



Progress in neutrino physics

Liudmila Kolupaeva (DLNP JINR)

Part I: Study of neutrino properties



Proton path

Neutrino transformed into μ -meson

Invisible neutrino collides with proton

Collision creates π -meson

The 'Neutrino Event'
Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber

Neutrino oscillations and mixing

Talk by
Prof. Yu. Kudenko on Wednesday

atmospheric
accelerator

short baseline reactor
accelerator

solar
long baseline reactor

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

Oscillation parameters and how precisely do we know them:

$$\theta_{12} \approx 34^\circ \quad (4.4\%)$$

$$\theta_{23} \approx 49^\circ \quad (5.2\%)$$

$$\theta_{13} \approx 9^\circ \quad (3.8\%)$$

$$\Delta m_{21}^2 \approx 7.4 \times 10^{-5} \text{ eV}^2 \quad (2.2\%)$$

$$\Delta m_{32}^2 \approx +2.5 \times 10^{-3} \text{ eV}^2 \quad (1.4\%)$$

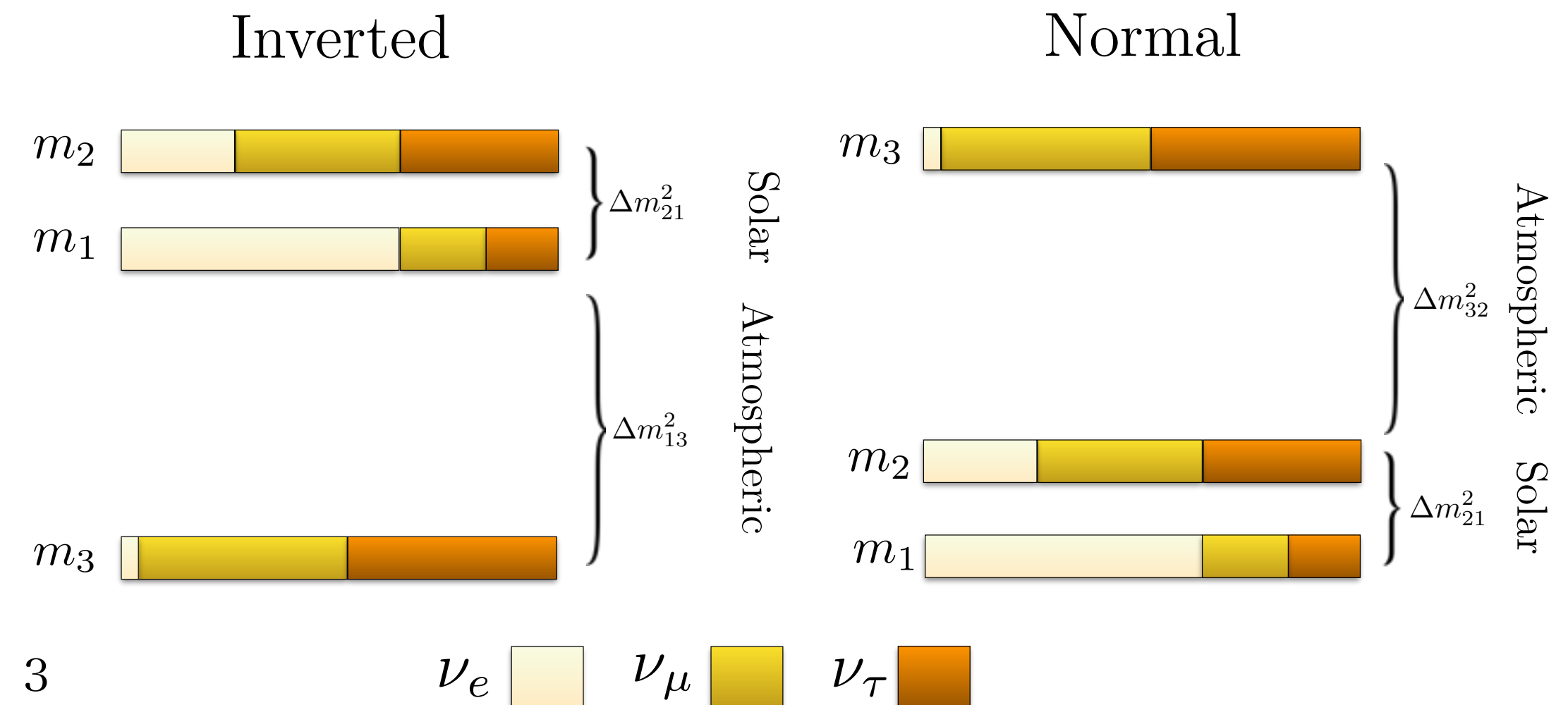


Open questions:

Is $\theta_{23} 45^\circ$?

Is there CP violation in lepton sector?

Neutrino mass hierarchy (ordering) is Normal or Inverted?



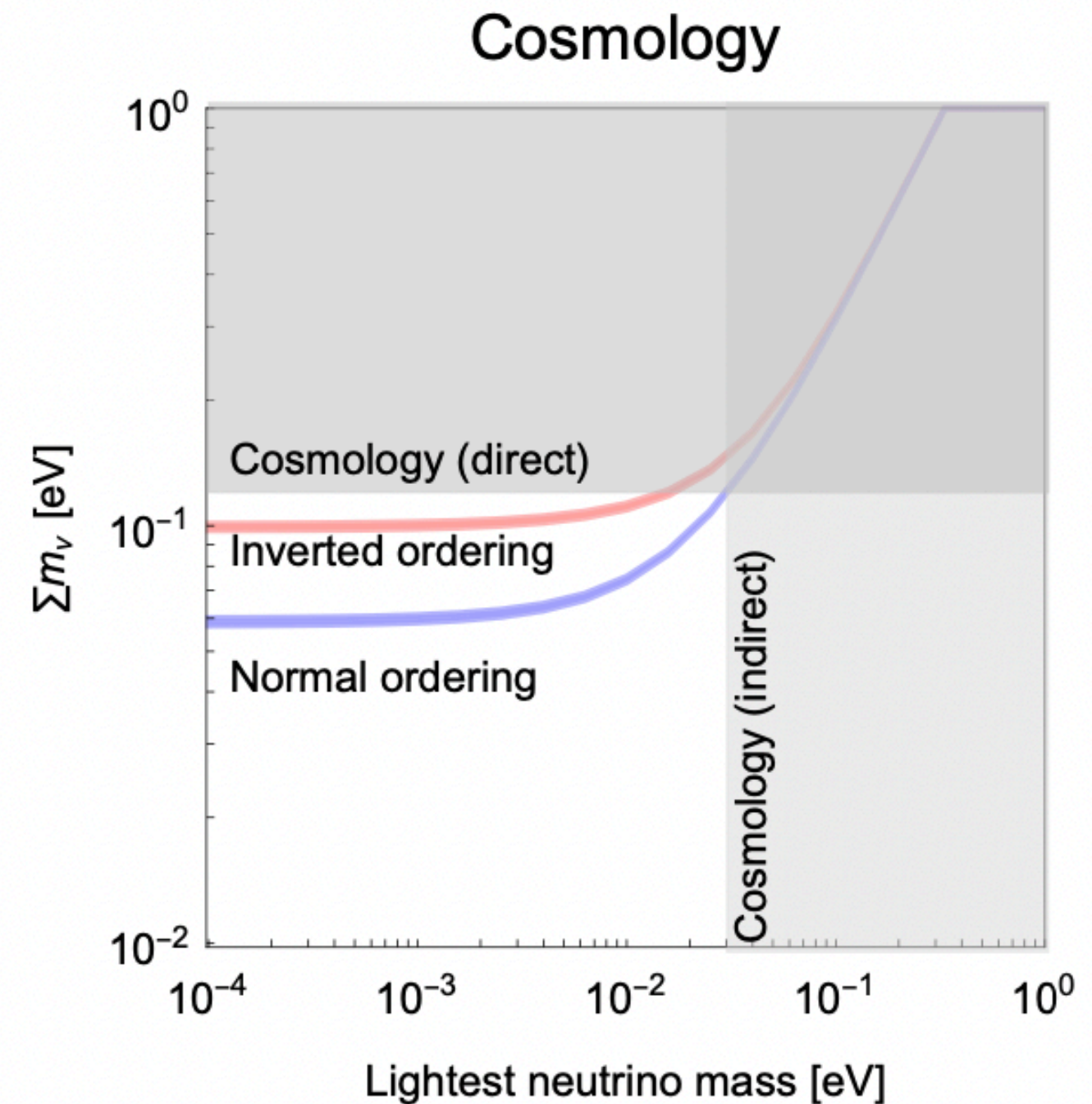
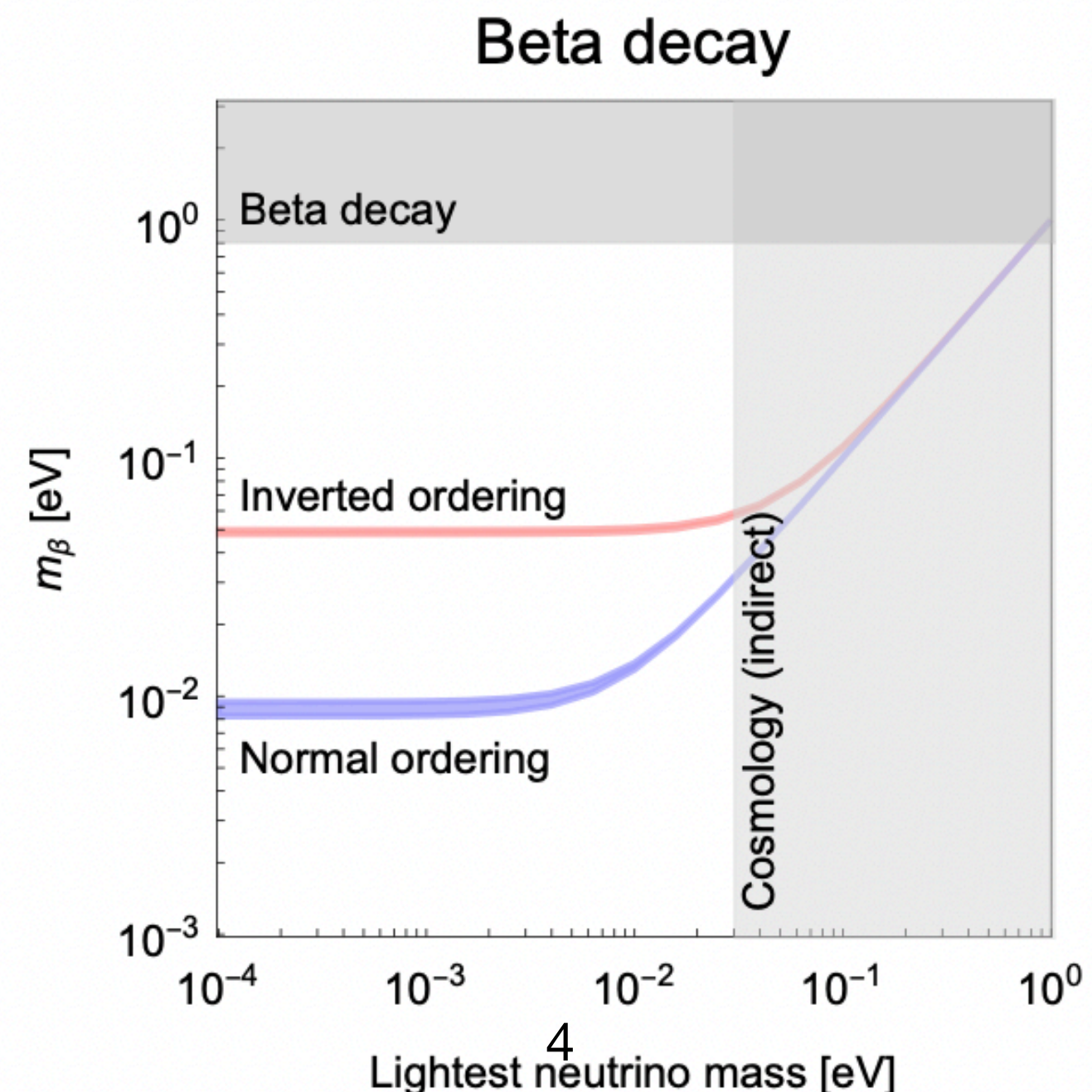
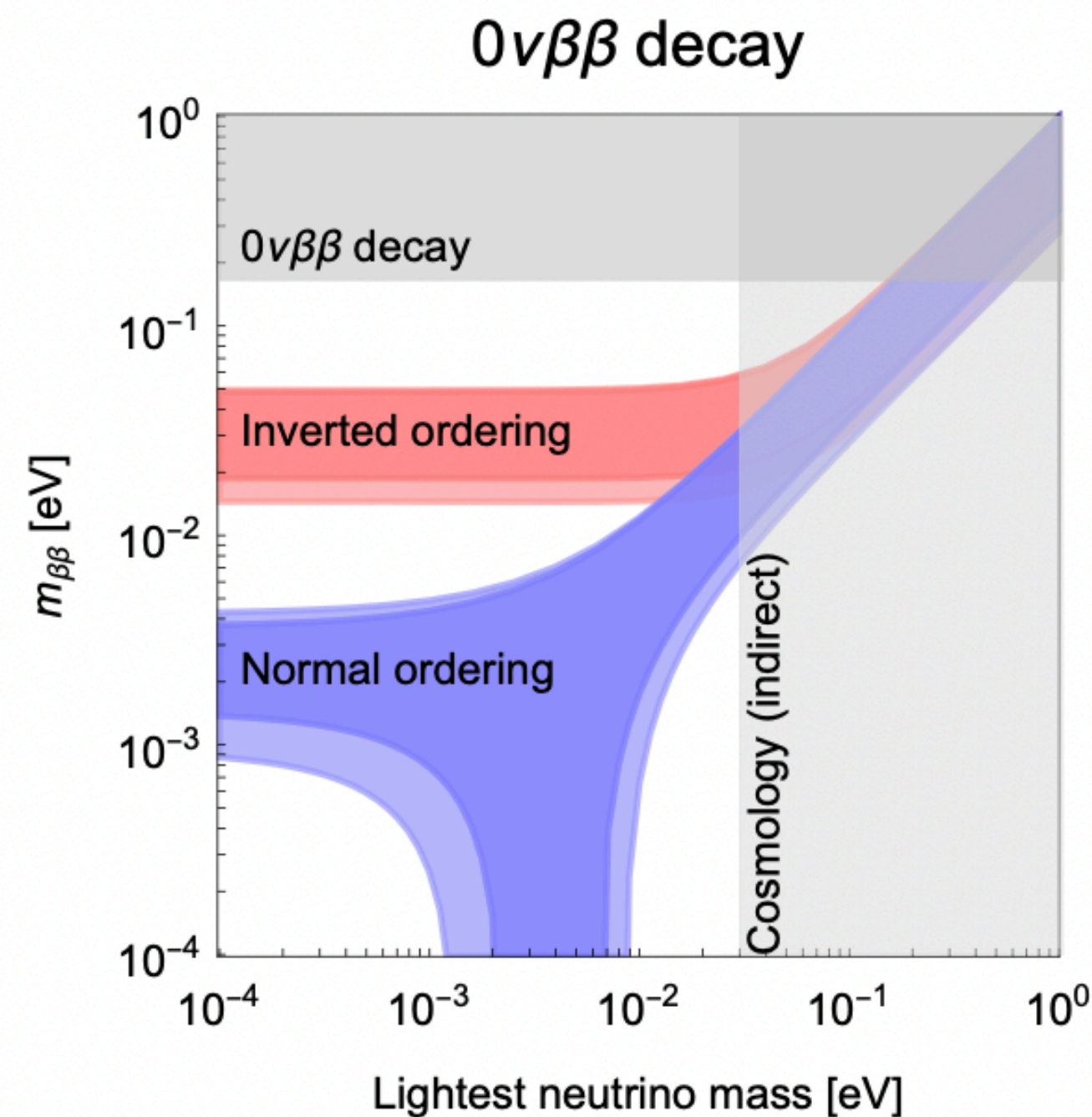
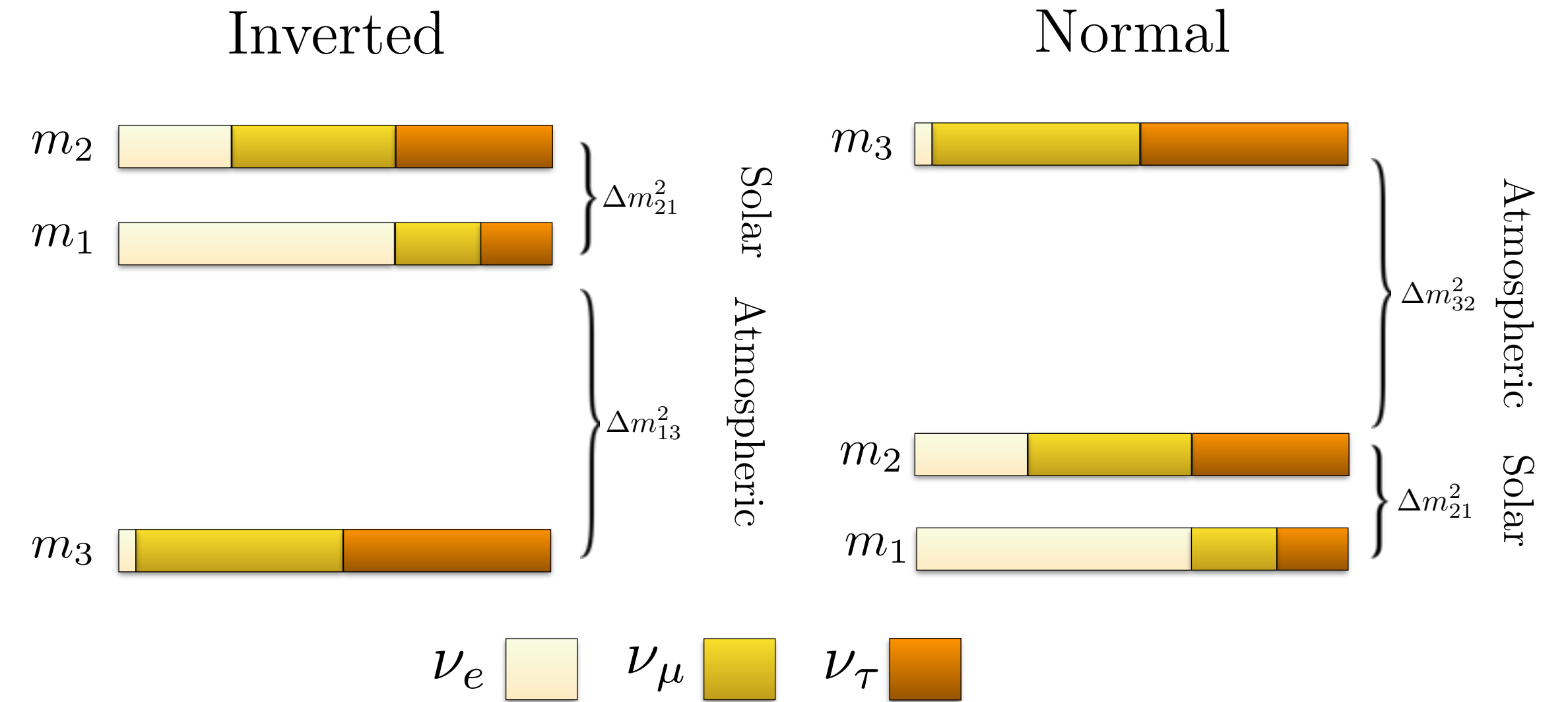
Motivation

Neutrino mass ordering

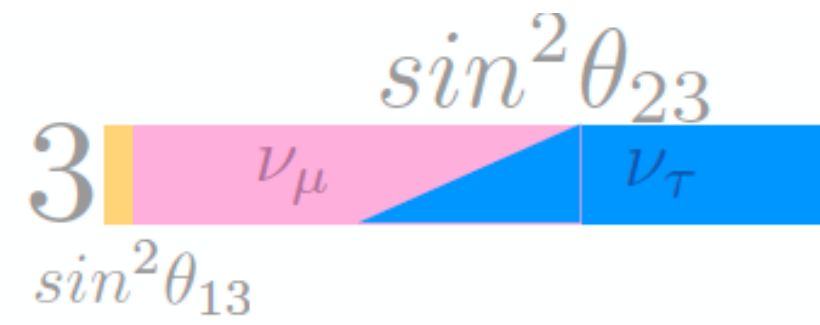
Mass hierarchy/ordering plays important role for:

- * neutrinoless double beta-decay searches,
- * supernova simulations,
- * relic neutrinos searches,
- * absolute ν mass measurements etc.

So it affects everything connected with ν masses



Motivation



θ_{23} is responsible for possible ν_μ and ν_τ symmetry in ν_3

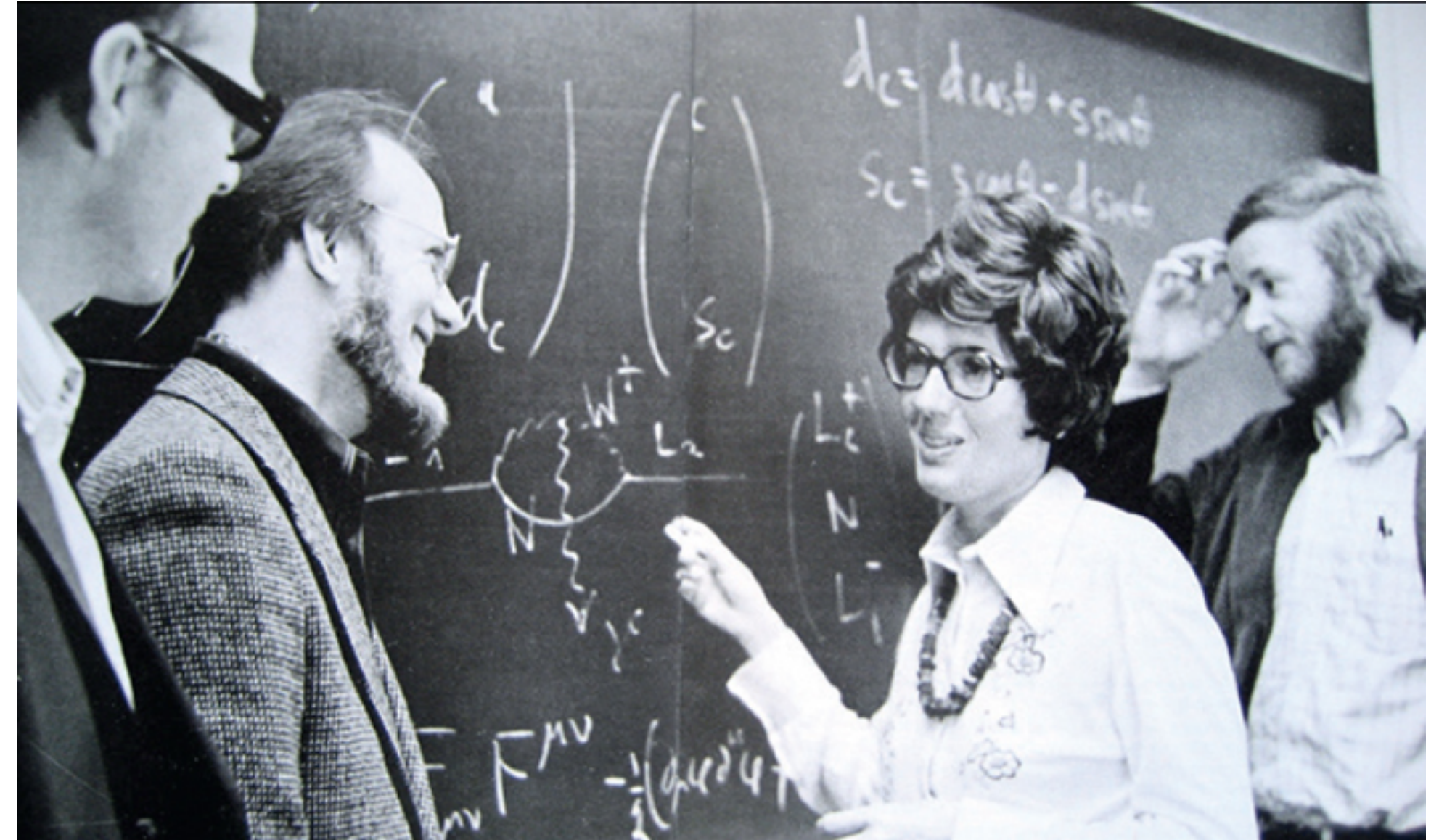
δ_{CP} may be connected with matter-antimatter asymmetry of the Universe (leptogenesis)

$$\frac{J_{\text{PMNS}}}{J_{\text{CKM}}} = \frac{3 \times 10^{-2}}{3 \times 10^{-5}} \sin(\delta_{\text{PMNS}})$$

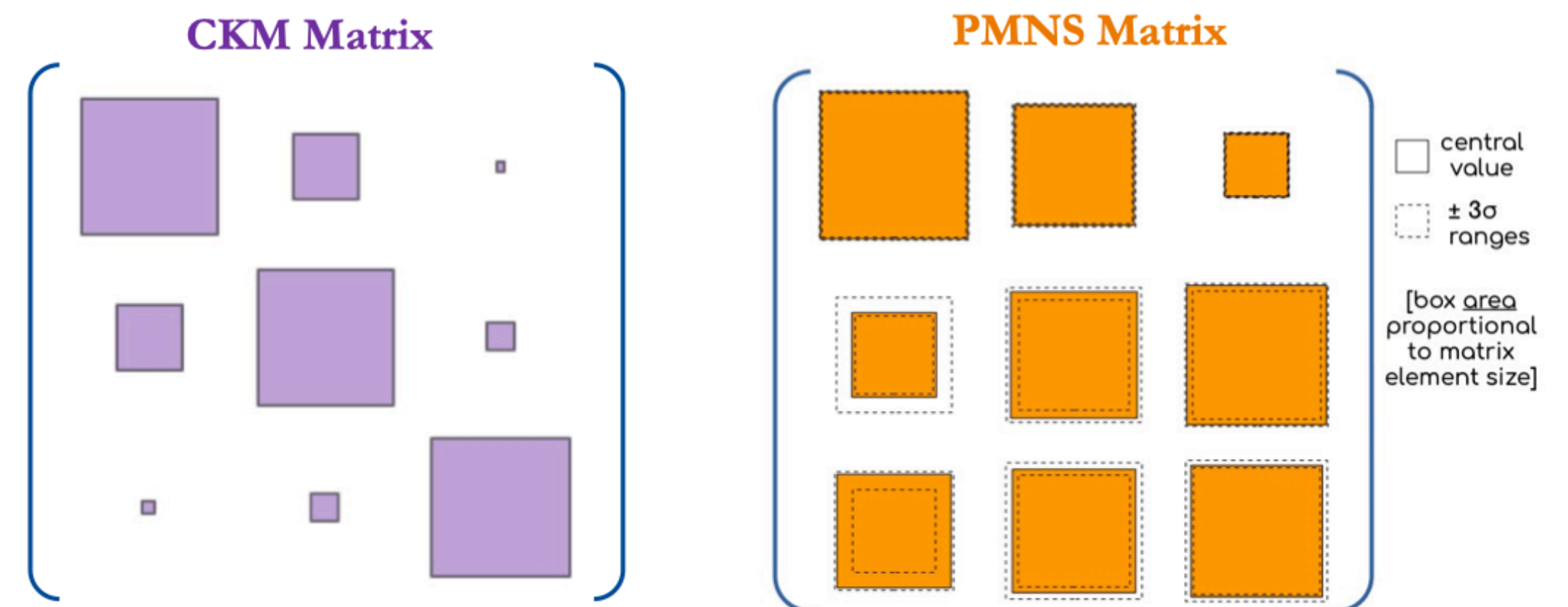
The very final goal of all these measurements is the creation of theory that can also explain the smallness of neutrino masses and mixing, and its unification with SM.

Neutrino parameters as test for theories (check sums).

Unitarity of mixing matrix.



$$J \equiv s_{12}c_{12}s_{13}c_{13}^2s_{23}c_{23} \sin \delta$$

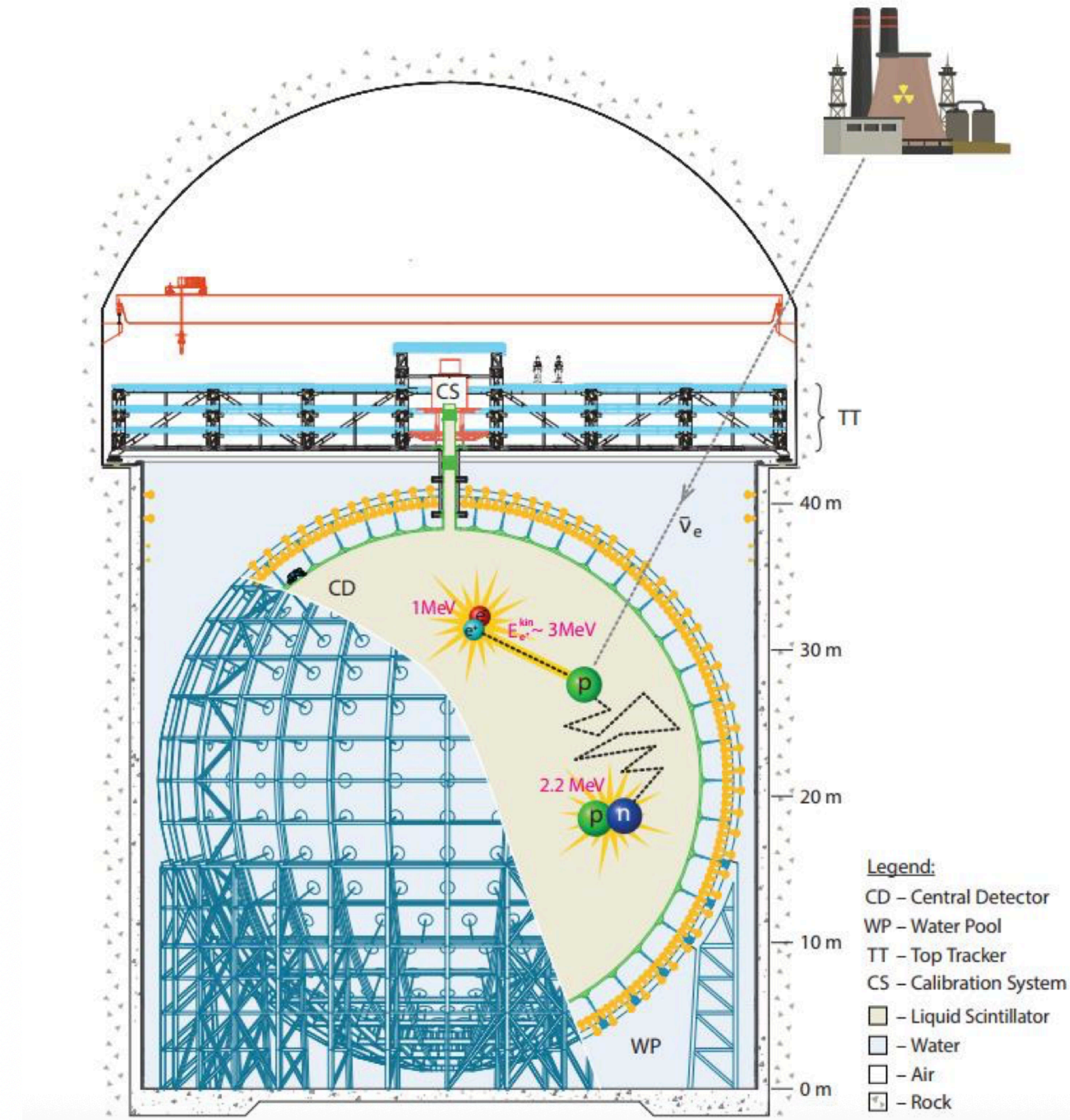
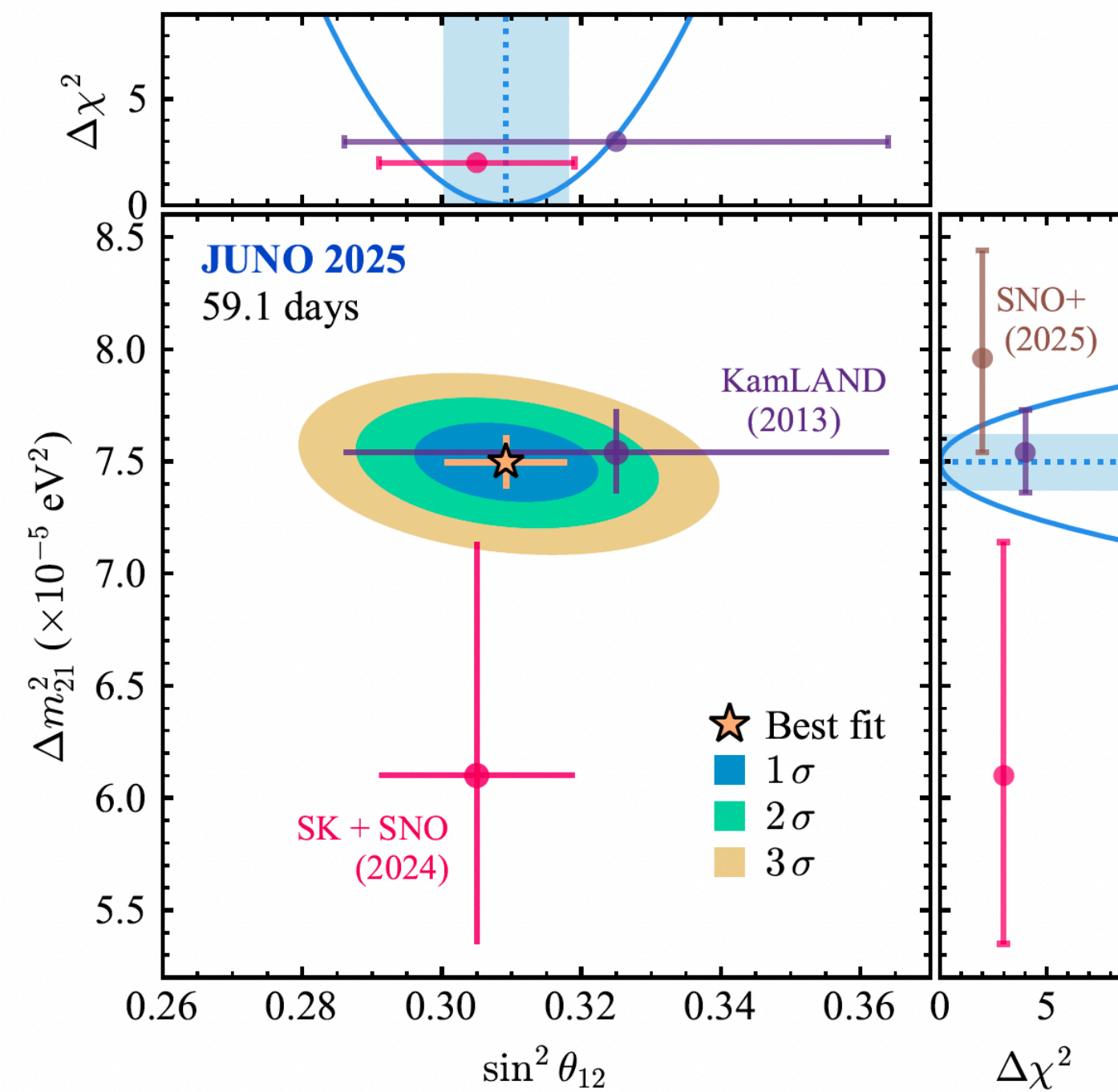


Three-flavo(u)r oscillations these days

Talk by D. Dolzhikov on Monday

Interesting highlights: JUNO start of data-taking

- * 20kt LS detector in China to measure oscillation parameters with reactor antineutrinos
- * First analysis with just 59 days of data in the end of 2025
 - * The most precise θ_{12} and Δm_{21}^2
- * Main goal is to measure NMO in 7 years at 3σ
 - * But energy resolution is crucial to achieve it. So far it's a little bit high in JUNO
- * Unprecedented sensitivity to Δm_{32}^2 , θ_{12} and Δm_{21}^2 that is not energy resolution dependent
- * And much much more



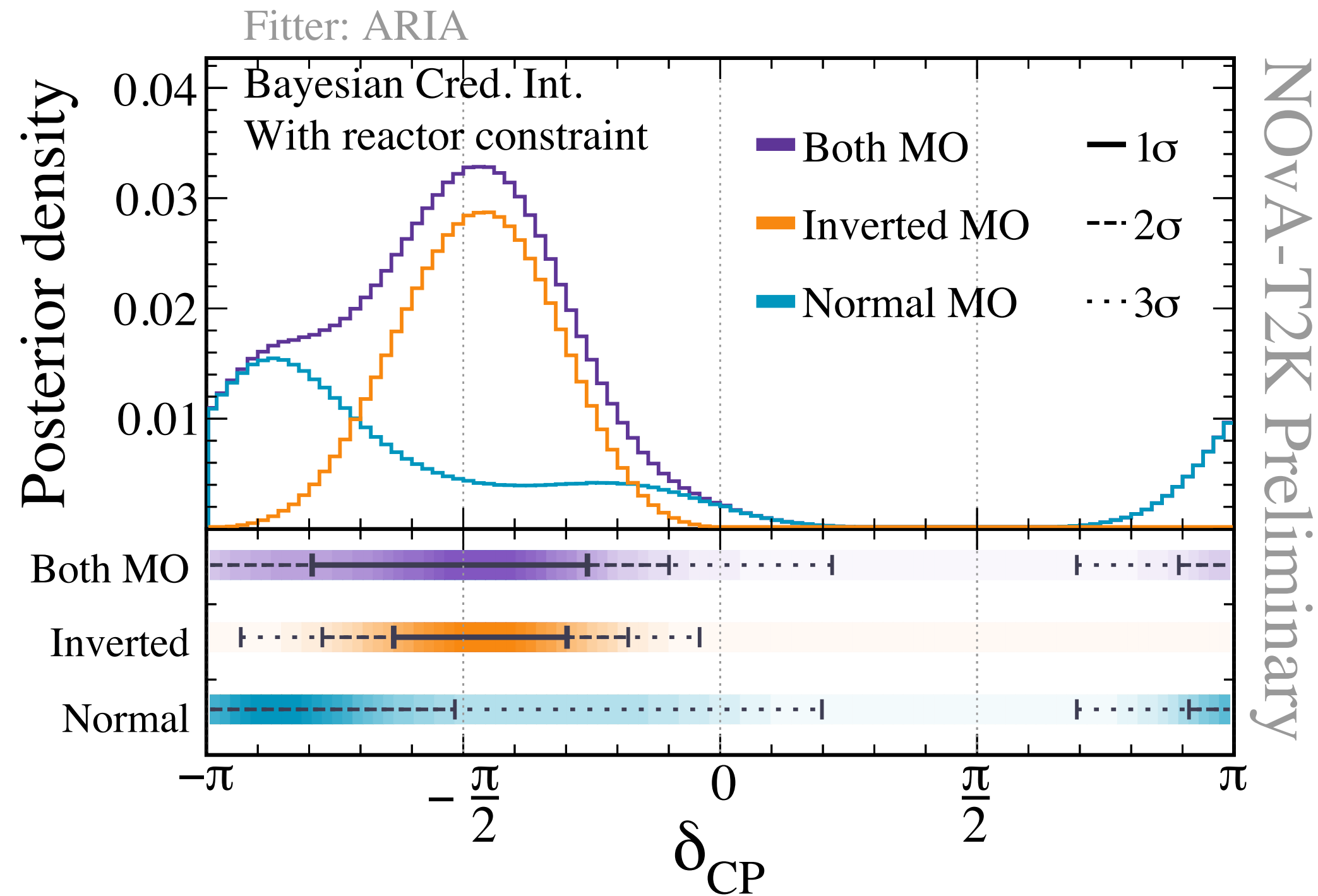
$$\sin^2 \theta_{12} = 0.3092 \pm 0.0087 \quad (2.8\%)$$

$$\Delta m_{21}^2 = (7.50 \pm 0.12) \times 10^{-5} \text{ eV}^2 \quad (1.6\%)$$

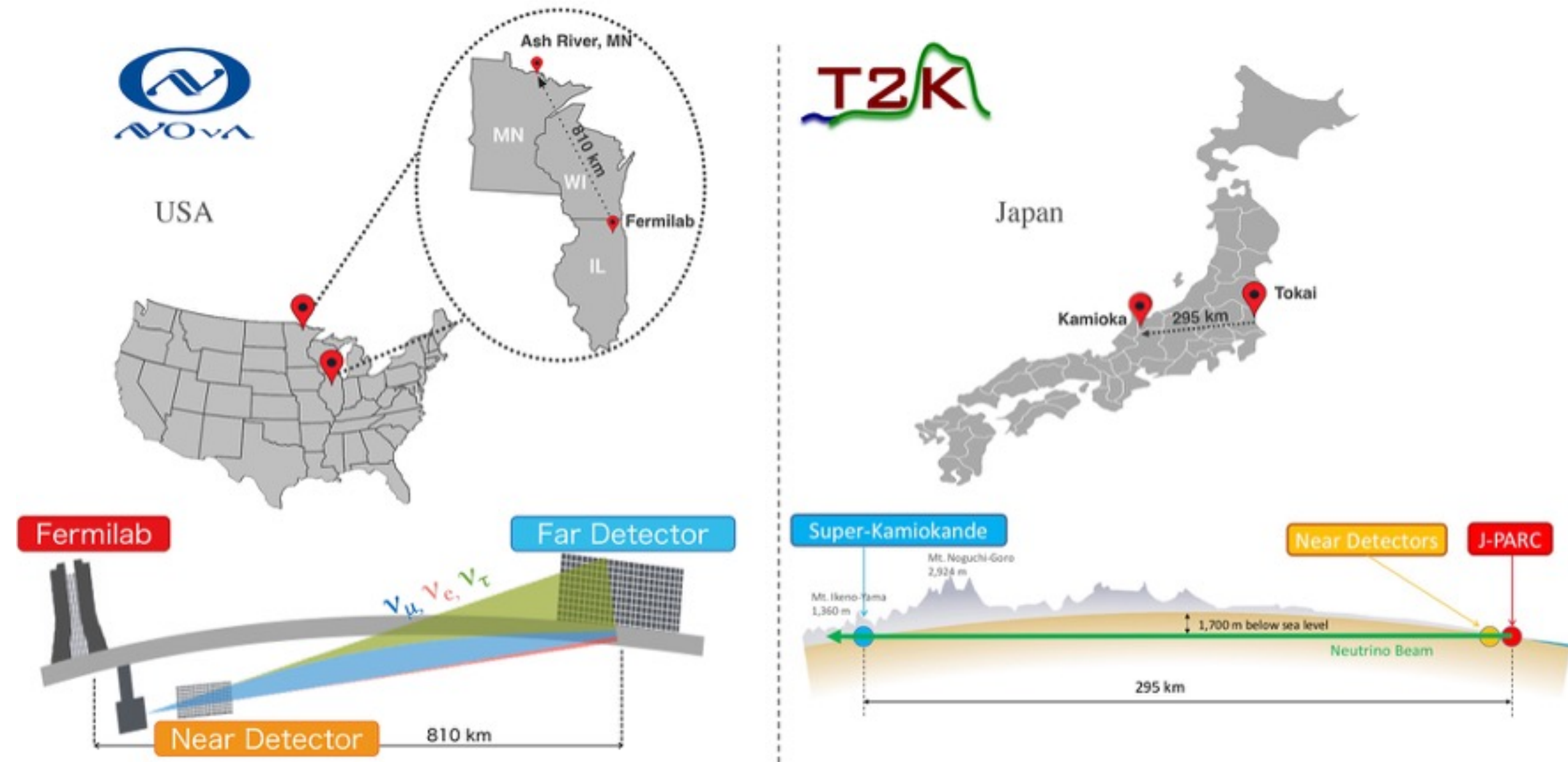
Three-flavo(u)r oscillations these days

Interesting highlights: full-fledged joint analysis of NOvA and T2K

- * First attempt of this kind for neutrino physics
- * NB: there were joint analyses in HEP (LEP, LHC)



Nature 646, 818–824 (2025)



- * Full implementation of:
 - * energy reconstruction and detector response;
 - * detailed likelihood from each experiment;
 - * consistent statistical inference across the full dimensionality.

Three-flavo(u)r oscillations these days

How are we doing with the goals?

- * It's clear that presently running experiments can't finalize the measurements of oscillation parameters. It is expected to be done by the next gen. of experiments.

- * Looks like we're in unlucky region of sensitivity.

- * Despite this, the strategy is to do the best measurements we can

- * Obtain the first indications on unmeasured parameters,

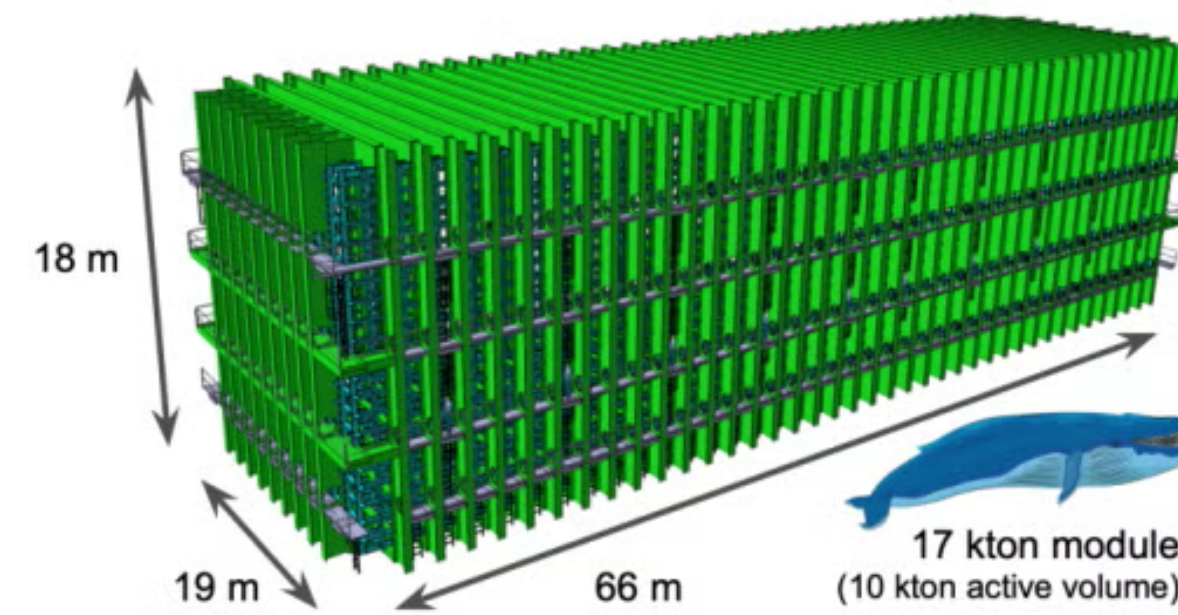
- * Improve the precision of other osc. parameters.

- * Another goal is creation of methodical basement for the next generation experiments by:

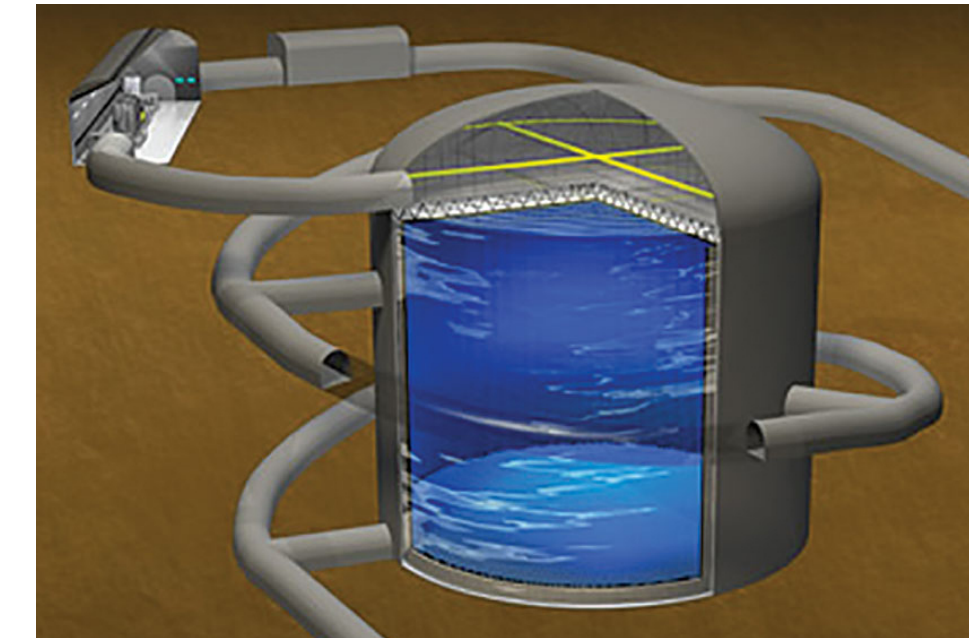
- * Refining the systematic uncertainties,

- * Improving the approaches for simulation, reconstruction, analysis, etc.

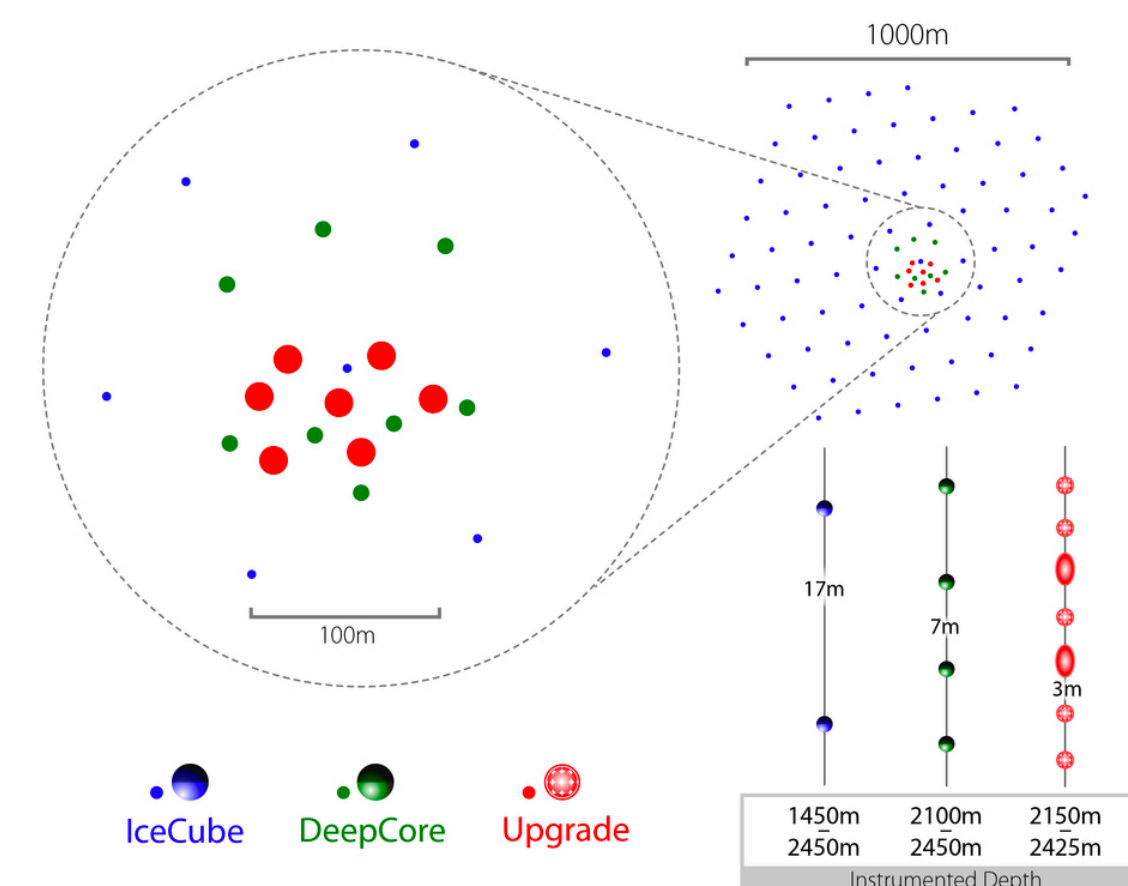
DUNE (start w/ acc. beam in ~2031)



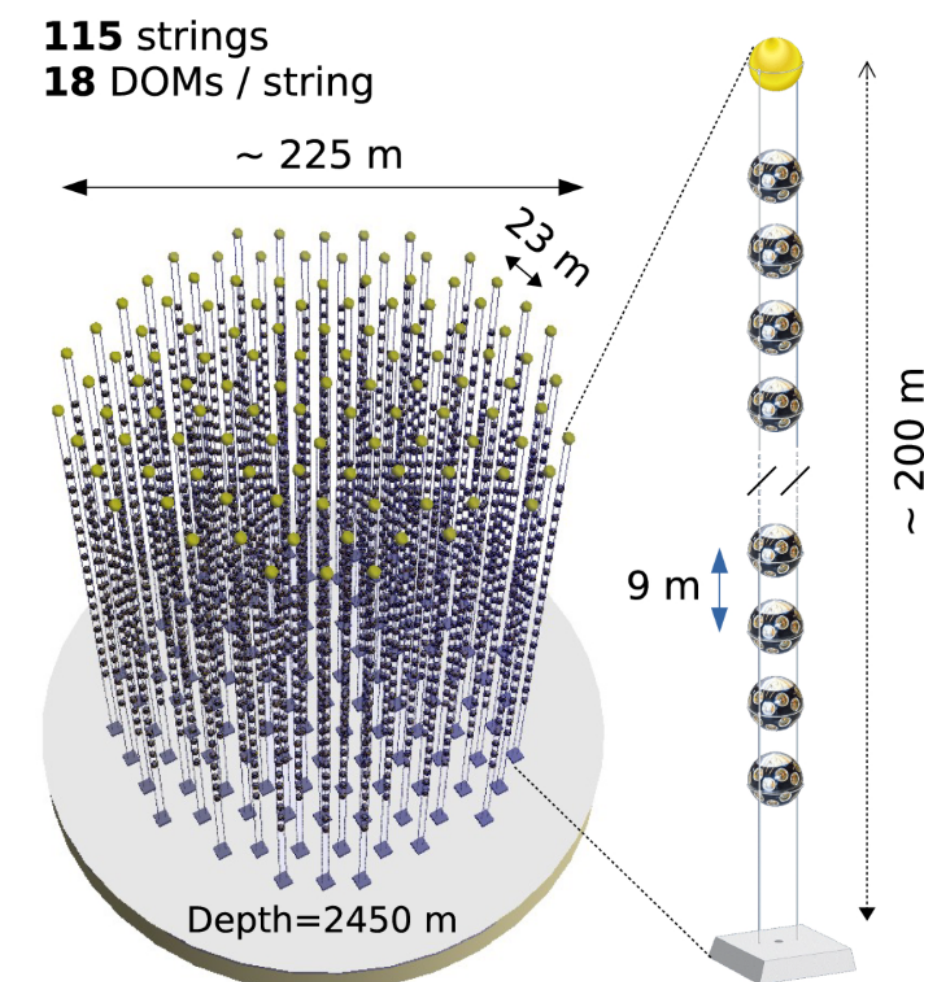
HyperK (start in ~2027)



IceCube Upgrade
(strings deployed in 2026)

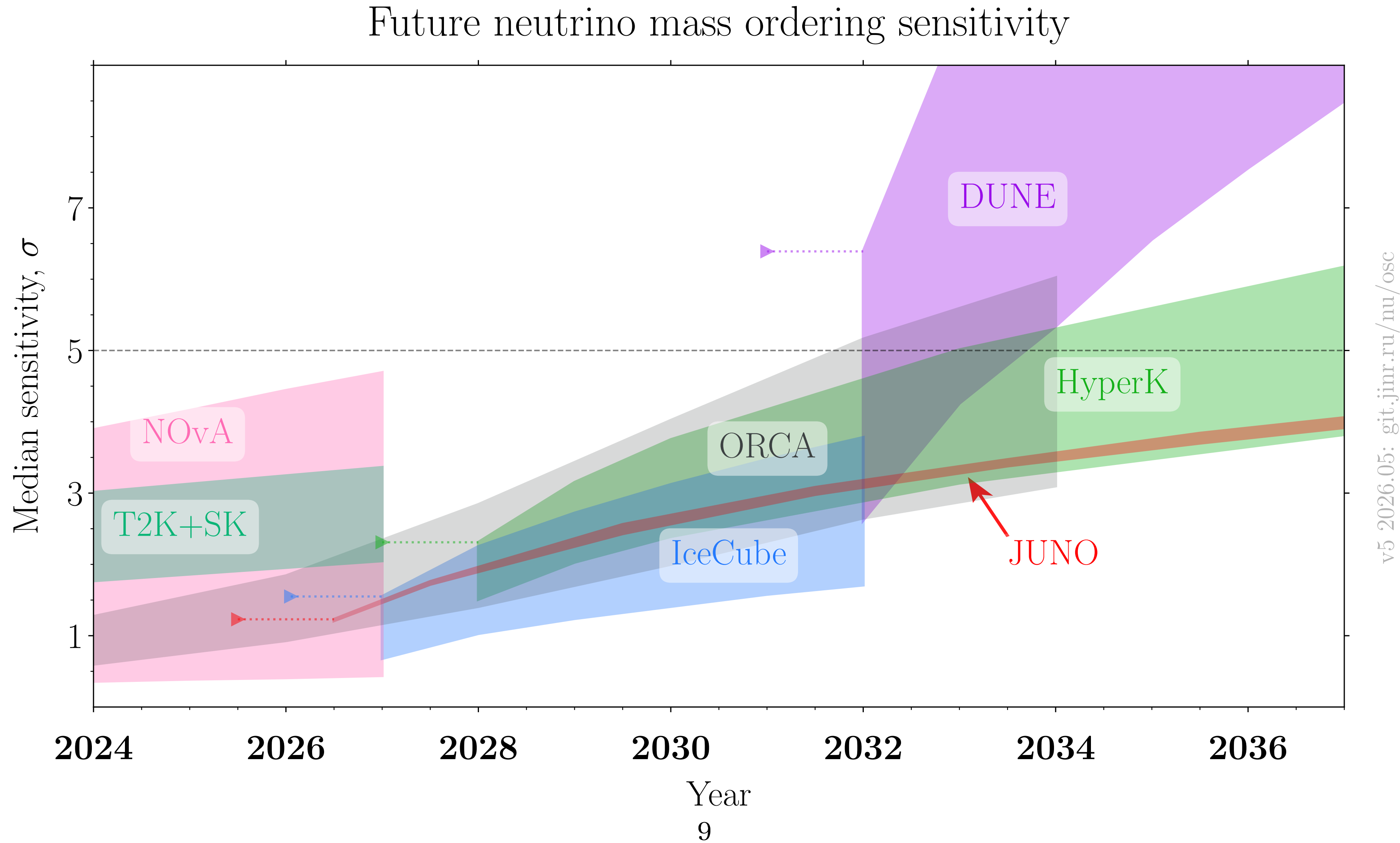


ORCA @ KM3NeT
(33/115 strings installed,
Complete by ~2030)



Three-flavo(u)r oscillations

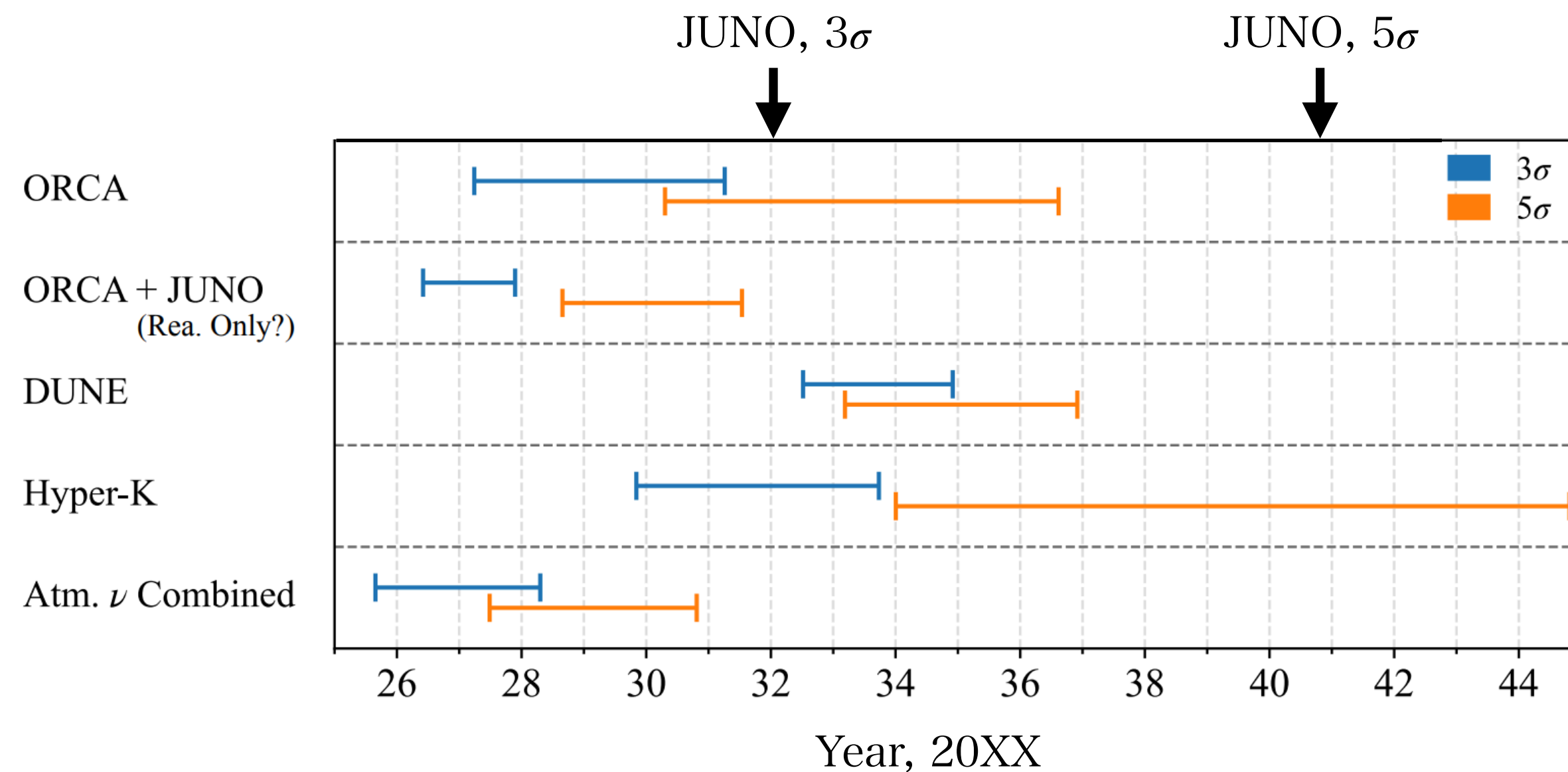
Future landscape: neutrino mass ordering



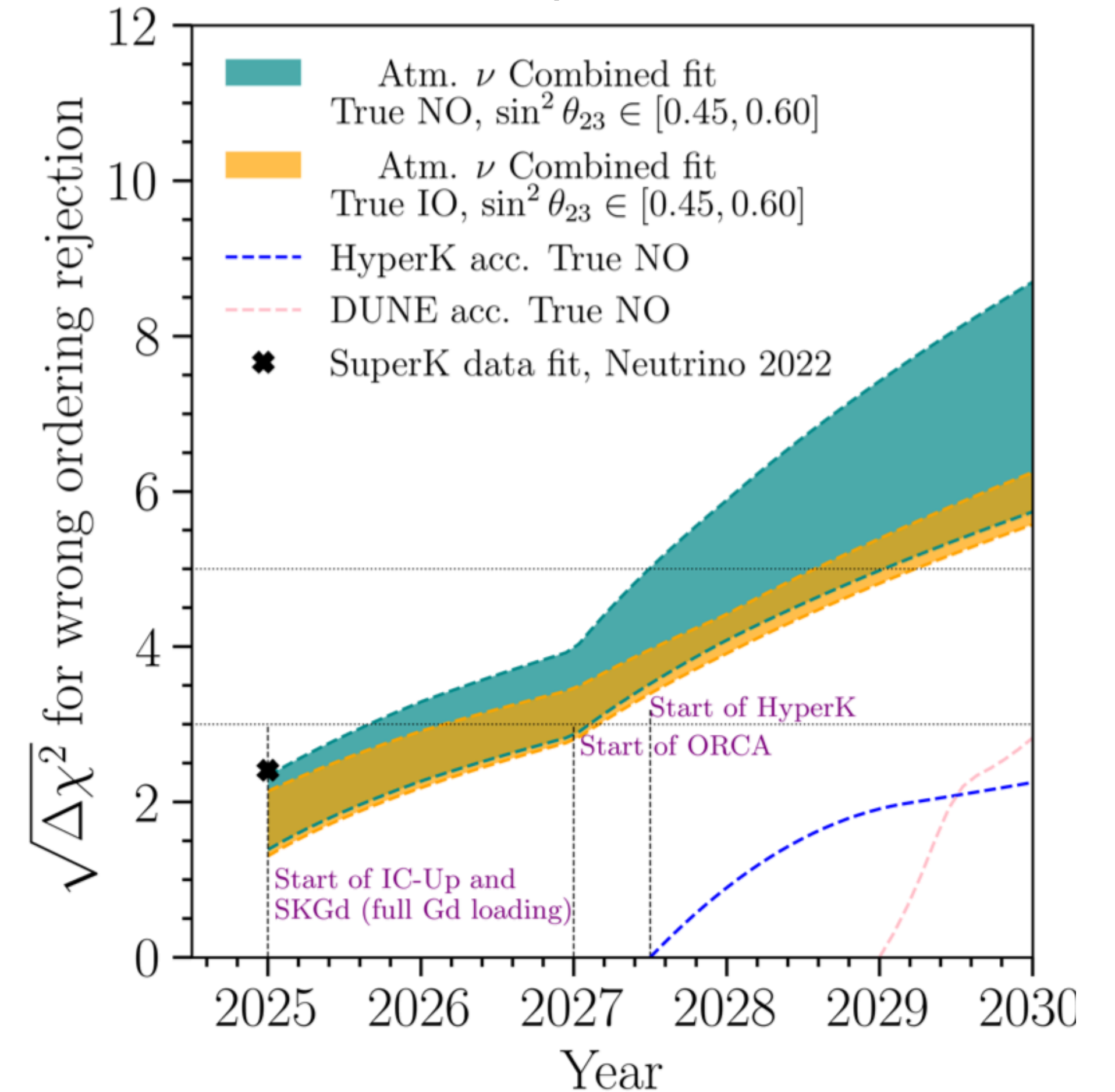
Three-flavo(u)r oscillations

Future landscape: joint analysis of atmospheric experiments?

- * Future can be even more competitive.
- * Although combined analysis can take more time than this optimistic scenario.



Phys. Rev. X 13, 041055

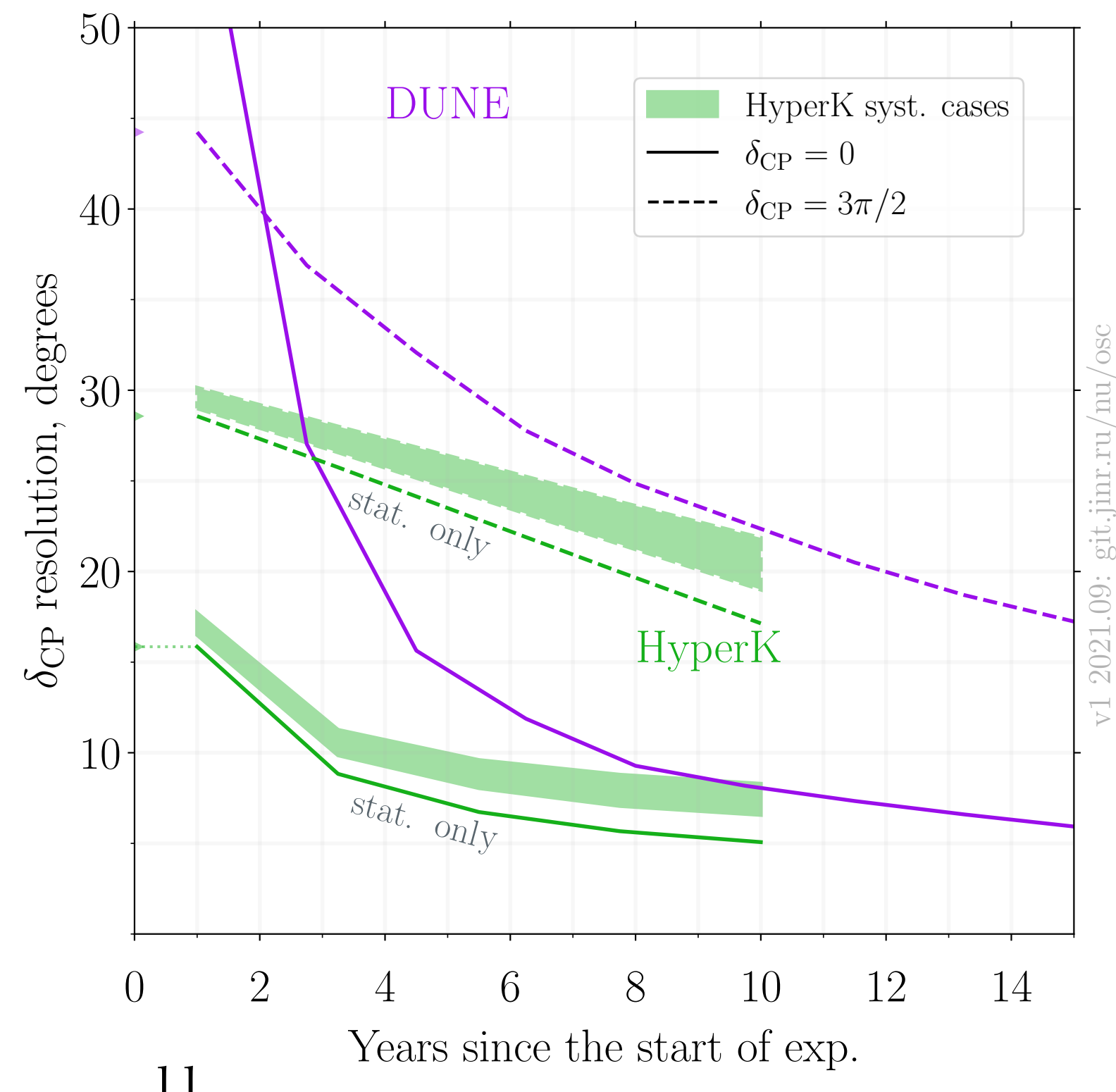
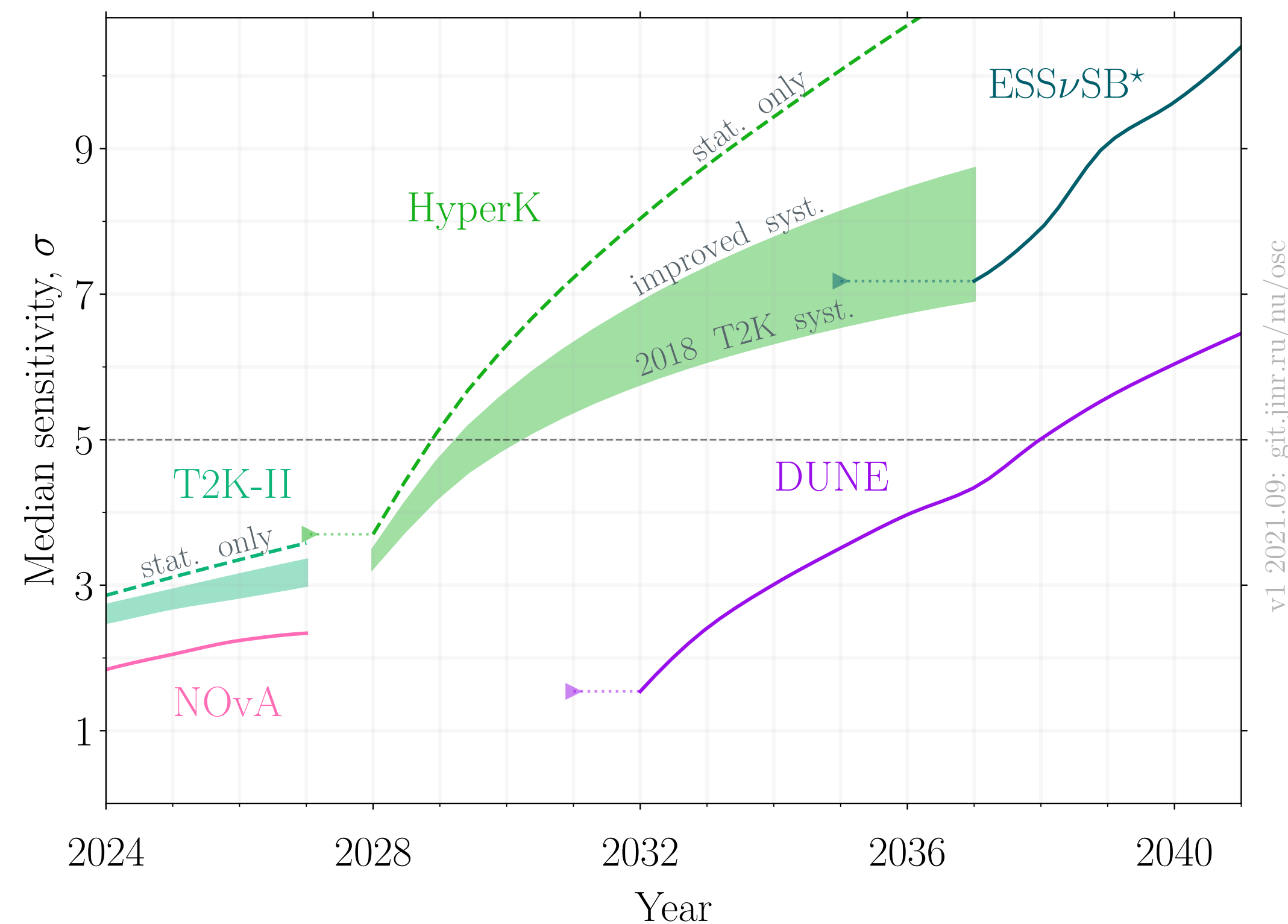


Three-flavo(u)r oscillations

Future landscape: δ_{CP}

- * Very competitive as well but accelerator nu experiments are the main hope.
- * And according to current results, that can be not an easy measurement.
- * Combination of atm. experiments can make an input here as well by 2030.

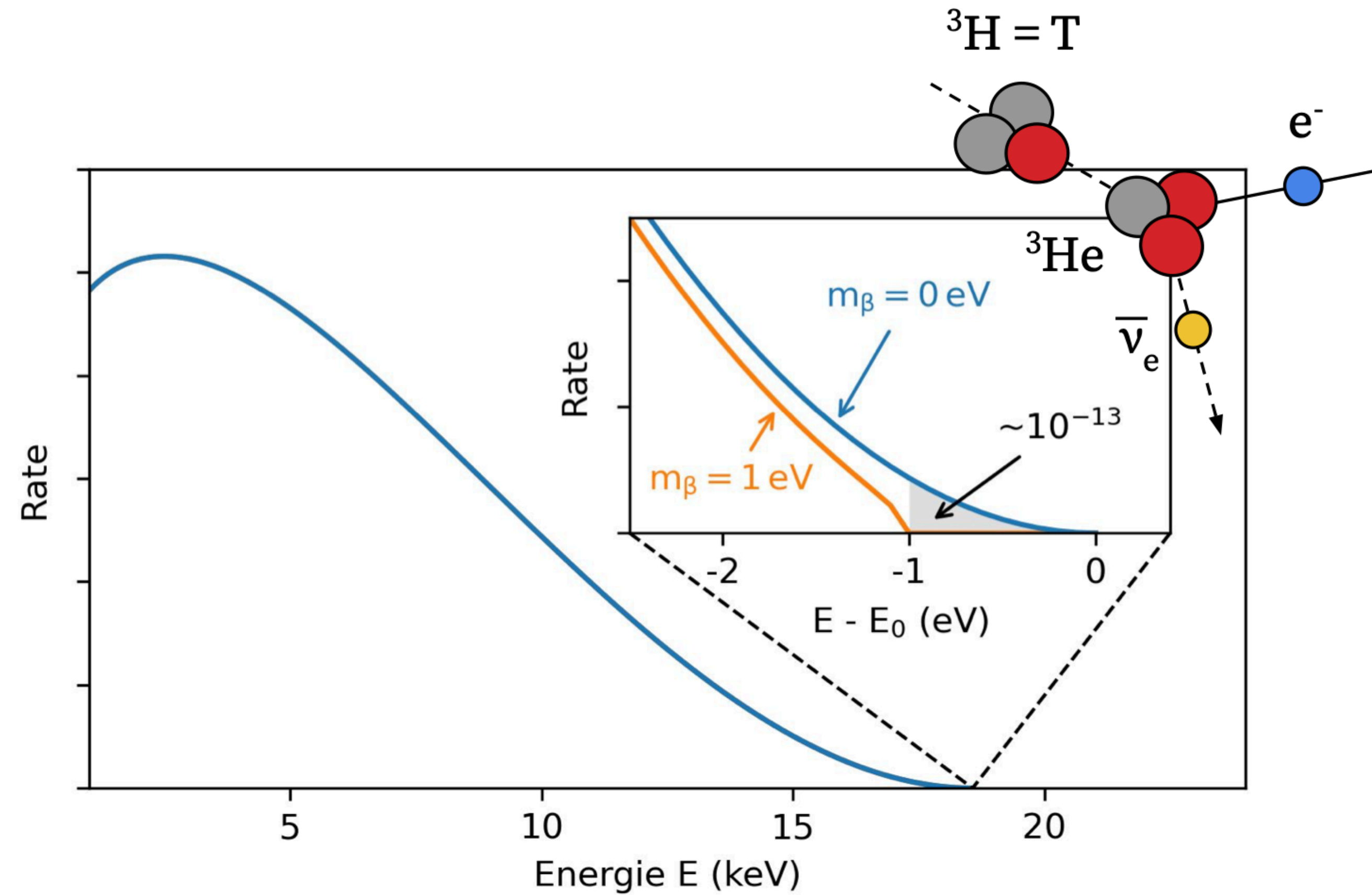
Significance of CPV determination for $\delta_{CP} = 3\pi/2$



- * HyperK claims to start in 2027.
- * DUNE beam physics start w/ ND is 2031.
- * Earlier start with atm. nus (not taken into account in these plots).

Absolute neutrino masses

- * Neutrinos have non-zero mass that is proven by existence of oscillations
- * What is exact value? Kinematic approach with molecular tritium beta-decay and E conservation:



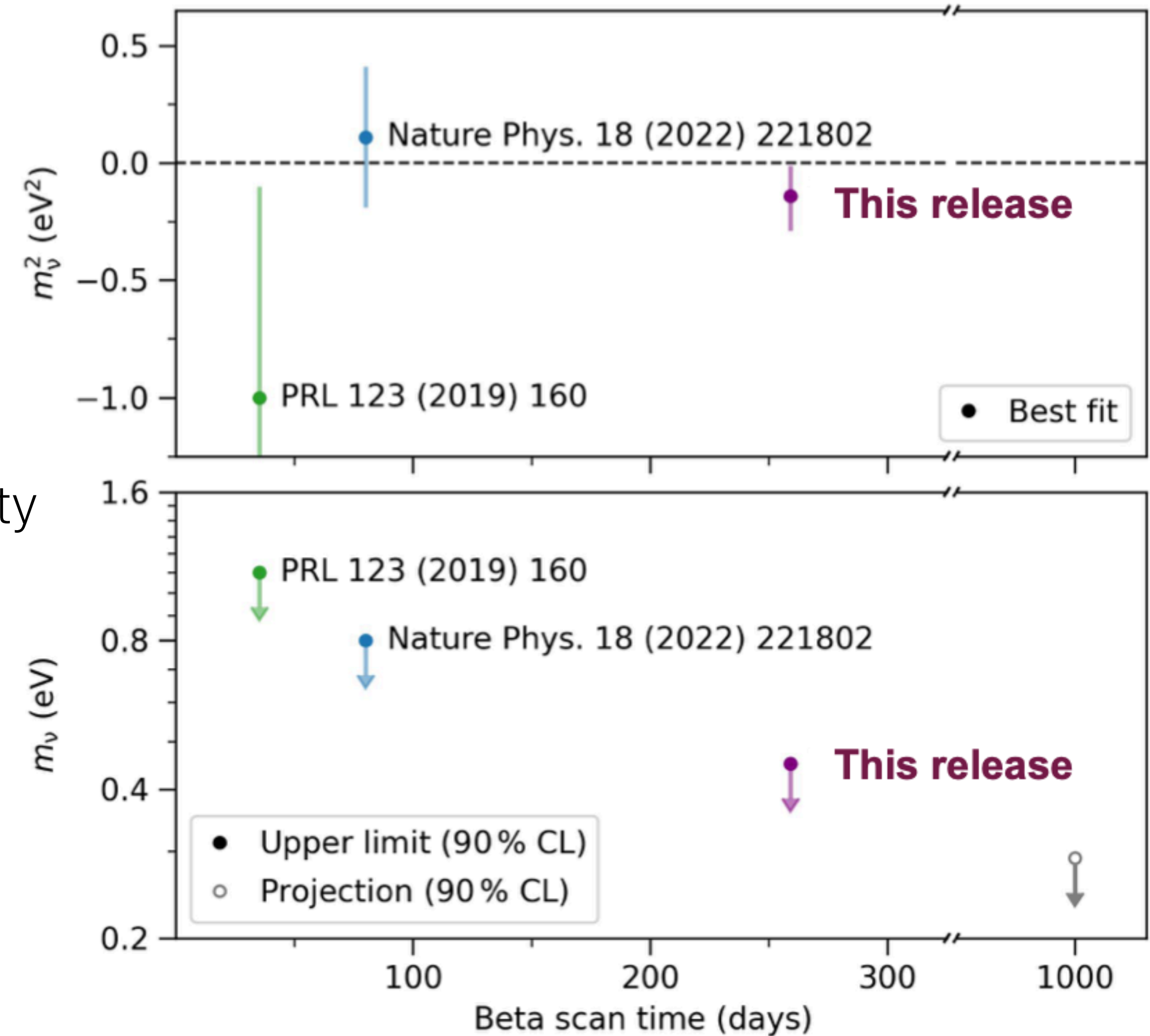
Probe effective $\bar{\nu}_e$ mass: $m_\nu^2 = \sum_{i=1}^3 |U_{ei}|^2 m_i^2$

Neutrino mass measurement

KATRIN latest results

- * 259 measurement days collected in 2019 - 2021;
 - * has x4 more data to analyse.
- * Latest upper limit $m_\nu < 0.45$ eV (90% CL).
- * Future plans:
 - * Data taking concluded at the end of 2025, target sensitivity below 0.3 eV (90% CL).
 - * 2026 - 2027: TRISTAN@KATRIN for sterile keV neutrino search.
 - * 2028 - 2034 R&D for the next apparatus (< 0.045 eV).

Science 388,180-185(2025)



Neutrino mass measurement

Other approaches

Since ~1970 the main tool to probe neutrino mass is spectrometric approach with Tritium.

Any alternative? – Yes!

KATRIN: $m_\nu < 0.45$ eV (90% CL)

(all dataset sens.: < 0.3 eV)

- * Cyclotron Radiation Emission Spectroscopy (~0.01– 0.05 eV sensitivity)
- * Hybrid spectroscopic techniques (sensitivity < 0.1 eV)
- * Low Temperature Calorimetry with electron capture in ^{163}Ho (1 – 2 eV sensitivity)

All these methods are:

- * Quite sophisticated and require lot's of R&Ds and ways to solve lot's of methodical challenges
- * Have higher sensitivity than KATRIN. If neutrino mass will not be measured by spectrometric approach with Tritium alternative methods will be the only way to make this measurement.

Neutrino mass measurement

Cyclotron Radiation Emission Spectroscopy

Measure cyclotron radiation of emitted electrons in Tritium decays captured in magnetic trap, expecting in the future ~ 0.01 - 0.05 eV sensitivity.

* Project 8:

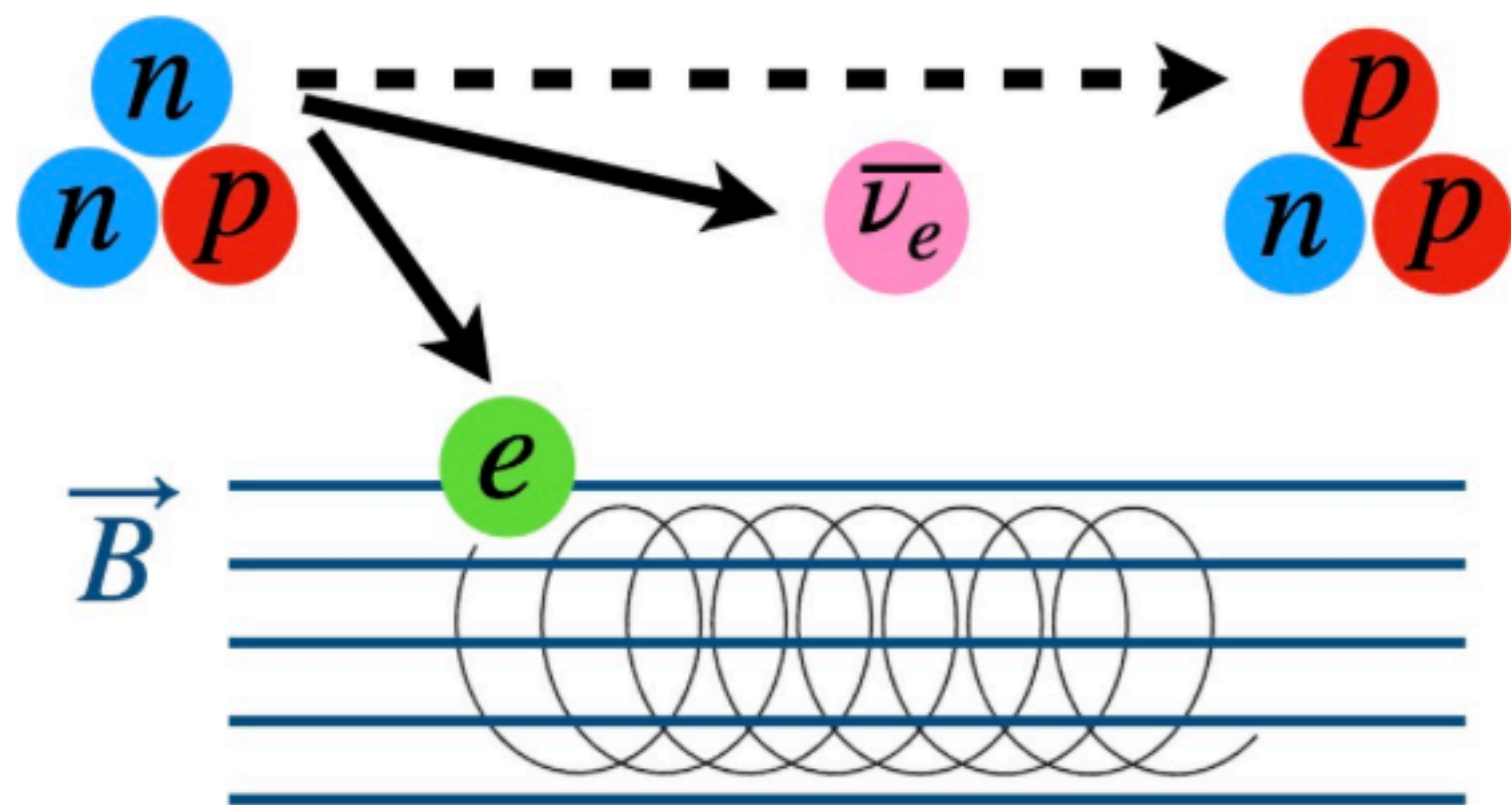
* 4 different experimental phases since 2009

* $m_\nu < 155$ eV 90% CL (phase II), phase III is ongoing

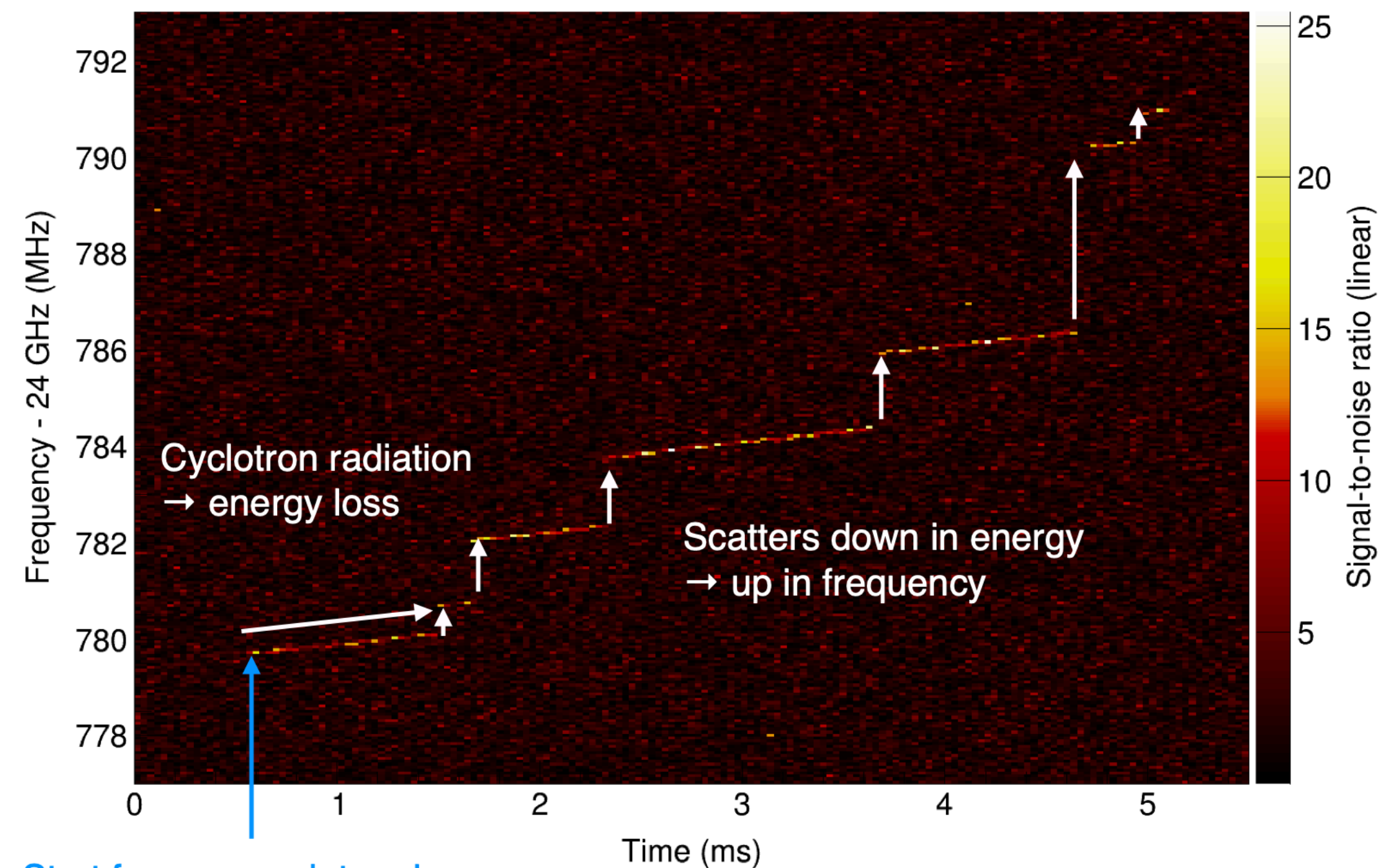
* QTNM: starting \sim now (New J. Phys. 27 (2025) 105006)

$$f_\gamma = \frac{\omega_c}{2\pi\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + K_e/c^2}$$

PROJECT 8



$$\frac{\Delta E}{m_e} = \frac{\Delta f}{f}$$



Start frequency: determines electron energy before losses

Phys.Rev.Lett. 131 (2023) 10, 102502

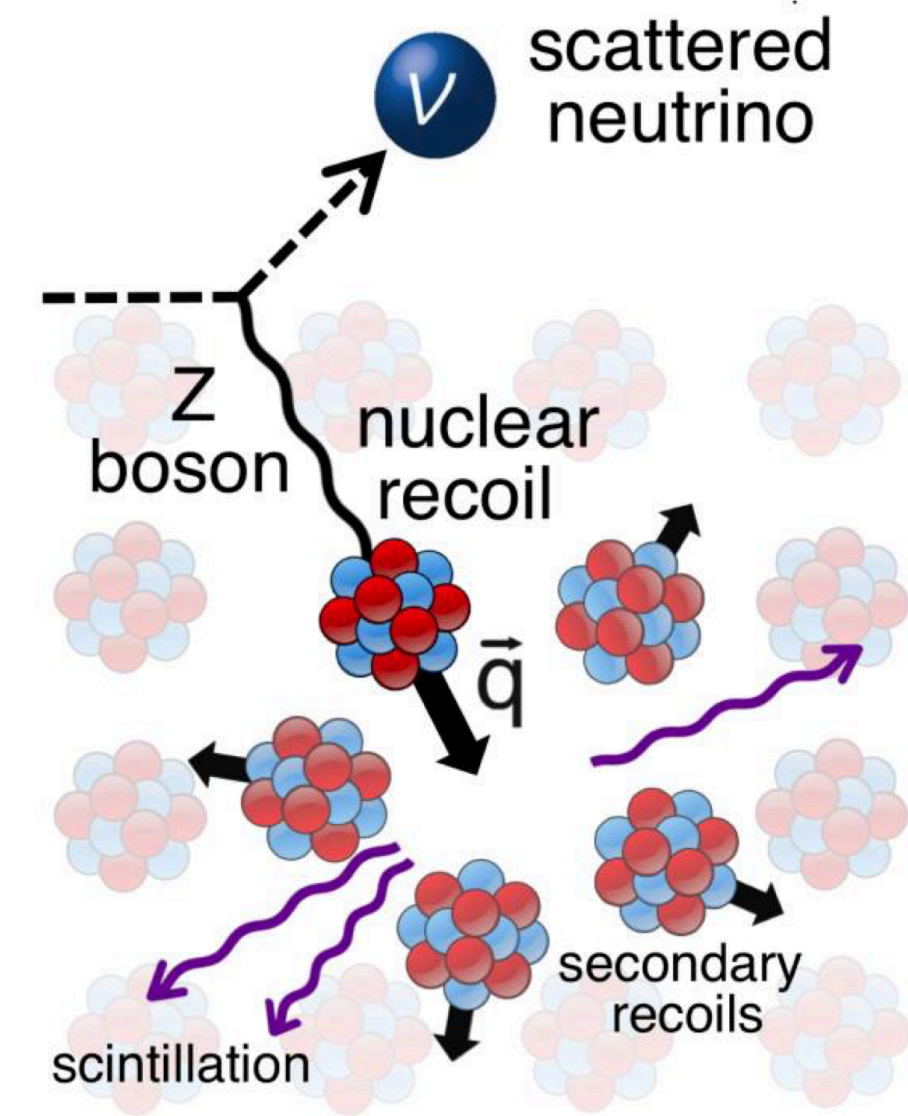
Coherent elastic νN scattering

* Dominant process for $E_\nu < 50$ MeV.

* Cons: recoil energy \sim keV.

Pros: cross-section $\sim N^2$.

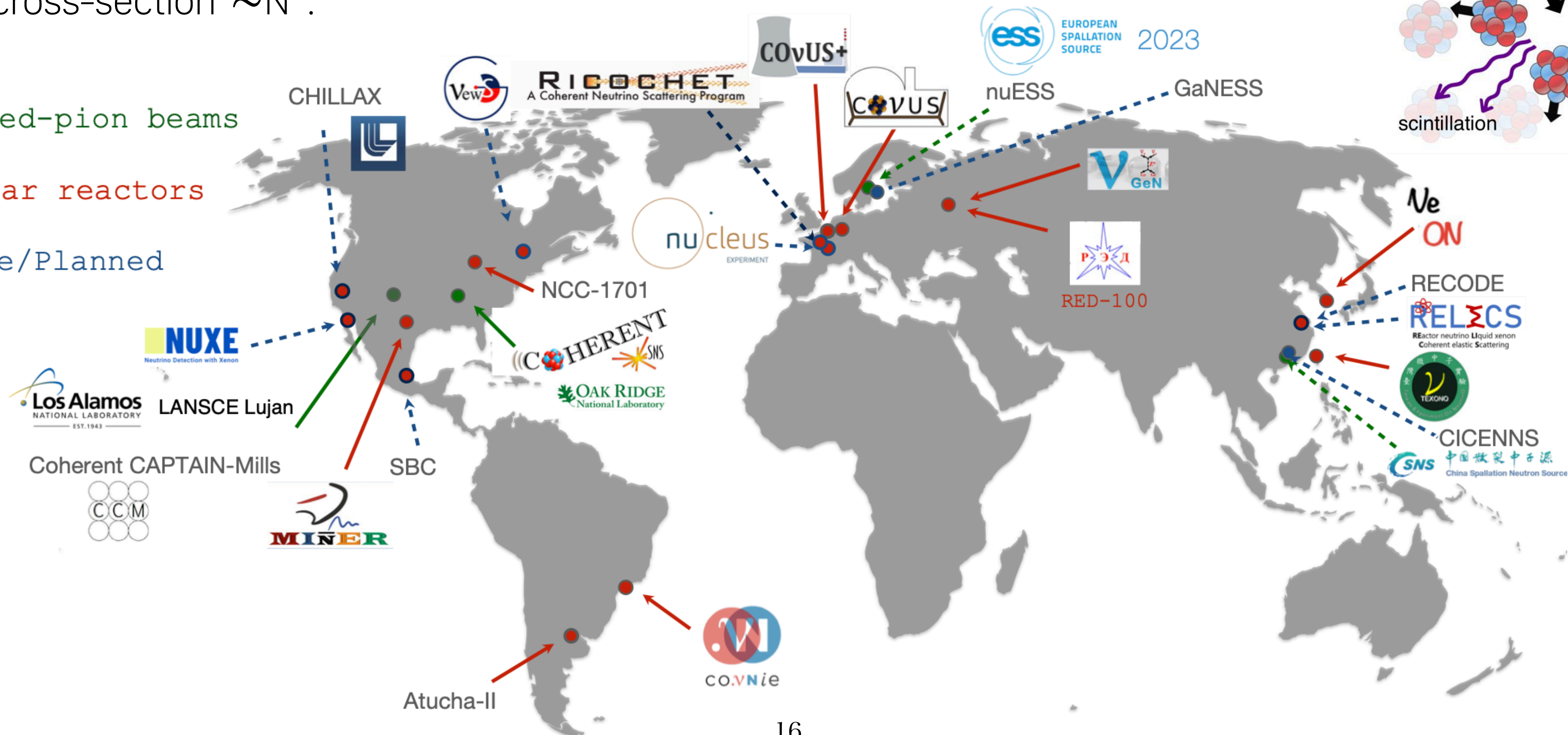
Discovered by COHERENT in 2017



● Stopped-pion beams

● Nuclear reactors

● Future/Planned

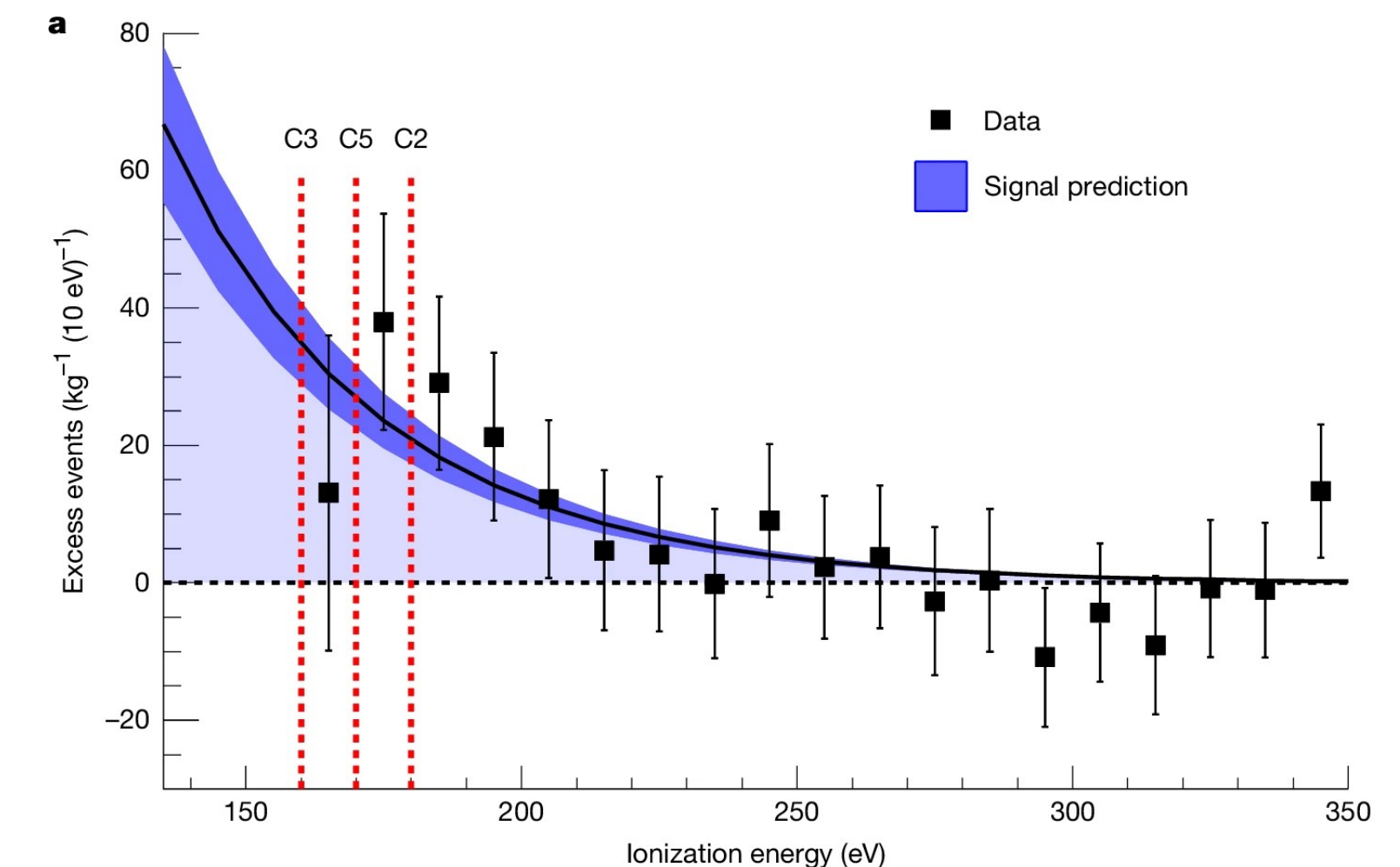
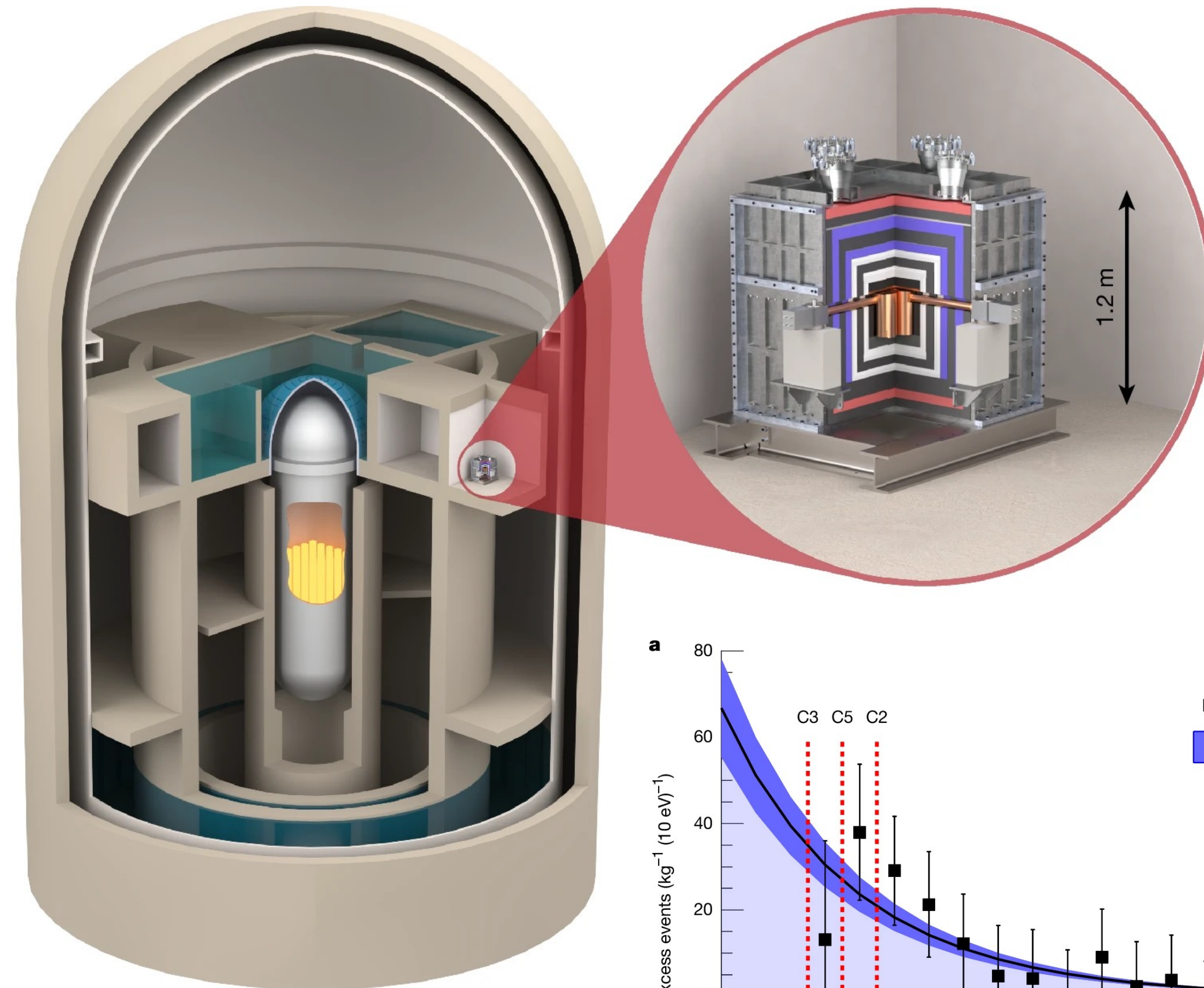


Coherent elastic νN scattering

Some highlights: CONUS+ recent results

Nature 643, 1229–1233 (2025)

- * Since 2023 @Leibstadt, CH (3.6 GWth)
 - * @20.7m $\rightarrow 1.45 \cdot 10^{13}$ n/cm²/s
 - * 10 tons total mass
 - * HPGe detectors (3.74 kg active mass)
 - * 119 days of reactor ON and 19 days OFF
- * First observation CEvNS in the fully coherent regime and with reactor $\bar{\nu}$'s at 3.7σ
- * has detected the lowest energy neutrinos (down to 4 MeV) via the CEvNS channel
- * accumulated the highest number of CEvNS counts in one single isotope
- * Plan: 3 * 2.4 kg new Ge detectors
 \rightarrow improved results in June?

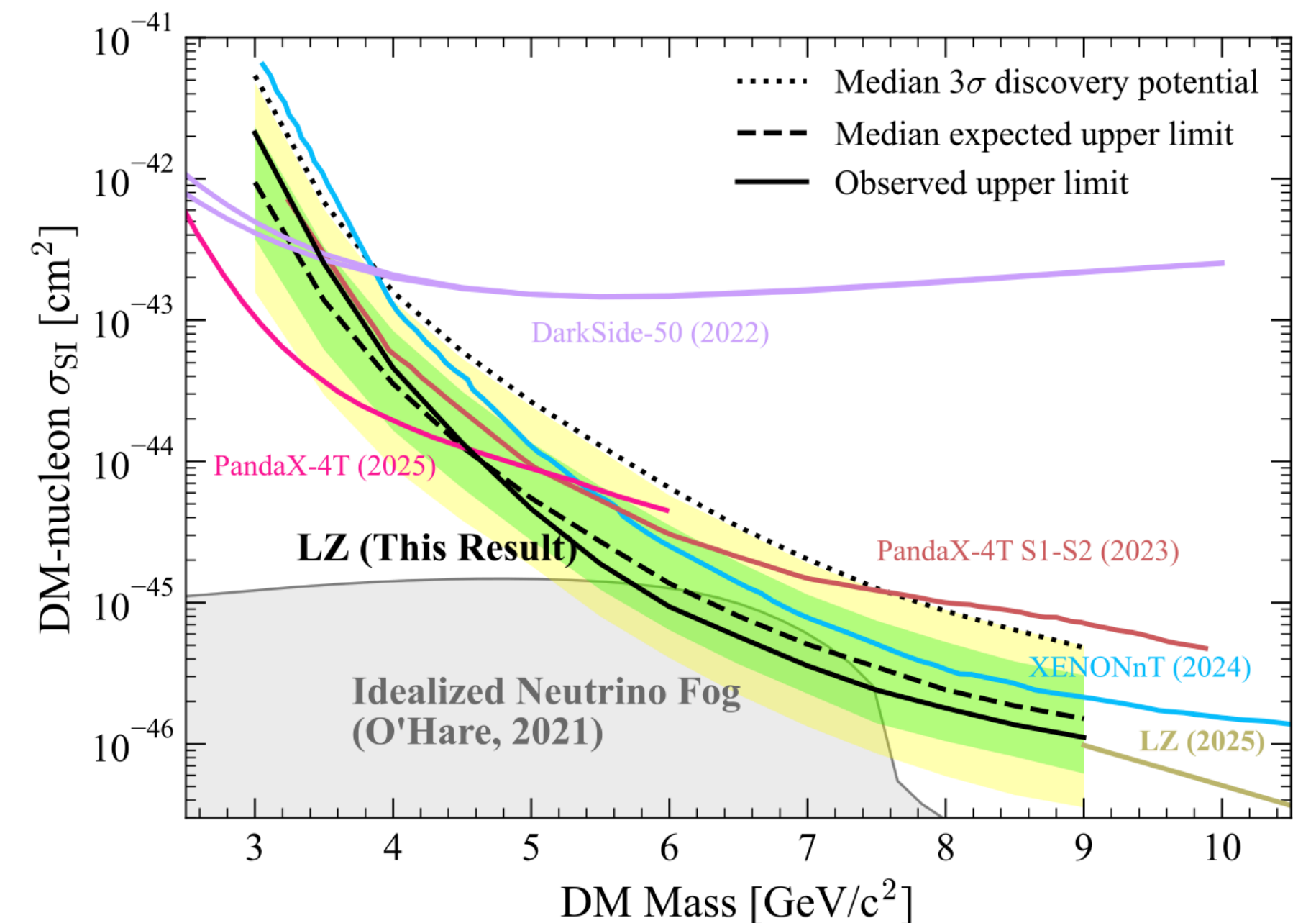
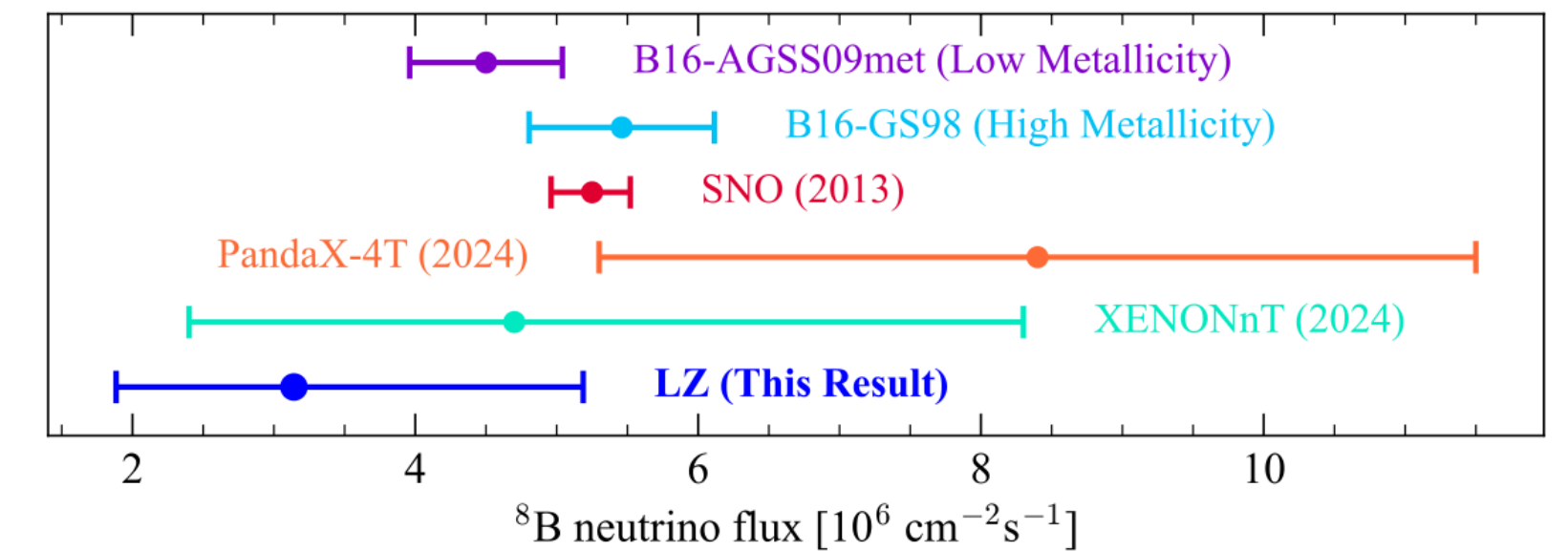


Coherent elastic νN scattering

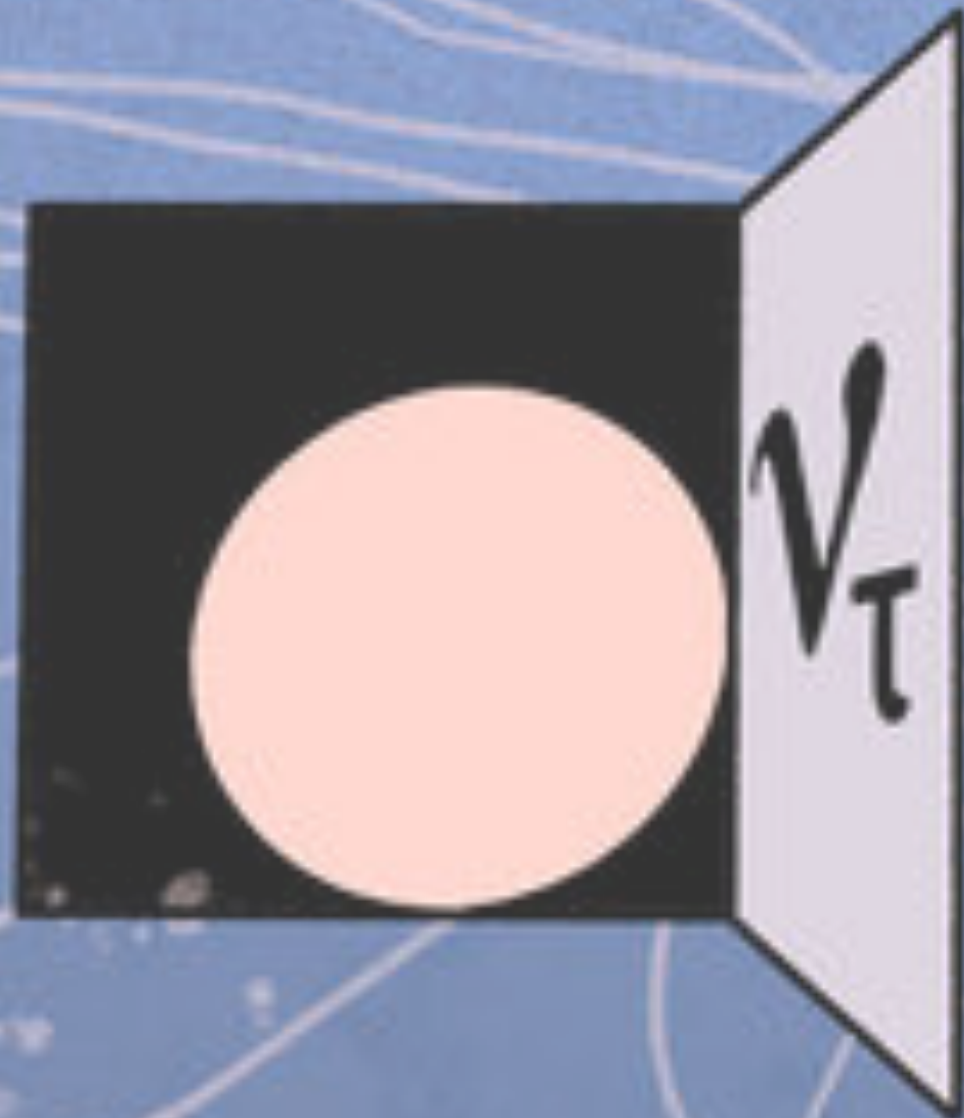
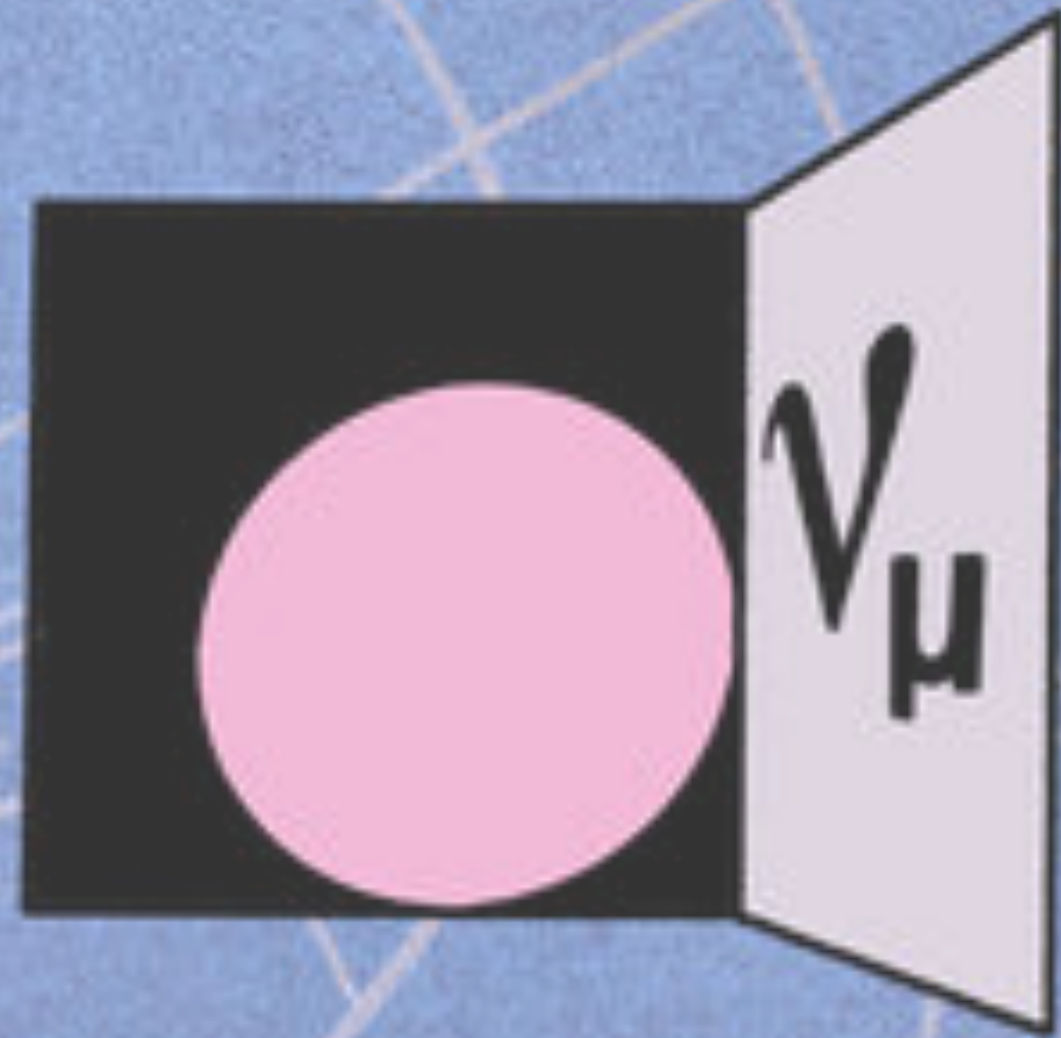
Some highlights: neutrino fog and LUX-ZEPLIN

2512.08065 [hep-ex]

- * Dual phase 7t Xe experiment to search for Dark Matter
 - * Start of data taking 2022
 - * currently the world's most sensitive WIMP direct detection experiment
- * Observed solar ^8B CEvNS events at 4.5σ
- * XENONnT: 2.73σ (Phys. Rev. Lett. 133, 191002 (2024))
- * PandaX-4T: 2.64σ (Phys.Rev.Lett. 133, 191001 (2024))

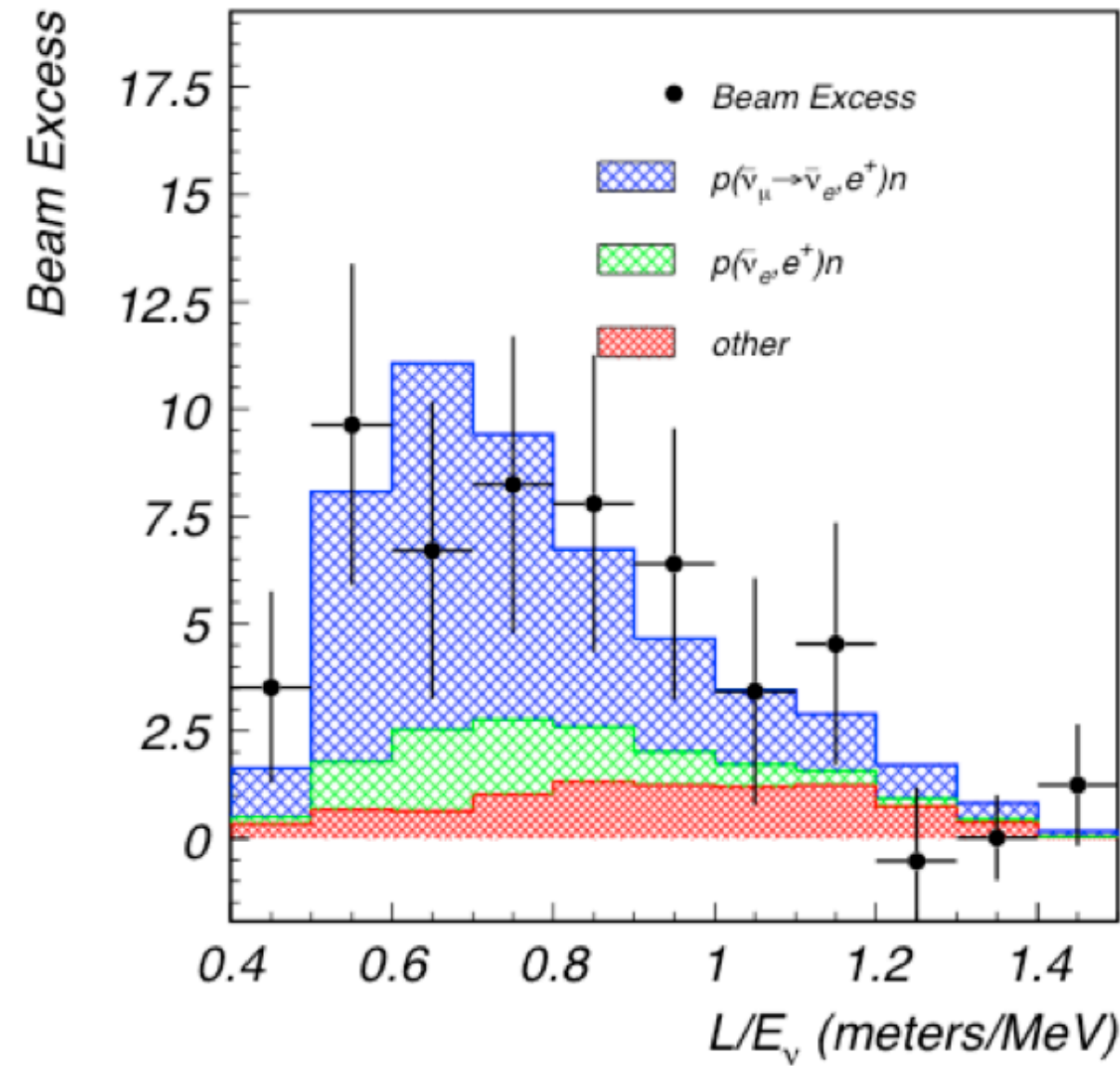


Part II: Possible discoveries



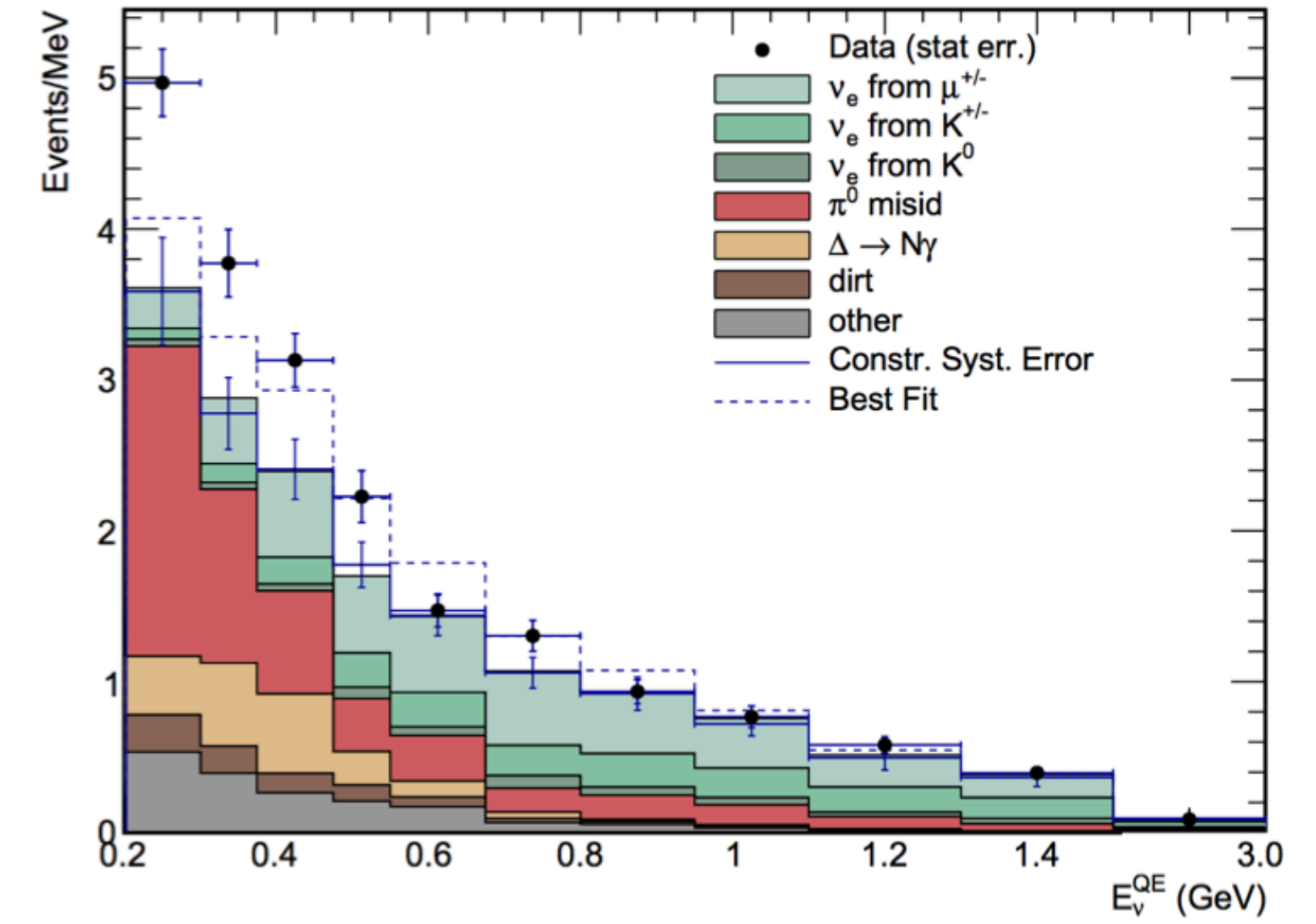
Sterile neutrino searches

Experimental origins

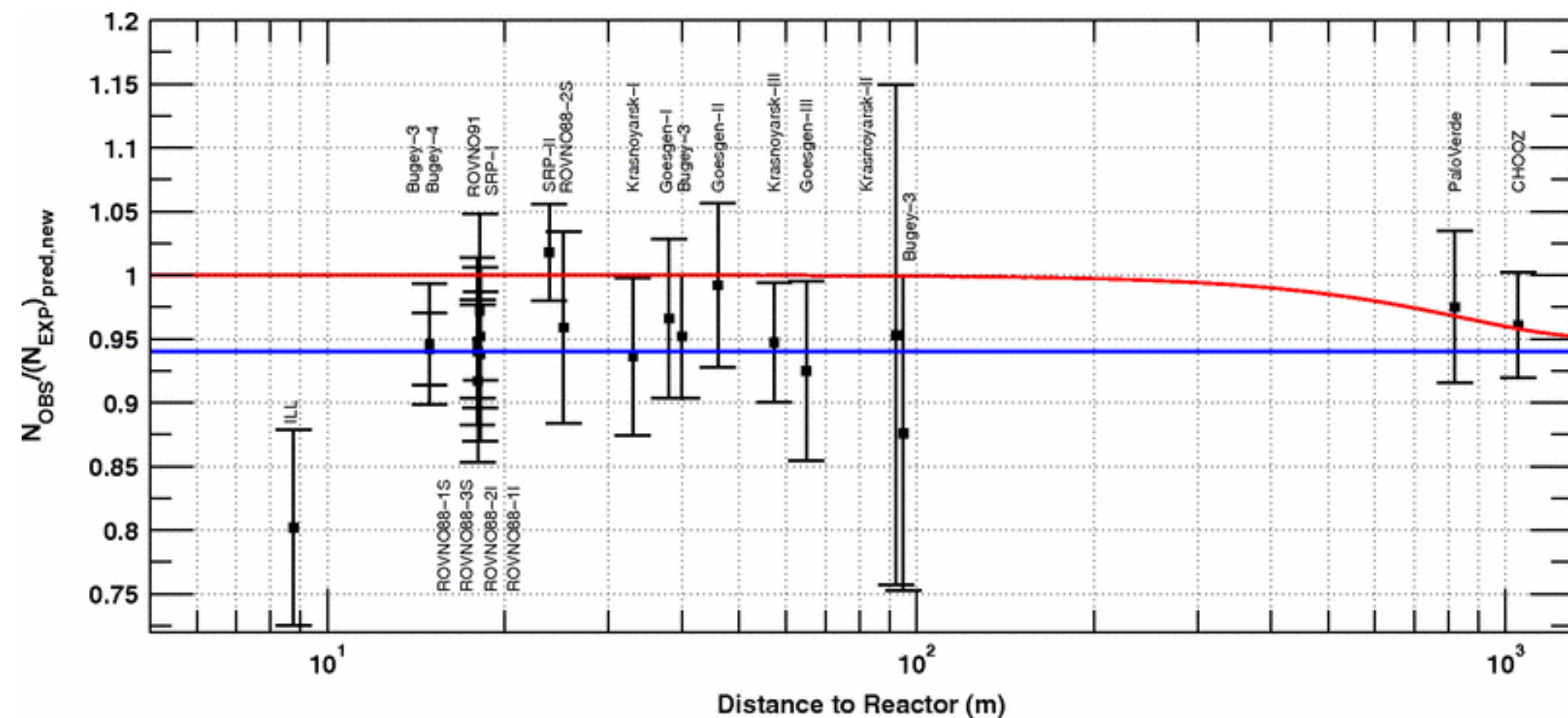


LSND detected $\bar{\nu}_e$'s with 3.8σ excess

MiniBooNE detected 4.8σ excess with ν_e 's

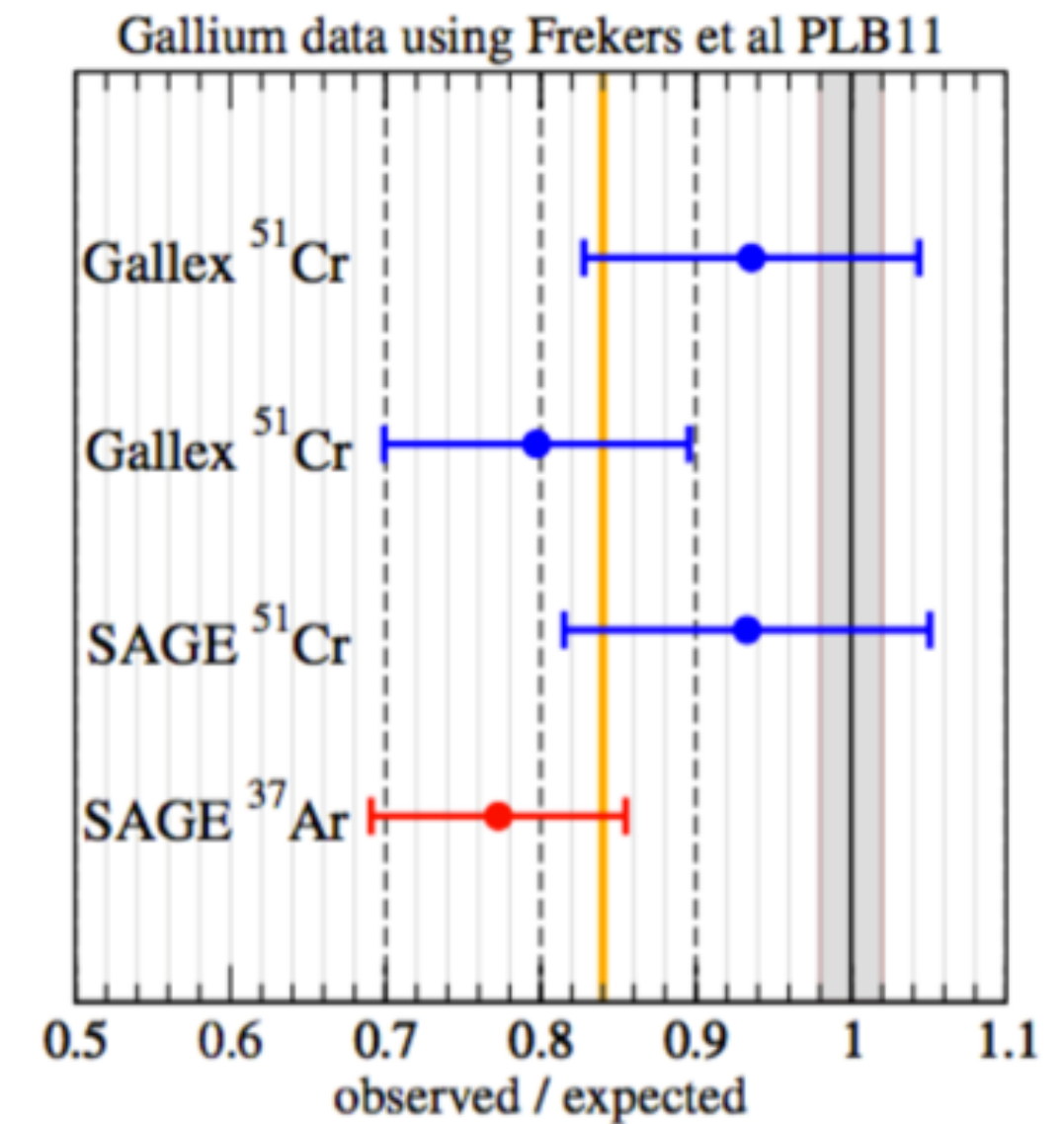


Absolute reactor $\bar{\nu}_e$ flux anomaly (RAA): 6% deficit (3σ)



Neutrino-4 (3σ) and BEST ($>5\sigma$) also see anomalies.

2.7σ deficit of ν_e 's from intense electron capture calibration sources



Sterile neutrino searches

Anomalies: accelerator

Long story short:

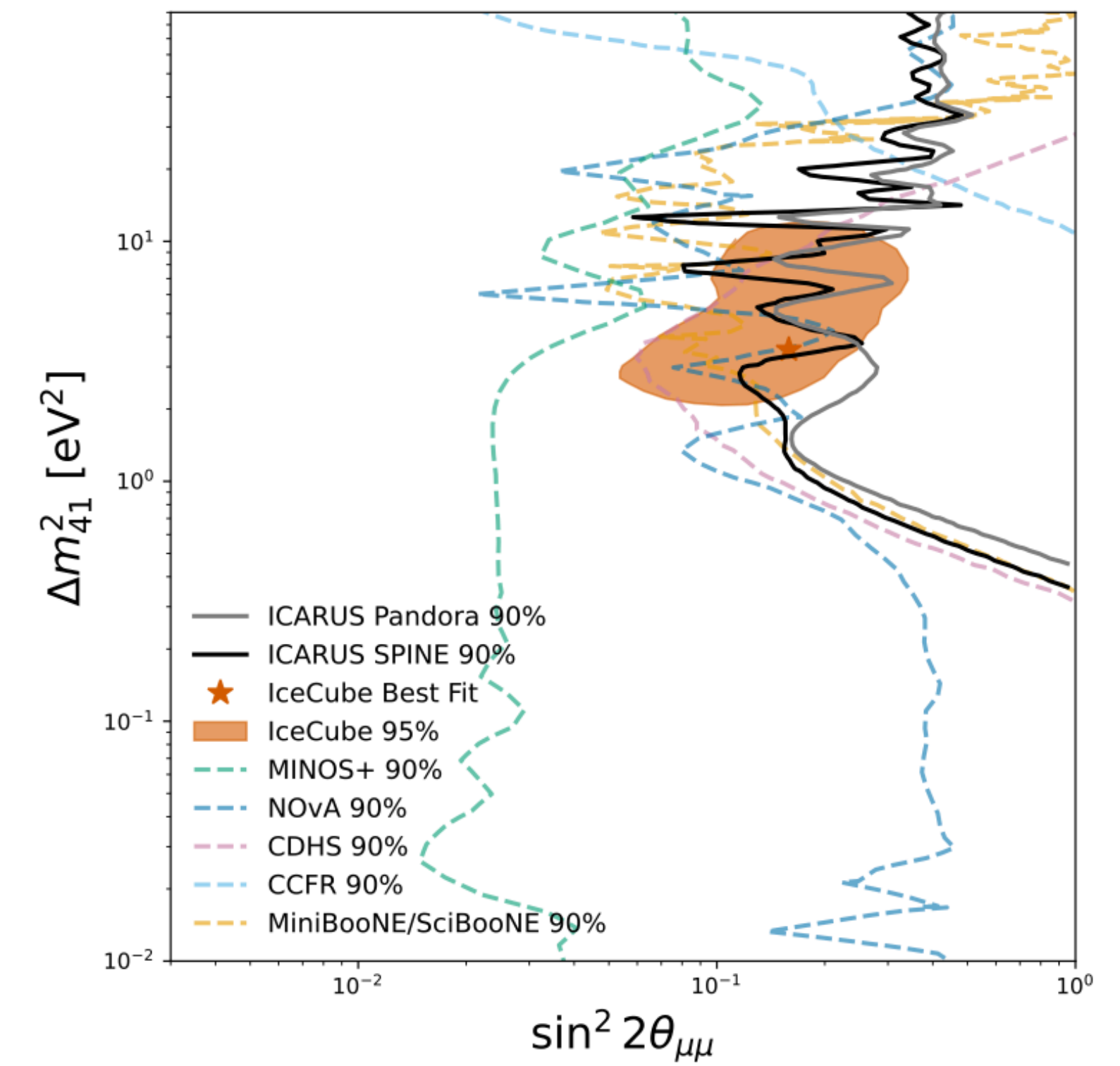
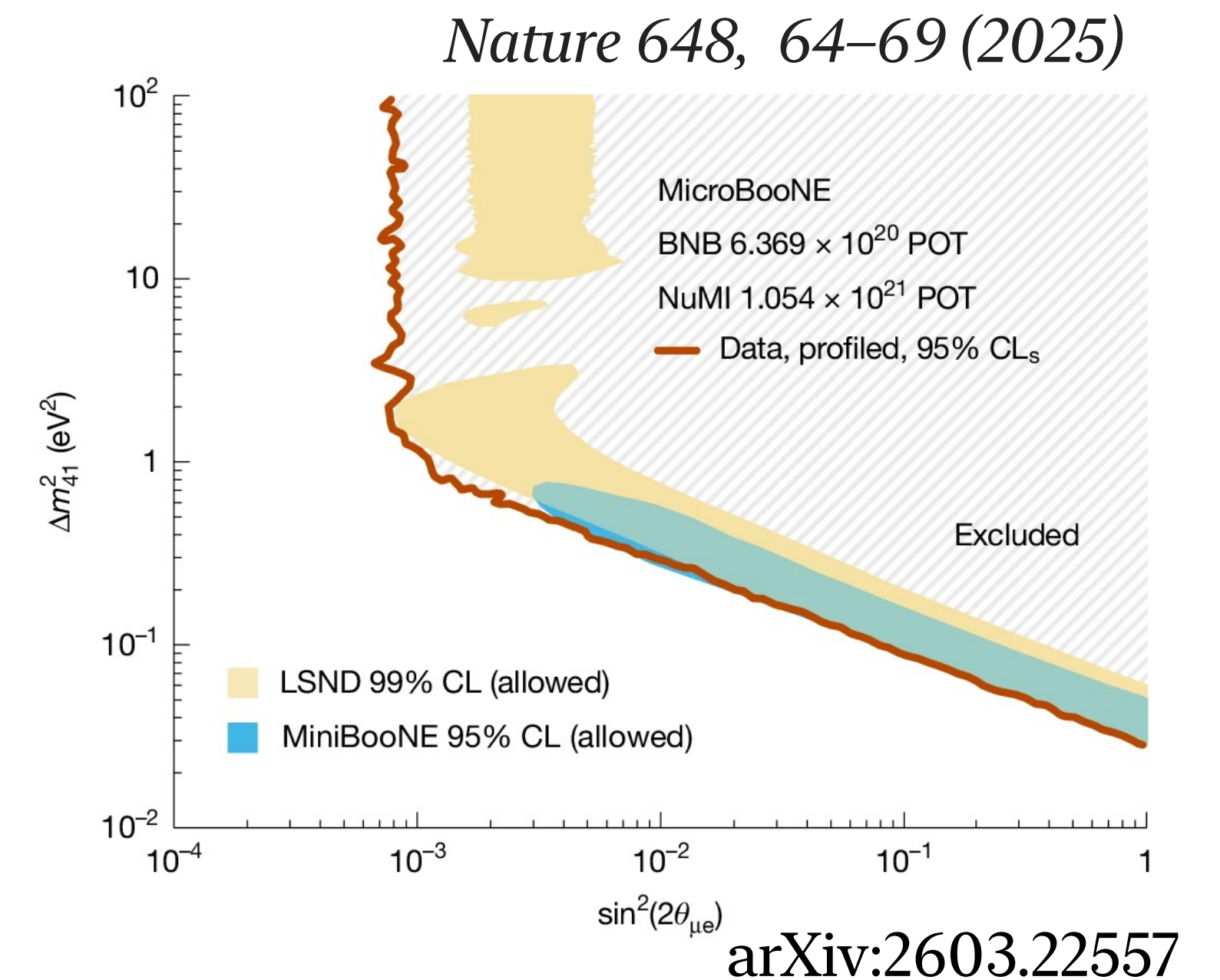
LSND ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) and MiniBooNE ($\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$), although low E MiniBooNE can't be explained only by steriles.

Current state and highlights:

- * MicroBooNE recent results with BNB and NuMI - improved constraints
- * No disappearance experiments see the anomaly (but IceCube closed contour, Phys. Rev. Lett. 133, 201804 (2024))
 - * First results of ICARUS, data taking is ongoing
- * First results of JSNS² arXiv:2602.06274 (direct probe of LSND with muon decay ν 's): no excess but sensitivity is poor yet

Future prospects:

- * SBN Program @ Fermilab: expect ICARUS + SBND joint results soon
- * Japan: JSNS² - II is under construction



Sterile neutrino searches

Anomalies: reactor antineutrino

Long story short:

Many experiments saw a deficit in absolute flux of reactor antineutrinos ($\sim 3\sigma$).

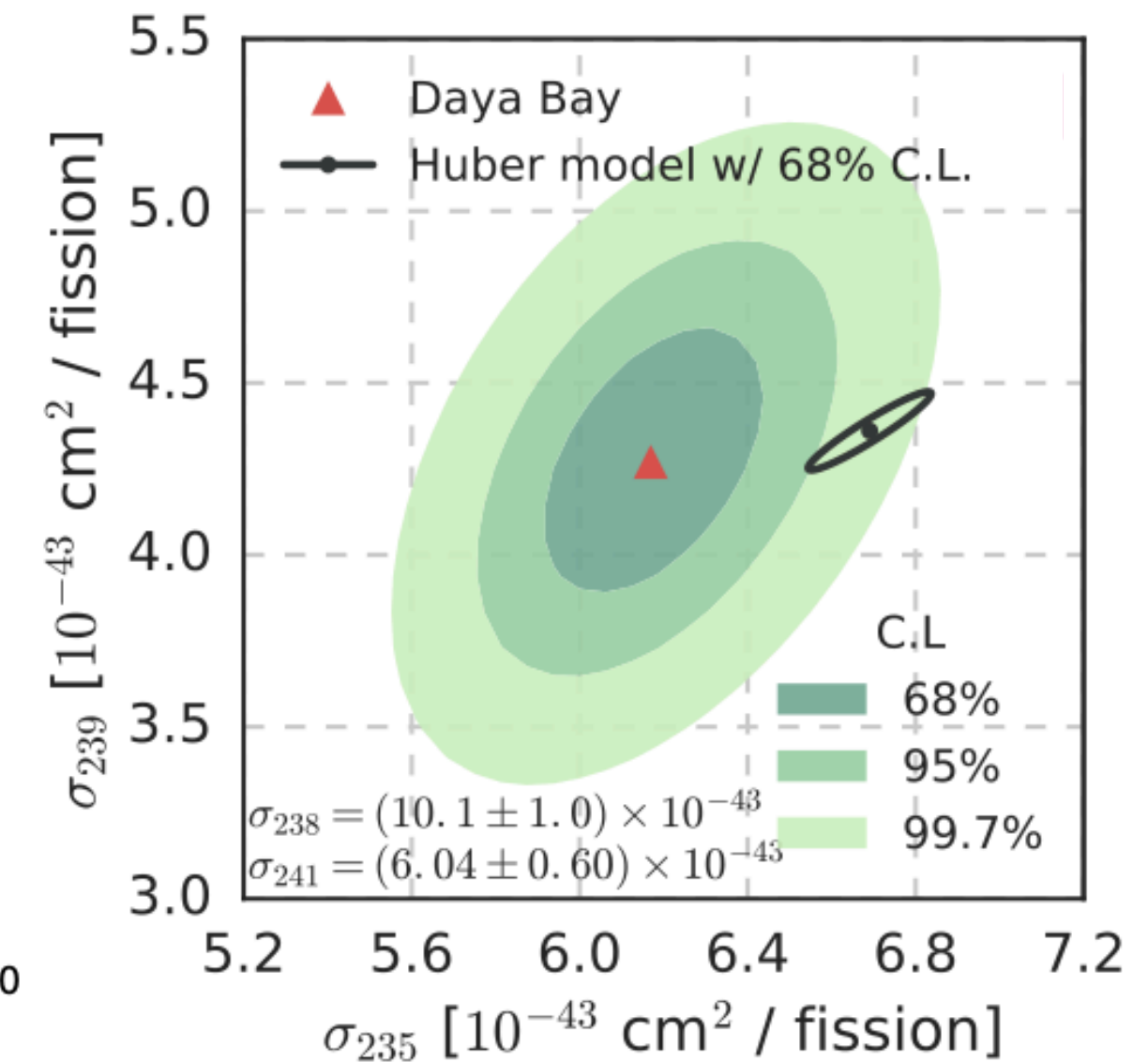
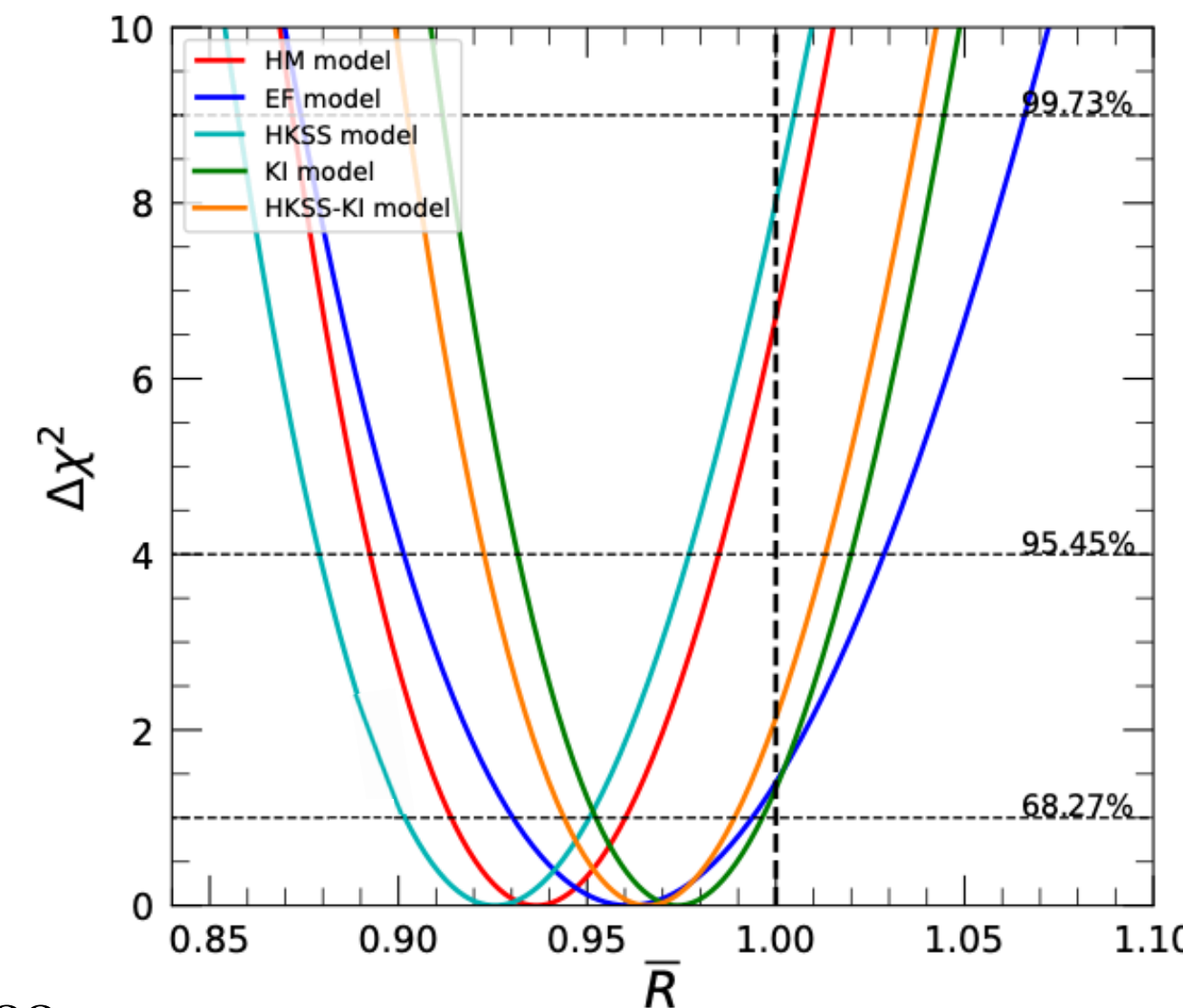
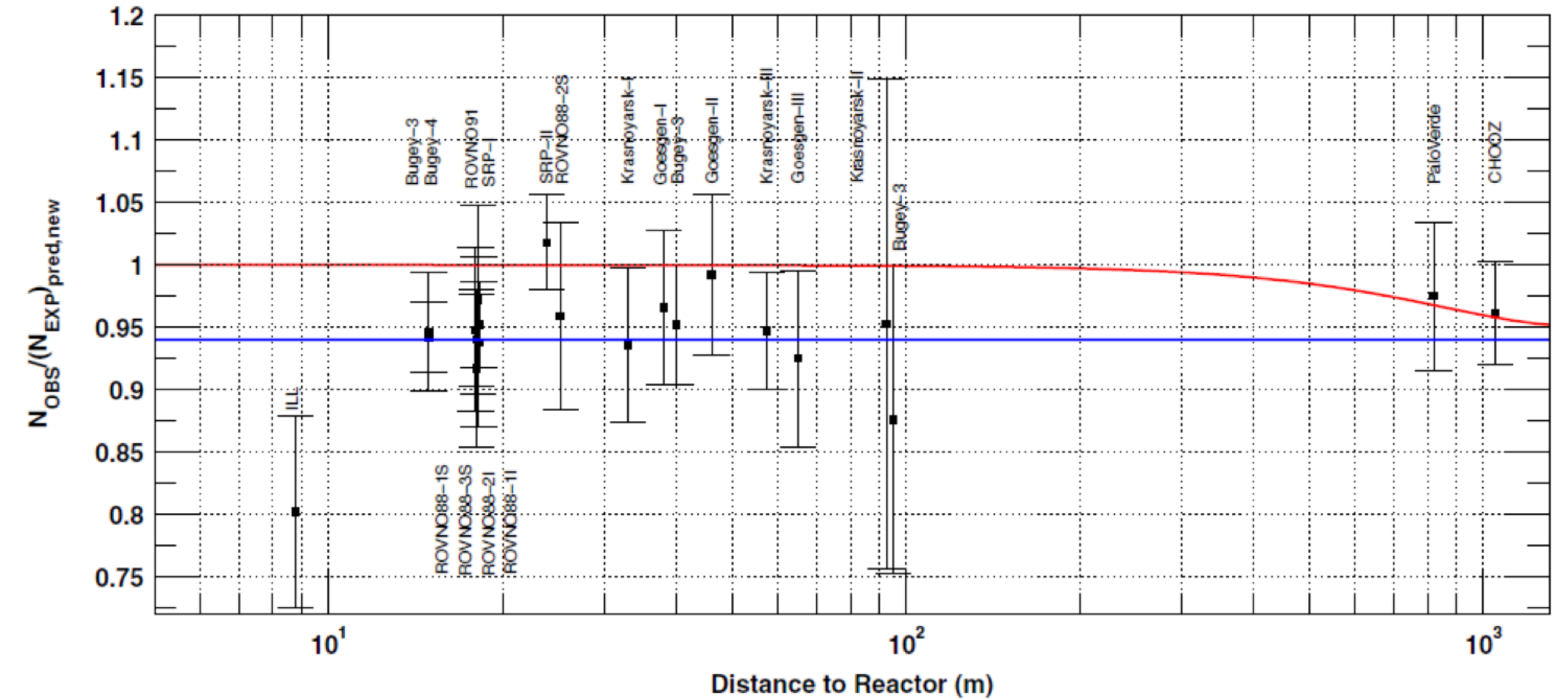
- * Since 2016: Daya Bay, RENO, STEREO, PROSPECT: ^{239}Pu mostly agrees with Huber-Mueller model, while ^{235}U substantially below.
- * 2020 and later: new reactor flux calculations nearly $\sim 3\sigma \rightarrow \sim 1\sigma$ disagreement.

Current status

- * Most likely RAA is not sterile nus.
- * But still some model mysteries: shape is still unclear, bump, high energy disagreement.

G. MENTION *et al.*

PHYSICAL REVIEW D 83, 073006 (2011)



Sterile neutrino searches

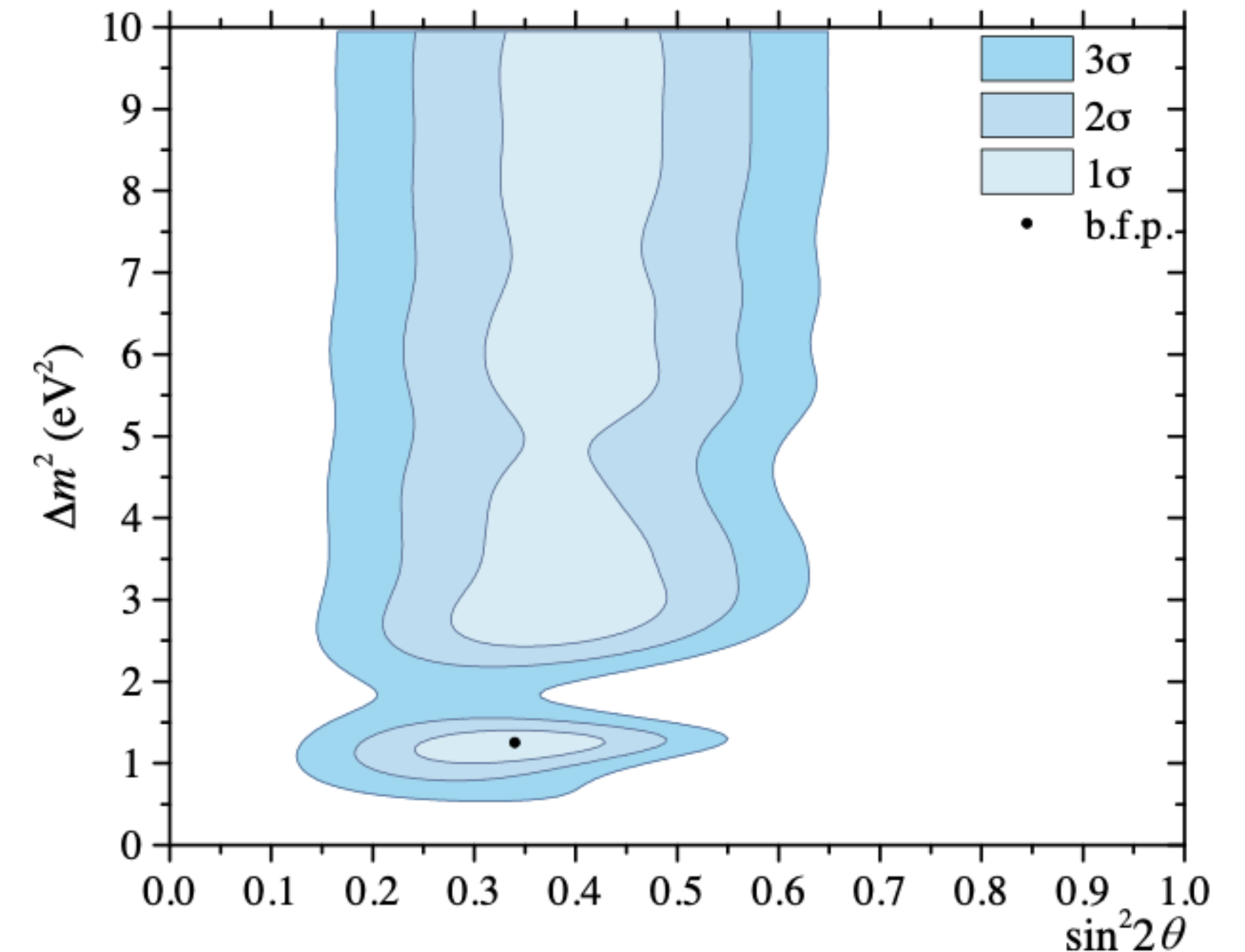
Anomalies: gallium

Long story short:

$^{71}\text{Ga} \rightarrow ^{71}\text{Ge} \nu$ capture cross-section was calibrated with intense ^{51}Cr and ^{37}Ar sources by GALLEX & SAGE (20 years ago). These measurements show a significant deficit with respect to the predicted values. Confirmed by BEST (2022) with the same Ga-Ge technology.

Current state: so far reasons are unclear, need more investigations.

- * Can gallium cross-section be overestimated?
- * ^{71}Ge half-life may be wrong, but needed "error" is very large.
- * Data suggest $\Delta m^2 \gtrsim 1 \text{ eV}^2$ but require very large θ_{ee} .
- * New experiment at Baksan is under consideration.



Sterile neutrino searches

Anomalies: Neutrino-4

Long story short:

For several years Neutrino-4 reports 3σ signal with $\Delta m^2 \sim 7 \text{ eV}^2$.

Current status and highlights:

* Most of parameter space (except very large Δm_{41}^2 from BEST) is excluded by different experiments, best fits are excluded at $>5\sigma$

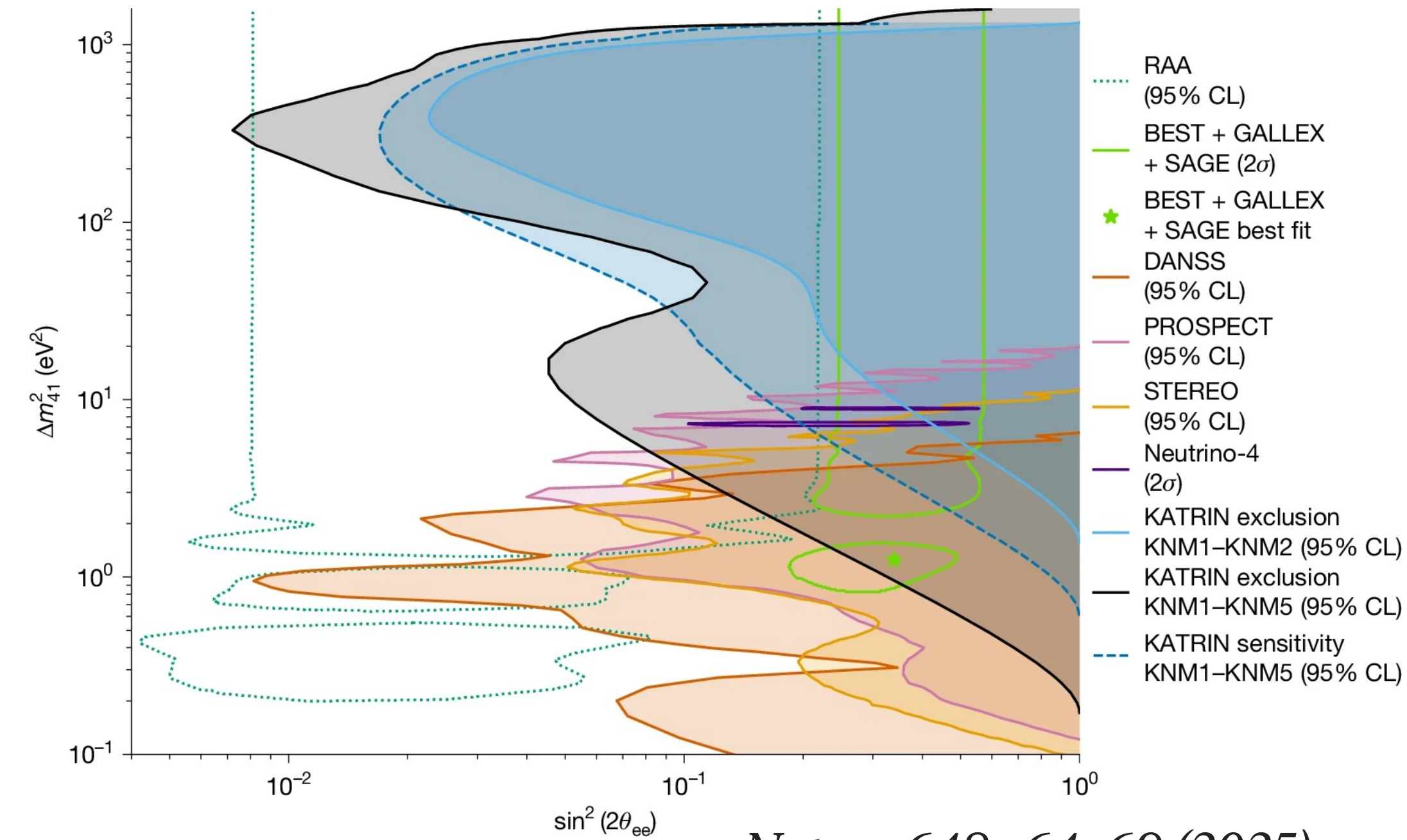
* Recent results from KATRIN and MicroBooNE with strong constraints

Future:

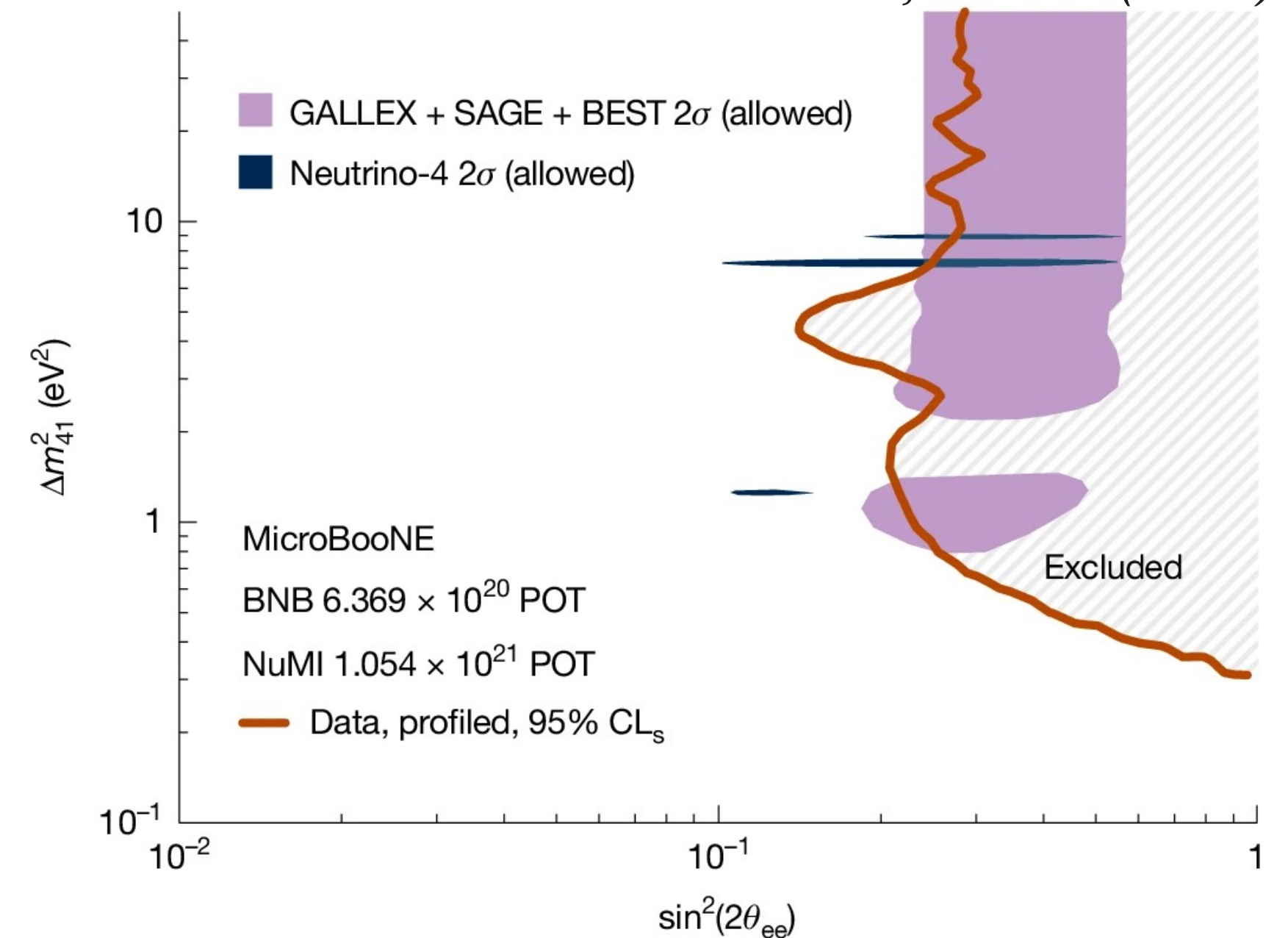
* Upgrades of: Neutrino-4, DANSS, NEOS, PROSPECT-II.

* Newcomers: CLOUD and JUNO-TAO.

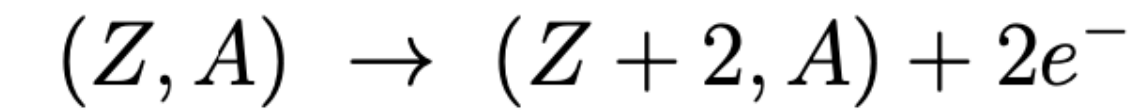
Nature 648, 70–75 (2025)



Nature 648, 64–69 (2025)

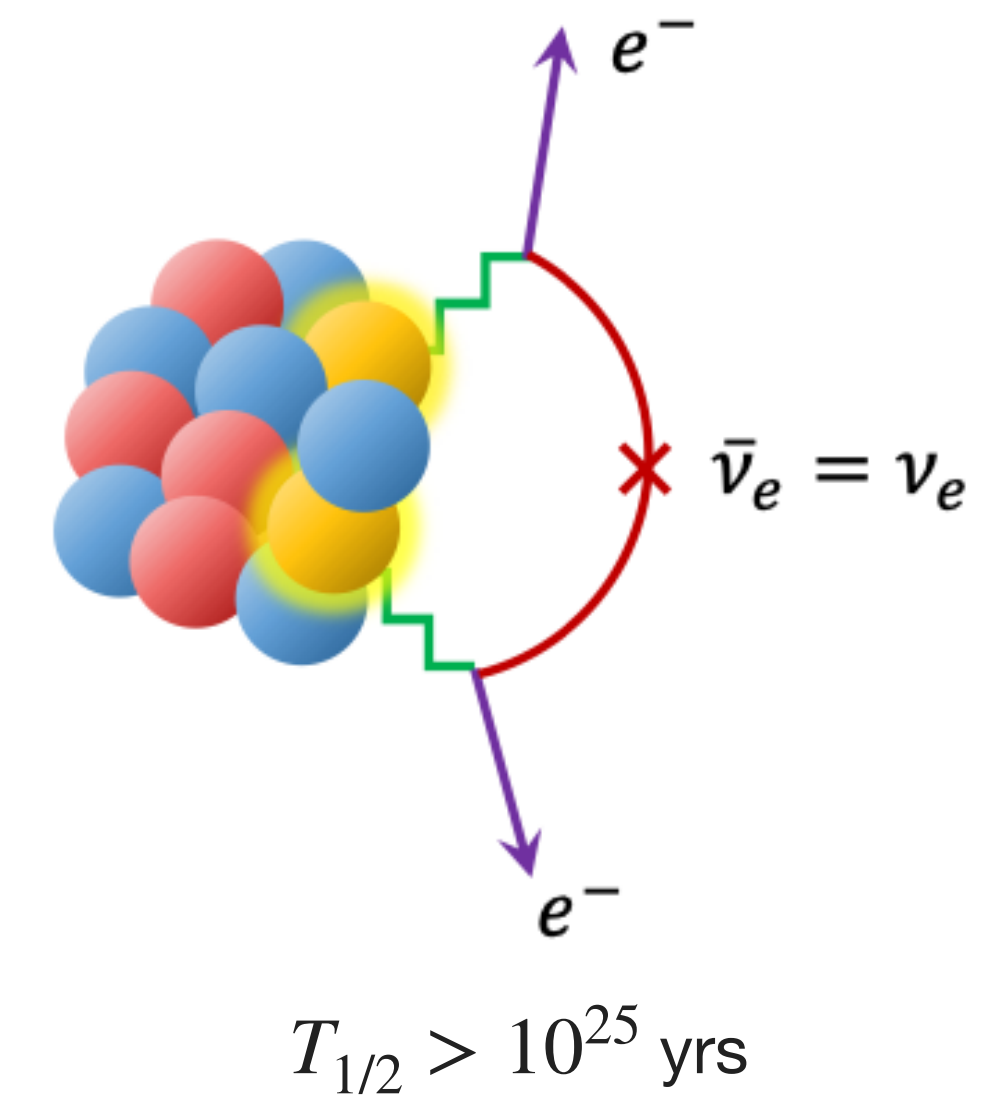
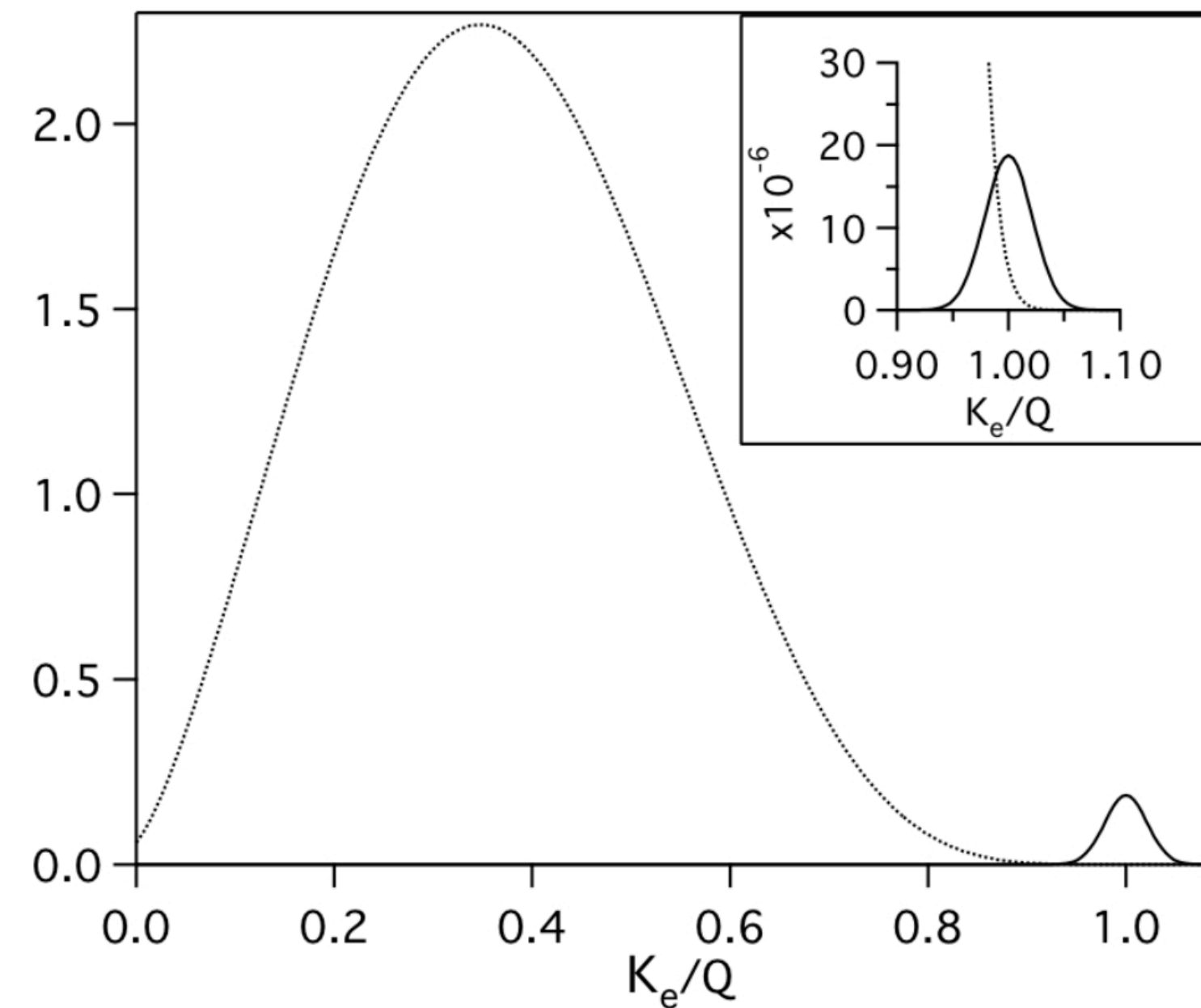
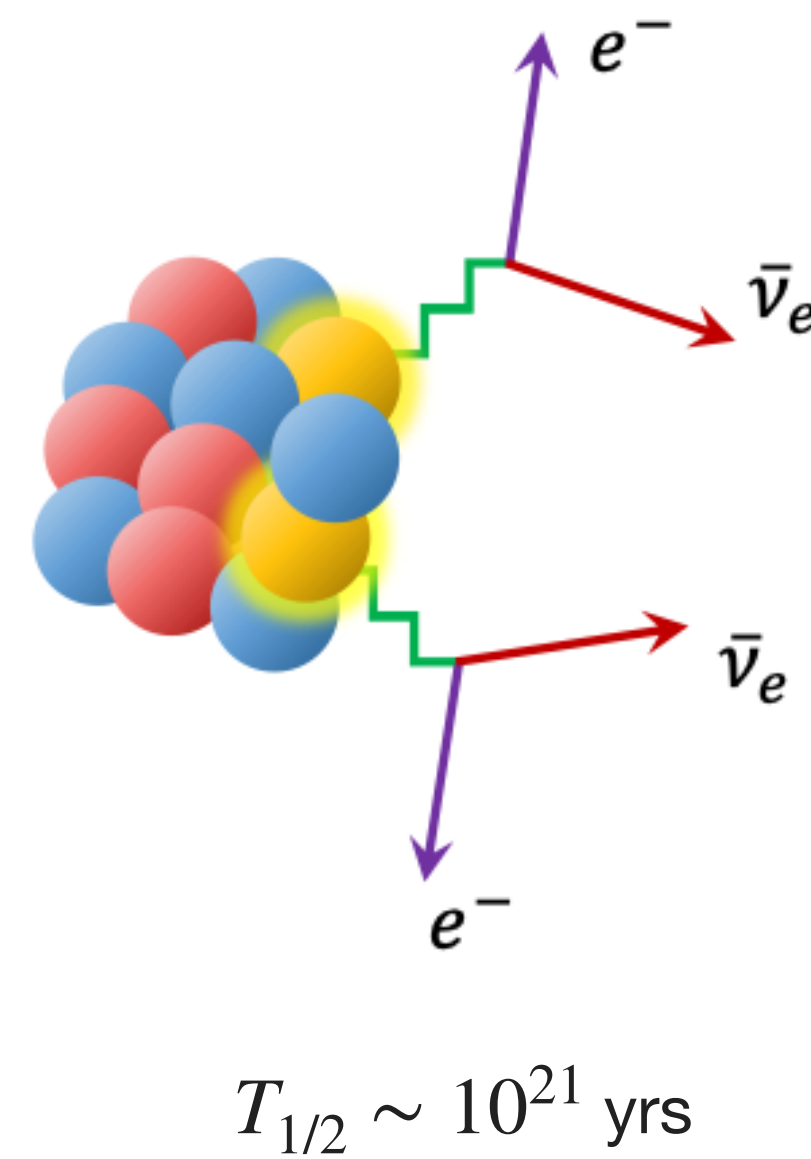


Neutrinoless double beta-decay



Answer the question whether neutrinos are Majorana particles.

Lepton number violation in weak processes can help to explain matter/antimatter asymmetry; smallness of neutrino masses.



Process is possible in isotopes that undergo SM-allowed $2\nu\beta\beta$ decay. About 10 isotopes are considered in the experiments.

$$T_{1/2}^{0\nu} \propto \epsilon \sqrt{\frac{m \cdot t}{B \cdot \sigma_E}}$$

isotope mass m , running time t , detection efficiency ϵ , bkg rate B , energy resolution σ_E

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} |M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta} \rangle}{m_e} \right)^2$$

phase space factor $G^{0\nu}$, nuclear matrix element (NME) $|M_{0\nu}|^2$, elements of PMNS matrix U_{ei}^2 , neutrino masses m_{ν_i}

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

Measure $T_{1/2} \rightarrow$ constraints for $\langle m_{\beta\beta} \rangle^2$

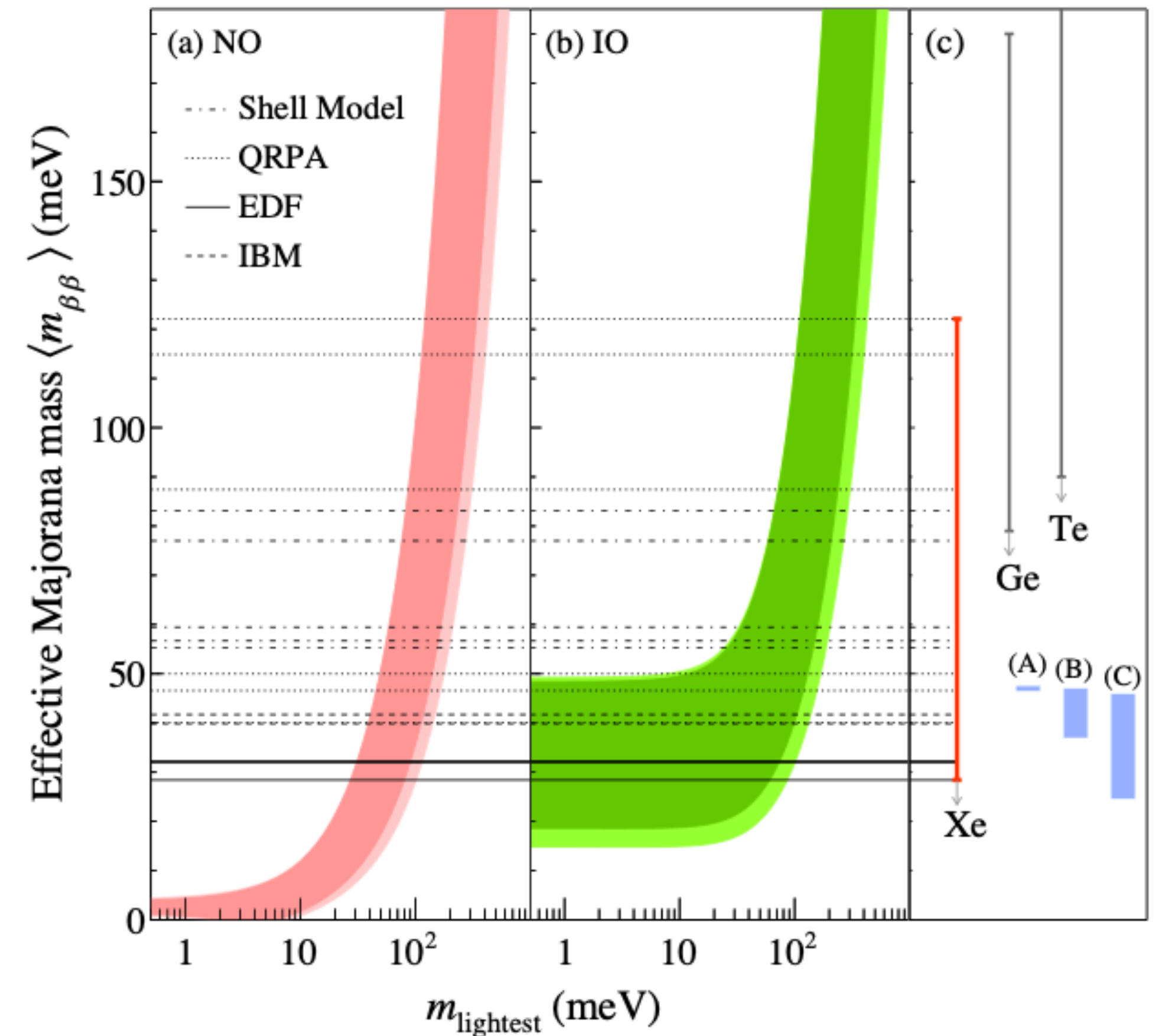
Neutrinoless double beta-decay

Current status

Current status and highlights:

- * KamLAND-Zen 800:
 - * $\langle m_{\beta\beta} \rangle < 28\text{--}122$ meV is the most precise so far and touched the IO region
 - * Experiment is upgrading to KamLAND2-Zen
- * CUORE (Science 390, 1029-1032 (2025))
 - * $\langle m_{\beta\beta} \rangle < 70\text{--}250$ meV
- * LEGEND-200 (Phys.Rev.Lett. 136 (2026) 2, 022701)
 - * $\langle m_{\beta\beta} \rangle < 75\text{--}200$ meV
- * NEXT-100 started in 2024, no results yet

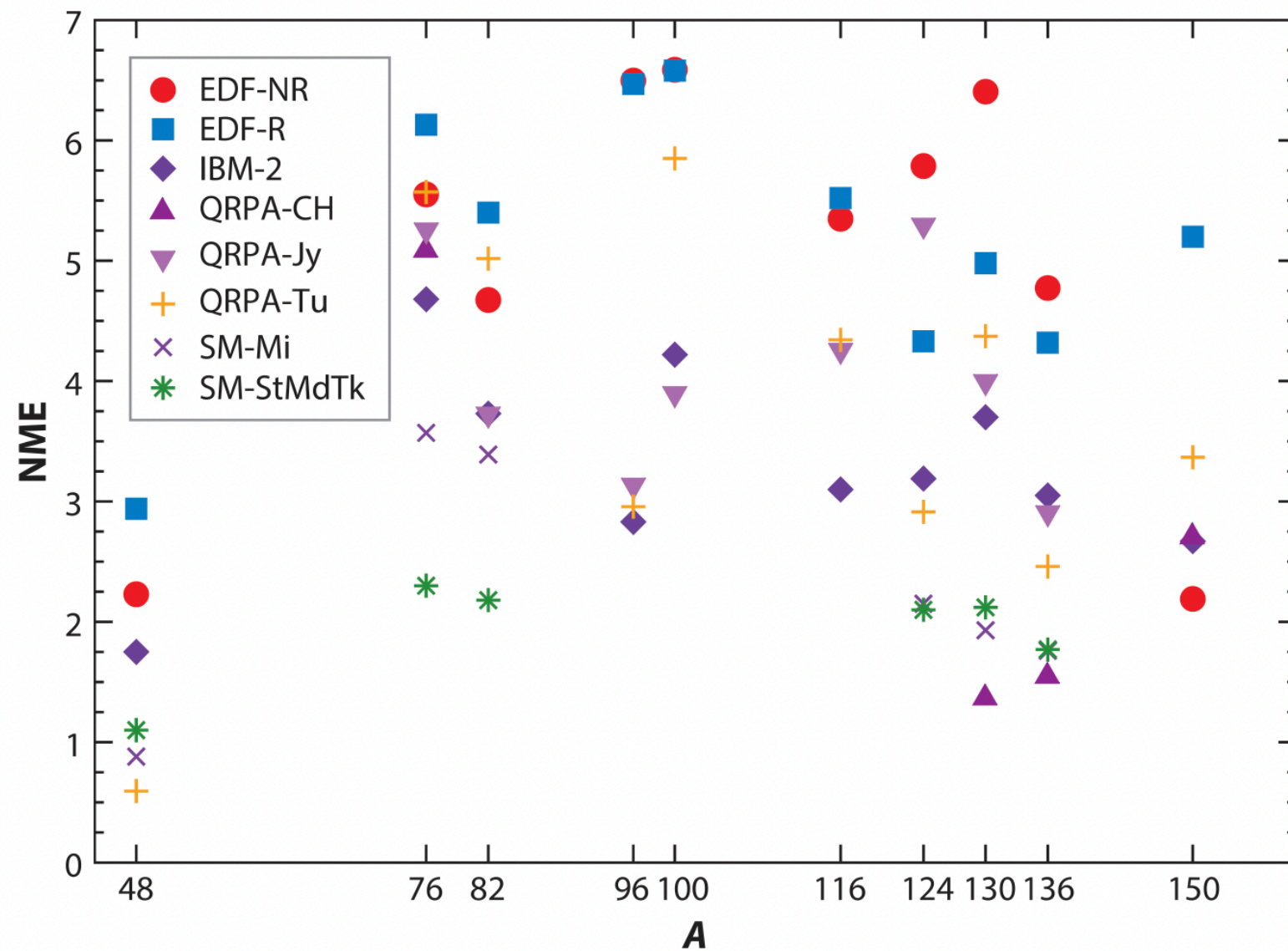
Phys.Rev.Lett. 135 (2025) 26, 262501



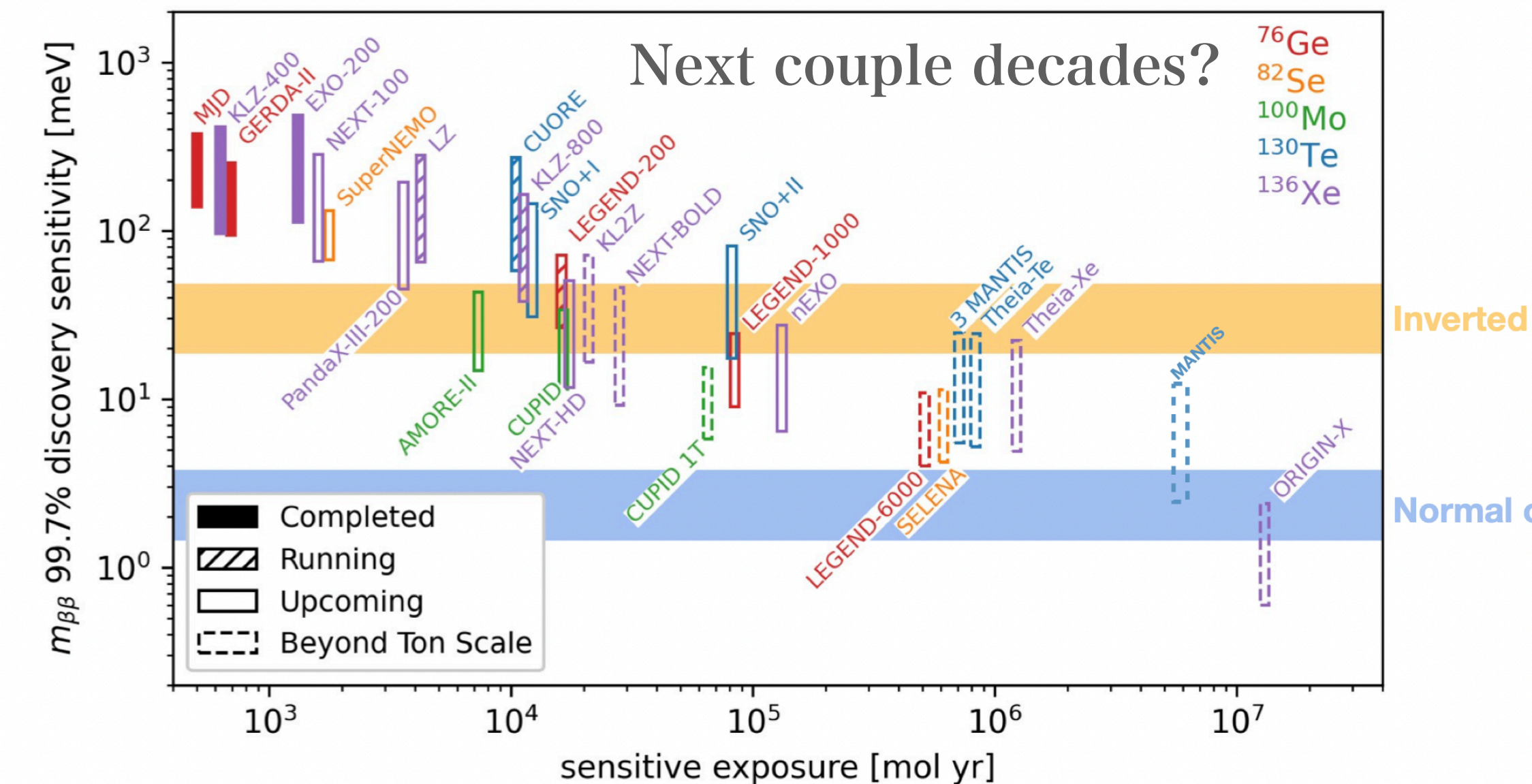
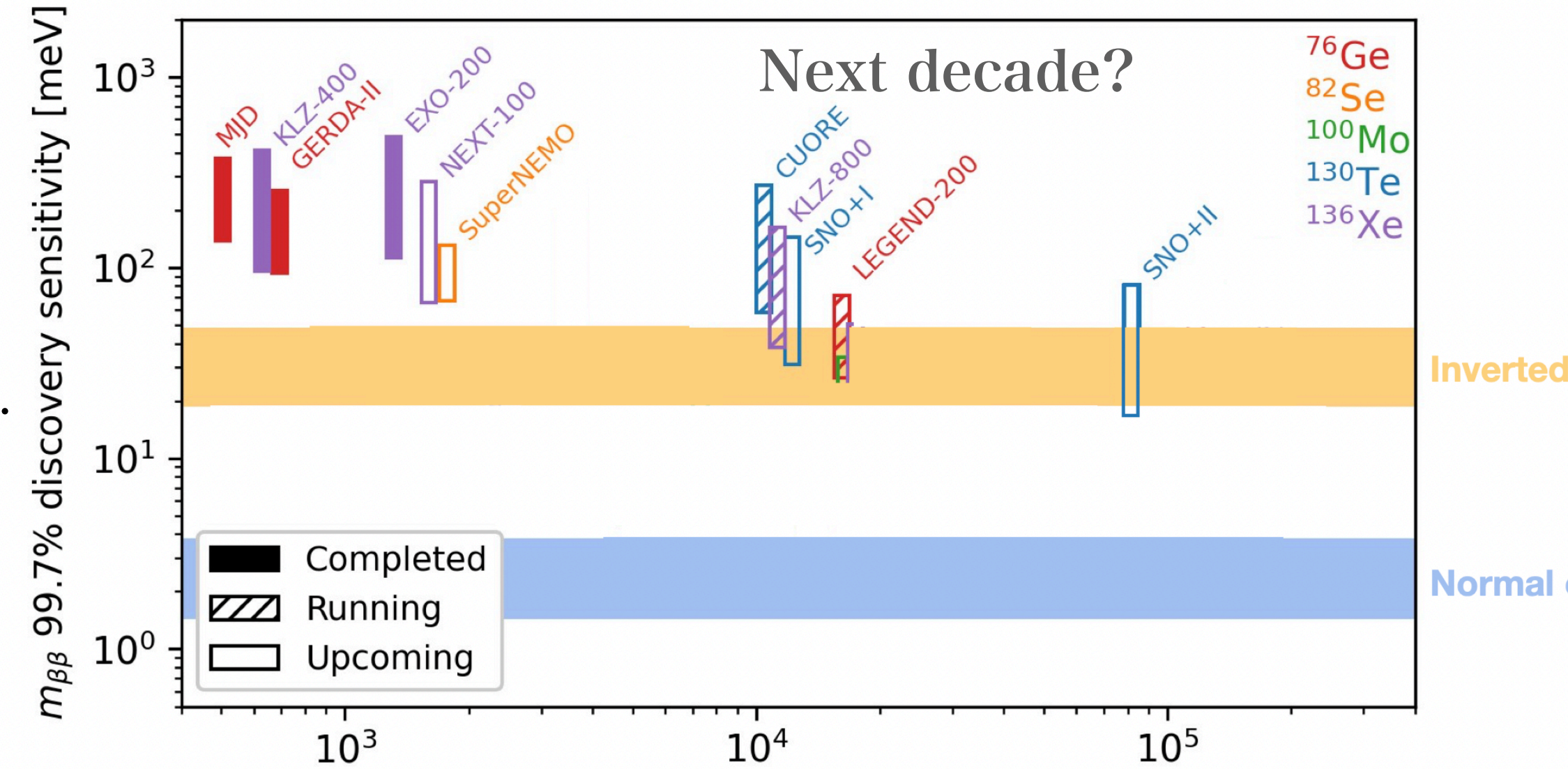
Neutrinoless double beta-decay

Future prospects

- * Starting soon: SNO+, SuperNEMO, AMoRE-II.
- * After this in the next decade tone scale experiments to come to cover all IO region (LEGEND-1000, CUPID, nEXO, NEXT-HD etc).
- * To touch the NO space significant technology advances are needed and huge detector volume.



Also serious theoretical community effort is needed to address NME.



Cosmological $\sum m_i$

- * Latest constraint from Planck with final dataset (Astron. Astrophys. 682 (2024), A37)

$$\sum m_i \leq 0.12 \text{ eV (95\% CL), needs physics prior}$$

- * Recent results from DESI

- * Combination with Planck and ACT

$$\sum m_i \leq 0.061 \text{ eV (95\% CL) , needs physics prior}$$

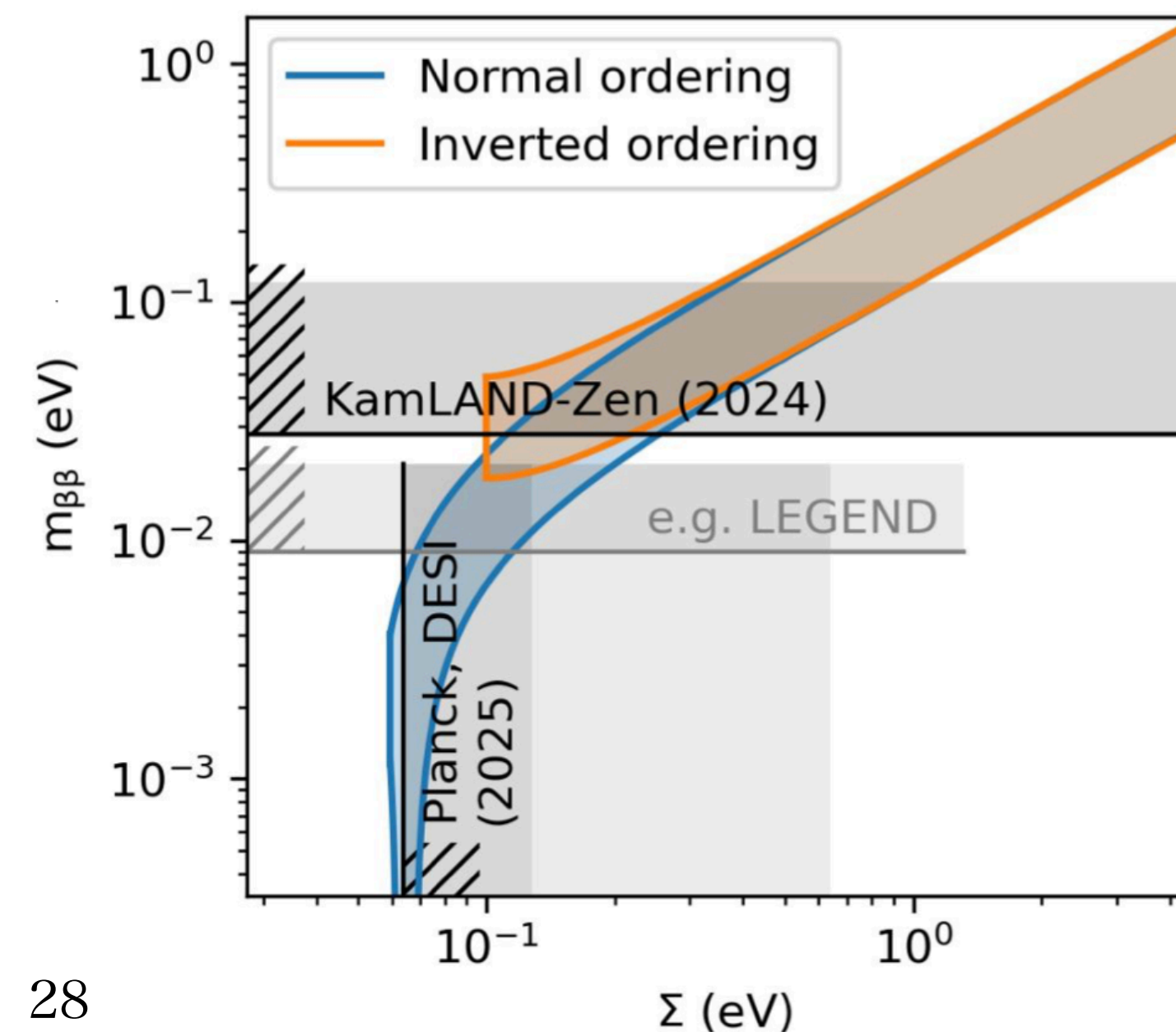
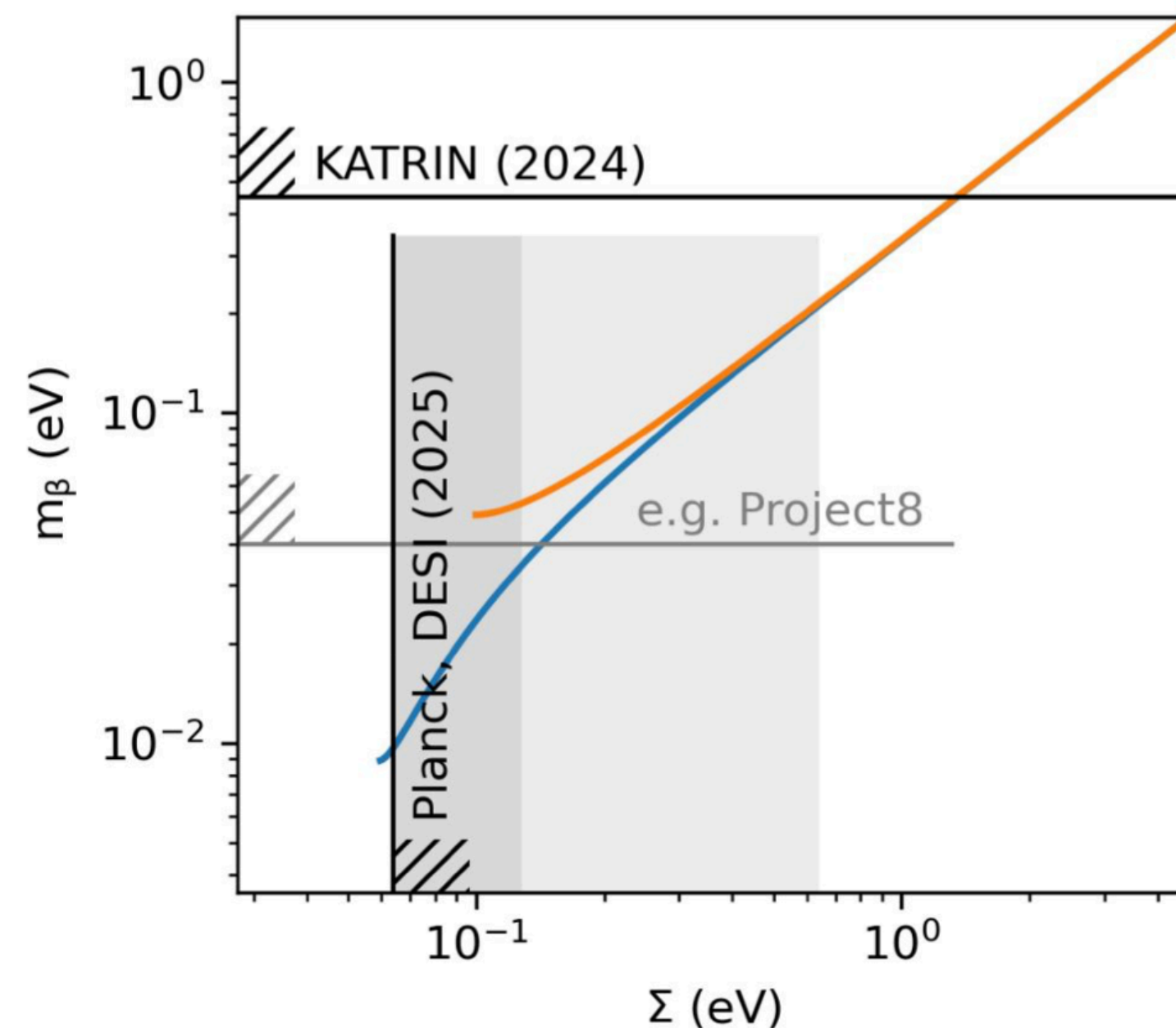
- * Tension with limits from ν osc if no constraints

$$\sum m_i \geq 0.058 \text{ eV (95\% CL) } \leftarrow \text{terrestrial. osc. exp.}$$

- * Extending the Λ CDM model to remove this tension:

$$\sum m_i \leq 0.152 \text{ eV (95\% CL)}$$

- * Next: ESA Euclid, LSST, CMB-S4



Astrophysical neutrinos

Talk by Prof. V. Aynutdinov on Wednesday

Current neutrino telescopes:

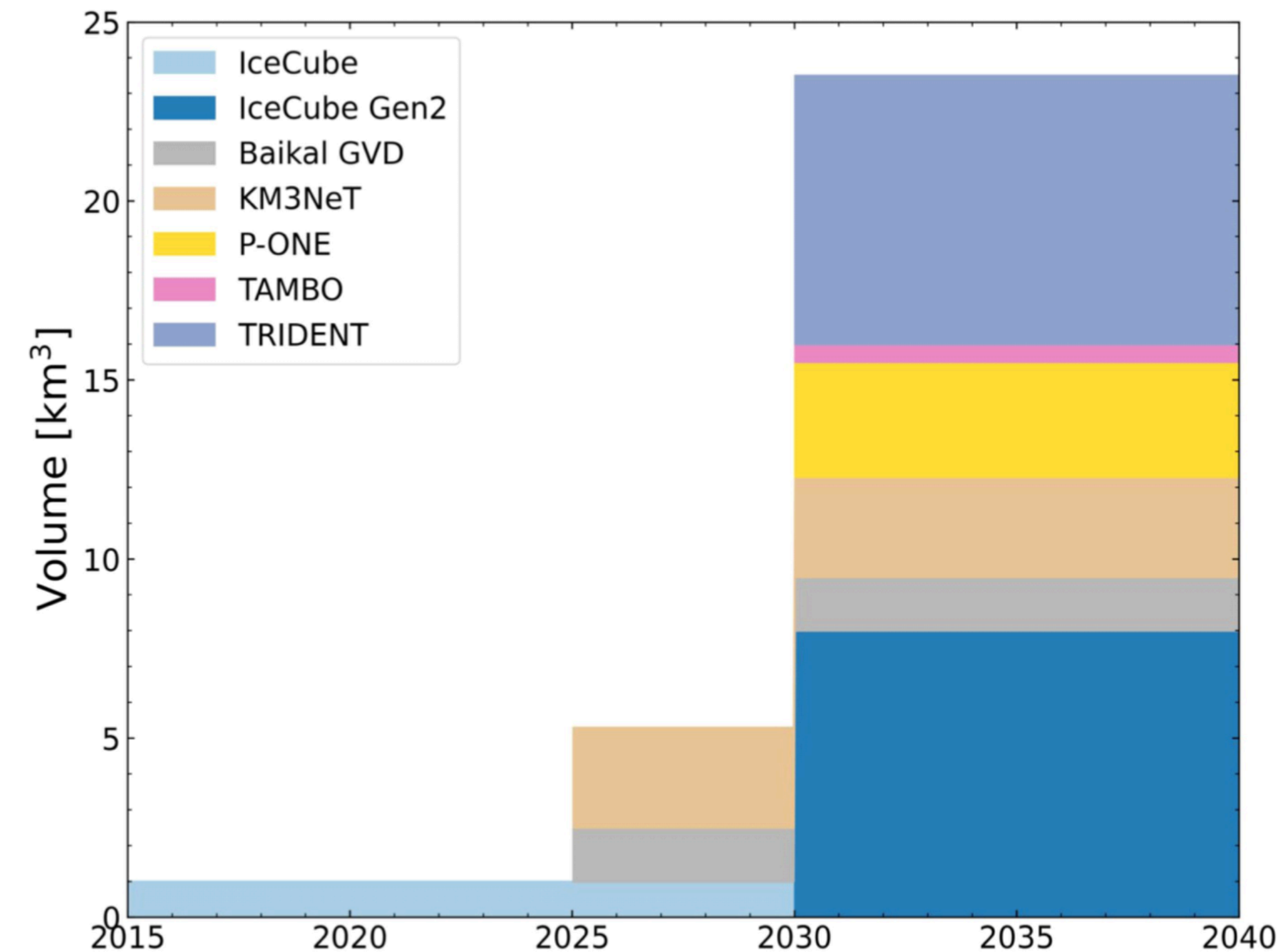
- * IceCube (discovery of astrophysical neutrinos in 2013),
- * Baikal-GVD (~80% of planned volume),
- * KM3NeT - ARCA (21% of planned volume, first 10s of PeV event).

Current goals:

- * Flux measurement, power law studies;
- * Pointing the sources: Galactic plane, Active galaxy, Blazar
(so far just three sources were detected by IC with high sign).

Future: P-ONE (Canada), HUNT (possibly in Baikal), NEON and TRIDENT (South China Sea), Ice-Cube gen2.

Multi-Wavelength Astronomy: synergy with e/m telescopes (Gamma-ray, x-ray) and gravitational waves observatories.



Relic neutrinos a.k.a. Cosmic Neutrino Background

*No evidence so far, but they should exist according to the Standard Cosmology Model.

*Average number density: $339 \text{ particles/cm}^3$; $T = 1.95 \text{ K}$, $\langle E \rangle = 10^{-4} \text{ eV}$.

*Detection method in lab: neutrino capture on beta-decaying nuclei.

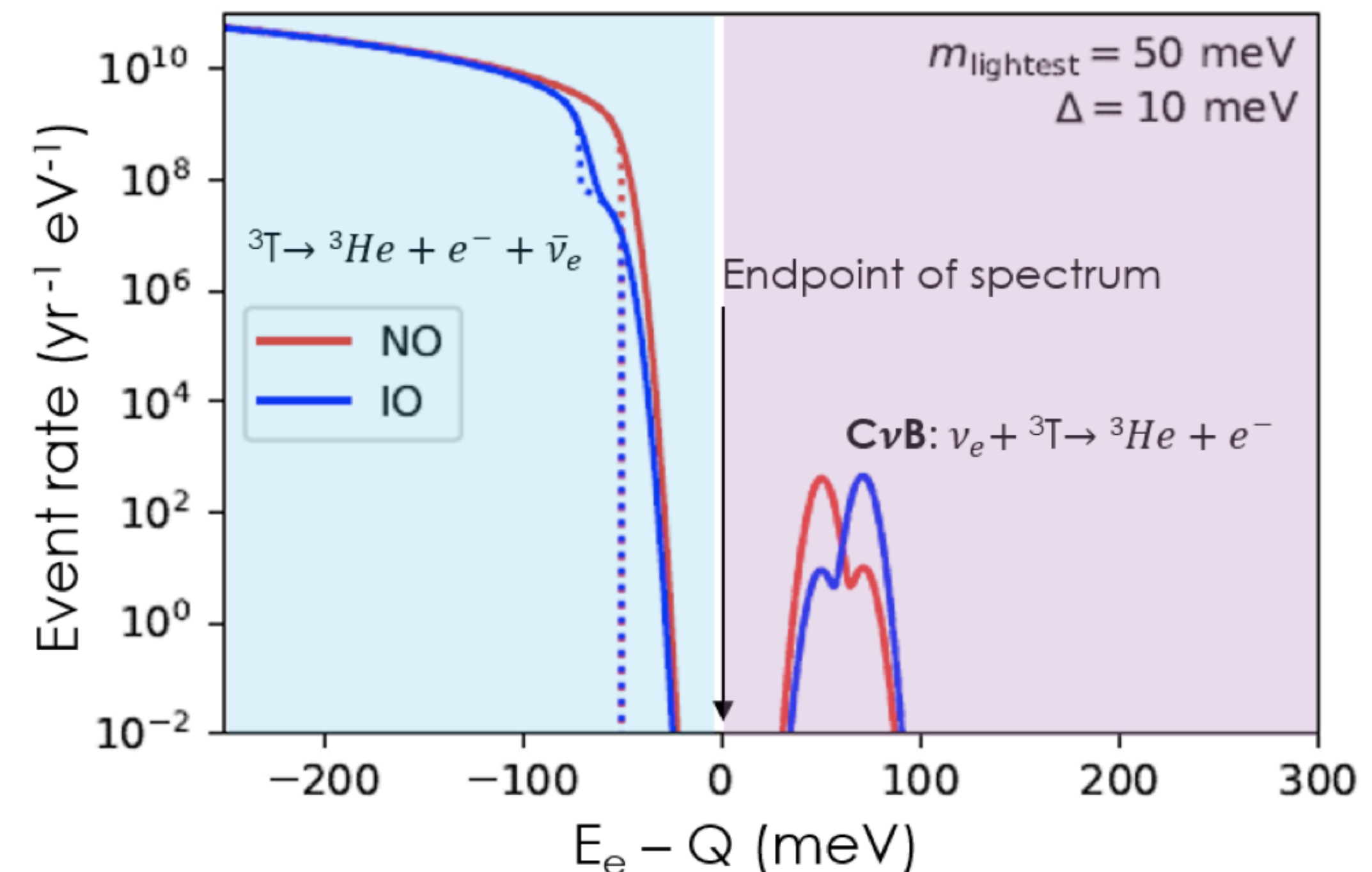
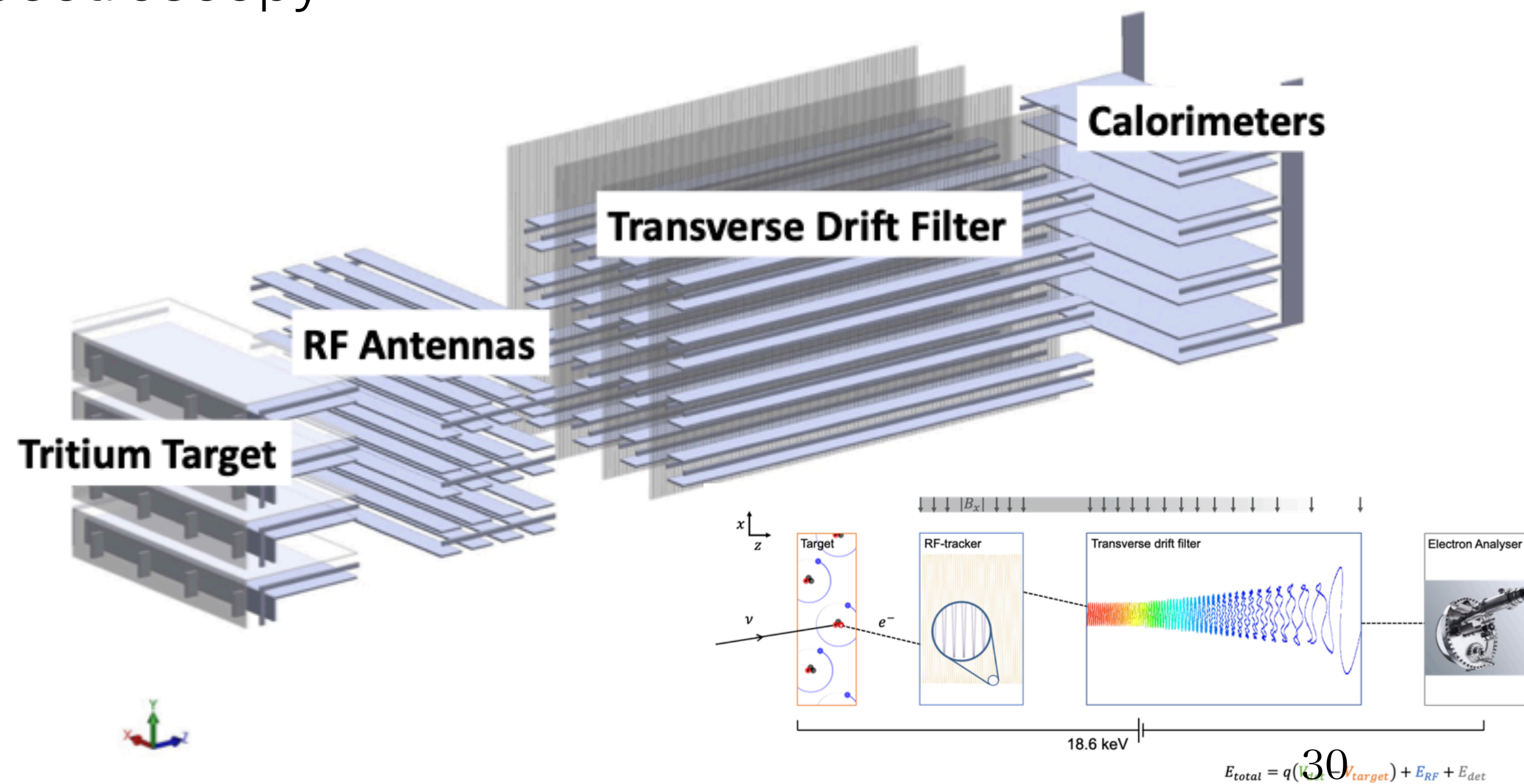
PTOLEMY experiment (prototype is under construction at LNGS, demonstrator at Princeton) combining:

* CRES to determine electron energy

* transverse drift filter to select and decelerate end-point electrons

* low temperature microcalorimeters for hi-res spectroscopy

First physics results are expected by 2030



Summary

- * Very exciting time for many areas of neutrino physics.
- * In the upcoming couple decades should get answers to many outstanding questions:
 - * Precise knowledge of oscillation parameters and NMO.
 - * Are there sterile neutrinos?
 - * Is there a $0\nu\beta\beta$ decay?
 - * What is the value of absolute neutrino mass?
 - * Any signs of relic neutrinos?
 - * What is the origin of ultra high energy astrophysical neutrinos?
 - * etc
- * Stay tuned!

