Neutrinos in Physics and Astrophysics

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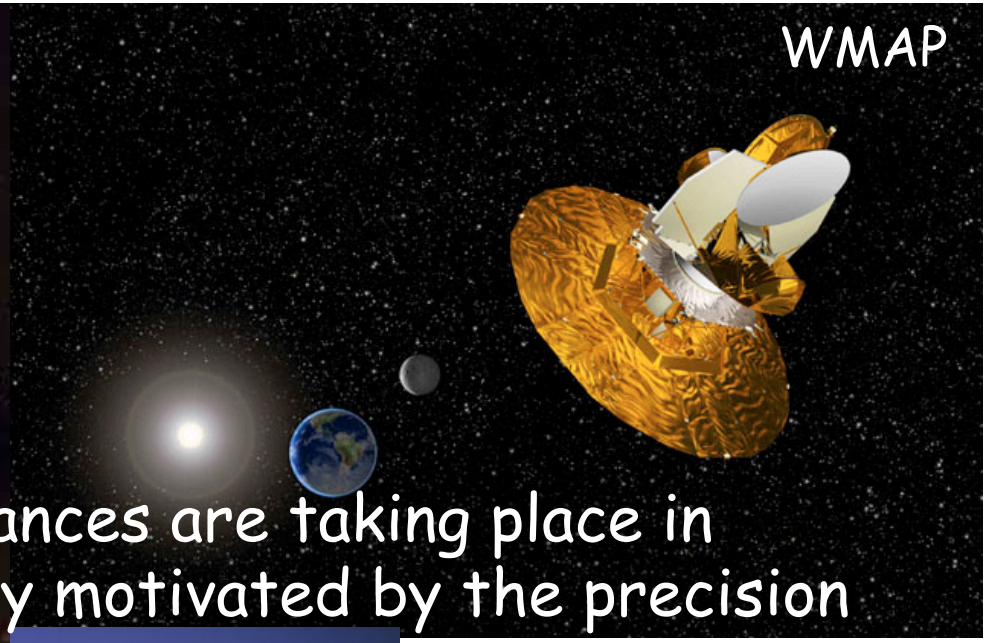
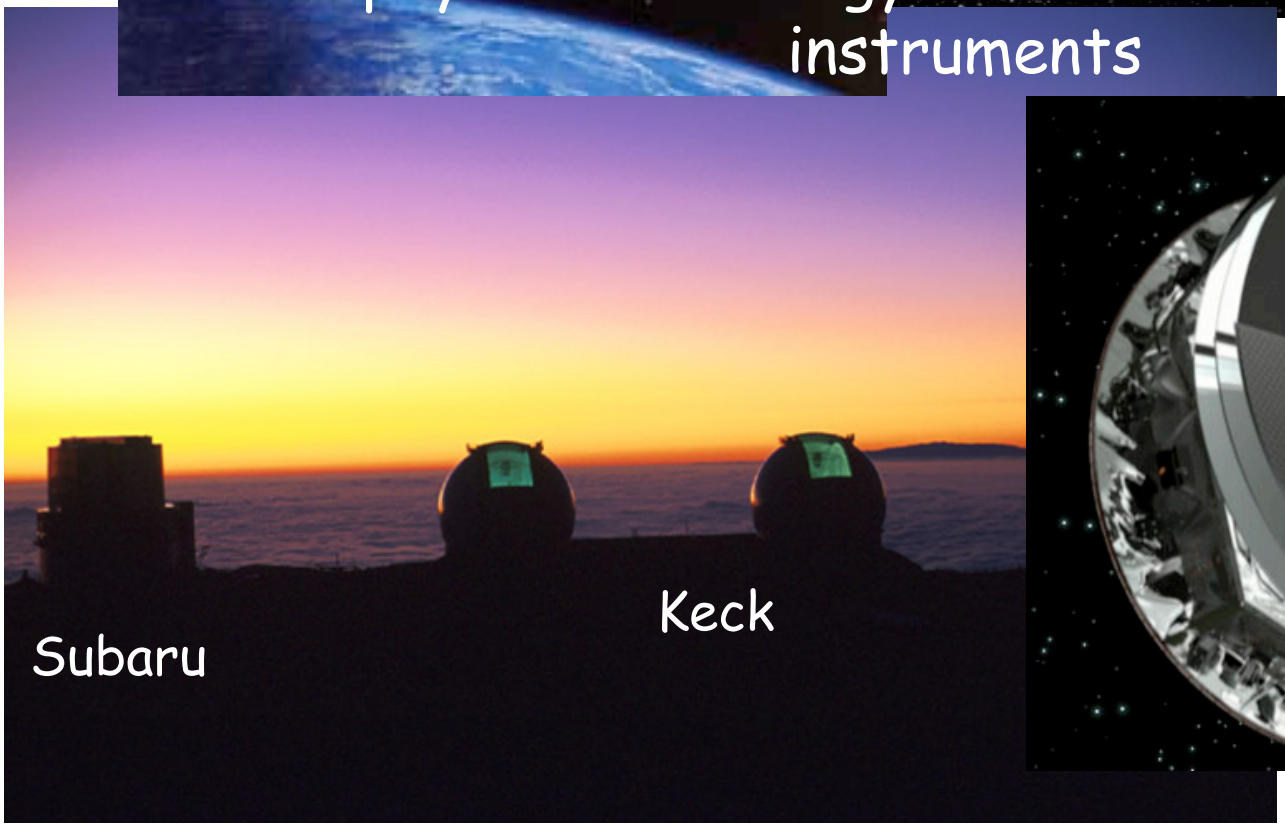
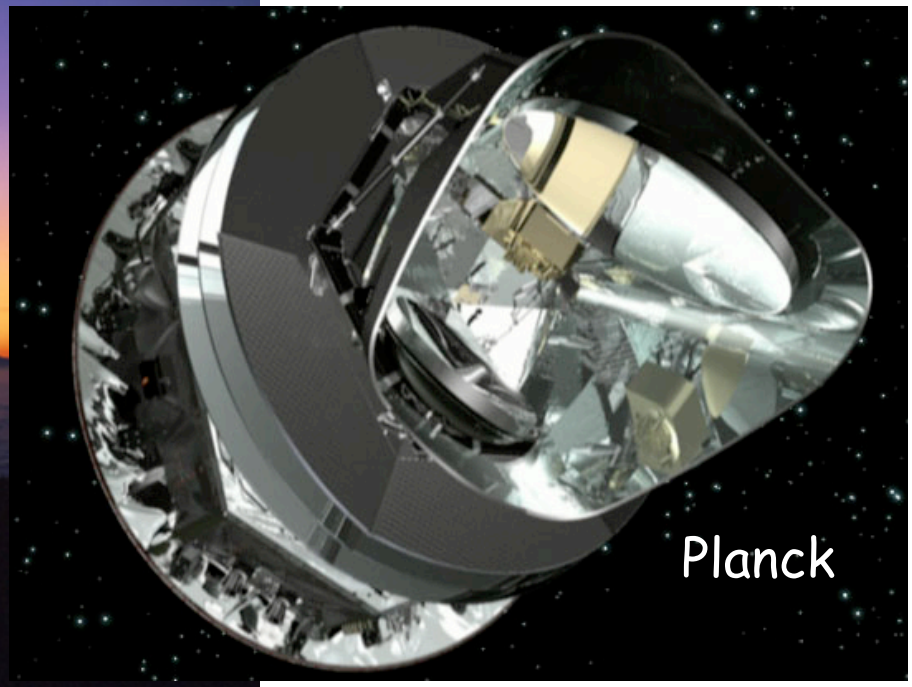
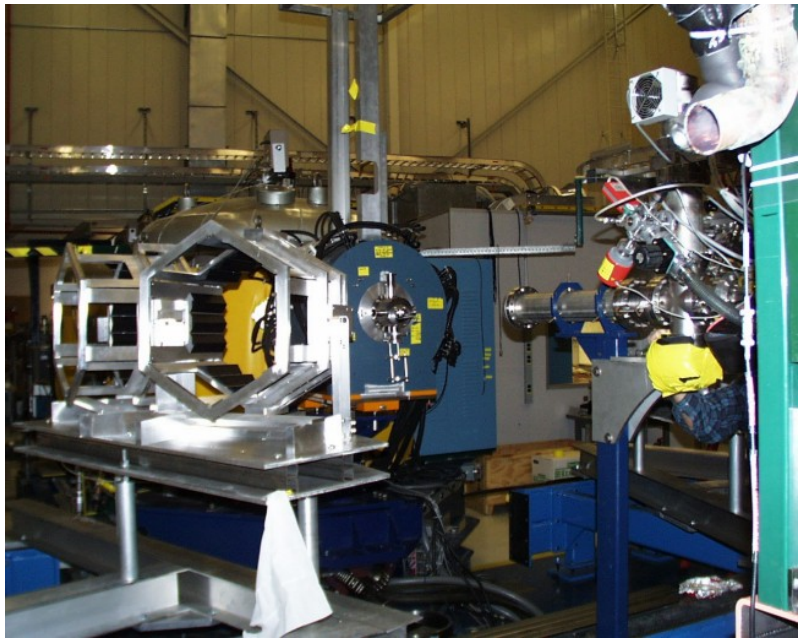
Workshop
Neutrinos in Nuclear Physics
July 29-31, 2016



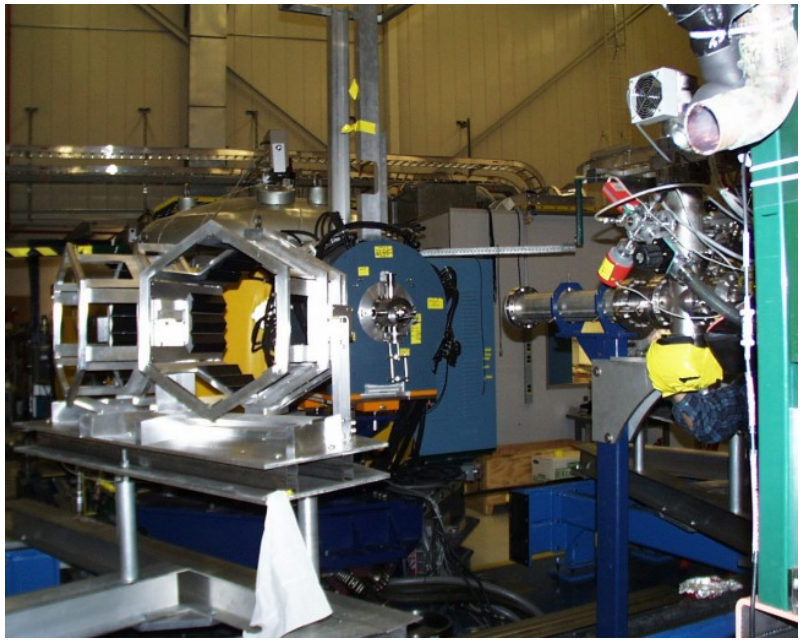
Revolutionary advances are taking place in astrophysics/cosmology motivated by the precision instruments







..and state of the art particle and nuclear physics facilities



..and state of the art nuclear and particle physics facilities

Neutrinos provide the bridge between the two!

Neutrino mixing, 3 active flavors

$$\left|\nu_{flavor}\right\rangle = T\left|\nu_{mass}\right\rangle$$

$$T = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\textit{atmospheric neutrinos}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\textit{reactor neutrinos}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\textit{solar neutrinos}}$$

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

$$P\left(\nu_e \to \nu_e\right) = 1 - \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\left(\Delta_{31}L\right) + \sin^2\theta_{12}\sin^2\left(\Delta_{32}L\right)\right] - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\Delta_{21}L\right)$$

$$\Delta_{ij} = \frac{\delta m_{ij}^2}{4E_\nu} = \frac{m_i^2 - m_j^2}{4E_\nu}, \qquad \Delta_{32} = \Delta_{31} - \Delta_{21}$$

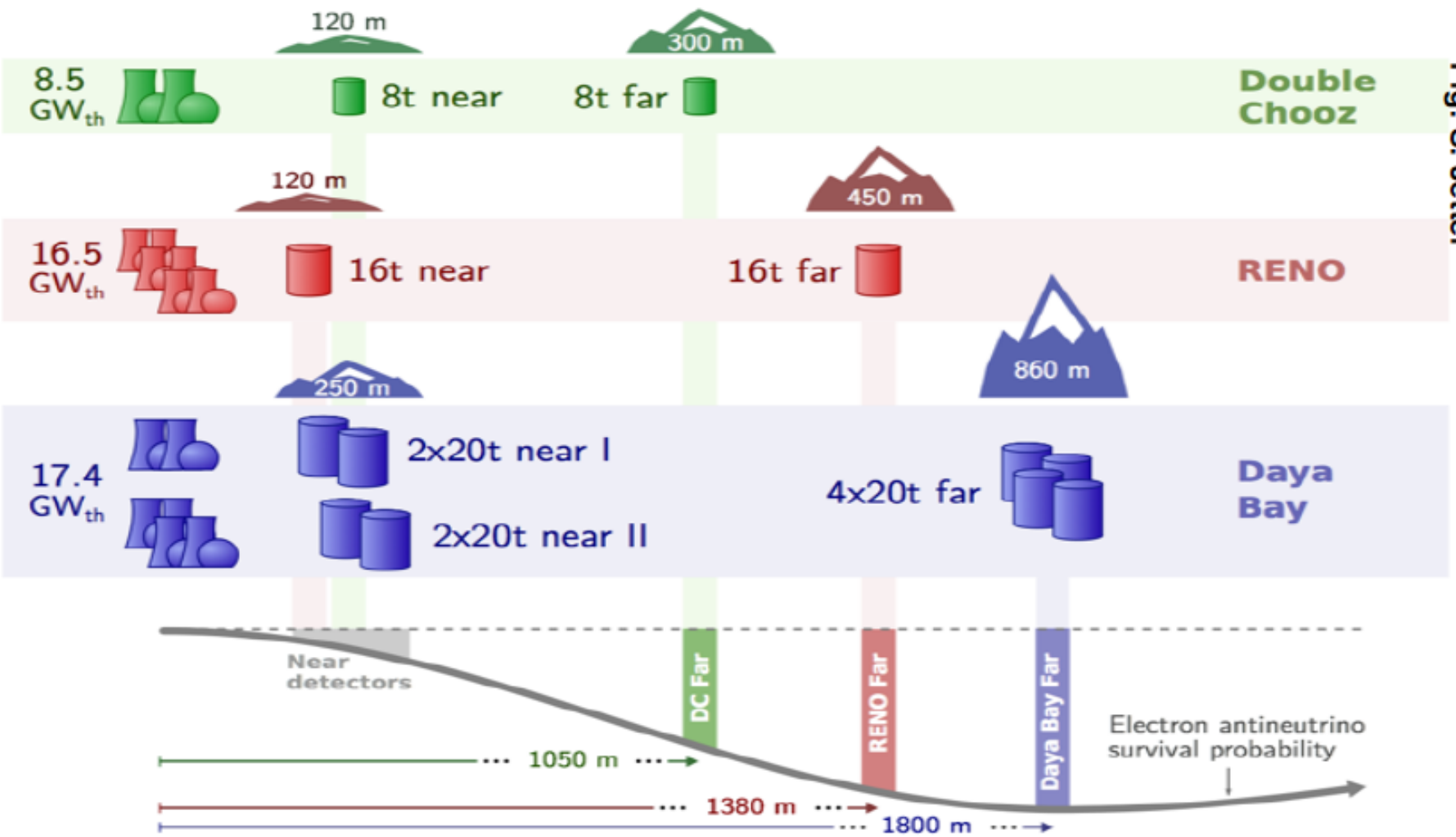
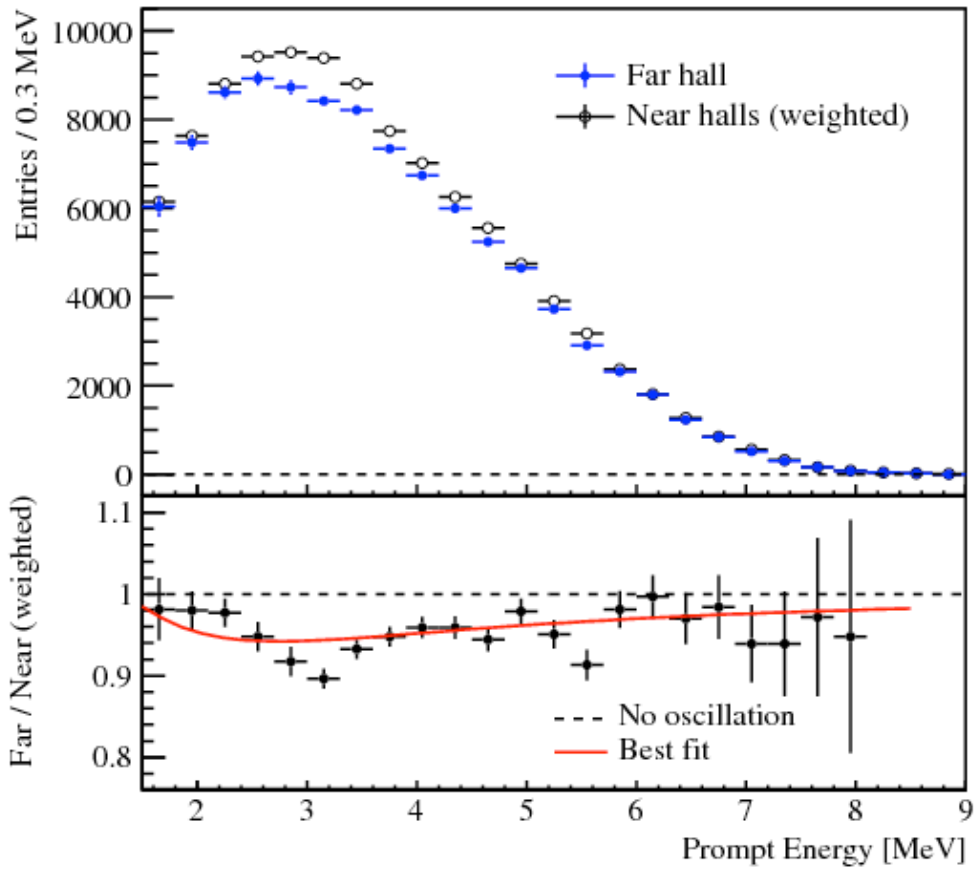

120 m
300 m
8.5 GWth
8t near
8t far
Double Chooz
120 m
450 m
16.5 GWth
16t near
16t far
RENO
860 m
250 m
17.4 GWth
2x20t near I
2x20t near II
4x20t far
Daya Bay
Near detectors
DC Far
RENO Far
Daya Bay Far
Electron antineutrino survival probability
1050 m
1380 m
1800 m

Fig: S. Jetter



Neutron capture on hydrogen:

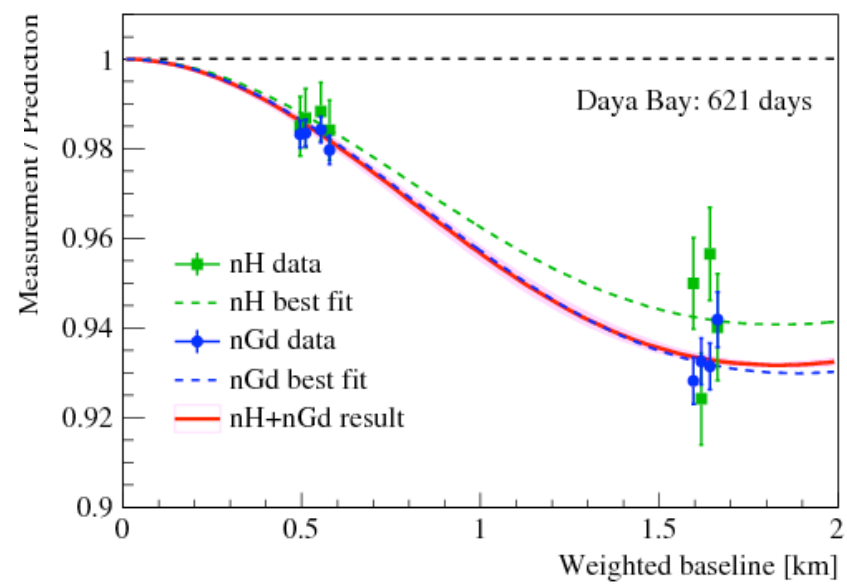
$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$

Neutron capture on Gd:

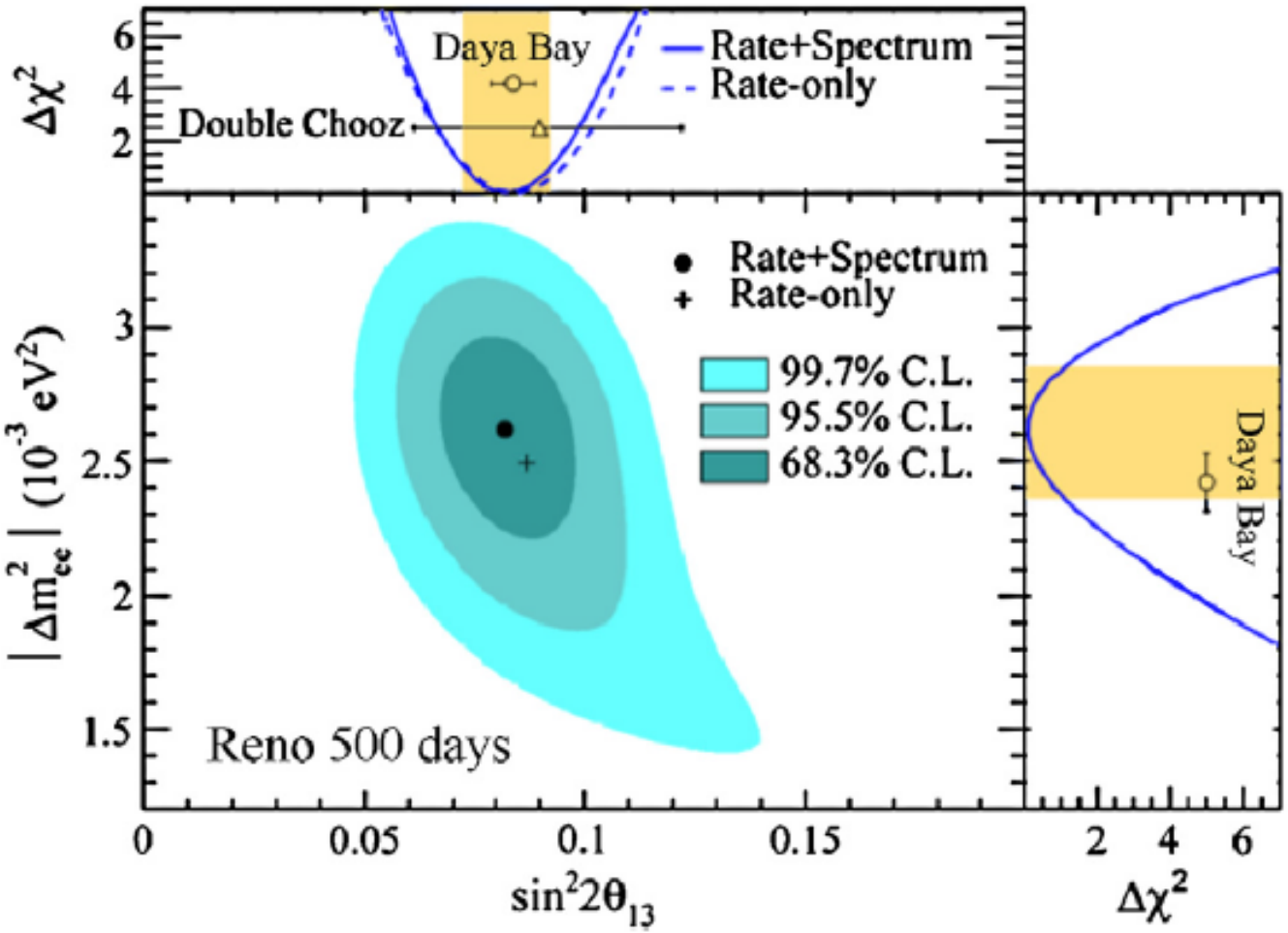
$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

Simultaneous fit:

$$\sin^2 2\theta_{13} = 0.082 \pm 0.004$$



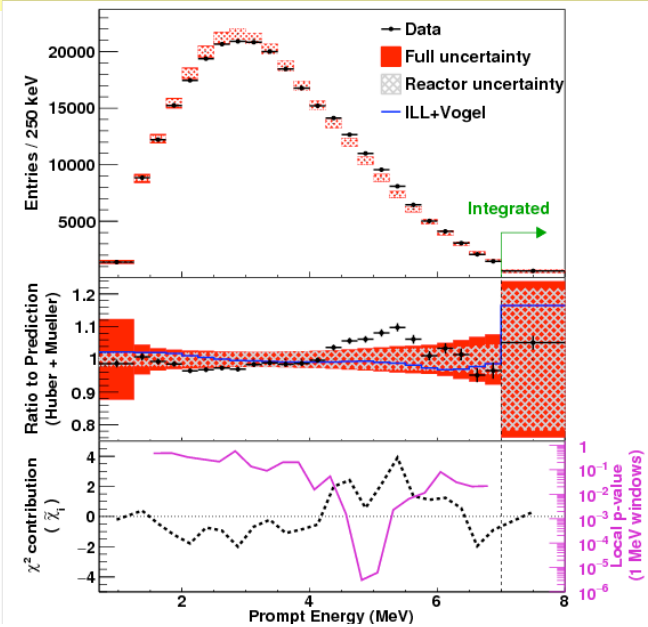
Phys.Rev. D93 (2016) 072011

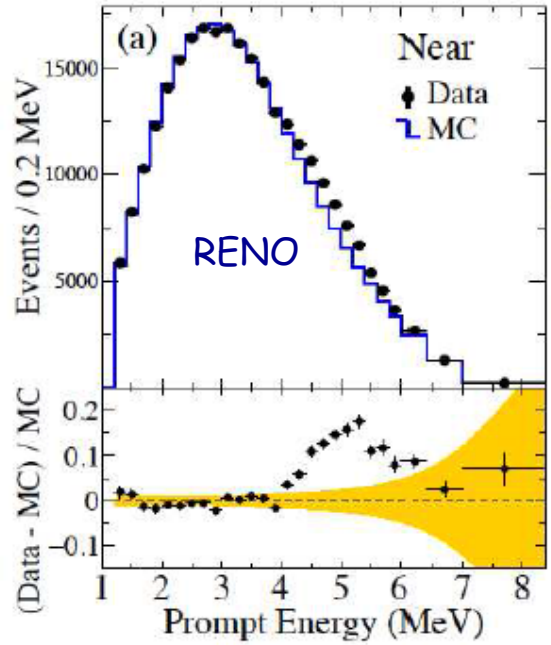


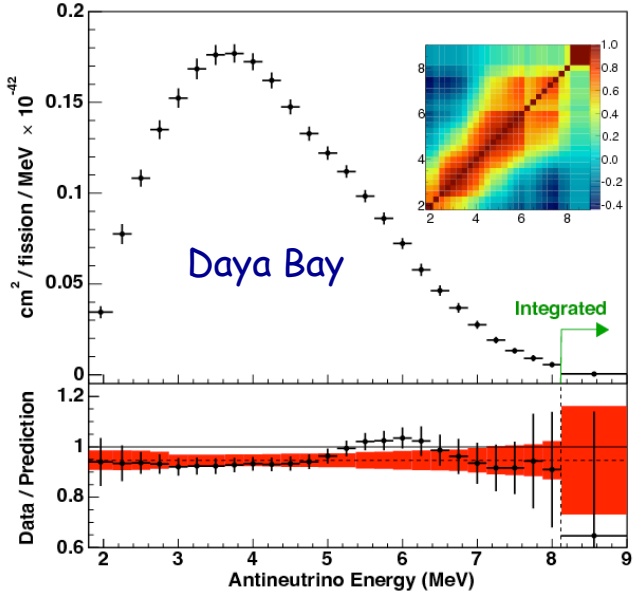
$$\sin^2 2\theta_{13} = 0.082 \pm 0.009 \text{ (stat.)} \pm 0.006 \text{ (syst.)}$$

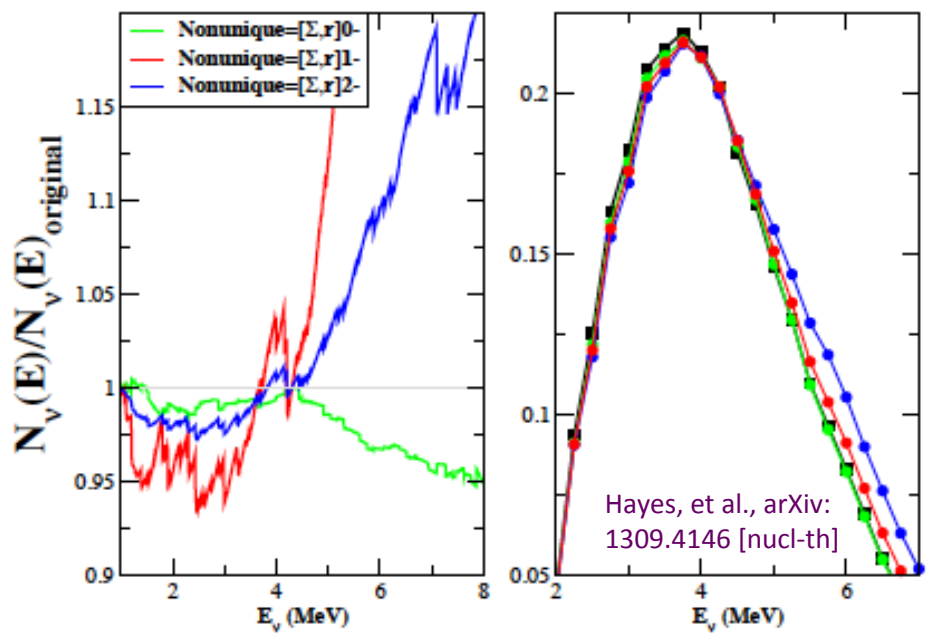
$$\left|\delta m^2_{ee}\right| = \left[2.62^{+0.21}_{-0.23} \text{ (stat.)}^{+0.12}_{-0.13} \text{ (syst.)}\right] \times 10^{-3} \text{ eV}^2$$

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



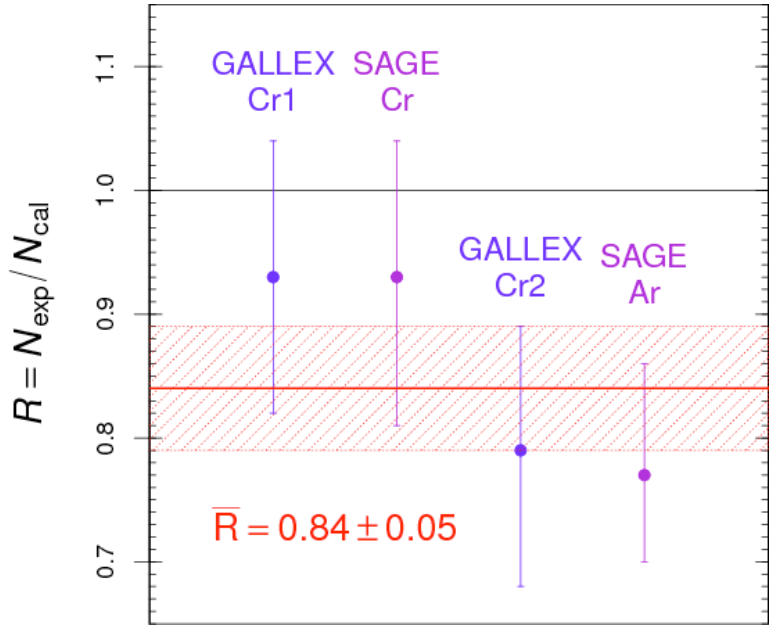


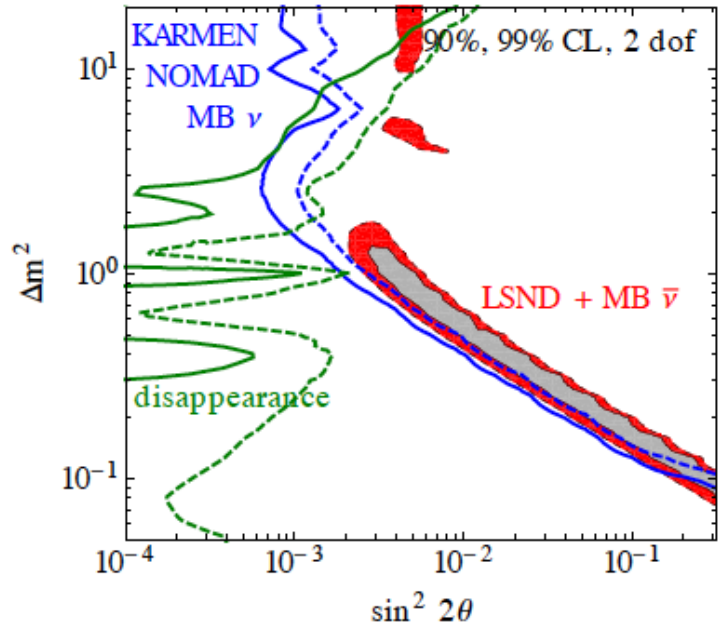


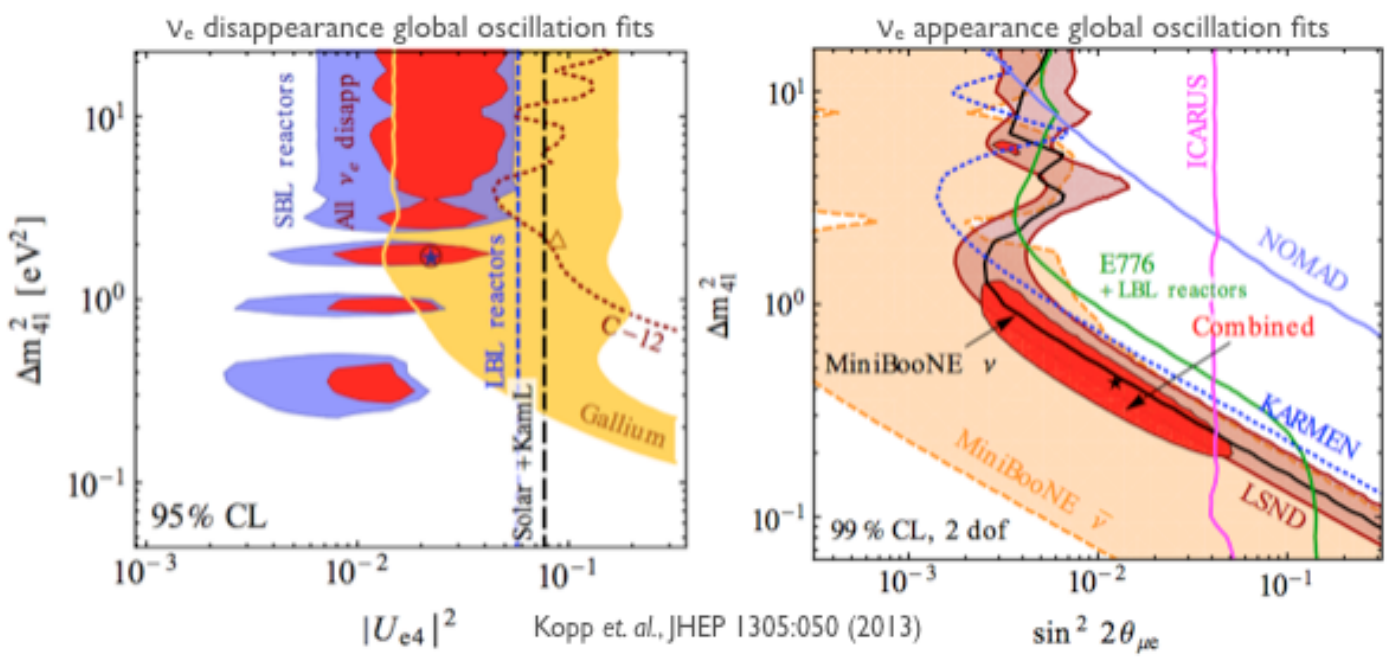


Can we know the reactor neutrino flux ever as well as we need?

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

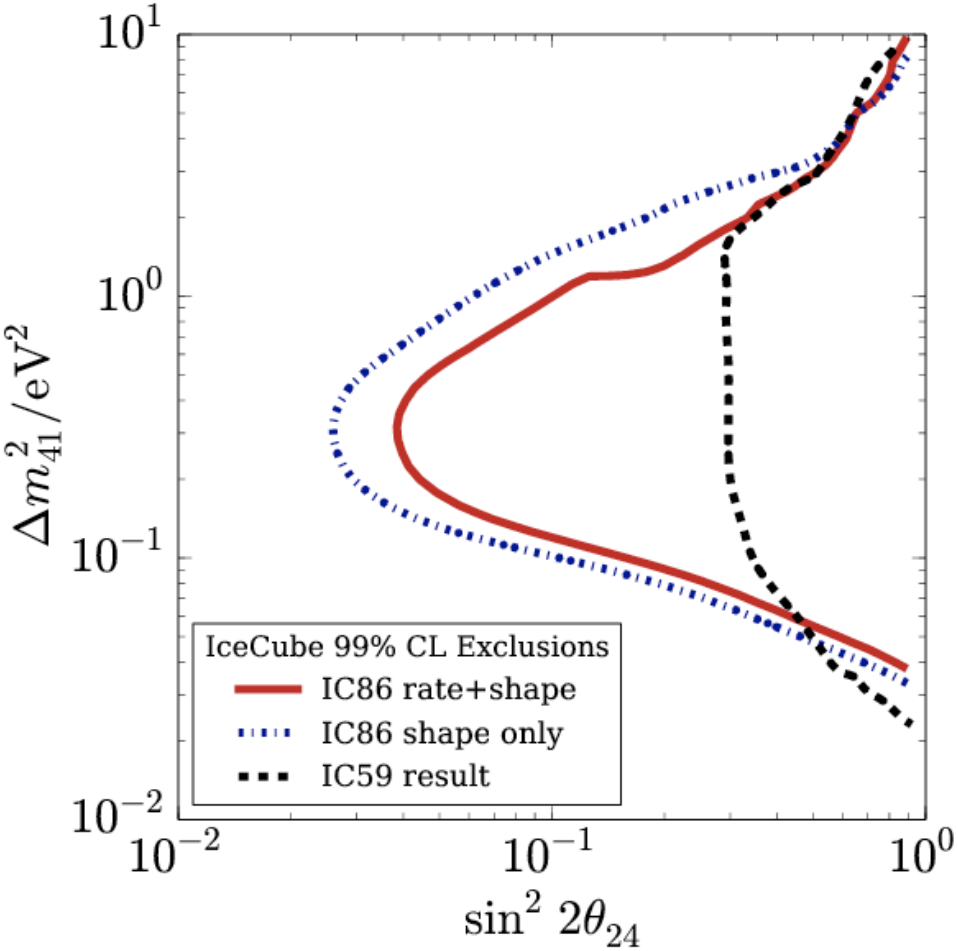


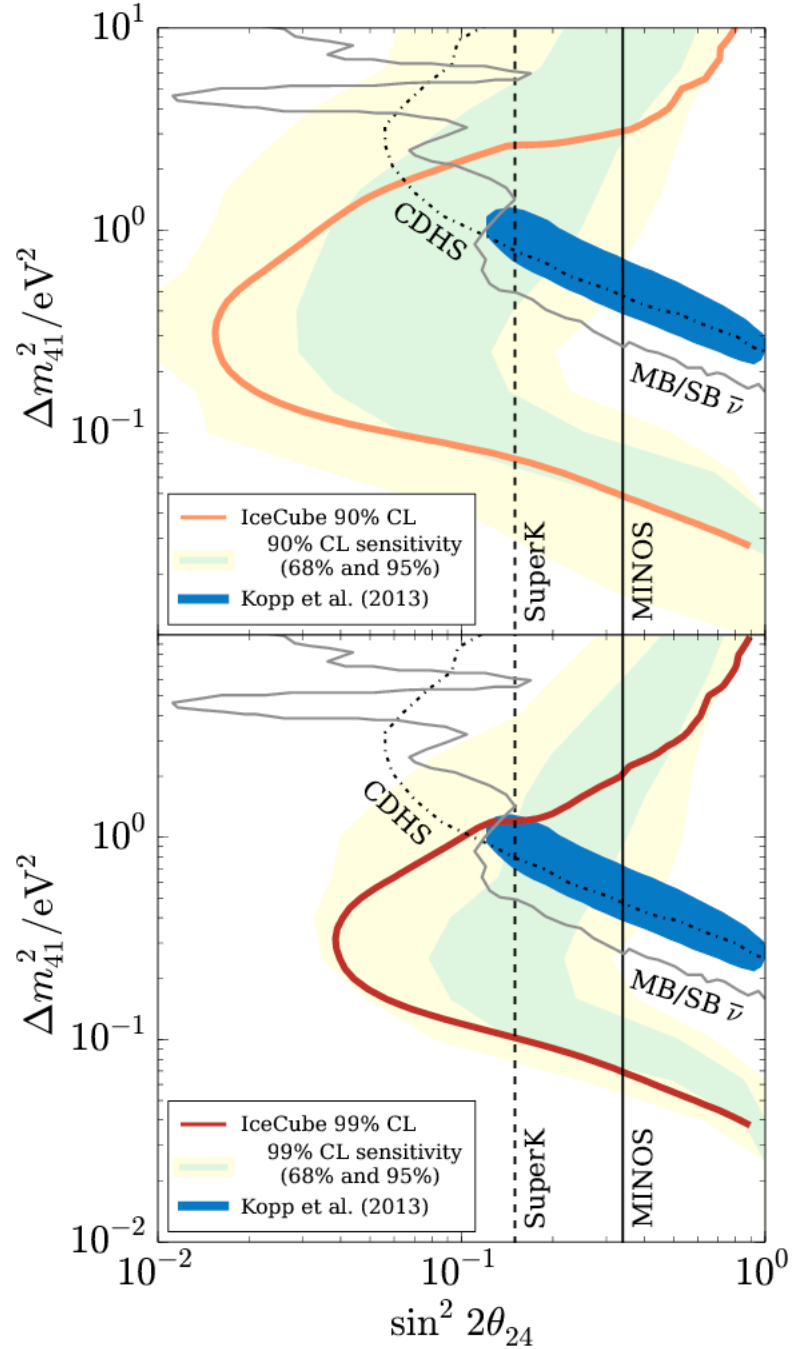




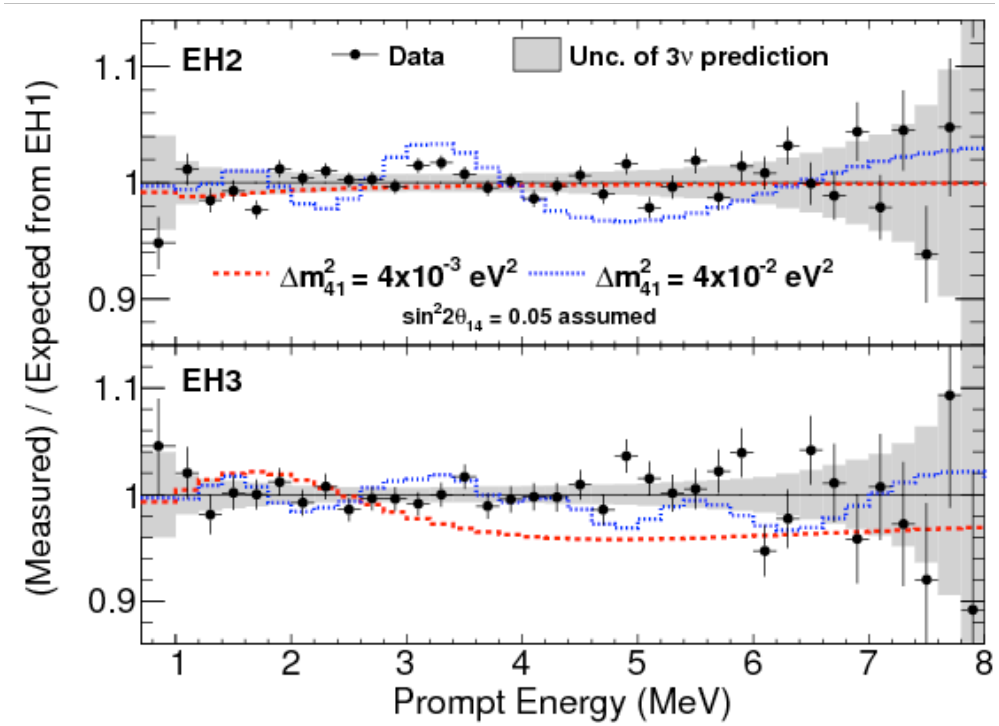
Kopp et. al., JHEP 1305:050 (2013)

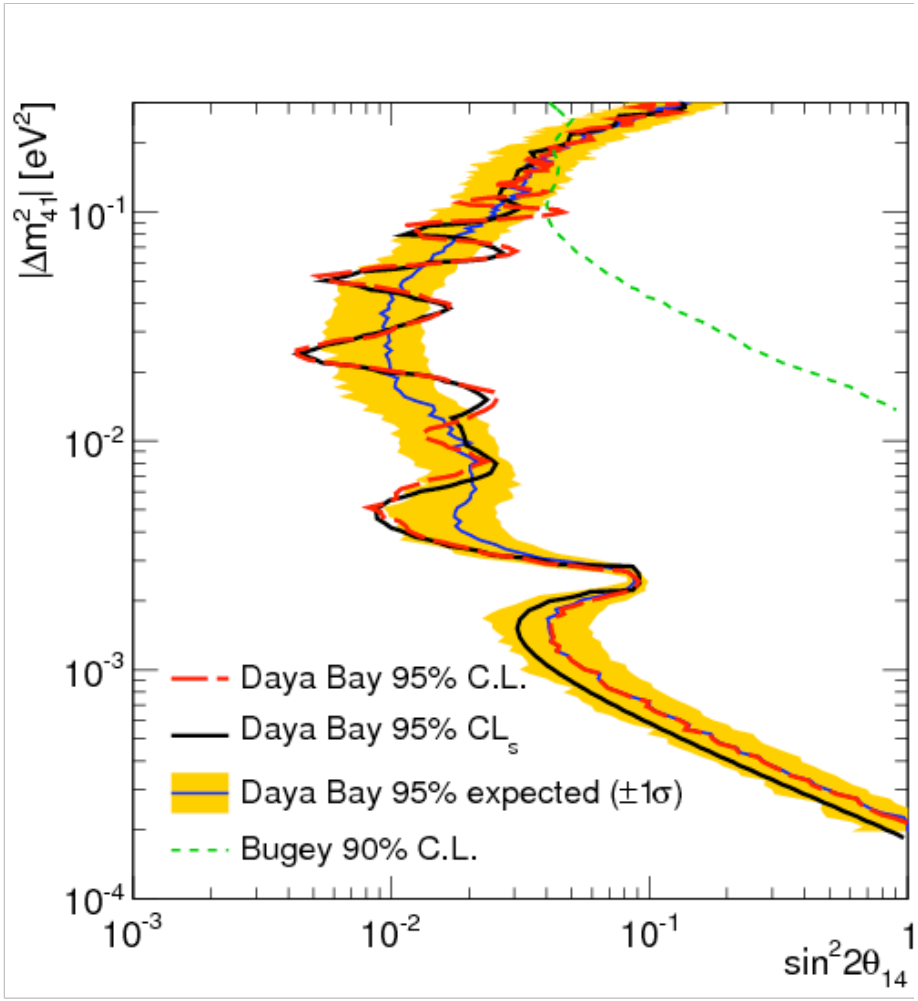
Sterile Neutrino Limits from ICECUBE – θ_{24}





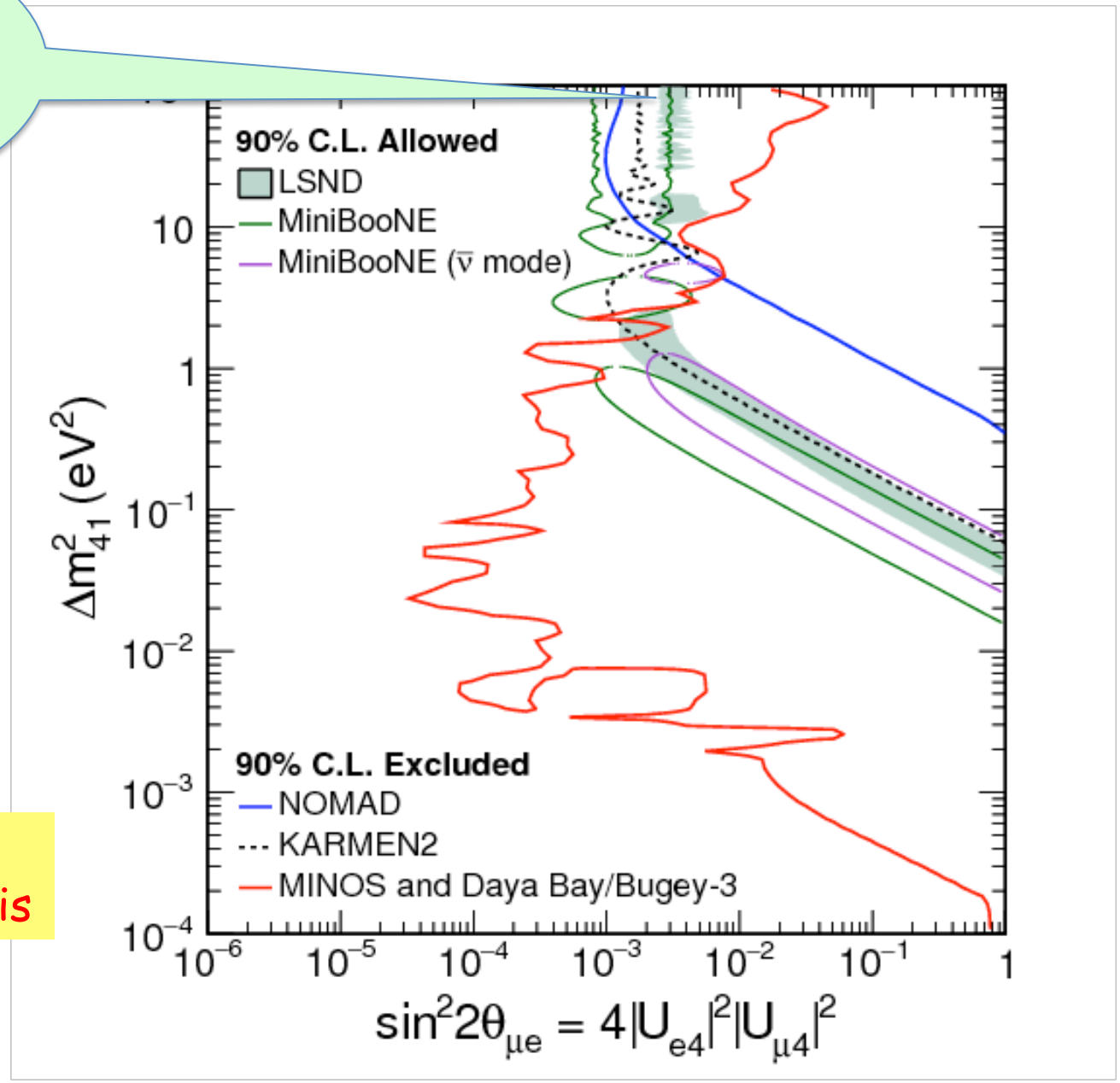
Sterile Neutrino Limits from Daya Bay – θ_{14}





arXiv:1607.01174 [hep-ex]

This region is still allowed for LSND/MiniBooNE



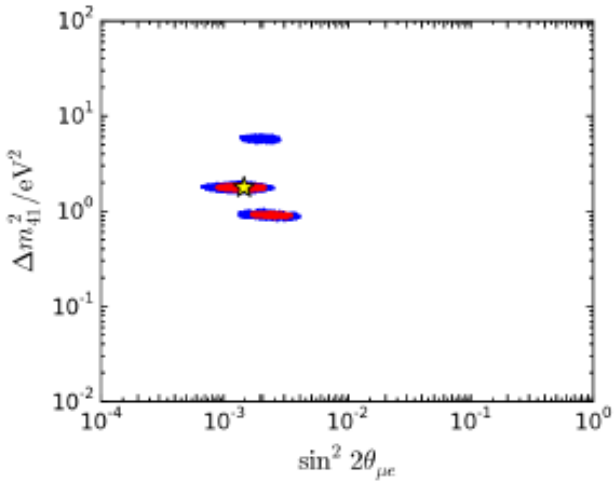
Daya Bay, Bugey, MINOS joint analysis

arXiv:1607.01177

A comparison of three fits

Collin, Arguelles, Conrad, Shaevitz

[NPB 908 (2016) 354]

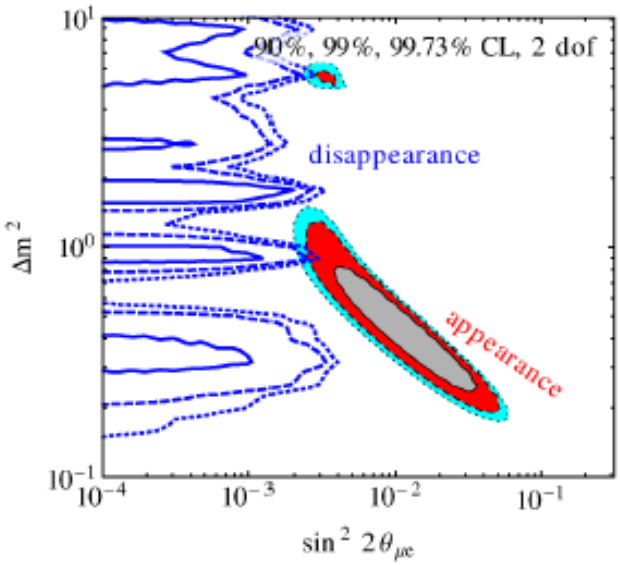


Best Fit: $\Delta m^2_{41} = 1.75\,\mathrm{eV}^2$

$|U_{e4}|^2 = 0.027$ $|U_{\mu 4}|^2 = 0.014$

Kopp, Machado, Maltoni, Schwetz

[JHEP 1305 (2013) 050]

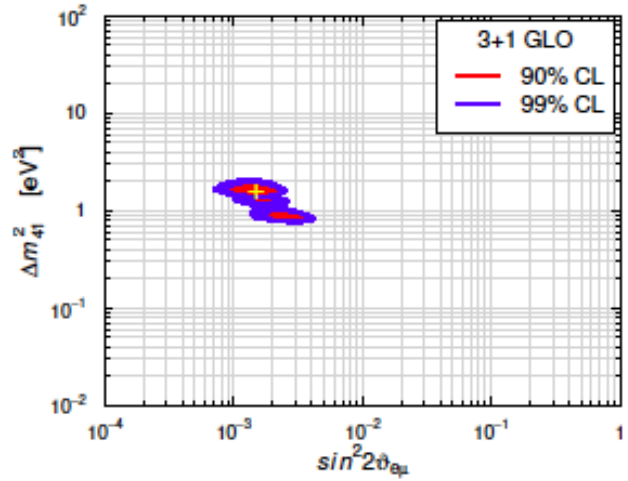


Best Fit: $\Delta m^2_{41} = 0.93\,\mathrm{eV}^2$

$|U_{e4}|^2 = 0.023$ $|U_{\mu 4}|^2 = 0.029$

Our Fit

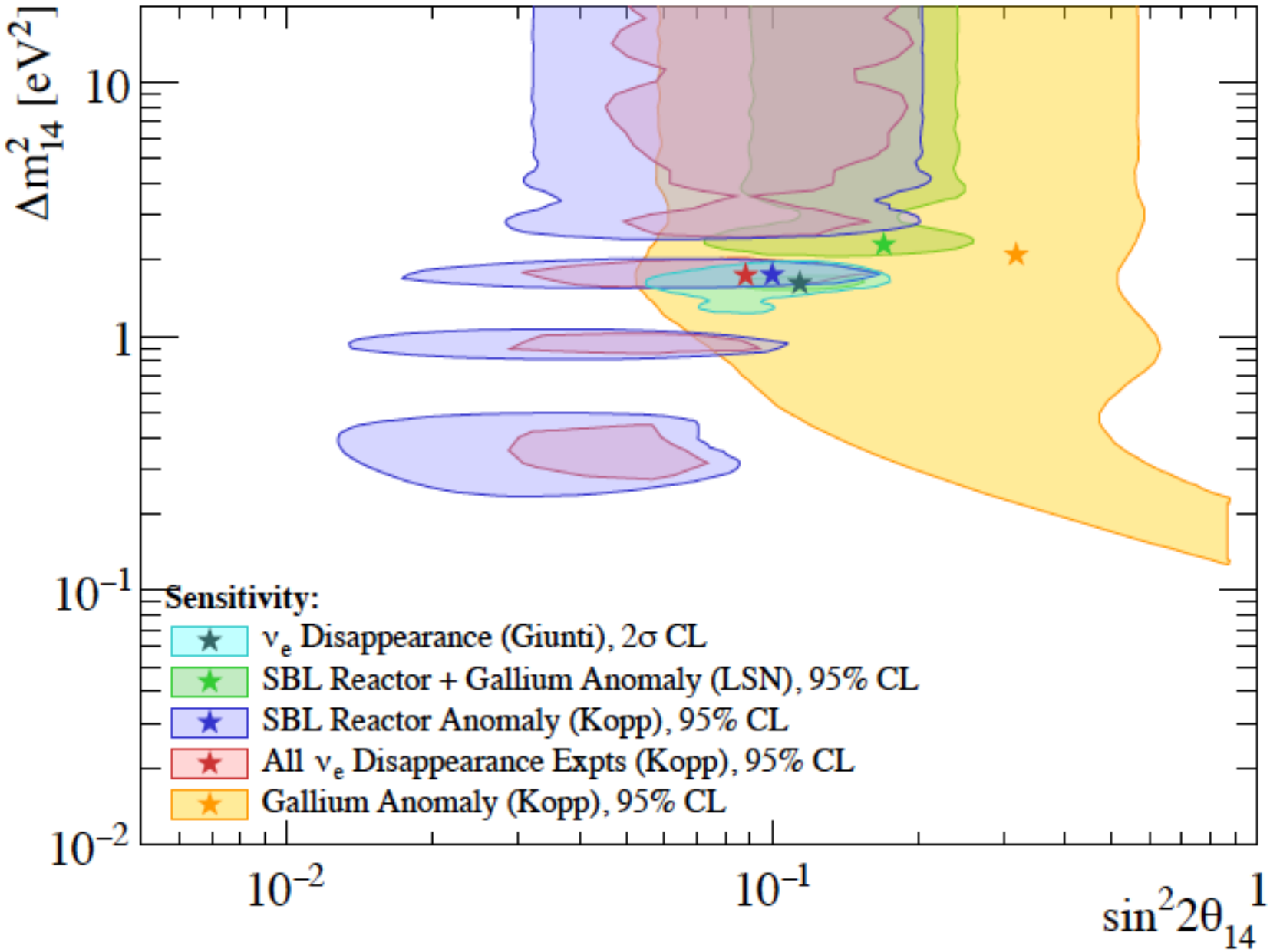
Update of [Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001]



Best Fit: $\Delta m^2_{41} = 1.6\,\mathrm{eV}^2$

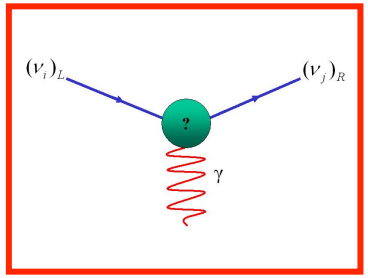
$|U_{e4}|^2 = 0.028$ $|U_{\mu 4}|^2 = 0.014$

Adopted from Giunti, NEUTRINO 2016



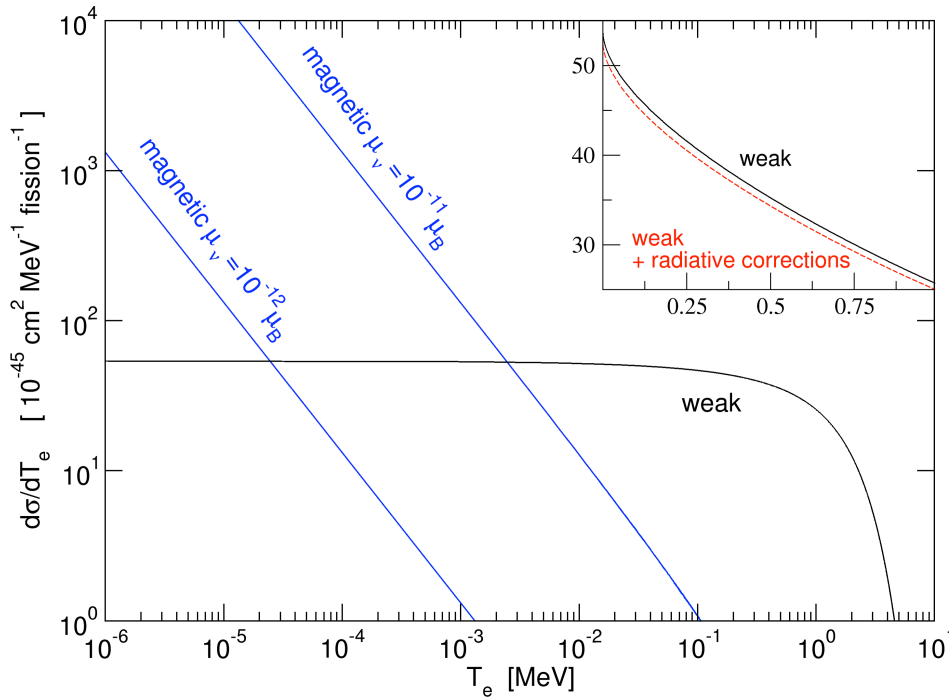
PROSPECT Collaboration, arXiv:1512.02202

Neutrino Magnetic Moment



$$\frac{d\sigma}{dT_e} = \frac{\alpha^2 \pi}{m_e^2} \mu_{\text{eff}}^2 \left[\frac{1}{T_e} - \frac{1}{E_\nu} \right]$$

$$\mu_{\text{eff}}^2 = \sum_i \left| \sum_j U_{ej} e^{-iE_j L} \mu_{ji} \right|^2$$



At lower energies, beyond Standard Model physics is described by local operators

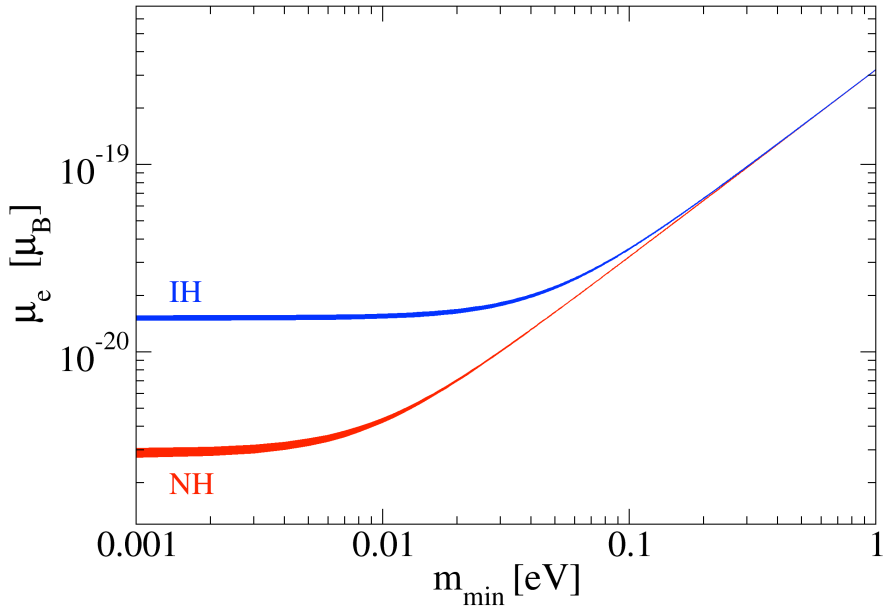
$$L = L_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} O_i^{(7)} + \ldots$$

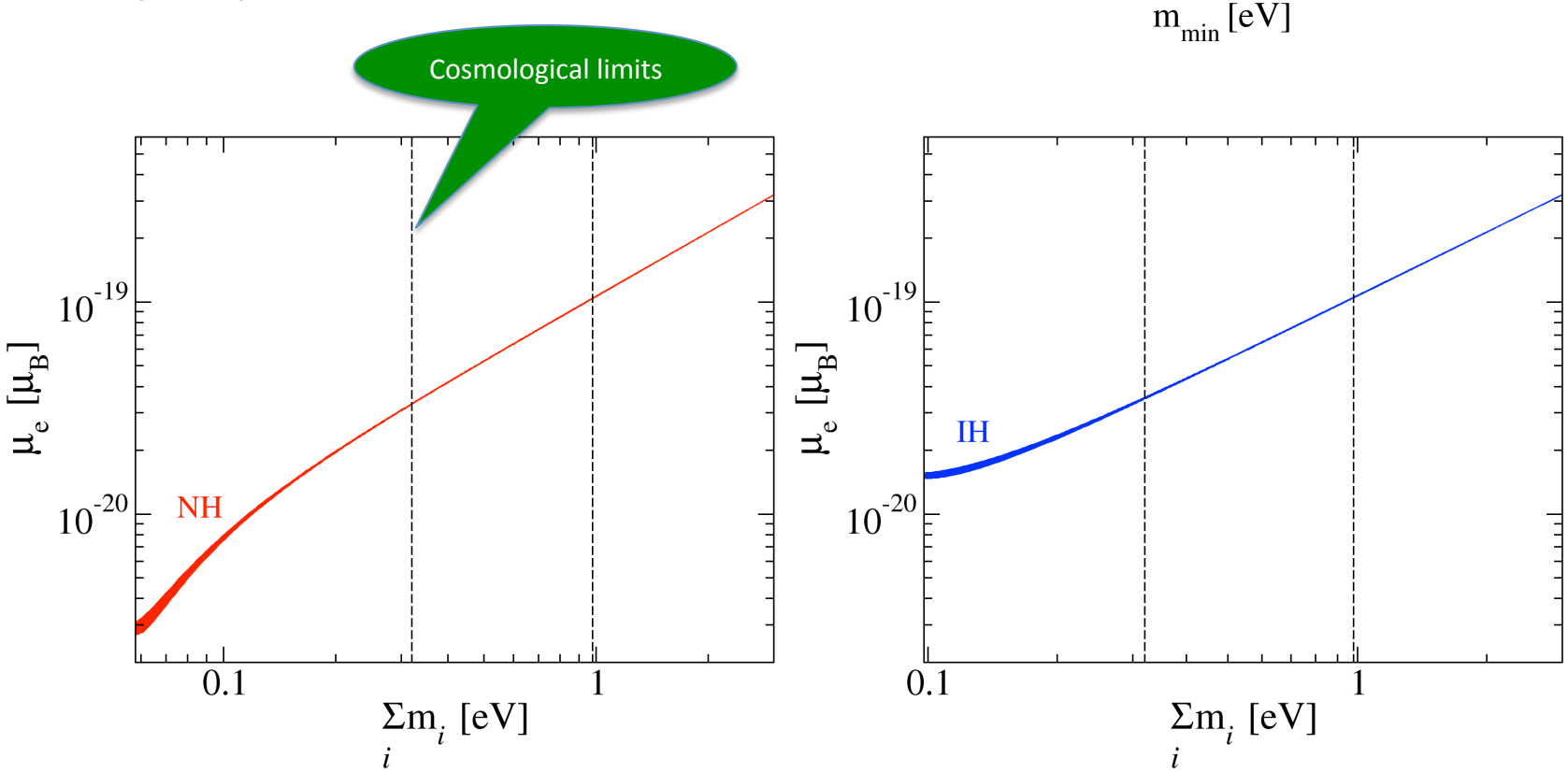
Majorana neutrino mass (unique)

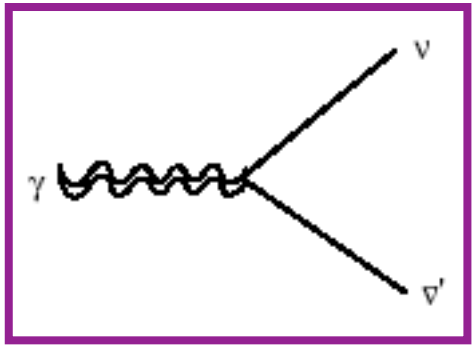
Includes Majorana neutrino magnetic moment

Minimally-extended Standard Model contribution to the Dirac neutrino magnetic moment measured at reactors

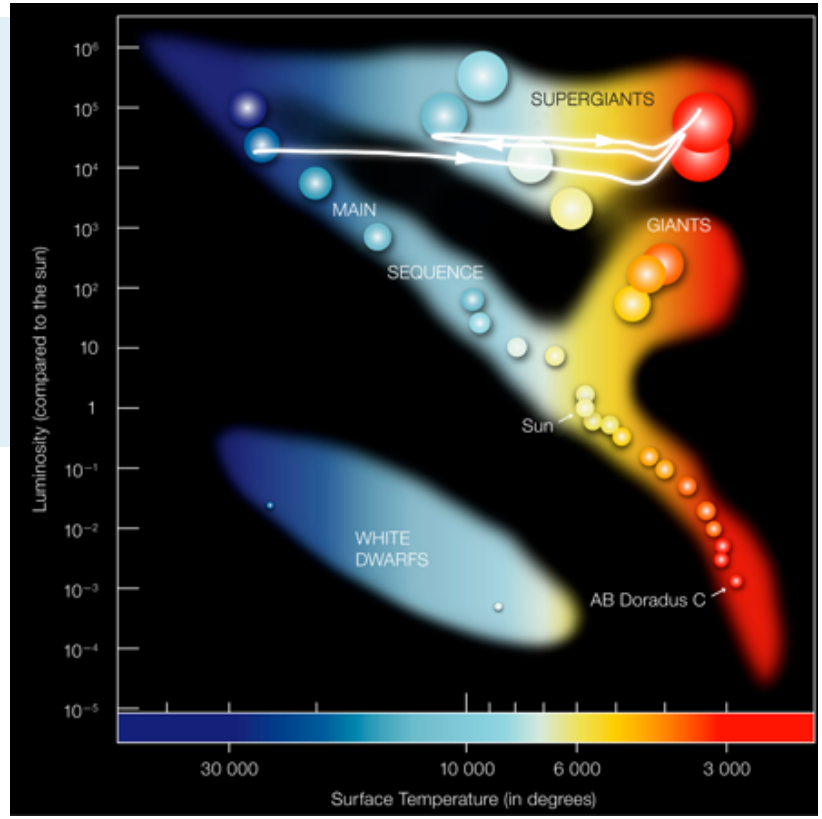
A.B.B., N. Vassh,
PRD **89** (2014) 073013

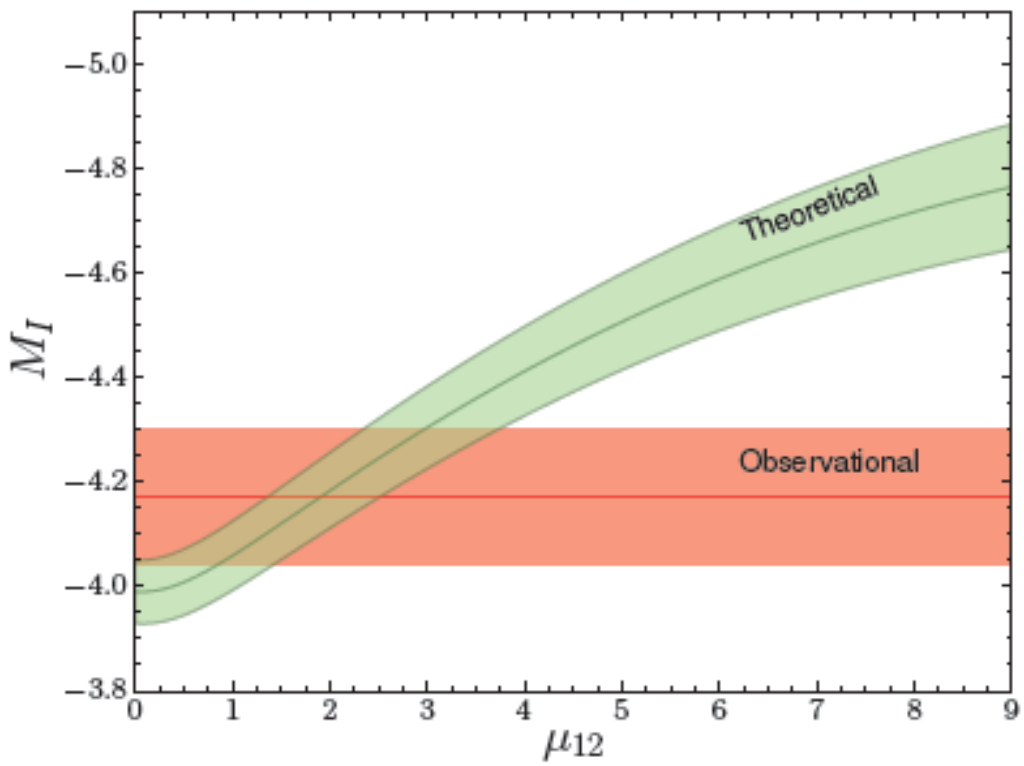






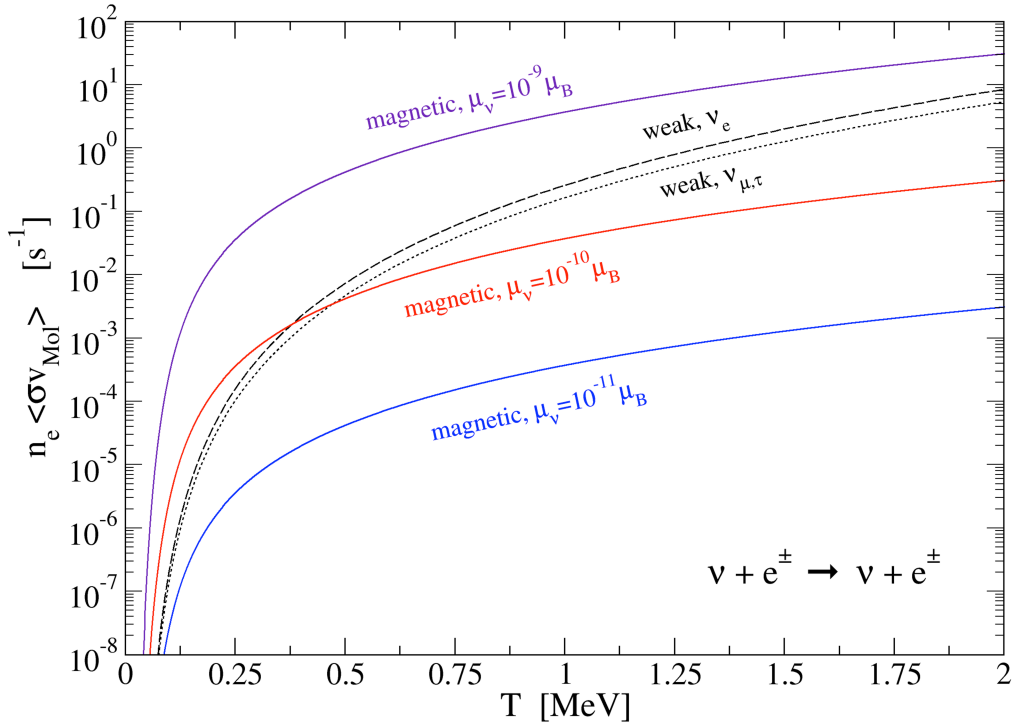
A large enough neutrino magnetic moment implies enhanced plasmon decay rate: $\gamma \rightarrow \nu\nu$. Since the neutrinos freely escape the star, this is turn cools a red giant star faster delaying helium ignition.





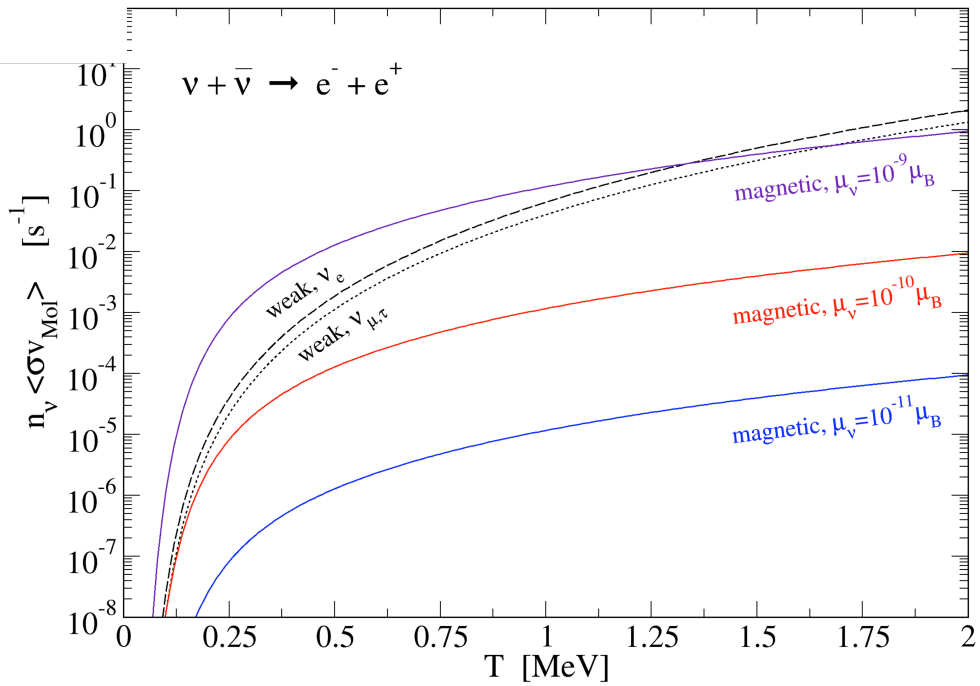
Globular cluster M5
➔ $\mu_\nu < 4.5 \times 10^{-12}\ \mu_B$
(95% C.L.)

arXiv:1308.4627

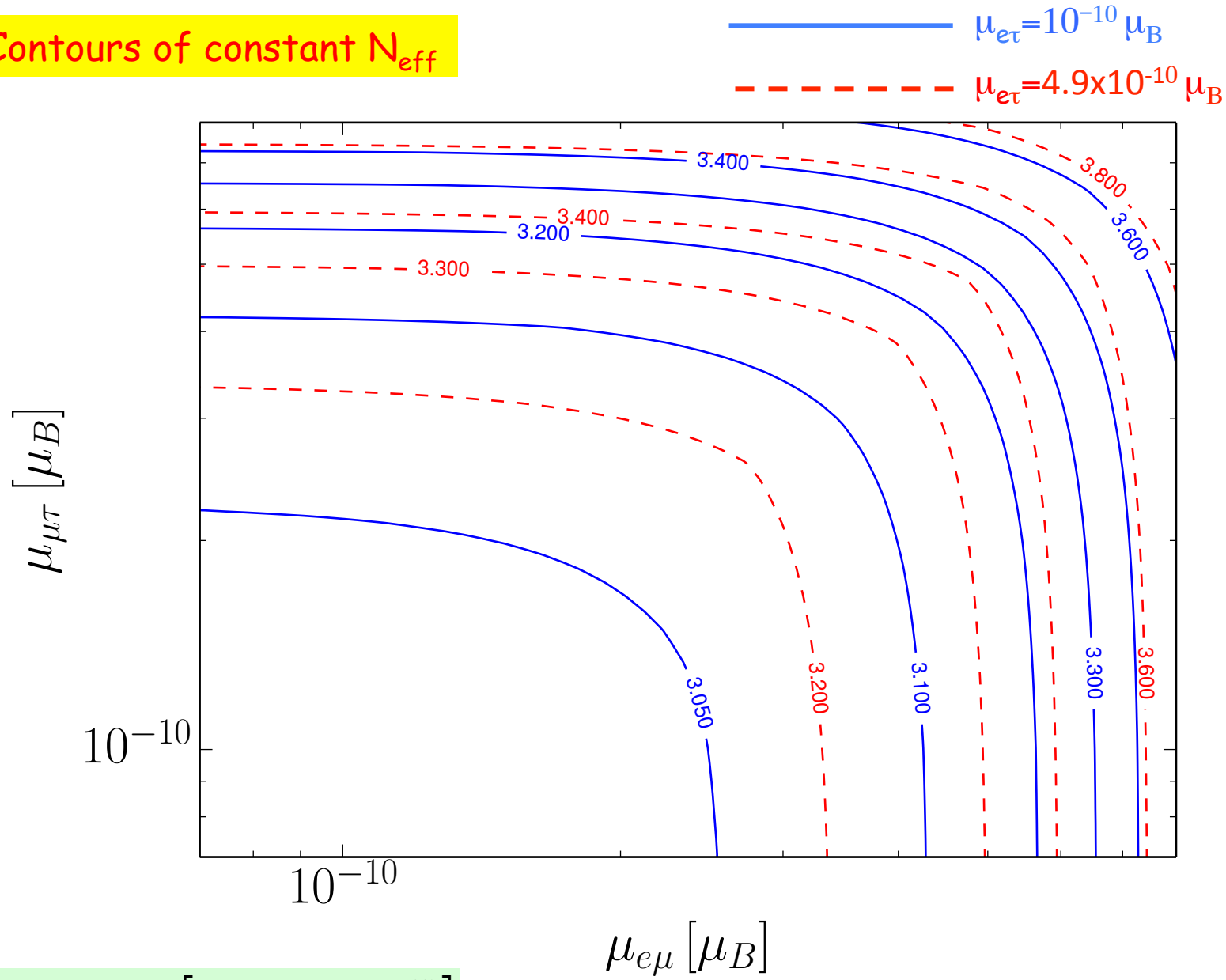


The effect of the neutrino magnetic moment on neutrino decoupling in the BBN epoch

Vassh, Grohs, Balantekin, Fuller, Phys. Rev. D **92**, 125020 (2015)



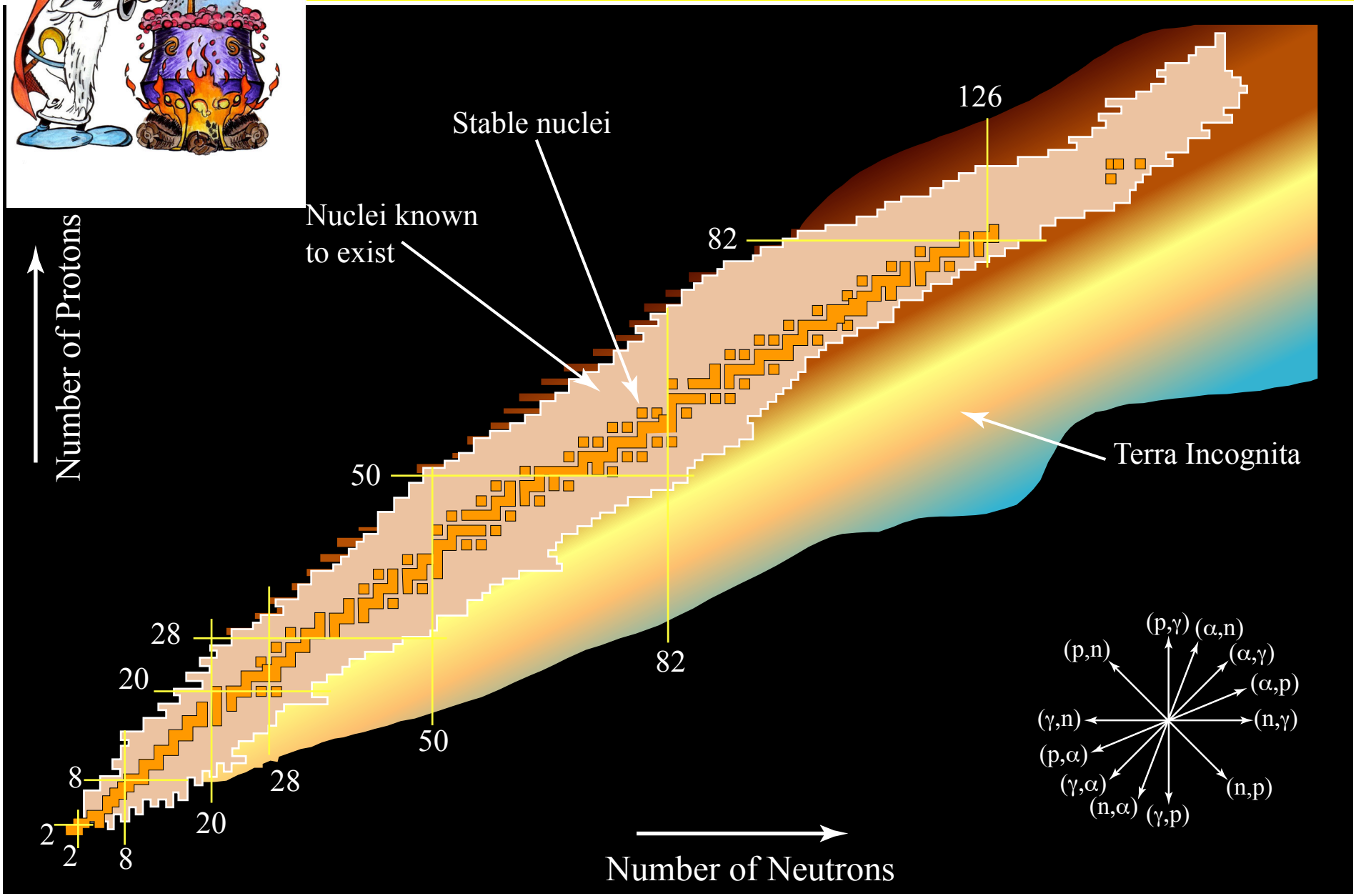
Contours of constant N_{eff}

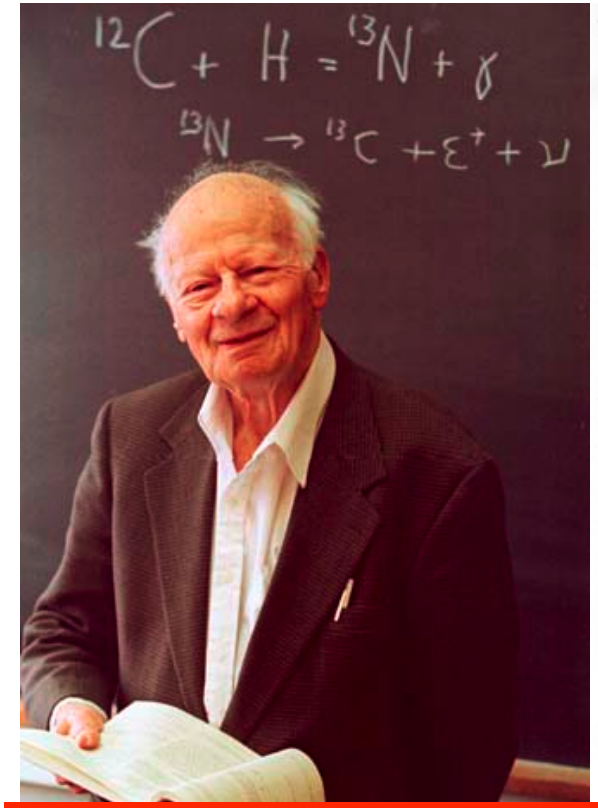


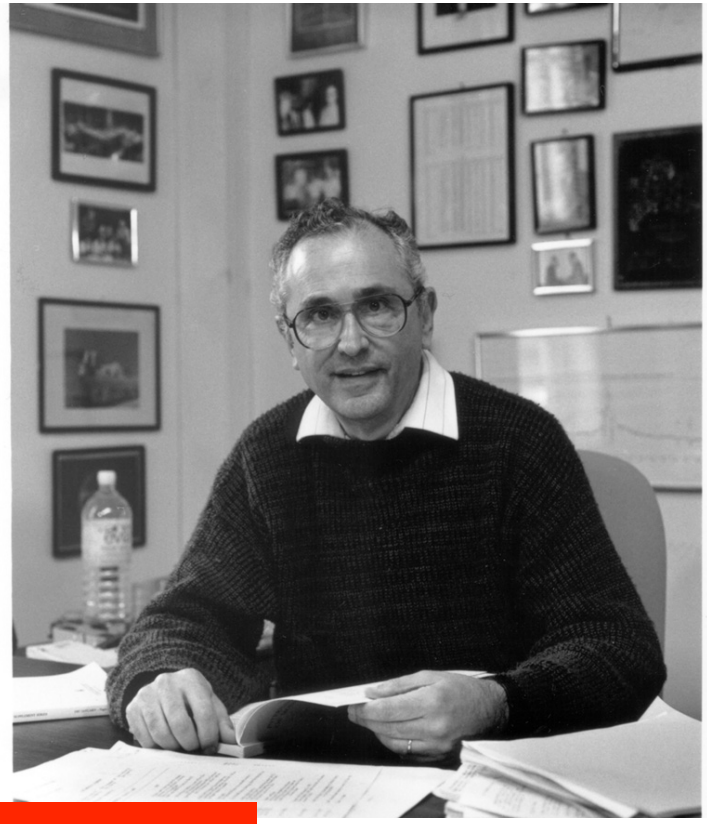
$$\rho_{\text{relativistic}} = \frac{\pi^2}{15} T_\gamma^4 \left[1 + \frac{7}{8} N_{\text{eff}} \left(\frac{4}{11} \right)^{4/3} \right]$$

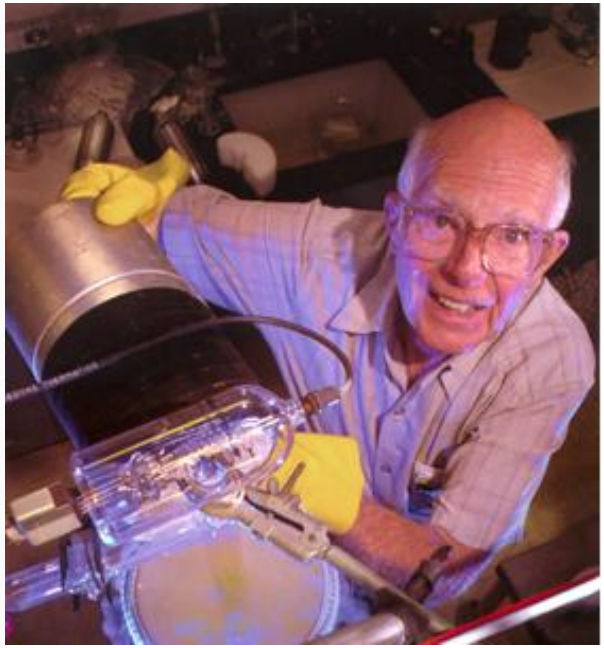
Planck: $N_{\text{eff}} = 3.30 \pm 0.27 \quad \Rightarrow \quad \mu \leq 6 \times 10^{-10}\,\mu_B$

How do you cook elements around us?





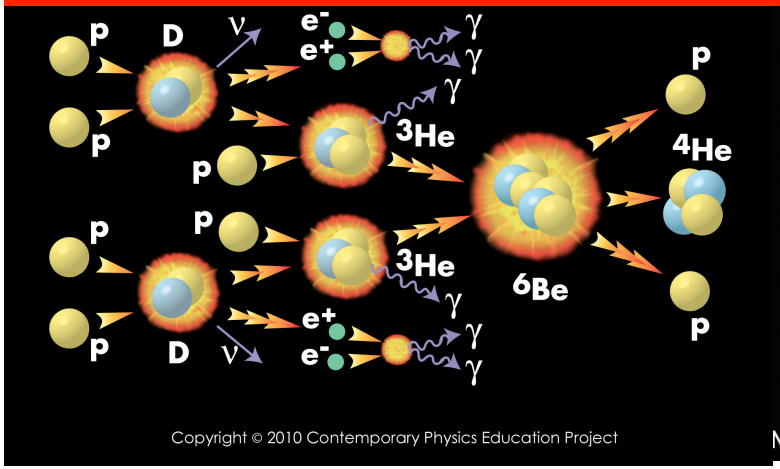


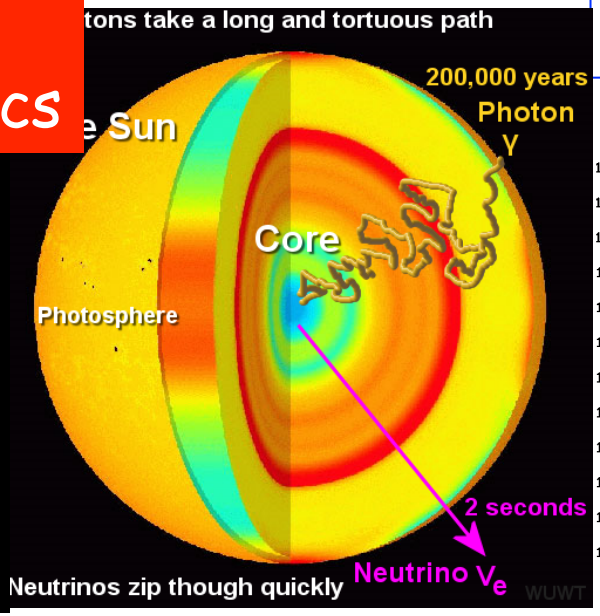


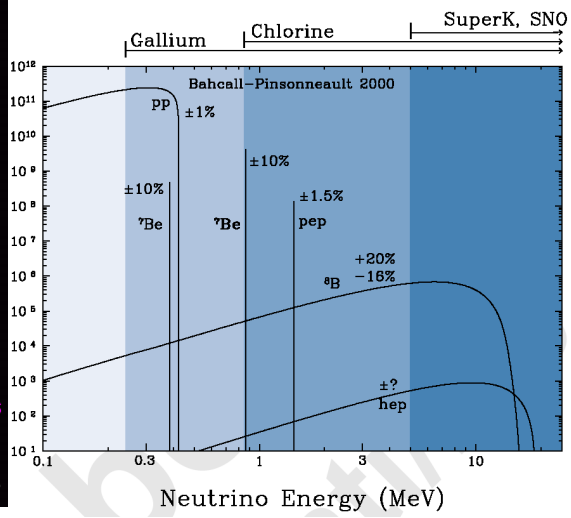
"...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation.."

Bahcall and Davis, 1964

Solar Neutrinos: Triumph of nuclear physics

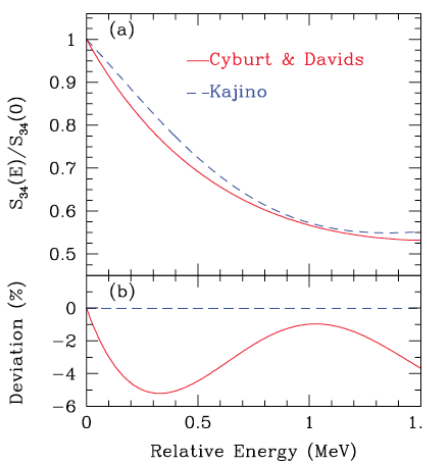




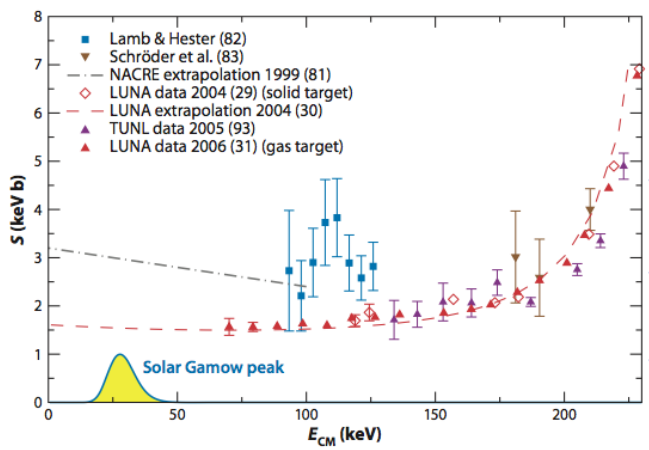


SSM Error Budget

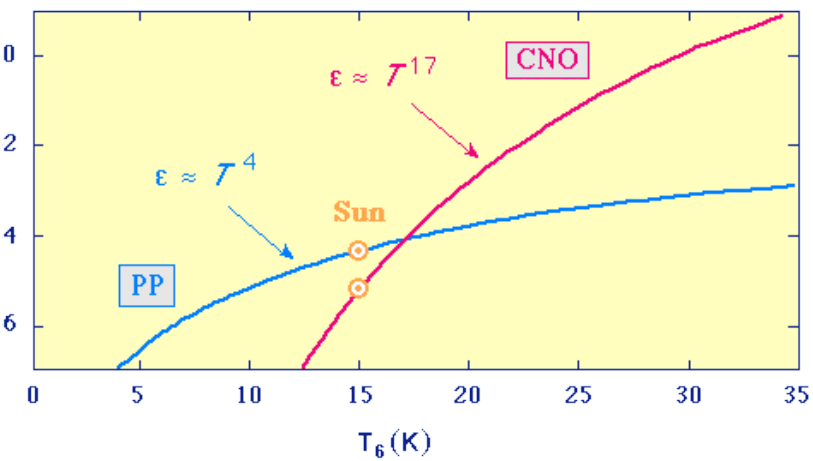
Source	Percentage Error
Diffusion coefficient of SSM	2.7%
Nuclear rates [mainly $^{7}Be(p,\gamma)^{8}B$ and $^{14}N(p,\gamma)^{15}O$]	9.9%
Neutrinos and weak interaction (mainly θ_{12})	3.2%
Other SSM input parameters	0.6%



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



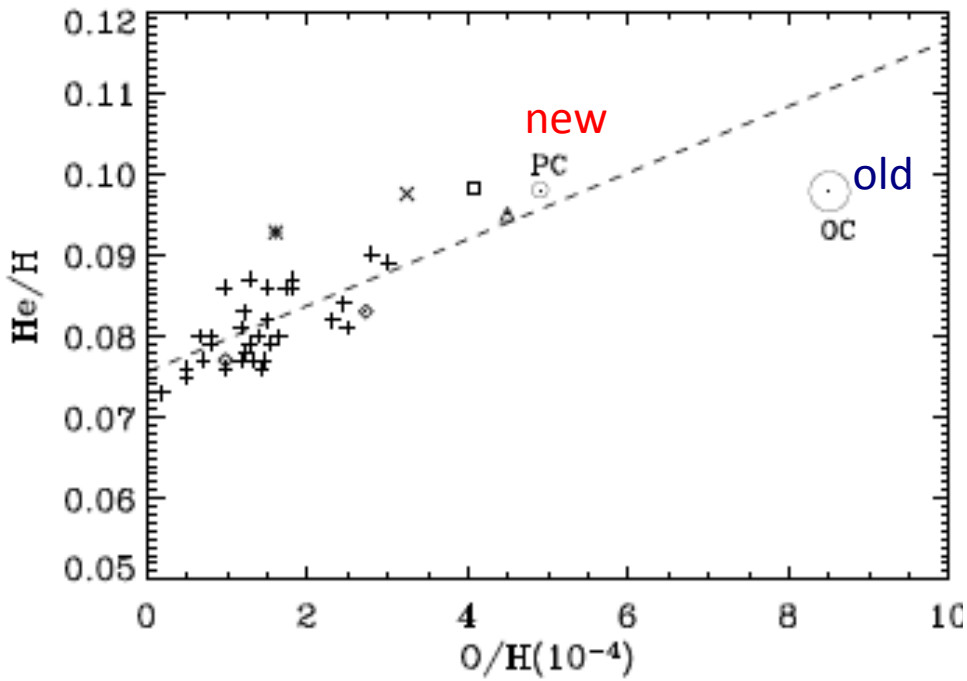
$^{14}N(p,\gamma)^{15}O$



New Solar abundances:

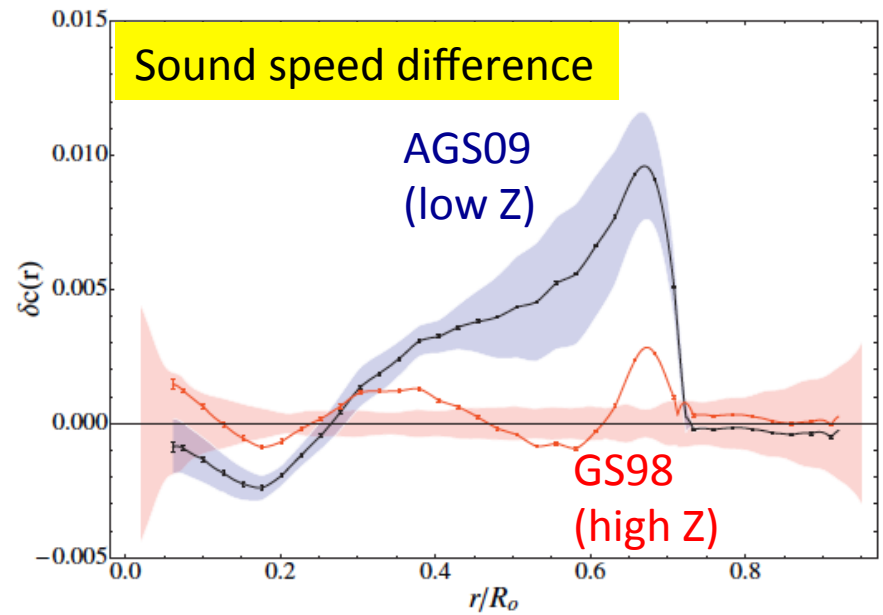
- Asplund *et al.* (AGS09), $(Z/X)_{\odot}=0.0178$
- Grevesse and Sauvel (GS98), $(Z/X)_{\odot}=0.0229$

This fixes some old puzzles



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

But creates new ones!



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

Old ^{8}B neutrino flux = 4×10^{6} $cm^{-2}s^{-1}$
New ^{8}B neutrino flux = 5.31×10^{6} $cm^{-2}s^{-1}$

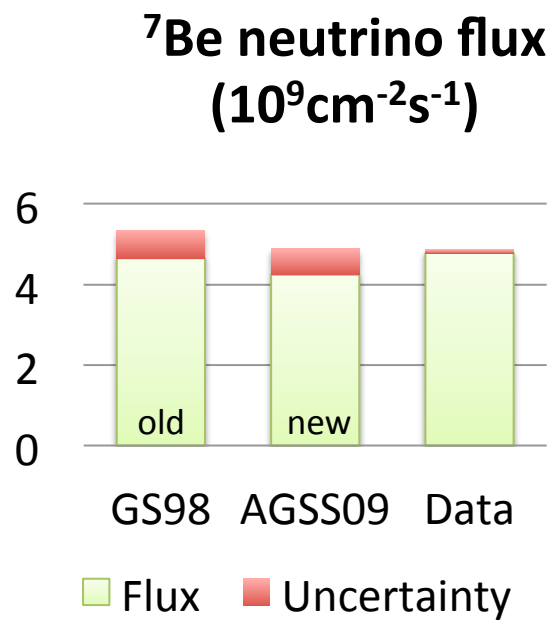
CNO Neutrinos are still not measured!

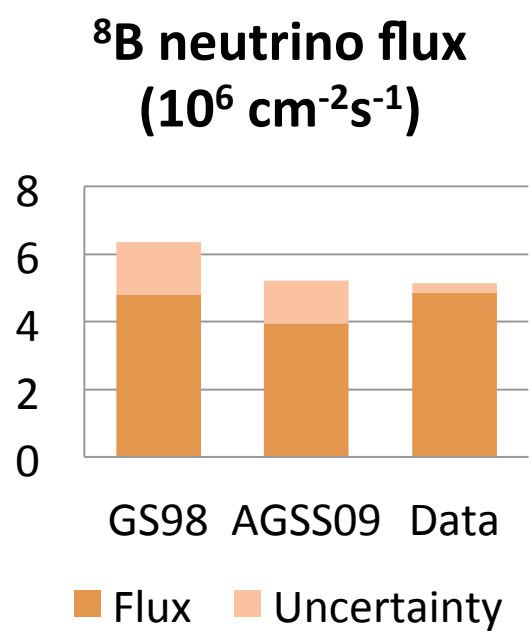
New Solar abundances:

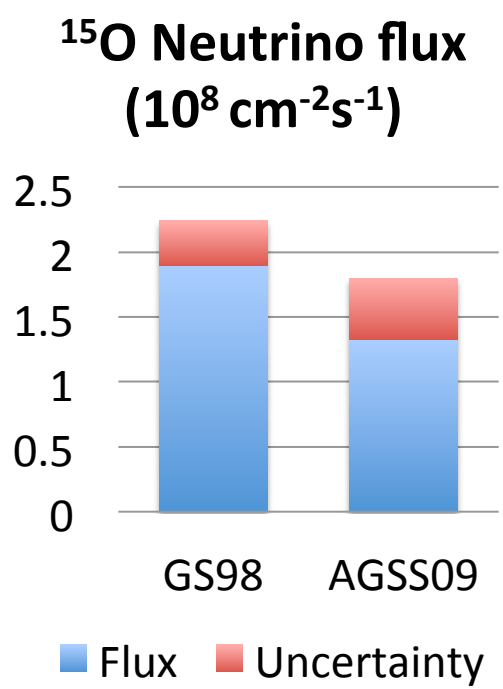
- Asplund *et al.* (AGSS09), $(Z/X)_{\odot}=0.0178$
- Grevesse and Sauvel (GS98), $(Z/X)_{\odot}=0.0229$

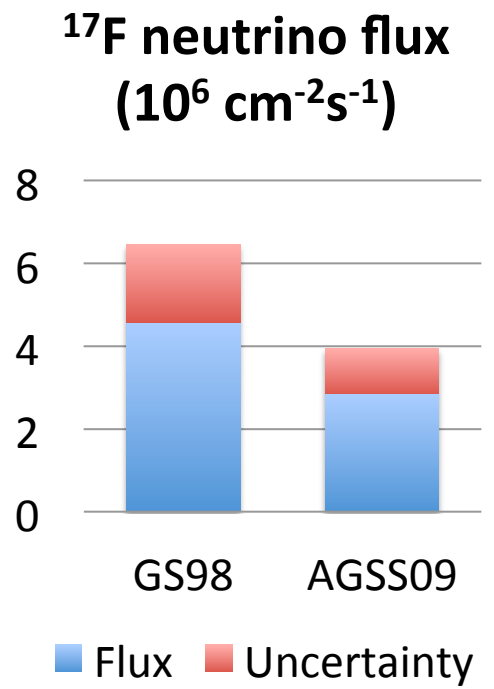
Drastically different!
Open problem in solar physics!

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

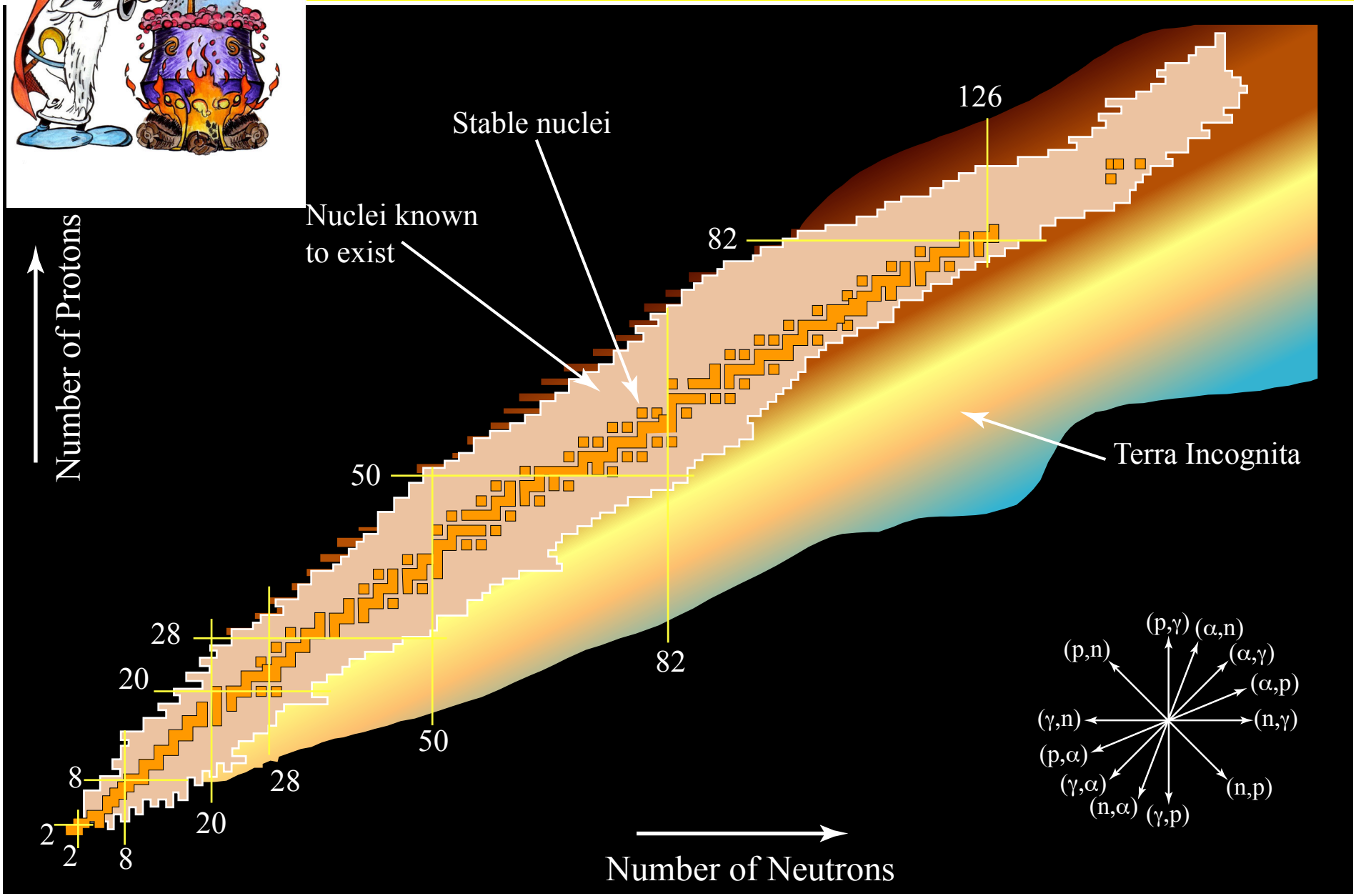








How do you cook elements around us?



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?

How do you cook elements around us?

Pop II stars
(metal poor)

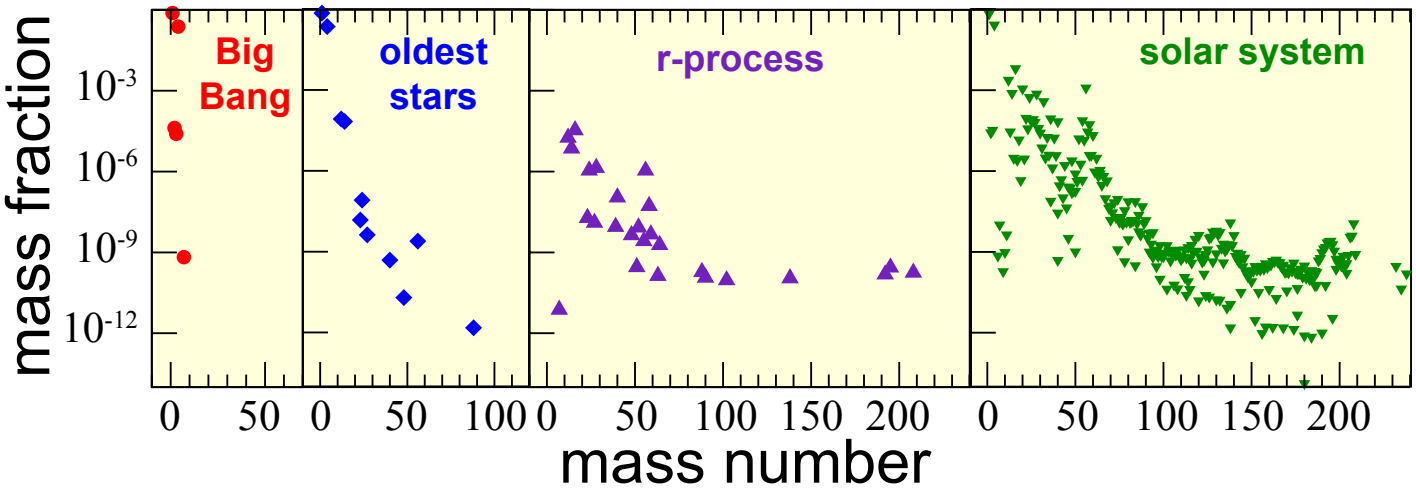
How do you cook elements around us?

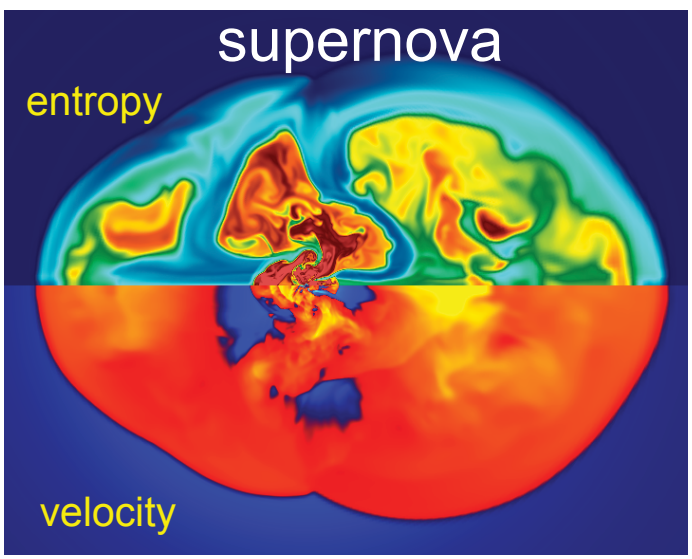
Some go supernova, producing U, Eu, Th… via the r-process

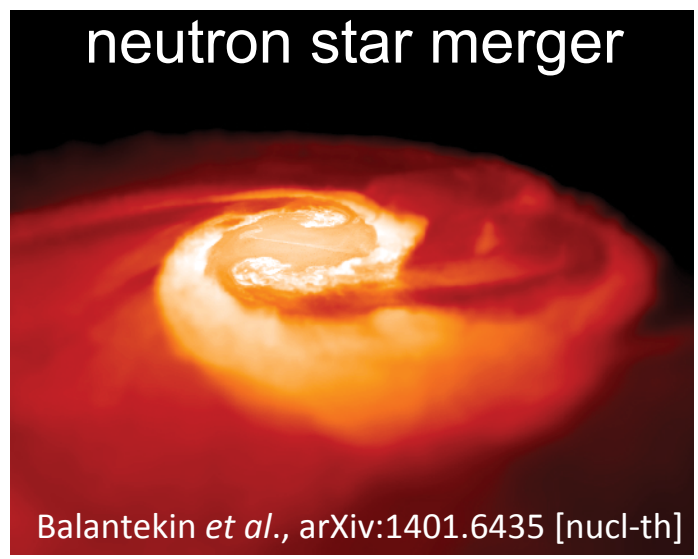
Pop II stars (metal poor)

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

The origin of elements



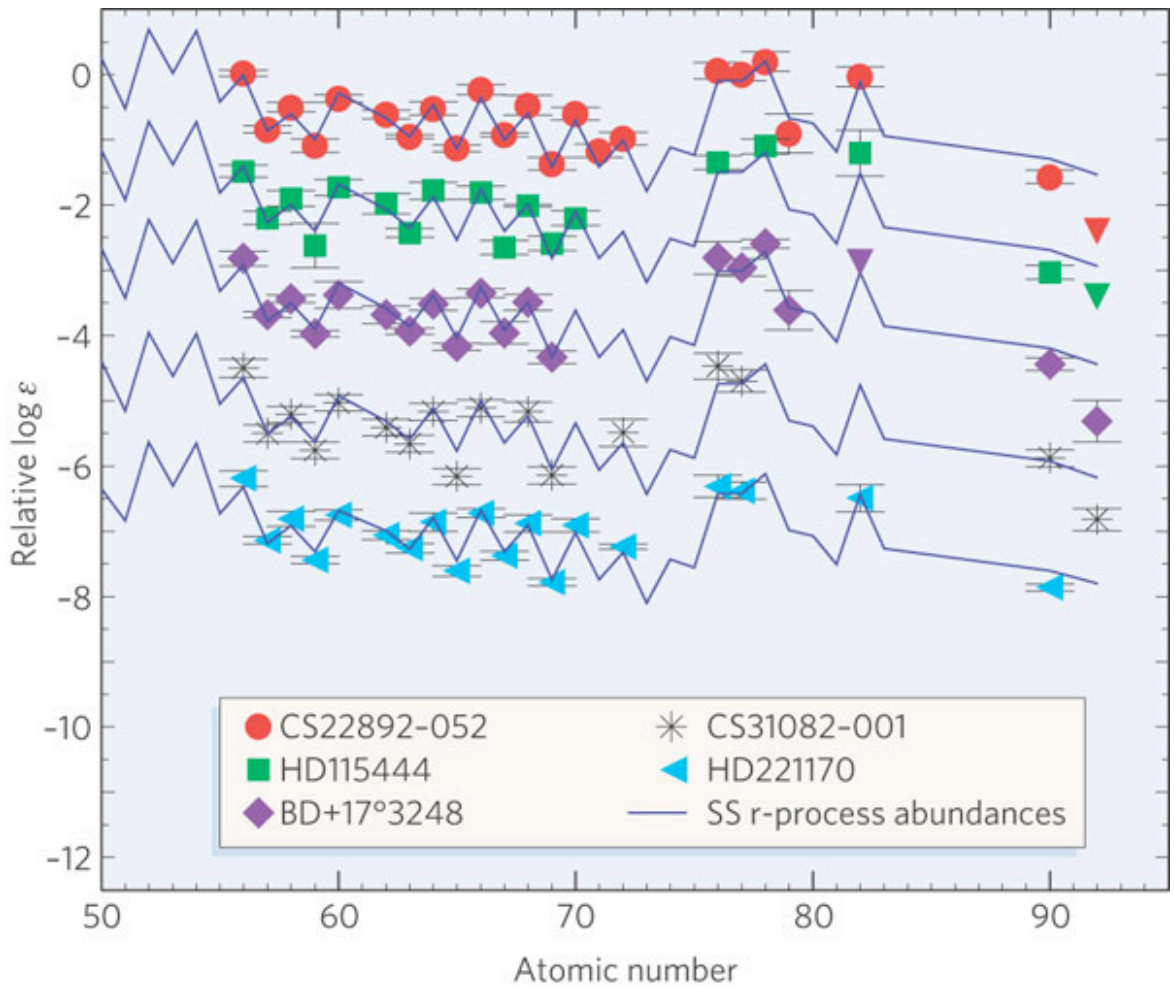


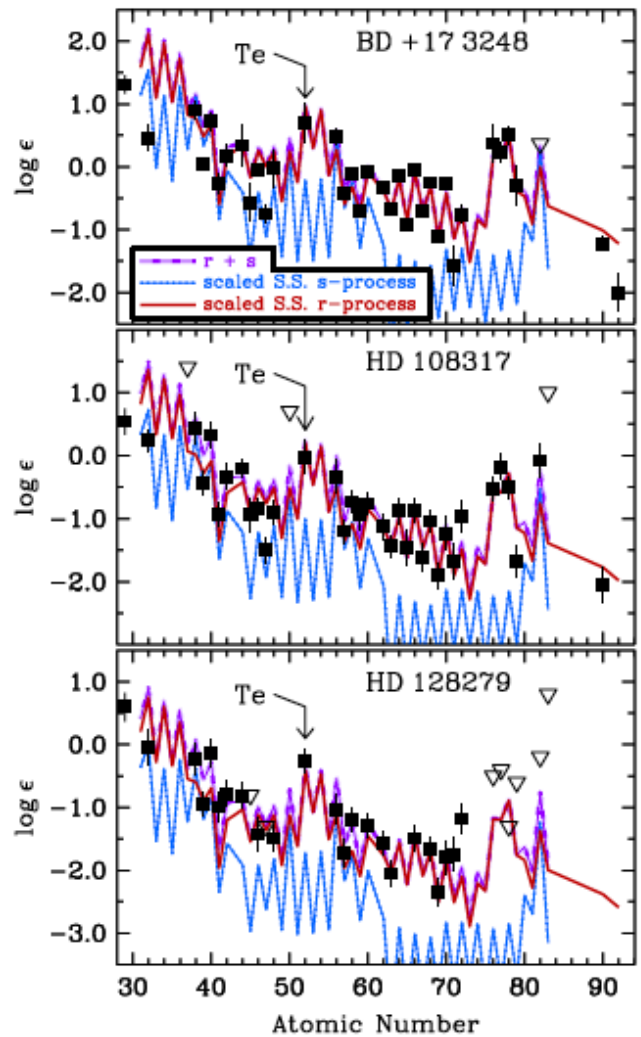


Possible sites for the r-process

Neutrinos not only play a crucial role in the dynamics of these sites, but they also control the value of the electron fraction, the parameter determining the yields of the r-process.

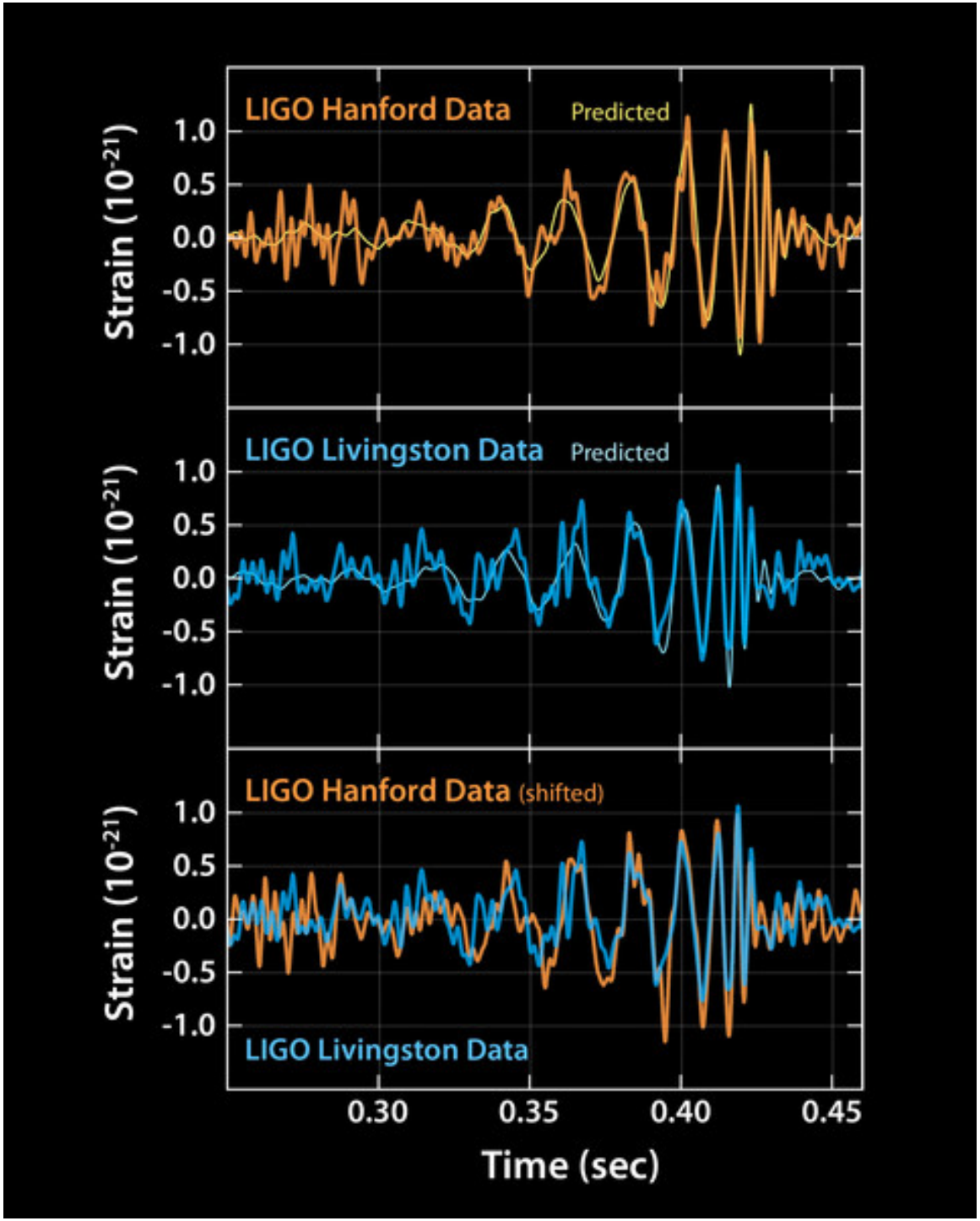
r-process nucleosynthesis





Roederer *et al.*, Ap. J. Lett. **747**, L8 (2012)

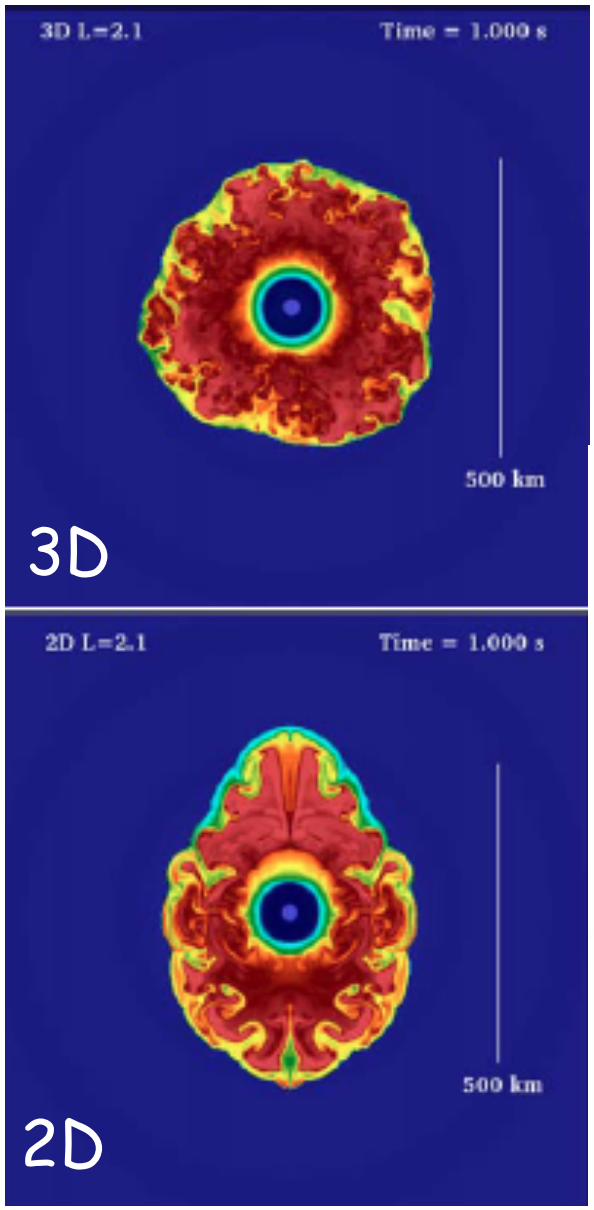
A > 100 abundance pattern fits the solar abundances well.



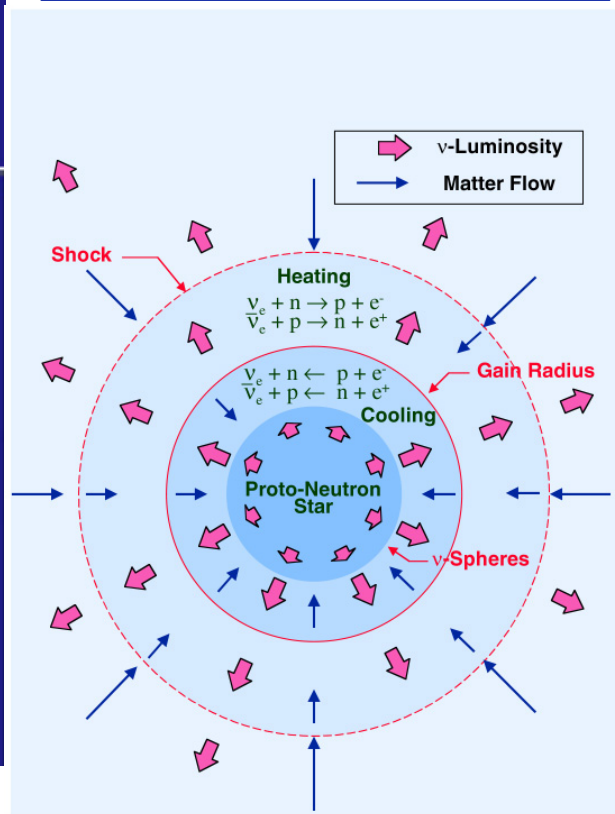
LIGO has detected gravitational waves from mergers of two black holes. Neutron star mergers also produce gravitational waves.
Their detection will help evaluate neutron star merger rate and hence the distribution of elements in the Cosmos!

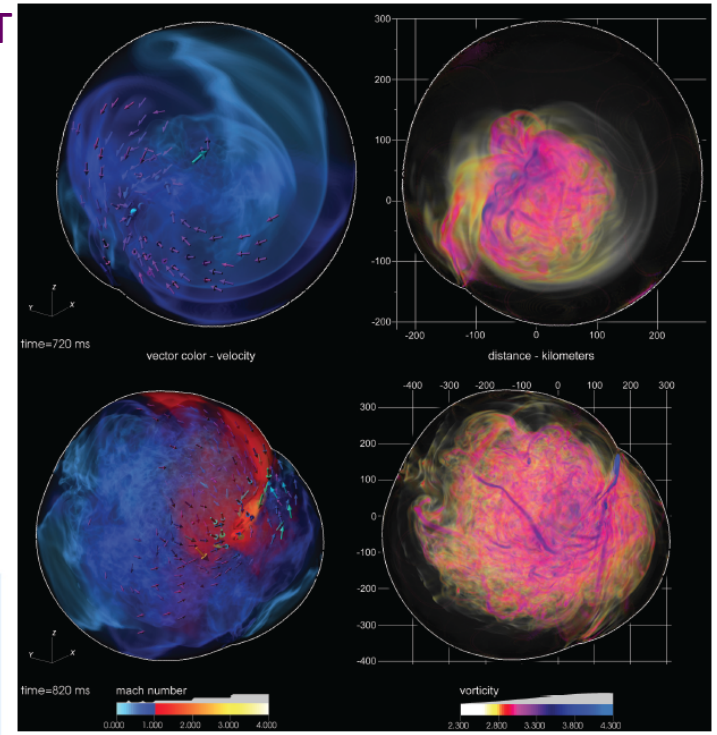
ORNL/UT

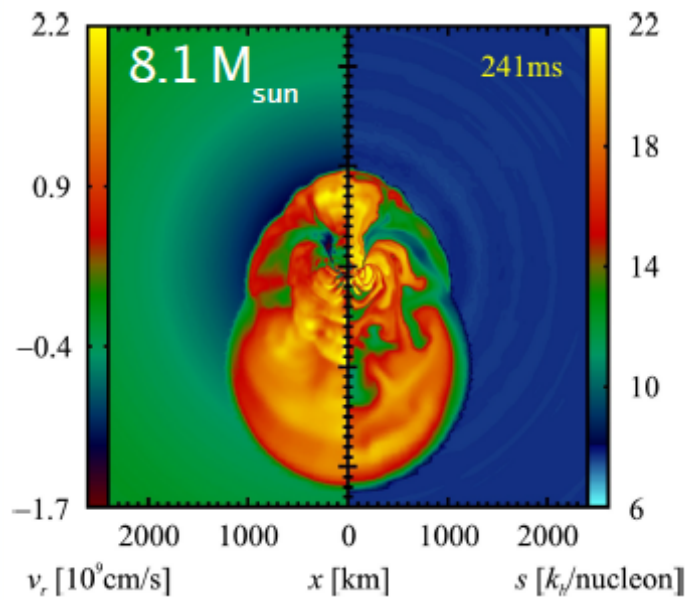
Development of 2D and 3D models for core-collapse supernovae: Complex interplay between turbulence, neutrino physics and thermonuclear reactions.



Princeton

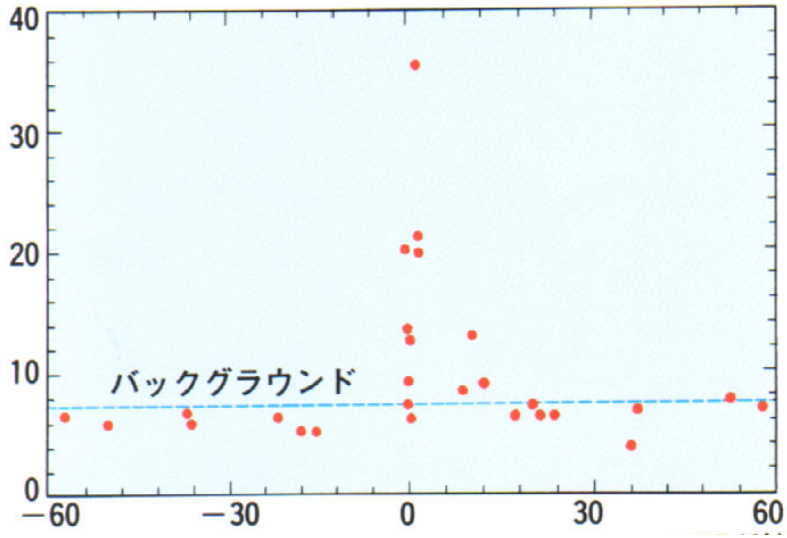


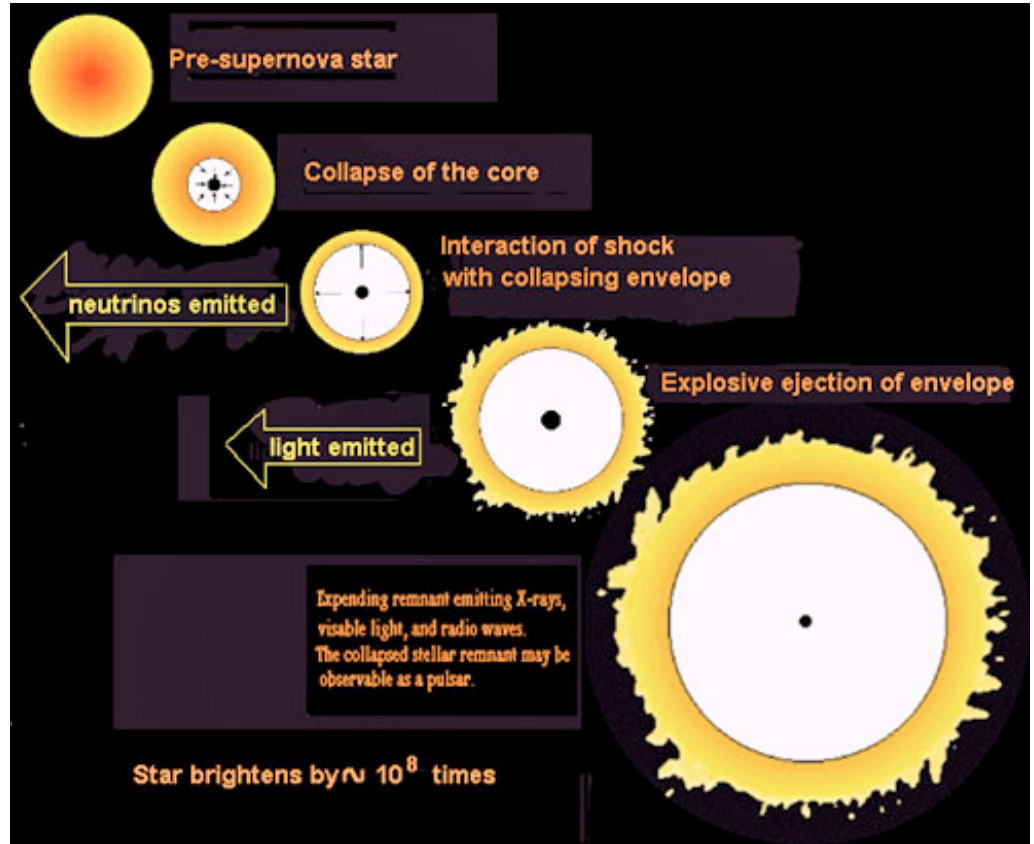




Munich

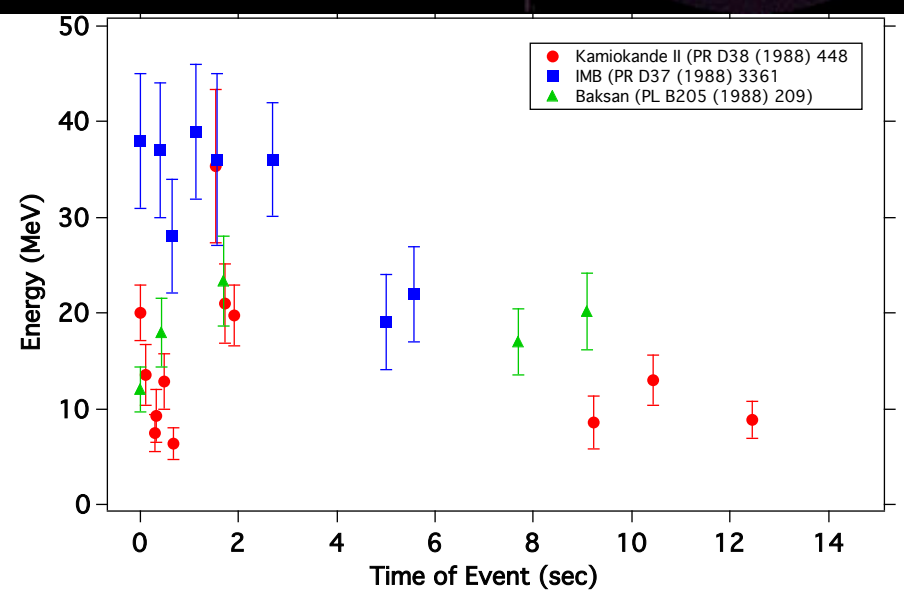
Neutrinos from core-collapse supernovae





- $M_{prog} \geq 8\ M_{sun} \Rightarrow \Delta E \approx 10^{53}$ ergs $\approx 10^{59}$ MeV

- 99% of the energy is carried away by neutrinos and antineutrinos with $10 \leq E_\nu \leq 30$ MeV $\Rightarrow 10^{58}$ neutrinos



Neutrinos dominate the energetics of core-collapse SN

Explosion only 1% of total energy

Total optical and kinetic energy = 10^{51} ergs

Total energy carried by neutrinos = 10^{53} ergs

10% of star's rest mass

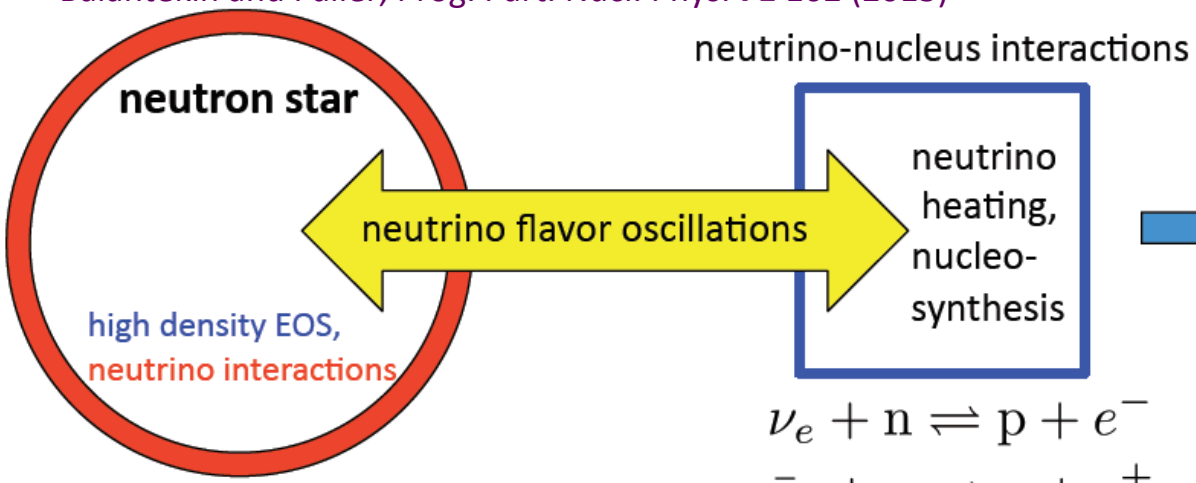
$$E_{grav} \cong \frac{3}{5}\frac{GM_{ns}^2}{R_{ns}} \approx 3\times 10^{53} ergs \left(\frac{M_{ns}}{1.4M_{sun}}\right)^2 \left(\frac{10km}{R_{ns}}\right)$$

Neutrino diffusion time, τ_ν ~ 2-10 s

$$L_\nu \approx \frac{GM_{ns}^2}{6R_{ns}}\frac{1}{\tau_\nu} \approx 4\times 10^{51} ergs/s$$

For example 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)



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

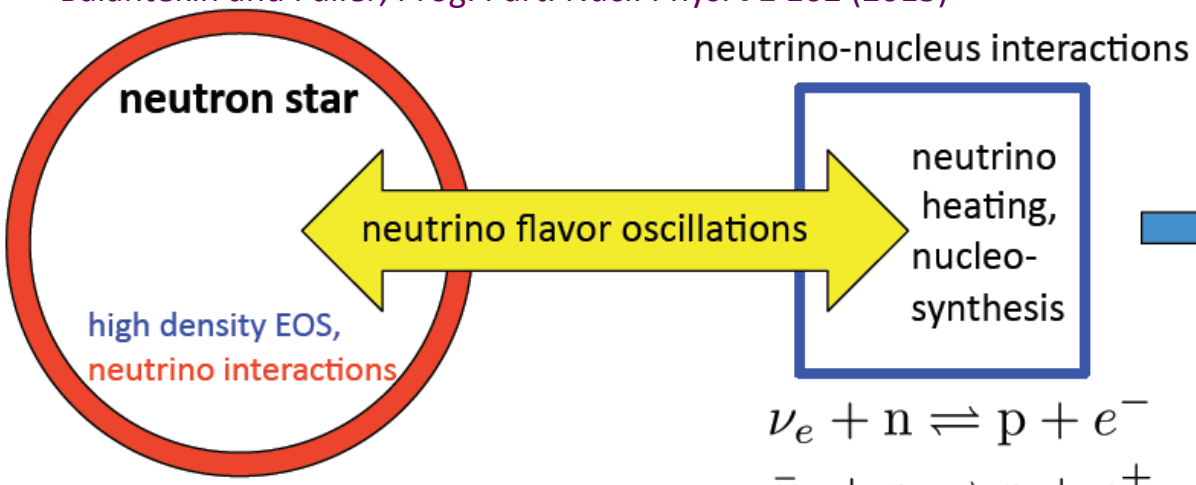
neutrino SN burst detection at earth

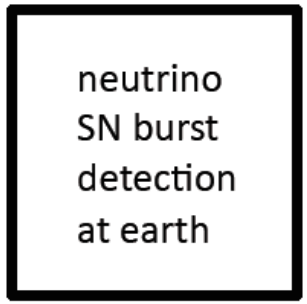
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$$
$$\nu_x + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Ar}^* + \nu_x$$

If we want to catch a supernova with neutrinos we'd better know what neutrinos do inside a supernova.

For example 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)

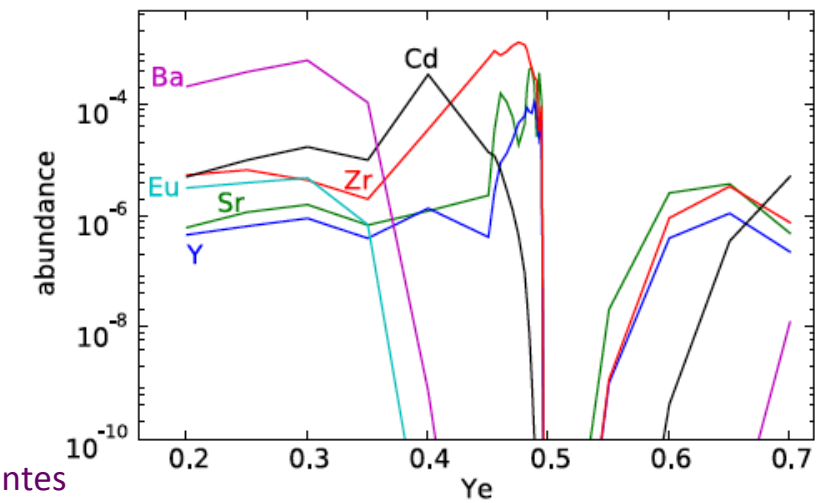




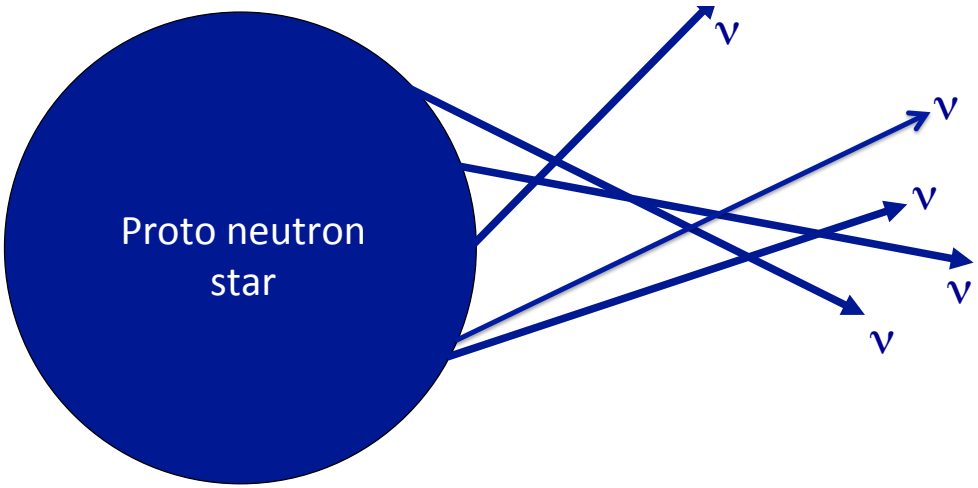
$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

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

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



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 νν interactions!

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

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

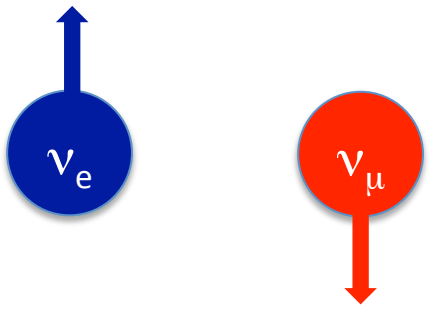
This is the only many-body system driven by the weak interactions:

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!

Neutrino flavor isospin



$$\hat{J}_+ = a_e^\dagger a_\mu \qquad \hat{J}_- = a_\mu^\dagger a_e$$

$$\hat{J}_0 = \frac{1}{2}\left(a_e^\dagger a_e - a_\mu^\dagger a_\mu\right)$$

These operators can be written in either mass or flavor basis

Free neutrinos at a single given energy (only mixing)

$$\hat{H} = \underbrace{\frac{m_1^2}{2E} a_1^\dagger a_1 + \frac{m_2^2}{2E} a_2^\dagger a_2}_{\text{matter basis}} = \underbrace{\frac{\delta m^2}{4E}\cos 2\theta\left(-2\hat{J}_0\right) + \frac{\delta m^2}{4E}\sin 2\theta\left(\hat{J}_+ + \hat{J}_-\right)}_{\text{flavor basis}}$$

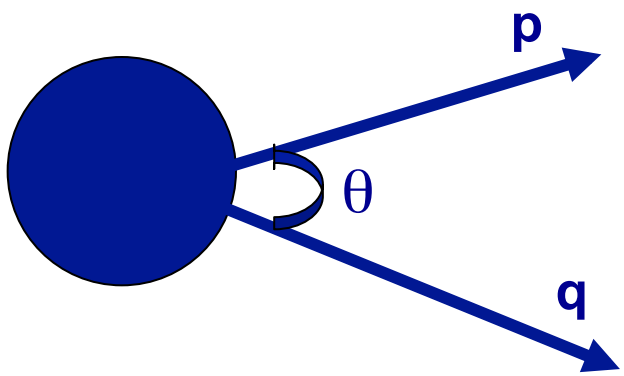
Interacting with background electrons

$$\hat{H} = \left[\frac{\delta m^2}{4E}\cos 2\theta - \frac{1}{\sqrt{2}} G_F N_e\right]\left(-2\hat{J}_0\right) + \frac{\delta m^2}{4E}\sin 2\theta\left(\hat{J}_+ + \hat{J}_-\right)$$

Neutrino-Neutrino Interactions

Smirnov, Fuller and Qian, Pantaleone, McKellar, Friedland, Lunardini, Duan, Raffelt, Balantekin, Kajino, Pehlivan …

$$\hat{H}_{\nu\nu} = \frac{\sqrt{2}G_F}{V}\int dp\, dq \left(1-\cos\theta_{pq}\right)\vec{\mathbf{J}}_p \cdot \vec{\mathbf{J}}_q$$



This term makes the physics of a neutrino gas in a core-collapse supernova a genuine many-body problem

Neutrino-Neutrino Interactions

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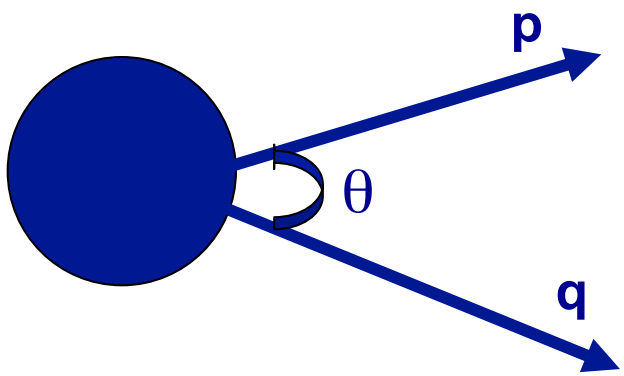


This term makes the physics of a neutrino gas in a core-collapse supernova a genuine many-body problem

$$\hat{H} = \int dp\left(\frac{\delta m^2}{2E}\vec{\mathbf{B}}\cdot\vec{\mathbf{J}}_p - \sqrt{2}G_F N_e \mathbf{J}_p^0\right) + \frac{\sqrt{2}G_F}{V}\int dp\, dq\left(1-\cos\theta_{pq}\right)\vec{\mathbf{J}}_p\cdot\vec{\mathbf{J}}_q$$

$$\vec{\mathbf{B}} = \left(\sin 2\theta,\ 0, -\cos 2\theta\right)$$

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").

Including antineutrinos

$$H = H_\nu + H_{\bar{\nu}} + H_{\nu\nu} + H_{\bar{\nu}\bar{\nu}} + H_{\nu\bar{\nu}}$$

Requires introduction of a second set of SU(2) algebras!

Including three flavors

Requires introduction of SU(3) algebras.

Both extensions are straightforward, but tedious!
Balantekin and Pehlivan, J. Phys. G **34**, 1783 (2007).

Single-angle approximation Hamiltonian:

$$H = \sum_p \frac{\delta m^2}{2p} J_p^0 + 2\mu \sum_{\substack{p,\,q \\ p \neq q}} \mathbf{J}_p \bullet \mathbf{J}_q$$

Eigenstates:

$$|x_i\rangle = \prod_{i=1}^{N} \sum_k \frac{J_k^\dagger}{\left(\delta m^2/2k\right) - x_i} |0\rangle$$

$$\underbrace{-\frac{1}{2\mu} - \sum_k \frac{j_k}{\left(\delta m^2/2k\right) - x_i} = \sum_{j \neq i} \frac{1}{x_i - x_j}}_{\text{Bethe ansatz equations}}$$

$$\mu = \frac{G_F}{\sqrt{2}V} \langle 1 - \cos\Theta \rangle$$

Invariants:

$$h_p = J_p^0 + 2\mu \sum_{\substack{p,\,q \\ p \neq q}} \frac{\mathbf{J}_p \bullet \mathbf{J}_q}{\delta m^2 \left(\frac{1}{p} - \frac{1}{q} \right)}$$

Pehlivan, ABB, Kajino, & Yoshida
Phys. Rev. D 84, 065008 (2011)

The duality between $H_{\nu\nu}$ and BCS Hamiltonians

The ν-ν Hamiltonian

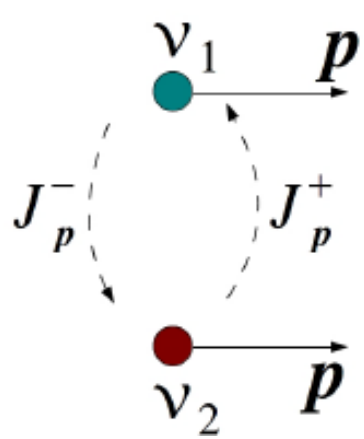
$$\hat{H} = \sum_p \frac{\delta m^2}{2p} \hat{B} \cdot \vec{J}_p + \frac{\sqrt{2} G_F}{V} \vec{J} \cdot \vec{J}$$

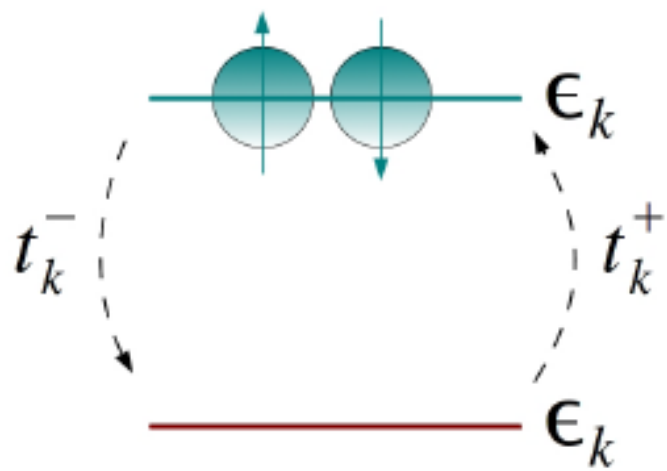
$\Longleftrightarrow$

The BCS Hamiltonian

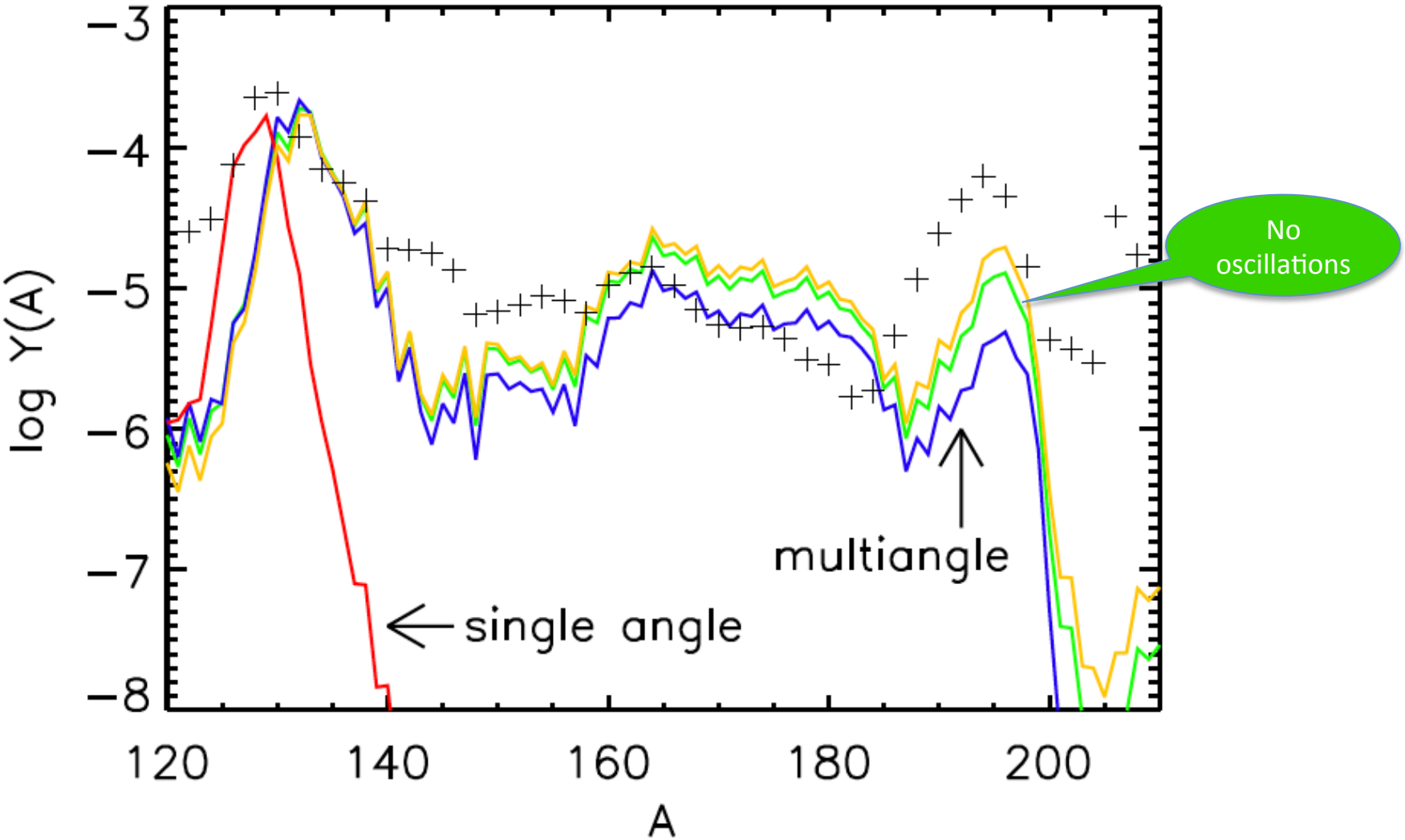
$$\hat{H}_{\mathrm{BCS}} = \sum_k 2\epsilon_k \hat{t}_k^0 - |G| \hat{T}^+ \hat{T}$$

Same symmetries leading to Analogous (dual) dynamics!
Pehlivan, Balantekin, Kajino, and Yoshida, Phys.Rev. D **84**, 065008 (2011)





This symmetry naturally leads to splits in the neutrino energy spectra and was used to find conserved quantities in the single-angle case.



Duan, Friedland, McLaughlin, Surman

What is the mean-field approximation?

$$\left[\hat{O}_1, \hat{O}_2\right] \cong 0$$

$$\hat{O}_1\hat{O}_2 \approx \hat{O}_1\left\langle\hat{O}_2\right\rangle + \left\langle\hat{O}_1\right\rangle\hat{O}_2 - \left\langle\hat{O}_1\hat{O}_2\right\rangle$$

Expectation values should be calculated with a state $\left|\Psi\right\rangle$ chosen to satisfy:

$$\left\langle\hat{O}_1\hat{O}_2\right\rangle = \left\langle\hat{O}_1\right\rangle\left\langle\hat{O}_2\right\rangle$$

This reduces the two-body problem to a one-body problem:

$$a^\dagger a^\dagger a a \Rightarrow \left\langle a^\dagger a\right\rangle a^\dagger a + \left\langle a^\dagger a^\dagger\right\rangle a a + \text{h.c.}$$

$$\hat{H}_{\nu\nu} = \frac{\sqrt{2}G_F}{V}\int dp\,dq\left(1-\cos\theta_{pq}\right)\vec{\mathbf{J}}_p\cdot\vec{\mathbf{J}}_q \cong \frac{\sqrt{2}G_F}{V}\int dp\,dq\left(1-\cos\theta_{pq}\right)\left\langle\vec{\mathbf{J}}_p\right\rangle\cdot\vec{\mathbf{J}}_q$$

Mean field

Neutrino-neutrino interaction

$$\bar{\psi}_{\nu L}\gamma^{\mu}\psi_{\nu L}\bar{\psi}_{\nu L}\gamma_{\mu}\psi_{\nu L} \Rightarrow \bar{\psi}_{\nu L}\gamma^{\mu}\psi_{\nu L}\left\langle\bar{\psi}_{\nu L}\gamma_{\mu}\psi_{\nu L}\right\rangle + \cdots$$

Antineutrino-antineutrino interaction

$$\bar{\psi}_{\bar{\nu} R}\gamma^{\mu}\psi_{\bar{\nu} R}\bar{\psi}_{\bar{\nu} R}\gamma_{\mu}\psi_{\bar{\nu} R} \Rightarrow \bar{\psi}_{\bar{\nu} R}\gamma^{\mu}\psi_{\bar{\nu} R}\left\langle\bar{\psi}_{\bar{\nu} R}\gamma_{\mu}\psi_{\bar{\nu} R}\right\rangle + \cdots$$

Neutrino-antineutrino interaction

$$\bar{\psi}_{\nu L}\gamma^{\mu}\psi_{\nu L}\bar{\psi}_{\bar{\nu} R}\gamma_{\mu}\psi_{\bar{\nu} R} \Rightarrow \bar{\psi}_{\nu L}\gamma^{\mu}\psi_{\nu L}\left\langle\bar{\psi}_{\bar{\nu} R}\gamma_{\mu}\psi_{\bar{\nu} R}\right\rangle + \cdots$$

Balantekin and Pehlivan, JPG **34**,1783 (2007)

Neutrino-antineutrino can also have an additional mean field

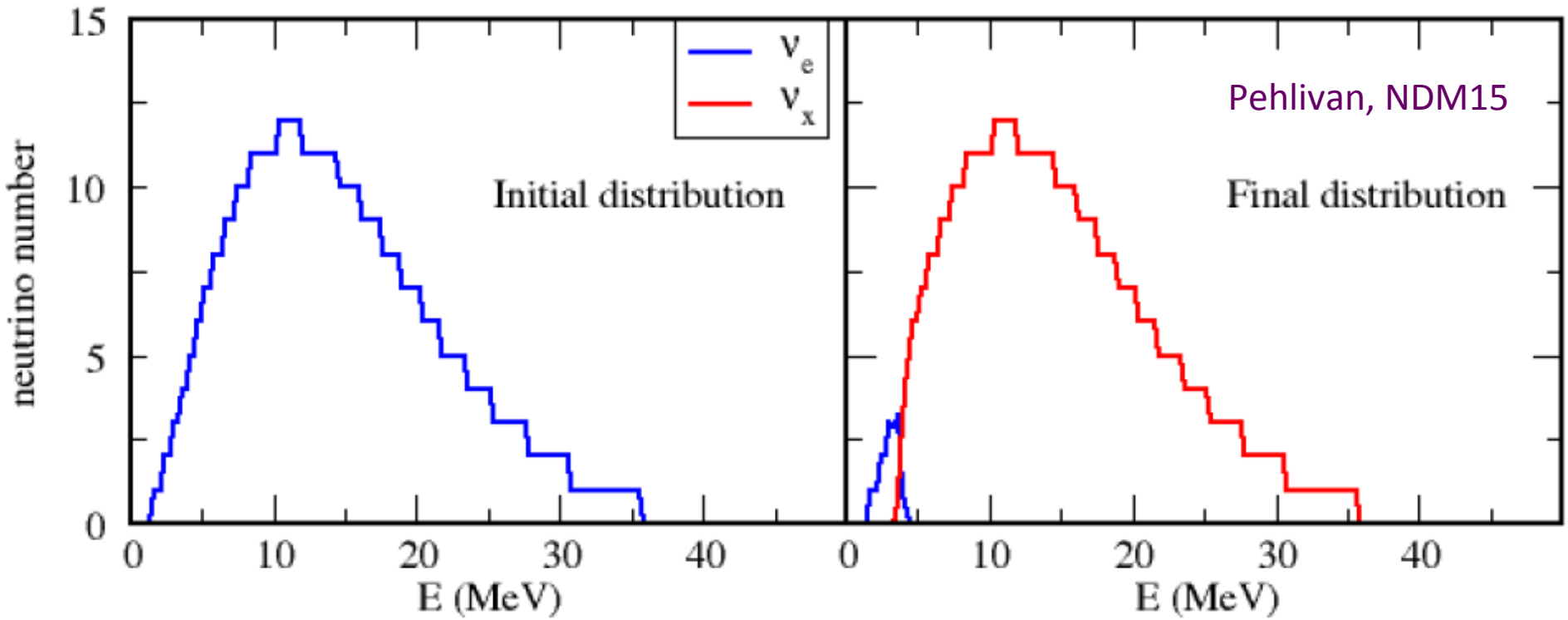
$$\bar{\psi}_{\nu L}\gamma^{\mu}\psi_{\nu L}\bar{\psi}_{\bar{\nu}R}\gamma_{\mu}\psi_{\bar{\nu}R} \Rightarrow \bar{\psi}_{\nu L}\gamma^{\mu}\left\langle \psi_{\nu L}\bar{\psi}_{\bar{\nu}R}\gamma_{\mu}\right\rangle \psi_{\bar{\nu}R} + \cdots$$

However note that

$$\left\langle \psi_{\nu L}\bar{\psi}_{\bar{\nu}R}\gamma_{\mu}\right\rangle \propto m_{\nu} \quad \text{(negligible if the medium is isotropic)}$$

Fuller *et al.*
Volpe

Away from the mean-field: First adiabatic solution of the *exact* many-body Hamiltonian



- Solutions of the Bethe ansatz equations for 250 neutrinos. Same behavior as the mean-field.
- Two flavors only
- Inverted hierarchy, no matter effect

Two-neutrino double-beta decay was first predicted by Maria Goeppert *Mayer.*

She was *awarded* the 1963 *Physics Nobel Prize* for the nuclear shell model, when the San Diego Union headline read "*San Diego Housewife Wins Nobel Prize*".

Suggestion of neutrinoless double beta decay

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

SULLA SIMMETRIA TRA PARTICELLE E ANTIPARTICELLE

Nota di GIULIO RACAH

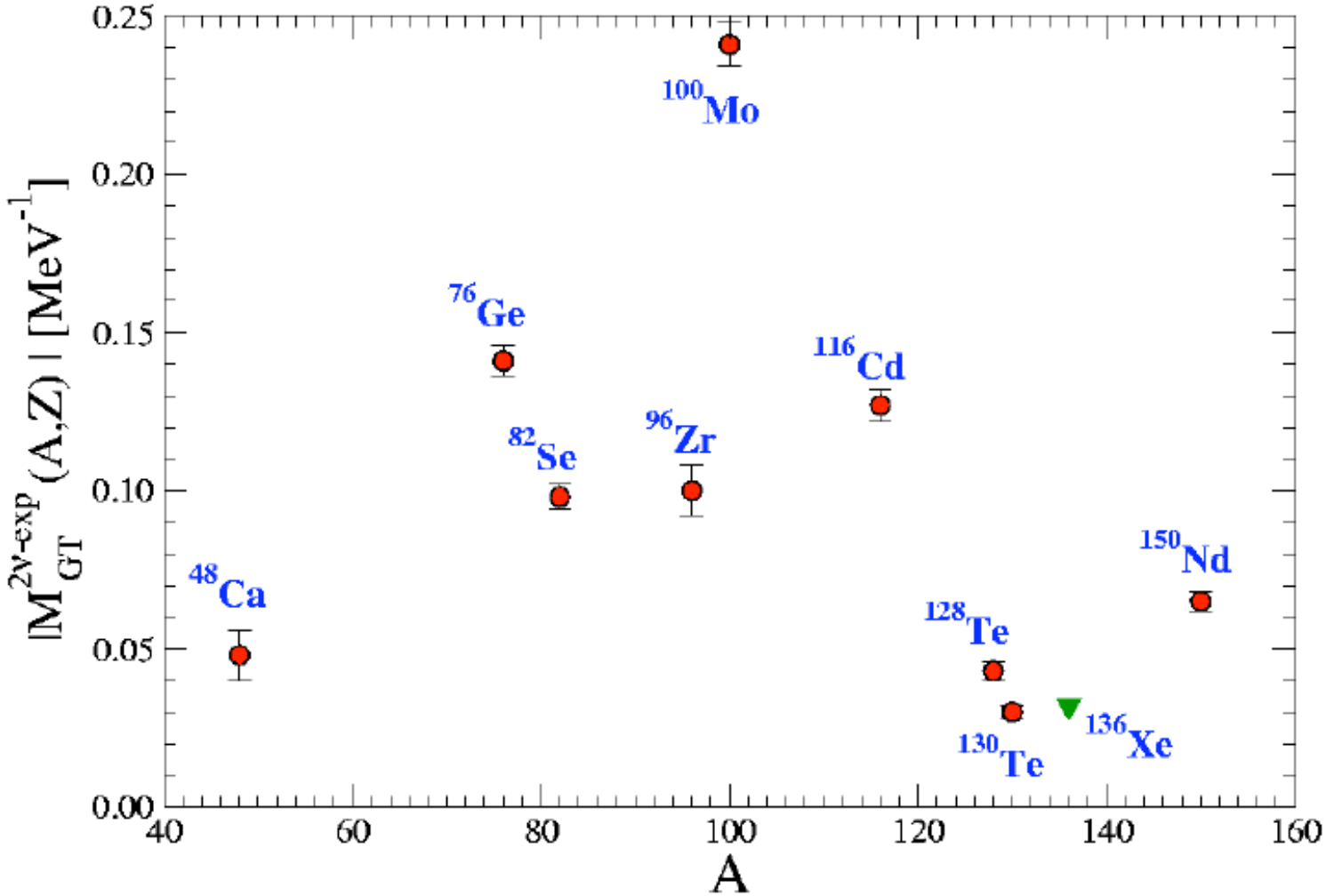
Sunto. - *Si mostra che la simmetria tra particelle e antiparticelle porta alcune modificazioni formali nella teoria di* FERMI *sulla radioattività β, e che l'identità fisica tra neutrini ed antineutrini porta direttamente alla teoria di* E. MAJORANA.

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.

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

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

For 2νββ there is a strong shell-model dependence of the matrix elements



Vogel

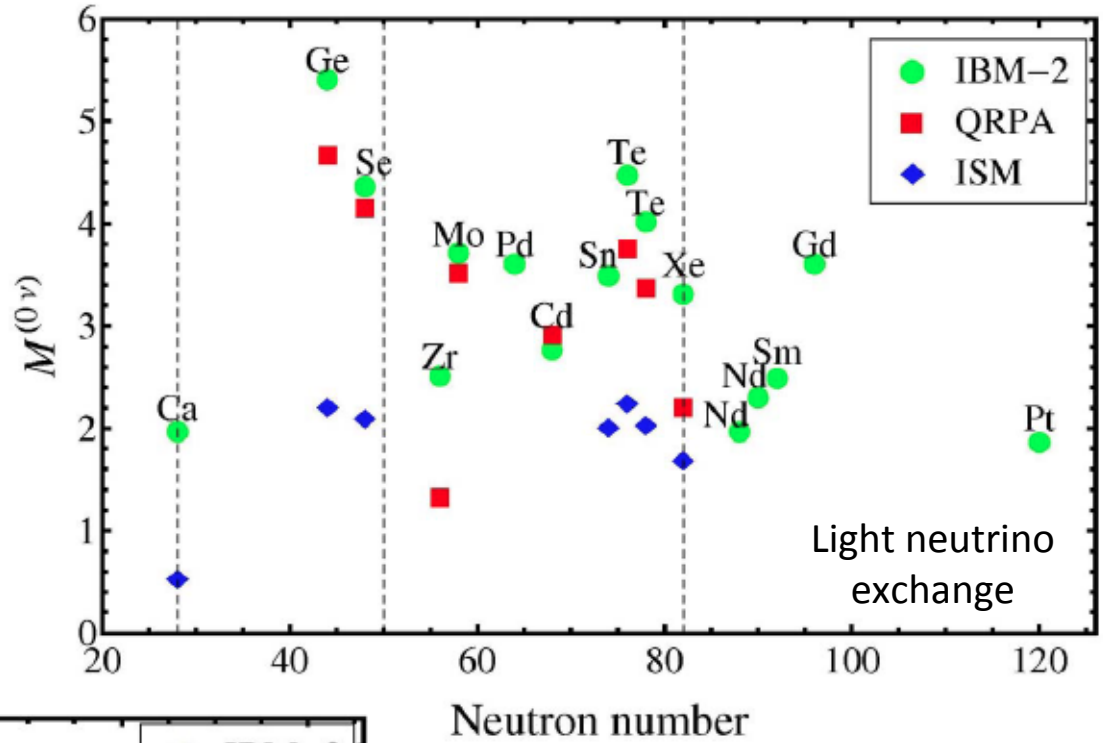
0ν double beta decay

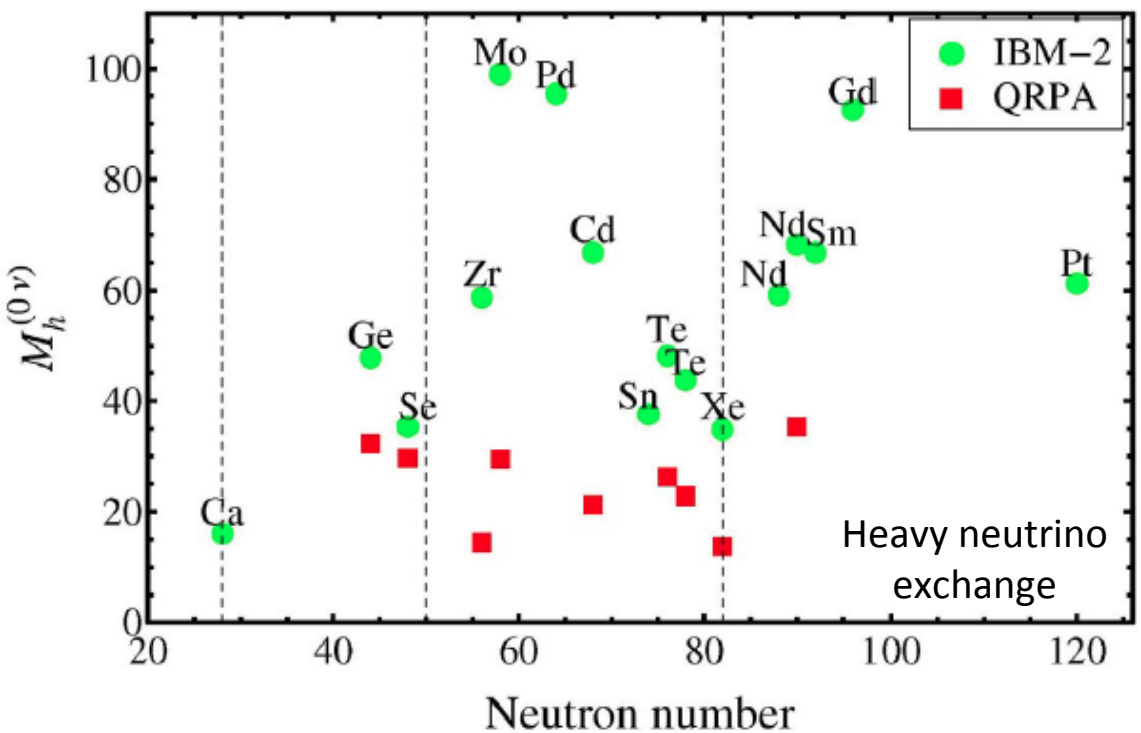
$(1/T_{1/2}) = G(E,Z)\, M^2 \langle m_{\beta\beta}\rangle^2$

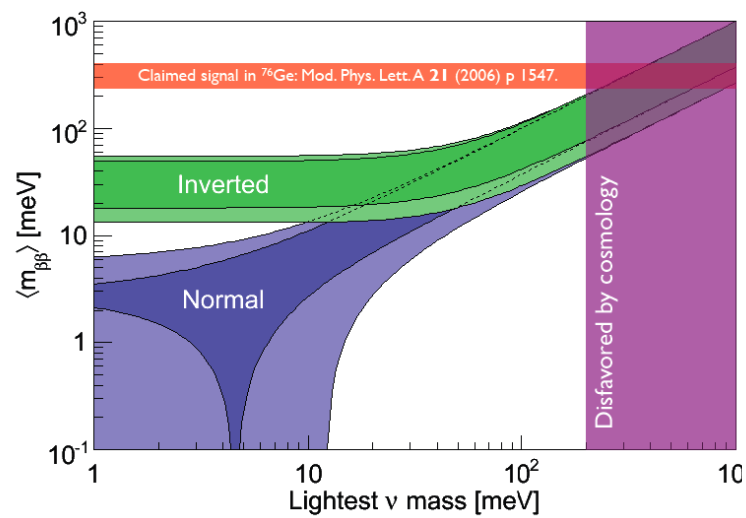
$G(E,Z)$: phase space

M : nuclear matrix element

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







Will want to discuss one example on the horizon:

$0\nu 2\beta$ decay.

But will first review some "well-known" aspects of simple $\beta\nu$ decay.

2a. Nuclear properties and log ft values in β-decay.

i) Occupancy of shell-model orbits.

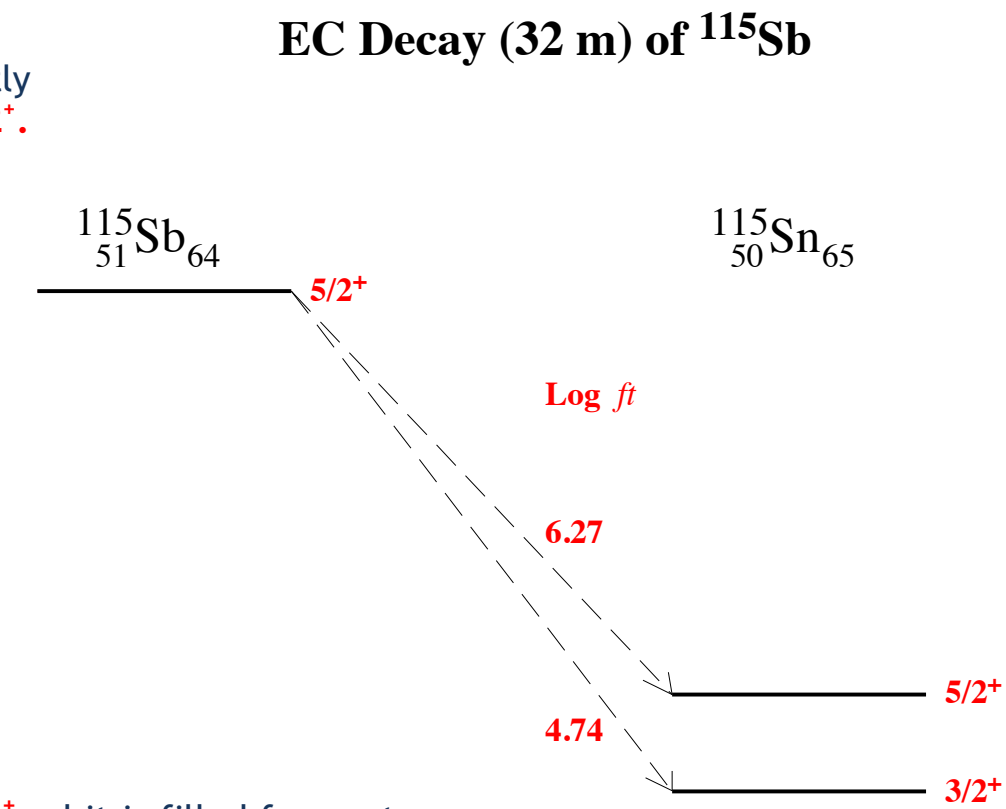
ii) Nuclear shapes.

Part of Schiffer's talk

i) Occupancies (from transfer reactions) related to β-decay rate.

The nucleus ^{115}Sb (spin **5/2$^+$**) decays predominantly to a **3/2$^+$** state and much more weakly to the **5/2$^+$.**

Why?



Because:

Transfer studies tell us that here the **5/2$^+$** orbit is filled for neutrons, while the **3/2$^+$** is empty. **No room for another** 5/2$^+$ **neutron** to be created:

As a consequence, the β-decay is **inhibited by a factor of ~33.**

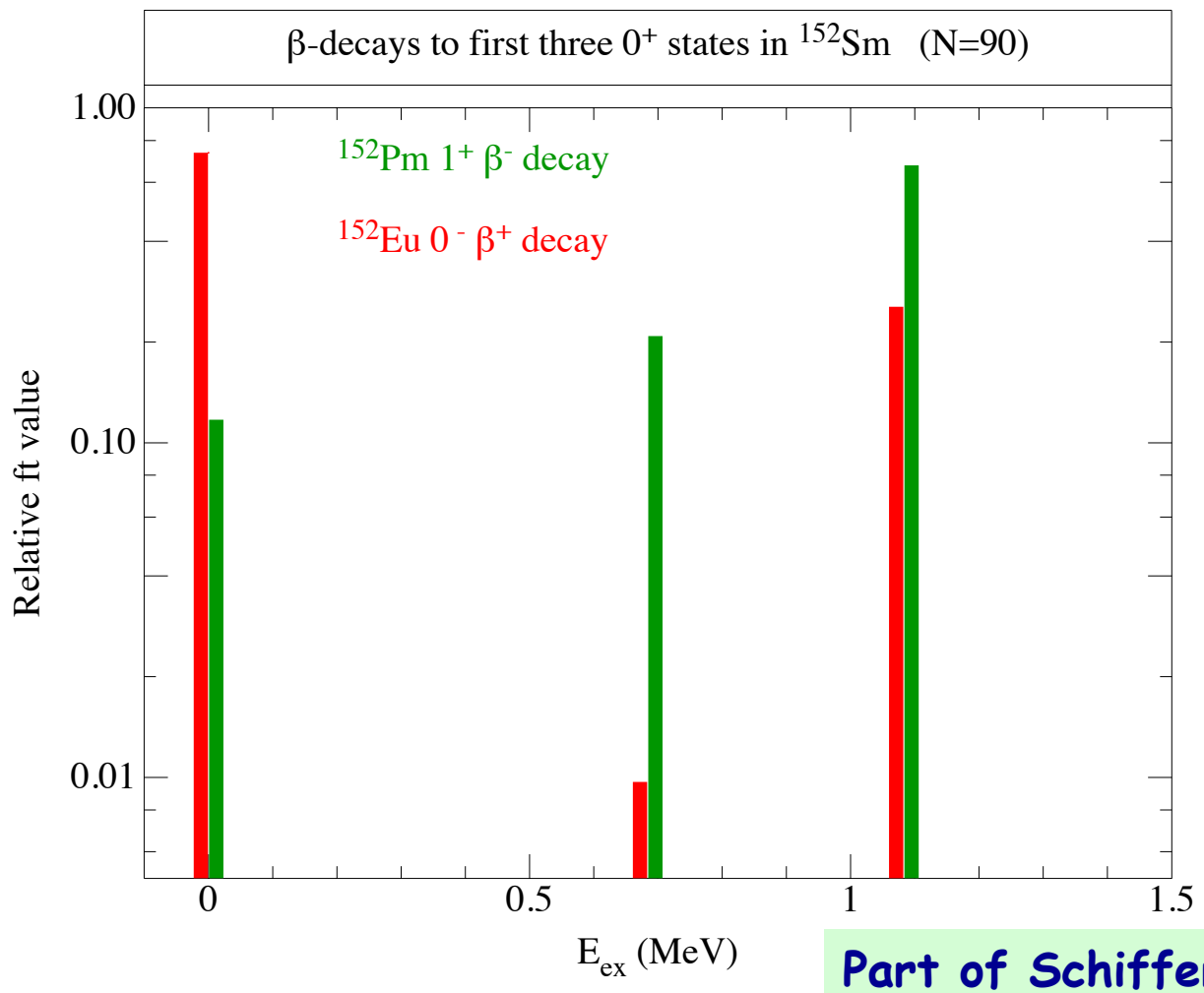
The occupancy of valence orbits has a huge effect on decay rates.

Part of Schiffer's talk

ii) Deformation plays a role.

^{152}Sm is on the border of deformation. The relative probabilities of β-decay to three of its **0^+** states change depending on the deformation of the parent state.

Change in shape can inhibit decay rates by order of magnitude.



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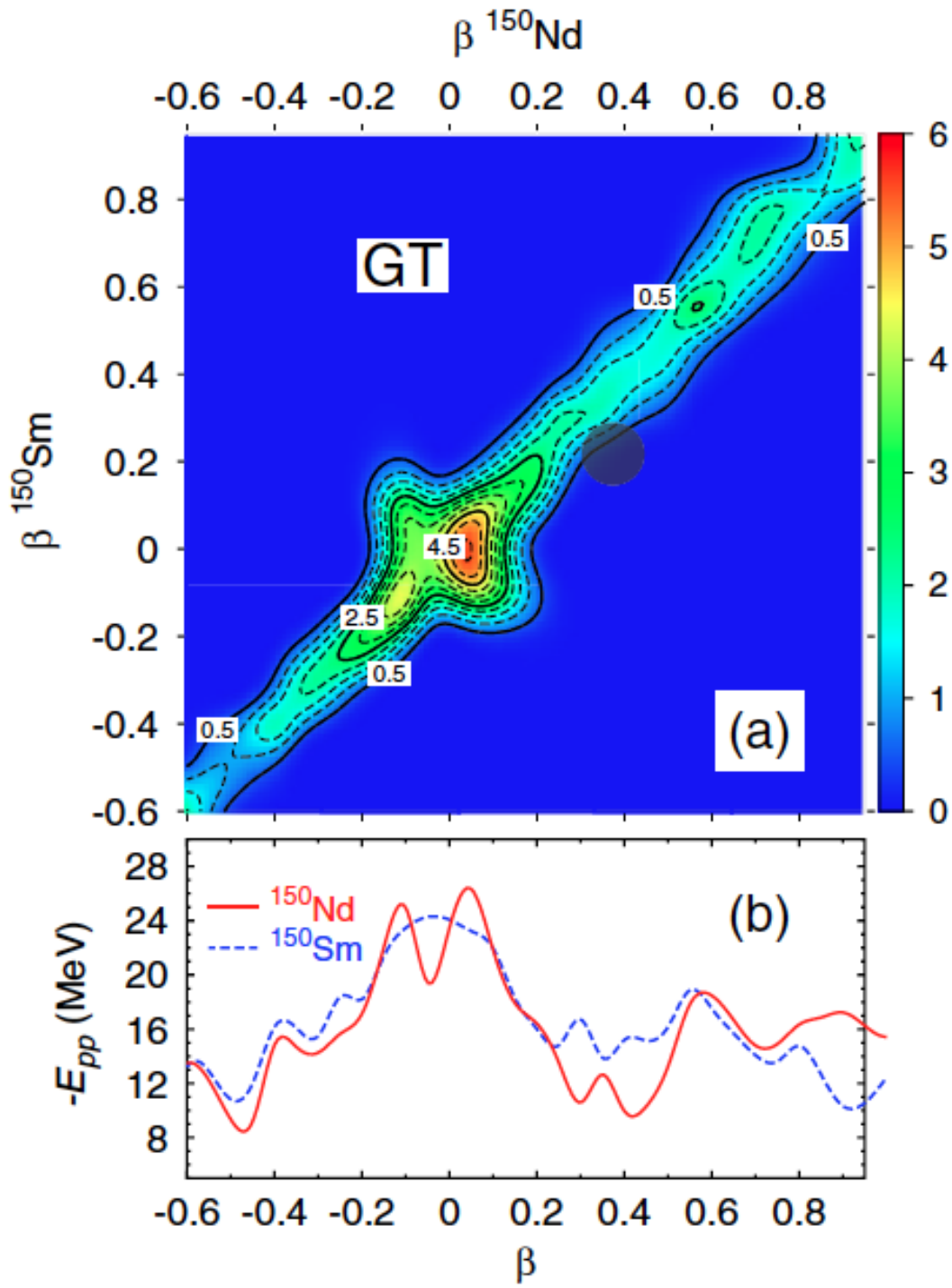
In neutrinoless double beta decay, the overlap between initial and final states should be not too small!

Example:

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



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

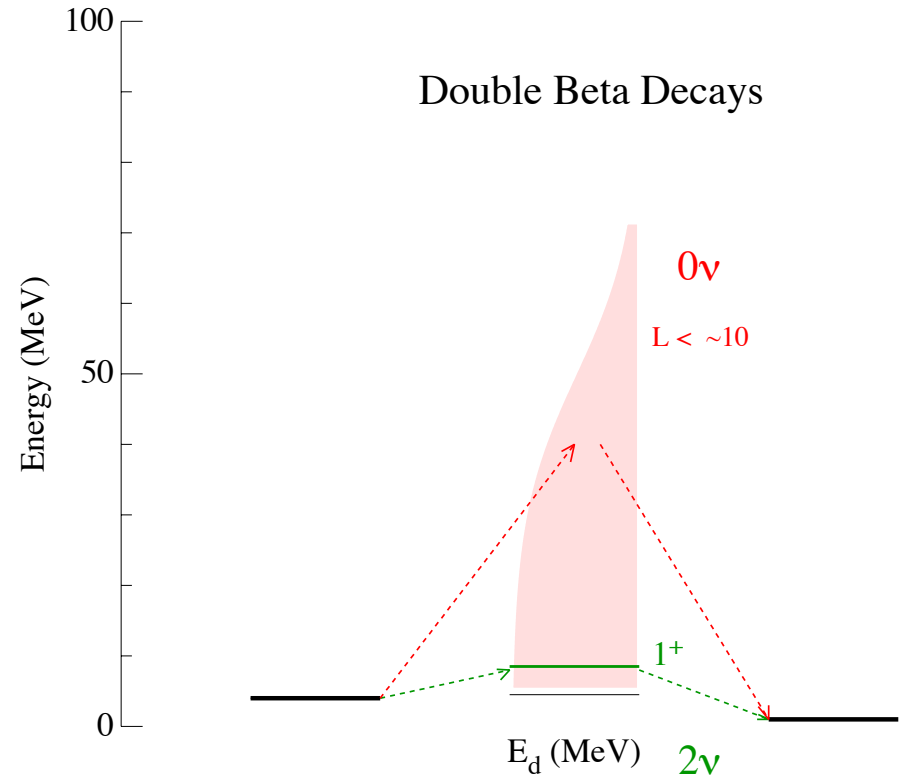
Nuclear Matrix Elements

Observability of $0\nu2\beta$ depends on its rate.

The hierarchy certainly matters, but so does the **structure of** the specific **nuclei**.

What aspects of structure matter?

The $0\nu2\beta$ decay mode **is different** from the $2\nu2\beta$: both involve virtual intermediate states. With two real ν-s, virtual momentum transfers are small, and only a few low-lying virtual 1^+ states are involved. In the 2ν mode the ν-s remain virtual and confined, virtual momentum transfers are ~100-300 MeV/c, capable of reaching ***all*** relevant particle-hole excitations (Giant Resonances), and **closure** may be invoked.



To a reasonable approximation, it would seem that only the properties of the **initial** and **final** states, and the **difference between them**, can matter.

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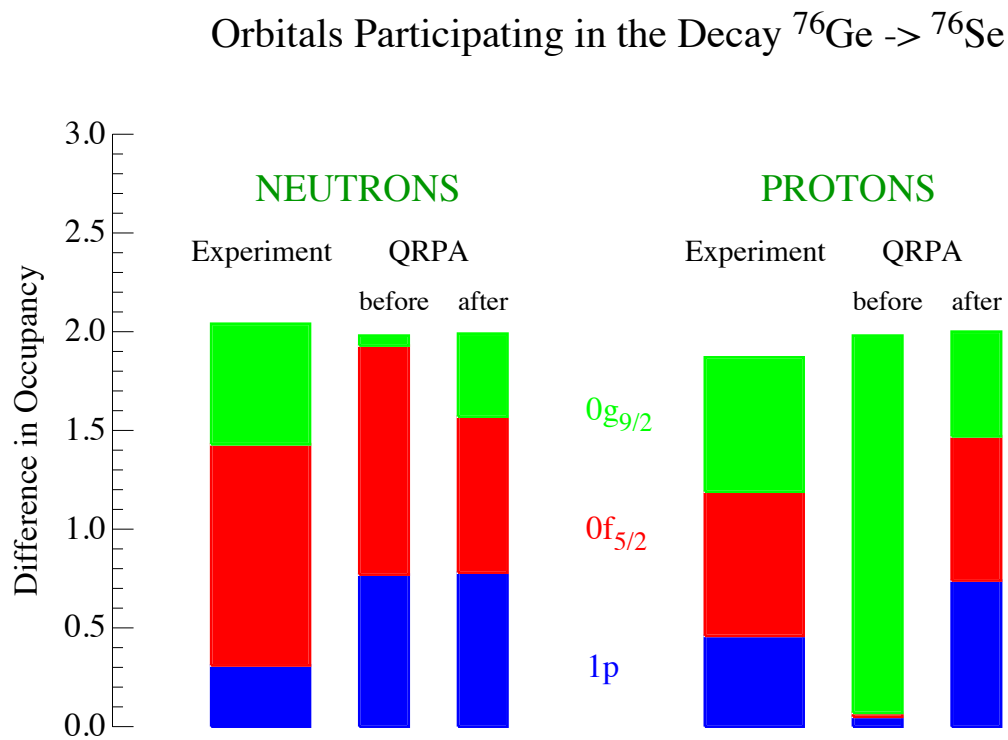
What matters for 0ν2β rates?

a) **Change in occupancy** of microscopic orbits – **probed by transfer reactions?**



Adjustments in QRPA to fit experiment caused a factor of 3-4 decrease in the M.E.: **an Order of Magnitude change in rate.**

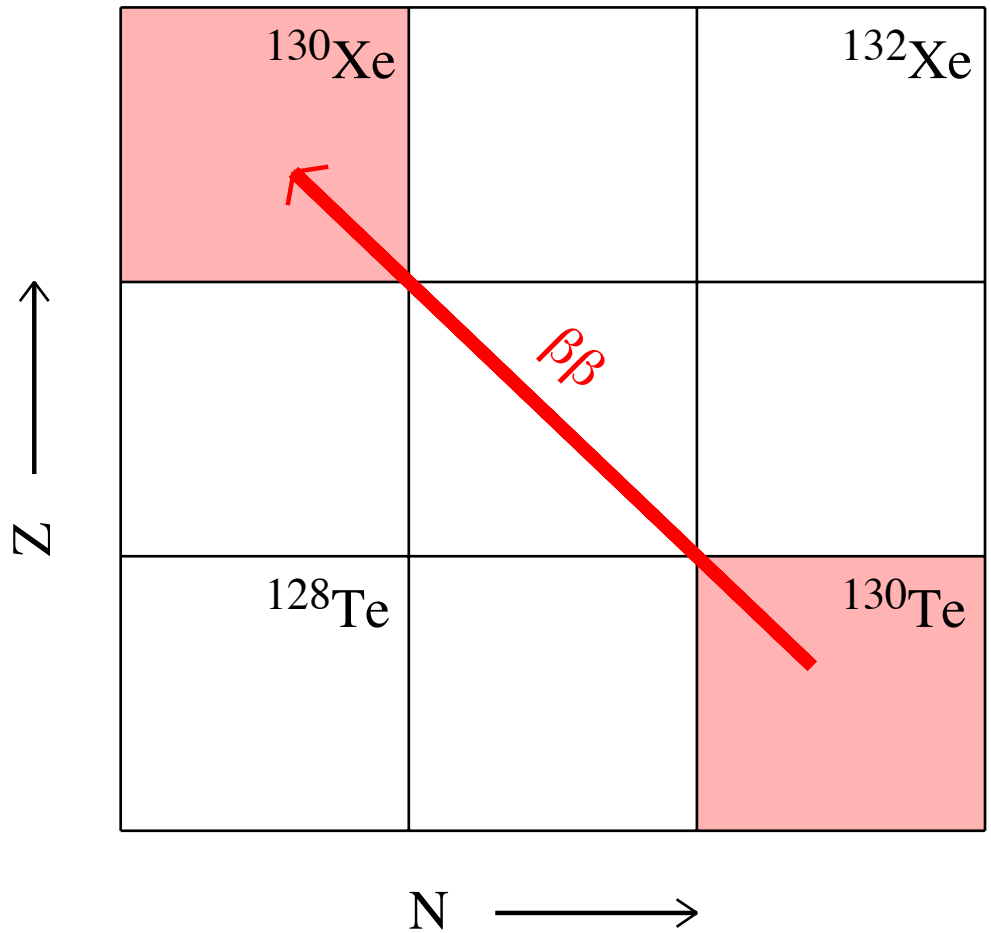
Similar data on the decay candidates: ^{100}Mo, ^{130}Te, ^{136}Xe, (^{150}Sm).

Not clear what aspects are responsible for change.

Part of Schiffer's talk

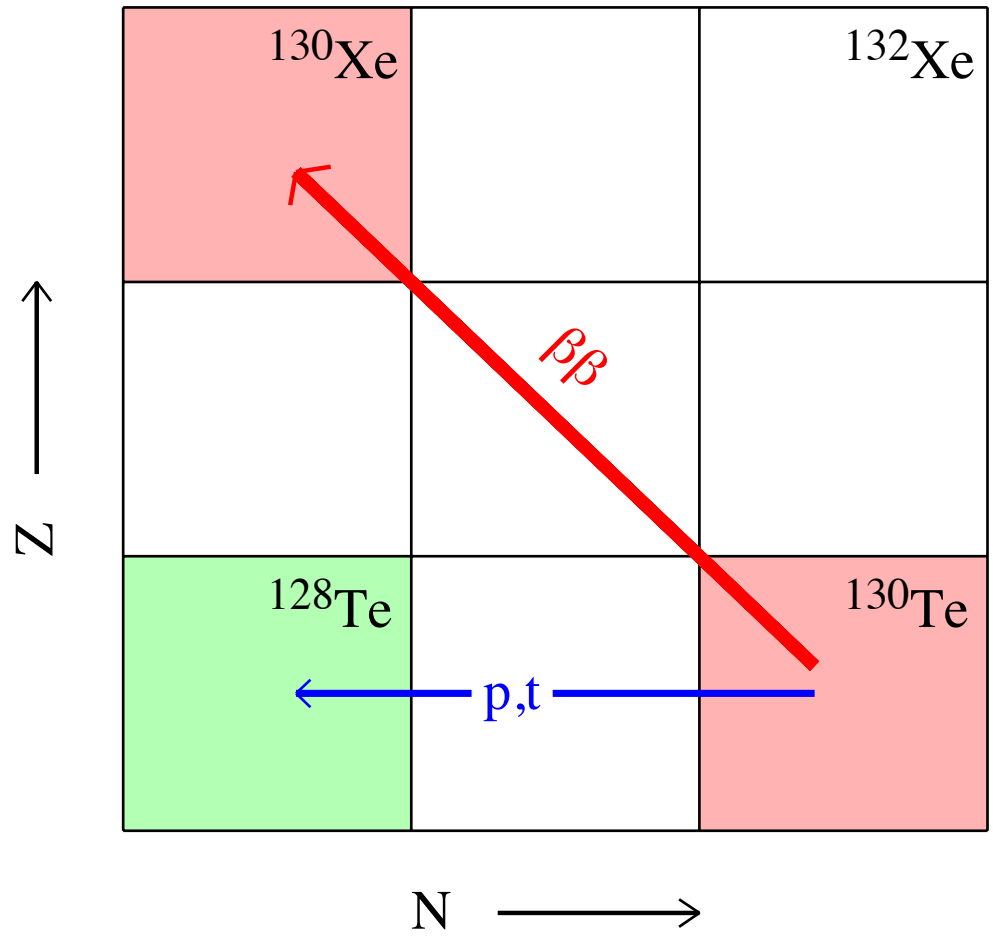
What matters for 0ν2β rates?

b) Coherence: **Pair correlations (BCS, etc.)** probed by pair transfer reactions.



Part of Schiffer's talk

Annihilation of a 0^+ neutron-pair boson, in the BCS condensate



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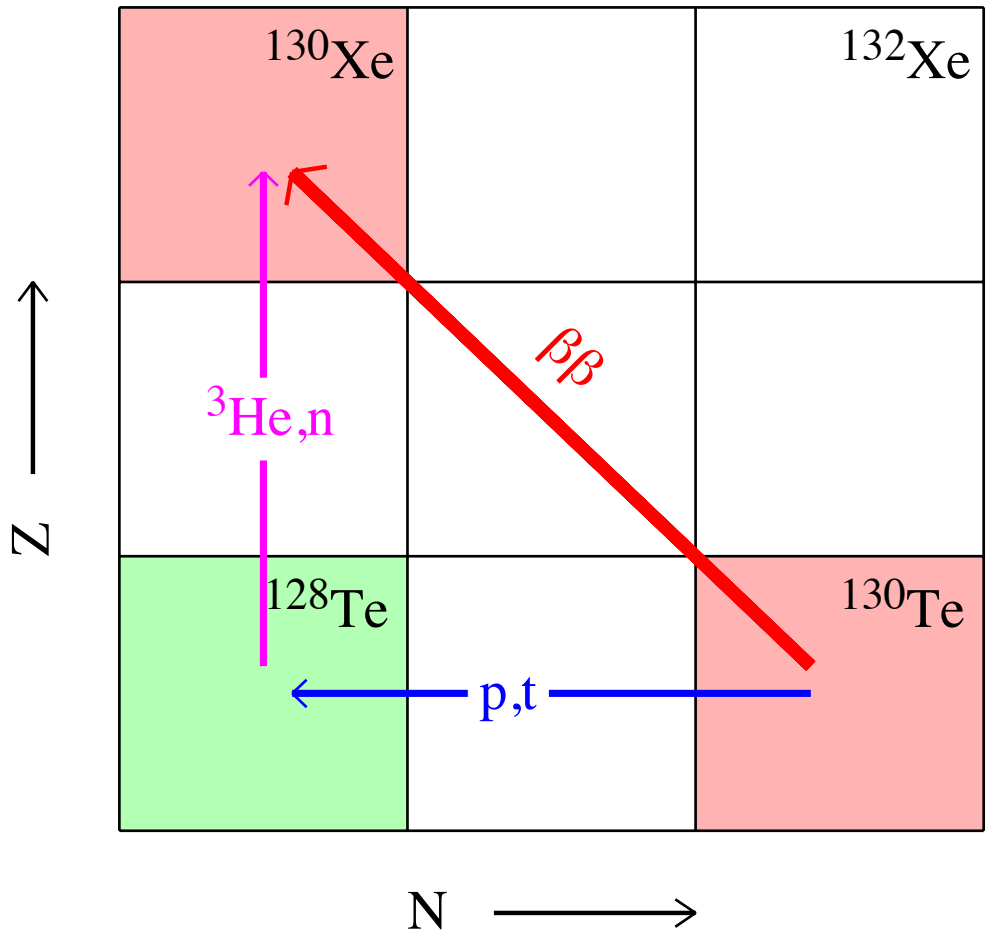
Creation of a proton-pair boson in the BCS sea



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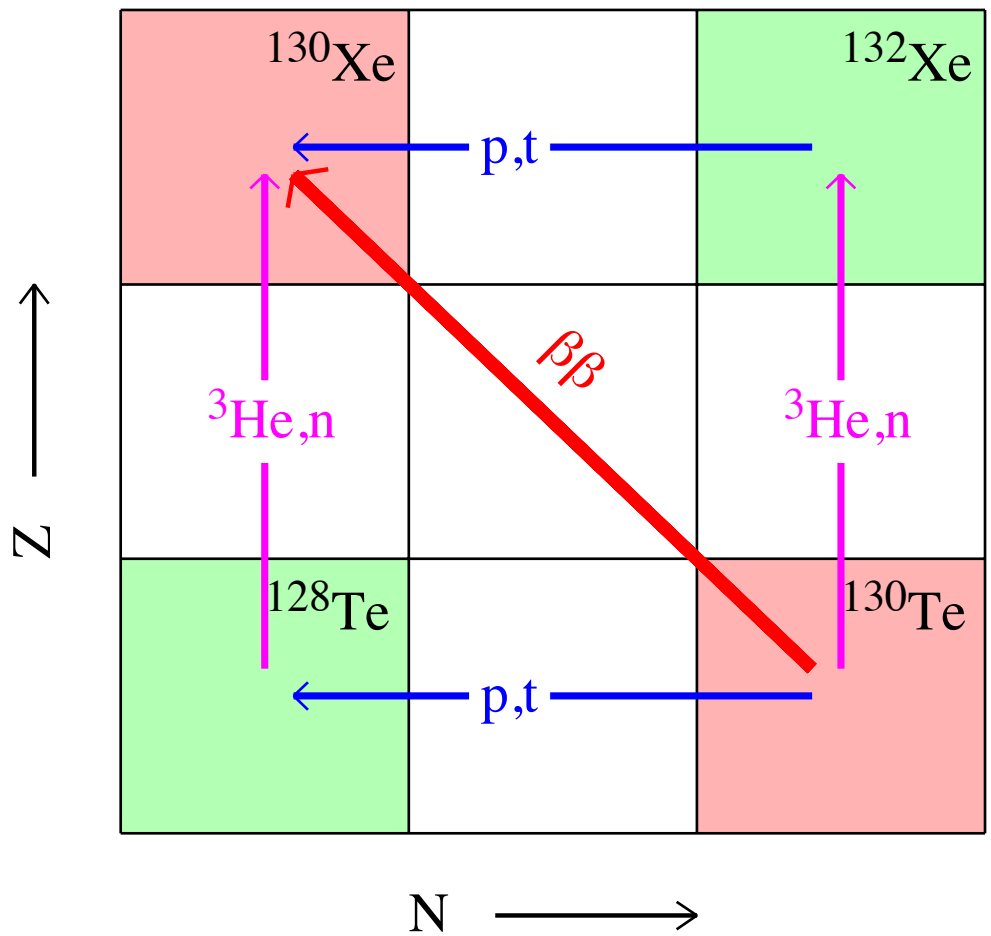
The pair creation/annihilation processes are the same.



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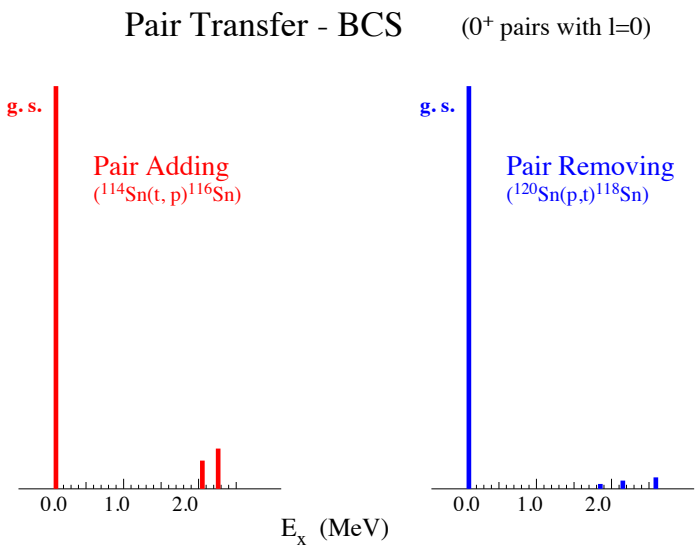
What matters for 0ν2β rates?

c) **BCS** pair correlations and **broken BCS symmetry?**

The primary evidence on correlations comes from pair transfer reactions. (S. Yoshida).

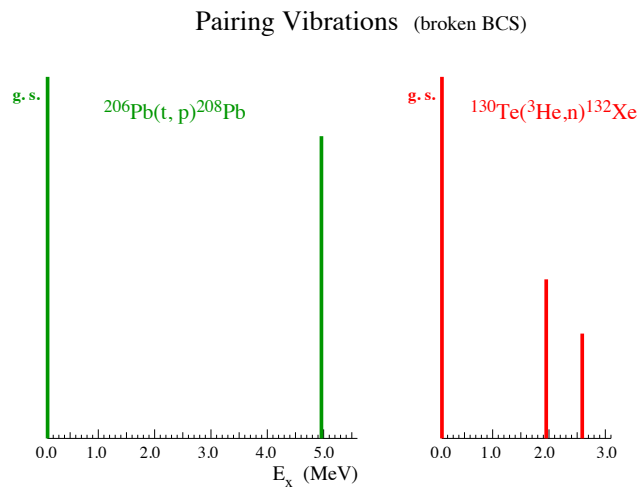
In reactions such as **(^{3}He,n)** and **(p,t)**.the $0^+ \rightarrow 0^+$(g.s.) transition is selected overwhelmingly – the coherent BCS correlations between localized, 0^+ pairs of nucleons, form a condensate.



The dominance of the ground-state in $0^+ \rightarrow 0^+$ is not universal, the simple BCS condensate is broken, *including* in some key nuclei for 0ν2β: ^{130}Te, ^{136}Xe, (^{150}Sm).

Part of Schiffer's talk

Such effects were named **Pairing Vibrations** by Bohr and Mottelson.



Simple BCS is built into **QRPA,** but not clear how to include such microscopic effects that break the coherence.

Shell-model could, in principle, reproduce it, but the model space is limited … not clear whether it does.

To what extent do the strong **enhancements** seen in pair-transfer reactions, and the modifications interpreted as "pairing vibrations" **apply to the ME-s in $0\nu 2\beta$?**
(0^+ pairs of identical nucleons, the bosons of the BCS condensate, are created and annihilated in both.)

Hand-waving arguments (size of boson space) suggest that they might **alter the rate by a factor of 5-15** in the **Xe-Te region**, compared to assuming simple BCS.

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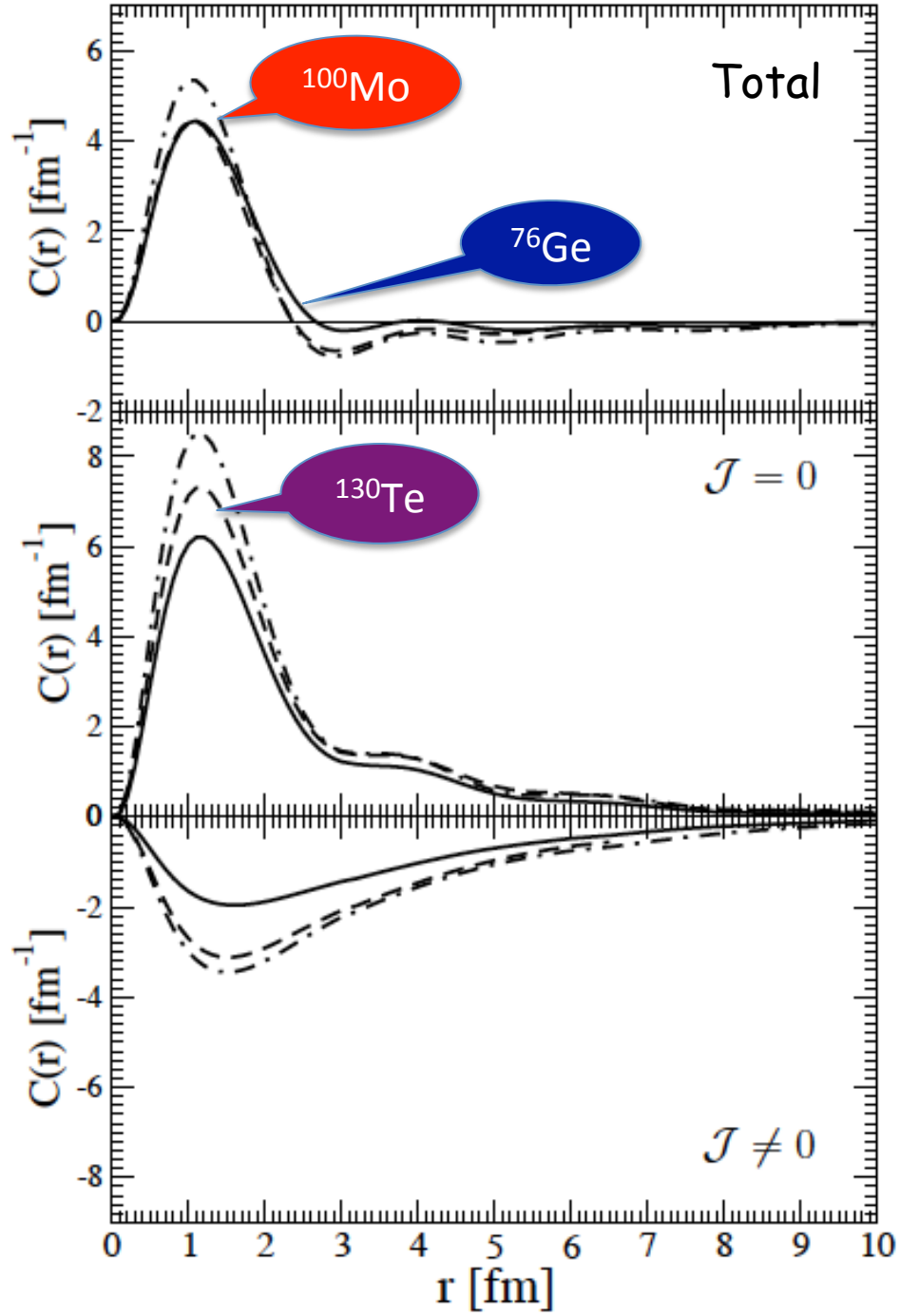
Nuclear matrix elements

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

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



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

Nuclei are delicate instruments that need to be calibrated by whatever means we have at our disposal -- a crude approximation such as QRPA may not describe transition probabilities very quantitatively.

It would be highly desirable to have some guidance from **schematic model calculations** on what accessible aspects might be important. *(perhaps we will have some guidance at this Workshop?*
)

To be sure, observing **$0\nu 2\beta$** in the first place has the highest priority. But the rate could depend sensitively on aspects of nuclear structure that could be determined with other probes.

Some guidance, based on understanding nuclear structure, would be highly desirable on the importance of

Occupancies and changes in occupancies
BCS pairing (if yes, then what if it is broken?)
Microscopic structure
Shape
etc.

Part of Schiffer's talk

Thank you very much