Neutrino Physics

Experimental - Part II

TAE 2024 - International Workshop on High Energy Physics

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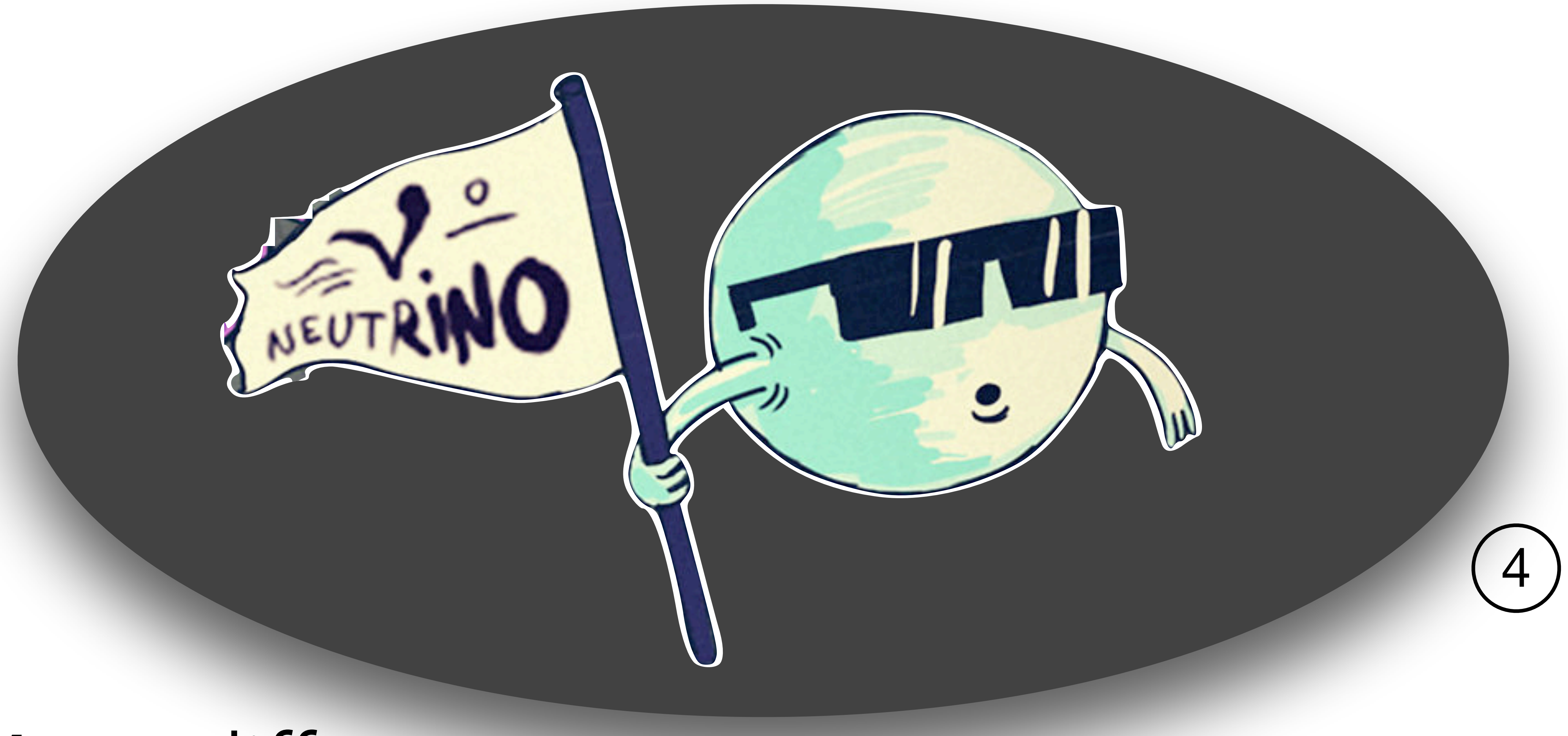
Centro de Ciencias Pedro Pascal

Benasque, 11 September 2024

Why do we study neutrinos?



① Fundamental Particle

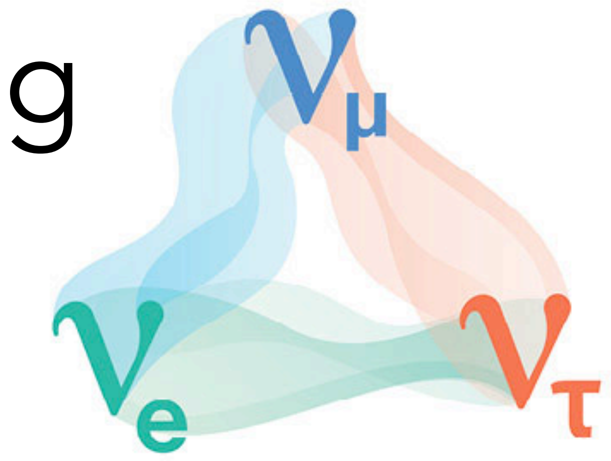
② Abundant

Massive particle more abundant in Nature

③ Elusive

Difficult but not impossible to catch

④ Oscillating



⑤ Lightweight

The weight almost nothing

⑥ Many different sources

⑦ Mysterious

Not fully understood yet

⑧ Key to understand the Universe

Are neutrino and anti-neutrino the same particle?

Why do we study neutrinos?

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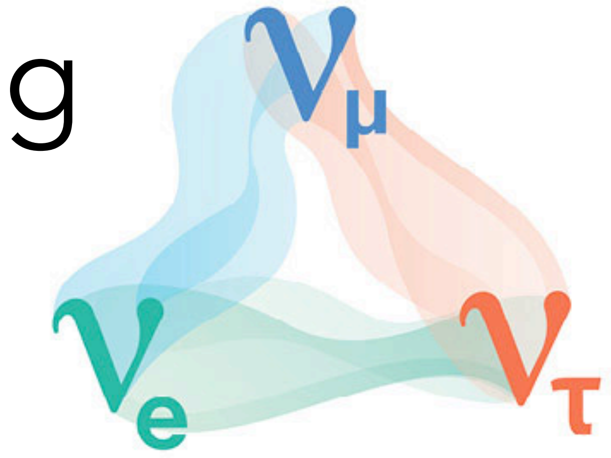
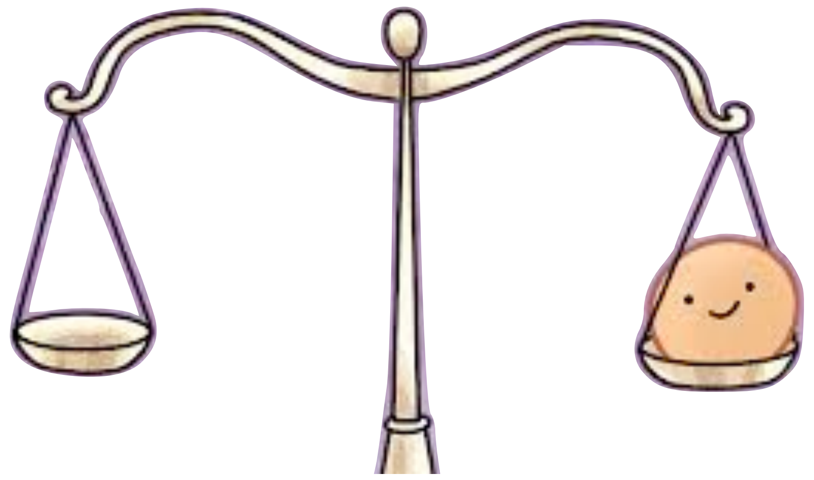


⑤ **Lightweight**

The weight almost nothing



✓ Many different sources

⑦ **Mysterious**

Not fully understood yet

⑧ **Key to understand the Universe**

Are neutrino and anti-neutrino the same particle?

Open questions in neutrino physics

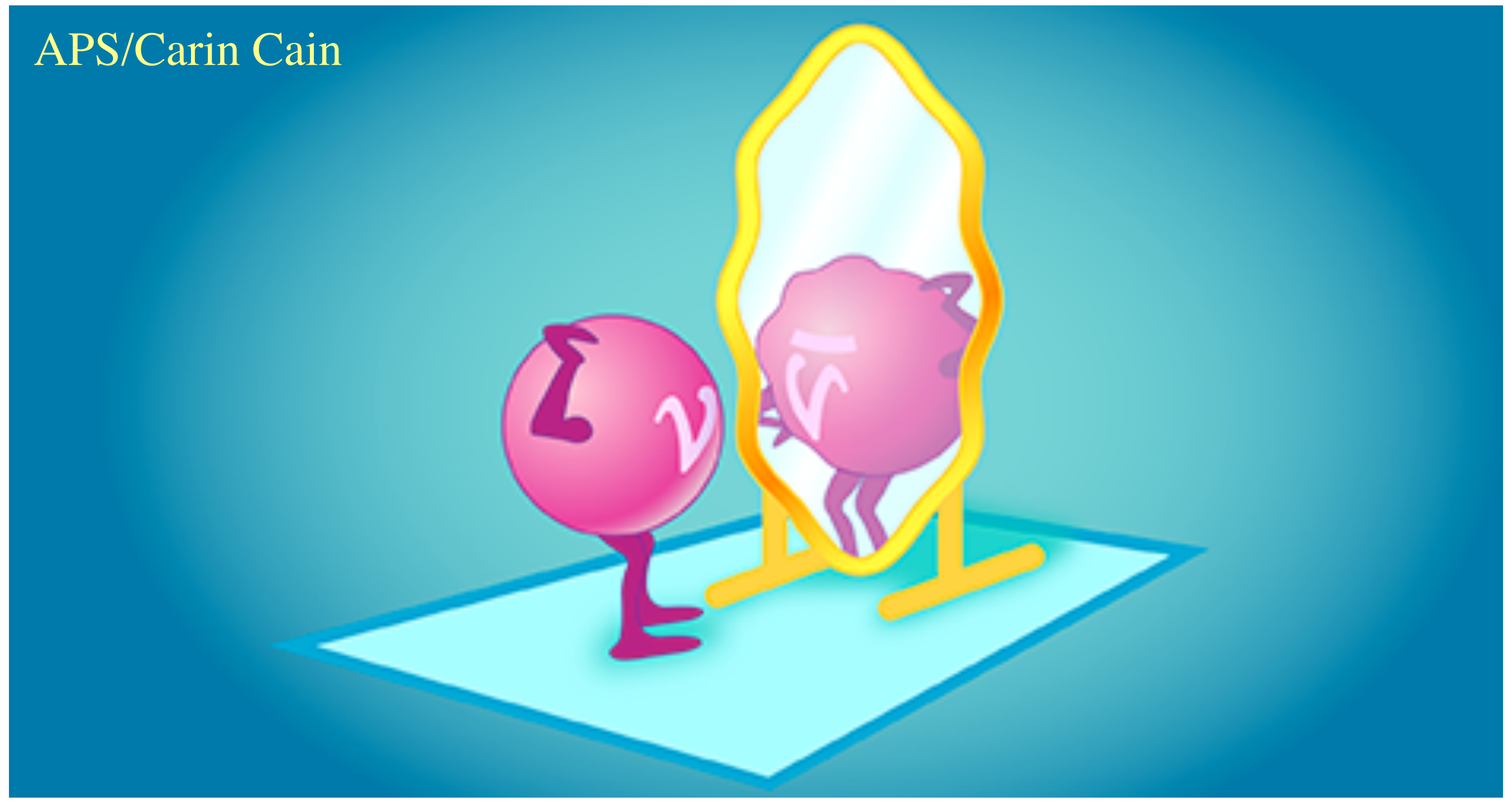
1) Is the CP phase non-zero? What it its value? Mixing

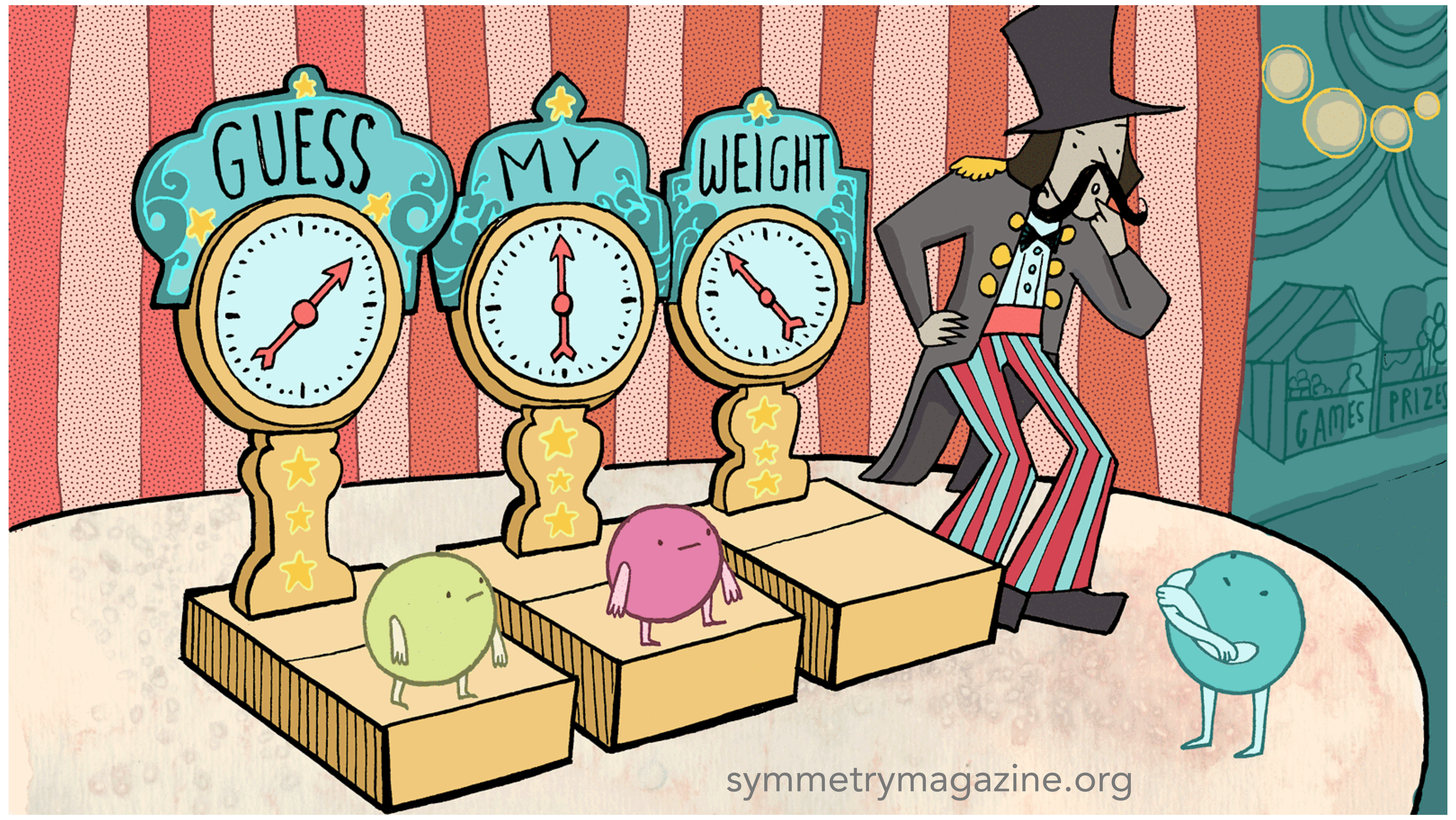
2) What is the mass ordering? Masses
What are the absolute values of the neutrinos masses?

3) Are neutrinos its own anti-particle? Nature
Are they Dirac or Majorana particles?

4) Are there any other types of neutrinos? Spieces

Many projects ahead to answer these questions





CP violation and neutrino mass ordering

Next generation oscillation experiments

- Future long baseline (LBL) experiments will have to close the three-flavour oscillation framework. Meaning:

  i) determine the mass ordering

  ii) study the existence of CP violation in the neutrino sector

$$\begin{bmatrix} \nu_\mathrm{e} \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta_\mathrm{CP}} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta_\mathrm{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- Including matter effects (MSW), there is an interplay between mass ordering and CP-phase in the 3-flavour oscillation probability for $\nu_\mu \longrightarrow \nu_e$ and $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

  - propagation in matter is different due to scattering of neutrinos in matter (in electrons particularly)
  - If $\delta_{CP} \neq 0$ neutrinos and antineutrinos behave in a different way $P(\nu_\mu \longrightarrow \nu_e) \neq P(\bar{\nu}_\mu \longrightarrow \bar{\nu}_e)$

Matter effects and δ_{CP} in oscillation experiments

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Phi_{31}-aL)}{(\Phi_{31}-aL)^2}\Phi_{31}^2$$

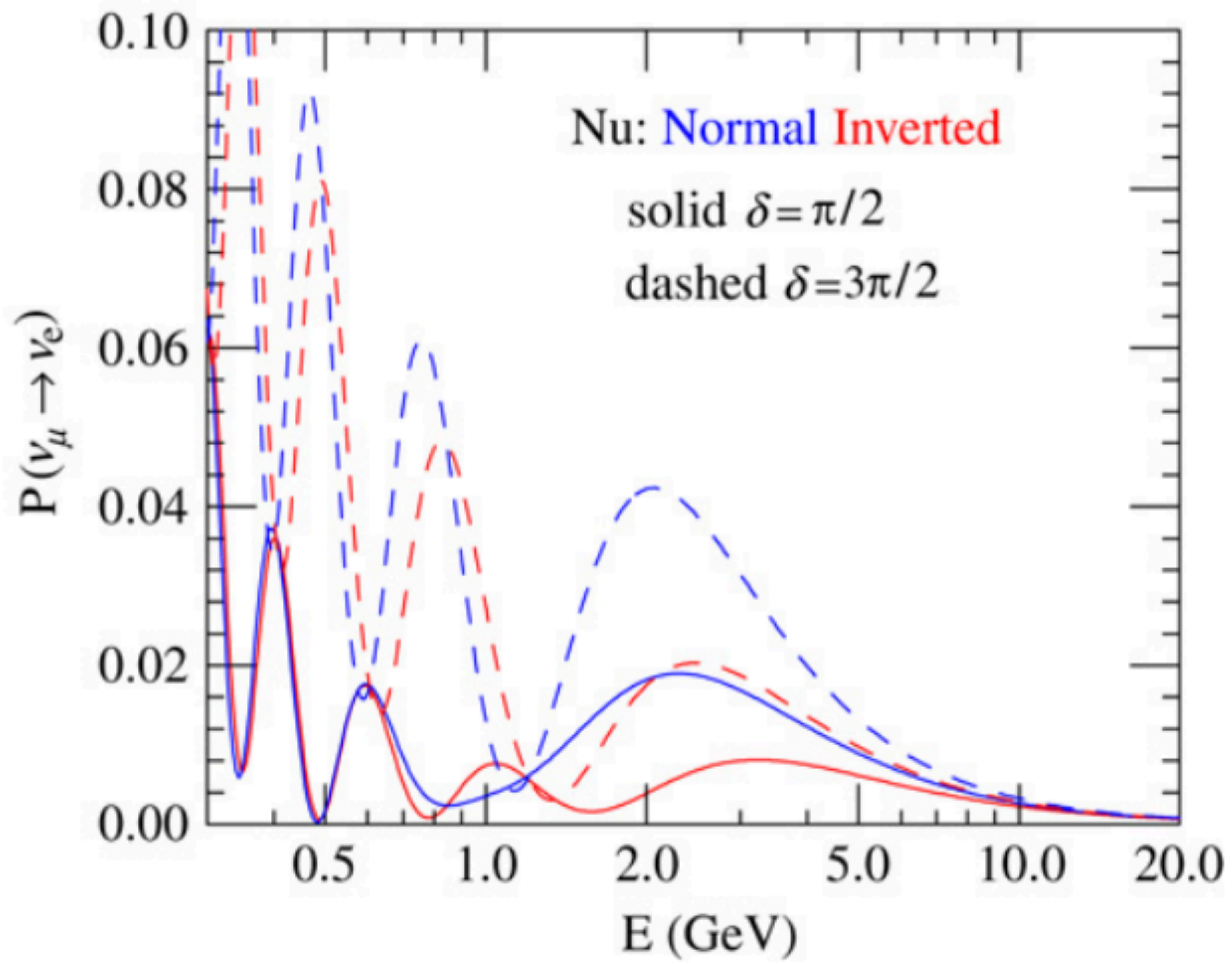
$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Phi_{31}-aL)}{(\Phi_{31}-aL)}\Phi_{31}\frac{\sin(aL)}{(aL)}\Phi_{21}\boxed{\cos(\Phi_{31}\underline{\pm}\delta_{\mathrm{CP}})}$$

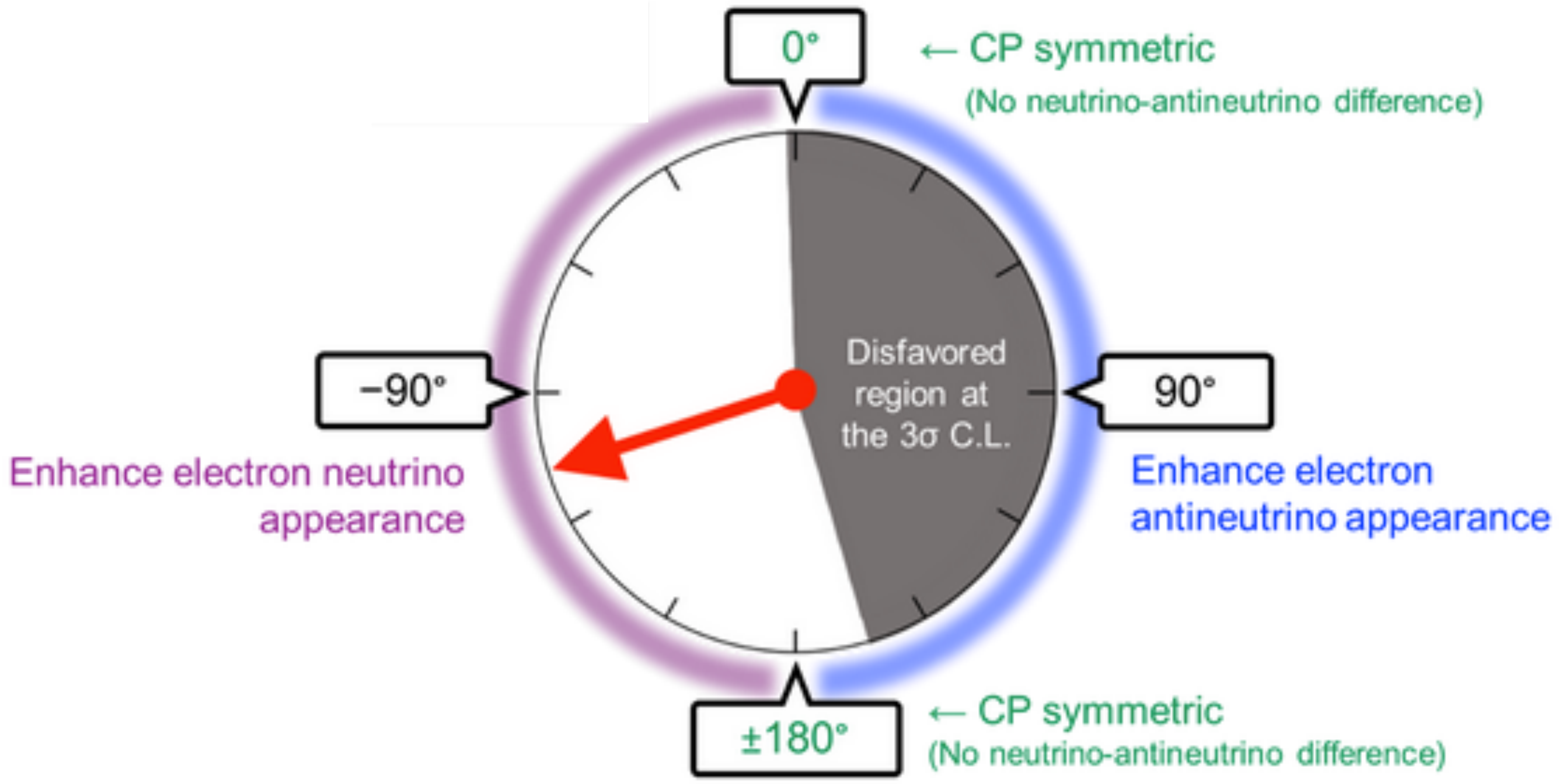
$$+ \dots$$

$$\Phi_{ji} = \frac{1.27\Delta m_{ji}^2 L}{E_\nu} \qquad a = \underline{\pm}\frac{G_F N_e}{\sqrt{2}}$$

Sign change for ν_e and $\bar{\nu}_e$

Interplay between mass ordering and CP-phase





Matter effects and δ_{CP} in oscillation experiments

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$$+\ldots$$
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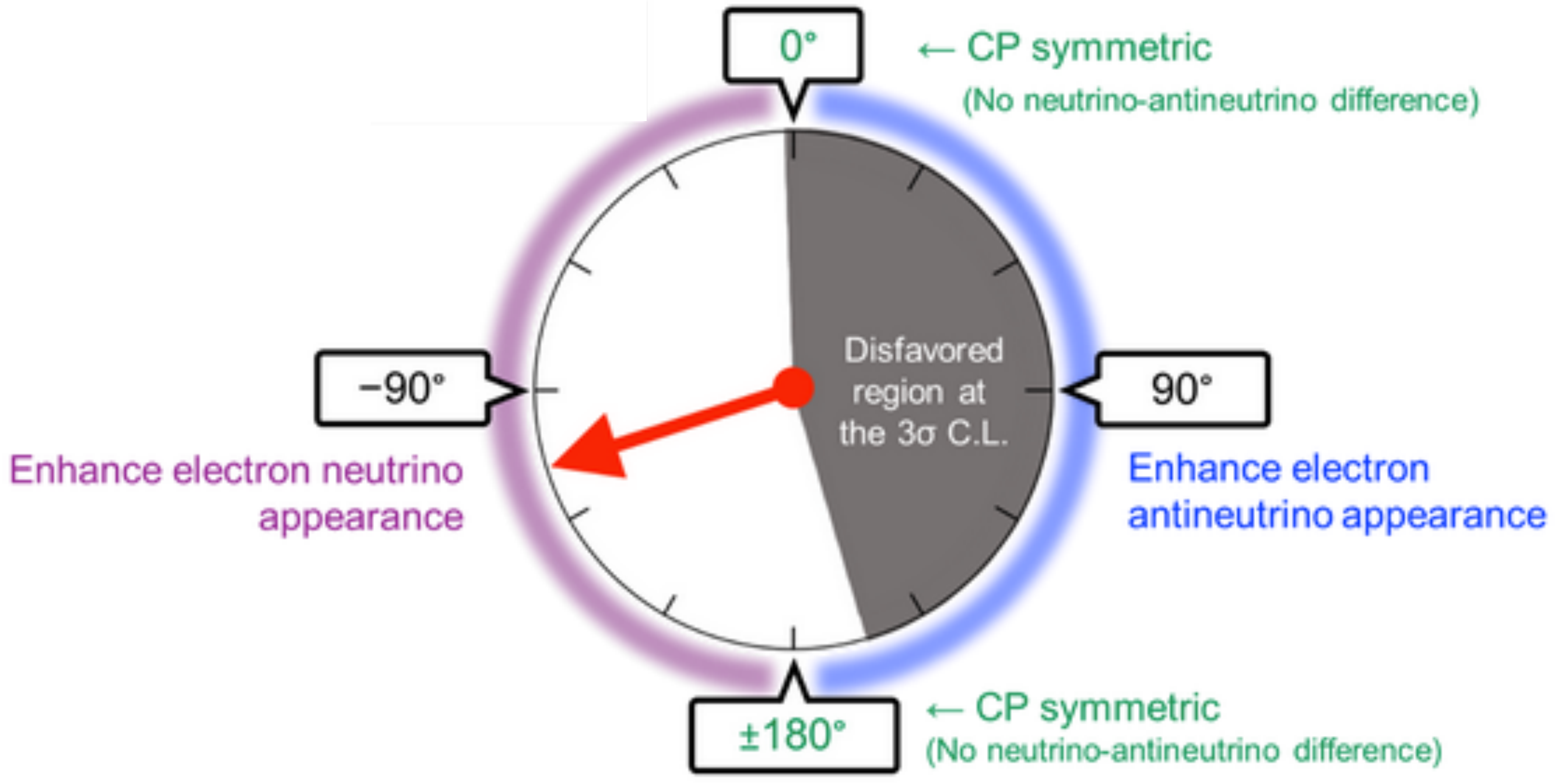
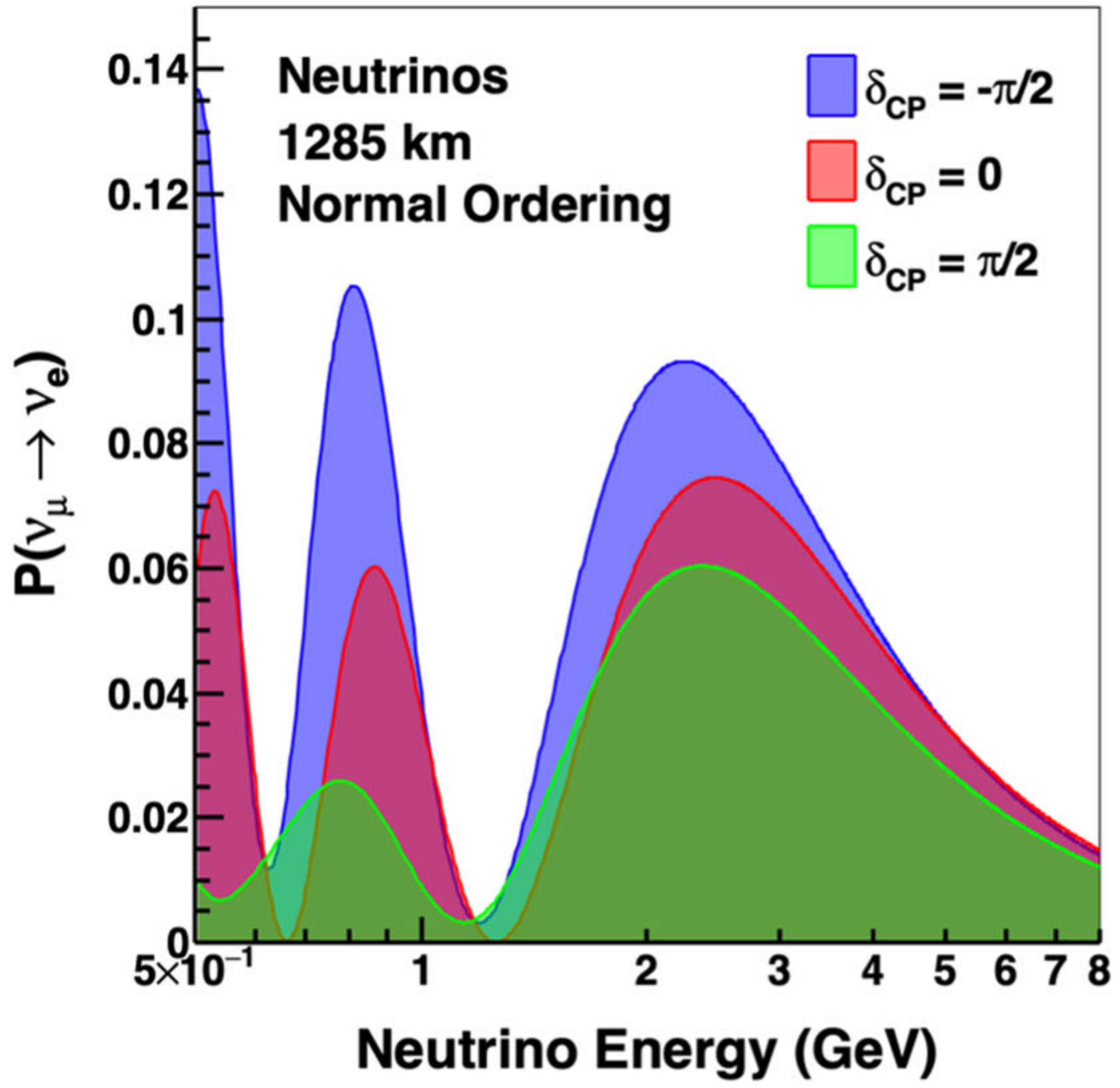
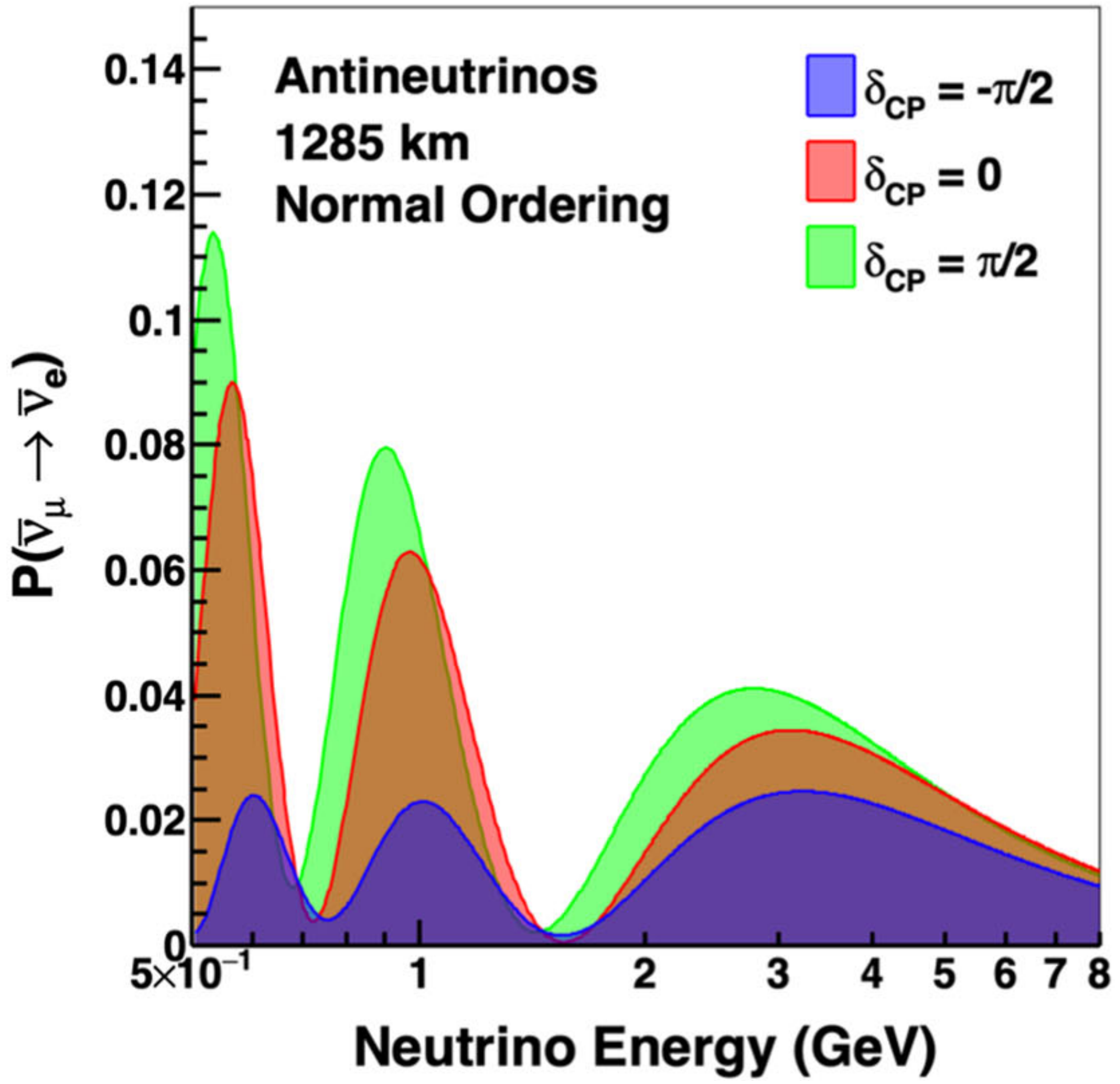
Sign change for ν_e and $\bar{\nu}_e$

Interplay between mass ordering and CP-phase







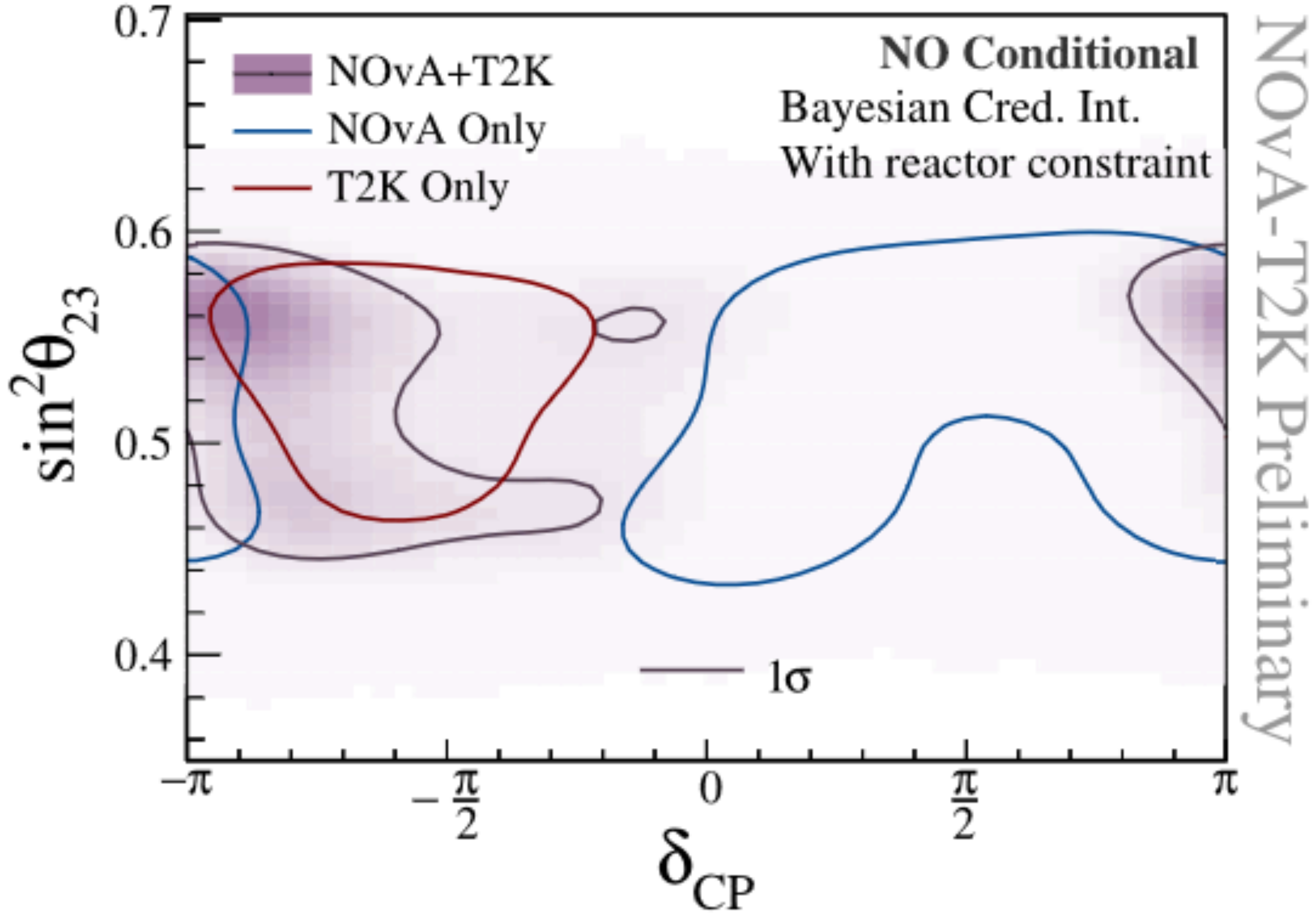
Current knowledge (NOvA & T2K)

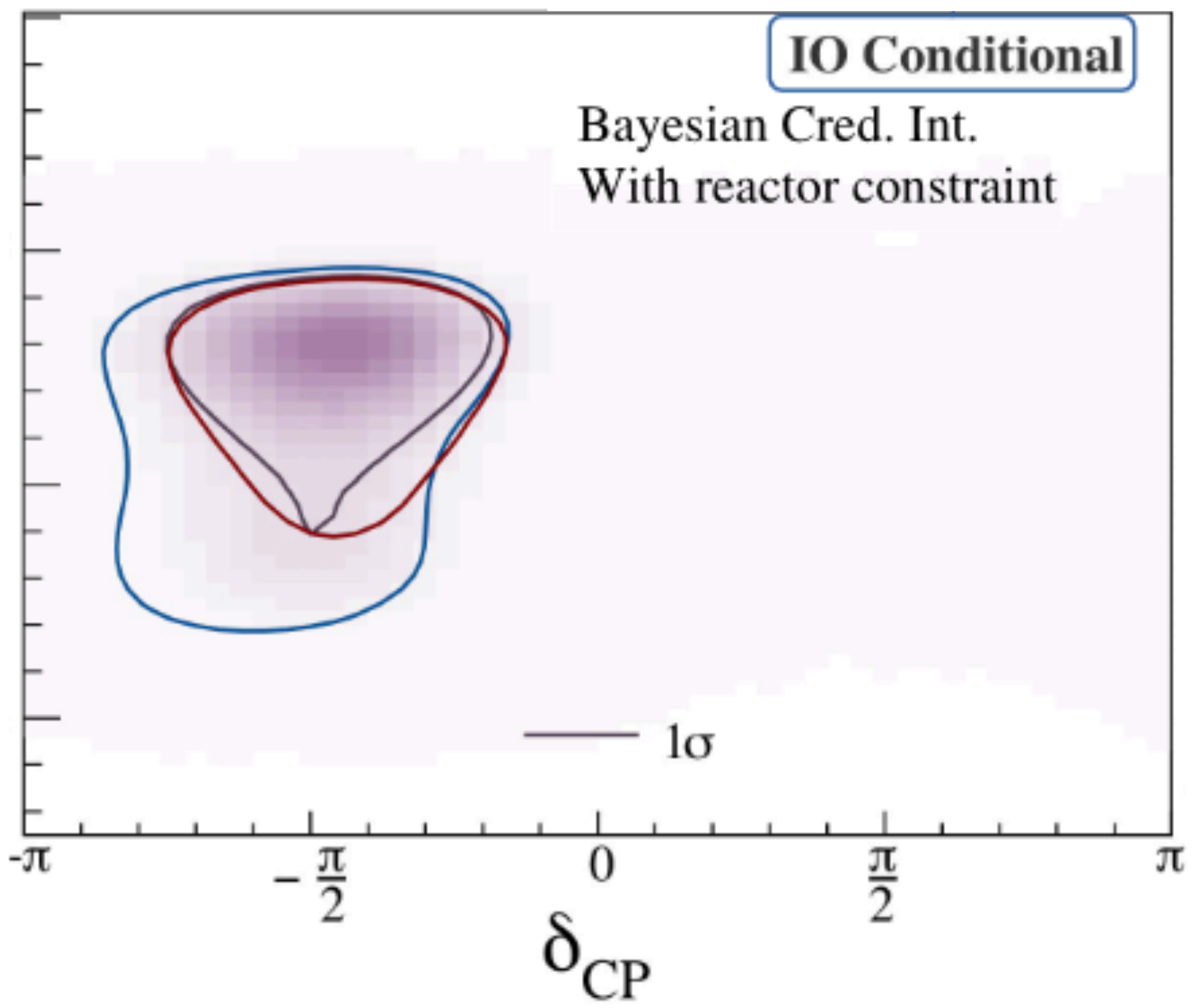
- NOvA + T2K combined results (Neutrino2024)

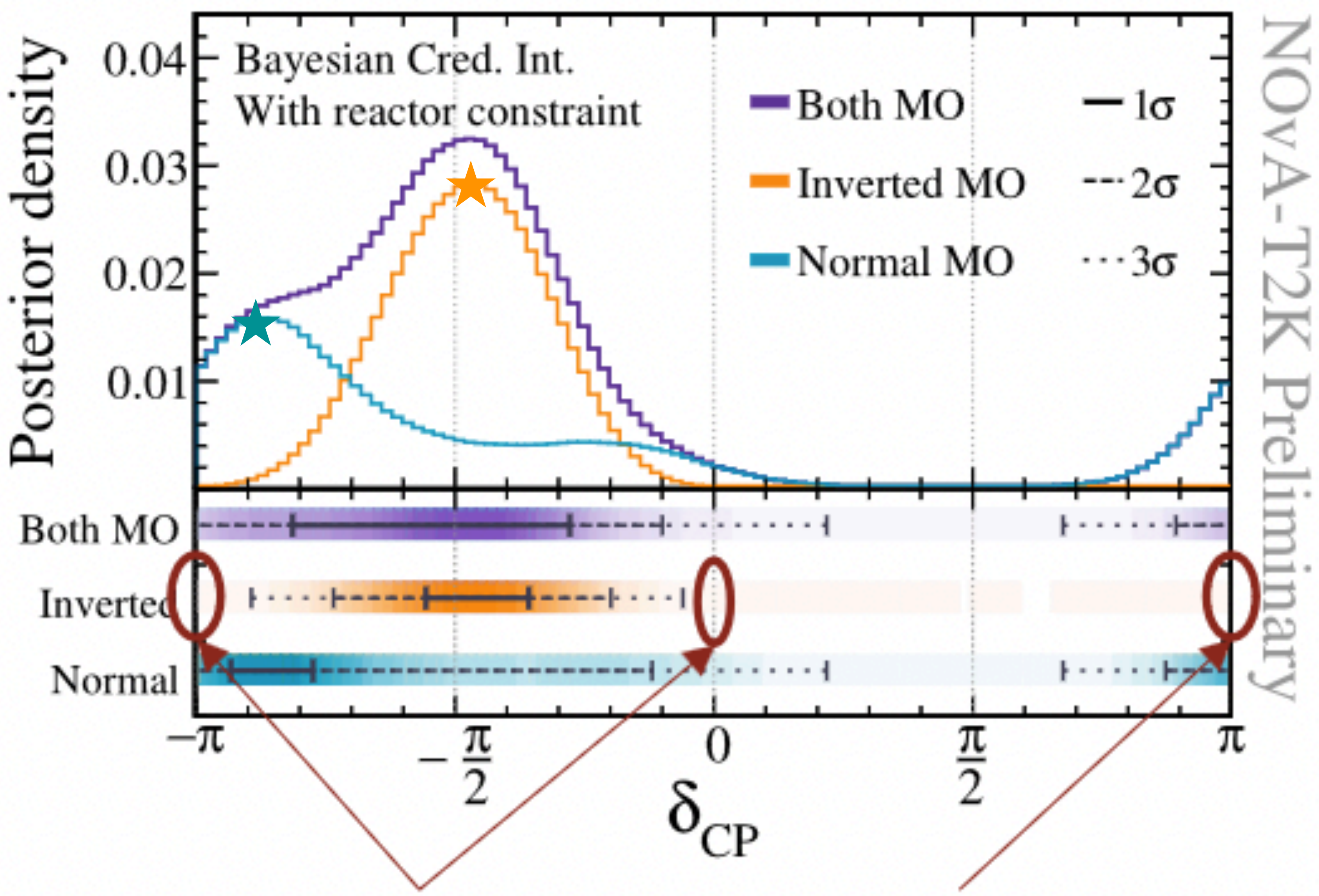
NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)

Some tension in the value of δ_{CP} for NO

Future LBL experiments needed to reach a conclusion







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

Expect CPV *if* ordering is inverted

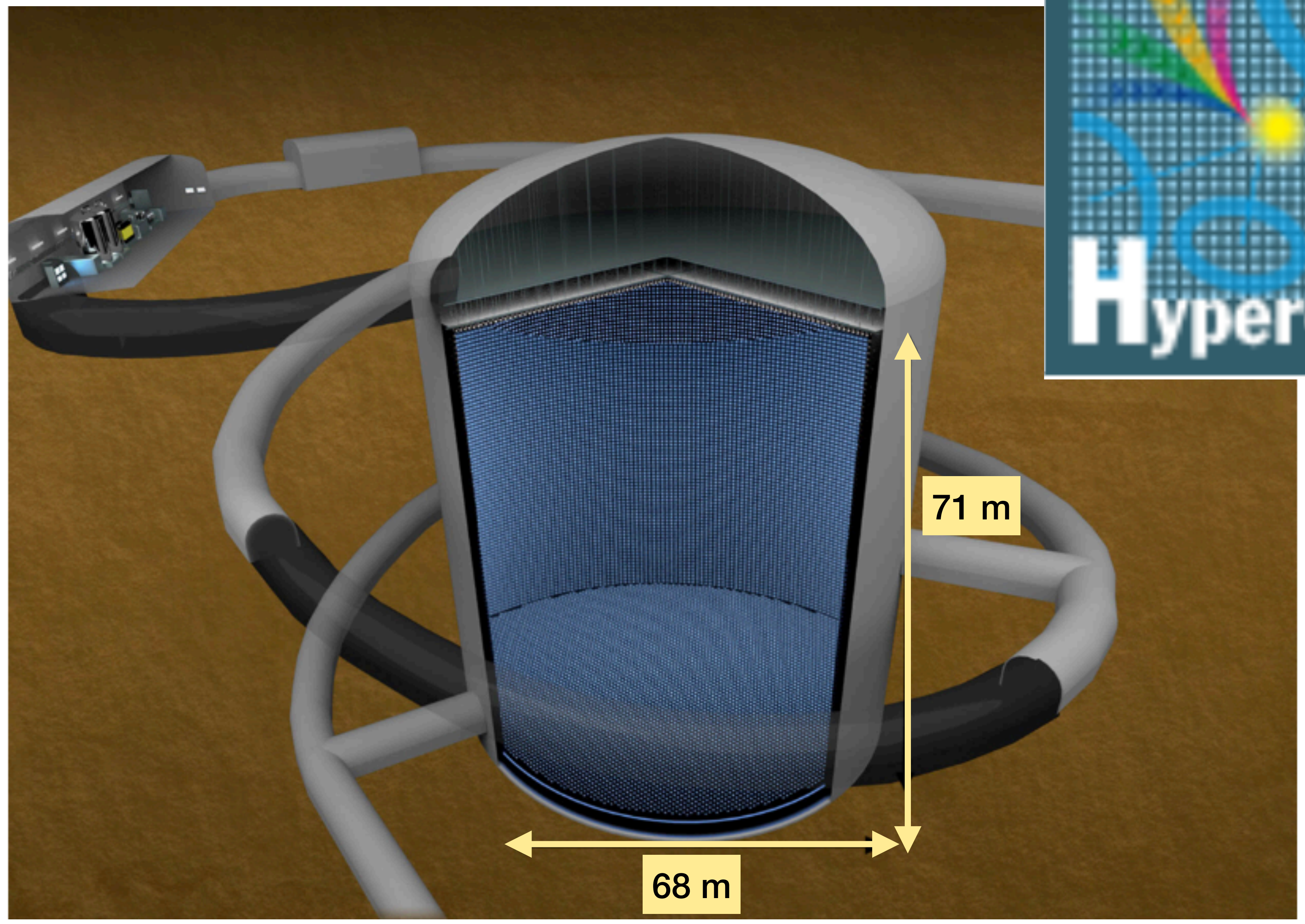
- **NOvA only:**
  - Preference for NO with $\pi/2 < \delta_{CP} < \pi$
  - Different trends NO and IO
- **T2K only:**
  - Preference for NO with $\delta_{CP} \sim -\pi/2$
  - Same trends NO and IO

- **NOvA + T2K combined:** Mild preference for IO

Hyper-Kamiokande

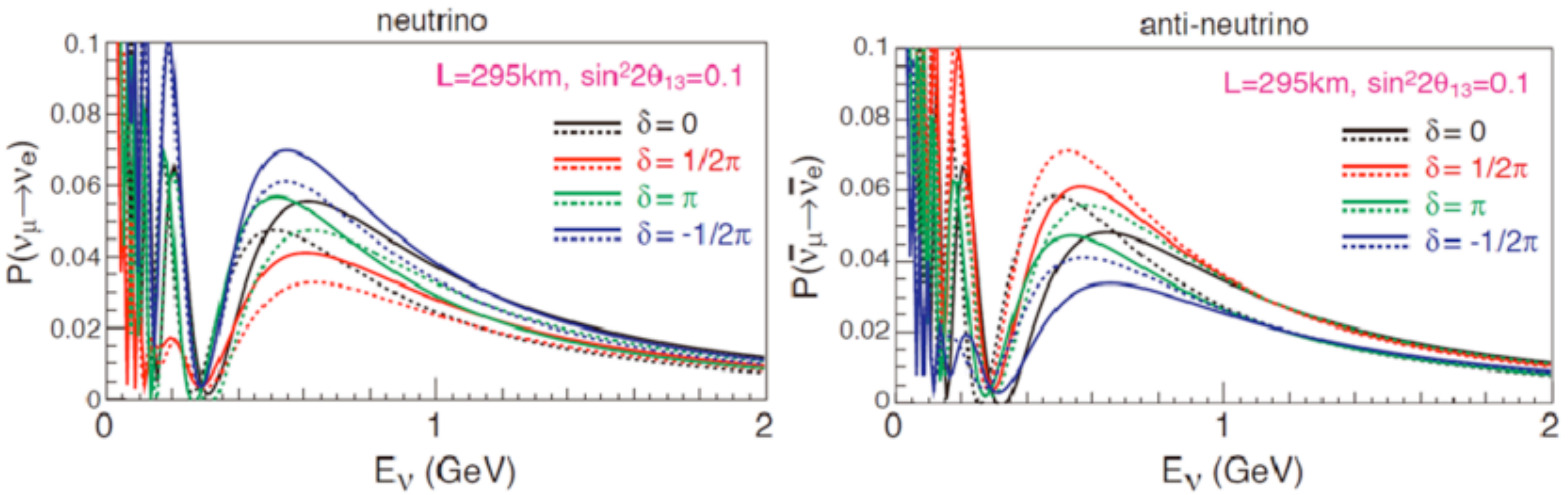
- Natural evolution of Super-Kamiokande (T2K —> T2HyperK)
- **Upgrade:** neutrino beam > 1.3 MW, off-axis angles, larger FD
- **Baseline:** 295 km (same)
- **Fiducial volume:** 200 kton pure water (8 times SK)
- Possibility to add a second FD in Korea (baseline 1100 km)
- Aiming to start operations in 2027

new cavern at Kamioka mine under construction



GOAL: Minimise matter effects + maximise statistics to focus on δ_{CP}

> 5σ CPV sensitivity in 10 years for 60% of the δ_{CP} values



Hyper-K collaboration (Neutrino2024)

DUNE (Deep Underground Neutrino Experiment)

A leading-edge international neutrino accelerator experiment based at Fermilab

① Muon neutrino beam

- 1.2 MW beam power
- Upgradeable up to 2.4 MW

② Near Detector (ND)

- 574m from the beam
- Unoscillated flux monitoring (energy spectra & composition)
- νAr cross-section measurements

③ Massive Far Detector (FD)

- 1300 km from the ND
- Measurement of oscillated neutrinos
- Technology: LArTPC

DUNE Physics

A leading-edge international neutrino accelerator experiment based at Fermilab

Measurement of ν_e appearance and ν_μ disappearance for a wide range of neutrino energies [0-10 GeV]

- 5σ measurement of the neutrino mass ordering
- Discovery potential for CP violation (wide range of δ_{CP})
- Precise measurements of neutrino mixing parameters

No Beam Physics:

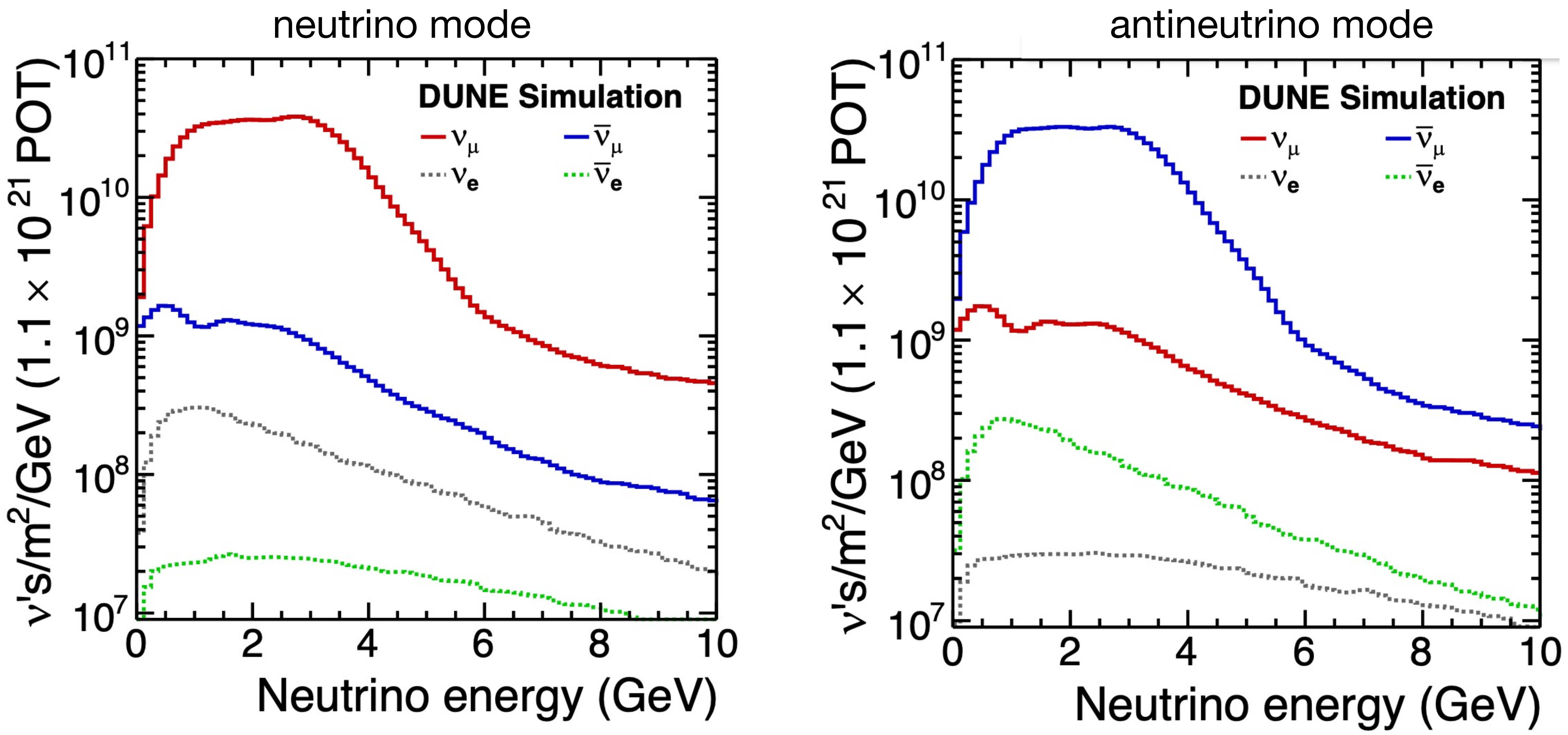
- Proton Decay $p \rightarrow K^+ \bar{\nu}$
- Supernova Neutrino Bursts (SNB)
- Solar neutrinos & BSM physics

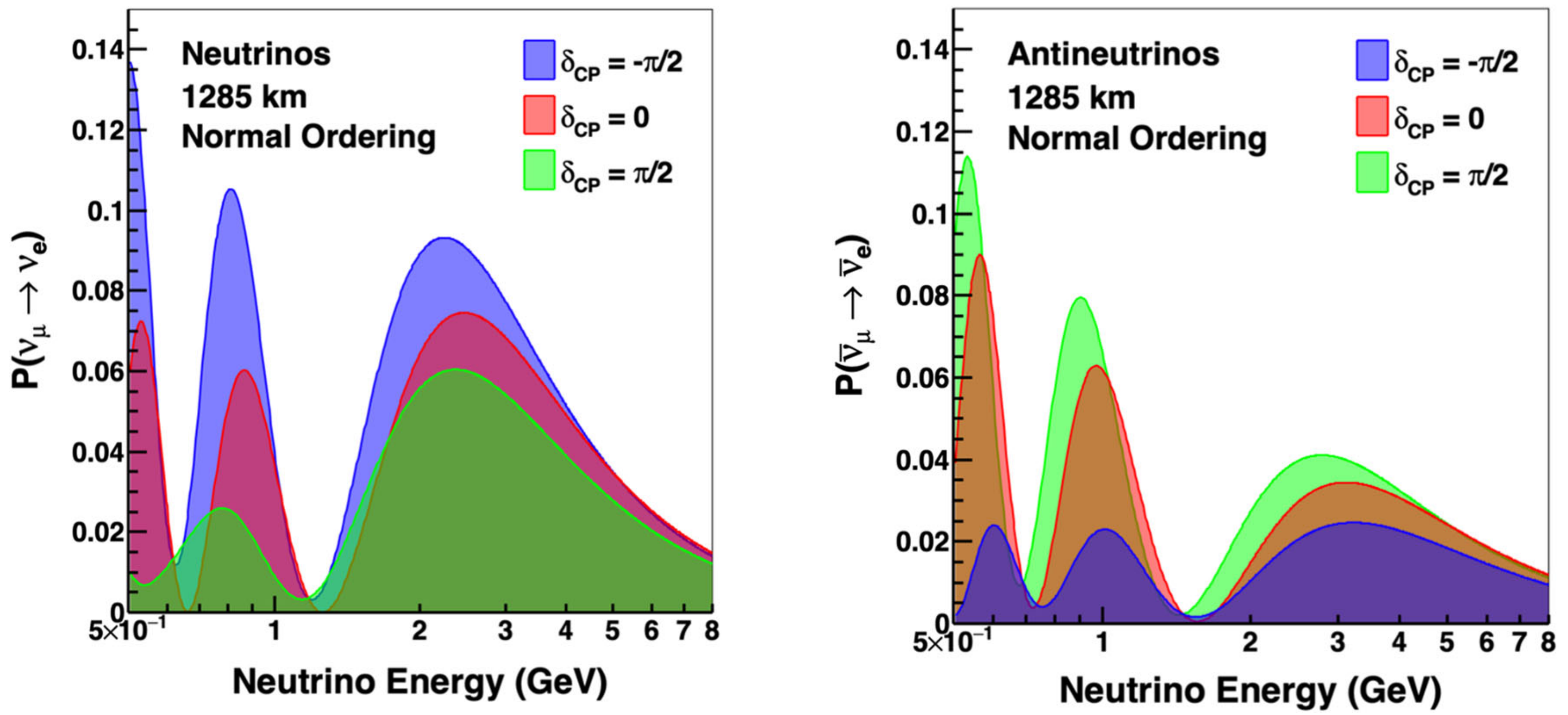
DUNE: beam and oscillation probability

Precision measurements of the parameters that govern:

$$\nu_\mu \longrightarrow \nu_e \qquad \bar{\nu}_\mu \longrightarrow \bar{\nu}_e$$

- The beam will provide neutrinos and antineutrinos with energies peaked at 2.5 GeV but with a broad range
- With a baseline of 1300 km, the oscillation probability has a strong dependence on both δ_{CP} and the mass ordering
- Access to different oscillation maxima to improve the sensitivity





DUNE: Far Detector (FD)

LArTPCs: liquid argon time projection chambers

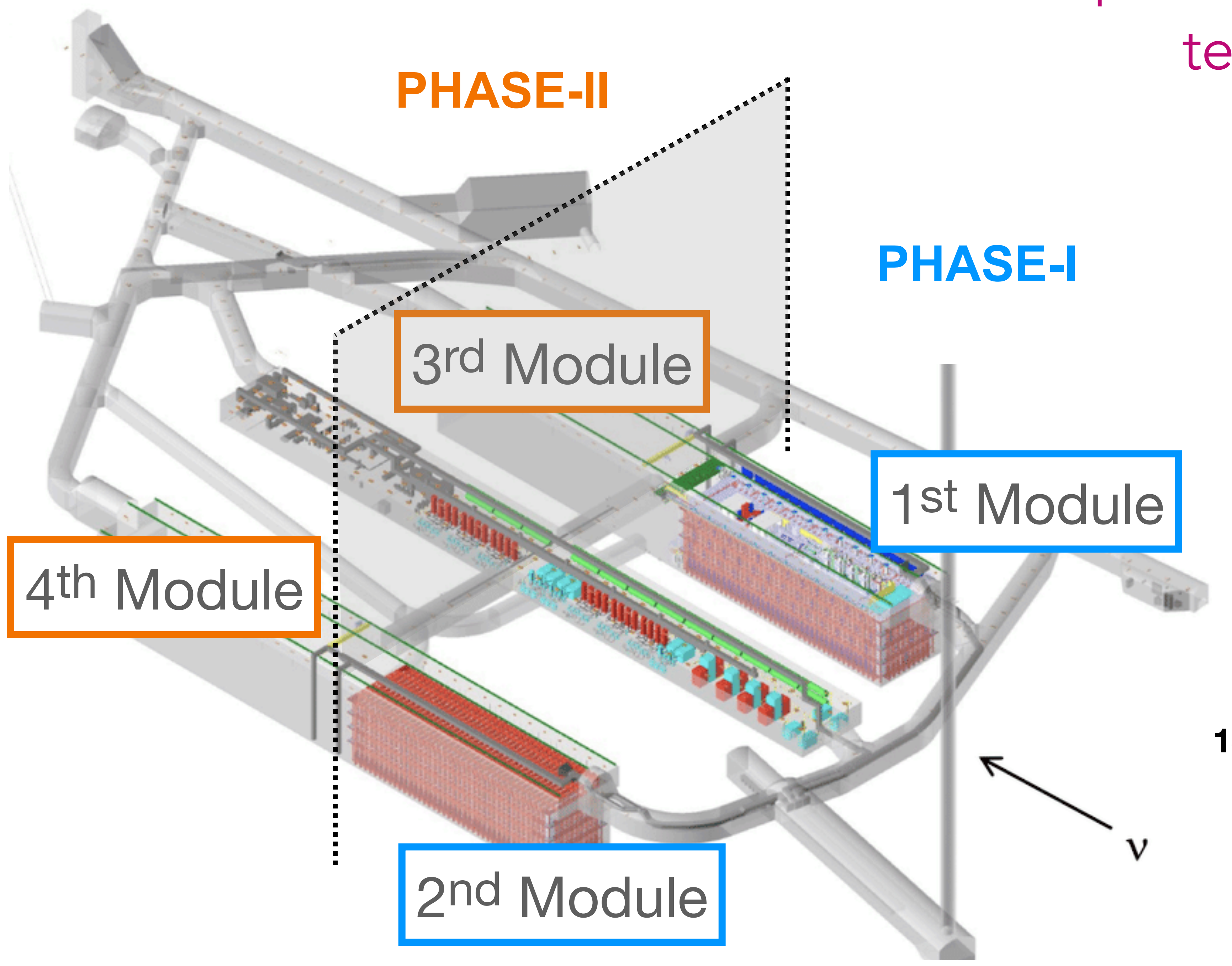
— 4 modules: 70 kton total mass —

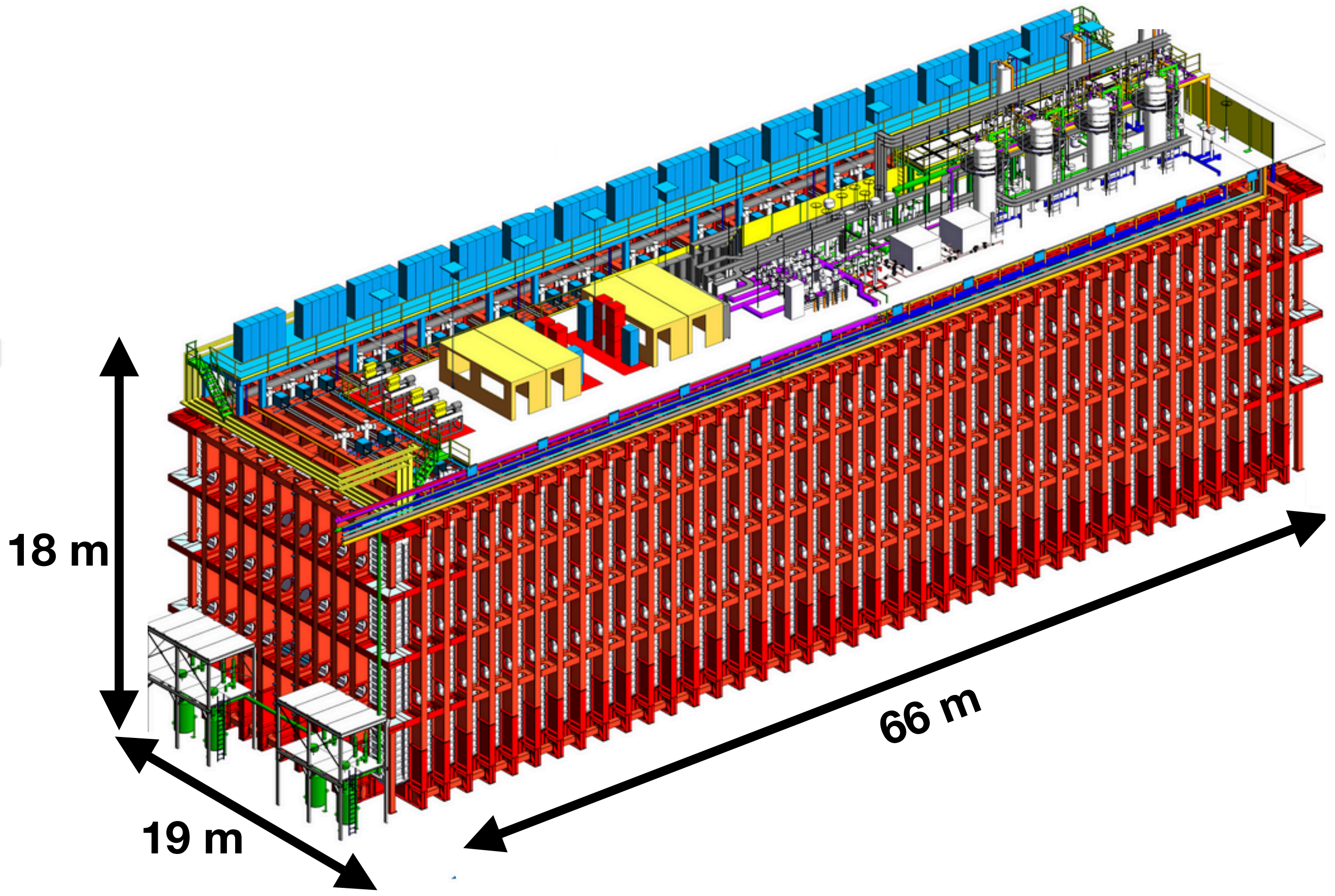
- Sanford Underground Research Facility (SURF)
- 1500 m underground (4300 m.w.e.)
- 4 detectors in 2 caverns
- Detector deployment in stages:

  - DUNE PHASE-I (Modules 1 & 2)

  - DUNE PHASE-II (Modules 3 & 4)

The two-phase approach will allow implementation of improvements in the technology during PHASE-II





***Phase-I**: detector installation by 2026 beam data by 2031*

DUNE: Near Detector (ND)

574m from the beam & 60m underground

- **Main Goal**: constrain uncertainties for oscillation measureme
    - Un-oscillated neutrino flux monitoring
    - ν-Ar cross section measurements
    - Three different detection systems on and off axis:

1) Liquid Argon Detector (50t FV)

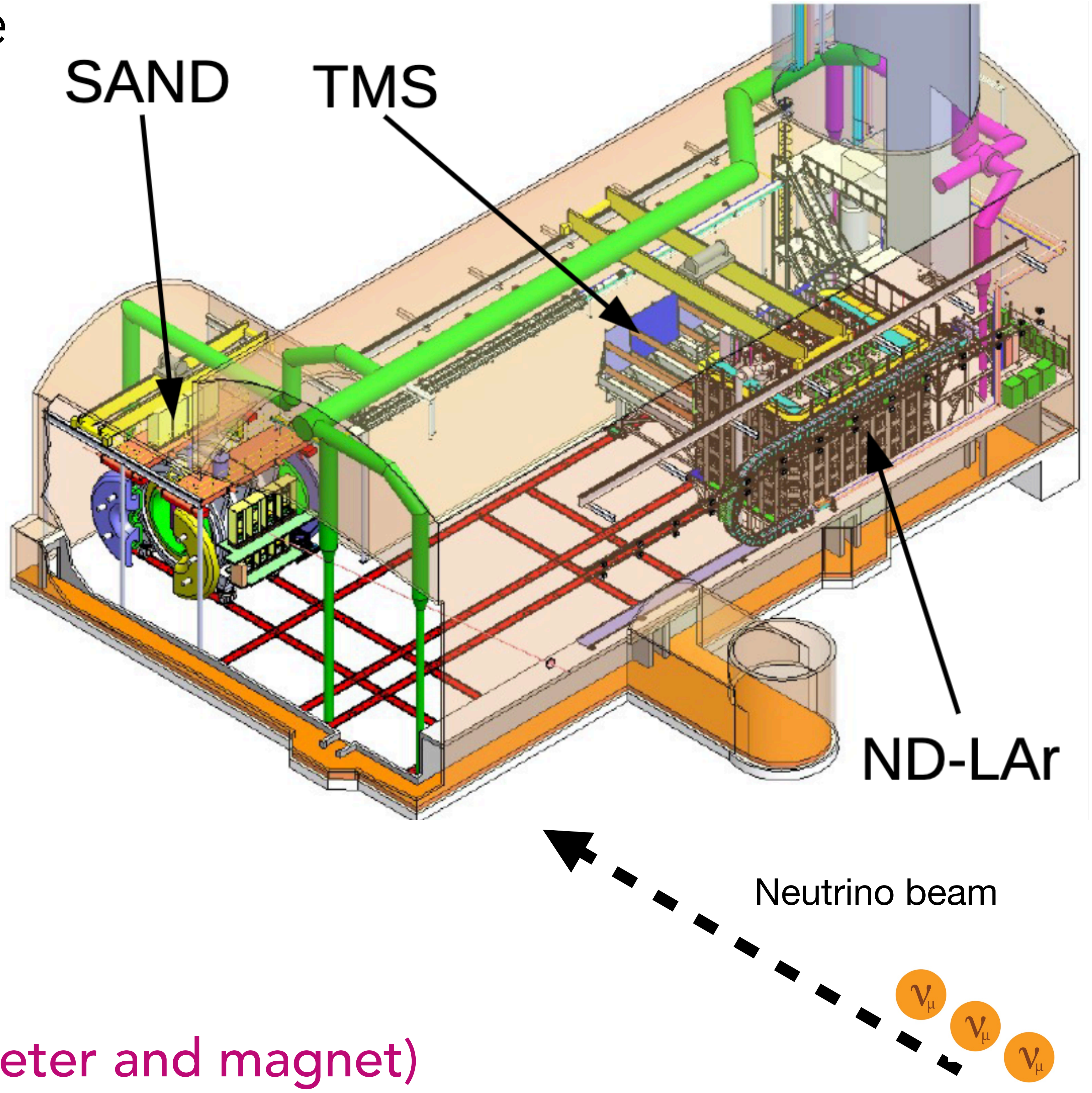
- Primary target, same technology as the far detector

2) Temporary muon spectrometer (TMS)

- Measure muons escaping the first detector

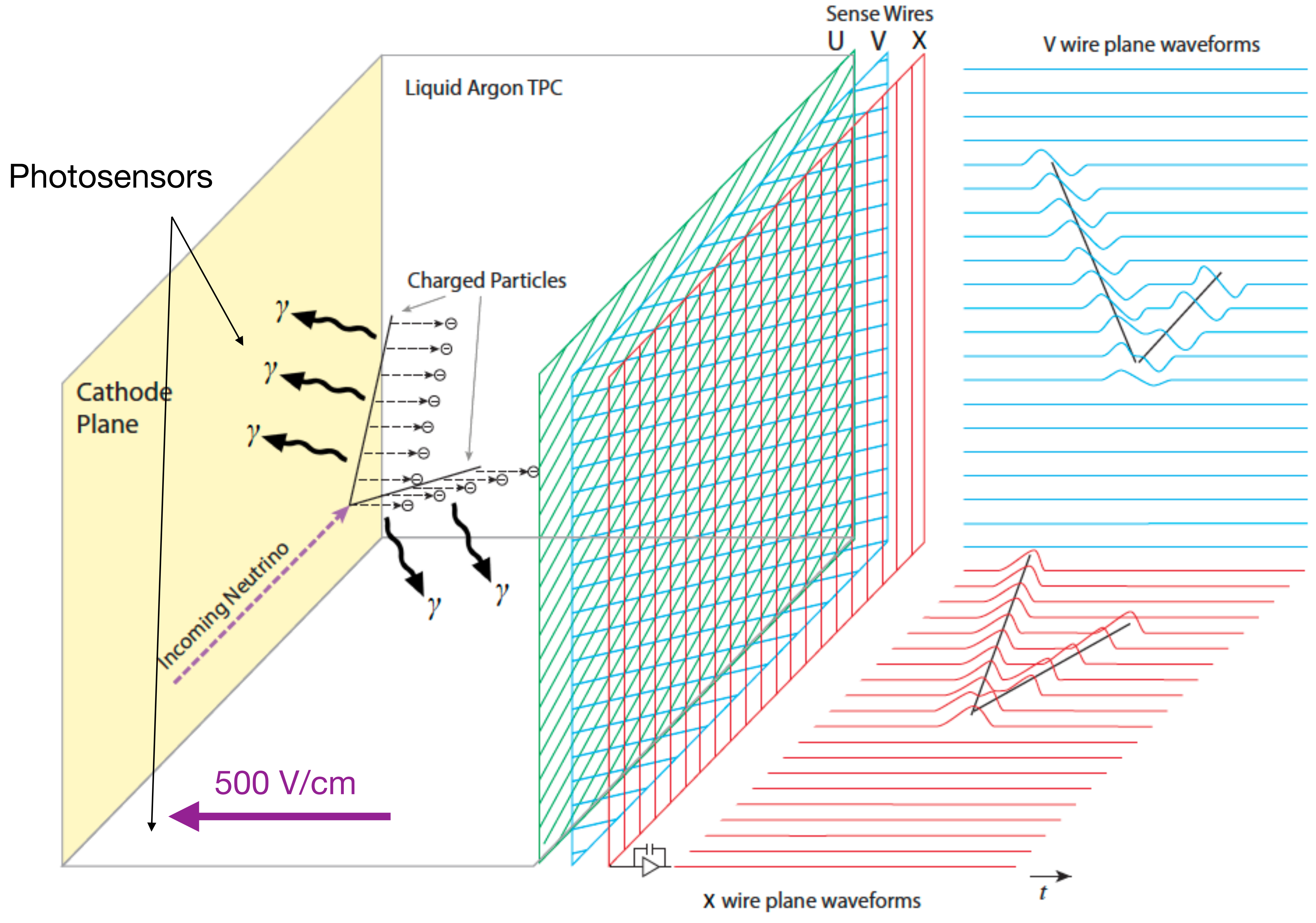
3) SAND (tracker surrounded by an electromagnetic calorimeter and magnet)

- Control the stability of the neutrino beam



Instruments 5 (2021) 4, 31

Working principle of LArTPC



Example of single phase & horizontal drift

Interactions in a LArTPC

two signals proportional to the energy

ionisation electrons

~27000 e^-/ MeV

scintillation photons

~24000 γ / MeV

For 500V/cm drift field

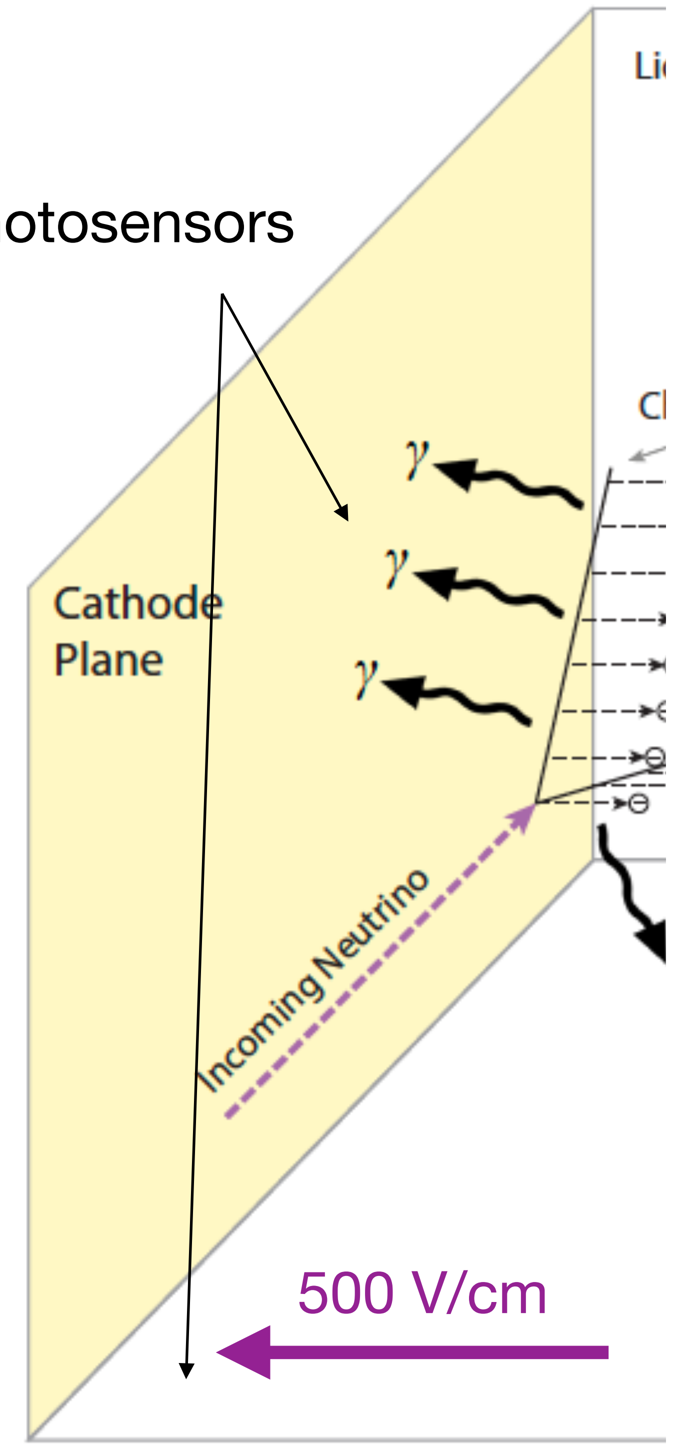
drifted and collected in charge readout planes

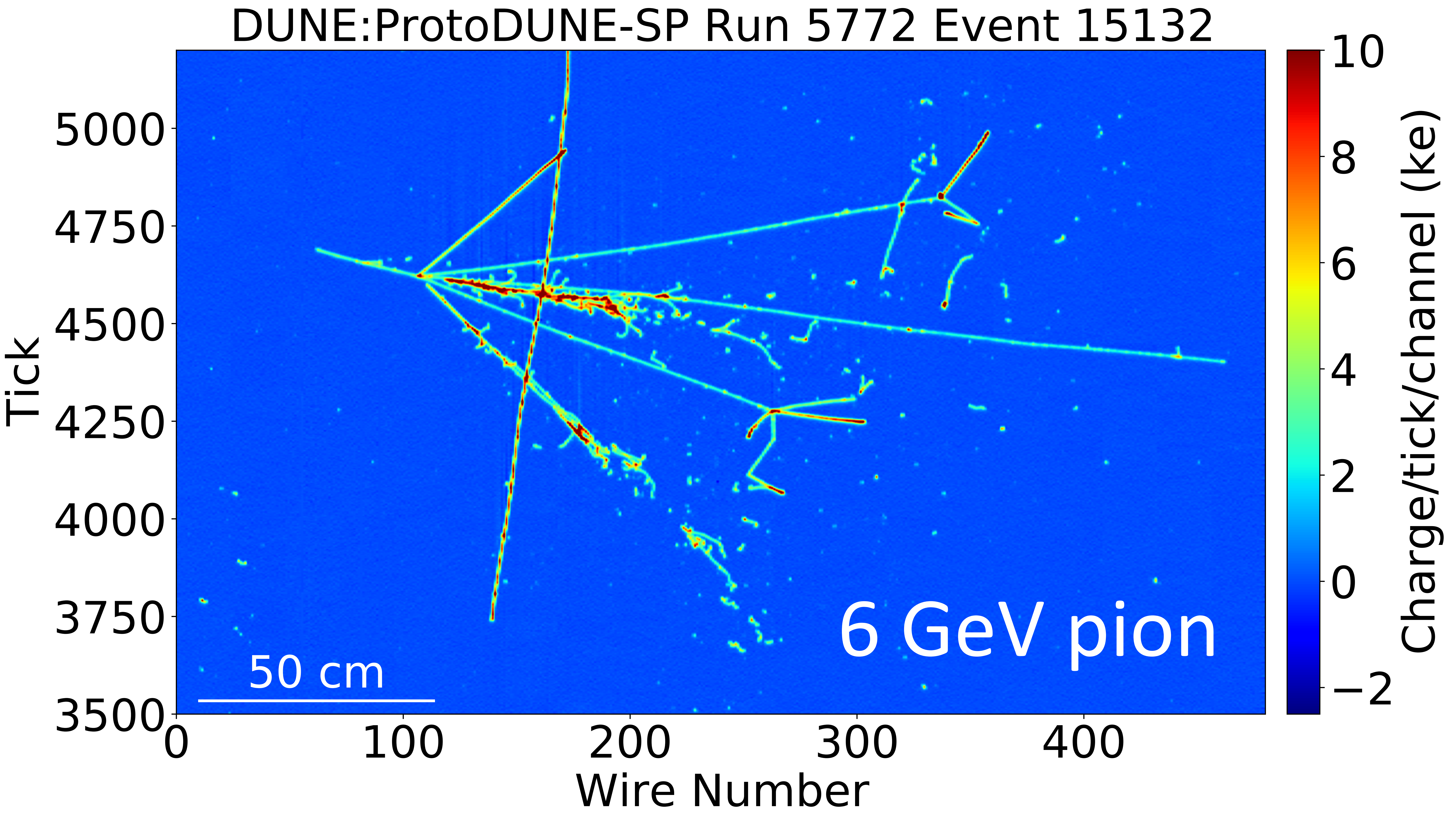
observed by the photon detection system

Precision tracking and calorimetry

t_0 and complementary calorimetry

Working principle of LArTPC





deposit

n photons

γ / MeV

↓

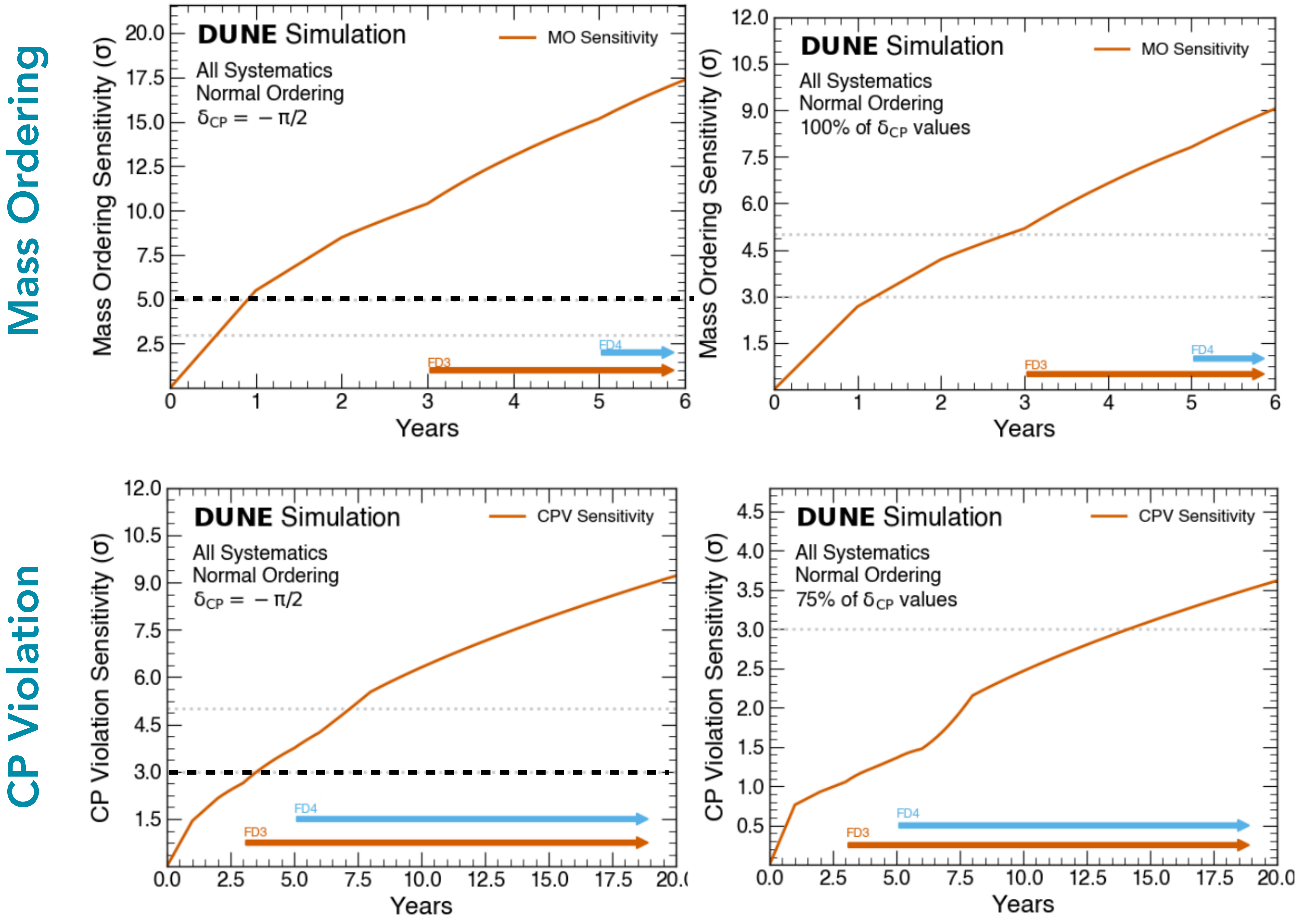
by the photon
ion system

↓

**nplementary
rimetry**

DUNE sensitivity

Eur. Phys. J. C 80, 978 (2020)



Best case scenario (δ_{CP} = -π/2)

> 5σ mass ordering sensitivity in 1 year

> 3σ CPV sensitivity in 3.5 year

Worst case scenario ($\delta_{CP} \neq$ -π/2)

> 5σ mass ordering sensitivity in 3 year

> 3σ CPV sensitivity in ~13 year

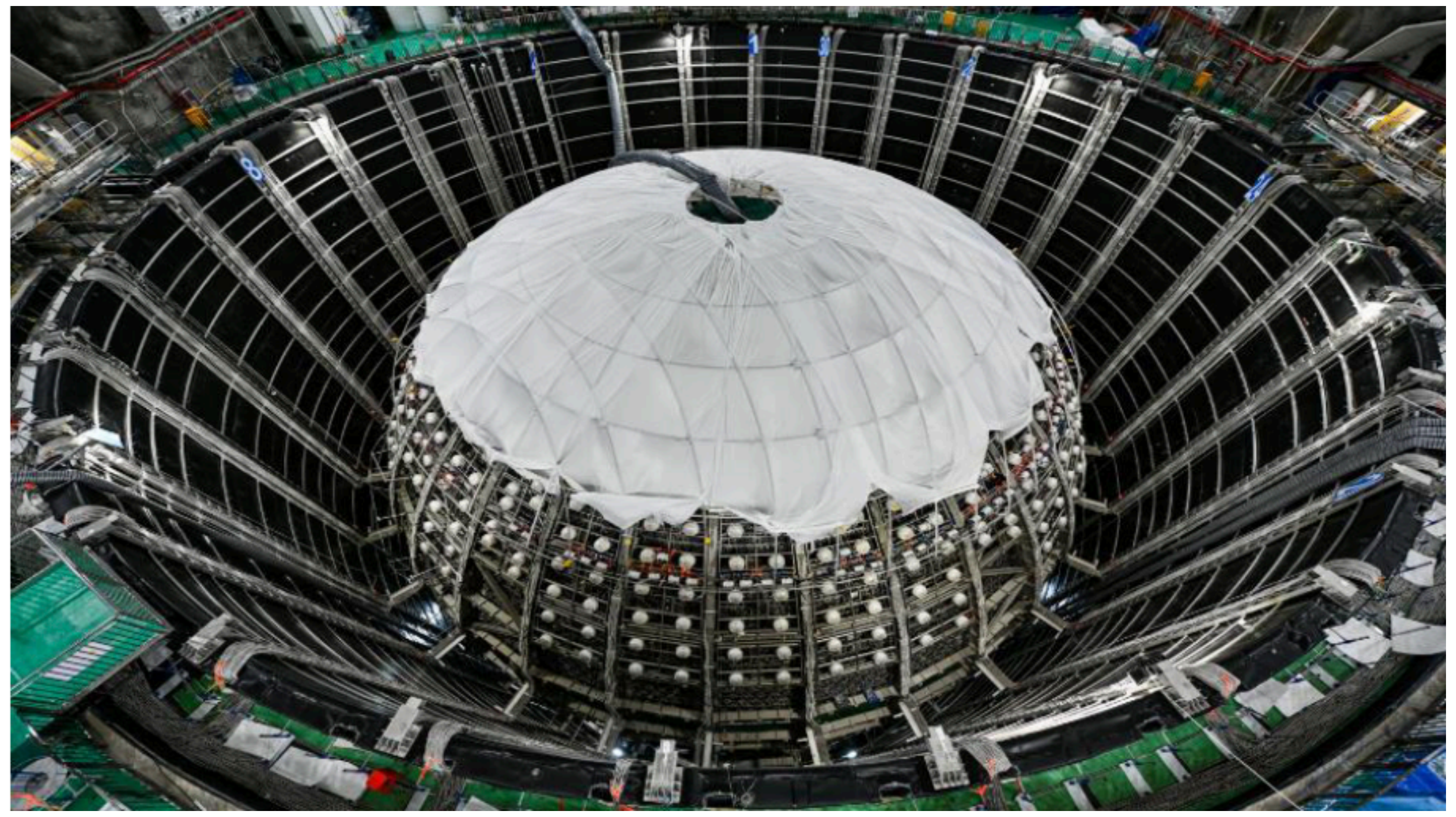
DUNE collaboration (Neutrino2024)

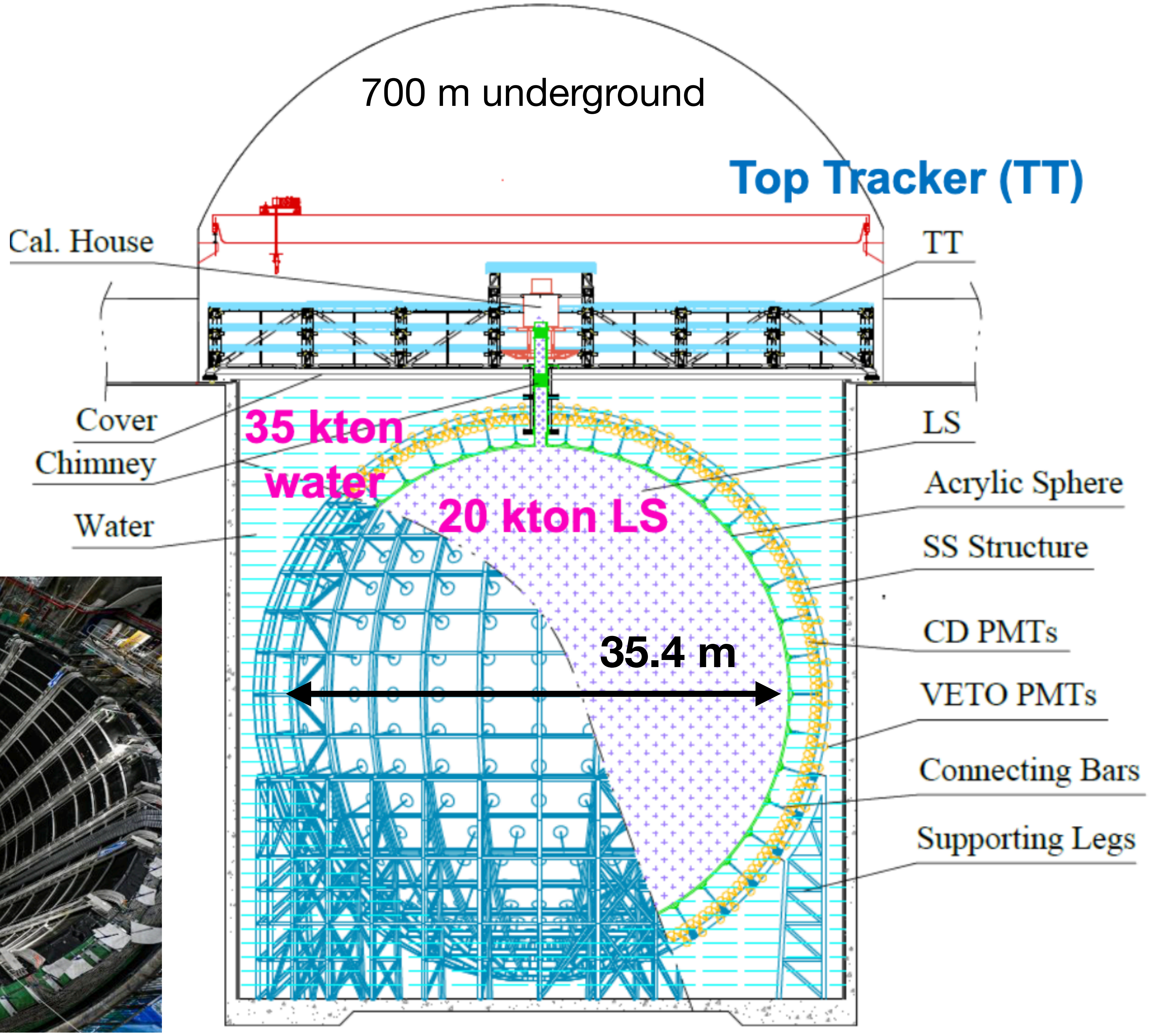
JUNO (Jiangmen Underground Neutrino Observatory)

- Next-generation Large Liquid Scintillator detector (à la KamLAND)
- It is a LBL reactor experiment in China. **Baseline 50 km**
- **Fiducial volume:** 20 kton
- Increased light yield for a better energy resolution (3% at 1 MeV)
- End of the construction + filling in 2024

MAIN GOAL: Mass ordering sensitivity

Design to reach 3σ precision on mass ordering determination after 6 years





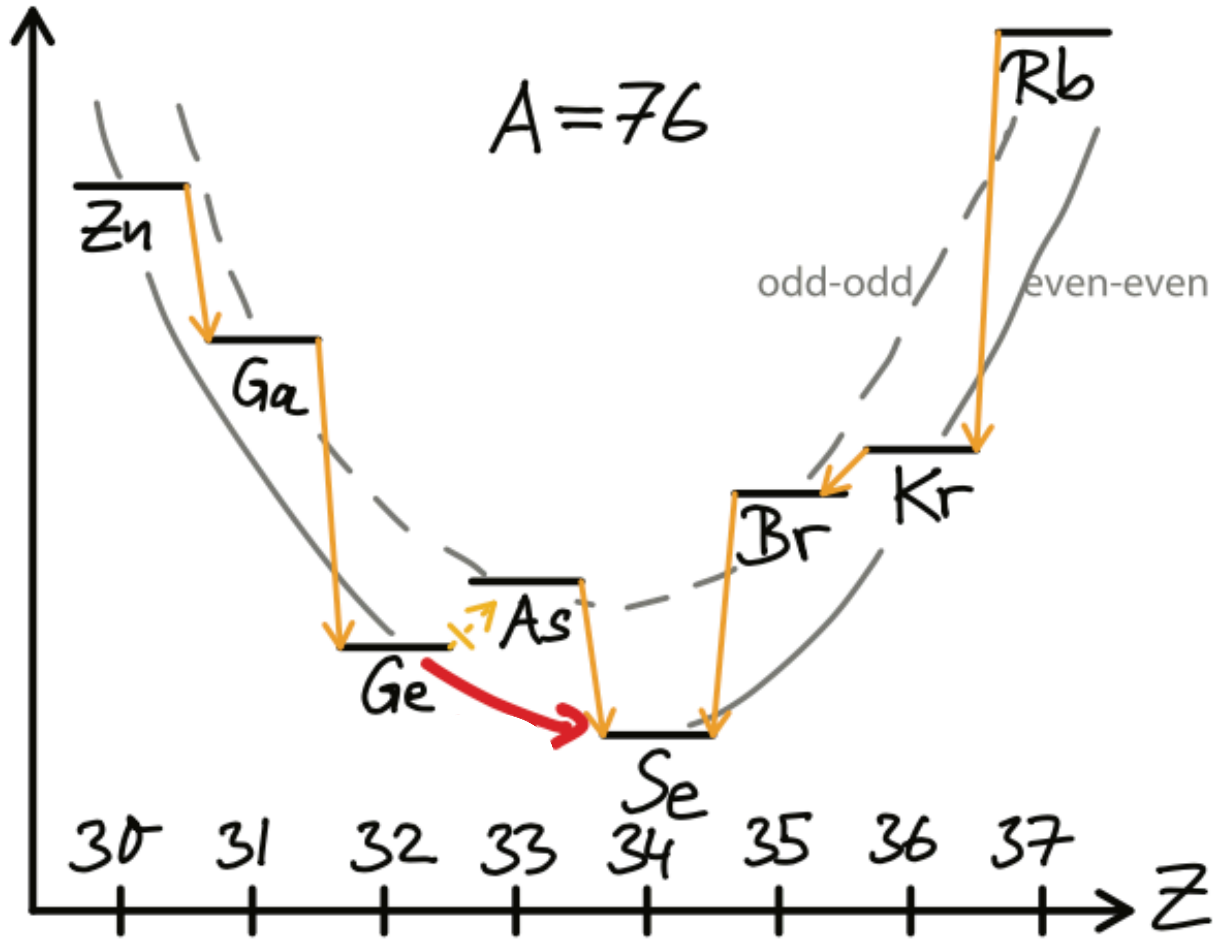
JUNO collaboration (Neutrino2024)

Neutrino Nature: Dirac or Majorana particle?

Double beta decays: introduction

Two-Neutrinos double beta decay ($2\nu\beta\beta$)

$$m(A,Z) > m(A,Z+2) + 2m_e$$



Predicted by Maria-Goeppert Mayer in 1935

Extremely rare nuclear process, but allowed in the Standard Model

$\Delta L = 0$

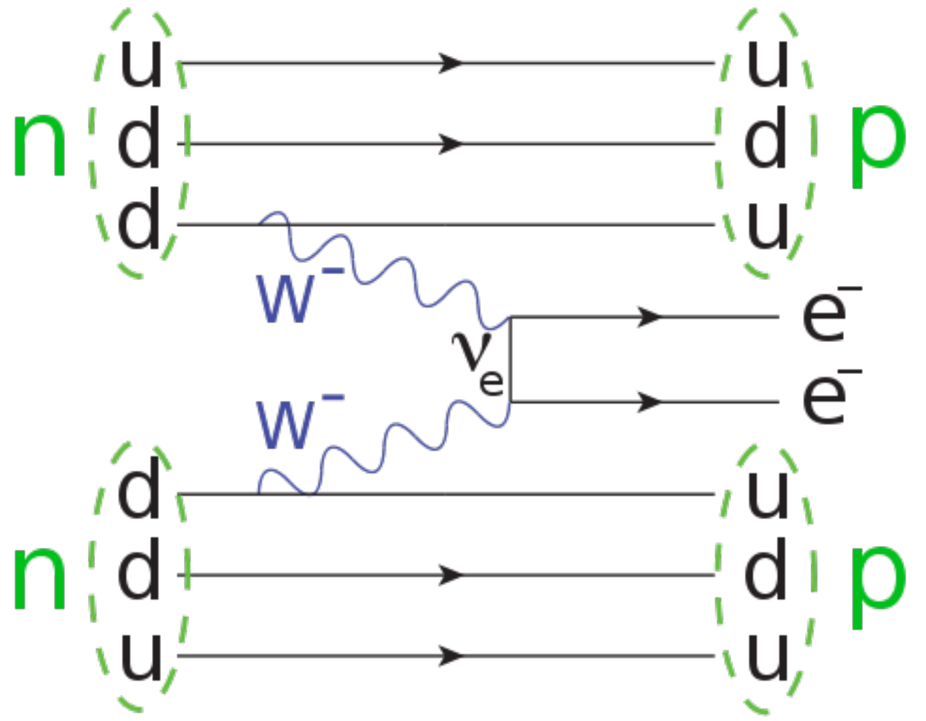
Observed in more that 10 nuclei: ⟶ $T_{1/2} > 10^{18}$ years

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U

Double beta decays: introduction

Neutrinoless double beta decay ($0\nu\beta\beta$)

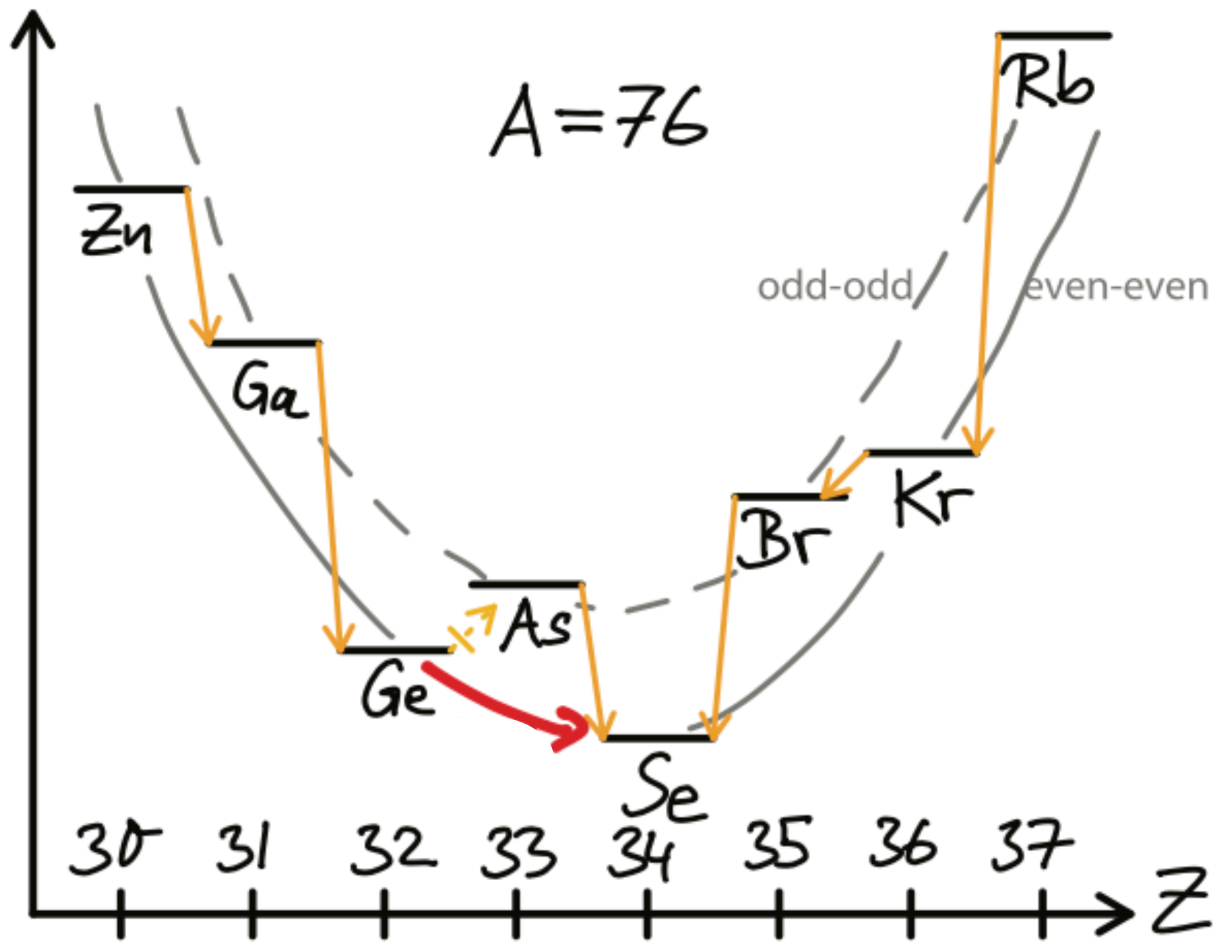
Extremely rare nuclear process, NEVER OBSERVED BEFORE



ΔL = 2

- ➢ Lepton number violation
- ➢ Neutrinos are their own anti-particle (Majorana fermions)

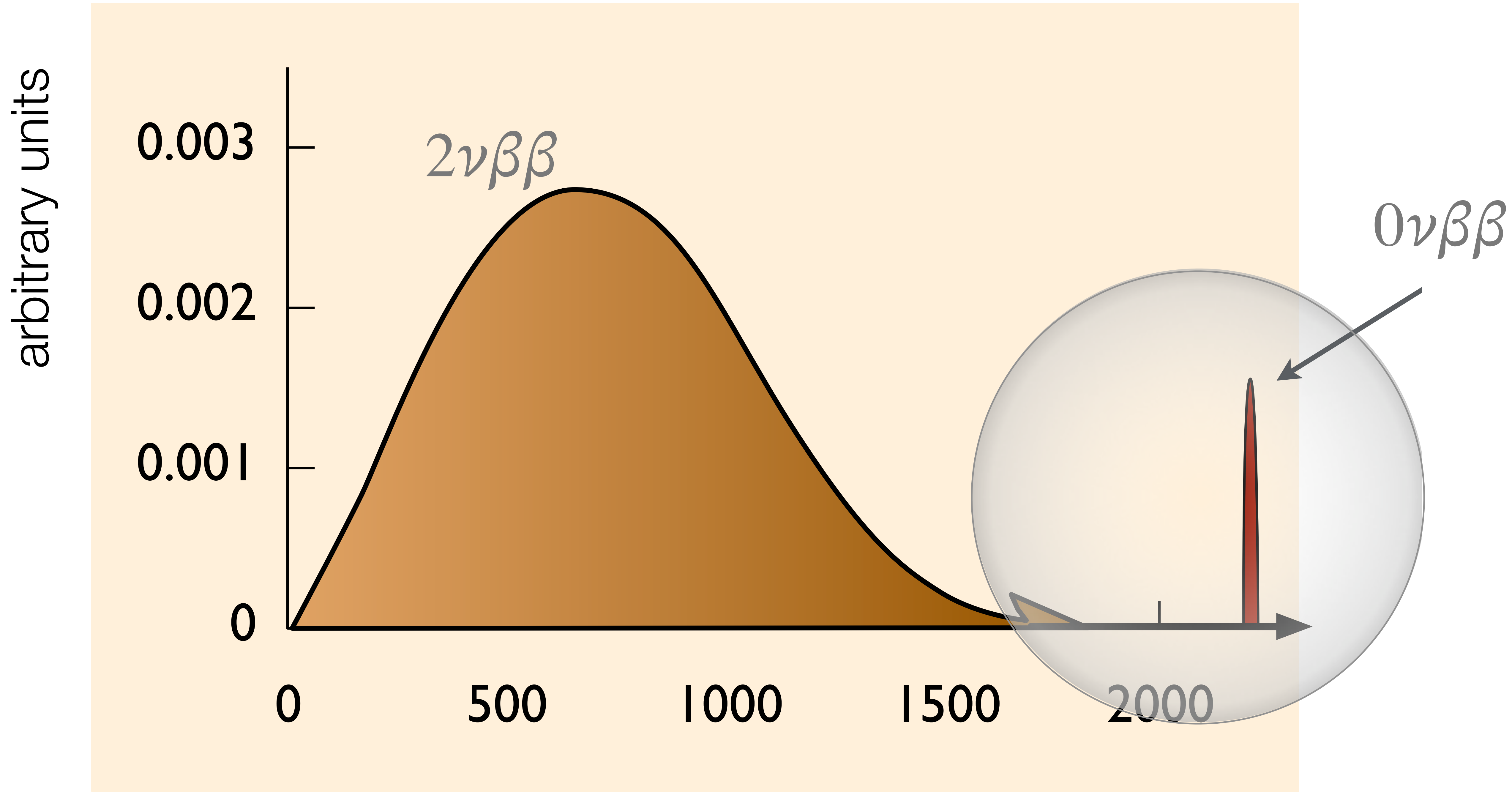
$$m(A,Z) > m(A,Z+2) + 2m_e$$



Predicted by Maria-Goeppert Mayer in 1935

Expected $0\nu\beta\beta$ signal

Sharp peak at the end of the $2\nu\beta\beta$ energy spectrum, Q-value



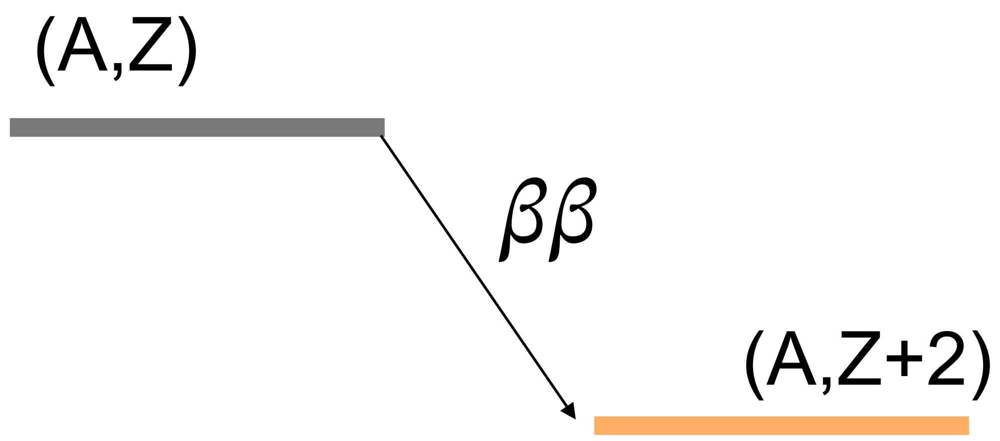
$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,m^2_{\beta\beta}$$

phase space factor

nuclear matrix element

Majorana mass

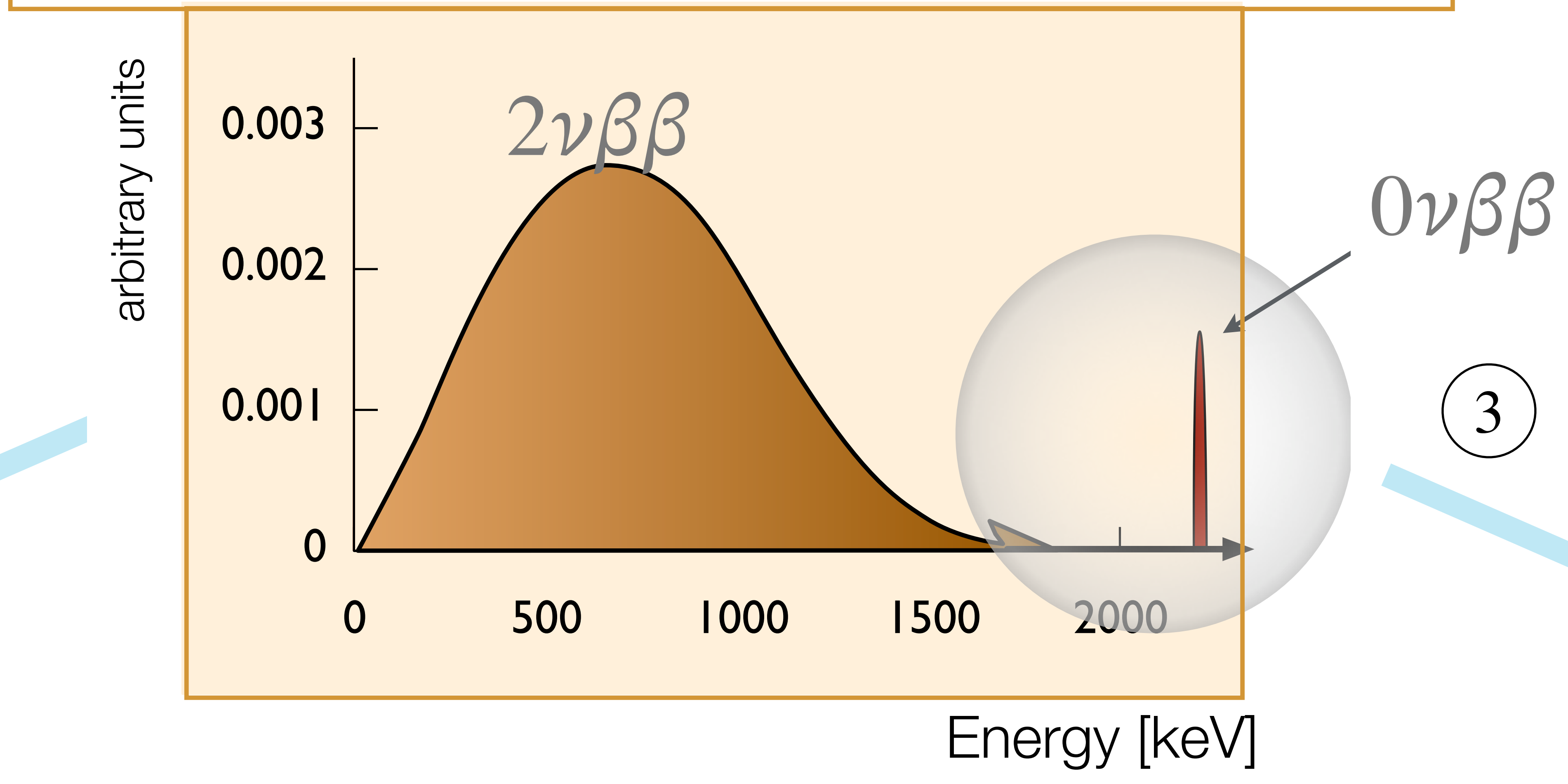
The half-life of the decay related to the Majorana mass



Q-value: mass difference between mother and daughter nucleus

What do we need to observe this signal?

$$T^{0\nu}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$



①

Large mass of a candidate isotope

✓ ~ tons of the active isotope

②

Excellent energy resolution

✓ resolution of < 1 % at the Q -value of the reaction

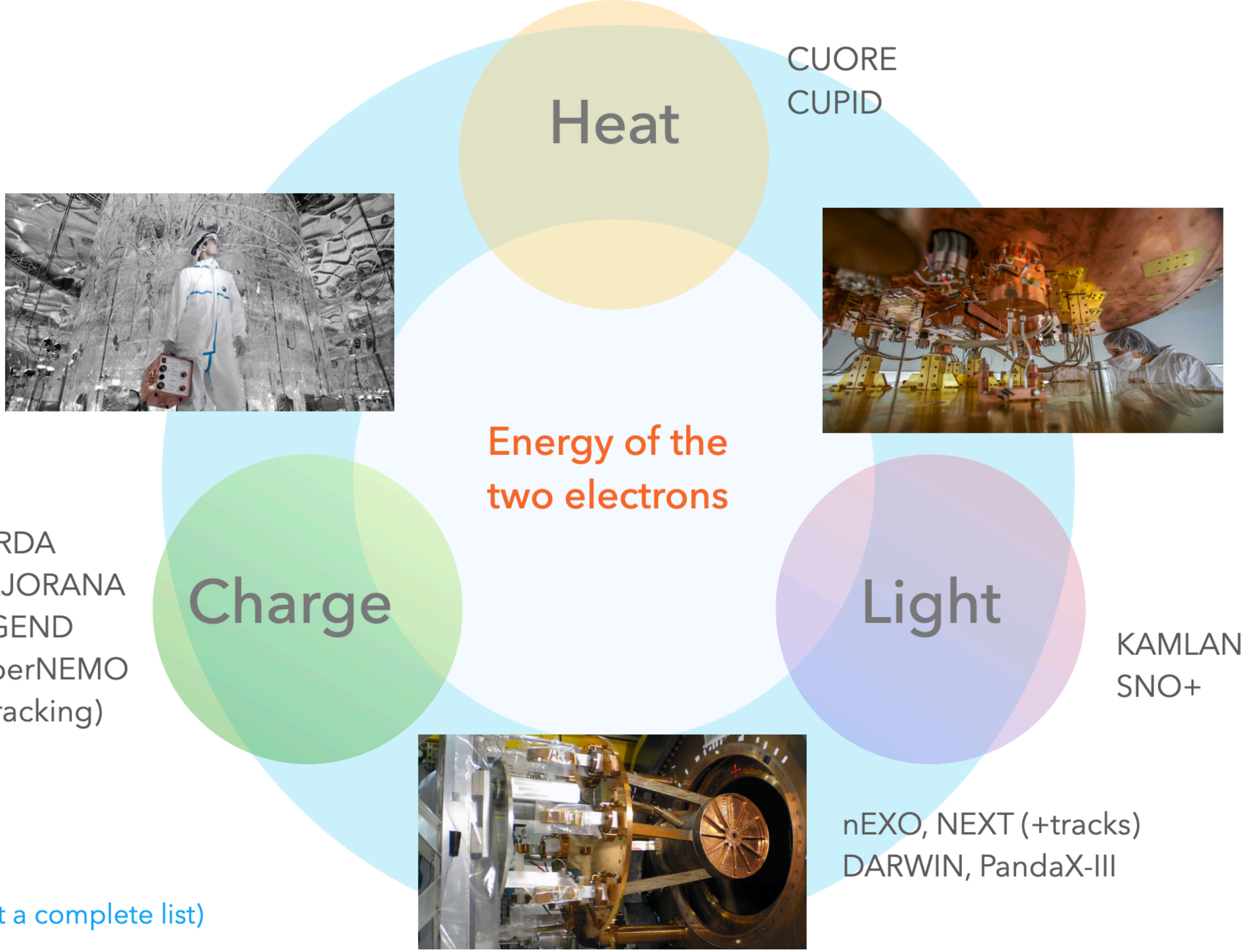
③

Ultra-low background

✓ Environment dominated by intrinsic backgrounds

- Material backgrounds subdominant
- Irreducible intrinsic background

Different experimental techniques



Heat

CUORE
CUPID

Energy of the two electrons

Charge

GERDA
MAJORANA
LEGEND
SuperNEMO
(+tracking)

Light

KAMLAND-Zen
SNO+

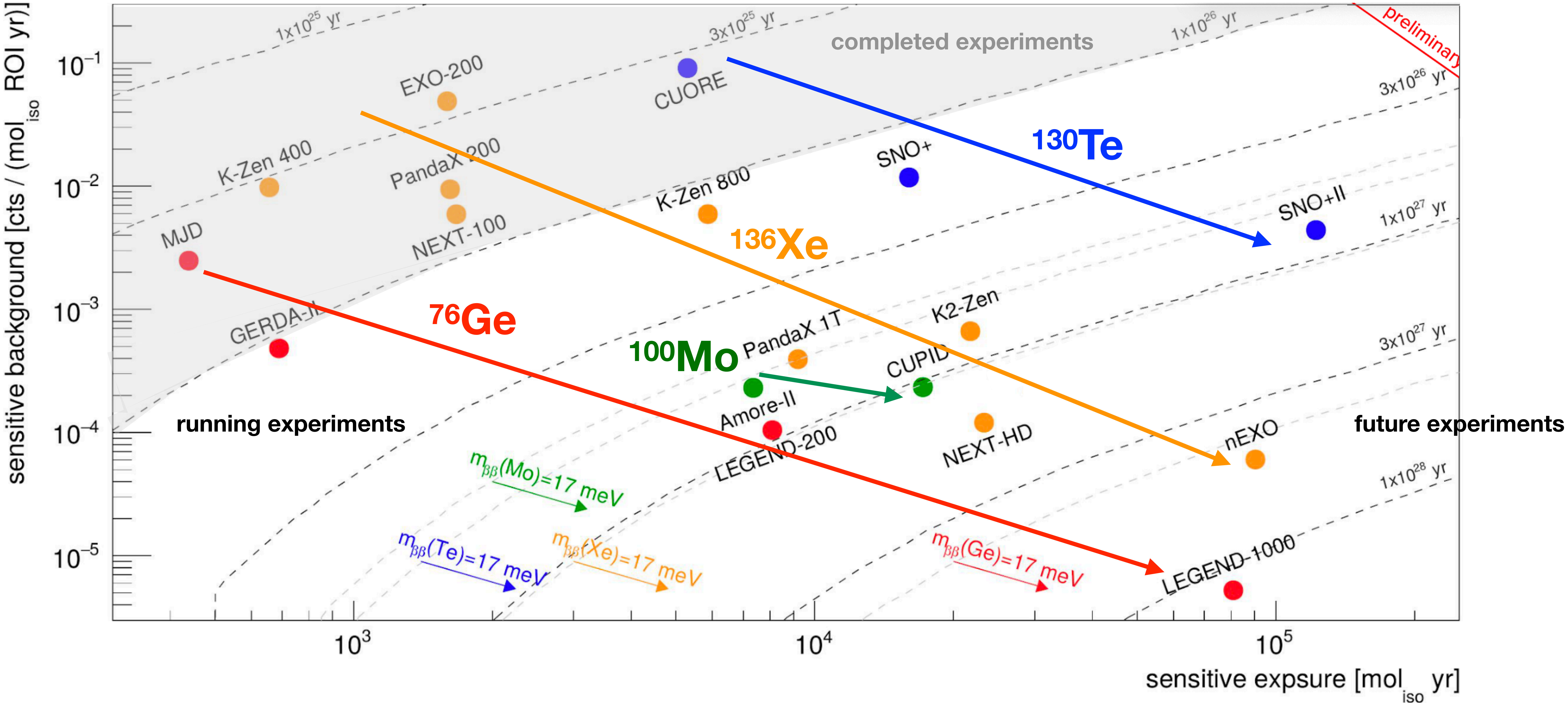
nEXO, NEXT (+tracks)
DARWIN, PandaX-III

(*not a complete list)

Laura Baudis, Fermilab Talk 2020

$0\nu\beta\beta$ experiments overview

Different experiments with different isotopes



Nowadays a very active, exciting and promising field

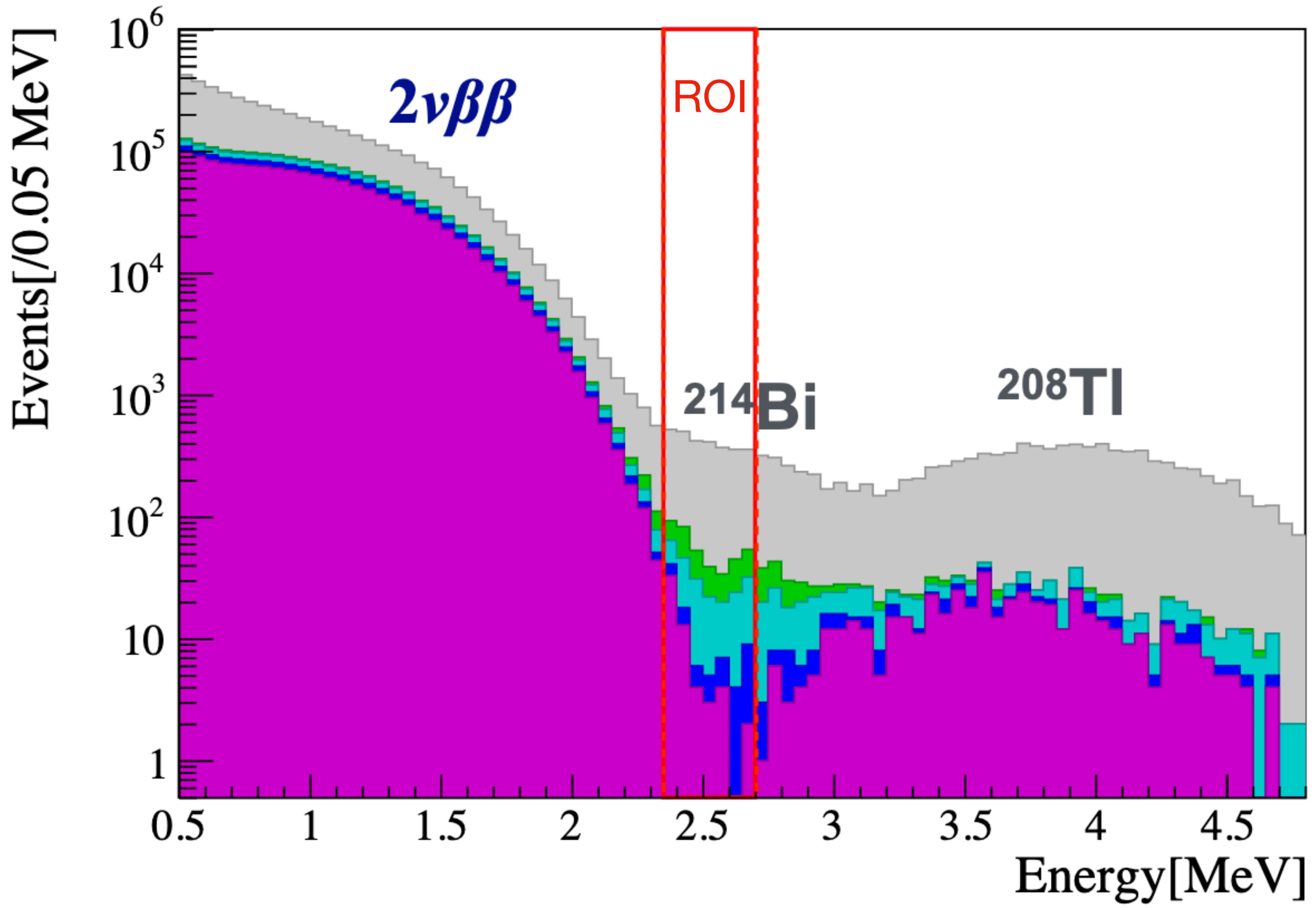
Figure adapted from M. Agostini in TAUP2019

KamLAND-Zen 800

LIGHT

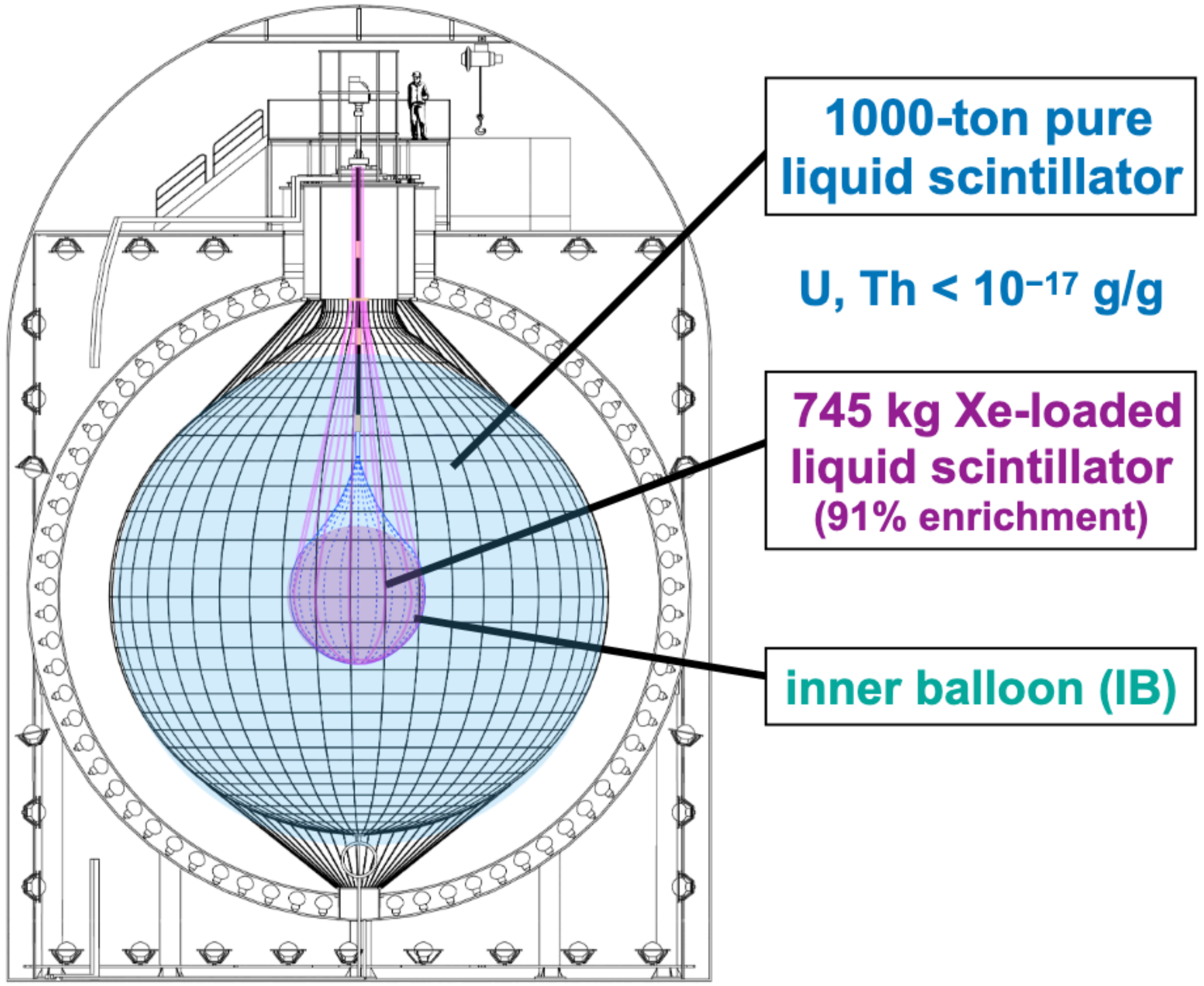
Ze**ro** N**eutrino Double Beta**

- Xe-loaded liquid scintillator: **~800 kg of ^{136}Xe** contained in a 3.8 m diameter nylon ballon suspended at the centre of KamLAND
- Ballon surrounded by 1000 ton of pure LS
- Light detected by PMTs
- Energy resolution ~7% FWHM at Q-value
- **5 years** of data (Feb. 2019 - Jan. 2024)



KamLAND-Zen, Neutrino 2024

KamLAND detector

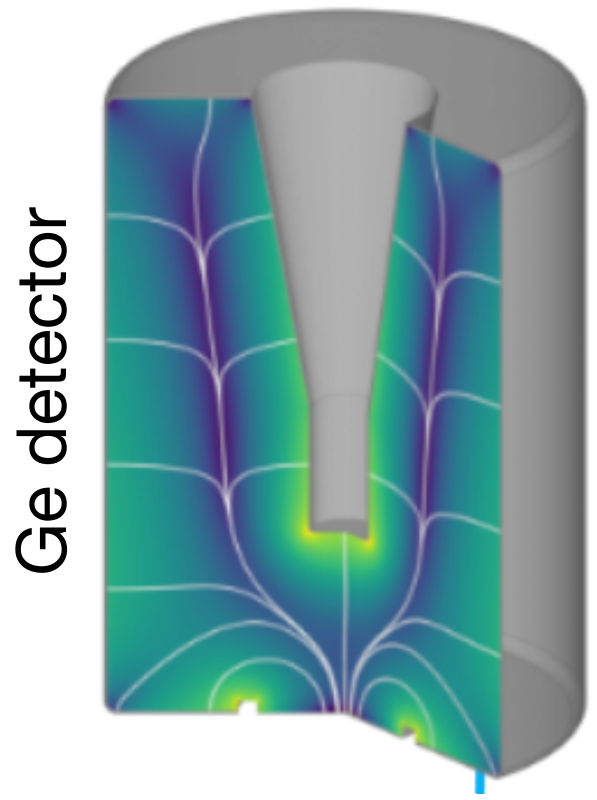


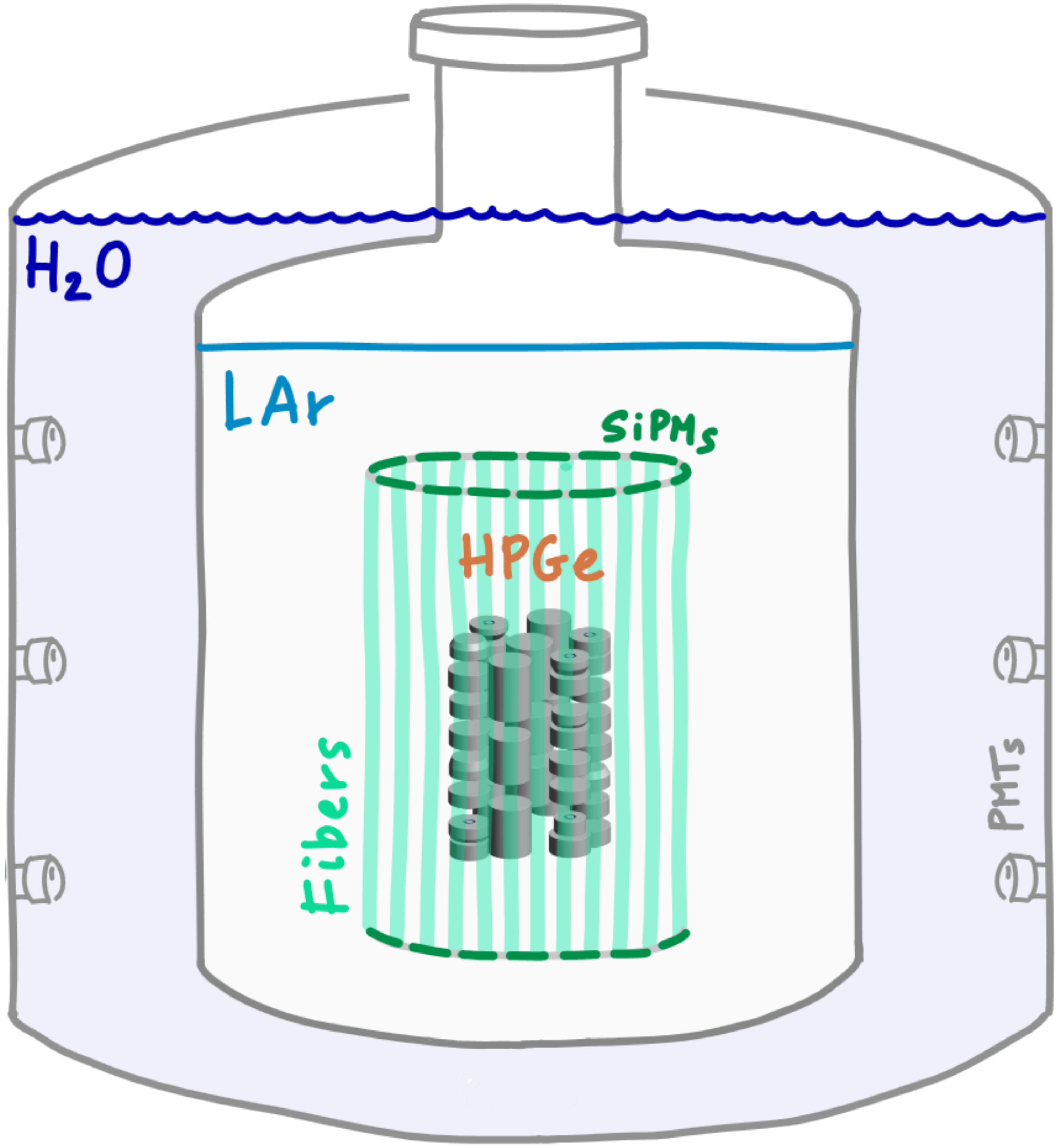
Zen 400	$T^{0\nu}_{1/2} > 0.9 \times 10^{26}$ yr
Zen 800	$T^{0\nu}_{1/2} > 3.4 \times 10^{26}$ yr
Combined	$\boldsymbol{T^{0\nu}_{1/2} > 3.8 \times 10^{26}}$ **yr**

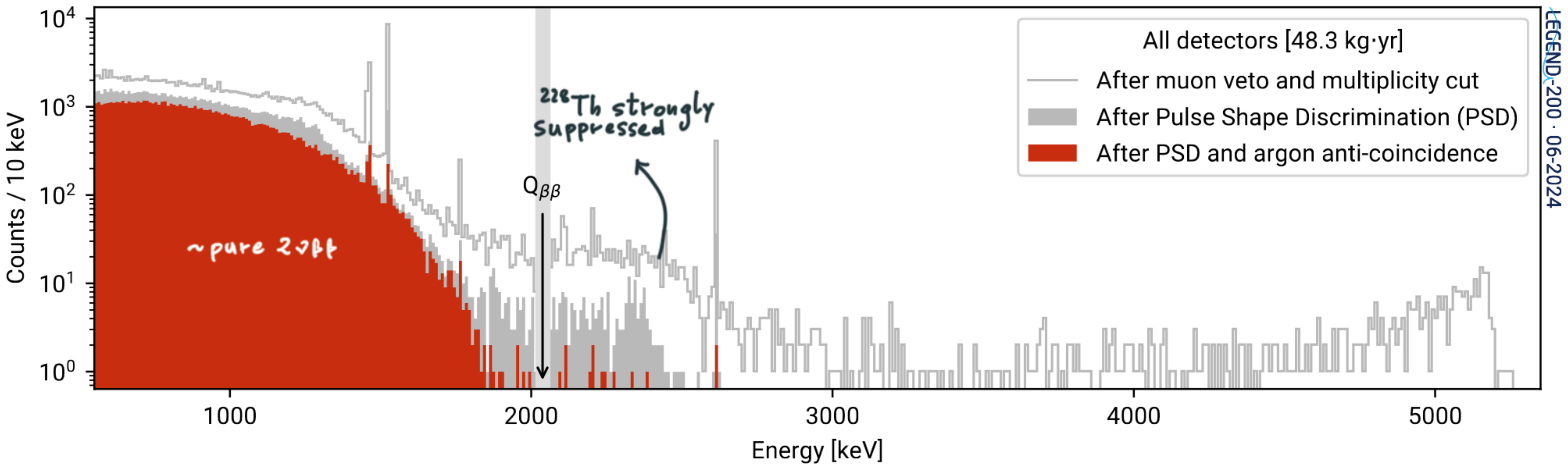
LEGEND-200

CHARGE

- 200 kg of Germanium (Ge) detectors isotopically enriched ~92% in ^{76}Ge
- Ge detectors are semiconductor diodes sensitive to ionizing radiation, excellent for gamma-spectrometry
- Surrounding vetos + ultra-low background materials
- Energy resolution at Q-value < 0.1% FWHM
- **1 year** of data with **142 kg** of Ge (since March 2023)







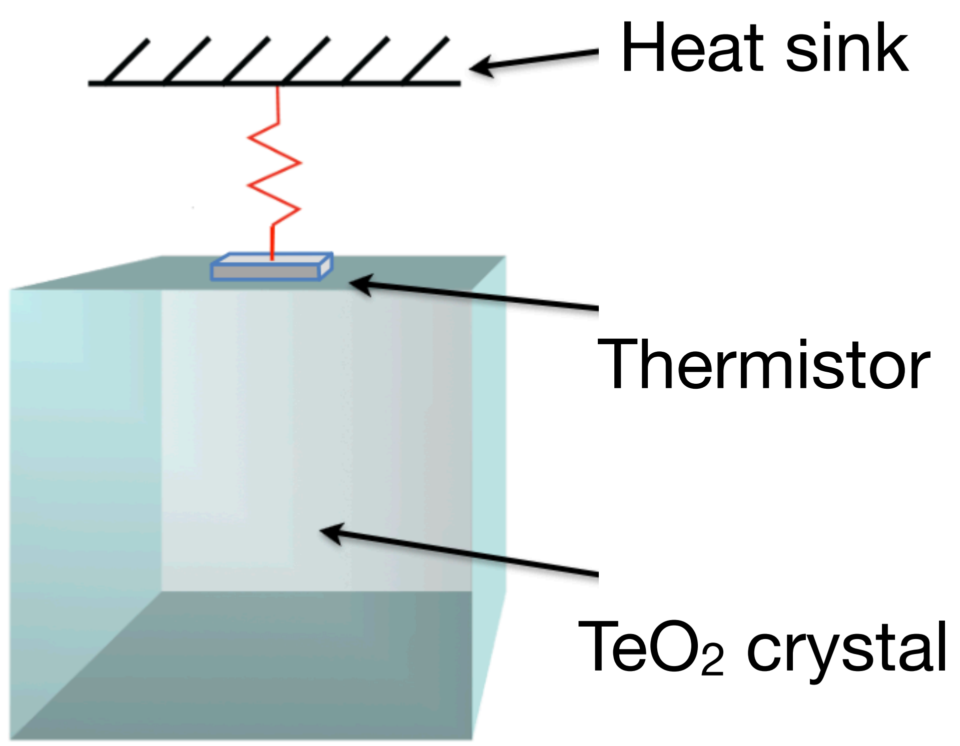
^{76}Ge $T_{1/2} > 1.9\times10^{26}$ yrs

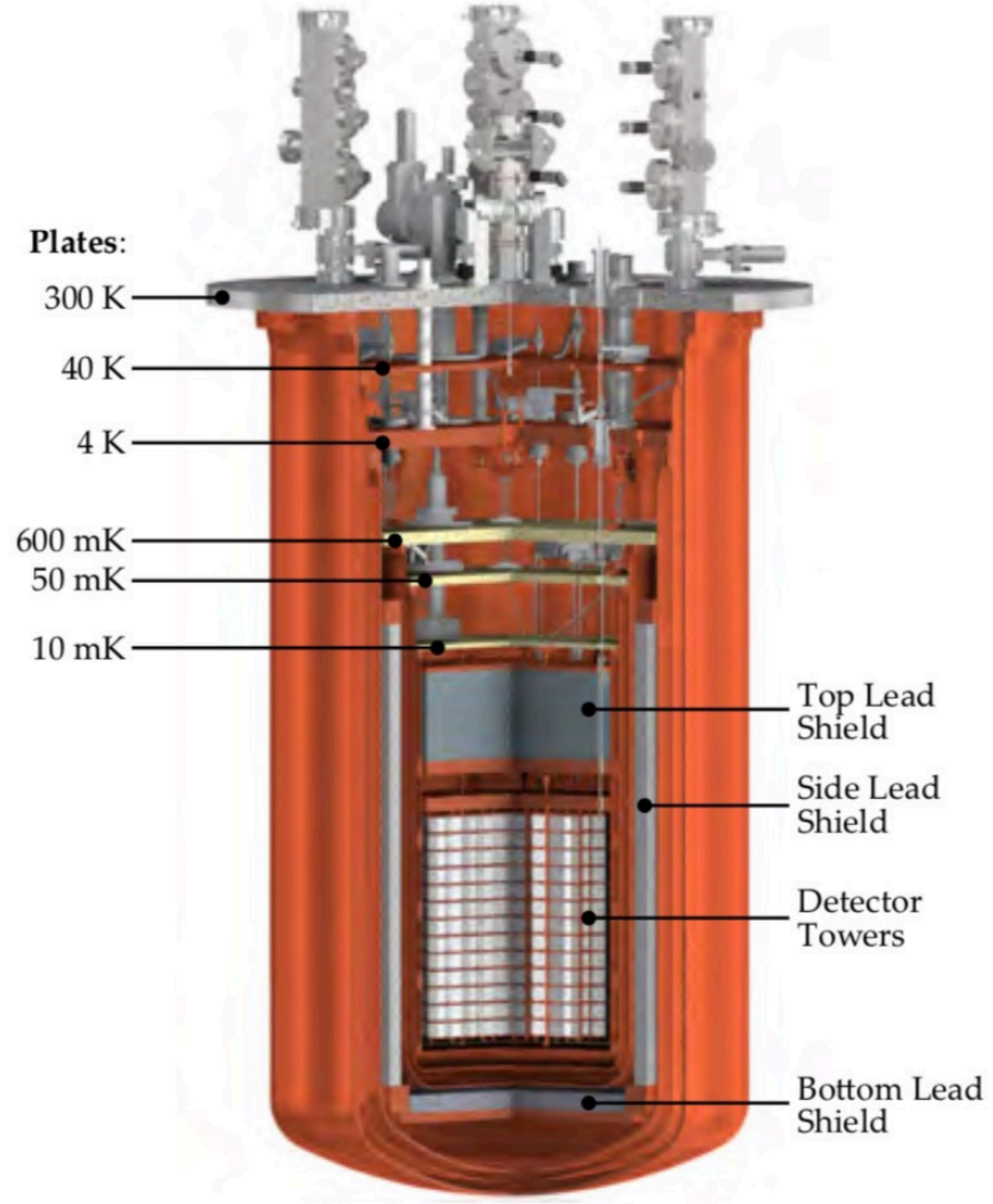
LEGEND-200, Neutrino 2024

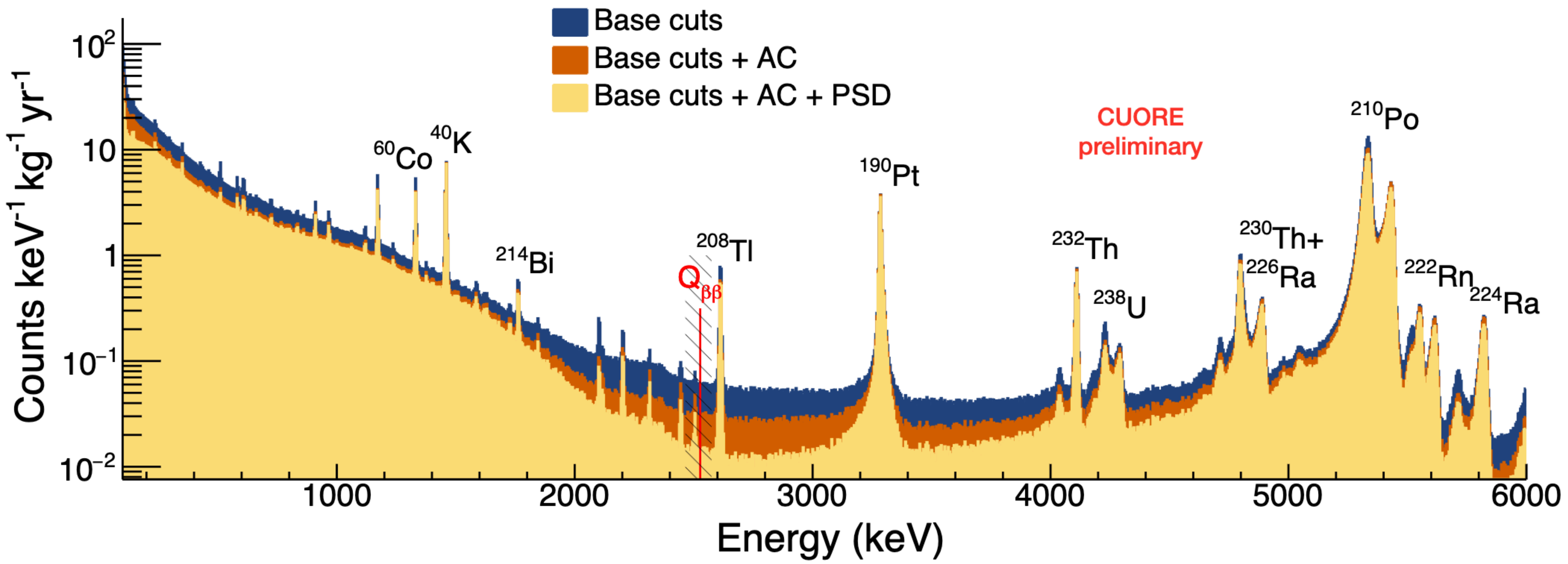
CUORE

HEAT

- Closely packed array of 988 TeO2 crystals (750 g each) working as **cryogenic calorimeters**
- The absorbed energy is converted into a variation of the crystal temperature
- Operating temperature: ~10 mK
- Energy resolution at Q-value ~0.3 % FWHM
- Total mass of TeO_2: 742 kg (~**206 kg of ^{130}Te**)
- **6 years** of data (May. 2017 - Apr. 2023)







^{130}Te $T_{1/2} > 3.8\times10^{25}$ yrs

Cuore, Neutrino 2024

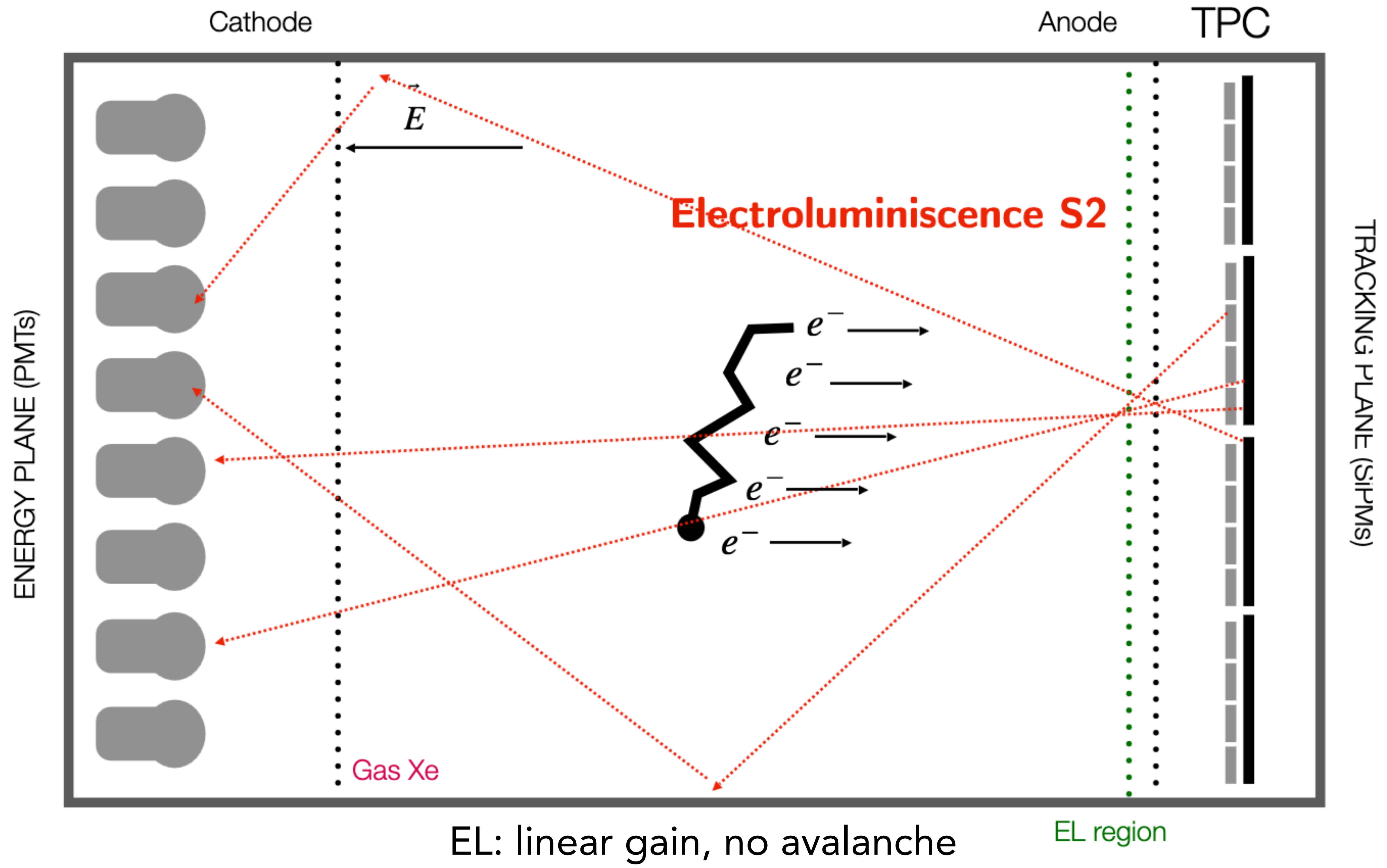
The NEXT-100 experiment at LSC (Spain)

Light + Charge

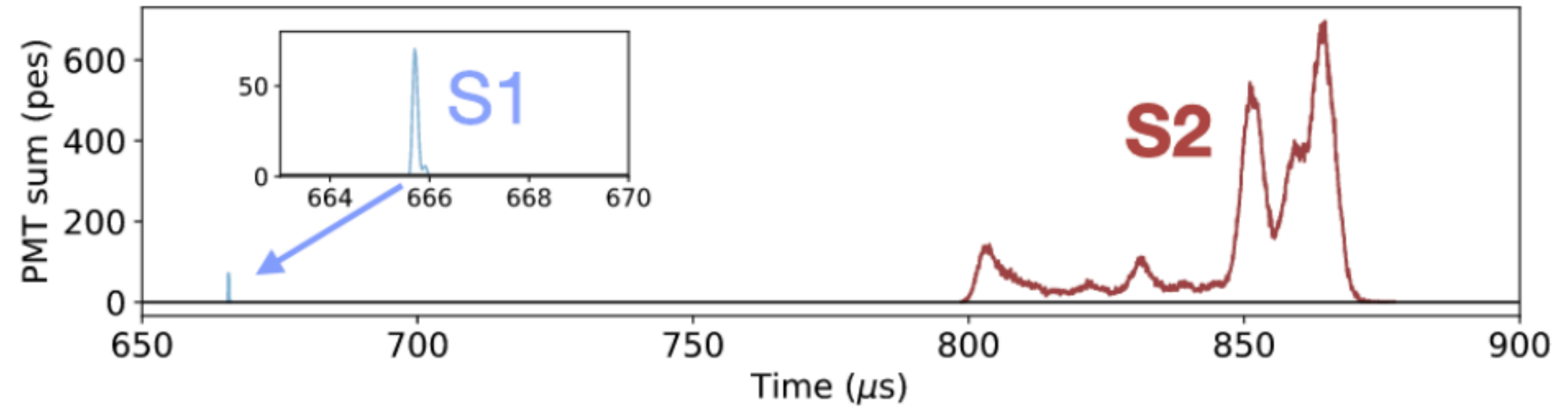
High pressure (15 bar) gas xenon TPC

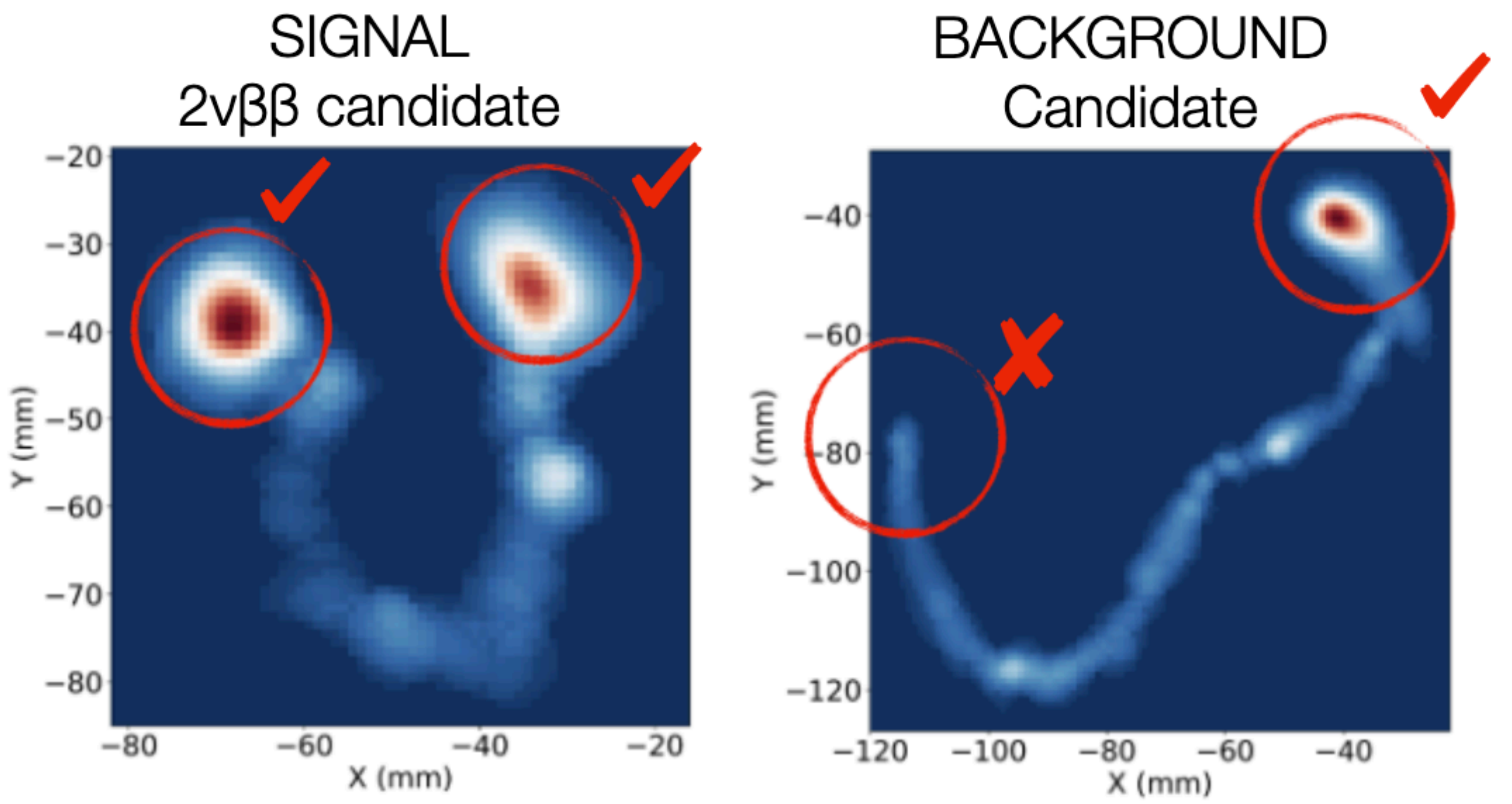
- Energy resolution at Q-value ~1 % FWHM
- Total mass ~80 kg (enriched ^{136}Xe)

fully built & under commissioning



EL: linear gain, no avalanche

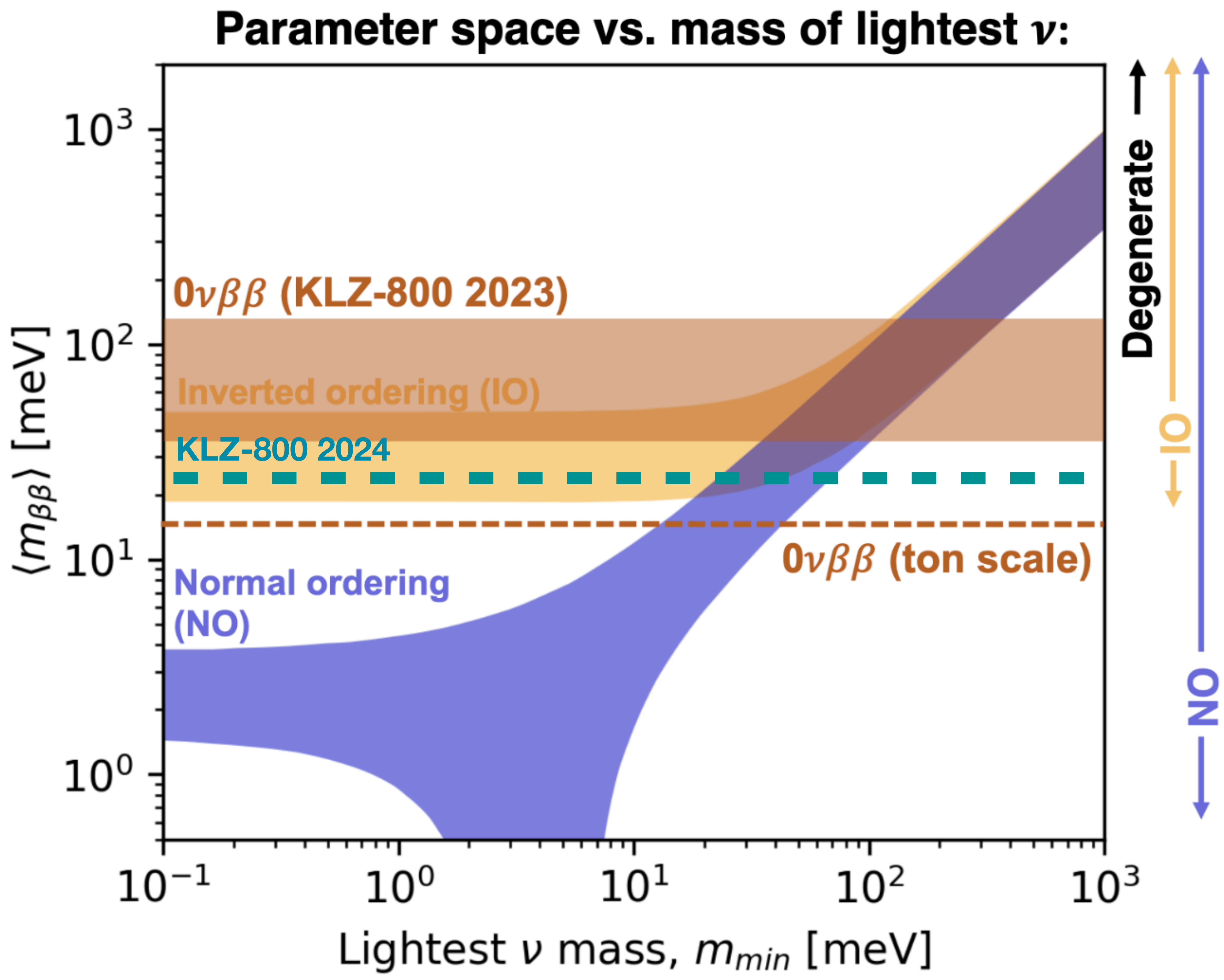




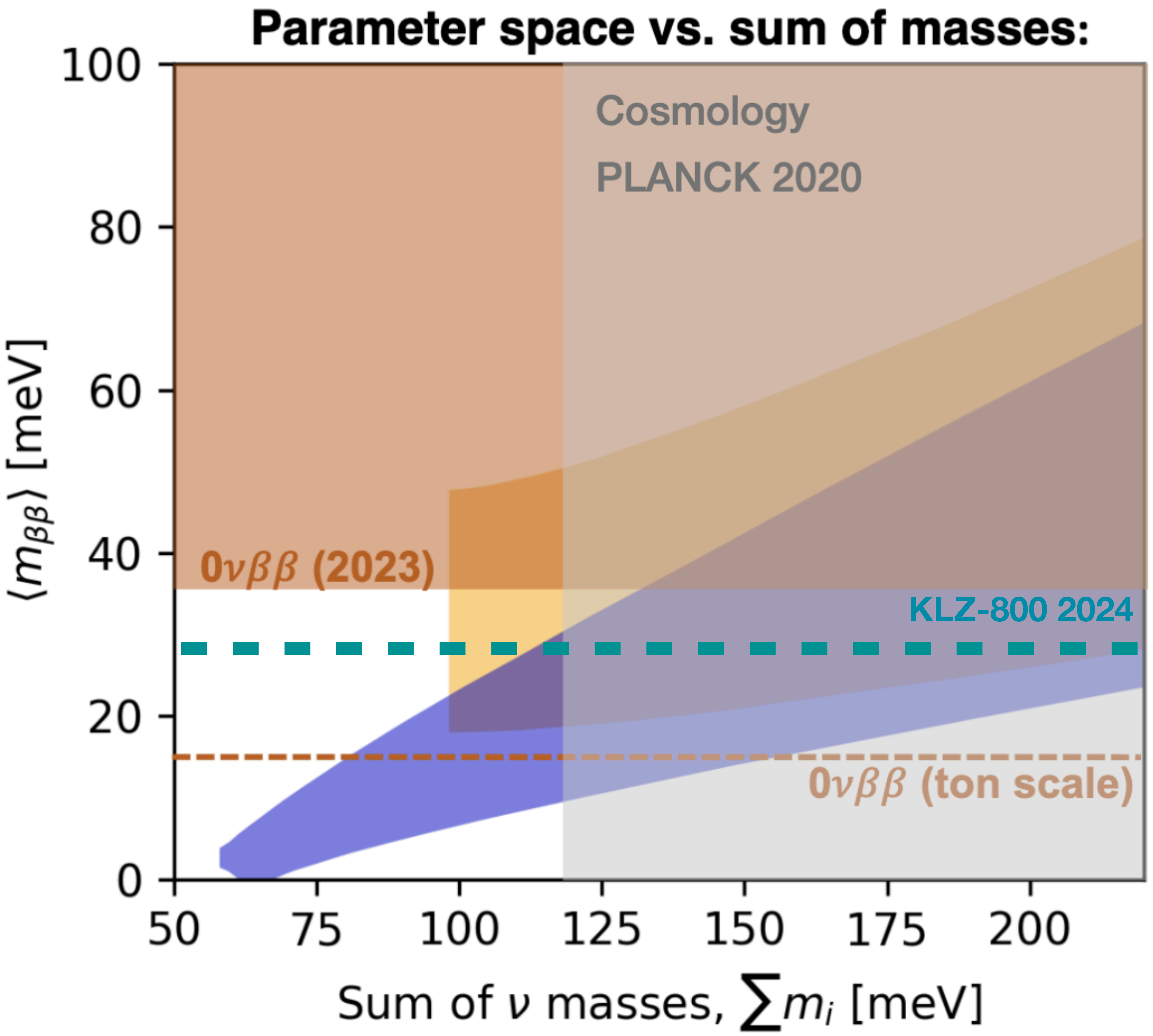
Although there are ionization and scintillation, the sensors only see light

Neus Lopez-March, LIDINE 2023

Comparison of the different experiments



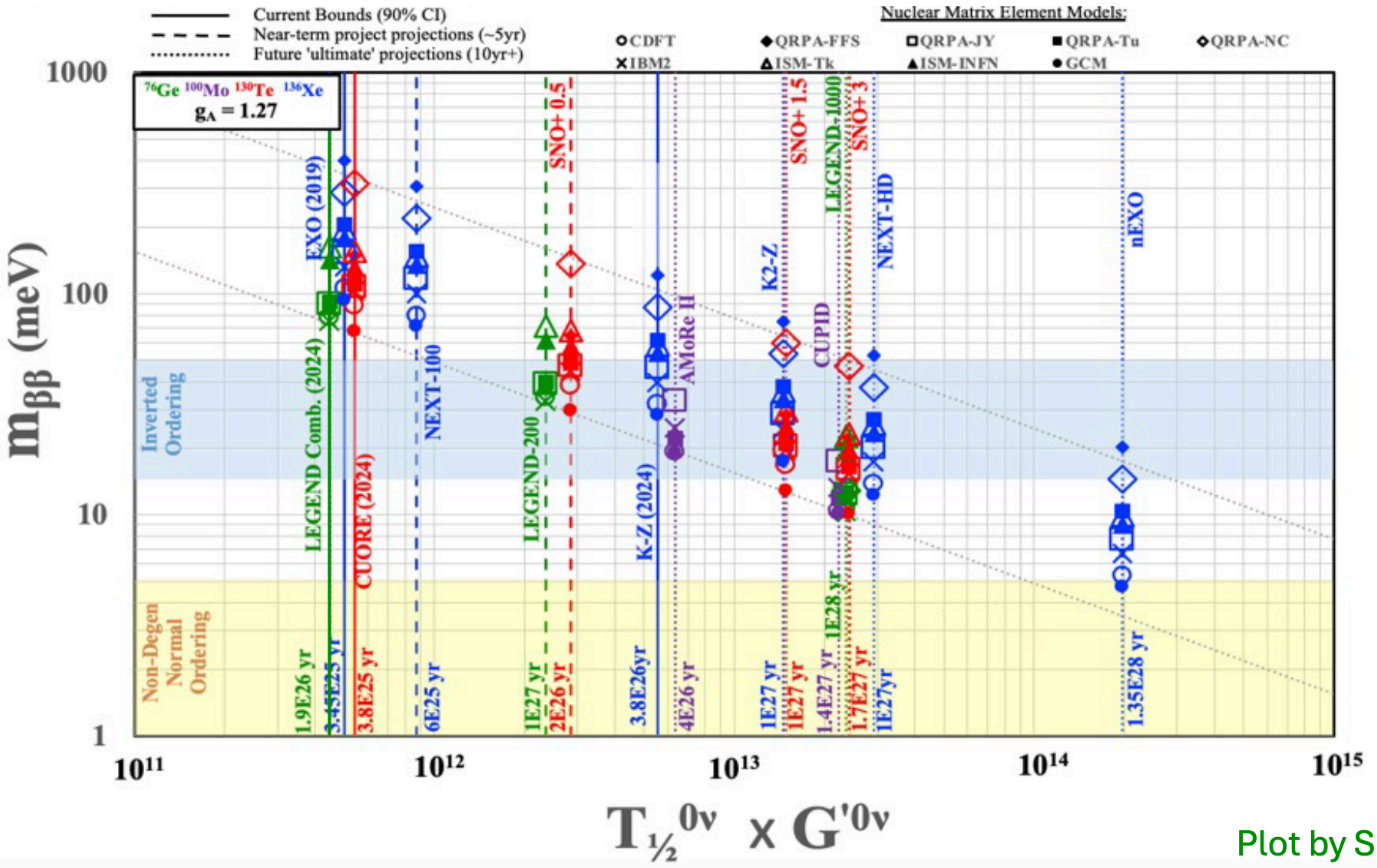
Parameter space vs. mass of lightest ν:



Parameter space vs. sum of masses:

From TAUP 2023 D. Moore

Comparison of the different experiments



Plot by S. Biller

- **Future goal:** ~2 orders of magnitud improvement in$T_{1/2}$ to cover the IO region and reach the NO
- **Problem**: Sensitivity rises with exposure, but strongly depends on backgrounds

Absolute neutrino mass

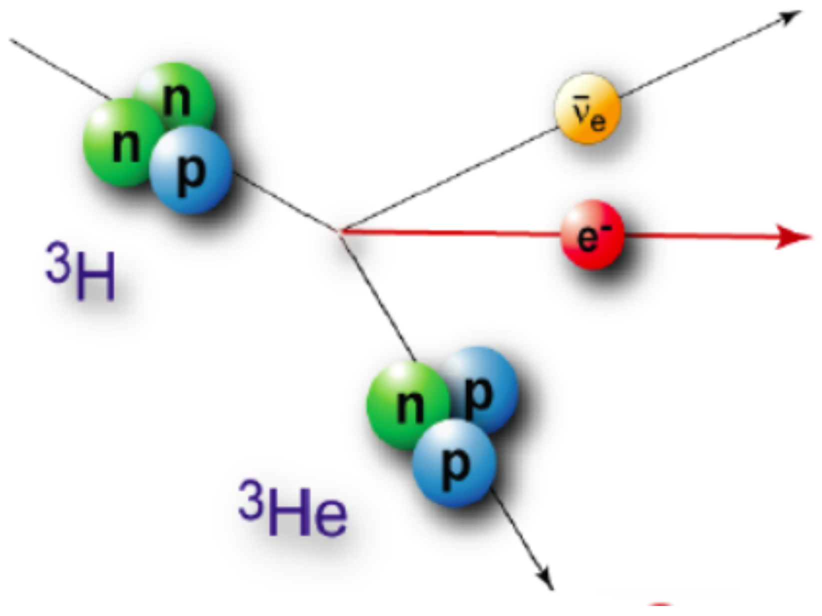
Neutrino absolute mass

From oscillations:
$m_\nu > 0.05$ eV

- 3 different approaches to obtain information about the neutrino mass

Direct measurements

spectrum of different beta decays



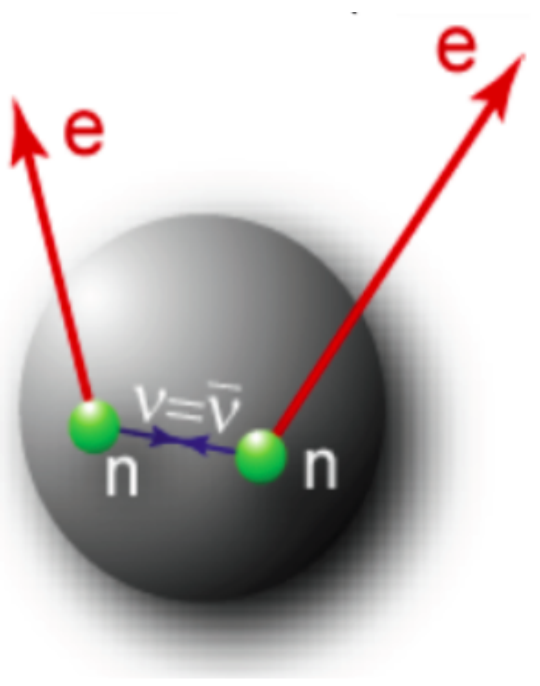
$$m_\nu \overset{\text{def}}{=} \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$

$$\boxed{m_\nu < 0.45\,\text{eV}\ \ (90\,\%\ \text{CL})}$$

KATRIN (Neutrino2024)

Neutrinoless double beta decay

if neutrinos are Majorana particles



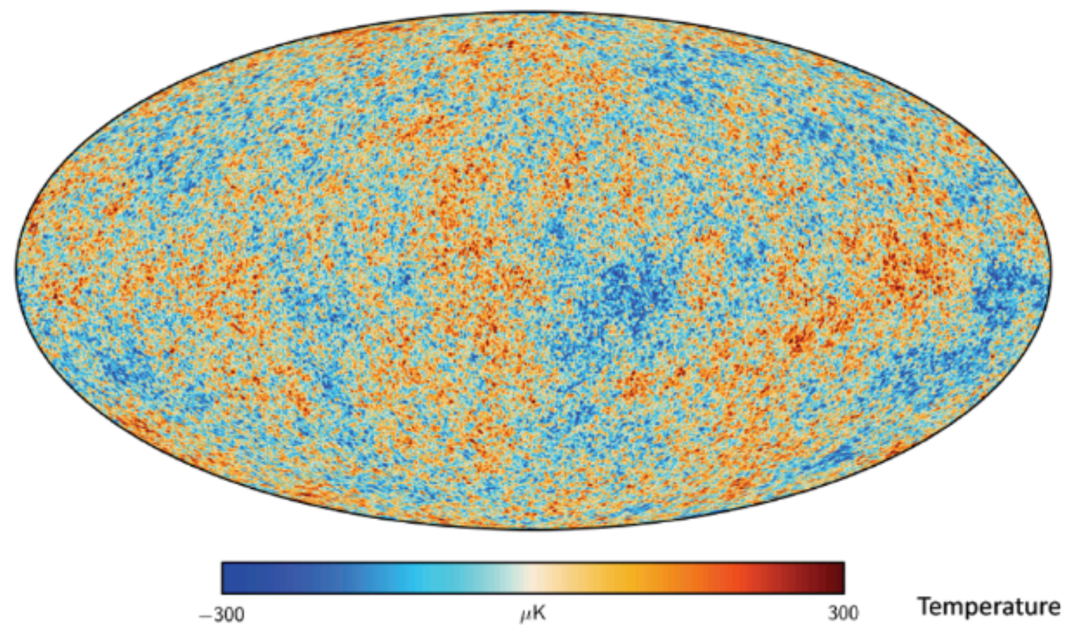
$$m_{\beta\beta} = \left| \sum_i U_{ei}^{\ 2} \cdot m_{\nu_i} \right|$$

$$\boxed{m_{\beta\beta} < 28 - 122\ \ meV}$$

KamLAND-Zen 800 (Neutrino2024)

Indirect Measurements

cosmological contrains



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

$$\boxed{m < 0.12\ \ eV}$$

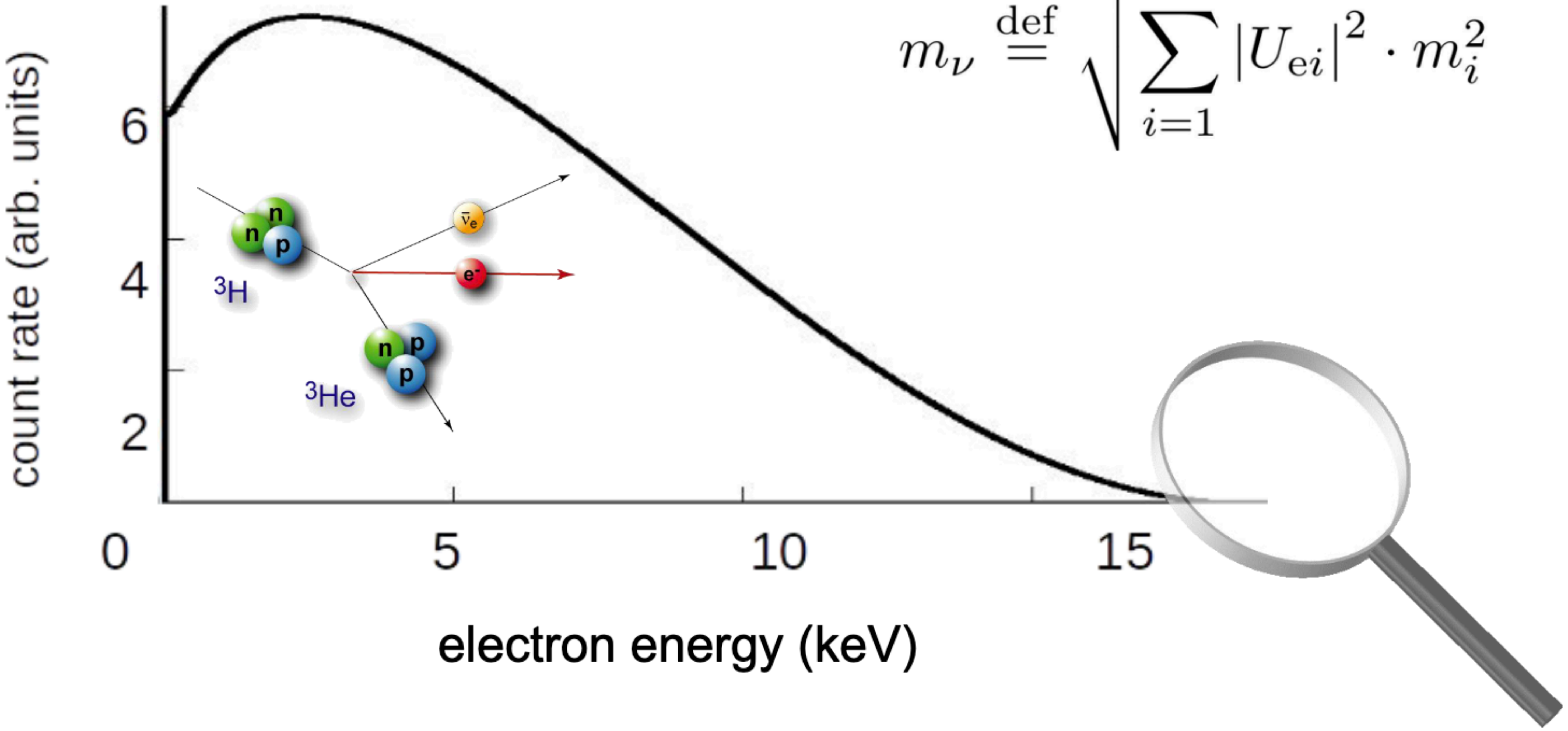
PLANCK (2018)

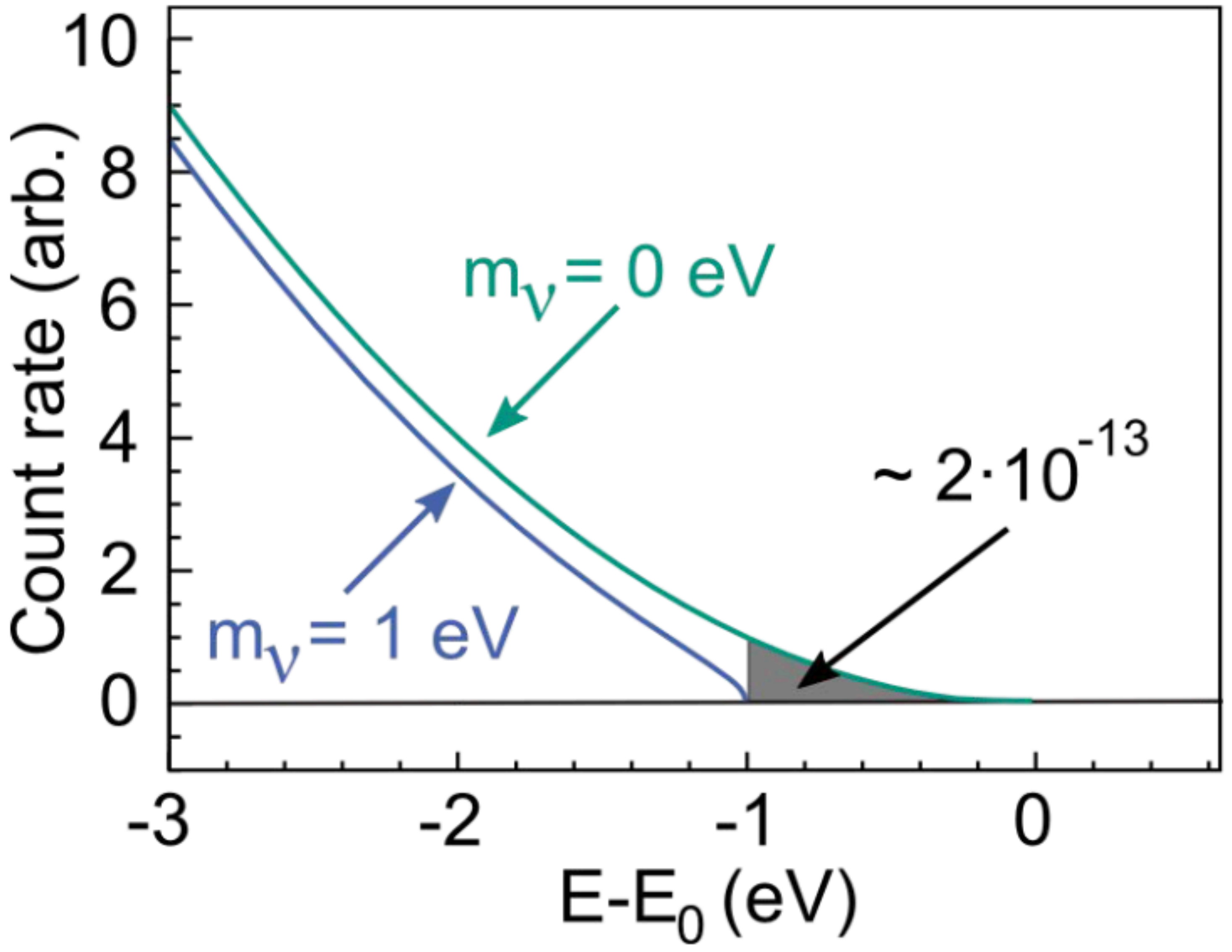
Direct measurements: tritium beta decay

Measurement of effective mass m_ν based on kinematic parameters & energy conservation

$$R_\beta(E) \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$

$$m_\nu \overset{\text{def}}{=} \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$



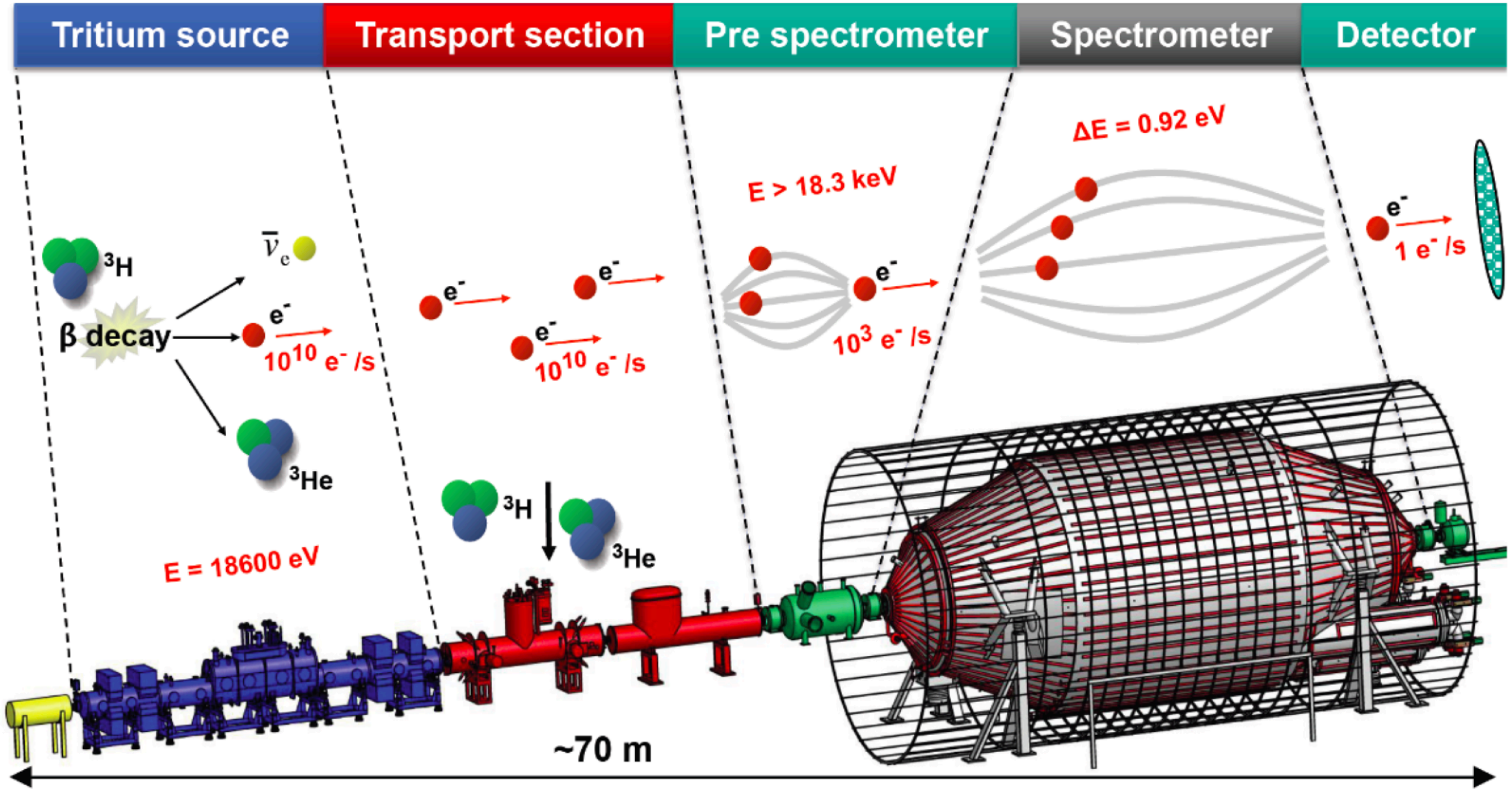


- High source activity
- Excellent energy resolution (~1 eV)
- Low background

KATRIN (Neutrino2024)

KATRIN Experiment

KATRIN: Karlsruhe Tritium Neutrino Experiment



To achieve a resolution 1/20000 the spectrometer needs a diameter of 10 m

KATRIN results

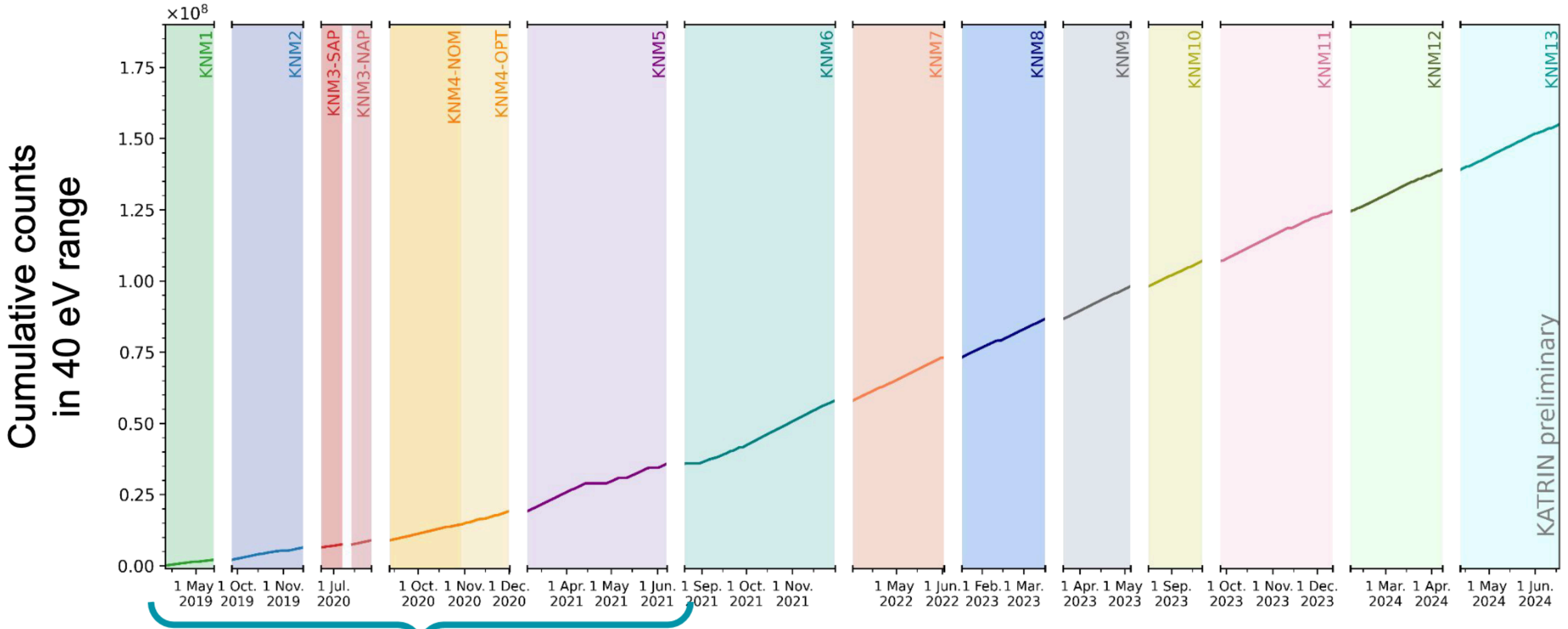
2019: m_ν < 1.1 eV (90% CL)

2022: m_ν < 0.8 eV (90% CL)

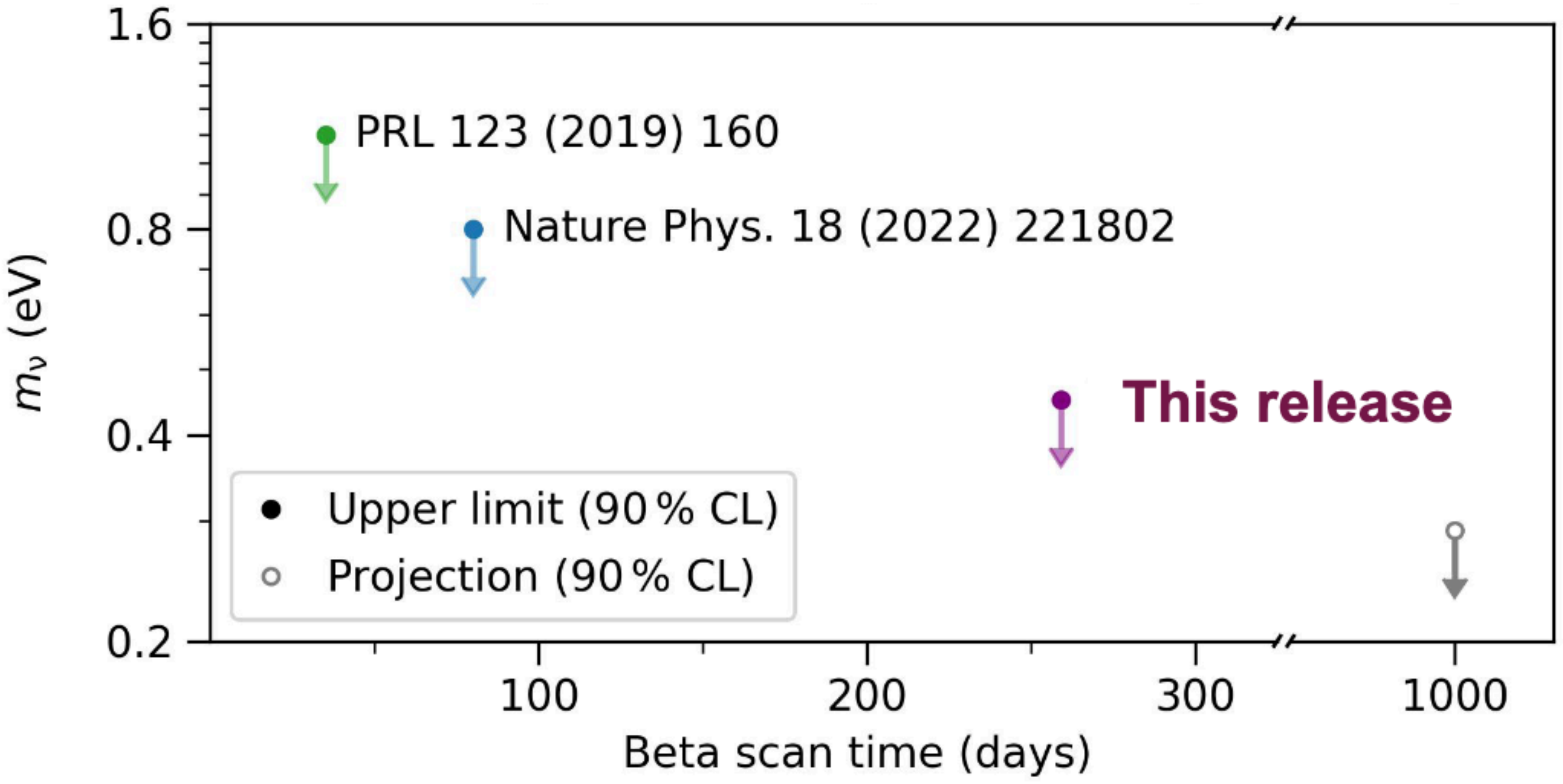
Neutrino 2024:

- **259** measurement days
- **1757** β-scans

$$\boxed{m_\nu < 0.45\,\text{eV}\ \ (90\,\%\ \text{CL})}$$



Neutrino 2024



KATRIN (Neutrino2024)

Anomalies and sterile neutrinos

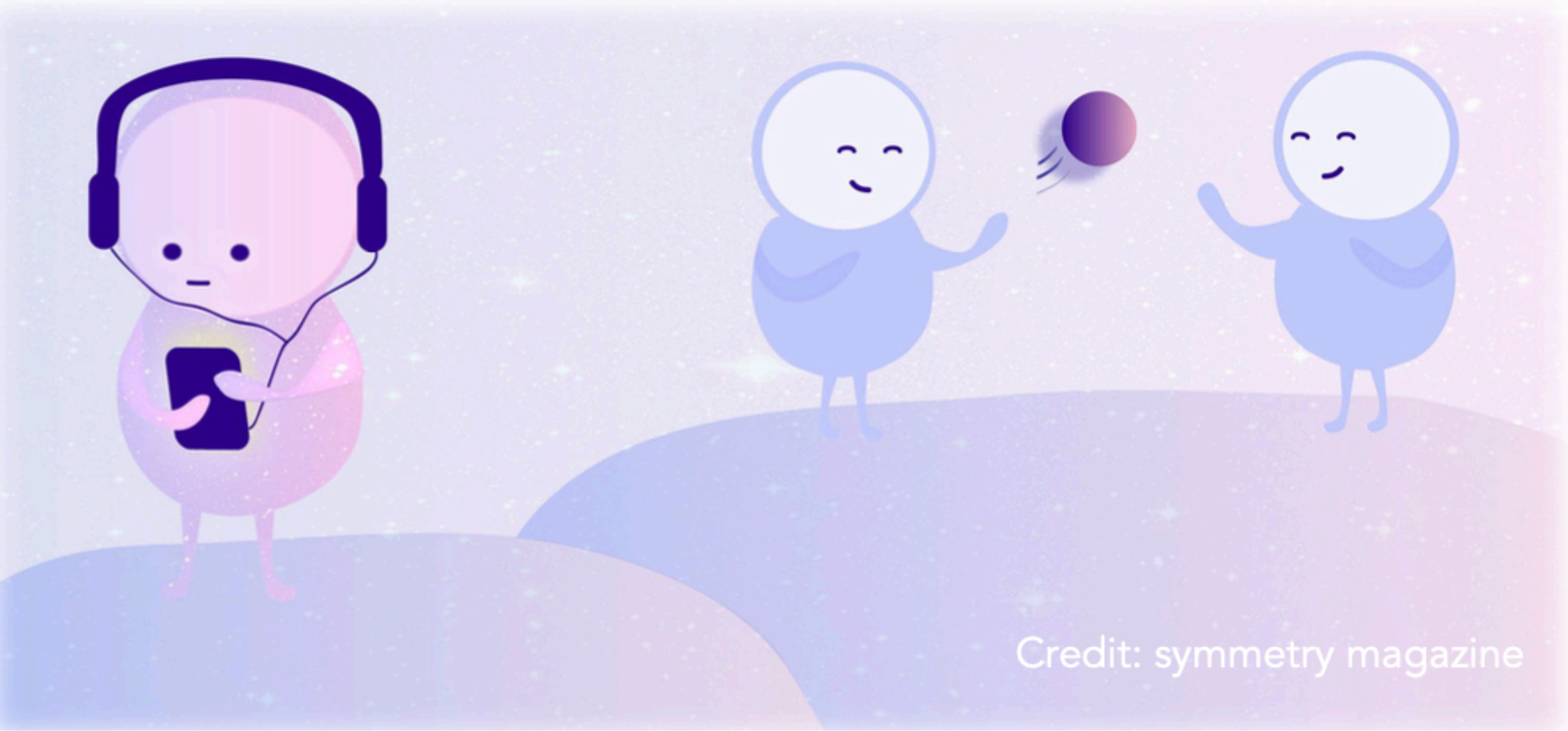
Sterile neutrinos

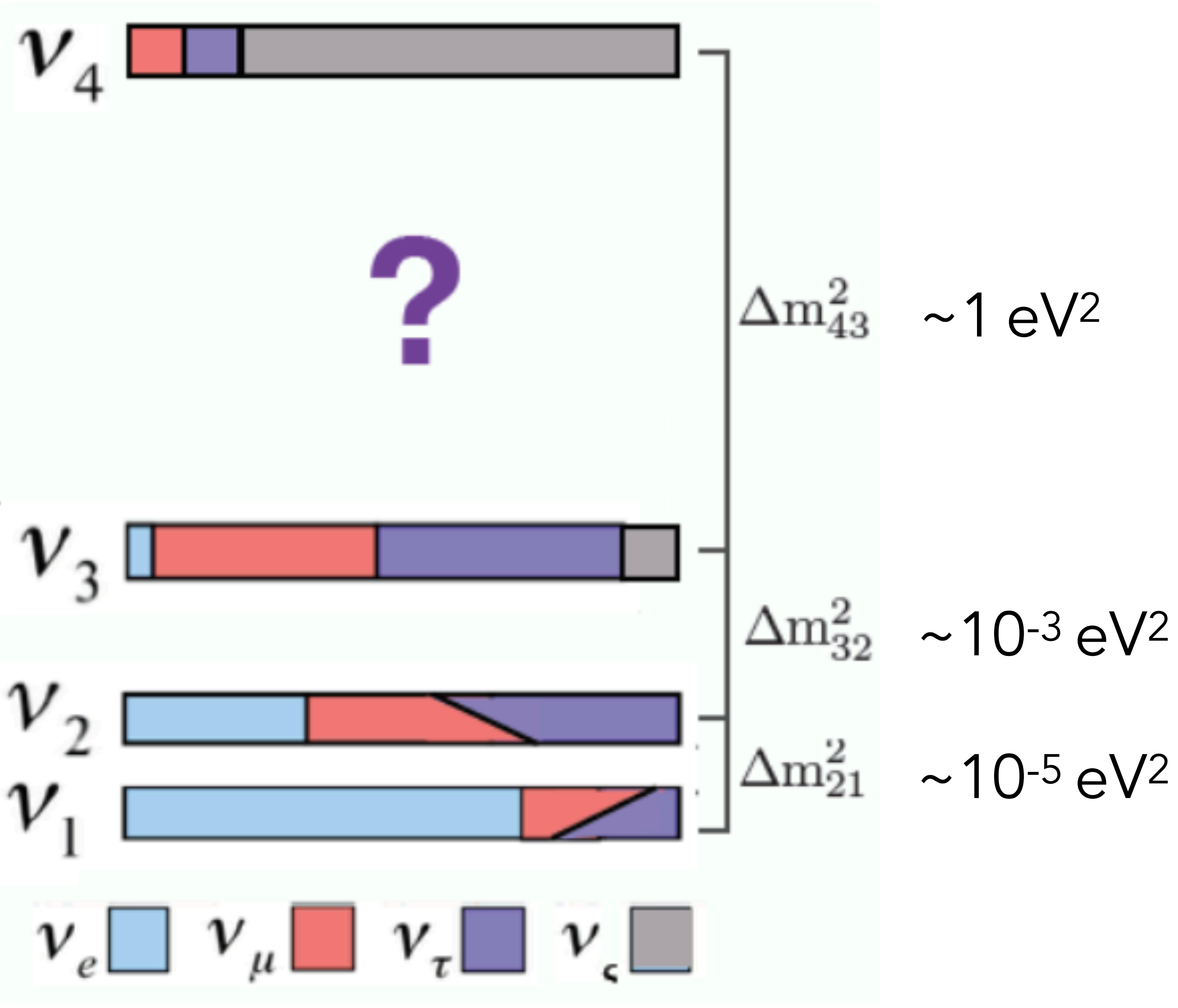
All the oscillation experiments seen so far explained their results with the standard 3-neutrino picture

Is the correct or the only possibility?

- Over the years, several experiments have observed anomalies not compatible with this theoretical framework
  - Reactor neutrino anomalies
  - Gallium anomaly
  - LSND anomaly

- **Are sterile neutrinos a reasonable possibility?**
  - The simplest 3+1 model in tension to cover all the anomalies
  - An extra neutrino in severe tensión with the cosmology data


Credit: symmetry magazine



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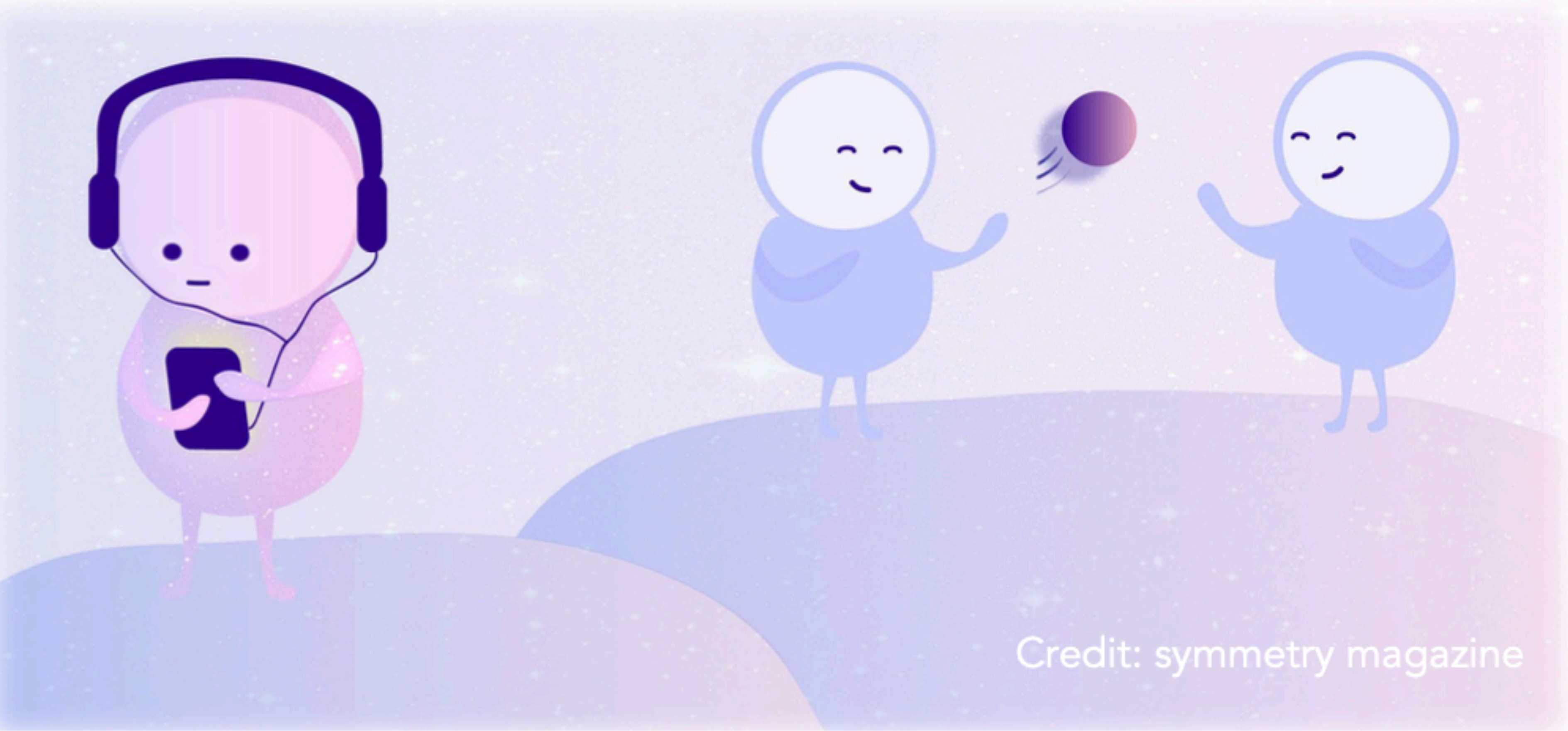
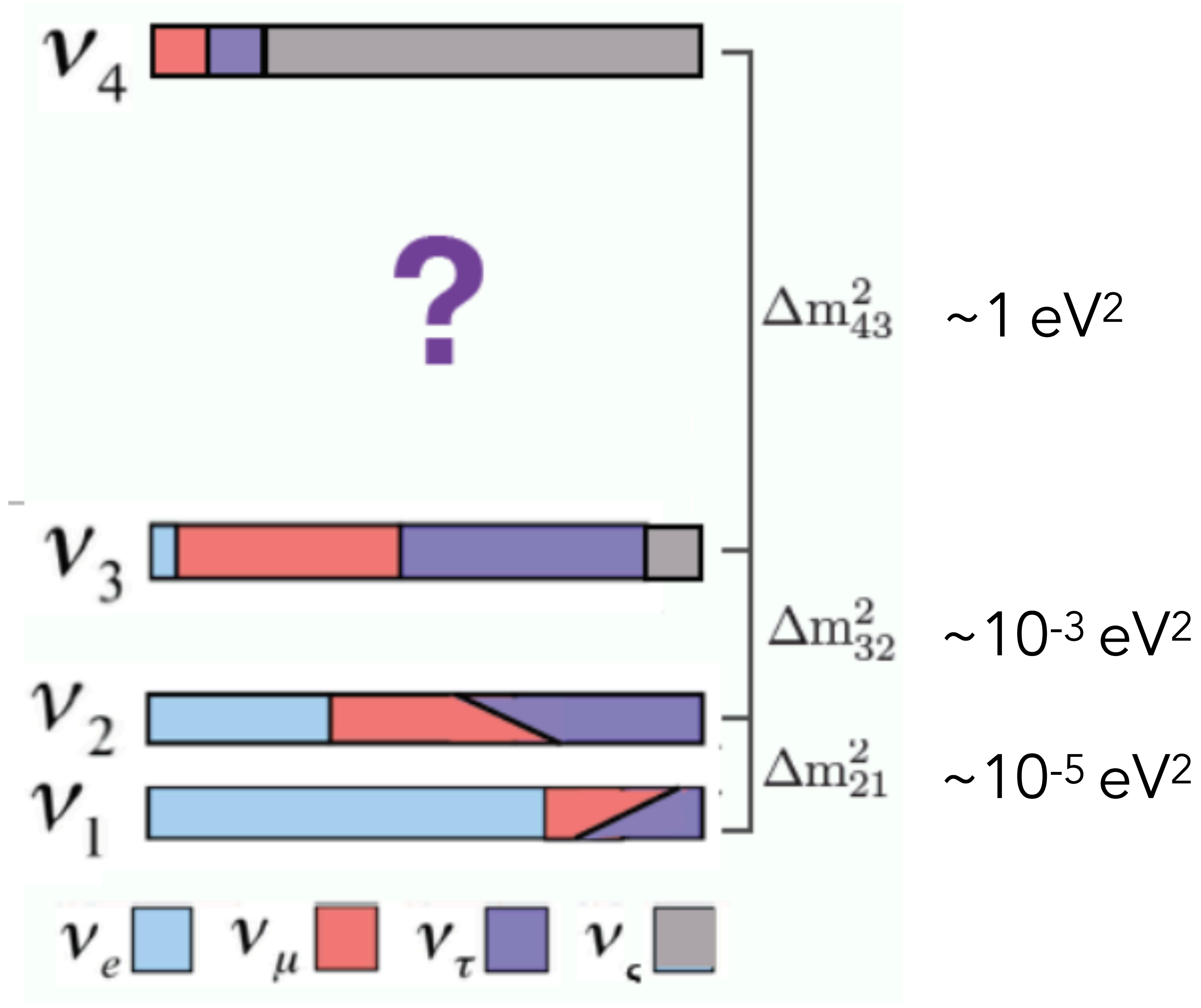

Credit: symmetry magazine



Gallium anomaly

- Solar neutrino experiments GALLEX and SAGE were calibrated with intense ^{51}Cr and ^{37}Ar sources **20 years ago**

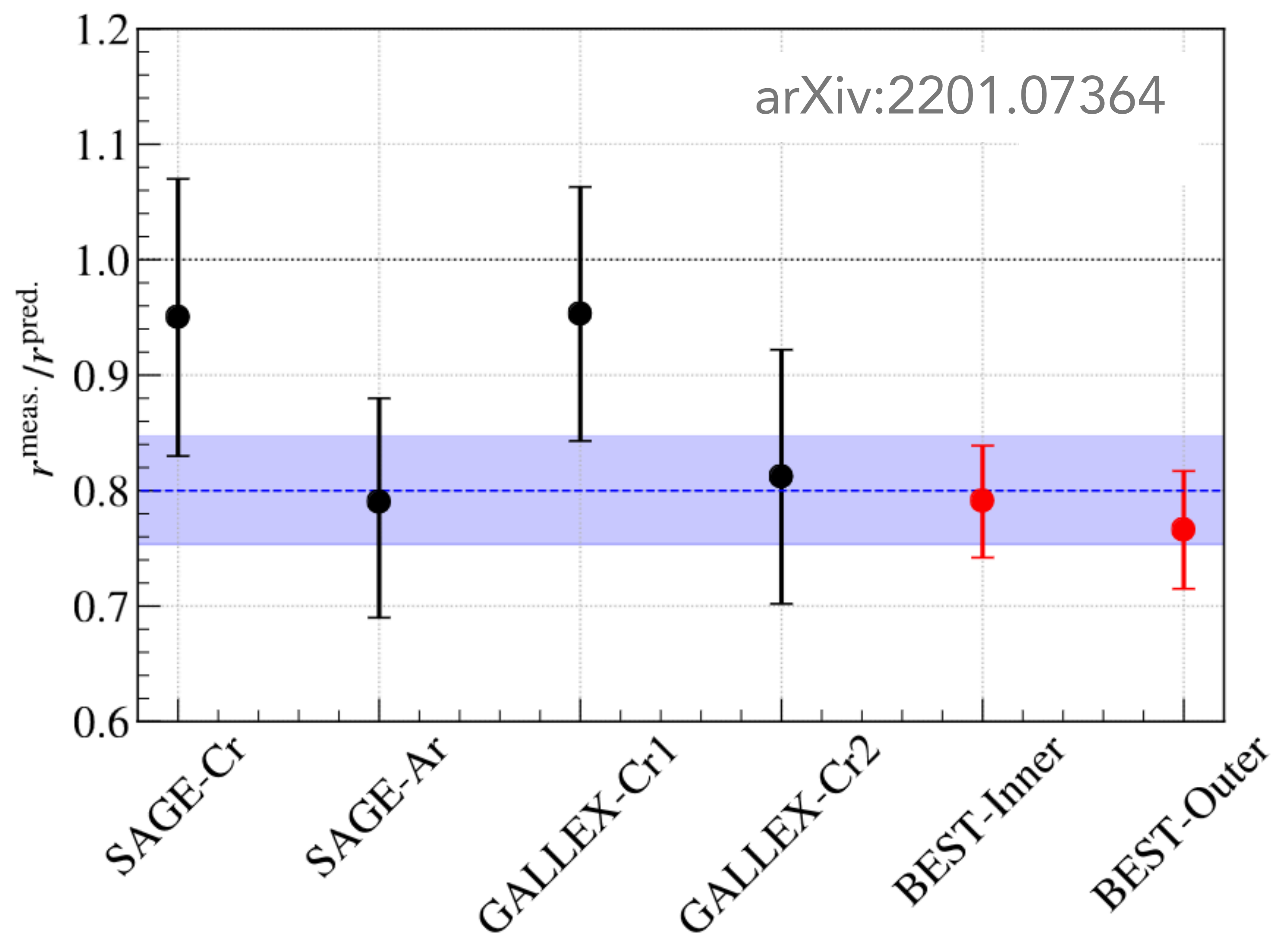
$$e^- + {}^{51}Cr \longrightarrow {}^{51}V + \nu_e$$
$$e^- + {}^{37}Ar \longrightarrow {}^{37}Cl + \nu_e$$

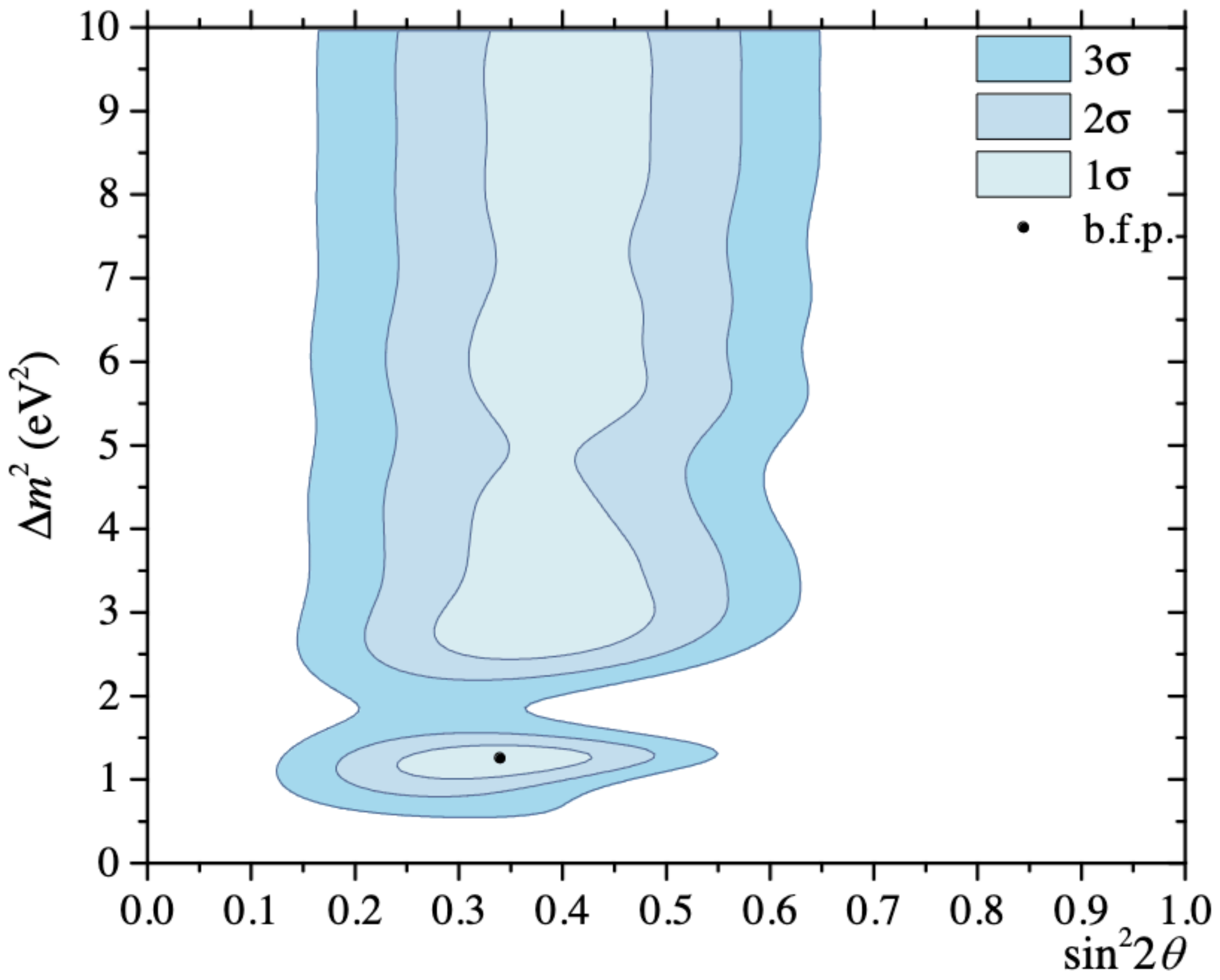
$$\longrightarrow \quad \nu_e + {}^{71}Ga \longrightarrow {}^{71}Ge + e^-$$

- The measurements showed a deficit in the expected rates of ^{71}Ge
- In **2022 the deficit was confirmed** by the experiment BEST

$$\frac{r^{meas.}}{r^{pred.}}(average) = 0.80 \pm 0.05$$

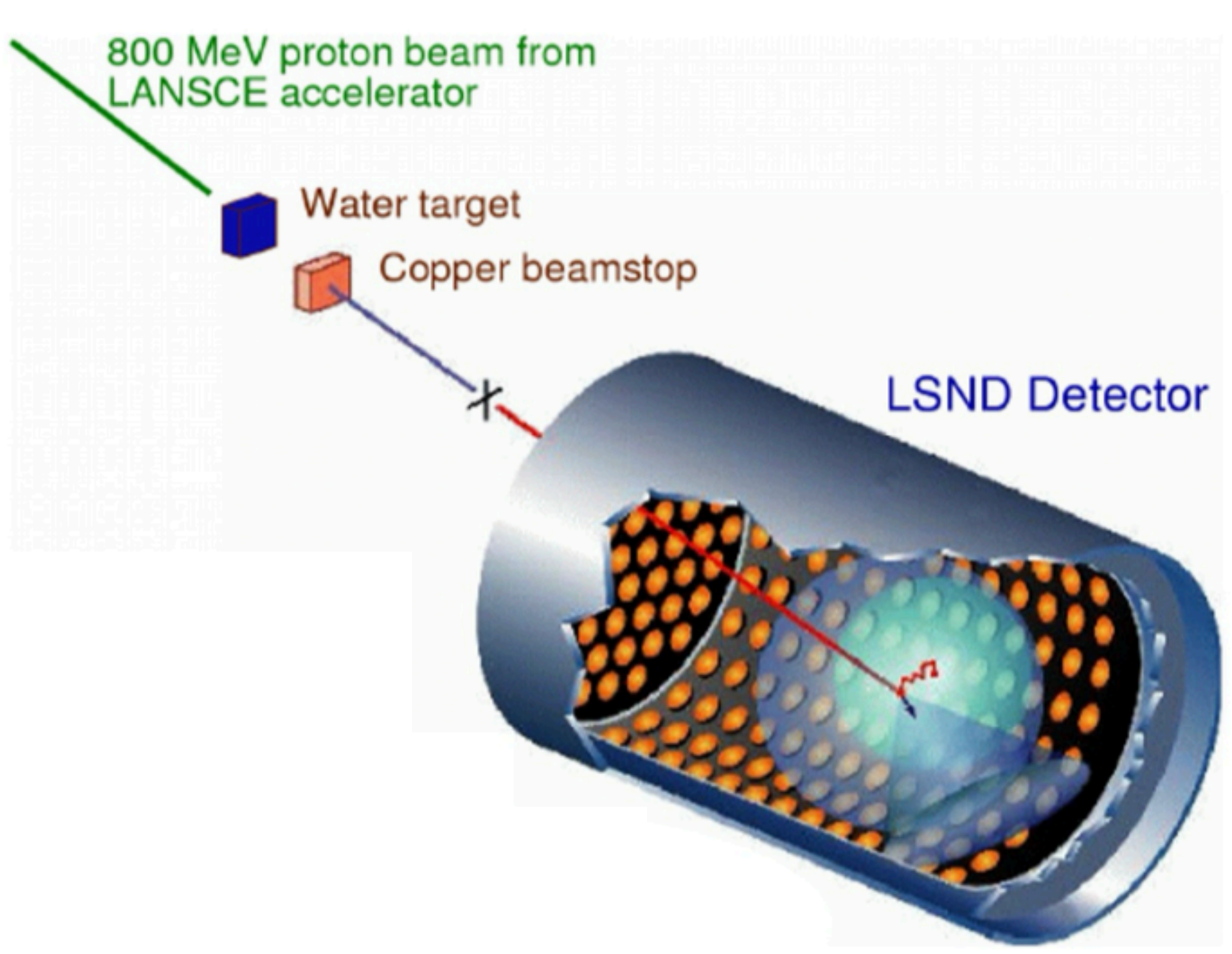
- Such deficit can be interpreted in terms of oscillations. Data suggests $\Delta m^2 > 1$ eV^2, but requires a very large mixing angle ~18°
- The anomaly seems real given the robustness of the experiments, but maybe it is not related to sterile neutrinos


arXiv:2201.07364

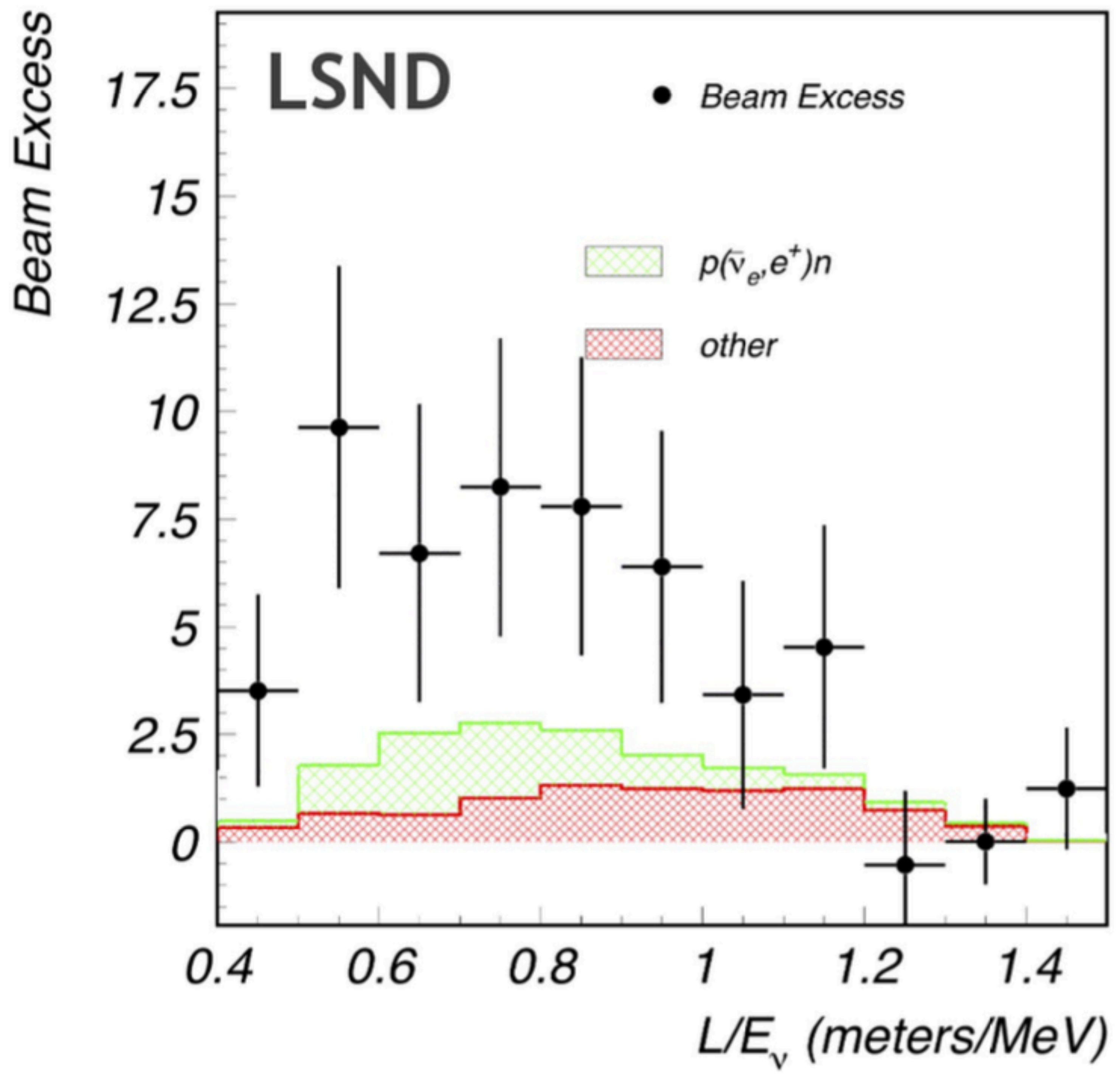


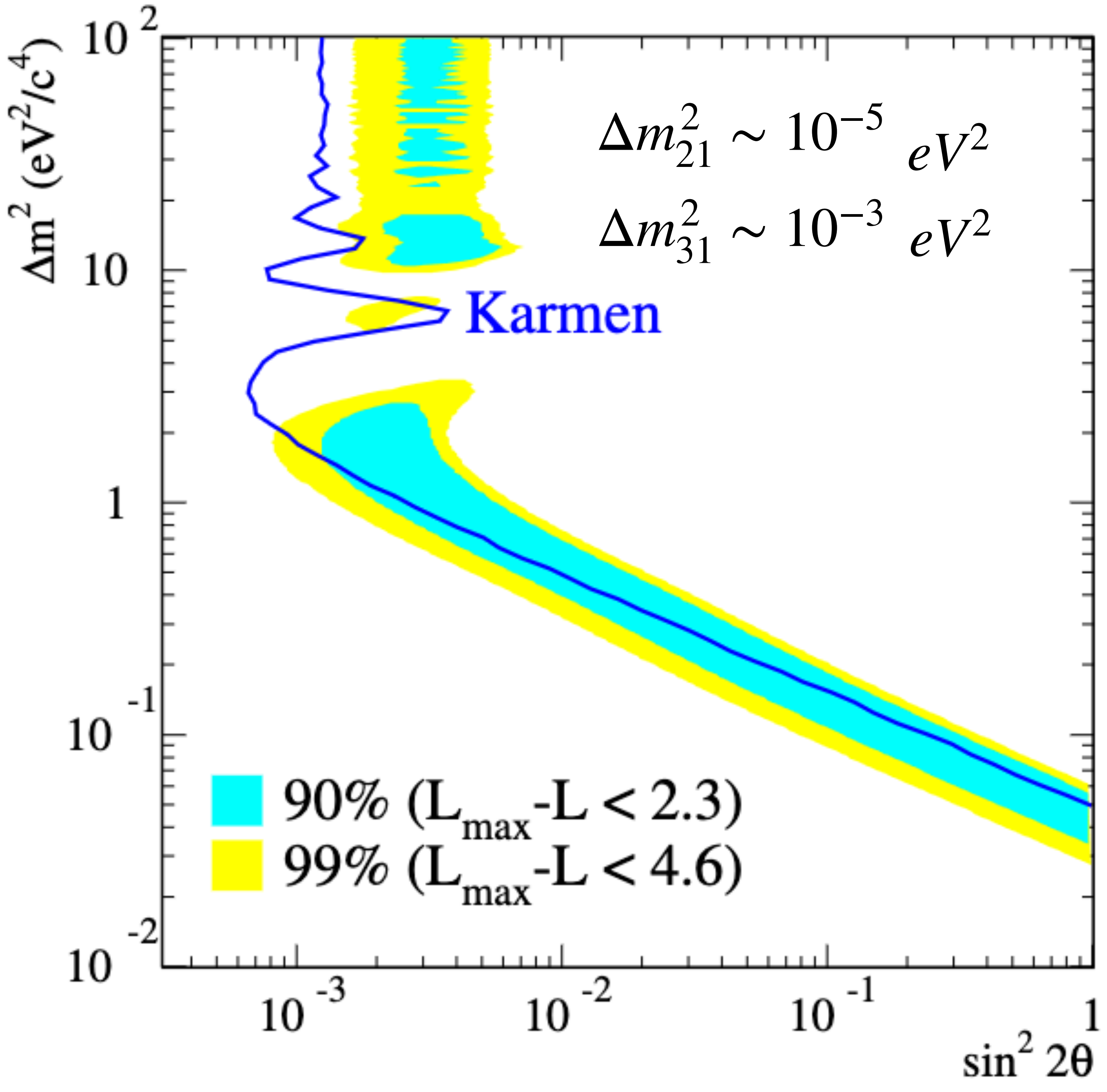
LSND anomaly

- In the 90's, the LSND experiment observed an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam, (E_ν ~30 MeV, L ~35m)
- The excess is compatible with $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ oscillations provided that $\Delta m^2 > 0.1 \;\; eV^2$
- The KARMEN collaboration (2002) did not confirm the LSND result, but could not fully exclude it



The explanation of this result with the mass-induced ν oscillations needs a new neutrino



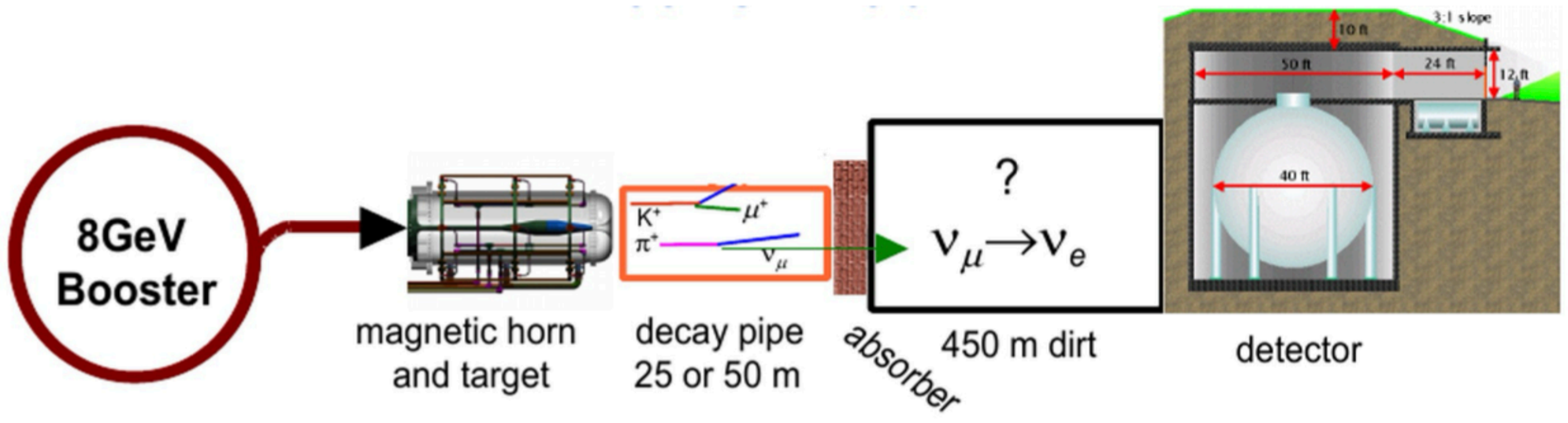


$\Delta m^2_{21} \sim 10^{-5} \;\; eV^2$

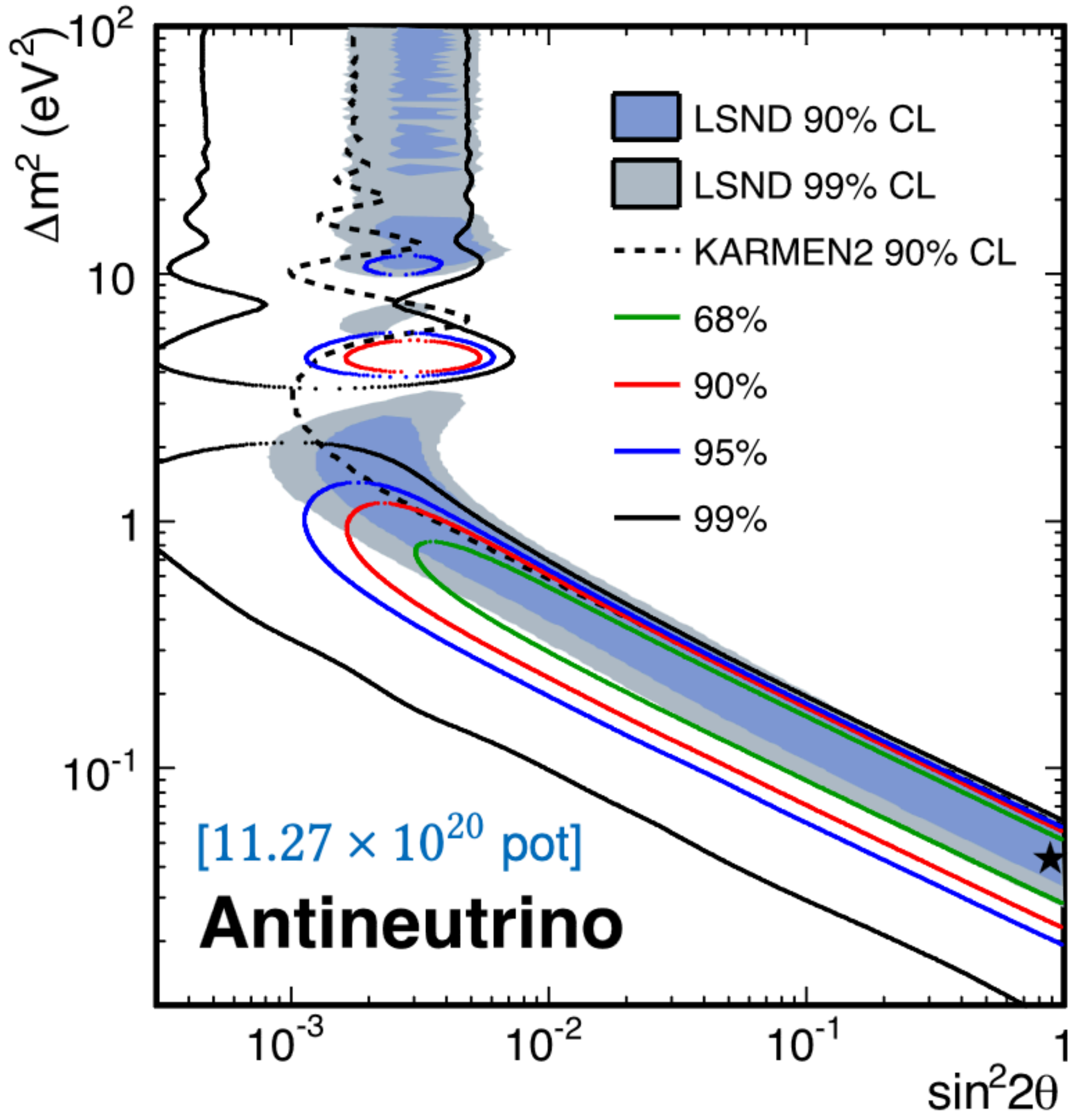
$\Delta m^2_{31} \sim 10^{-3} \;\; eV^2$

The MiniBooNE experiment

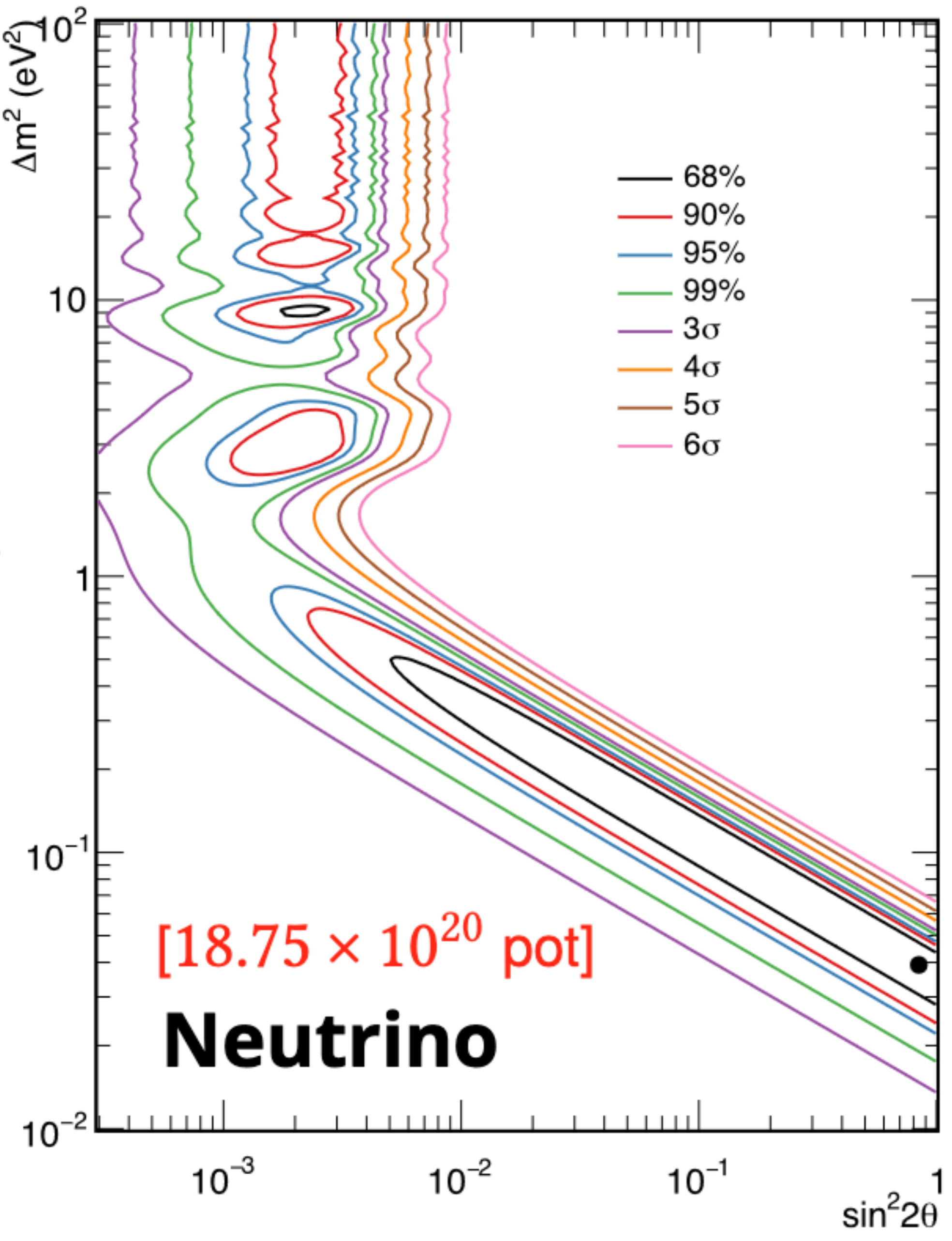
- **Goal:** Ultimate test of the LSND anomaly at Fermilab (2007)
- Searches for $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ and $\nu_\mu \longrightarrow \nu_e$. Same L/E as the LSND experiment (E = 200 - 1250 MeV, L = 540m).
- Detector technology: Cherenkov detector with pure mineral oil
- **Result:** excess in both $\bar{\nu}$ and ν channels. In fact, **oscillations compatible with the LSND results**



Detector: 12.2 m sphere filled with pure mineral oil + PMTs



+



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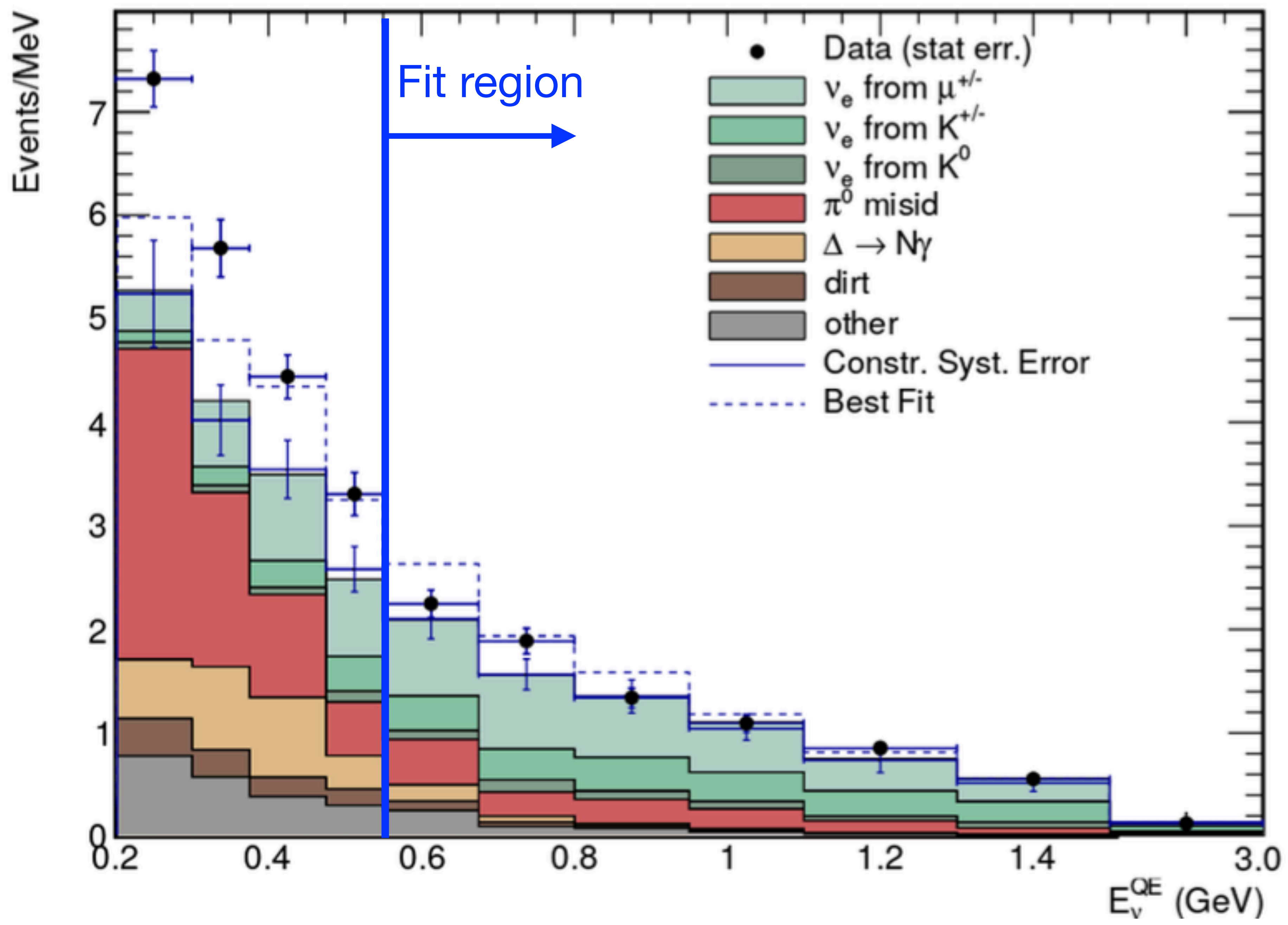
- Detector technology: Cherenkov detector with pure mineral oil
- **Result:** excess in both $\bar{\nu}$ and ν channels. In fact, **oscillations compatible with the LSND results**

PROBLEM: there was an excess of electron-neutrino-like events at low energies (below their analysis threshold) imposible to explain with oscillations

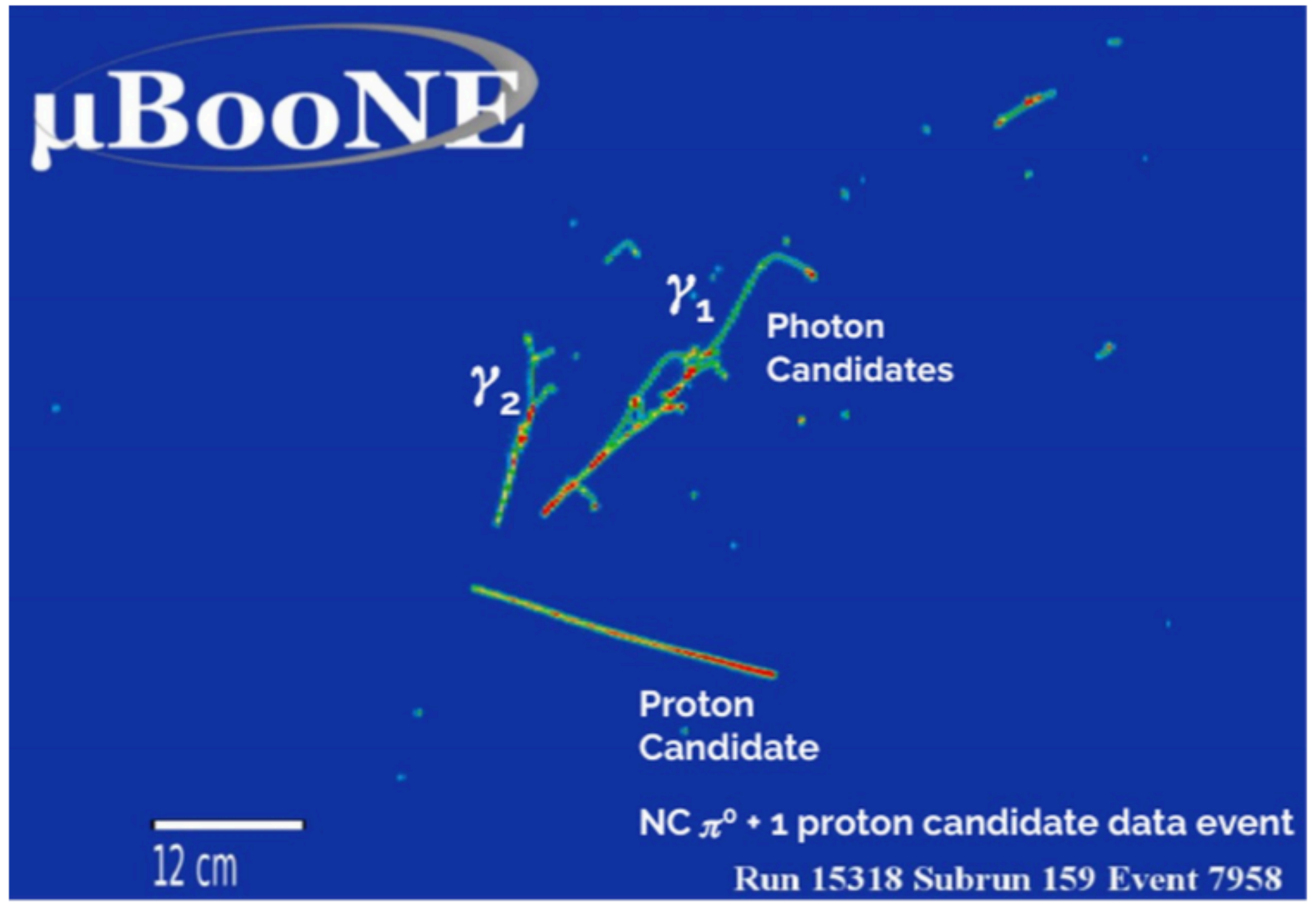
- possibly a systematic effect related to the mis-identification of electron and photons

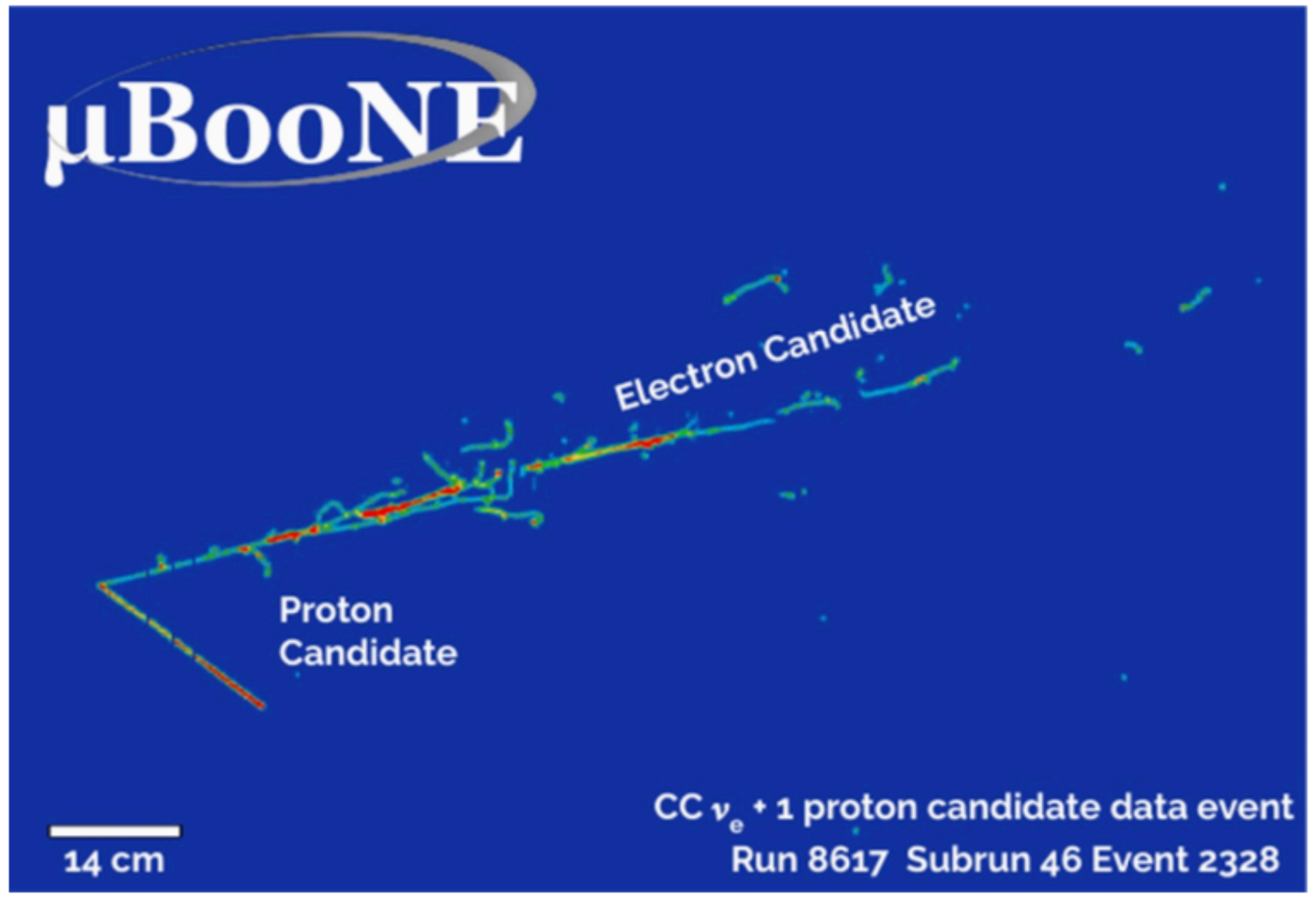
independent confirmation required

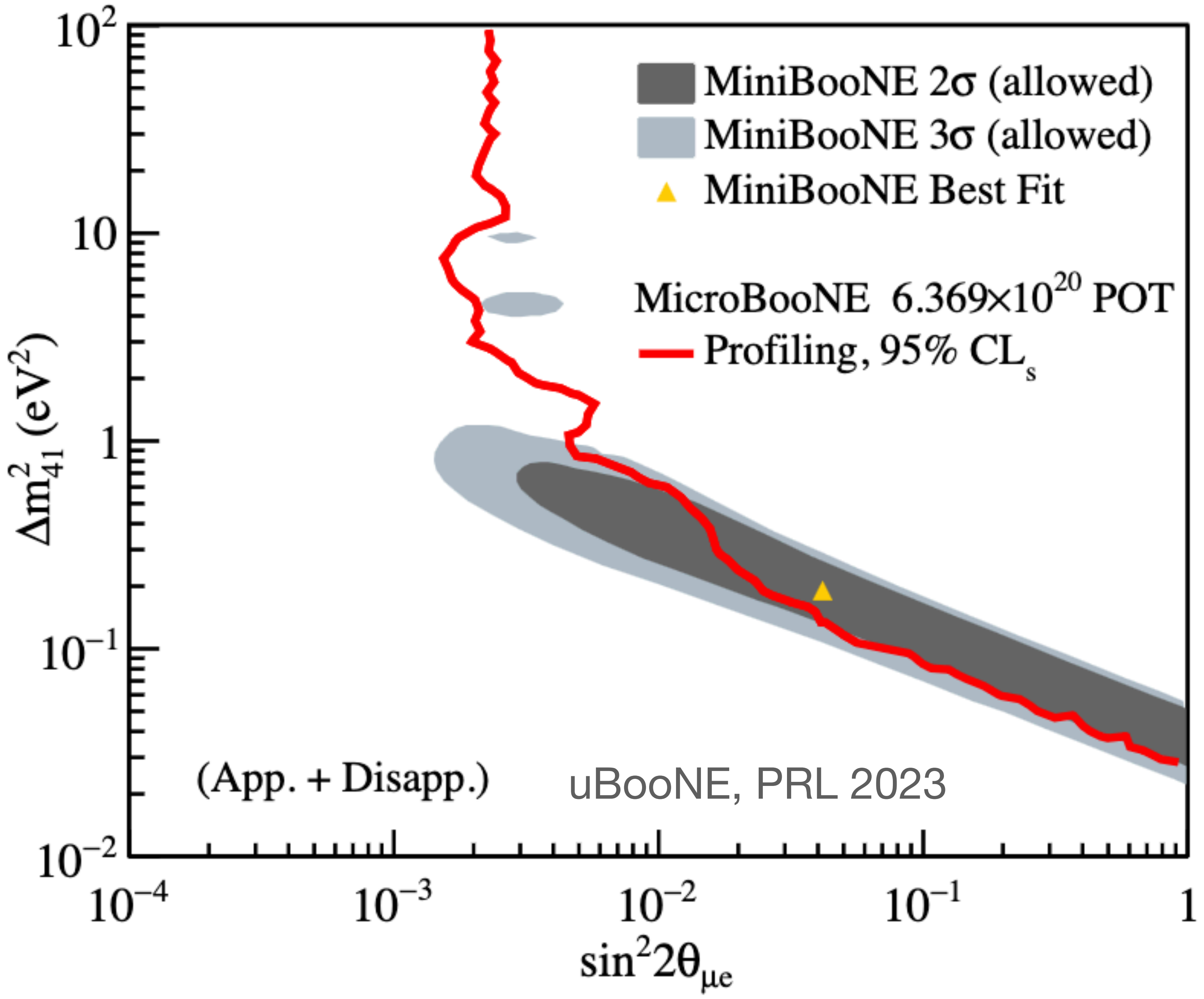


The MicroBooNE experiment

- **Goal:** Ultimate test of the MiniBooNE anomaly at Fermilab (2021)
- Same location as MiniBooNE (72.5 m apart), same beam, different technology
- Detector technology: LArTPC, to distinguish electromagnetic showers started by photons vs. electrons
- **Result:** no evidence of ν_e excess over SM prediction but imposible to reject the MiniBooNe result

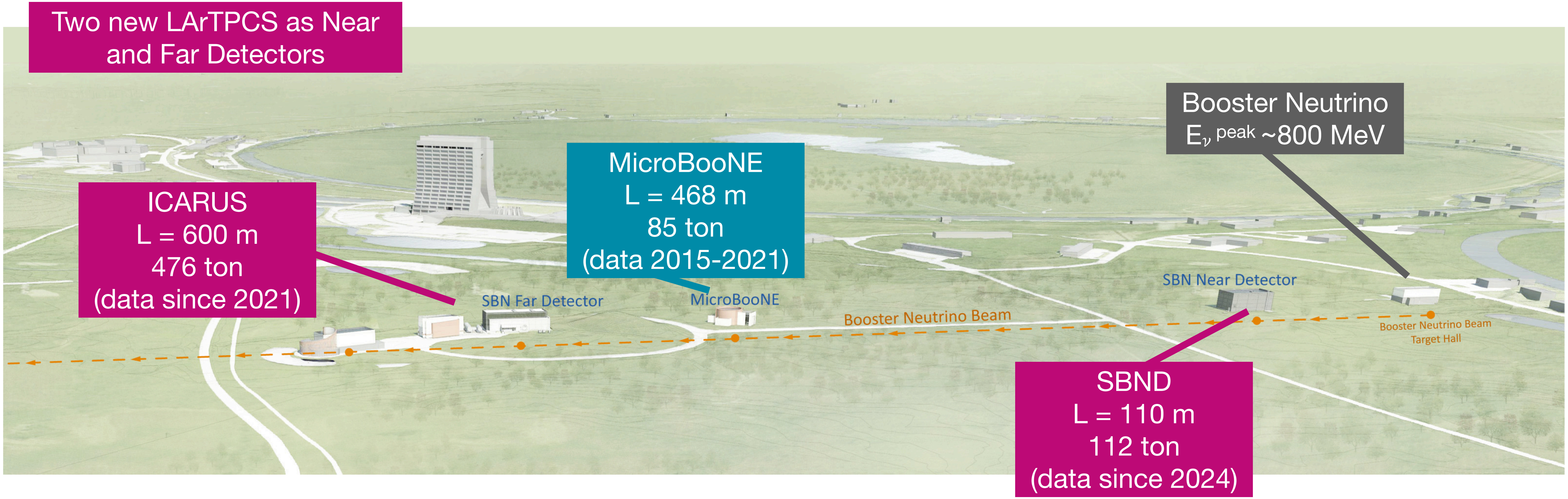






The Short Baseline Neutrino Programa

- **3 LArTPCs** in the same neutrino beam (E_ν^{peak} ~800 MeV)
- **Goal**: Investigate the eV-scale sterile neutrino oscillations (anomalies from LSND, MiniBooNE & MicroBooNE)



Two new LArTPCS as Near and Far Detectors

ICARUS
L = 600 m
476 ton
(data since 2021)

MicroBooNE
L = 468 m
85 ton
(data 2015-2021)

Booster Neutrino
E_ν^{peak} ~800 MeV

SBND
L = 110 m
112 ton
(data since 2024)

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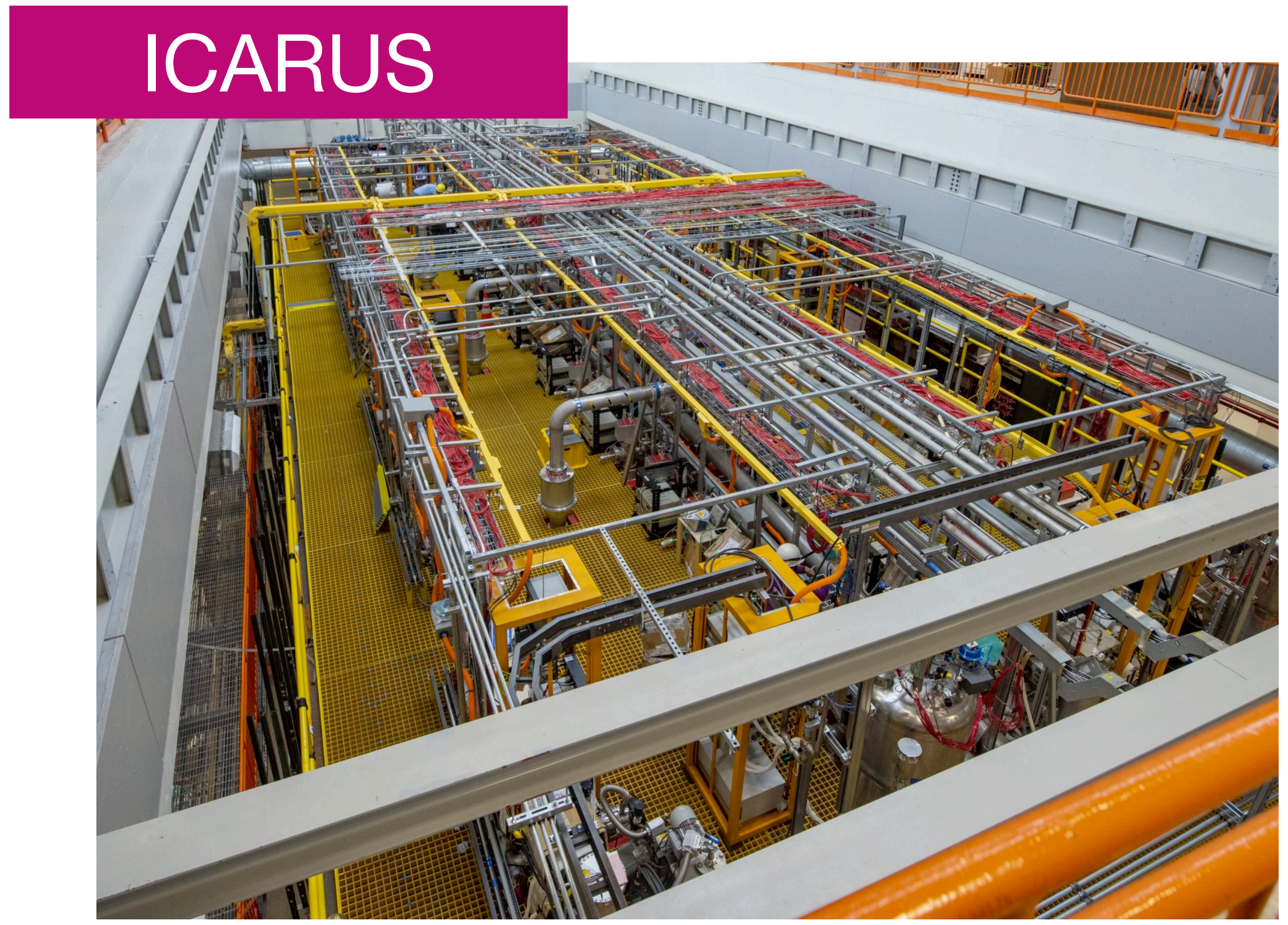
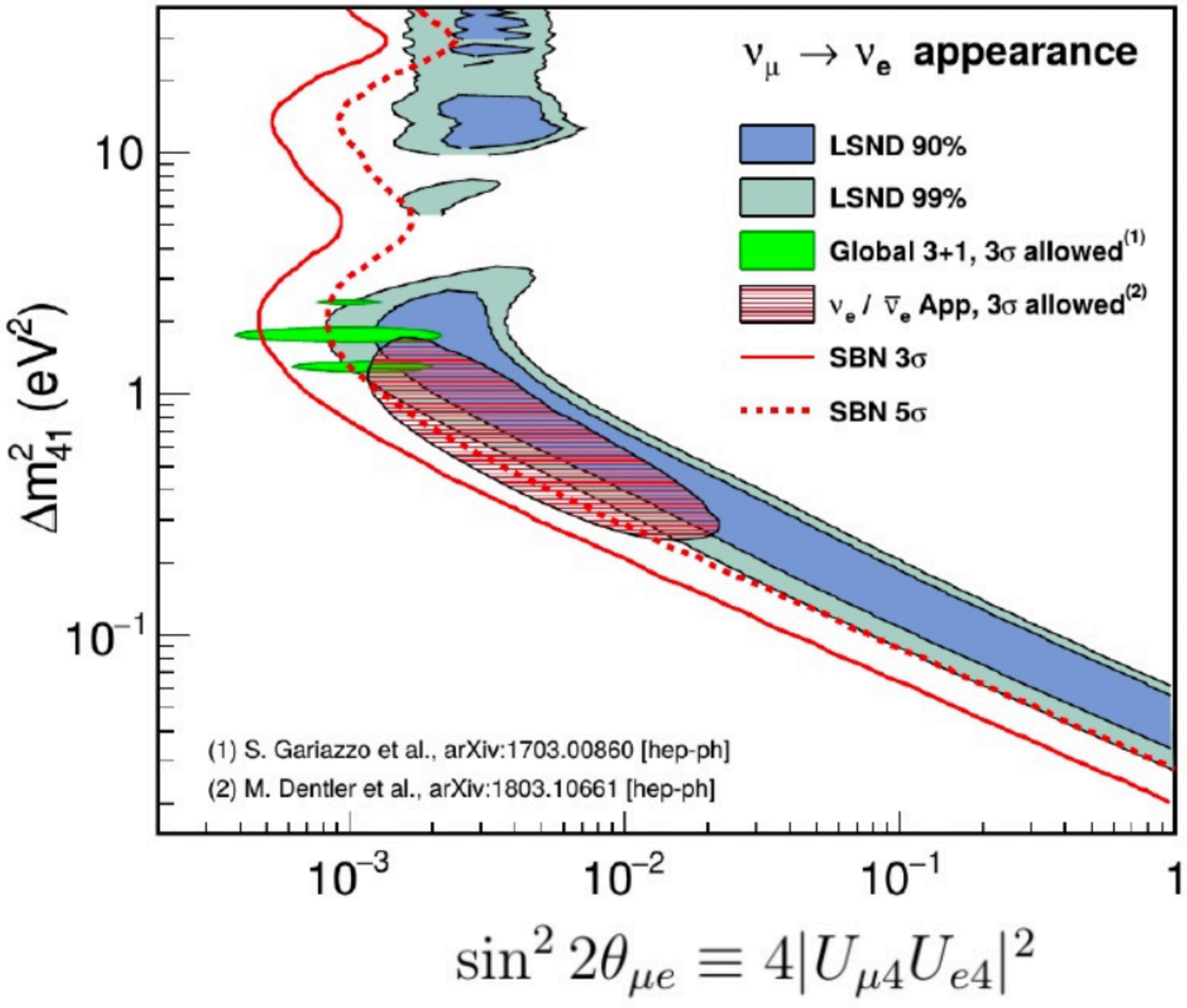




(1) S. Gariazzo et al., arXiv:1703.00860 [hep-ph]
(2) M. Dentler et al., arXiv:1803.10661 [hep-ph]

Looking forward to a final conclusion about this long-standing neutrino anomaly

Summary and conclusions

Summary and Conclusions

- Neutrinos are one of the most interesting particles of the SM
    - They are abundant (many and diverse sources + very broad energy spectrum)
    - They are the only experimental evidence of physics beyond the SM
- Neutrinos do oscillate and this implies they have non-zero mass.
- The 3-flavour oscillation framework is firmly established and characterised (most of the parameters measured)
- The are still many questions that remain unsolved:
    - Do neutrinos and antineutrinos behave in the same way (CP violation?
    - What are the absolute values of the masses?
    - What is the mass ordering?
    - What is the origin of these small masses?
    - Are the neutrinos Majorana particles?
    - Are there more than 3 neutrinos?

Back Up

Matter effects and δ_{CP} in oscillation experiments

- Neutrino propagation in Earth is very important for long-baseline neutrino experiments

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Phi_{31}-aL)}{(\Phi_{31}-aL)^2}\Phi_{31}^2$$

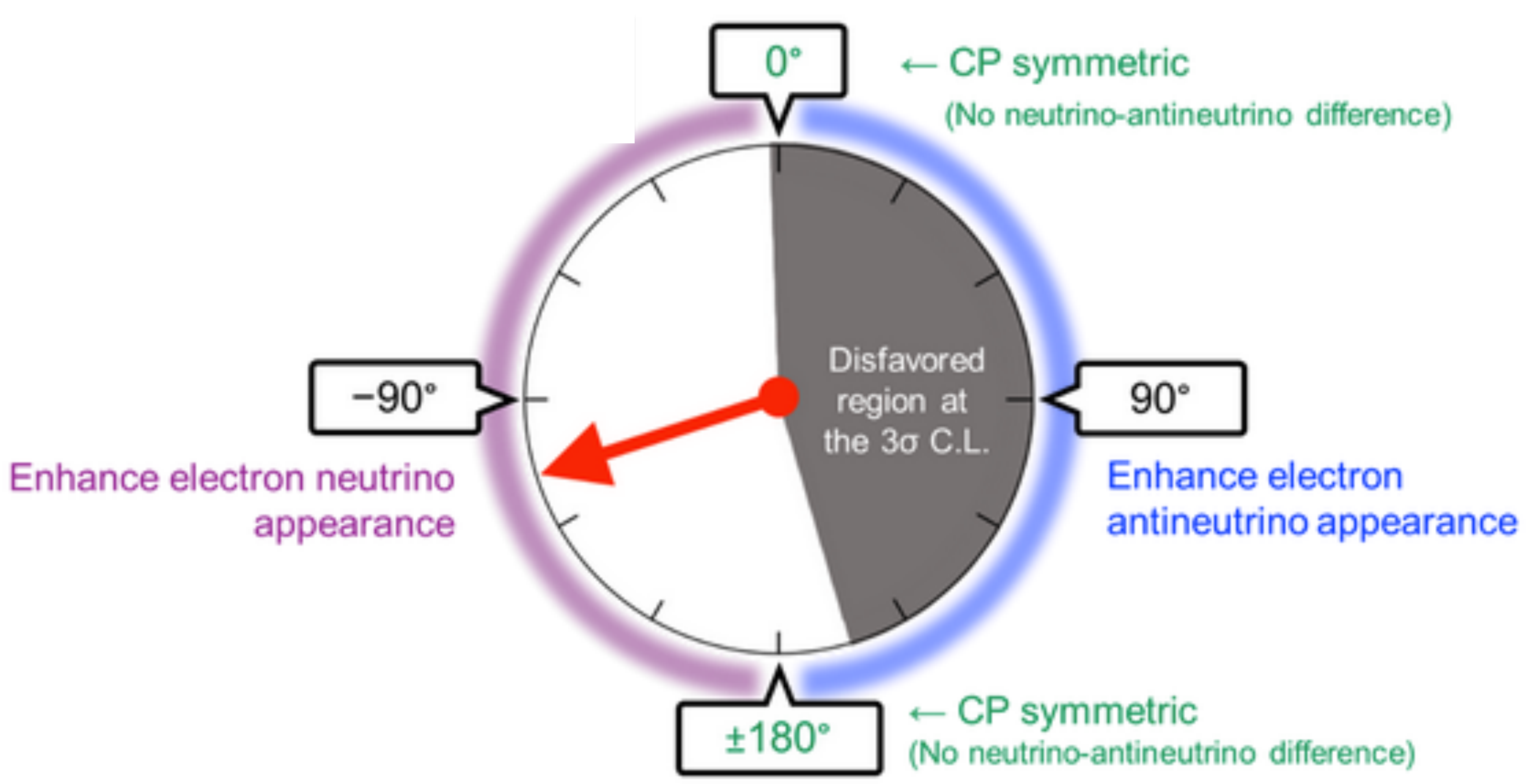
$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Phi_{31}-aL)}{(\Phi_{31}-aL)}\Phi_{31}\frac{\sin(aL)}{(aL)}\Phi_{21}\boxed{\cos(\Phi_{31}\underline{\pm}\,\delta_{\mathrm{CP}})}$$

$$+ \dots$$

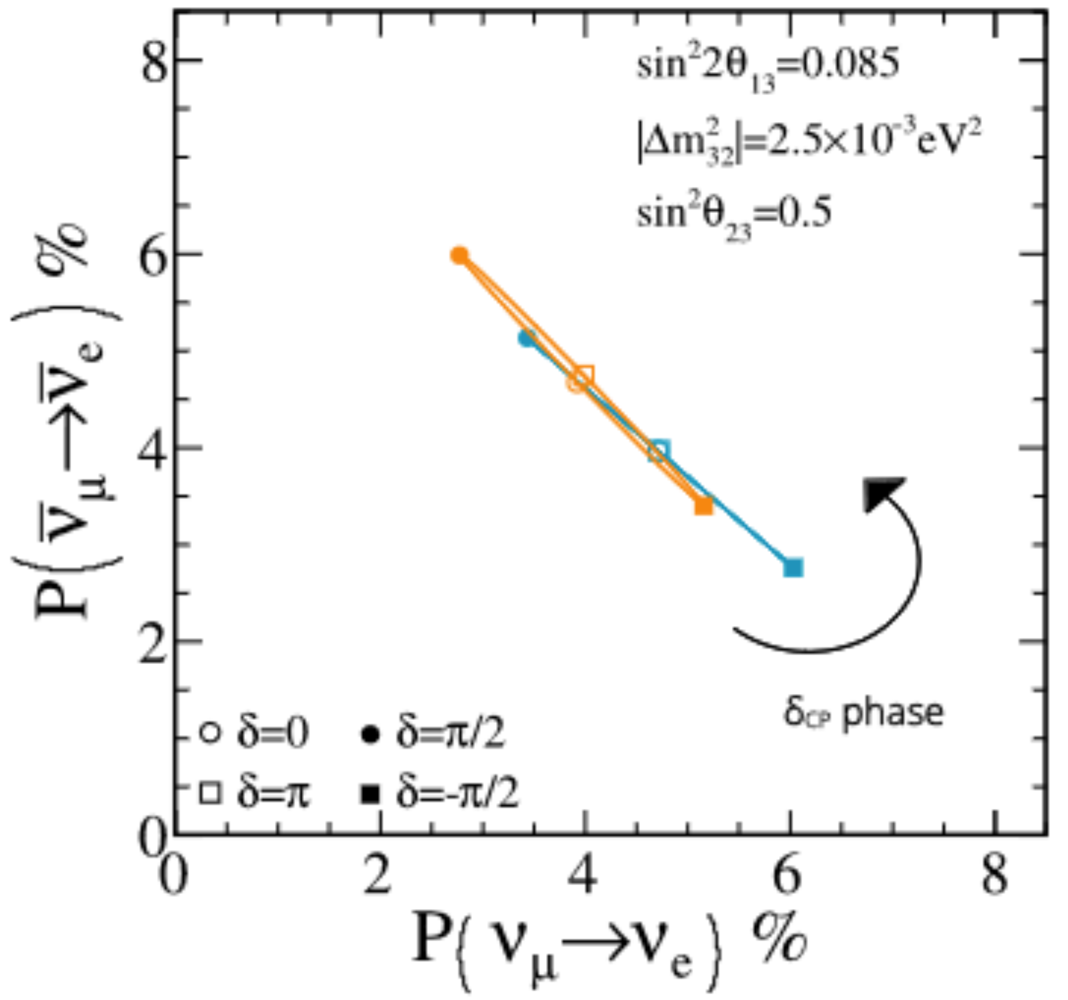
$$\Phi_{ji} = \frac{1.27\Delta m_{ji}^2 L}{E_\nu} \qquad a = \underline{\pm}\frac{G_F N_e}{\sqrt{2}}$$

Sign change for ν_e and $\bar{\nu}_e$

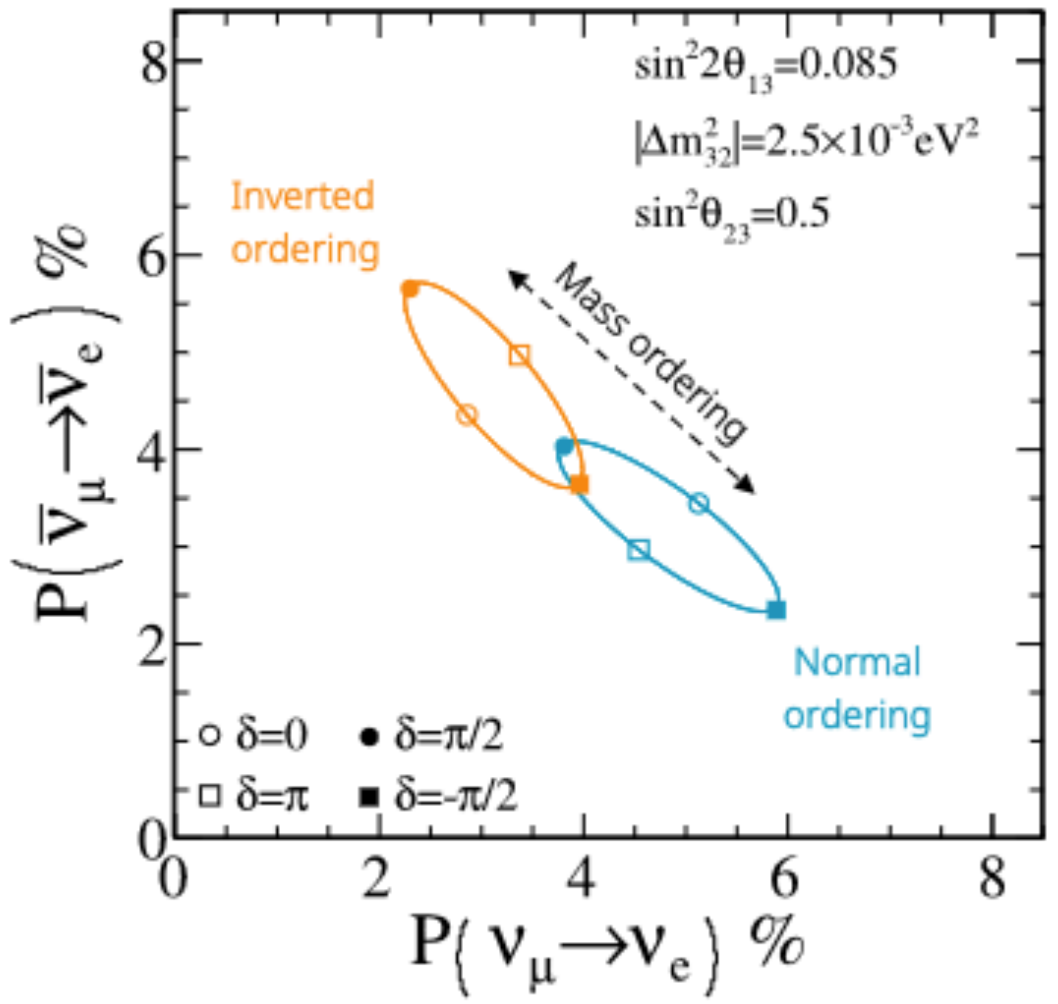
Interplay between mass ordering and CP-phase



T2K: L=295 km, E=0.6 GeV



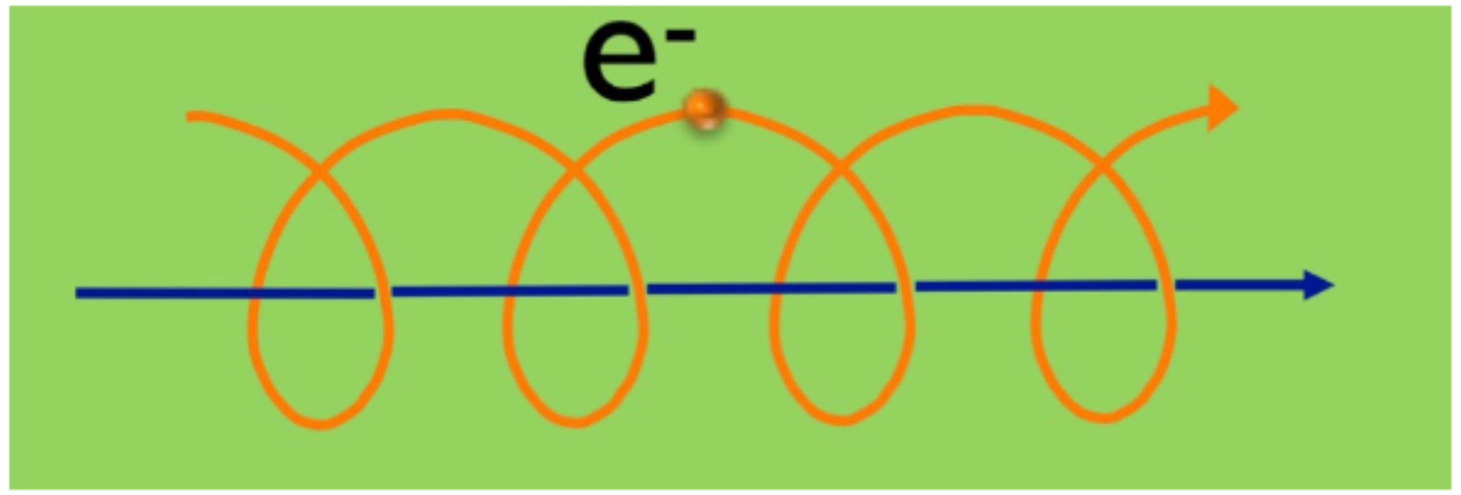
NOvA: L=810 km, E=2.0 GeV

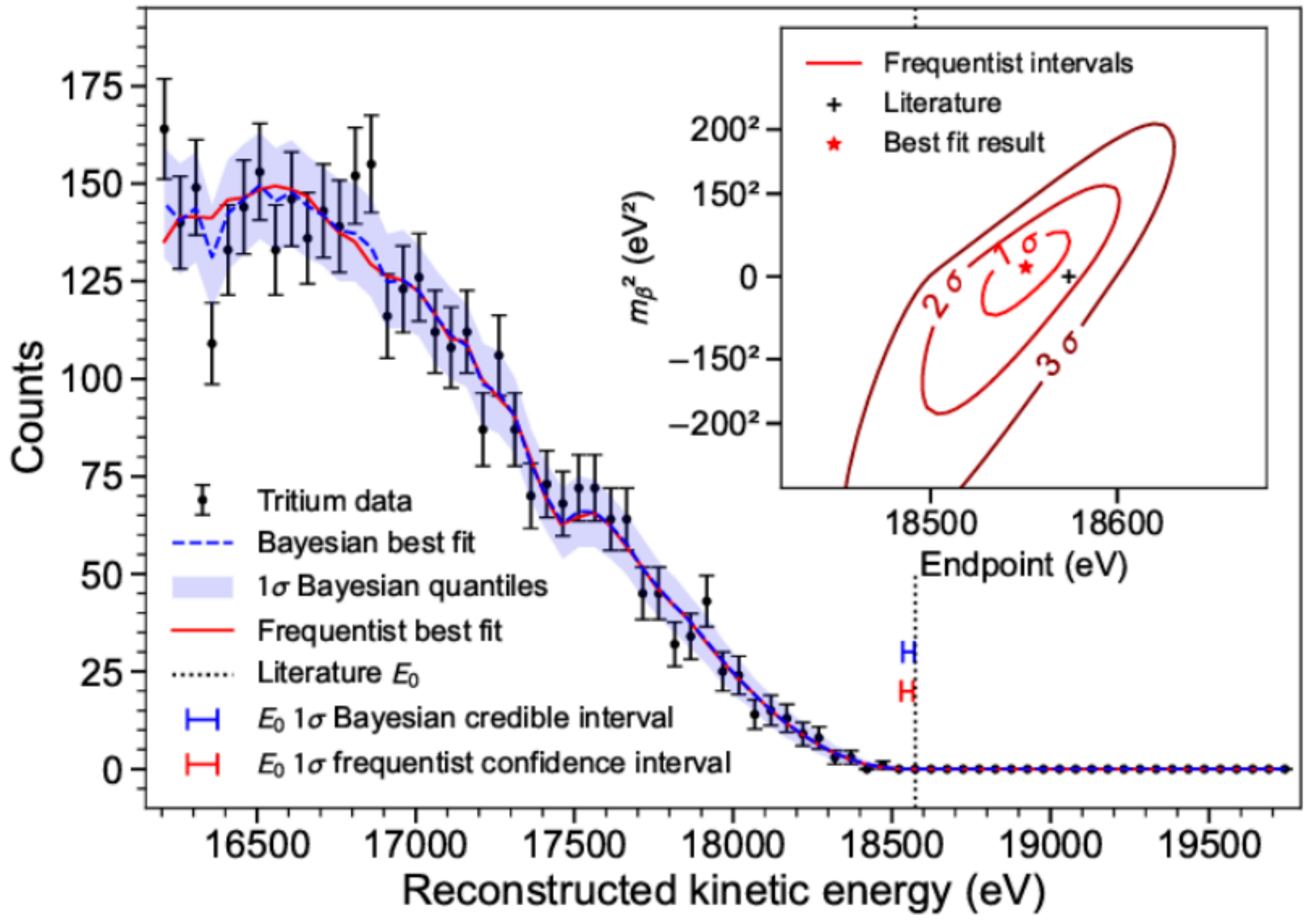


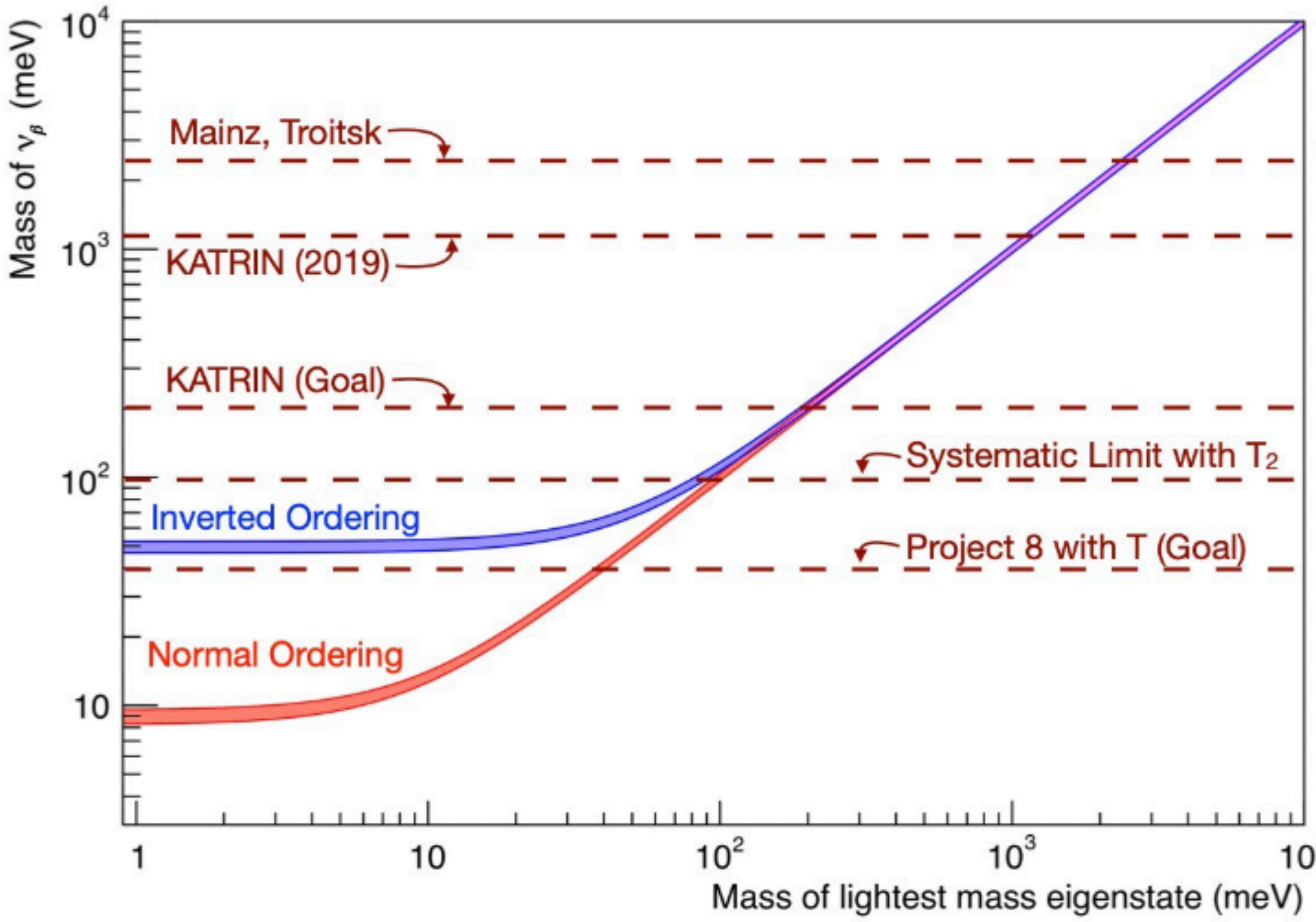
Project 8 experiment

- Beta decay tritium next generation experiment
- Cyclotron Radiation Emission Spectroscopy (CRES), first demonstrated by the collaboration in 2014

  - Tritium gas in an enclosed volume with a magnetic field
  - Decay electrons spiral around field lines
  - The frequency of the emitted cyclotron radiation depends on t relativistic boost (electron energy)







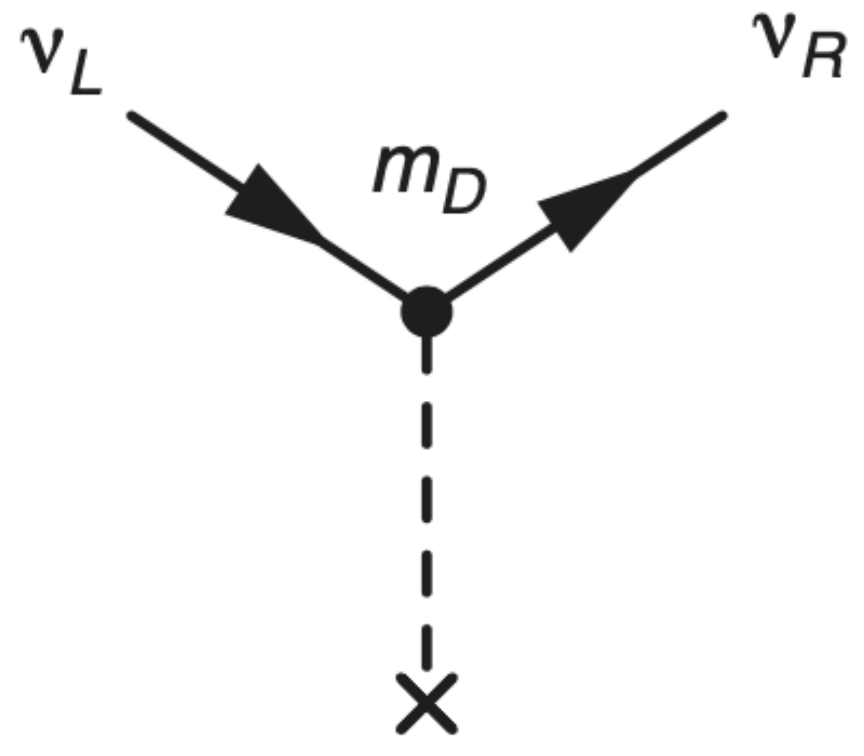
Plot by K. Kazkaz

Neutrino mass mechanism

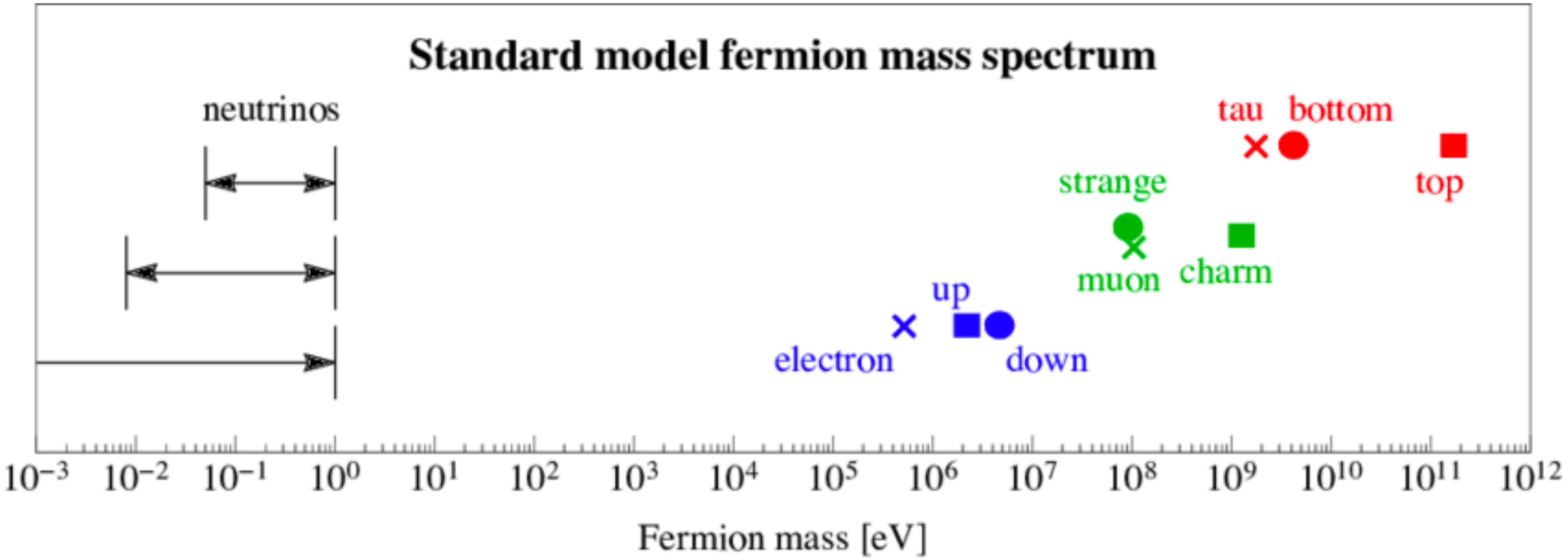
- The right-handed chiral neutrino states ν_R do not participate in any of the interactions of the SM ⇒ **No direct evidence that they exist**

- Neutrino oscillate ⇒ neutrinos do have mass ⇒ there must be a corresponding mass term in the Lagrangian

- In the SM, the gauge invariant Dirac mass term for the neutrino would be: $\mathscr{L}_D = -m_D(\bar{\nu}_R\nu_L + \bar{\nu}_L\nu_R)$. If this is the origin of neutrino masses ⇒ ν_R exist!



Dirac term



- This mass spectrum suggest that another mechanism for generating neutrino mass might be present

Dirac or Majorana neutrinos

- Most general Lagrangian: both types of neutrino masses (Dirac & Majorana)

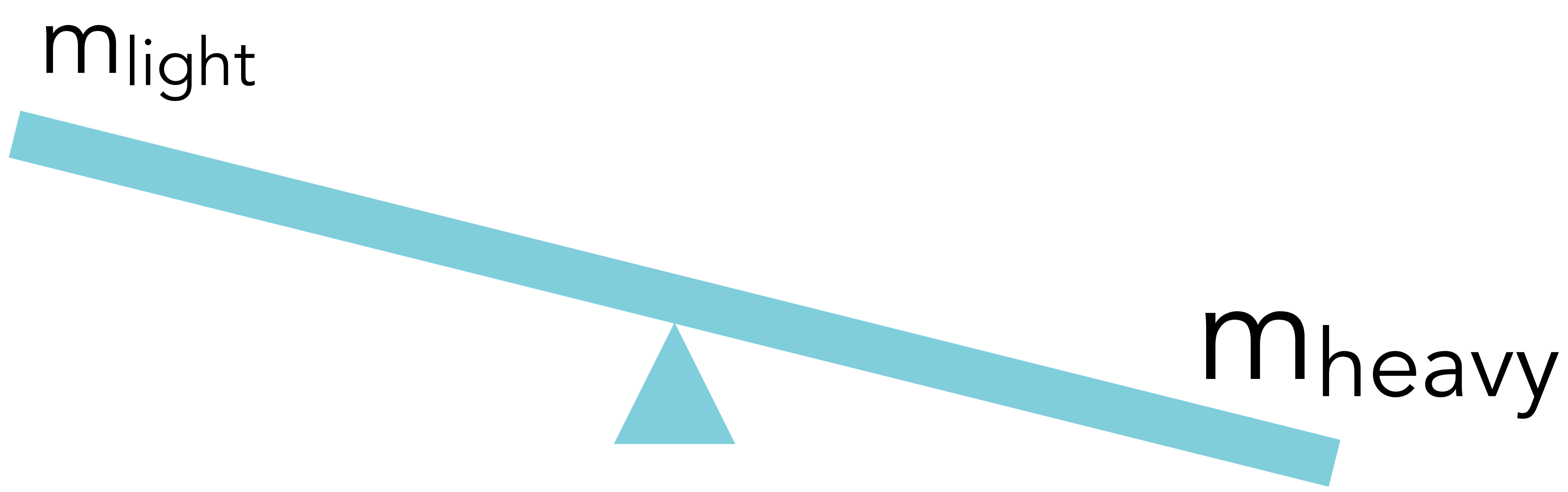
$$\mathscr{L}_{DM} = -\frac{1}{2}[\underbrace{m_D\bar{\nu}_L\nu_R + m_D\bar{\nu}^{\bar{c}}_R\nu^c_L}_{\text{Dirac term}} + \underbrace{M\bar{\nu}^c_R\nu_R}_{\text{Majorana term}}] + h.c.$$

- **Dirac particle**: neutrino acquires mass as the other SM fermions, with Yukawa couplings unusally small
- **Majorana particle**: neutrinos are their own anti-particle and their mass is explained via the see-saw mechanism

- **Neutrino Masses**: If we take M >> m_D —> we obtain a light and heavy neutrino states with masses:

$$m_{light} \approx \frac{m_D^2}{M} \qquad m_{heavy} \approx M$$

see-saw mechanism



- This mechanism provides an interesting hypothesis for the smallness of neutrino masses

The effective Majorana mass

- The effective Majorana neutrino mass parameter: embeds all the dependance on neutrino quantities

$$|m_{\beta\beta}| = |m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{2\phi_1} + m_3 U_{e3}^2 e^{2i(\phi_2 - \delta)}|$$

- A mixture of m_1, m_2, m_3 with U_{ei}

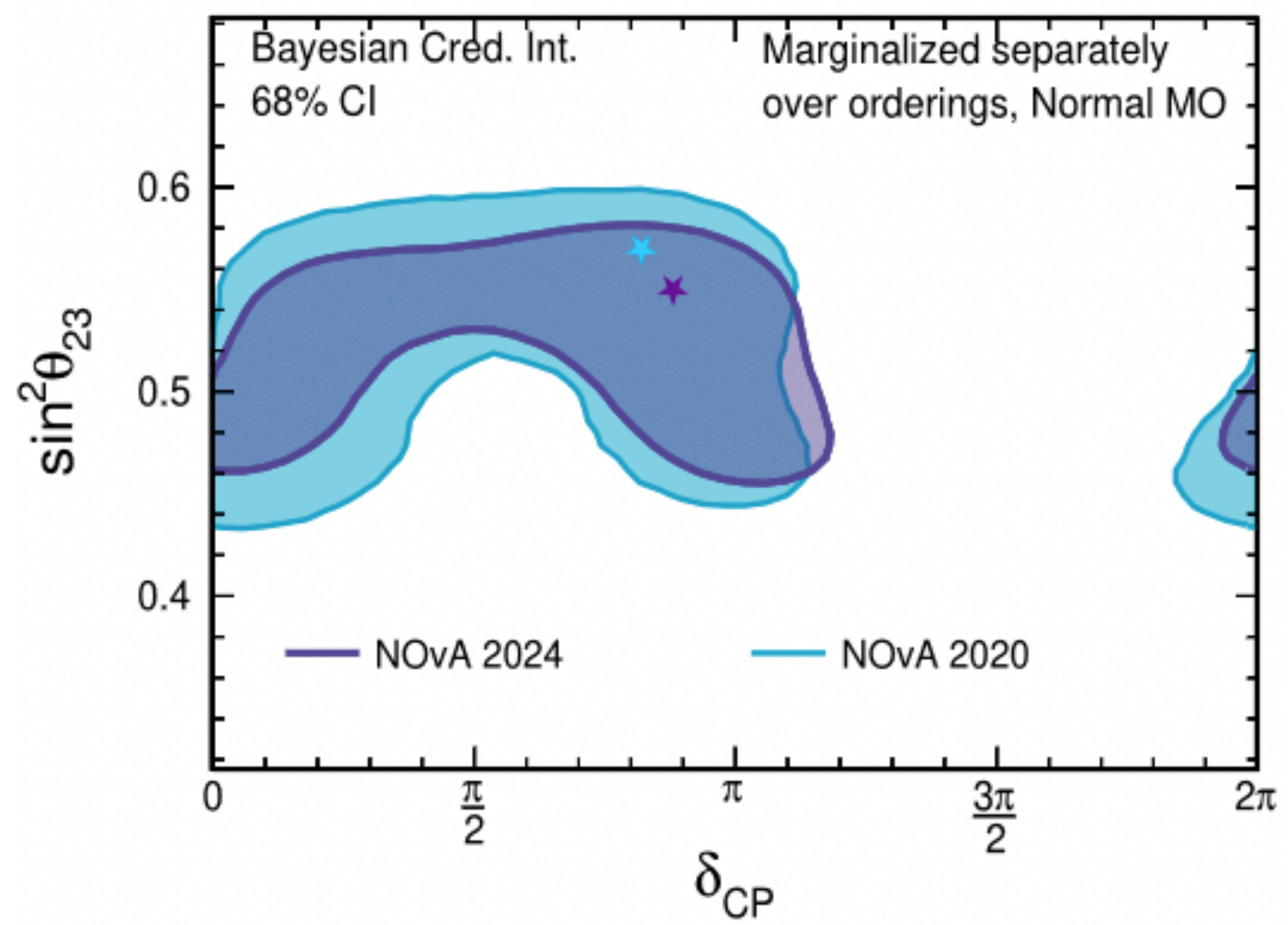
$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

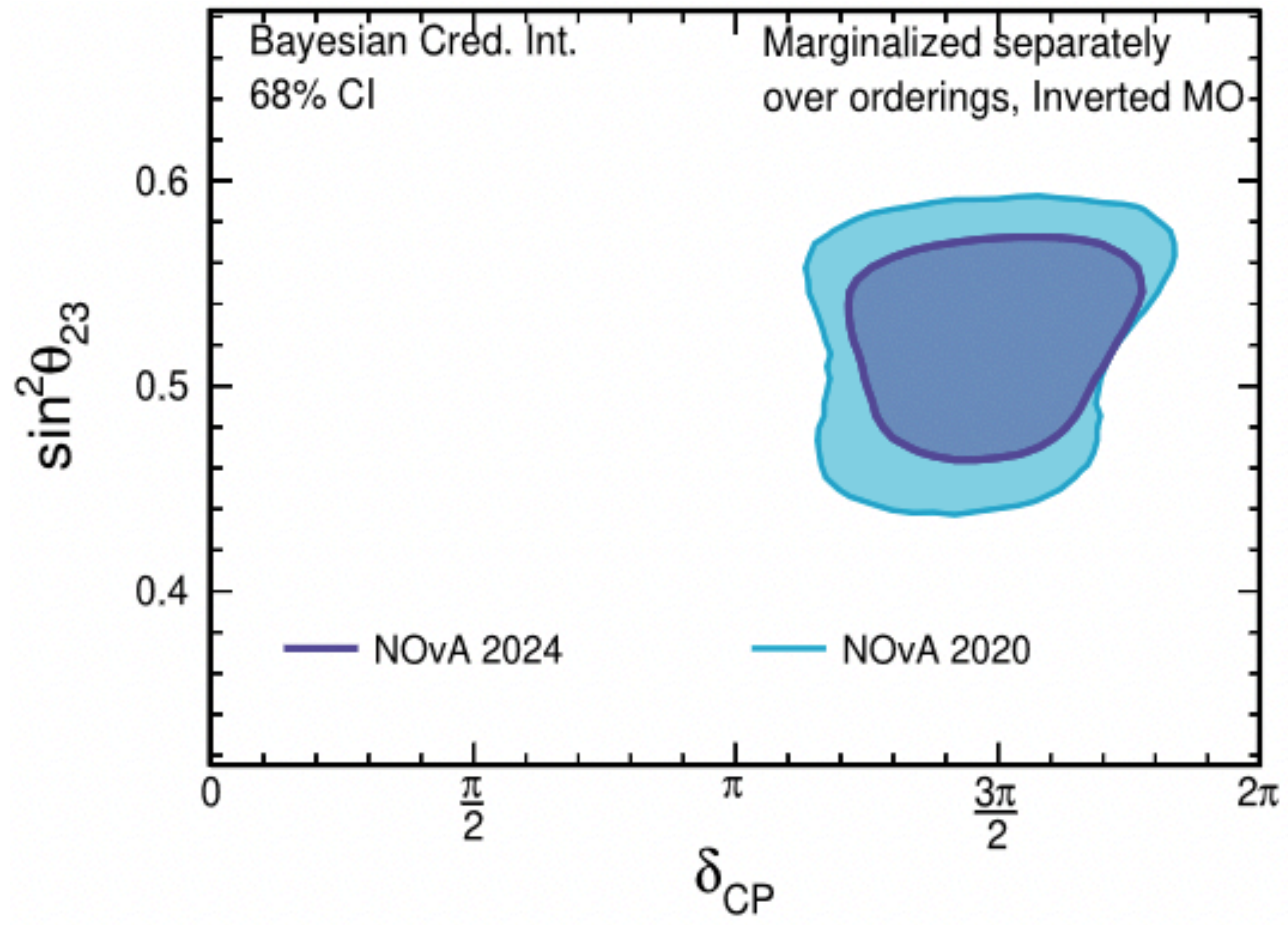
Majorana phases

- If neutrinos are Majorana particles, left- and right-handed fields are correlated. Hence only a common phase of three left-handed fields can be redefined. Two phases are allowed (α_1 & α_2)

- **Note**: for Dirac particles, no phases are needed

Current knowledge (NOvA & T2K)





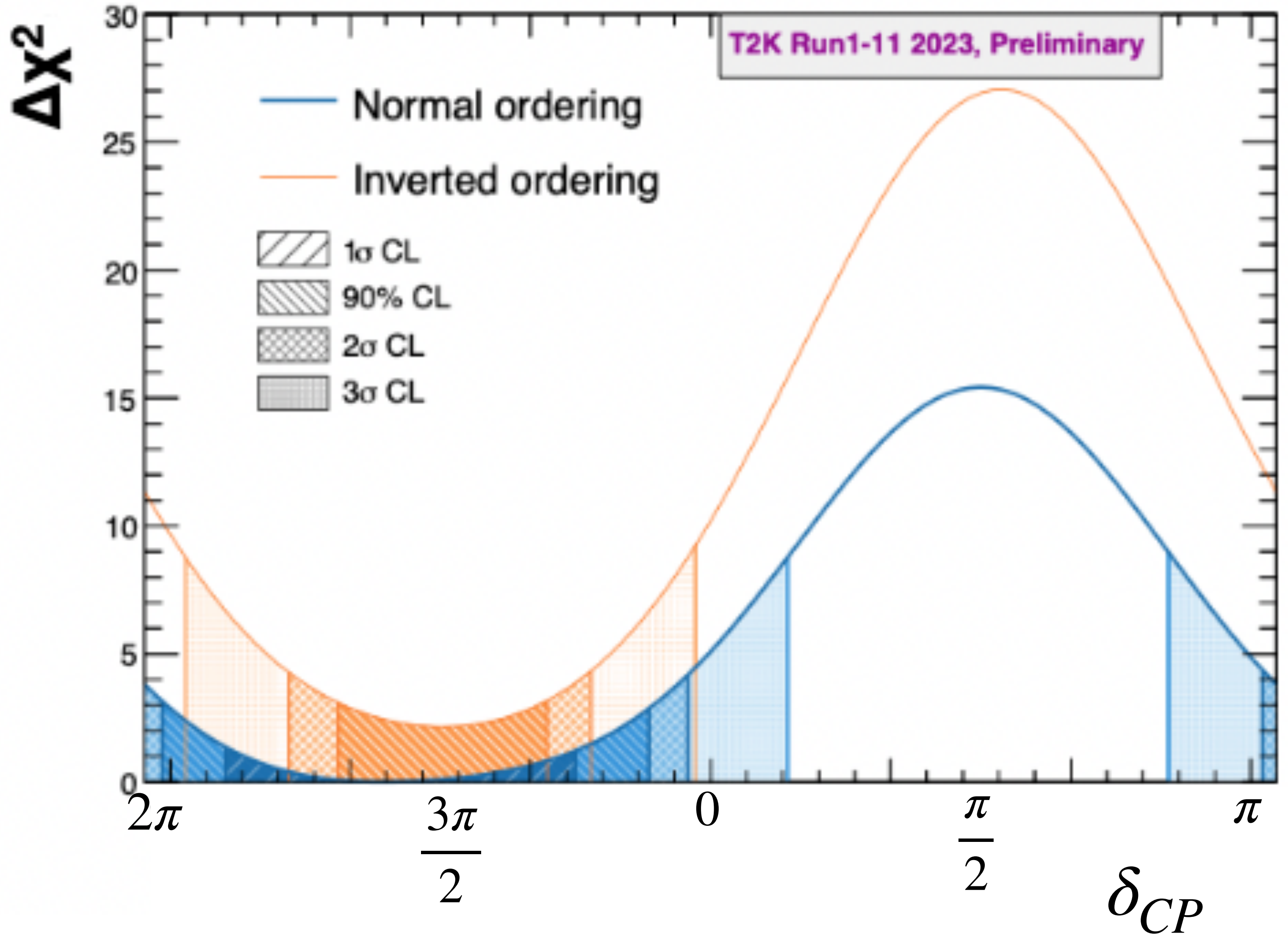
NOvA Preliminary, Neutrino2024

Preference for NO with $\pi/2 < \delta_{CP} < \pi$

- different trends NO/IO

There are hints for CP violation ($\delta_{CP} \neq 0$) from both NOvA and T2K, although with some tension for NO results

T2K Preliminary, Neutrino2024

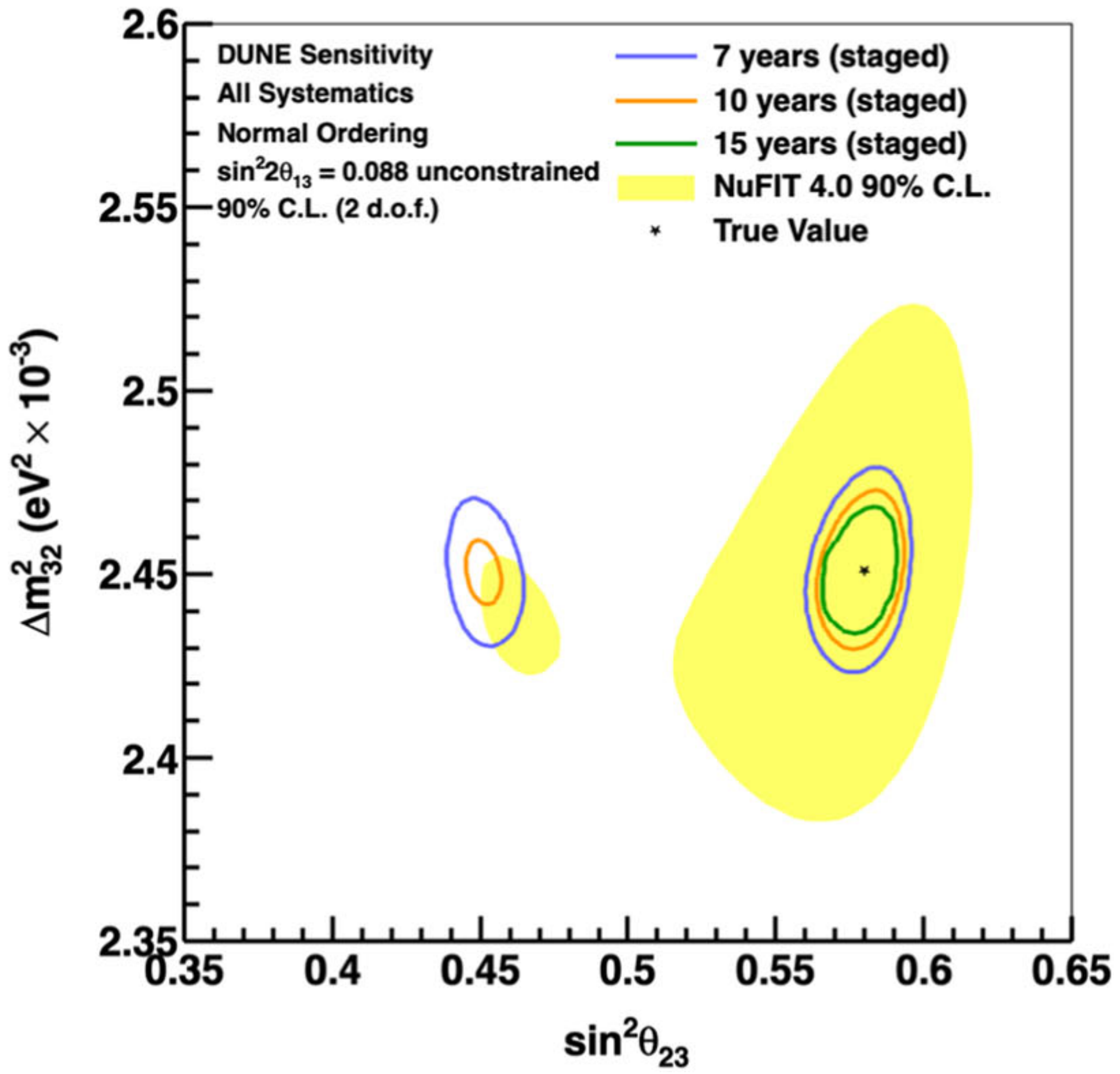


Preference for NO with δ_{CP}~3π/2, but CP conserving values are within the 2σ interval

- similar trend for NO and IO

Additional Physics Program in DUNE

- Precise measurement of oscillation parameters with $P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu)$
- Proton decay (through Kaon identification) $p \rightarrow K^+ \bar{\nu}$
- Detection of neutrinos from core-colapse supernovae (~10 MeV)
- Detection of solar neutrinos (~10 MeV)



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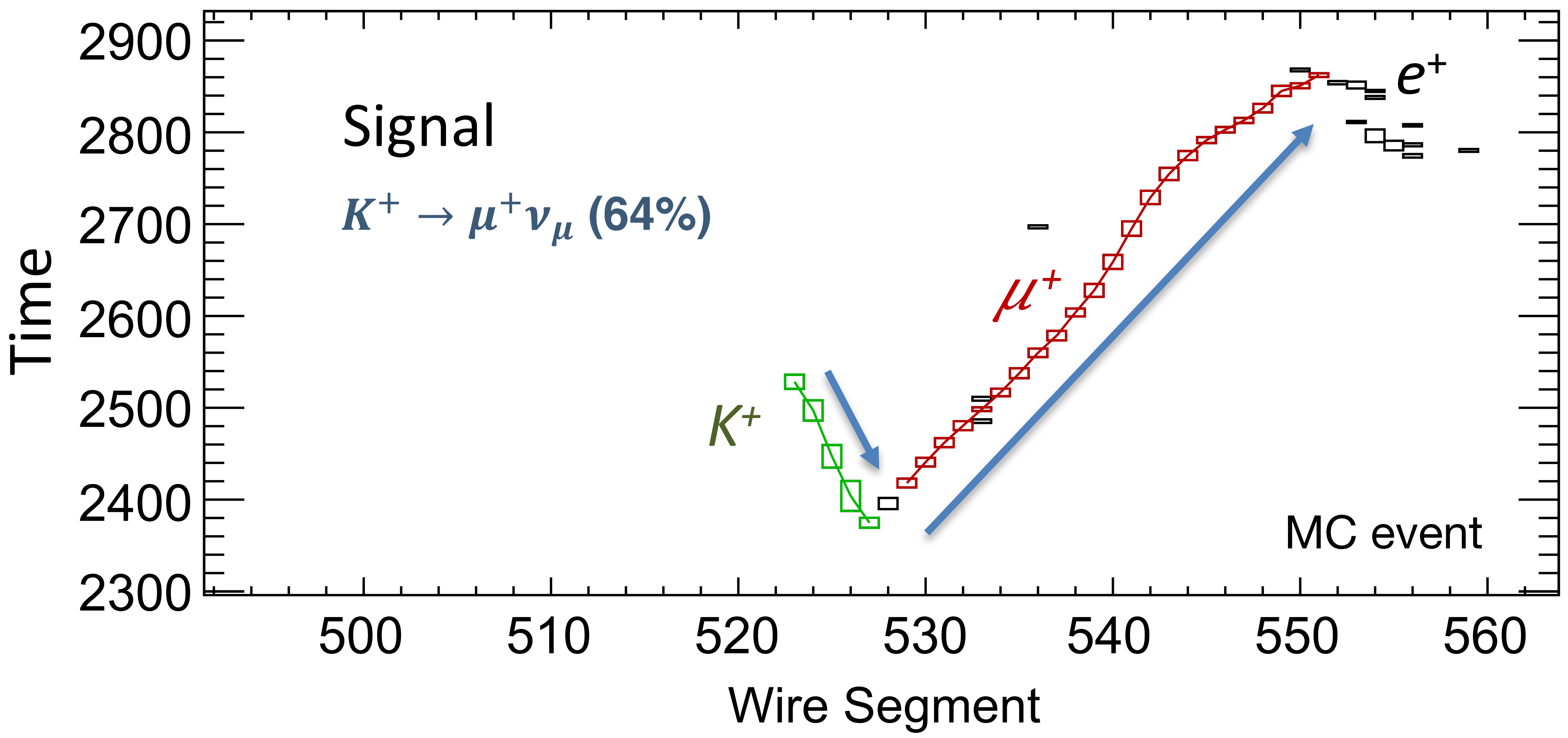
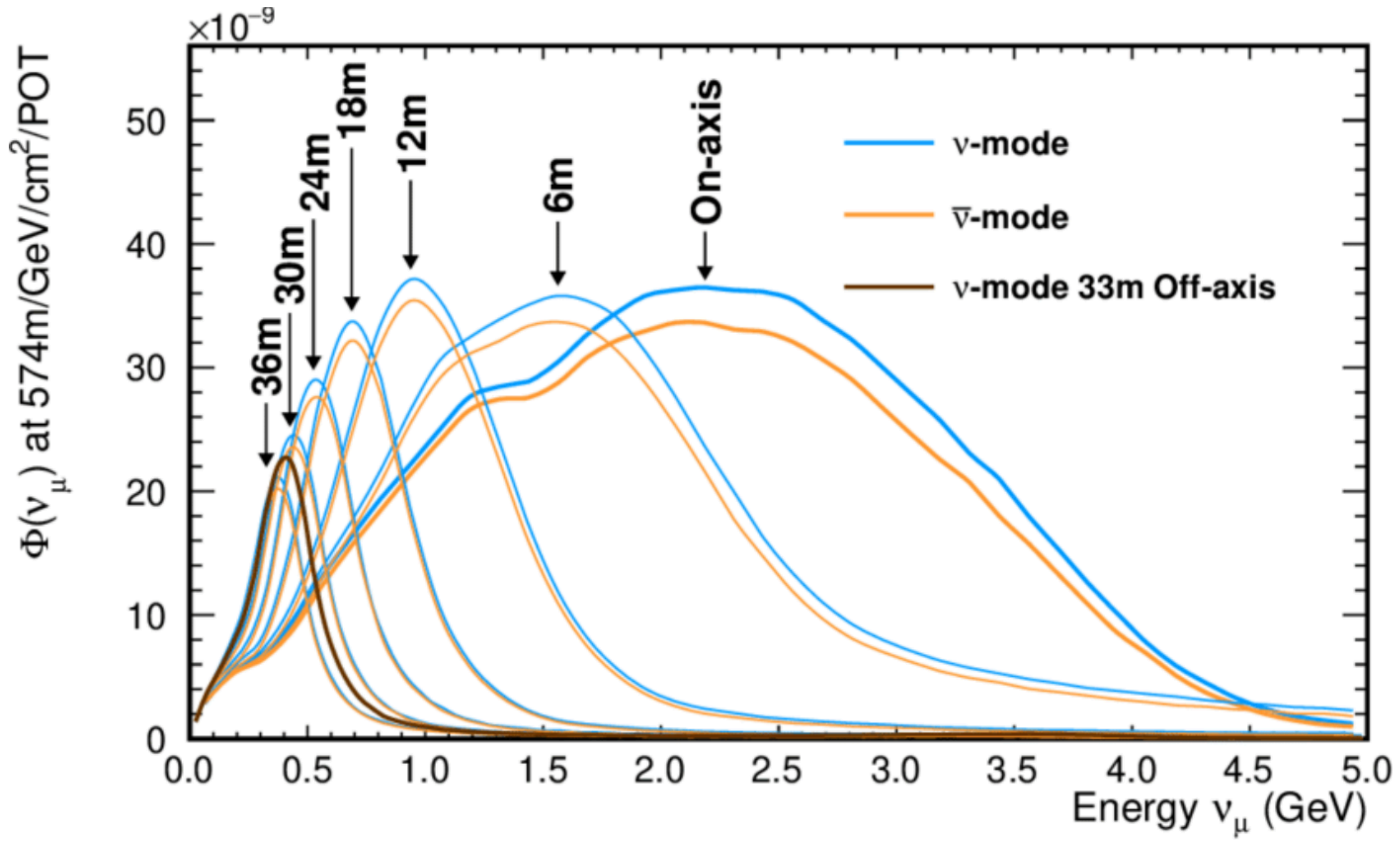
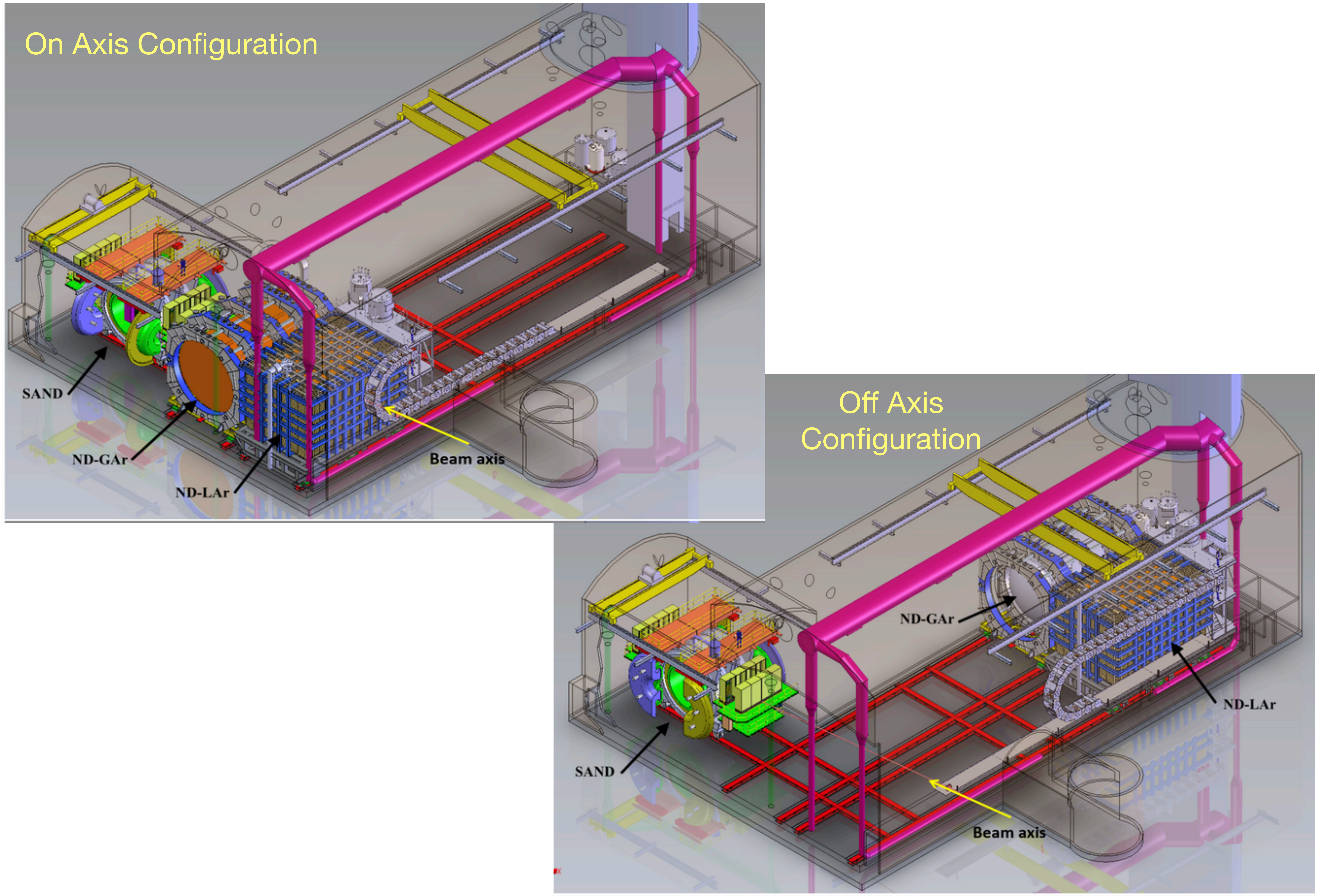


DUNE: Near Detector (ND)

- **Main Goal**: constrain uncertainties for oscillation measurements



The movement system allows for different neutrino energy spectra



Neutrino Masses

- The masses of the physical neutrino states will be the eigenvalues of the mass matrix in $\mathscr{L}_{DM}$
- In this model the masses of the neutrinos will be $m_{\pm} = \dfrac{M \pm M\sqrt{1 + 4m_D^2/M^2}}{2}$
- If we take $M \gg m_D \Rightarrow$ we obtain a light and heavy neutrino state as solutions with masses: $m_{light} \approx \dfrac{m_D^2}{M}$ and $m_{heavy} \approx M$ (Seesaw mechanism)
- The physical neutrino states, which are obtained from the eigenvalues of the mass matrix, are (in our case where $M \gg m_D$):

$$\nu \approx (\nu_L + \nu_L^c) \; - \; \frac{m_D}{M}(\nu_R + \nu_R^c)$$ (same coupling as the SM neutrinos)

$$N \approx (\nu_R + \nu_R^c) \; + \; \frac{m_D}{M}(\nu_L + \nu_L^c)$$ (almost RH ⇒ not participate in the weak currents)

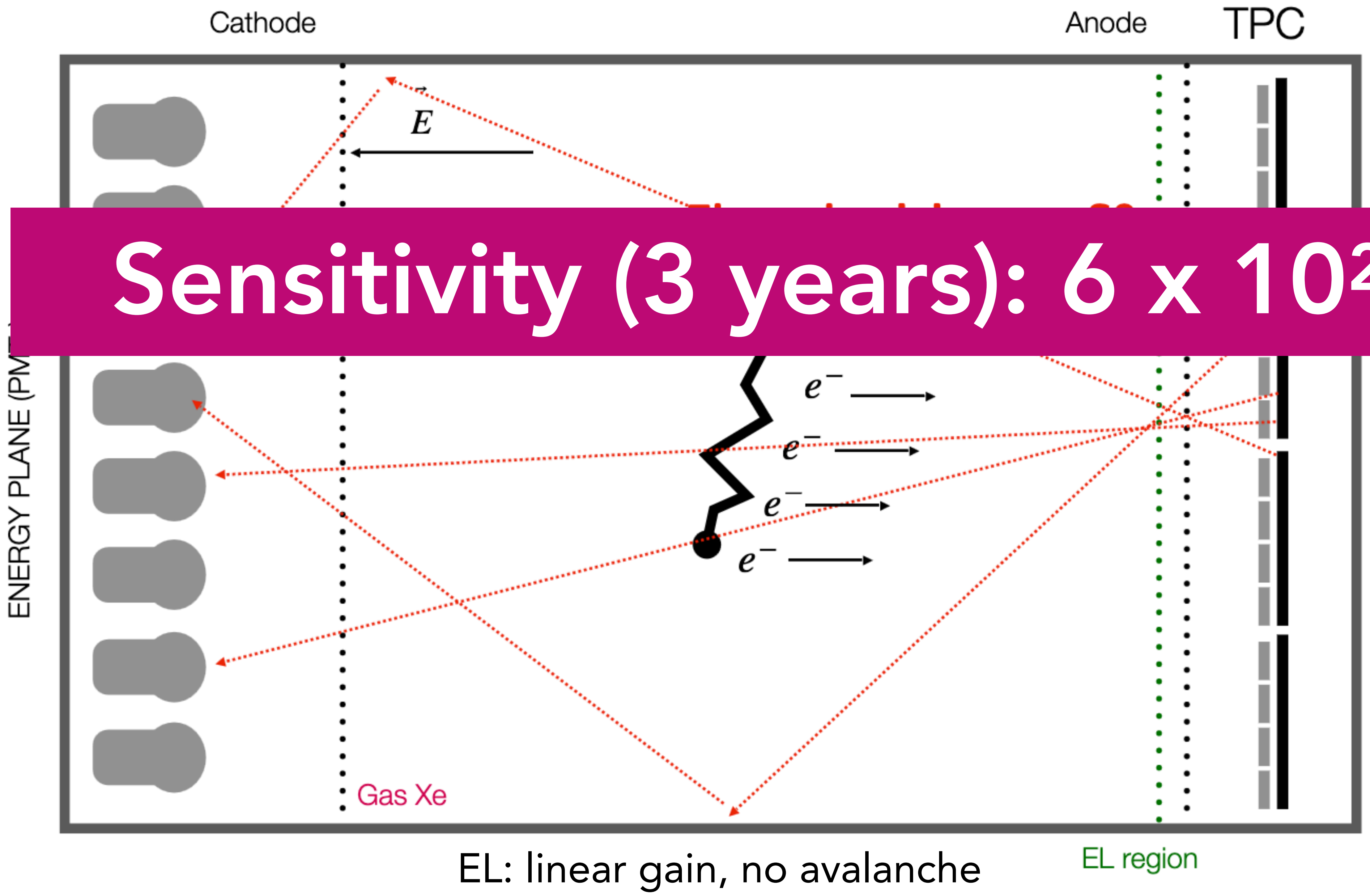
- The seesaw mechanism provides an interesting hypothesis for the smallness of neutrino masses

The NEXT-100 experiment at LSC (Spain)

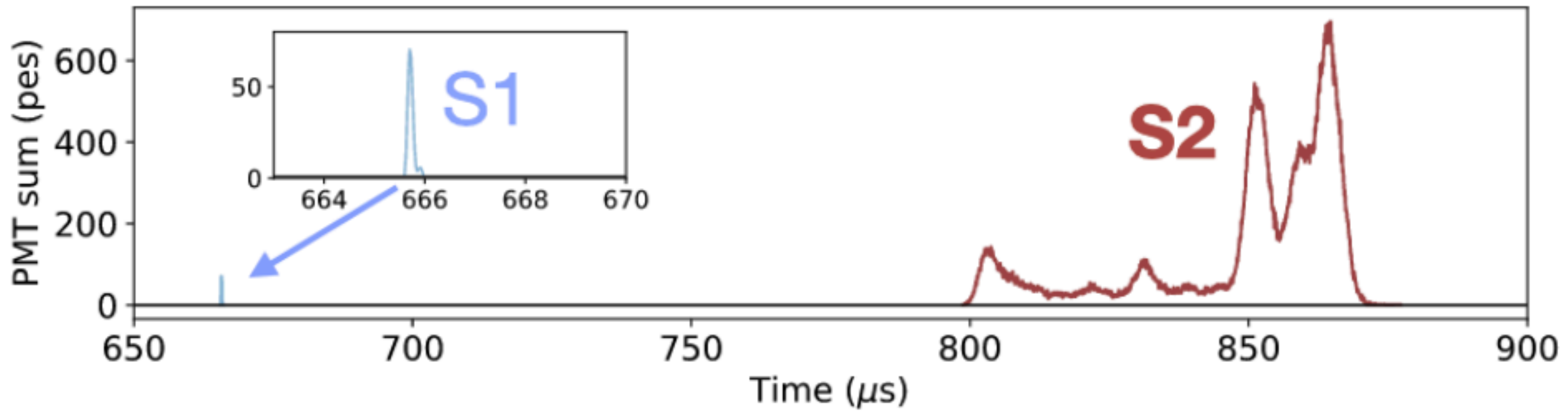
Light + Charge

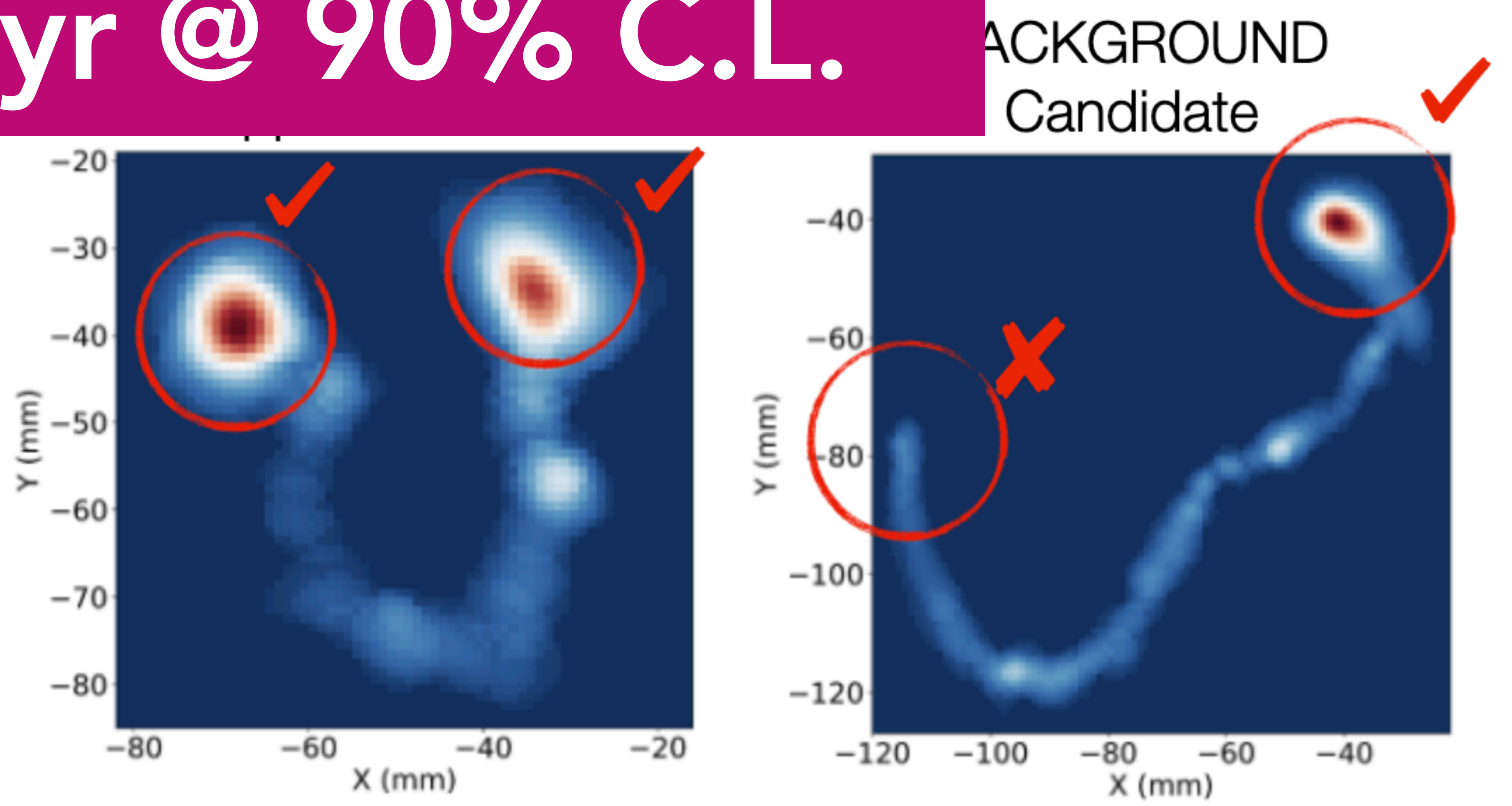
High pressure (15 bar) gas xenon TPC

- Energy resolution at Q-value ~1 % FWHM
- Total mass ~80 kg (enriched ^{136}Xe)



EL: linear gain, no avalanche





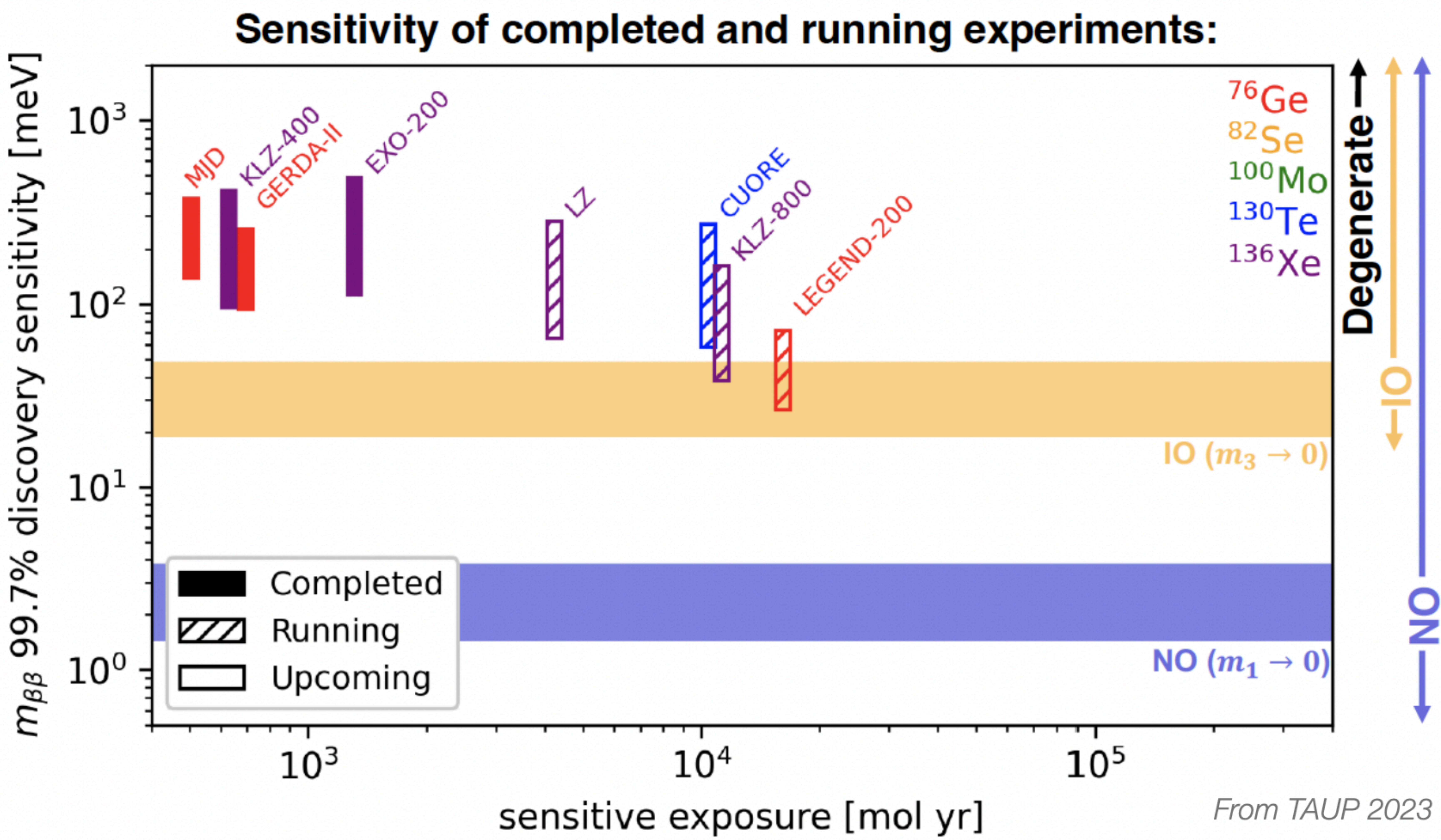
Sensitivity (3 years): 6 x 10^{25} yr @ 90% C.L.

fully built & under commissioning

Although there are ionization and scintillation, the sensors only see light

LIDINE 2023 & Neutrino 2024

Comparison of the different experiments



From TAUP 2023 D. Moore

^{163}Ho experiments

Other experiments with ^{163}Ho using low temperature calorimeters

- Holmes
- ECHo