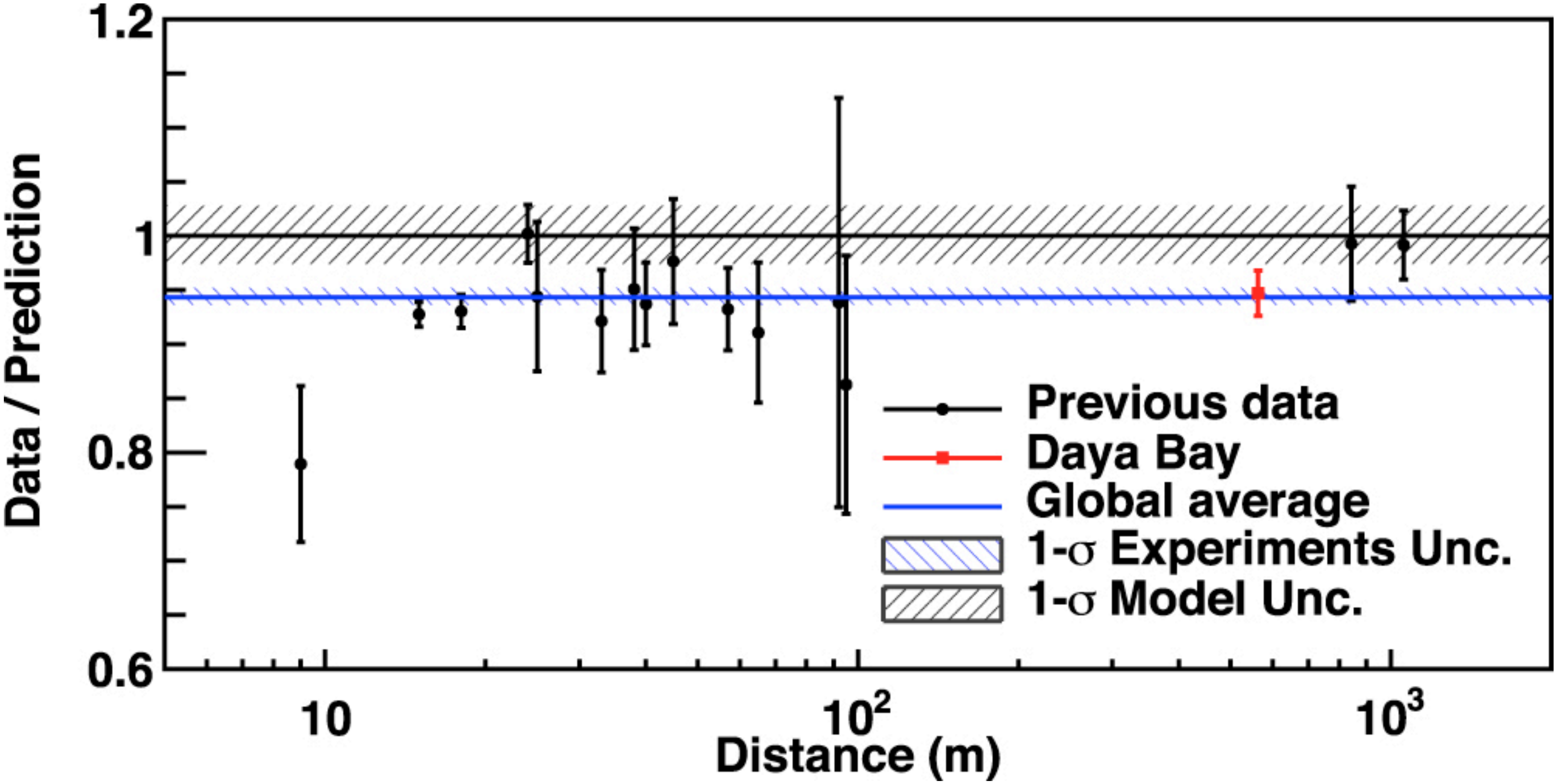
Neutrino Physics

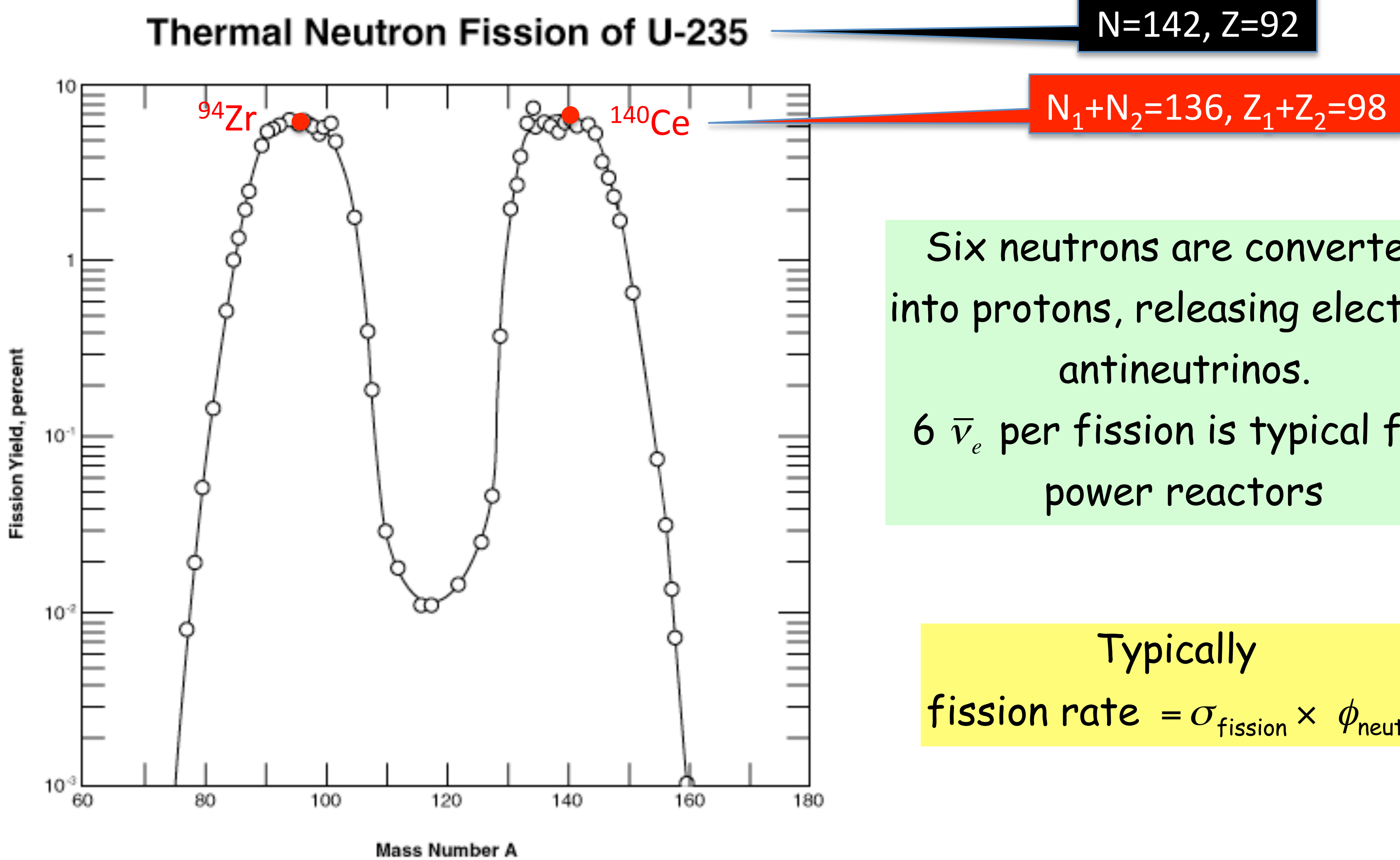
A.B. Balantekin
University of Wisconsin - Madison
NNPSS 2017, Boulder

Lecture 2

“The reactor anomaly”



99.9% of the power in a reactor comes from the fissions of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu



Six neutrons are converted into protons, releasing electron antineutrinos.

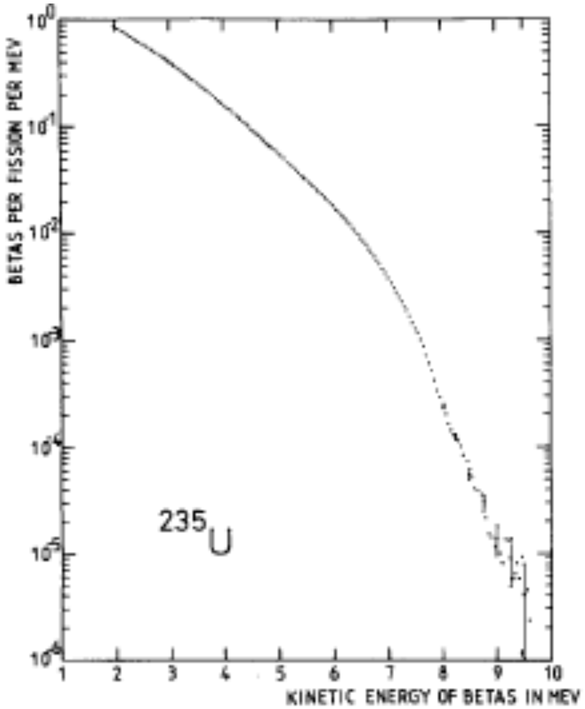
6 $\bar{\nu}_e$ per fission is typical for power reactors

Typically

fission rate $= \sigma_{fission} \times \phi_{neutron}$

How to determine the neutrino spectrum?

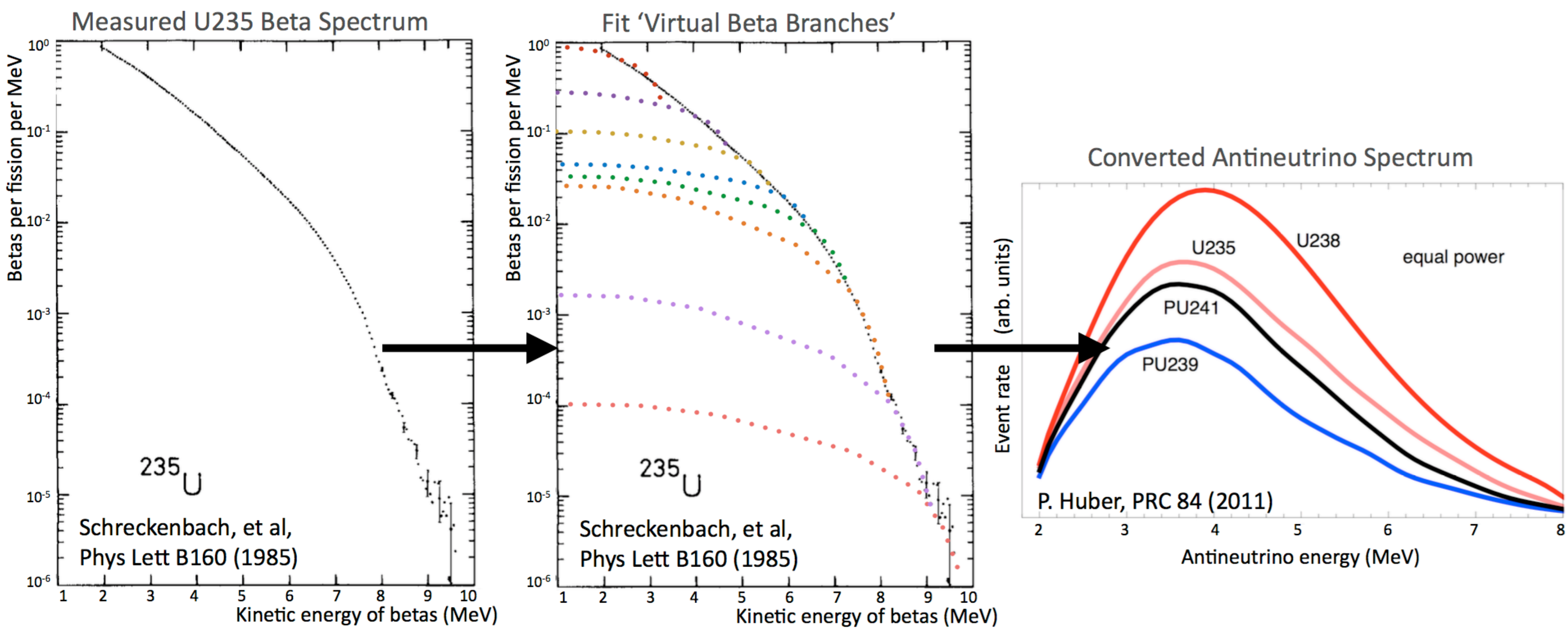
Method 1: Start with the measured electron spectra



Schreckenbach, et al. PLB 1985

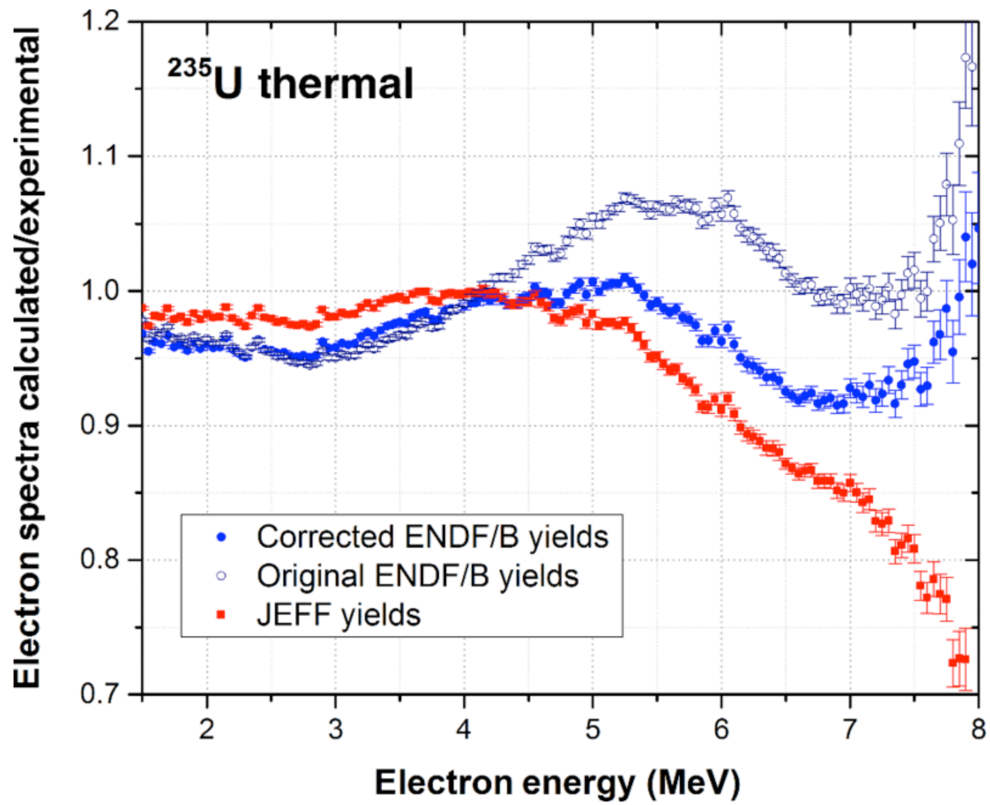
..and convert it into electron antineutrino spectra

Modeling antineutrino production in a reactor



How to determine the neutrino spectrum?

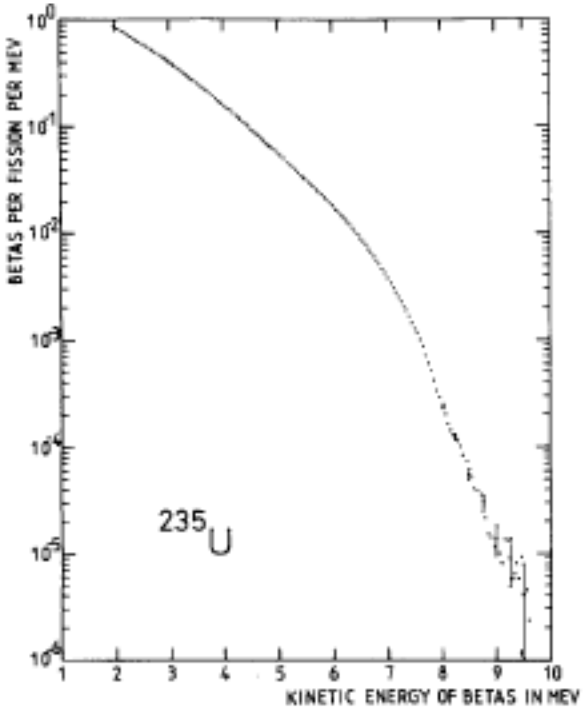
Method 2: Directly sum fission yields using nuclear data compilations



Sonzogni et. al, PRL **116,** 132502 (2016)

How to determine the neutrino spectrum?

Method 1: Start with the measured electron spectra



Schreckenbach, et al. PLB 1985

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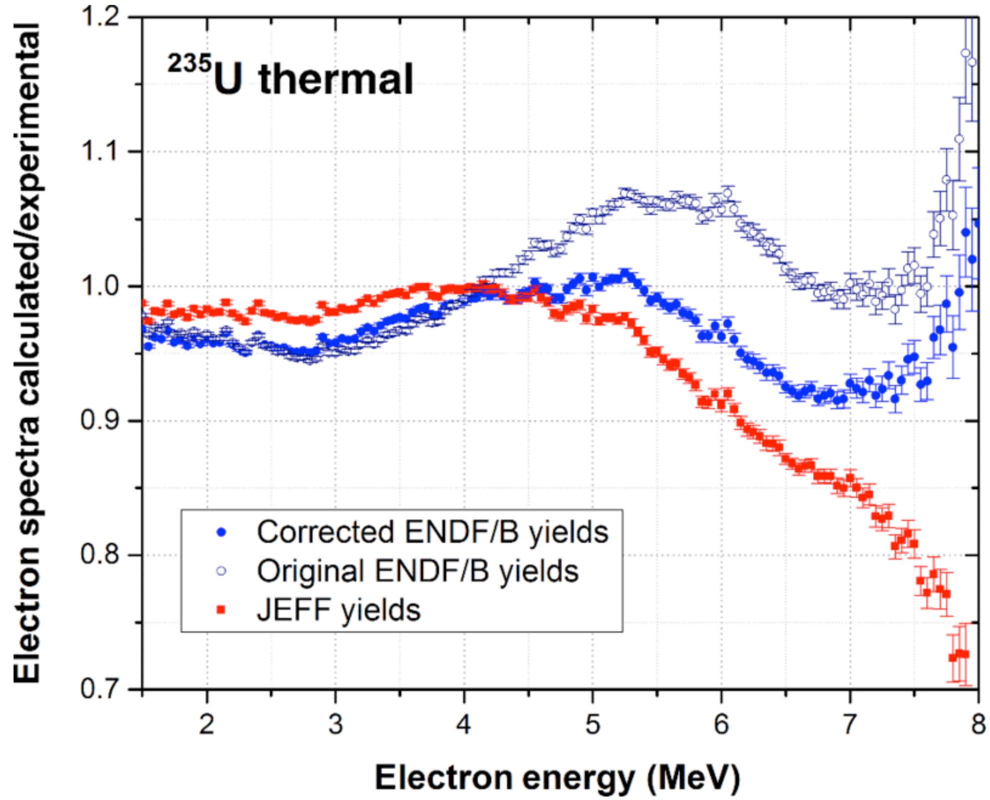
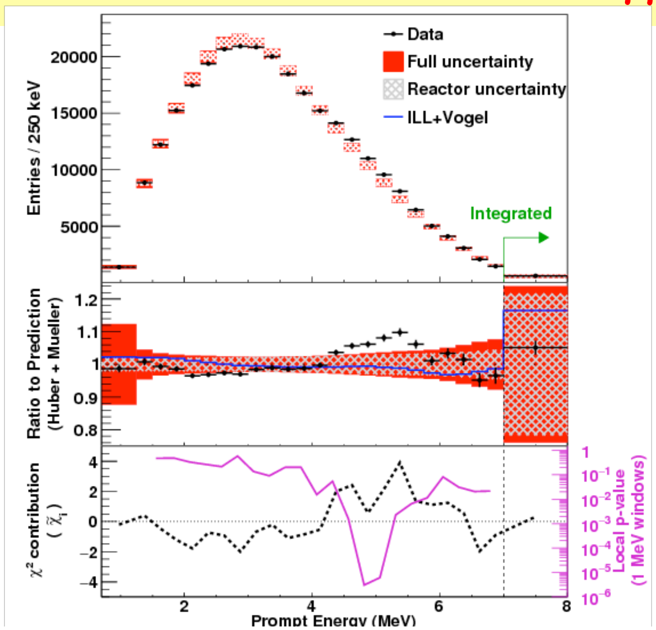
Method 2: Directly sum fission yields using nuclear data compilations

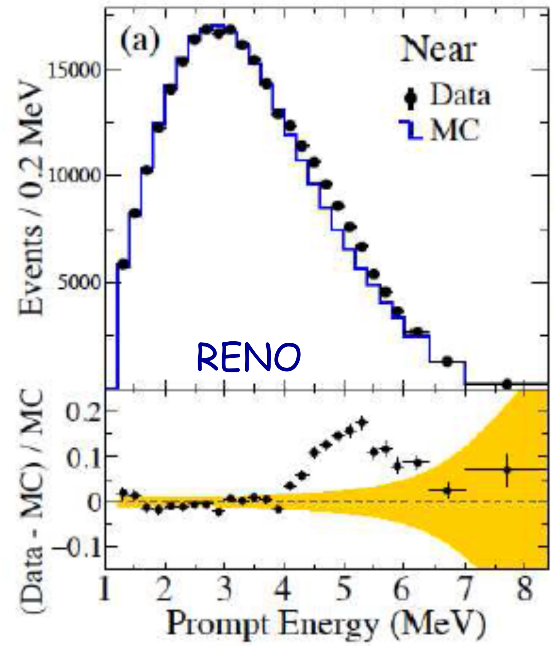


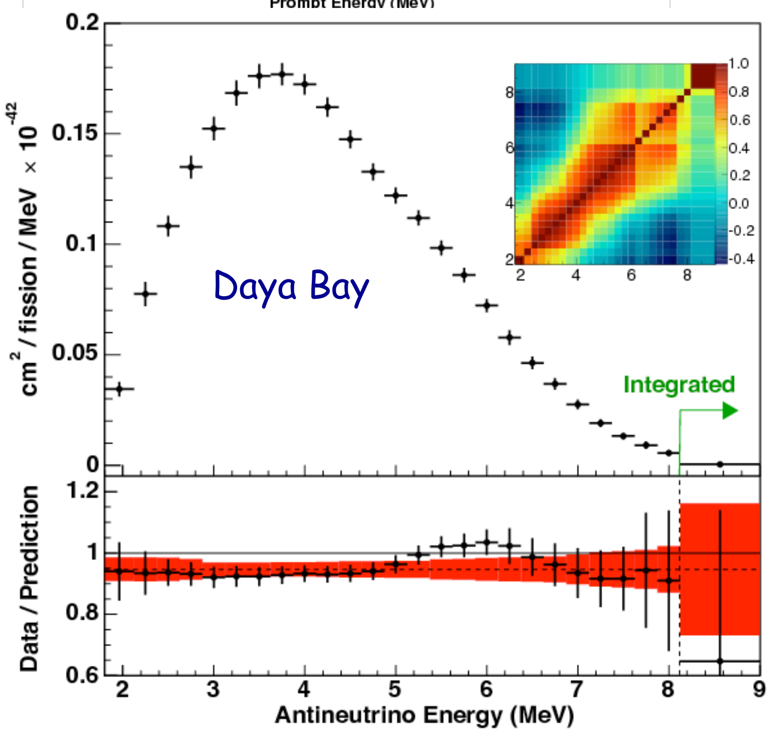
Sonzogni et. al, PRL **116,** 132502 (2016)

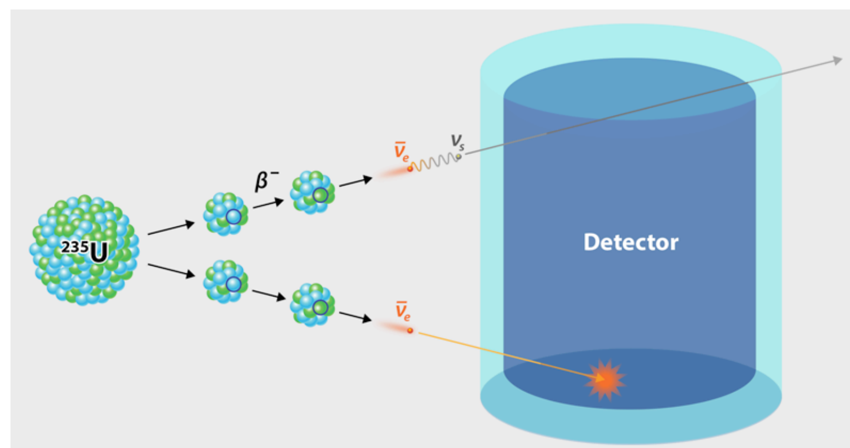
They do not quite agree! One should use a hybrid approach.

Then comes the bump!



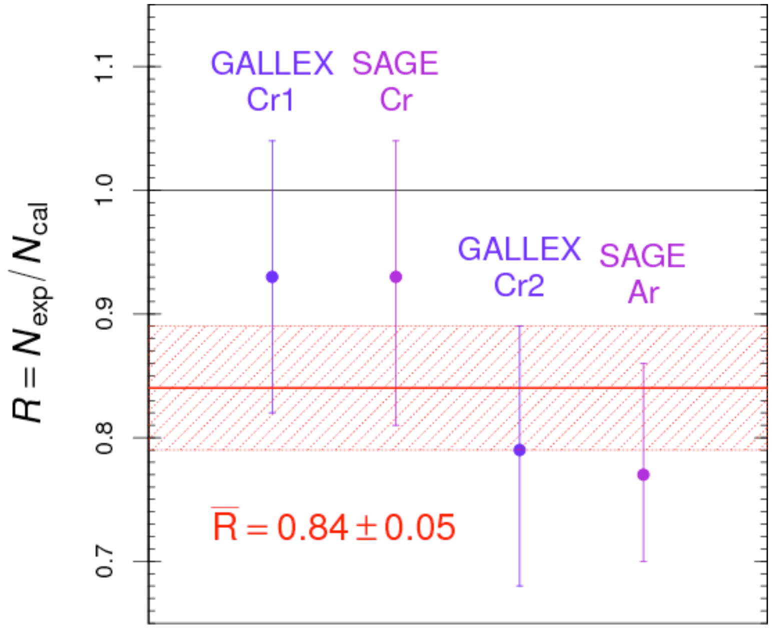


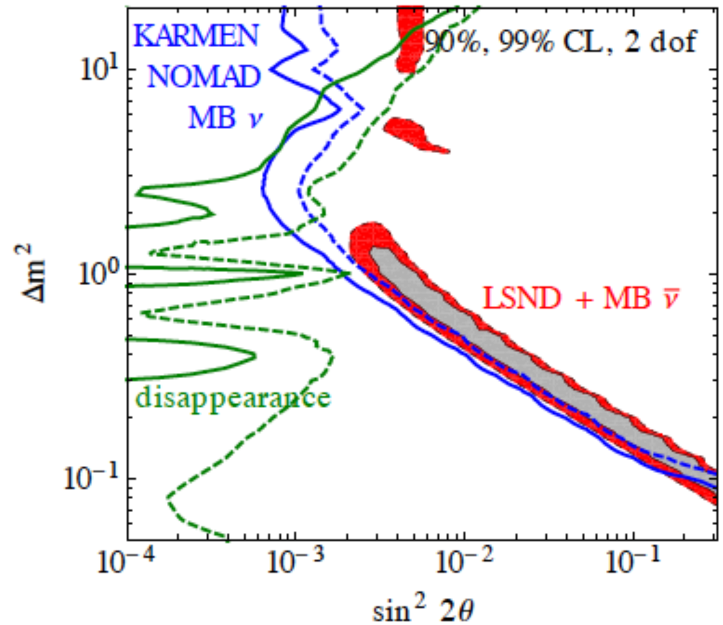


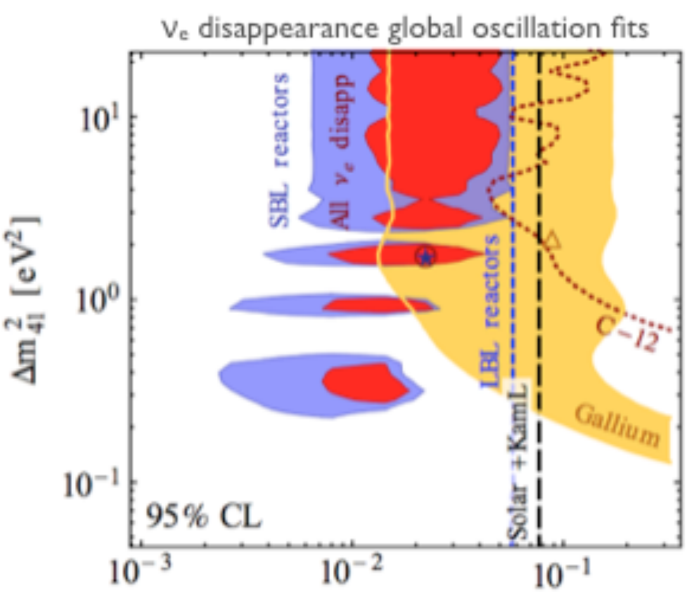


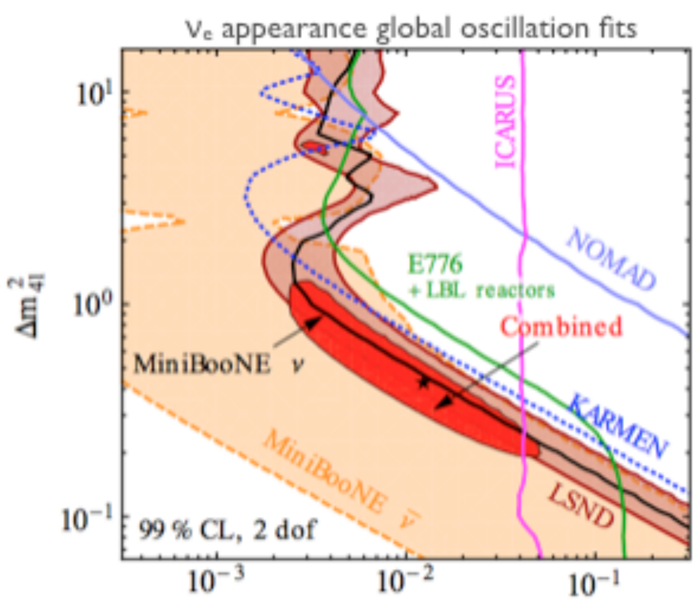
Source: APS

Does the reactor-flux anomaly imply active-sterile neutrino mixing?



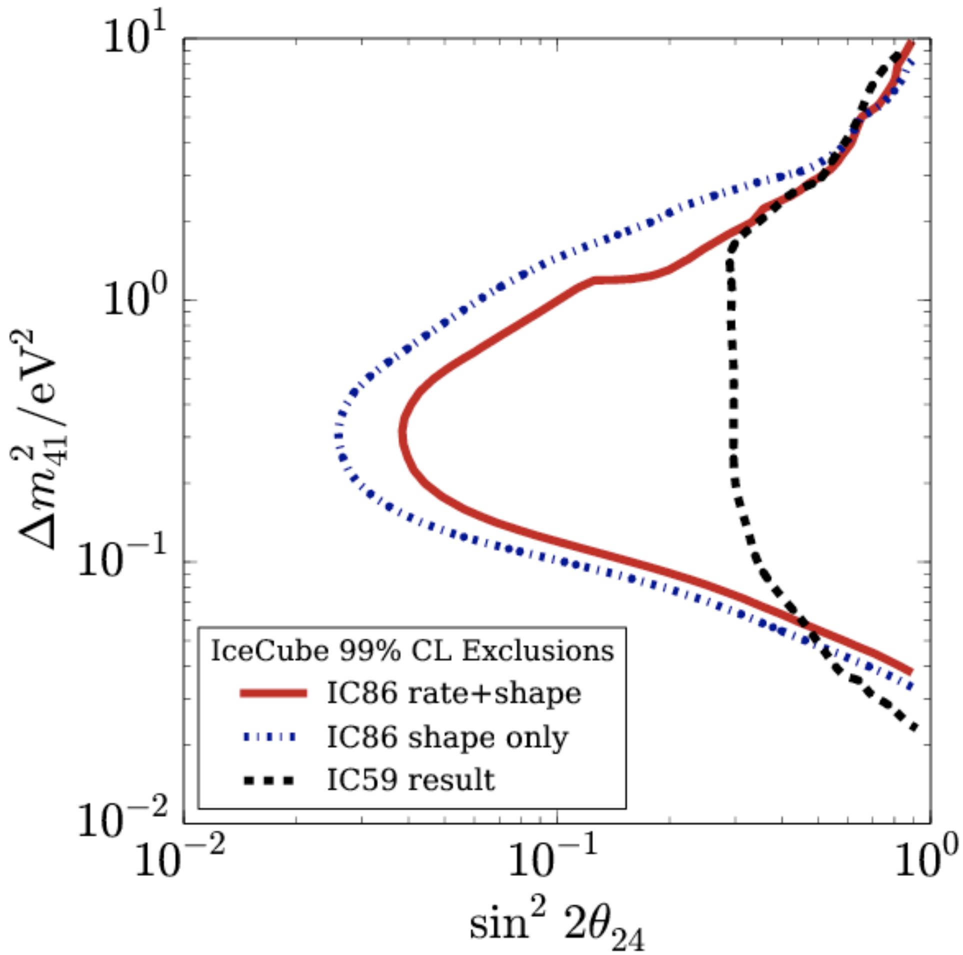


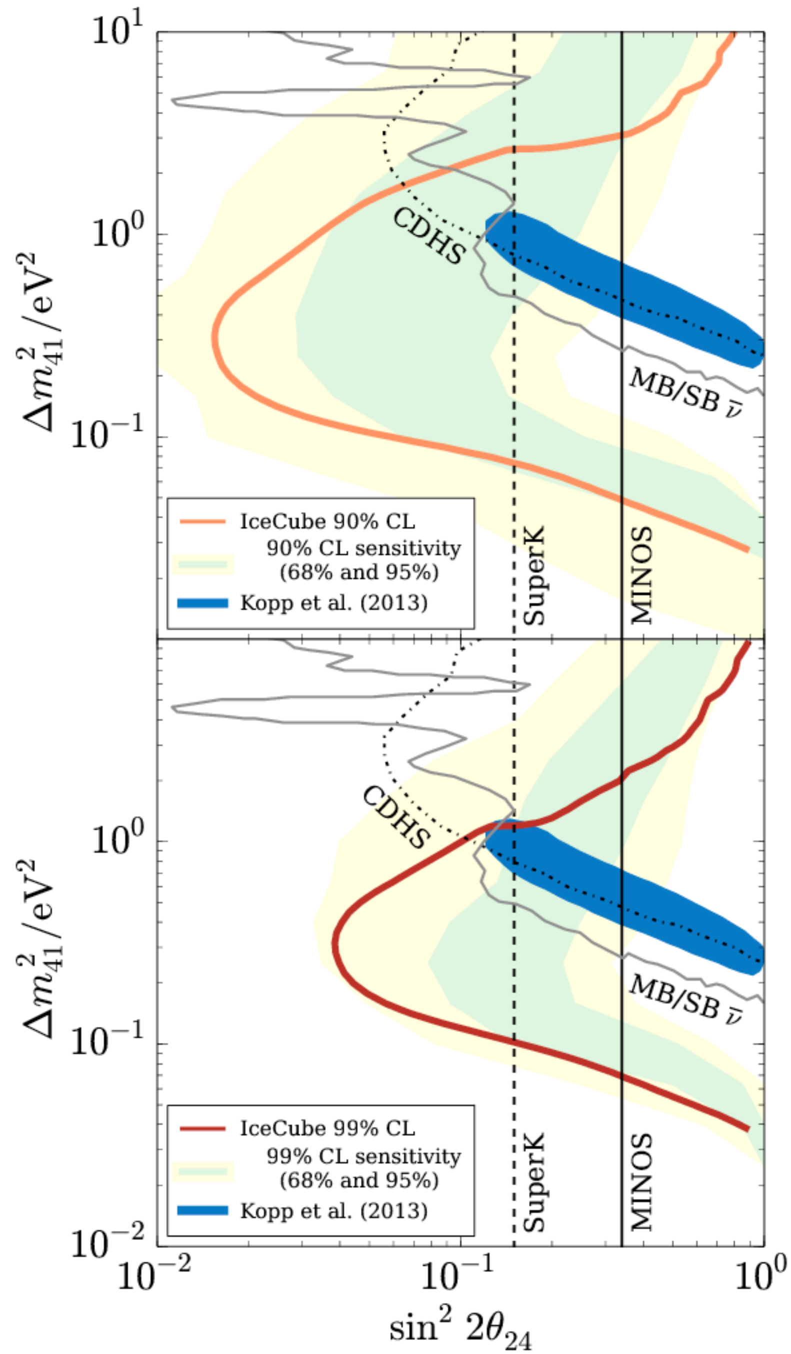




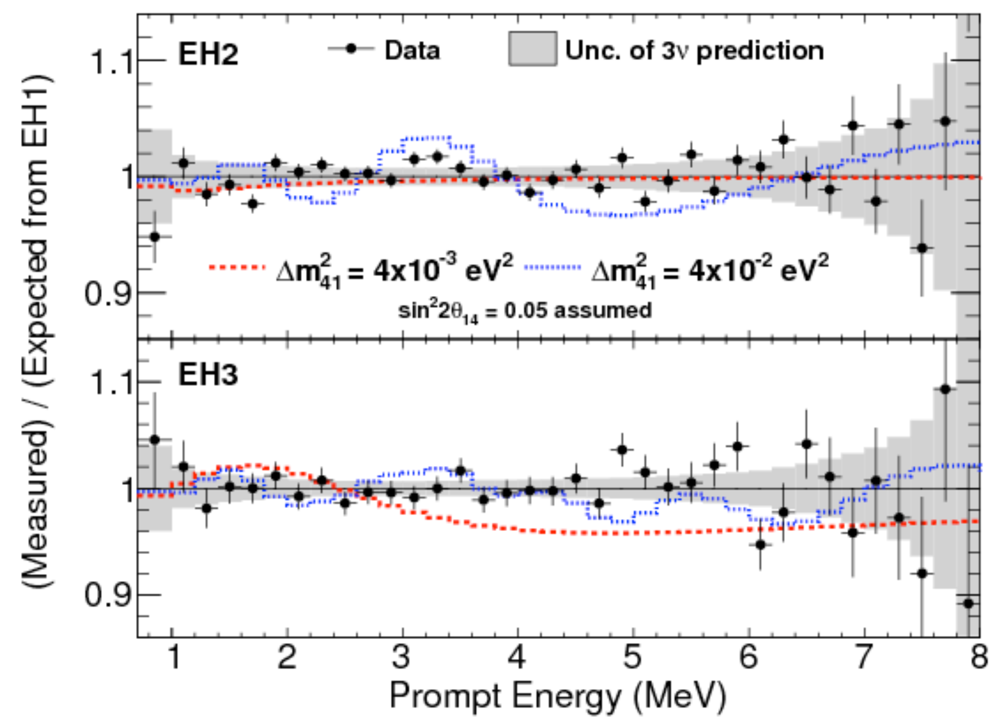
Kopp et. al., JHEP 1305:050 (2013)

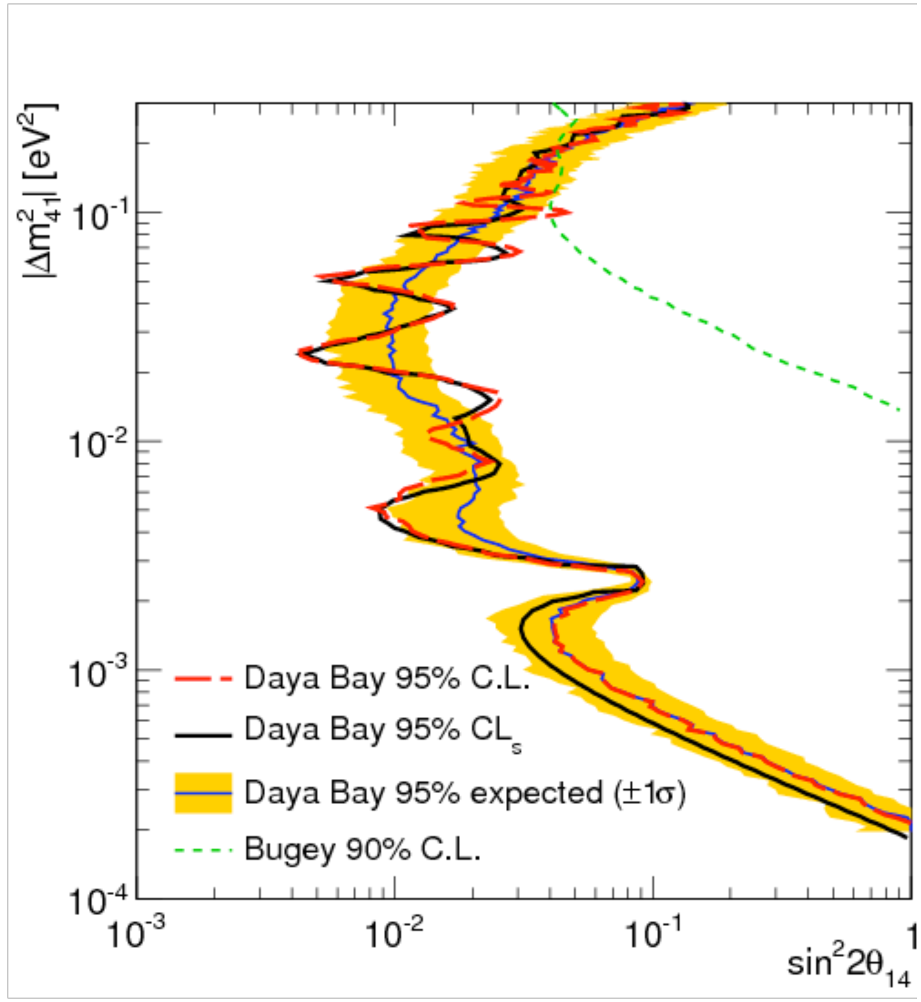
Sterile Neutrino Limits from ICECUBE – θ_{24}





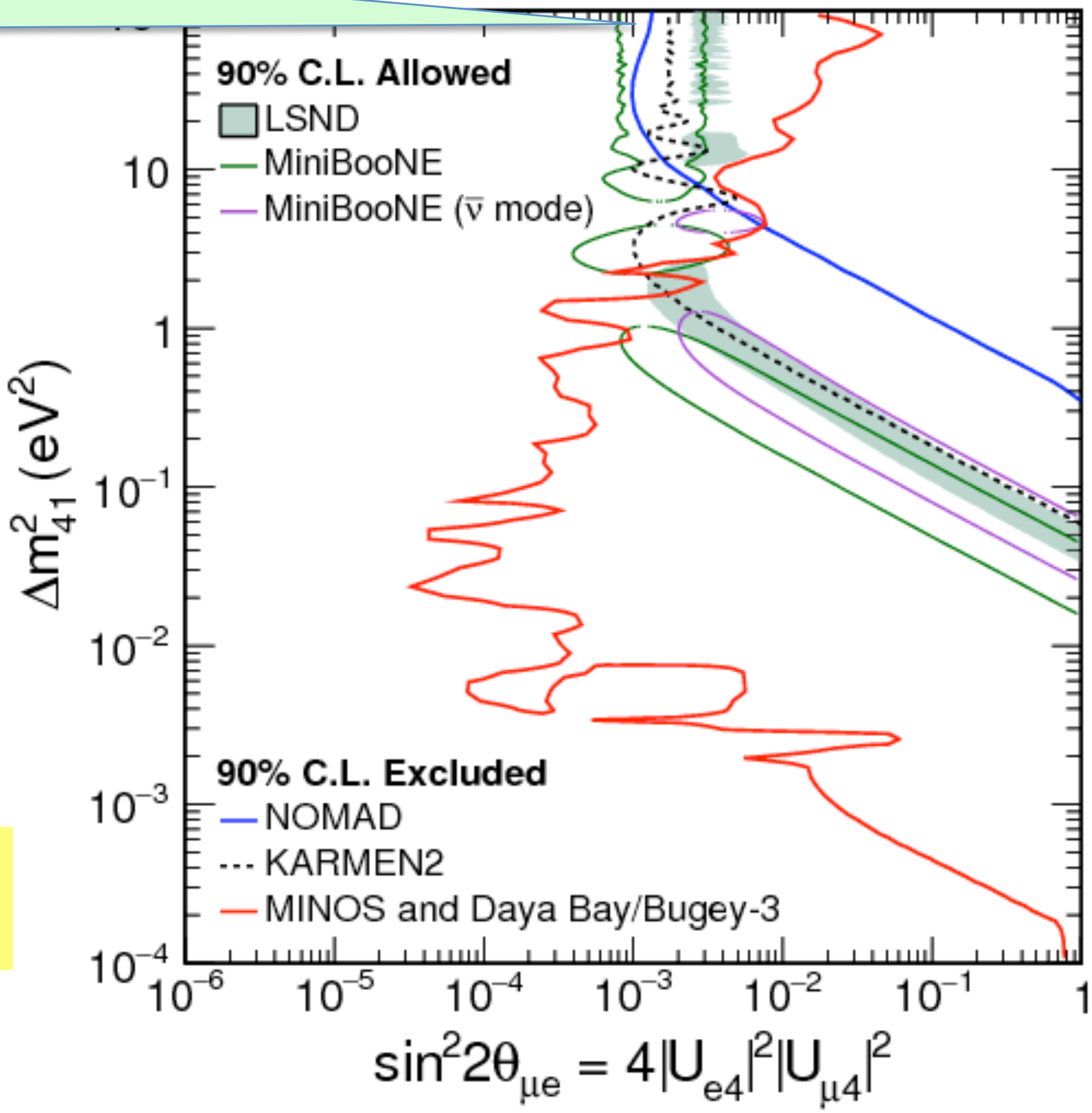
Sterile Neutrino Limits from Daya Bay – θ_{14}





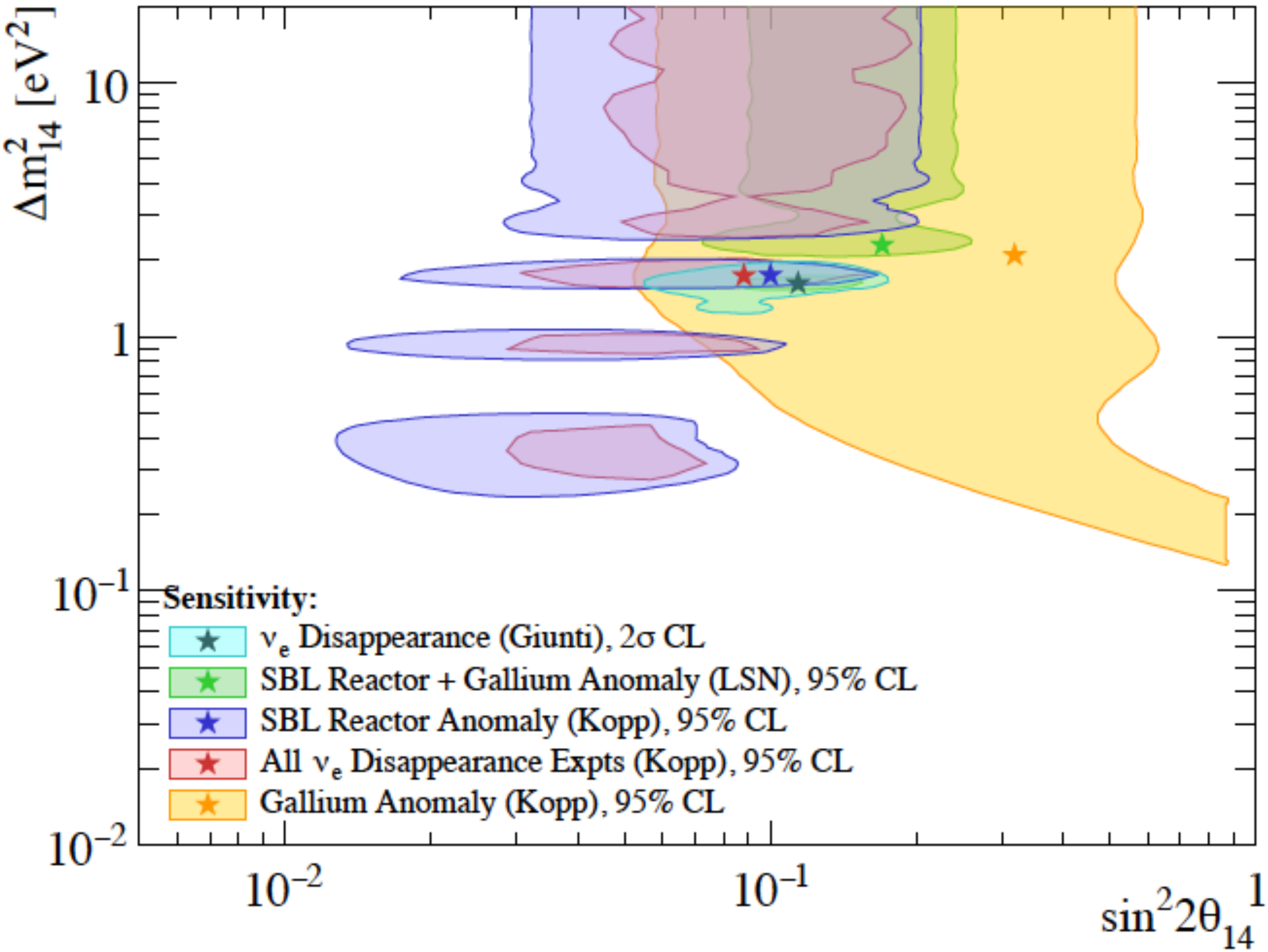
arXiv:1607.01174 [hep-ex]

This region is still allowed for LSND/MiniBooNE

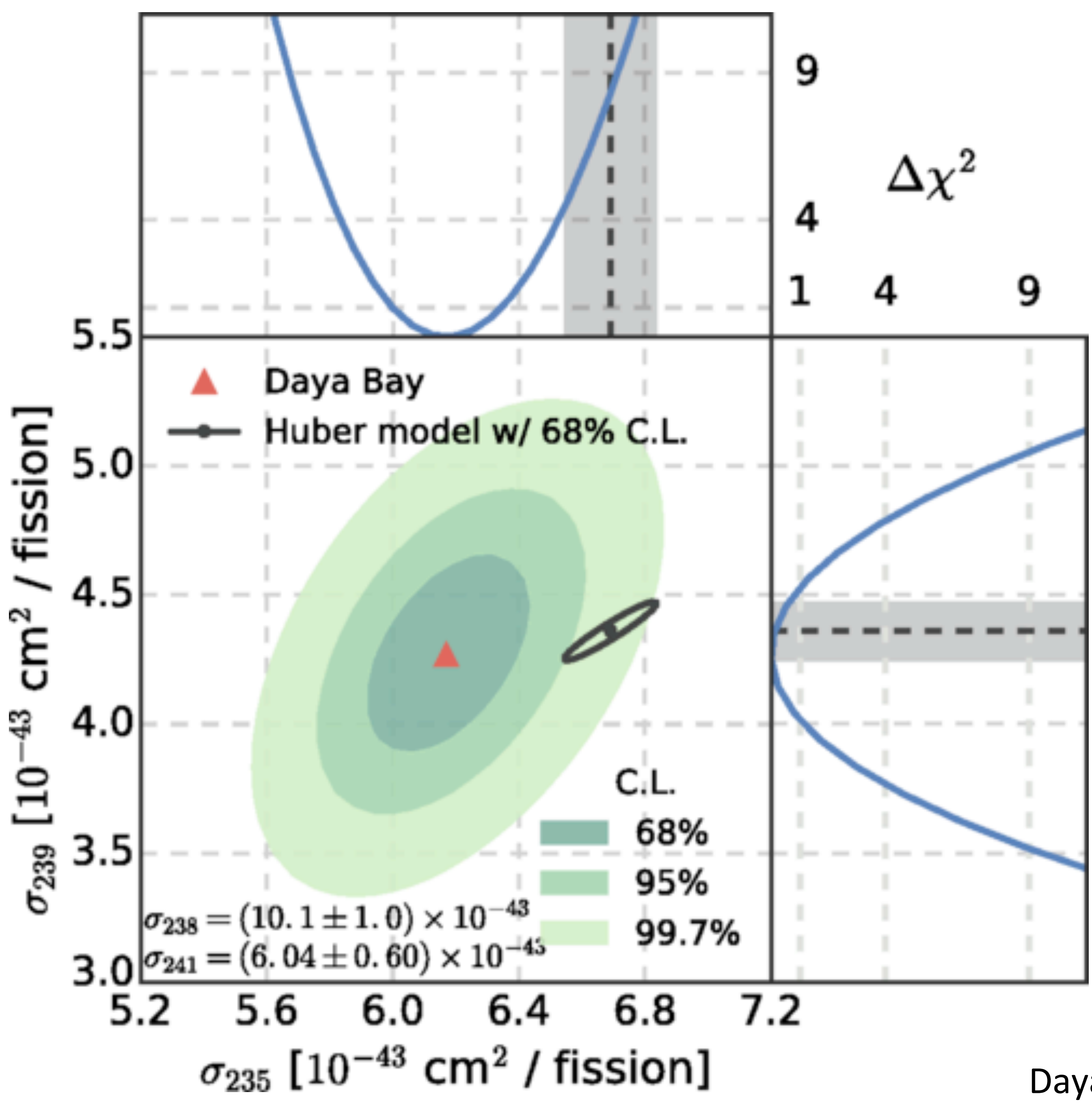


Daya Bay, Bugey, MINOS joint analysis

arXiv:1607.01177



PROSPECT Collaboration, arXiv:1512.02202

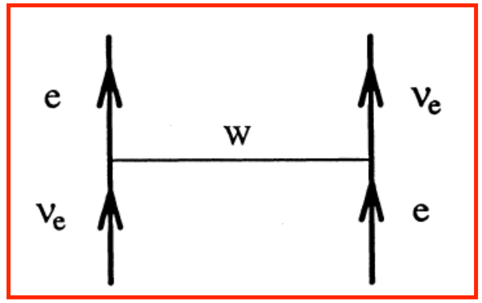


Daya Bay 2017

The MSW Effect

In vacuum: $E^2 = \mathbf{p}^2 + m^2$
In matter:
$(E - V)^2 = (\mathbf{p} - \mathbf{A})^2 + m^2$
$\Rightarrow E^2 = \mathbf{p}^2 + m^2_{\text{eff}}$
V $\propto$ background density
$\mathbf{A} \propto \mathbf{J}_{\text{background}}$ (currents) or
$\mathbf{A} \propto \mathbf{S}_{\text{background}}$ (spin)
In the limit of static,
charge-neutral, and
unpolarized background
V$\propto N_e$ and $\mathbf{A} = 0$
$\Rightarrow m^2_{\text{eff}} = m^2 + 2EV + \mathcal{O}(V^2)$

The potential is provided by the coherent forward scattering of ν_e's off the electrons in dense matter



There is a similar term with Z-exchange. But since it is the same for all neutrino flavors, it does not contribute to phase differences *unless* we invoke a sterile neutrino.

Note that matter effects induce an effective CP-violation since the matter in the Earth and the stars is not CP-symmetric!

Matter effects

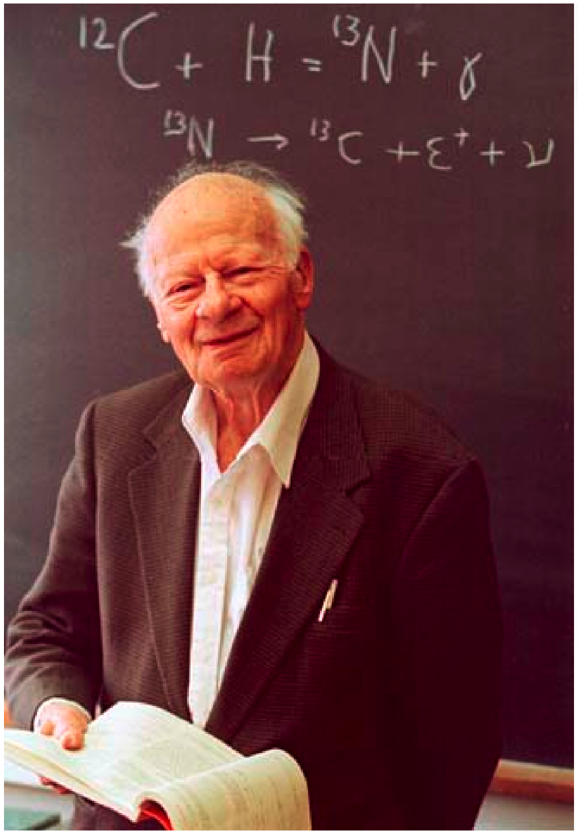
$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_e\\ \psi_\mu\\ \psi_\tau\end{pmatrix} = \left[T\begin{pmatrix}E_1 & 0 & 0\\ 0 & E_2 & 0\\ 0 & 0 & E_3\end{pmatrix}T^\dagger + \begin{pmatrix}V_c+V_n & 0 & 0\\ 0 & V_n & 0\\ 0 & 0 & V_n\end{pmatrix}\right]\begin{pmatrix}\psi_e\\ \psi_\mu\\ \psi_\tau\end{pmatrix}$$

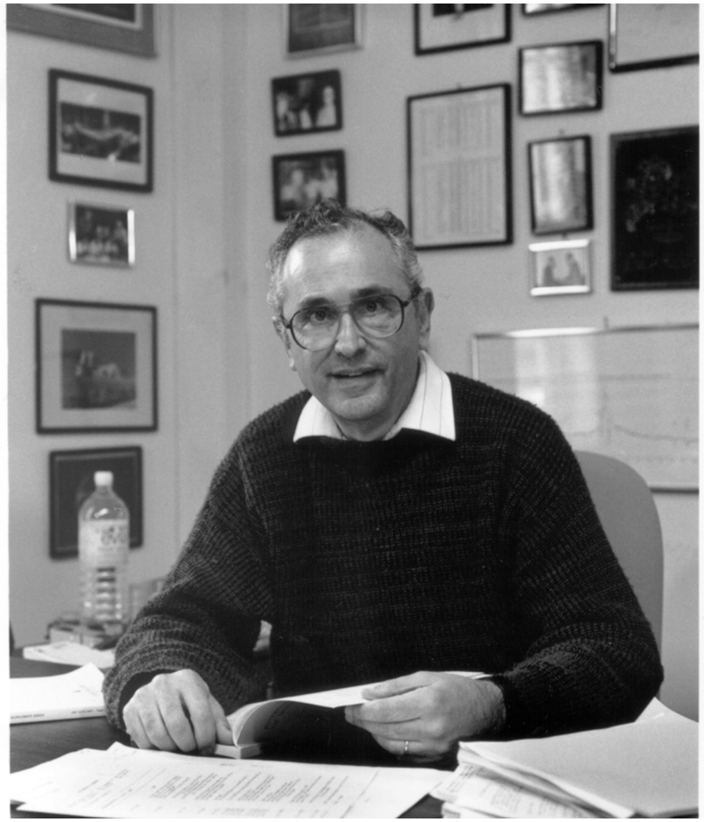
$$V_c = \sqrt{2}G_F N_e \qquad V_n = -\frac{1}{\sqrt{2}}G_F N_n$$

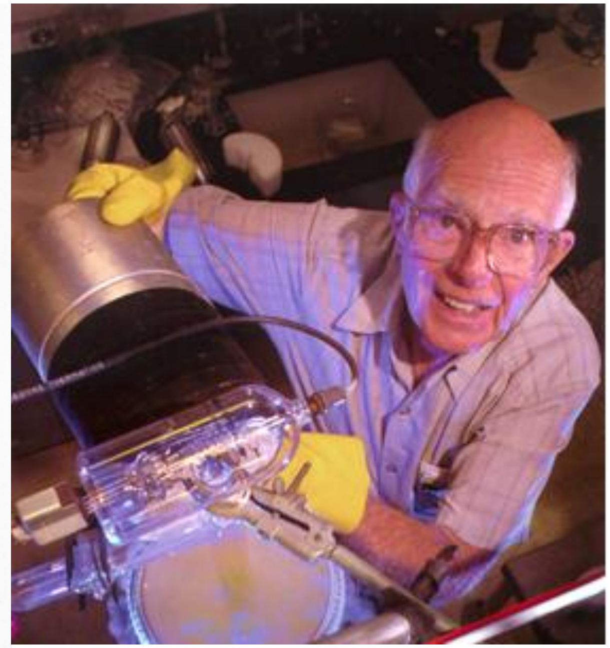
Two-flavor limit

$$i\frac{\partial}{\partial t}\begin{pmatrix}|\nu_e\rangle\\ |\nu\mu\rangle\end{pmatrix} = \begin{pmatrix}\varphi & \frac{\delta m^2}{4E}\sin 2\theta\\ \frac{\delta m^2}{4E}\sin 2\theta & -\varphi\end{pmatrix}\begin{pmatrix}|\nu_e\rangle\\ |\nu\mu\rangle\end{pmatrix}$$

$$\varphi = -\frac{\delta m^2}{4E}\cos 2\theta + \frac{1}{\sqrt{2}}G_F N_e$$



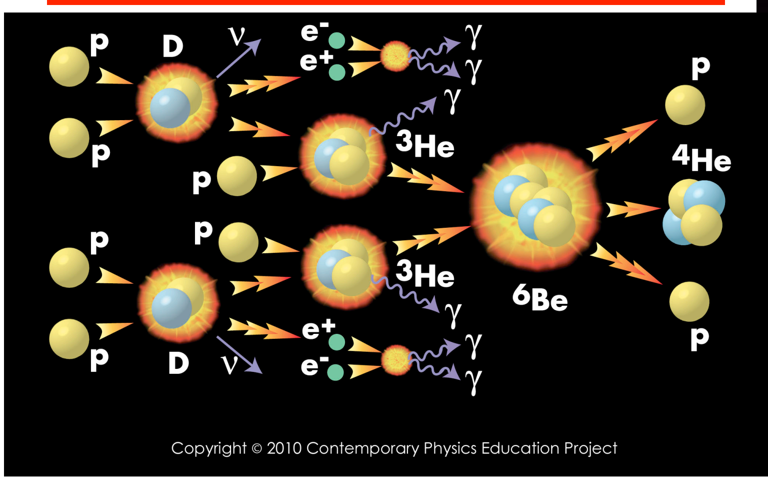


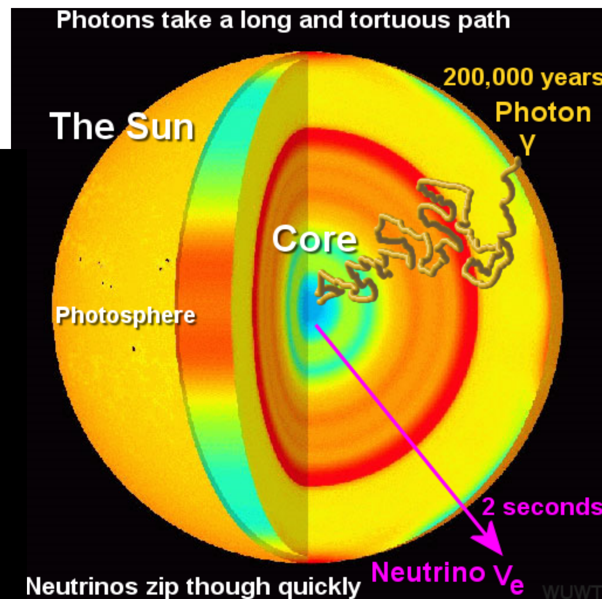


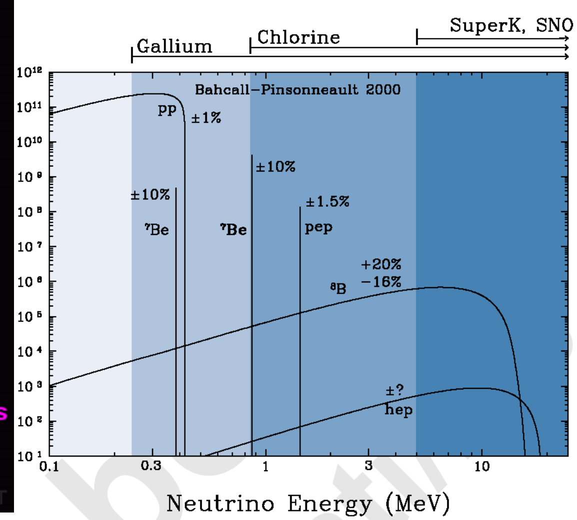
"...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation.."

Bahcall and Davis, 1964

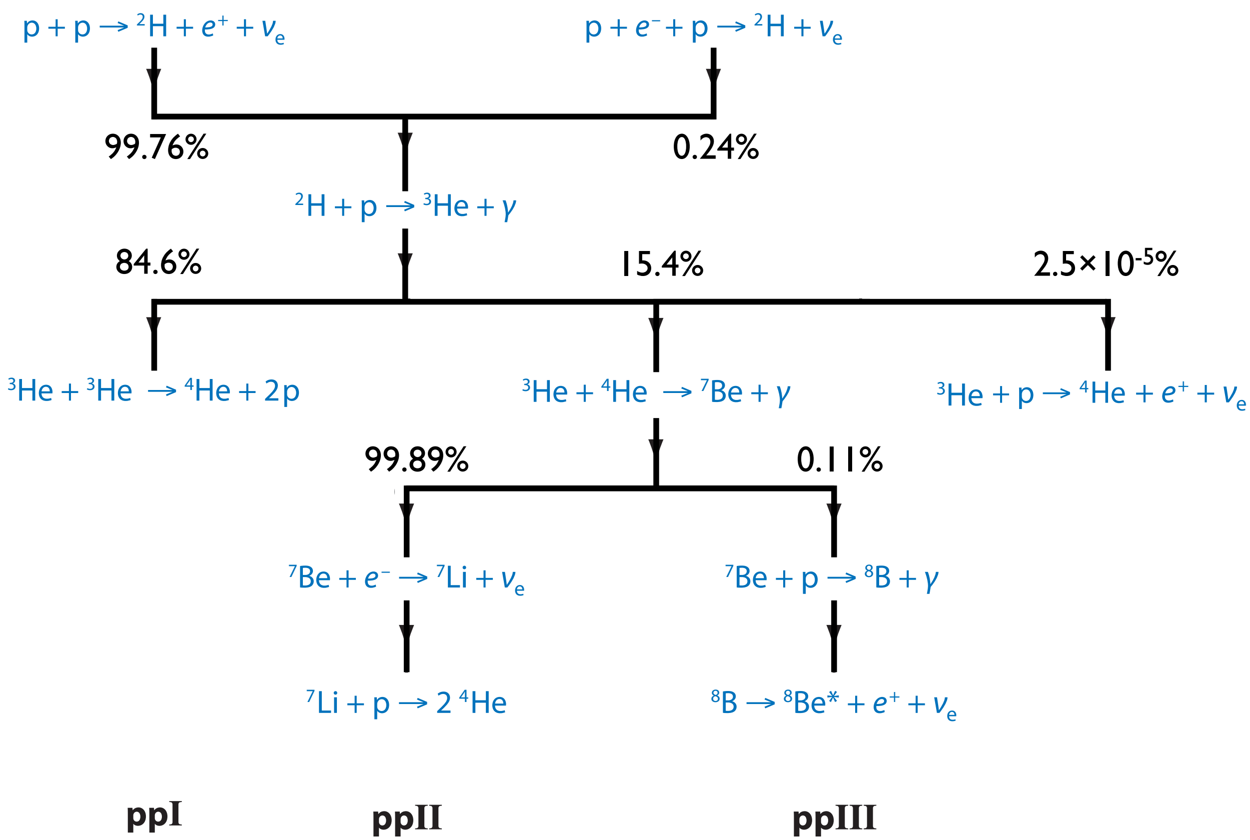
Solar Neutrinos

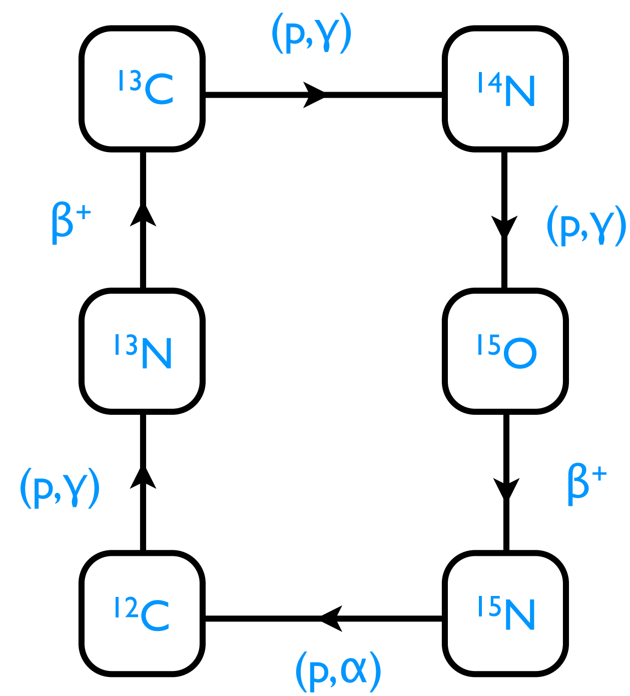






Neutrino producing reactions in the stars

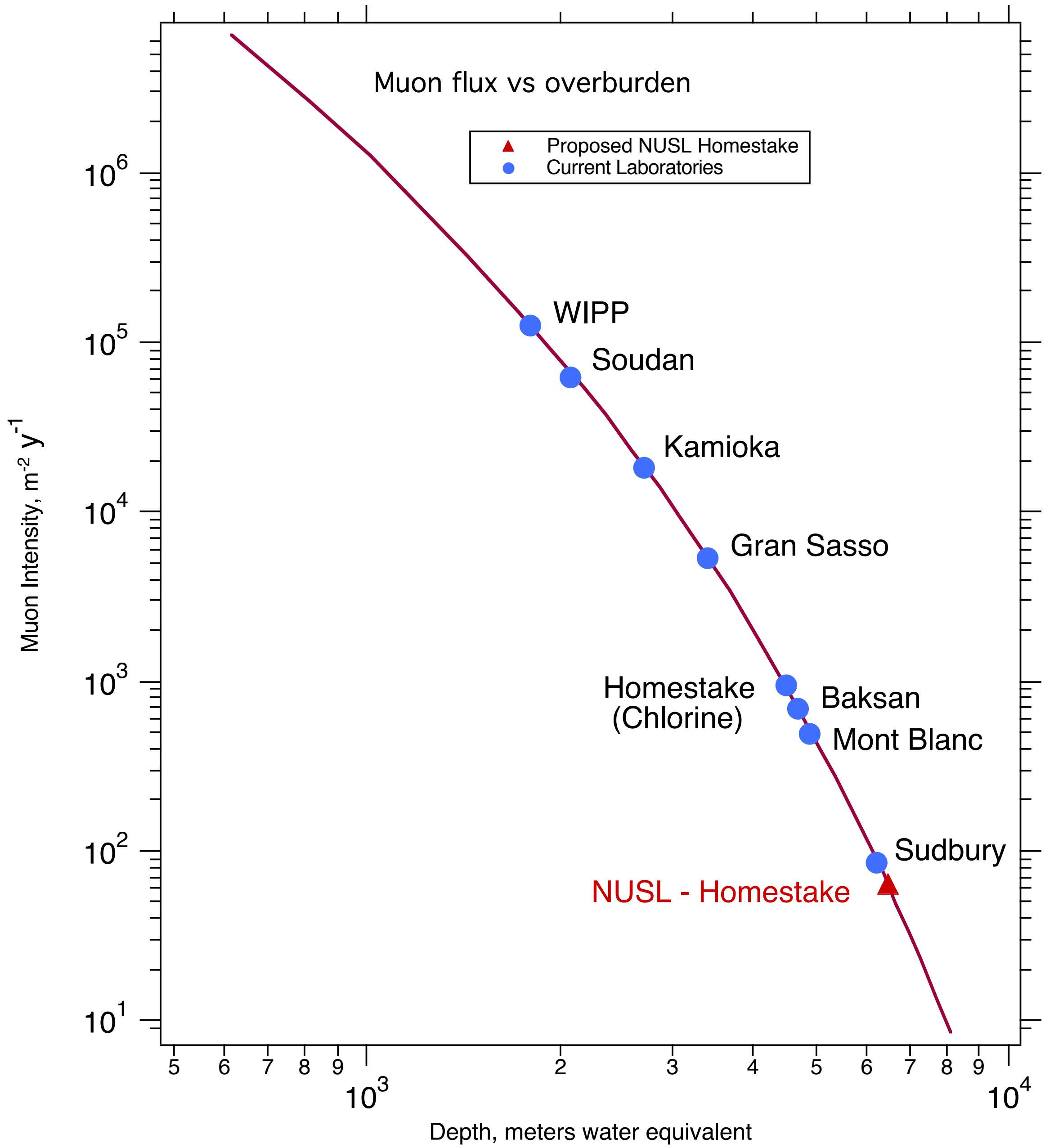


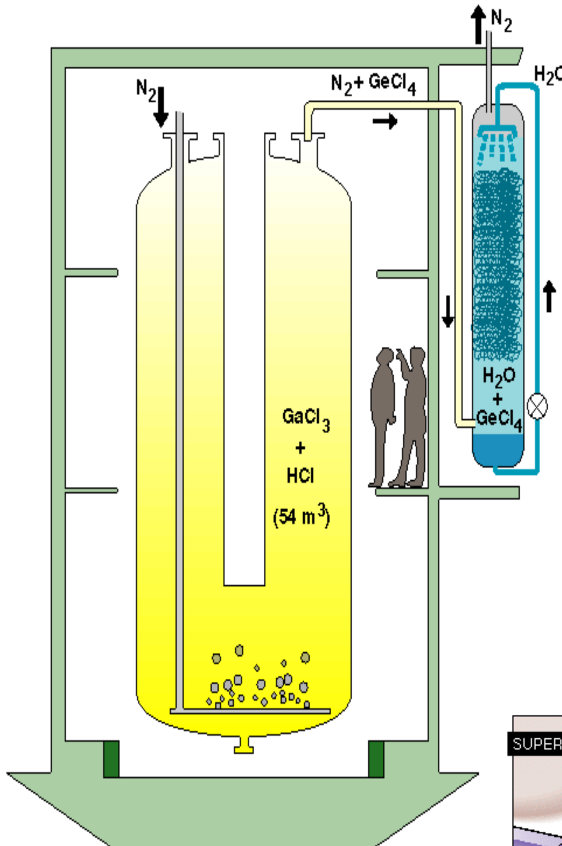


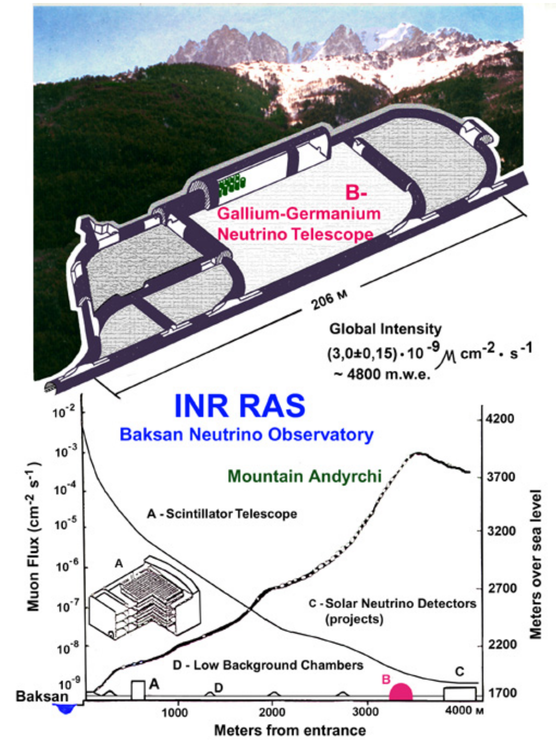
CN cycle

Why do we need to go deep underground to look at the Sun?

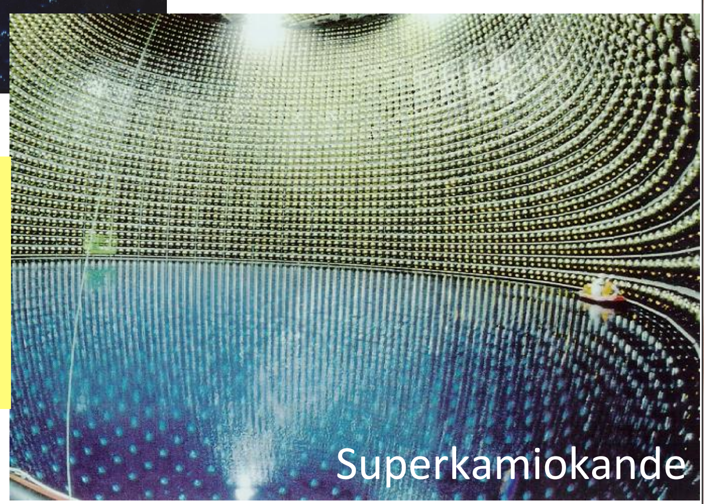
Because the neutrinos interact only weakly. Cosmic ray flux incident to Earth's surface overwhelms this tiny rate. You need to go underground to filter that background.

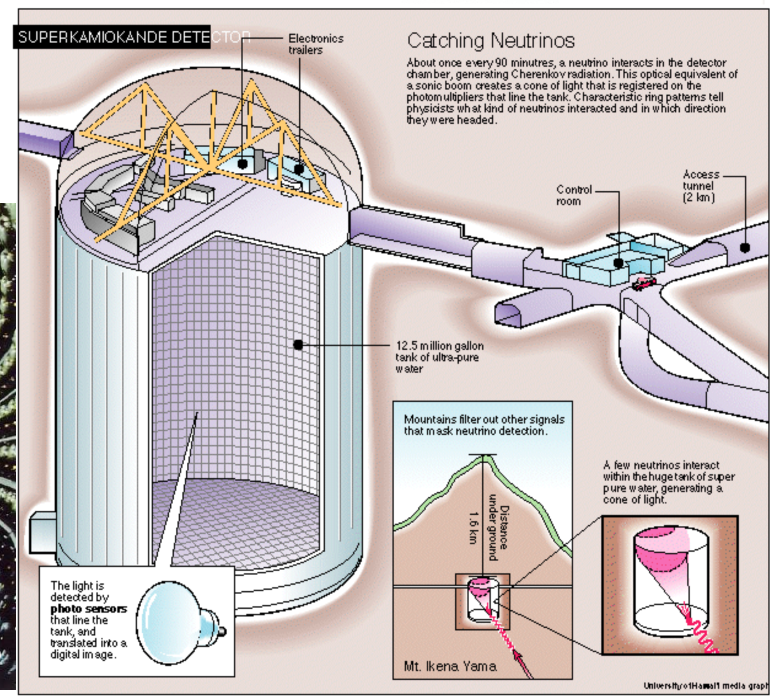


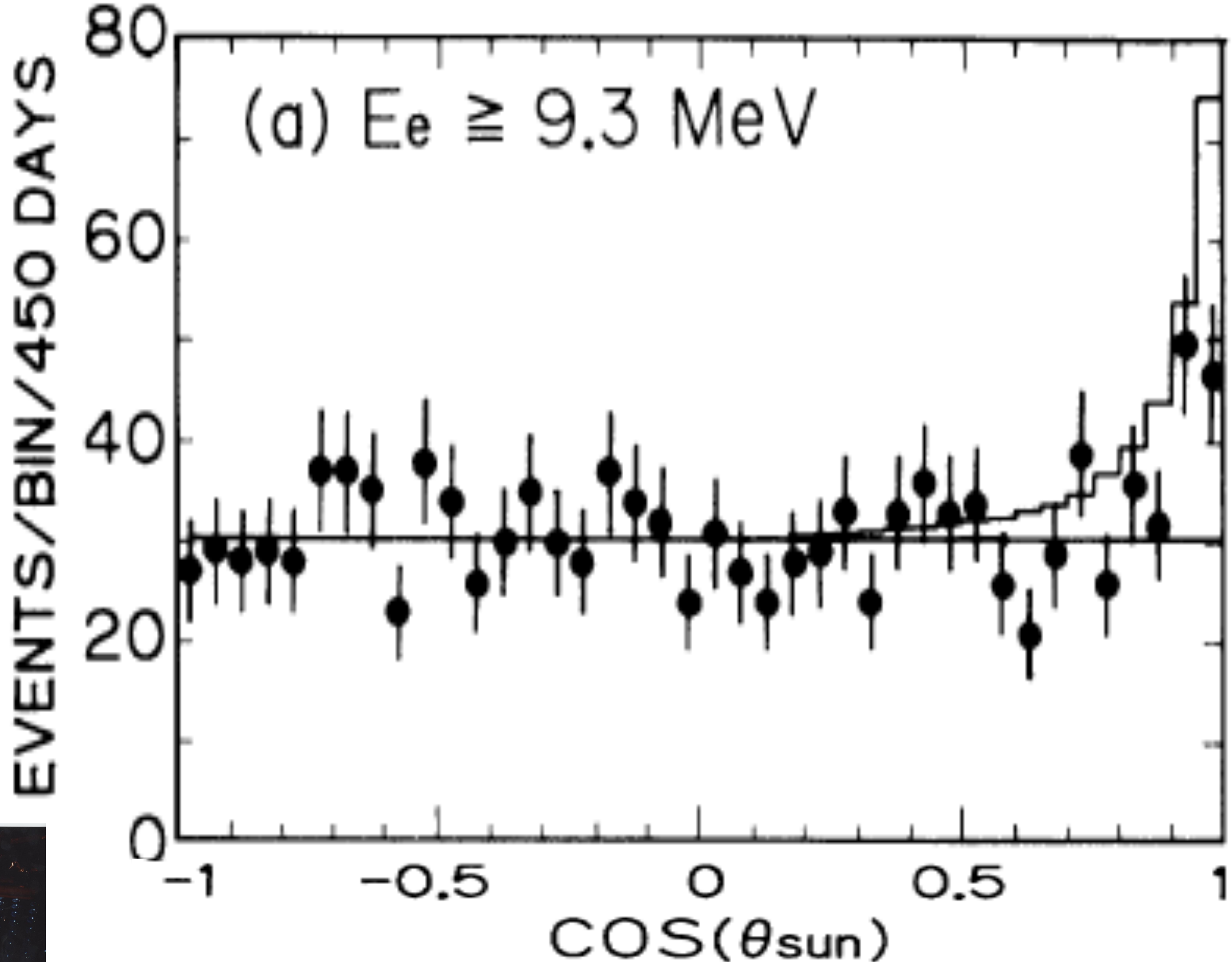


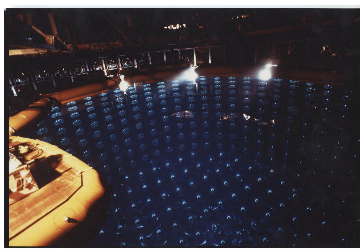


Solar neutrino experiments



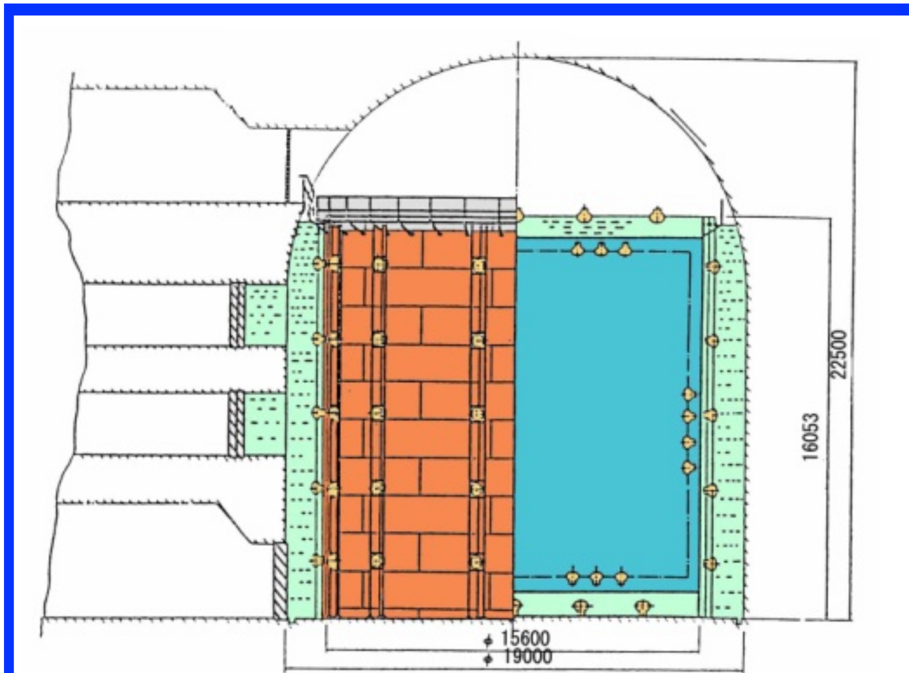




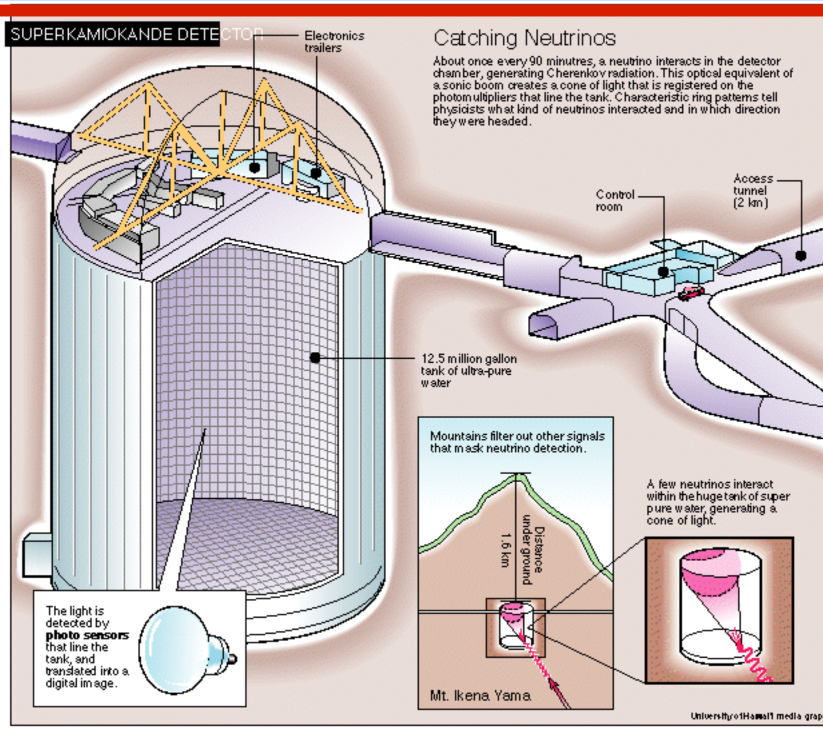


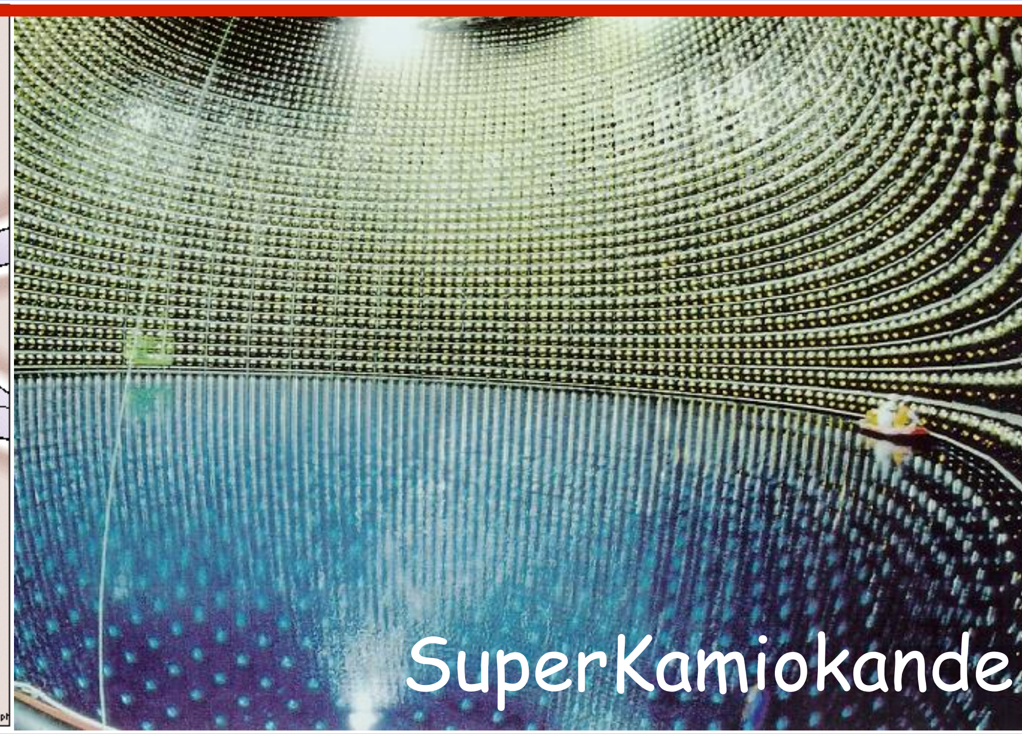
A historic plot: Kamiokande (1987-1988)

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

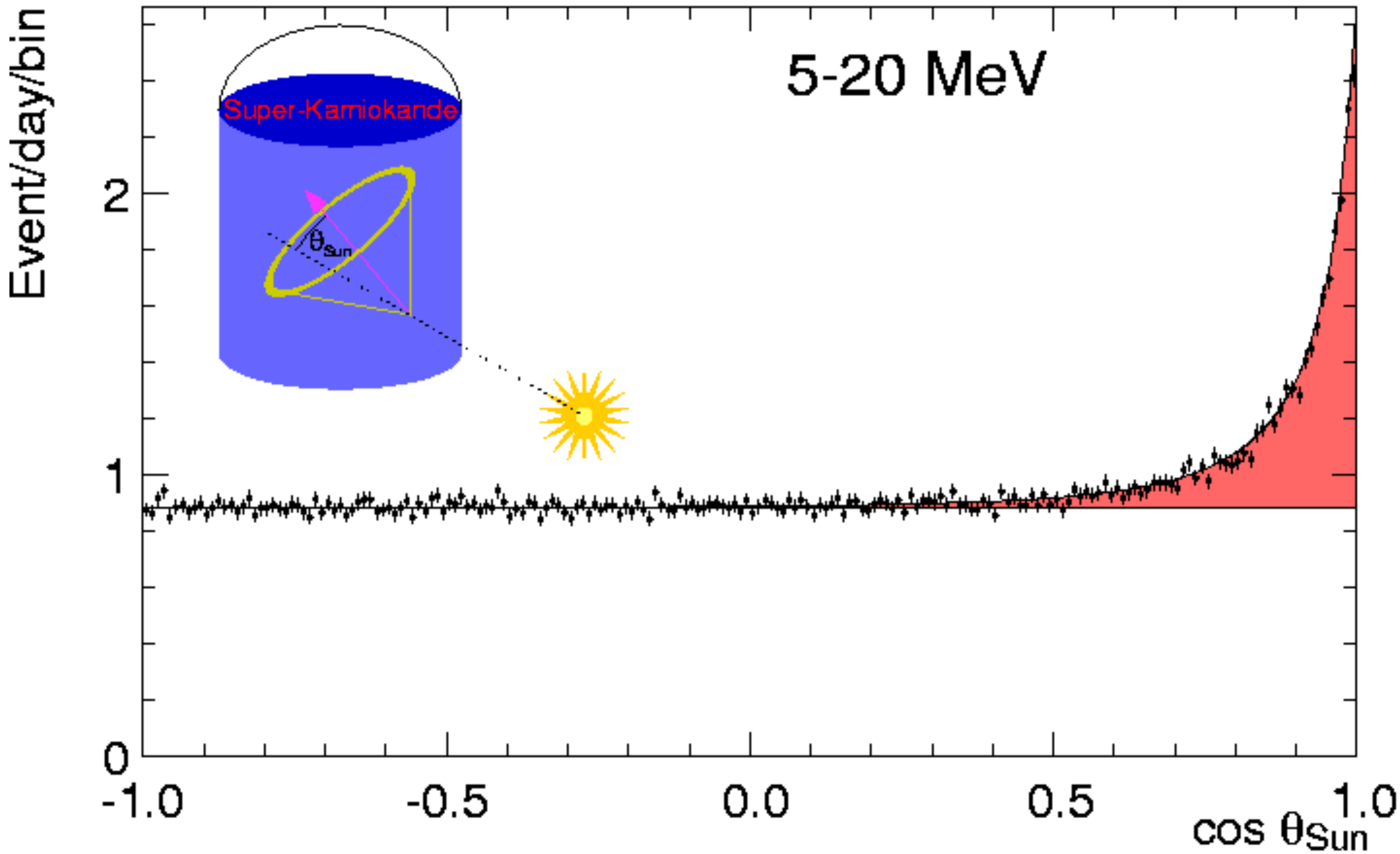

22500
16053
ϕ 15600
ϕ 19000


Kamiokande

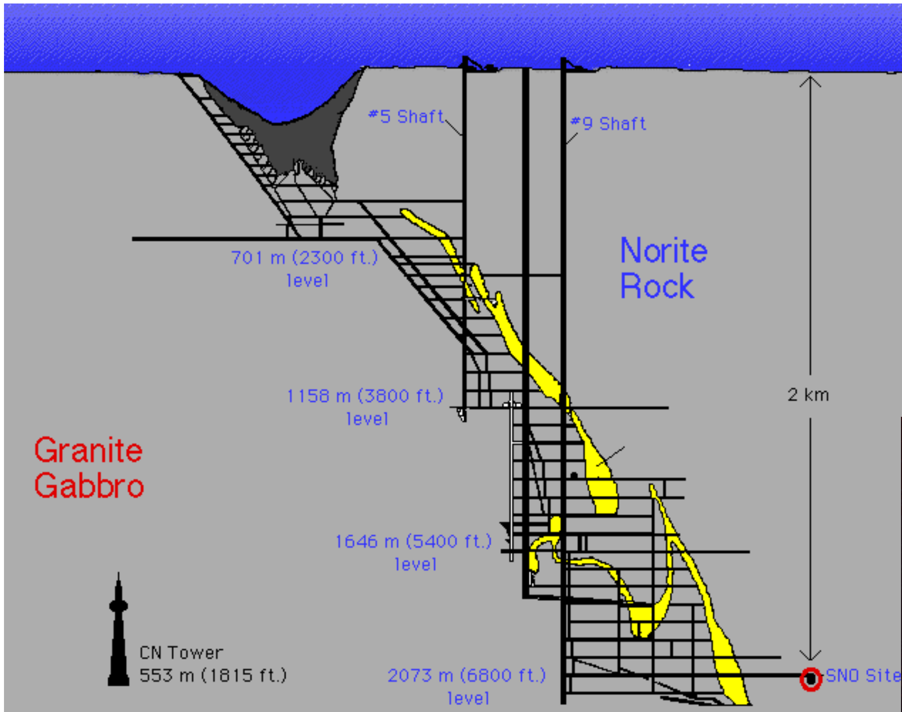

SUPERKAMIOKANDE DETECTOR
Electronics trailers
Catching Neutrinos
About once every 90 minutres, a neutrino interacts in the detector chamber, generating Cherenkov radiation. This optical equivalent of a sonic boom creates a cone of light that is registered on the photomultipliers that line the tank. Characteristic ring patterns tell physicists what kind of neutrinos interacted and in which direction they were headed.
Control room
Access tunnel (2 km)
12.5 million gallon tank of ultra-pure water
Mountains filter out other signals that mask neutrino detection.
Distance under ground
1.6 km
Mt. Ikena Yama
A few neutrinos interact within the huge tank of super pure water, generating a cone of light.
The light is detected by **photo sensors** that line the tank, and translated into a digital image.
University of Hawaii media graph

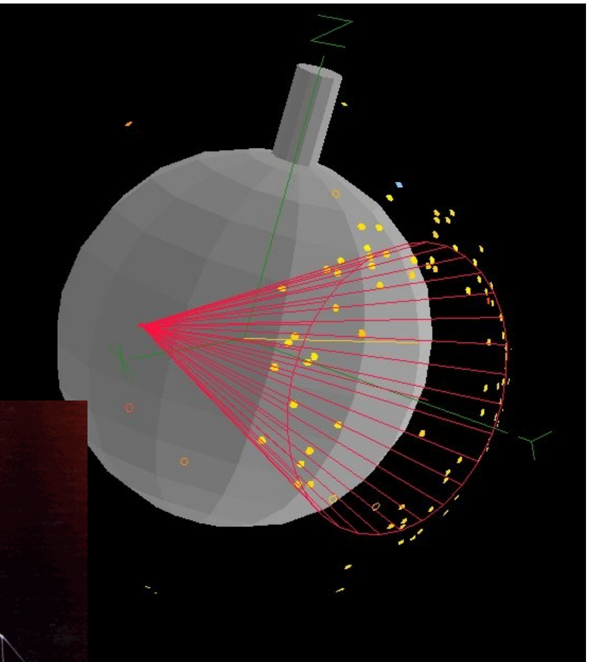

SuperKamiokande

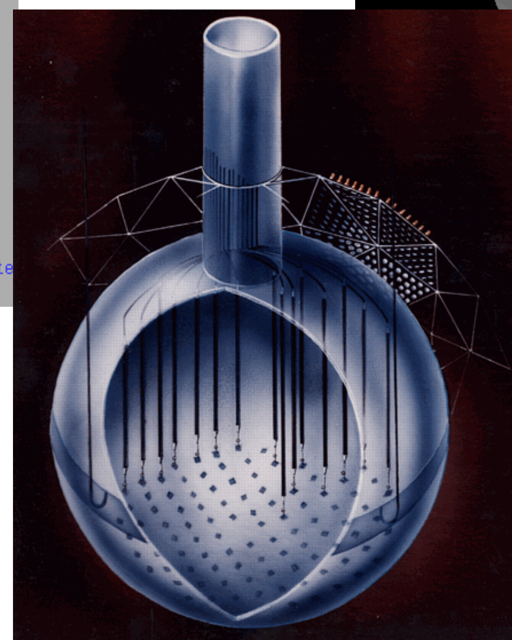
SuperKamiokande-I ^8B solar ν's

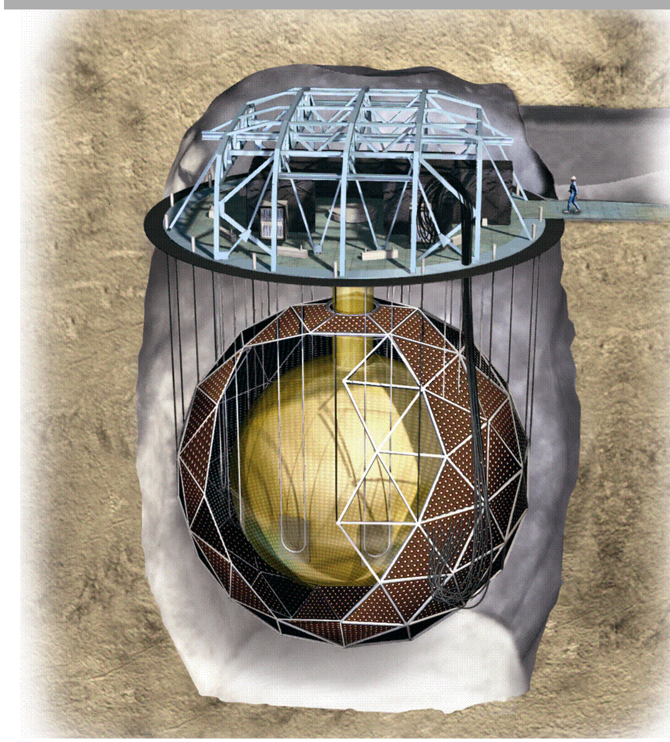


Sudbury Neutrino Observatory (SNO)





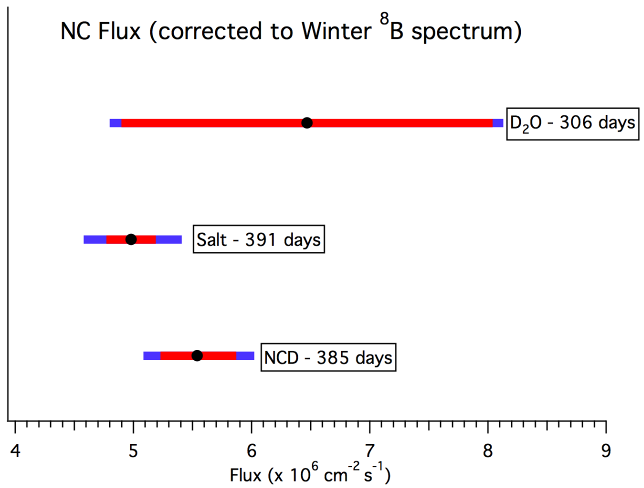


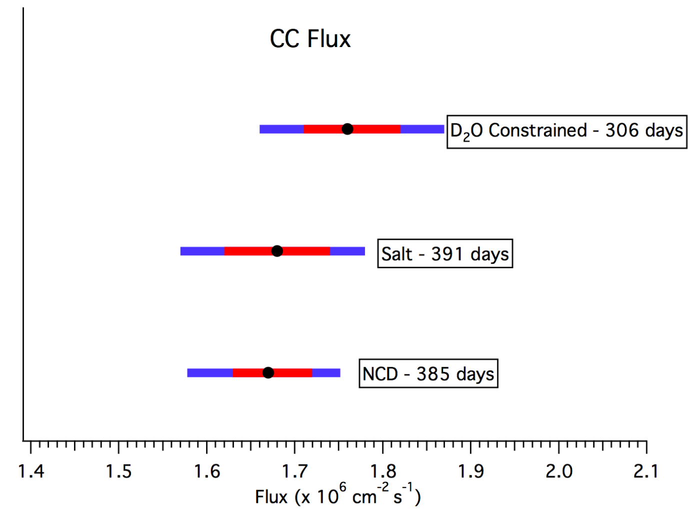


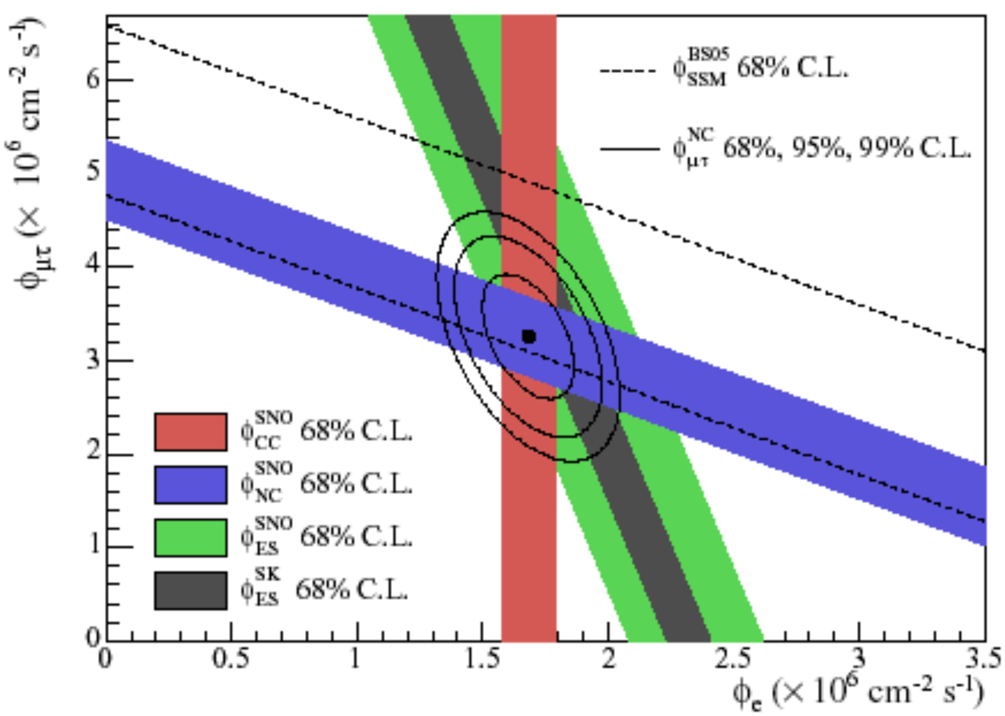
$\nu_e + d \rightarrow p + p + e^-$	CC
$\nu_e + e \rightarrow \nu_e + e$	ES
$\nu_x + d \rightarrow \nu_x + p + n$	NC

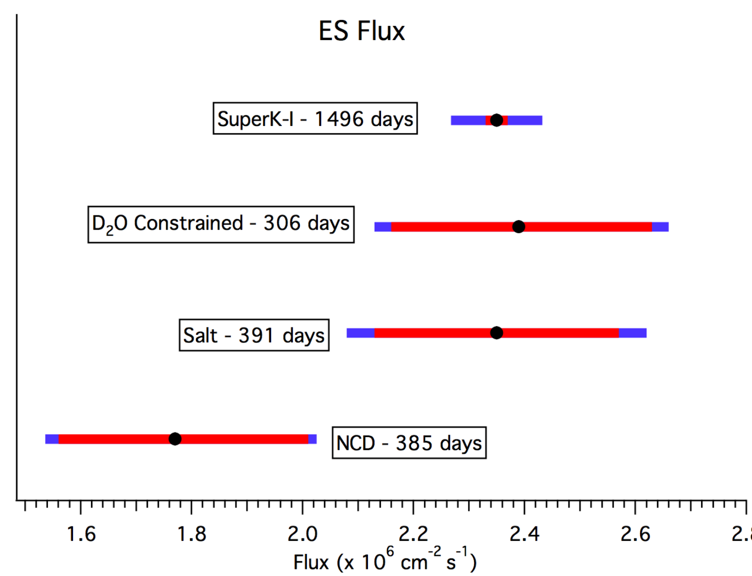
Three phases of SNO

stat   stat + syst

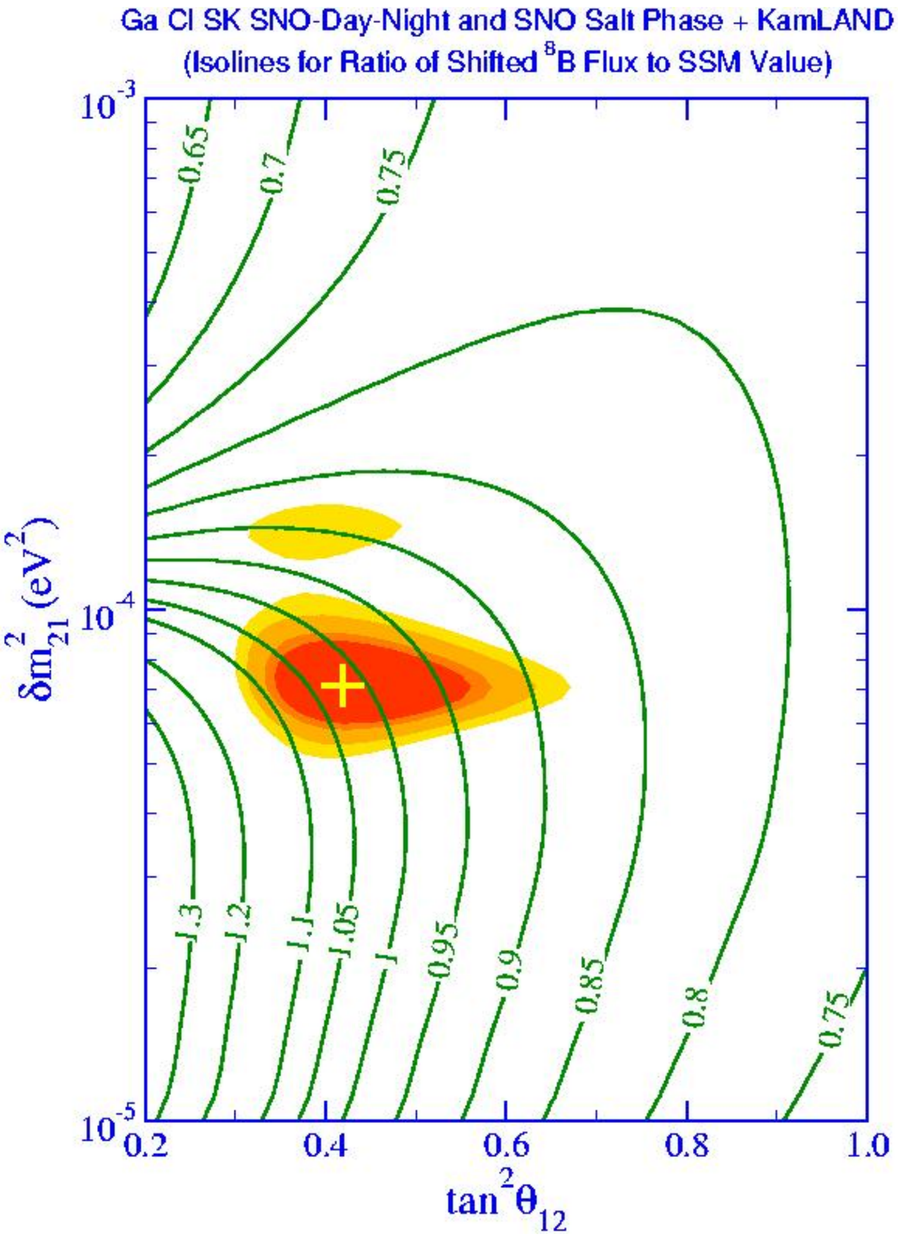


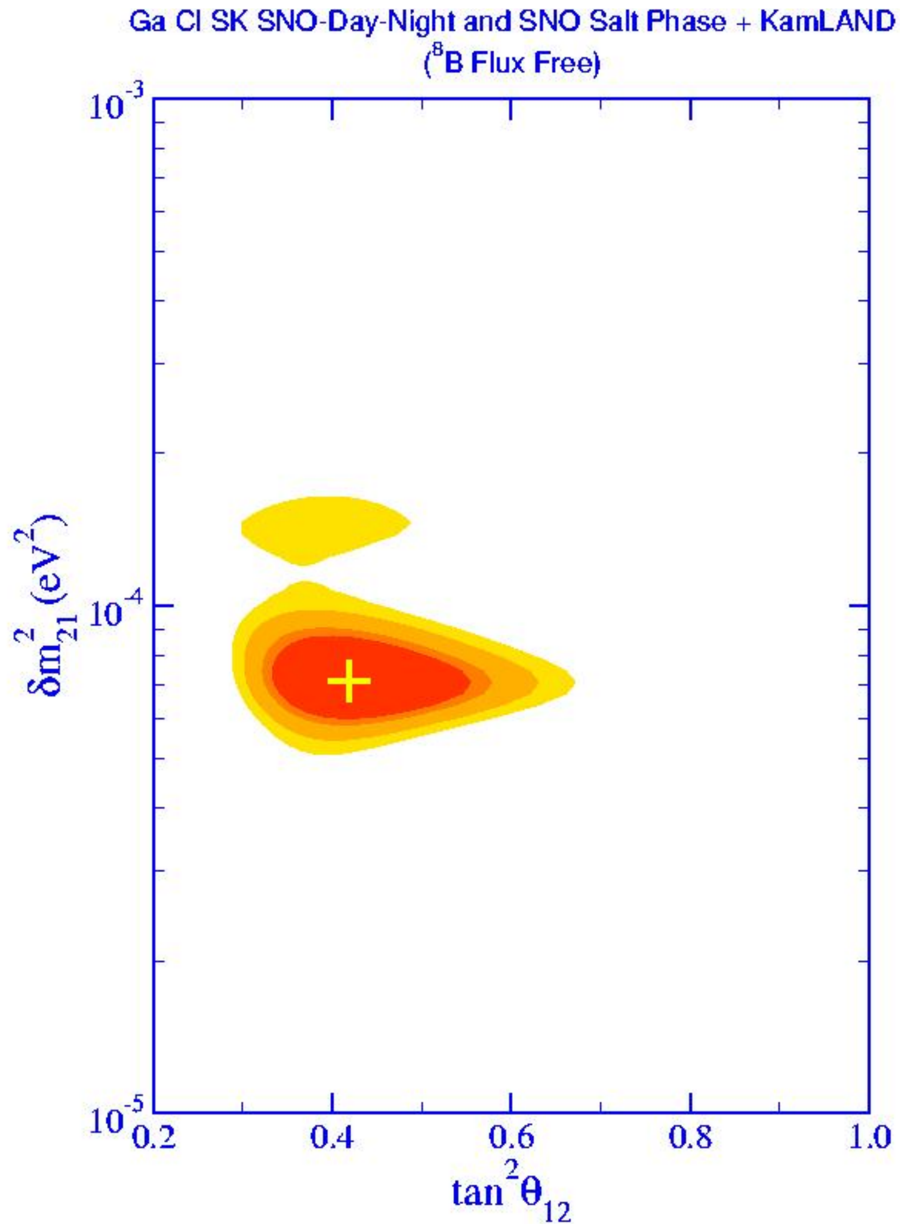






Already first SNO neutral current (salt) results could be analyzed without referring to the Standard Solar Model, A.B.B. & Yuksel, PRD 68, 113002 (2003)

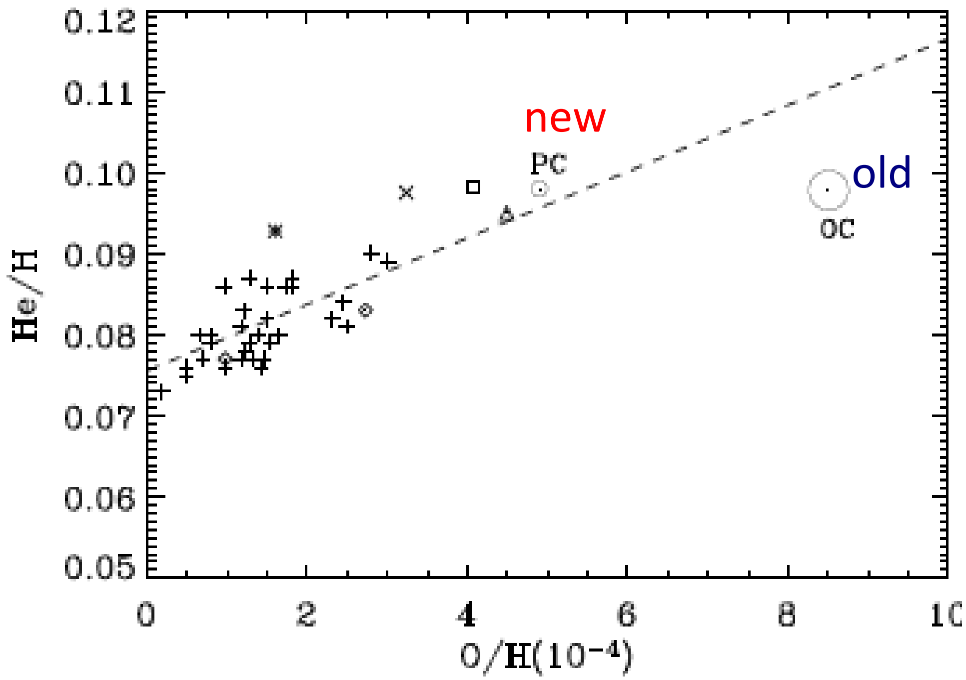




New Solar abundances:

- Asplund *et al.* (AGS09), $(Z/X)_\odot$=0.0178
- Grevesse and Sauvel (GS98), $(Z/X)_\odot$=0.0229

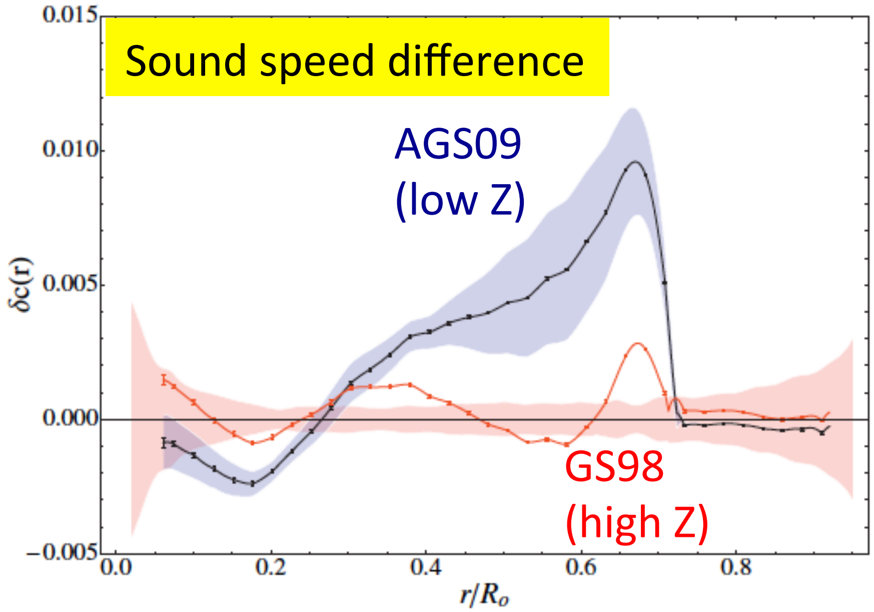
This fixes some old puzzles



Sun is no longer an "odd" star enriched in heavy elements!

Old ^{8}B neutrino flux = 4x10^6 cm^{-2}s^{-1}
New ^{8}B neutrino flux = 5.31x10^6 cm^{-2}s^{-1}

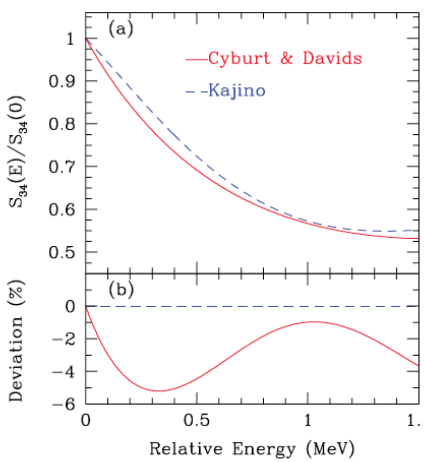
But creates new ones!



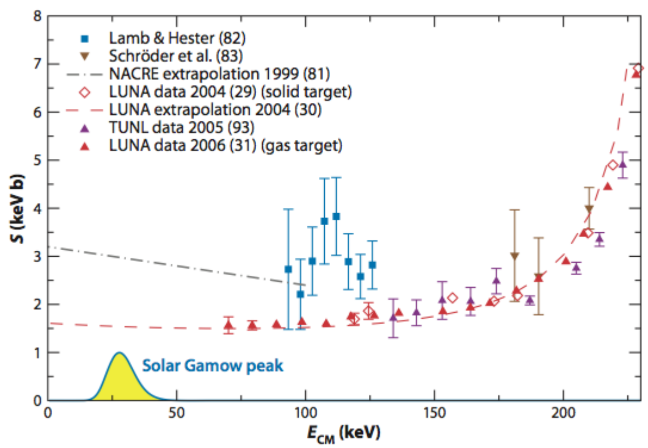
There is mismatch between the surface and the interior of the Sun!

SSM Error Budget

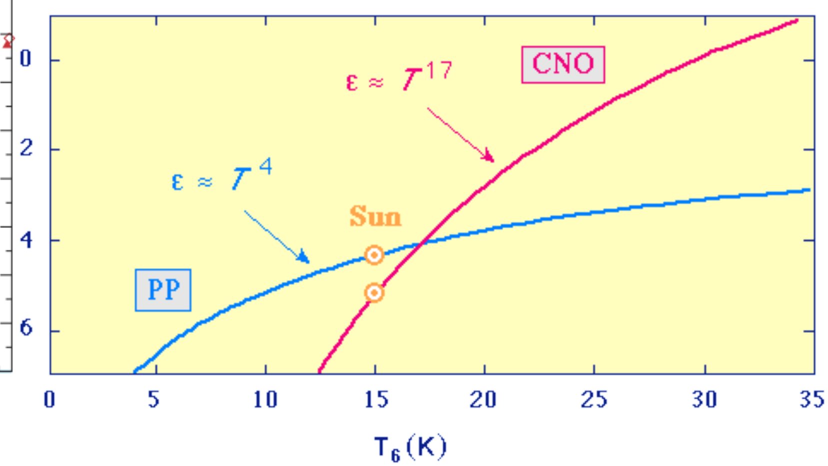
Source	Percentage Error
Diffusion coefficient of SSM	2.7%
Nuclear rates [mainly $^7Be(p,\gamma)^8B$ and $^{14}N(p,\gamma)^{15}O$]	9.9%
Neutrinos and weak interaction (mainly θ_{12})	3.2%
Other SSM input parameters	0.6%



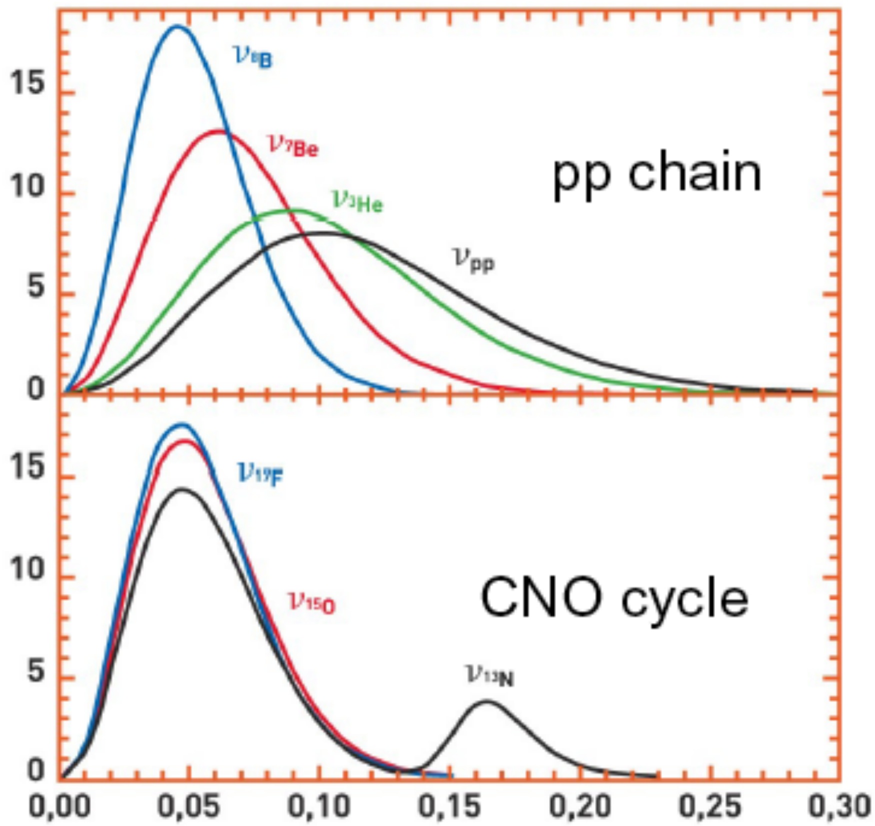
$^3He(\alpha,\gamma)^7Be$

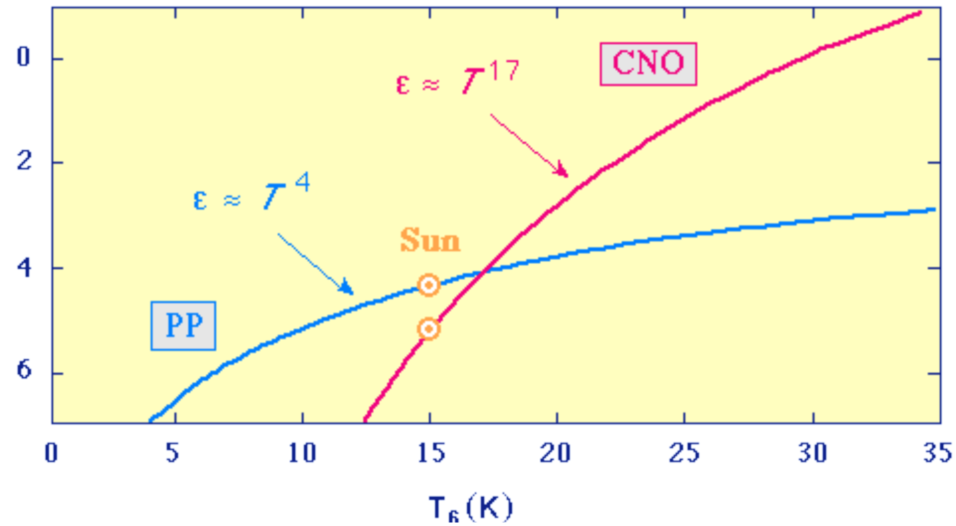


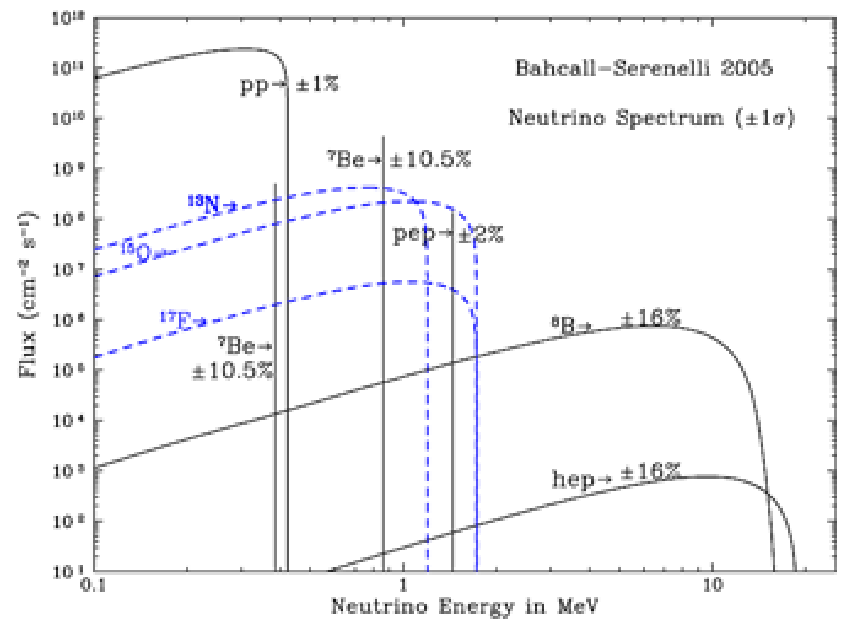
$^{14}N(p,\gamma)^{15}O$



How much does the CNO cycle contribute in the Sun?







In SSM CNO cycle contribute about 0.8% of the neutrino flux. Data are consistent with this. A more precise measurement of the CNO contribution will provide a test of SSM and solar system formation..

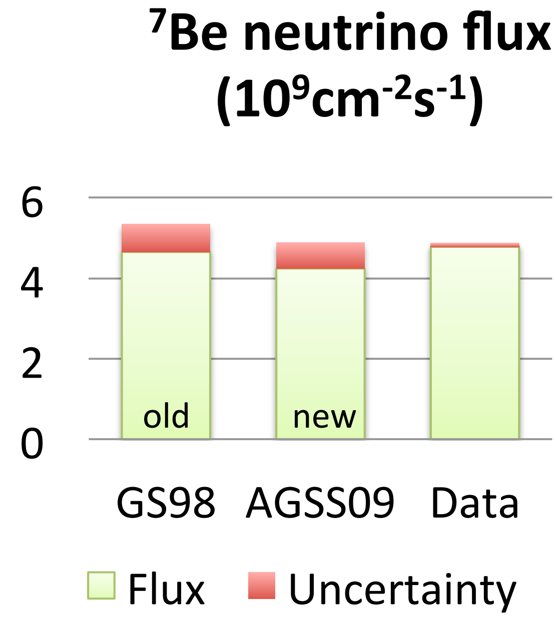
CNO Neutrinos are still not measured!

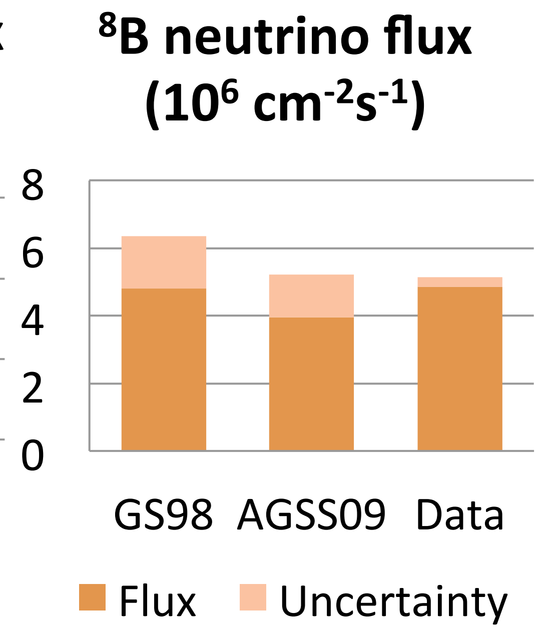
New Solar abundances:

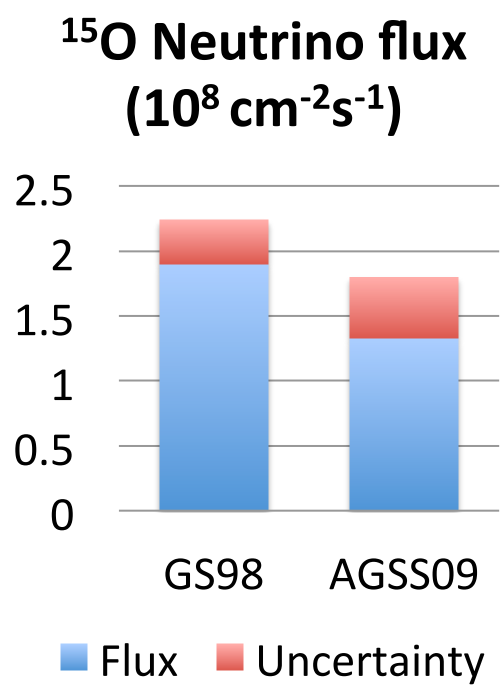
- Asplund *et al.* (AGSS09), $(Z/X)_\odot=0.0178$
- Grevesse and Sauvel (GS98), $(Z/X)_\odot=0.0229$

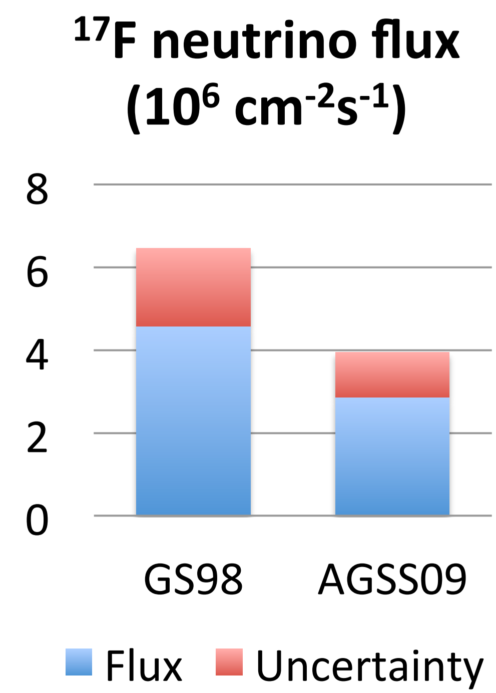
Drastically different!
Open problem in solar physics!

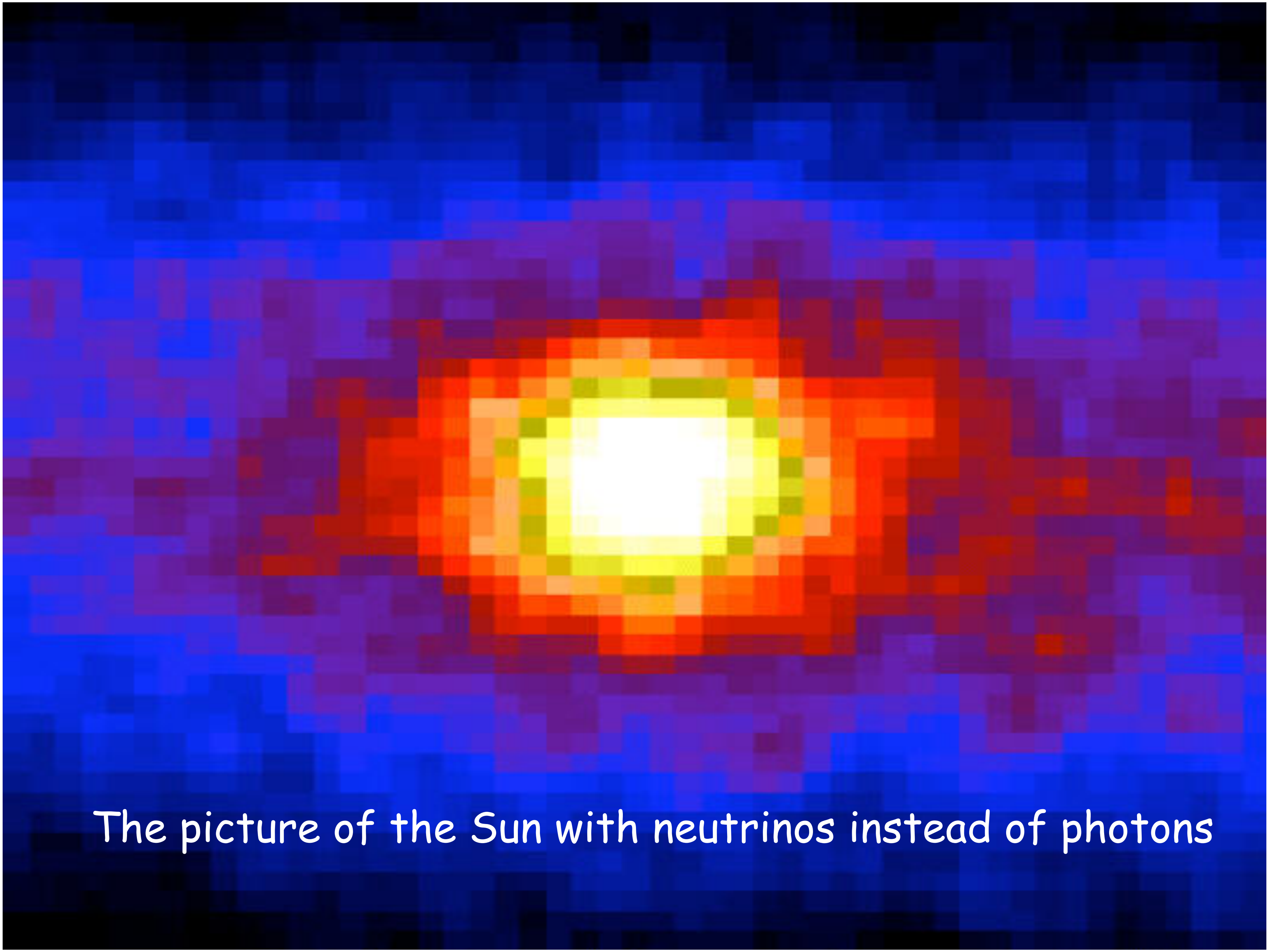
- New Evaluation of the nuclear reaction rates: Adelberger et al. (2011)
- New solar model calculations:Serenelli





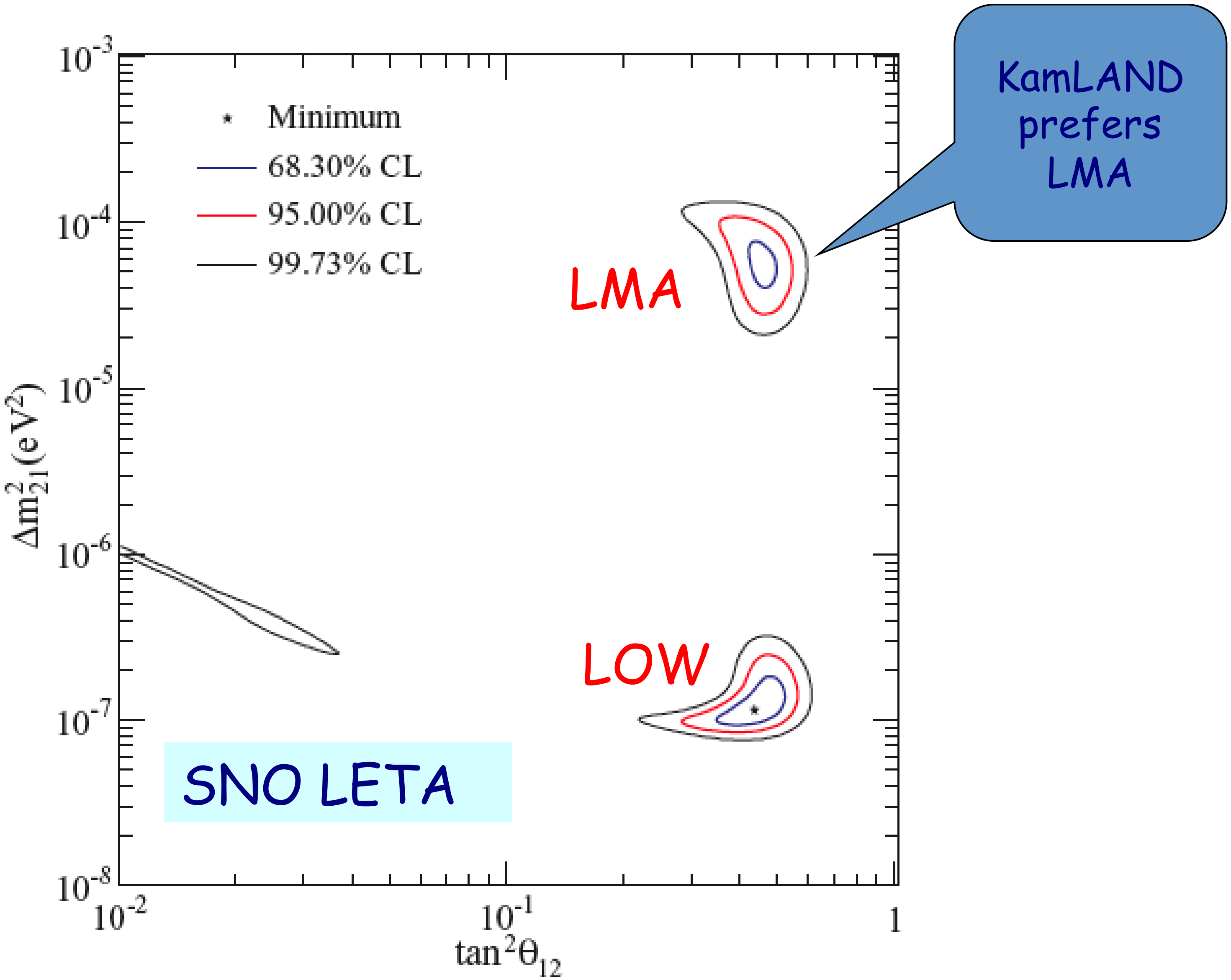


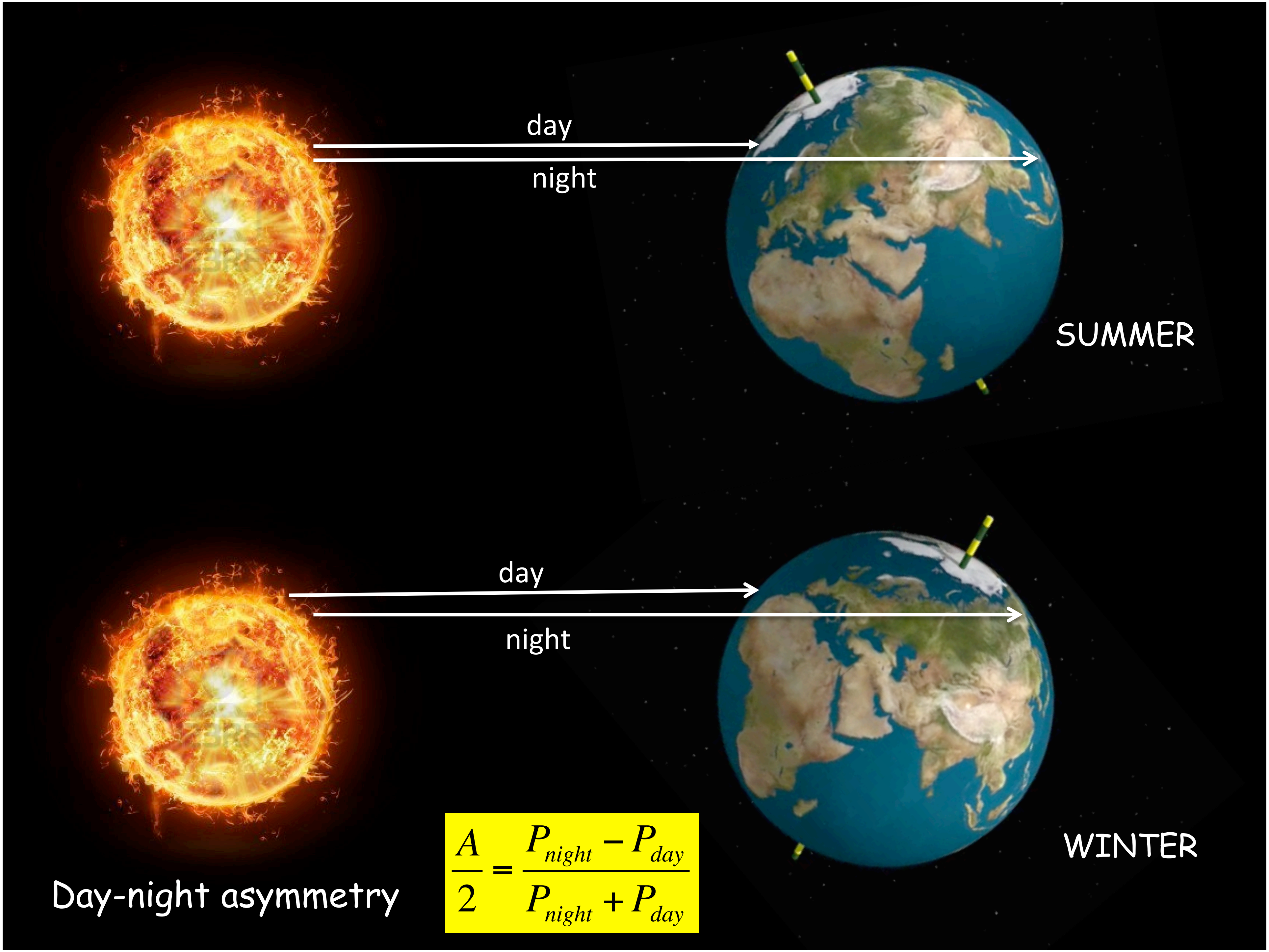




The picture of the Sun with neutrinos instead of photons

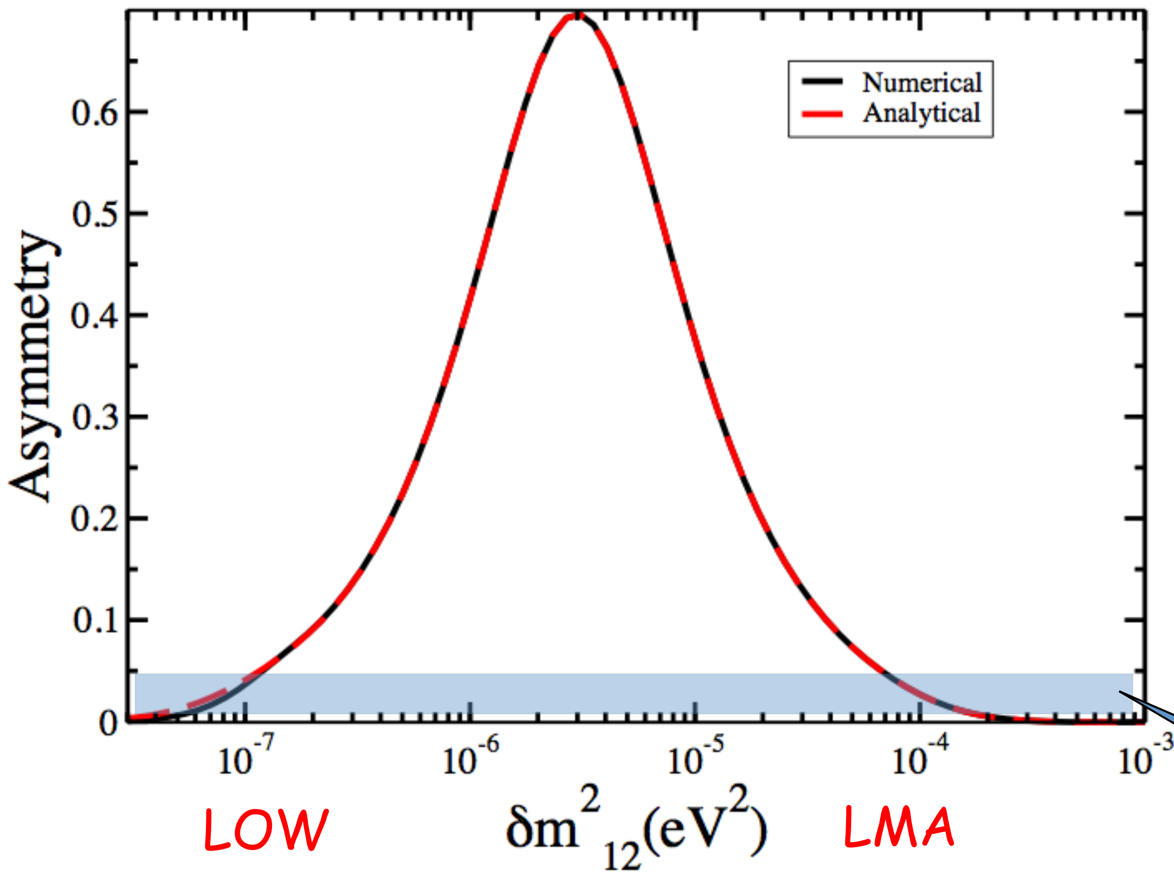
Do antineutrinos mix the same way neutrinos do?





day
night
SUMMER
day
night
WINTER
Day-night asymmetry
$$\frac{A}{2} = \frac{P_{night} - P_{day}}{P_{night} + P_{day}}$$

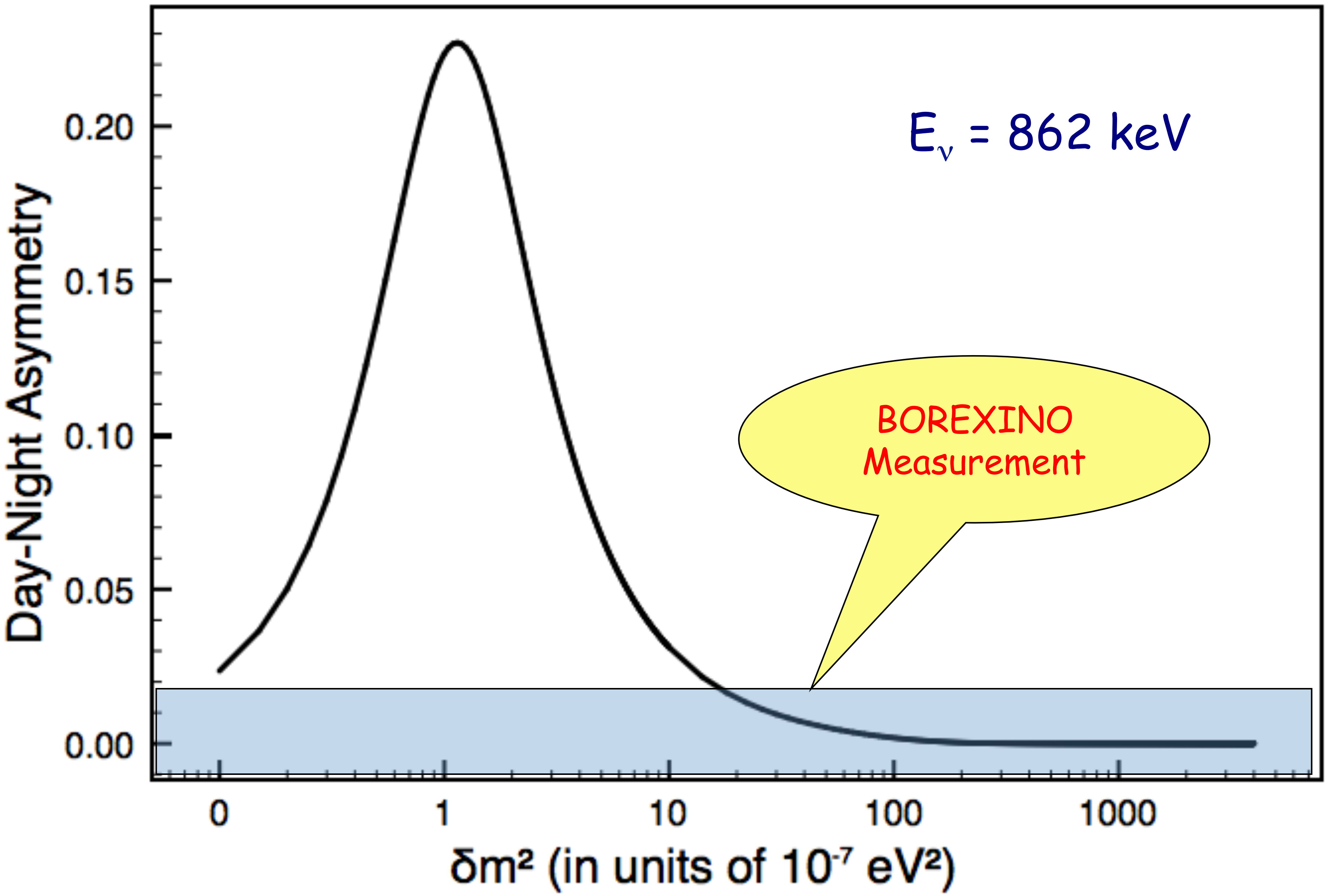
Day-night asymmetry expected at SNO for E_ν=10MeV



SNO LTE

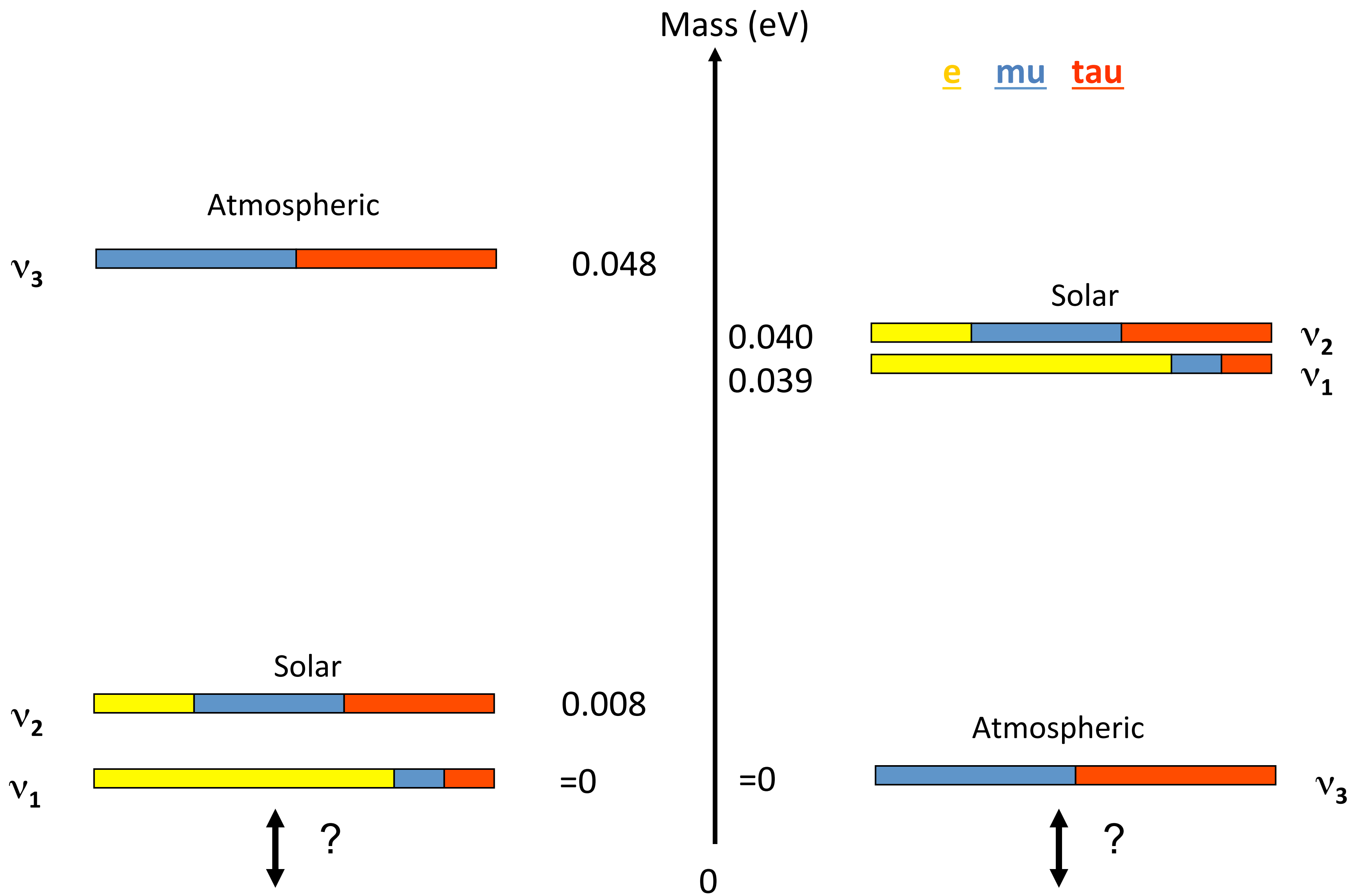
$$\frac{A}{2} = \frac{P_{night} - P_{day}}{P_{night} + P_{day}}$$

Experiments primarily sensitive to higher energy solar neutrinos cannot distinguish between LMA and LOW regions! It is desirable to pick the ***neutrino*** parameter region without KamLAND's ***antineutrinos***.



Day-Night Asymmetry
0.00
0.05
0.10
0.15
0.20
0
1
10
100
1000
δm² (in units of 10⁻⁷ eV²)
E$_\nu$ = 862 keV
BOREXINO
Measurement

Neutrino Masses and Flavor Content



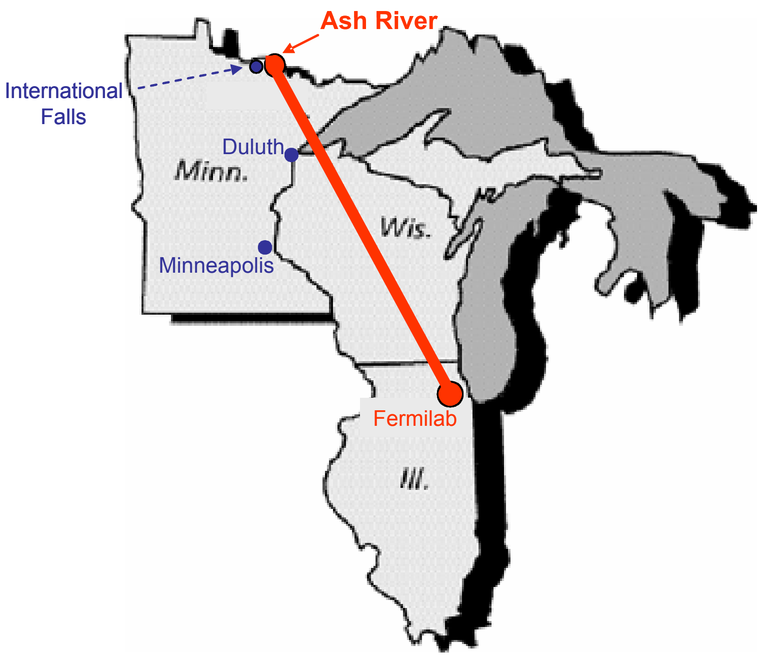
Long-baseline oscillations at GeV energies

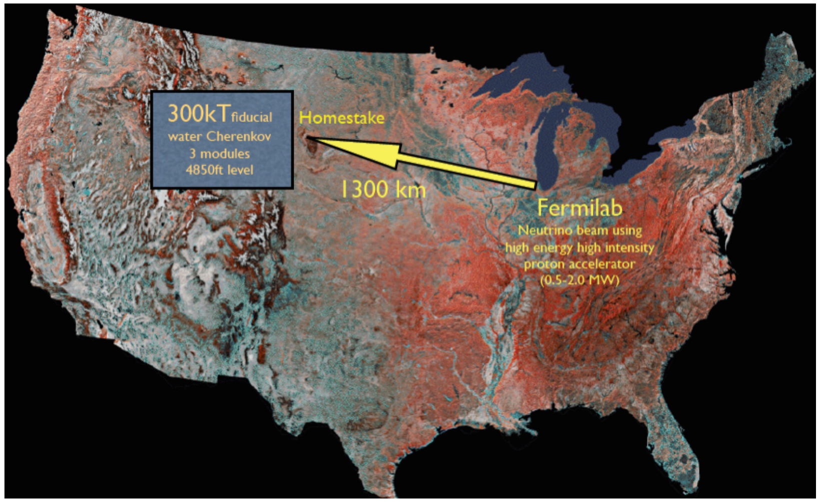
Osc. max. $L \sim E$ + Flux at source $\sim E^2$

Flux (L) = Flux $(L=0)/L^2$

Flux $(L) \sim 1$ + $\sigma \sim E$ (DIS)

Event rate $\sim E$





Matter effects in long-baseline oscillations

Example: two flavors and normal hierarchy

$$P(\nu_e \to \nu_e) = \sin^2 2\theta \left[1 + \frac{4\sqrt{2} G_F N_e}{\delta m^2} \cos 2\theta \right] \sin^2 \left[\left(\frac{\delta m^2}{4E} + \ldots \right) L \right]$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta \left[1 - \frac{4\sqrt{2} G_F N_e}{\delta m^2} \cos 2\theta \right] \sin^2 \left[\left(\frac{\delta m^2}{4E} + \ldots \right) L \right]$$

- This can be used to distinguish normal from inverted hierarchy
- Matter effects mimic CP-violation!
- Matter effects increase with energy, E_{MSW} ~ 10 GeV for Earth's mantle

Typical Appearance Experiment

$$P_{\nu_\mu \to \nu_e} \sim \frac{\sin^2 2\theta_{13} \sin^2 \theta_{23}}{(1 - 2\sqrt{2} G_F N_e E / \delta m^2)^2} \sin^2 \left[\left(\frac{\delta m^2_{31}}{4E} - \frac{G_F N_e}{\sqrt{2}} \right) L \right]$$

$$+\mathcal{O}(g)$$

$$g = \frac{\delta m^2_{21}}{\delta m^2_{31}} \sim 0.03$$

Typical Appearance Experiment

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} &\sim \frac{\sin^2 2\theta_{13} \sin^2 \theta_{23}}{(1 - 2\sqrt{2} G_F N_e E / \delta m^2)^2} \sin^2 \left[\left(\frac{\delta m^2_{31}}{4E} - \frac{G_F N_e}{\sqrt{2}} \right) L \right] \\
- \quad & g \frac{\sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}}{(1/2 - 2\sqrt{2} G_F N_e E / \delta m^2_{31}) - 1/4} \cos \left(\delta + \frac{\delta m^2_{31} L}{4E} \right) \\
\times \quad & \cos \left(\frac{\delta m^2_{31} L}{4E} \right) \sin \left(\frac{G_F N_e L}{\sqrt{2}} \right) \sin \left[\left(\frac{\delta m^2_{31}}{4E} - \frac{G_F N_e}{\sqrt{2}} \right) L \right] \\
+ \quad & \mathcal{O}(g^2)
\end{aligned}
$$

$$
g = \frac{\delta m^2_{21}}{\delta m^2_{31}} \sim 0.03
$$

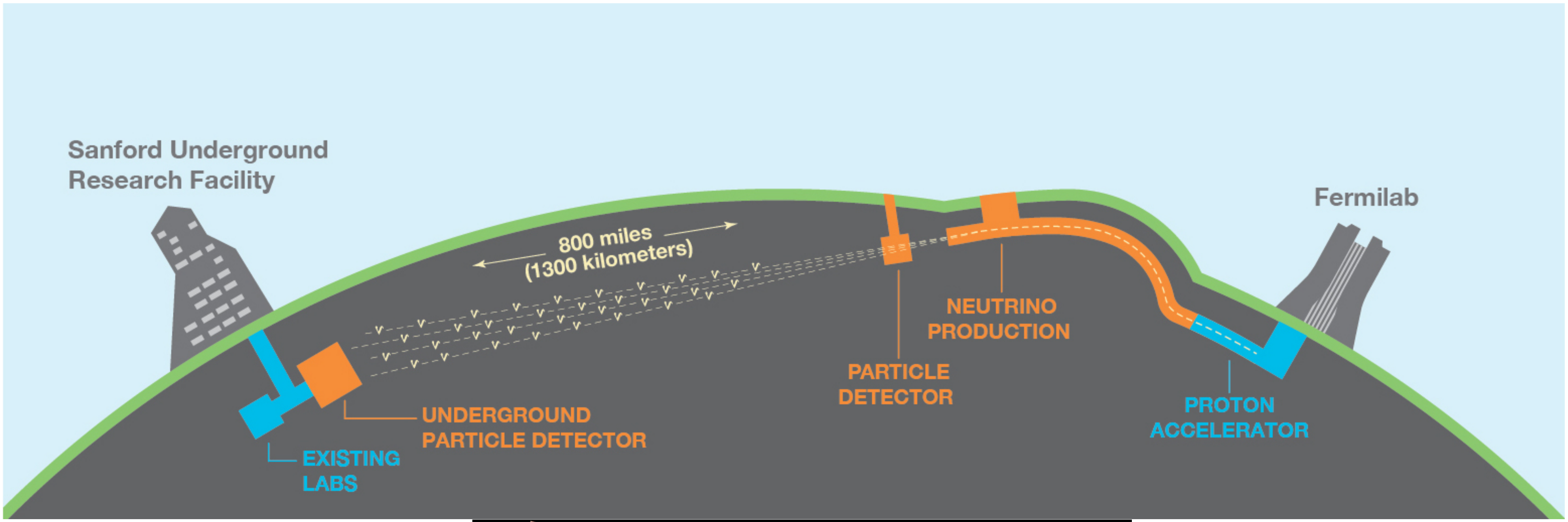
Typical Appearance Experiment

$$
\begin{aligned}
P_{\nu_\mu\to\nu_e} \sim\ & \frac{\sin^2 2\theta_{13}\sin^2\theta_{23}}{(1-2\sqrt{2}G_F N_e E/\delta m^2)^2}\sin^2\left[\left(\frac{\delta m^2_{31}}{4E}-\frac{G_F N_e}{\sqrt{2}}\right)L\right] \\
- \ & g\frac{\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}}{(1/2-2\sqrt{2}G_F N_e E/\delta m^2_{31})-1/4}\cos\left(\delta+\frac{\delta m^2_{31}L}{4E}\right) \\
\times \ & \cos\left(\frac{\delta m^2_{31}L}{4E}\right)\sin\left(\frac{G_F N_e L}{\sqrt{2}}\right)\sin\left[\left(\frac{\delta m^2_{31}}{4E}-\frac{G_F N_e}{\sqrt{2}}\right)L\right] \\
+ \ & \mathcal{O}(g^2)
\end{aligned}
$$

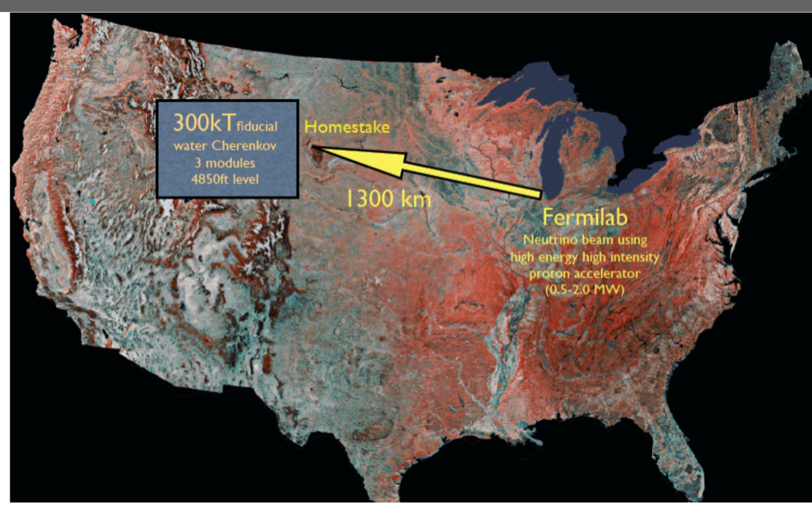
Is equal to
zero for
the magic baseline

$$g=\frac{\delta m^2_{21}}{\delta m^2_{31}}\sim 0.03$$

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



The flagship experiment…



CP-violation

$$T_{23}T_{13}T_{12} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij} \qquad s_{ij} = \sin\theta_{ij}$$

$$i\frac{\partial}{\partial t}\begin{pmatrix} \psi_e \\ \tilde{\psi}_\mu \\ \tilde{\psi}_\tau \end{pmatrix} = \left[T_{13}T_{12} \begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix} T_{12}^\dagger T_{13}^\dagger + \begin{pmatrix} V_{e\mu} & 0 & 0 \\ 0 & s_{23}^2 V_{\tau\mu} & -c_{23}s_{23}V_{\tau\mu} \\ 0 & -c_{23}s_{23}V_{\tau\mu} & c_{23}^2 V_{\tau\mu} \end{pmatrix} \right] \begin{pmatrix} \psi_e \\ \tilde{\psi}_\mu \\ \tilde{\psi}_\tau \end{pmatrix}$$

$$\tilde{\psi}_\mu = \cos\theta_{23}\psi_\mu - \sin\theta_{23}\psi_\tau$$

$$\tilde{\psi}_\tau = \sin\theta_{23}\psi_\mu + \cos\theta_{23}\psi_\tau$$

$$V_{e\mu} = 2\sqrt{2}G_F N_e \left[1 + O\left(\alpha \frac{m_\mu}{m_W}\right)^2 \right]$$

$$V_{\tau\mu} = -\frac{3\sqrt{2}\alpha G_F}{\pi \sin^2\theta_W}\left(\frac{m_\tau}{m_W}\right)^2 \left[\left(N_p + N_n\right)\log\frac{m_\tau}{m_W} + \left(\frac{N_p}{2} + \frac{N_n}{3}\right) \right]$$

We need to solve an evolution equation

$$i\frac{\partial}{\partial t}U = HU$$

If we ignore $V_{\tau\mu}$ it is easy to show that the CP-violating phase factorizes:

$$U(\delta) = SU(\delta = 0)S^{\dagger} \qquad S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}$$

This factorization still holds when collective oscillations are included, but breaks down if there is spin-flavor precession

This factorization implies that neither

$$P\left(\nu_e \rightarrow \nu_e\right)$$

nor

$$P\left(\nu_\mu \rightarrow \nu_e\right) + P\left(\nu_\tau \rightarrow \nu_e\right)$$

depend on the CP-violating phase δ.

If the ν_μ and ν_τ luminosities are the same at the neutrinosphere of a core-collapse supernova, this factorization implies that ν_e and ν_e fluxes observed at terrestrial detectors will not be sensitive to the CP-violating phase! To see its effects you need to measure ν_μ and ν_τ luminosities separately!

If you see the effects of δ in either charged- or neutral current scattering that may mean any of the following:

- There are new neutrino interactions beyond the standard model operating either within the neutron star or during propagation.
- Standard Model loop corrections (very easy to quantify) are seen.
- There are sterile neutrino states.

Factorization of the CP-violating phase if there are no sterile neutrinos

$$H(\delta) = H_{\nu} + H_{\nu\nu} = \mathbf{S} H(\delta = 0) \mathbf{S}^{\dagger}$$

$$\mathbf{S} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}$$

Holds if neutrino magnetic moment is ignored.

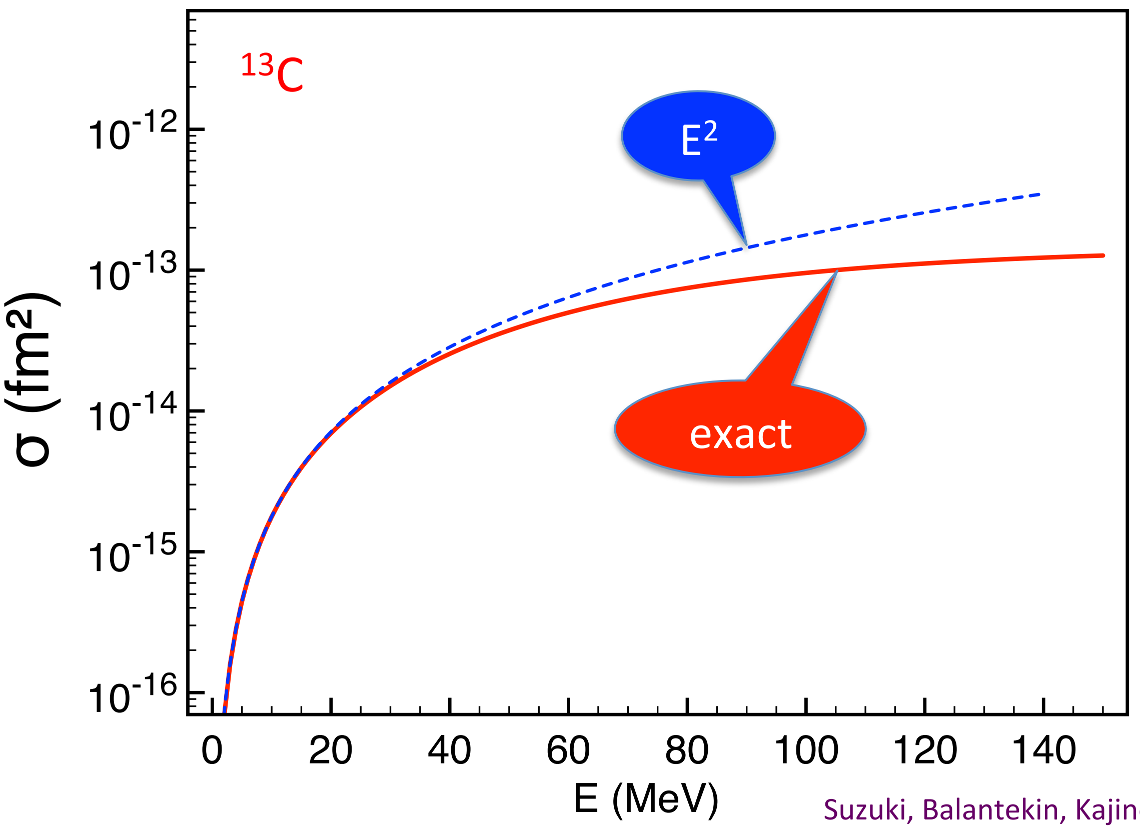
- MSW Hamiltonian: Balantekin, Gava, Volpe, Phys. Lett B662, 396 (2008).
- Collective Hamiltonian in the mean-field approximation: Gava, Volpe, Phys. Rev. D78, 083007 (2008).
- Exact collective Hamiltonian: Pehlivan, Balantekin, Kajino, Phys. Rev. D90, 065011 (2014).

Neutrino Coherent Scattering

$$\nu + A \rightarrow \nu + A$$

$$\frac{d\sigma}{d\cos\theta} = \frac{G_F^2}{8\pi}\left[Z^2\left(4\sin^2\theta_W - 1\right) + N\right]^2 E_\nu^2\left(1+\cos\theta\right)\left[F\left(Q^2\right)\right]^2$$

$$T_{\text{max}} = \frac{2E_\nu^2}{2E_\nu + M}$$



Suzuki, Balantekin, Kajino, Chiba

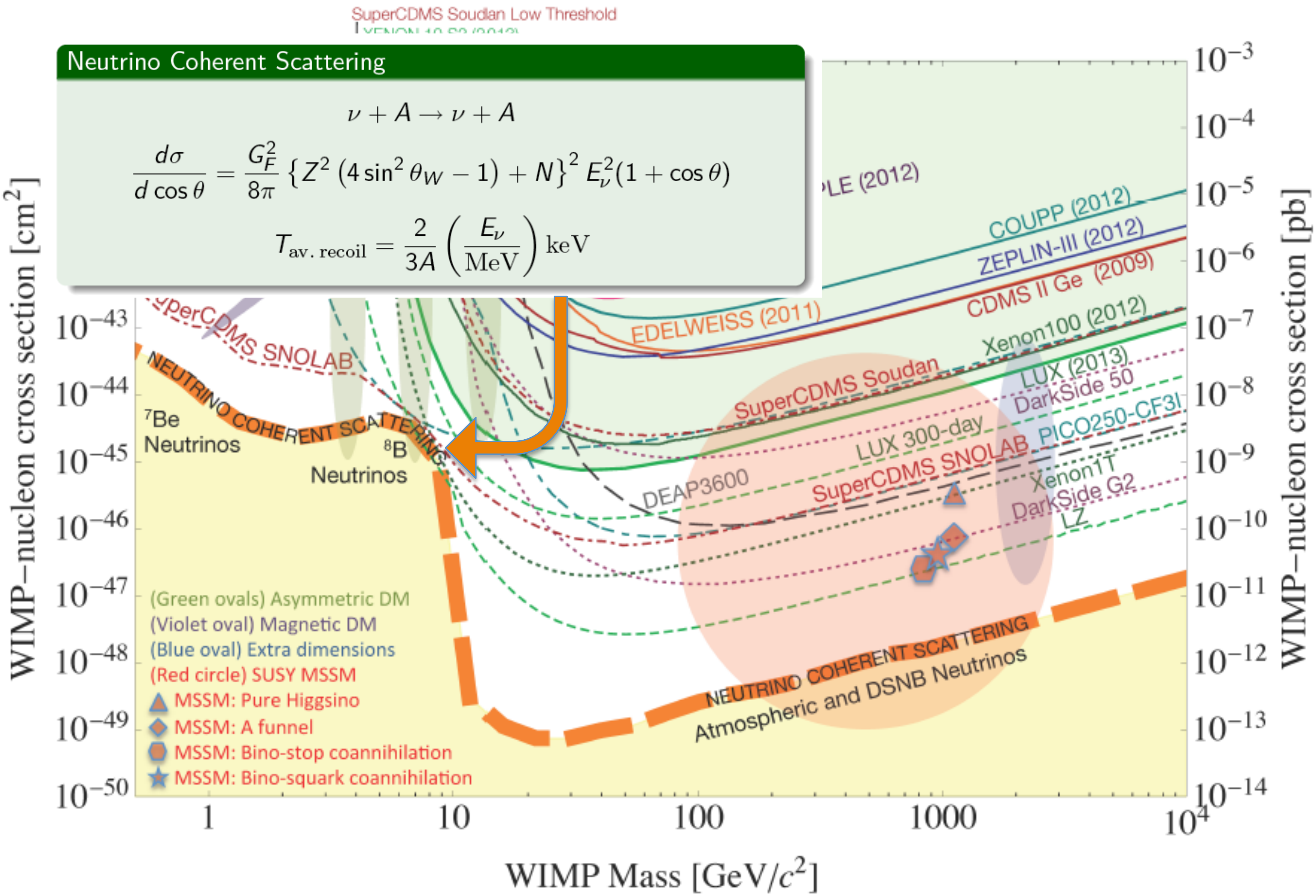
- First calculated by Freedman.
- This reaction is background to the dark matter searches with nuclear targets.
- Nuclear form factors need to be included. McLaughlin, Engel.
- A calculation for scintillators with the state-of-the-art nuclear interactions is shown on the left.

Neutrino Coherent Scattering

$$\nu + A \rightarrow \nu + A$$

$$\frac{d\sigma}{d\cos\theta} = \frac{G_F^2}{8\pi}\left\{Z^2\left(4\sin^2\theta_W - 1\right) + N\right\}^2 E_\nu^2(1+\cos\theta)$$

$$T_{\mathrm{av.\ recoil}} = \frac{2}{3A}\left(\frac{E_\nu}{\mathrm{MeV}}\right)\mathrm{keV}$$



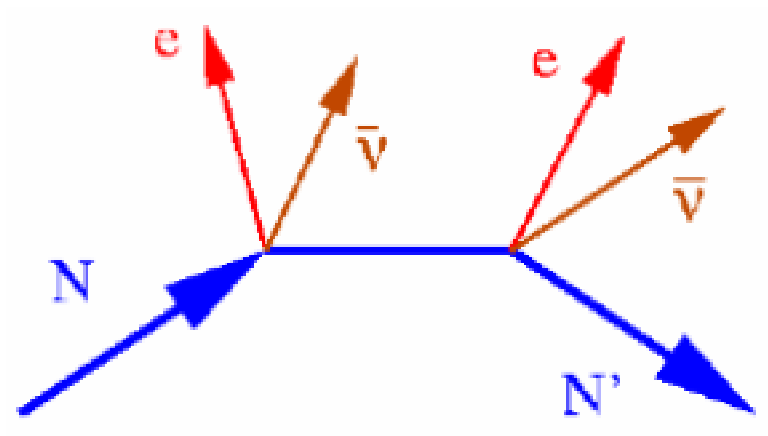
Double Beta Decay

The second order process, where two neutrinos are emitted, is also possible.

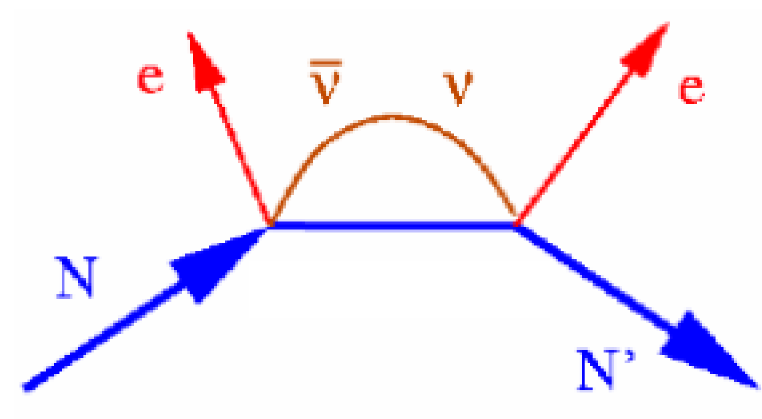
Maria Mayer, 1935

Maria Goeppert *Mayer* was *awarded* the 1963 *Nobel* for the nuclear shell model, the San Diego Union headline read "*San Diego Housewife Wins Nobel Prize*".

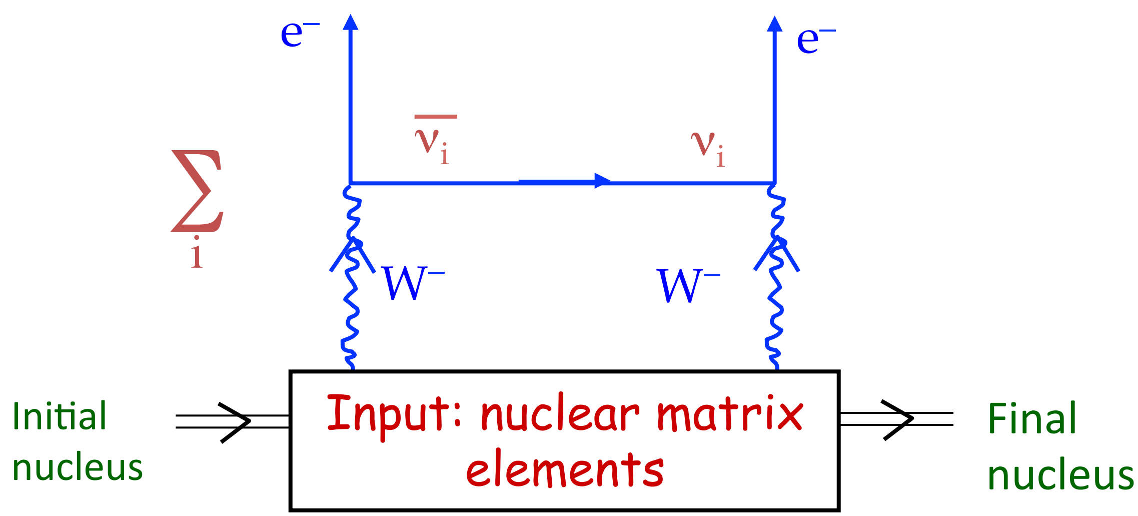
2νββ



0νββ



Majorana nature of the neutrinos permit neutrinoless double beta decay:



Suggestion of neutrinoless double beta decay

Nuovo Cimento, **14**, pp 322-328 (1937)

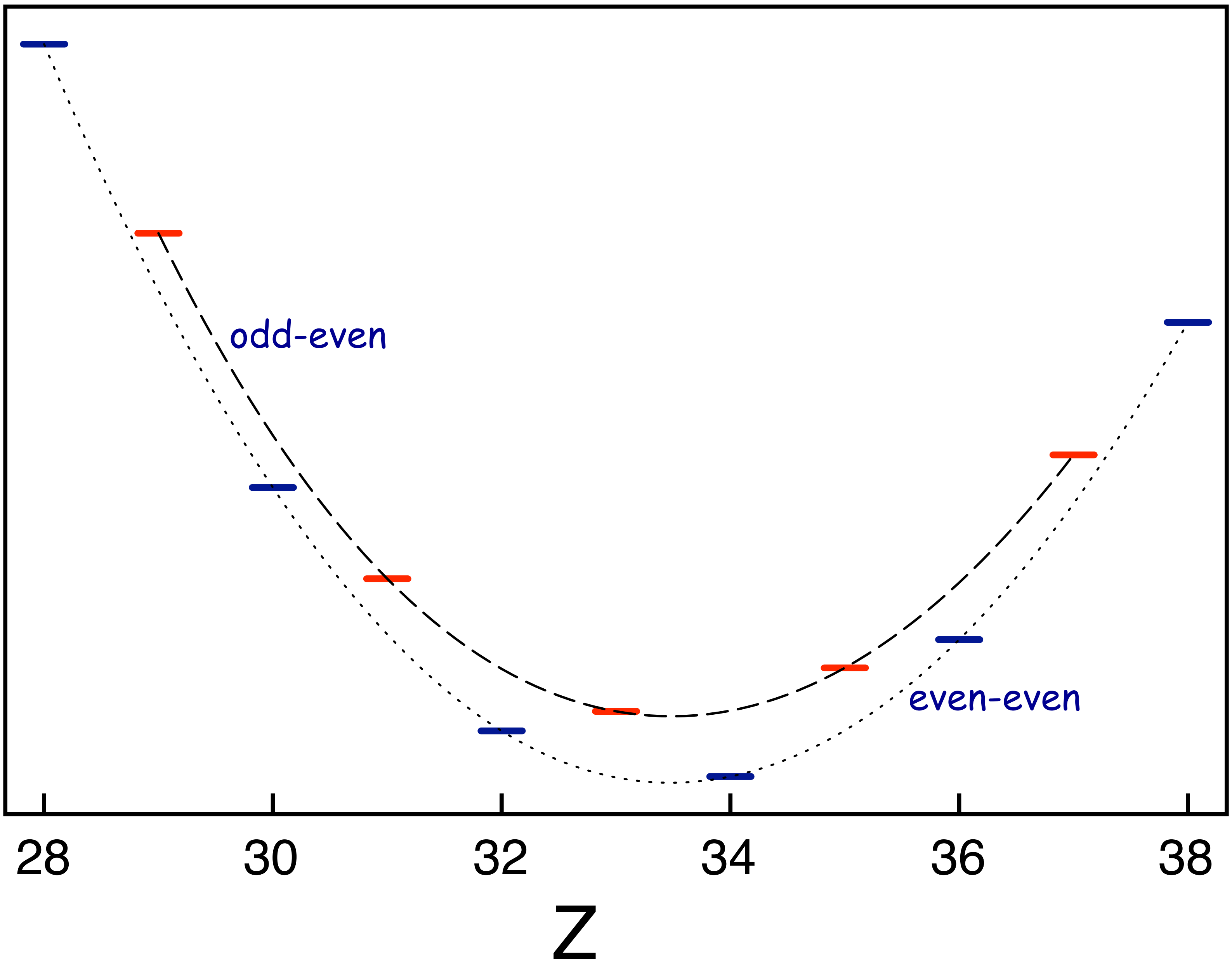
SULLA SIMMETRIA TRA PARTICELLE
E ANTIPARTICELLE

Nota di GIULIO RACAH

Sunto. - *Si mostra che la simmetria tra particelle e antiparticelle porta alcune modificazioni formali nella teoria di* FERMI *sulla radioattività* β, *e che l'identità fisica tra neutrini ed antineutrini porta direttamente alla teoria di* E. MAJORANA.

Summary - This article shows that the symmetry between particles and antiparticles leads some formal amendments in the theory of Fermi β radioactivity, and that the physical identity between neutrinos and antineutrinos leads directly to the theory of E. Majorana.

Pairing gives rise to double beta decay:



Current limits on 0ββ decay

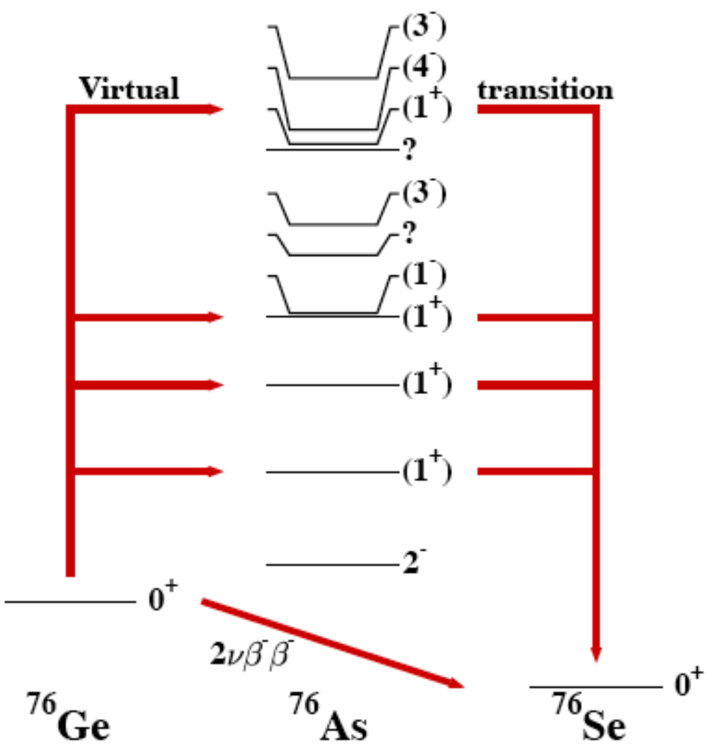
Nucleus	Q-value (MeV)	$T_{1/2}$ (years) limit	$\langle m_\nu \rangle$ (eV) limit
^{48}Ca	4.276	> 1.14 x 10^{22}	< 7.2
^{76}Ge	2.039	> 1.6 x 10^{25}	< 0.33
^{82}Se	2.992	> 1.9 x 10^{23}	< 1.3
^{100}Mo	3.034	> 5.8 x 10^{23}	< 0.8
^{116}Cd	2.804	> 1.7 x 10^{23}	< 1.7
^{128}Te	0.876	> 7.7 x 10^{24}	< 1.1
^{130}Te	2.529	> 3 x 10^{23}	< 0.46
^{136}Xe	2.467	> 4.4 x 10^{23}	< 1.8
^{150}Nd	3.368	> 1.2 x 10^{21}	< 7

$$\langle m_\nu \rangle = \sum_{i=1}^{3} U_{ie}^2 m_i$$

Some measurements of 2ββ decay

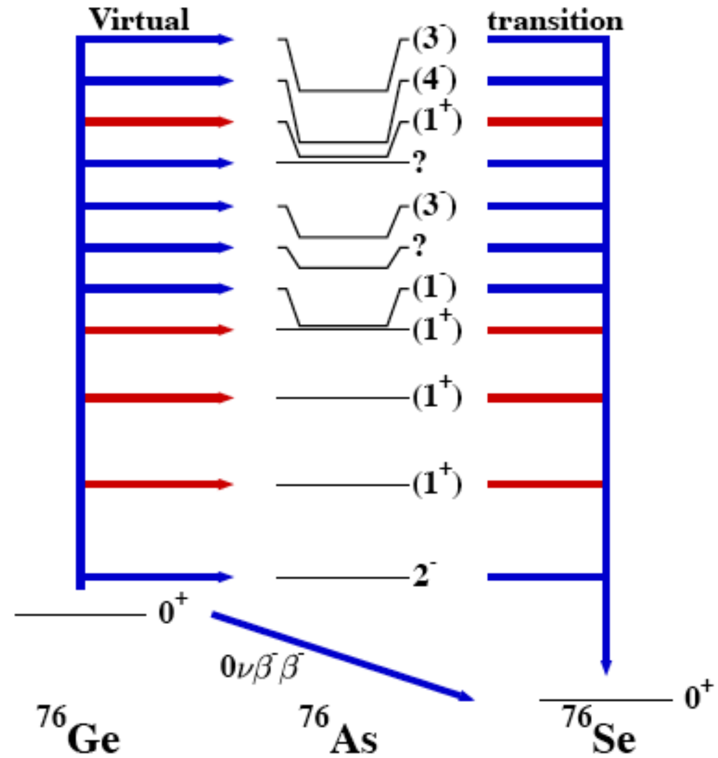
Nucleus	Q-value (MeV)	T1/2 (years)
^{48}Ca	4.276	$(3.9\pm0.7\pm0.6) \times 10^{19}$
^{76}Ge	2.039	$(1.7\pm0.2) \times 10^{21}$
^{82}Se	2.992	$(9.6\pm0.3\pm1.) \times 10^{19}$
^{100}Mo	3.034	$(7.11\pm0.02\pm0.54) \times 10^{18}$
^{116}Cd	2.804	$(2.8\pm0.1\pm0.3) \times 10^{19}$
^{128}Te	0.876	$(2.0\pm0.1) \times 10^{24}$
^{130}Te	2.529	$(7.6\pm1.5\pm0.8) \times 10^{20}$
^{136}Xe	2.467	$(1.1) \times 10^{25}$
^{150}Nd	3.368	$(9.2\pm0.25\pm0.73) \times 10^{21}$

Why are matrix elements of $0\nu\beta\beta$ and $2\nu\beta\beta$ different?



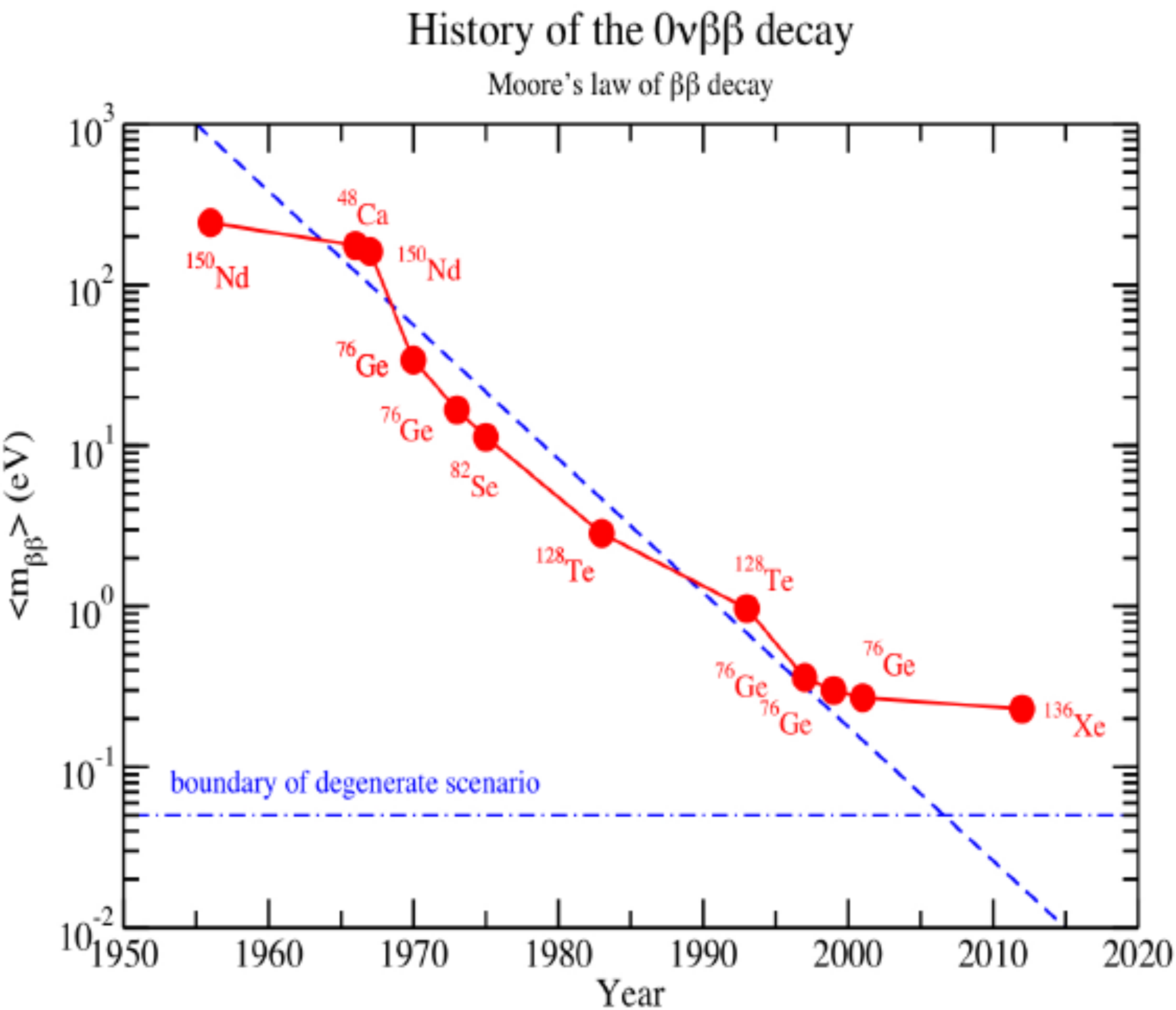
2νββ

Only intermediate 1^+ states contribute (single-state dominance approximation?)
q< a few MeV: $e^{iqr} \sim 1$

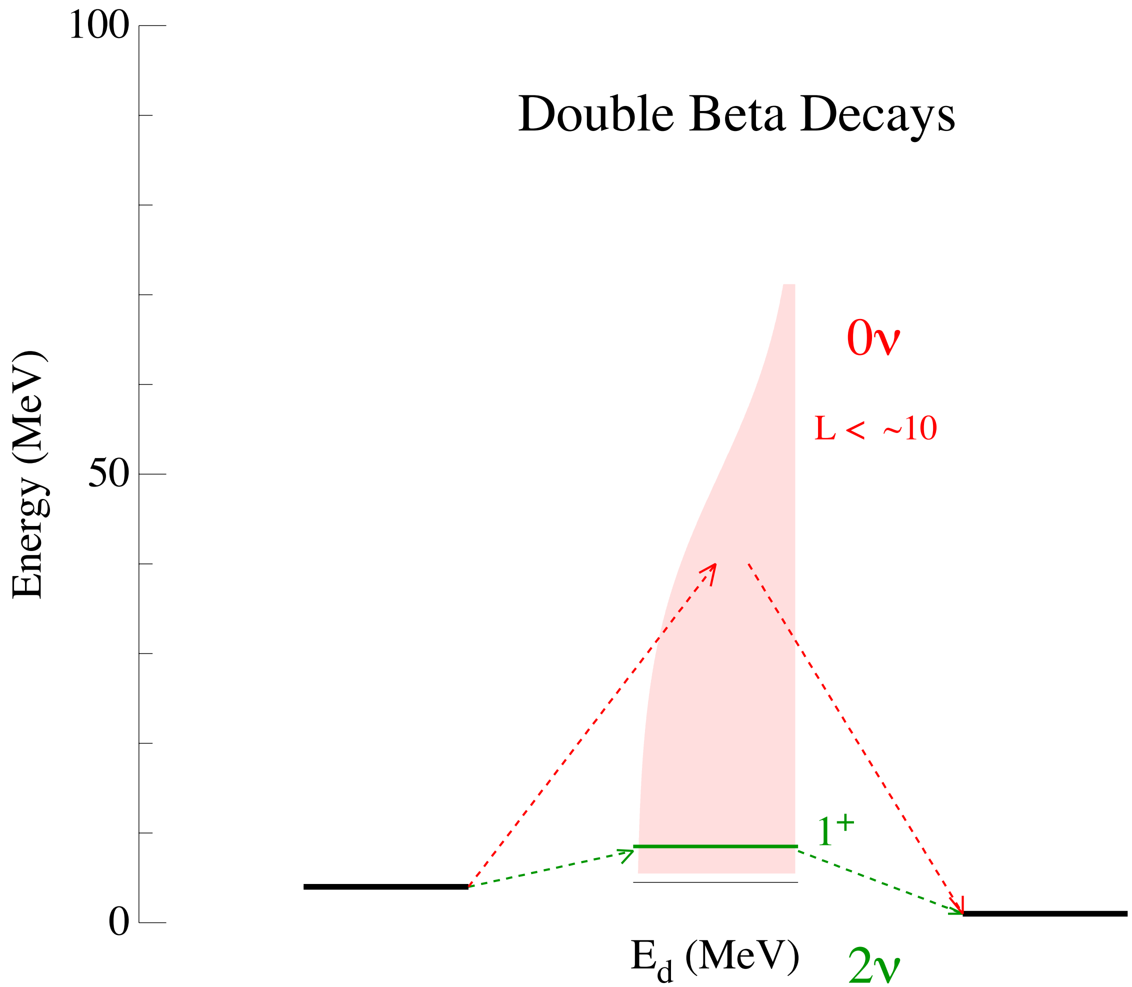


0νββ

All intermediate states contribute (closure approximation?) q ~ a few 100 MeV: $e^{iqr} = 1 + iqr - (qr)^2 + \ldots$


History of the 0νββ decay
Moore's law of ββ decay
<m_ββ> (eV)
Year
150Nd
48Ca
150Nd
76Ge
76Ge
82Se
128Te
128Te
76Ge
76Ge
76Ge
136Xe
boundary of degenerate scenario
1950
1960
1970
1980
1990
2000
2010
2020
10^3
10^2
10^1
10^0
10^-1
10^-2

Vogel

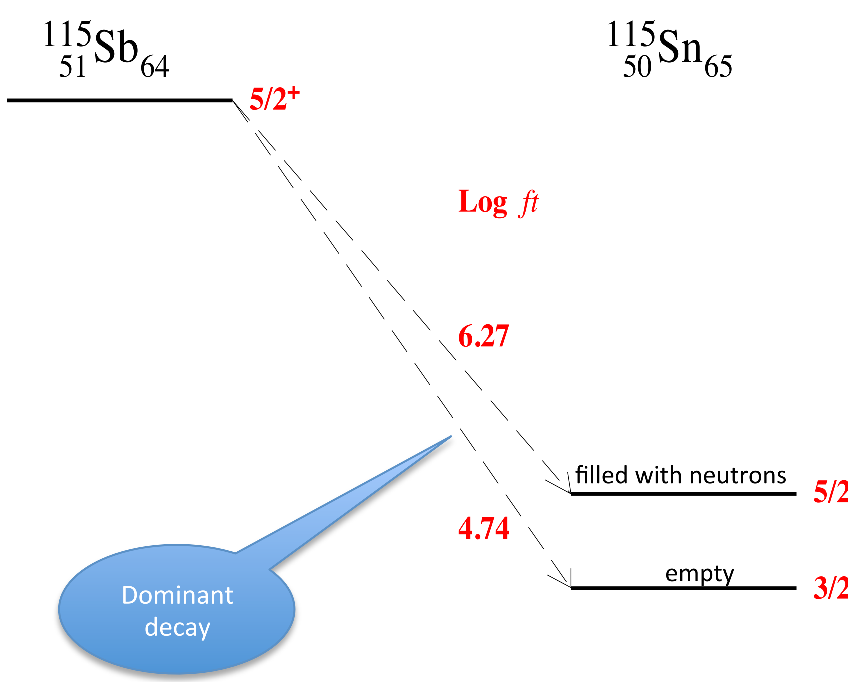


$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}(Q,Z)\left|M^{2\nu}\right|^2$$

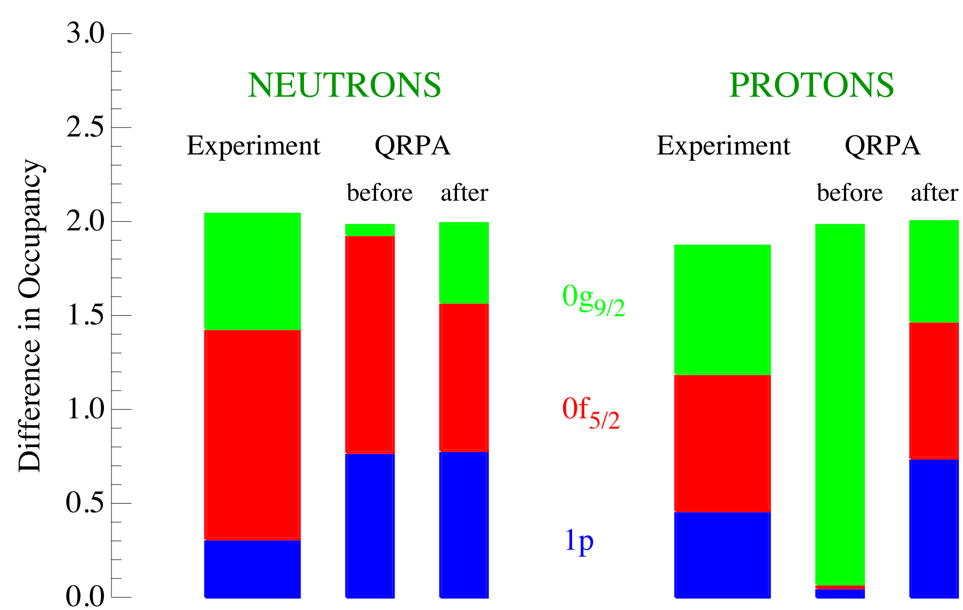
$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \left|\sum_i U_{ei}^2 m_i\right|^2$$

It is the best to test nuclear theory assumptions with appropriate experiments

EC Decay (32 m) of ^{115}Sb



Orbitals Participating in the Decay ^{76}Ge -> ^{76}Se



Slide adopted from J. Schiffer

Nuclear matrix elements for double beta decay

$$M^{2\nu} = \sum_n \frac{< f \,||\, \vec{\sigma}\tau_+ \,||\, n > \cdot < n \,||\, \vec{\sigma}\tau_+ \,||\, i >}{E_n - E_i + E_0}$$

Two-neutrino ββ decay

Nuclear matrix elements for double beta decay

$$M^{2\nu} = \sum_n \frac{< f \,\|\, \vec{\sigma}\tau_+ \,\|\, n > \cdot < n \,\|\, \vec{\sigma}\tau_+ \,\|\, i >}{E_n - E_i + E_0}$$

Two-neutrino ββ decay

$$M^{0\nu} = M_{GT}^{0\nu} - \frac{M_F^{0\nu}}{g_A^2} + M_T^{0\nu}$$

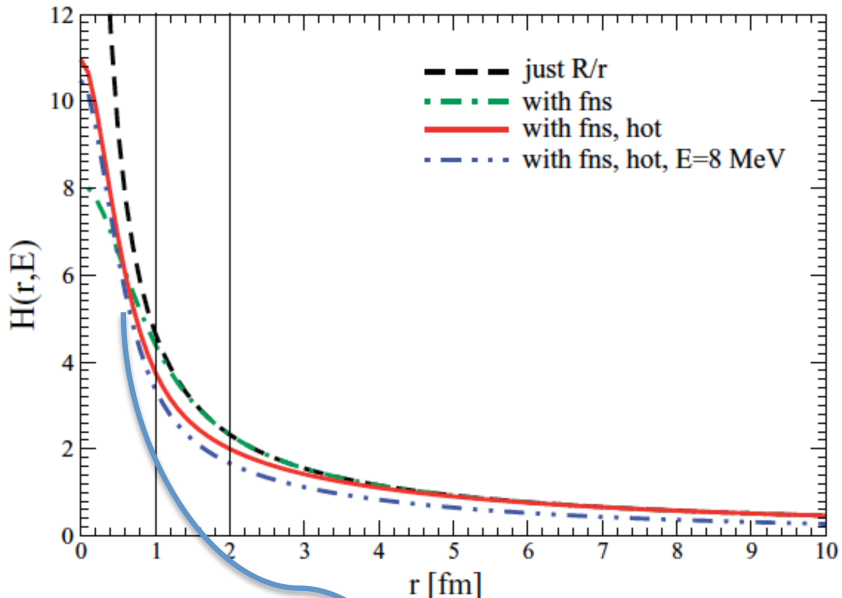
$$M_{GT}^{0\nu} \approx < f \,|\, \sum_{j,k} \frac{1}{r_{jk}} \vec{\sigma}(j) \cdot \vec{\sigma}(k)\ \tau_+(j)\tau_+(k) \,|\, i >$$

Neutrinoless ββ decay

Nuclear matrix elements for double beta decay

$$M^{2\nu} = \sum_n \frac{<f\|\vec{\sigma}\tau_+\|n>\cdot<n\|\vec{\sigma}\tau_+\|i>}{E_n - E_i + E_0}$$

Two-neutrino ββ decay



$$M^{0\nu} = M^{0\nu}_{GT} - \frac{M^{0\nu}_F}{g_A^2} + M^{0\nu}_T$$

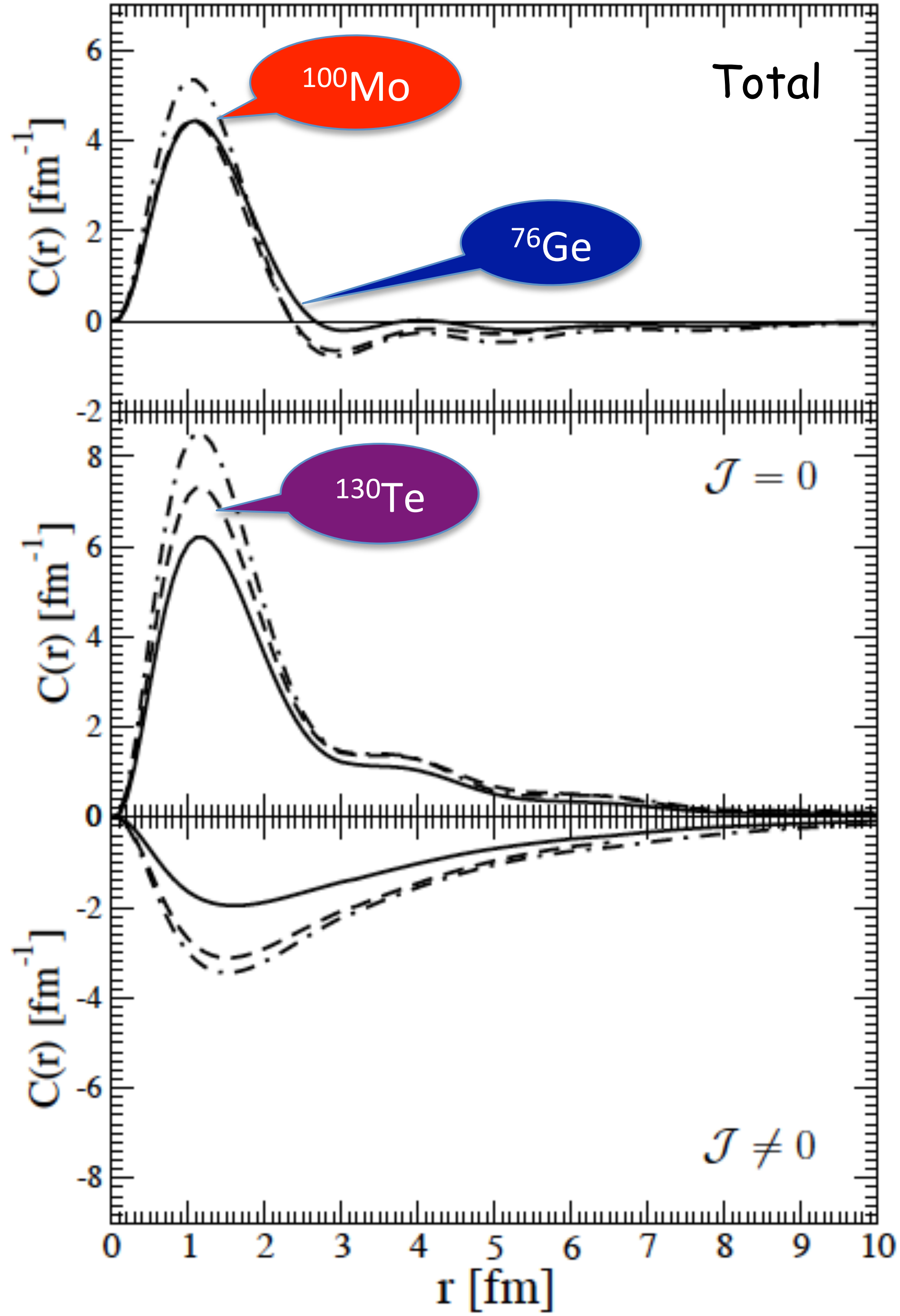
$$M^{0\nu}_{GT} \approx <f|\sum_{j,k}\frac{1}{r_{jk}}\vec{\sigma}(j)\cdot\vec{\sigma}(k)\ \tau_+(j)\tau_+(k)|i>$$

Neutrinoless ββ decay

Nuclear matrix elements

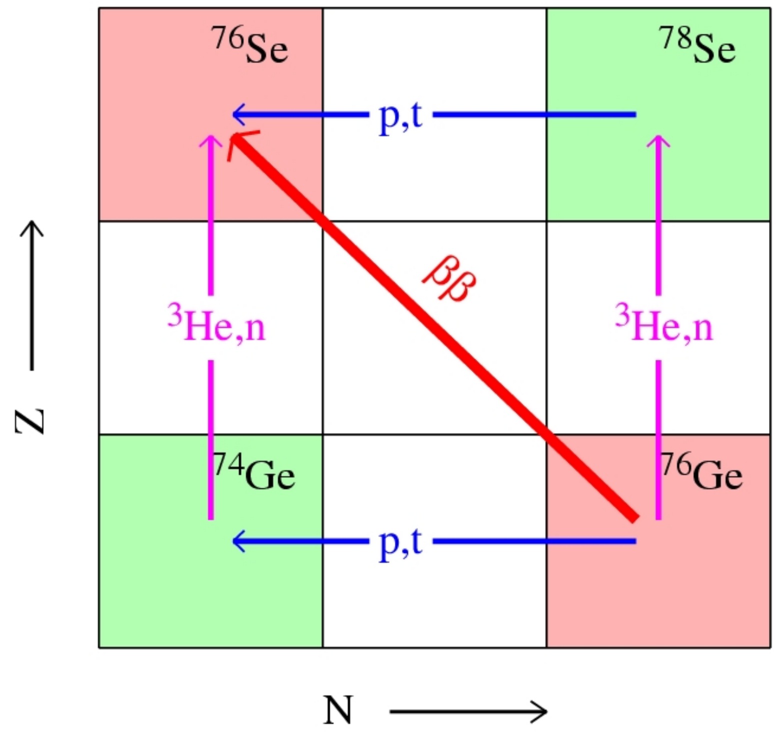
$$M_{GT}^{0\nu} = \int_0^\infty C_{GT}^{0\nu}(r)\,dr$$

Momentum of virtual neutrino, q ~ 1/r
r ~ 2 fm
q ~ 100 MeV

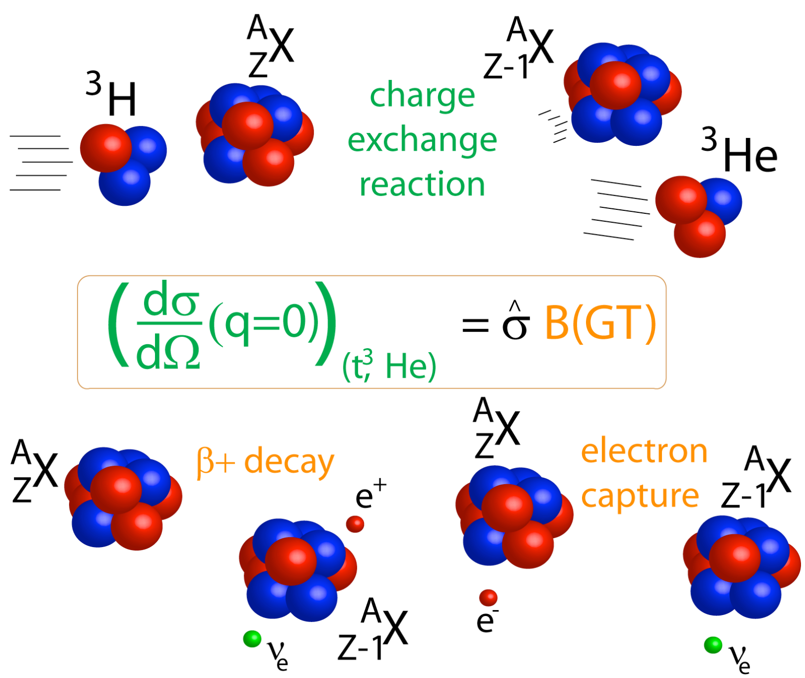


P. Vogel, J. Phys G **39**, 124002 (2012)

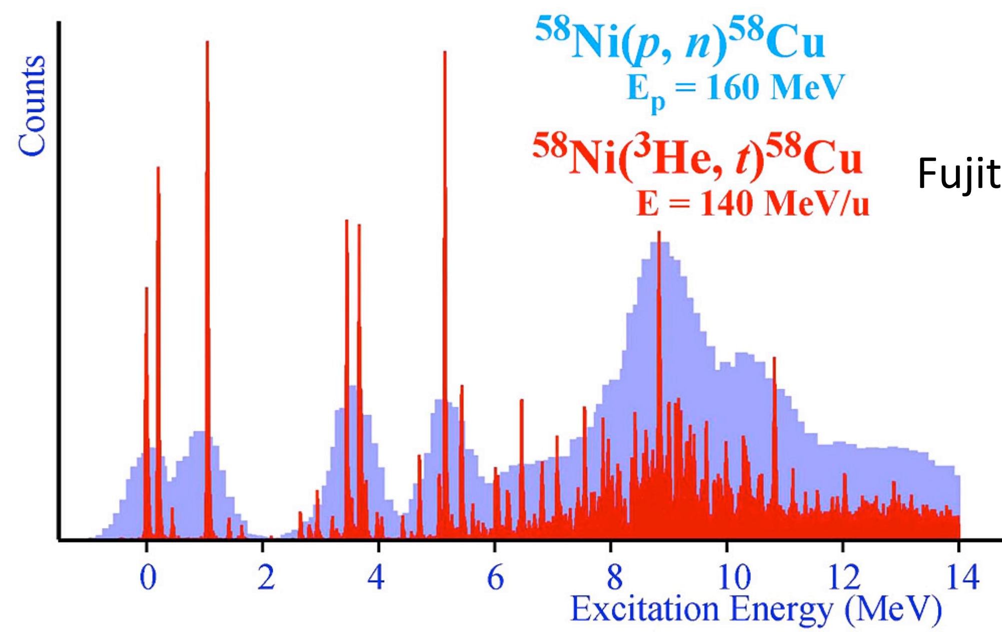
Charge-exchange reaction experiments both with direct and inverse kinematics will help. Recently there have been significant developments in this area.



Schiffer



Zegers



Fujita

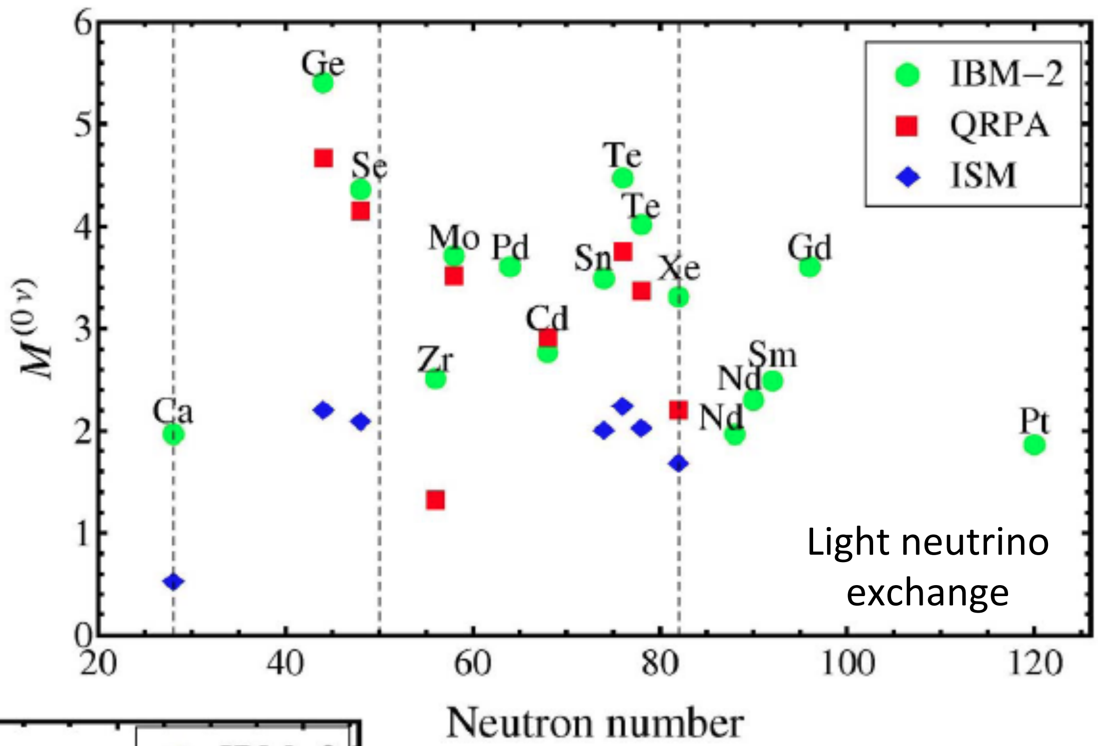
0ν double beta decay

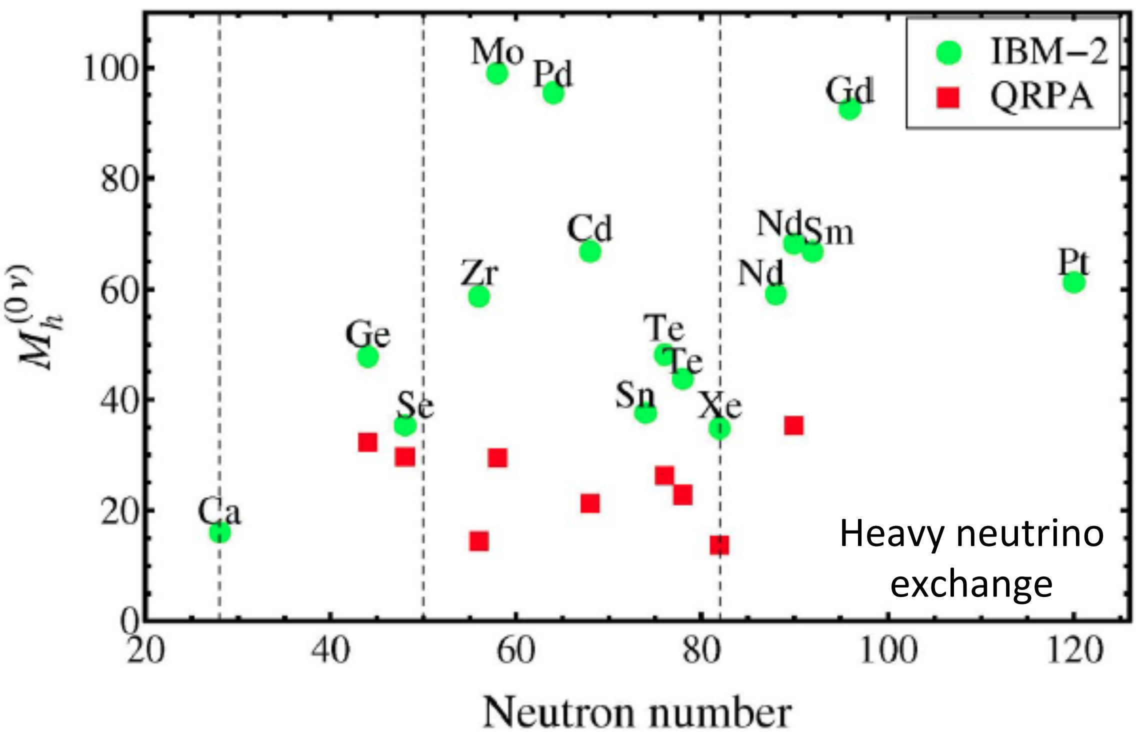
$(1/T_{1/2}) = G(E,Z)\, M^2 \langle m_{\beta\beta}\rangle^2$

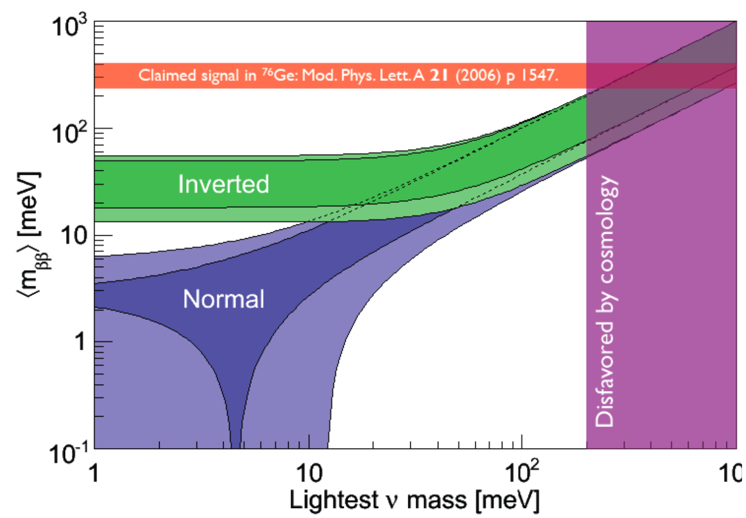
$G(E,Z)$: phase space

M : nuclear matrix element

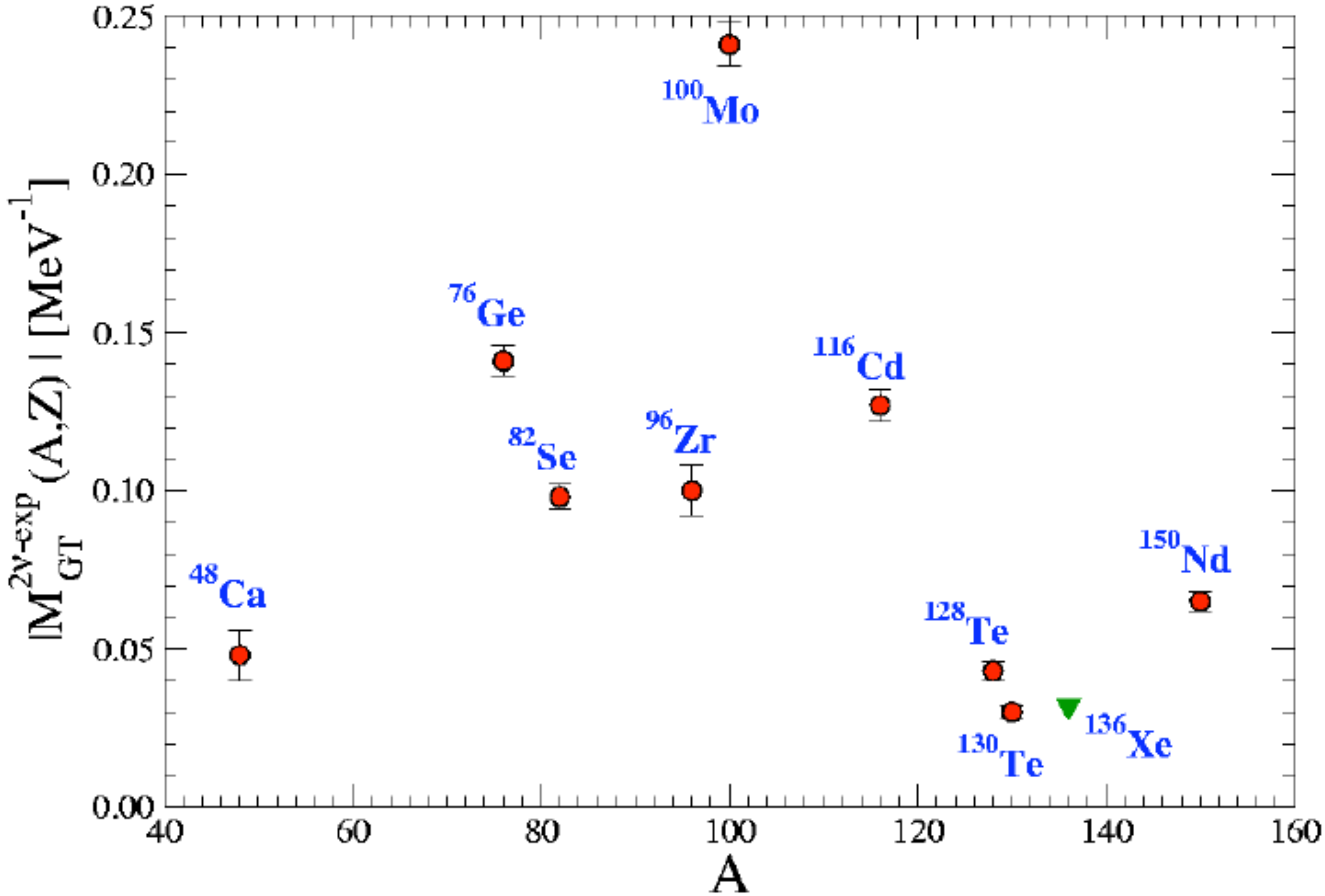
$\langle m_{\beta\beta}\rangle = |\sum_j |U_{ej}|^2 m_j e^{i\delta(j)}|$







For $2\nu\beta\beta$ there is a strong shell-model dependence of the matrix elements



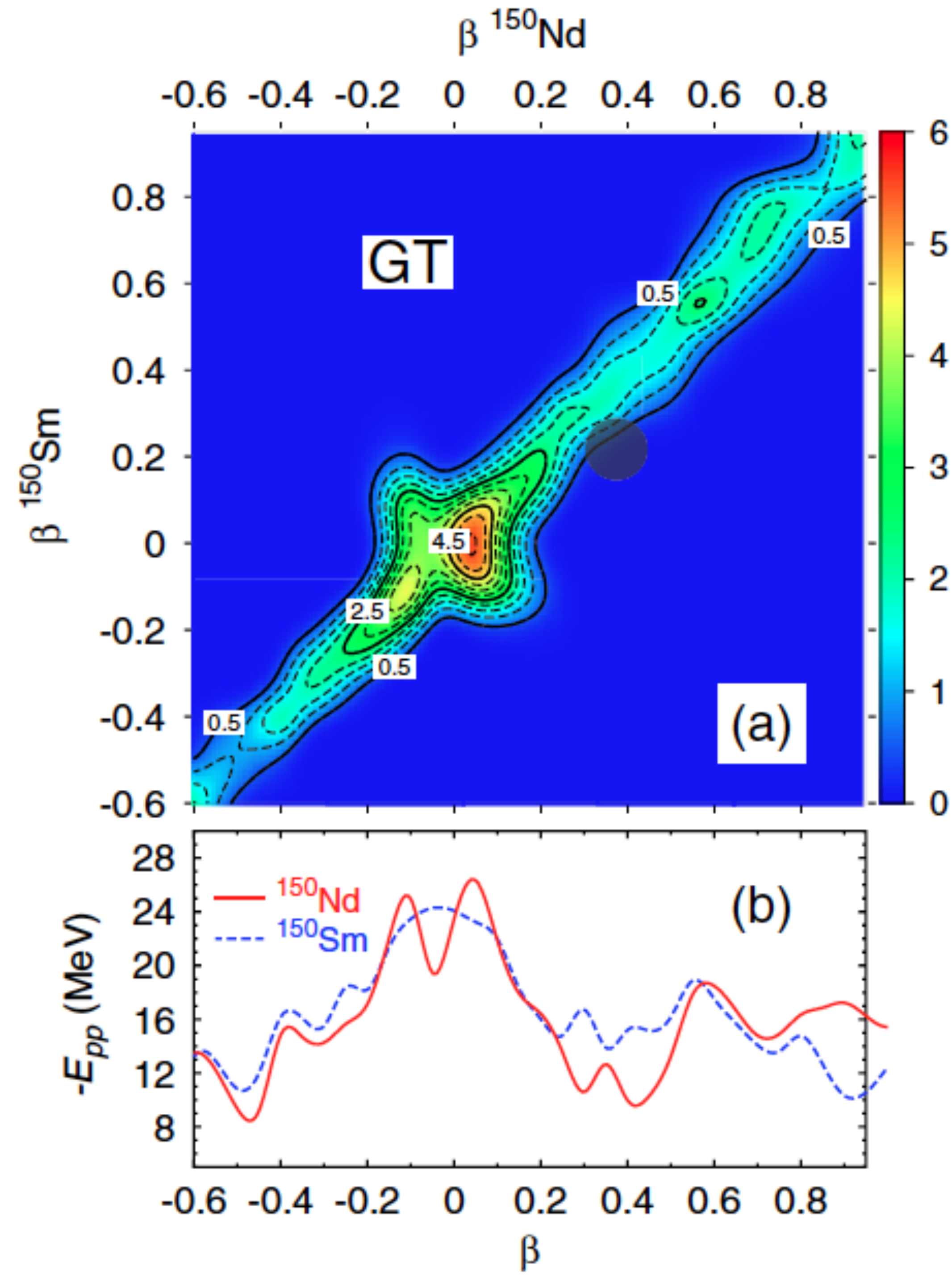
Vogel

In neutrinoless double beta decay, the overlap between initial and final states should be not too small!

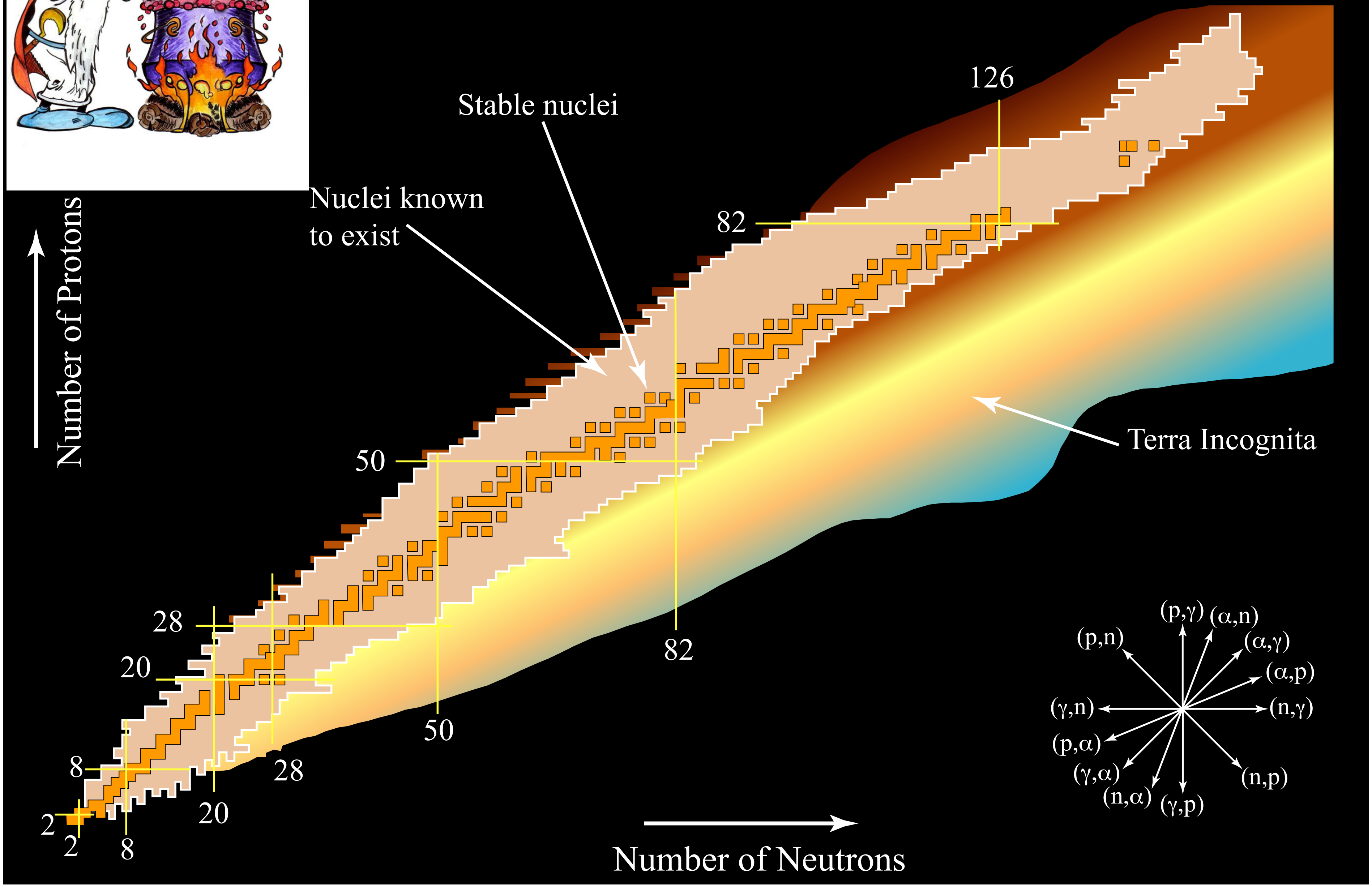
Example:

$^{150}Nd \rightarrow ^{150}Sm + ee$

Rodriguez & Martinez-Pinedo, PRL **105,** 252503 (2010)



How do you cook elements around us?



How do you cook elements around us?

How do you cook elements around us?

Pop III stars
(very big and very
metal poor)

How do you cook elements around us?

How do you cook elements around us?

Ti

Mg

O

C

Sr

N

Ca

Fe

Si

How do you cook elements around us?

How do you cook elements around us?

Some go supernova, producing U, Eu,Th… via the r-process

Pop II stars (metal poor)

AGB stars produce Ba, La, Y,…. via the s-process

Core-collapse supernovae are very sensitive to ν physics

Gravitational collapse yields very large values of the Fermi energy for electrons and ν_e's (~10^{57} units of electron lepton number). ν_μ's and ν_τ's are pair-produced, so they carry no μ or τ lepton number. Any process that changes neutrino flavor could increase electron capture and reduce electron lepton number.

Almost the entire gravitational binding energy of the progenitor star is emitted in neutrinos. Neutrinos transport entropy and the lepton number.

Electron fraction, or equivalently neutron-to-proton ratio (the controlling parameter for nucleosynthesis) is determined by the neutrino capture rates:

$$\nu_e + n \rightleftarrows p + e^-$$

$$\overline{\nu_e} + p \rightleftarrows n + e^+$$

λ_p: proton weak loss rate (rate for $\bar{\nu}_e + p \rightarrow e^+ + n$ and $e^- + p \rightarrow \nu_e + n$ reactions)

λ_n: neutron weak loss rate (rate for $\nu_e + n \rightarrow e^- + p$ and $e^+ + n \rightarrow \bar{\nu}_e + p$ reactions)

$$\frac{dN_p}{dt} = -\lambda_p N_p + \lambda_n N_n$$

Electron fraction: $Y_e \equiv \dfrac{\text{Net number of electrons}}{\text{Number of baryons}}$

Neutral medium, only protons and neutrons: $Y_e = \dfrac{N_p}{N_p + N_n}$

$$\frac{d}{dt} Y_e = \lambda_n - \left(\lambda_p + \lambda_n\right) Y_e$$

λ_p: proton weak loss rate (rate for $\bar{\nu}_e + p \to e^+ + n$ and $e^- + p \to \nu_e + n$ reactions)

λ_n: neutron weak loss rate (rate for $\nu_e + n \to e^- + p$ and $e^+ + n \to \bar{\nu}_e + p$ reactions)

$$\frac{dN_p}{dt} = -\lambda_p N_p + \lambda_n N_n$$

Electron fraction: $Y_e \equiv \dfrac{\text{Net number of electrons}}{\text{Number of baryons}}$

Neutral medium, only protons and neutrons: $Y_e = \dfrac{N_p}{N_p + N_n}$

Neutral medium, with protons, neutrons and alphas: $Y_e = \dfrac{N_p + 2N_\alpha}{N_p + N_n + 4N_\alpha}$

Mass fraction of alphas: $X_\alpha = \dfrac{4N_\alpha}{N_p + N_n + 4N_\alpha}$

$$\frac{d}{dt}\left[Y_e - \frac{1}{2}X_\alpha\right] = \lambda_n - \left(\lambda_p + \lambda_n\right)Y_e + \frac{1}{2}\left(\lambda_p - \lambda_n\right)X_\alpha$$

Vanishes if weak interactions of alphas are ignored

$dY_e/dt = 0$

$$Y_e = \frac{\lambda_n}{\lambda_p + \lambda_n} + \frac{1}{2}\frac{\lambda_p - \lambda_n}{\lambda_p + \lambda_n} X_\alpha$$

If alpha particles are present

$$Y_e^{(0)} = \frac{1}{1 + \lambda_p / \lambda_n}$$

If alpha particles are absent

$$Y_e = Y_e^{(0)} + \left(\frac{1}{2} - Y_e^{(0)}\right) X_\alpha$$

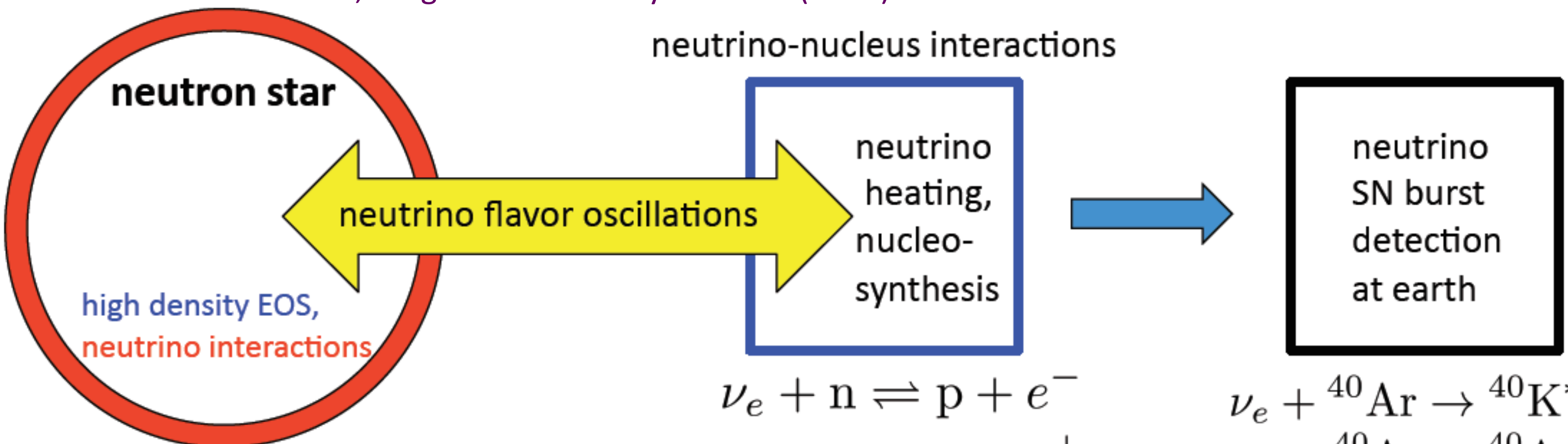
If $Y_e^{(0)} < 1/2$, non-zero X_α increases Y_e. If $Y_e^{(0)} > 1/2$, non-zero X_α decreases Y_e.

Non-zero X_α pushes Y_e to 1/2

Alpha effect

Understanding a core-collapse supernova requires answers to a variety of questions some of which need to be answered by nuclear physics, both theoretically and experimentally.

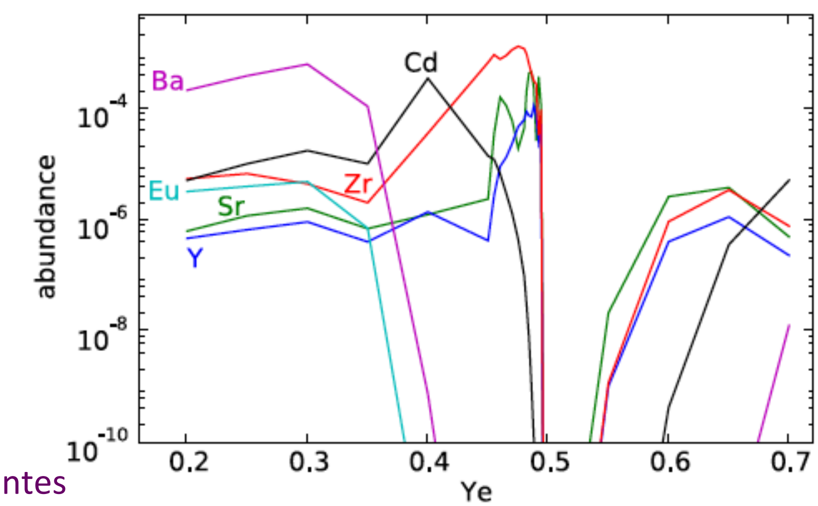
Balantekin and Fuller, Prog. Part. Nucl. Phys. **71** 162 (2013)



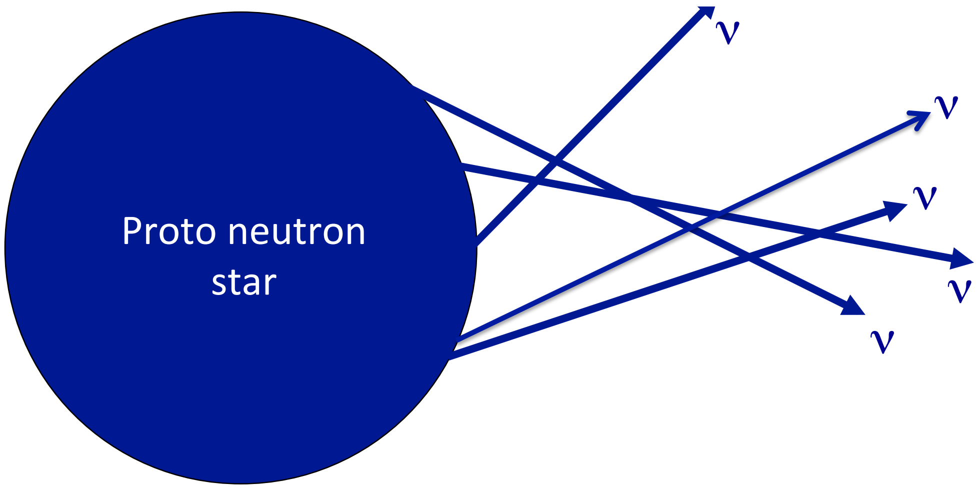
$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$$
$$\nu_x + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Ar}^* + \nu_x$$

$$Y_e = \frac{N_p}{N_p + N_n} = \frac{1}{1 + \lambda_p / \lambda_n}$$



Arcones and Montes



Energy released in a core-collapse SN: $\Delta E \approx 10^{53}$ ergs $\approx 10^{59}$ MeV
99% of this energy is carried away by neutrinos and antineutrinos!
~ 10^{58} Neutrinos!
This necessitates including the effects of $\nu\nu$ interactions!

$$H = \underbrace{\sum a^{\dagger} a}_{\text{describes neutrino oscillations interaction with matter (MSW effect)}} + \underbrace{\sum (1-\cos\theta) a^{\dagger} a^{\dagger} a a}_{\text{describes neutrino-neutrino interactions}}$$

The second term makes the physics of a neutrino gas in a core-collapse supernova a very interesting many-body problem, driven by weak interactions.

Neutrino-neutrino interactions lead to novel collective and emergent effects, such as conserved quantities and interesting features in the neutrino energy spectra (spectral "swaps" or "splits").

Many neutrino system

This is the only many-body system driven by the weak interactions:

Table: Many-body systems

Nuclei	Strong	at most ∼250 particles
Condensed matter	E&M	at most N_A particles
ν**'s in SN**	Weak	$\sim 10^{58}$particles

Astrophysical extremes allow us to test physics that cannot be tested elsewhere!