

Exploring the connection between fundamental symmetries and low-energy nuclear physics/nuclear astrophysics

A.B. Balantekin

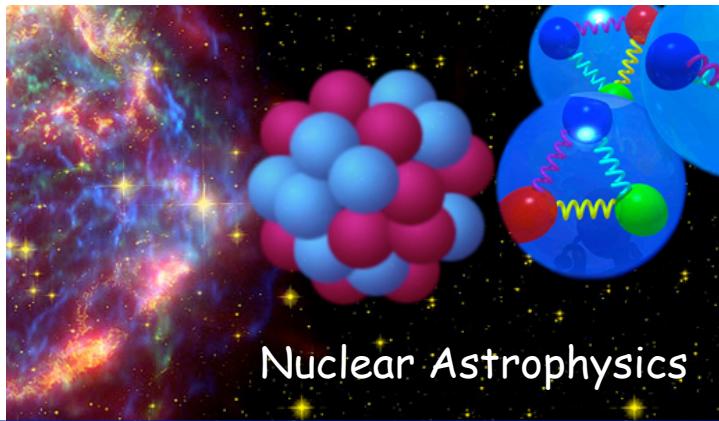
Joint DNP Town Meetings on Nuclear Structure and Nuclear Astrophysics



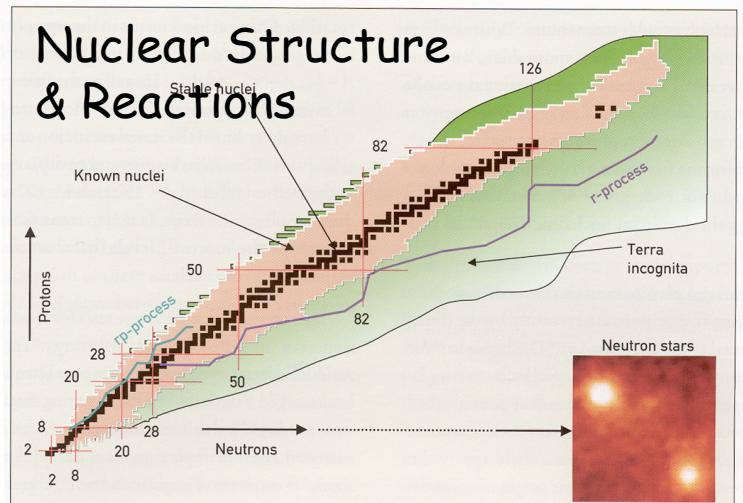
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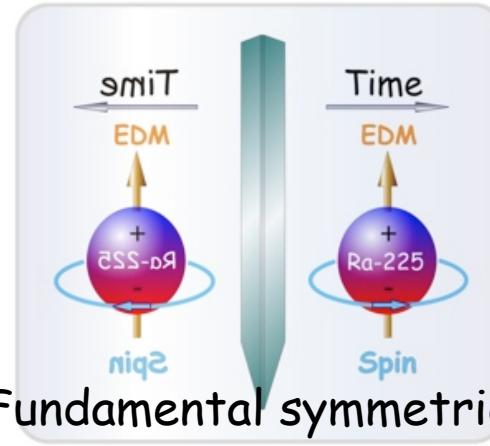
Which science drives physics with rare isotopes?



Origin of new elements, rare isotopes
powering stellar explosions, neutron star
crust



Limits of existence: what makes nuclei stable?
New shapes, new collective behavior.



Fundamental symmetries

Use of rare isotopes as laboratories
where symmetry violations are amplified.



Nuclear applications

Materials, medical physics, reactors,..

- Unitarity of the CKM matrix.
- CP-violation and nuclear EDMs.
- Lepton number violation and double beta decay.
- A few words about astrophysical neutrinos.

Fundamental symmetries is a rich and diverse subject. Here I will highlight only a few examples that directly connect to the low-energy nuclear structure physics and nuclear astrophysics.

CKM Unitarity

Superallowed $(0^+ \rightarrow 0^+)$ beta decays:

$$|V_{ud}| = 0.97425 \pm 0.00022 \text{ (2008 Hardy and Towner)}$$

$$\Rightarrow |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999(6) !$$

Isospin-breaking Coulomb corrections:

$$|M_F|^2 \rightarrow |M_F^0|^2 (1 - \delta_C)$$

Miller & Schwenk

Auerbach

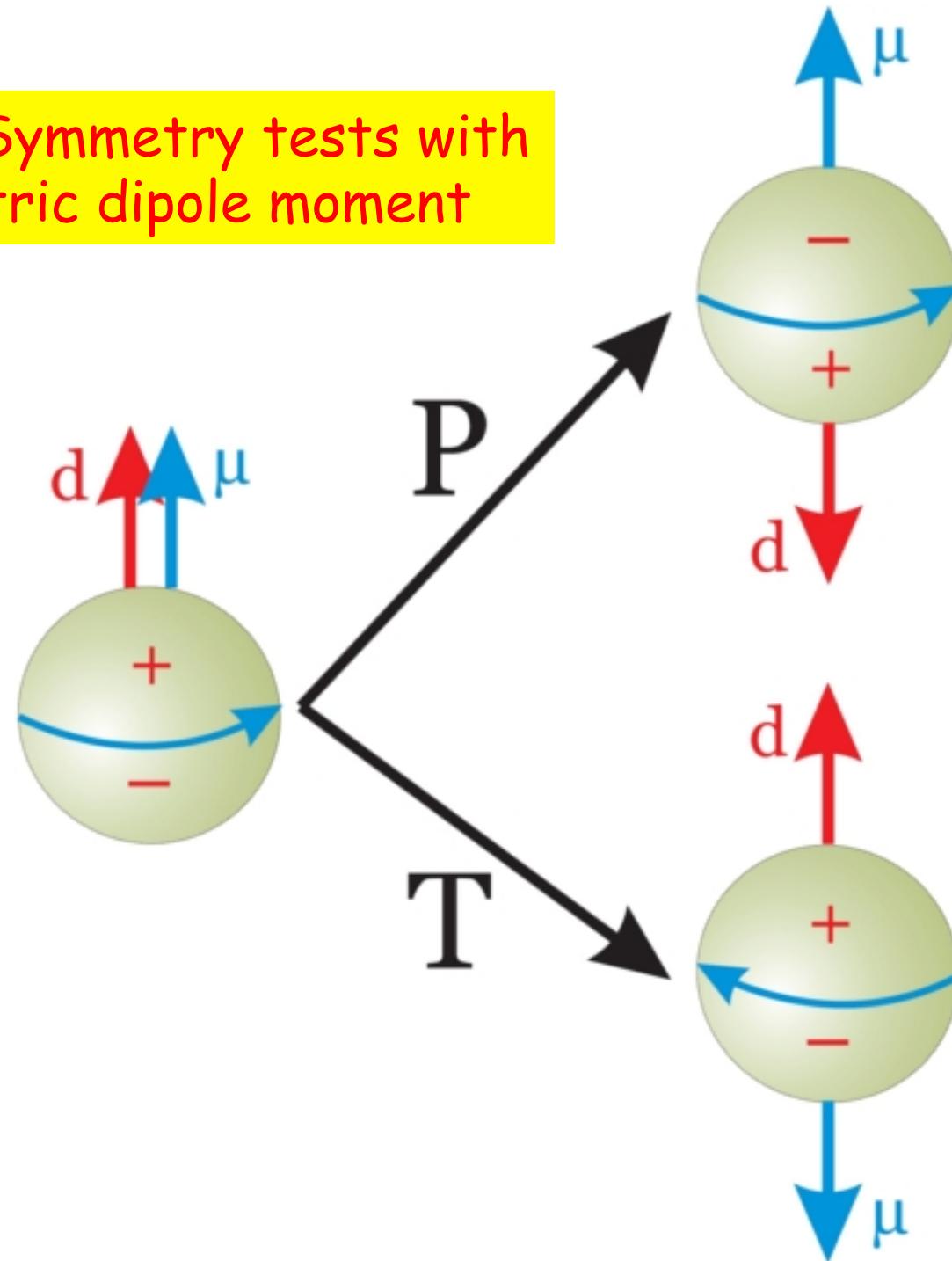
Liang, van Giai, Meng

Satula, Dobaczewski, Nazarewicz, Werner
Sagawa, *et al.*

$$\text{Liang, et al.: } |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9971 - 0.9978 \text{ (different effective interactions)}$$

$$\text{Satula, et al. (DFT): } |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99935(67) - 0.99978(68)$$

Fundamental Symmetry tests with nuclei: Electric dipole moment



In effective field theories at lower energies,
beyond Standard Model physics is described by
local operators

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

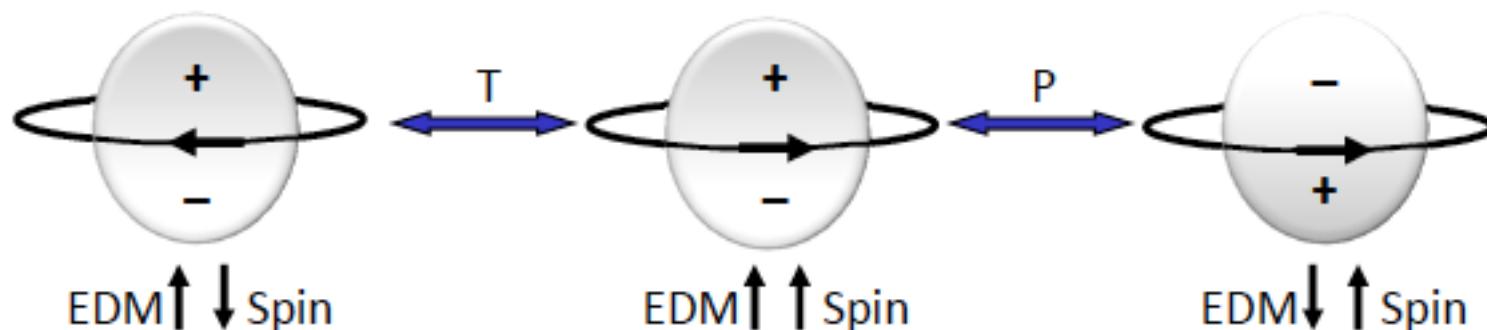
Majorana
neutrino
mass
(unique)

$$+ \quad -\theta \frac{g_s^2}{32\pi^2} \text{Tr } F_{\mu\nu} \tilde{F}^{\mu\nu}$$

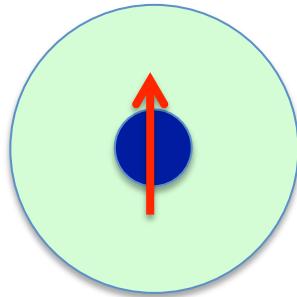
$$H \approx -d \mathbf{J} \cdot \mathbf{E}$$

Electric
dipole
moment

$$d_i \propto \frac{m_i}{\Lambda^2} \sin \phi_{CP}$$



Nuclear EDM's and the Schiff moment



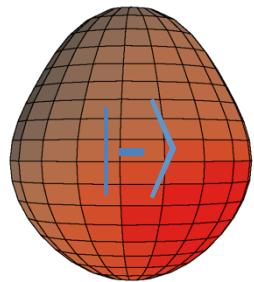
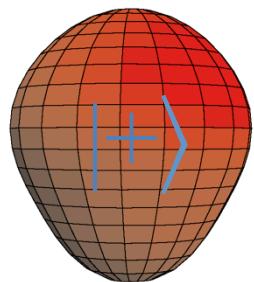
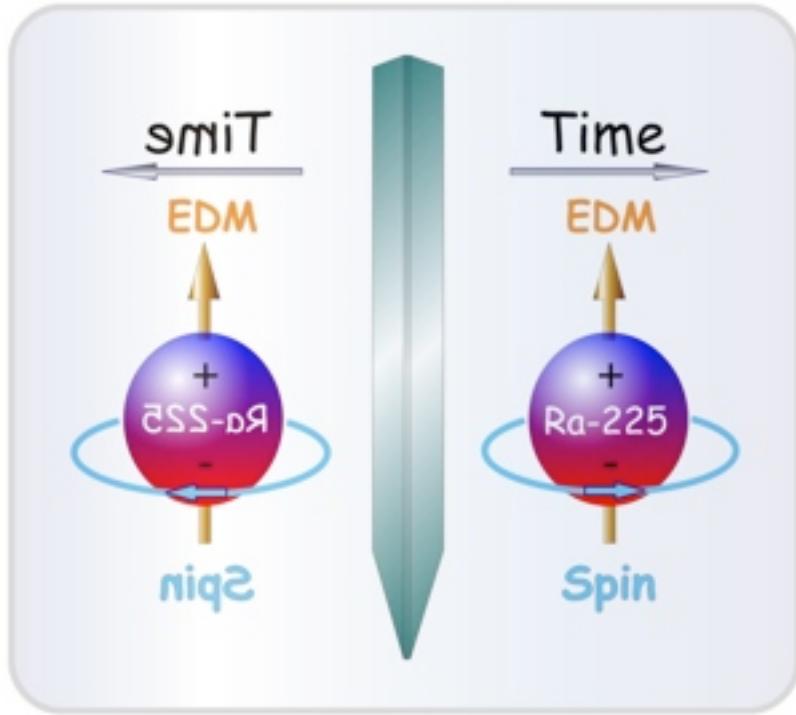
Schiff shielding: $d_{\text{atom}} = d_{\text{electronic}} + d_{\text{nuclei}} \approx 0$

However, since the nuclear charge distribution is not isotropic, one obtains the **Schiff moment**:

$$\mathbf{S} = \frac{1}{10} \sum_i e_i \left(r_i^2 - \frac{5}{3} \langle r^2 \rangle_{\text{ch}} \right) \mathbf{r}_i \times \begin{cases} 1 & \text{isoscalar} \\ \boldsymbol{\tau}_{zi} & \text{isovector} \end{cases}$$

Note that, since this is a difference of two large quantities, it involves many subtle nuclear physics issues, such as identifying contributions of single-particle states, low-lying dipole resonances...

Auerbach, Dobaczewski, Engel, Flambaum, Haxton, Kriplovich, Ramsey-Musolf, Shlomo, Zelevinsky.....



$$\Psi^- = (|+\rangle - |-\rangle)/\sqrt{2}$$

$$\Psi^+ = (|+\rangle + |-\rangle)/\sqrt{2}$$

ΔE

Enhancement of EDM from octupole deformation

No spin-correlation suggests

$$\langle \Psi^+ | \mathbf{d}_{internal} | \Psi^+ \rangle = 0$$

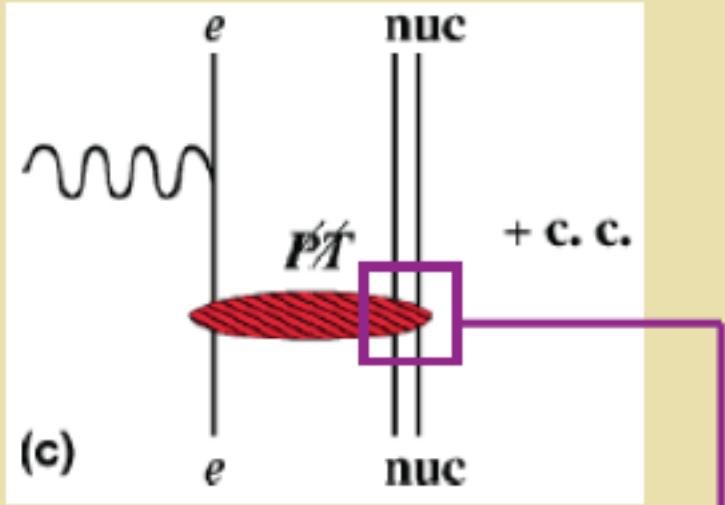
A interaction which is T- and P- odd would mix the states

$$\Psi = \Psi^+ + \alpha \Psi^-$$

$$\alpha = \frac{\langle \Psi^+ | \mathbf{d}_{internal} | \Psi^- \rangle}{\Delta E}$$

$$\langle d_z \rangle_{lab} = 2\alpha d_{internal} \frac{l}{l+1}$$

Haxton & Henley; Auerbach, Flambaum & Spevak;
Dobaczewski & Engel



Nuclear Schiff Moment

$$S \sim \int d^3x x^2 \vec{x} \rho(\vec{x})^{\text{CPV}}$$

$(R_N/R_A)^2$ suppression

Parameterize Schiff moment as

$$S = \frac{2m_N g_A}{F_\pi} \left(a_0 \bar{g}_\pi^{(0)} + a_1 \bar{g}_\pi^{(1)} + a_2 \bar{g}_\pi^{(2)} \right)$$

$\bar{g}_\pi^{(0)}$: isoscalar

$\bar{g}_\pi^{(1)}$: isovector

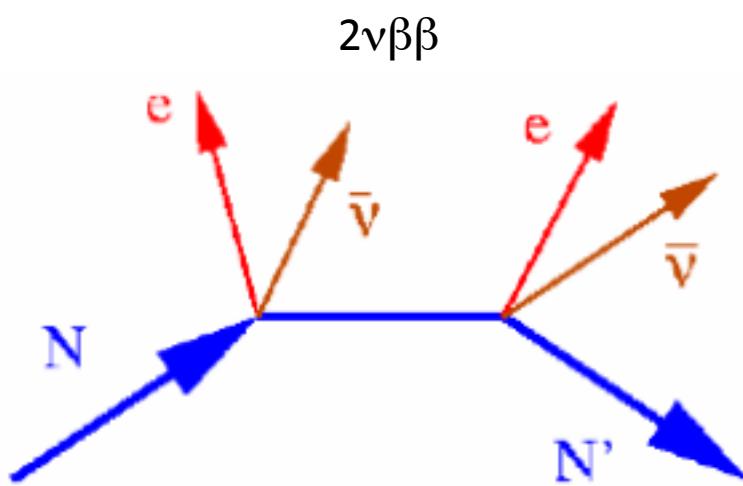
$\bar{g}_\pi^{(2)}$: isotensor

Nuclear Matrix Elements

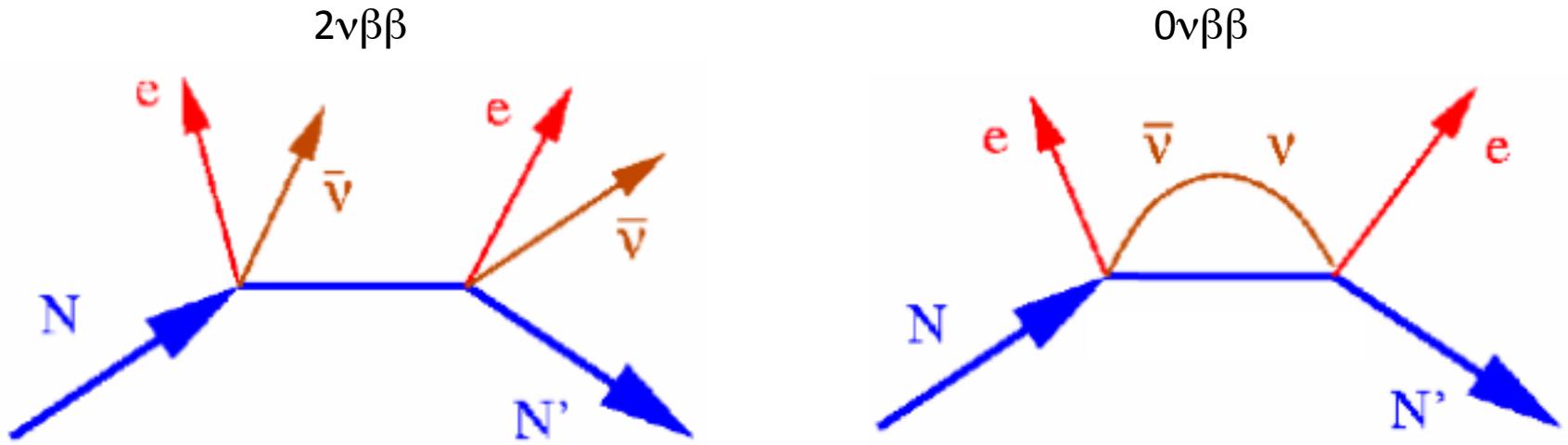
$$S = a_0 g \bar{g}_\pi^{(0)} + a_1 g \bar{g}_\pi^{(1)} + a_2 g \bar{g}_\pi^{(2)}$$

Nucl.	Best value		
	a_0	a_1	a_2
^{199}Hg	0.01	± 0.02	0.02
^{129}Xe	-0.008	-0.006	-0.009
^{225}Ra	-1.5	6.0	-4.0

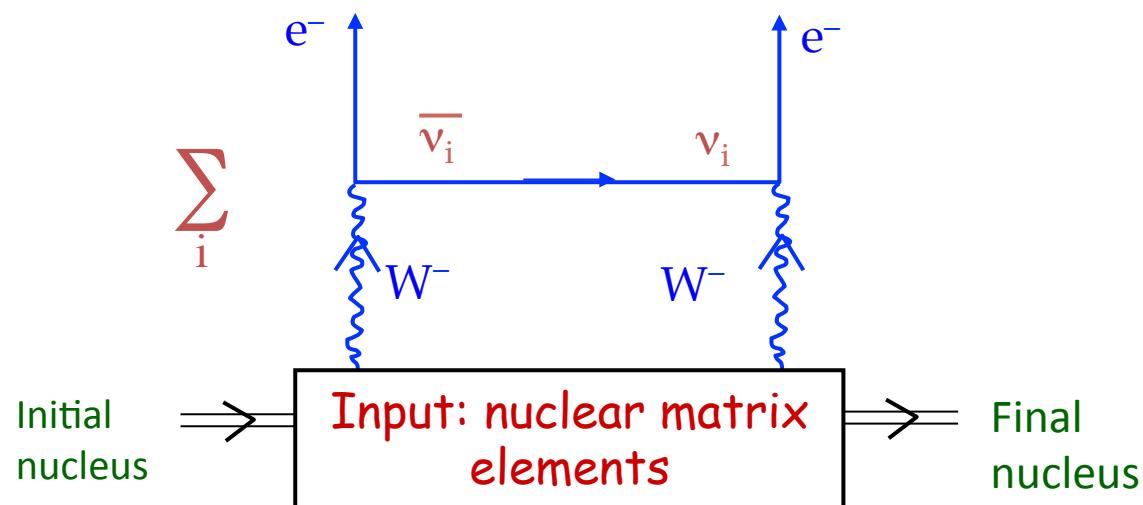
Range	a_0	a_1	a_2
0.005–0.05		-0.03-(+0.09)	0.01–0.06
-0.005–(-0.05)		-0.003–(-0.05)	-0.005–(-0.1)
-1–(-6)		4–24	-3–(-15)



Maria Goeppert Mayer



Total lepton number violation: Majorana nature of the neutrinos permit neutrinoless double beta 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
 $\beta\beta$ decay

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

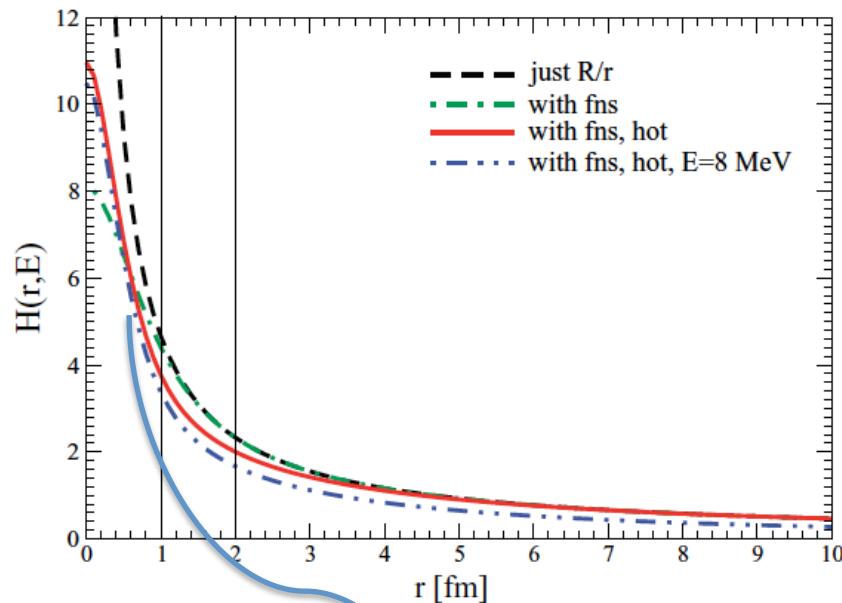
$$M_{GT}^{0\nu} \approx < f | \sum_{j,k} \frac{1}{r_{jk}} \vec{\sigma}(j) \cdot \vec{\sigma}(k) \tau_+(j) \tau_+(k) | f >$$

Neutrinoless
 $\beta\beta$ decay

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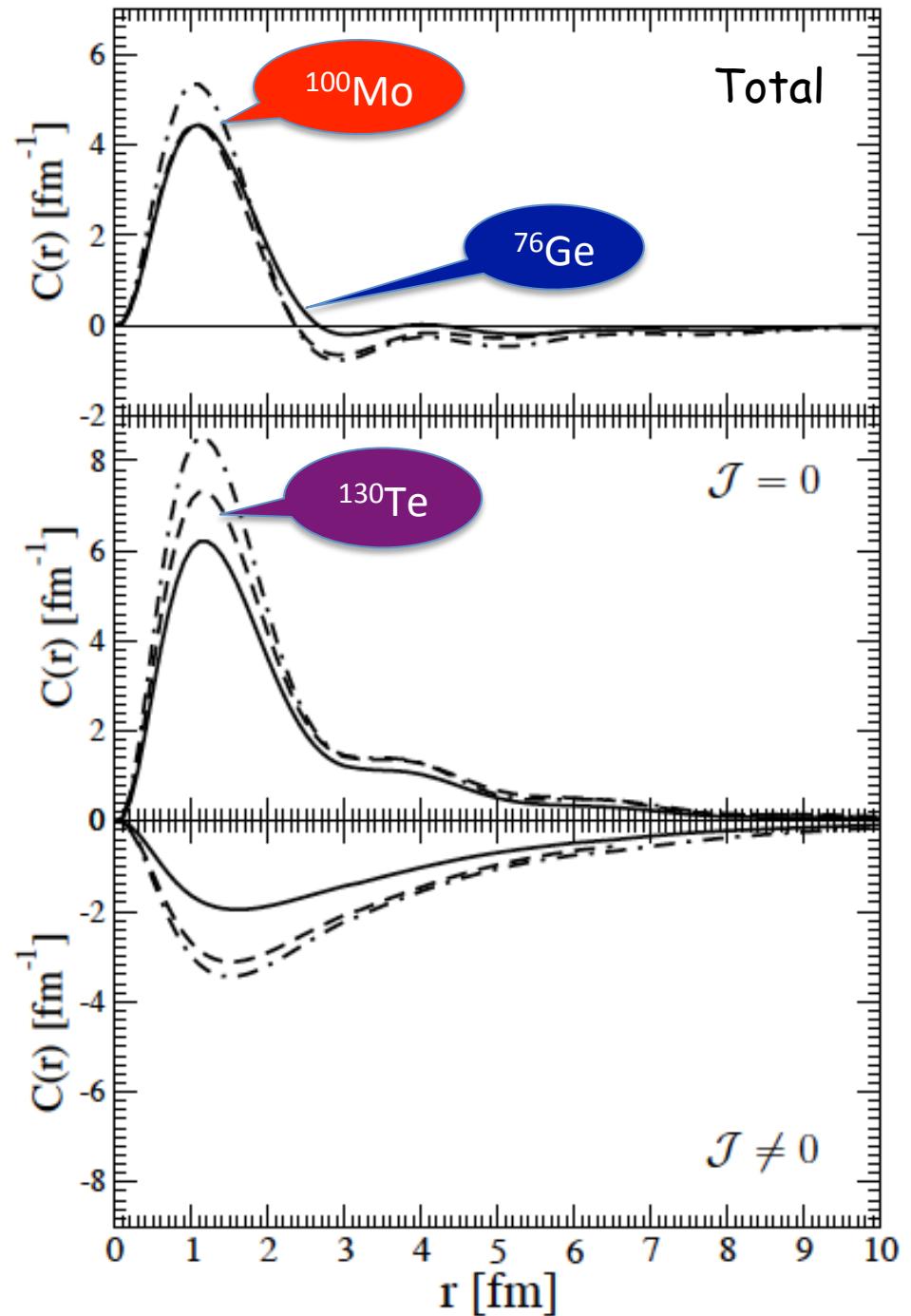
Neutrinoless
 $\beta\beta$ decay

Nuclear matrix elements

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

Momentum of virtual neutrino, $q \sim 1/r$
 $r \sim 2 \text{ fm}$
 $q \sim 100 \text{ MeV}$

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

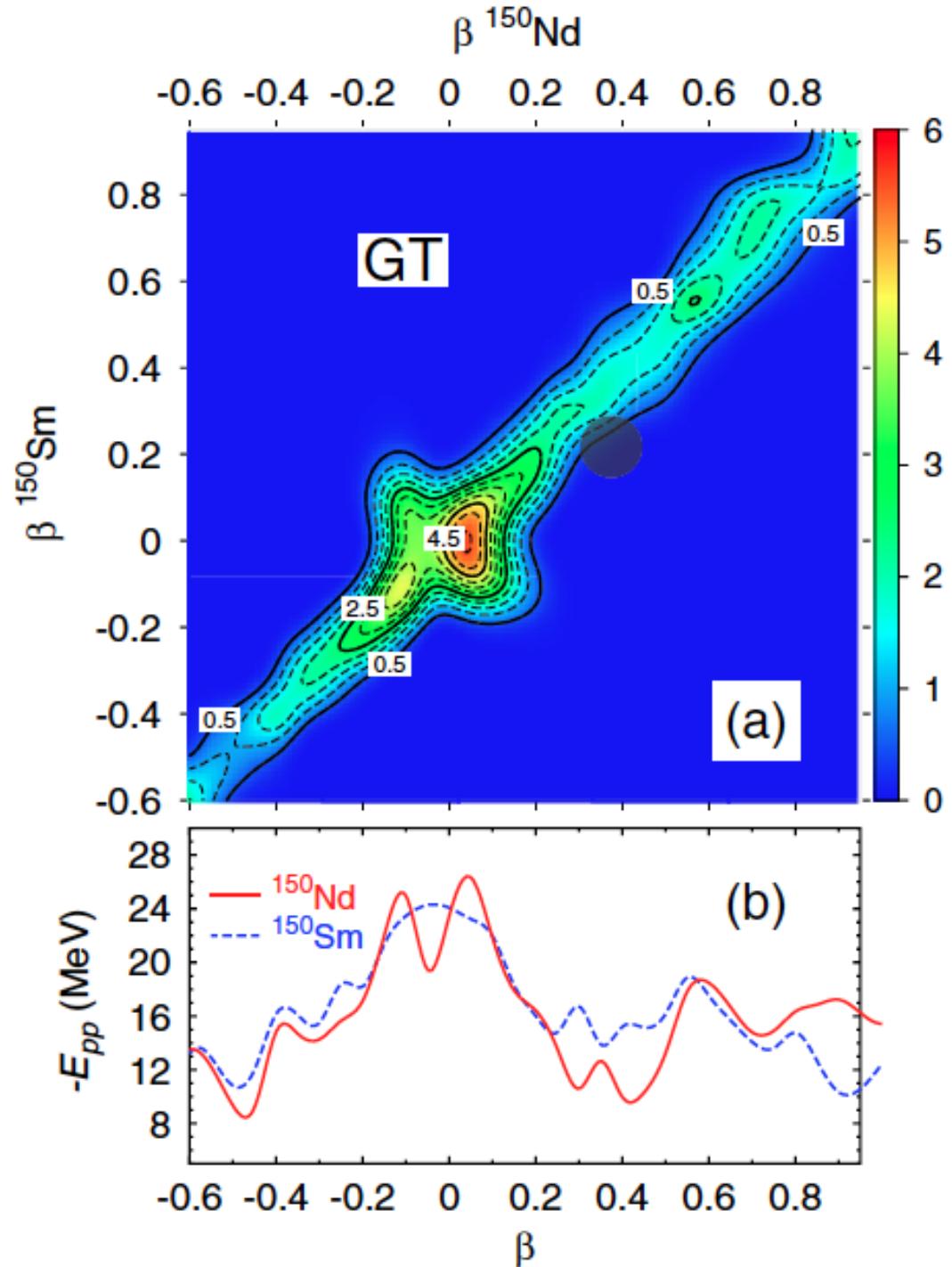


In neutrinoless double beta decay, the overlap between initial and final states should be not too small!

Example:

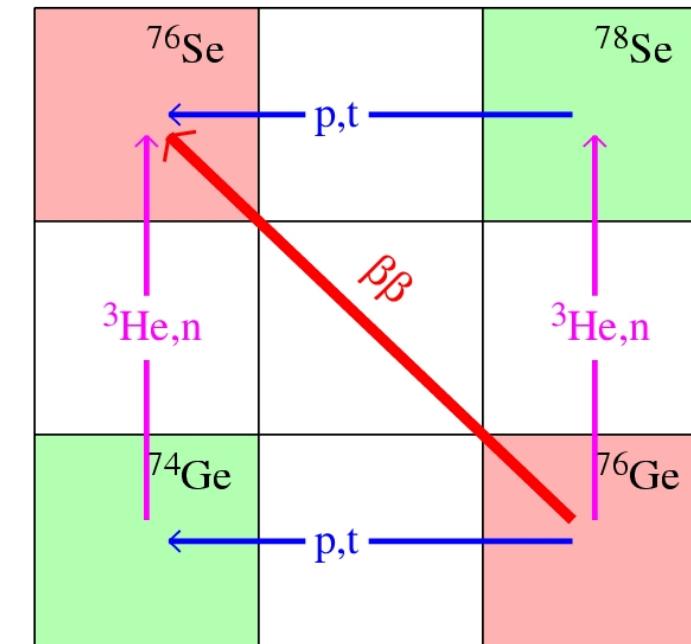
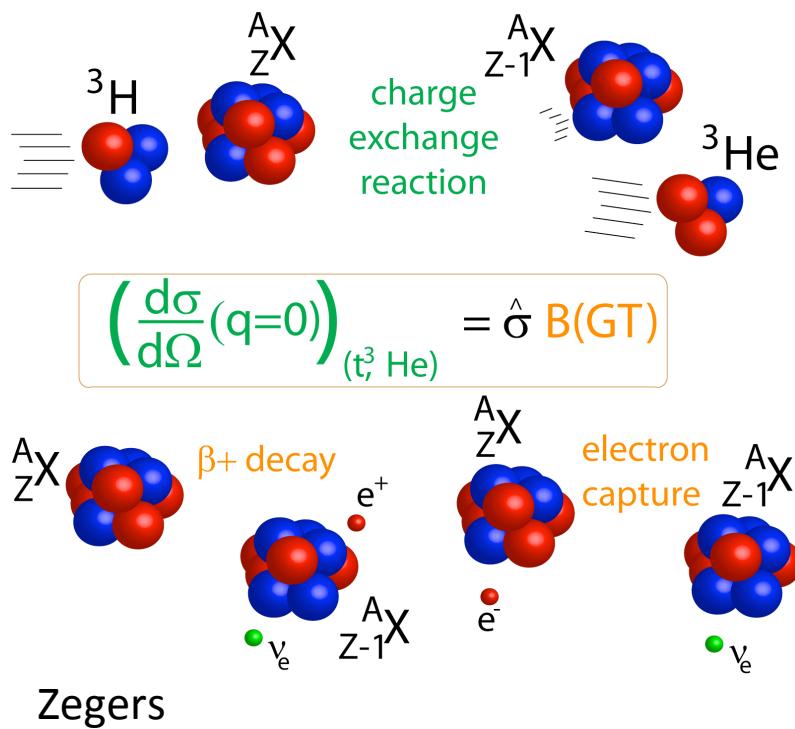


Rodriguez & Martinez-Pinedo,
PRL 105, 252503 (2010)

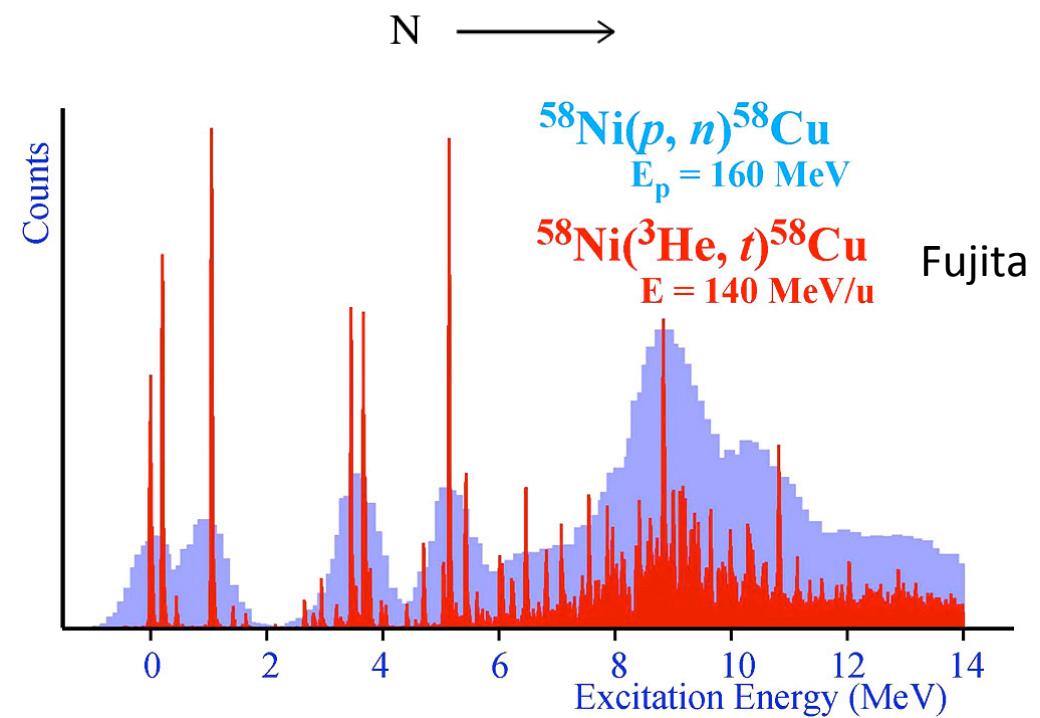


- $2\nu \beta\beta$ -decay: small momentum transfer
- $0\nu \beta\beta$ -decay: large momentum transfer (~ 100 MeV)
- 100 MeV covers **all** giant resonances and details of the structure of the intermediate nucleus may or may not be very important.
- Schiffer's argument: Since initial and final states contribute much, determine the composition of the Fermi surface: the distribution of the valence nucleons that participate in the decay.

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



Schiffer



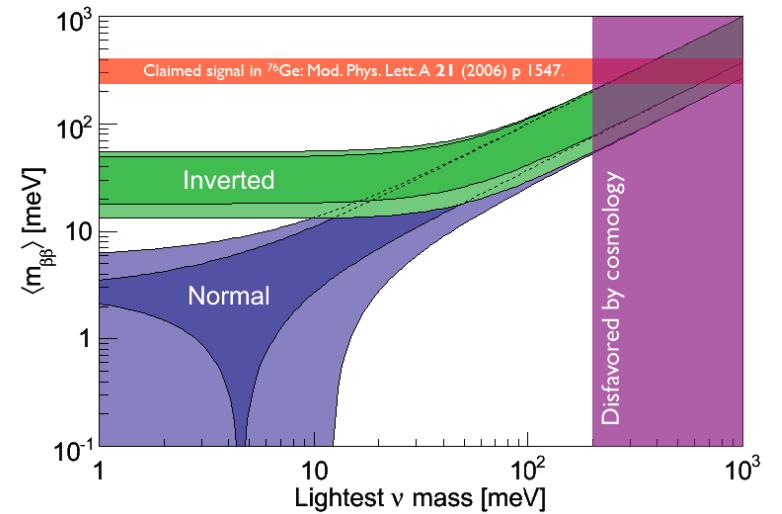
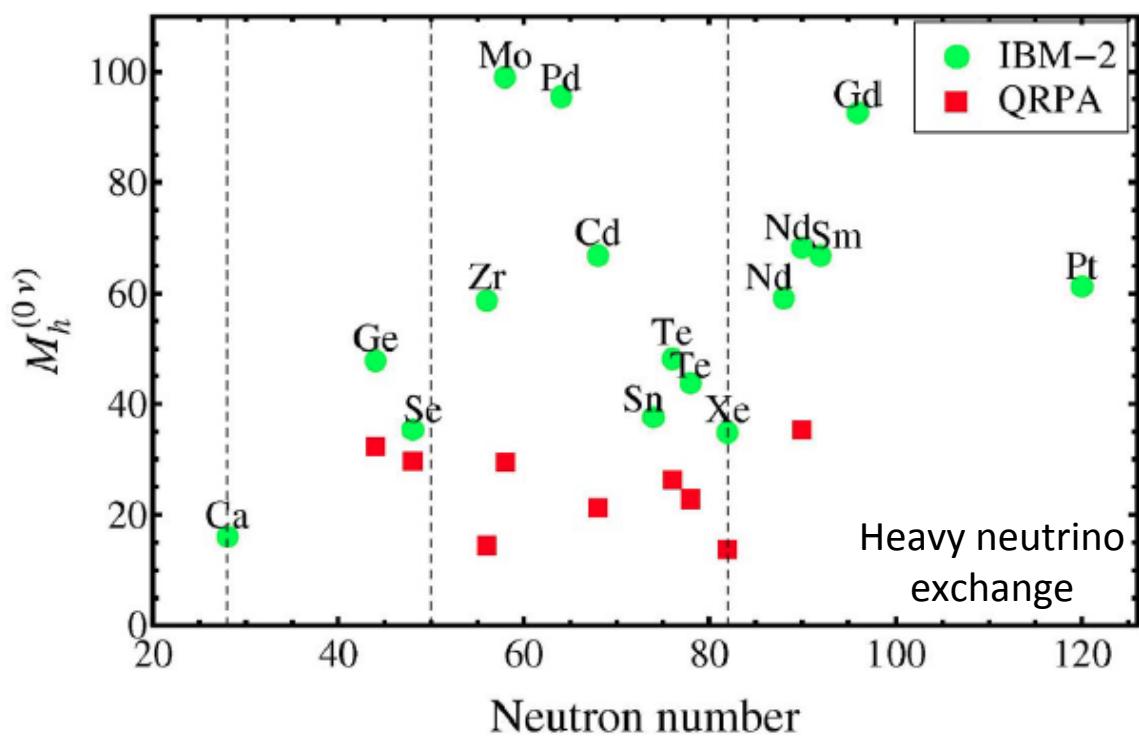
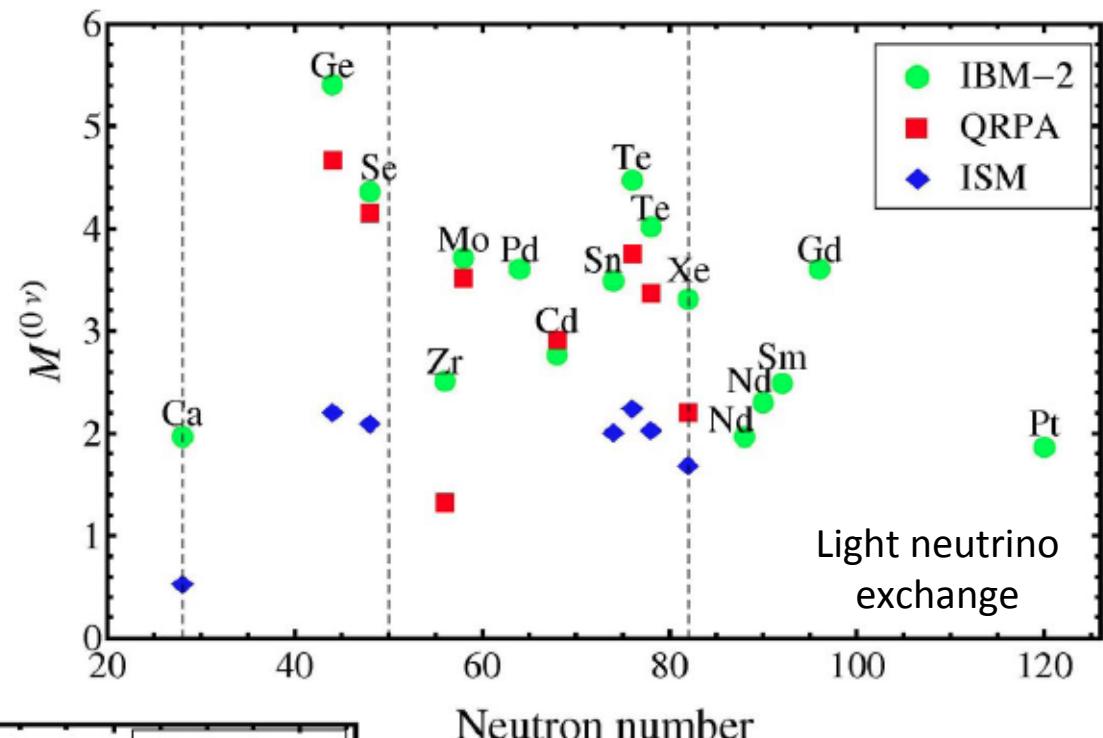
Ov double beta decay

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

$G(E, Z)$: phase space

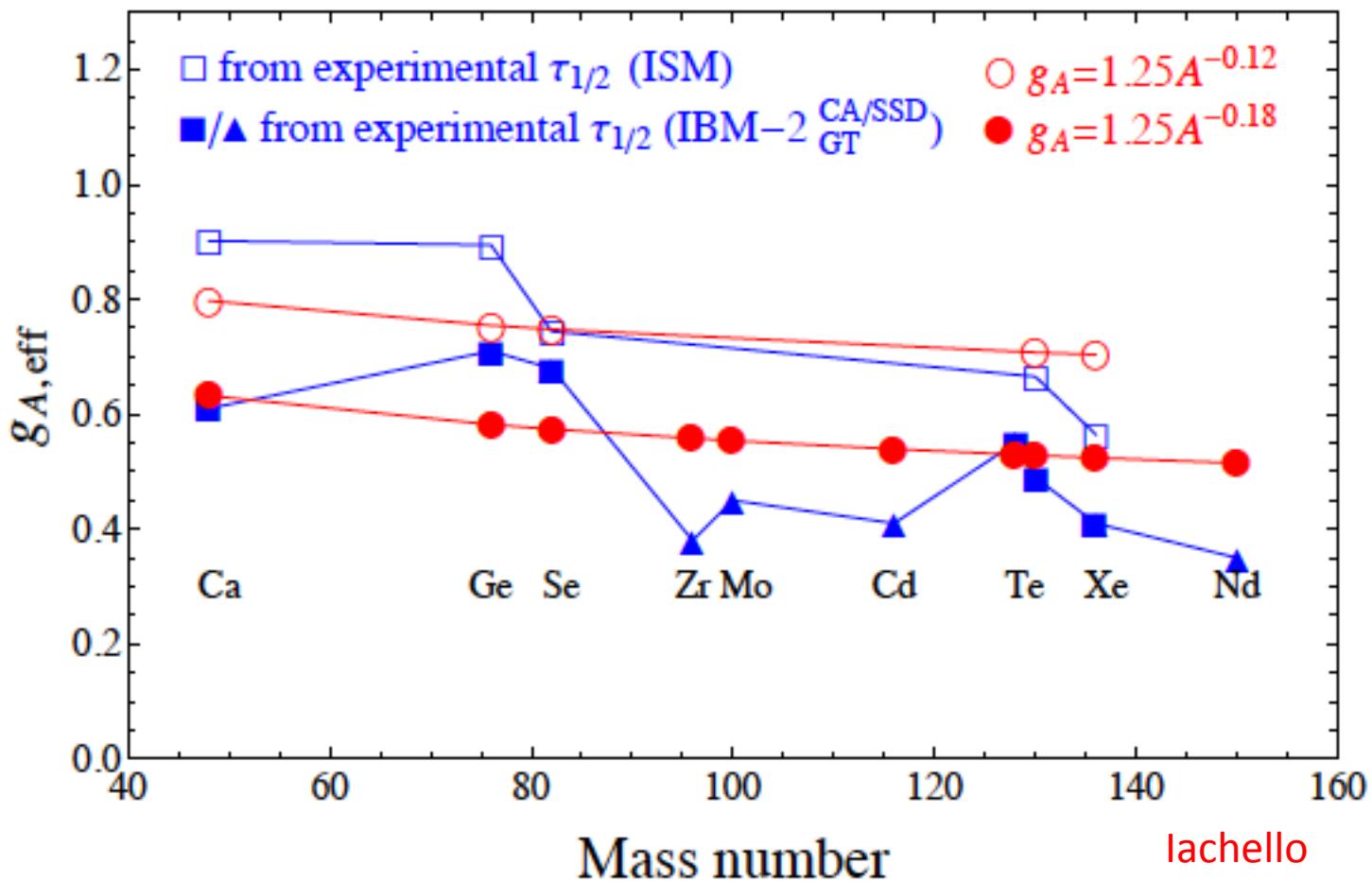
M : nuclear matrix element

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

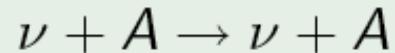


g_A is strongly renormalized in 2ν double beta decay, but typically the free nucleon value is used in neutrinoless double beta decay calculations.

$$\text{Decay rate} \approx g_A^4$$



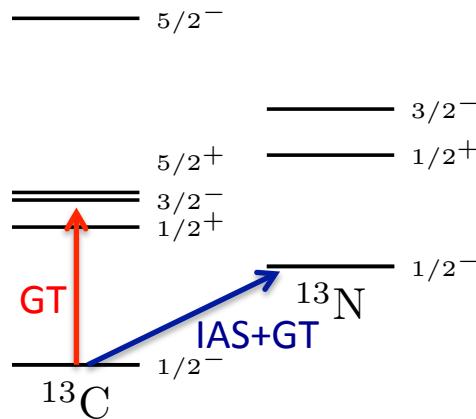
Neutrino Coherent Scattering



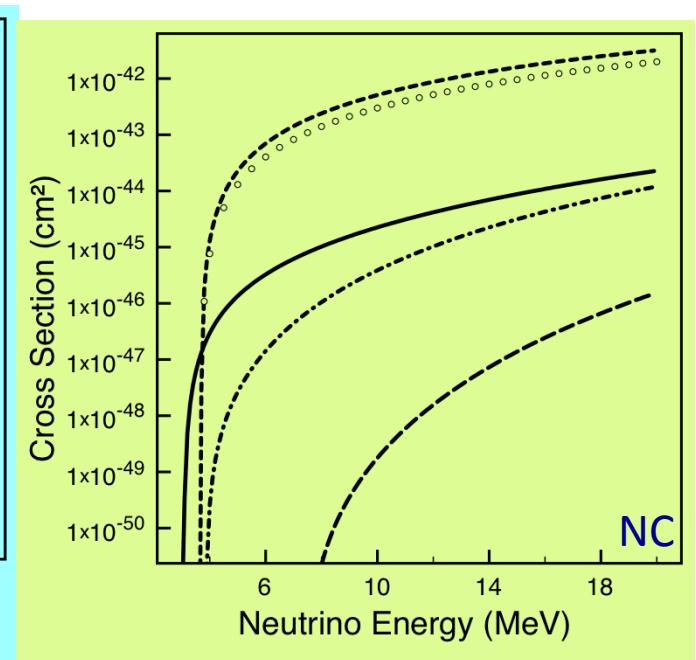
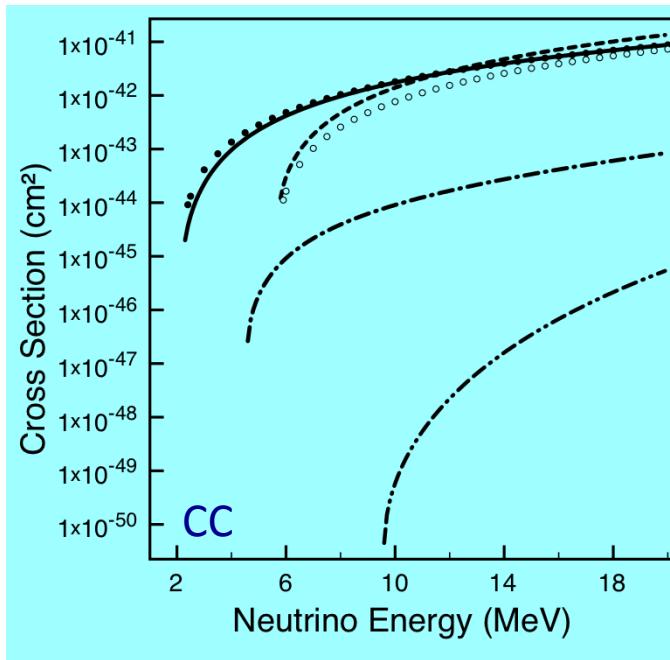
$$\frac{d\sigma}{d \cos \theta} = \frac{G_F^2}{8\pi} \left\{ Z^2 (4 \sin^2 \theta_W - 1) + N \right\}^2 E_\nu^2 (1 + \cos \theta)$$

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

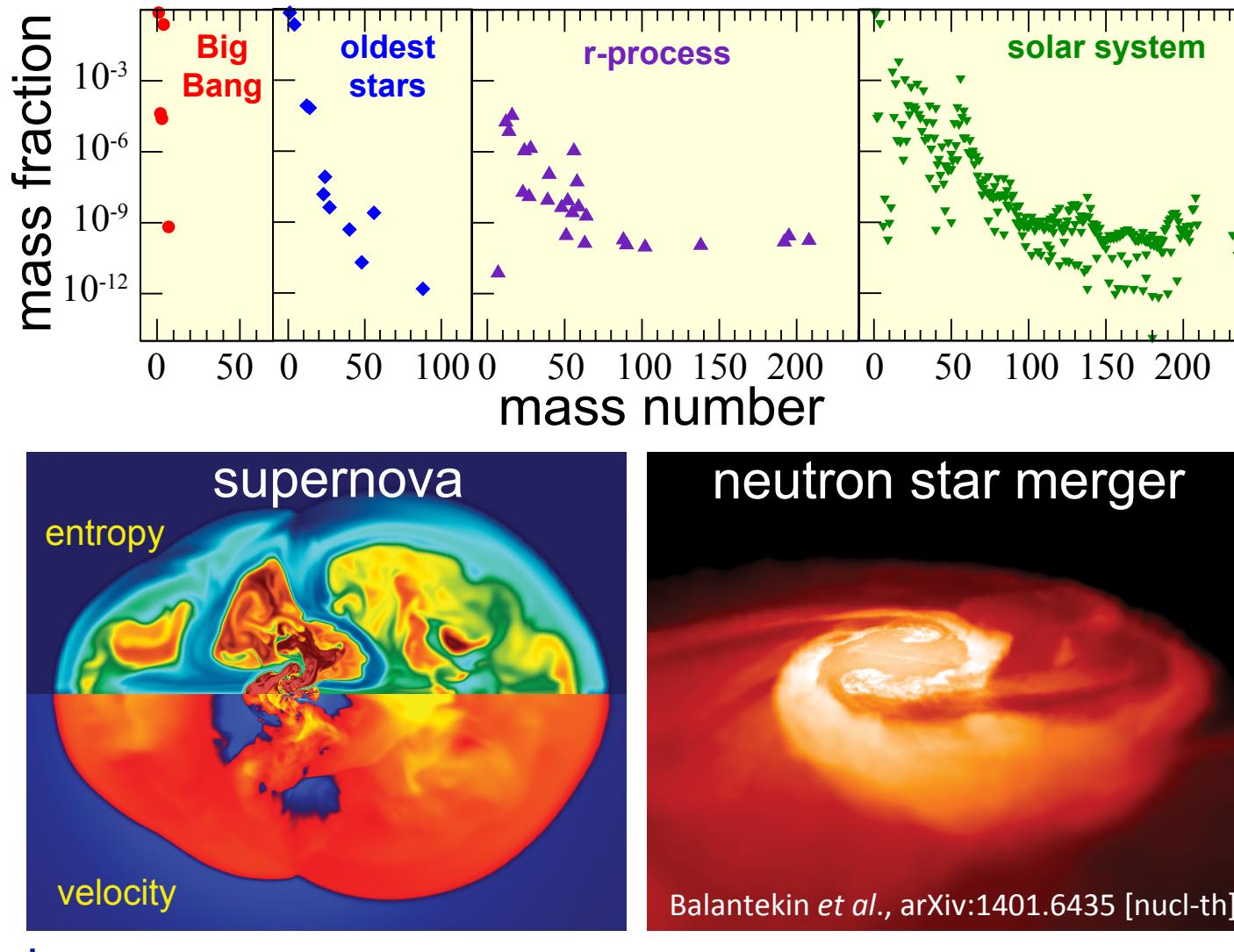
- This reaction is background to the dark matter searches with nuclear targets.
- Nuclear form factors need to be included. McLaughlin, Engel.



Suzuki, Balantekin, Kajino



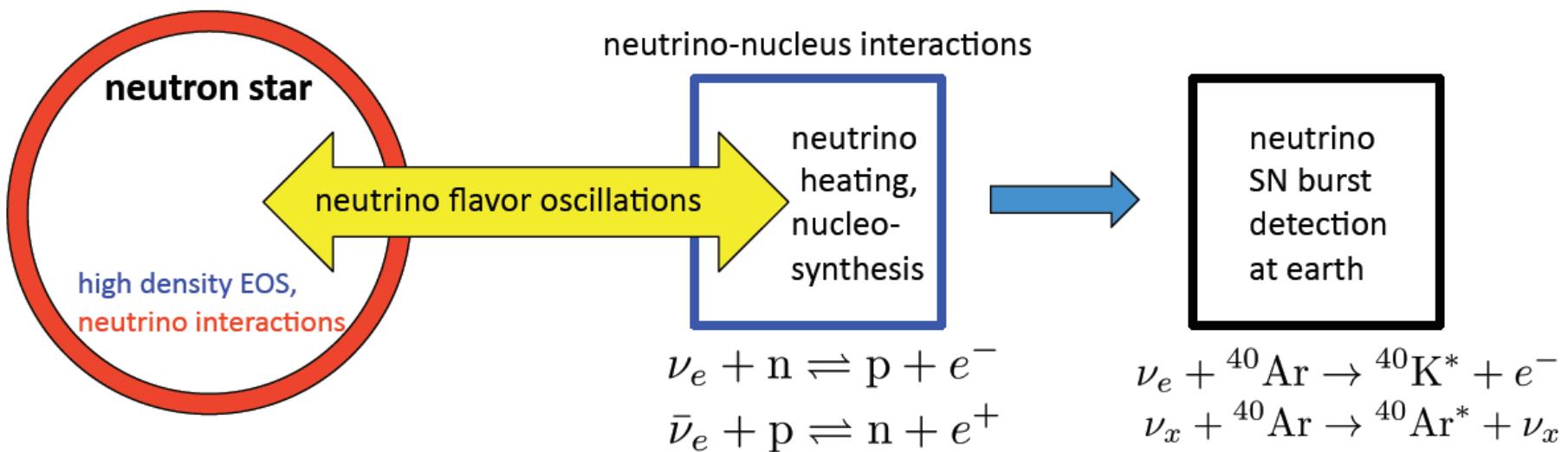
The origin of elements



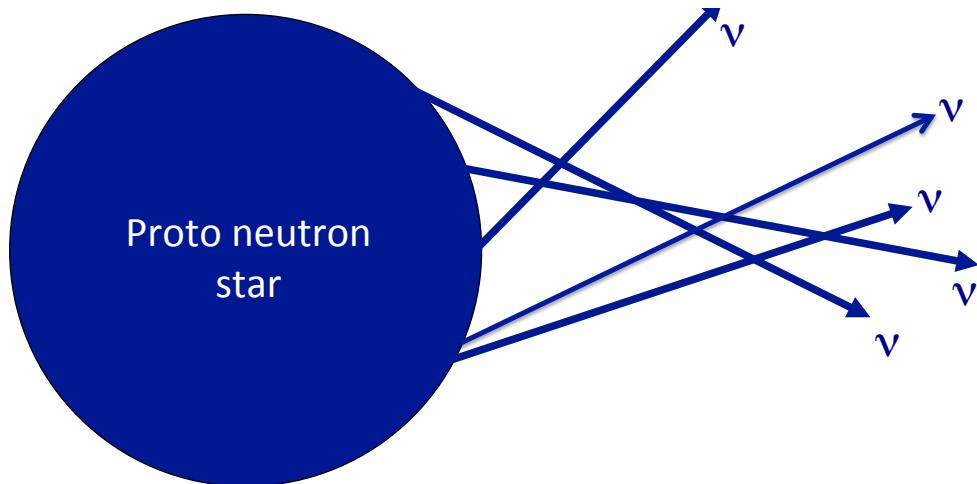
Neutrinos not only play a crucial role in the dynamics of these sites, but they also control the value of the electron fraction, the parameter determining the yields of the r-process.

Possible sites for the r-process

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).



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!
 $\sim 10^{58}$ Neutrinos!
 This necessitates including the effects of $\nu\nu$ interactions!

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

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").



Symmetry magazine

If we catch a supernova with neutrinos we'd better understand the signal very well. For that we need nuclear physics!



Symmetry magazine

Thank you!