Recent Results in Neutrino Physics Experiments

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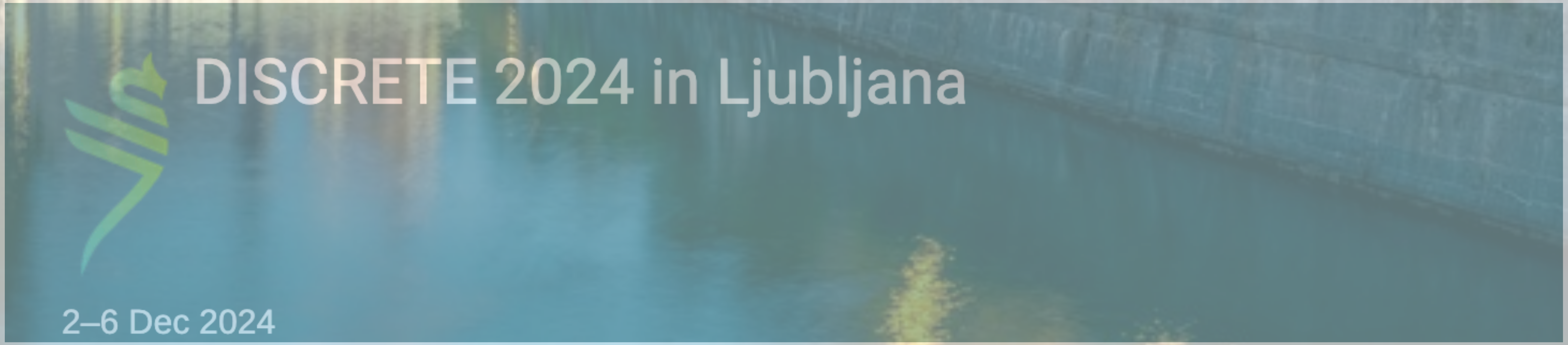
9th Symposium on Prospects in the Physics of Discrete Symmetries - DISCRETE 2024

Ljubljana - 2-6 December 2024



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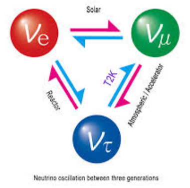
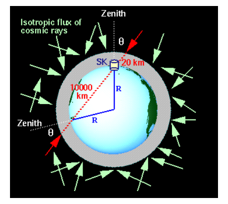
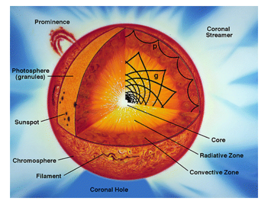
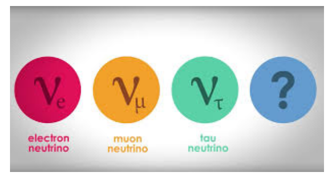
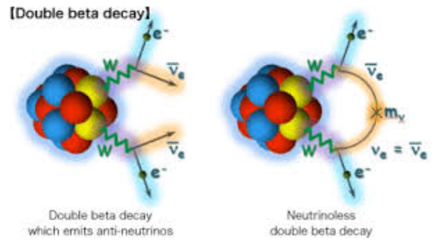
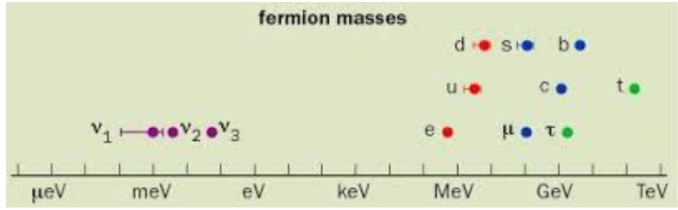
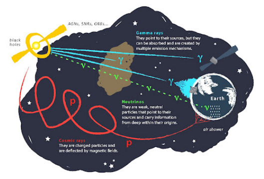
Outline

- Oscillation Basics. 
- Accelerator Neutrinos. 

- Atmospheric Neutrinos. 
- Solar Neutrinos. 
- Reactor Neutrinos. 
- Oscillation Anomalies. 
- $0\nu\beta\beta$ searches. 

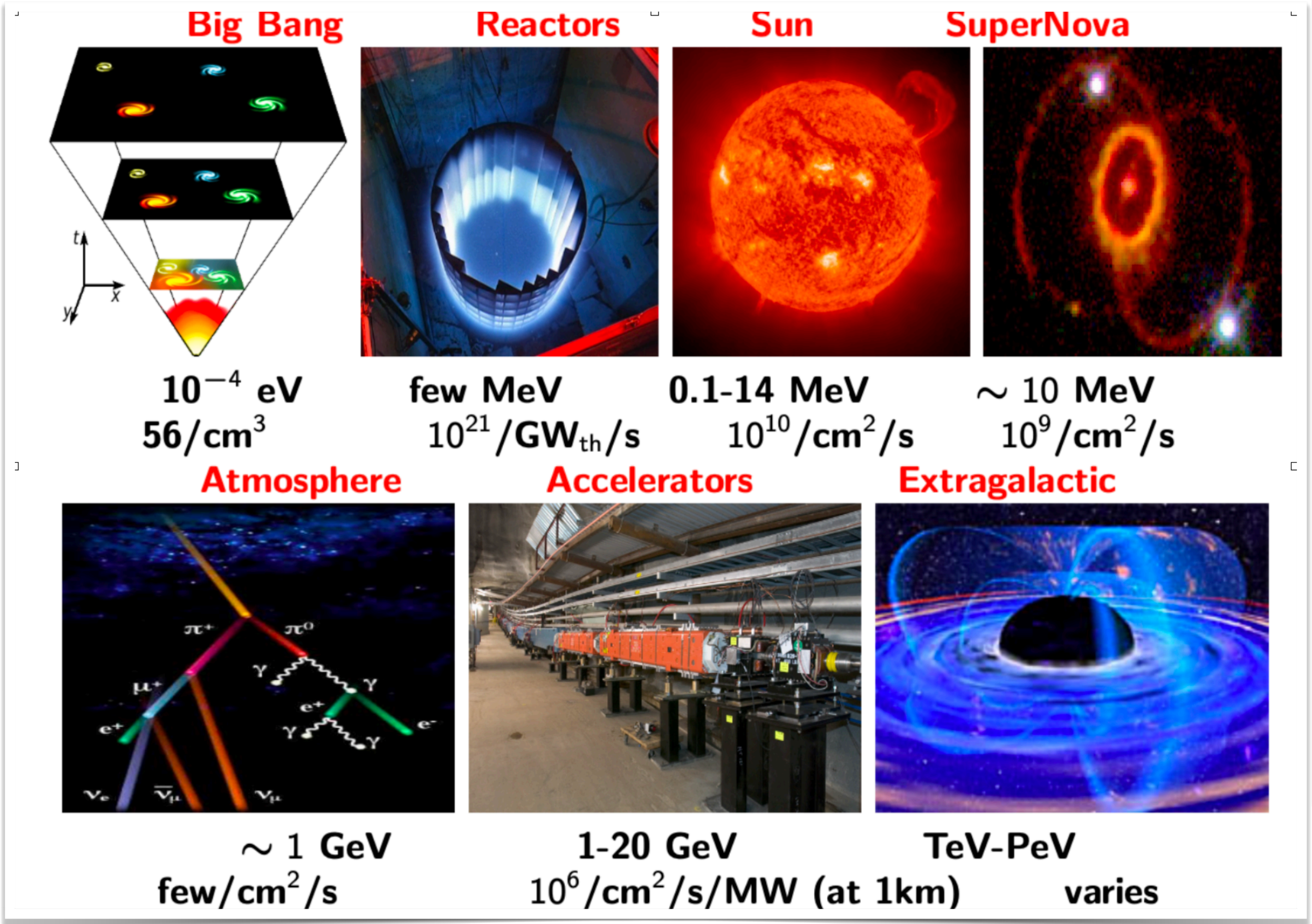
- Neutrino Mass Measurements. 

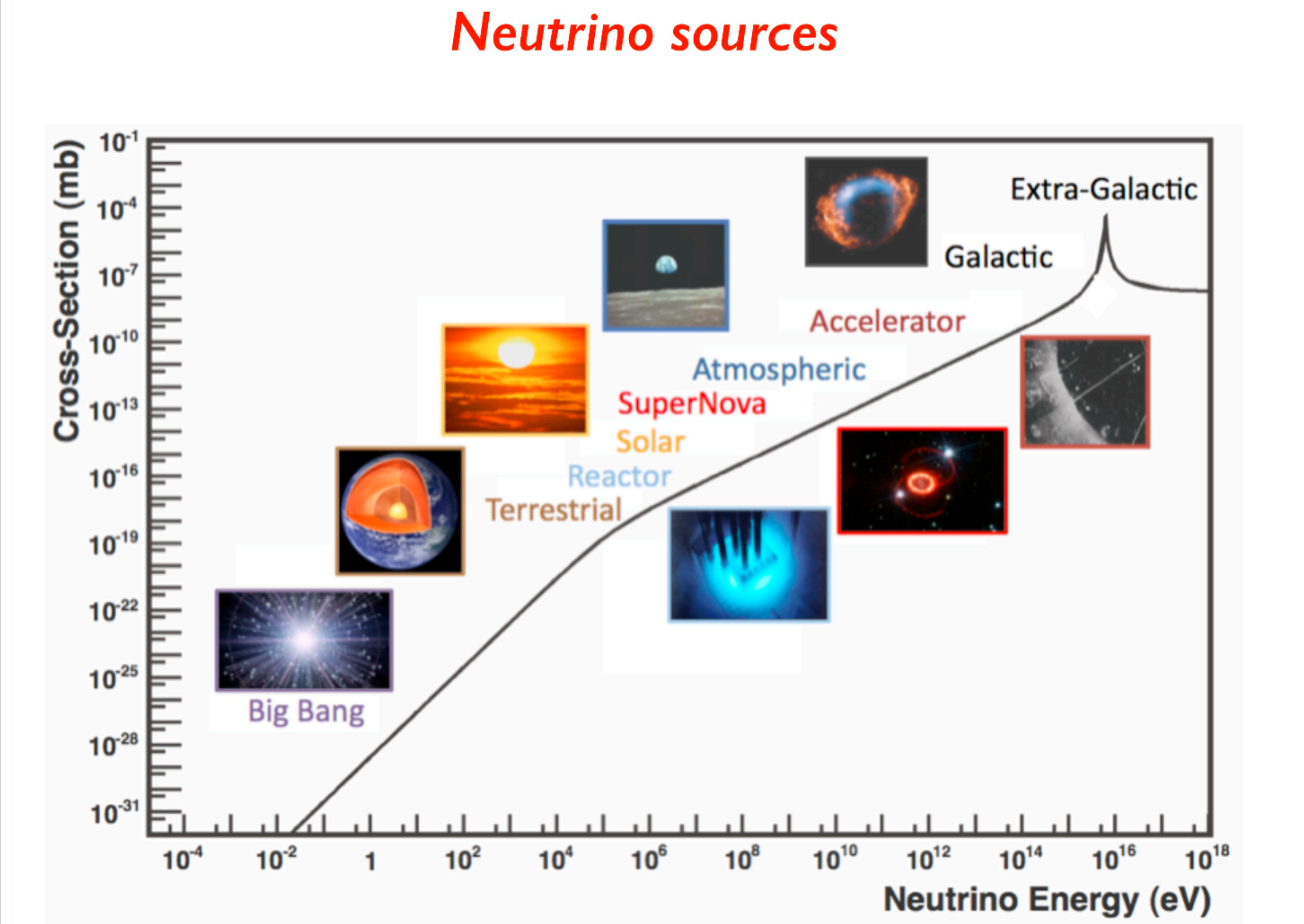
- Searches for Astrophysical and Cosmological Neutrinos. 

Disclaimer: The field of neutrino oscillations is broad and extremely active. I tried to give the general overview and main highlights, possibly at the expenses of no citing all the experiments.

Sources of Neutrinos

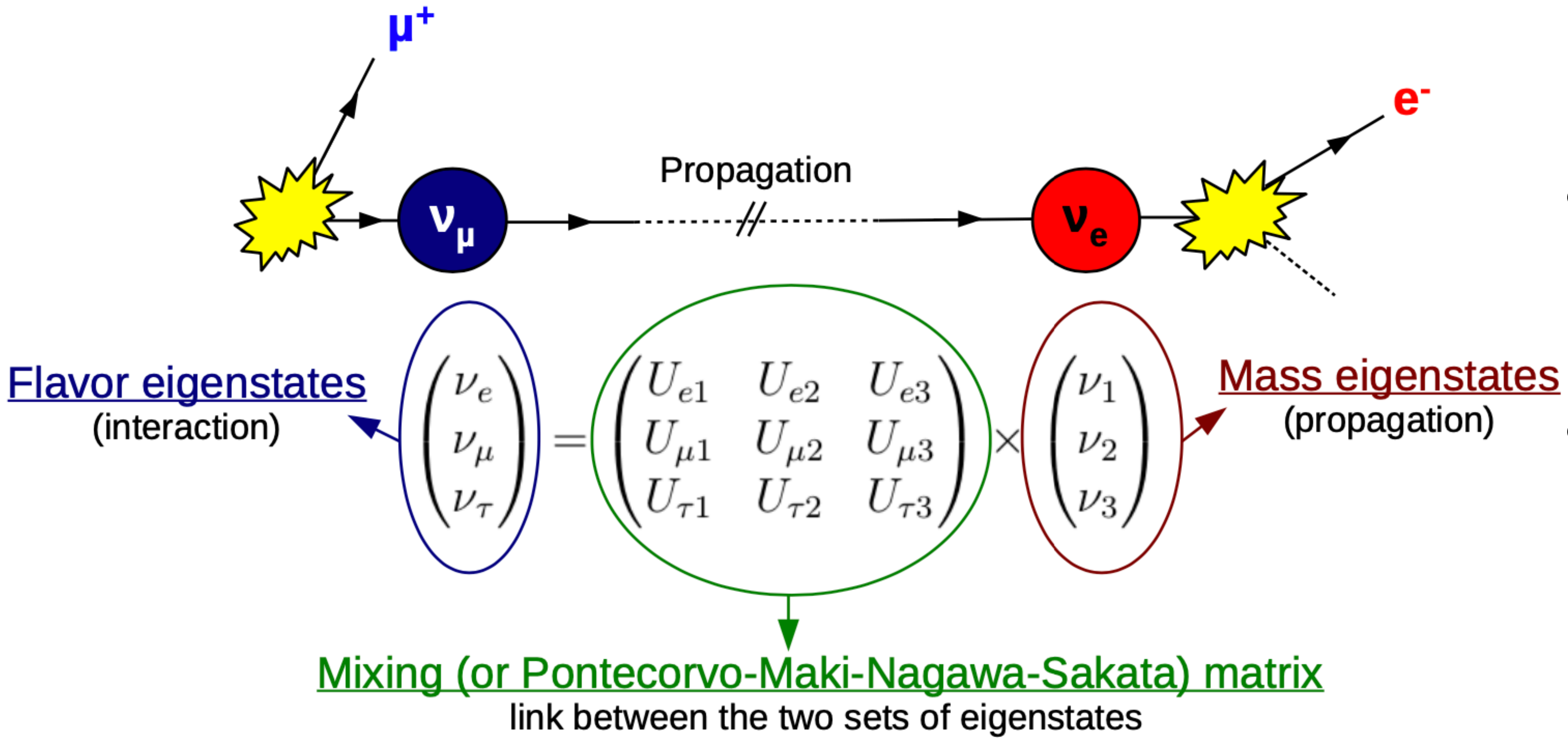
- Astrophysical and human-made sources detected by neutrino experiments.
- Wide energy span.





J. Formaggio and S. Zeller, 1305.7513

Neutrino Mixing ⇒ Oscillations



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix} \times \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- PMNS (3x3 Unitary) matrix: from neutrino mass-eigenstate to flavour.
- 3 real parameters ($\theta_{12}, \theta_{23}, \theta_{13}$) and a phase ($\delta_{CP}$) [$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$ below]
- Decomposed into three matrices:

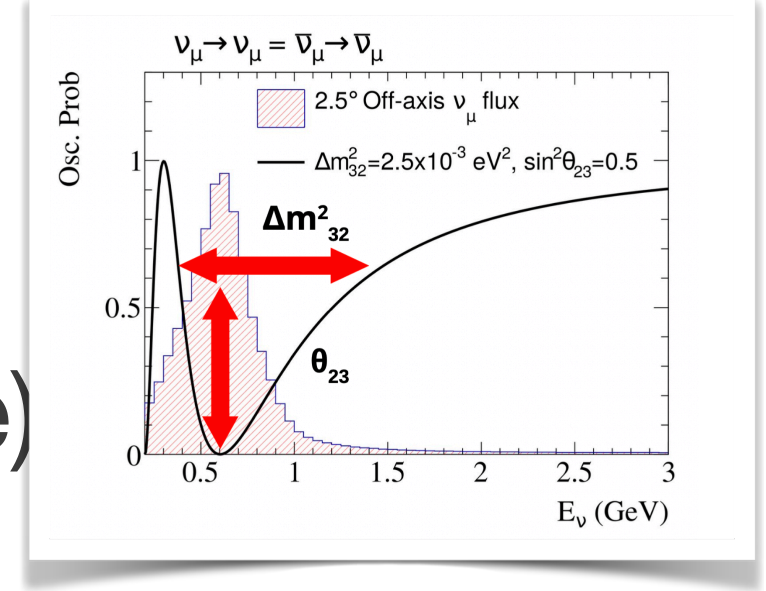
Atmospheric, Reactor, Solar

$$U = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

- ν's propagation over time depends on its energy, mass and distance travelled (since $t \approx L$) and PMNS mixing matrix parameters.

$$P(\nu_\alpha \to \nu_\beta) = |\langle\psi(\beta)|\psi(\alpha)\rangle|^2 = \left|\sum_j U^*_{\alpha j} U_{\beta j} e^{-i\frac{m_j^2 L}{2E}}\right|^2$$

- Experimentally, three types of environments w/ different E and L:
  - Solar - neutrinos are predominantly affected by 1 and 2 mass-eigenstates,
  - Atmospheric - neutrinos predominantly affected by 2 and 3 mass-eigenstates,
  - Reactor - neutrinos predominantly affected by 1 and 3 mass-eigenstates (and phase)



- In addition, Long-Baseline Neutrino Experiments are sensitive to $\theta_{13}, \theta_{23}, \delta_{CP}$.

Neutrino Mixing ⇒ Implications

- Neutrino oscillation ⇒neutrinos are massive.
- Vacuum oscillations depend on the mass splittings.
- Many questions:
  - Values of the oscillation parameters?
  - CP symmetry (is $\delta_{CP} = 0$?)?
    - Indications it is non-zero.
  - Ordering of the neutrino masses MO (i.e. sign of Δm^2_{32})?
  - Additional neutrino states?
    - Implications for New Physics.

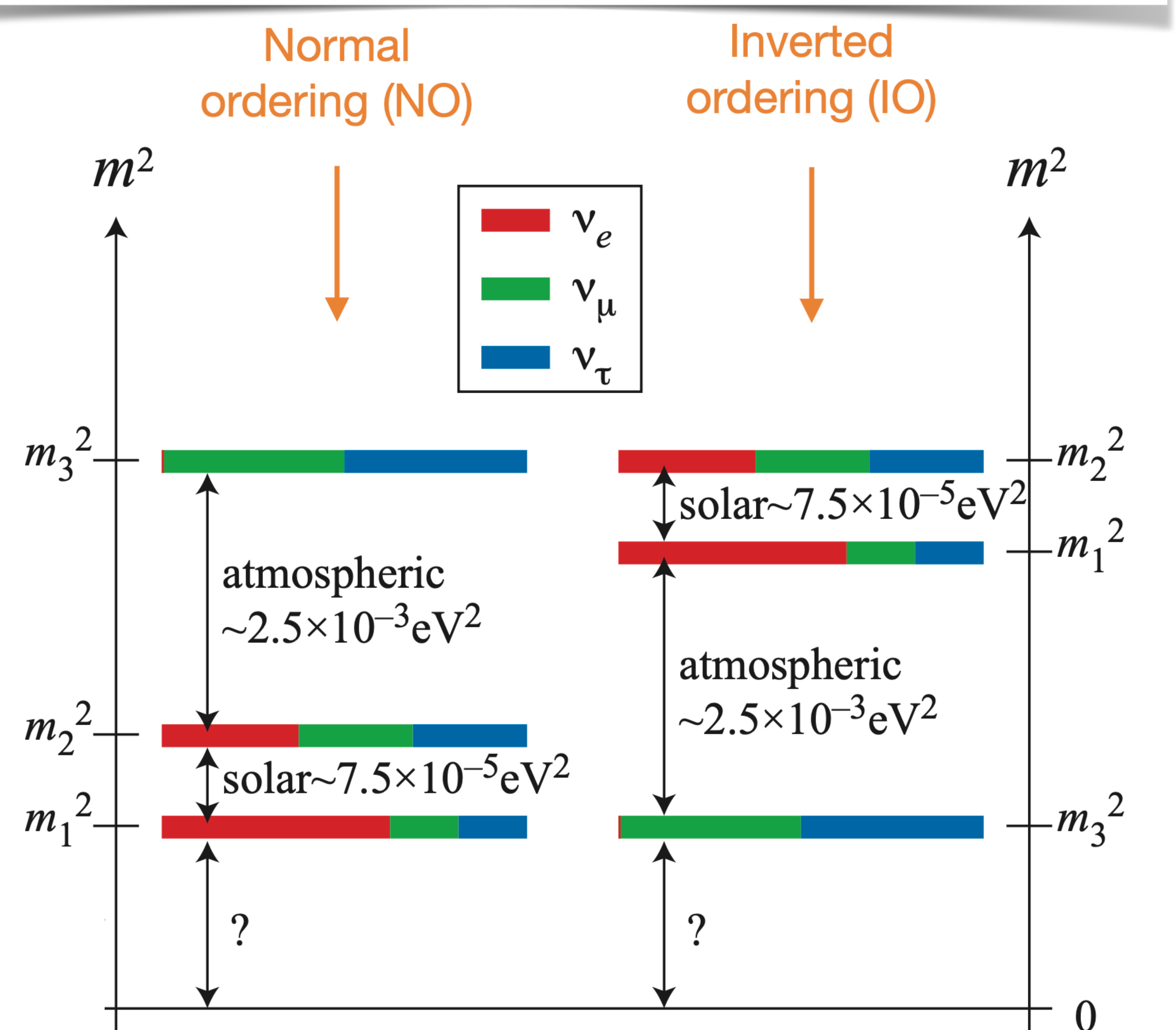
$$\sin^2\theta_{12}, \Delta m^2_{21}\ \sin^2\theta_{23}, \Delta m^2_{32}, \sin^2\theta_{13}$$

From PDG 2024

Parameter	Measurement	Precision
$\sin^2(\theta_{12})$	0.307 ± 0.013	4.2%
$\Delta\ m^2_{21}$	$(7.53 \pm 0.18) \times 10^{-5}\mathrm{eV}^2$	2.4%
$\sin^2(\theta_{23})$	$0.558^{+0.015}_{-0.021}$	3.2%
$\Delta\ m^2_{32}$	$(2.455 \pm 0.028) \times 10^{-3}\mathrm{eV}^2$	1.1%
$\sin^2(\theta_{13})$	0.0219 ± 0.0007	3.2%

All parameters are known to a few percent!

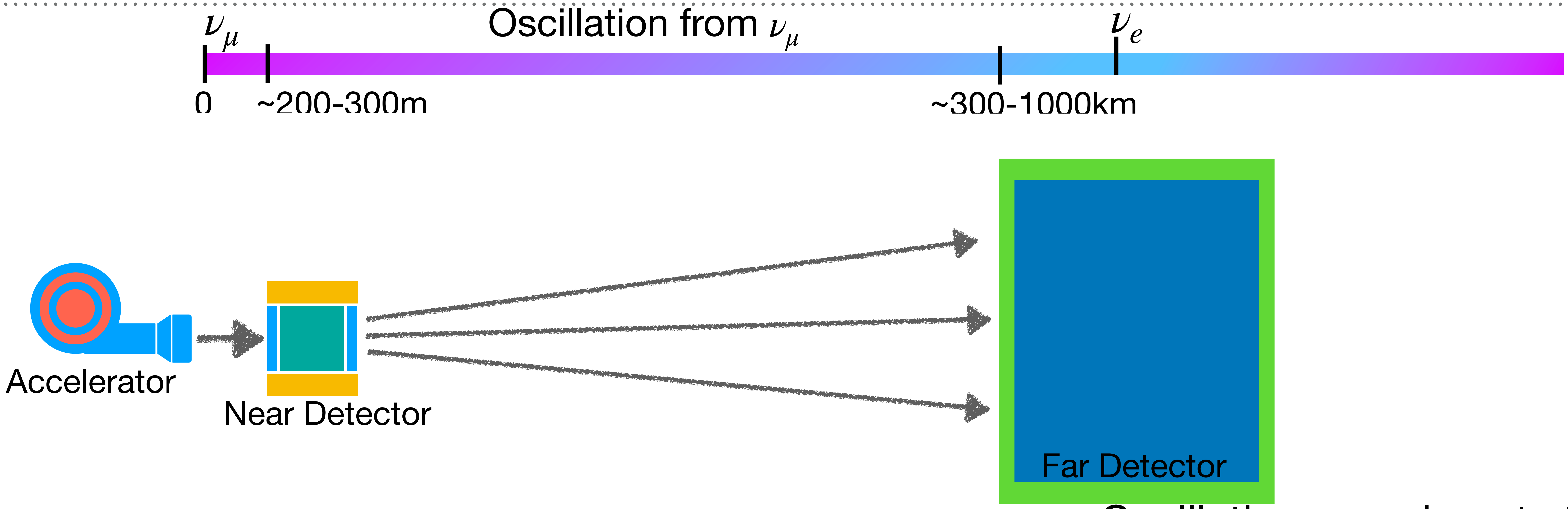
Better precision is needed: e.g. to determine the θ_{23} octant.



Credit: H. Murayama

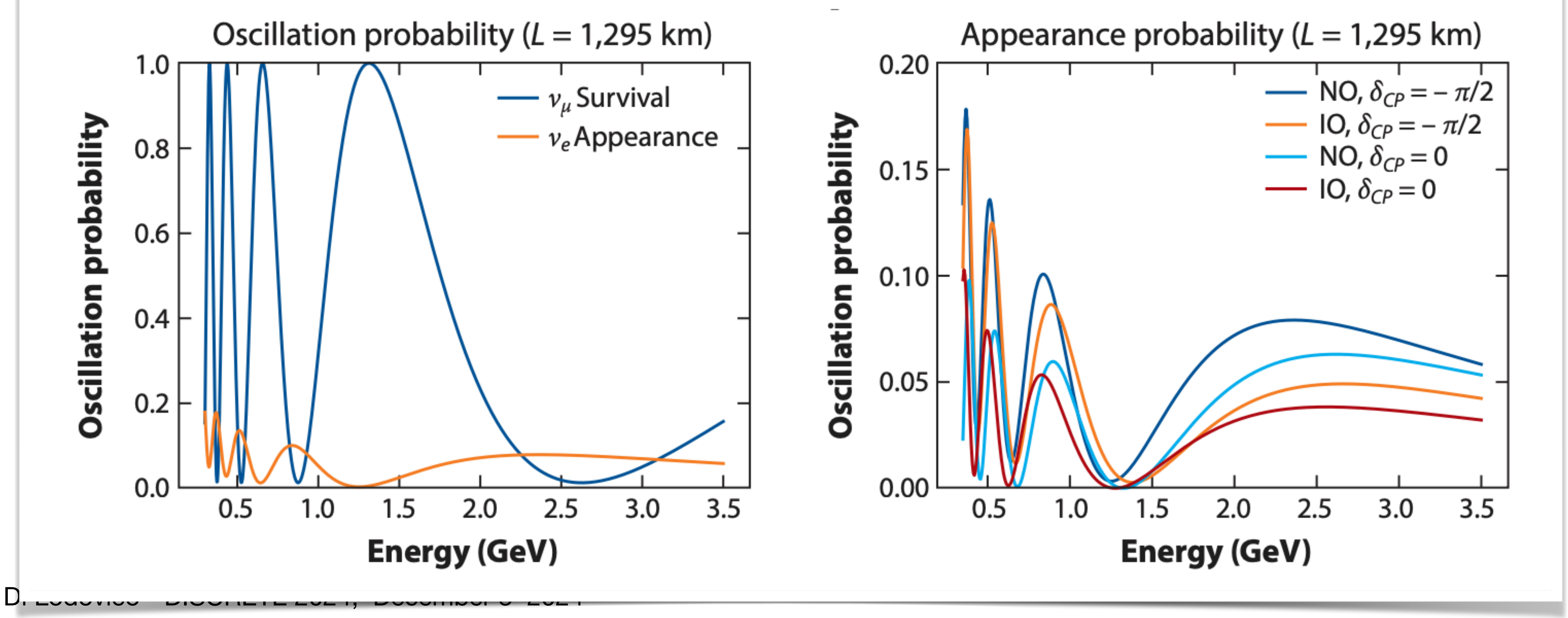
Matter interactions help to distinguish sign.

Neutrino Oscillation Experiments

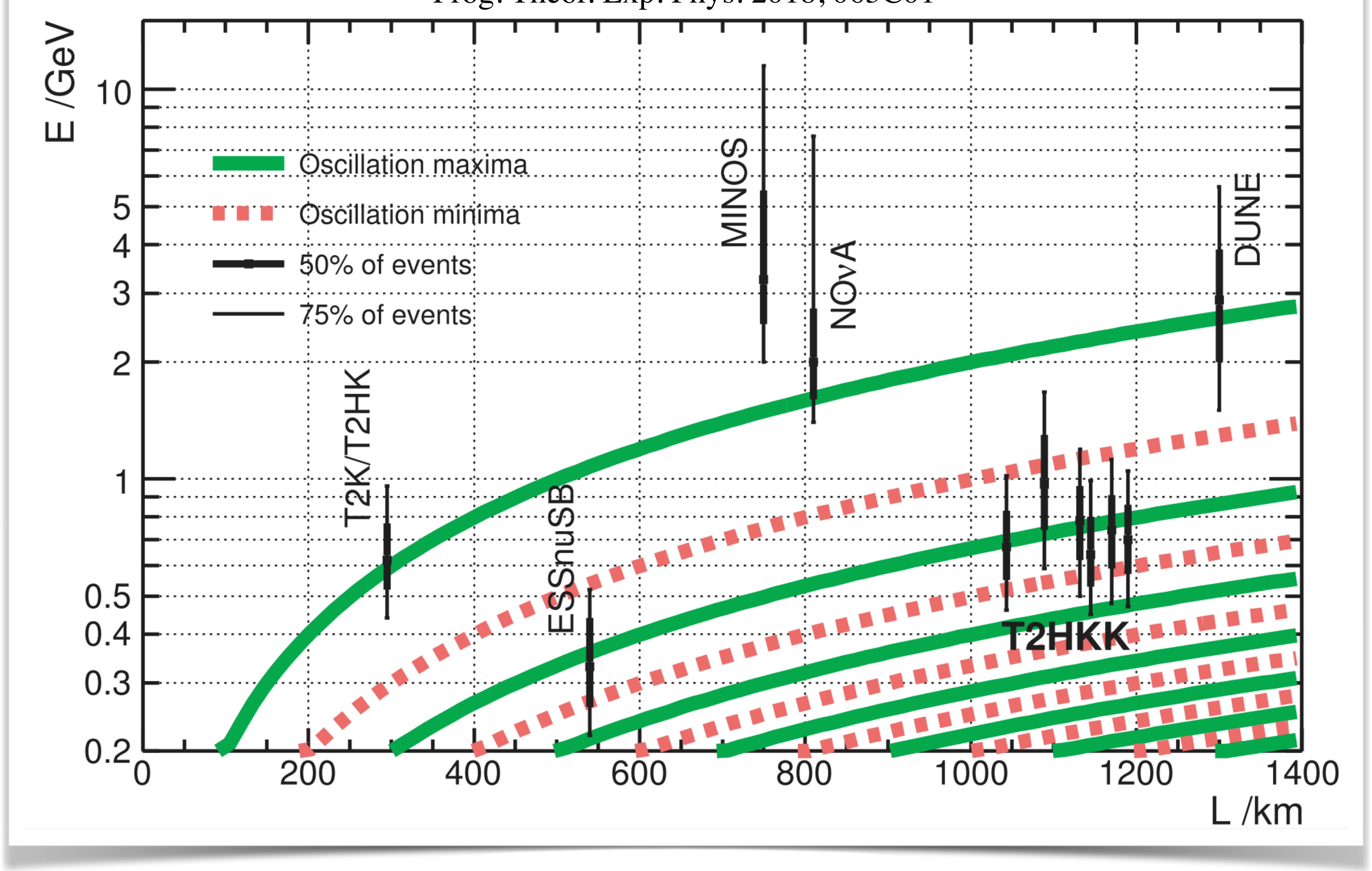


Oscillation experiments take advantage of oscillation maxima.

Annu. Rev. Nucl. Part. Sci. 2023. 73:69–93

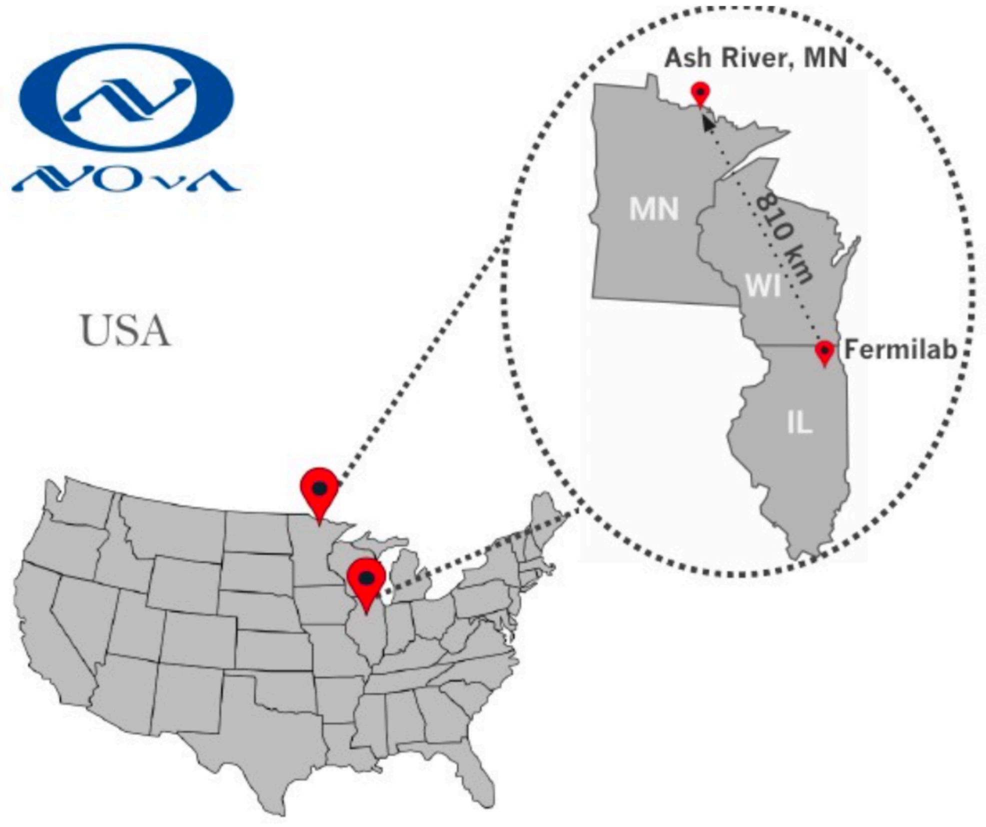


Prog. Theor. Exp. Phys. 2018, 063C01

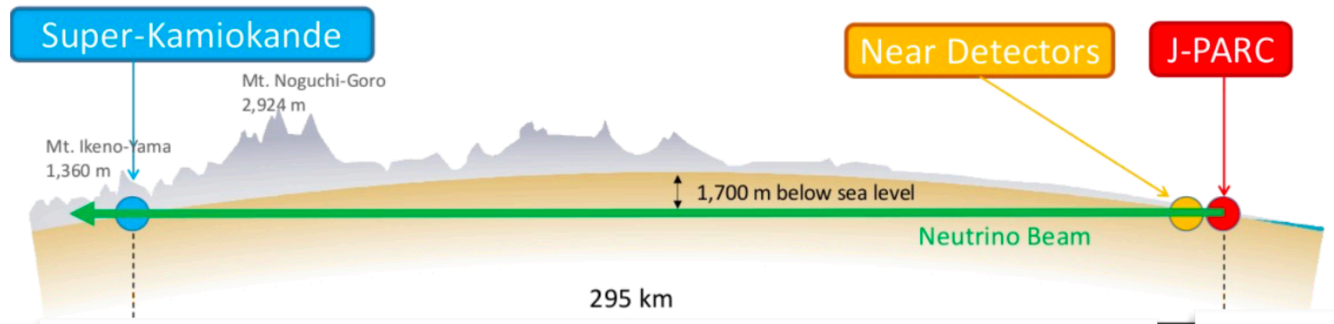


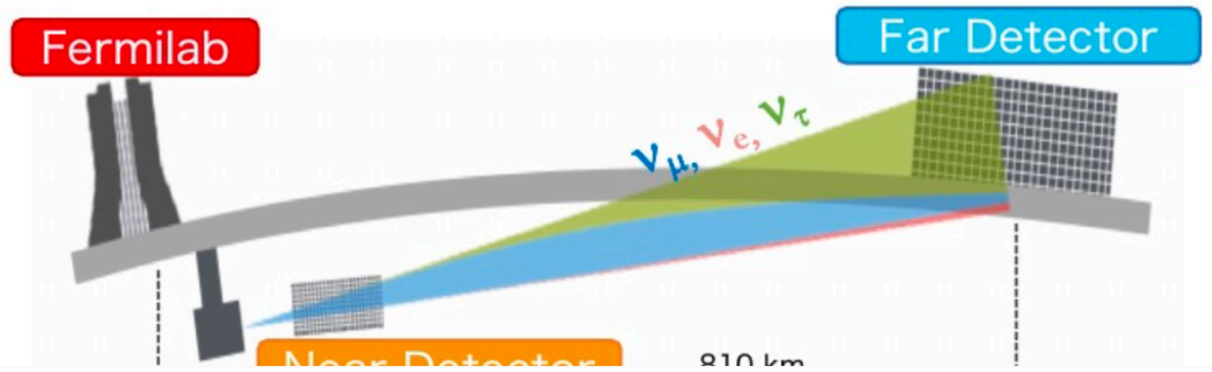
T2K and NOvA

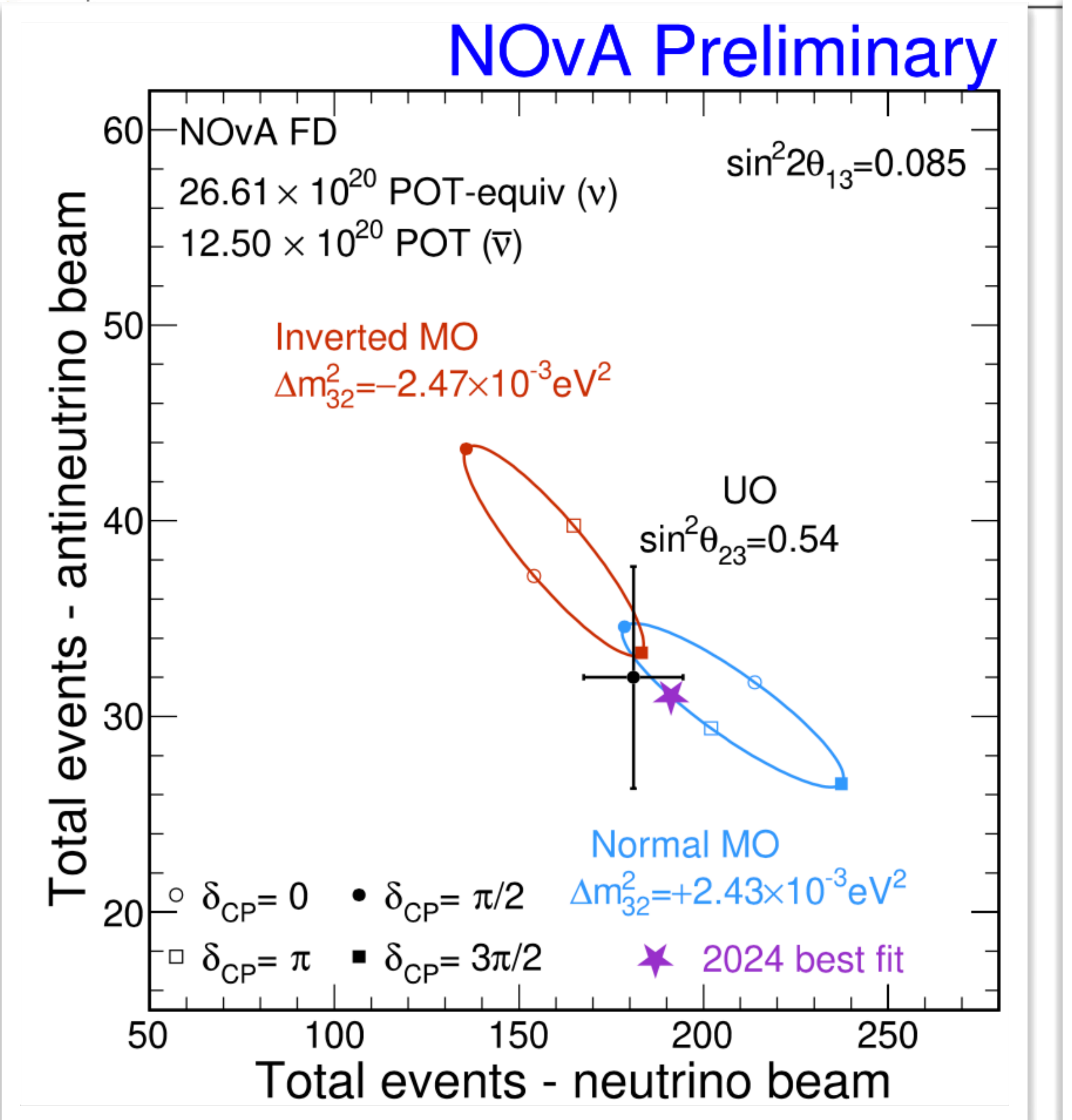
	T2K	NOvA
baseline	**295** km	**810** km
peak energy	**600** MeV	**2** GeV
CP effect	32%	22%
Matter effect	9%	29%

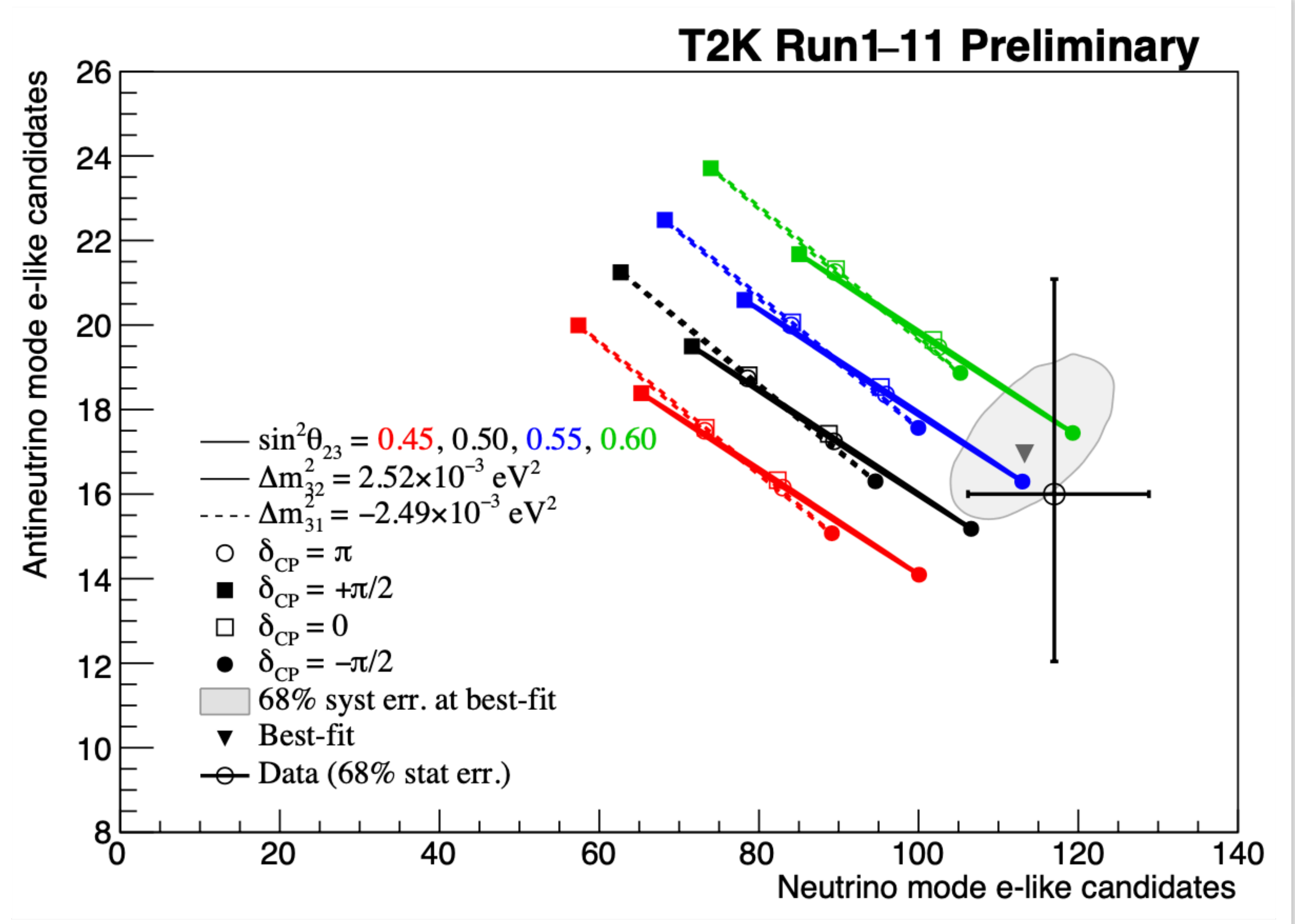


- Primary goals: $\sin^2\theta_{23}$, $\left|\Delta m^2_{32}\right|$, mass ordering, δ_{CP}, $\sin^2\theta_{13}$
- Use ν_μ (or $\overline{\nu}_\mu$) disappearance and ν_e (or $\overline{\nu}_e$) appearance.
- **NOvA** has better sensitivity to mass-ordering.
- **T2K** has better sensitivity to δ_{CP}.







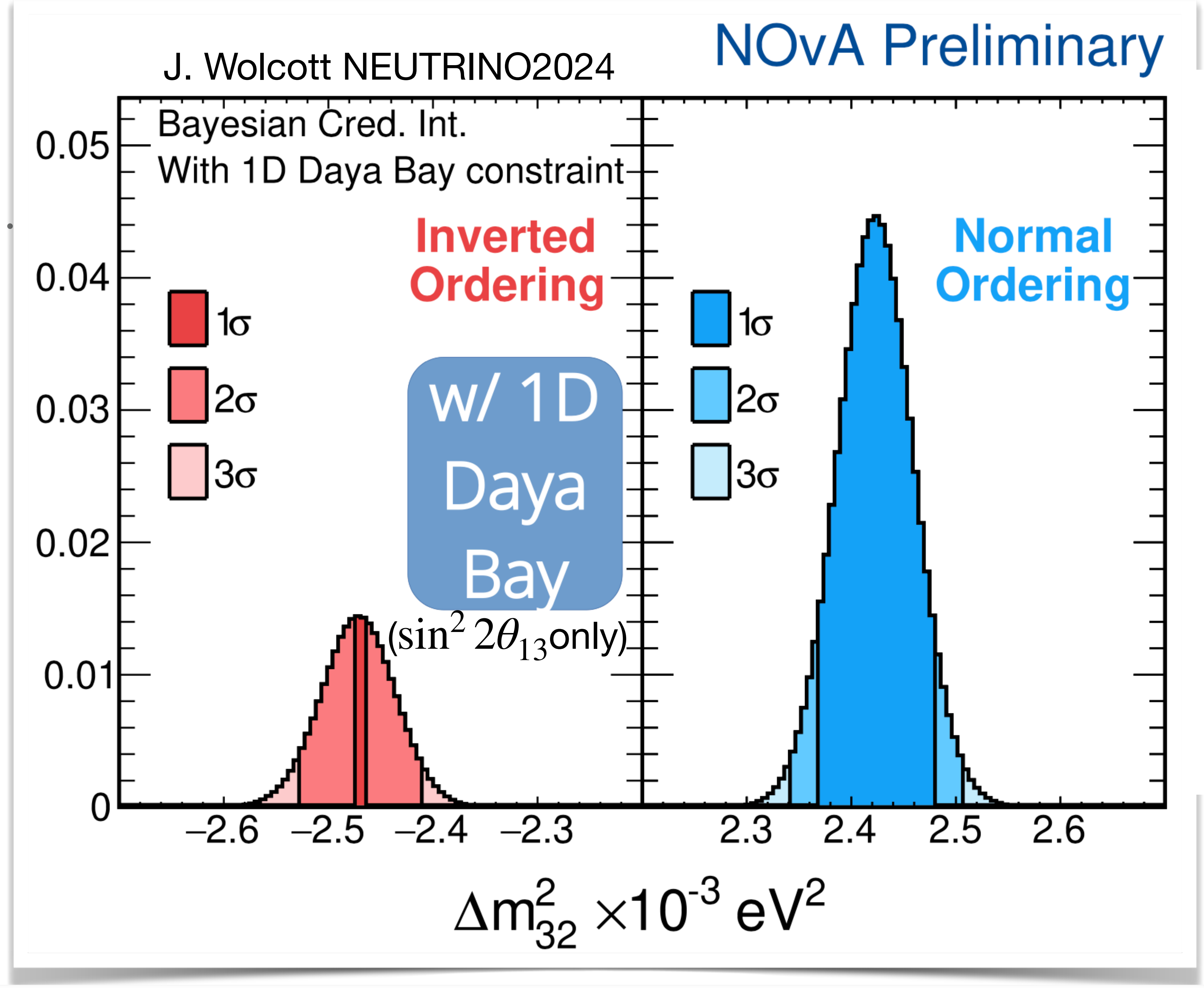


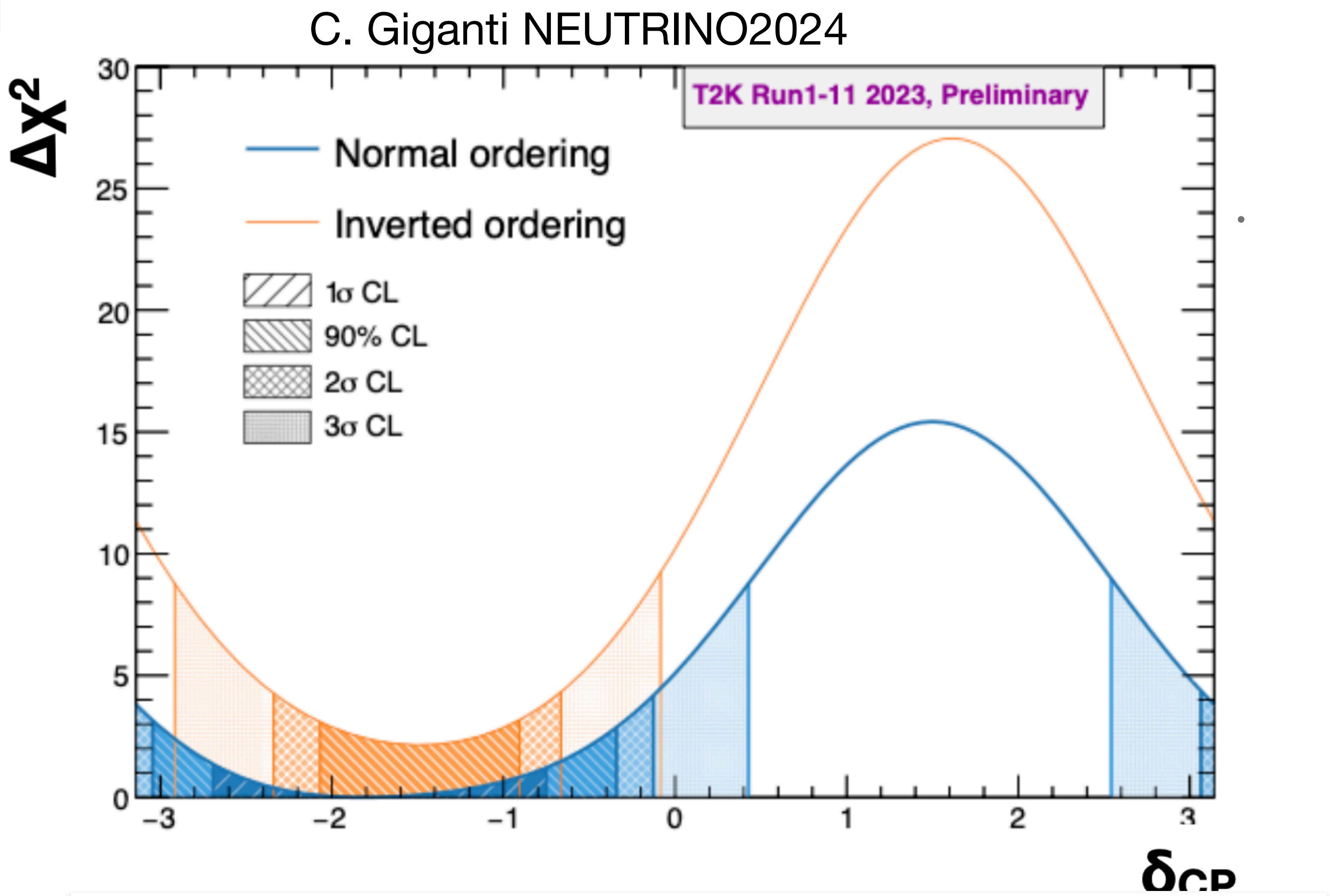
T2K and NOvA

- Both experiments have a slight preference for the upper octant of θ_{23} and the normal mass ordering (NO).

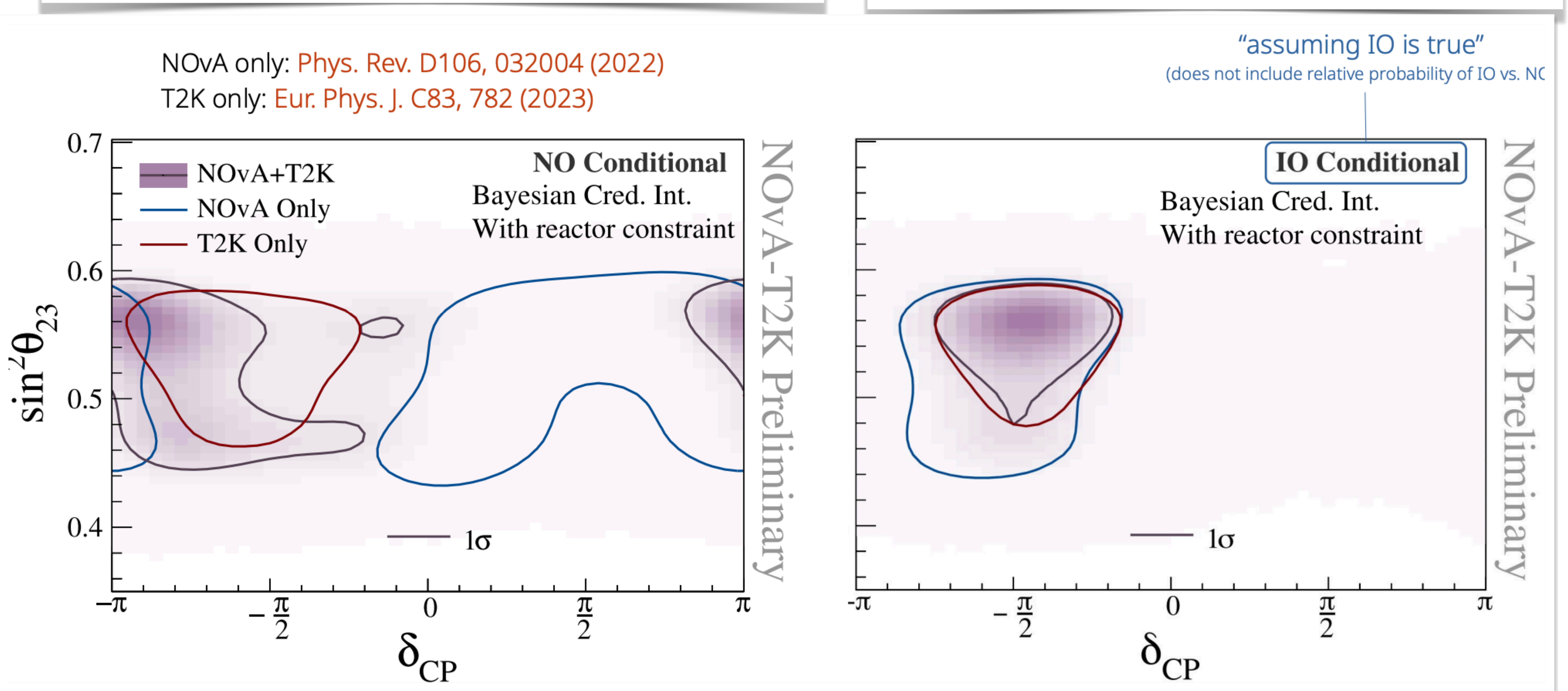
	NO preference Bayes Factor
NOvA-only	3.2
T2K-only	3.3

- But they prefer different regions of δ_{CP} in the NO case.
- First recently completed joint fit splits the difference in the NO case, improves constraint in IO case.





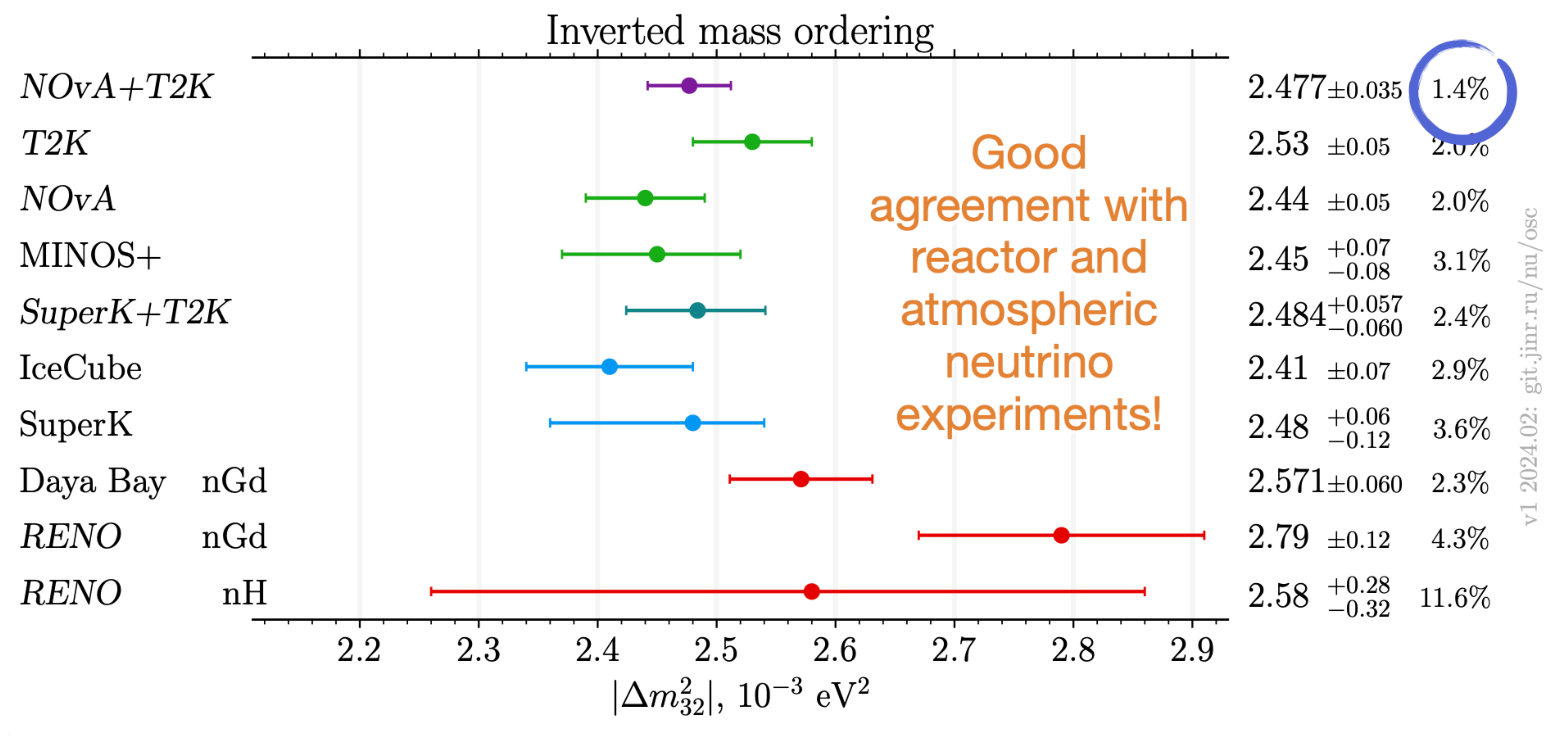
Preference for $\delta_{CP} \sim -\pi/2$ but CP conserving values are within the 2σ interval.



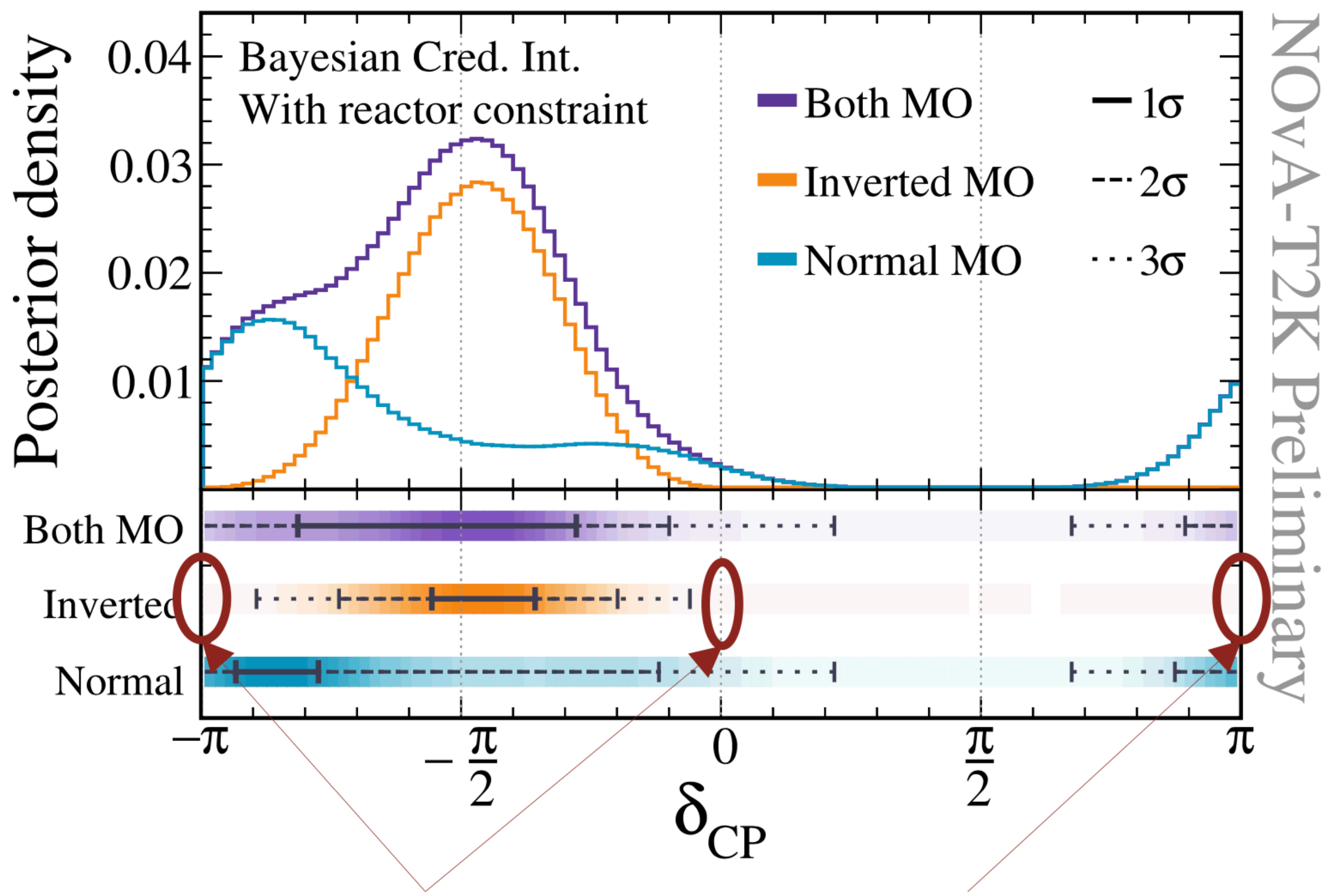
Joint Analysis Results

- Joint analysis of both experiments has fit both dataset successfully.
- Mild preference for Inverted Ordering but influenced by θ_{13} constraint.
- Advancing the precision frontier on $|\Delta m^2_{32}|$ <2% measurement!

NOvA+T2K only	NOvA+T2K + 1D θ_{13}	NOvA+T2K + 2D (θ_{13}, Δm^2_{32})
IO (71%)	IO (57%)	NO (59%)



Strongly favor CP violation in Inverted Ordering scenario

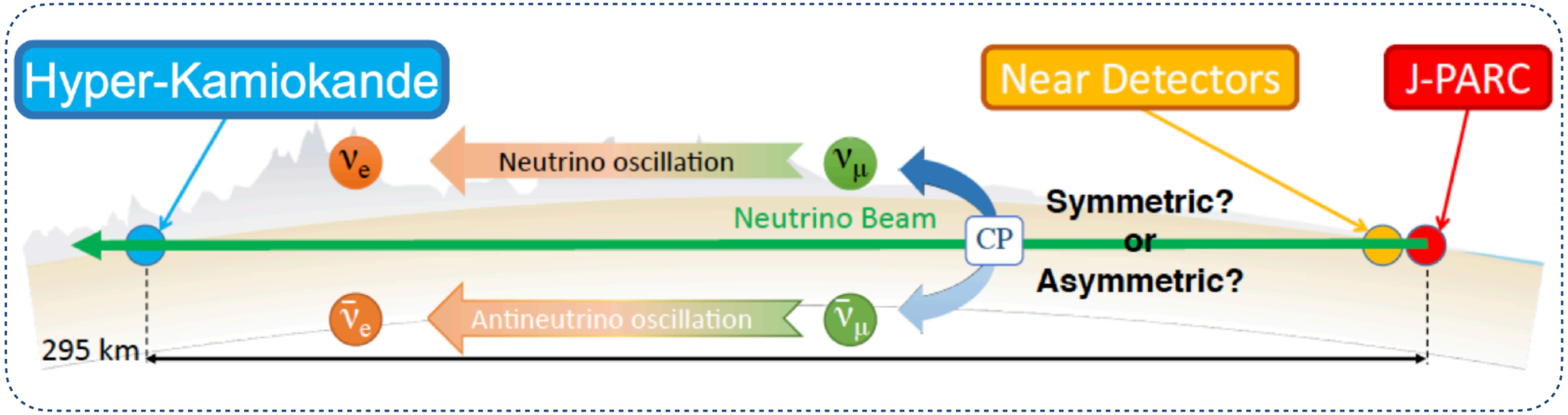


CP-conserving points are *outside* 3σ intervals in IO

Expect CPV *if* ordering is inverted

Hyper-Kamiokande and DUNE

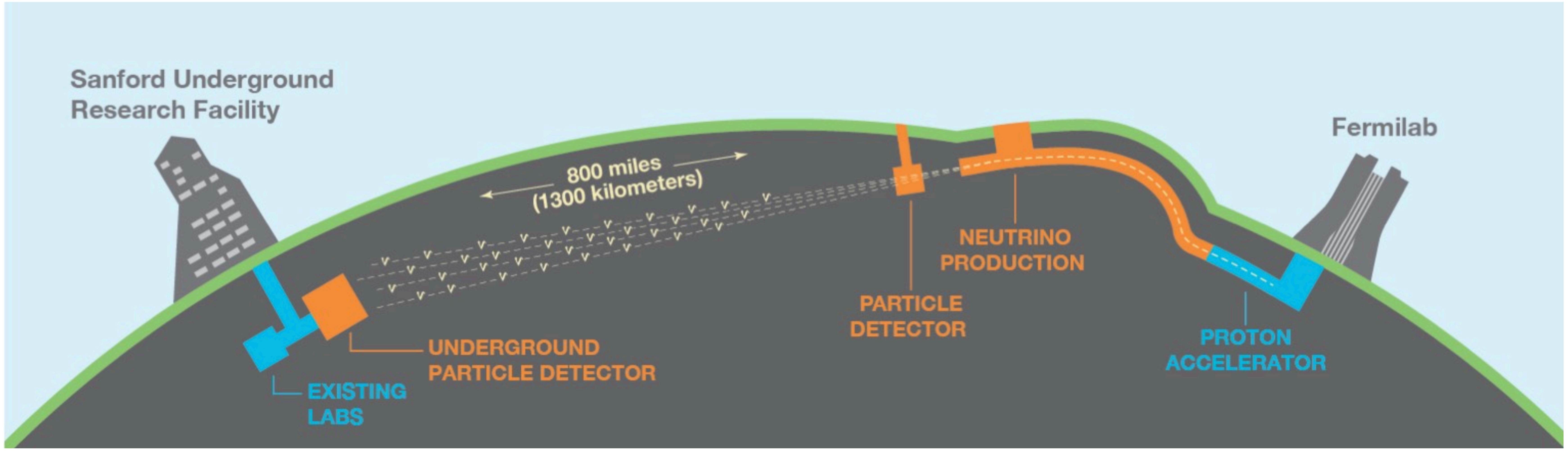
- Hyper-Kamiokande:
  - 1.3 MW beam
  - Water Cherenkov far detector
  - 190 kton far detector fiducial mass
  - Completion detector by 2027, physics thereafter.



Large degree of complementarity:

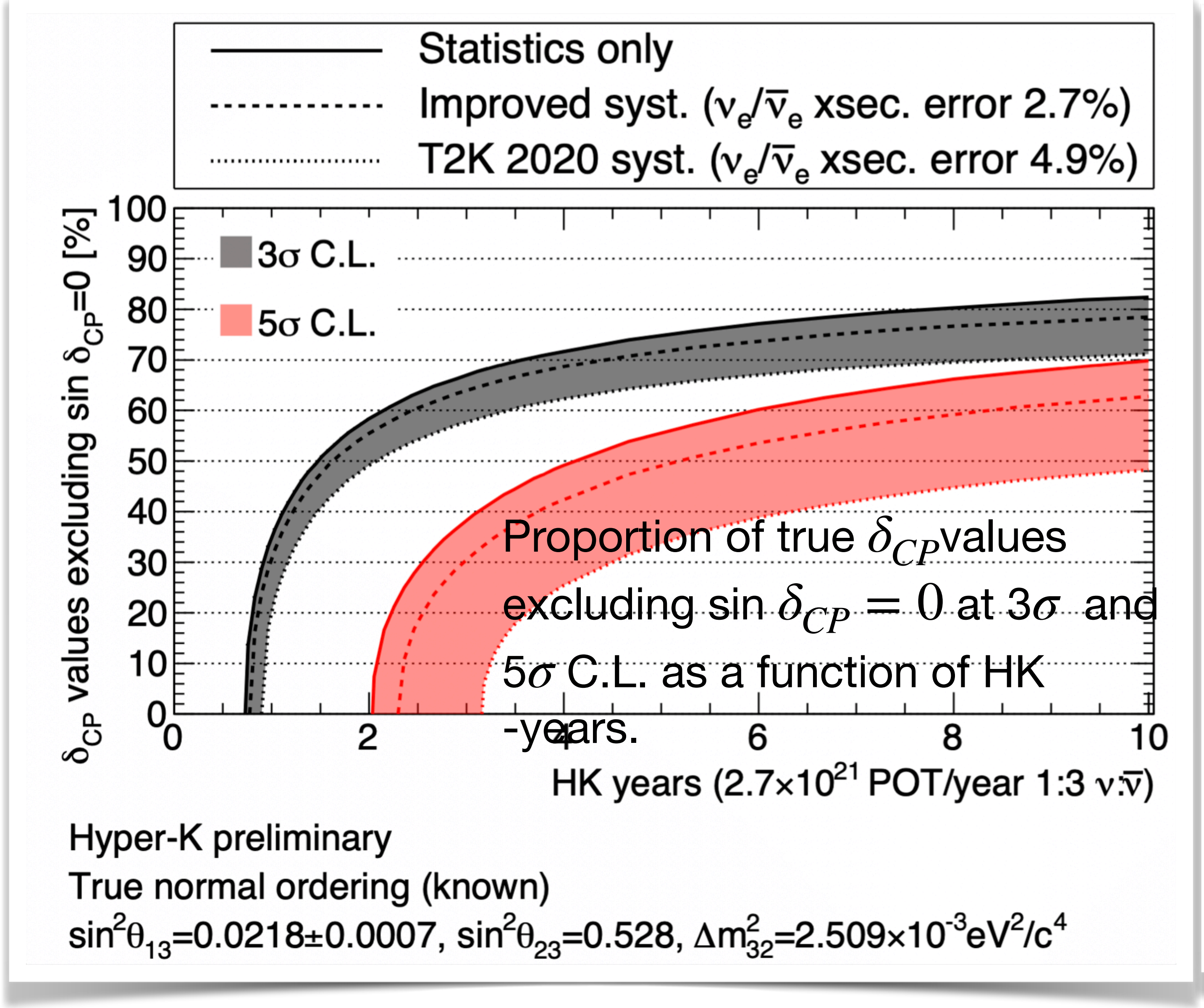
	matter effects	energy spectrum	detection systematics
Hyper-Kamiokande	Small	Narrow band, lower energy	Water Cherenkov Detector
DUNE	Large	Wide band, higher energy	LAr TPC

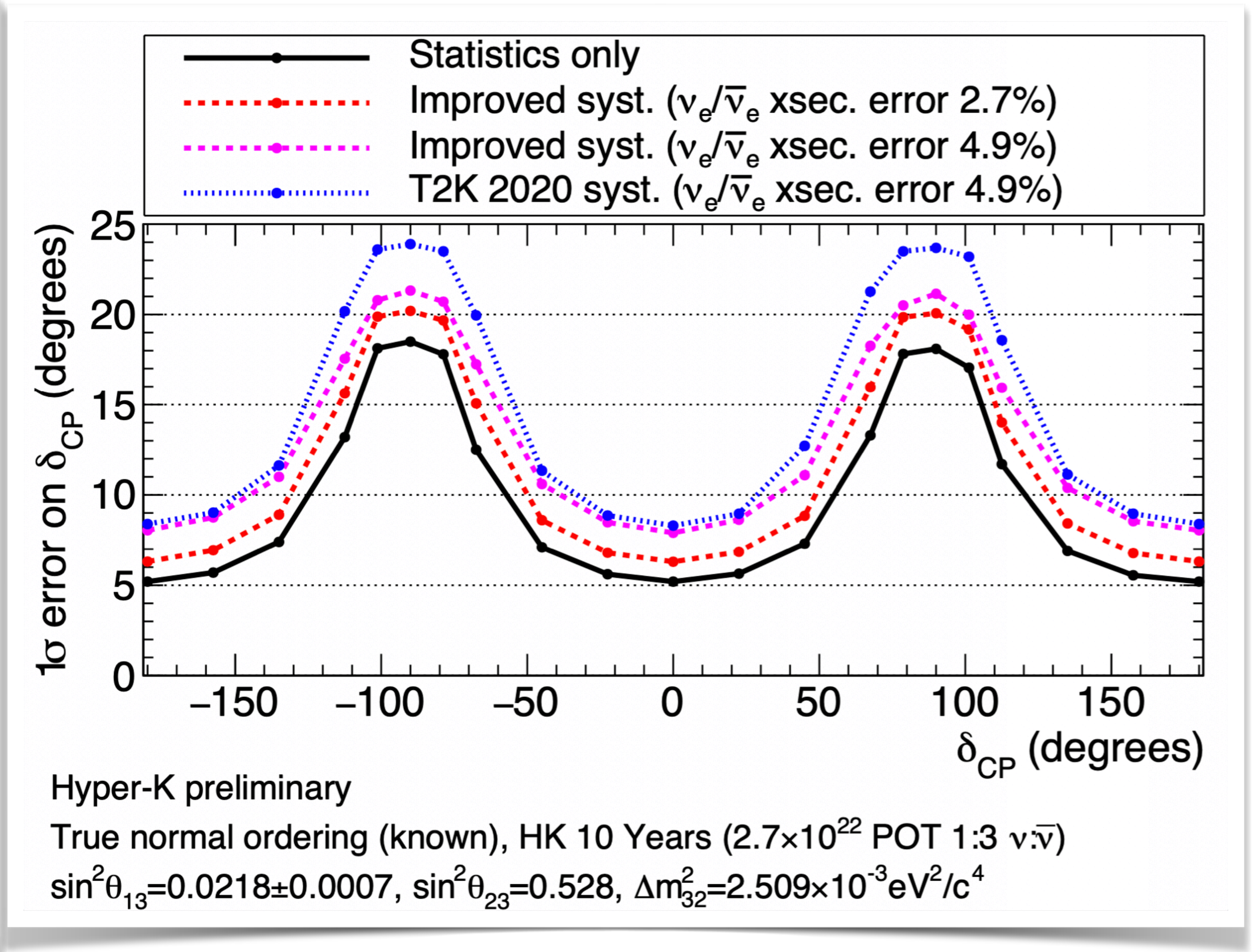
- DUNE:
  - Beam:
    - 1.2 MW Phase I - first 6 y
    - 2.3 MW Phase II - after 6 y
  - Liquid-Argon TimeProjection Chamber (LArTPC) technology
  - Far detector fiducial mass
    - 2 FD (10kton/each) - Phase I
    - 4 FD (10kton/each) - Phase II
  - First physics in 2029.



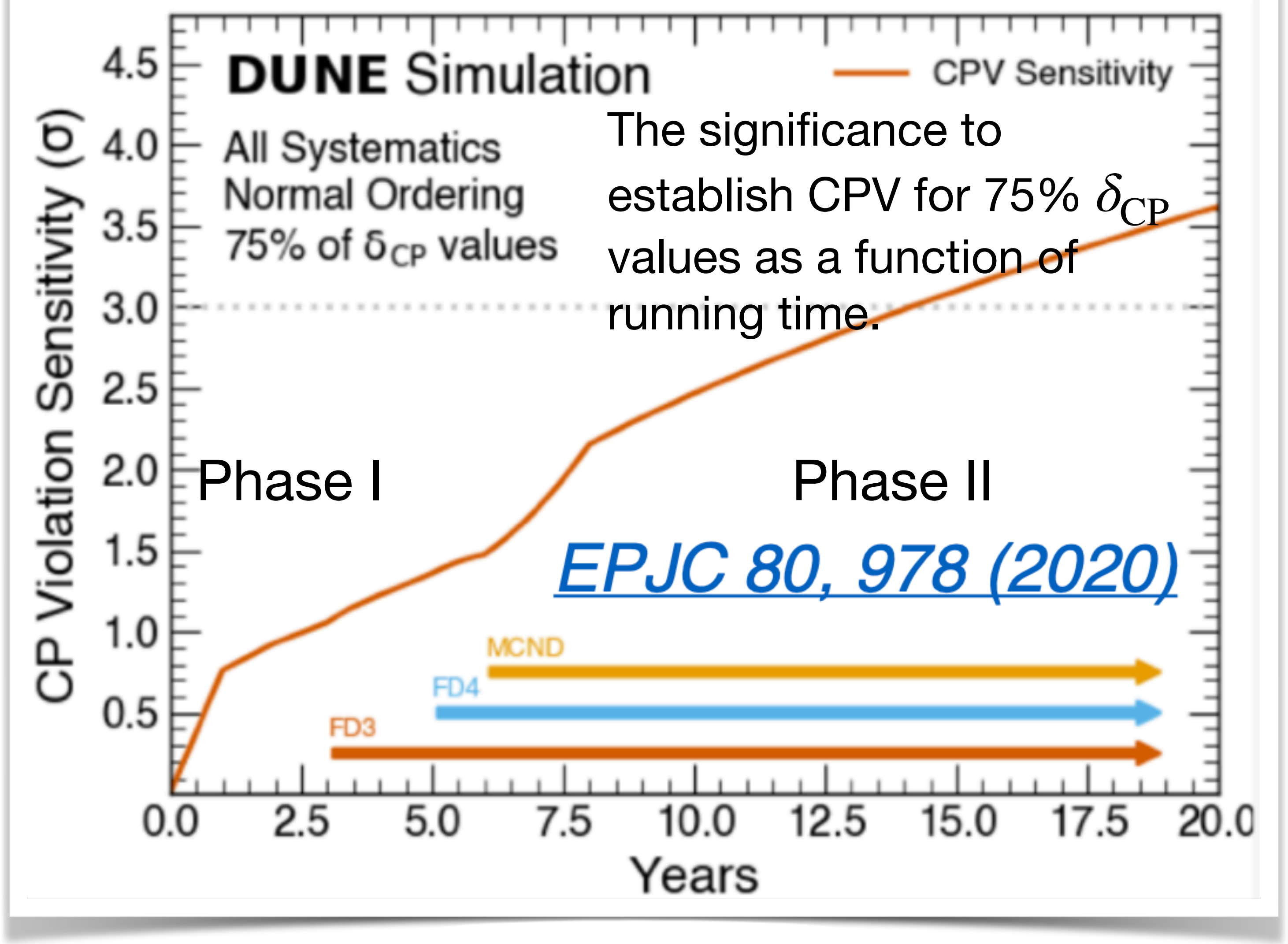
Hyper-Kamiokande and DUNE

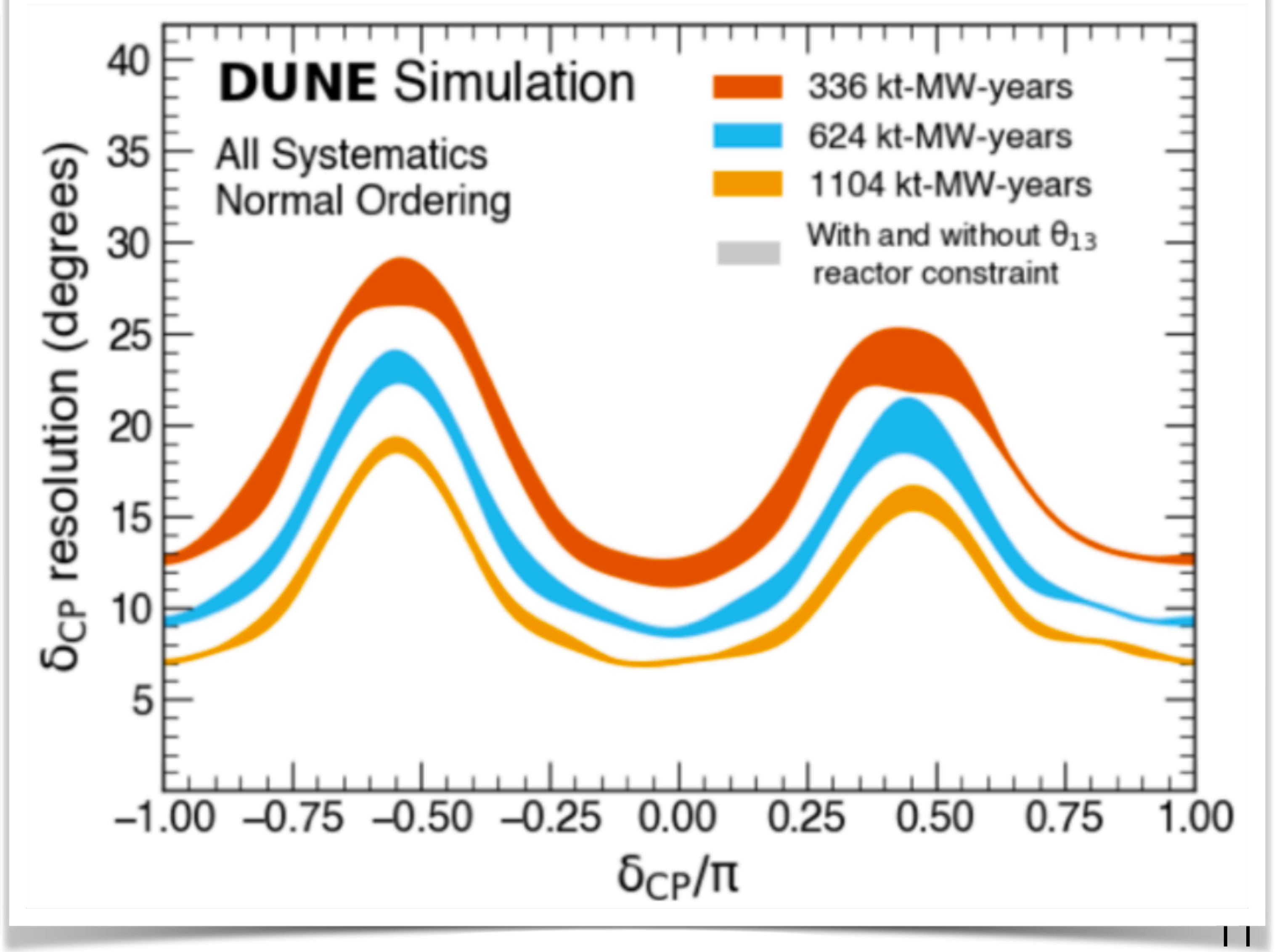
- Mass ordering:
  - Hyper-Kamiokande: from atmospherics+beam fit. Up to 6y for 5σ. arXiv:1805.04163v2 [physics.ins-det]
  - DUNE: 1 and 3 years to reach 5σ.
- Oscillation parameters:
  - Long term high precision for Δm^2_{31} and θ_{13} sensitive to ν_e physics in comparison with reactor measurements.
- CP violation:
  - Long term establishment of CP violation at 3σ over 75% of δ_{CP} values.
  - Similar 10-year precision of $\sim 6-18^\circ$ in δ_{cp} in both experiments.





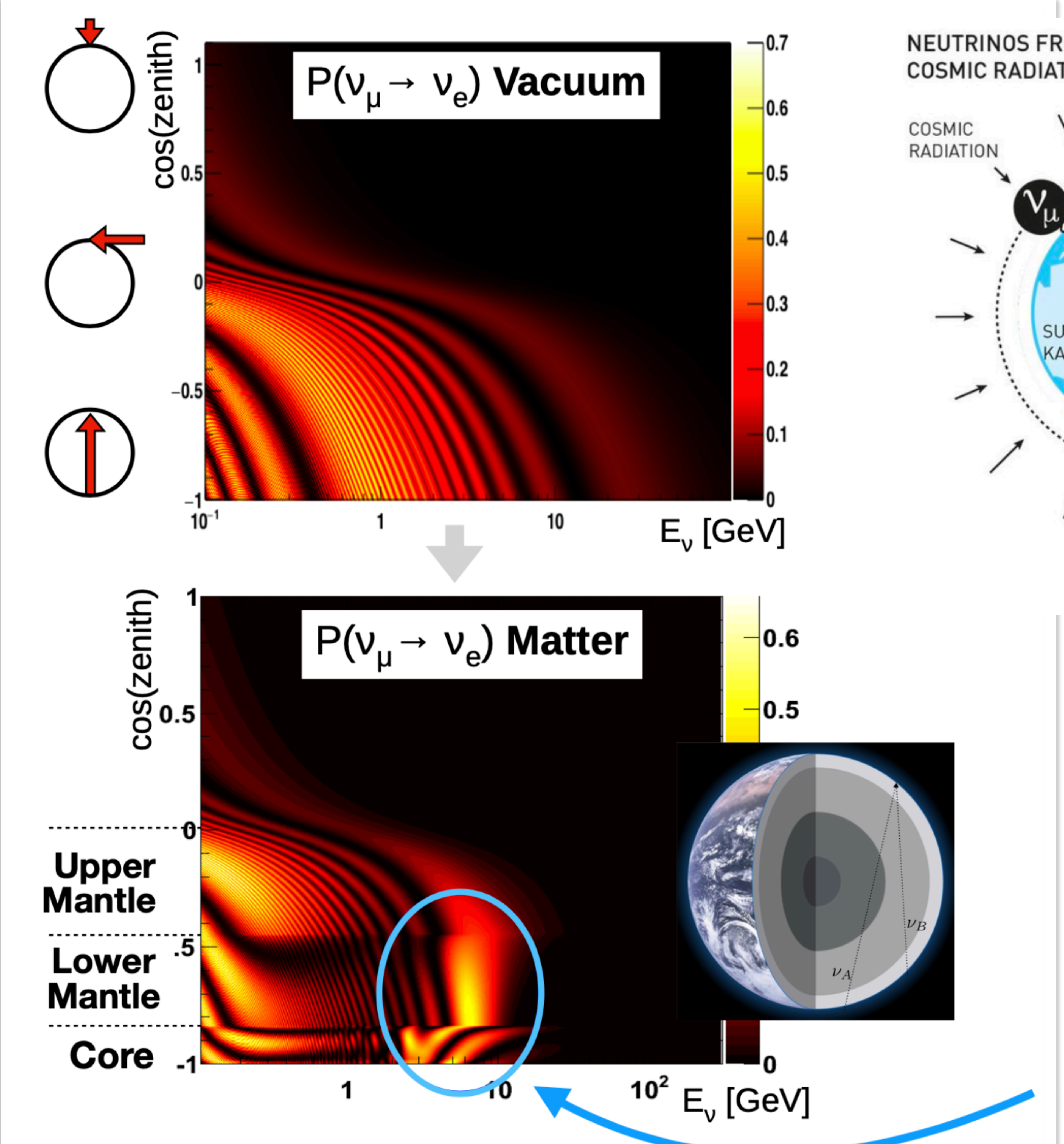
arXiv:2408.12725v1 [physics.ins-det] 22 Aug 2024



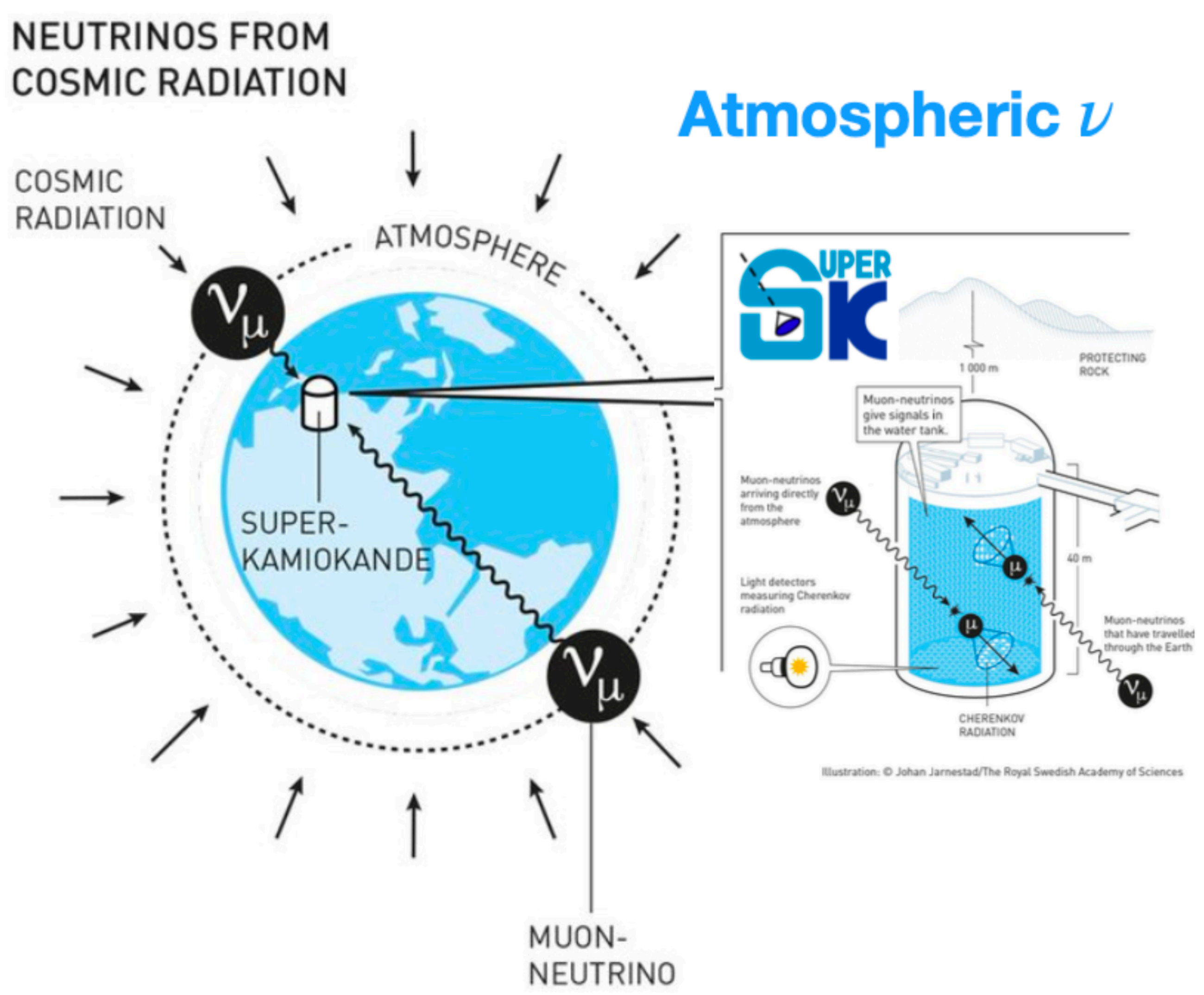


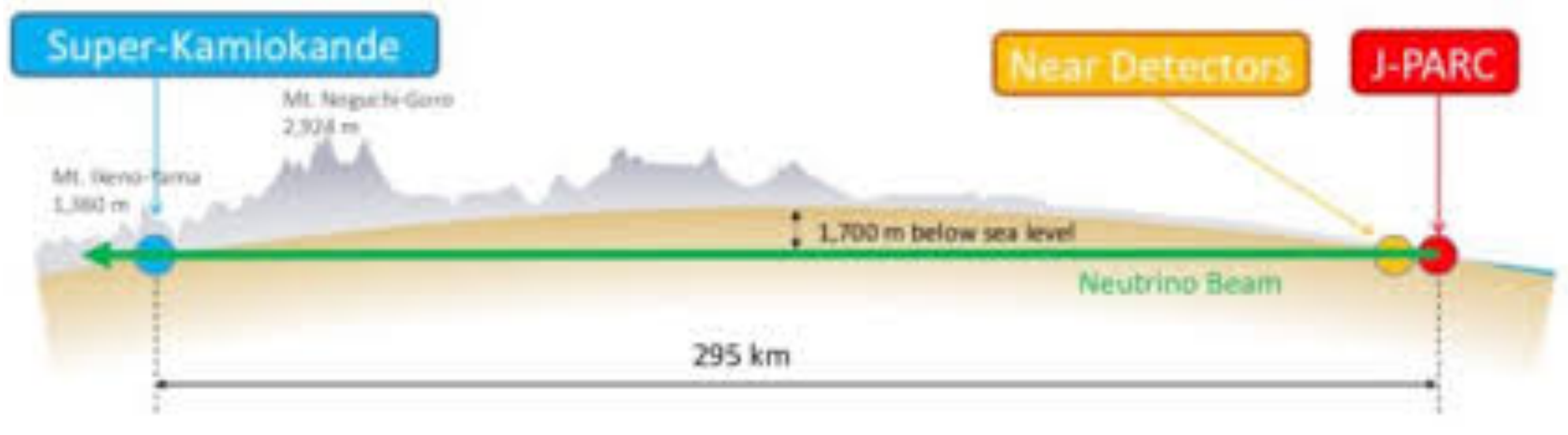
Next-to-next generation experiment (ESSνSB) using 5MW European Spallation Neutron Source proton linac being developed: EPJST 231, 3779-3955 (2022).

Super-Kamiokande and T2K



Oscillograms from:
C. Bronner for SK collaboration, at ICTP Advanced Workshop on Physics of Atmospheric Neutrinos 2018





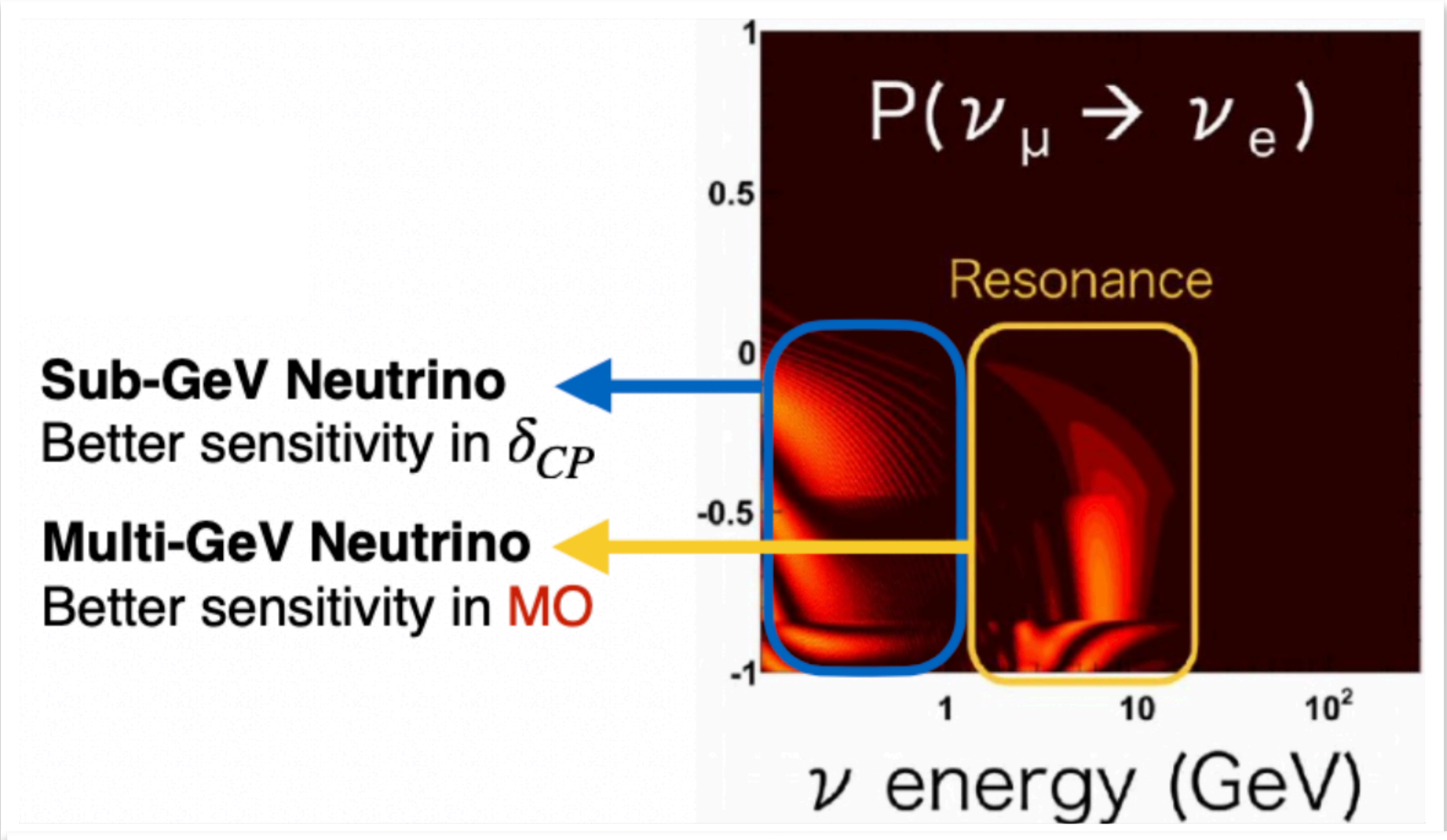
- SK has stronger discrimination of the mass ordering thanks to the presence of a resonance driven by θ_{13}-induced matter effects between 2 and 10 GeV.
- Only for ν in NO; only for $\bar{\nu}$ in IO.
- Size of the effect depends on $\sin^2\theta_{23}$ → sensitive to θ_{23} octant.
- Some sensitivity to δ_{CP} from sub-GeV e-like events.
- SK is sensitive to the mass ordering and breaks the T2K δ_{CP} degeneracy in joint fits.

SK (atmospherics) +T2K (Accelerator)

Motivation for a joint fit: :

- SK helps to break the degeneracy between δ_{CP} and mass ordering in T2K.
- T2K can constrain $\sin^2\theta_{23}$ better → improve the mass ordering sensitivity in SK.

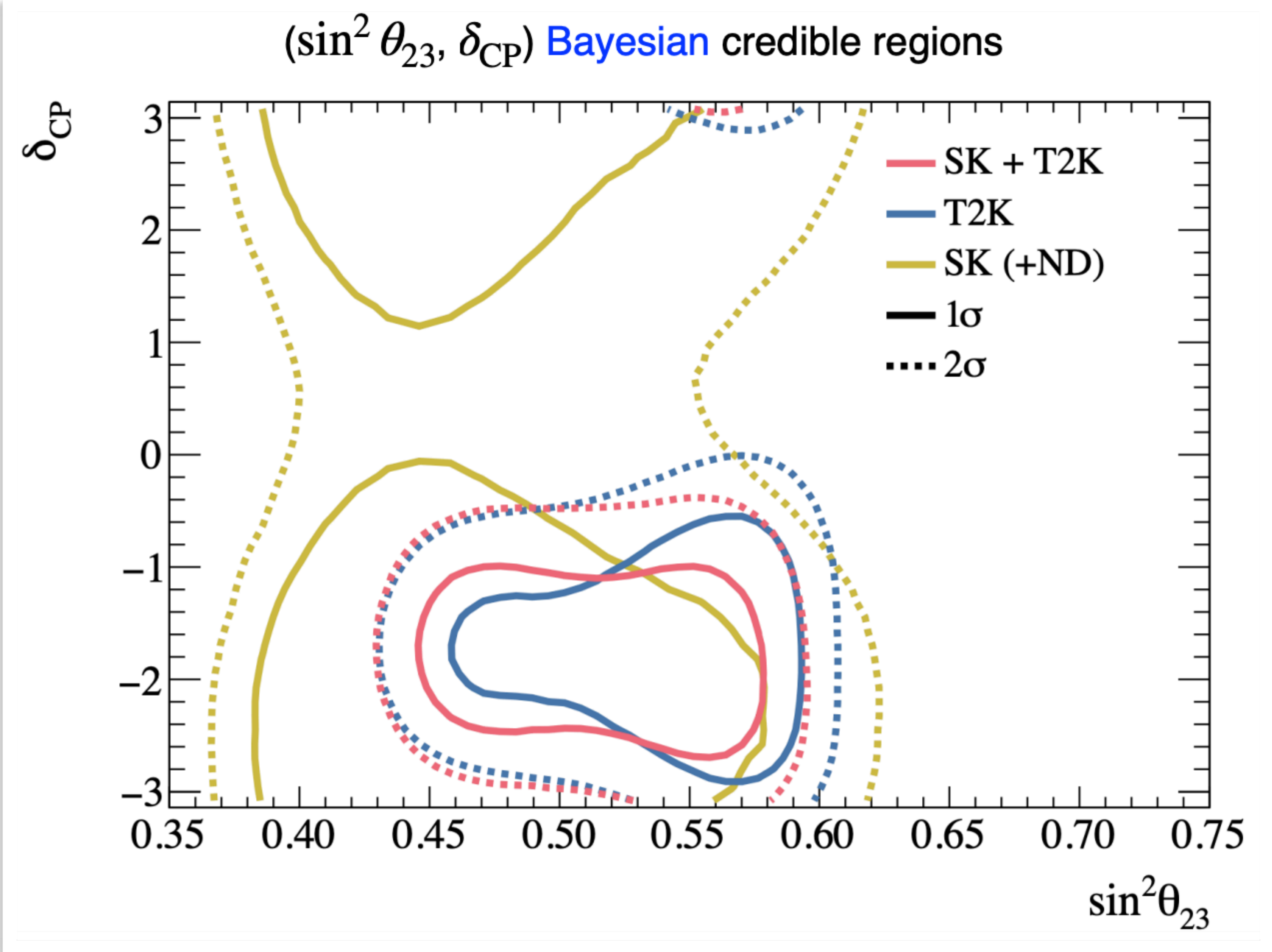
T2K near detector can be used to constrain the cross-section uncertainties for the low-energy atmospheric samples.

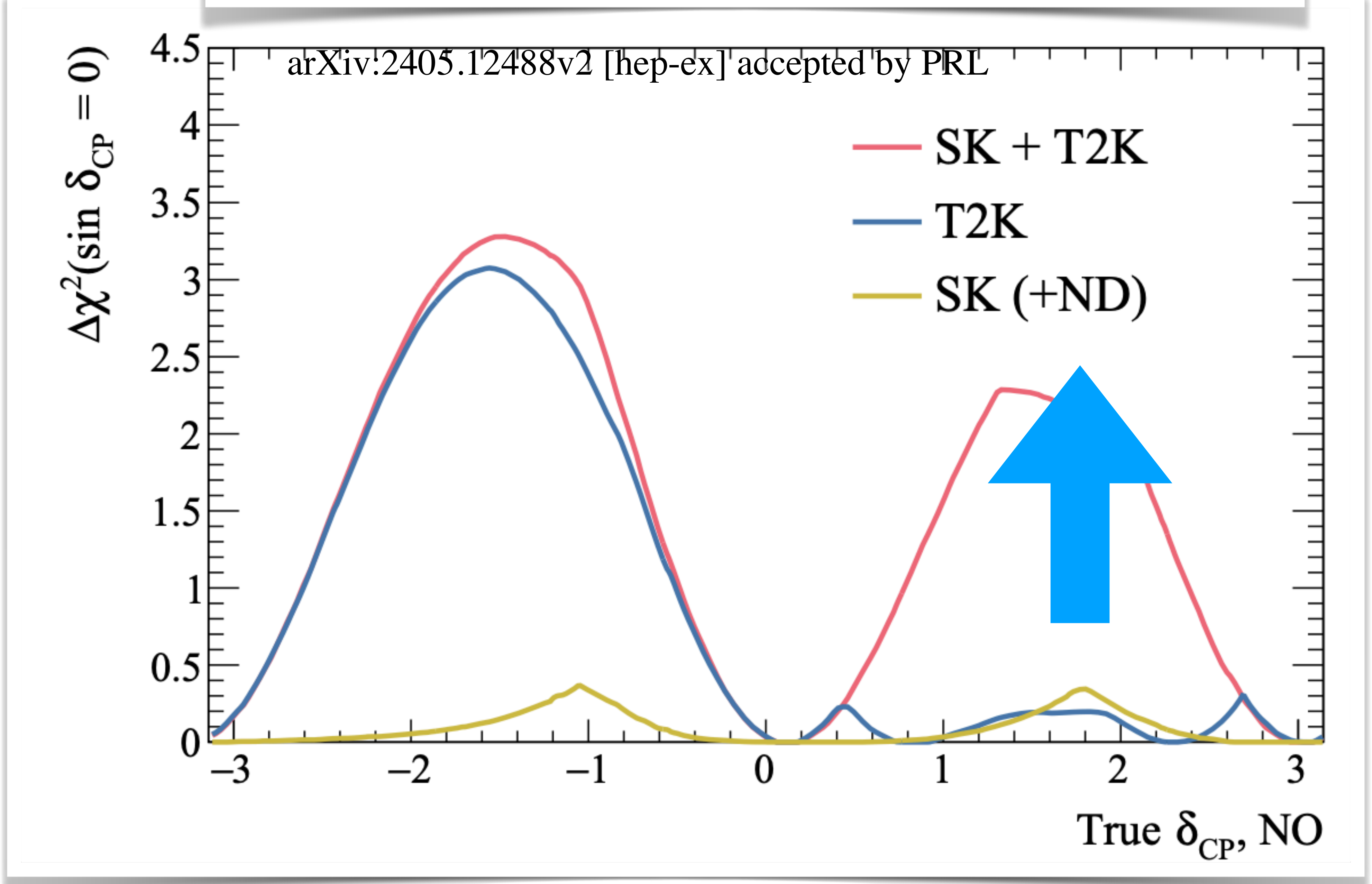


Sensitivity to reject the CP-conserving hypothesis for different true values of δ_{CP} assuming the normal MO.

Results:

- A limited rejection of IO at 90% C.L.
- CP-conservation ($J_{CP} = 0$) rejected at slightly below 2σ.
- No preference on the θ_{23} octant.

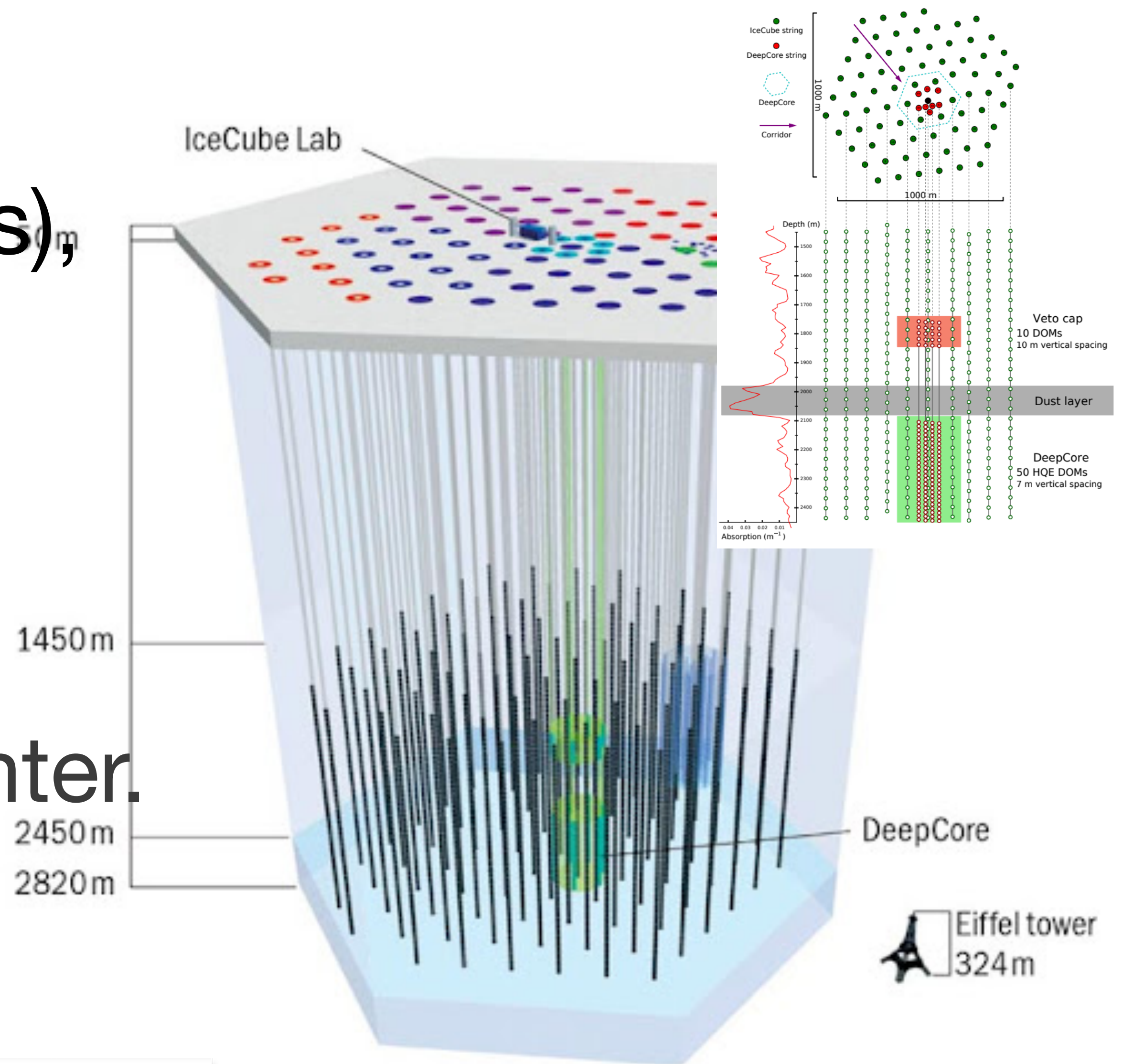


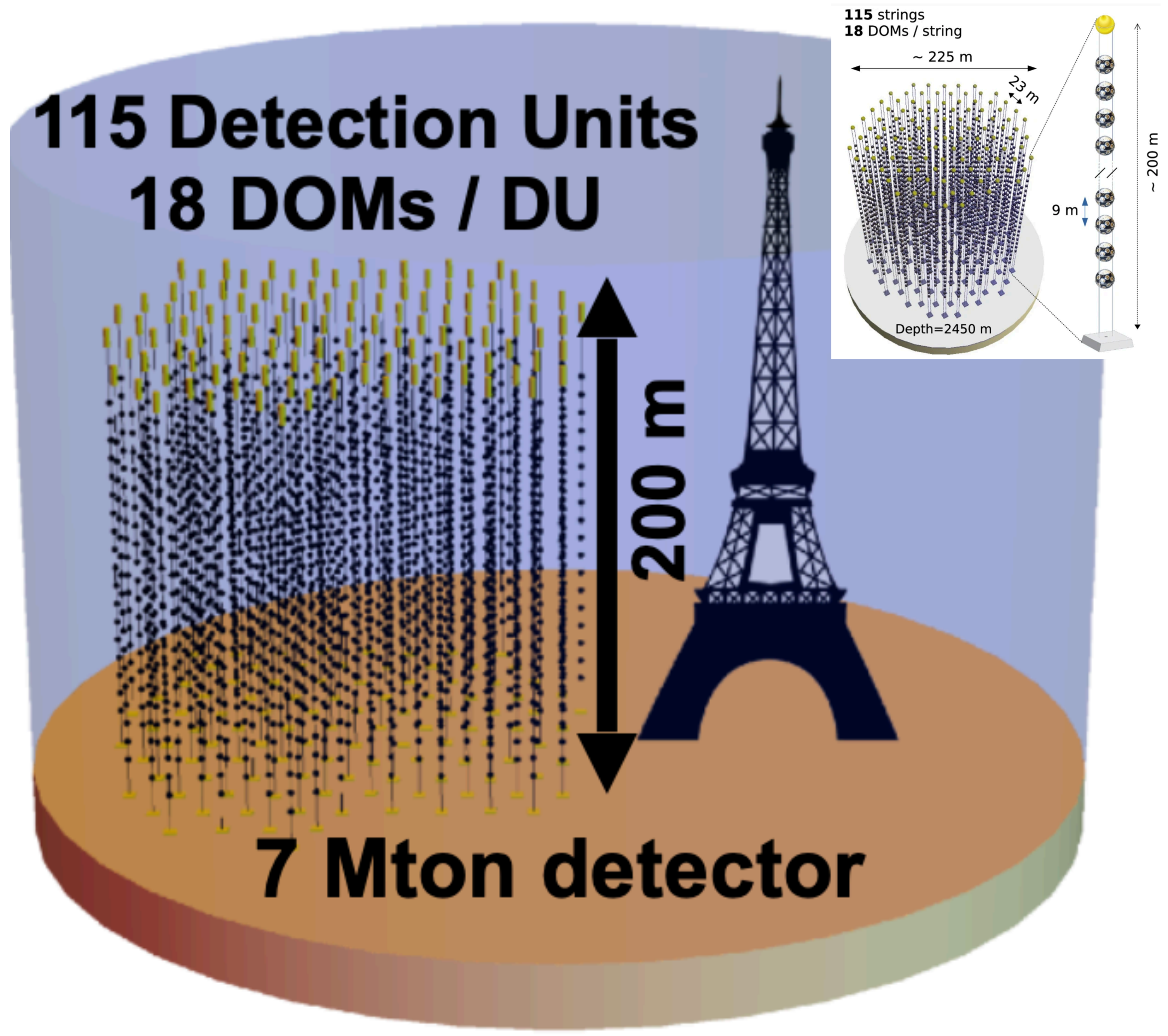


Icecube and KM3NET/ORCA

IceCube: ~$1\ \text{km}^3$ of ice instrumented with strings of Digital Optical Modules (DOMs), each with a PMT. ~100 GeV energy threshold.

- DeepCore: densely instrumented region at the center. ~10 GeV energy threshold.

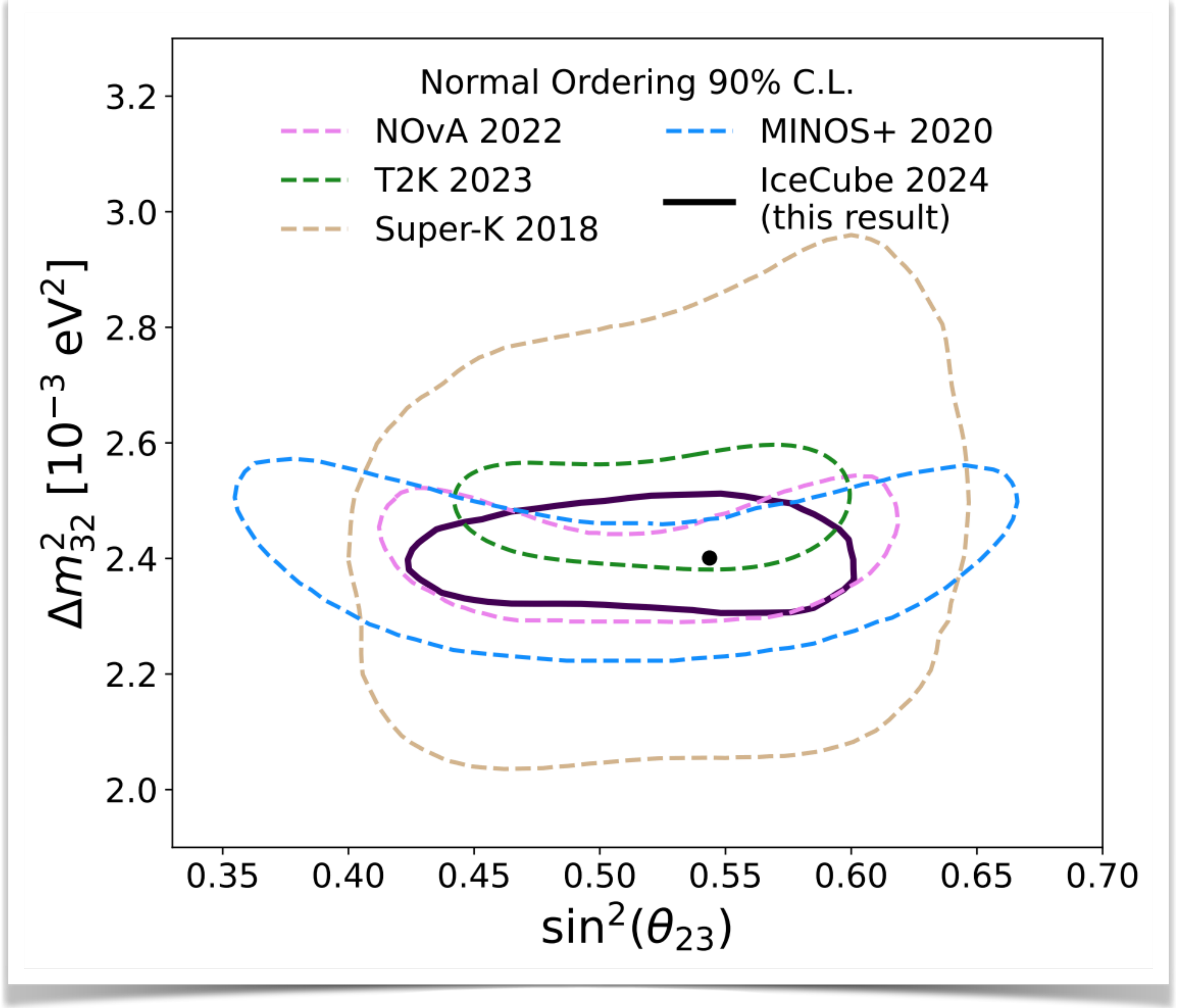




KM3NeT/ORCA:

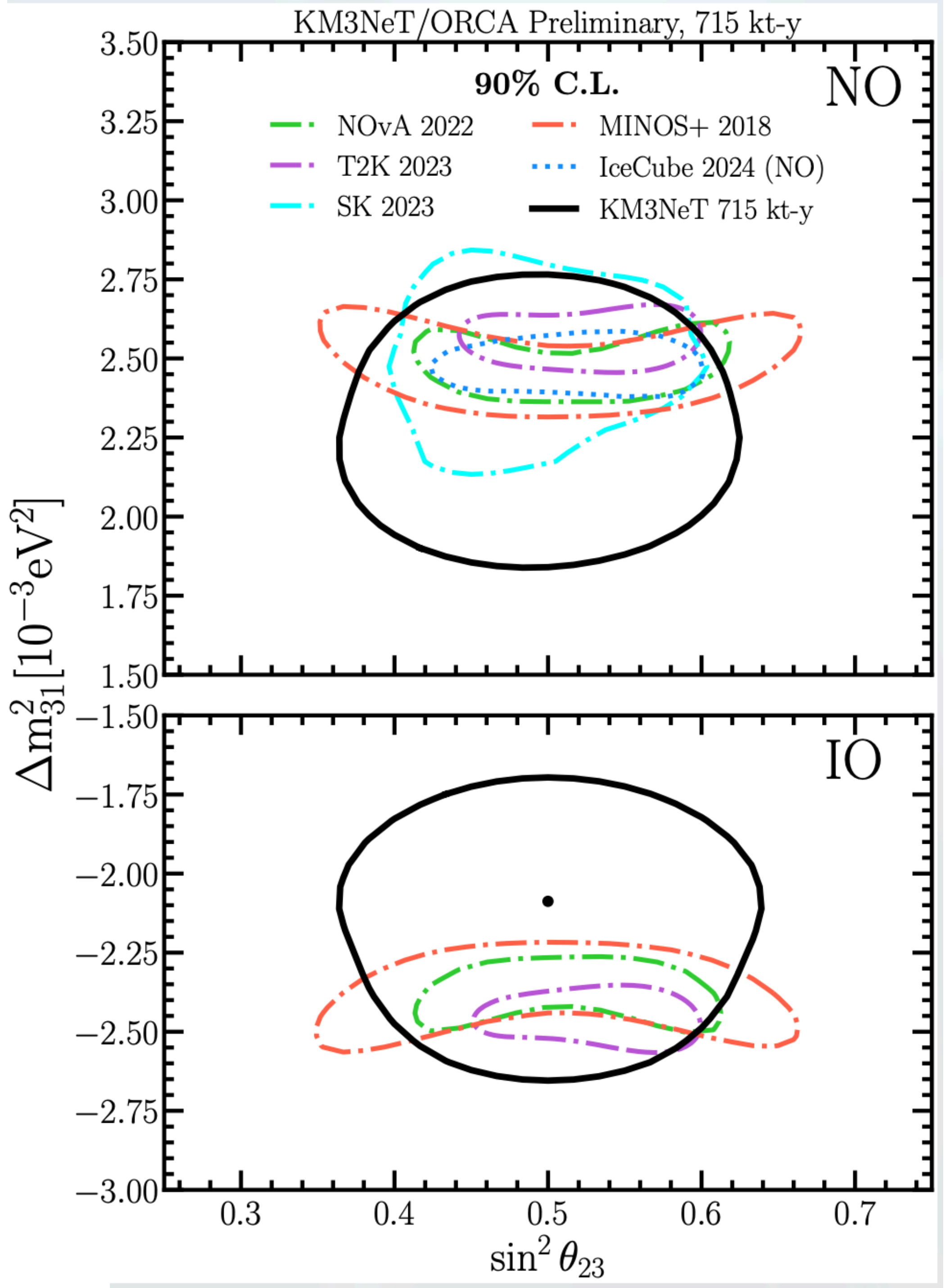
- 115 strings optimised for neutrino oscillation measurements.
- Each DOM has 31 3-inch PMTs
- About 20% of DOMs already installed.
- ORCA optimised to detect atm ν in the 1-100 GeV range

arXiv:2405.02163v1 [hep-ex]



- Oscillation results with 9.3 years of DeepCore data.
- Slight preference for NO with current results.

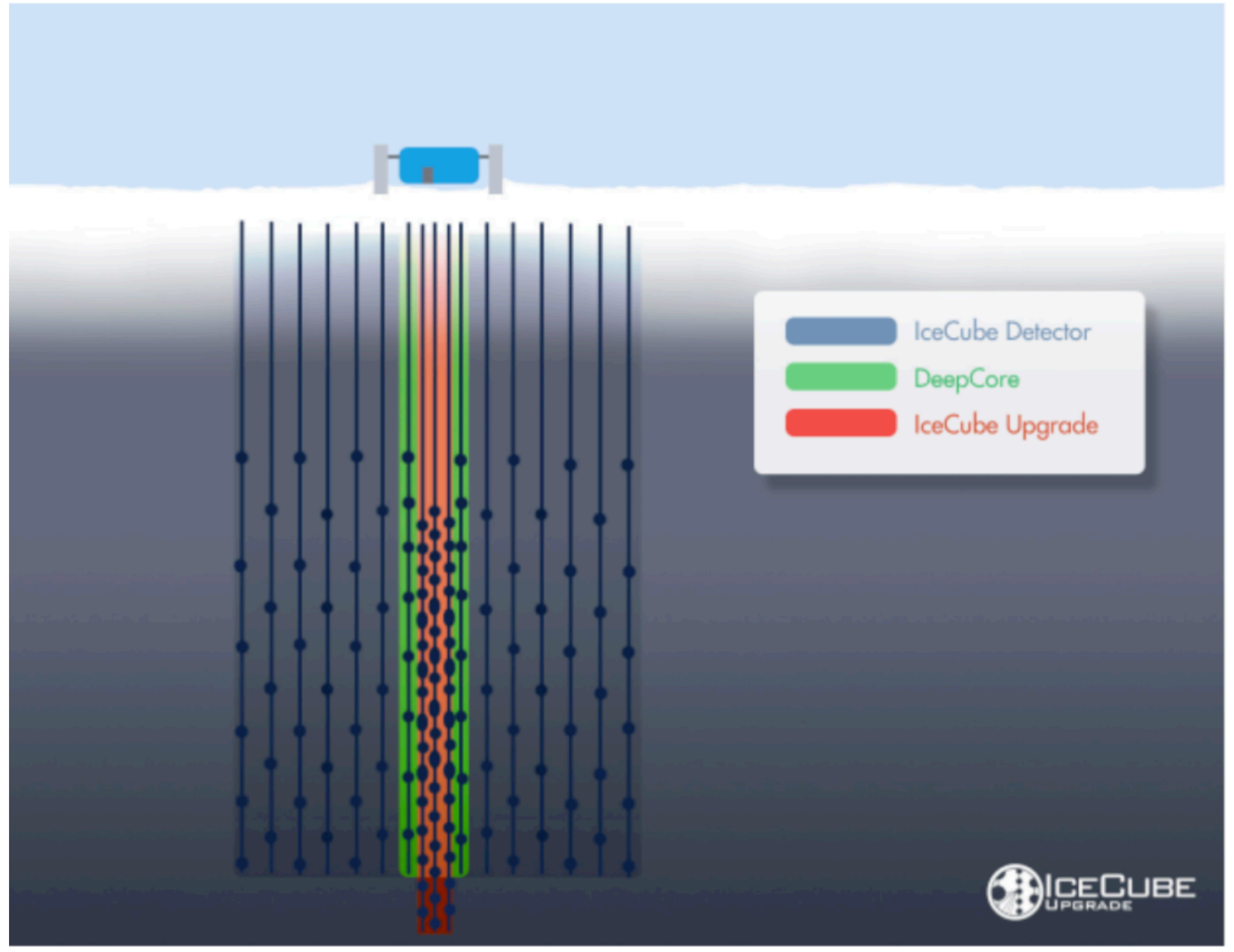
- 715 kton-yr dataset.
- Approaching competitive measurement of θ_{23}, not yet in Δm^2_{31}.

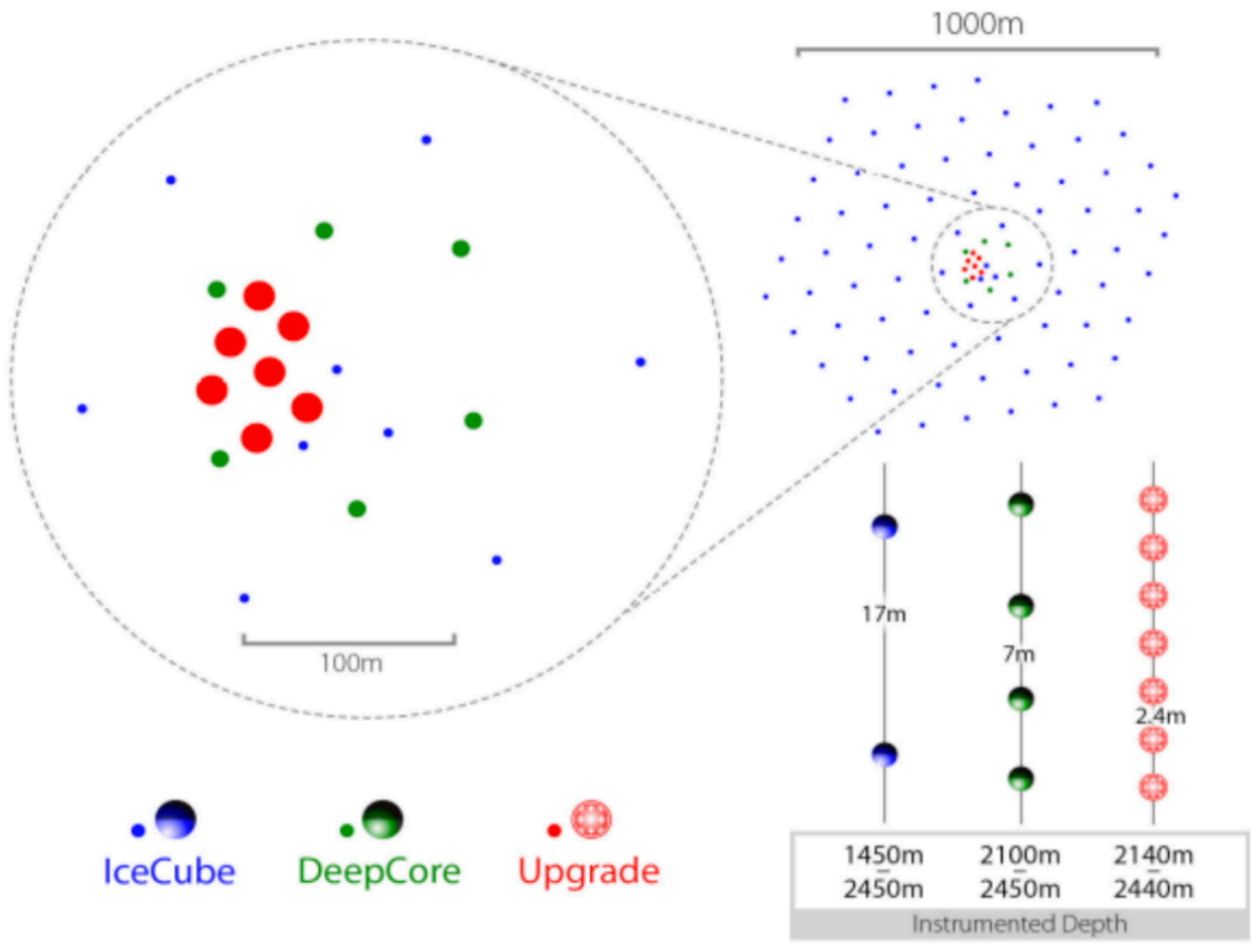


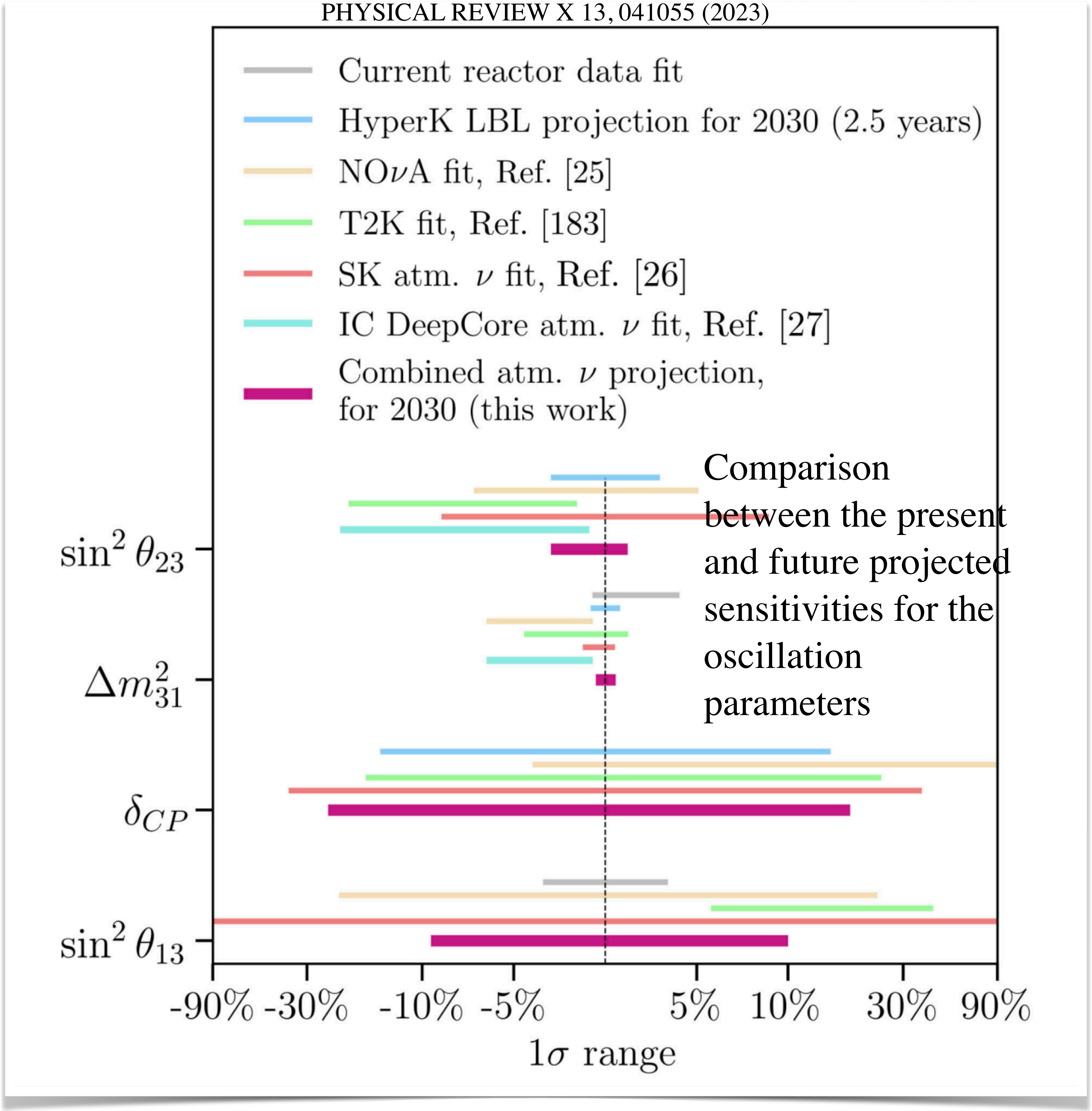
Good agreement and comparable precision with accelerator results

Atmospheric Neutrinos Future

- Currently/Soon: Super-Kamiokande (with Gd), KM3NeT/ORCA, IceCube Upgrade (~2025-26) [reduce energy threshold to a few GeV].
- 2027-29: Hyper-Kamiokande and DUNE.





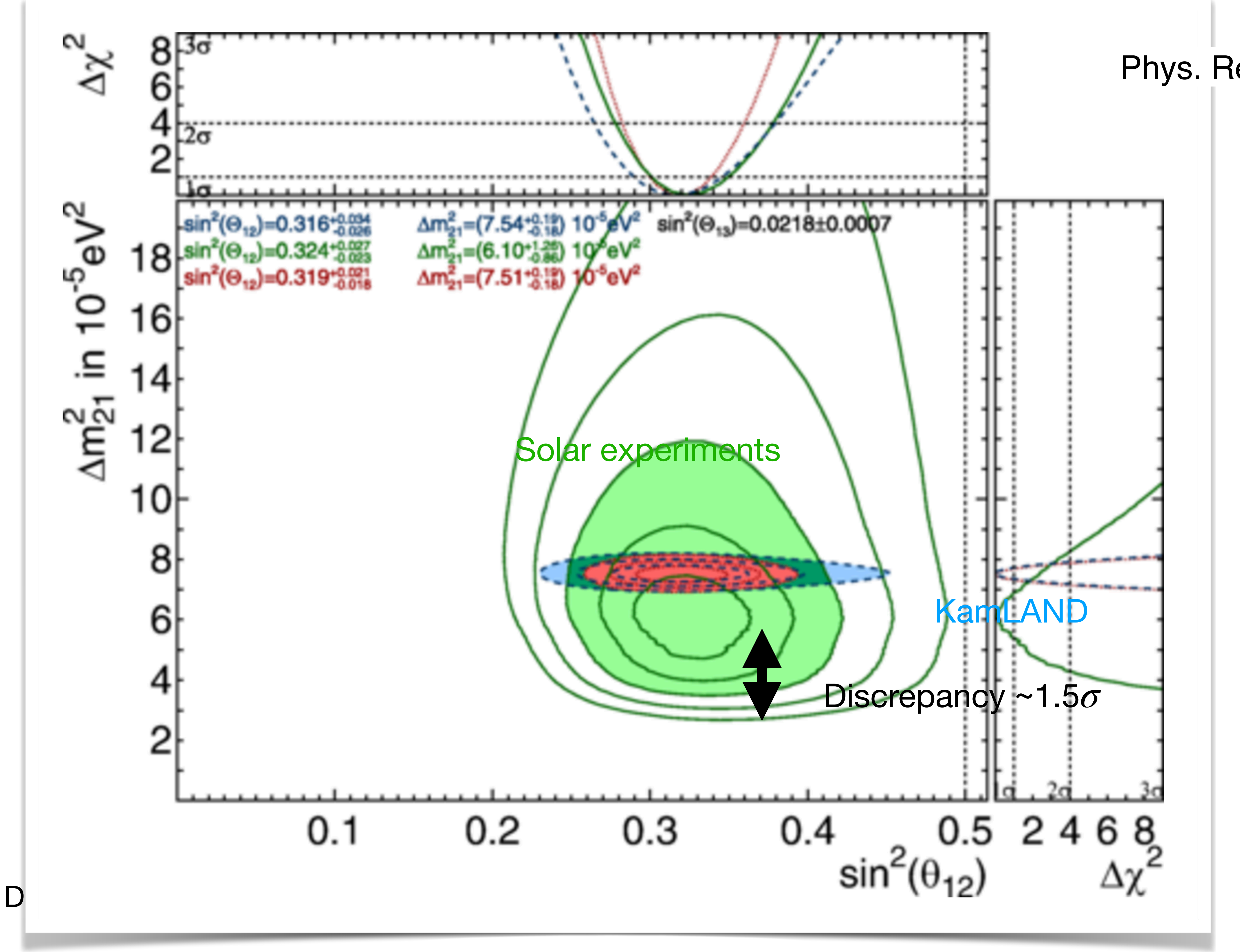


Also combination with JUNO can be exploited (JHEP 2022, 55 (2022) and PRD 101, 032006 (2020)).

Solar Neutrinos

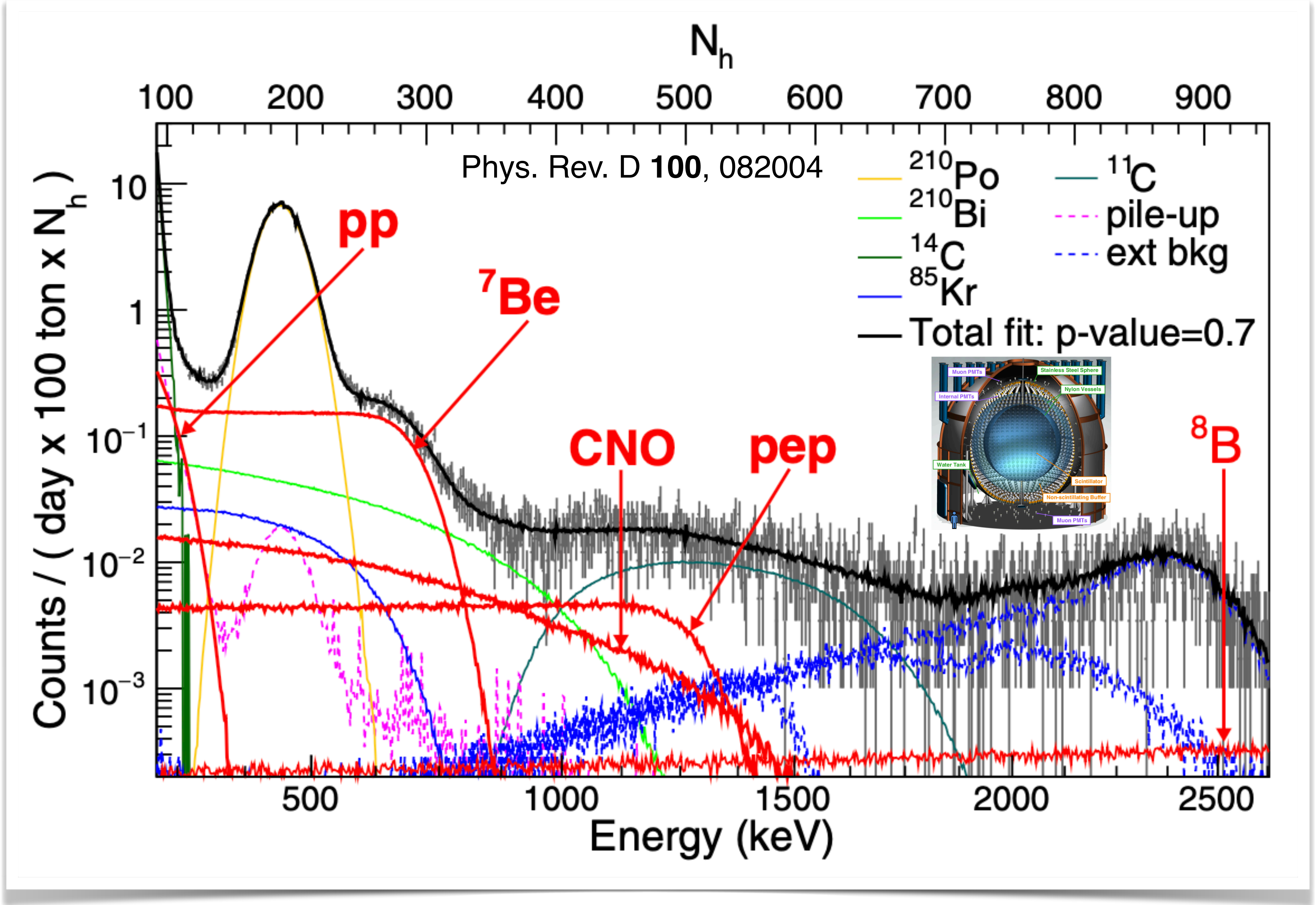
Global analysis of solar and KamLAND data

- Best information on $\sin^2\theta_{12}$ comes from solar neutrino measurements.
- Solar neutrino measurements from Radiochemical experiments (Homestake, GALLEX/ GNO, and SAGE), Super-Kamiokande, SNO, Borexino.
- Best information on Δm^2_{12} comes from KamLAND.



Solar Neutrino Flux status

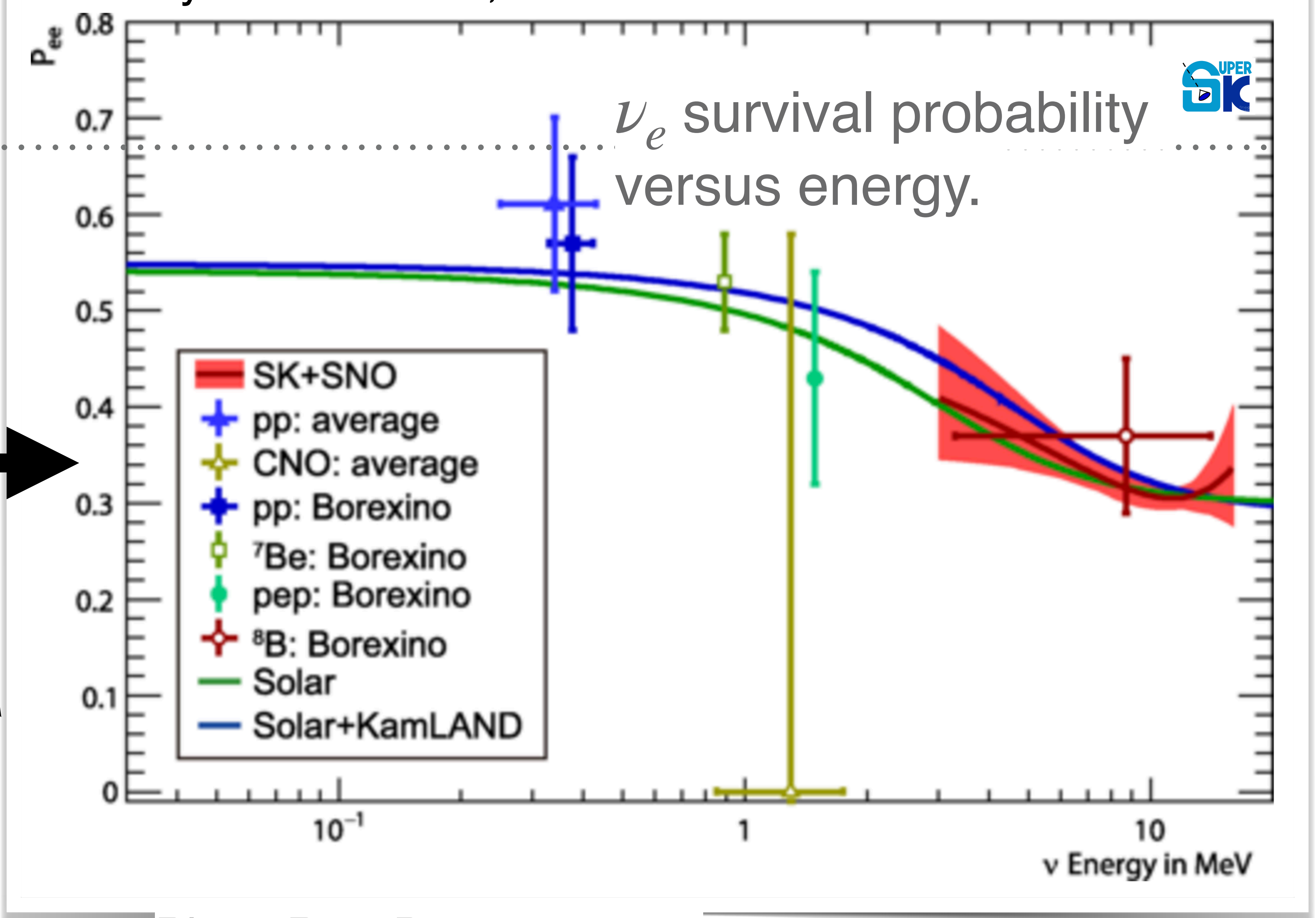
- SK / SNO lead on the ^{8}B flux
- hep neutrinos yet to be observed.
- Borexino: Achieved unprecedentedly high radiopurity and low threshold (100 keV).
- Global fit to the Borexino data in an extended energy range (0.19–2.93) MeV:



Solar Neutrinos

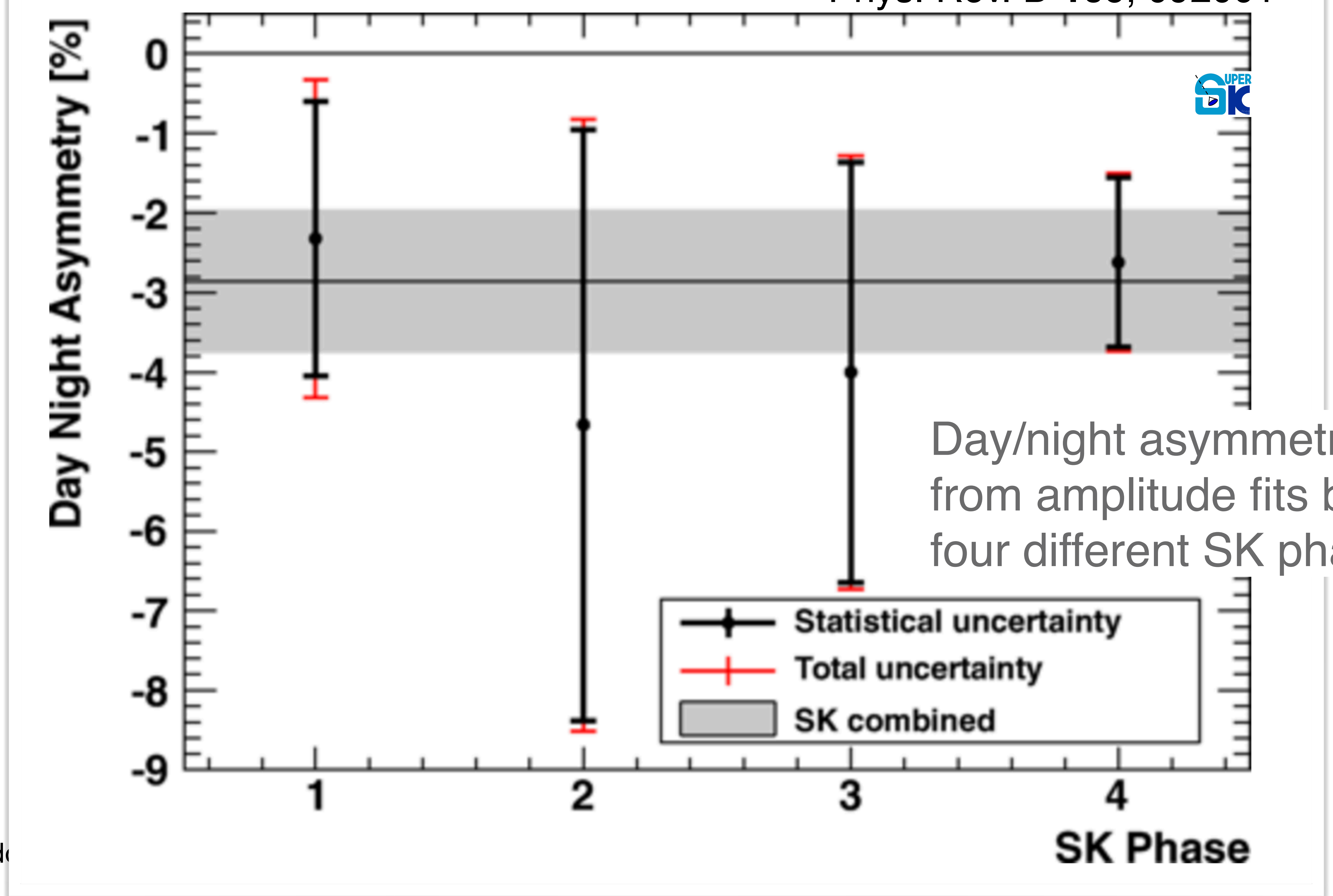
Two important quantities to be measured:
- The "upturn" caused by the transition between vacuum and matter dominance in the Sun.
- The day/night asymmetry induced by matter-effects in the Earth.

Phys. Rev. D **109**, 092001



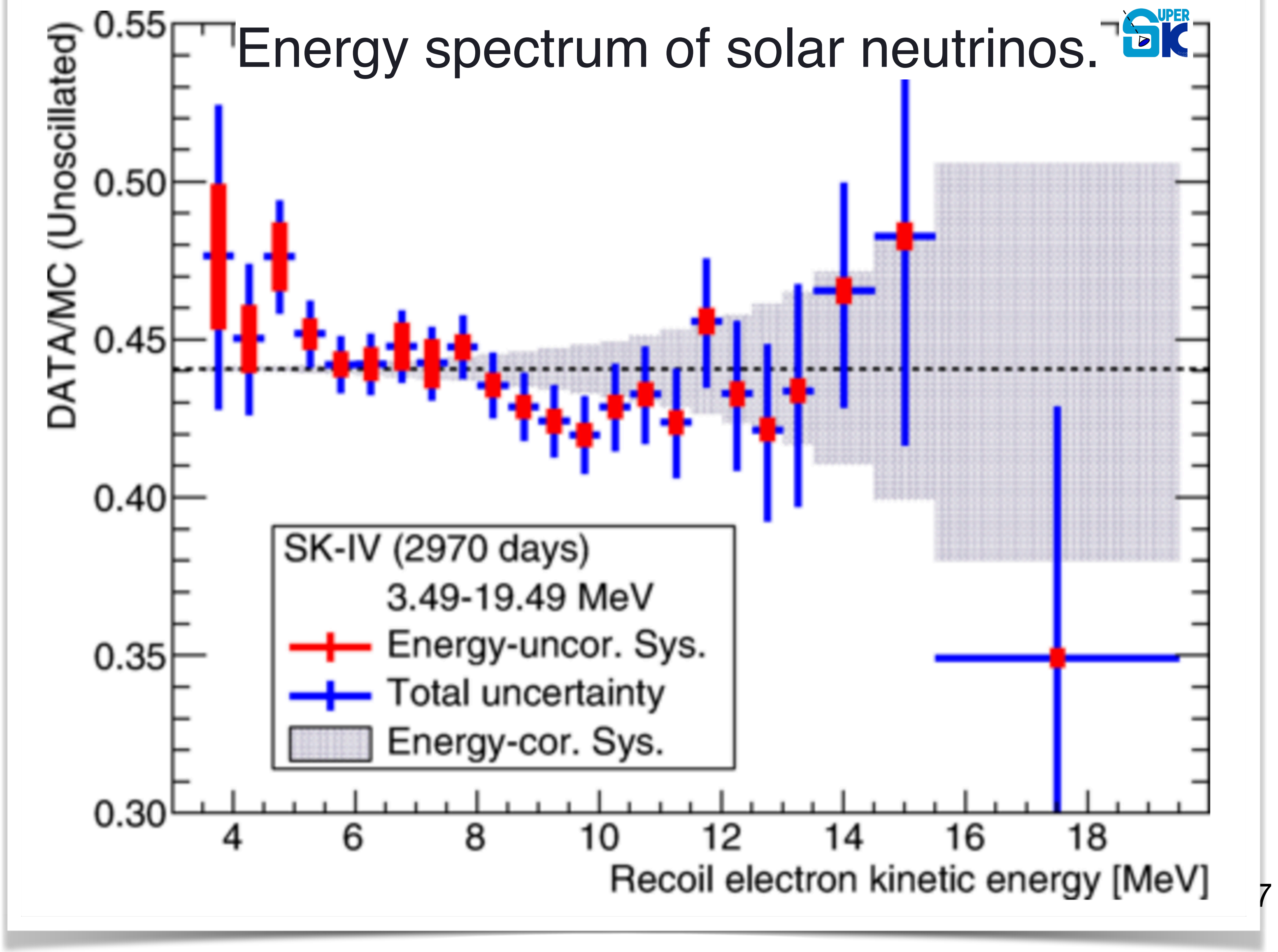
ν_e survival probability versus energy.

Phys. Rev. D **109**, 092001



Day/night asymmetries from amplitude fits by the four different SK phases.

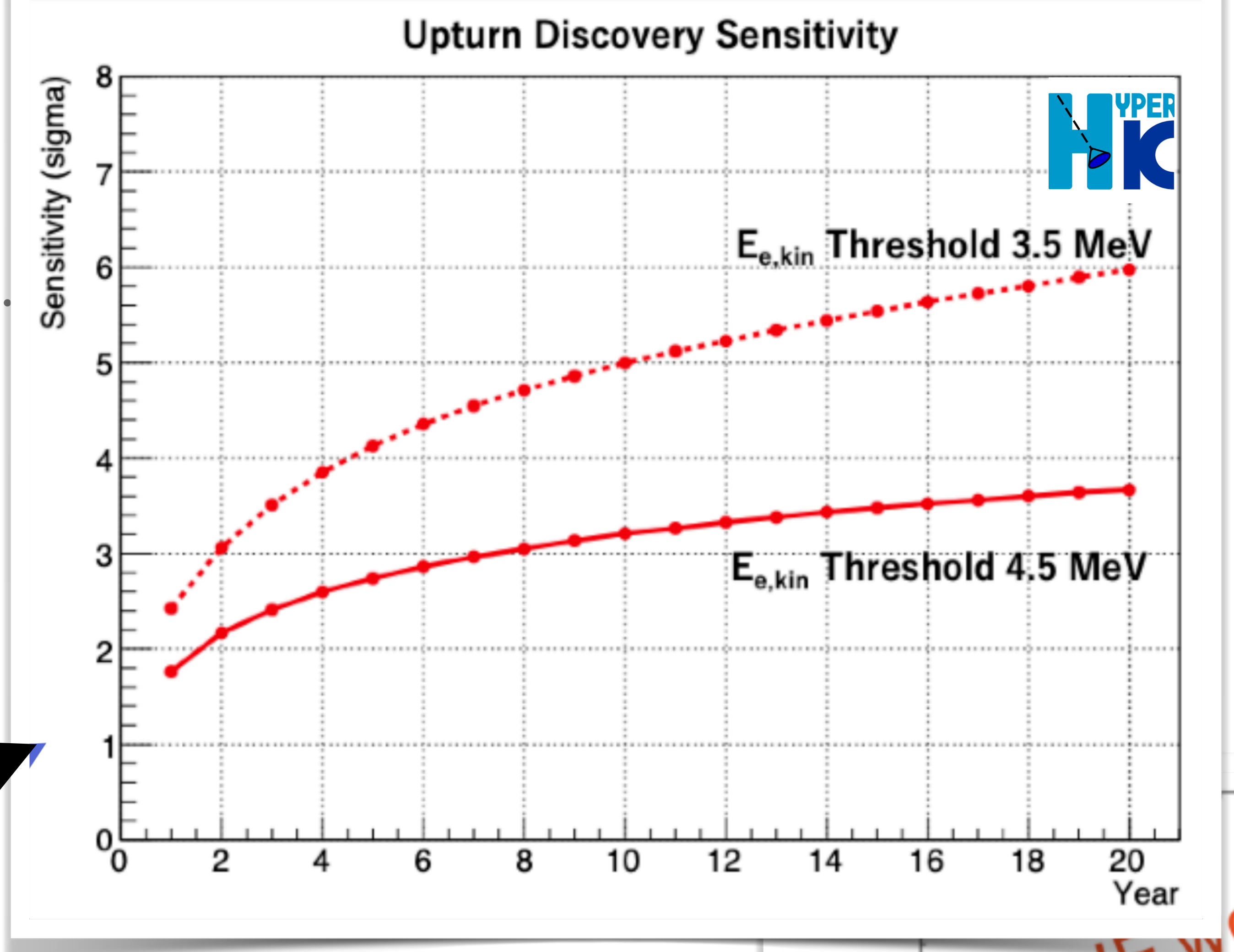
Phys. Rev. D **109**, 092001

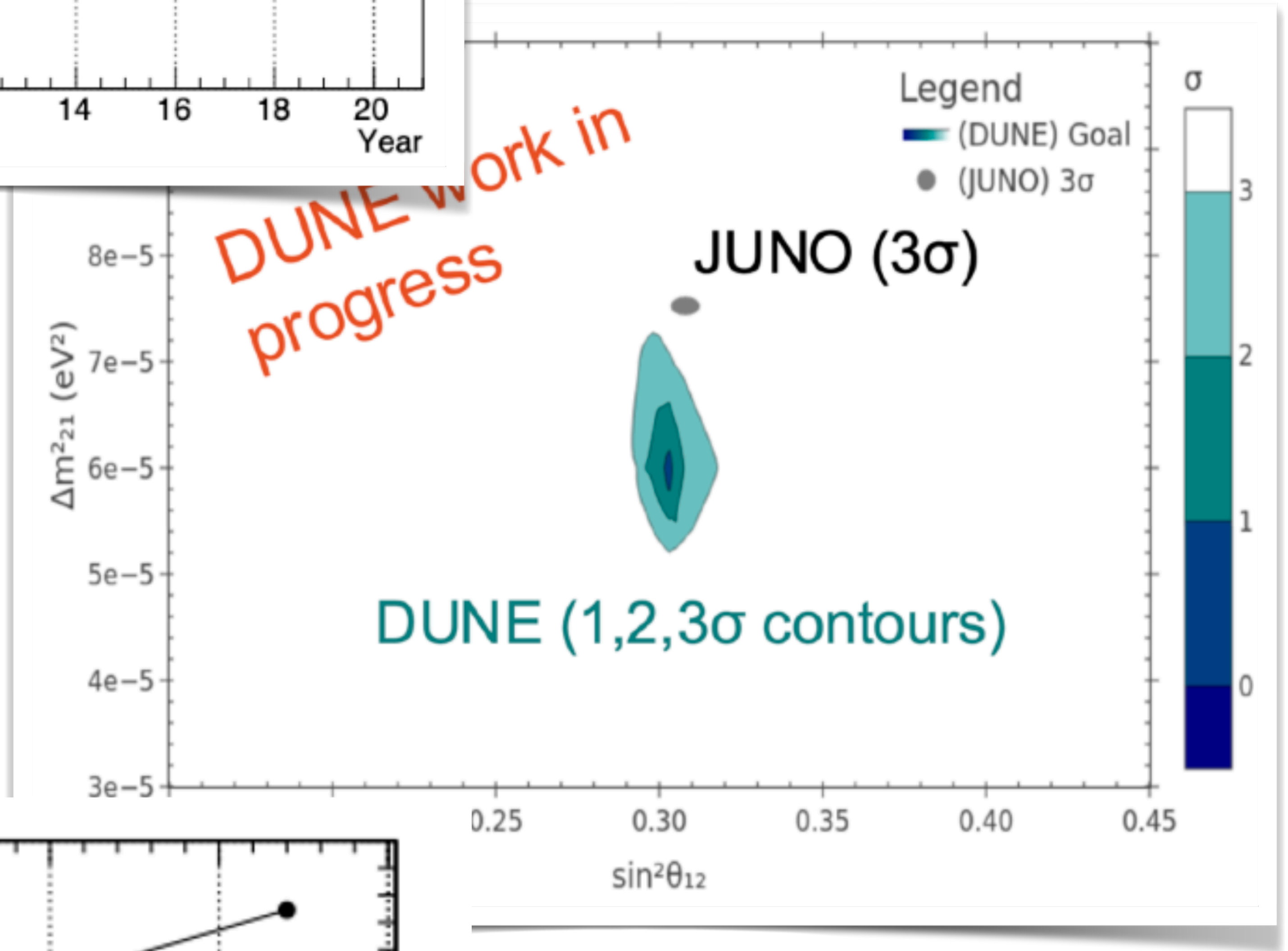


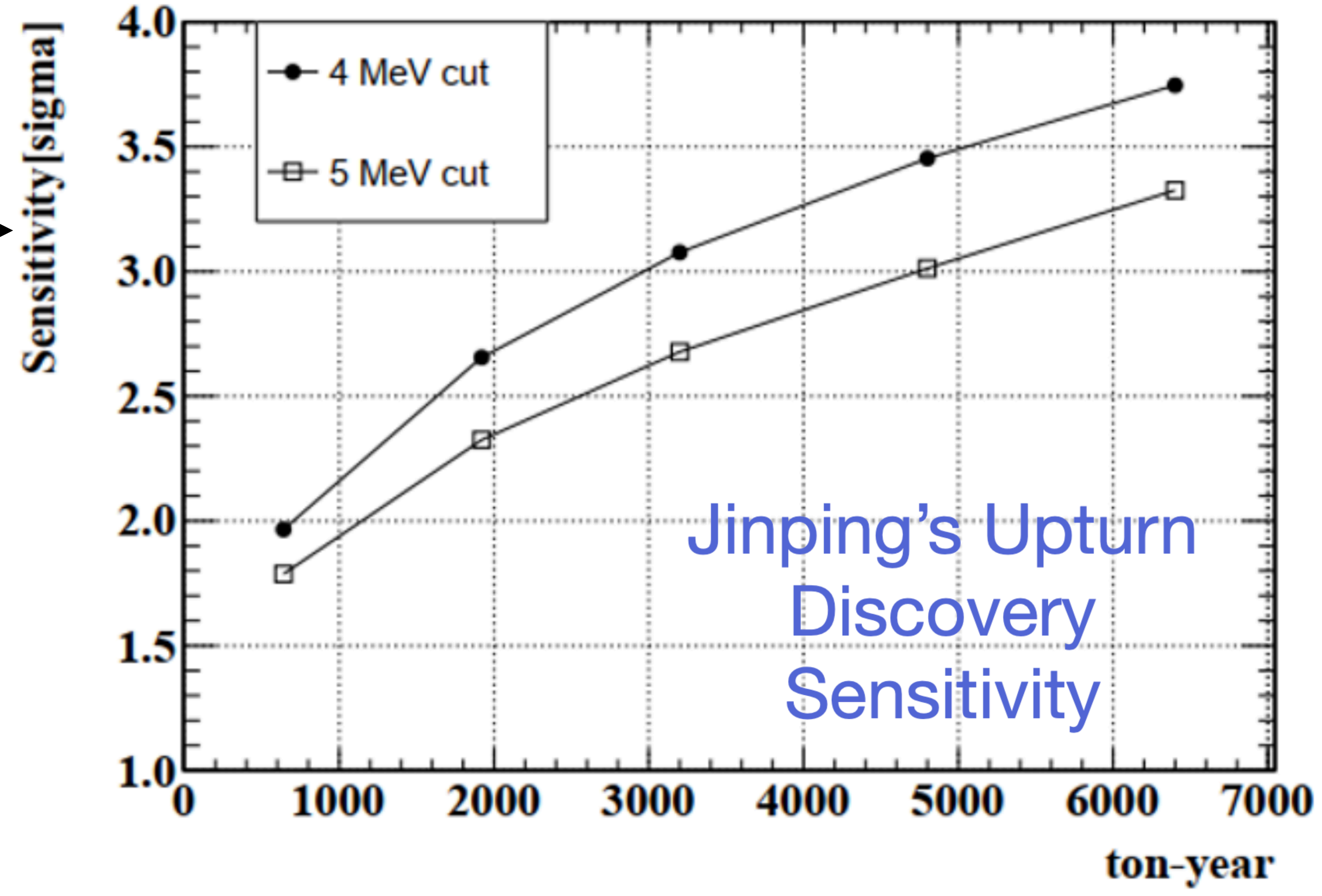
Energy spectrum of solar neutrinos.

Solar Neutrinos Future

- SNO+ - Water phase results published, Scintillator phase data-taking ongoing; results to come shortly. Reactor and solar neutrino experiment capabilities.
- Hyper-Kamiokande - Largest solar detector starting in 2027. Upturn and daylight sensitivity.
- DUNE - Largest LArTPCs ever built starting in 2029. Sensitivity to ^{8}B neutrinos $\gtrsim 10\mathrm{MeV}$.
- JUNO - From 2025. Reactor and solar neutrino experiment capabilities. Potential to improve on some low-energy solar neutrino measurements from Borexino
- Jingping Neutrino Experiment - Big overburden, $500\ \mathrm{m}^3$. Possibility of using LiCl as medium
- New technologies and opportunities under active R&D:
  - THEIA: Hybrid scintillation+Cherenkov detector
  - LiquidO: Topology discrimination and In doping via opaque scintillation



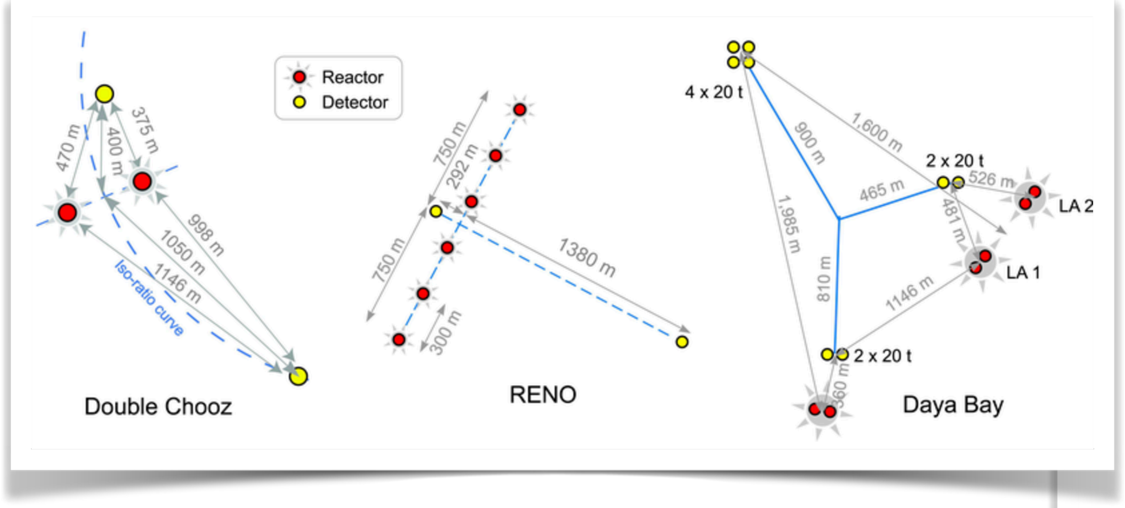


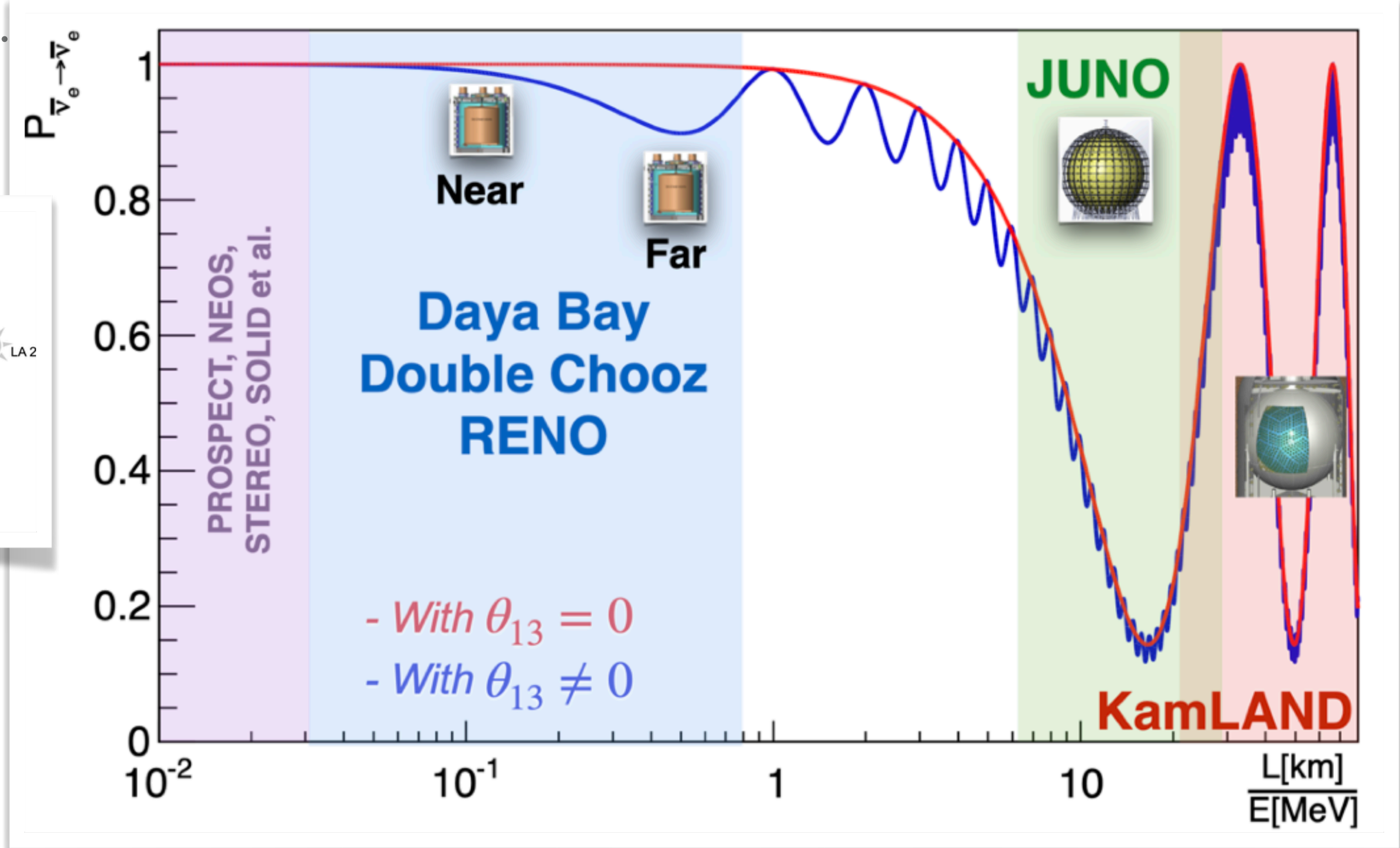


Reactor Neutrinos

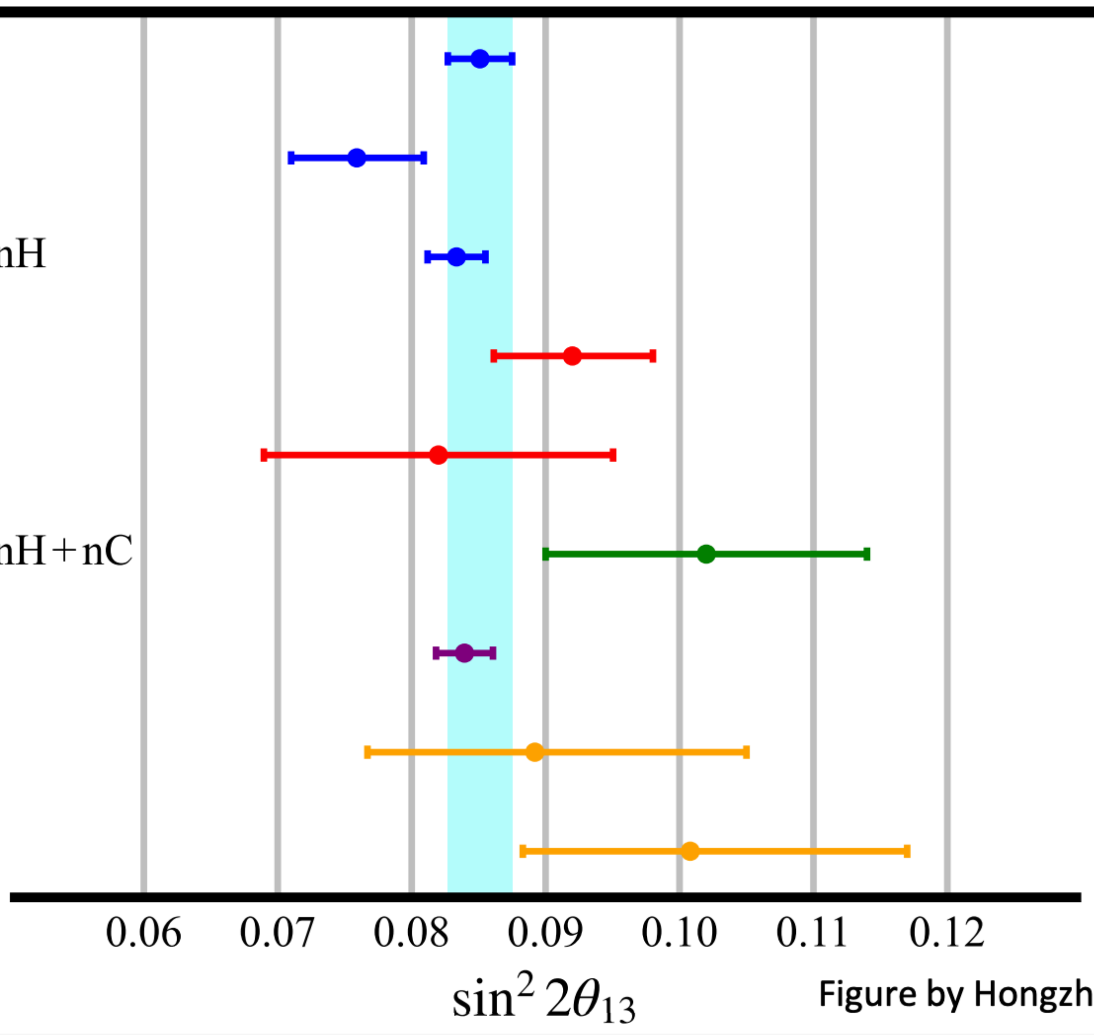
Best information on Δm^2_{21} and $\sin^2\theta_{13}$ comes from reactor experiments

- $\Delta m^2_{21} \Rightarrow$ KamLAND
- $\sin^2 2\theta_{13} \Rightarrow$ short baseline (< 2 km) experiments that access first maximum modulated by $\sin^2 2\theta_{13}$:
  - Use neutron capture on Hydrogen (nH) and/or on Gadolinium (nGd) to identify $\bar{\nu}_e$'s (detection channel $\bar{\nu}_e + p \rightarrow e^+ + n$).
- Current reactor measurement of θ_{13} likely to remain the world's most precise for a long time.
- Proposal for a Super CHOOZ with LiquidO technology under development (corresponding detector prototype CLOUD).





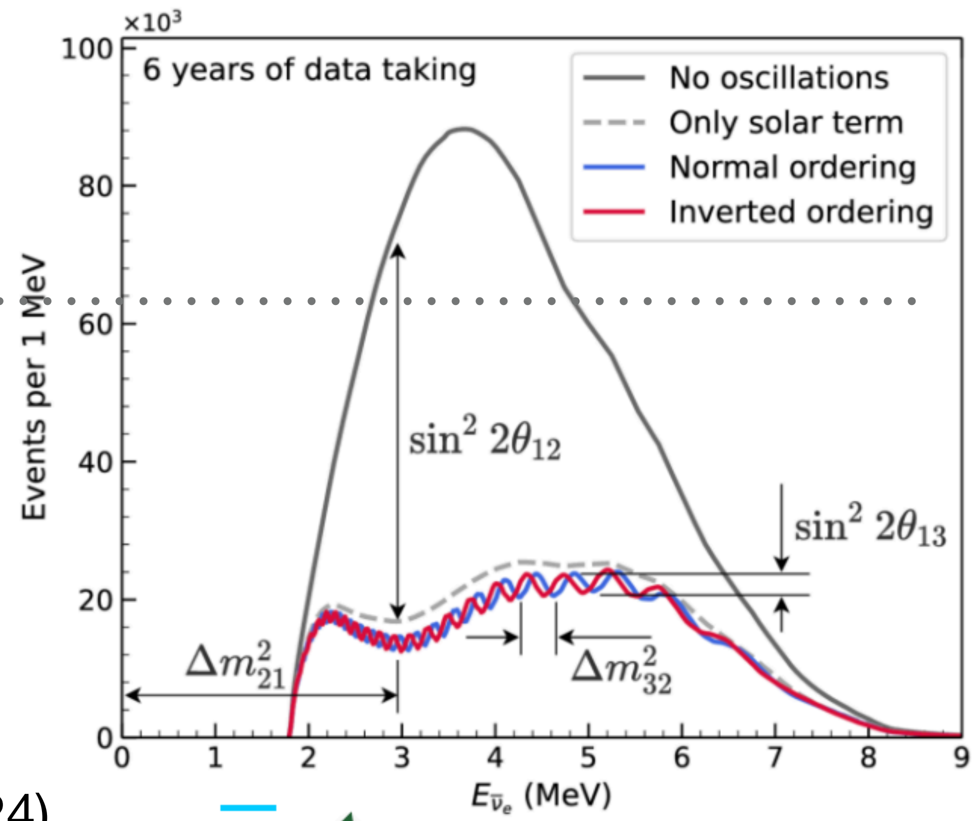
By combining all reactor results, ultimate precision of $\sin^2 2\theta_{13}$: 2.5 % [Neutrino 2024 Zeyuan Zu]



Experiment		Value	
Daya Bay	nGd	0.0851 ± 0.0024	2.8%
	nH	$0.0759^{+0.0050}_{-0.0049}$	6.5%
	nGd+nH	0.0833 ± 0.0022	2.6%
RENO	nGd	$0.0920^{+0.0060}_{-0.0059}$	6.5%
	nH	0.082 ± 0.013	15.9%
Double Chooz	nGd+nH+nC	0.102 ± 0.012	11.8%
Reactor Average		0.0839 ± 0.0021	2.5%
T2K + NOνA	NO	$0.0892^{+0.0158}_{-0.0125}$	15.9%
	IO	$0.1008^{+0.0162}_{-0.0125}$	14.2%

Reactor Neutrinos Future

- JUNO is a next-generation reactor experiment expected to begin data collection in 2025:
  - 20 kton liquid scintillator detector
  - Baseline of ~ 52.5 km from 8 nuclear reactors
  - Energy resolution of 3% @ 1 MeV
  - Aims:
  - - Determine the neutrino mass ordering.
  - - Measure $\Delta m^2{}_{31}$, Δm_{2121}, and $\sin^2 2\theta_{12}$ with sub-percent precision.
- Mass ordering determination with unique approach that does not rely on matter effects



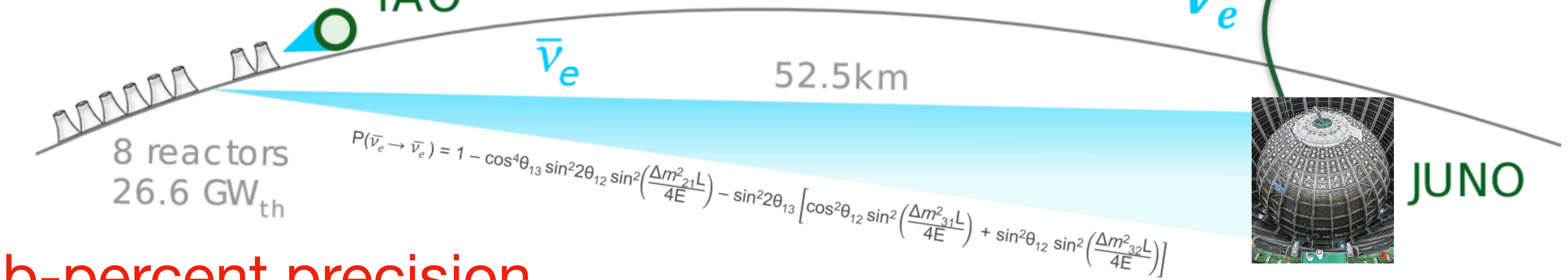
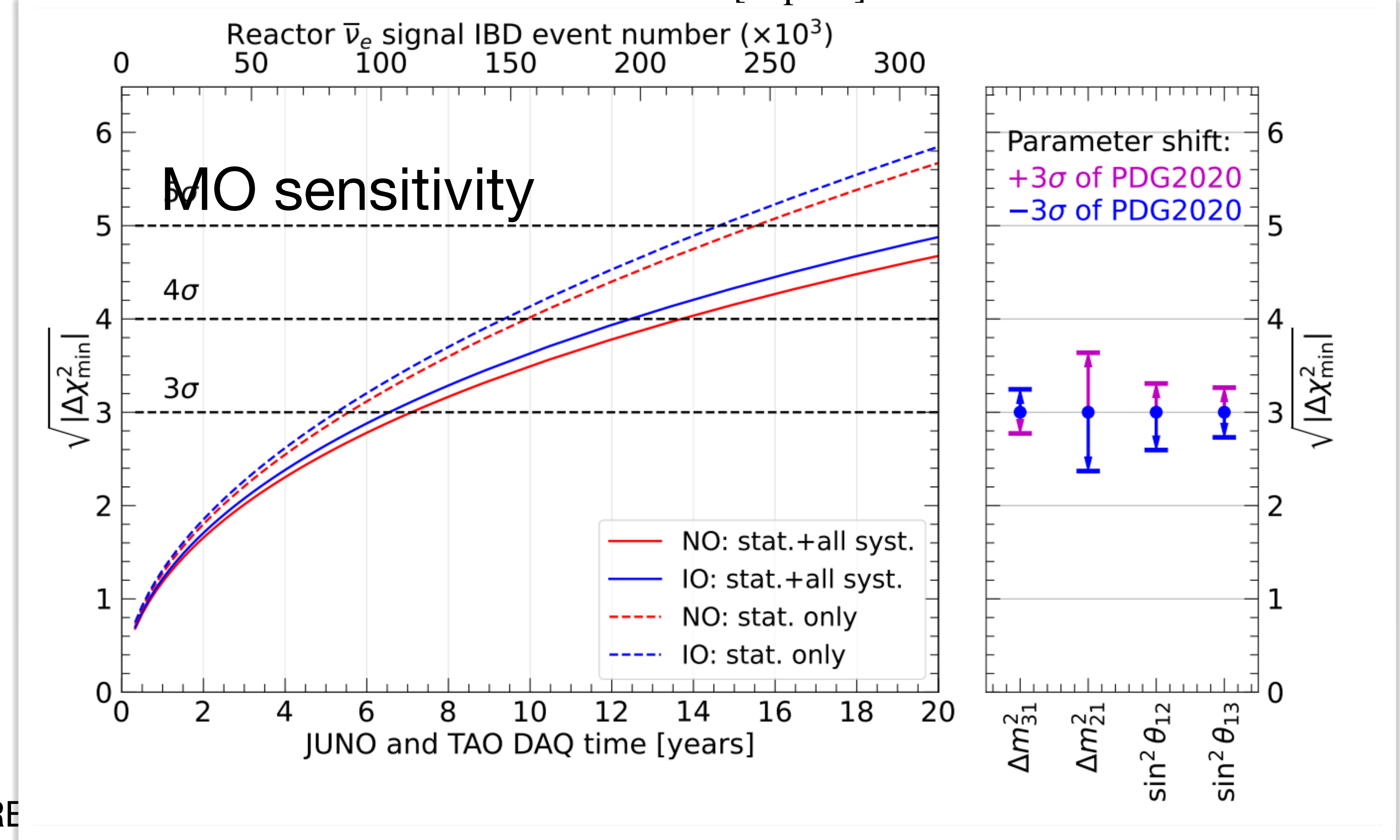


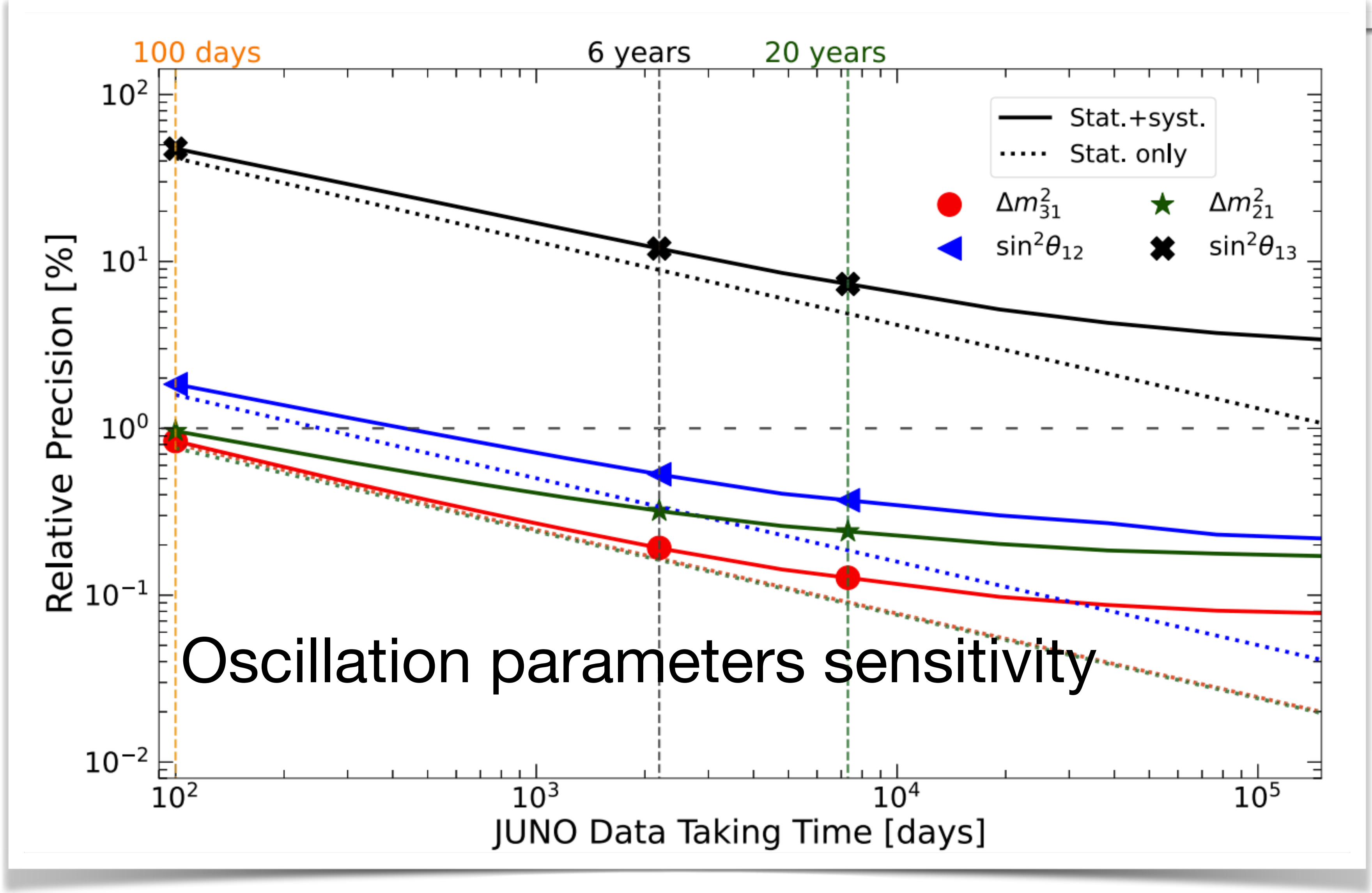
Figure from S. Calvez (ICHEP2024)

Parameter	$\sin^2\theta_{12}$	Δm^2_{21}	Δm^2_{32}
Current Precision (PDG)	4.2%	2.4%	1.1%
Juno 6 years	0.5%	0.3%	0.2%

arXiv:2405.18008v1 [hep-ex]

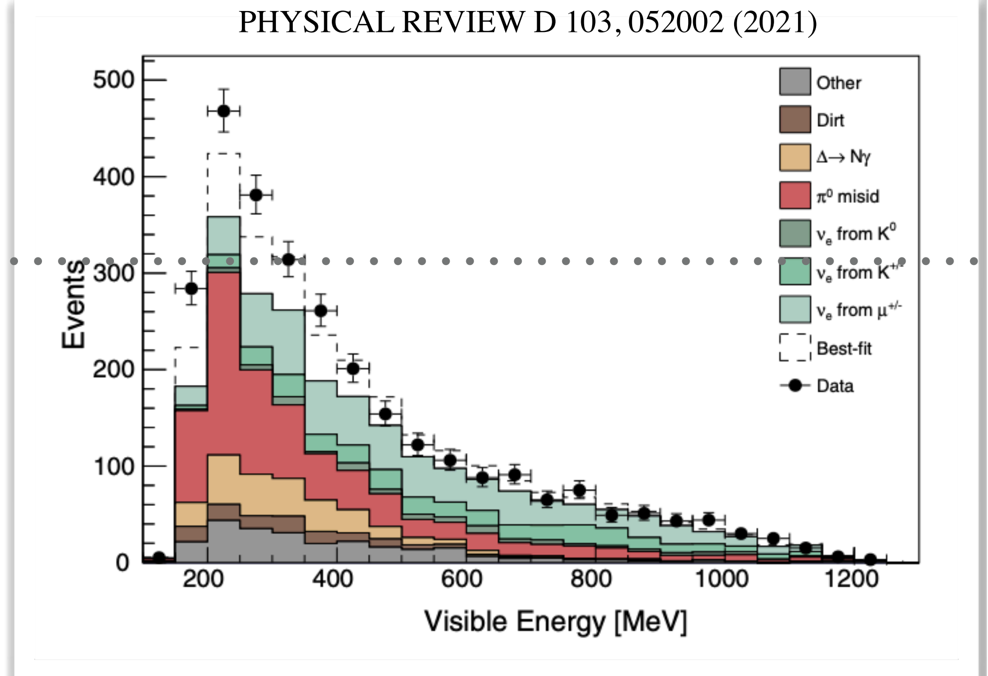


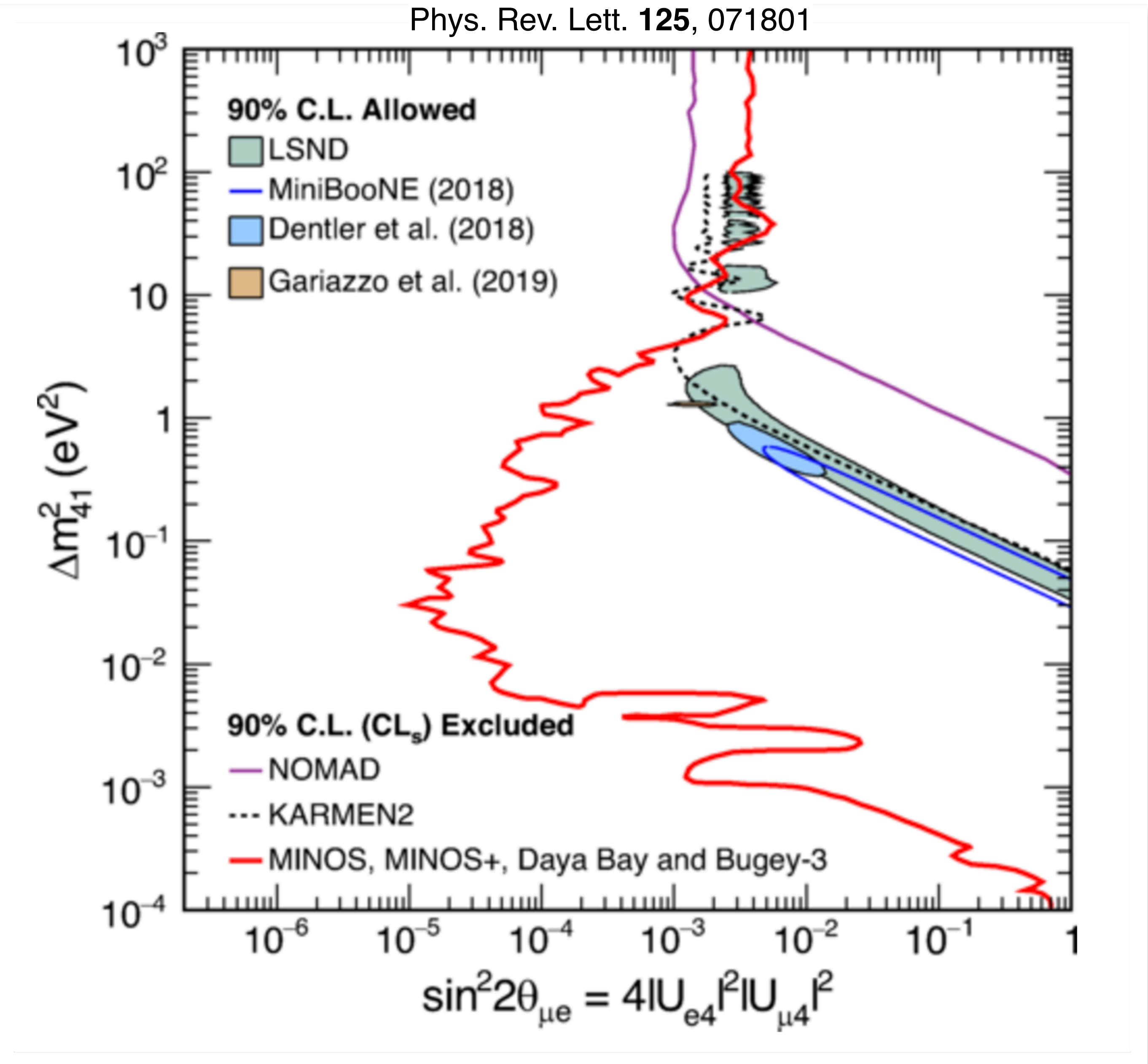
Chinese Phys. C 46 123001



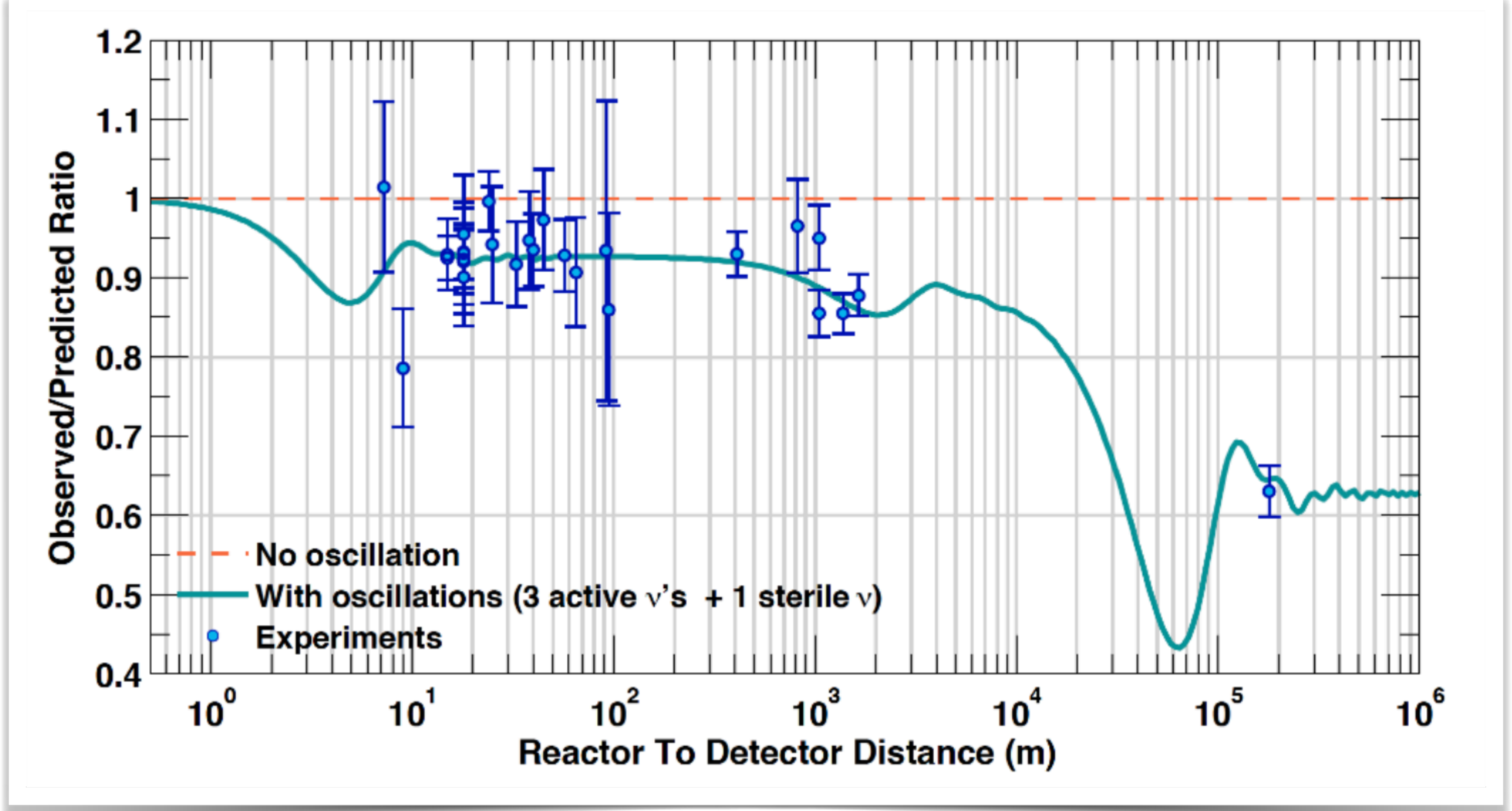
Oscillation Anomalies

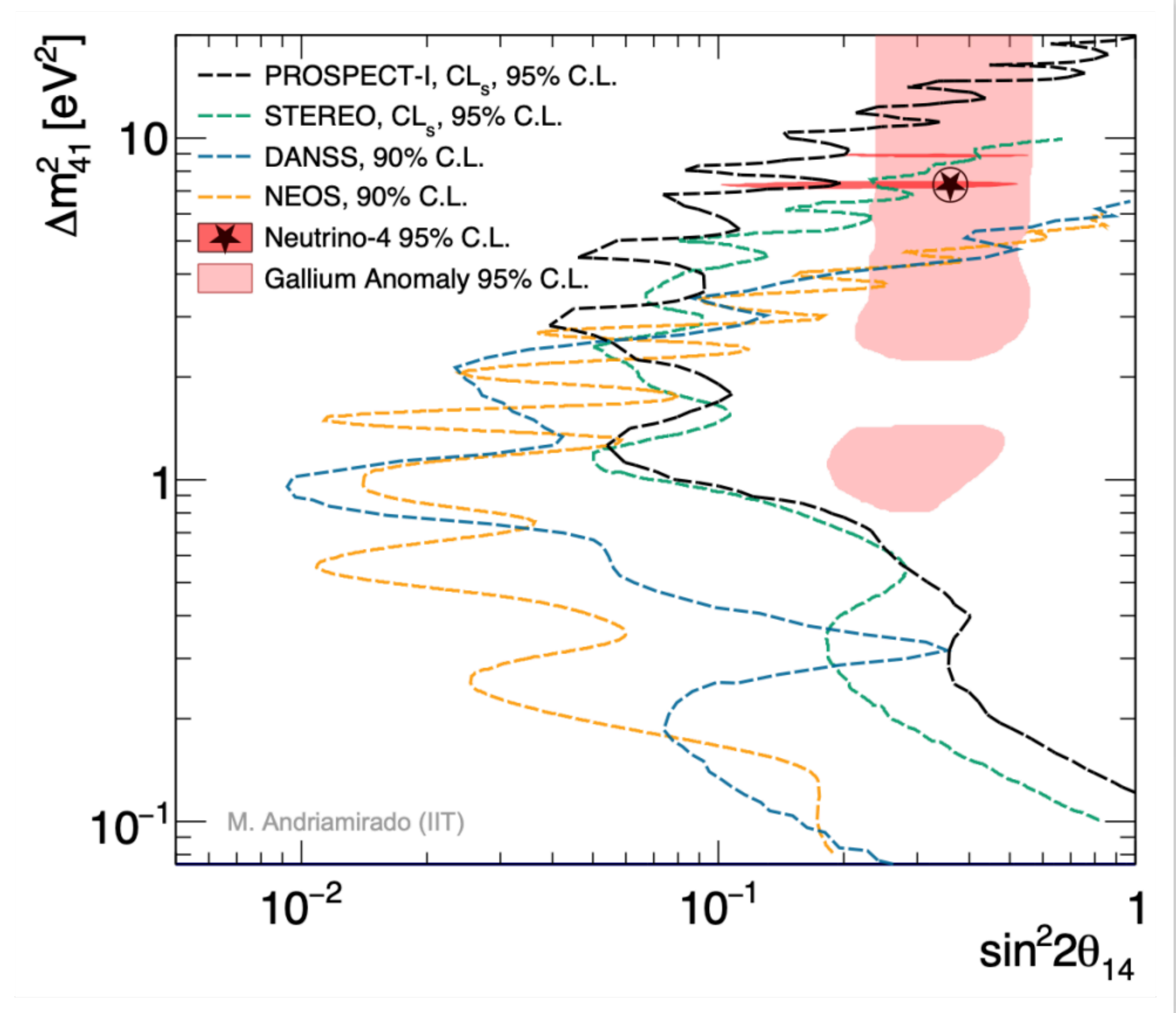
- LSND + MiniBooNE: $\sim 6\sigma$ excess of electron (anti)neutrinos in a muon (anti)neutrino beam.
  - eV-scale sterile ν oscillations in conflict with accelerator and reactor disappearance measurements.
  - The Fermilab SBN and J-PARC JSNS^2 experiments will provide definite tests of the oscillation hypothesis.



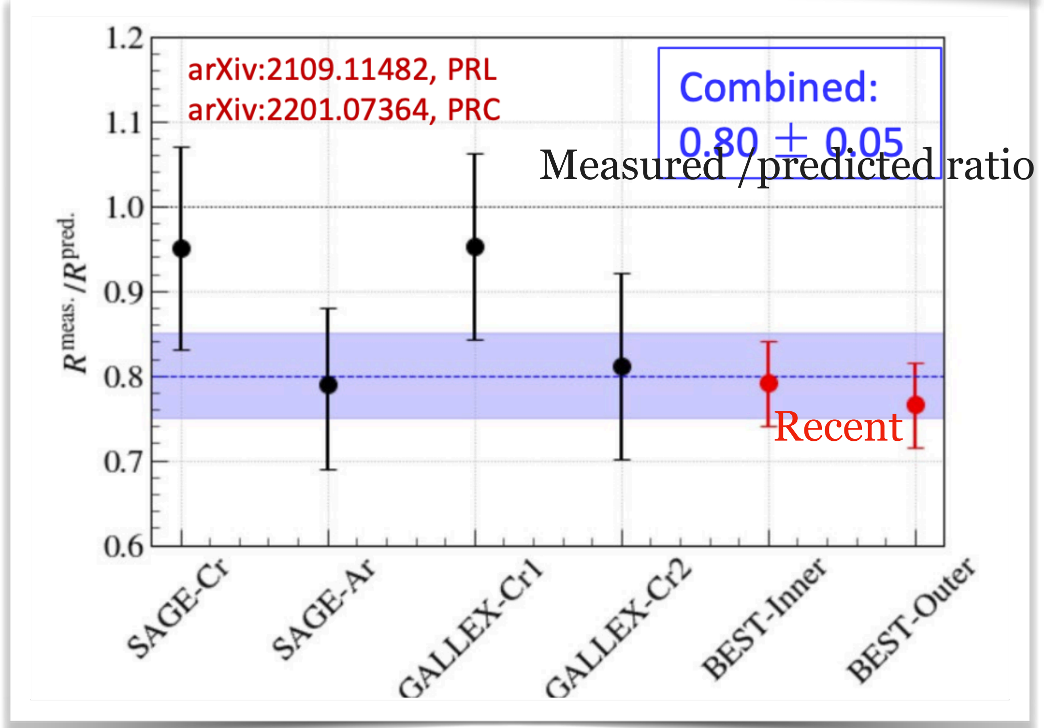


- Reactor Anomaly: a 6% deficit with 3σ significance in the measured total reactor $\bar{\nu}_e$ flux versus the prediction from the Huber+Mueller model at short baselines.
  - Not observed by other experiments apart from Neutrino-4 2023.

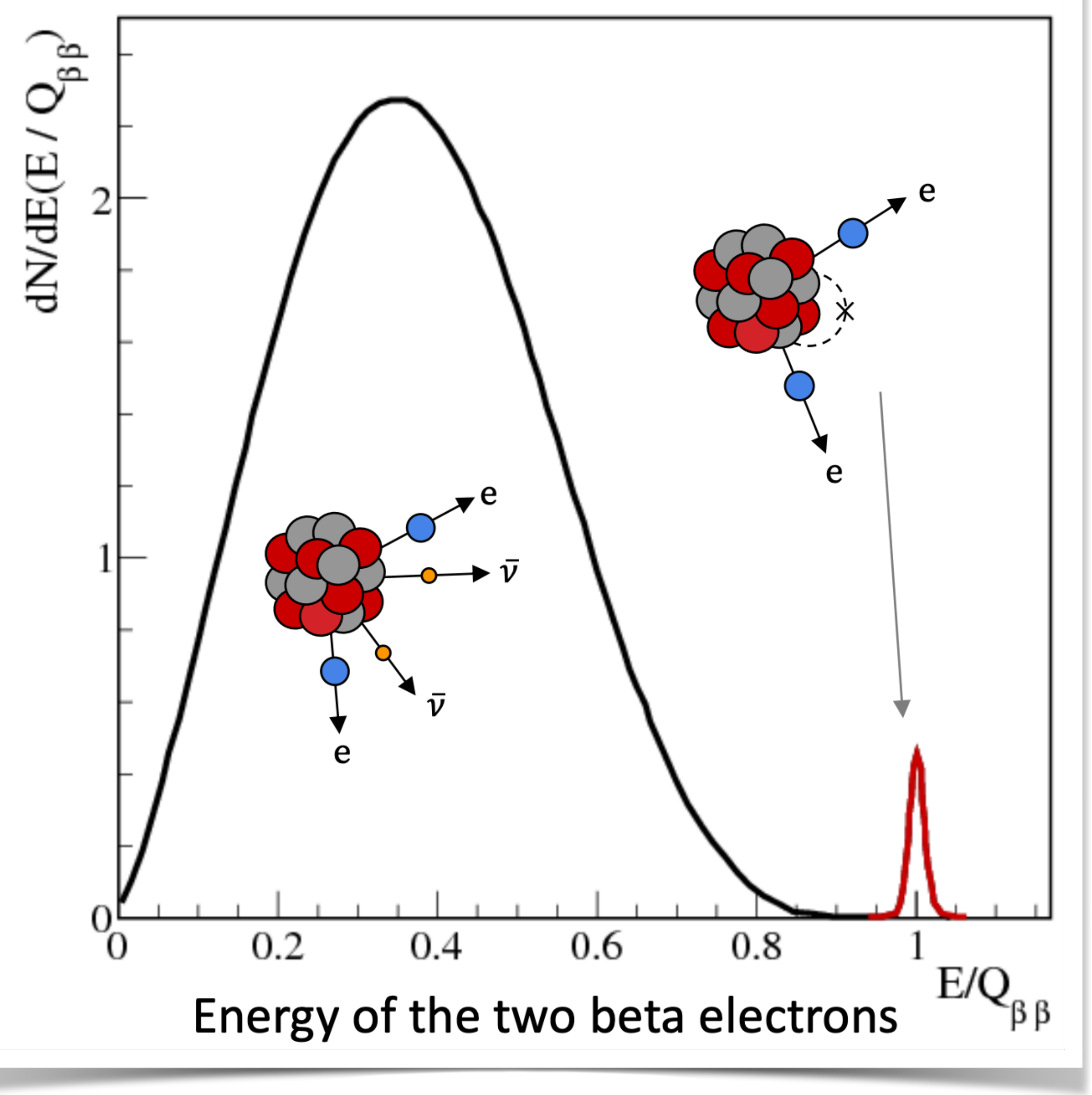




- Gallium Anomaly: Capture rates of ν_e from calibration sources on $^{71}\mathrm{Ga}$ are below expectation.
  - Seems not due to sterile neutrinos but other explanations should be looked for.



$0\nu\beta\beta$ Searches



^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{110}Pd, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{136}Xe, ^{150}Nd

Observed half-life:

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}\, g_A^4\, (M_{0\nu})^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

- $G_{0\nu}$: phase space — Accurately calculated
- g_A^4: coupling
- $(M_{0\nu})^2$: nuclear matrix element — Significant theory uncertainties.
- $m_{\beta\beta}^2$: effective mass

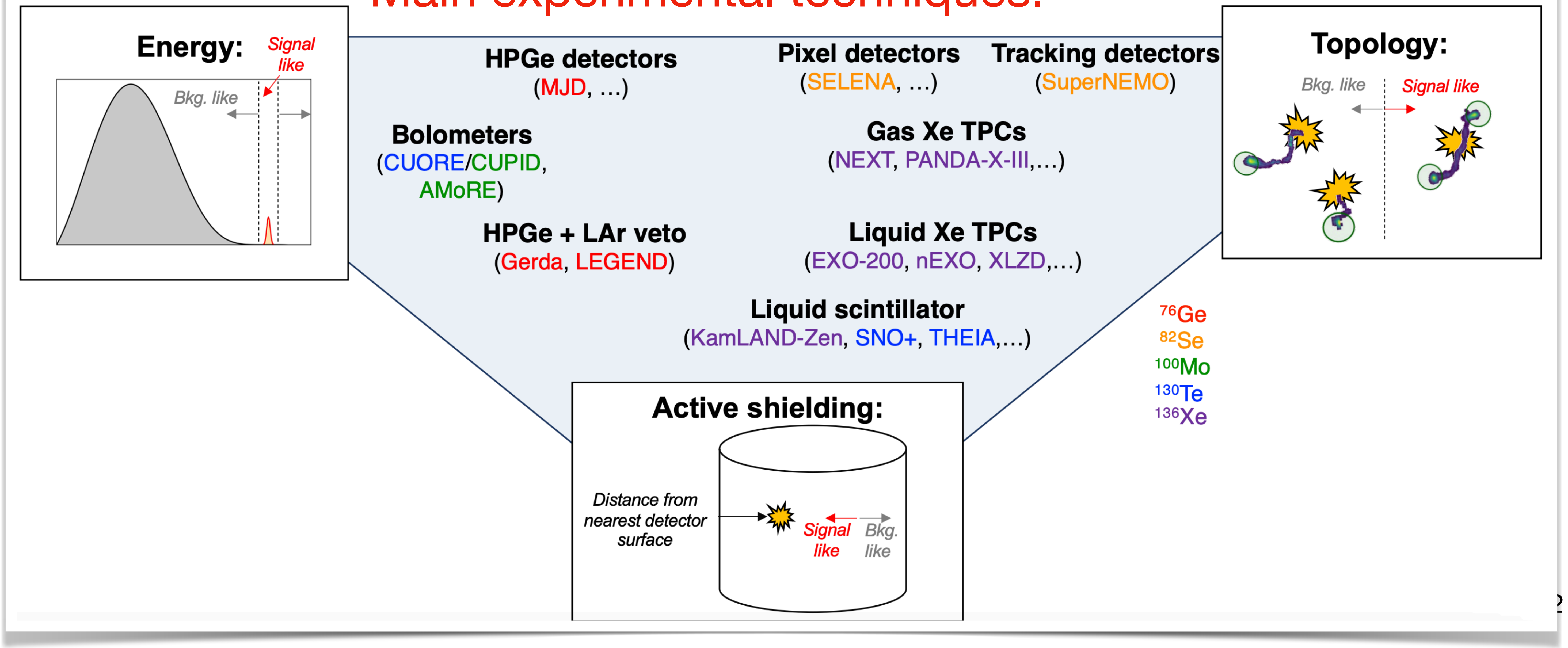
$$\langle m_{\beta\beta}\rangle = \left|\sum |U_{ei}|^2 e^{i\phi_i} m_i\right|$$
$$= \left|c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i\beta}\right|$$

Effective mass depends on the mixing matrix parameters. α, β are unknown Majorana phases. Not measurable in oscillation experiments.

Key requirements:

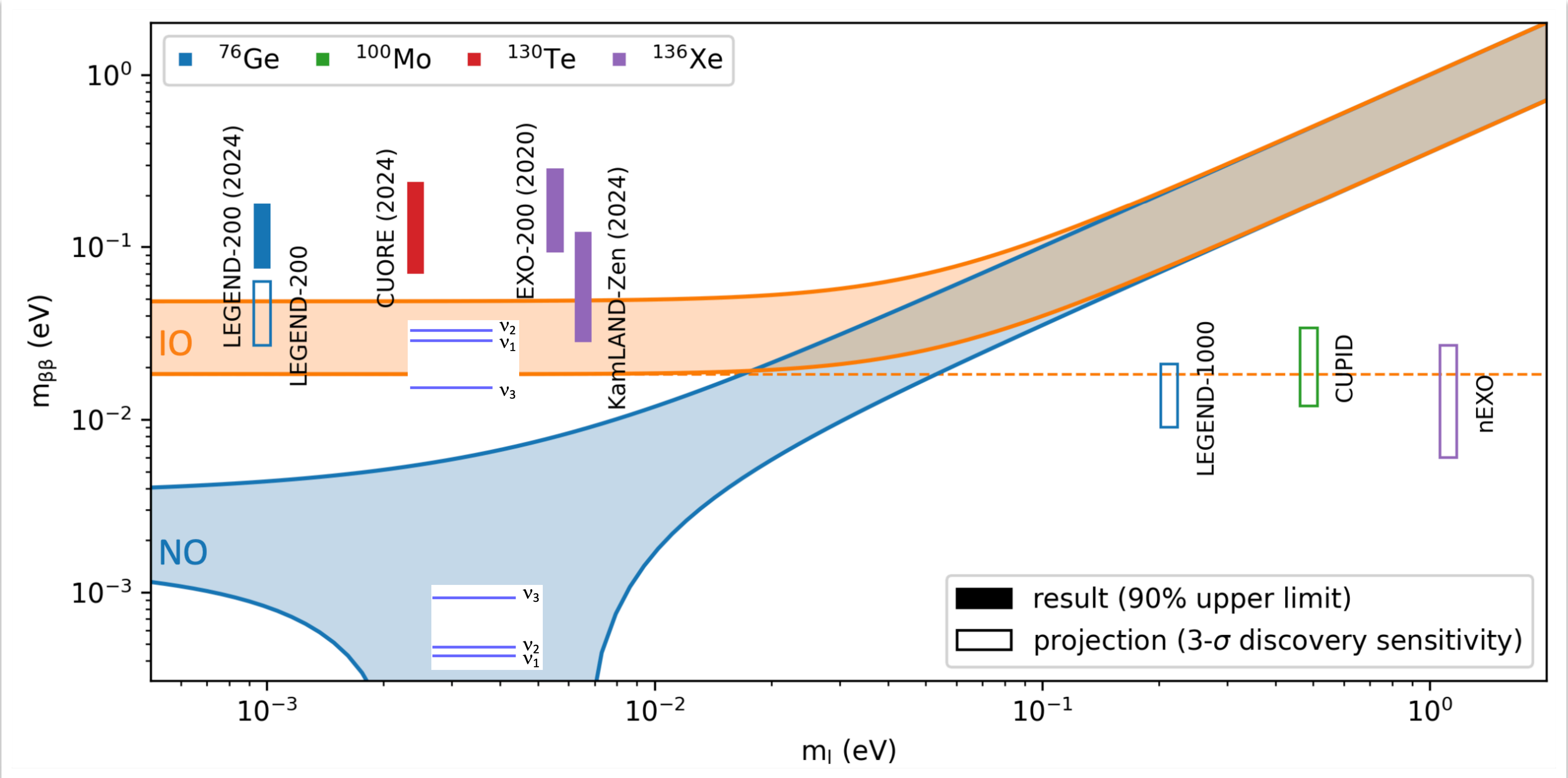
- Large exposure (ton-scale)
- Low background (< 1 cts/year/t/ROI)
- Excellent energy resolution ($< 1\,\%\,@\,Q_{\beta\beta}$)

Main experimental techniques.



$0\nu\beta\beta$ Searches

Parameter space:



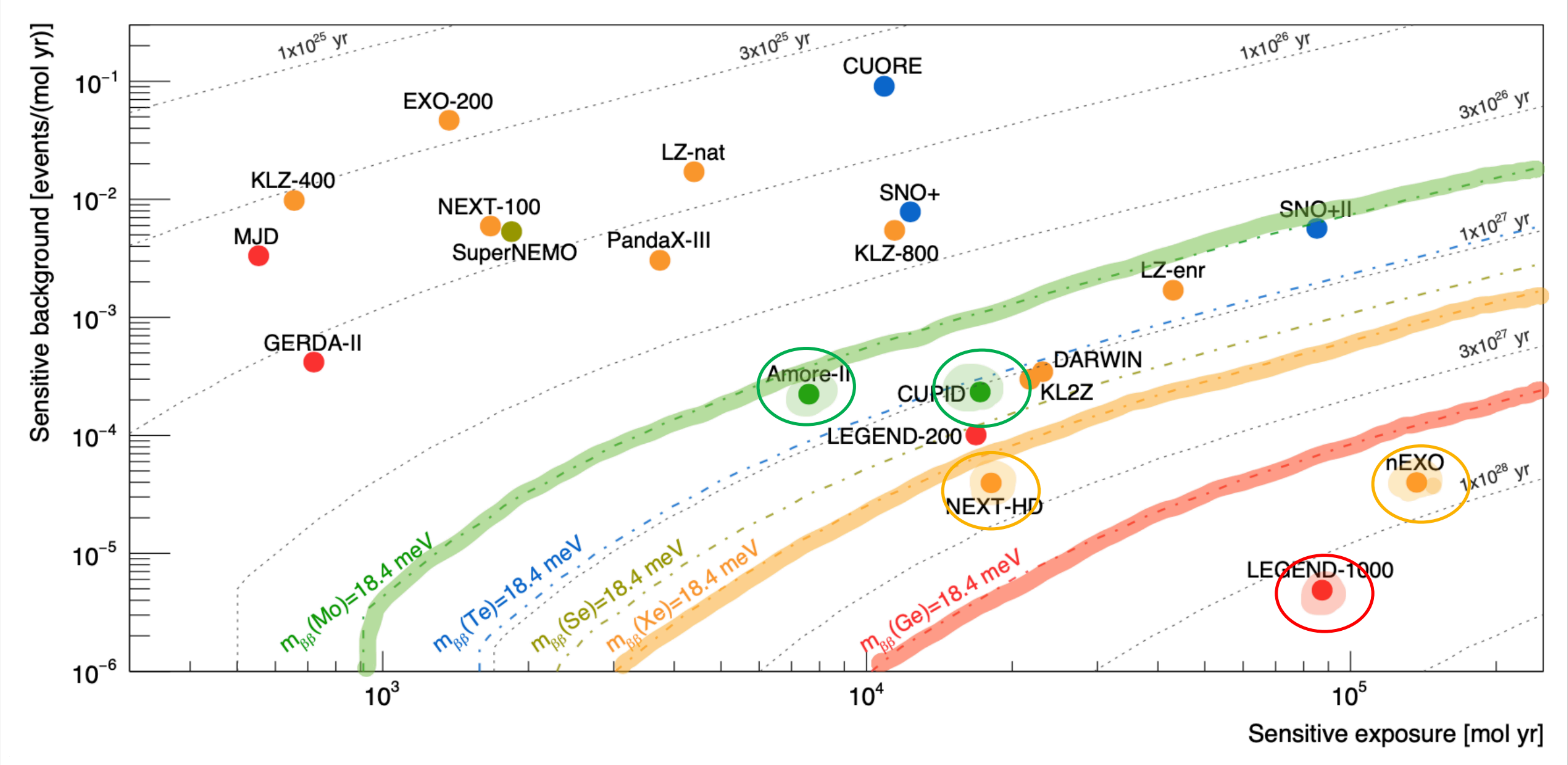
- If neutrinos are Majorana, experimental results must fall in the shaded regions.
- Extent of the regions determined by uncertainties on mixing matrix elements and Majorana phases.

- Ongoing / completed projects probe degenerate regime e.g. LEGEND-200, CUORE, EXO, KamLAND-ZEN. 2024 results from. LEGEND-200, CUORE and KamLAND-ZEN.
- Planned projects will fully cover the inverted ordering scenario e.g. LEGEND-1000, CUPID, nEXO..

$0\nu\beta\beta$ Searches

Sensitive background and exposure for recent and future experiments

ABDMV, RMP 2022, arXiv:2202.01787



- Grey dashed lines: discovery sensitivity on the $T_{1/2}$(isotope-independent)
- Colored dashed lines: $m_{\beta\beta}$ sensitivities to get to the bottom of the IO region for specific isotopes, taking into account NME (nuclear matrix element) & phase space

Direct Neutrino Mass Measurements

- From cosmology: $\Sigma m_i < \sim 0.1\,\mathrm{eV} @ 95\,\%\,\mathrm{CL}$

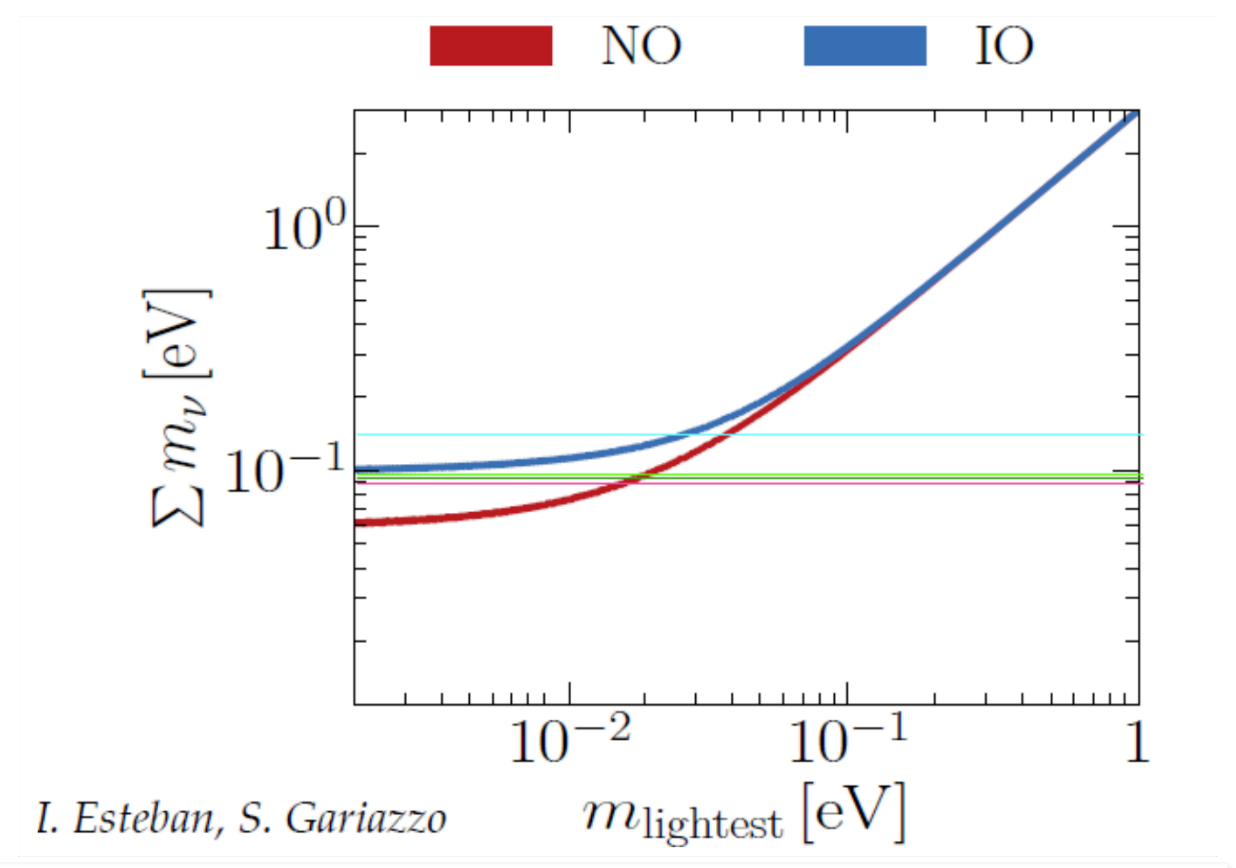
- Future experiments may determine the mass (4σ) in 10 years

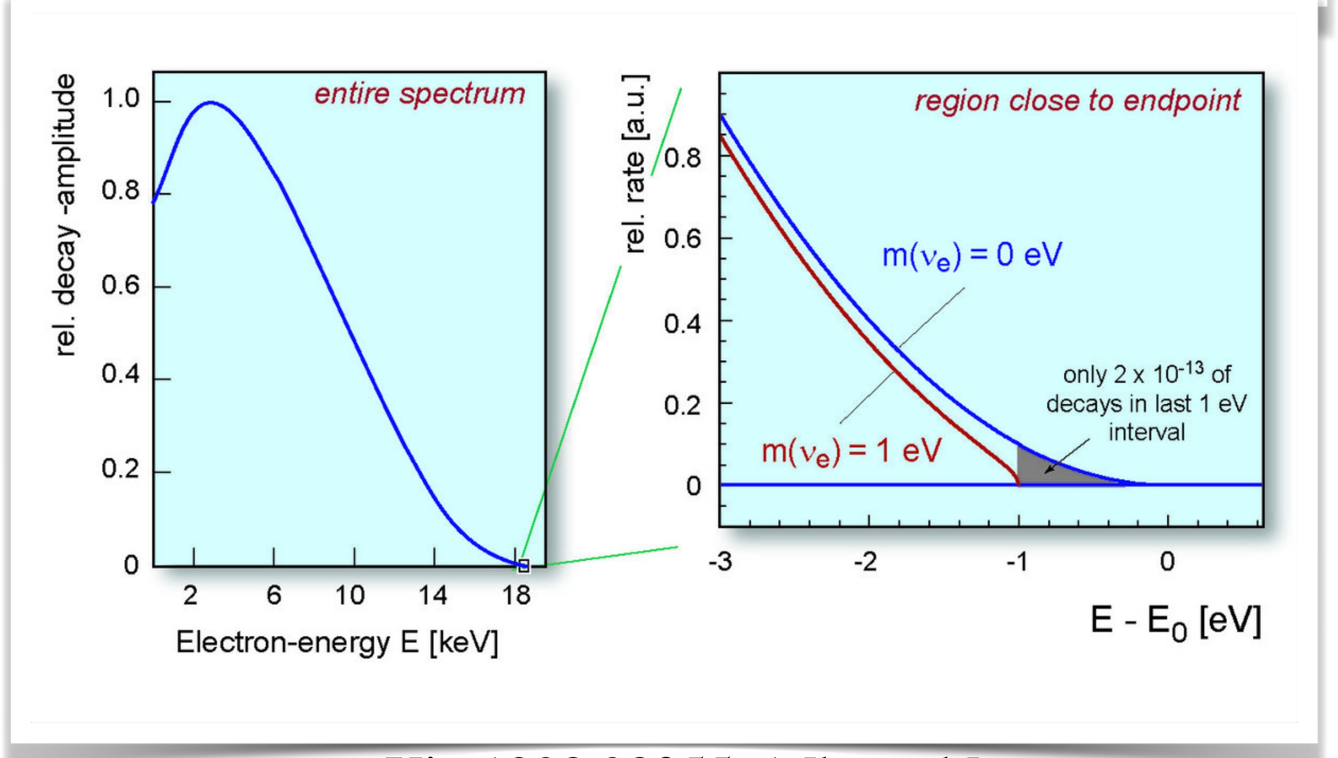
  - β decays can probe $m_\beta \sim 0.2\,\mathrm{eV}$ (future 0.02 eV ?)

$$m_\beta = \left[\Sigma_i \left|U_{ei}\right|^2 \; m^2_{\nu_i}\right]^{1/2}$$

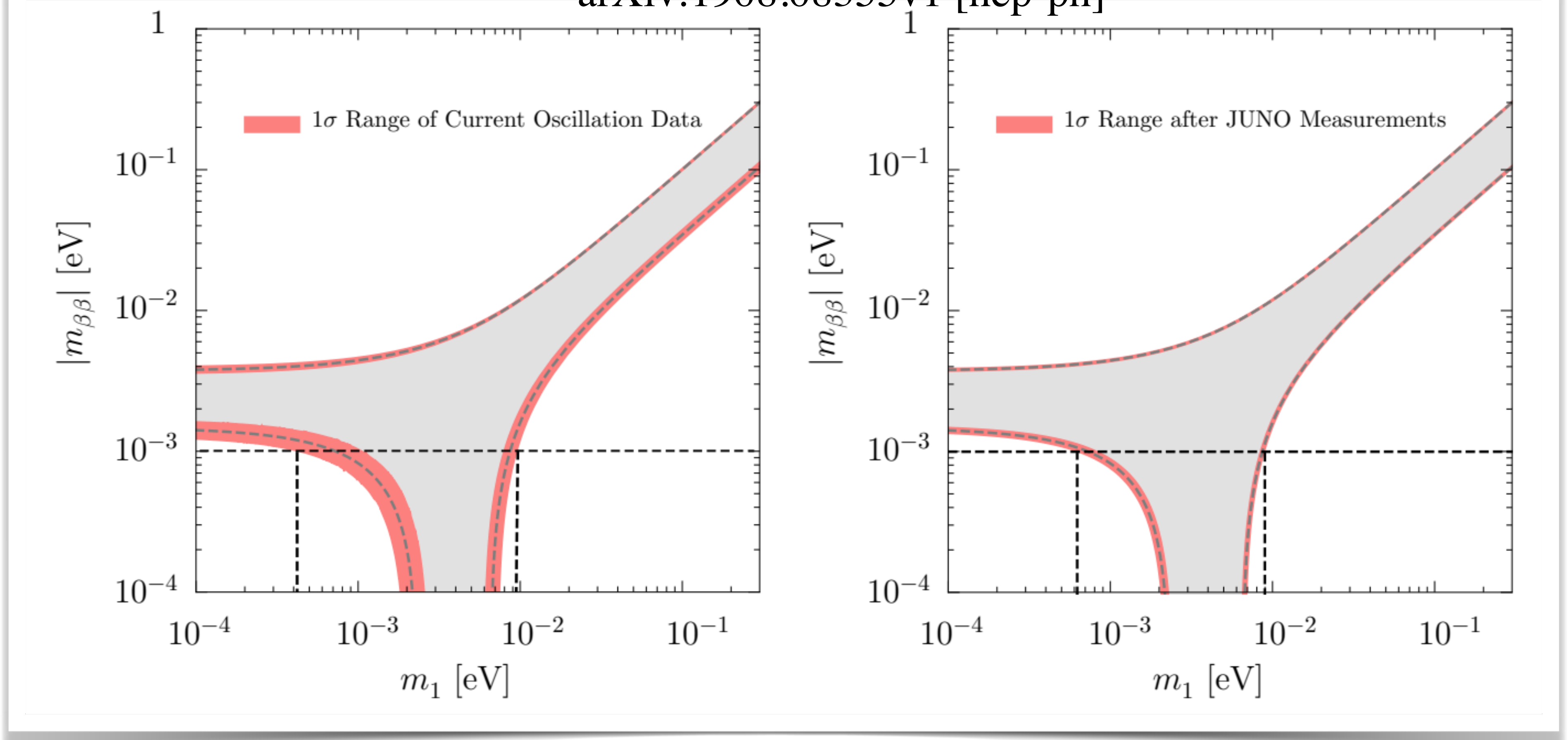
  - $0\nu\beta\beta$ decays can probe $M_{\beta\beta} \sim 0.01\,\mathrm{eV}$

$$\left|M_{\beta\beta}\right| = \left|\Sigma_i \left(U_{ei}\right)^2 \; m_{\nu_i}\right|$$

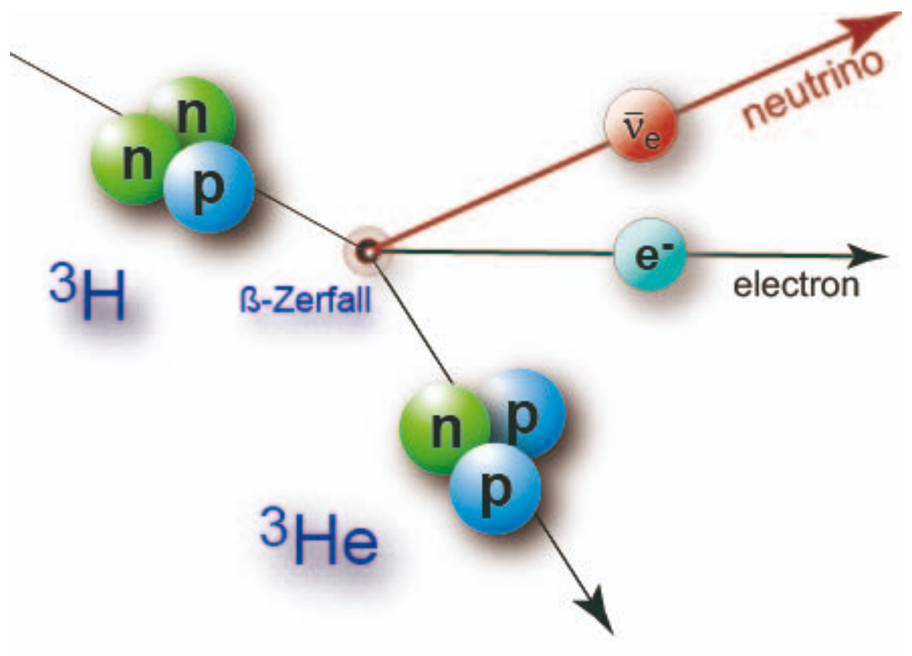




arXiv:1908.08355v1 [hep-ph]

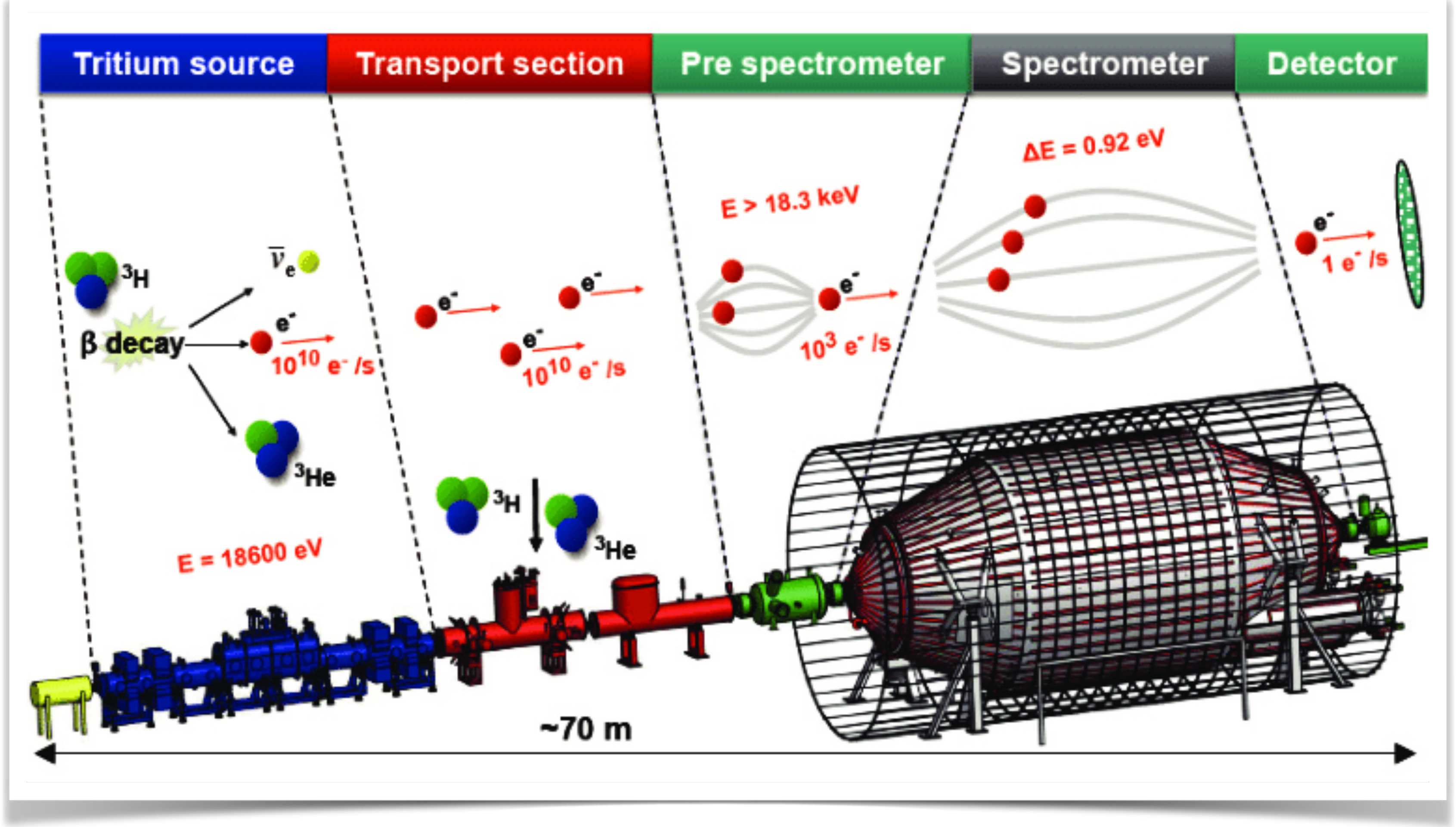


Direct Neutrino Mass Measurements

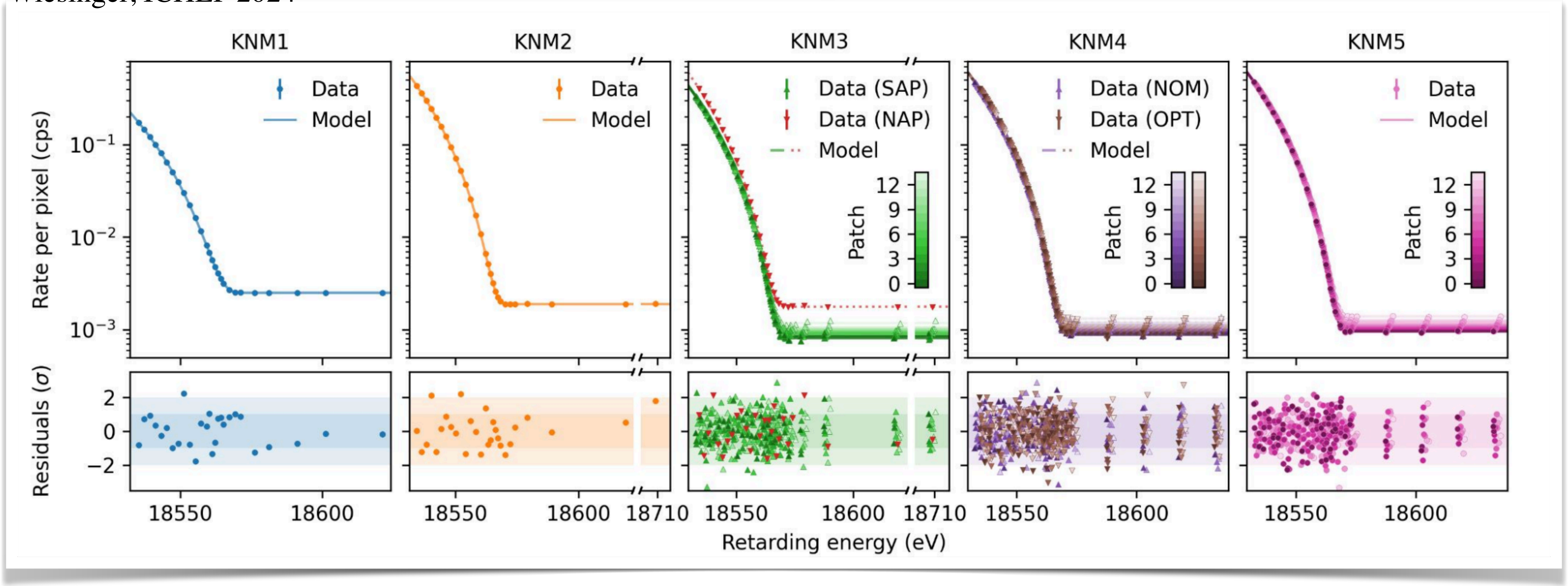


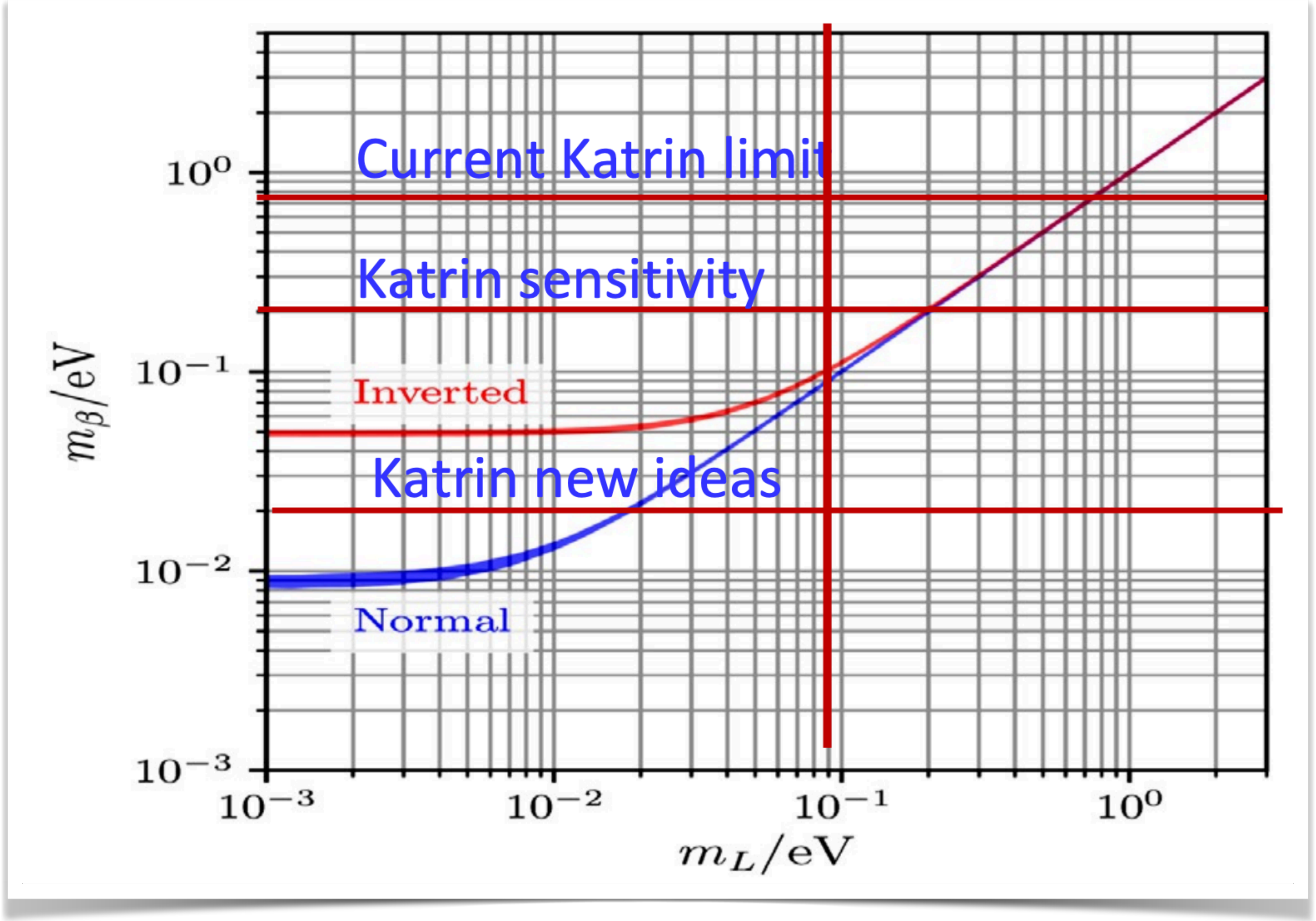
Key requirements:

- Strong radioactive source
- Tritium (12.3 years, $E_0 = 18.6\mathrm{keV}$)
- Holmium (4500 years, $E_0 = 2.8\mathrm{keV}$)
- Excellent energy resolution (1 eV)
- Low background (< 100 mcps)
- Understanding of spectral shape



arXiv:2406.13516v1 [nucl-ex]
Wiesinger, ICHEP 2024



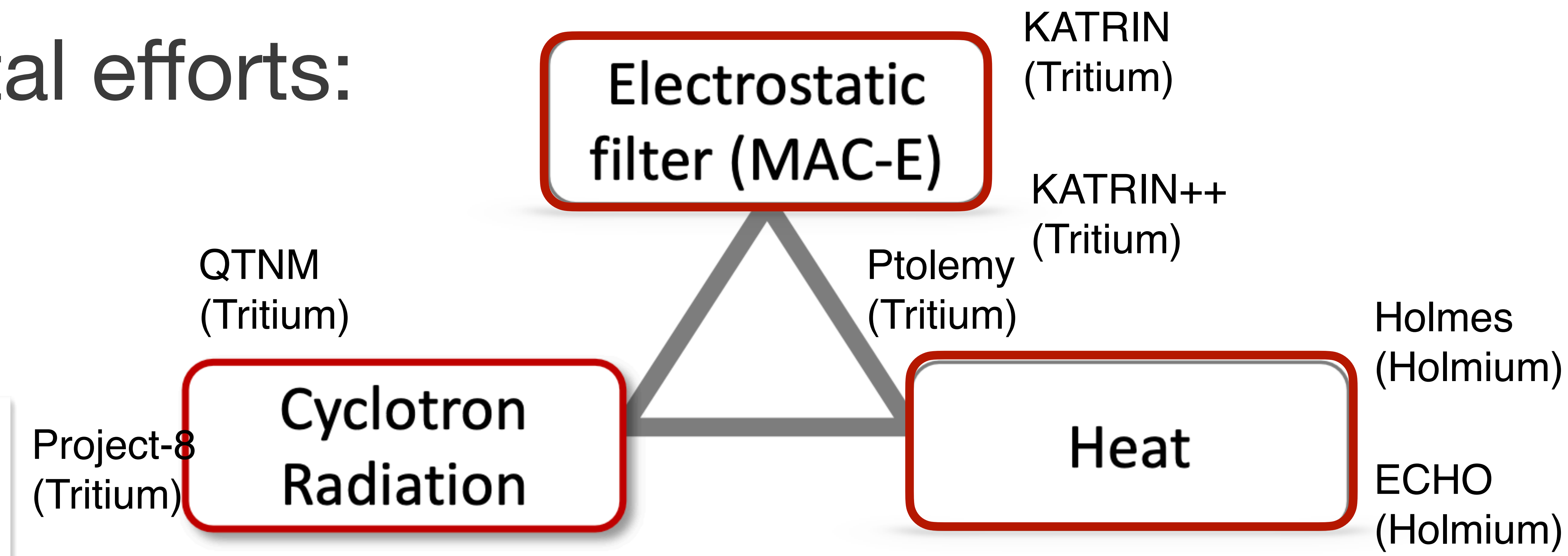


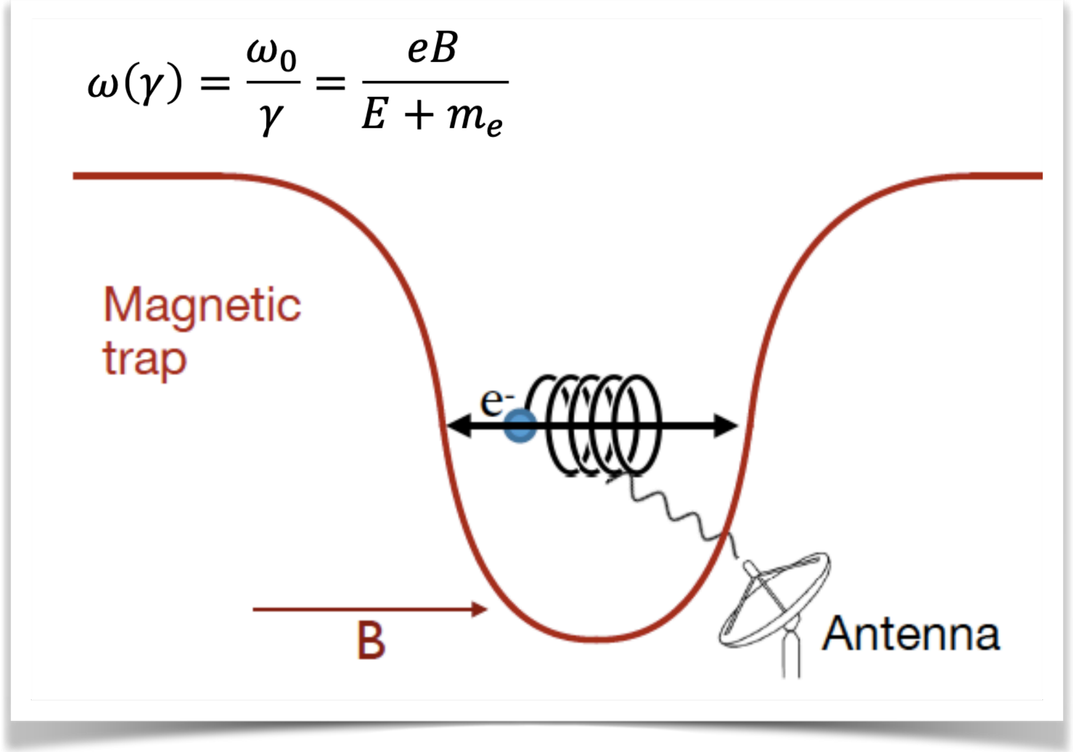
- 7 different configurations, 59 spectra, 1609 data points, parameter correlations across datasets.
- p -value =0.84, squared neutrino mass best-fit: $m_\nu^2 = -0.14^{+0.13}_{-0.15}\ eV^2$

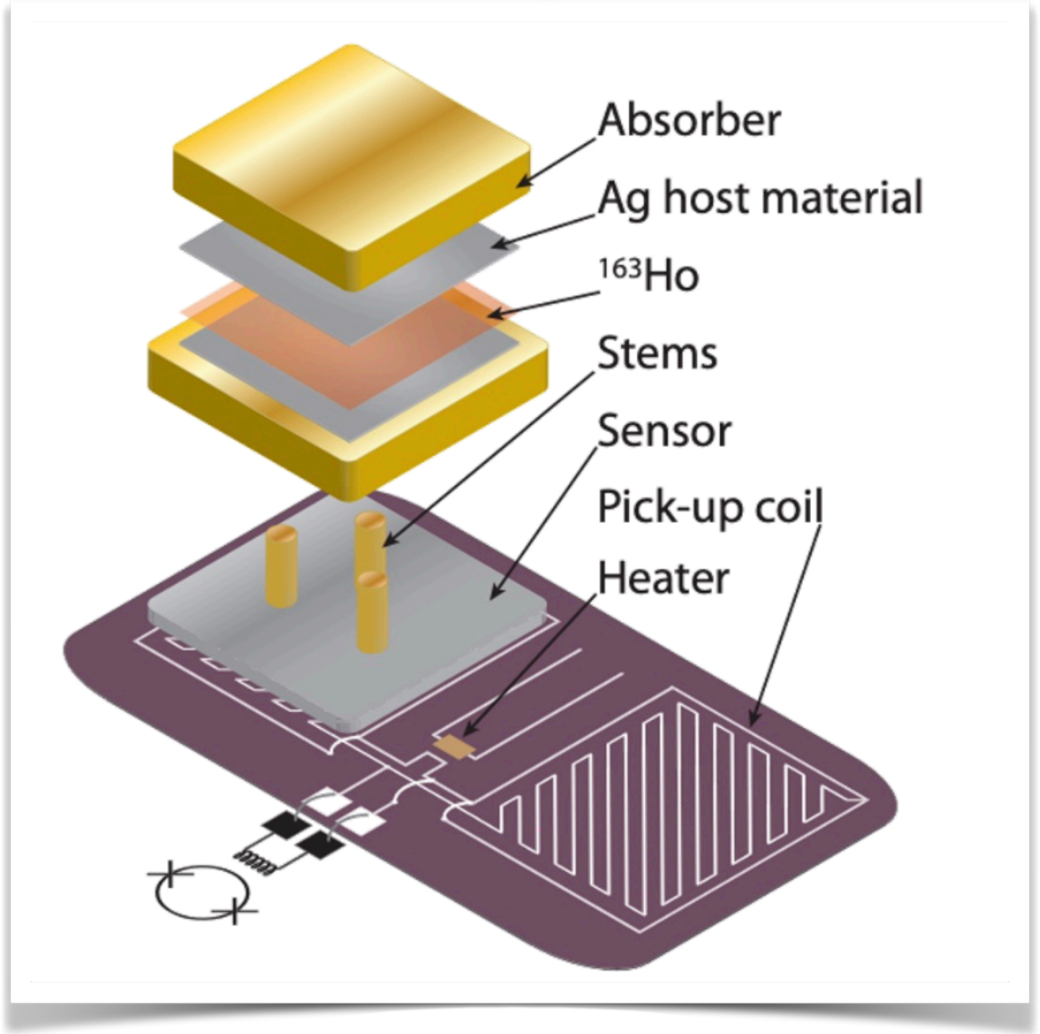
resulting in an upper limit of $m_\nu <$ 0.45 eV at 90 % confidence level.

Direct Neutrino Mass Measurements

Experimental efforts:







ECHO & HOLMS

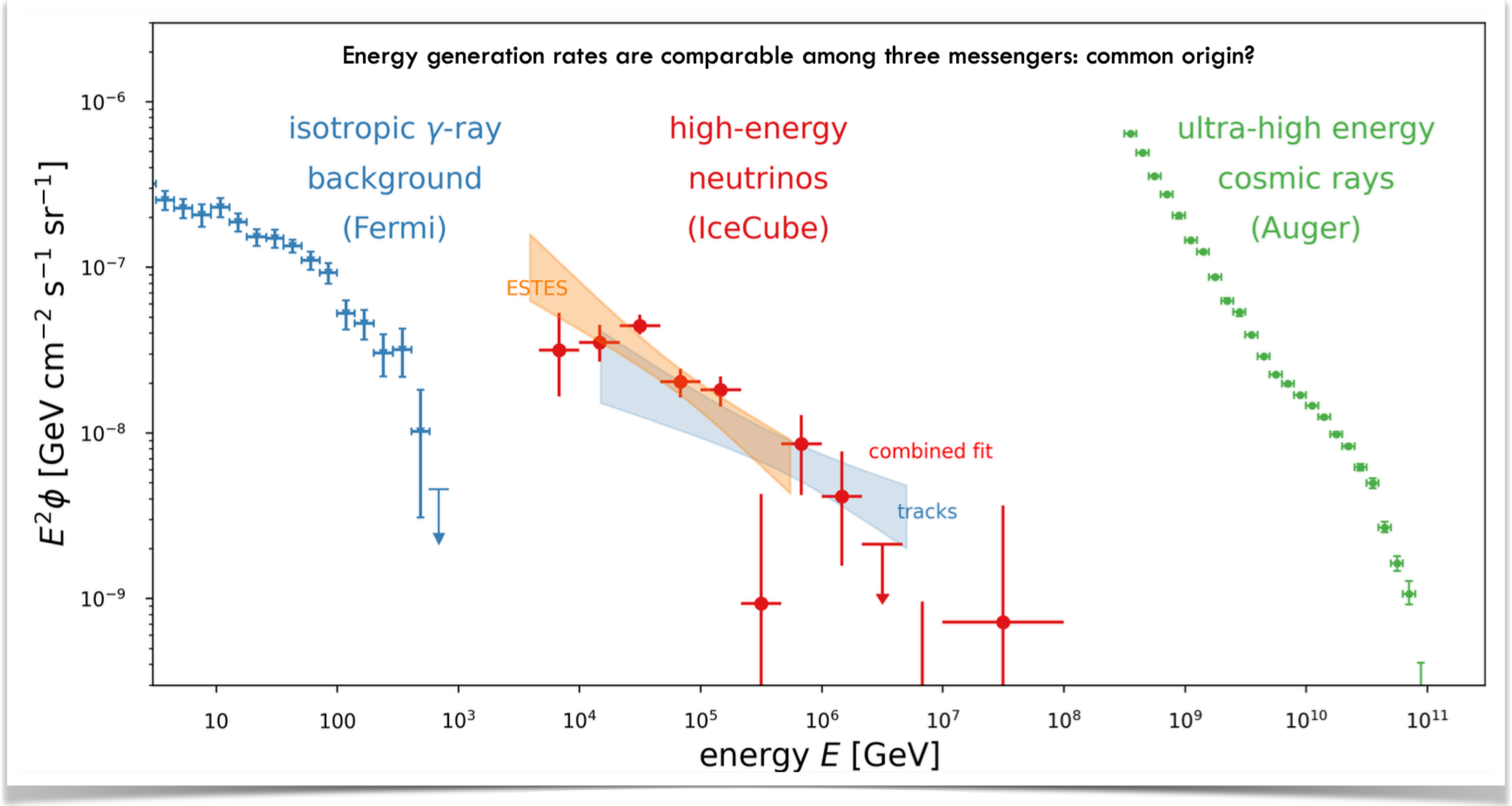
- Calorimetric sensors coupled to $^{163}\mathrm{Ho}$ implanted sources
- Obtained neutrino mass limit: 150 eV
- Promise: ~1eV

Project 8: Cyclotron Radiation Spectroscopy(CRES)

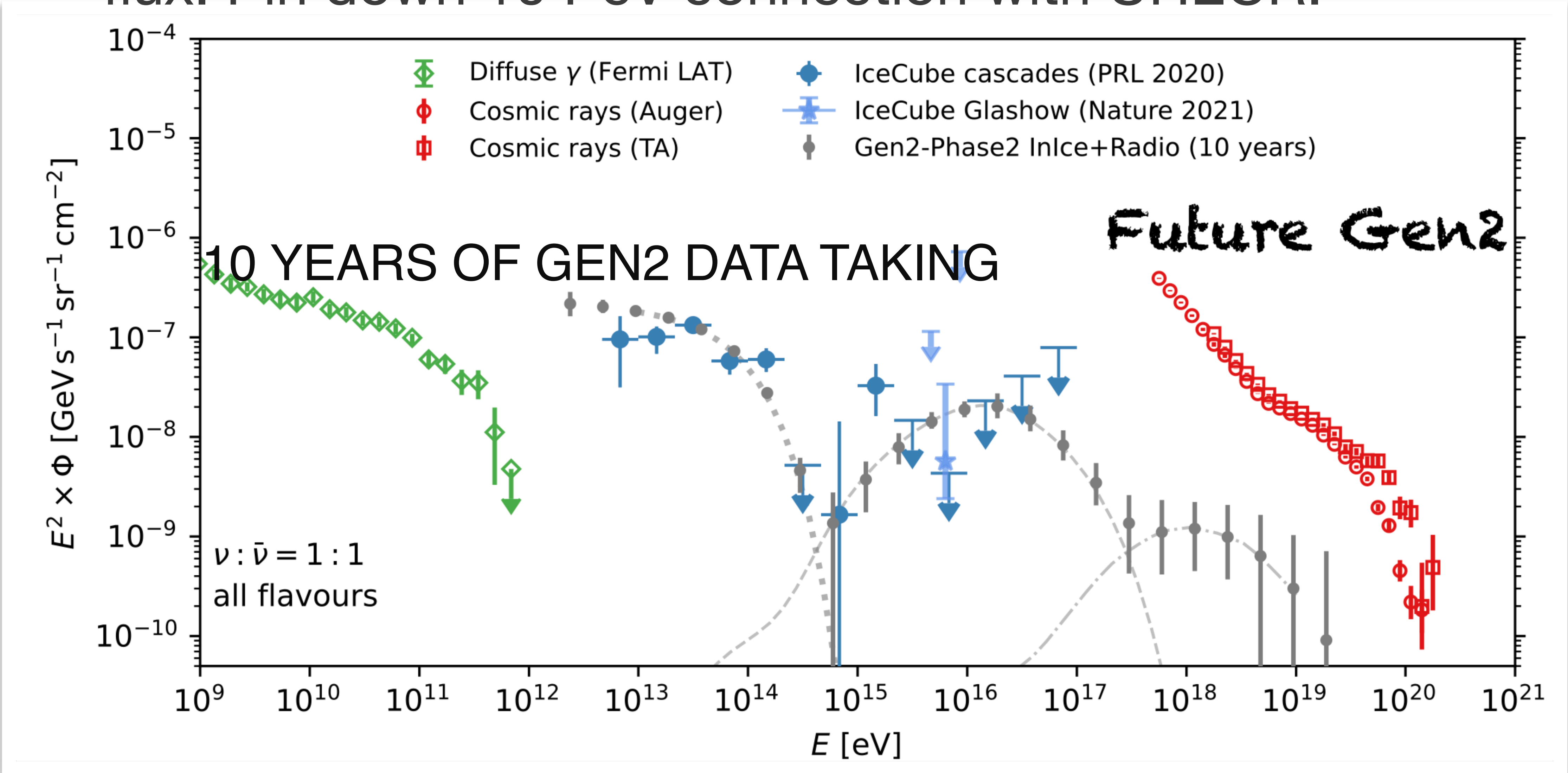
- Phase I: prove of principle (2016)
- Phase II successful (2016-2020)
  - Uncertainties understood
  - $\mathrm{m}_\beta < 178\mathrm{eV}$ @90% C.L.
- Phase III (ongoing):
  - Atomic T system & Larger cavity
  - Goal in 5 years: $m_\beta < 0.4\mathrm{eV}$
- Phase IV:
  - Goal: $\mathrm{m}_\beta < 0.04\mathrm{eV}$

Cosmic Neutrinos and Multimessangers

- Astrophysical neutrinos firstly observed by Icecube
  - Diffused flux and sources "identified". Several other observations (Glashow resonance, flavour measurements and identified ν_τ candidates, ν from the Galactic plane, etc.
  - Baikai-GVD confirmed the flux result, KM3NET is joining
- Multi-messengers detectors to provide a wide range of measurements:
  - neutrinos: JUNO, Hyper-K, DUNE, ...
  - GWs: LIGO, Virgo,Kagro, Cosmic-Explorer, LISA,...
  - Cosmic-rays and HE γ's: CTA, HWAC, HESS, Magic, LHAASO, CTA, ...
  - γ-rays and X-rays in space: Swift, Fermi, GECAM, eXTP,...
- A bright new era for astrophysics:
  - Are high-energy neutrinos linked to ultra-high-energy sources?
  - When and how will the first cosmogenic neutrino be detected?
  - What are the primary sources contributing to the IceCube diffuse flux?



- Gen2: Precise characterisation of Astrophysical Diffuse flux. Pin down 10 PeV connection with UHECR.



Conclusions

- Increasing precision of neutrino experiments, but still important discoveries ahead of us and experiments are soon starting to take data:
  - CP violation observation, mass ordering, θ_{23} octant,..
  - Neutrino Dirac or Majorana.
  - Neutrino mass
  - Sterile neutrinos
  - Astrophysical neutrinos.

- Stay tuned for more exciting results and (bopefully) some surprises!