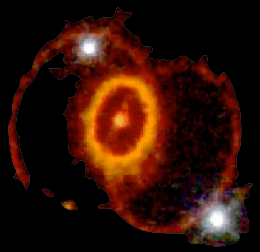
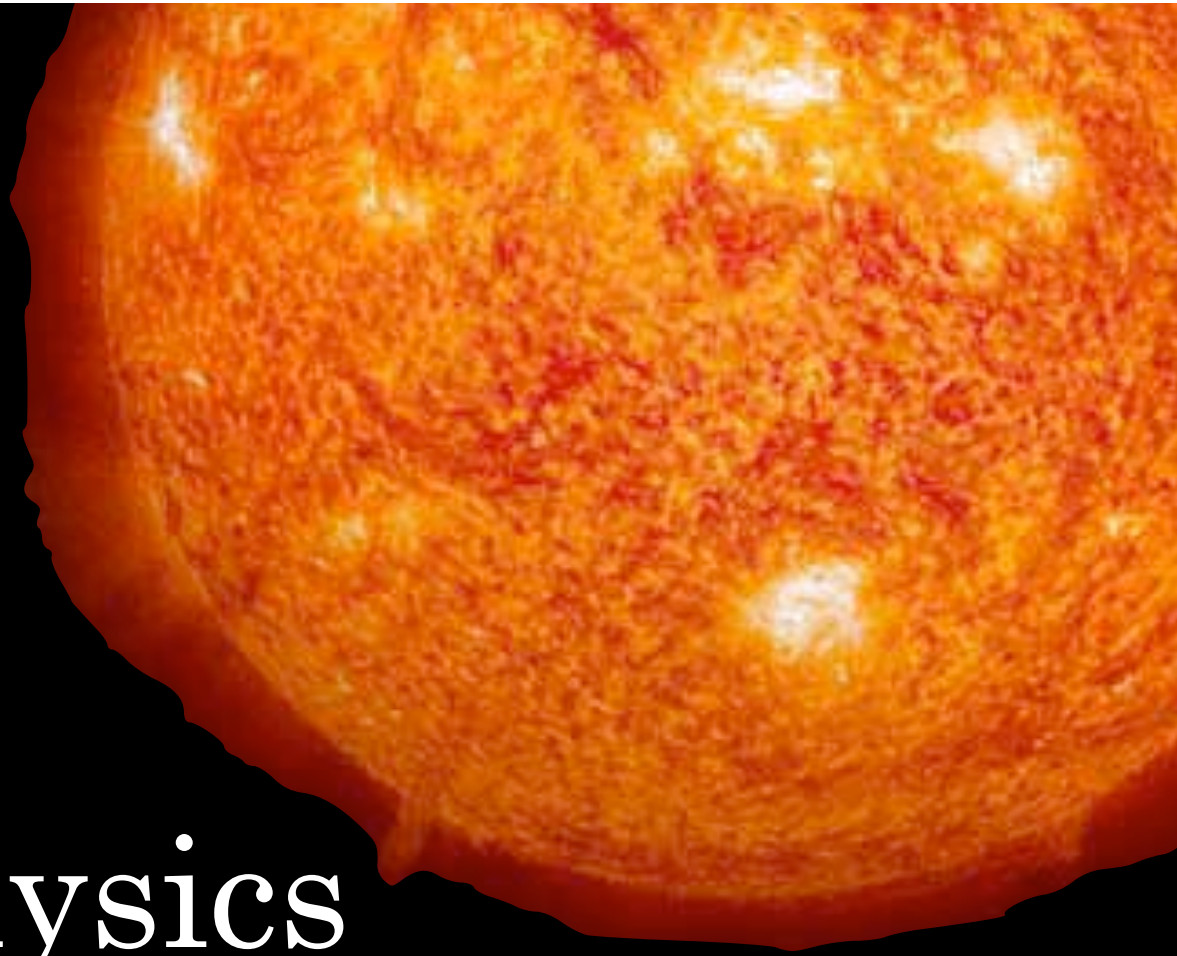




Low Energy Neutrino Physics

Lindley Winslow
MIT

You may be a low energy neutrino physicist if....

You may be a low energy neutrino physicist if….

You spend more time on www.nndc.bnl.gov than pdg.lbl.gov

You may be a low energy neutrino physicist if....

You prefer ^{238}U to pions.

You may be a low energy neutrino physicist if....

Your main argon problem is ^{39}Ar.

What makes it low energy neutrino physics?

- It's energy, MeV vs. GeV.
- It's nuclear physics.
- It's the sources i.e. non-accelerator.

What makes it low energy neutrino physics?

- As you can tell there is some gray area between what is high energy and low energy (especially when it comes to funding).
- Fundamentally, there is a synergy between the measurements that the low energy community makes and those from the high energy community.

Let’s do a little history and then move into the flagship low energy measurement being pursued at the moment, neutrinoless double-beta decay.

I am going to assume that you know about neutrino flavor and oscillations and highlight the low energy aspects of some things you may already have heard about.

Let’s go back...way back....

Beta decay is not conserving energy.....

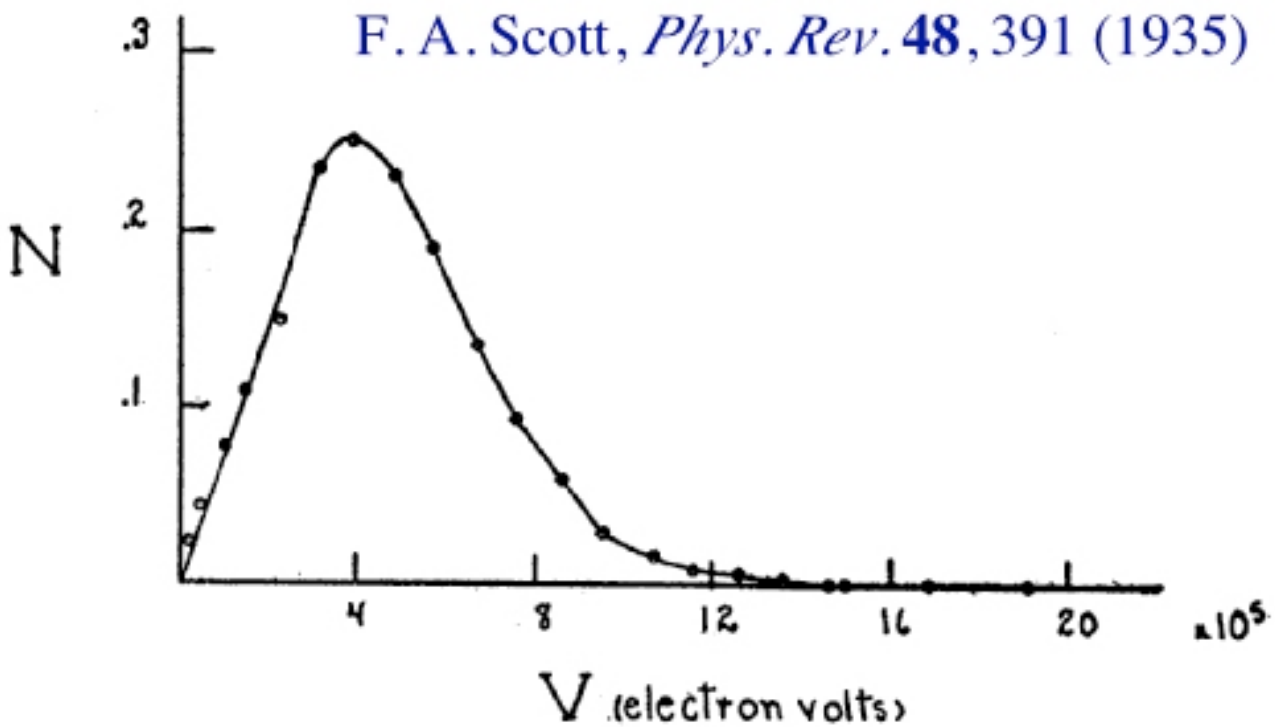


FIG. 5. Energy distribution curve of the beta-rays.

$n \rightarrow p + e^-$

$E_n \neq E_p + E_{e^-}$

Beta spectrum of RaE (otherwise know as ^{210}Bi).

Neutrino Saves the Day!

Rather than abandon energy conservation a new particle is born. At first called the neutron, Fermi will later re-name it the neutrino.

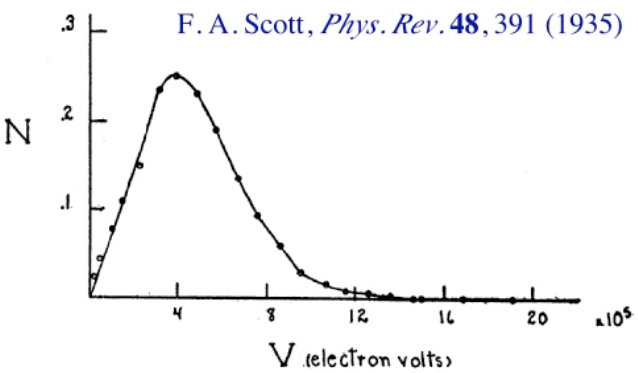


FIG. 5. Energy distribution curve of the beta-rays.

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und

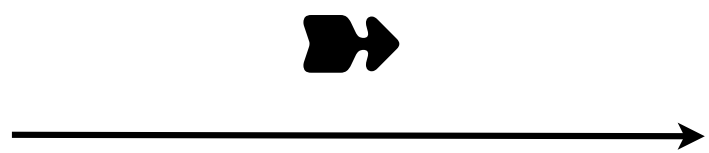
$$m_\nu = 0?$$

And now for handedness....

Quarks and Leptons are Fermions...

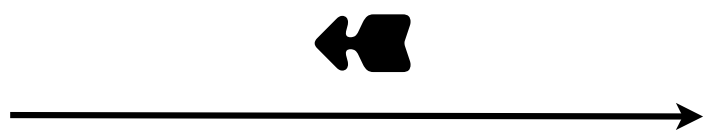
Therefore they have spin...

This spin can be aligned with the direction of motion....



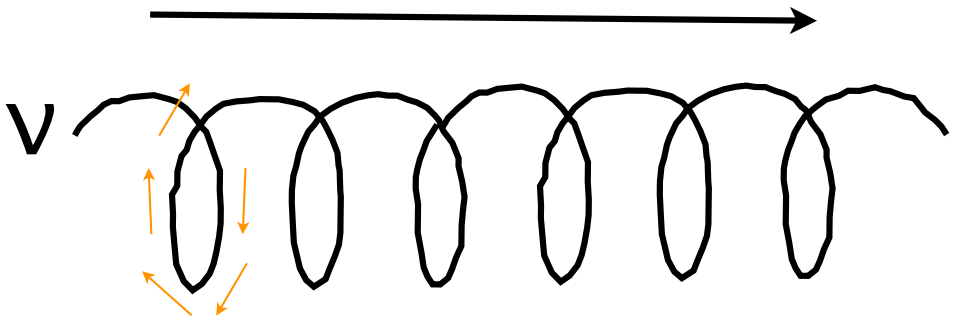
right handed

This spin can be opposite the direction of motion....



left handed

If a particle has mass, you can always boost to a reference frame where the helicity flips.



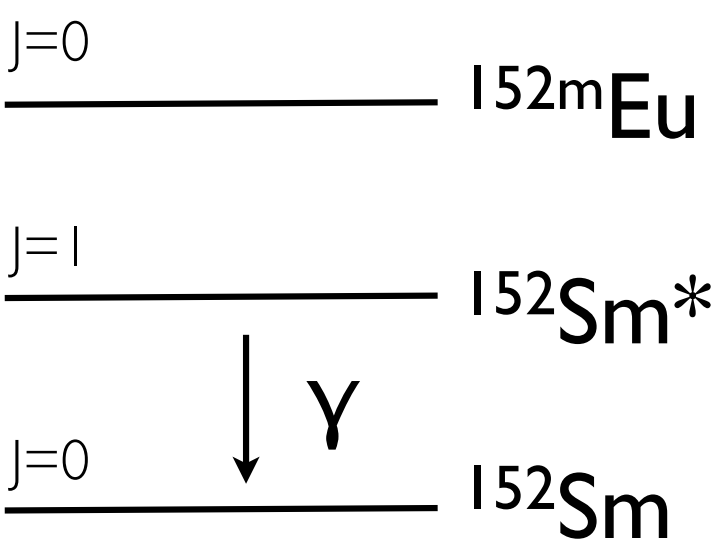
Massless particles can exist in pure helicity states or more correctly pure chiral states.

- The weak interaction maximally violates parity.
- It only interacts with left handed particles
- It only interacts with right handed anti-particles.
- Experiment indicates that neutrinos exist in pure chiral states.

Measure the Helicity of the Neutrino:

The Goldhaber, Grodzins and Sunyar experiment is a logic problem.....

$$^{152m}Eu + e^- \rightarrow {}^{152}Sm^* + \nu_e$$



1. To conserve angular momentum the recoiling nucleus and the neutrino must have the same helicity.

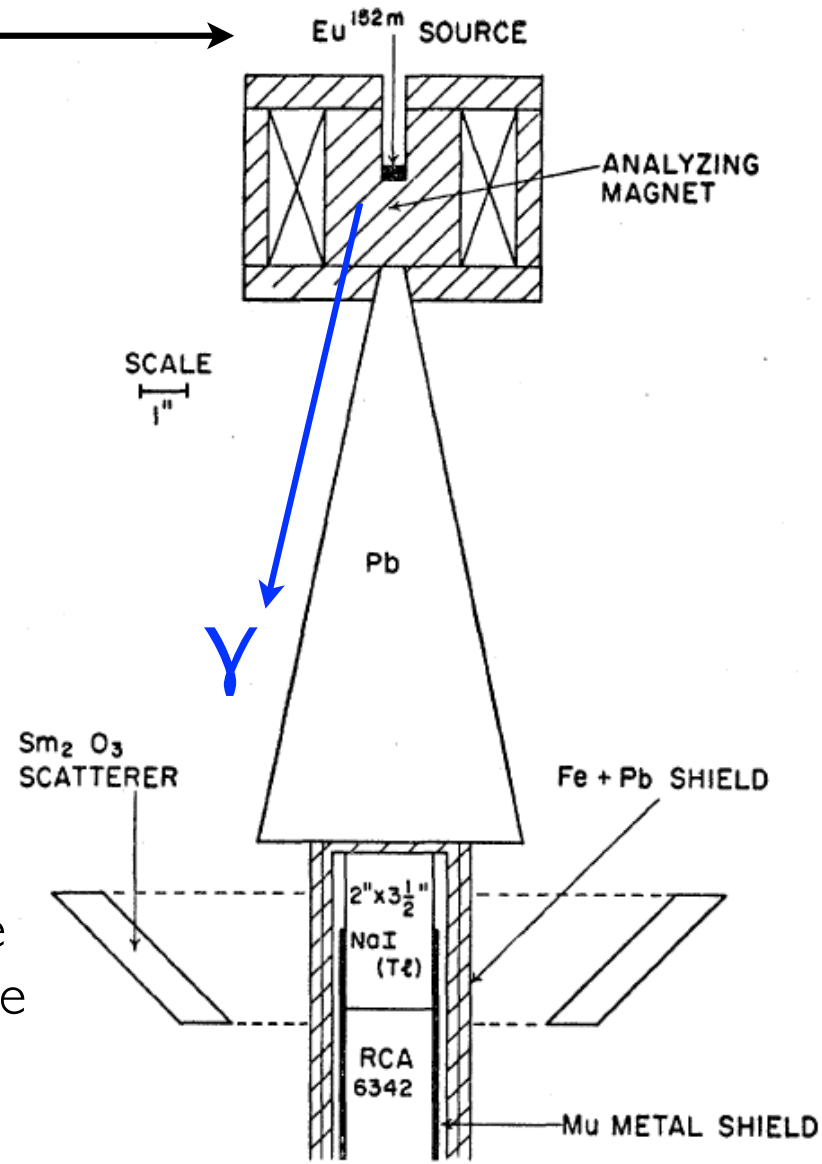
2. If you select the forward going gamma rays (those with the highest energy) then to conserve angular momentum, they too must have the same helicity of the neutrinos.

So Here is the Experiment:

Your source made in a nearby reactor.

Depending on the direction of the magnet field different polarizations will transmit better.

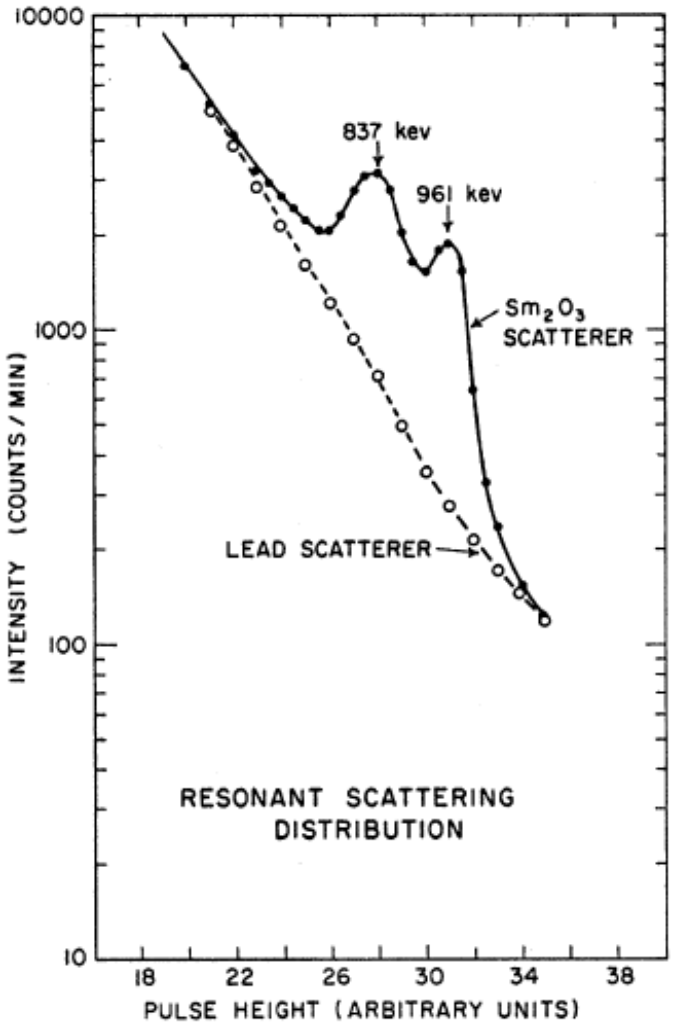
Now if the gamma ray makes it through the magnet, only those with the highest energy will be able to re-excite the Sm and lead to a count in the very well shielded NaI detector.



Phys.Rev. 109, 1015, (1958)

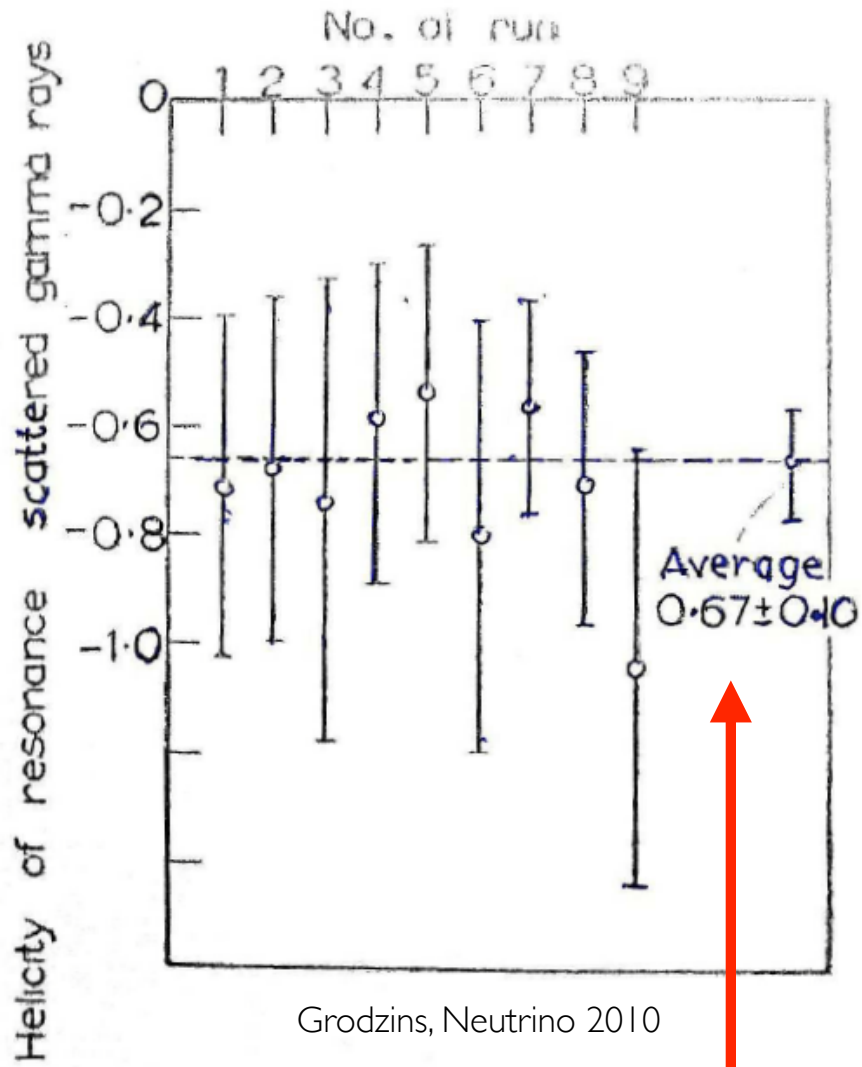
And the results.....

The Spectrum of the Re-Excited Sm.



Phys.Rev. 109, 1015, (1958)

The Helicity of the Gamma Rays.

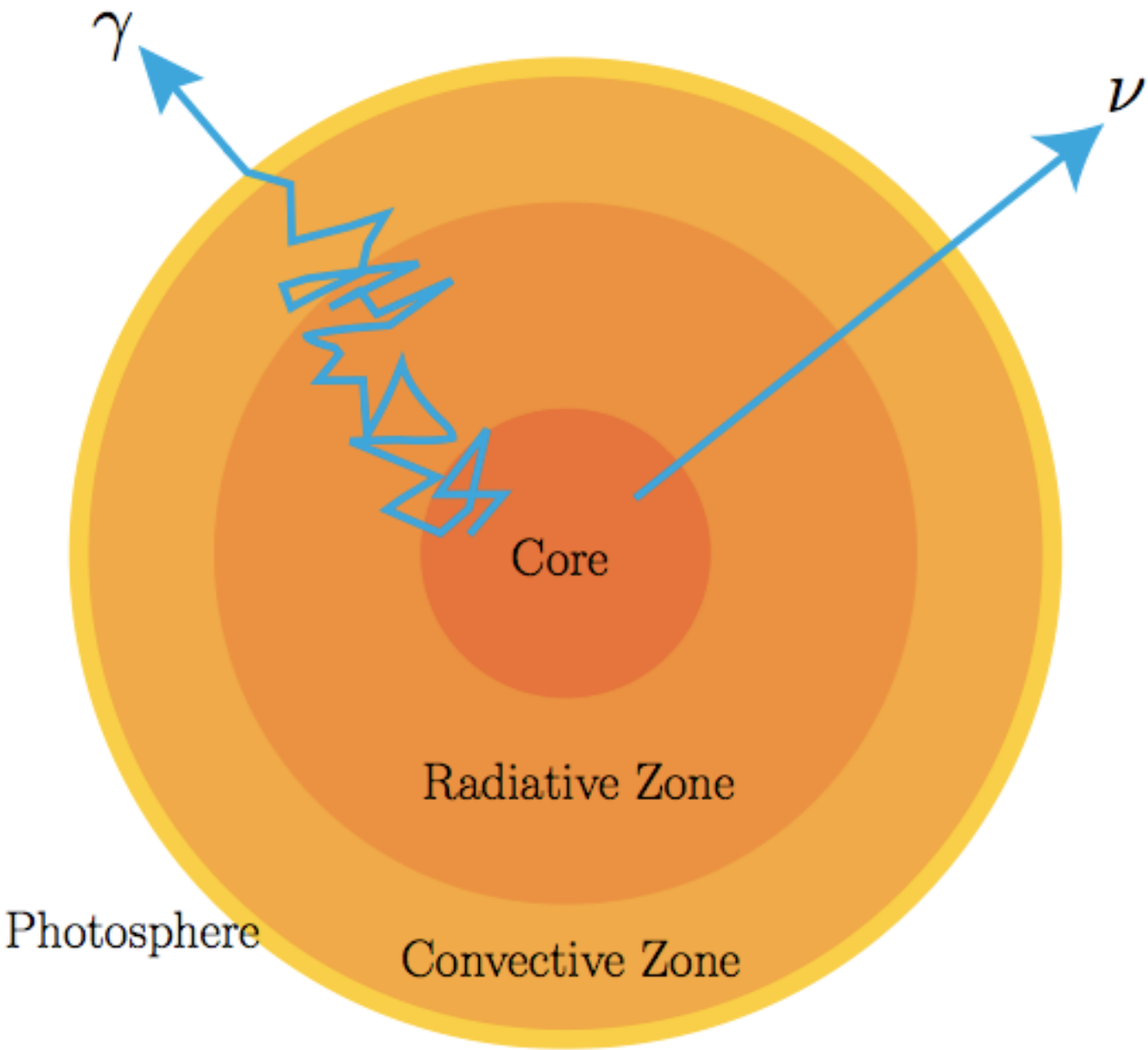


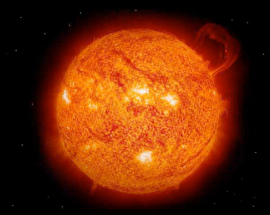
Grodzins, Neutrino 2010

-0.67 = -1.0, right?

$$m_\nu = 0$$

The Cartoon Sun:





Fusion Powers the Sun

$p+p \rightarrow {}^{2}H+e^{+}+\nu_e$

$p+e^{-}+p \rightarrow {}^{2}H+\nu_e$

99.77%

0.23%

${}^{2}H+p \rightarrow {}^{3}He+\gamma$

84.7%

13.8%

~2×10^{-5}

${}^{3}He+{}^{4}He \rightarrow {}^{7}Be+\gamma$

${}^{3}He+{}^{3}He \rightarrow {}^{4}He+p+p$

${}^{3}He+p \rightarrow {}^{4}He+e^{+}+\nu_e$

13.78%

0.02%

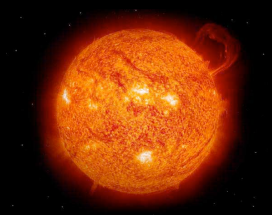
${}^{7}Be+e^{-} \rightarrow {}^{7}Li+\gamma+\nu_e$

${}^{7}Li+p \rightarrow {}^{4}He+{}^{4}He$

${}^{7}Be+p \rightarrow {}^{8}B+\gamma$

${}^{8}B \rightarrow {}^{8}Be+e^{+}+\nu_e$

$\rightarrow {}^{4}He+{}^{4}He$



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99.77%

0.23%

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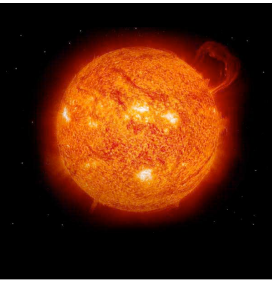
84.7%

${}^{3}He+{}^{3}He \rightarrow {}^{4}He+p+p$



Fusion Powers the Sun

$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$

99.77%

$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$

0.23%

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

13.8%

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

13.78%

0.02%

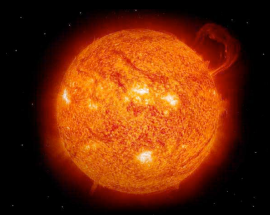
${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$

${}^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$

${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e$

$\rightarrow {}^{4}He + {}^{4}He$



Fusion Powers the Sun

$p+p \rightarrow {}^{2}H+e^{+}+\nu_e$

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99.77%

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${}^{2}H+p \rightarrow {}^{3}He+\gamma$

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~2×10^{-5}

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13.78%

0.02%

${}^{7}Be+e^{-} \rightarrow {}^{7}Li+\gamma+\nu_e$

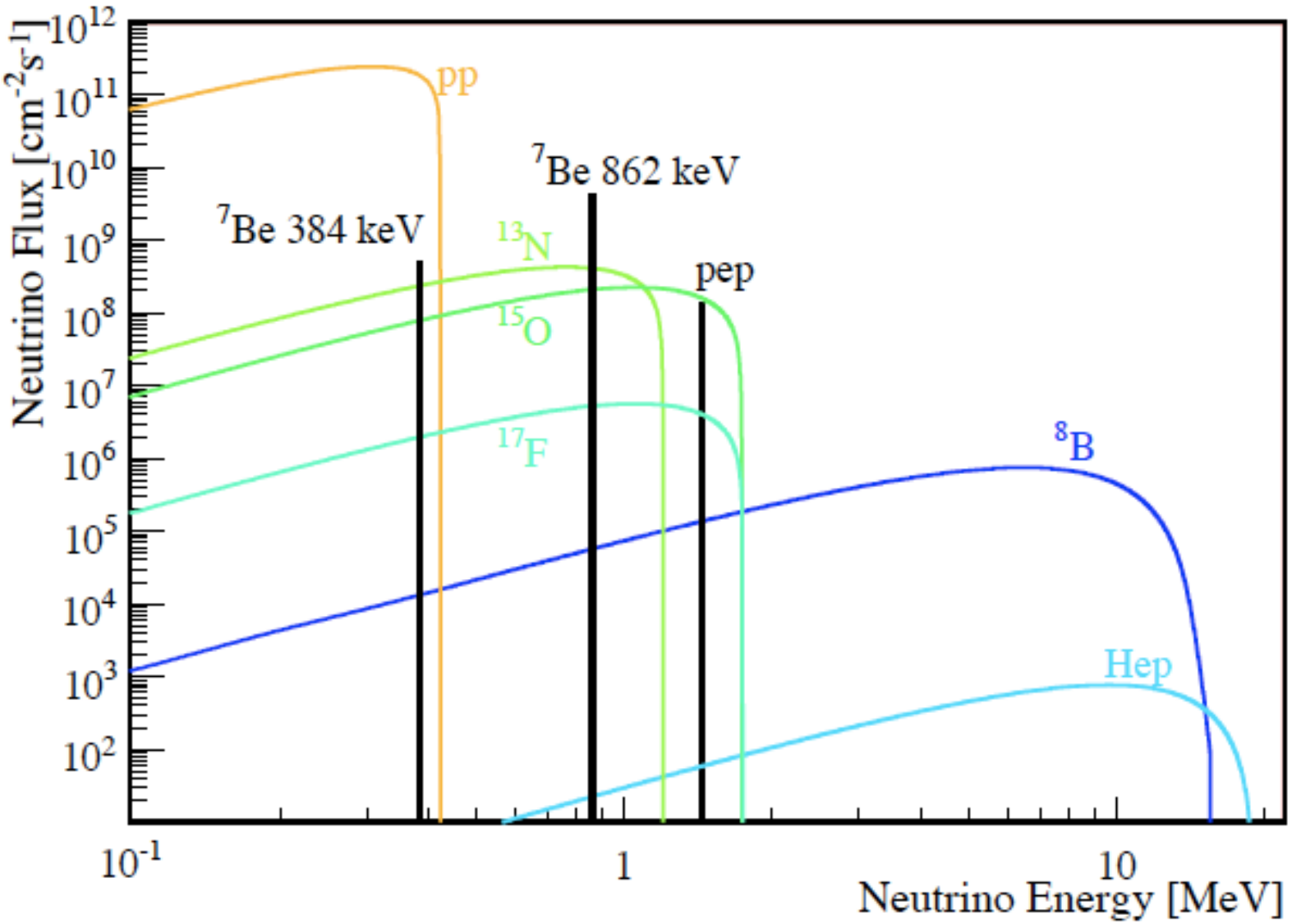
${}^{7}Li+p \rightarrow {}^{4}He+{}^{4}He$

${}^{7}Be+p \rightarrow {}^{8}B+\gamma$

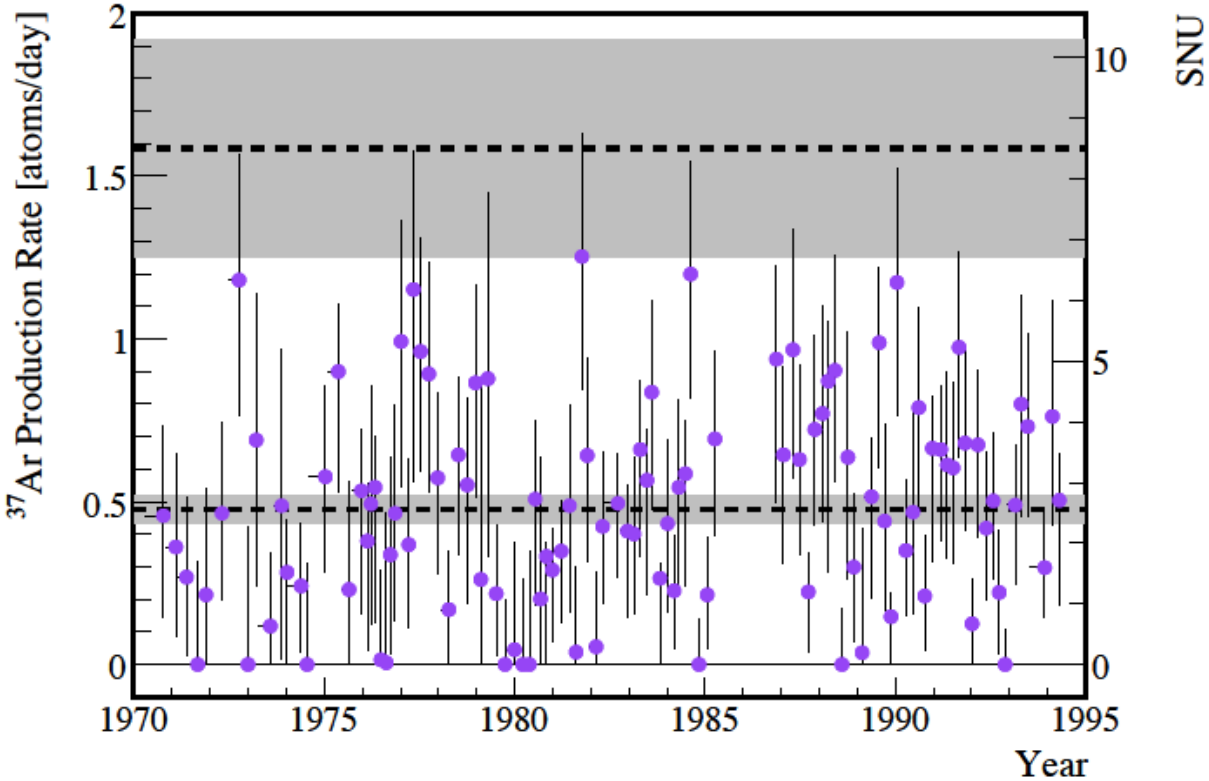
${}^{8}B \rightarrow {}^{8}Be+e^{+}+\nu_e$

$\rightarrow {}^{4}He+{}^{4}He$

Predicted Solar Neutrino Fluxes:

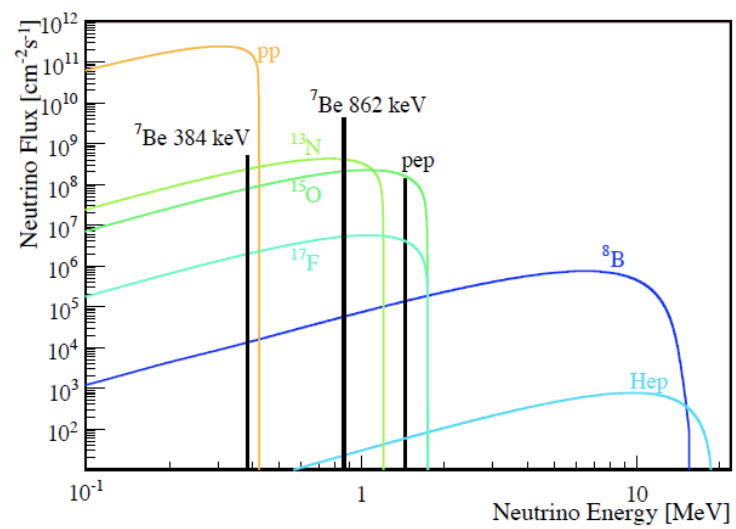


The Solar Neutrino Problem:



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

Threshold 0.8 MeV.



SNO

- Heavy Water, D_2O

$\nu_e + d \rightarrow p + p + e^-$ Charged Current

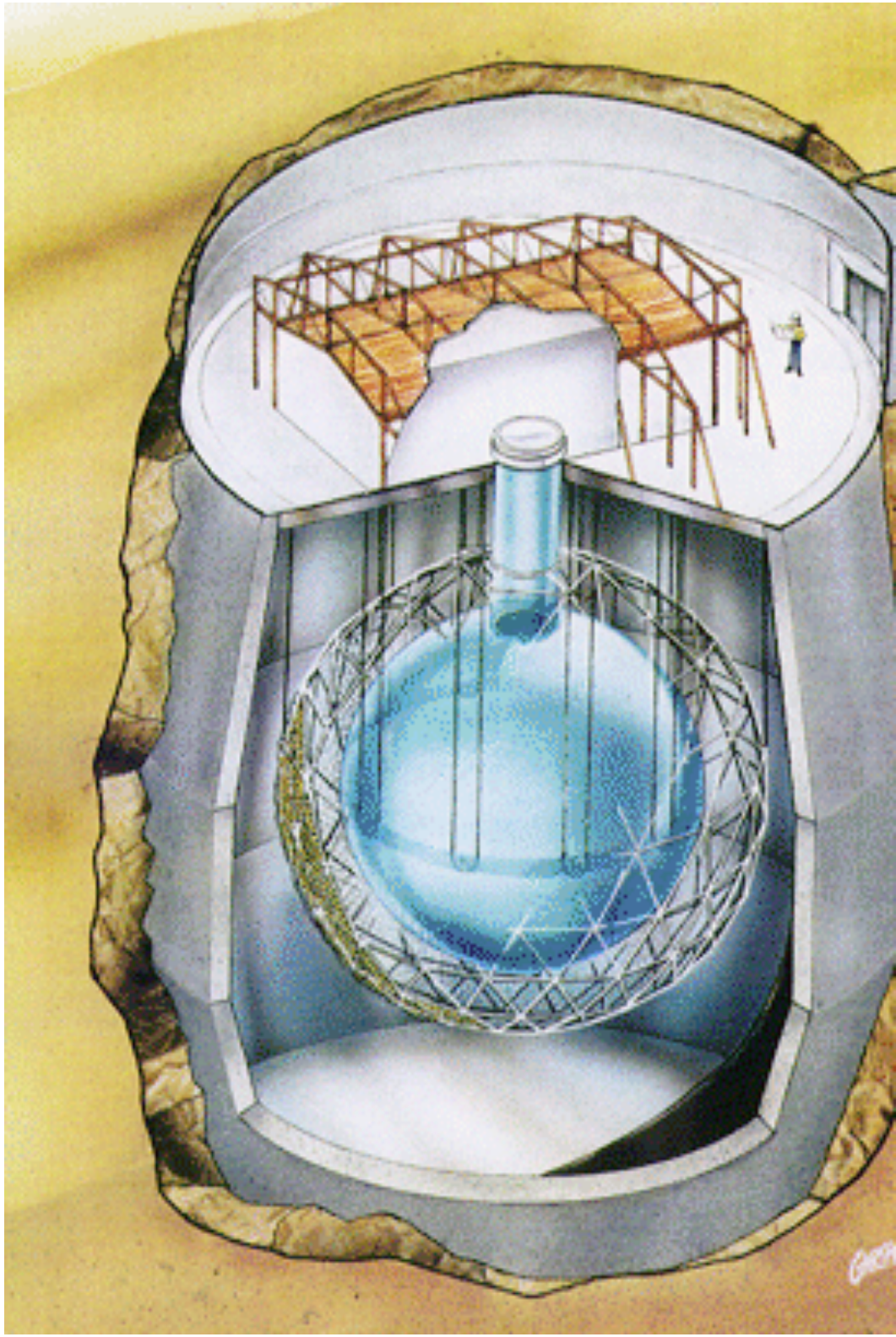
Sensitive only to electron flavor neutrinos.

$\nu + d \rightarrow p + n + e^-$ Neutral Current

Equally sensitive to all flavor neutrinos, so this is a measurement of the total flux.

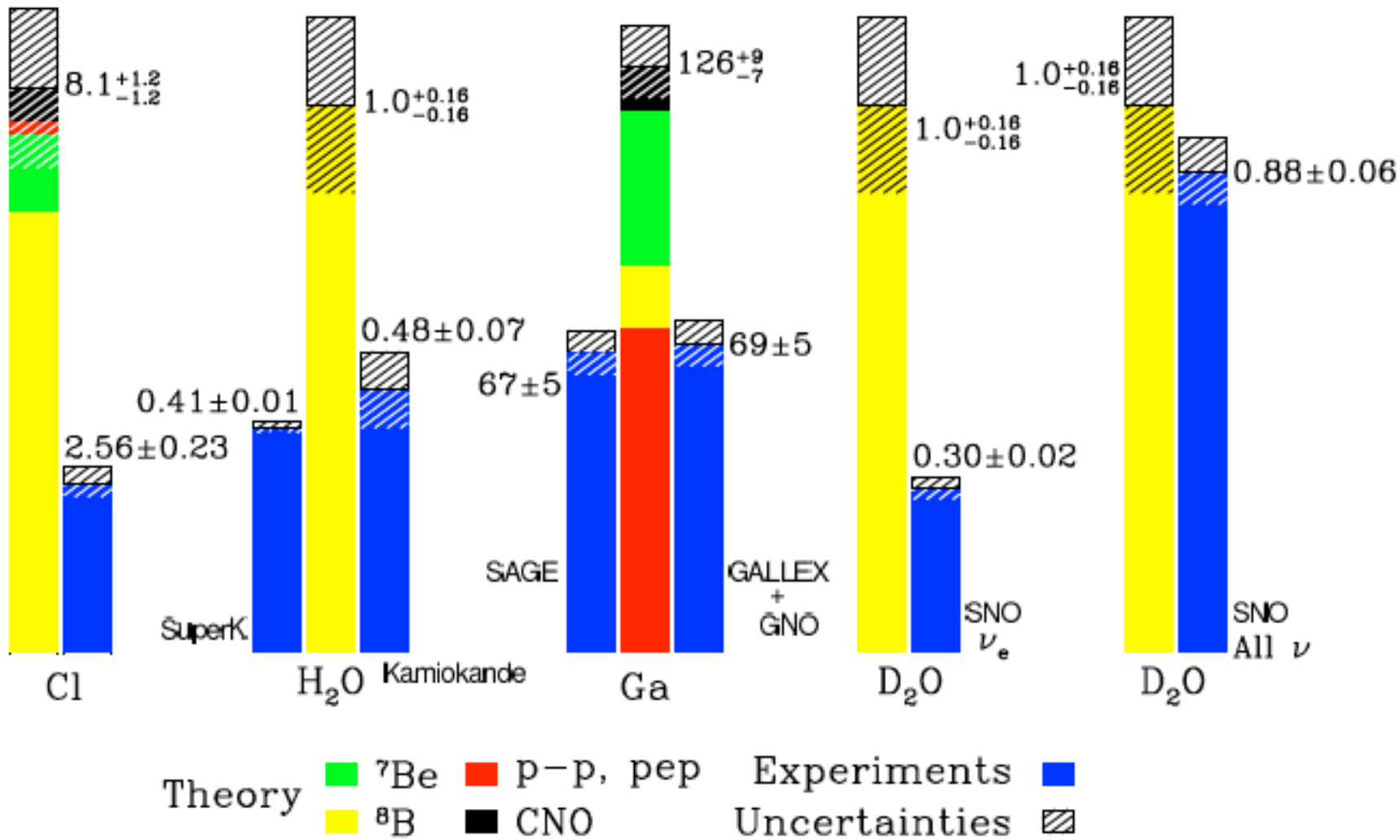
$\nu + e^- \rightarrow \nu + e^-$ Elastic Scattering

More sensitive to electron flavor, but some sensitivity to the other flavors.



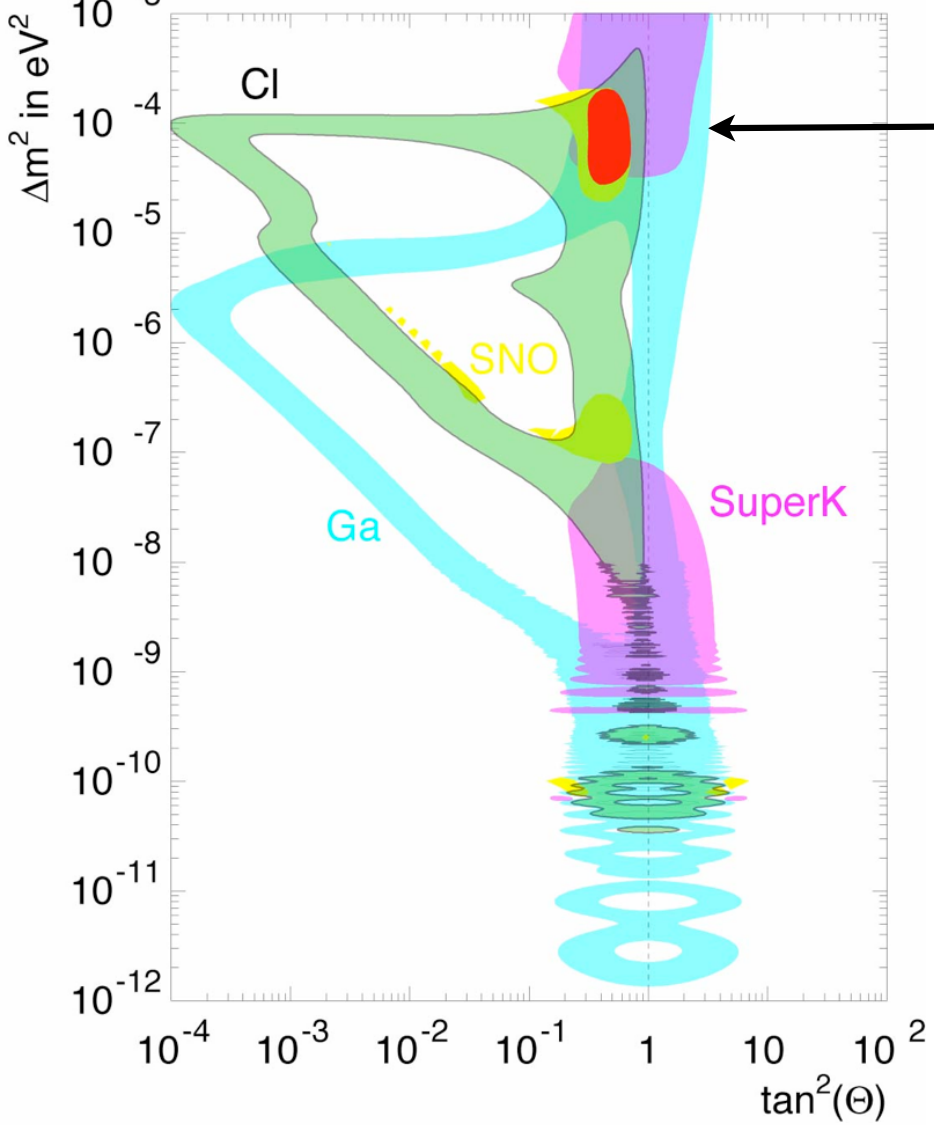
Total Rates: Standard Model vs. Experiment

Bahcall–Serenelli 2005 [BS05(OP)]



Impact on Mixing Parameters

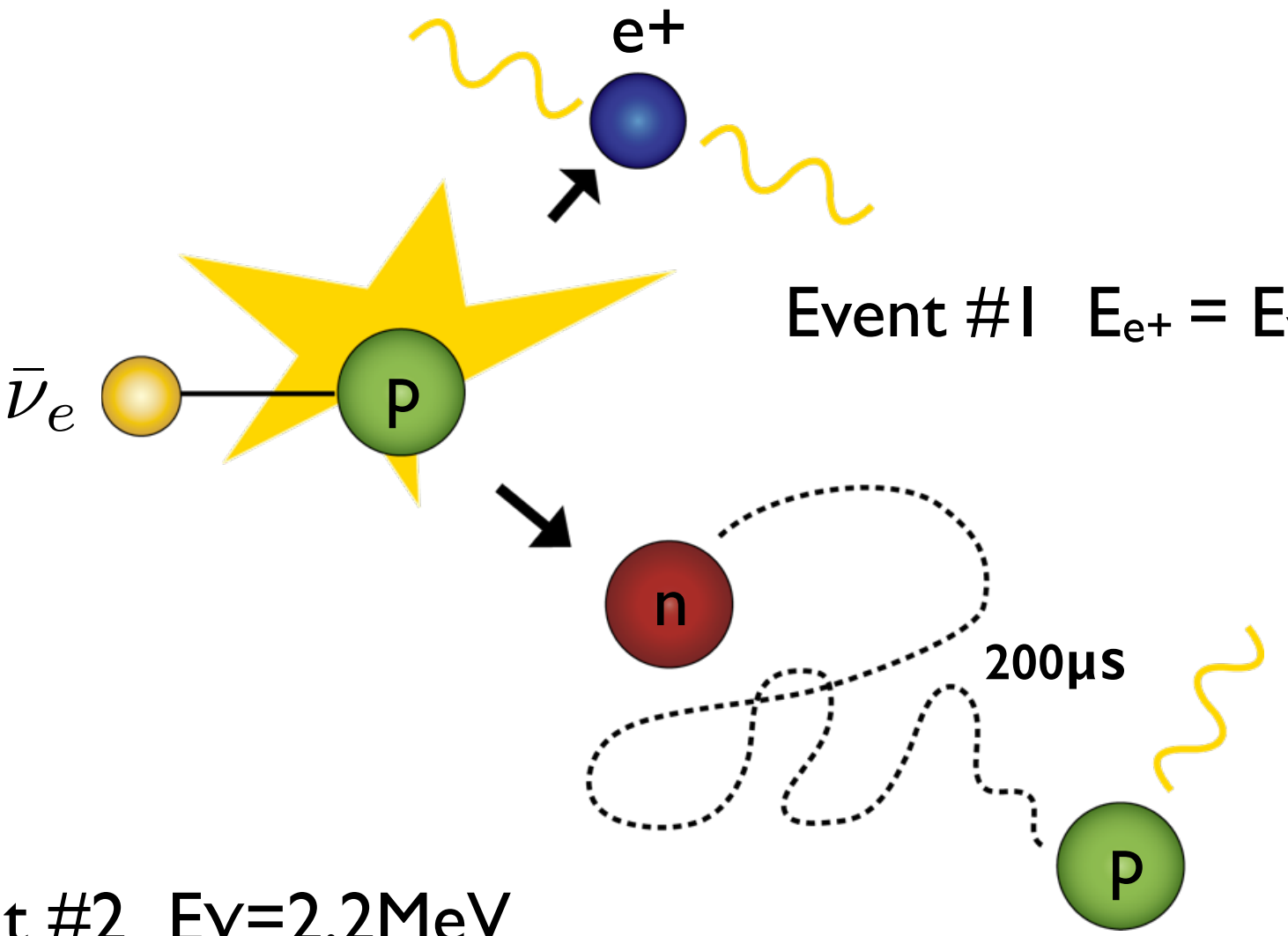
arXiv:hep-ex/0208004



Large Mixing Angle Solution

What about the discovery of the neutrino?

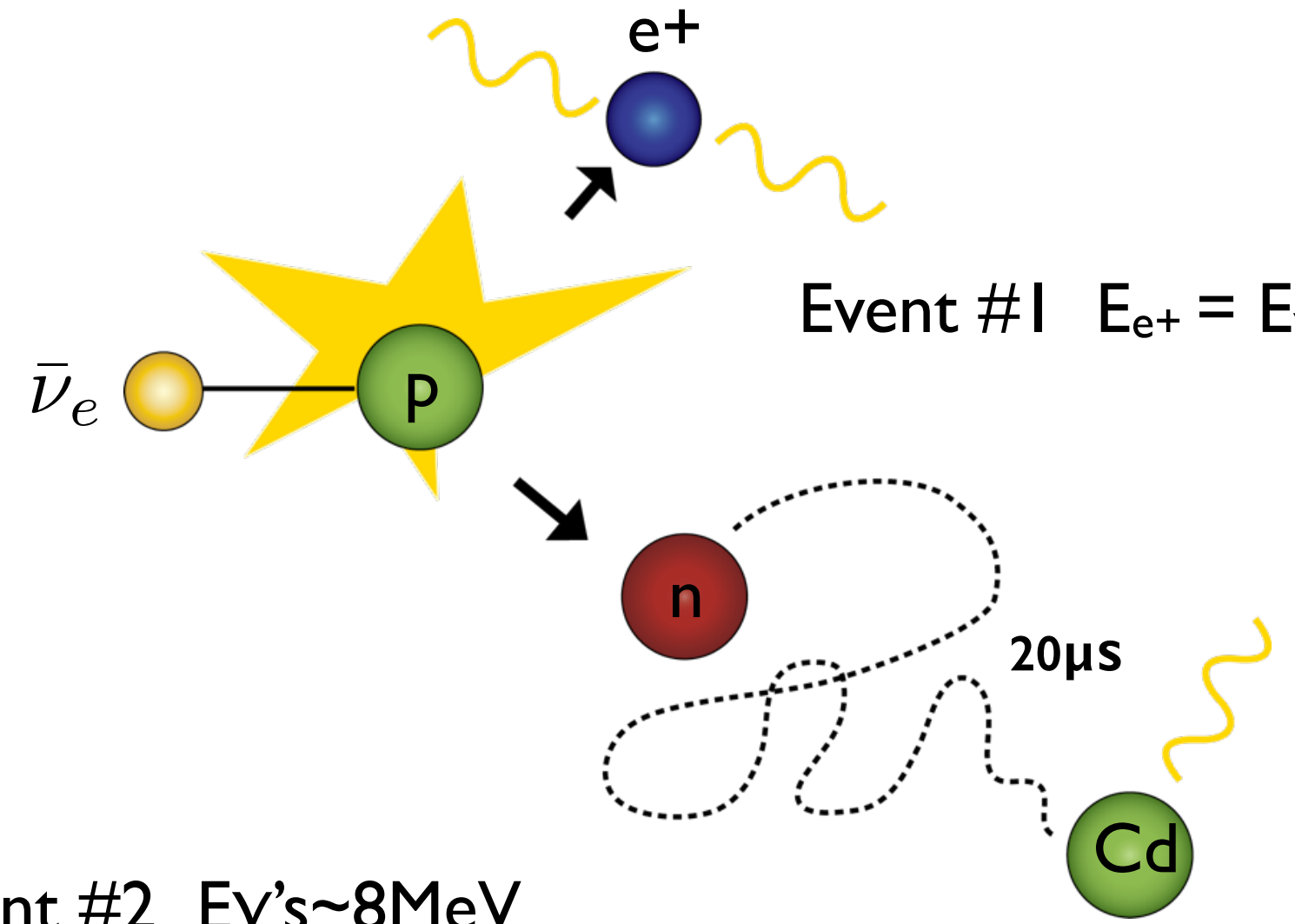
Inverse Beta Decay:



Event #1 $E_{e+} = E_\nu - 0.8\text{MeV}$

Event #2 $E_\gamma = 2.2\text{MeV}$

or capture on something else...

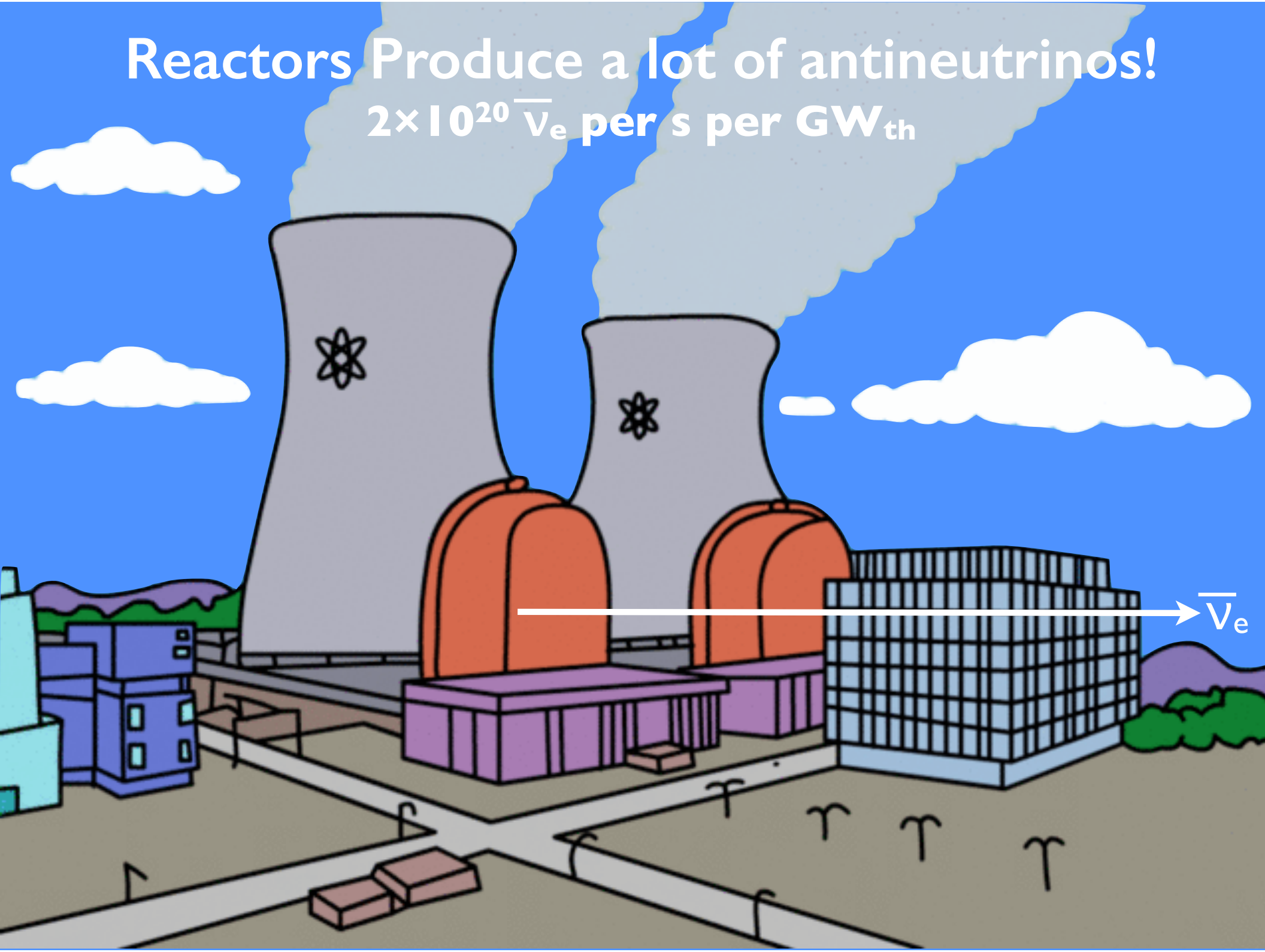


Event #1 $E_{e+} = E_\nu - 0.8\text{MeV}$

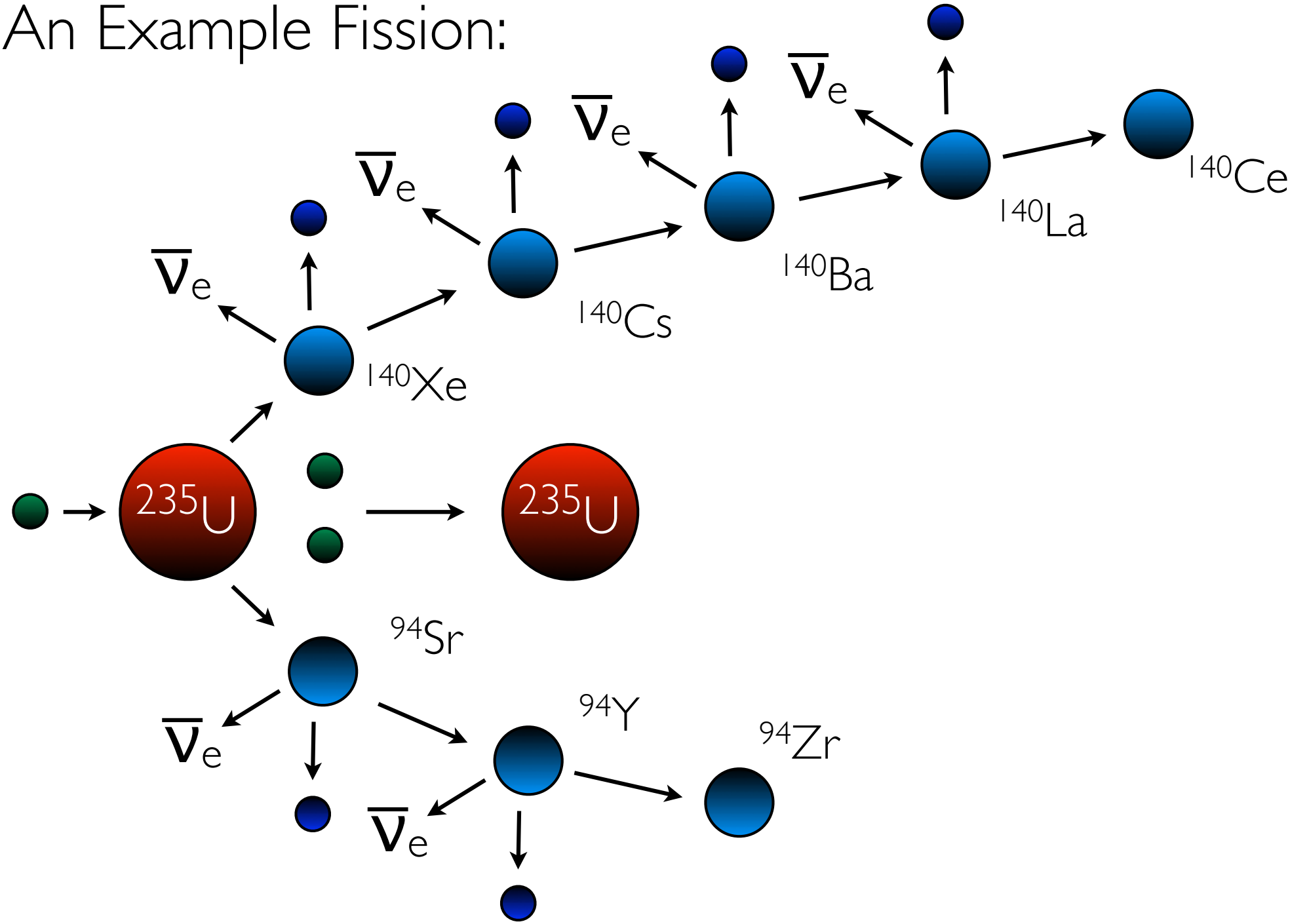
Event #2 Eγ's~8MeV

Reactors Produce a lot of antineutrinos!

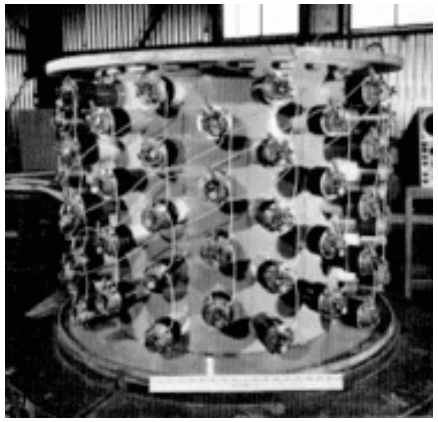
$2\times10^{20}\ \bar{\nu}_e$ per s per GW_{th}

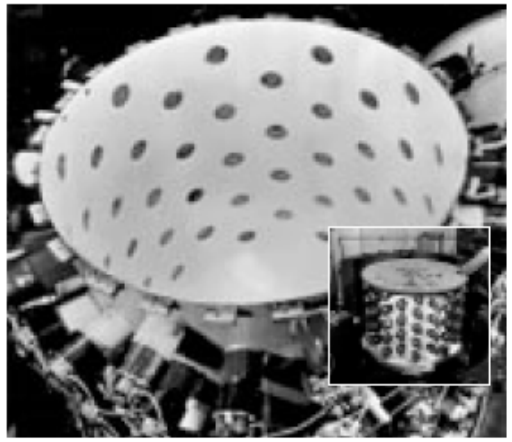


An Example Fission:



First hints at Hanford Reactor:





Poltergeist Experiment

"The lesson of the work was clear: It is easy to shield out the noise men make, but impossible to shut out the cosmos. Neutrons and gamma rays from the reactor, which we had feared most, were stopped in our thick walls of paraffin, borax and lead, but the cosmic ray mesons penetrated gleefully, generating backgrounds in our equipment as they passed or stopped in it. We did record neutrino-like signals but the cosmic rays with their neutron secondaries generated in our shields were 10 times more abundant than were the neutrino signals. We felt we had the neutrino by the coattails, but our evidence would not stand up in court."

Discovery at Savannah River:

PHYSICAL REVIEW VOLUME 117, NUMBER 1 JANUARY 1, 1960

Detection of the Free Antineutrino*

F. REINES,† C. L. COWAN, JR.,‡ F. B. HARRISON, A. D. MCGUIRE, AND H. W. KRUSE
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received July 27, 1959)

The antineutrino absorption reaction $p(\bar{\nu},\beta^+)n$ was observed in two 200-liter water targets each placed between large liquid scintillation detectors and located near a powerful production fission reactor in an antineutrino flux of 1.2×10^{13} cm^{-2} sec^{-1}. The signal, a delayed-coincidence event consisting of the annihilation of the positron followed by the capture of the neutron in cadmium which was dissolved in the water target, was subjected to a variety of tests. These tests demonstrated that reactor-associated events occurred at the rate of 3.0 hr^{-1} for both targets taken together, consistent with expectations; the first pulse of the pair was due to a positron; the second to a neutron; the signal dependended on the presence of protons in the target; and the signal was not due to neutrons or gamma rays from the reactor.

A segmented detector:

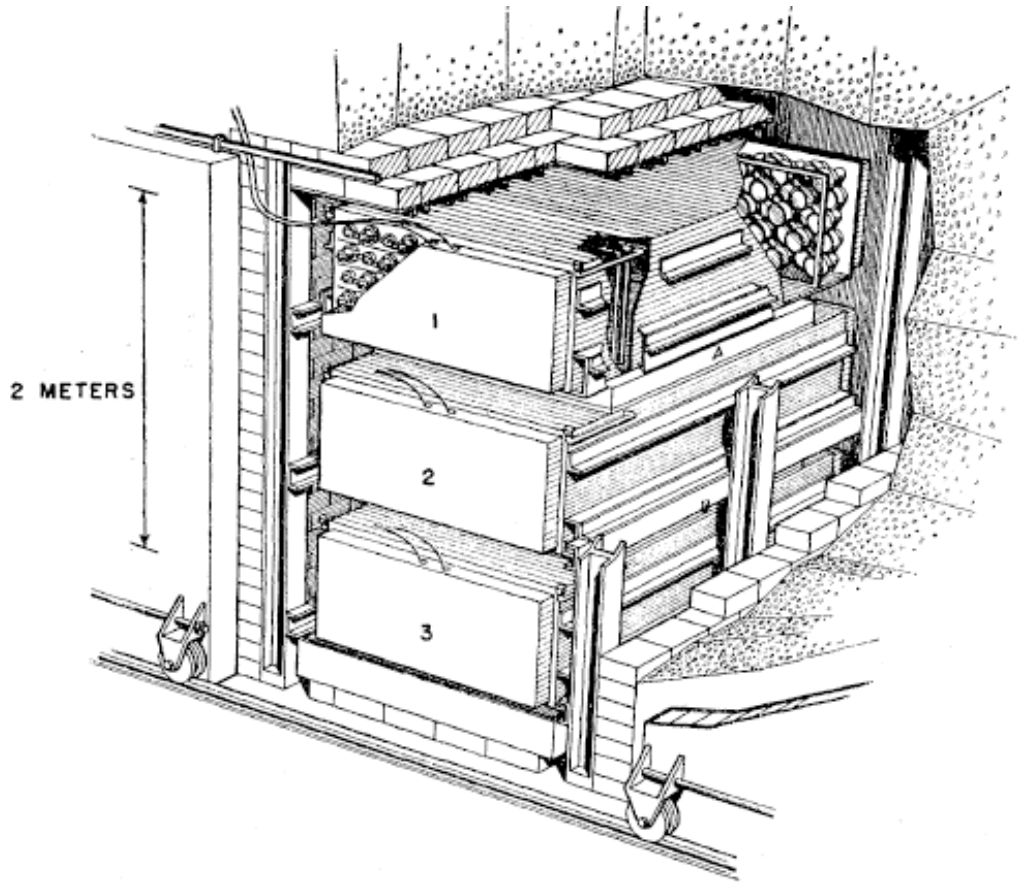


FIG. 2. Sketch of detectors inside their lead shield. The detector tanks marked 1, 2, and 3 contained liquid scintillator solution which was viewed in each tank by 110 5-in. photomultiplier tubes. The white tanks contained the water-cadmium chloride target, and in this picture are some 28 cm deep. These were later replaced by 7.5-cm deep polystyrene tanks, and detectors 1 and 2 were lowered correspondingly. A drip tank, not shown here, was later set underneath tank 3 in the event of a leak. Because of the weight it was necessary to move the lead doors with a hydraulic system.

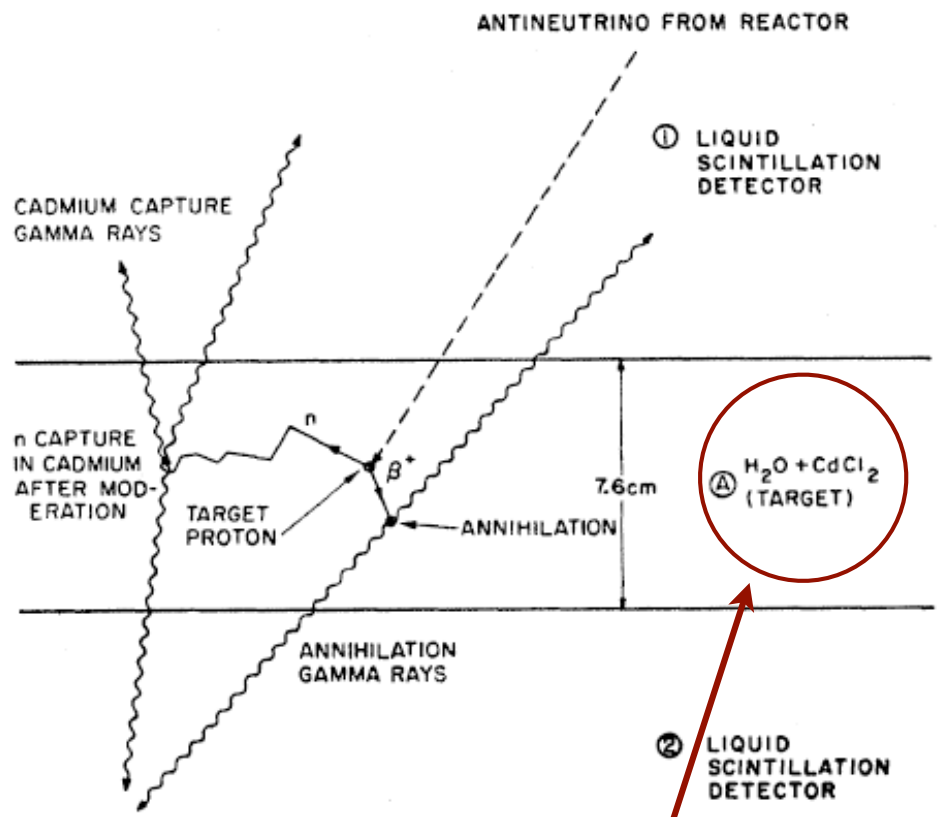
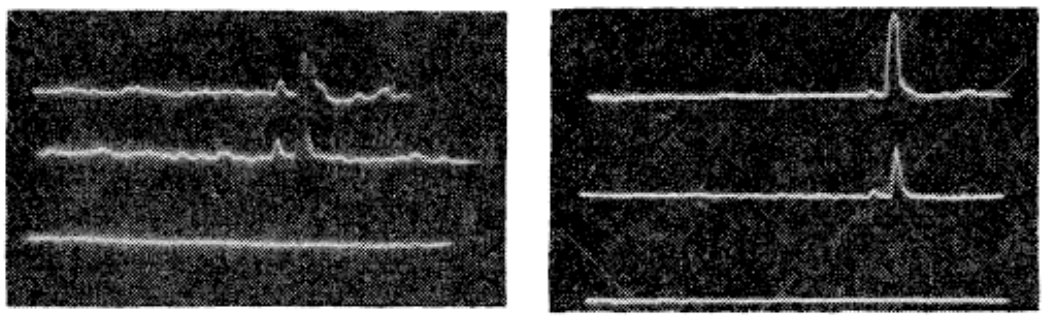


FIG. 1. Schematic diagram of antineutrino experiment.

water target doped with Cd.

The Data:



β^+ scope (a) n scope

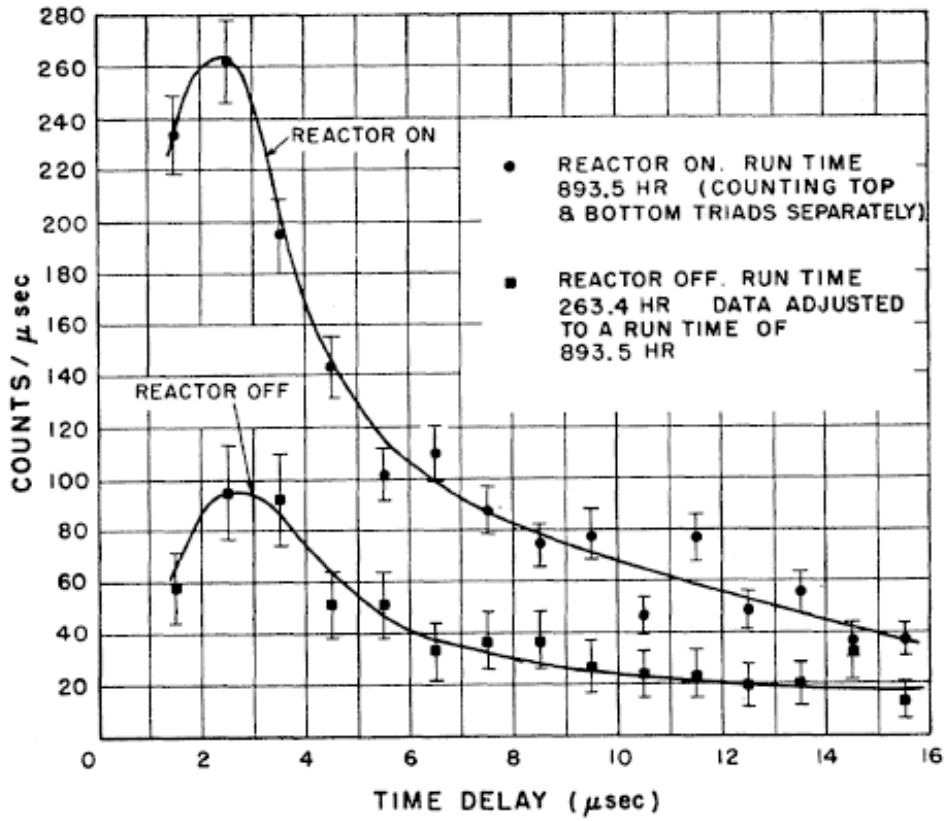
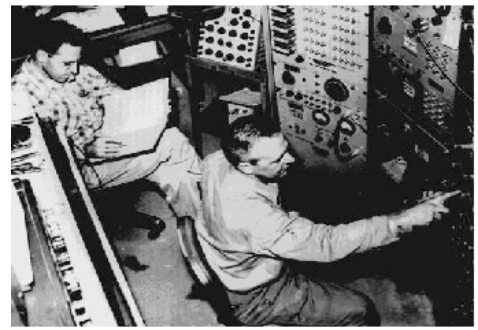
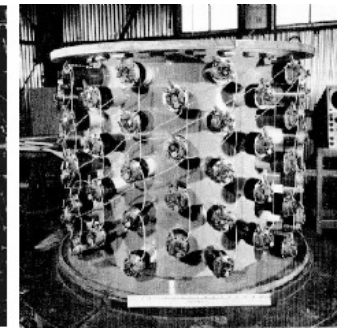


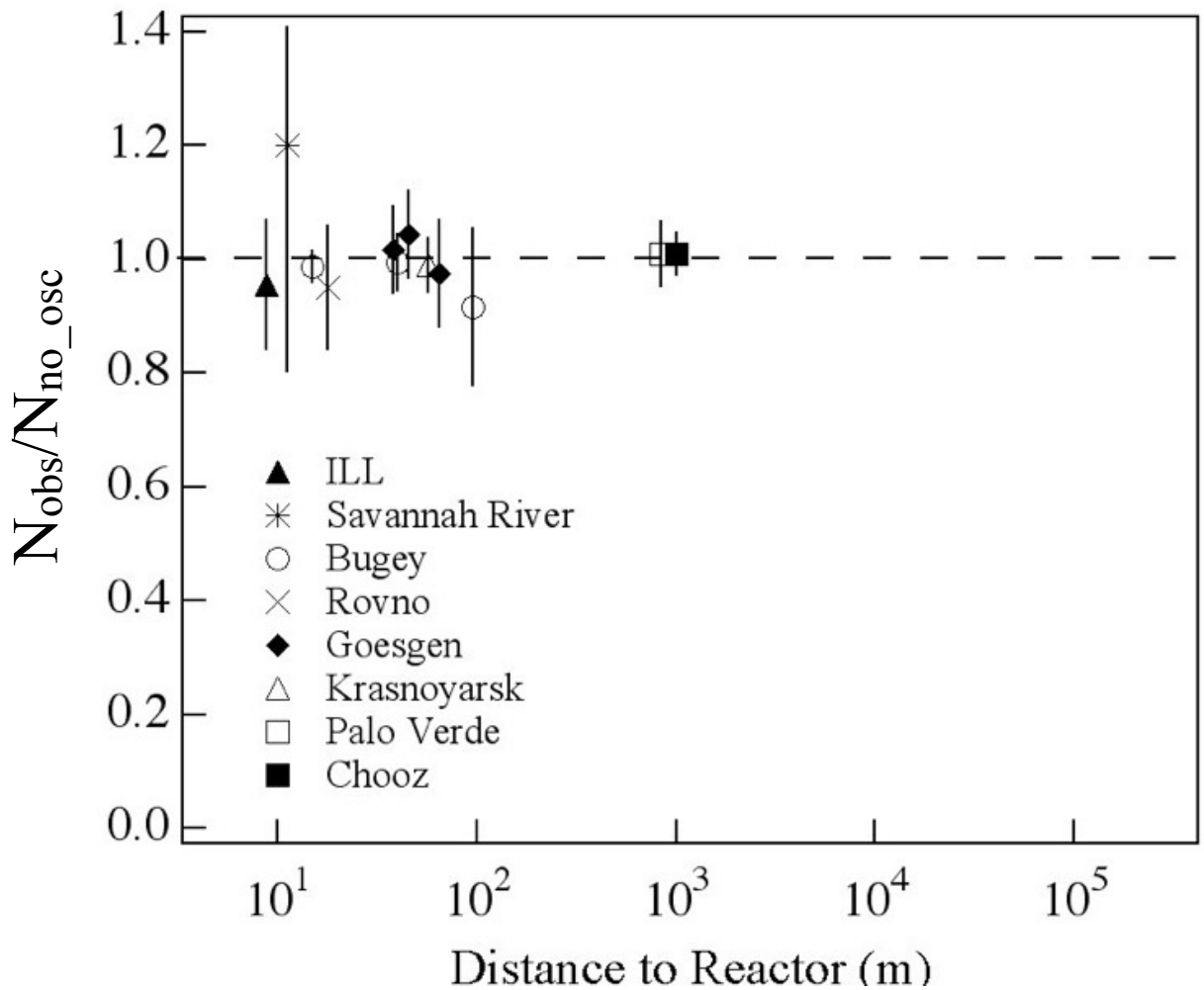
FIG. 7. Time-delay spectrum first series. Curves show theoretical distribution for $\alpha=0.005$ plus accidental background. Theoretical calculations are not considered reliable beyond 10 μsec because statistical errors in Monte Carlo method increase with decreasing sample available in that range.

Reactor Anti-neutrino Anti-Problem!

- Reactor experiments do not see a deficit of antineutrinos as of 2001.

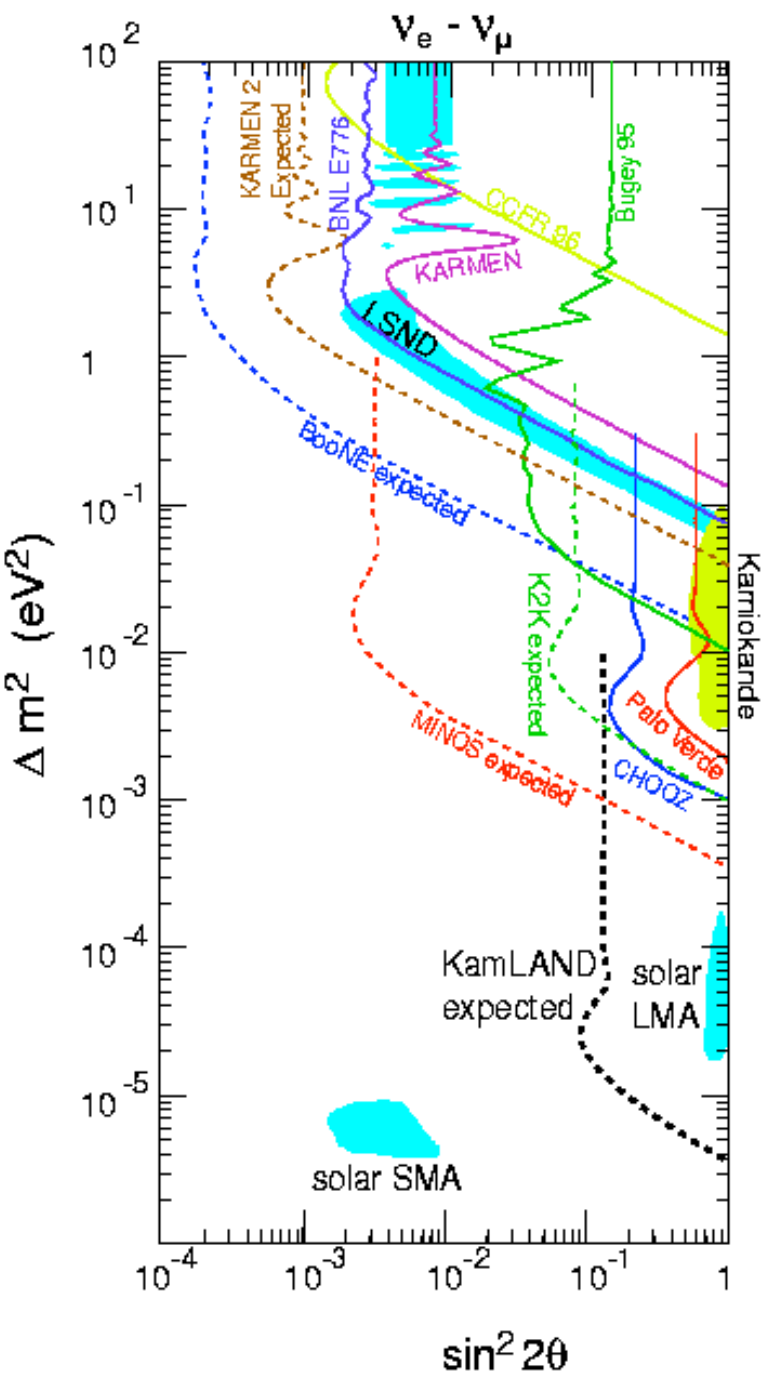


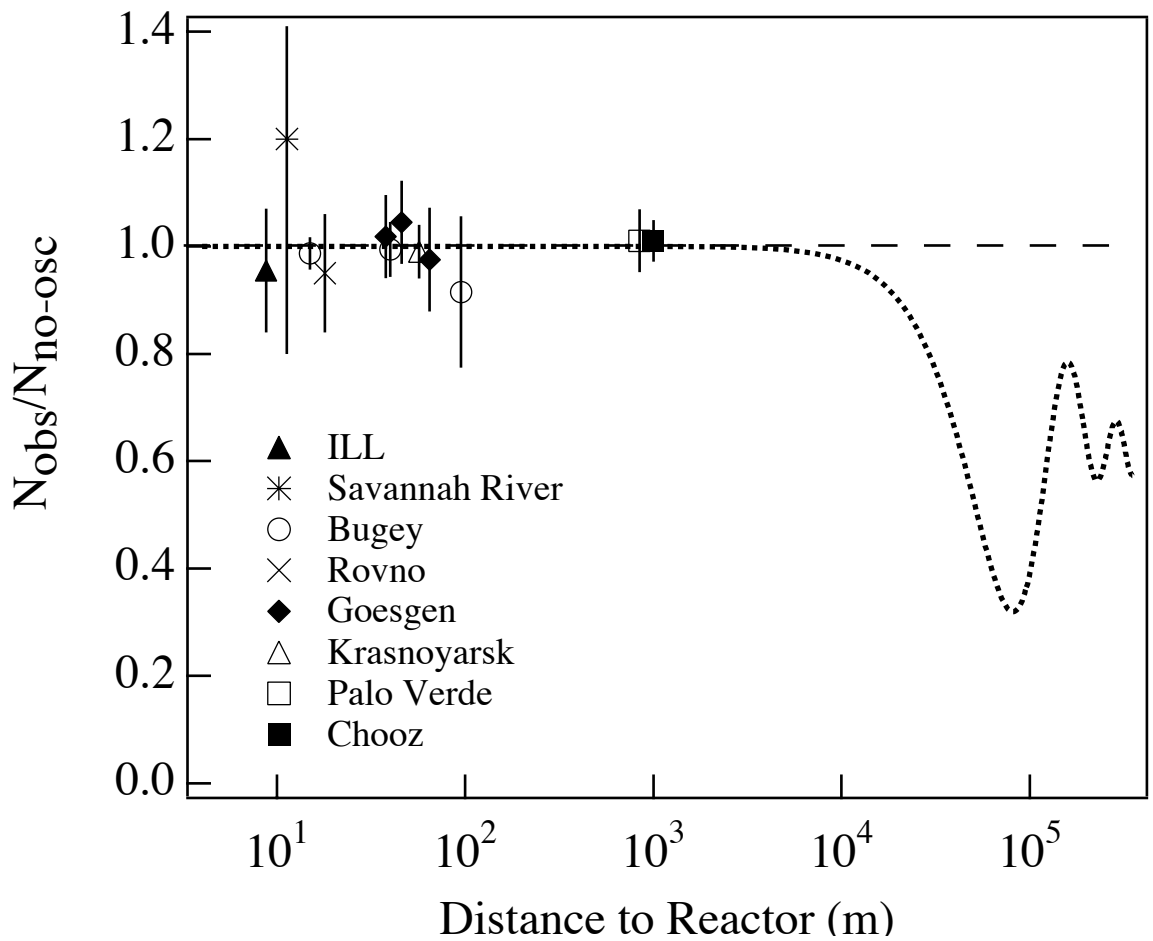




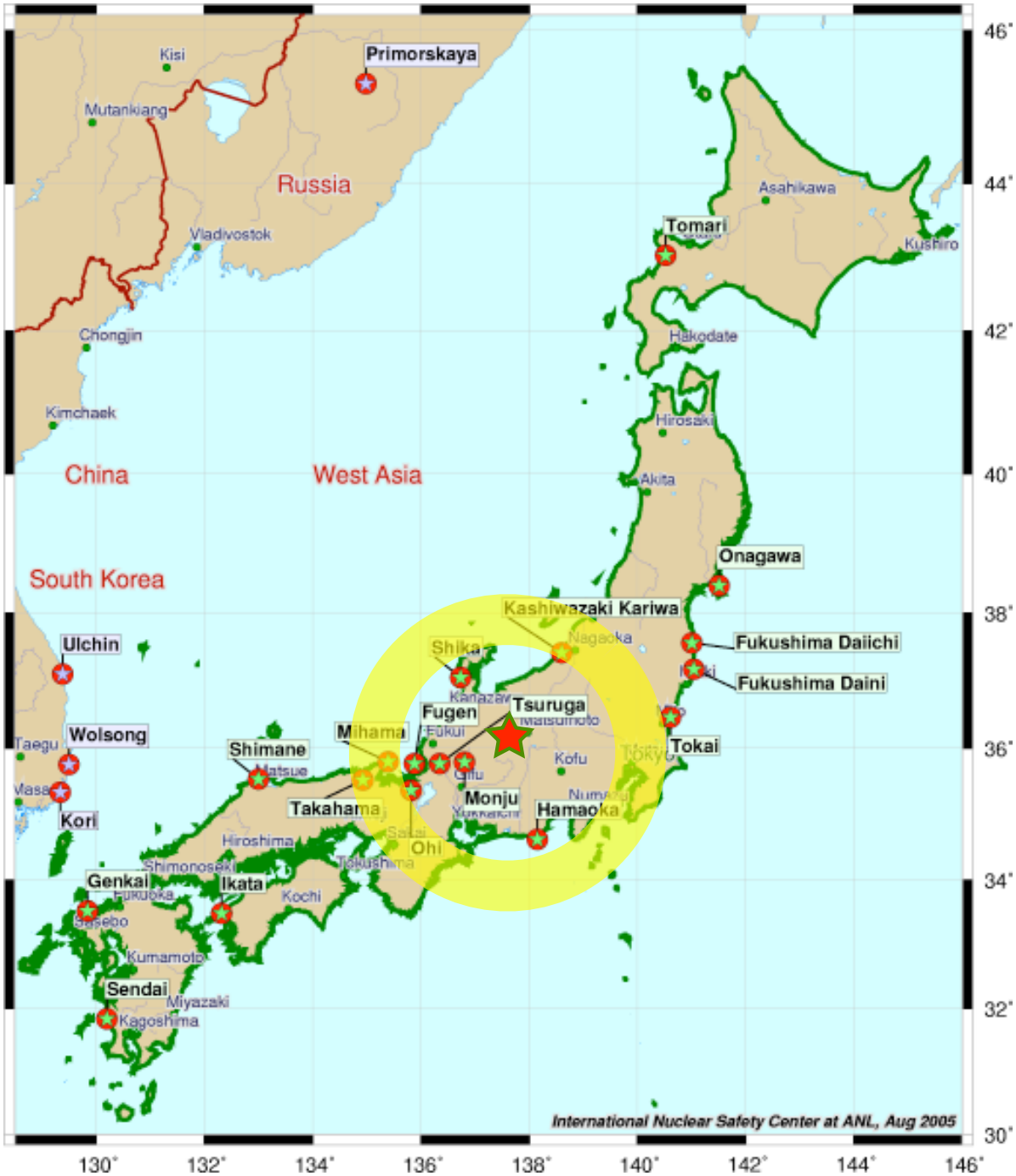
Planning For KamLAND

- If large mixing angle solution is right then an experiment will need to be more than 100 km from the source.



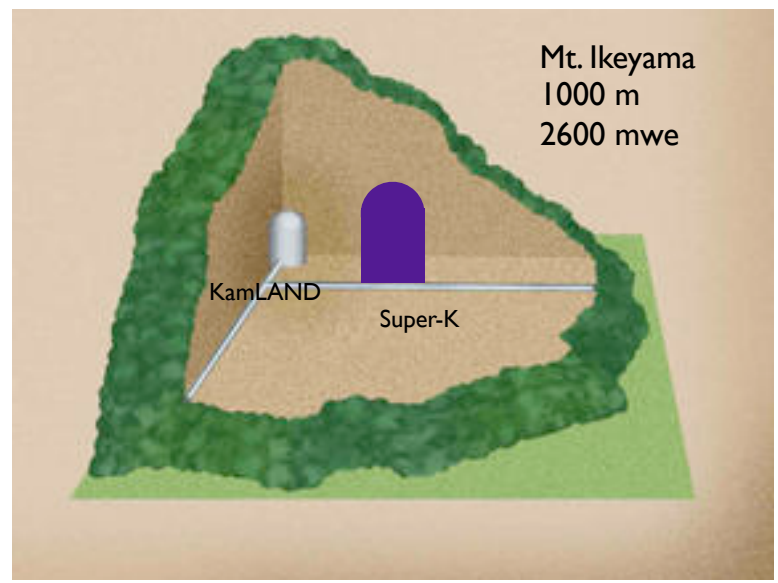


From KamLAND proposal.



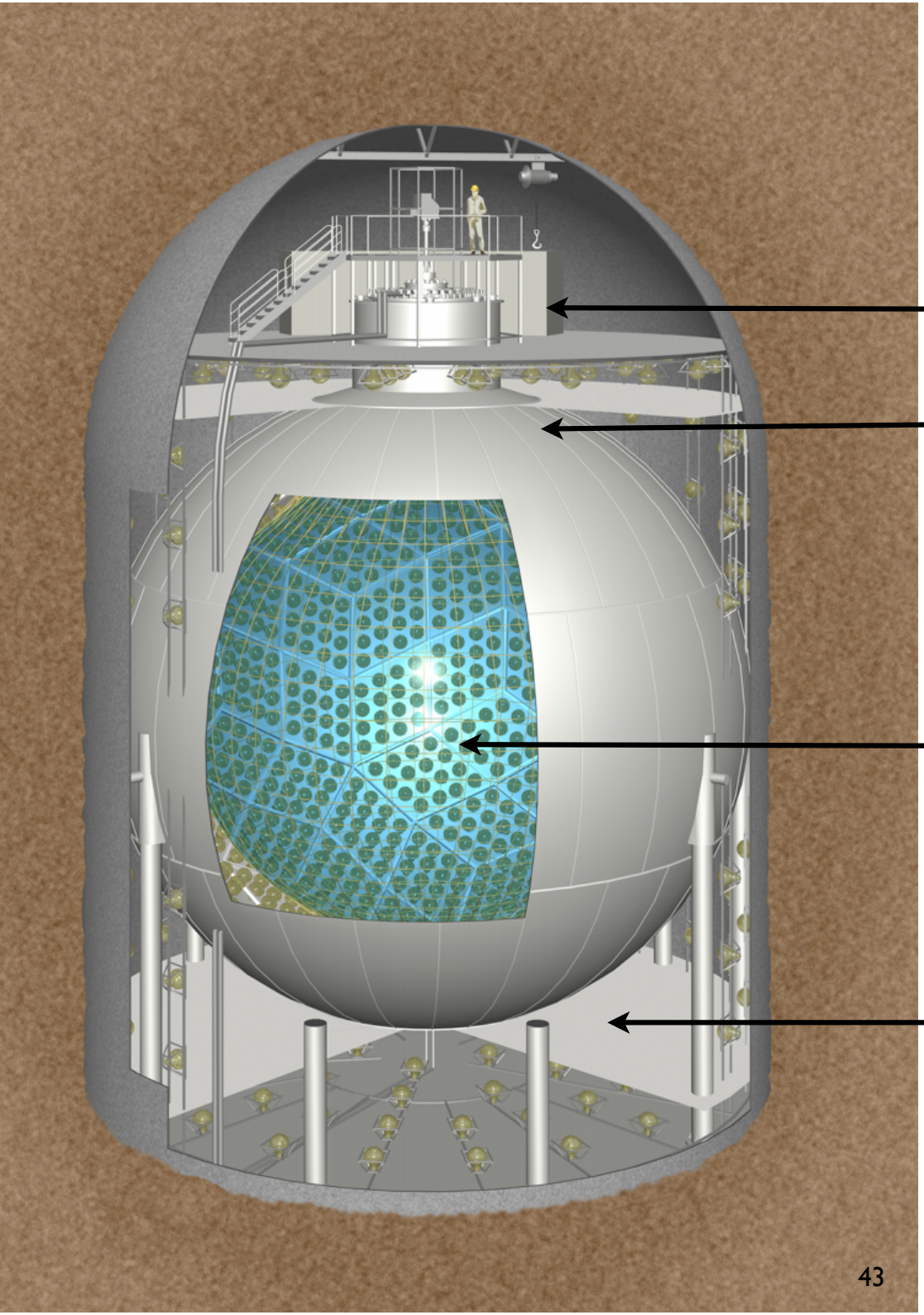
Planning For KamLAND

- The Kamioka mine in Japan is a logical place to house such a experiment.
- Japan is the third largest producer of nuclear power.
- Most reactors right on the coast.



KamLAND: The Detector

A Kilo-Tonne Liquid Scintillator!



Electronics Hut

Stainless Steel Sphere
- 8.5m radius
- 1325 17" PMTs
- 554 20" PMTs

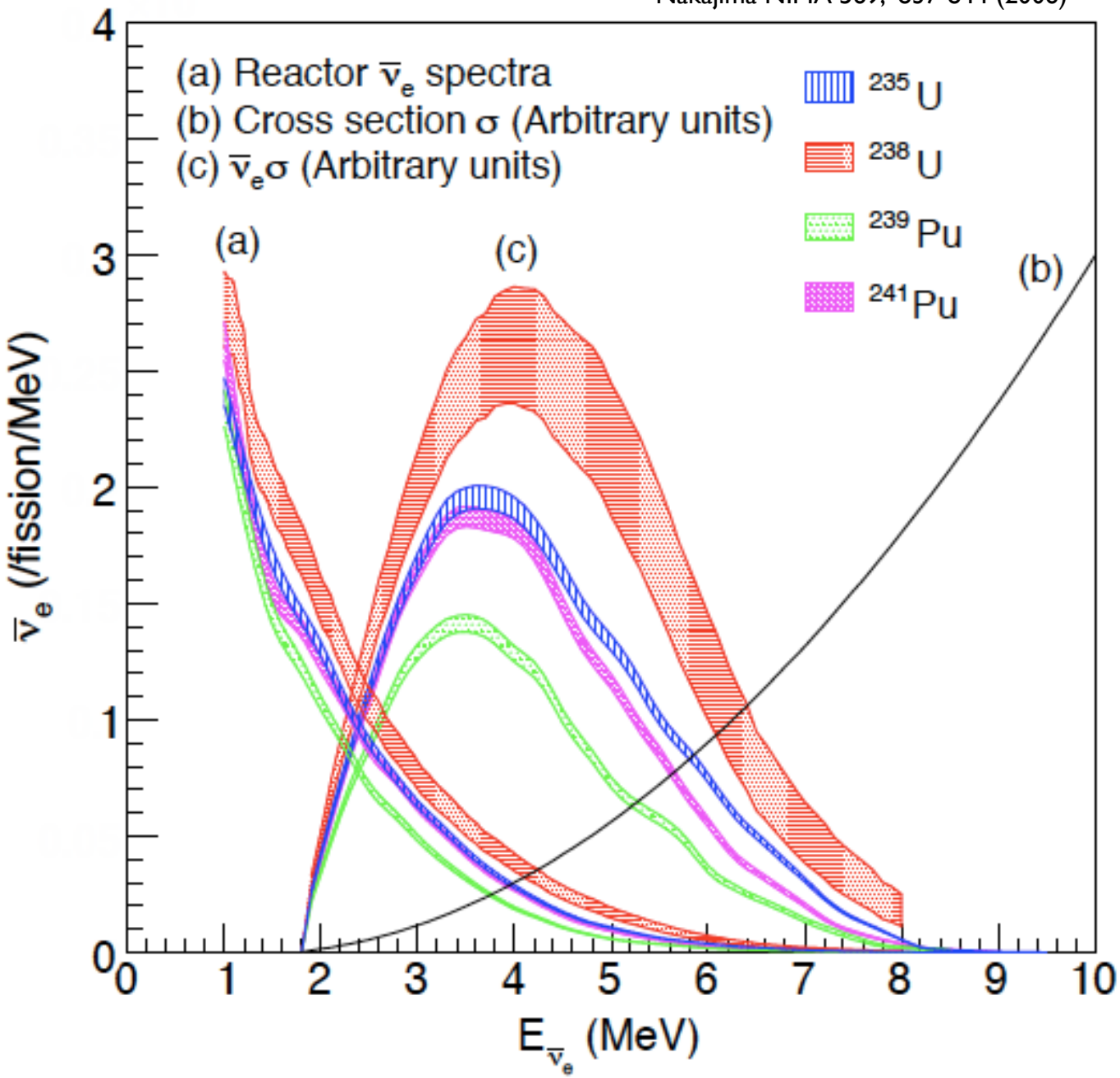
Nylon Balloon
- 6.5m radius
- Separates BO and LS.

Water Cerenkov Veto
- 225 20" PMTs

KamLAND LS is 80% mineral oil, 20% psuedo-cumene, and 1.36 g/L PPO.

Antineutrino Energy ➞ Event #1 Energy

Nakajima NIMA 569, 837-844 (2006)



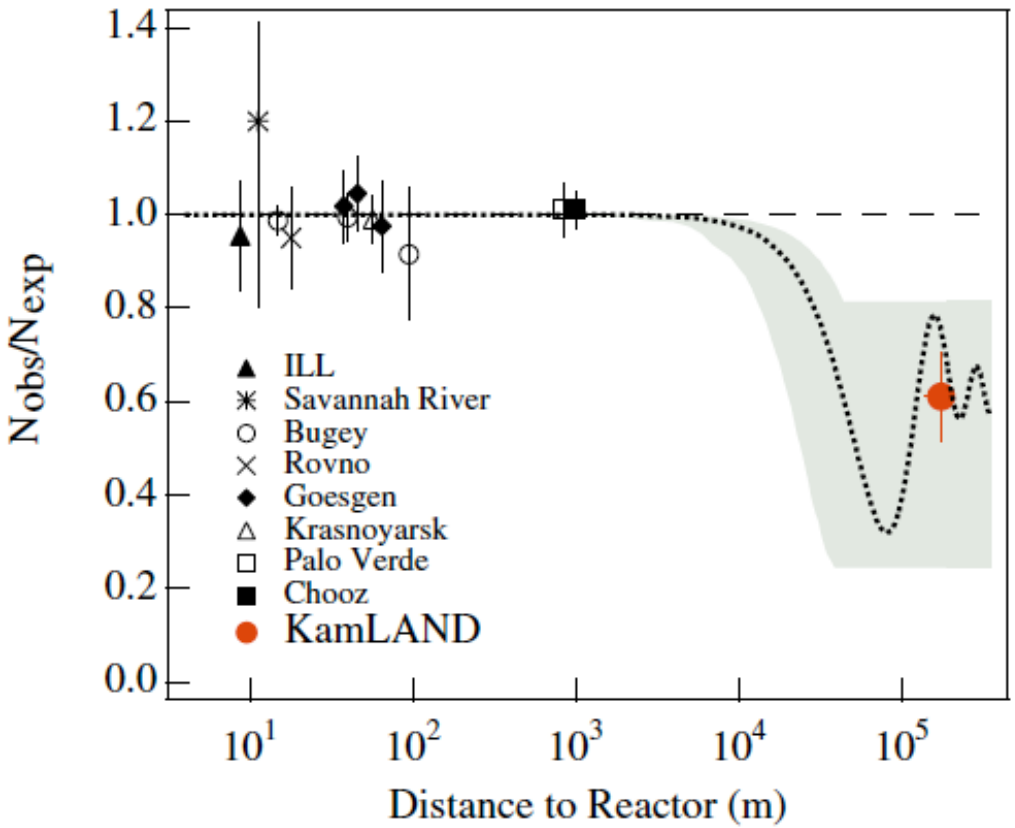
VOLUME 90, NUMBER 2 PHYSICAL REVIEW LETTERS week ending 17 JANUARY 2003

First Results from KamLAND: Evidence for Reactor Antineutrino Disappearance

K. Eguchi,[1] S. Enomoto,[1] K. Furuno,[1] J. Goldman,[1] H. Hanada,[1] H. Ikeda,[1] K. Ikeda,[1] K. Inoue,[1] K. Ishihara,[1] W. Itoh,[1] T. Iwamoto,[1] T. Kawaguchi,[1] T. Kawashima,[1] H. Kinoshita,[1] Y. Kishimoto,[1] M. Koga,[1] Y. Koseki,[1] T. Maeda,[1] T. Mitsui,[1] M. Motoki,[1] K. Nakajima,[1] M. Nakajima,[1] T. Nakajima,[1] H. Ogawa,[1] K. Owada,[1] T. Sakabe,[1] I. Shimizu,[1] J. Shirai,[1] F. Suekane,[1] A. Suzuki,[1] K. Tada,[1] O. Tajima,[1] T. Takayama,[1] K. Tamae,[1] H. Watanabe,[1] J. Busenitz,[2] Z. Djurcic,[2] K. McKinny,[2] D.-M. Mei,[2] A. Piepke,[2] E. Yakushev,[2] B. E. Berger,[3] Y. D. Chan,[3] M. P. Decowski,[3] D. A. Dwyer,[3] S. J. Freedman,[3] Y. Fu,[3] B. K. Fujikawa,[3] K. M. Heeger,[3] K. T. Lesko,[3] K.-B. Luk,[3] H. Murayama,[3] D. R. Nygren,[3] C. E. Okada,[3] A. W. P. Poon,[3] H. M. Steiner,[3] L. A. Winslow,[3] G. A. Horton-Smith,[4] R. D. McKeown,[4] J. Ritter,[4] B. Tipton,[4] P. Vogel,[4] C. E. Lane,[5] T. Miletic,[5] P. W. Gorham,[6] G. Guillian,[6] J. G. Learned,[6] J. Maricic,[6] S. Matsuno,[6] S. Pakvasa,[6] S. Dazeley,[7] S. Hatakeyama,[7] M. Murakami,[7] R. C. Svoboda,[7] B. D. Dieterle,[8] M. DiMauro,[8] J. Detwiler,[9] G. Gratta,[9] K. Ishii,[9] N. Tolich,[9] Y. Uchida,[9] M. Batygov,[10] W. Bugg,[10] H. Cohn,[10] Y. Efremenko,[10] Y. Kamyshkov,[10] A. Kozlov,[10] Y. Nakamura,[10] L. De Braeckeleer,[11] C. R. Gould,[11] H. J. Karwowski,[11] D. M. Markoff,[11] J. A. Messimore,[11] K. Nakamura,[11] R. M. Rohm,[11] W. Tornow,[11] A. R. Young,[11] and Y.-F. Wang[12]

(KamLAND Collaboration)

First Result:

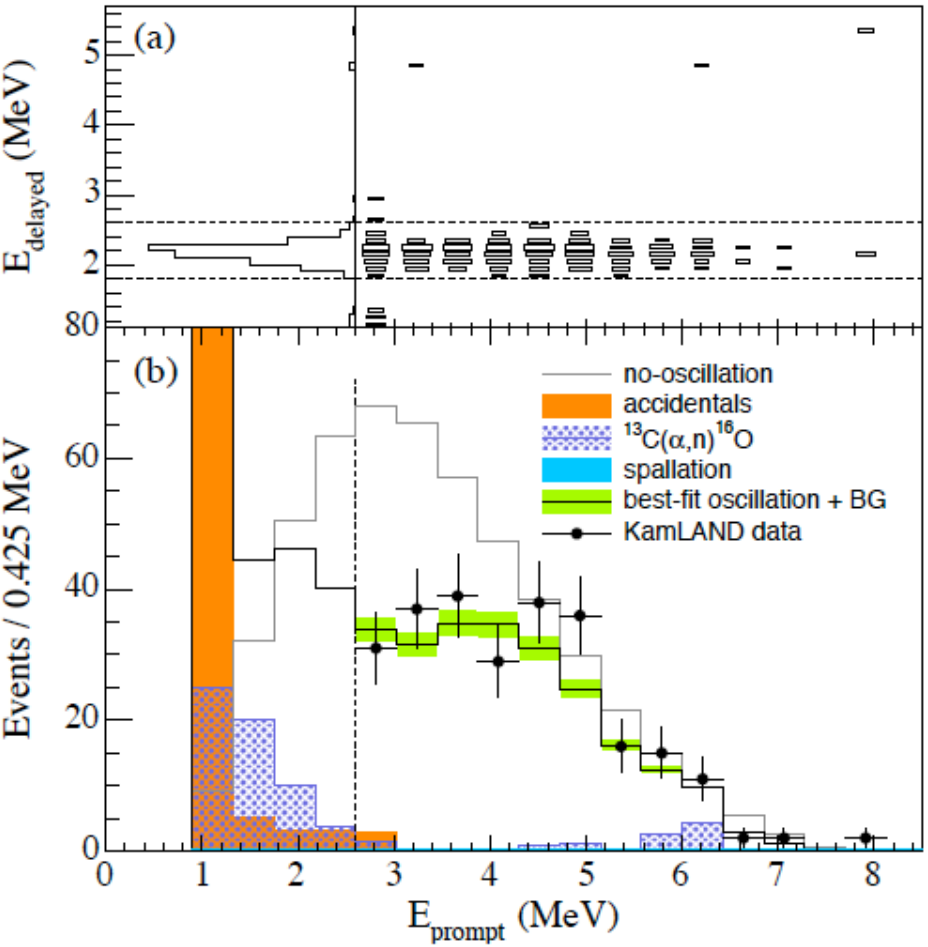


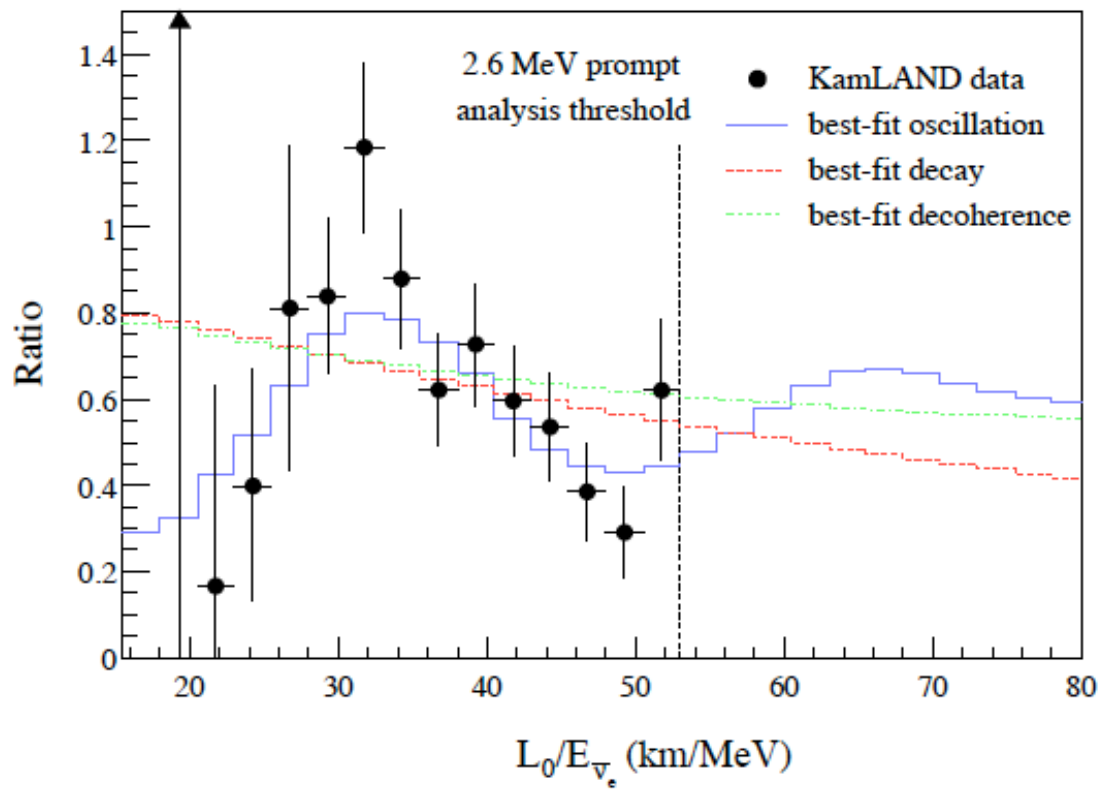
54 events detected,
86.8 were predicted.

$$\frac{N_{\text{obs}} - N_{\text{BG}}}{N_{\text{expected}}} = 0.611 \pm 0.085(\text{stat}) \pm 0.041(\text{syst}).$$

Second Result:

Measurement of Neutrino Oscillation with KamLAND: Evidence of Spectral Distortion

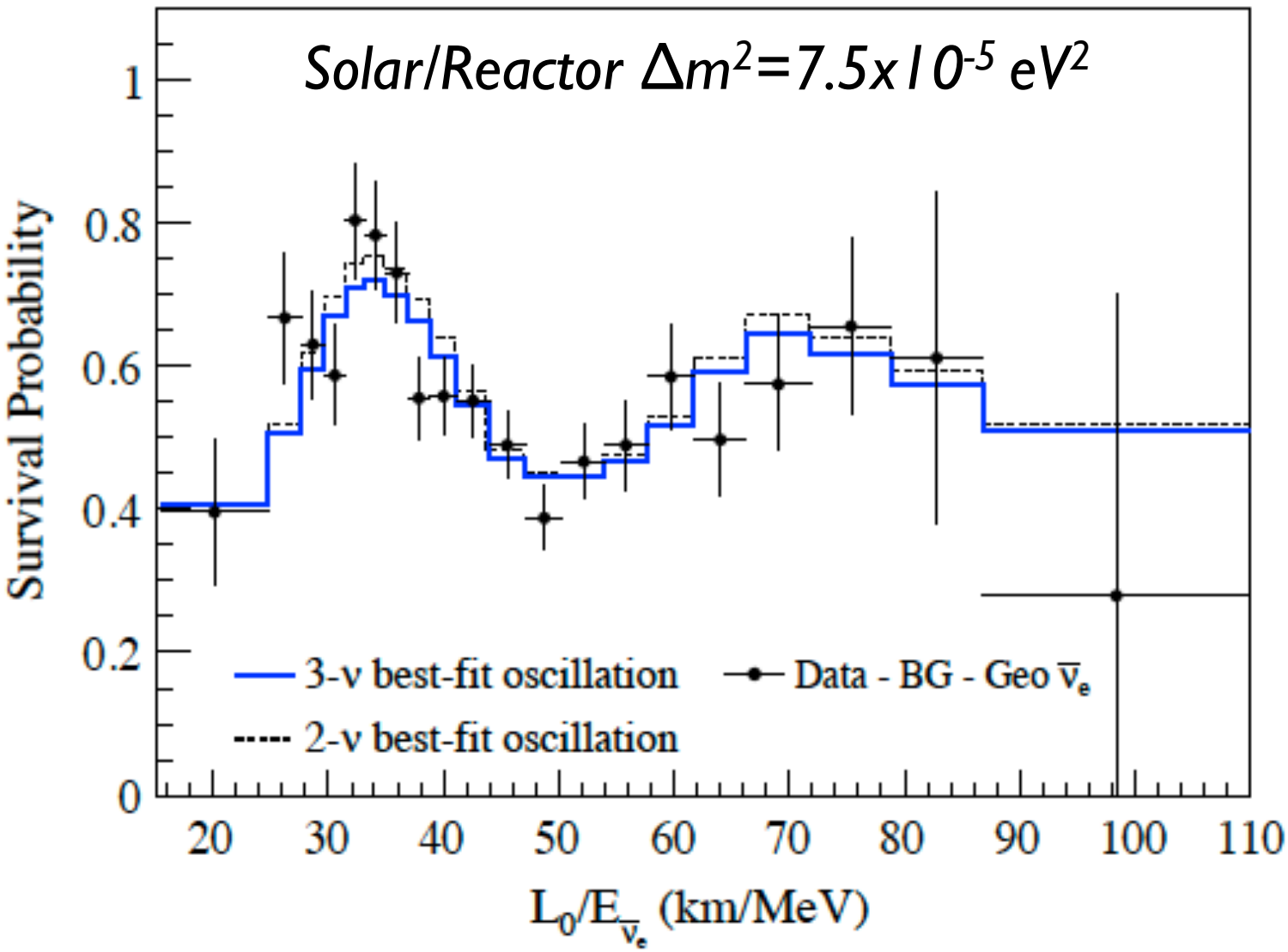




Remember neutrino oscillation signature is the L/E dependence.

KamLAND Data:

$$P_{survival} = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



see Phys.Rev. D83 (2011) 052002

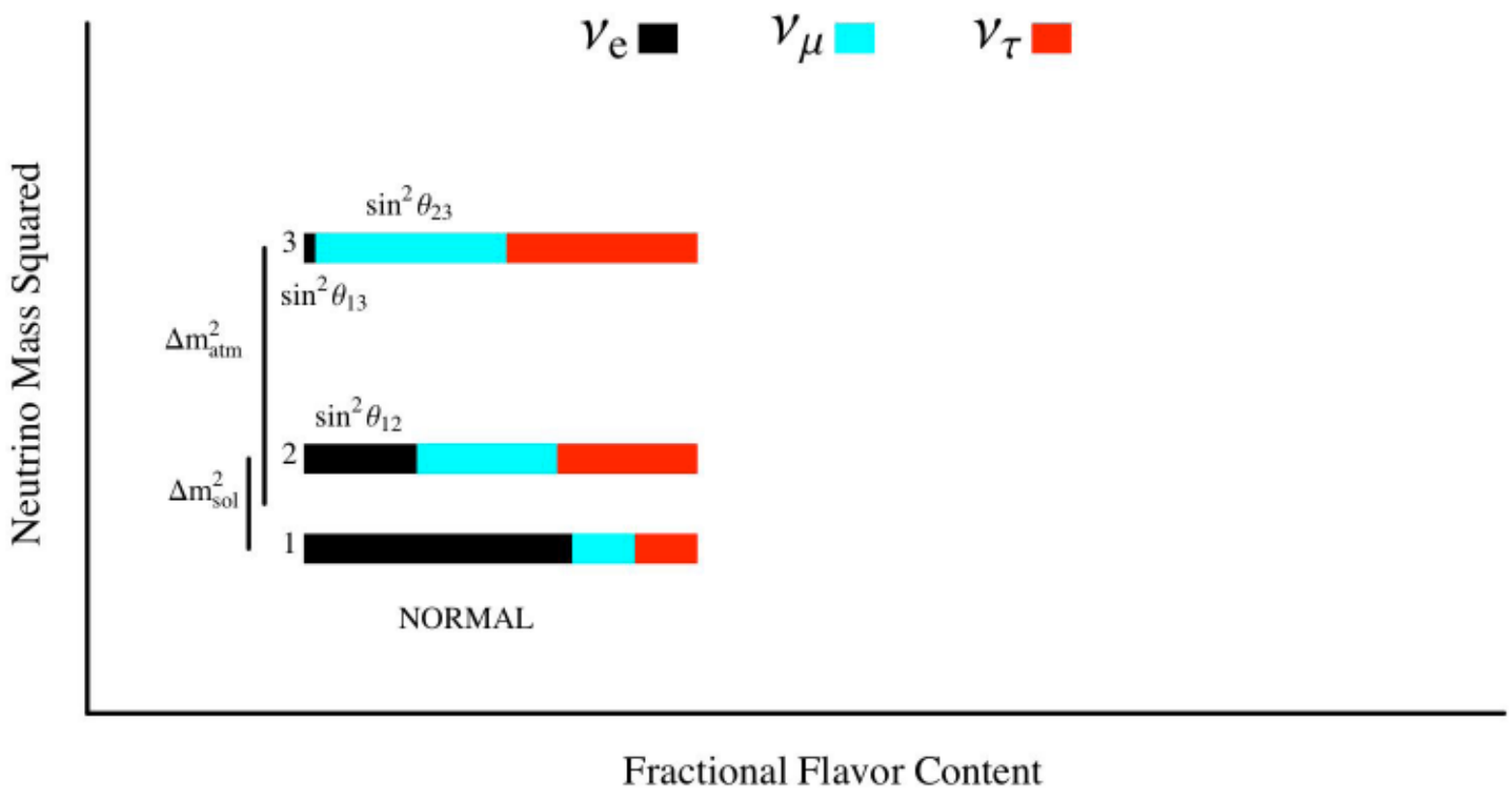
Neutrino Oscillation

$\downarrow$

$m_\nu \neq 0$

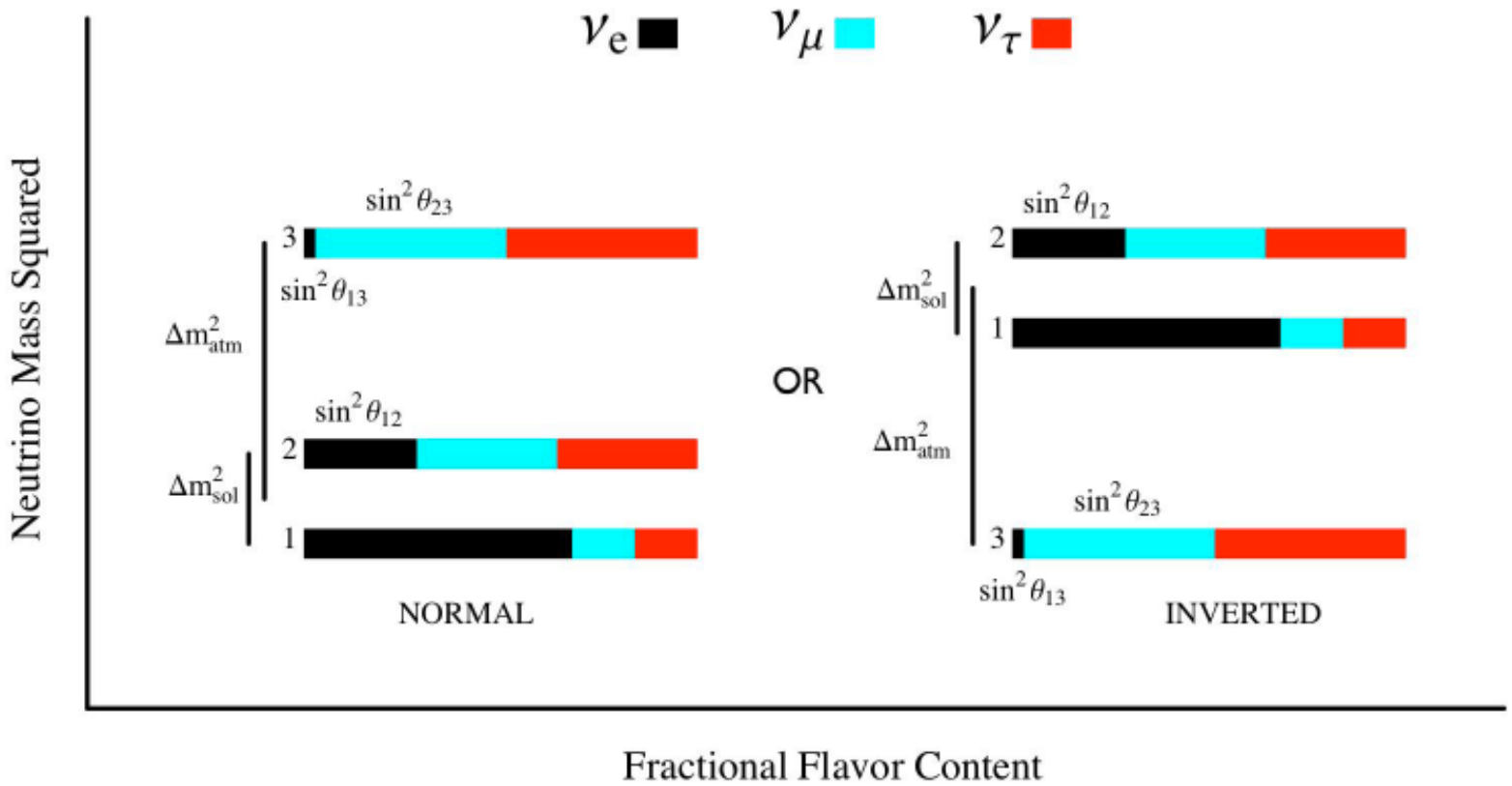
Neutrino mass is complicated.

Everything we know about neutrino mass comes from oscillation experiments...

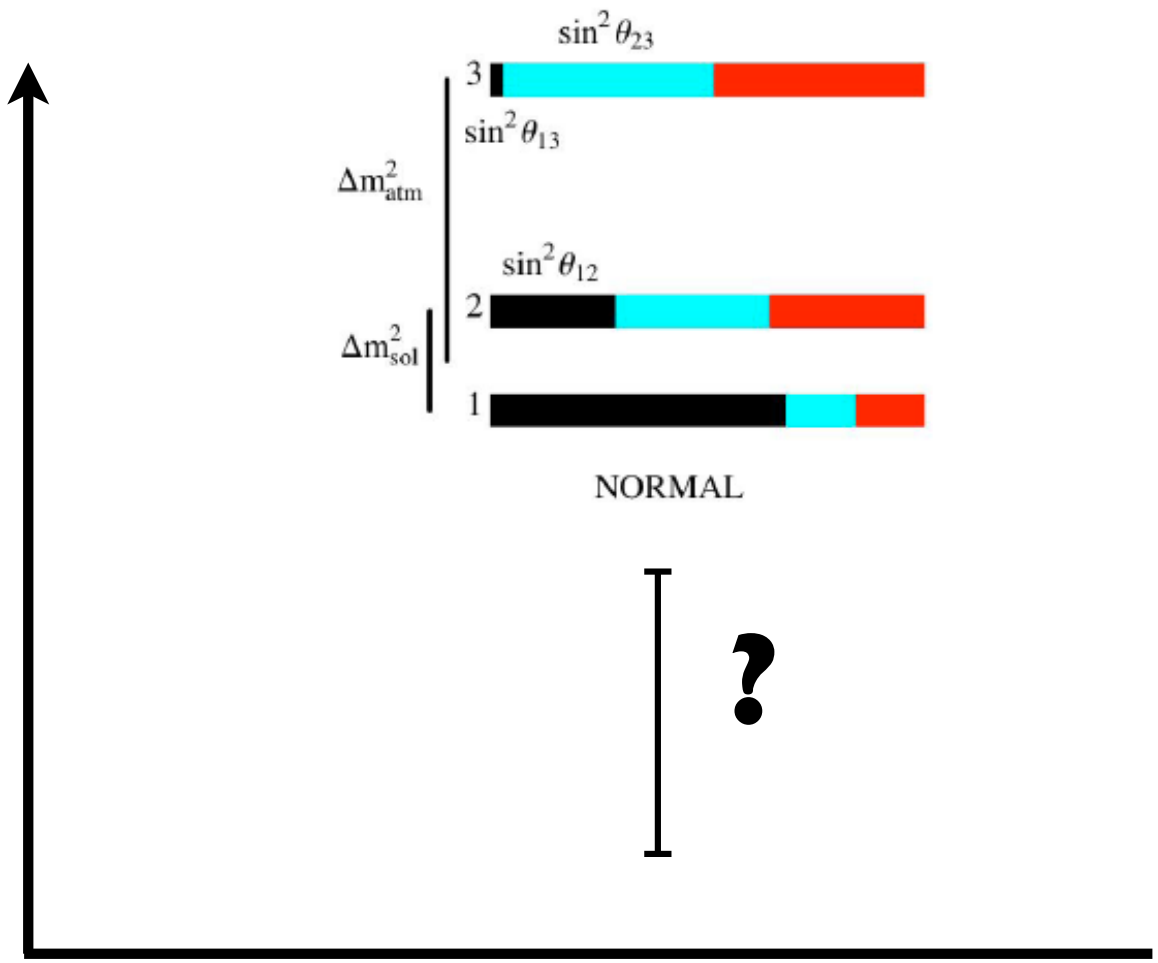


Kayser and Parke 2009

There is some ambiguity with how to arrange the mass eigenstates...

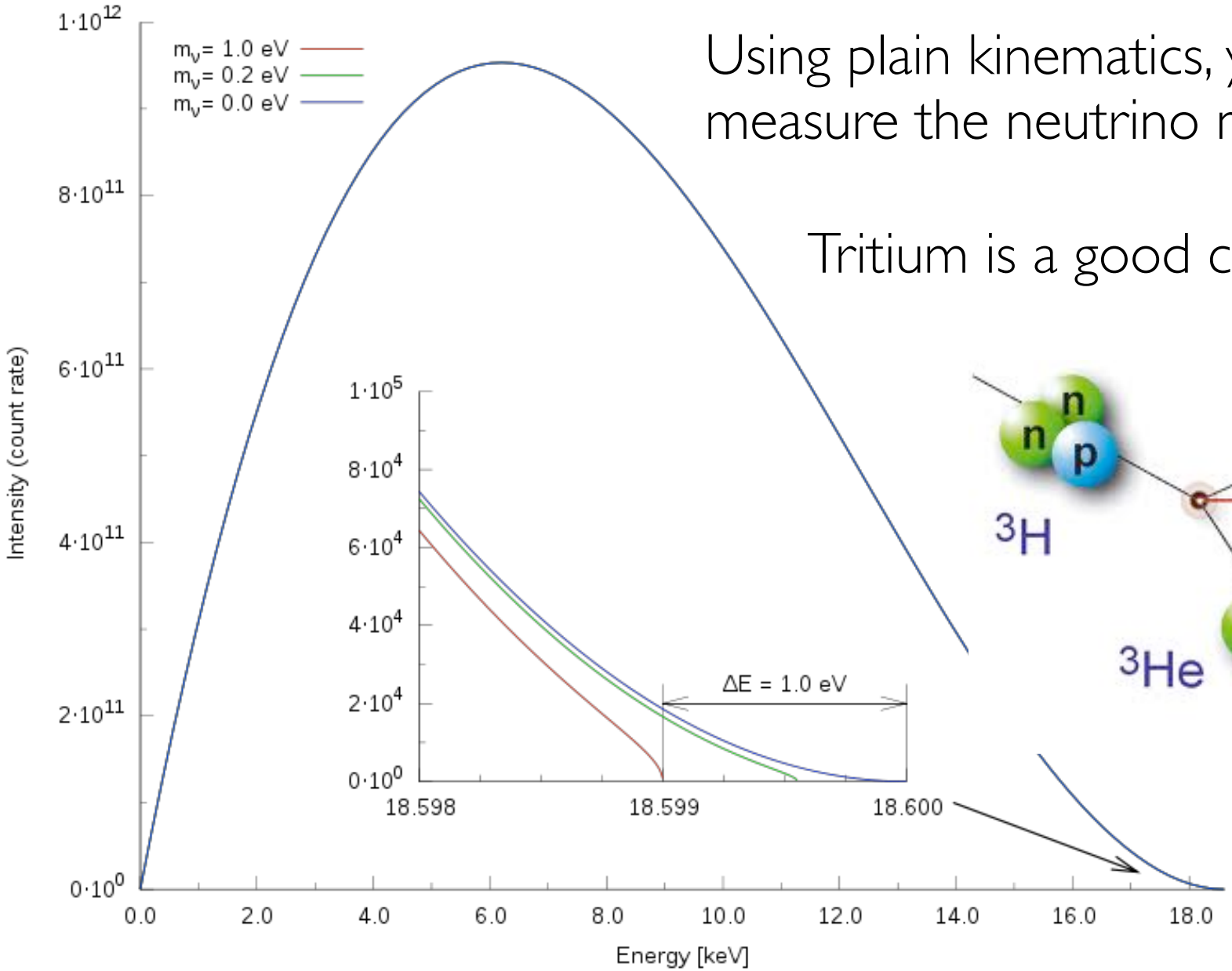


Kayser and Parke 2009



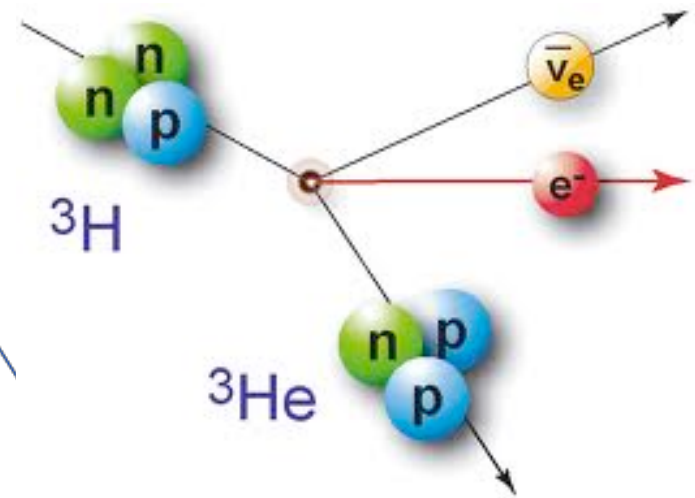
....and we still need to measure the absolute mass.

Beta Decay Endpoint Measurement:



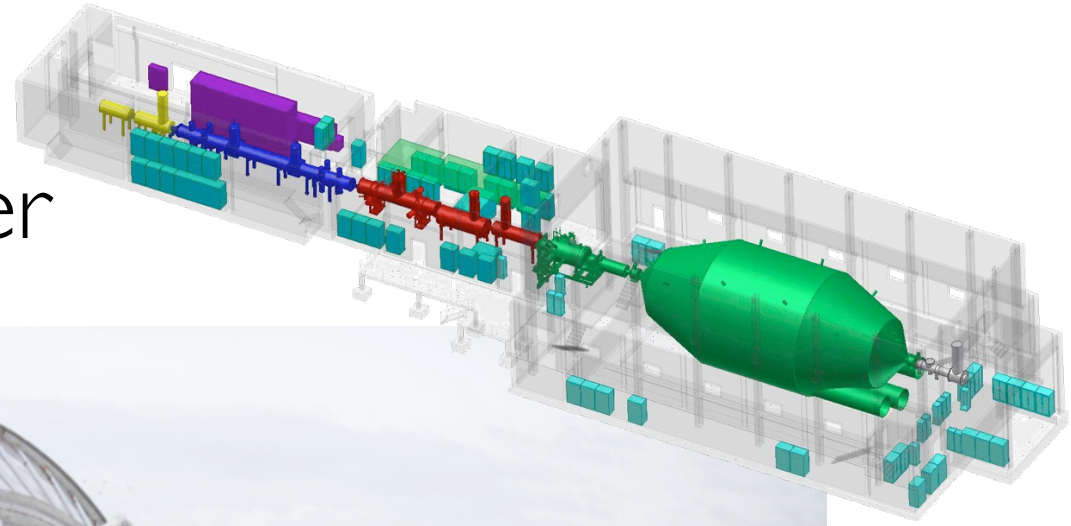
Using plain kinematics, you can measure the neutrino mass.

Tritium is a good choice.



KATRIN

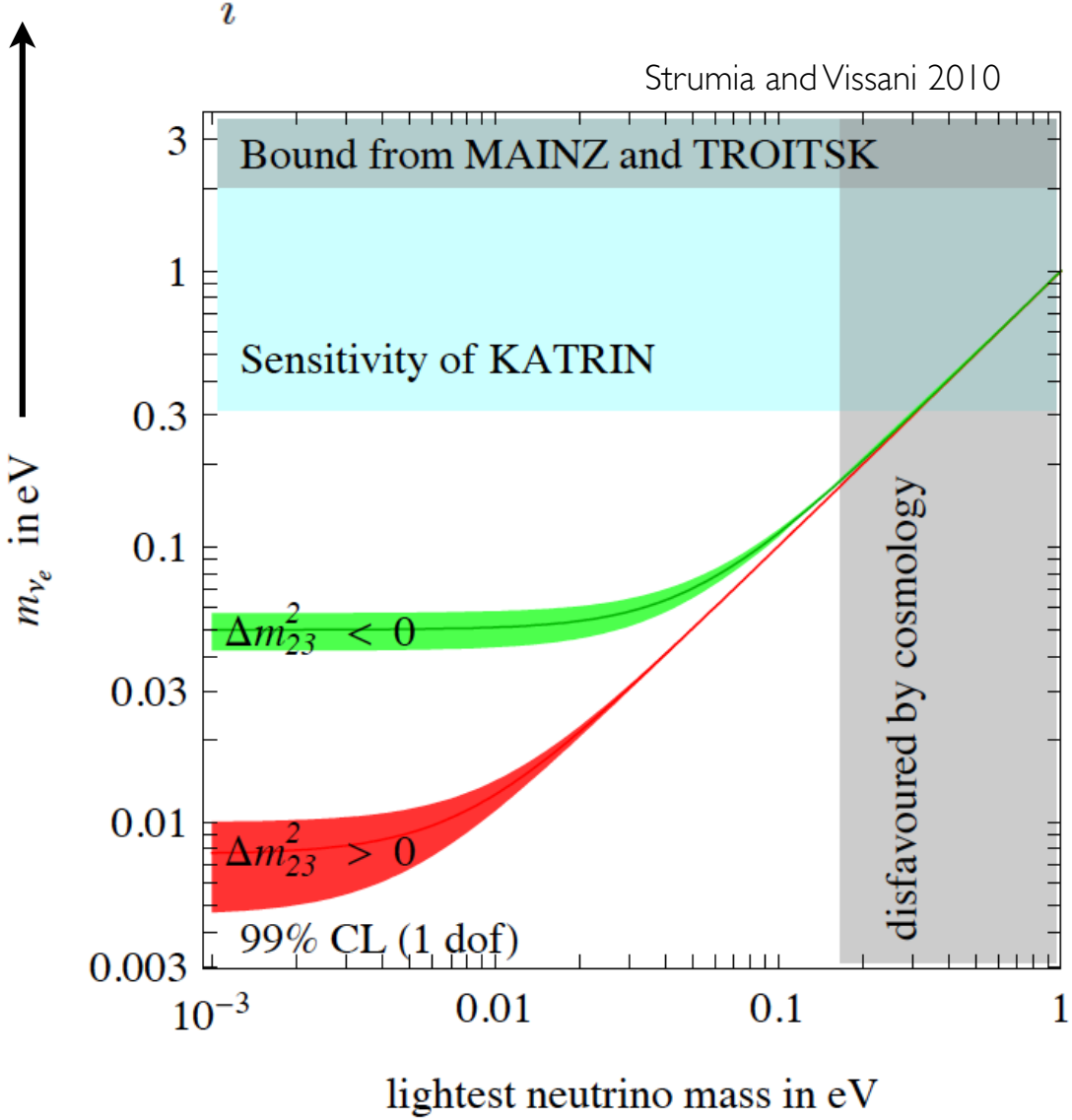
A Gigantic Spectrometer



What does KATRIN actually measure?

$$m_{\nu_e}^2 = \sum_i |V_{ei}^2| m_i^2 = \cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}$$

Strumia and Vissani 2010



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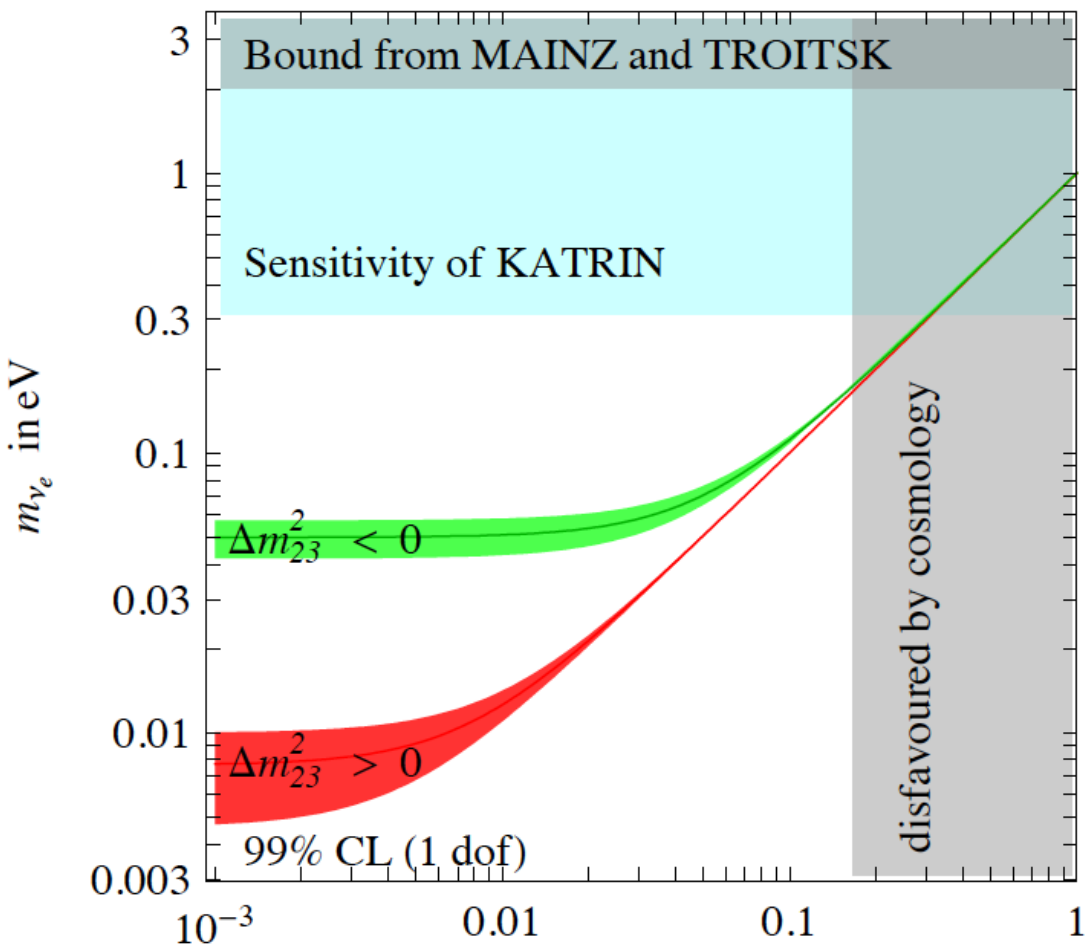

lightest neutrino mass in eV → m_1 or m_3

What does KATRIN actually measure?

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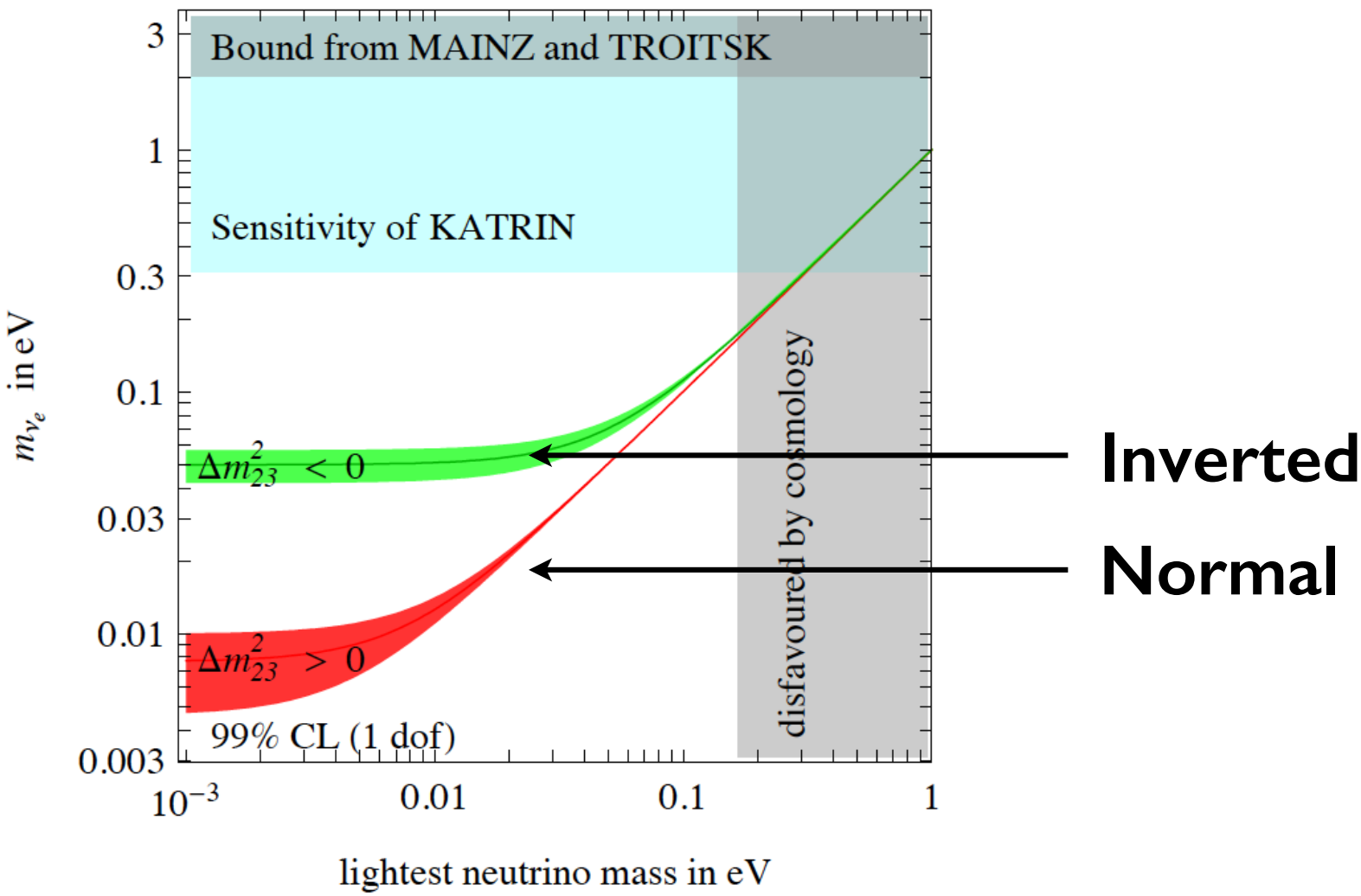
Strumia and Vissani 2010



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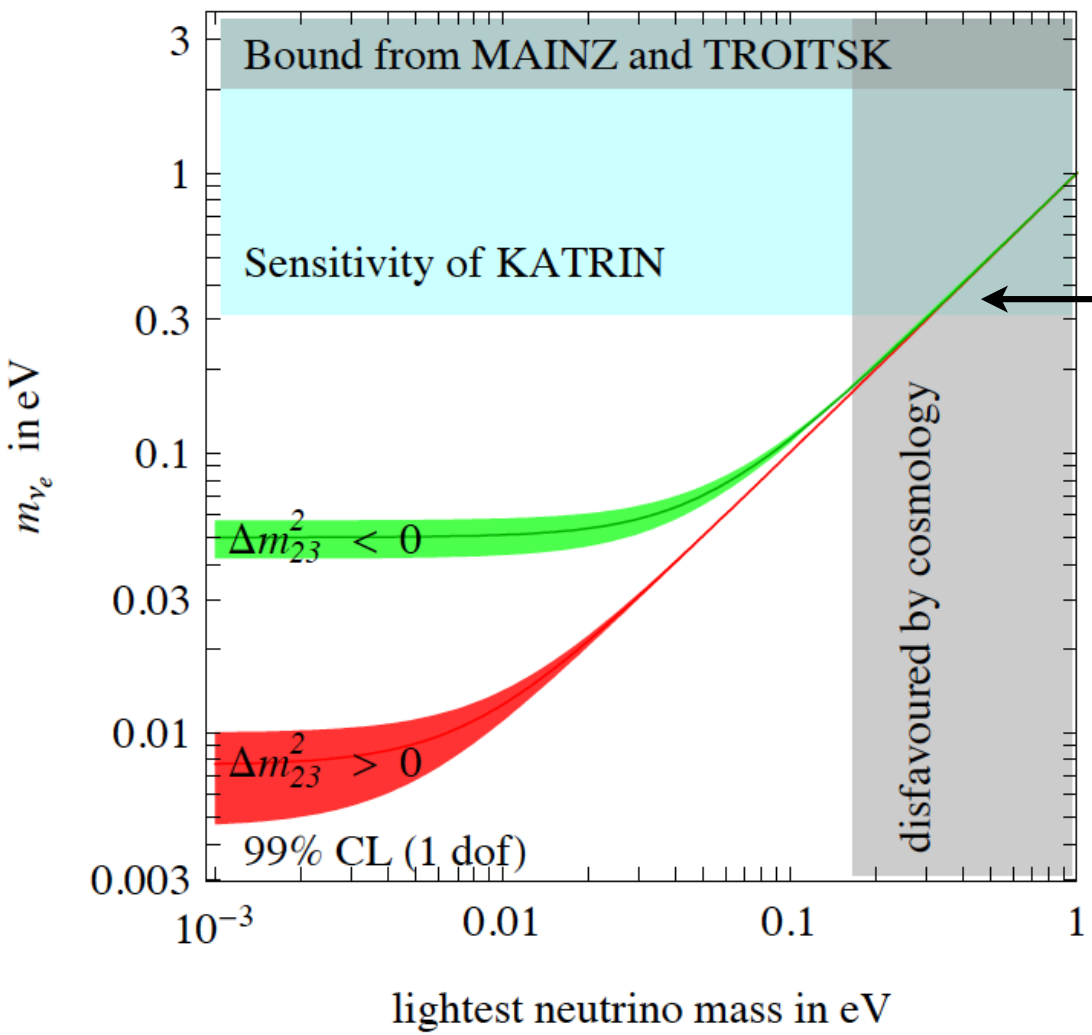
Strumia and Vissani 2010

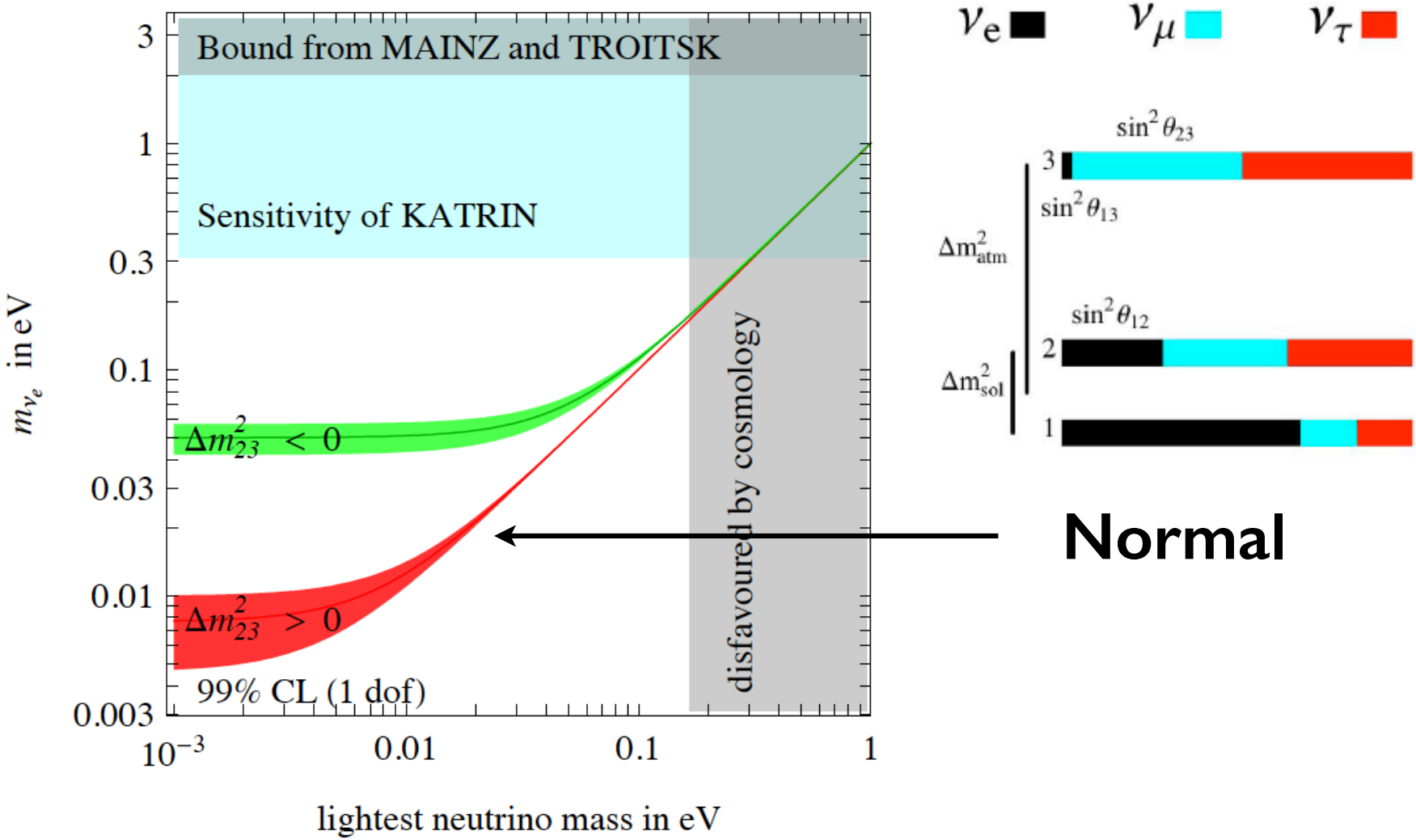


Degenerate (neutrino heavy enough that it does not matter)

What does KATRIN actually measure?

$$m_{\nu_e}^2 = \sum_i |V_{ei}^2| m_i^2 = \cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}$$

Strumia and Vissani 2010



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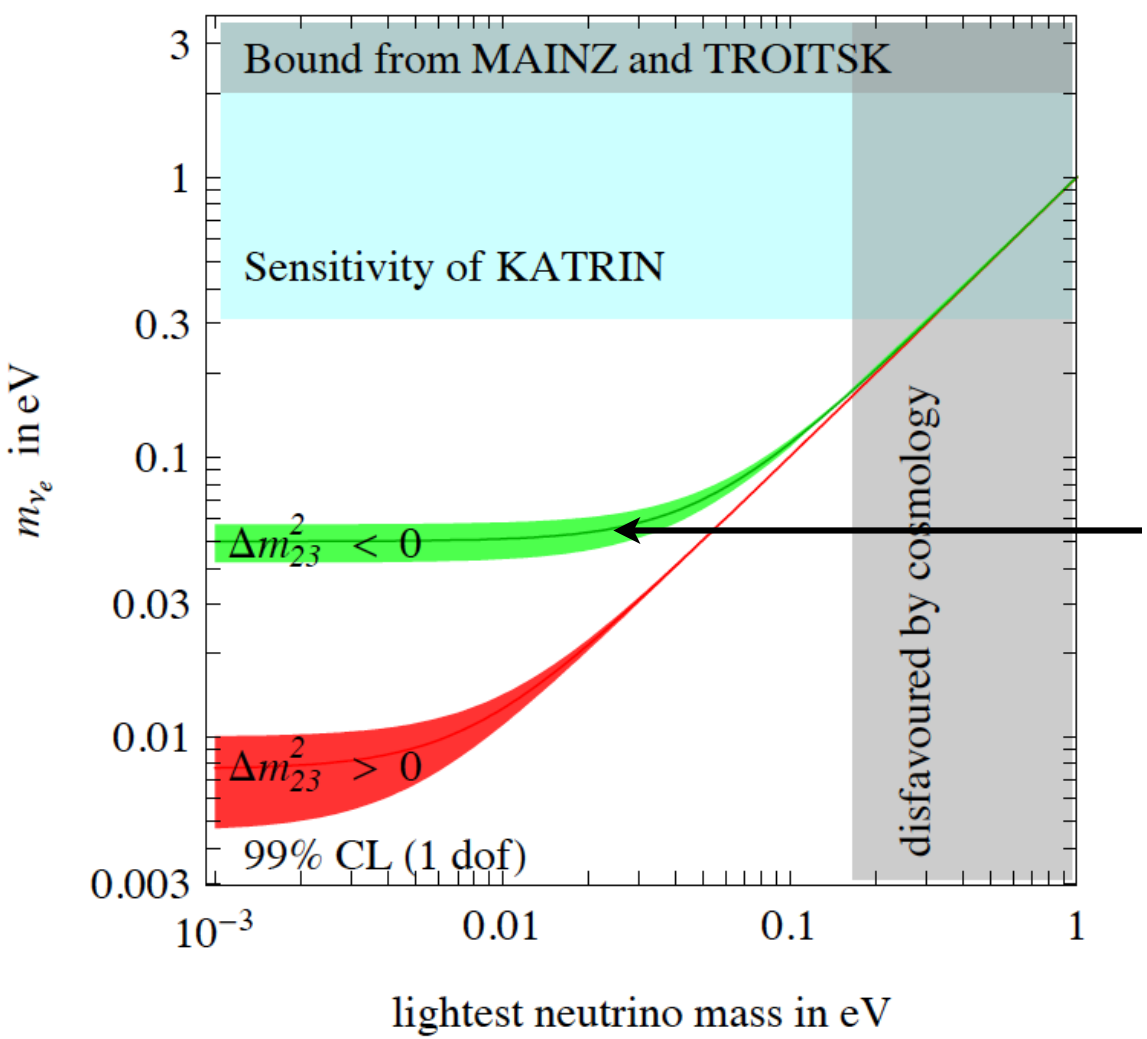
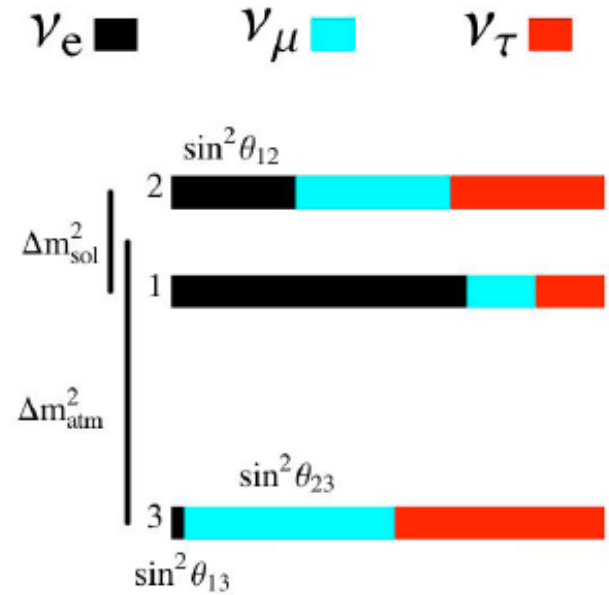
Strumia and Vissani 2010





Inverted

Neutrino mass can be even more complicated.

Dirac Neutrinos

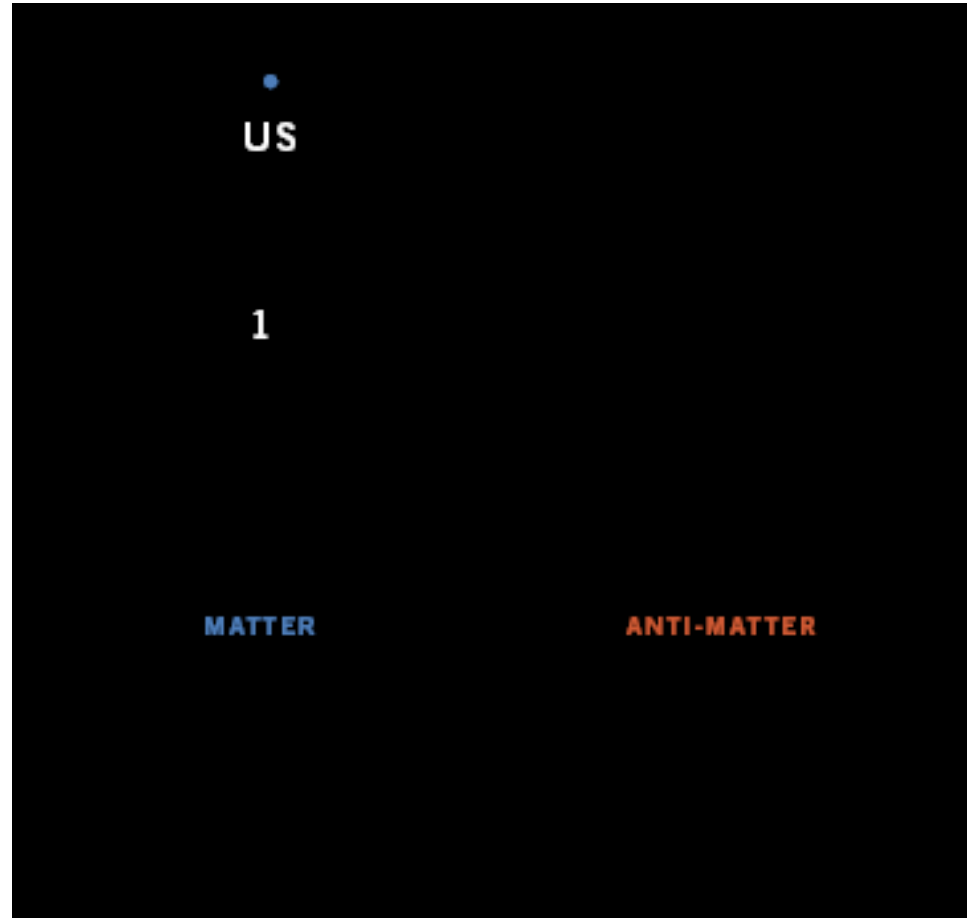
neutrino and antineutrino different particles

Majorana Neutrinos

neutrino and antineutrino different helicity state of the same particle

Why do we like Majorana neutrinos so much?

We have a big problem…



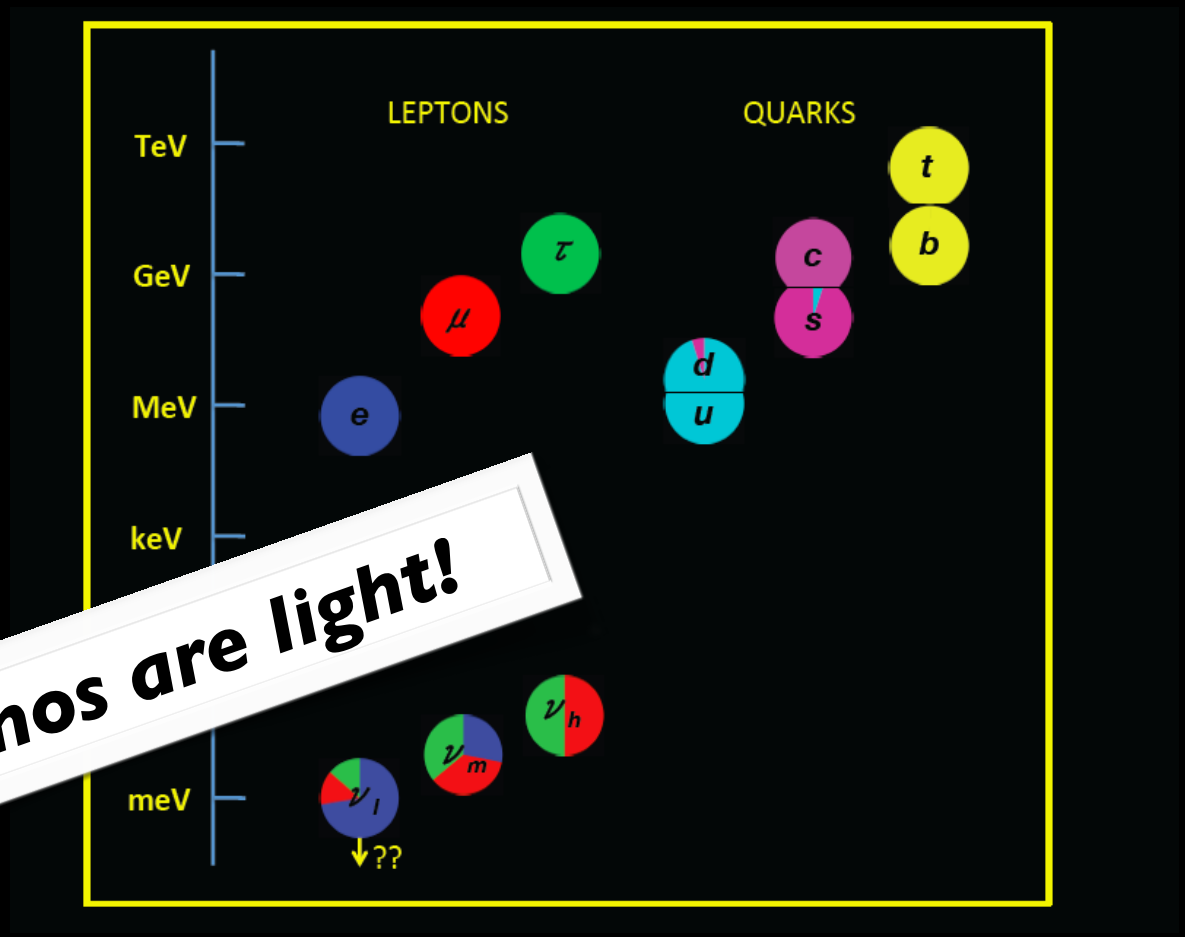
From H. Murayama

Sakharov Conditions

The solution needs…

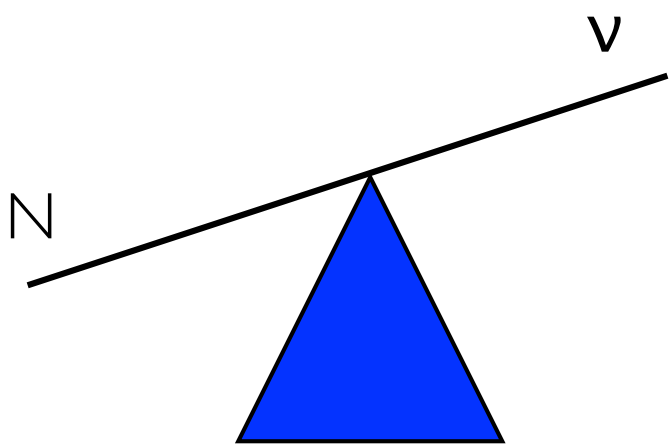
1) *Processes to make more matter than antimatter.* ➡ **Lepton Number Violation**
2) *Reactions that are different for matter and antimatter.* ➡ **C and CP Violation**
3) *Interactions out of equilibrium.*

Masses of the Standard Model Particles



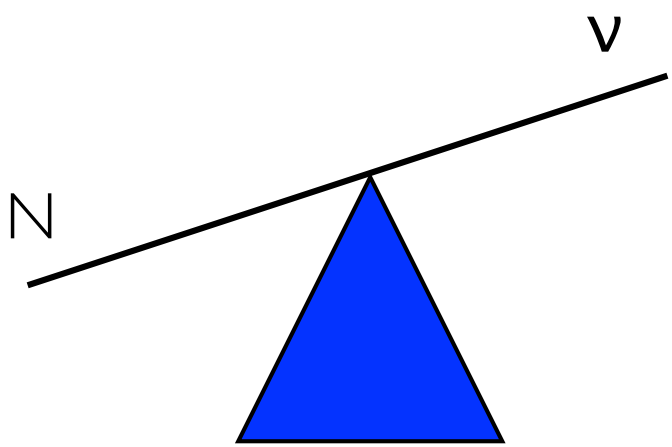
Neutrinos are light!

See-Saw Mechanism



A **big** Majorana mass splits the Dirac neutrino into two neutrinos: the light neutrino **ν** and a heavy neutrino N.

See-Saw Mechanism



The m_D is normal Dirac mass and should be about the same order as the quarks or charged leptons.

$$L_m = -\frac{1}{2}\frac{m_D^{\,2}}{m_R}\overline{\nu}\nu - \frac{1}{2}m_R\overline{N}N$$

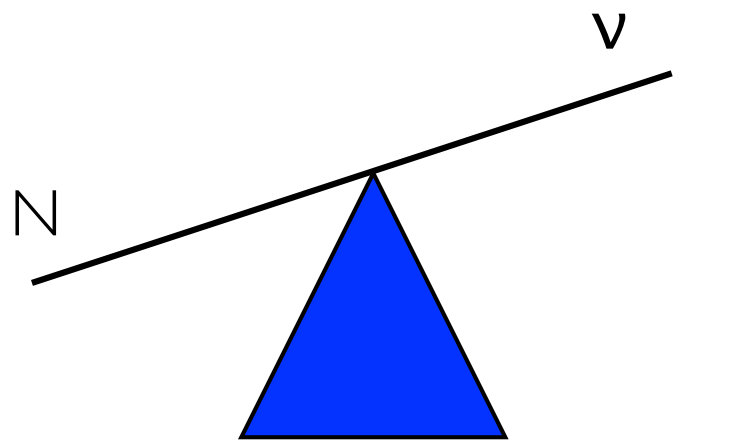
The m_R is the Majorana mass and can be much heavier.

Our Standard Light ν

Its much heavier big sister

And now for some hand waving.....

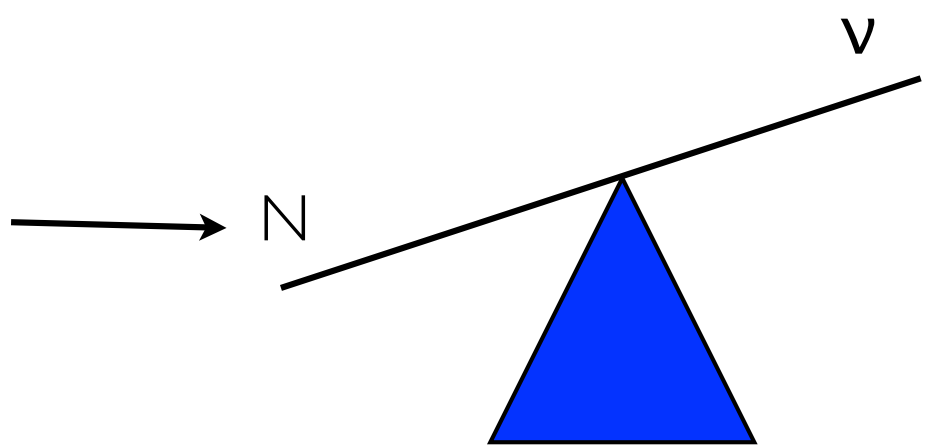
Its these that we can make and detect.



And now for some hand waving.....

Its these that we can make and detect.

Its these guys that will be made in the Big Bang and it's CP Violation and Lepton number violation in their decays that can be turned into the matter antimatter asymmetry.



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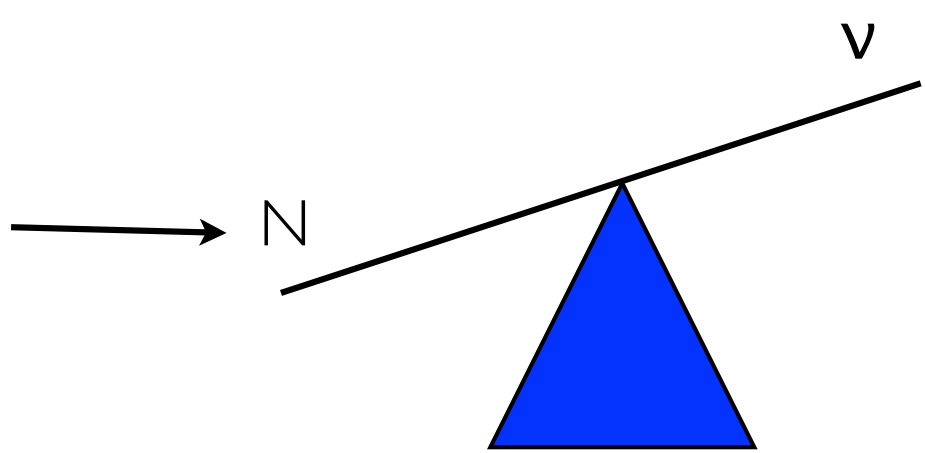
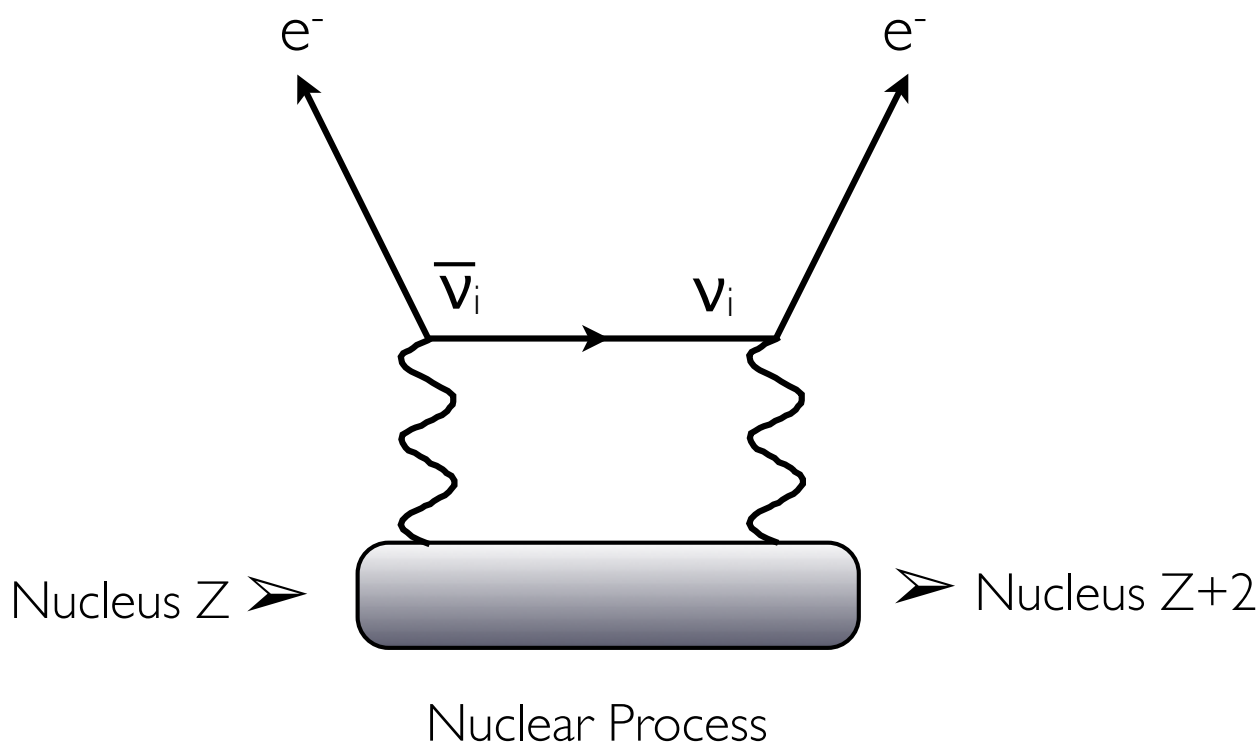


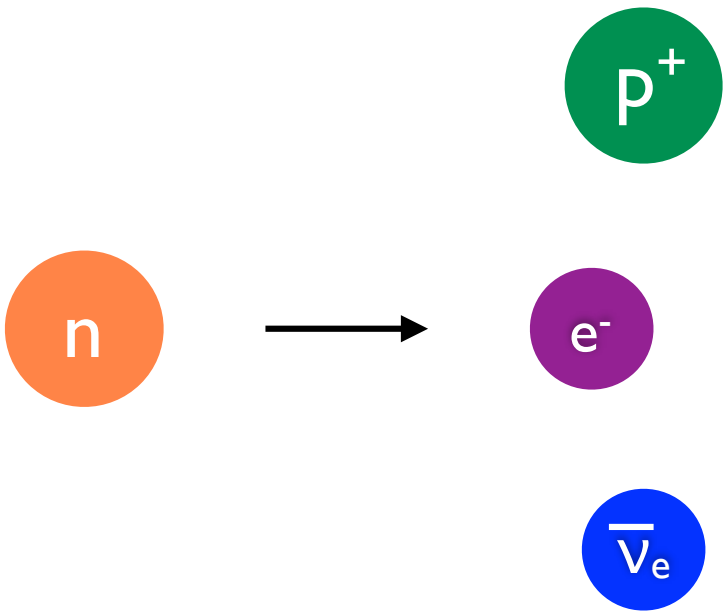
So if we detect CP violation and Lepton number violation in the ν then it would be difficult to construct a theory of the N that do not have the same properties.

How do we find out if neutrinos are Majorana?

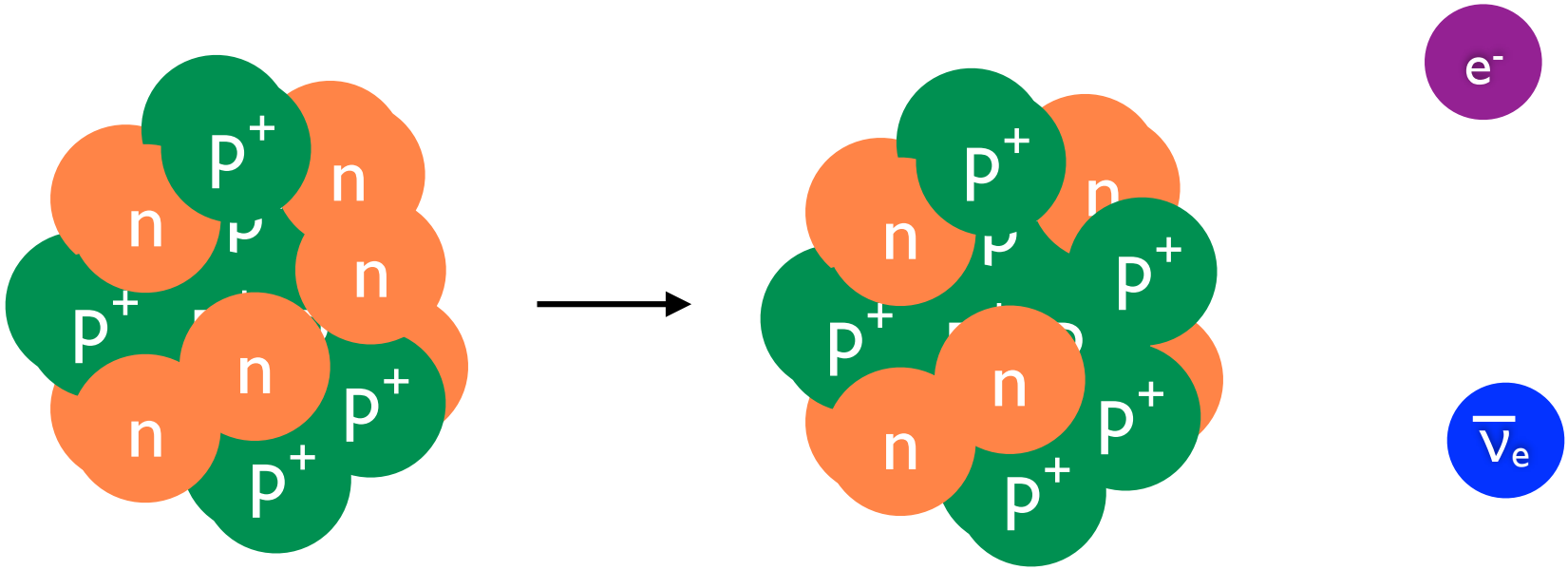


Neutrinoless Double Beta Decay

This is beta decay.



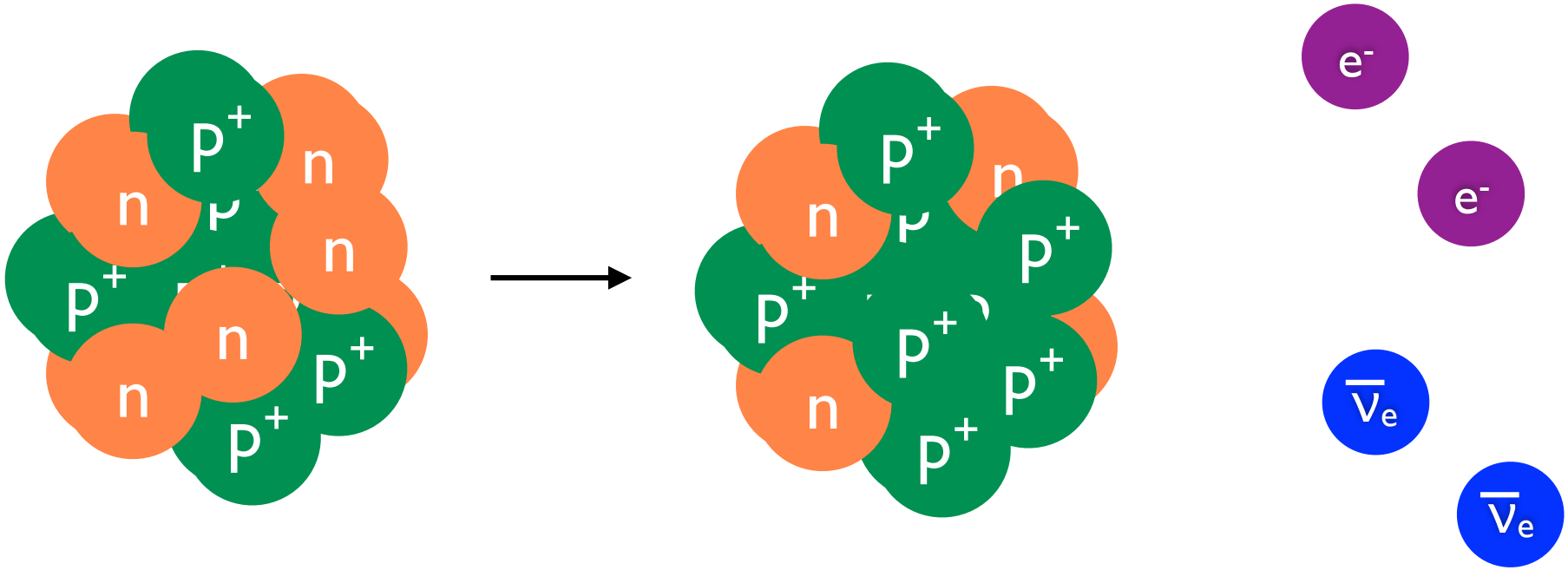
It usually takes place in a nucleus.



Z=number of protons
A=number of neutrons plus protons

Z+1
A=same

This is double-beta decay.

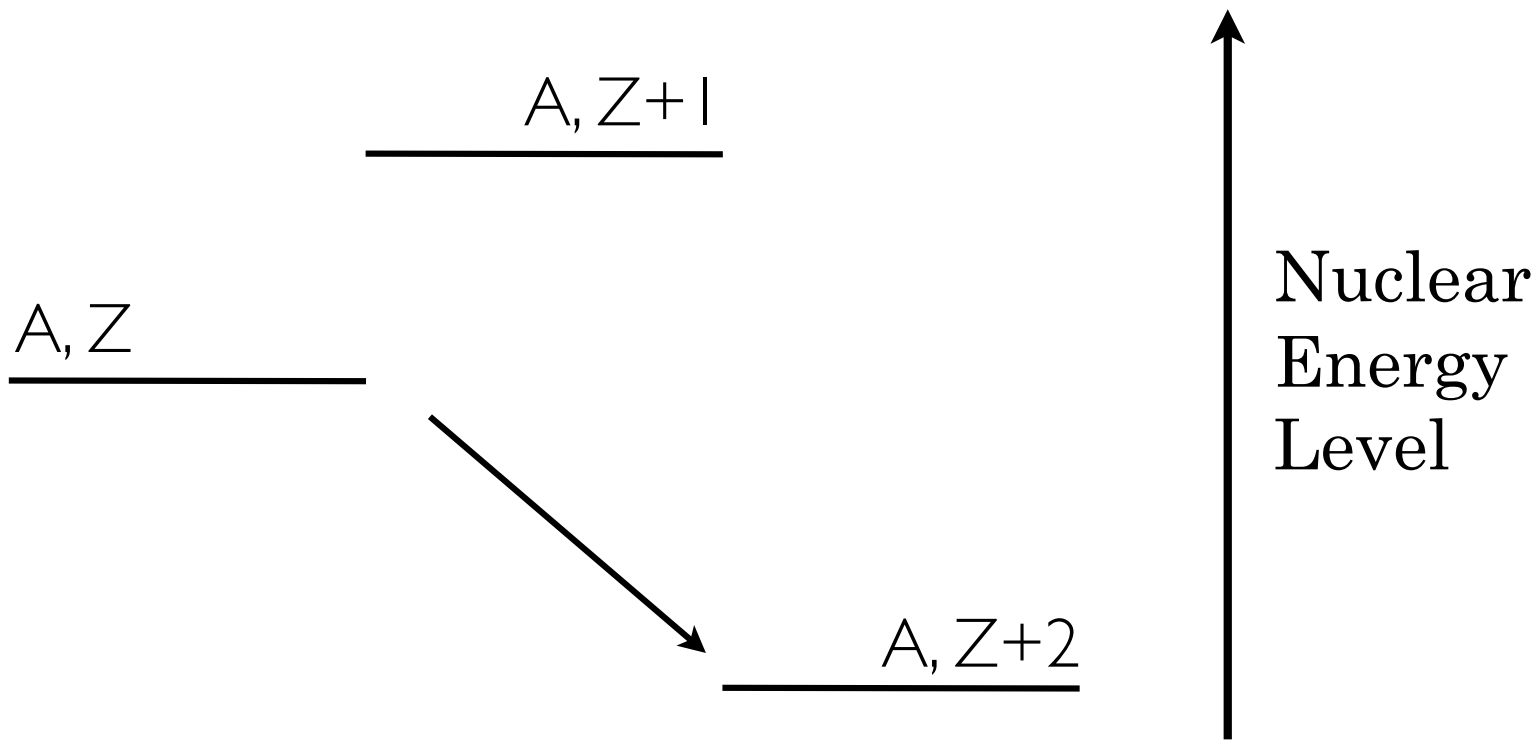


Z+2
A=same

Change in number of leptons is zero.

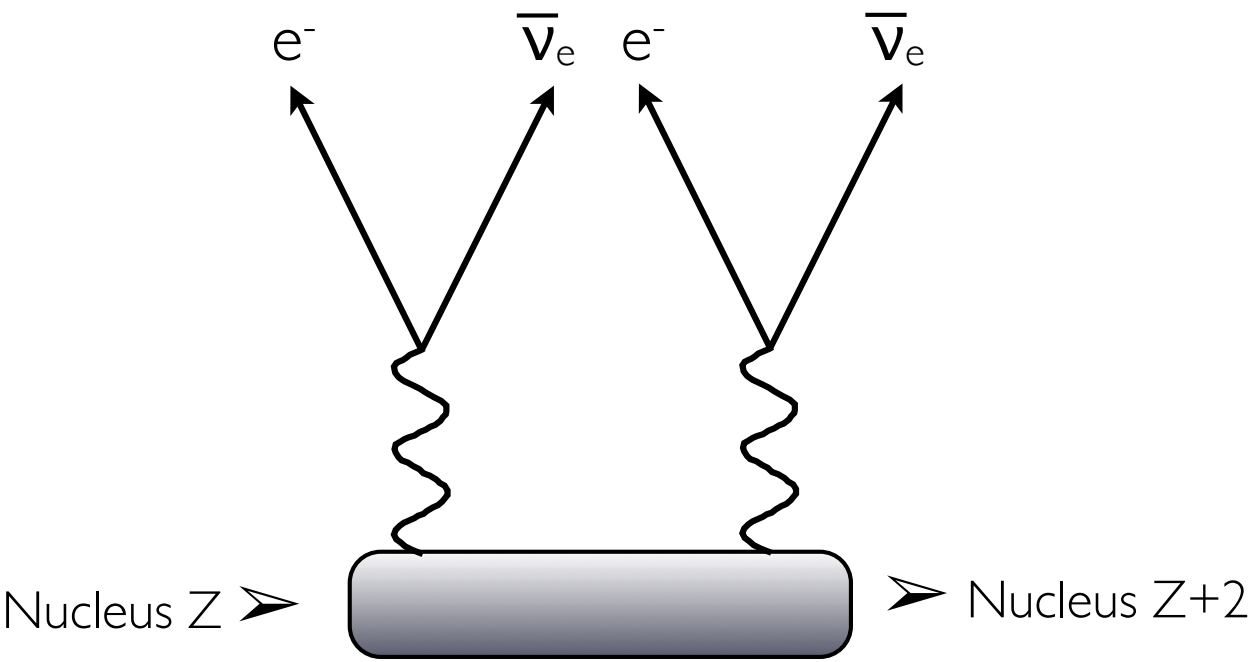
Double Beta Decay

Due to energy conservation some nuclei can't decay to their daughter nucleus, but can skip to their "granddaughter" nucleus.



The Standard Model Process

This process is completely allowed and the rate was first calculated by Maria Goeppert-Mayer in 1935.

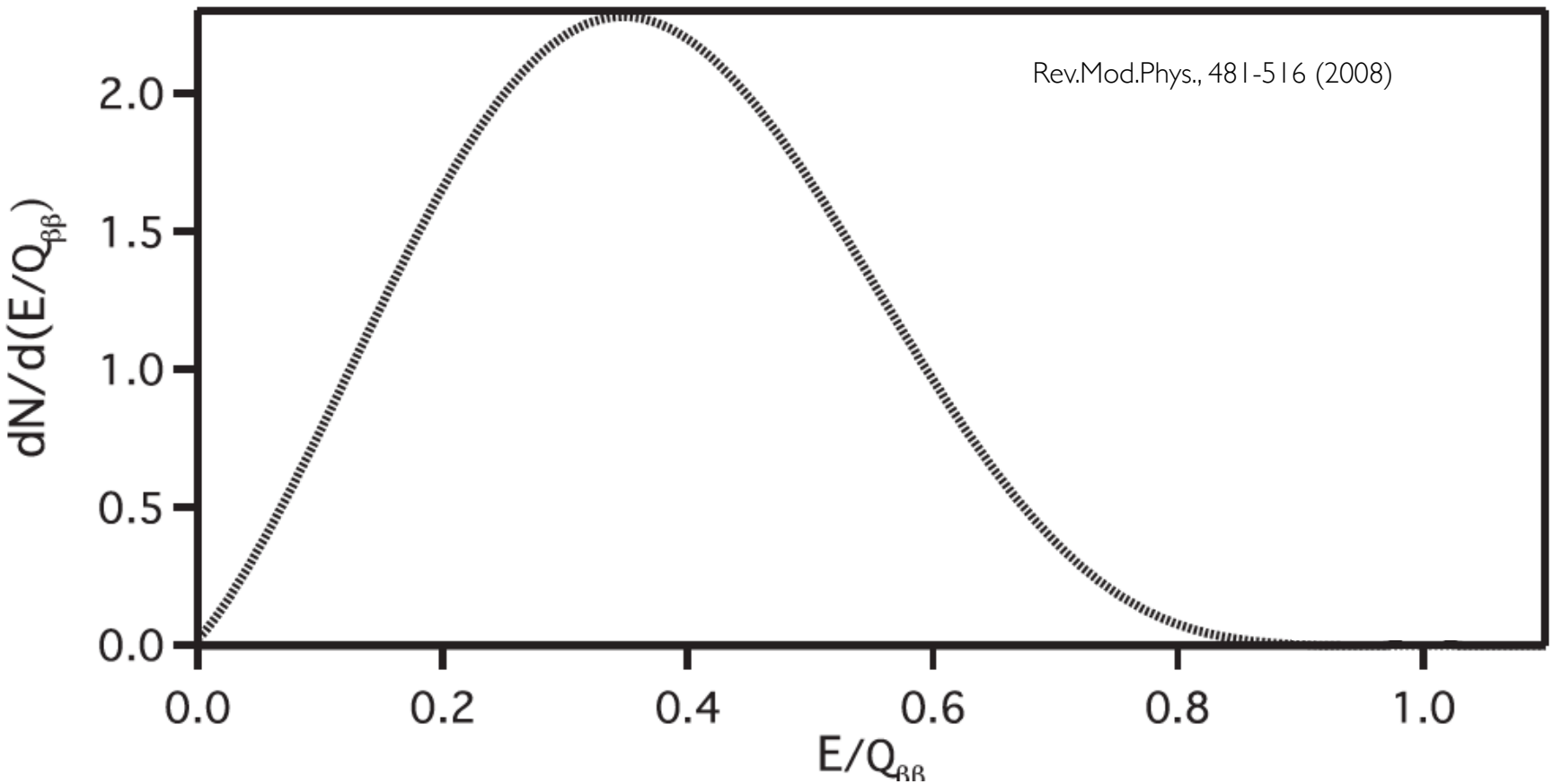


Nuclear Process

Phys. Rev. 48, 512-516 (1935)

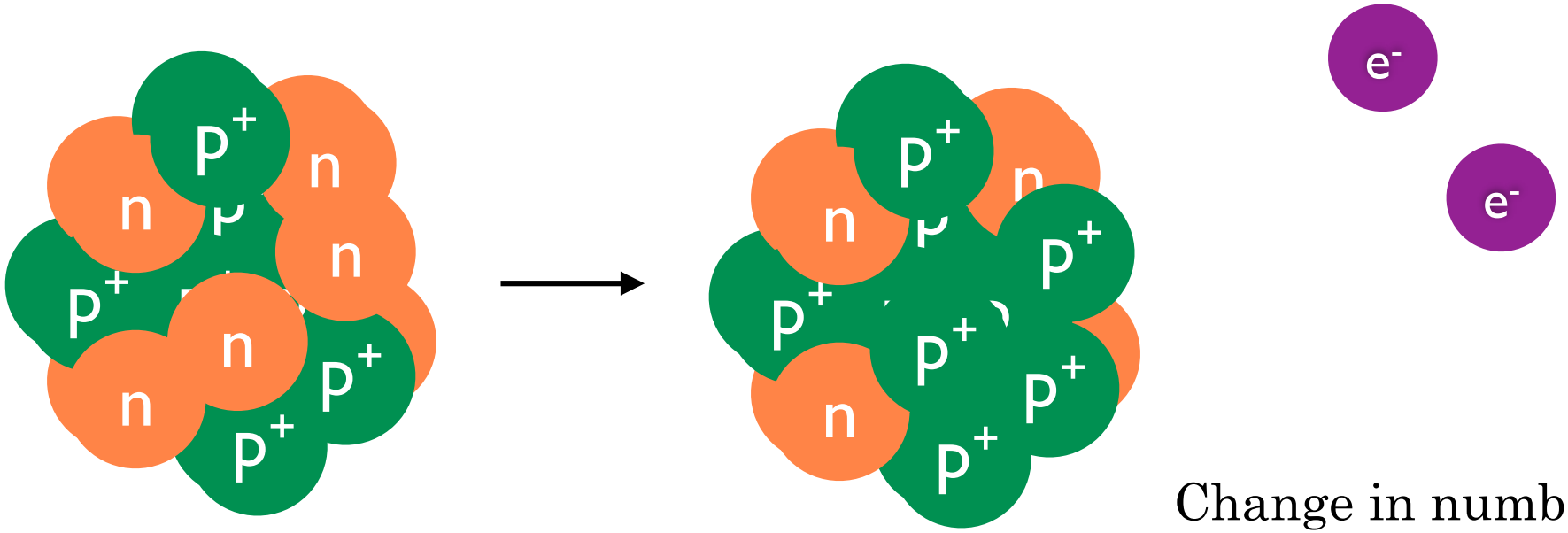
Double Beta Decay

The sum of the electron energies gives a spectrum similar to the standard beta decay spectrum.

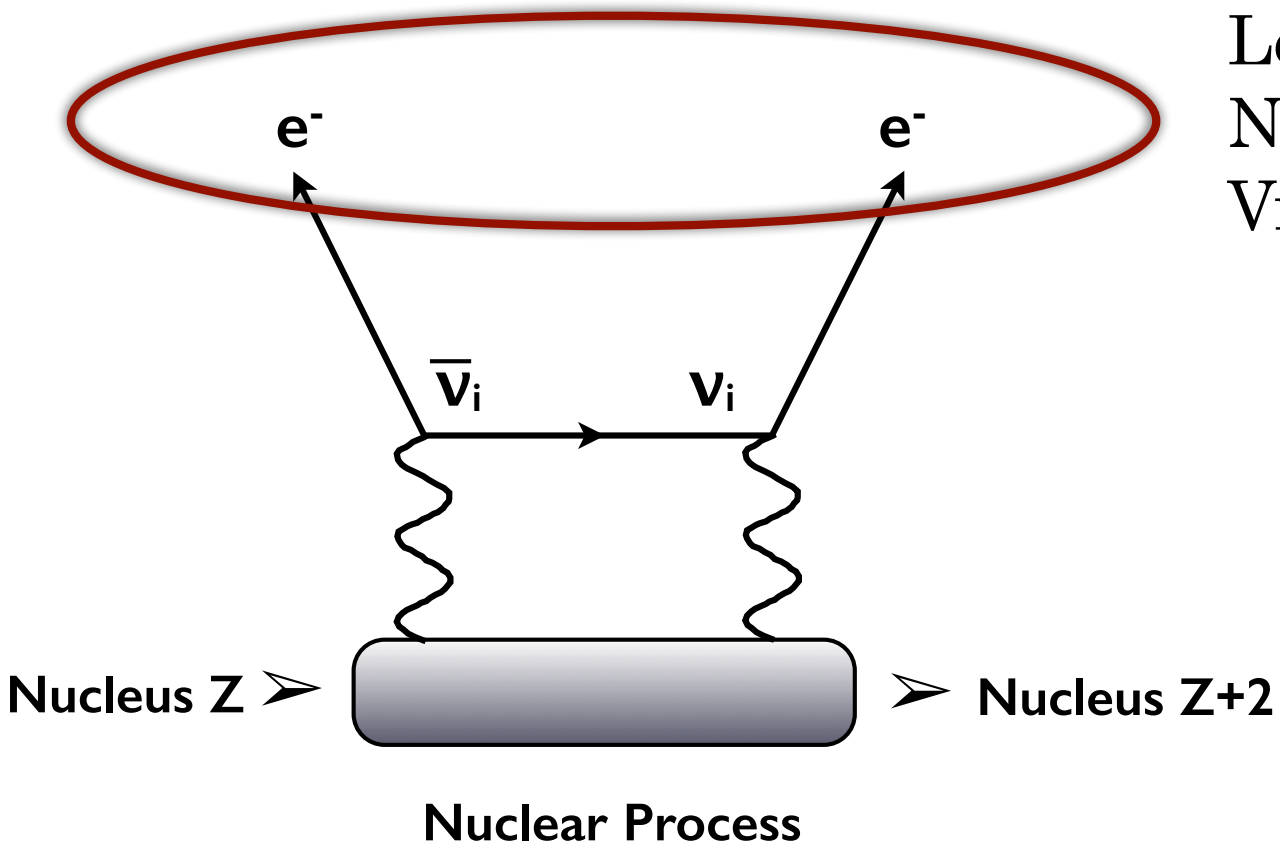


This has been observed in most interesting isotopes.

This is neutrinoless double-beta decay.



Change in number of leptons is plus 2!



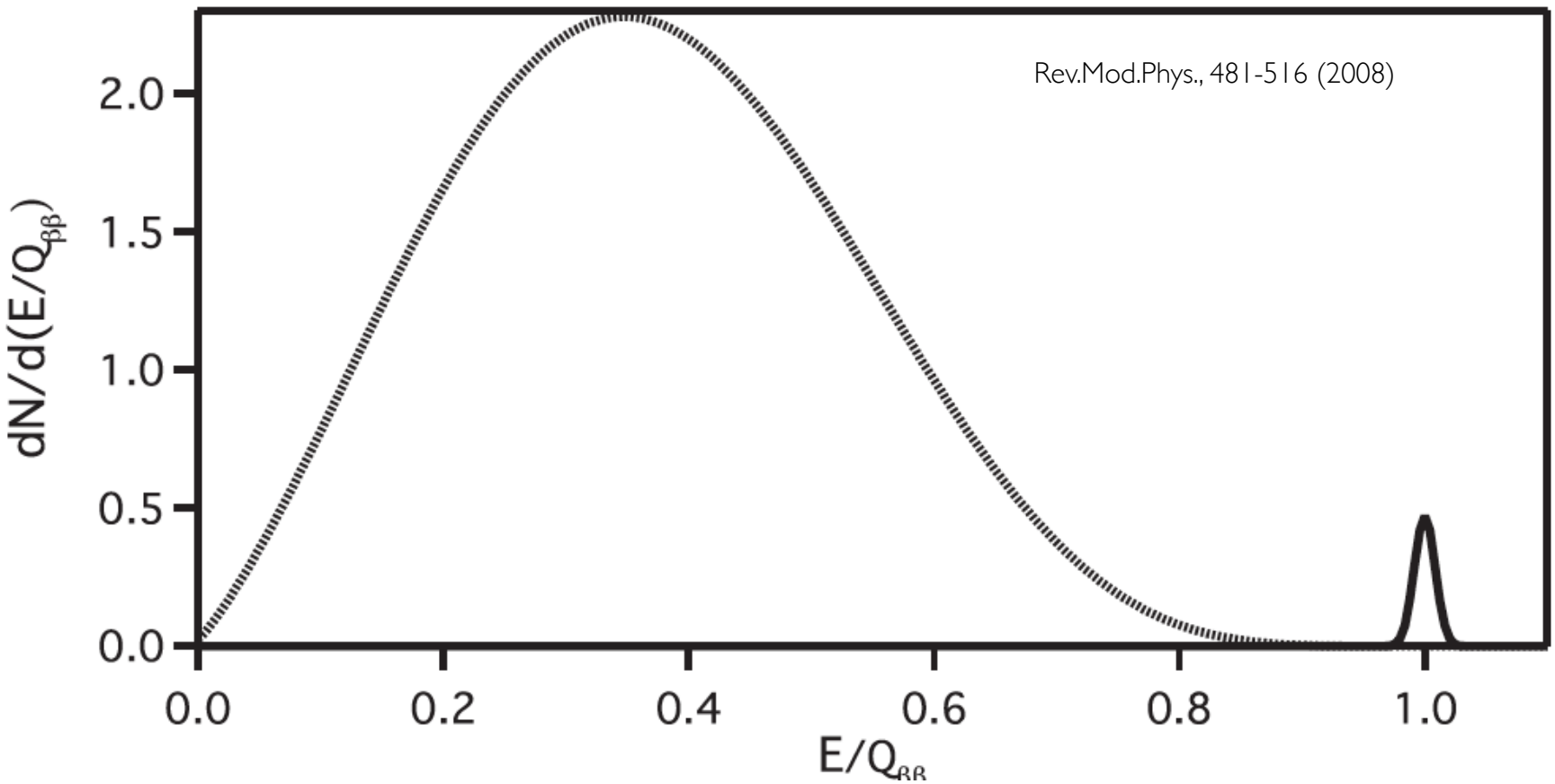
Lepton Number Violation!

Neutrinoless Double Beta Decay

Light Majorana Neutrino Exchange (LMNE)

Double Beta Decay

The sum of the electron energies gives a spike at the endpoint of the 2v double beta decay.



What is measured is a half-life...

The half-life of the neutrinoless decay via LMNE:

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

Phase space factor

- This is a difficult calculation with some dependence on the decay mechanism.
- Notice higher endpoint means faster rate.

Common Candidates:

Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.187%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.533 MeV	34.5%
^{136}Xe	2.479 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%
^{128}Te	0.868 MeV	31.7%

See ATOMIC DATA AND NUCLEAR DATA TABLES 61, 43-90 (1995) for all 69+19!

What is measured is a half-life:

The half-life of the neutrinoless decay via LMNE:

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

Nuclear Matrix Element

This is a VERY difficult calculation with large errors and substantial variation between isotopes...motivates searches with multiple isotopes!

What is measured is a half-life:

The half-life of the neutrinoless decay via LMNE:

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

Effective Majorana
Mass of the neutrino

Electron Neutrino Mass:

$$m_{\nu_e}^2 = \sum_i |V_{ei}^2| m_i^2 = \cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}$$

Effective Majorana Mass:

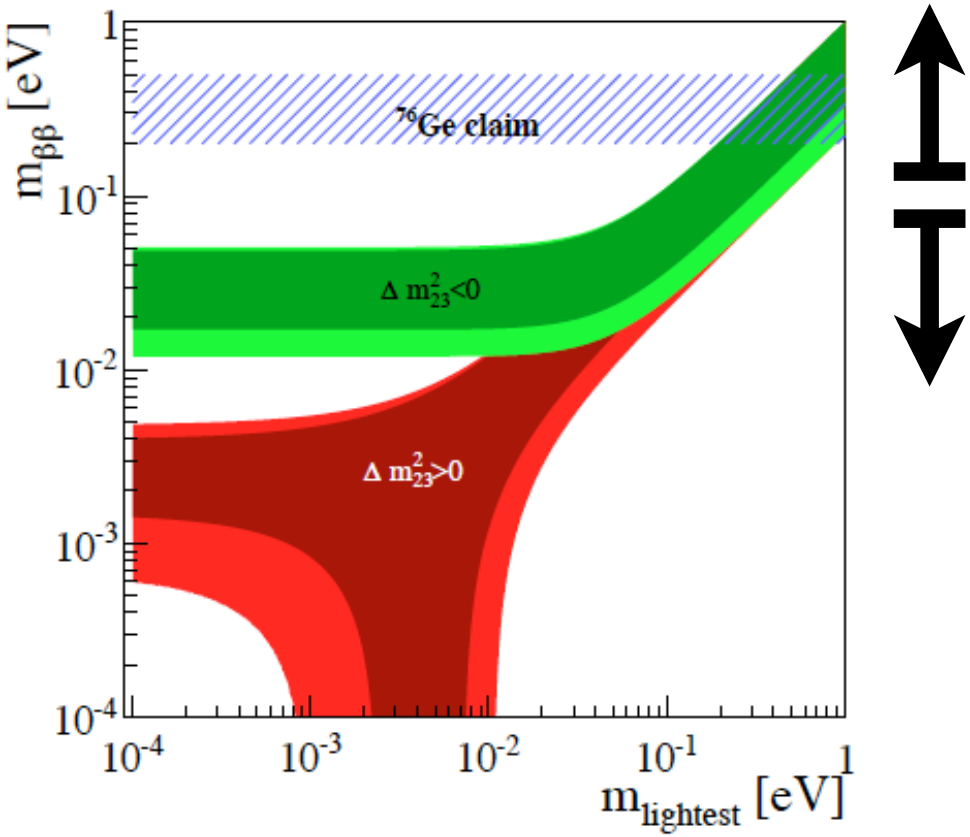
$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3\sin^2\theta_{13}$$

Two more phases!

Double Beta Decay Parameter Space:

Double Beta Decay Visualizing the Equations:

$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 \sin^2\theta_{13}$$



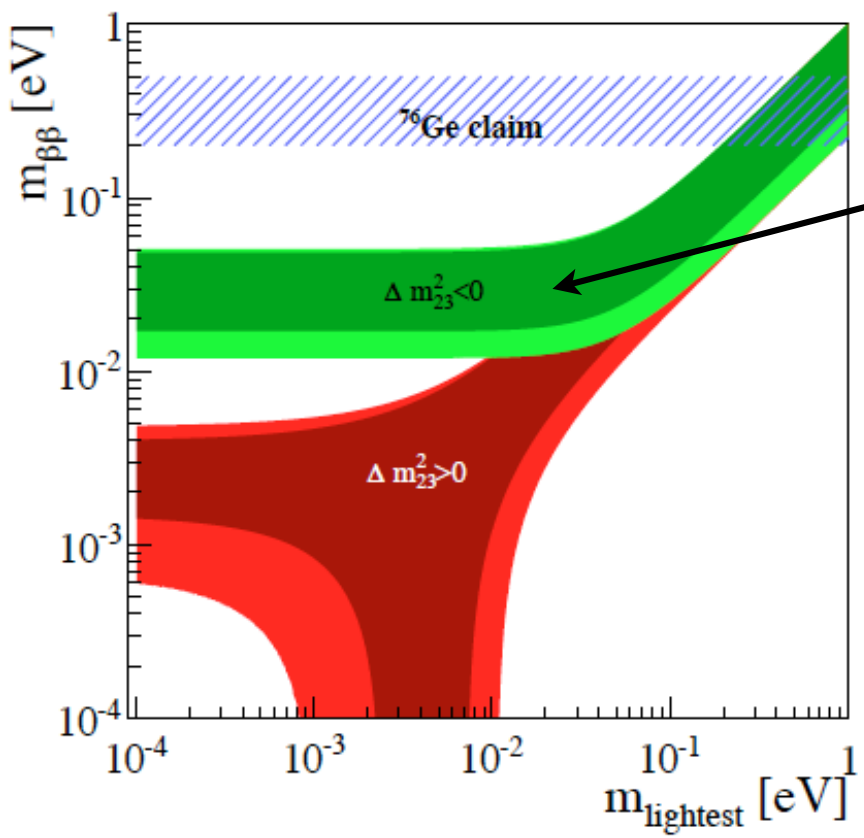
excluded

more sensitive experiments needed

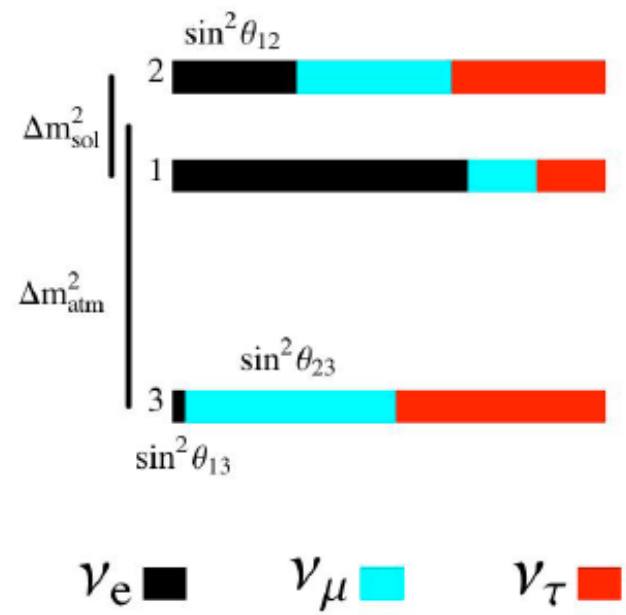
As experiments become more sensitive they push down in this parameter space excluding larger masses.

Double Beta Decay Visualizing the Equations:

$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 \sin^2\theta_{13}$$

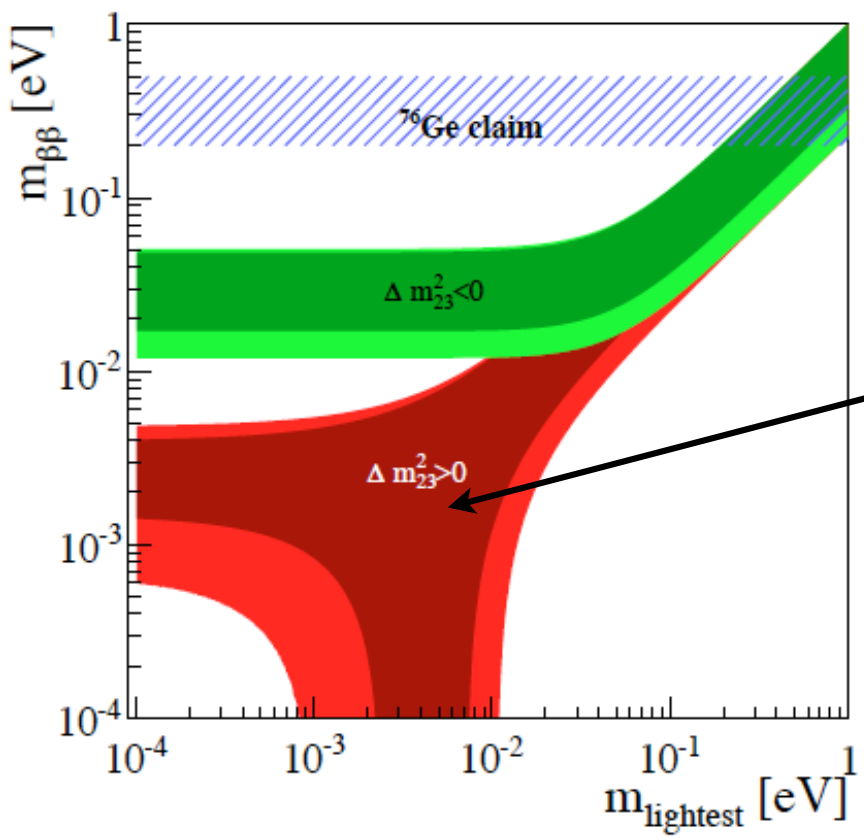


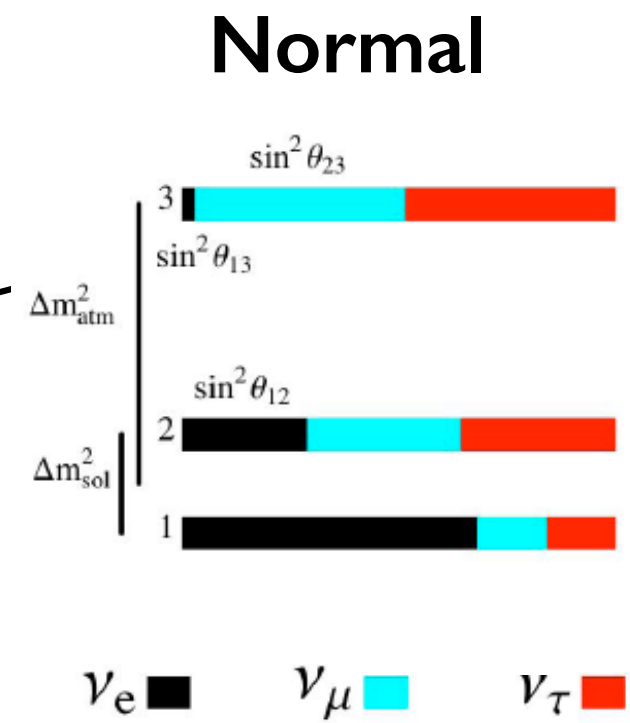
Inverted



Double Beta Decay Visualizing the Equations:

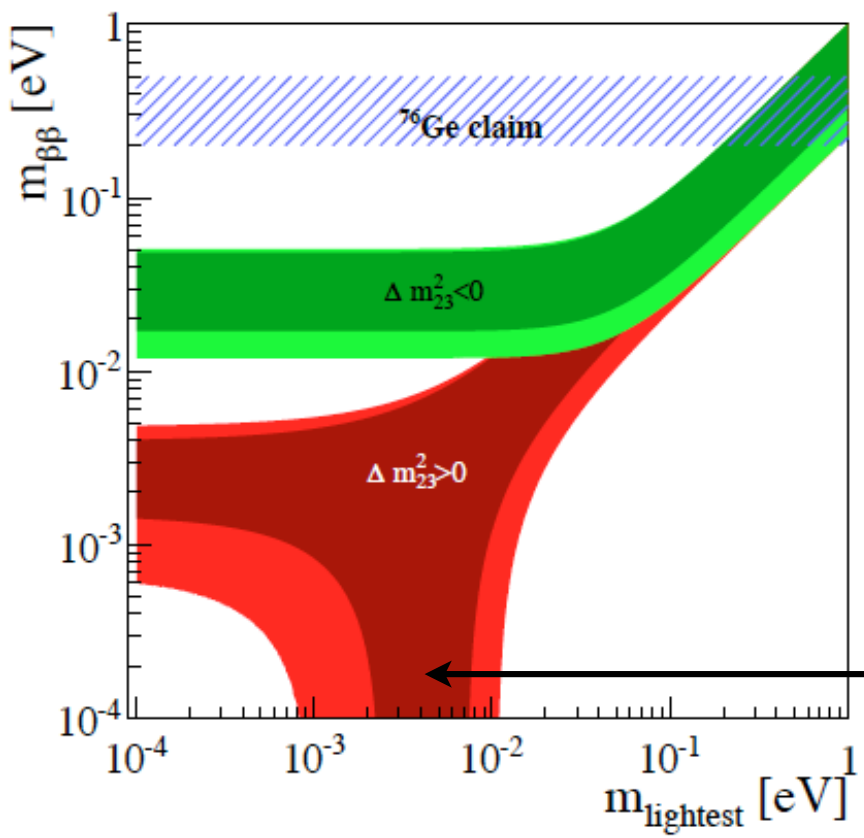
$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 \sin^2\theta_{13}$$





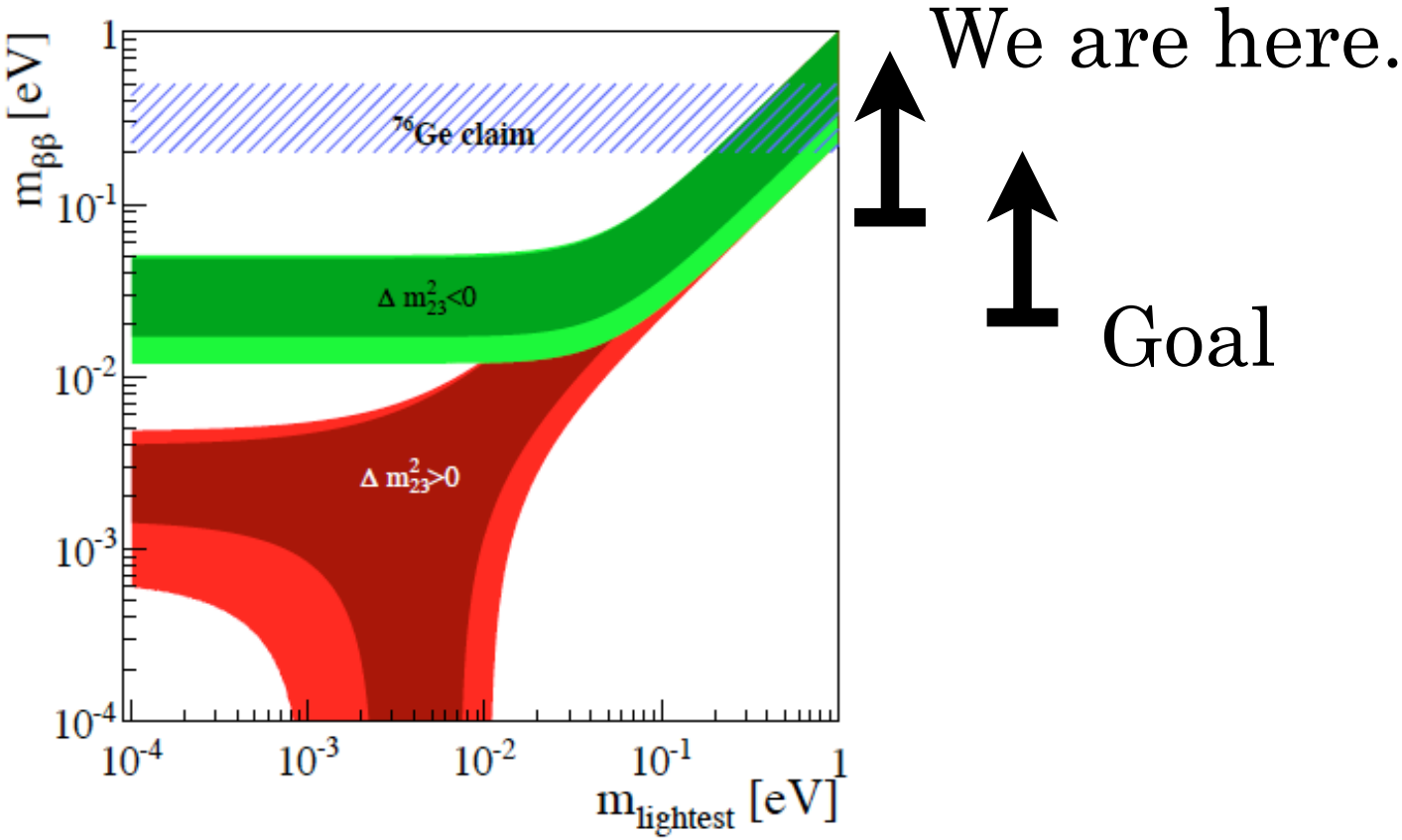
Double Beta Decay Visualizing the Equations:

$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 \sin^2\theta_{13}$$

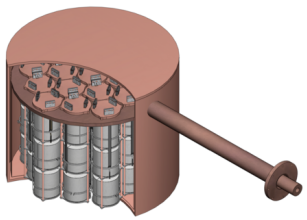


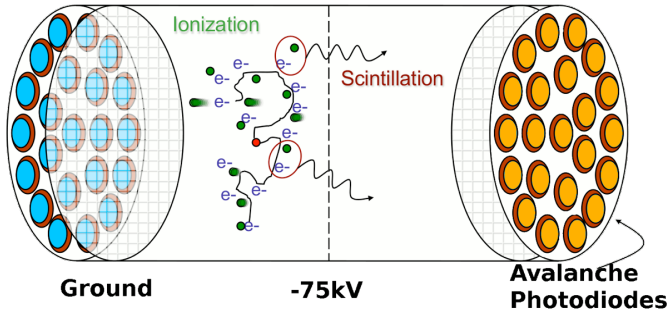
The dark part of the width of these bands is real and if nature is cruel there could be some very nasty interference.

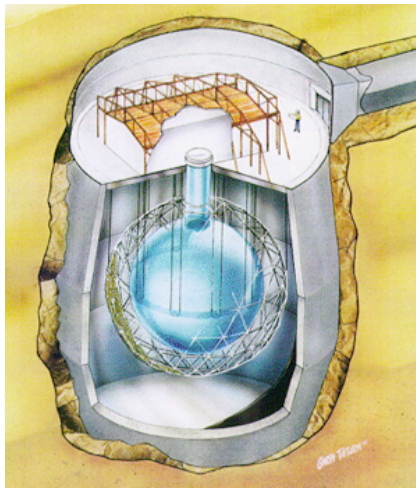
Goal: Definitive search in the Inverted Hierarchy (IH)

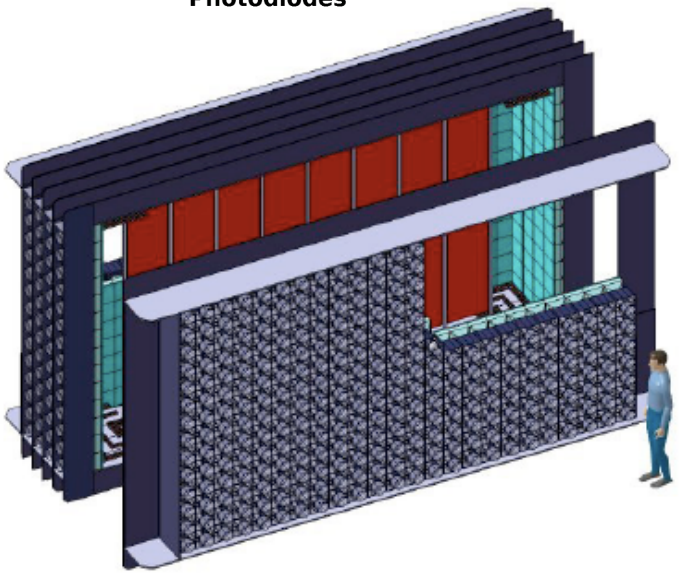


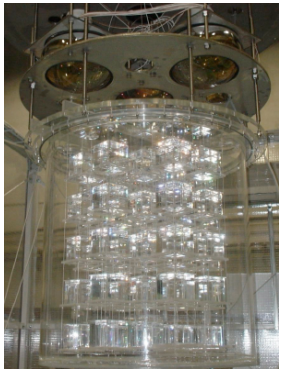
A lot of detector ideas:

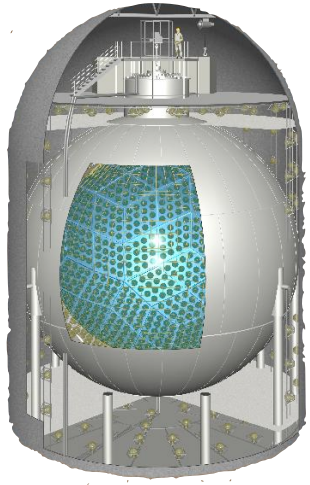


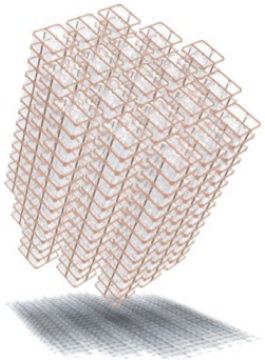


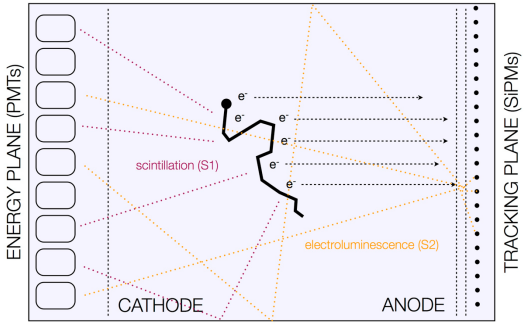




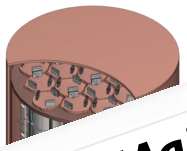




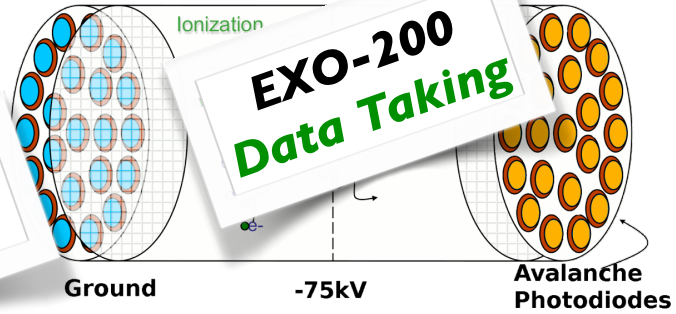




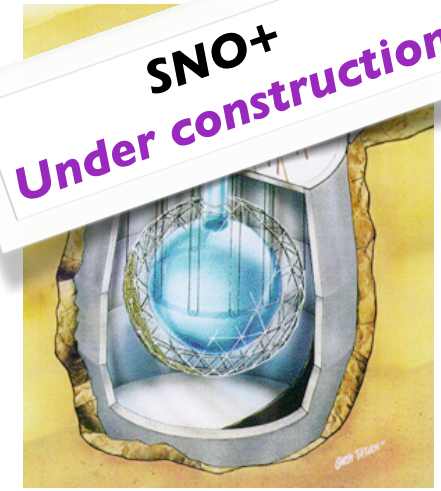
A lot of detector ideas:



Majorana
Data Taking



EXO-200
Data Taking



SNO+
Under construction

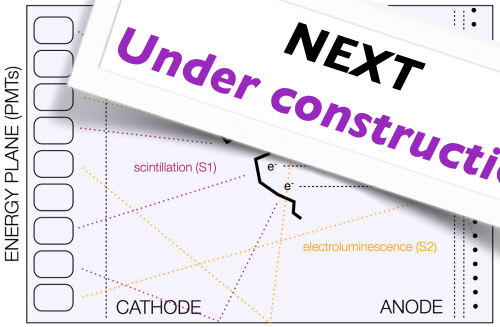
GERDA
Data Taking

SuperNEMO
Under construction

CANDLES
Complete

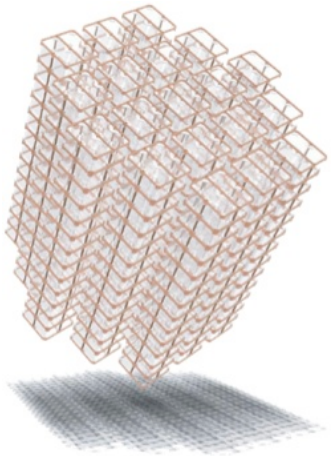
KamLAND-Zen
Data Taking

CUORE
Data Taking



NEXT
Under construction

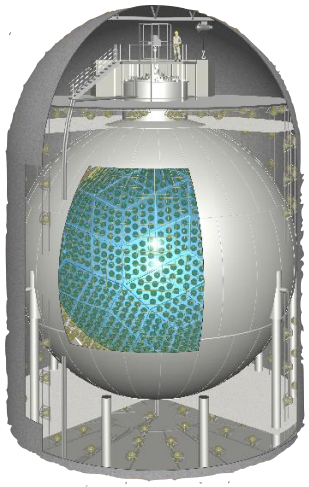
Good
Energy
Resolution



Bolometers

More Difficult
to make big.

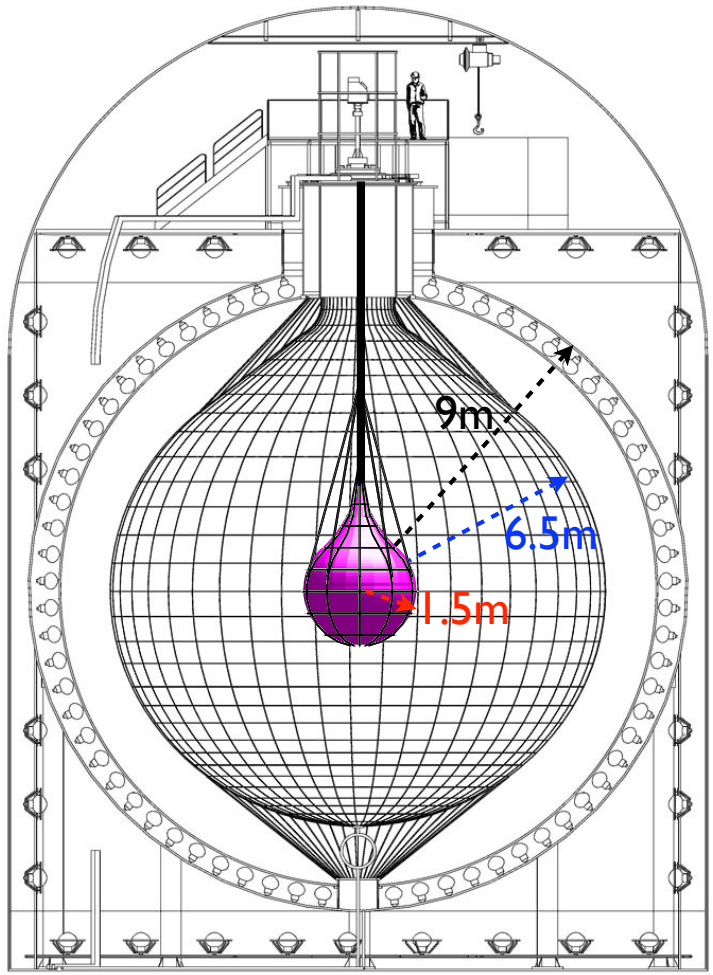
Good
at Size



Scintillator

Bad Energy
Resolution

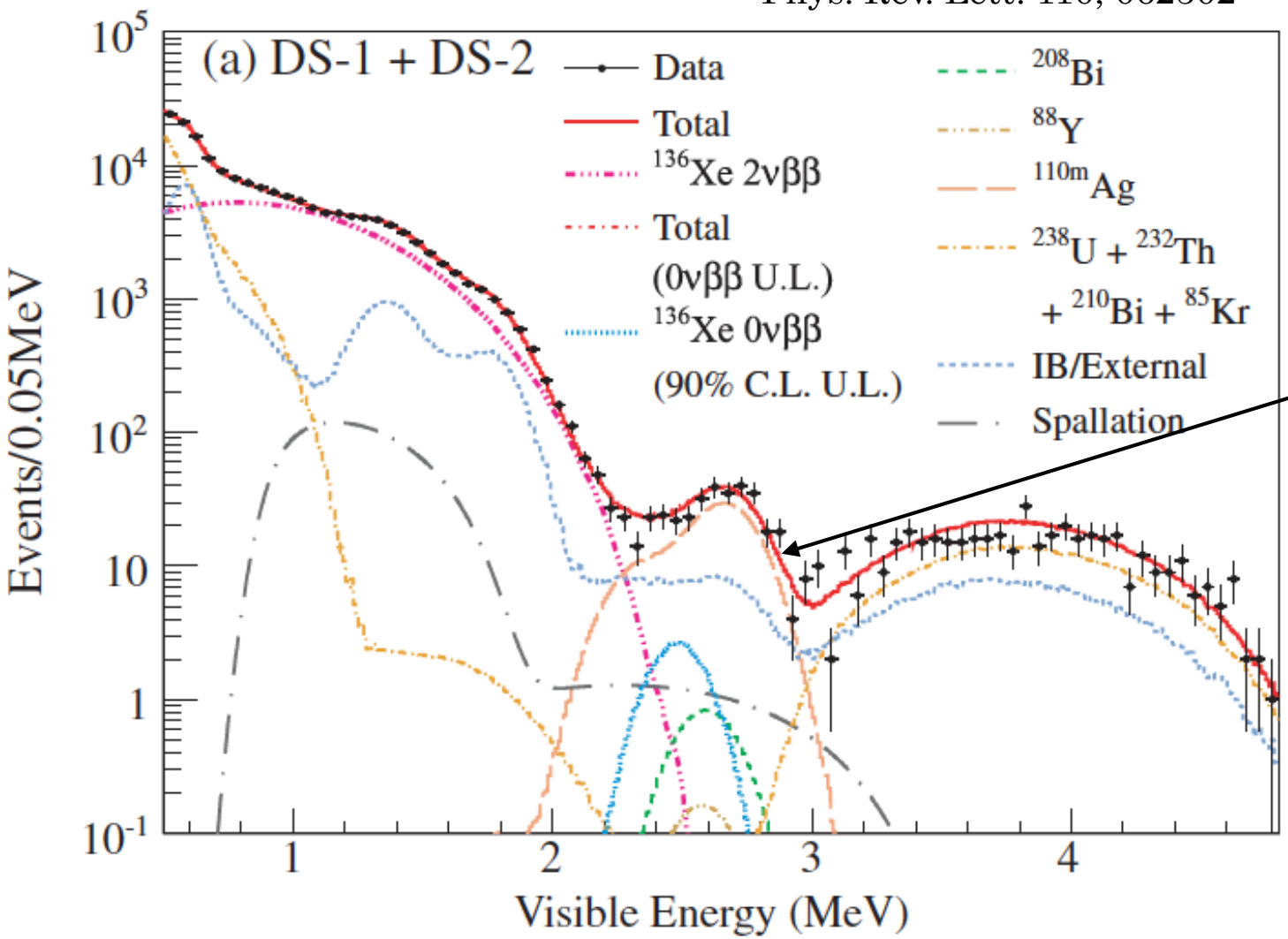
KamLAND-Zen



Phase I: 320 kg 90% enriched ^{136}Xe
Phase II: 380 kg

KamLAND-Zen started in 2011:

Phys. Rev. Lett. 110, 062502

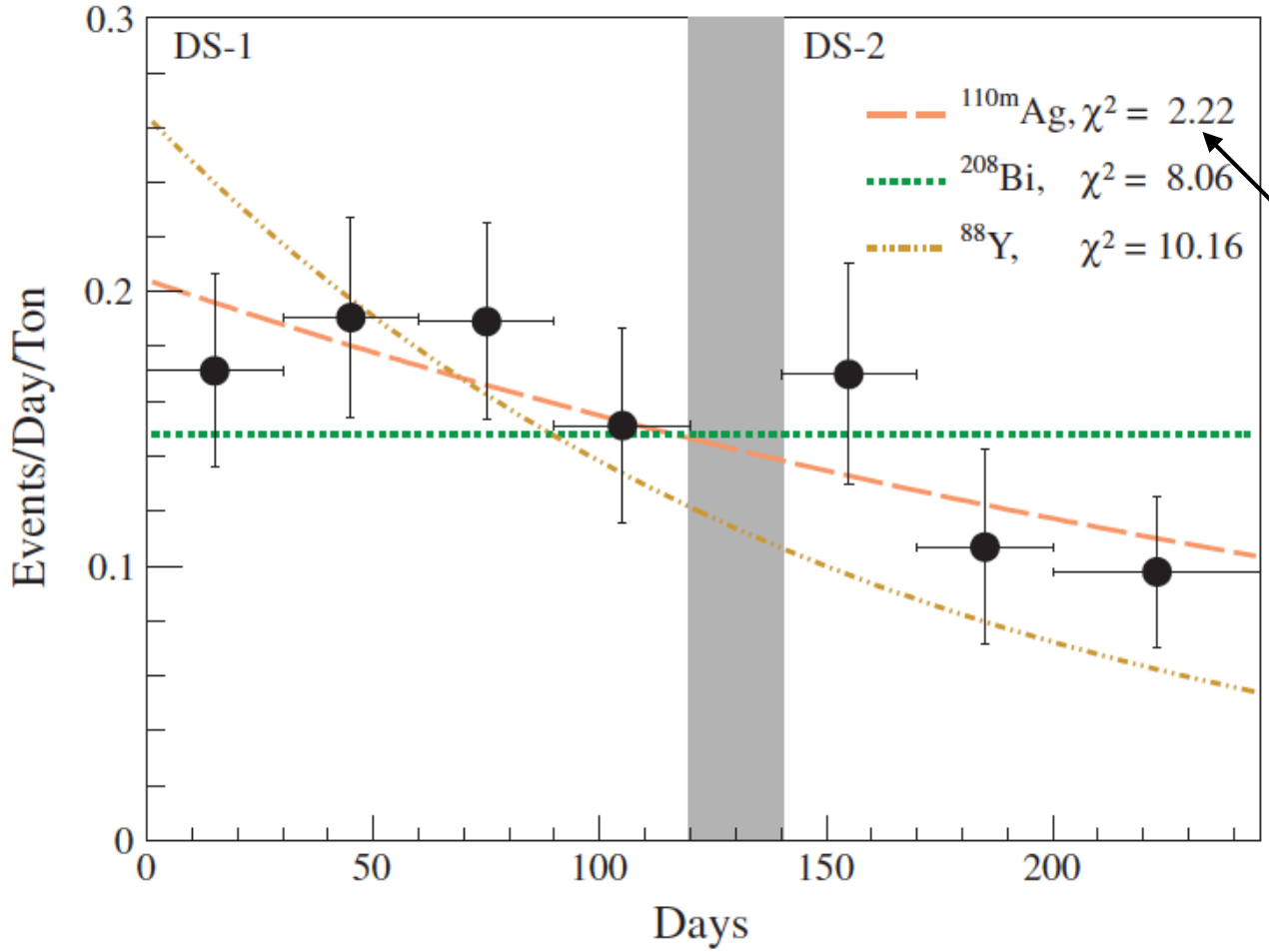


What is this?

Exposure=89.5 kg-years.

KamLAND-Zen started in 2011:

Phys. Rev. Lett. 110, 062502



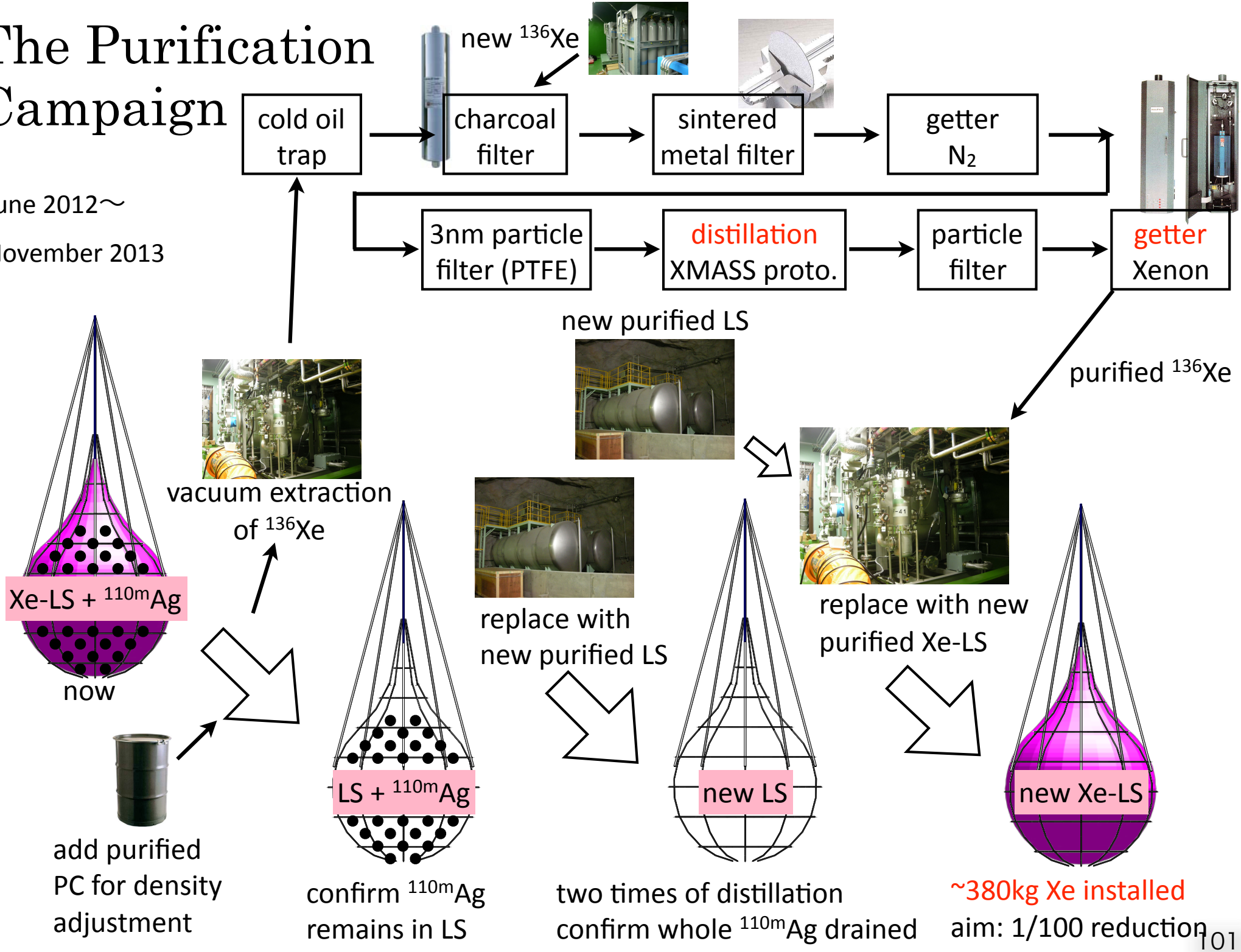
Decay matches a metastable silver isotope which is a common fission product.

Exposure=89.5 kg-years.

The Purification Campaign

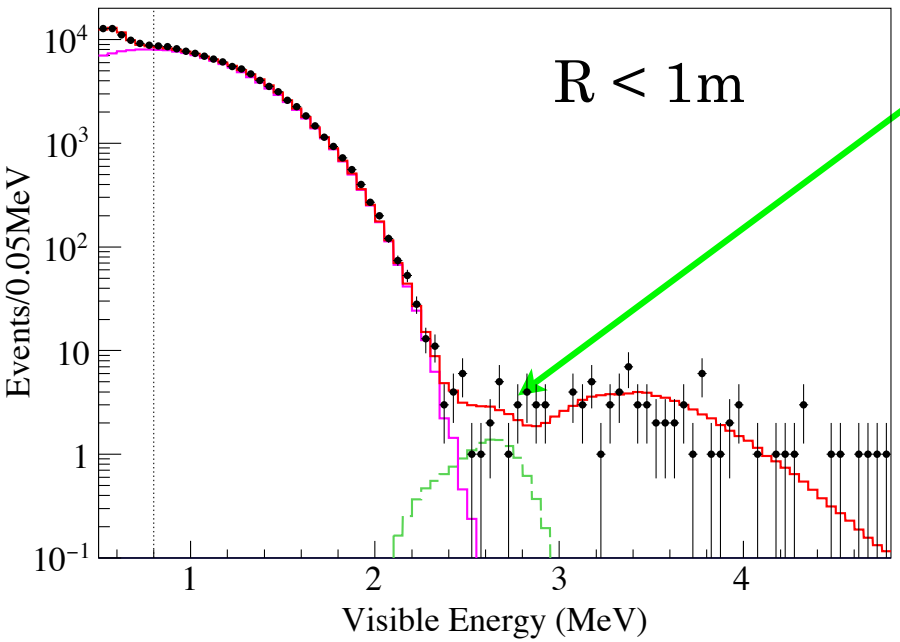
June 2012～

November 2013



KamLAND-Zen Phase 2: Post Purification

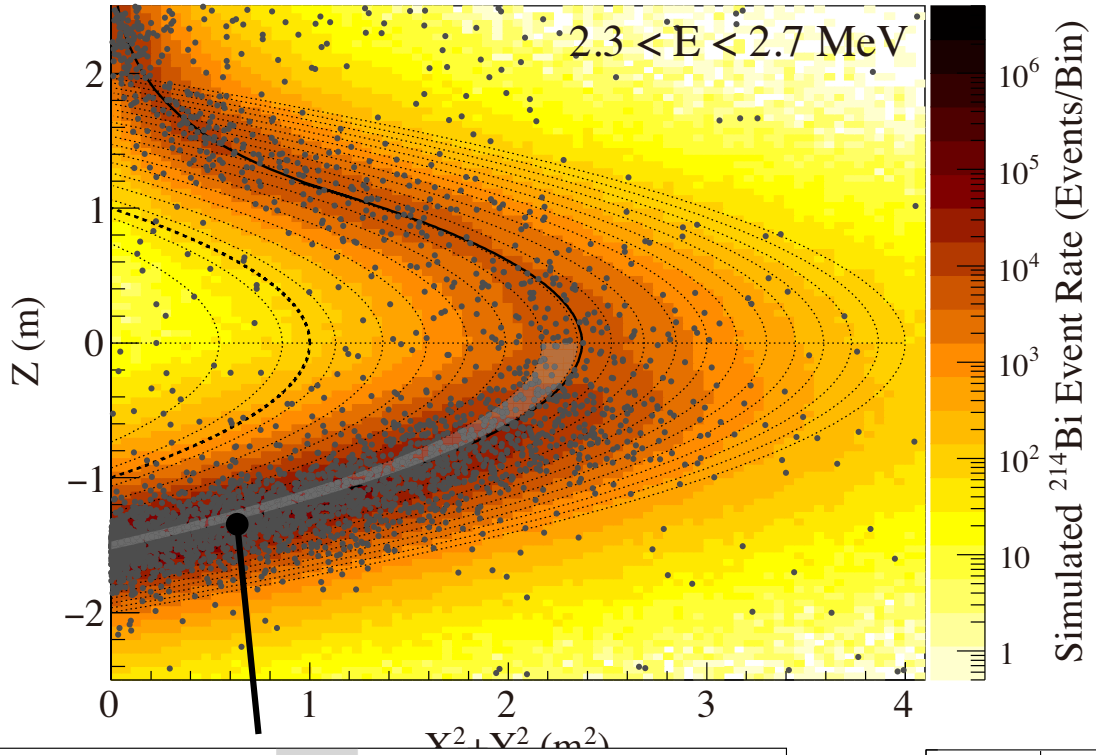
^{110m}Ag still exists?



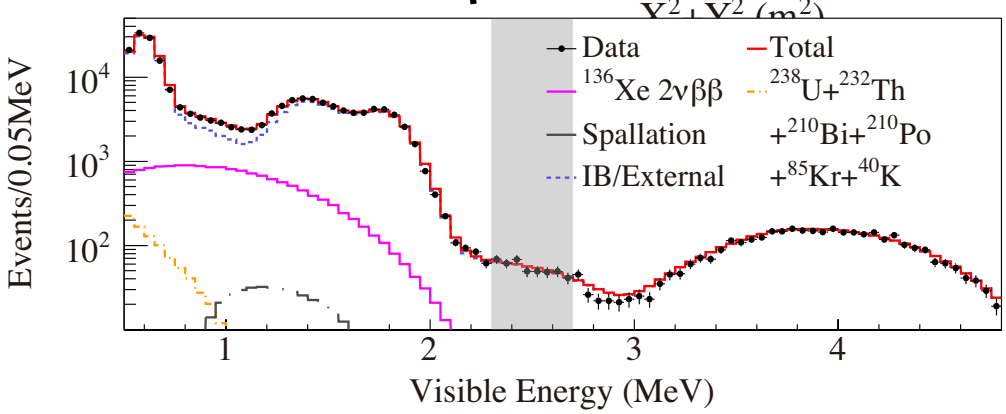
Full phase-2 data-set

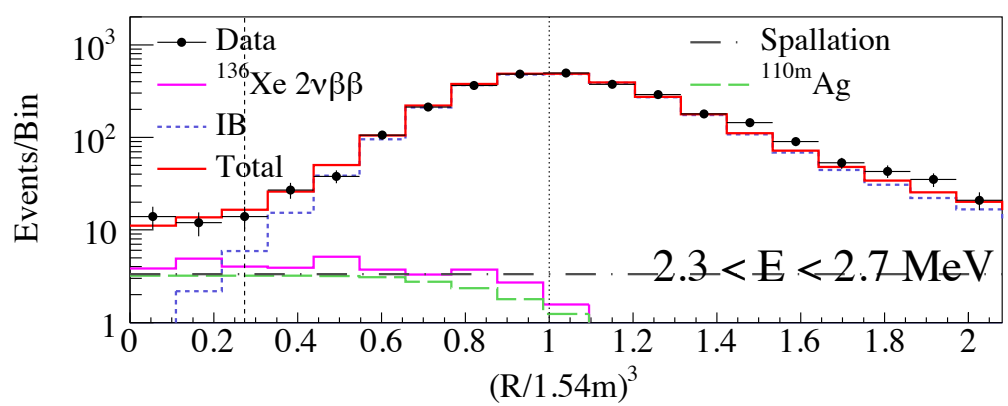
- After Purification
- December 2013 - October 2015
- Livetime 534.5 days, exposure 504 kg-yr
- For Reference: $T_{1/2}(^{110m}Ag)$ = 250 days.

Analysis uses Energy and Position!



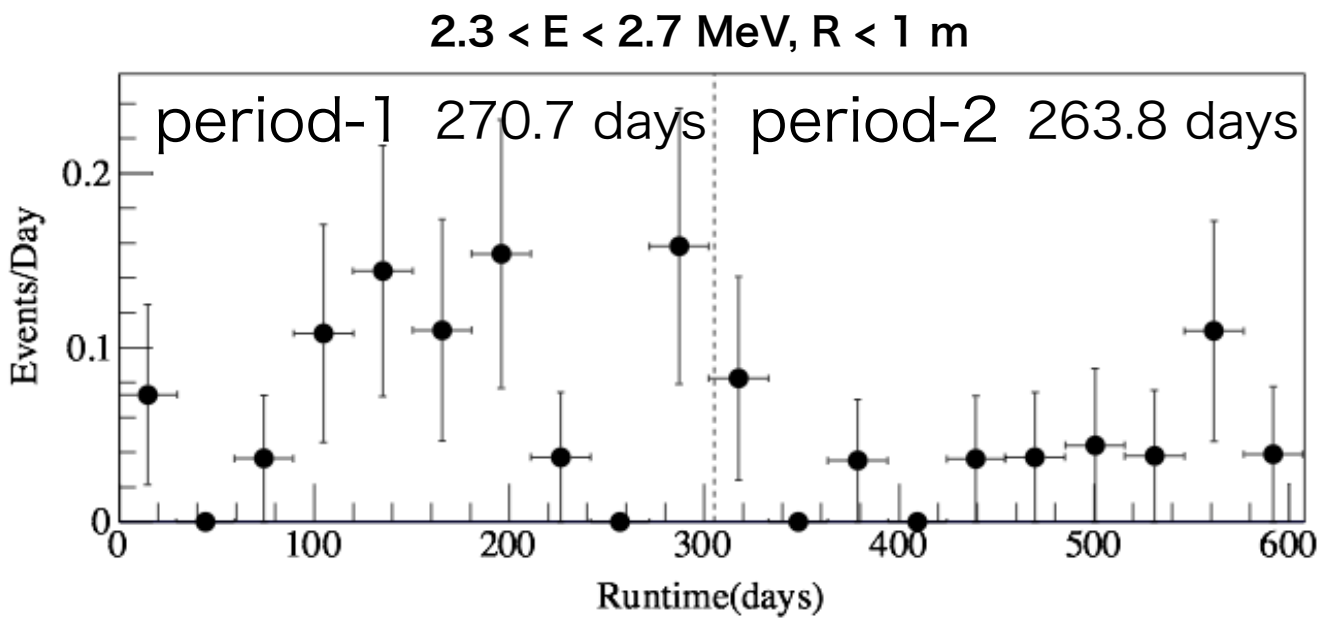
Fit constructed from 40 Equal volume bins.





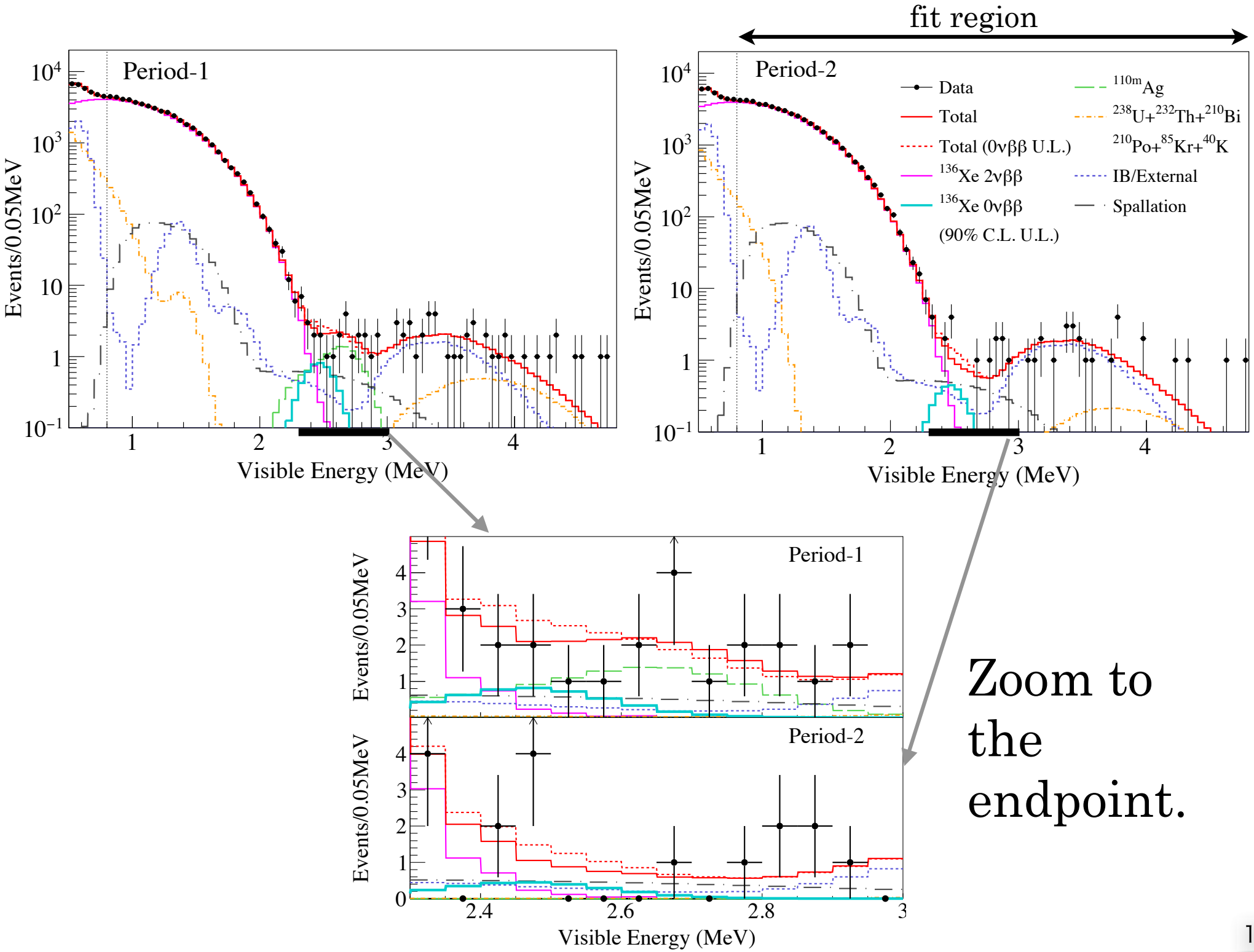
Energy and radial distributions are well-reproduced by known BGs.

Analysis uses two time periods.



22 events 11 events

Hypothesis is that “dust” sank, however also consistent with a simple decay at 2σ.


fit region
Period-1
Period-2
Events/0.05MeV
Visible Energy (MeV)
Data
Total
Total (0νββ U.L.)
136Xe 2νββ
136Xe 0νββ
(90% C.L. U.L.)
110mAg
238U+232Th+210Bi
210Po+85Kr+40K
IB/External
Spallation
Zoom to the endpoint.

Phase 2 - Results on 0ν2β

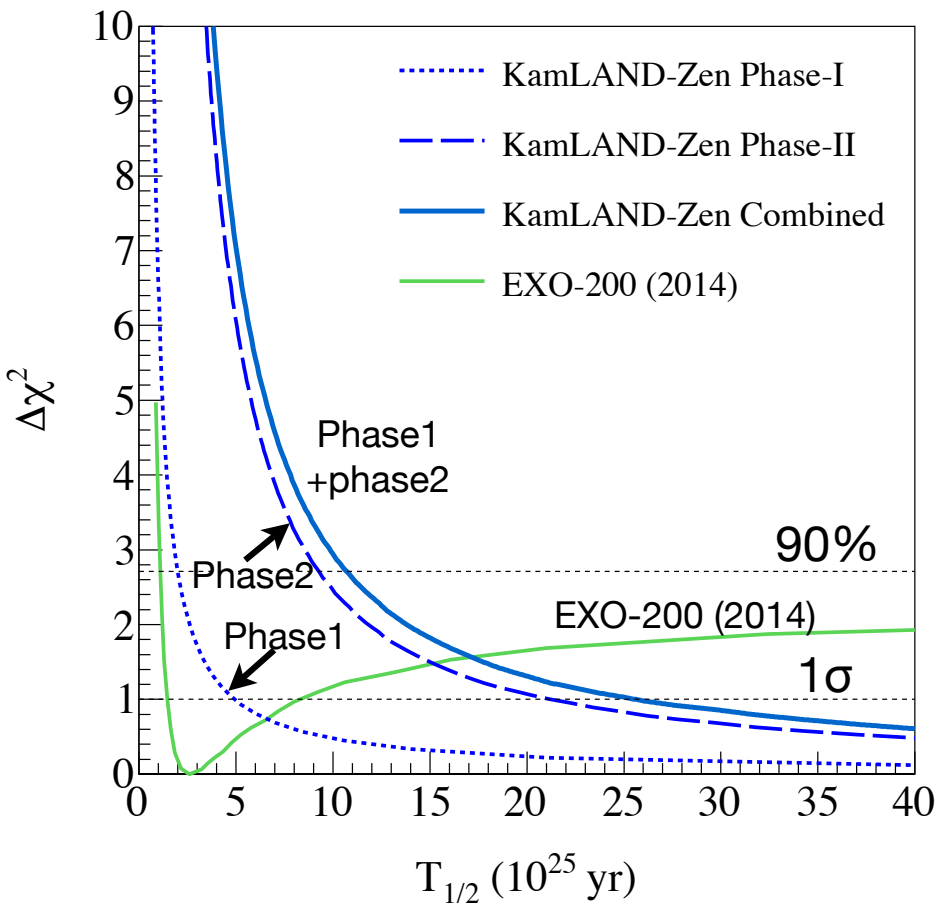
	period-1	period-2
livetime	270.7 days	263.8 days
^{136}Xe 0ν2β decay rate	< 5.5 /kton/day	< 3.5 /kton/day

combined < 2.4 /kton/day (90%C.L.)

^{136}Xe 0ν2β half-life > 9.2×10^{25} yr (90%C.L.)

sensitivity > 4.9×10^{25} yr (11% probability)

^{136}Xe 0νββ Decay Half-life



KamLAND-Zen
Half-life limit (@90%C.L.)

Phase1 $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr

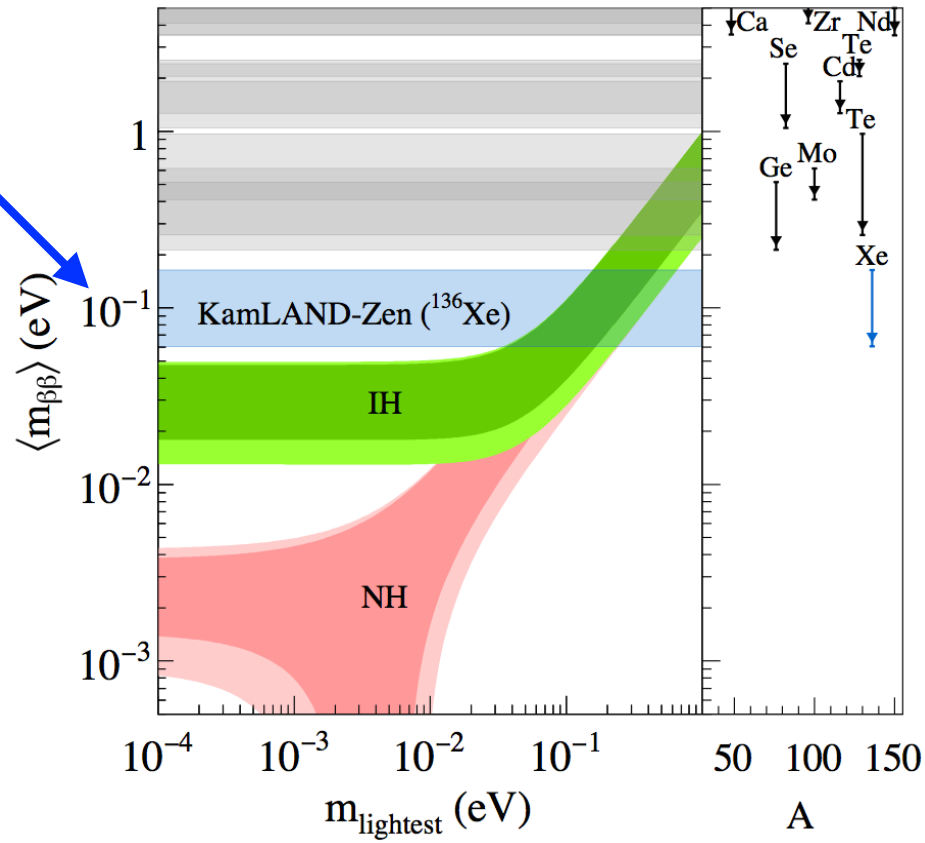
Phase2 $T^{0\nu}_{1/2} > 9.2 \times 10^{25}$ yr

Combined $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr

^{136}Xe 0νββ Decay Half-life

$\langle m_{\beta\beta} \rangle$ < (61- 165) meV

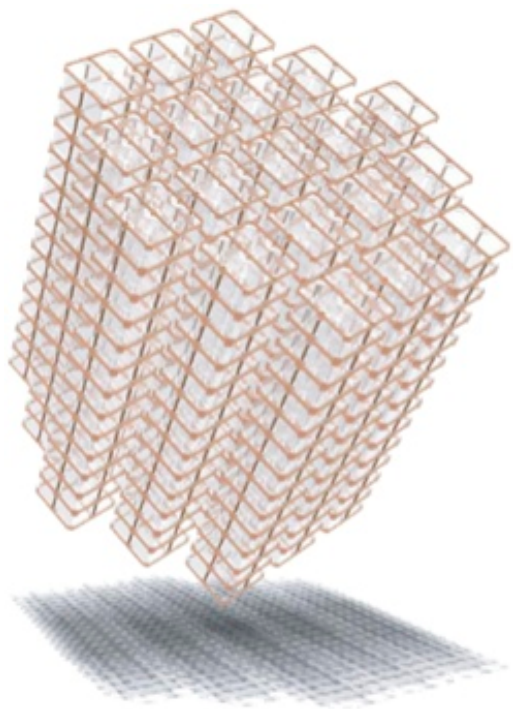
90%C.L. upper limits on $\langle m_{\beta\beta} \rangle$



Commonly used NME with g_A~1.27,
Improved phase space calculations.

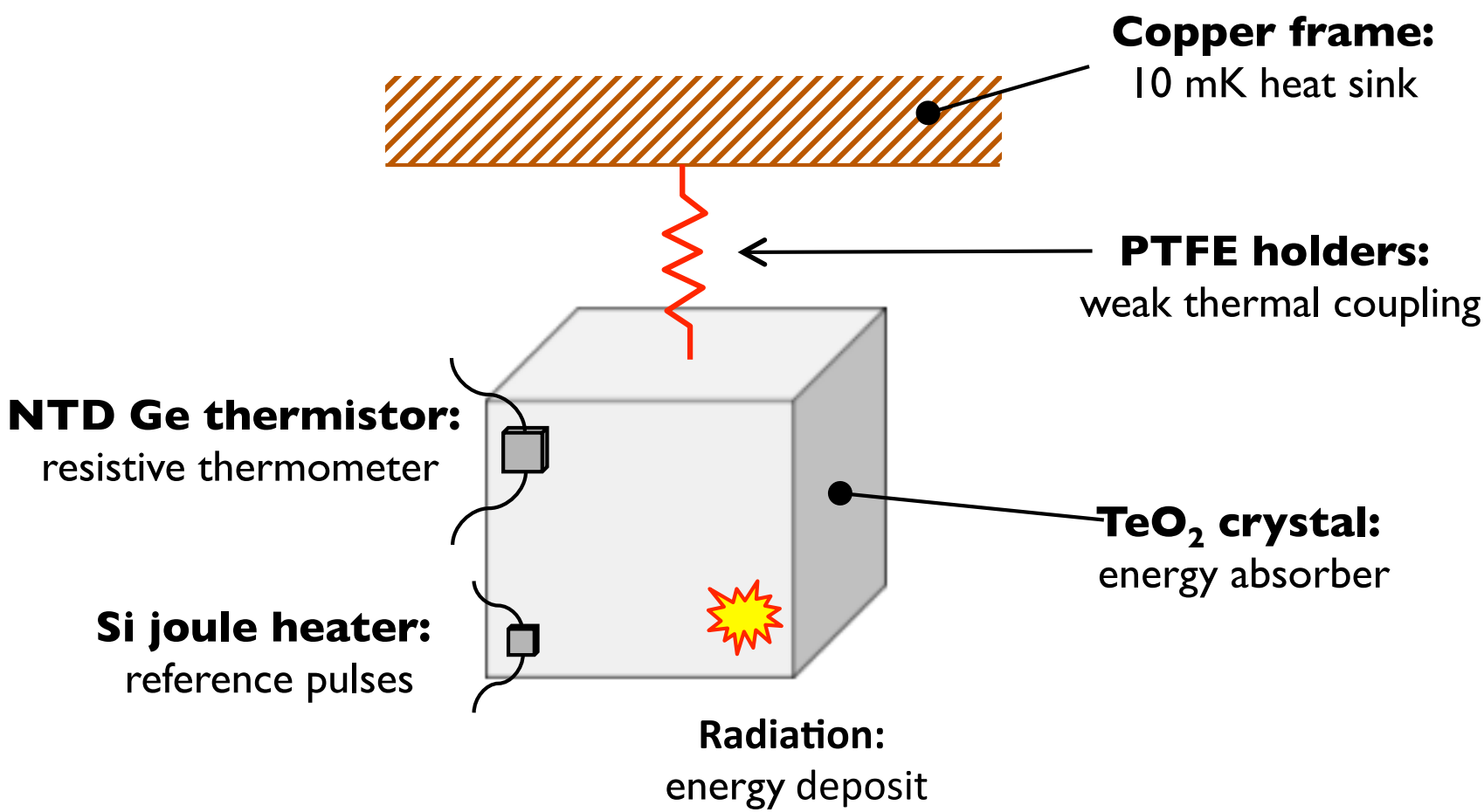
Getting Ready to enter the inverted hierarchy with KamLAND-Zen 800!

CUORE:
Cryogenic Underground Observatory for Rare Events



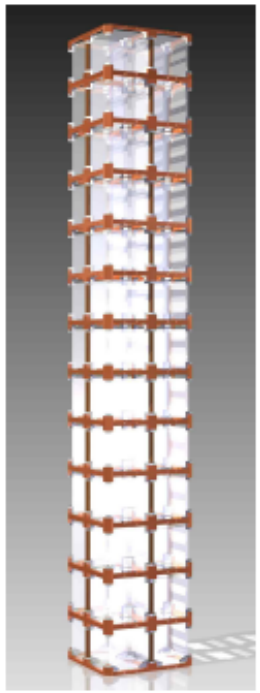
Super Cool

How Bolometers work:

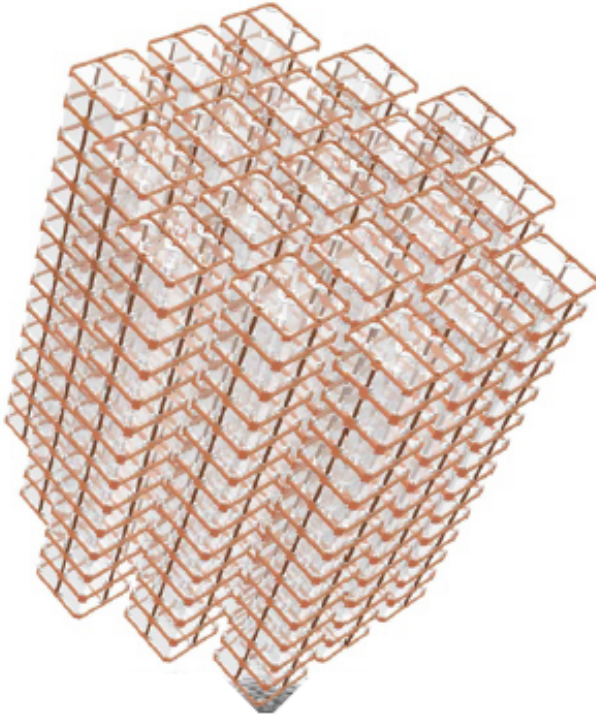


CUORE:
Cryogenic Underground Observatory for Rare Events

CUORICINO
11 kg



CUORE-0
11 kg



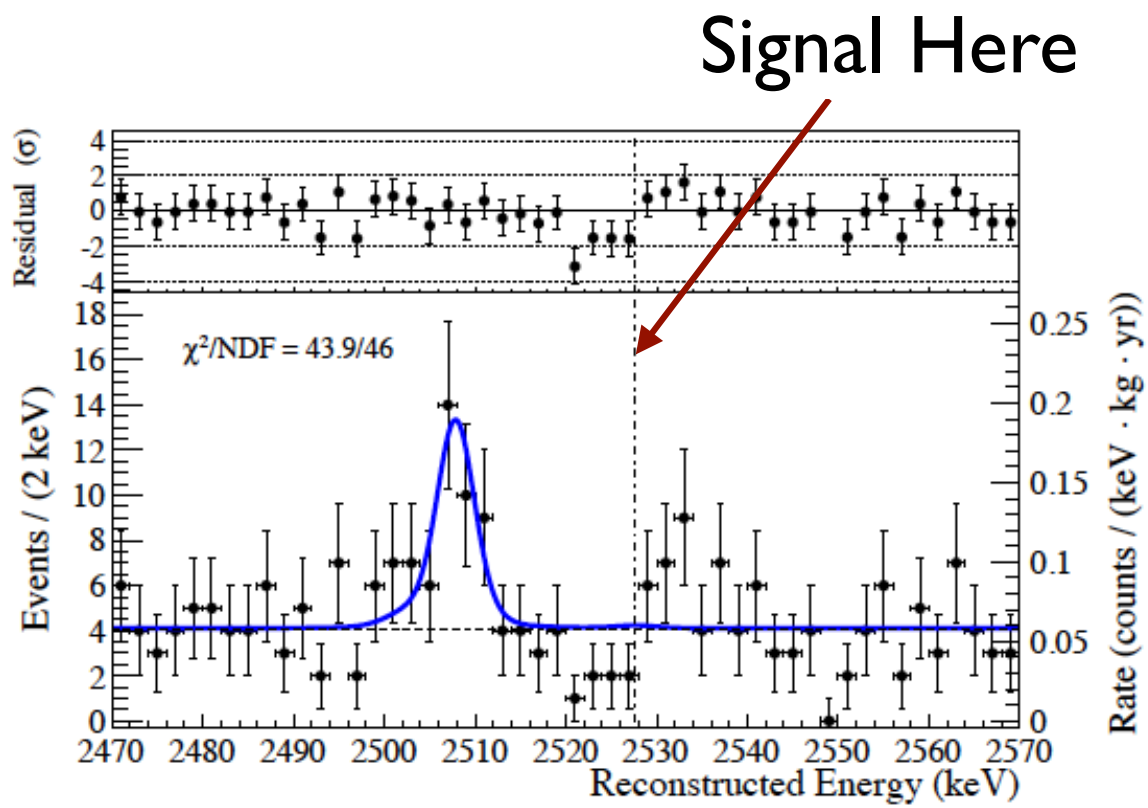
CUORE
206 kg

CUORE:
Cryogenic Underground Observatory for Rare Events

$$T^{0\nu}_{1/2} > 4.0 \times 10^{24}\ \mathrm{yr}$$

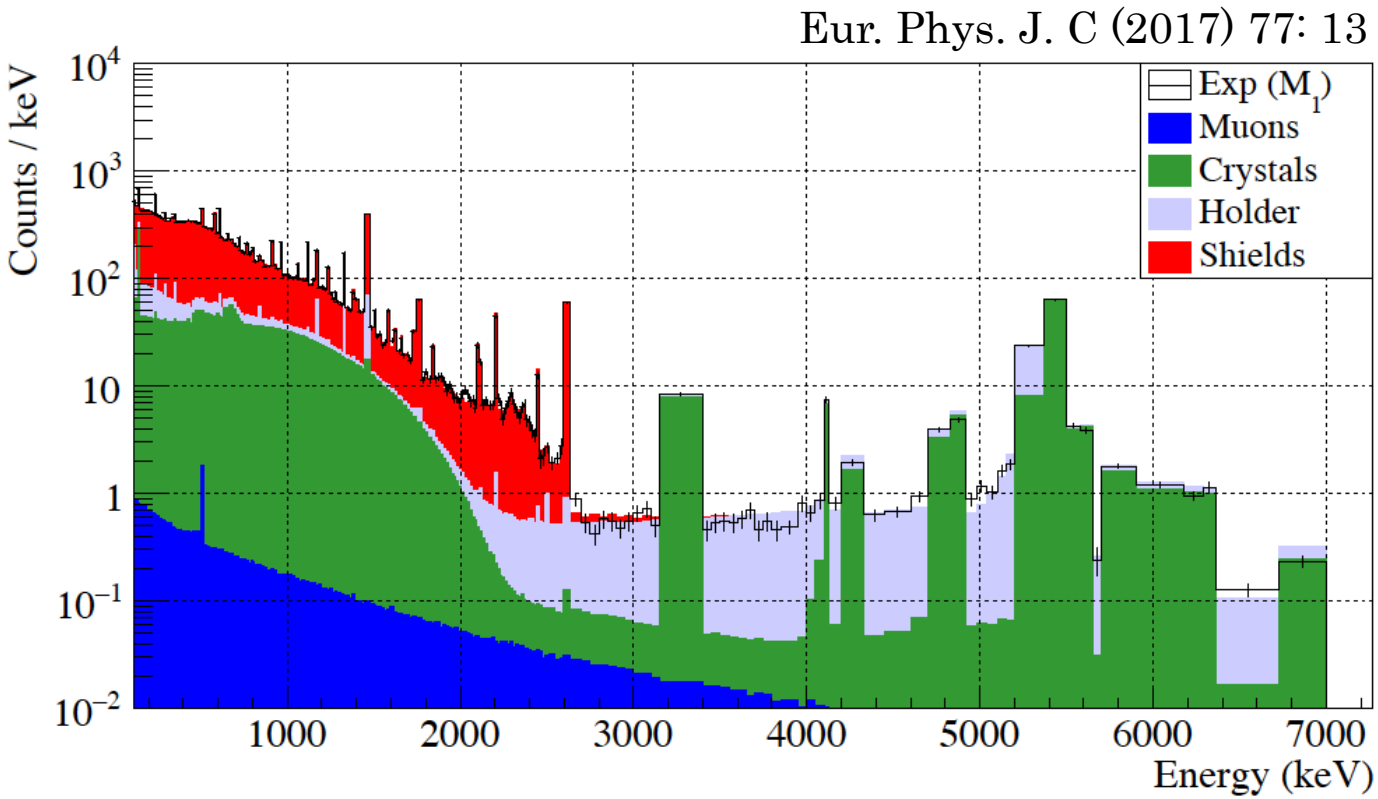
(90% C.L.)

Phys.Rev.Lett. 115 (2015) 10, 102502



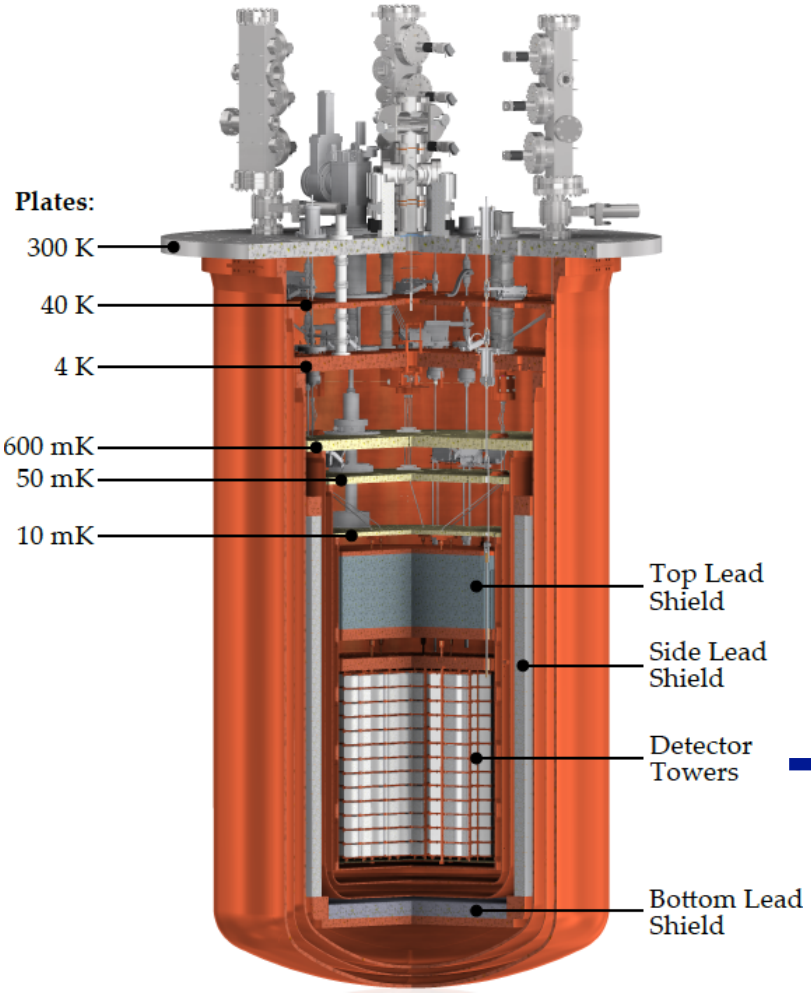
- First results from CUORE-0 (one CUORE-style tower operated in old cryostat).

CUORE:
Cryogenic Underground Observatory for Rare Events

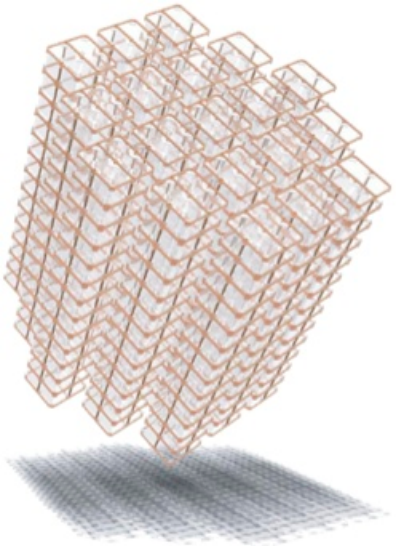


- A detailed study of the backgrounds in CUORE-0 gives us confidence in the background levels in the full CUORE detector.

CUORE:
Cryogenic Underground Observatory for Rare Events

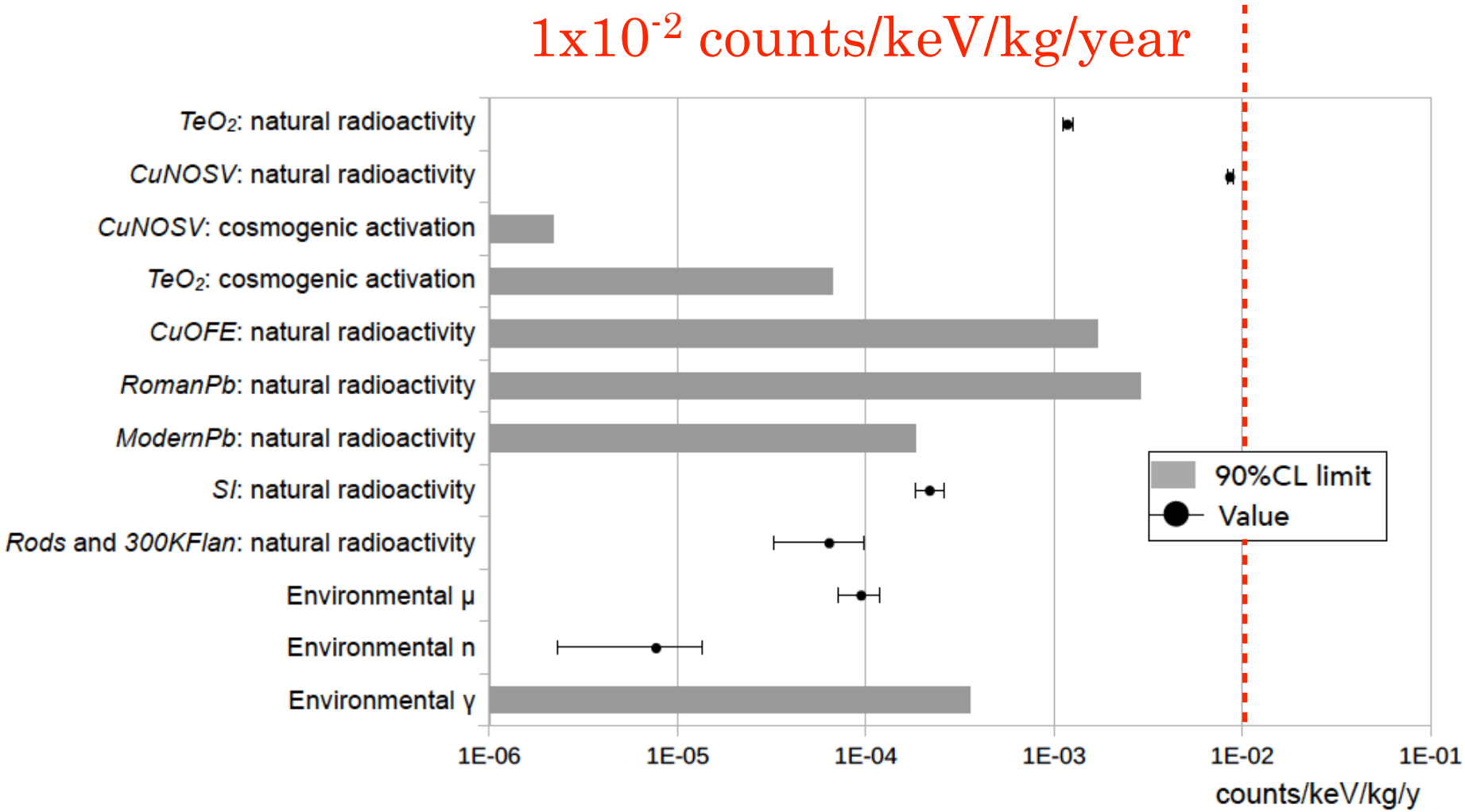


- 19 Towers, 988 TeO_2 crystals operated as bolometers.
- We are the "Coldest cubic meter in the known universe".



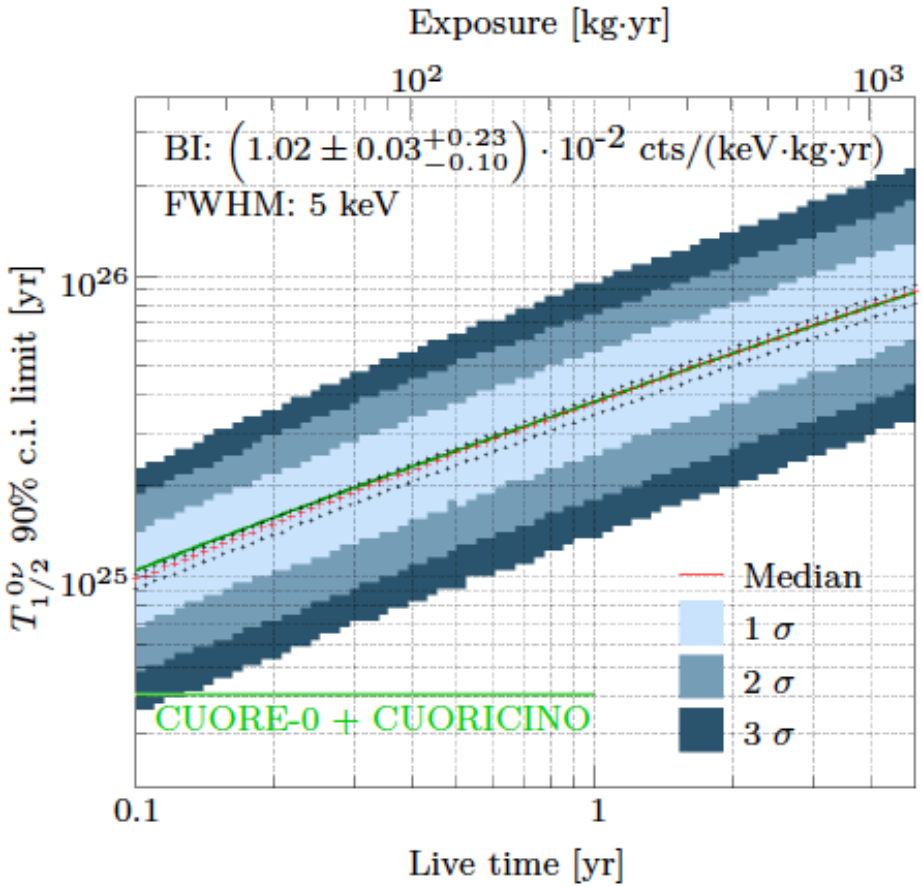
CUORE:
Cryogenic Underground Observatory for Rare Events

Goal:
$1x10^{-2}$ counts/keV/kg/year



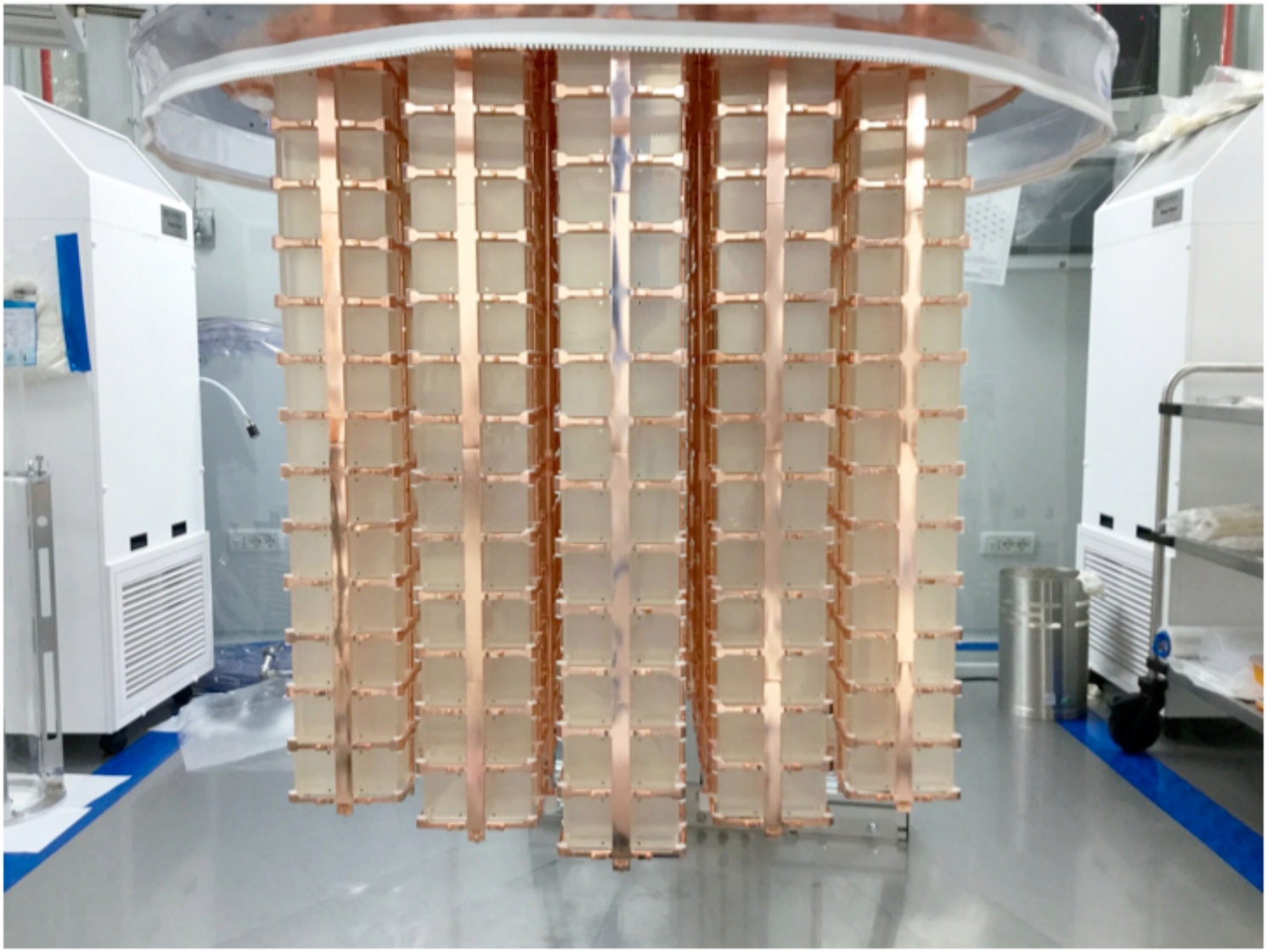
arXiv:1704.08970

CUORE:
Cryogenic Underground Observatory for Rare Events

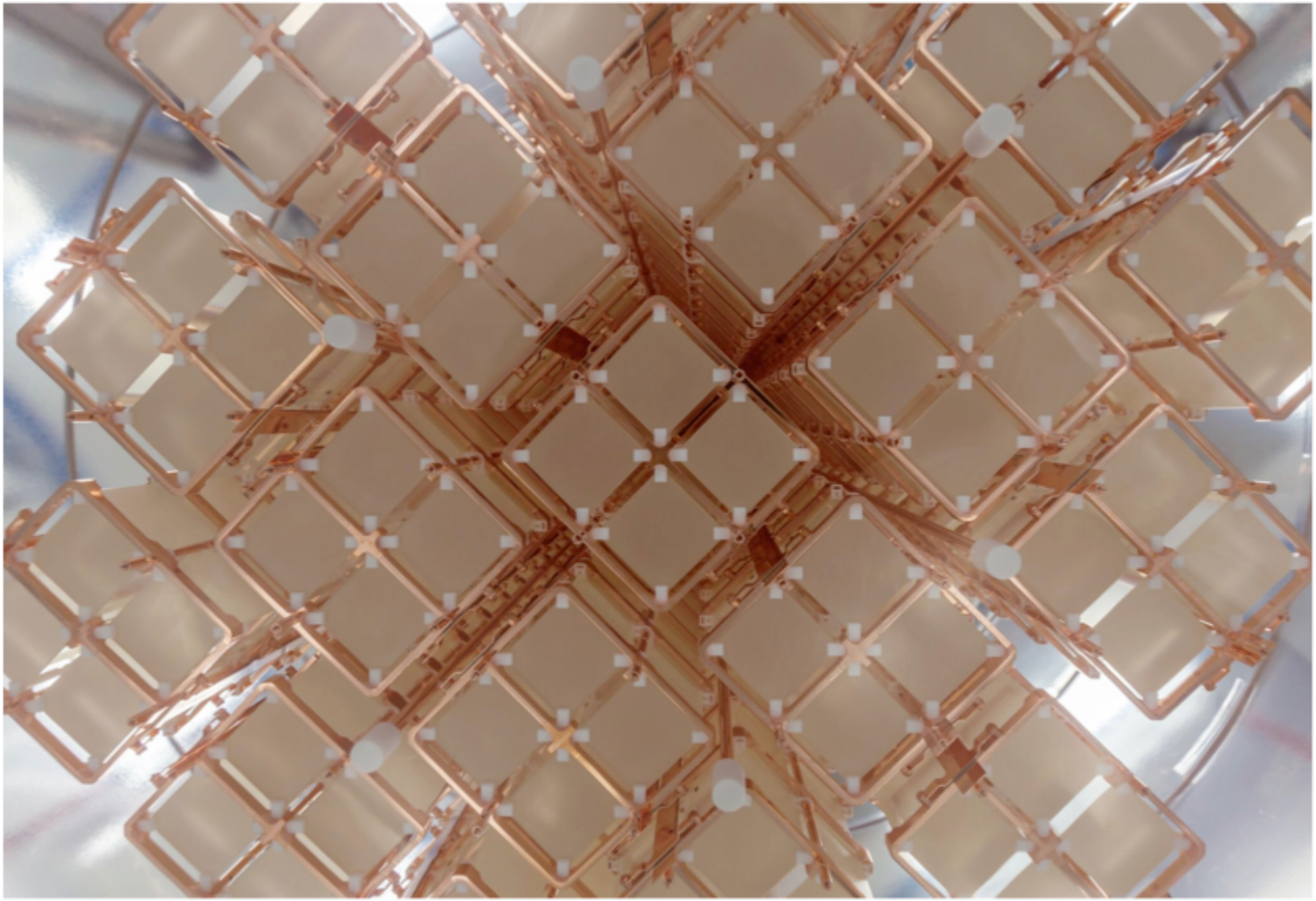


arXiv:1705.10816

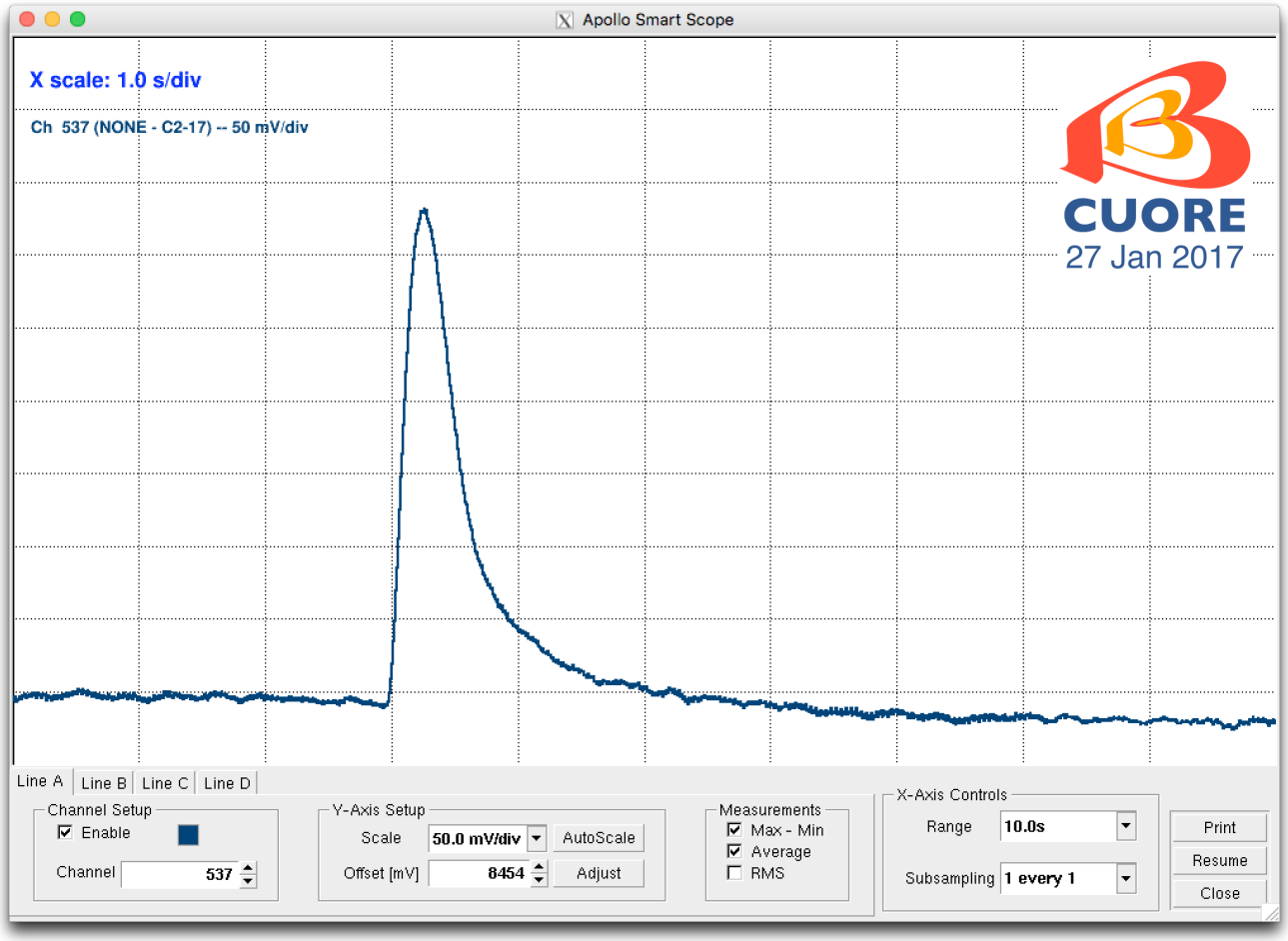
CUORE:
Cryogenic Underground Observatory for Rare Events



CUORE:
Cryogenic Underground Observatory for Rare Events



Data Taking has Started!



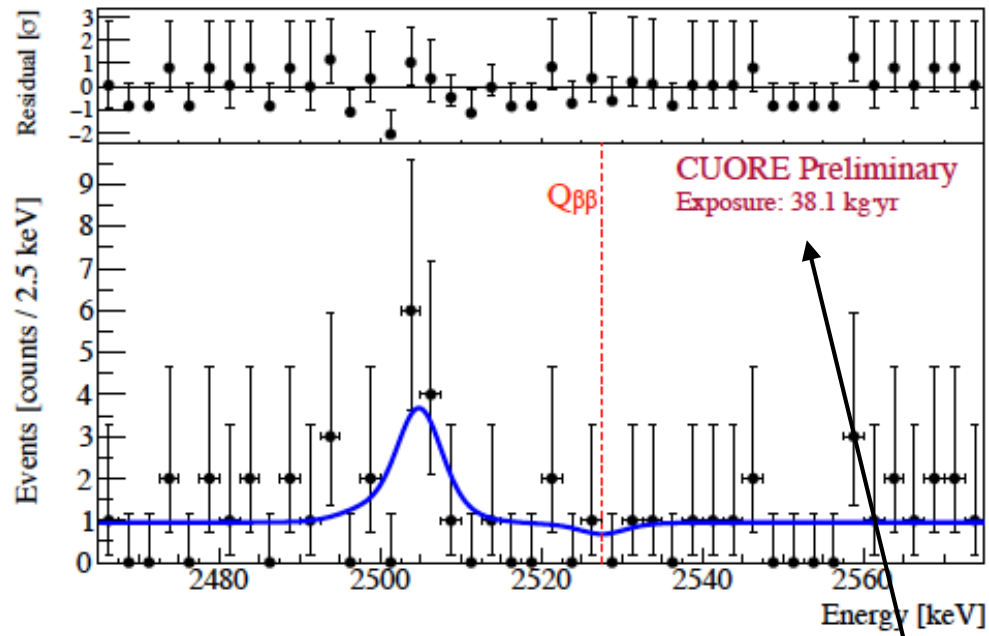
The commissioning was completed in April 2017.

Hot off the press!

Fit in the ROI

- We determined the yield of 0νββ events by performing a simultaneous UEML fit in the energy region 2465-2575 keV
- The fit has 3 components:
  - a posited peak at the Q-value of ^{130}Te
  - a floating peak to account for the ^{60}Co sum gamma line (2505 keV)
  - a constant continuum background, attributed to multi scatter Compton events from ^{208}Tl and surface alpha events

Unblinded spectrum fit

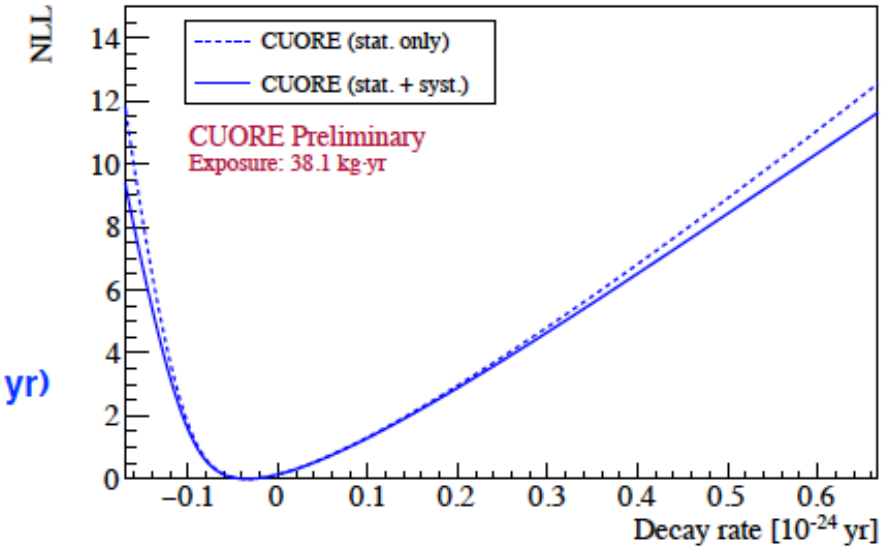


Only 3 weeks of data!

Fit in the ROI

- Profile likelihood
- Integrated on the physical region

- Region of interest: **2565 to 2575 keV**
- Overall signal efficiency ; **(55.3 ± 3.0)%**
- ROI background index: **$(9.8_{-1.5}^{+1.7}) \times 10^{-3}$ c/(keV·kg·yr)**
- Events in the region of interest: **50**
- Best fit for ^{60}Co mean: **(2504.8 ± 1.2) keV**



- Best fit decay rate: **$(-0.03_{-0.04}^{+0.07}$ (stat.) ± 0.01 (syst.))$\times 10^{-24}$ / yr**
- Decay rate limit (90% CL, including systematics): **0.15×10^{-24} / yr**
- Half-life limit (90% CL, including systematics): **4.5×10^{24} yr**
- $m_{\beta\beta}$ lower limits: **< 210–590 meV**
- Median expected sensitivity: **3.6×10^{24} yr (arXiv:1705.10816)**

Combination with previous results

- We combined the CUORE result with the existing ^{130}Te
  - 19.75 kg·yr of Cuoricino
  - 9.8 kg·yr of CUORE-0

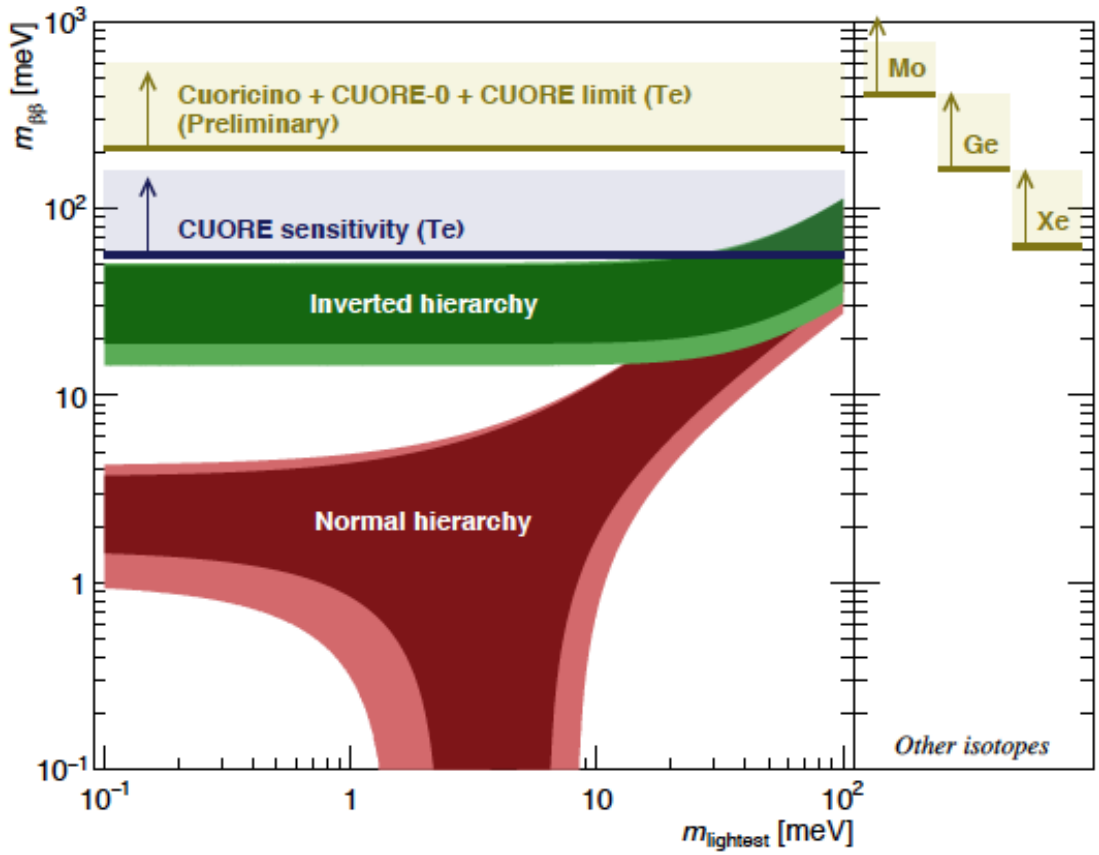
- The combined 90% C.L. limit is

$$T_{0\nu} > 6.6 \times 10^{24}\ \text{yr}$$

$$m_{\beta\beta} < 210\text{–}590\ \text{meV}$$

NME:
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 91, 024613 (2015)
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. Lett. 105, 252503 (2010)

Experiments:
^{130}Te: 6.5 × 1024 yr from this analysis
^{76}Ge: 5.3 × 1025 yr from Nature 544, 47–52 (2017)
^{136}Xe: 1.1 × 1026 yr from Phys. Rev. Lett. 117, 082503 (2016)
^{100}Mo: 1.1 × 1024 yr from Phys. Rev. D 89, 111101 (2014)
CUORE sensitivity: 9.0 × 10^{25} yr



How do you determine the Majorana nature of the neutrino in the normal hierarchy (5 meV)?

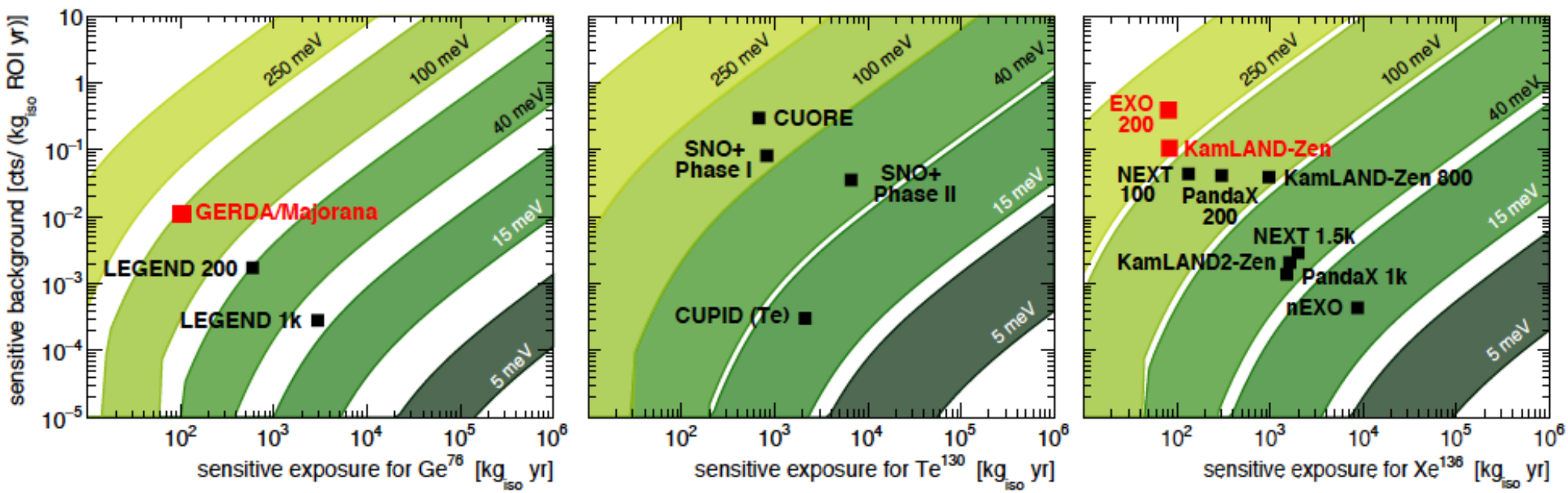
arXiv:1705.02996v2

Discovery probability of next-generation neutrinoless double-β decay experiments

Matteo Agostini*
Gran Sasso Science Institute, L'Aquila, Italy

Giovanni Benato†
Department of Physics, University of California, Berkeley, CA 94720 - USA
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 74720 - USA

Jason Detwiler‡
Center for Experimental Nuclear Physics and Astrophysics,
and Department of Physics, University of Washington, Seattle, WA 98115 - USA



Conclusion

- I didn't even tell you about the short baseline reactor experiments, new methods to measure the mass of the neutrino, coherent neutrino scattering, oh my!
- Low energy experiments provide important complimentary measurements to high energy counter parts and have been integral to forming our current understanding of neutrino physics.
- Many exciting results on the way!

New Mini-Balloon Leak Checking and Installation

MIT Undergraduates Hannah Taylor and Andrea Herman

Summer 2016