UC Berkeley P290e

How to “see” a neutrino?

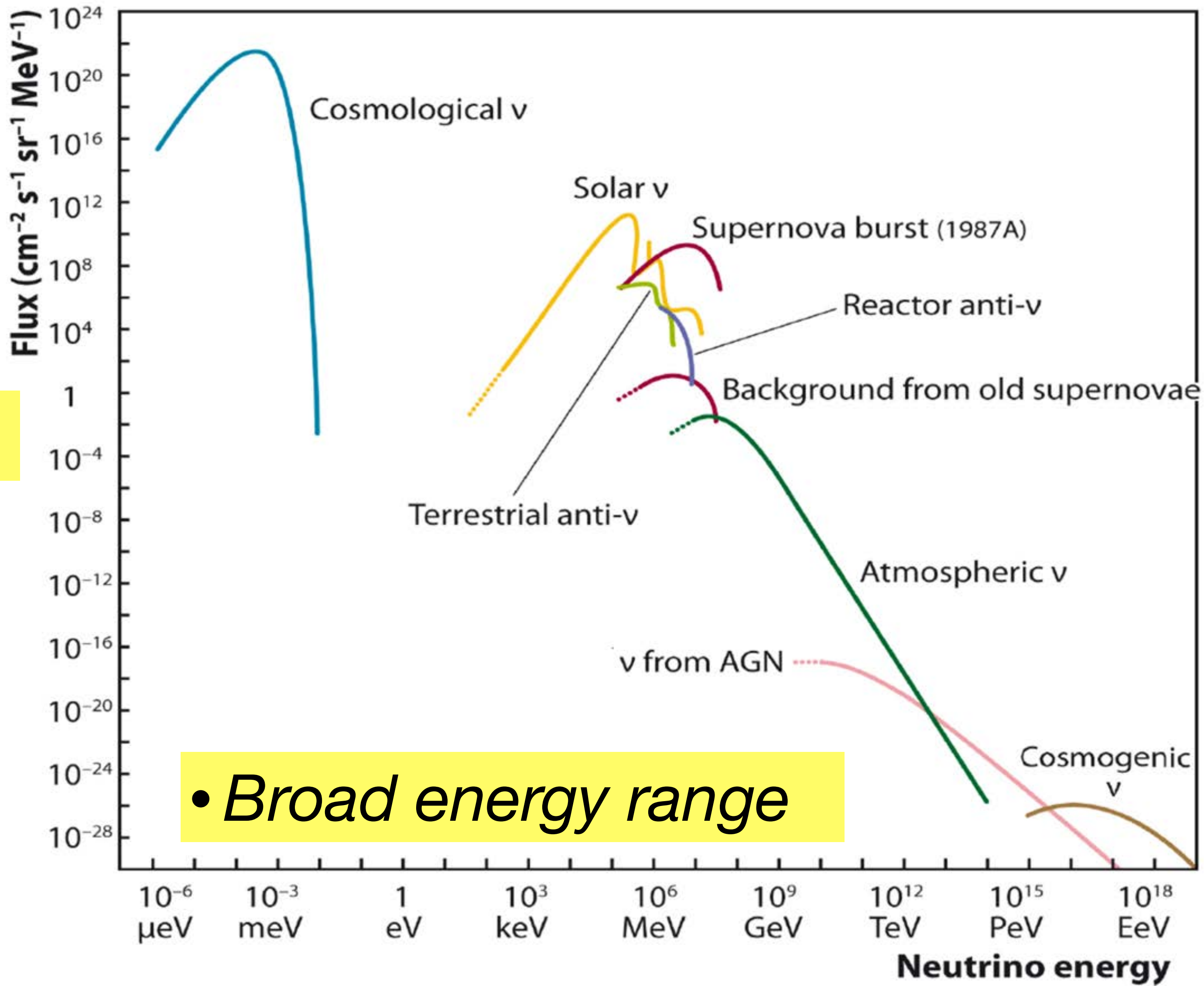
Alan Poon

2017.09.27

Neutrino Sources

Most neutrino sources are natural (not from accelerators and reactors)

- *Huge flux*

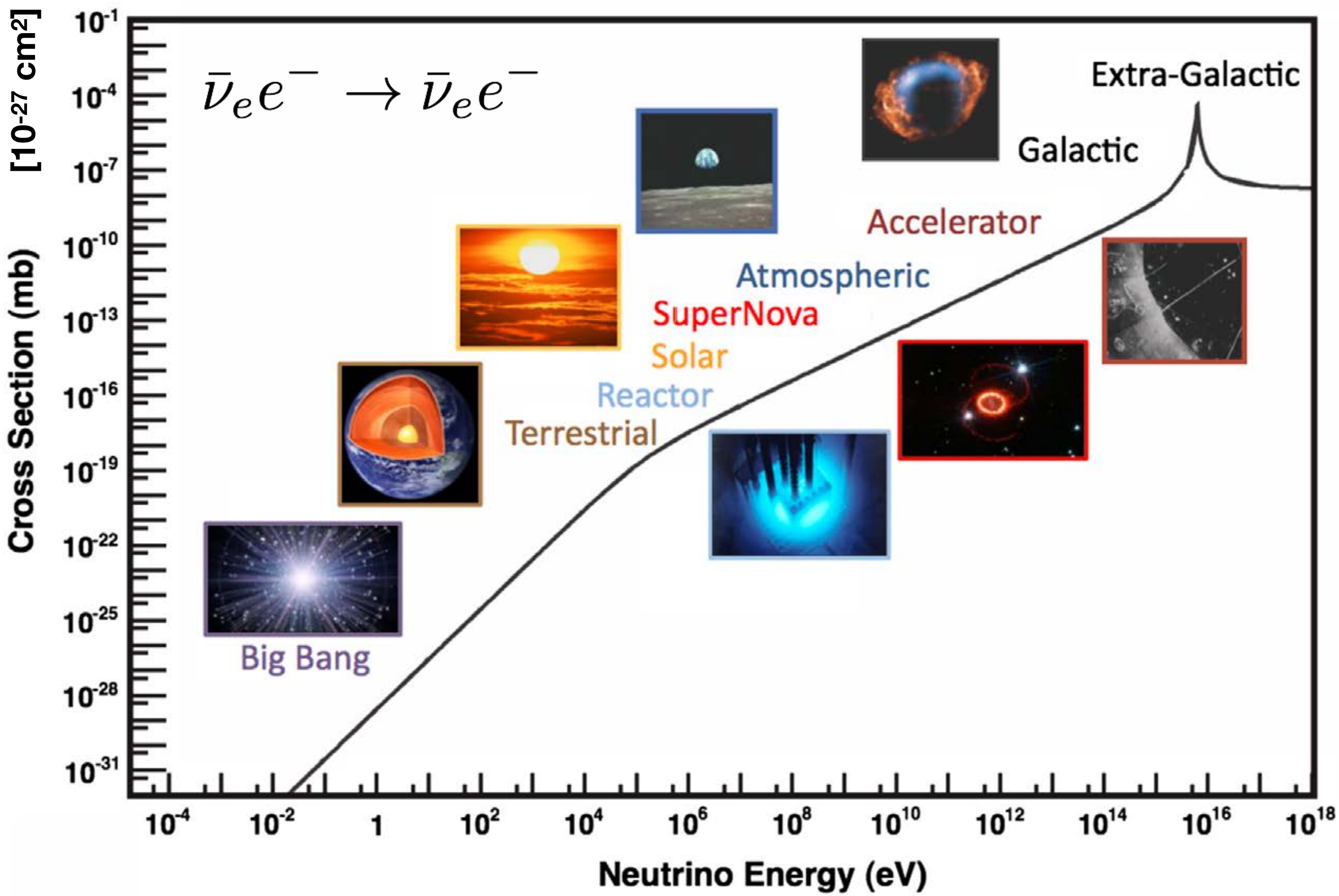


- *Broad energy range*

Figure from https://masterclass.icecube.wisc.edu/en/learn/detecting-neutrinos

Why is it so hard to detect neutrinos?

Neutrinos participate only in weak interactions



Formaggio and Zeller, Rev. Mod. Phys. **84**, 1307 (2012)

Why is it so hard to detect neutrinos?

- **Look for its decay?**
  (AFAIK) Neutrinos don't decay

- **Look for its interactions?**
  Ex: 1-MeV $\bar{\nu}_e$ scattering of atomic electrons in Pb:

$$\lambda = \frac{1}{\rho\sigma}$$ **attenuation length**

$$\rho = \frac{(82\ e/\text{atom})(11.3\ \text{g/cm}^3)(6.02 \times 10^{23}\ \text{atom/mole})}{(207\ \text{g/mole})} = 2.7 \times 10^{24}\ e/\text{cm}^3$$

$$\sigma \sim 10^{-43}\ \text{cm}^2\ @1\ \text{MeV}$$

$$\lambda \sim 4 \times 10^{16}\ \text{m}\ =\ 4\ \text{light years}$$

Need:
HUGE flux
HUGE target

An explosive idea - Reines and Cowan

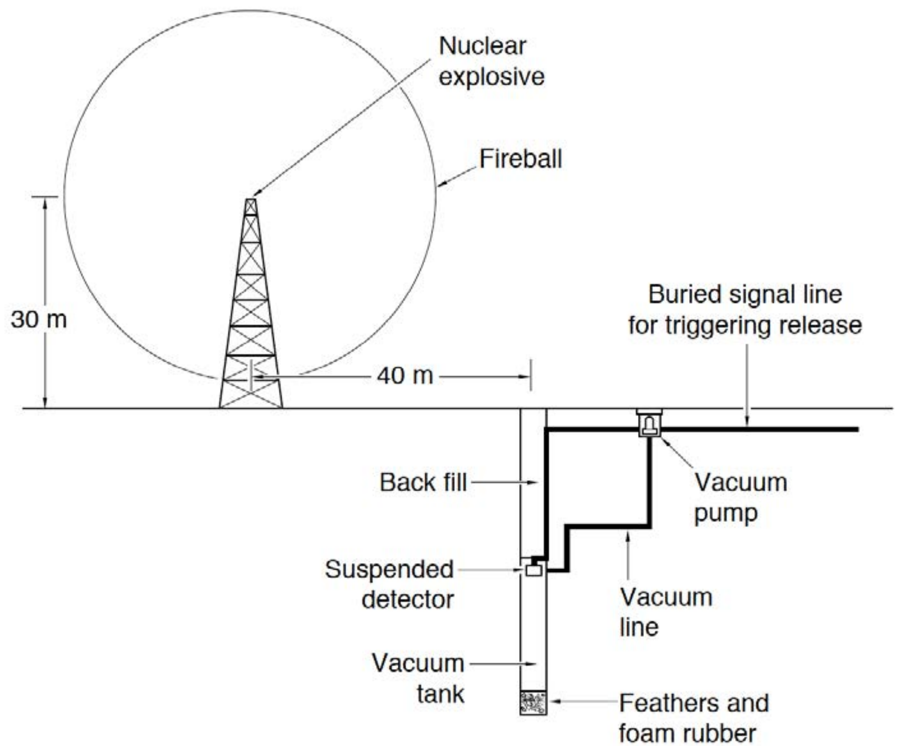


Figure 1. Detecting Neutrinos from a Nuclear Explosion
Antineutrinos from the fireball of a nuclear device would impinge on a liquid scintillation detector suspended in the hole dug below ground at a distance of about 40 meters from the 30-meter-high tower. In the original scheme of Reines and Cowan, the antineutrinos would induce inverse beta decay, and the detector would record the positrons produced in that process. This figure was redrawn courtesy of Smithsonian Institution.

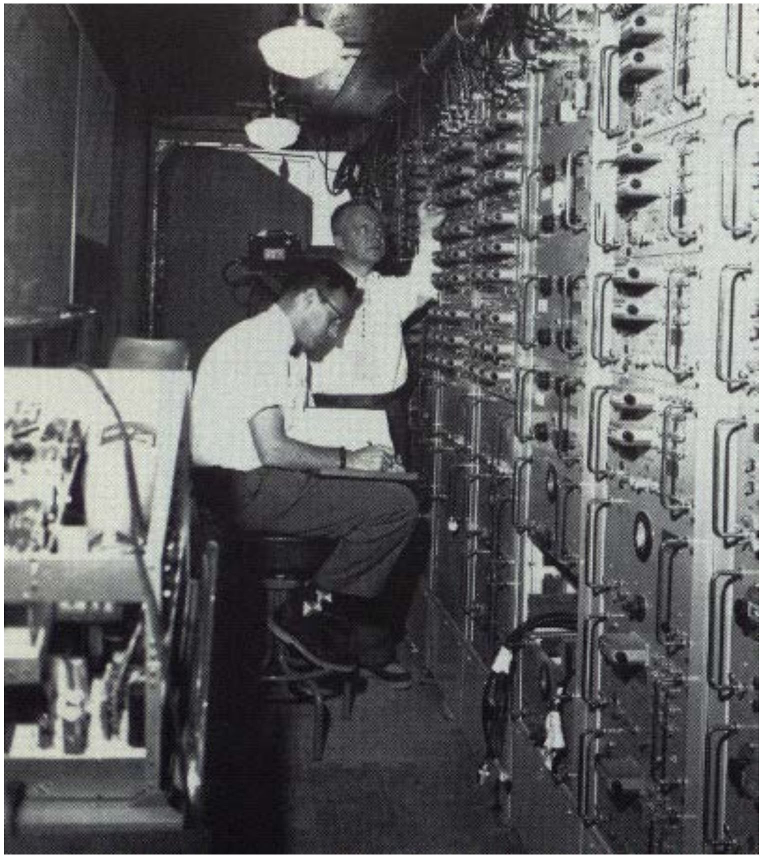
"Our crude knowledge of the expected energy spectrum of neutrinos from a fission bomb suggested that the inverse beta decay reaction would occur several times in a several-ton detector located about 50 meters from the tower-based explosion of a 20-kiloton bomb. (Anyone untutored in the effects of nuclear explosions would be deterred by the challenge of conducting an experiment so close to the bomb, but we knew otherwise from experience and pressed on). The detector we dreamed up was a giant liquid scintillation device, which we dubbed 'El Monstro.' This was a daring extrapolation of experience with the newly born scintillation technique. The biggest detector until Cowan and I came along was only a liter or so in volume."

- Fred Reines

Reines and Cowan scrapped this idea.

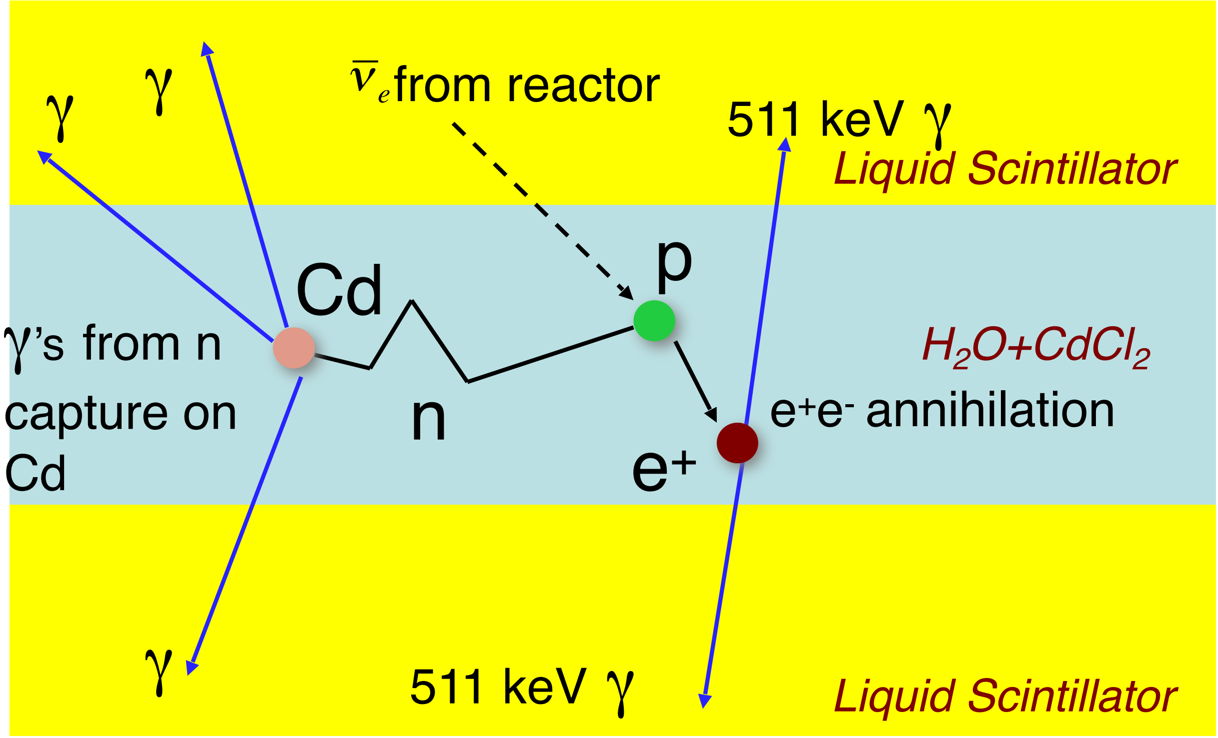
Discovery of the (Anti-)Neutrinos

- F. Reines & C.L. Cowan [*Physical Review* **117**, 160 (1960)]
- Detection at Savannah River reactor plant

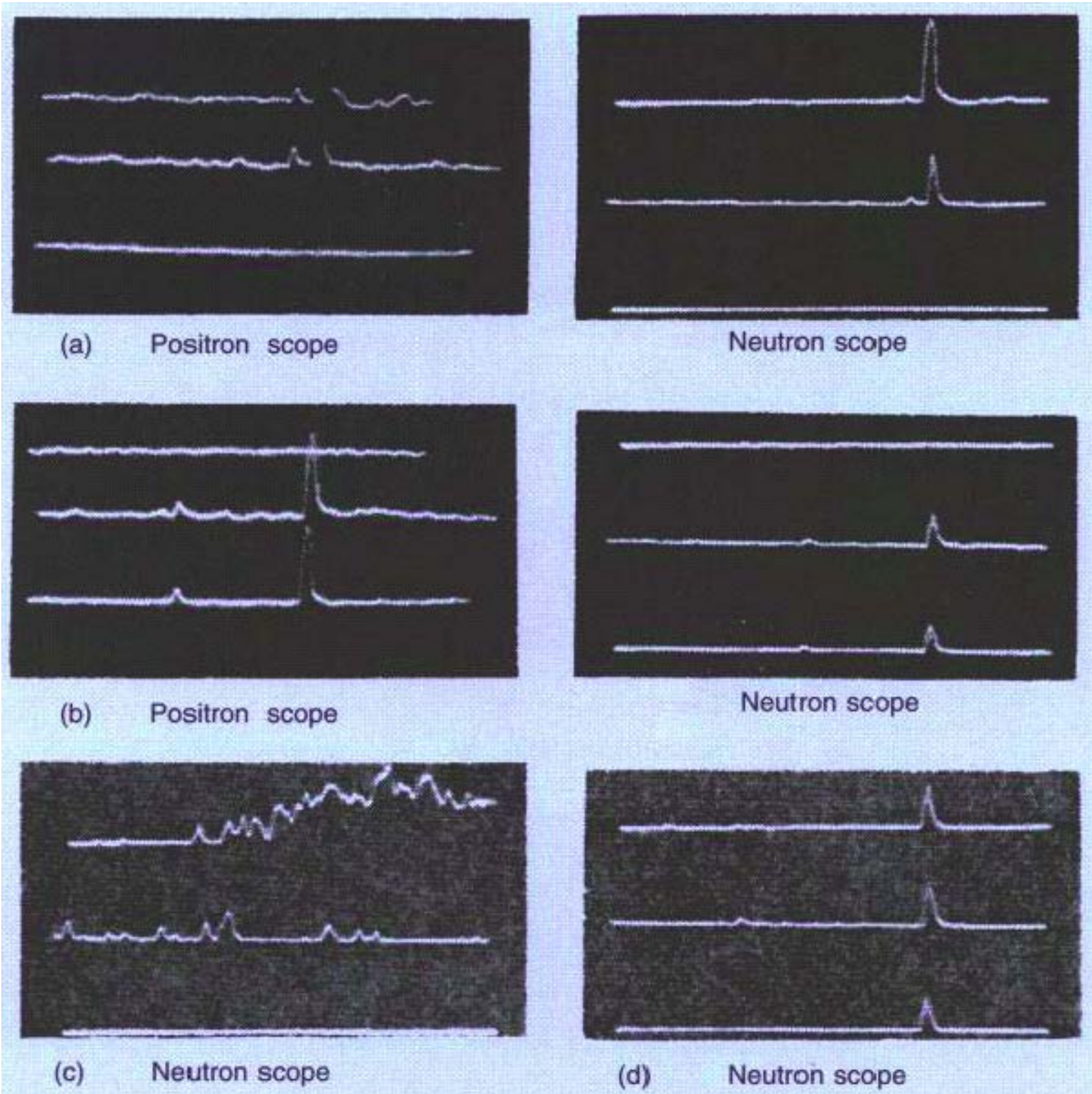


Inverse Beta Decay

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



"Saw" the coincidences!



neutrino

neutrino

noise

cosmic ray

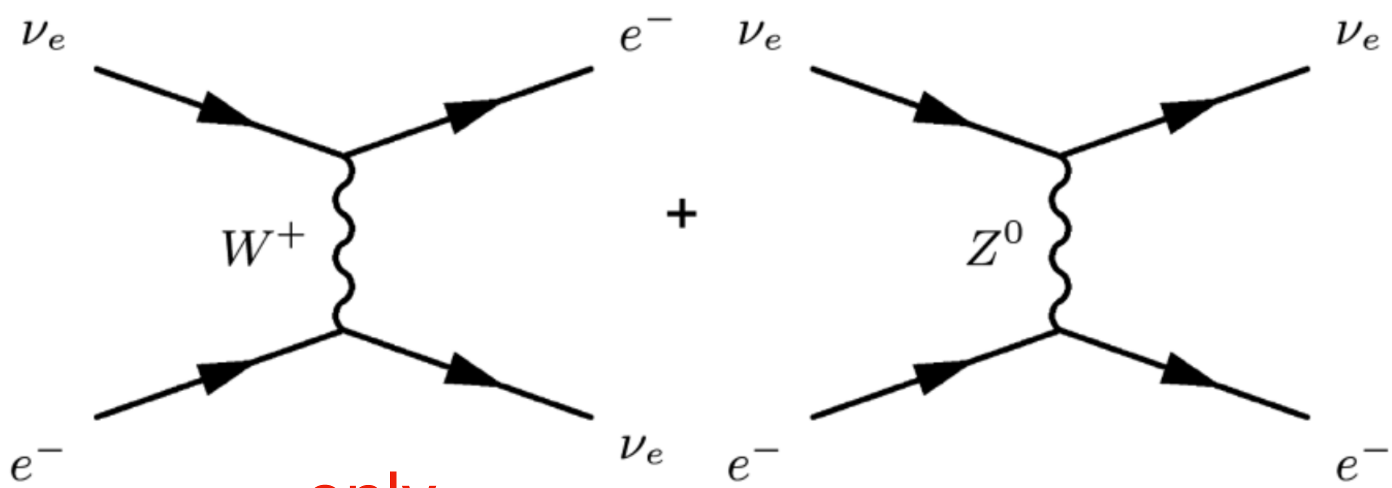
Leptonic processes
and
coherent elastic neutrino-nucleus scattering

Neutrino-electron scattering

Targets have a lot of atomic electrons

Tree level diagrams:

Charged Current (CC) **Neutral Current (NC)**



ν_e only

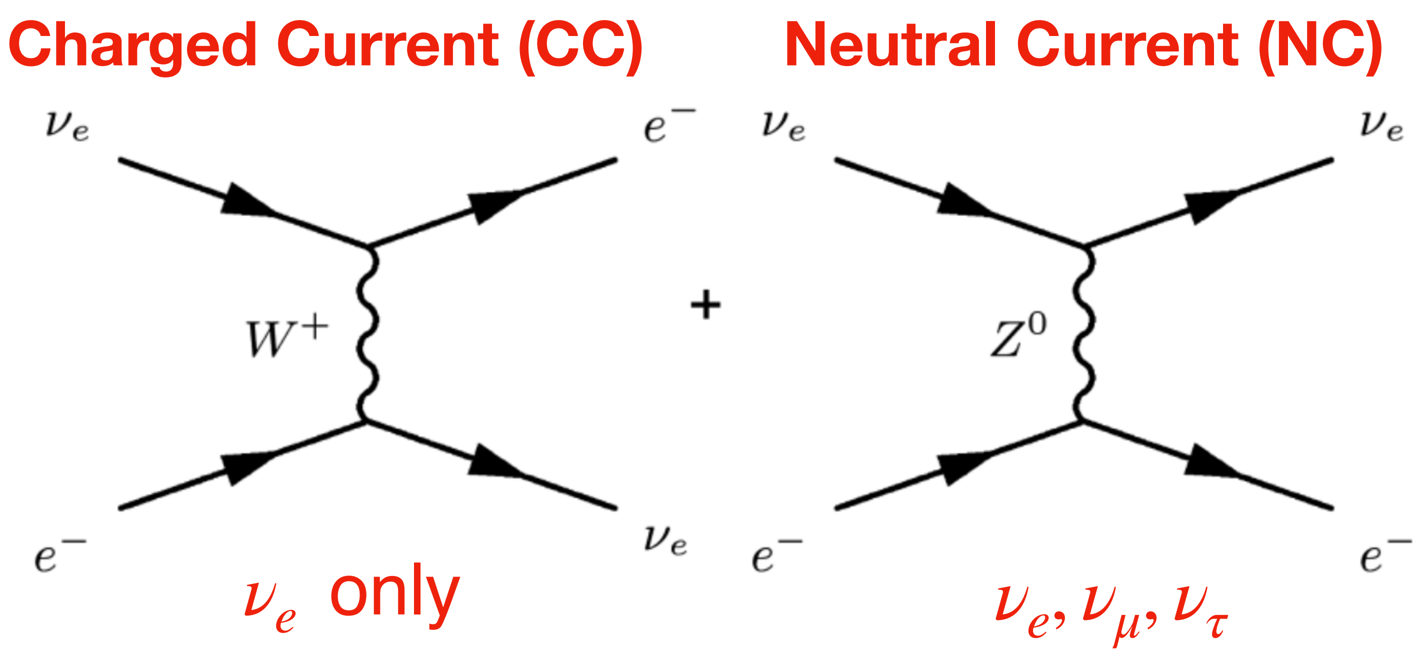
ν_e, ν_μ, ν_τ

$$\mathscr{L} = -\frac{G_F}{\sqrt{2}}[\bar{\nu}_e\gamma^\mu(1-\gamma^5)e][\bar{e}\gamma_\mu(1-\gamma^5)\nu_e] + [\bar{\nu}_e\gamma^\mu(1-\gamma^5)\nu_e][\bar{e}\gamma_\mu(g_V^e - g_A^e\gamma^5)e)]$$

Neutrino-electron scattering

Targets have a lot of atomic electrons

Tree level diagrams:



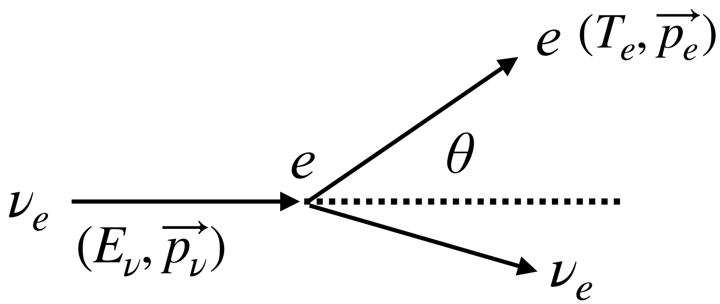
$$\sigma = \frac{2G_F^2 m_e}{\pi}[(g_L^2 + \frac{g_R^2}{3}E_\nu) - \frac{g_L g_R}{2}m_e]$$

$$g_L = \sin^2\theta_W \pm^{e}_{\mu,\tau} \frac{1}{2}$$

$$g_R = \sin^2\theta_W$$

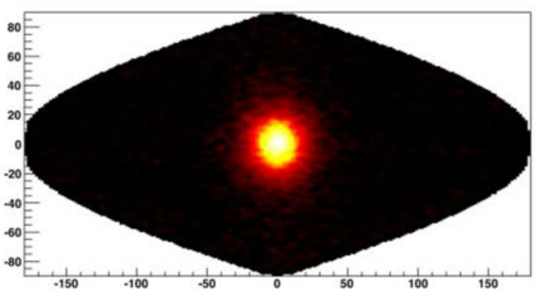
$$g_L \leftrightarrow g_R \text{ for } \bar{\nu}$$

Neutrino-electron scattering



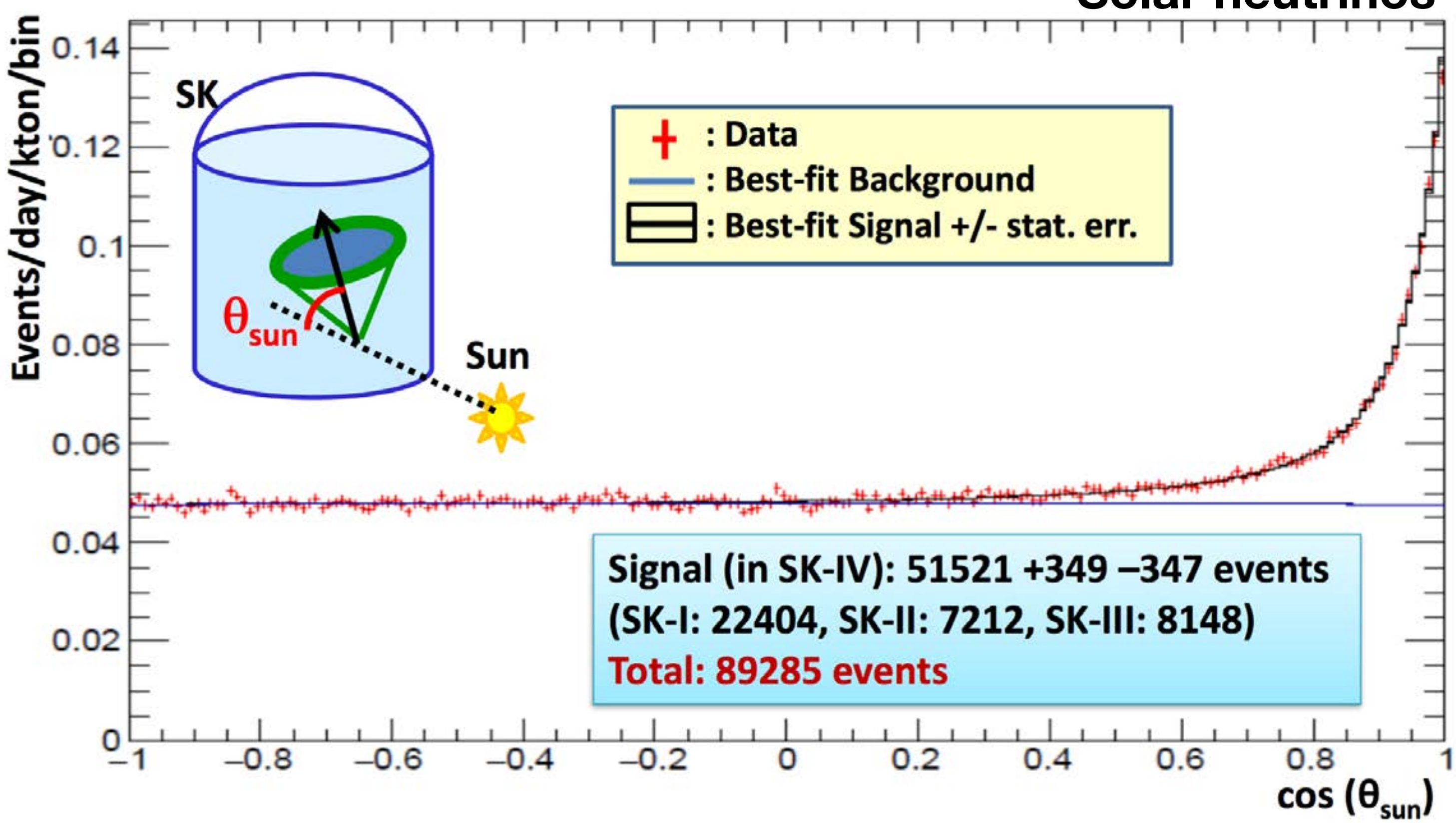
$$T_e = \frac{2m_e E_\nu^2 \cos^2\theta}{(m_e + E_\nu)^2 - E_\nu^2 \cos^2\theta}$$

- Electron emitted at very small angle with respect to the neutrino direction : $E_e\theta_e^2 \leq 2m_e$



Solar neutrino image

Solar neutrinos

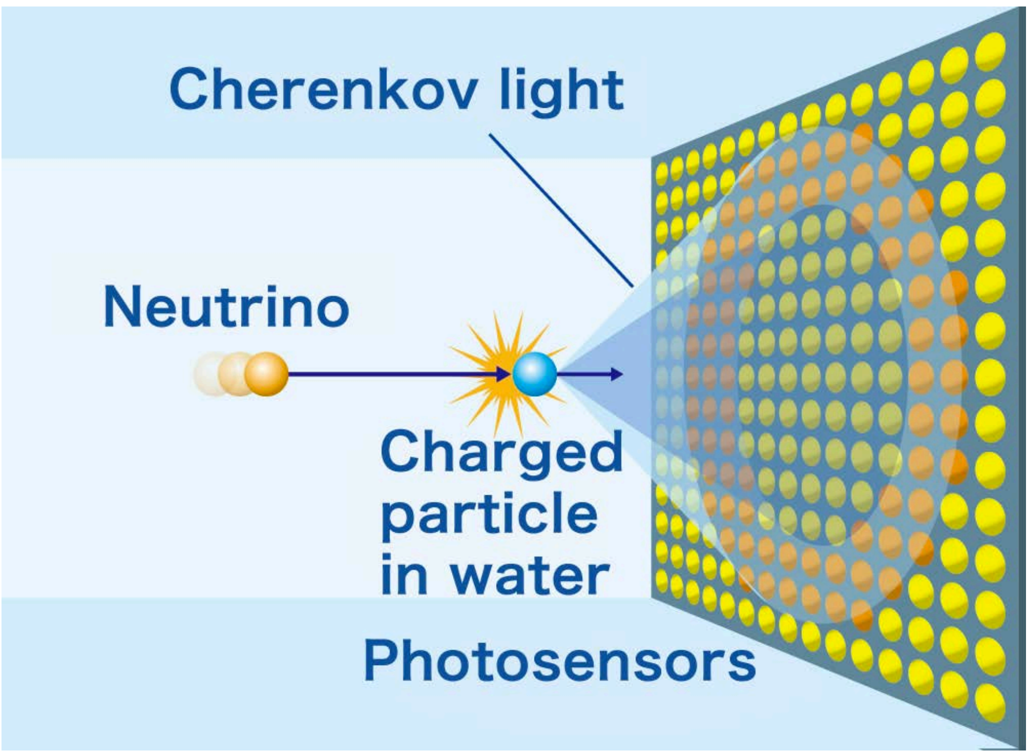


Cherenkov radiation - seeing relativistic charged particles

Cherenkov light is emitted when a charged particle passes through a dielectric medium at a speed higher than the speed of light in that medium.

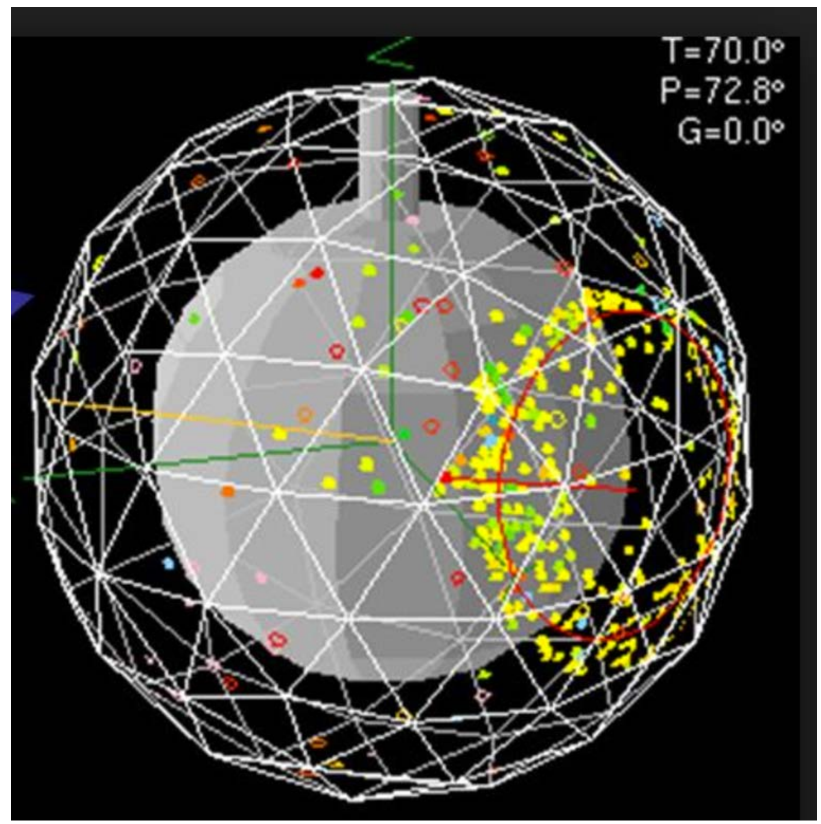
$$\cos\theta_C = \frac{1}{\beta n}$$

$$\theta_C = 41^\circ \text{ in } H_2O\ (\beta \sim 1)$$



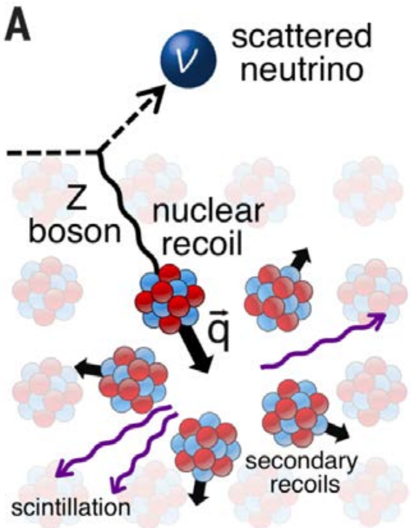
Graphics from http://physicsopenlab.org/

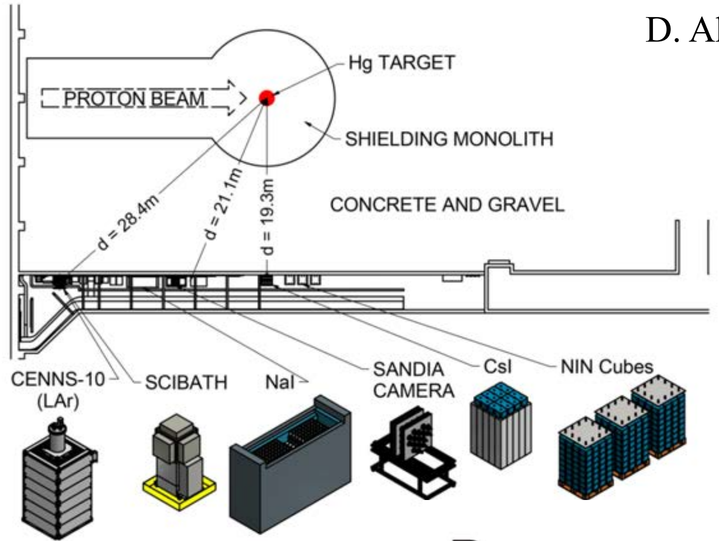
Event in SNO

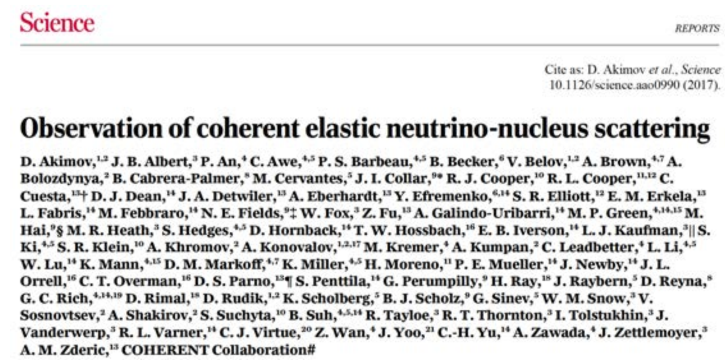


Coherent Elastic Neutrino-Nucleus Scattering

D. Akimov et al., Science 10.1126/science.aao0990 (2017).






Science

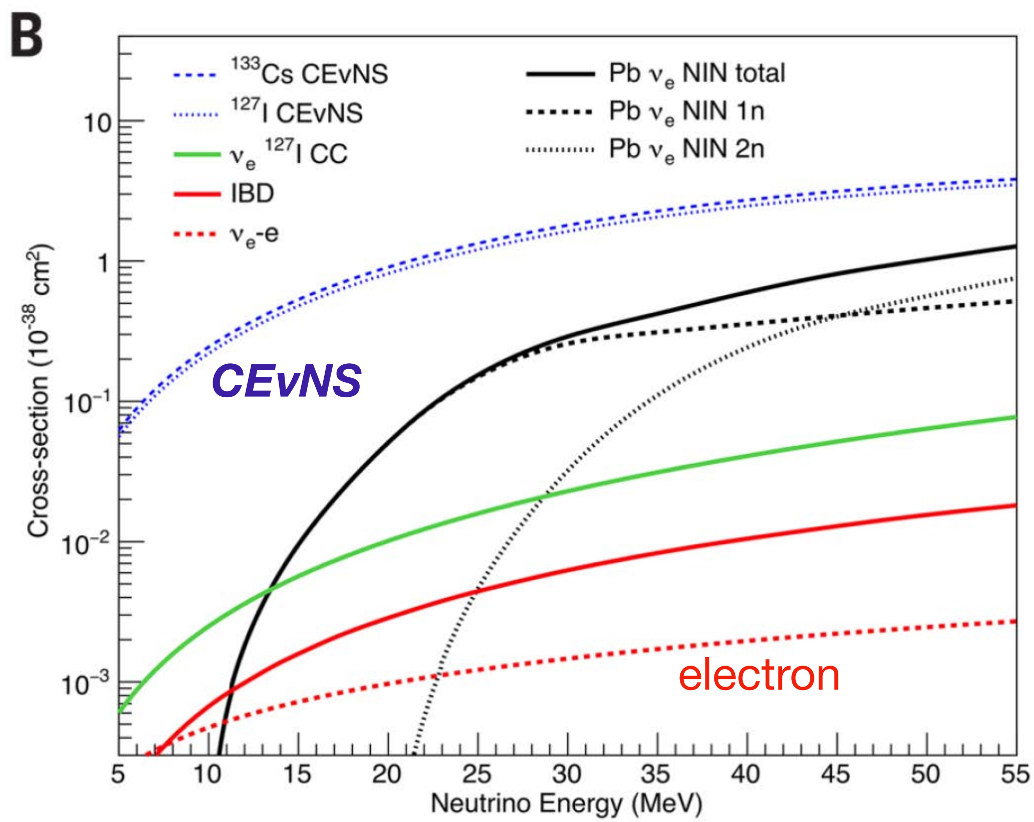
REPORTS

Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

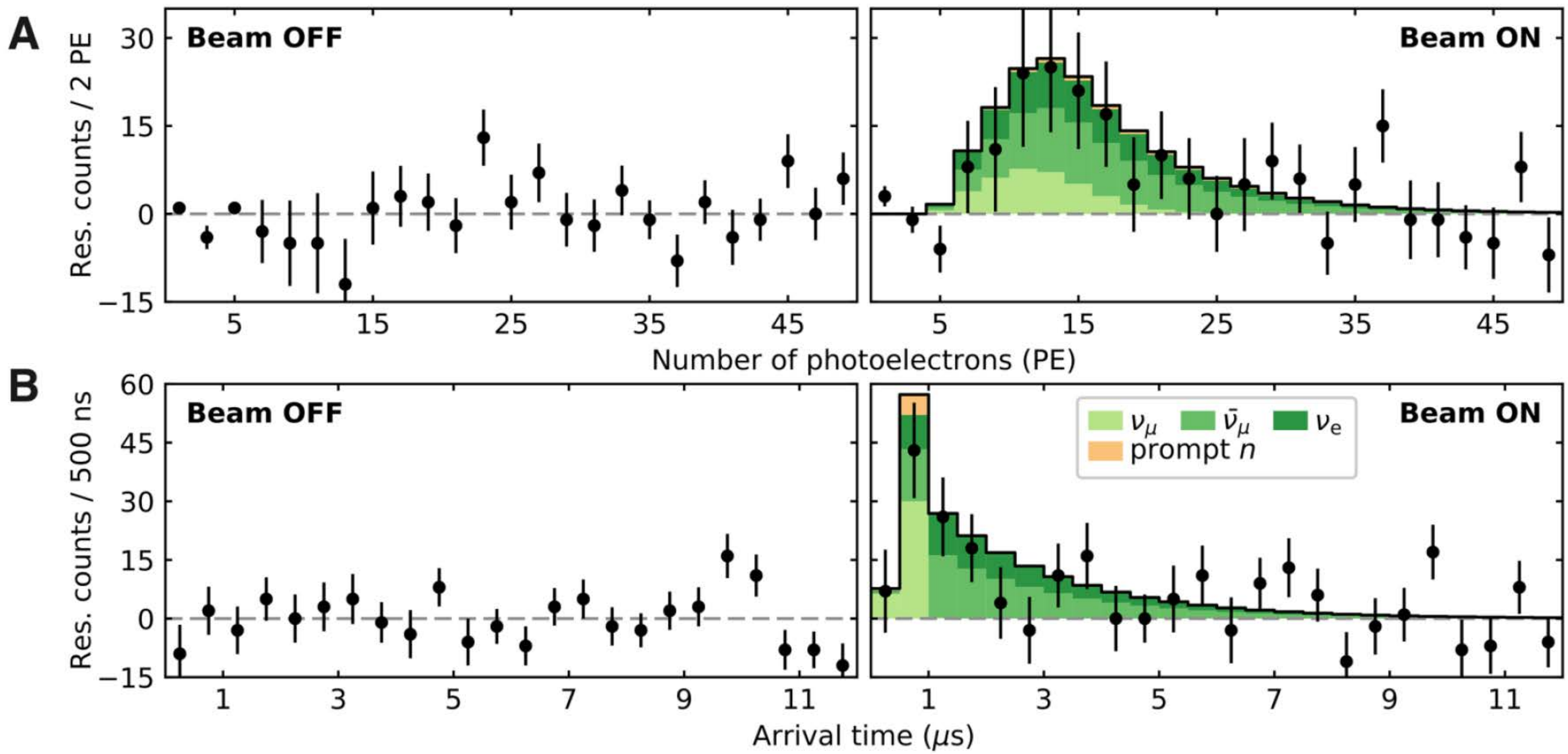
Observation of coherent elastic neutrino-nucleus scattering

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9*] R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13†] D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9‡] W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9§] M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3||] S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13¶] S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#

- When q << 1/R (E_ν < 50 MeV), $\sigma_{Total} \sim N^2$, but the nucleus recoil energy is very low.
- First observation was made in a CsI detector using neutrinos from the Spallation Neutron Source at ORNL.

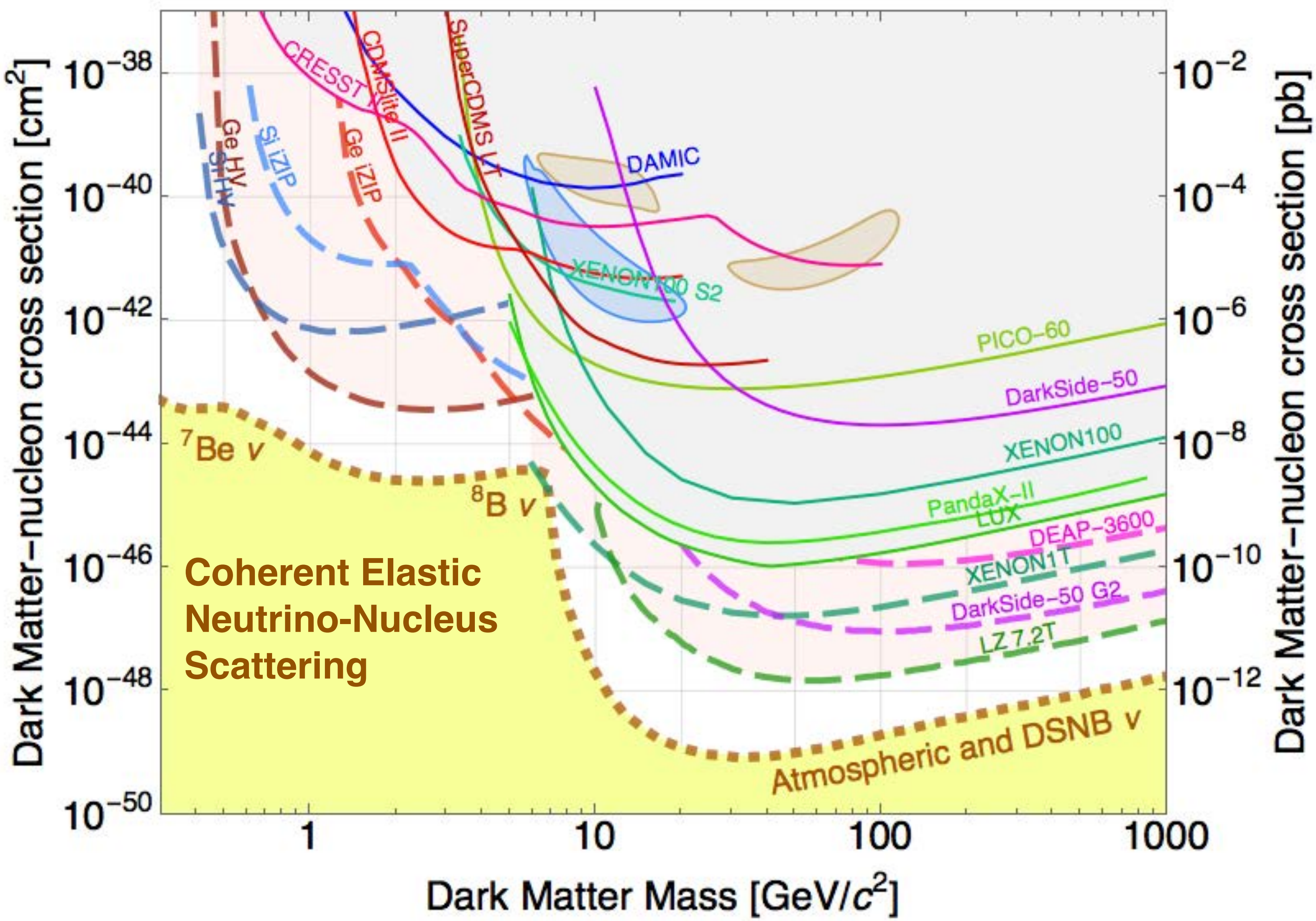


Coherent Elastic Neutrino-Nucleus Scattering



D. Akimov et al., Science 10.1126/science.aao0990 (2017).

Their signals, your backgrounds



Inverse beta decay
and
low-energy neutrino-nucleus interactions

Inverse Beta Decay (IBD)

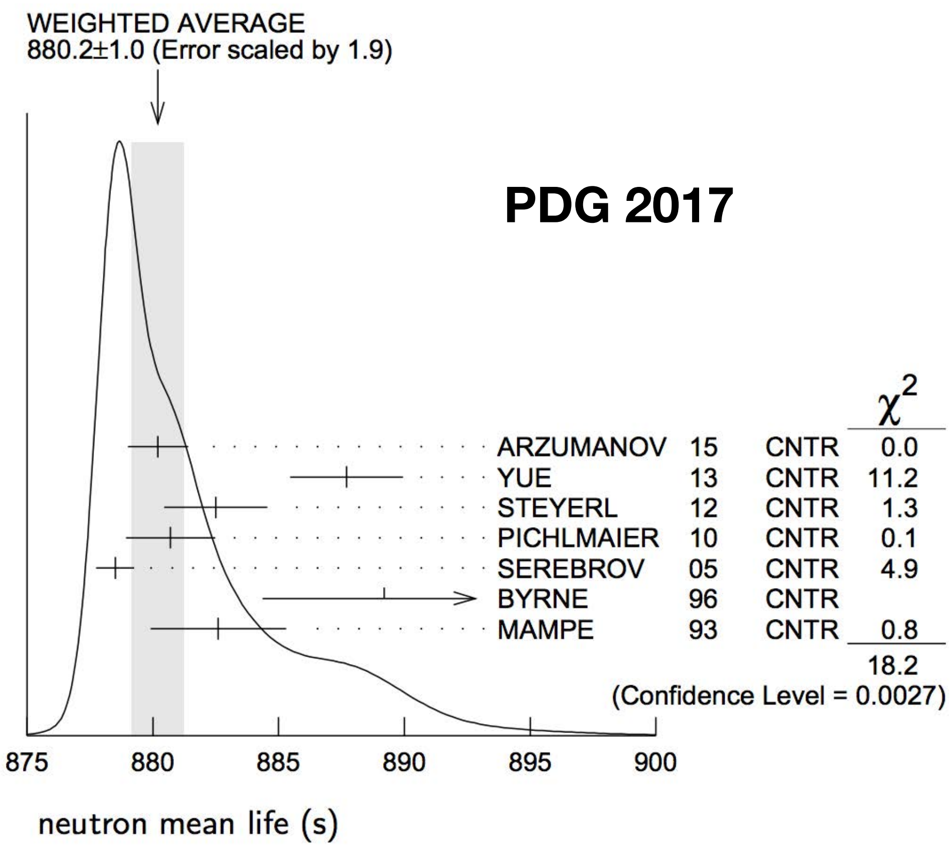
- Recall (the discovery of neutrinos by Reines & Cowan):

Inverse Beta Decay: $\bar{\nu}_e + p \rightarrow n + e^+ \qquad E_{\bar{\nu}_e} > 1.8\,\mathrm{MeV}$

- The cross section of this process at low neutrino energy (~ a few MeV) is:

$$\sigma_{tot} = \frac{2\pi^2}{m_e^5}\frac{E_{e^+}p_{e^+}}{f\tau_n}$$

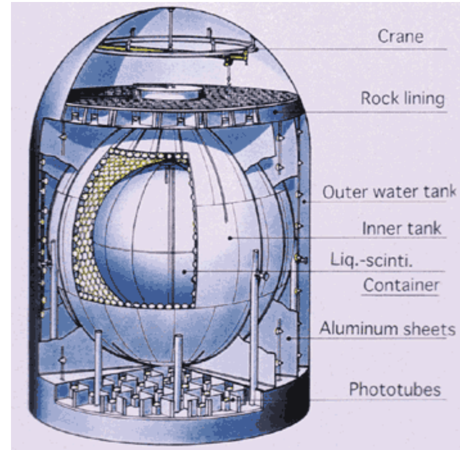
where f = 1.715 and τ_n = 880.2 (1.0) s (but with controversial measurements).

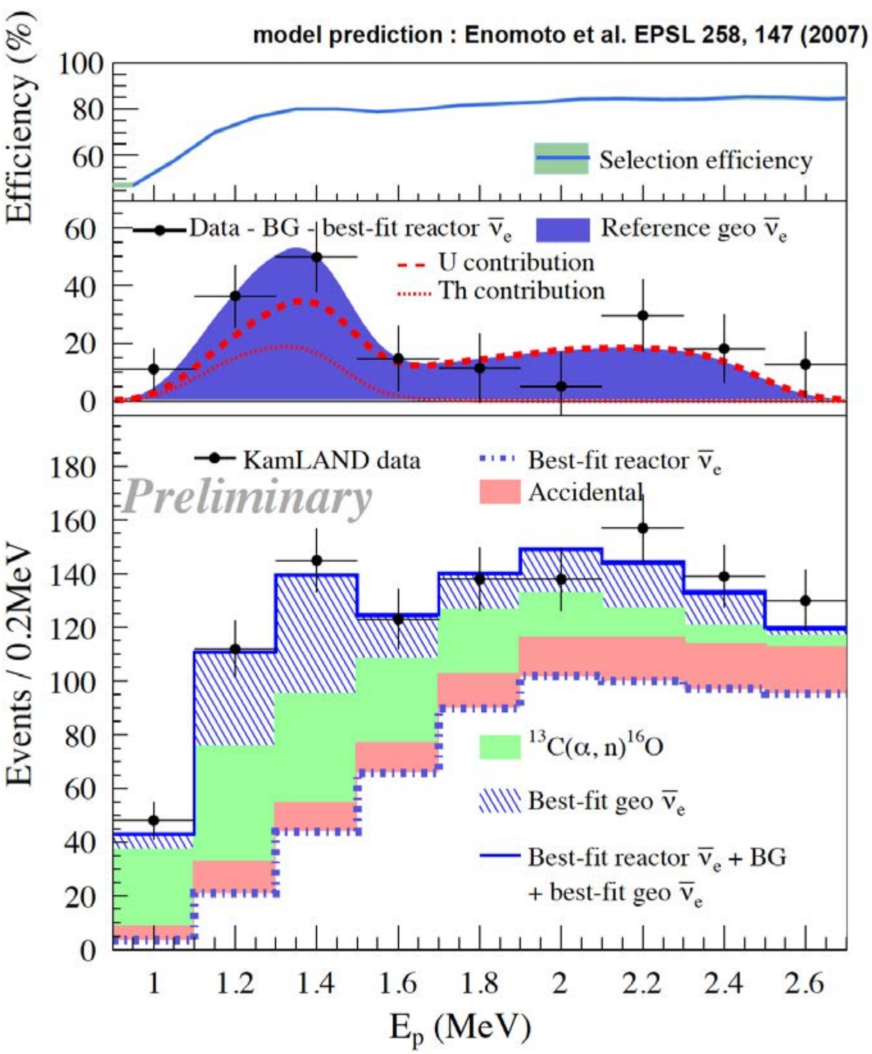


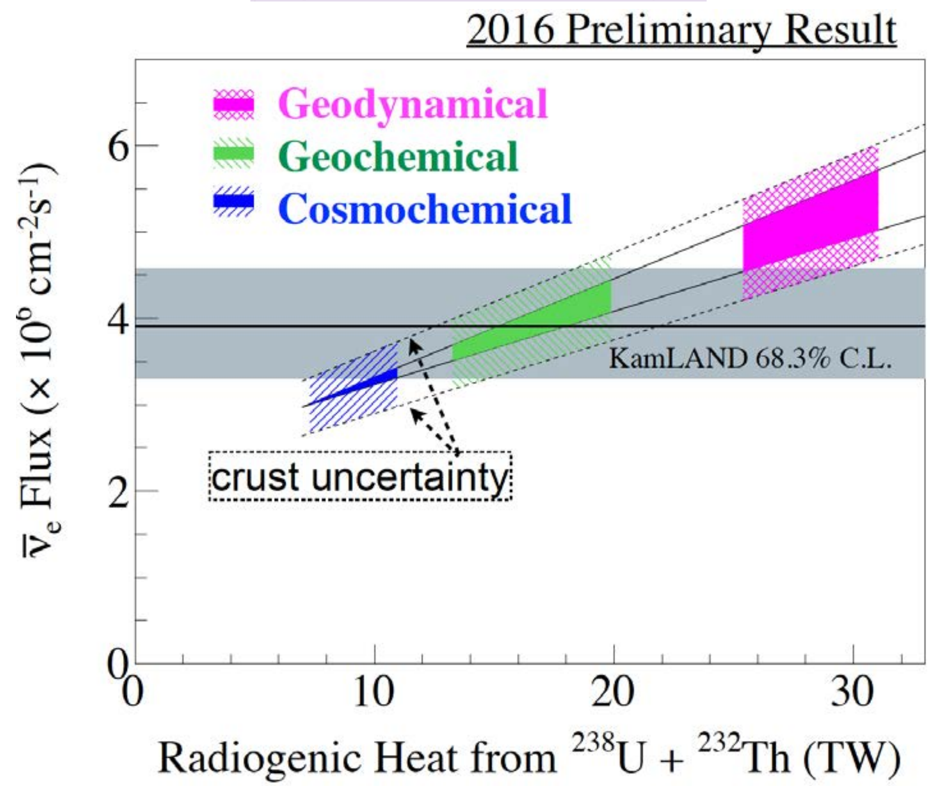
- The neutron lifetime is an important parameter that fixes the cross section for single nucleon processes.

Geo-neutrinos

- 1 kt liquid scintillator
- Detect anti-neutrinos from reactors and earth’s core by IBD







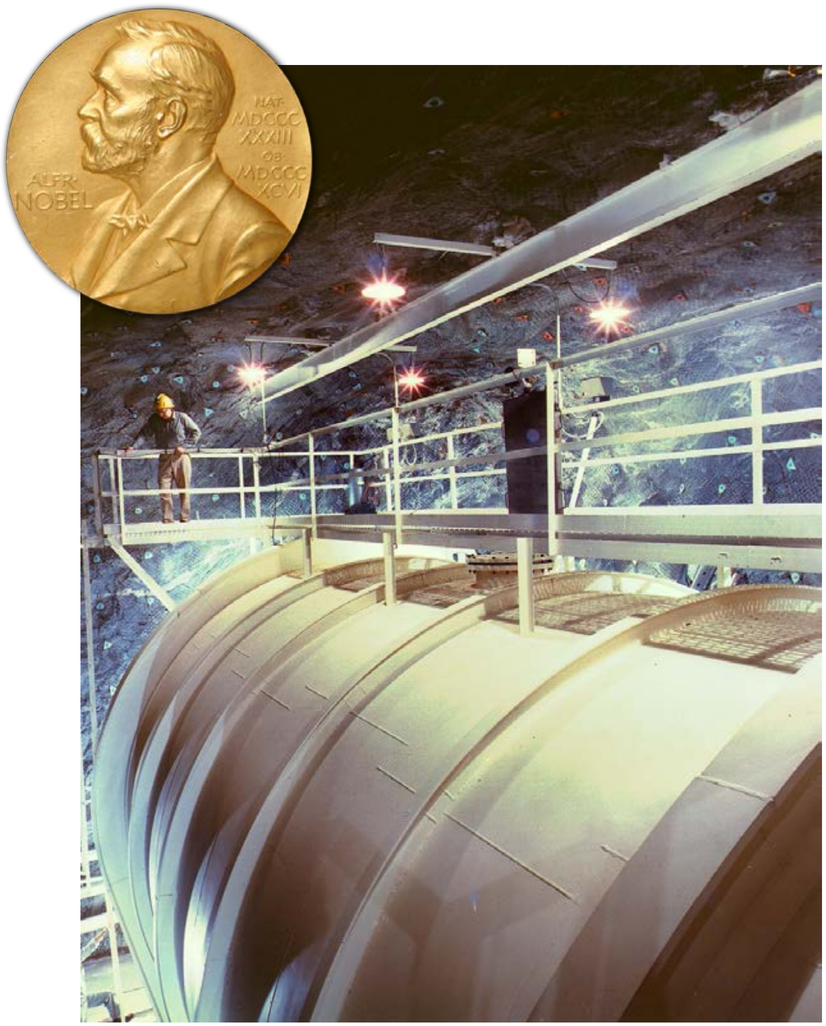
☑ Radiogenic Heats : $15.5^{+6.5}_{-6.3}$ TW

☑ Cosmochemical, Geodynamical Models are getting to be rejected

Shirahata 2017

Using other nucleus as neutrino target

- The first detection of solar neutrinos by Ray Davis (615t of C_2Cl_4 at Homestake mine (now SURF) in SD:

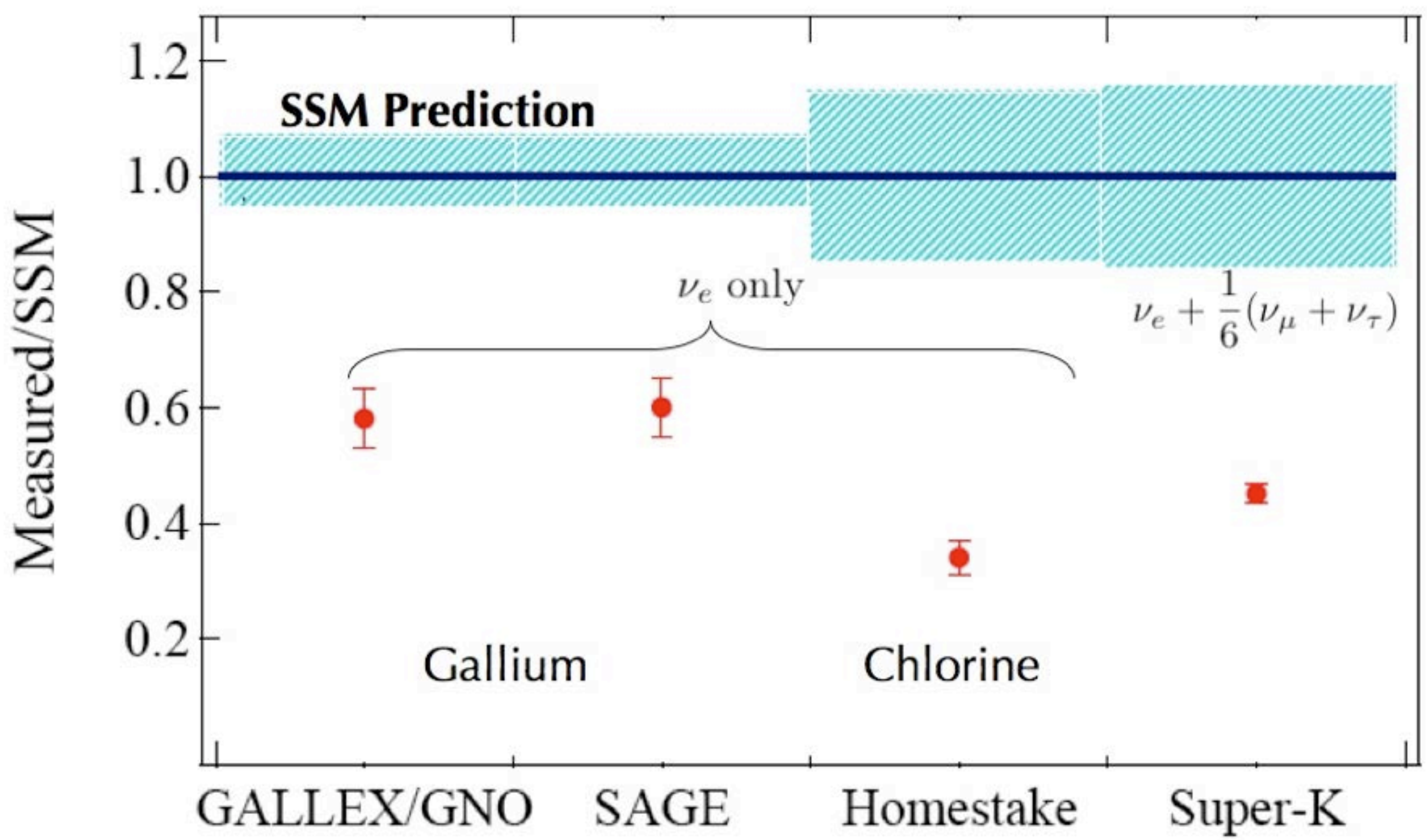


$$\nu_e + {}^{37}\mathrm{C}l \rightarrow {}^{37}\mathrm{Ar} + e^- \, (E_\nu > 0.814 \,\mathrm{MeV})$$

- Flushed tank, collect ^{37}Ar, looked for its decay back to ^{37}Cl.
- Solar Neutrino Problem: only 1/3 of the expected number of solar neutrinos was observed.
- Ray Davis won the Nobel Prize in Physics (with M. Koshiba) in 2002.
- **Note**:
    - The Sun only emits ν_e (*p-p* chain)
    - Charged-current (in detection) only sensitive to ν_e

Solar Neutrino Problem (~2000)

- Are the Standard Solar Model predictions wrong?
- Or is there something about the neutrinos that we don't understand?



Measure CC and NC (ν_e vs all flavors)

Measure:

$$\frac{CC}{NC} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

Alternatively…

$$\frac{CC}{ES} = \frac{\nu_e}{\nu_e + 0.15(\nu_\mu + \nu_\tau)}$$

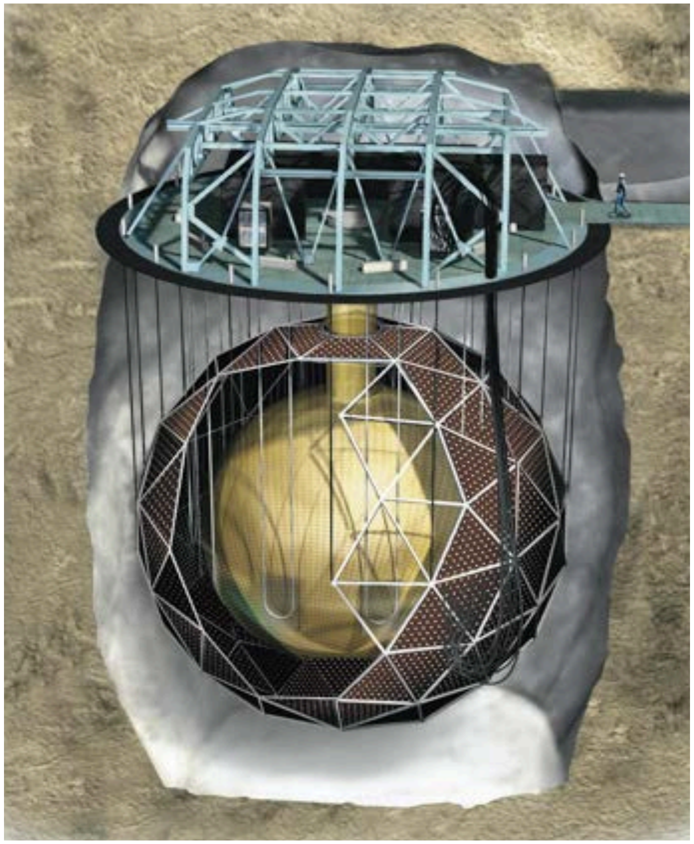
Transformation to another active flavor if:

$$\phi^{CC}(\nu_e) < \phi^{NC}(\nu_x)$$

$$\phi^{CC}(\nu_e) < \phi^{ES}(\nu_x)$$

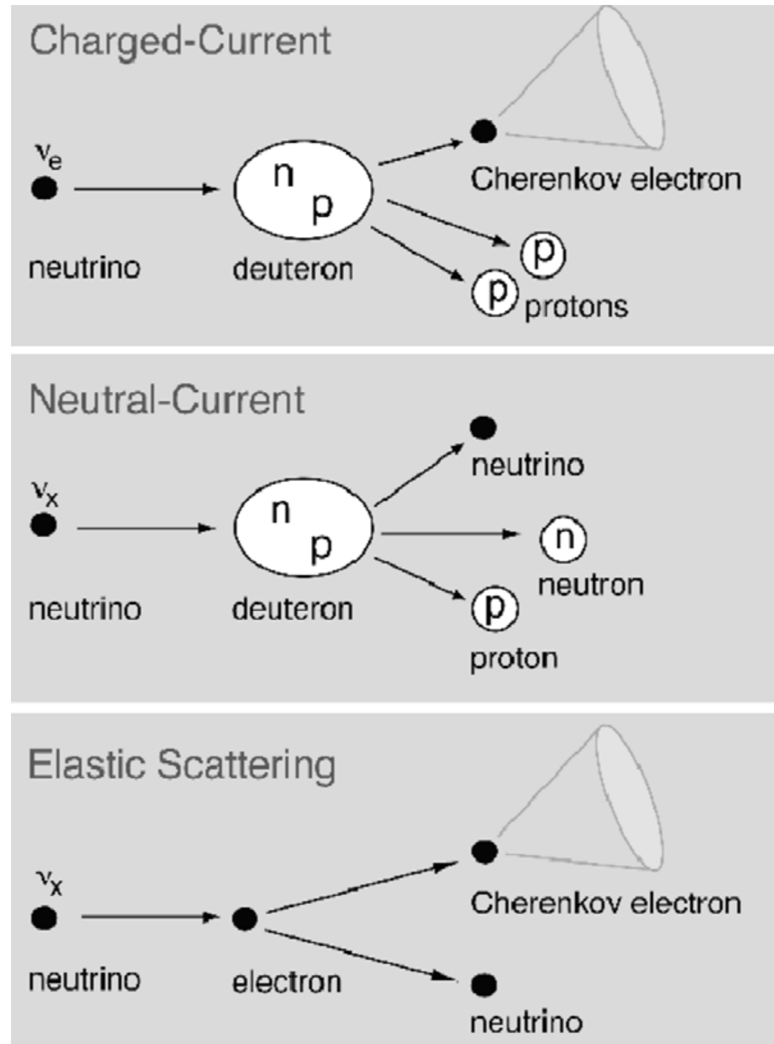
Flavor transformation (particle physics) can be tested without any assumption on the Standard Solar Model prediction of the total neutrino flux.

Is there a magic target ?



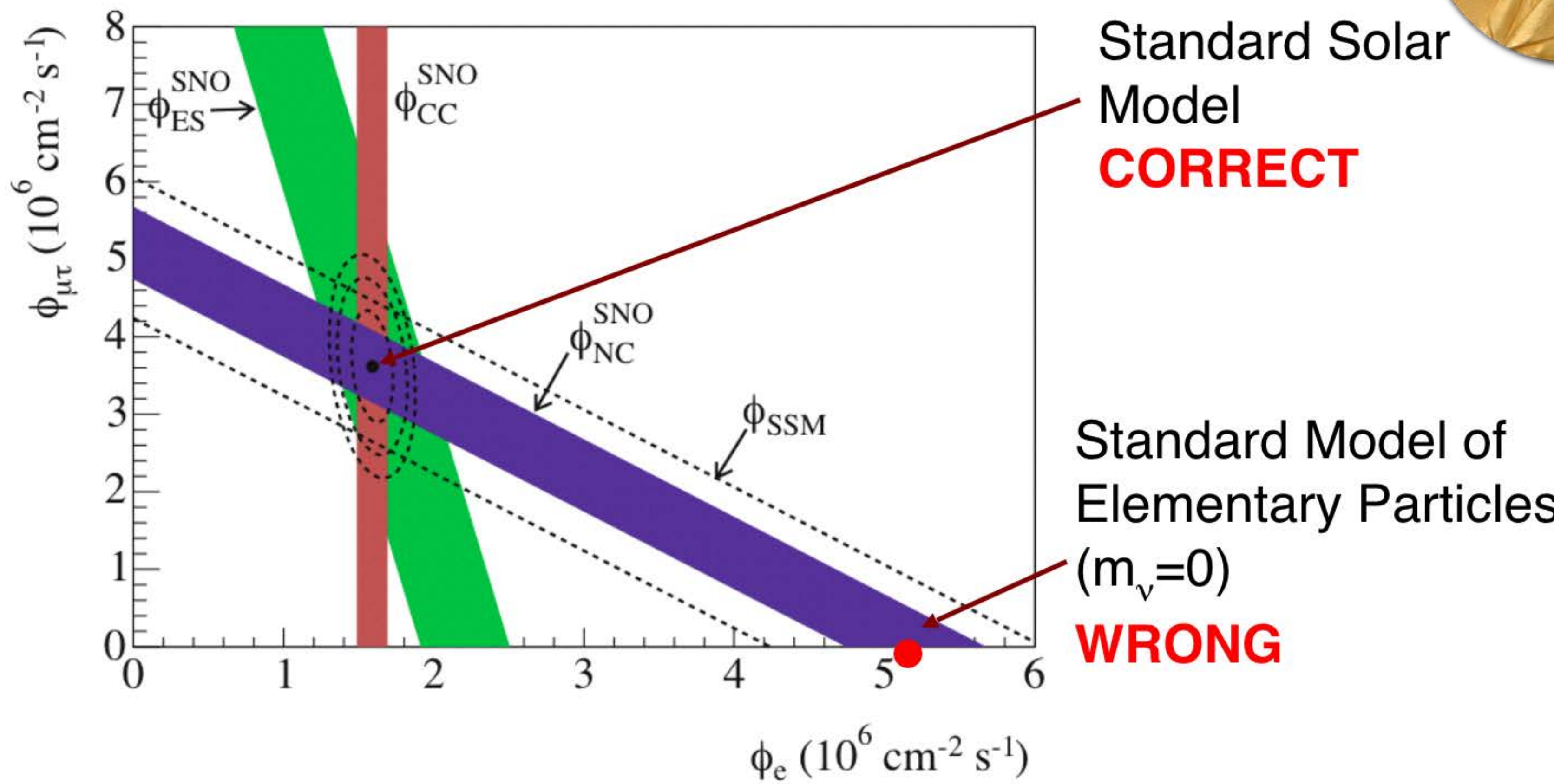
The deuteron

- 2 km underground at Vale's Creighton mine near Sudbury, ON, Canada
- 1000t of D_2O in a 12-m ϕ acrylic sphere



CC	$\nu_e + d \rightarrow p + p + e^-$
NC	$\nu_x + d \rightarrow p + n + \nu_x'$
ES	$\nu_x + e^- \rightarrow \nu_x + e^-$

Sudbury Neutrino Observatory (SNO)



~2/3 of the ν_e produced in the Sun have transformed into ν_μ or ν_τ

SNO provided the first direct observation of neutrino flavor transformation (which requires neutrinos to be massive)

Aside: neutrino mixing

- A weak eigenstate $|\nu_\alpha\rangle$ is a linear combination of mass eigenstates $|\nu_i\rangle$:

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}|\nu_i\rangle$$

where U = Maki-Nakagawa-Sakata-Pontecorvo (MNSP) matrix.

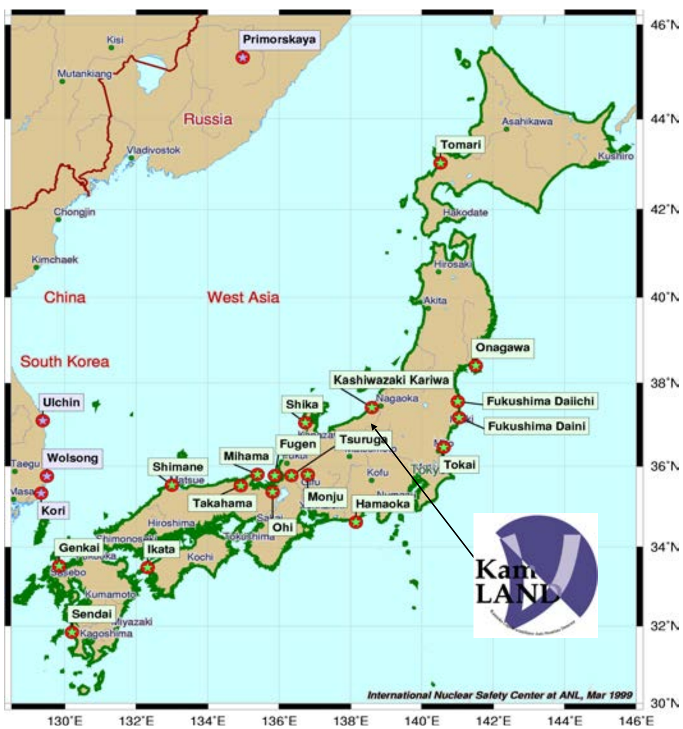
$$|U| = \begin{pmatrix} 0.779 \leftrightarrow 0.848 & 0.510 \leftrightarrow 0.604 & 0.122 \leftrightarrow 0.190 \\ 0.183 \leftrightarrow 0.568 & 0.385 \leftrightarrow 0.728 & 0.613 \leftrightarrow 0.794 \\ 0.200 \leftrightarrow 0.576 & 0.408 \leftrightarrow 0.742 & 0.589 \leftrightarrow 0.775 \end{pmatrix}$$

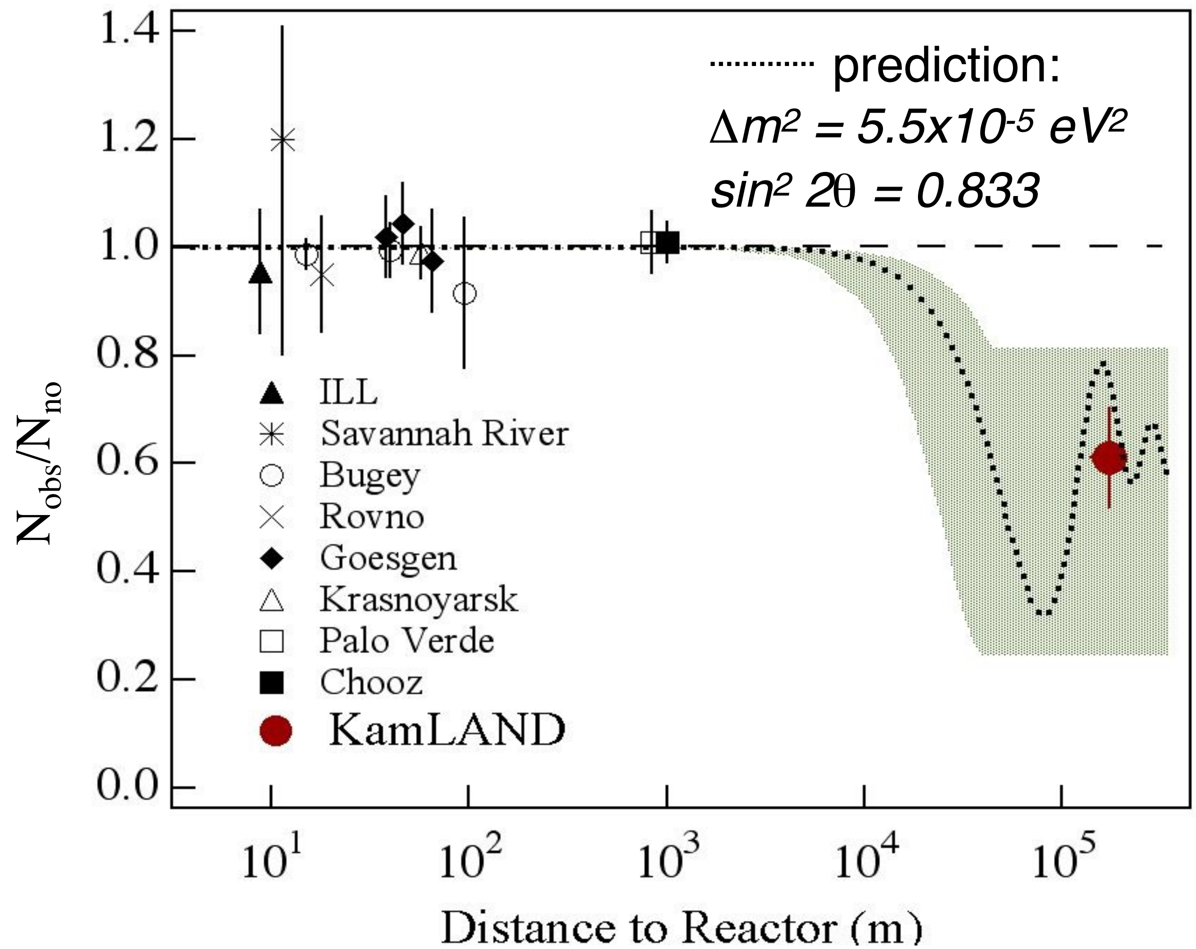
$$\begin{aligned} |\nu_e\rangle &= (\sim 0.81)\,|\nu_1\rangle + (\sim 0.55)\,|\nu_2\rangle + (\sim 0.16)\,|\nu_3\rangle \\ |\nu_\mu\rangle &= (\sim 0.38)\,|\nu_1\rangle + (\sim 0.56)\,|\nu_2\rangle + (\sim 0.70)\,|\nu_3\rangle \\ |\nu_\tau\rangle &= (\sim 0.39)\,|\nu_1\rangle + (\sim 0.58)\,|\nu_2\rangle + (\sim 0.68)\,|\nu_3\rangle \end{aligned}$$

KamLAND - Reactor Anti-Neutrino

KamLAND showed that neutrino oscillation is the original of flavor transformation seen in SNO

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 [\mathrm{eV}^2]\, L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$





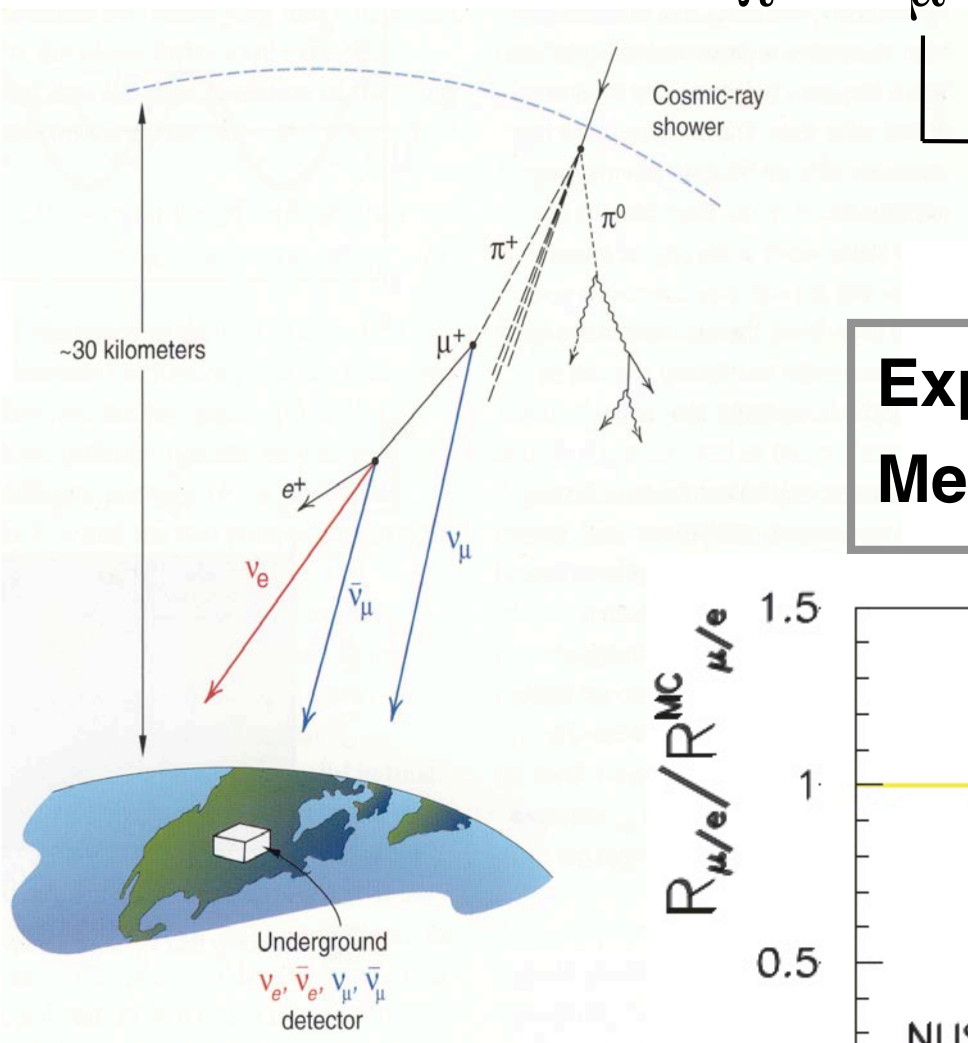
Other nuclear targets for ν detection

- A common target is liquid scintillator (lots of C and H), but there have been other nuclei that have been studied quite extensively
- Theory vs experimental cross section agreement generally good for low energy (1-300 MeV)

Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{2}H	$^2\mathrm{H}(\nu_e, e^-)pp$	Stopped π/μ	LAMPF	52 ± 18(tot)	54 (IA) (Tatara, Kohyama, and Kubodera, 1990)
^{12}C	$^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$	Stopped π/μ	KARMEN	9.1 ± 0.5(stat) ± 0.8(sys)	9.4 [Multipole](Donnelly and Peccei, 1979)
		Stopped π/μ	E225	10.5 ± 1.0(stat) ± 1.0(sys)	9.2 [EPT] (Fukugita, Kohyama, and Kubodera, 1988).
		Stopped π/μ	LSND	8.9 ± 0.3(stat) ± 0.9(sys)	8.9 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
	$^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}^*$	Stopped π/μ	KARMEN	5.1 ± 0.6(stat) ± 0.5(sys)	5.4–5.6 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
		Stopped π/μ	E225	3.6 ± 2.0(tot)	4.1 [Shell] (Hayes and Towner, 2000)
		Stopped π/μ	LSND	4.3 ± 0.4(stat) ± 0.6(sys)	
	$^{12}\mathrm{C}(\nu_\mu, \nu_\mu)^{12}\mathrm{C}^*$	Stopped π/μ	KARMEN	3.2 ± 0.5(stat) ± 0.4(sys)	2.8 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
	$^{12}\mathrm{C}(\nu, \nu)^{12}\mathrm{C}^*$	Stopped π/μ	KARMEN	10.5 ± 1.0(stat) ± 0.9(sys)	10.5 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
	$^{12}\mathrm{C}(\nu_\mu, \mu^-)X$	Decay in flight	LSND	1060 ± 30(stat) ± 180(sys)	1750–1780 [CRPA] (Kolbe, Langanke, and Vogel, 1999) 1380 [Shell] (Hayes and Towner, 2000) 1115 [Green's Function] (Meucci, Giusti, and Pacati, 2004)
	$^{12}\mathrm{C}(\nu_\mu, \mu^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$	Decay in flight	LSND	56 ± 8(stat) ± 10(sys)	68–73 [CRPA] (Kolbe, Langanke, and Vogel, 1999) 56 [Shell] (Hayes and Towner, 2000)
^{56}Fe	$^{56}\mathrm{Fe}(\nu_e, e^-)^{56}\mathrm{Co}$	Stopped π/μ	KARMEN	256 ± 108(stat) ± 43(sys)	264 [Shell] (Kolbe, Langanke, and Martínez-Pinedo, 1999)
^{71}Ga	$^{71}\mathrm{Ga}(\nu_e, e^-)^{71}\mathrm{Ge}$	^{51}Cr source	GALLEX, ave.	0.0054 ± 0.0009(tot)	0.0058 [Shell] (Haxton, 1998)
		^{51}Cr	SAGE	0.0055 ± 0.0007(tot)	
		^{37}Ar source	SAGE	0.0055 ± 0.0006(tot)	0.0070 [Shell] (Bahcall, 1997)
^{127}I	$^{127}\mathrm{I}(\nu_e, e^-)^{127}\mathrm{Xe}$	Stopped π/μ	LSND	284 ± 91(stat) ± 25(sys)	210–310 [Quasiparticle] (Engel, Pittel, and Vogel, 1994)

Intermediate-energy and high-energy neutrino-nucleus interactions

Atmospheric ν problem (before 1998)



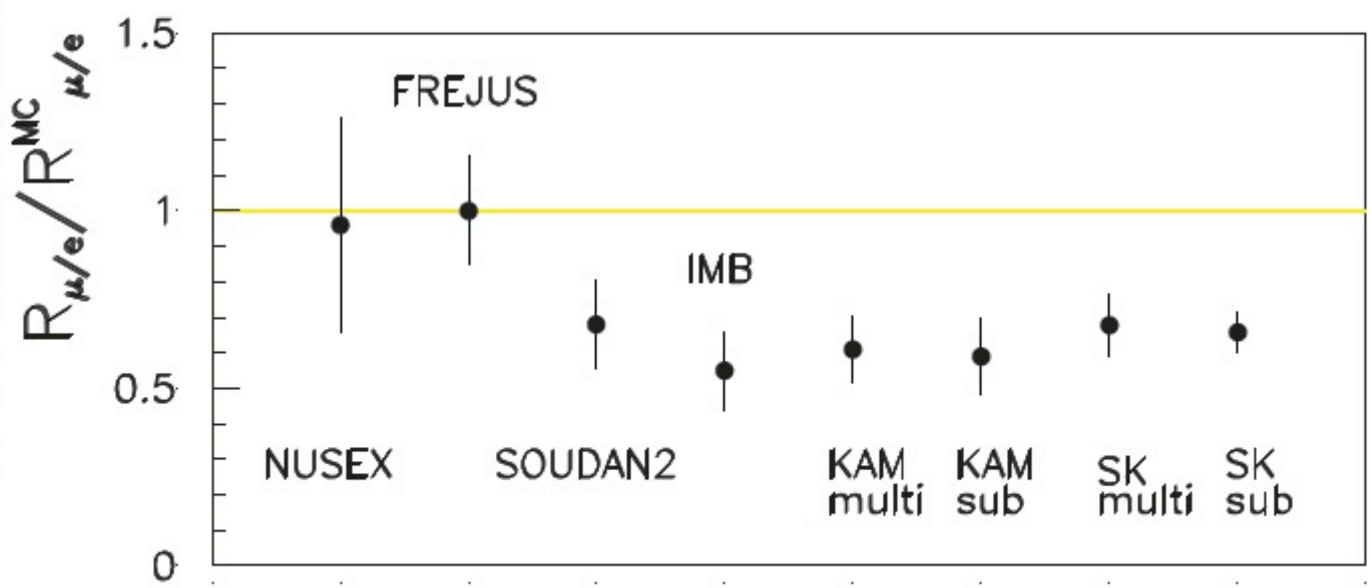
Much higher energy than solar neutrinos

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu \qquad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

Expect $R_{\mu/e}$: $(\nu_\mu + \bar{\nu}_\mu) / (\nu_e + \bar{\nu}_e) \sim 2$

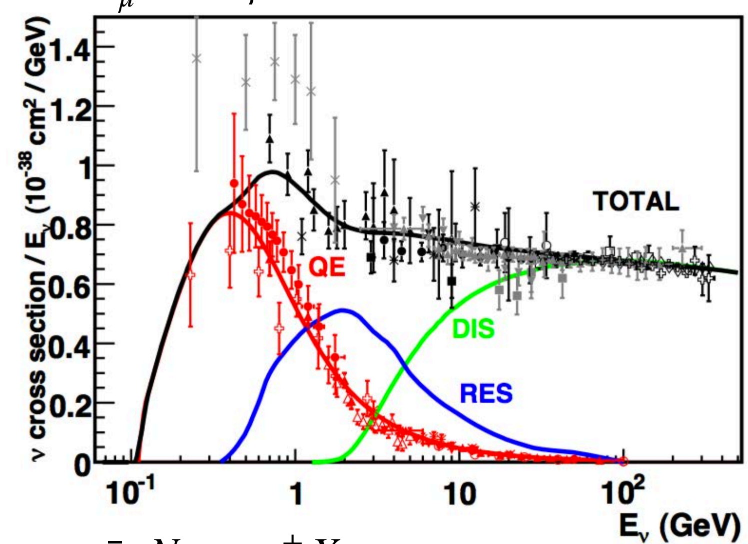
Measured ~ 0.6-0.7 of expectation



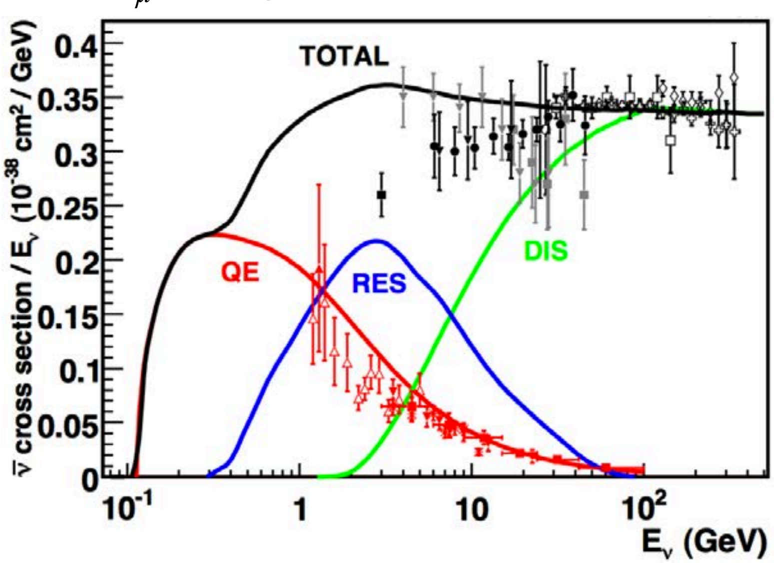
Intermediate-energy neutrino cross section

- The nucleus is typically described in terms of individual quasi-free nucleons that participate in the scattering process

$\nu_\mu N \to \mu^- X$



$\bar{\nu}_\mu N \to \mu^+ X$



1. Quasielastic scattering (QE)

- Example: $\nu_\mu n \to \mu^- p \;,\; \bar{\nu}_\mu p \to \mu^+ n$
- Final-state nucleon usually invisible in water Cherenkov detector

2. Resonant (RES)

- Neutrino interaction produces a baryon resonance, which quickly decays and most often to a nucleon and single pion final state:

$$\nu_\mu N \to \mu^- N^* \,;\, N^* \to \pi N'$$

3. Deep Inelastic Scattering (DIS)

- Both CC and NC possible
- Example: $\nu + q \to l^- q' \,;\, q' \to \text{hadrons}$

4. NC Neutrino-Nucleon Interactions

$$\nu + N \to \nu + X$$

The axial mass M_A puzzle

QE scattering at O(GeV) needs to take into account the nucleon structure:

$$j^\mu = [F_1^V(Q^2)\gamma^\mu + i\frac{\kappa}{2M}F_2^V(Q^2)\sigma^{\mu\nu}q_\nu - F_A(Q^2)\gamma^\mu\gamma^5 + F_P(Q^2)q^\mu\gamma^5]\tau^\pm$$

The axial mass M_A puzzle

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Vector - OK
(from electron scattering)

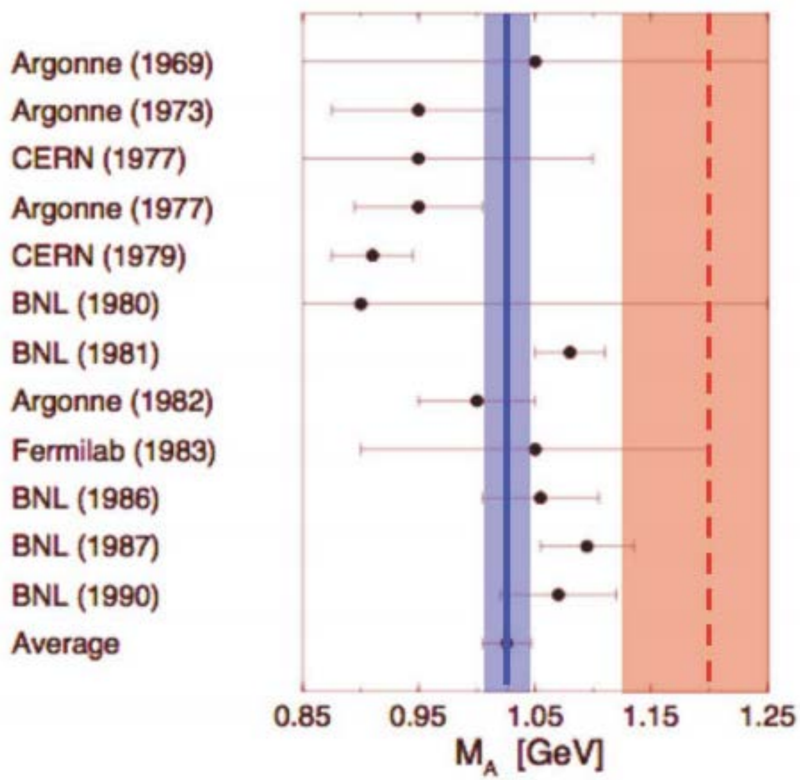
Pseudoscalar - small
$(\sim m_l/M)^2$

The axial mass M_A puzzle

QE scattering at O(GeV) needs to take into account the nucleon structure:

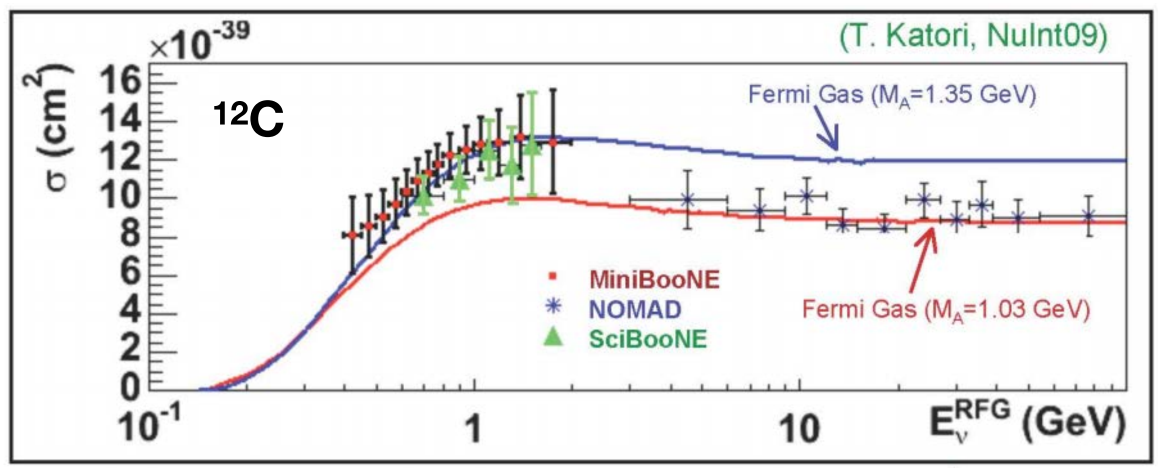
$$j^\mu = [F_1^V(Q^2)\gamma^\mu + i\frac{\kappa}{2M}F_2^V(Q^2)\sigma^{\mu\nu}q_\nu - F_A(Q^2)\gamma^\mu\gamma^5 + F_P(Q^2)q^\mu\gamma^5]\tau^\pm$$

$$F_A(Q^2) = \frac{1.267}{\left(1 + Q^2/M_A^2\right)^2}$$

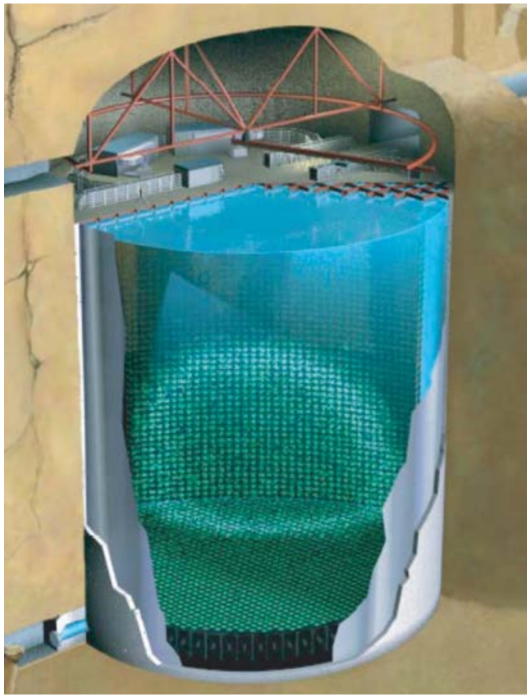


Old (pre-1990) average: $M_A = 1.03 \pm 0.02$ GeV

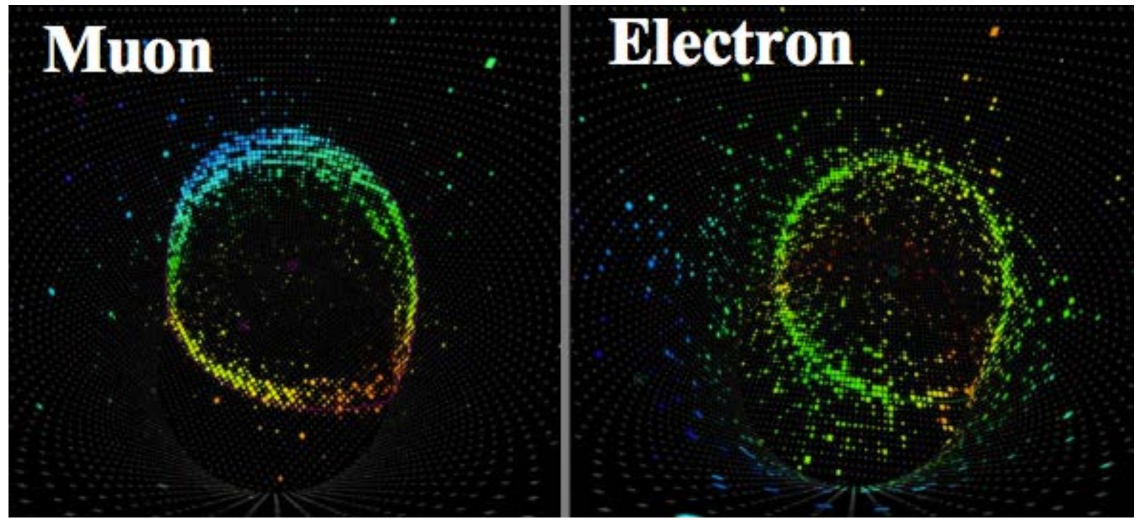
*Newer measurements (K2K, MINOS, MiniBooNE…etc) are higher, up to ~***1.35 GeV**



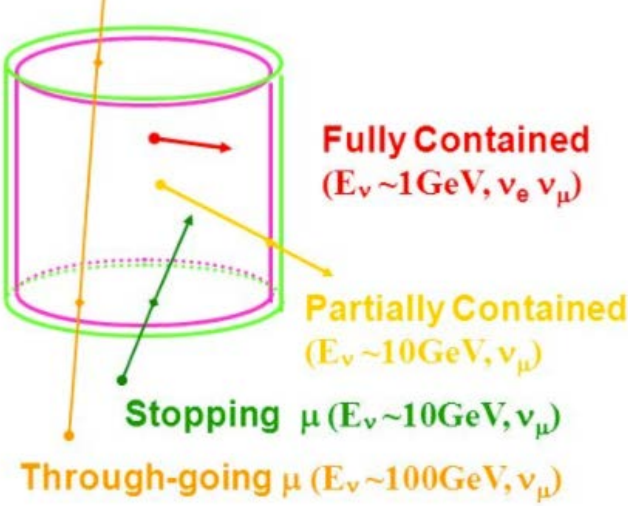
Super-Kamiokande

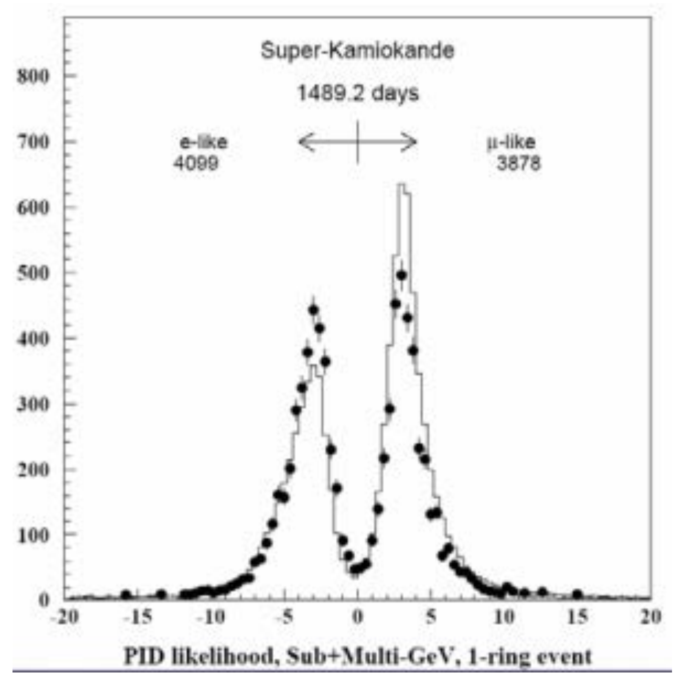


- 50 kt H_2O, 22 kt fiducial volume
- Water Cherenkov detector

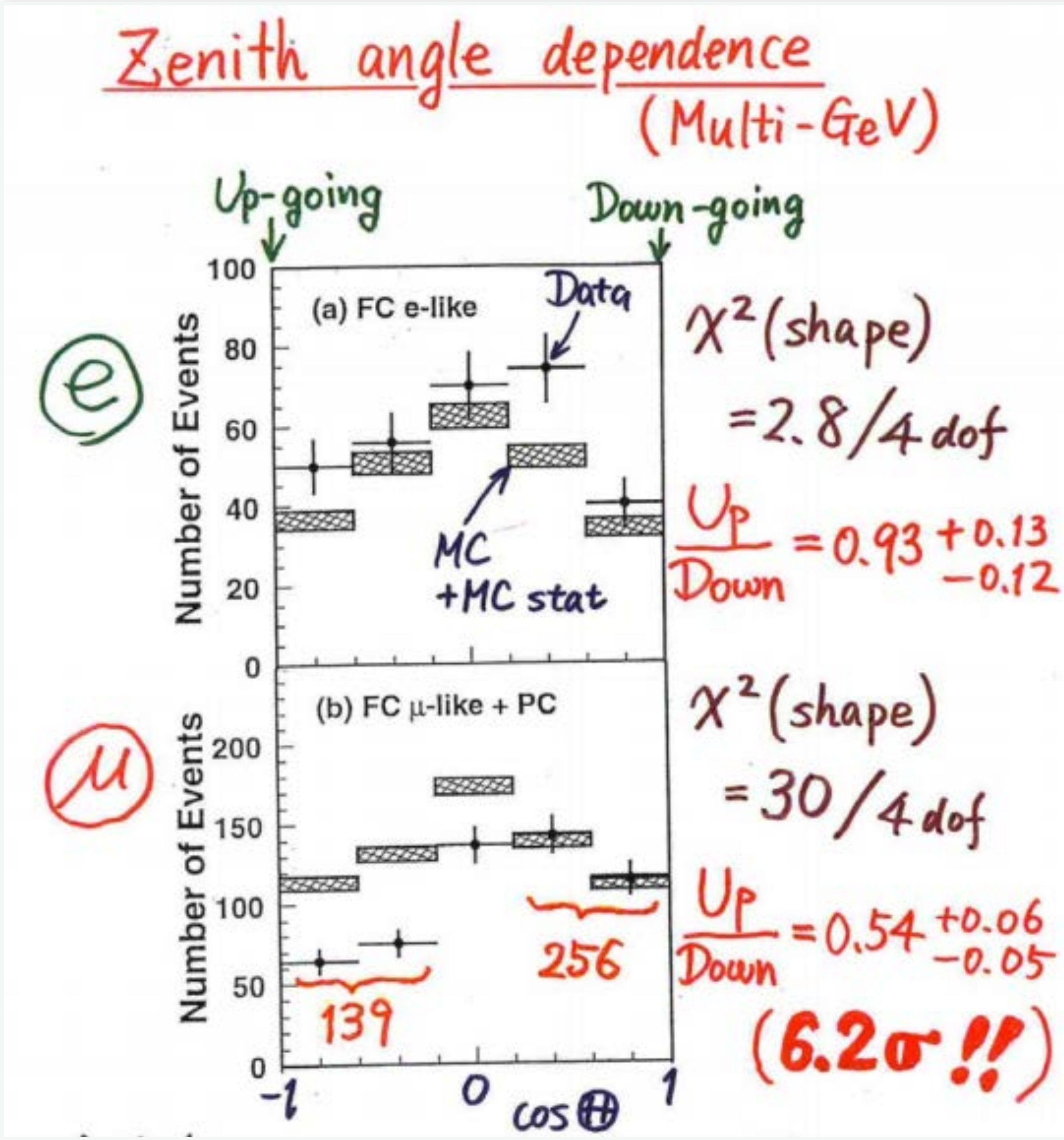


Event classification

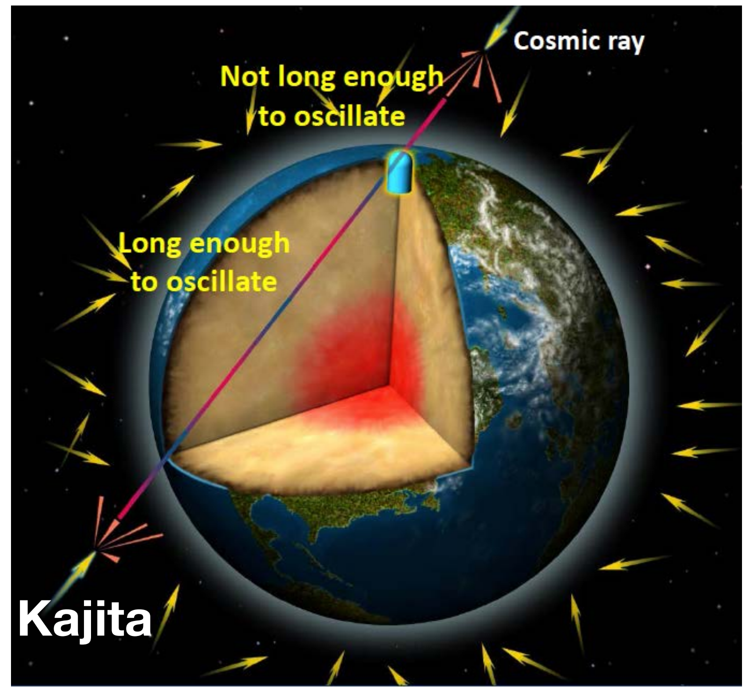




Super-Kamiokande



First demonstration of physics beyond the Standard Model (neutrino oscillations, hence neutrino mass)

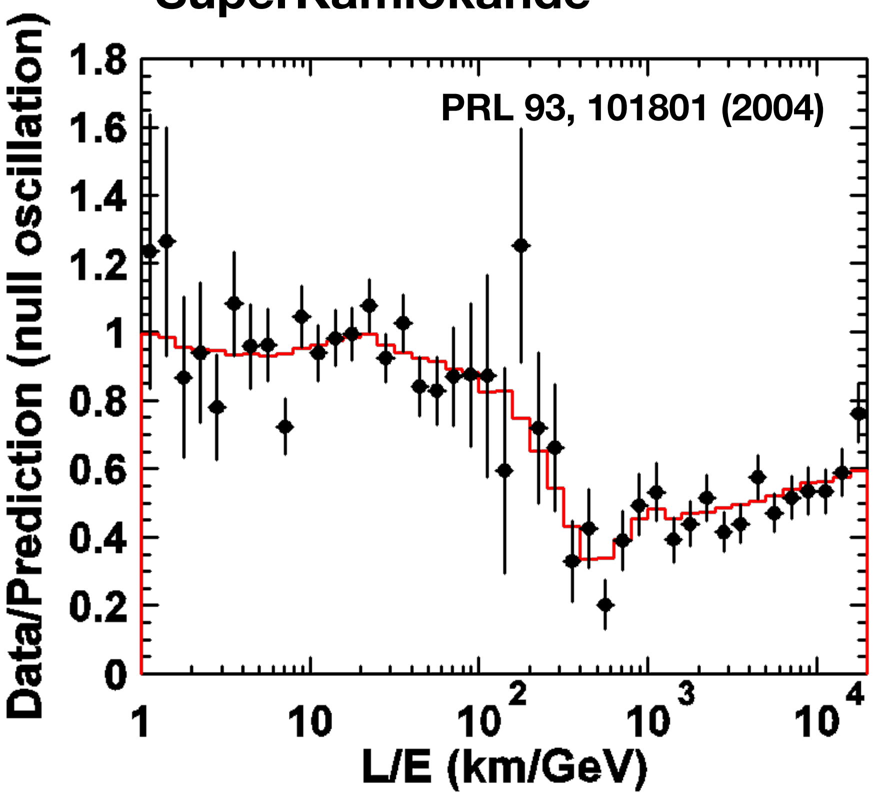


Reminder:
Segre Lecture - Kajita
5:30pm, Oct 30, 2017

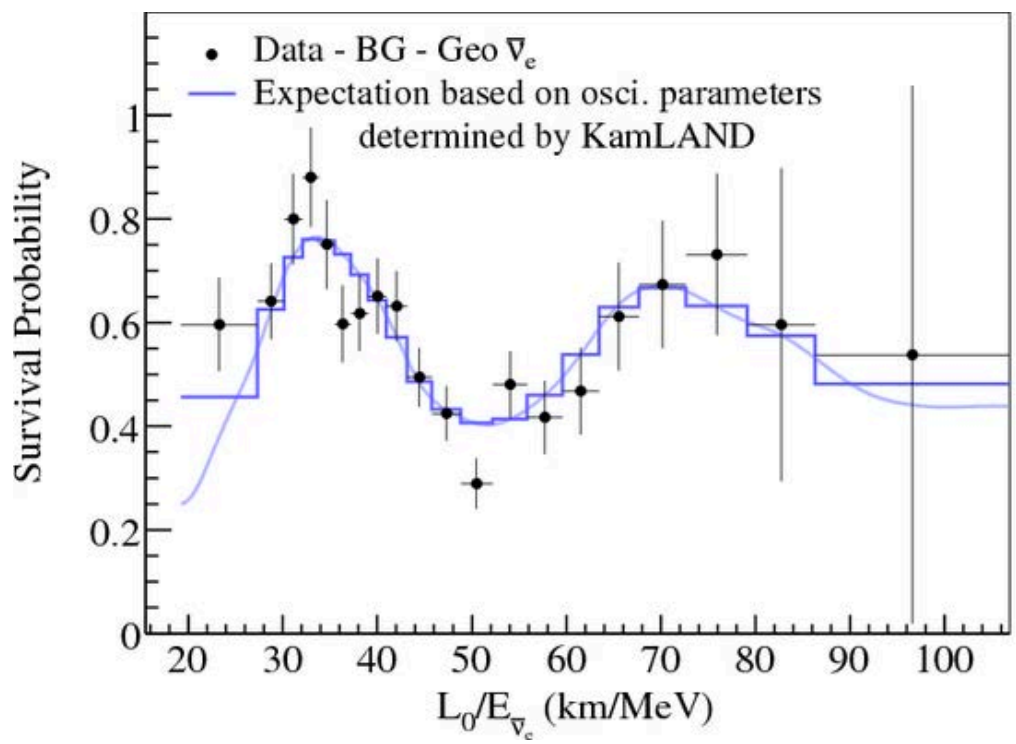
L/E (Further evidence of neutrino oscillation)

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2[\mathrm{eV}^2]\, L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$

SuperKamiokande

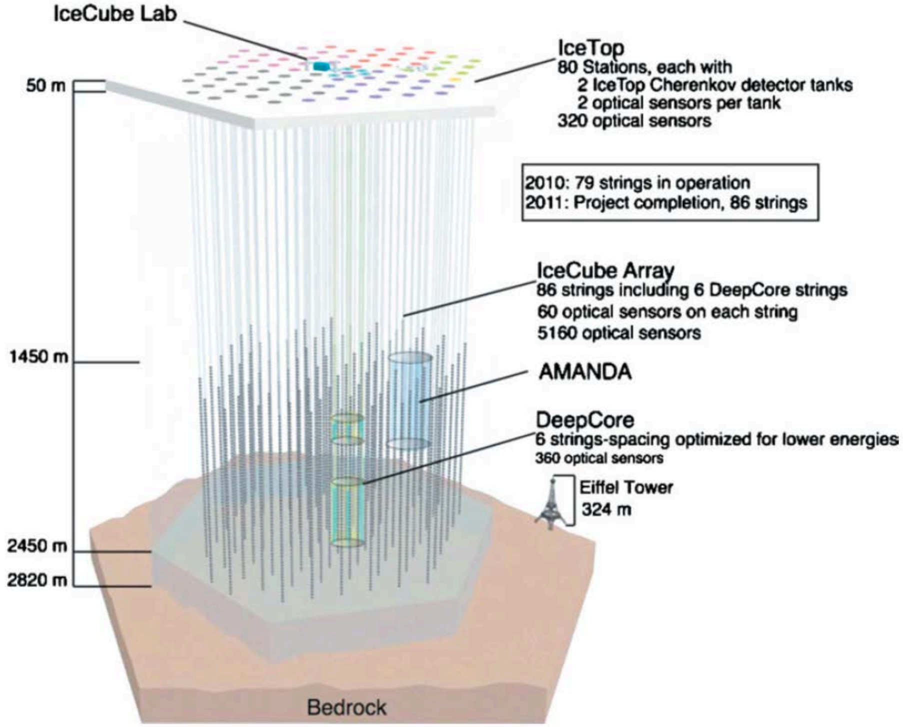


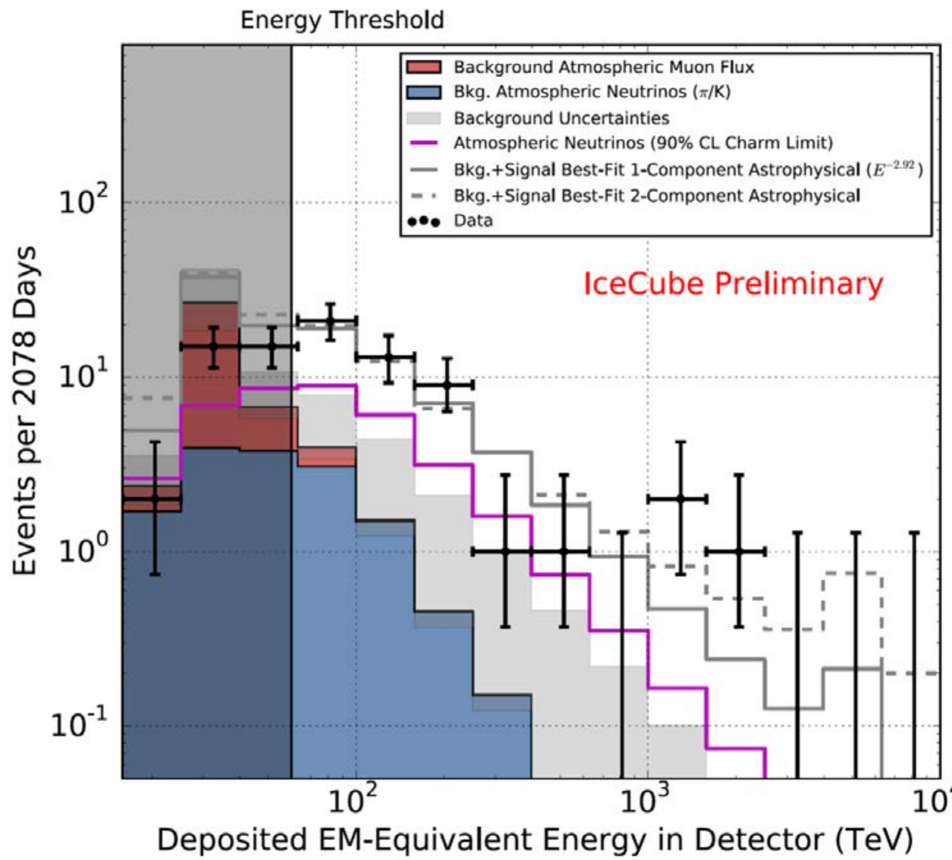
KamLAND



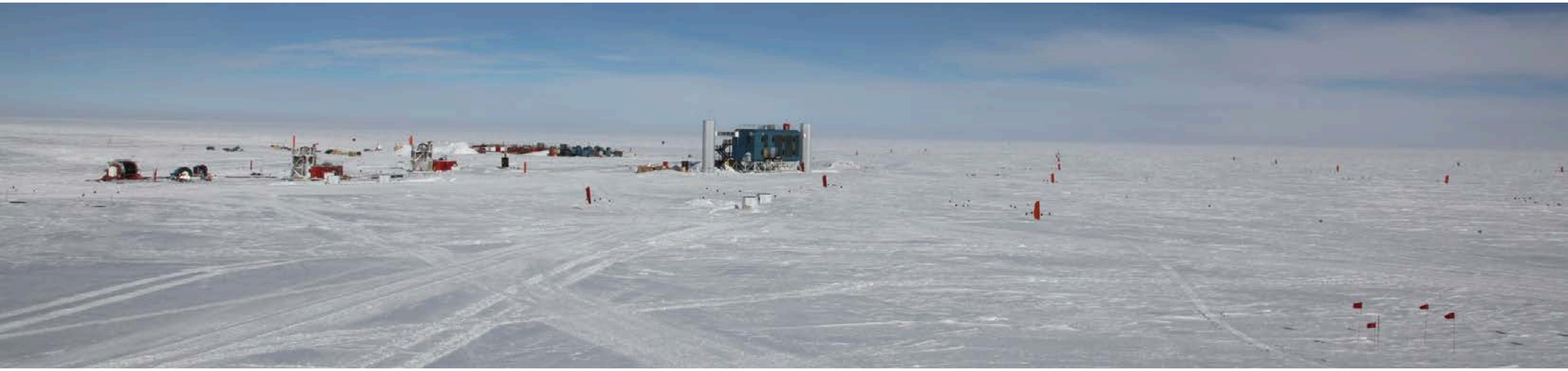
Cosmic Messenger

IceCube



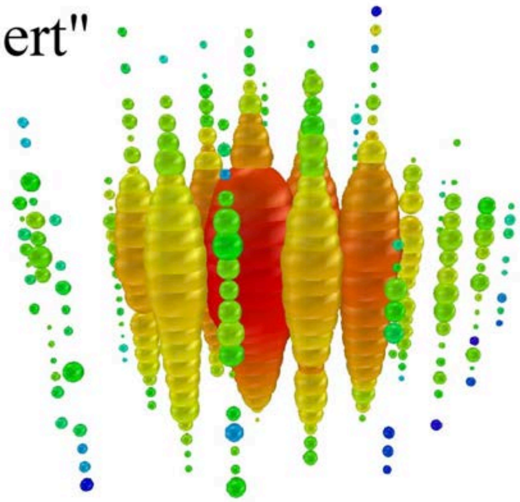


80+2 events in 6 years (54 in 4 years)



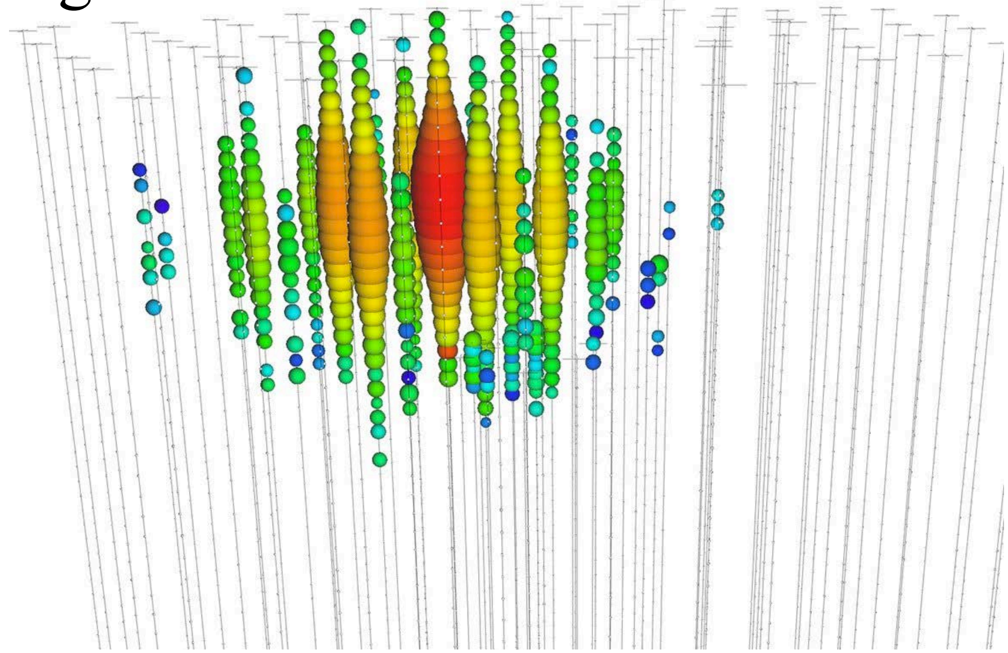
Highest-energy neutrinos observed IceCube

"Bert"



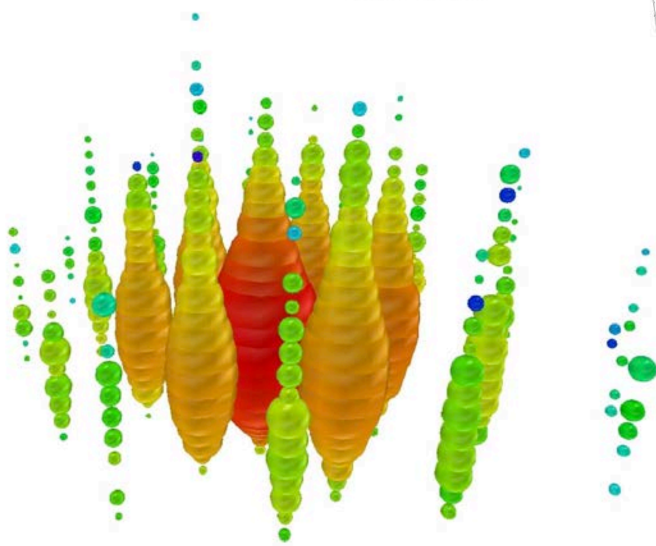
1.04 PeV

“Big Bird”



2 PeV

"Ernie"



1.14 PeV

1 PeV =10^{15} eV

How to measure the neutrino mass?

How to measure the mass of the neutrino?

(in a model independent way)

$$\pi^+ \to \mu^+ + \nu_\mu$$

How to measure the mass of the neutrino?

- Finding the missing mass at accelerator. For example:

$$\pi^+ \to \mu^+ + \nu_\mu$$

- Energy-momentum conservation says (for pion decay at rest):

$$m_{\nu_\mu}^2 = m_{\pi^+}^2 + m_{\mu^+}^2 - 2m_{\pi^+}(m_{\mu^+}^2 + p_{\mu^+}^2)^{1/2}$$

- How well can the momentum of the muon be measured? At an experiment at PSI **[Phys. Rev. D53, 6065 (1996)]**, it was measured to ~ 4 ppm:

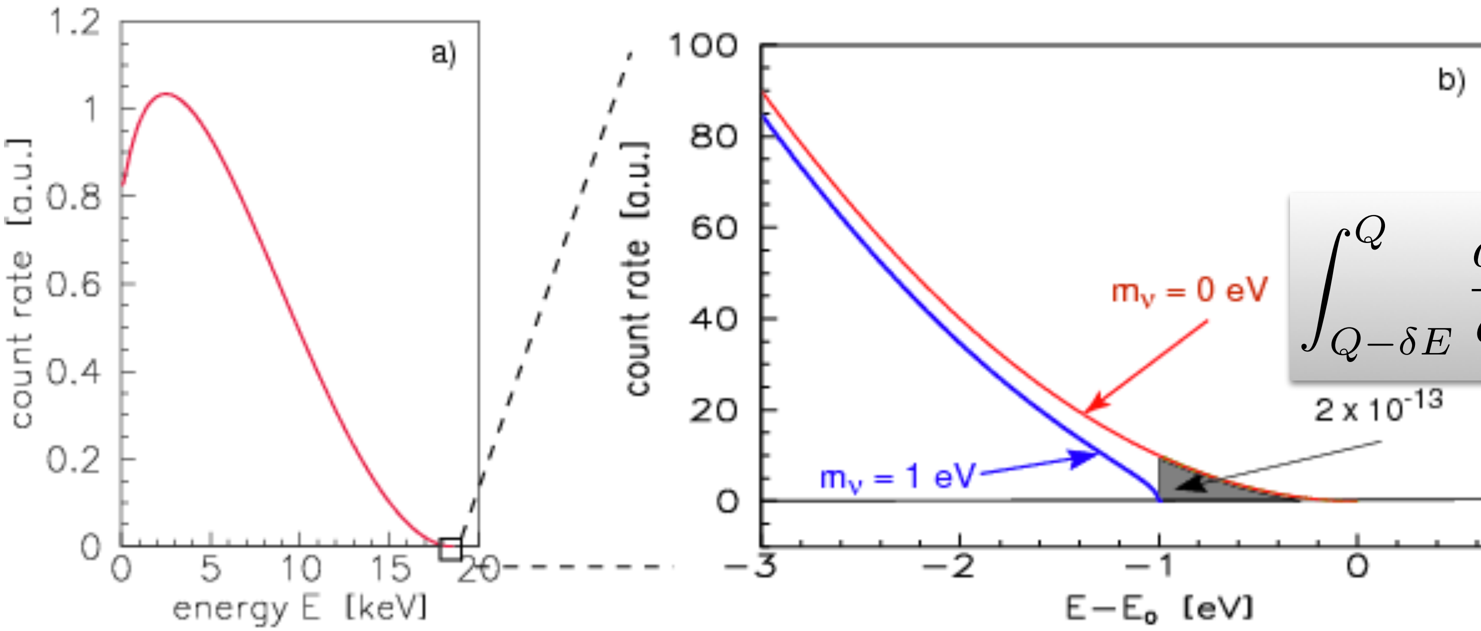
$$p_{\mu^+} = (29.79200 \pm 0.00011)\ \mathrm{MeV/c}$$

Not good enough !

(when you want to measure neutrino mass to sub-eV level) !

Determining the neutrino mass from β endpoint

$$\frac{dN}{dE} \propto F(E,Z)p(E+m_e)(Q-E)\sum_i |U_{ei}|^2 \sqrt{(Q-E)^2 - m_i^2}$$

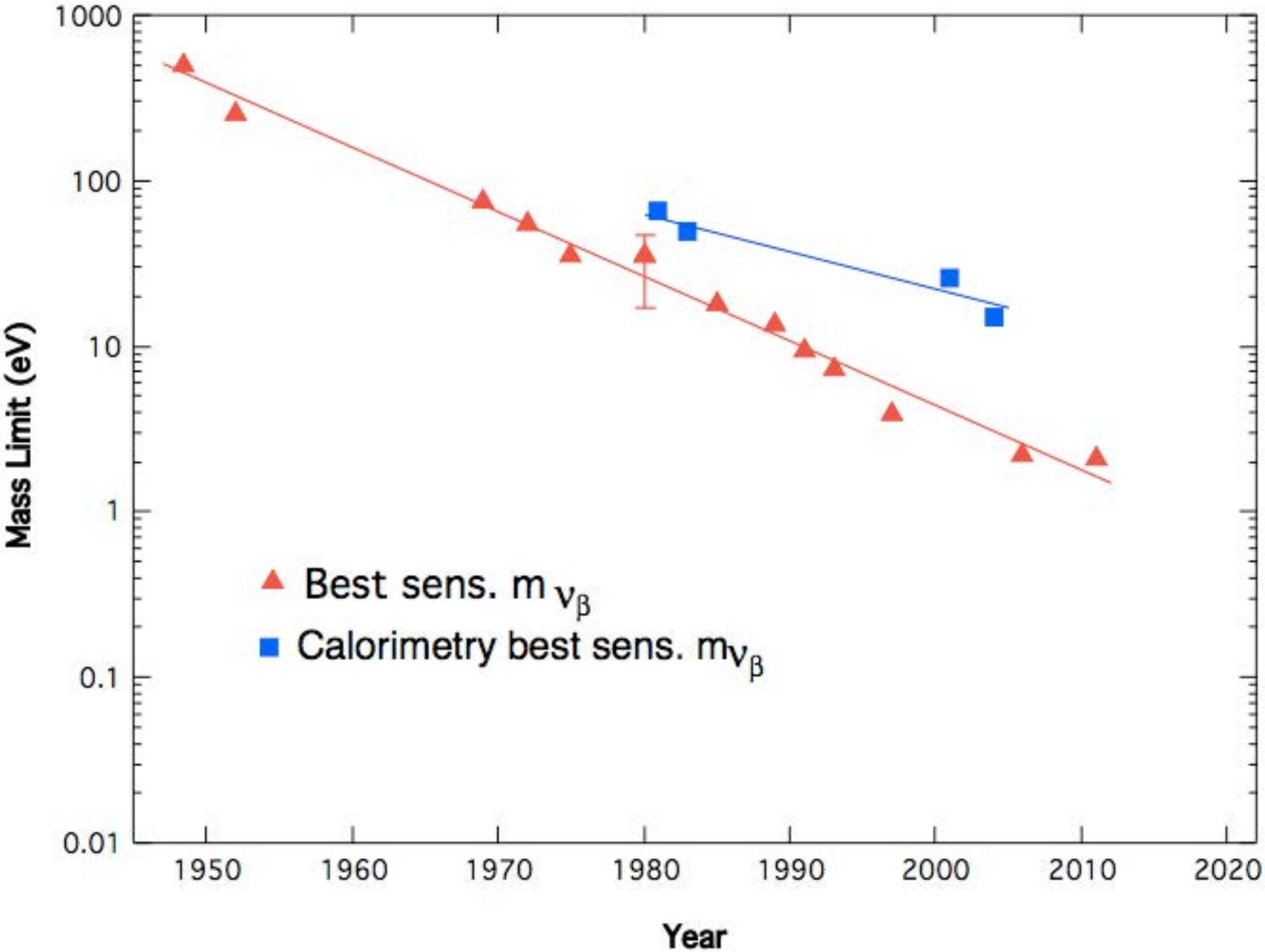


$$\int_{Q-\delta E}^{Q} \frac{dN}{dE} dE \approx 2\left(\frac{\delta E}{Q}\right)^3$$

Only a tiny fraction of decays will end up near the endpoint

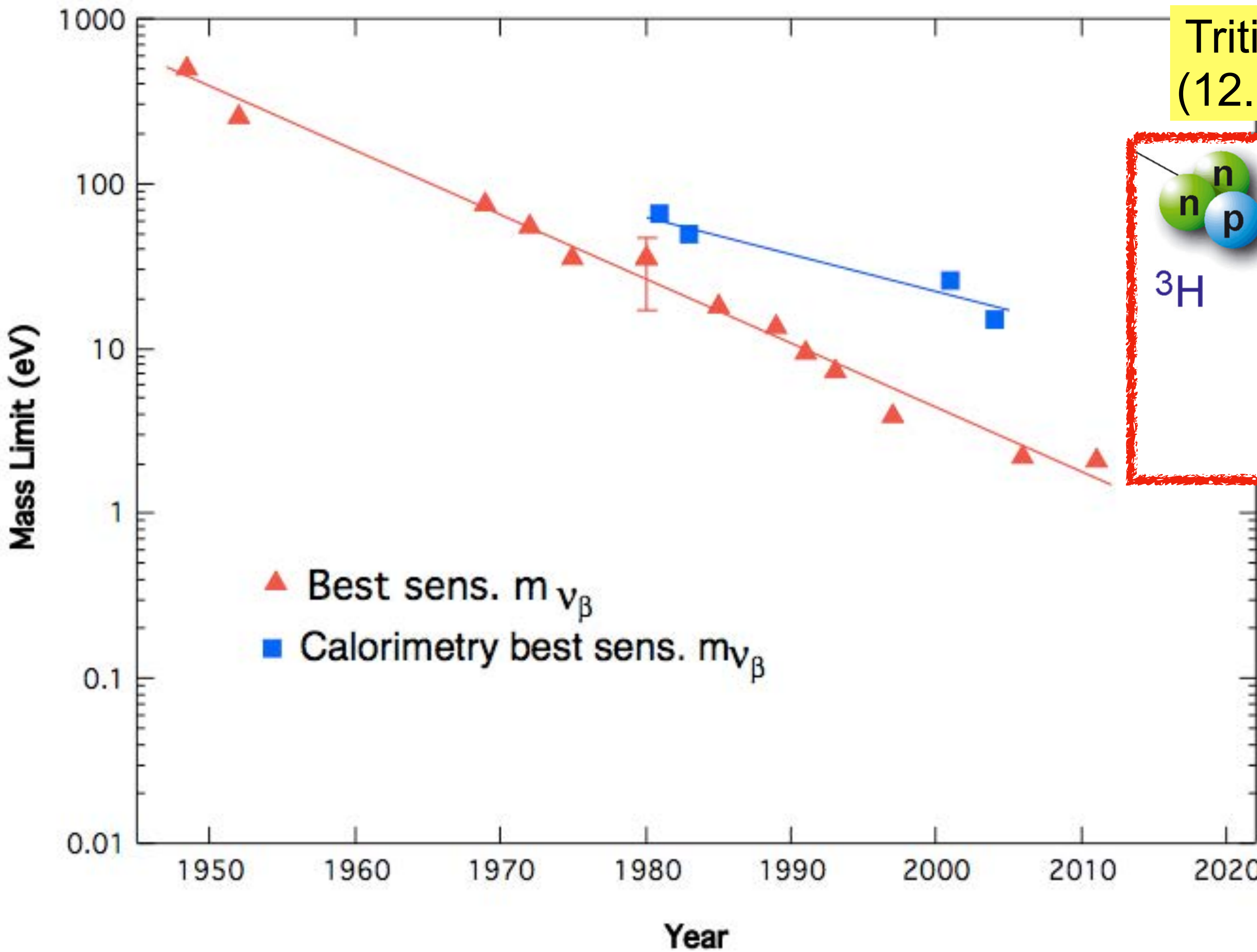
An ideal isotope would have very small Q

Neutrino mass limit from beta-decays

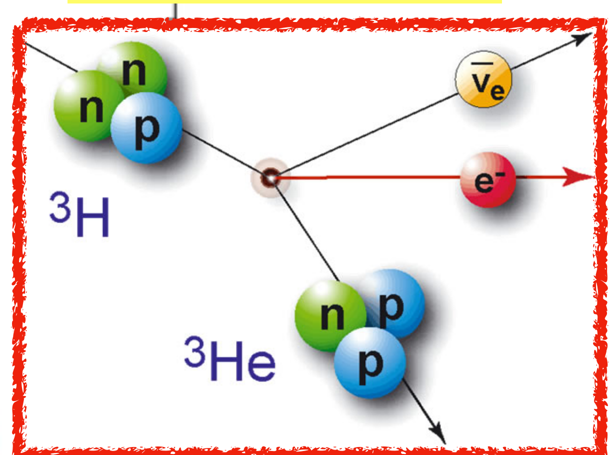


Wilkerson 2012

Neutrino mass limit from beta-decays

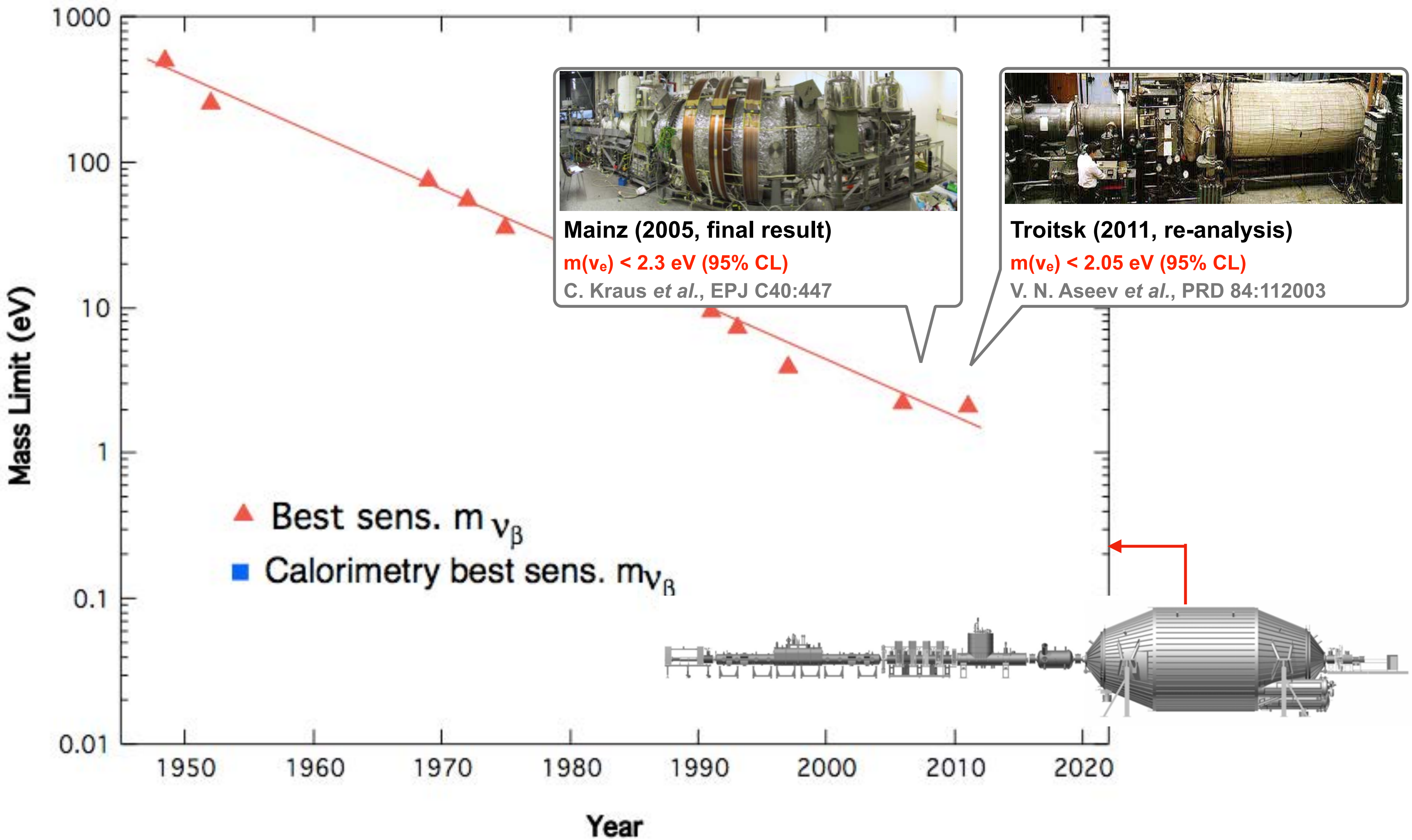


Tritium β-decay
(12.3 yr half-life)



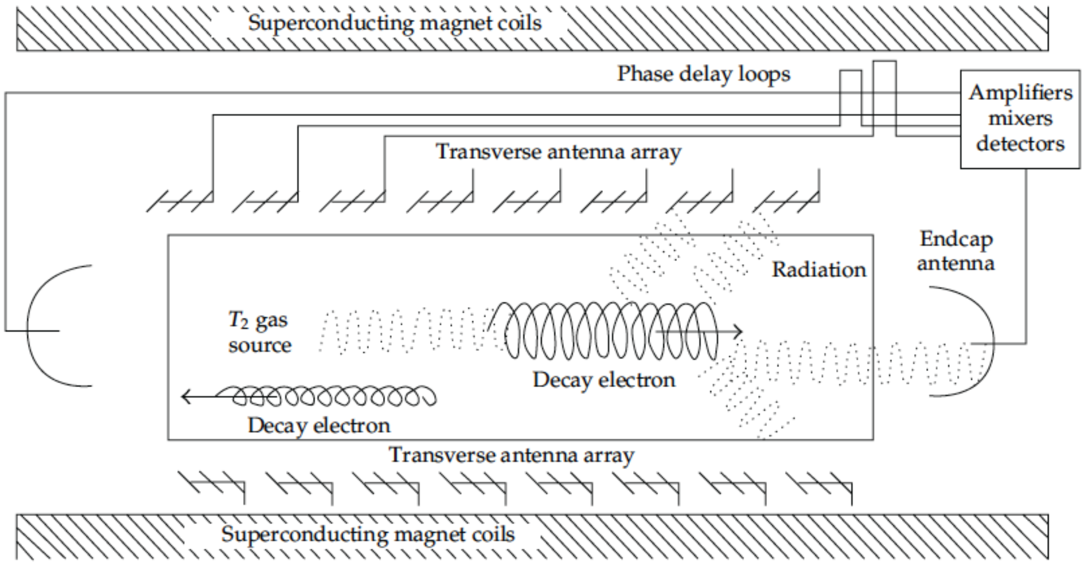
Wilkerson 2012

Neutrino mass limit from beta-decays



Wilkerson 2012

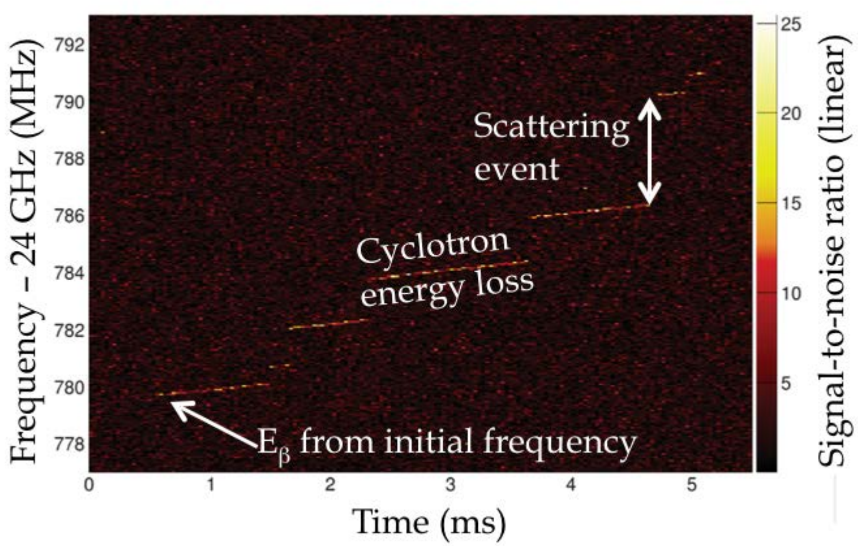
Another way to “see” the beta-electrons

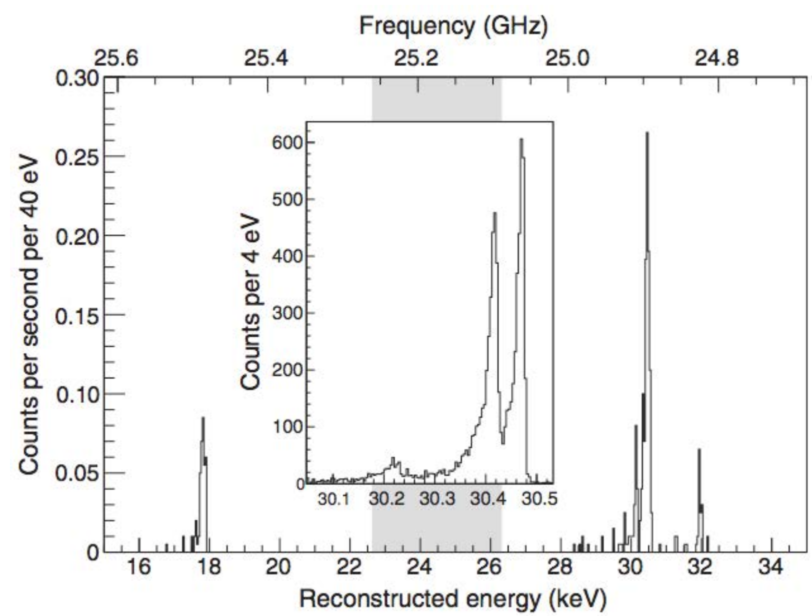


coherent cyclotron radiation

$$\omega = \frac{\omega_\circ}{\gamma} = \frac{qB}{m_e + E}$$

^{83m}Kr test

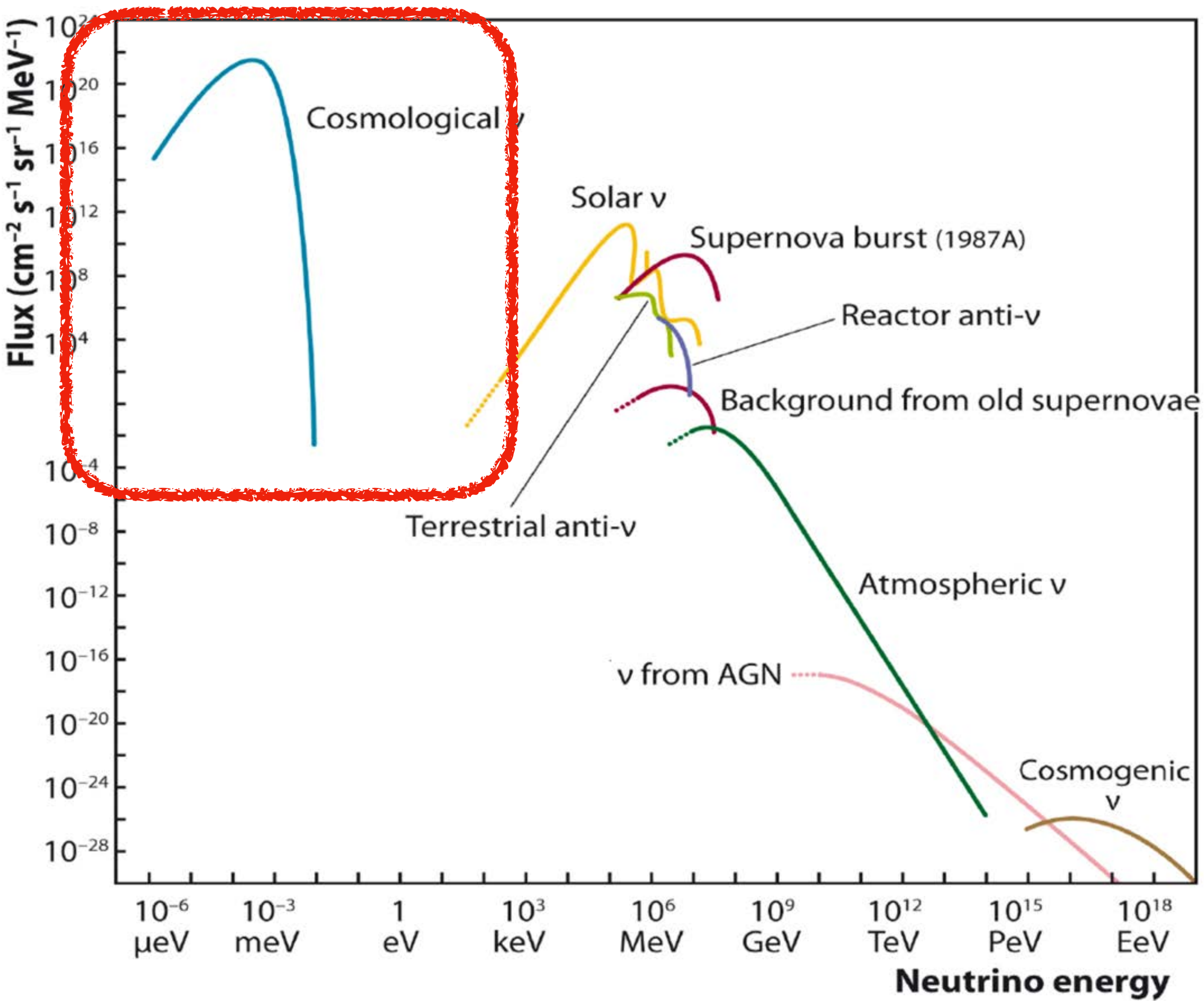




Asner et al., PRL ***114*** *(2015) 162501*

A Nobel idea….

Seeing the cosmic neutrino background



$$n_\nu = \left(\frac{3}{4}\right)\left(\frac{4}{11}\right) n_\gamma = 112/\text{cm}^3$$

per (neutrino+antineutrino) species

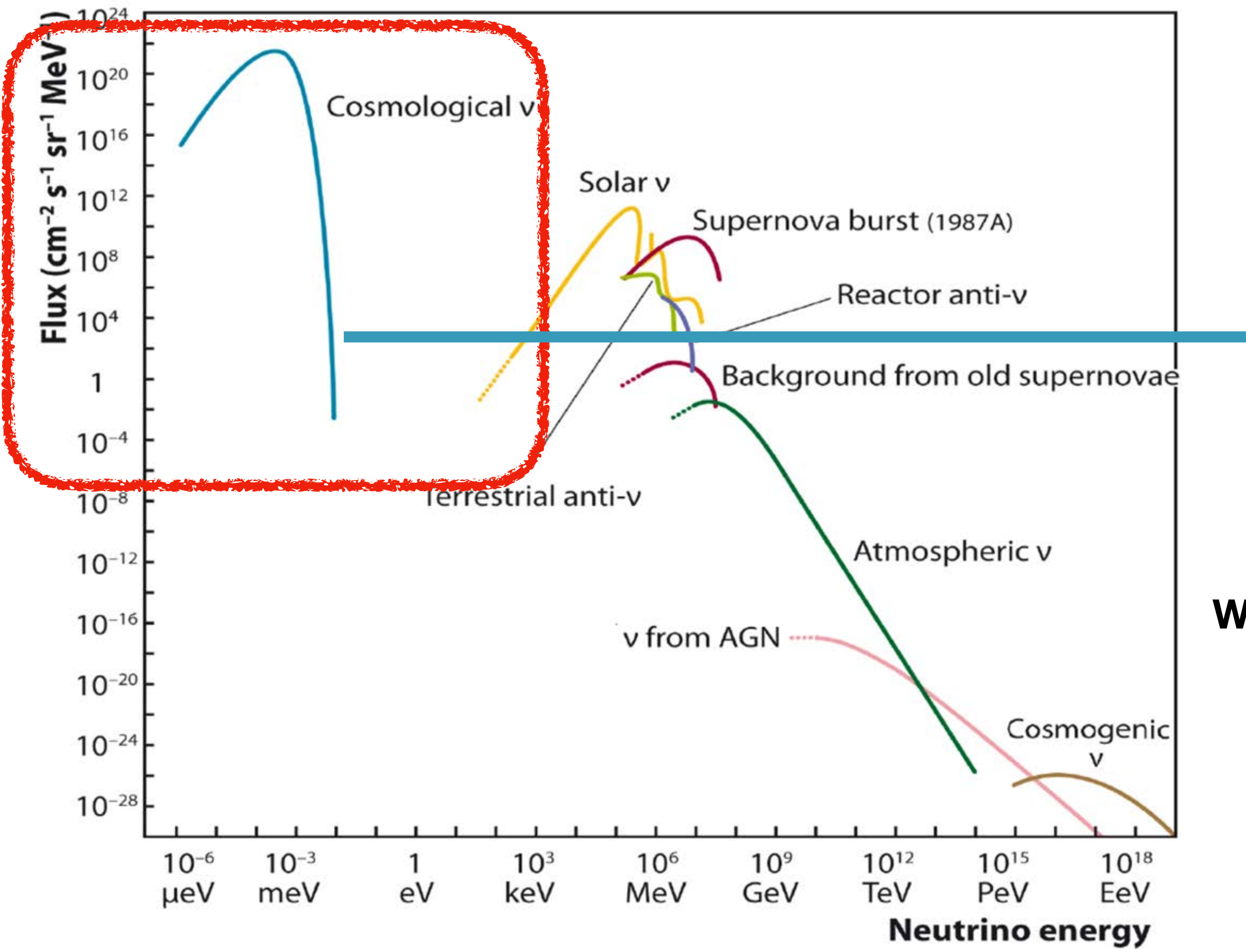
$$T_\nu = 1.95 \text{ K}$$

cf $T_\gamma = 2.725$ K

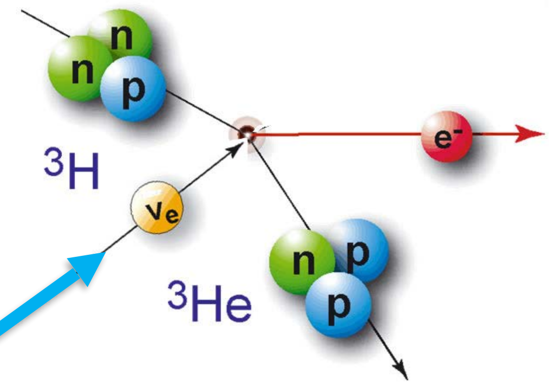
The energy is so low

HOW?

Seeing the cosmic neutrino background



Neutrino capture on Tritium



With 100 g of tritium, event rate is

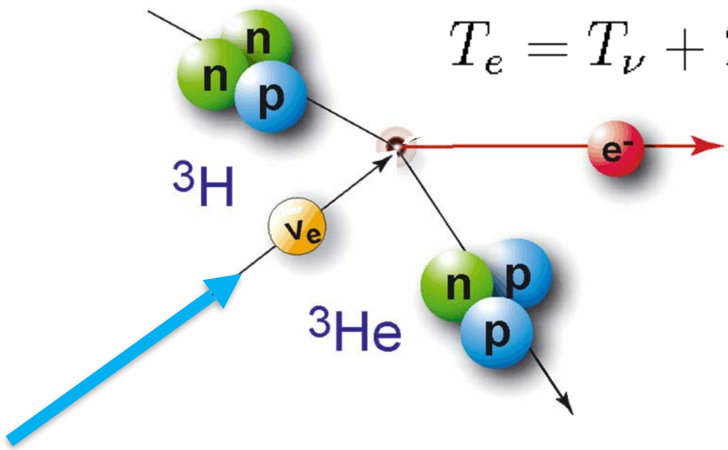
~O(10) per year

Tritium and other isotopes studied for relic neutrino capture in:
Cocco, Mangano, Messina, JCAP 0706 (2007)015

Seeing the cosmic neutrino background

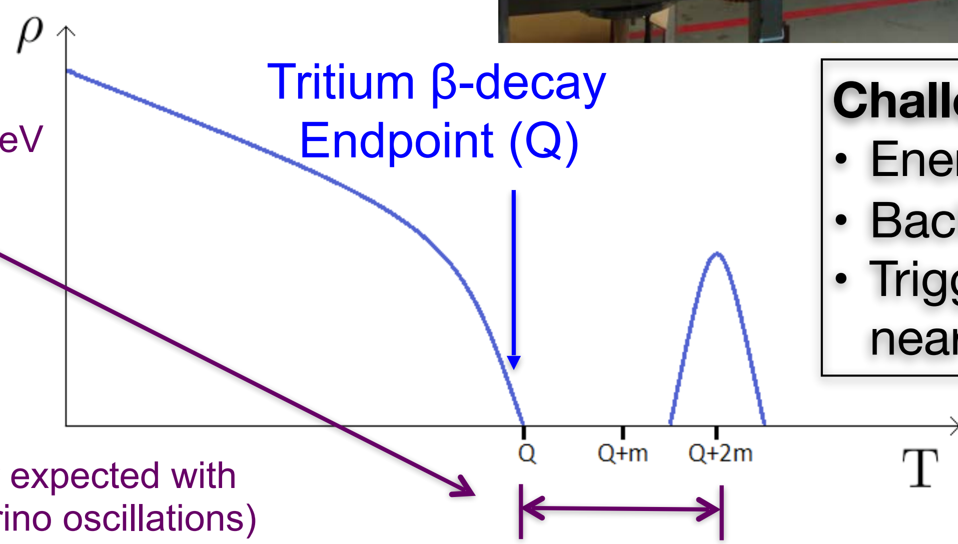
Neutrino capture on Tritium

$$T_e = T_\nu + 2m_\nu + Q$$



What do we know?

Gap (2m) constrained to < ~0.6eV from Cosmology



(some electron flavor expected with 2m>0.1eV from neutrino oscillations)

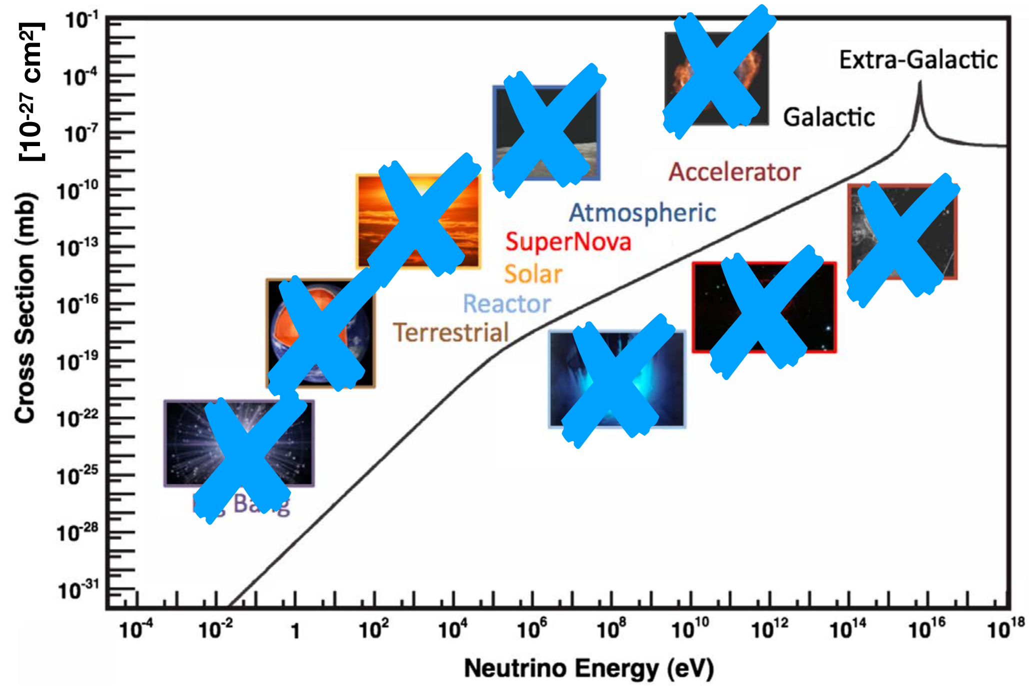
Figure 1: Emitted electron density of states vs kinetic energy for neutrino capture on beta decaying nuclei. The spike at $Q + 2m$ is the CNB signal

Challenges:
- Energy resolution
- Background
- Triggering on the electrons near endpoint

Tully 2017

Neutrino topics that I didn't cover (many):

- Long baseline neutrino experiments (CP violation and neutrino mass hierarchy)
- Neutrino astronomy
- Neutrinoless double beta decays
- Sterile neutrinos (from reactor and beam experiments)
- Neutrinos in cosmology….



But I have covered how to "see" the neutrinos in the energy ranges of the sources in Slide 3, so you can explore these additional topics on your own.

References

- Christine Sutton, *Spaceship Neutrinos*, Cambridge University Press (1992).
- H. Gallagher et al., *Neutrino-Nucleus Interactions*, Annu. Rev. Nucl. Part. Sci. 61, 355 (2011).
- J. A. Formaggio and G. P. Zeller, *From eV to EeV: Neutrino cross sections across energy scales*, Rev. Mod. Phys. 84, 1307 (2012).
- T. W. Donnelly et al., *Foundations of Nuclear and Particle Physics*, Cambridge University Press (2017).

Neutrino interactions

Useful Formulae

$\hbar = 6.58 \times 10^{-25}$ GeV sec $= 1$

$\hbar c = 0.197$ GeV F $= 1$

$(1 \text{ GeV})^{-2} = 0.389$ mb

$$\alpha = \frac{e^2}{4\pi} = \frac{1}{137}$$

$x^\mu = (t, \mathbf{x})$, $\quad p^\mu = (E, \mathbf{p}) = i\left(\frac{\partial}{\partial t}, -\nabla\right) = i\partial^\mu$

$p \cdot x = Et - \mathbf{p}\cdot\mathbf{x}$, $\quad p^2 = p^\mu p_\mu = E^2 - \mathbf{p}^2 = m^2$

$(\square^2 + m^2)\phi = 0$, $\quad (i\gamma^\mu \partial_\mu - m)\psi = 0.$

In an electromagnetic field, $i\partial^\mu \to i\partial^\mu + eA^\mu$ (charge $-e$)

$j^\mu = -ie(\phi^* \partial^\mu \phi - \phi \partial^\mu \phi^*)$, $\quad j^\mu = -e\bar{\psi}\gamma^\mu\psi$

γ-Matrices

$\gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2g^{\mu\nu}$, $\quad \gamma^{\mu\dagger} = \gamma^0\gamma^\mu\gamma^0.$

$\gamma^{0\dagger} = \gamma^0$, $\quad \gamma^0\gamma^0 = I$; $\quad \gamma^{k\dagger} = -\gamma^k$, $\quad \gamma^k\gamma^k = -I$, $\quad k = 1, 2, 3.$

$\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3$, $\quad \gamma^\mu\gamma^5 + \gamma^5\gamma^\mu = 0$, $\quad \gamma^{5\dagger} = \gamma^5.$

(Trace theorems on pages 123 and 261)

Standard representation:

$$\gamma^0 \equiv \beta = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}, \quad \boldsymbol{\gamma} = \beta\boldsymbol{\alpha} = \begin{pmatrix} 0 & \boldsymbol{\sigma} \\ -\boldsymbol{\sigma} & 0 \end{pmatrix}, \quad \gamma^5 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Spinors

$$(\not{p} - m)u = 0, \quad \bar{u}(\not{p} - m) = 0 \qquad \begin{cases} \bar{u} \equiv u^\dagger\gamma^0 \\ \not{p} \equiv \gamma_\mu p^\mu \end{cases}$$

$u^{(r)\dagger}u^{(s)} = 2E\delta_{rs}$, $\quad \bar{u}^{(r)}u^{(s)} = 2m\delta_{rs}$, $\quad \sum_{s=1,2} u^{(s)}\bar{u}^{(s)} = \not{p} + m = 2m\Lambda_+$

$\frac{1}{2}(1 - \gamma^5)u \equiv u_L$, $\quad \frac{1}{2}(1 + \gamma^5)u \equiv u_R.$

If $m = 0$ or $E \gg m$, then u_L has helicity $\lambda = -\frac{1}{2}$, u_R has $\lambda = +\frac{1}{2}$.

Kinematics

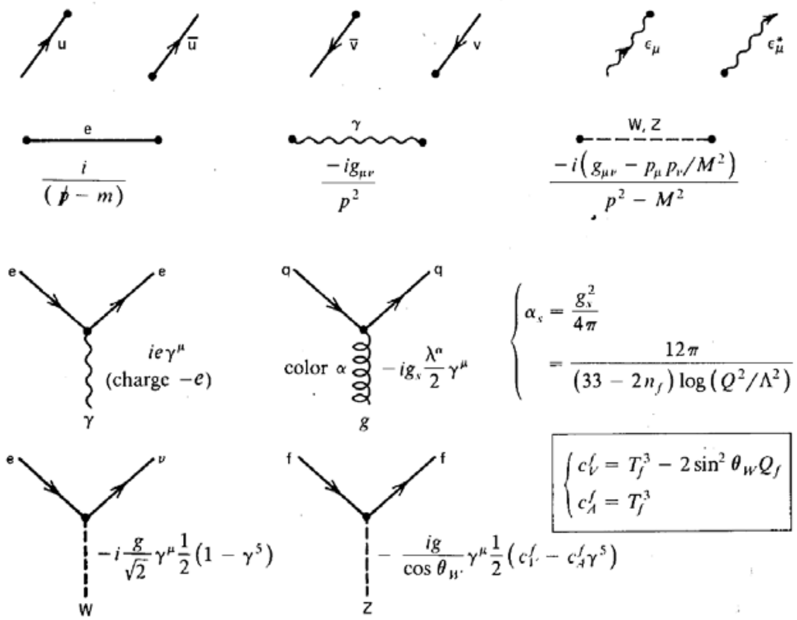
Lorentz invariant phase space ($P \to p_1 + \cdots p_n$)

$$dQ = (2\pi)^4 \delta^4(P - p_1 - \cdots p_n) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i}$$

Scattering: $\left.\frac{d\sigma}{d\Omega}\right|_{\text{cm}} = \frac{1}{64\pi^2 s}\frac{p_f}{p_i}|\mathcal{M}|^2$

Decay: $d\Gamma(A \to 1 + \cdots n) = \frac{|\mathcal{M}|^2}{2m_A} dQ.$

Feynman Rules for $-i\mathcal{M}$



f	Q_f	$(T_f^3)_L$	$(T_f^3)_R$
u, c, t	$+\frac{2}{3}$	$\frac{1}{2}$	0
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	0
ν_e, ν_μ, ν_τ	0	$\frac{1}{2}$	—
e^-, μ^-, τ^-	-1	$-\frac{1}{2}$	0

$\sin^2\theta_W \simeq 0.23$, $g\sin\theta_W = e$, $G = \frac{\sqrt{2}g^2}{8M_W^2} \simeq 1.17 \times 10^{-5}$ GeV^{-2}

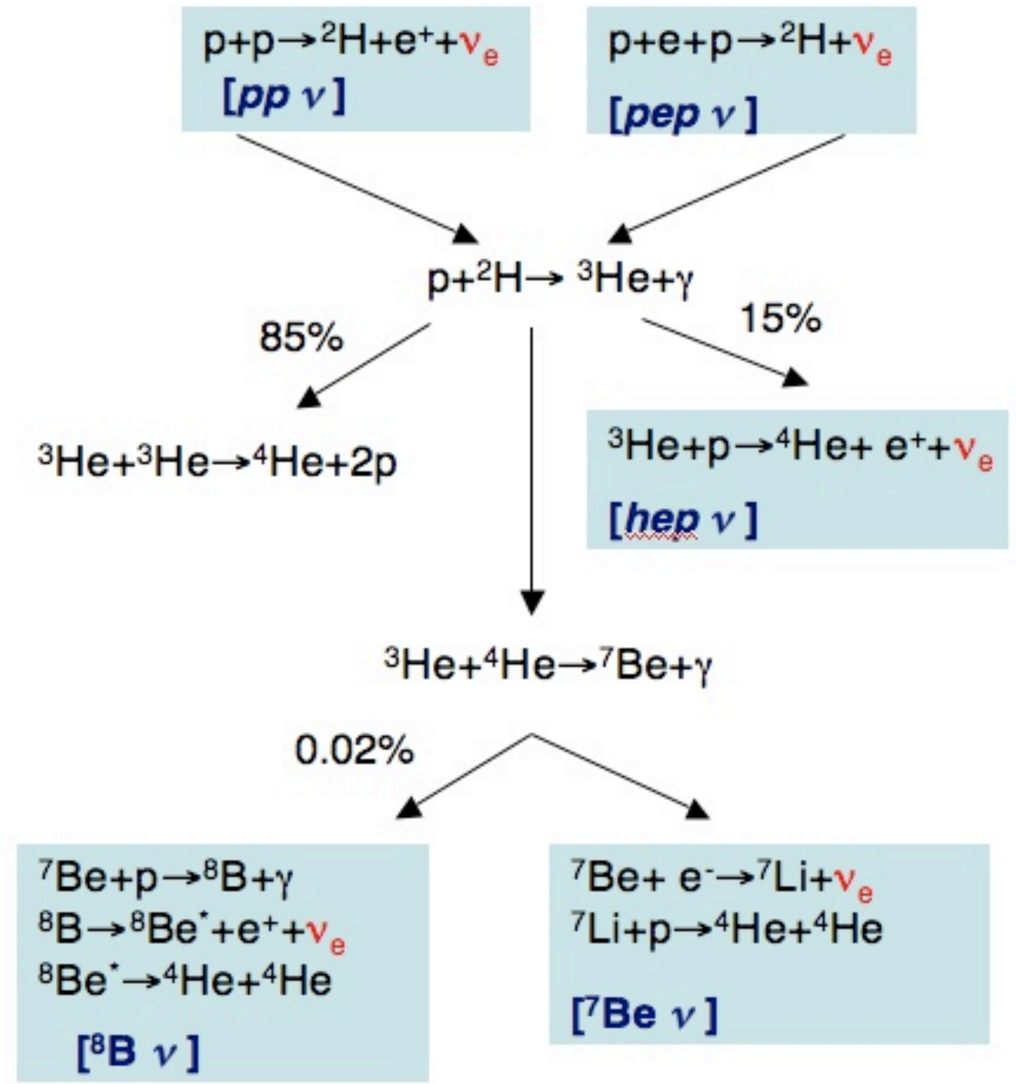
Halzen & Martin

Solar Neutrinos

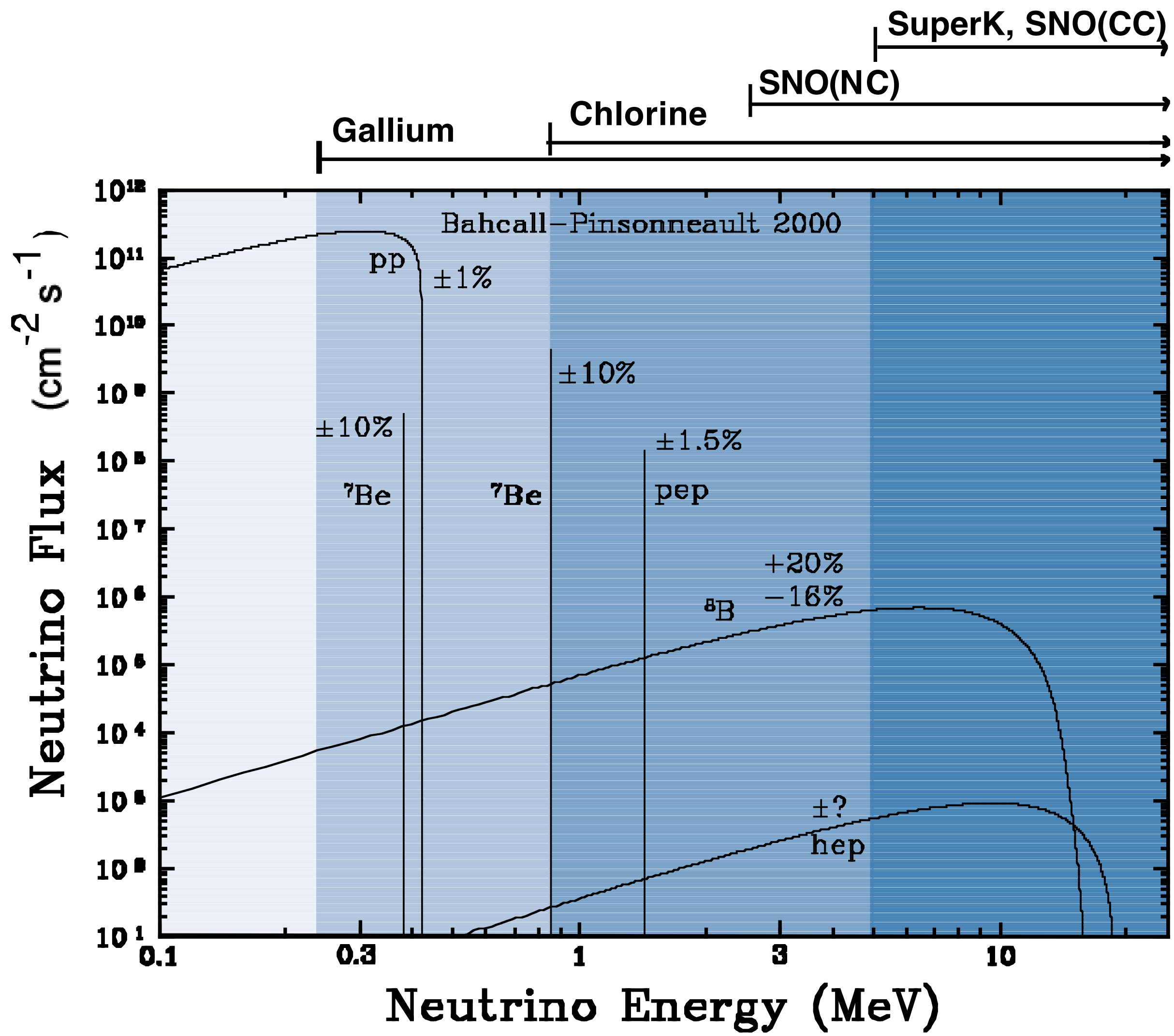
pp chain:
$4p + 2e \rightarrow {}^4He + 2\nu_e + 26.7\ MeV$

Detailed computer model of solar evolution

Standard Solar Model



Standard Solar Model



pp chain should only produce ν_e

Aside: Neutrino Oscillations

Standard Parameterization of Mixing Matrix (as CKM)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

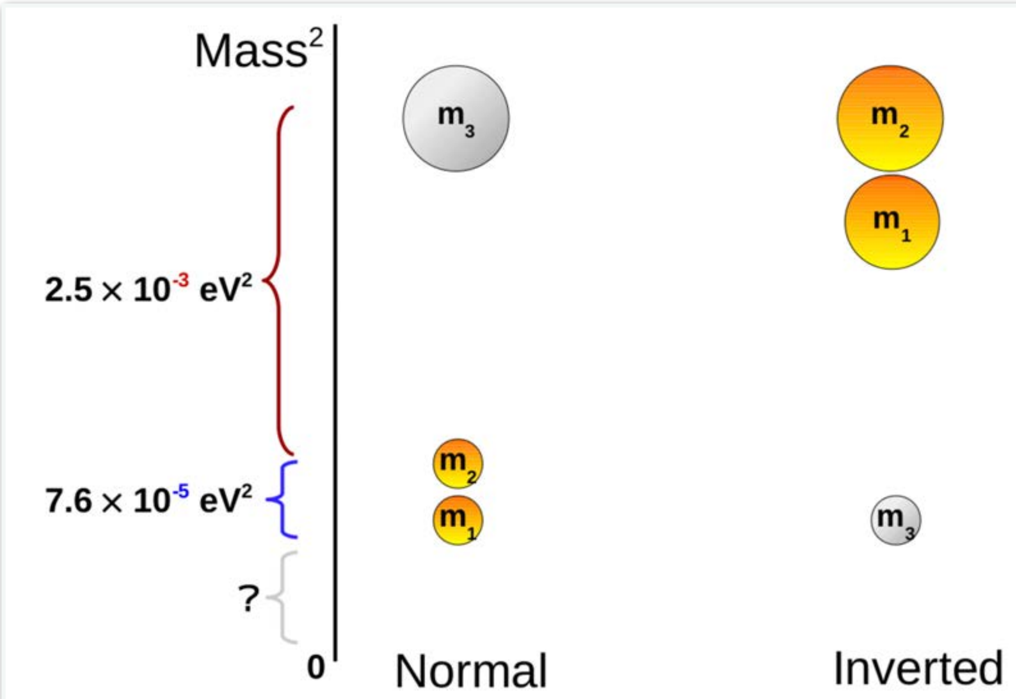
$c_{ab} \equiv \cos\vartheta_{ab}$ $\quad s_{ab} \equiv \sin\vartheta_{ab}$ $\quad 0 \le \vartheta_{ab} \le \frac{\pi}{2}$ $\quad 0 \le \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$

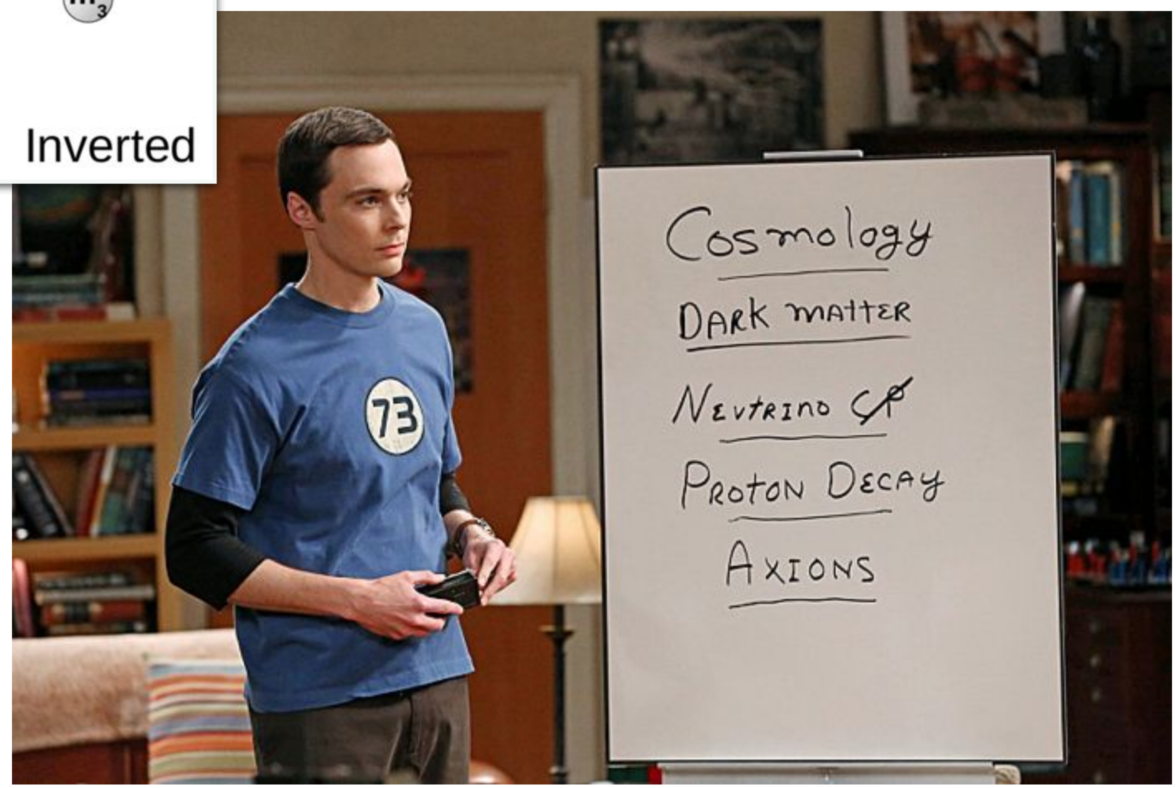
OSCILLATION PARAMETERS
- 3 Mixing Angles: ϑ_{12}, ϑ_{23}, ϑ_{13}
- 1 CPV Dirac Phase: δ_{13}
- 2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: Δm^2_{21}, Δm^2_{31}

2 CPV Majorana Phases: λ_{21}, $\lambda_{31} \Longleftrightarrow |\Delta L| = 2$ processes

C. Guinti

Mass Hierarchy & CPV - Future

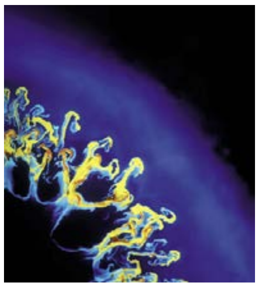




CPV & MH - Future

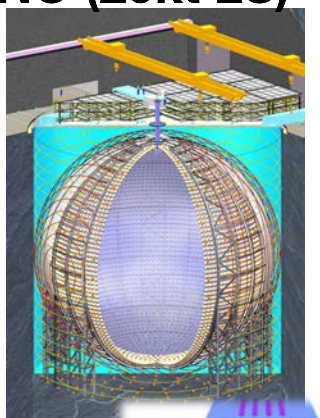
Now — 2026 →

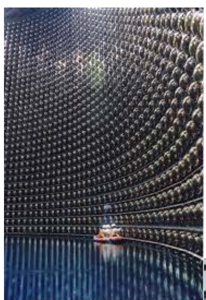
Supernovae



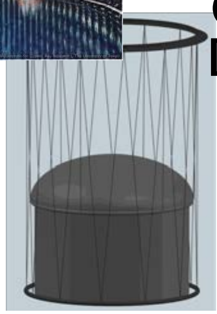
[Scholberg]

JUNO (20kt LS) [Gu]

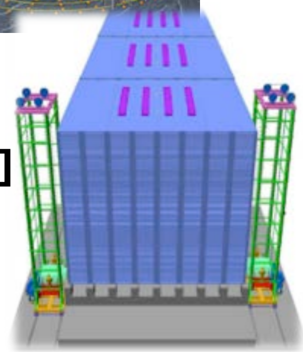




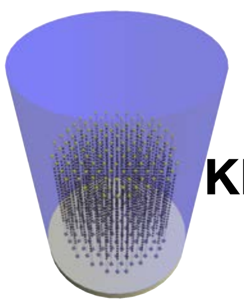
SuperK
[Mine]



CHIPS
[Thomas]



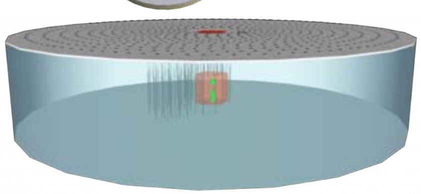
INO
[Singh]



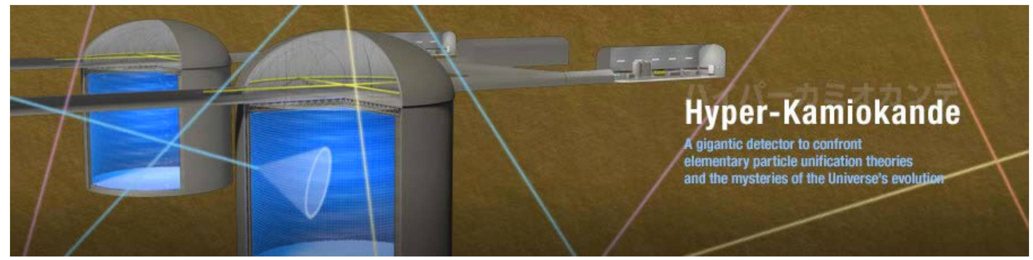
KM3Net-ORCA
[Coelho]

T2K

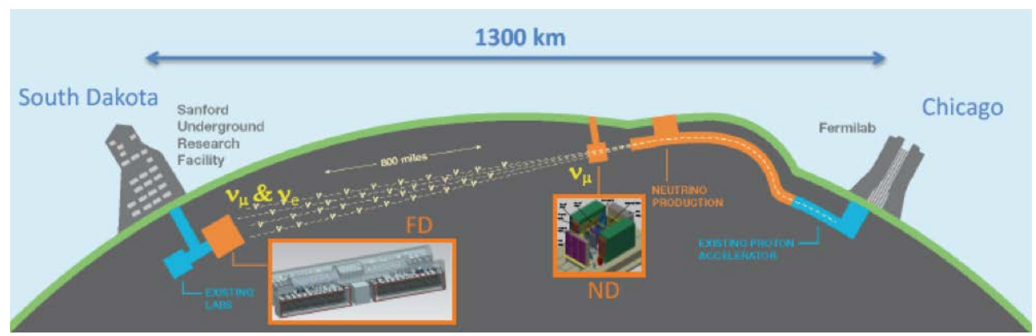
NOvA



IceCube/DeepCore/PINGU [DeYoung]



Hyper-K (187 kt H_2O FV) [Takeuchi]



DUNE (40 kt LAr) [Ji]

BERKELEY LAB

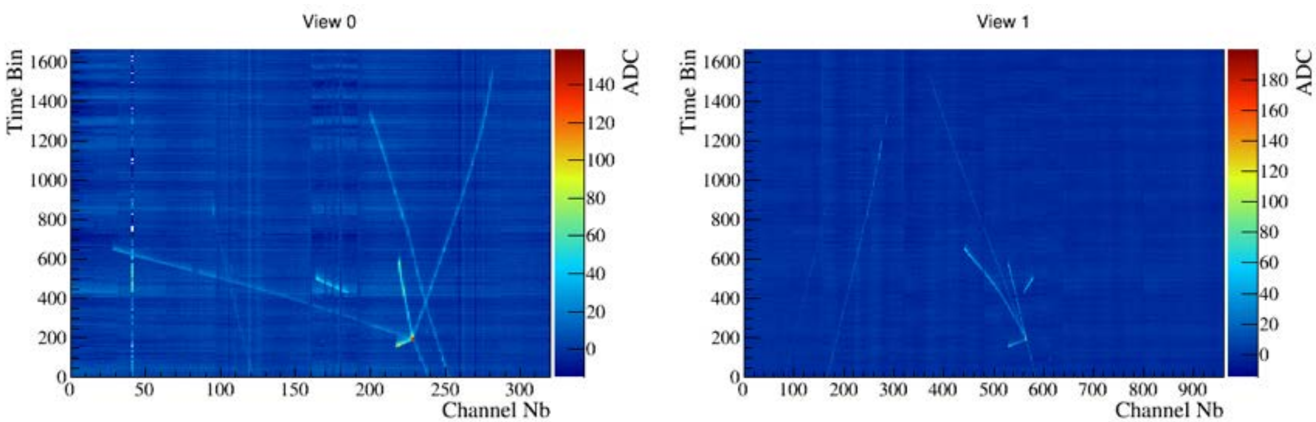
CPV & MH - Future

Technologies that I found impressive

Hyper-K

- Current performance of new 50 cm PMT
  - SK-PMT x2 photon detection
  - SK-PMT x2 timing resolution (~1.1ns)
  - Higher pressure tolerance (> 80 m)
  - Dark rate: 7.5 kHz (as of 2016)
    - → trying to reduce to SK-PMT level (< 4kHz)

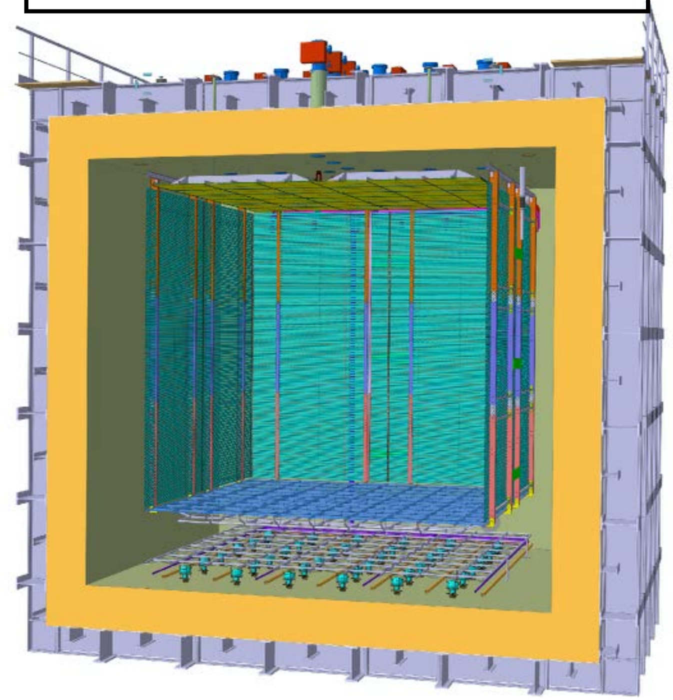
[Takeuchi]



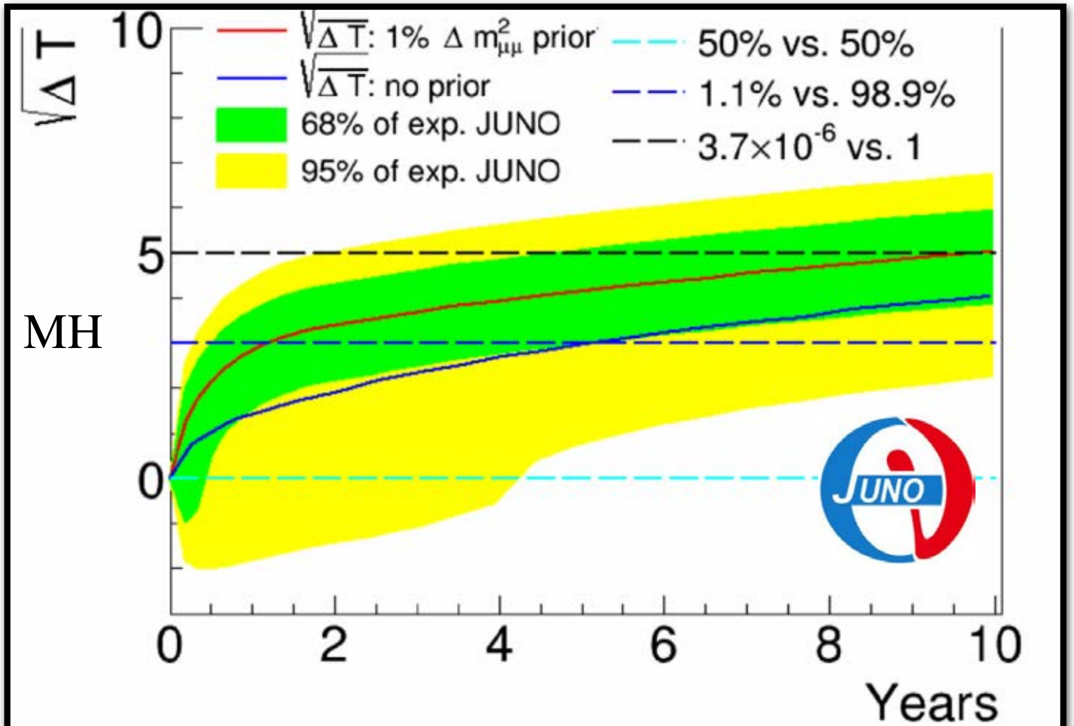
Reached design spec of 2.5 kV/cm extraction field

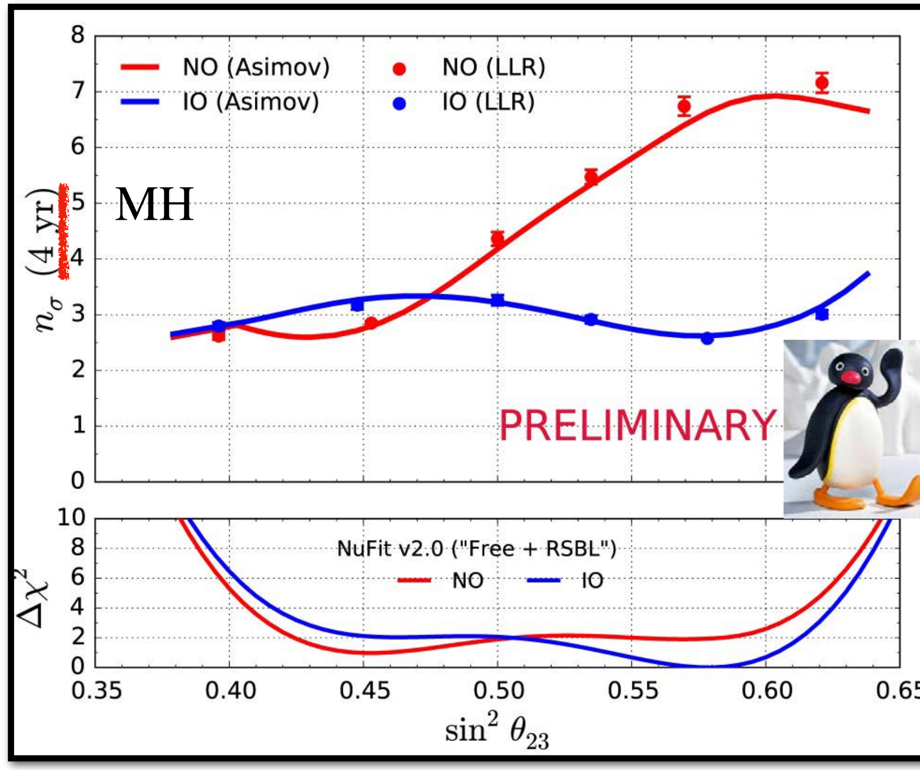
[Zambelli]

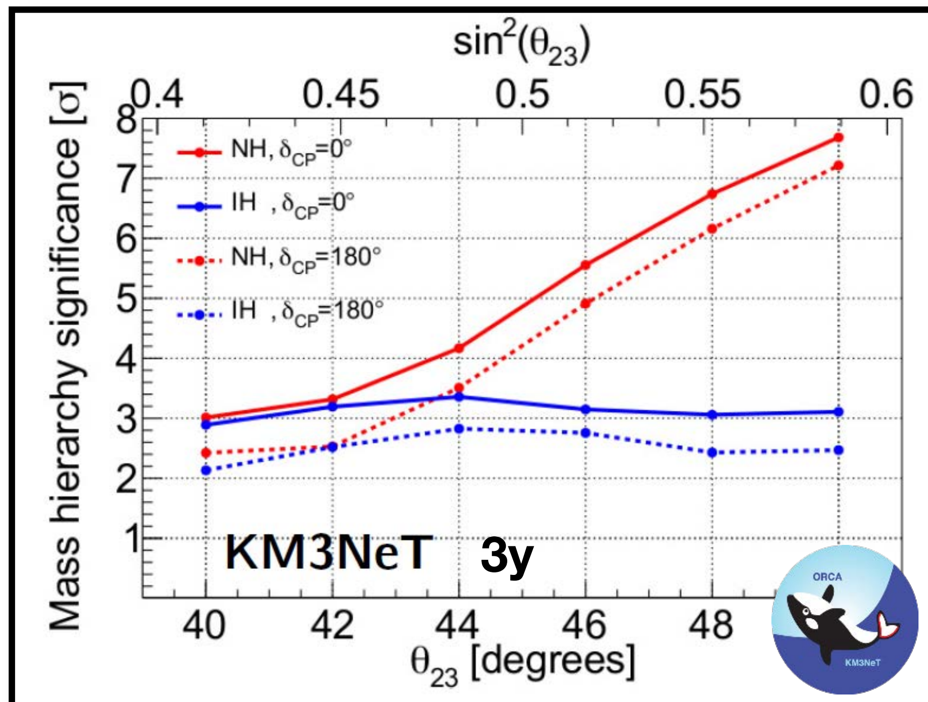
protoDUNE dual-phase LAr TPC R&D



CPV & MH - Future

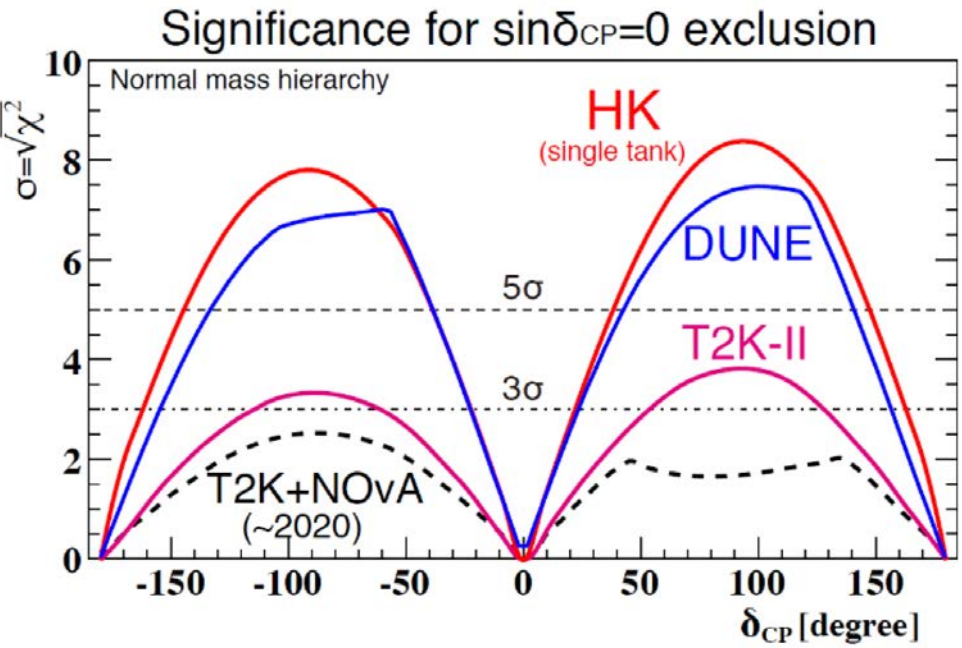


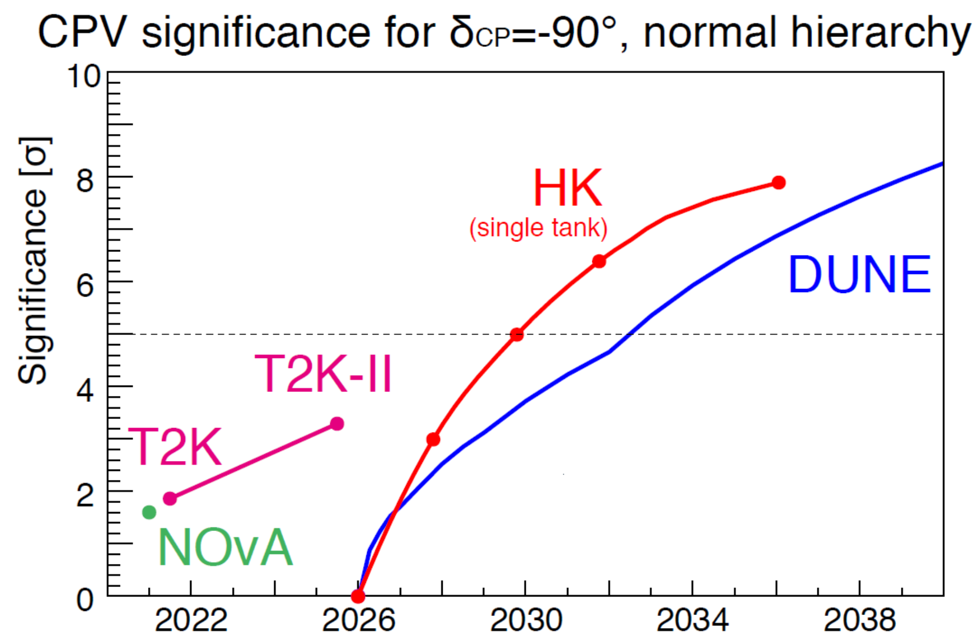




Gu, DeYoung, Coelho

CPV & MH - Future





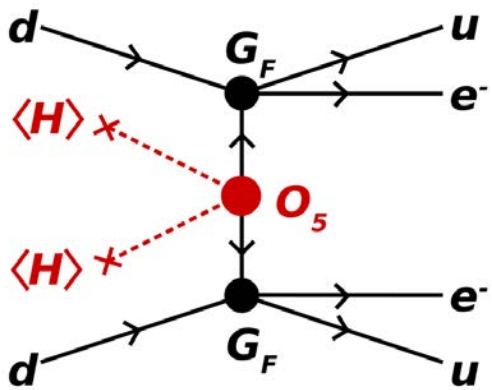
1.3 MW × 10 years (10^8 sec), $\nu:\bar{\nu}$ = 1:3

- ~8σ exclusion if δ_{CP} = +/-90°
  ~6σ exclusion if δ_{CP} = +/-45°
- Observe CPV for 60% of δ_{CP} with >5σ significance

- T2K favors δ_{CP} = -90°
  - PRL 118, 151801 (2017)
  - Super-K atmospheric ν data also
- It could be possible that ongoing experiments discover CPV (~3σ)
- T2K → T2K-II → Hyper-K
- Seamless program to get timely results

Takeuchi, Ji

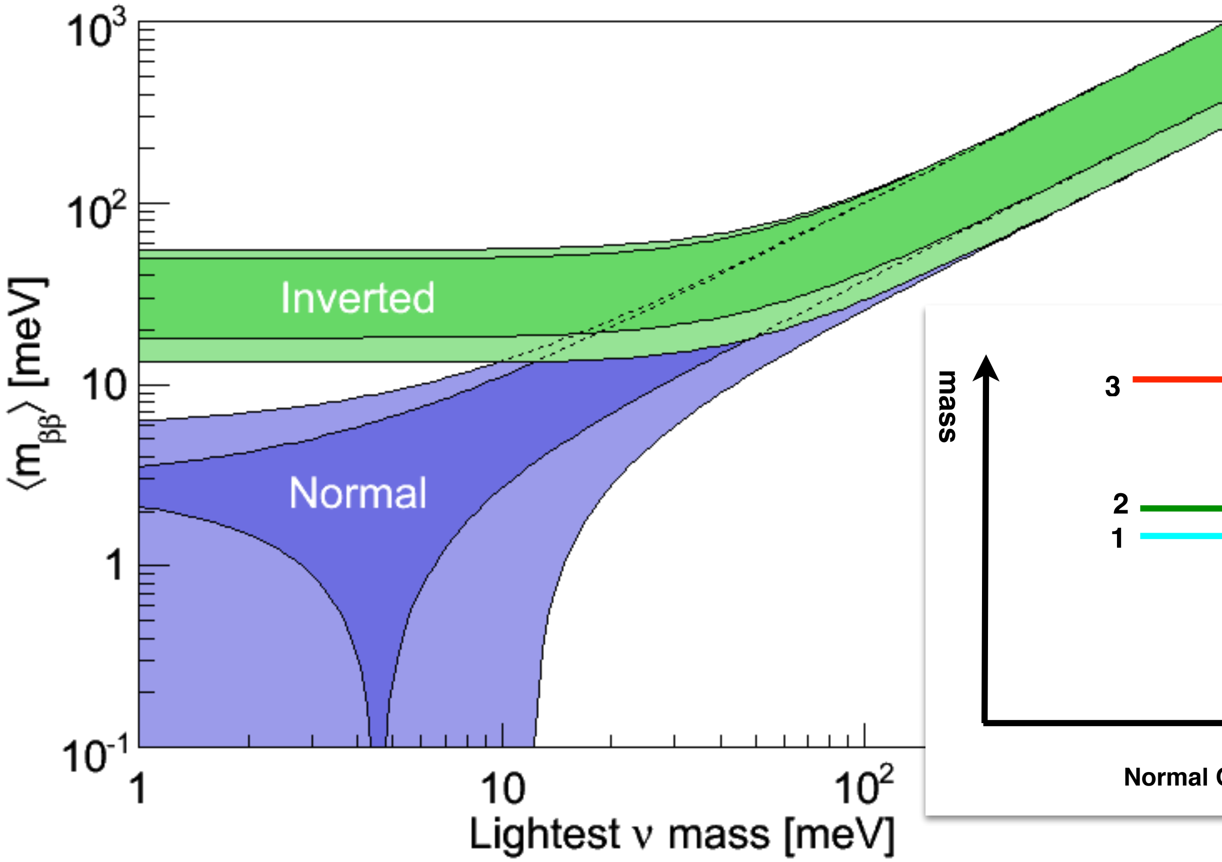
“Vanilla” mass mechanism



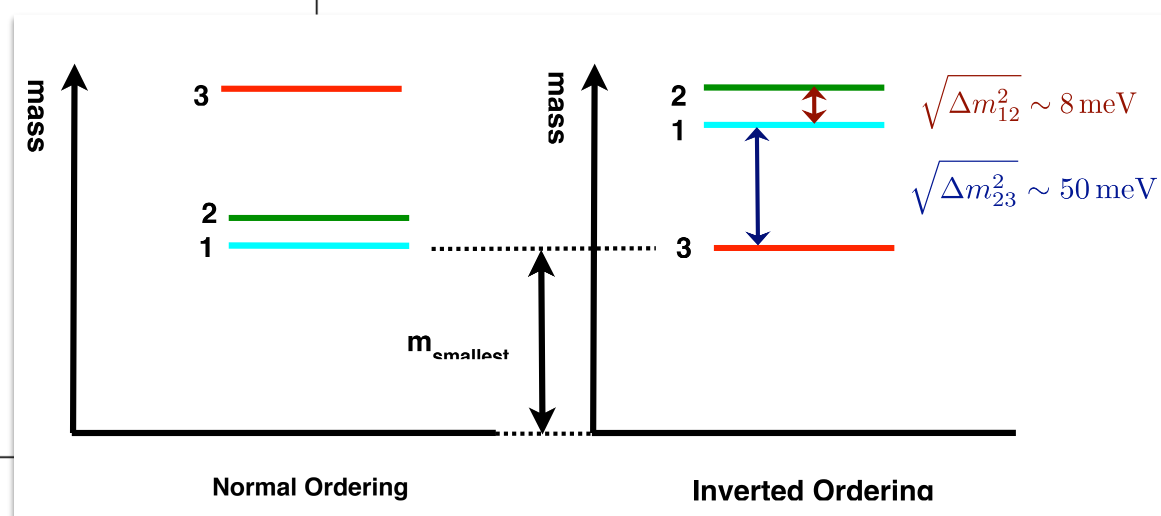
Halfliffe → **mass scale**

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\,|M_{0\nu}|^2\,\langle m_{\beta\beta}\rangle^2$$

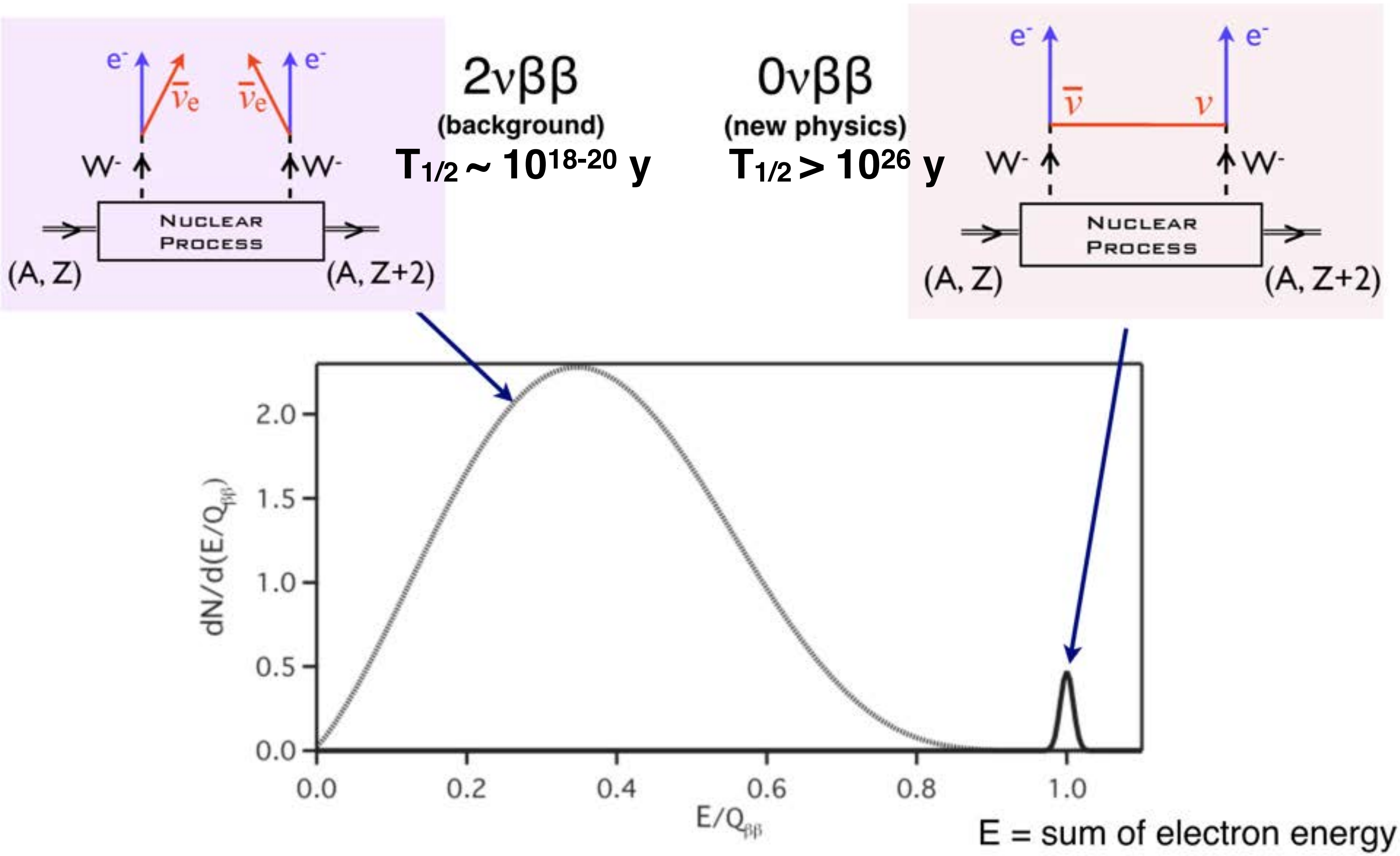
form factor — *nuclear matrix element* — *effective Majorana mass*



$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$



Signal



Energy resolution and low backgrounds are keys!

Considerations

$$T^{0\nu}_{1/2}(\mathrm{FOM}) \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

- Preferably:
  - high isotopic abundance
  - high efficiency
  - large mass
  - long exposure
  - low background
  - good energy resolution

There is not an obvious choice of isotope or detector technology

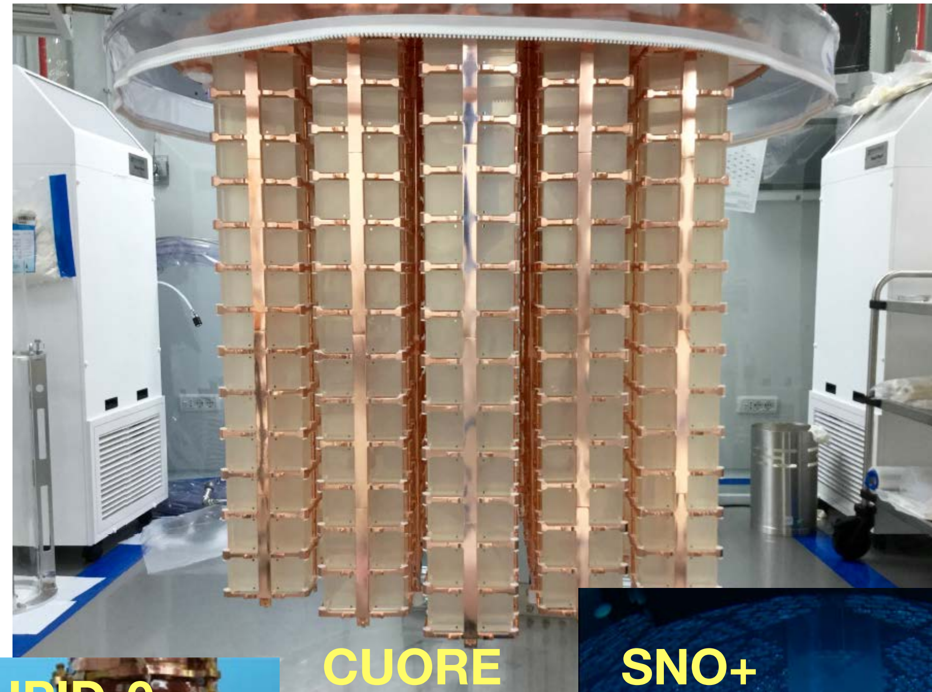
Many experimental ideas…presented here

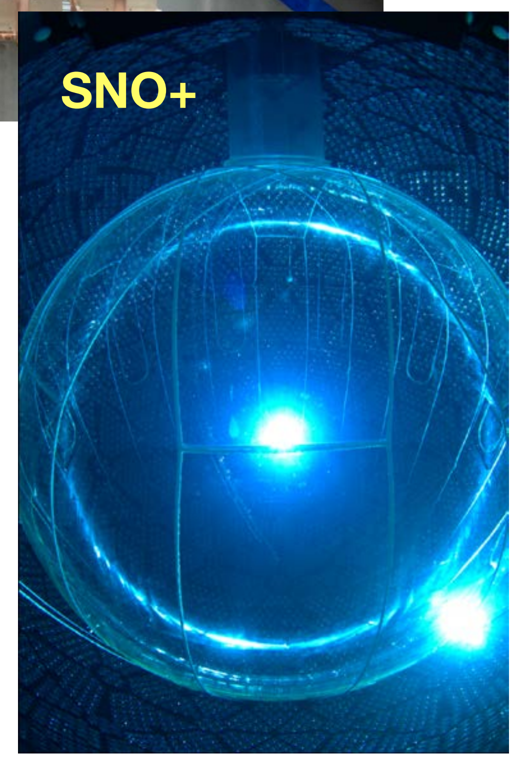
Table 1. Overview of present and future $0\nu\beta\beta$ decay experiments, their energy resolution and sensitivity to event topology (i.e. the individual energy of the electrons and/or their angular correlation, useful to distinguish mechanisms). Timescales, references and details can be found in [7, 14, 16].

Name	Isotope	Source = detector			Source ≠ detector
		ΔE high	ΔE low	Topology	Topology
AMoRE	^{100}Mo	✓	—	—	—
CANDLES	^{48}Ca	—	✓	—	—
COBRA	^{116}Cd (and ^{130}Te)	—	—	✓	—
CUORE	^{130}Te	✓	—	—	—
CUPID	^{82}Se / ^{100}Mo / ^{116}Cd / ^{130}Te	✓	—	—	—
DCBA/MTD	^{82}Se / ^{150}Nd	—	—	—	✓
EXO	^{136}Xe	—	—	✓	—
GERDA	^{76}Ge	✓	—	—	—
KamLAND-Zen	^{136}Xe	—	✓	—	—
LUCIFER	^{82}Se / ^{100}Mo / ^{130}Te	✓	—	—	—
LUMINEU	^{100}Mo	✓	—	—	—
MAJORANA	^{76}Ge	✓	—	—	—
MOON	^{82}Se / ^{100}Mo / ^{150}Nd	—	—	—	✓
NEXT	^{136}Xe	—	—	✓	—
SNO+	^{130}Te	—	✓	—	—
SuperNEMO	^{82}Se / ^{150}Nd	—	—	—	✓
XMASS	^{136}Xe	—	✓	—	—

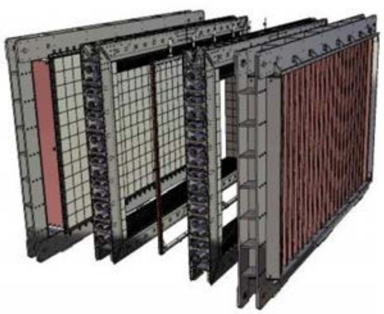
Päs & Rodejohann, New J. Phys. 17 115010 (2015)

Many experimental ideas…presented here





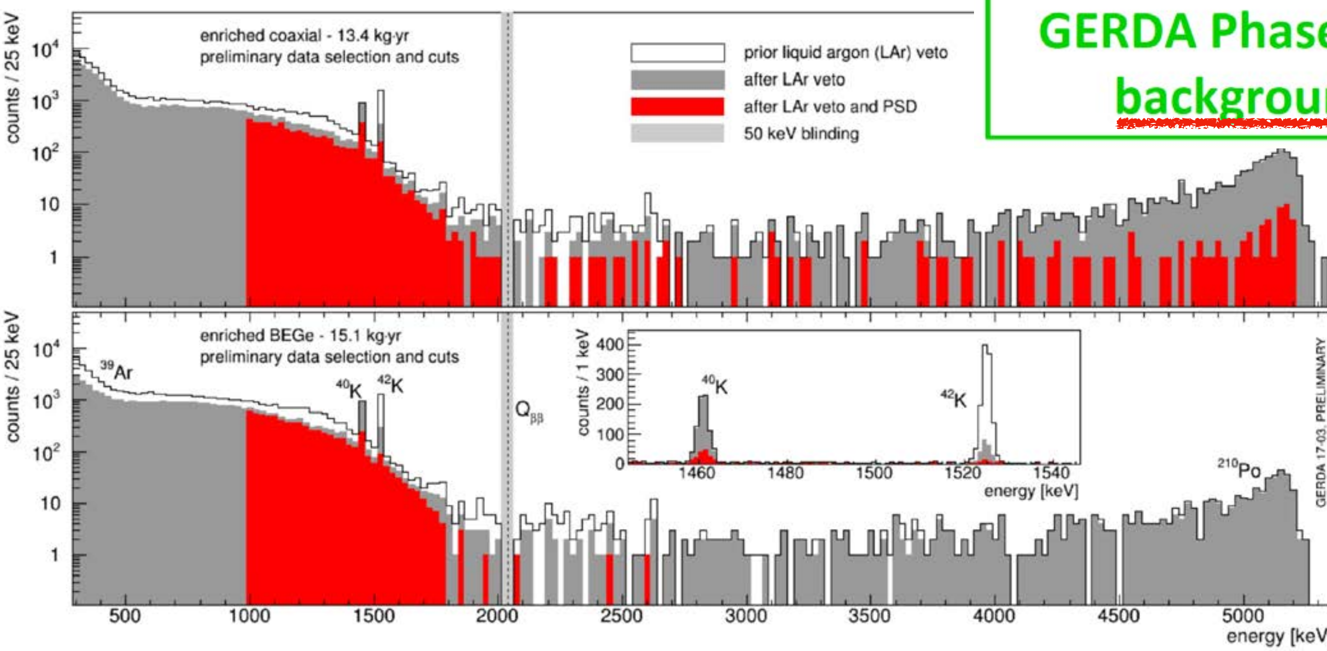
NEMO-3 (2003 - 2011)



SuperNEMO
démonstrateur (≥ 2016)

**Schütz, Fujikawa, Nones,
Casali, Giuliani, Barrros, Hogan**

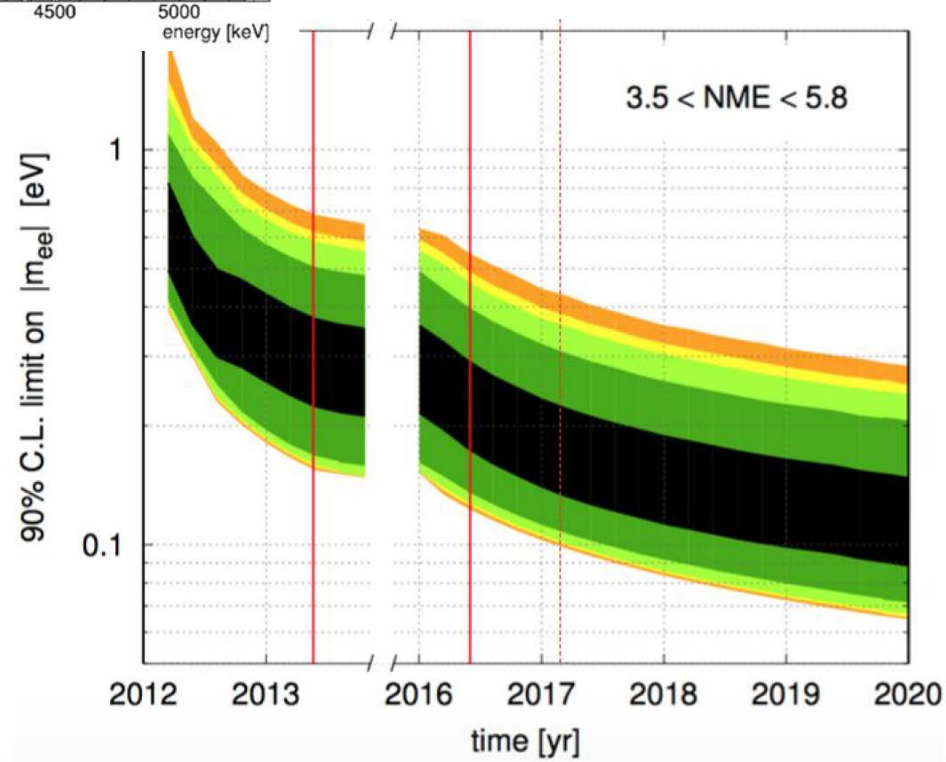
0νββ news - GERDA (^{76}Ge)



GERDA Phase II is the high-resolution and background-free 0νββ experiment

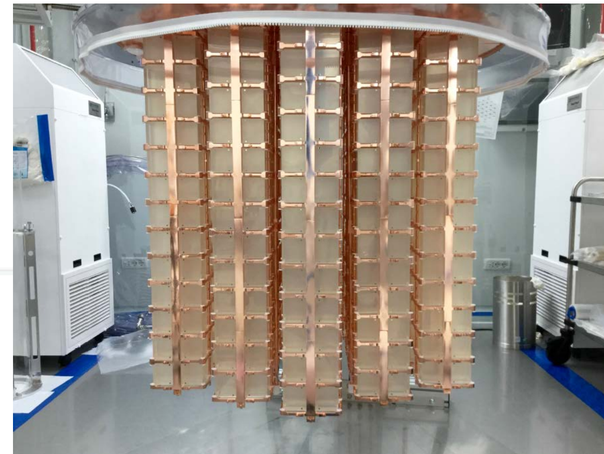
Phase IIa achievements	
background	~10^{-3} cts/(keV·kg·yr)
exposure	10.8 kg·yr
limit	$T^{0\nu}_{1/2}$ > $5.3 \cdot 10^{25}$ yr (90%CL) $m_{\beta\beta}$ < (0.15-0.33) eV (90%CL)

Phase II goals	
background	~10^{-3} cts/(keV·kg·yr) ✓
exposure	≳ 100 kg·yr
limit	$T^{0\nu}_{1/2} > 10^{26}$ yr



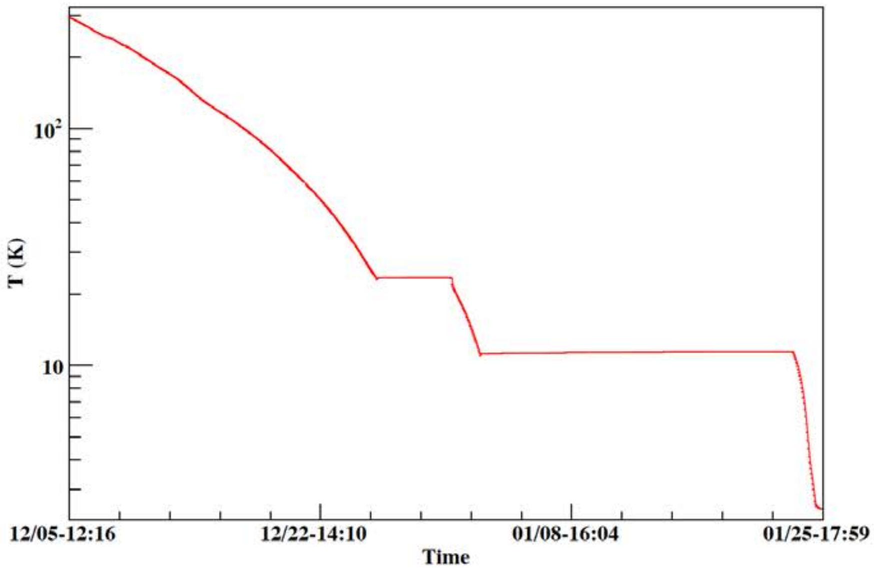
Schütz

0νββ news - CUORE (^{130}Te)

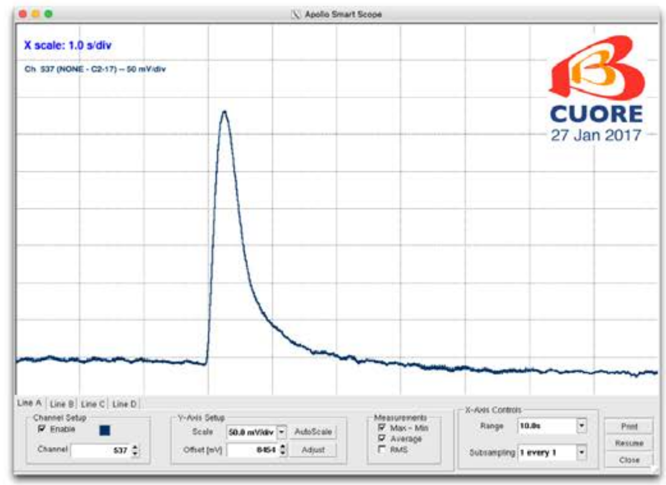


CUORE is cold and running!

Diode thermometer at 10mK plate



Reached 8 mK: 26 Jan 2017



First pulse: 27 Jan 2017

Current status of CUORE:

- End of commissioning and beginning of data-taking: April 2017
- Blind analysis currently in progress
- Expect first results within the next few months

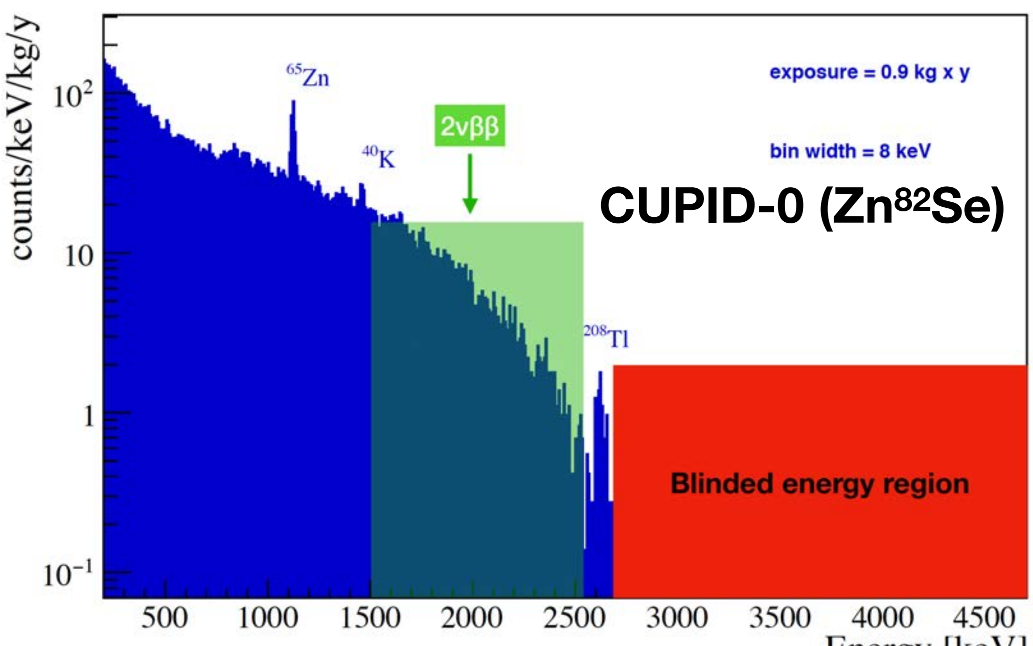
Fujikawa

0νββ trailers - CUPIDs

Problem: alpha background

Nucleus	I. A. [%]	Q-value [keV]	Materials successfully tested as bolometers in crystalline form (**underlined compounds: scintillators**)
^{76}Ge	7.8	2039	Ge
^{136}Xe	8.9	2479	NONE
^{130}Te	33.8	2527	TeO_2 ← Cherenkov + scintillation; TeO_2 is a very weak scintillator
^{116}Cd	7.5	2802	$CdWO_4$, $CdMoO_4$
^{82}Se	9.2	2995	ZnSe, $LiInSe_2$
^{100}Mo	9.6	3034	$PbMoO_4$, $CaMoO_4$, $SrMoO_4$, $CdMoO_4$, $SrMoO_4$,, $ZnMoO_4$,Li_2MoO_4, $MgMoO_4$
^{96}Zr	2.8	3350	ZrO_2
^{150}Nd	5.6	3367	NONE → many attempts
^{48}Ca	0.187	4270	CaF_2, $CaMoO_4$

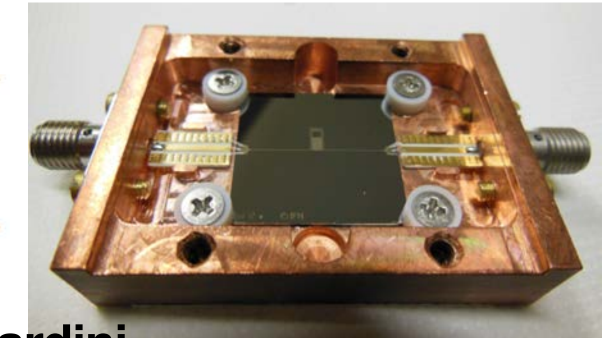
Nones



CUPID-0 ($Zn^{82}Se$)

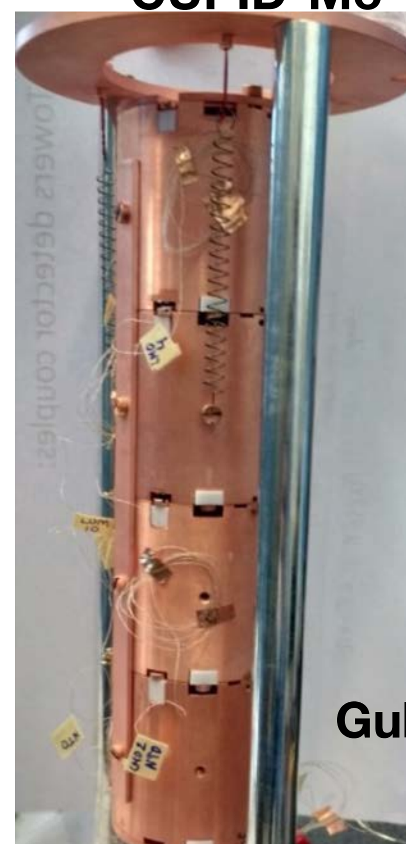
Spectrum with only basic cuts

Kinetic Inductance Detectors



Cardini

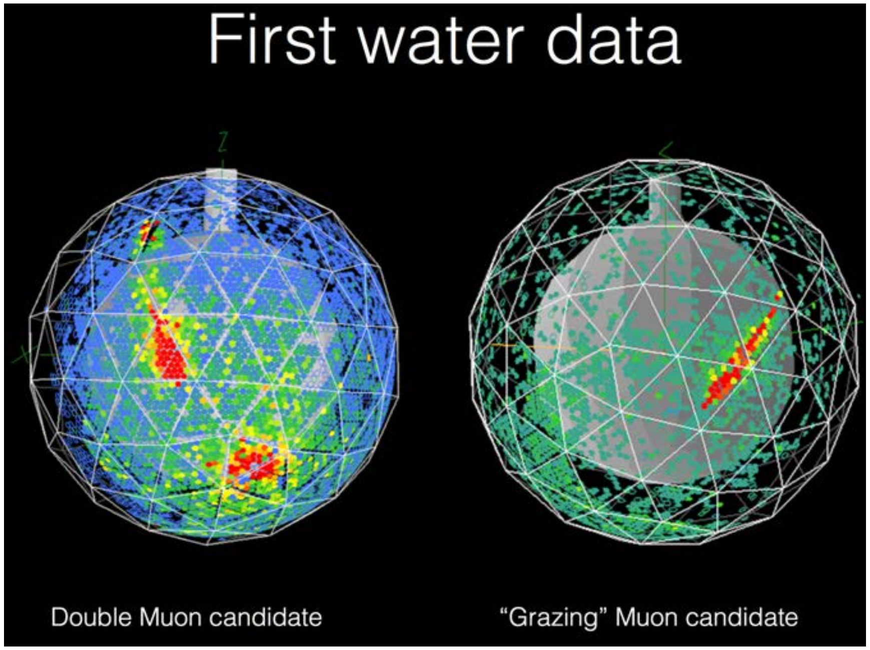
CUPID-Mo



Guliani

0νββ trailers

SNO+



- **Loading method: Te acid + butanediol (TeBD)**
  - Initially loading 0.5% (funding secured)
    - ~1330 kg of ^{130}Te

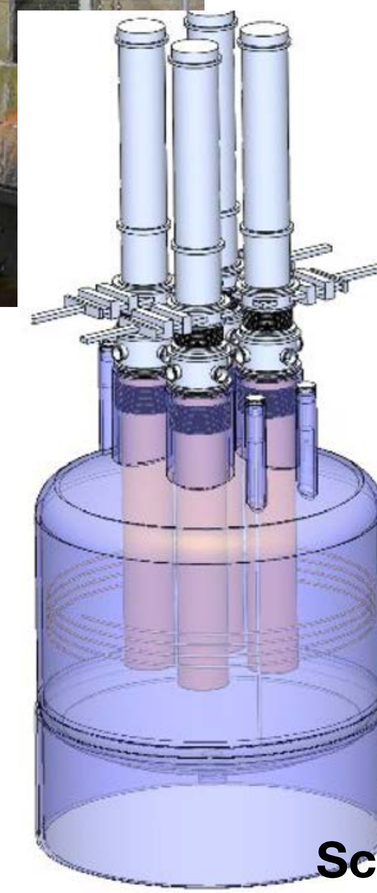
Barros

↑

"ton-scale"

SuperNEMO

LEGEND



Schütz

Mass sensitivity