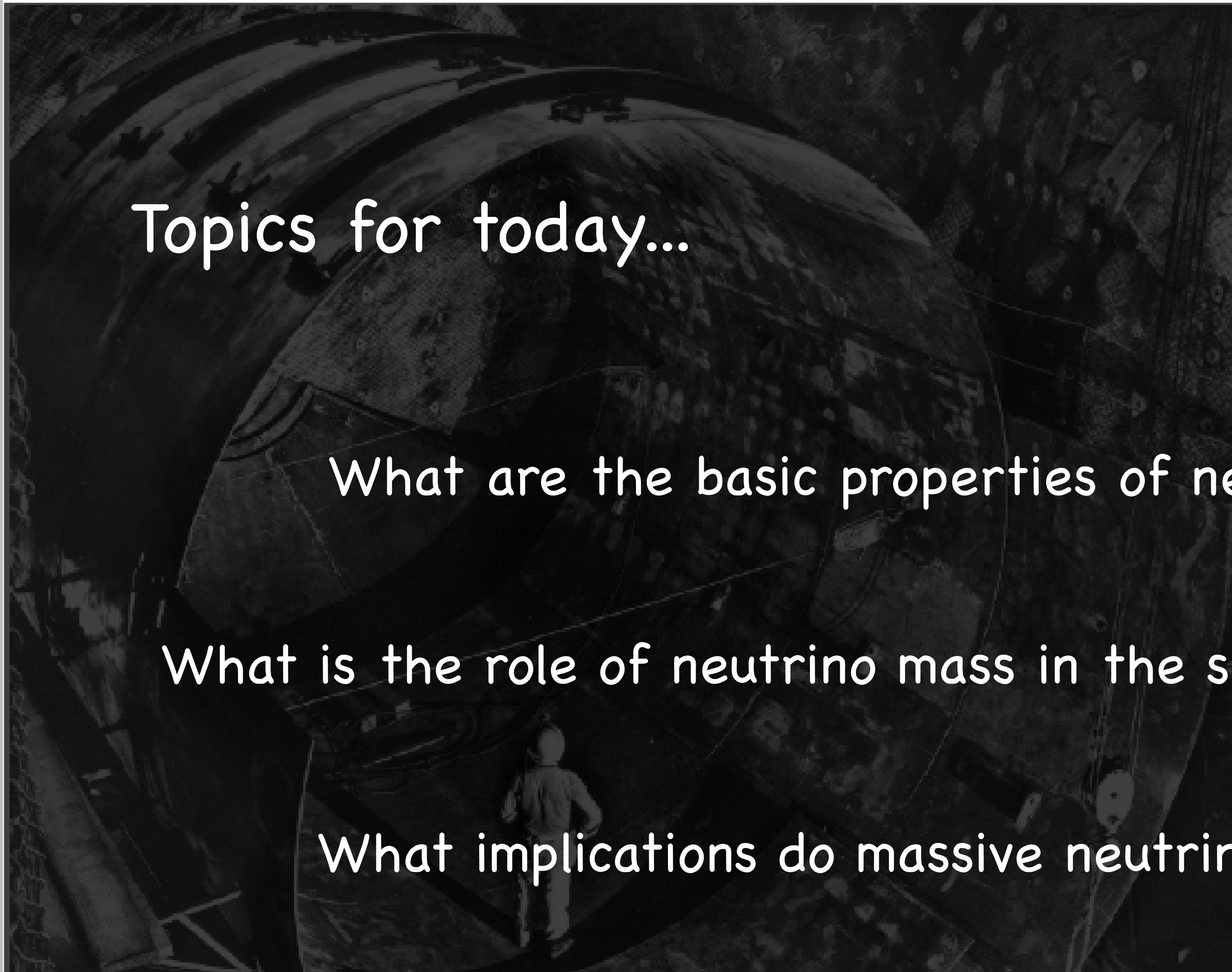
The Quest for Neutrino Mass

J. A. Formaggio
MIT

NEPPSR 2006

Cape Cod, MA
August 16th, 2006



Topics for today...

What are the basic properties of neutrinos?

What is the role of neutrino mass in the standard model?

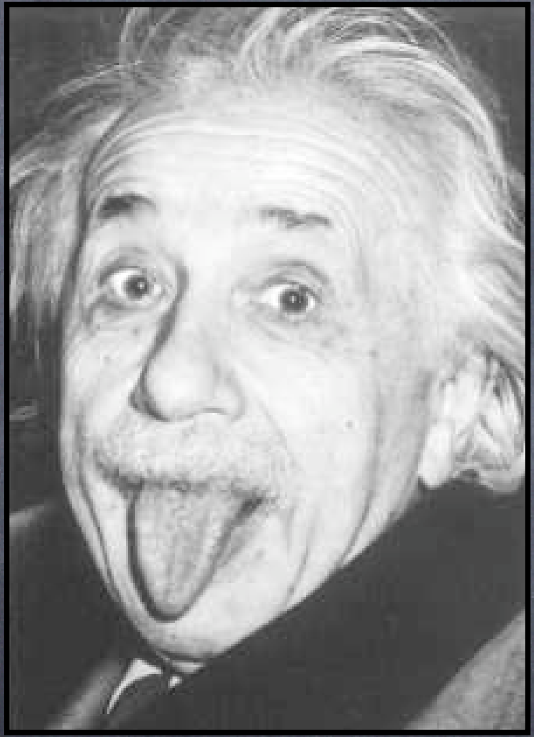
What implications do massive neutrinos have?

How can we measure neutrino mass?

Lesson #1: Neutrinos in our world

"I have hit on a desperate remedy..."

A Wild Idea



- 101 years ago Einstein presents his paper on special relativity

A Wild Idea

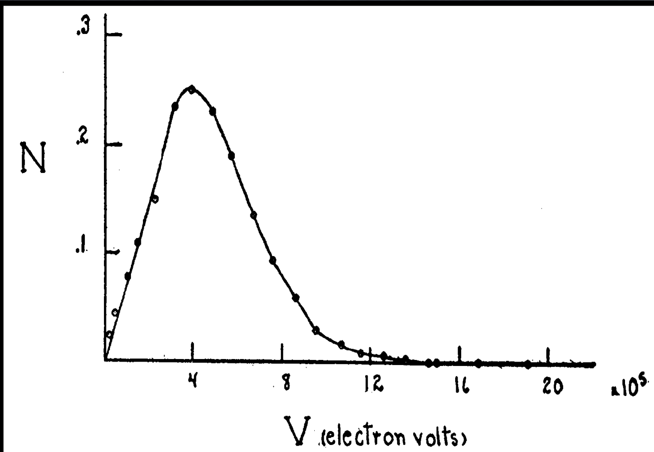
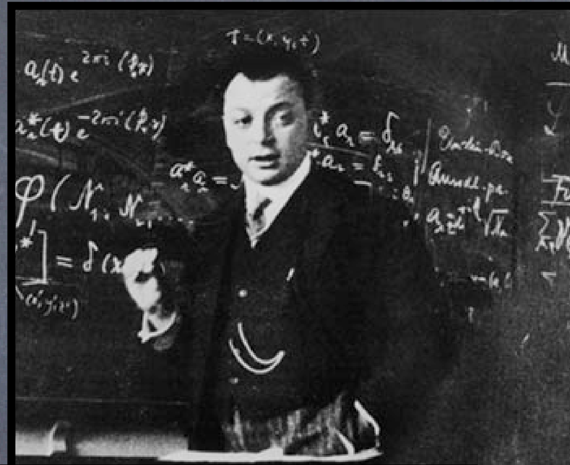


FIG. 5. Energy distribution curve of the beta-rays.



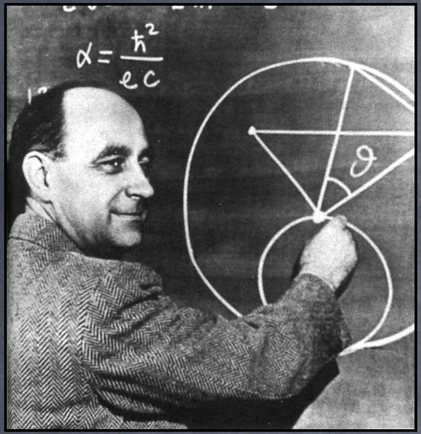
4th December 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

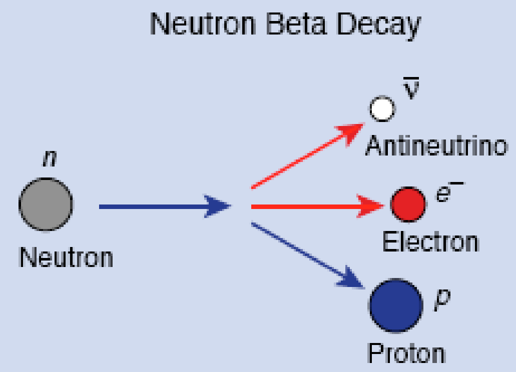
- 101 years ago Einstein presents his paper on special relativity and...
- 76 years ago, Pauli introduces the idea of neutrinos to help resolve the energy conservation crisis.
- The concept of the neutrino is born.

Path to Discovery

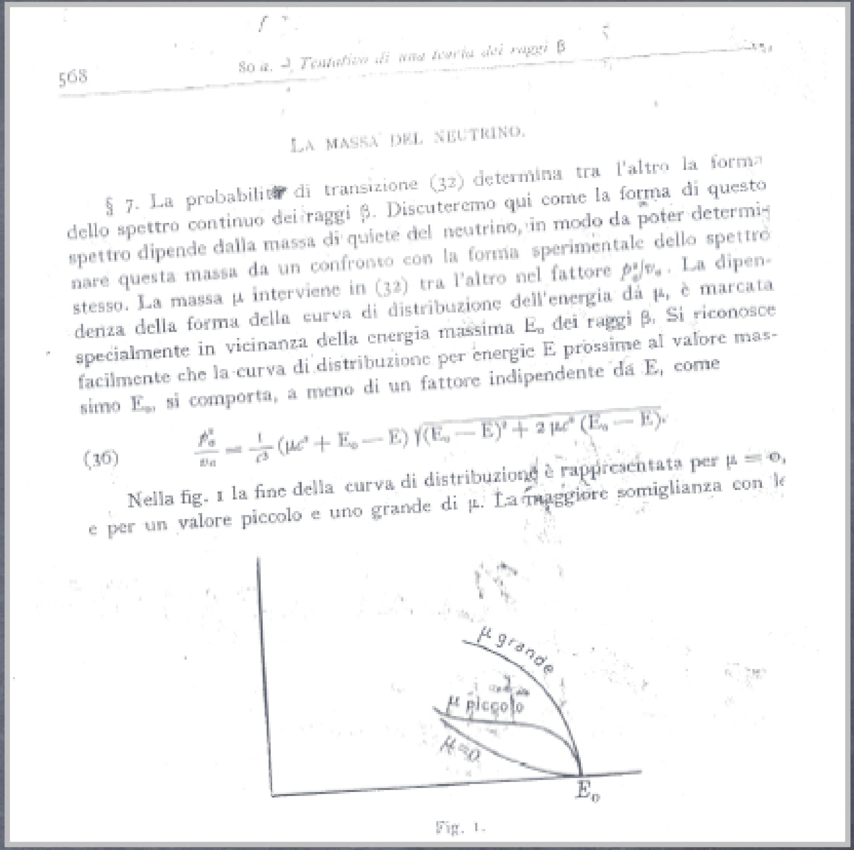


1934 Enrico Fermi establishes the theory of weak decay, providing a framework for neutrinos.

Fermi's "Neutrino"



$$\mathcal{H} = G_F(\bar{\Psi}_p \gamma_\mu \Psi_{\mathrm{n}})(\bar{\Psi}_e \gamma^\mu \Psi_\nu)...$$



568 80 a. – Tentativo di una teoria dei raggi β

LA MASSA DEL NEUTRINO.

§ 7. La probabilità di transizione (32) determina tra l'altro la forma dello spettro continuo dei raggi β. Discuteremo qui come la forma di questo spettro dipende dalla massa di quiete del neutrino, in modo da poter determinare questa massa da un confronto con la forma sperimentale dello spettro stesso. La massa μ interviene in (32) tra l'altro nel fattore p_σ^2/v_σ. La dipendenza della forma della curva di distribuzione dell'energia da μ, è marcata specialmente in vicinanza della energia massima E_0 dei raggi β. Si riconosce facilmente che la curva di distribuzione per energie E prossime al valore massimo E_0, si comporta, a meno di un fattore indipendente da E, come

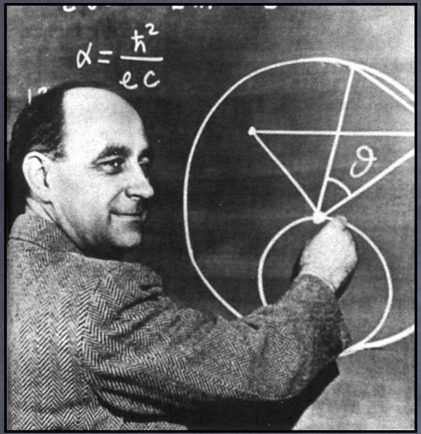
$$\frac{p_\sigma^2}{v_\sigma} = \frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}. \quad (36)$$

Nella fig. 1 la fine della curva di distribuzione è rappresentata per μ = 0, e per un valore piccolo e uno grande di μ. La maggiore somiglianza con le

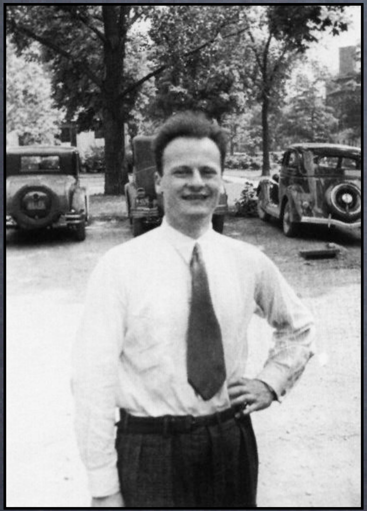
Fig. 1.

- Fermi formulates the theory of **weak decay**, describing the decay of neutrons inside nucleii *(March 25th letter to La Ricerca Scientifica)*.
- Uses 4-point interaction to describe this new force; remarkably accurate for modern day understanding of interaction...
- Fermi already appreciates the effect of neutrino masses (more on that later...)

Path to Discovery



1934 Enrico Fermi establishes the theory of weak decay, providing a framework for neutrinos.

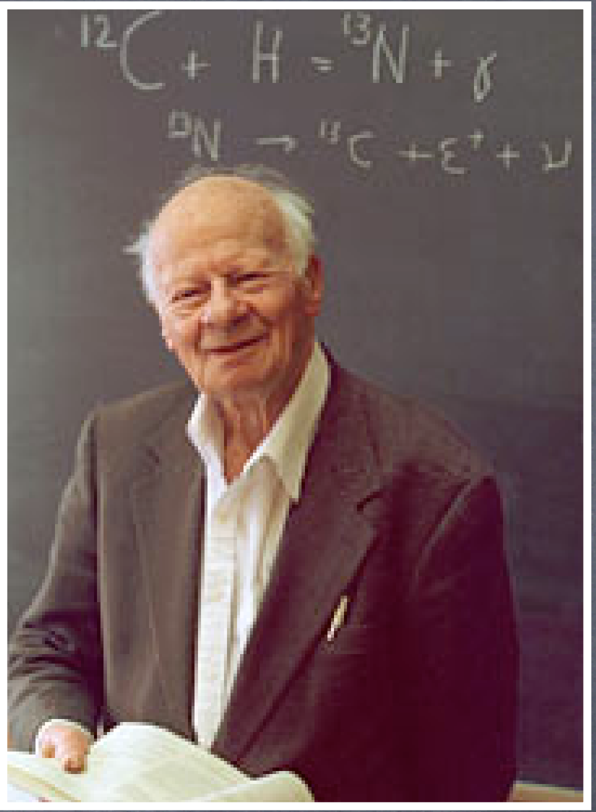


1935 Hans Bethe calculates the probability detecting a neutrino experimentally.

Detecting the Impossible...

$$\nu + n \longrightarrow p + e^-$$

$$\bar{\nu} + p \longrightarrow n + e^+$$

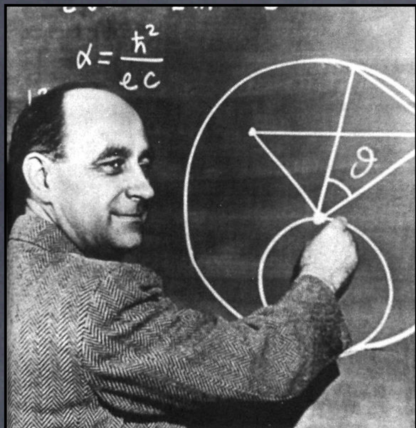


Hans Bethe (1906-2005)

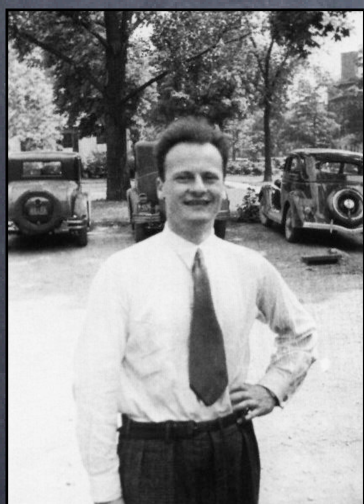
- Bethe & Peirls use decay rates measured from nuclear decay and Fermi's formulation to calculate the inverse process (neutrino interacting with matter).
- Allows for neutrino detection from inverse beta decay
- Alas, the cross-section is a bit small...

$$\sigma_{\nu p} \sim 10^{-43}\ \mathrm{cm}^2\ !$$

Path to Discovery



1934 Enrico Fermi establishes the theory of weak decay, providing a framework for neutrinos.



1935 Hans Bethe calculates the probability detecting a neutrino experimentally.

1956 Reines & Cowan use their Poltgergeist experiment to provide first detection of the neutrino.

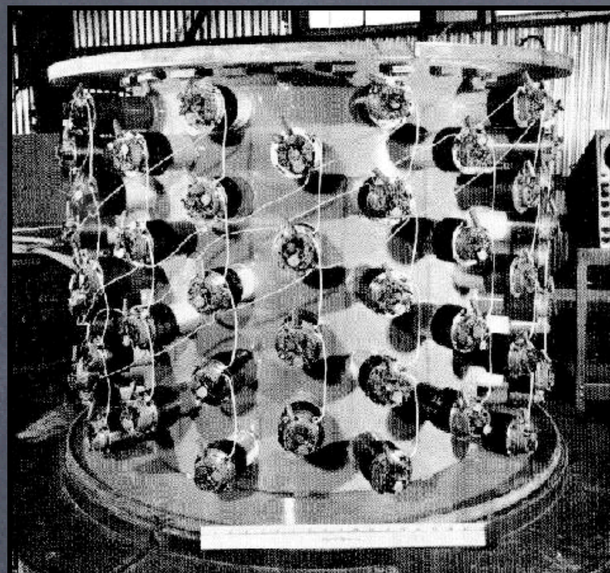
Searching for the Impossible

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

$$n + {}^{113}\mathrm{Cd} \rightarrow \gamma' s$$ and here!

- Neutrino detection must battle the fact that the interaction rate is far smaller than with anything else.
- Reines and Cowen decided to use the coincidence of the primary anti-neutrino interaction (positron emission) and detection of the neutron.
- Coincidence signal allows for powerful background rejection.

Experimental Neutrino Physics Begins...



Project Poltergeist

W E S T E R N   U N I O N

June 14, 1956

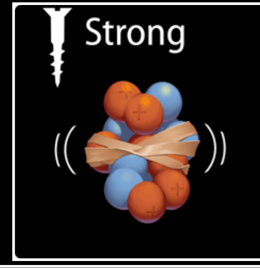
Dear Professor Pauli,

We are happy to inform you that we have definitely detected neutrinos. . .

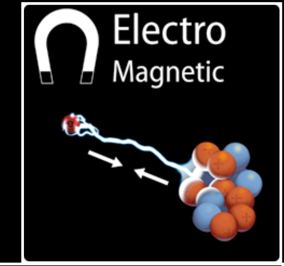
Fred Reines
Clyde Cowan

- Neutrinos finally detected (it took 26 years) !
- OK, now things get interesting...

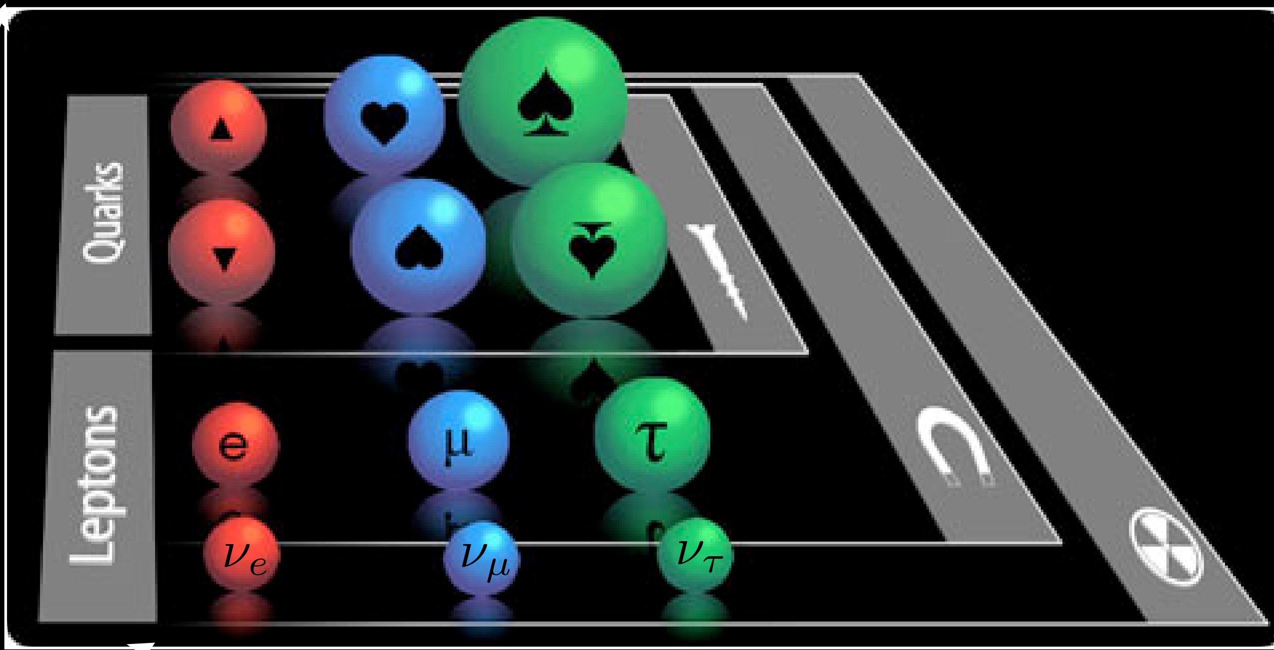
Within the Framework



Binds nucleii;
mediated by gluons;
only couples to quarks

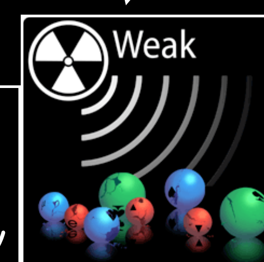


Couples to charge;
mediated by photons;
felt by quarks and leptons



Spin 1

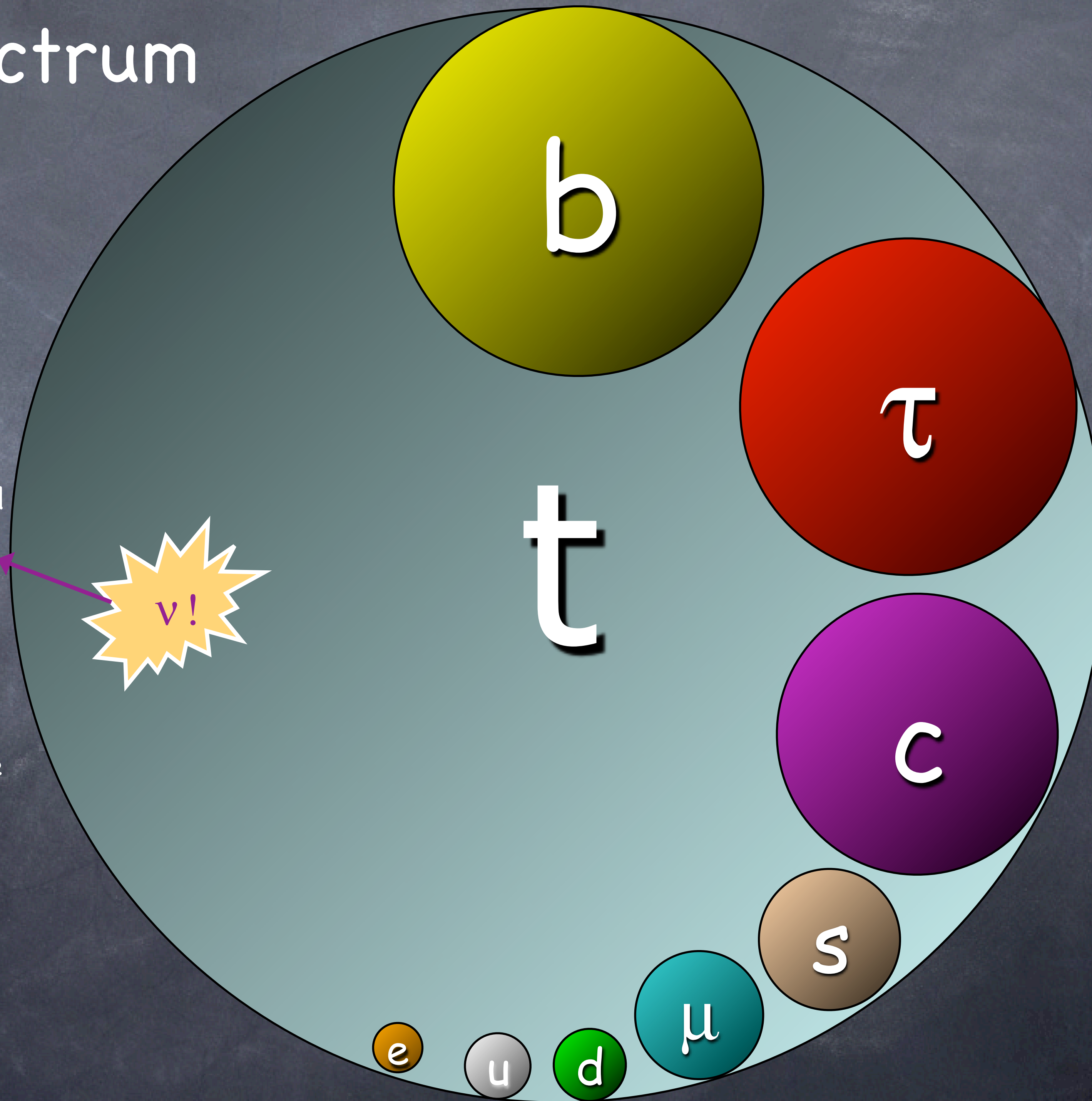
Spin 1/2



Common to all particles;
mediated by the $W^{\pm}/Z^0$ bosons;
Neutrinos can only interact weakly

The Mass Spectrum

- Various symmetries distinguish neutrinos from other quarks and leptons.
- Neutrinos would be a period at the end of this sentence.
- Insight into the mass spectrum.
- Insight into the scale where new physics begins to take hold.



Handedness vs. Helicity

- All particles have "helicity" associated with them.
- Helicity is the projection of spin along the particle's trajectory.
- Can be aligned with or against the direction of motion.

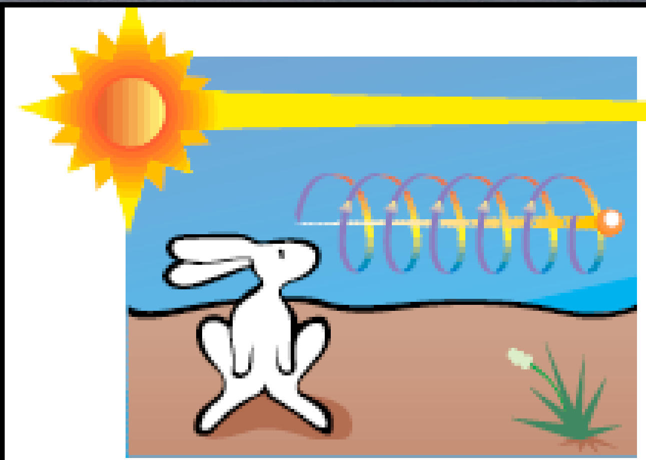
Right-helicity

Spin along direction of motion

Left-helicity

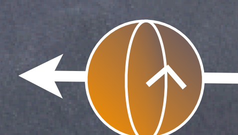
Spin anti-along direction of motion

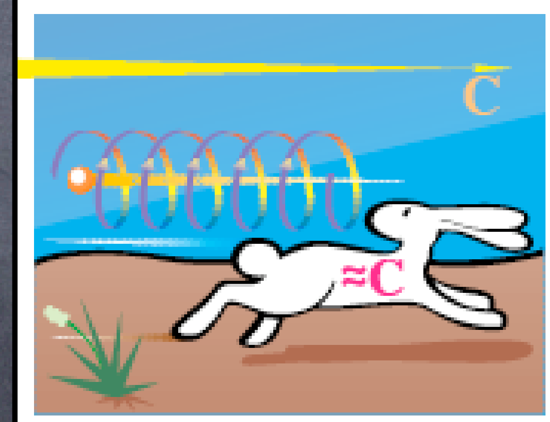
Handedness vs. Helicity



Looks like a left-handed corkscrew.

- Helicity is not invariant under Lorentz transformations.
  - Changes depending on the frame of reference.
- Since related to angular momentum (and angular momentum is conserved), the helicity can be directly measured.





No—like a right-handed corkscrew!

Handedness vs. Helicity

- One can also describe a particle's **handedness** or **chirality**.
- Chirality IS Lorentz invariant. It does not depend on the frame of reference. It is the LI counterpart to helicity.
- In the limit that the particle mass is zero, helicity and chirality are the same.

Left-handed

Right-handed

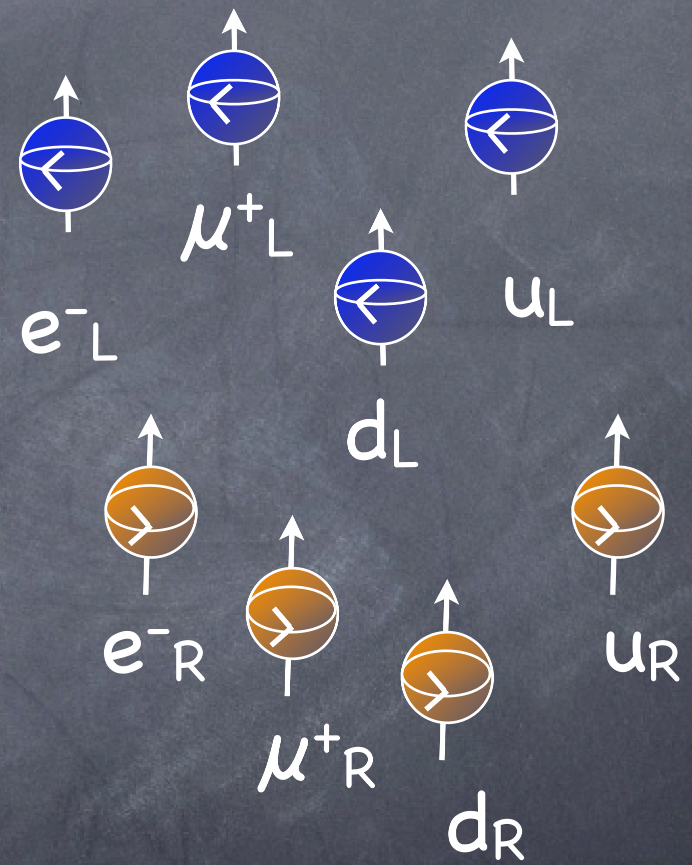
$$\psi_L = \frac{1}{2}(1-\gamma^5)$$

$$\psi_R = \frac{1}{2}(1+\gamma^5)$$

What makes neutrinos different...

- All charged leptons and quarks come in both left-handed and right-handed states...

This implies parity conservation



Weak force does not conserve parity....

C. S. Wu demonstrates parity violation in the weak force using ^{60}Co decay

"Parity Violation"

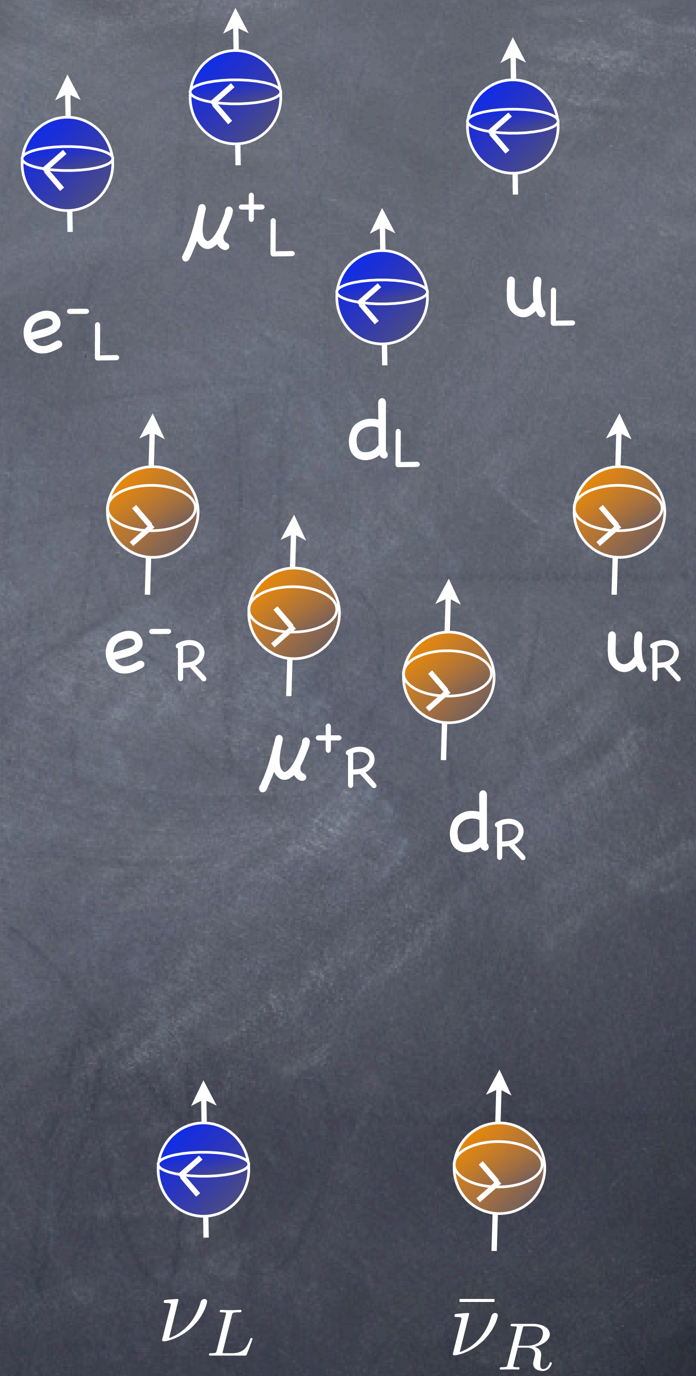
- All other forces studied at the time (electromagnetism and the strong force) rigidly obeyed parity conservation.
- Weak force violates parity conservation completely.

What makes neutrinos different...

- All charged leptons and quarks come in both left-handed and right-handed states...

  This implies parity conservation

- ...except for neutrinos!
- Neutrinos only come as left-handed particles (or right-handed anti-particles).



Mass & Handedness

- Left- and right-handed components come into play when dealing with mass terms in a given Lagrangian…

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi$$

$$\mathcal{L}_{\text{mass}} = m(\bar{\psi}\psi)$$

$$= m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

- Because neutrinos only appear as left-handed particles (or right-handed anti-particles), the Standard Model wants massless neutrinos.

- All other spin 1/2 particles have both right-handed and left-handed components.

Set m = 0!
and the right-handed neutrinos never appear

Mass & Handedness

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi$$

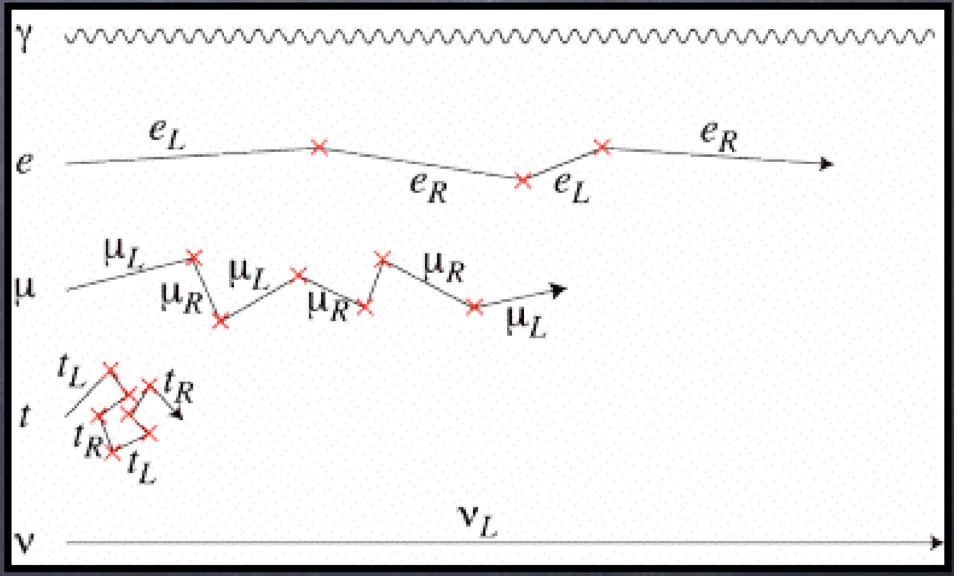
- Left- and right-handed components come into play when dealing with mass terms in a given Lagrangian...

$$\mathcal{L}_{\text{mass}} = m(\bar{\psi}\psi)$$

$$= m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

- Because neutrinos only appear as left-handed particles (or right-handed anti-particles), the Standard Model wants massless neutrinos.

- All other spin 1/2 particles have both right-handed and left-handed components.



How to Introduce Neutrino Mass…

- **Introduce right-handed neutrino:**
  - Would allow a Dirac mass in the model.
  - Introduces two new states to the standard model.
  - New states would be sterile neutrinos (no coupling to the $W^{\pm}$)
- **Introduce neutrinos as Majorana particles:**
  - Neutrino & anti-neutrino as the same particle.
  - Mass introduced through charge conjugate term.

$$\psi = \psi_L + \psi_R$$

Sterile term

Complex conjugate term

$$\psi = \psi_L + \psi_R^c$$

Naturalness of Neutrino Mass

- Why is the neutrino mass so small compared to the other particles?
- Perhaps neutrinos hold a clue to theories beyond the Standard Model.
- For example, a number of Grand Unified Theories {Left-Right Symmetric; SO(10)} predict the smallness of neutrino mass is related to physics that take place at the unification level.

The See-Saw Mechanism

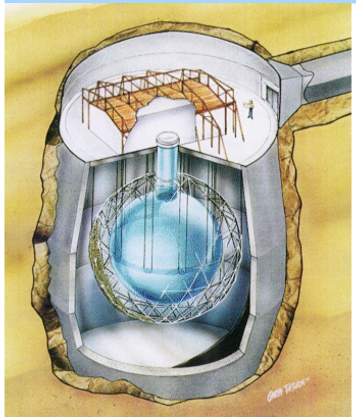
$$\mathcal{L} = (\bar{\phi}_L \; \bar{\phi}_R)\mathcal{M}\begin{pmatrix}\phi_L \\ \phi_R\end{pmatrix} \qquad \mathcal{M} = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$

$$m_R \sim m_{\mathrm{GUT}}$$

$$m_\nu \sim \frac{m_D^2}{m_R}$$

Four Methods

Neutrino Oscillations



Probe mass differences

Use quantum mechanical effects

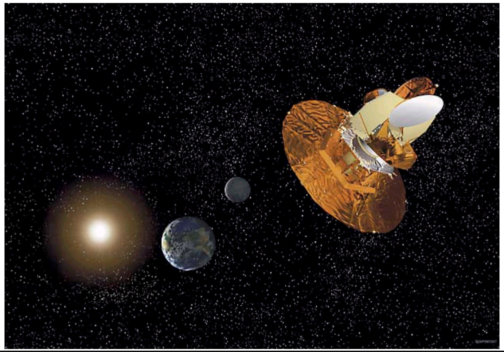
Sources: Reactor, solar, atmospheric, beams

Cosmology

Probe total neutrino mass

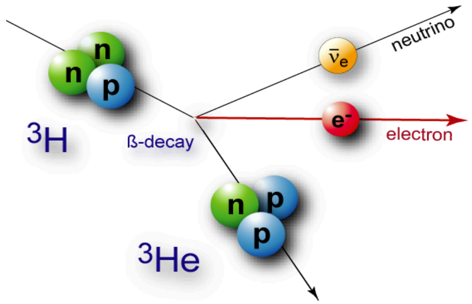
Use Gen. relativity

Satellites & ground observatories



ν

Single Beta Decay



Probe absolute mass scale

Use conservation of energy

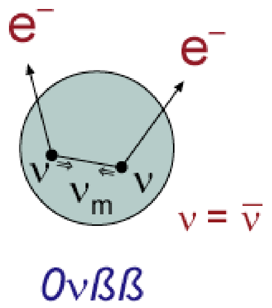
Model-independent

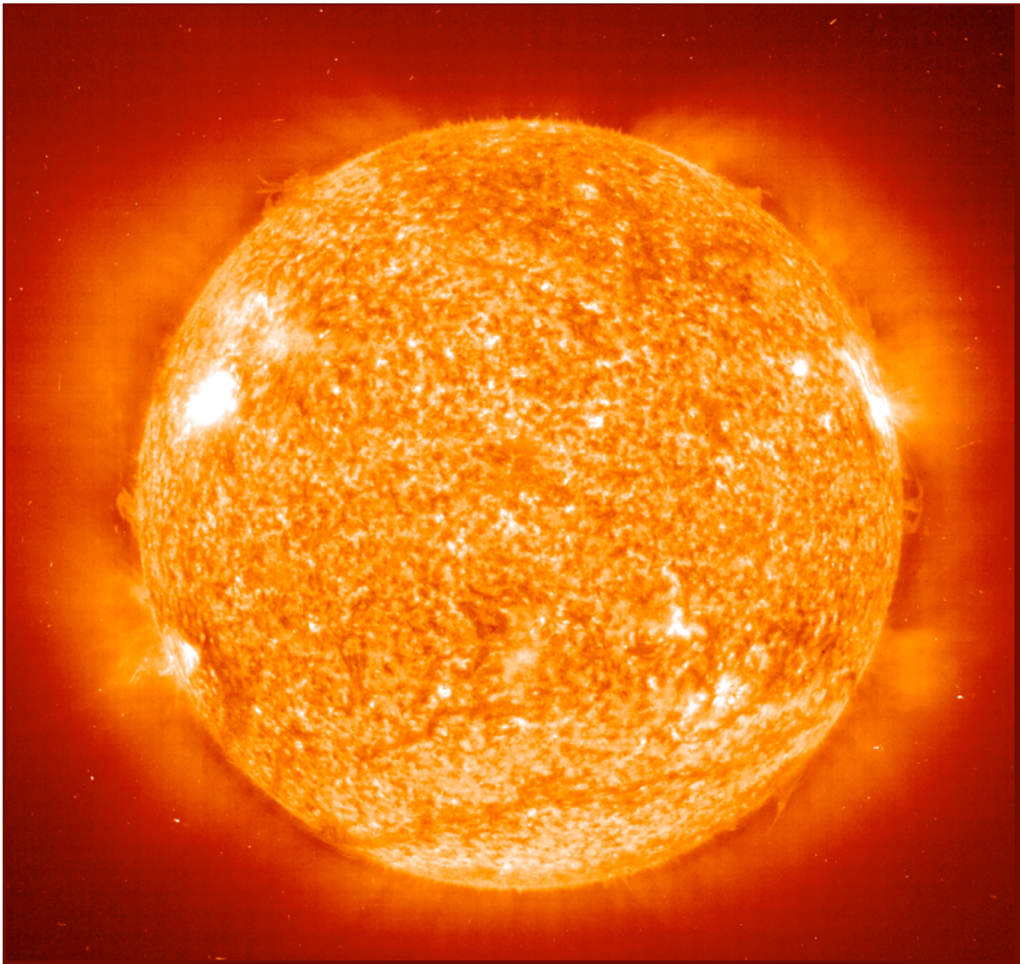
0ν Double Beta Decay

Probe Majorana masses

Use rarest decays on Earth

Probe identity of neutrinos





In 1854, von Helmholtz postulates that gravitational energy is responsible for solar burning.

In 1920, Eddington postulates that nuclear processes in the solar core may drive solar burning.

"We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a hotter place."

In 1938, Bethe and Critchfield calculate a solution...

In Bethe's original paper, neutrinos are not even in the picture.

(H. A. Bethe, Phys. Rev. 33, 1939)

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. INTRODUCTION

THE progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up *before* the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. \qquad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{aligned} &C^{12}+H=N^{13}+\gamma, && N^{13}=C^{13}+\epsilon^+ \\ &C^{13}+H=N^{14}+\gamma, && \\ &N^{14}+H=O^{15}+\gamma, && O^{15}=N^{15}+\epsilon^+ \\ &N^{15}+H=C^{12}+He^4. && \end{aligned} \qquad (2)$$

The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

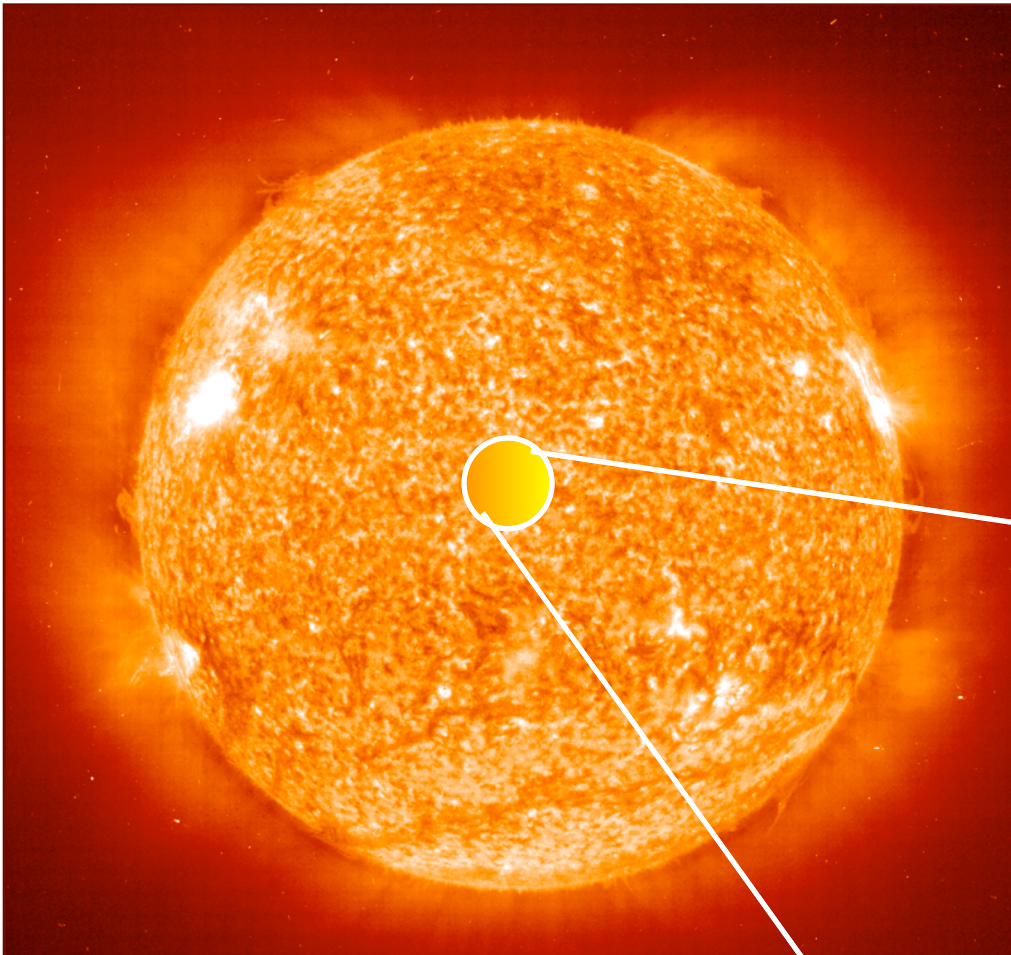
* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. + \nu' s\ ! \qquad (1)$$

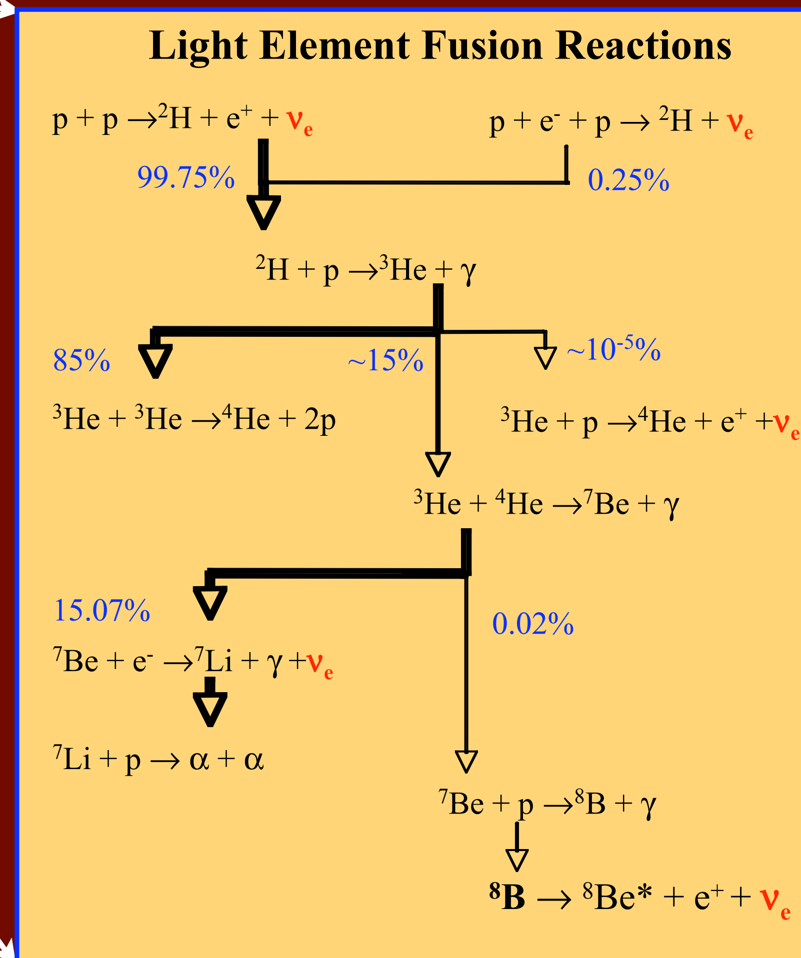
The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{aligned} &C^{12}+H=N^{13}+\gamma, && N^{13}=C^{13}+\epsilon^+ \\ &C^{13}+H=N^{14}+\gamma, && \\ &N^{14}+H=O^{15}+\gamma, && O^{15}=N^{15}+\epsilon^+ \\ &N^{15}+H=C^{12}+He^4. && \end{aligned} \qquad (2)$$



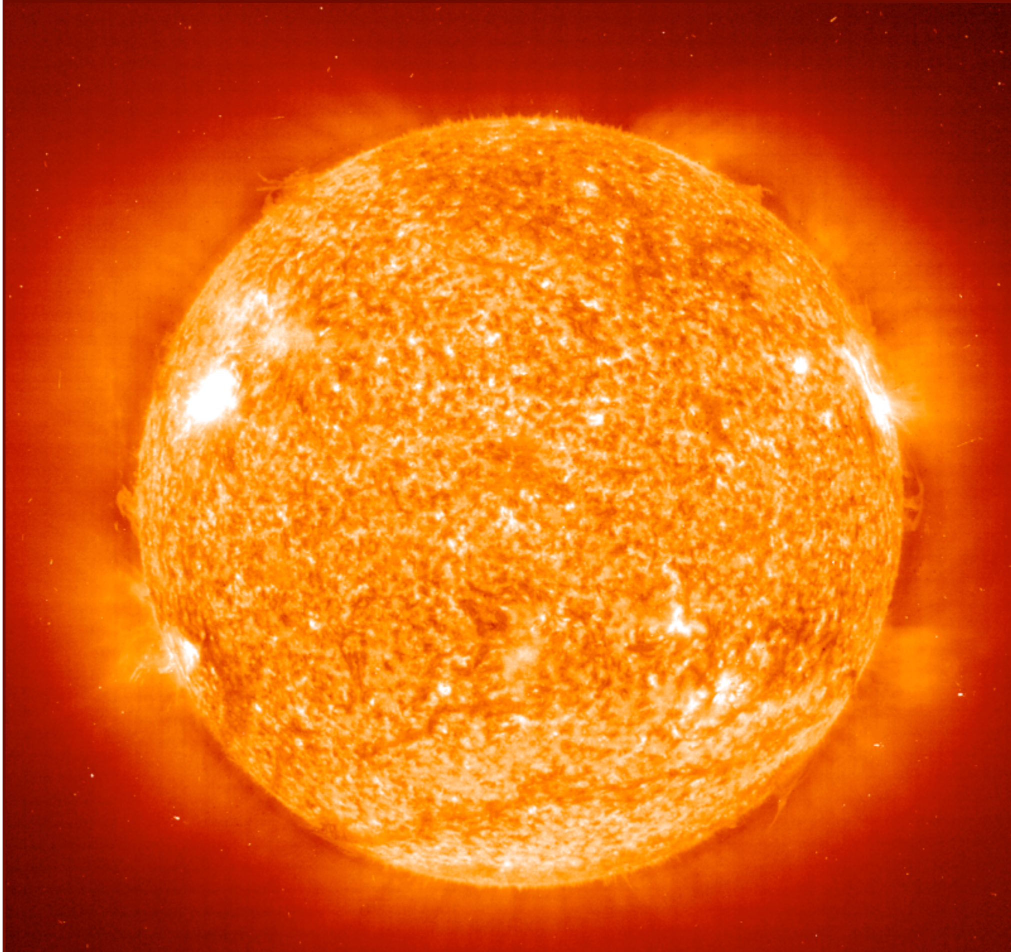
Basic Process:

$$4p + 2e^- \rightarrow He + 2\nu_e + 26.7\ \mathrm{MeV}$$



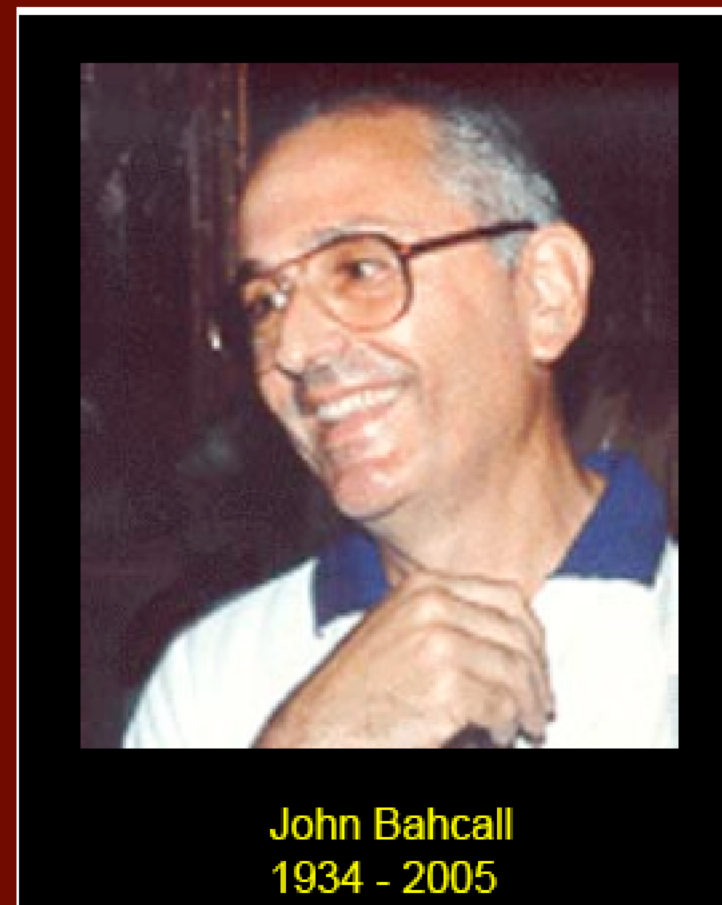
More detailed...

This is known as the pp fusion chain.



In the sixties, John Bahcall calculates the neutrino flux expected to be produced from the solar pp cycle.

Basic assumptions of what is known as the Standard Solar Model...



John Bahcall
1934 - 2005

(1) Sun is in hydrostatic equilibrium.

(2) Main energy transport is by photons.

(3) Primary energy generation is nuclear fusion.

(4) Elemental abundance determined solely from fusion reactions.

Measuring Neutrinos from the Sun

Gallium

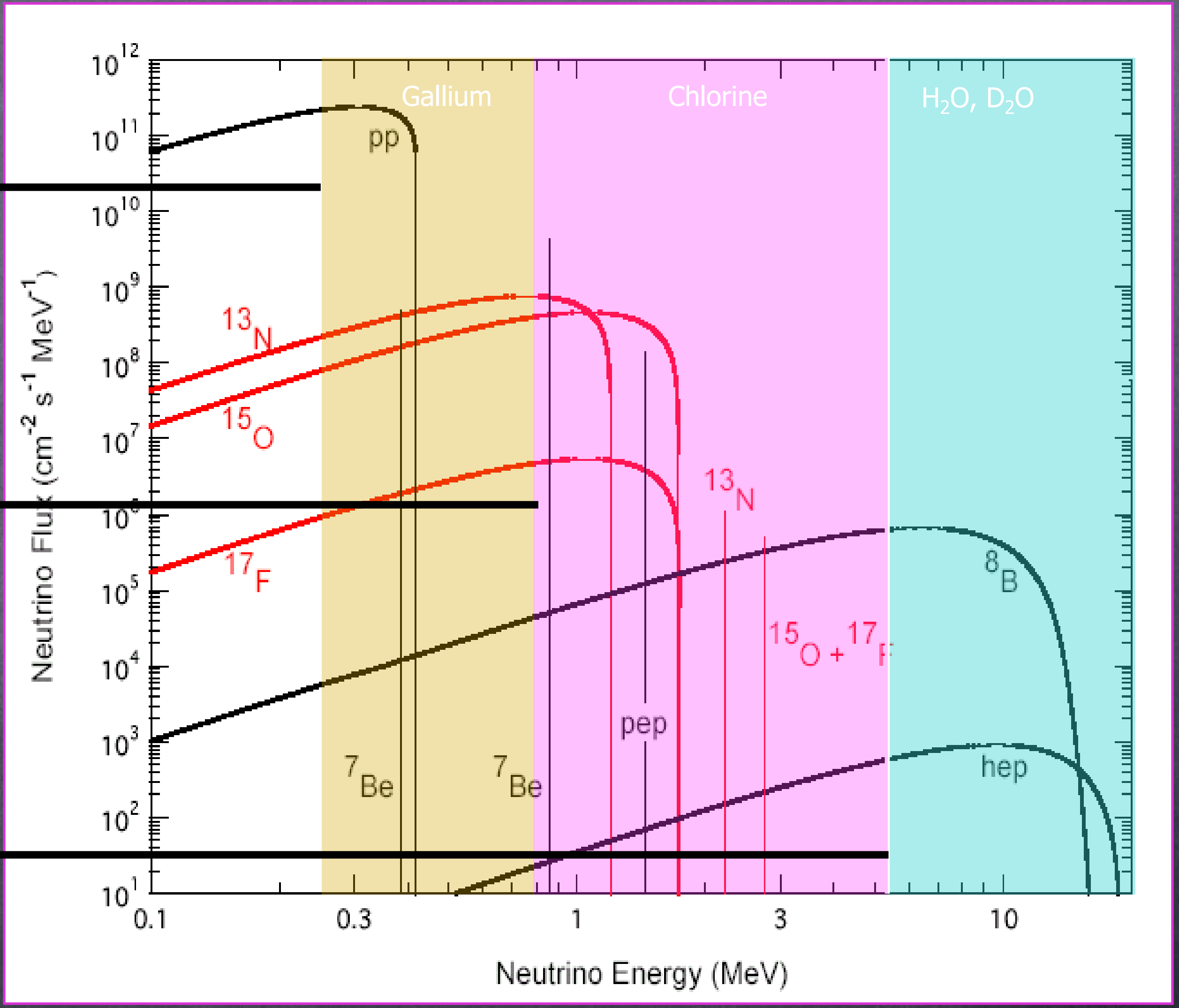
Technique: Radiochemical

Chlorine

Technique: Radiochemical

H_2O & D_2O

Technique: Cherenkov; Real Time



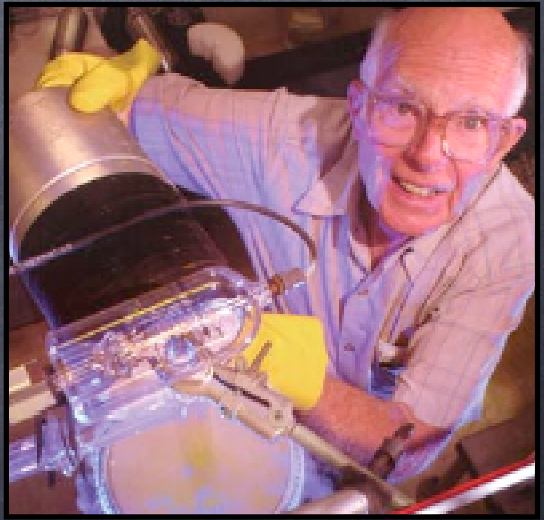
The Solar Puzzle Begins..

- Davis designs first experiment to measure electron neutrinos coming from the sun.
- Experiment counted individual argon atoms (~40 atoms/mo).

HOMESTAKE

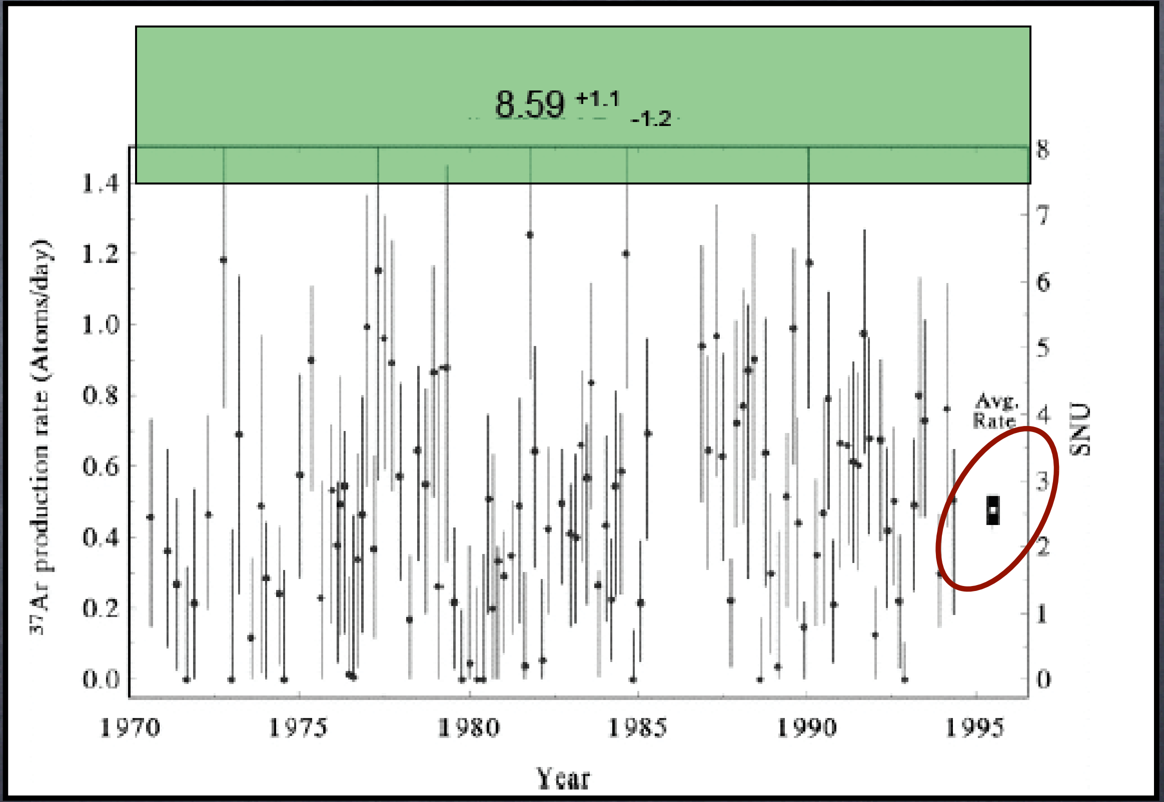
$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$

Raymond Davis, Jr.
Winner of 2002 Nobel Prize in Physics

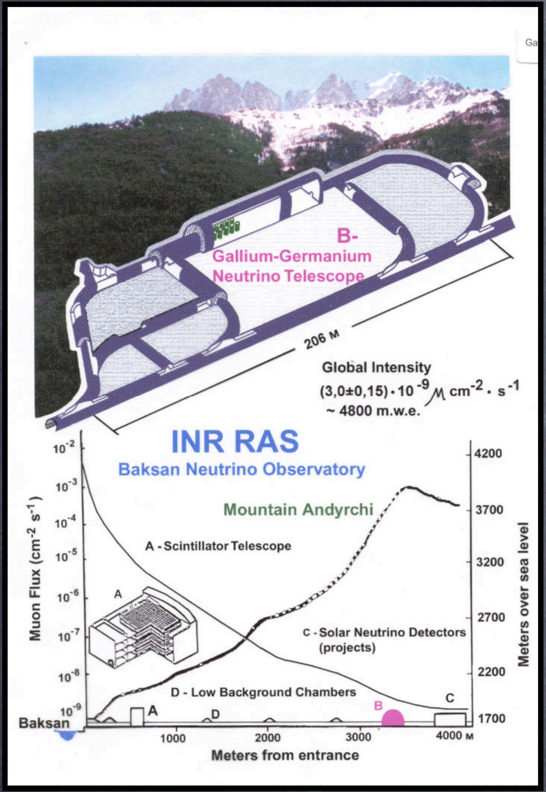


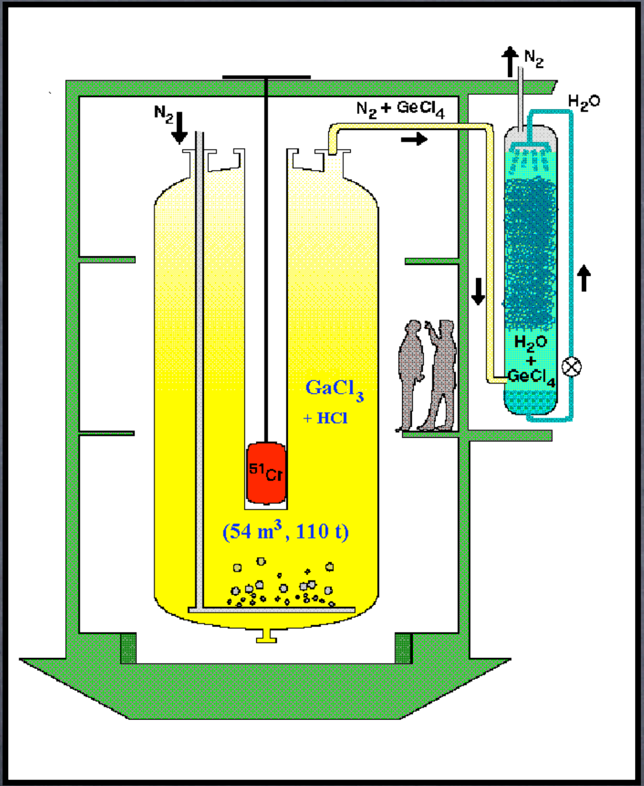
Homestake Results (1970-1994)

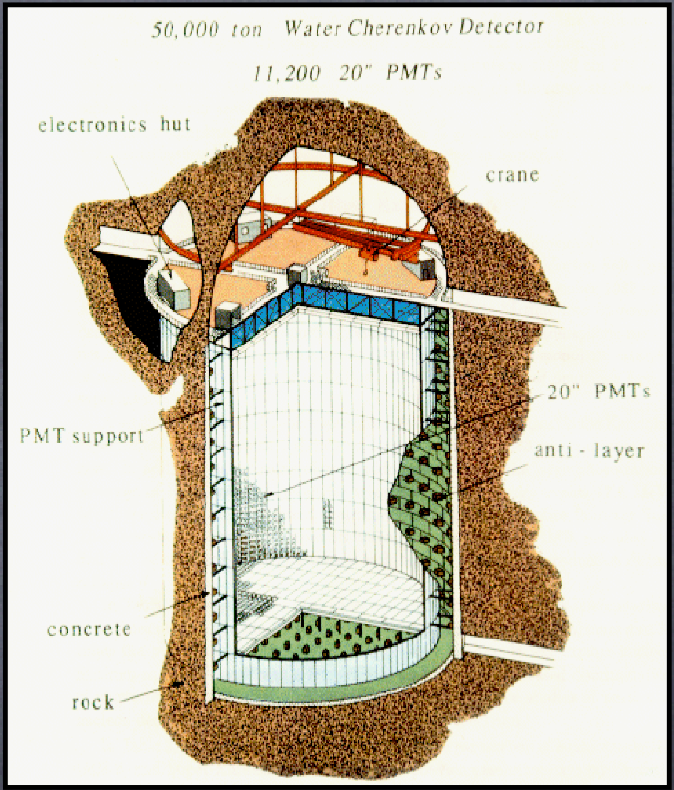
- Only 1/3 of the neutrinos expected from the sun are seen in the Homestake experiment.
- Doubts on hydrodynamic calculations and/or experimental data are raised.
- When in doubt, do it again.



Repeat as necessary...







SAGE

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

Measures 1/2 of expected flux

Gallex/GNO

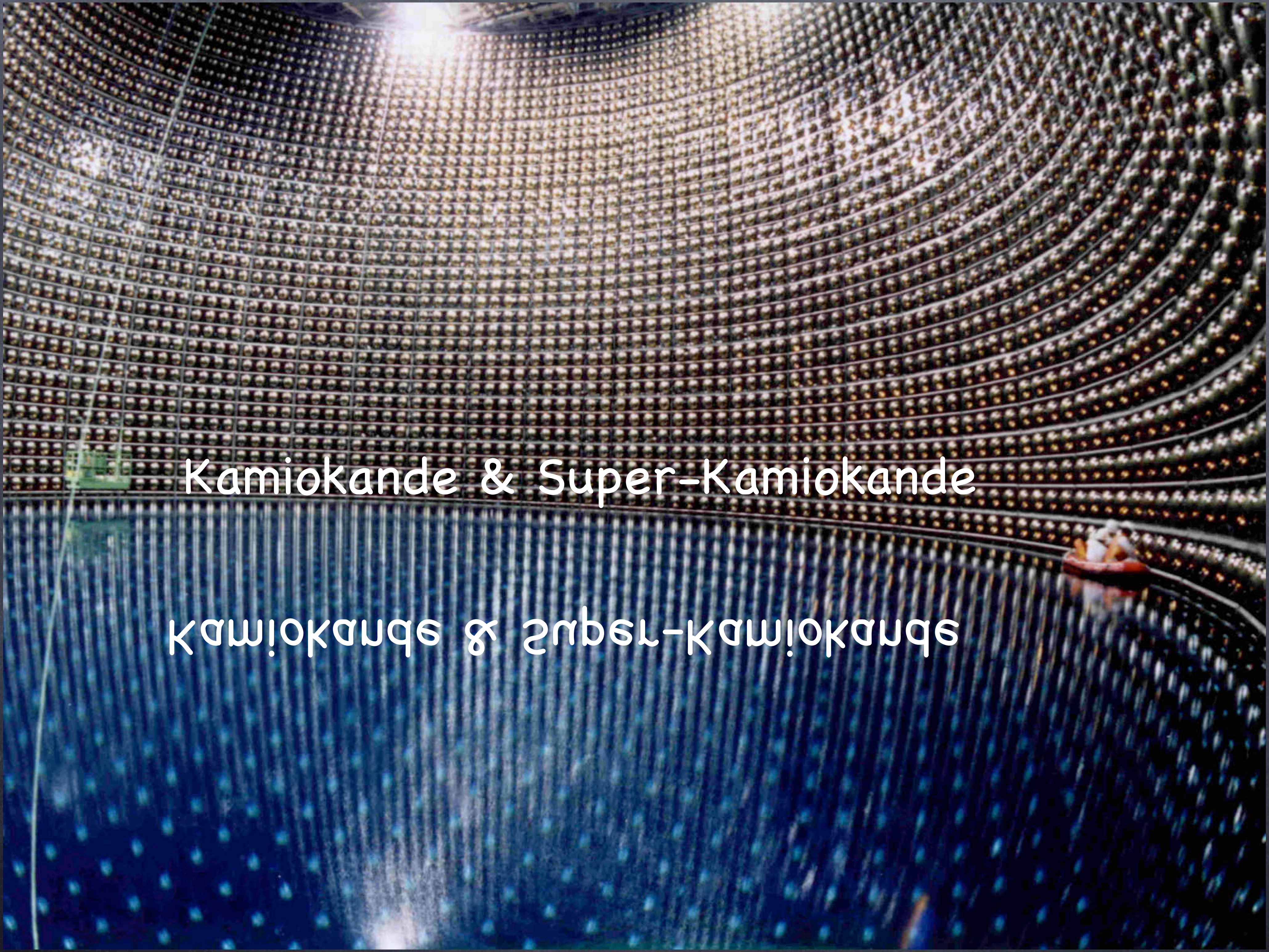
$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

Measures 1/2 of expected flux

Super-Kamiokande

$e^- + \nu_e \rightarrow \nu_e + e^-$

Measures 40% of expected flux

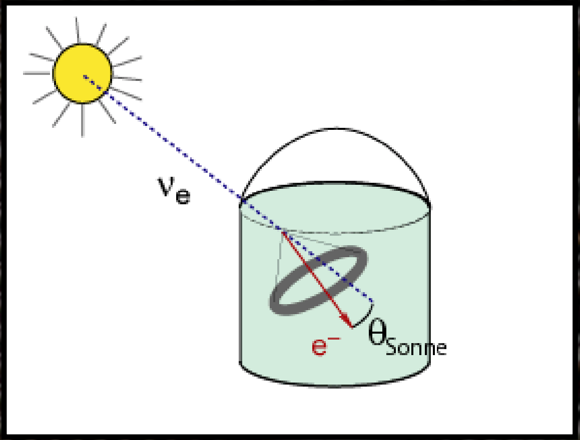

Kamiokande & Super-Kamiokande

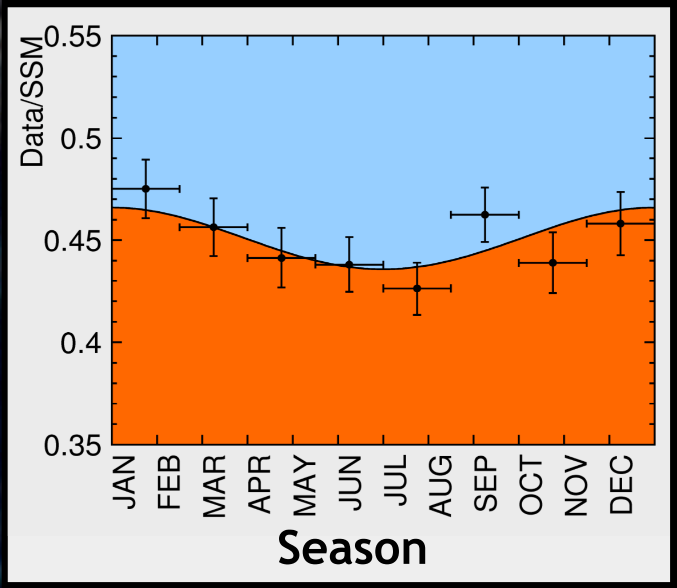
Kamiokande & Super-Kamiokande

- First time Cerenkov, real-time detection is used for solar neutrinos.
- Use of elastic scattering as detection channel

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

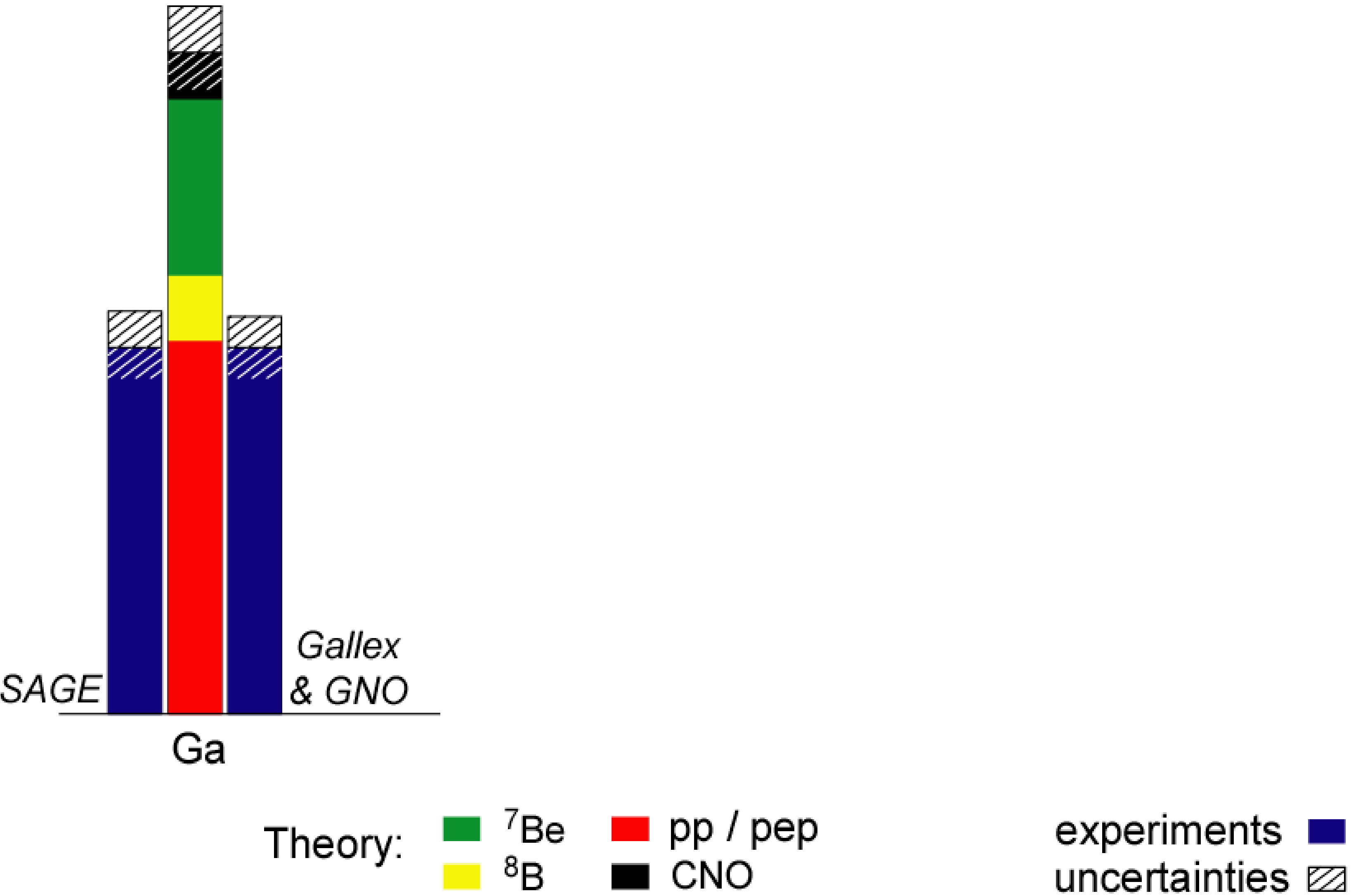
- Sensitive to highest energy (^{8}B) neutrino.
- Use neutrino direction to discern from background.



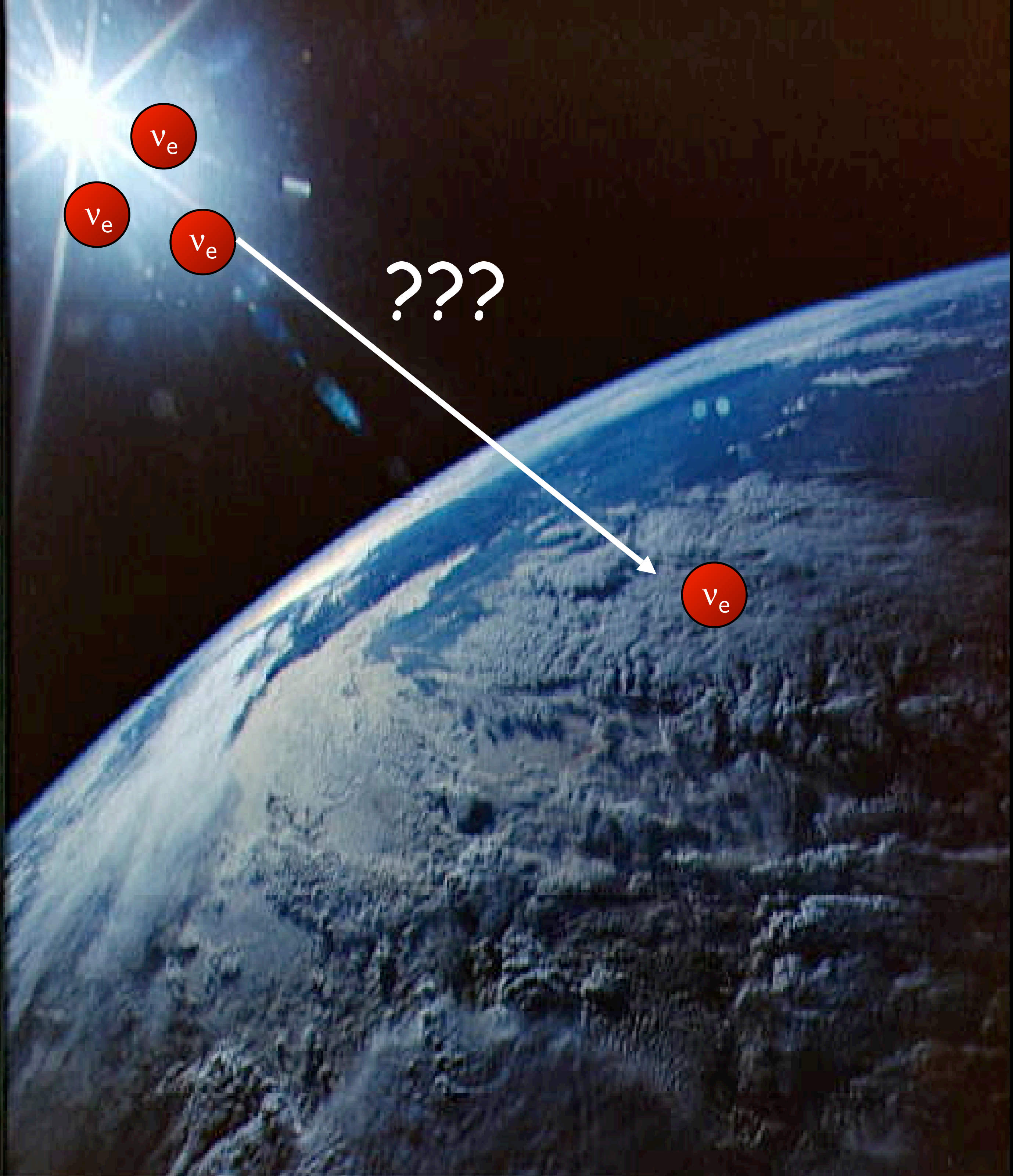


Comparison of total rates

experiments and SSM (Bahcall-Pinsonneault



H. Murayama

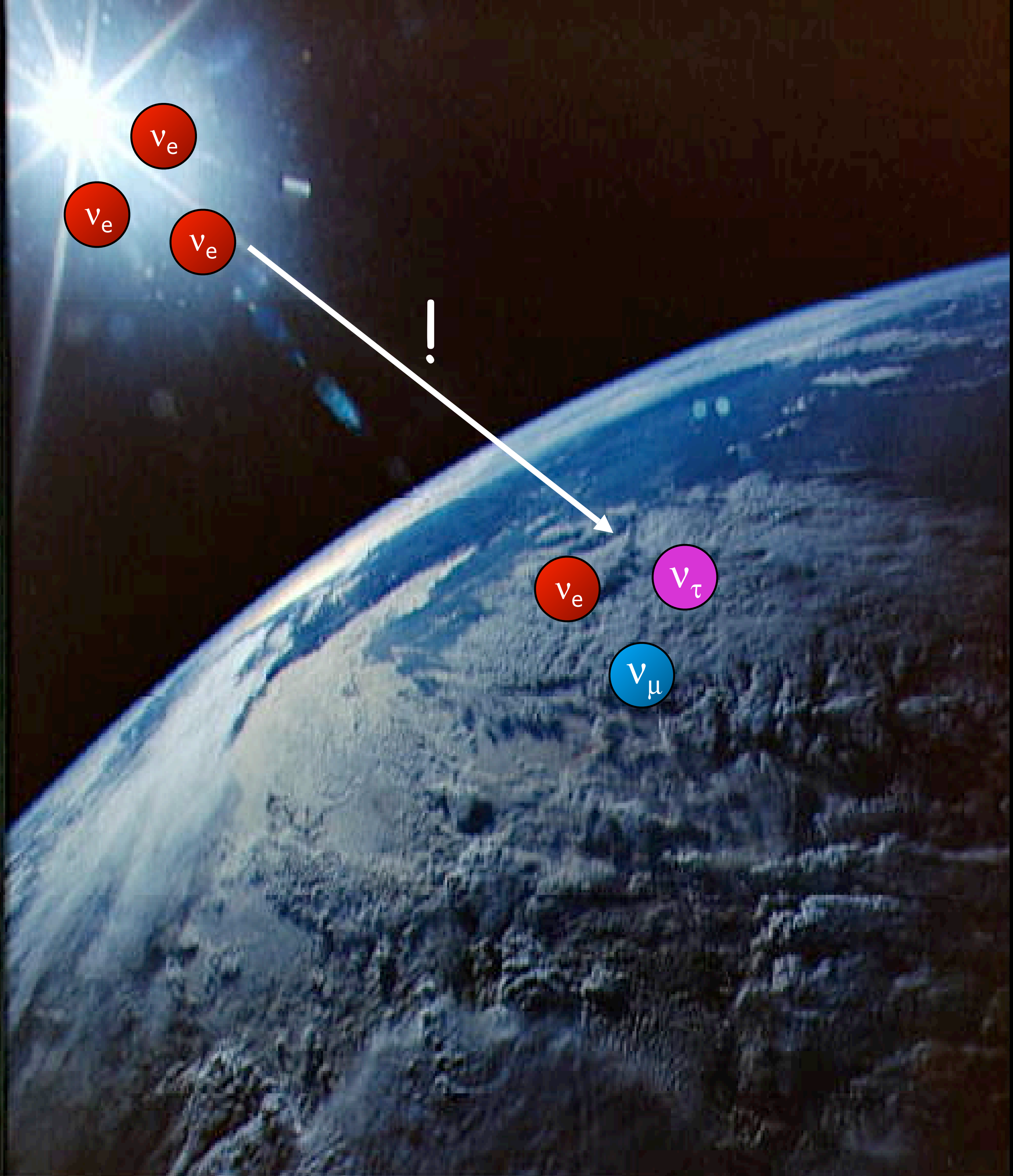


The sun only makes "electron-type" neutrinos

Detectors only detect electron-type neutrinos.

What if neutrinos are changing from one type to the other?

Need to measure ALL neutrino types, regardless of what kind (flavor) they are…



The sun only makes "electron-type" neutrinos

Detectors only detect electron-type neutrinos.

What if neutrinos are changing from one type to the other?

Need to measure ALL neutrino types, regardless of what kind (flavor) they are…

Neutrino Oscillations

- Neutrino oscillations is the mechanism by which neutrinos can change from one type to the other...

Flavor $\neq$ Mass

- Mixing occurs if...
  - Neutrino flavors mix
  - Neutrinos have mass
- Look for appearance of different neutrino type or deficit of the total neutrinos expected.

$$\left|\nu\right\rangle = U_{e1}e^{-iE_1 t}\left|\nu_1\right\rangle + U_{e2}e^{-iE_2 t}\left|\nu_2\right\rangle + U_{e3}e^{-iE_3 t}\left|\nu_3\right\rangle = \left|\nu_e\right\rangle$$

$$\left|\nu\right\rangle = e^{-iE_1 t}(U_{e1}\left|\nu_1\right\rangle + U_{e2}e^{-iE_2 t+iE_1 t}\left|\nu_2\right\rangle + U_{e2}e^{-iE_3 t+iE_1 t}\left|\nu_3\right\rangle)$$

$$E_j - E_i \approx (m_j^2 - m_i^2)\frac{L}{2E}$$

$$P(\nu_\alpha - \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{j>i} U_{\alpha,j}U_{\beta,j}U_{\alpha,i}U_{\beta,i}\sin^2(1.27\Delta m_{ij}^2 L/E)$$

Neutrino Oscillations

- In general, we have a 3 x 3 matrix that describes neutrino mixing (the Maki-Nakagawa-Sakata-Pontecorvo, or MNSP mixing matrix):

- However, the picture simplifies if one of the mixing angles is small...

Bruno Pontecorvo

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor, accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

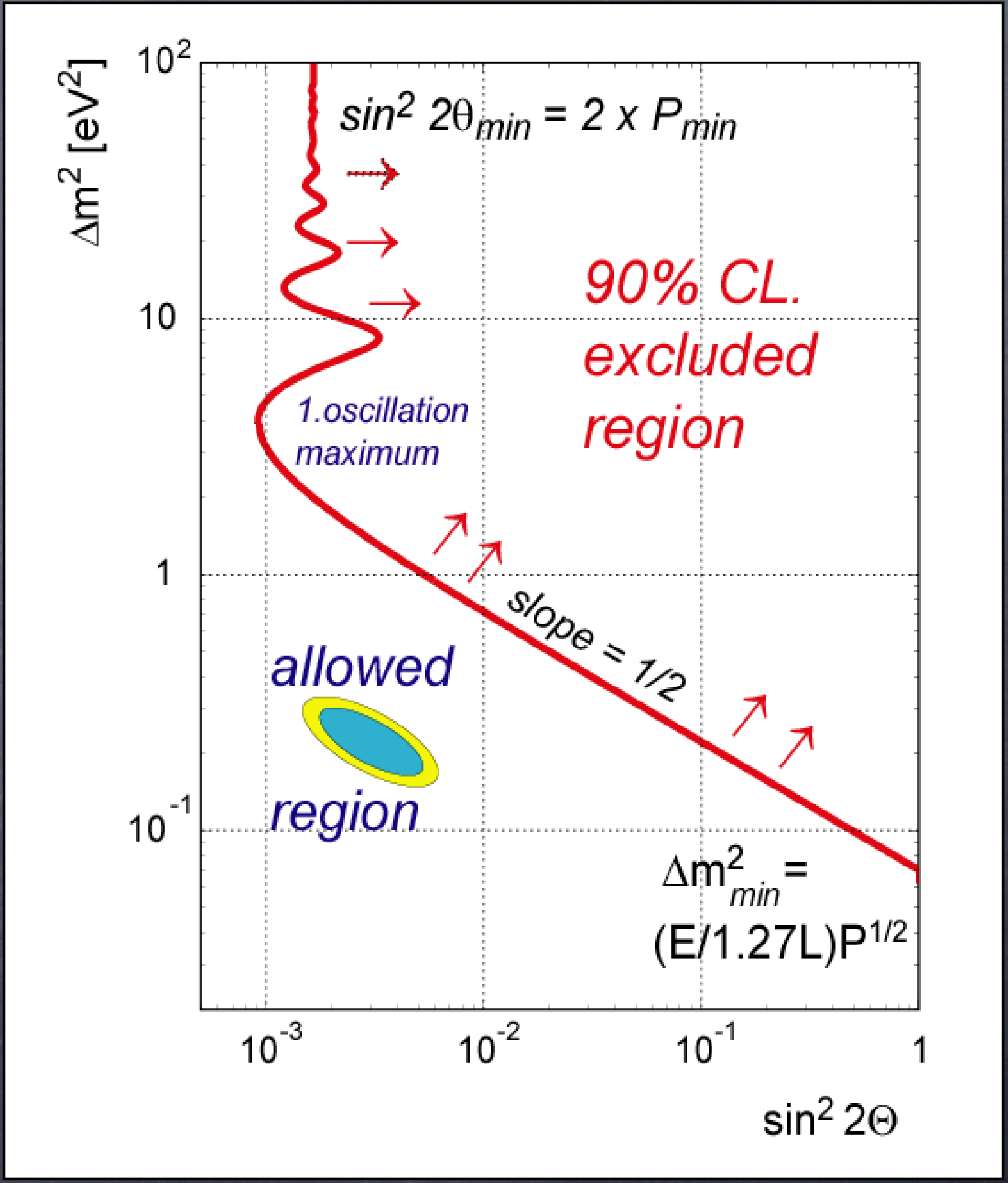
- Depends only on two fundamental parameter and two experimental parameters (for a given neutrino species).

$$\mathcal{P}_{\text{surv}} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E_\nu} L\right)$$

Neutrino Oscillations

- One often uses mass-mixing plots to denote exclusion/allowed regions.
- Fair to use in 2 x 2 approximation (but can be confusing if more than one neutrino mixing is shown).

$$\mathcal{P}_{\rm surv} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E_\nu} L\right)$$




Neutrinos?
The Sudbury Neutrino
Observatory
(surface view)

The Sudbury Neutrino Observatory

2092 m underneath the surface
(6800 ft level)

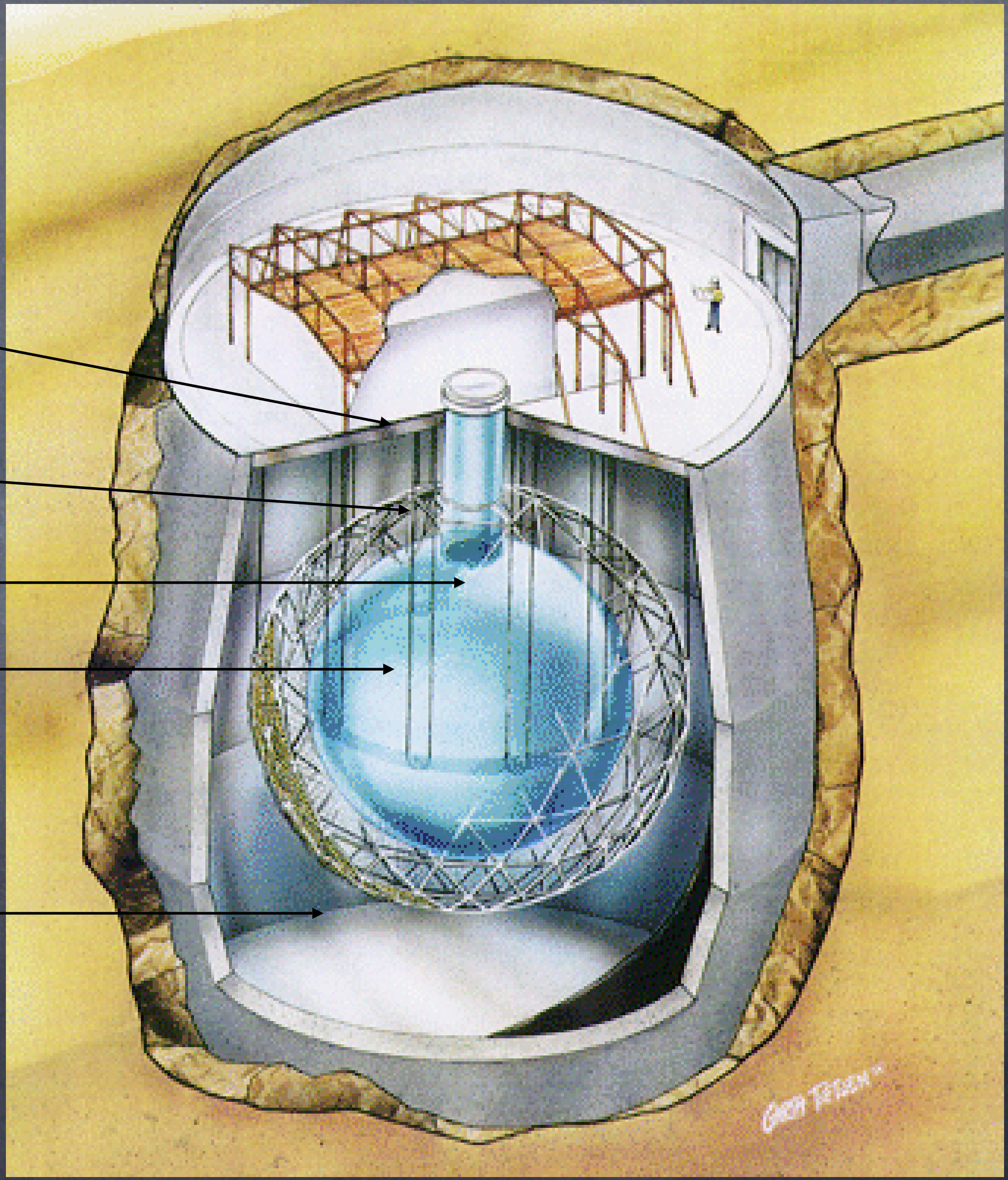
Almost 10,000 phototubes to detect light emitted when neutrinos interact.

Acrylic vessel 12 meter diameter

1000 Tonnes heavy water

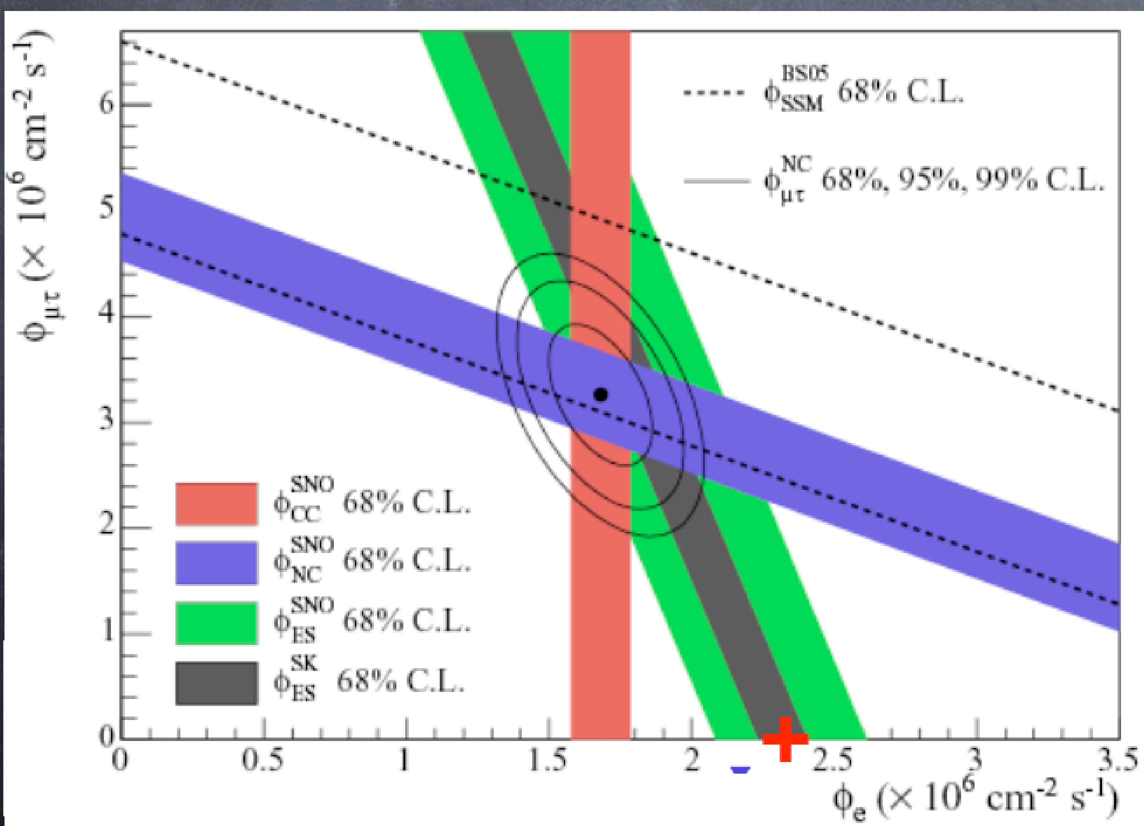
7000 Tonnes of ultra clean water, as a shield.

Urylon Liner and Radon Seal



Neutrino Mixing Confirmed

- Neutrino mixing established (non-electron flavors coming from the sun).
- Original ^8B fluxes confirmed.
- Solar core temperature known to 1%.



Fluxes

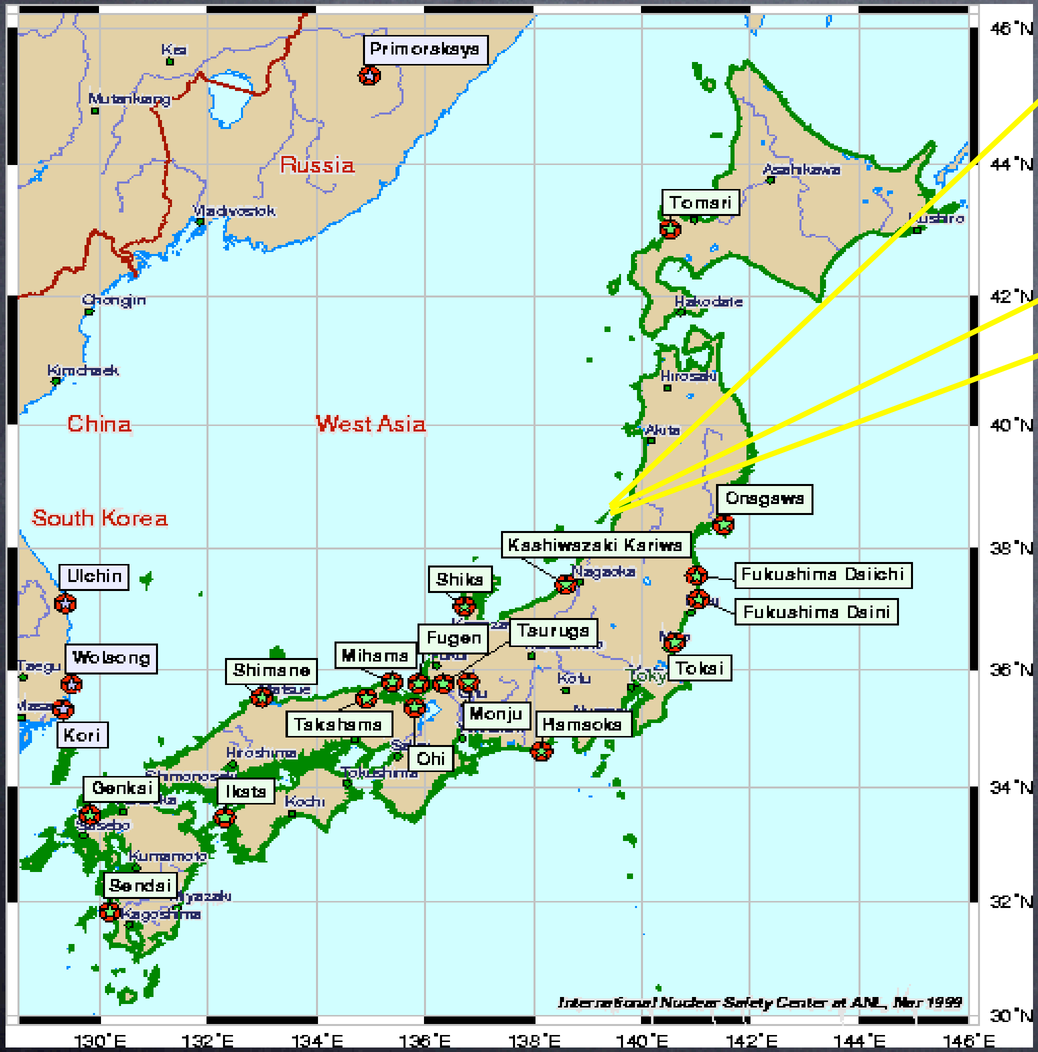
(10^6 cm^{-2} s^{-1})

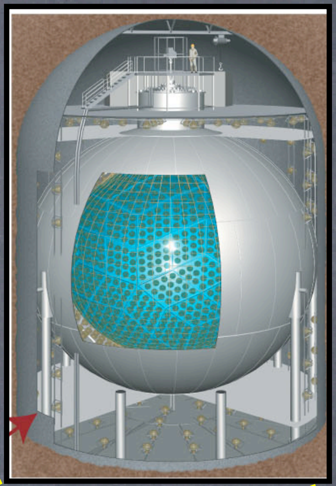
ν_e:	1.68(11)
$\nu_{\mu\tau}$:	3.26(47)
ν_{total}:	4.94(43)
ν_{SSM}:	5.69

KamLAND

- Using reactor neutrinos to match the sun...

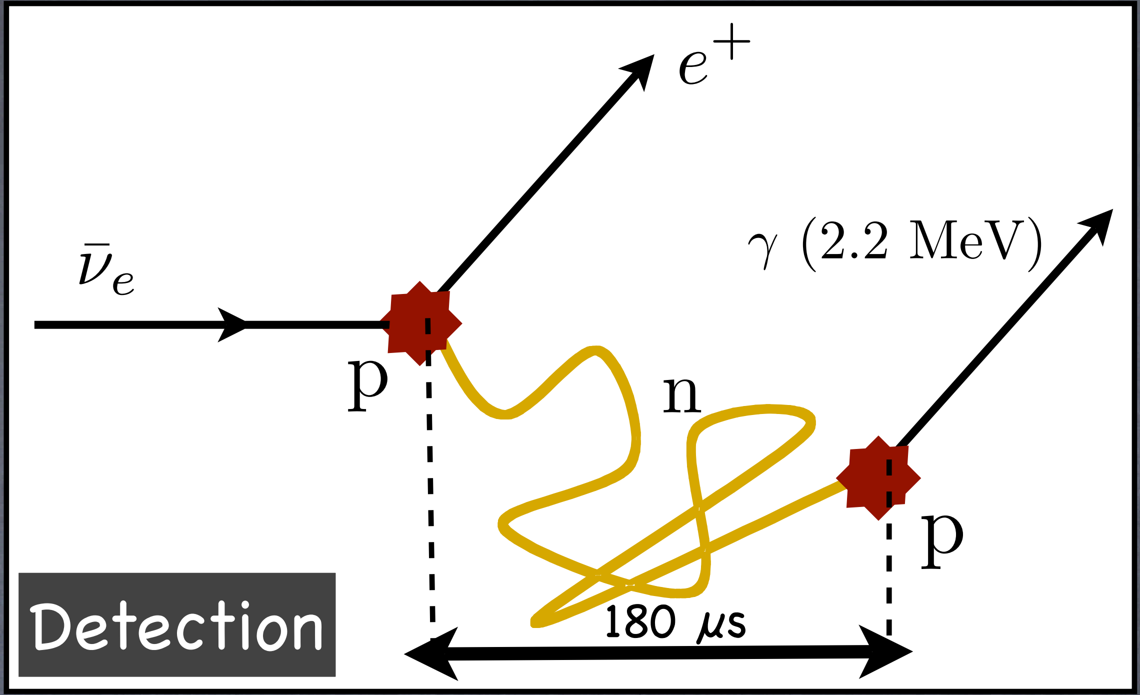
KamLAND

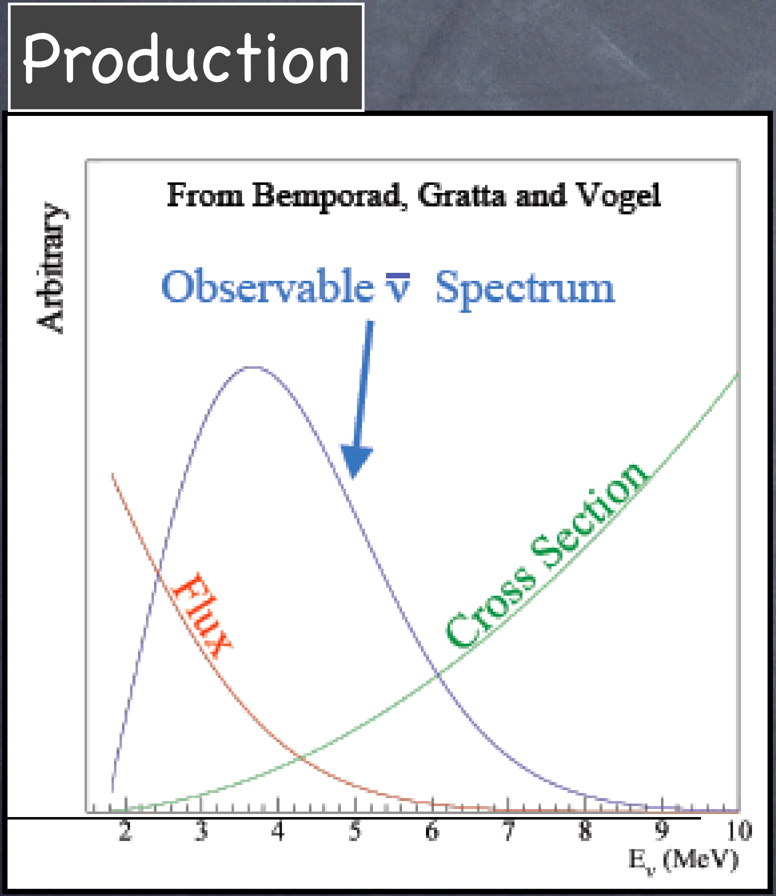




- Located approximately 180 km (average) from strongest reactors
- Distance is selected so as to probe same oscillation length as solar experiments.

Reactor Flux & Interactions

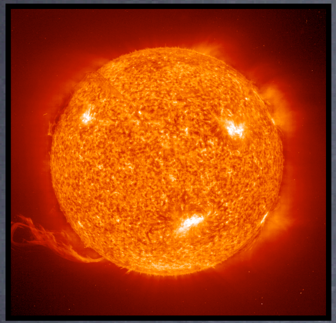


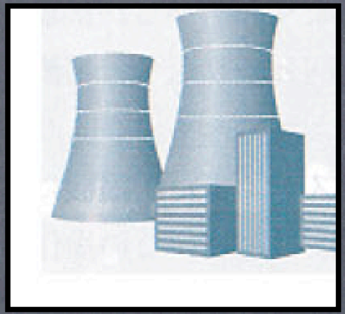


- Combination of falling flux and rising cross-section yields average energy ≈ 4 MeV.
- Sensitive to both θ_{13} and θ_{12}.

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Solar vs. KamLAND





Produced in the sun (fusion).

MSW/matter effects.

Neutrinos.

Baseline ≈ 10^{11} km

Nuclear reactors (fission)

No matter effects

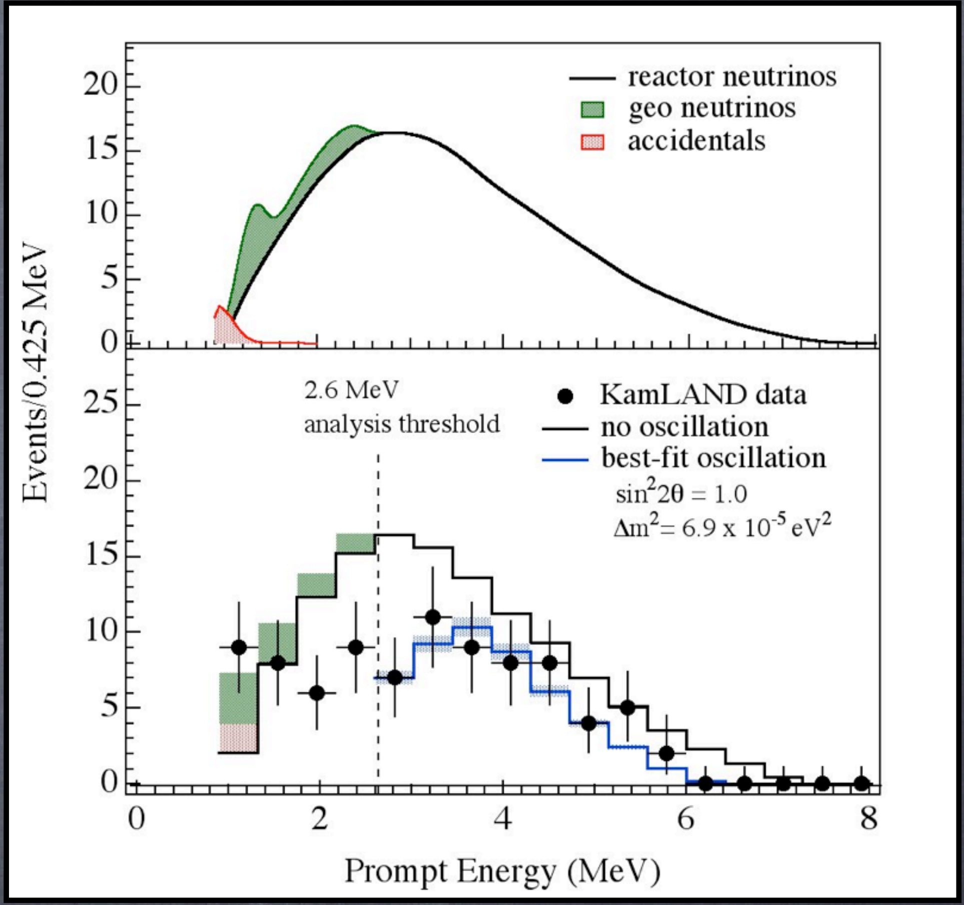
Anti-neutrinos.

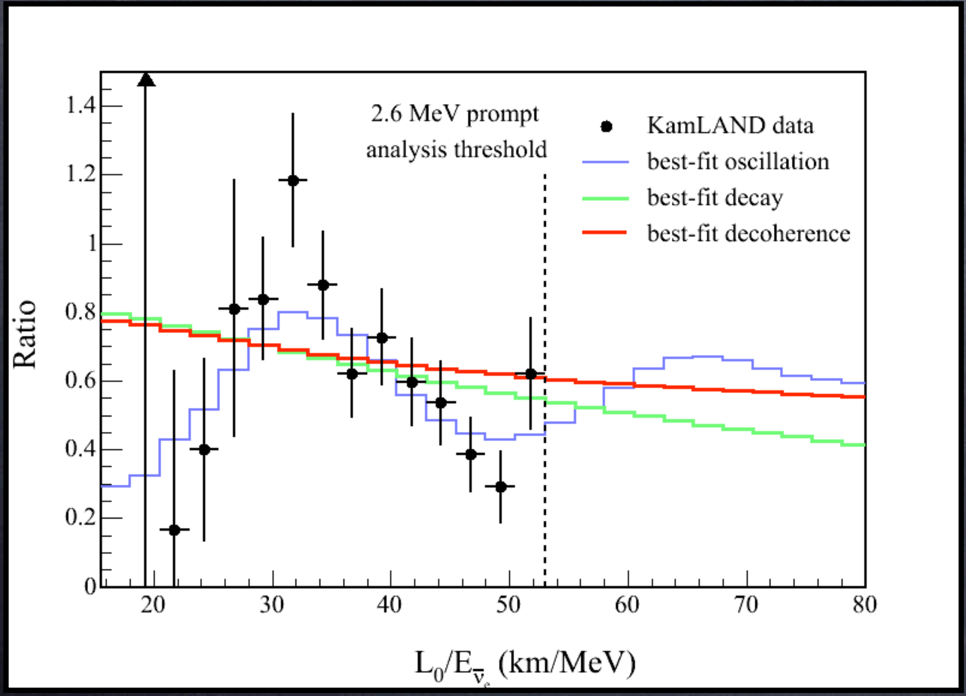
Baseline ≈ 10^{3} km

No common systematics!

Confirmation!

- Can look at deficit in neutrinos OR L/E behavior.
- Both consistent with solar neutrino oscillations (in vacuum)

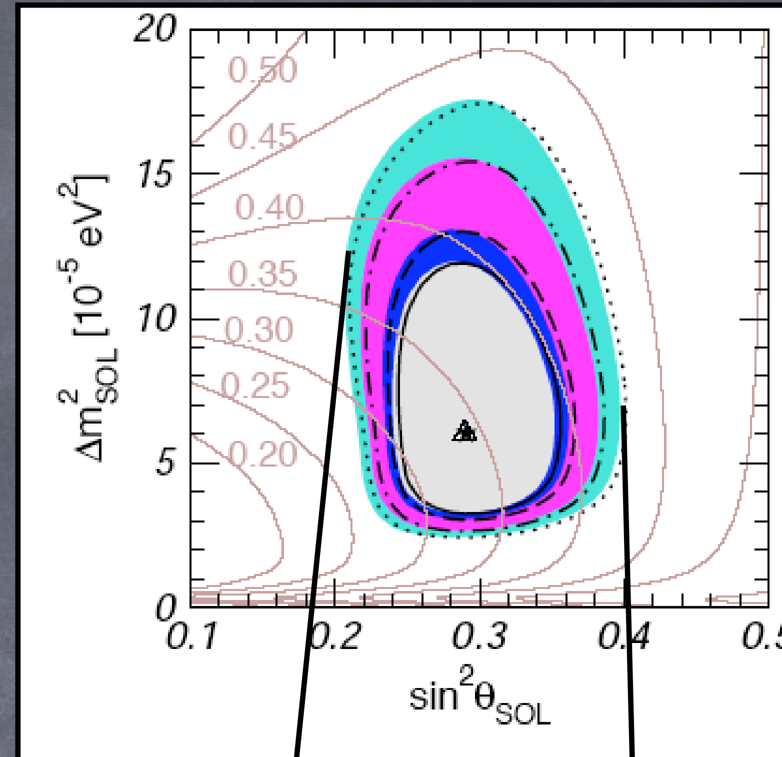


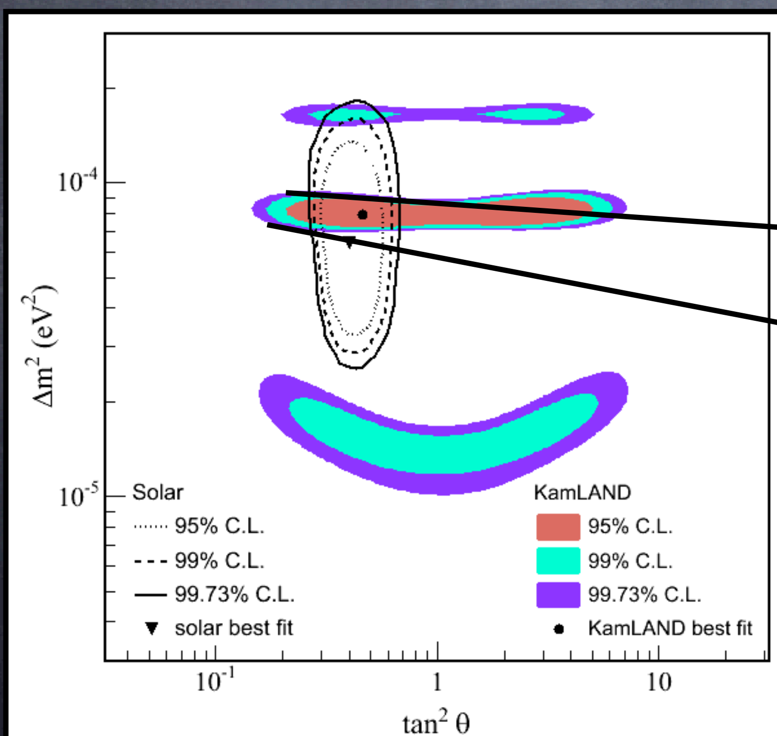


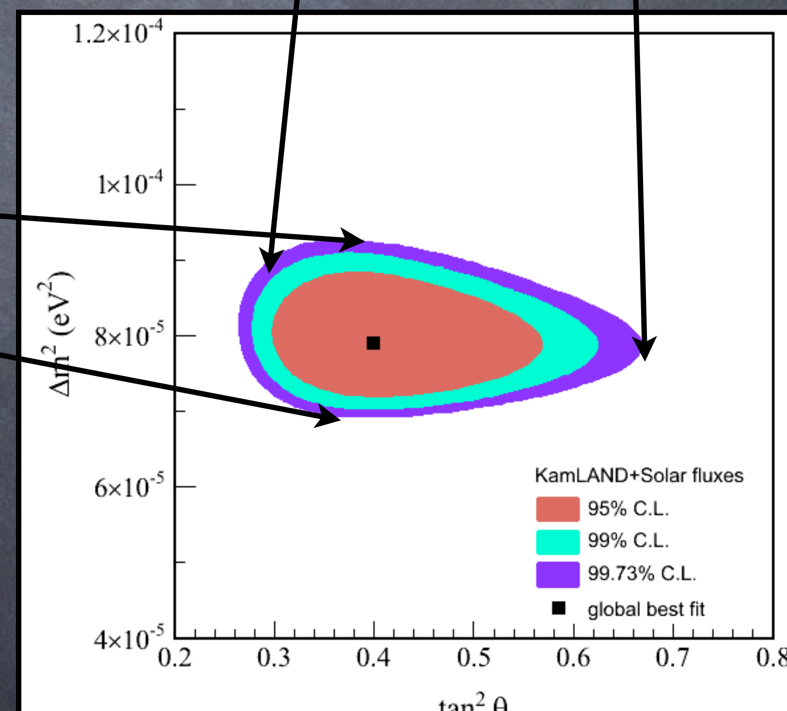
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Confirmation

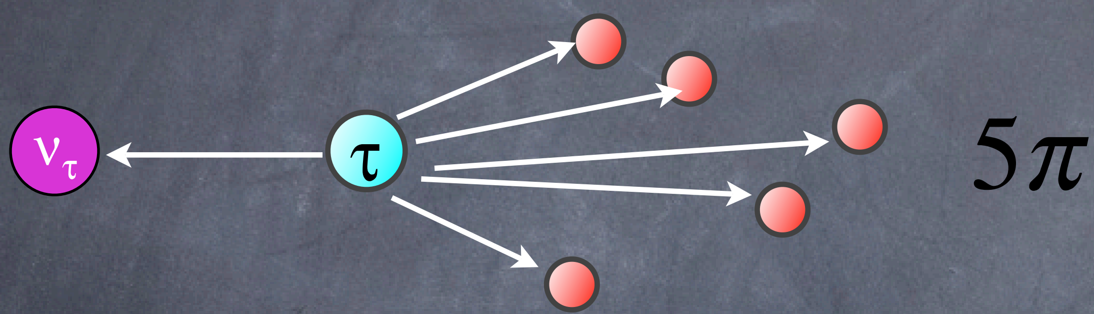
- Combination of reactor and solar data confirms oscillation mechanism.
- Rule out various exotic explanations (CPT violation, etc.)

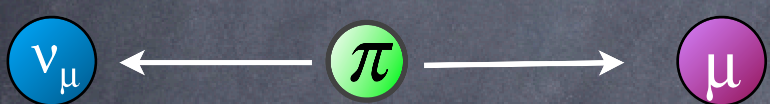


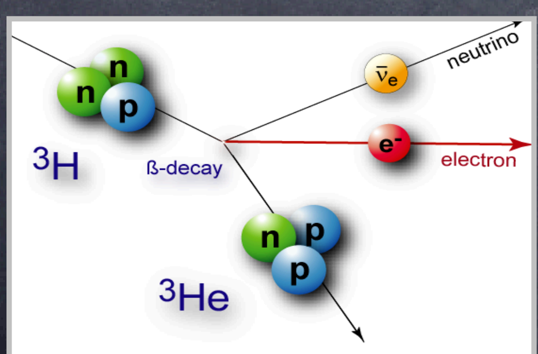




Direct Measurements







$m_{\nu_\tau} < 18.2$ MeV (95% CL)

(ALEPH 1998)

$m_{\nu_\mu} < 170$ keV (90%CL)

(PSI 1996)

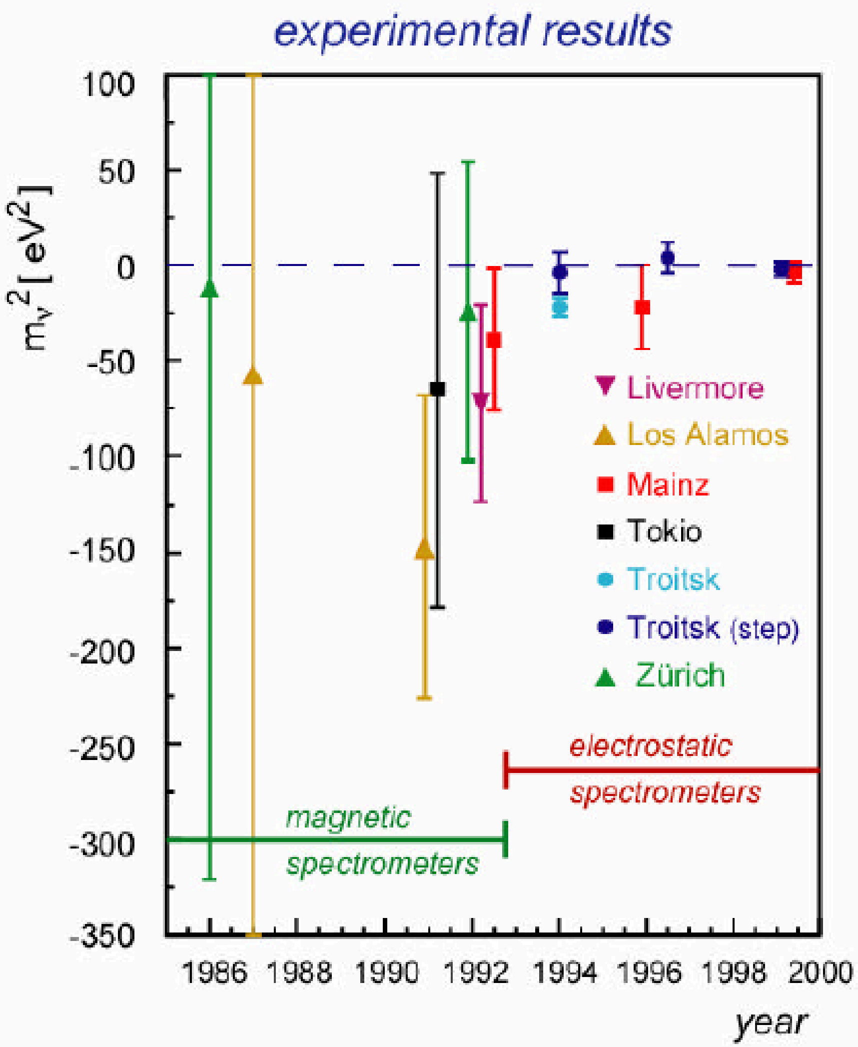
$m_{\nu_e} < 2.2$ eV (95% CL)

(Mainz 2000)

Oscillation results tell us probing ν_e probes all neutrinos at once !

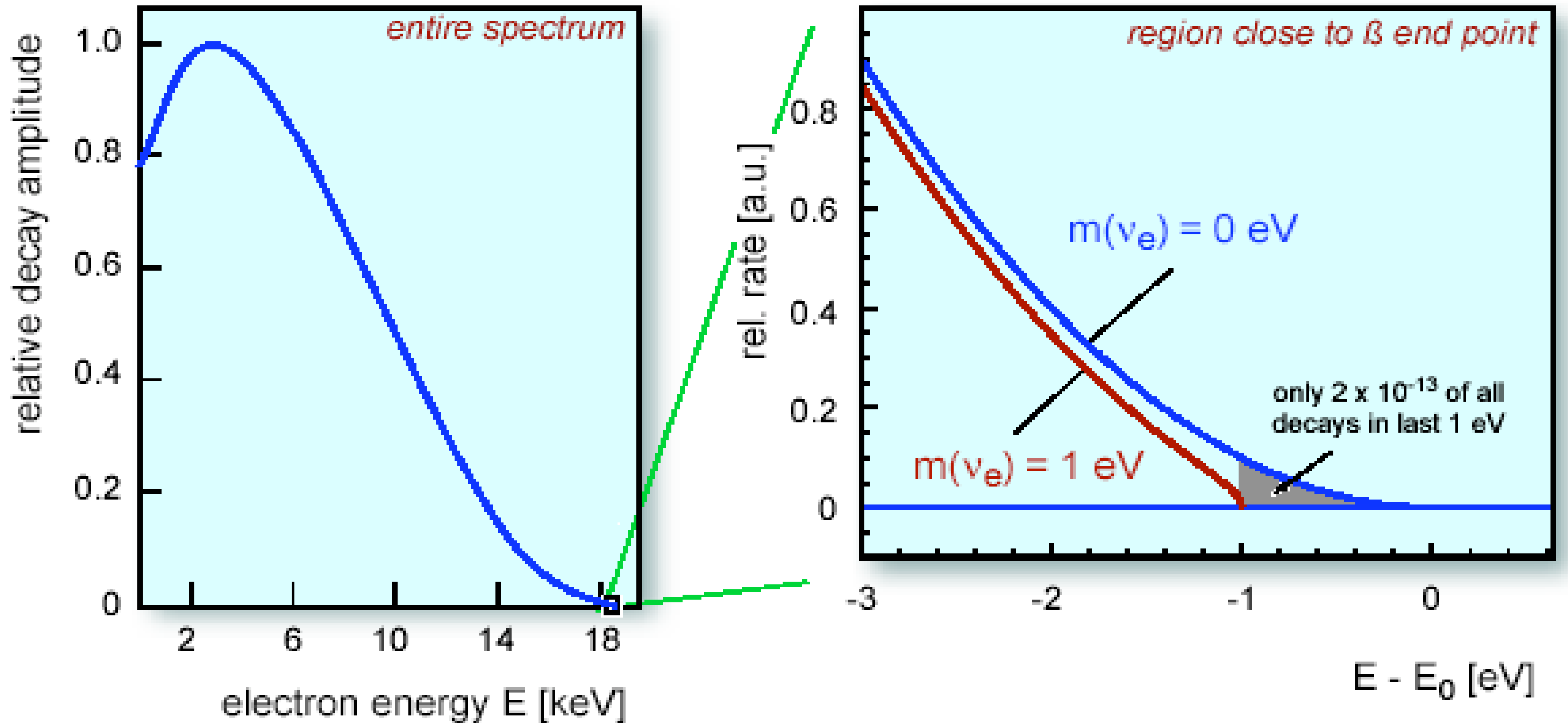
The Past....

	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokio *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 7.0 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	< 2.2 eV
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.2 eV



β-decay Endpoint Measurement

$$\frac{dN}{dE} = C \times F(Z,E) p_e (E + m_e^2)(E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 + m_i^2}$$

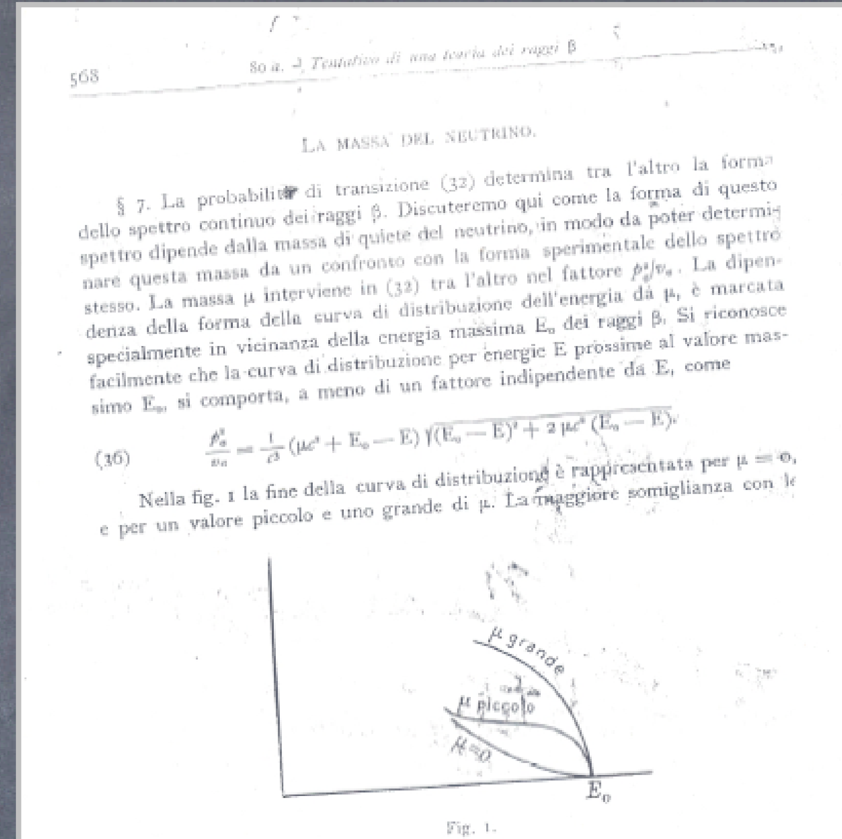


Tritium β-decay allows precise measurement of the absolute neutrino mass scale.

Essentially a search for a distortion in the shape of the β-spectrum in the endpoint energy region.

Beta Decay from Tritium

- Matrix element independent of neutrino mass.
- Mass term comes from kinetic (energy conservation) term.
- Final states need to be understood or avoided.



568 80 a. – *Tentativo di una teoria dei raggi β*

LA MASSA DEL NEUTRINO.

§ 7. La probabilità di transizione (32) determina tra l'altro la forma dello spettro continuo dei raggi β. Discuteremo qui come la forma di questo spettro dipende dalla massa di quiete del neutrino, in modo da poter determinare questa massa da un confronto con la forma sperimentale dello spettro stesso. La massa μ interviene in (32) tra l'altro nel fattore p_σ^2/v_σ. La dipendenza della forma della curva di distribuzione dell'energia da μ, è marcata specialmente in vicinanza della energia massima E_0 dei raggi β. Si riconosce facilmente che la curva di distribuzione per energie E prossime al valore massimo E_0, si comporta, a meno di un fattore indipendente da E, come

$$\frac{p_\sigma^2}{v_\sigma} = \frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}. \quad (36)$$

Nella fig. 1 la fine della curva di distribuzione è rappresentata per μ = 0, e per un valore piccolo e uno grande di μ. La maggiore somiglianza con le

μ grande

μ piccolo

μ=0

E_0

Fig. 1.

$$F(Z,E) = \frac{x}{1 - exp{-x}}(a_0 a_1 \cdot \beta);$$

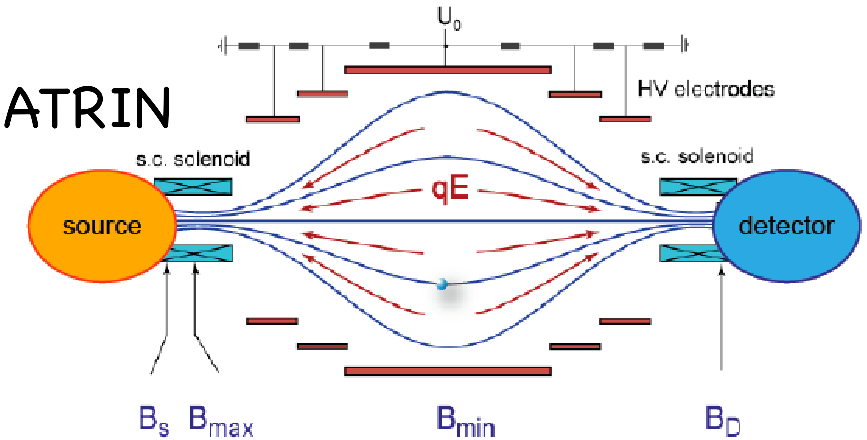
$$a_0 = 1.002037, a_1 = -0.001427, x = \frac{2\pi Z \cdot \alpha}{\beta}$$

$$\frac{dN}{dE} = C \times F(Z,E) p_e (E + m_e^2)(E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 + m_i^2}$$

Two Techniques

Spectroscopy

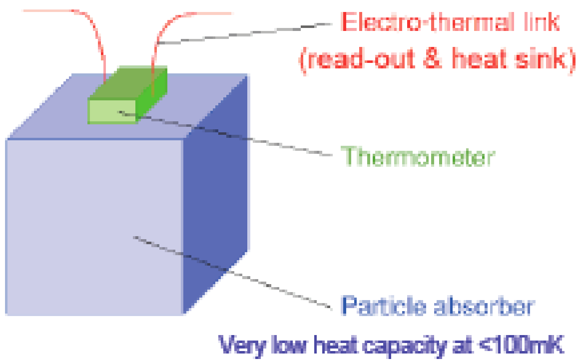
KATRIN



$$^3\mathrm{He} \rightarrow {}^3\mathrm{H} + e^- + \bar{\nu}_e$$

Bolometry

MIBETA
&
MARE



$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^- + \bar{\nu}_e$$

Examines only region of interest.

Excellent statistics.

Excellent resolution (1 eV).

Disadvantages: final states, scattering

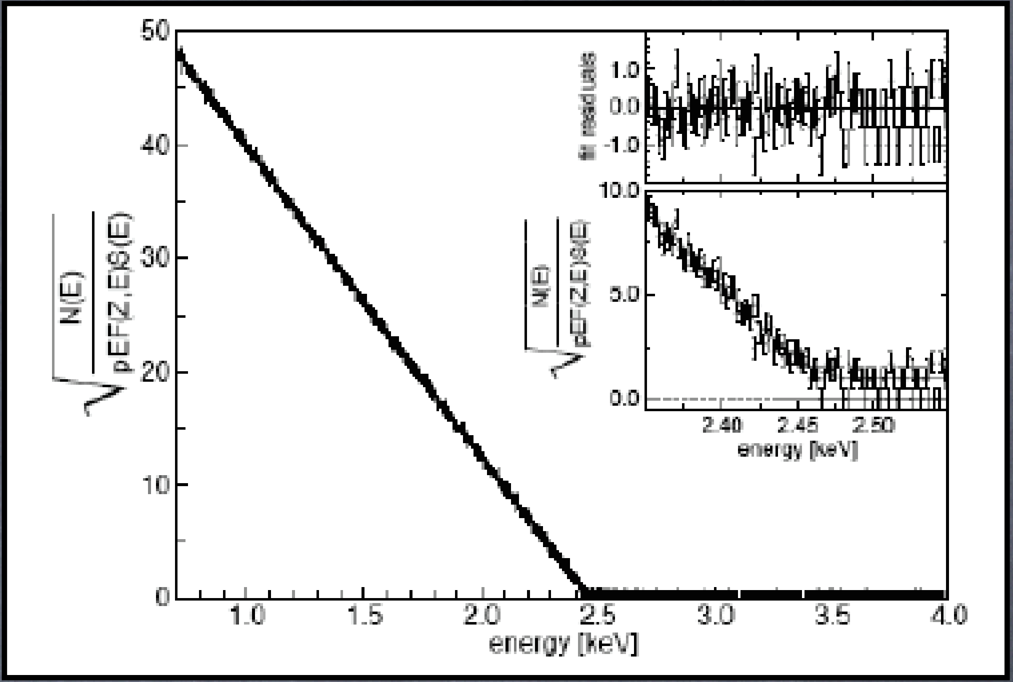
Detection of all energy, including final states.

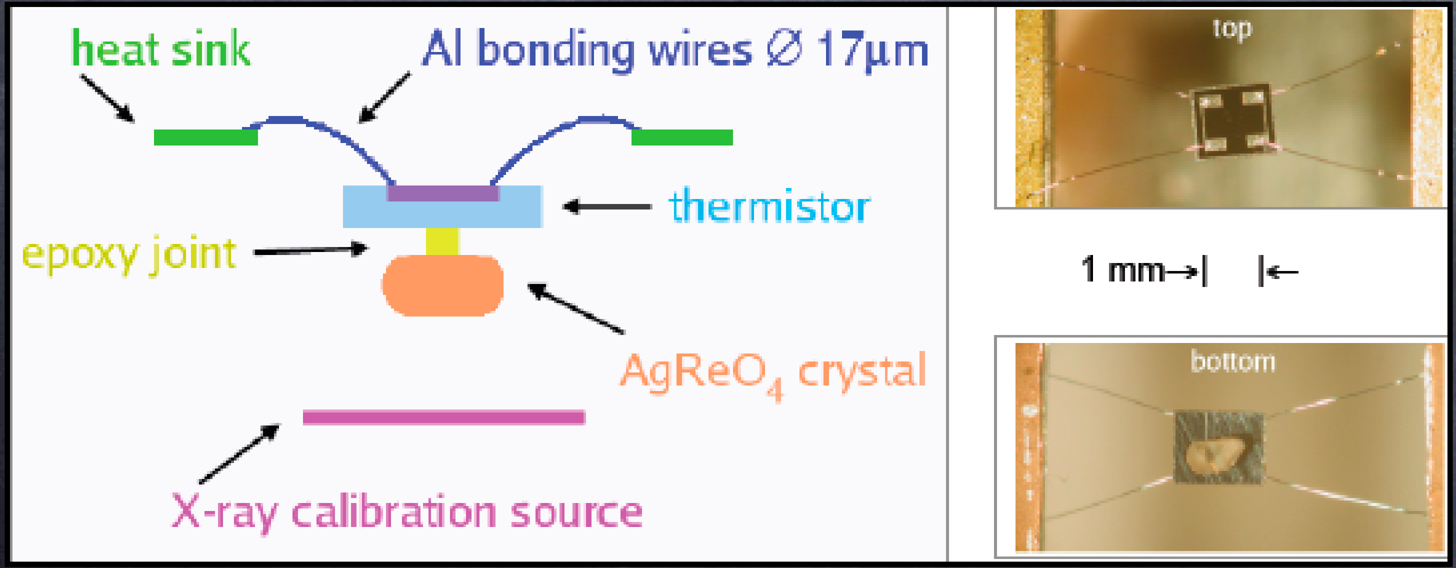
Potential next-next-generation.

Disadvantages: measures all spectrum (pile-up); multiple detectors

Bolometry

- Bolometry uses instrument both as source and as detector.
- Measures all energy from the decay (except neutrino). No issues with final state losses.
- Small units (necessary, if one wants to avoid pile-up from multiple decays.



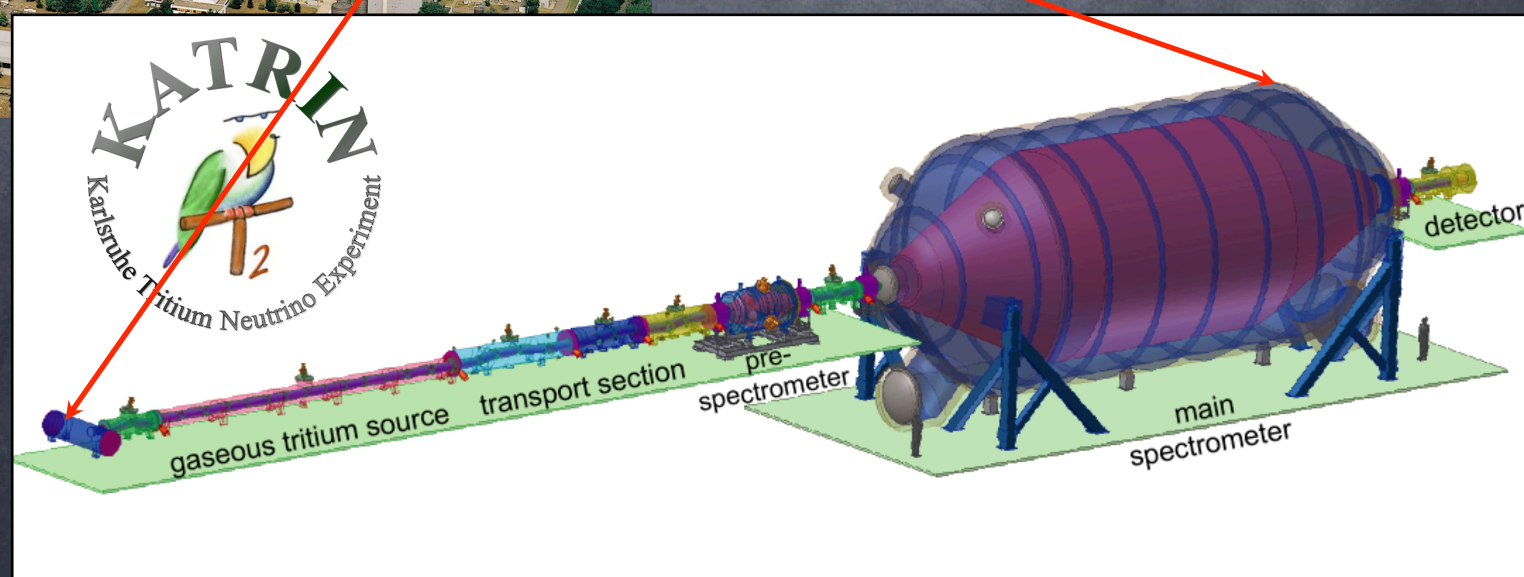


Current sensitivity:

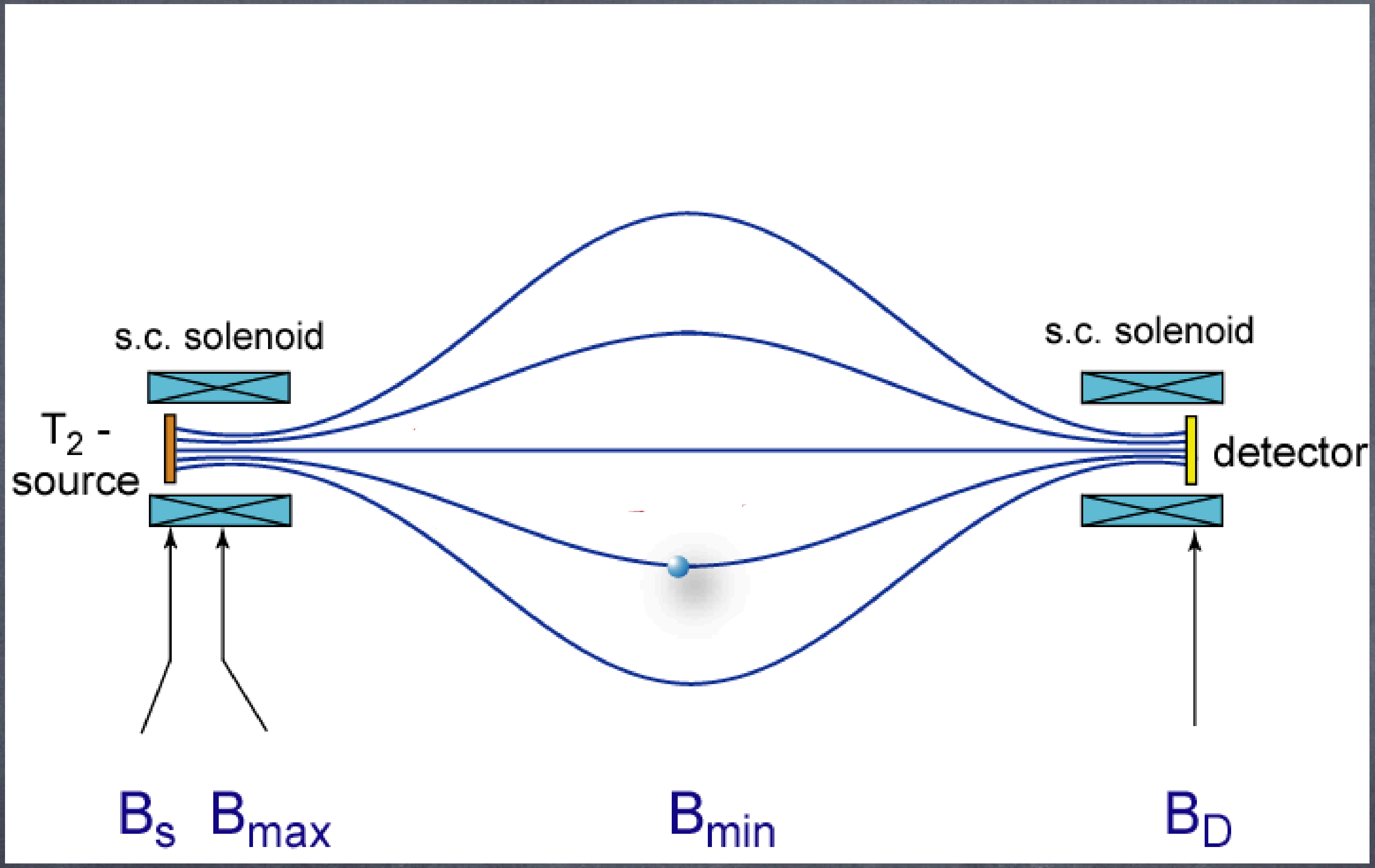
m < 15 eV (90% C.L.)

KATRIN

The KArlsruhe TRItium Neutrino Experiment



MAC-E Filter Technique



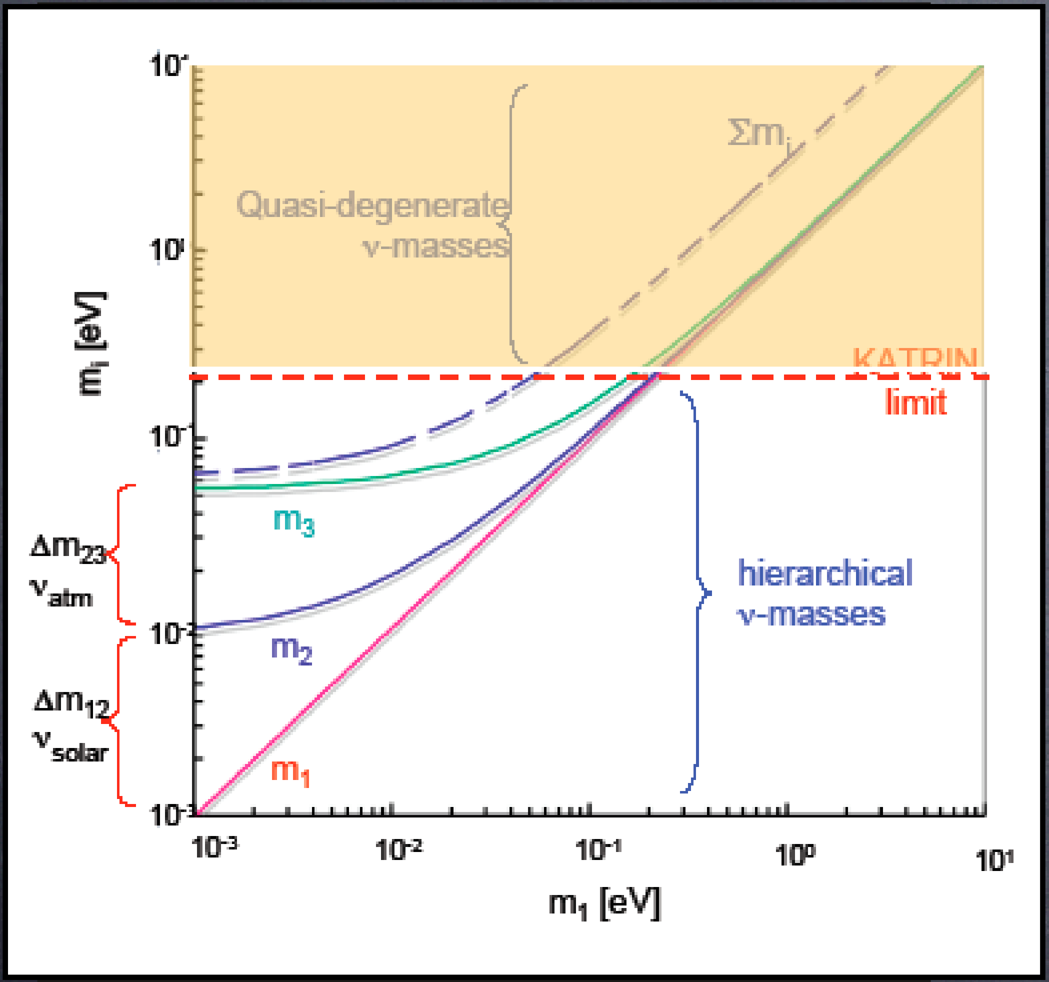
Magnetic Adiabatic Collimation:

- Use adiabatic guiding to move β^- particles along B-field lines.
- Field constrained by 2 s.c magnets.

Electrostatic Filter:

- Use retarding potential to remove β^- particle below threshold.
- High pass filter (variable potential)

Final Sensitivity



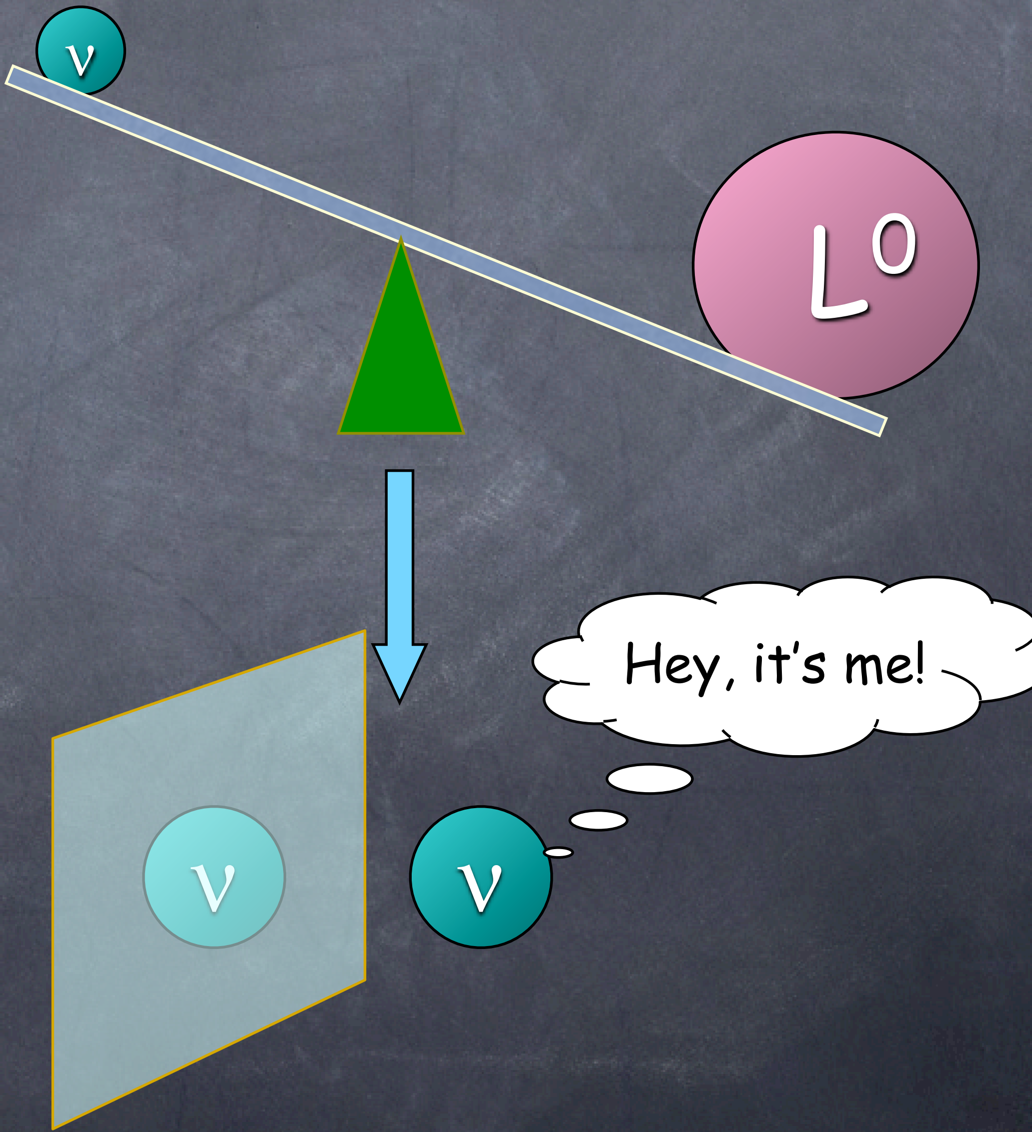
- Concentrating on last 10 eV allows better handle on theoretical systematics
- Maximum sensitivity achieved in 3 years of running.

m_ν < 0.25 eV (90 % C.L.)

- If m_ν > 0.39 eV, it will correspond to a 5 sigma signal.
- Solve whether masses are degenerate or hierarchical.

The Nature of Neutrino Mass

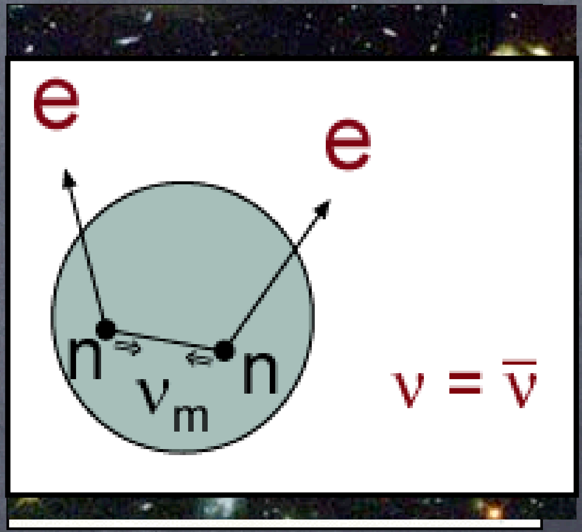
- Beyond the Mass Spectrum
  - One outstanding question is the mechanism behind the smallness of the neutrino mass
  - Possible incorporate the neutrino mass within theories beyond the Standard Model
- Implications → the neutrino & anti-neutrino are the same particle!
- Neutrinos would then be known as Majorana particles.



How to measure Majorana mass?

- For us to distinguish neutrinos as their own anti-particles, the neutrinos must possess a finite mass.
- To measure it, we need to measure what is probably the rarest decay known to exist (double beta decay).
- Only certain select nuclei can participate in this process.

How rare is it?

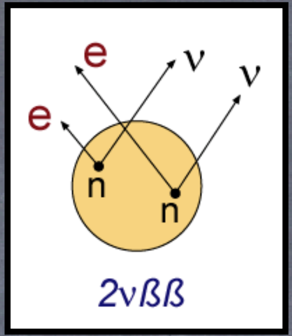


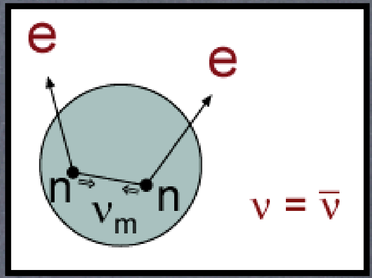
Neutrinoless Double Beta Decay...

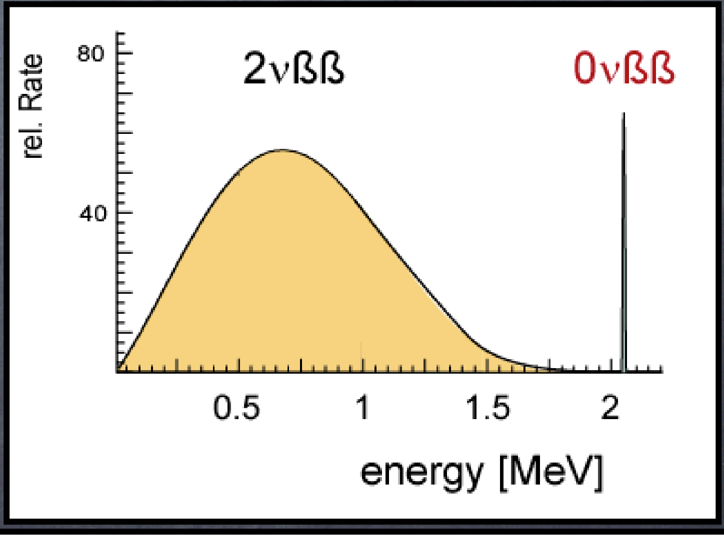
$\sim 10^{25}$ years

Majorana Masses

- Prohibited by lepton number conservation.
- Depends only on matrix elements and the Majorana mass.
- Though other exotic processes can mediate process, still implies neutrino Majorana mass.



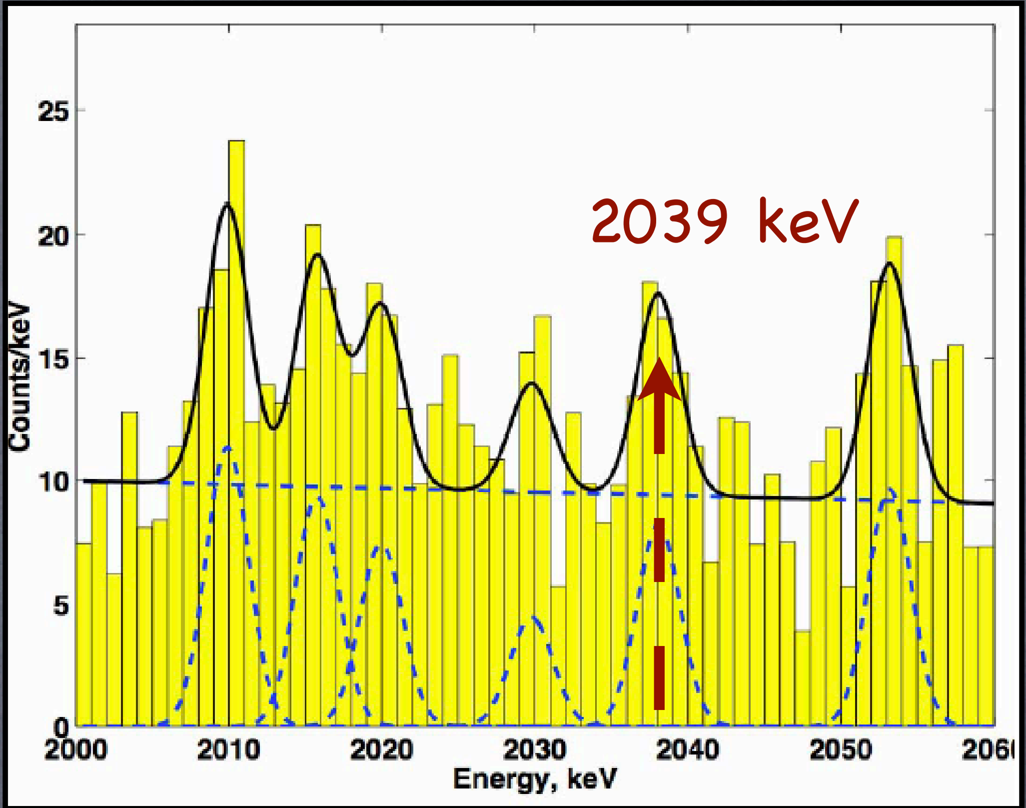




$$[T^{0\nu}_{1/2}(0^+ \rightarrow 0^+)]^{-1} = |M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2} M^{0\nu}_F|^2 \times \left(\frac{\langle m_\nu \rangle}{m_e}\right)^2 \times G^{0\nu}_1$$

Possible Signal?

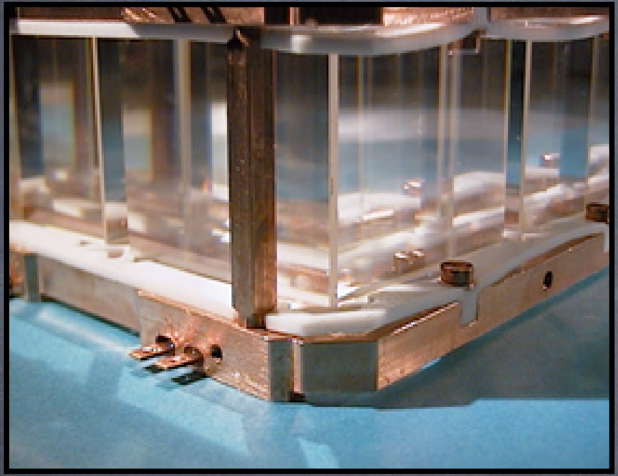
- Possible (4.2 sigma) signal claimed by the Heidelberg-Moscow Germanium experiment.
- Highly controversial:
  - Unknown lines
  - Rejected by part of the collaboration
  - No other measurement to verify it.
- If true, it does imply a neutrino Majorana mass that can be measured in the near future.

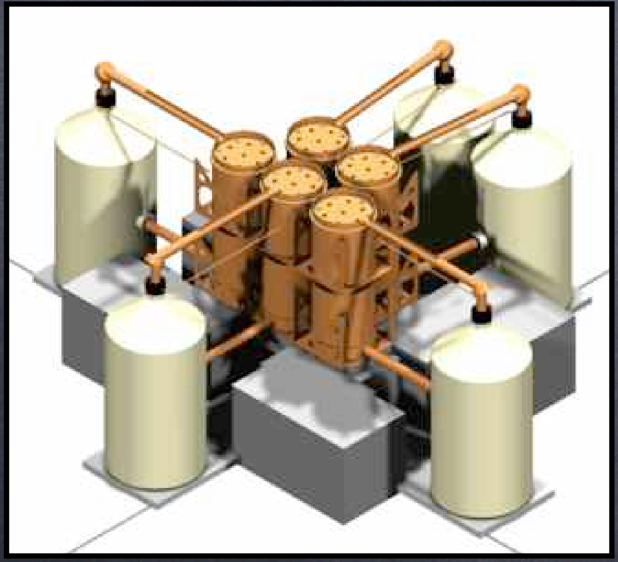


Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

$$0.24 < m_\nu < 0.58 \ (\pm\, 3\ \sigma)$$

Experiments on the Horizon





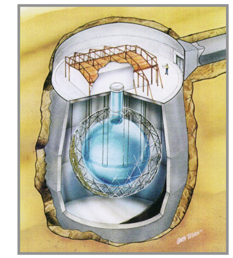
- CUORE
  - Use 750 kg of natural tellurium (^{130}Te). They already have 200 kg of it.
  - Cryogenic detectors
- Majorana
  - Use enriched ^{76}Ge germanium (very well-tested technique).
  - Extremely precise energy measurement of all particles that interact in the medium.

Complementarity

Neutrino Oscillations

Sets lowest mass

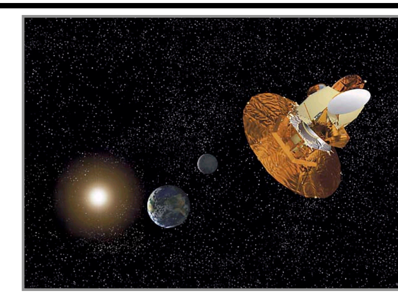
$m_\nu > 50$ meV



Cosmology

Look at the sky to determine mass

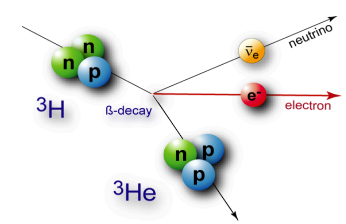
$\sum m_\nu < 200 - 700$ meV --> $m_\nu < 50$ meV



Tritium Beta Decay

Look at kinematics to find mass

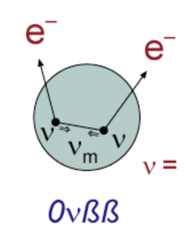
$m_\nu < 2.2$ eV --> $m_\nu < 200$ meV



Double Beta Decay

Nature of neutrino mass measured

$\sum m_\nu < 200 - 700$ meV --> $m_\nu < 50$ meV



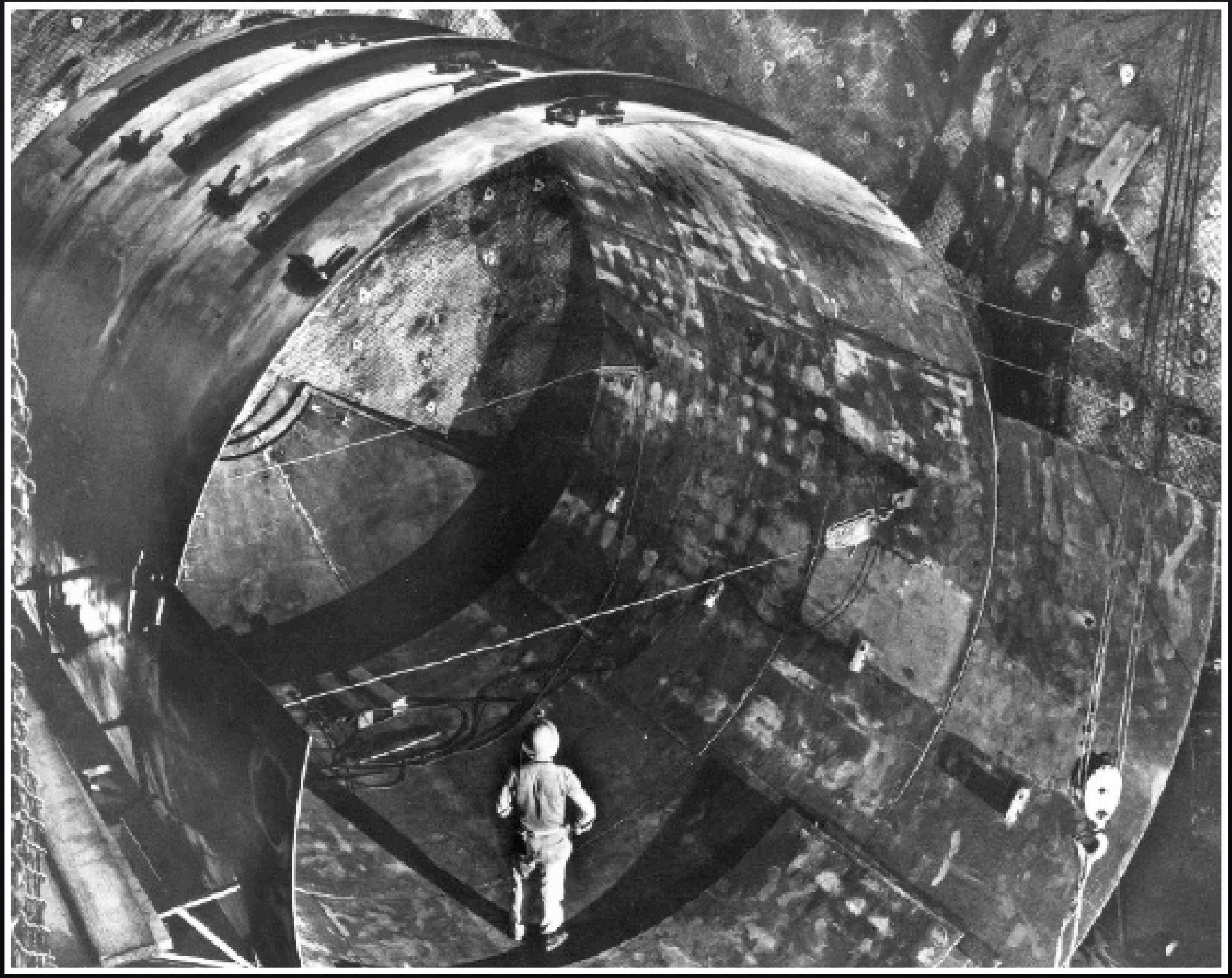
Closing in...

$$50 \text{ meV} < m_\nu < 2.2 \text{ (350) eV}$$

- The culmination of different experiments and experimental techniques have shown that neutrinos are massive particles.
- The absolute (and nature) of neutrino mass presents itself as the next challenge in neutrino physics.
- New experiments will shed light on the nature and scale of neutrino mass.

On Friday...

High Energy Neutrinos



Let’s Eat!