Current neutrino measurement results and plans

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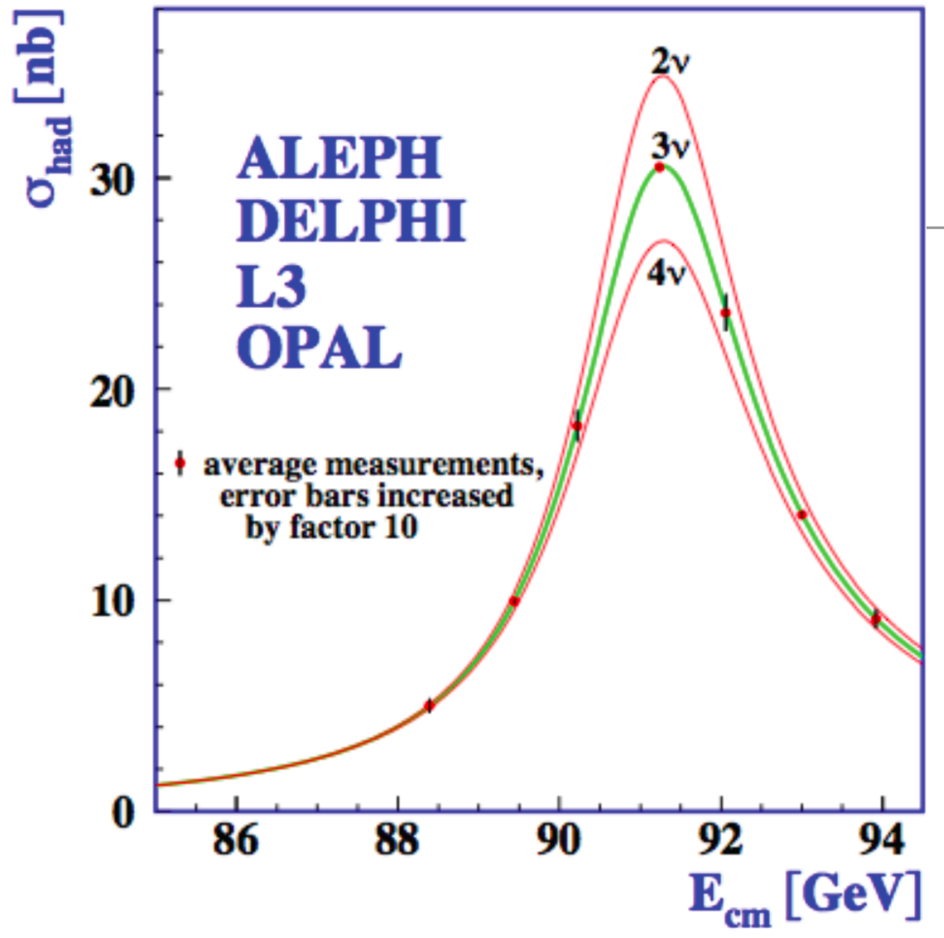
Disclaimer

- Imposible to cover all neutrino physics results in one talk
- (My personal) selection of some results
- Apologies for omissions

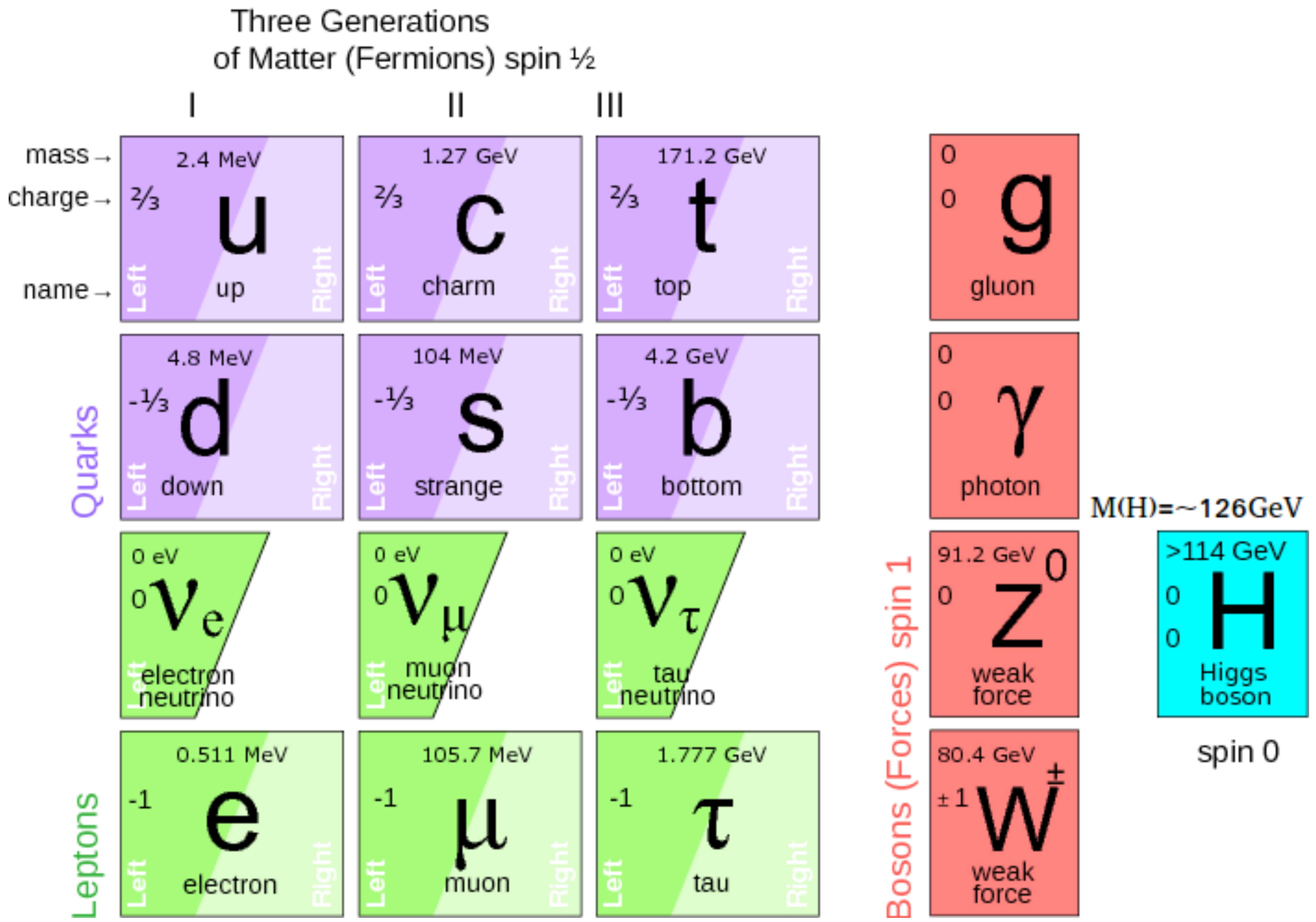
Outline

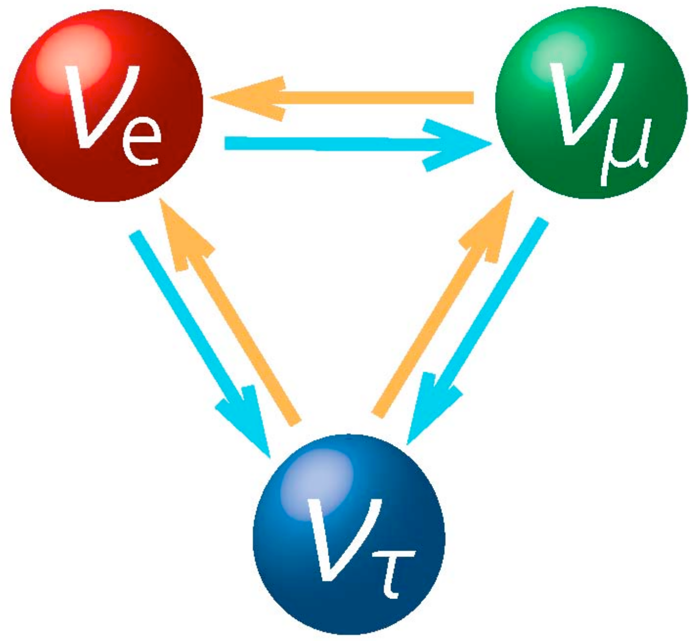
- Where do we stand?
- Neutrino oscillation measurements
  - ✦ Global fits
  - ✦ Solar, reactor neutrino results
  - ✦ LBL, atmospheric neutrino results
  - ✦ Anomalies
  - ✦ Prospects: JUNO, HK, DUNE
- Neutrino mass measurements
- Neutrinoless double beta decay searches
- CEvNS
- Astrophysical neutrinos
- Conclusions

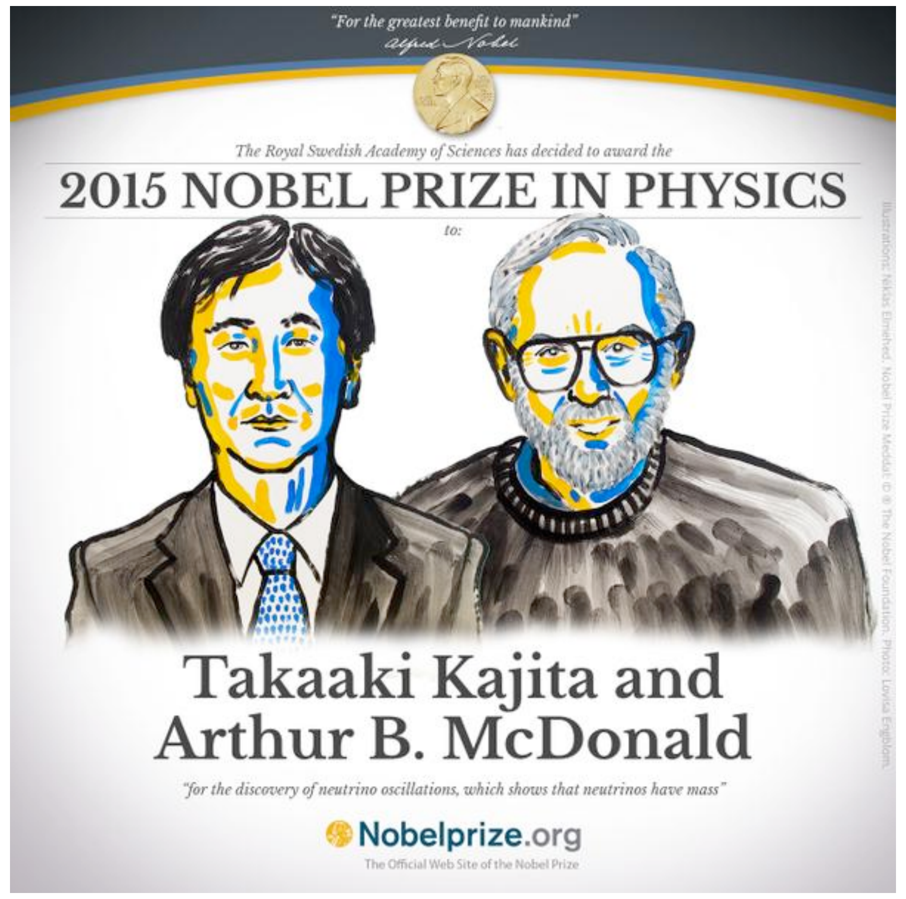
Neutrinos beyond the Standard Model



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



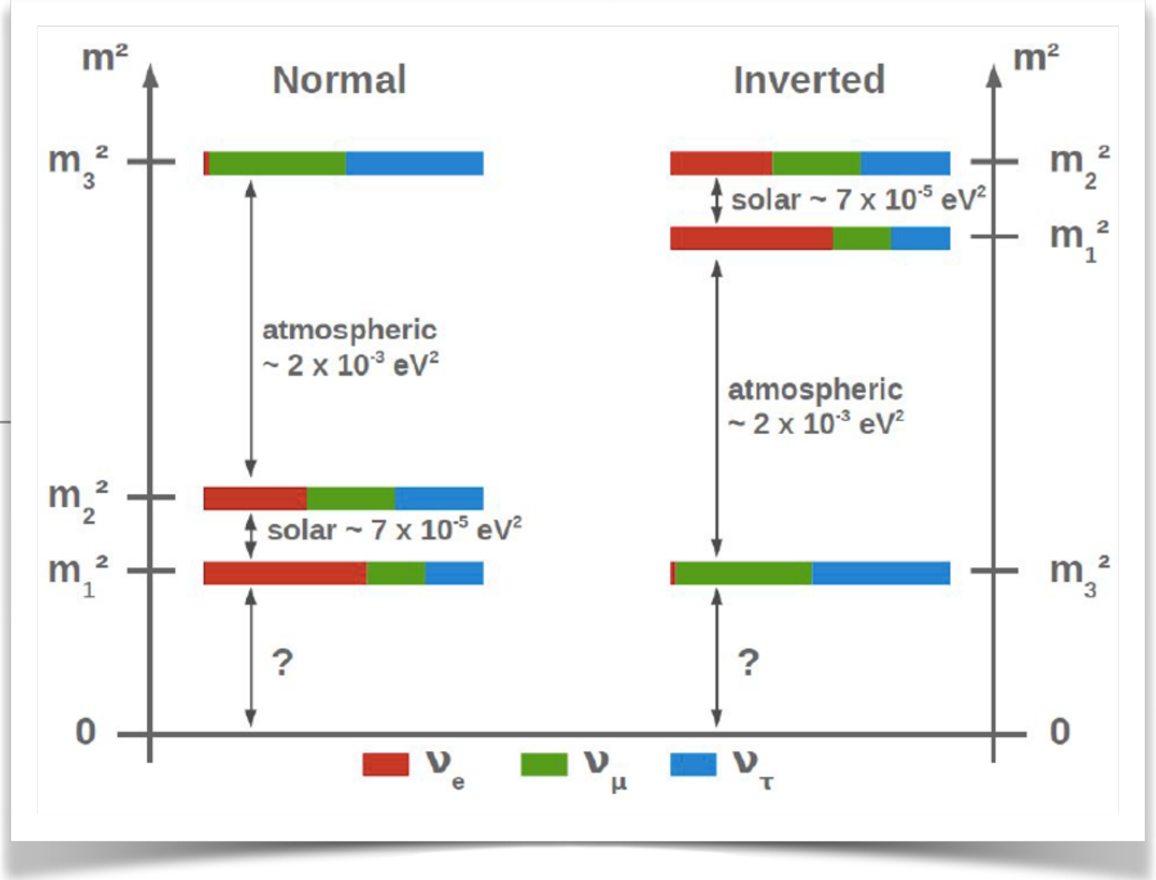




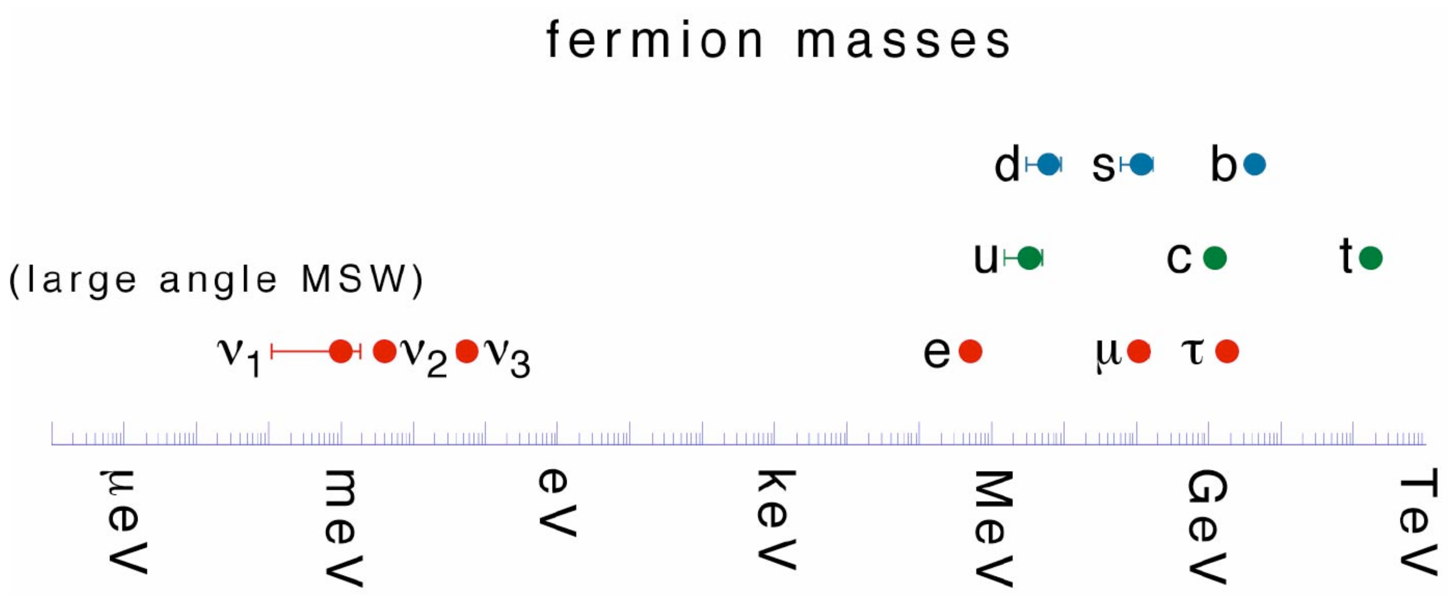
- Observation of neutrino oscillations → **non-vanishing neutrino mass** (flavor mixing)
- First evidence of **physics beyond the Standard Model**

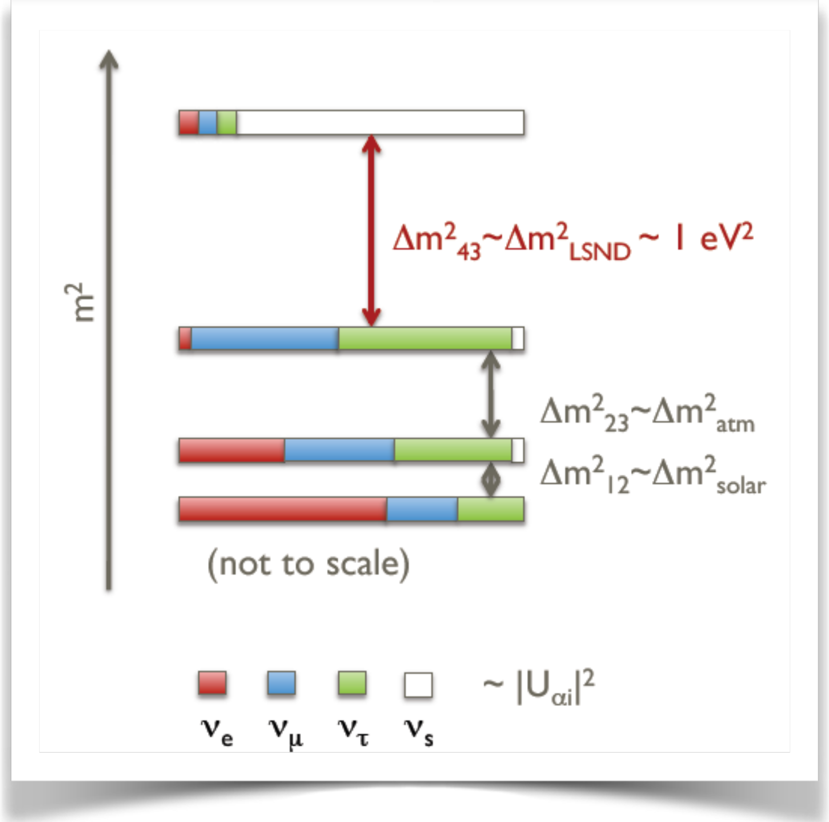
Main open questions

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



- ✦ What is the absolute neutrino mass scale?
- ✦ Dirac or Majorana neutrinos?
- ✦ Why are neutrinos much lighter than the other fermions?
- ✦ What is the neutrino mass ordering?
- ✦ Is the CP-phase non-zero? What is its value?
- ✦ Are there any sterile neutrino states? If so, what are their masses?
- ✦ Deviations from unitarity of the PMNS matrix?

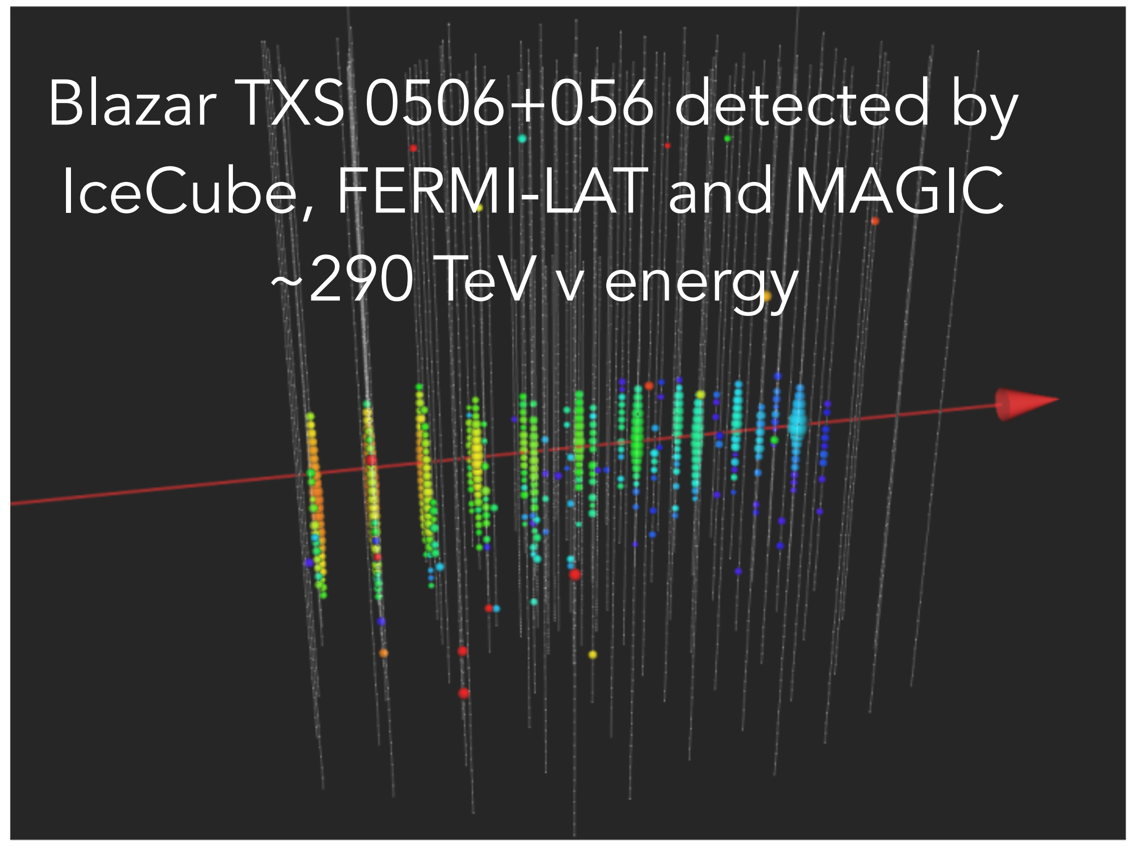


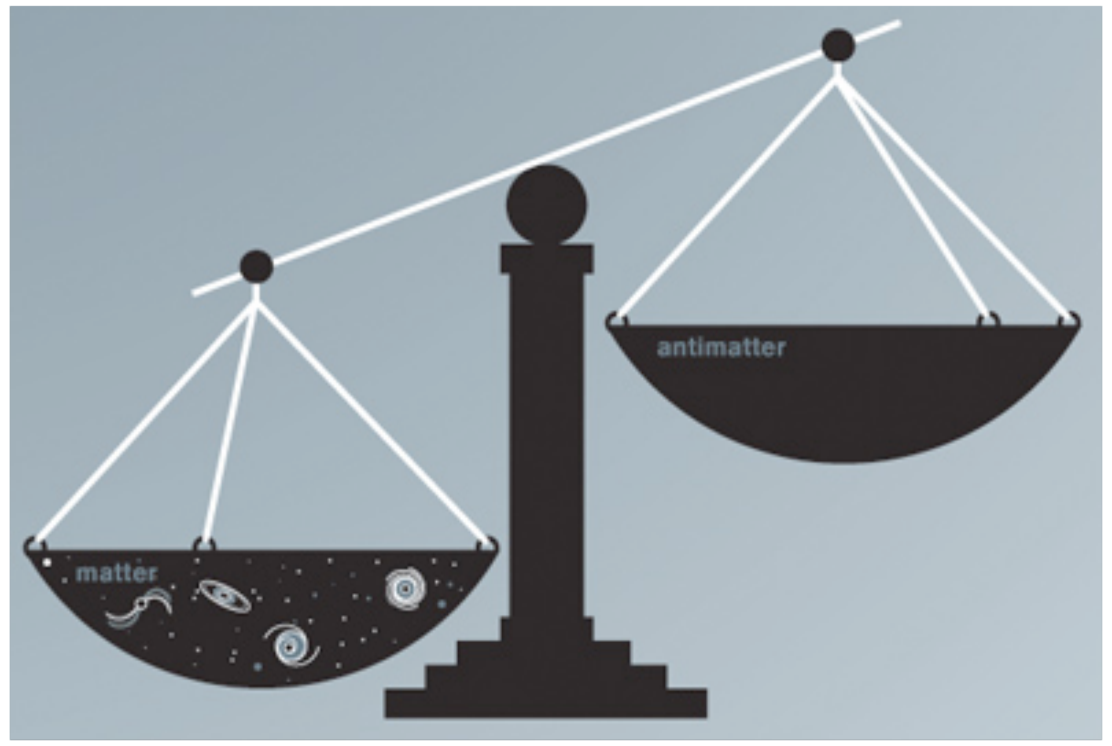


Connection with astrophysics and cosmology

Neutrinos as **probes of the Universe**:

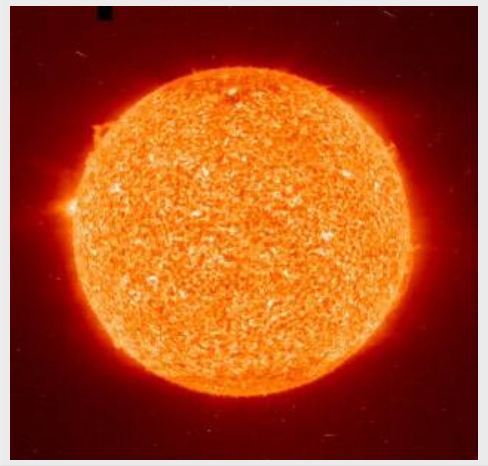
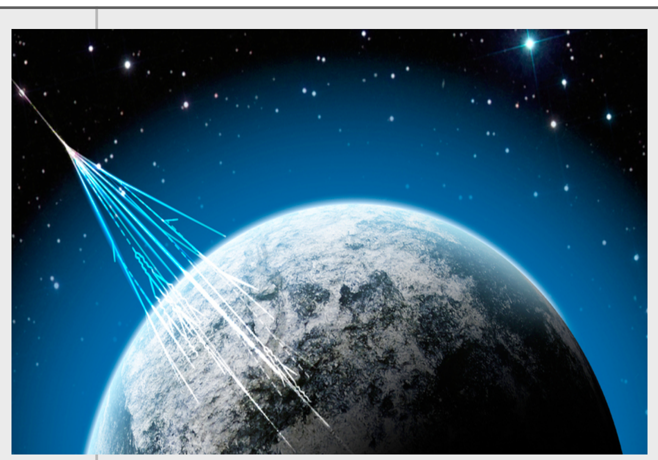
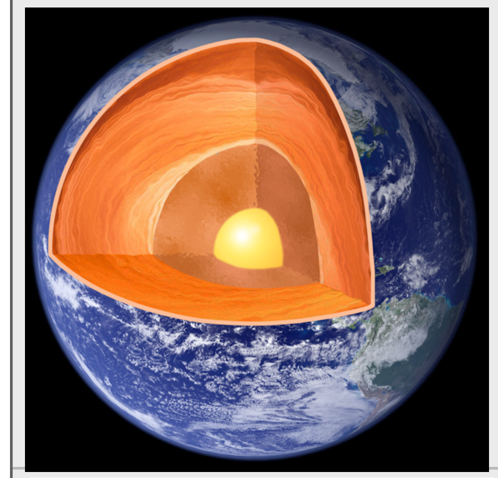
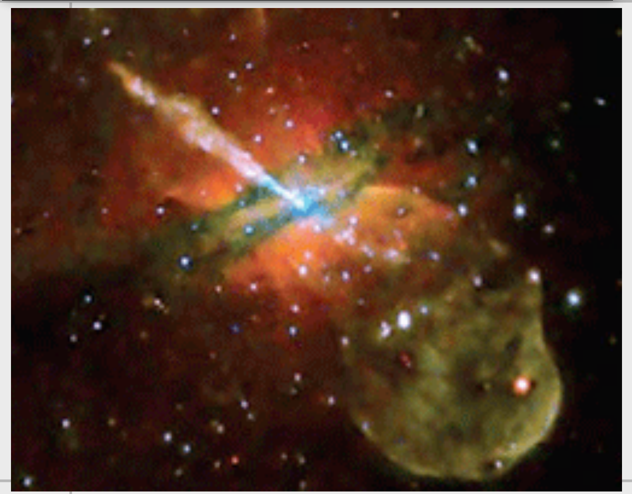
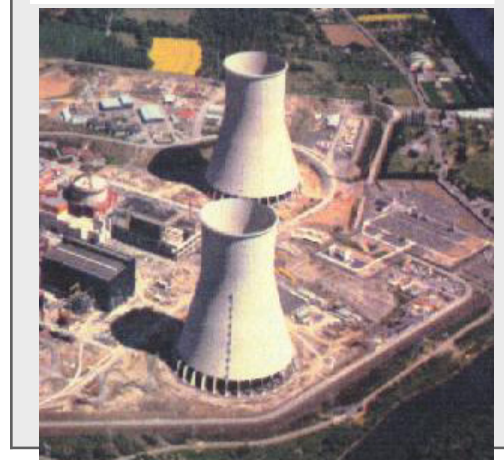
- ✦ High-energy neutrino physics
- ✦ New astrophysical sources
- ✦ Core-collapse supernova and diffuse SN neutrino background
- ✦ Relic neutrinos from early Universe
- ✦ Matter-antimatter asymmetry relation
- ✦ Sterile neutrinos as dark matter?





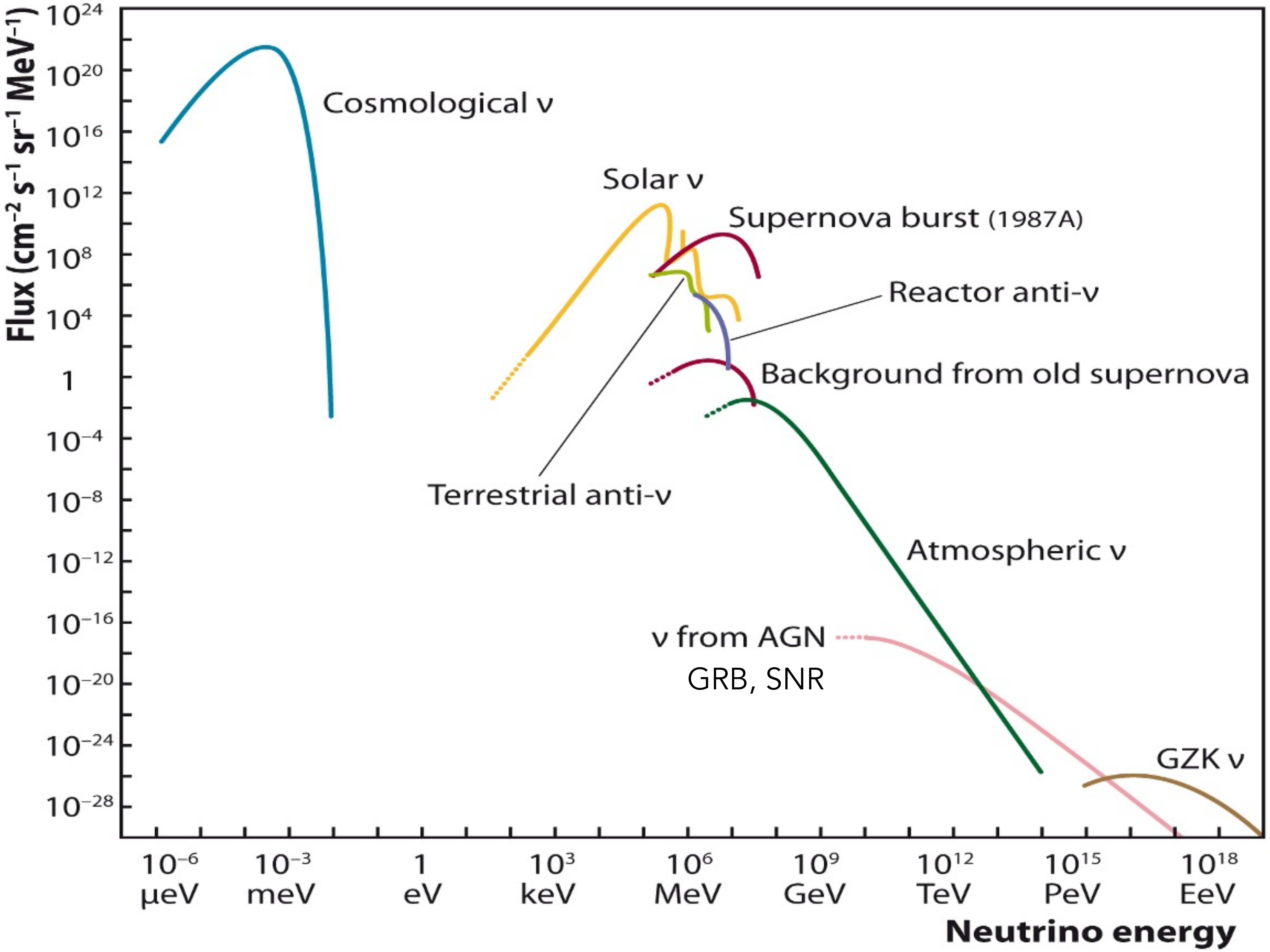
Neutrino sources

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 ≲ meV Big Bang L ~ Mpc		E ~ TeV-PeV Astrophysics Accelerators L ~ kpc- Mpc
	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

ARTIFICIAL

Neutrino fluxes at Earth



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} — Atmospheric + LBL acc.

θ_{13}, δ_{CP} — SBL reactors + LBL acc.

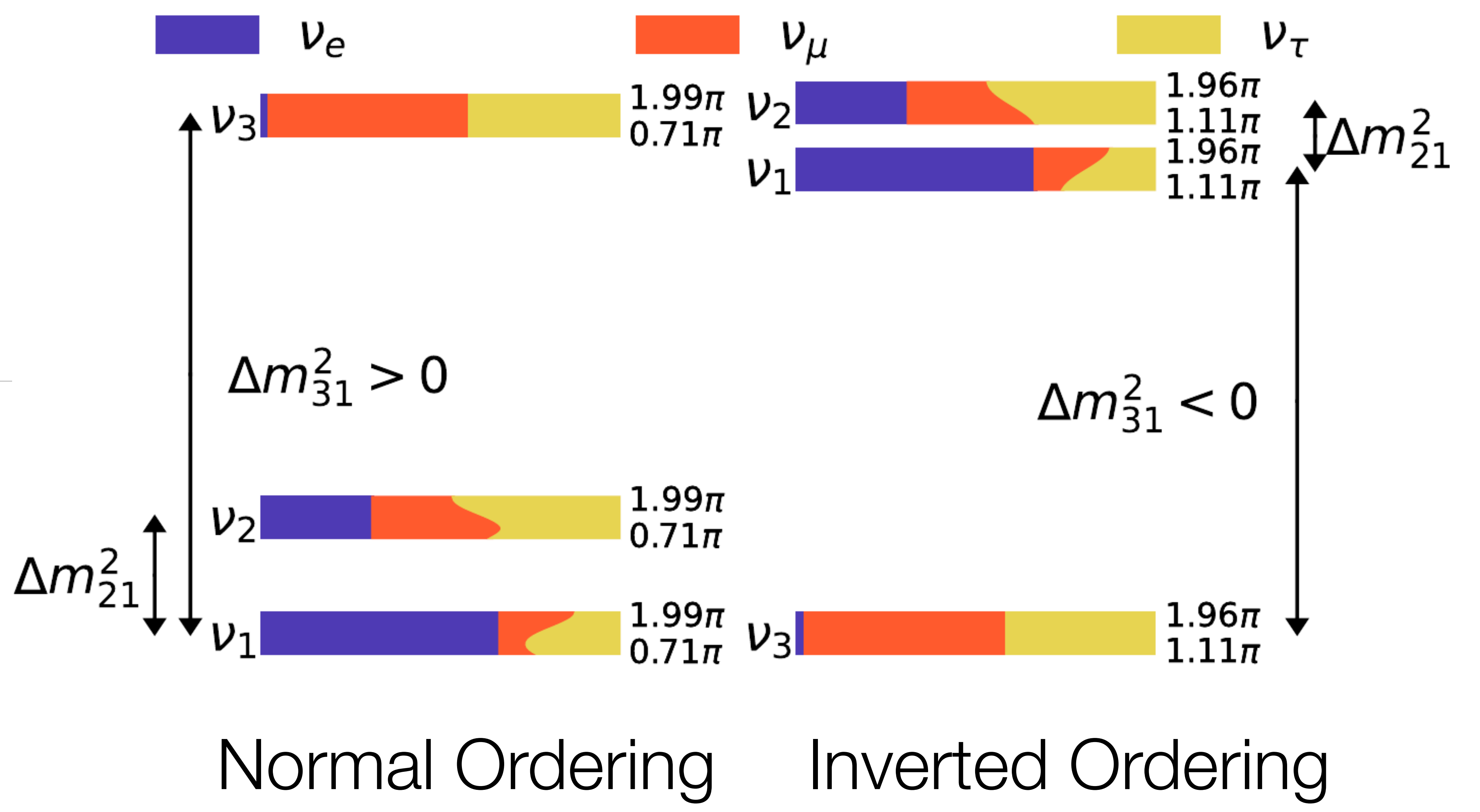
θ_{12} — Solar + KamLAND

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

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



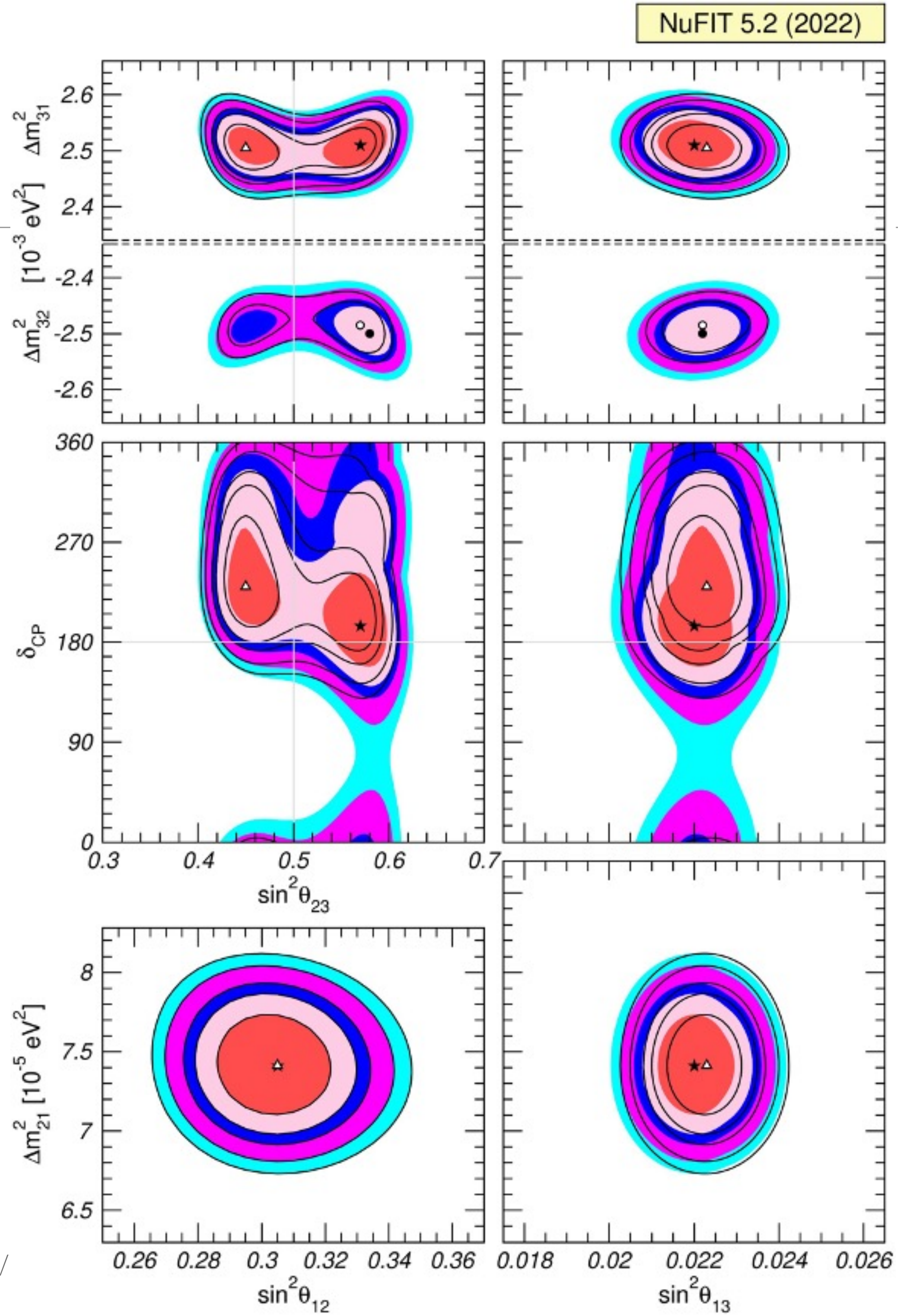
Unknown parameters: mass ordering (sign of Δm^2_{31}), δ_{CP}, octant of θ_{23}

Global fit information

Global 6-parameter fit (including δ_{CP}):

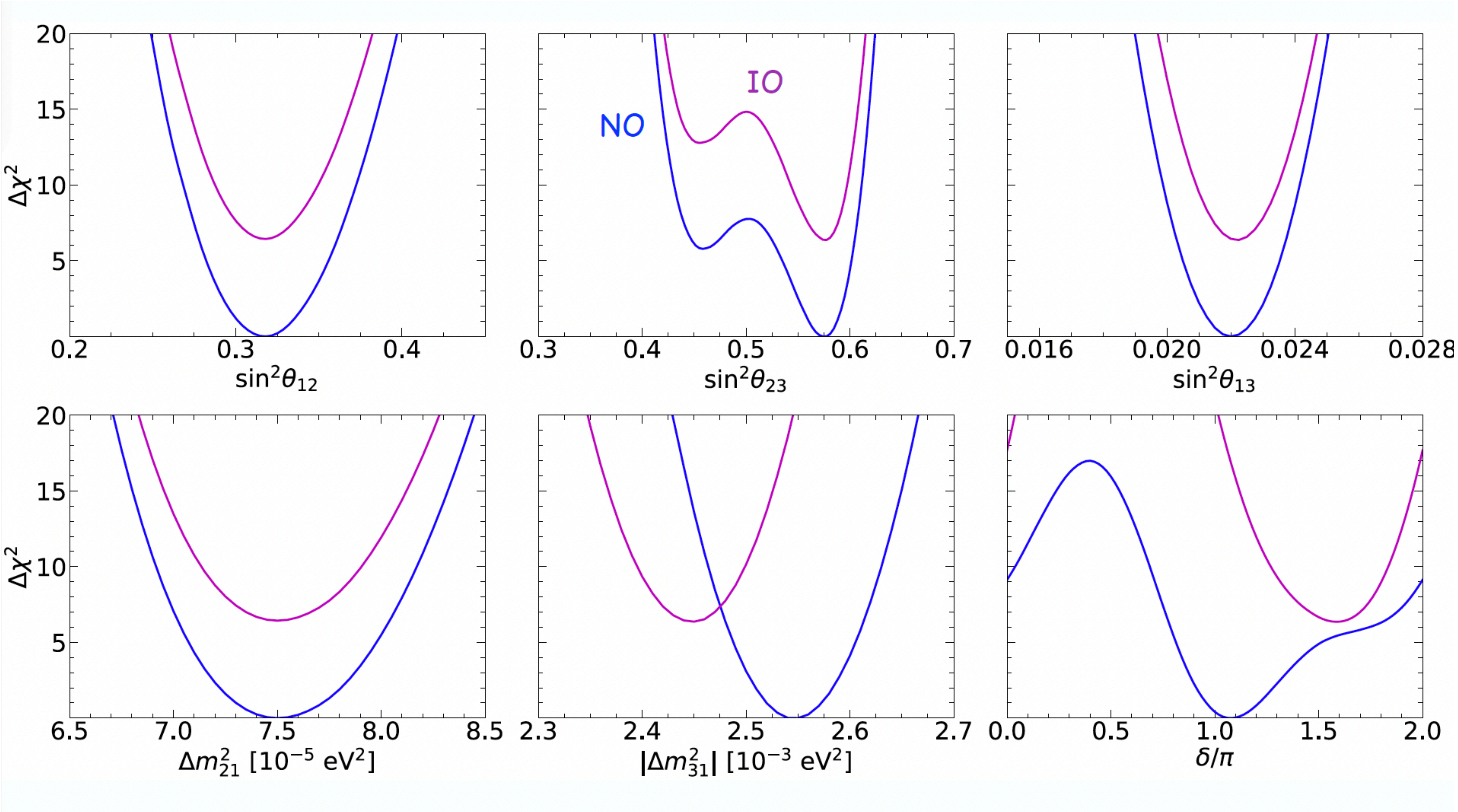
- **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + Borexino;
- **Atmospheric**: SK-1 + SK-2 + SK-3 + SK-4; + IceCube
- **Reactor**: KamLAND + Double-Chooz + Daya-Bay + Reno;
- **Accelerator**: Minos (DIS+APP) + T2K (DIS+APP);
  + NOvA (DIS+APP)

- **θ_{23} octant** is **not resolved** yet (slight preference for the second octant)
- The sign of **Δm^2_{32}** is **unknown** (Normal Ordering preferred at ~2.5σ)
- **δ_{CP} unknown**: Some tension between current LBL and atm experiments in NO. CP-violation for IO at ~3σ



Global fit results

de Salas et al., JHEP 02 (2021) 071



Global fit results

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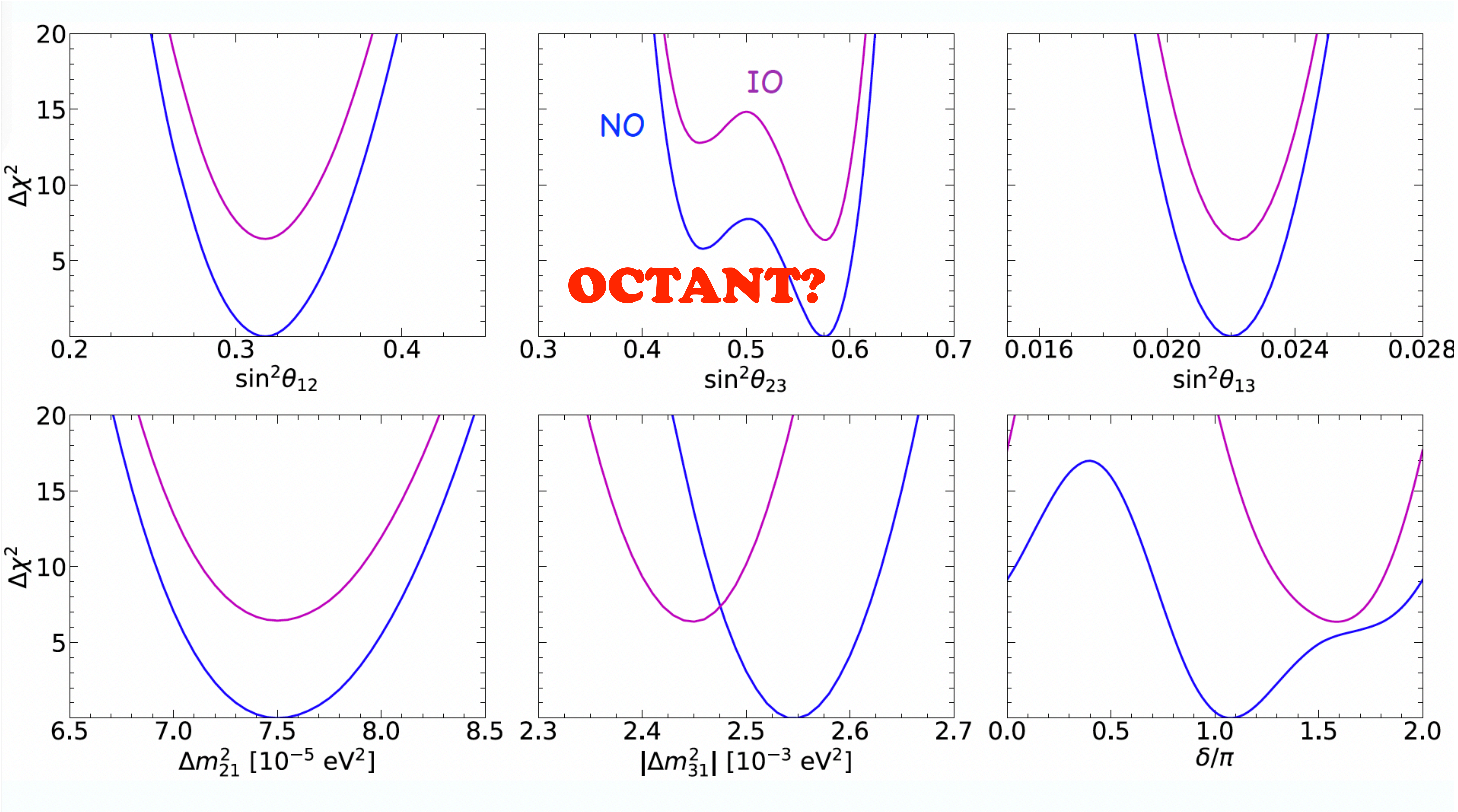
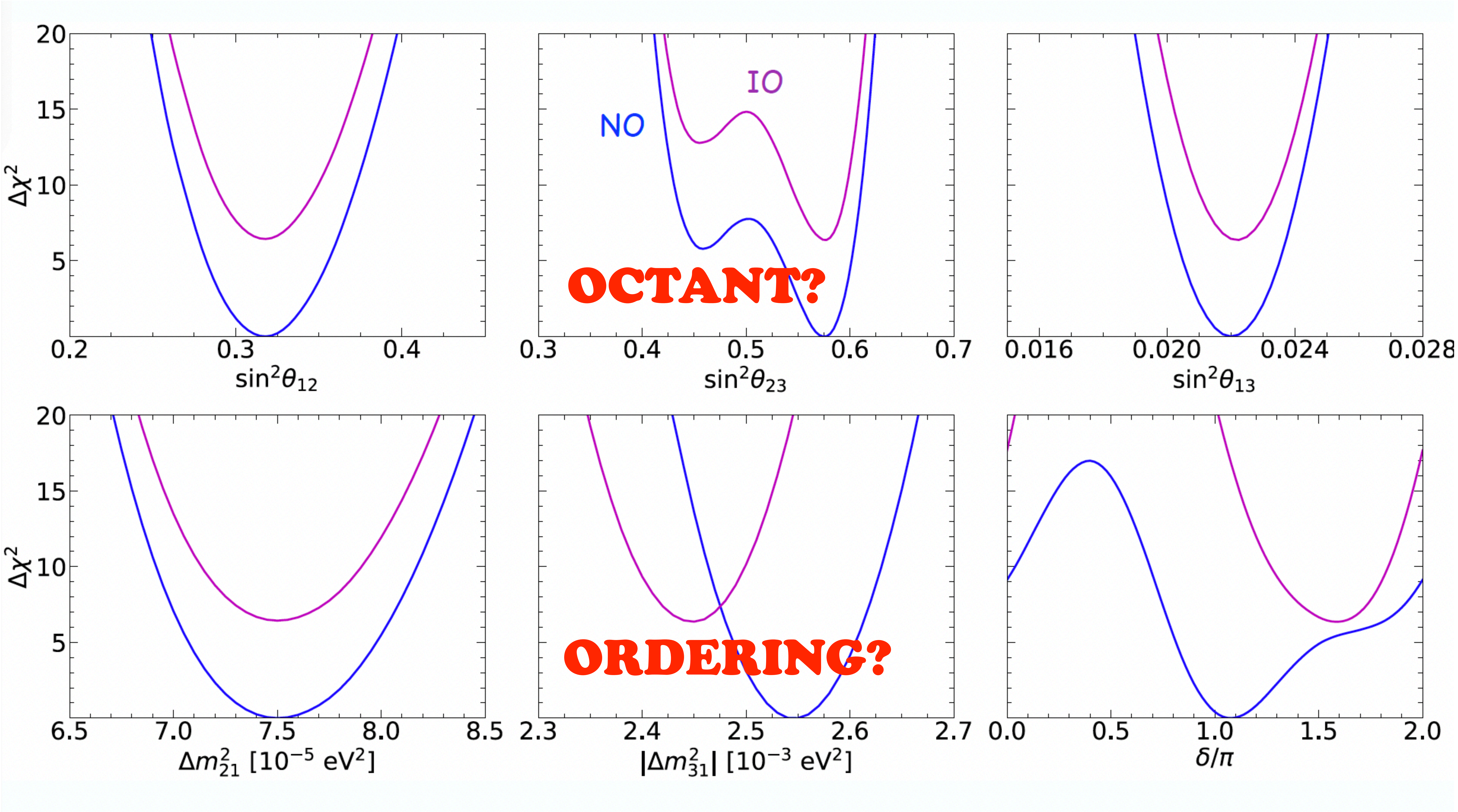


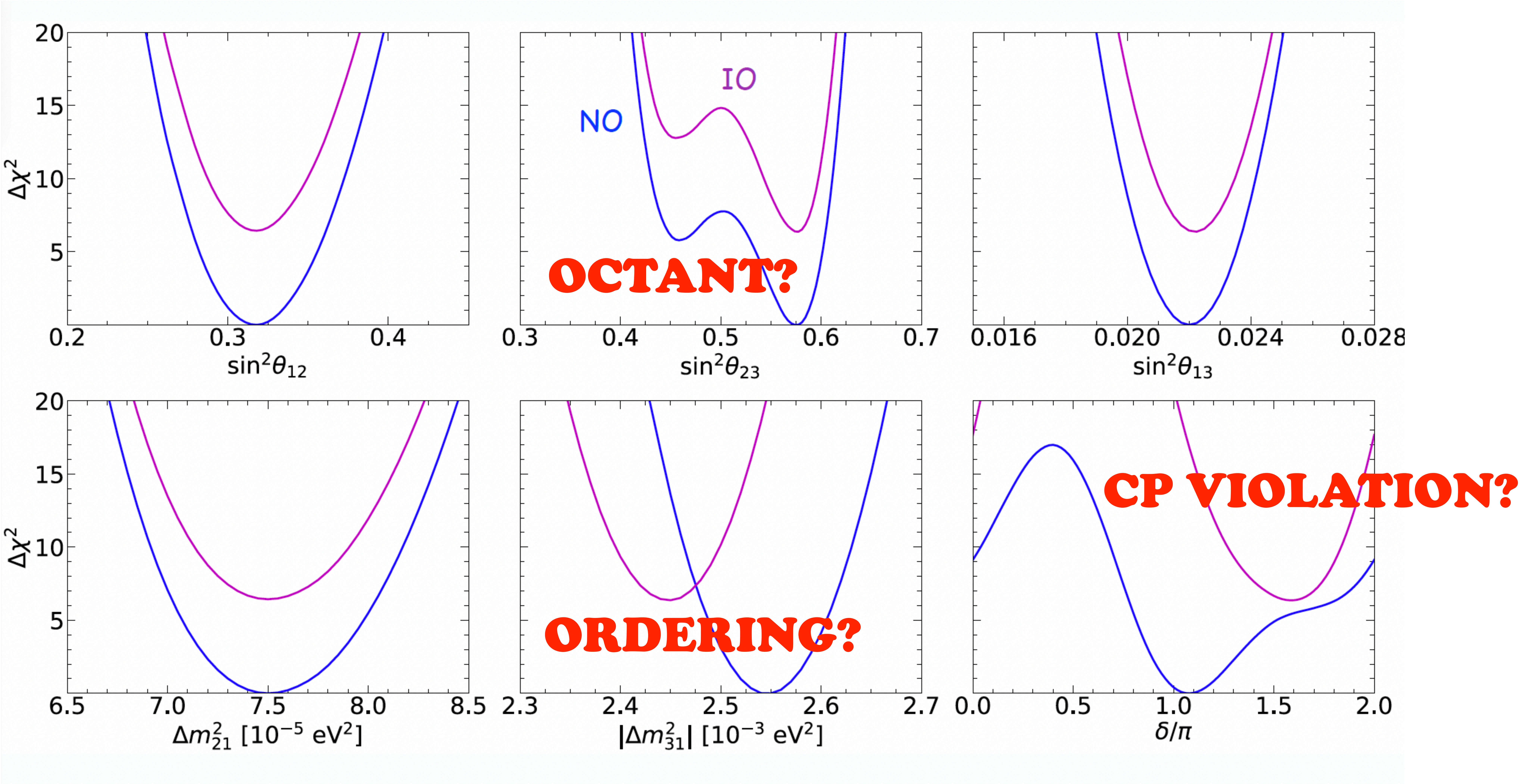
Global fit results

de Salas et al., JHEP 02 (2021) 071



Global fit results

de Salas et al., JHEP 02 (2021) 071



Oscillation Parameters

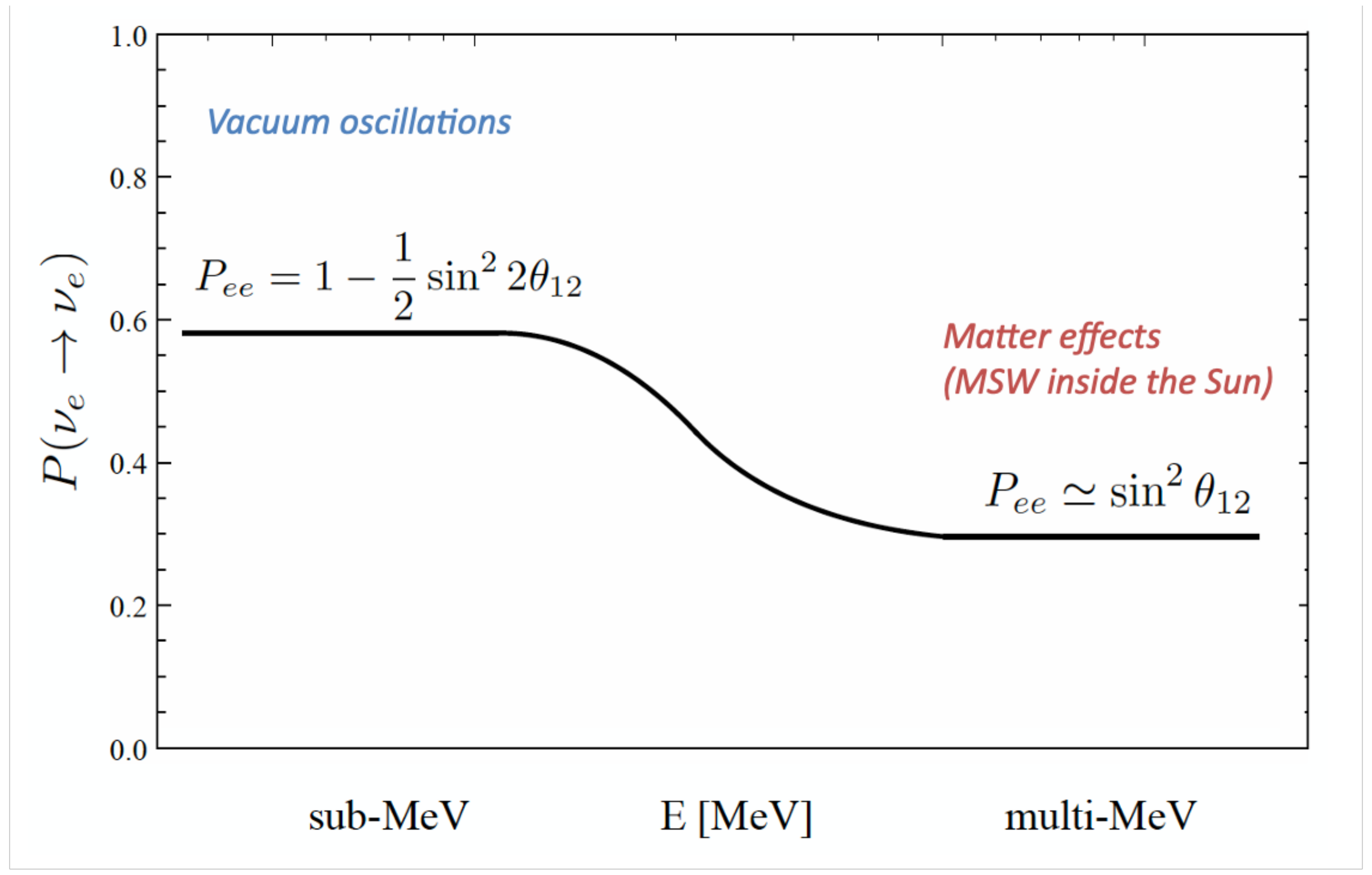
de Salas et al., JHEP 02 (2021) 071

parameter	best fit ± 1σ	3σ range	*Relative precision at 1σ*	
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	6.94–8.14	3%	Precision
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.47–2.63	1%	**SIGN UNKNOWN**
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.37–2.53		
$\sin^2\theta_{12}$ $/10^{-1}$	3.18 ± 0.16	2.71–3.69	5%	Precision
$\sin^2\theta_{23}$ $/10^{-1}$ (NO)	5.74 ± 0.14	4.34–6.10	5%	**OCTANT UNKNOWN**
$\sin^2\theta_{23}$ $/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	4.33–6.08		
$\sin^2\theta_{13}$ $/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.000–2.405	3%	Precision
$\sin^2\theta_{13}$ $/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.018–2.424		
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.71–1.99		**CP VIOLATION**?
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.11–1.96		

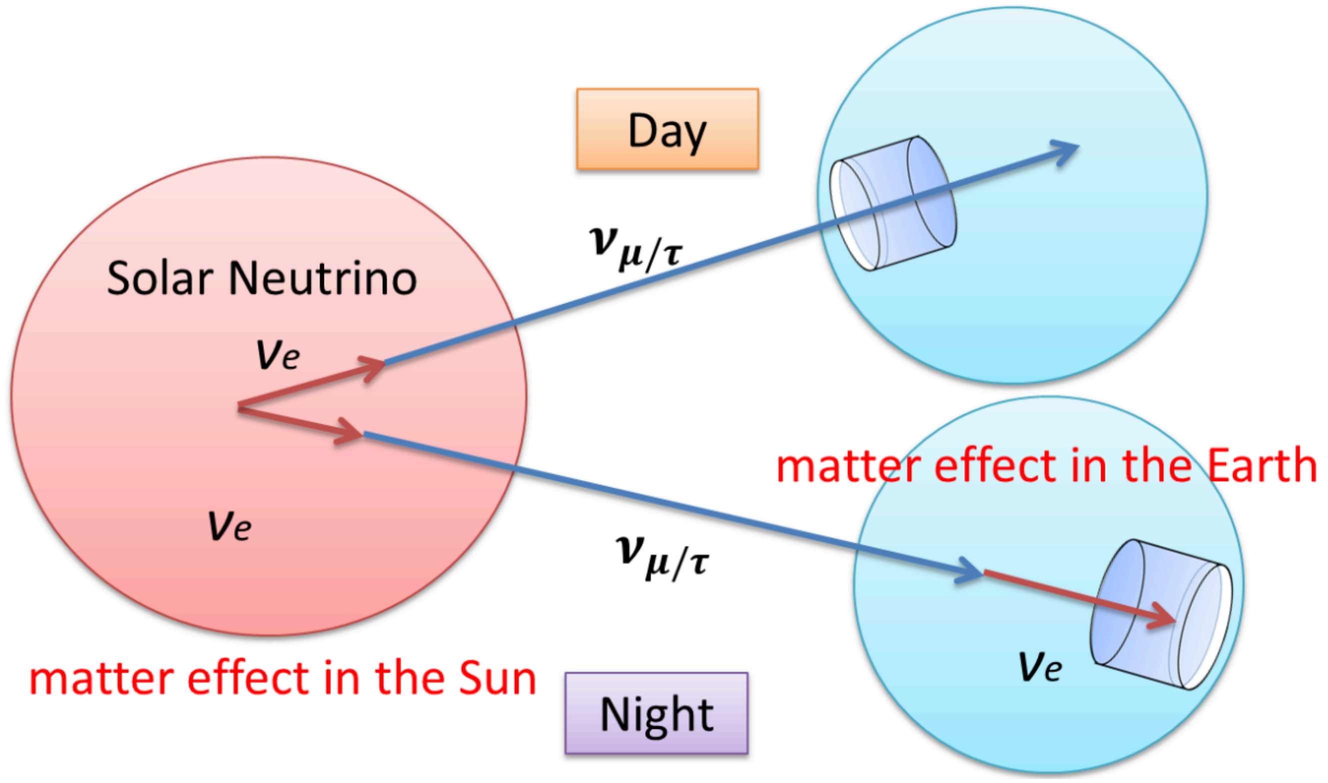
Solar and reactor neutrino oscillations

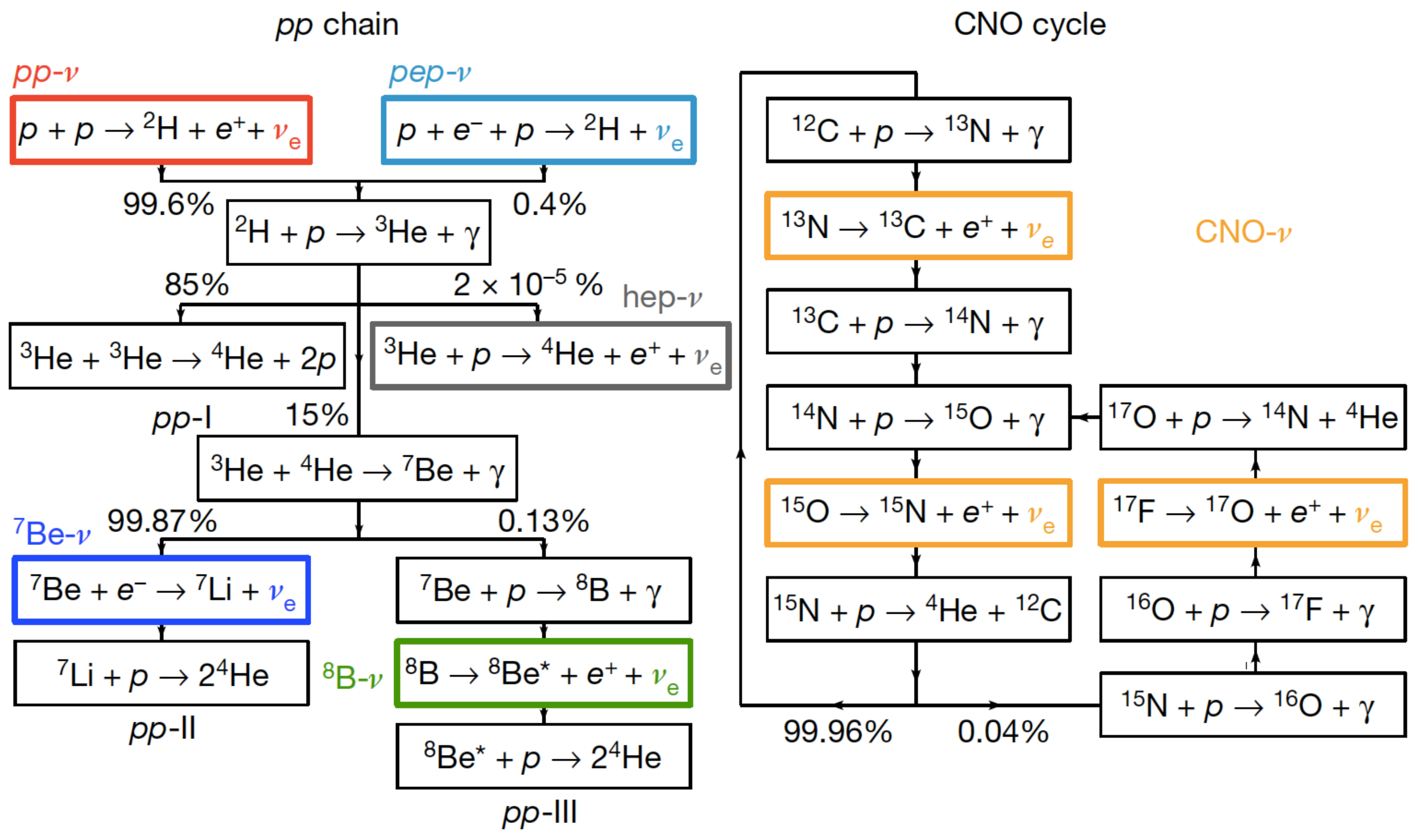
Solar neutrinos

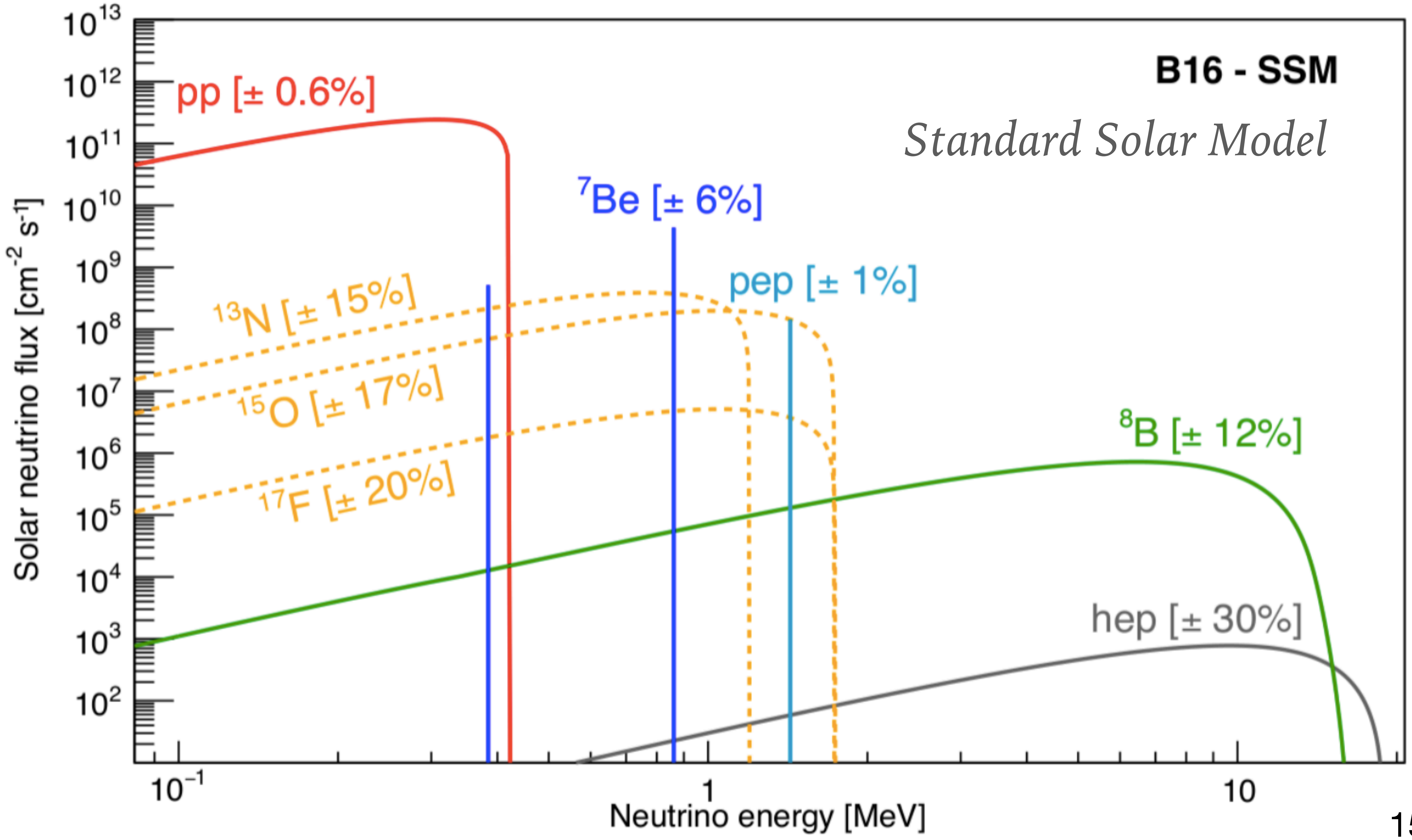
Neutrino spectrum



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

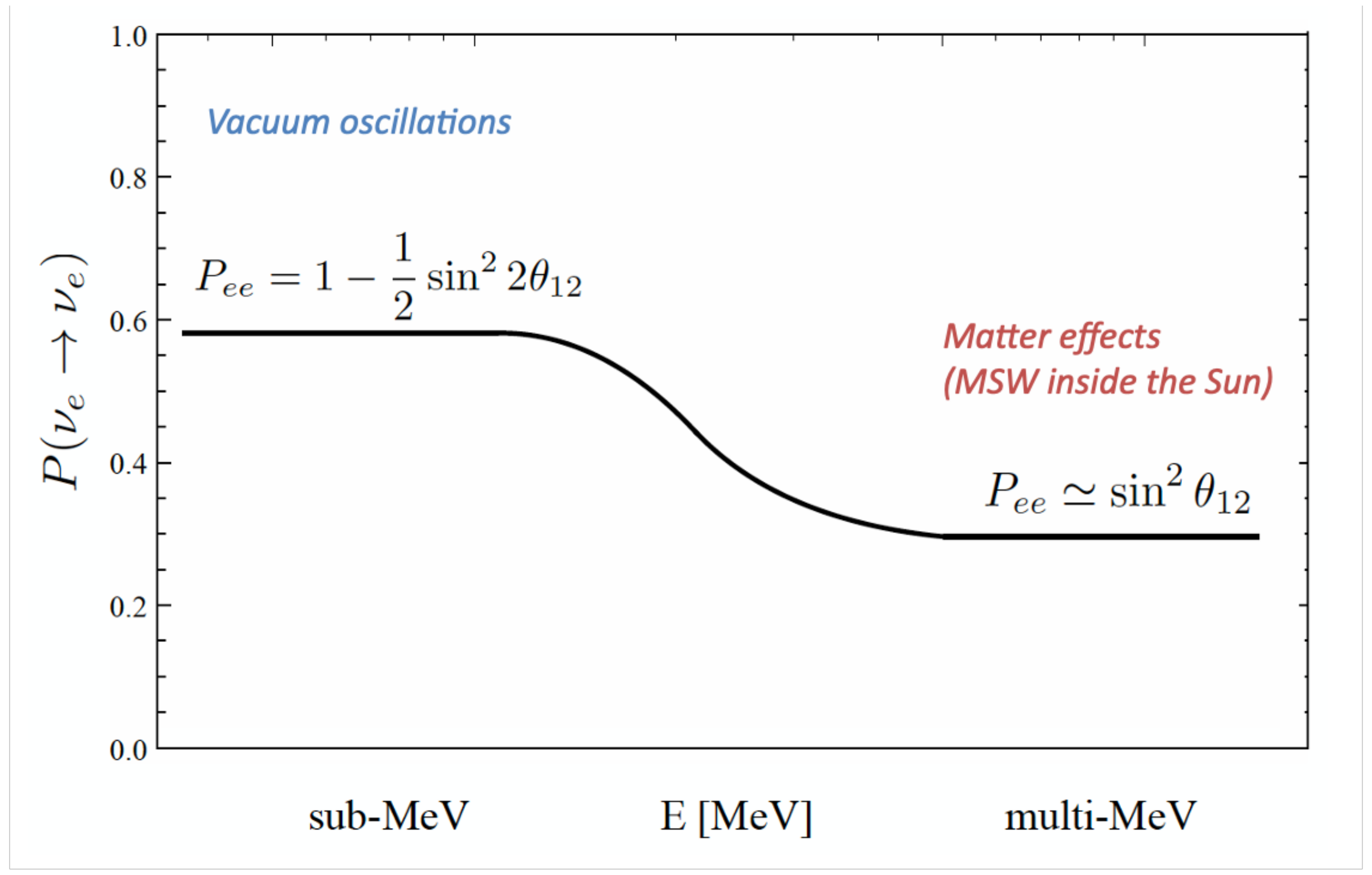




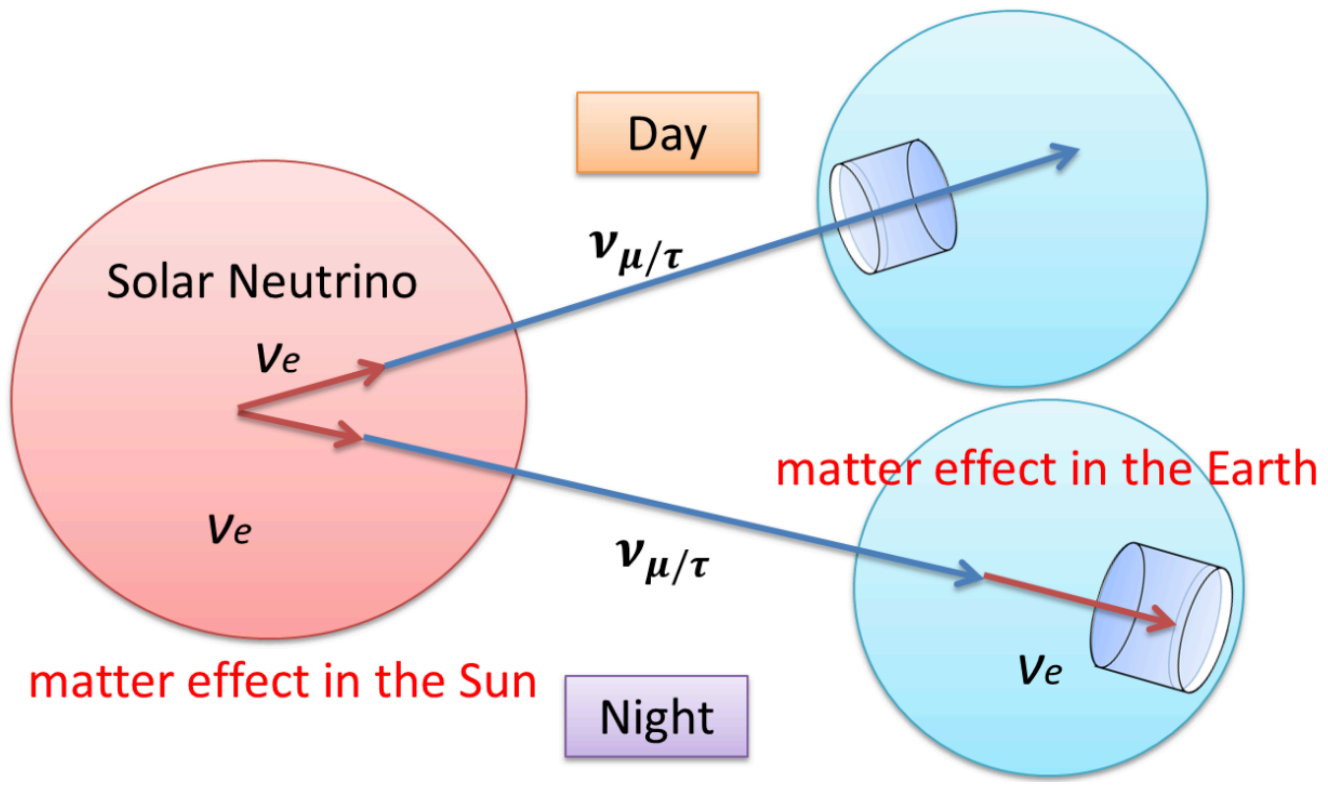


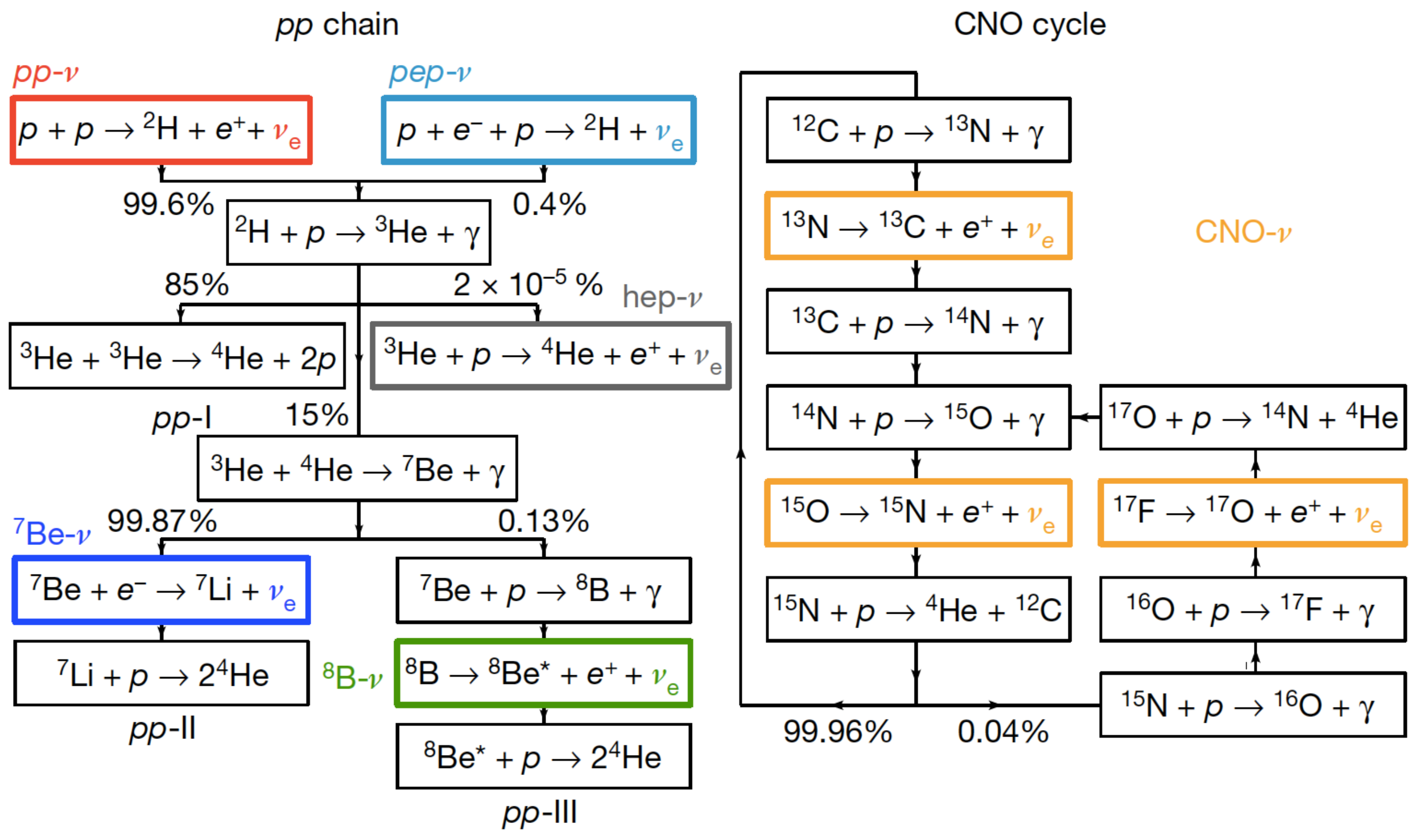
Solar neutrinos

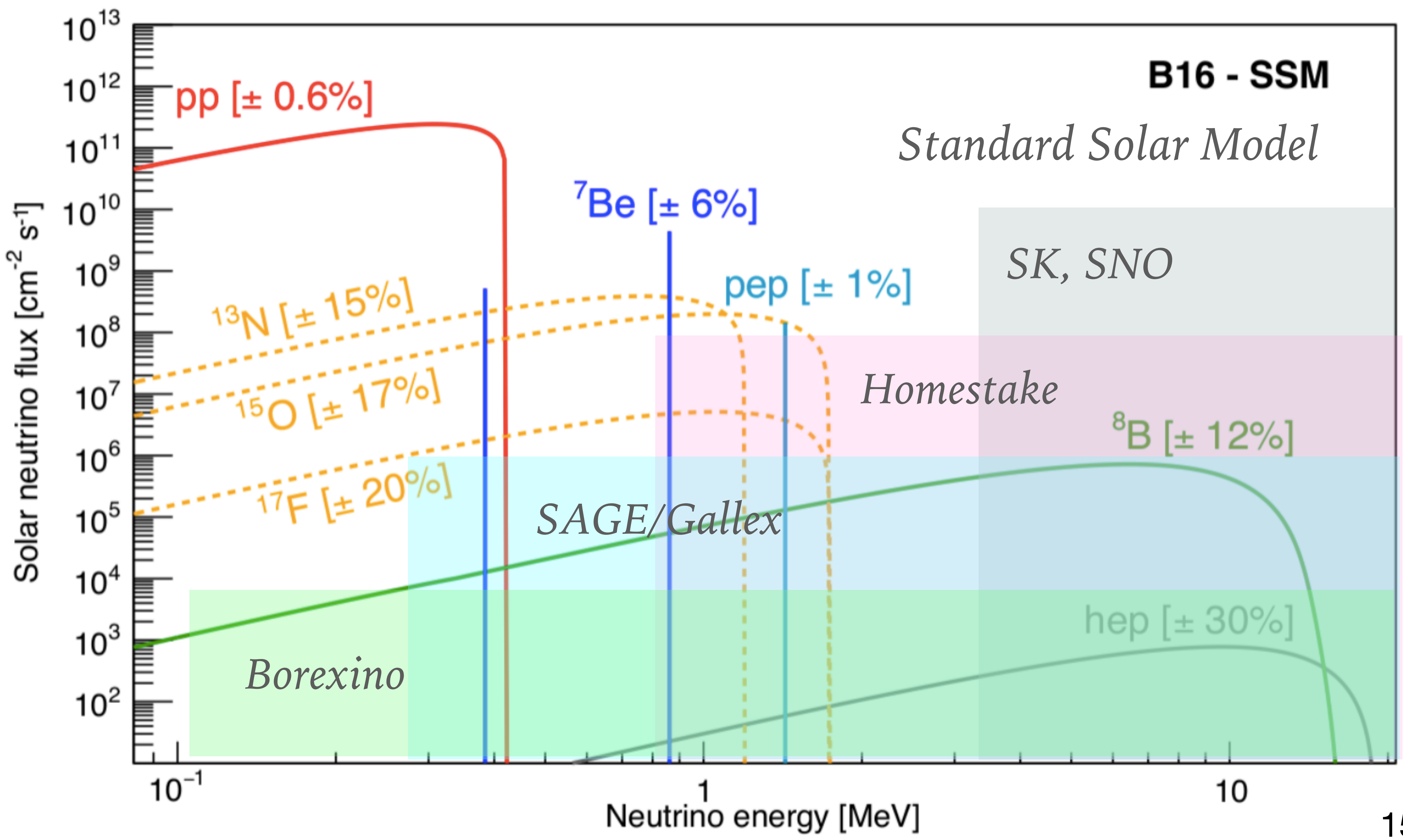
Neutrino spectrum



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







SNO / Super-K detectors

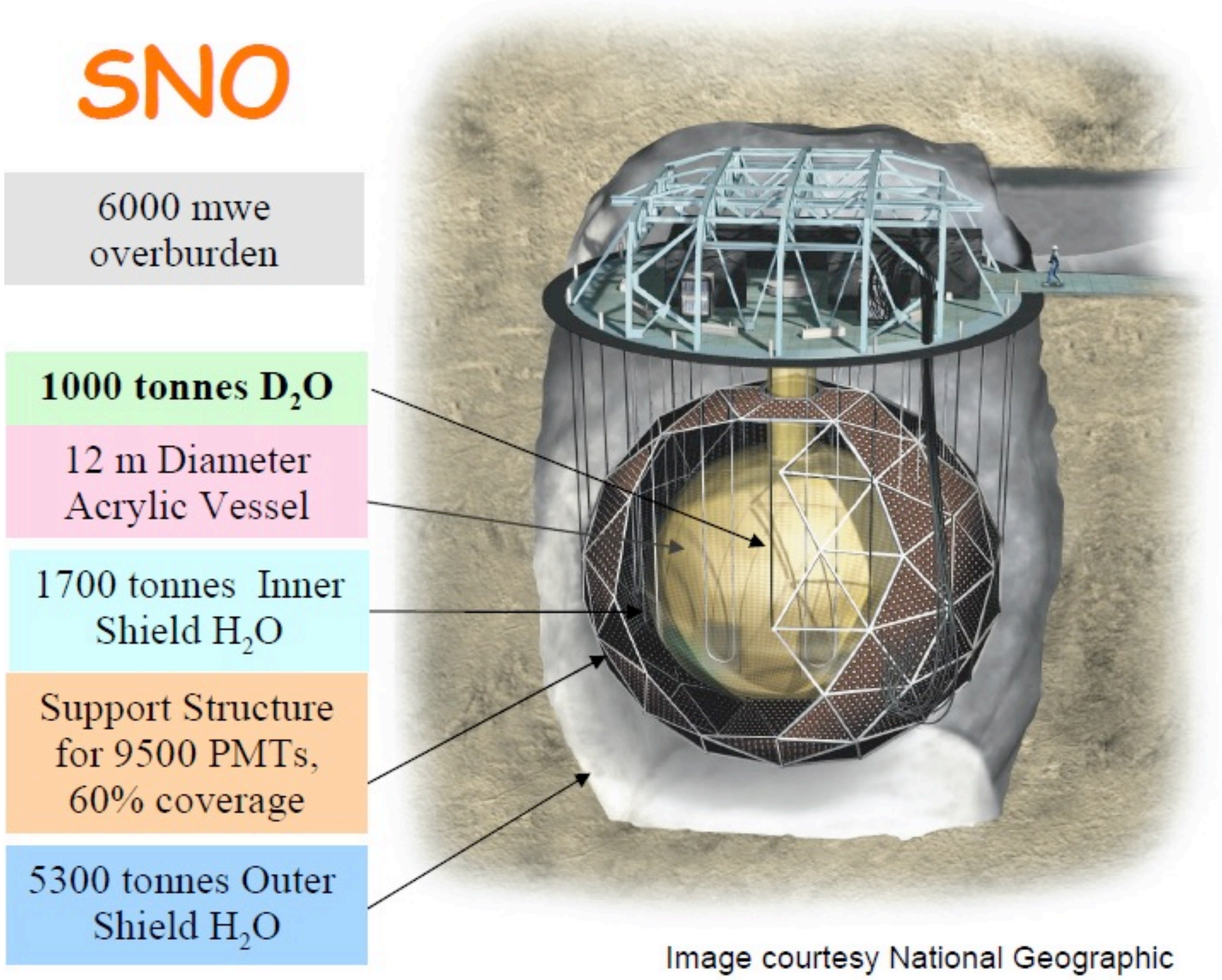
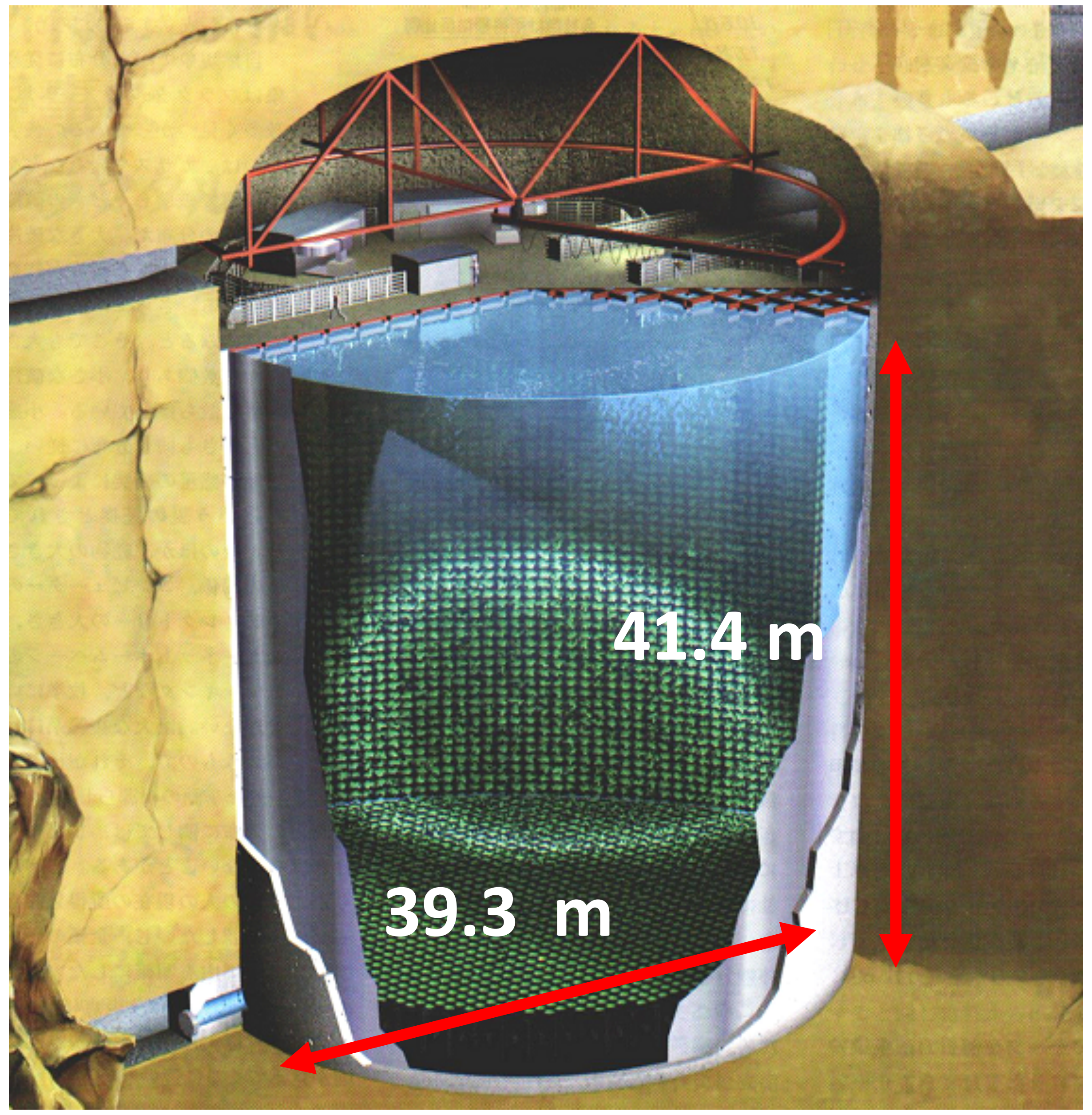


Image courtesy National Geographic

Super-K

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

(solar channel)



CC $\nu_e + d \Rightarrow p + p + e^-$

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

NC $\nu_x + d \Rightarrow p + n + \nu_x$

- 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

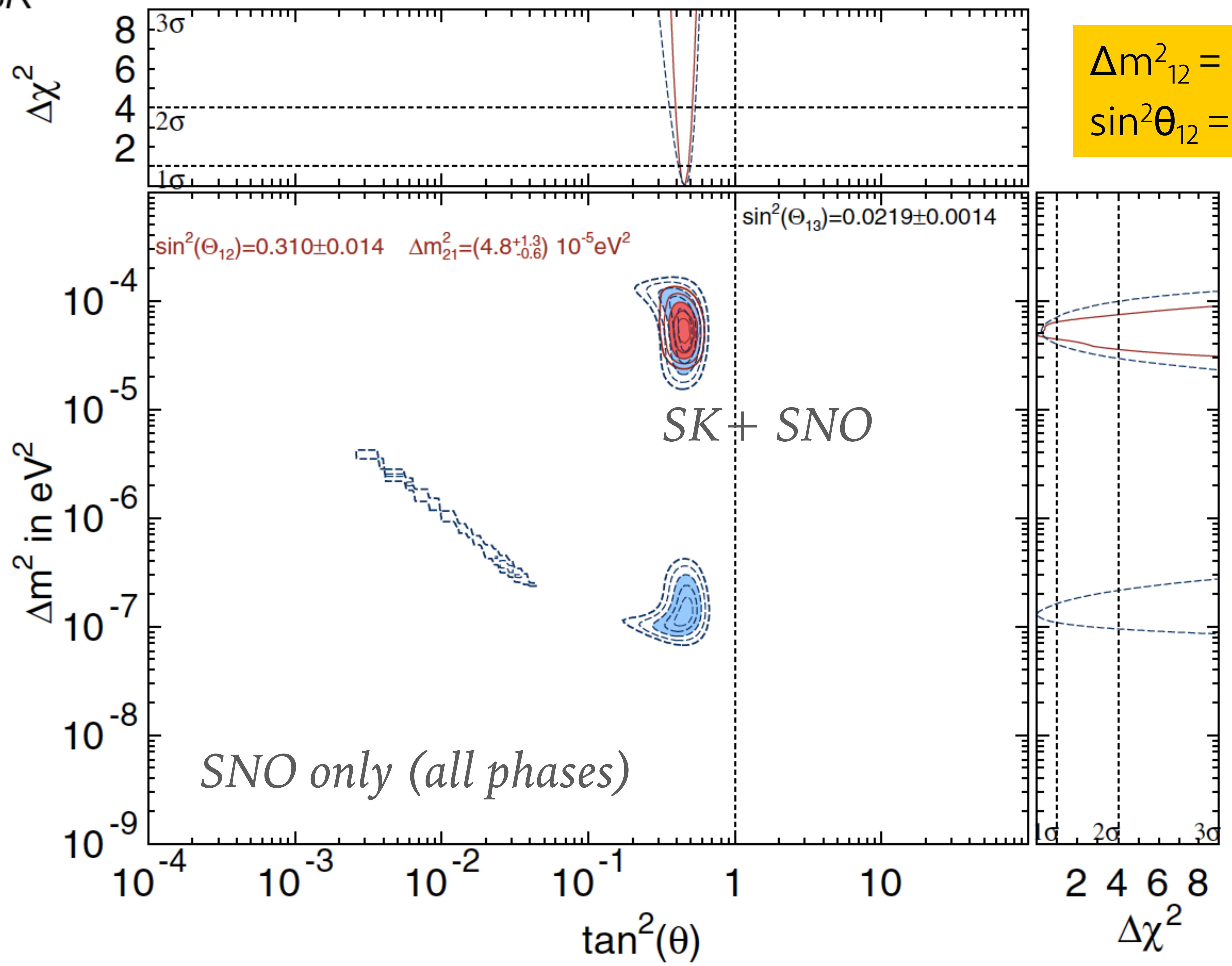
- 50 kt (22.5 kt fid) Water Cerenkov detector (taking data since 1996) in Kamioka mine (Japan)
- Provides direction and energy of solar neutrinos

Oscillation of solar neutrinos

- Best solar ν measurements by SNO and SuperKamiokande

Phys. Rev. C88, 025501 (2013) - SNO

Phys. Rev. D94, 052010 (2016) - SK



$\Delta m^2_{12} = 4.8^{+1.3}_{-0.6} \times 10^{-5}$ eV^2

$\sin^2\theta_{12} = 0.310 \pm 0.014$

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

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

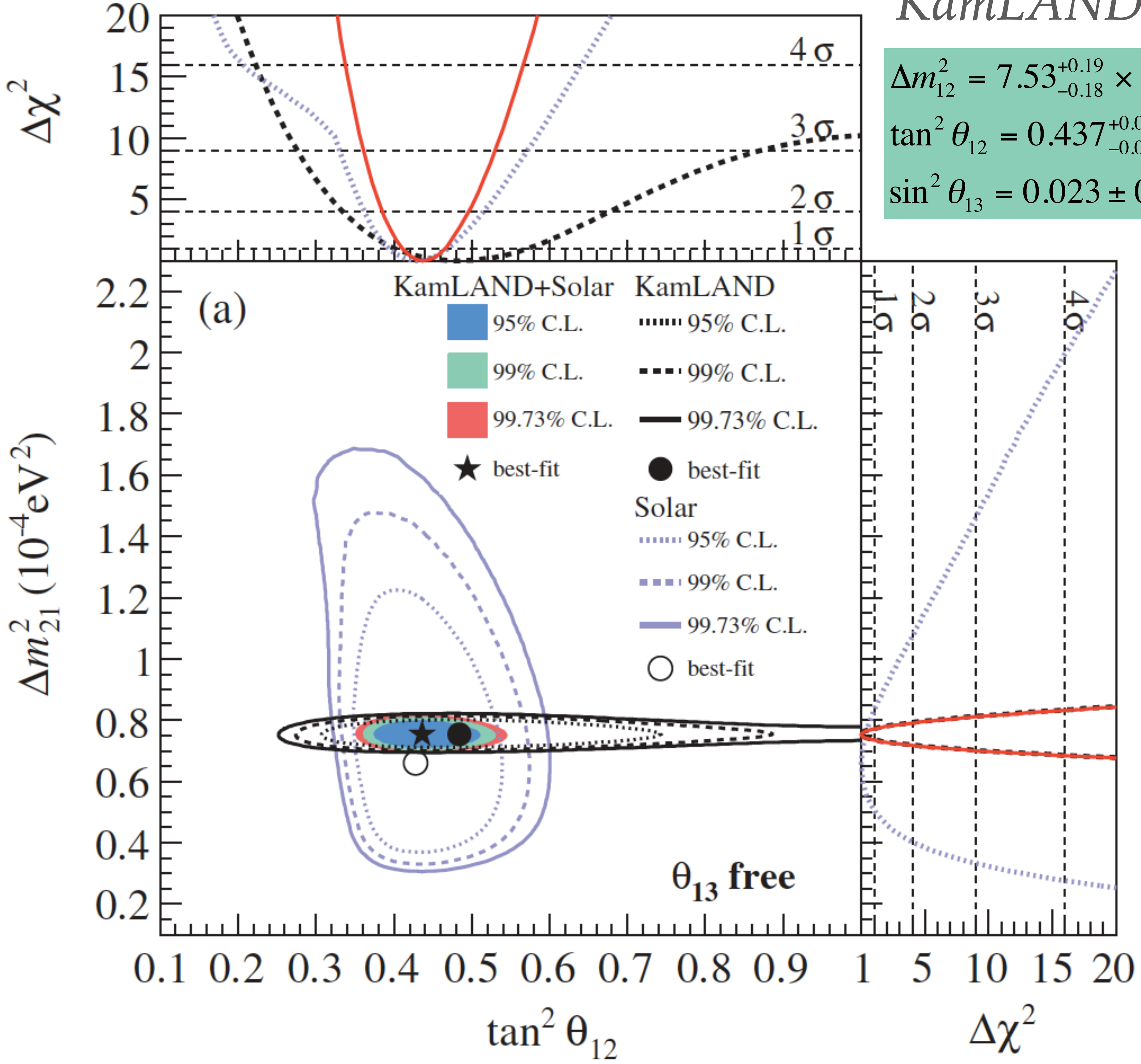
Slight disagreement between solar (electron neutrino oscillation) and KamLAND (electron antineutrino oscillation) at ~1.5σ

KamLAND+Solar

$\Delta m^2_{12} = 7.53^{+0.19}_{-0.18} \times 10^{-5}\, eV^2$

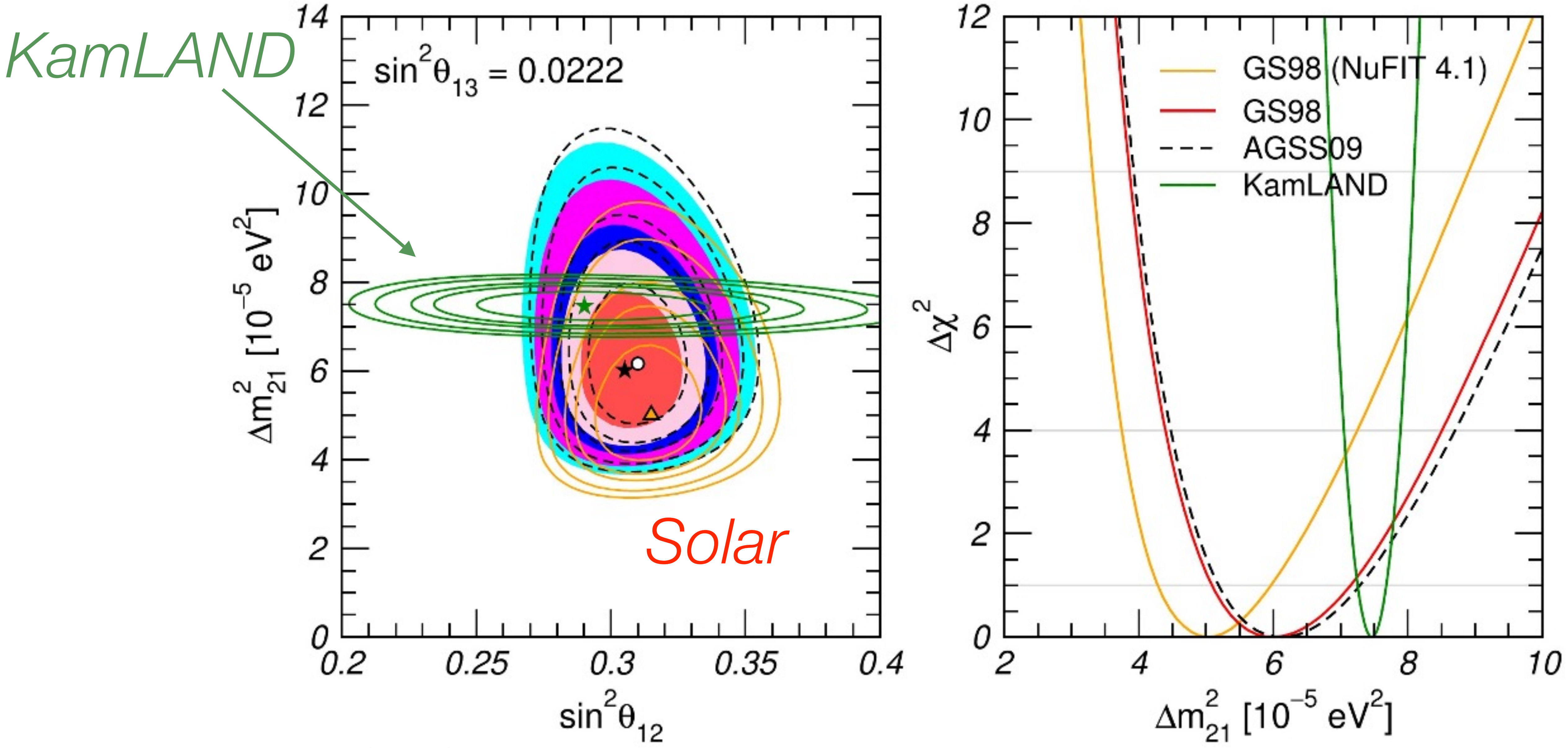
$\tan^2\theta_{12} = 0.437^{+0.029}_{-0.026}$

$\sin^2\theta_{13} = 0.023 \pm 0.015$



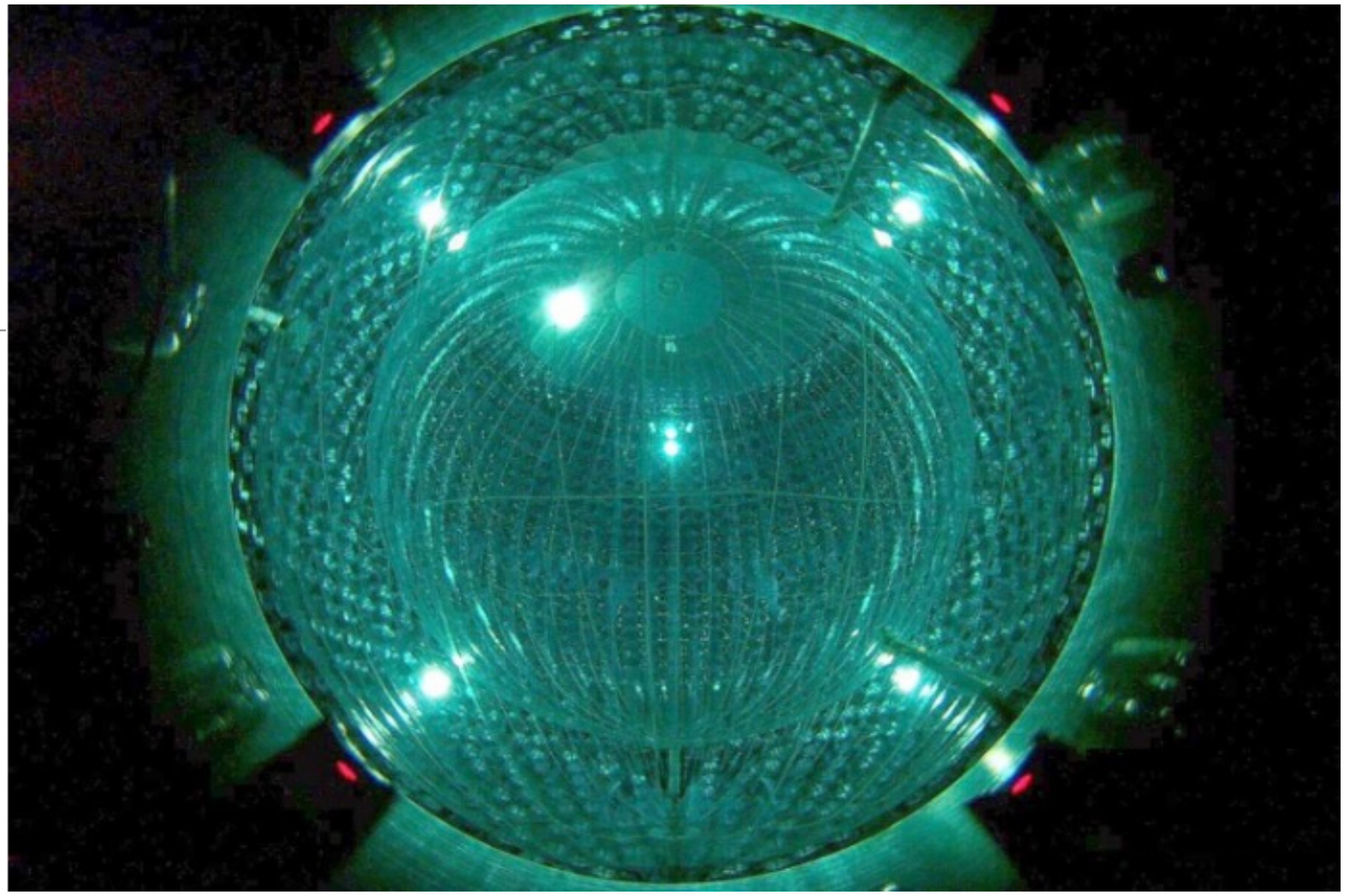
Phys. Rev. D 88, 033001 (2013)

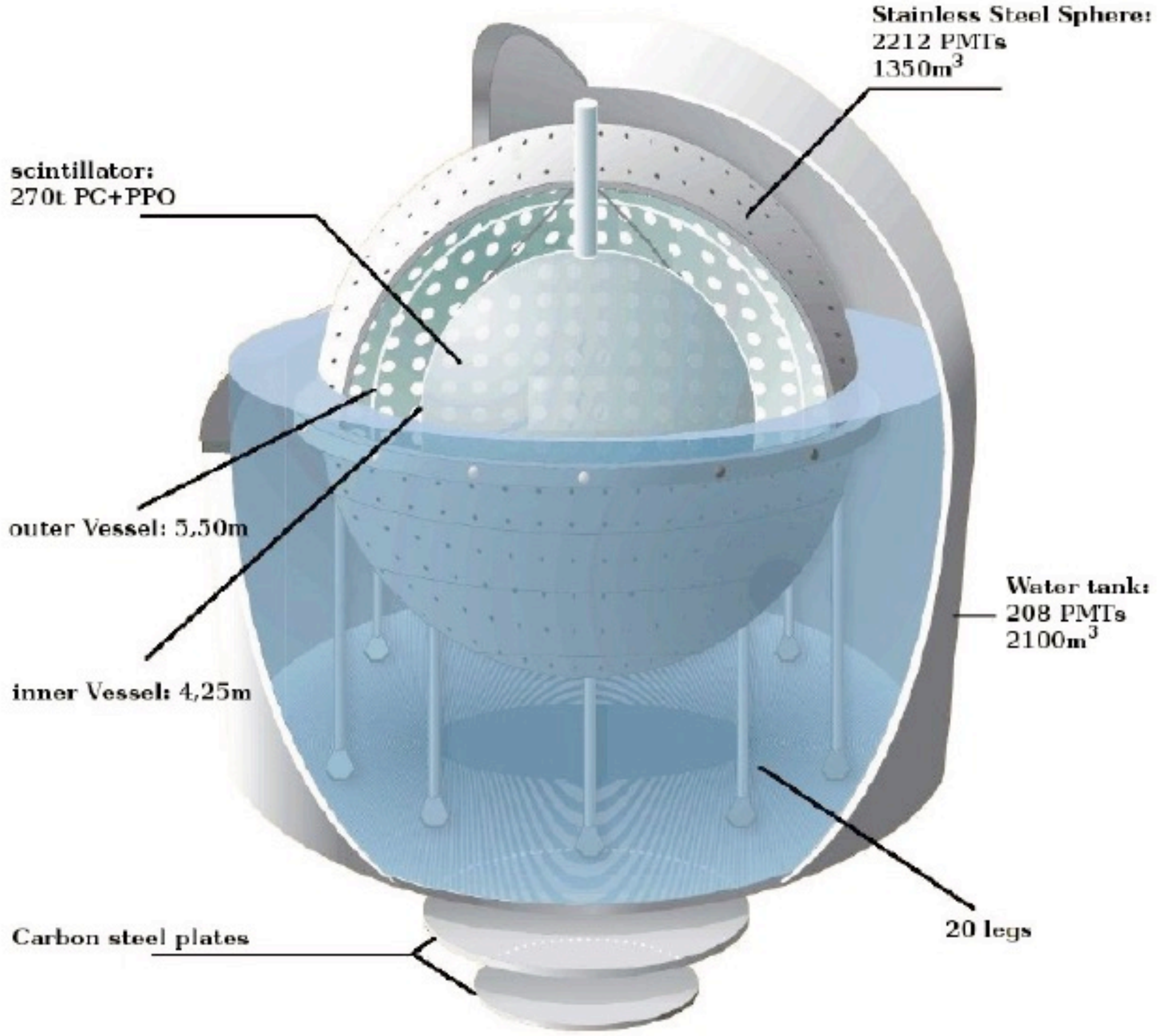
NuFIT 5.2 (2022)



Borexino

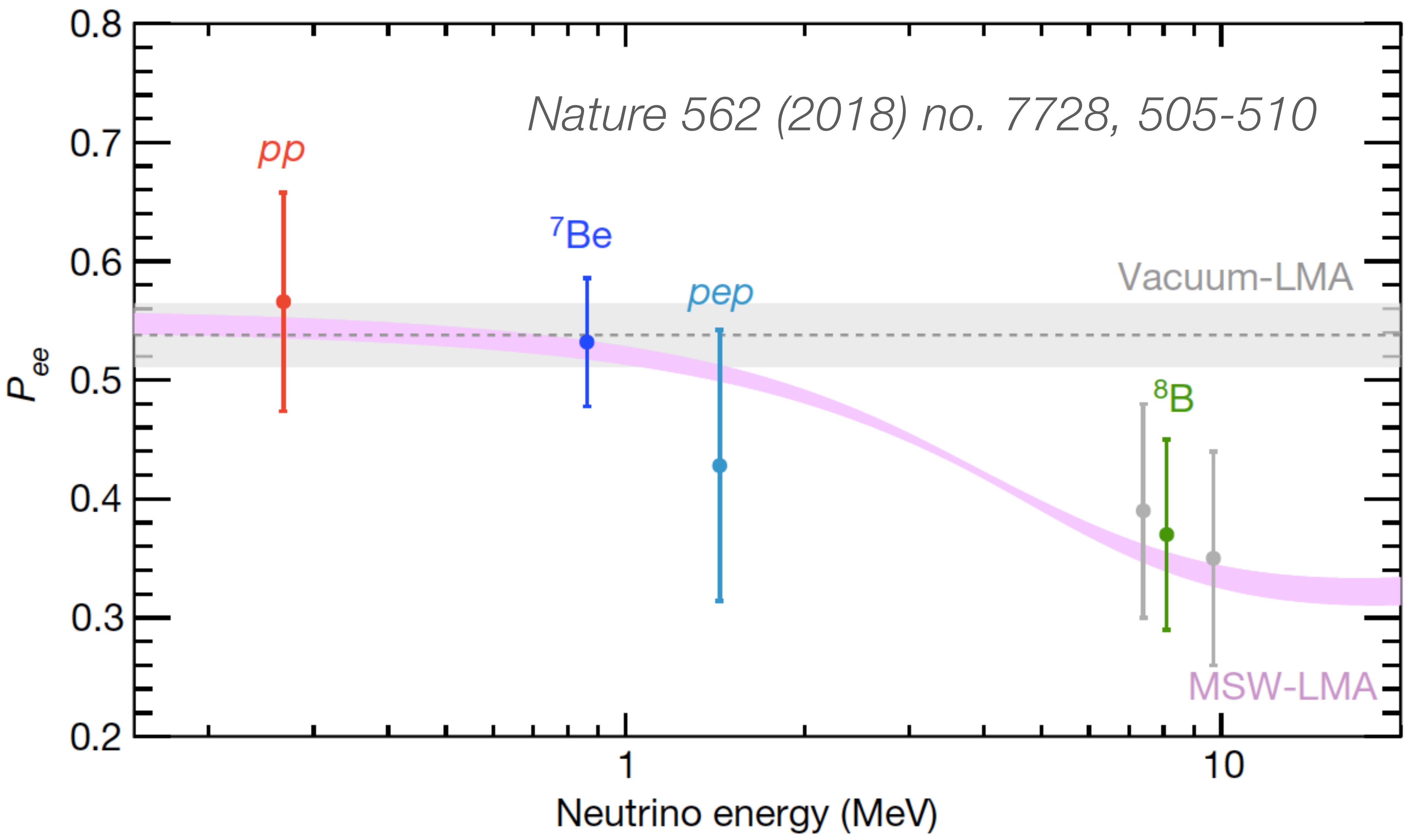
- 278 ton liquid scintillator ν-e scattering (Gran Sasso Laboratory - Italy)
- Real time measurements of the MeV-subMeV flux and spectrum of solar neutrinos:
    - ✦ Monochromatic ^{7}Be ν (0.86 MeV) & ^{8}B , pep, CNO, pp measurements
    - ✦ High radiopurity requirements
- 200 keV energy threshold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

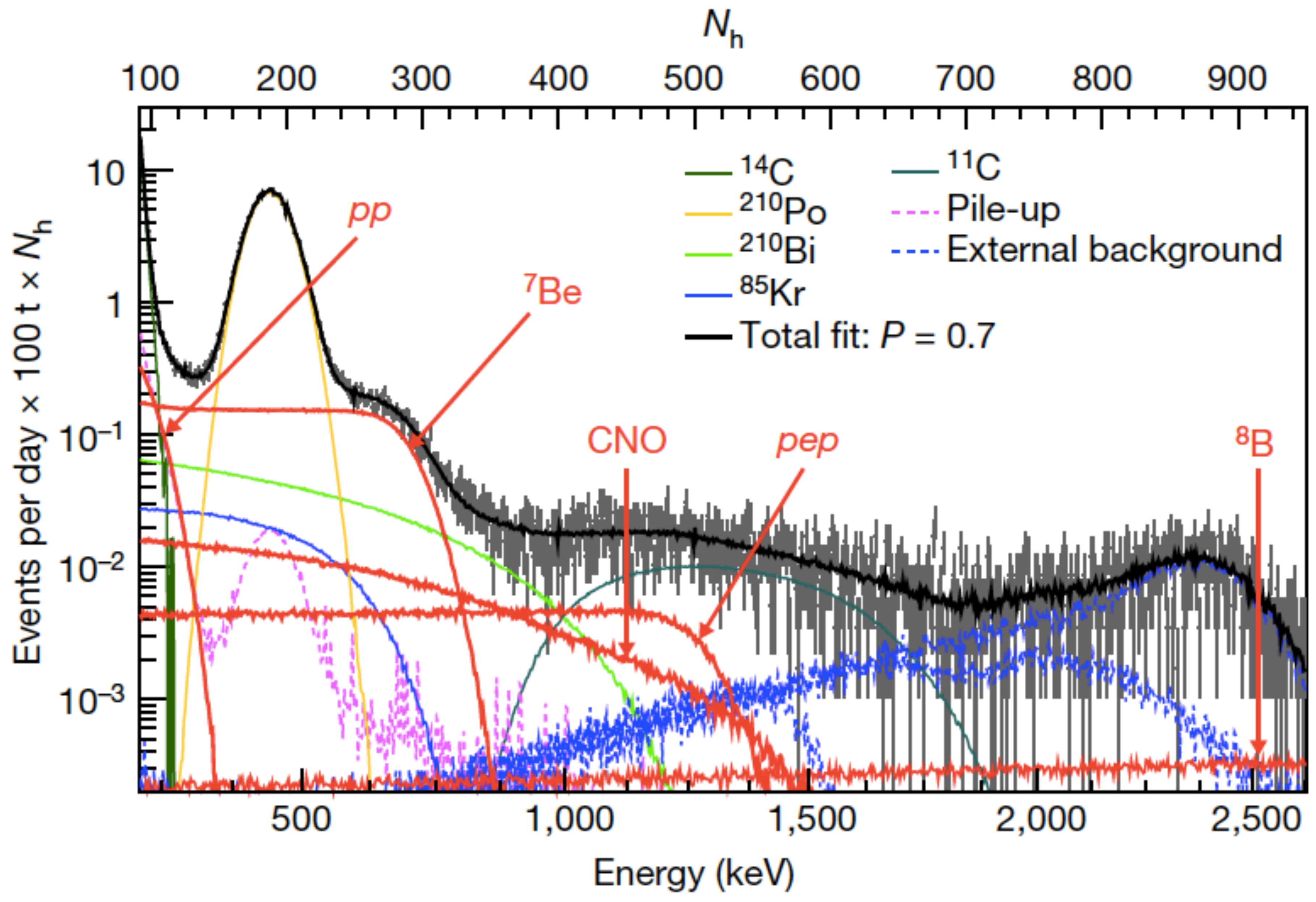


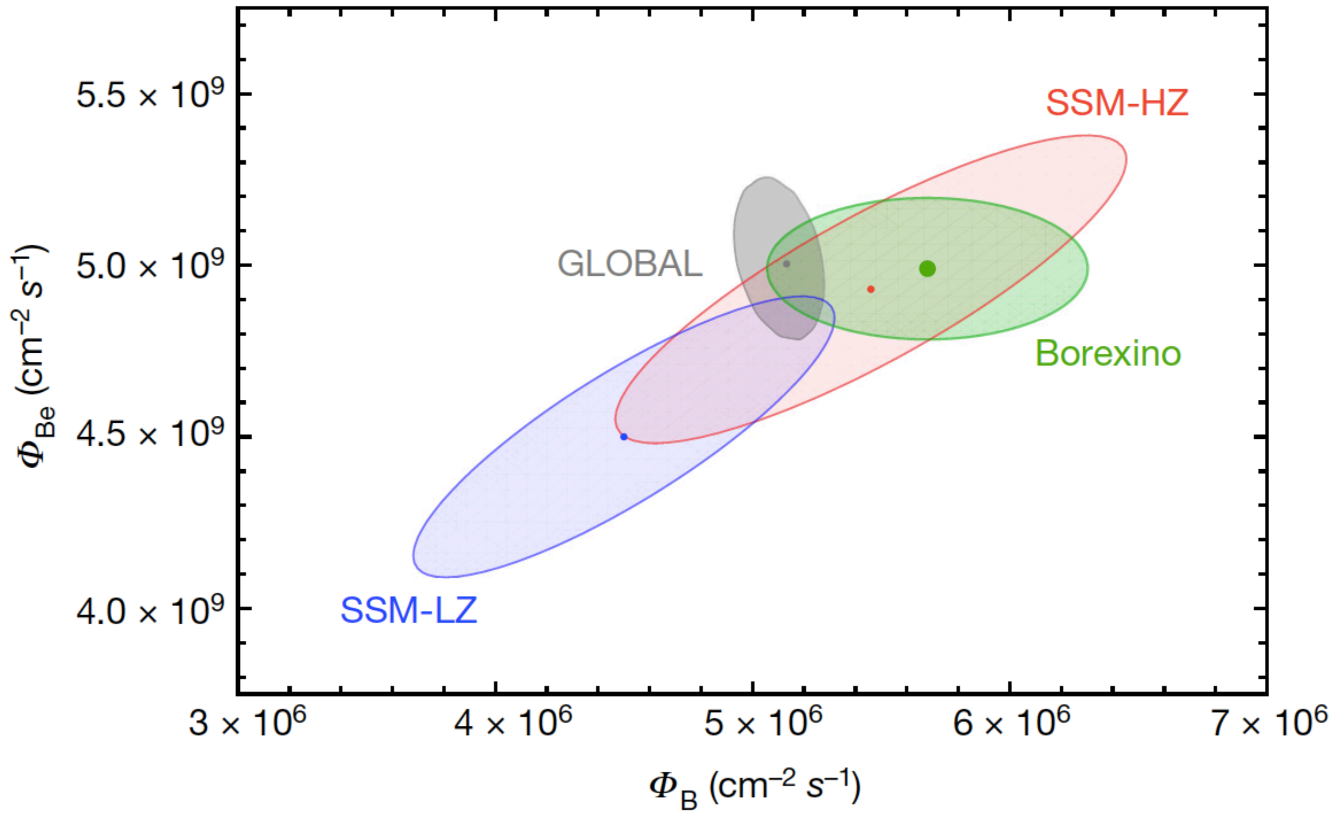


Borexino - pp measurement

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





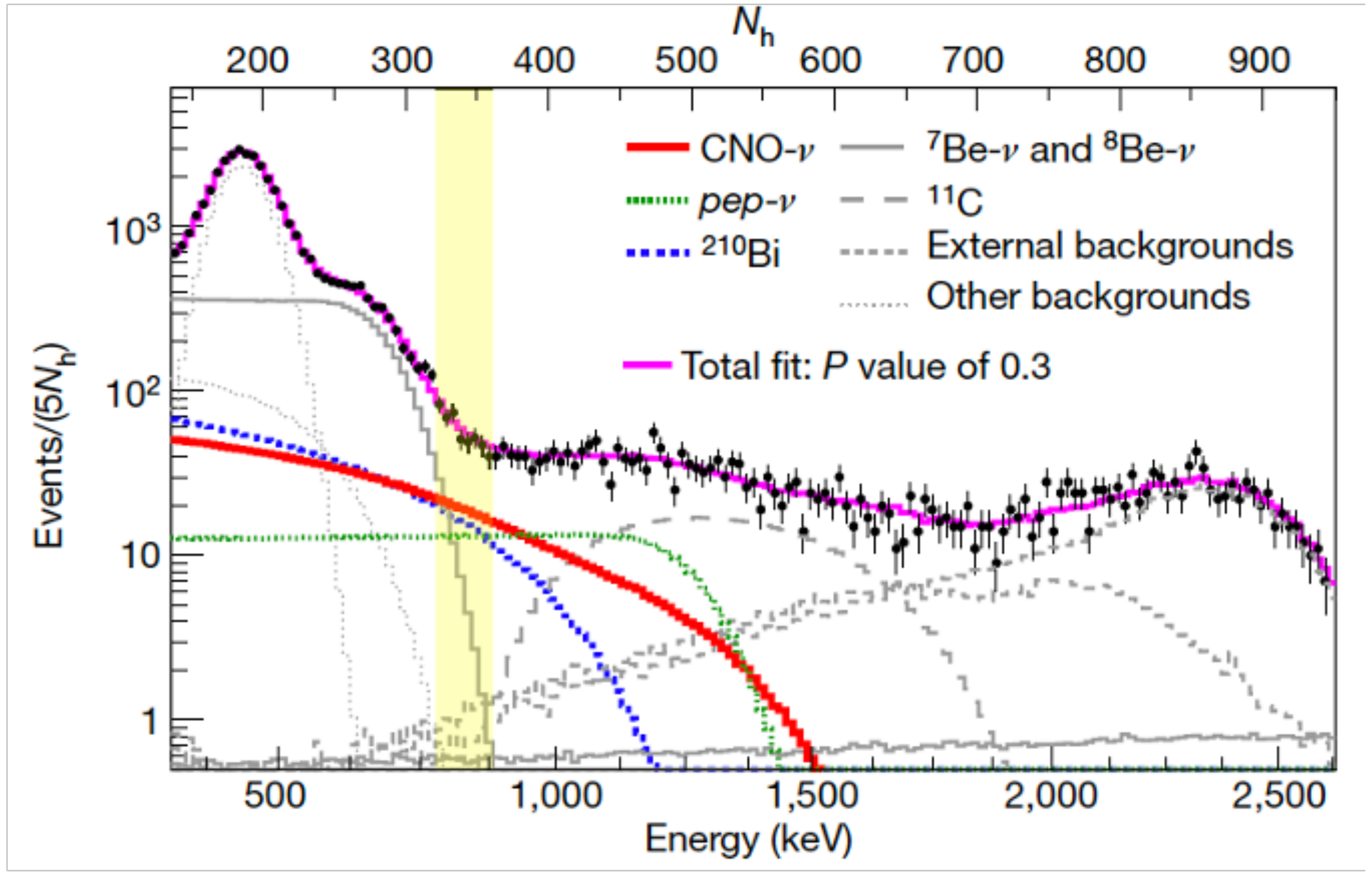


Test of solar metallicity: hint favoring SSM-HZ prediction

Nature 587 (2020) 577-582

First evidence of CNO solar neutrinos

- CNO is dominant in stars heavier than 1.3 $M_\odot$
  - ✦ Never directly observed before
  - ✦ The abundance of these elements is related to the solar metallicity
- Data taking: 2018-2020
- Challenge:
  - ✦ Small expected signal: 5 cpd/100t
  - ✦ Measure the backgrounds: pep-v and ^{210}Bi (main problem)
- Thermal stabilization to constrain the ^{210}Bi contaminating the scintillator (^{210}Bi < 11.5 ± 1.3 cpd/100t)

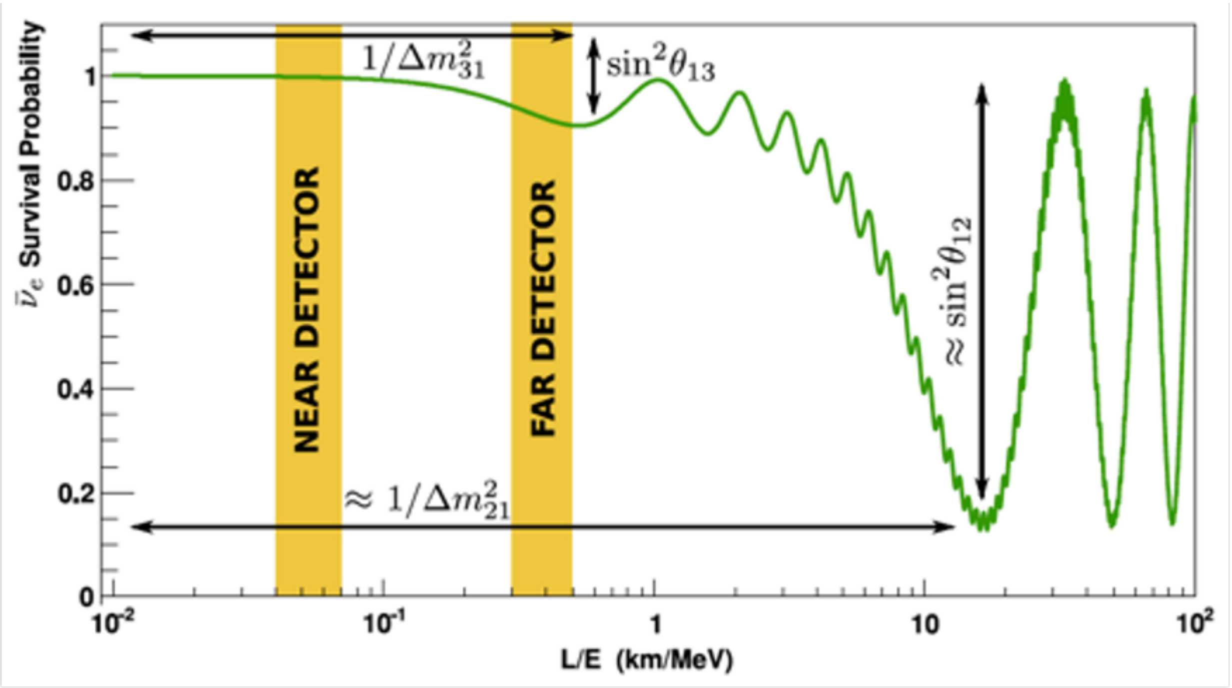


CNO result (68% CL stat+sys) = 7.2 +3.0 -1.7 cpd/100t

No CNO hypothesis disfavored at 5σ

(Short-baseline) Reactor neutrino experiments

Pure θ_{13} measurement from electron antineutrino disappearance

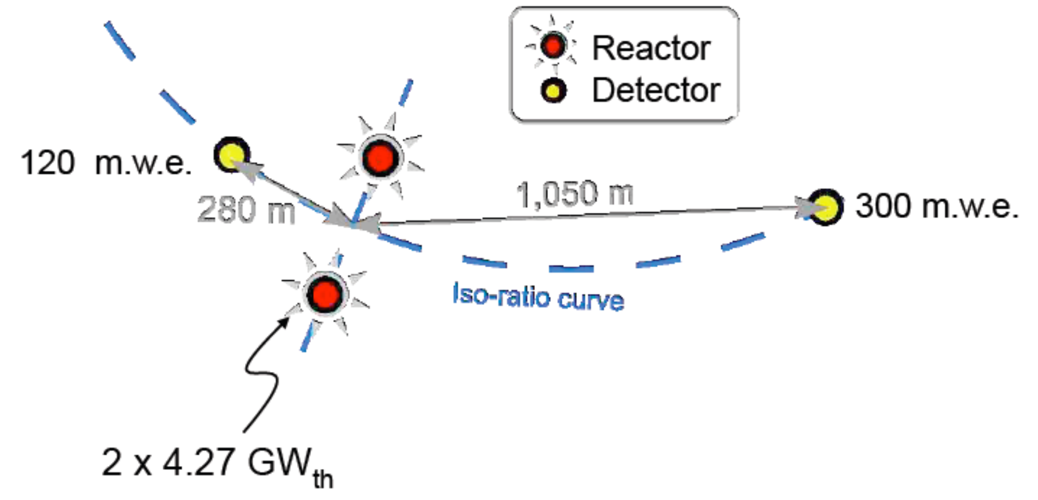


$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}{}^2 L}{4E_\nu}\right)$$

Liquid scintillators doped with Gd

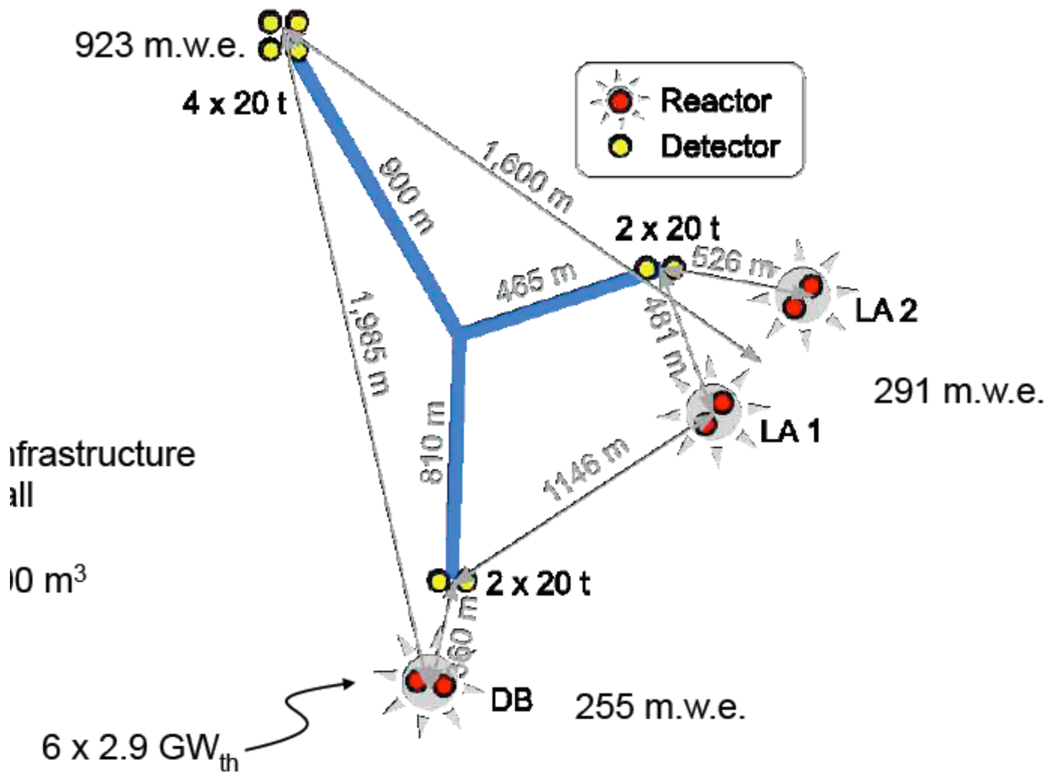
Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

Double Chooz



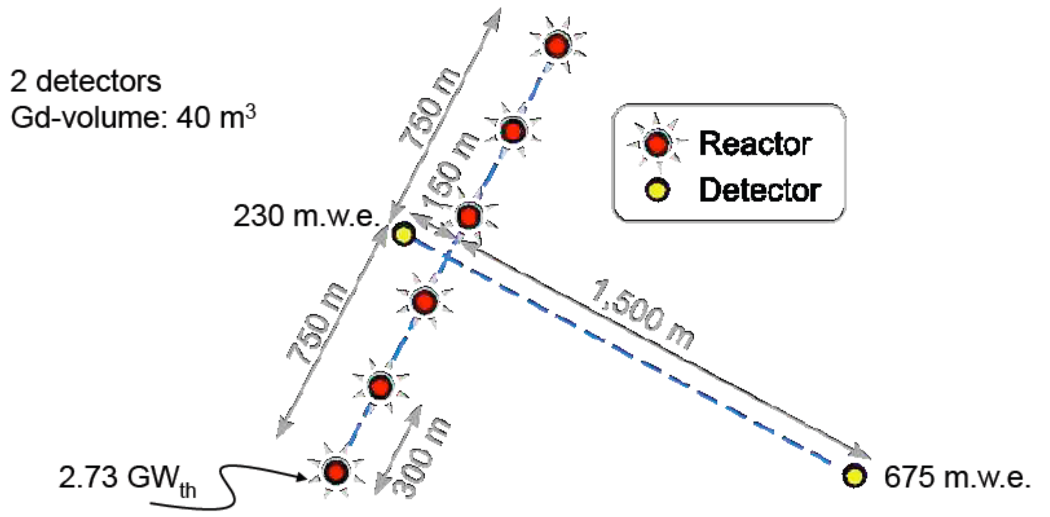
France

Daya Bay



China

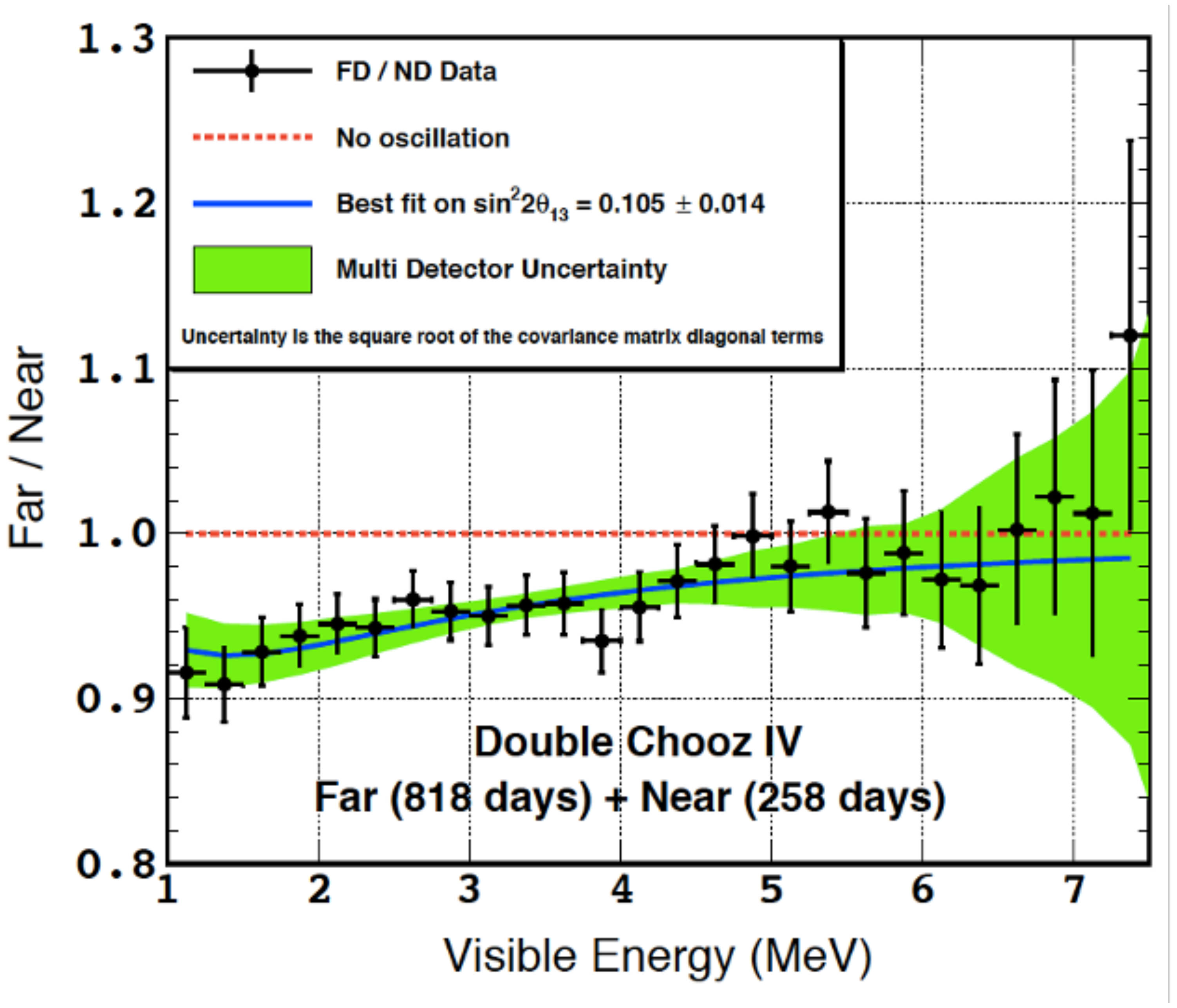
RENO



Korea

Reactor neutrino status

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

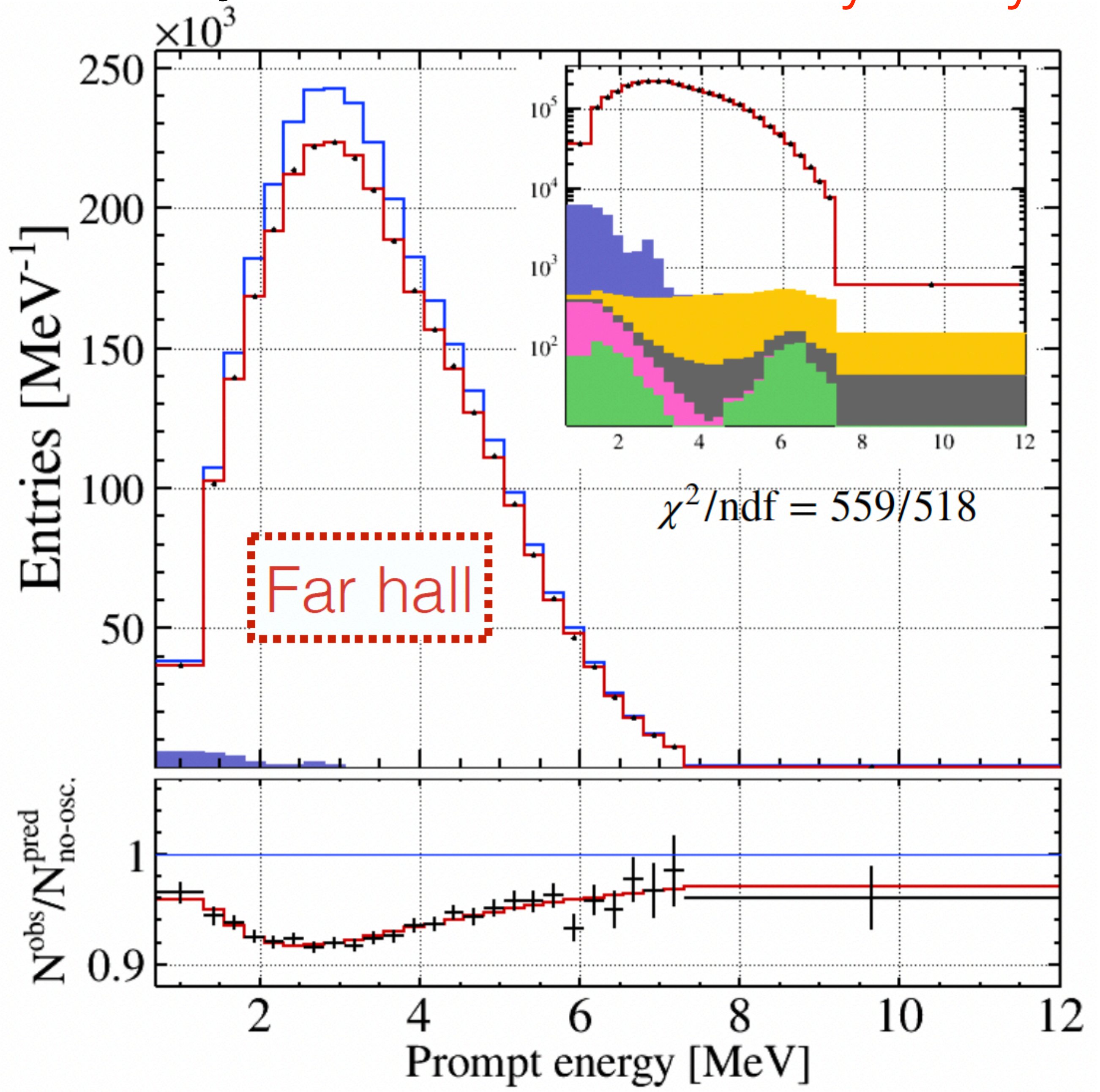


$\sin^2(2\theta_{13}) = 0.105 \pm 0.014$ (stat + sys)

χ^2/dof = 182/112 (D2MC result)

3158 days Daya Bay

PRL 130, 161802 (2023)



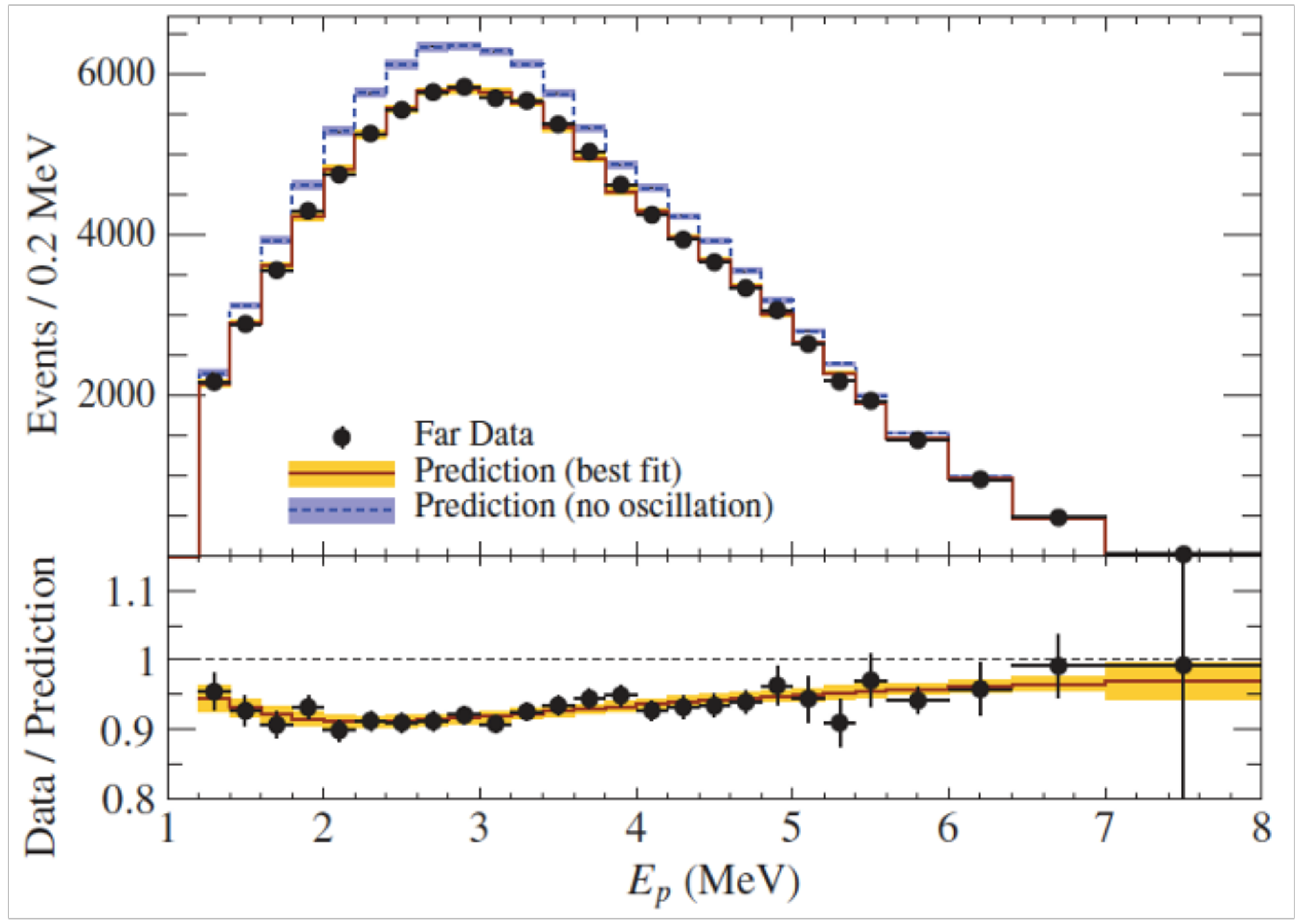
$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$

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

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

RENO 2200 days

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



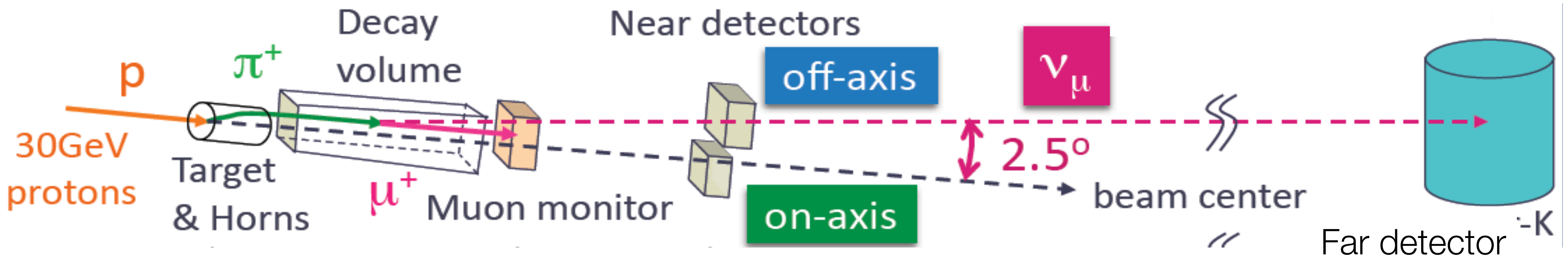
$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\text{stat}) \pm 0.0047(\text{syst})$

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

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

LBL and atmospheric neutrino oscillations

Long-baseline accelerator neutrinos



Survival probability

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

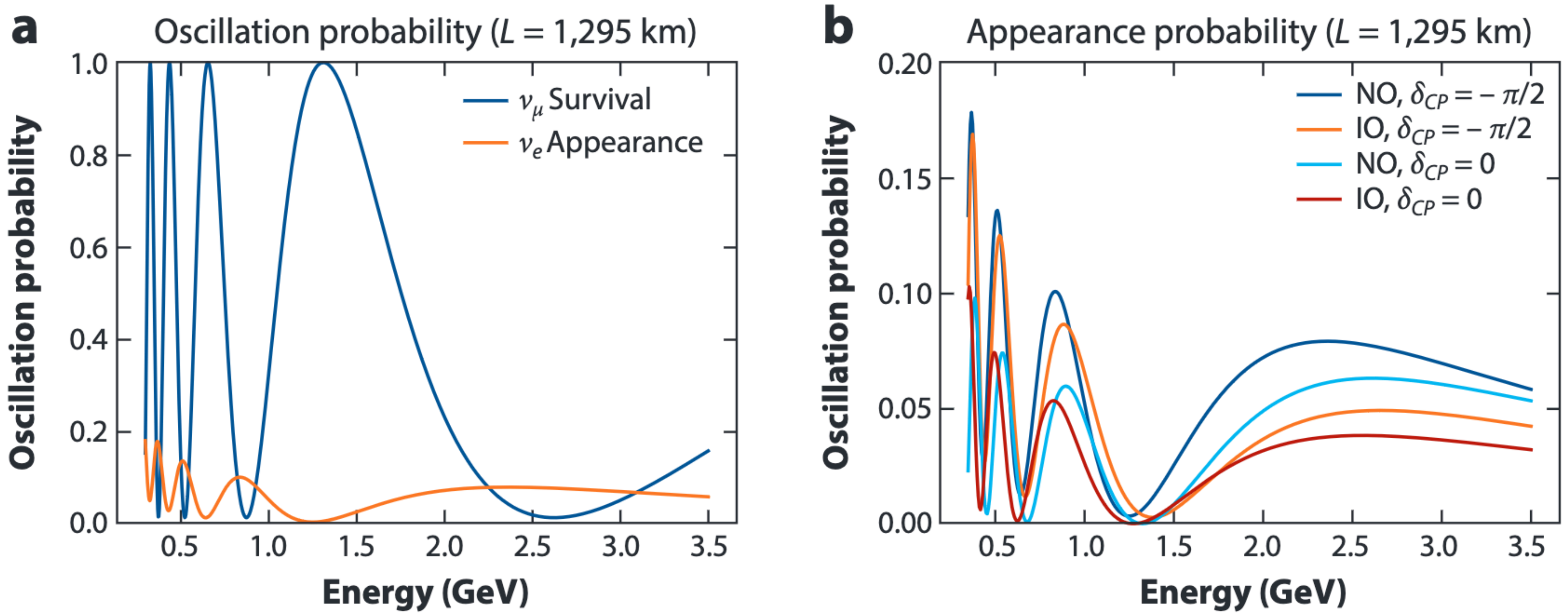
$$\approx 1 - \cos^2\theta_{13} \sin^2(2\theta_{23}) \sin^2 \frac{\Delta m^2_{32} L}{4E_\nu} + \mathcal{O}(\alpha, s^2_{13})$$

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

Appearance probability

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

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



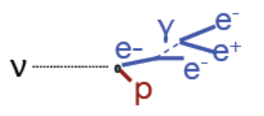
- SIGNAL
  - CCQE

ν_μ signal

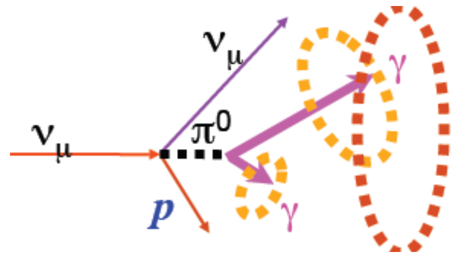
$$\nu_\mu + n \to p + \mu^-$$

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, $\overline{\nu}_\mu$ beams
- Experimental challenges: ν beam intensity, flavor contamination, flux properties, ν-N interactions

T2K (Tokai to Kamioka) in Japan

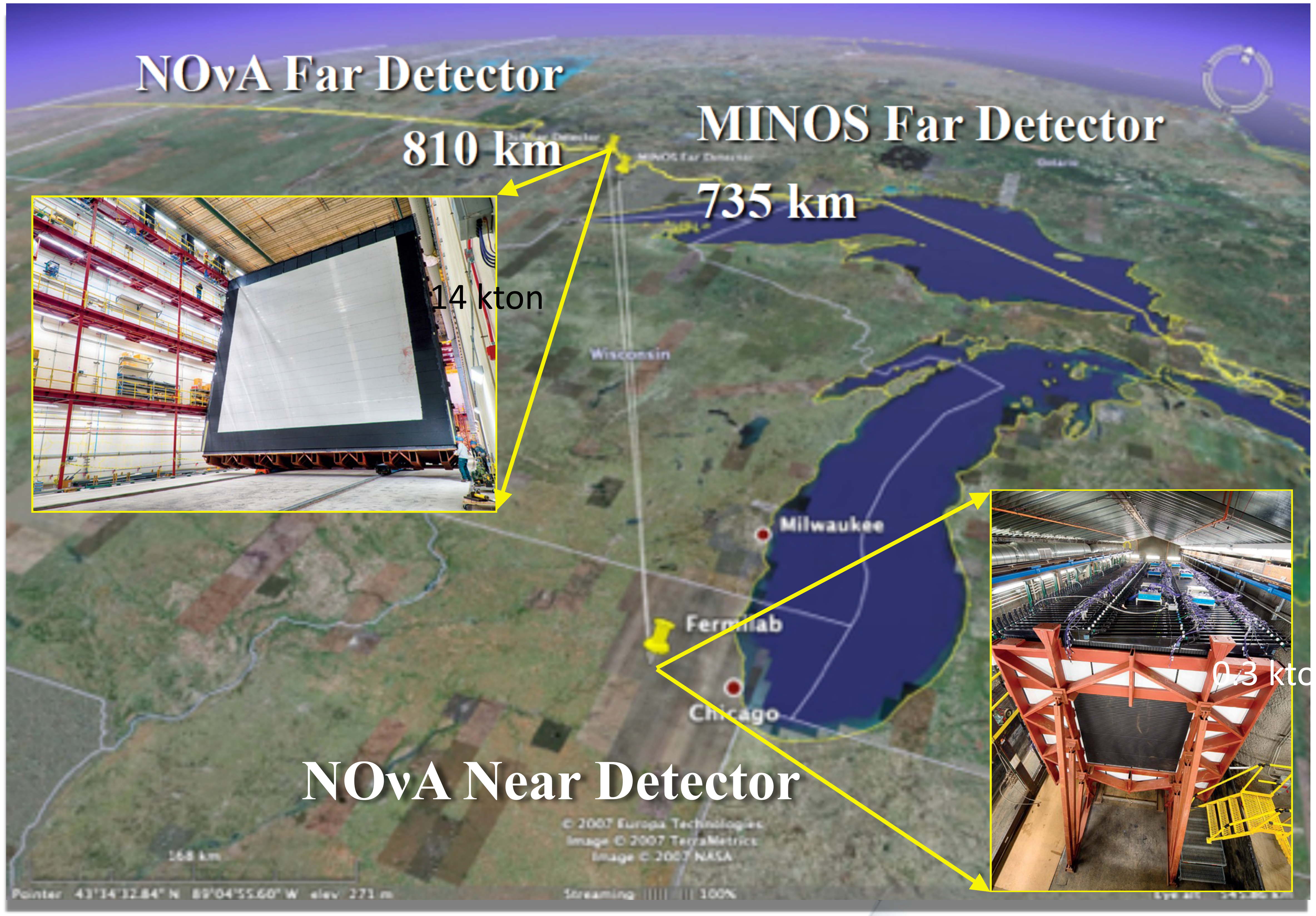
Proton beam, ~500 kW

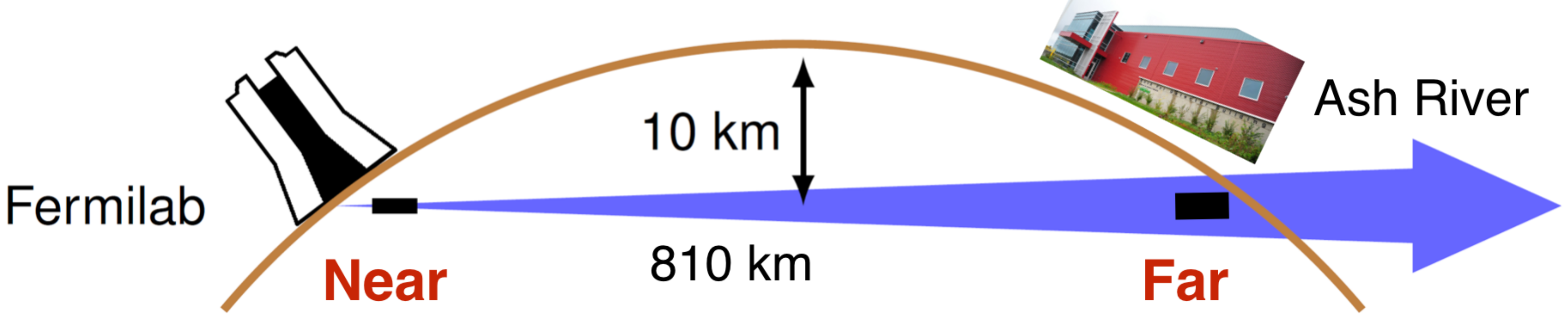
50 kton, 22.5 kton fiducial

- 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 neutrino beam
- Both detectors are 2.5° off ν beam axis ($E_{peak} \approx$ 600 MeV)

NOvA (NuMI Off-Axis Nue Appearance) in USA

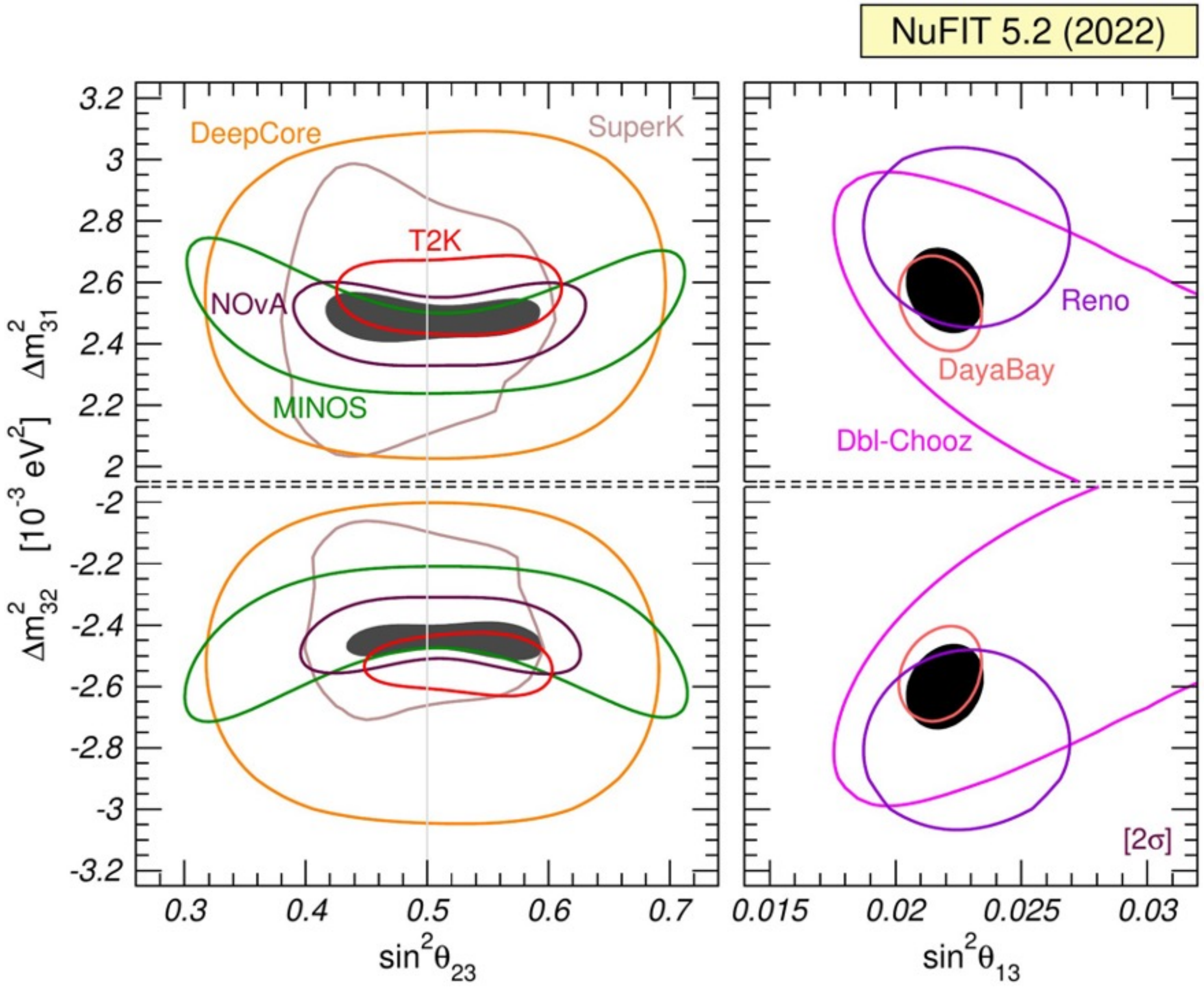
- 810 km baseline from Fermilab to Ash River, MN
- 700 kW NuMI neutrino beam at Fermilab
- Near and Far Detectors placed 14 mrad off the NuMI beam axis
- Measure $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ to:
  - Determine ν mass hierarchy
  - Determine the θ_{23} octant
  - 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
  - …



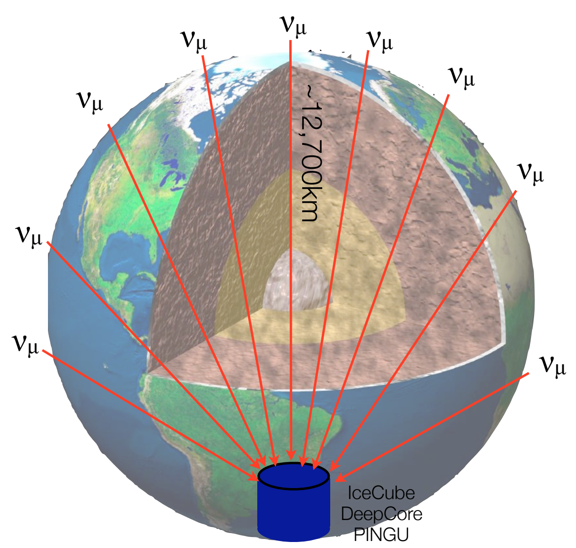


Octant and mass ordering from LBL

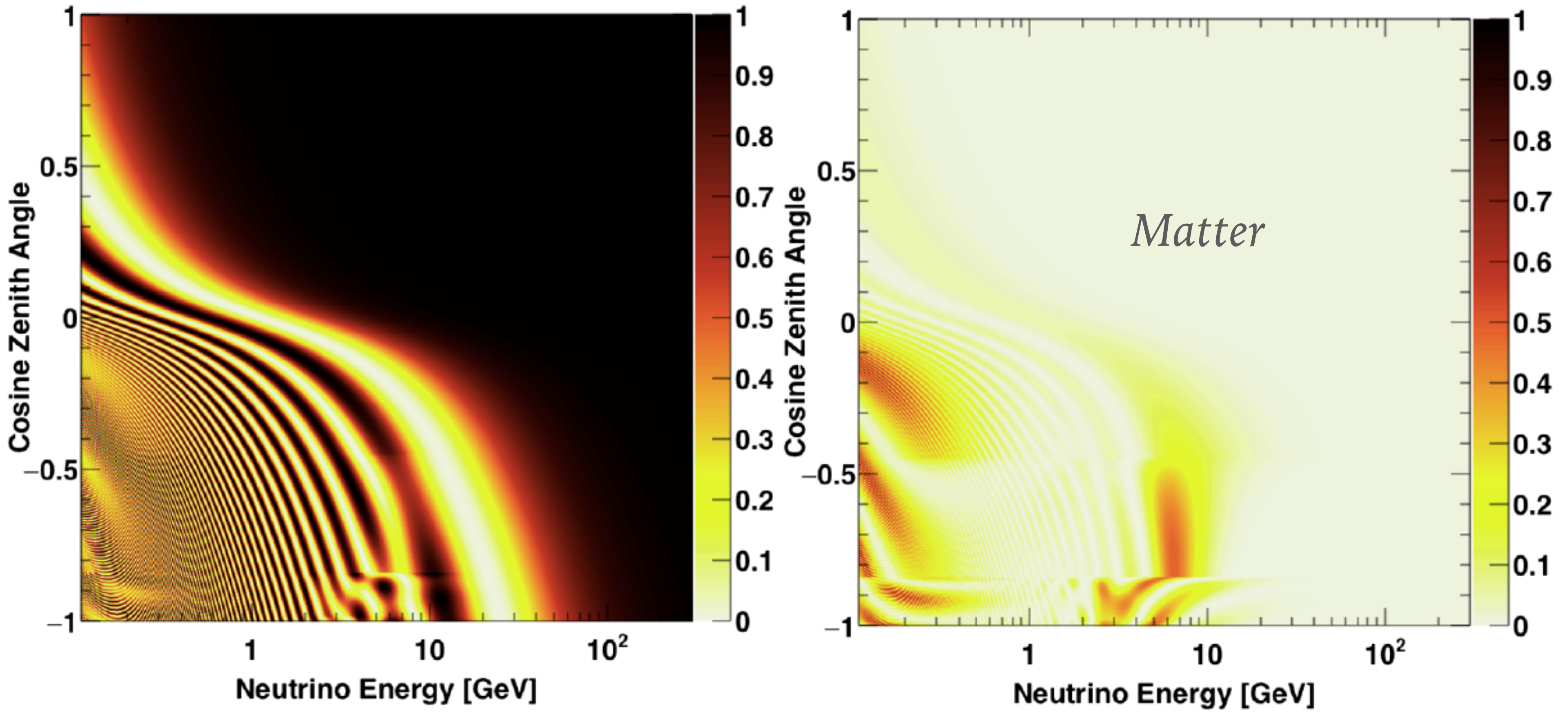
- Results consistent with maximal disappearance
- Slight preference for the second octant for NO
- Δm^2_{32} measurement dominated by NOvA
- $\sin^2\theta_{23}$ measurement dominated by T2K



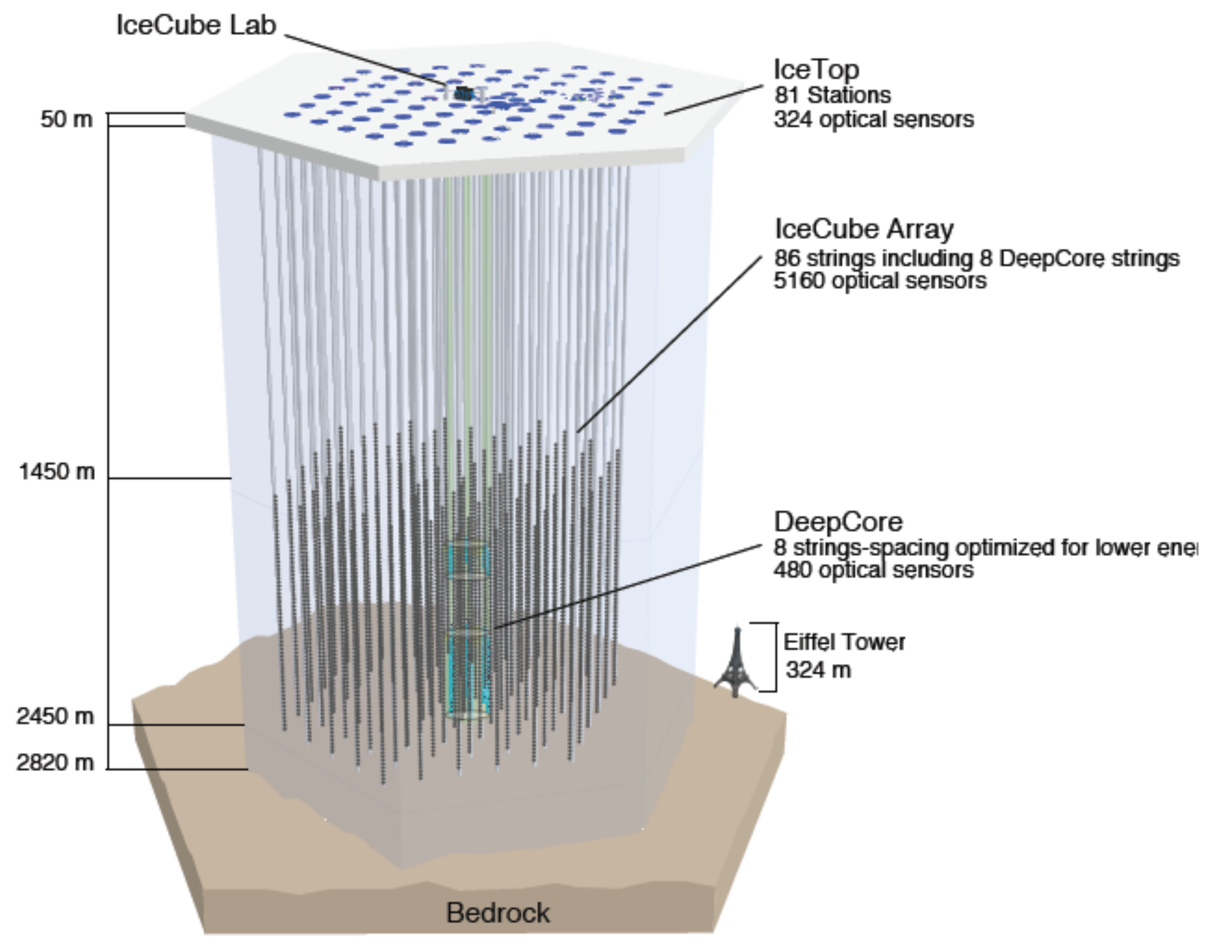
Atmospheric neutrinos with SK and IceCube

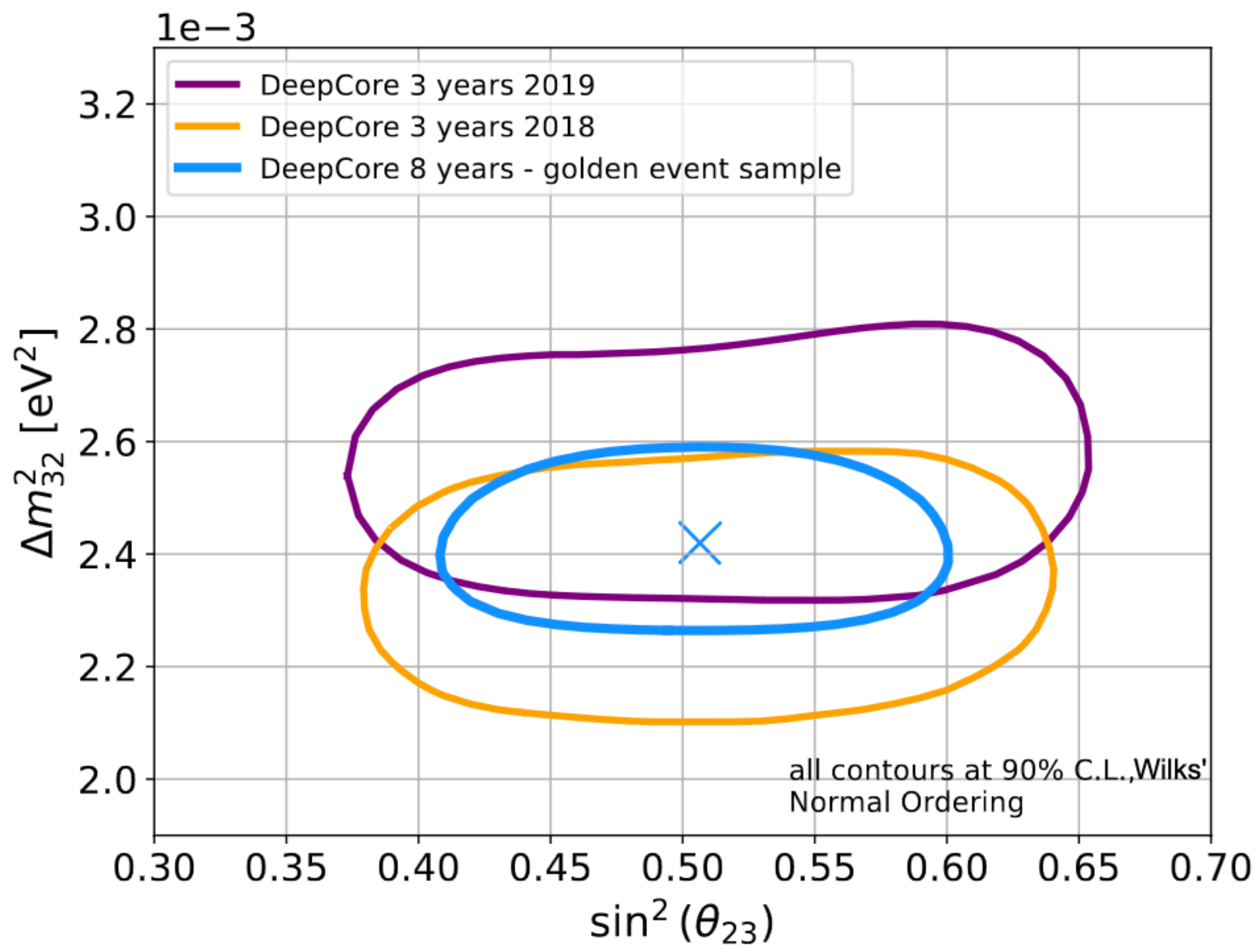


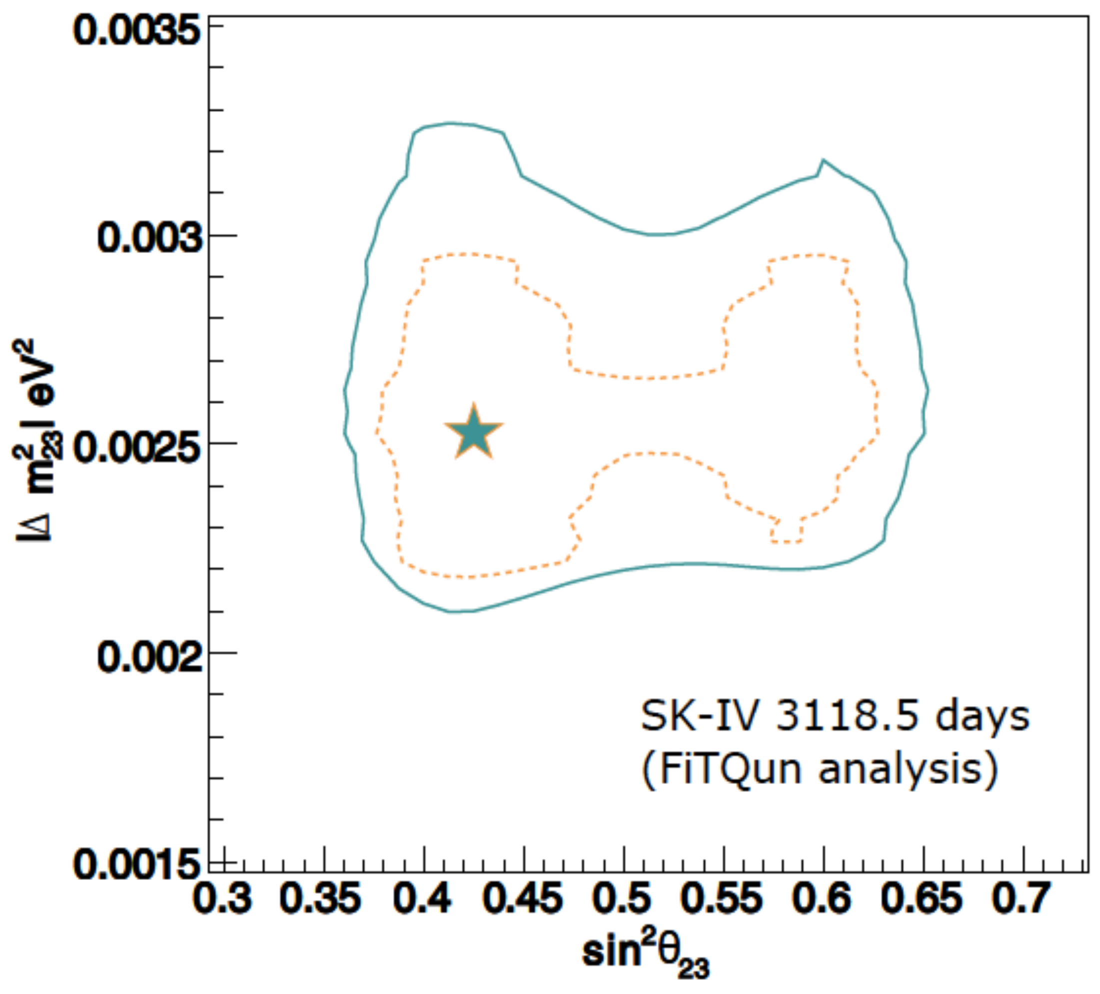
- **Matter effects** in Earth modify the oscillation pattern and arise in neutrinos (for NO) or antineutrinos (for IO) for energies < 15 GeV
- **Super-K** atmospheric results (3ν oscillation analysis) *Prog. Theor. Exp. Phys. 2019, 053F01*
  - ✦ Data shows a **weak preference for normal mass ordering**, disfavoring the inverted mass ordering at 74% assuming oscillation parameters at the best fit point
  - ✦ **No strong preference for θ_{23} octant** is observed
- **IceCube (DeepCore)** results *Phys. Rev. D 108, 012014 (2023)*
  - ✦ Neutrinos from full sky with reco energies from 5.6 to 56 GeV
  - ✦ Three years of data - recent update with 8 years golden sample
  - ✦ Results consistent with other experiments (**maximal mixing**)



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







CP violation results from LBL

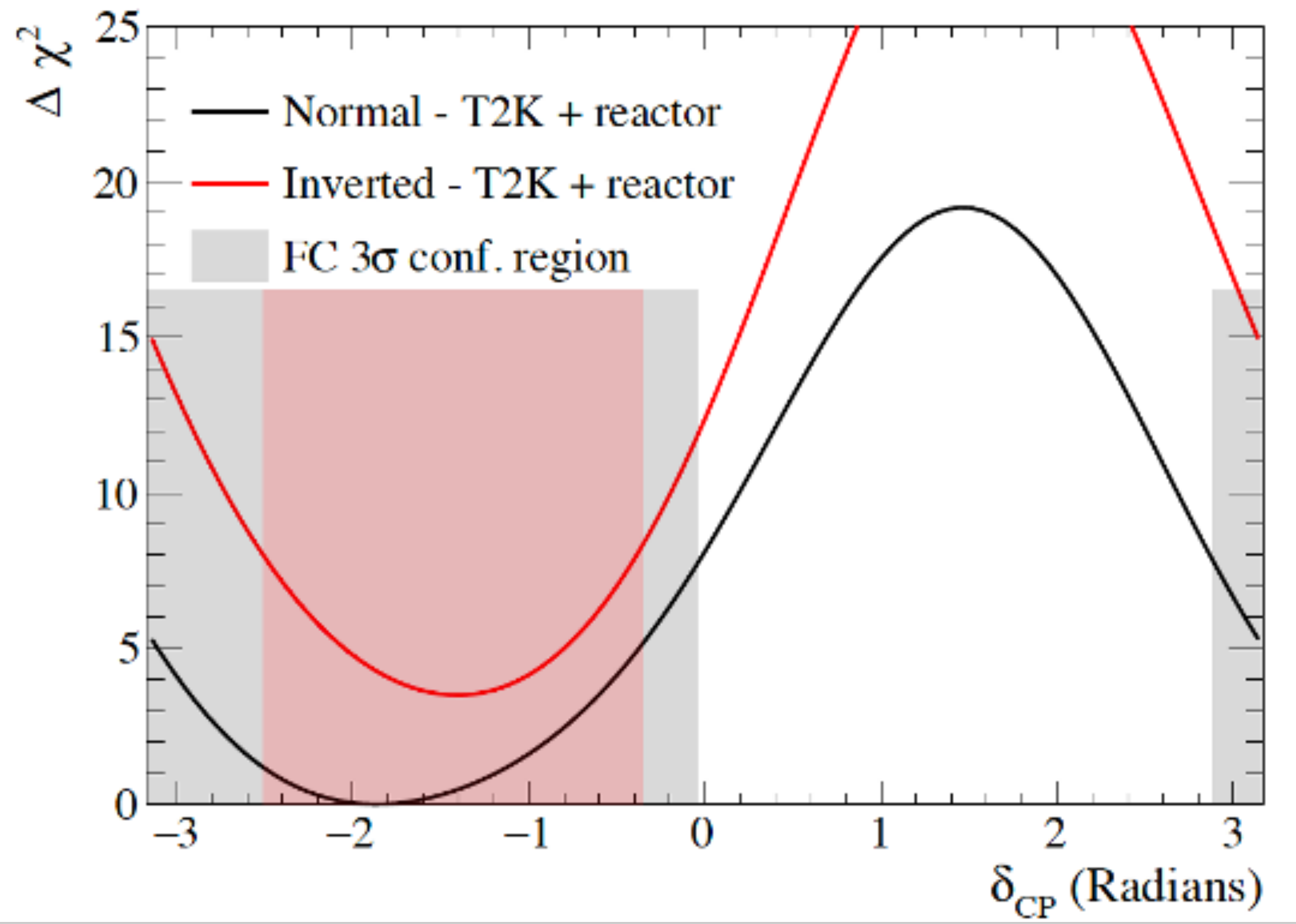
First evidence (4.4σ) of $\overline{\nu}_e$ appearance in $\overline{\nu}_\mu$ beam

Phys. Rev. D 103, 112008

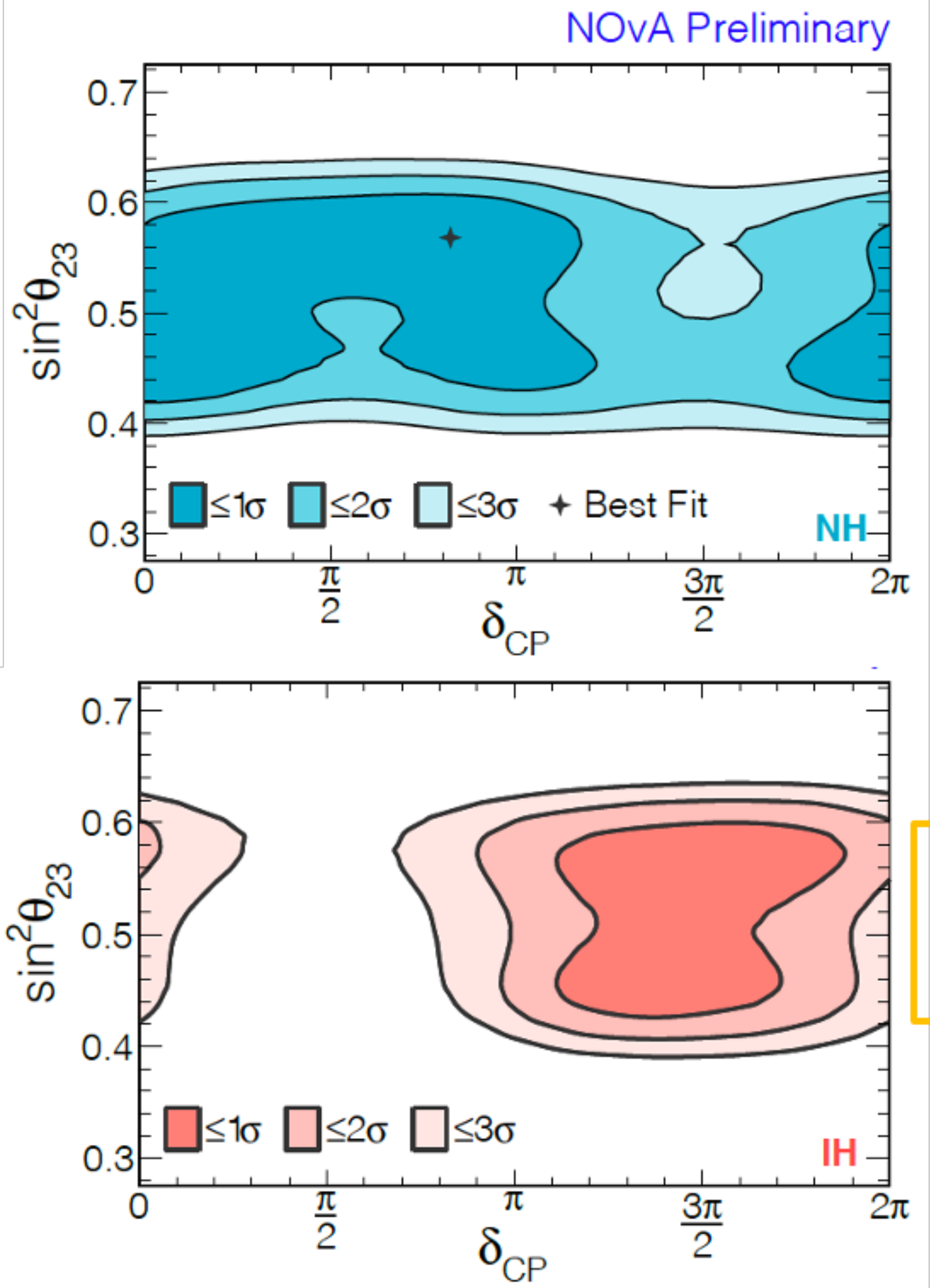
Weak preference for NH and upper θ_{23} octant

Parameter	Best-fit and 1σ interval NO	IO
δ_{CP}	$-1.89^{+0.70}_{-0.58}$	$-1.38^{+0.48}_{-0.55}$
$\sin^2\theta_{23}$	$0.532^{+0.030}_{-0.037}$	$0.532^{+0.029}_{-0.035}$
$\Delta m^2_{32}\ /10^{-3}\text{eV}^2c^{-4}$	$2.45^{+0.07}_{-0.07}$	
$\mid\Delta m^2_{13}\mid\ /10^{-3}\text{eV}^2c^{-4}$		$2.43^{+0.07}_{-0.07}$

Excludes CP conservation at 2σ



easurements



Phys. Rev. Lett. 123, 151803

IH disfavored at 1.0σ

Disfavor the lower θ_{23} octant at 1.2σ

Best Fit

Normal hierarchy

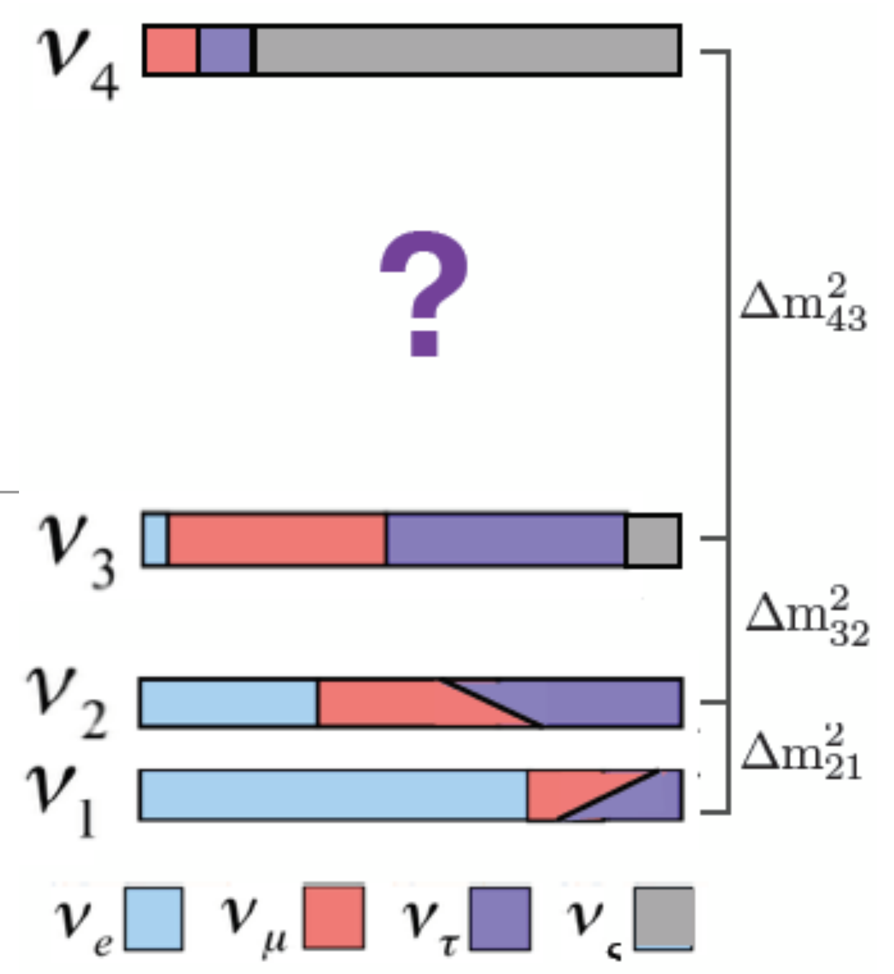
$\Delta m^2_{32} = (2.41\pm0.07)\times10^{-3}\ \text{eV}^2$

$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

$\delta = 0.82\pi$

Exclude $\delta_{CP}=\pi/2$ in IH at >3σ and $\delta_{CP}=3\pi/2$ in NH at ~2σ

Tension between T2K and NOvA in CP phase for NO

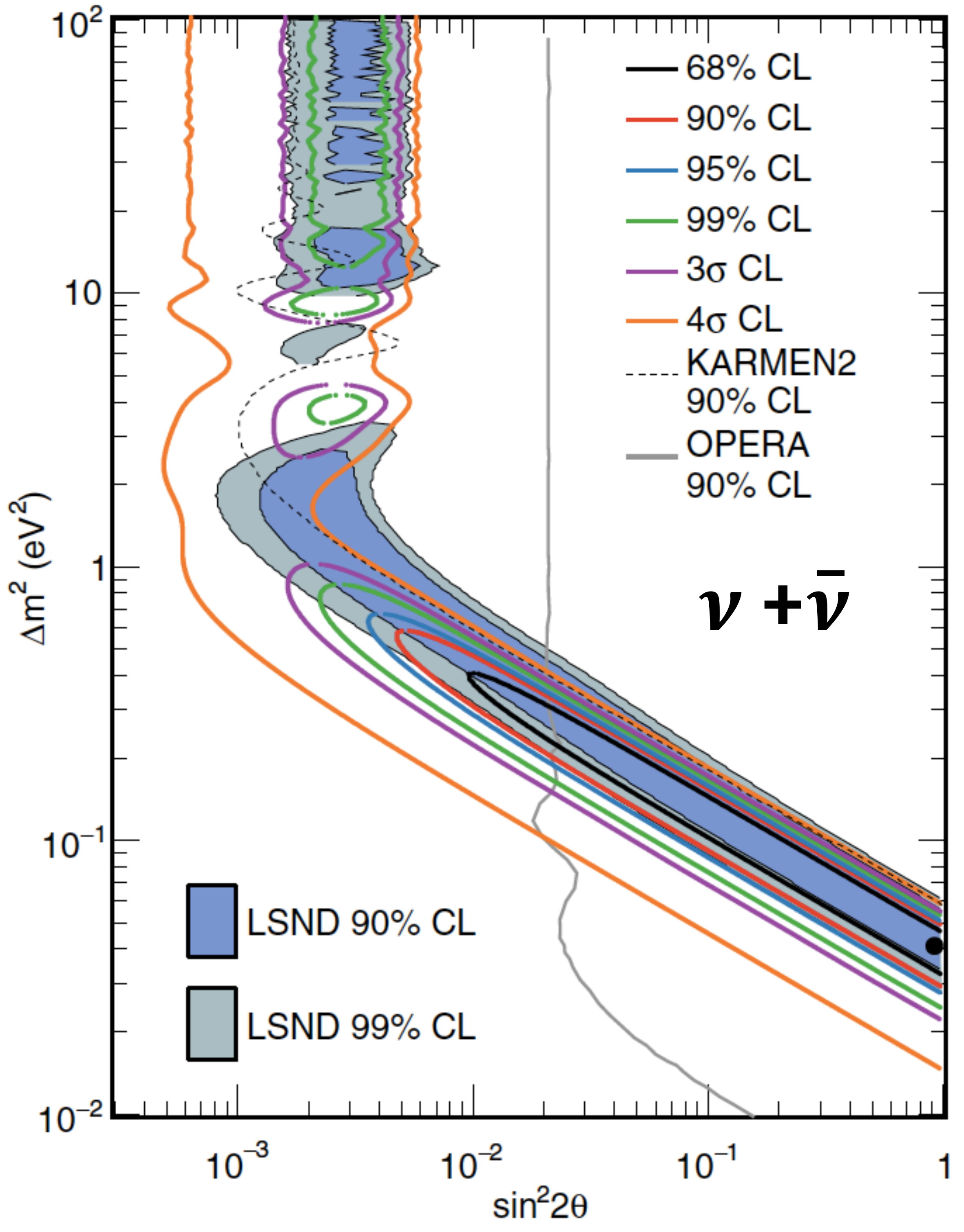


Neutrino oscillation anomalies

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

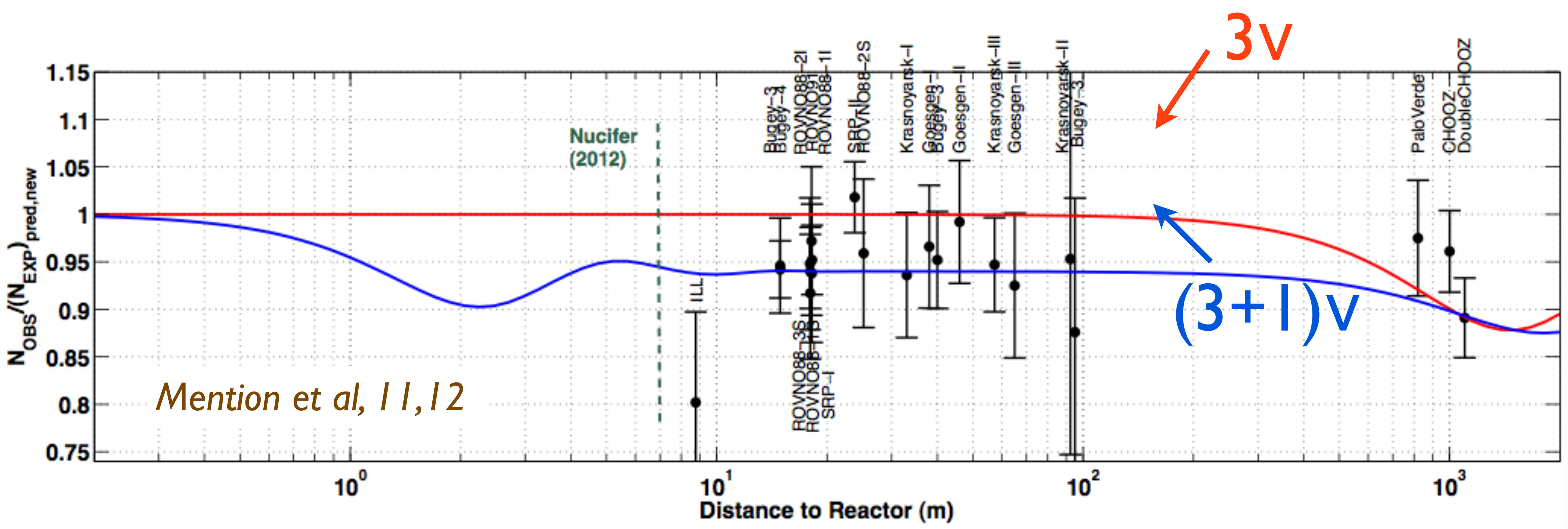
LSND + MiniBooNE

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



Phys. Rev. Lett. 121 (2018) 221801

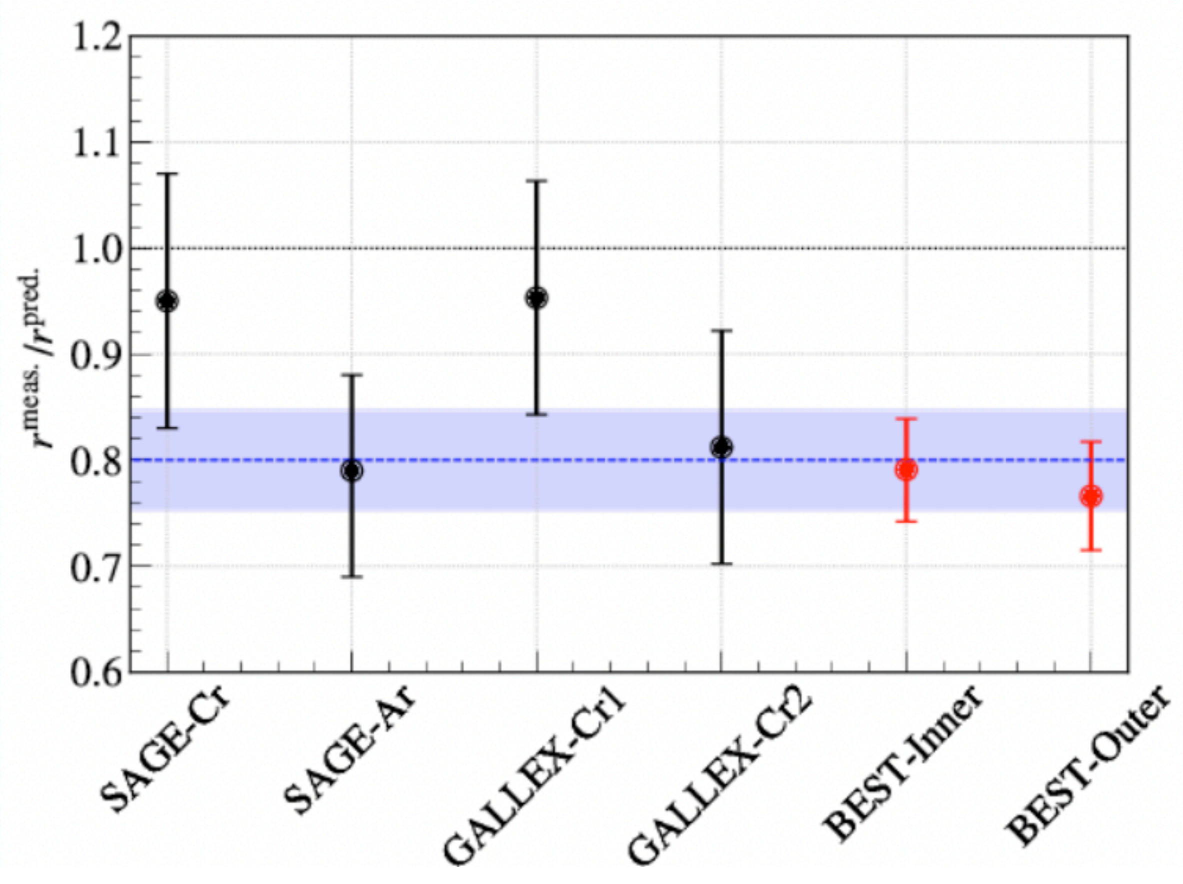
Reactor neutrino anomaly



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

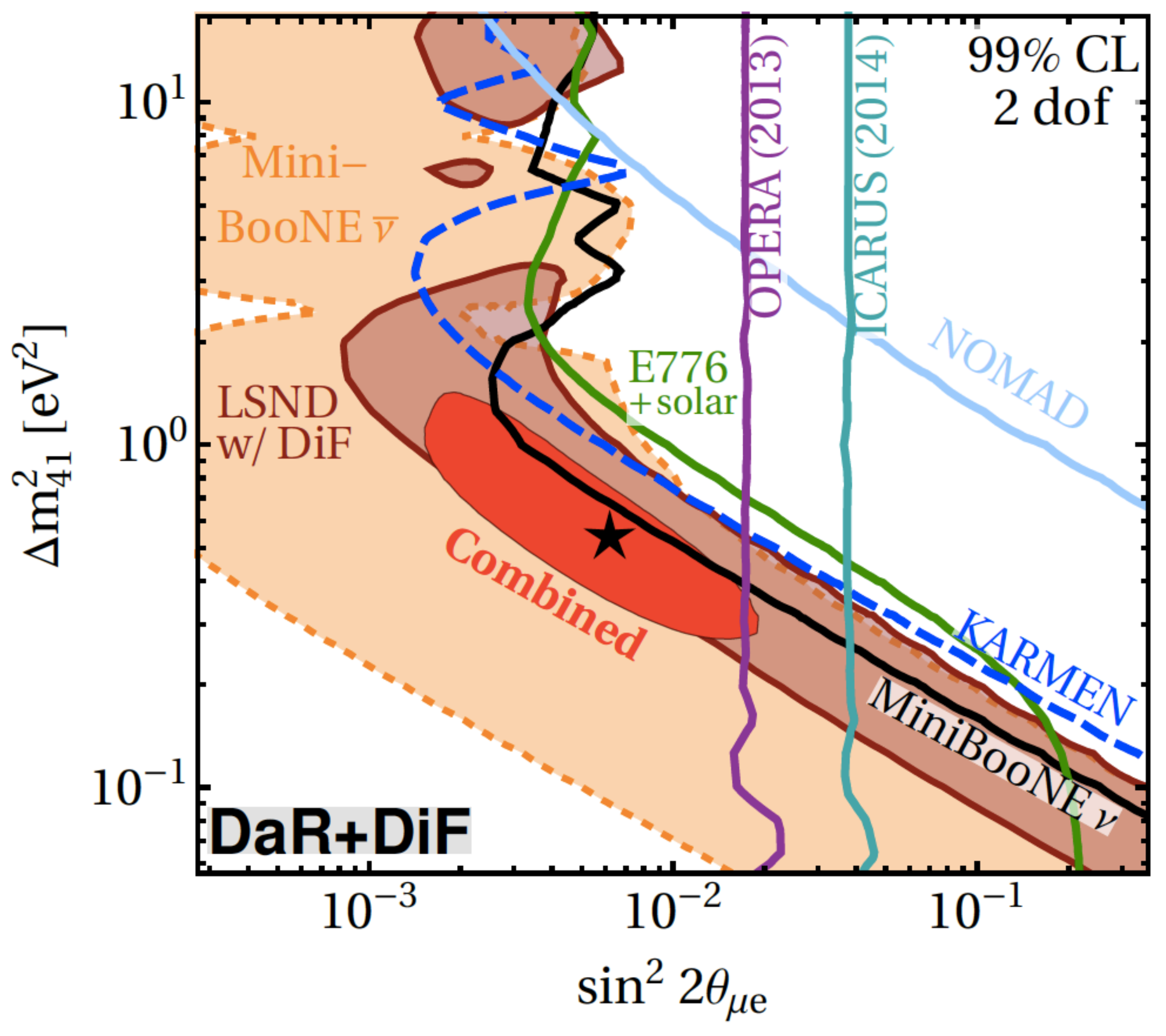


Intense ^{51}Cr and ^{37}Ar neutrino sources show deficit wrt predictions. Recently confirmed by BEST

Global sterile results

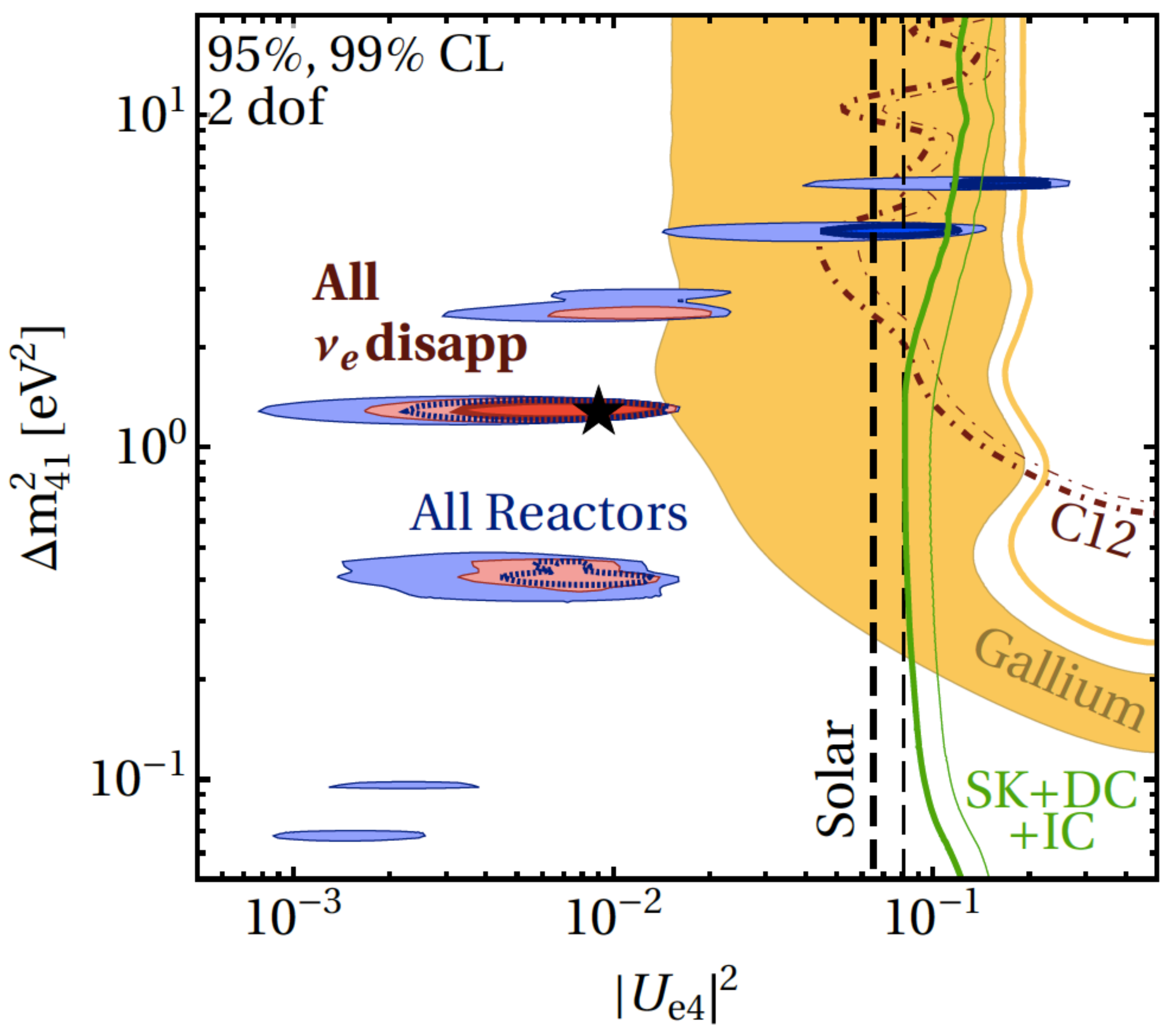
- Tension between the three results
- Sterile neutrino models fail to simultaneously account for all experimental data (strong tension between appearance and disappearance experiments)

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



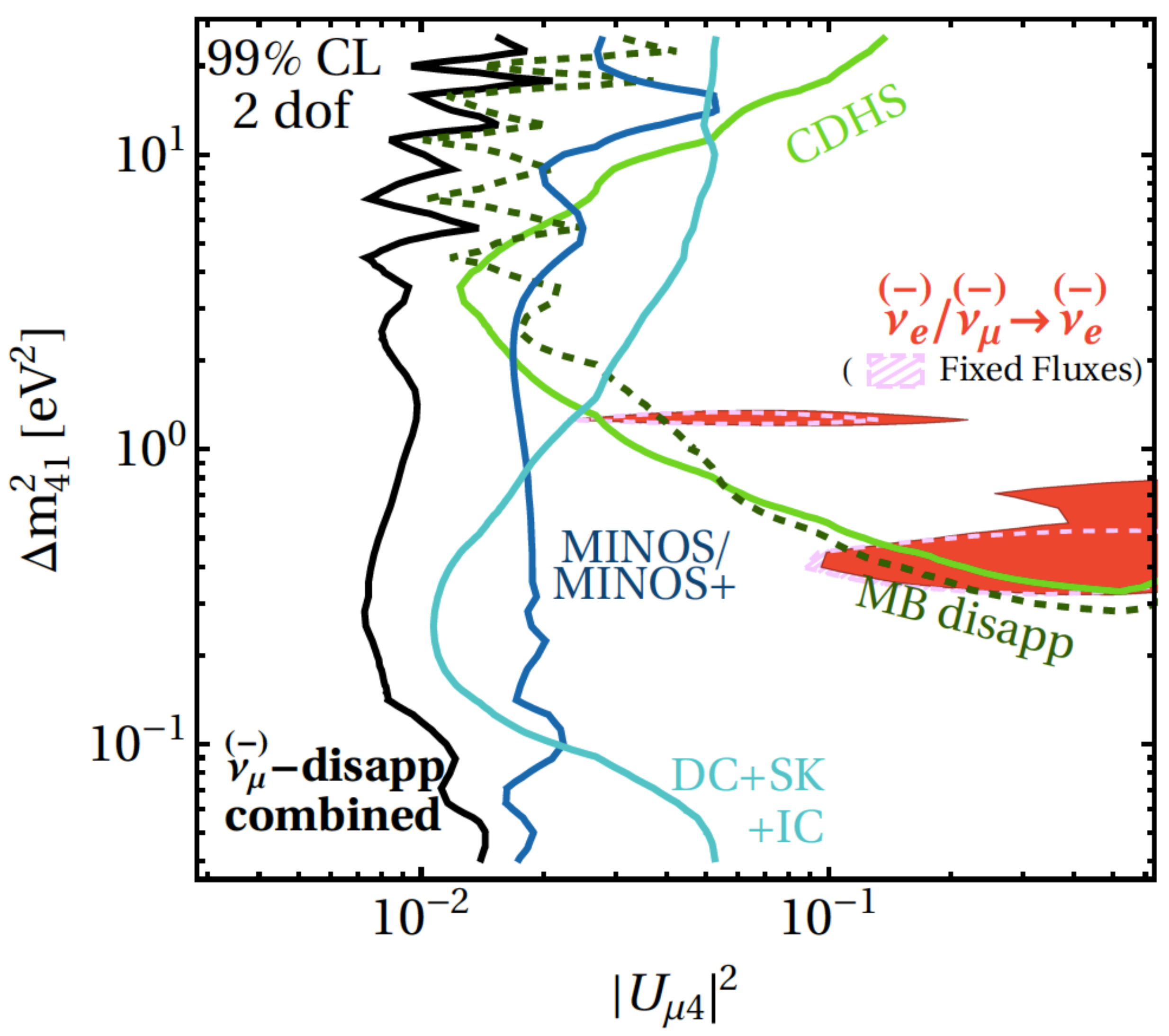
Observation by LSND & MiniBooNE

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



Observation by reactors & radioactive sources

ν_μ **disappearance**



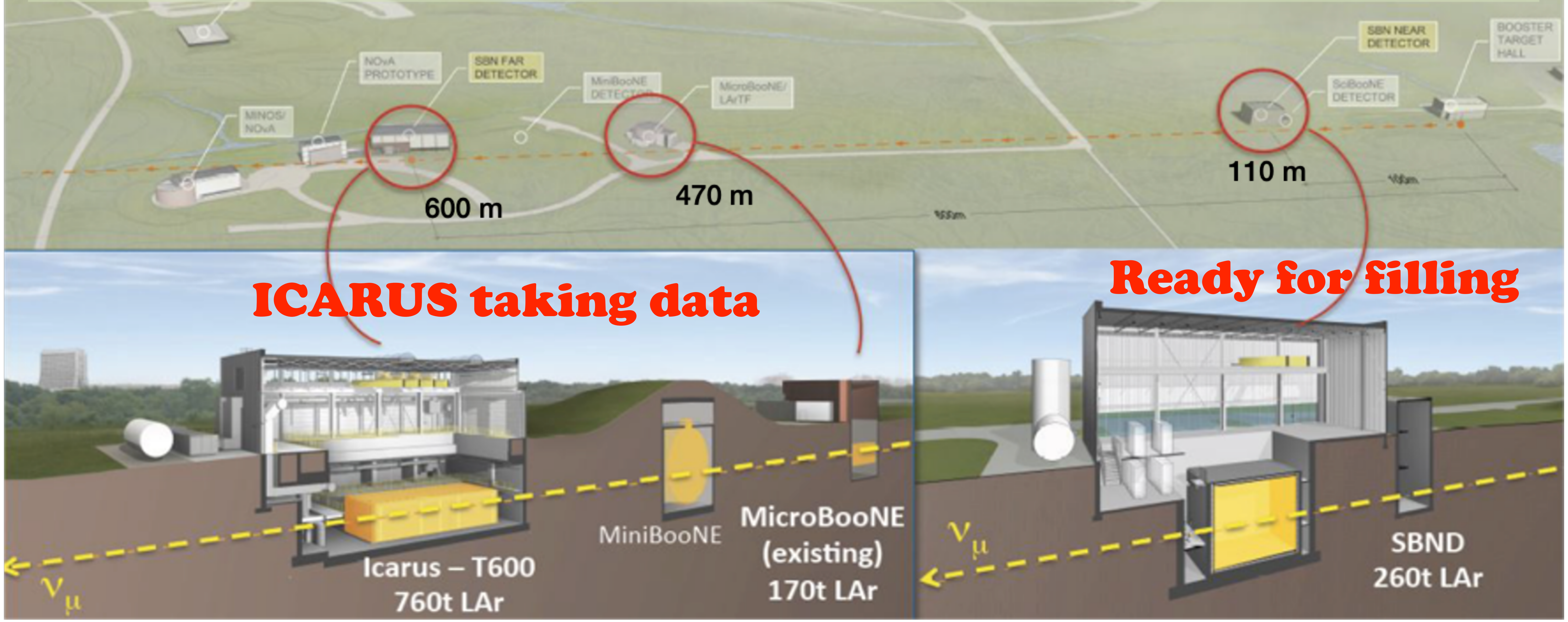
Non observation

JHEP 08 (2018) 010

Short-Baseline Neutrino Program at Fermilab

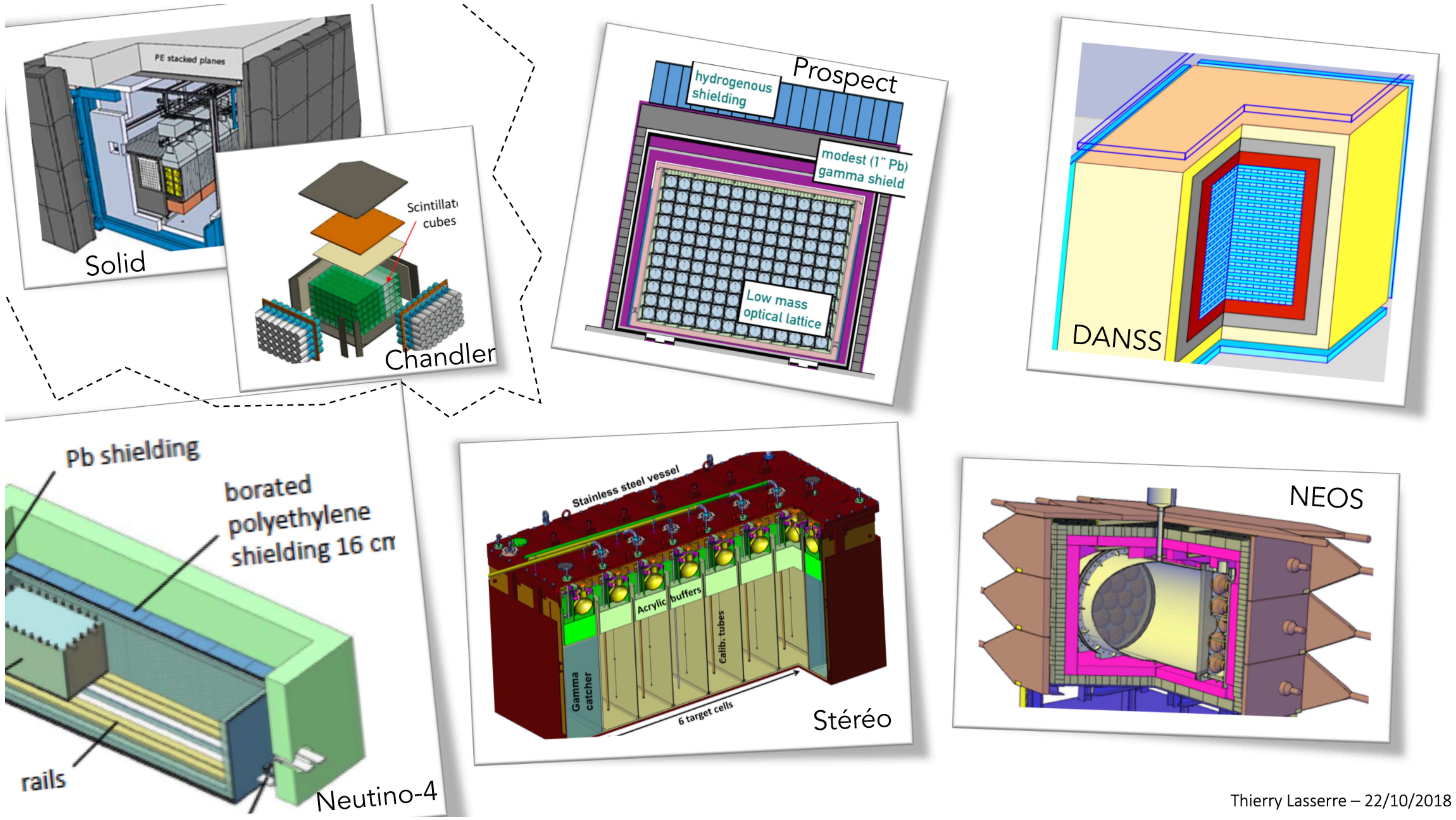
3 LAr TPC detectors in the ν beam from the 8 GeV Booster E_{ν}^{peak} ~800 MeV to

- 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



Other experiments (VSBL reactors)

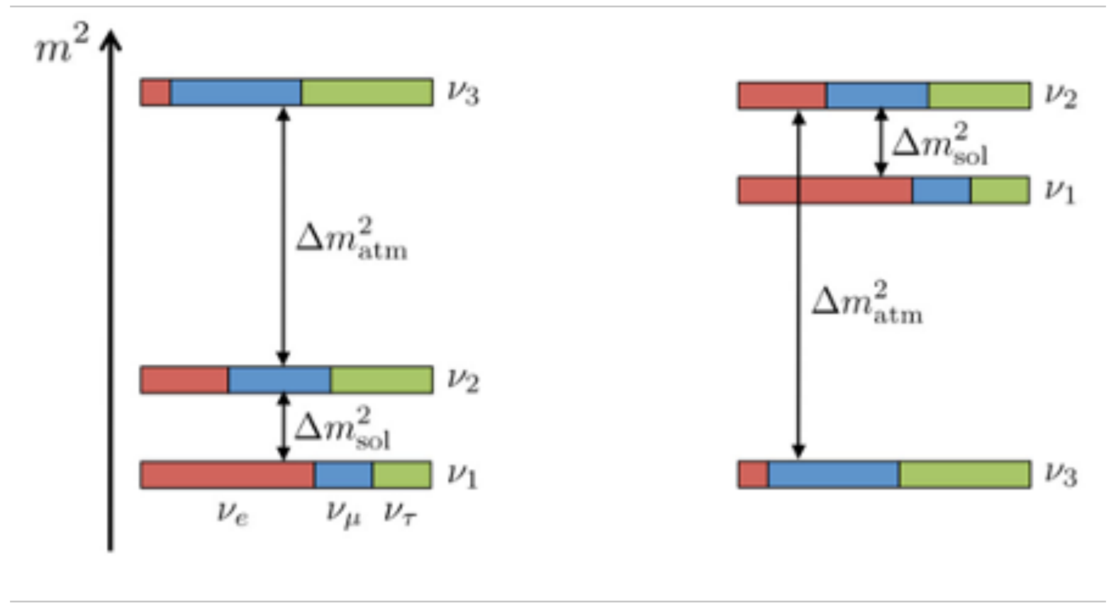
- Large number of very short-baseline reactor experiments ongoing (sterile neutrino searches)
  - ✦ Stereo, SoLid, Neutrino-4, NEOS, DANSS, Prospect, …
- CEvNS reactor experiments: CONNIE, CONUS, …



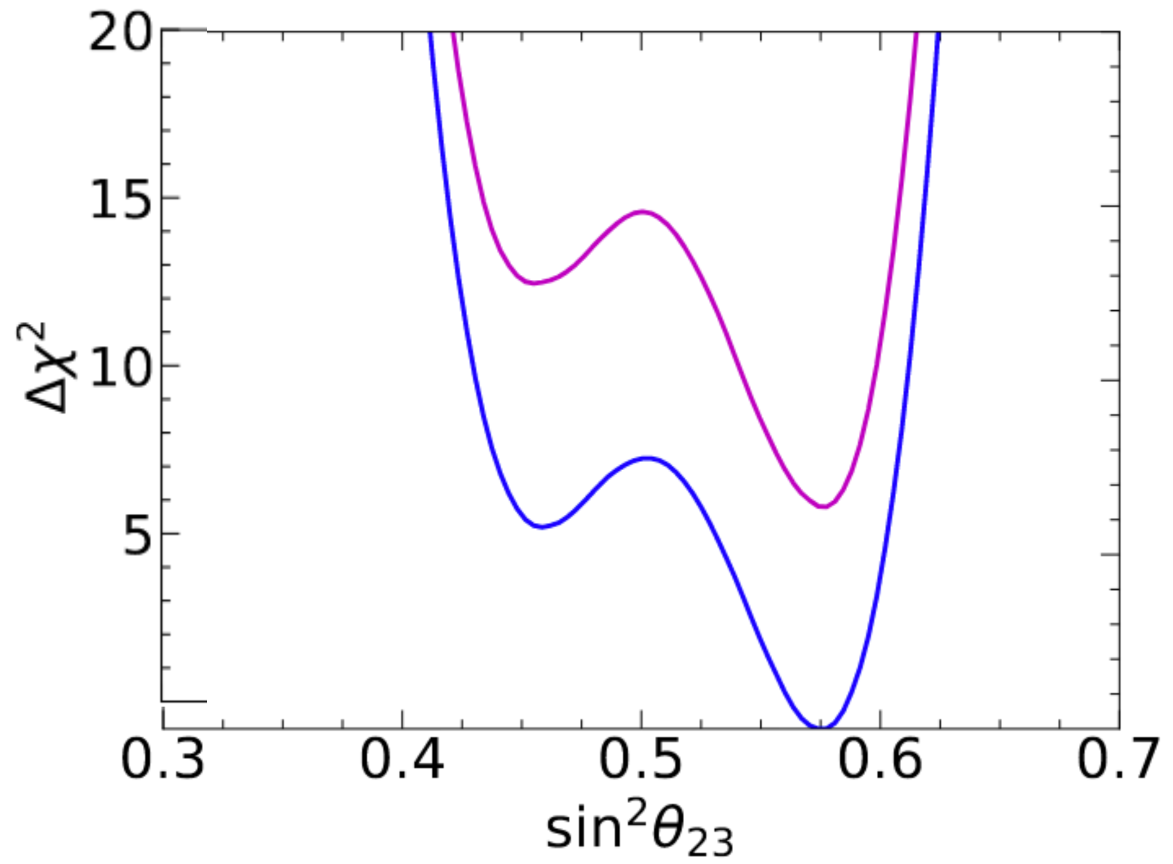
Prospects in neutrino oscillations

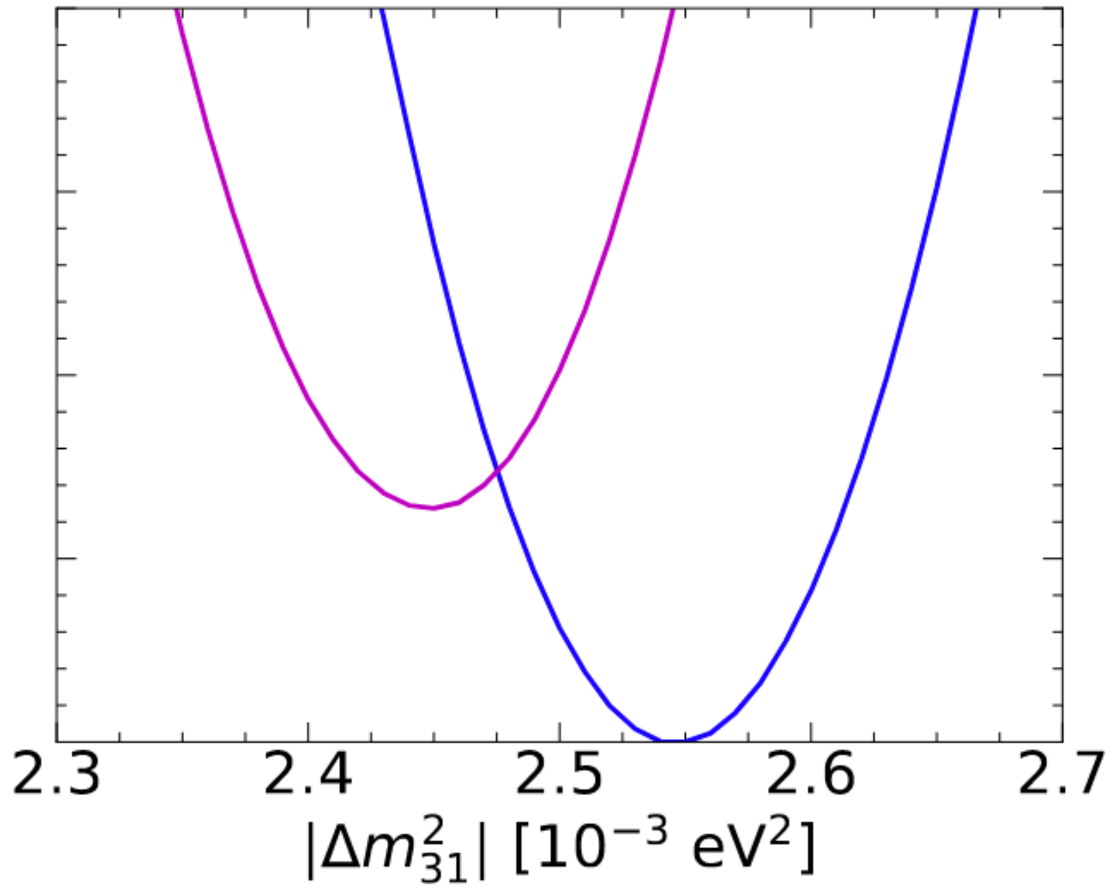
Discovery opportunities

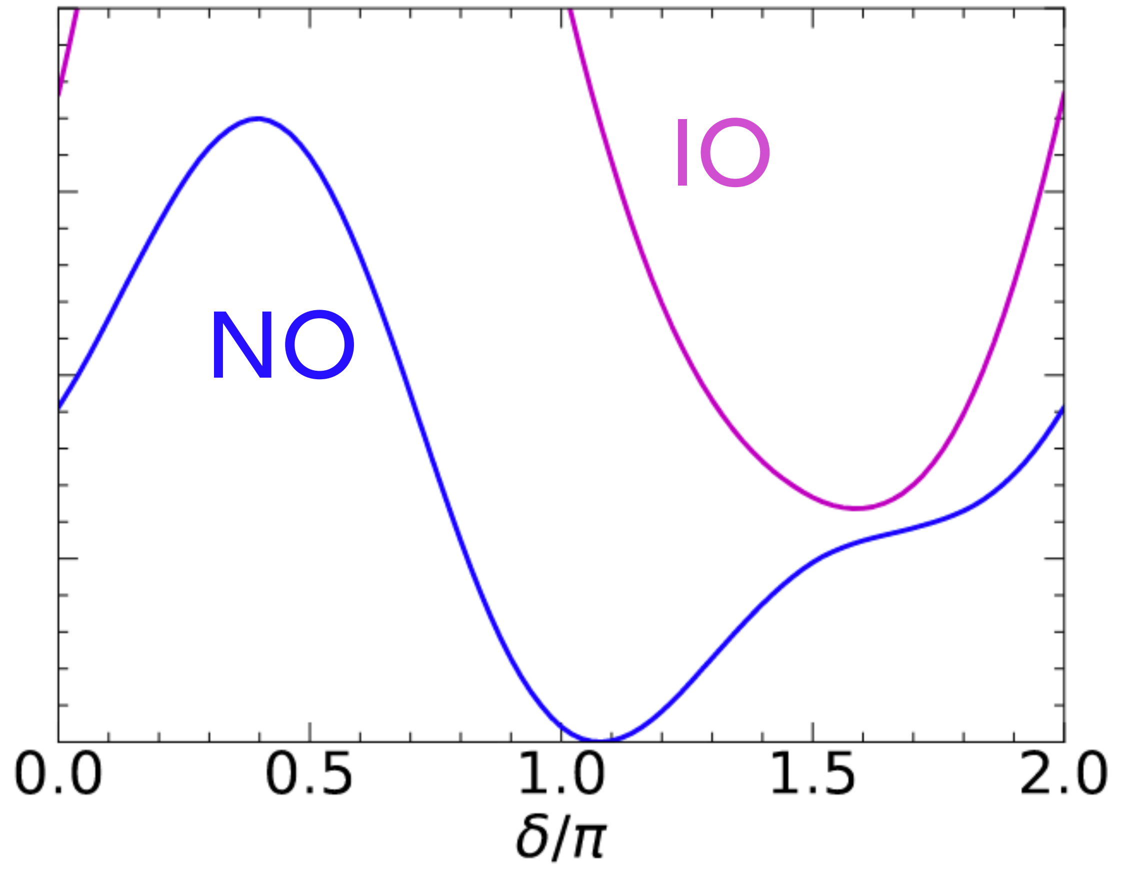
- **CP violation**
  - ✦ T2K and NOvA could reach 3σ sensitivity to CPV over the next years
  - ✦ To reach discovery and precise measurement, **larger detectors** and (upgraded or new) **beams** are needed
- **Neutrino mass ordering**
  - ✦ Small preference for NO with current data (not conclusive)
- **Octant of θ₂₃**
  - ✦ 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



JHEP 02 (2021) 071

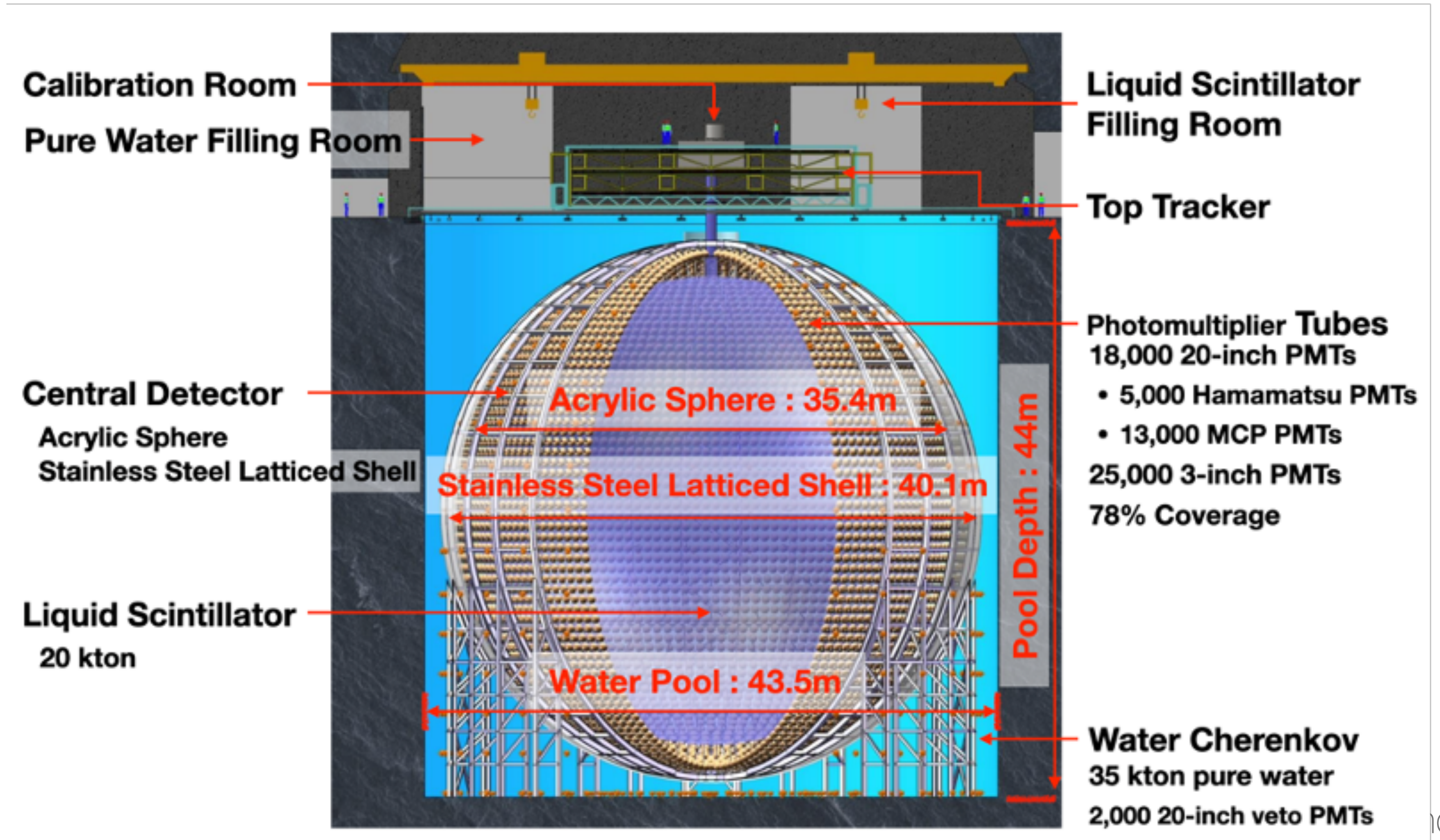


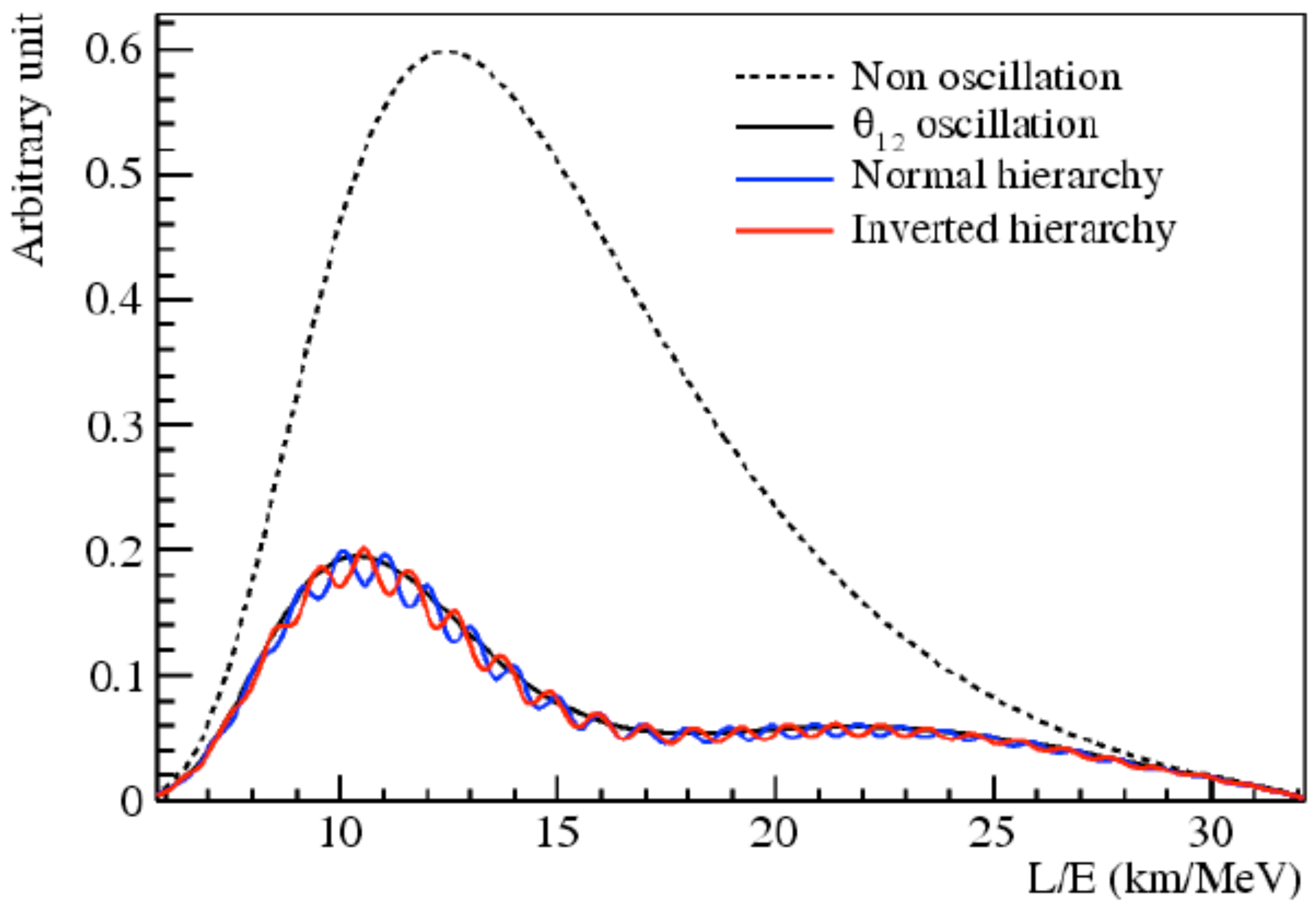




JUNO (Jiangmen Underground Neutrino Observatory)

- 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 2024!
- Design to reach 3σ precision on mass ordering determination after 6y + precise solar oscillation parameters (<0.5%) in 6y + other low-E physics





Looking for interference between P_{31} and P_{32}

$$F(L/E) = \phi(E)\sigma(E)P_{ee}(L/E)$$

$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$

$$\Delta_{21} << \Delta_{31} \approx \Delta_{32}$$

$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \mathrm{NH:}\ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \mathrm{IH:}\ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$

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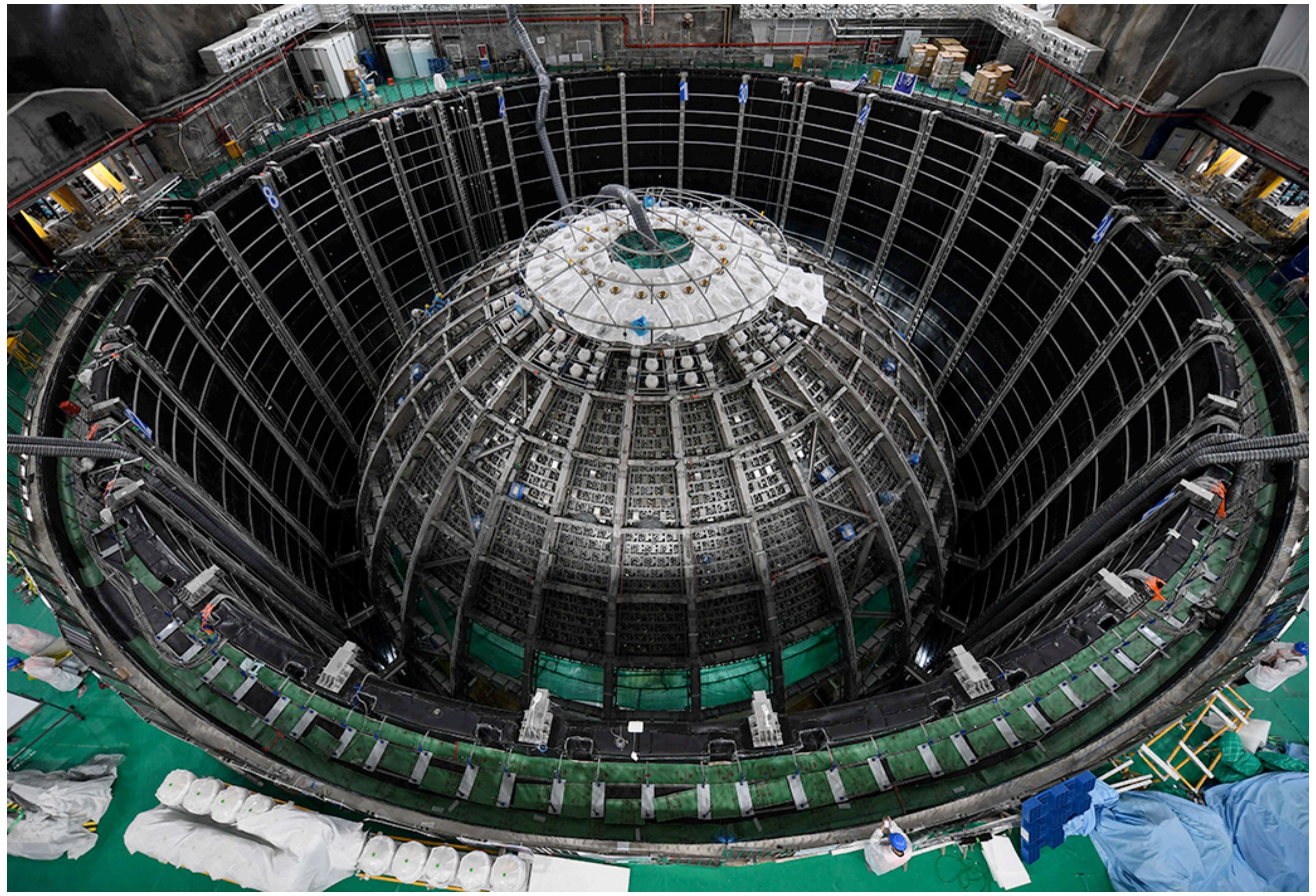

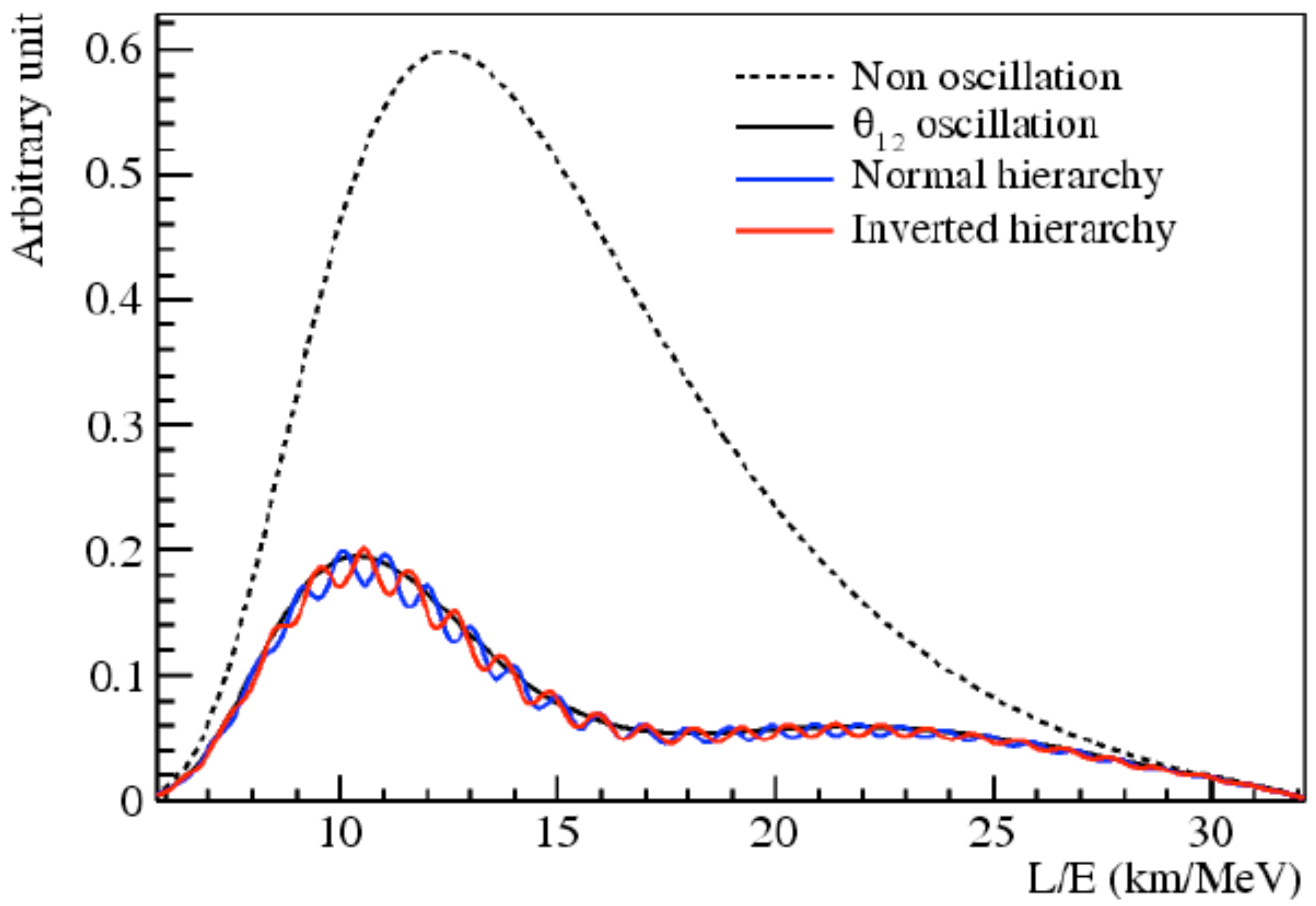

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P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}$$

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$$\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\mathrm{NH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\mathrm{IH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}$$

Long-baseline neutrino accelerator experiments

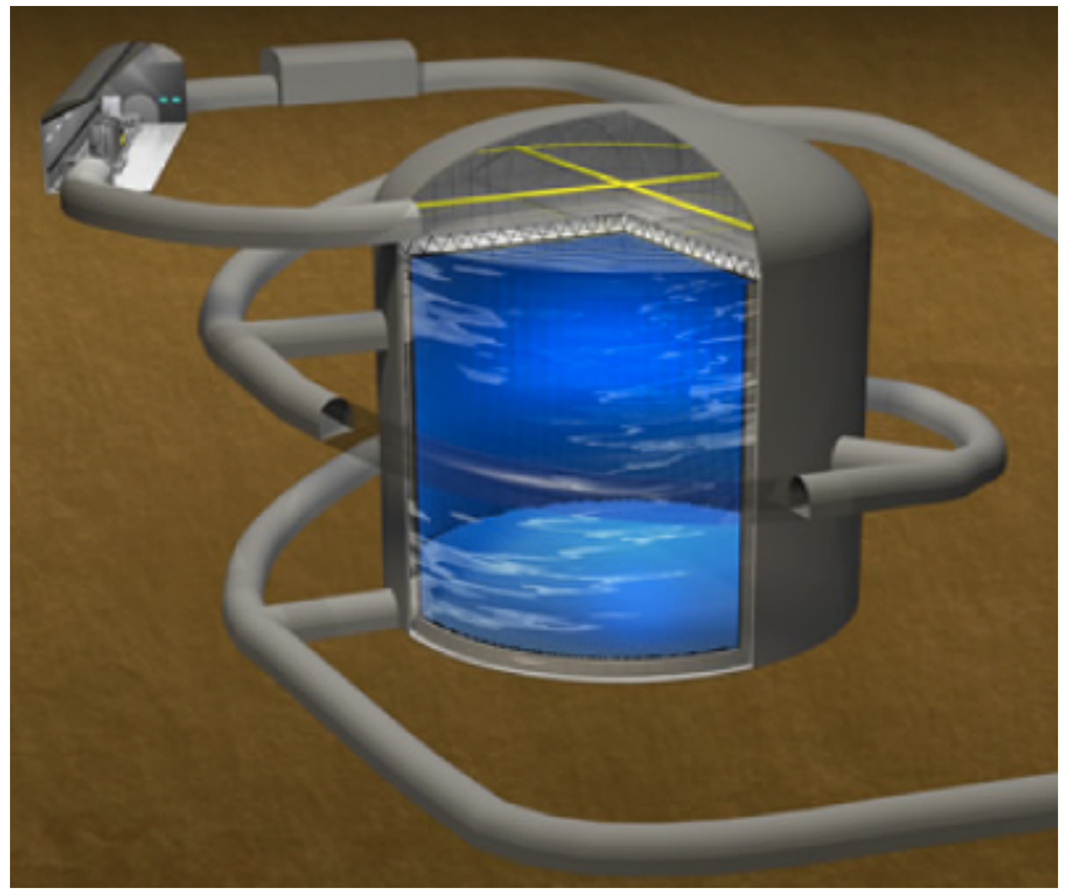
Oscillation probability in matter

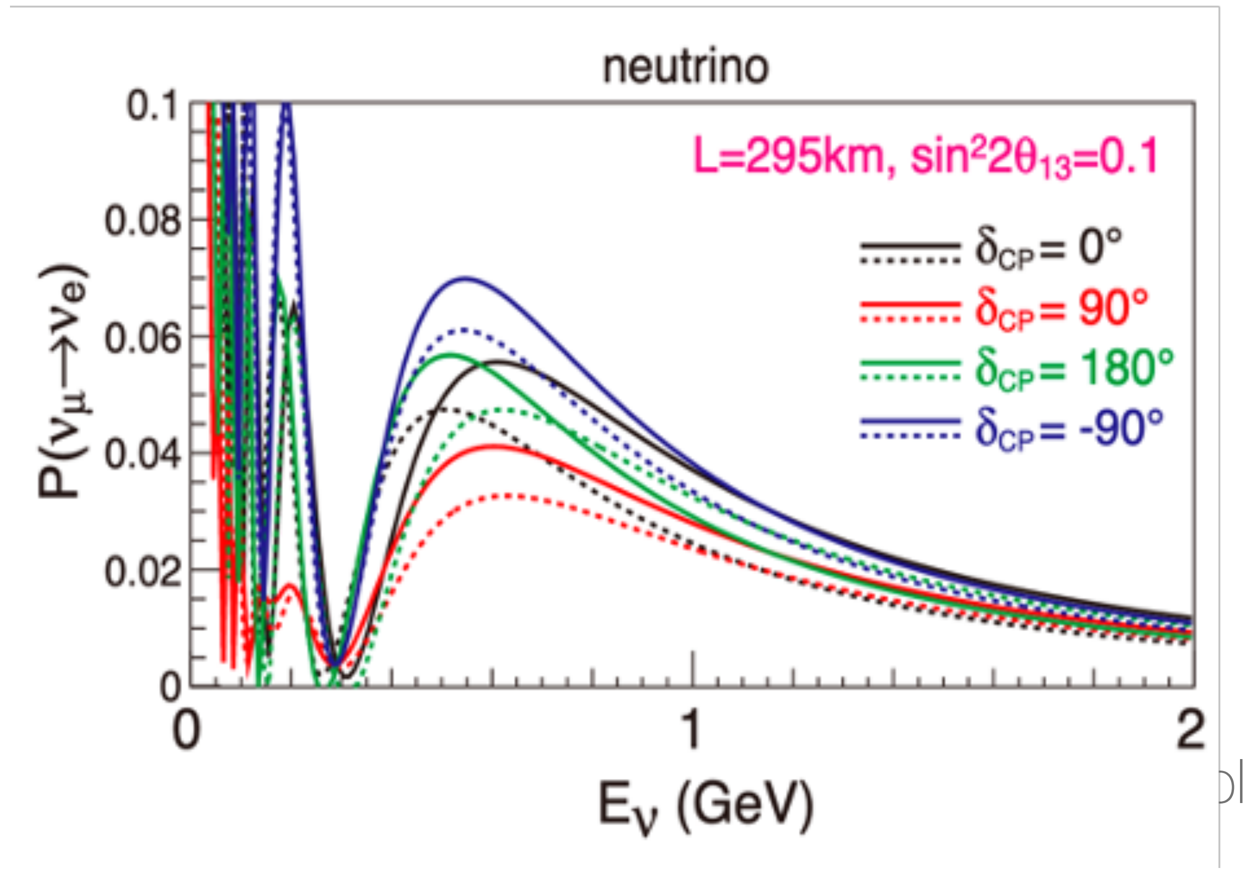
$$P(\overset{(-)}{\nu_\mu} \to \overset{(-)}{\nu_e}) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{CP})$$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

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

T2HK: Tokai to HyperK

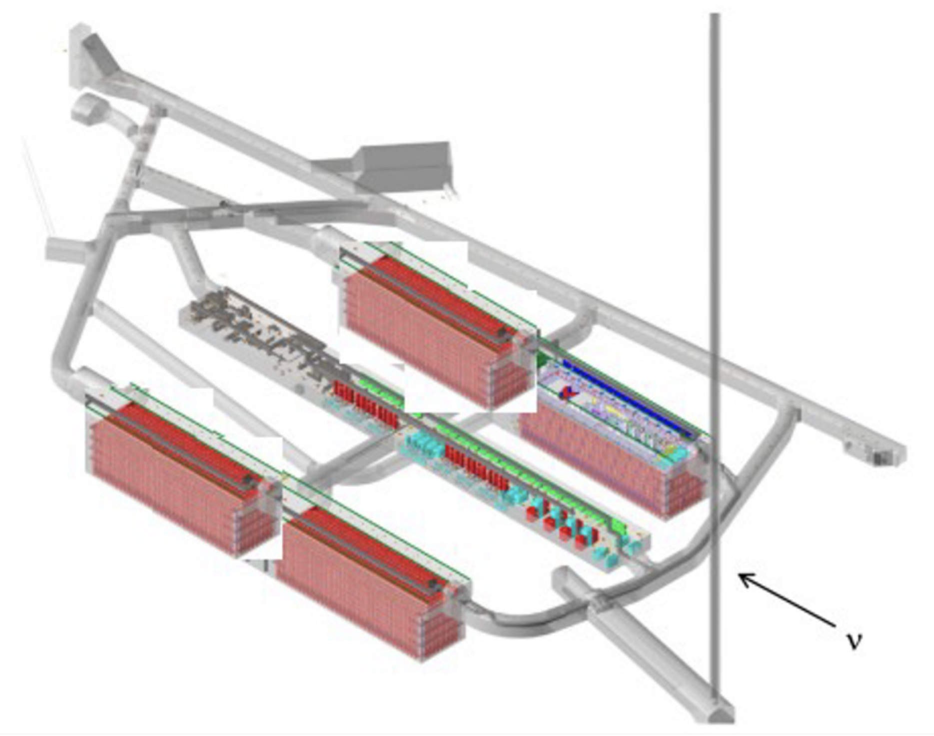
- ✦ Minimize matter effects and maximize statistics to focus on CPV discovery (MO and other parameters must be known by other means) + non-beam physics program
- ✦ Narrow-band beam (~0.6 GeV; 500 kW → 1.3 MW) and Water-Cerenkov detector (190 kt fiducial)

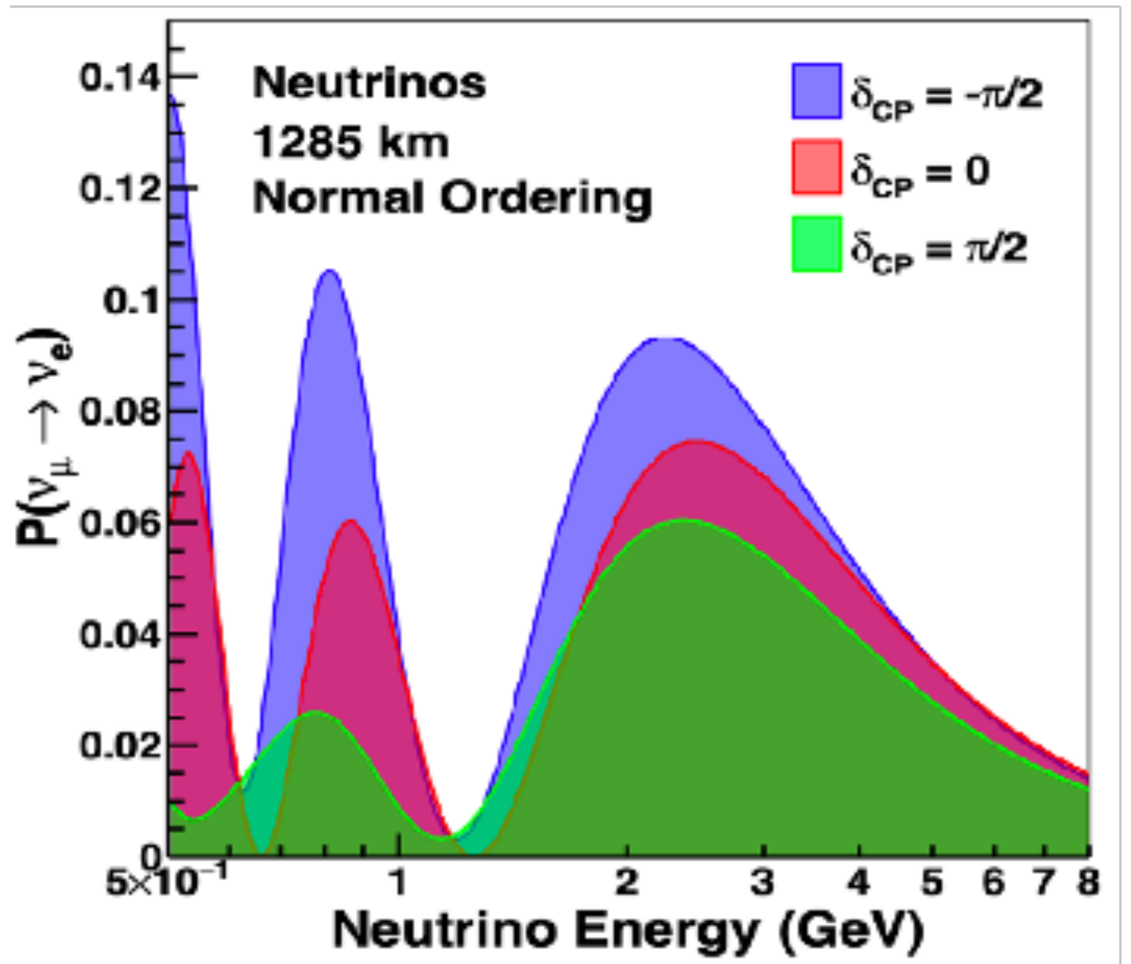




DUNE: FNAL to SURF

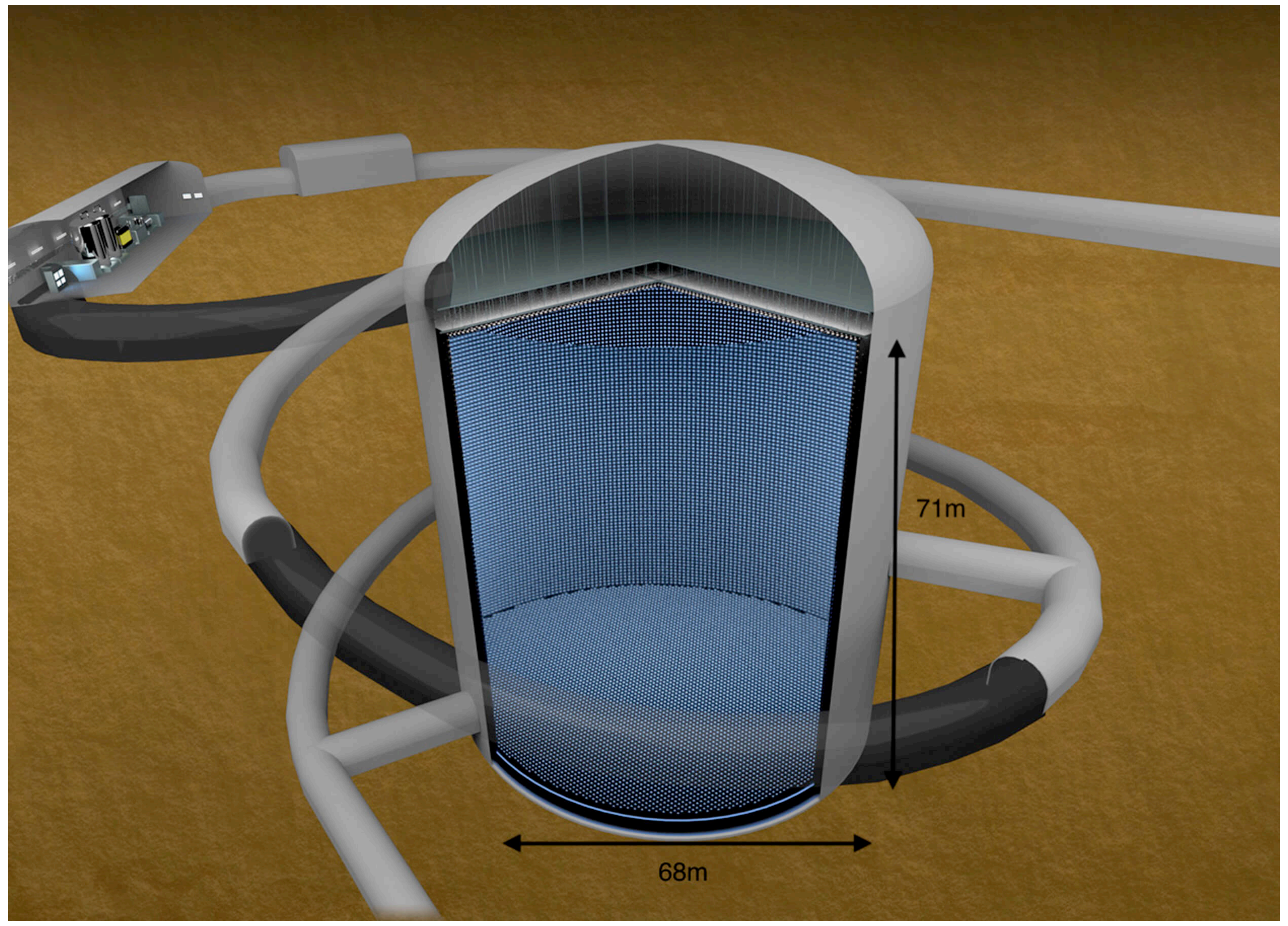
- Measure first and second oscillation maxima to disentangle CPV and matter effects and access to all neutrino oscillation parameters + non-beam physics program
- Wide-band beam (0.5-5 GeV; 1.2 → 2.4 MW) and liquid Argon TPC (>40 kt fiducial)





Hyper-Kamiokande

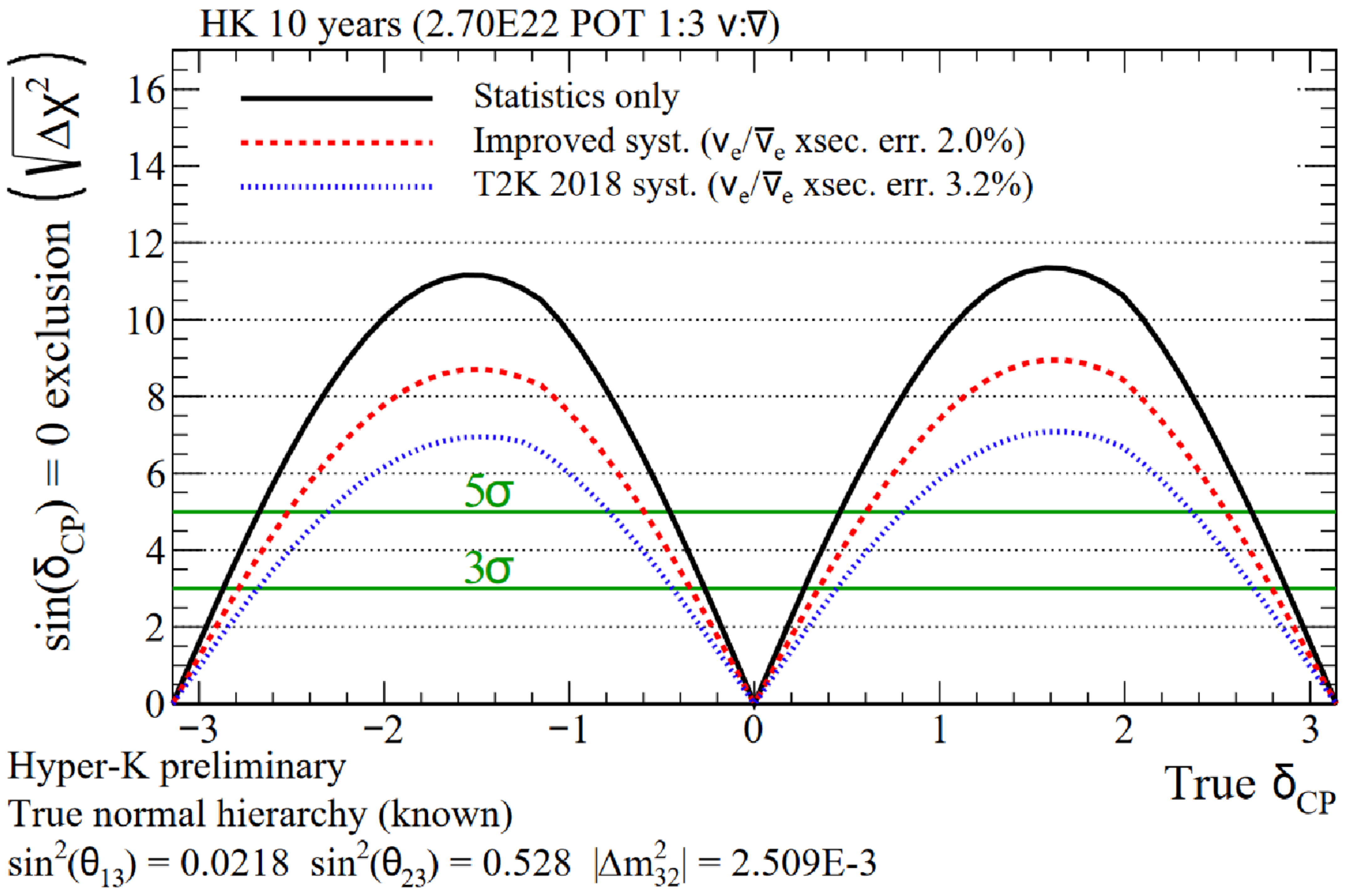
- Upgrade J-PARC neutrino beam with expected power >750 kW, 2.5º off-axis angle
- Baseline: 295 km
- Possibility to add a second far detector in Korea (baseline 1100 km)
- Aiming to start operation in 2027



- ➤ WC Total volume: 260 kton pure water, Inner detector: 216 kton, Fiducial volume: **~200 kton (x 8 SK)**
- ➤ Between 20-40% photocathode coverage
- ➤ Front-end electronics inside the tank
- ➤ New cavern in a different part of Kamioka mine under construction

Hyper-Kamiokande sensitivity

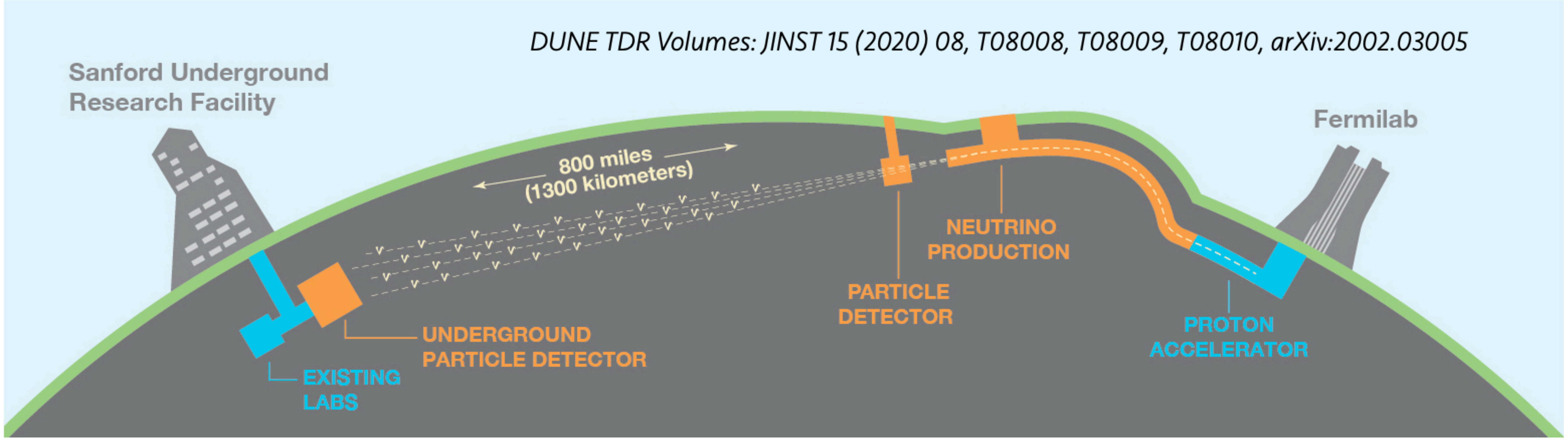
- Able to exclude CP conservation at 3σ for 76% of δ_{CP} values (if MO known) in 10 years for nominal power (or can exclude 57% of true δ_{CP} values at 5σ)
- 3σ MO determination for $\sin^2\theta_{23} > 0.42$ (0.43) for normal (inverted) hierarchy for 10y of data taking



ICHEP 2020, M. Scott

DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT



- 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 2.4 MW
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DUNE

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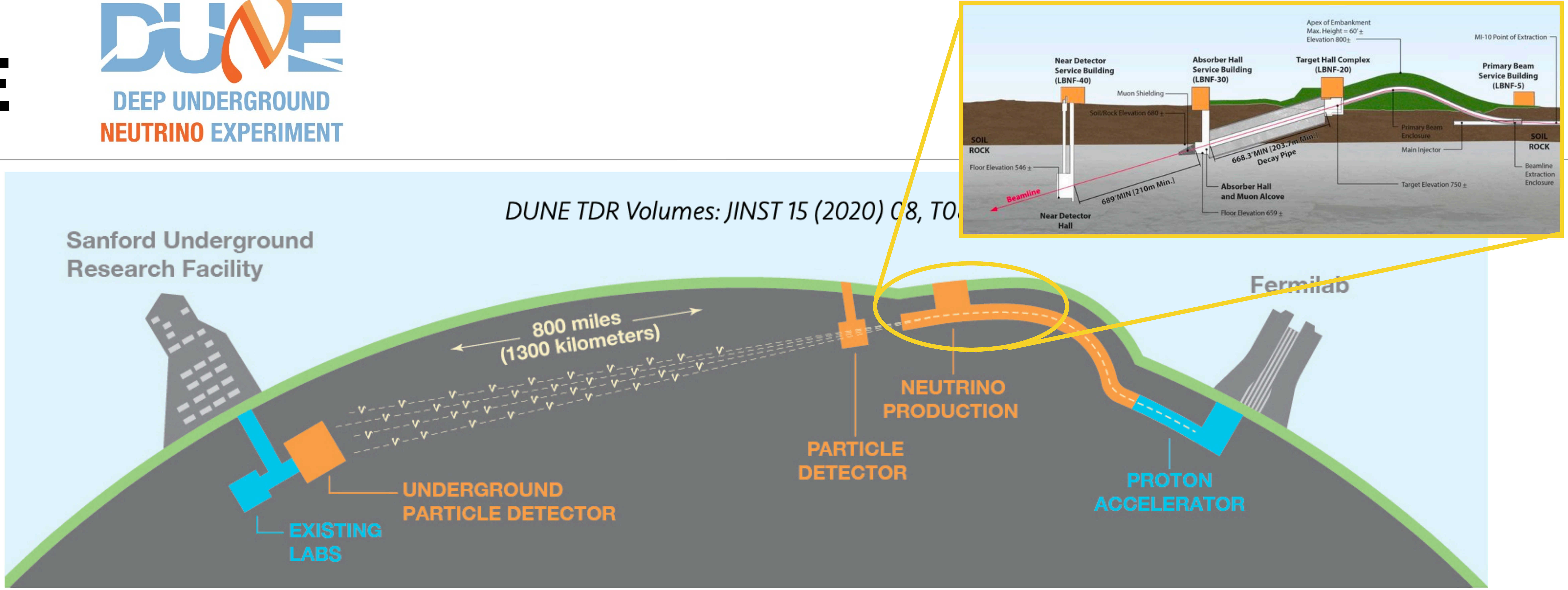
NEUTRINO EXPERIMENT



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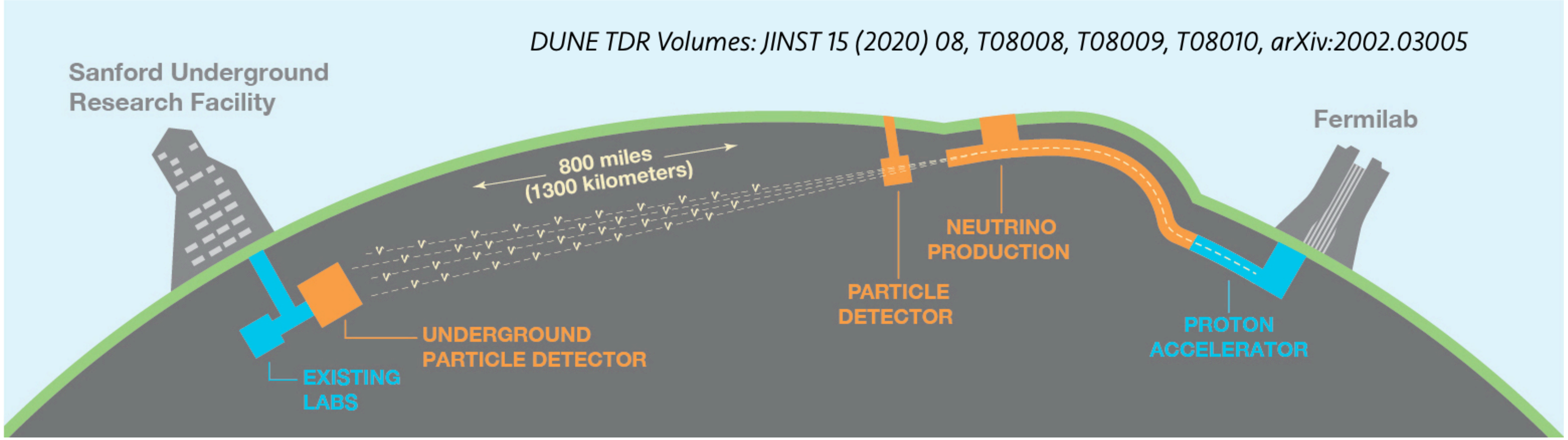

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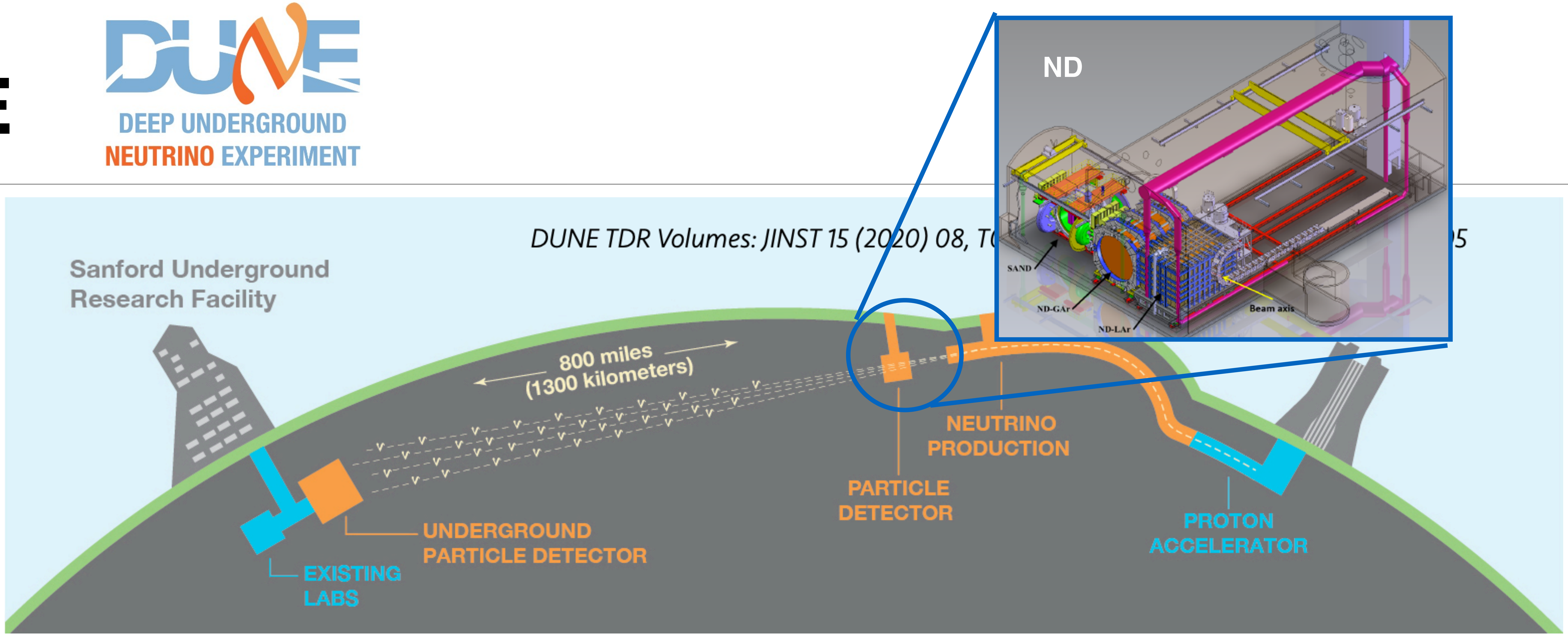

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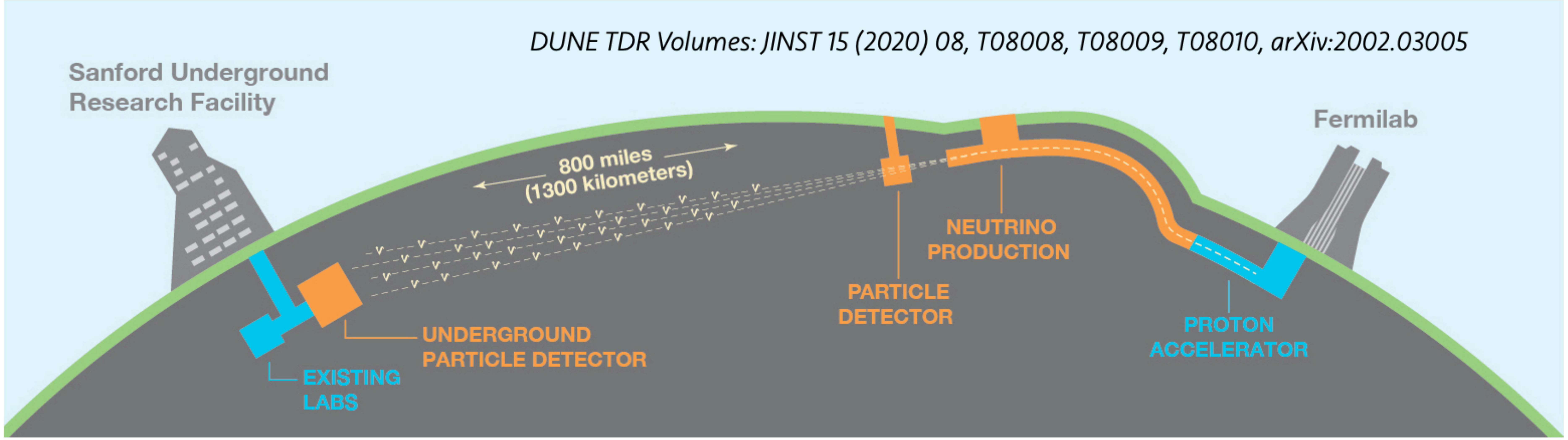

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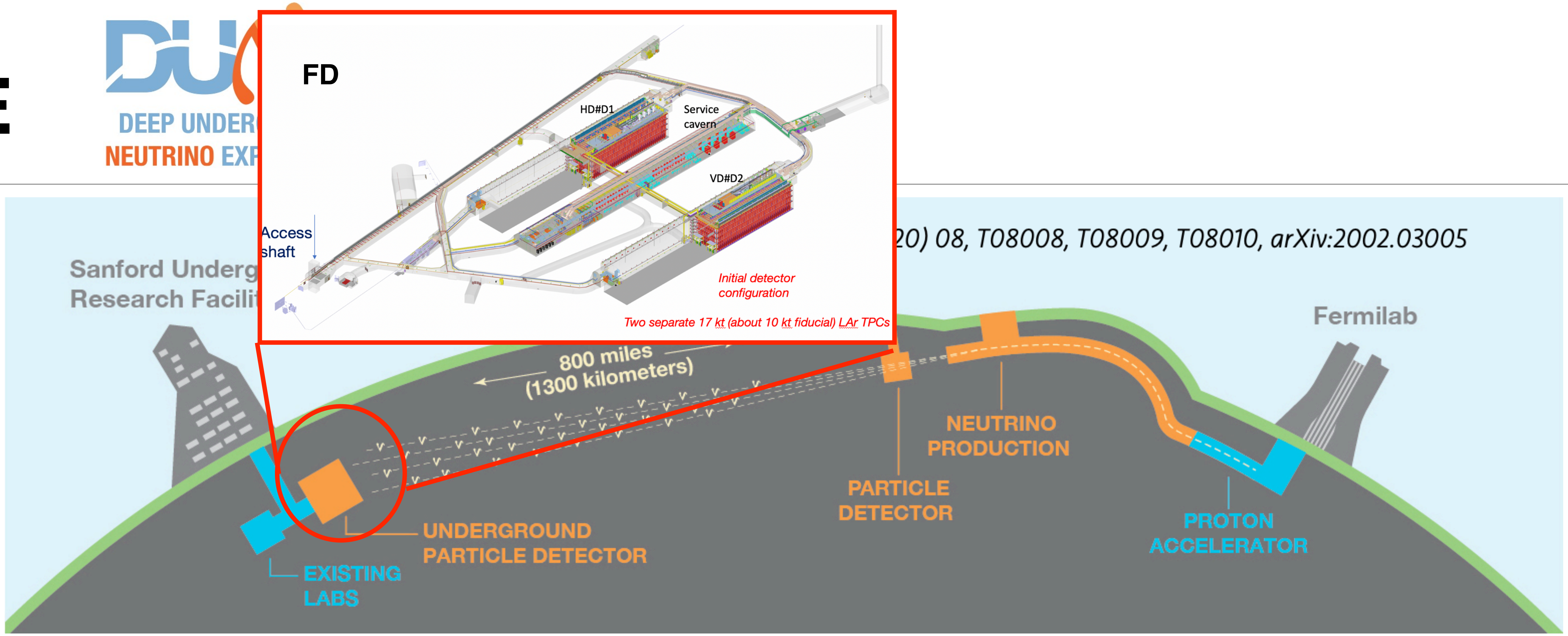

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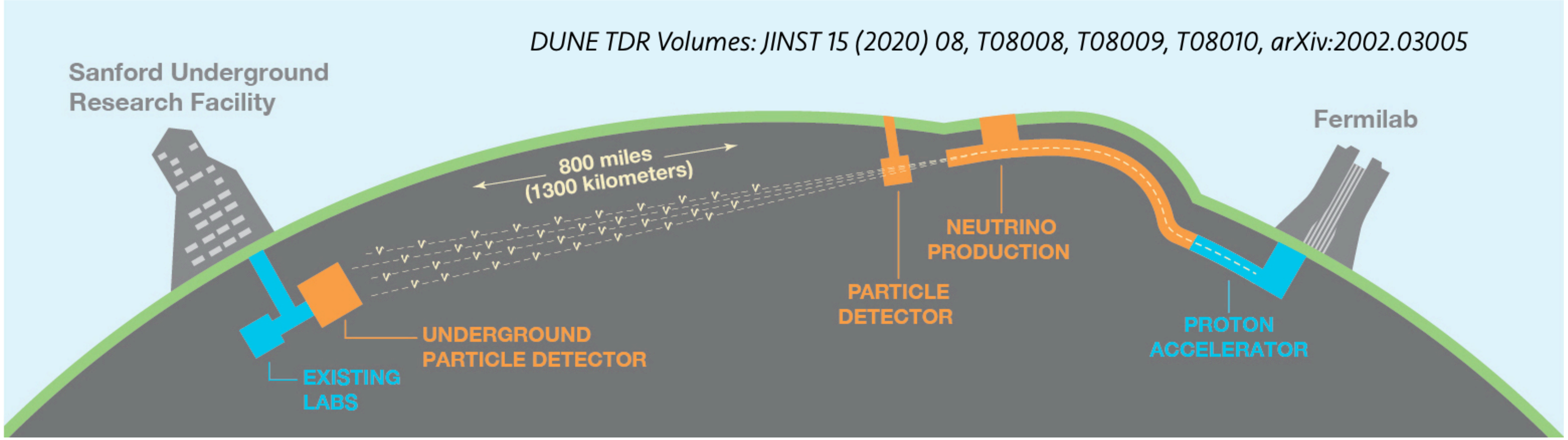

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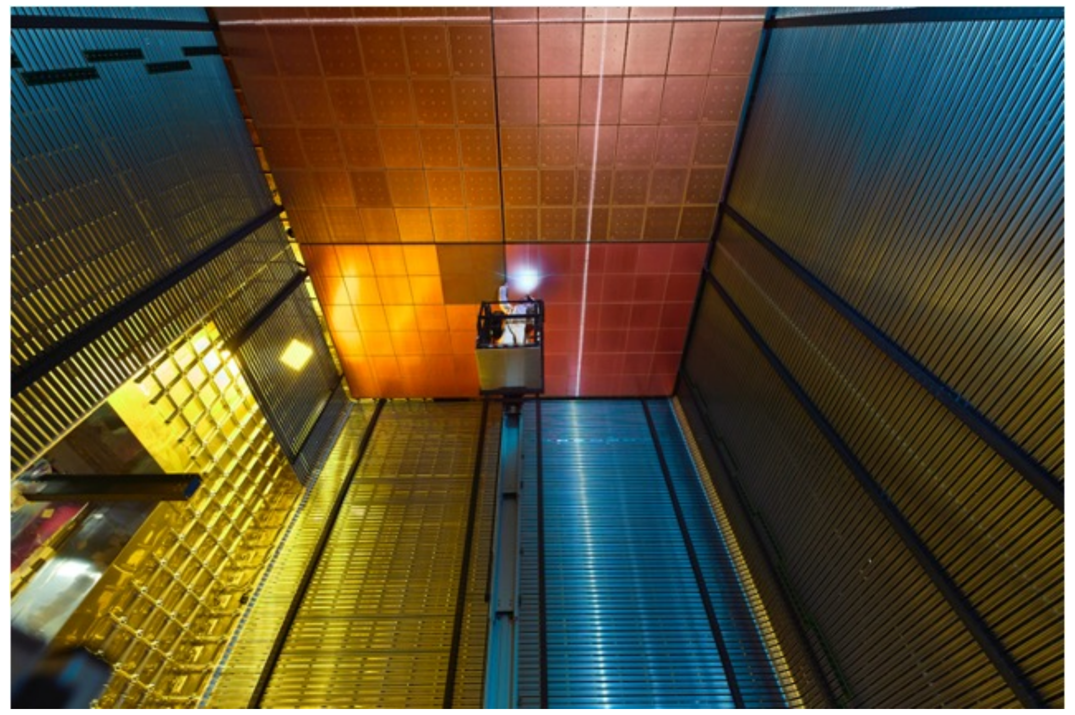
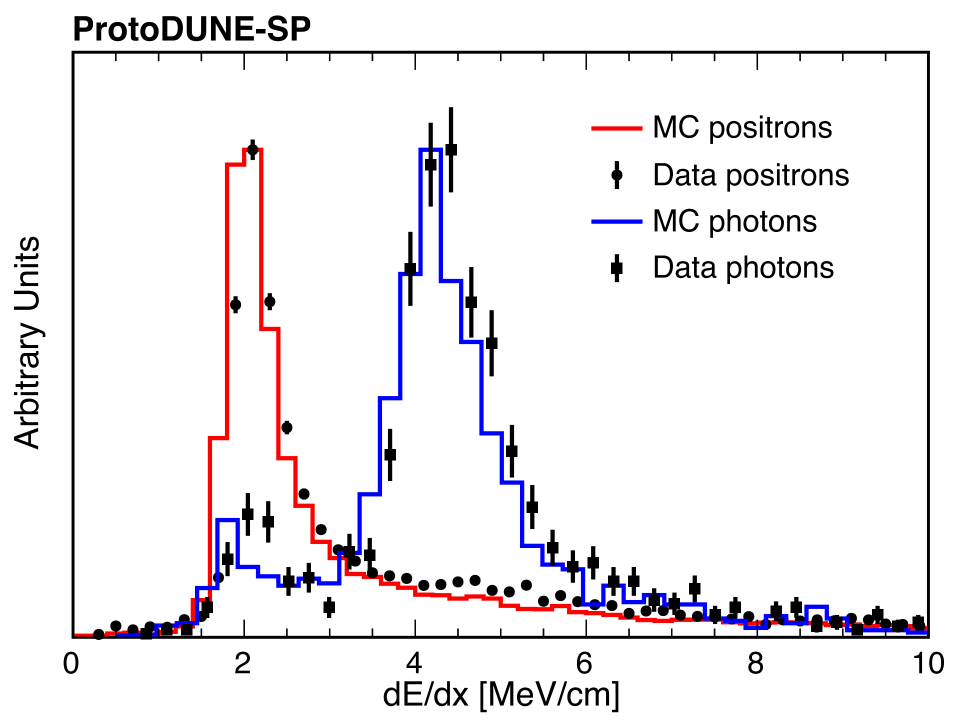
CERN Neutrino Platform

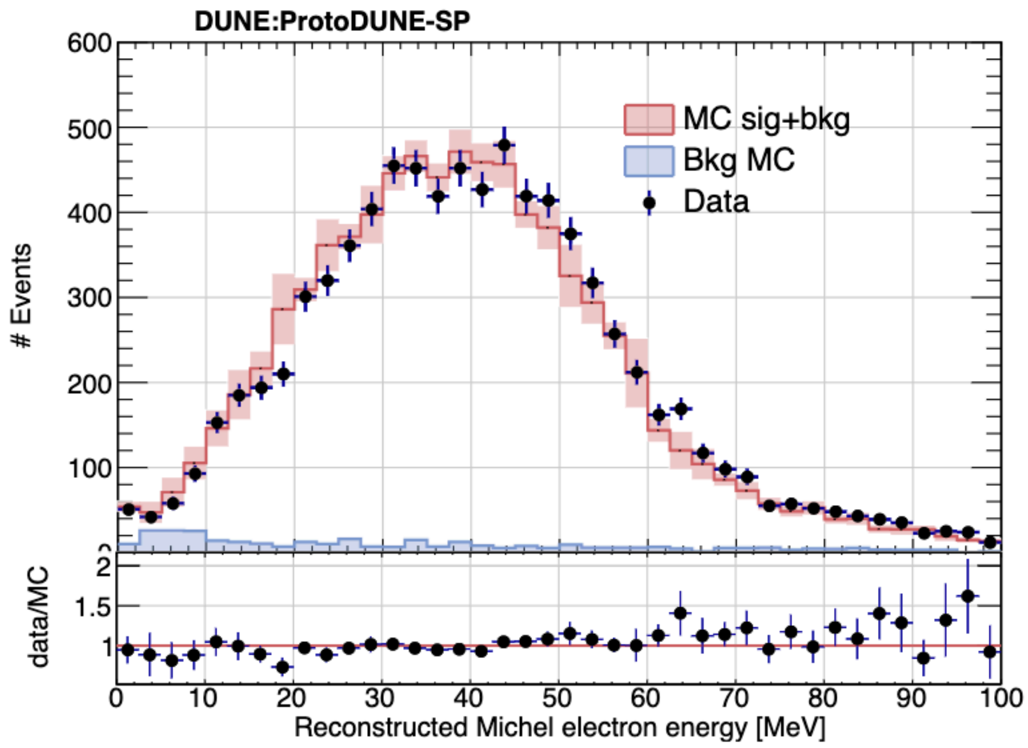
ProtoDUNEs operation at CERN

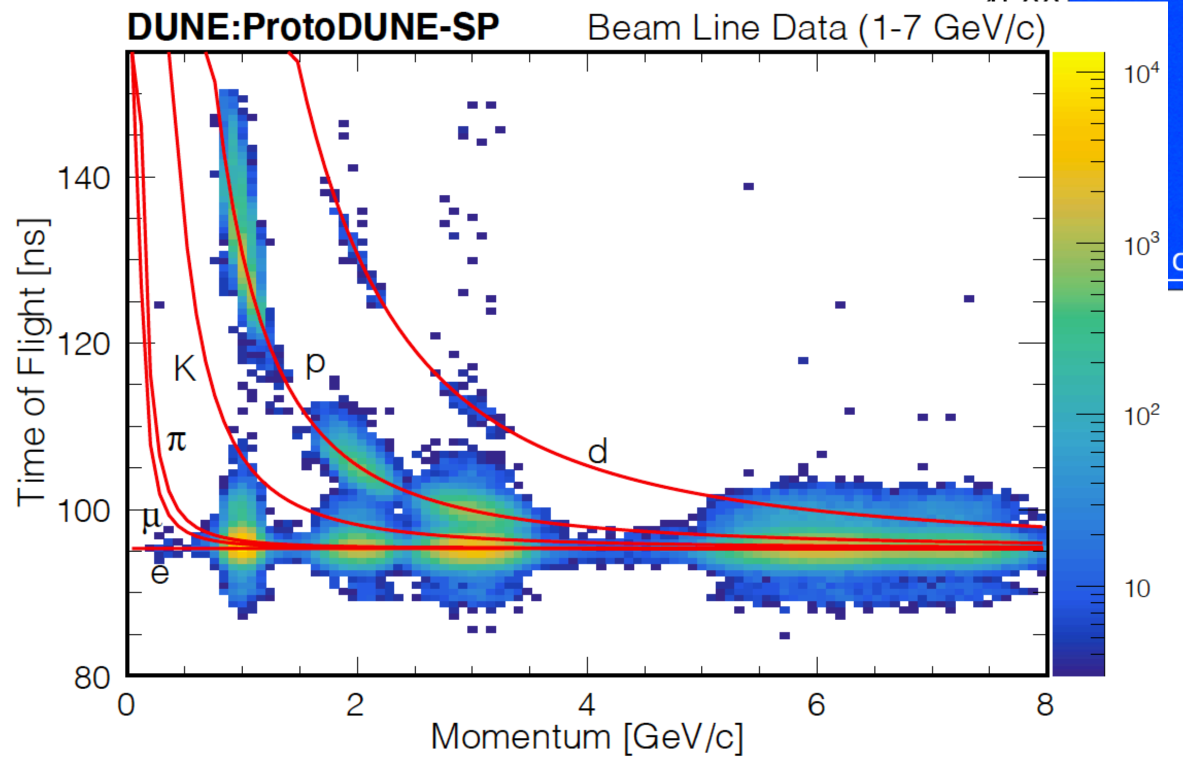
FIRST PHASE PROTODUNEs

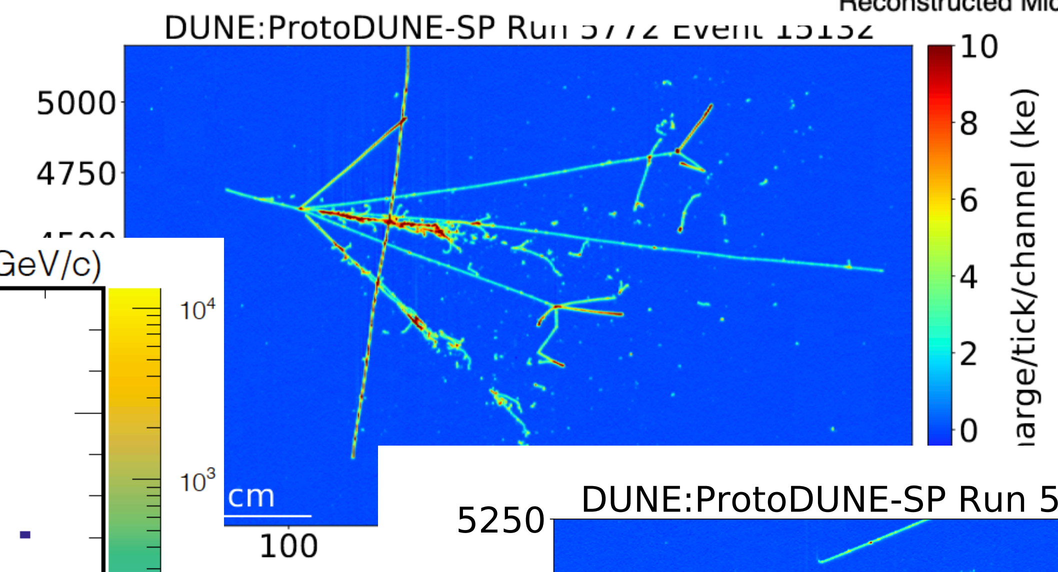
- Construction and operation of ProtoDUNEs at CERN between 2018 and 2020
- Successful demonstration of the DUNE LAr TPC performance

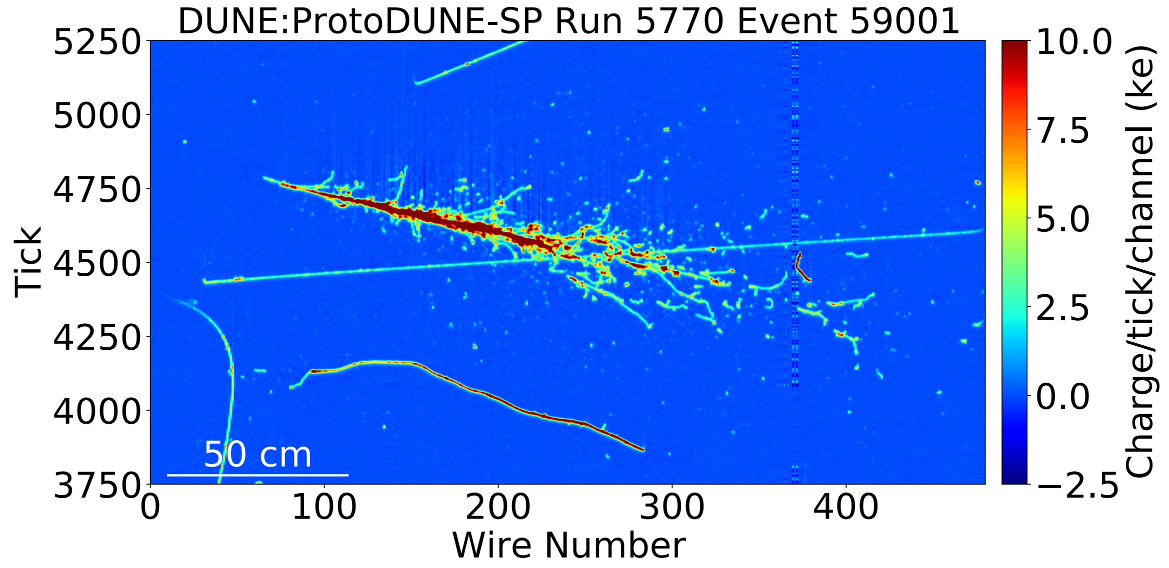












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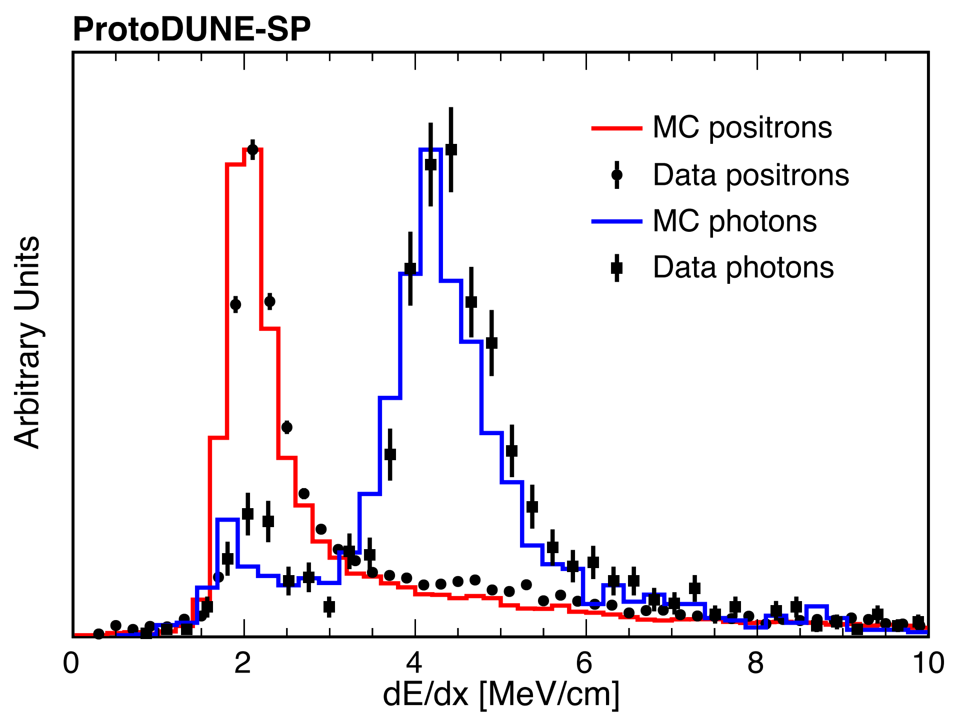

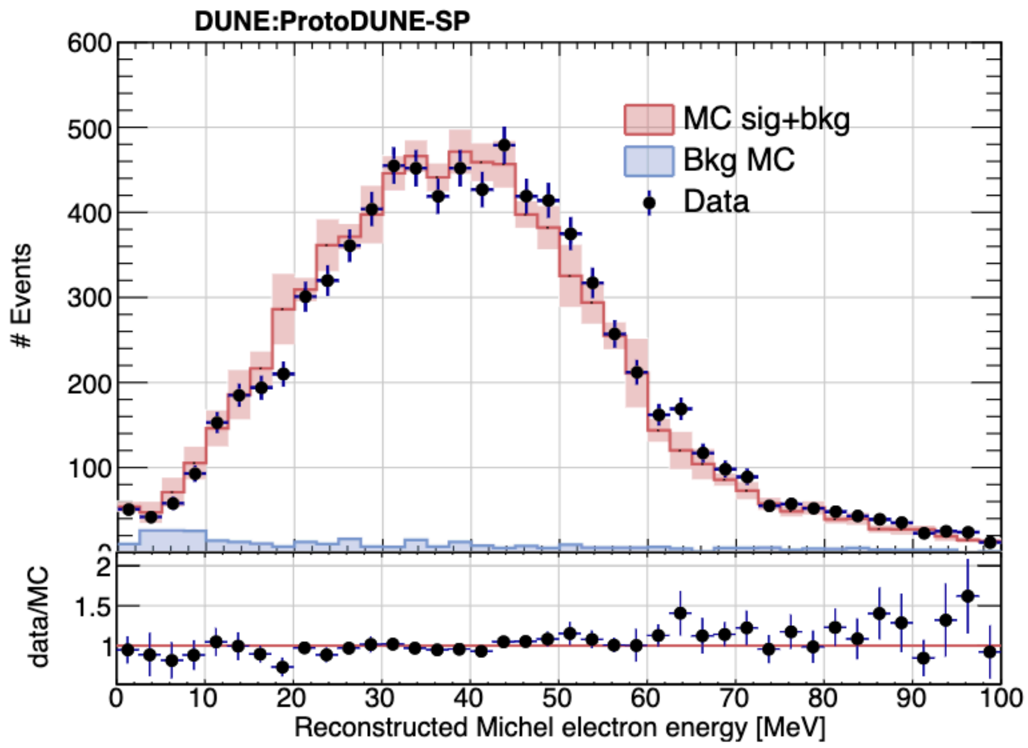

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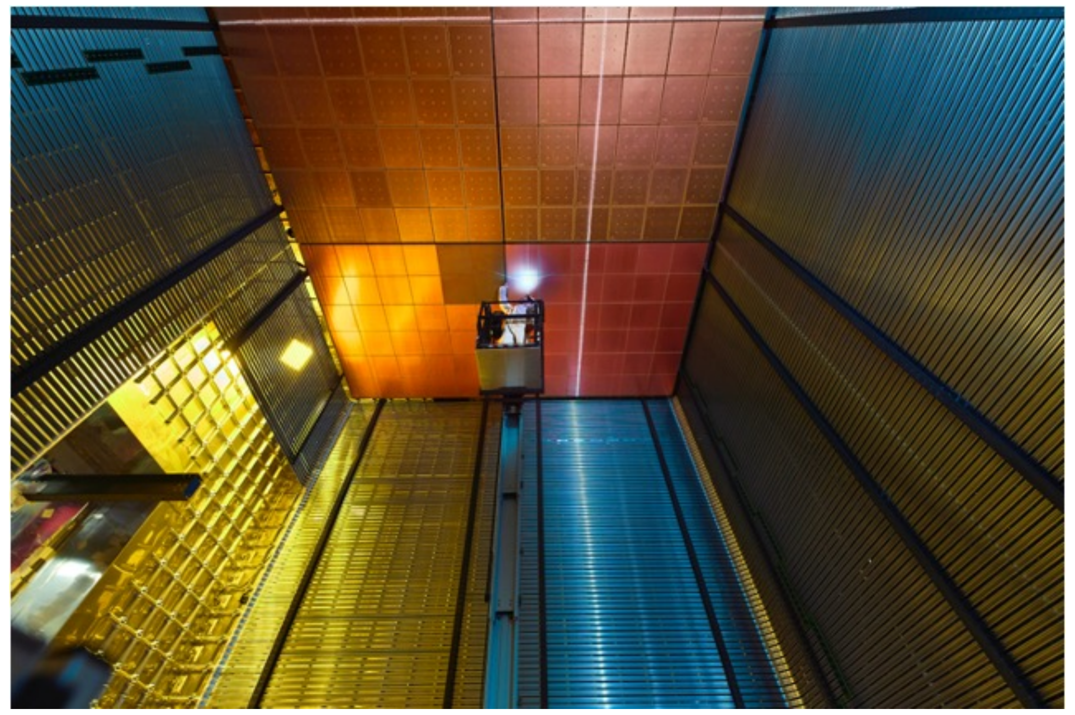
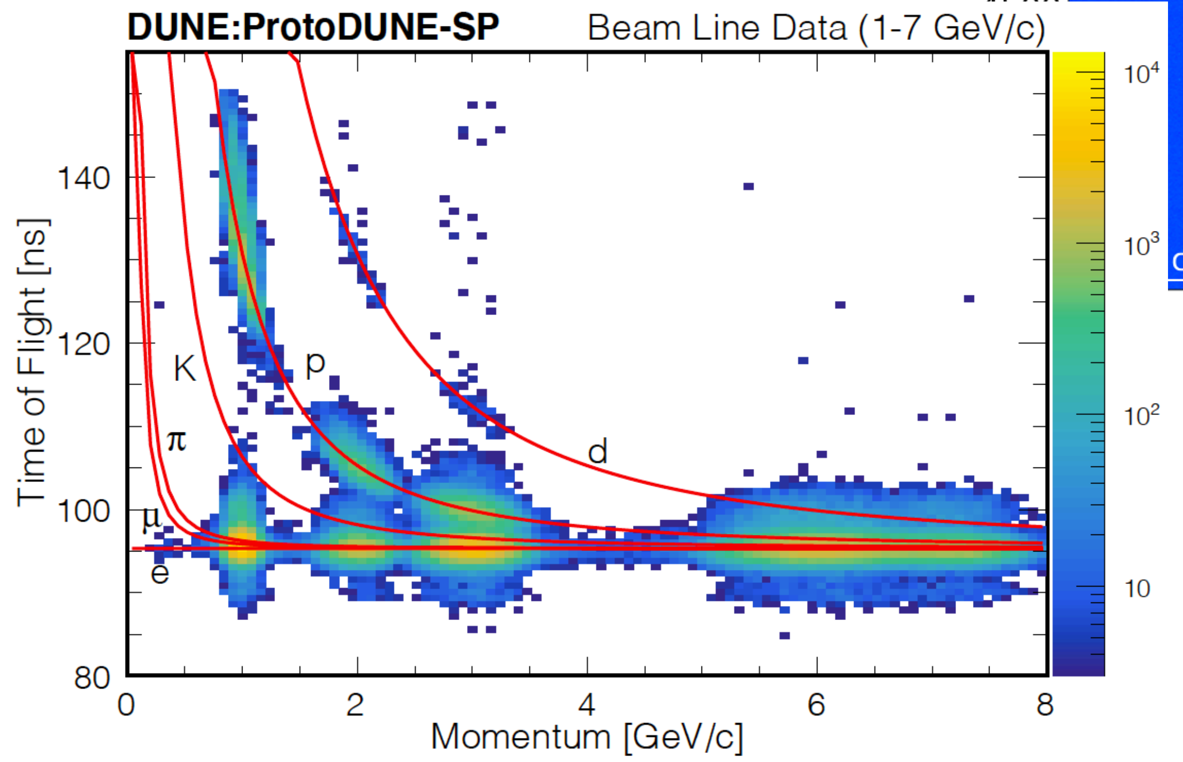
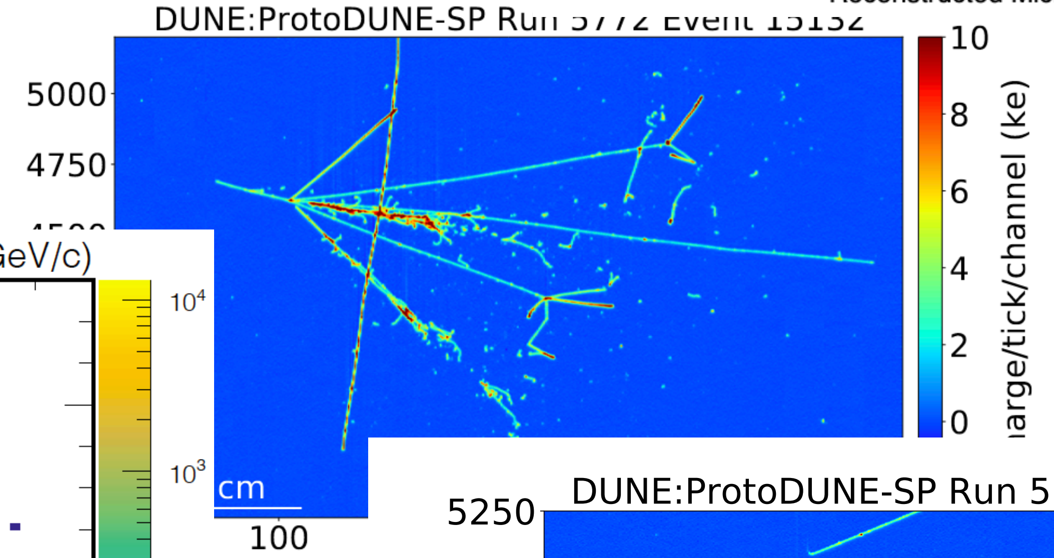
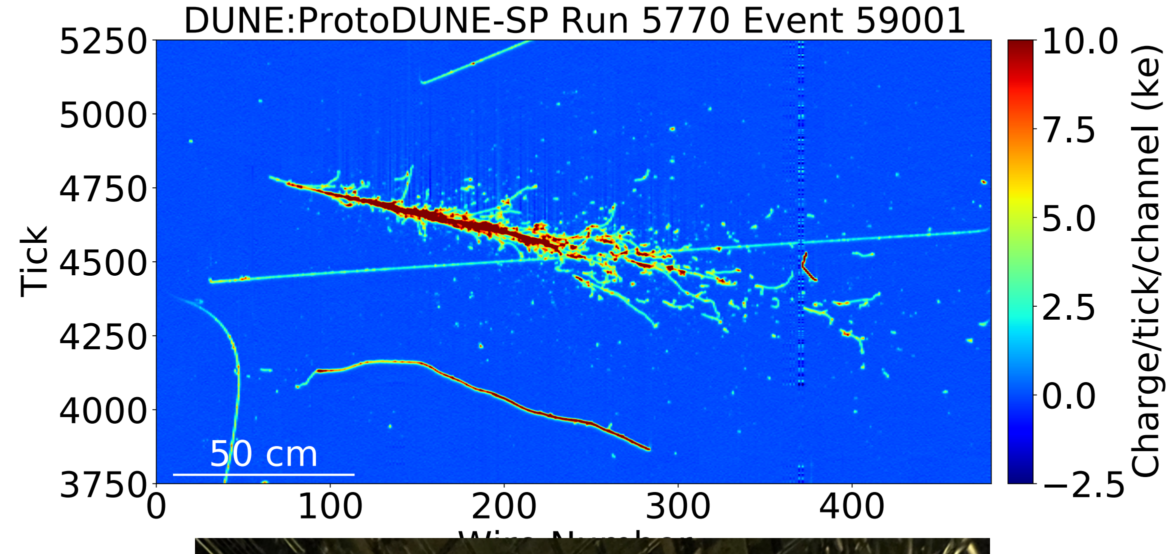


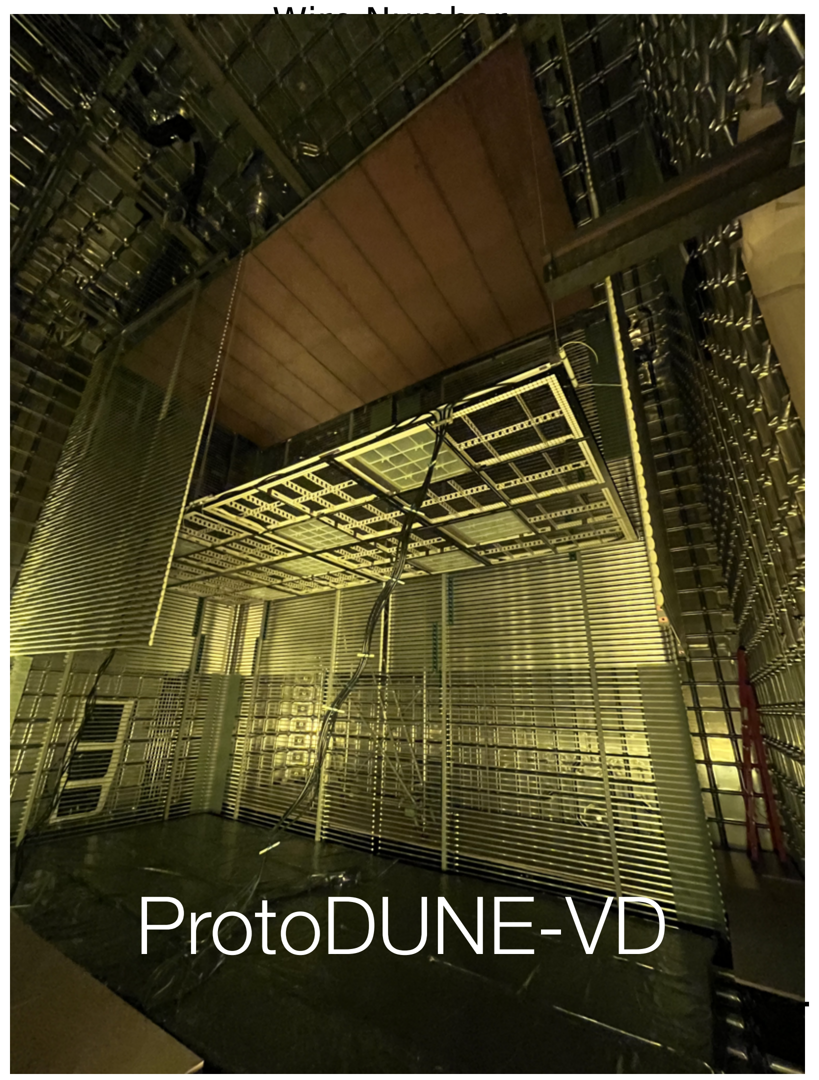






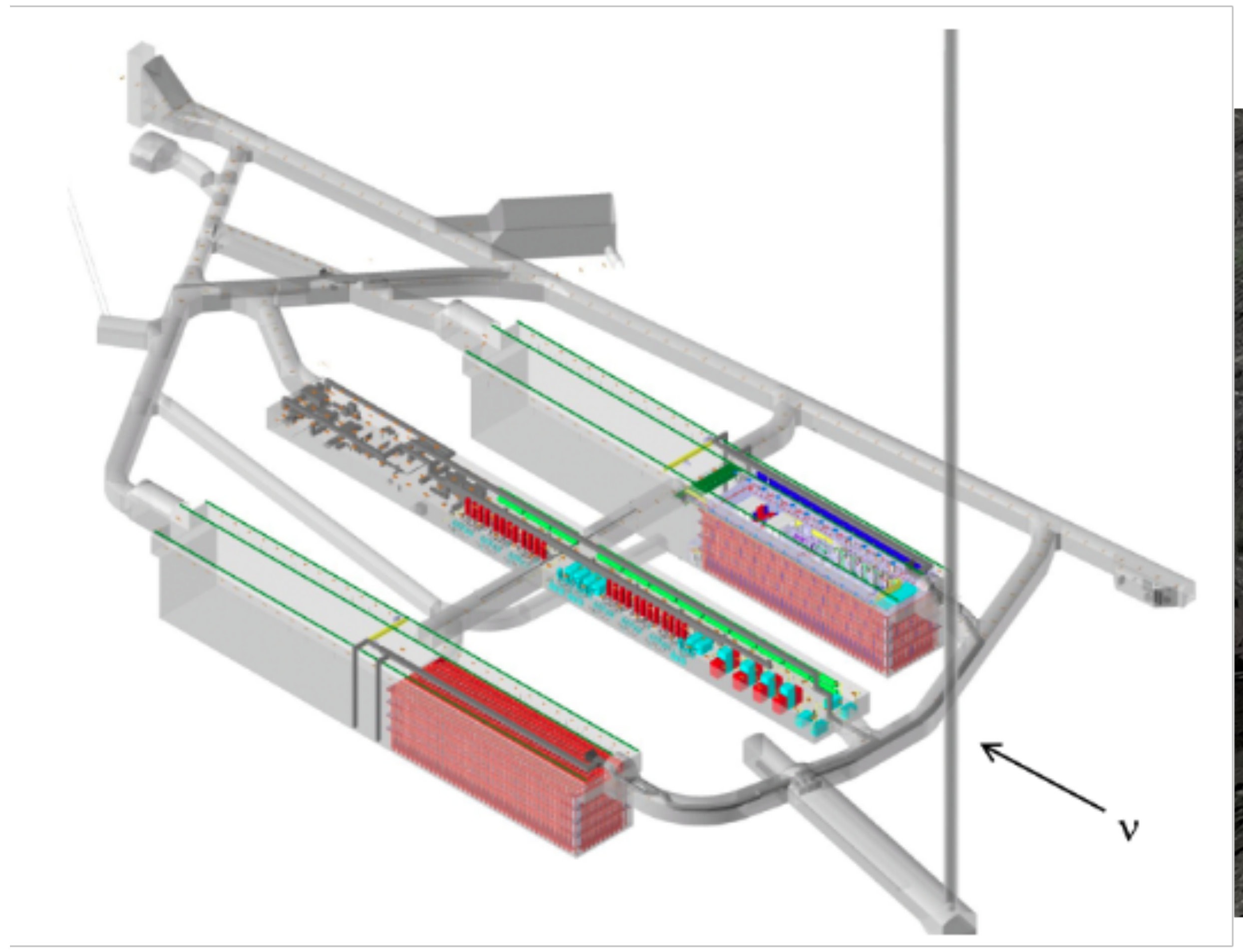
SECOND PHASE PROTODUNEs (2020-2023 construction + operation ≥2024)

- ProtoDUNE-HD
  - ✦ Final technical solutions for all FD1 subdetectors
  - ✦ Installation completed and waiting for filling and data taking in 2024 with test-beam and cosmic muons
- ProtoDUNE-VD
  - ✦ Realization of a Module-0 detector in 2022-2023; ready for filling and data taking in 2024

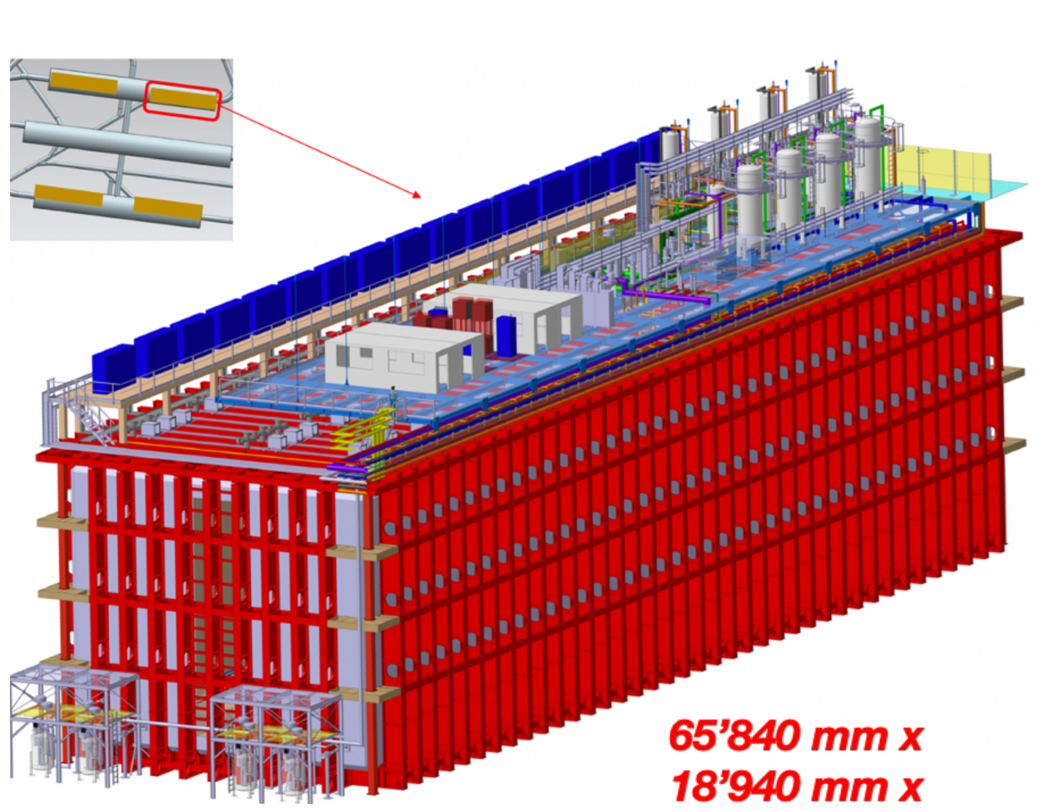


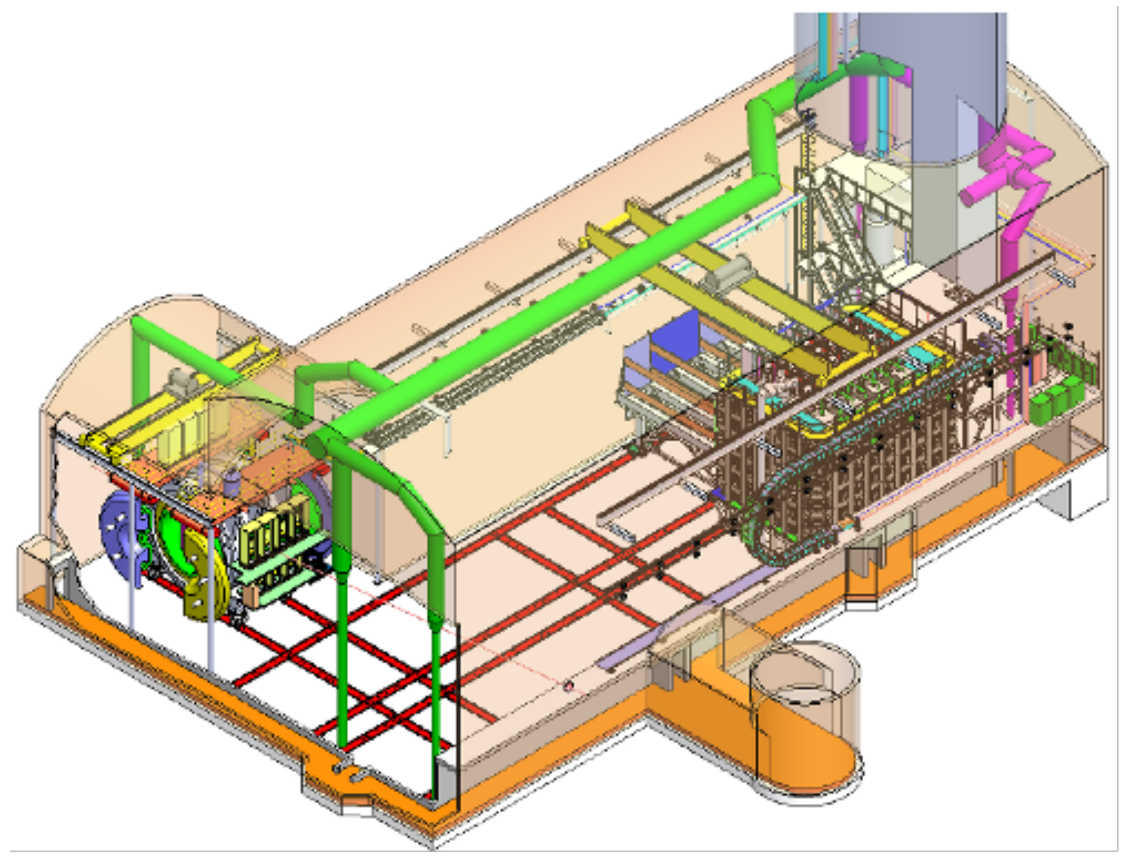
DUNE Phases

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



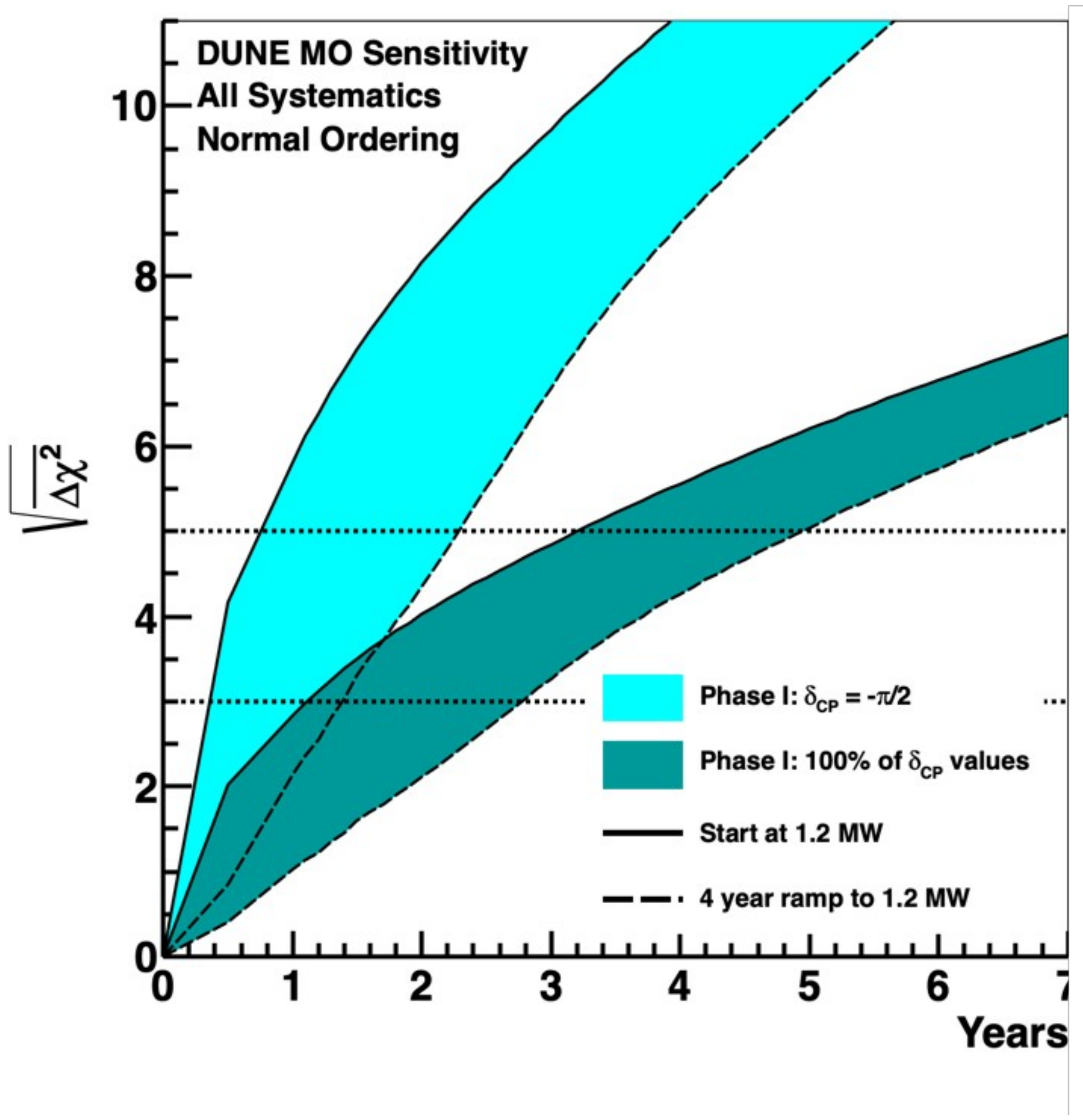
70% excavation work completed

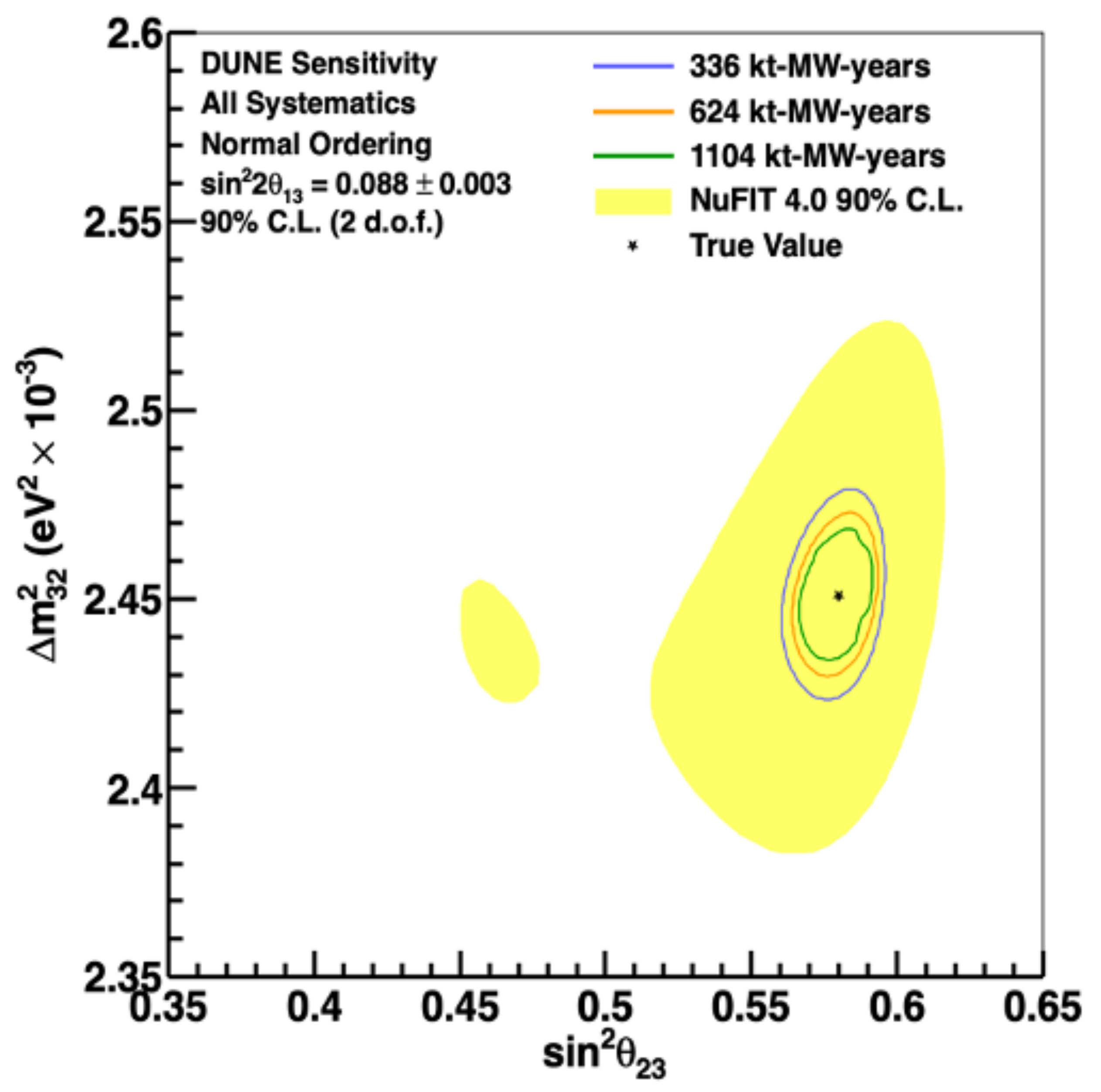


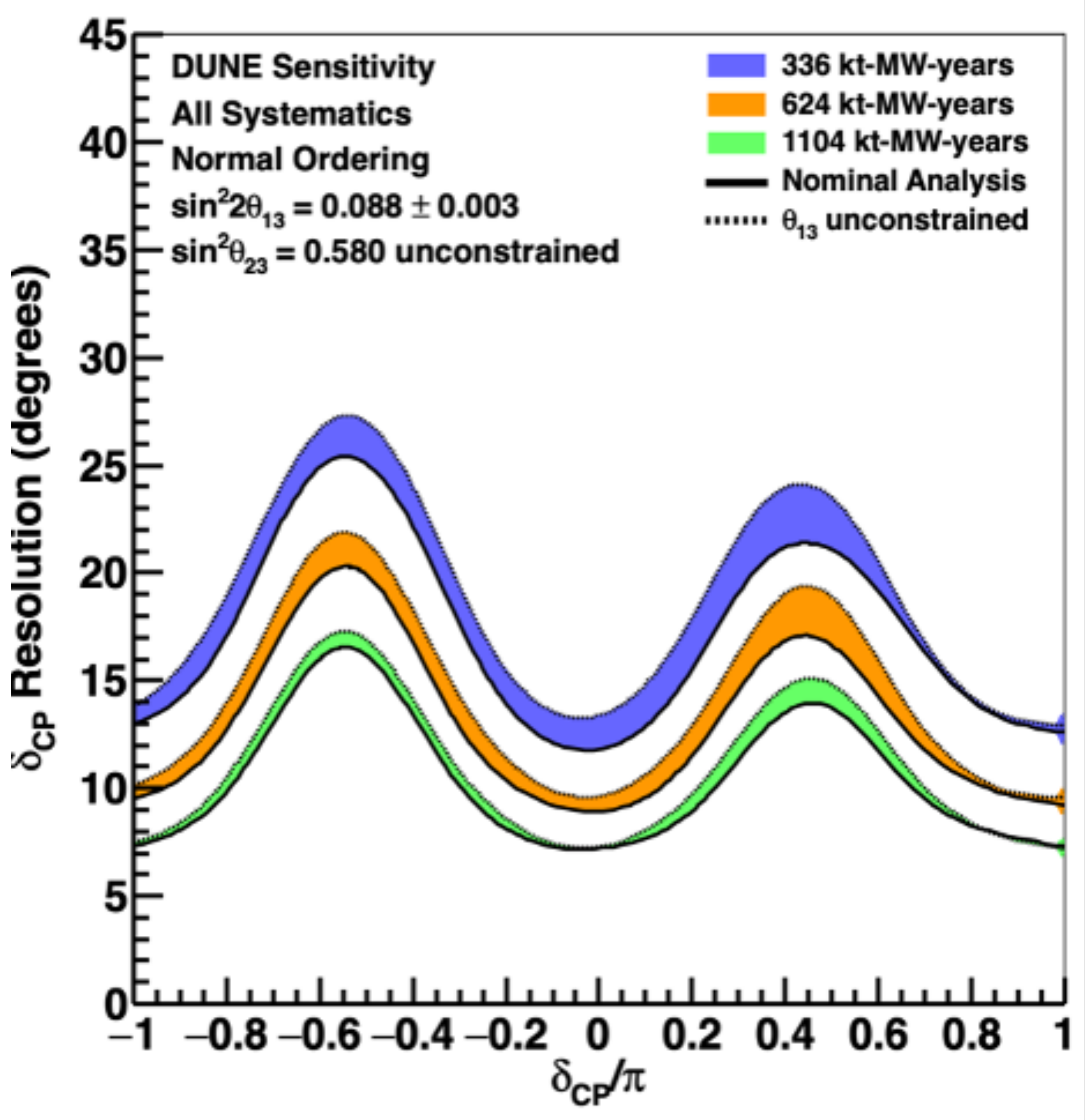


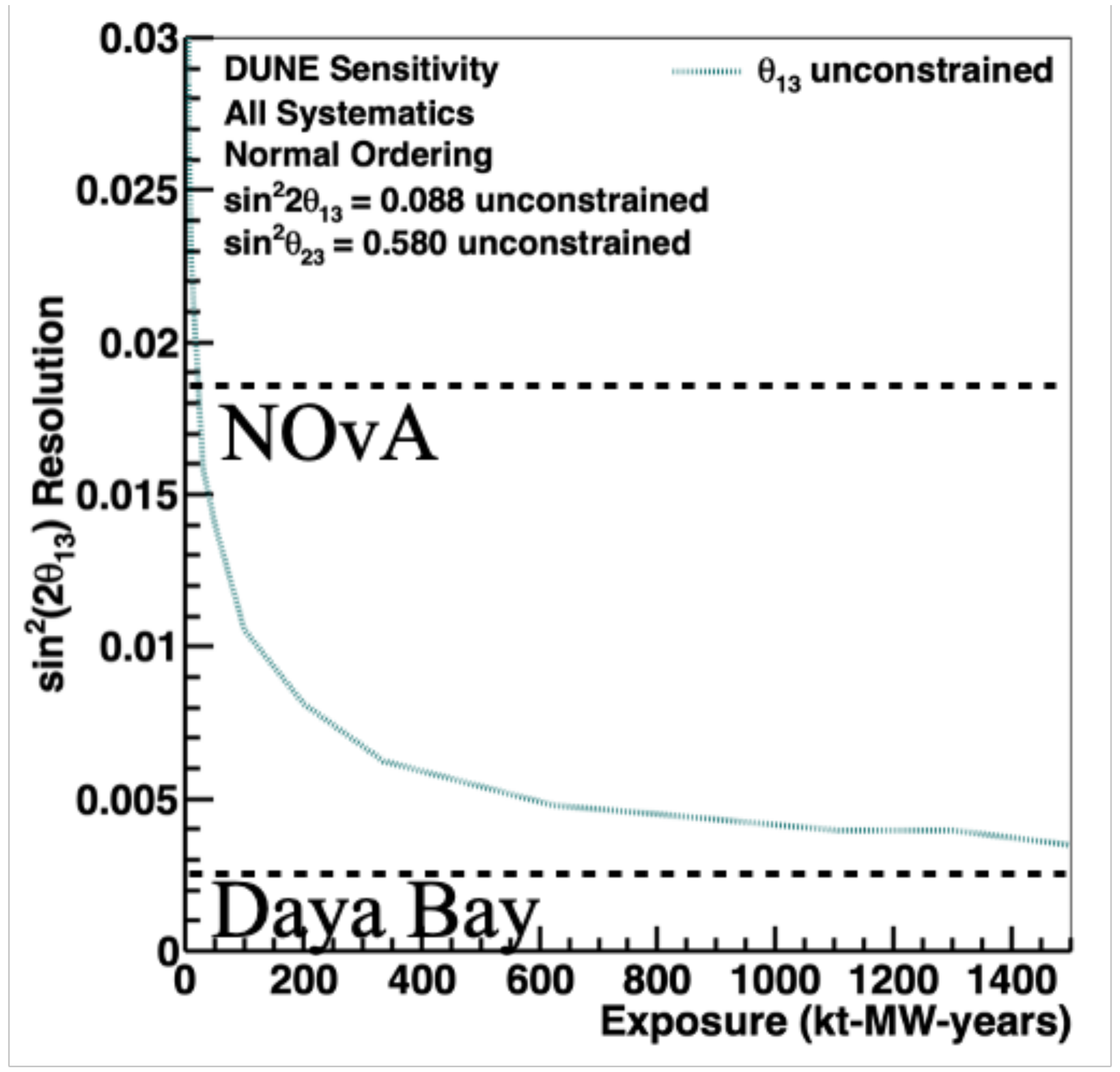
DUNE Physics Program

- 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 3y (7y), 5σ CPV for 50% 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

From oscillations:
$m_\nu > 0.05$ eV

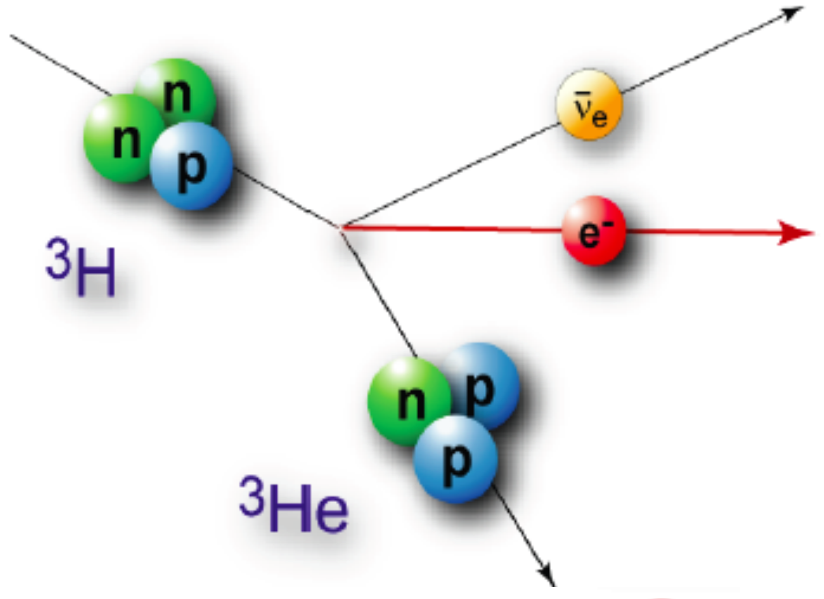
Neutrino mass measurements

- **Direct measurements**:

  Tritium beta decay experiments:

  ✦ KATRIN 2019: **m < 0.8 eV (90% CL)**

  ✦ KATRIN (goal): m < 0.2 eV (90% CL)



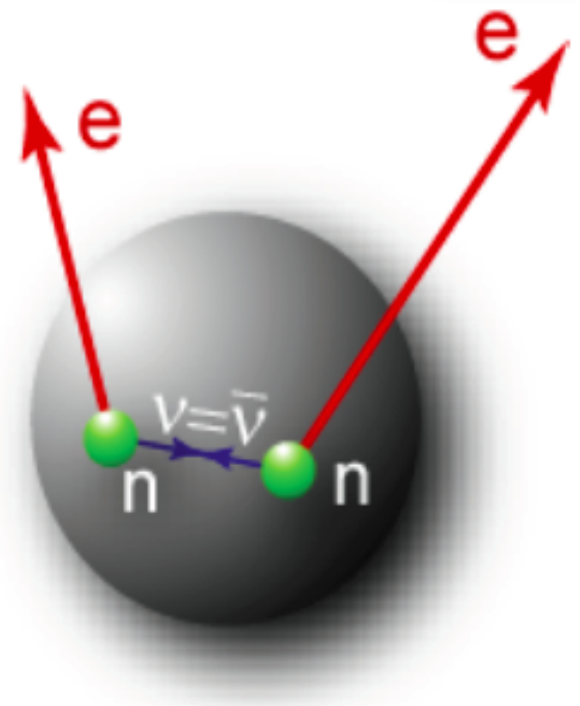
$$m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$$

- **Neutrinoless double beta decay**:

  ✦ If measured, neutrinos are Majorana particles

  ✦ GERDA, EXO, CUORE, CUPID, NEMO-3, KamLAND-Zen: **$m_{\beta\beta}$ < 36-156 meV (90% CL)**

  ✦ Future ton scale: $m_{\beta\beta}$ < 10 meV (only IO)



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

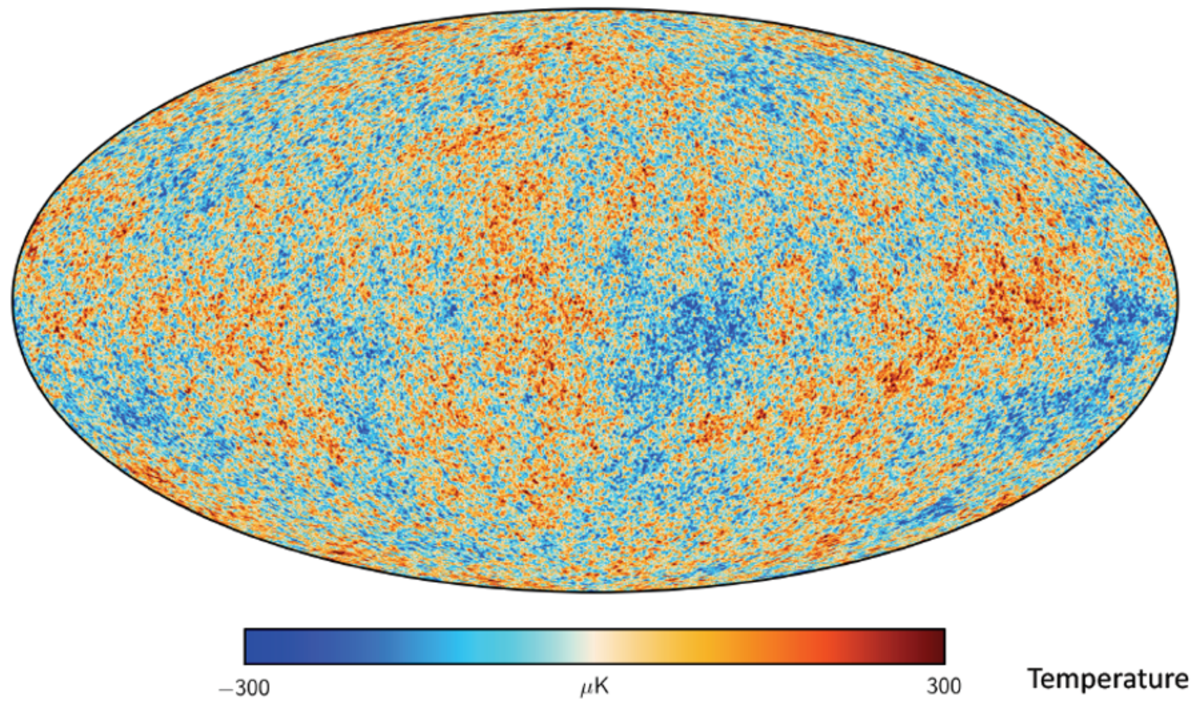
- **Indirect measurements (Cosmology)**:

  PLANCK 2018: A&A 641 (2020) A6

  ✦ **$\sum m_\nu$ < 0.12 eV** (Planck TT,TE,EE +low E +lensing +BAO)

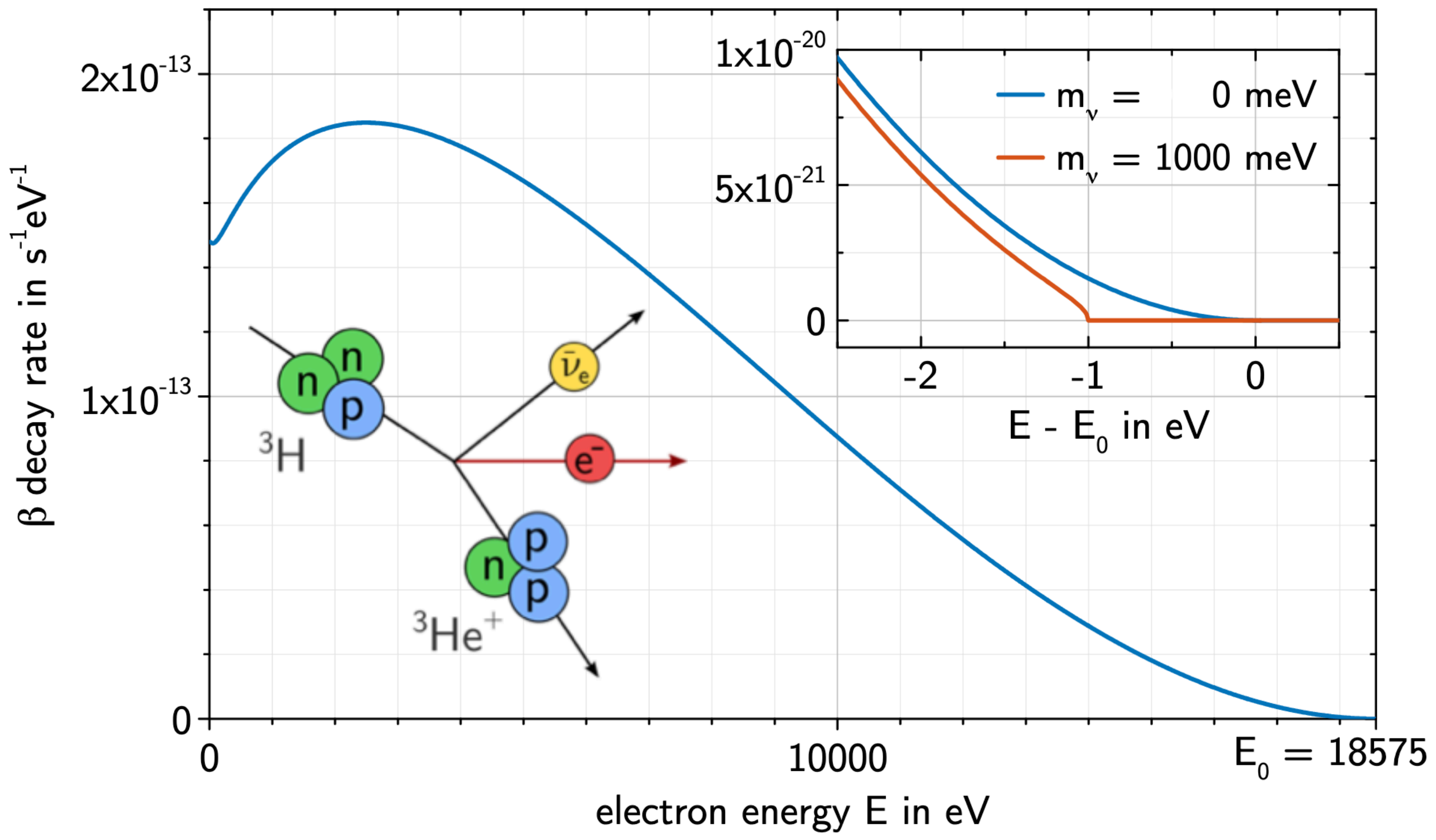
  ✦ N_{eff} = 4 excluded at > 99%CL

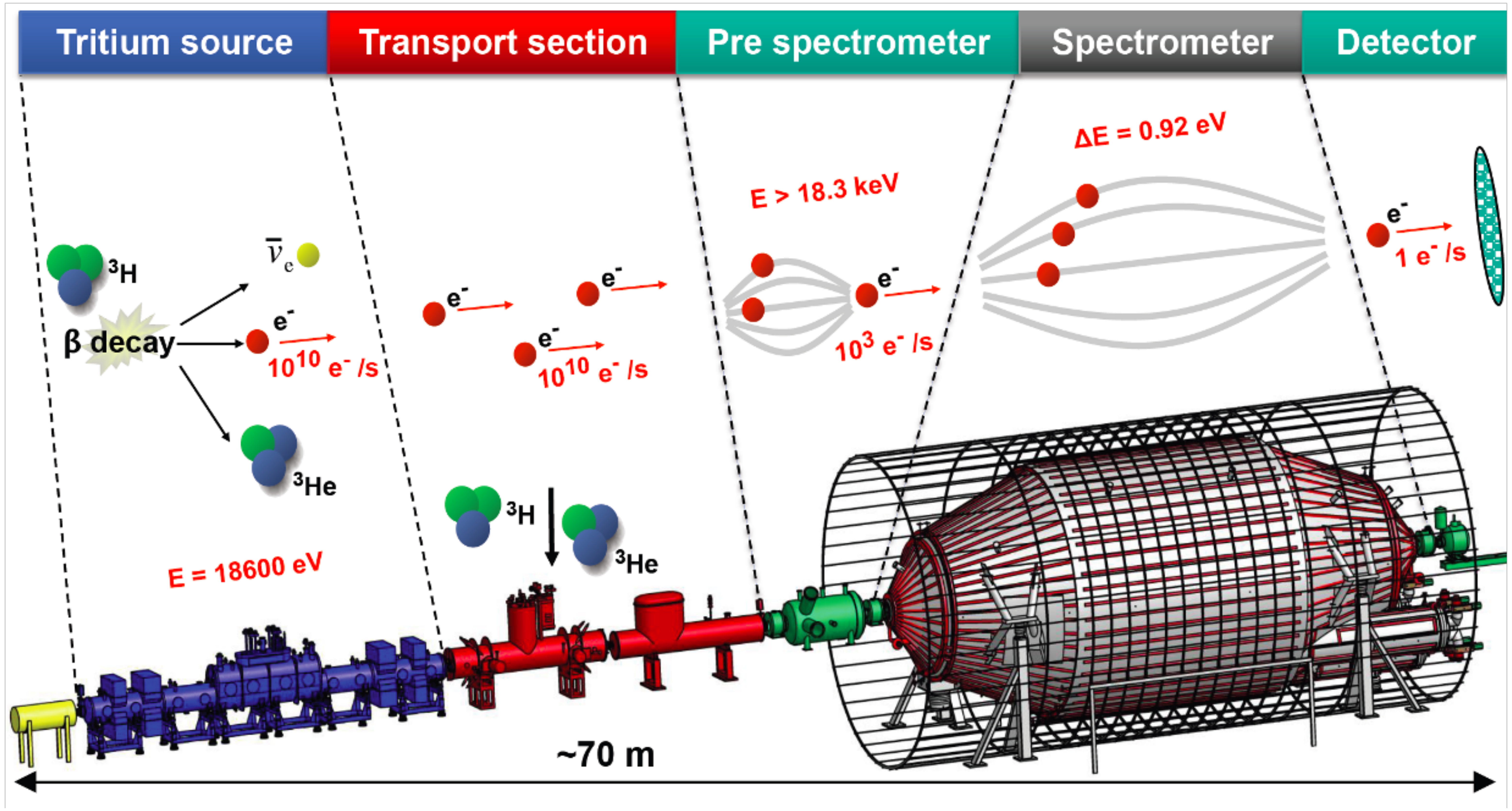
  ✦ $N_{eff} = 2.99^{+0.34}_{-0.33}$ (Planck TT,TE,EE +low E +lensing +BAO)



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

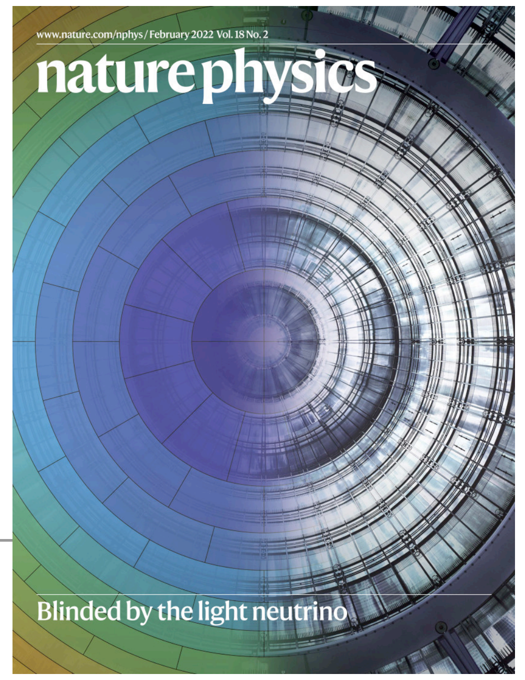
Status of KATRIN

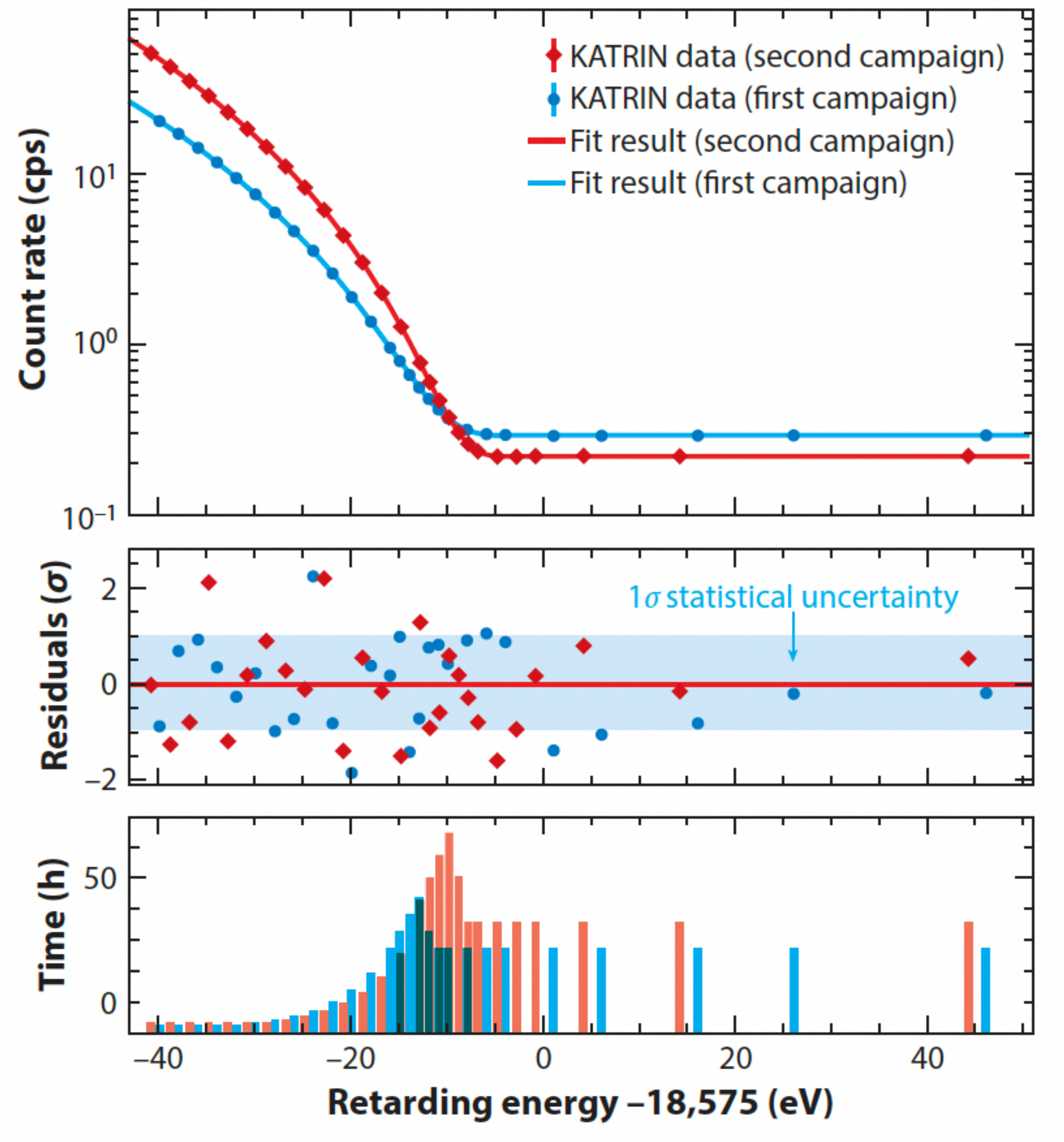


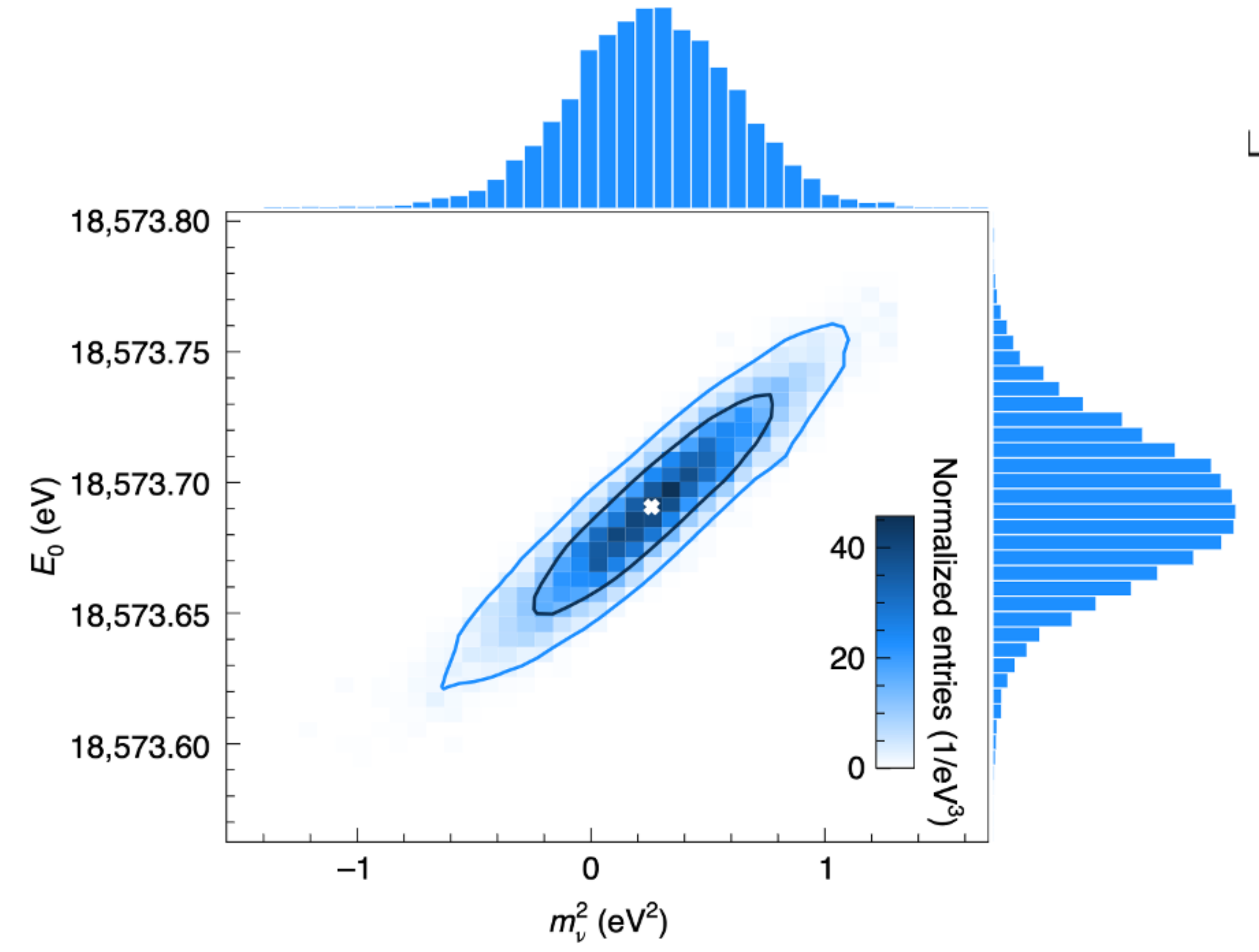


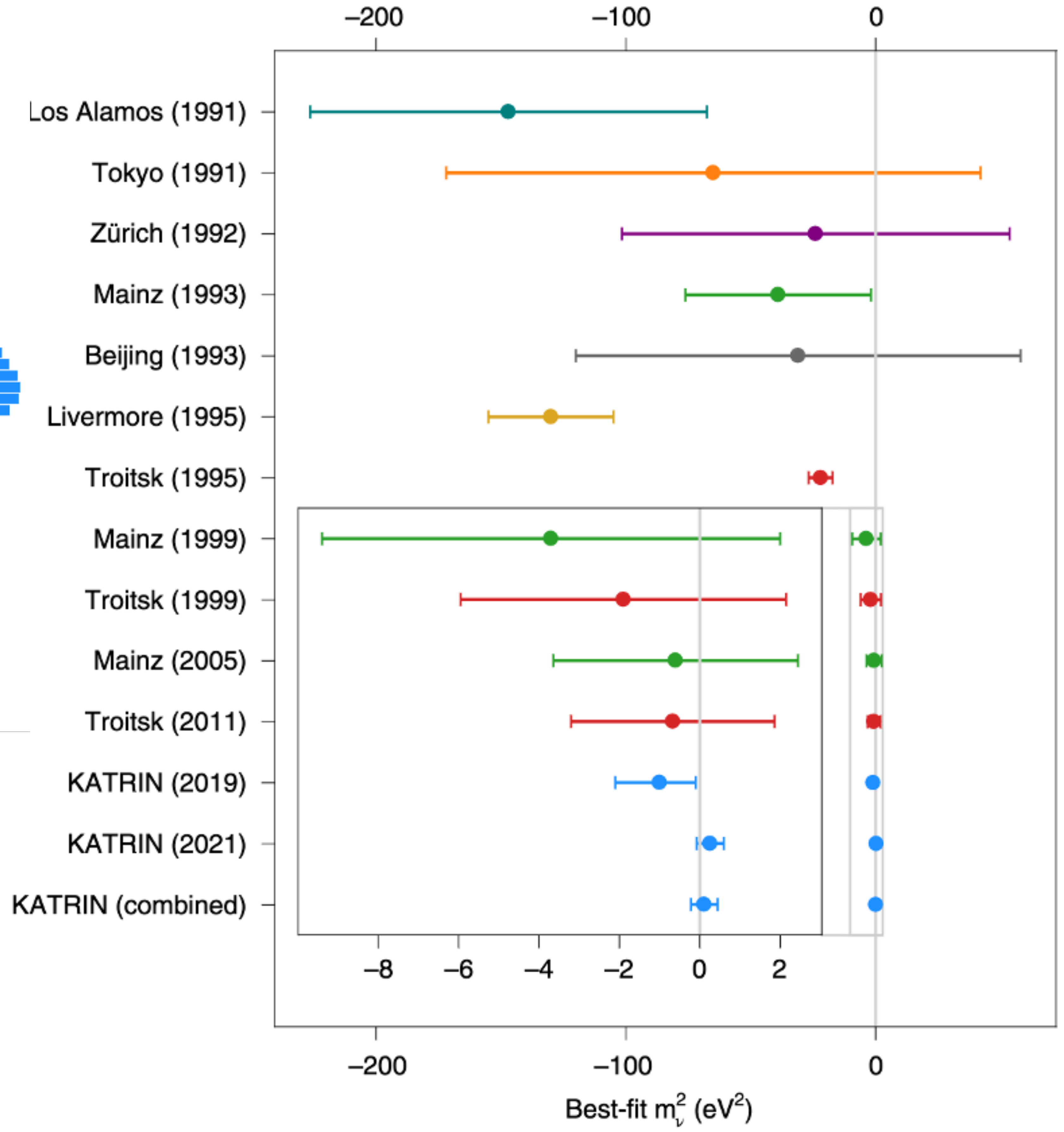
Latest KATRIN result

Nature Physics 18, 160-166 (2022)





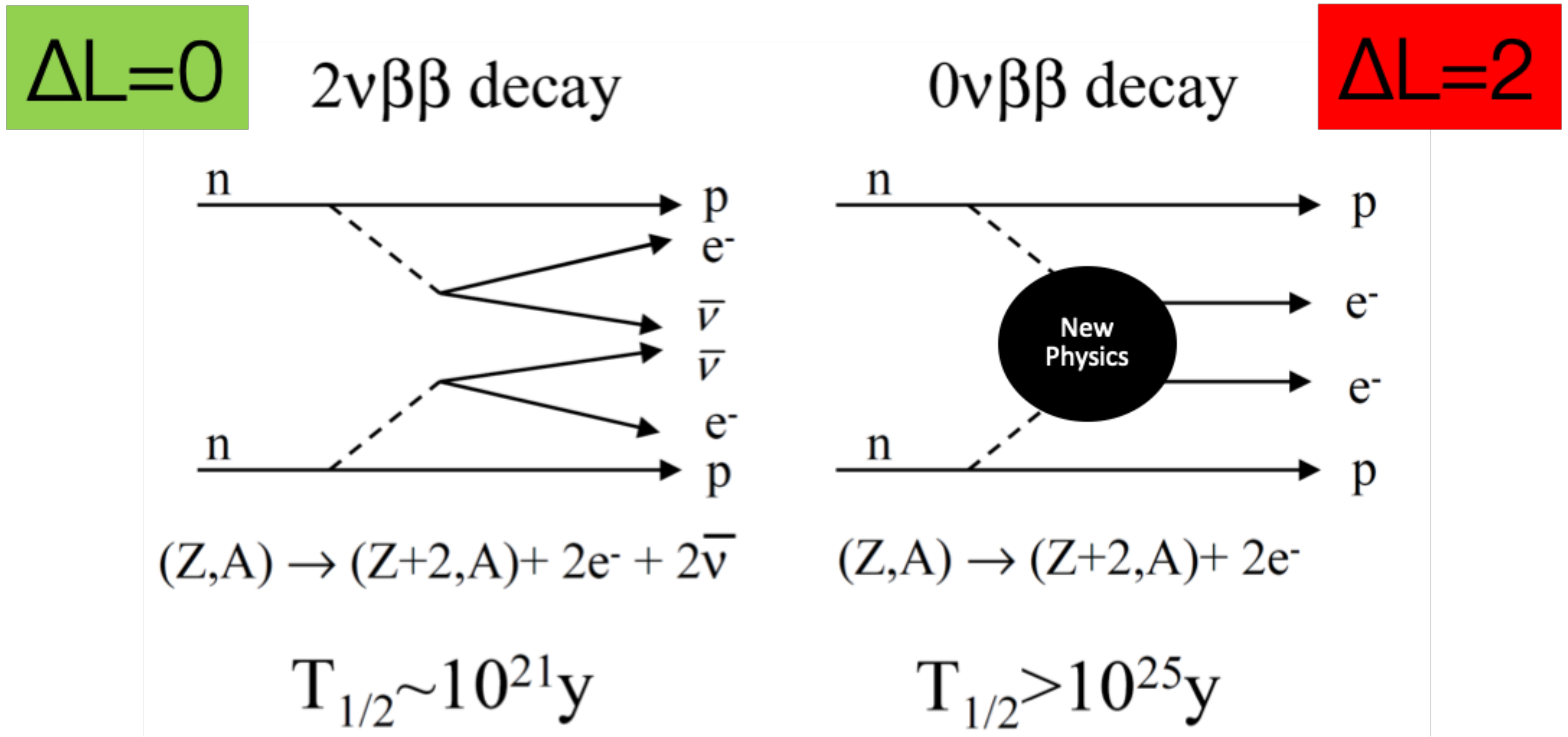


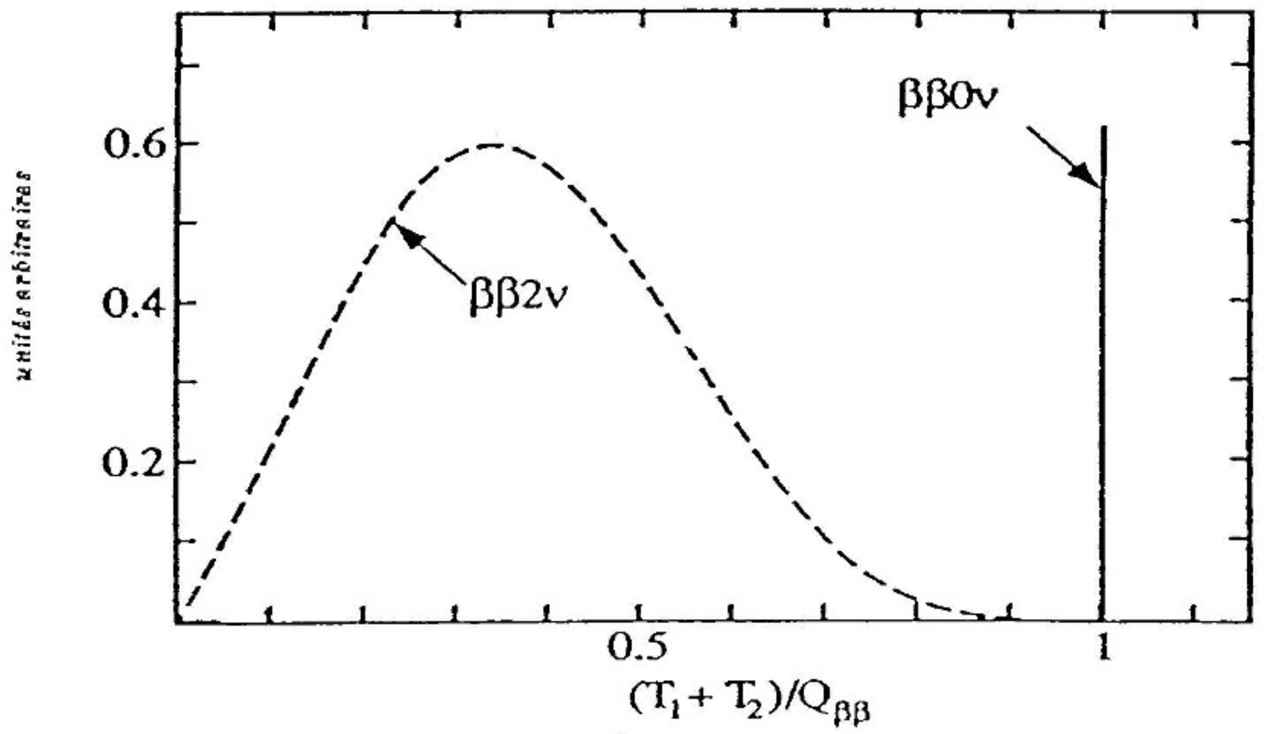


$m_\nu < 0.8$ eV (90% CL)

Expectation after 1000 days of measurement time: $\mathbf{m_\nu < 0.2}$ **eV**

Neutrinoless double beta decay





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

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

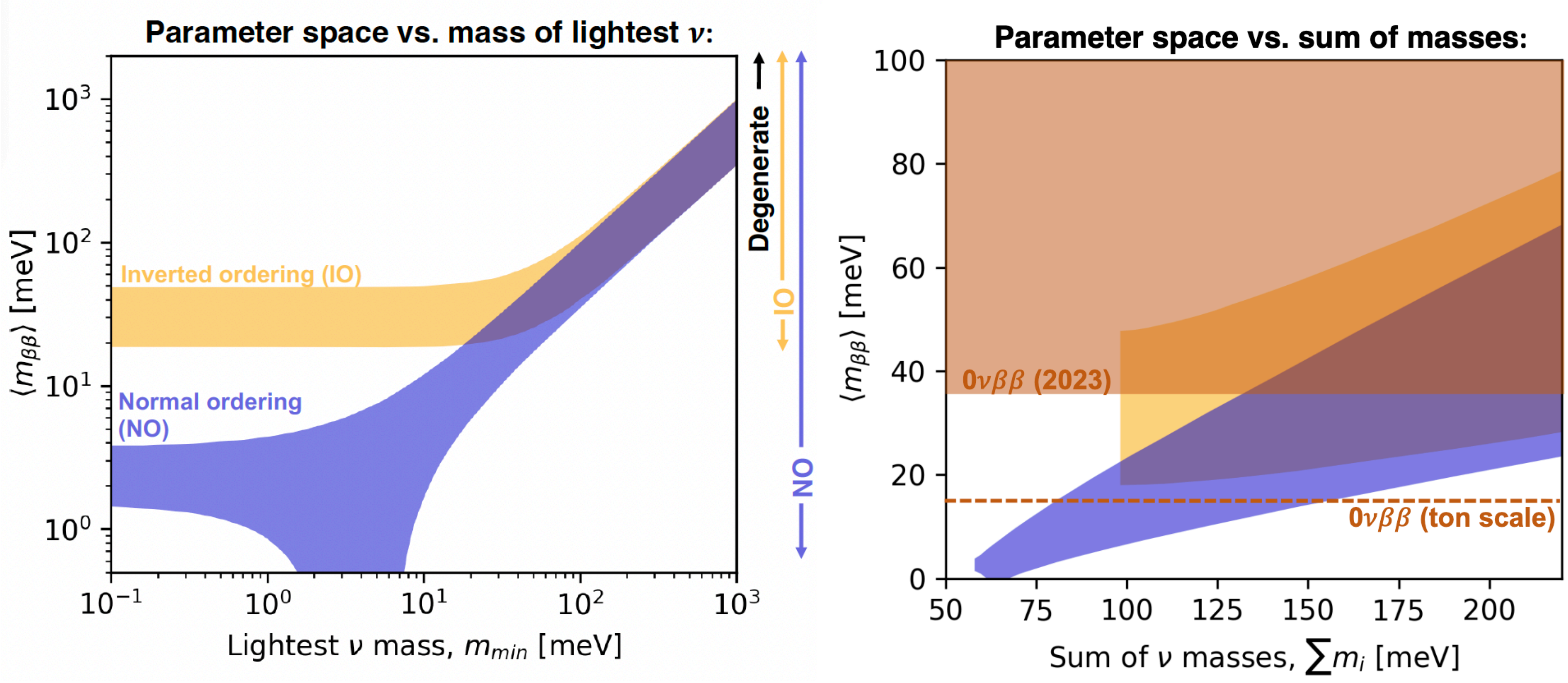
Phase space — Nuclear matrix elements — Effective Majorana neutrino mass

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

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

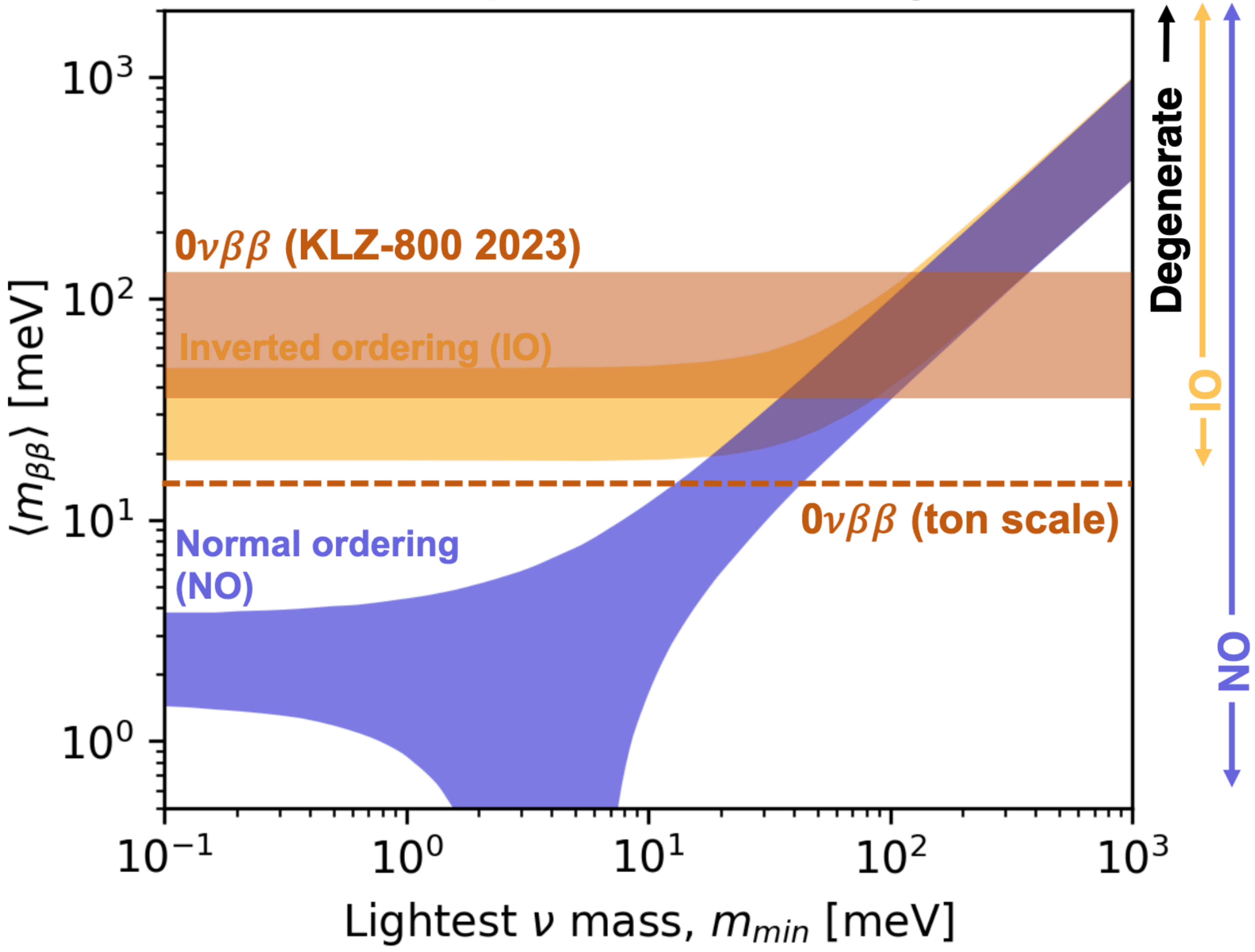
- **2νββ** has been observed in more than 10 isotopes (lifetimes 10^{18} – 10^{21} y)
- **0νββ** has not been observed yet (lifetimes > 10^{25} – 10^{26} y):
  - ✦ It would imply **total lepton number violation** (LNV) and **neutrino Majorana mass**
  - ✦ Different mechanisms are possible: SUSY, leptoquarks,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

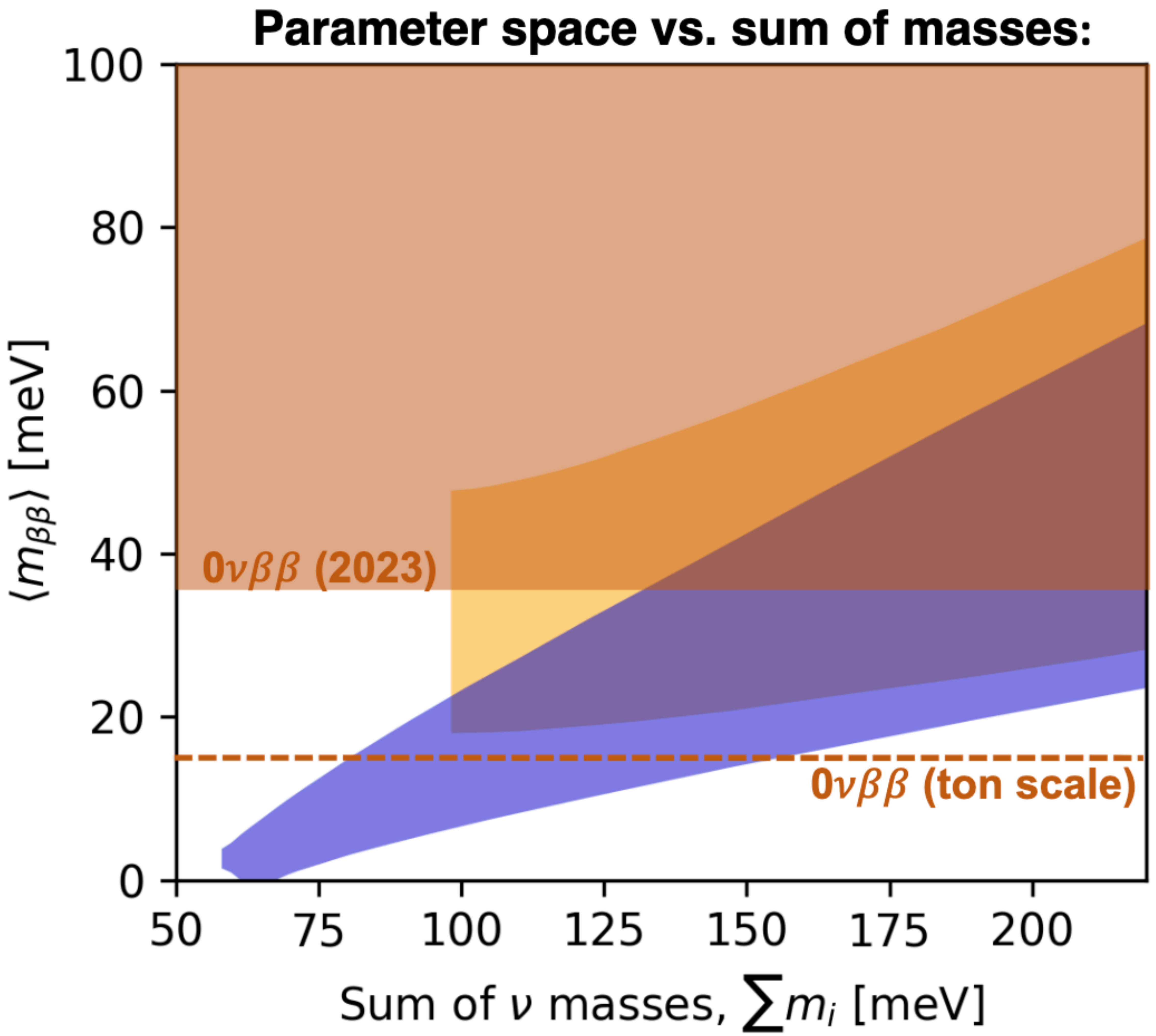
Current status of 0νββ searches



From TAUP 2023 D. Moore

Current status of 0νββ searches





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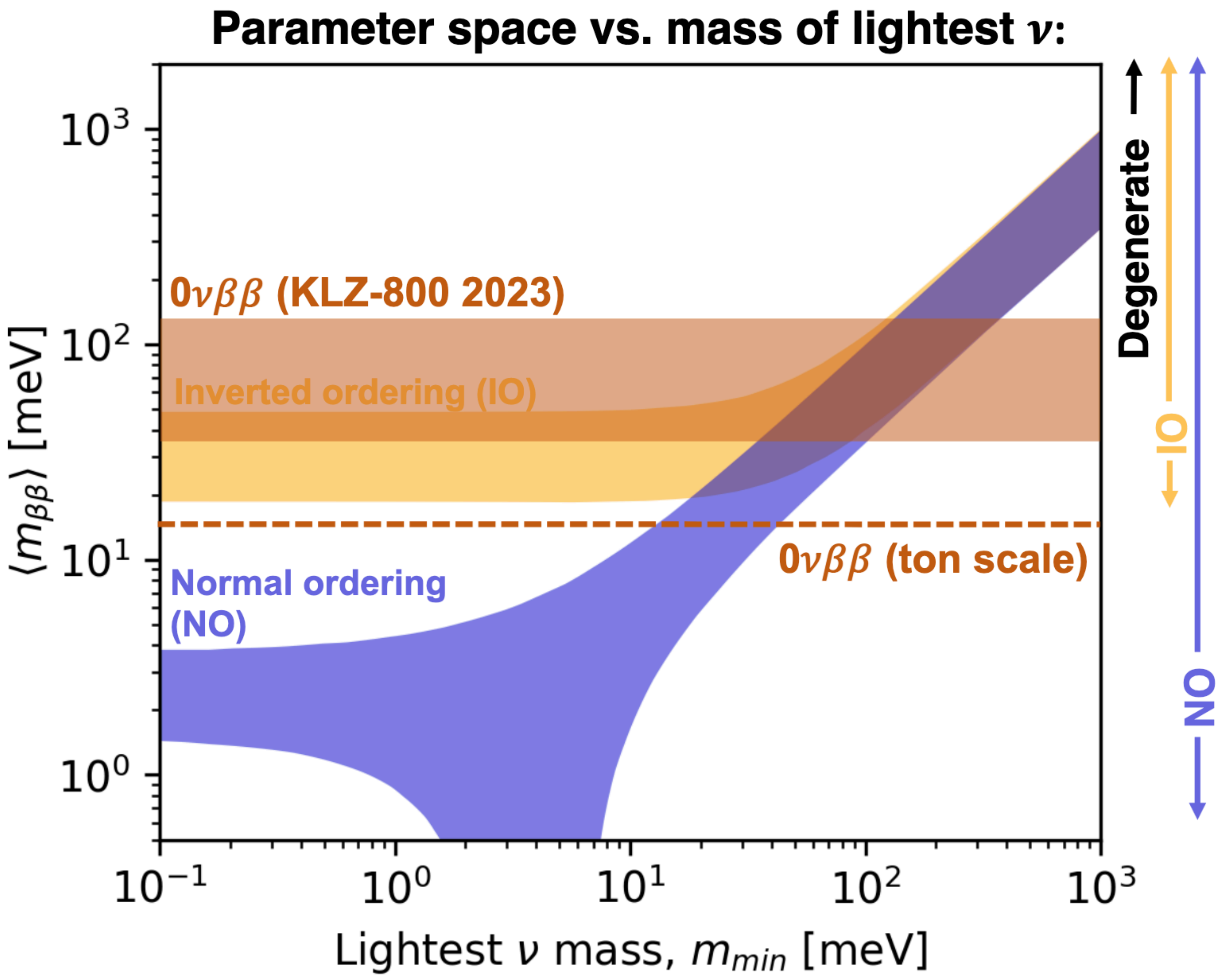
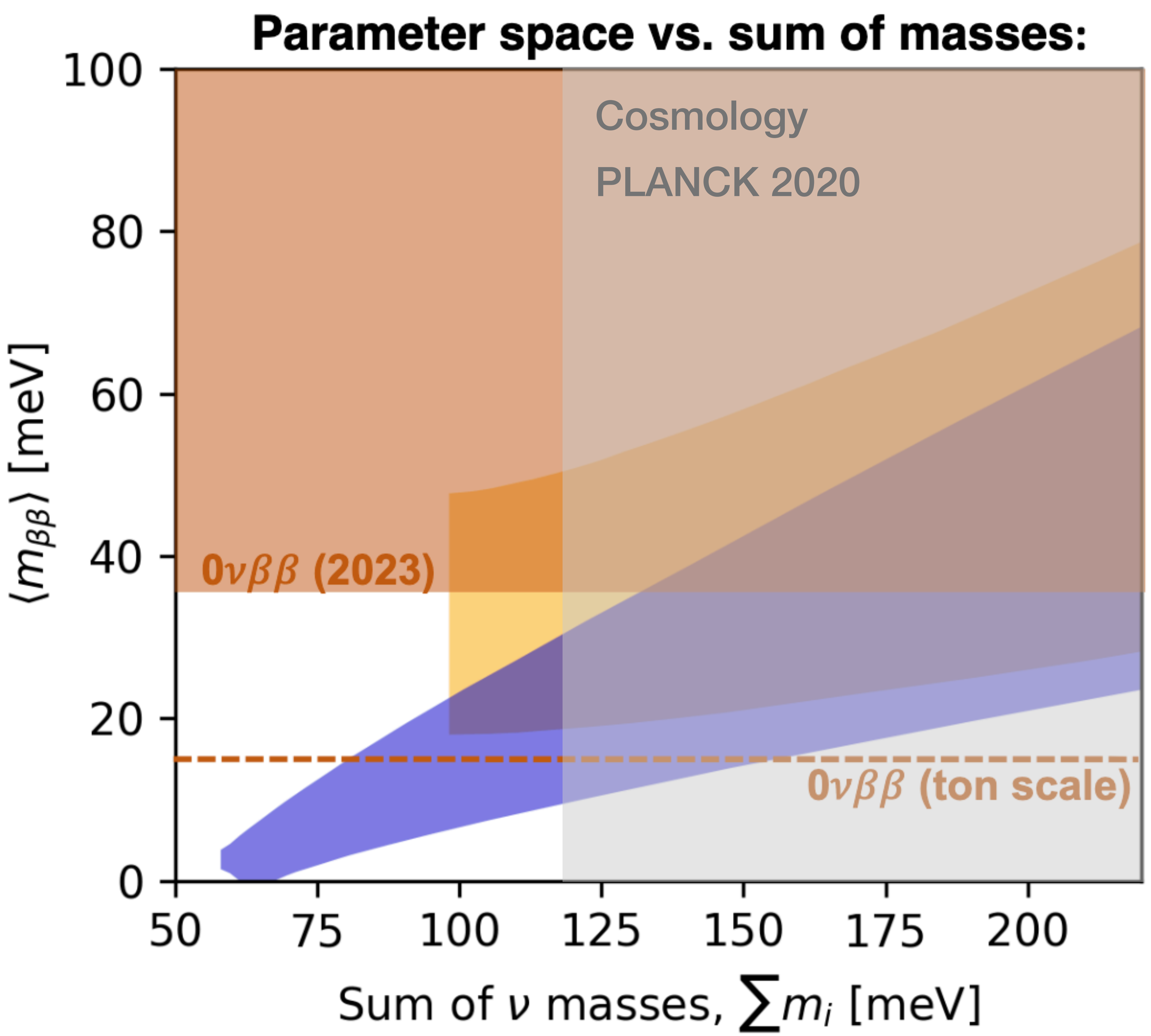
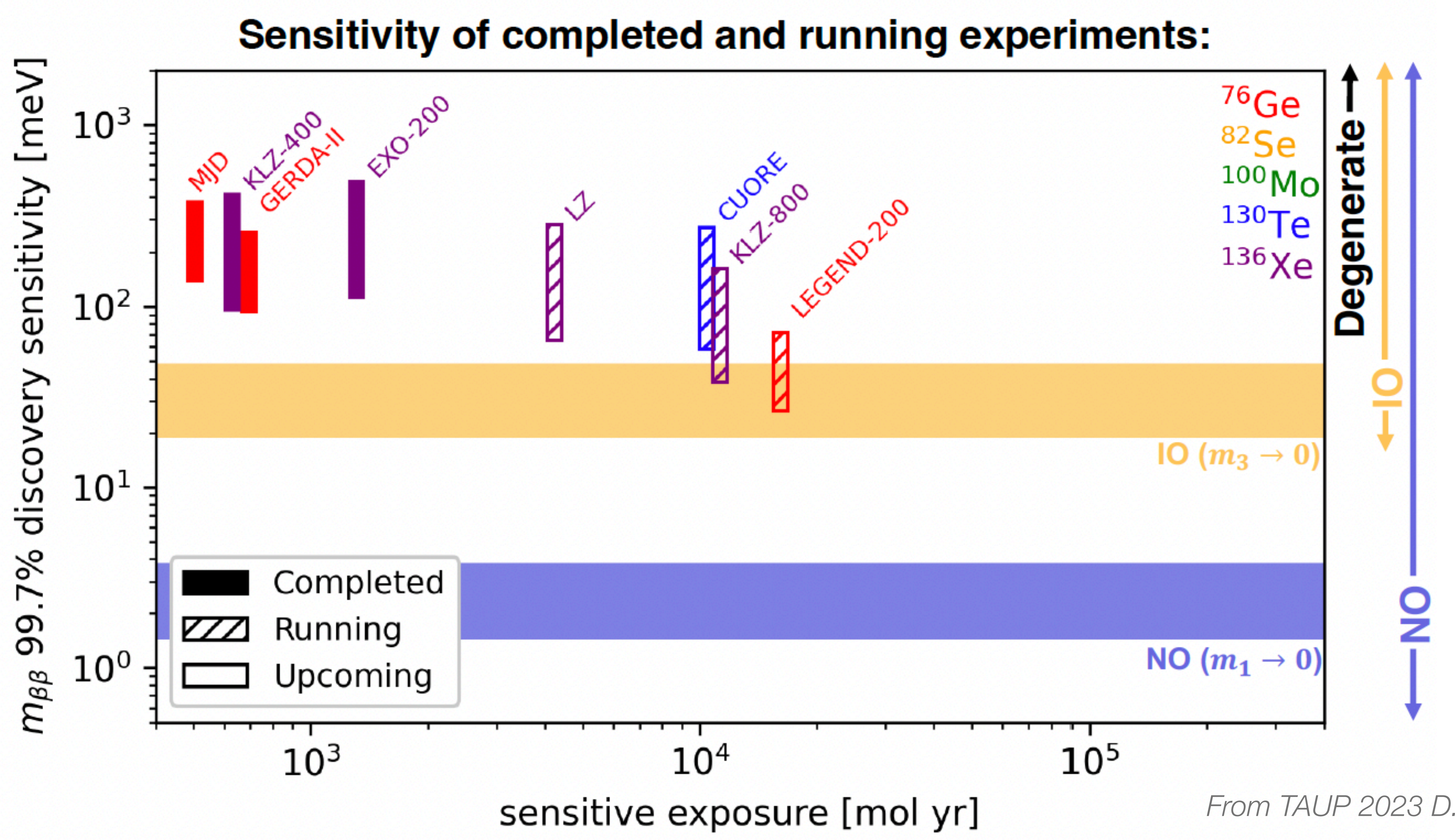




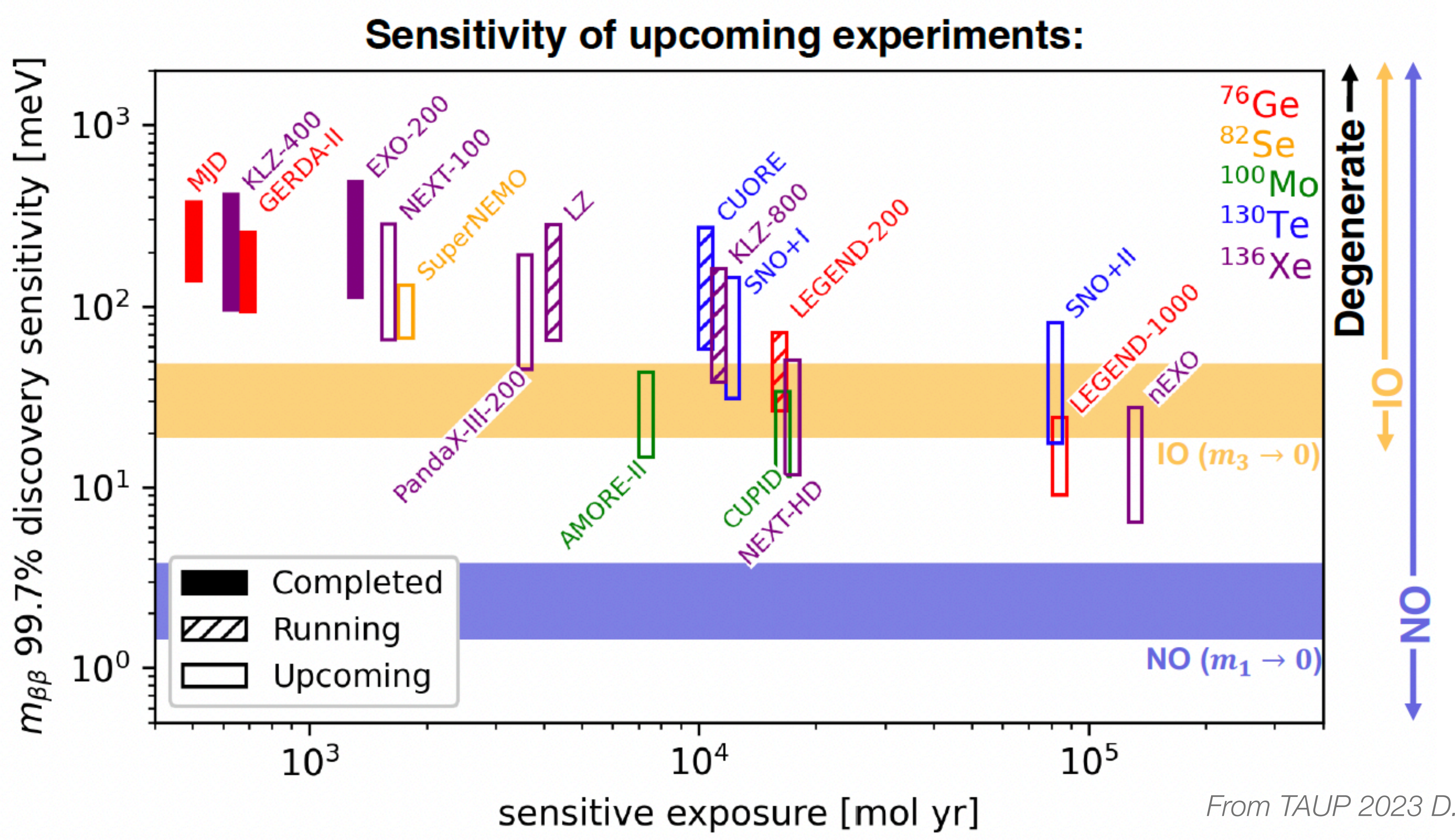
From TAUP 2023 D. Moore

Current and future sensitivity



From TAUP 2023 D. Moore

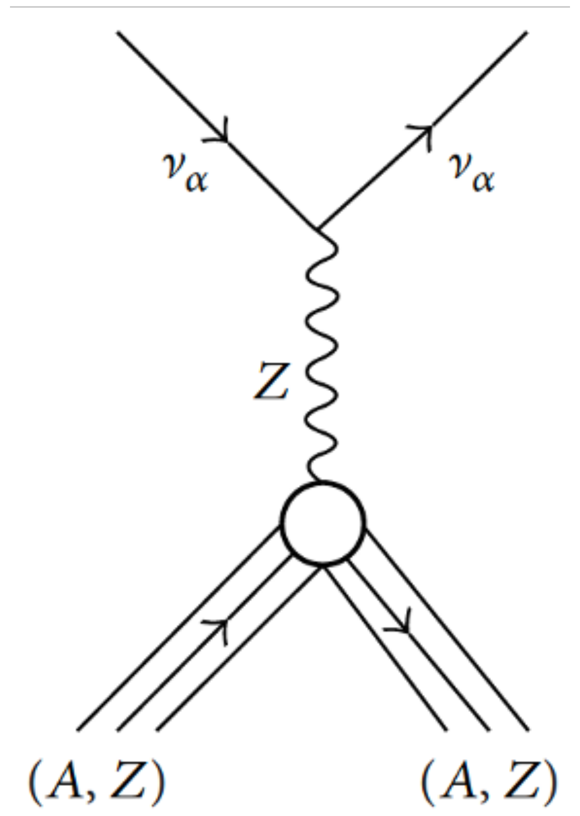
Current and future sensitivity

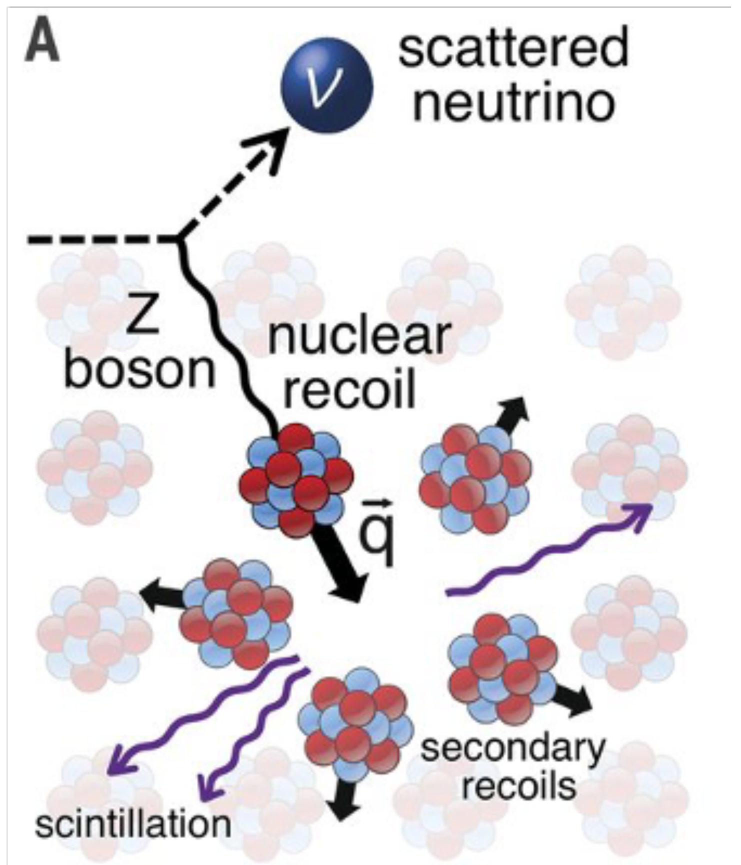


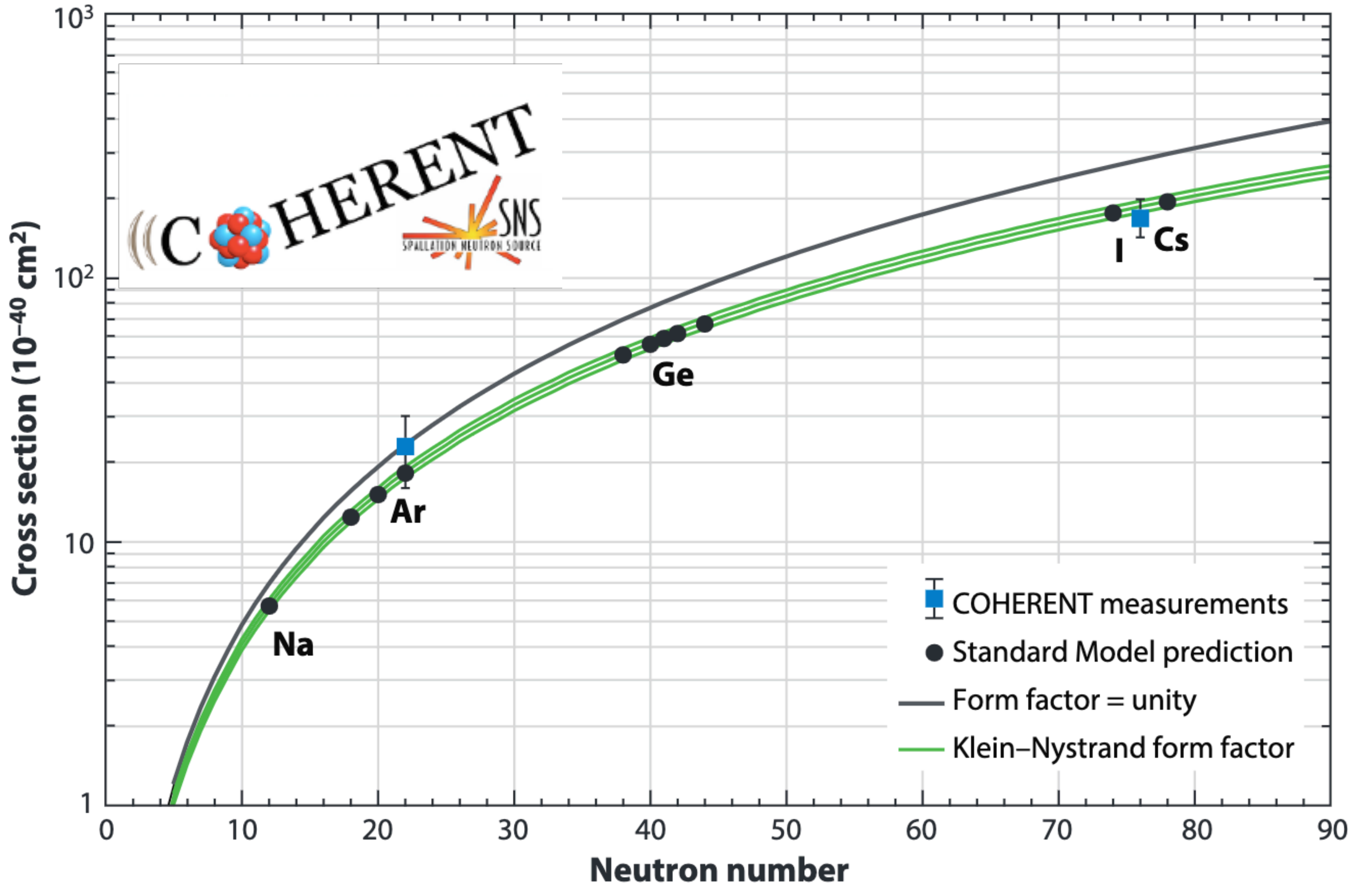
From TAUP 2023 D. Moore

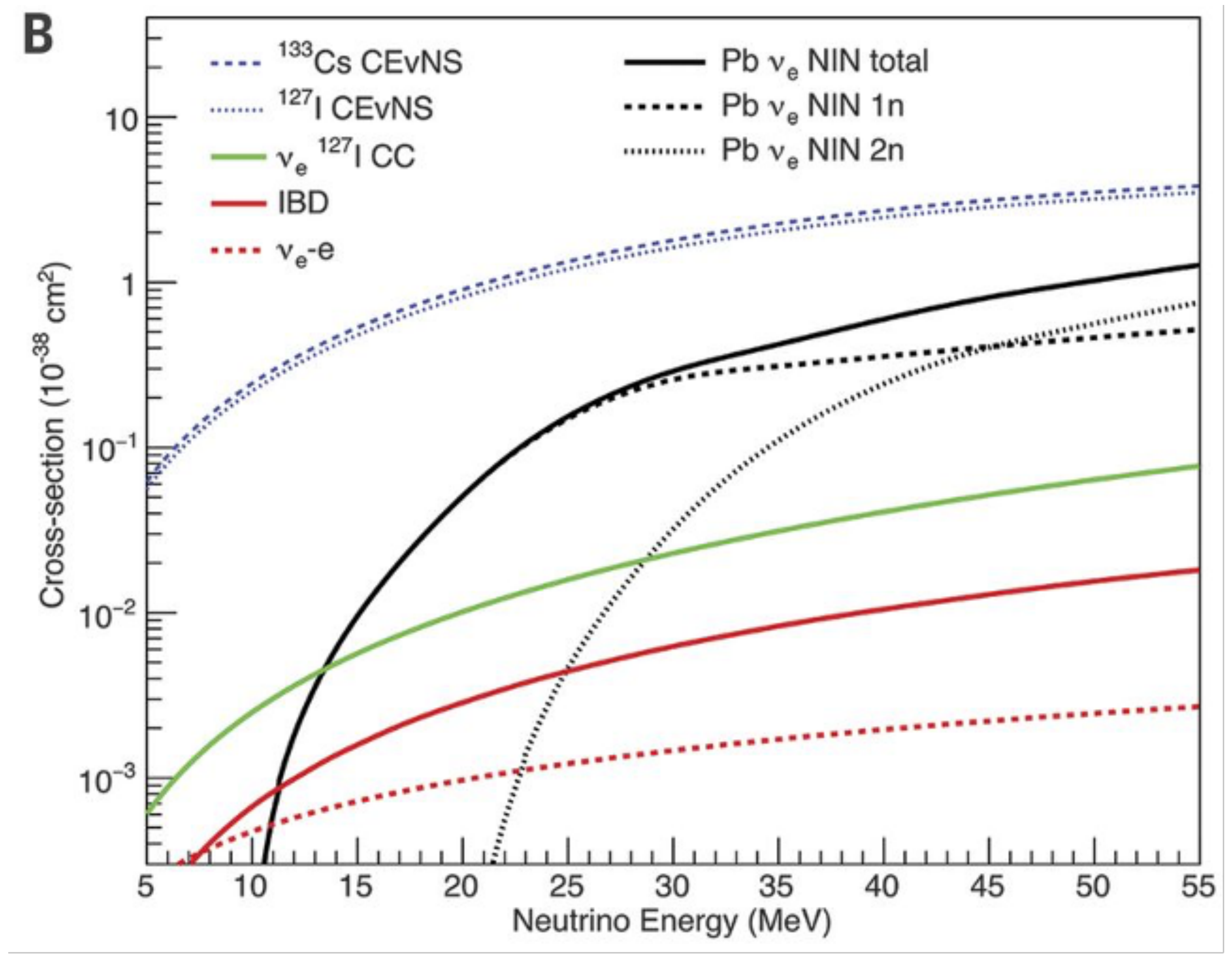
CEvNS (Coherent Elastic neutrino-Nucleon Scattering)

- Neutral current process predicted by Freedman (1974)
- Neutrino scatters off an entire nucleus (**ν + A → ν + A**)
- Cross-section scales with the (number of neutrons)^2 in the target nucleus
- First measurement by **COHERENT** in 2017 at the Spallation Neutron Source at ORNL
  - ✦ CEvNS measurements open the way to use this technique for reactor neutrino detection and many BSM physics topics (DM, sterile osc., NSI, neutrino electromagnetic properties, etc.)



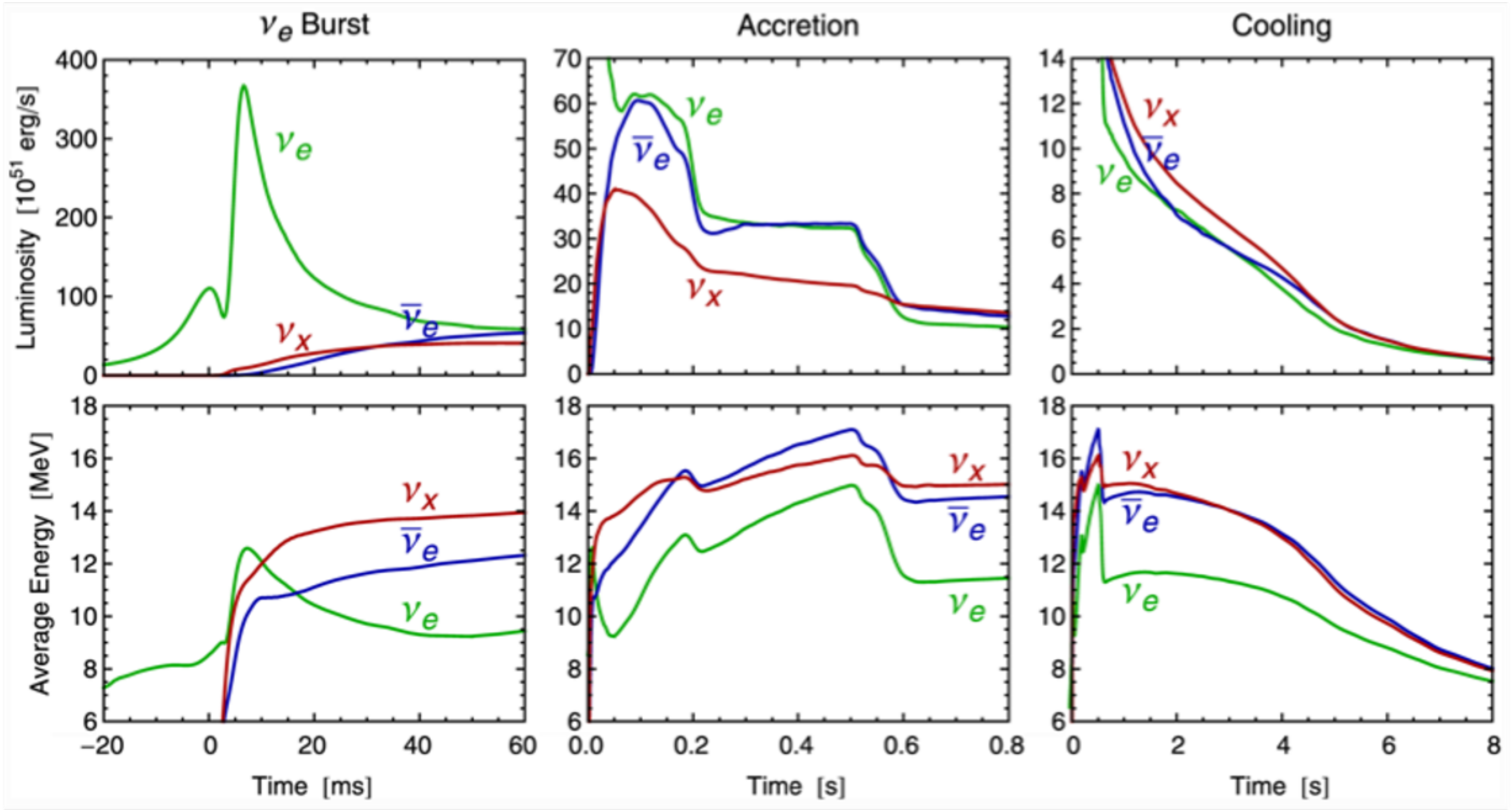




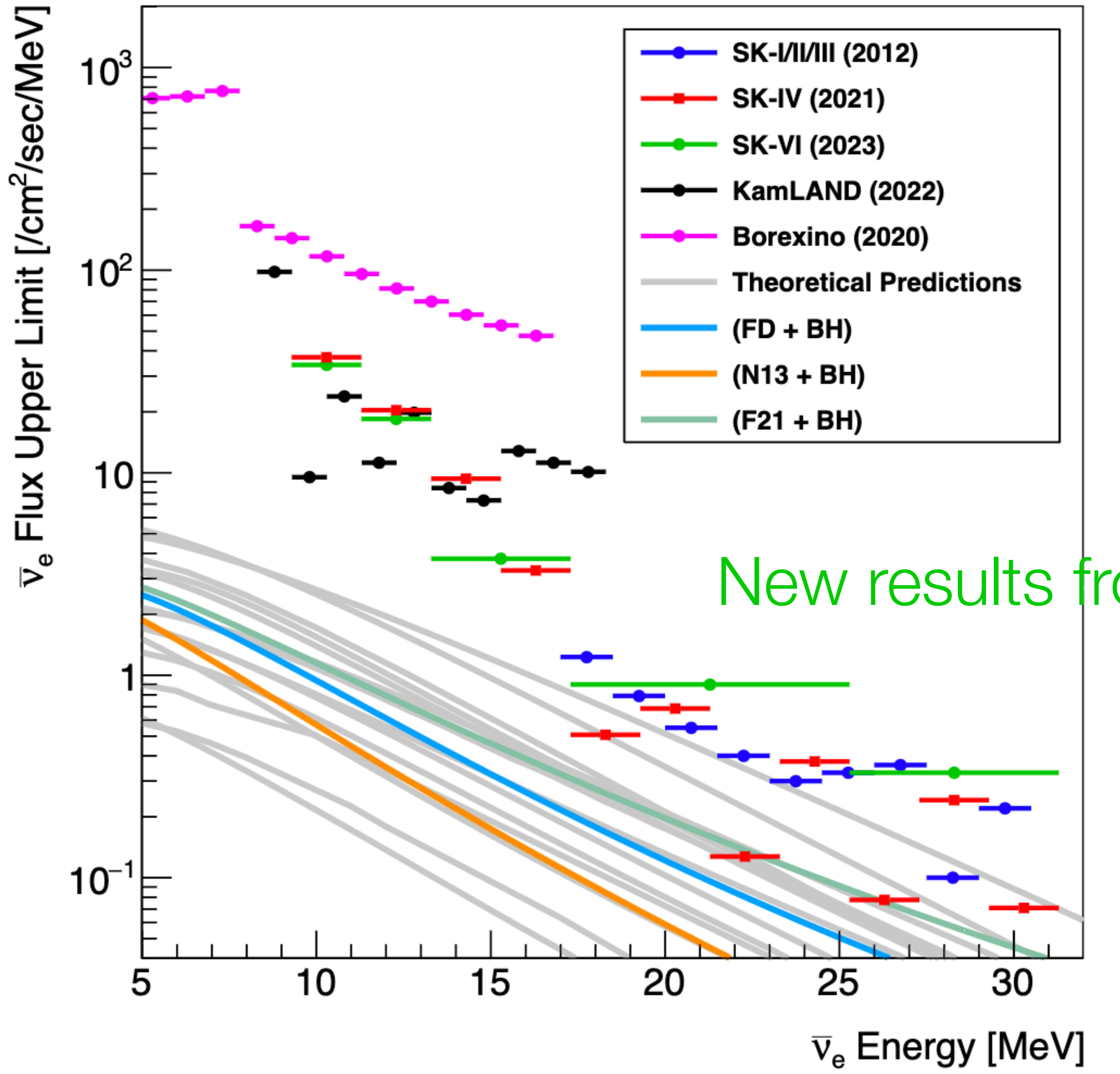


Astrophysical neutrinos - Supernova burst and DSNB

- 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

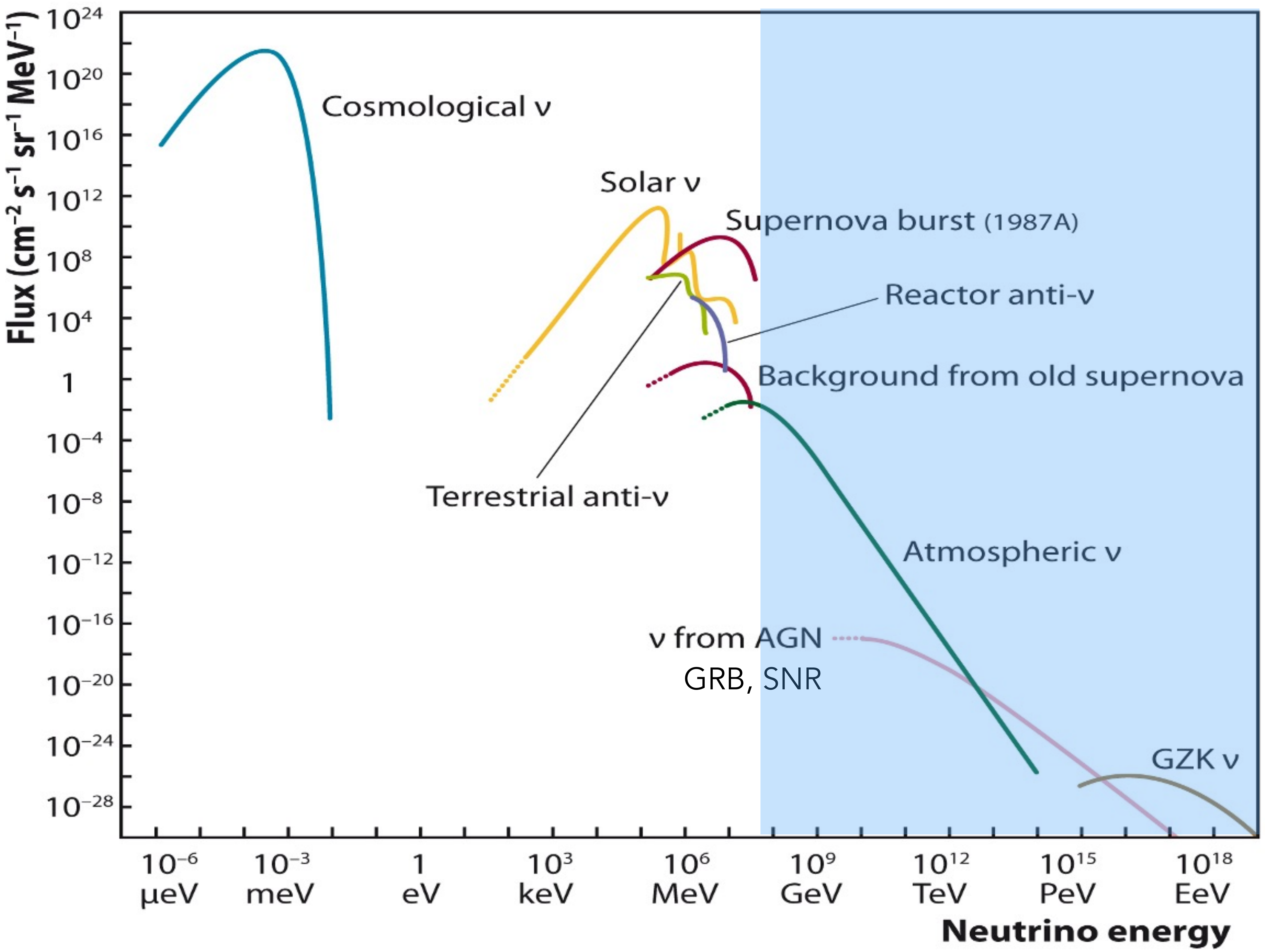


- Detection of **diffuse supernova neutrino background** (averaged neutrino flux from all supernovae)
  - ✦ No detected yet
  - ✦ Best upper limits from Super-K



New results from SK-Gd

Astrophysical neutrinos - high-energy neutrinos



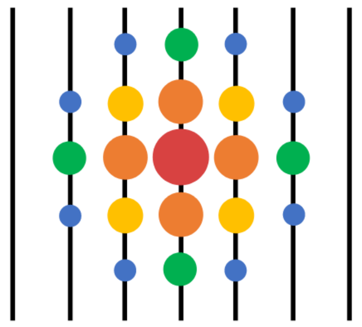
- Atmospheric neutrinos
  - ✦ Up to 100 TeV
- Cosmic neutrinos (~TeV-PeV)
  - ✦ From AGN, GRB, SNR
- Cosmogenic neutrinos (PeV-EeV)
  - ✦ From cosmic ray interactions with CMB photons (not detected yet)
- Production: $p + \gamma \rightarrow n + \pi^+$

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

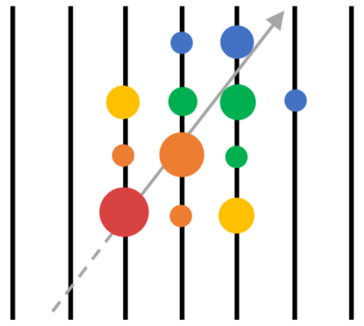
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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

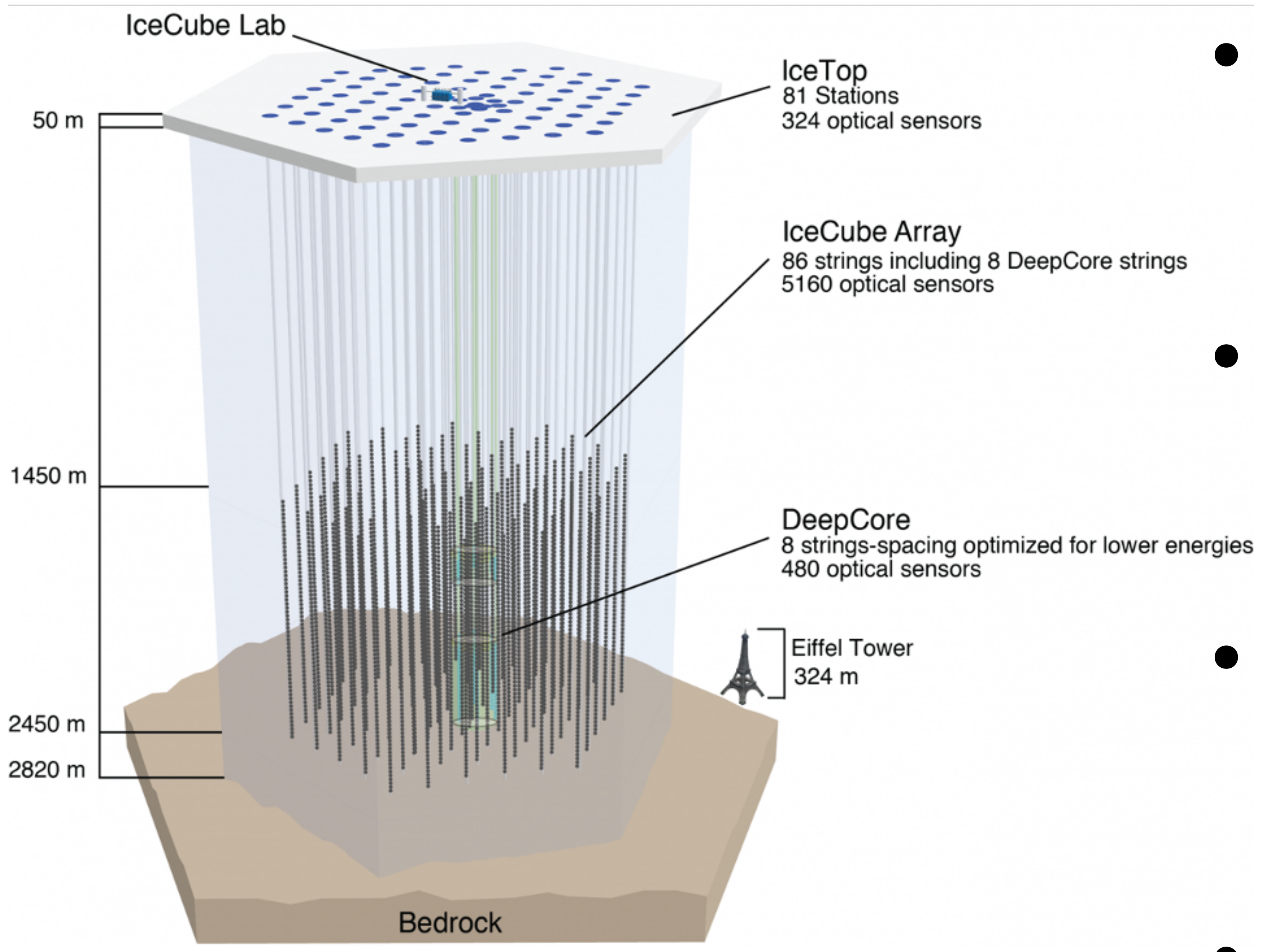
ν_eCC, ν_τCC, NC



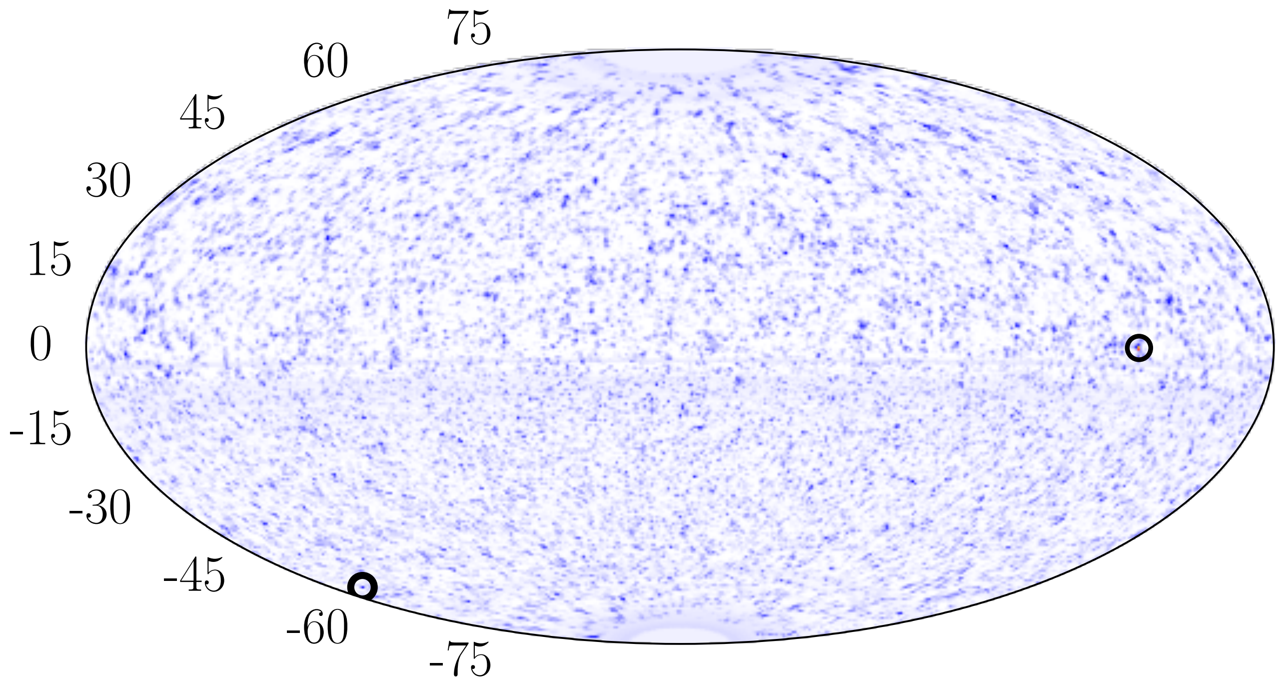
ν_μCC



IceCube results

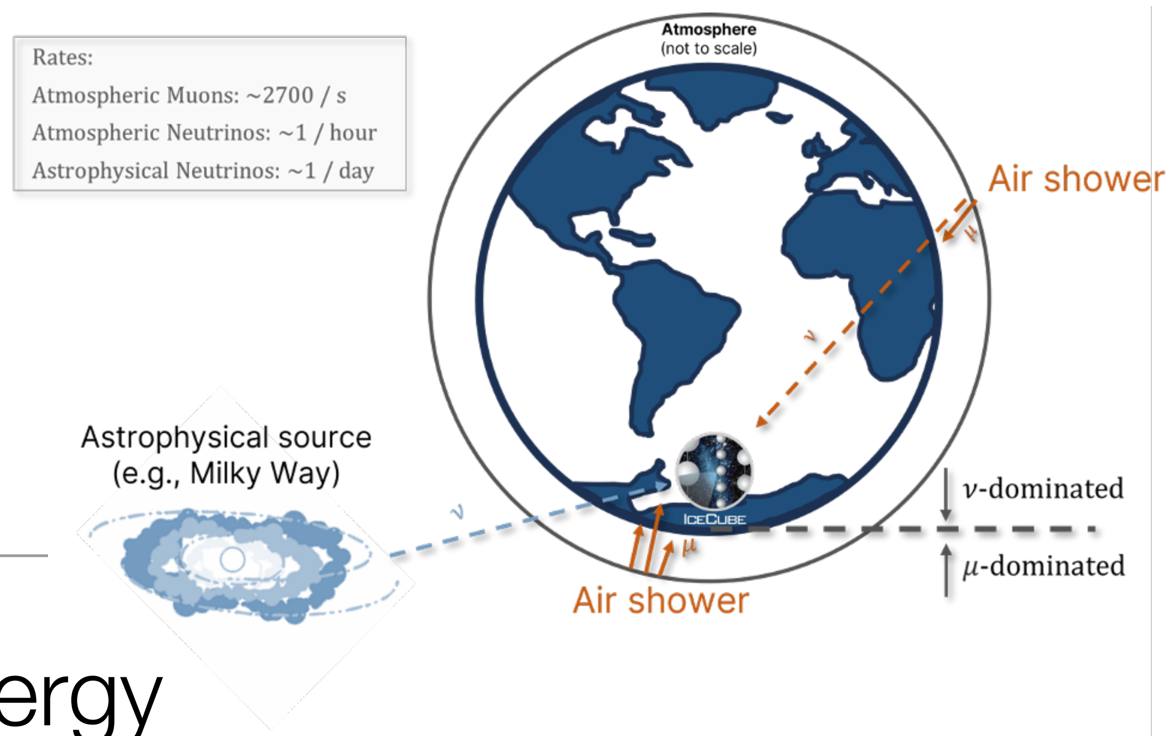


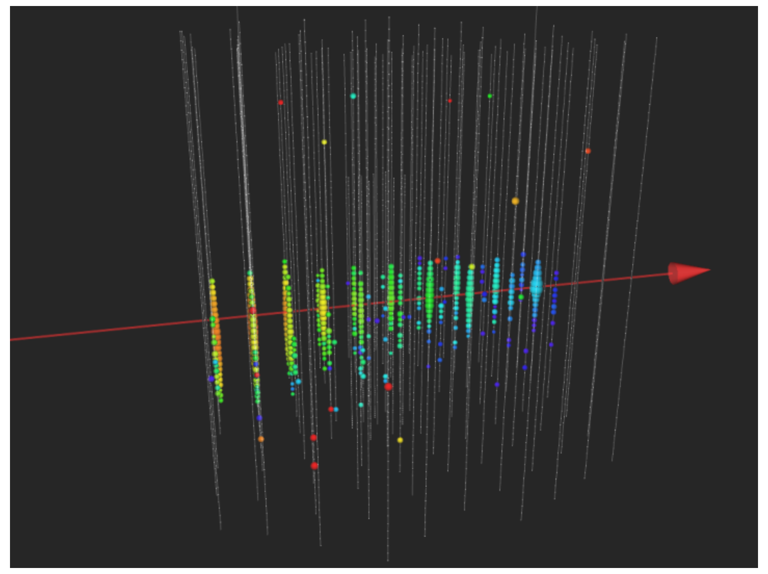
- Discovery of high-energy astrophysical neutrino flux (2013)
- Neutrino emission from blazar TXS 0506+056 (2017)
- Neutrino emission from the active galaxy NGC1068 (2022)
- Evidence of neutrinos from the Galactic plane (2023)

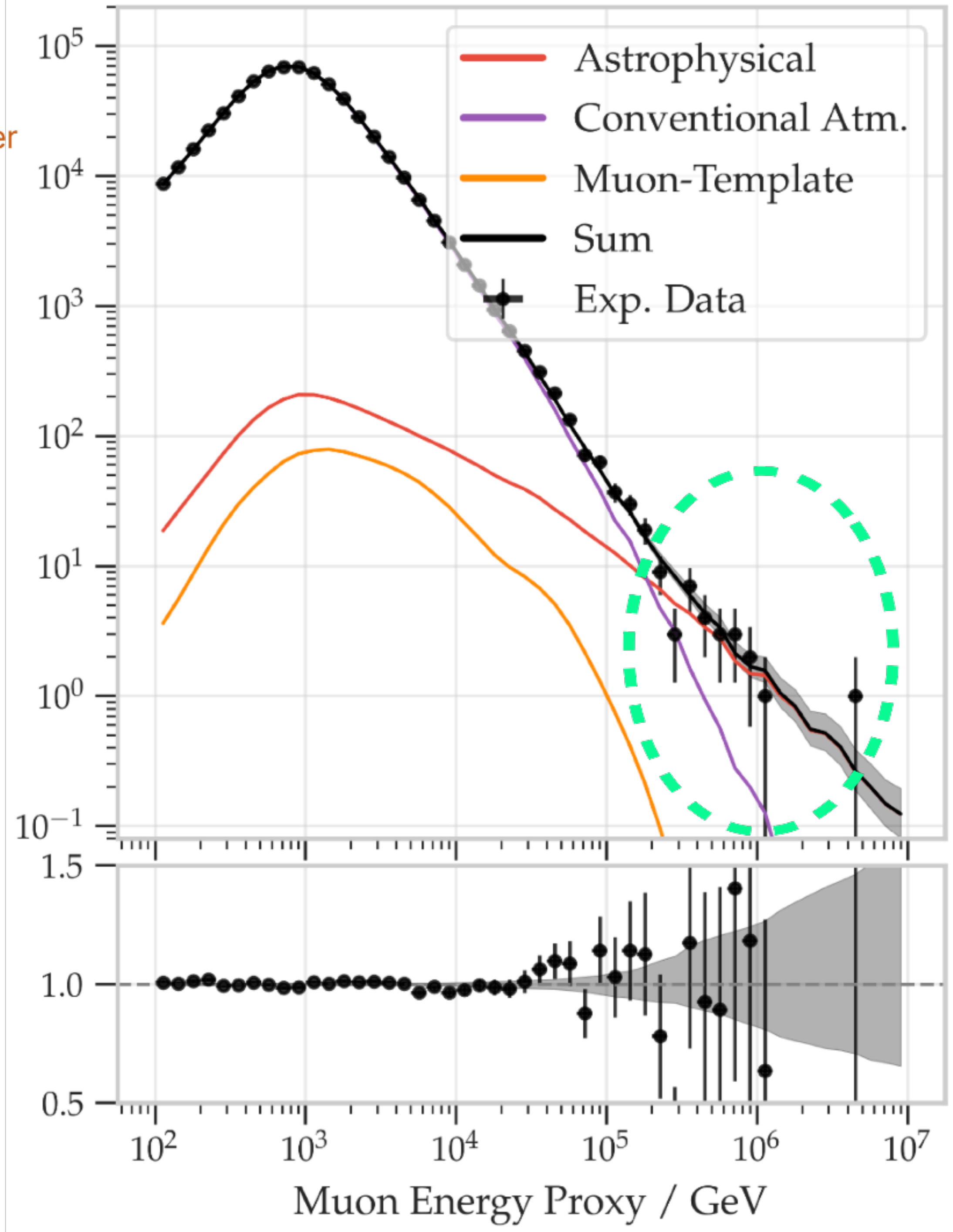


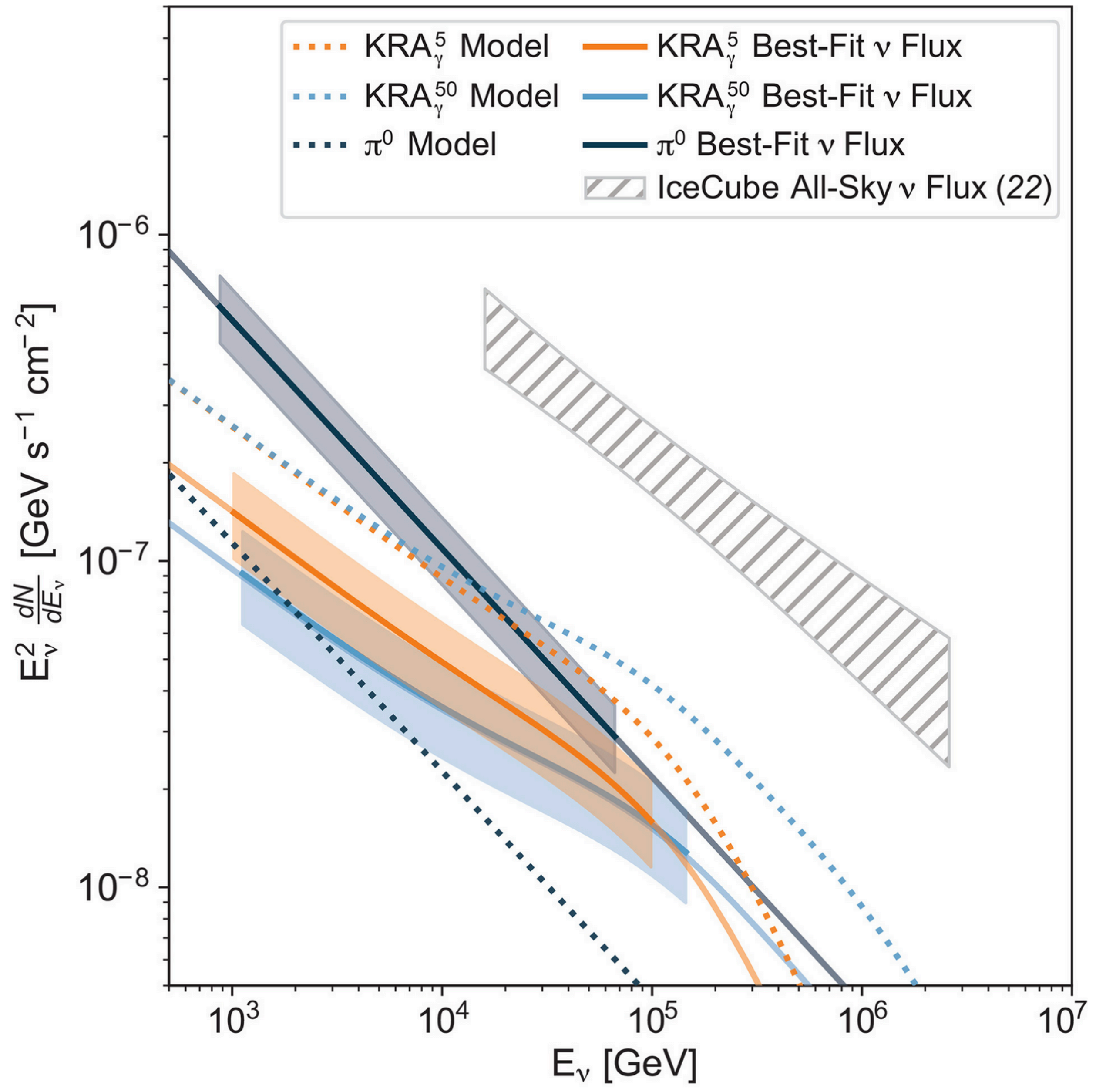
Neutrino astronomy is an exciting field

KM3NeT also taking data!









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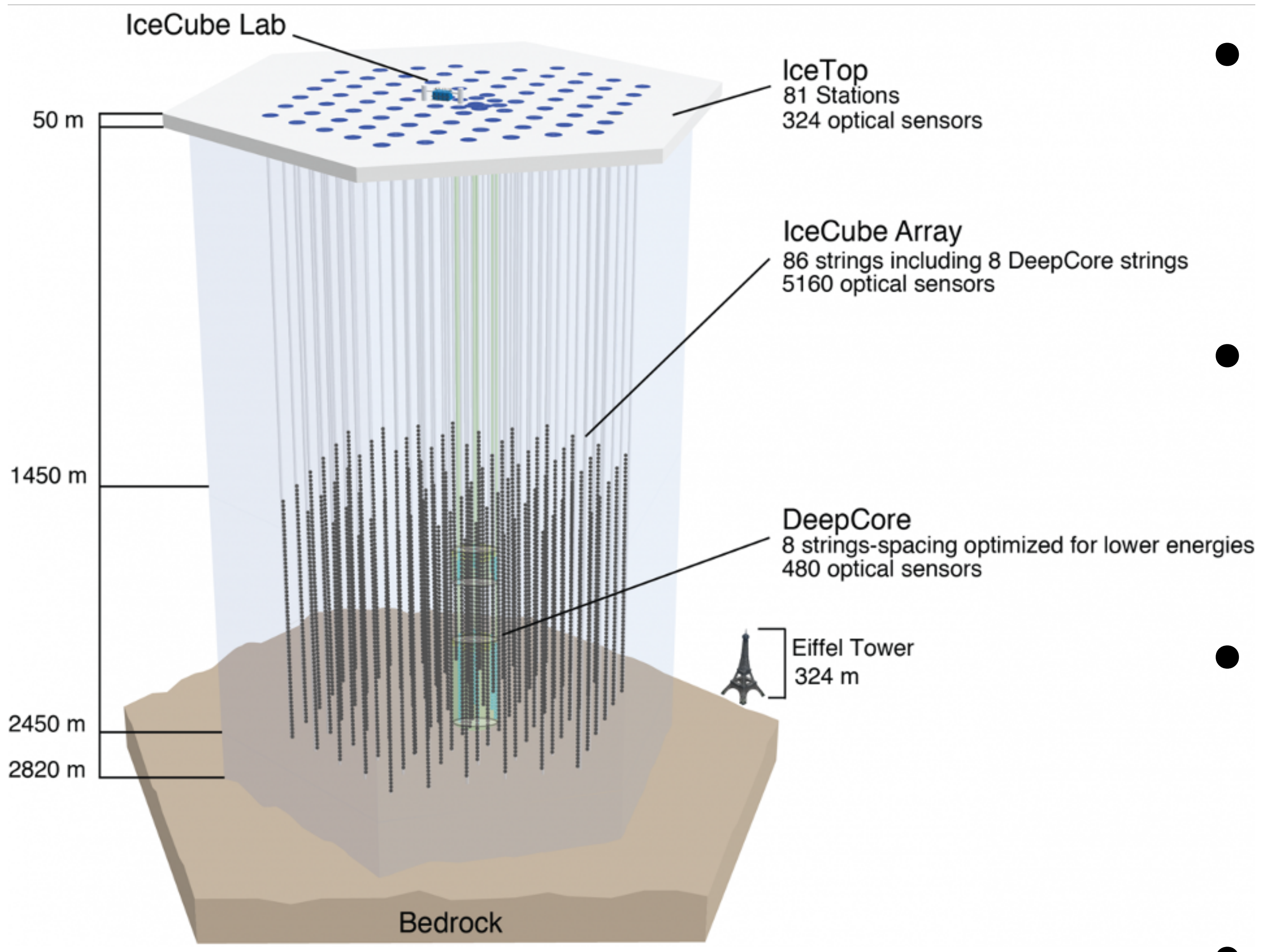

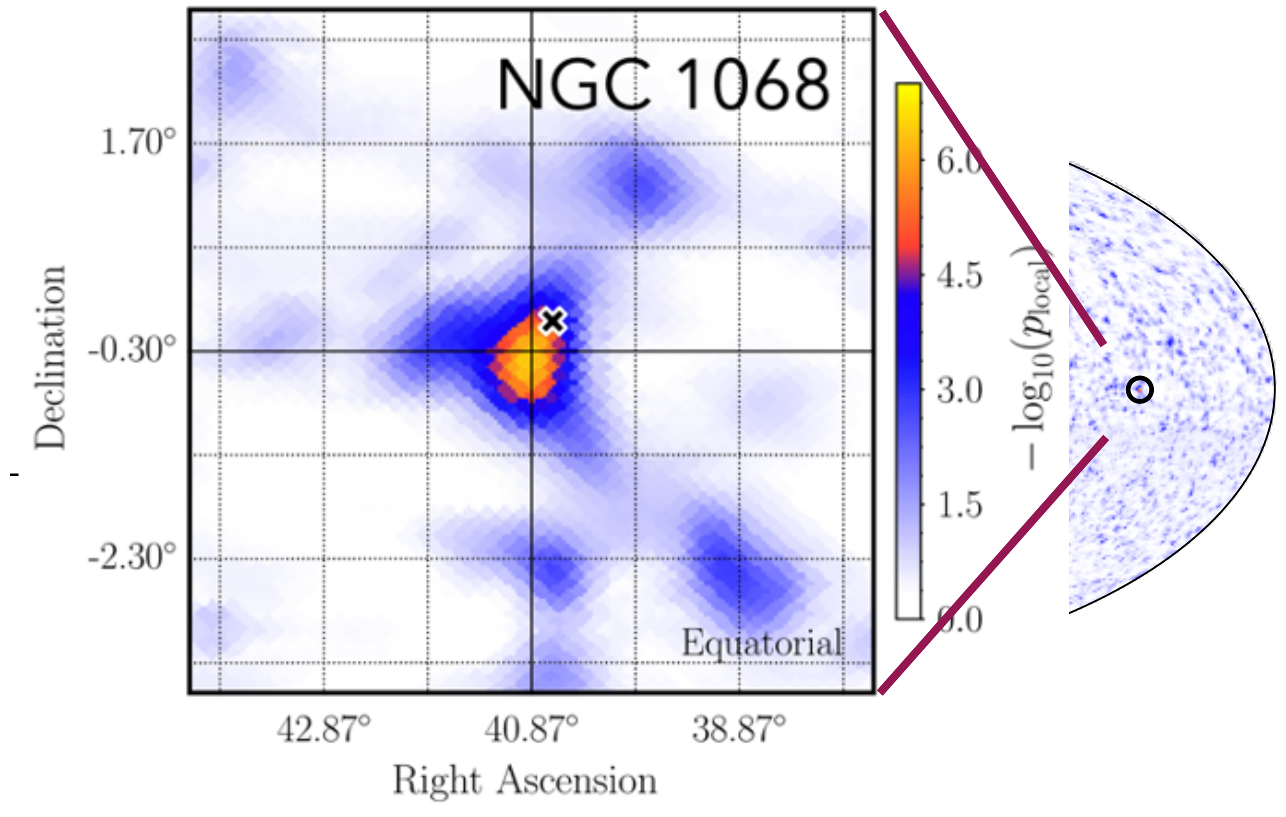

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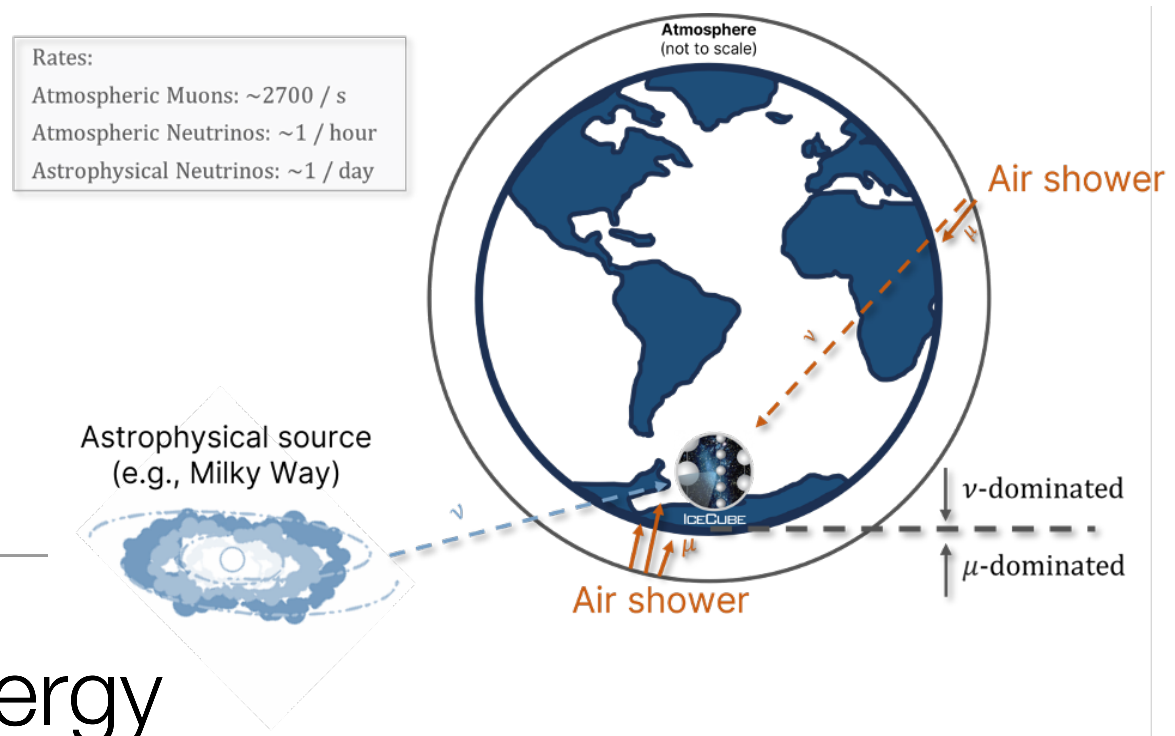

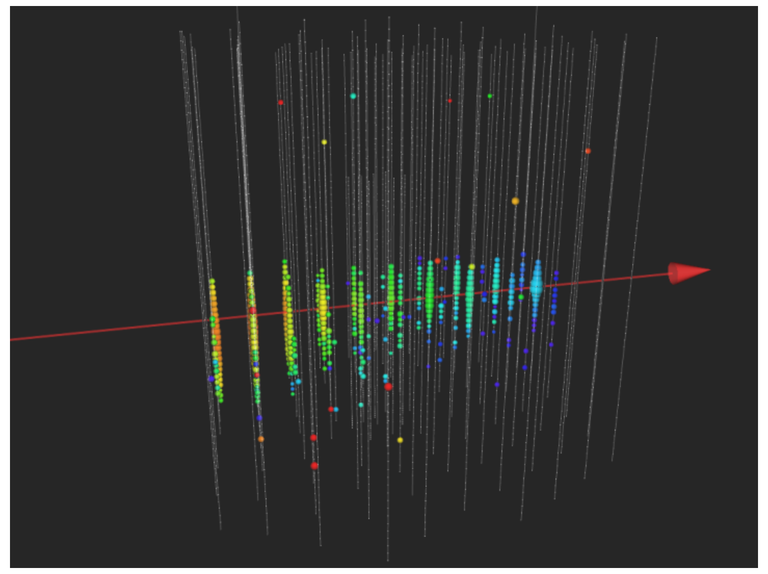

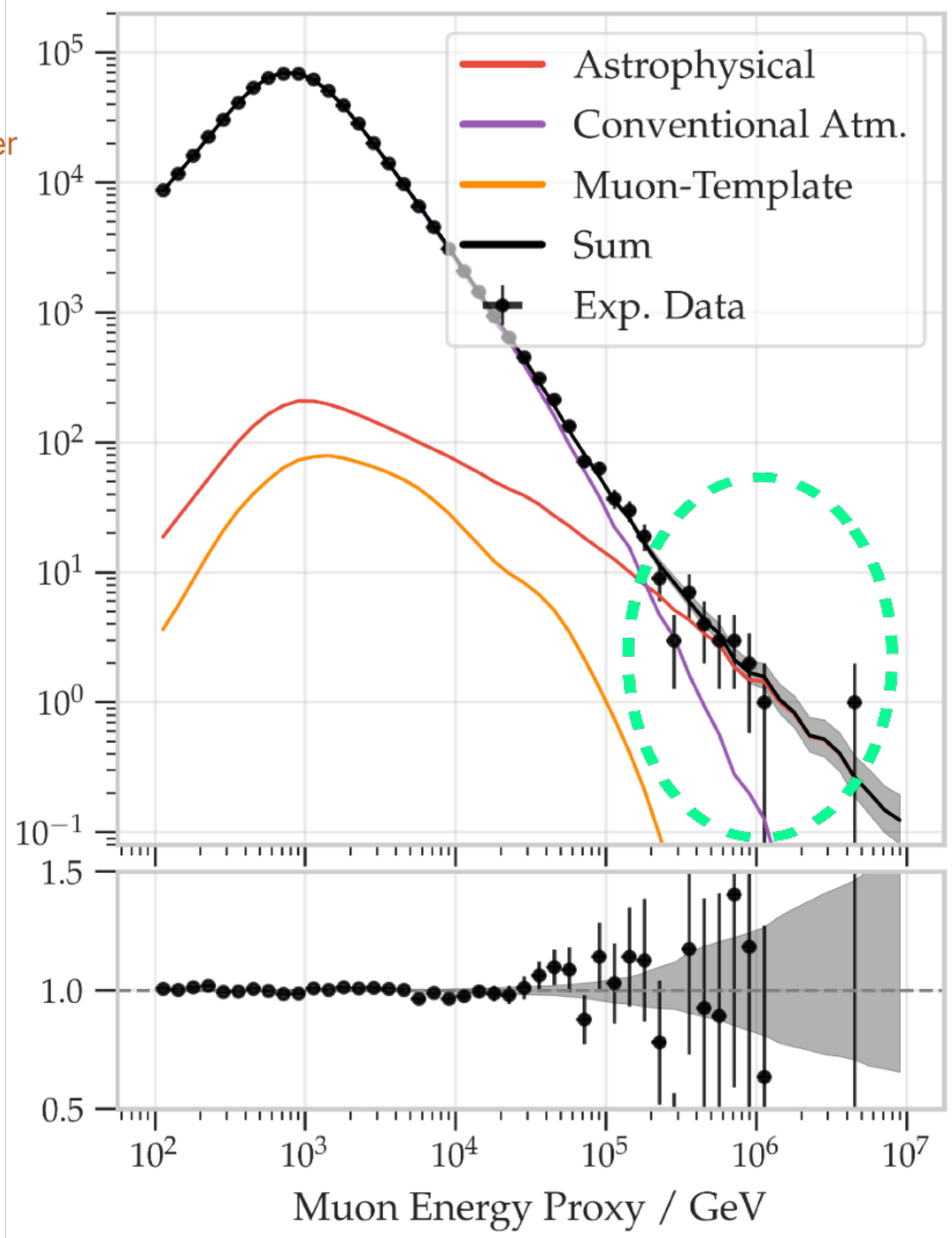

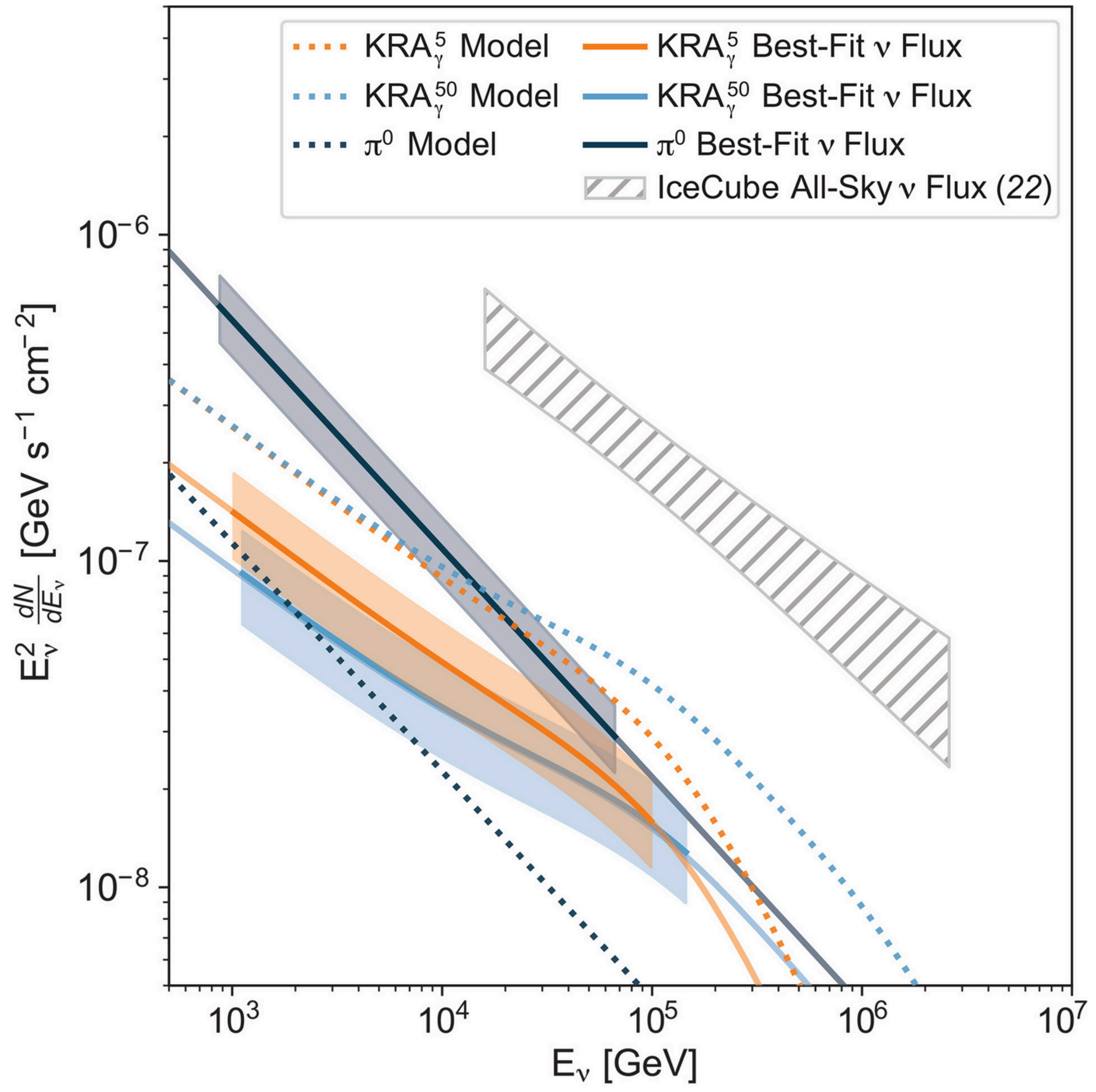

Conclusions

- 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 discover CP violation, determine the neutrino mass ordering and measure with precision all neutrino oscillation parameters
- 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!

GRACIAS