A personal perspective on FRIB Science

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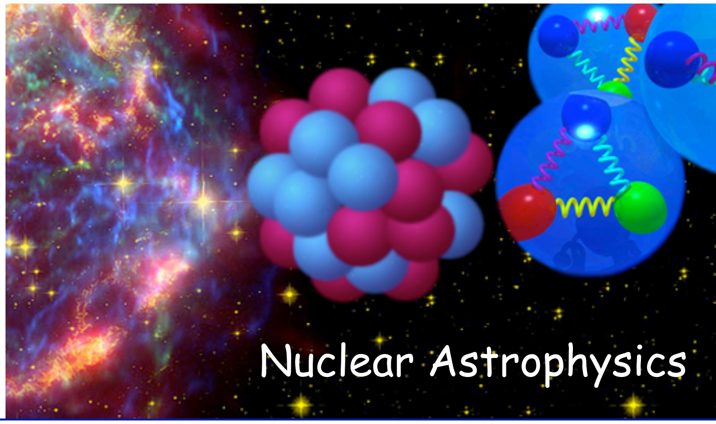
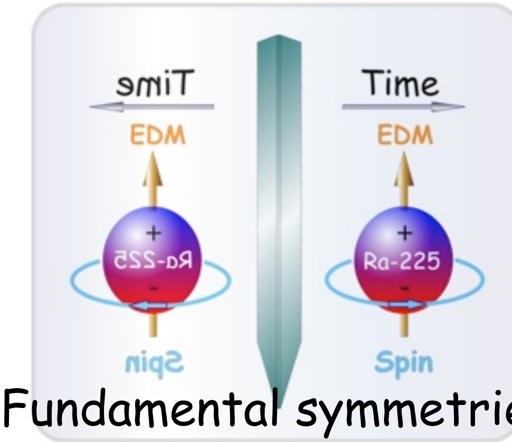
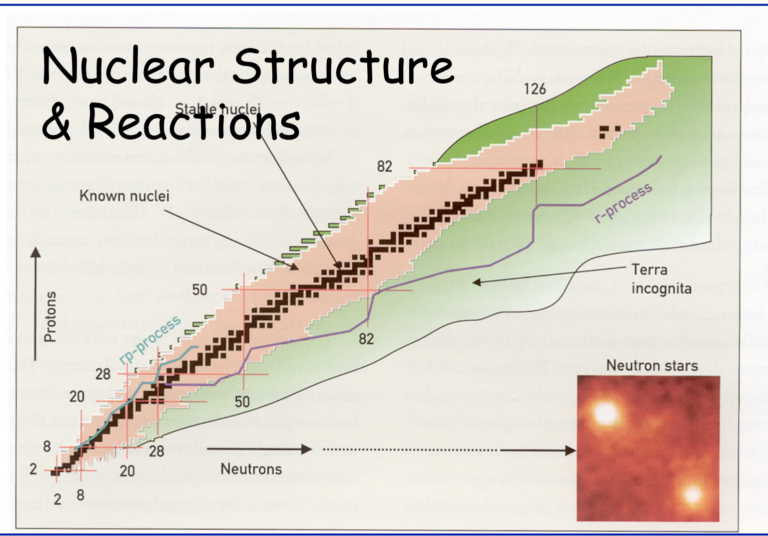
Which science drives physics with rare isotopes?



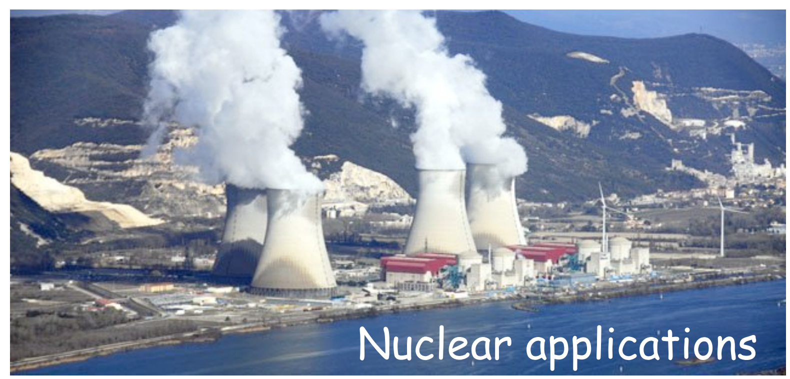
Origin of new elements, rare isotopes powering stellar explosions, neutron star crust



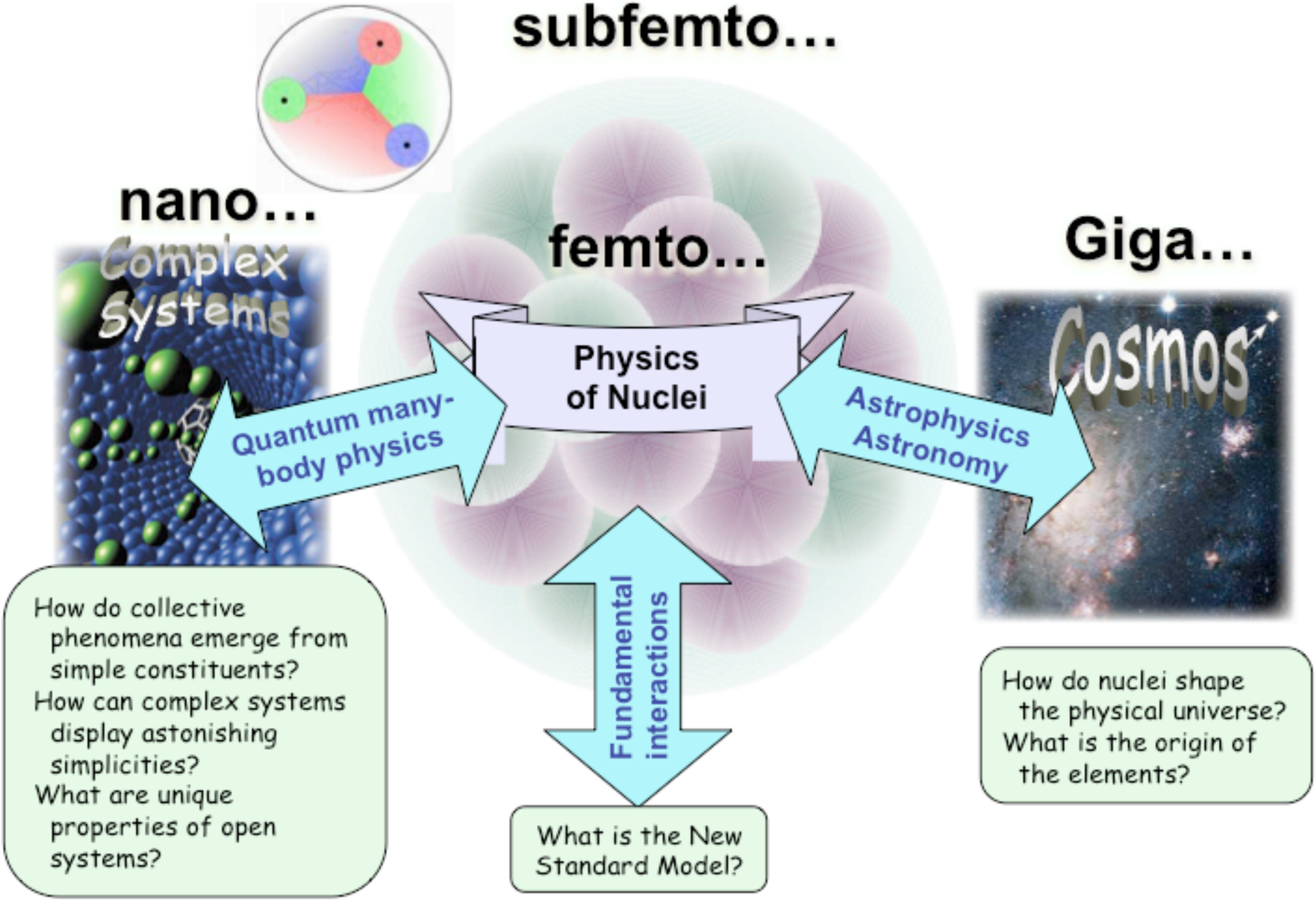
Use of rare isotopes as laboratories where symmetry violations are amplified.



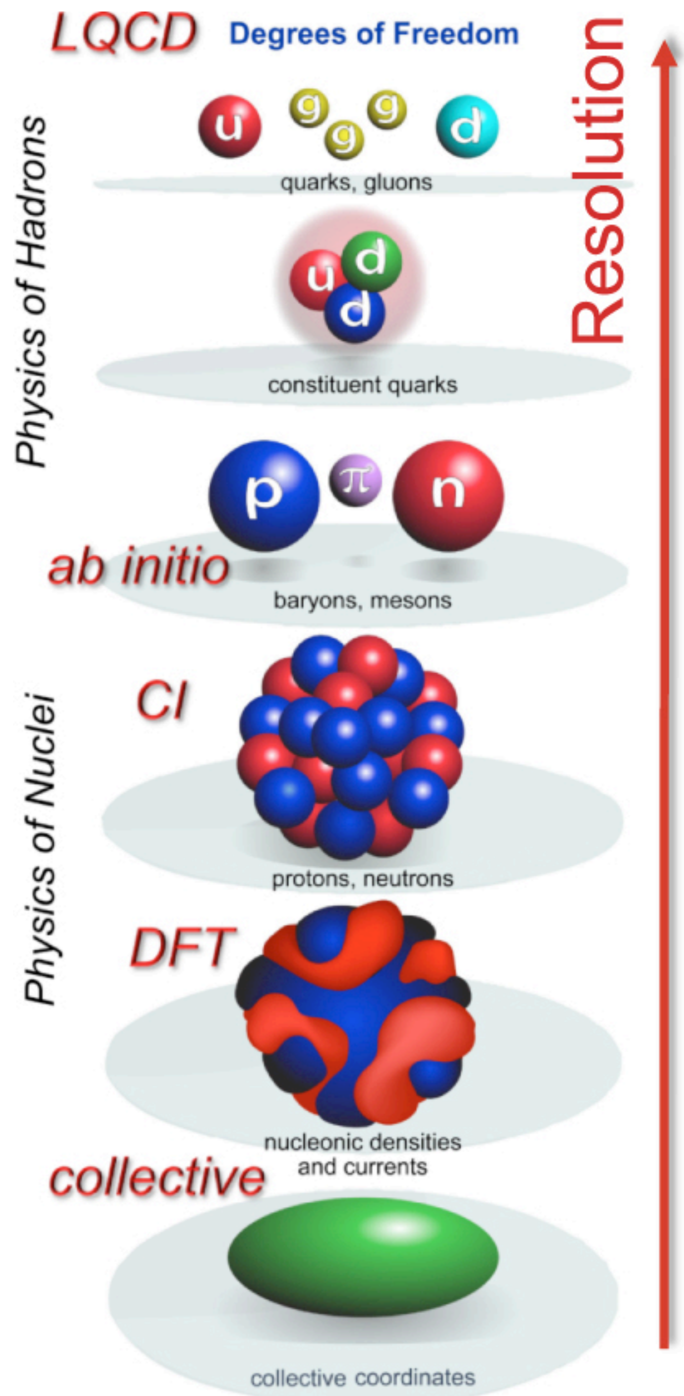
Limits of existence: what makes nuclei stable? New shapes, new collective behavior.



Materials, medical physics, reactors,..


subfemto...
nano...
Complex Systems
femto...
Giga...
Cosmos
Physics of Nuclei
Quantum many-body physics
Astrophysics Astronomy
Fundamental interactions
How do collective phenomena emerge from simple constituents?
How can complex systems display astonishing simplicities?
What are unique properties of open systems?
What is the New Standard Model?
How do nuclei shape the physical universe?
What is the origin of the elements?

There is interesting physics at all scales!



Hot QCD
Cold QCD

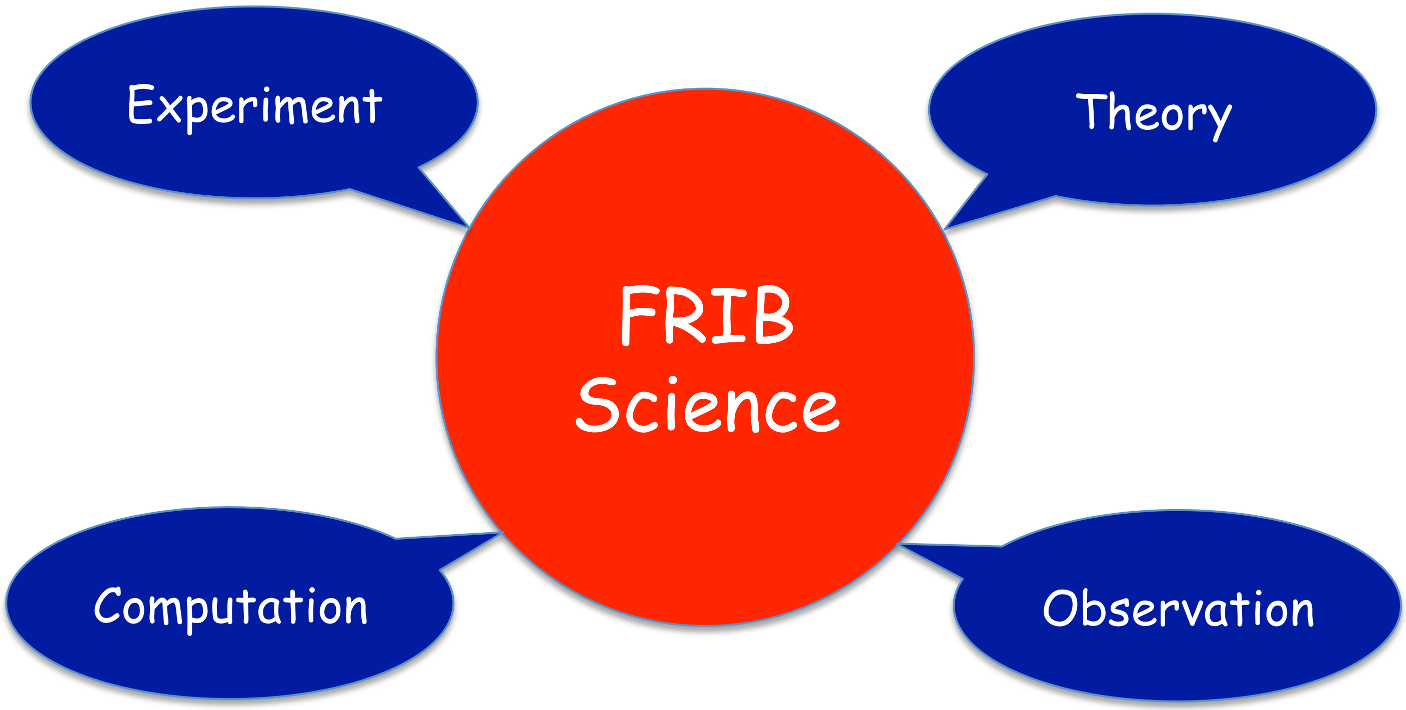
Hadron-Nuclear interface

Nuclear structure
Nuclear reactions

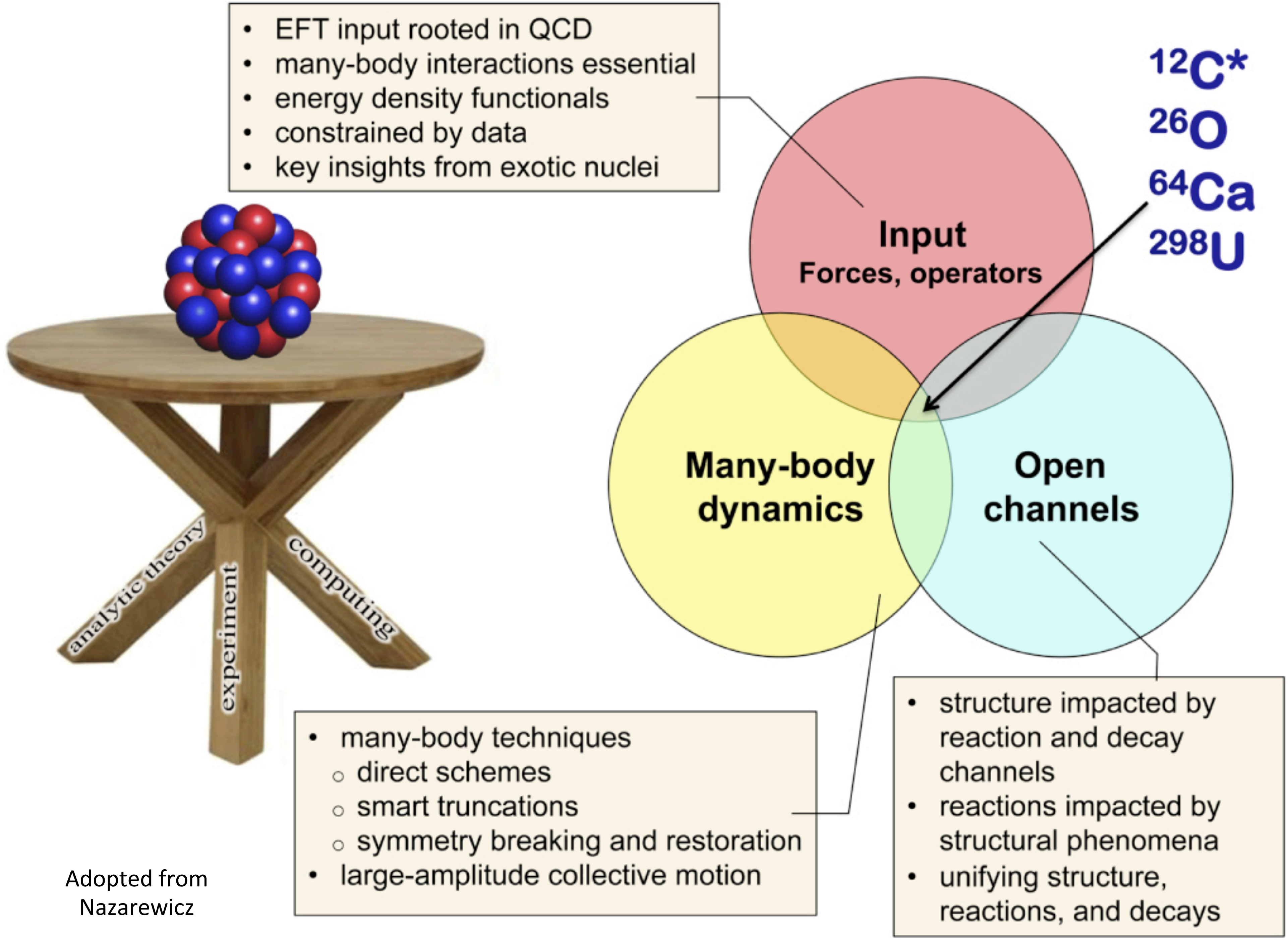
Nuclear astrophysics
New standard model

Applications of nuclear science

Four modes of carrying out FRIB-related research

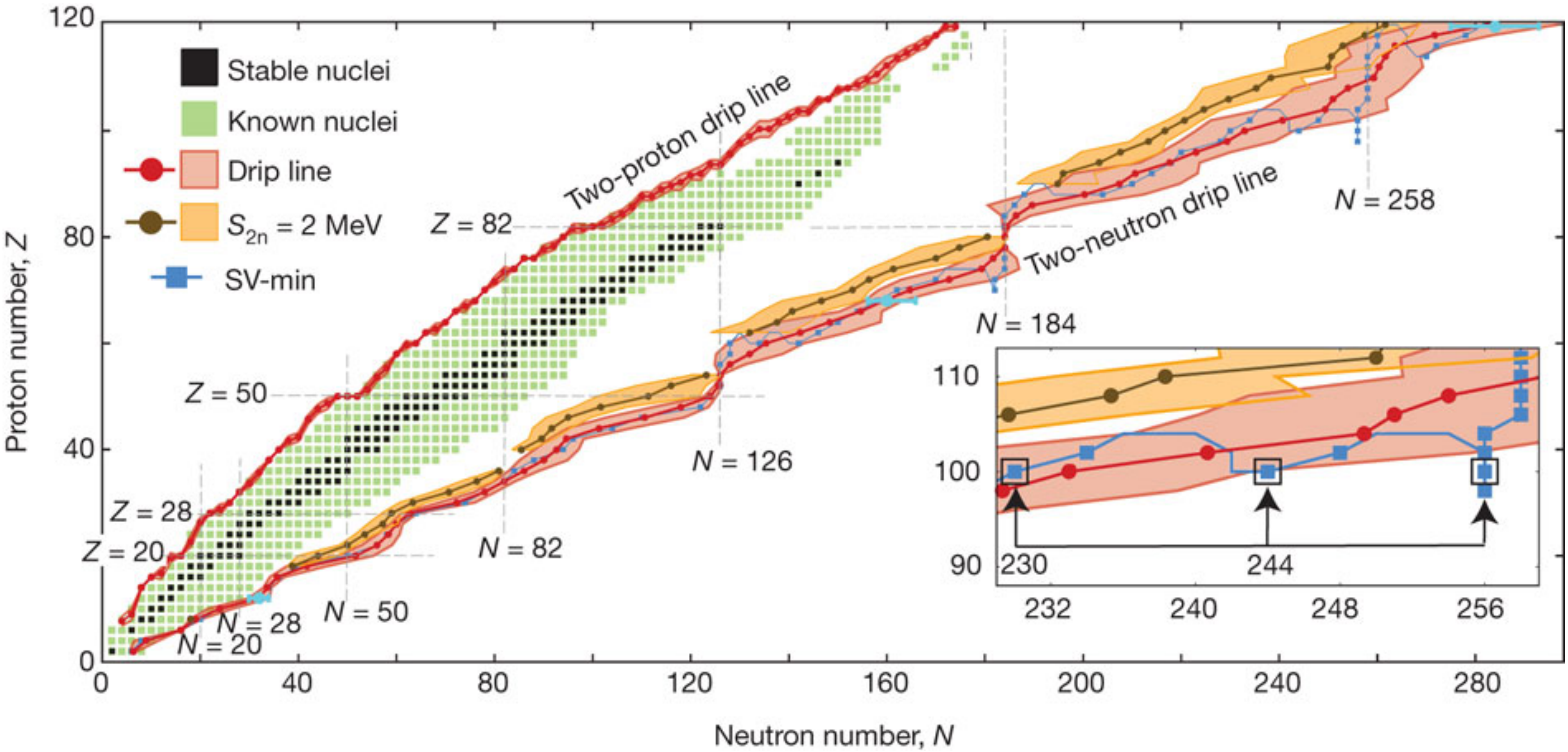


For scientific progress all four modes are essential and they complement each other!



Adopted from
Nazarewicz

In recent years major advances in computational capabilities have pushed the boundaries of what can be calculated by microscopic *ab initio* methods in nuclear theory



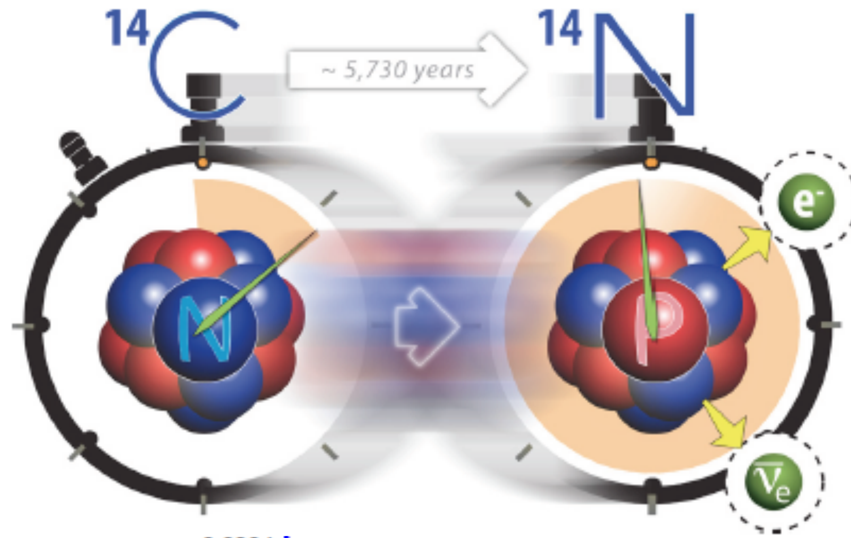
J. Erler *et al. Nature* **486**, 509-512 (2012)

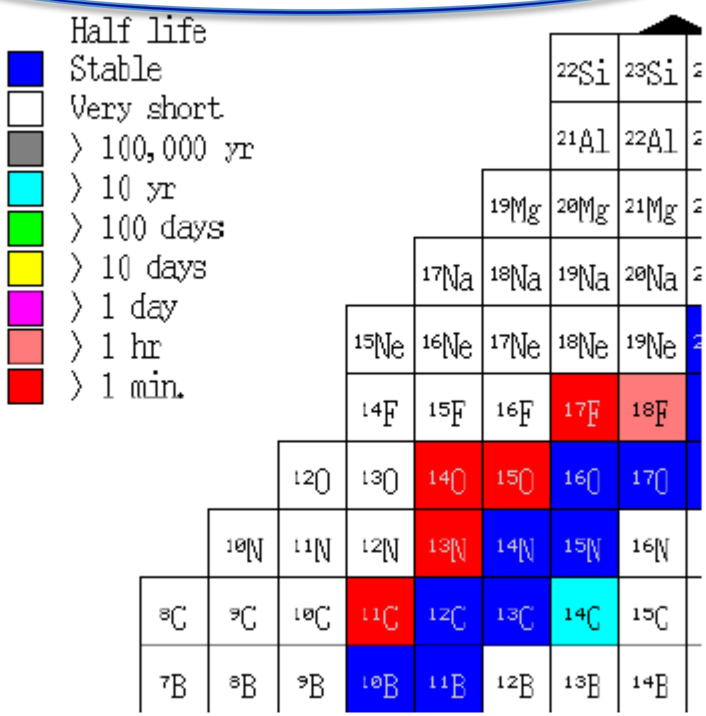
"Why does Carbon-14 live so long?"

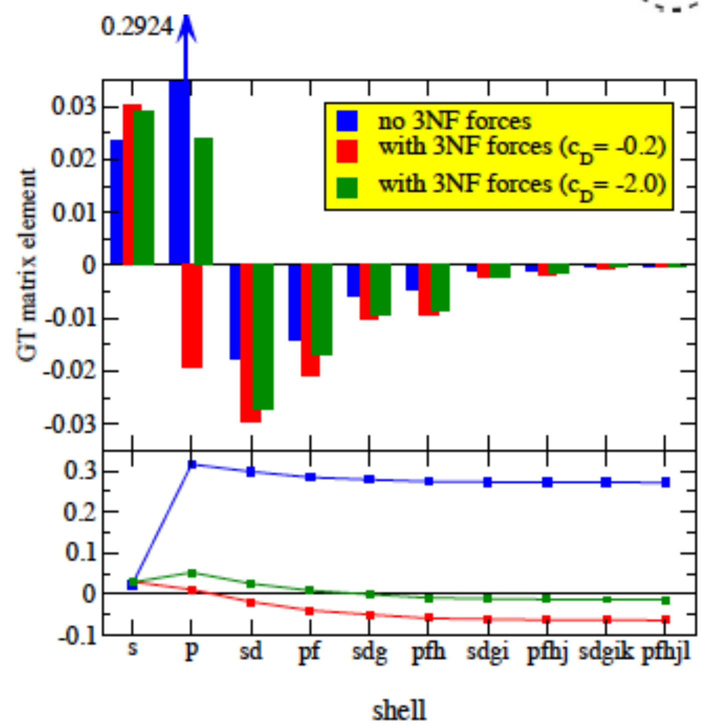
Carbon-14 dating relies on ~5,730 year half-life, but other light nuclei undergo similar beta decay with half-lives less than a day!

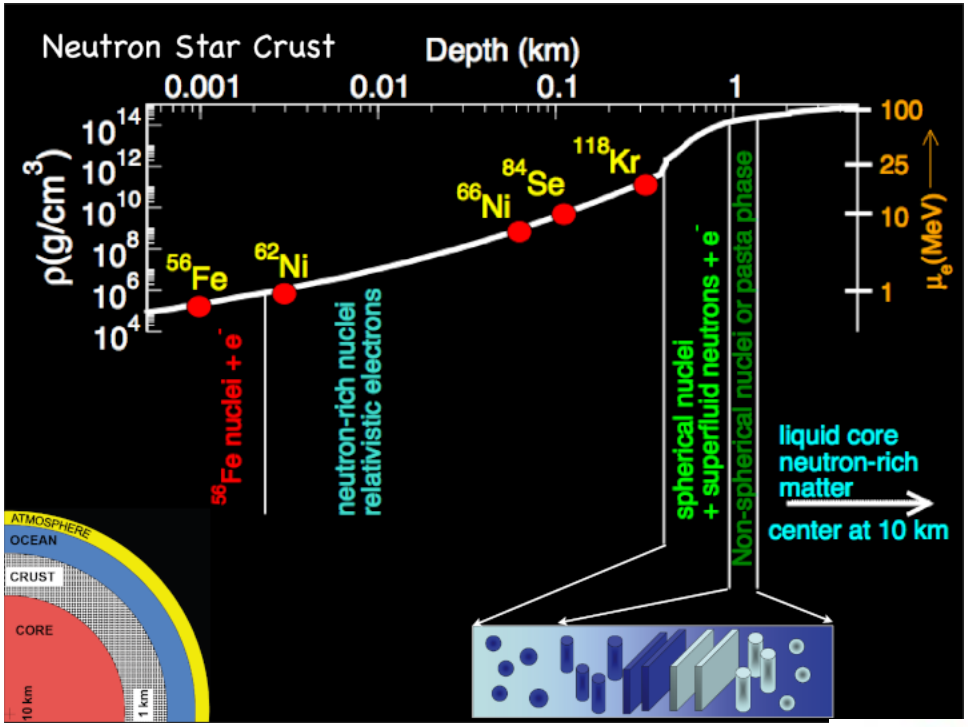
UNEDF SciDAC Collaboration
Universal Nuclear Energy Density Functional

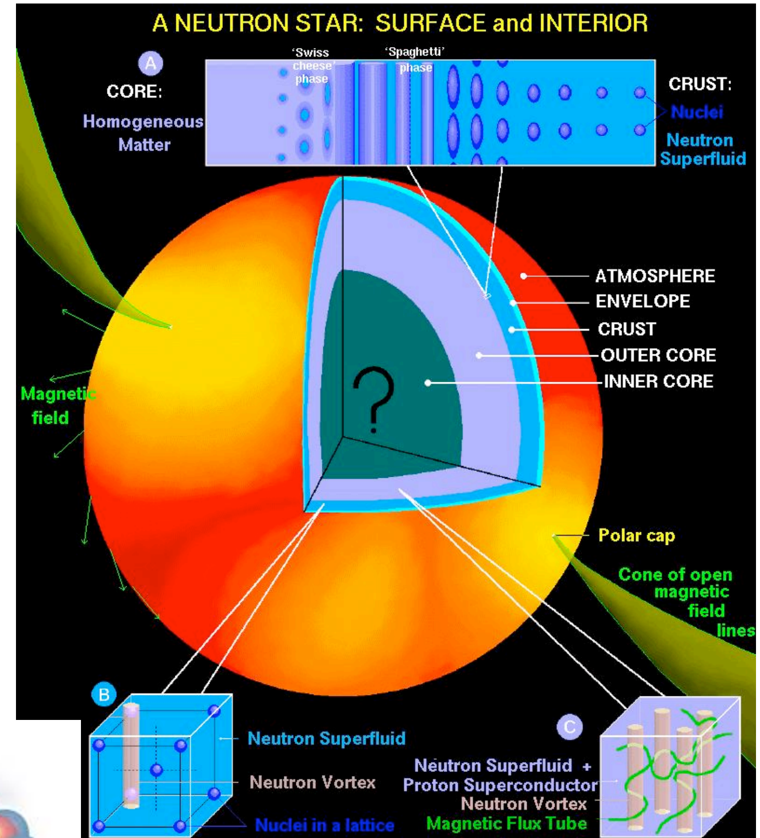
- Members of UNEDF collaboration made microscopic nuclear structure calculations to solve the puzzle
- Used systematic chiral Hamiltonian from low-energy effective field theory of QCD
- Key feature: consistent *3-nucleon* interactions



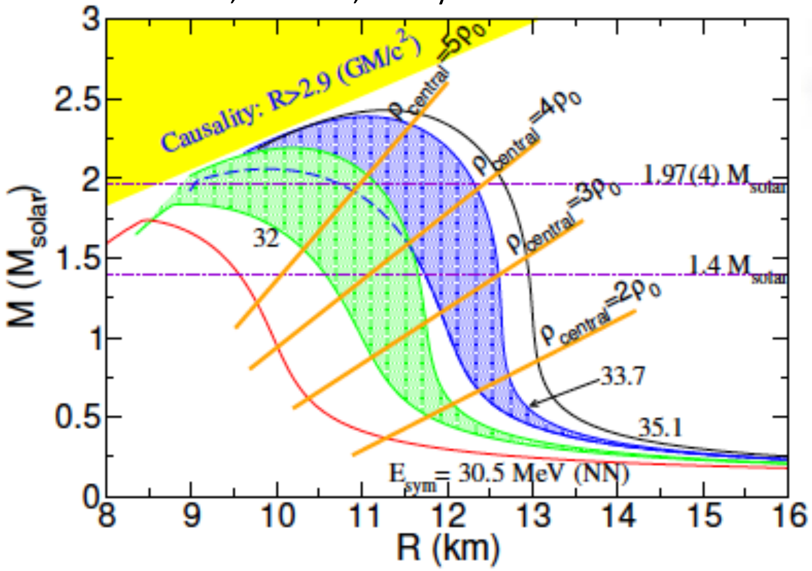


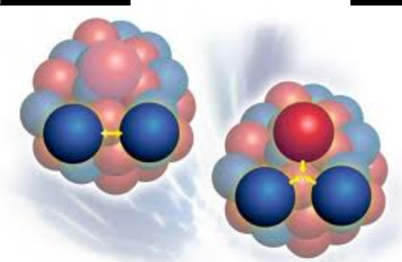




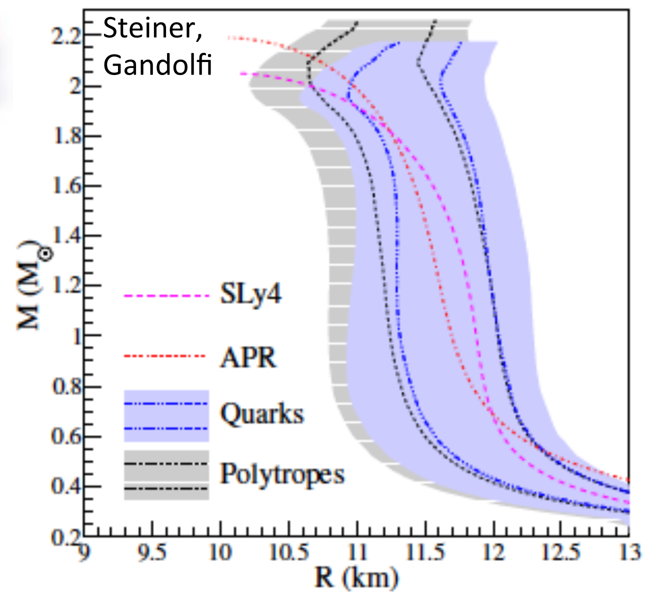


Gandolfi, Carlston, Reddy

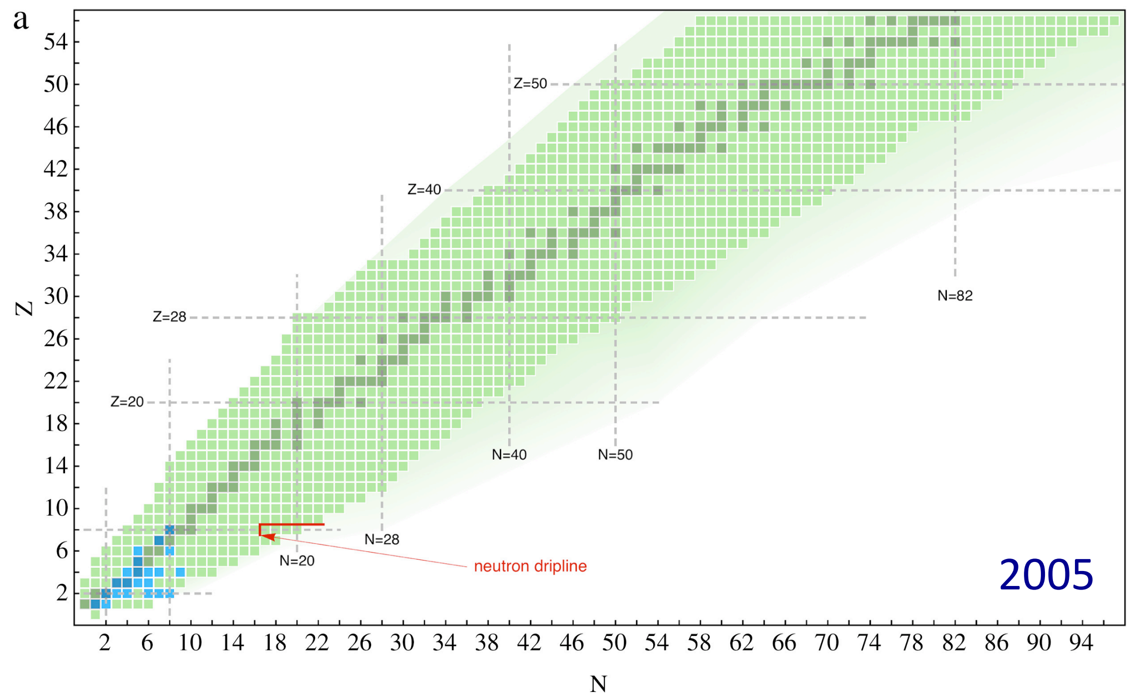


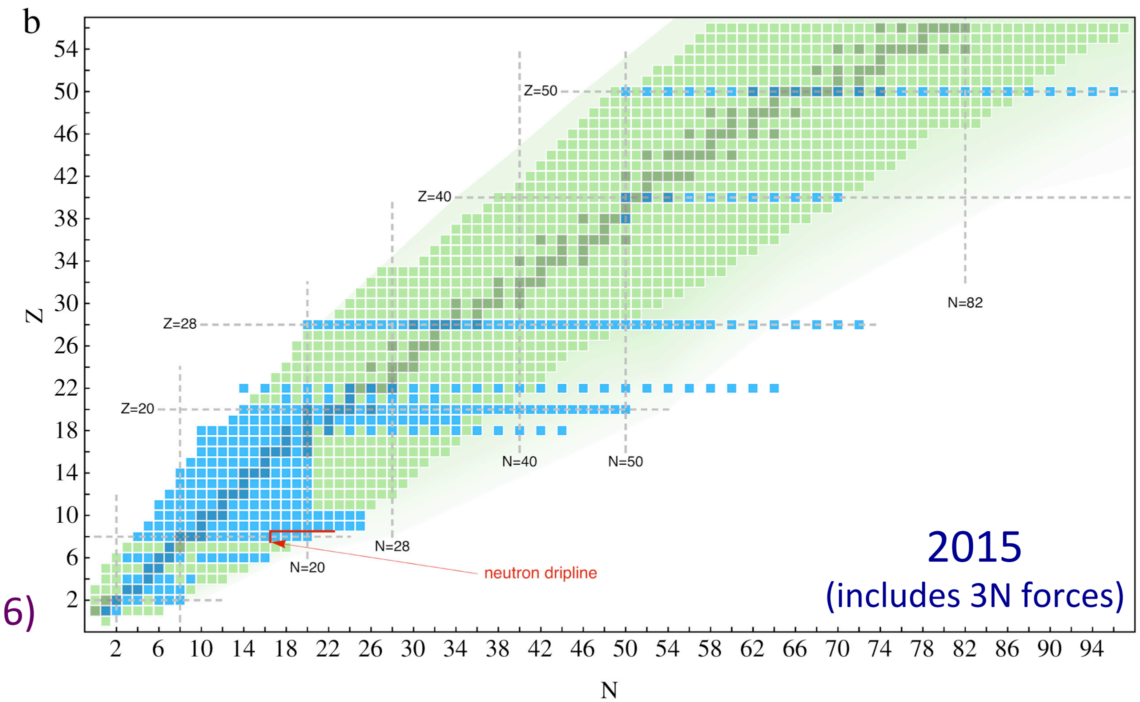


3-body forces are crucial for neutron-star physics!



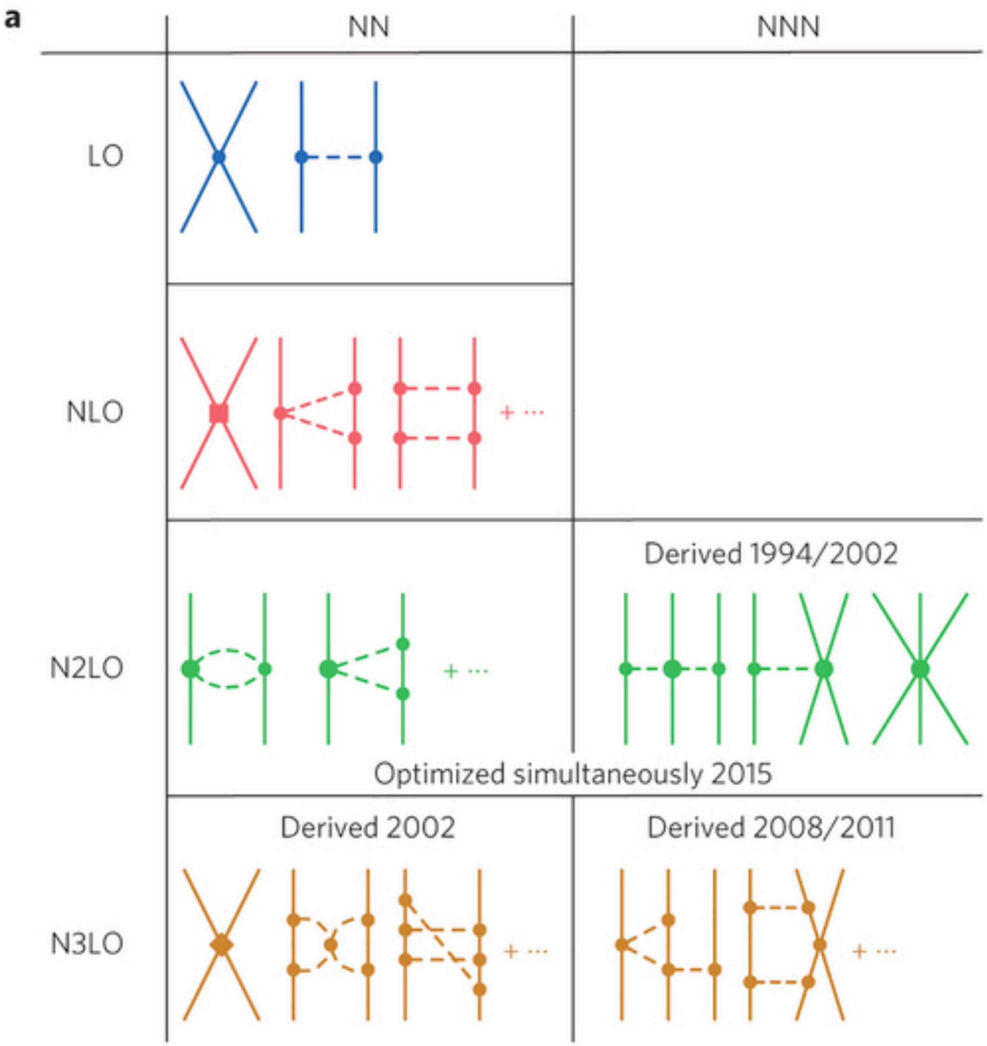
Ab initio calculations are attempted for many nuclei!



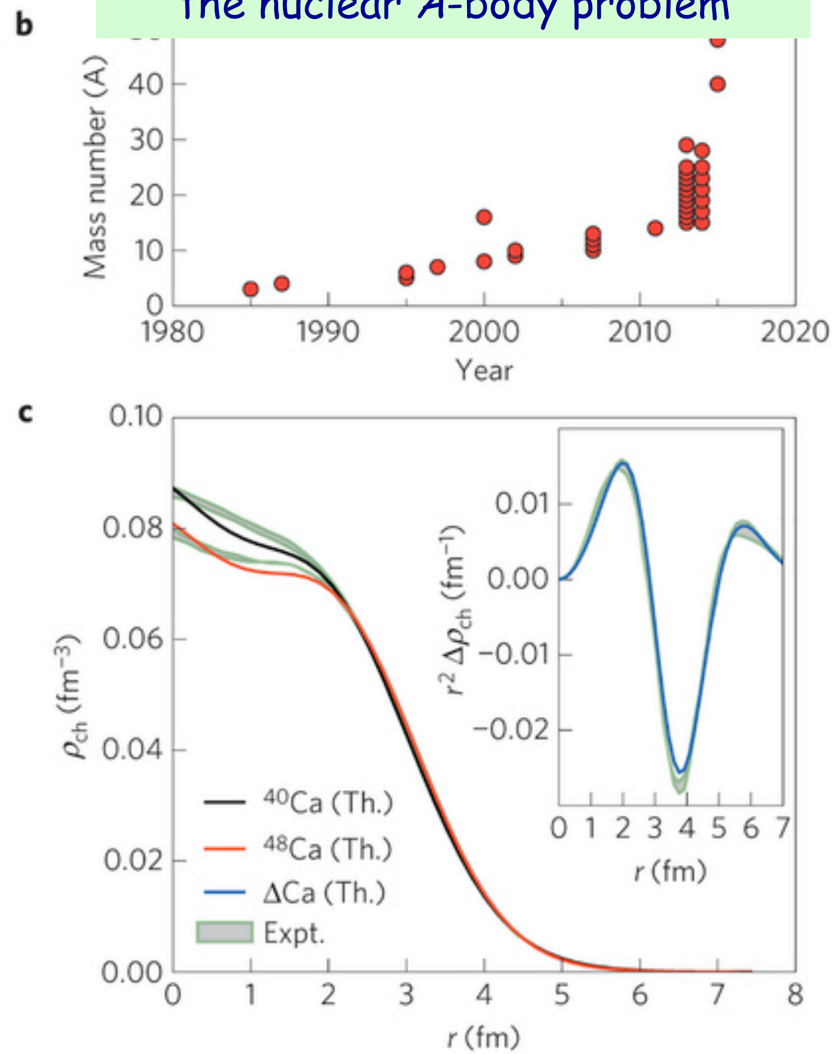


Hergert et al., Phys. Rep. **621**, 165 (2016)

Nuclear forces based on chiral effective field theory



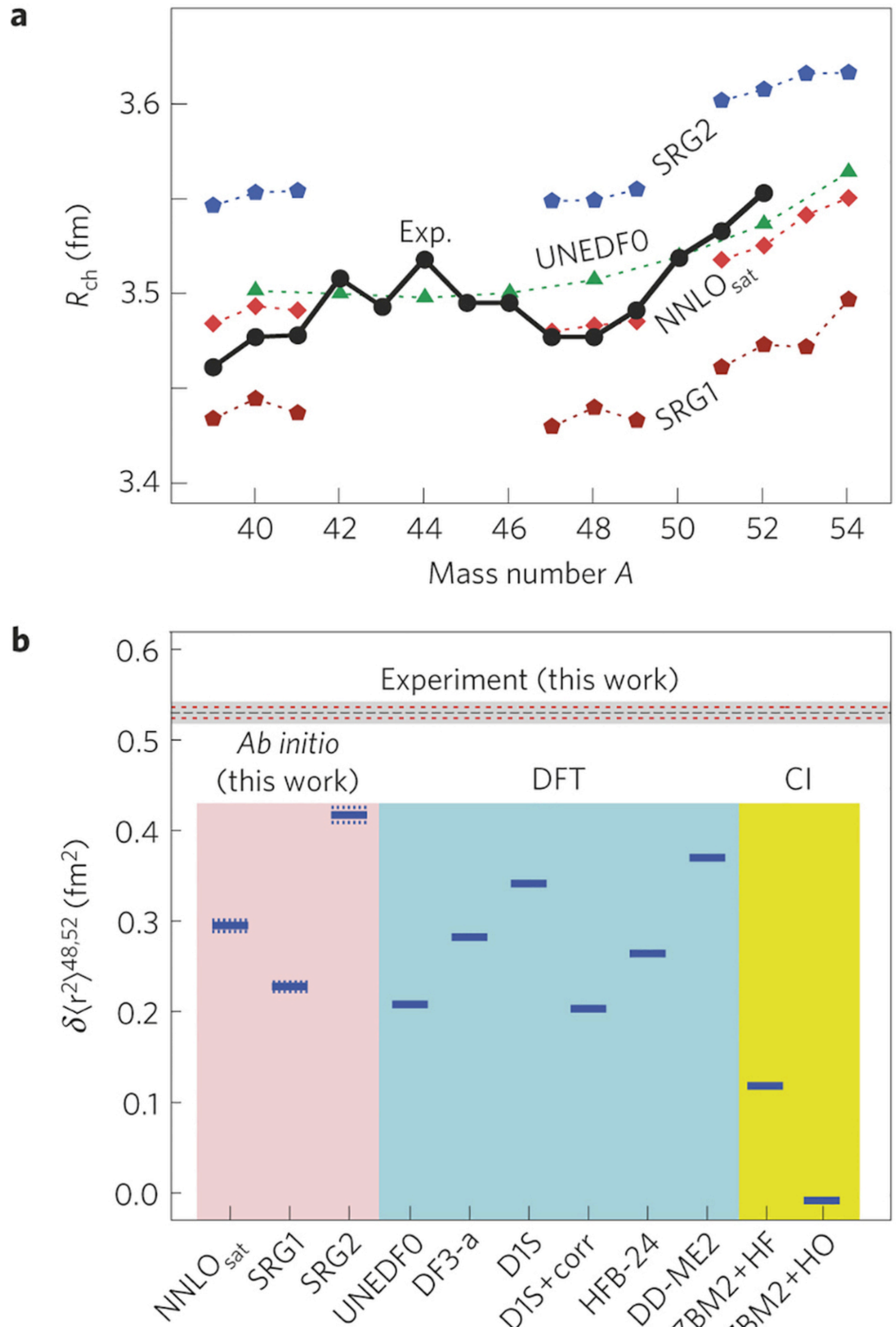
Increasing computational power: realistic *ab initio* calculations for the nuclear *A*-body problem



Hagen et al., Nature Phys. **12**, 186 (2016)

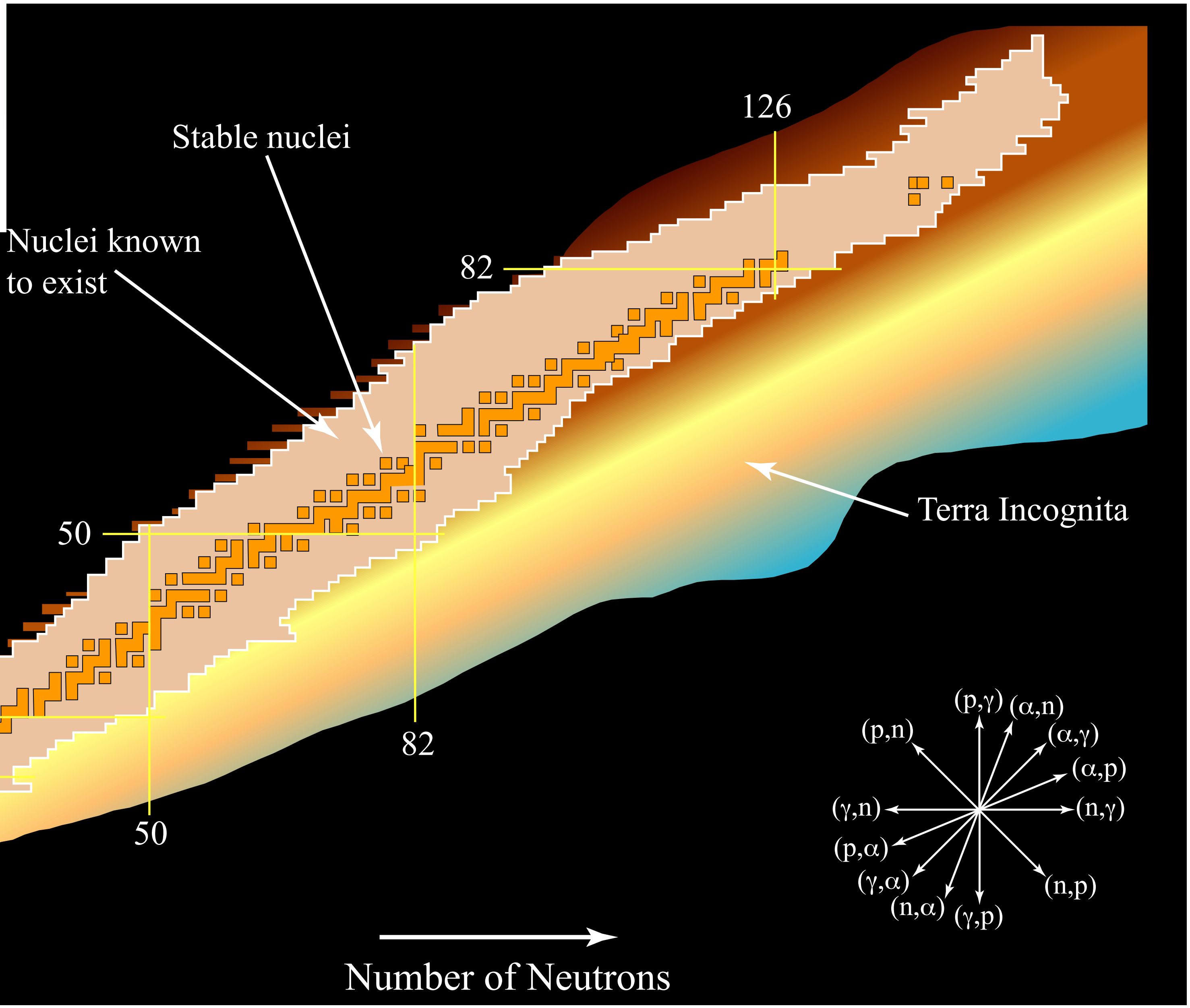
Ab initio predictions for charge densities in ^{40}Ca and ^{48}Ca compared to experiment

What is the evolution of nuclear sizes away from stability? Experimental charge radii for Ca isotopes as compared various to *ab initio*, density functional theory (DFT) and configuration interaction (CI) calculations.



Garcia Ruiz et al., Nature Phys. **12**, 594 (2016)

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?

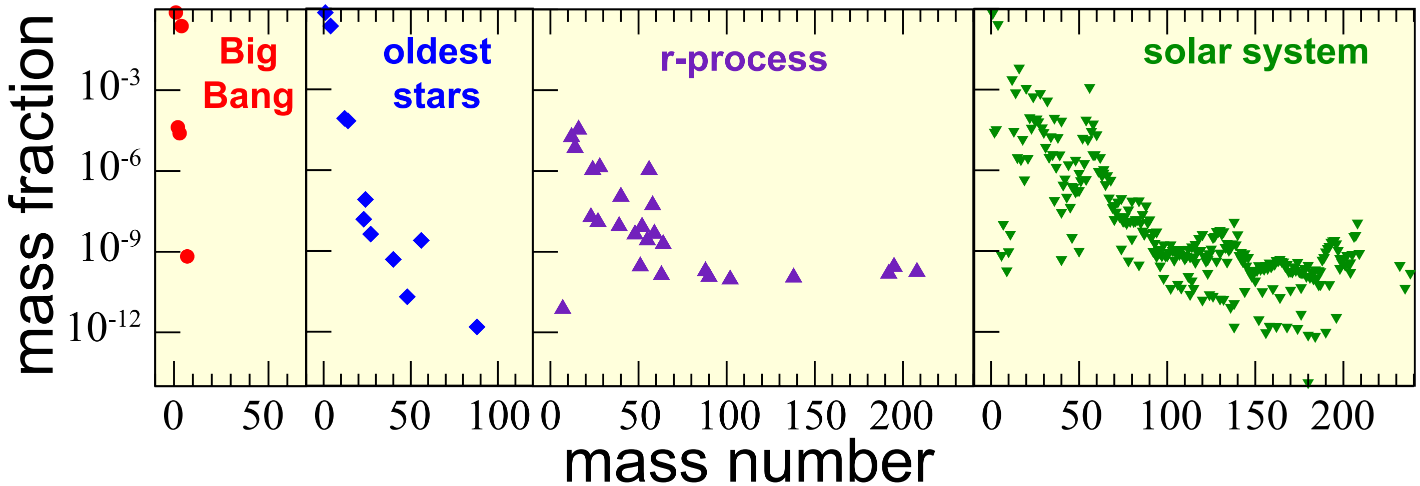
How do you cook elements around us?

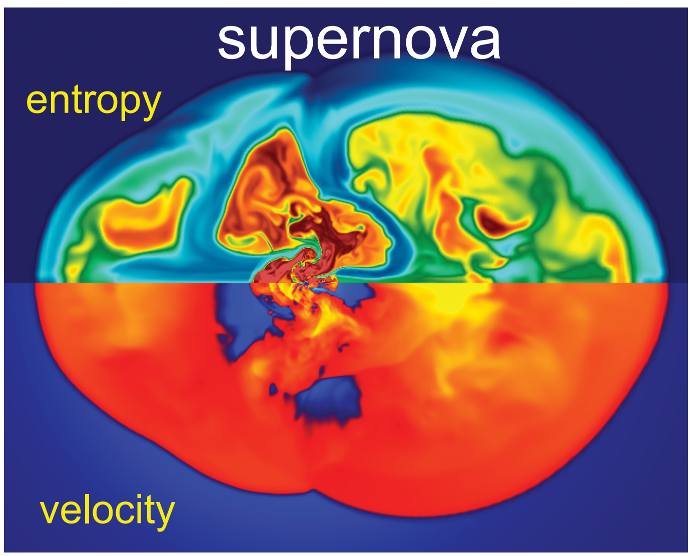
Some go supernova, producing U, Eu,Th… via the r-process

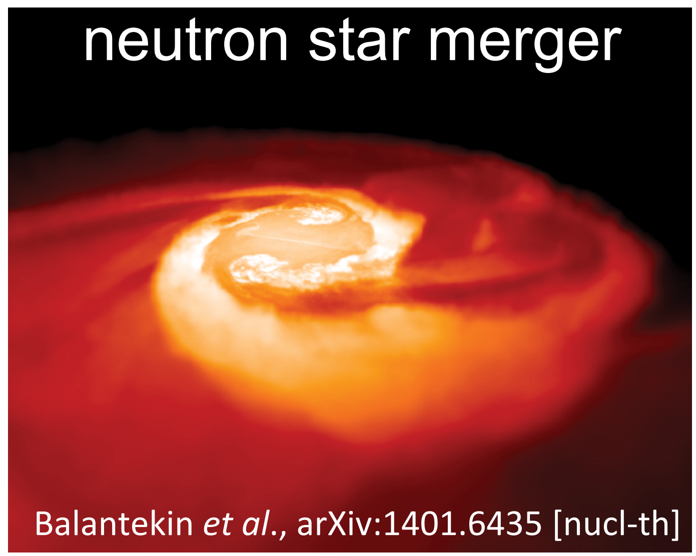
Pop II stars (metal poor)

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

The origin of elements



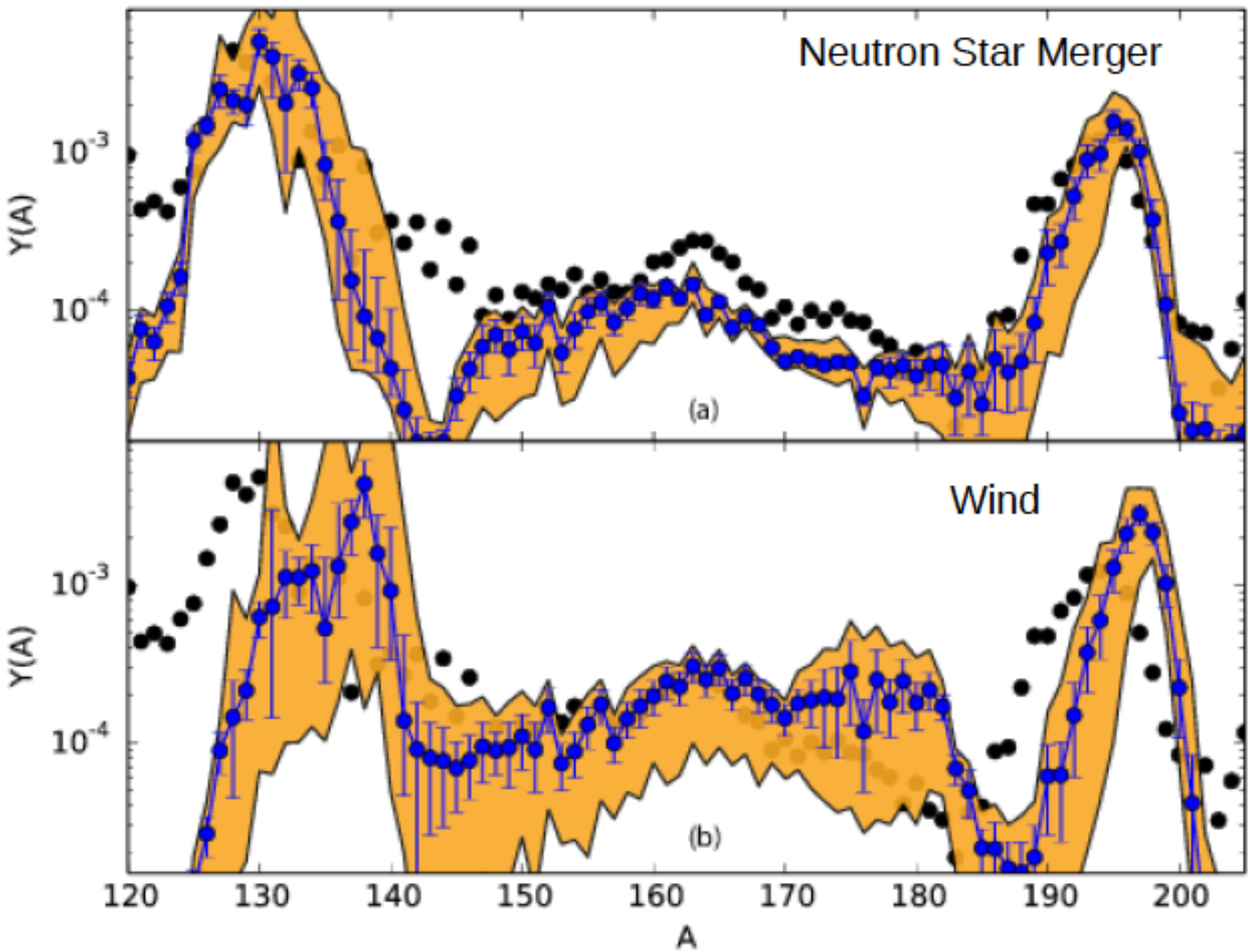




Possible sites for the r-process

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.

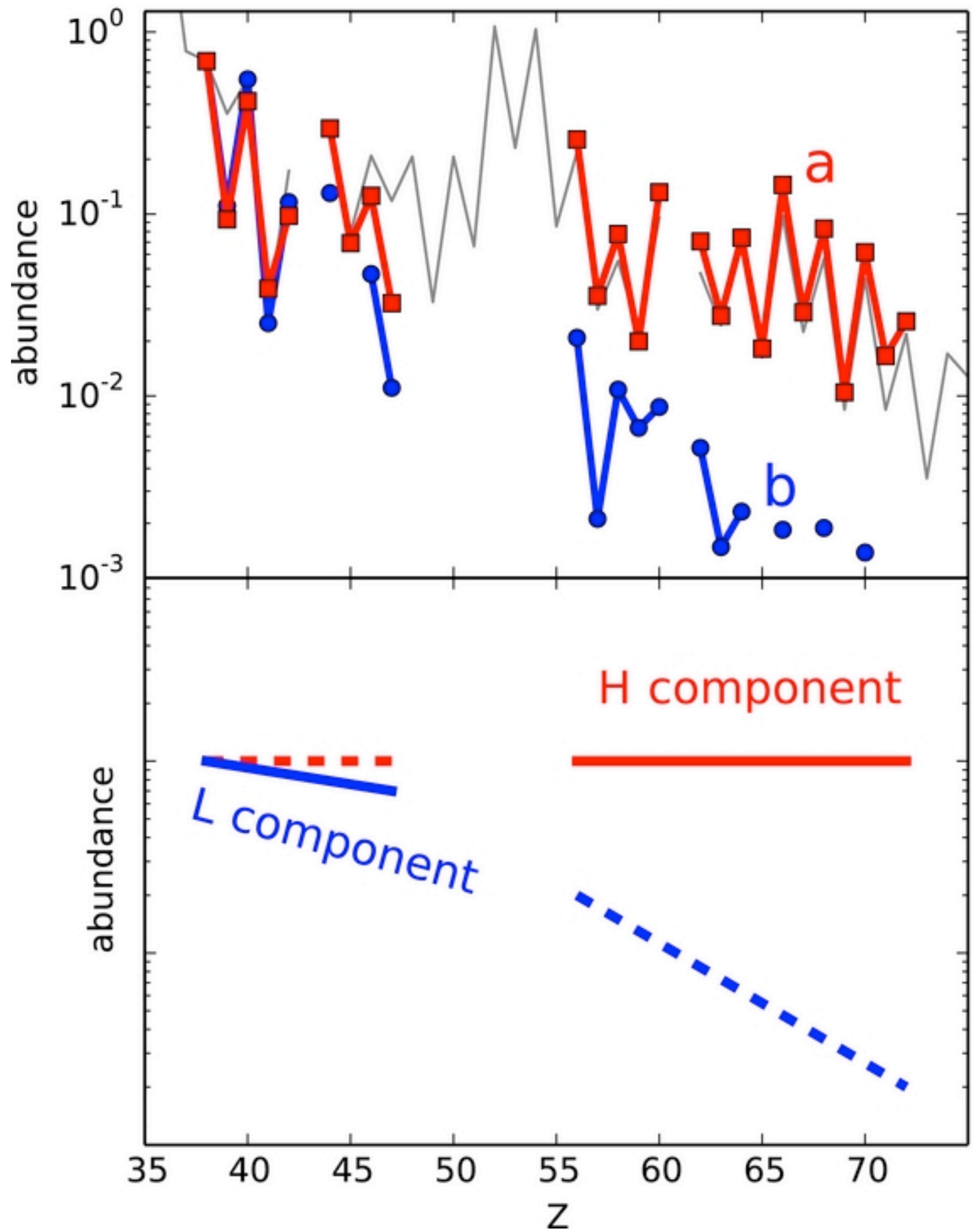
Estimated Final Abundances With Uncertainties

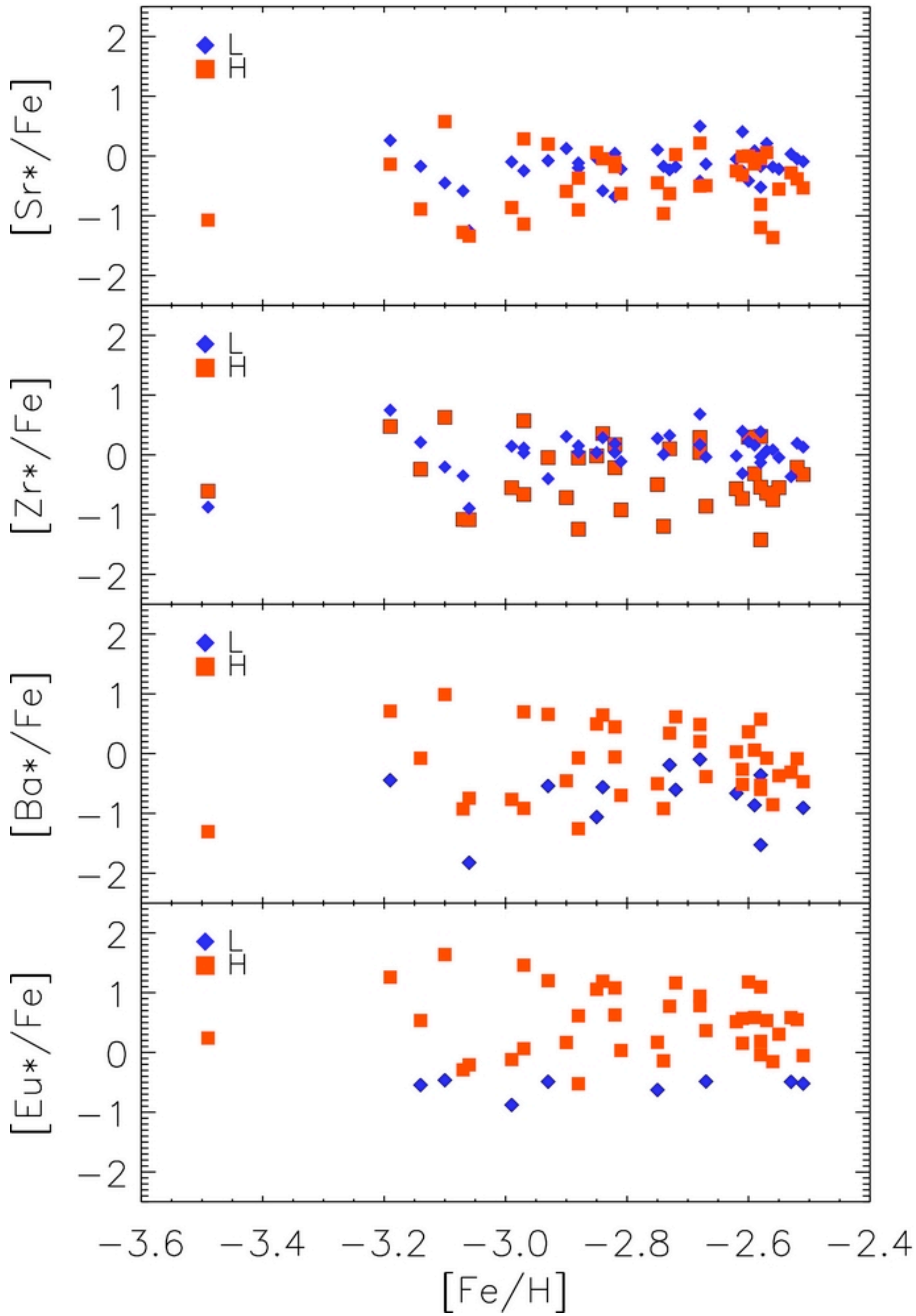


Variations in masses of N~82 and N~126 nuclei of +/- 1 MeV

Mumpower et al.

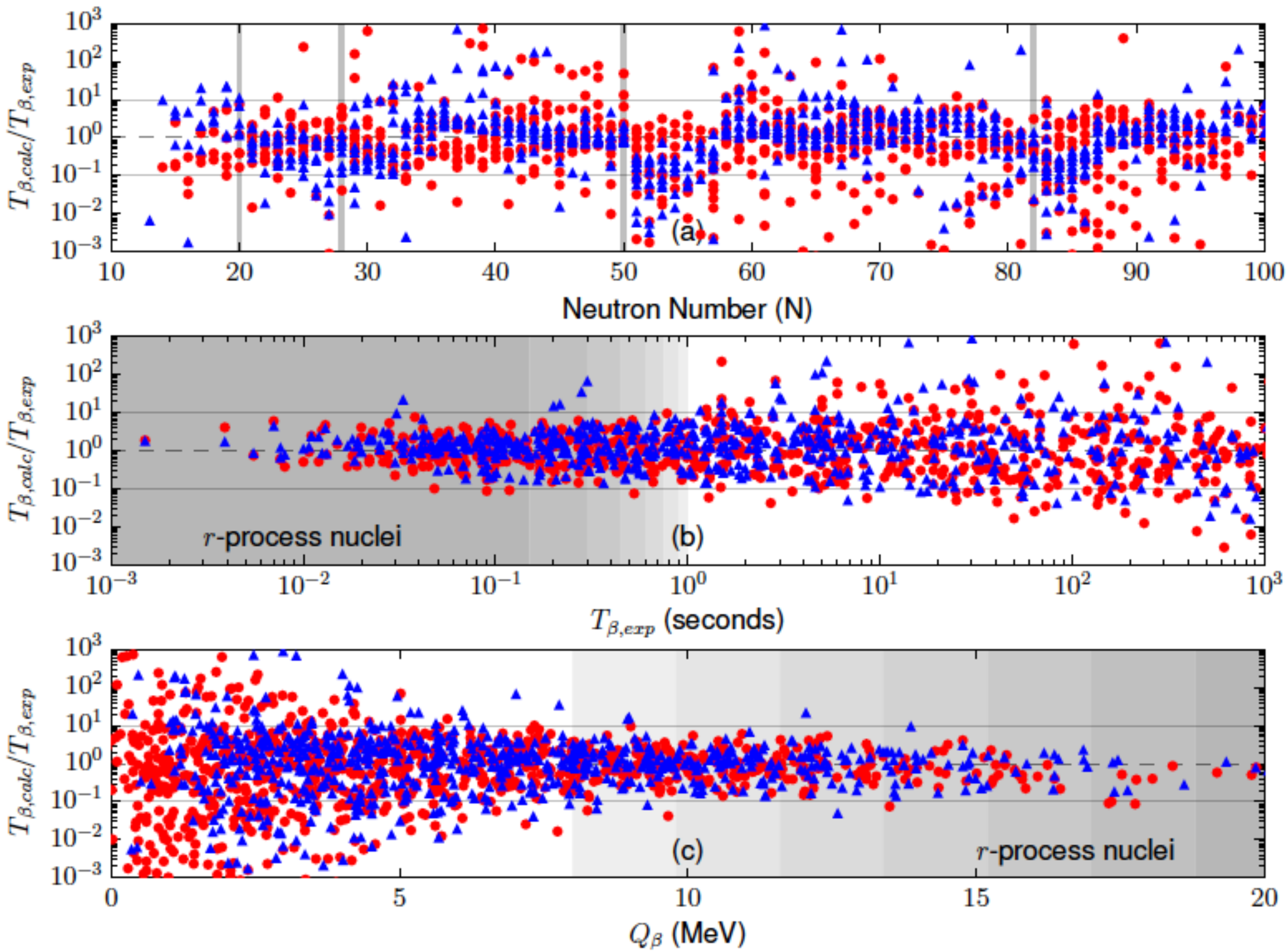
Ultra metal poor stars with high (H) and low (L) enrichment of r-process nuclei: At least two components or sites (Qian & Wasserburg)





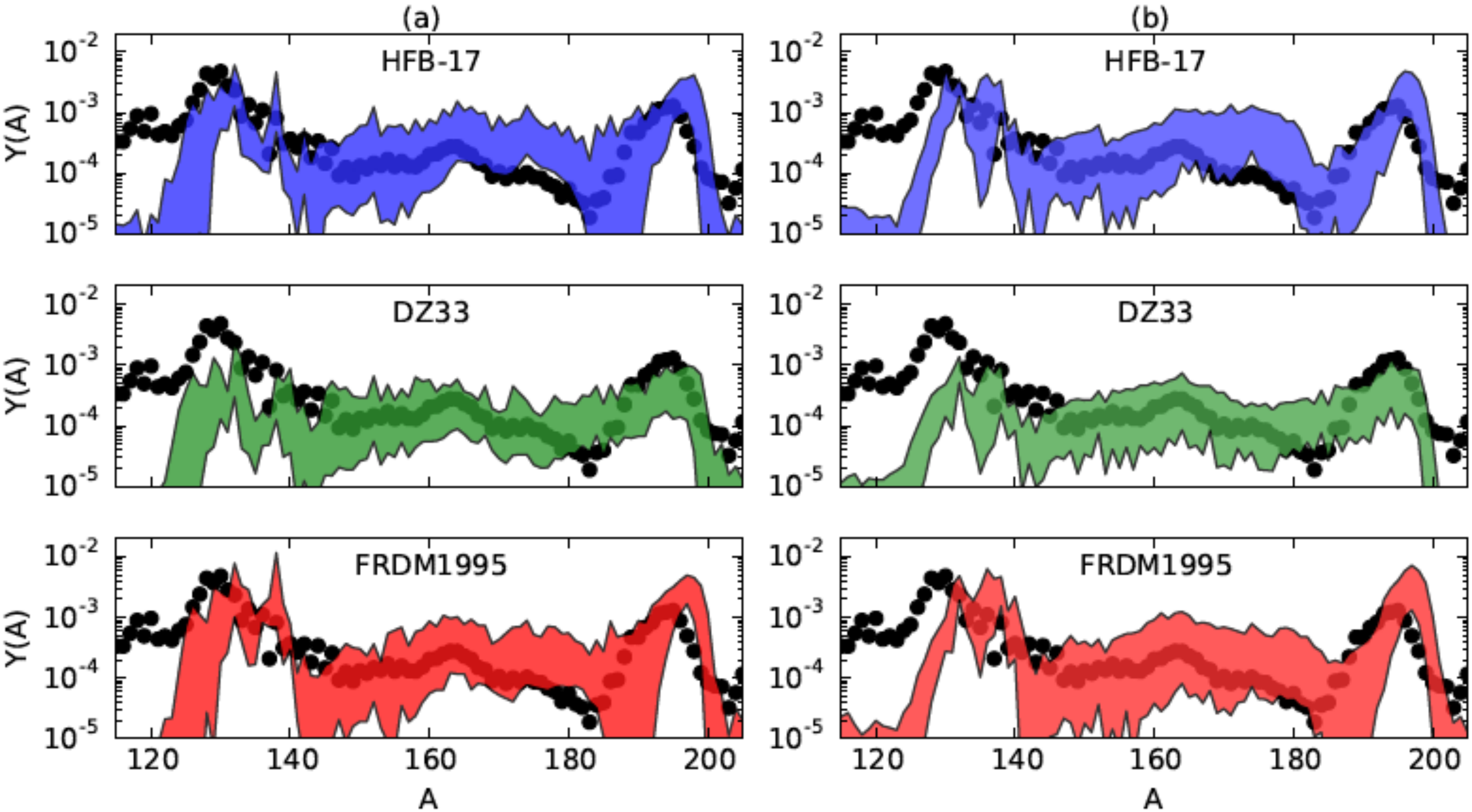
Hansen, Montes, and Arcones, Ap.J. **797**, 2 (2014).

Comparison of the theoretical beta decay half-lives to the measured values



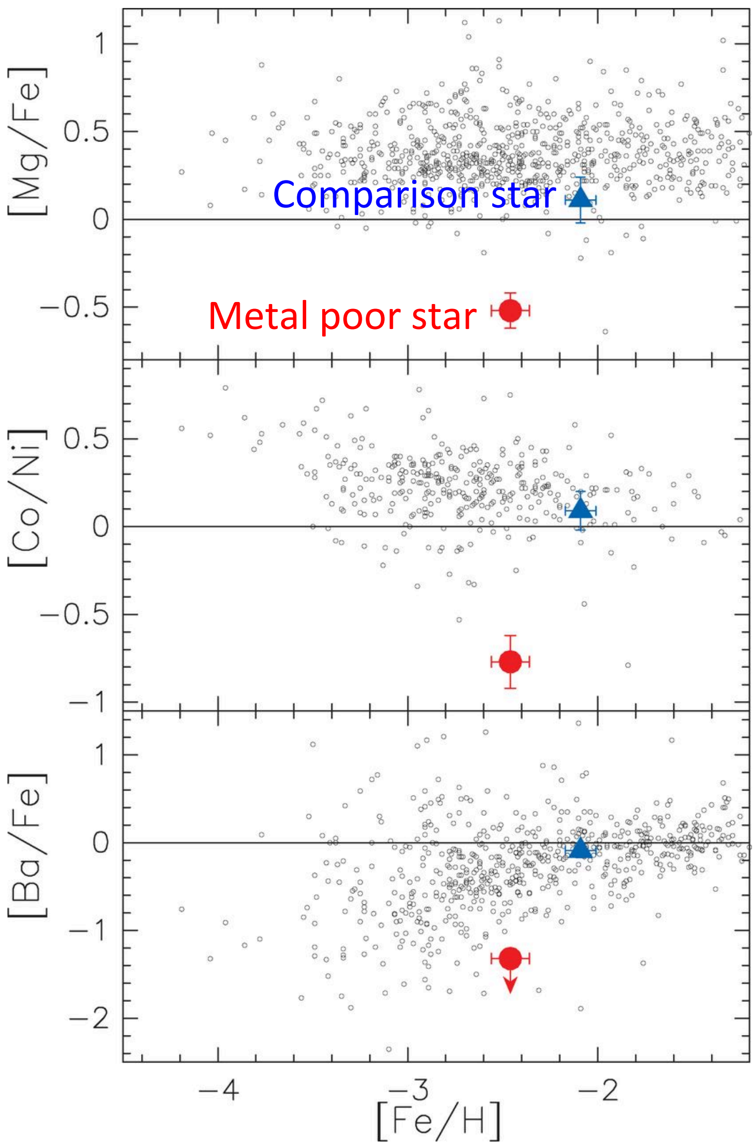
Mumpower et al., Prog. Part. Nucl. Phys. **86**, 86 (2016)

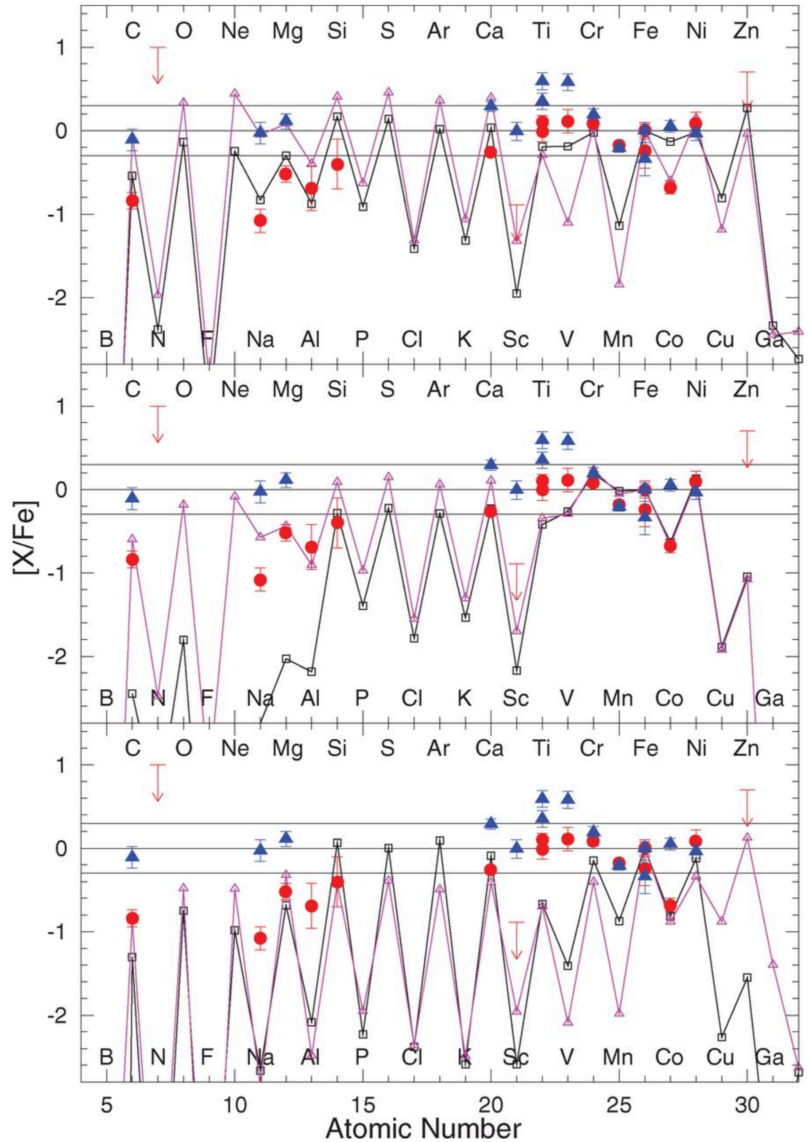
Variances in isotopic abundance patterns for three different nuclear mass models a) uncertain beta-decay half lives, b) uncertain neutron capture rates



Mumpower et al., Prog. Part. Nucl. Phys. **86**, 86 (2016)

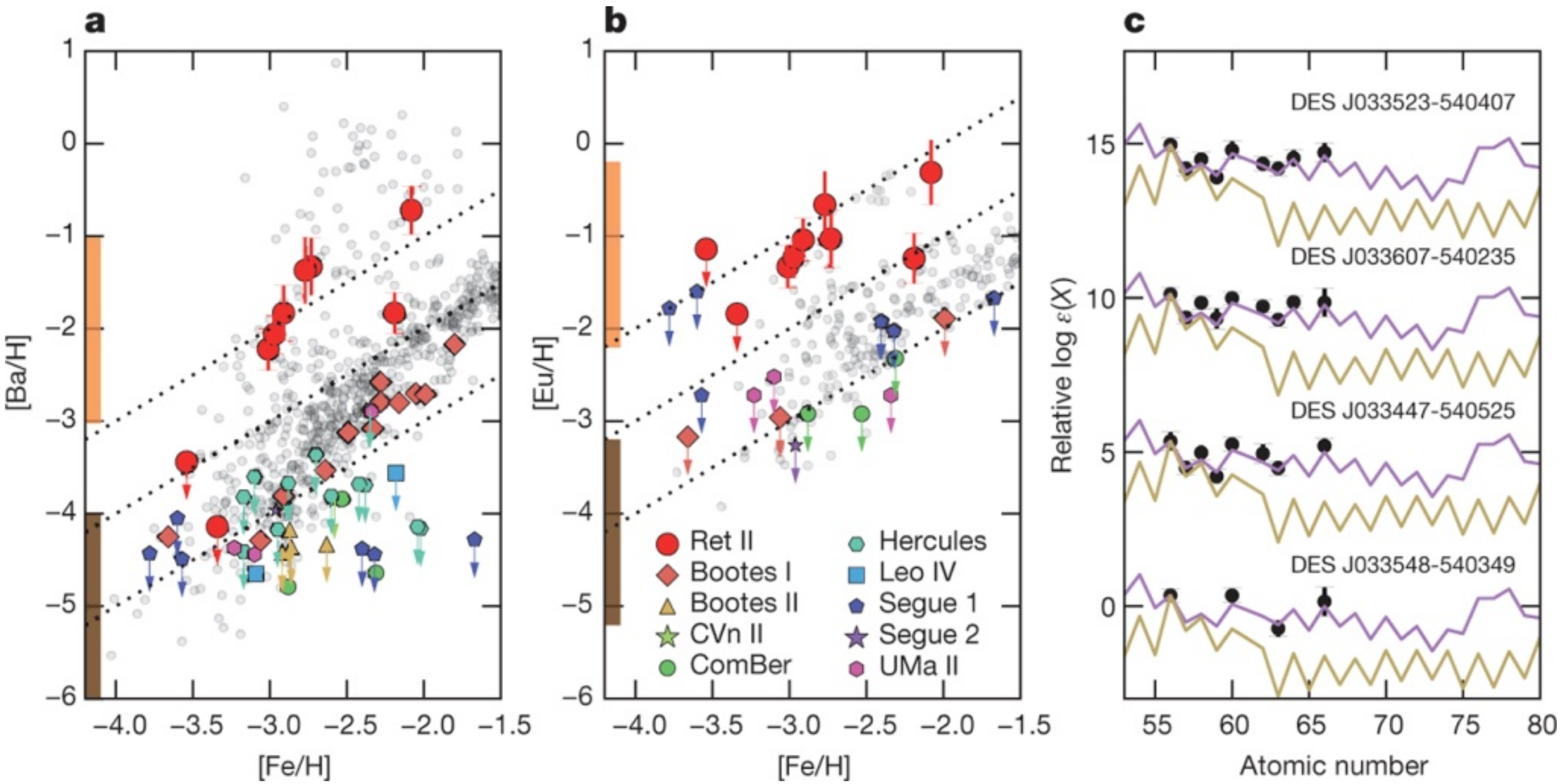
We are now able to observe very old (pop III) stars





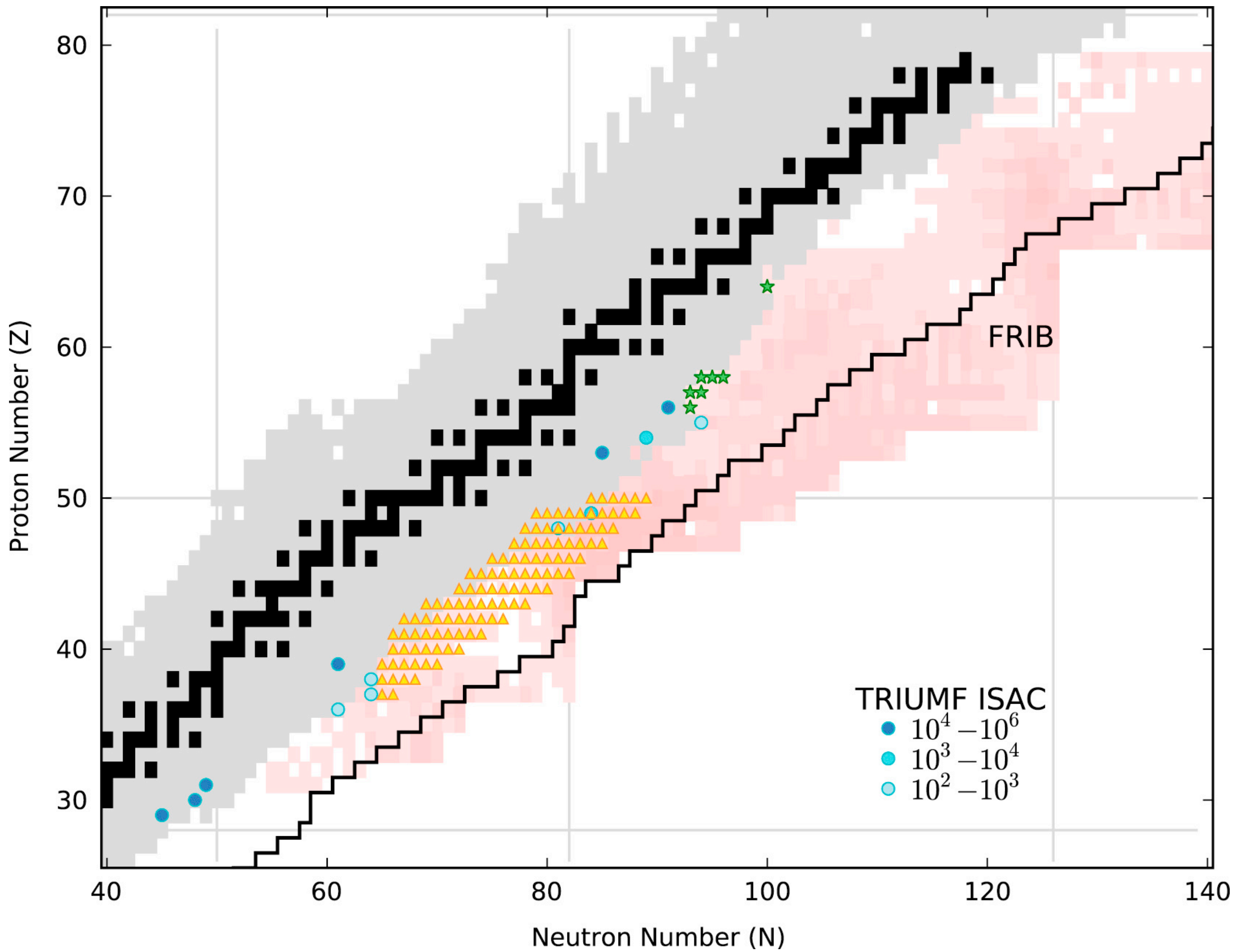
Aoki et. al., Science **345**, 912 (2014)

Recent discovery of strong enhancement of r-process element abundances
Several orders of magnitude greater enhancement than that seen in other ultra-faint dwarf galaxies, implying that a single rare event produced the r-process material (Neutron-star mergers?)



Ji *et al. Nature* 531, 610 (2016)

Recent measurements on neutron-rich nuclei and estimated capabilities at the future FRIB (black line: 10^{-4} particles per second



Mumpower et al., Prog. Part. Nucl. Phys. **86**, 86 (2016)

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

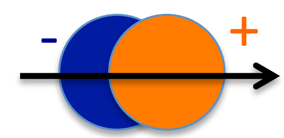
$$L = L_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} O_i^{(7)} + \ldots$$

Majorana neutrino mass (unique)

+

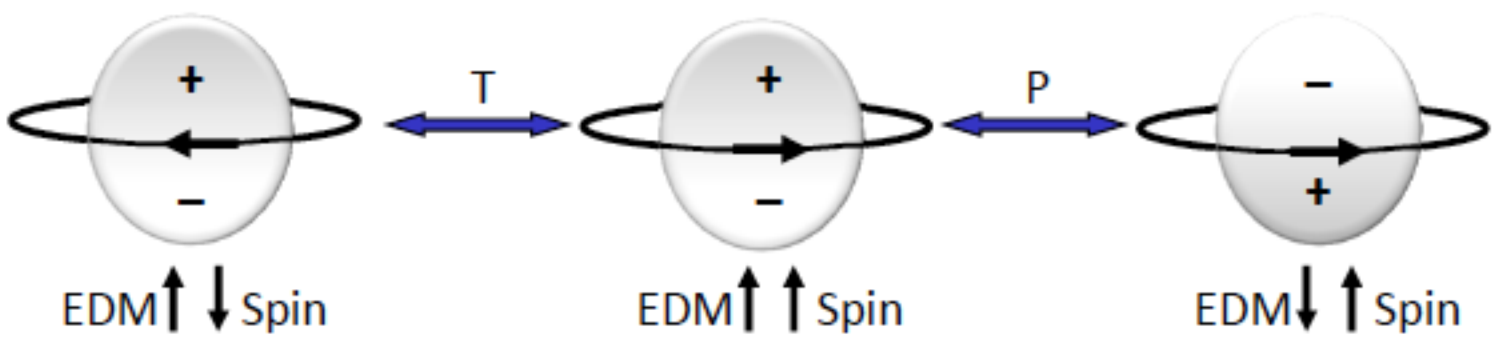
$$-\theta \frac{g_s^2}{32\pi^2} \mathrm{Tr}\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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

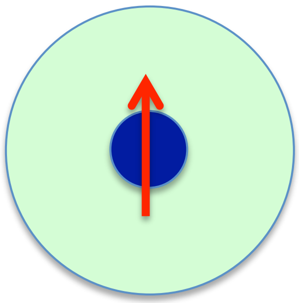


Electric dipole moment

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



Nuclear EDM's and the Schiff moment

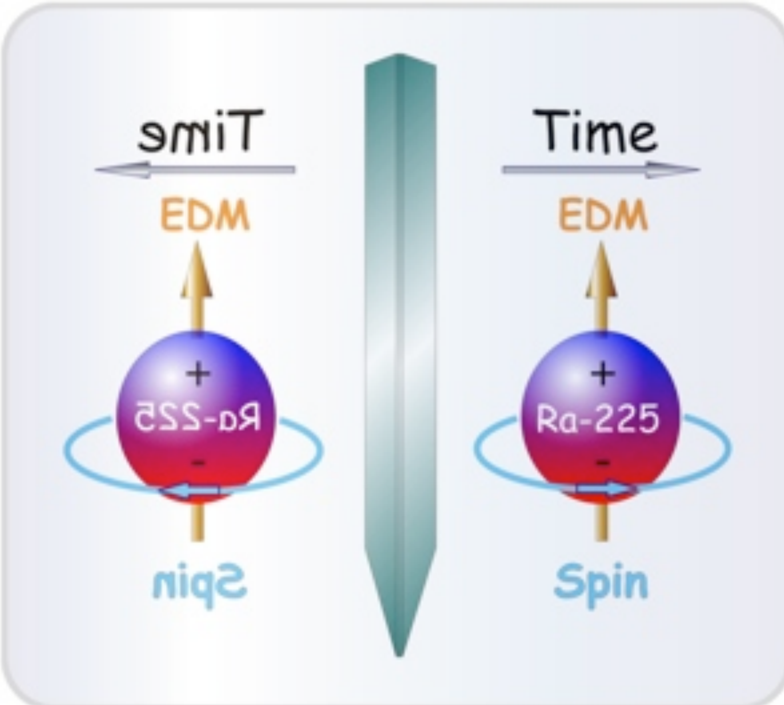


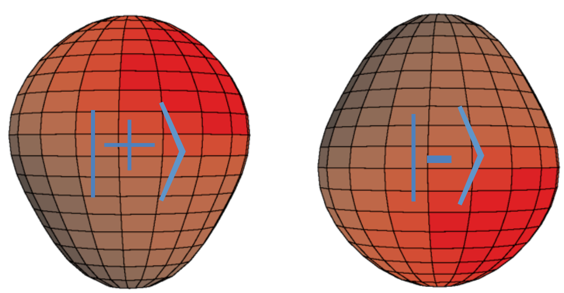
Schiff shielding: $d_{\text{atom}} = d_{\text{electronic}} + d_{\text{nuclei}} \cong 0$

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

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

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……





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

ΔE

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

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

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

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

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

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

Reactor neutrino experiments to measure the remaining mixing angle also measure the reactor neutrino flux

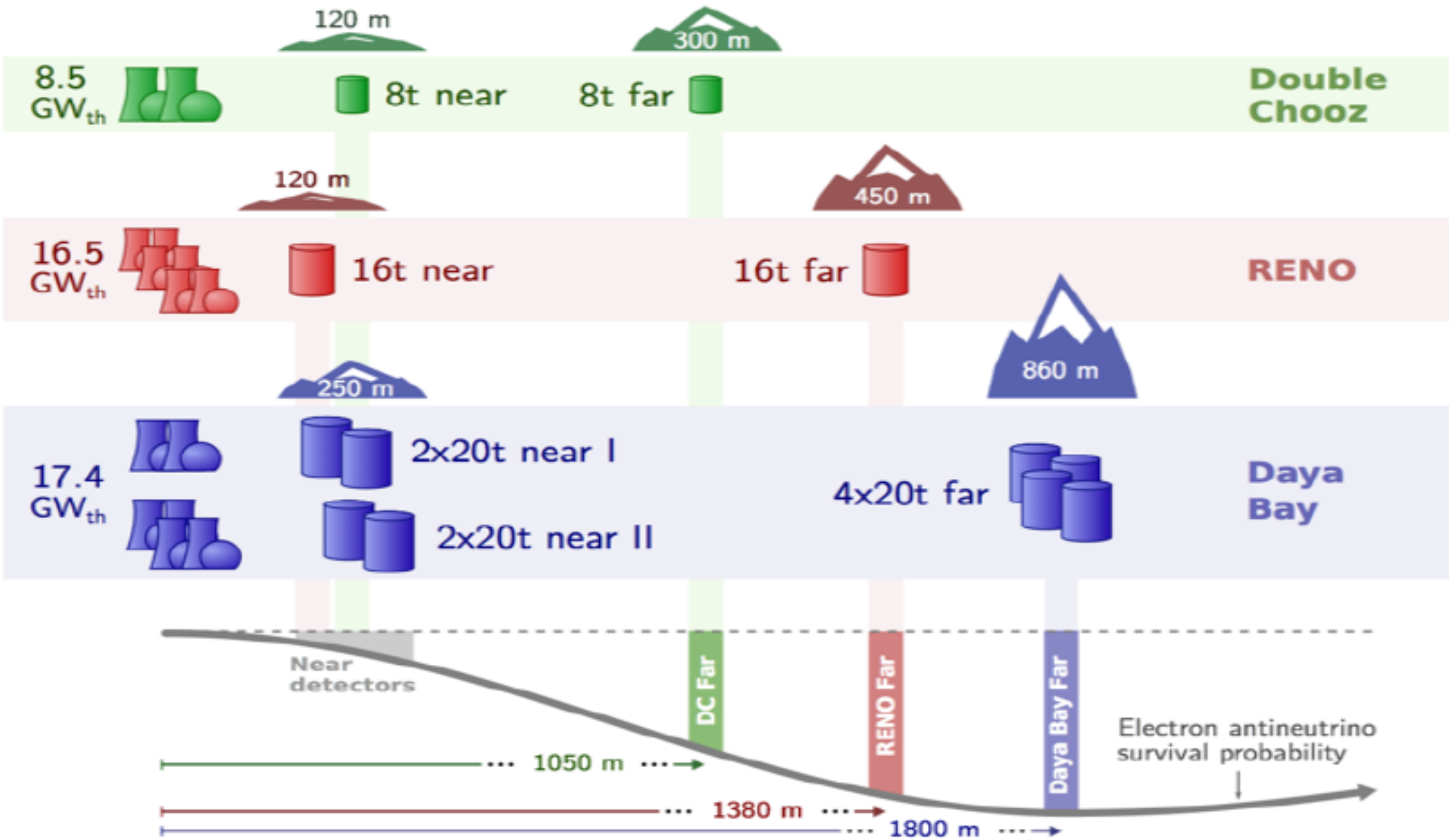
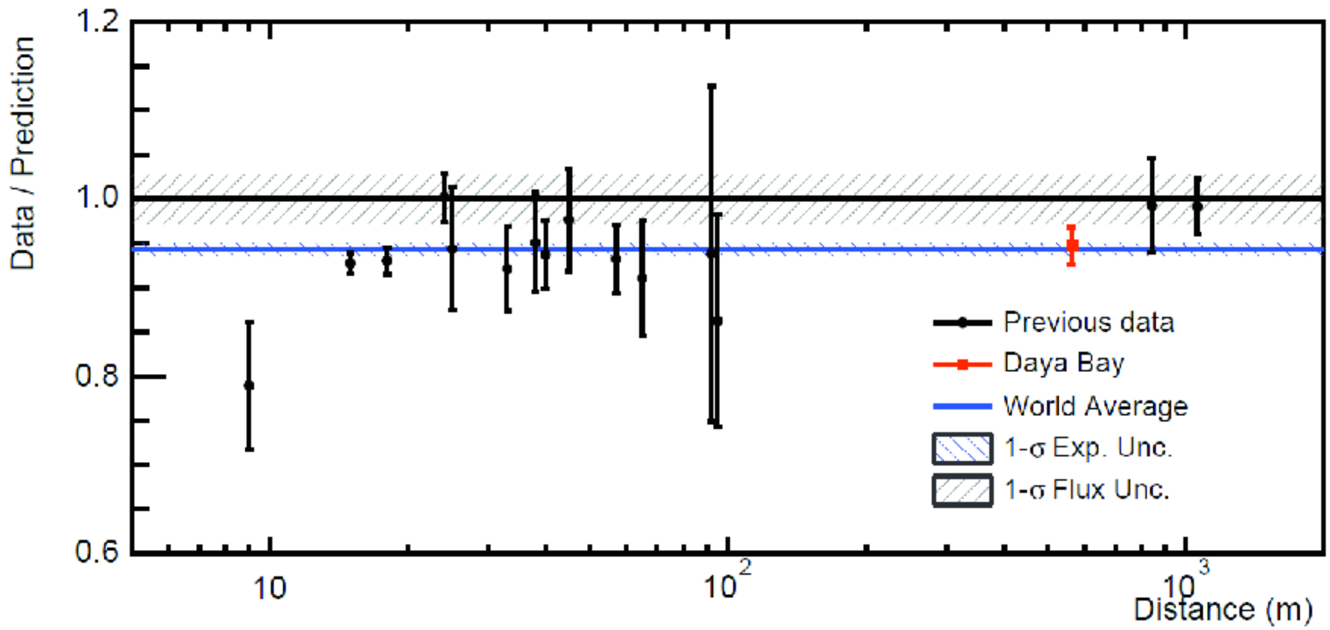
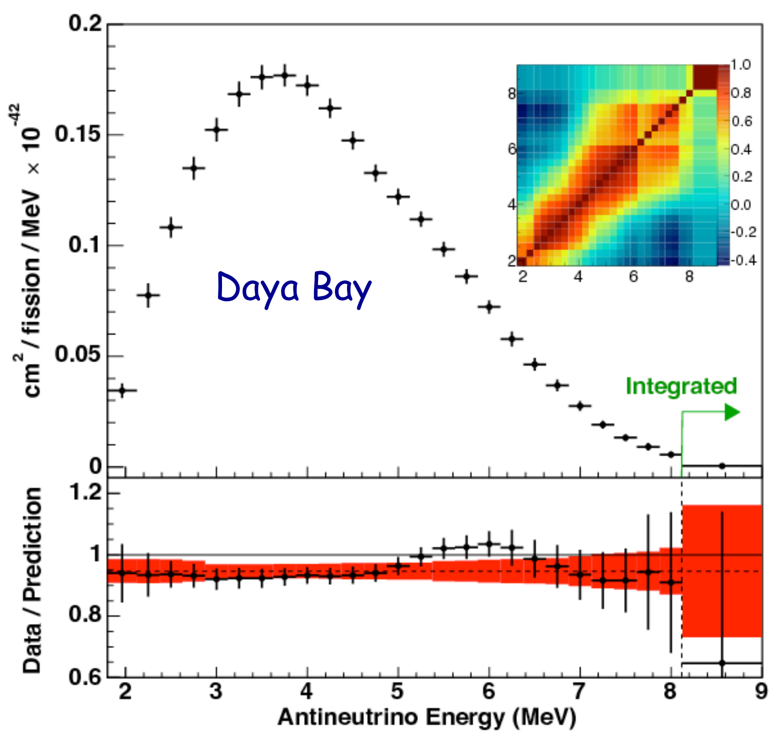
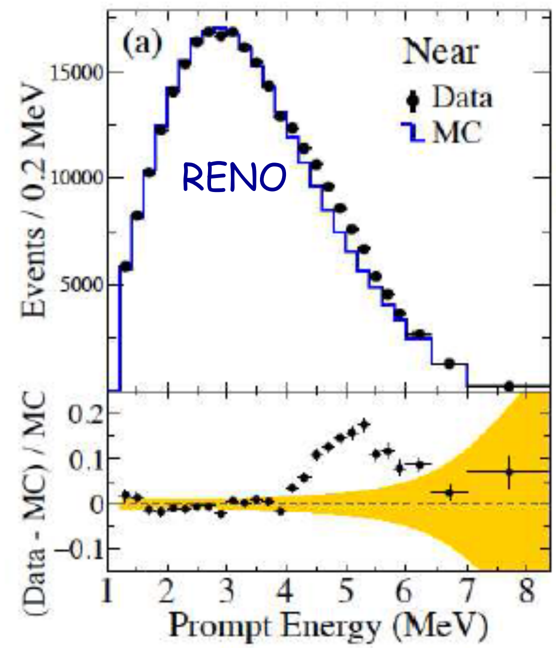


Fig: S. Jetter

…but they also bring a surprise!



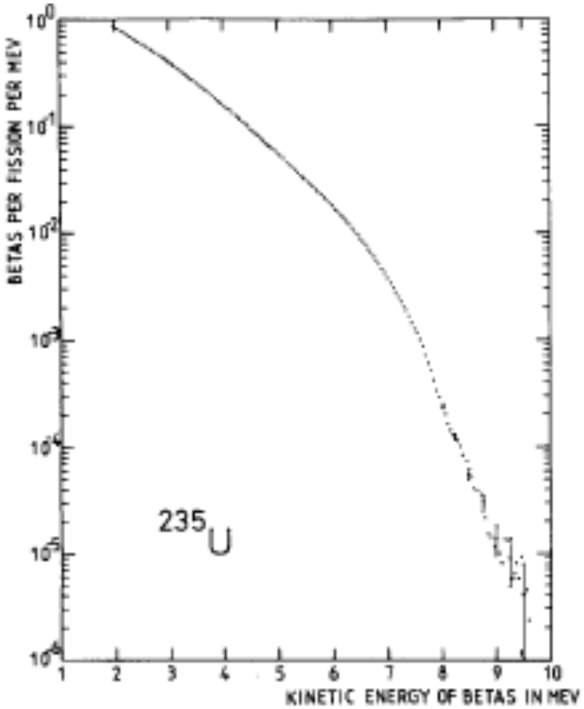




Can we know the reactor neutrino flux ever as well as we need?

How to determine the neutrino spectrum?

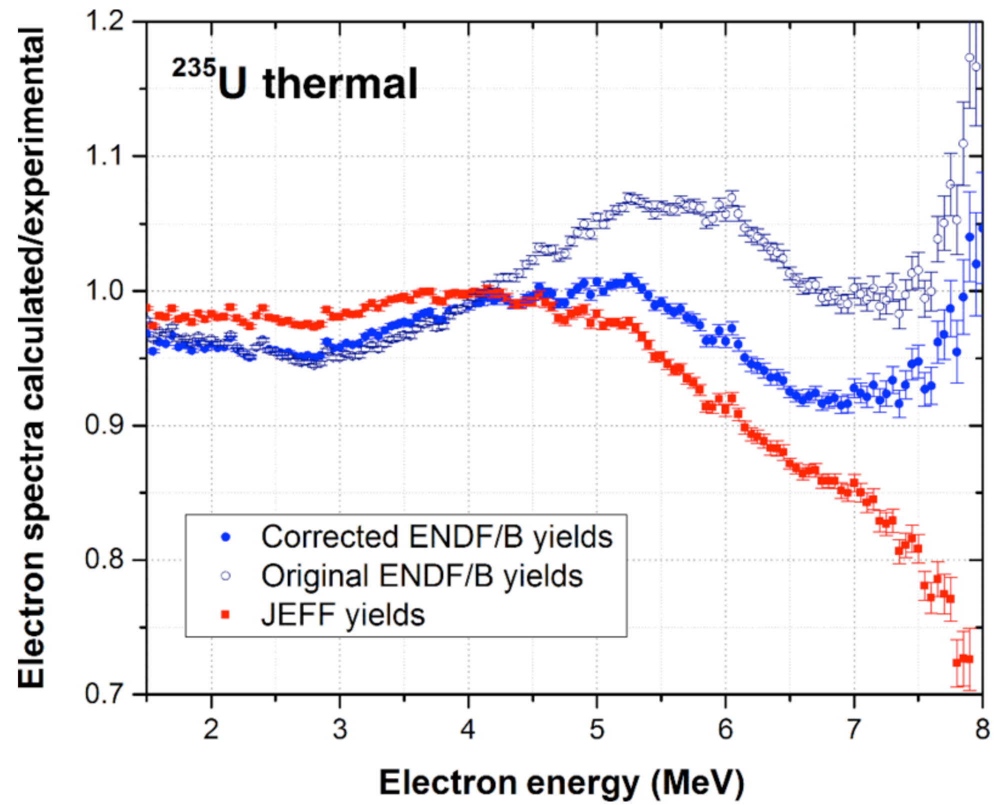
Method 1: Start with the measured electron spectra



Schreckenbach, et al. PLB 1985

..and convert it into electron antineutrino spectra

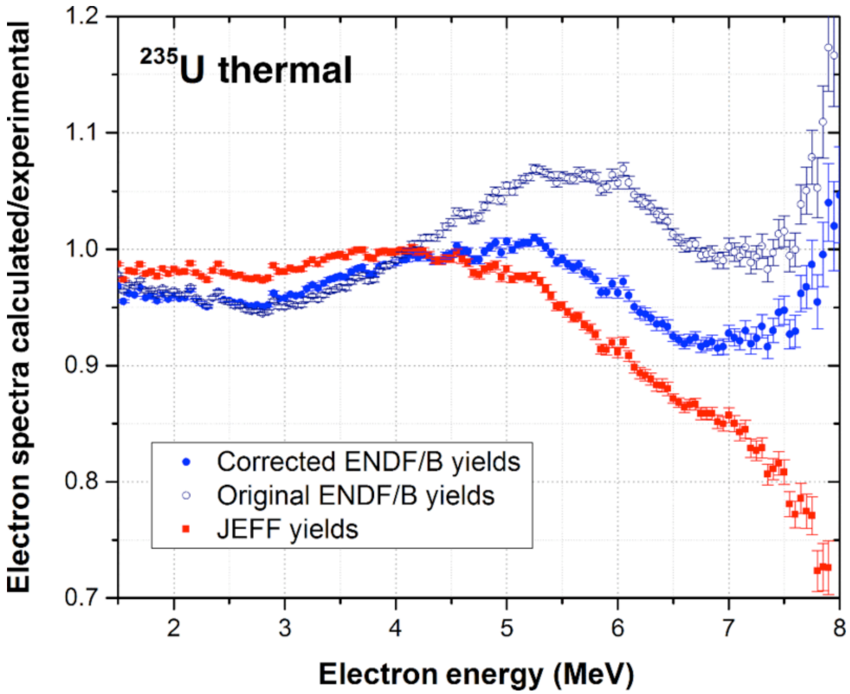
Method 2: Directly sum fission yields using nuclear data compilations



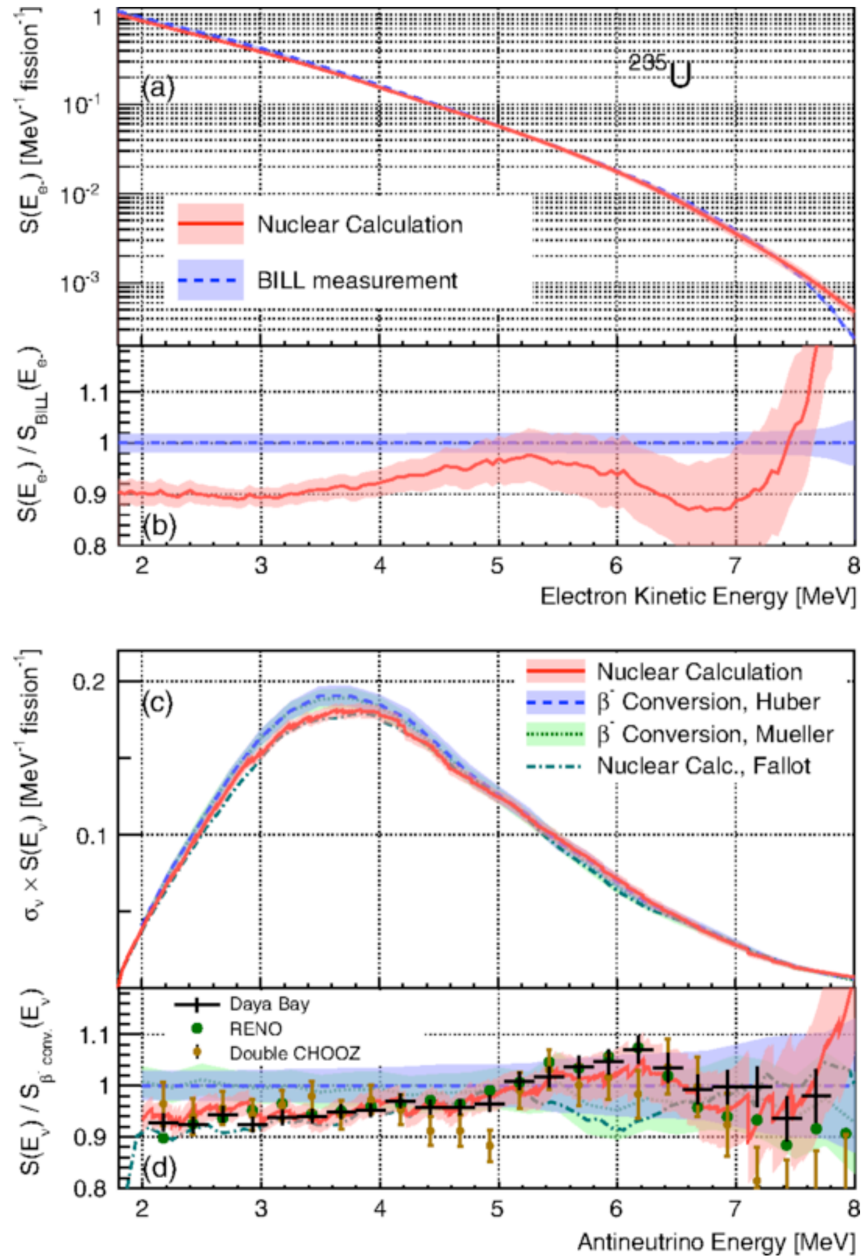
Sonzogni et. al, PRL **116,** 132502 (2016)

They do not quite agree!

Note that two different direct sum calculations (with many assumptions) produce similar bumps!

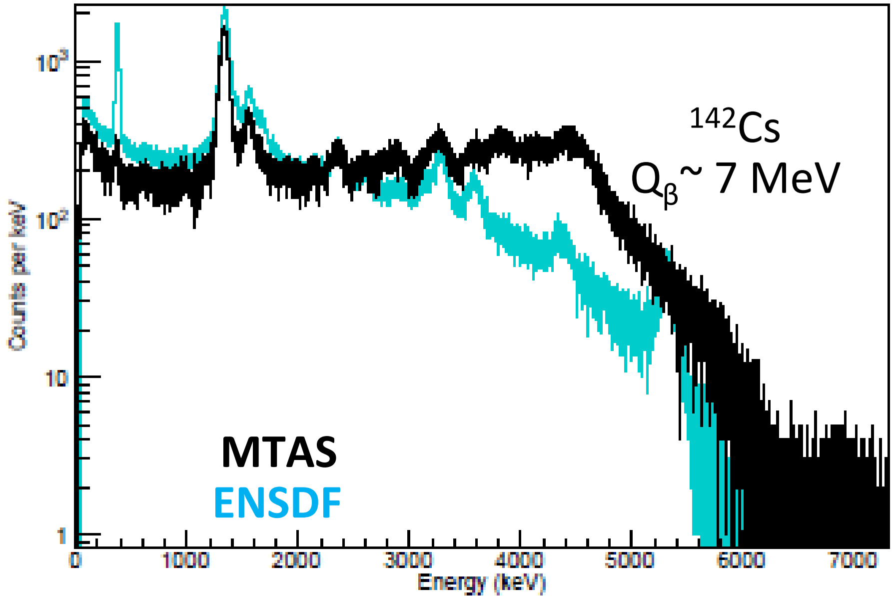


Sonzogni et. al, PRL **116,** 132502 (2016)

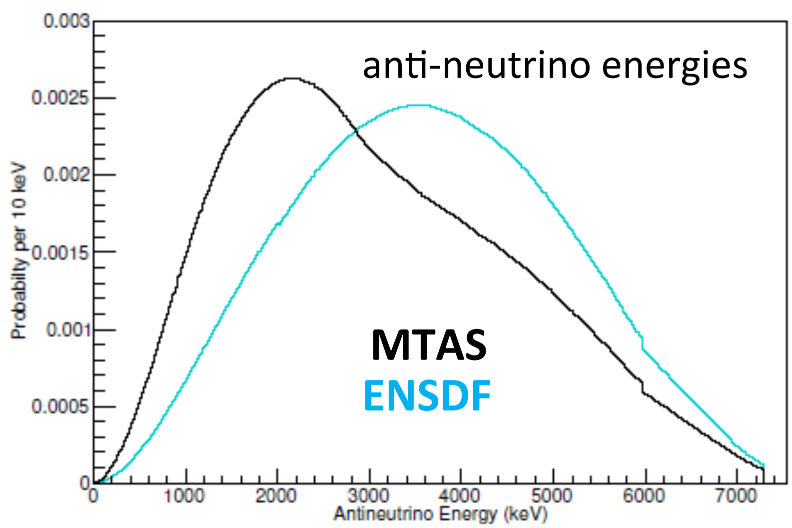


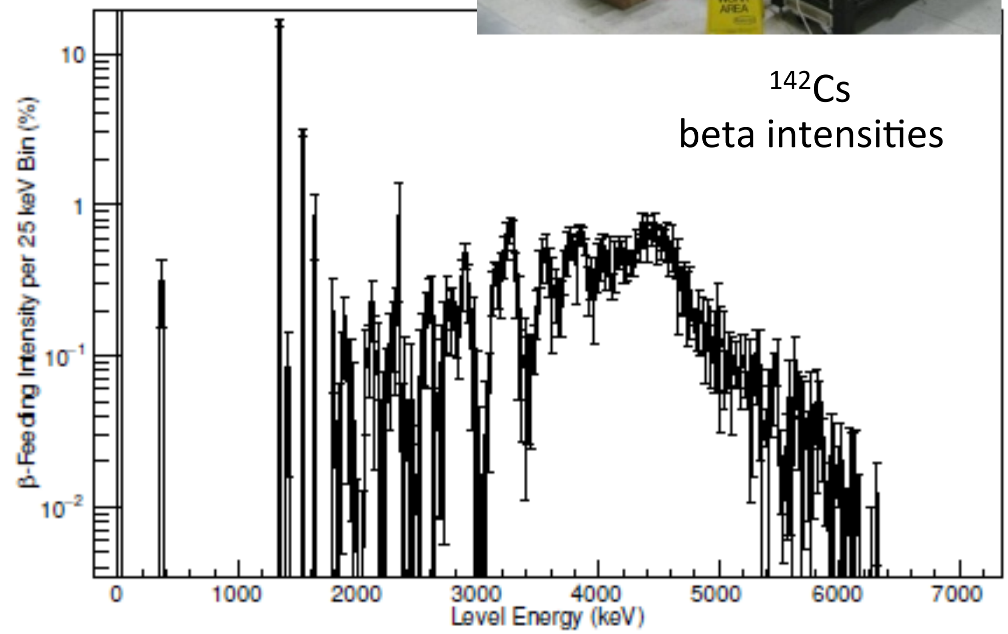
Dwyer and Langford, PRL **114**, 012502

^{142}Cs among top three contributors to the neutrino "shoulder"



Decay studies of fissionproducts with Modular Total Absorption Spectrometer (MTAS)





MTAS results for ^{142}Cs **only**:
"anomaly" is reduced, from 95(2)% to 96(2)%
"shoulder" is increased, from ~ 10% to ~ 12%

B.C. Rasco et al., Phys. Rev. Letters, in press
M. Wolińska-Cichocka et al., NDS 120, 22, 2014, and to be published

Adopted from Rykaczewski

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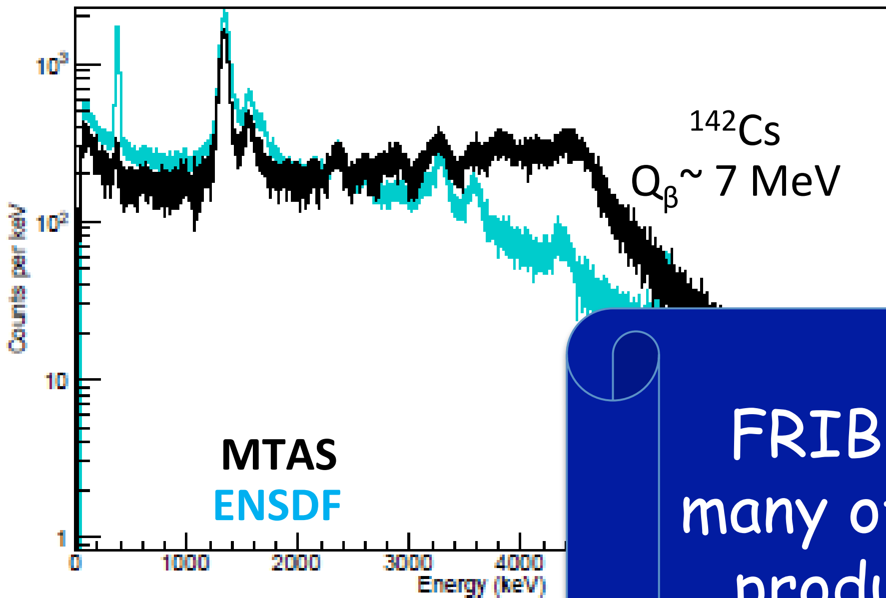

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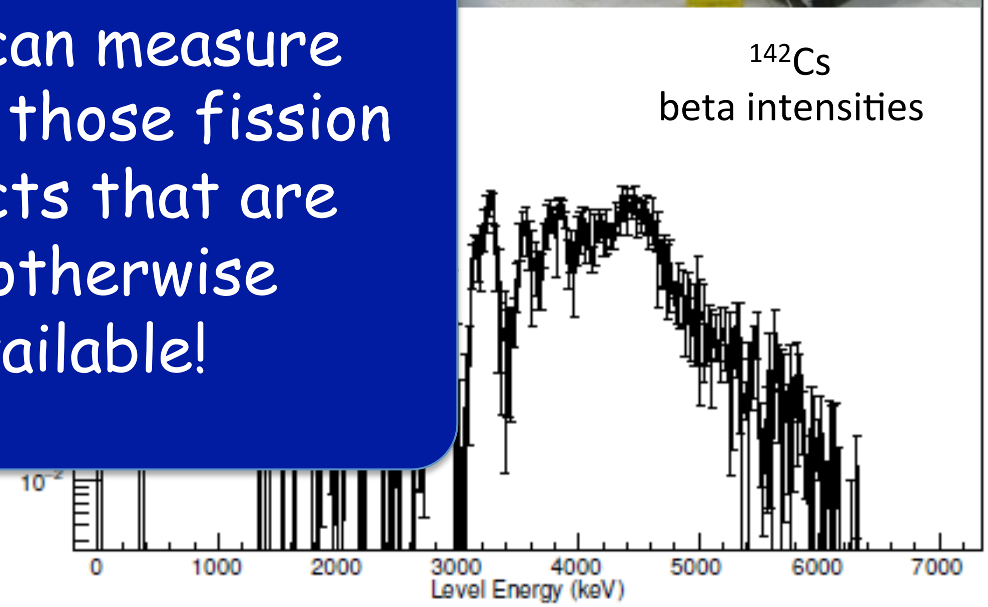
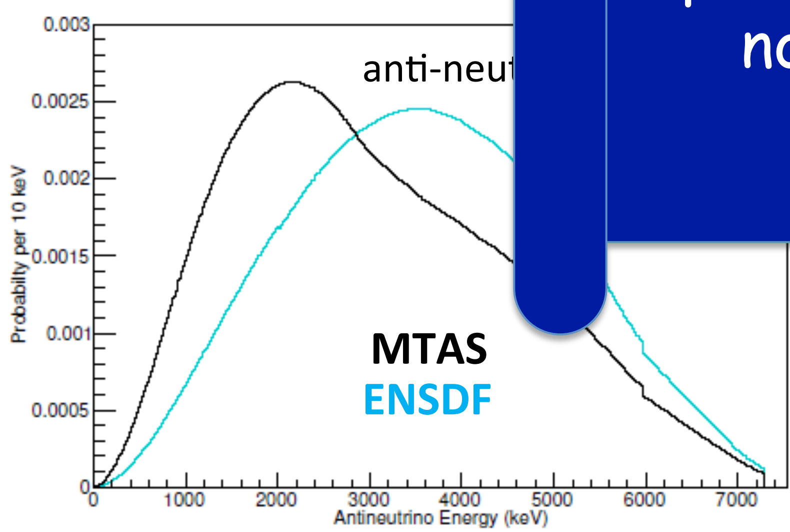


FRIB can measure many of those fission products that are not otherwise available!



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