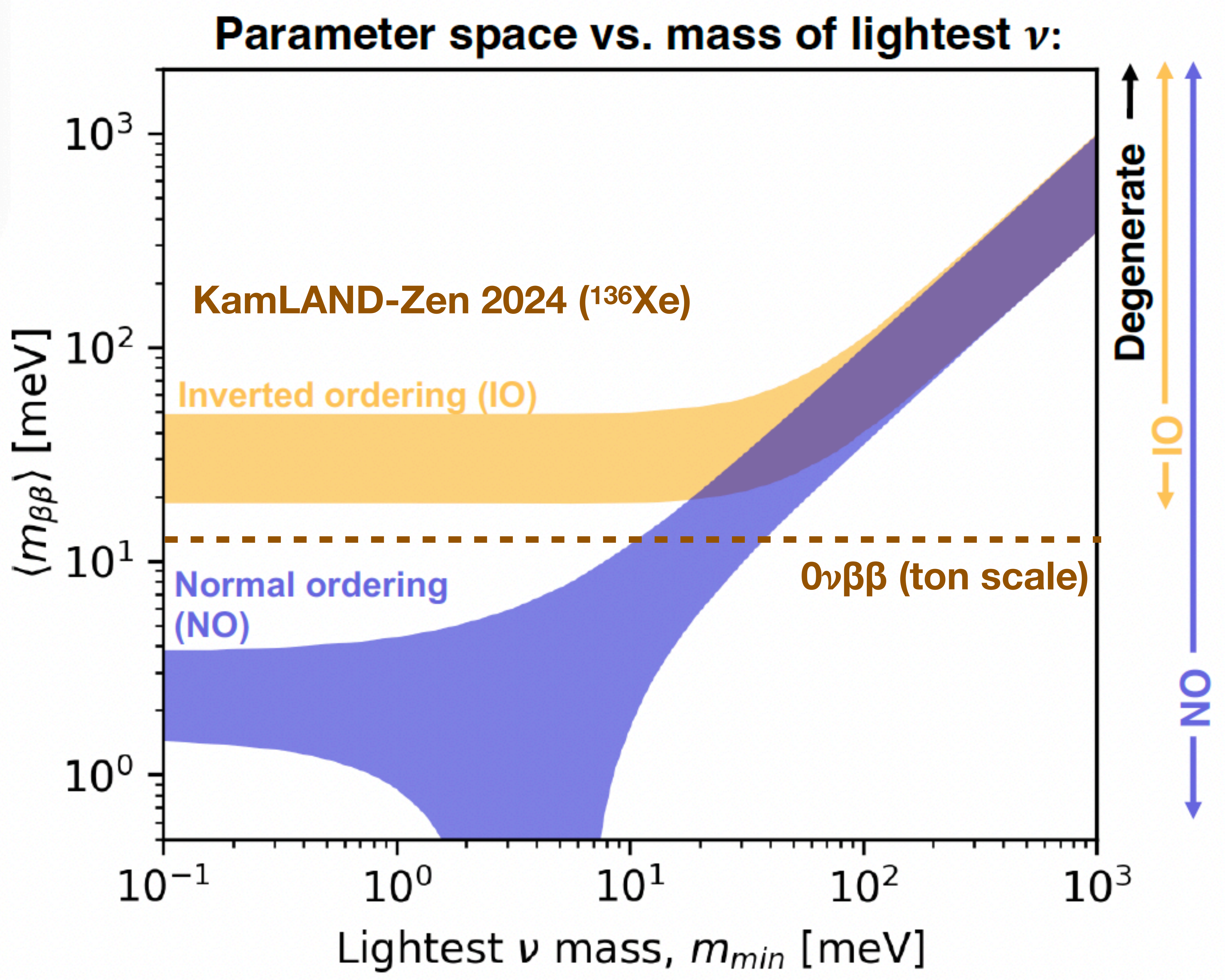

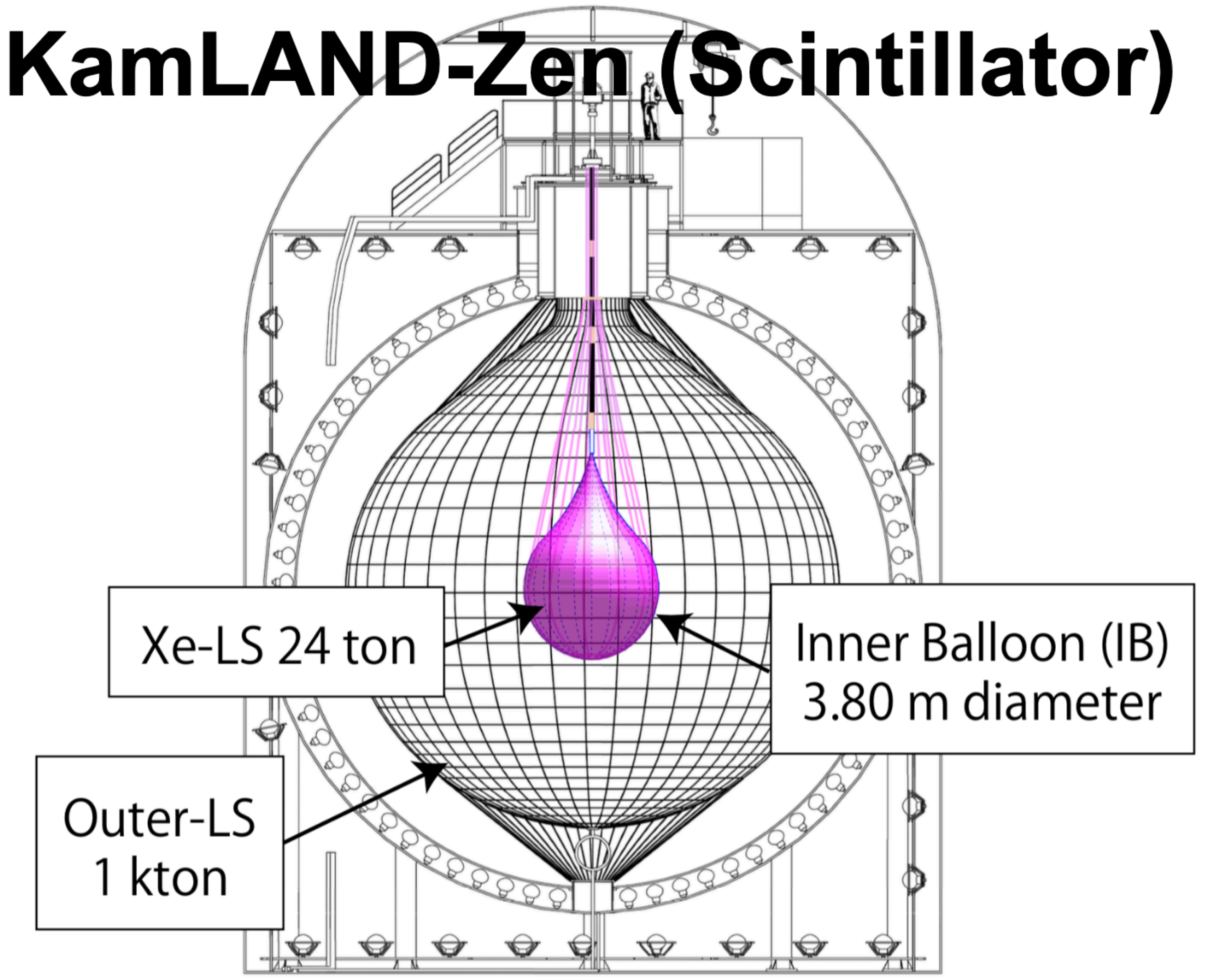

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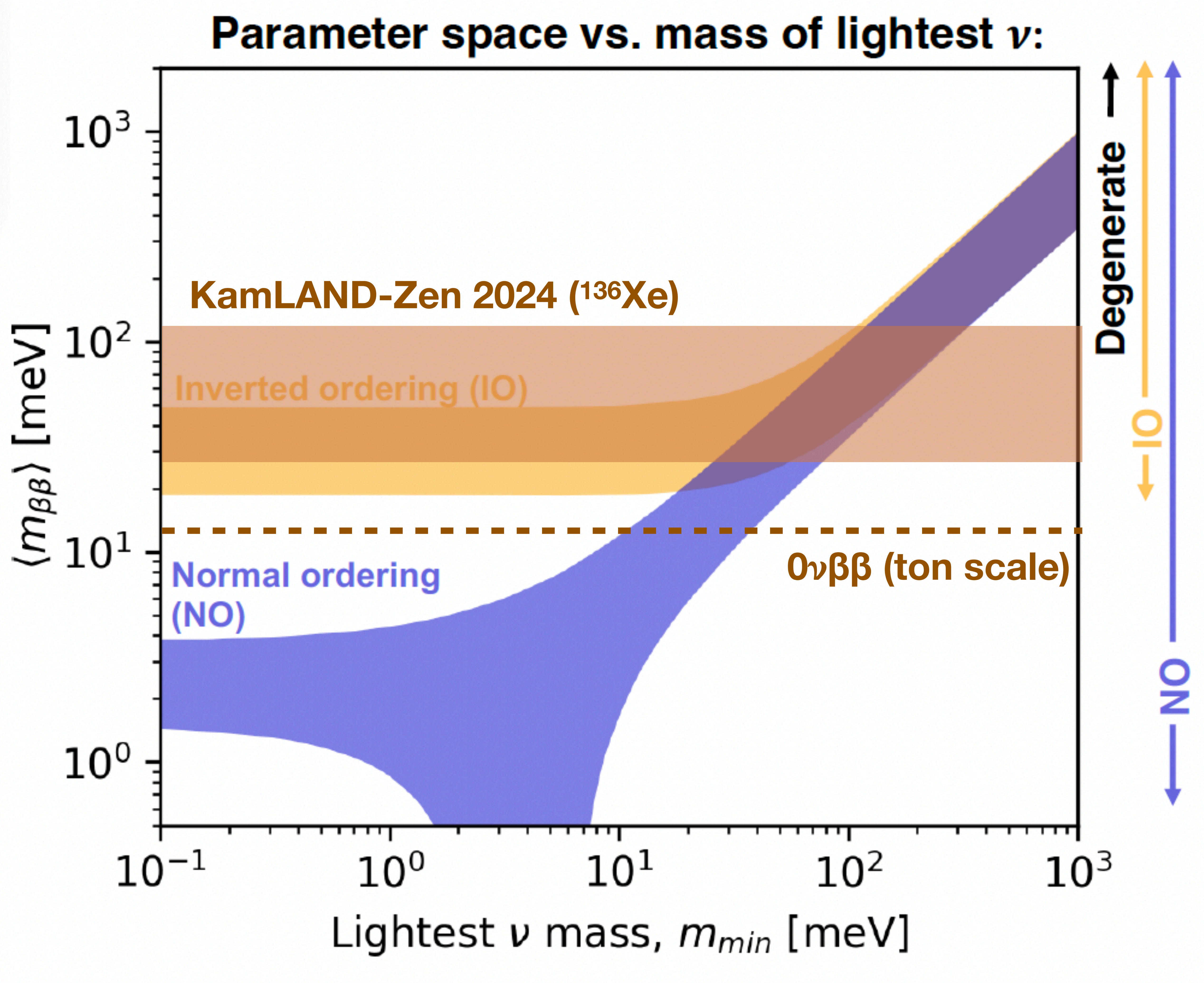

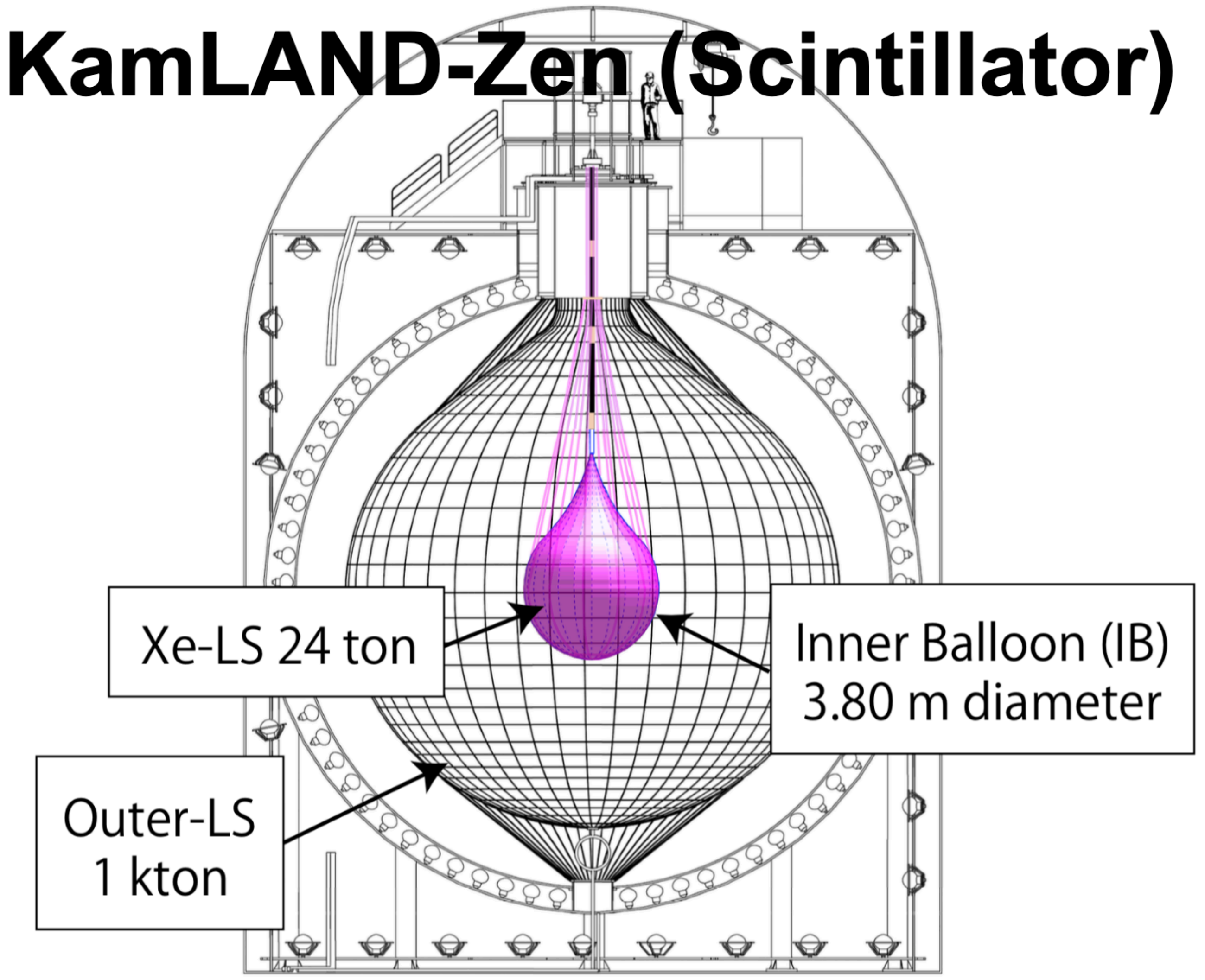

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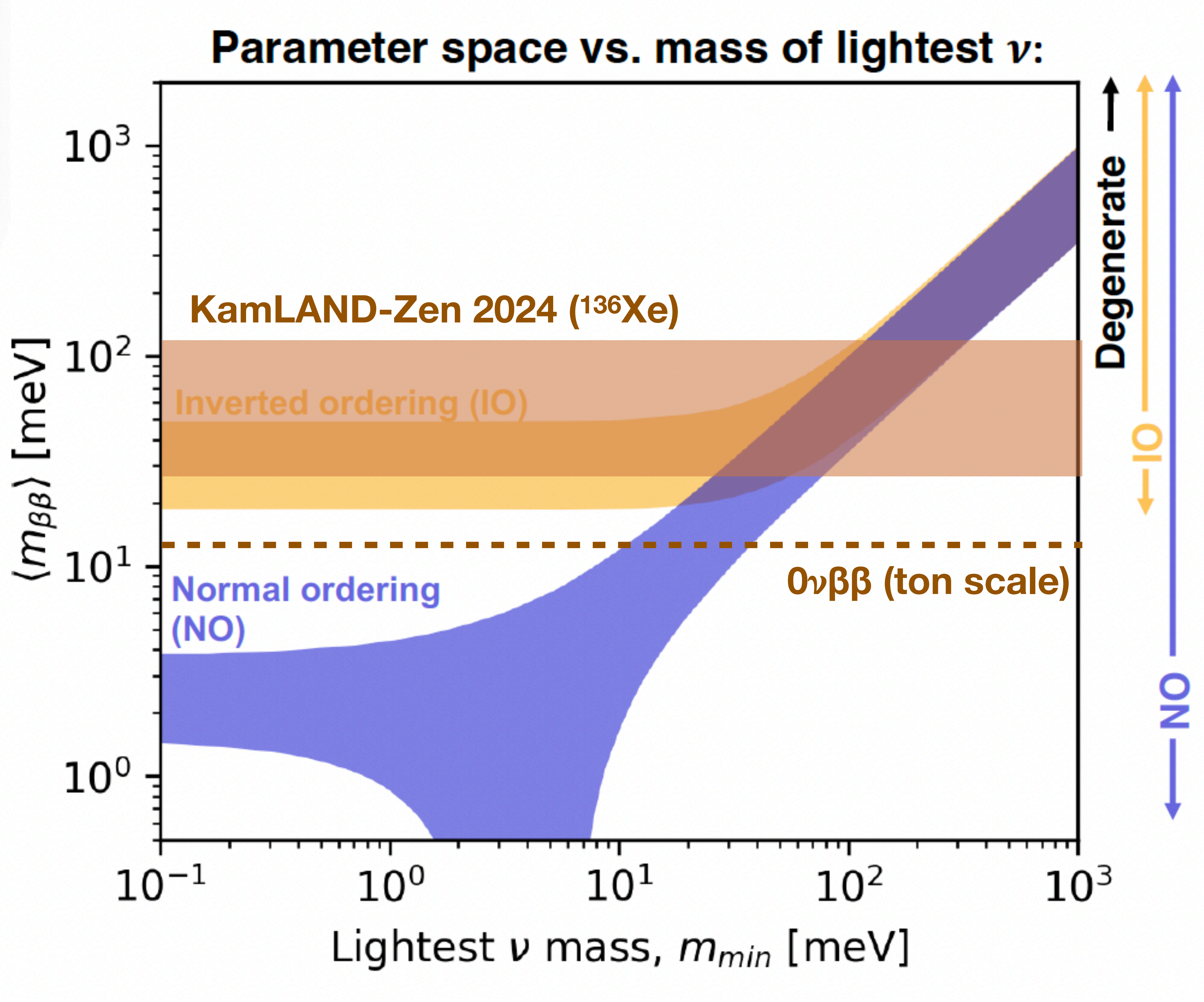
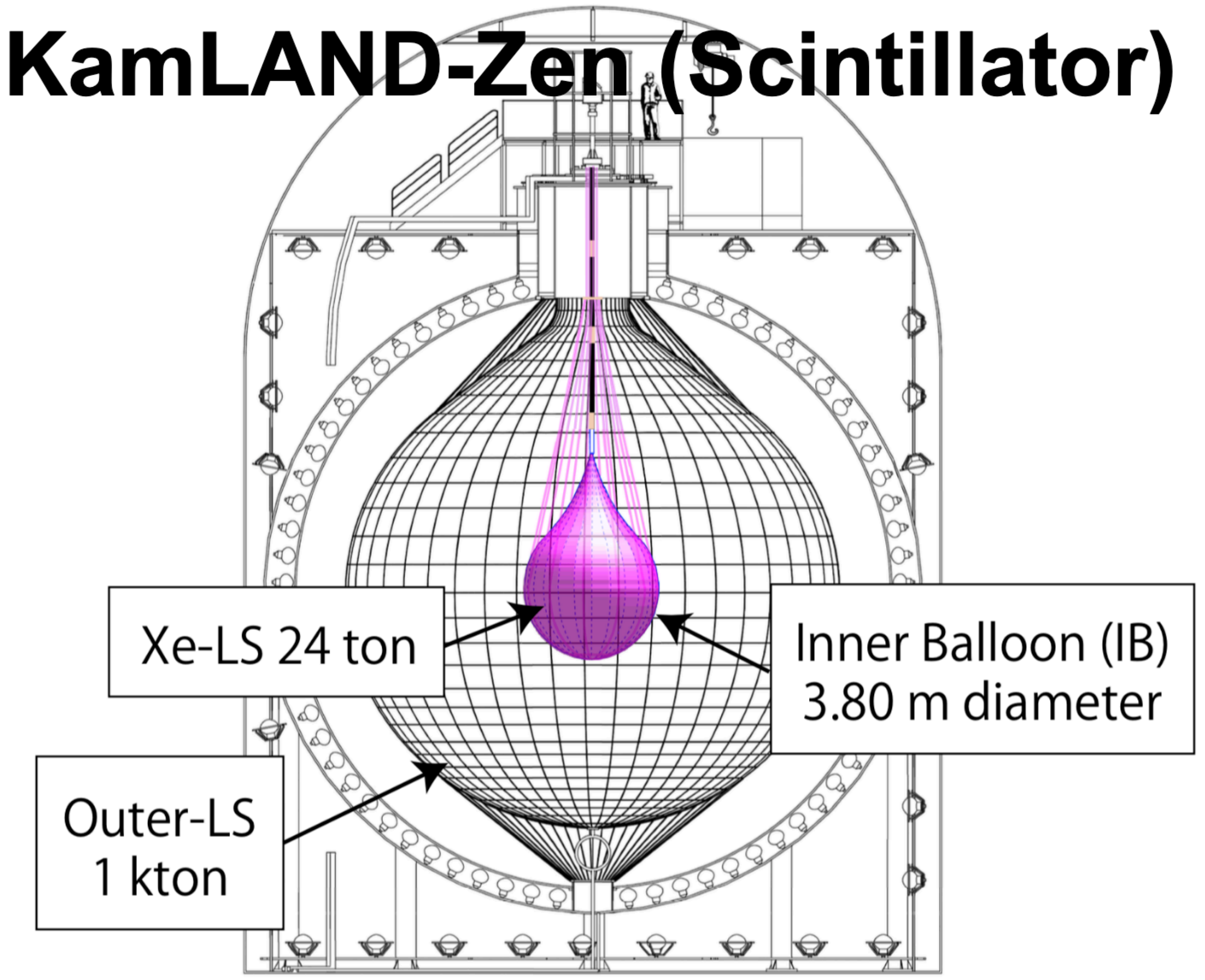


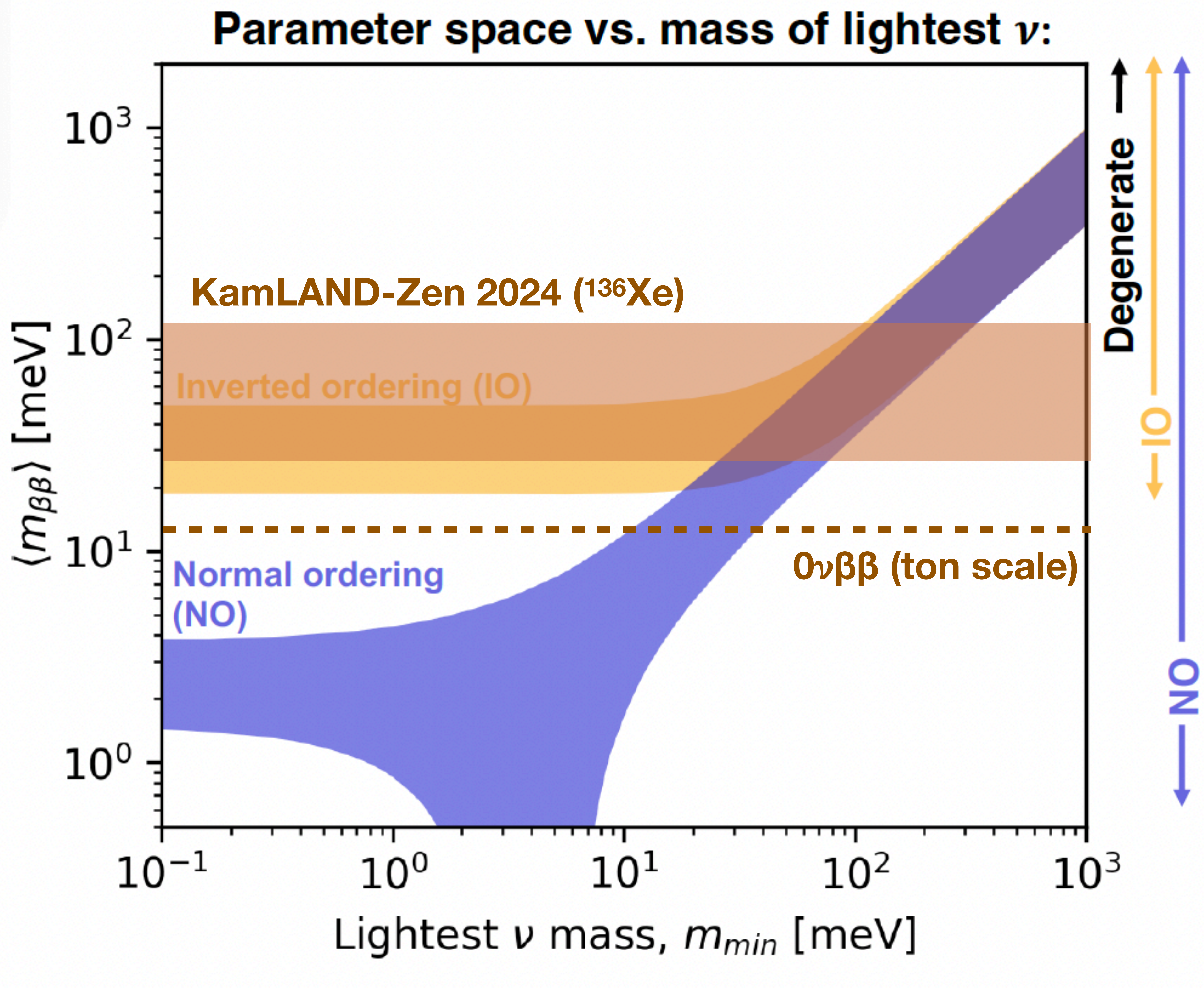


KamLAND-Zen

$\langle m_{\beta\beta} \rangle$ < 28-122 meV

$m_{lightest}$ < 84 - 353 meV

Current status of 0νββ searches



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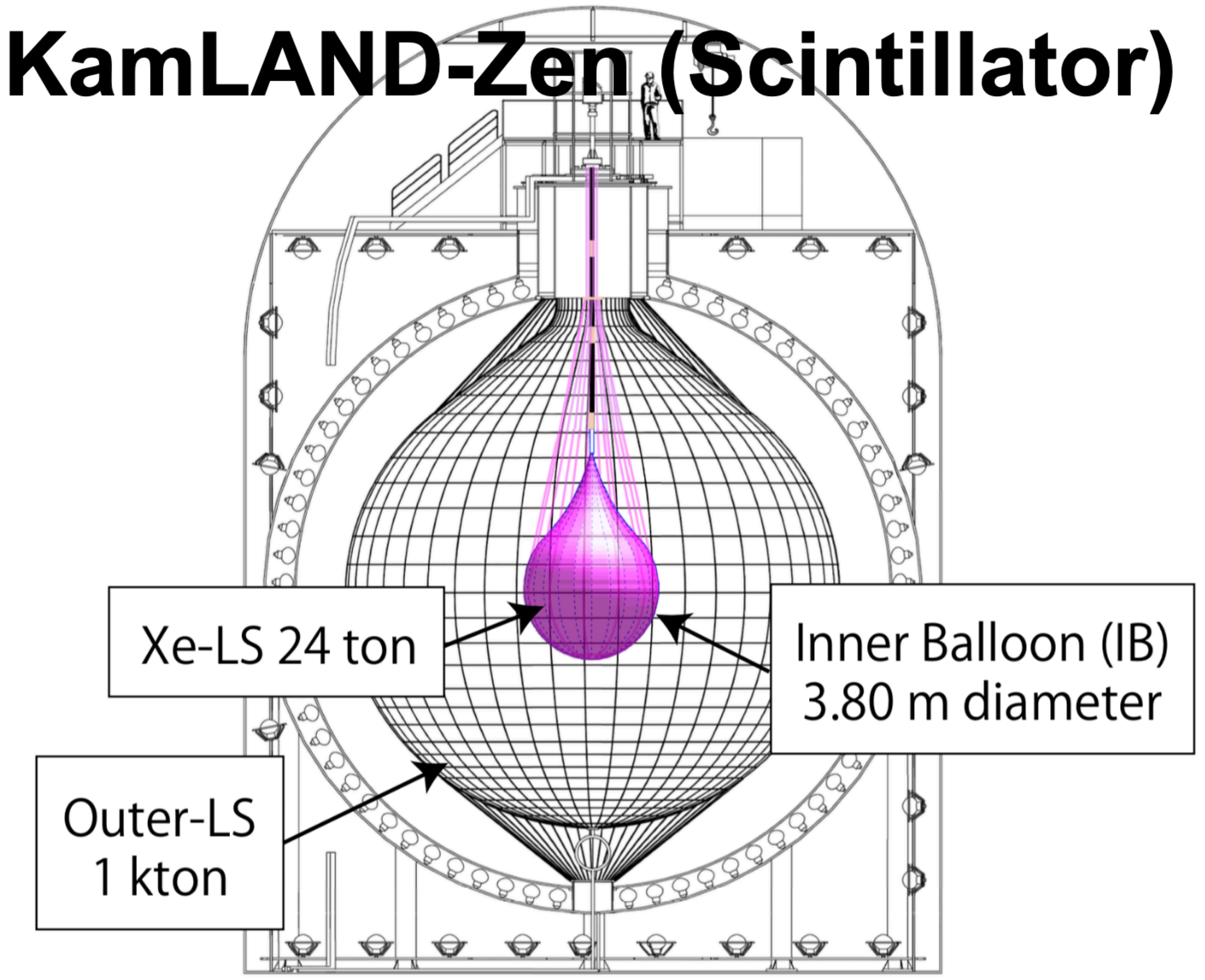

KamLAND-Zen

$\langle m_{\beta\beta} \rangle$ < 28-122 meV

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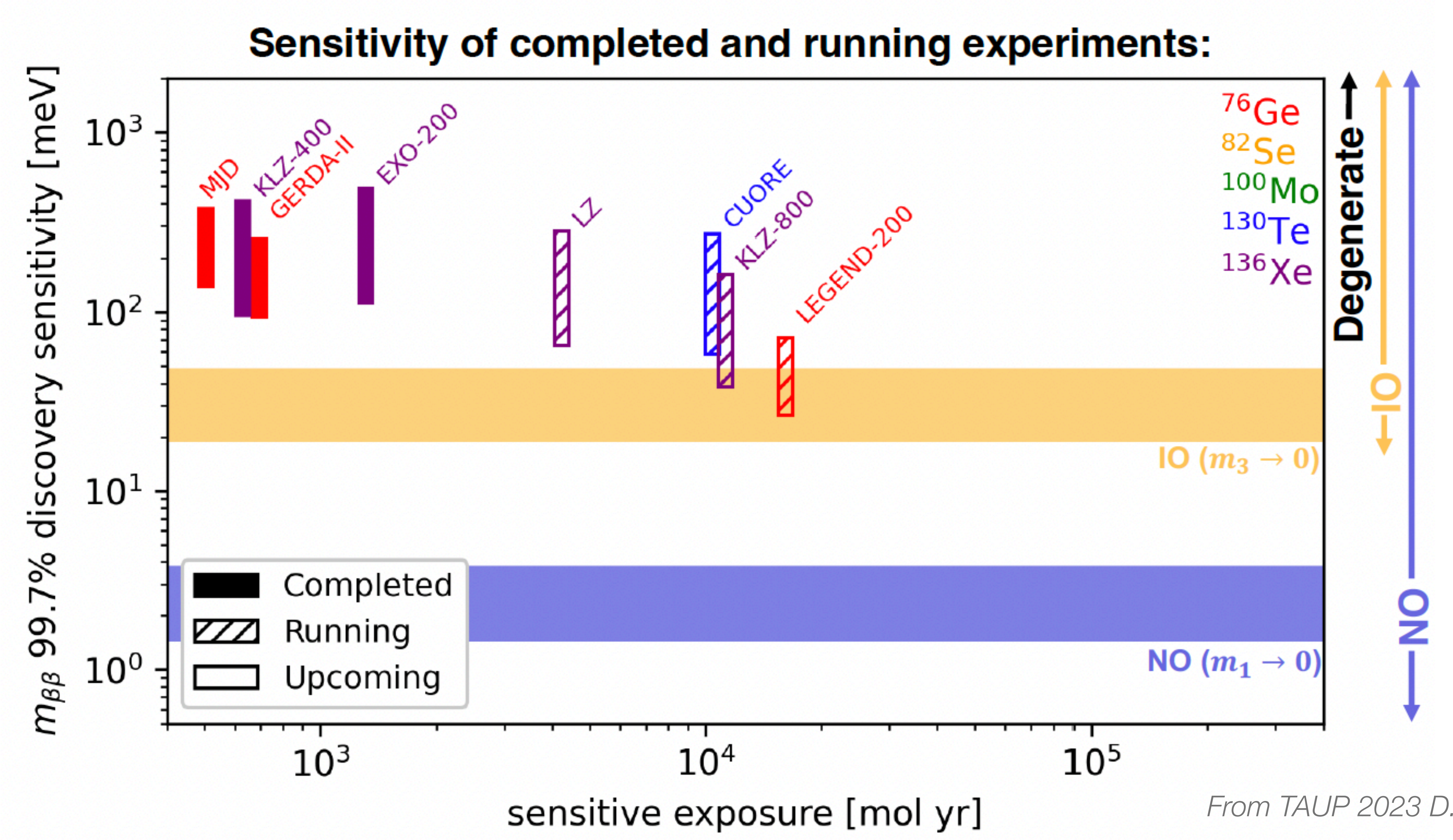
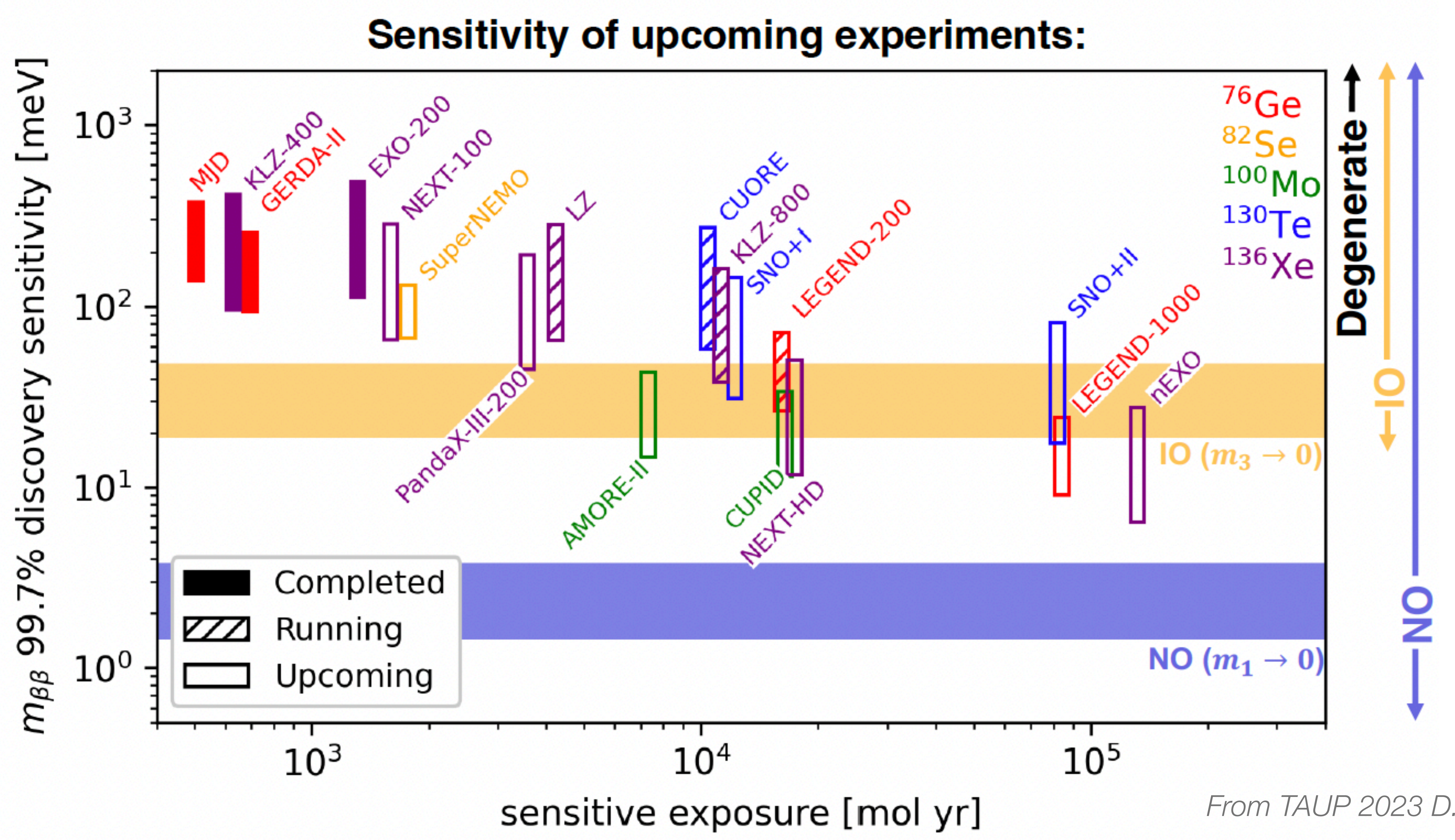
The most sensitive search to date for 0νββ

Current and future sensitivity



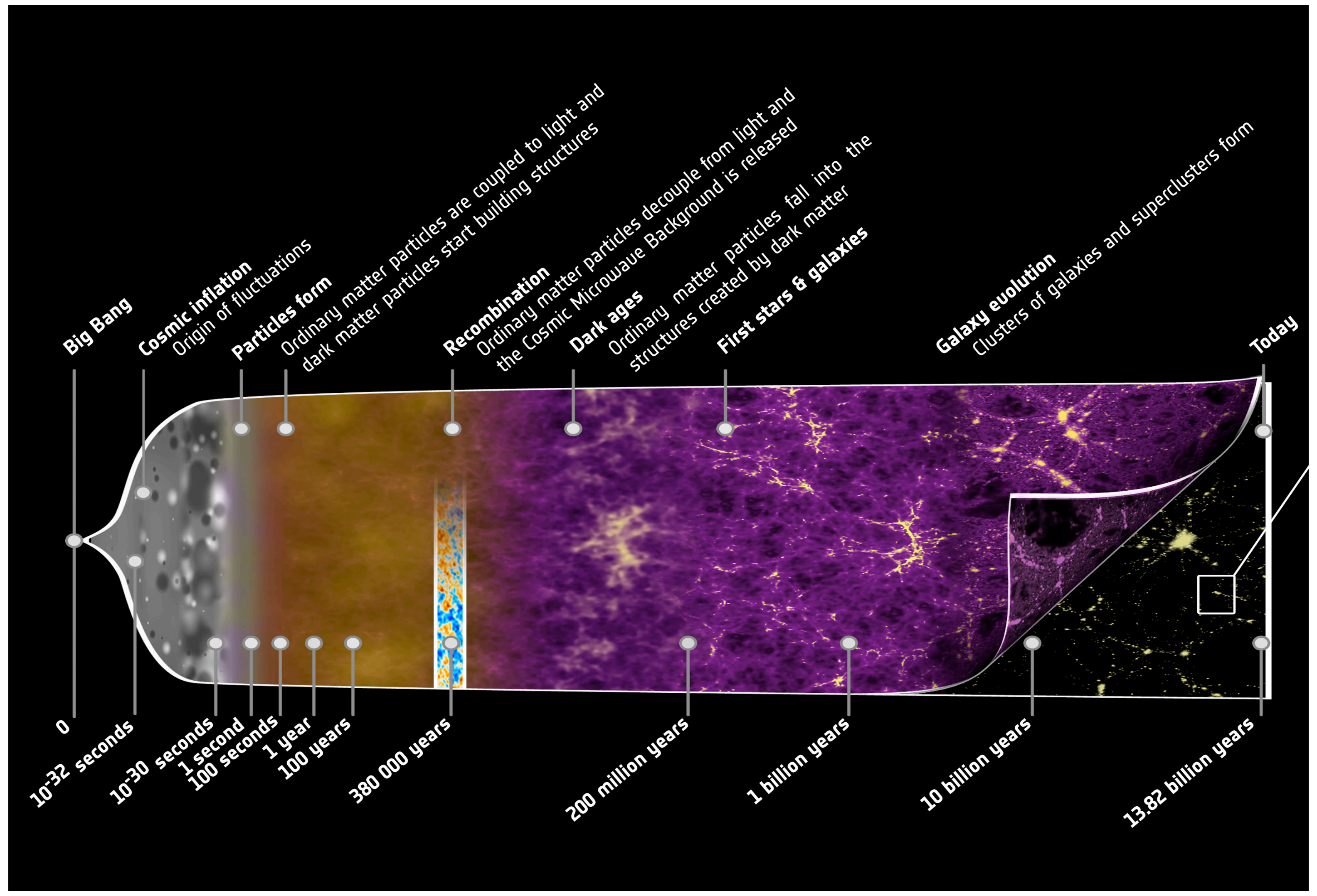
From TAUP 2023 D. Moore

Current and future sensitivity

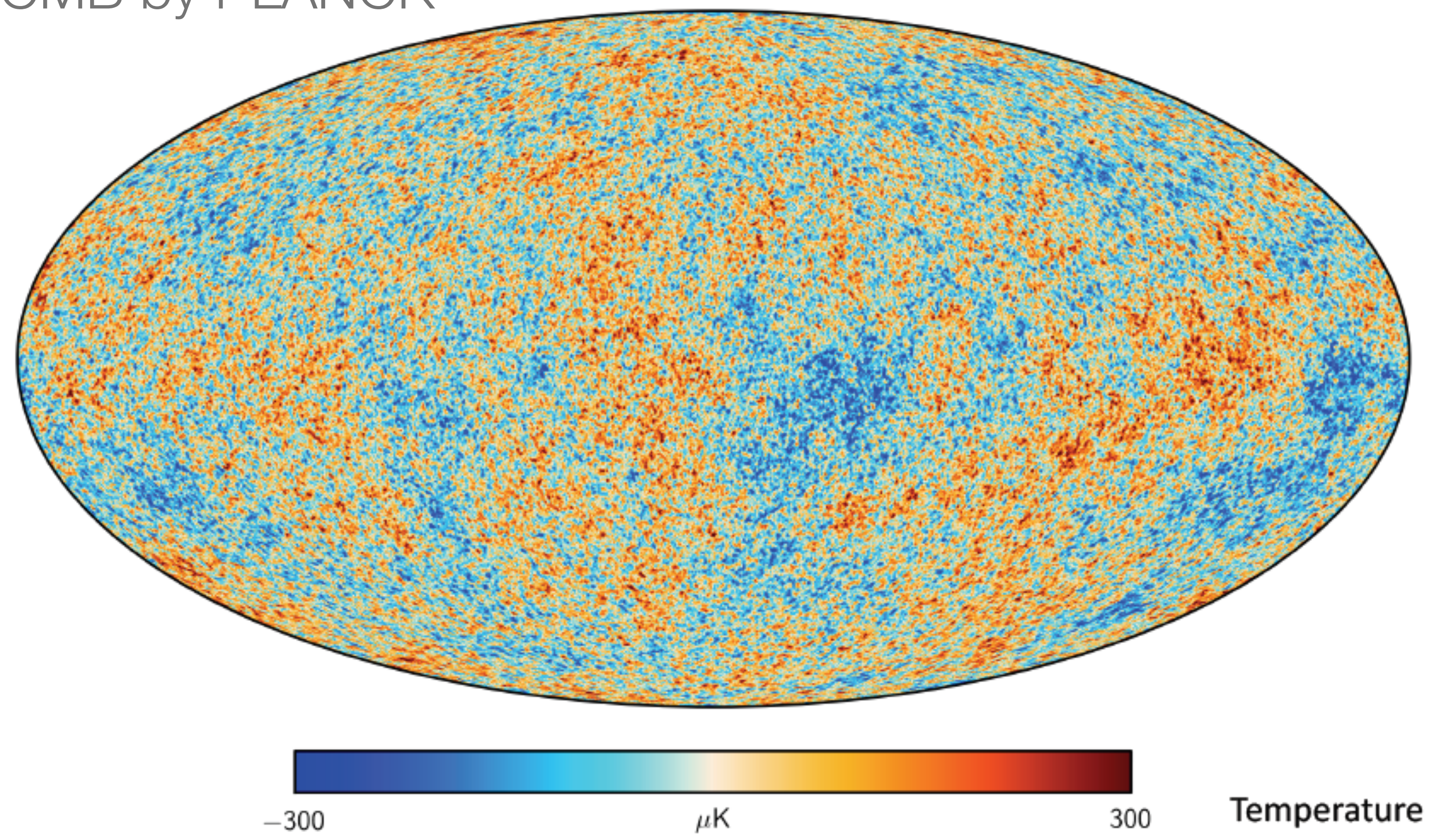


From TAUP 2023 D. Moore

Cosmology



CMB by PLANCK



- Neutrinos are everywhere in the Universe and their presence and interactions must be incorporated into astrophysical and cosmological models.
- Cosmological neutrinos are very abundant
  - ✦ They contribute to radiation at early times and to matter at late times
  - ✦ Cosmological observables can be used to test standard or non-standard properties
- Neutrino parameters: sum of neutrino masses ($\sum m_\nu$) & effective number of neutrinos (N_{eff})
- New result from CMB + DESI BAO (2024), 95%:

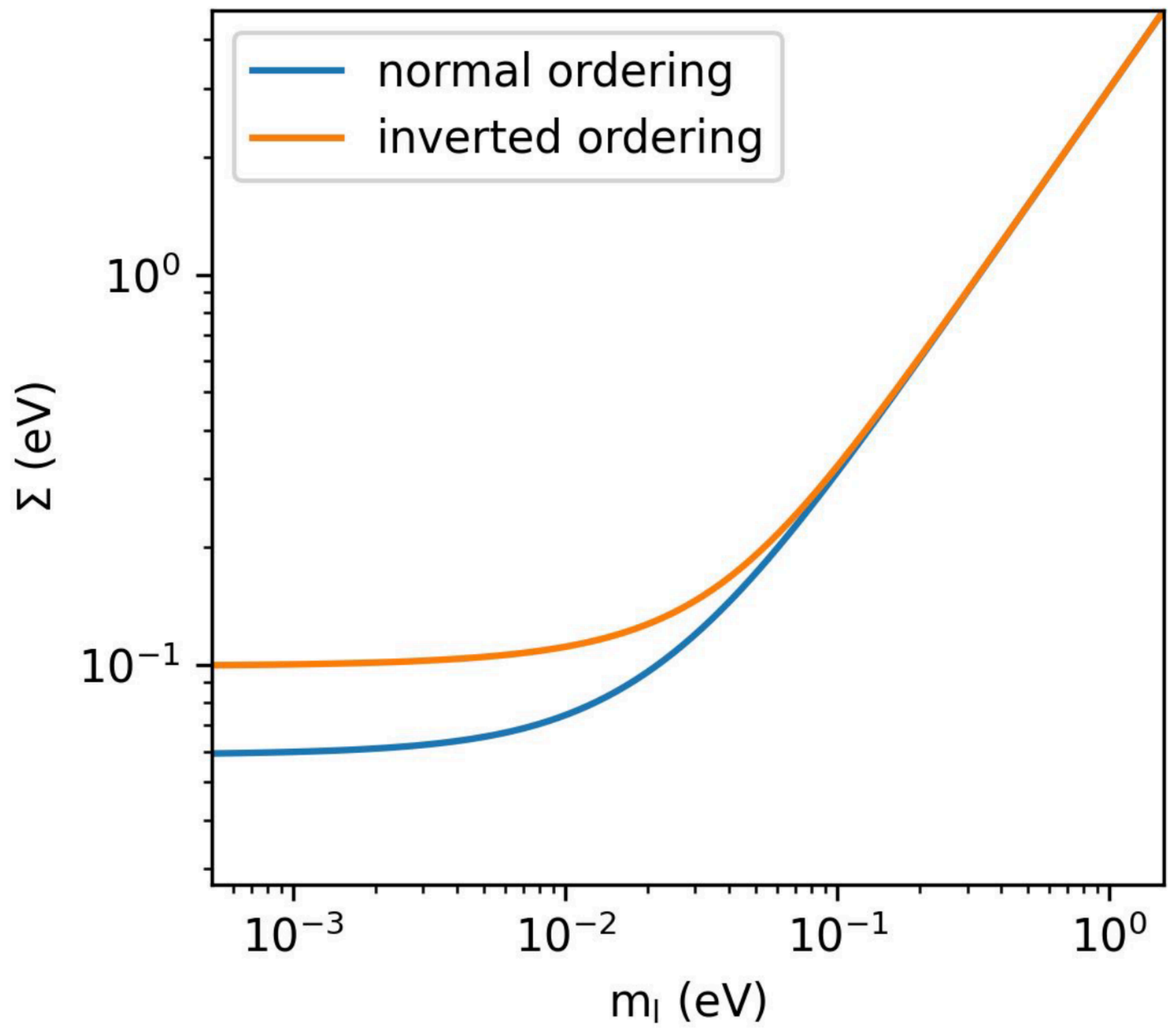
$$\sum m_\nu > \begin{cases} 0.058\,\mathrm{eV} & (\mathrm{NO}) \\ 0.10\,\mathrm{eV} & (\mathrm{IO}) \end{cases} \text{ from osc.}$$

$$\sum m_\nu < 0.21\,\mathrm{eV} \quad (\mathrm{CMB})$$

$$N_\nu = 2.9963 \pm 0.0074 \text{ from LEP}$$

$$N_{\mathrm{eff}} = 2.98 \pm 0.20 \quad (\mathrm{CMB})$$

[NuFIT 5.3, nu-fit.org]



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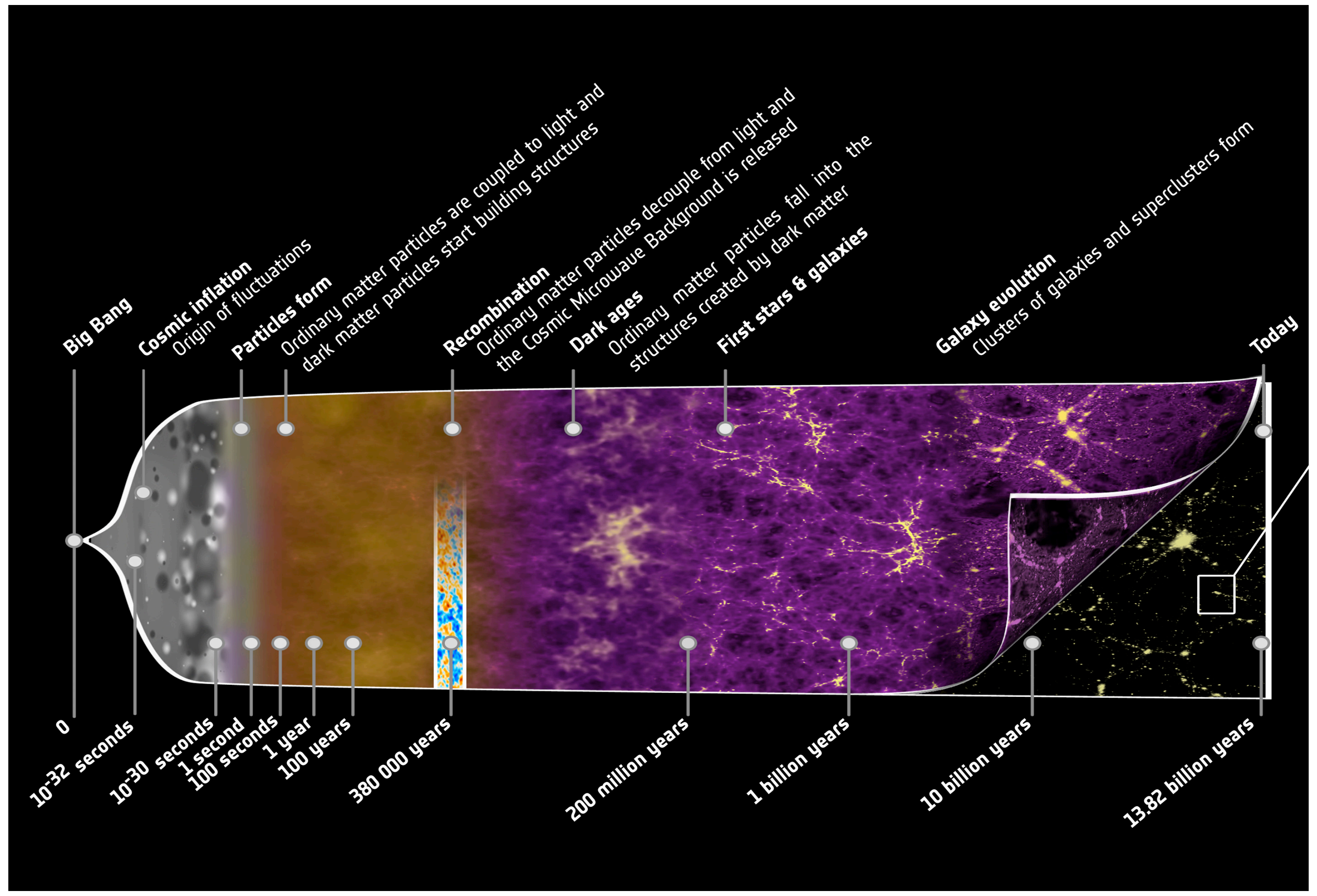

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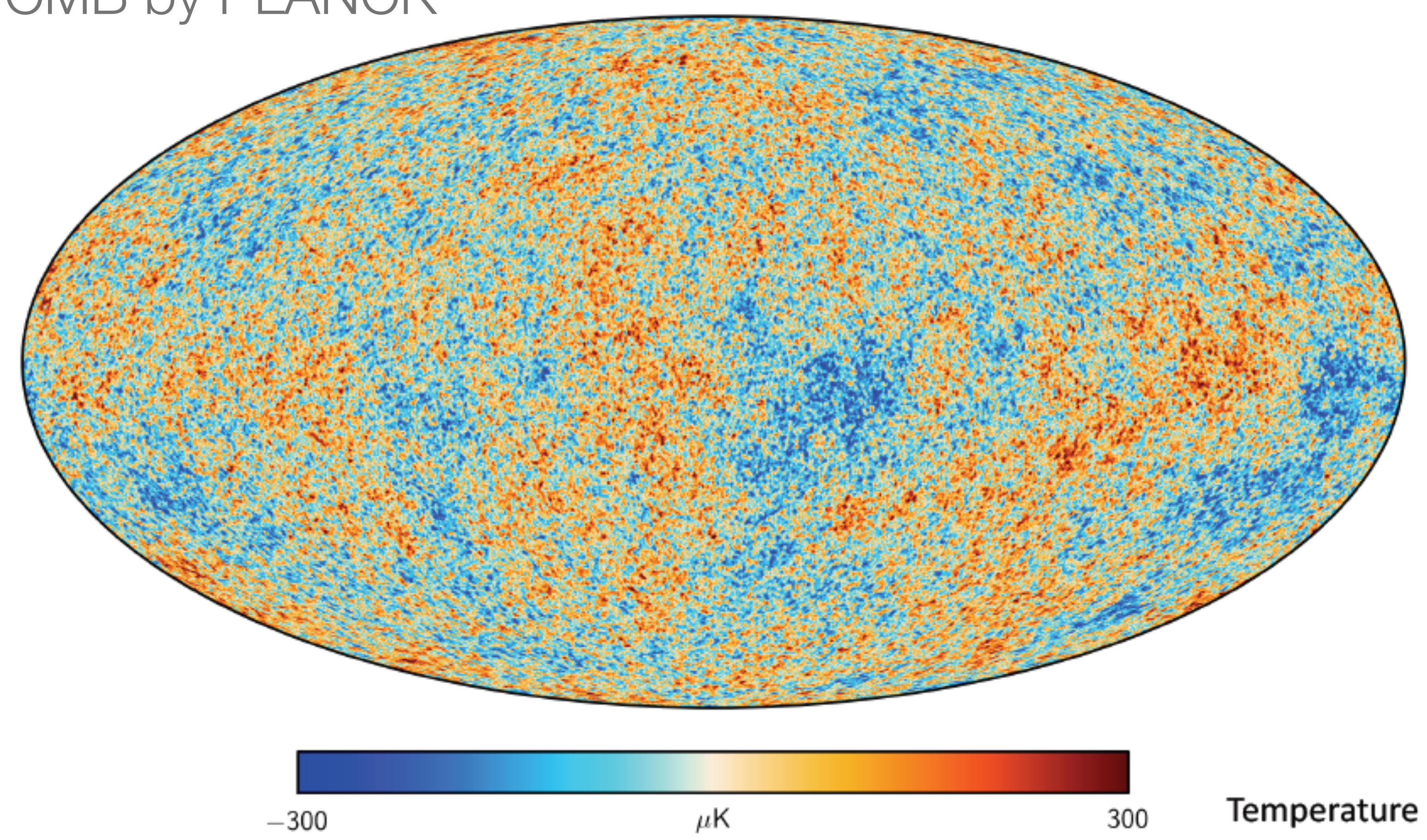

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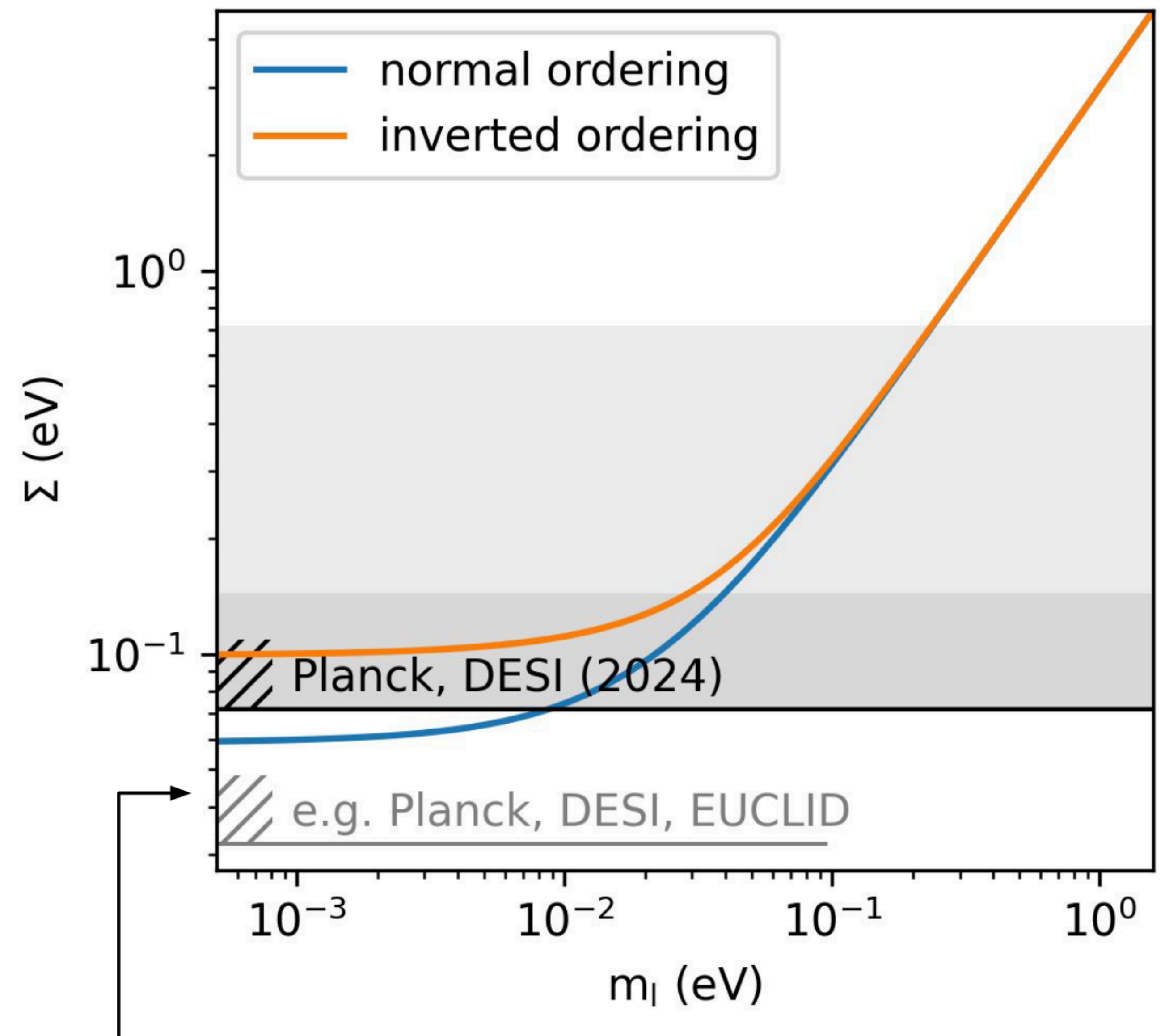
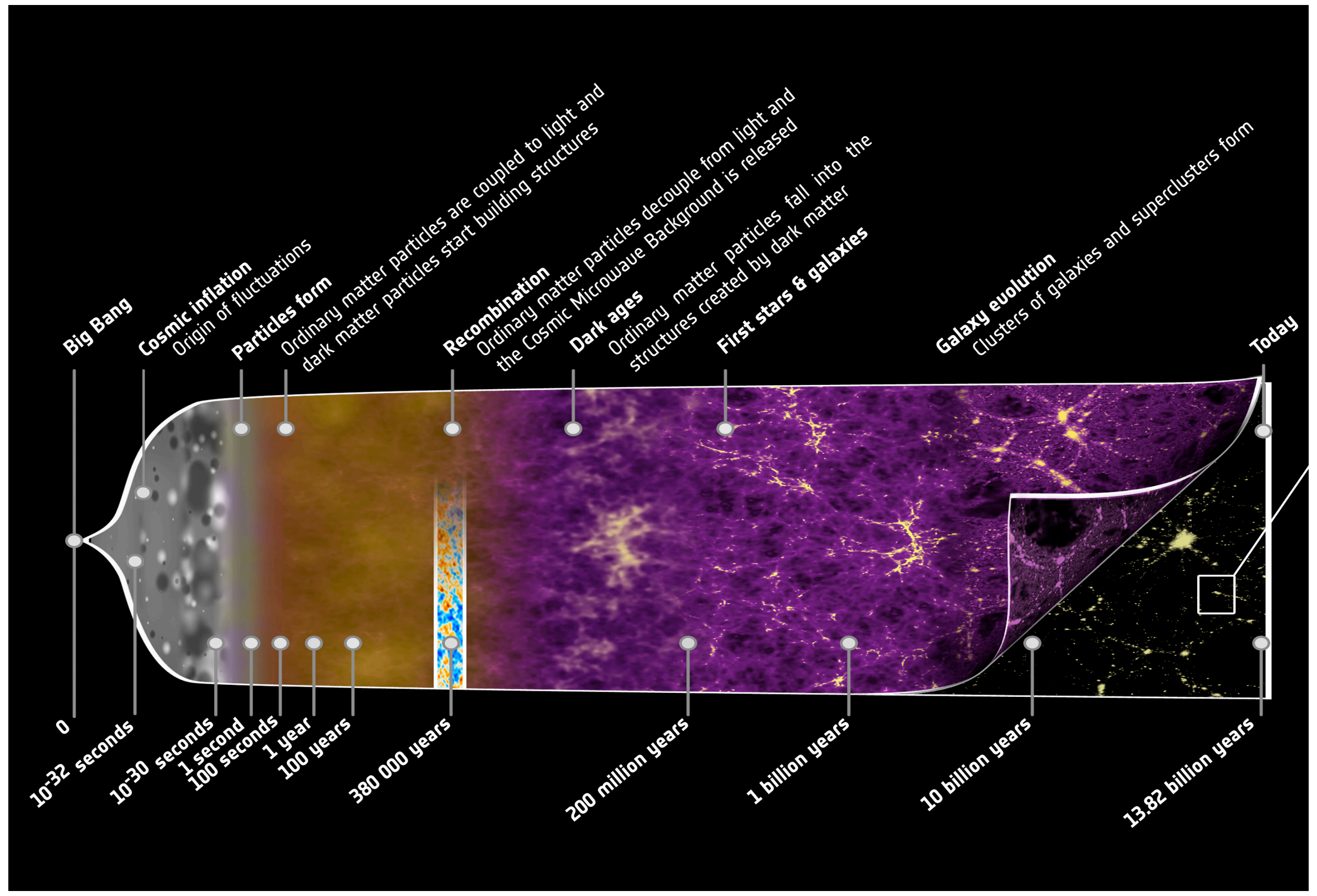


standard scenario **predicts detection**

Cosmology



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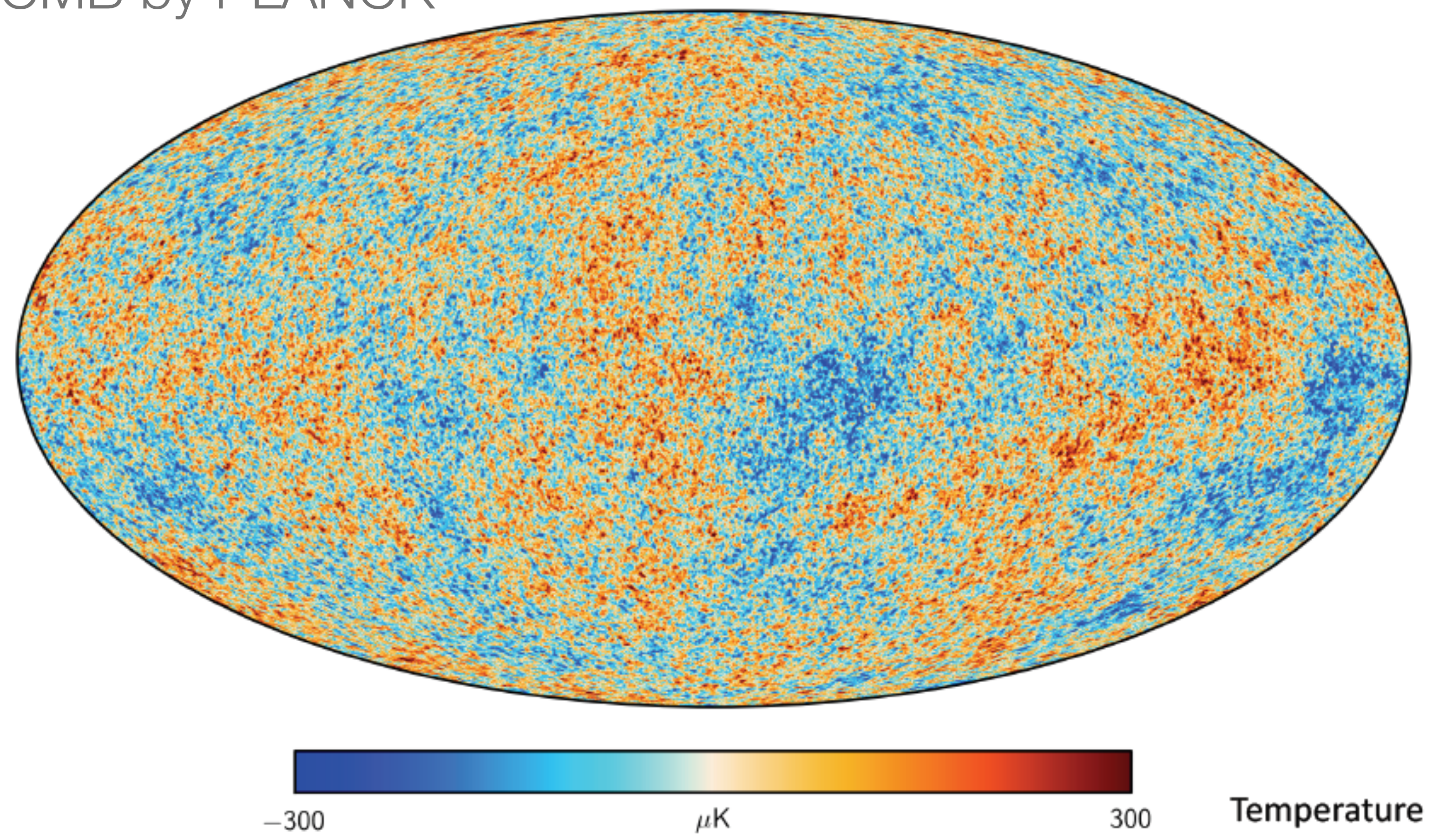

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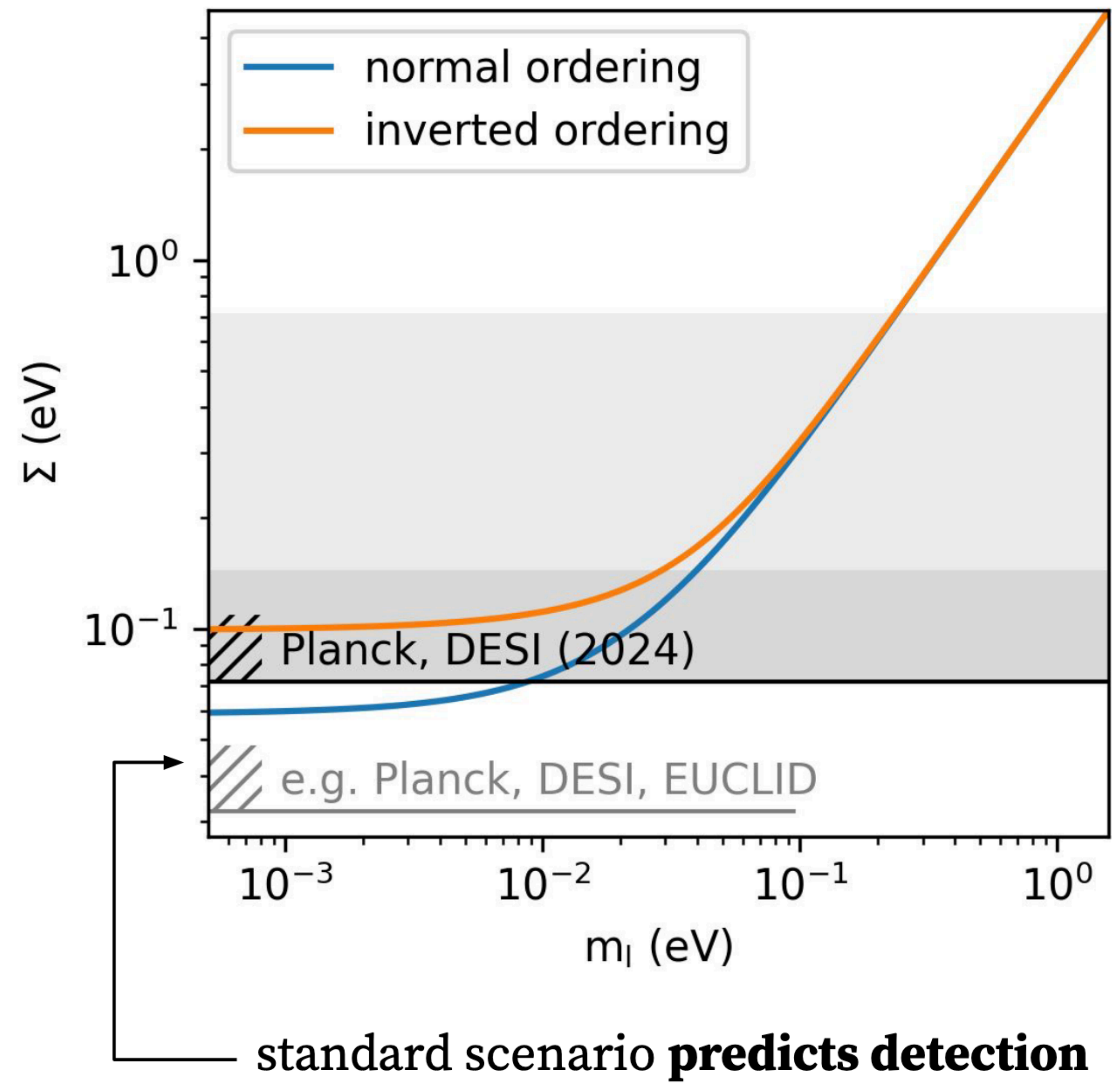
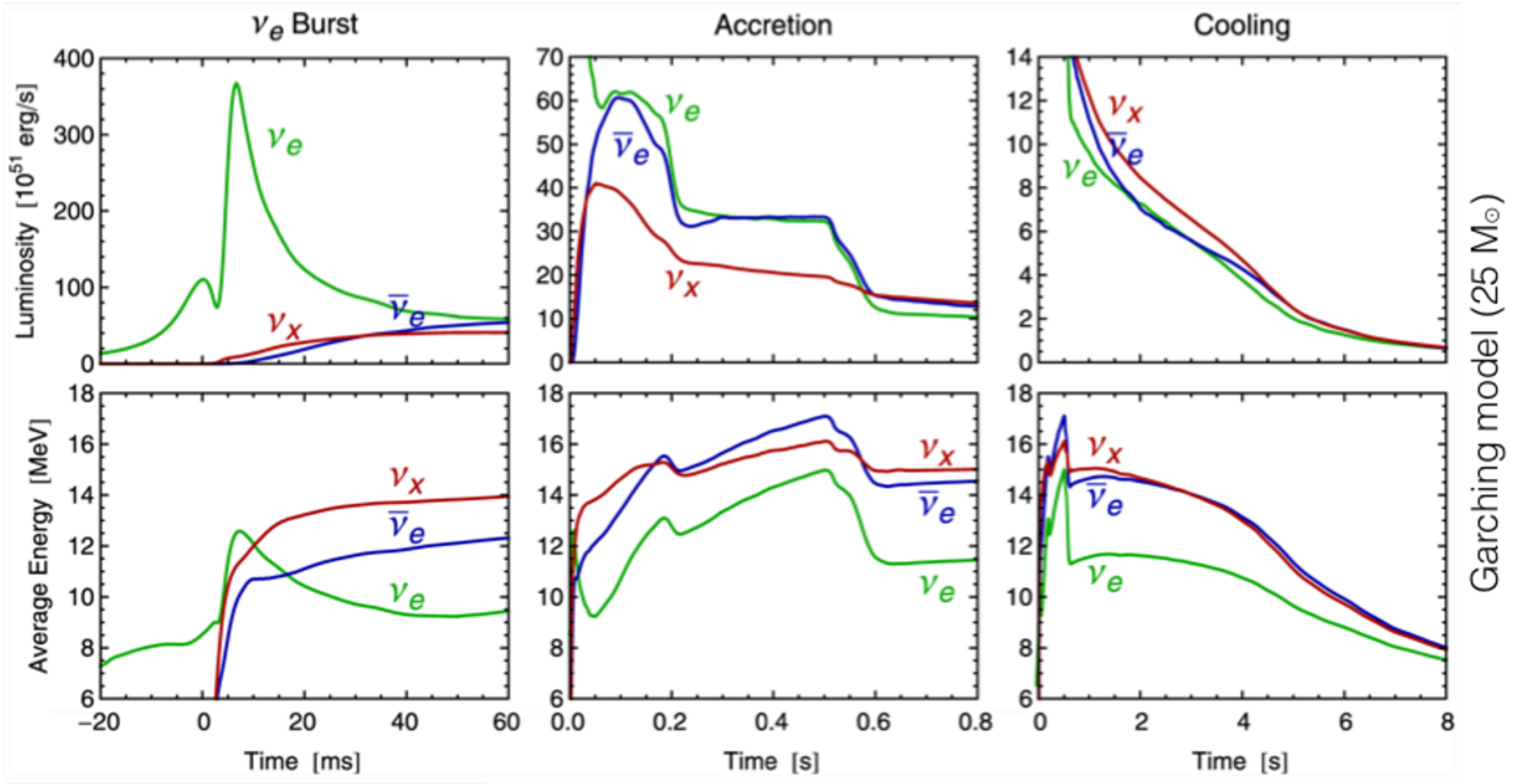


Astrophysical neutrinos

Astrophysical neutrinos - Supernova burst and DSNB

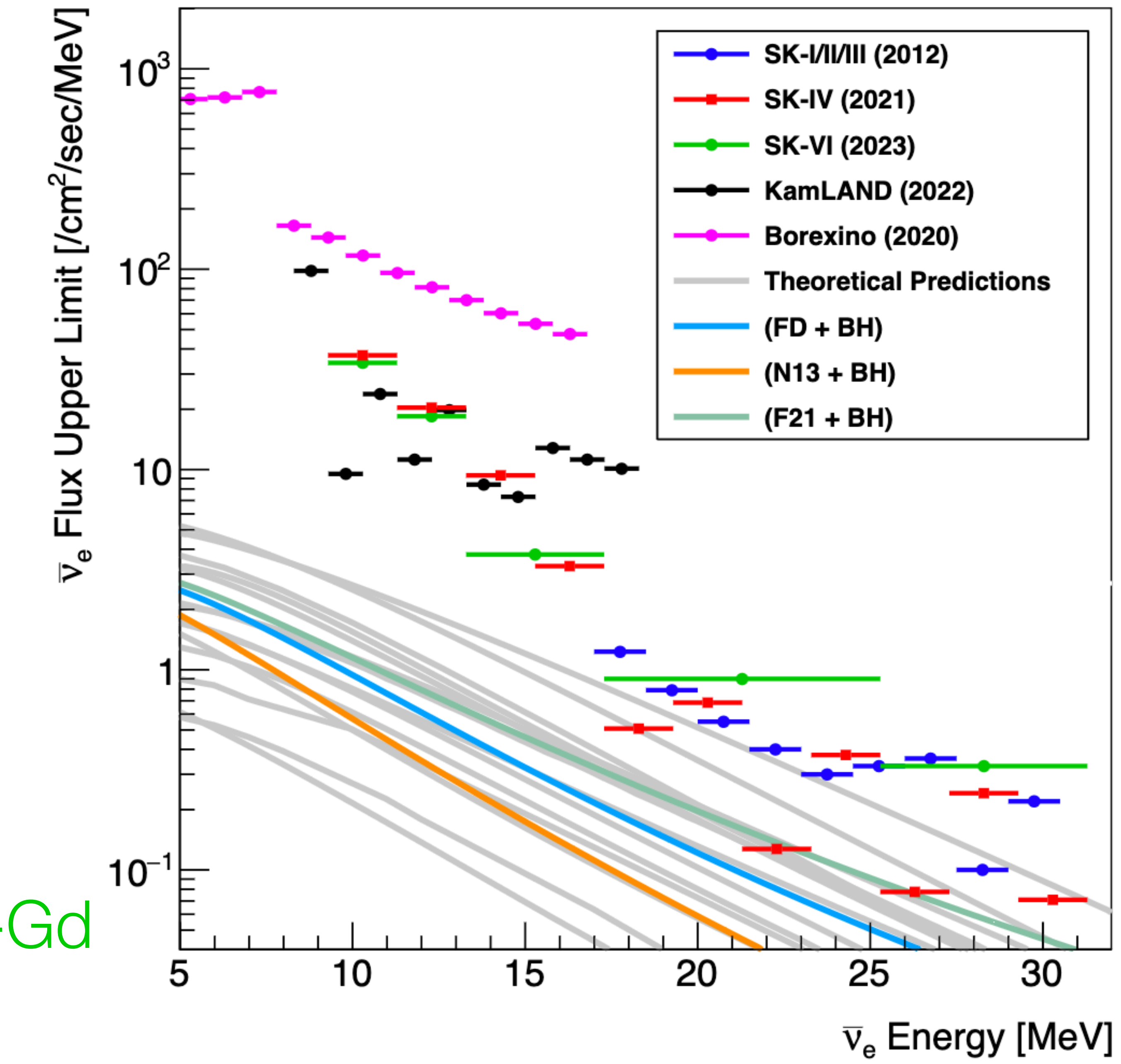
Detection of **core-collapse supernova neutrinos** (99% SN binding energy emitted in ~10 seconds by neutrinos) provides information about:

- ✦ Core-collapse explosion mechanism
- ✦ Neutrino properties

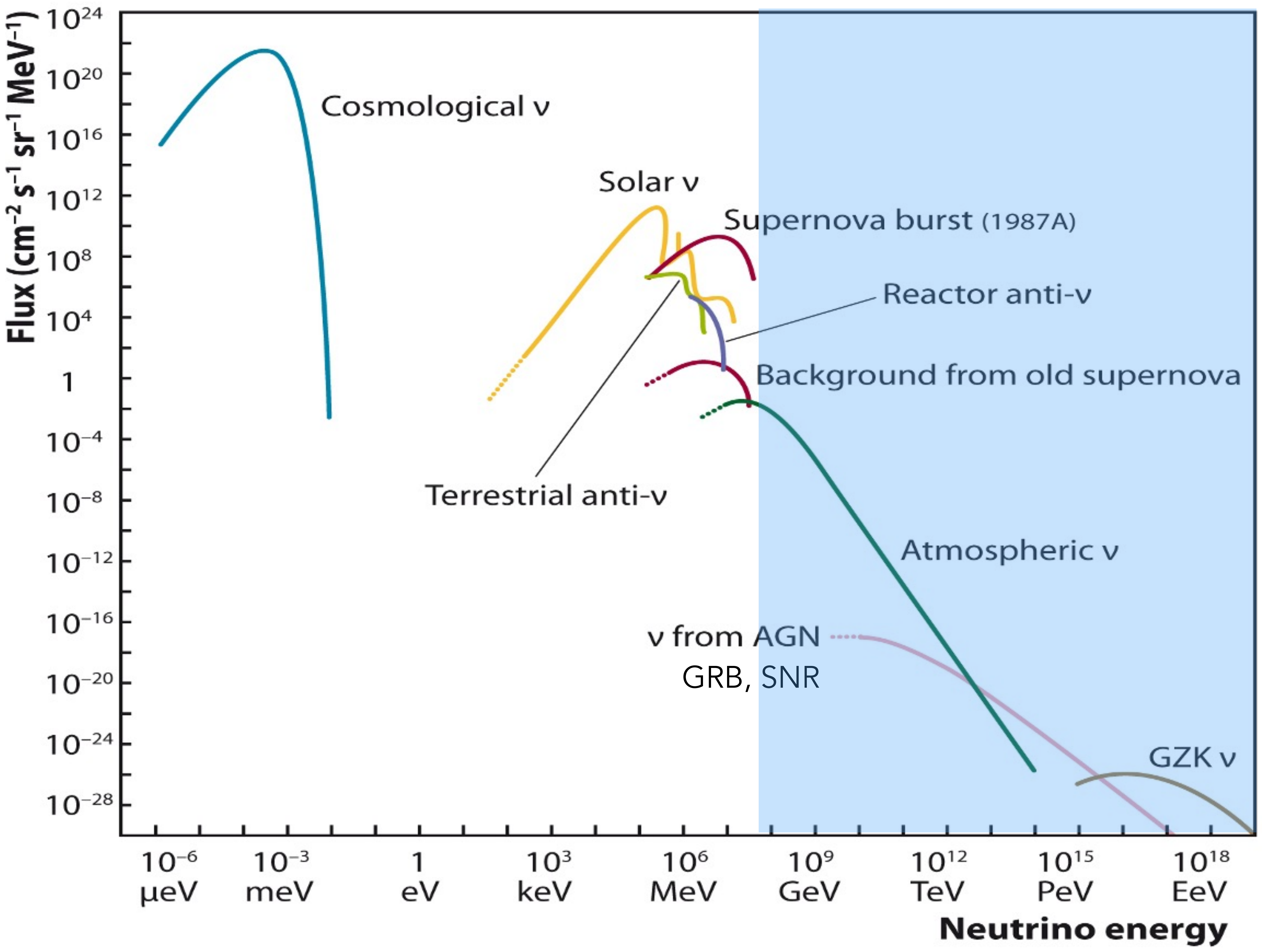


- Detection of **diffuse supernova neutrino background** (averaged neutrino flux from all supernovae)
  - ✦ No detected yet
  - ✦ Best upper limits from Super-K

New results from SK-Gd



Astrophysical neutrinos - high-energy neutrinos

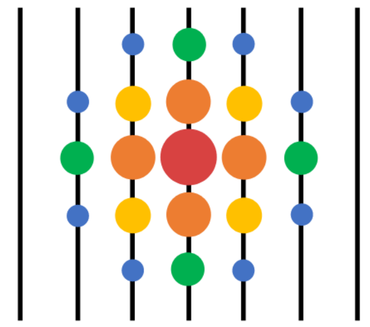


- **Atmospheric** neutrinos
  - ✦ Up to 100 TeV
- **Cosmic** neutrinos (~TeV-PeV)
  - ✦ From AGN, GRB, SNR
- **Cosmogenic** neutrinos (PeV-EeV)
  - ✦ From cosmic ray interactions with CMB photons (not detected yet)
- Production: $p + \gamma \rightarrow n + \pi^+$

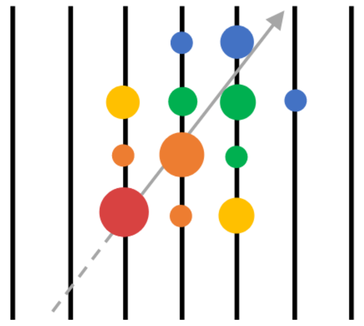
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- Detection of astrophysical neutrinos
  - ✦ Interaction with water/ice producing Cherenkov photons (shower vs tracks)

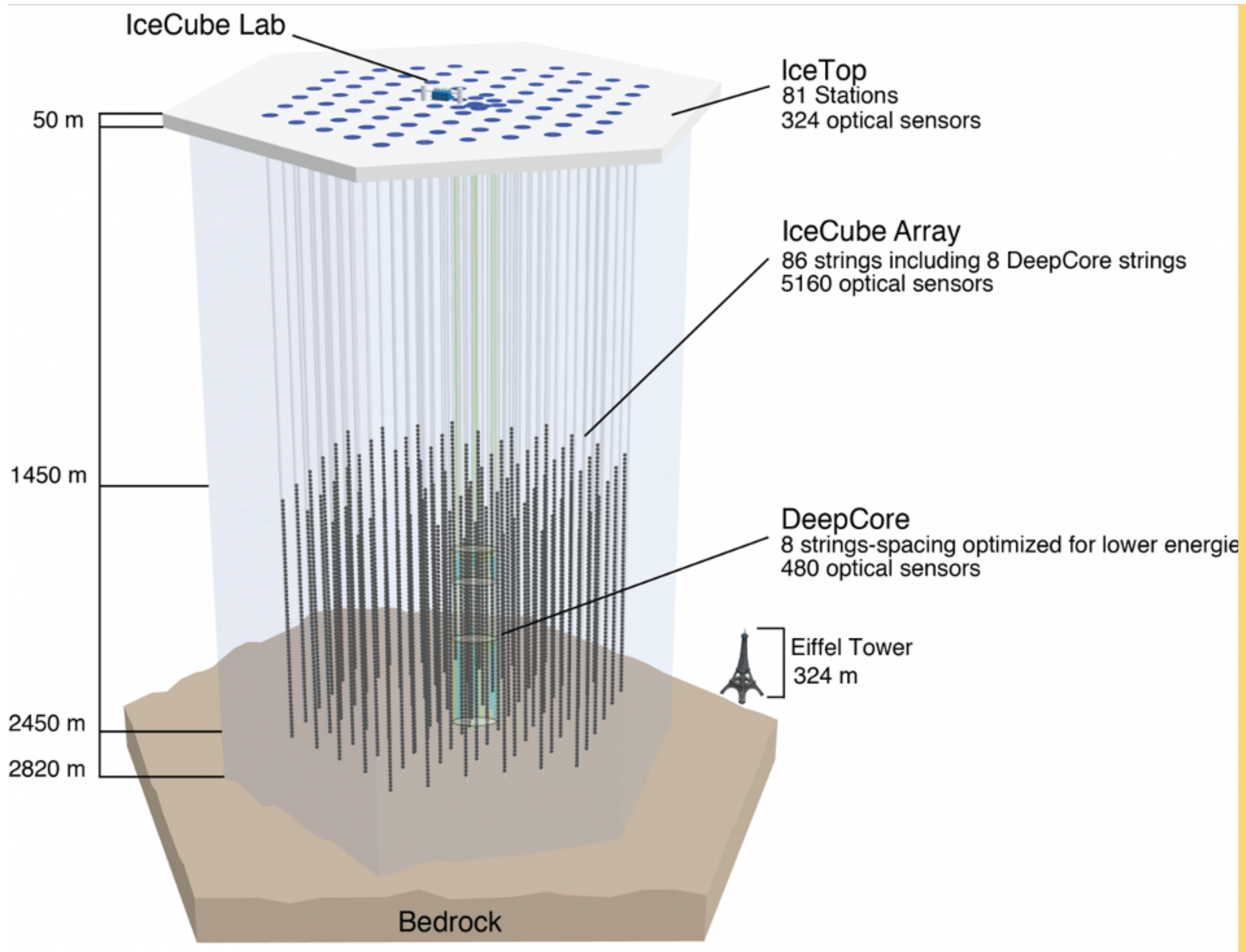
ν_eCC, ν_τCC, NC



ν_μCC



IceCube results



- 2013: Discovery of high-energy astrophysical neutrino flux
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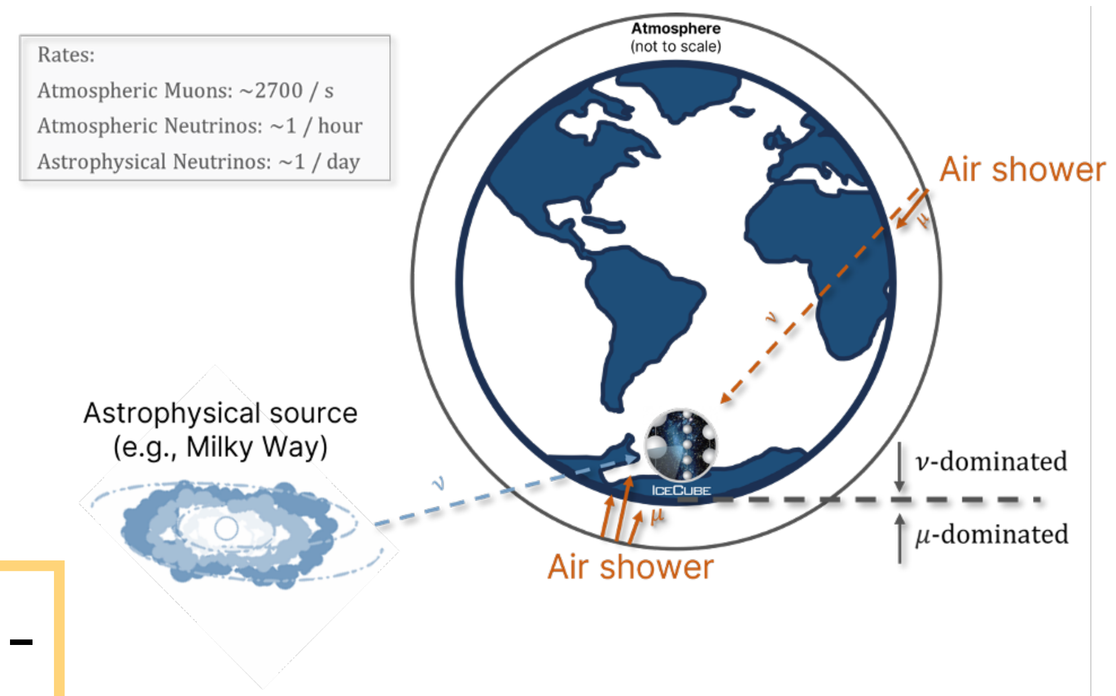

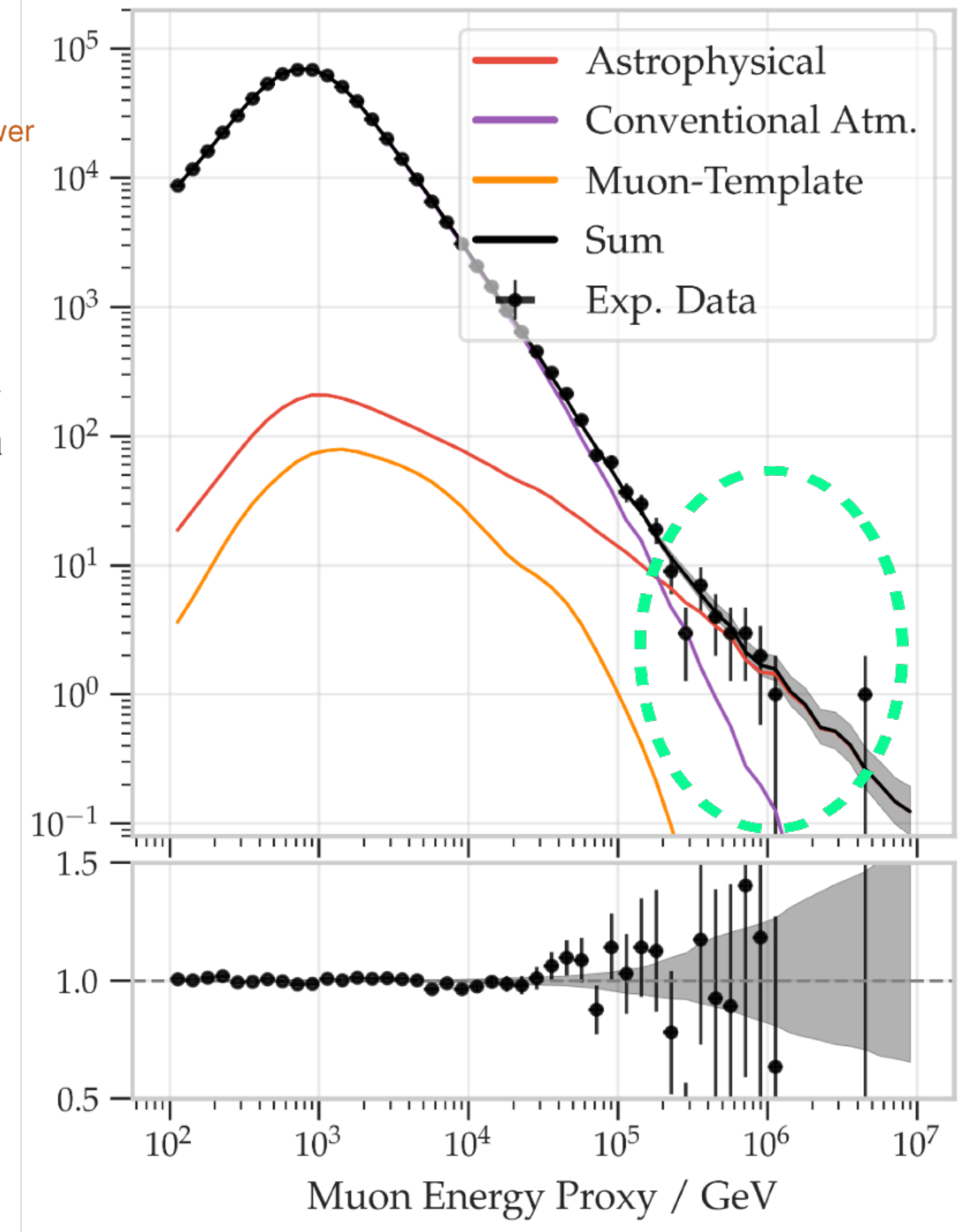

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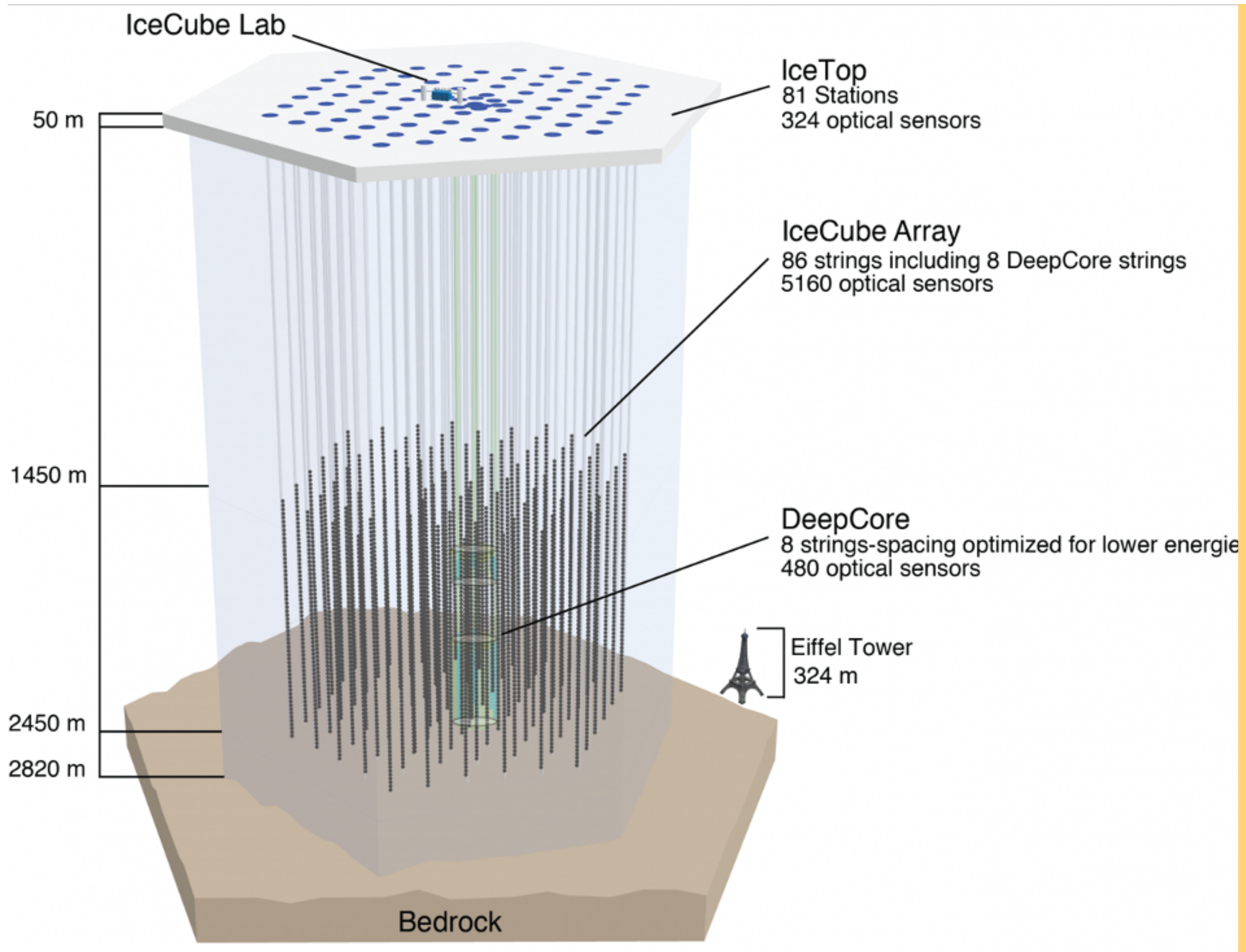

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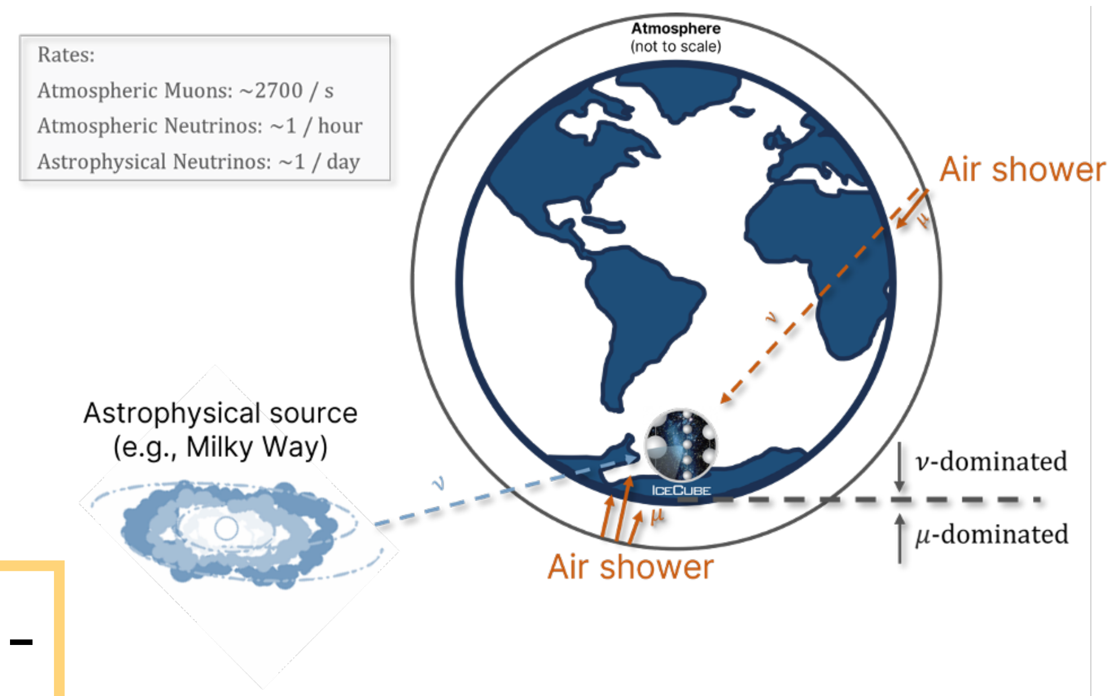

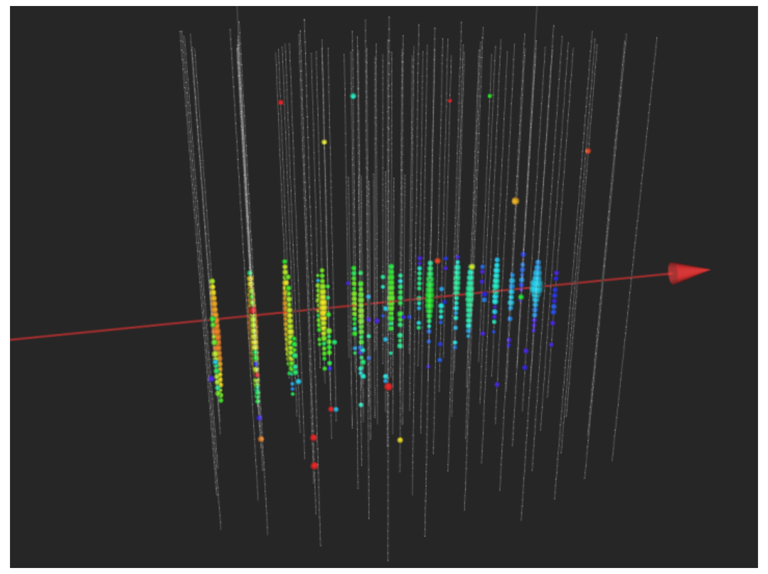

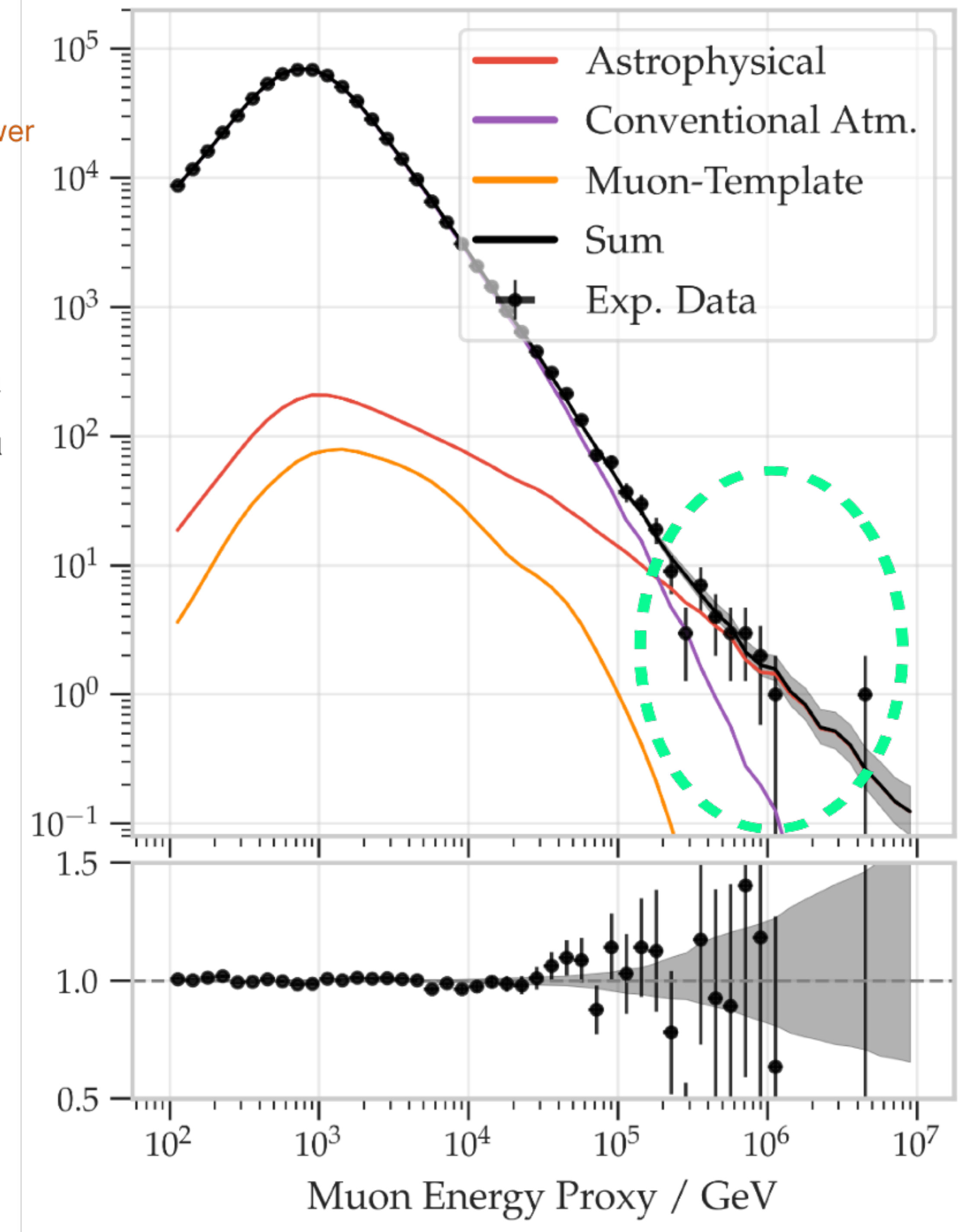

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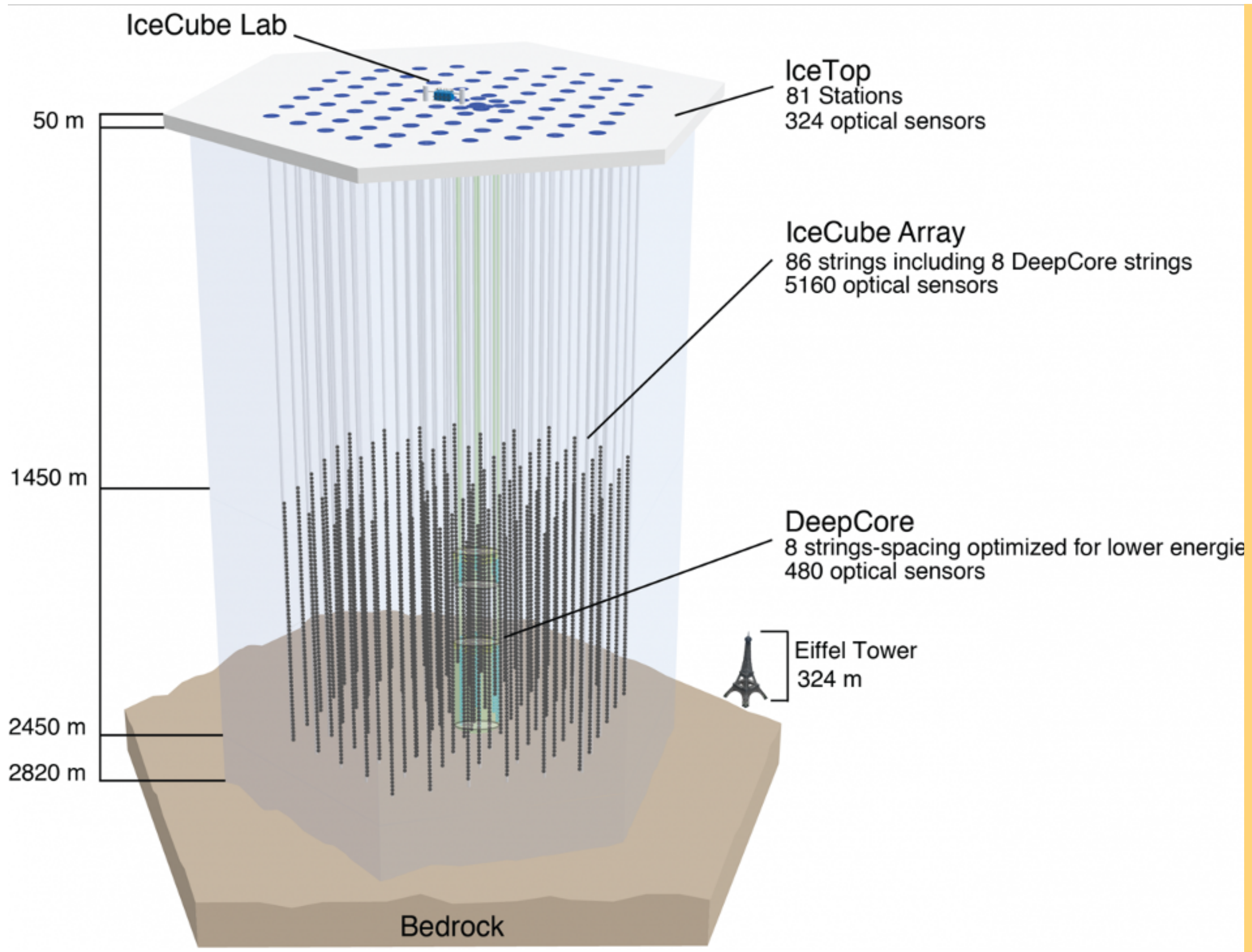

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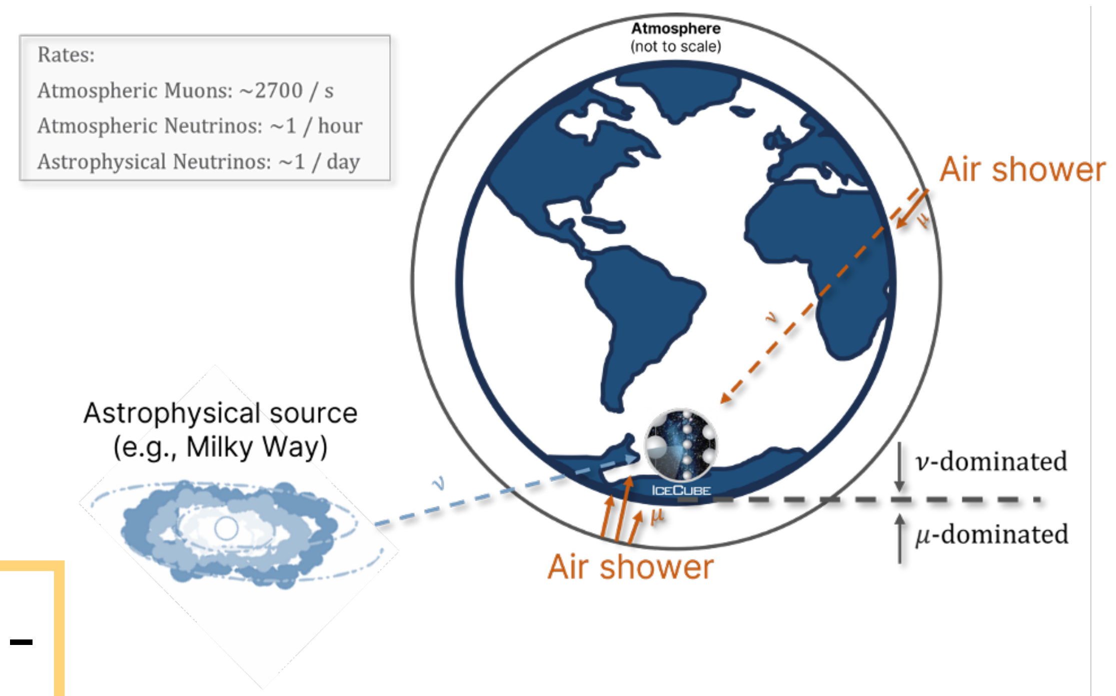

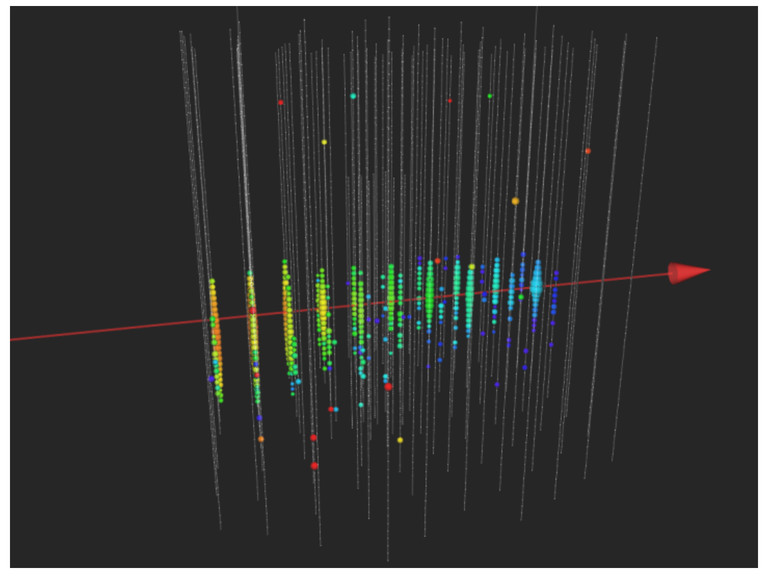

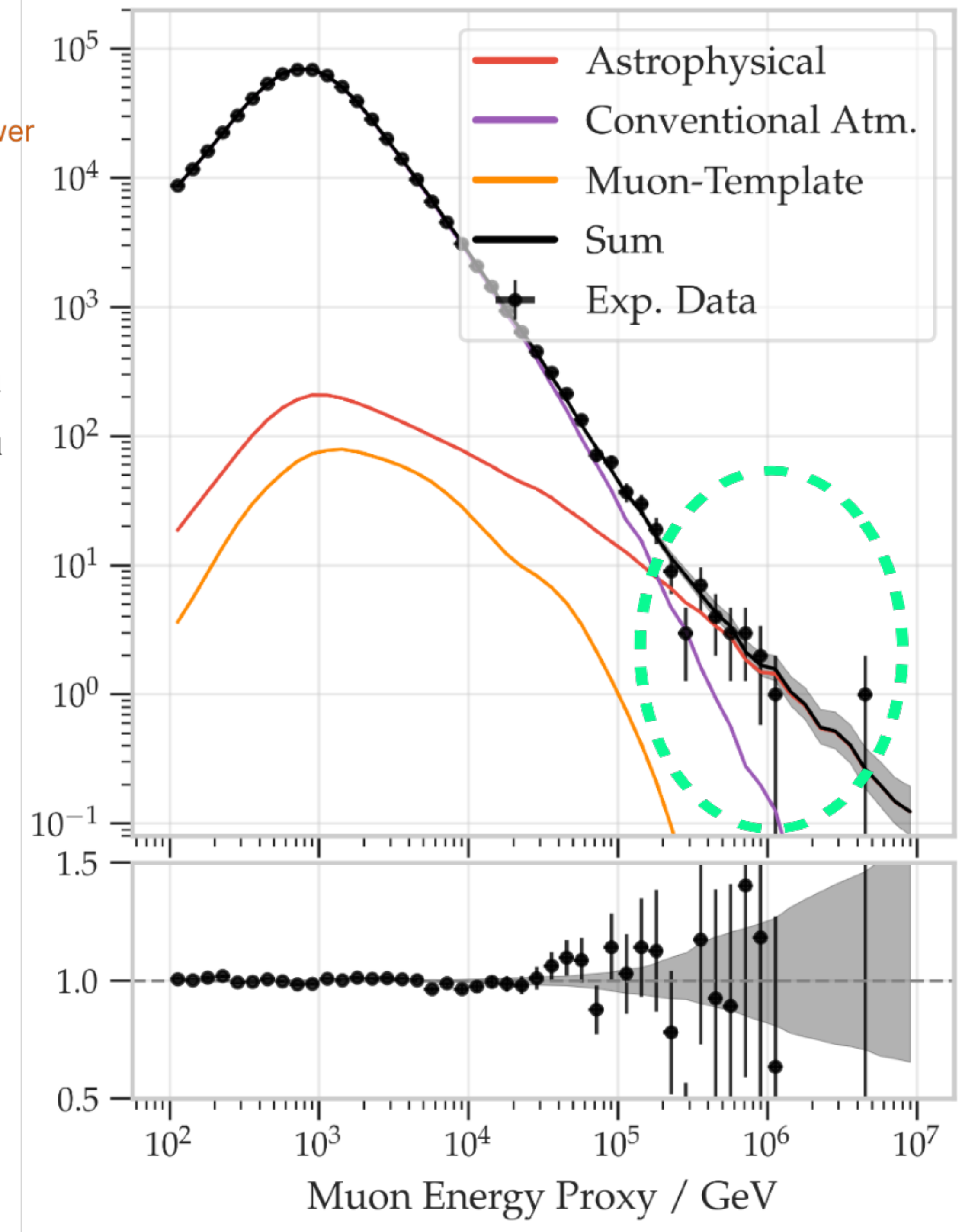

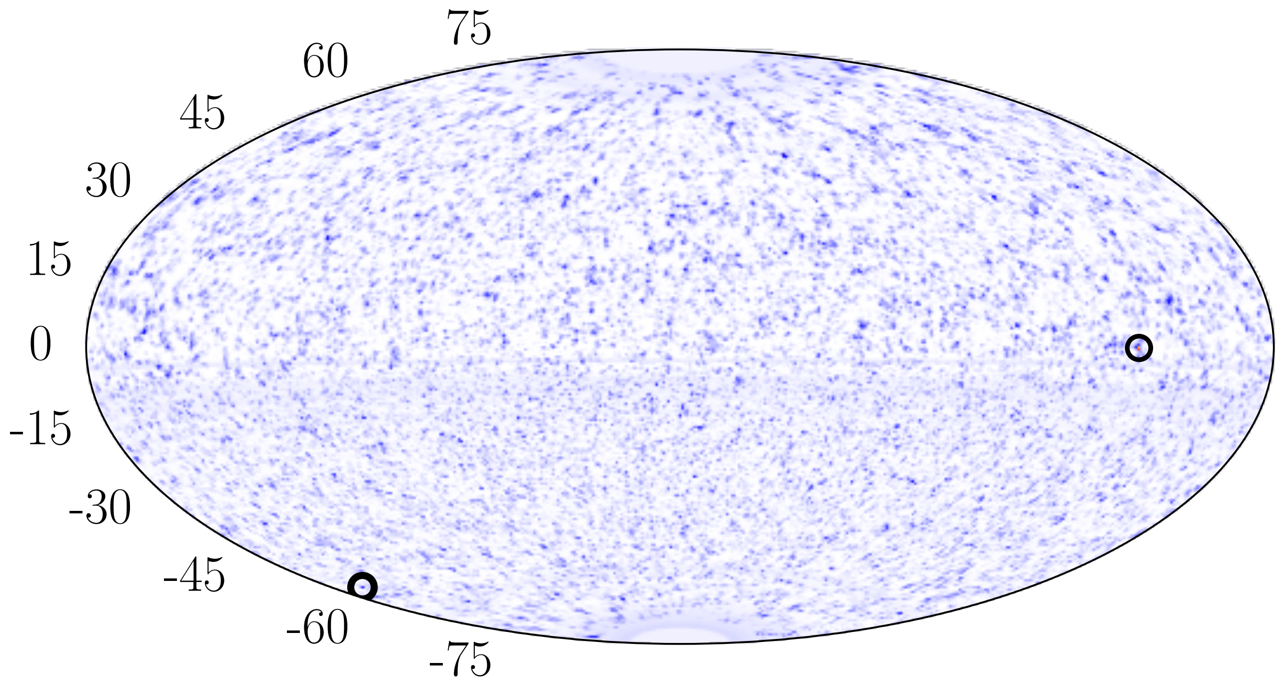

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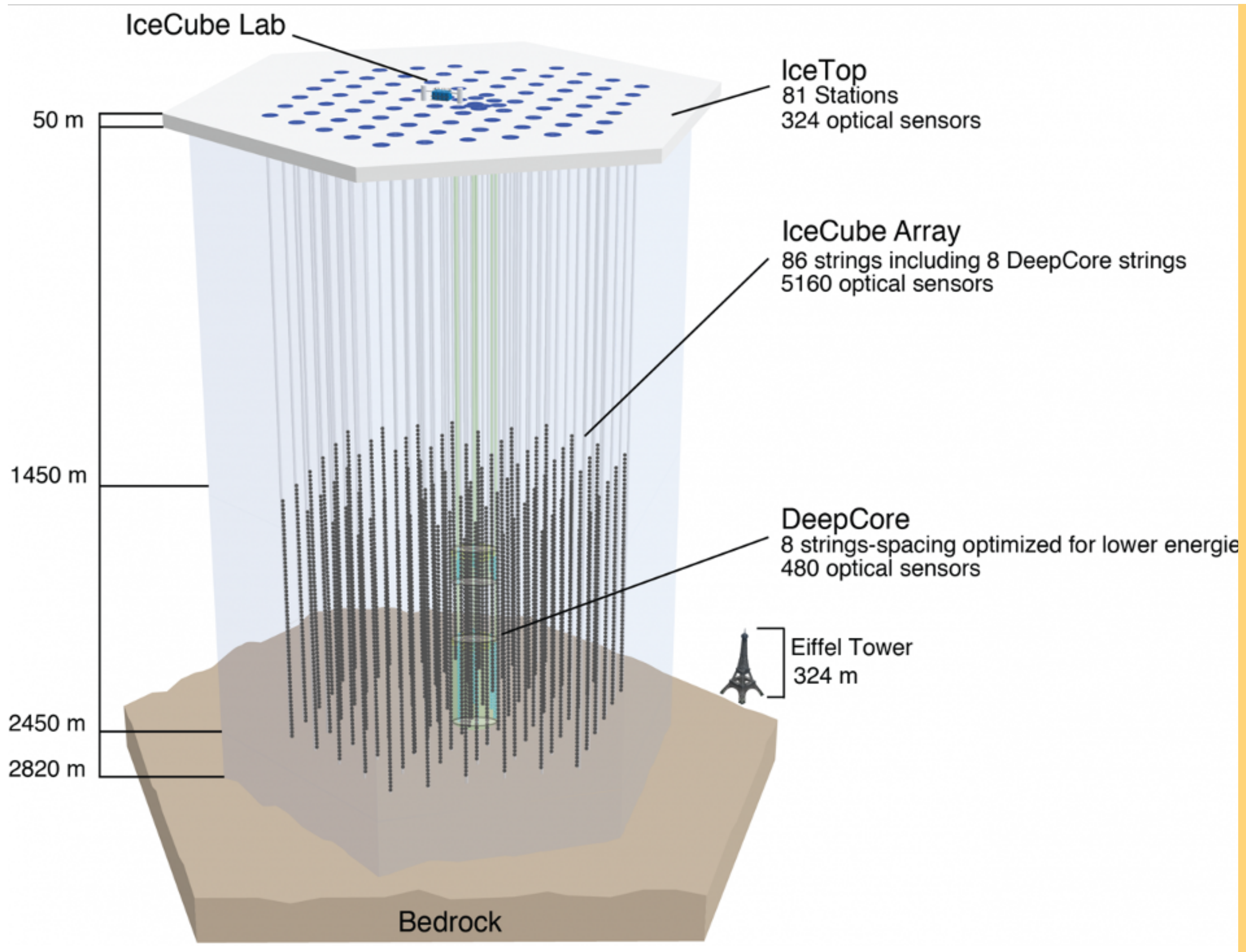

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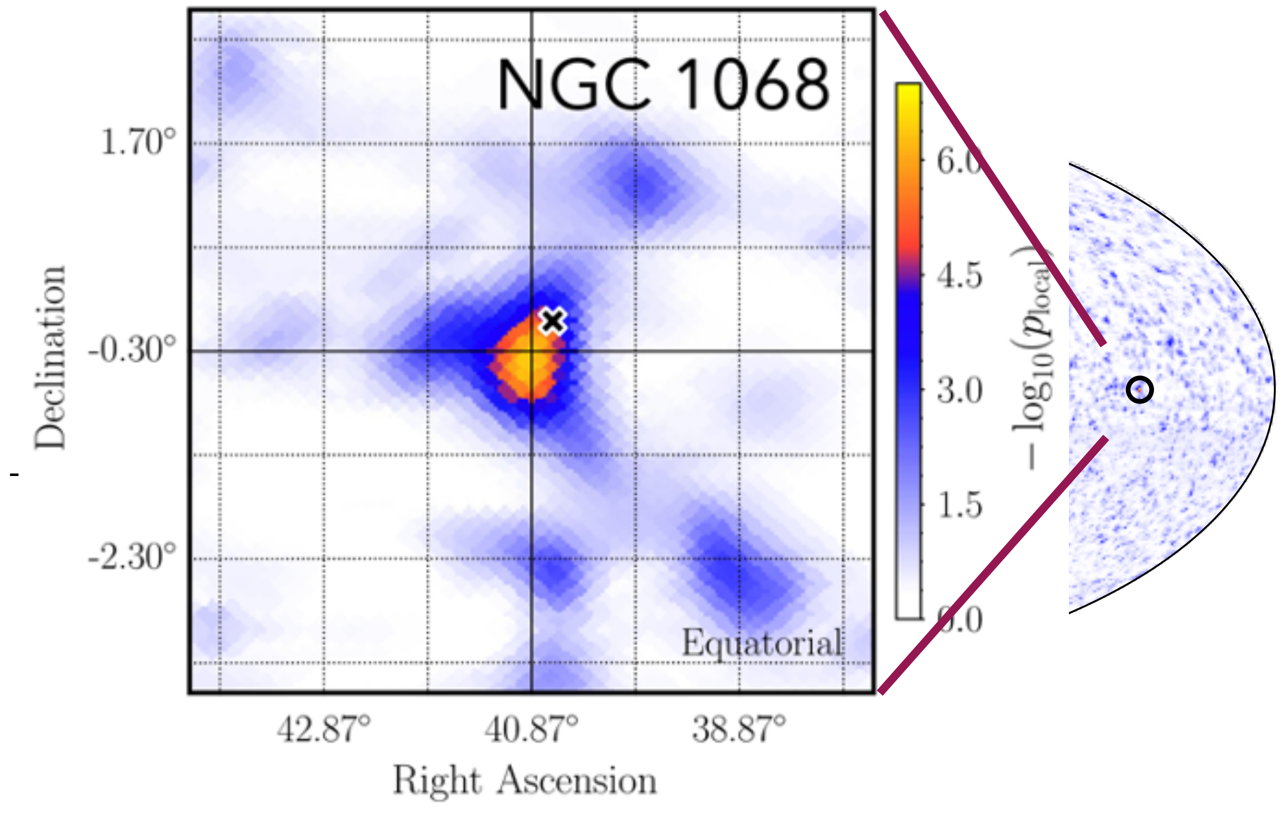

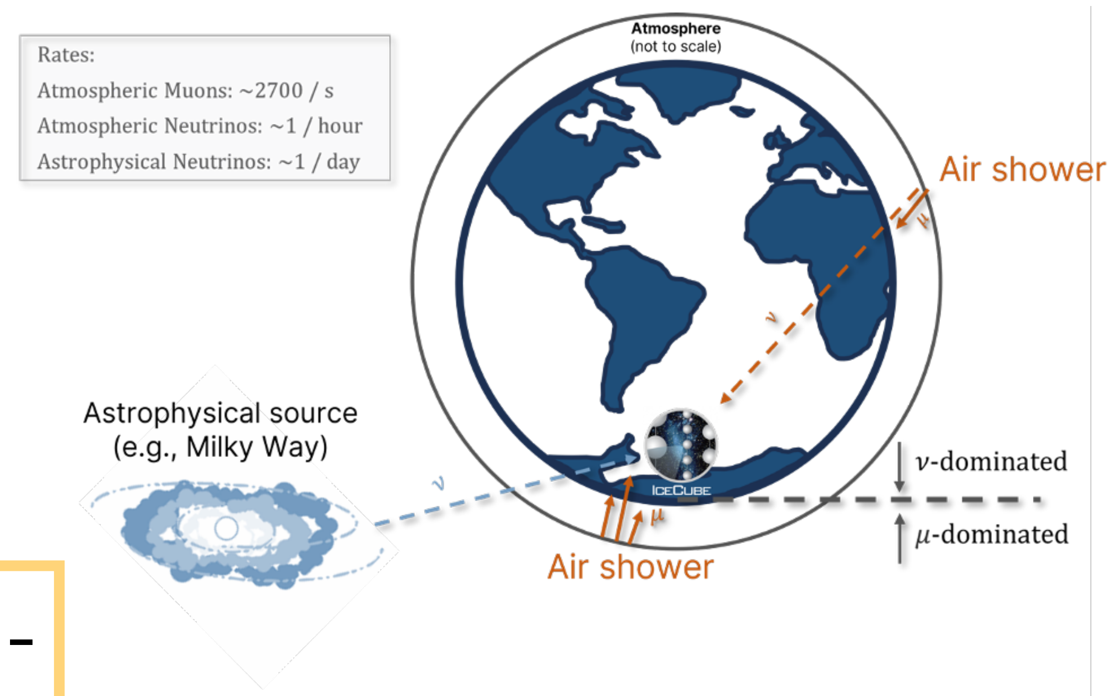

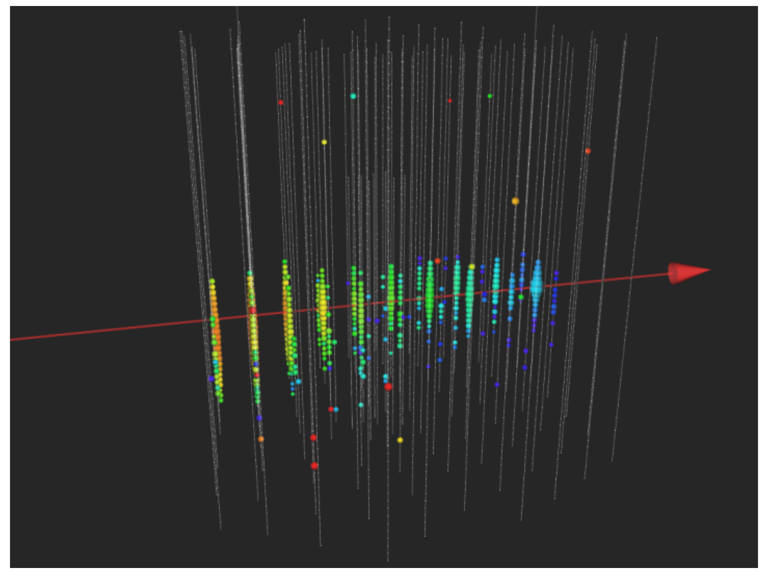

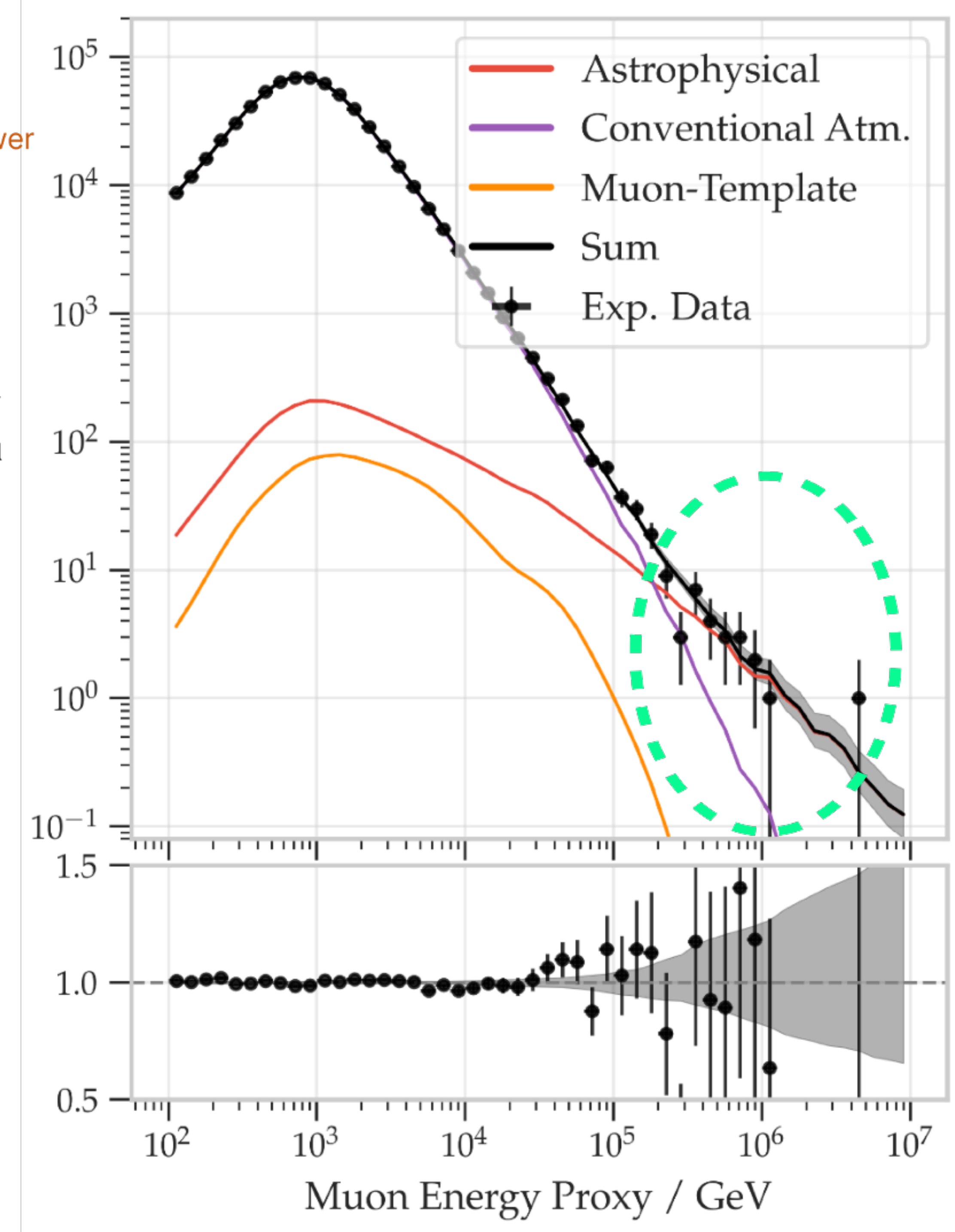

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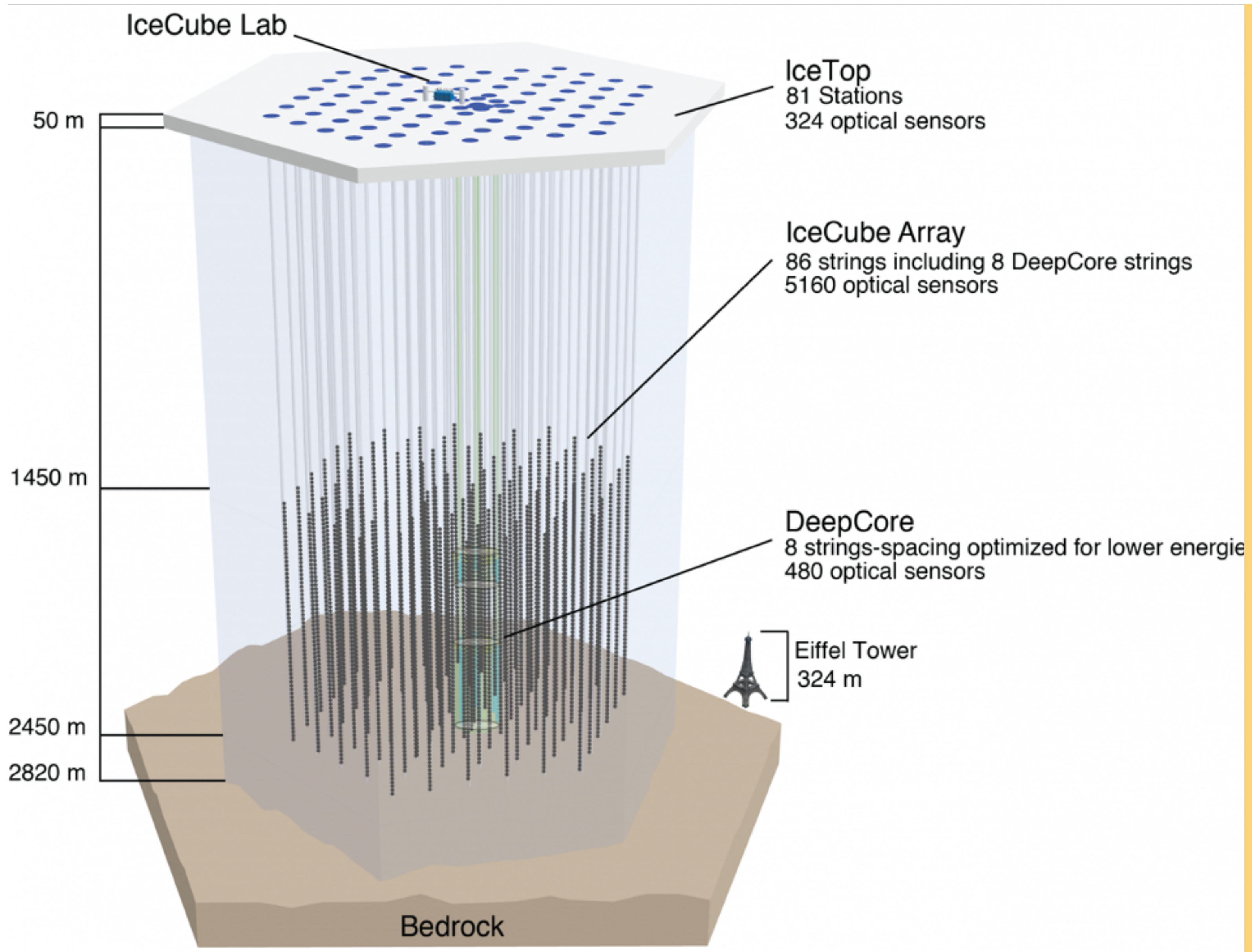

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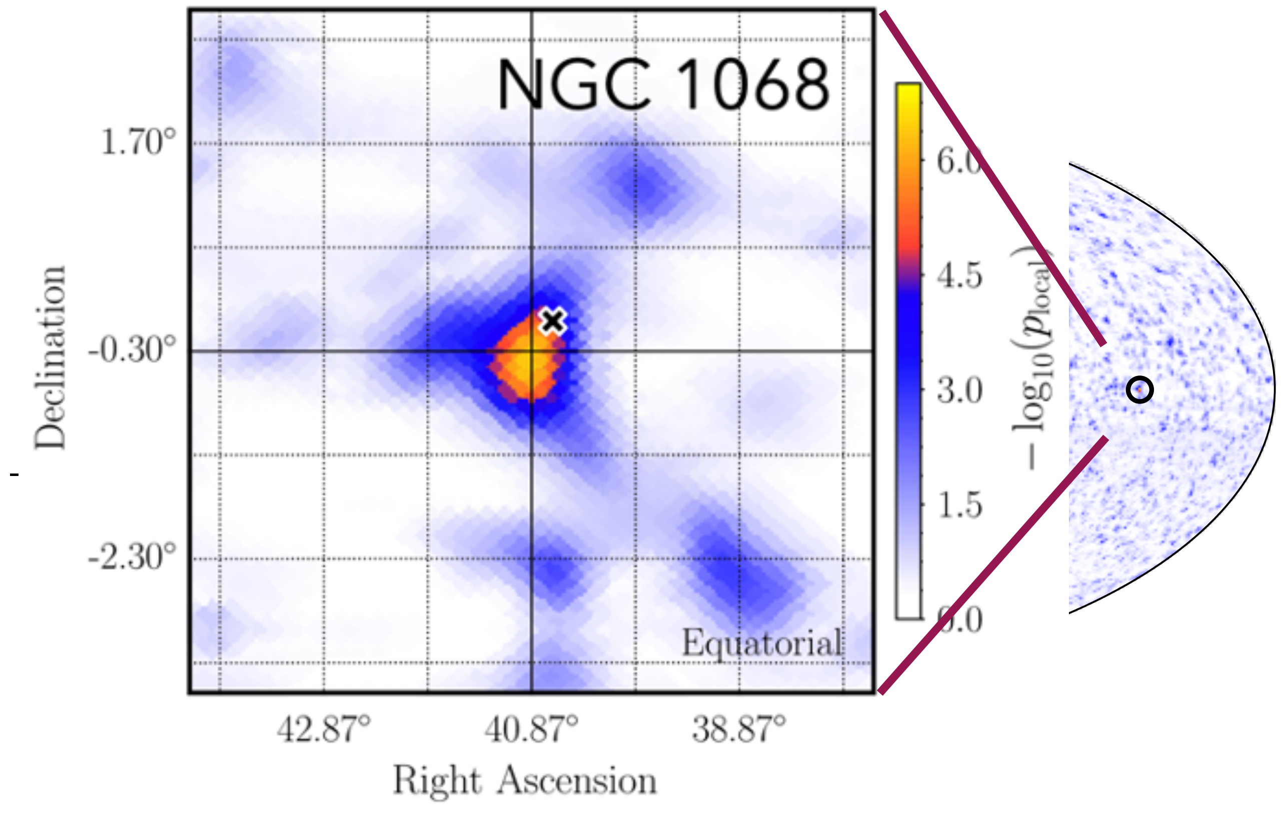

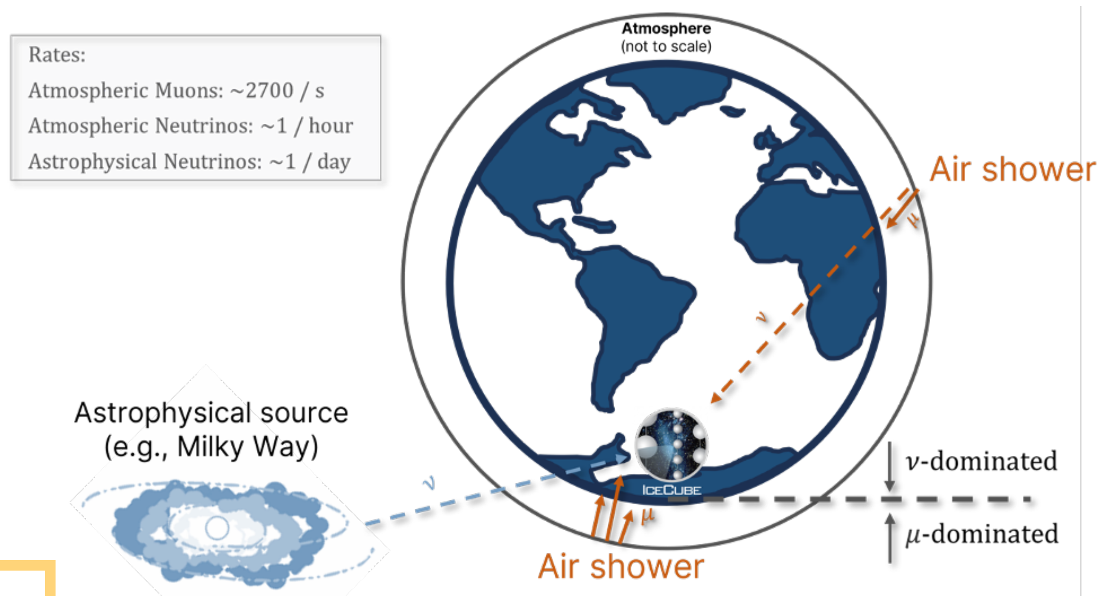

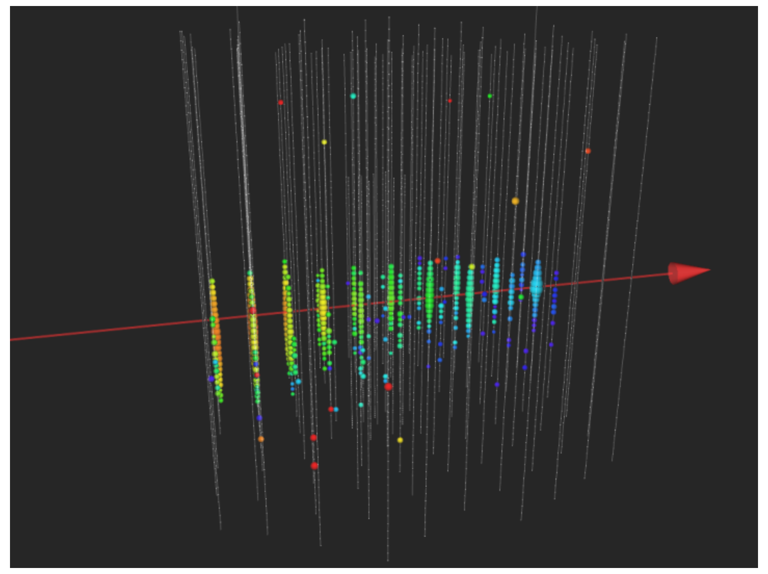

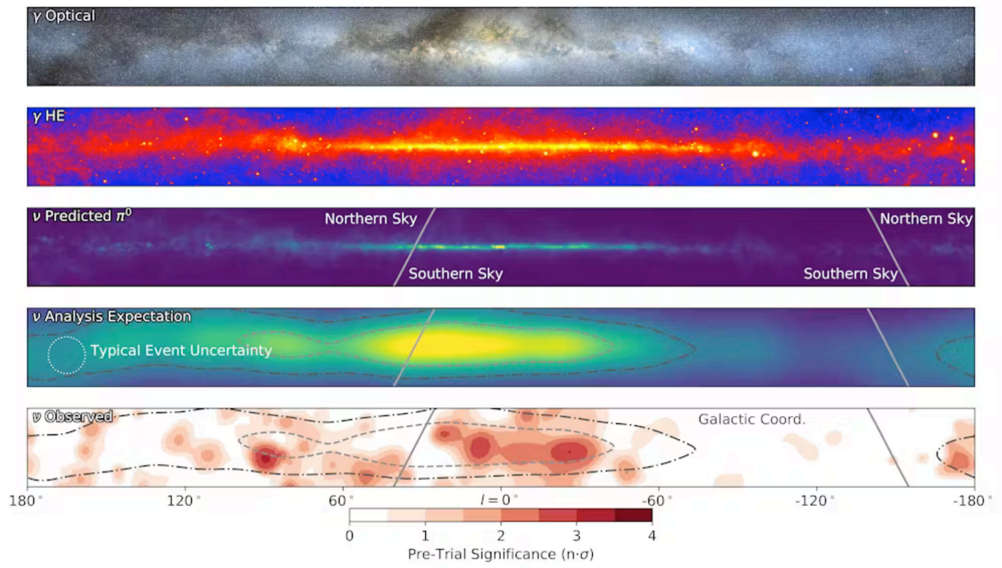

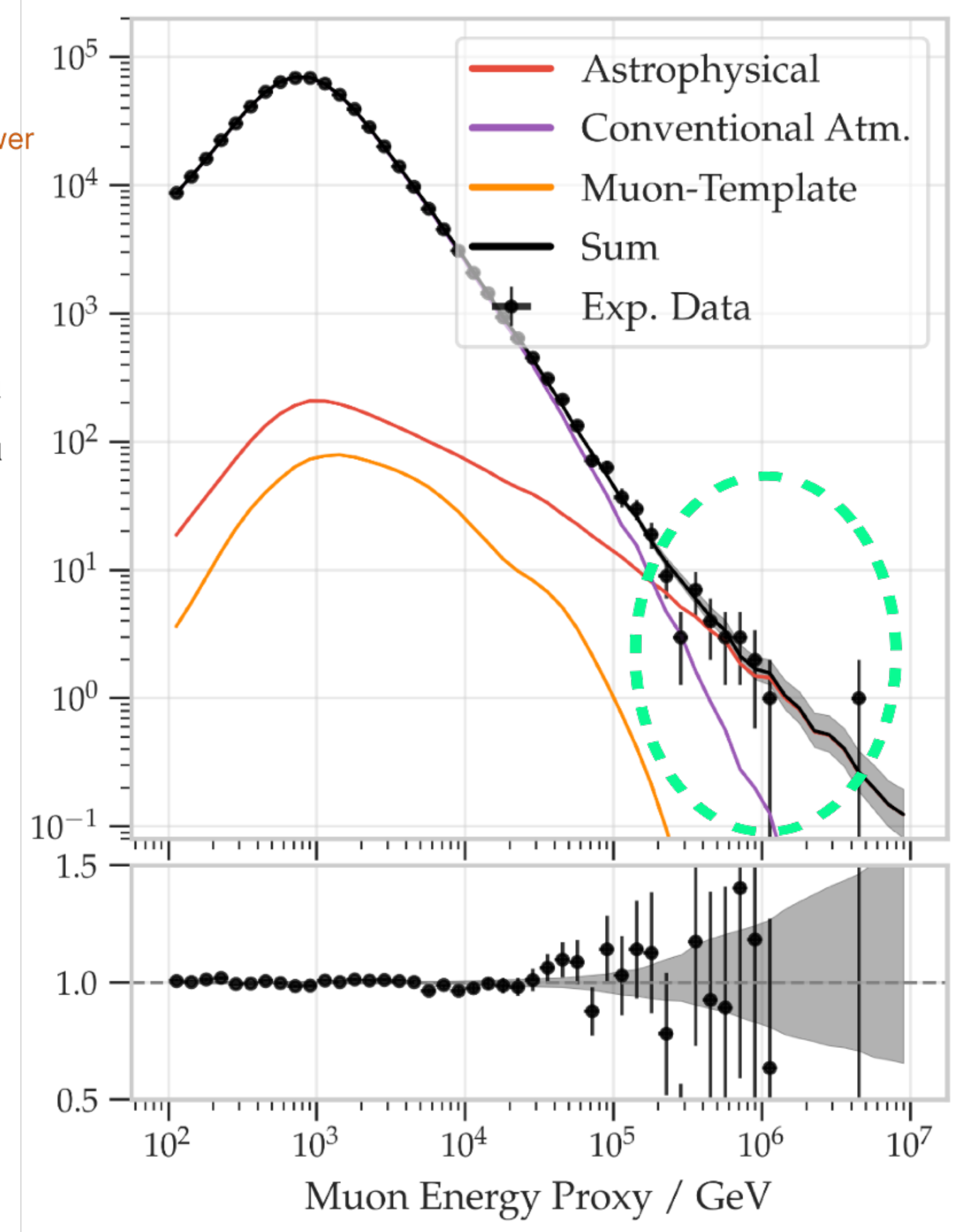

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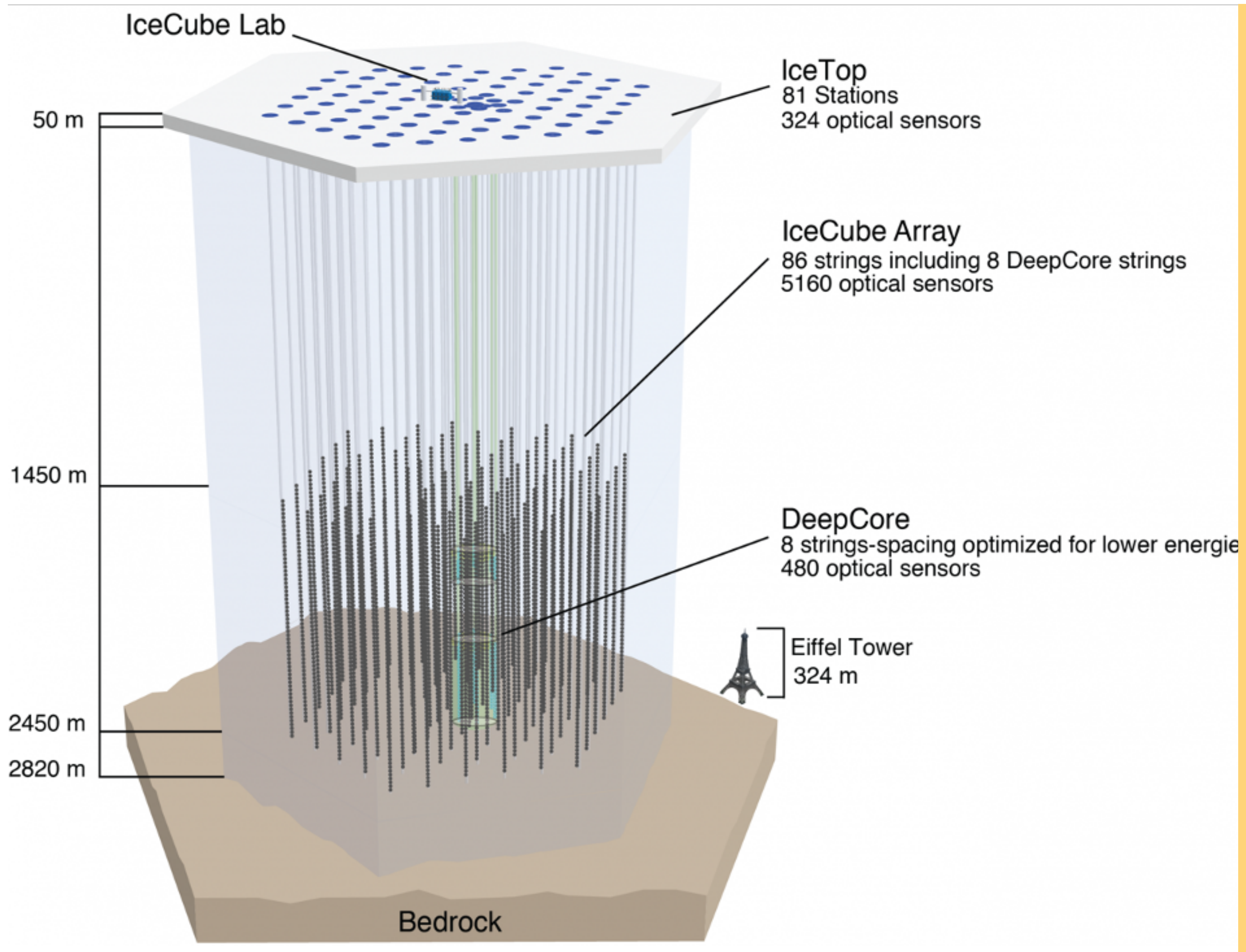

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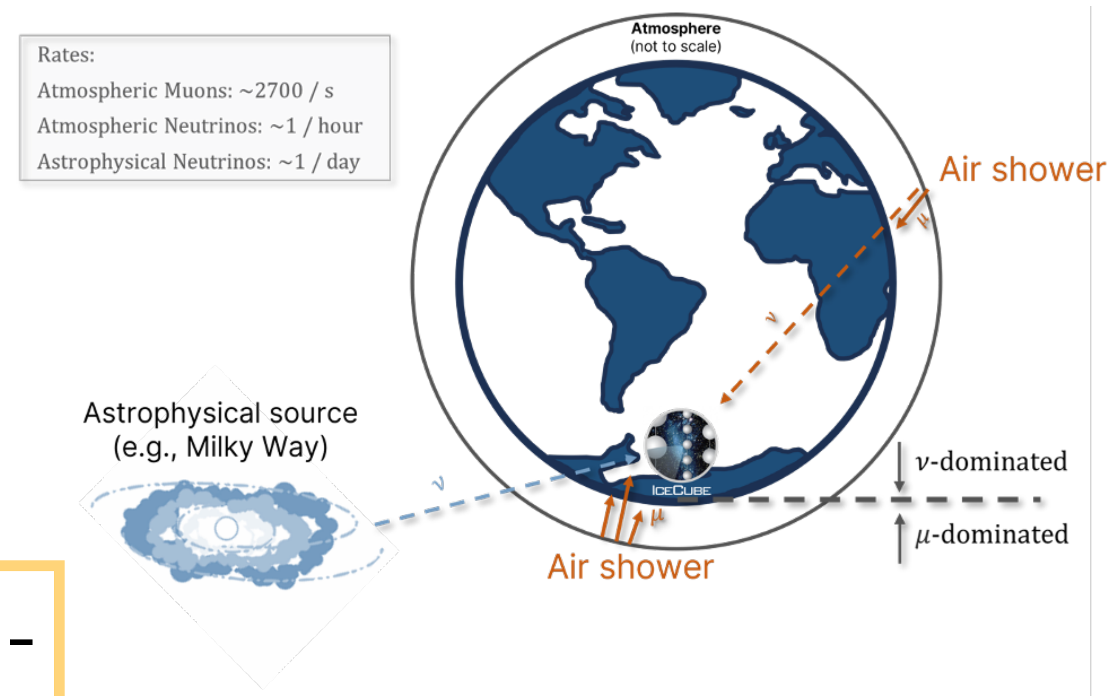
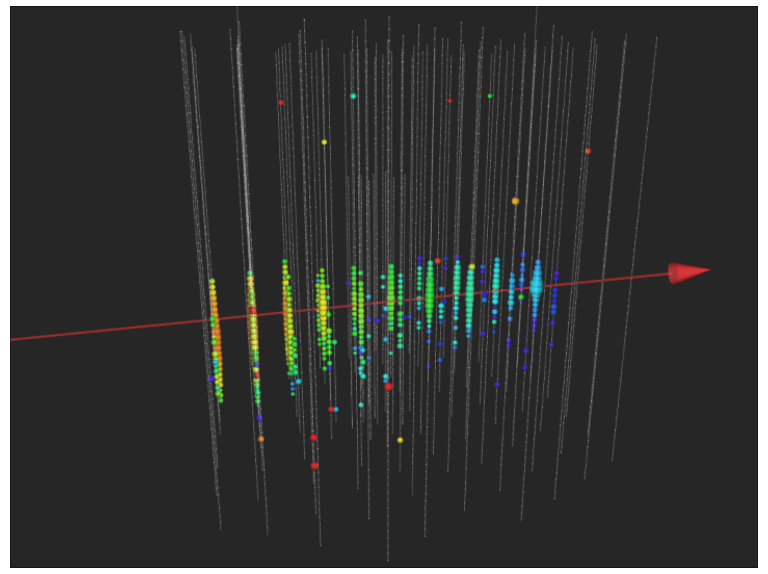
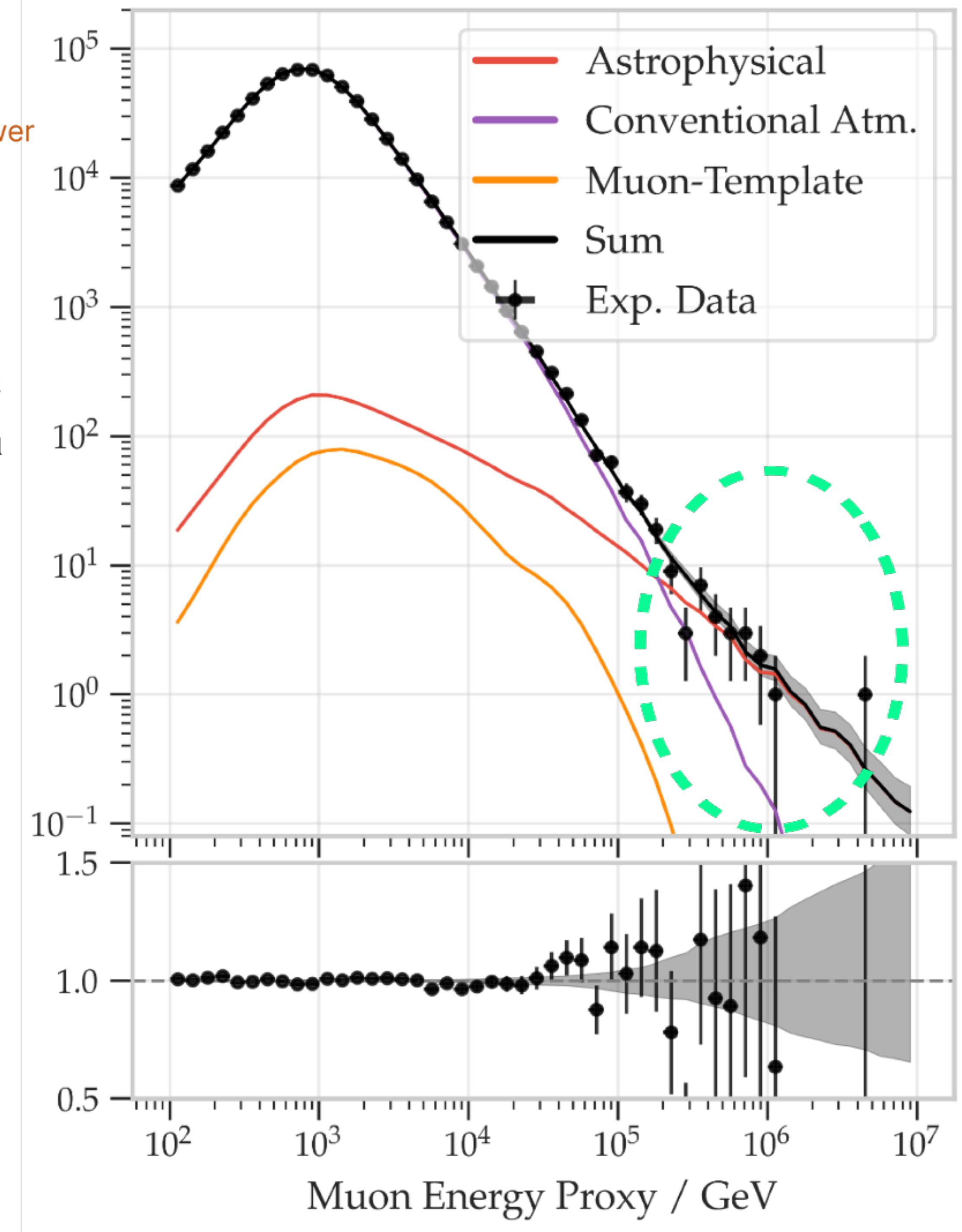
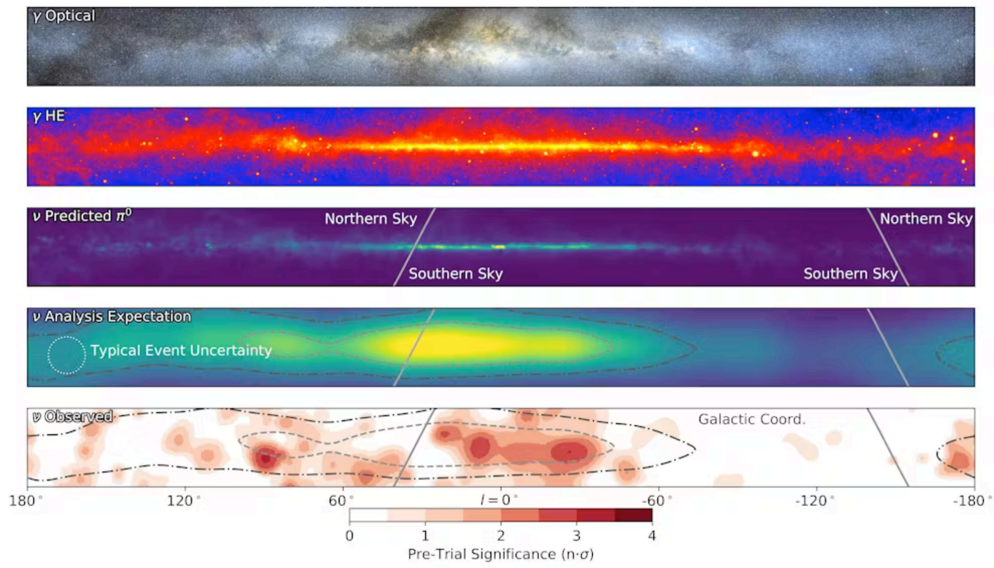
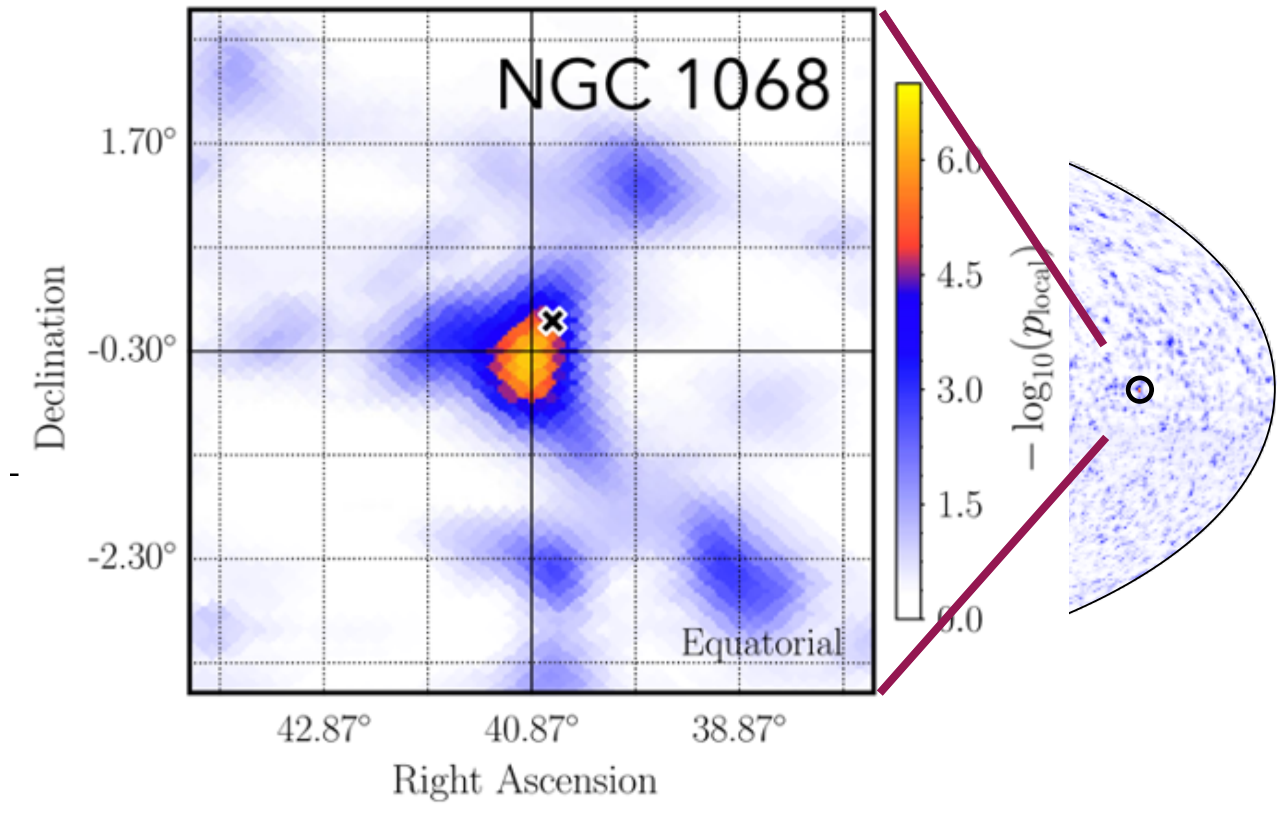






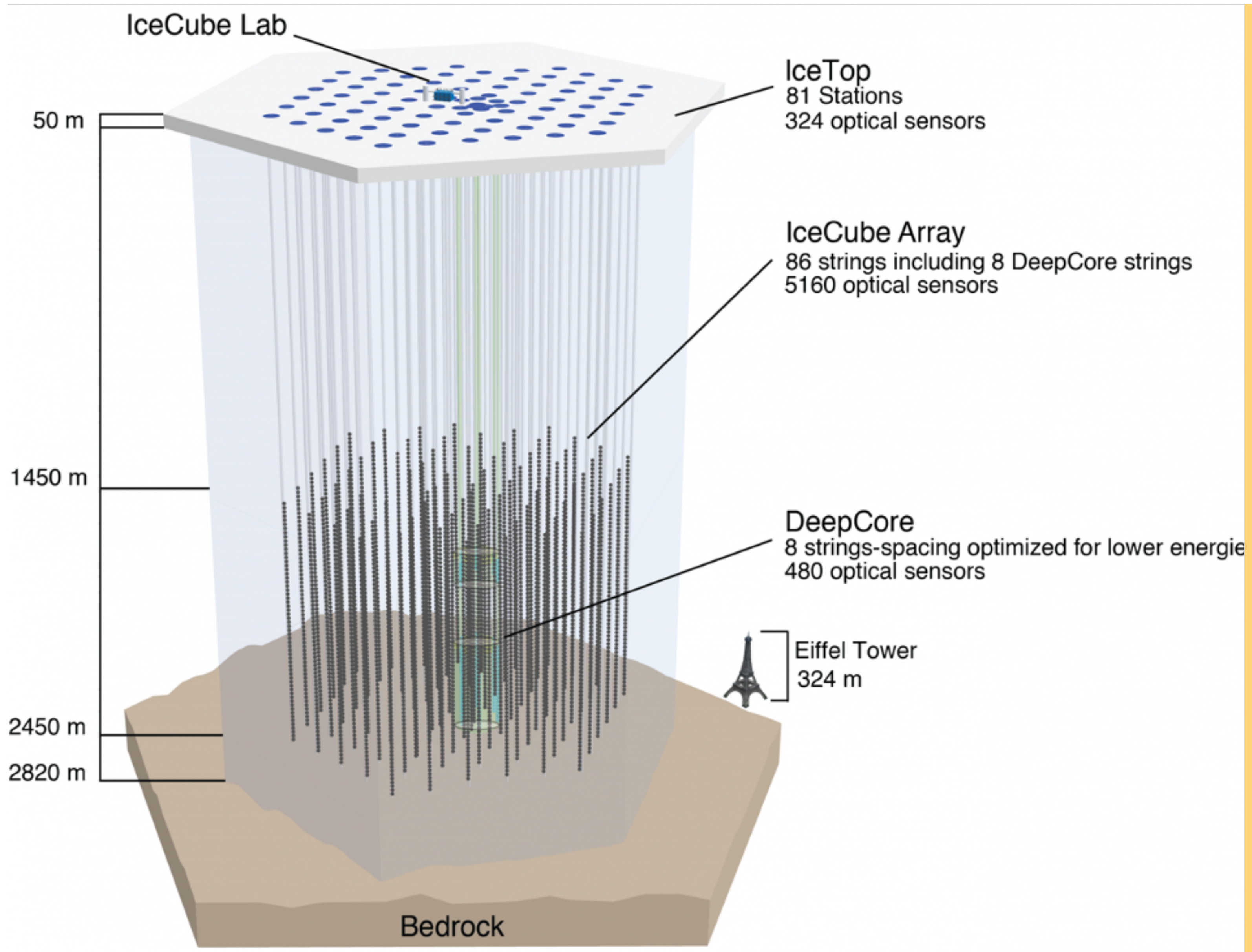


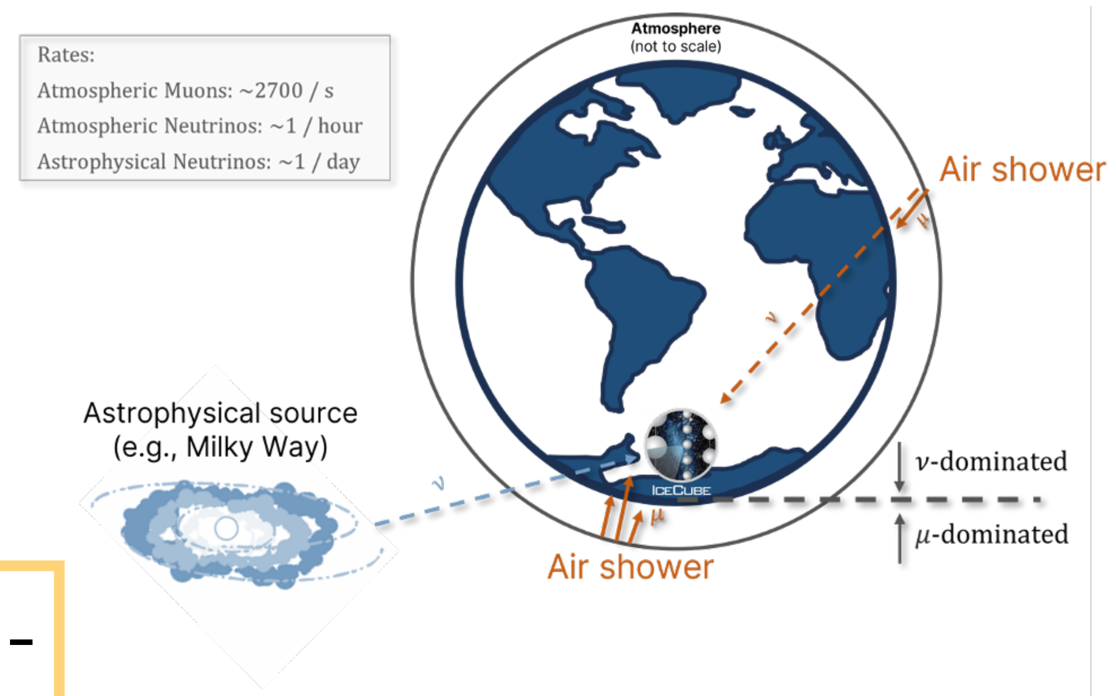


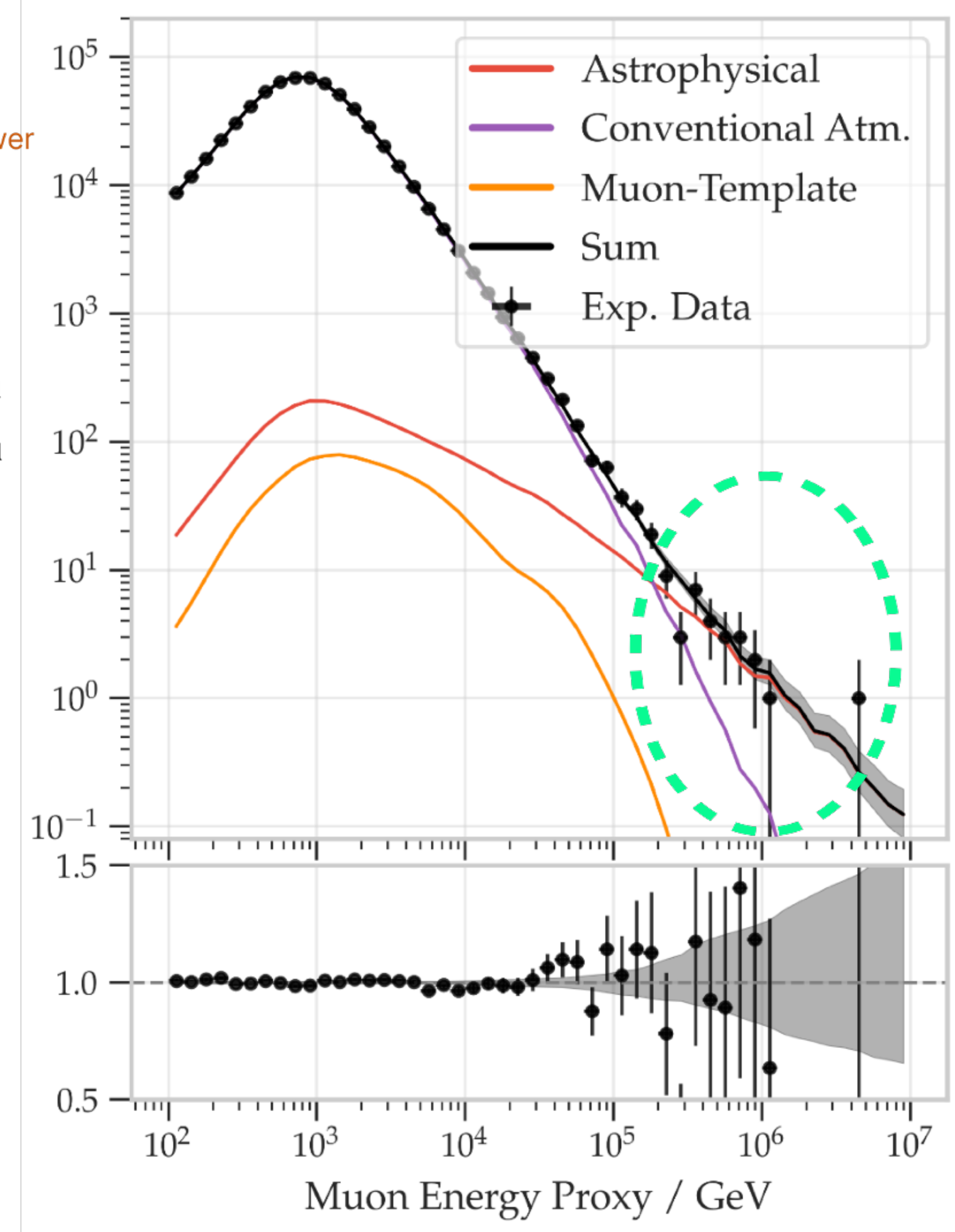
Neutrino astronomy is an exciting field

KM3NeT also taking data!

IceCube results







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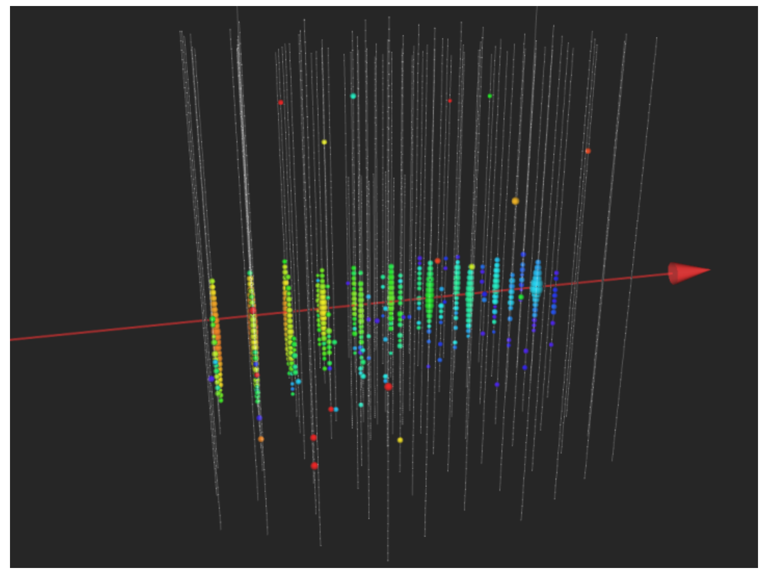
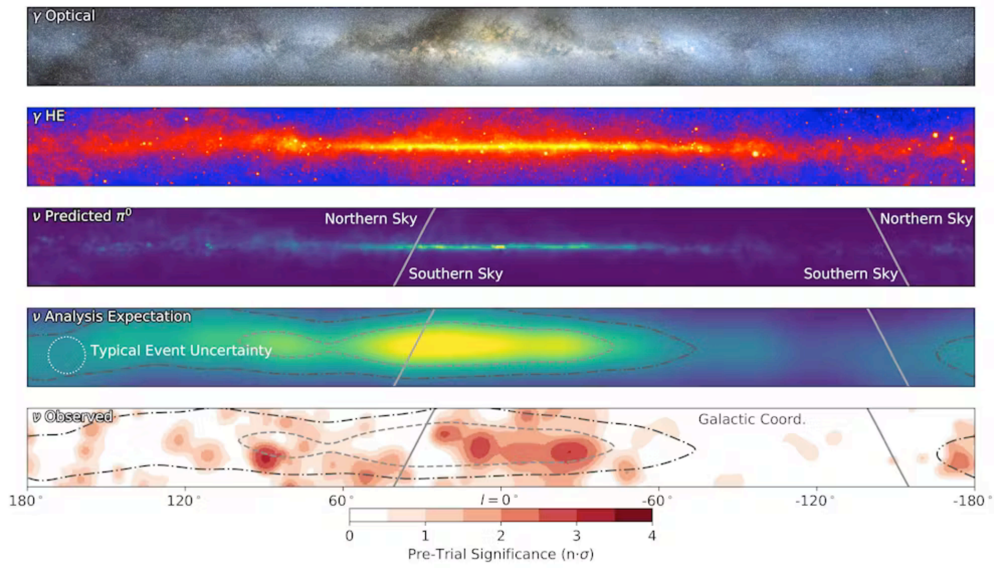
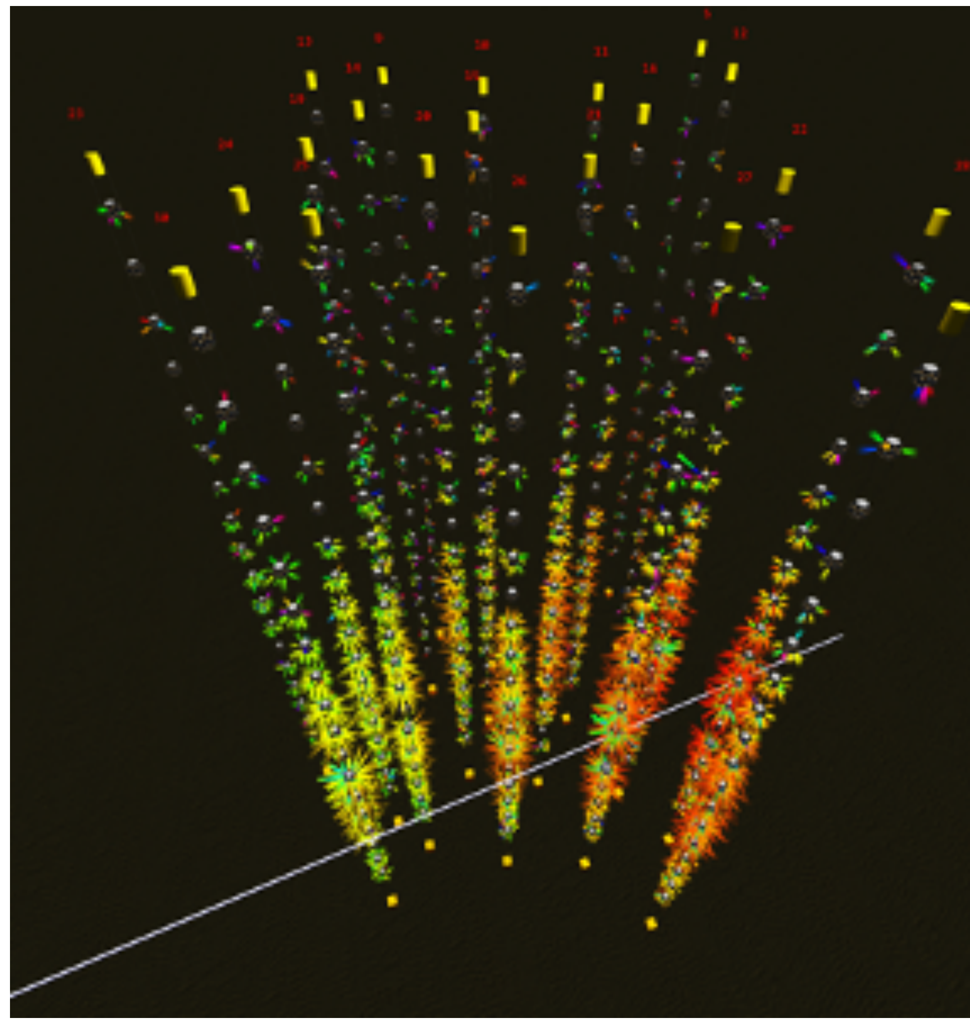
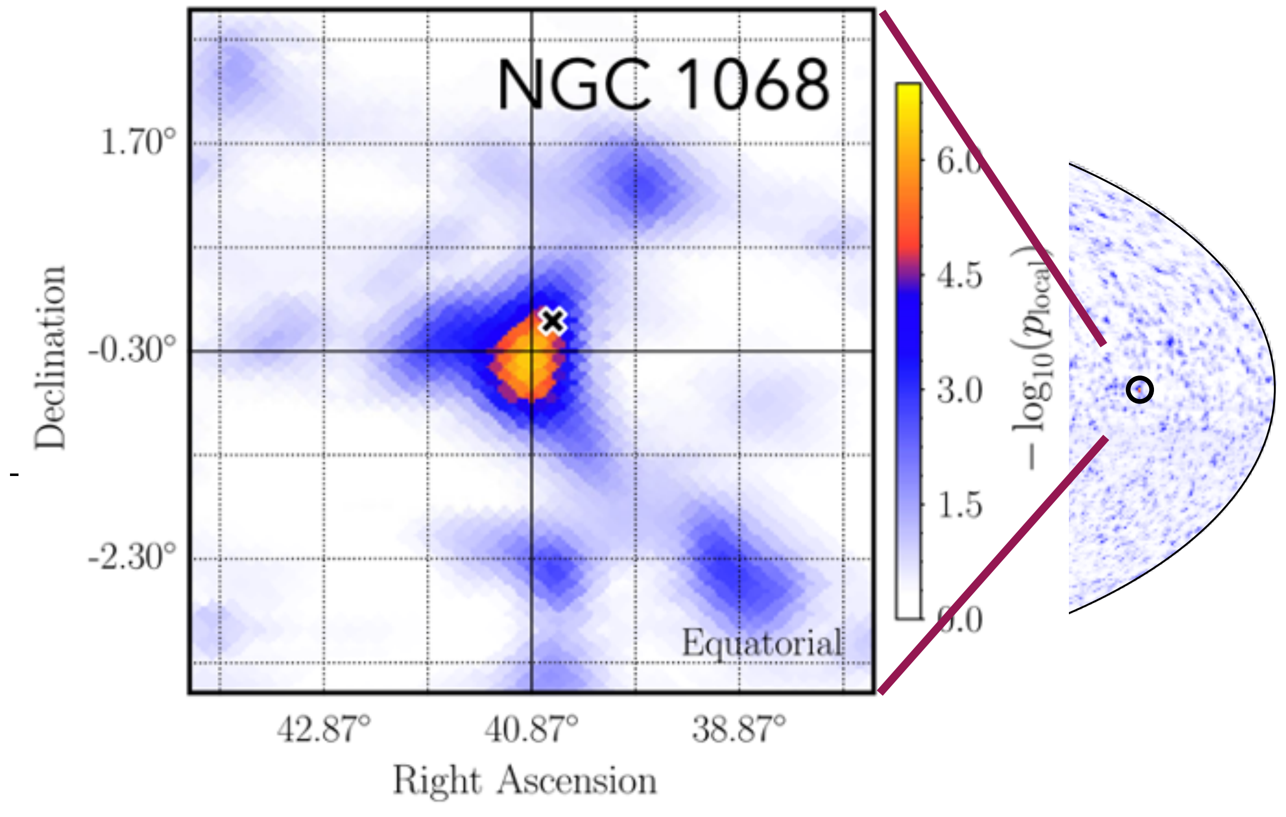
- 2022: Neutrino emission from the active galaxy NGC1068
- 2023: Evidence of neutrinos from the Galactic plane





Event (likely 10's of PeV) detected by KM3NeT





Neutrino astronomy is an exciting field

KM3NeT also taking data!

Conclusions

- Neutrinos are **massive** particles - breakthrough in Particle Physics → SM needs to be extended (how do neutrinos acquire their mass?)
- Neutrino **oscillations** are still one of the most important topics/priorities in Particle and Astroparticle Physics (beyond the Standard Model)
- Neutrino oscillations are under intense study but **next generation** of experiments with more capable detectors and powerful (anti-)neutrino beams are needed to <u>discover CP violation</u>, determine the <u>neutrino mass ordering</u> and measure with <u>precision all neutrino oscillation parameters</u>
- Many opportunities for **Beyond SM** with neutrinos (heavy neutrinos, NSI, …)
- Neutrino **mass** measurement is hopefully around the corner (in the lab and in cosmology)
- **Majorana or Dirac** neutrinos: intensive neutrinoless double beta experimental campaign trying to cover the IO range → an important technological step will be needed to explore lower masses
- More precise **solar** and **supernova** neutrino measurements will be provided by bigger and complementary detectors
- The beginning of a golden era for **high-energy neutrino** detection (and multi-messenger astronomy)

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Exciting neutrino physics program!

Merci beaucoup!