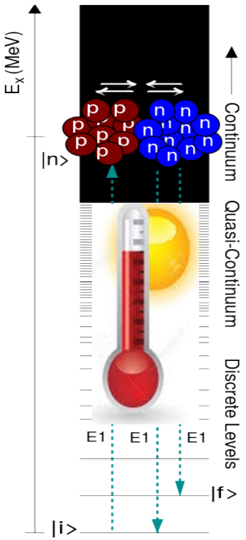
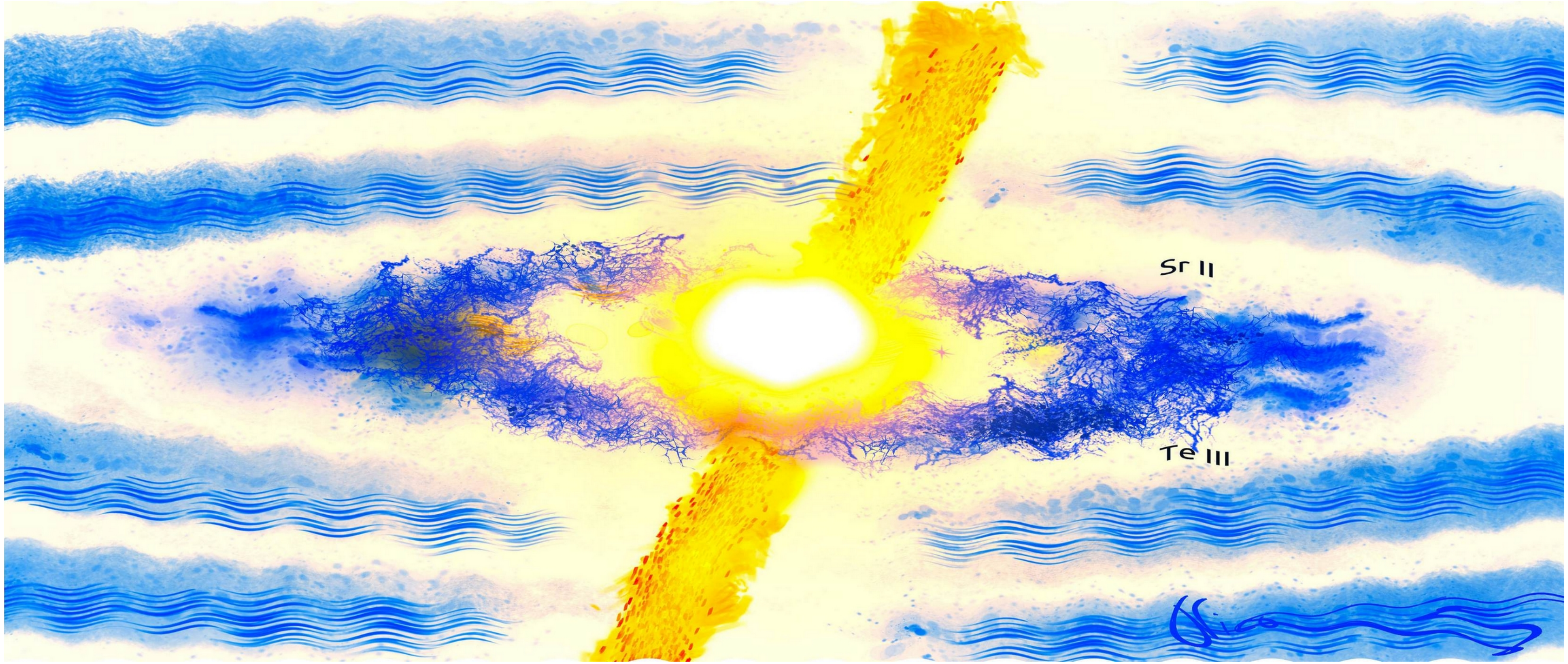
Nuclear thermometers (GDRs) reveal the origin of universal abundance of heavy elements





RESPICE PROSPICE
UNIVERSITY of the WESTERN CAPE

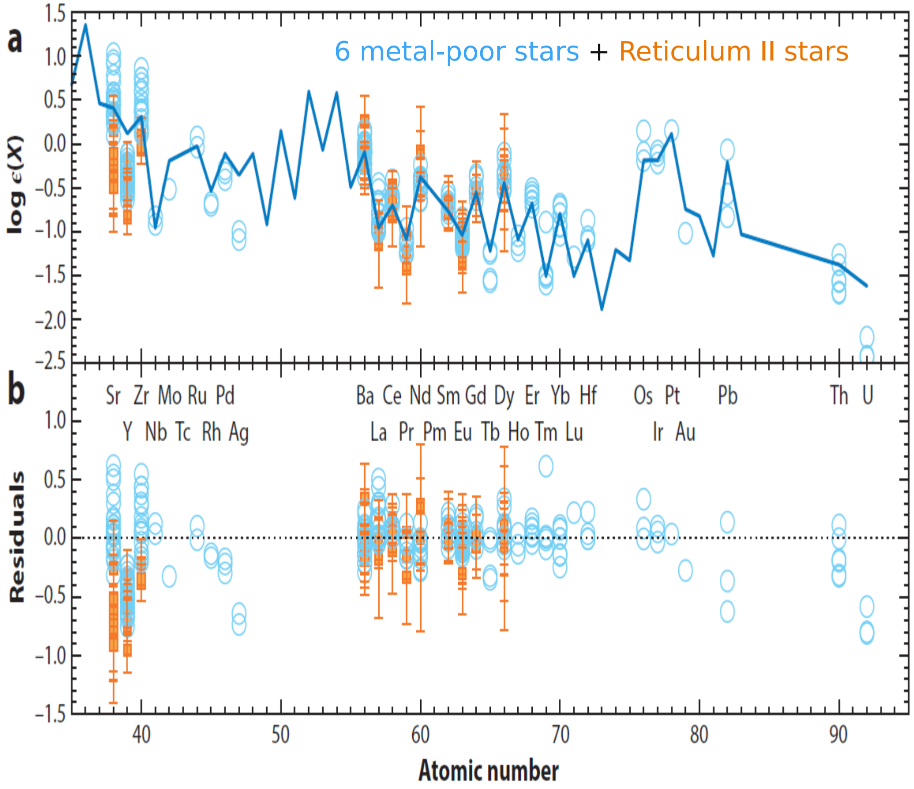
Nico Orce

NITheCS
National Institute for Theoretical and Computational Sciences

ISOLDE Workhop and Users Meeting 29 November 2024

Universality of elemental r-process abundances (from Ba to Pb)

Normalized r-process-element abundances of six undisturbed (~13-billion-year-old) r-process Galactic halo + Reticulum II (first r-process galaxy) stars overlaid with the scaled solar r-process pattern (blue line)

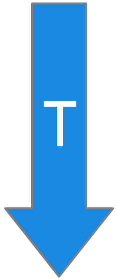


Given that the Sun formed billions of years after metal-poor stars – from gas that was enriched by many stellar generations in various ways – the astounding agreement between the patterns suggests that the **r-process is universal**.

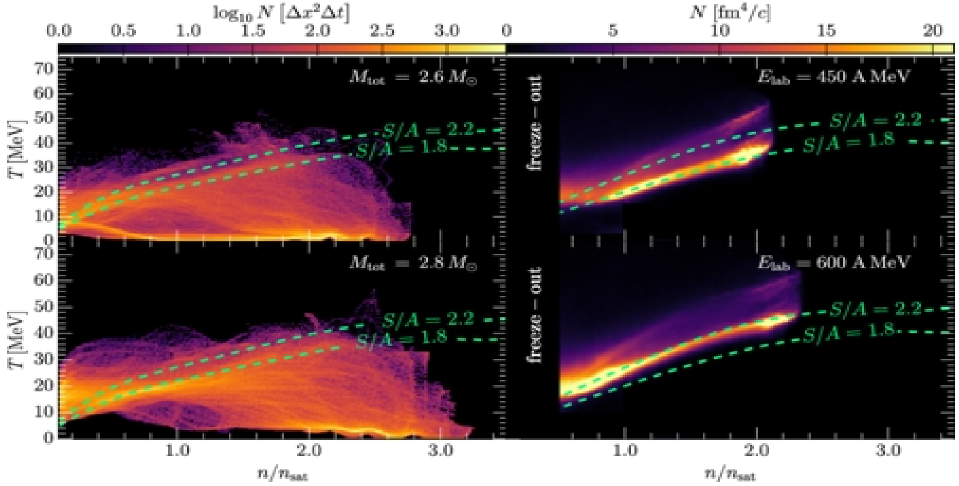
We do not know if this may be only an artifact of nuclear properties such as binding energies and β-decay rates, or it may point to a single cosmic site with astrophysical conditions that are generated uniformly throughout cosmic time."

Kajino *et al*., Prog. Part. Nucl. Phys. (2019)
Sneden, Cowan, and Gallino, Ann. Rev. AA (2008)
Ji, Frebel, Chiti *et al*. Nature (2016)
Frebel, Annu. Rev. Nucl. Part. Sci. (2018)

Cooling down of neutron star mergers: from kilonova to ground state



High T ~ 40-50 MeV ~ 5×10^{11} K→
Merger of neutron stars (BNSM vs HIC), gamma-ray burst, kilonova ejecta: hadrons, quark-gluon plasma,
protons + neutrons (HADES @ GSI)



$T \sim 0.7$-1 MeV = 0.8-1.2×10^{10} K → Temperatures where seed elements are created before charge reactions freeze out (high neutron/seed ratio)

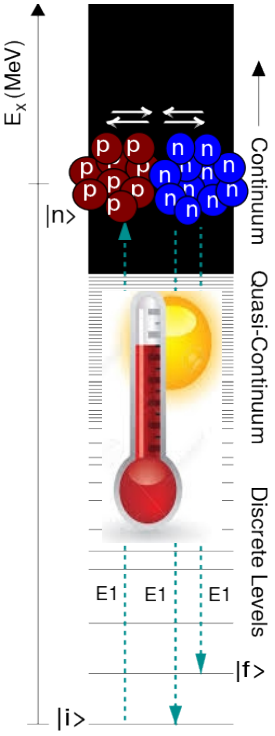
$T \lessapprox 0.5$ MeV ~ 6×10^{9} K → **Rapid n-capture (r-process) occurring** until it also freezes out: (less neutrons, lower T)

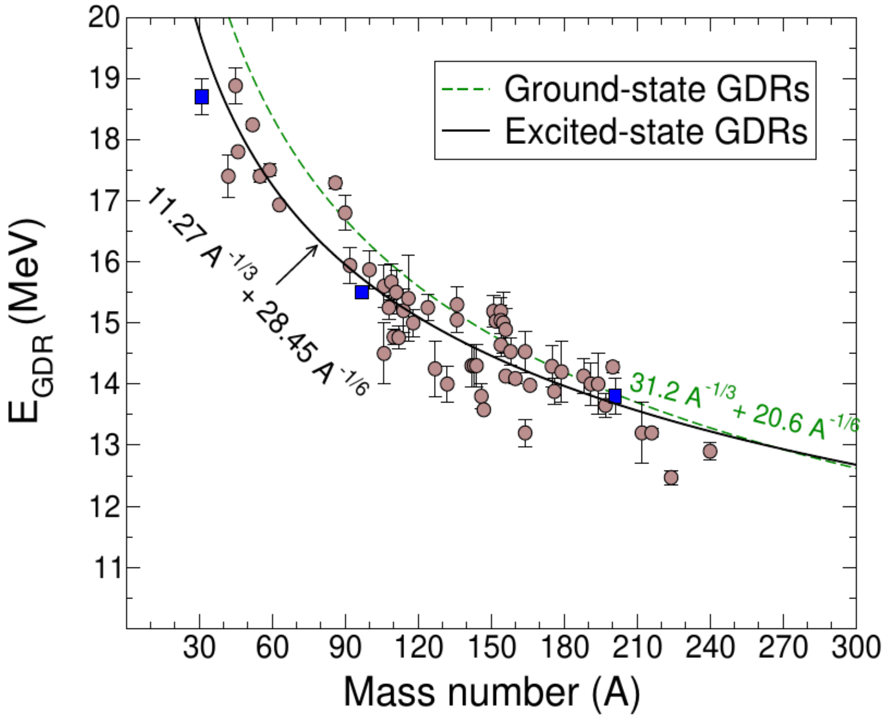
$T \sim 0.03$ MeV ~ 10^{8} K → neutrons are finally consumed (T=0 ground state)

Most *et al.*, PRD (2023)
Kilonovae, Metzger, Living Reviews in Relativity (2020)
Probing dense baryon-rich matter with virtual photons. The HADES-Collaboration. Nature Physics (2019)
Neutron Star Mergers & Nucleosynthesis of Heavy Elements, Thielemann, Eichler, Panov & Wehmeyer, ARNPS (2017)

Validity of the Brink-Axel hyphotesis → Nuclear Thermometers

A GDR can be built on every state in a nucleus



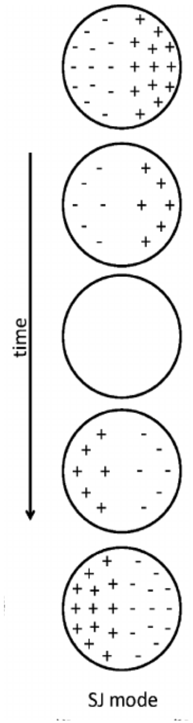


GDRs built on excited states present for moderate average temperature ($\lesssim$ 1 MeV) and spin J similar centroid energies and resonance strengths relative to the Thomas-Reiche-Kuhn dipole sum rule as those found for the ground-state counterparts → **Common physical origin for all GDRs**

Schiller, Thoennessen, At. Data Nucl. Data Tables 2007
Snover, Annual Review of Nuclear and Particle Science 1986
Gaardhøje, Annual Review of Nuclear and Particle Science 1992
Orce, submitted to MNRAS 2024 https://arxiv.org/pdf/2411.17852

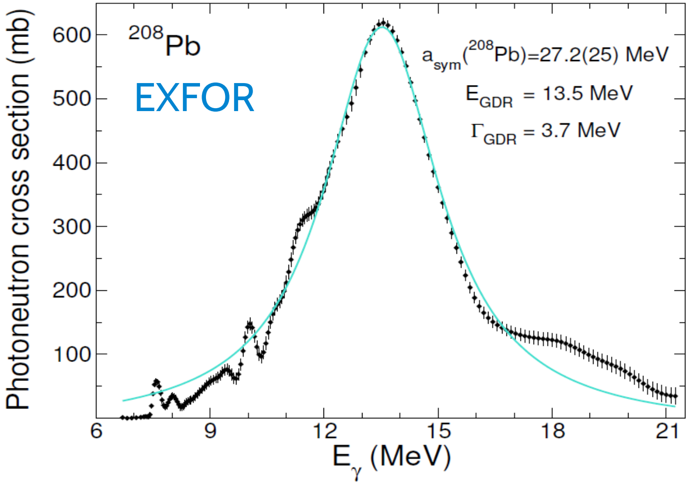
Brink, PhD thesis, University of Oxford 1955
Axel, Physical Review 1962

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



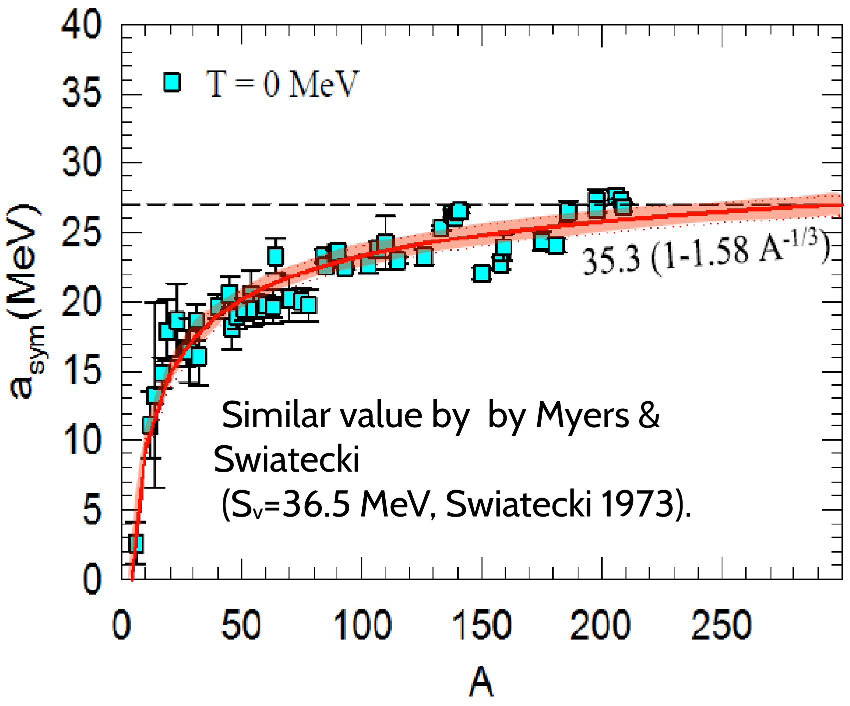
Spherical nuclei (modified SJ model with width)

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



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

a_{sym} saturates @ ≈27

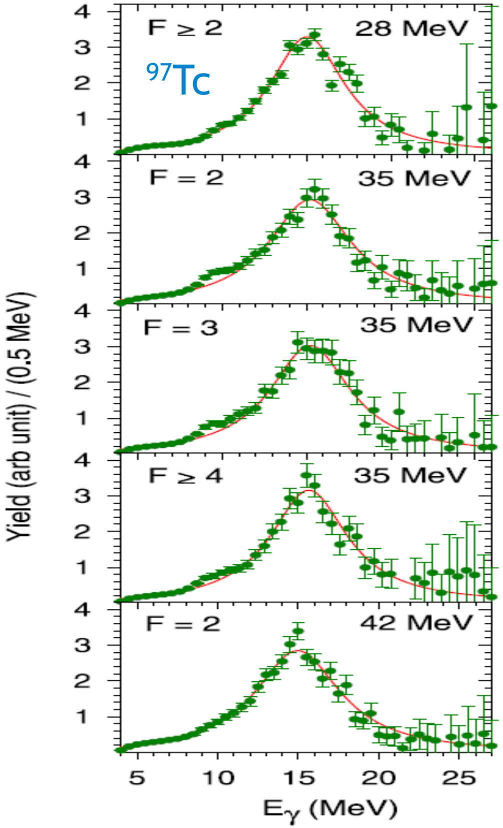


Similar value by by Myers & Swiatecki (S_v=36.5 MeV, Swiatecki 1973).

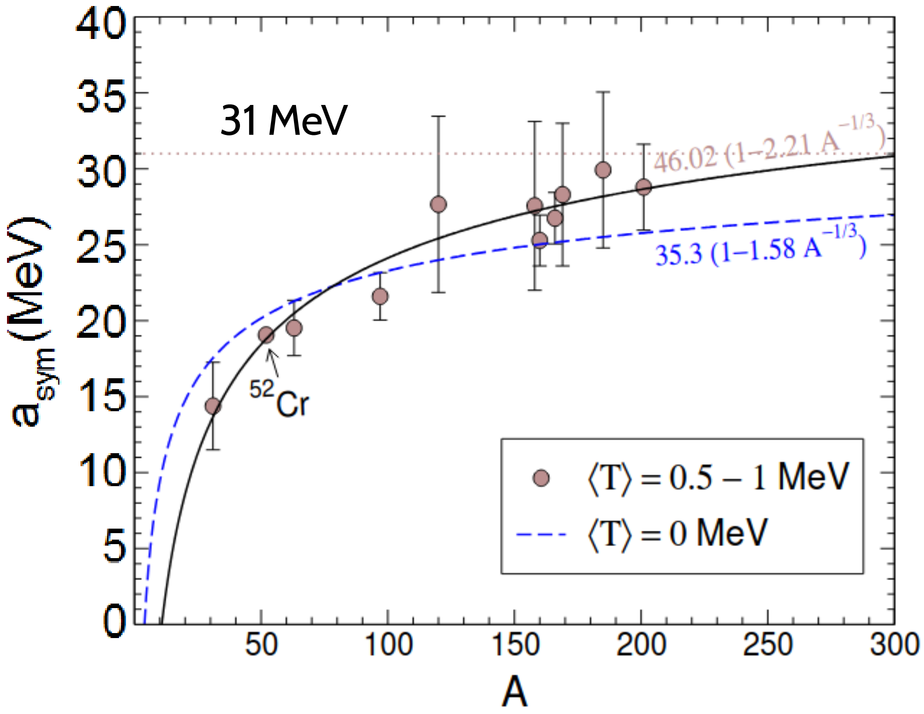
Danos, Nuclear Physics (1958)
Trippa, Colò, Vigezzi, PRC (2008)
Orce, Dey, Ngwetsheni, Bhattacharya, Pandit MNRAS (2023)

Symmetry energy extracted @ T~0.5-1 MeV (GDRs built on excited sates)

Fold-gated γ-ray spectra, where F is the number of multiplicity detectors fired (γ-ray multiplicity) in coincidence with the high energy γ rays

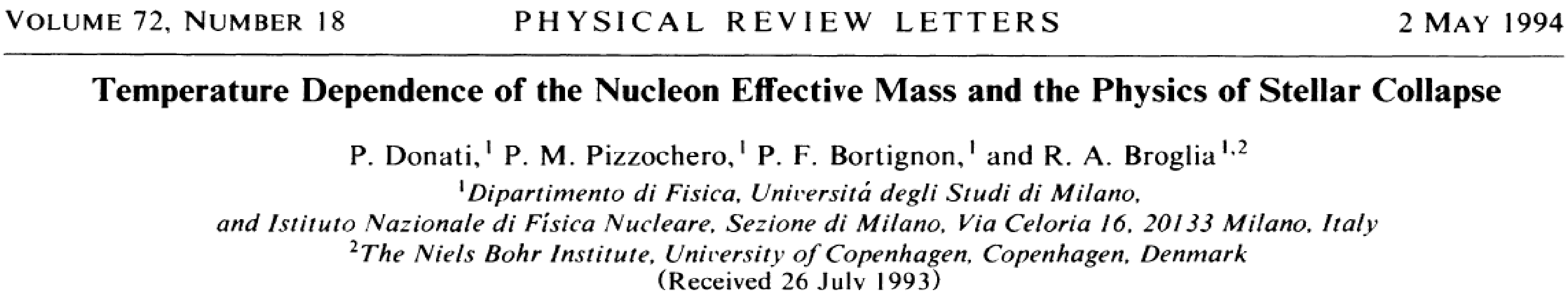


Increase of ~5% in the centroid energy for T~0.5-1 MeV



Orce, submitted to MNRAS 2024 https://arxiv.org/pdf/2411.17852
Dey *et al.*, PLB (2014), Mondal *et al.*, PLB (2018)
Schiller, Thoennessen., At. Data Nucl. Data Tables 2007
Pandit, NIM A 2010

Effect of the temperature dependence of the ω mass on the symmetry energy



VOLUME 72, NUMBER 18 PHYSICAL REVIEW LETTERS 2 MAY 1994

Temperature Dependence of the Nucleon Effective Mass and the Physics of Stellar Collapse

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and Istituto Nazionale di Física Nucleare, Sezione di Milano, Via Celoria 16, 20133 Milano, Italy
[2] *The Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
(Received 26 July 1993)

Mean field is dynamic. Fermions couple to the collective motion → non-locality absorbed by the effective ω mass, $m_\omega < m$.
This effective mass decreases as T increases, and yields an increase in the symmetry energy of ~8% for medium and heavy mass nuclei.
The low-lying 2_1^+ and 3_1^- states play the most important role in the determination of the ω mass.

Supported

Fantina, Margueron, Donati, Pizzochero, J. Phys. G 2011 → improve density of states around the Fermi surface
Severyukhin, Margueron, Borzov, Van Giai, , Phys. Rev. C 2015 → improve Skyrme functionals for β-decay rates

Unsupported

Dean, Koonin, Langanke, Radha, PLB 1995 → Monte Carlo shell model calculations using the KB3 interaction found no systematic temperature dependence of the symmetry energy

Smooth behaviour of a_{sym} between T~0.5-1.3 MeV

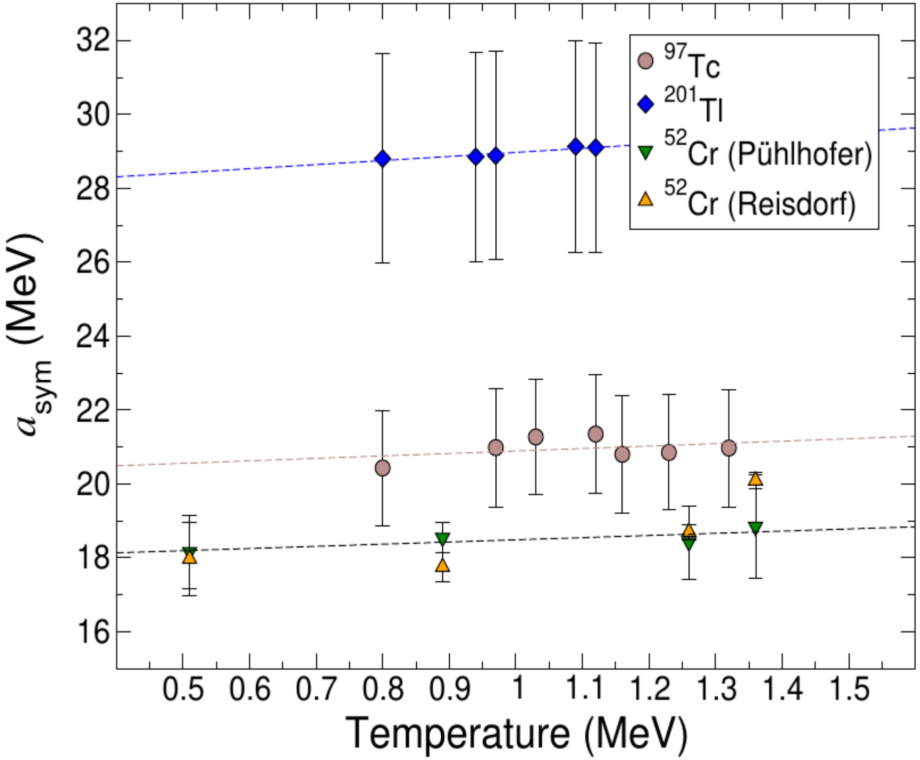
Neutron capture starts occurring @ T≈0.5 MeV

T=40-50 MeV or (~5×10^{11} K) → Merger of neutron stars (BNSM vs HIC)) → kilonova, γ-ray burst, quarks + gluons, protons + neutrons

T~ 0.7-1 MeV (0.8-1.2 ×10^{10} K) → seed elements are created before charge reactions freeze out.

T $\lesssim$ 0.5 MeV (~5× 10^{9} K) → r-process

A few 10^{8} K → neutrons are consumed



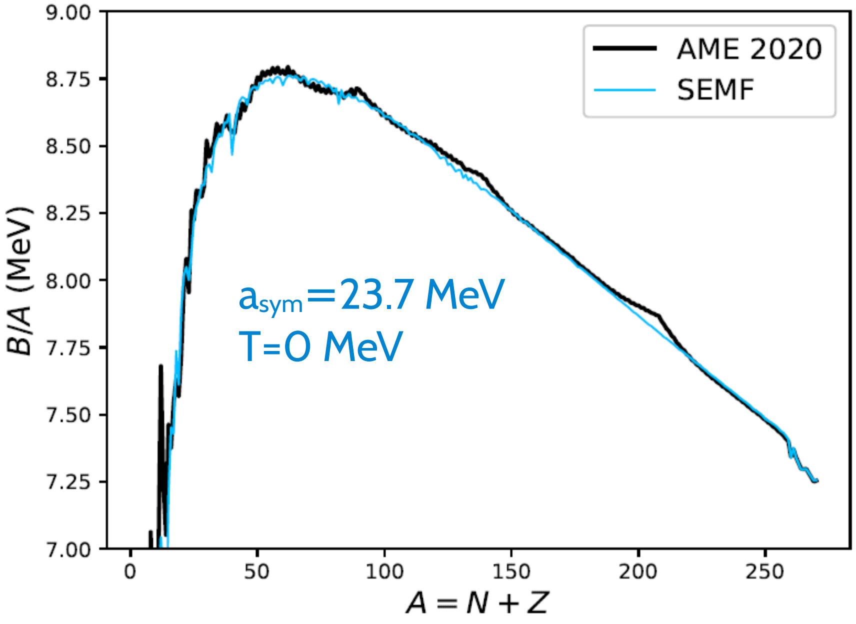
https://arxiv.org/pdf/2411.17852

Reduction of B/A as a_{sym} increases

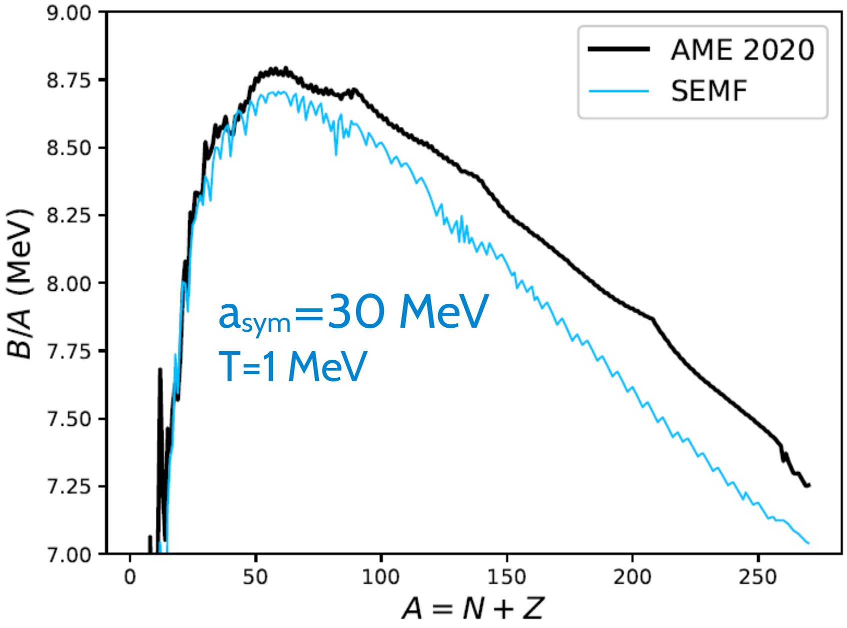
Reduction of the neutron-capture cross section by a factor of ~100 in the A=200 mass region (TALYS and EMPIRE)

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

(or modified SEMF, HFB-21, FRDM, WS, DZ...)

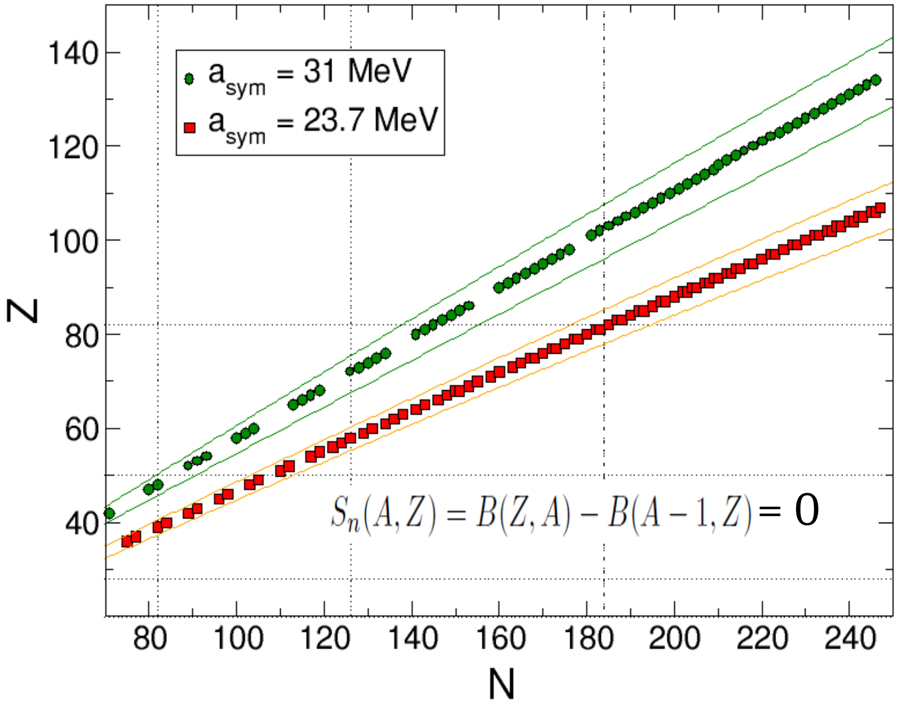


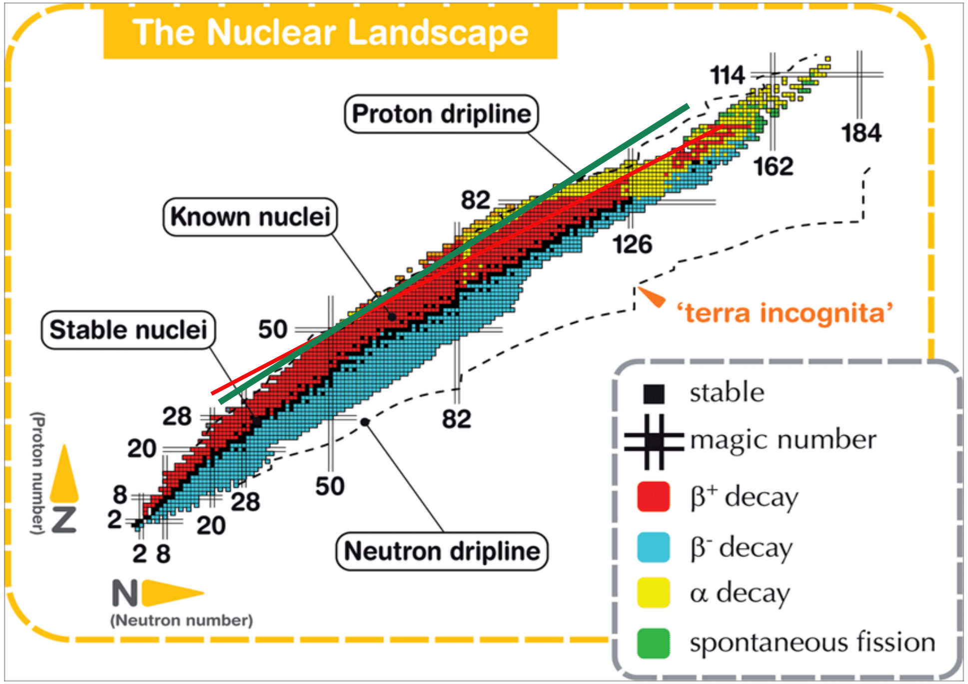
Rohlf, "Modern Physics from alpha to Z0", Wiley (1994)



The convergence of a_{sym} for heavy nuclei establishes the frontier of the neutron drip line

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



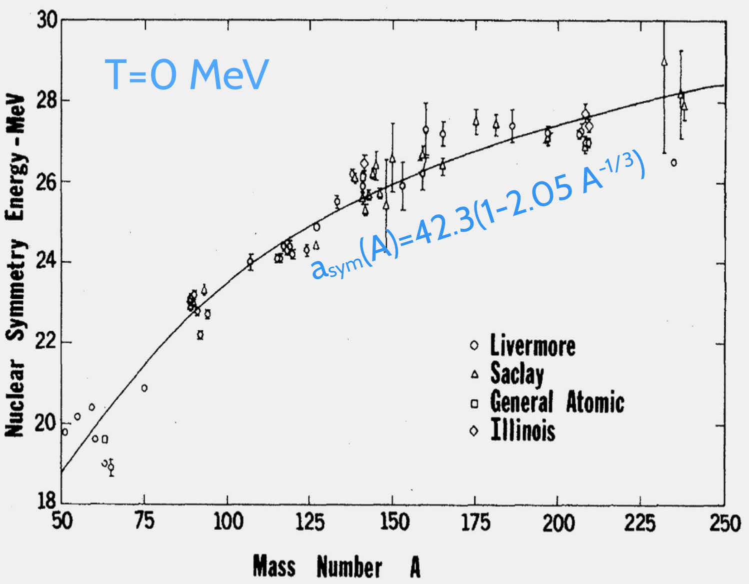


Consequence → Neutron drip line shifts towards the line of stability

Shift of the neutron drip line for heavy elements

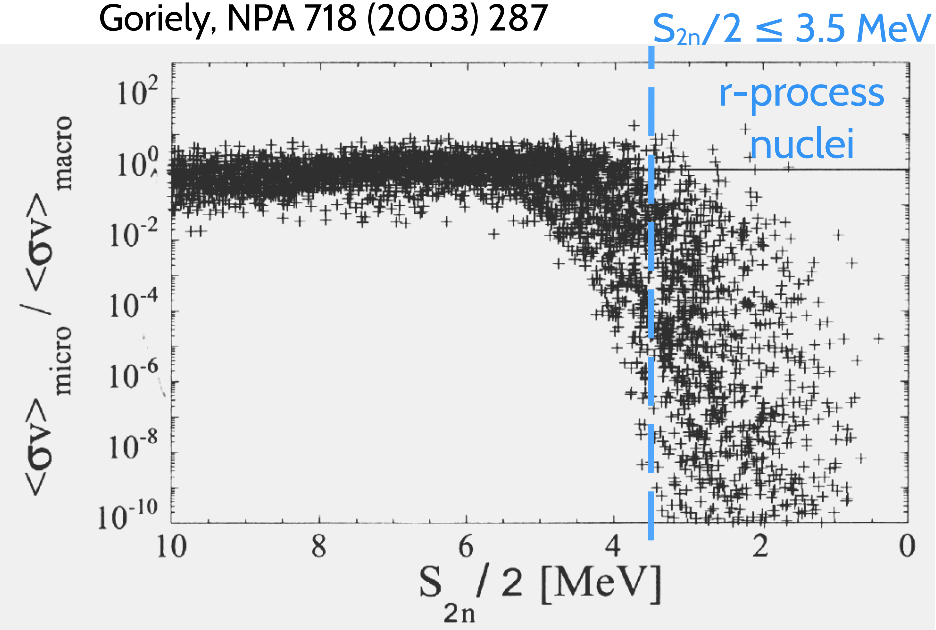
Not first time being suggested

Herman & Fultz, Rev. Mod. Phys. **47** (1975) 713



"This large value for this ratio favors a "close-in" neutron drip line for heavy elements, and hence argues against the production of superheavy elements by the r-process in supernovae."

Goriely, NPA 718 (2003) 287



"The "universality" of the r-process abundances could possibly be explained by the rapid drop of microscopic 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)."

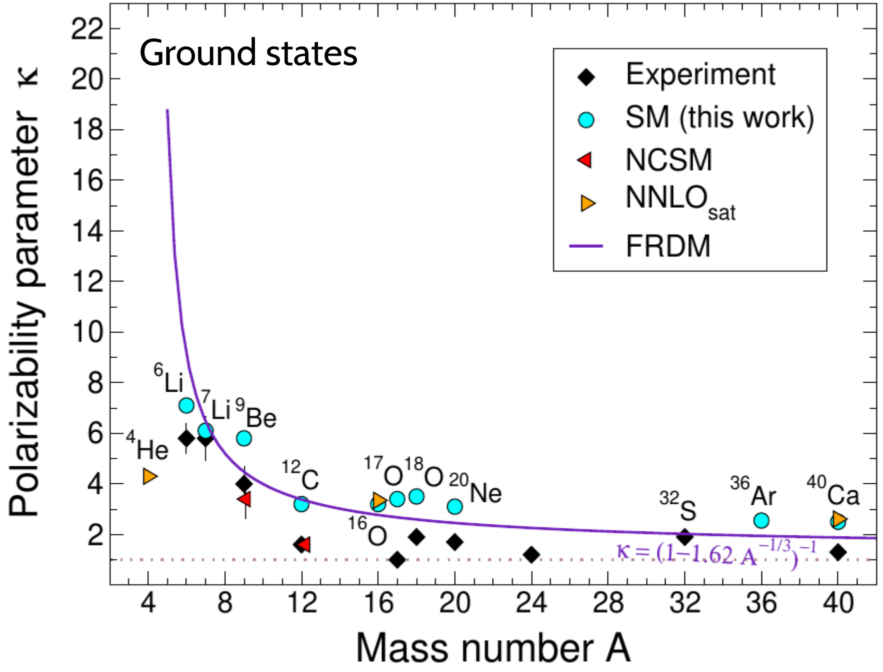
$1\hbar\omega$ SM calculations using WBP and FSU interaction within the *spsdpf* model space of the dipole polarizability α_{E1}

$$\alpha_{E1} = 1.11 \frac{ZA^{2/3}}{\langle i \parallel \hat{E2} \parallel f\rangle} \sum_{J_n,\Delta T} \frac{\mathscr{S}(E1)}{W(\lambda_{in}\ \lambda_{nf}\ J_i\ J_f, \lambda\ J_n)},$$

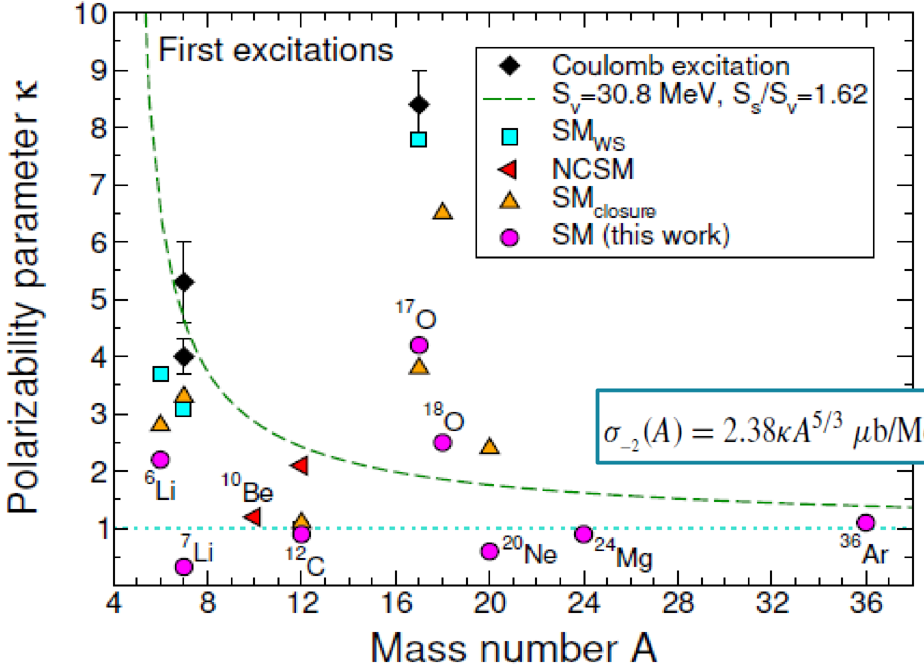
$$\sigma_{-2} = 0.155 \frac{ZA^{2/3}}{\langle i \parallel \hat{E2} \parallel f\rangle} \sum_{J_n,\Delta T} \frac{\mathscr{S}(E1)}{W(\lambda_{in}\ \lambda_{nf}\ J_i\ J_f, \lambda\ J_n)}$$

$$\mathscr{S}(E1) = \frac{1}{2J_i+1} \sum_{J_n,\Delta T} W(\lambda_{in}\ \lambda_{nf}\ J_i\ J_f, \lambda\ J_n) \frac{\langle i \parallel \hat{E1} \parallel n\rangle\langle n \parallel \hat{E1} \parallel f\rangle}{E_n - E_i}$$

$$\alpha_{E1} = \frac{2e^2}{2J_i+1} \sum_n \frac{|\langle i \parallel \hat{E1} \parallel n\rangle|^2}{E_n - E_i} = \frac{9\hbar c}{8\pi^3}\sigma_{-2}$$



Orce, Ngwetsheni & Brown, PRC (2023)

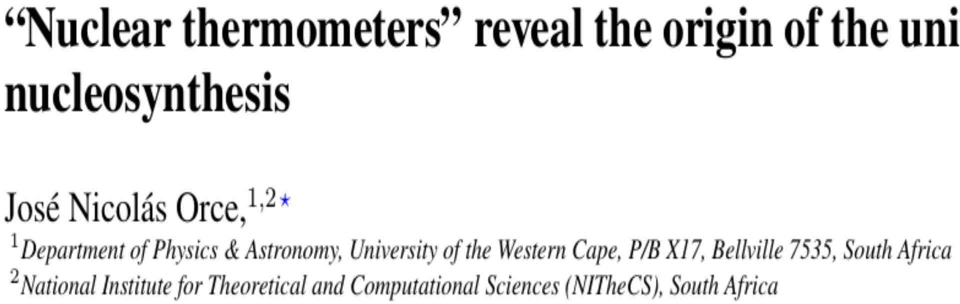


$$\sigma_{-2}(A) = 2.38\kappa A^{5/3}\ \mu b/\text{MeV}$$

Orce & Ngwetsheni, JPG (2024)
Orce, PRC (2015) and (2016)

Drop of polarizability at 2^+_1 states may arise from additional binding energy provided by α clusters

Reduced dipole polarizability of 2_1^+ states from destructive contribution of off-diagonal E1 matrix elements



"Nuclear thermometers" reveal the origin of the universal r-process nucleosynthesis

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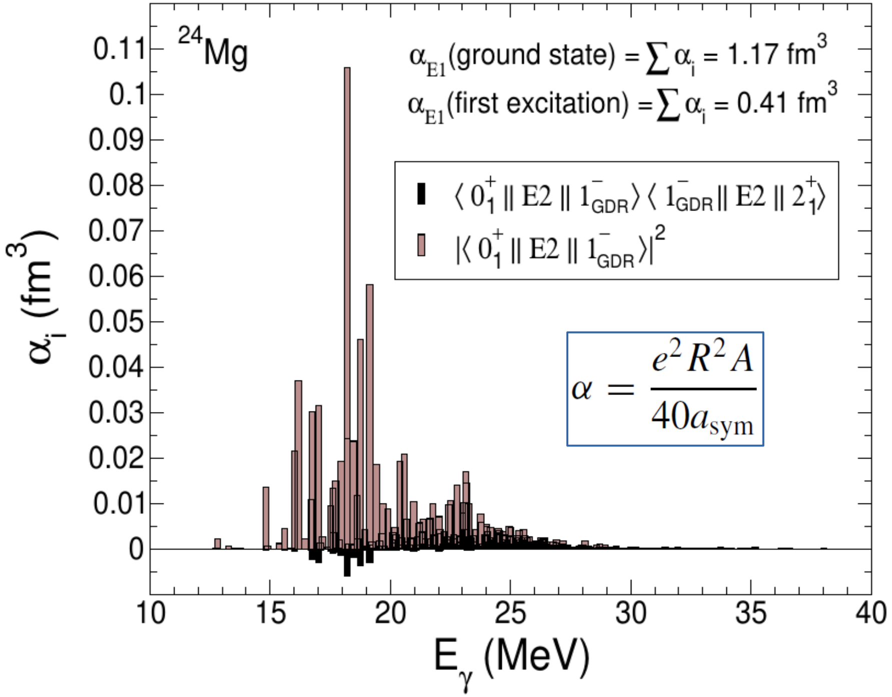
[2]National Institute for Theoretical and Computational Sciences (NITheCS), South Africa

$$\alpha_{E1}(\text{ground state}) = \frac{2e^2}{2J_i+1}\sum_n \frac{|\langle i \,||\, \hat{E}1 \,||\, n\rangle|^2}{E_\gamma}$$

$$\alpha_{E1}(2_1^+) = 4.295\,\frac{ZA^{2/3}S(E1)}{\langle 0_1^+ \,||\, \hat{E}2 \,||\, 2_1^+\rangle}\ \text{fm}^3$$

$$S(E1) := \frac{1}{2J_i+1}\sum_{J_n,\Delta T} W_{inf}\,\frac{\langle i \,||\, \hat{E}1 \,||\, n\rangle\langle n \,||\, \hat{E}1 \,||\, f\rangle}{E_\gamma}$$



Submitted to MNRAS
https://arxiv.org/abs/2411.17852

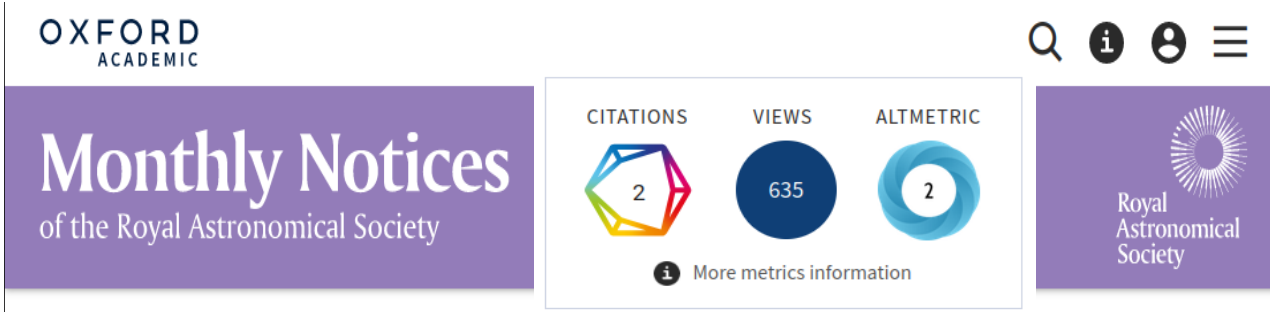
Conclusions

We use GDRs built on excited states as "thermometers" to determine a larger symmetry energy @ $T \approx 0.5$-1 MeV → results in a shift of the neutron drip line towards the line of stability → constrains the r-process flow and narrows down the nucleosynthesis path
→ **explanation of the universal pattern of r-process abundances.**

Caution + Further Work

1) Mass models assume g.s. masses and largely diverge as N increases → RMS $\lesssim$ 100 keV for accurate r-process predictions and distinguish astrophysical environment).
2) Validity of the Brink-Axel hypothesis → ala IS559: The γ-ray strength function and nuclear level density of ^{67}Ni @ HIE-ISOLDE (Oslo group + iThemba LABS).
3) Temperature dependence $0 \lesssim T \lesssim 0.5$ MeV (lack of information) → GDRs @ $T<0.5$ MeV using (α,α') inelastic scattering + GAMKA spectrometer @ iThemba LABS (GAMKA Science Case).
4) Pygmy vs GDR contributions → a much larger pygmy contribution in neutron-rich nuclei would enhance the dipole polarizability and reduce the symmetry energy ?????
5) More astronomical observations of metal-poor stars → SALT:HRS/Infrared high-resolution spectroscopy of metal-poor stars: just got our first results!
6) $1\hbar\omega$ SM calculations of the dipole polarizability for neutron-rich nuclei relevant to the r-process
7) Dipole polarizability of excited states in even-even nuclei never been measured → High-priority Coulex experiments with GAMKA @ iThemba LABS and HIE-ISOLDE (to be proposed).

Acknowledgments to the INSA collaboration



Enhanced symmetry energy may bear universality of r-process abundances FREE

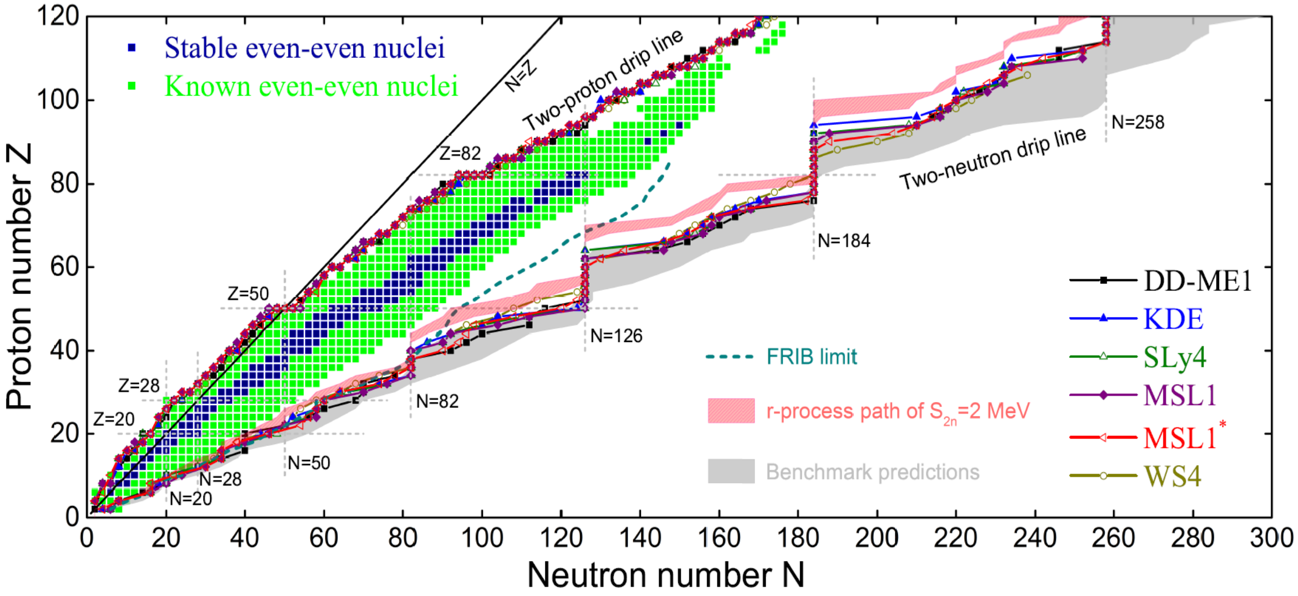
José Nicolás Orce ✉, Balaram Dey ✉, Cebo Ngwetsheni, Srijit Bhattacharya,
Deepak Pandit ✉, Brenden Lesch, Andile Zulu

Monthly Notices of the Royal Astronomical Society, Volume 525, Issue 4, November 2023, Pages 6249–6256, https://doi.org/10.1093/mnras/stad2539

Published: 04 September 2023 **Article history ▾**

Predictions of drip lines and r-process paths → Limits of Nuclear Existence

Density Functional Theory with different interactions (4 Skyrme and 1 relativistic)

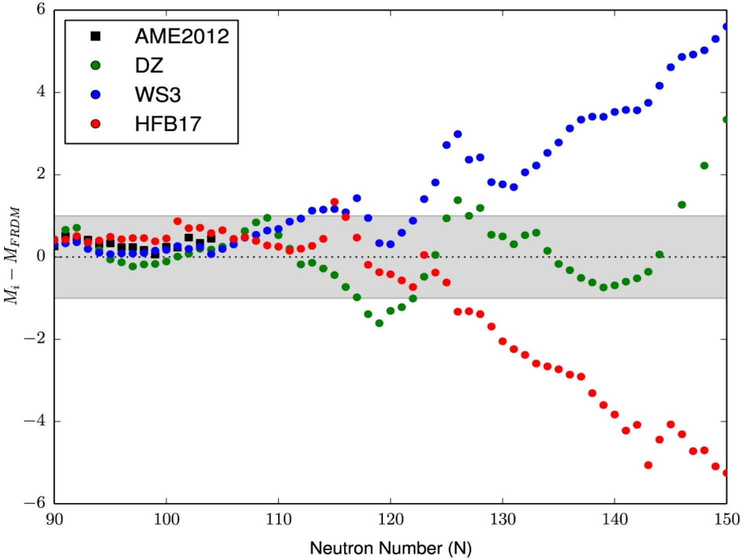


Predictions for neutron drip line and the **r-process paths** involving heavy neutron-rich nuclei exhibit a **significant variation** due to wide range of conditions not accurately determined.

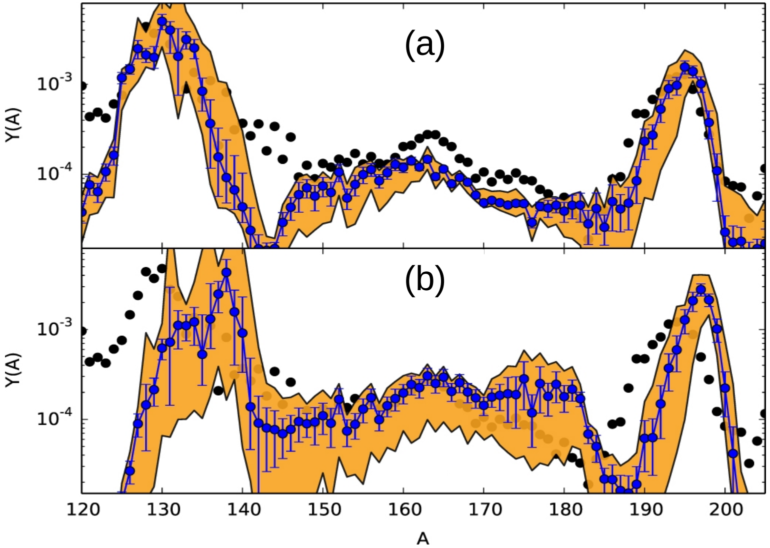
Rui Wang & Lie-Wen Chen, PRC **92** (2015) 031303
Jochen Erler *et al.*, Nature **486** (2012) 509

Sensitivity studies of r-process network calculations → Impact of uncertain masses

Both theoretical and experimental approaches have reached a dead end!



Difference between theoretical mass predictions. The gray band at ±1 MeV shows the mass variation size for the sensitivity studies.



Uncertainty in final abundances for (a) the neutron star merger and (b) hot wind r-process based off ±1 MeV variation of nuclear masses from FRDM

Only a reduction of global rms errors <100 keV may (currently $\gtrsim$ 300 keV) allow for accurate r-process predictions and differentiation between model predictions, which can range orders of magnitude.

Mumpower M. R., Surman R., Aprahamian A., JPG & EPJ Web of Conferences 2015