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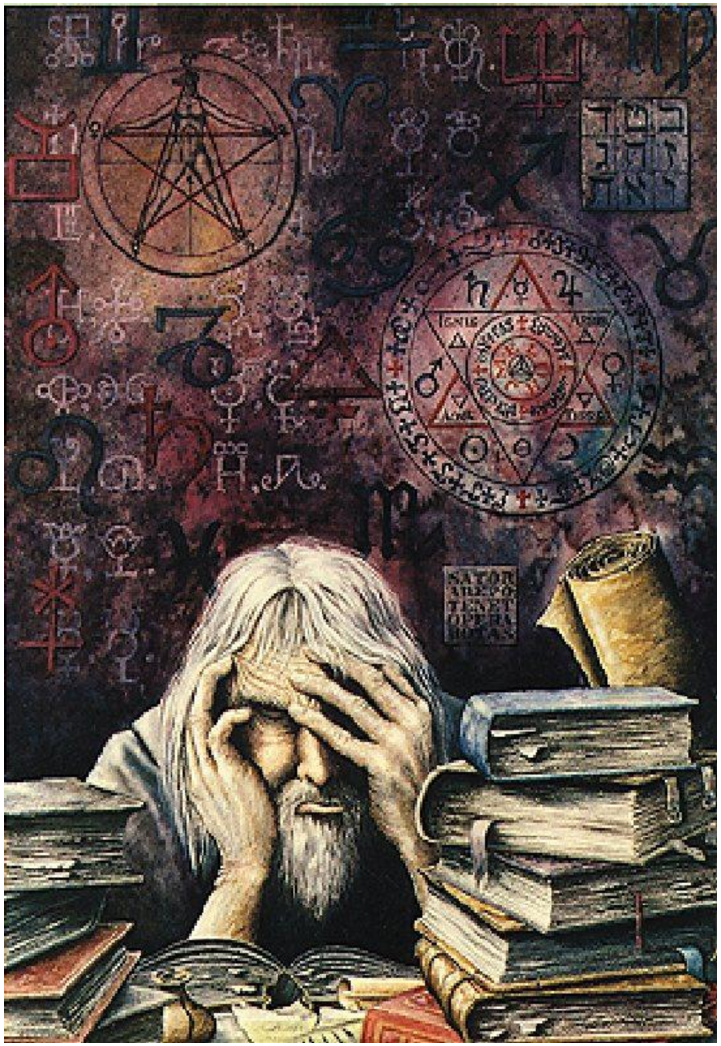


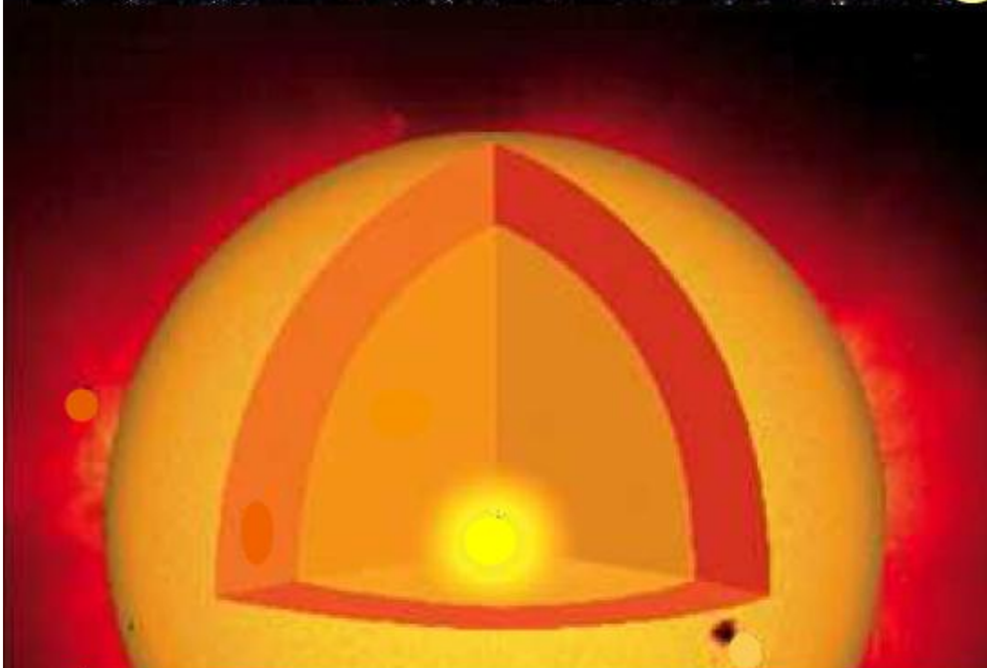
- ★ Lecture 1:
  History
  Neutrinos in the Standard Model
  Evidence for neutrino masses (oscillations)
- ★ Lecture 2:
  Evidence for neutrino masses (c‘td)
  Absolute neutrino mass measurements (beta, double beta decay)
- ★ Lecture 3:
  Double beta decay (c‘td)
  What‘s next? Future activities
  Things to do

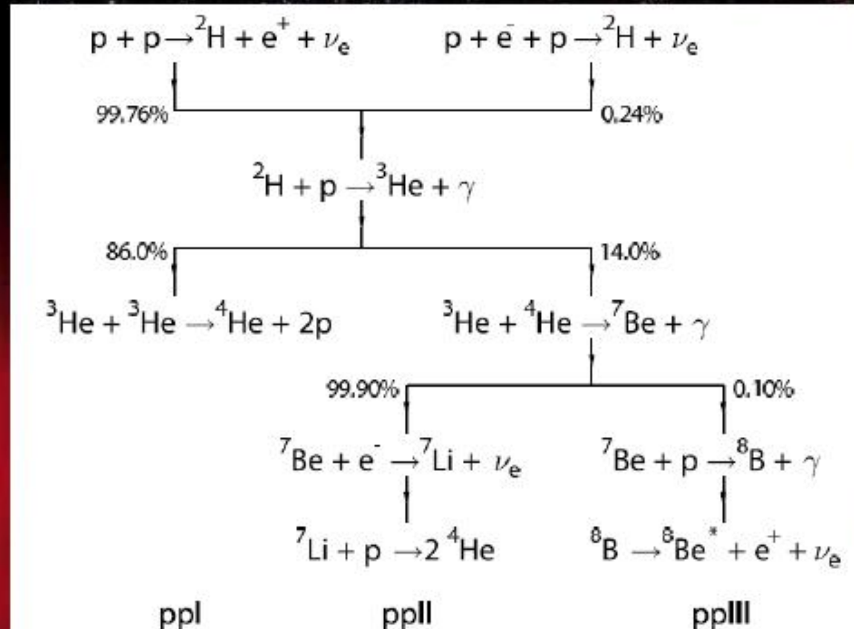
Summary so far

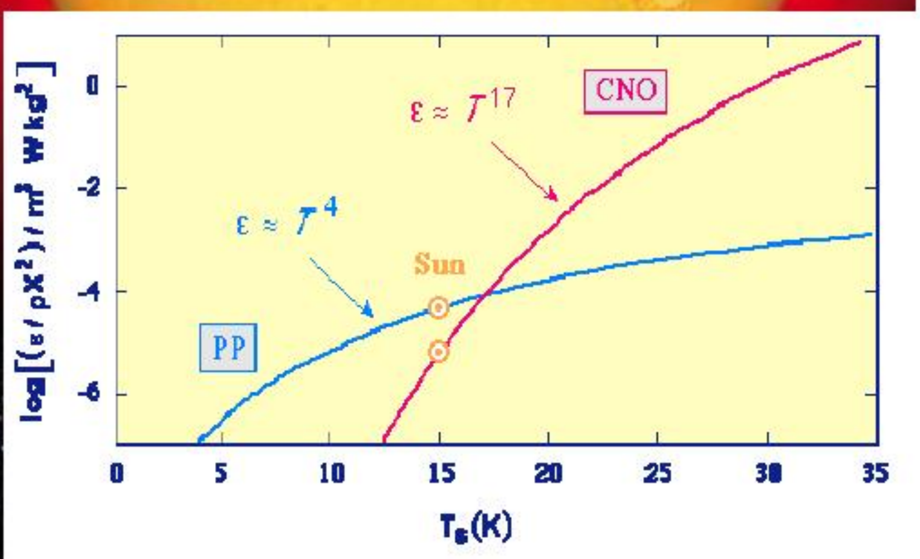
- ★ Neutrinos have a non-vanishing rest mass
- ★ Observed in atmospheric neutrinos, confirmed by accelerators (long baseline experiments)
- ★ Best fit is

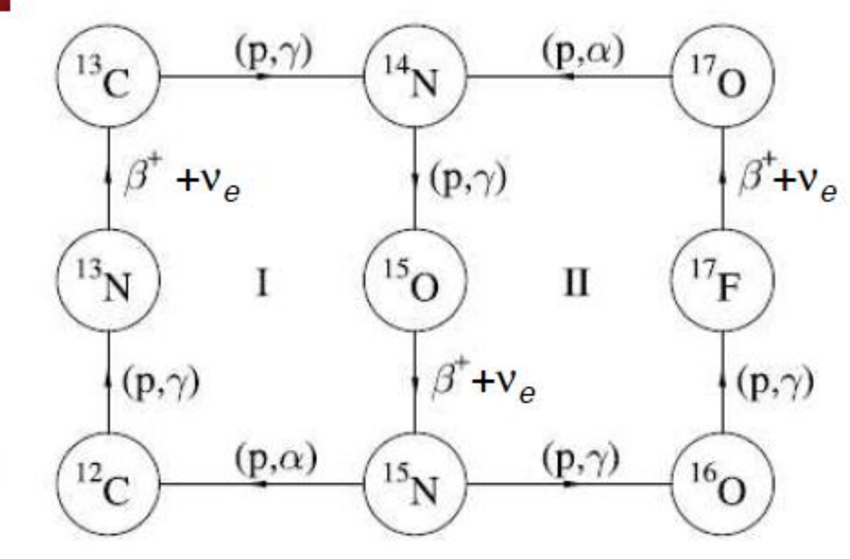
$$|\Delta m^2| = (2.32 \pm 0.10) \times 10^{-3}\ \mathrm{eV}^2 \ \text{(90\% C.L.)}$$
$$\sin^2 2\theta = 1$$

Solar Energy Sources





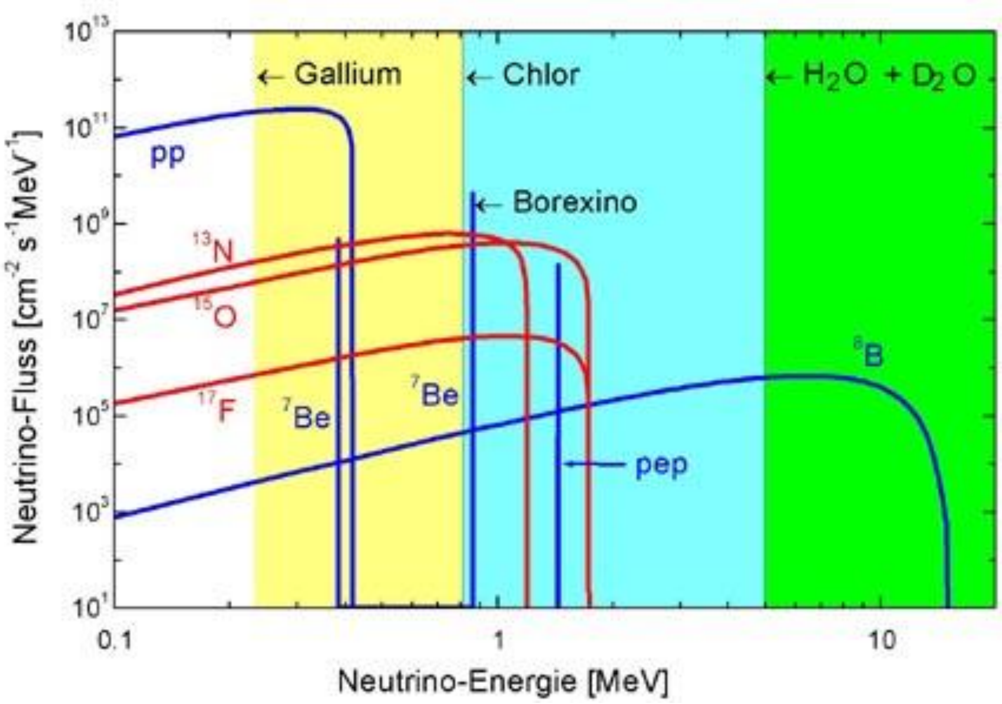


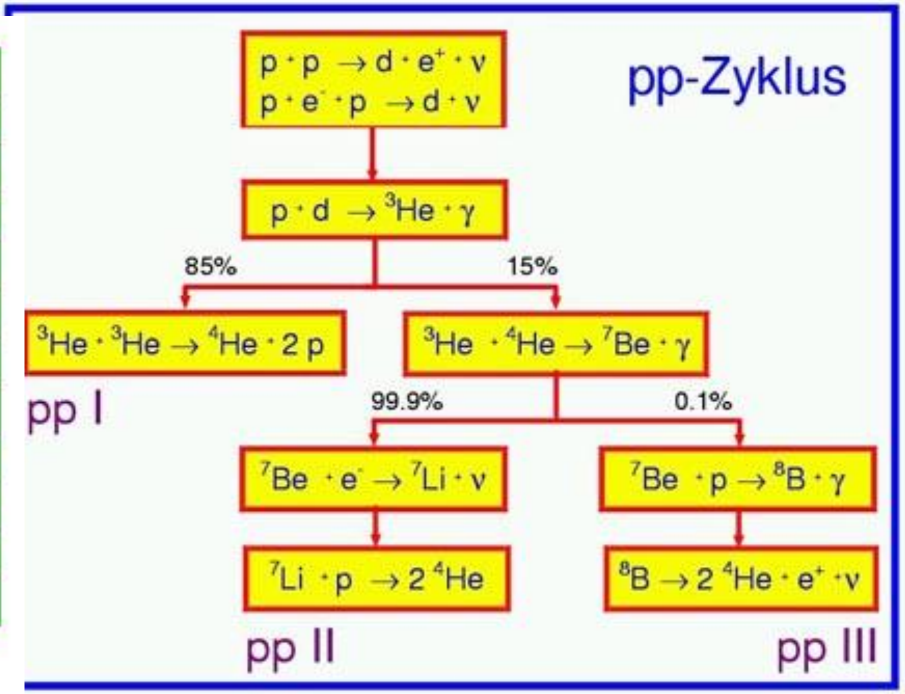


Standard Solar Models

Assumption: Sun is producing energy by nuclear fusion

$$2e^- + 4p \rightarrow {}^4\mathrm{He} + 2\nu_e + 26.73\ \mathrm{MeV}$$





60 billion neutrinos pass per cm² every second

Detection principle

radiochemical (CC)

$$\nu_e + (A, Z) \rightarrow e^- + (A, Z+1)$$

+: low energy -: not real-time

1 SNU = 10^{-36} captures/target atom/s

elastic electron-neutrino scattering (ES)

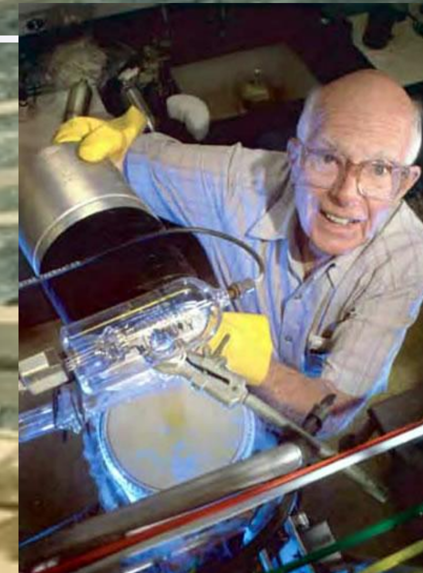
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

+: real time -: high energy

reactions on deuterium (CC + NC)

Homestake Experiment

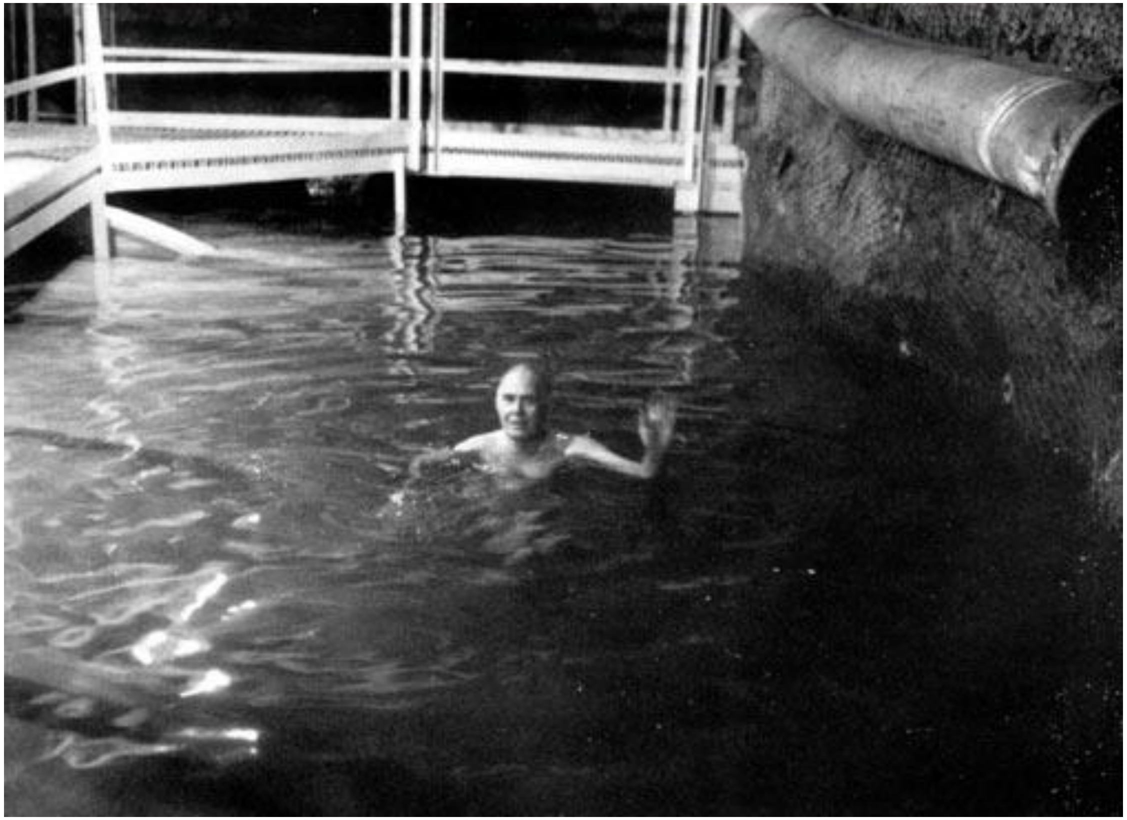
Ray Davis Jr.



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

The art of low-level physics or how to get 10 atoms out of 600 t

Impressions



Swimming pool (shielding)
4500 mwe underground

Short before
beginning operation

Cl-experiment - Results

B.T. Cleveland et al. / Nuclear Physics B (Proc. Suppl.) 38 (1995) 47–53

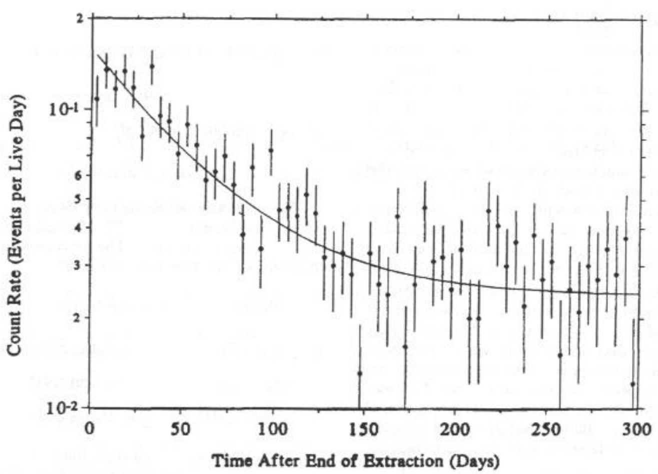


Figure 3 : Time Distribution of Events Within the Acceptance Window

Figure 3 : Time Distribution of Events Within the Acceptance Window

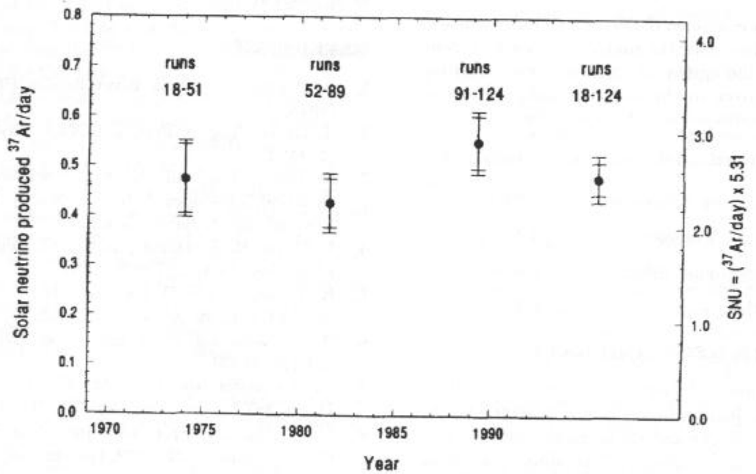


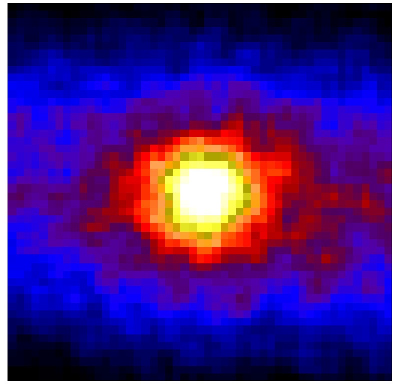
Figure 4 : Time – Averaged ^{37}Ar Production Rate

Rate = 2.56 ± 0.23 SNU

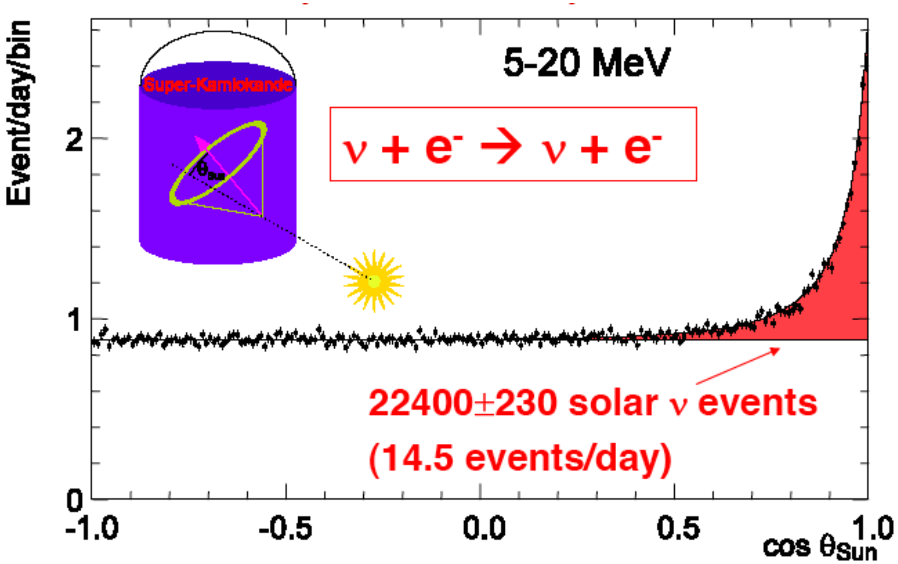
B.T Cleveland et al., Astrophys.J.496:505-526,1998

Super-Kamiokande

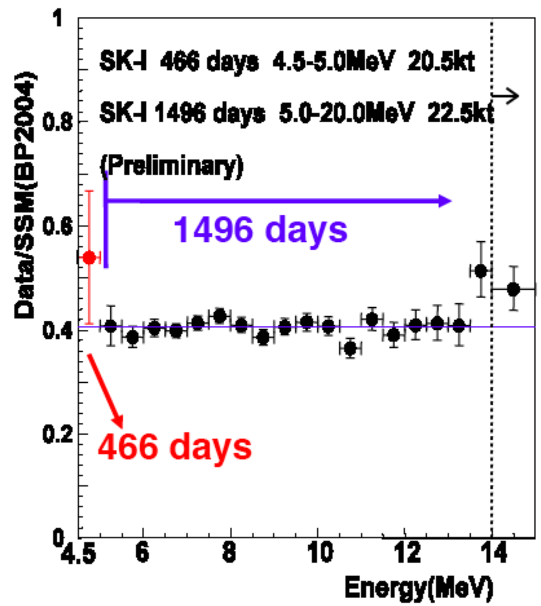
$$\nu_x + e^- \rightarrow \nu_x + e^-$$



NO significant day/night asymmetry

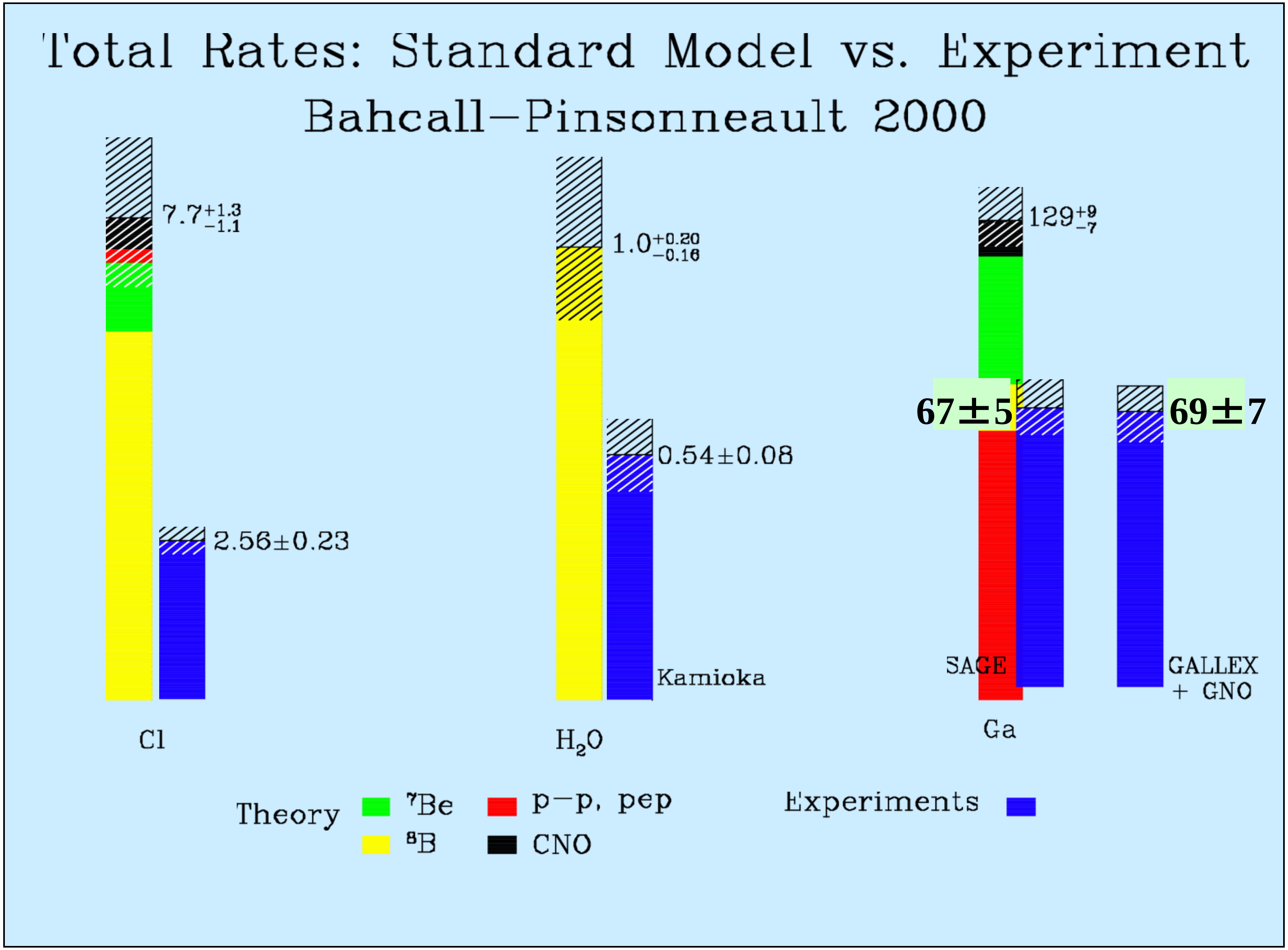


^{8}B flux : 2.35 ± 0.02 ± 0.08 [x 10^6 /cm^2/sec]

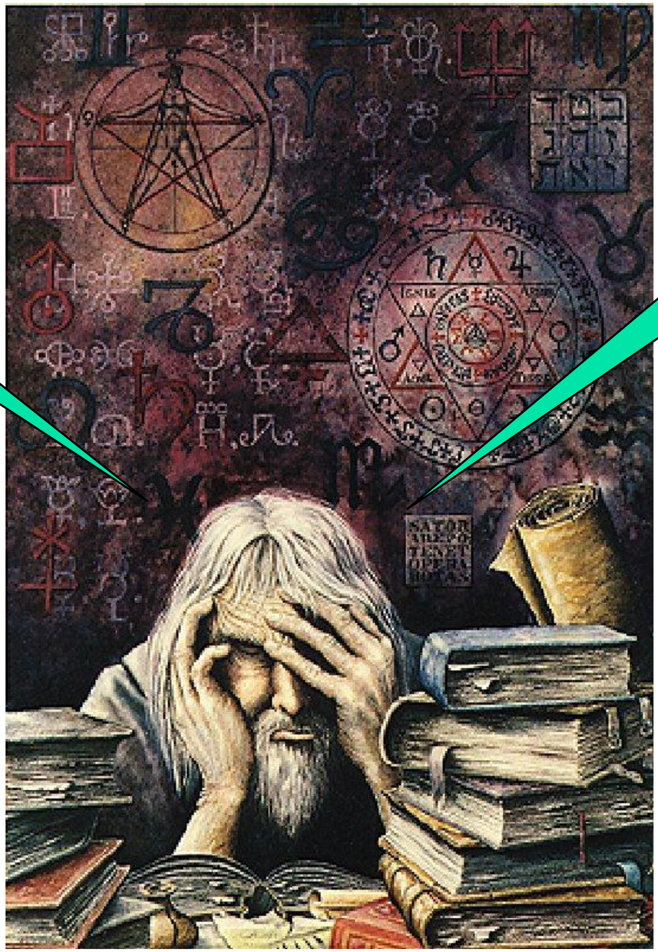


SK-II data consistent with SK-I data

All experiments measure only 30-50% of predicted flux



Who is responsible?



Sun

Core temperature

$\phi(^{8}B) \propto T^{18}$

Chem. composition

Magnetic field

Cosmions

Nuclear cross sections

Astrophysicists: 5% change in core temperature is too much

Neutrino

Vacuum oscillations

Matter oscillations

Magnetic moment

Neutrino decay

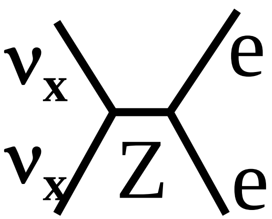
All require neutrino mass

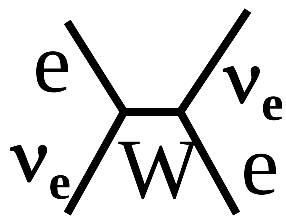
Solutions with oscillations

vacuum oscillations:

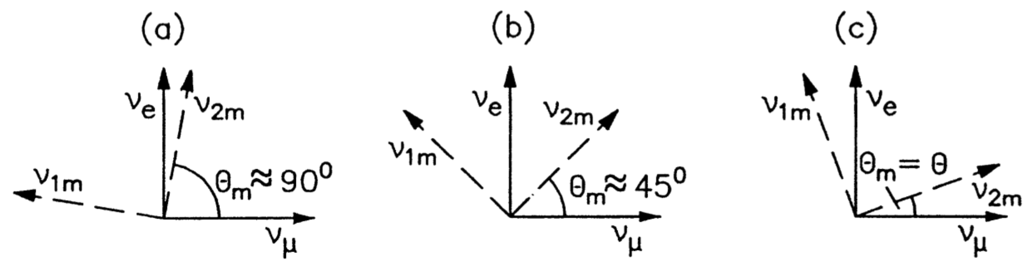
$$\Delta m^2 \approx \frac{E}{L} \approx \frac{1MeV}{10^{11}m} = 10^{-11} eV^2$$

Matter oscillations





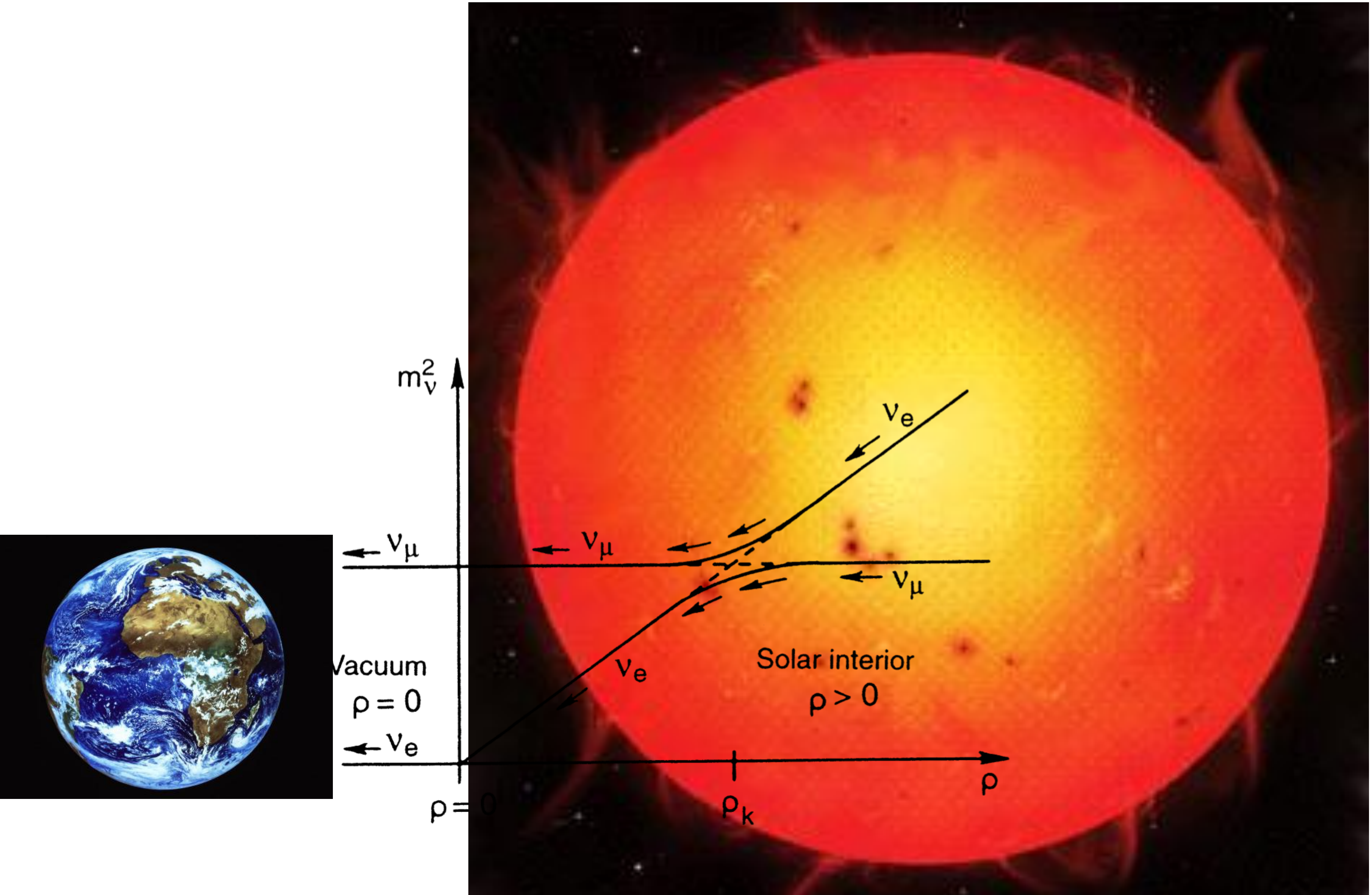
potential $V_e - V_\mu = \sqrt{2}\, G_F n_e$



new matter eigenstates ν_{1m},ν_{2m}
with new mixing angle
depending on E, n_e

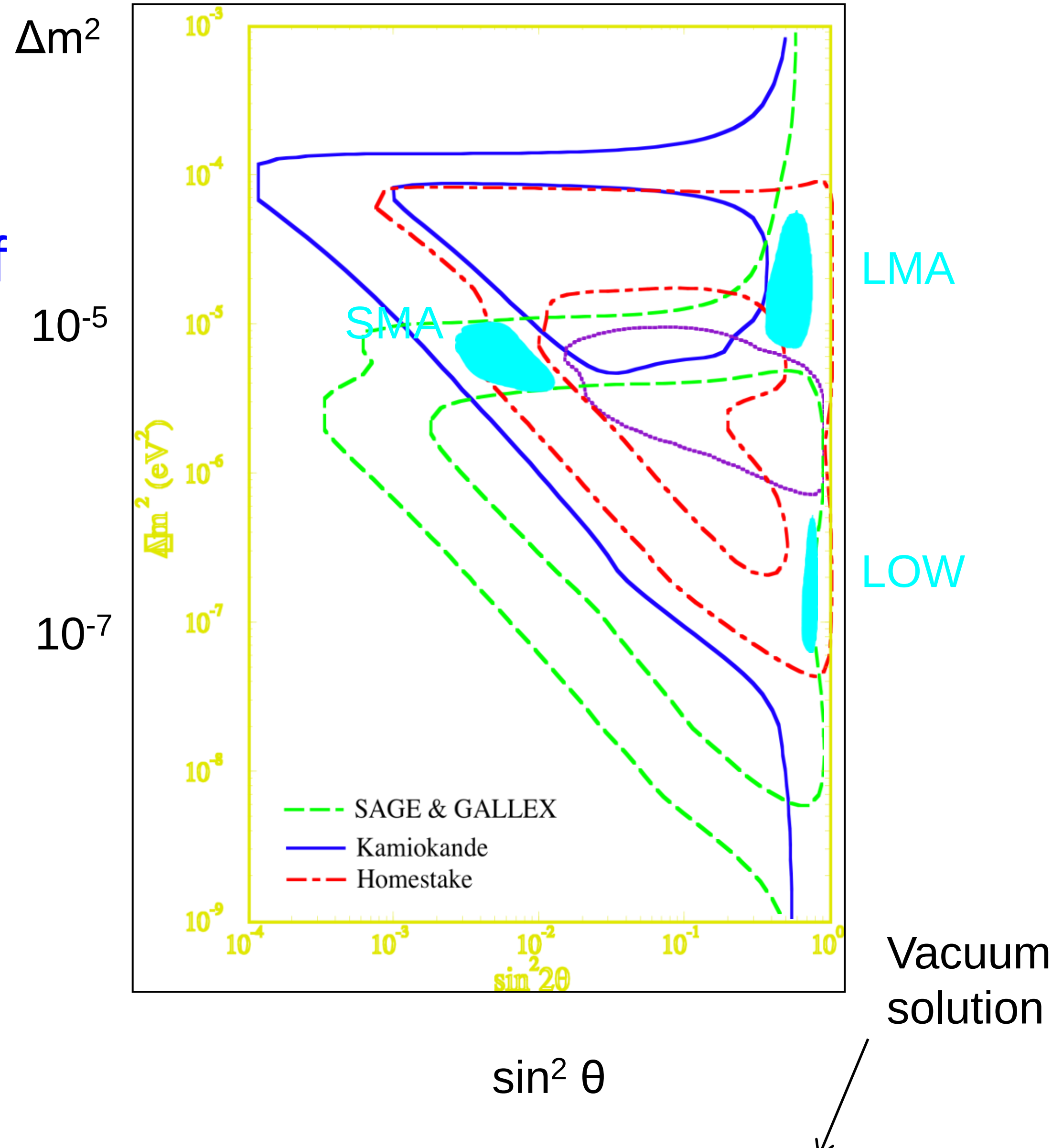
$$H = \begin{pmatrix} \frac{\Delta m^2 cos2\theta_{12}}{4E} - \frac{\sqrt{2}G_F n_e}{2} & \frac{\Delta m^2 sin2\theta_{12}}{2E} \\ \frac{\Delta m^2 sin2\theta_{12}}{2E} & -\frac{\Delta m^2 cos2\theta_{12}}{4E} + \frac{\sqrt{2}G_F n_e}{2} \end{pmatrix}$$

Matter effects



Matter-Oscillations

MSW results in dramatic extension of possible Δm^2 regions

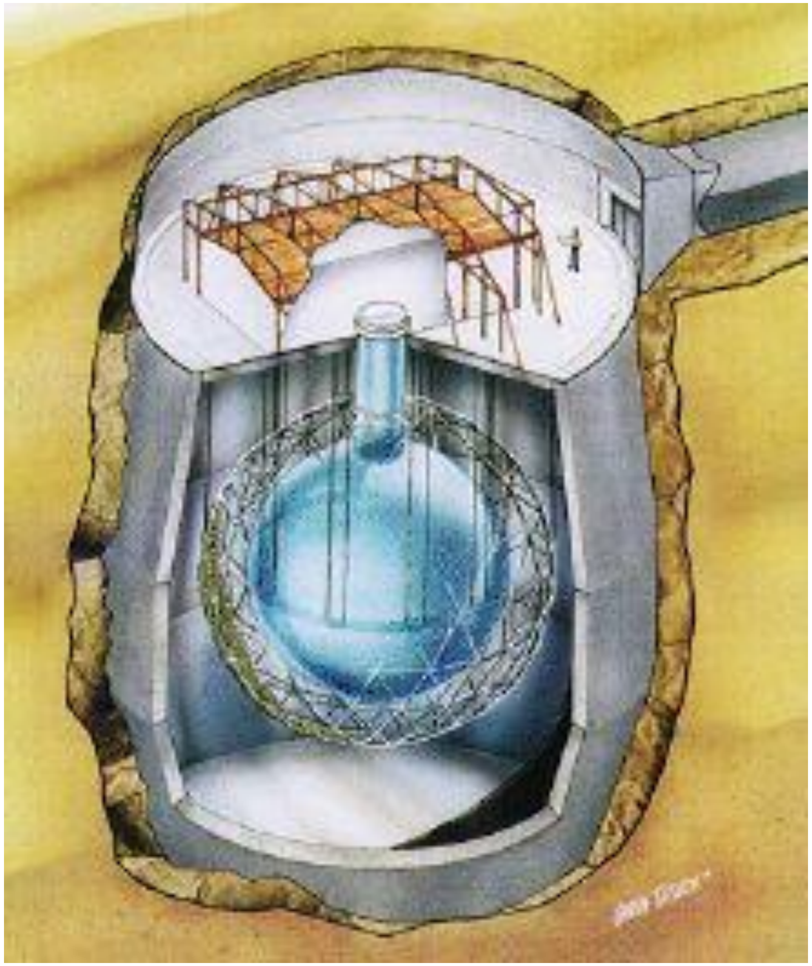


Only "weak" evidence

- needs definite proof
- Independent of SSM


The Sudbury
Neutrino Observatory (SNO)

SNO – The smoking gun



1000 t heavy water (D_20)

CC $\nu_e + d \Rightarrow p + p + e^-$

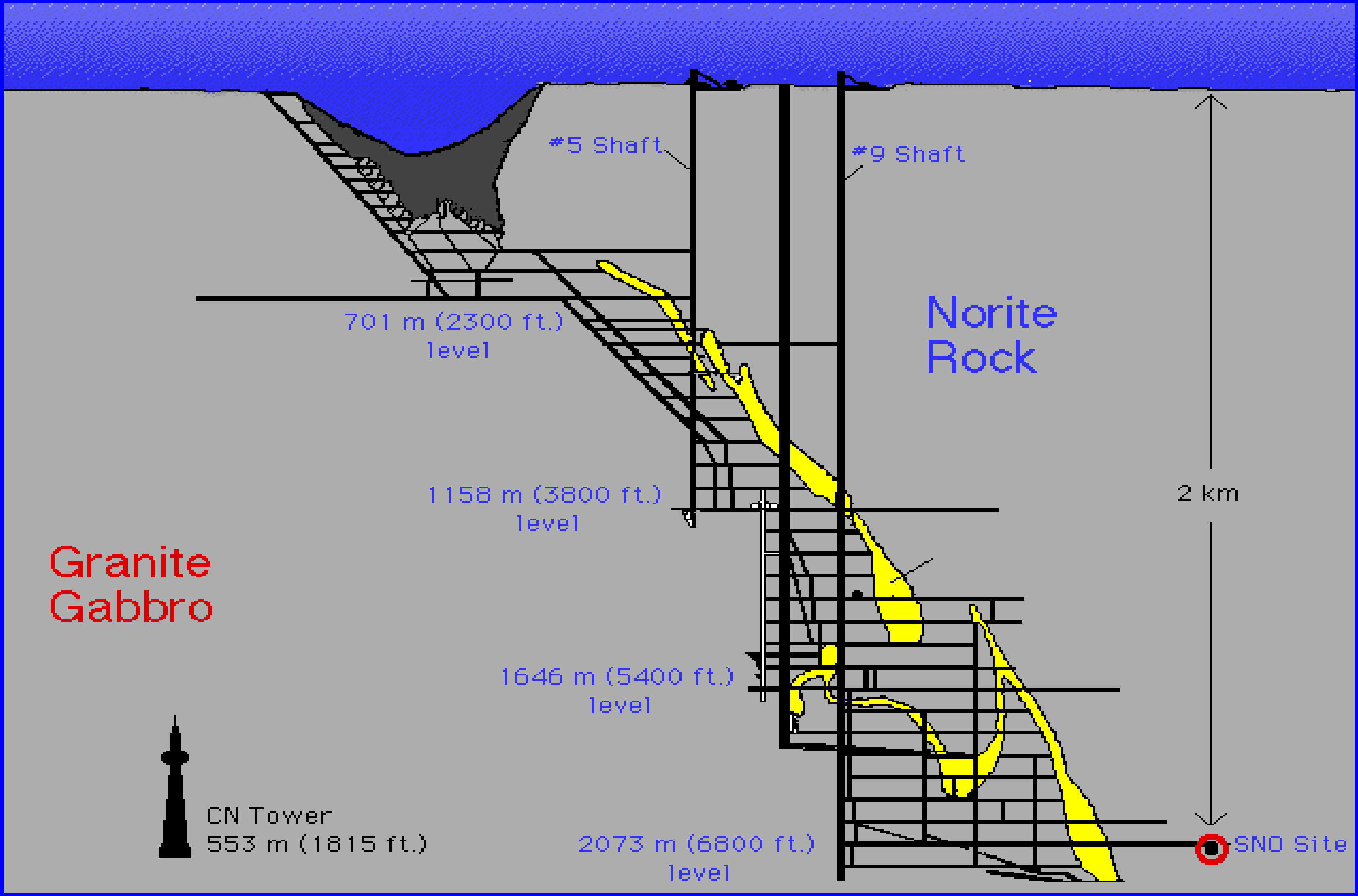
NC $\nu_x + d \Rightarrow p + n + \nu_x$

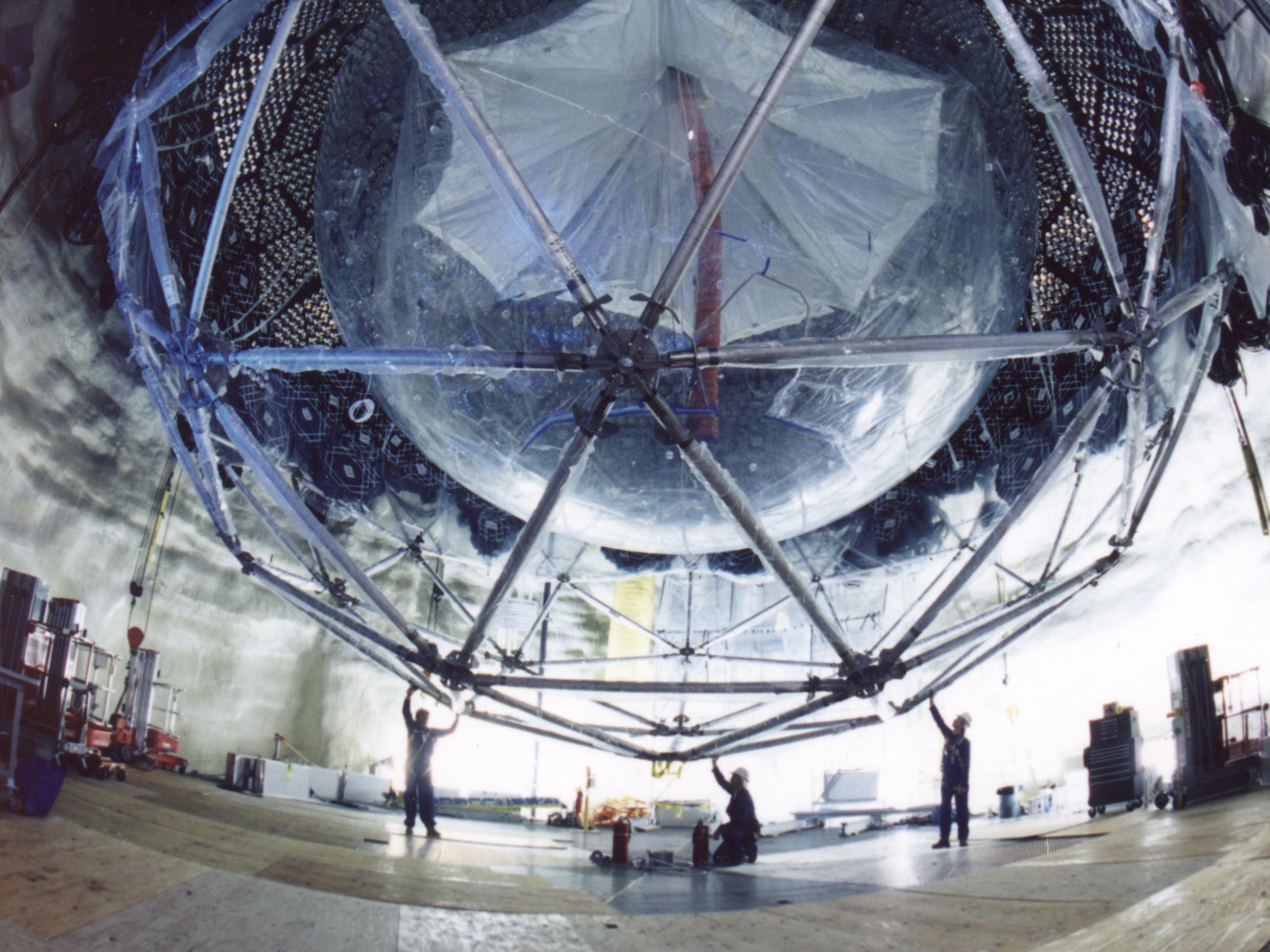
ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

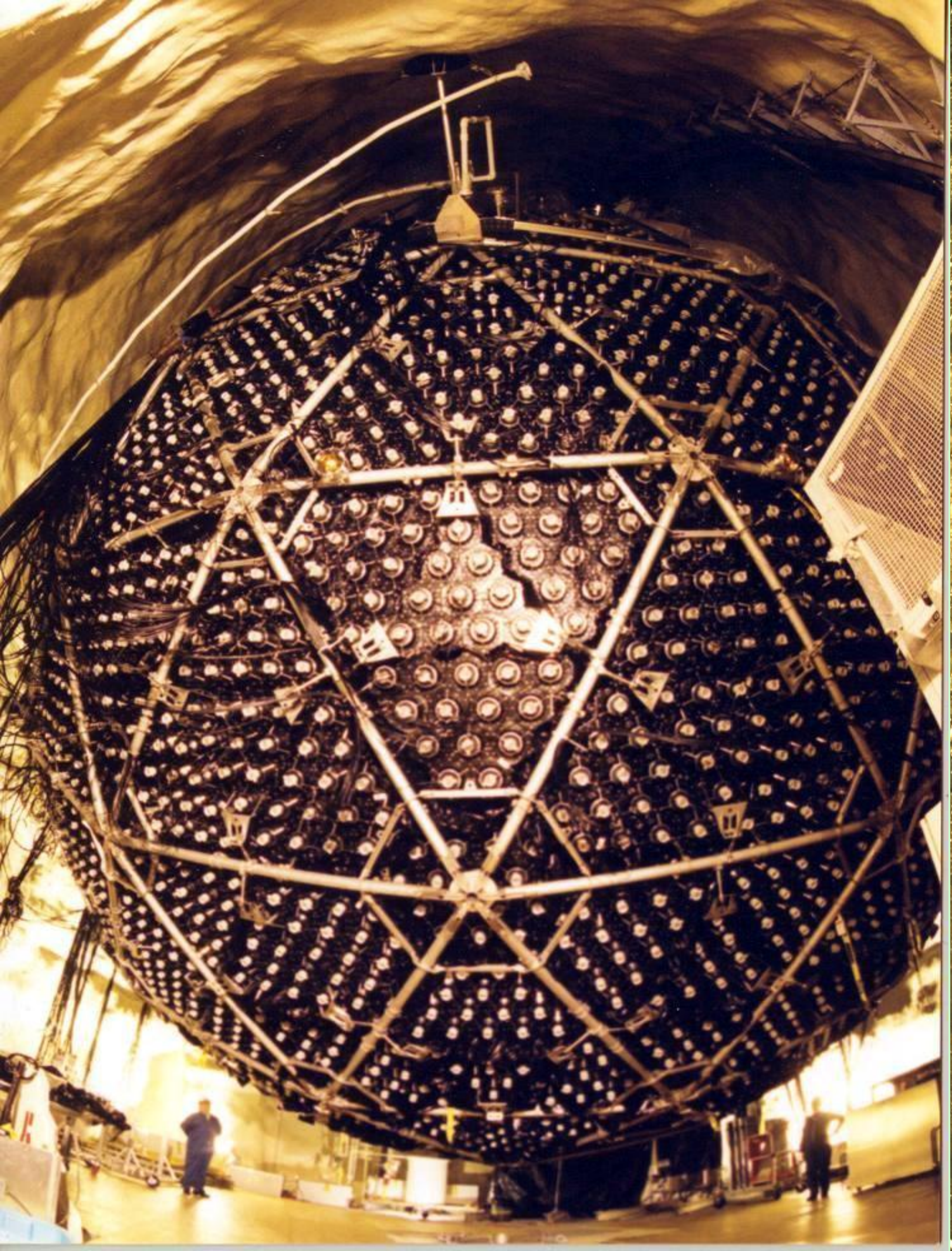
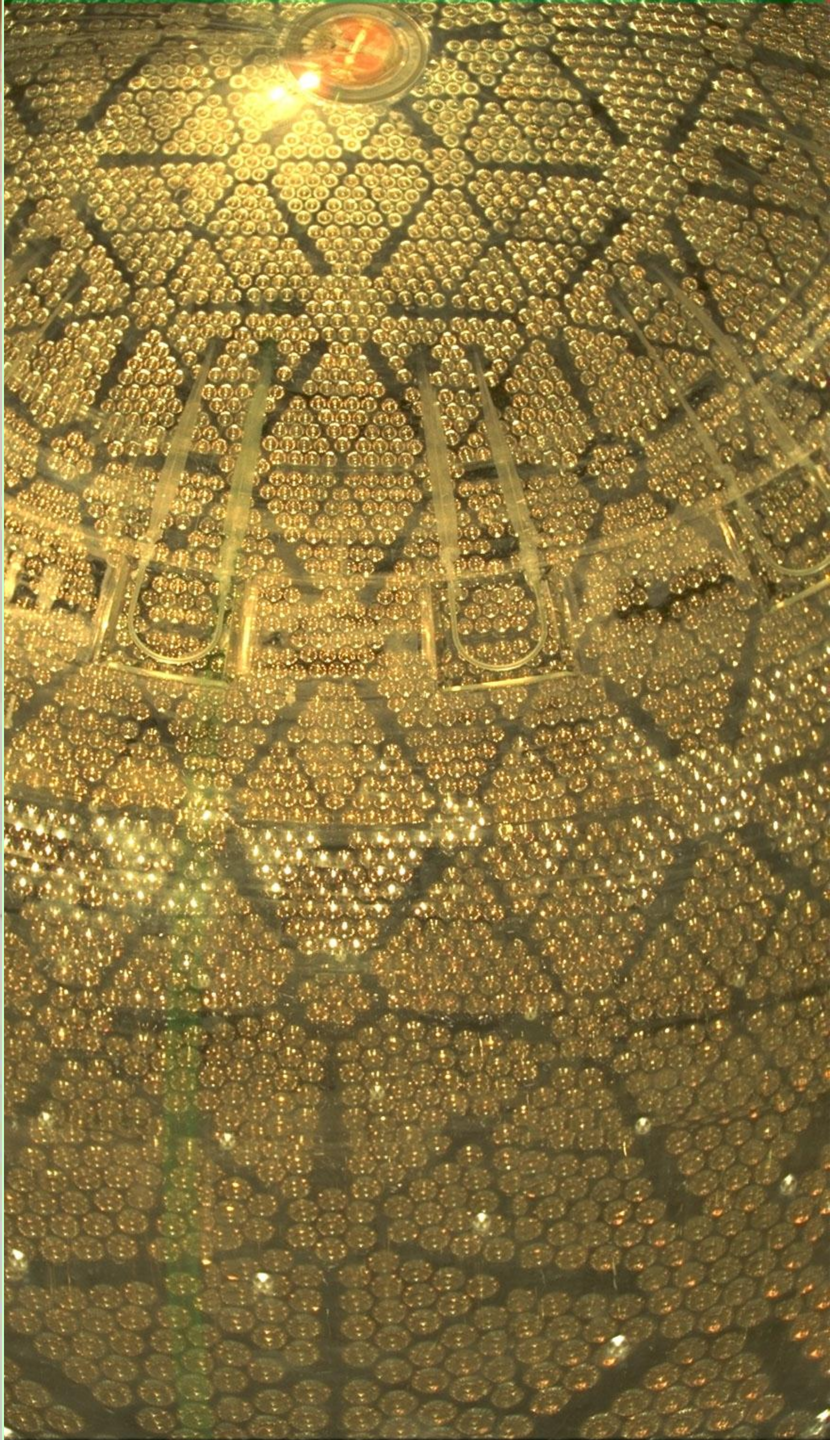
$$\frac{CC}{ES} = \frac{\nu_e}{\nu_e + 0.14(\nu_\mu + \nu_\tau)}$$

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

The SNO Detector





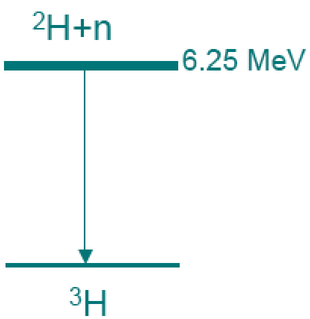



A SNO$_{W}$ day

SNO Run Sequence

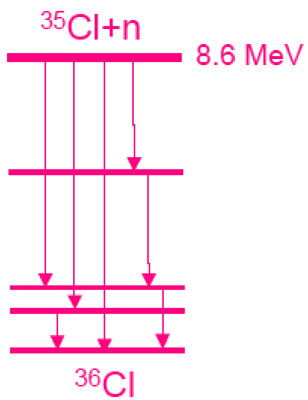
Phase I (D_2O)
Nov. 99 - May 01

n captures on
$^2H(n, \gamma)^3H$
σ = 0.0005 b
Observe 6.25 MeV γ
PMT array readout
Good CC



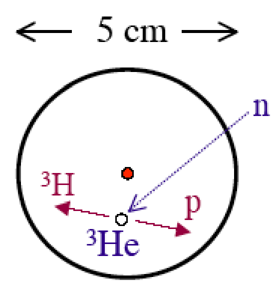
Phase II (salt)
July 01 - Sep. 03

2 t NaCl. n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
σ = 44 b
Observe multiple γ's
PMT array readout
Enhanced NC

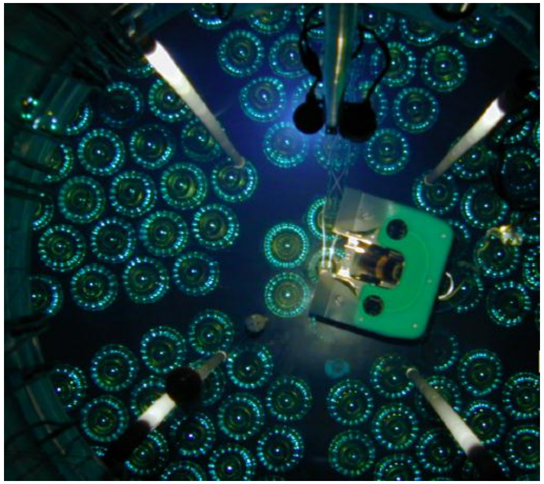


Phase III (^3He)
Summer 04 - Dec. 06

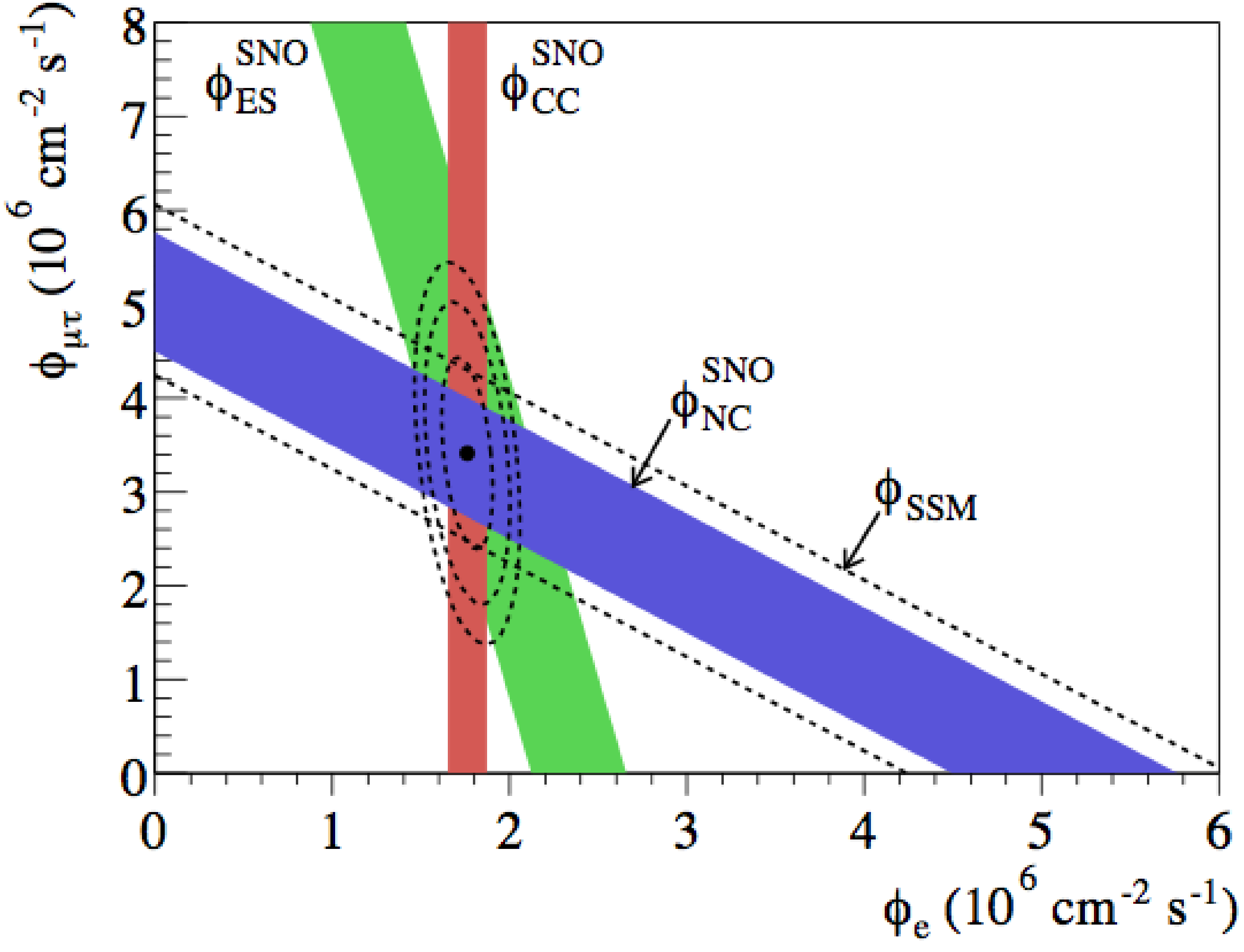
40 proportional counters
$^3He(n, p)^3H$
σ = 5330 b
Observe p and ^3H
PC independent readout
Event by Event Det.



$n + {}^3He \rightarrow p + {}^3H$



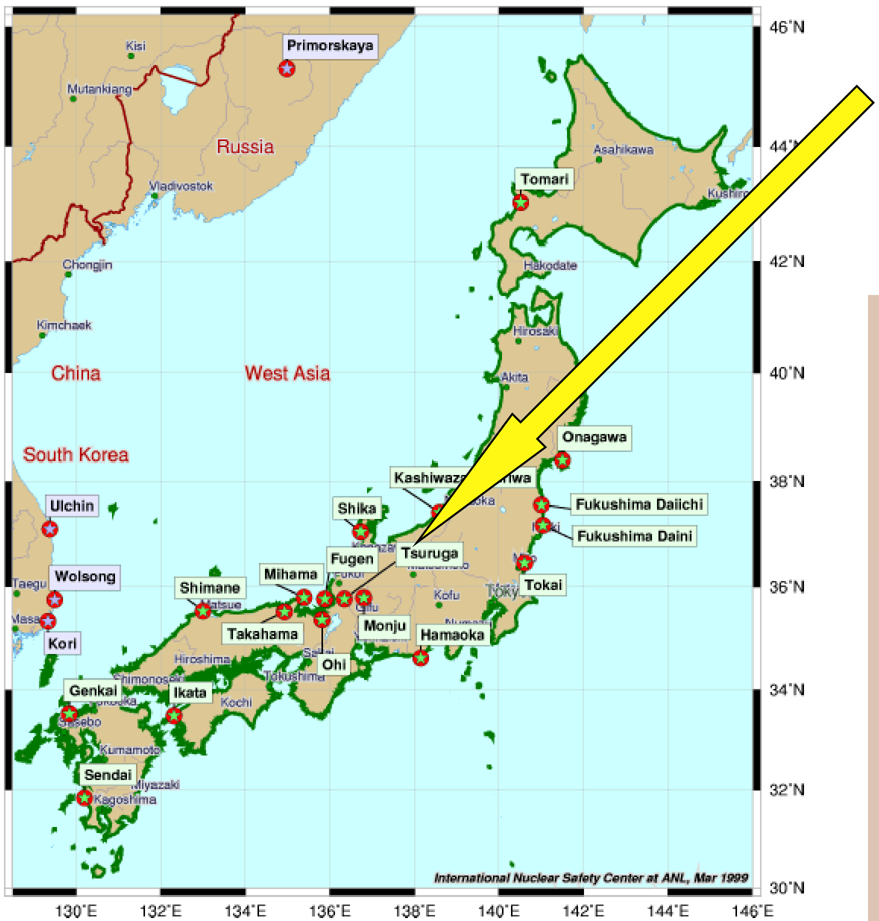
SNO Results



All neutrinos are coming but 60-70% in wrong flavour

KamLAND

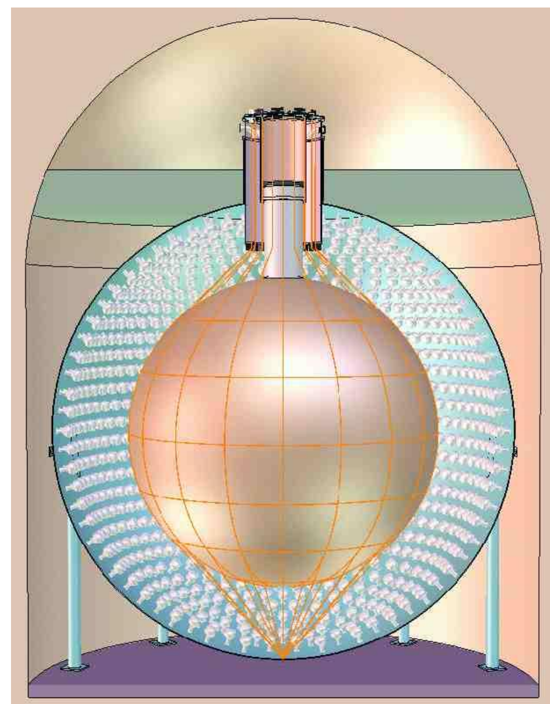
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



★ Large number of nuclear power plants around Kamioka mine

★ Concentration at about 180 km distance

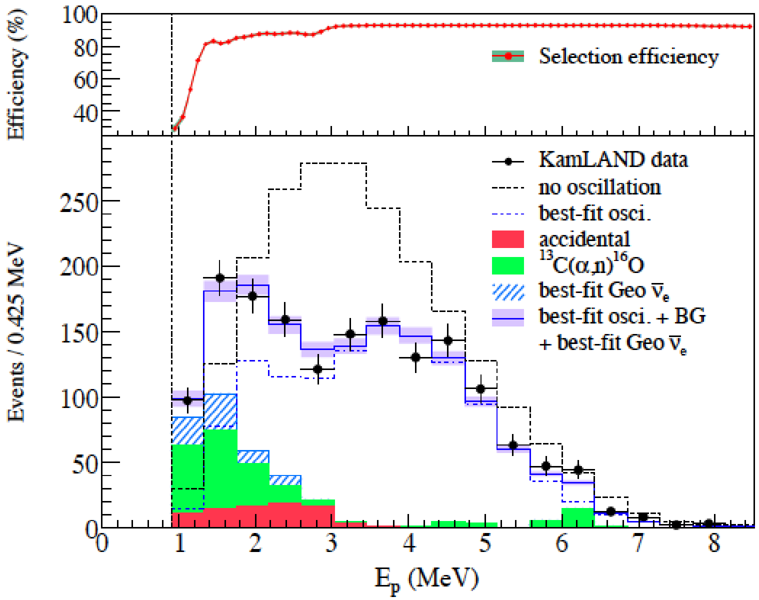
★ Test of LMA solution



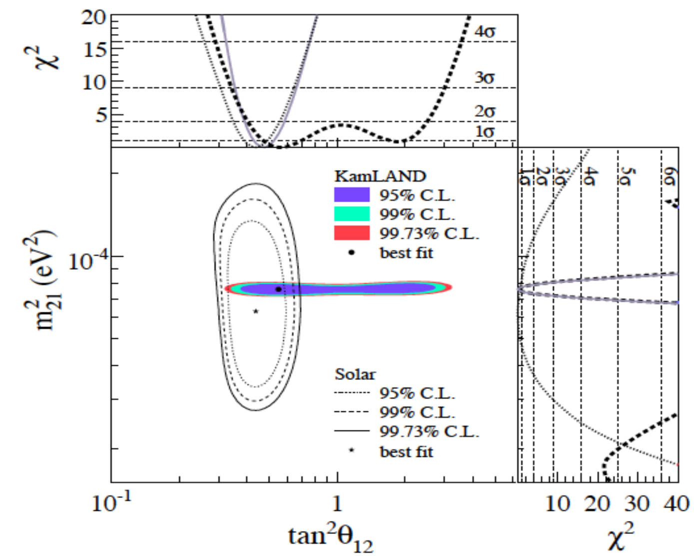
1000 t Liquid scintillator

KamLAND - Results

2179 ± 89 events expected,
1609 observed



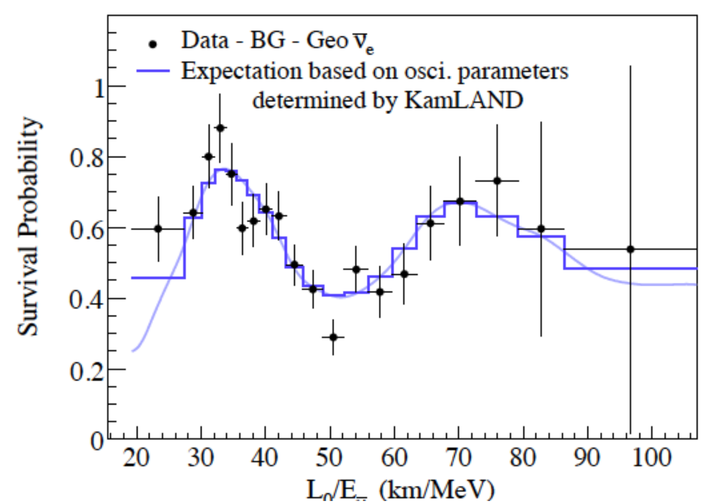
S. Abe et al, arXiv.0801.4589 (2008)



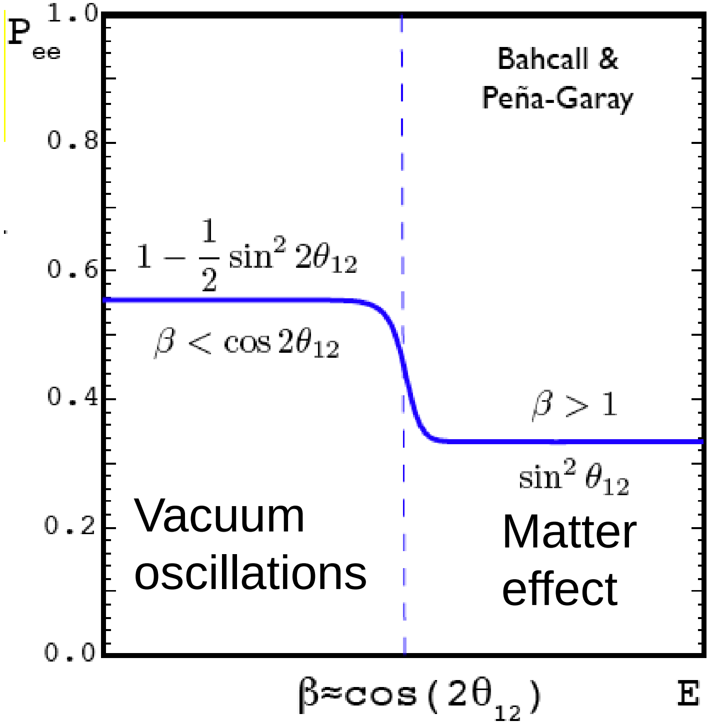
LMA solution is correct

$$\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\,\mathrm{eV}^2$$

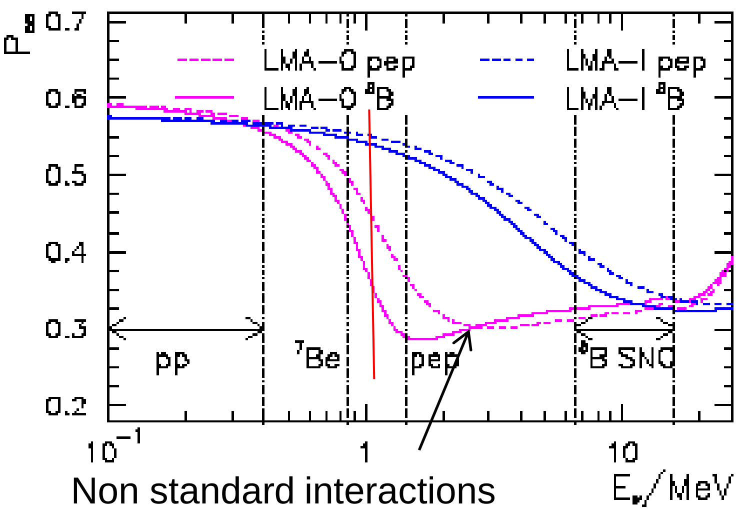
$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$



Survival probability



Friedland, Lunardini, Pena-Garay PLB 594 (2004)



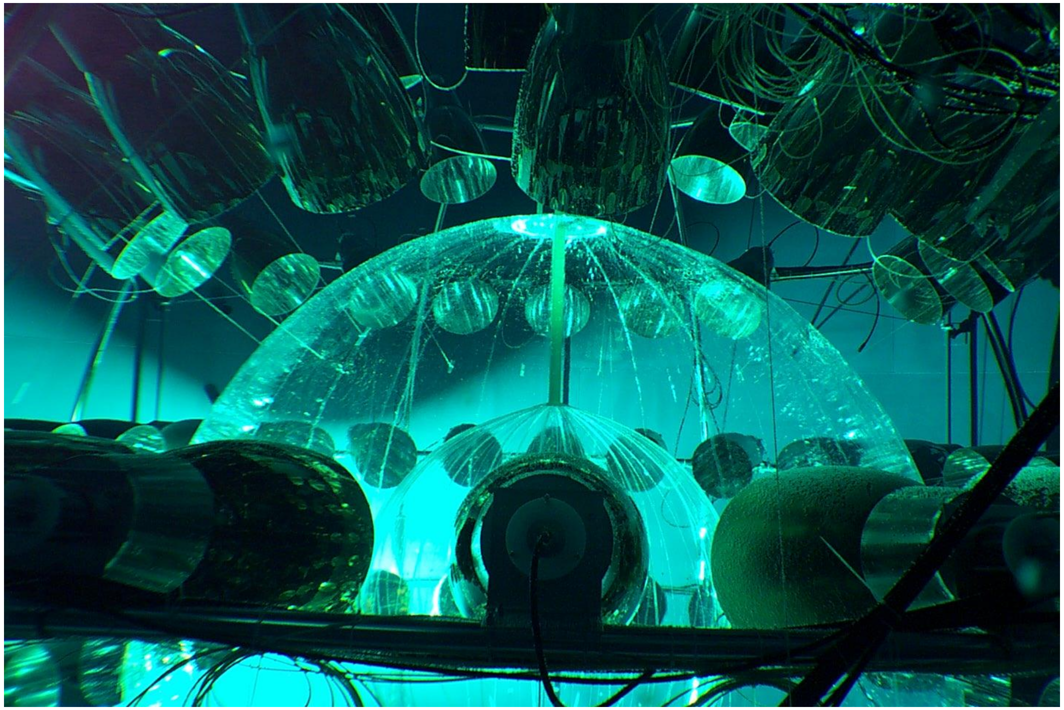
$$\beta = \frac{2^{3/2} G_F N_e E}{\Delta m^2} = 0.22 \left[\frac{E}{1\ \mathrm{MeV}}\right] \left[\frac{\rho \cdot Z/A}{100\ \mathrm{g\ cm^{-3}}}\right] \left[\frac{7\times 10^{-5}\ \mathrm{ev}^2}{\Delta m^2}\right]$$

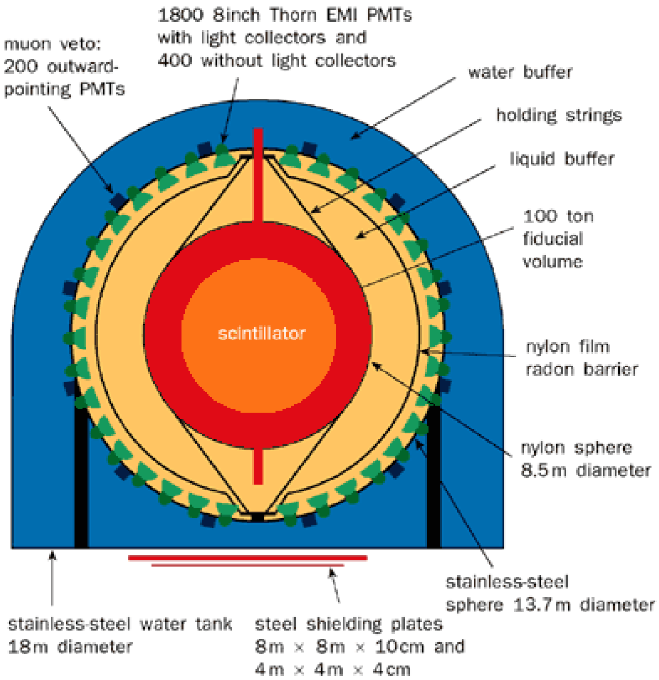
$$E[\mathrm{MeV}] = 6.8\times 10^6 \frac{\cos(2\theta_{12})\Delta \mathrm{m}_{12}^2[\mathrm{eV}^2]}{\rho[\mathrm{g/cm}^3]\mathrm{Z/A}} \simeq 1\text{–}2\ \mathrm{MeV}$$

Borexino

300 t Liquid Scintillator

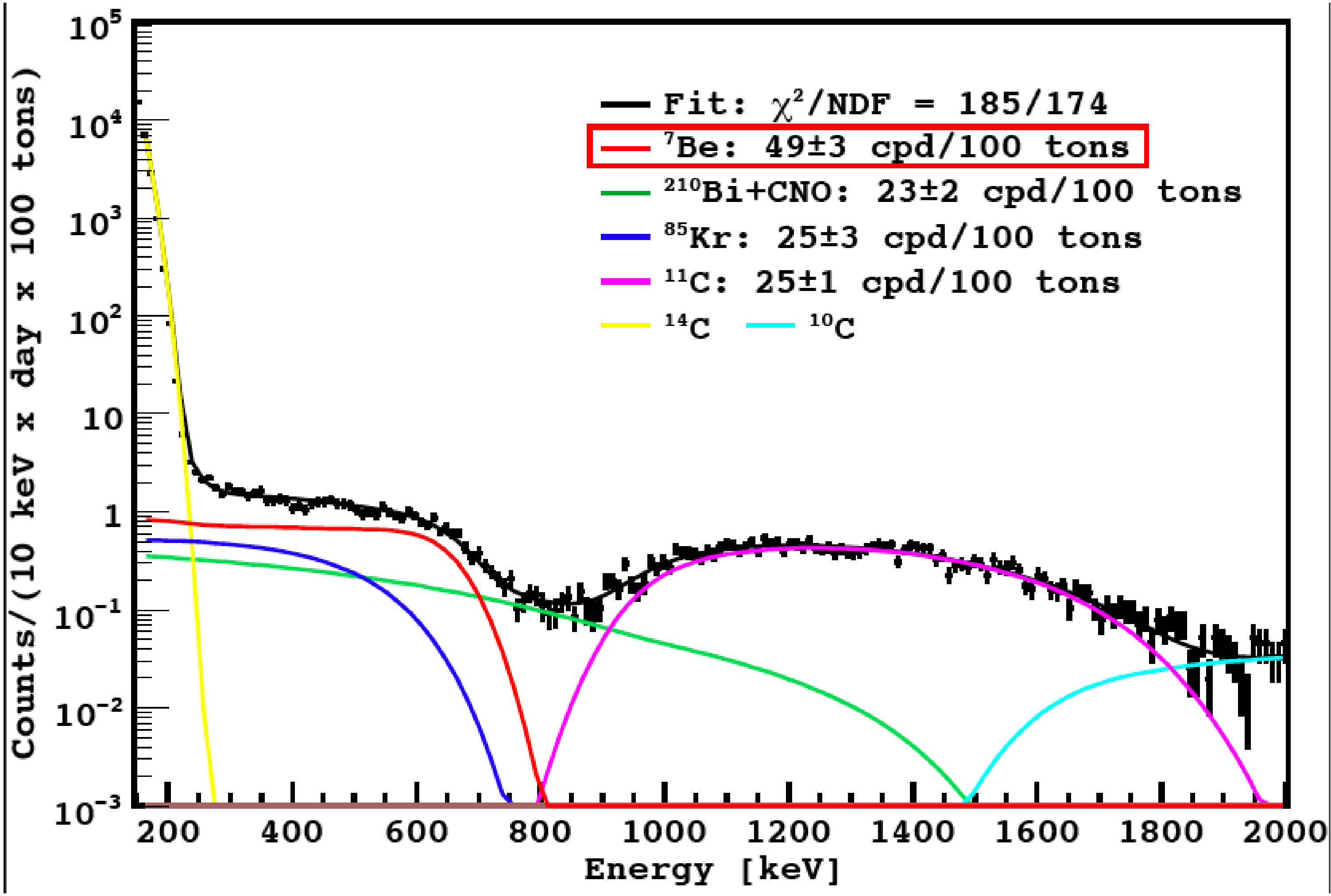
$$\nu_x + e^- \rightarrow \nu_x + e^-$$



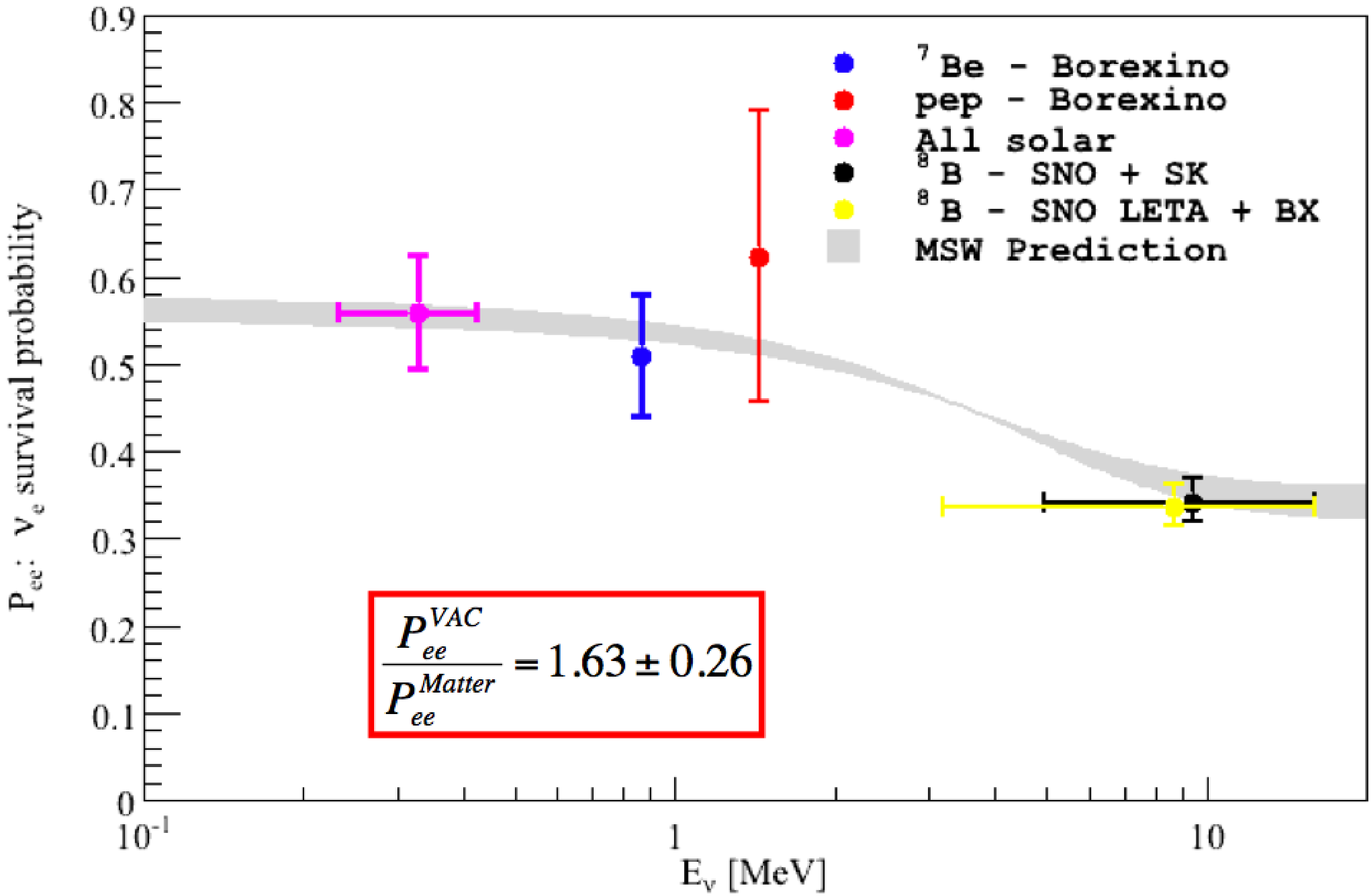


Real time detection of ^{7}Be neutrinos

Borexino - First results



Borexino - results



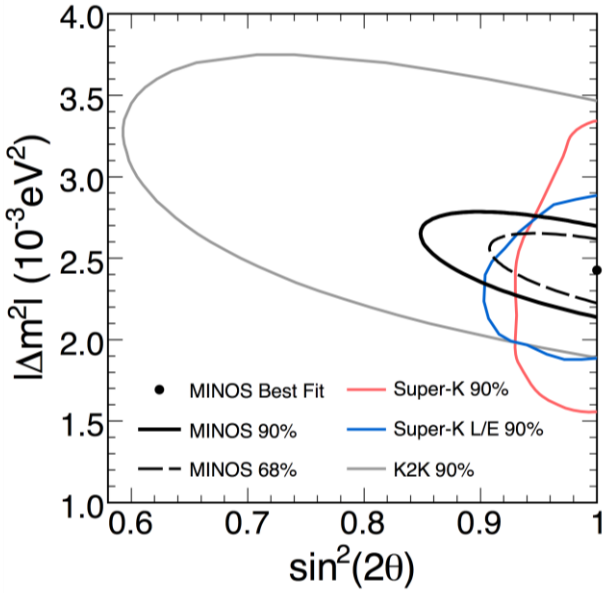
TAUP 2011 conference

Oscillation - evidences

depending on $\Delta m^2 = m_i^2 - m_j^2$

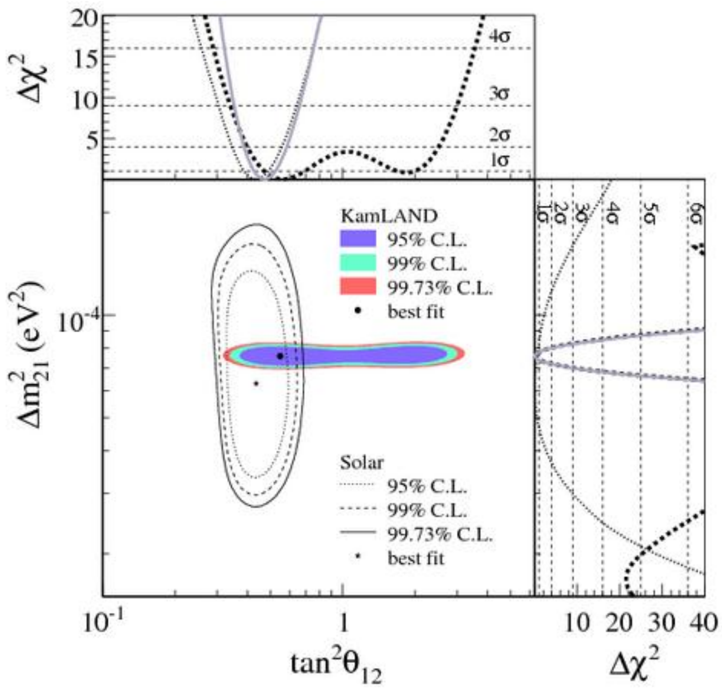
Atmospheric neutrinos

$\sin^2 2\theta_{23} = 1.00$, $\Delta m^2 = 2.3 \times 10^{-3}$ eV^2



Solar and reactor

$\sin^2 2\theta_{12} = 0.81$, $\Delta m^2 = 7.6 \times 10^{-5}$ eV^2



Incredible progress in last 10-15 years !!!!

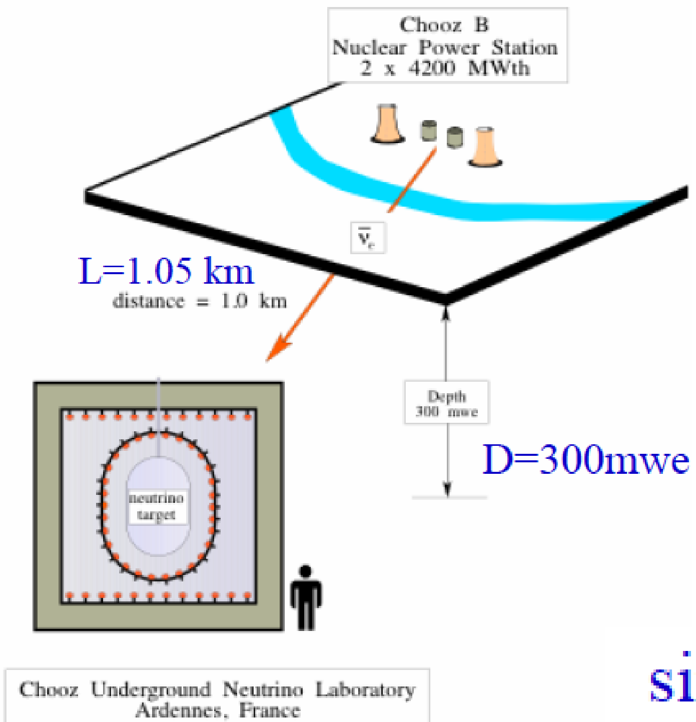
Limits on Θ_{13}

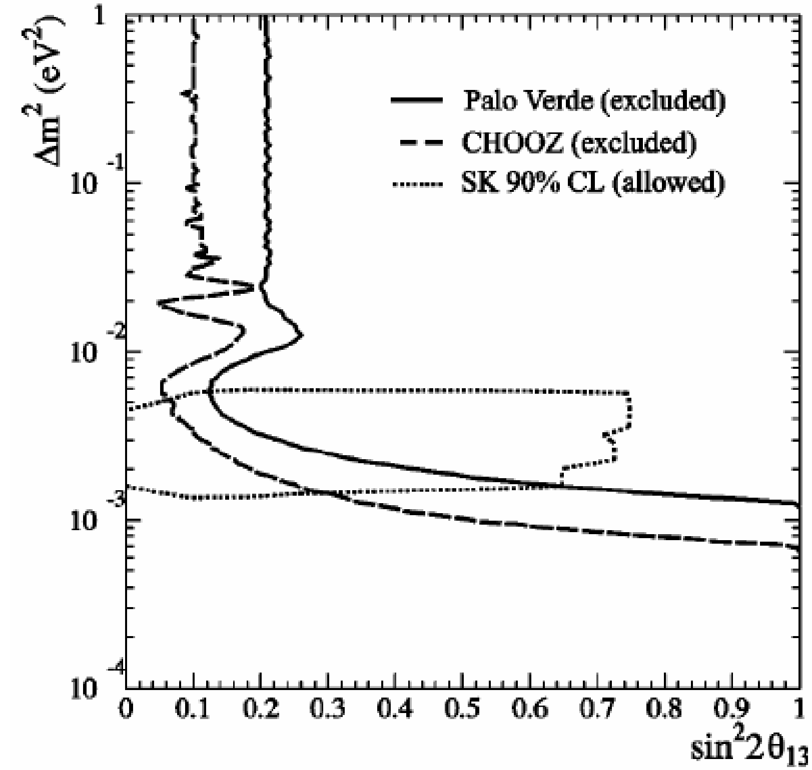
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

P=8.4 GW_{th}

L=1.05 km

D=300mwe





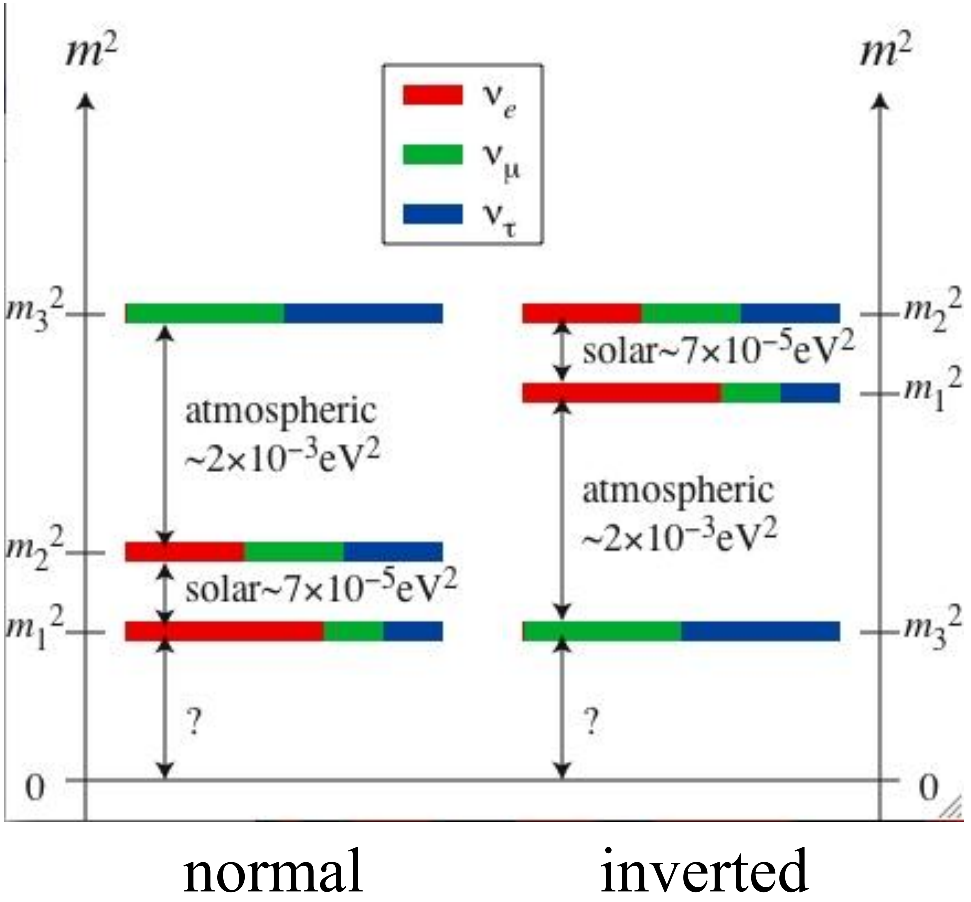
$\sin^2 2\theta_{13} < 0.15$ for $\Delta m^2 = 2.5\times10^{-3}$ eV^2

m = 5 tons, Gd-loaded liquid scintillator

Neutrino mass schemes

- almost degenerate neutrinos $m_1 \approx m_2 \approx m_3$

- hierarchical neutrino mass schemes



Neutrino mixing

Leptons :

$$|U_{\mathrm{PMNS}}| \simeq \begin{pmatrix} 0.82 & 0.58 & 0 \\ 0.64 & 0.58 & 0.71 \\ 0.64 & 0.58 & 0.71 \end{pmatrix}$$

Compare to

Quarks:

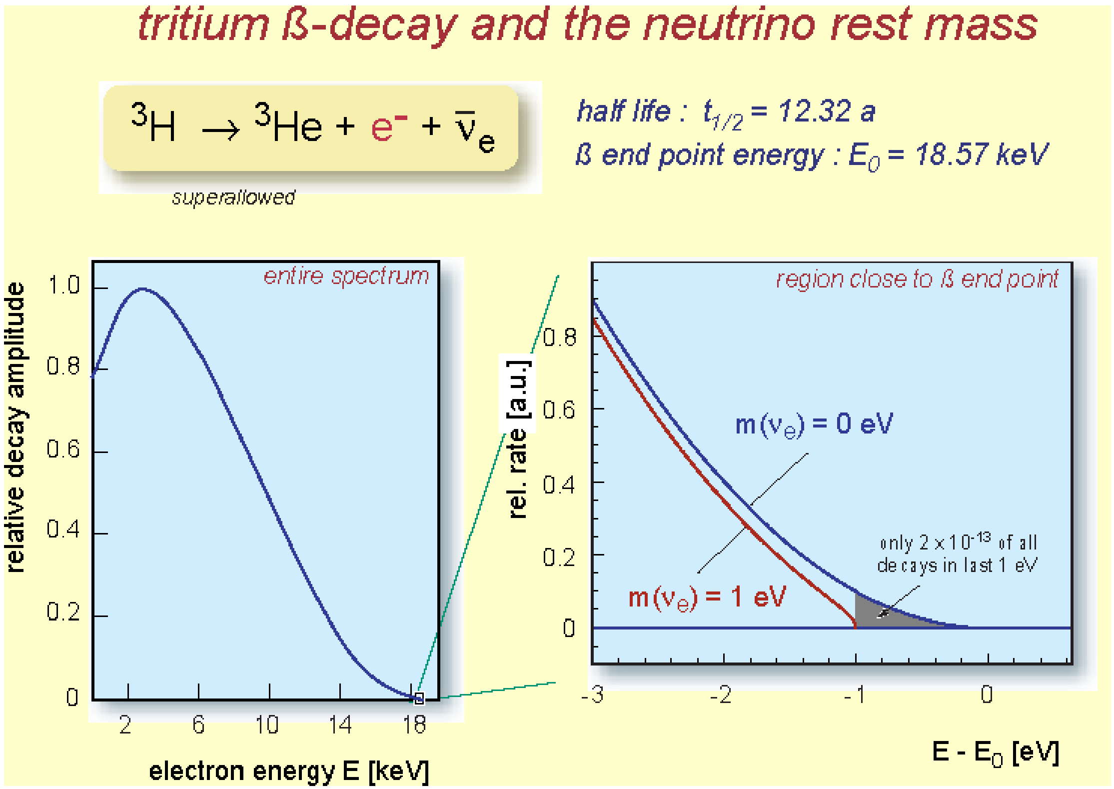
$$|V_{\mathrm{CKM}}| \simeq \begin{pmatrix} 0.97419 & 0.2257 & 0.00359 \\ 0.2256 & 0.97334 & 0.0415 \\ 0.00874 & 0.0407 & 0.999133 \end{pmatrix}$$

$\Theta_{12} + \theta_C \approx 45^\circ$, $\theta_{23} \approx 45^\circ$ Is nature telling us something???

Beta decay

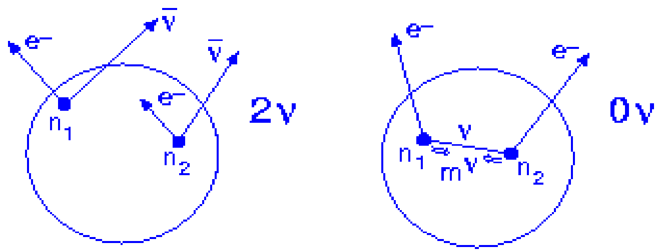
E.W. Otten, C. Weinheimer, Rep. Prog. Phys. 71,086201 (2008)

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



Double beta decay

- $(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}_e$ $2\nu\beta\beta$
- $(A,Z) \rightarrow (A,Z+2) + 2\,e^-$ $0\nu\beta\beta$



Unique process to measure the mass of the neutrino

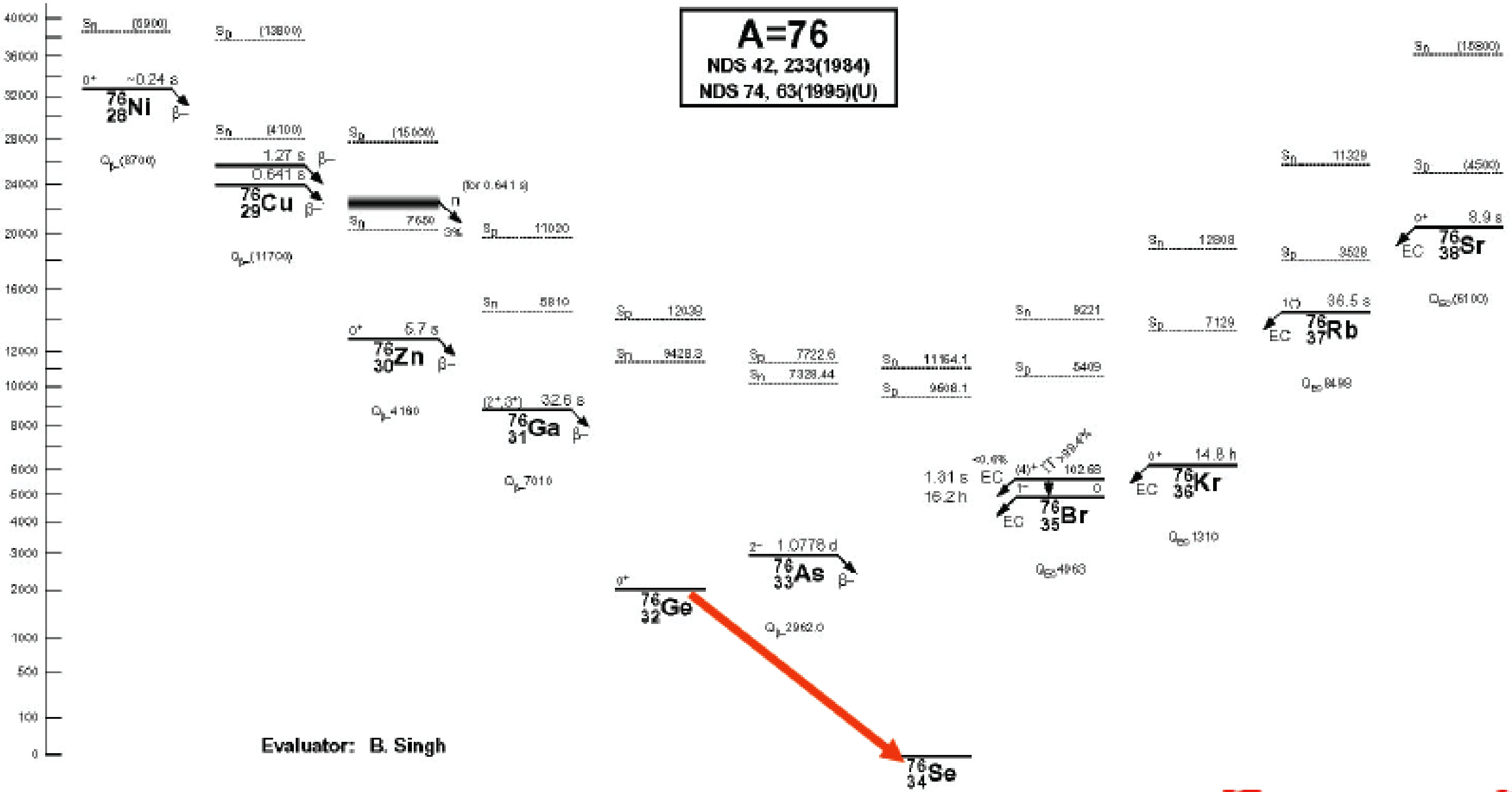
Unque process to measure character of neutrino

Requires half-life measurements well beyond 10^{20} yrs!!!!

The smaller the neutrino mass the longer the half-life

Example - Ge76

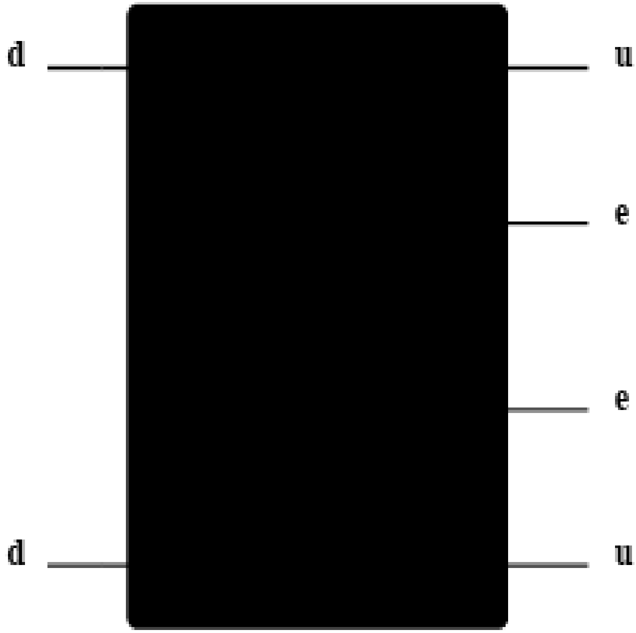
All ground state transitions are $0^+ \rightarrow 0^+$



There are only 35 candidates

0νββ

Any ΔL=2 process can contribute to 0νββ



R_p violating SUSY
V+A interactions
Extra dimensions (KK- states)
Leptoquarks
Double charged Higgs bosons
Compositeness
Heavy Majorana neutrino exchange
Light Majorana neutrino exchange
...

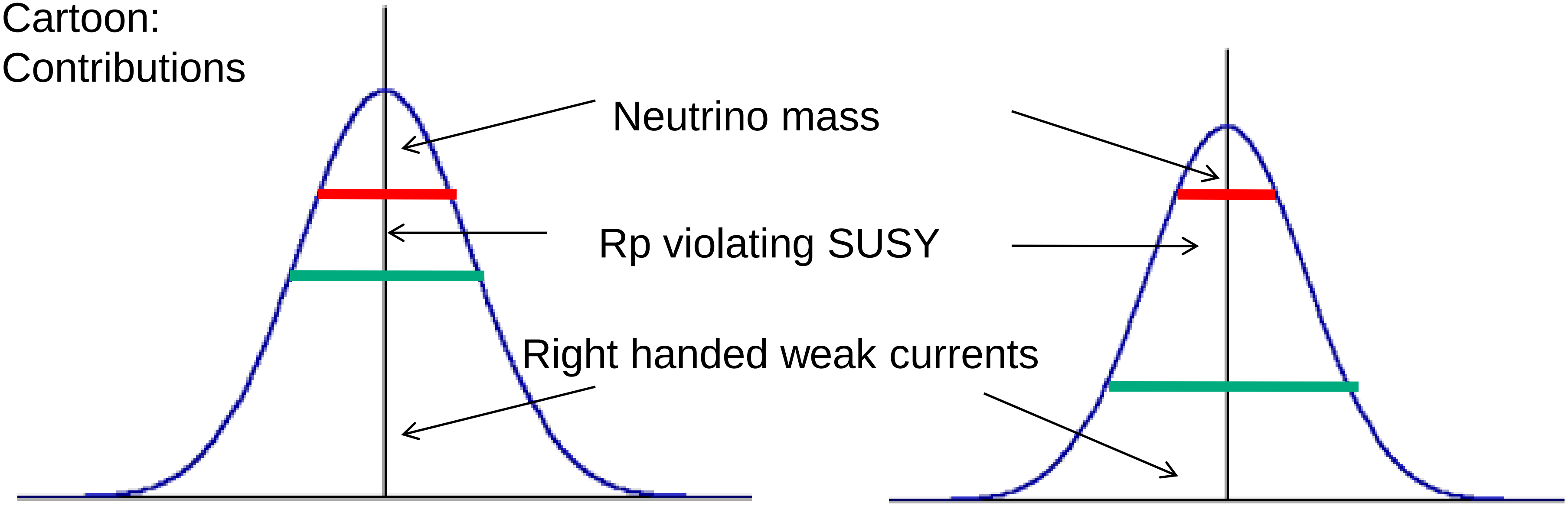
$$1 / T_{1/2} = PS * NME^2 * \varepsilon^2$$

Nice interplay with LHC,see A. de Roeck talk

0νββ

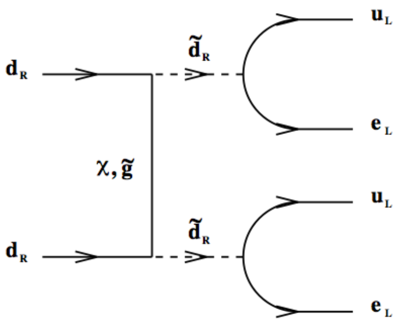
If peak is ever observed 0νββ, the real work begins

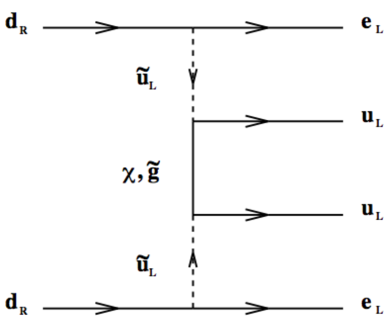
Cartoon:
Contributions

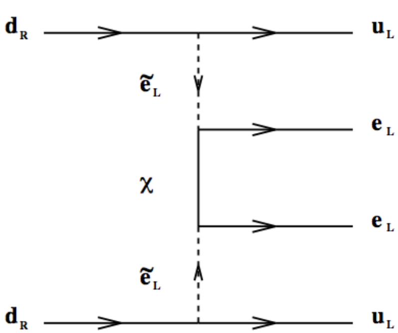


Could be more contributions....

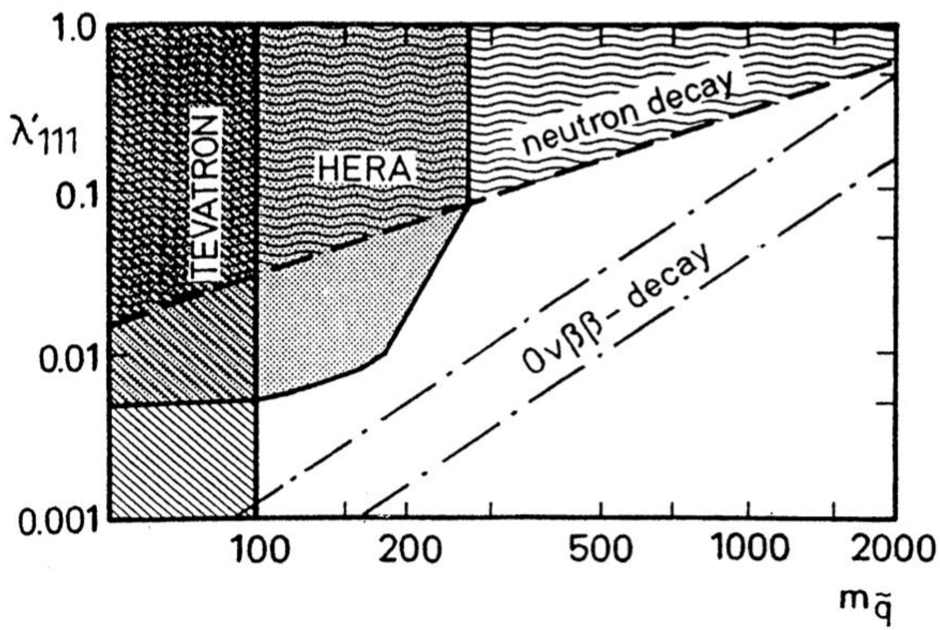
0νββ







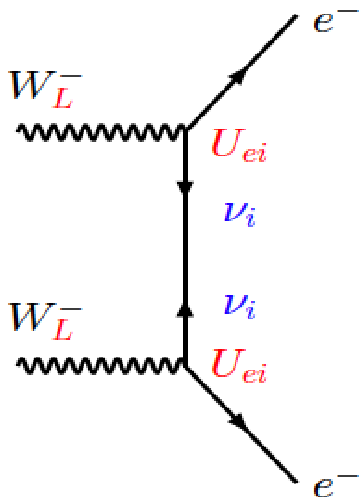
$$[T^{0\nu}_{1/2}(0^+ \to 0^+)]^{-1} \sim G_{01}(\frac{\lambda'^2_{111}}{m^4_{\tilde{q},\tilde{e}} m_{\tilde{g}\chi}} M)^2$$



My wish list for LHC (I'm willing to help/collaborate):

- Good limits on gluino and squark masses or find it!
- Bound on λ'_{111}
- Search for W_R
- Search for double charged Higgs
- If you have time.... Leptoquarks, KK states

Light Majorana neutrinos



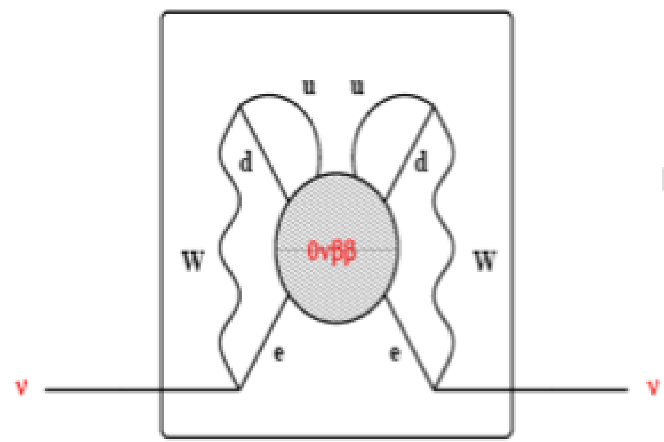
$$\varepsilon \equiv \langle m_\nu \rangle = \sum_i U_{ei}^2 m_{\nu_i}$$

$$\langle m_\nu \rangle = \sum_i U_{ei}^2 m_{\nu_i} = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_1} m_2 + s_{13}^2 e^{i\alpha_2} m_3$$

$$1 / T_{1/2} = PS * NME^2 * (\langle m_\nu \rangle / m_e)^2$$

Schechter and Valle 1982:

Independent of mechanism for neutrinoless DBD
Majorana neutrino mass will appear in higher order!

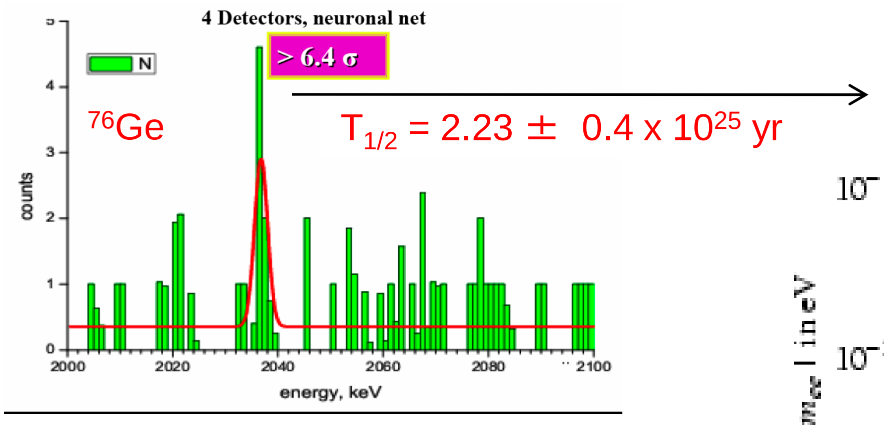


Observe $0\nu\beta\beta$ decay

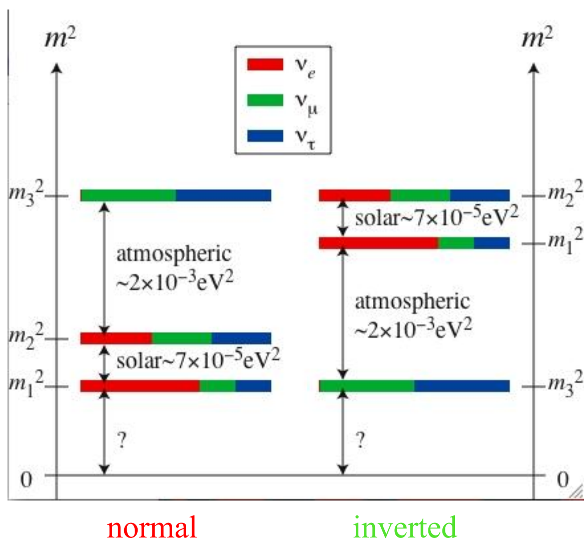
$\equiv$

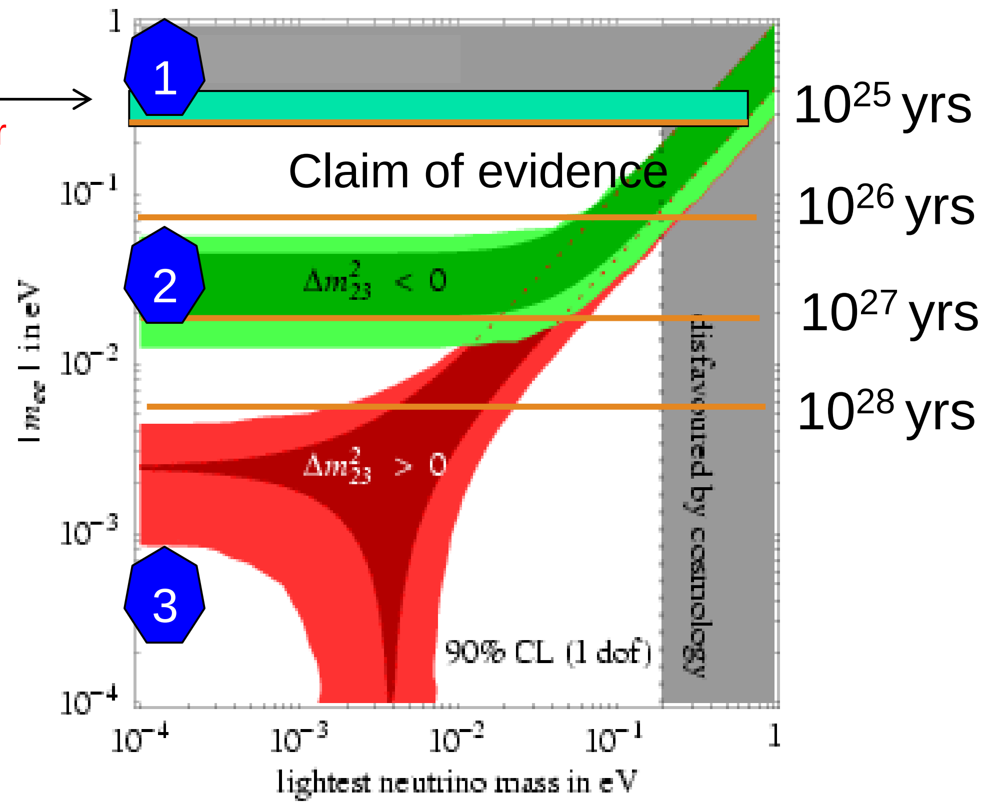
Neutrinos are Majorana particles

Mass hierarchies and DBD



H.V. Klapdor-Kleingrothaus, I. Krivosheina, Mod.Phys.Lett.A21:1547-1566 (2006)





1.) Is the claimed evidence correct?

2.) Can we probe the inverted hierarchy?

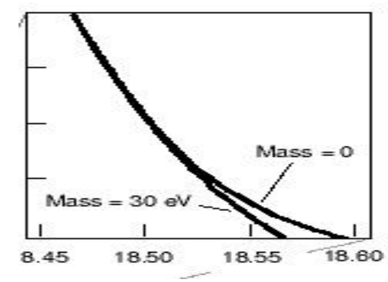
3.) What about the normal hierarchy?

DBD and neutrino masses

Also other neutrino physics matters

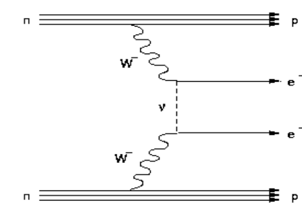
Beta decay:

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$



Double beta decay:

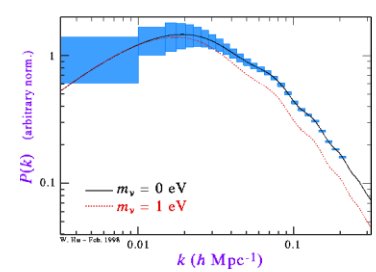
$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



Cosmology:

$$\Sigma = m_1 + m_2 + m_3$$

$$\Omega_\nu h^2$$



+ oscillation parameters