Andes meeting, UTFSM
Valparaiso, January 11-12, 2012

Truth and Untruth in Neutrino Physics and its present Status

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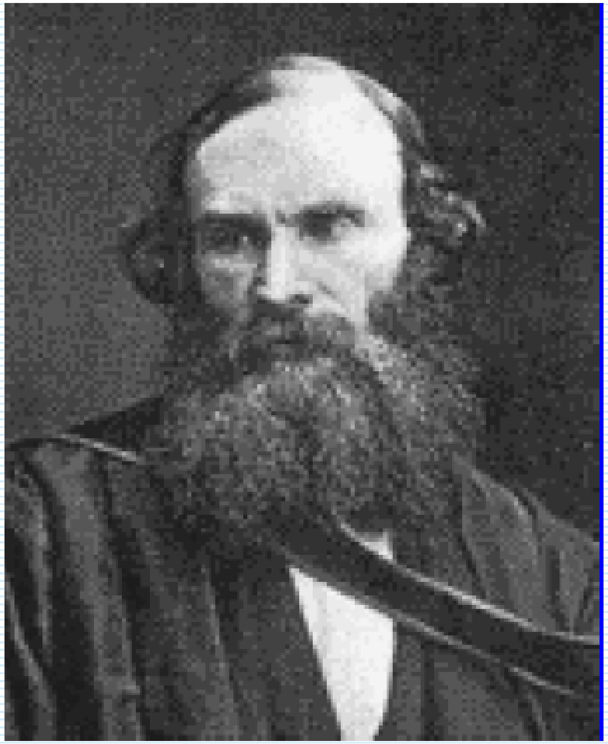
Main aims of my talk

- Advertise the field of ν physics
- Role of analogy in ν physics
- It is not easy to be right in ν physics
- Many important new discoveries are expected in ν physics in near future

Physics at the beginning of 20th century



**„There is nothing new to be discovered in physics now,
All that remains is more and more precise measurements“**

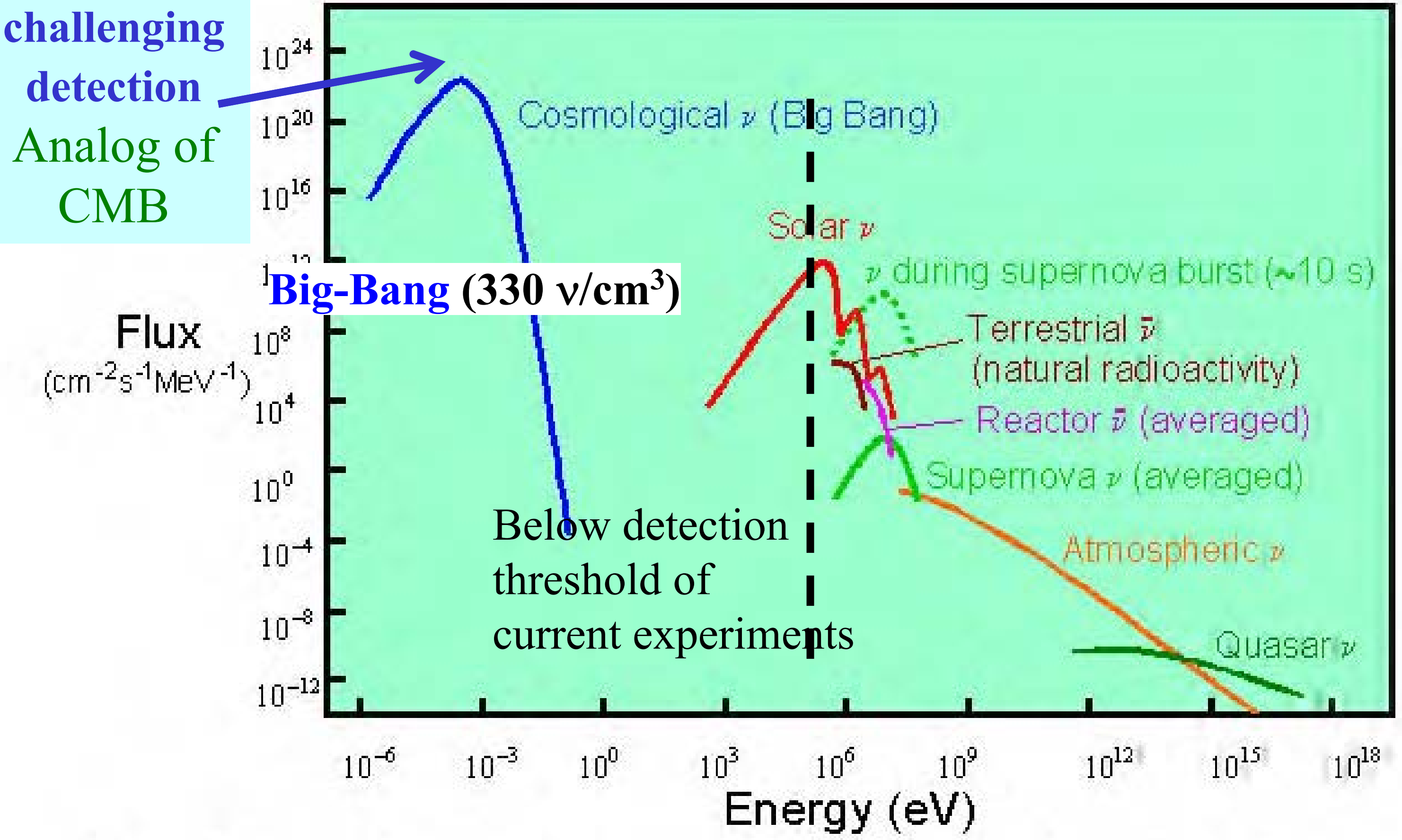
Kelvin. 1900

Sources of neutrinos

Abundant but challenging detection

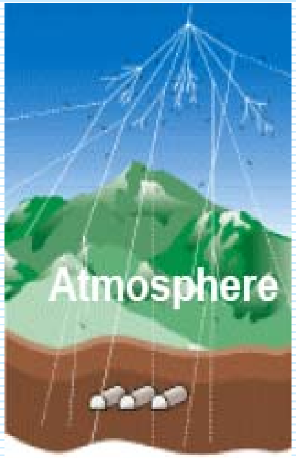
Analog of CMB

D. Vignaud and M. Spiro, Nucl. Phys.A 654 (1999) 350



Big-Bang (330 ν/cm^3)

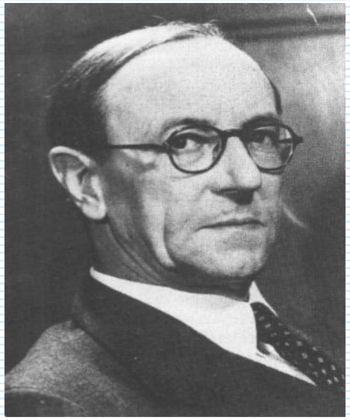
Below detection threshold of current experiments

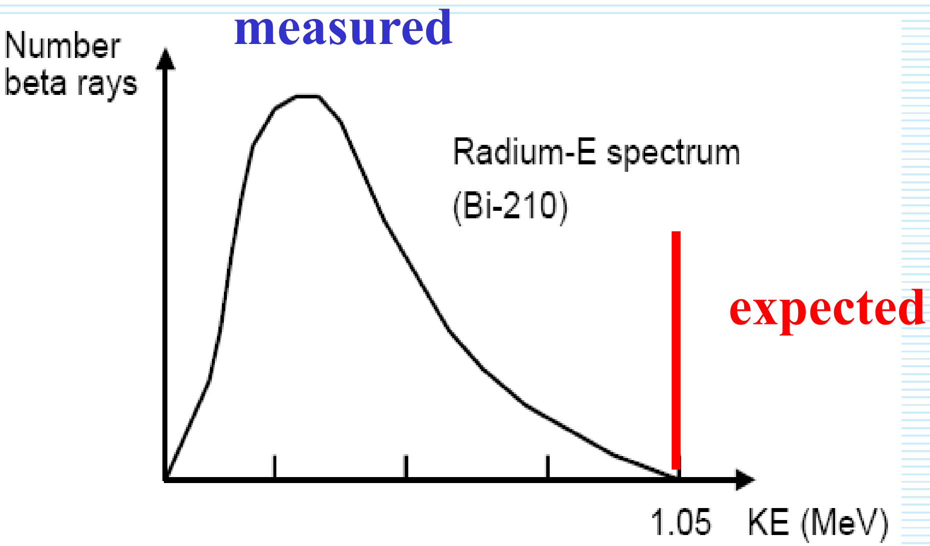


1.8 10^{39} ν/s come from the Sun on Earth, ~100 bilion pass through your finger nail (1 cm^2)

Your body will stop ~1 neutrino which passes through it in a lifetime

The first world energy crisis





Problems:

- nucleus (A,Z) thought to be A protons + (A-Z) electrons
- beta decay: (A,Z) → (A,Z+1) + e^- (two body decay, monoenergetic e^-)

Wrong explanations:

- **L. Meitner:** β^- undergo secondary interactions in nuclei losing energy that goes into additional γ-rays
- **N. Bohr:** energy not conserved in β decay

Further problems with spin of nuclei ($_3^6$Li and $_7^{14}$N) measured to be integer

- $_3^6$Li: 6 protons + 3 electrons = 9 fermions
- $_7^{14}$N: 14 protons + 7 electrons = 21 fermions

Desperate idea of Pauli
(81 years ago)

A letter to Tuebingen
“Liebe Radioaktive Damen and Herren!”
(L. Meitner, H. Geiger)

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 be decay a neutron is emitted in addition to the electron such that the sum o the energies of the neutron and the electron is constant...

Human body = 20 mg of *Potassium* 40.
Humans emit 340 million *neutrinos* per day!

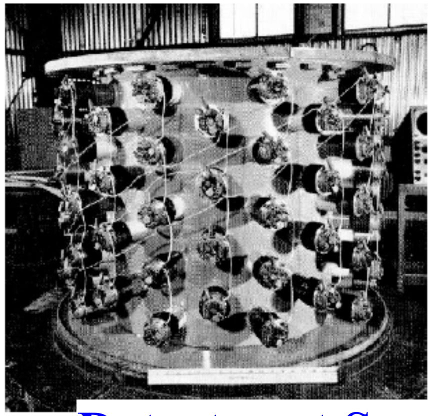
Pauli proposes existence of ”neutron” (with spin ½ and mass not more than 0.01 mass of proton) in nucleus. β-decay is then a three body decay with continues distribution of energy among constituents.

4 December 1930
A letter to Tuebingen

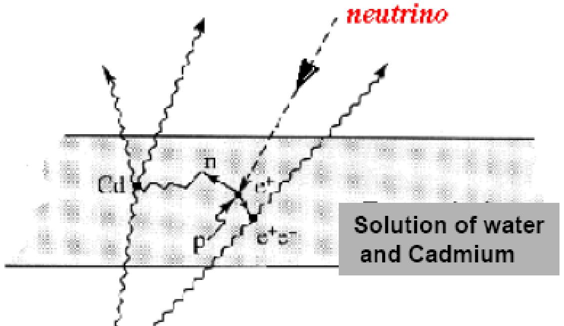
I have done
a terrible thing
I invented a
particle that
cannot be
detected
W. Pauli

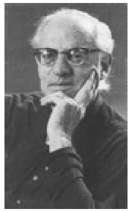
3 events per hour

We are happy
to inform you
(Pauli)
that we have
definitely detected
ν
Reines & Cowan



Detector at Savannah River
Nuclear reactor (1956)





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

Reines: 1995 Nobel Prize

Signals due to:
i) e^+ annihilation,
ii) n-capture

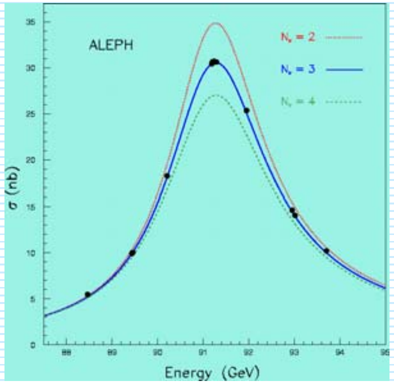
$\sigma = (1.1\pm0.3)\ 10^{-43}\ \text{cm}^2$

in agreement with
Fermi theory of
β-decay

Fundamental properties of neutrinos

After 55 years we know

- 3 families of light (V-A) neutrinos: ν_e, ν_μ, ν_τ
- ν are massive: we know mass squared differences
- relation between flavor states and mass states (neutrino mixing) only partially known



Claim for evidence of the $0\nu\beta\beta$-decay

H.V. Klapdor-Kleingrothaus et al.,NIM A 522, 371 (2004); PLB 586, 198 (2004)

- Absolute ν mass scale from the $0\nu\beta\beta$-decay. (cosmology, ^{3}H, ^{187}Rh ?)
- ν's are their own antiparticles – Majorana.

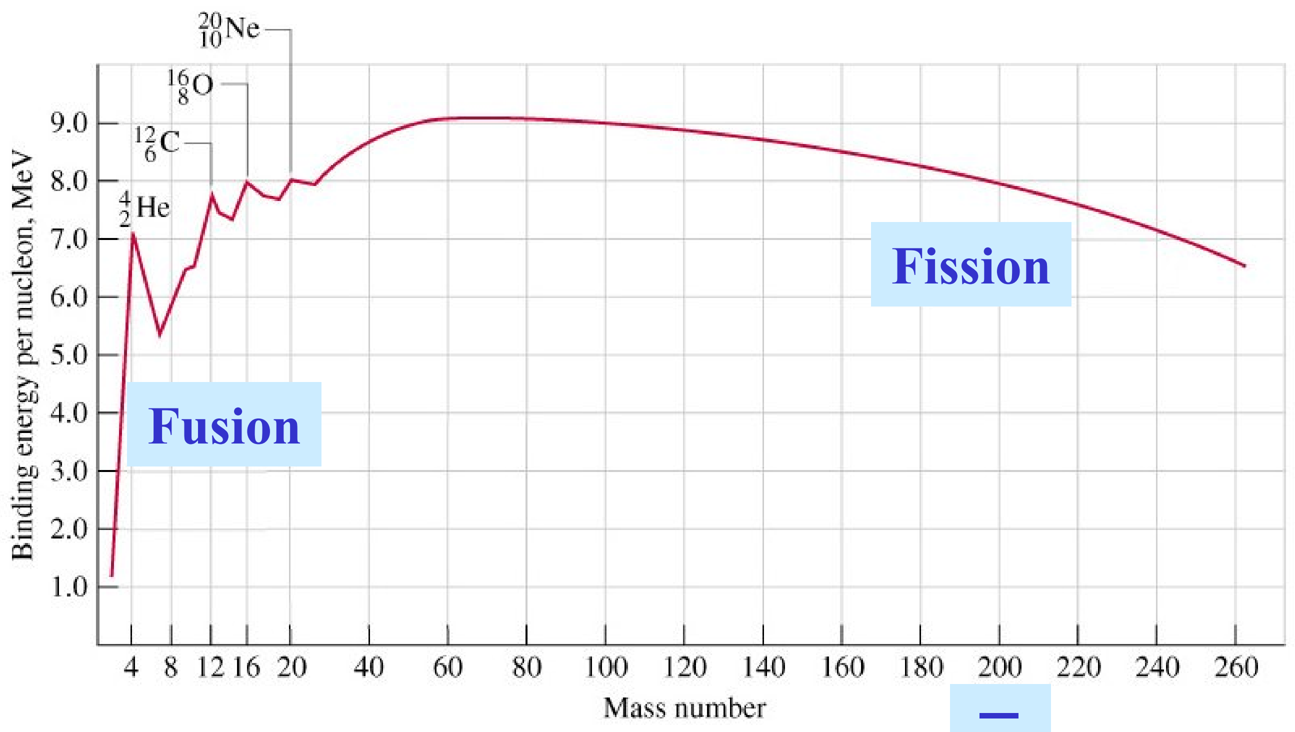
No answer yet

- Is there a CP violation in ν sector? (leptogenesis)
- Are neutrinos stable?
- What is the magnetic moment of ν?
- Sterile neutrinos?
- Statistical properties of ν? Fermionic or partly bosonic?

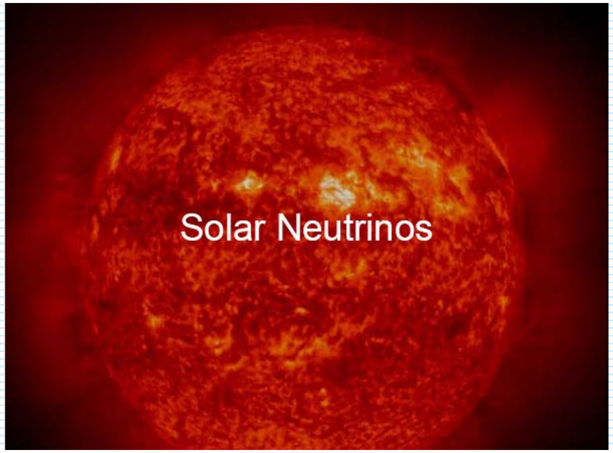
Weak nuclear transitions

$(A,Z)\rightarrow(A,Z-1)+e^{+}+\nu_e$
$e^{-}_{b}+(A,Z)\rightarrow(A,Z-1)+\nu_e$

$(A,Z)\rightarrow(A,Z+1)+e^{-}+\overline{\nu}_e$



ν_e



$\overline{\nu}_e$

$\overline{\nu}_e$

Atmospheric and accelerator ν

The beam is comprised almost entirely from ν_μ

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

$$K^+ \to \mu^+ \nu_\mu$$

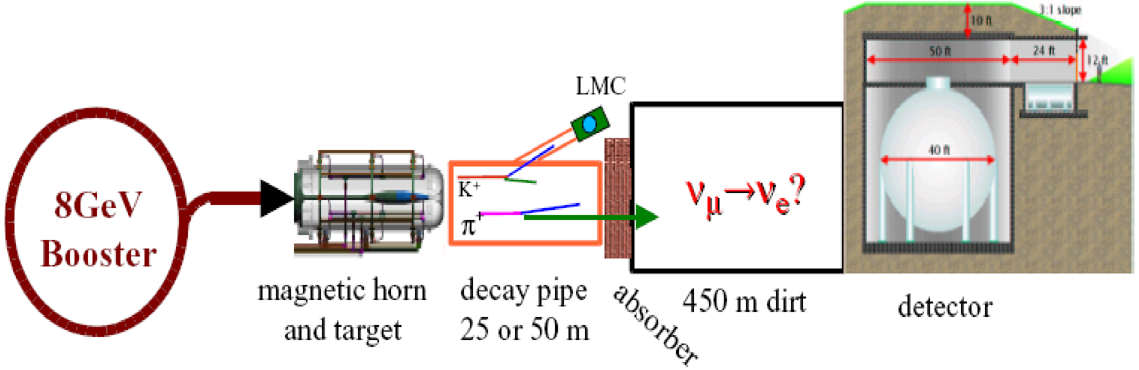
$$\to \pi^+ \pi^0$$

$$p + Be \to \pi^+, K^+, K^0_L$$

☞8GeV protons from Fermilab Booster

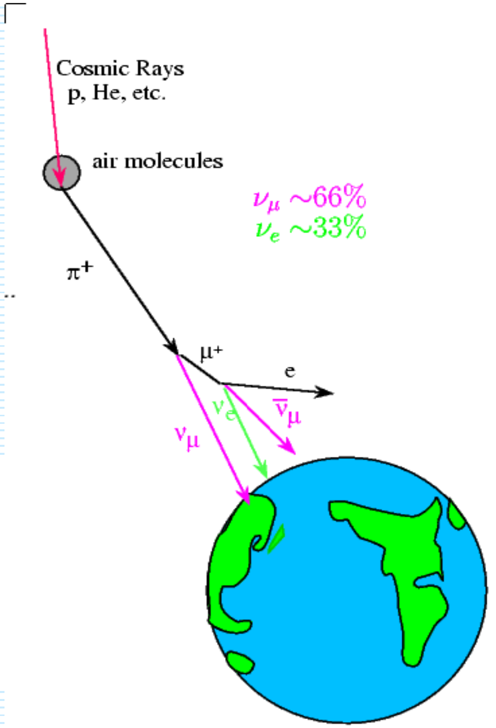
☞Incident on Be target

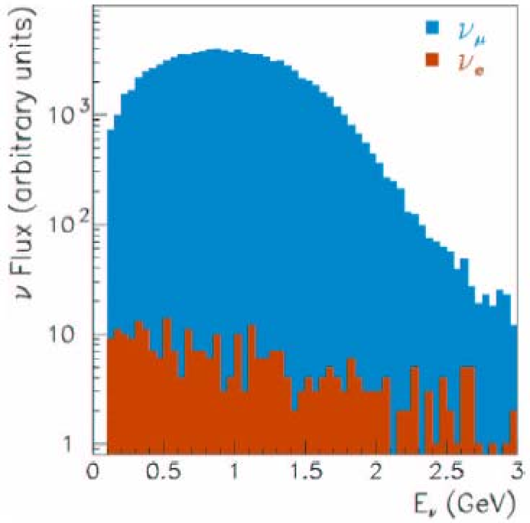
☞Magnetic horn focuses interaction products



☞ π and K secondaries traverse decay pipe

☞Traverse beam absorber + berm



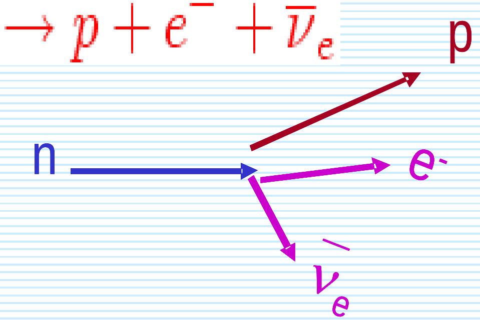


Neutrino interactions

1934 Fermi theory of β-decay

Fermi, Z. Physik 88 (1934) 161

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



Fermi 4-fermion contact interaction, Lagrangian of interaction (in analogy with electrodynamics):

$$\mathcal{L}(x) = -\frac{G_F}{\sqrt{2}}\left[\overline{\phi}_p(x)\gamma^{\mu}\phi_n(x)\right]\left[\overline{\phi}_e(x)\gamma^{\mu}\phi_{\nu}(x)\right]$$

G_F = Fermi coupling constant = (1.16637±0.000001) 10^{-5} GeV^{-2}

Cross section for interactions with nucleons:
10^{-38} cm^2 at 1 GeV and increasing with energy

1935 Gamow and Teller interaction when final spin different to initial nucleus:

$$\mathcal{L}(x) = -\frac{G_F}{\sqrt{2}}\left[\overline{\phi}_p(x)\Gamma^{i}\phi_n(x)\right]\left[\overline{\phi}_e(x)\Gamma_{i}\phi_{\nu}(x)\right]$$

Possible interactions: $\gamma_i = 1, \gamma_5, \gamma_{\mu}, \gamma_{\mu}\gamma_5, \sigma_{\mu\nu}$ = S, P, V, A, T

1958 V-A theory of weak interaction, Feynman, Gell-Mann

Two-component neutrinos:

Massless fermion => Chirality = Helicity

$$j_\mu = \bar{\nu}\gamma_\mu(1-\gamma_5)e = 2\overline{\nu_L}\,\gamma_\mu\, e_L \qquad \nu_L \equiv \frac{1-\gamma_5}{2}\nu \qquad \gamma_5\,\nu_L = -\nu_L$$

Landau, NP 3 (1957) 127,
Salam, Nuovo Cim. 5 (1957) 299
Lee and Yang, Phys. Rev. 105 (1957) 1671

Chiral representation:

Left-handed chirality

$$\gamma_5 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \Longrightarrow \frac{1-\gamma_5}{2} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad \nu = \begin{pmatrix} \chi_R \\ \chi_L \end{pmatrix} \Longrightarrow \nu_L = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 0 \\ \chi_L \end{pmatrix}$$

V-A current interaction is violating parity: PV=-V, PA=A, (V-A)(V-A)=VV+AA – 2AV
P (V-A)(V-A)=VV+AA + 2AV

Weak Hamiltonian is combination of vector (V) and axial-vector (A) currents

$$\mathcal{H}_{weak} = \frac{G_F}{\sqrt{2}} J^\mu J^\dagger_\mu, \qquad J_\mu = J^{hadr.}_\mu + j^{lept}_\mu$$

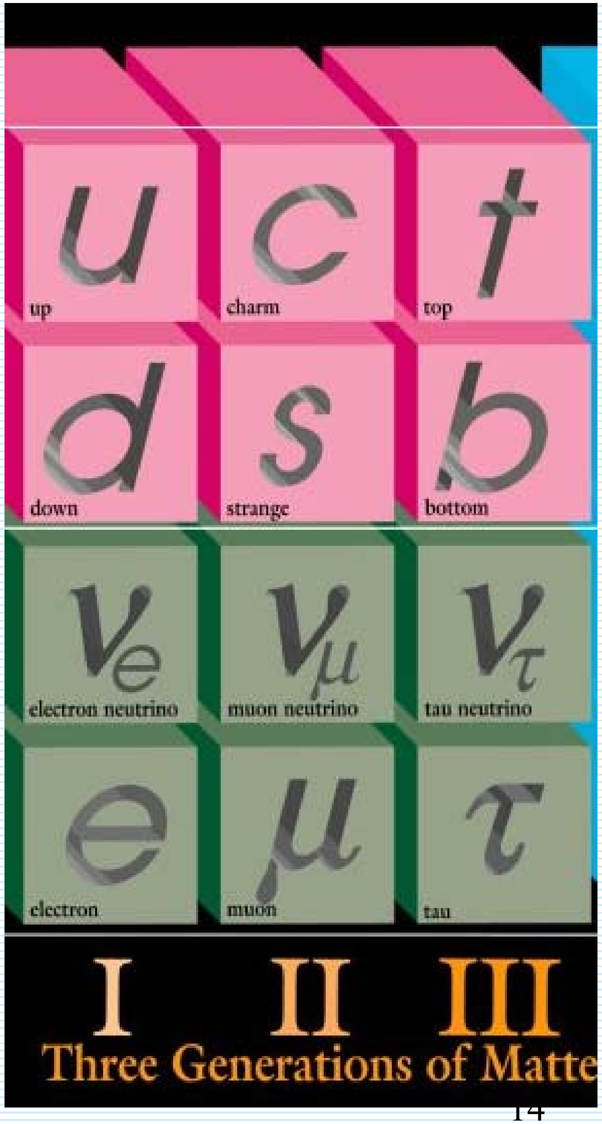
β-decay Hamiltonian

$$\mathcal{H}_\beta = \frac{G_F}{\sqrt{2}} (\bar{n}\gamma^\mu(1-g_A\gamma_5)p)\ \ (\bar{\nu}\gamma^\mu(1-\gamma_5)e) + H.c.$$

$n \to p + e^- + \bar{\nu}_e$ *semi – leptonic weak decay*
$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ *pure – leptonic weak decay*
$\pi^- \to \mu^- + \bar{\nu}_\mu$ *semi – leptonic weak decay*
$n \to p + e^- + \bar{\nu}_e$ *semi – leptonic weak decay*
$\Lambda^0 \to \pi^- + p$ *pure – hadronic weak decay*

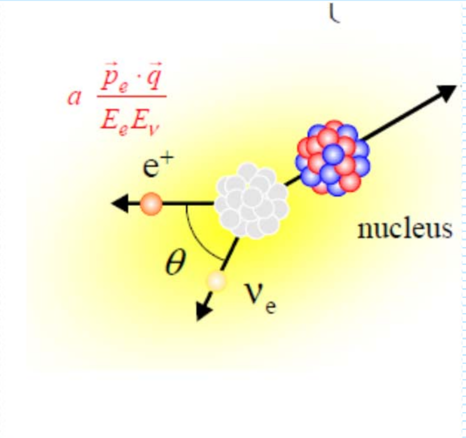
Neutrinos in the Standard Model

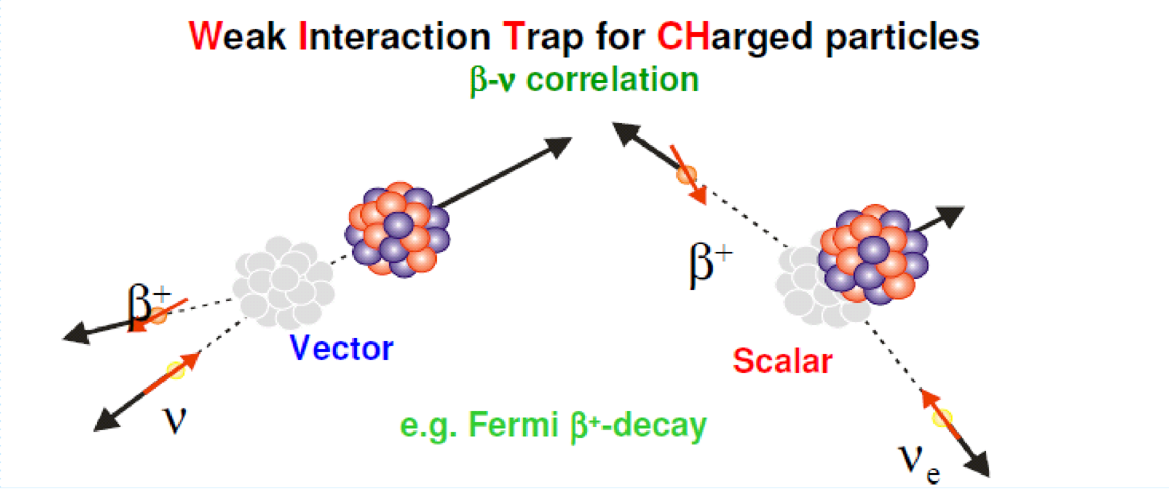
- Neutrinos are massless
- Neutrinos only interact via the Weak force
- Neutrinos are left-handed, anti-neutrinos are right-handed
- Neutrinos are electrically neutral
- Neutrinos have three flavors: electron, muon, tau



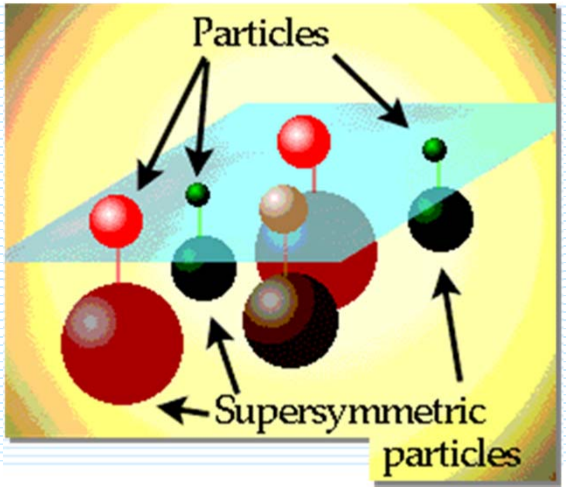
Search for Exotic (scalar and tensor type) Weak-Interactions

WITCH double-Penning trap
system at ISOLDE-CERN





Weak Interaction Trap for CHarged particles
β-ν correlation

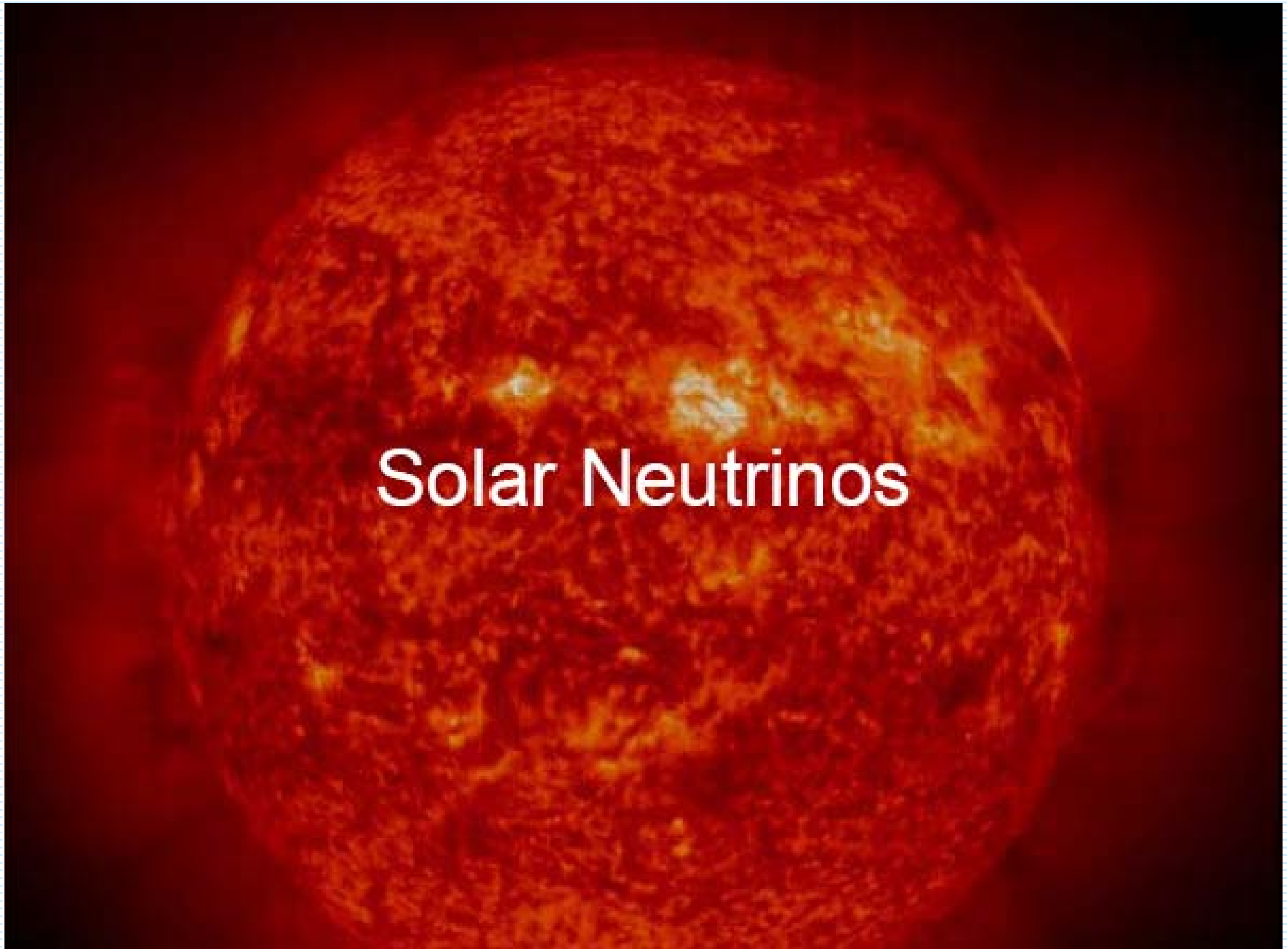


R-parity violating SUSY vertex

$$\mathcal{L}^{eff}_{SUSY} = \frac{G_F}{\sqrt{2}} \left(\frac{1}{4}\eta_{(q)LR} \sum_i U^*_{ei} \left(\overline{\nu}(1+\gamma_5)e\right) \left(\overline{u}(1+\gamma_5)d\right) \qquad (S,P) \right.$$

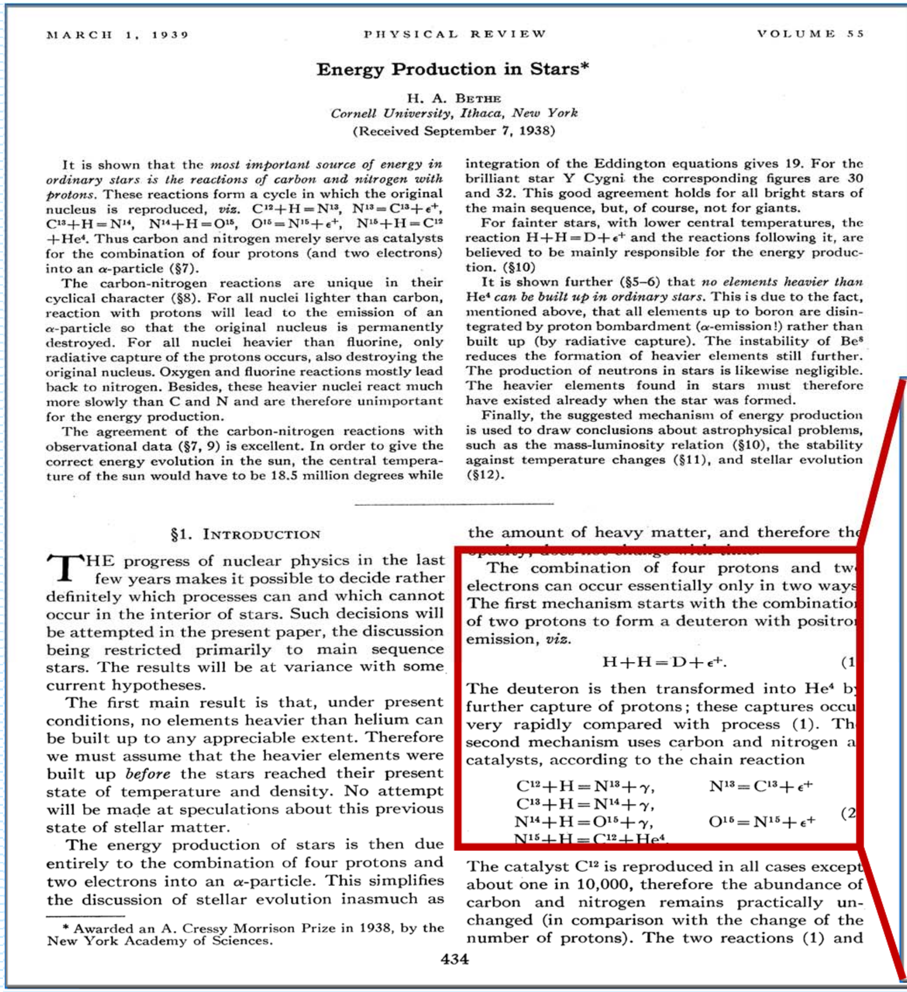
$$\left. + \frac{1}{8}\eta_{(q)LR} \sum_i U^*_{ei} \left(\overline{\nu}\sigma_{\alpha\beta}(1+\gamma_5)e\right) \left(\overline{u}\sigma^{\alpha\beta}(1+\gamma_5)d\right) + h.c. \right) \qquad (Tensor)$$

Why sun is shining?



1939 Energy production in Stars (Bethe)

Nobel prize 1967



MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

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.*

$$H+H=D+\epsilon^+. \tag{1}$$

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

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

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

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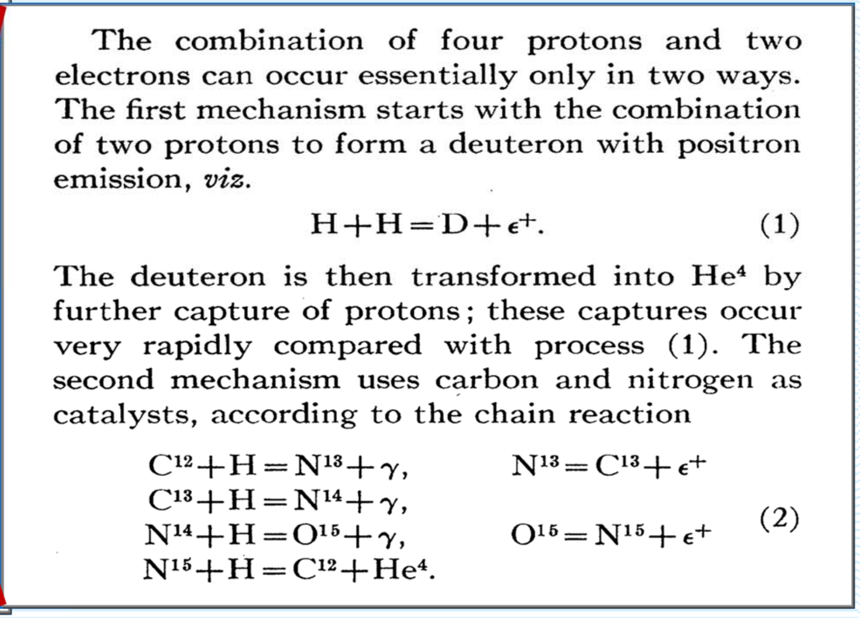
* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

pp chain

CNO cycle

NARA/Harris & Ewing



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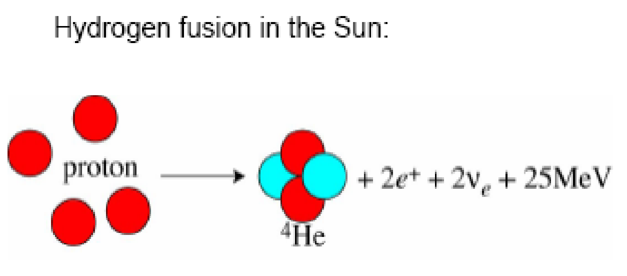
Standard Solar Model (SSM)

Observables: **Mass** (M=2 10^{30}kg), **luminosity** (L=4 10^{26} W), **Radius** (7 10^{8} m), **metal content of the photosphere, Age, Inferences of solar interior** (ρ,P,T)

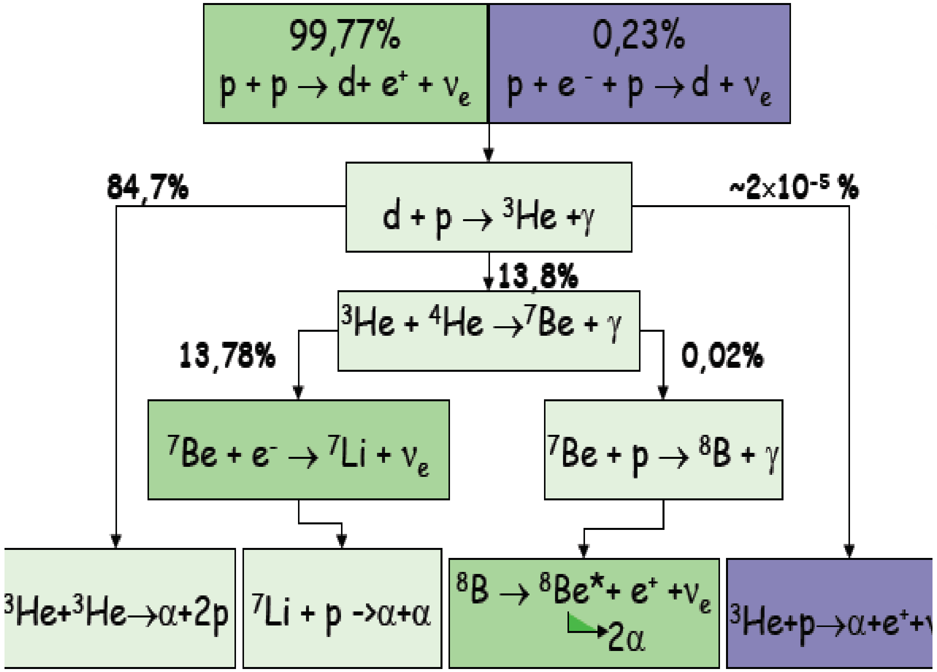


Total neutrino flux (only ν_e): $\phi(\nu_e) = 6.6\ 10^{10}\ cm^2 s^{-1}$

small theoretical uncertainty (~1%) by pp neutrinos

large theoretical uncertainty (~20%) by ^{8}B neutrinos

The pp-chain



99,77% $p + p \to d + e^+ + \nu_e$

0,23% $p + e^- + p \to d + \nu_e$

$d + p \to {}^3He + \gamma$

84,7%

~2×10-5 %

13,8%

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

13,78%

0,02%

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

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

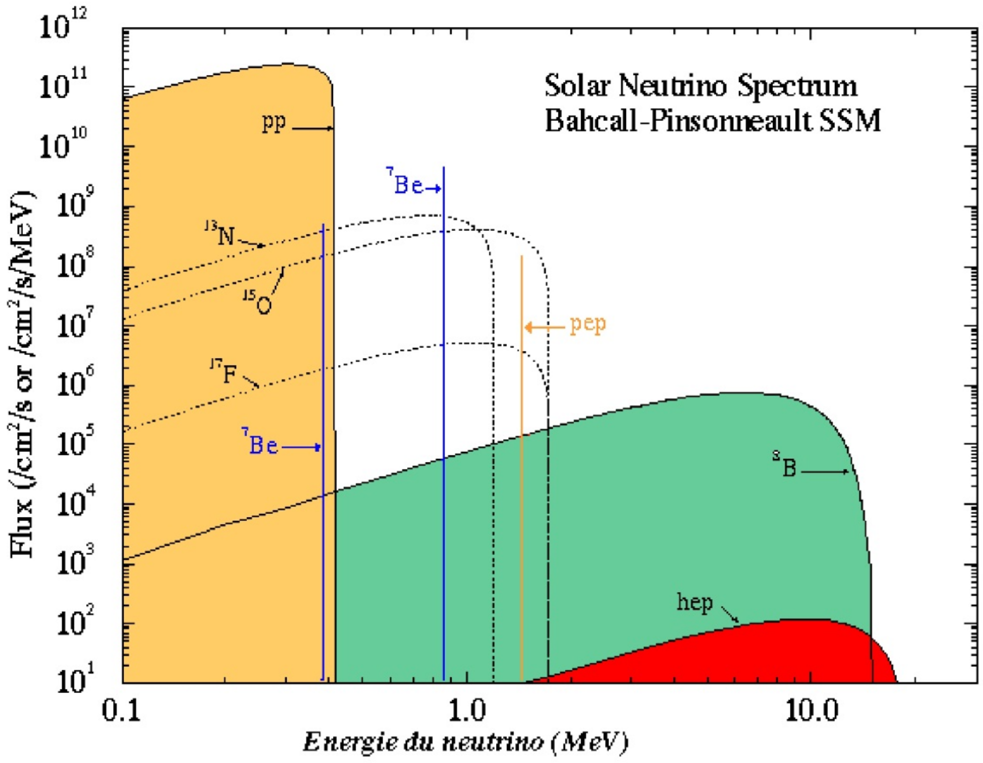
$^3He + {}^3He \to \alpha + 2p$

$^7Li + p \to \alpha + \alpha$

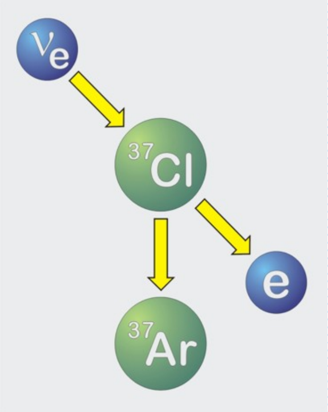
$^8B \to {}^8Be^* + e^+ + \nu_e$, $\to 2\alpha$

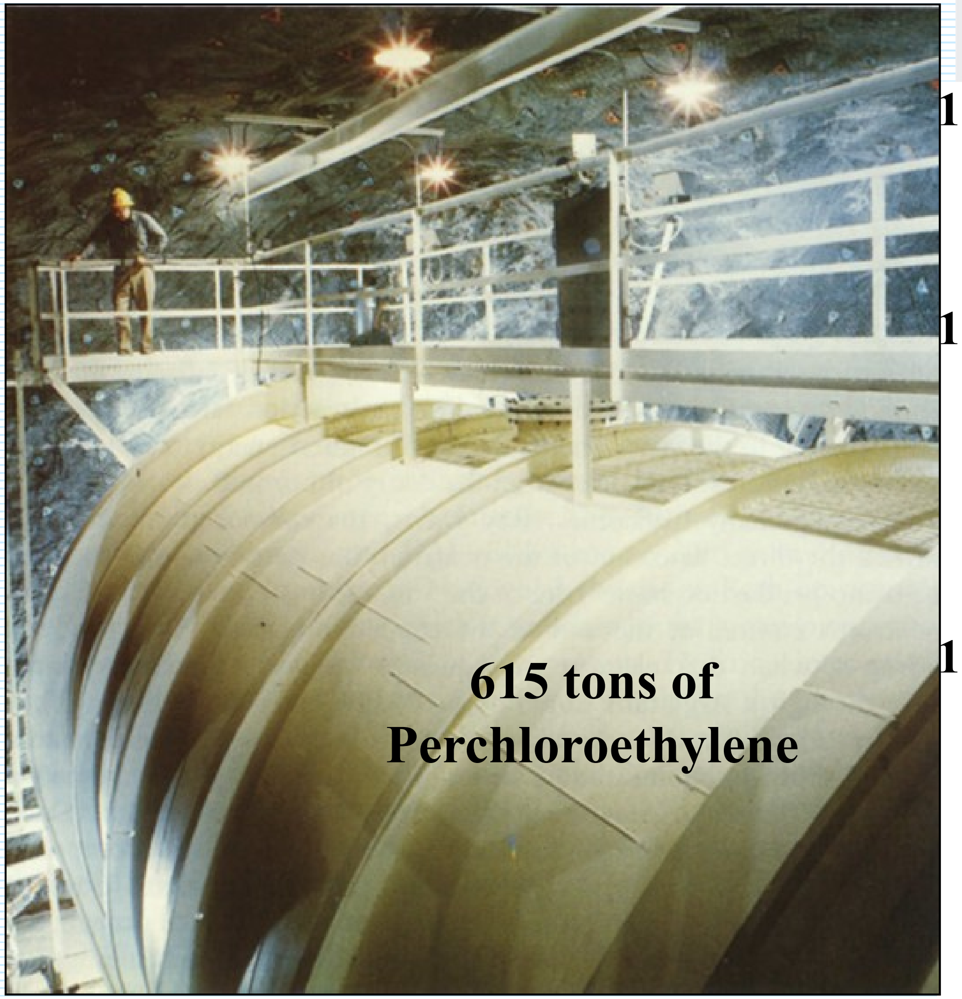
$^3He + p \to \alpha + e^+ +$

Solar Neutrino Energy Spectrum



Homestake solar neutrino observatory (1967–2002)





Davis, Harmer and Hoffman, Phys. Rev. Lett. 20 (1968) 1205

1964 **John Bahcall and Ray Davis have idea to detect solar neutrinos using the Pontecorvo reaction**

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

1967 **Homestake experiment starts taking data**

- **615 ton of cleaning fluid in a tank 4,100 mwe underground**
- **^{37}Ar extracted chemically every few months (single atoms!)**
- **event rate: ~ 1 neutrino capture per day!**

1968 **First results: only 34% of predicted neutrino flux**

Why ?

Experiment observed: 2.56±0.23 SNU

SSM prediction: 7.7 ±1.2 SNU

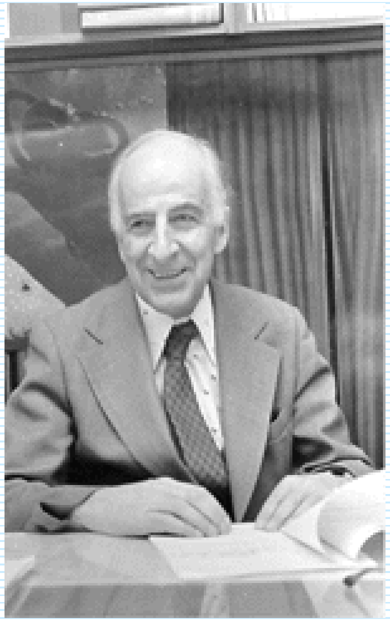
1 SNU = 10^{-36} interactions/(target atom)/ s

Next 20 years no other solar neutrino experiment

Neutrino oscillations

1957 Neutrino oscillations

In analogy with oscillations of kaons



Bruno Pontecorvo

(Dubna 1957)

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

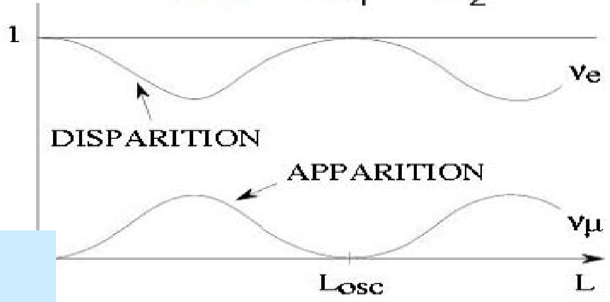
$$|\nu(t=0)\rangle = |\nu_e\rangle$$
$$|\nu(t)\rangle = \exp(-iE_1t)\cos\theta\,|\nu_1\rangle + \exp(-iE_2t)\sin\theta\,|\nu_2\rangle$$

$$P(\nu_e \rightarrow \nu_\mu) = |\langle\nu_\mu|\nu(t)\rangle|^2 = \boxed{\sin^2 2\theta\,\sin^2(\Delta m^2/4E\,t)}$$

$$\Delta m^2 = m_1^2 - m_2^2$$

Neutrino mixing

Mass squared diff., distance



L_{osc} (m) = 2.5 E_ν (MeV) / Δm

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

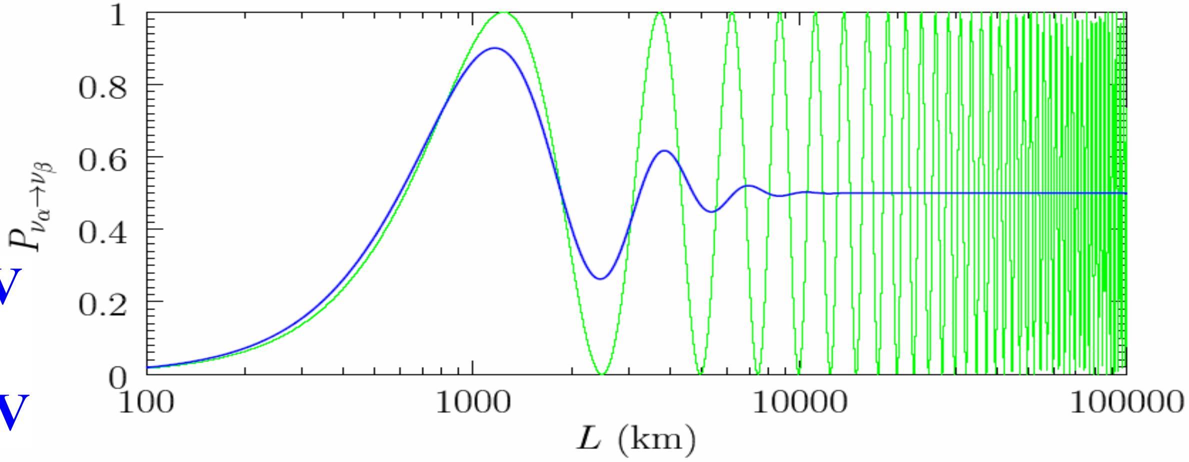
Rumours that Ray Davis have seen $\bar{\nu}_e$ with this reaction(?!)

$\bar{\nu}_e + {}^{37}Cl \not\rightarrow {}^{37}Ar + e^-$

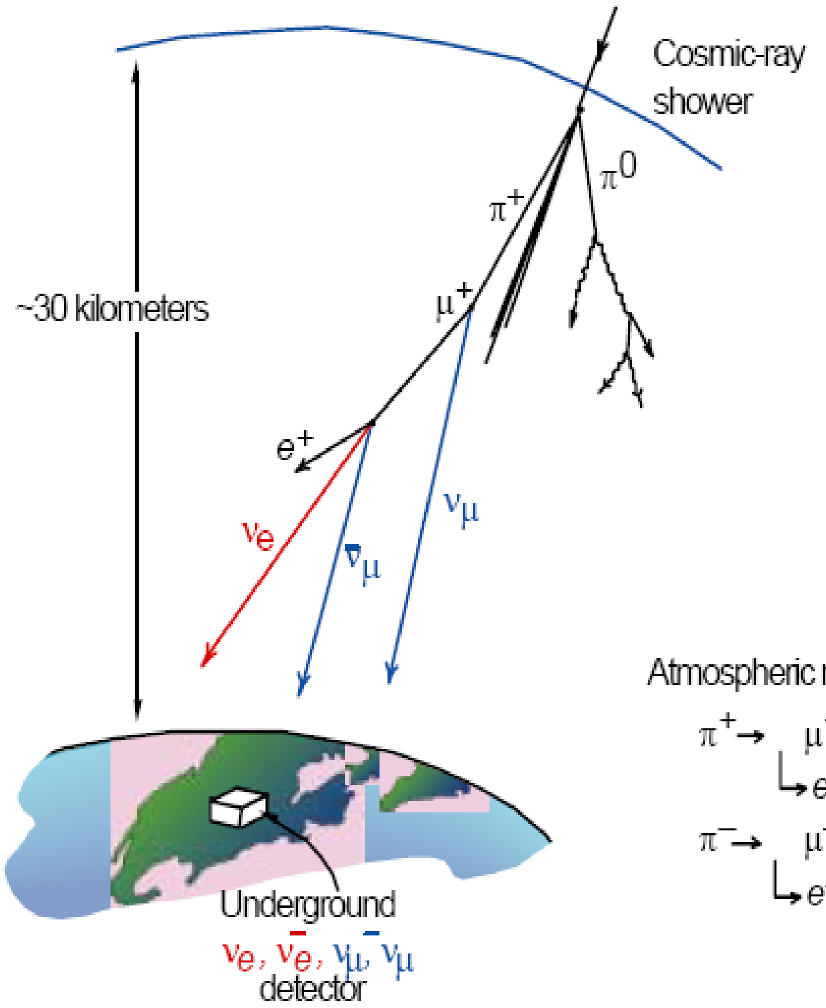
$\Delta m^2 = 10^{-3}$ eV

$\sin^2 2\theta = 1$

$\langle E\rangle = 1$ GeV



Neutrino production in the atmosphere



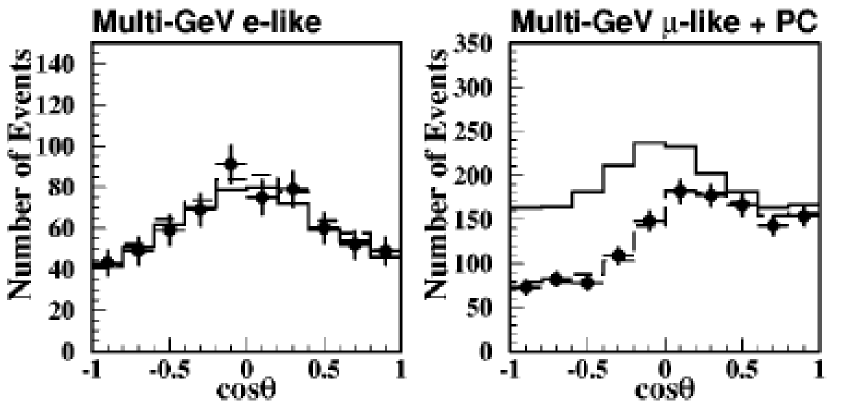
Atmospheric neutrino sourc

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$

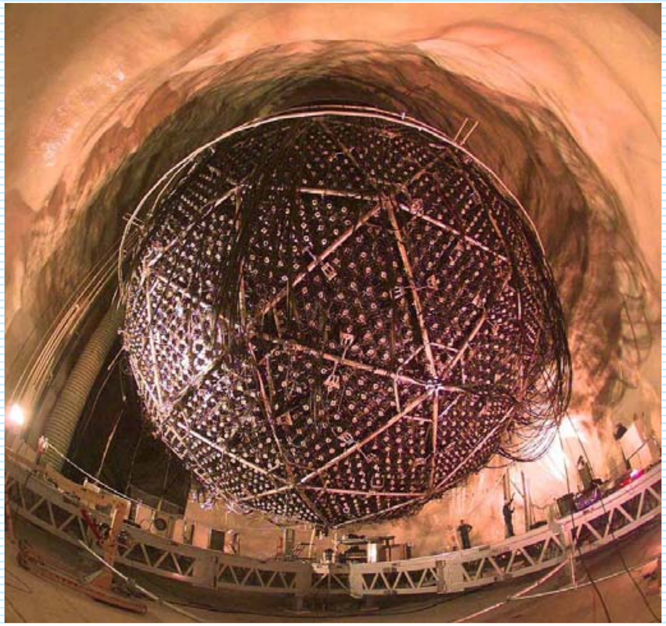


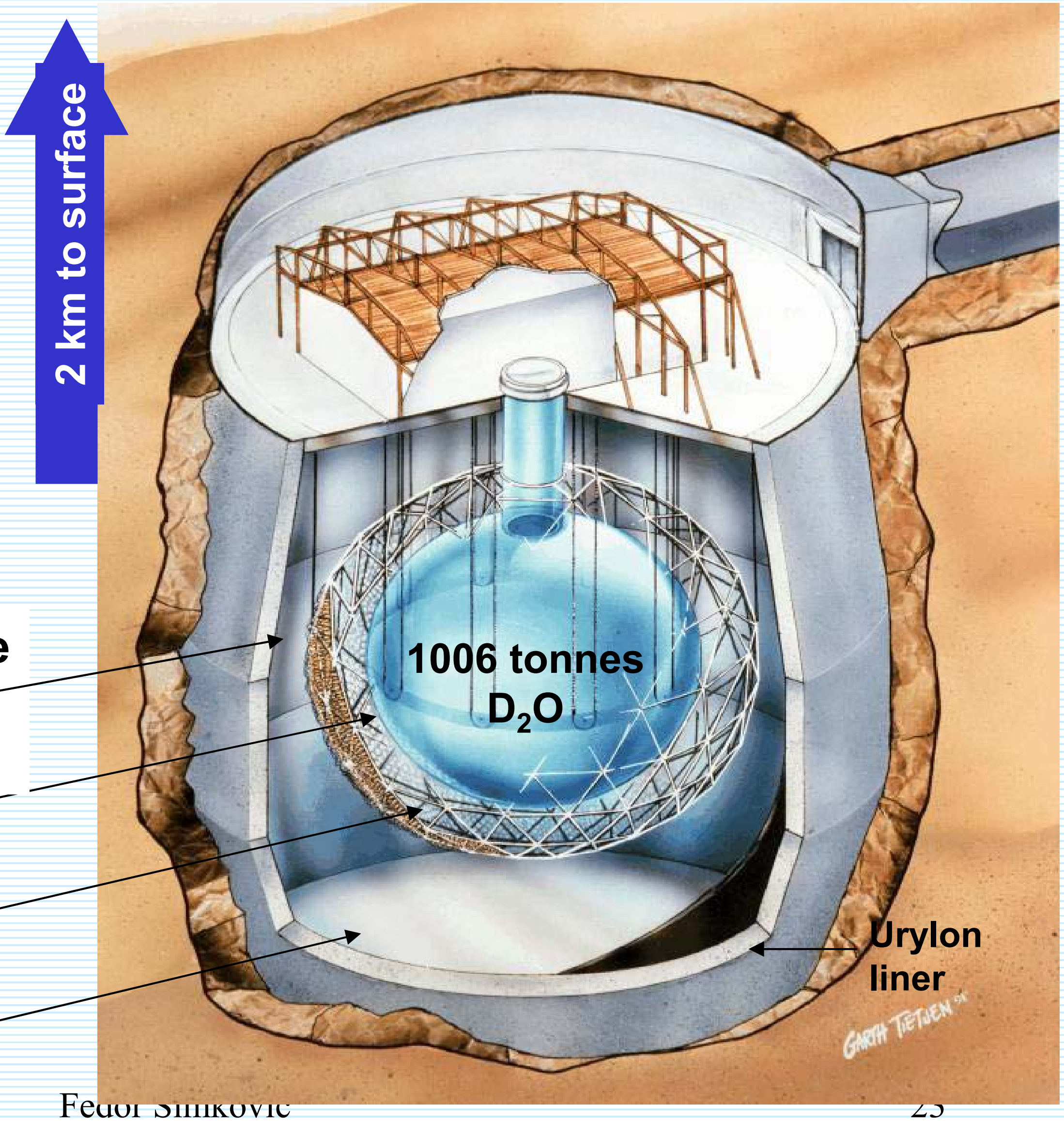
Up moving ν_μ

Down moving ν_μ

2 ν_μ for each ν_e

2000 Sudbury Neutrino Observatory





17.8m dia. PMT Support Structure
9456 20-cm dia. PMTs
56% coverage

12.01m dia. acrylic vessel

1700 tonnes of inner shielding H_2O

5300 tonnes of outer shielding H_2O

Nucl. Inst. Meth. A449, 127 (2000)

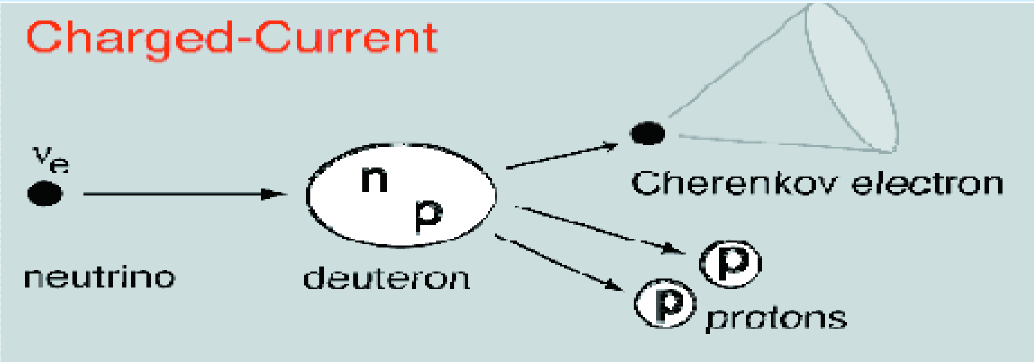
ν Detection at SNO

SNO can determine both $\Phi(\nu_e)$ and $\Phi(\nu_e+\nu_\mu+\nu_\tau)$

Threshold energy 5 MeV => sensitive to ^{8}B ν

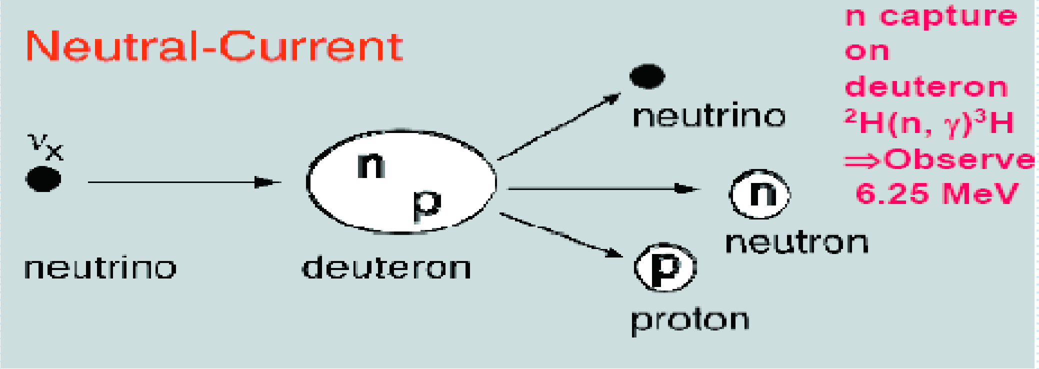
CC: $\nu_e+d\rightarrow p+p+e^-$

Measurement of ν_e energy spectrum,
weak directionality


Charged-Current

NC: $\nu_x+d\rightarrow p+n+\nu_x$

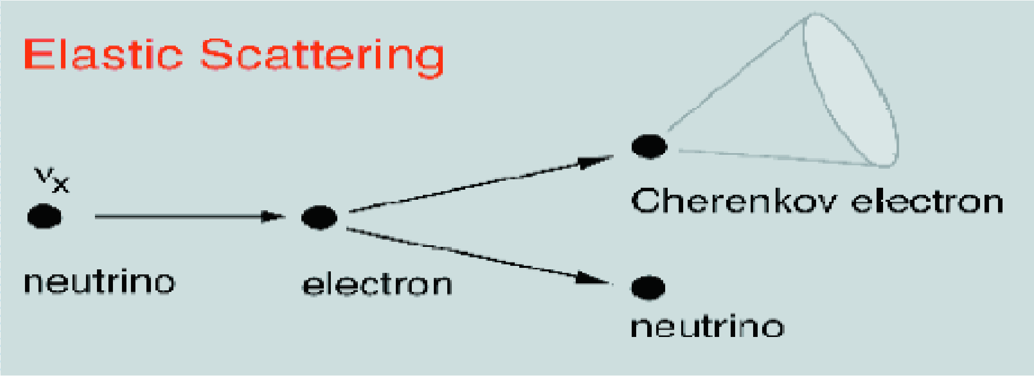
Measure total ^{8}B ν
equally sensitive to all ν
$\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$


Neutral-Current

n capture on deuteron $^2H(n,\gamma)^3H$
⇒Observe 6.25 MeV

ES: $\nu_x+d\rightarrow \nu_x+e^-$

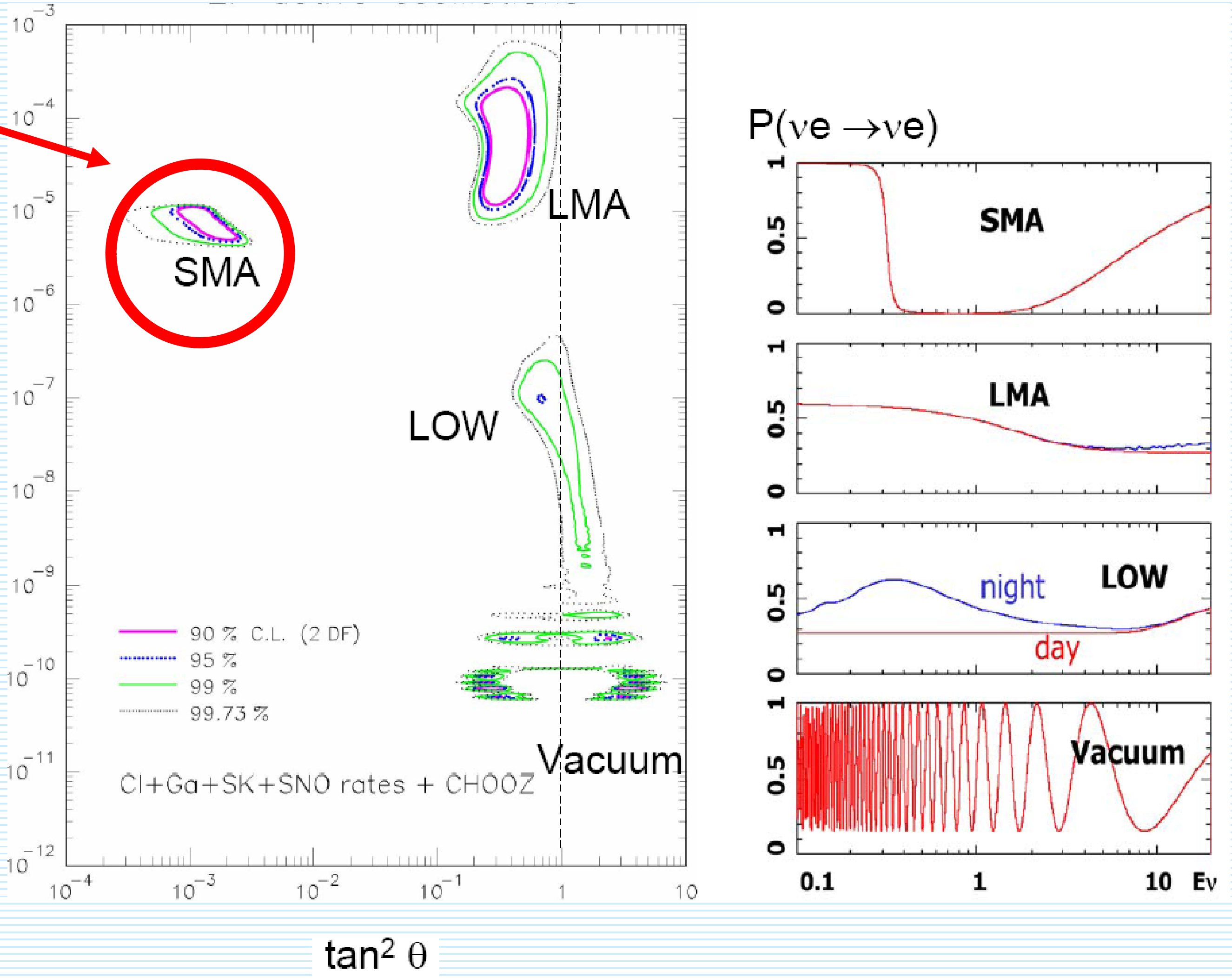
Low statistics
$\sigma(\nu_e) \approx 7\ \sigma(\nu_\mu) \approx 7\ \sigma(\nu_\tau)$
strong directionality


Elastic Scattering

Two-neutrino active oscillations

Solar ν Oscillation Solutions

In analogy with CKM matrix

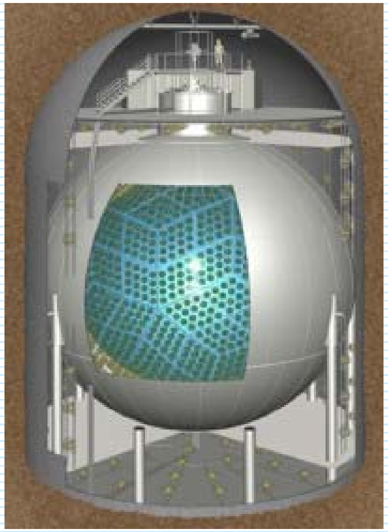


Fit to the rates of all solar neutrons events from all experiments

Idea: The same solution
for neutrinos and antineutrinos
CPT symmetry

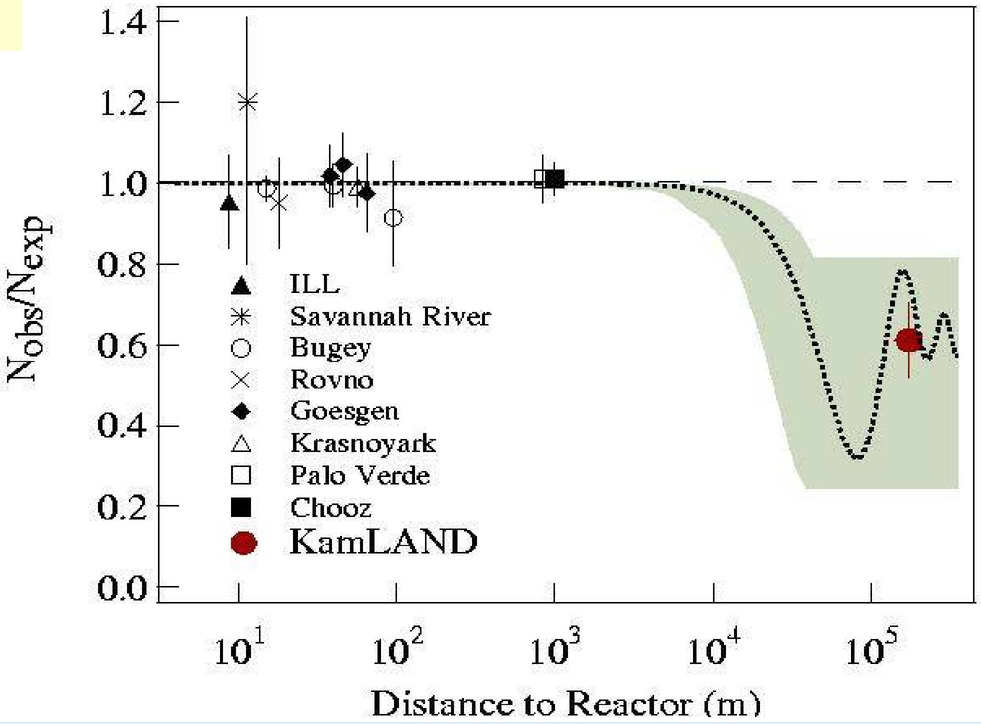
$$P_{\nu_\alpha \to \nu_\beta} \xrightarrow{\text{CPT}} P_{\bar{\nu}_\beta \to \bar{\nu}_\alpha}$$

KamLAND Scintillator-Detector
(1000 t)



2002 KamLAND exp.

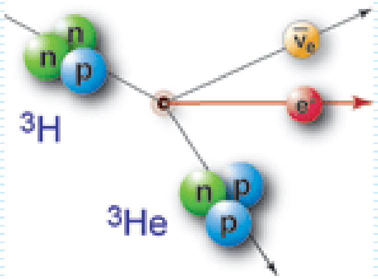
$\bar{\nu}_e \to \bar{\nu}_e$ disappearance experiment



Dashed: Best fit LMA
$\sin^2 2\theta=0.833$, $\Delta m^2=5.5\ 10^{-5}$ eV^2
shaded: 95% CL
LMA solar neutrino data

Neutrino masses

Tritium beta decay: $^{3}H \rightarrow {}^{3}He + e^{-} + \bar{\nu}_e$

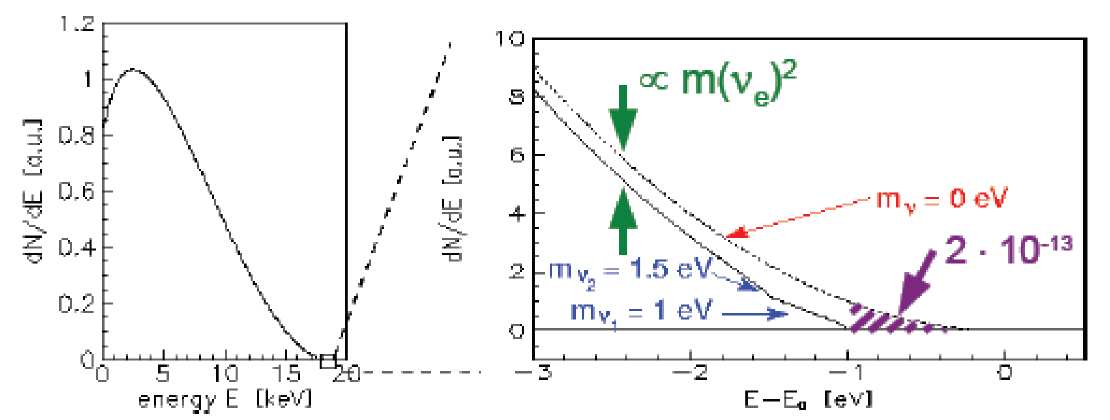


$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |M|^2 F(E)\, pE\,(Q-T)\sqrt{(Q-T)^2 - m_{\nu_e}^2}$$

1934 – **Fermi** pointed out that shape of electron spectrum in β–decay near the endpoint is sensitive to **neutrino mass**

First measured by **Hanna** and **Pontecorvo** with estimation $m_\nu \sim 1$ keV [Phys. Rev. 75, 983 (1940)]

$Q = M_H - M_{He} - m_e$
$= 1858$ keV



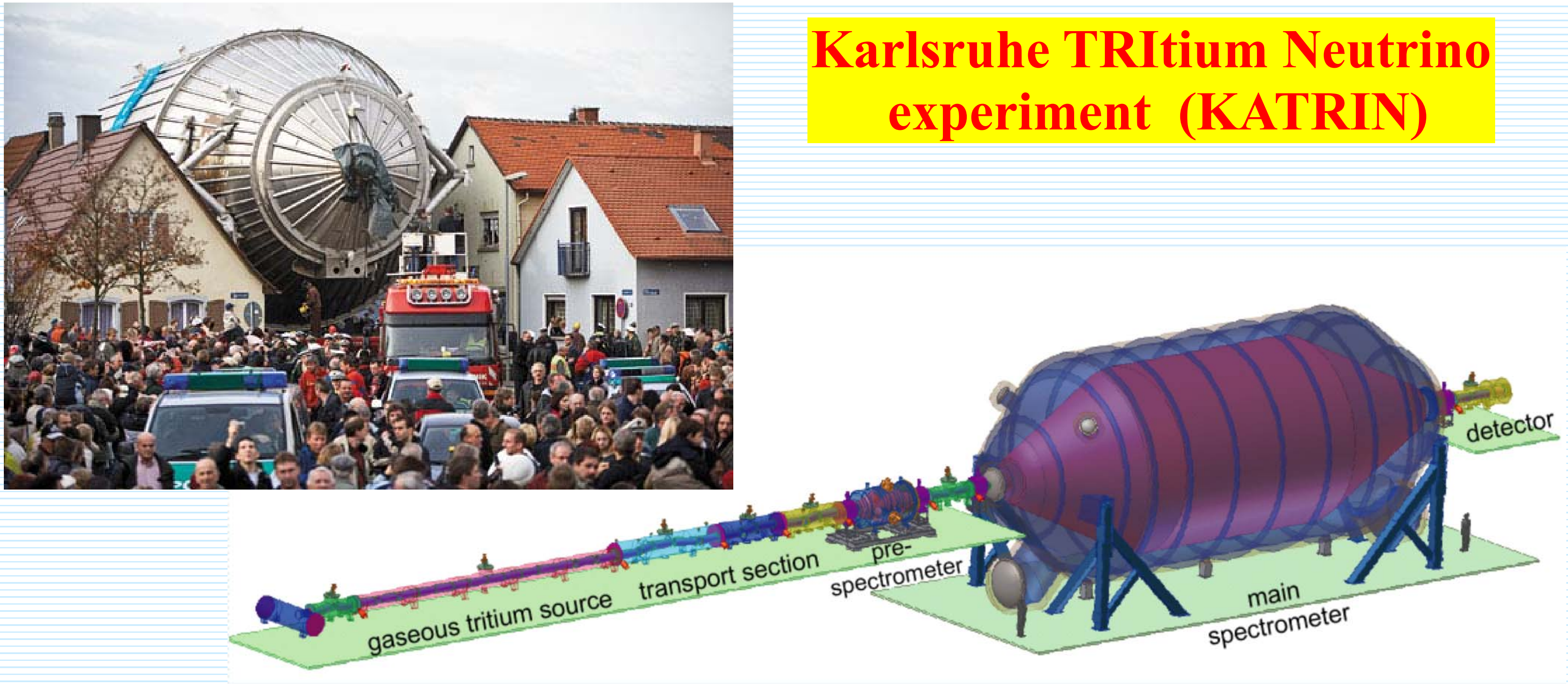
Troitsk

$m_\nu^2 = -2.3 \pm 2.5 \pm 2.0$ eV^2
$m_\nu \leq$ 2.2 eV (95% CL.)

Mainz

$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1$ eV^2
$m_\nu \leq$ 2.2 eV (95% CL.)

Karlsruhe TRItium Neutrino experiment (KATRIN)



$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2\ m_i^2}$$

Evidence for neutrino mass signal
KATRIN discovery potential:

$m_\beta = 0.35$ eV (5σ)
$m_\beta = 0.30$ eV (3σ)

No neutrino mass signal
KATRIN sensitivity

$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2} < 0.2\ eV \qquad m_\beta \approx m_1$$

Relativistic approach to ^{3}H decay
nuclear recoil (3.4 eV) taken into account

Standard approach

- **non-relativistic nuclear w.f.**
- **nuclear recoil neglected**
- **phase space analysis**

$$E_e^{\max} = M_i - M_f - m_\nu$$

$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, pE\, (Q-T)\sqrt{(Q-T)^2 - m^2_{\nu_e}}$$

Relativistic EPT approach (Primakoff)

- **Analogy with n-decay**
  (^{3}H,^{3}He) ↔ (n,p)
- **nuclear recoil of 3.4 eV by $E_e^{\max}$**
- **relevant only phase space**

$$E_e^{\max} = \frac{1}{2M_f}\left[M_i^2 + m_e^2 - \left(M_f^2 - m_\nu^2\right)\right]$$

$$\begin{aligned}
\frac{d\Gamma}{dE_e} &= \frac{1}{(\pi)^3}(G_F\cos\theta_c)^2 F(Z,E_e)p_e \\
&\quad \times \frac{M_i^2}{(m_{12})^2}\sqrt{y\left(y + 2m_\nu\frac{M_f}{M_i}\right)} \\
&\quad \times \left[(g_V+g_A)^2 y\left(y + m_\nu\frac{M_f}{M_i}\right)\frac{M_i^2(E_e^2 - m_e^2)}{3(m_{12})^4}\right. \\
&\quad \underline{(g_V+g_A)^2}(y + m_\nu\frac{M_f+m_\nu}{M_i})\frac{(M_iE_e - m_e^2)}{m_{12}^2} \\
&\quad \times (y + M_f\frac{M_f+m_\nu}{M_i})\frac{(M_i^2 - M_iE_e)}{m_{12}^2} \\
&\quad - (g_V^2 - g_A^2)M_f\left(y + m_\nu\frac{(M_f+M_\nu)}{M_i}\right) \\
&\quad \times \frac{(M_iE_e - m_e^2)}{(m_{12})^2} \\
&\quad \left. +(g_V-g_A)^2 E_e\left(y + m_\nu\frac{M_f}{M_i}\right)\right]
\end{aligned}$$

$$\begin{aligned}
y &= E_e^{max} - E_e \\
(m_{12})^2 &= M_i^2 - 2M_iE_e + m_e^2
\end{aligned}$$

Numerics:

Practically the same dependence of Kurie function on m_ν for $E_e \approx E_e^{\max}$

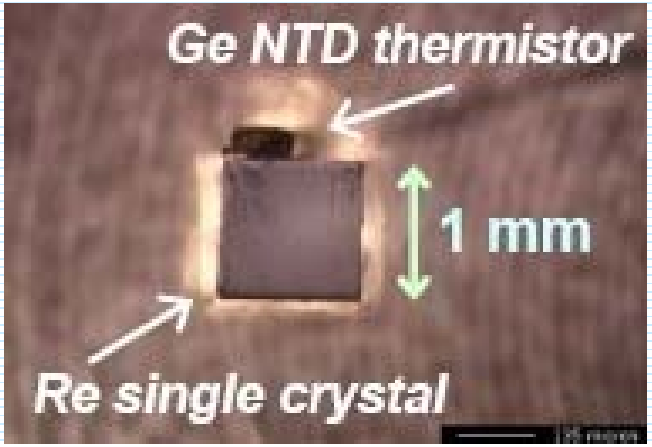
F.Š., R. Dvornický, A. Faessler, PRC 77 (2008) 055502

Rhenium beta decay

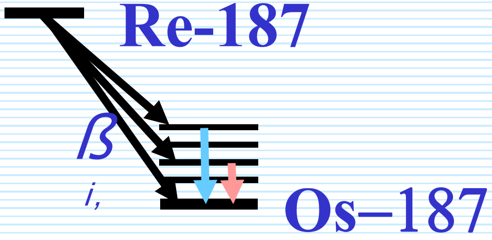
$$^{187}Re \rightarrow {}^{187}Os + e^- + \tilde{\nu}_e$$

MARE experiment

- Beta emitter of g.s.→g.s. transition with lowest known Q value (2.47 keV)
- Relative high half-live ($T_{1/2}$=4.35 x 10^{10} y) ~ age of the universe (cosmo – chronometer)
- Natural abundance 63%



Bolometer source=detector



Dvornický, F. Š., Muto, Faessler, PPNP (2009)

$$\frac{d\Gamma}{dE} = \frac{G_F^2 V_{ud}^2}{2\pi^3} |M|^2 \, pE(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}\, \frac{1}{3} R^2 \left(p^2 F_1(Z,E) + k^2 F_0(Z,E) \right)$$

Electron in the $p_{3/2}$ state

Electron in the $s_{1/2}$ state

$$^{115}In \rightarrow {}^{115}Sn^* + e^- + \tilde{\nu}_e$$

Indium beta decay

$$9/2^+ \rightarrow 3/2^+ \Rightarrow \Delta J^\pi = 3^+$$

Beta transition of g.s.→ex. s. with lowest known Q value (155 ±24 eV)

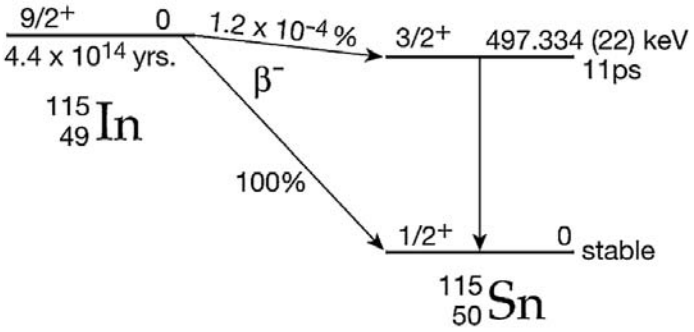


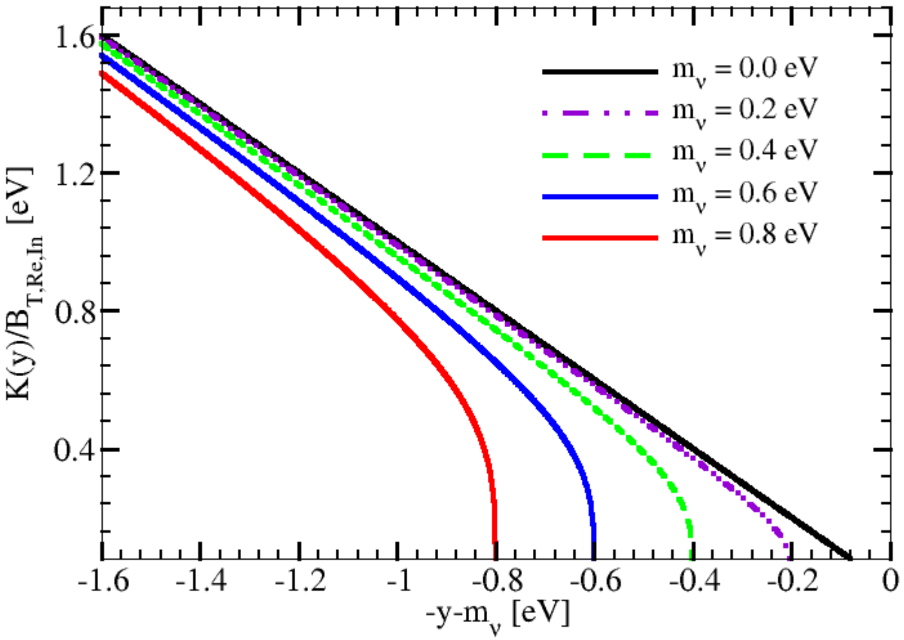
FIG. 1. Level scheme for the beta decay of the ground state of ^{115}In showing relevant half-lives and branching ratios.

Normalised Kurie functions become identical

p_e^{max} = 12.6 keV **[PRL 103, 122502 (2009)**

k^{max} = 155 eV

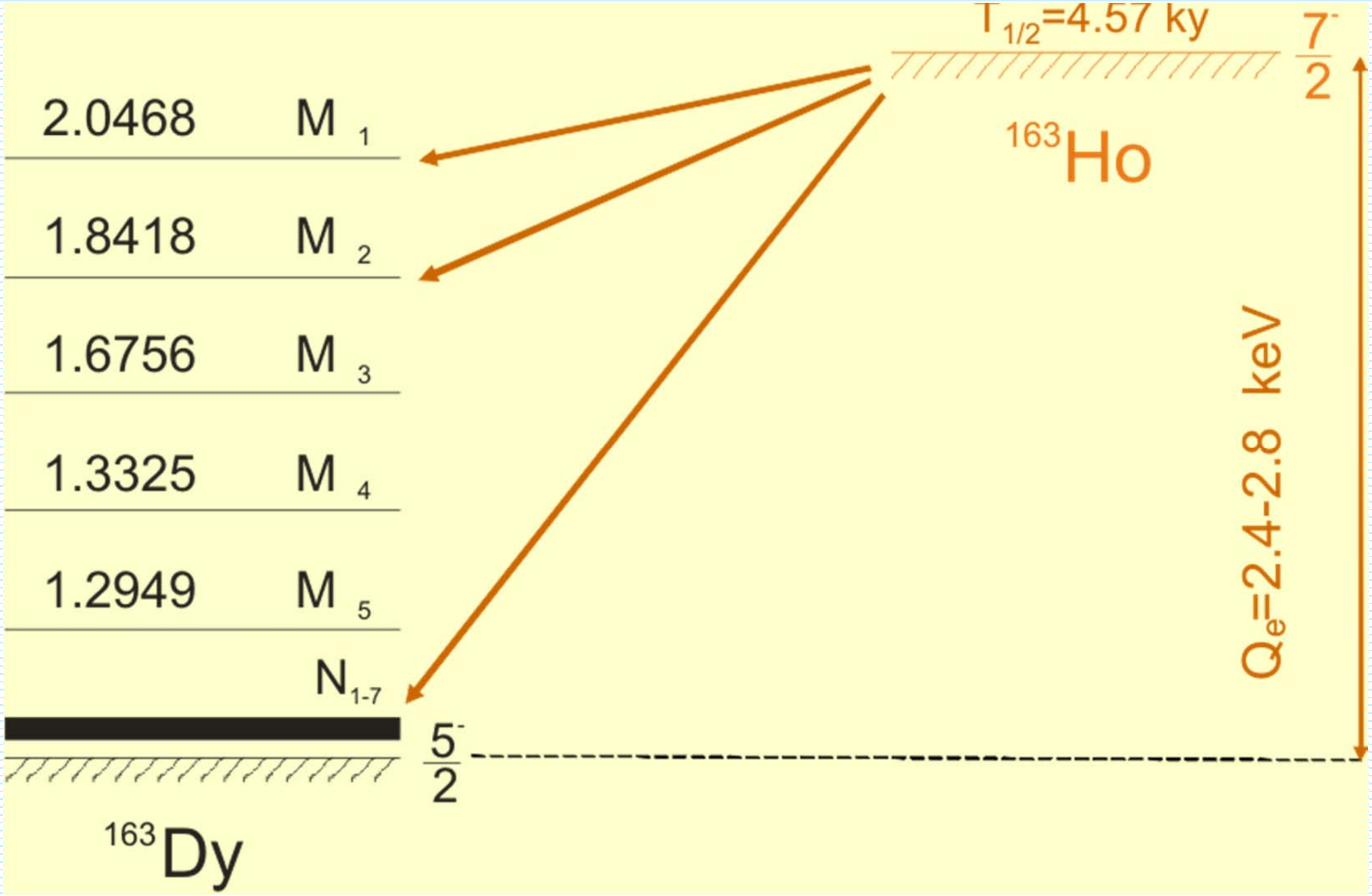
$$K(E)/B_{re} \cong K(E)/B_{In} \cong K(y)/B_T$$



Mass of Neutrino: electron-capture in ^{163}Ho

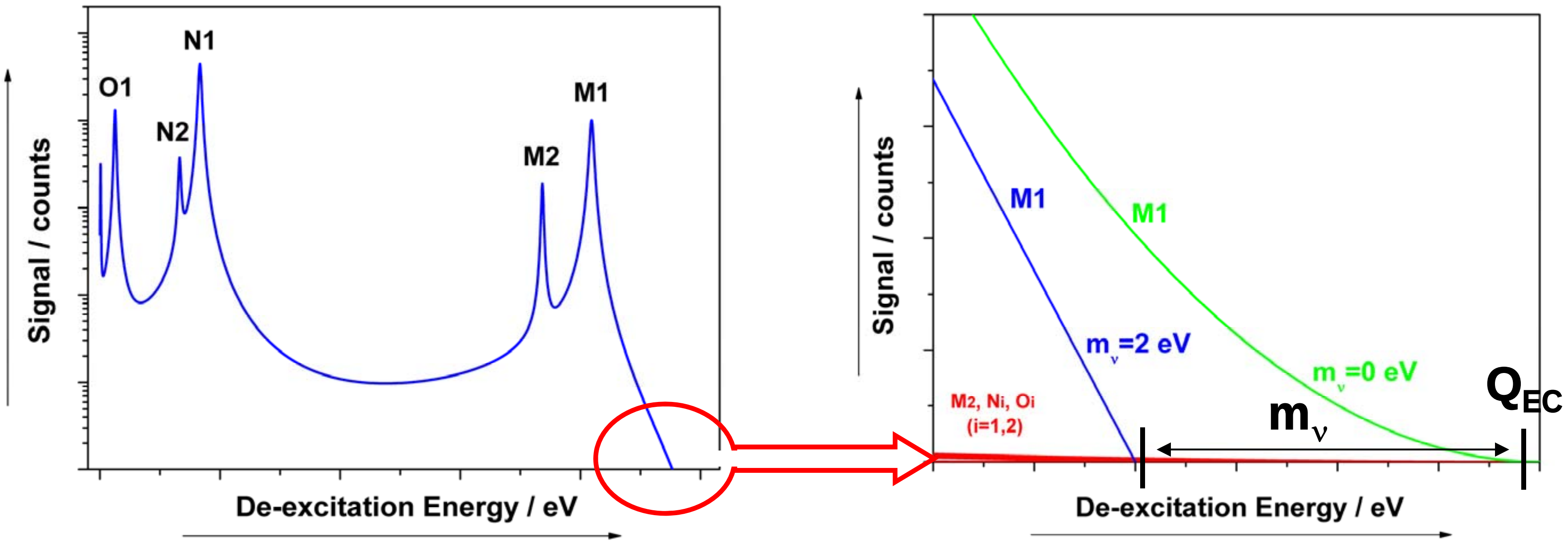
$$^{163}\mathrm{Ho} \longrightarrow {}^{163}\mathrm{Dy}^{h} + \nu_e\,(E_\nu)$$
$$\hookrightarrow {}^{163}\mathrm{Dy} + E_c$$

analysis of calorimetric spectrum → m_ν



Mass of Neutrino: electron-capture in ^{163}Ho

Typical m-calorimetric de-excitation spectrum of EC in ^{163}Ho



Cryogenic m-calorimeters (Group of Prof. Enss, KIP, Uni Heidelberg)
end point with accuracy ~ 1 eV

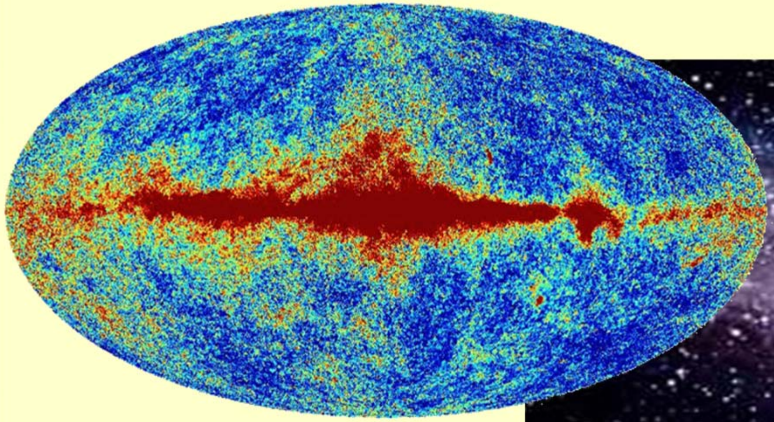
PENTATRAP (Group of Prof.K. Blaum, MPI-K, HD)
Q_{EC}-value with accuracy ~ 1 eV

m_ν ~ 1 eV

Laboratory detection of relic (cosmic) neutrinos?

Gravitational clustering of neutrinos

- We know that neutrinos of CνB are now non-relativistic and weakly-clustered
  - Massive neutrinos ($m_\nu \sim 1$ eV) will be gravitationally clustered on the scale of ~Mpc (~3×10^{19}km) → the scale of galaxy clusters
- The expected over-densities with respect to the average CνB neutrinos density ~ 10^3-10^4

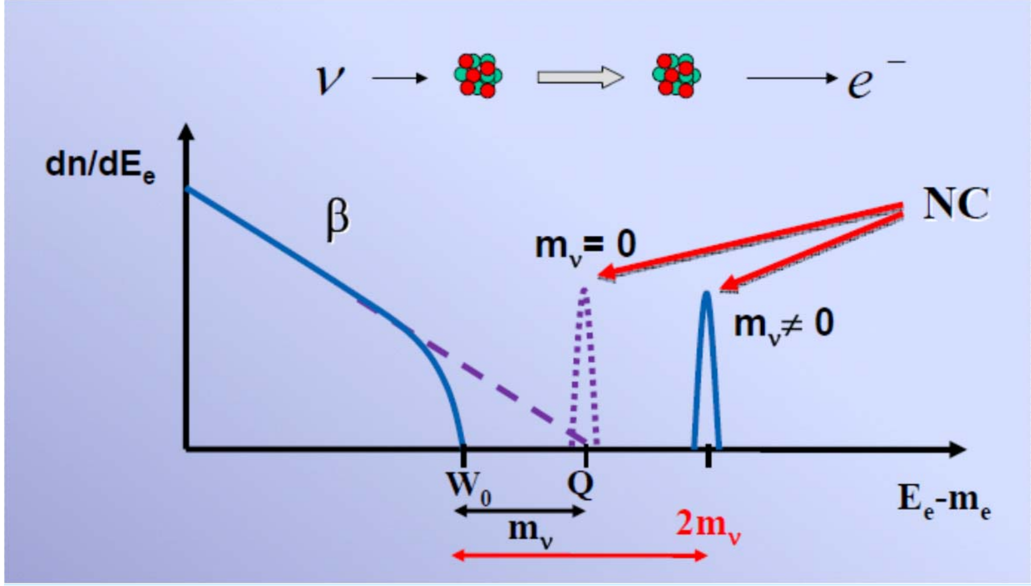


R. Lazauskas, P. Vogel, C. Volpe, J. Phys. G 35 (2008)

Detection of relic neutrinos by KATRIN experiment

$$\nu + {}^3H((1/2)^+) \rightarrow {}^3He((1/2)^+) + e^-$$

$$\Gamma^\nu({}^3H) = \frac{1}{\pi} G_\beta^2 \, F_0(2,p) \, p \, p_0 \, \left(|M_F|^2 + g_A^2 \, |M_{GT}|^2\right) \, \frac{\eta_\nu}{<\eta_\nu>} \, <\eta_\nu>$$



Assuming M_F=1, M_{GT}=√3 and η_ν=<η_ν> the capture rate

$$\Gamma^\nu({}^3H) = 4.2 \; 10^{-25} \; y^{-1}$$

KATRIN will use ~50 μg of ^{3}H

Faessler, Hodák, Kovalenko, F.Š,
J. Phys. G 38 (2011) 052504

$$N^\nu_{capt}(KATRIN) \approx 4.2 \; 10^{-6} \; \frac{\eta_\nu}{<\eta_\nu>} \; y^{-1}$$

Even considering effect of clustering of ν, η_ν/<η_ν> ~ 10^3-10^4 :
N^ν_{capt}(KATRIN) < 1 y^{-1}

Experiment MARE (The Microcalorimeter Arrays for a Rhenium Experiment)

Faessler, Hodák, Kovalenko, F.Š,
J. Phys. G 38 (2011) 052504

$$\nu + {}^{187}\mathrm{Re}^{5/2^{+}} \rightarrow {}^{187}Os^{1/2^{-}} + e^{-}$$

- Measuring neutrino mass in the sub-eV range with the unique first **forbidden** β - decay of ^{187}Re
- For the **capture rate** of this process we derive

$$\boxed{\Gamma^{\nu}({}^{187}\mathrm{Re}) = \frac{1}{\pi} G_{\beta}^{2} \frac{1}{3} F_{1}(76, p)(pR)^{2} B.p.p_{0} \frac{\eta_{\nu}}{\langle \eta_{\nu} \rangle} \langle \eta_{\nu} \rangle = 2.75 \times 10^{-32}\, y^{-1}}$$

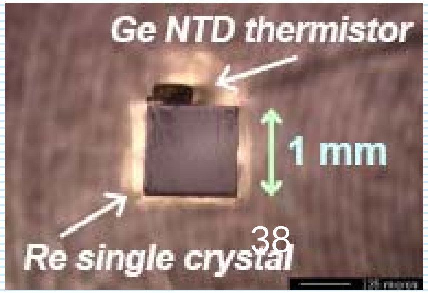
Beta strength

$$\boxed{B = \frac{g_{A}^{2}}{6} \left| \left\langle {}^{187}Os^{1/2^{-}} \left\| \sqrt{\frac{4\pi}{3}} \sum_{n} \tau_{n}^{+} \frac{r_{n}}{R} \left\{ \sigma_{n} \otimes Y_{1}(\Omega_{r_{n}} \right\}_{2} \right\| {}^{187}\mathrm{Re}^{5/2^{+}} \right\rangle \right|^{2}}$$

- Investigation the β -decay of ^{187}Re with absorbers of **$AgReO_4$ crystals**
- Using about **760 g** of **^{187}Re** **($T_{1/2}^{\beta}$ = 4.35 x10^{10} y)**

  for **number of neutrino capture events**

$$\boxed{N_{capt}^{\nu}(MARE) \approx 7.6 \times 10^{-8} \frac{\eta_{\nu}}{\langle \eta_{\nu} \rangle} y^{-1}}$$



Neutrino mixing

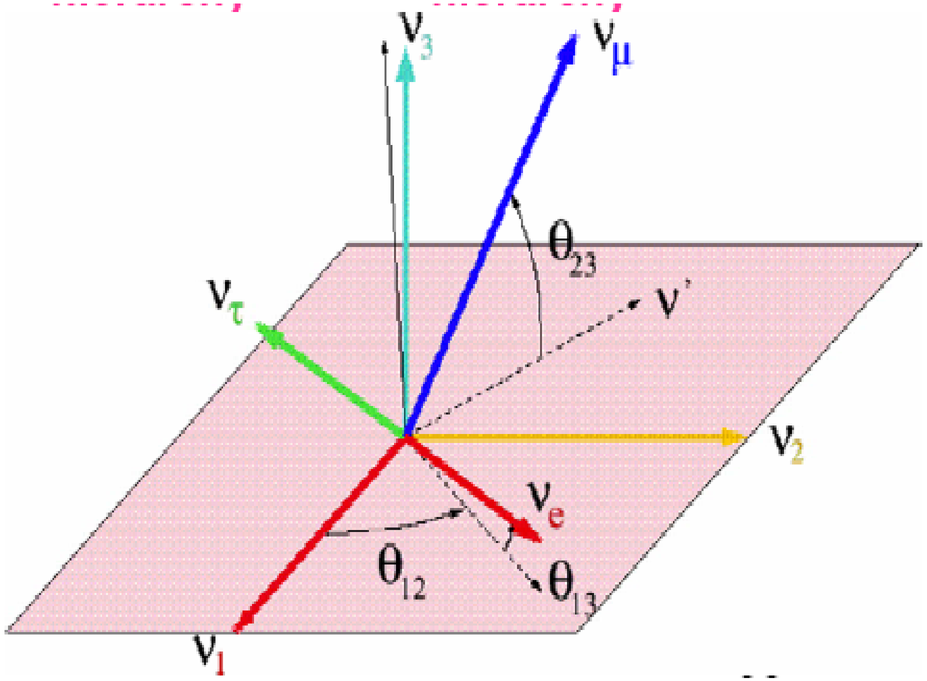
Mixing of 3 light Neutrinos

Pontecorvo -Maki-Nakagawa-Sakata matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor eigenstates

Mass eigenstates



Mass matrix

$$\begin{pmatrix} M_{ee} & M_{e\mu} & M_{e\tau} \\ M_{\mu e} & M_{\mu\mu} & M_{\mu\tau} \\ M_{\tau e} & M_{\tau\mu} & M_{\tau\tau} \end{pmatrix}$$

$$m_{\beta\beta} = \Sigma\, U_{ei} U_{ei}\, m_i$$

Is there analogy between lepton mixing matrix and quark mixing?

PMNS Lepton Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

CKM Quark Mixing Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Large off diagonal elements

$$\begin{pmatrix} 0.7 & 0.7 & < 0.2\ e^{i\delta_{13}} \\ -0.5 & 0.5 & 0.7 \\ 0.5 & -0.5 & 0.7 \end{pmatrix}$$

CP violating Phases:
$\delta_{13}, \delta_{\mathrm{CKM}}$

$$\begin{pmatrix} 0.97 & 0.22 & 0.003\ e^{i\delta_{CKM}} \\ -0.22 & 0.97 & 0.04 \\ 0.01 & -0.04 & 0.999 \end{pmatrix}$$

Disperity and challange
for quark-lepton unified theories

PMNS for Majorana neutrinos

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

What is the nature of neutrinos?

The answer to the question whether neutrinos are their own antiparticles is of central importance, not only to our understanding of neutrinos, but also to our understanding of the origin of mass.

$\nu \Rightarrow$

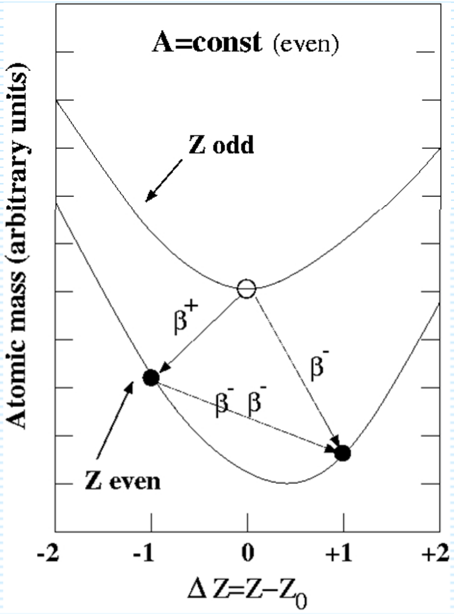
GUT's

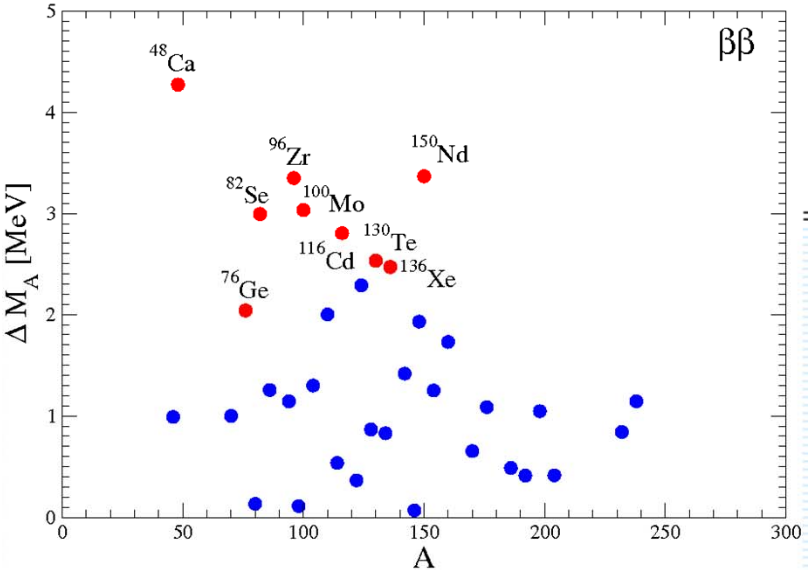
Only the 0νββ-decay can answer this fundamental question

Analogy with kaons: K_0 and $\overline{K}_0$

Analogy with π_0

The double beta decay process can be observed due to nuclear pairing interaction that favors energetically the even-even nuclei over the odd-odd nuclei





$$\frac{1}{T^{0\nu}_{1/2}} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 G^{01}(E_0, Z) \left|M^{0\nu}\right|^2$$

transition	$G^{01}(E_0,Z)$ $\times 10^{14} y$	$Q_{\beta\beta}$ [MeV]	Abund. (%)	$\lvert M^{0\nu}\rvert^2$
$^{150}Nd \rightarrow {}^{150}Sm$	26.9	3.667	6	?
$^{48}Ca \rightarrow {}^{48}Ti$	8.04	4.271	0.2	?
$^{96}Zr \rightarrow {}^{96}Mo$	7.37	3.350	3	?
$^{116}Cd \rightarrow {}^{116}Sn$	6.24	2.802	7	?
$^{136}Xe \rightarrow {}^{136}Ba$	5.92	2.479	9	?
$^{100}Mo \rightarrow {}^{100}Ru$	5.74	3.034	10	?
$^{130}Te \rightarrow {}^{130}Xe$	5.55	2.533	34	?
$^{82}Se \rightarrow {}^{82}Kr$	3.53	2.995	9	?
$^{76}Ge \rightarrow {}^{76}Se$	0.79	2.040	8	?

The NMEs for 0νββ-decay must be evaluated using tools of nuclear theory

Lepton number violating nuclear processes

$$(A,Z) \rightarrow (A,Z+2) + e^- + e^-$$

Perturbation theory

$$\frac{1}{T^{0\nu}_{1/2}} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 G^{01}(E_0, Z) \left|M^{0\nu}\right|^2$$

- 2νββ-decay background can be a problem
- Uncertainty in NMEs factor ~2, 3
- $0^+ \rightarrow 0^+, 2^+$ transitions
- Large Q-value
- ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe …
- Many exp. in construction, potential for observation in the case of inverted hierarchy (2020)

$$e^- + e^- + (A,Z) \rightarrow (A,Z-2)^{**}$$

Breit-Wigner form

$$\Gamma^{0\nu ECEC}(J^\pi) = \frac{|V_{\alpha\beta}(J^\pi)|^2}{(M_i - M_f)^2 + \Gamma^2_{\alpha\beta}/4}\,\Gamma_{\alpha\beta}$$

- 2νεε-decay strongly suppressed
- NMEs need to be calculated
- $0^+ \rightarrow 0^+, 0^-, 1^+, 1^-$ transitions
- Small Q-value
- Q-value needs to be measured at least with 100 eV accuracy
- ^{152}Gd, looking for additional
- small experiments yet

Quark-Lepton Complemenarity

QLC- relations:

H. Minakata, A.S.
Phys. Rev. D70: 073009 (2004)
[hep-ph/0405088]

$\theta^{l}_{12} + \theta^{q}_{12} \sim \pi/4$

$\theta_{12} + \theta_{C} = 46.5^{o} +/- 1.3^{o}$

$\theta^{l}_{23} + \theta^{q}_{23} \sim \pi/4$

$\theta_{23} + \theta_{23} = 43.9^{o} + 5.1/-3.6^{o}$

Qualitatively correlation:

- **2-3 leptonic mixing is close to maximal because 2-3 quark mixing is small**
- **1-2 leptonic mixing deviates from maximal substantially because 1-2 quark mixing is relatively large**

$\theta_{13} \neq 0$: How Big or How Small?

Convincing flavor theory has been lacking—it is at present impossible to predict fermion masses, flavor mixing angles and CP phases fundamental level ⇒ the flavor problem

Bi-maximal mixing

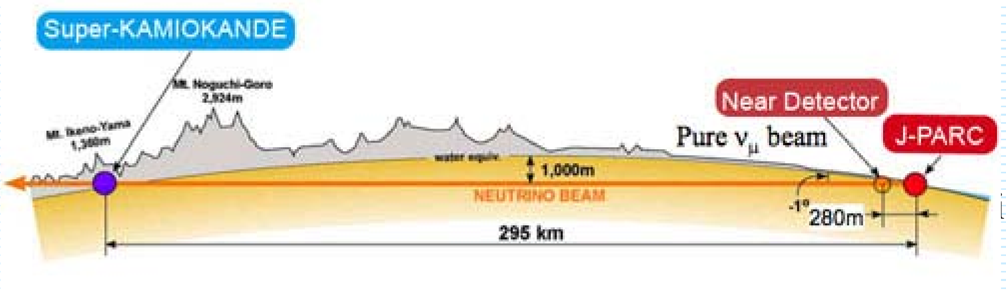
$$U_{bm} = \begin{pmatrix} \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \sqrt{\frac{1}{2}} \\ \frac{1}{2} & -\frac{1}{2} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

$U_{bm} = U_{23}{}^{m} U_{12}{}^{m}$

As dominant structure?
Zero order?

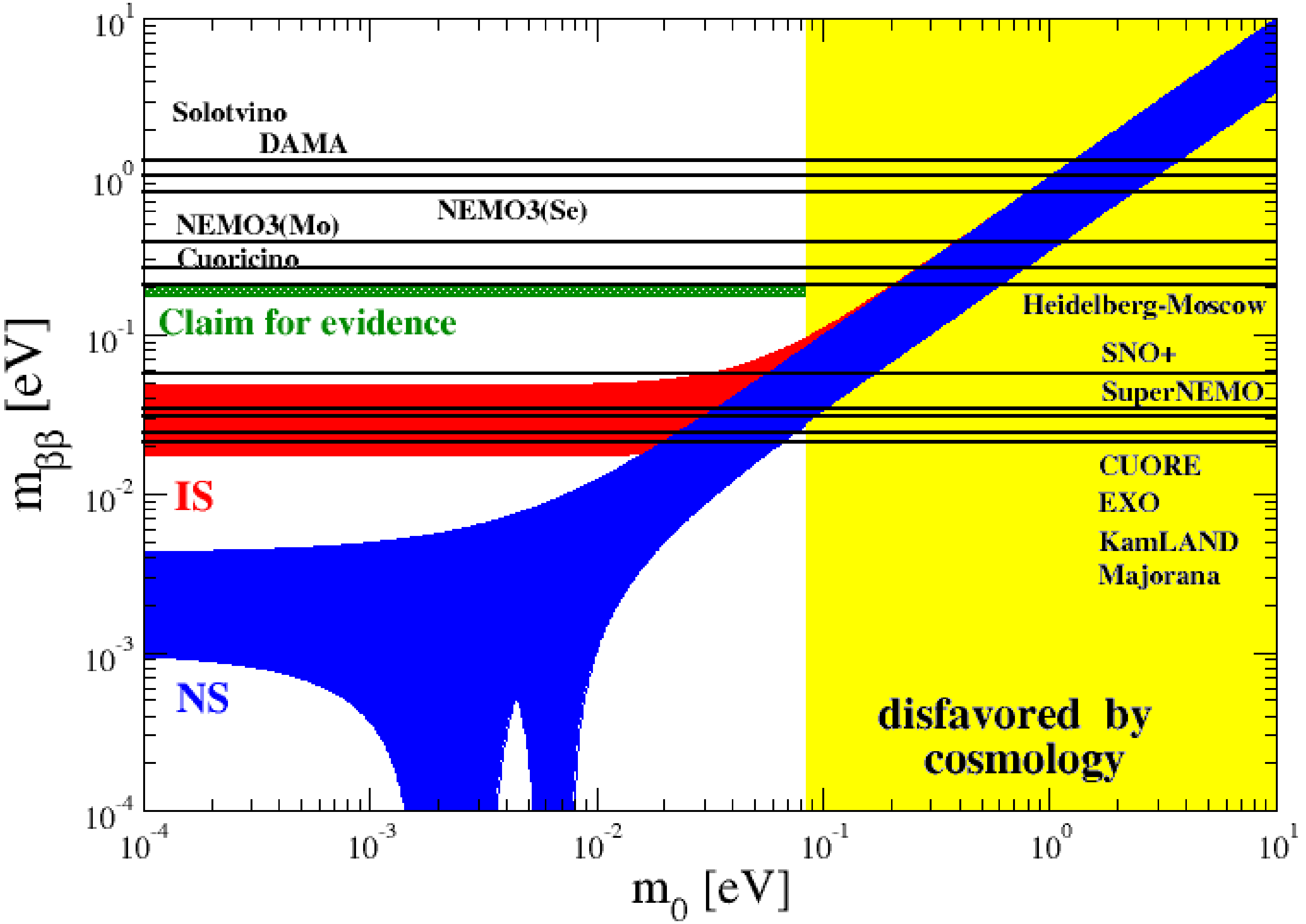
θ_{13} has a role!

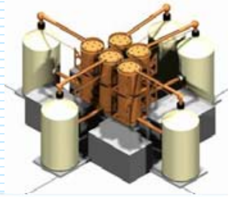
T2K: $0.03 < \sin^2 2\theta_{13} < 0.34$ (June 2011)
DOOBLE CHOOZ: $\sin^2 2\theta_{13} = 0.085 \pm 0.051$ (9.11.2011)

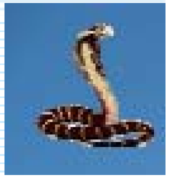


DOOBLE CHOOZ: $\sin^2 2\theta_{13}$ =0.085±0.051 (9.11.2011)

$$|m_{\beta\beta}{}^{(3\ \nu)}| = |c_{12}^2 c_{13}^2 e^{2i\alpha_1} m_1 + c_{13}^2 s_{12}^2 e^{2i\alpha_2} m_2 + s_{13}^2 m_3|$$





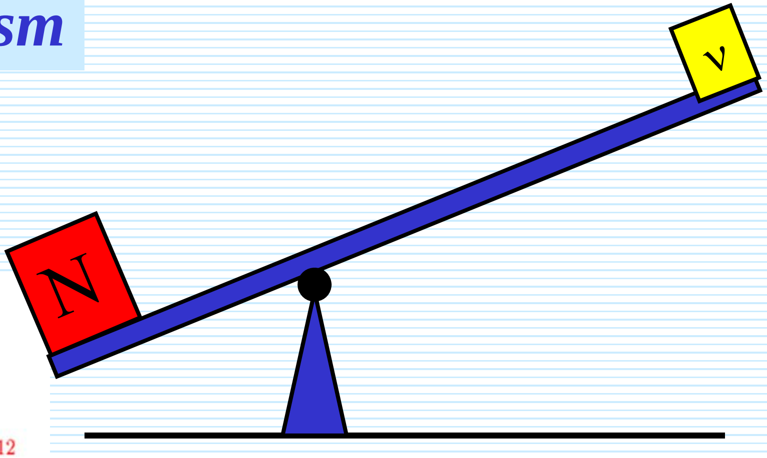


$$\Delta m_A^2 = (2.43 \pm 0.13) \times 10^{-3}\ \mathrm{eV}^2 \quad (Minos)$$
$$\Delta m_S^2 = (7.65^{+0.13}_{-0.20}) \times 10^{-5}\ \mathrm{eV}^2 \quad (global\ fit)$$
$$\tan^2\theta_{12} = 0.452^{+0.035}_{-0.033} \quad (solar - KamLAND)$$
$$\sin^2(2\theta_{13}) = 0.085 \pm 0.029\ (stat)\ \pm 0.042\ (syst) \quad (Dooble\ Chooz)$$

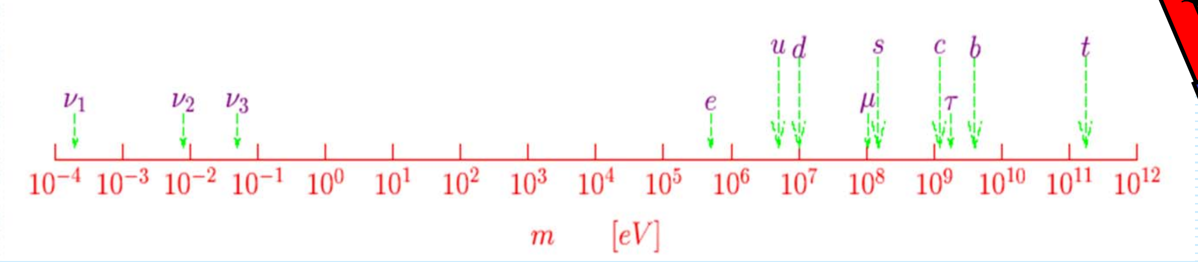
Sterile neutrinos

Assumption $M_R \gg m_D$

See-Saw mechanism



$$\begin{pmatrix} \overline{\nu}_L & \overline{(\nu_R)^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} (\nu_L)^c \\ \nu_R \end{pmatrix}$$



Left-right symmetric models SO(10)

$$\nu_{eL} = \sum_{i=1}^{light} U_{ei}\chi_{iL} + \sum_{i=1}^{heavy} U_{ei}N_{iL}$$

large **small**

$$(\nu_{eR})^c = \sum_{i=1}^{light} V_{ei}\chi_{iL} \sum_{i=1}^{heavy} V_{ei}N_{iL}$$

small **large**

Probability of Neutrino Oscillations

As N increases, the formalism gets rapidly more complicated!

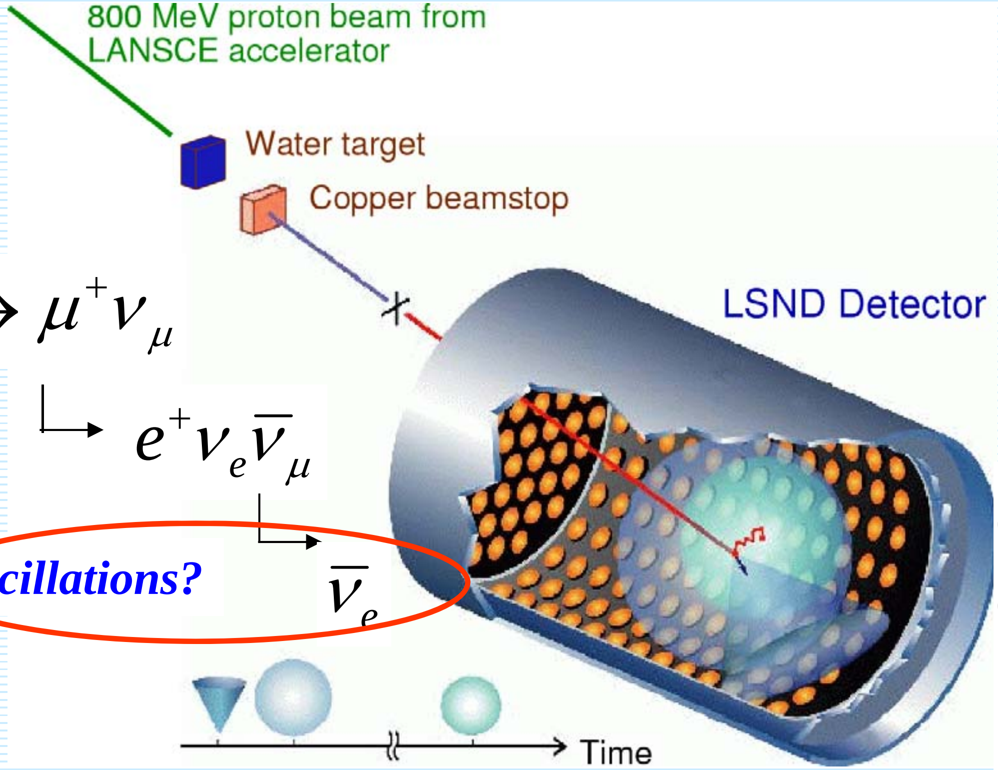
N	Δm_{ij}^2	θ_{ij}	CP
2	1	1	0
3	2	3	1
6	5	15	10

The LSND Experiment: Evidence sterile ν (3.8 σ)

LSND took data from 1993-98

- L = 30m and 20 < E_ν < 53 MeV

Saw an excess of ν_e : 87.9 ± 22.4 ± 6.0 events.



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

↳ $e^+ \nu_e \bar{\nu}_\mu$

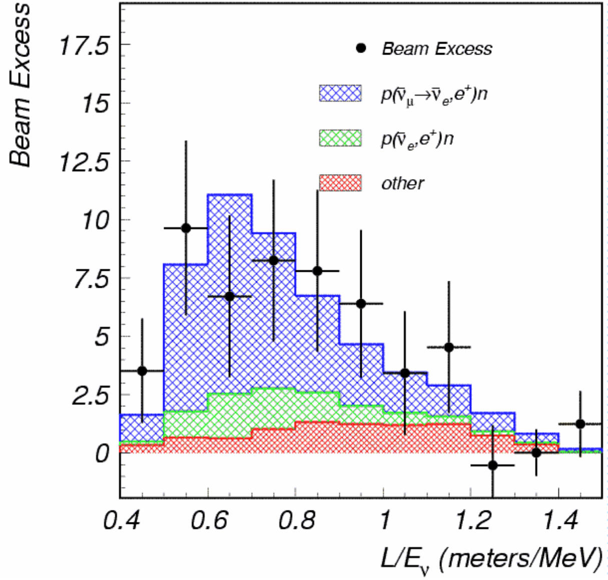
↳ $\bar{\nu}_e$

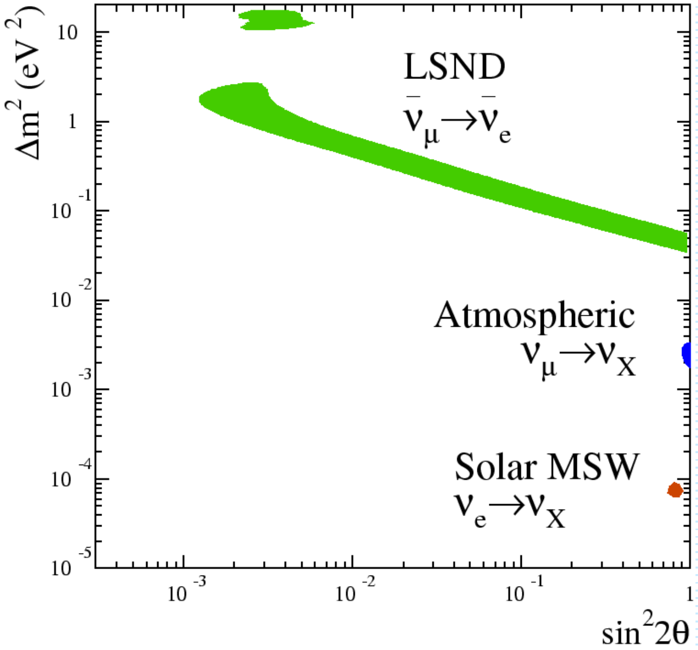
Oscillations?

$\bar{\nu}_e$

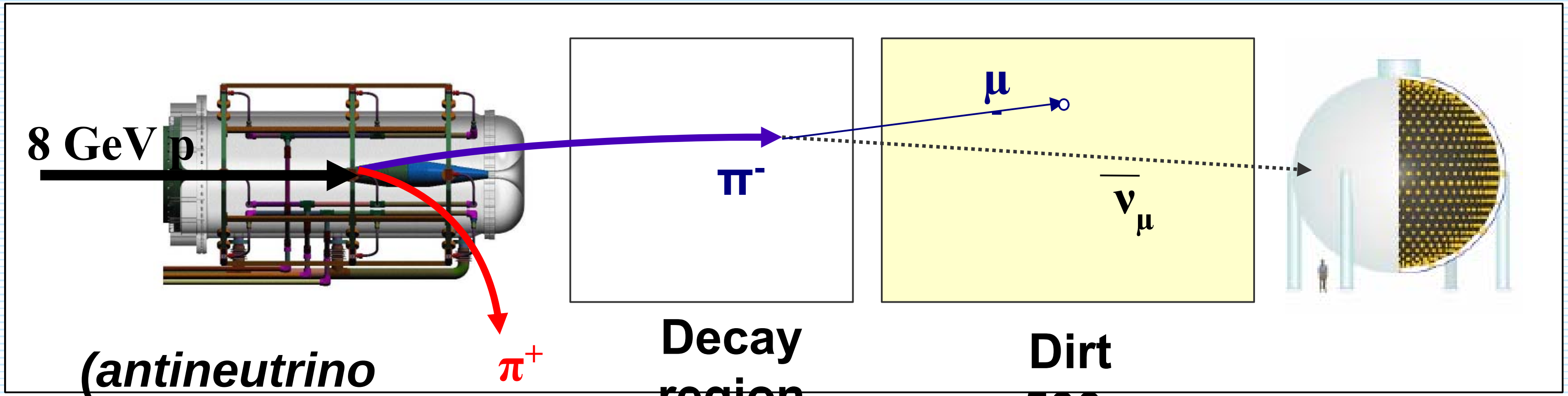
↳ **Signal: $p \to e^+ n$**

$n\,p \to d\,\gamma$(2.2MeV)





MiniBooNE was designed to test the LSND signal



(antineutrino mode)

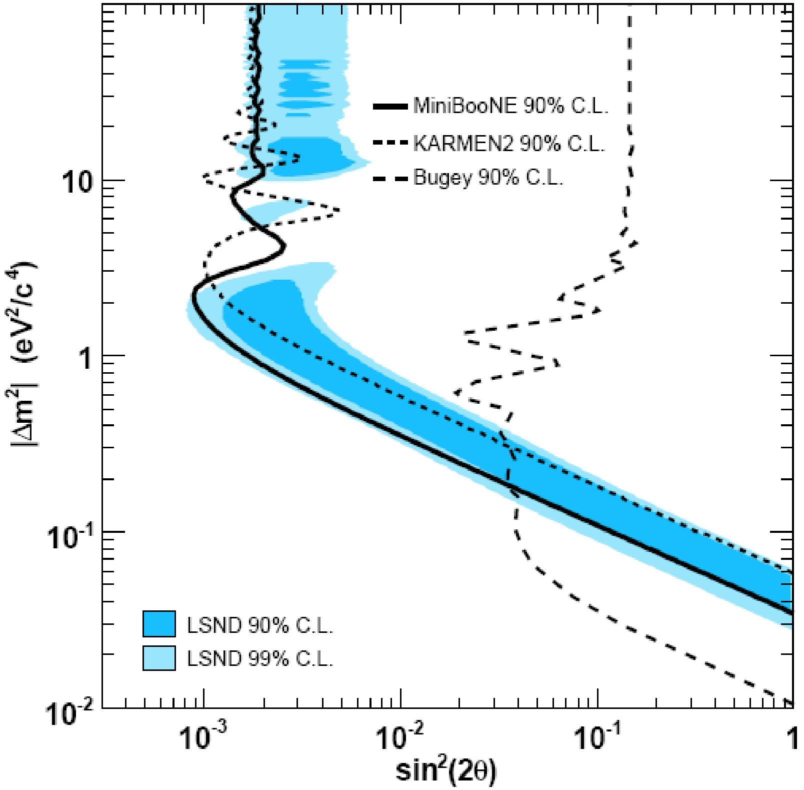
Decay region ~50m

Dirt ~500m

- Similar **L/E** as LSND
  - MiniBooNE **~500m/~500MeV**
  - LSND ~**30m/~30MeV**
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800 tons mineral oil Cherenkov detector
- Detector running since early 2003

Excess of events observed at lower energy:

128.8 ± 20.4 ± 38.3 (3.0σ)



Reactor neutrinos anomaly (January 2011)

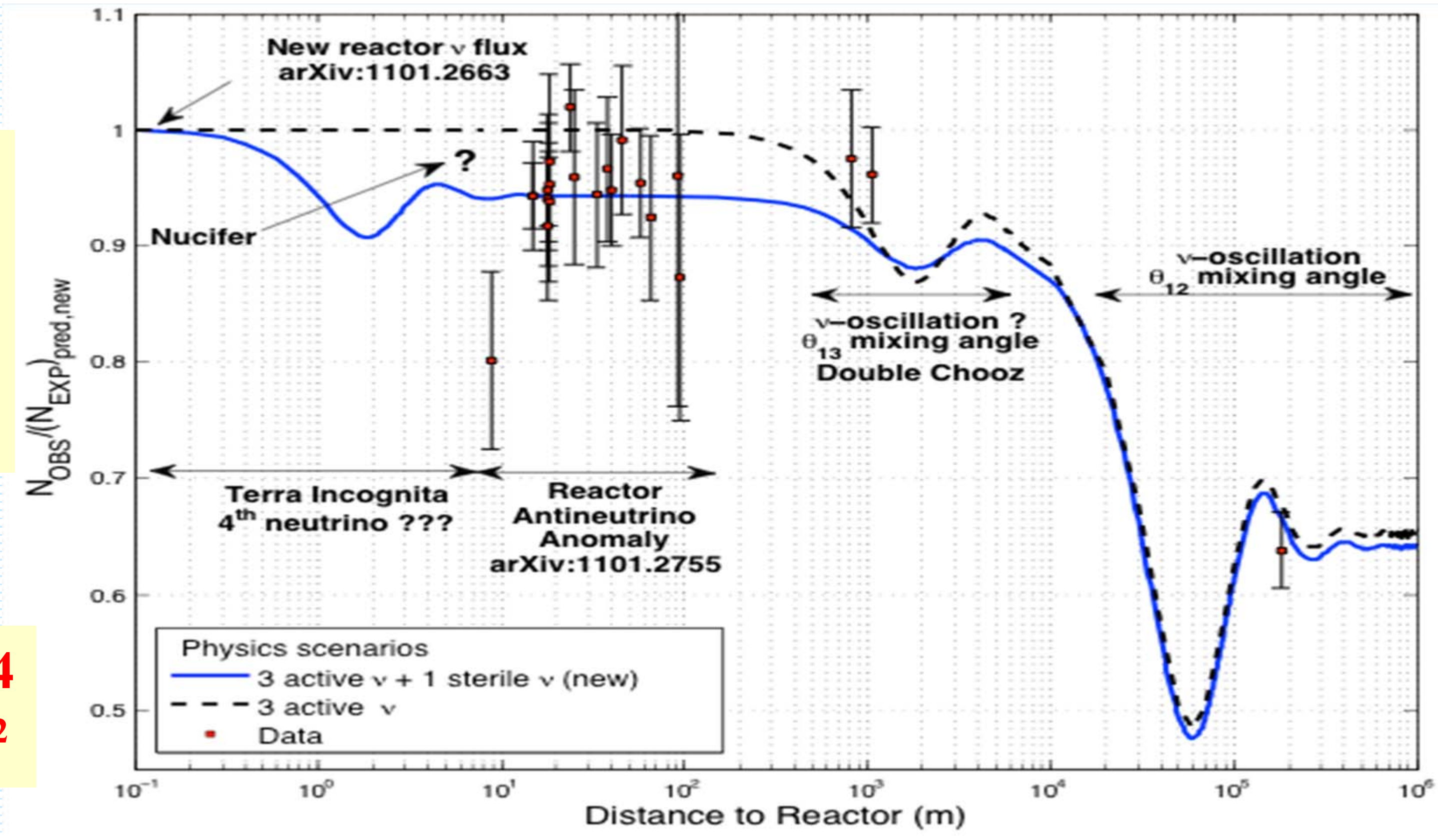
Double Chooz re-evaluated reactor antineutrino flux (PRD 83, 073006 (2011))

- **previous procedure used a phenomenological model based 30 effective beta branches**
- **new analysis used detailed knowledge of the decays of 10,000 + fission products**

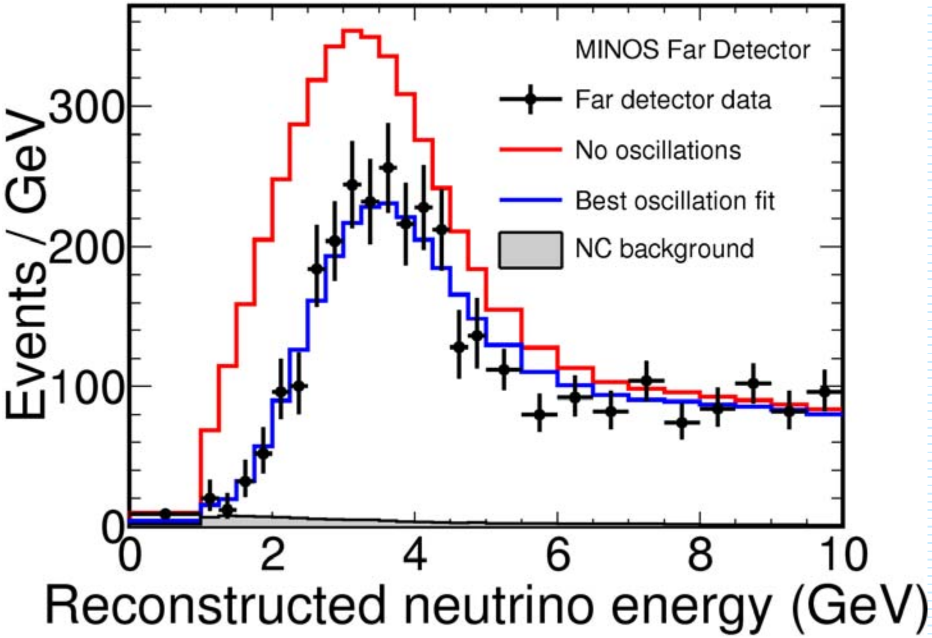
New calculations results in flux increase of 3.5% in reactor antineutrinos

$\sin^2(2\theta_{new}) \sim 0.14$

$\Delta m_{new}^2 > 1.5\ eV^2$



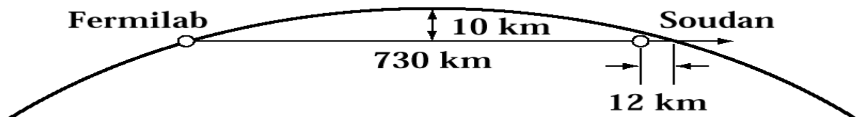
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)^2 \cos^4\theta_{13} \sin^2 2\theta_{12}$$



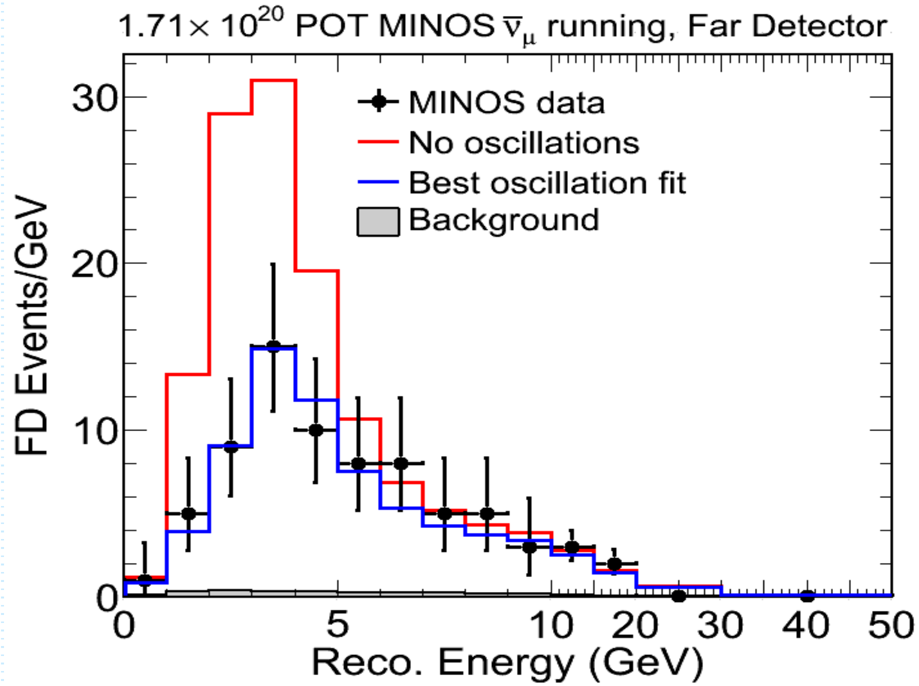
Muon neutrinos

$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \text{eV}^2$$
$$\sin^2(2\theta) > 0.9 \text{ at } 90\% \text{ C.L.}$$

Phys. Rev. Lett. 106, 181801 (2011)



CPT Violation 3+1 Model



Muon antineutrinos

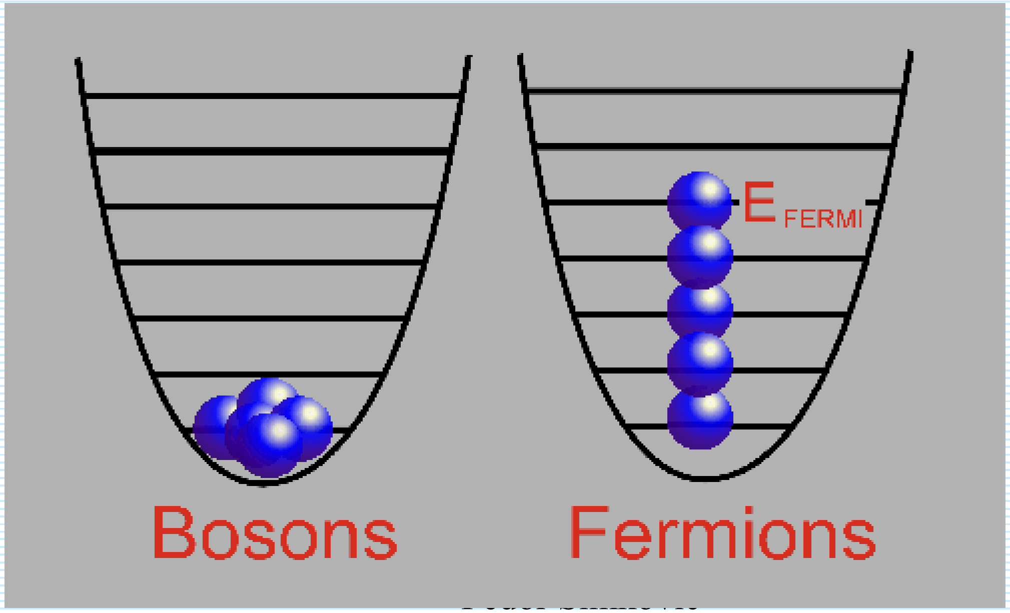
$$|\Delta \overline{m}^2| = 3.36^{+0.46}_{-0.40} \times 10^{-3}\ \text{eV}^2$$
$$\sin^2(2\overline{\theta}) = 0.86^{+0.11}_{-0.12}$$

Phys. Rev. Lett. 107, 021801 (2011)

(Partly)bosonic or fermionic neutrinos?

Fermions:
No two fermions can occupy the same state, so in the ground state (T=0), fermions stack from The lowest energy level to higher Energy levels, leaving no holes.

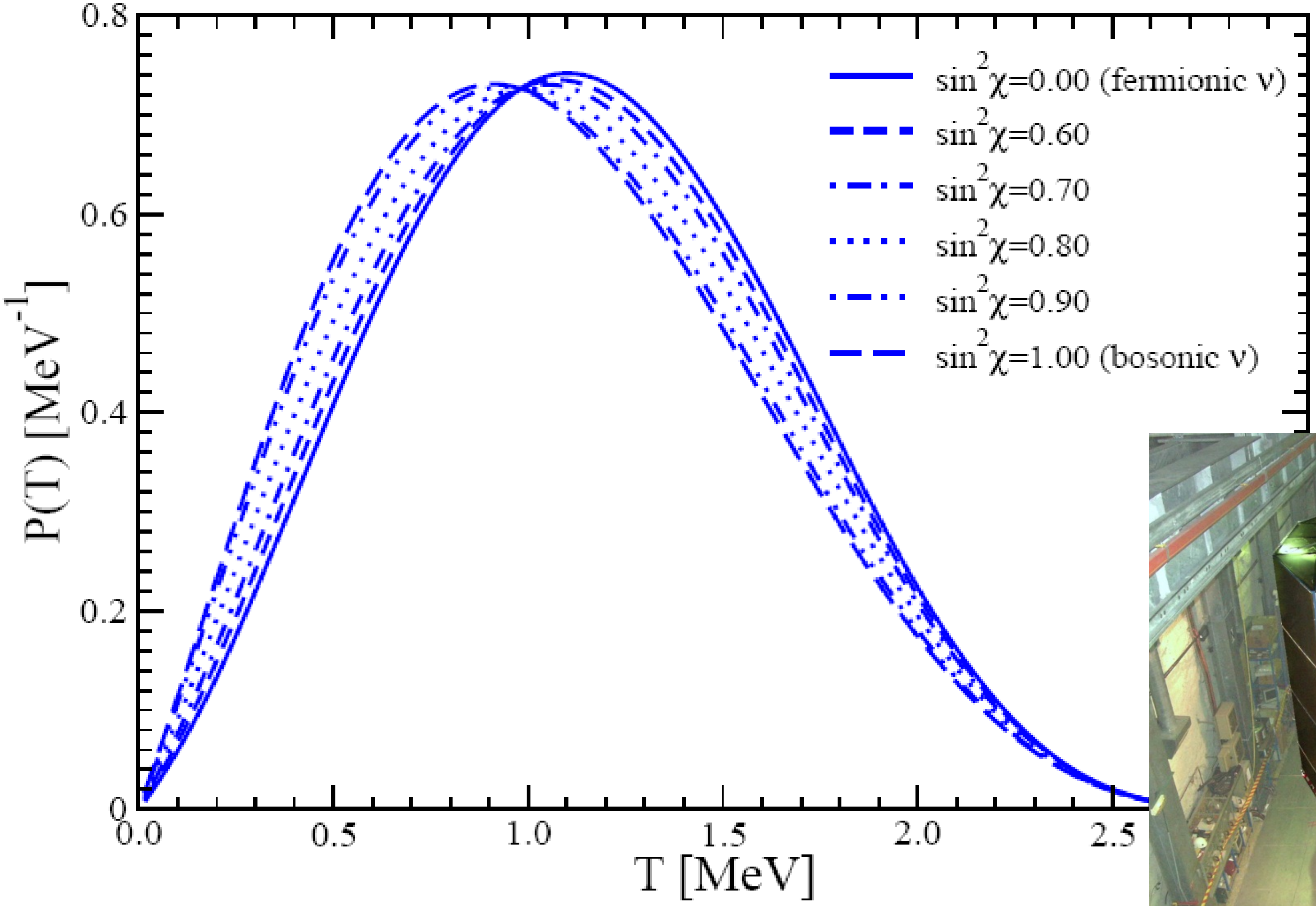
Bosons:
In the ground state (T=0) all bosons occupy lowest energy state.



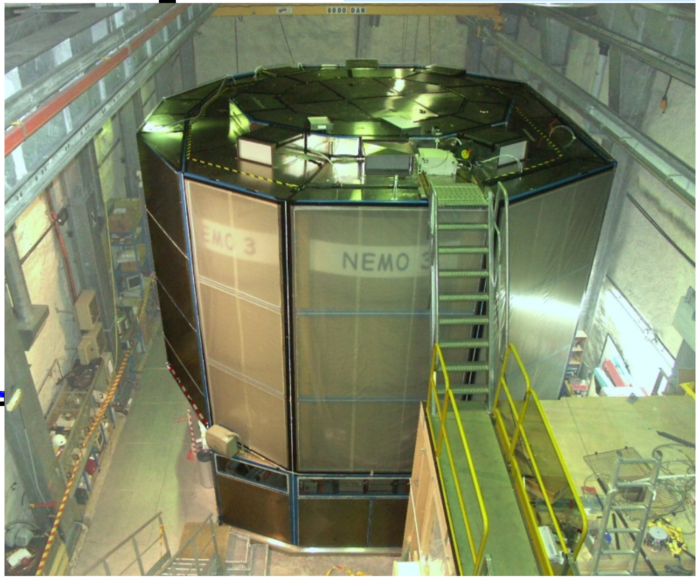
2νββ-decay
Mixed ν excluded for
$\sin^2\chi < 0.6$

$$\begin{aligned} W^{2\nu} &= \cos\chi^4 \, W^f + \sin\chi^4 \, W^b \\ &= (1-b^2)\, W^f + b^2 \, W^b \end{aligned}$$

$^{100}Mo \rightarrow {}^{100}Ru$ (SSD)



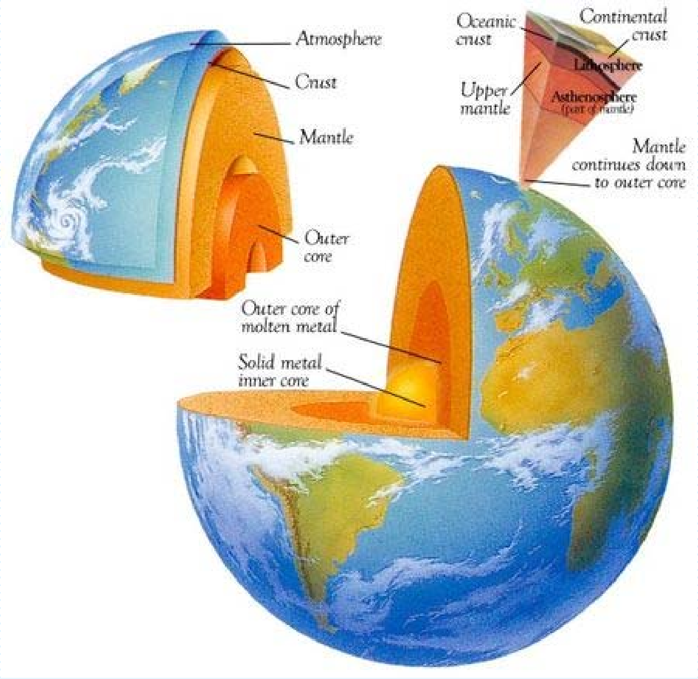
NEMO 3



Geo-neutrinos: anti-neutrinos from Earth

U, Th and ^{40}K in the Earth release heat together with anti-ν, in a well fixed ratio:

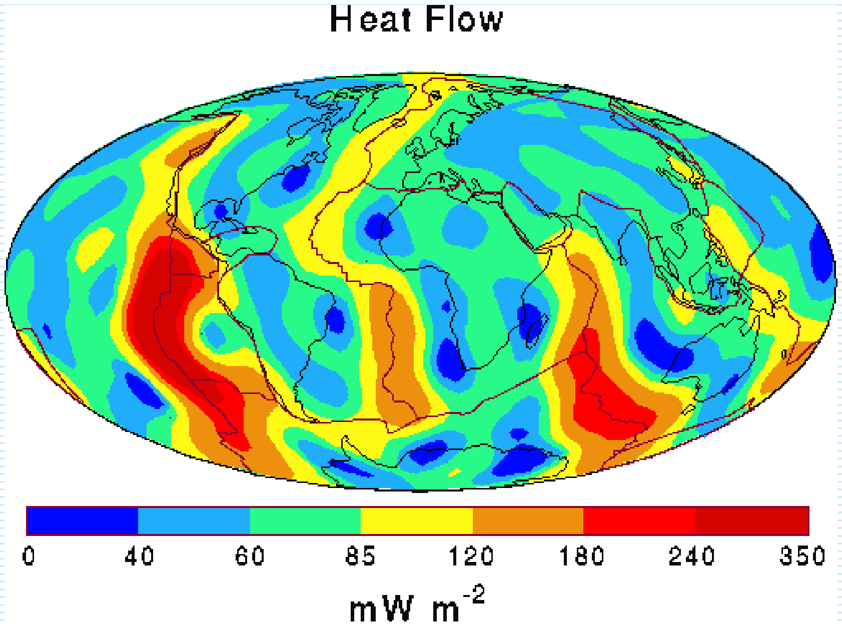
Decay	$T_{1/2}$ [10^9 yr]	$E_{\max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [kg^{-1}s^{-1}]	ε_H [W/kg]
$^{238}\mathrm{U} \to {}^{206}\mathrm{Pb} + 8\,{}^4\mathrm{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}\mathrm{Th} \to {}^{208}\mathrm{Pb} + 6\,{}^4\mathrm{He} + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}\mathrm{K} \to {}^{40}\mathrm{Ca} + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}



Open questions about natural radioactivity in Earth

- **What is the radiogenic contribution to terrestrial heat production?**
- **How much U and Th in the crust?**
- **How much U and Th in the mantle?**
- **What is hidden in the Earth's core (geo-reactor, ^{40}K, …)?**
- **Is the standard geochemical model consistent with geo-neutrino data?**

Energetics of the Earth and the missing heat source mystery



Heat flow from the Earth is equivalent of some **10 000** nuclear power plants

H_{earth}=(30-40) TW

(There are about 500 operating nuclear power plants around the world. Nuclear reactors, the enemy of geo-neutrinos)

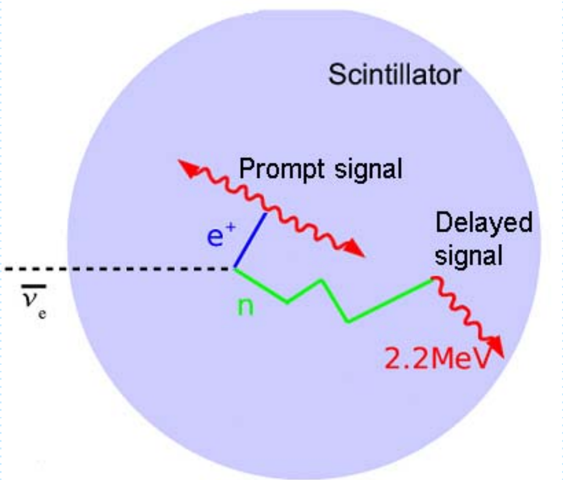
The standard geochemical model (BSE), based on cosmochemical arguments, predicts a radiogenic heat production of 19 TW:

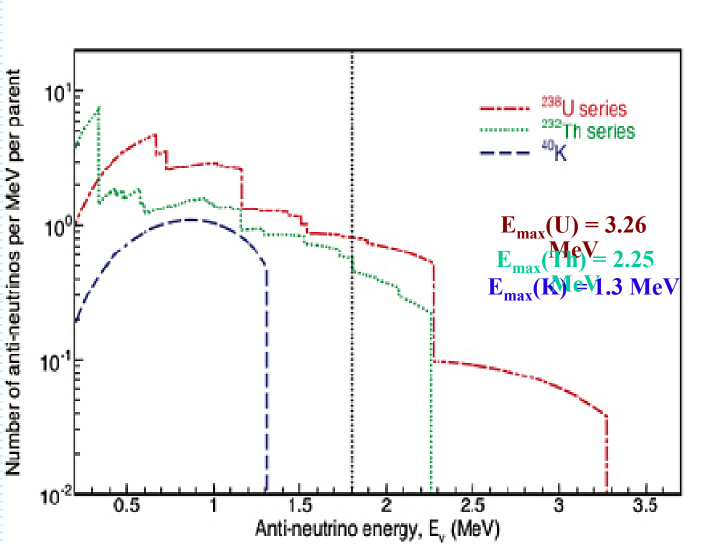
- **9 TW** estimated from radioactivity in the (continental) crust
- **10 TW** supposed from radioactivity in the mantle
- **0 TW** assumed from a core

deepest hole is 12 km; only crust and upper mantle can be tested directly
seismology brings information on the density profile within the Earth

KamLAND experiment

Inverse beta decay reaction

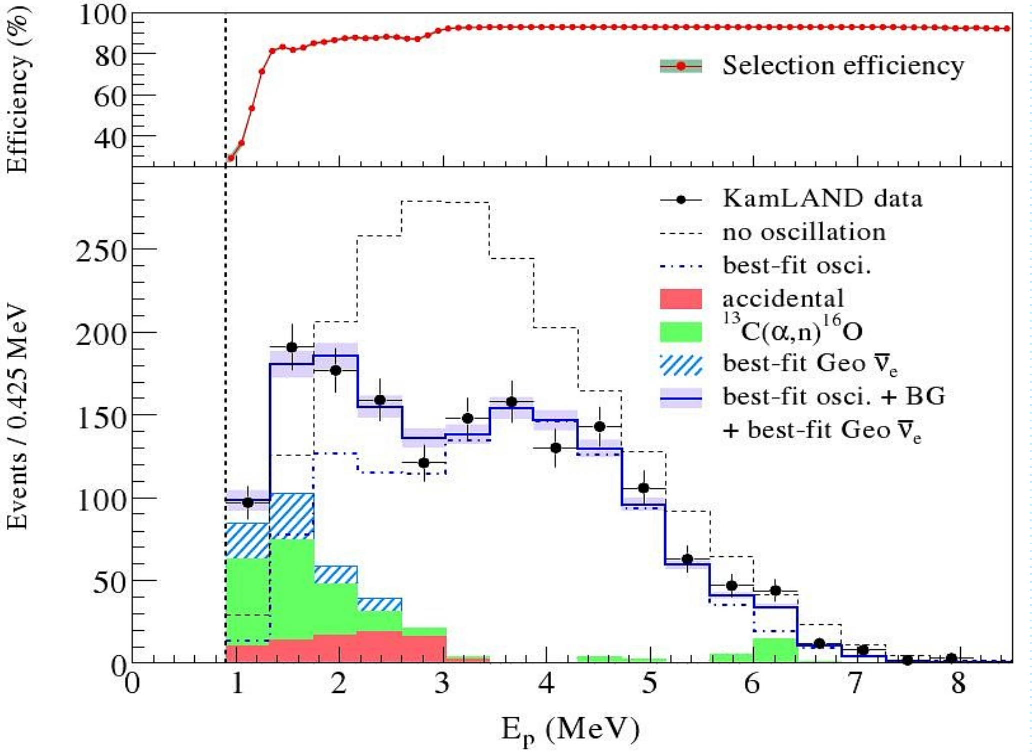




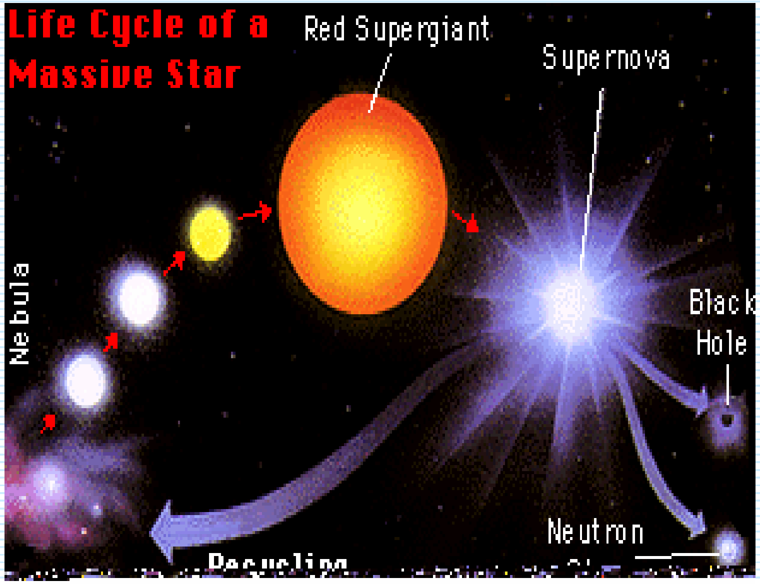
2008 results: 73±27 ev (~ 2.5σ)

The indication of an excess of low-energy anti-neutrinos consistent with an interpretation as geo-neutrinos persists.

Phys. Rev. Lett. 100 (2008) 22



Supernovae

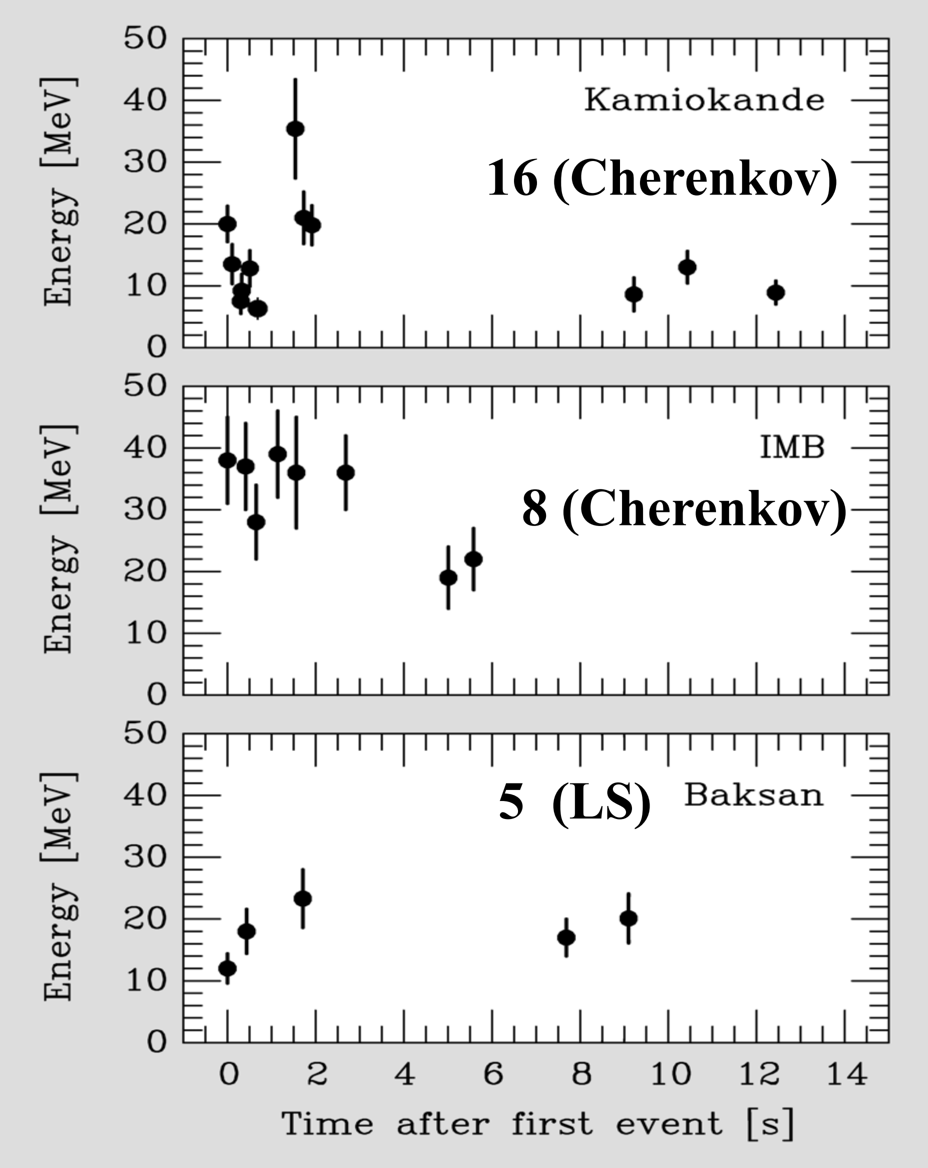


The observed neutrino burst

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

can confirmed the Supernova theory (Chandrasekar)

Observation of SN1987A
(29 events)




Scanned at the American Institute of Physics

23rd Feb 1987, 170 000 light years, Large Megallanic Cloud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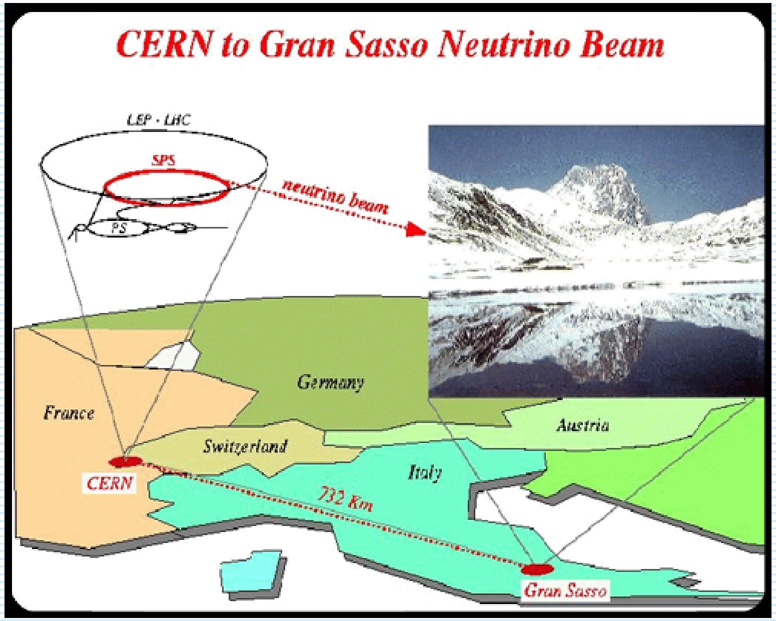
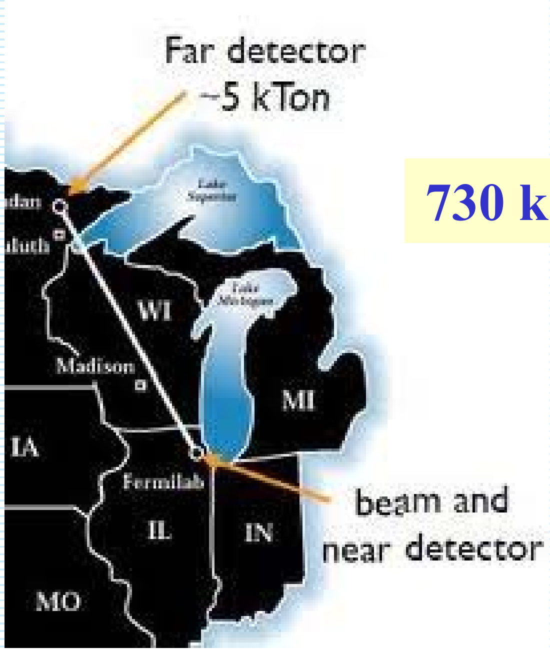
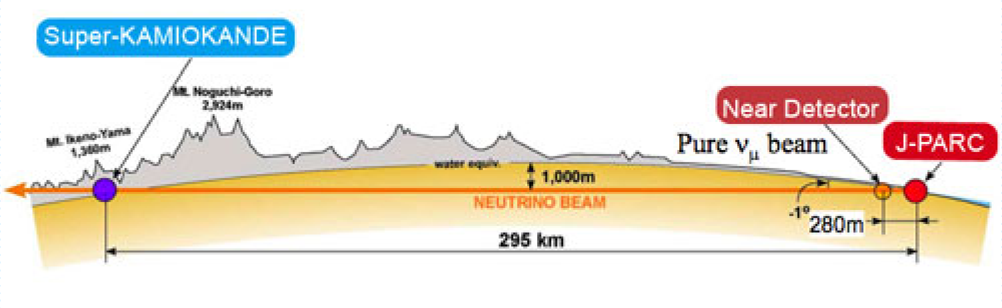
Neutrinos that travel faster than light?

$(v-c)/c = (5.1 \pm 2.9) \times 10^{-5}$





730 km



Like most people,
physicists enjoy a good mystery.

When you start investigating a mystery
you rarely know where it is going

Mathematics is Egyptian

Neutrino physics is Babylonian

The truth is covered in ν–experiments.

Thanks to neutrinos we understand Sun, Supernova, Earth (nuclear reactions)