Mysteries in Neutrino Physics

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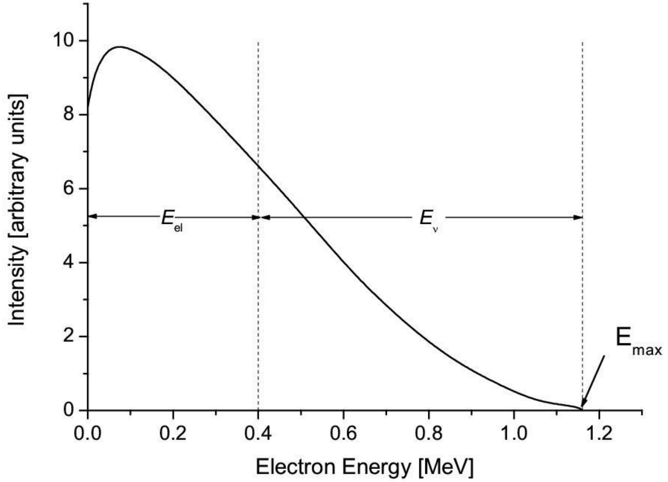
Overview

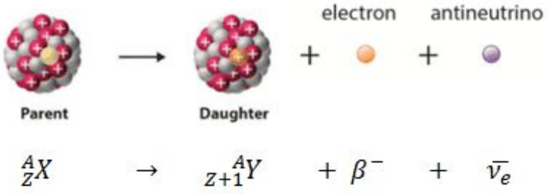
- Neutrinos in the standard model
- The solar neutrino problem and neutrino oscillations
- Remaining mysteries in neutrino physics, and how we're trying to solve them.

Postulating a new particle

- The neutrino was first hypothesized by Wolfgang Pauli in 1930 to explain the measured energy spectrum of the electrons emitted in beta decays.

- Electrically neutral a tiny or zero mass.

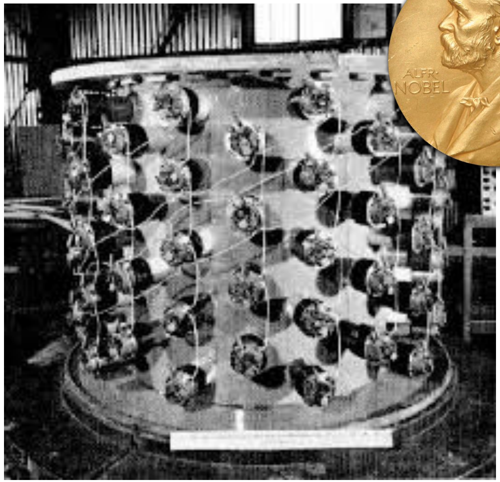


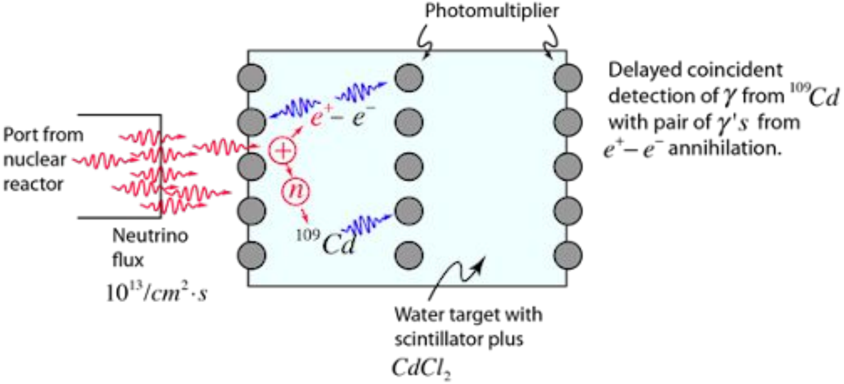


"I have done a terrible thing: I have postulated a particle that cannot be detected."

Discovery of the neutrino

- The neutrino was discovered (1956) by Cohen and Reines as part of "Project Poltergeist" at a Savannah River nuclear power plant (1995 nobel prize).

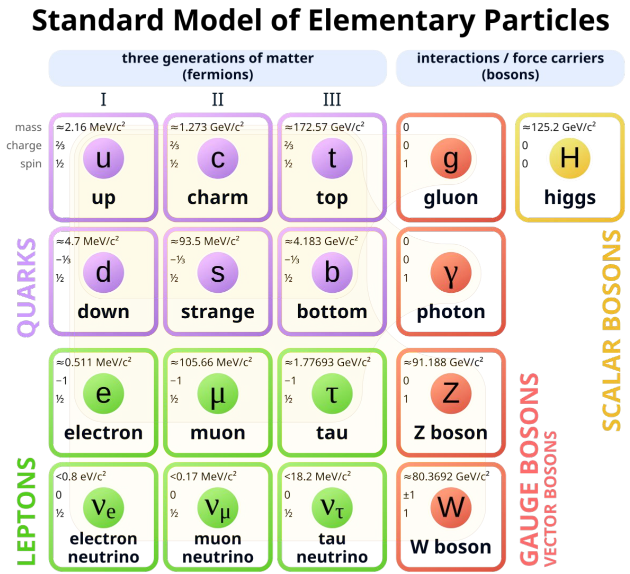




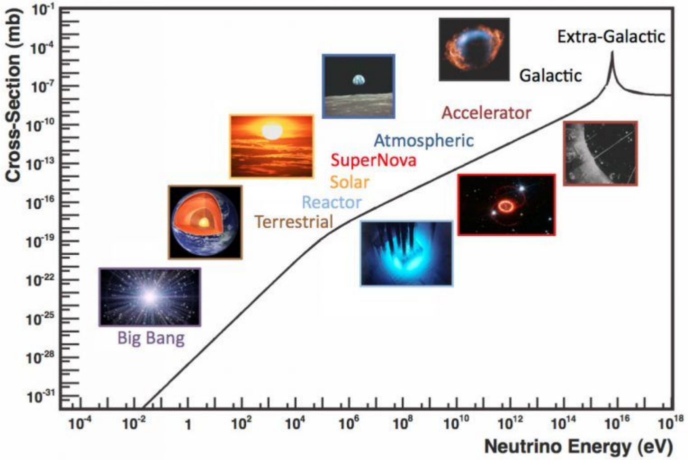
"Thanks for the message. Everything comes to him who knows how to wait."

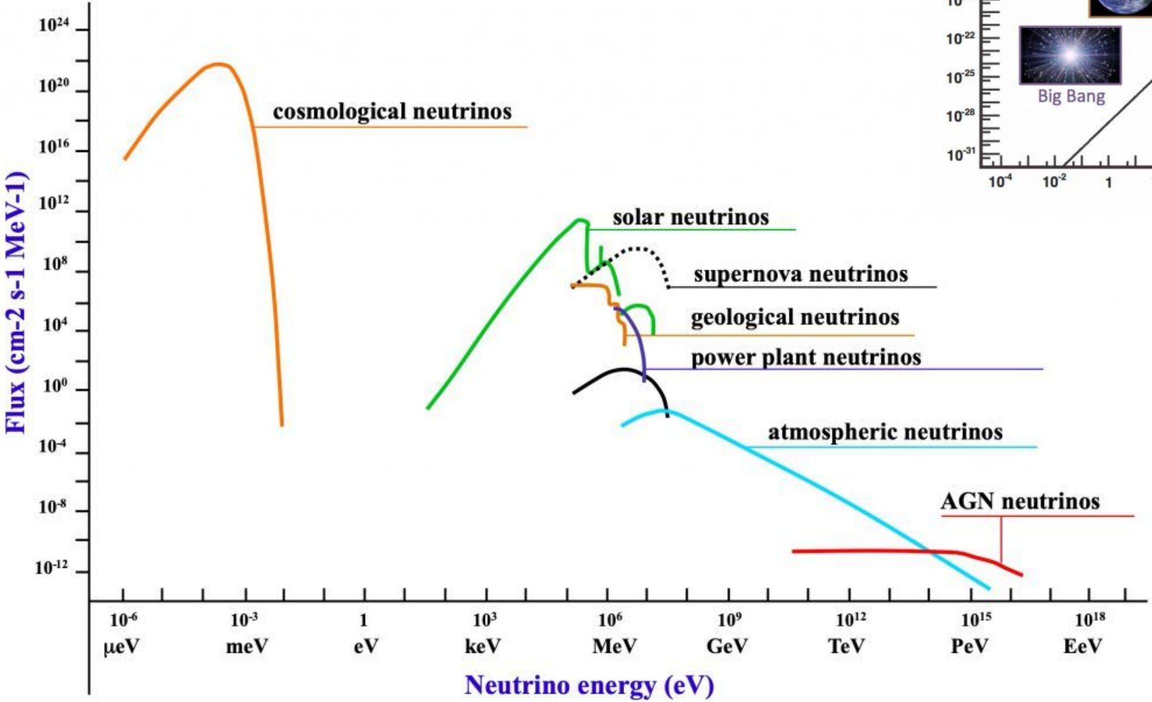
The Neutrino

- spin ½ fermions
- Three leptonic flavors: electron, muon (1988 nobel prize), and tau.
- Each neutrino has a corresponding antiparticle.
- Electrically neutral and only interacts via the weak force.
- Massless in the standard model, but we know they have a small, non-zero mass.
- Weak interactions produce left (right) handed neutrinos (antineutrinos) and the mirror images are not produced.



Where do neutrinos come from?





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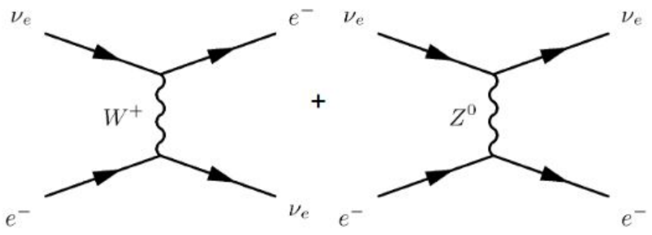
How do neutrinos interact?

- Threshold-less processes: coherent scattering (very difficult to detect due to small recoil energy)

$$\nu + A_N^Z \rightarrow \nu + A_N^{*Z}$$

- Neutrino-lepton scattering, both CC and NC. These are the workhorse for MeV-scale neutrino physics, as the charged lepton can be easily detected.
- Inverse-beta decay: capture of electron antineutrino (E > 1.8 MeV) on a proton of extreme importance for reactor, geo, and supernova neutrino physics.

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



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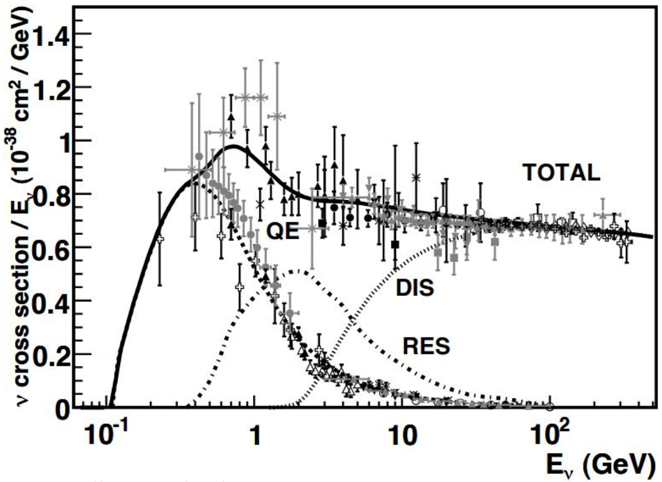
How do neutrinos interact?

- At higher energies (above 100 MeV) the neutrino interactions begin to probe the nuclear structure, and, with enough energy, start to resolve the individual quark structure of the nucleon. The measurement and calculation of these cross-section is an area of active research.



https://arxiv.org/pdf/1305.7513

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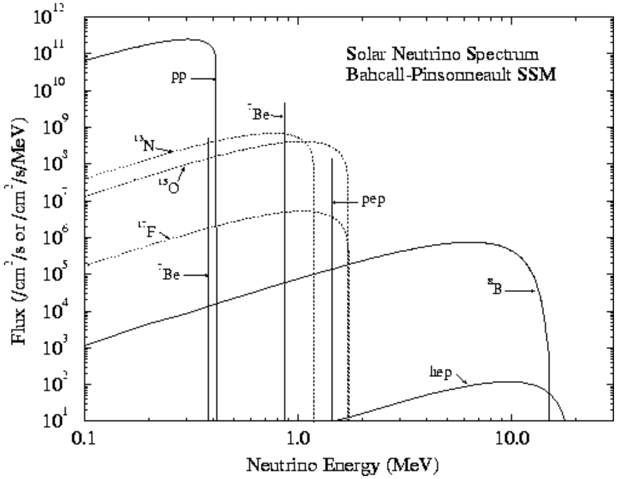
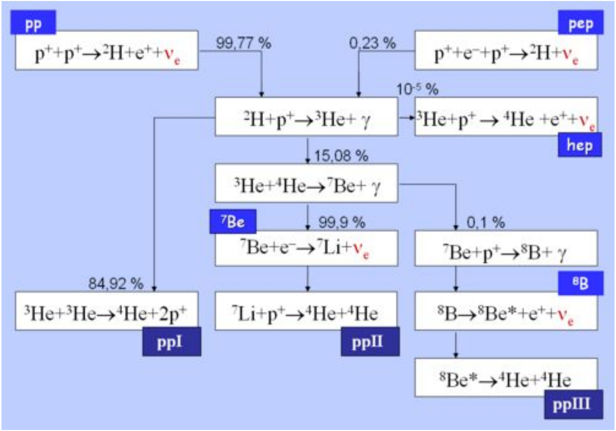
The solar neutrino problem

- The sun produces a huge flux of neutrinos with energies ranging from roughly 0.1 to 10 MeV (The flux of solar neutrinos at Earth is several tens of billions per square centimetre per second, mostly from the Sun's core.)

- In the 1960s Ray Davis (experimentalist) and John Bahcall (theorist) built an enormous underground experiment to detect solar neutrinos for the first time.





The solar neutrino problem

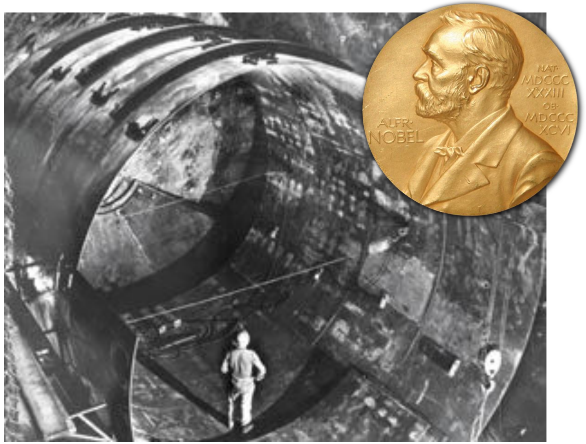
- The Homestake experiment (2002 Nobel Prize) was located underground in the Homestake gold mine in South Dakota.
- An enormous tank was filled with chlorine-based dry cleaning fluid.

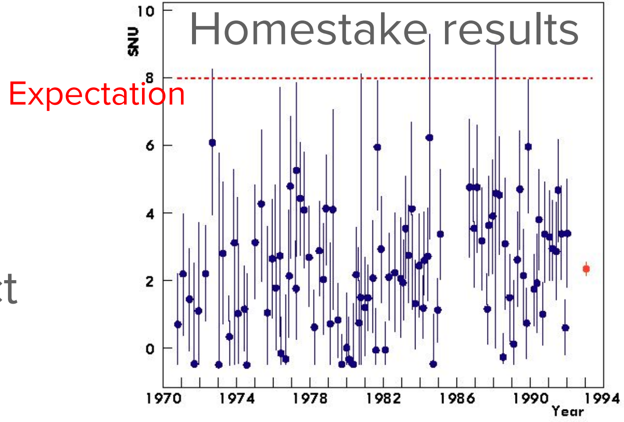
$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar}^{+} + \mathrm{e}^{-}$$

(Q = 0.8 MeV)

- R. Davis bubbled helium through the tank to collect and counted the argon atoms

- Detected significant deficit w.r.t theoretical predictions



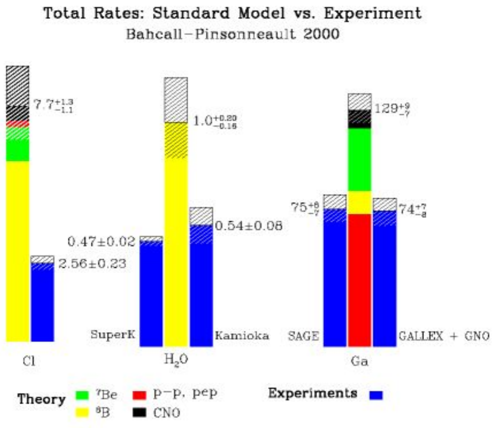


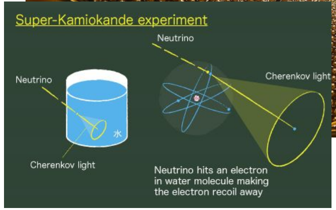
The solar neutrino problem

- Many subsequent radiochemical and water Cherenkov neutrino detects confirmed the problem.

- The Kamiokande experiment was constructed in 1983 to search for proton decay. Enormous underground cavern filled with water and surrounded by light detectors (PMTs).

- Using the Cherenkov light produced in neutrino interactions, the detector can measure the incoming neutrino direction.





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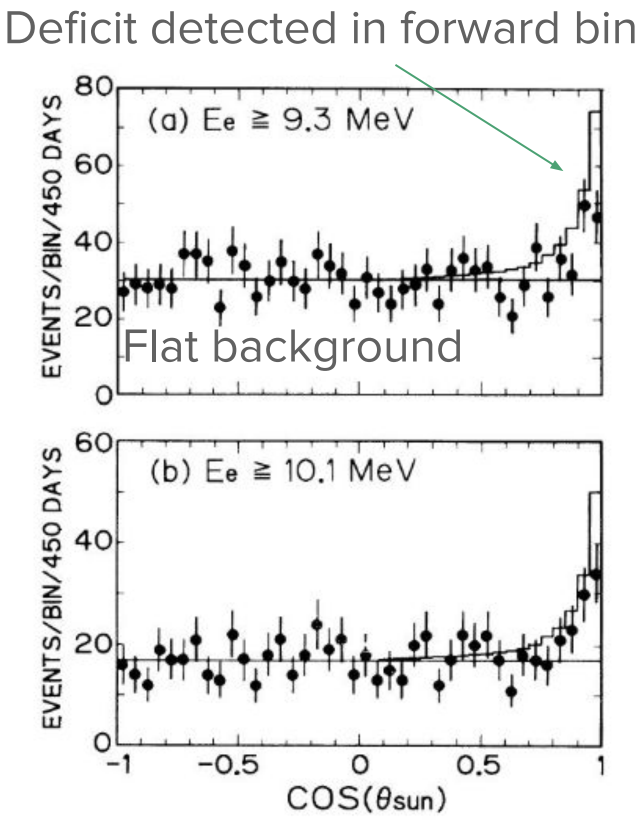

The solar neutrino problem: proposed solutions

- Many attempts to explain away the solar neutrino problem by questioning the theoretical predictions.

- Bruno Pontecorvo proposed that the neutrinos could be changing lepton flavors as they traveled, causing what would appear to be a deficit for experiments only sensitive to detecting electron flavor neutrinos.

“Listen to simple experiments — they often reveal the deepest surprises.”

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ChatGPT

“Listen to simple experiments — they often reveal the deepest surprises.”

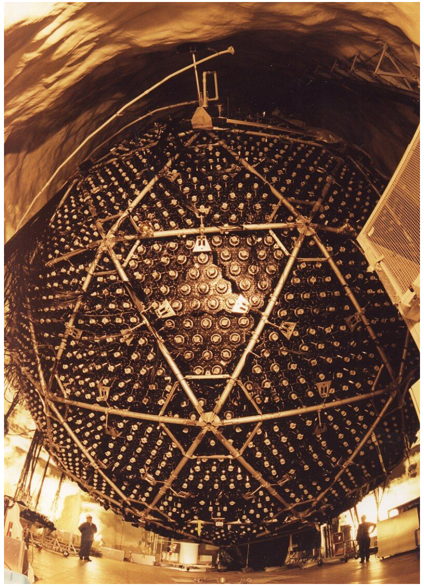
The solar neutrino problem: solution

- The Sudbury Neutrino Observatory (SNO) experiment was explicitly designed to test the predictions of neutrino oscillations.

- Large, deep underground acrylic tank filled with heavy water (D_2O)

CC Charged Current Reaction	$\upsilon_e + d \rightarrow p + p + e^-$	$E_{threshold} = 1.4 MeV$
NC Neutral Current Reaction	$\upsilon_x + d \rightarrow \upsilon_x + p + n$	$E_{threshold} = 2.2 MeV$
ES Elastic Scattering Reaction	$\upsilon_x + e^- \rightarrow \upsilon_x + e^-$	$E_{threshold} \approx 0$

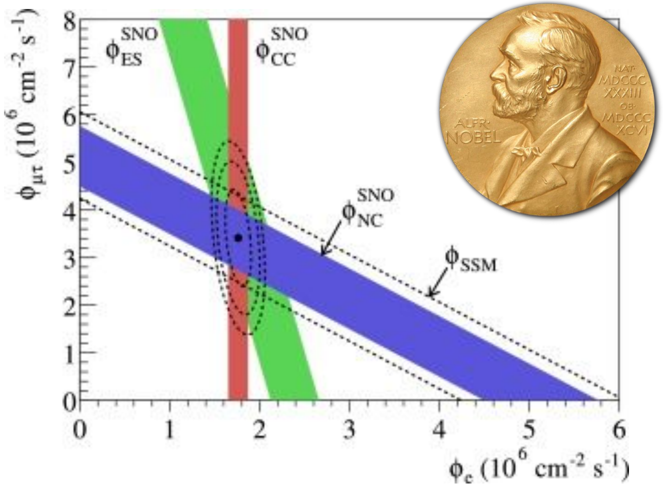
x denotes that this reaction will take place with any neutrino.

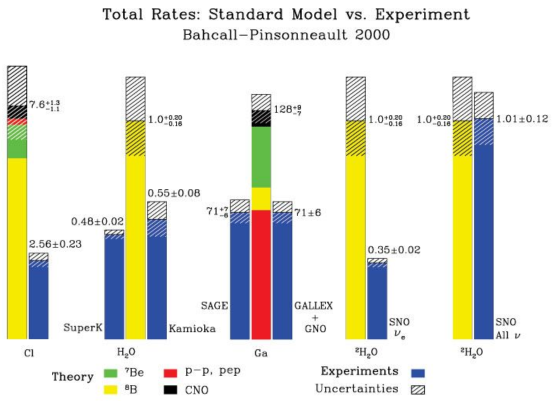


The solar neutrino problem: solution

- SNO results, using all interaction channels, were in good agreement with standard solar model.

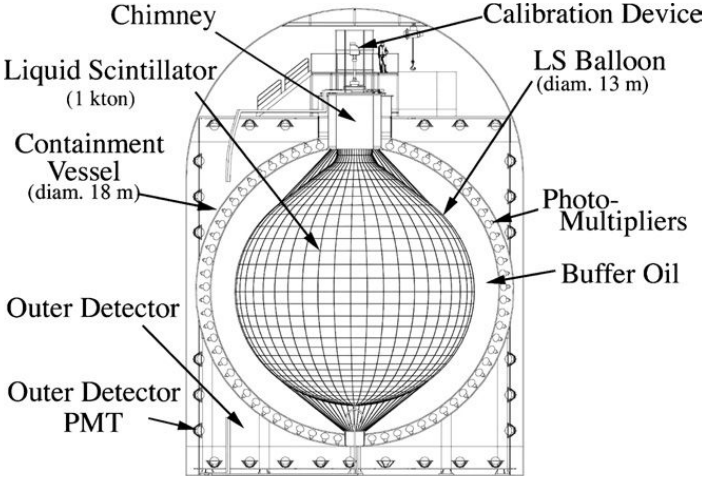
- First clear evidence that neutrinos “oscillate” or change flavor as they propagate (2015 Nobel Prize, shared with Kamiokande collaboration).

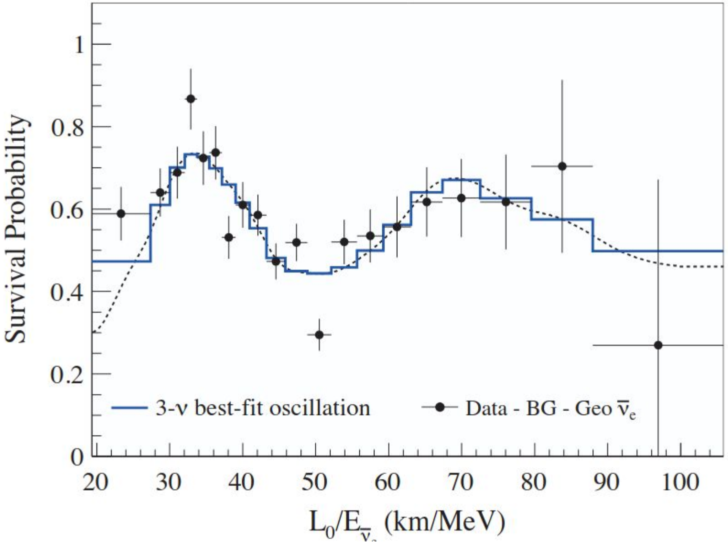




The evidence becomes overwhelming

- First evidence of oscillation pattern by KamLAND experiment (2002) using antineutrinos produced in distance nuclear reactors.





Neutrino oscillations

- Neutrino oscillations are quantum mechanical phenomenon (in analogy with K_0 - $\overline{K}_0$ oscillations)
- Generated by the interference of different massive neutrinos, which are produced and detected coherently.
- In other words, the neutrinos are created and interact in the flavor eigenstates, but propagate in the mass eigenstates.

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$ Created in pure flavor state

$$|\nu_j(t)\rangle = e^{-i\left(E_j t - \vec{p}_j \cdot \vec{x}\right)} |\nu_j(0)\rangle$$ Mass eigenstates propagate as plane waves

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- Probability of detecting a neutrino with flavor β if it was created with flavor α with energy E and it has traveled a distance L (ultra-relativistic limit)

$$P_{\alpha\to\beta} = \left| \langle \nu_\beta \,|\, \nu_\alpha(L) \rangle \right|^2 = \left| \sum_j U_{\alpha j}^* \, U_{\beta j} \, e^{-i m_j^2 L/(2E)} \right|^2$$

Transition probability

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

Two flavor mixing

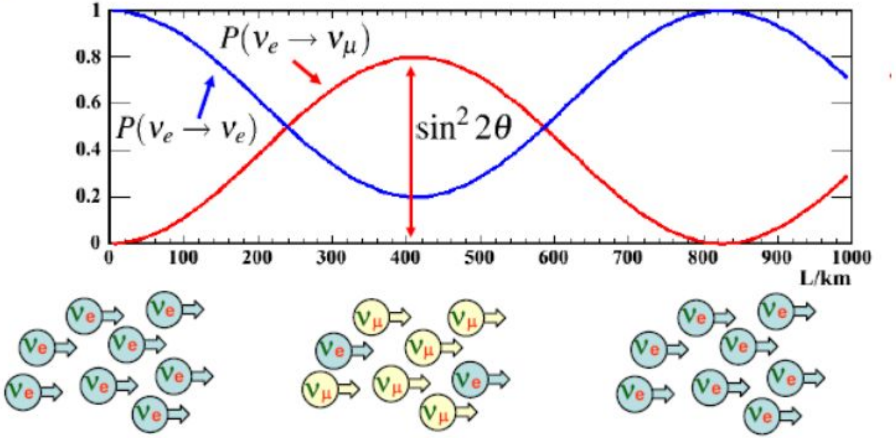
- Amplitude of oscillations set by θ and wavelength set by Δm^2, L, and E

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

•e.g. $\Delta m^2 = 0.003\,\mathrm{eV}^2$, $\sin^2 2\theta = 0.8$, $E_\nu = 1\,\mathrm{GeV}$



https://warwick.ac.uk/fac/sci/physics/staff/academic/boyd/stuff/neutrinolectures/lec_oscillations.pdf

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Three flavor mixing in vacuum

$$P_{\alpha\to\beta} = \left| \langle \nu_\beta \mid \nu_\alpha(L) \rangle \right|^2 = \left| \sum_j U_{\alpha j}^* \, U_{\beta j} \, e^{-i m_j^2 L/(2E)} \right|^2$$

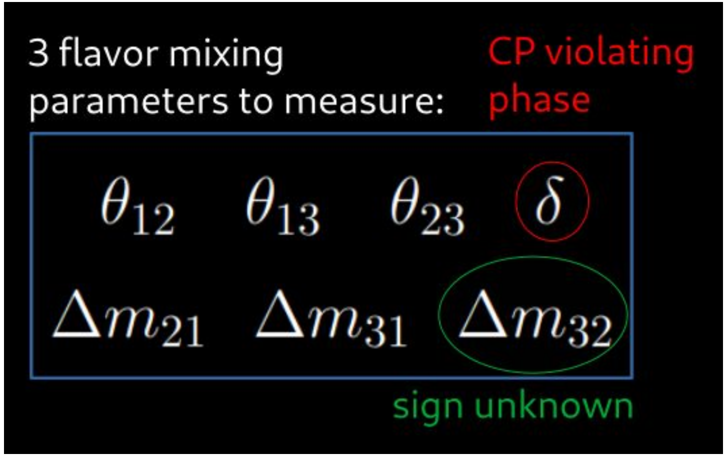
- Three flavor mixing gets more complicated

PMNS matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta} & c_{23} c_{13} \end{bmatrix}$$



$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4 \sum_{j>k} \mathcal{R}_e \left\{ U_{\alpha j}^* \, U_{\beta j} \, U_{\alpha k} \, U_{\beta k}^* \right\} \sin^2\left(\frac{\Delta_{jk} m^2 \, L}{4E} \right)$$

$$+ 2 \sum_{j>k} \mathcal{I}_m \left\{ U_{\alpha j}^* \, U_{\beta j} \, U_{\alpha k} \, U_{\beta k}^* \right\} \sin\left(\frac{\Delta_{jk} m^2 \, L}{2E} \right),$$

where $\Delta_{jk} m^2 \equiv m_j^2 - m_k^2$.

Three flavor mixing

- The oscillation parameters have been measured by a variety of different experiments across decades of measurements.
- Primary sources: solar, atmosphere, reactor, and beam neutrinos

Table 14.1: Characteristic values of L and E for experiments performed using various neutrino sources and the corresponding ranges of $|\Delta m^2|$ to which they can be most sensitive to flavour oscillations in vacuum. SBL stands for Short Baseline, VSBL stands for Very Short Baseline , MBL stands for Medium Baseline, and LBL for Long Baseline.

Experiment		L (m)	E (MeV)	$\|\Delta m^2\|$ (eV^2)
Solar		10^{10}	1	10^{-10}
Atmospheric		$10^4 - 10^7$	10^2–10^5	$10^{-1} - 10^{-4}$
Reactor	VSBL–SBL–MBL	$10 - 10^3$	1	$1 - 10^{-3}$
	LBL	$10^4 - 10^5$		$10^{-4} - 10^{-5}$
Accelerator	SBL	10^2	10^3–10^4	> 0.1
	LBL	$10^5 - 10^6$	$10^3 - 10^4$	$10^{-2} - 10^{-3}$

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Three flavor mixing

- The oscillation parameters have been measured by a variety of different experiments across decades of measurements.
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Table 14.6: Experiments contributing to the present determination of the oscillation parameters.

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\lvert\Delta m^2_{31,32}\rvert$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\lvert\Delta m^2_{31,32}\rvert$, θ_{13},δ_{CP}
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\lvert\Delta m^2_{31,32}\rvert$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

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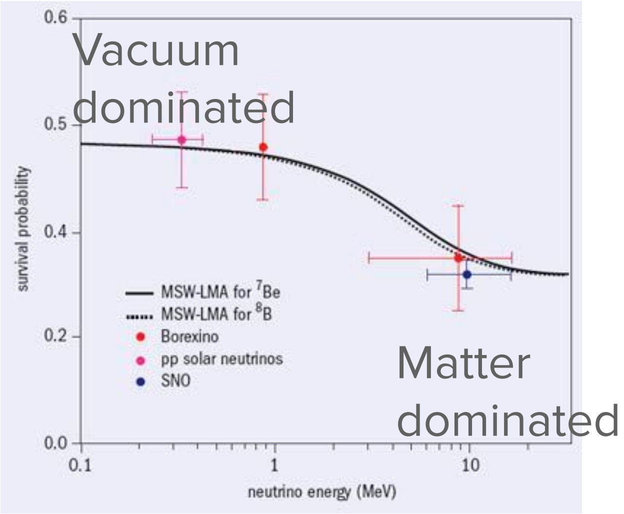
Neutrino mixing in matter

- The charged-current scattering of ν_e on electrons in matter can modify the vacuum oscillations
- The vacuum Hamiltonian is modified by some potential and thus the neutrinos behave with a different effective mass
- In a very dense environment (e.g., the sun) it can be shown that the average survival probability (for E > 5 MeV)

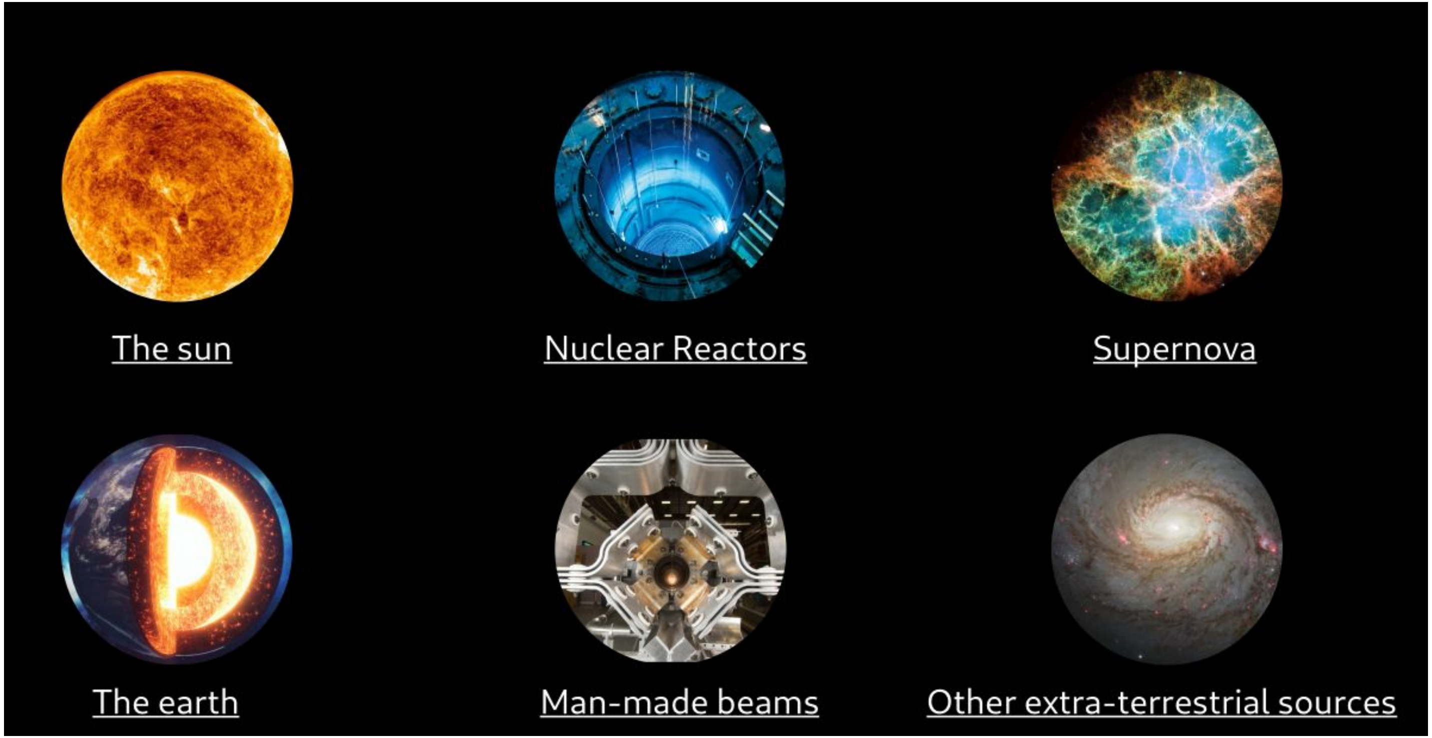
$$P_{ee} = \sin^2 \theta_s$$

- For low energy solar neutrino the matter effect is negligible (size of the solar core is much larger than the oscillation lengths)

See detailed treatment in: Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti and Chung W. Kim



Neutrino sources



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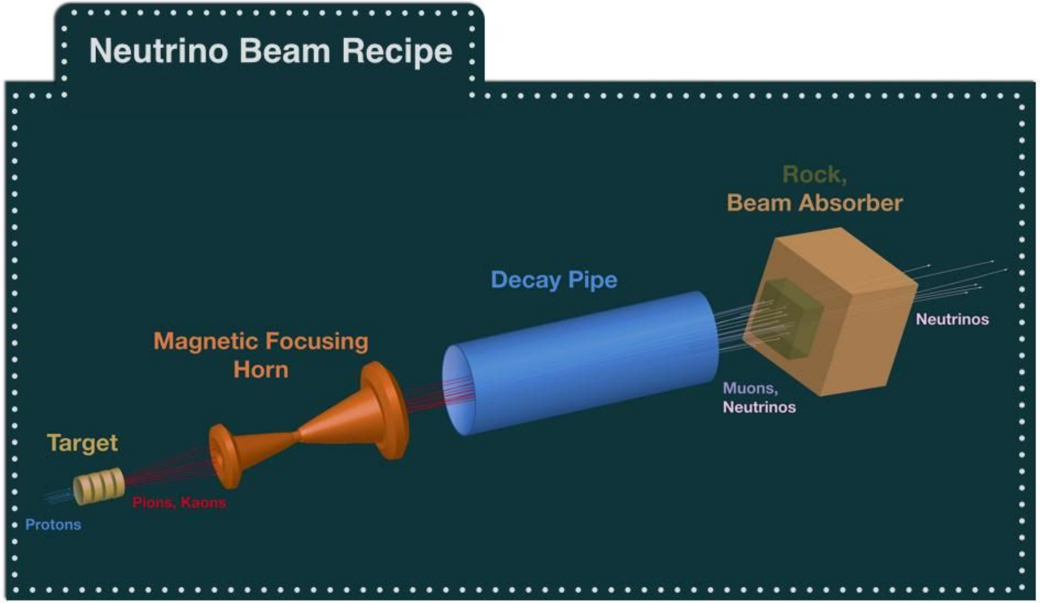
Brief aside: neutrino "beams"

- It is possible to create man-made beams of neutrinos at particle accelerators, which have been used to great effect to do neutrino oscillation physics (control of L/E).



Principles of neutrino detection

- Detectors should be very large (small cross-sections) and deep underground (cosmic ray muons are a dangerous background).
- Target material must produce an observable signal from neutrino interactions.

For low energy neutrinos (0.1 - 20 MeV, e.g., solar or reactor neutrinos):

- Detectors must be ultra-clean to reduce backgrounds from radiological signals

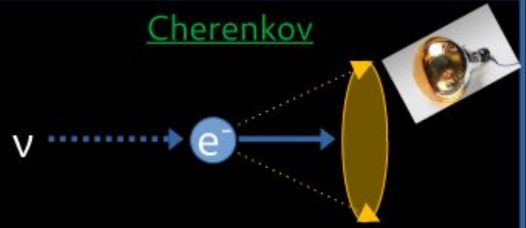
For high energy neutrinos (0.1 - 10 GeV, e.g., atmospheric or beam neutrinos):

- Particle tracking becomes important in complicated interactions with the nucleus

Neutrino detection principles

Deep underground, enormous, monolithic neutrino detectors

Cherenkov



~100s optical photons / MeV

Directional, high threshold

Neutrino detection principles

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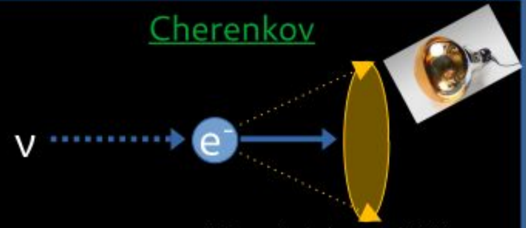

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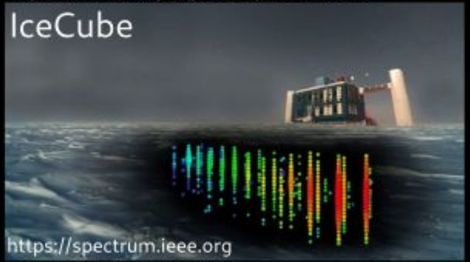
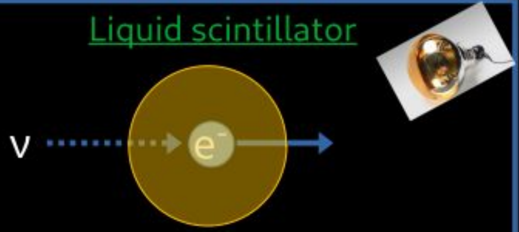


Directional, high threshold

Liquid scintillator



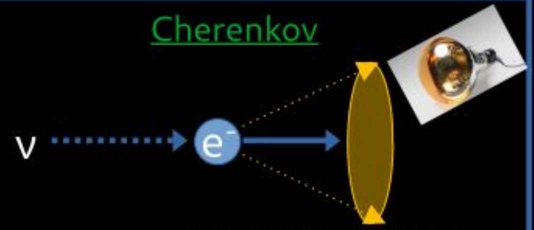
~10,000 optical photons / MeV

Low threshold, good res., no direction

Neutrino detection principles

Deep underground, enormous, monolithic neutrino detectors

Cherenkov



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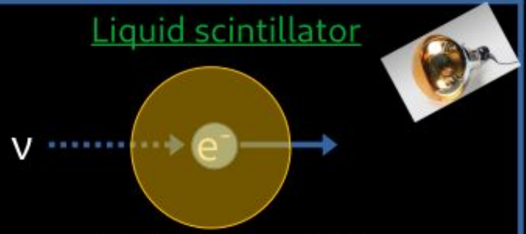

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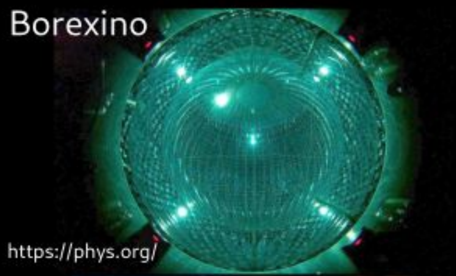
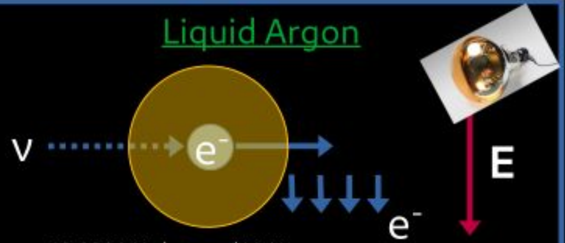


Low threshold, good res., no direction

Liquid Argon



~10,000 UV photons / MeV

Excellent 3D reconstruction

What are the remaining mysteries?

1. A precision era of neutrino physics has determined many of the neutrino oscillation parameters; however there are still a few unknown parameters: δ_{cp} and the mass ordering.
2. Neutrino oscillations have clearly established that neutrinos have mass, but what are their masses and how do they get their mass (e.g., through the Higg's mechanism)?
3. Is the neutrino a Dirac or Majorana particle?
4. Is the three neutrino paradigm complete? Experimental hints of more than three neutrinos.
5. What else about the universe can we learn by studying neutrinos?

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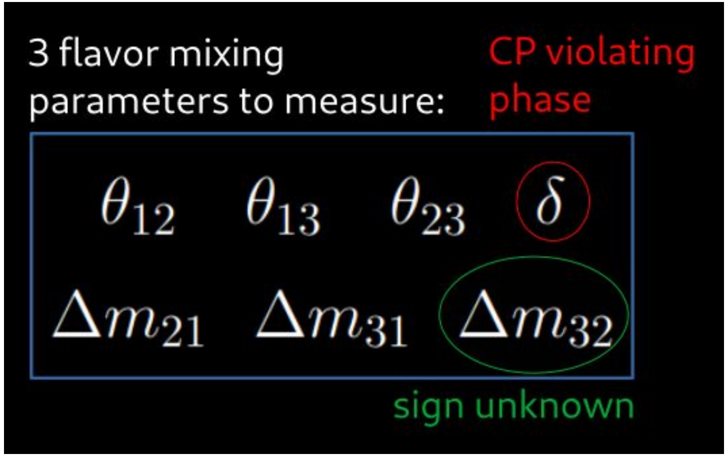
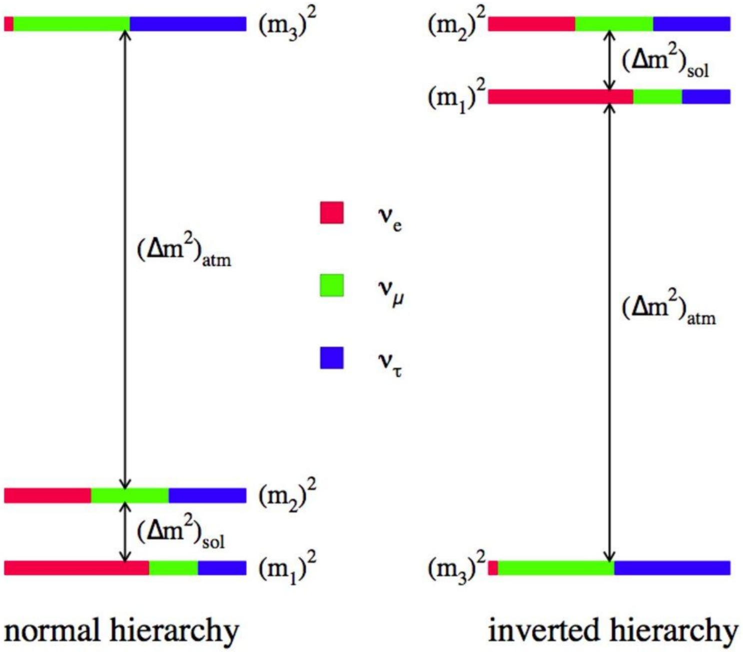
Unknown oscillation parameter: mass hierarchy

- The ordering of the neutrino masses:
  $m_1 < m_2 < m_3$
  $m_3 < m_1 < m_2$
  is unknown.





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- The JUNO experiment in China will likely be the first to measure the neutrino mass hierarchy.

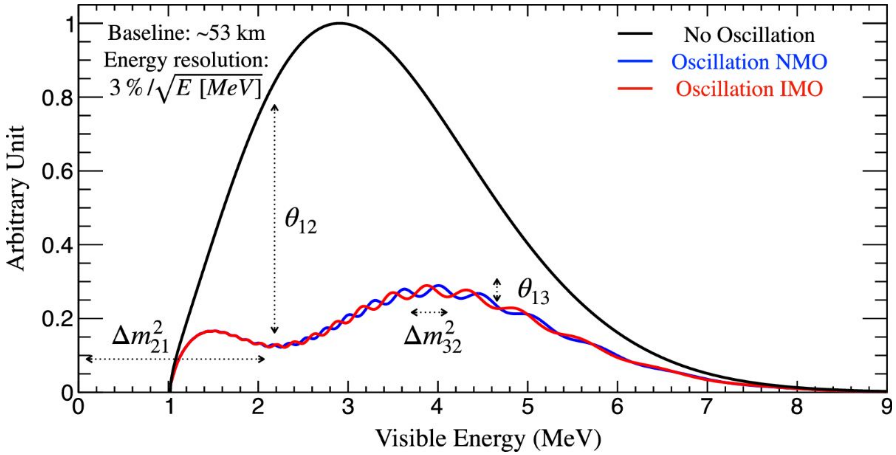
20 kiltonne scintillation detector

Unknown oscillation parameter: mass hierarchy

- The ordering of the neutrino masses:
  $m_1 < m_2 < m_3$
  $m_3 < m_1 < m_2$
  is unknown.

- The JUNO experiment in China will likely be the first to measure the neutrino mass hierarchy.

- The determination is important for future measurements of supernova, neutrinoless double beta decay, etc.



https://arxiv.org/abs/2008.11280

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Unknown oscillation parameter: δ_{cp}

- A non-(zero/pi) value of δ_{cp} would indicate that neutrinos and antineutrinos oscillate differently, and would violate CP symmetry.

$$\Delta P_{\nu\bar{\nu}\,\alpha\beta} \equiv P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = -16 J_{\alpha\beta} \sin\Delta_{12} \sin\Delta_{23} \sin\Delta_{31}$$

$$J_{\alpha\beta} \equiv \Im(U_{\alpha 1} U^*_{\alpha 2} U^*_{\beta 1} U_{\beta 2}) = \pm J, \quad J \equiv s_{12} c_{12} s_{23} c_{23} s_{13} c^2_{13} \sin\delta$$

Jarlskog Invariant

- The determination of this parameter has implications for questions about baryogenesis (matter/antimatter asymmetry) [the Sakharov conditions for baryogenesis require CP violation]

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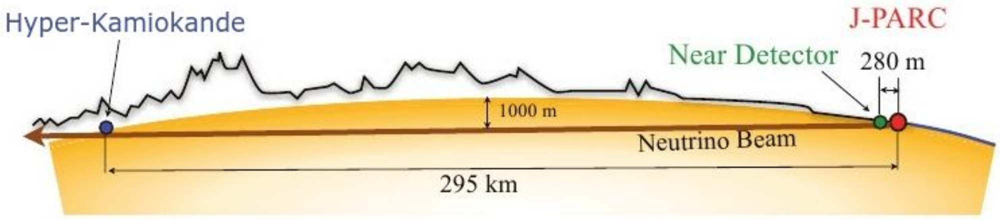
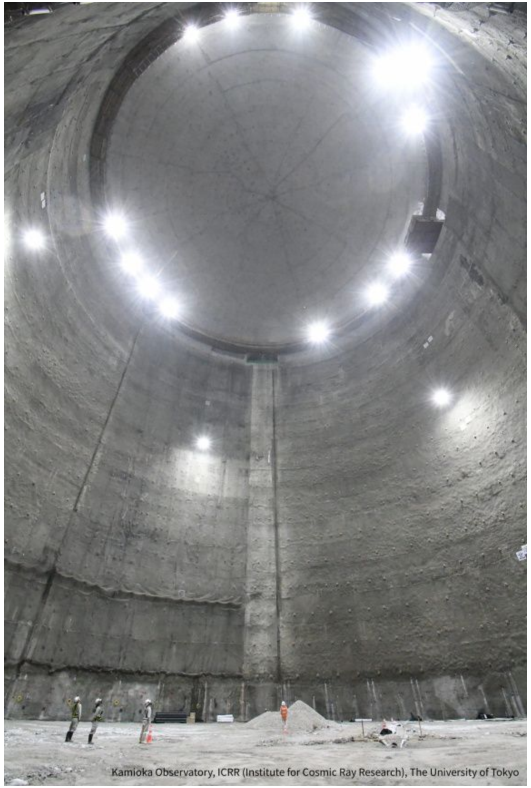
Hyper-Kamiokande

- Upgrade to the Super-Kamiokande detector with 260 kilotonne water target.

- Powerful neutrino beam created at J-PARC, capable of neutrino and antineutrino modes.





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Hyper-Kamiokande

- Sensitive to δ_{cp}, neutrino mass hierarchy, and precision measurements of other oscillation parameters (θ_{23})

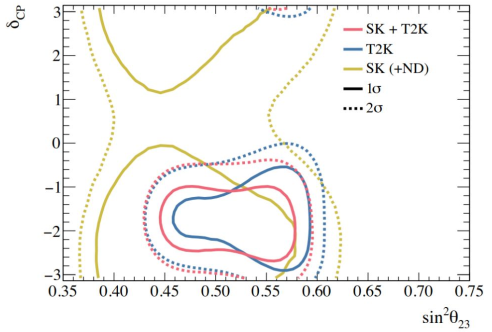
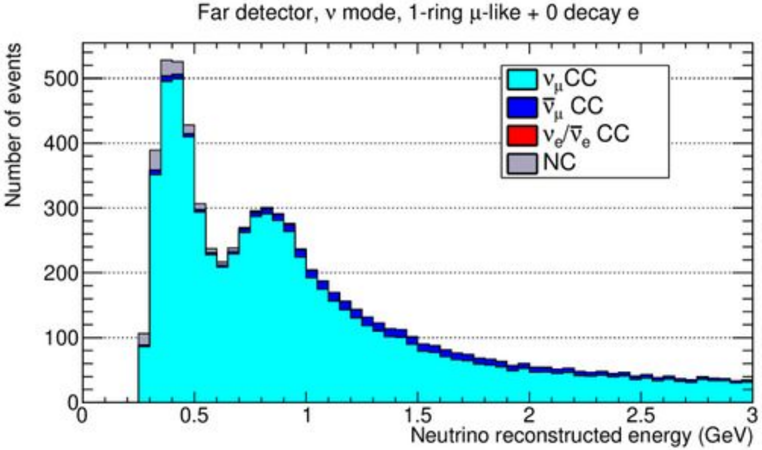
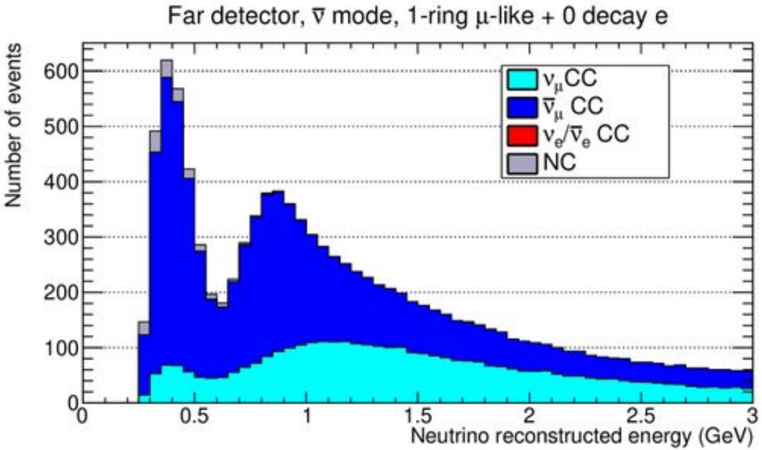


FIG. 1. The ($\sin^2\theta_{23}$, δ_{CP}) credible regions obtained with the SK, T2K, and combined datasets. The MO is marginalized over and a prior uniform in δ_{CP} is used.

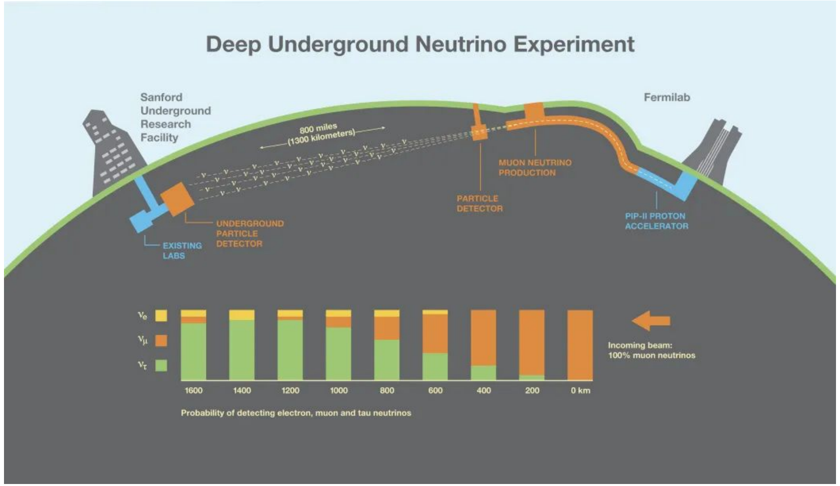


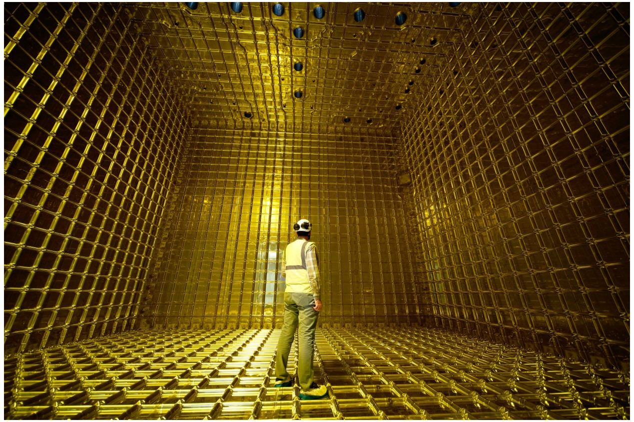


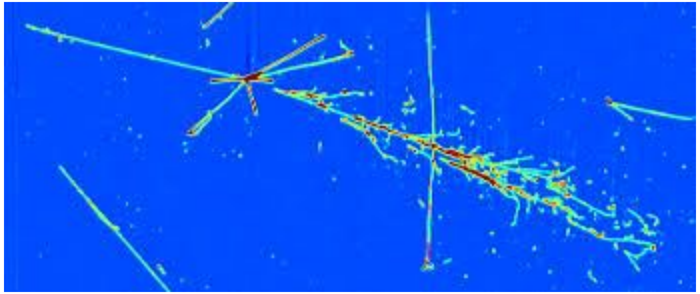
https://arxiv.org/html/2505.15019v1

DUNE

- Flagship US particle physics experiment for the coming decades
- Neutrino beam created at Fermilab capable of neutrino & antineutrino modes
- Using liquid argon time-projection chamber as the far detector, in South Dakota







Event display for LAr TPC.

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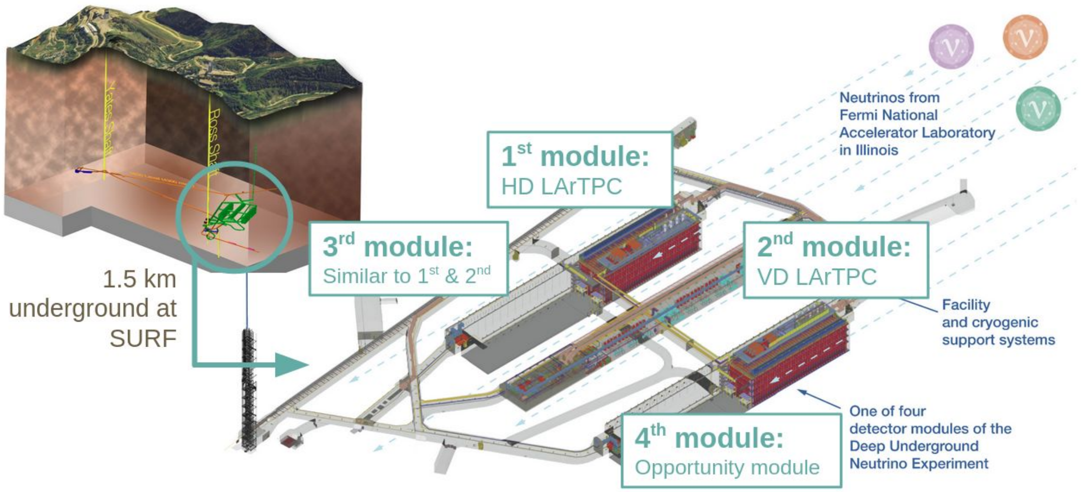
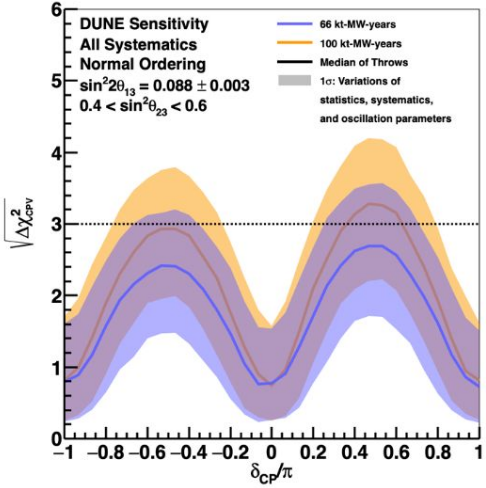
DUNE

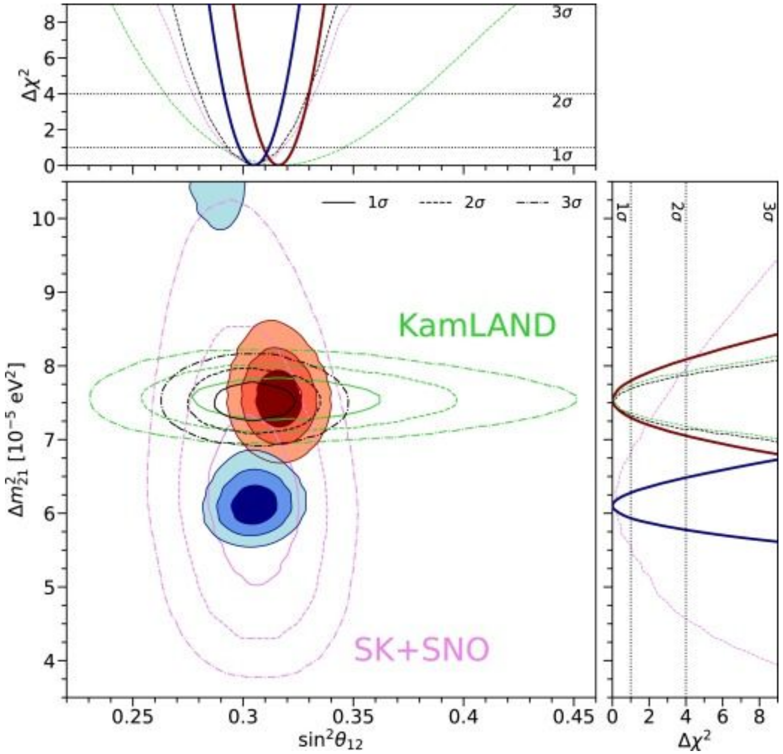
- Far detector location consists of four separate caverns, each to be used for a single detector.
- Primary goal is precision measurement of δ_{cp}





https://arxiv.org/pdf/2109.01304

A brief aside: remaining tension in oscillation results



https://arxiv.org/abs/2307.09509

What are the remaining mysteries?

1. A precision era of neutrino physics has determined many of the neutrino oscillation parameters; however there are still a few unknown parameters: δ_{cp} and the mass ordering.
2. **Neutrino oscillations have clearly established that neutrinos have mass, but what are their masses and how do they get their mass (e.g., through the Higg's mechanism)?**
3. Is the neutrino a Dirac or Majorana particle?
4. Is the three neutrino paradigm complete? Experimental hints of more than three neutrinos.
5. What else about the universe can we learn by studying neutrinos?

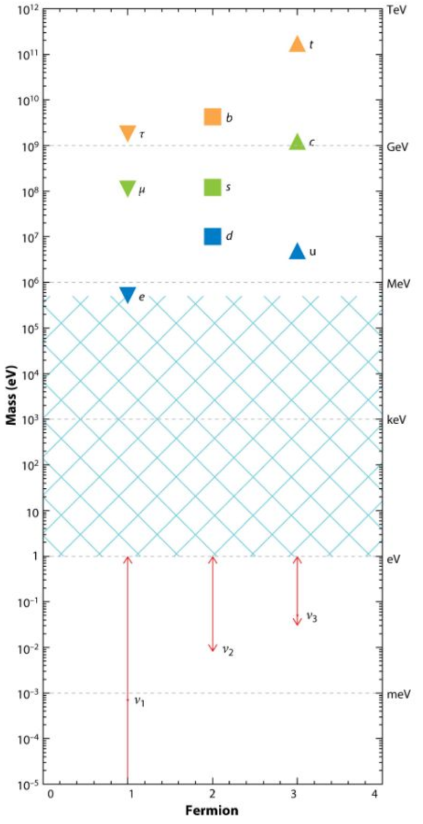
Neutrino mass

- The standard model treats neutrinos as massless, but neutrino oscillations imply small, but non-zero masses.

- The neutrino masses are 6-9 orders of magnitude smaller than the other fermions.

- How do the neutrinos get their mass? Why are they so much smaller?

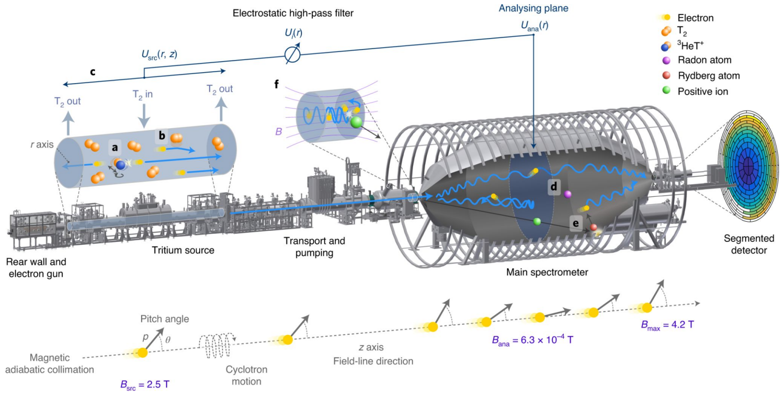
"Neutrino mass is by far the most important subject of study in neutrino physics." Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti and Chung W. Kim



de Gouvêa A. 2016.
Annu. Rev. Nucl. Part. Sci. 66:197–217

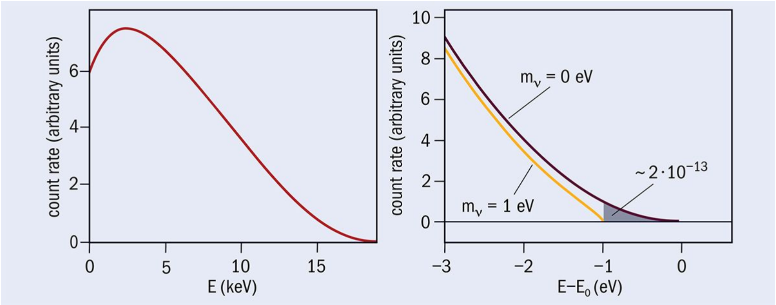
Neutrino mass measurements

- Direct neutrino mass measurements (e.g., KATRIN) rely on incredibly precise measurements of electrons emitted in beta decays (tritium, Q = 18.6 keV)



- Rate of decays at endpoint proportional to neutrino mass

$$N_s = rt \sum_{i=1,3} |U_{ei}|^2[(\Delta E)^2 - m_i^2]^{3/2}$$
$$\simeq rt(\Delta E)^3 \left[1 - \frac{3}{2}\frac{\sum_{i=1,3}|U_{ei}|^2 m_i^2}{(\Delta E)^2}\right].$$



- Current best limits on the neutrino mass are 0.45 eV

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Neutrino mass: Dirac

- The typical way to include mass in the Standard Model is through a Dirac mass, but this term requires both left and right chiral terms in the Lagrangian. In order to include a Dirac neutrino mass into the SM, one needs only introduce a right-handed component of the neutrino field (minimally extended Standard Model).

- The neutrinos would get their mass in the same way as the other leptons: through the SM Higgs mechanism.

- But then why are the Yukawa couplings so small? And why are there sterile left-handed neutrinos that do not participate in interactions?

Neutrino mass: Majorana

- Because the neutrino is neutral (unlike the other fermions) it is possible that it is a Majorana particle. Majorana particles are defined by the condition that their wavefunctions are not effect by charge conjugation (the particle and the antiparticle are equal).
- With Majorana masses, it is possible to write a mass term with only left-handed neutrinos (two-component spinor).
- Majorana neutrino with negative helicity = neutrino
- Majorana neutrino with positivity helicity = antineutrino

See-saw mechanism a “natural” explanation of small neutrino masses, requires Majorana mass terms at GUT scale. (see: https://arxiv.org/pdf/2305.00994)

See excellent treatment in: Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti and Chung W. Kim
See slides here: https://www.to.infn.it/~giunti/slides/2010/giunti-1005-phd-to-4.pdf

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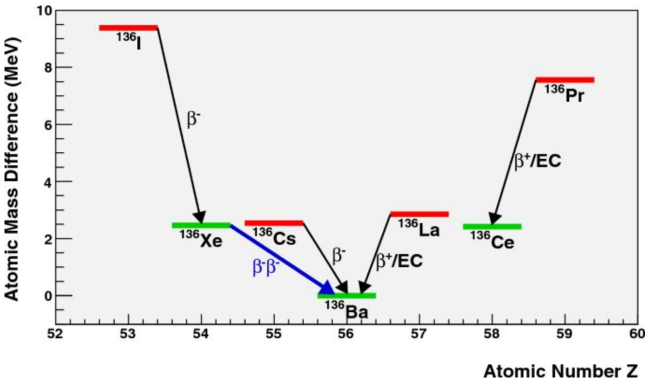
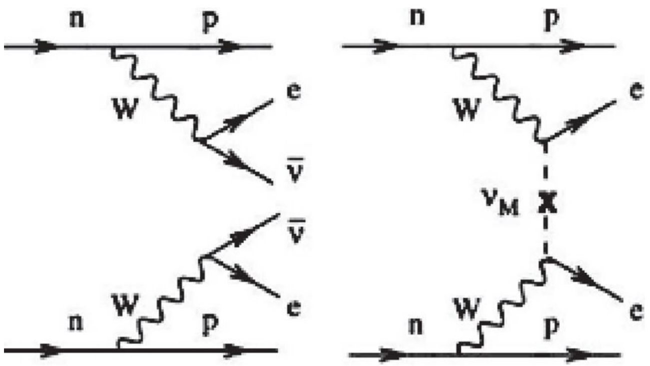
0νββ

- The most promising method for searching for measuring Majorana neutrinos is a process called neutrinoless double beta decay (0νββ).
- Standard model process called double beta decay (2νββ) known to occur in a handful of isotopes
- Rates of 2νββ are extremely small (half-lives on the order of 10^{21} years)
- Process can be mediated by new physics, simplest version is light neutrino exchange*.
- Violates lepton number conservation by two units.



2νββ

0νββ



*more details: https://arxiv.org/pdf/2108.09364

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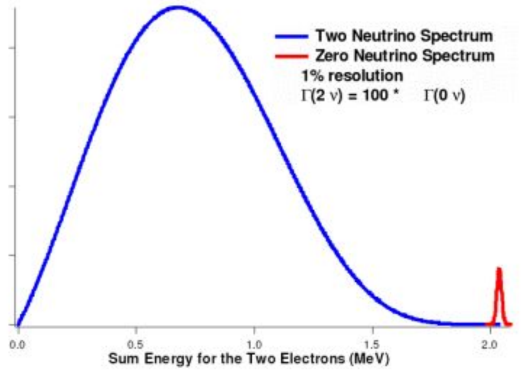
0νββ

- Experimental signature is a bump at the endpoint energy of the 2νββ signal.
- Decay rate for 0νββ is proportional to an effective Majorana mass, phase space factor, and matrix element



$$\Gamma^{0\nu}_{\beta\beta} = \frac{1}{T^{0\nu}_{\beta\beta}} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta}\rangle^2$$

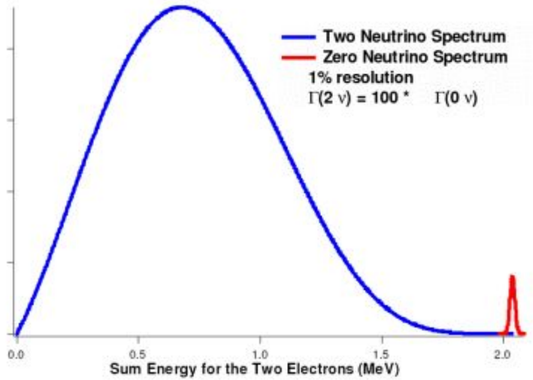
$$\langle m_{\beta\beta}\rangle = \sum_i U_{ei}^2 m_i$$

Uncertainties are a factor of 2 or larger.

2νββ isotopes

Nuclide	Half-life, 10^{21} years	Mode	Transition	Method	Experiment
^{48}Ca	$0.064^{+0.007}_{-0.006} \pm ^{+0.012}_{-0.009}$	$\beta^-\beta^-$		direct	NEMO-3[12]
^{76}Ge	1.926 ± 0.094	$\beta^-\beta^-$		direct	GERDA[11]
^{78}Kr	$9.2^{+5.5}_{-2.6} \pm 1.3$	εε		direct	BAKSAN[11]
^{82}Se	$0.096 \pm 0.003 \pm 0.010$	$\beta^-\beta^-$		direct	NEMO-3[11]
^{96}Zr	$0.0235 \pm 0.0014 \pm 0.0016$	$\beta^-\beta^-$		direct	NEMO-3[11]
^{100}Mo	0.00693 ± 0.00004	$\beta^-\beta^-$		direct	NEMO-3[11]
	$0.69^{+0.10}_{-0.08} \pm 0.07$	$\beta^-\beta^-$	$0^+ \to 0^+_1$		Ge coincidence[11]
^{116}Cd	$0.028 \pm 0.001 \pm 0.003$ $0.026^{+0.009}_{-0.005}$	$\beta^-\beta^-$		direct	NEMO-3[11] ELEGANT IV[11]
^{128}Te	7200 ± 400 1800 ± 700	$\beta^-\beta^-$		geochemical	[11]
^{130}Te	$0.82 \pm 0.02 \pm 0.06$	$\beta^-\beta^-$		direct	CUORE-0[13]
^{124}Xe	$11 \pm 2 \pm 1$	εε		direct	XENON1T[14]
^{136}Xe	$2.165 \pm 0.016 \pm 0.059$	$\beta^-\beta^-$		direct	EXO-200[11]
^{130}Ba	(0.5 – 2.7)	εε		geochemical	[15][16]
^{150}Nd	$0.00911^{+0.00025}_{-0.00022} \pm 0.00063$	$\beta^-\beta^-$		direct	NEMO-3[11]
	$0.107^{+0.046}_{-0.026}$	$\beta^-\beta^-$	$0^+ \to 0^+_1$		Ge coincidence[11]
^{238}U	2.0 ± 0.6	$\beta^-\beta^-$		radiochemical	[11]

0νββ experimental requirements



1. Isotope known to undergo 2νββ
2. Extremely good energy resolution
3. Very low backgrounds around the endpoint
4. Significant amounts of isotope

There are many excellent technologies employed by a variety of detector around the world to search for 0νββ. I will focus on the detector that I work on: SNO+.

Ideally: many detector technologies and many different isotopes.

$$\Gamma^{0\nu}_{\beta\beta} = \frac{1}{T^{0\nu}_{\beta\beta}} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta}\rangle^2$$

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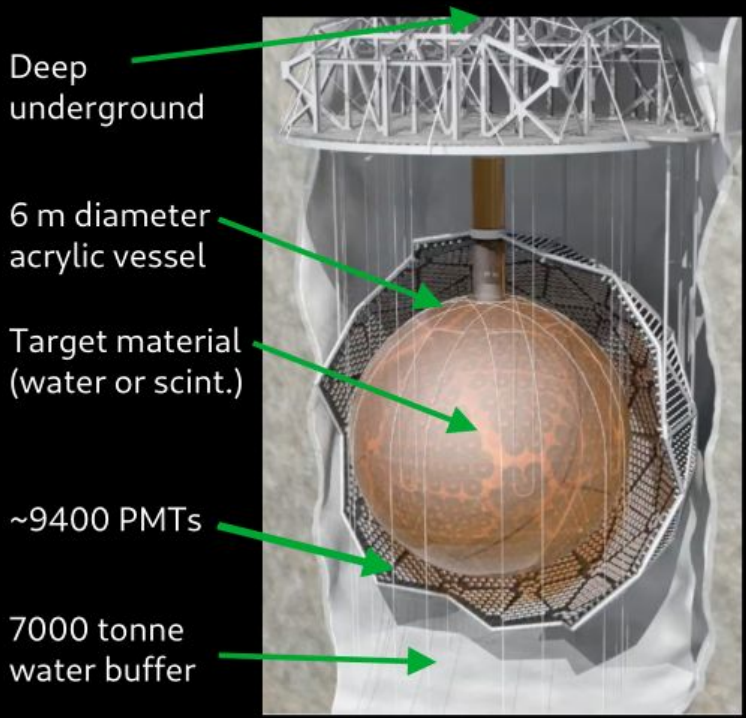
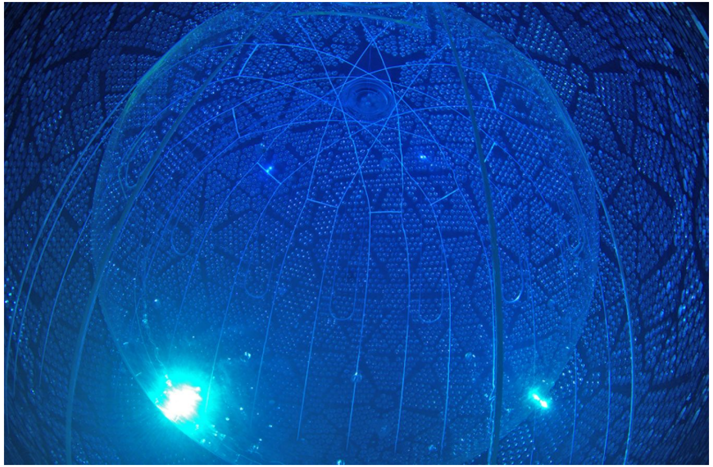
SNO+

- SNO+ is a ktonne-scale neutrino detector, upgraded from SNO, located underground (6010 m.w.e overburden) in Sudbury, Ontario



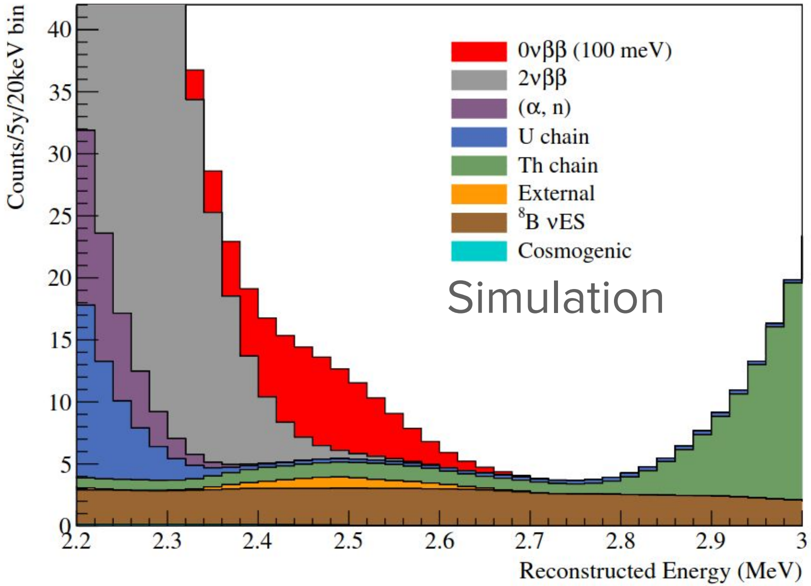
SNO+ as a 0νββ detector



- The SNO detector was upgraded, starting in 2014, to fill with liquid scintillator.
- Plan to load the scintillator with natural tellurium (34% ^{130}Te) next year.
- Advantages: Enormous detector allows for large amounts of isotope. Very broad program of neutrino physics simultaneous to 0νββ search.
- Disadvantages: Relatively poor energy resolution and higher backgrounds at the endpoint.

Double-beta candidate	Q-value (MeV)	Phase space $G_{01}(y^{-1})$	Isotopic abundance (%)	Enrichable by centrifugation	Indicative cost normalized to Ge
^{48}Ca	4.27226 (404)	6.05×10^{-14}	0.187	No	—
^{76}Ge	2.03904 (16)	5.77×10^{-15}	7.8	Yes	1
^{82}Se	2.99512 (201)	2.48×10^{-14}	9.2	Yes	1
^{96}Zr	3.35037 (289)	5.02×10^{-14}	2.8	No	—
^{100}Mo	3.03440 (17)	3.89×10^{-14}	9.6	Yes	1
^{116}Cd	2.81350 (13)	4.08×10^{-14}	7.5	Yes	3
^{130}Te	2.52697 (23)	3.47×10^{-14}	33.8	Yes	0.2
^{136}Xe	2.45783 (37)	3.56×10^{-14}	8.9	Yes	0.1
^{150}Nd	3.37138 (20)	1.54×10^{-13}	5.6	No	—

SNO+ sensitivity



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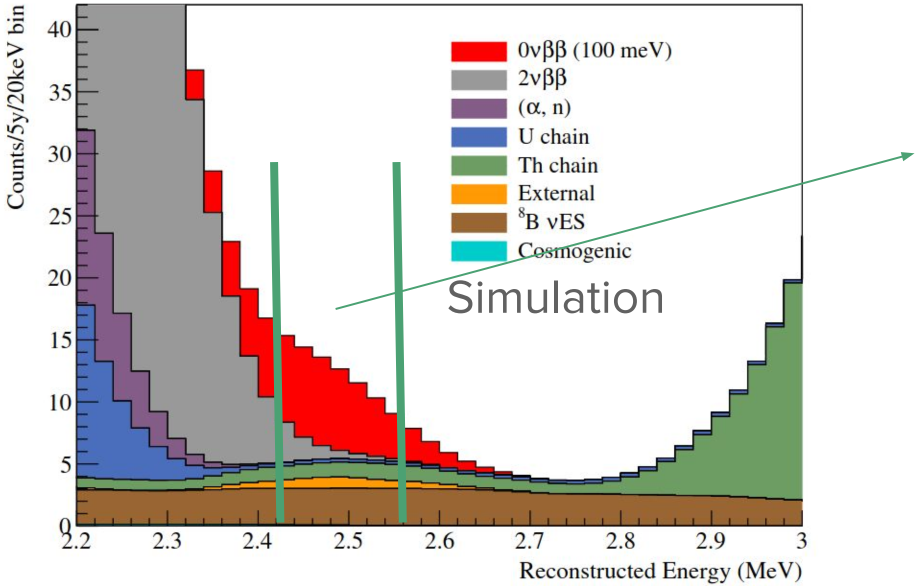
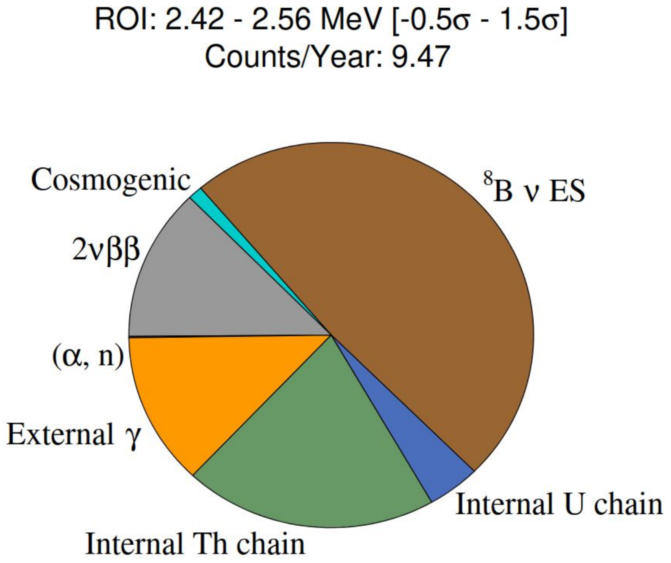
SNO+ sensitivity





5-year 90% C.L. sensitivity:

$T_{1/2} > 2.1 \times 10^{26}$ years

$m_{\beta\beta} < 37 - 89$ meV

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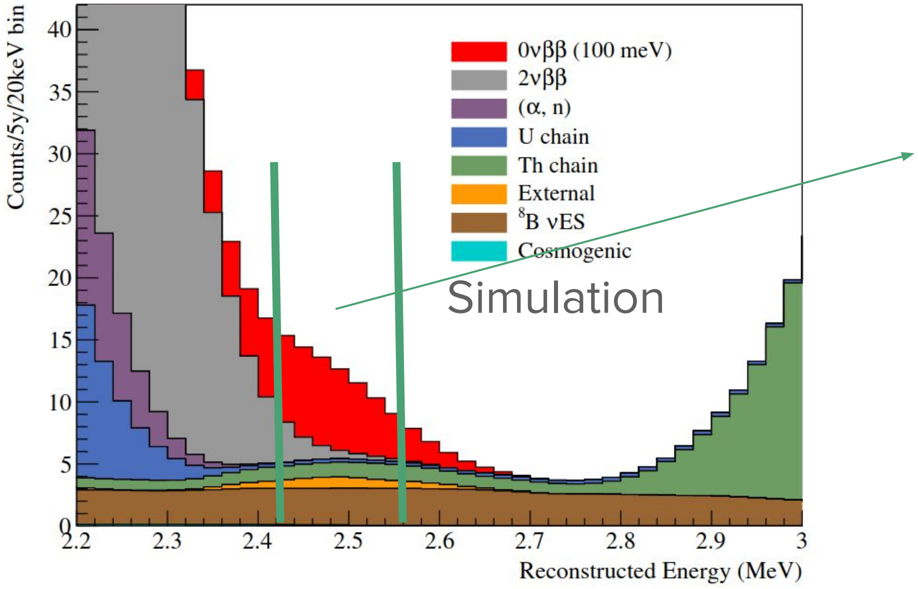
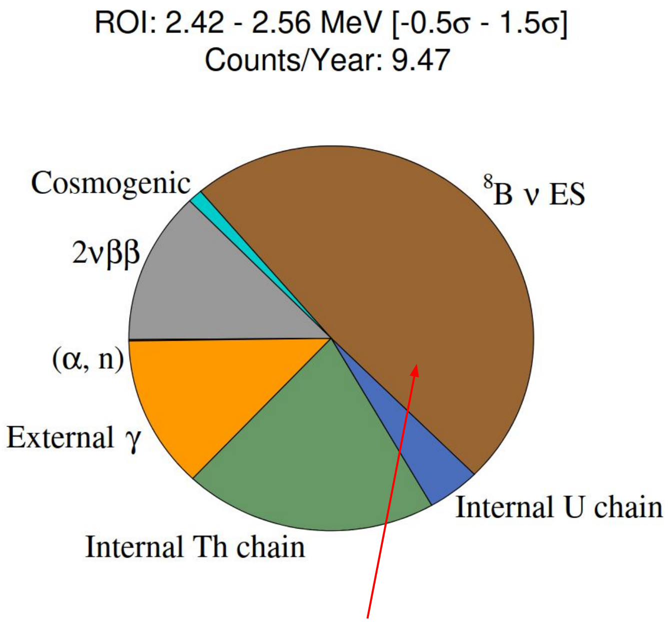
SNO+ sensitivity





5-year 90% C.L. sensitivity:
$T_{1/2} > 2.1 \times 10^{26}$ years
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Largest background is from solar neutrinos

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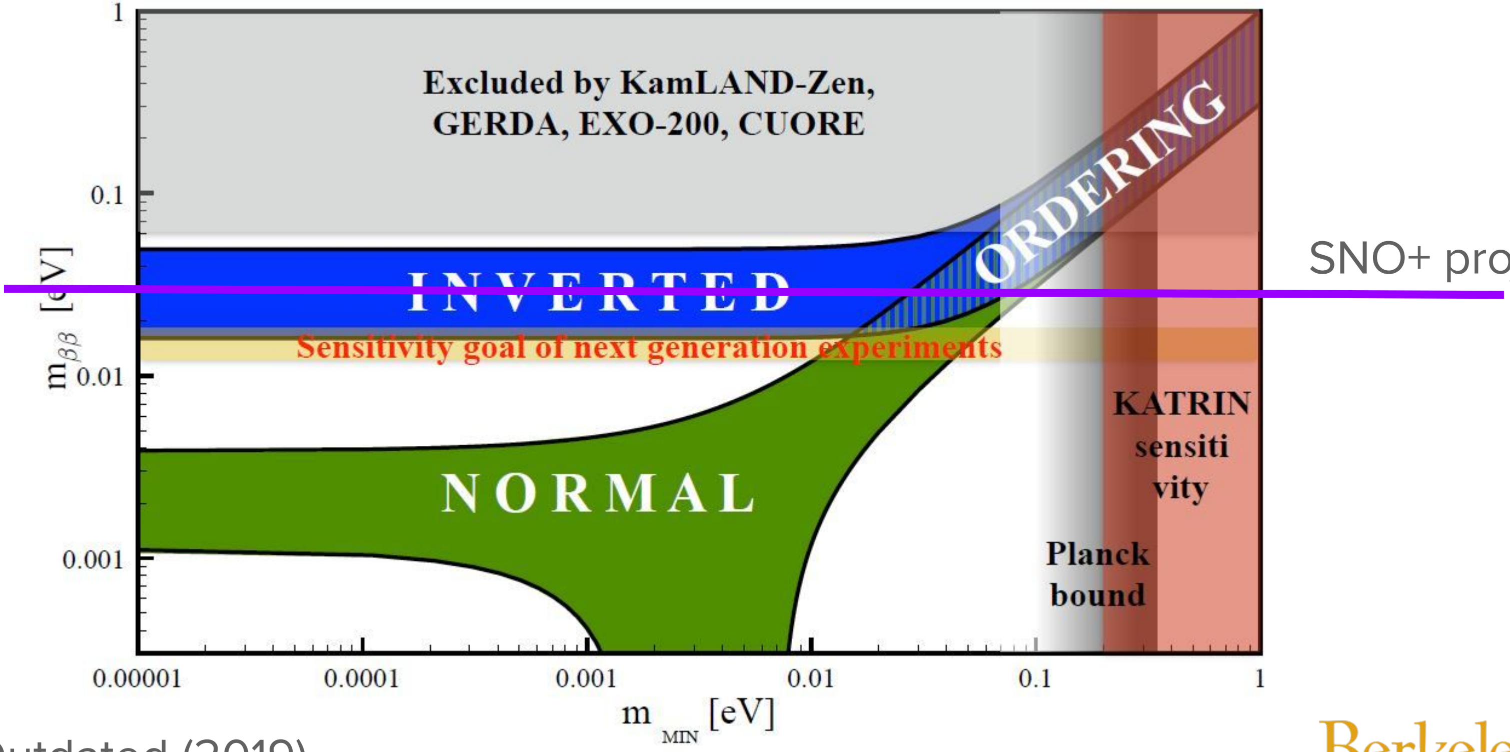
State of the experimental sensitivities



SNO+ projection

Outdated (2019)

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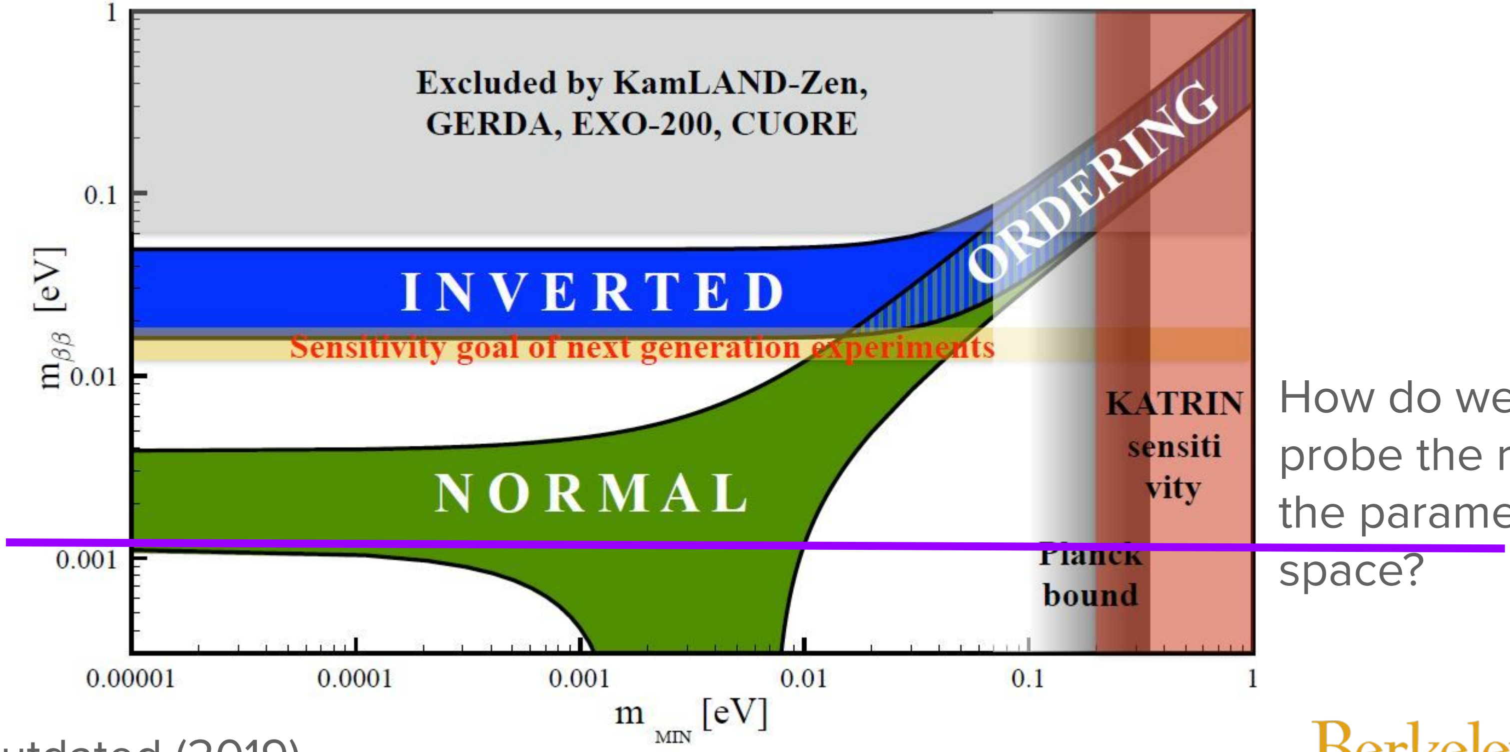
State of the experimental sensitivities



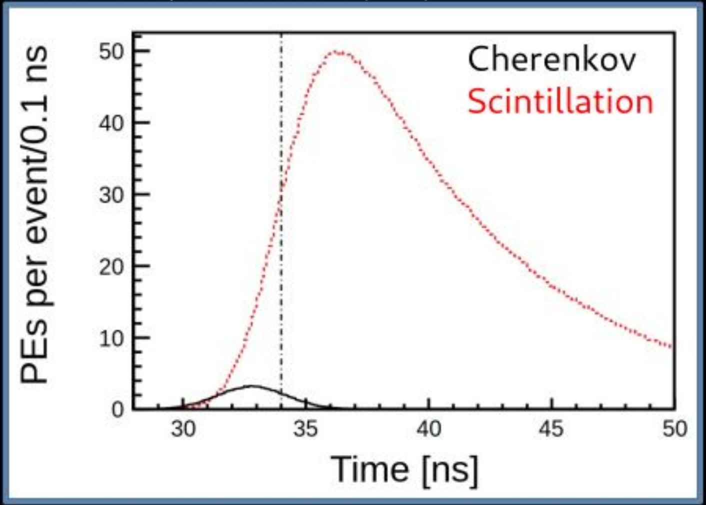
How do we probe the rest of the parameter space?

Outdated (2019)

Improving on SNO+

For future detectors, how can we expand on SNO+ in order to
maximize future physics potential?

C. Aberle et al., JINST 9 P06012 (2014)



Utilize both the Cherenkov and scintillation signals

A high light yield, low-threshold, directional detector, with excellent PID

Challenge: Overwhelming scintillation light yield drowns the Cherenkov signal

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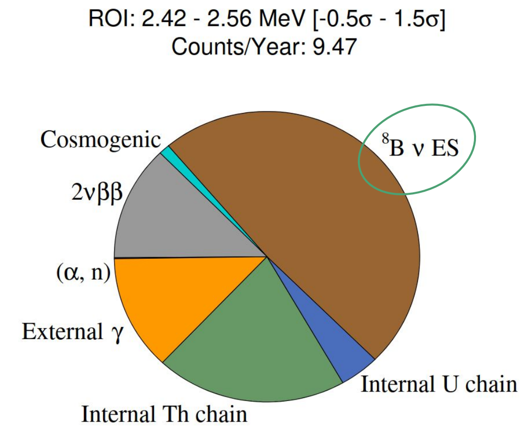

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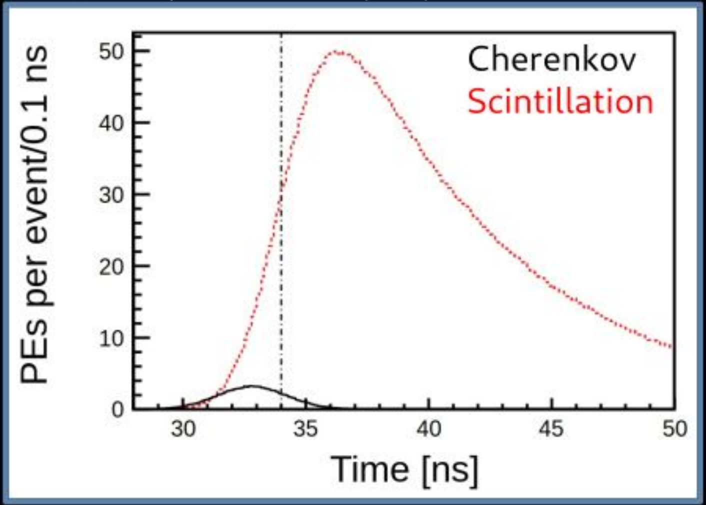

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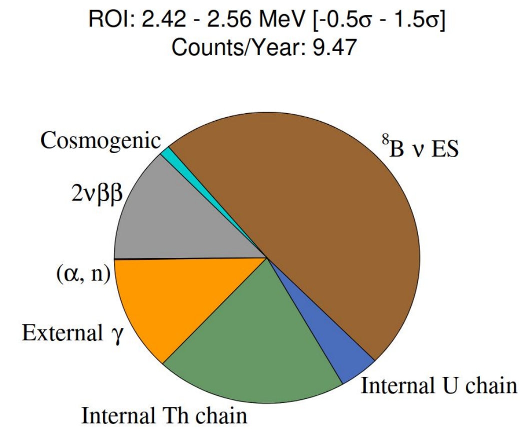

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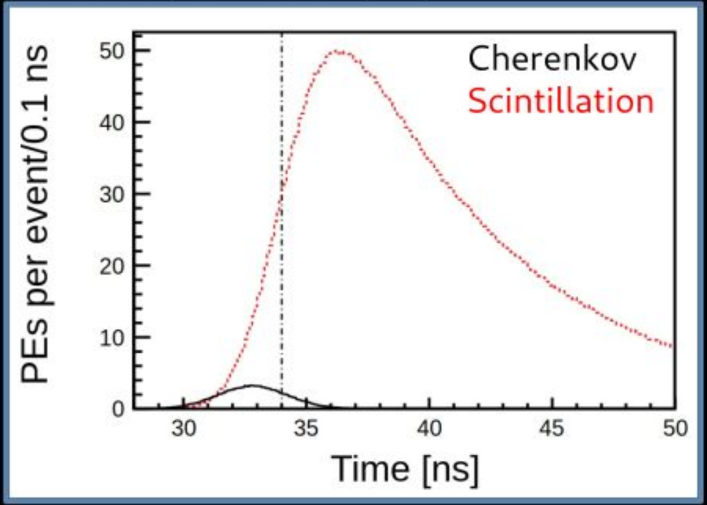

Etcheverry Hall, UC Berkeley

Utilize both the Cherenkov and scintillation signals

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Challenge: Overwhelming scintillation light yield drowns the Cherenkov signal

THEIA

THEIA is an enormous (25-100 kton) proposed scintillation-based neutrino detector that would utilize advanced, hybrid technology to realize a broad physics program

Design:

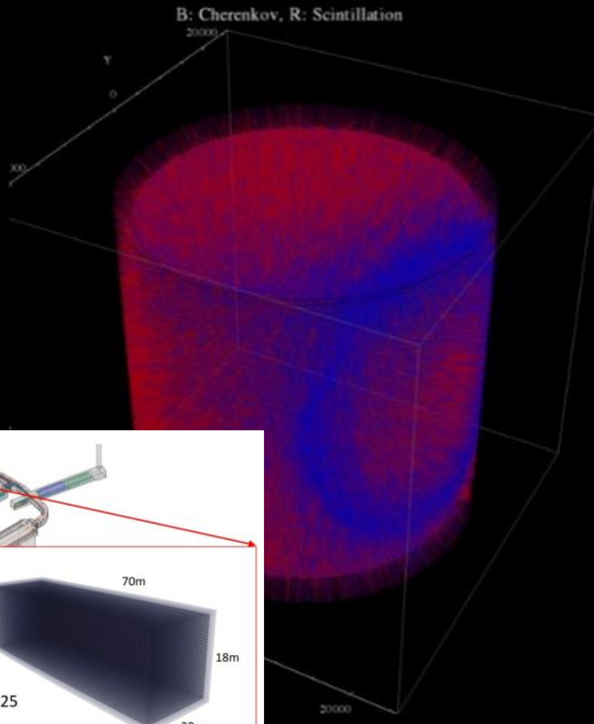
1. Deep underground (e.g., Homestake)

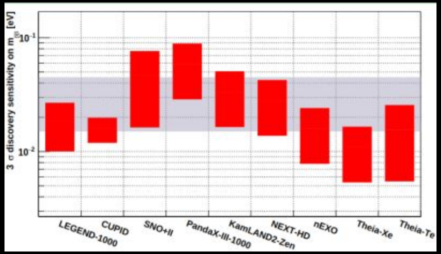
2. Fast, HQE PMTs or LAPPDs, high coverage + dichroicons

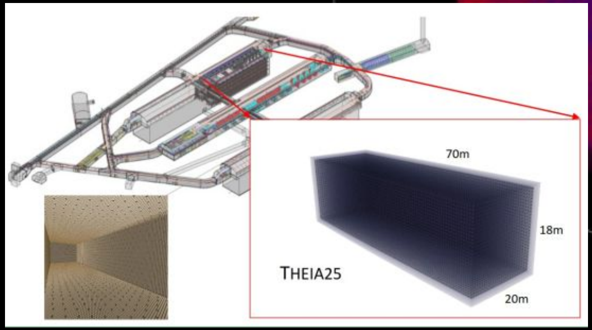
3. Novel target material (e.g., WbLS or slow scint.)

4. Possible isotope loading (e.g., Te, Li, Gd)

5. Flexible!







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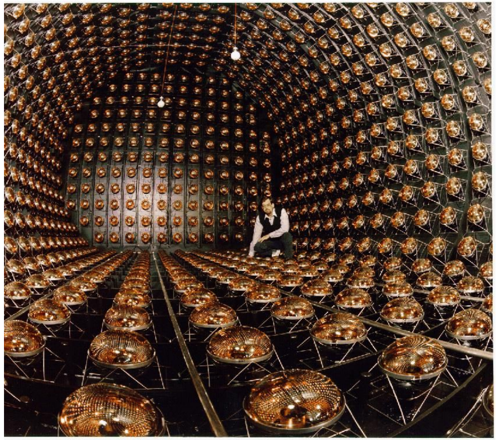
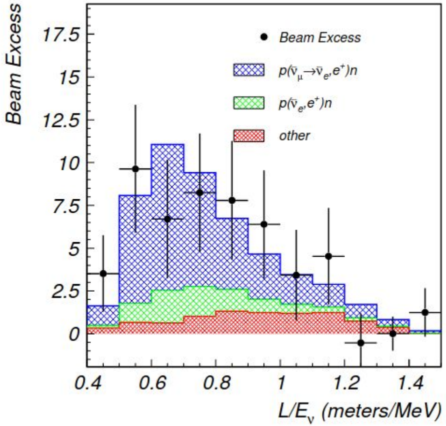
Sterile neutrinos: experimental hints

- LSND (1993) is an experiment consisting of 160 tons of mineral oil, located at Los Alamos about 30 meters from a neutrino source (very pure $\overline{\nu}_{\mu}$ beam).

- Searching for an unexpected oscillation with Δm^2 about 1 meV^2.

- Data is consistent with an excess of electron antineutrinos, suggesting an unexpected oscillation or some other unknown process.





https://arxiv.org/pdf/1306.6494

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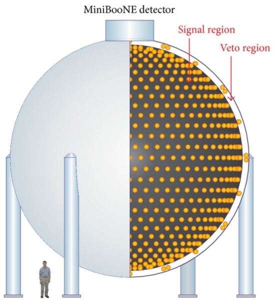
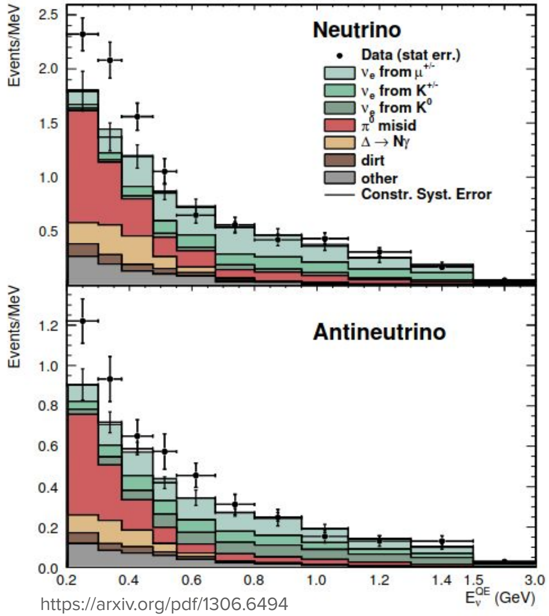
Sterile neutrinos: experimental hints

- MiniBooNE searched for the same signal in 2002 using 800 tonnes of mineral oil located 540 m downstream from a neutrino beam at Fermilab (similar L/E to LSND).

- Capable of running in neutrino and antineutrino mode.

- Identified a similar, but not completely consistent signal to LSND. Both report an excess for muon-flavor to electron flavor appearance signals.





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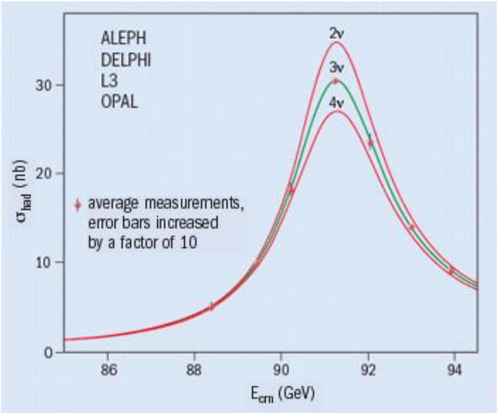
Sterile neutrinos

- One potential explanation for this data is that there is a fourth neutrino contributing to oscillations.

- The fourth neutrino cannot interact via the weak-force (experimentally constrained), but it could be a sterile neutrino that only interacted gravitationally, but participated in oscillations.

- This would introduce new mixing angles, and mass differences that could be measured in oscillation experiments.



$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

More details:
https://arxiv.org/pdf/1306.6494

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Sterile neutrinos

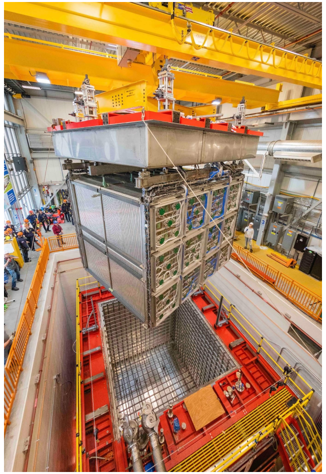
- 3+1 picture has trouble fitting the existing data.

  See review paper: https://arxiv.org/abs/1703.00860

- Many theoretical models have been tried (e.g., 3 + 2 sterile neutrinos, neutrino decay, etc.) but nothing is compelling so far.

Sterile neutrinos: current experiments

- Currently operating suite of detectors at Fermilab to try and finally solve this problem. Same beam as MiniBooNE with different detector technology.



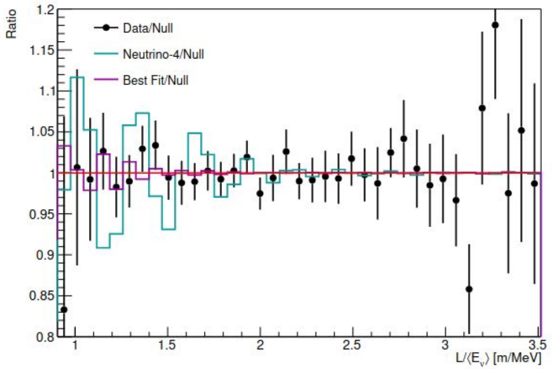
SBND

μBooNE

ICARUS

Sterile neutrinos: very short baseline experiments

- Variety of experiments pushed close to a nuclear reactor to test sterile neutrino hypothesis (e.g., PROSPECT (2024) at HFIR reactor in Oakridge).
- Ability to vary detector location and segment detector (and thus vary L/E)
- No compelling evidence of oscillations from these experiments



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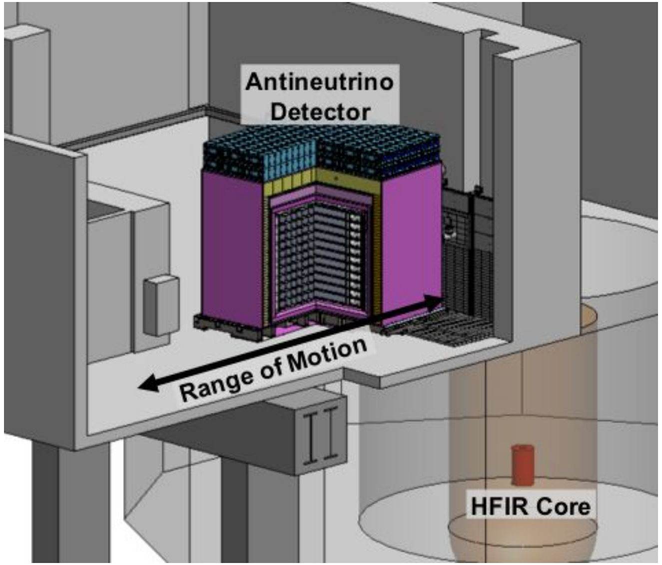

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What are the remaining mysteries?

1. A precision era of neutrino physics has determined many of the neutrino oscillation parameters; however there are still a few unknown parameters: δ_{cp} and the mass ordering.
2. Neutrino oscillations have clearly established that neutrinos have mass, but what are their masses and how do they get their mass (e.g., through the Higg's mechanism)?
3. Is the neutrino a Dirac or Majorana particle?
4. Is the three neutrino paradigm complete? Experimental hints of more than three neutrinos.
5. **What else about the universe can we learn by studying neutrinos?**

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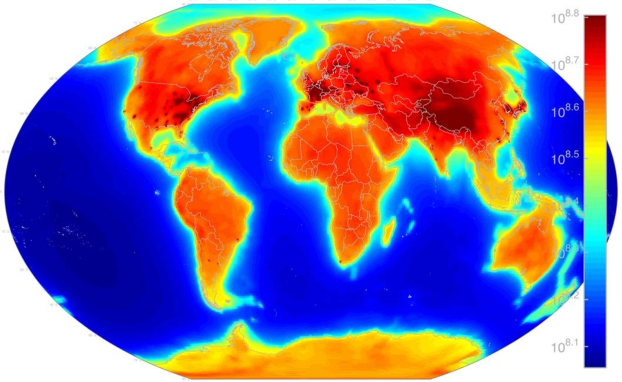
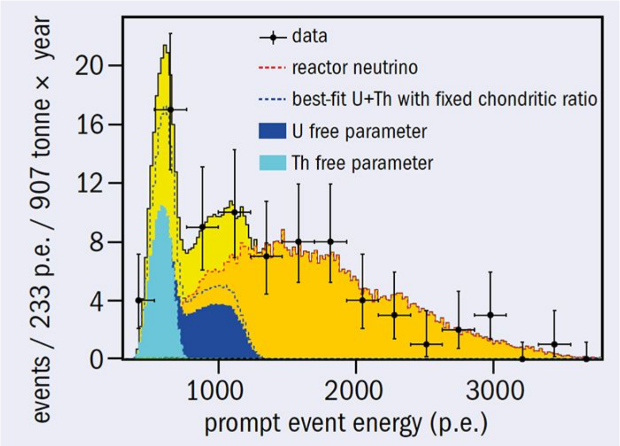
Geoneutrinos



- Neutrinos are produced by the naturally occuring uranium, thorium, and potassium in the Earth's crust and mantle.

- Geological estimates of the composition of the mantle and the relative amount of heat production from radioactive decays vary significantly



- These decays all produce neutrinos, which can be used to measure the content of the Earth's mantle and give information about the heat production within the Earth!

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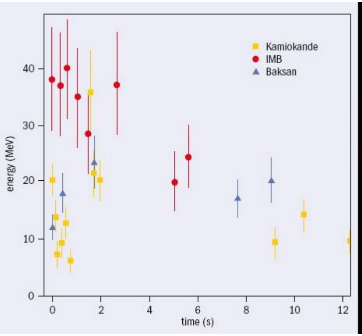
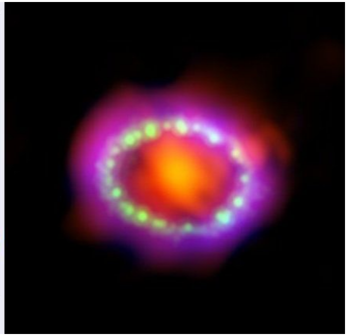
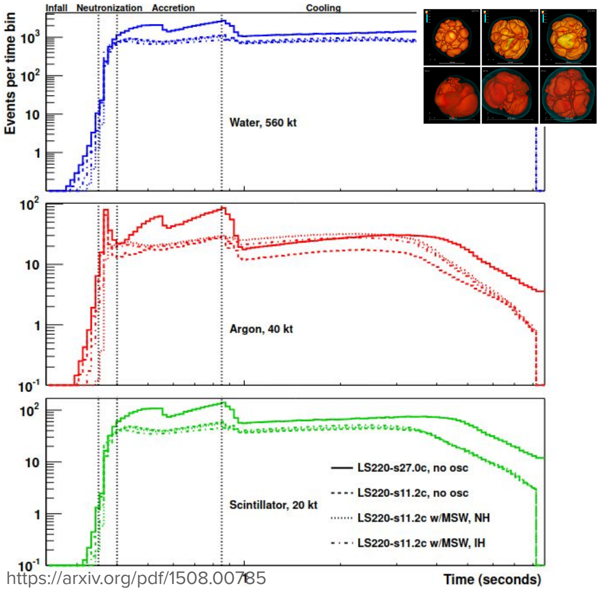
Supernova neutrinos

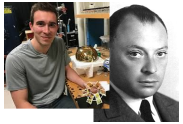




- Only sample of supernova neutrinos comes from the several dozen detected during 1987A.
- There are now a huge number of online neutrino detectors with significantly improved capabilities for observing a measuring the properties (timing, energy, etc) of supernova neutrinos.
- Measuring the energy, flavor composition, and timing of the supernova neutrinos would provide extremely valuable information to better understand the dynamics of solar collapse and would be sensitive to new physics.



https://arxiv.org/pdf/1508.00785



"Thanks for the message. Everything comes to those who know how to wait."

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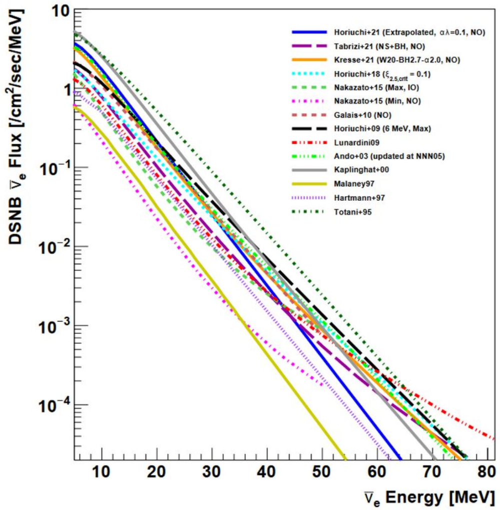
DSNB

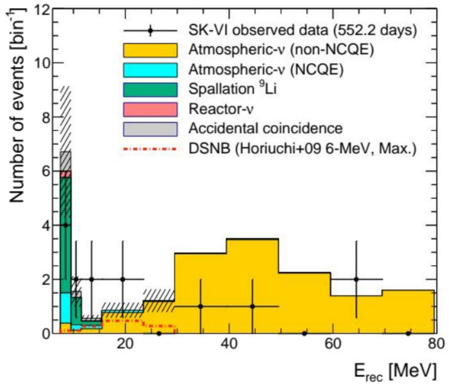
- The diffuse supernova neutrino background (DSNB) is a theoretical population of neutrinos cumulatively originating from all core-collapse supernovae events throughout the history of the universe.

- Many different models with different predictions for the flux, energy spectra, etc.

- First ever measurement with Super-Kamiokande is expected to come soon.

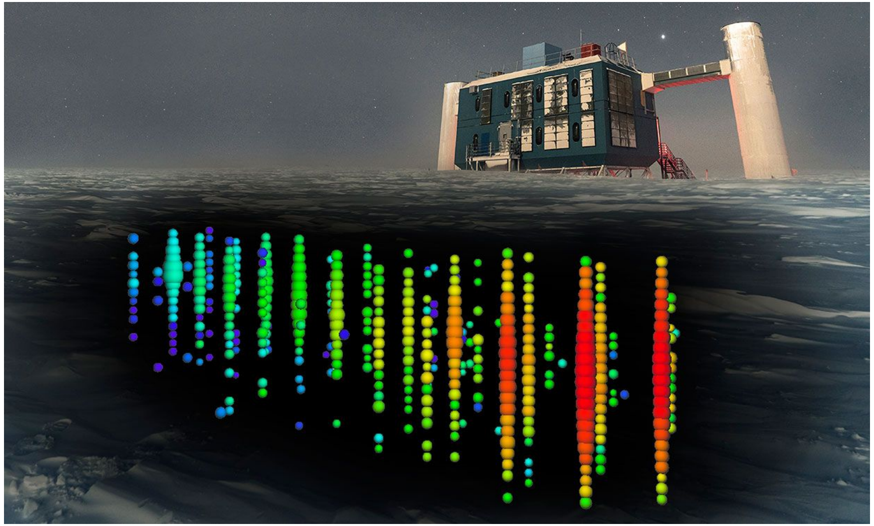


Spectrum-independent analysis (M. Harada)

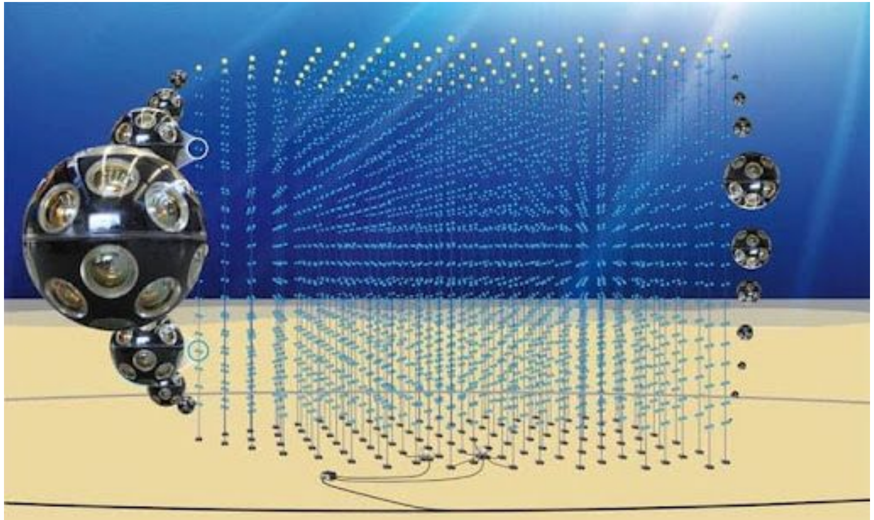


High energy astrophysical neutrinos

- Extremely high energy (> 1 TeV) neutrinos are created when high energy cosmic rays interact in the atmosphere.



Icecube



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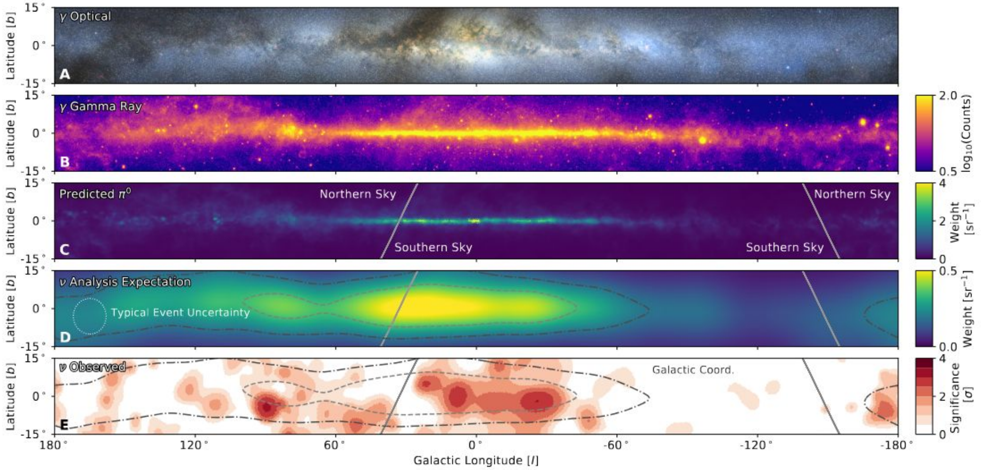
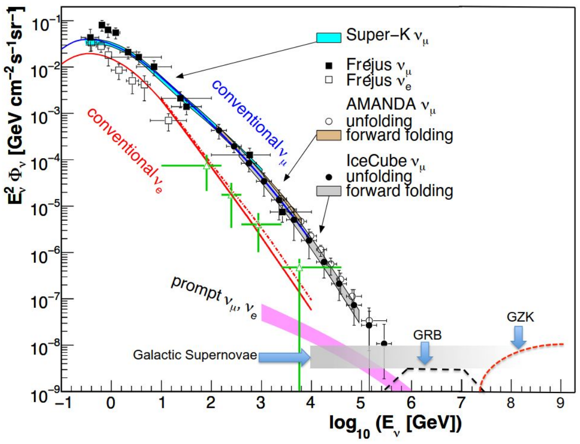
IceCube

- Using Cherenkov light allows for pointing, most precise “neutrino telescope”
- Measuring these high energy cosmic rays helps us understand various astrophysical sources (e.g., black holes, neutron stars, pulsars, etc.)
- Atmospheric neutrino detection sensitive to oscillation parameters, including mass hierarchy.





https://arxiv.org/pdf/2202.00694

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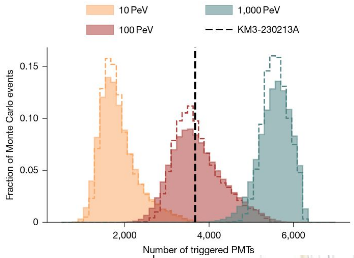
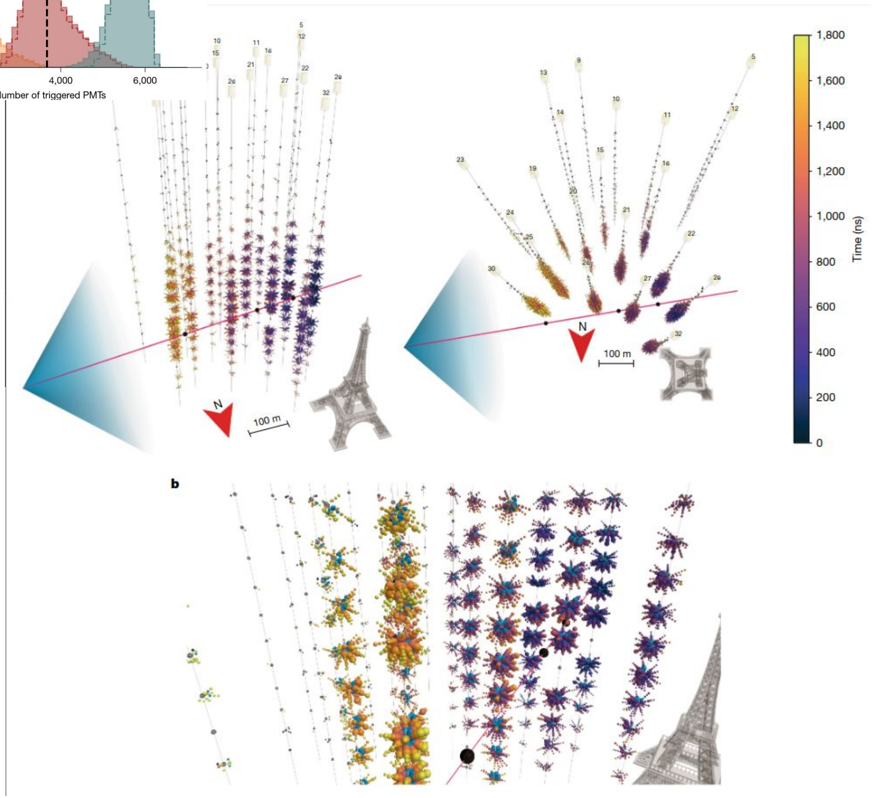
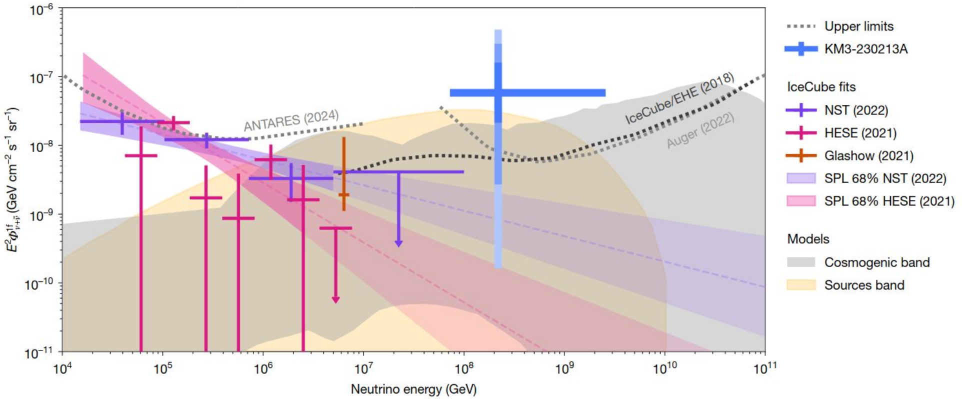
KM3NeT

- Recent measurements of the highest energy neutrino [120 PeV] (Nature paper: https://www.nature.com/articles/s41586-024-08543-1)







https://www.nature.com/articles/s41586-024-08543-1

Questions?