Enhanced symmetry energy behind the universality of heavy-element abundances

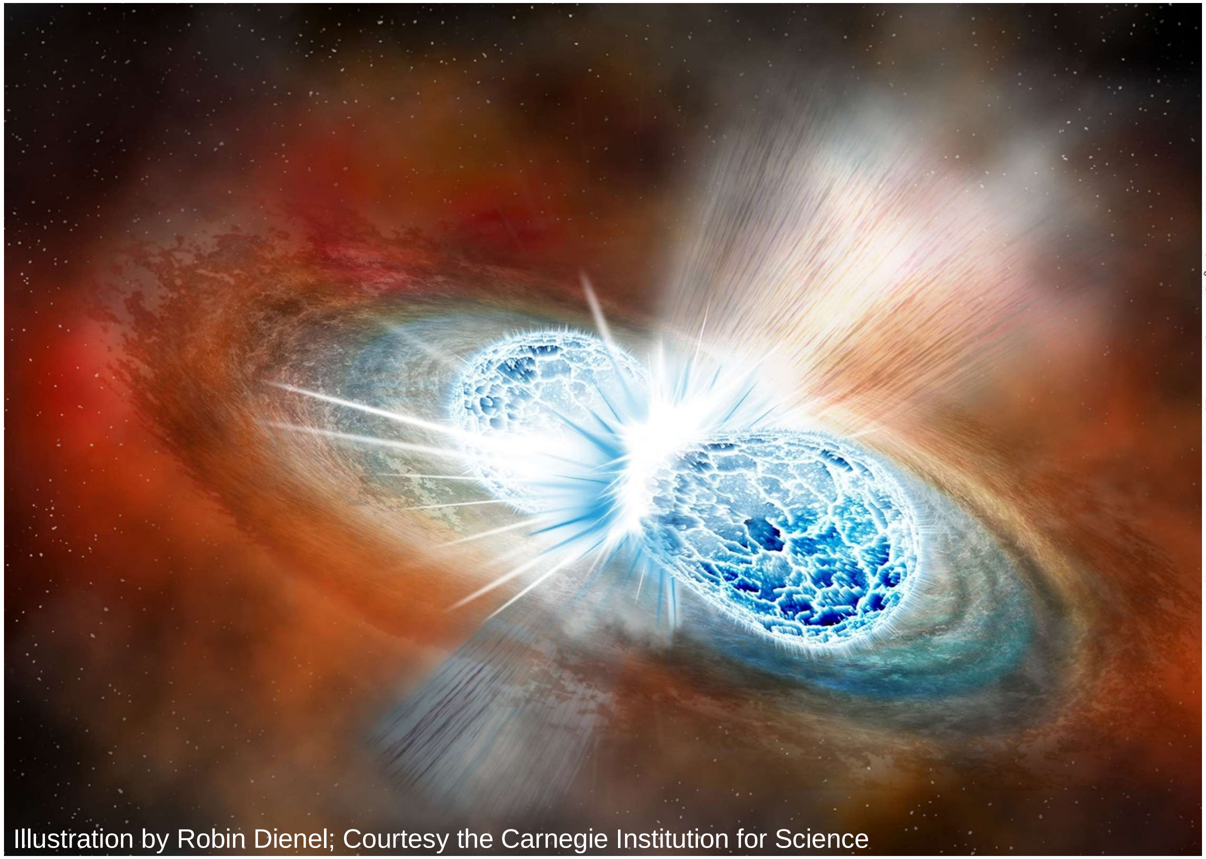
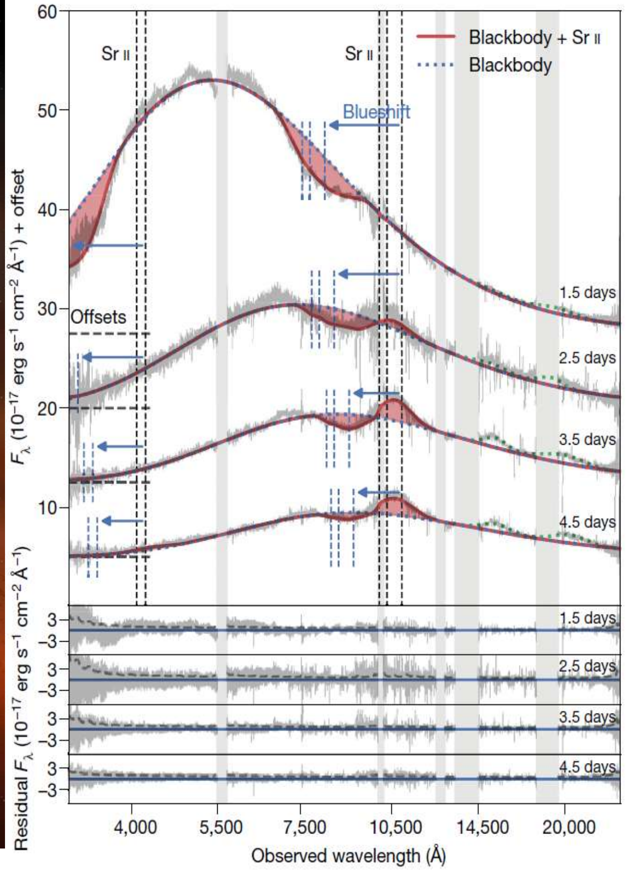


Illustration by Robin Dienel; Courtesy the Carnegie Institution for Science

D. Watson *et al.*, Nature (2019)



UNIVERSITY of the WESTERN CAPE

NITheCS
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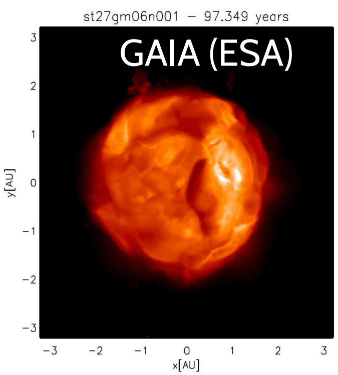
Nico Orce

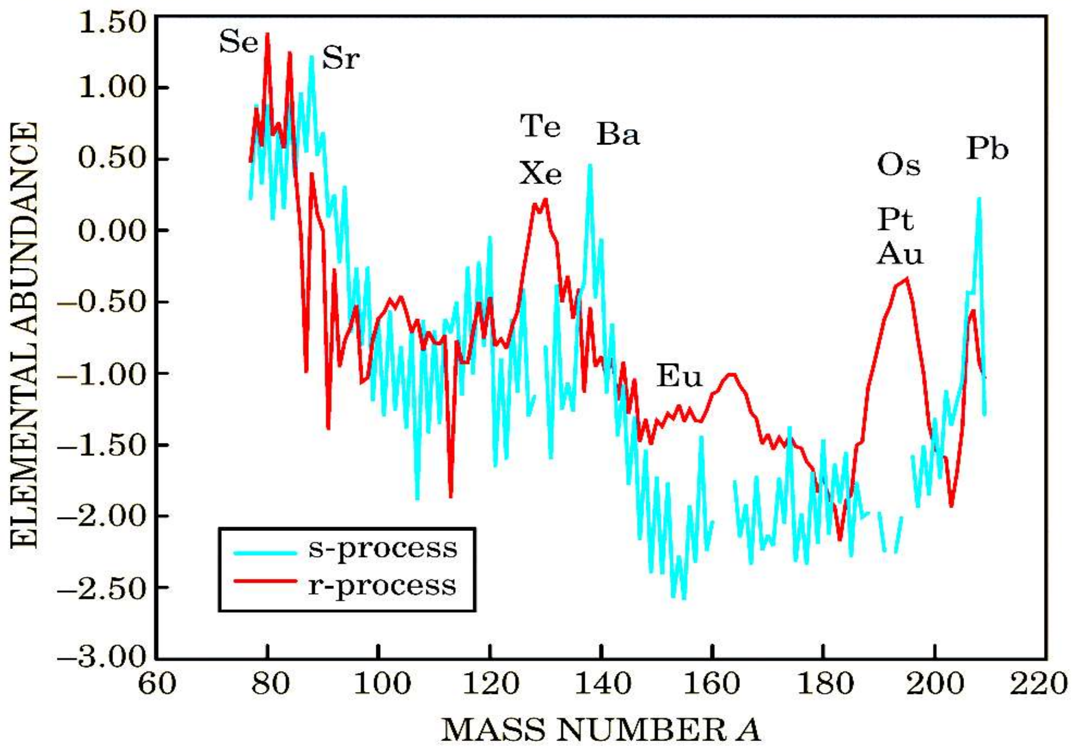
ISOLDE Workshop and Users meeting

14-16 December 2021

Abundance of elements above iron

Assuming we know s-process abundances, the remaining must come from r-process

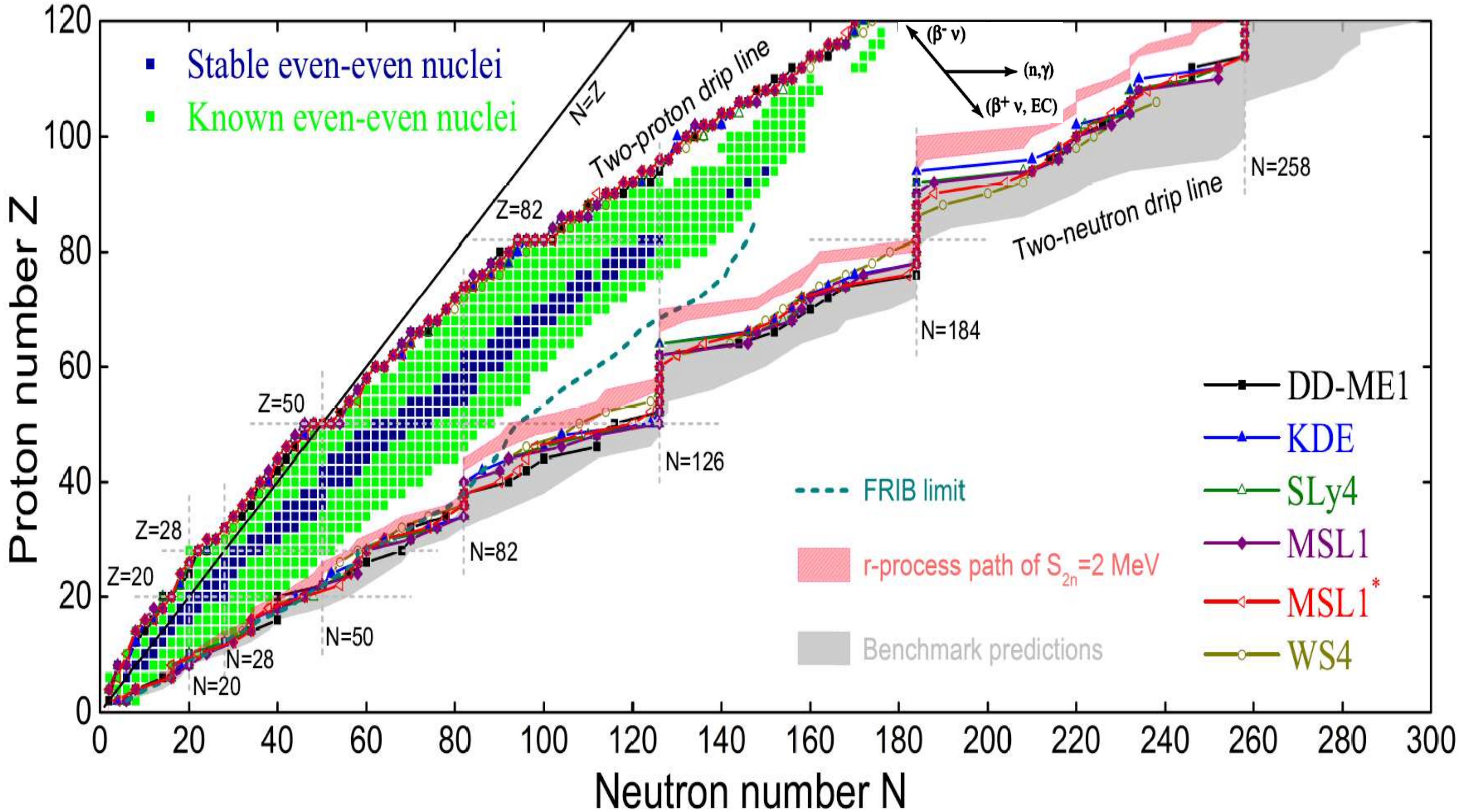




Main s-process (90 < A < 204) in thermally pulsating AGB stars
(10^4 yr and 10^{5-6} neutrons/cm^3)

r-process (e.g. neutron-star mergers) only source of elements beyond Pb and Bi
(microseconds and 10^{23-24} neutrons/cm^3)

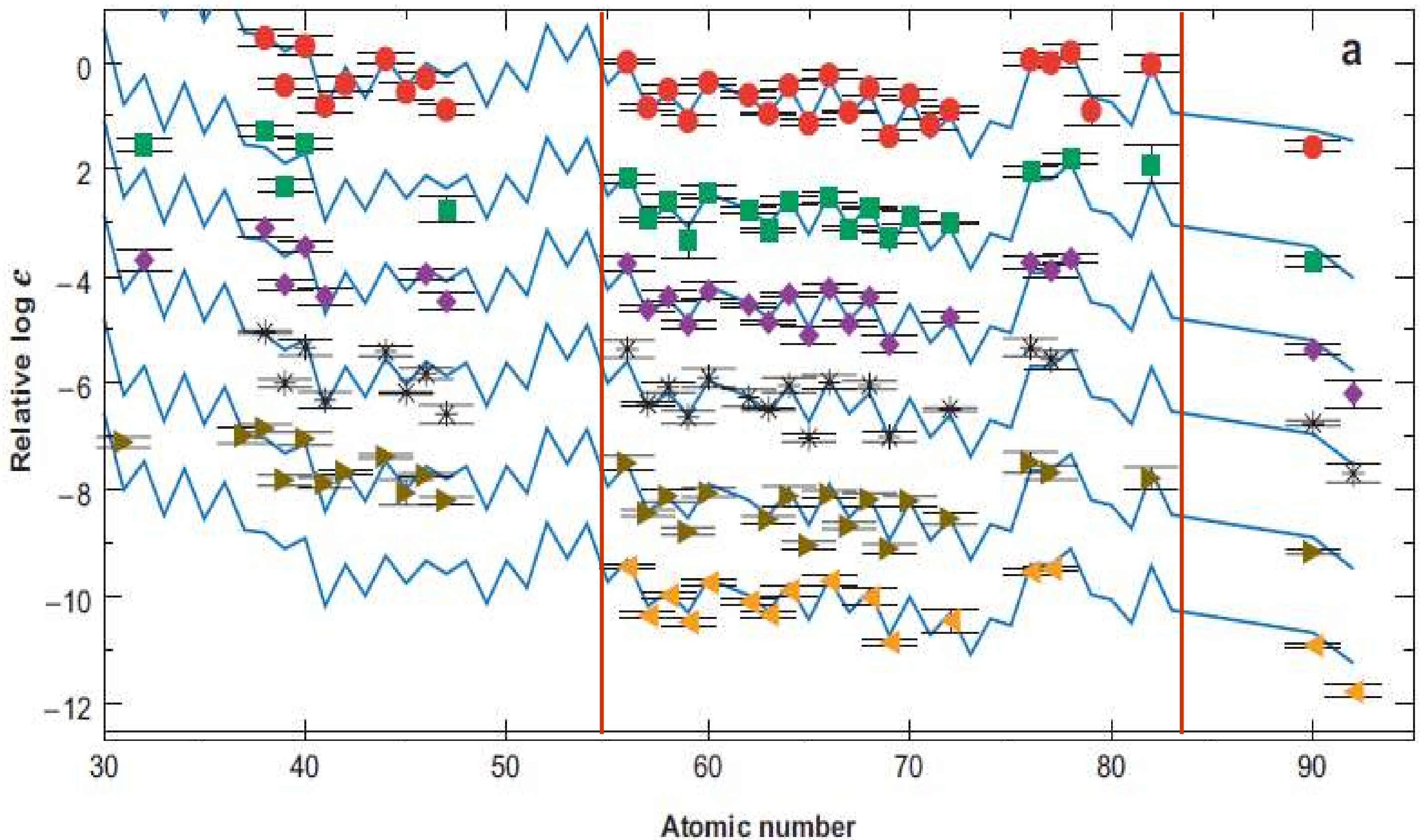
Significant variation of predictions for neutron drip line and r-process paths due to wide range of conditions not accurately determined



Density Functional Theory with different interactions (4 Skyrme and 1 relativistic)
Rui Wang & Lie-Wen Chen PRC **92** (2015) 031303(R)
Jochen Erler *et al.*, Nature **486** (2012) 509

Universality of heavy-element abundances

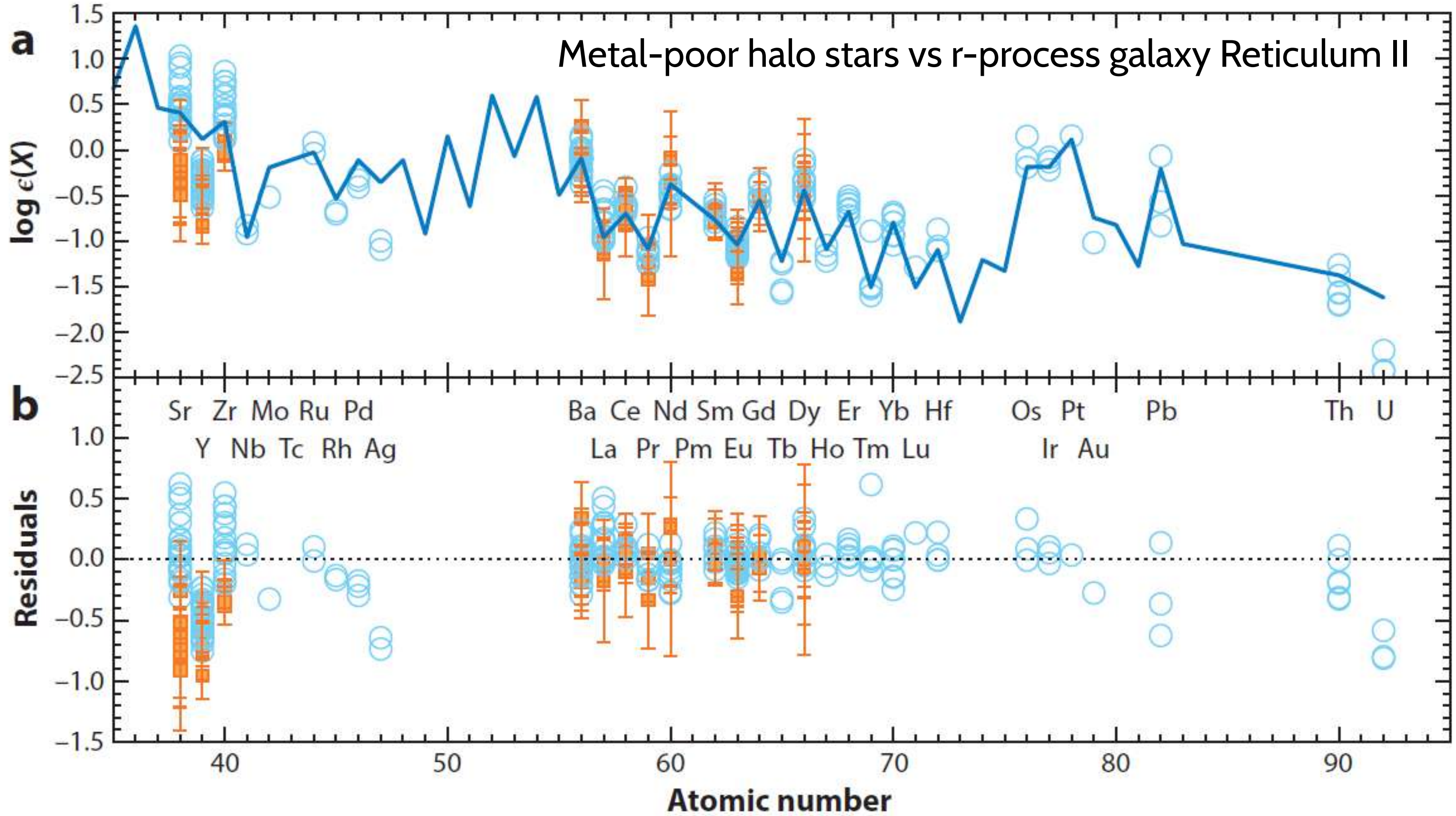
Comparisons of abundances in six r-process Galactic halo stars with the Solar-system



"The abundance patterns of the heavy stable elements from Ba through Pb in the most metal-poor stars are consistent with the scaled Solar system r-process-only element abundance pattern."

Sneden, Cowan, and Gallino, Ann. Rev. Astron. Astrophys. **46** (2008) 241

Why are elemental abundances universal?

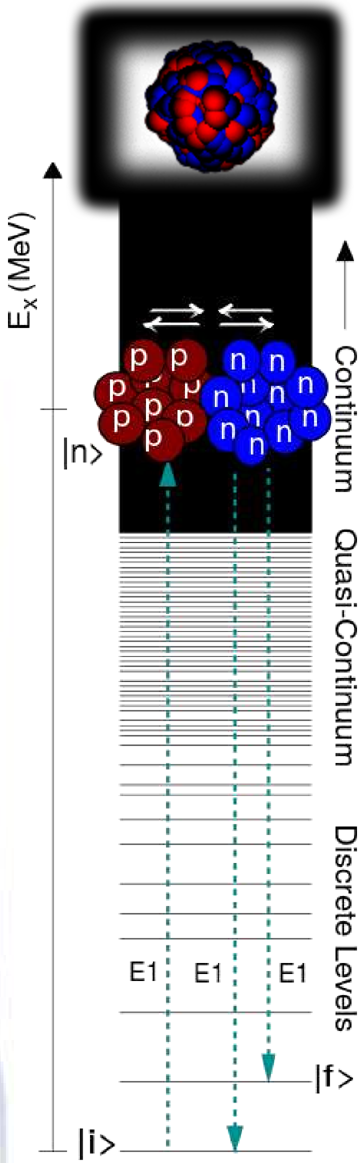


"These facts suggest a rather well-defined origin of heavy elements beyond iron. **We do not know** if this may be only an **artifact of nuclear properties** such as binding energies and β-decay rates, or it may point to **a single cosmic site with astrophysical conditions that are generated uniformly throughout cosmic time**."

Kajino *et al*. Progress in Particle and Nuclear Physics **107** (2019) 109–166
Frebel, Annu. Rev. Nucl. Part. Sci. **68** (2018) 237–69

Symmetry energy $a_{sym}(A)$ is the fundamental parameter describing the GDR

B. L. Herman and S. C. Fultz, Rev. Mod. Phys. **47** (1975) 713



Second-order Perturbation Theory

$$\alpha = 2e^2 \sum_n \frac{\langle i\|\hat{E}1\|n\rangle\langle n\|\hat{E}1\|i\rangle}{E_\gamma}$$
$$= \frac{e^2\hbar^2}{M}\sum_n \frac{f_{\rm in}}{E_\gamma^2} = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma_{\rm total}(E_\gamma)}{E_\gamma^2}dE_\gamma$$
$$= \frac{\hbar c}{2\pi^2}\sigma_{-2},$$

Hydrodynamic Model (liquid drop)

$$\alpha = \frac{e^2R^2A}{40a_{\rm sym}}$$

$$a_{sym}(A) = \frac{e^2R^2\pi^2A}{20\,\hbar c\,\sigma_{-2}} \approx 5.2\times10^{-3}\,\frac{A^{5/3}}{\sigma_{-2}}$$

A.B. Migdal, JETP USSR **15** (1945) 81

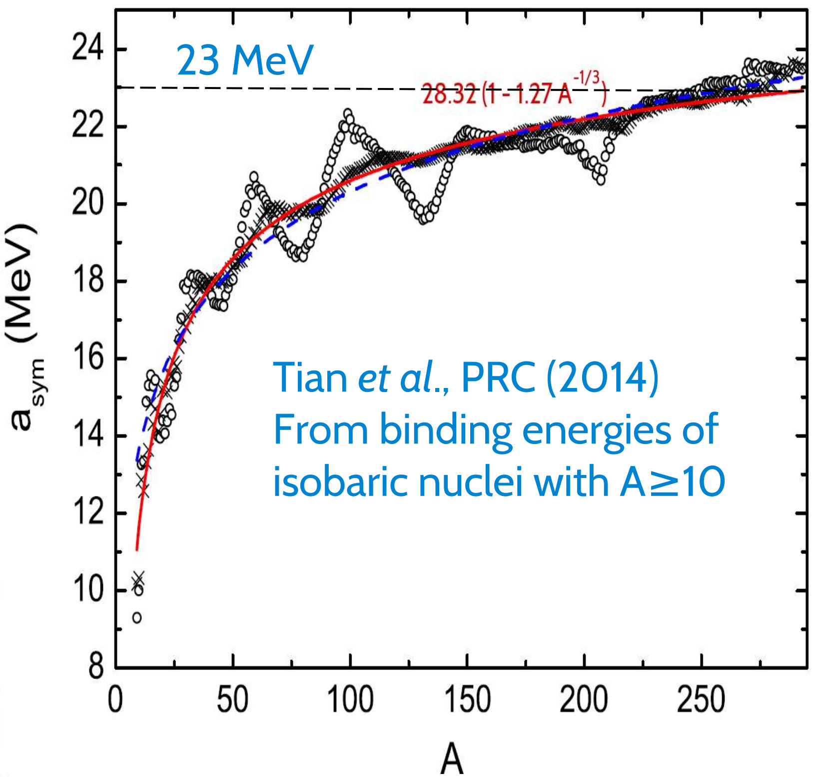
J.N. Orce, IJMP E **29** (2020) 2030002

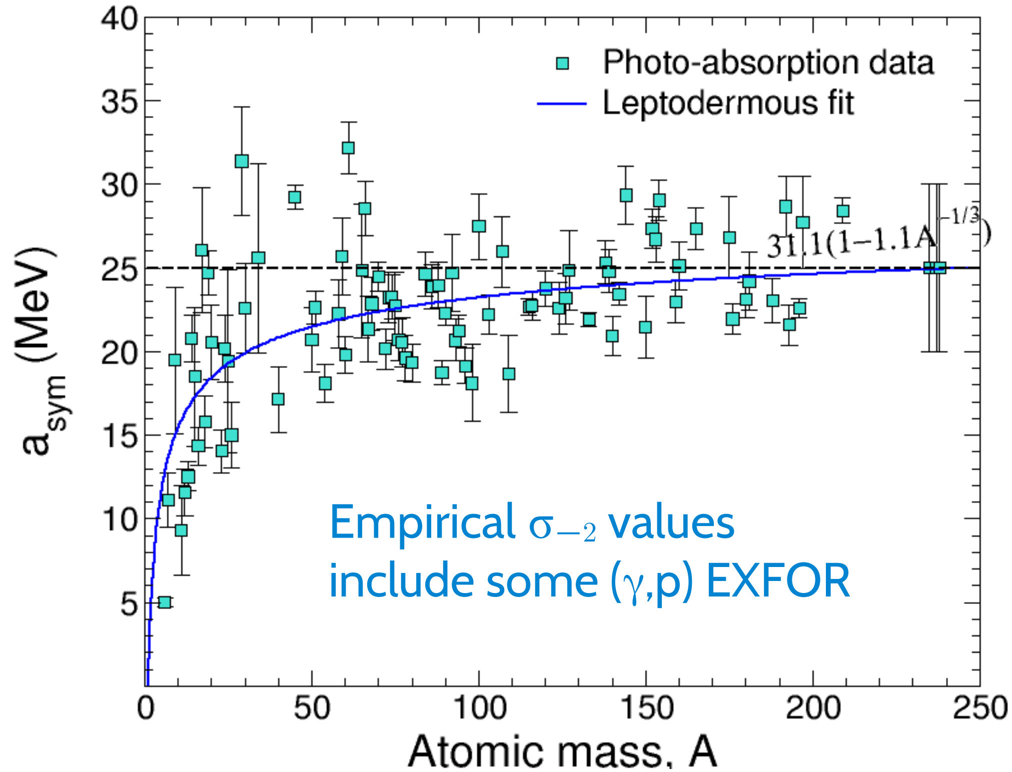
Symmetry energy extracted from binding energies and σ_{-2} values

a_{sym} converges @ 23-27 MeV for heavy nuclei

$$a_{\rm sym}(A) = S_v\left(1 - \frac{S_s}{S_v A^{1/3}}\right)$$

$$a_{sym}(A) = \frac{e^2 R^2 \pi^2 A}{20\ \hbar c\ \sigma_{-2}} \approx 5.2\times10^{-3}\ \frac{A^{5/3}}{\sigma_{-2}}$$





This particular leptodermous parametrization was chosen on the account of its better fit to the masses of isobaric nuclei.

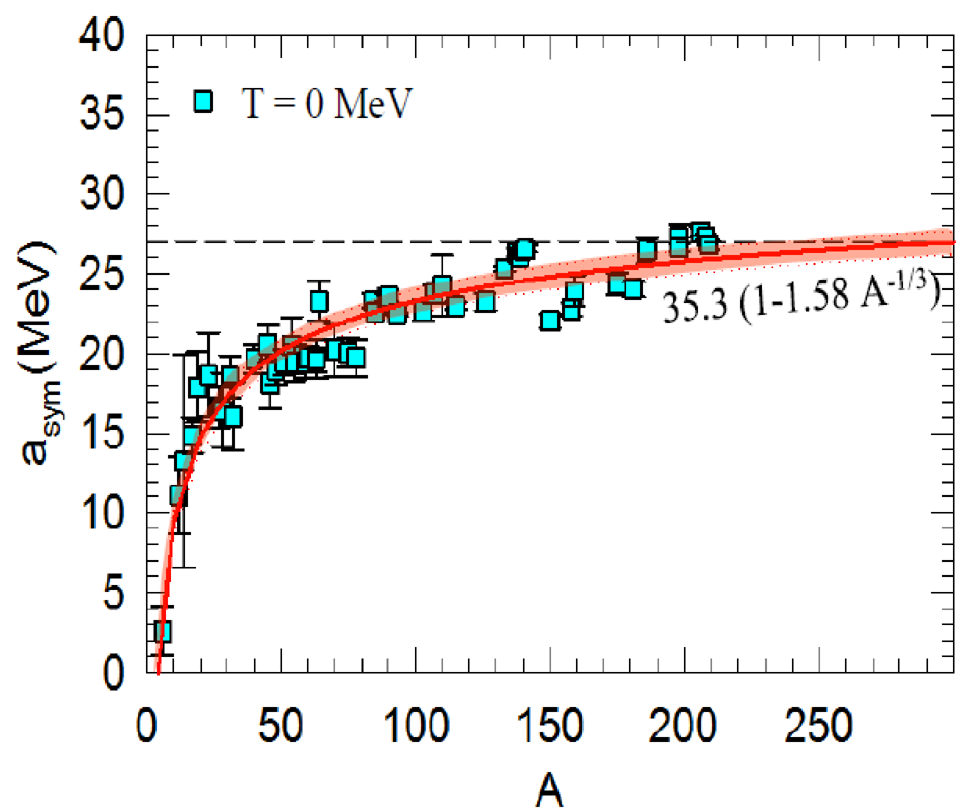
Symmetry energy extracted @ T=0 MeV (ground state GDRs)

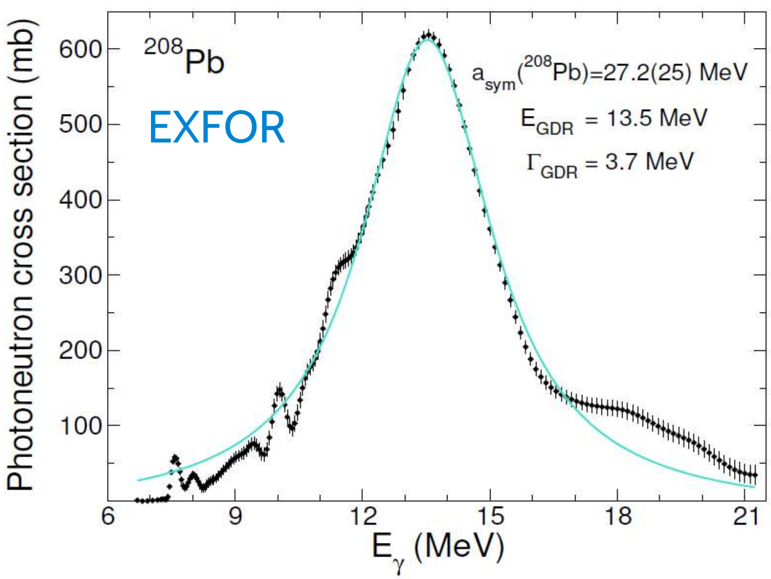
a_{sym} saturates @ 27 MeV

Spherical nuclei (modified SJ model)

$$a_{sym}(A) = \frac{MA^2}{8\hbar^2K^2NZ}\frac{E^2_{GDR}}{1-\left(\frac{\Gamma_{GDR}}{2E_{GDR}}\right)^2} \approx 1\times10^{-3}\left(\frac{A^{8/3}}{NZ}\right)\frac{E^2_{GDR}}{1-\left(\frac{\Gamma_{GDR}}{2E_{GDR}}\right)^2}$$

M. Danos, Nucl. Phys. **5** (1958) 23.

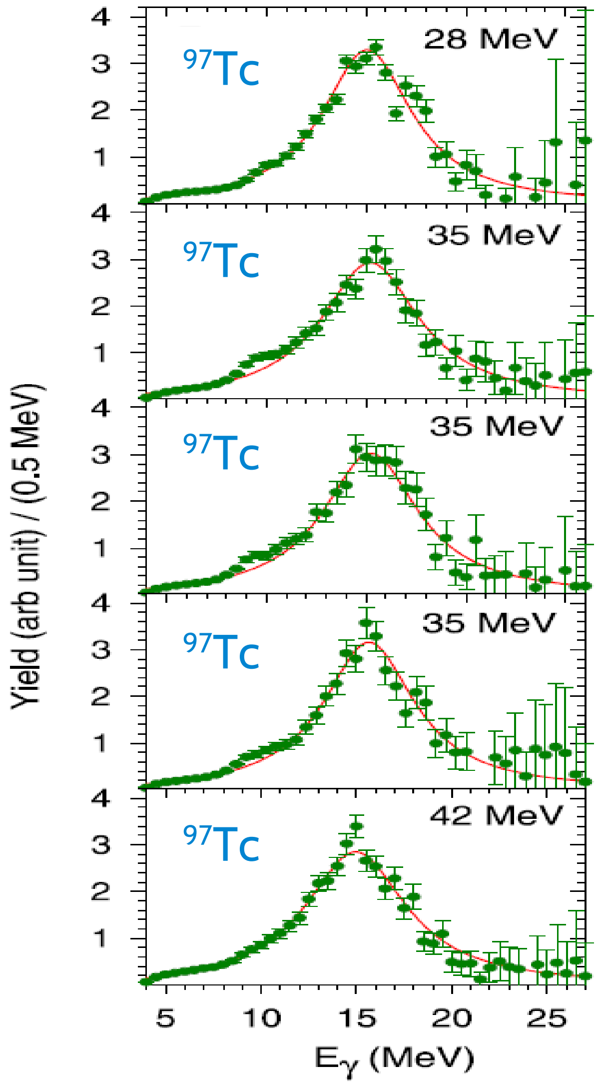


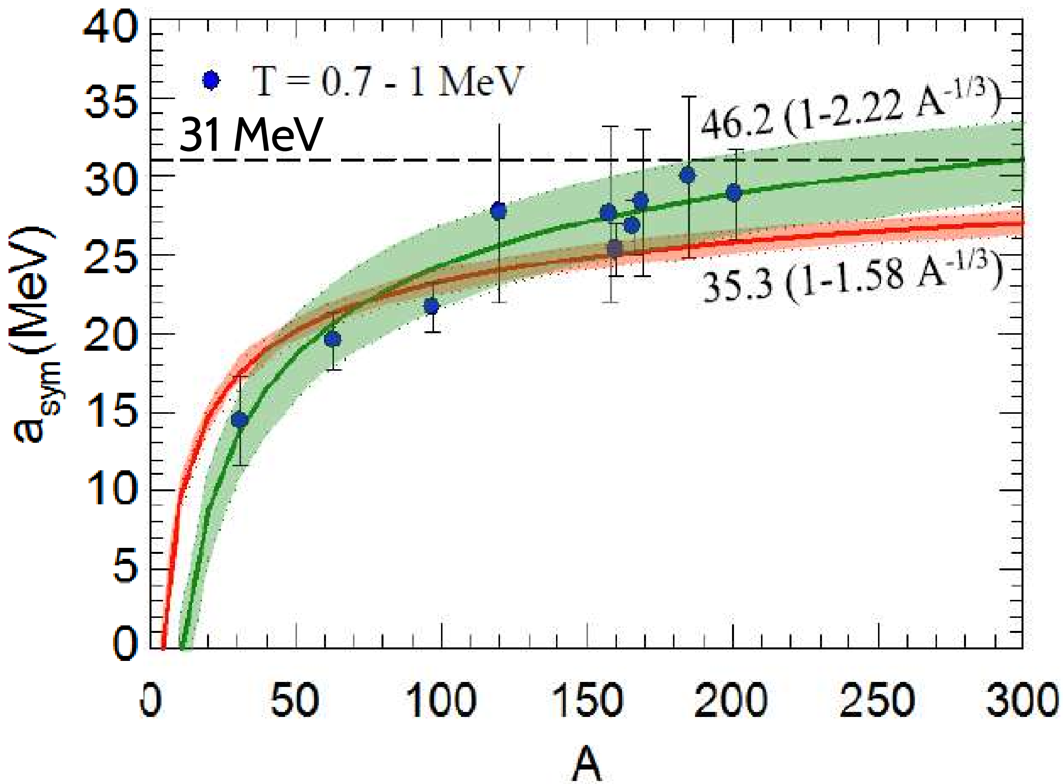


Similar equation for deformed nuclei, but using the average centroid energy and the FWHM of the total Lorentzian

Symmetry energy extracted @ T~0.7-1 MeV (GDRs built on excited sates)

Increase of 3-5% in the centroid energy for T~0.7-1 MeV

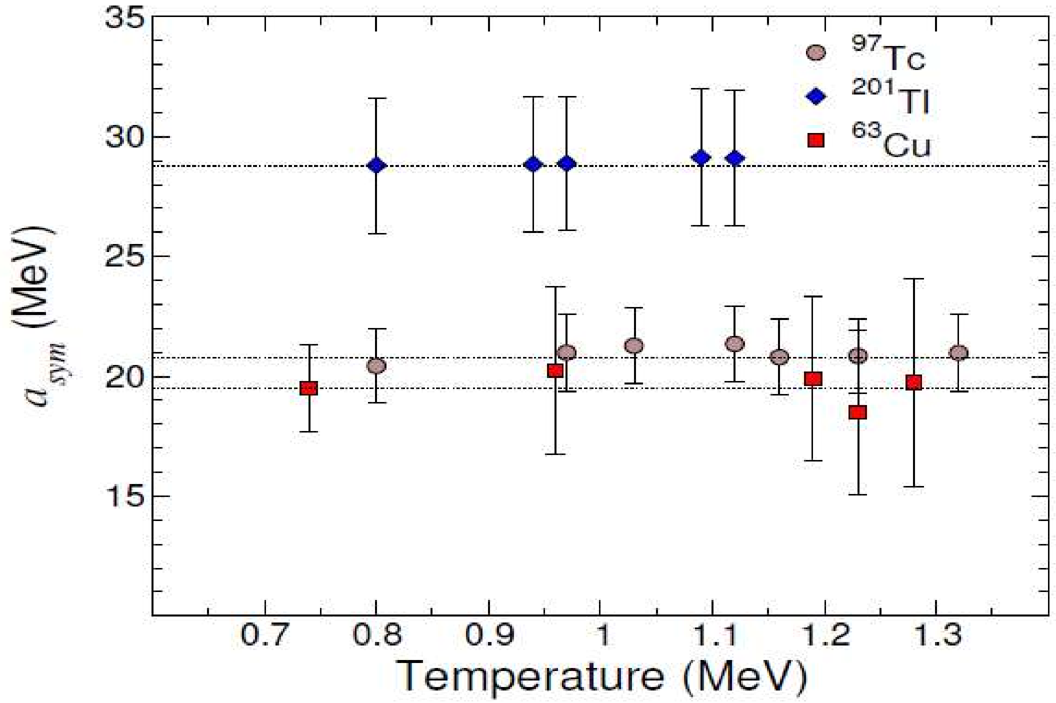




Effective mass of the nucleon decreases as T increases (dynamic mean field), and yields an increase in the symmetry energy of ~8% at T~1 MeV for medium and heavy mass nuclei (Donati *et al.*, PRL **72** (1994) 2835)

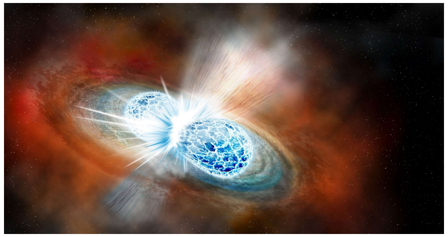
B. Dey *et al.*, PLB **731** (2014) 92, D. Mondal *et al.*, PLB **784** (2018) 423
P. Heckman *et al.*, PLB **555** (2003) 43, D. Pandit *et al.*,PLB **713** (2012) 434
M. Kicinska-Habior *et al.*, PRC **36** (1987) 612

Constant a_{sym} between T~0.7-1.3 MeV,
but neutron capture may occur @ T<0.5 MeV



T

High T (70 MeV) → kilonova, gamma-ray burst, quarks + gluons, protons + neutrons
T~ 0.7-1 MeV → likely the temperatures where seed elements are created before charge reactions freeze out.
T< 0.5 MeV → neutron-capture may start occurring.
A few 10^8 K → neutrons are finally consumed.

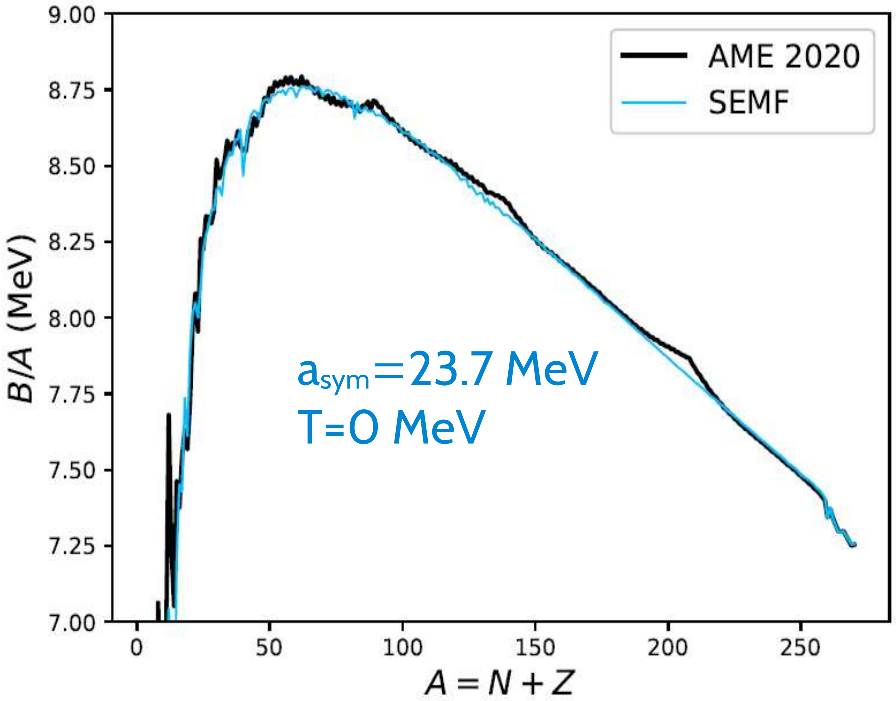


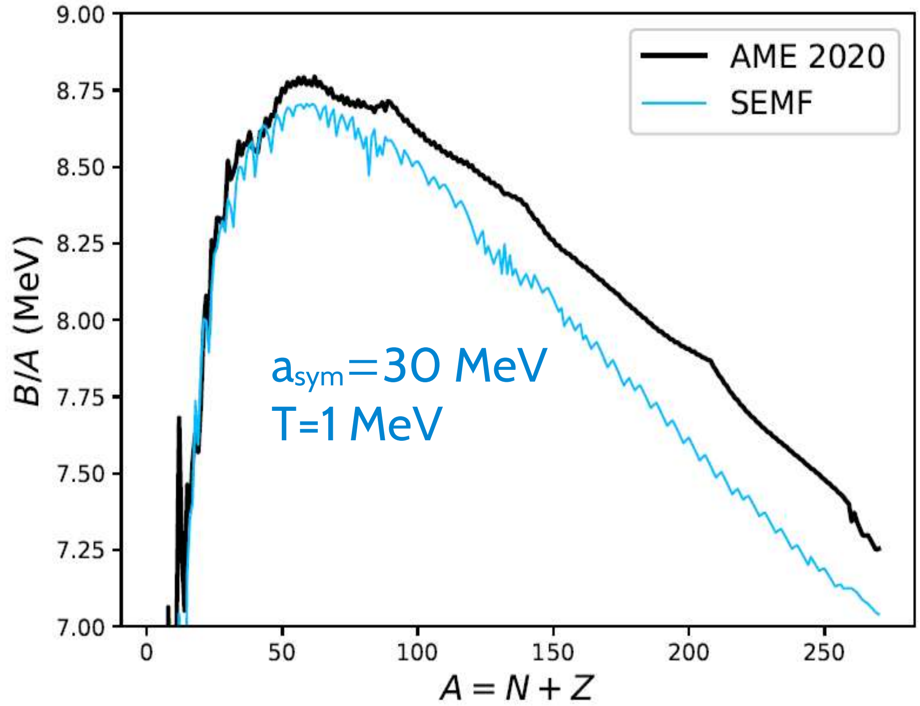
Reduction in the binding energy per nucleon as a_{sym} increases

The convergence of a_{sym} for heavy nuclei establishes the frontiers of the neutron dripline

$$B(Z,A) = a_v A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - a_{asym} \frac{(A-2Z)^2}{A} \pm \frac{a_p}{A^{3/4}}$$

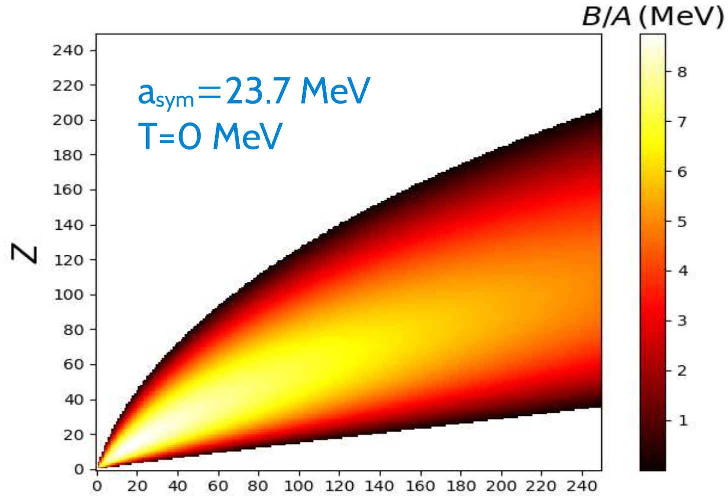
J. W. Rohlf, "Modern Physics from alpha to Z0", Wiley (1994)

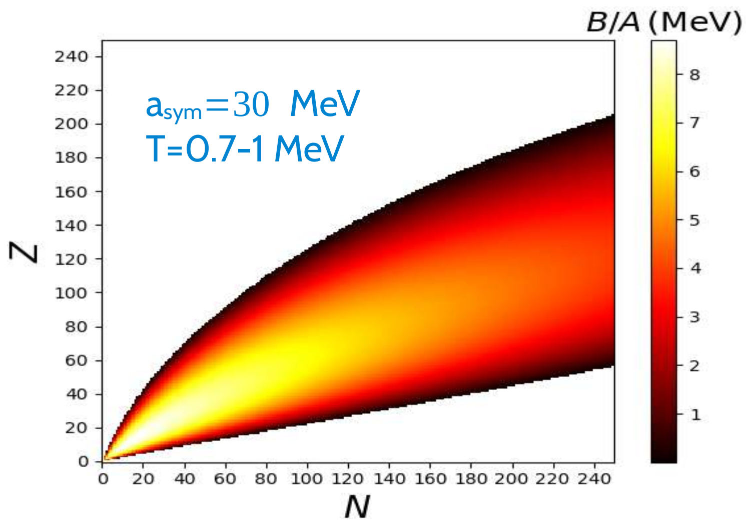




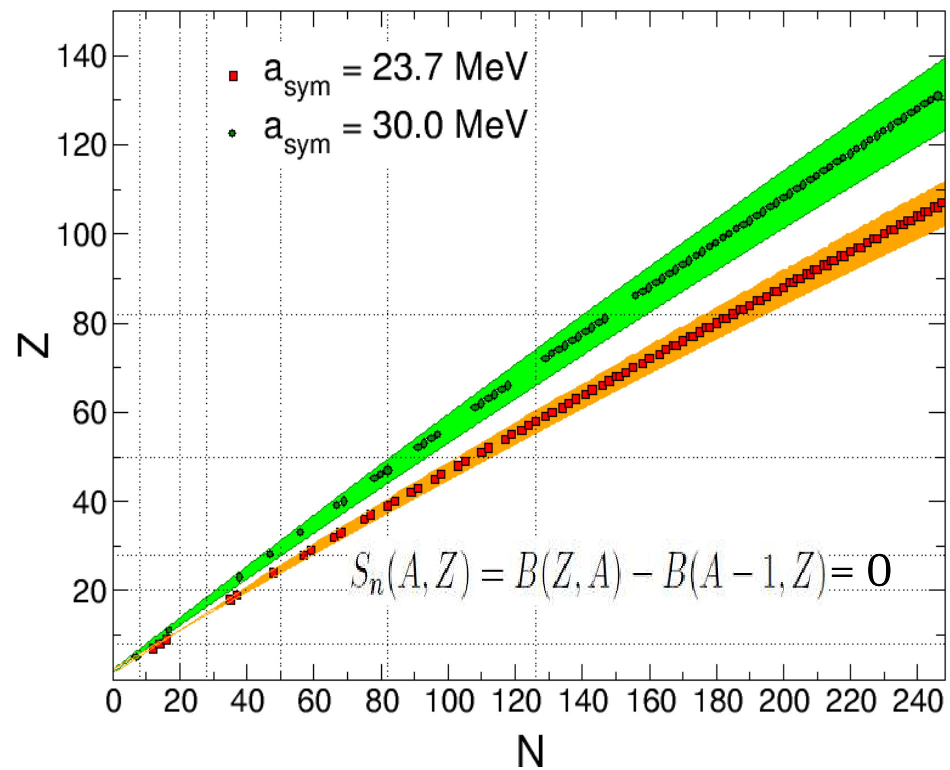
Nuclear chart given by the semi-empirical mass formula

Close-in neutron dripline for heavy elements





$$B(Z,A) = a_v A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - a_{asym} \frac{(A-2Z)^2}{A} \pm \frac{a_p}{A^{3/4}}$$

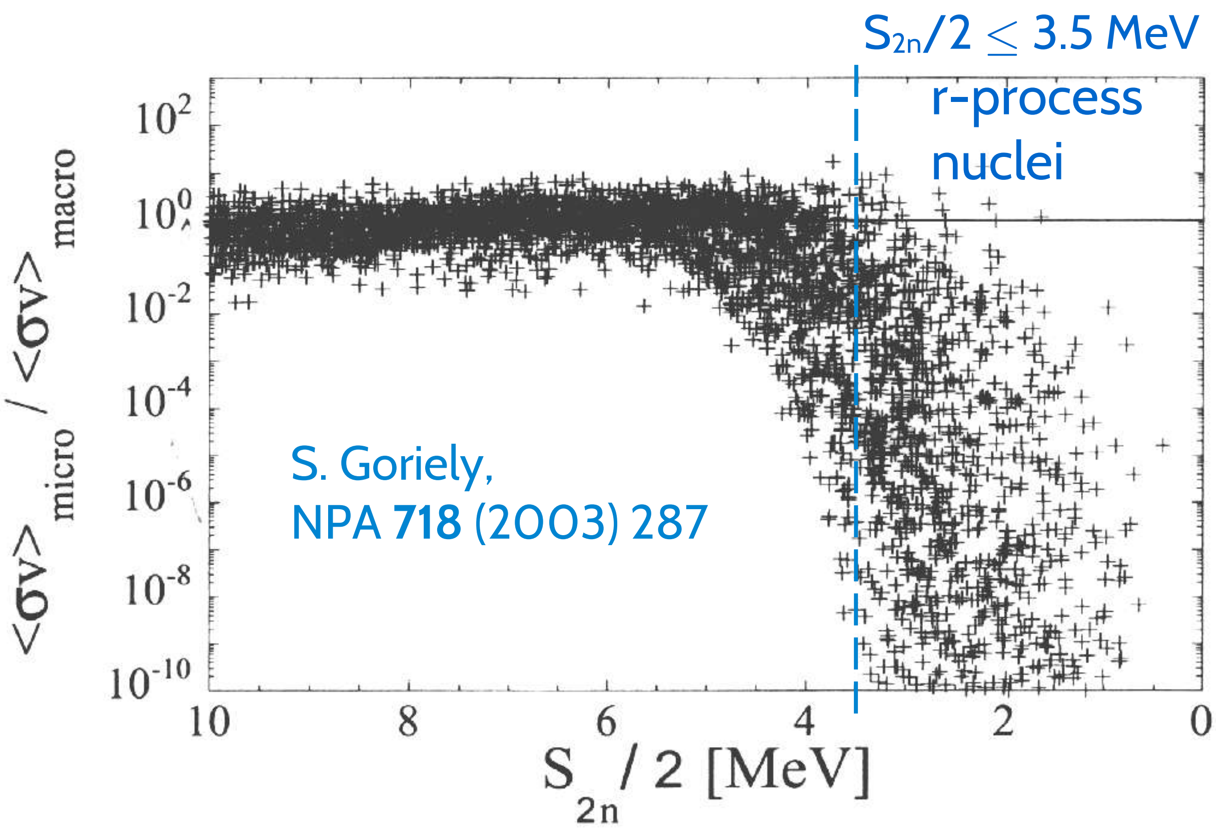


Reduction of the neutron-capture cross section by a factor of ~100 in the A=200 mass region (TALYS and EMPIRE)

The convergence of a_{sym} for heavy nuclei establishes the frontiers of the neutron dripline

Microscopic neutron capture rates dramatically smaller for r-process nuclei

Close-in neutron dripline for heavy elements



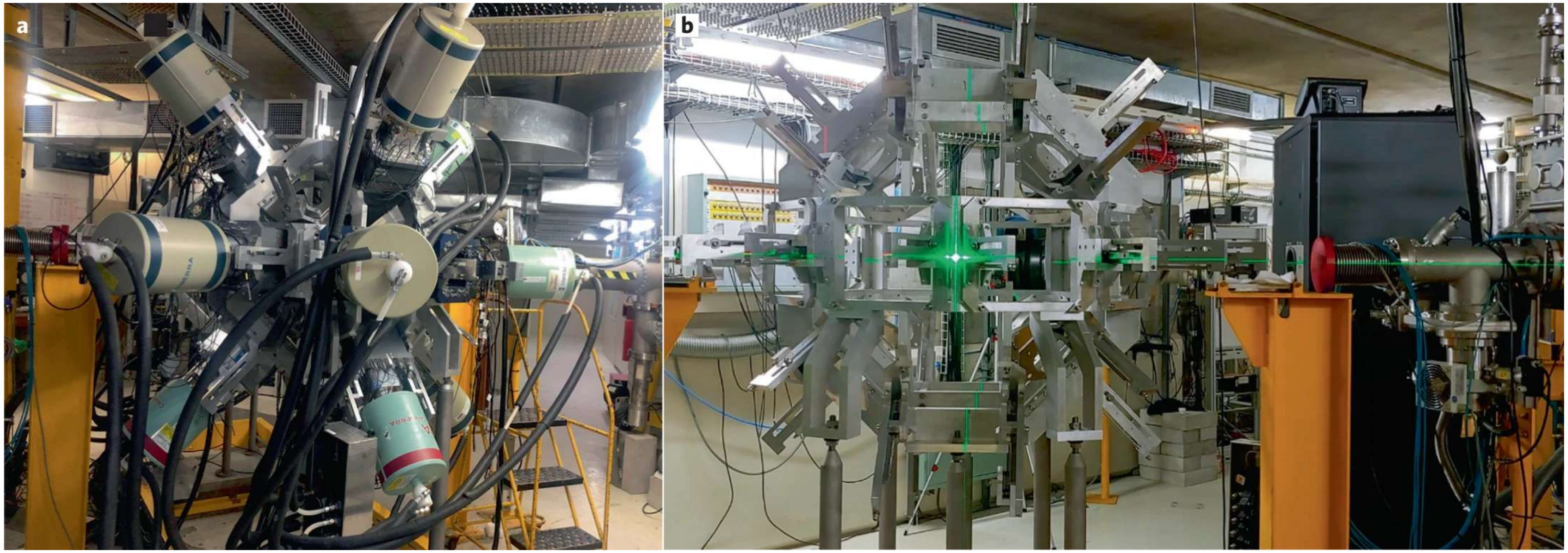
"The "universality" of the r-process abundances could possibly be explained by the rapid drop of the neutron capture rates at increasing neutron excesses (which constrains the r-process flow to remain in the narrow region of the nuclear chart characterized by low β half-lives and large neutron capture rates)."

Conclusions

A larger symmetry energy @ T~0.7-1 MeV results in a close-in neutron dripline which constrains the r-process flow and narrows down the nucleosynthesis of elements.

This may be reason for the universal pattern of r-process abundances observed in galactic halo nuclei and our Sun.

Further work is needed: GDRs @ $0<T<0.5$ MeV (e.g. GAMKA now commissioned in South Africa), reaction rates (FRIB, GSI, RIKEN, SPIRAL2,...), what happens far from stability?



Acknowledgments

Enhanced symmetry energy bears universality of the r-process

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