EXPLORING THE "ν" WORLD:

WHAT WE KNOW ABOUT NEUTRINOS AND WHAT IS STILL TO BE LEARNED

Neutrino Geoscience 2025

27 October 2025

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Institute of Particle Physics & Queen's University

Neutrinos: Numerous & Ubiquitous

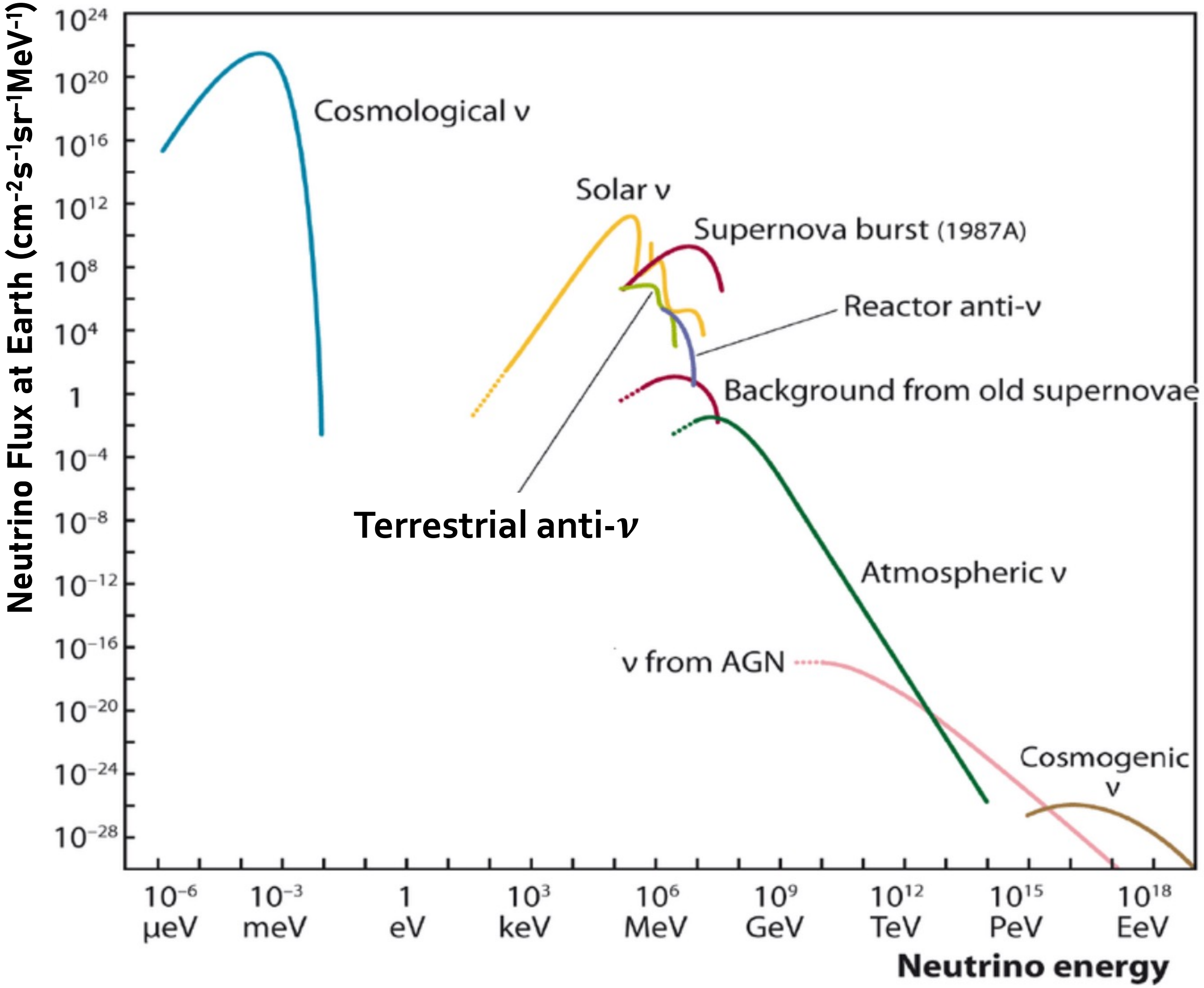
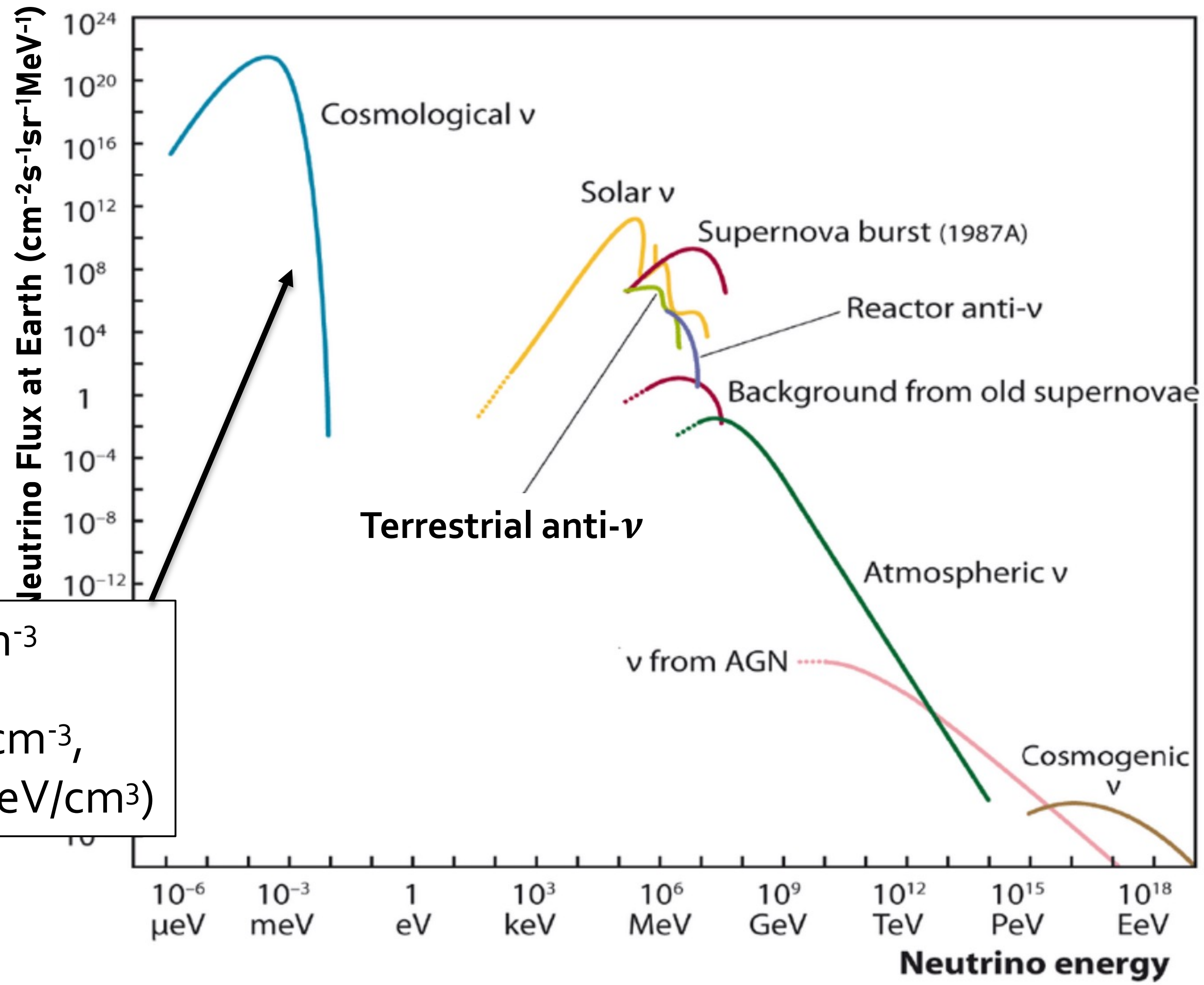


Image: Prog. Part. Nucl. Phys., 67:651–704 (2012)

Neutrinos: Numerous & Ubiquitous



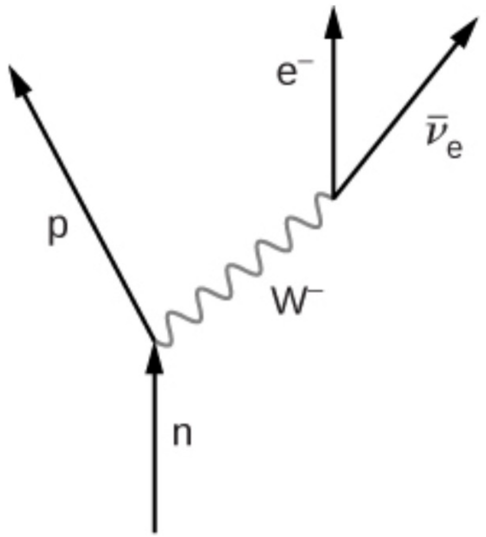
$n_{C\nu B}$ ~110 cm^{-3}

c.f. n_{CMB} ~410 cm^{-3},
(Dark Matter ~0.3 GeV/cm^3)

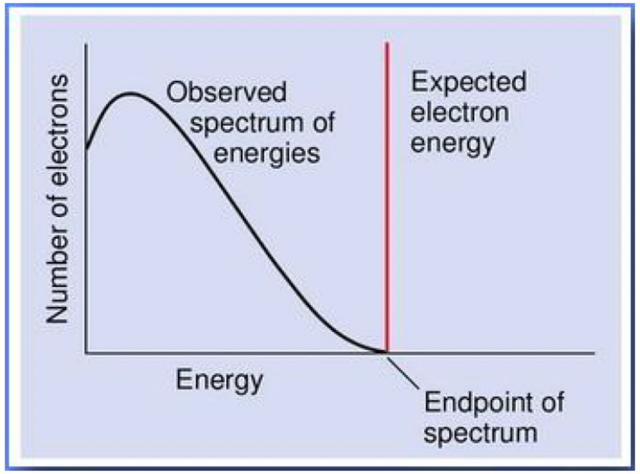
Image: Prog. Part. Nucl. Phys., 67:651–704 (2012)

Discovery of Neutrinos

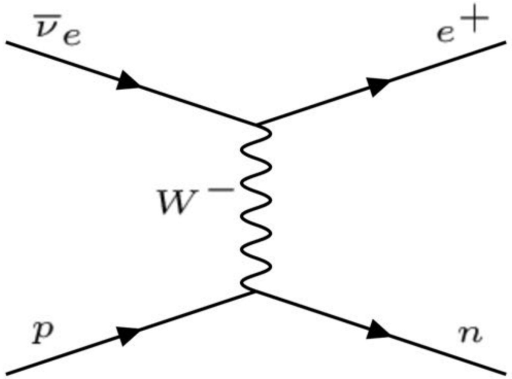
- Existance of neutrinos was postulated by Pauli in 1930 in a "desperate attempt" to preserve energy conservation in the face of the continuous beta decay spectrum
- Initially thought undetectable, but reactor antineutrinos were detected in 1956 (Reines & Cowan)



Beta Decay



Kinetic energy of electrons from β-decay



"Inverse Beta Decay"

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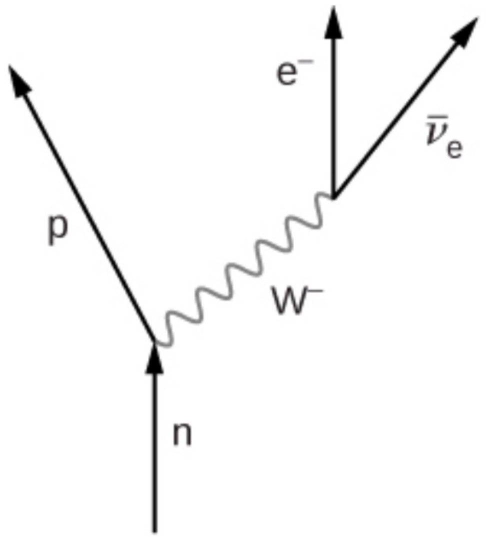
These are the same channels as the production and detection of geo-neutrinos



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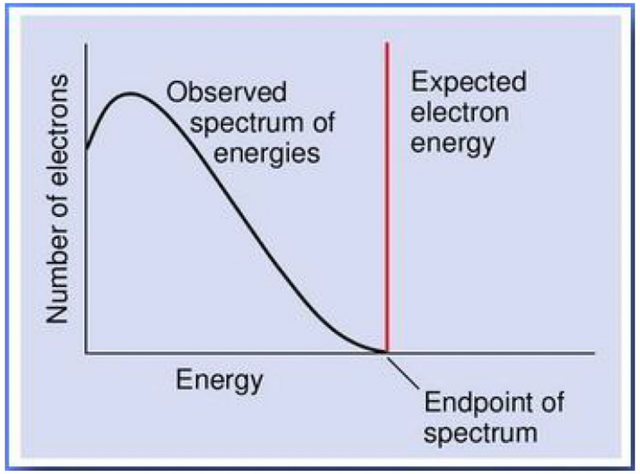

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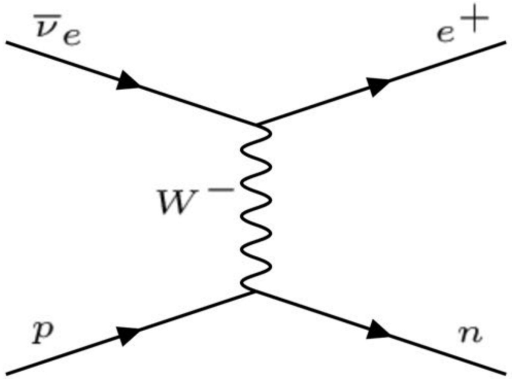


"Inverse Beta Decay"

What are neutrinos?

- Neutral fundamental fermions
- Interact only through weak interaction & gravity
  - Tiny interaction cross section: $10^{-45} cm^2$
- Three neutrino "flavours"
  - Defined by interactions with charged leptons

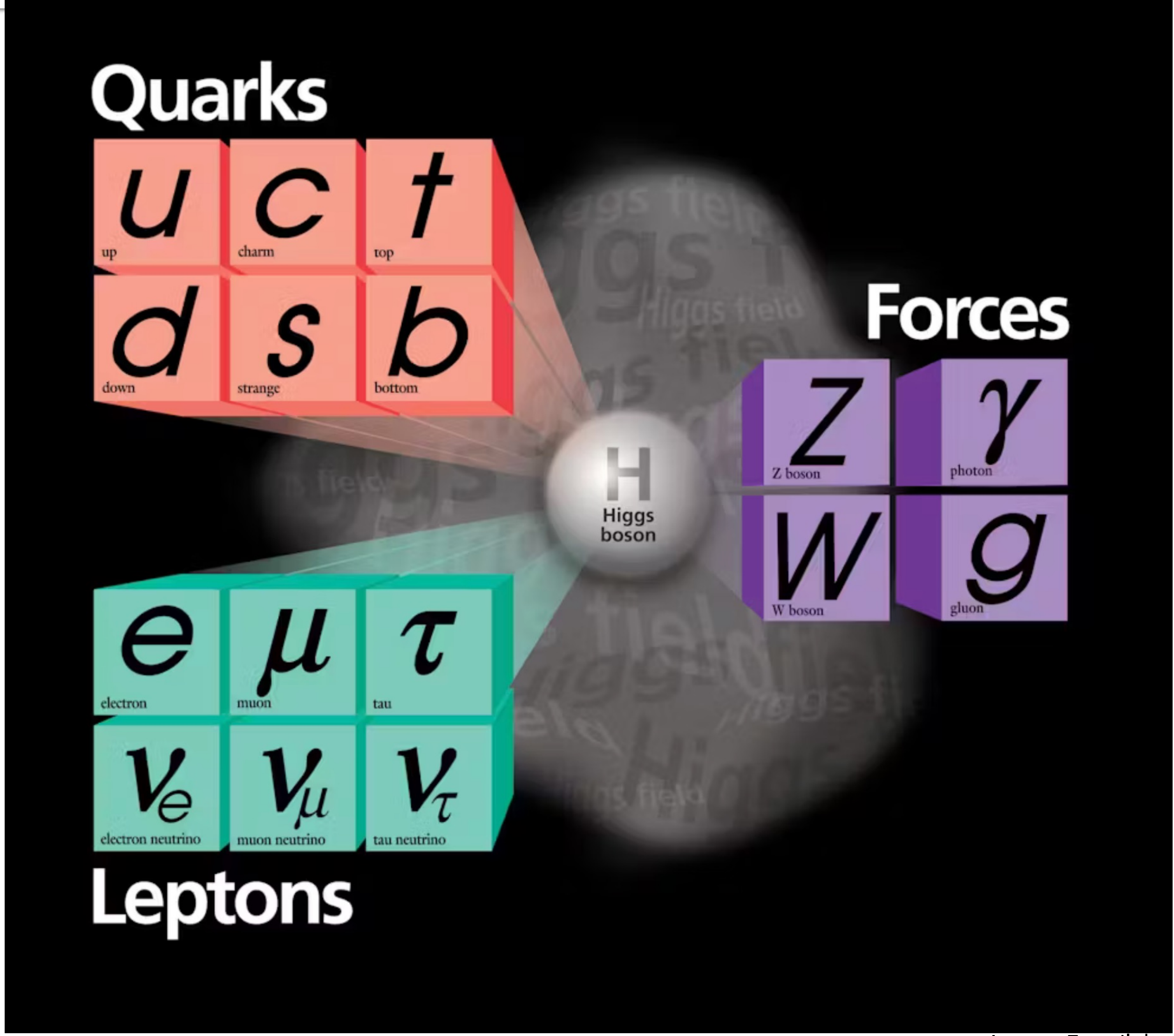
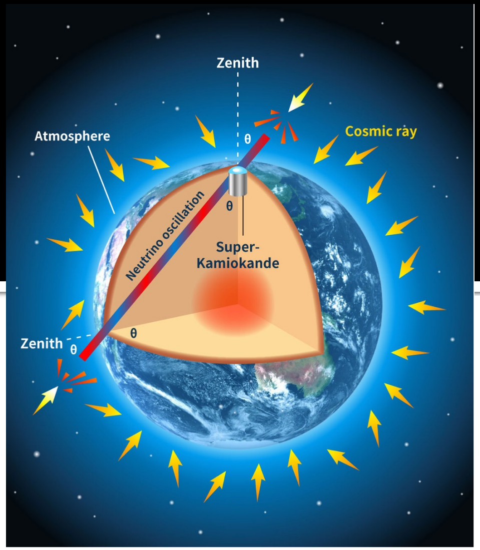


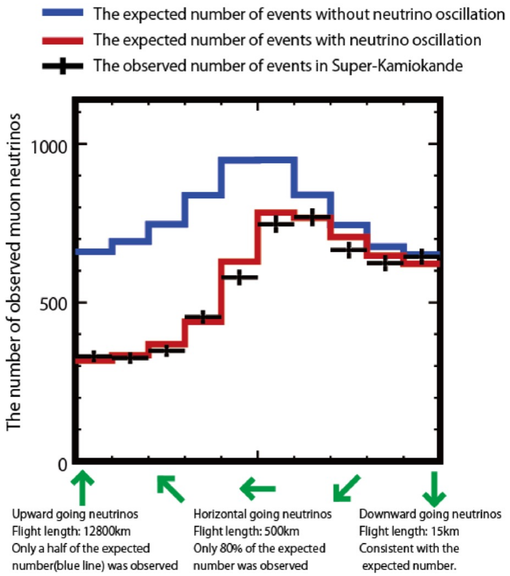
Image: Fermilab

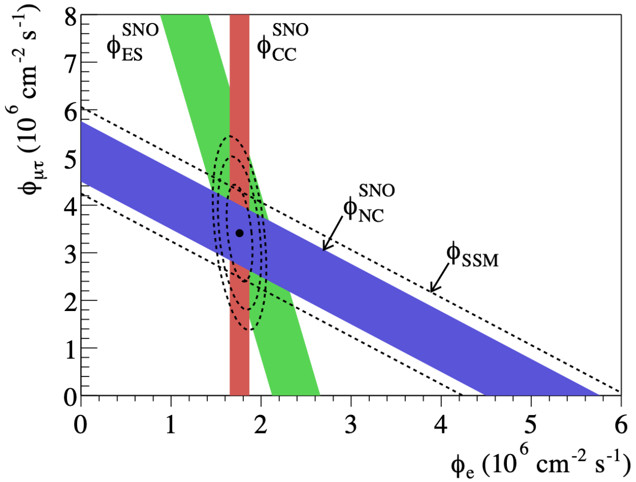
Neutrino Flavour Change

- Neutrinos were originally assumed massless
- In 1998 SuperKamiokande (atmospheric neutrinos) and later SNO (solar neutrinos) showed that neutrinos change their flavour as they propagate
- Flavour change proves that neutrinos have mass



https://www-sk.icrr.u-tokyo.ac.jp

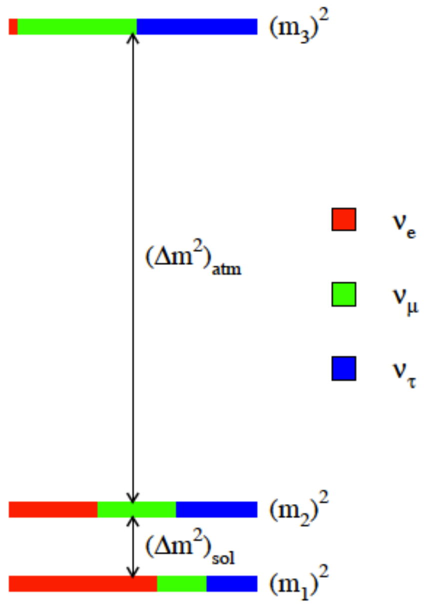




Phys. Rev. Lett. volume 89, No. 1, 011301 (2002)

Neutrino Oscillations

- Neutrino flavour and mass eigenstates "misaligned"
- Related by the PMNS matrix
  - Unitary mapping with 3 mixing angles (θ_{12}, θ_{13}, θ_{23}), perhaps two Majorana phases (α_1, α_2), and one CP violating phase (δ)



hep-ph/0411274

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$-s_{23}$ = $-\sin(\theta_{23})$

c_{13} = $\cos(\theta_{13})$

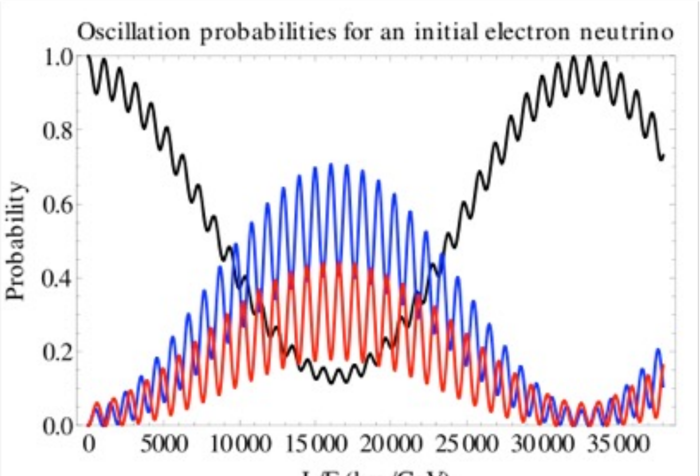
wikipedia.org

Neutrino Oscillations

- Producing a neutrino in a flavour eigenstate produces a superposition of mass eigenstates
- Phase differences acquired in mass eigenstate propagation change apparent flavour content:

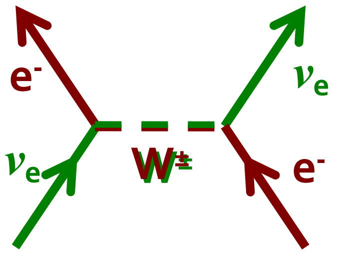
$$P_{ee} = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}}{4\overline{p}}L\right) - \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}}{4\overline{p}}L\right) - \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32}}{4\overline{p}}L\right)$$

Symmetry Magazine



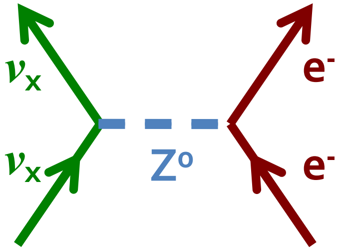
wikipedia.org

The Matter of Matter



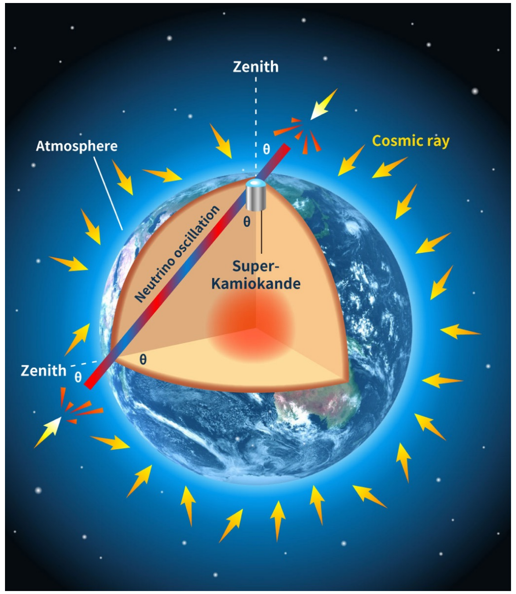
- When neutrinos propagate in matter, charged current interactions add an additional term to ν_e flavour in Hamiltonian mass matrix:

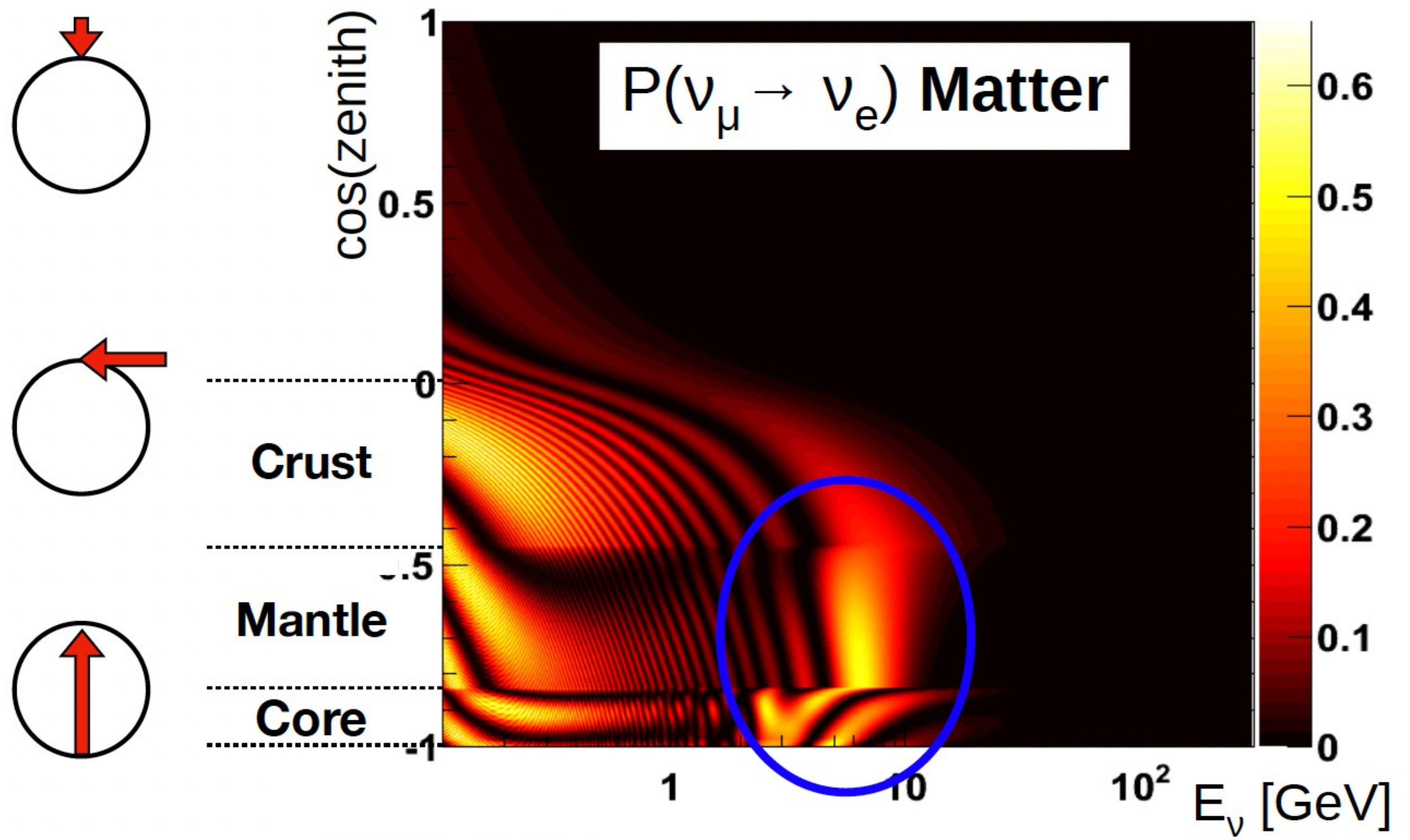
$$\begin{pmatrix} -\frac{\Delta m_{12}^2}{4E}\cos 2\theta_{12} + \sqrt{2}G_F N_e & \frac{\Delta m_{12}^2}{4E}\sin 2\theta_{12} \\ \frac{\Delta m_{12}^2}{4E}\sin 2\theta_{12} & \frac{\Delta m_{12}^2}{4E}\cos 2\theta_{12} \end{pmatrix}$$



- This has a large effect in solar neutrino propagation, and a small but important effect on neutrino propagation in the Earth

The Matter of Matter





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

Neutrino Experiments

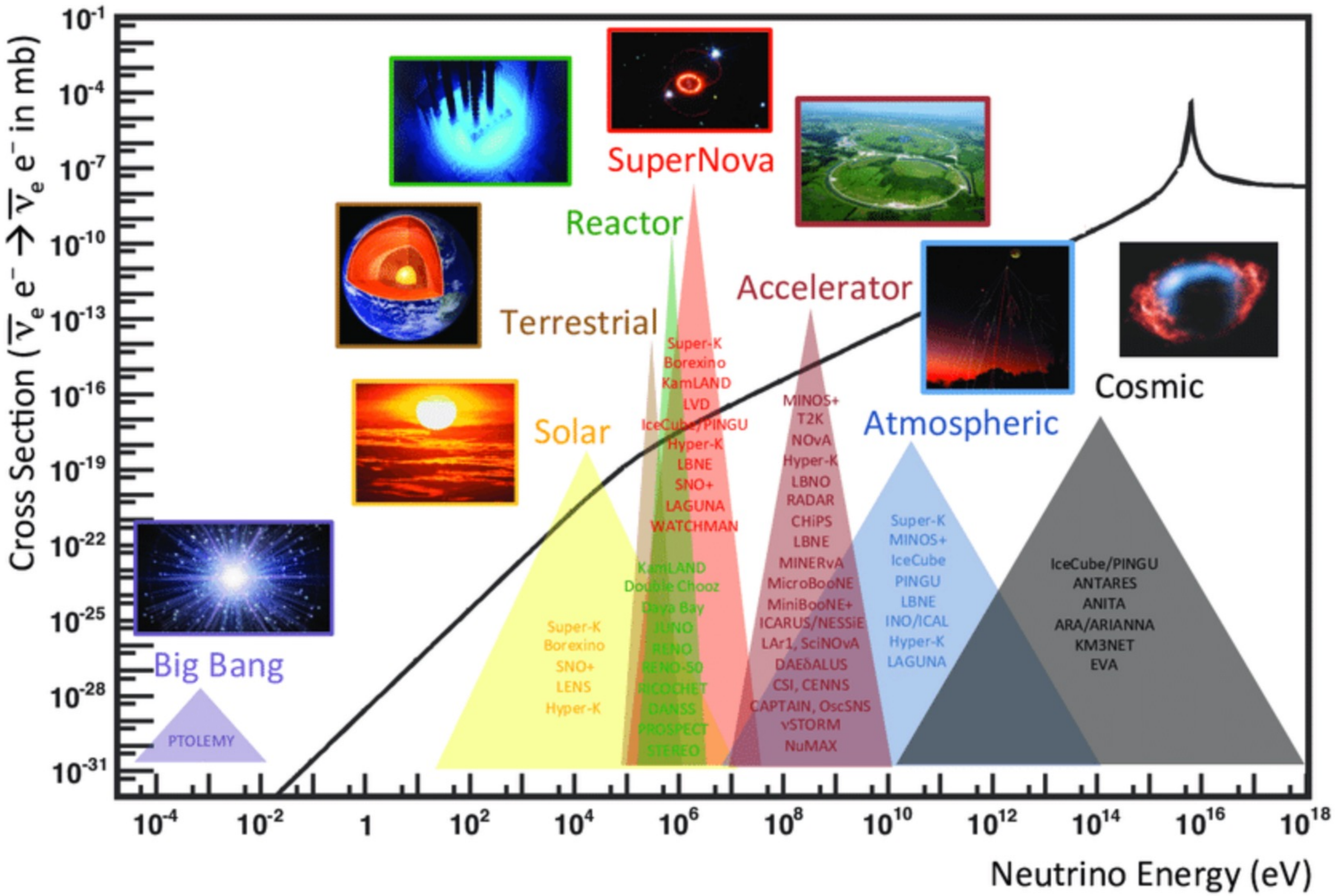


Image: SNOMASS 2013

Neutrino Oscillation Experiments

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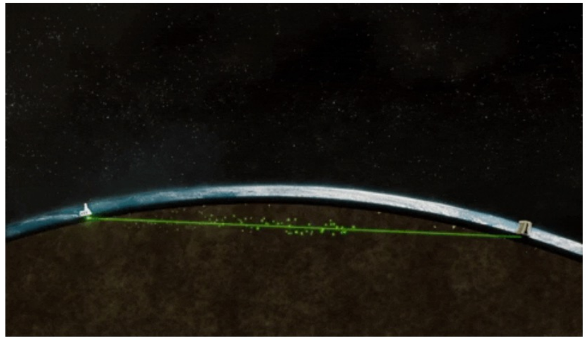
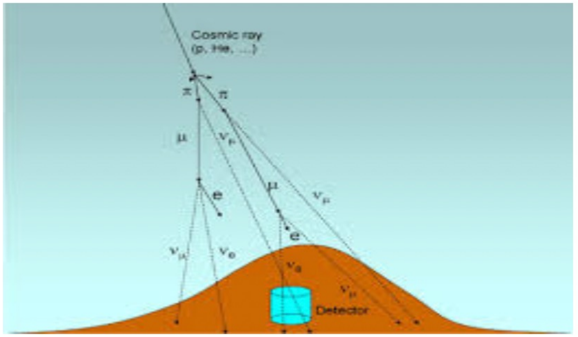
Accelerator neutrinos



Atmospheric neutrinos



Reactor neutrinos

Solar neutrinos

Images: M. Tortola, Neutrino 2024

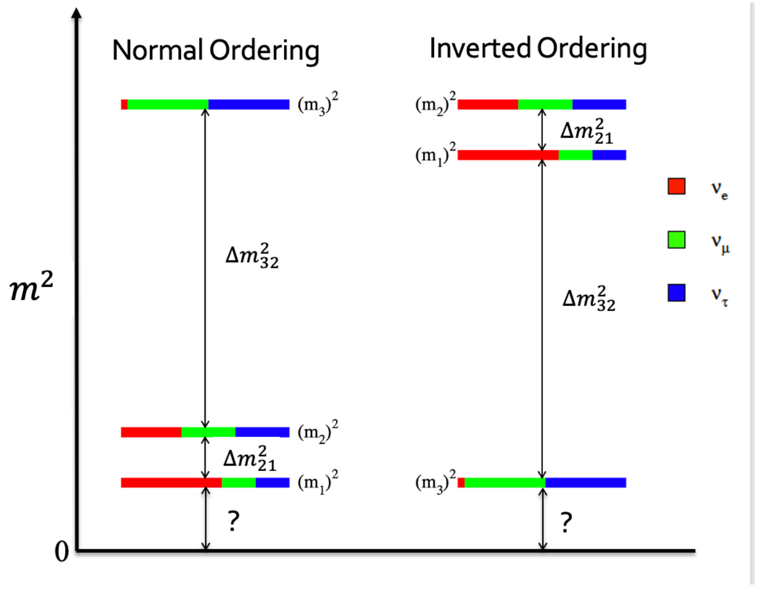
Current Status

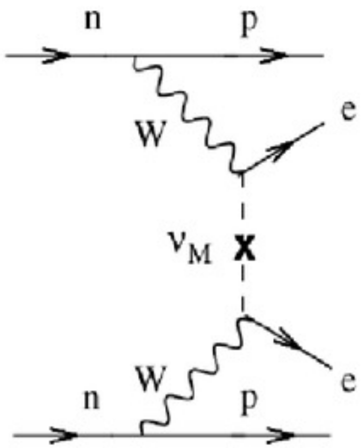
Parameter	Value	Precision
Δm^2_{21}	$(7.50 \pm 0.19)\times 10^{-5}$ eV²	2.5%
Δm^2_{32}	$(-2.527 \pm 0.034)\times 10^{-3}$ eV² (IO)	~1.2%
	$(2.451 \pm 0.026)\times 10^{-3}$ eV² (NO)	
$\sin^2(\theta_{12})$	0.307 ± 0.012	3.9%
$\sin^2(\theta_{23})$	$0.534^{+0.015}_{-0.019}$	2.8%
$\sin^2(\theta_{13})$	0.0216 ± 0.0006	2.8%
δ	$1.21^{+0.19}_{-0.22}\,\pi$ rad	17%

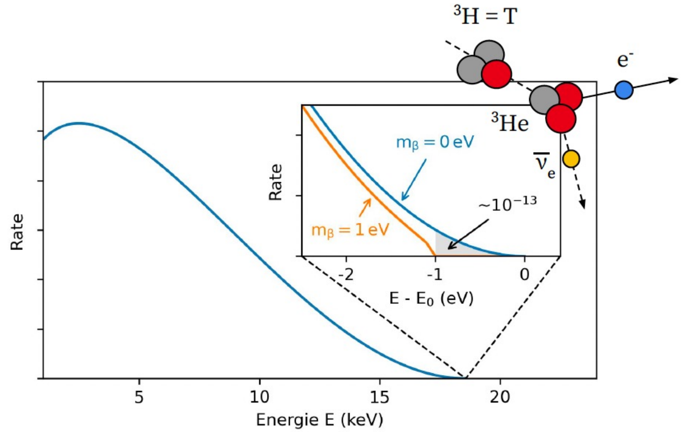
PDG 2025

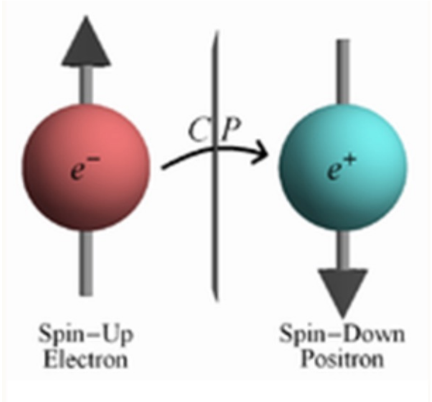
Open Questions

- Neutrino mass hierarchy
- Absolute neutrino mass
- CP phase
- Nature of the neutrino mass









Neutrino Mass Hierarchy

- Mass splittings are known from neutrino oscillation experiments, but the sign of Δm^2_{32} is unknown
  - The sign of Δm^2_{21} is known because the hierarchy matters in the solar matter effect
- Slight (~90%) prefence for normal ordering from current data (SuperK, T2K, NOvA, cosmology)
- JUNO, Hyper Kamikande, and DUNE are all expected to measure the mass hierarchy with high confidence in the coming years

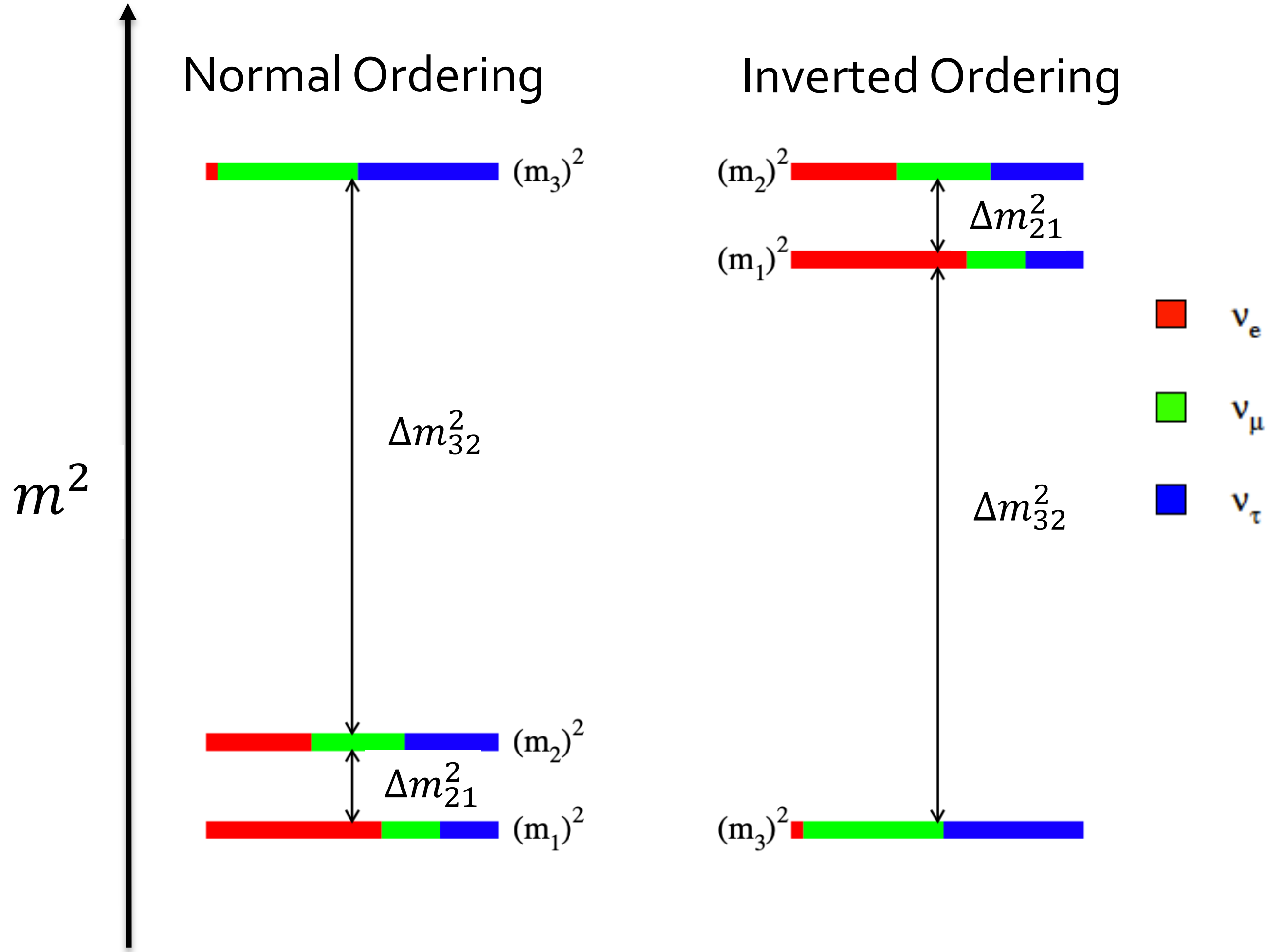


Figure adapted from hep-ph/0411274

Absolute Neutrino Mass

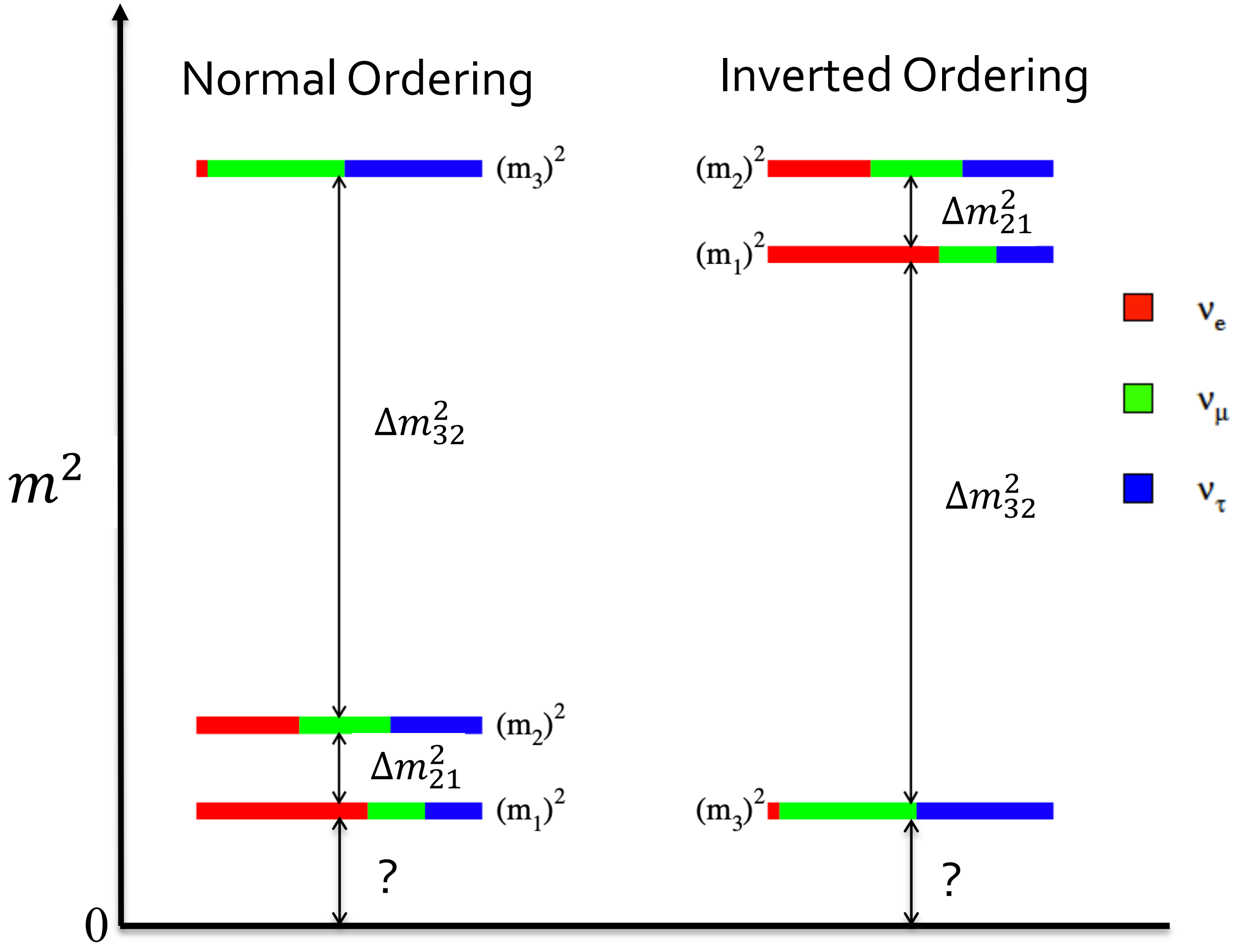
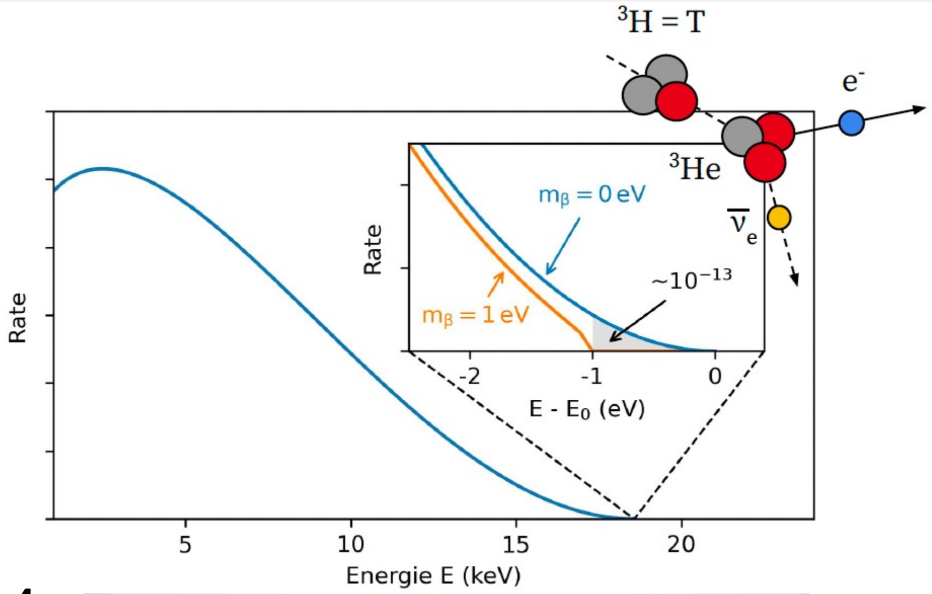


Figure adapted from hep-ph/0411274

Absolute Neutrino Mass

- Directly constrainted by beta decay endpoint measurements
- Electrostatic filter technique mature
  - KATRIN current: $m_{\nu_e} < 0.45$ eV (90% CL)
  - KATRIN future: $m_{\nu_e} < 0.3$ eV (90% CL)
- R&D approaches to go further ($m_{\nu_e} < 0.04$ eV envisioned)
  - Cyclotron radiation emission spectroscopy (e.g. Project8)
  - Cryogenic calorimetry (e.g. ECHO, HOLMES)



Images: Christoph Wiesinger, TAUP 2025; Karlsruhe Institute of Technology

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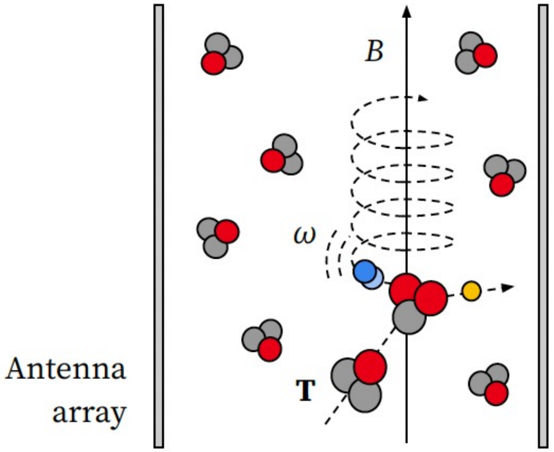

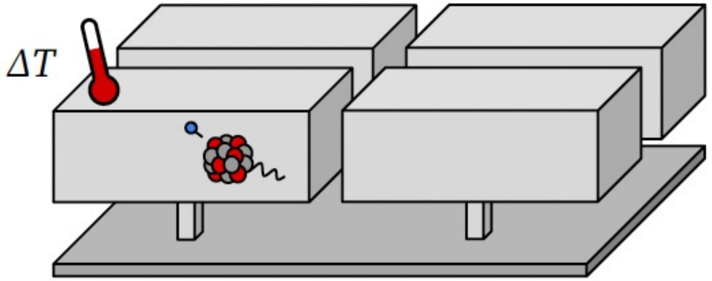

Thermal bath (mK)

Images: Christoph Wiesinger, TAUP 2025

Absolute Neutrino Mass

- Effect of neutrino mass on cosmology can be used to constrain neutrino mass
- Current cosmological fits using DESI data prefer very light neutrinos – maybe even in tension with oscillation mass splittings!
- Improved cosmological constraints (and perhaps a measurement) expected soon

$\sum m_{\nu_i} = 0$ $\sum m_{\nu_i} = 500\text{eV}$

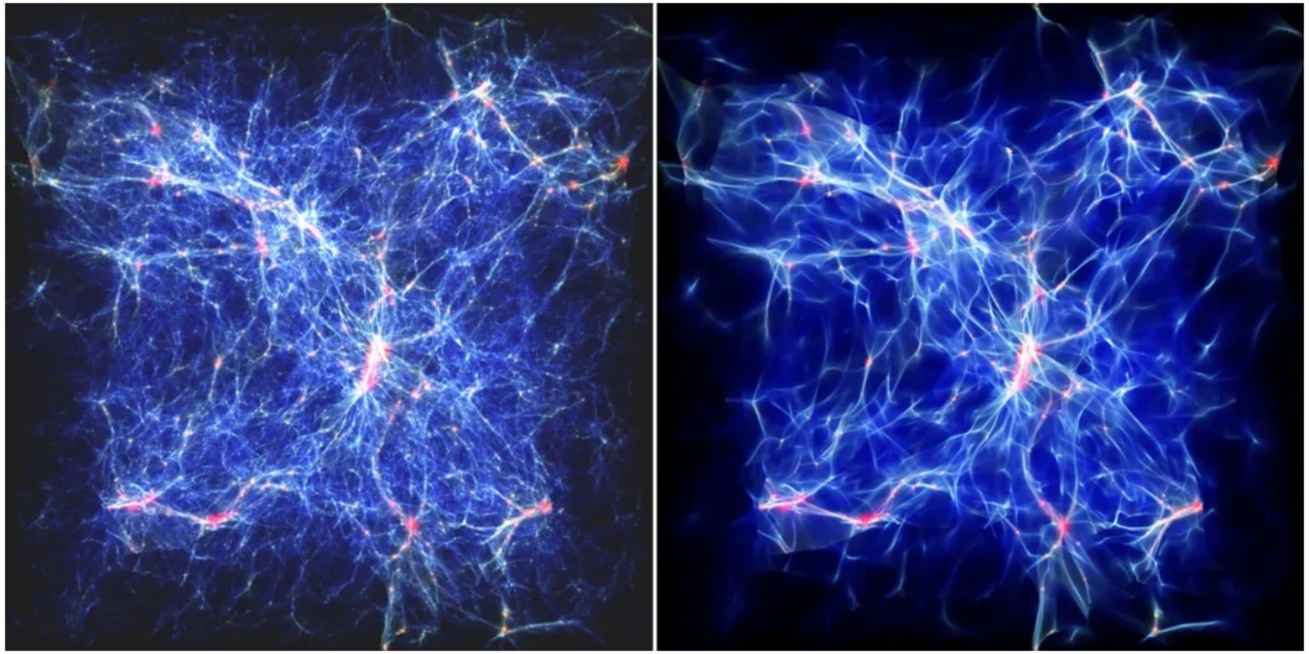

Image: Julien Bauer via sciencenews.org

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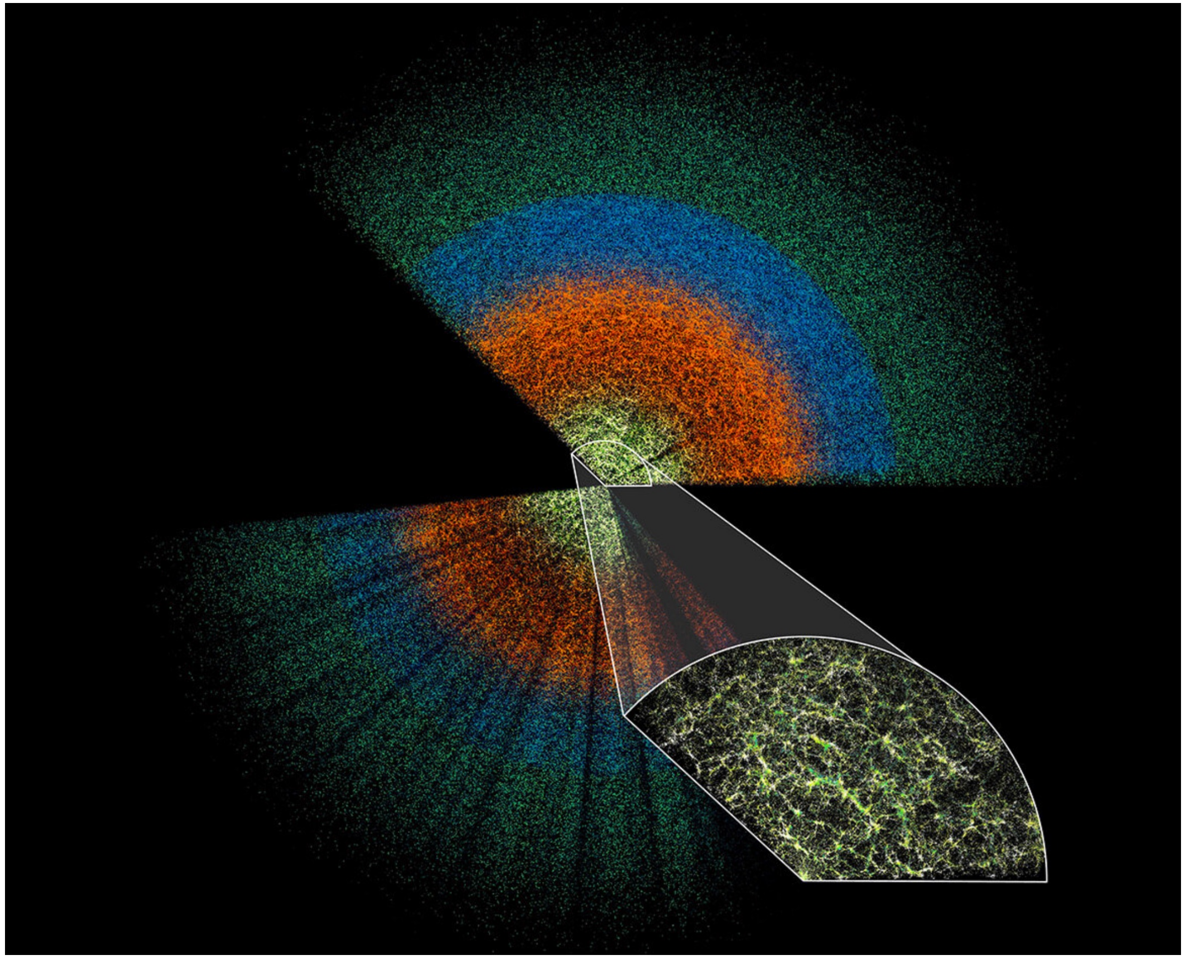

Image: Claire Lamman/DESI collaboration via phys.org

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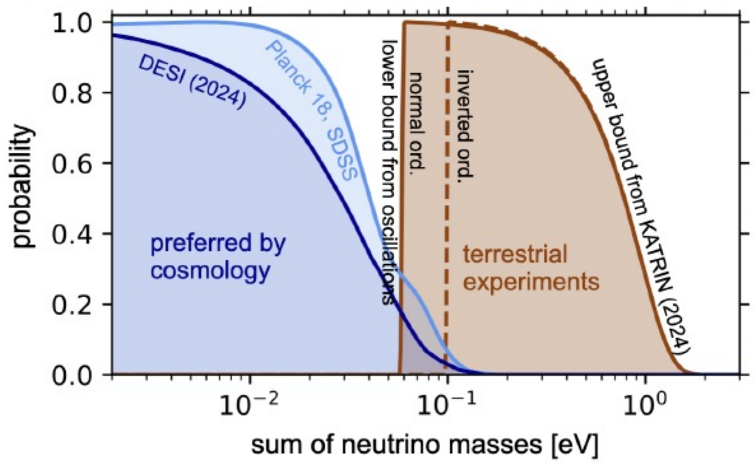
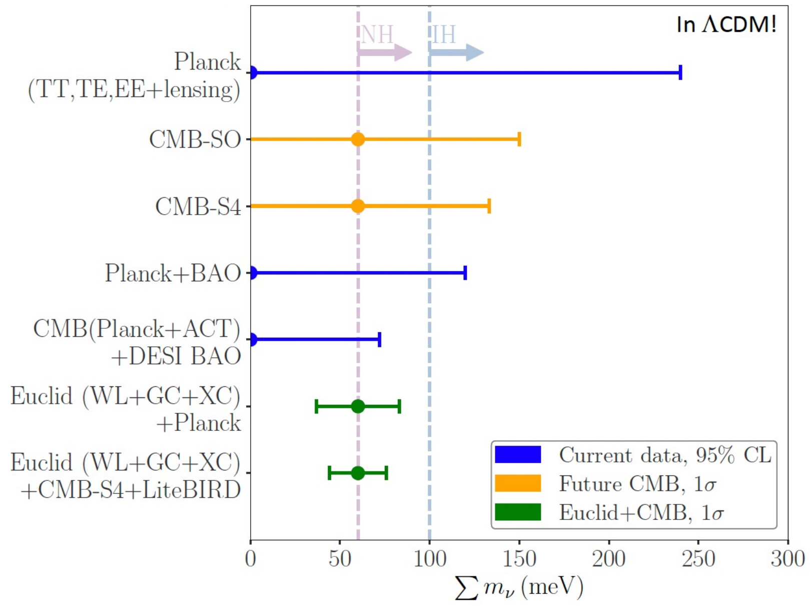
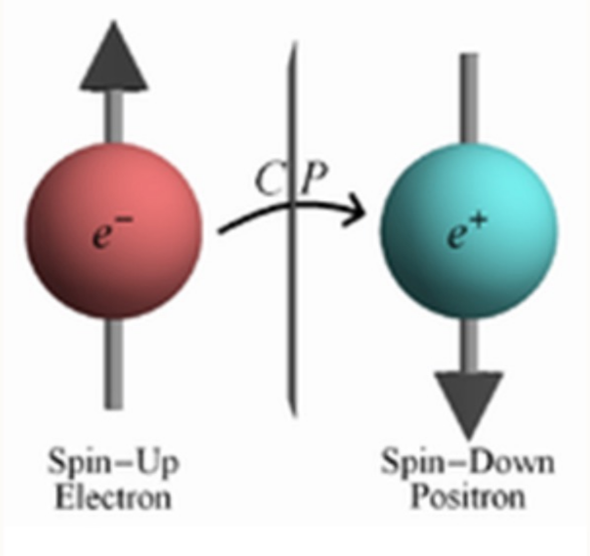


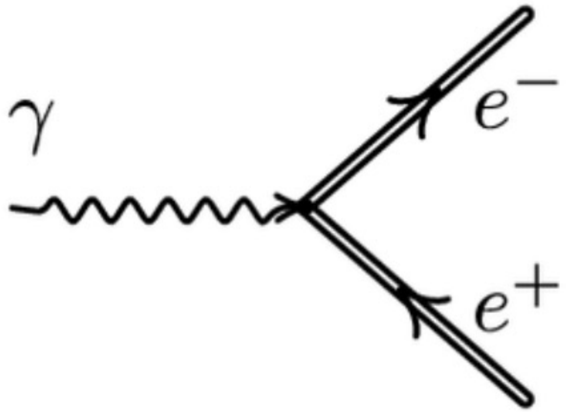


Images: Th. Schwetz, TAUP 2025; M. Archidiacono, NEUTRINO 2024

CP Phase

- If δ is non-zero it implies that neutrinos violate the "Charge-Parity" symmetry (i.e. particles and antiparticles act differently).
- CP violation is needed to explain how we live in a matter-dominated Universe
  - CP violation has been observed in the quark sector, but is too small
  - "Leptogenesis" via CP violation in the neutrino sector is a possible explanation





Images: timeone.ca; doi 10.1142/S0217732315501114

CP Phase

- Measurement of δ is the primary goal of accelerator neutrino experiments
    - Run with neutrino and antineutrino beams and look for differences in oscillation probability
- T2K and NOvA provide evidence for non-zero δ at $> 3\sigma$ assuming inverted hierarchy, and at $\sim 2\sigma$ for normal hierarchy
- T2HK and DUNE aim to measure δ (assuming it's not tiny!)

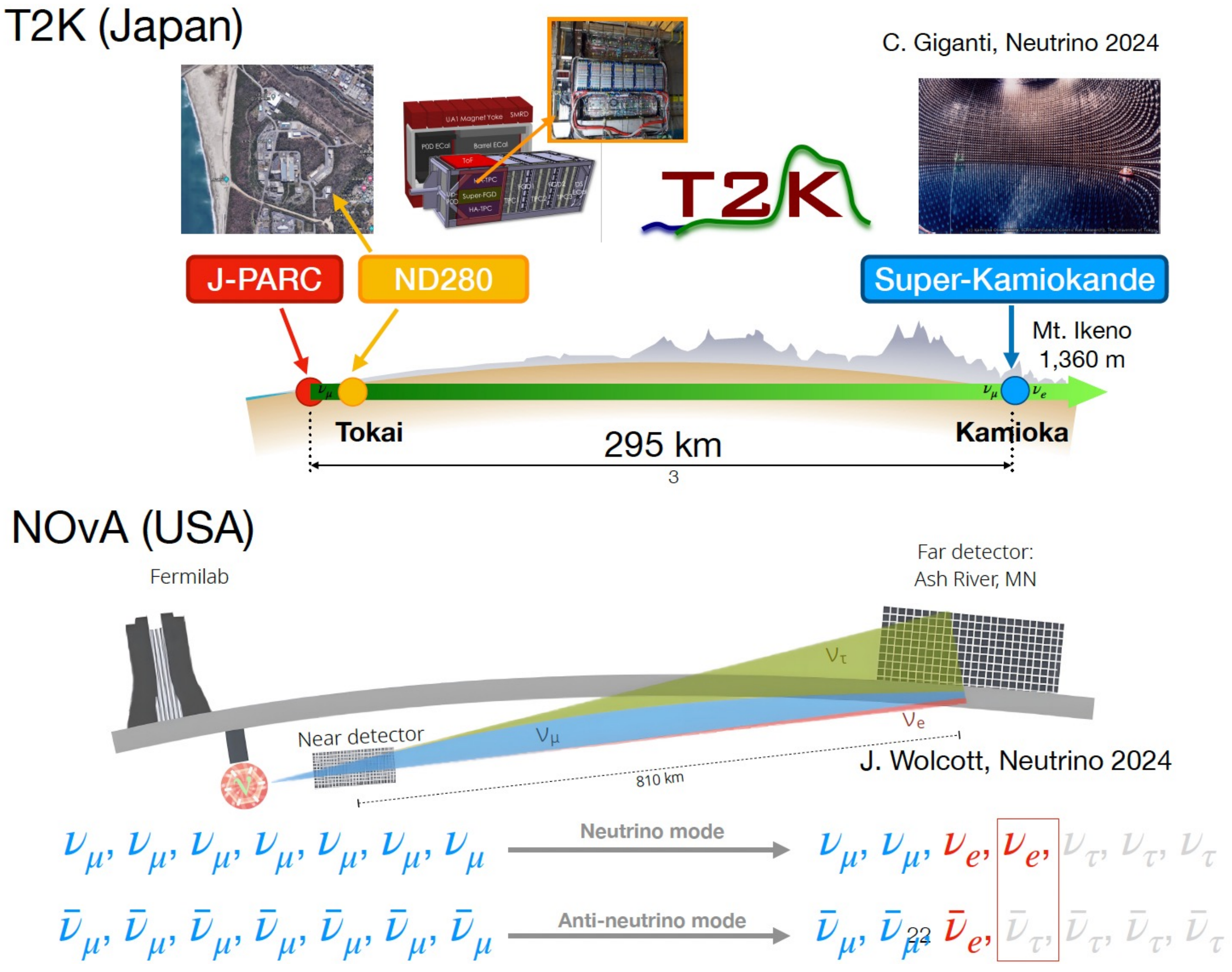


Image: L. Burns, TAUP 2025

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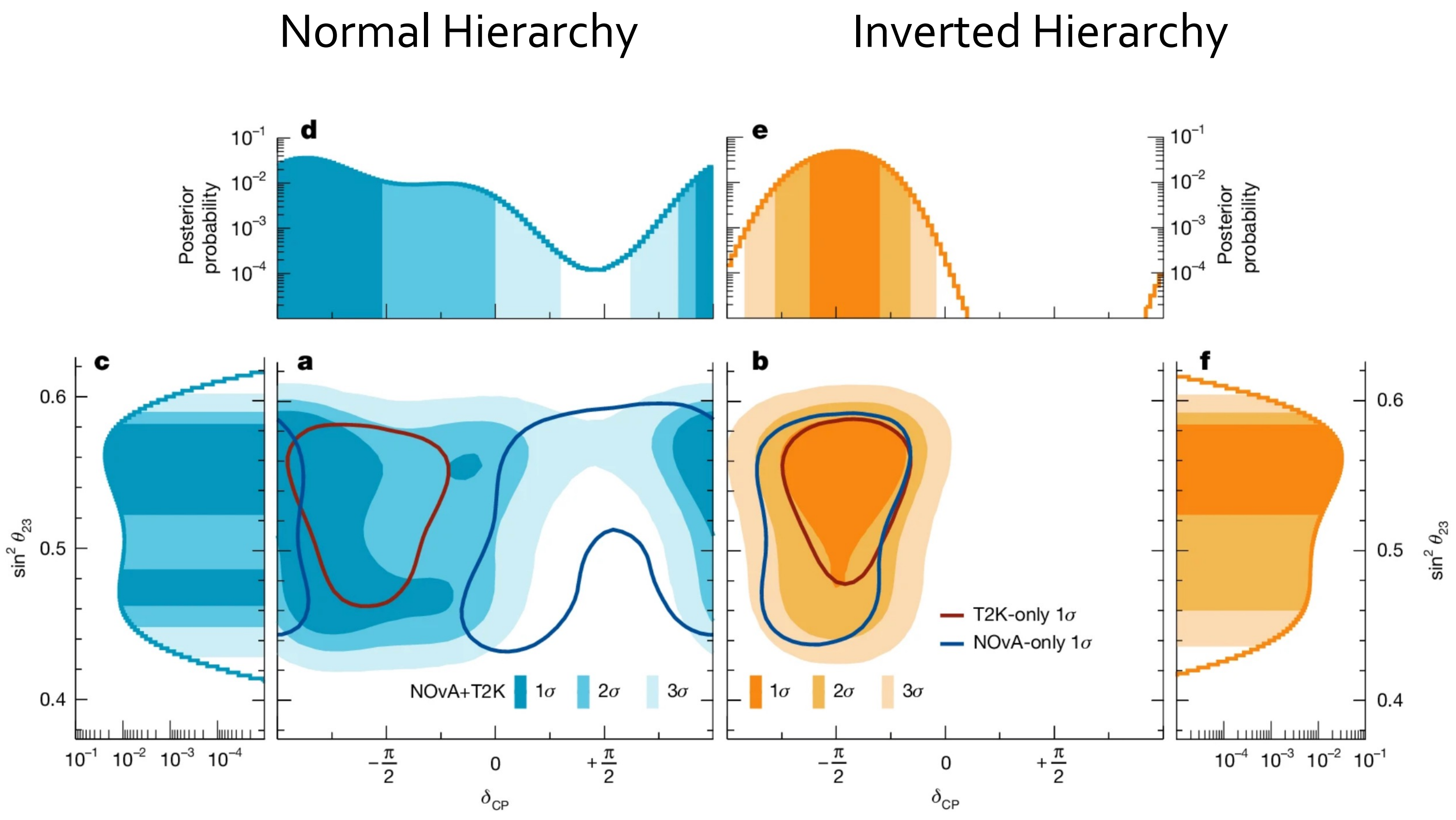

Image: T2K & NOvA, Nature **646**, pages 818–824 (2025)

The Nature of the Neutrino Mass

- The neutrino mass scale is very different from other particles
- There are two possible "types" of neutrinos: "Majorana" and "Dirac"
  - Other fermions are Dirac
- Dirac particles get their masses through the "Higgs Mechanism." Majorana neutrinos can do that, too, but could also get their mass from the "Majorana Mechanism" (or the "see-saw")
  - Majorana neutrinos could obtain their mass in a completely different way than all of the other particles.

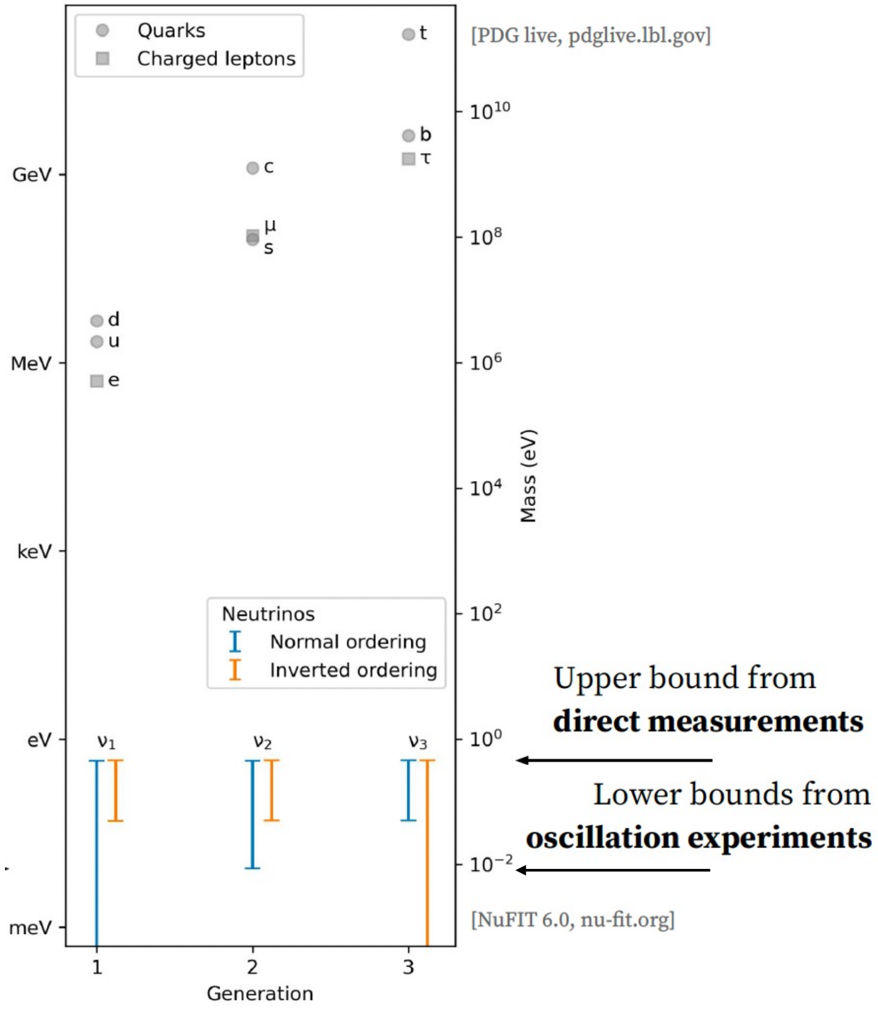

Image: Christoph Wiesinger, TAUP 2025

Neutrinoless Double Beta Decay

- Dirac-type neutrinos have two active and two sterile states, while Majorana neutrinos have only the two active states
  - In Majorana neutrinos the right handed neutrino acts as the "antineutrino" – the neutrino is its own anti-particle
- Majorana neutrinos allow double beta decay to proceed via a virtual neutrino exchange
  - Detecting "Neutrinoless Double Beta Decay" proves neutrinos are Majorana (and provides a measurement of the absolute neutrino mass)
  - Many experiments are searching for NLDBD, limits are improving, but no detection yet

Dirac

Particles | Anti-Particles

$$\begin{pmatrix} \nu_L & \nu_R \\ \bar{\nu}_L & \bar{\nu}_R \end{pmatrix}$$

Majorana

"Particle" | "Anti-Particle"

$$\begin{pmatrix} \nu_L & \\ & \nu_R \end{pmatrix}$$

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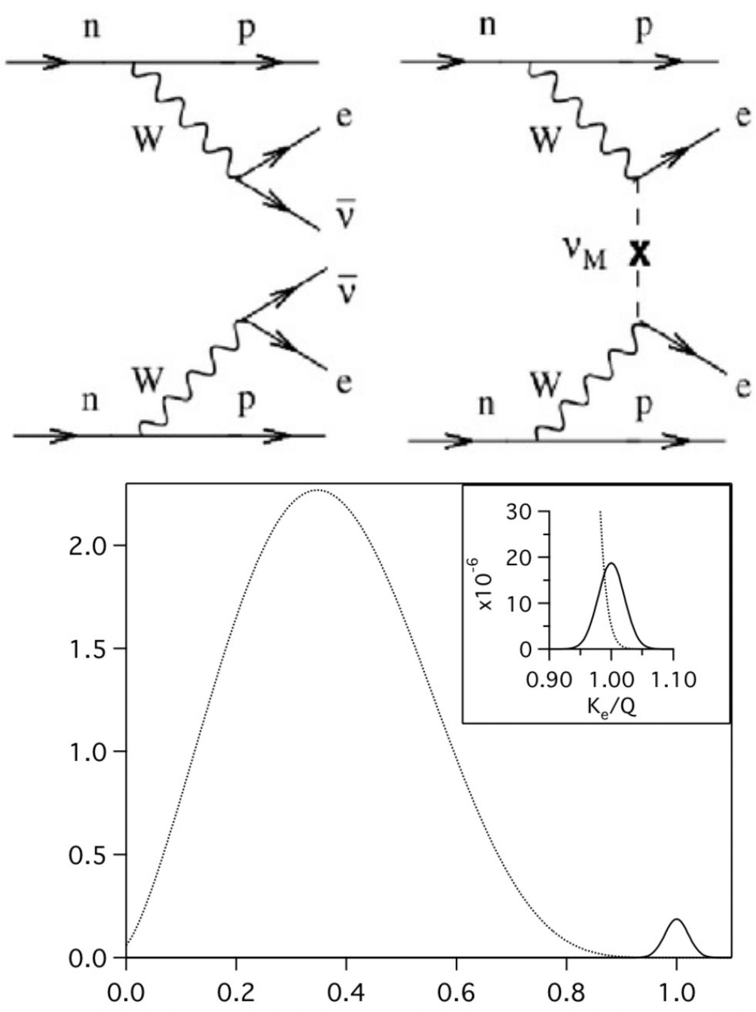

Image: hep-ph/0202254

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[NuFIT 6.0, nu-fit.org]

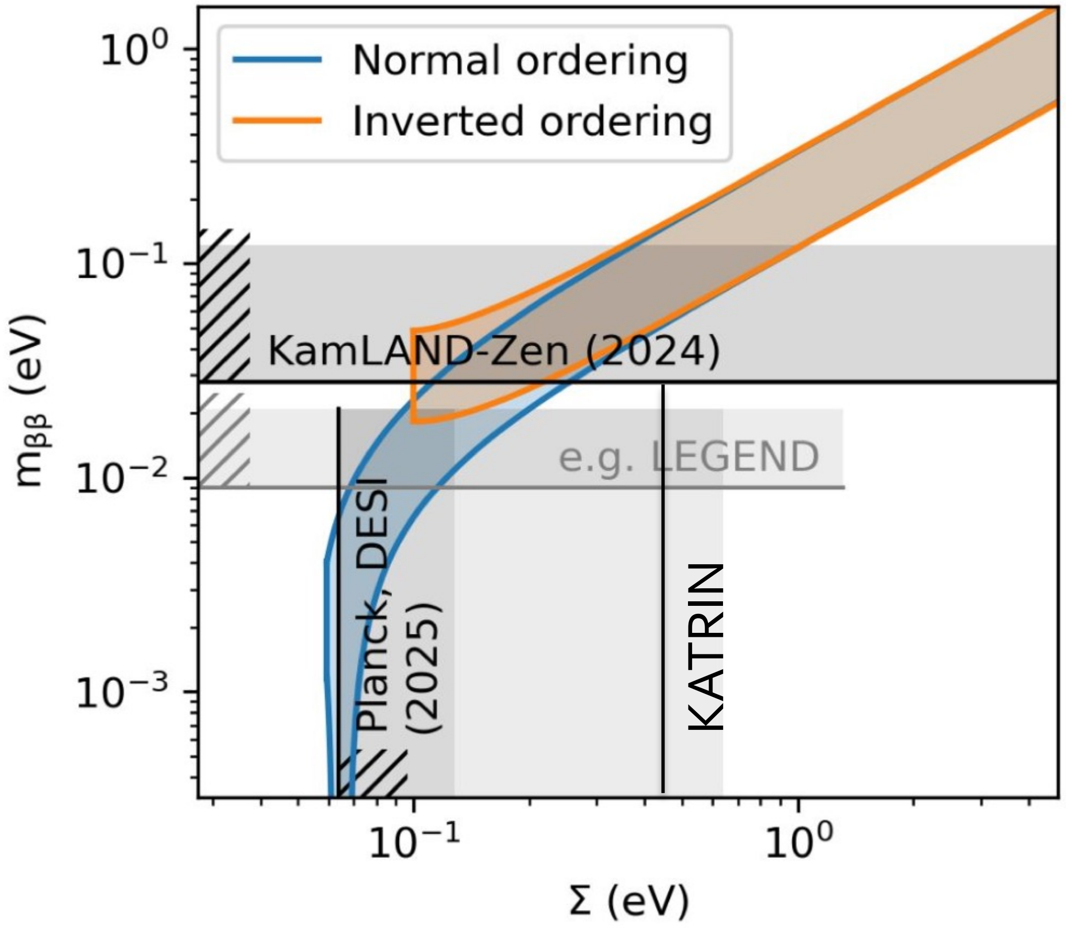

Image: Christoph Wiesinger, TAUP 2025

Summary

- In the ~25 years since neutrino mass was discovered, great progress has been made in measuring the neutrino oscillation parameters
- Next-generation experiments will (hopefully!) determine the neutrino mass hierarchy and measure the CP violating phase
- Direct constraints on the the absolute neutrino mass have improved; cosmological constraints have become significant, and may soon yield a lower limit
- Increasingly sensitive neutrinoless double beta decay search experiments are attempting to demonstrate the Majorana nature of the neutrino
- We look forward to continued progress in the next 25 years!