Nuclear properties for astrophysics: an overview

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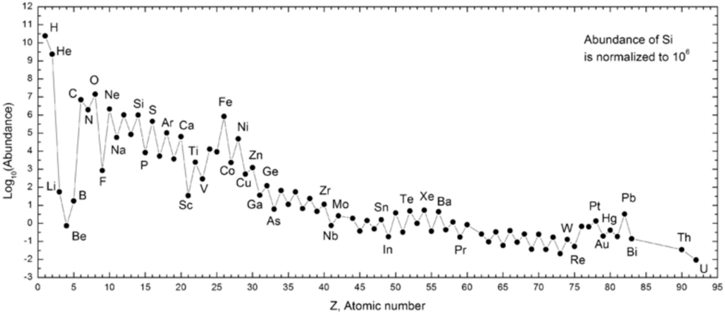
Fifth Gogny Conference

December 10 – 13, 2024

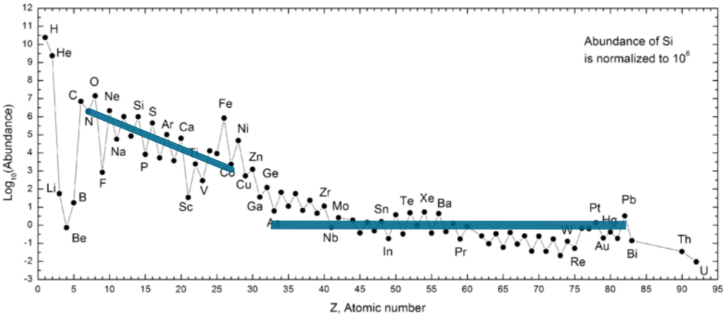
Paris, France

Solar system elemental abundances



Data sources: Mostly solar spectra, meteorites and terrestrial isotopic composition.

Solar system elemental abundances

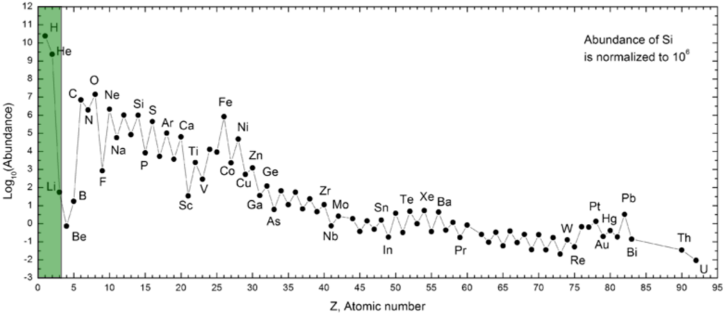


Data sources: Mostly solar spectra, meteorites and terrestrial isotopic composition.

Features:

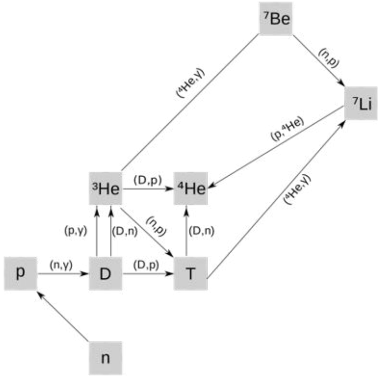
- 12 orders of magnitude span.
- H $\sim$ 75%; He $\sim$ 23%; C $\rightarrow$ U $\sim$ 2%.
- Exponential decrease up to Fe, almost flat distribution beyond Fe.

Primordial Big-Bang nucleosynthesis



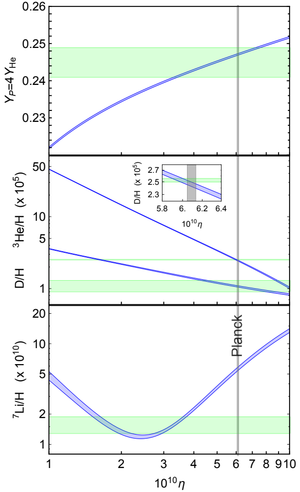
- D, He and (some) Li: Primordial Big-Bang nucleosynthesis.

Primordial Big-Bang nucleosynthesis



- D, He, and Li formed when $10^9 \gtrsim T \gtrsim 10^8$ K.
- Nuclear network: 11 reactions (+ neutron decay)
- High-precision era: very good agreement between observations and theoretical predictions.
- Li problem: ^{7}Li overestimated by a factor 2–4, ^{6}Li underestimated by 3 orders of magnitude.
- Precise estimation of charged particle and neutron reactions, weak decays.

Primordial Big-Bang nucleosynthesis



C. Pitrou *et al.*, Phys. Rep. **754** 1-66 (2018)

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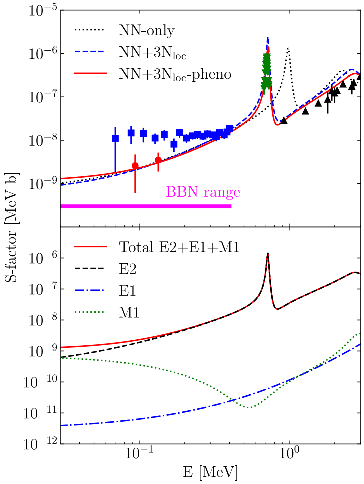
Big-Bang nucleosynthesis of ^{6}Li



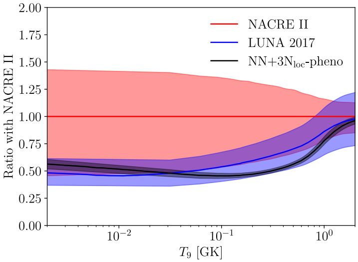
PHYSICAL REVIEW LETTERS **129,** 042503 (2022)

Ab Initio **Prediction of the ^{4}He$(d,\gamma)^6$Li Big Bang Radiative Capture**

C. Hebborn,[1,2,*] G. Hupin,[3] K. Kravvaris,[2] S. Quaglioni,[2] P. Navrátil,[4] and P. Gysbers[4,5]

- ^{6}Li mostly produced by ^{4}He$(d,\gamma)^6$Li.
- Radiative capture rate poorly known at BBN energies $E = 30 - 400$ keV.
- S factor from no-core shell model with continuum with NN+3N.
- $E1$ transitions negligible, enhancement below 100 keV due to $M1$.
- Uncertainty in termonuclear reaction rate reduced by a factor 7.

Big-Bang nucleosynthesis of ^{6}Li



PHYSICAL REVIEW LETTERS **129,** 042503 (2022)

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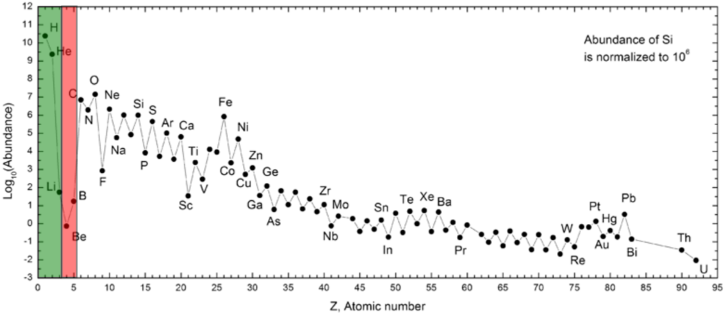
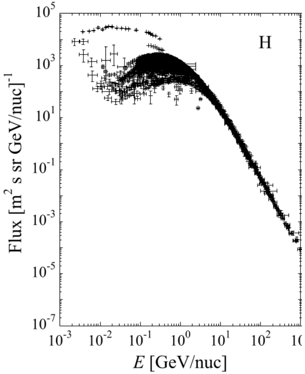
Spallation reactions



- (some) Li, B and Be: Galactic cosmic rays (GCR) on interstellar medium.

GCR and spallation reactions

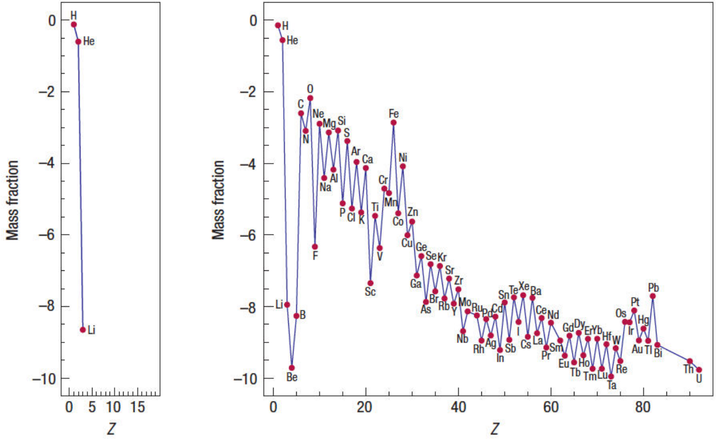


Arnould and Goriely, PPNP **112** (2020)

- ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B produced by nuclear interaction of mostly protons and α particles with heavier (C-N-O) nuclei.
- Cosmic ray observations with a 1−3% precision.
- Interpretation limited by uncertainties in nuclear cross sections (20−50%).
- Can heavier nuclei be produced through GCR spallation?

How do we fill de gap?

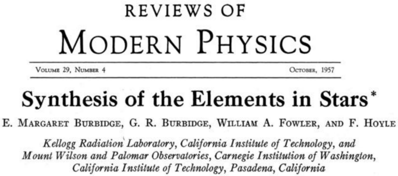
Credit: A. Hager



Stellar nucleosynthesis

B^{2}FH, Rev. Mod. Phys. 29, 547 (1957) ; A. Cameron, Report CRL-41 (1957)

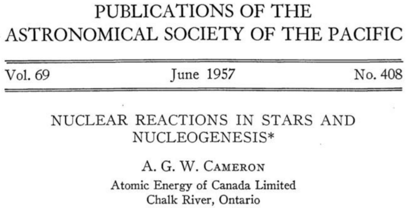
Credit: M. Liotta


REVIEWS OF
MODERN PHYSICS
VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

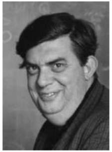
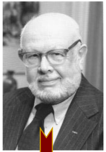
E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California


PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC
Vol. 69 June 1957 No. 408

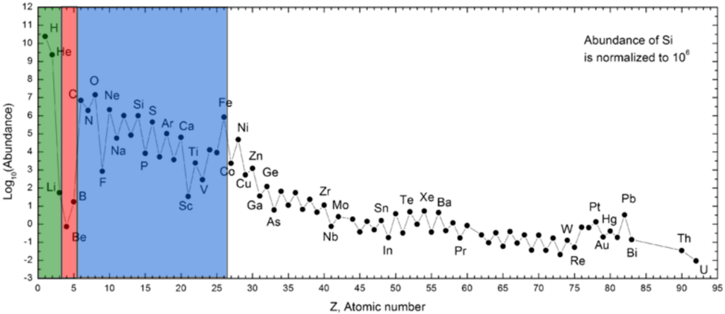
NUCLEAR REACTIONS IN STARS AND NUCLEOGENESIS*

A. G. W. CAMERON
Atomic Energy of Canada Limited
Chalk River, Ontario


Nobel Prize
1983

Fusion in stellar interiors

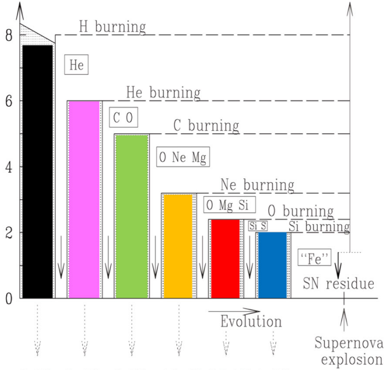


- Nuclei up to ^{56}Fe: Fusion reactions in stellar interiors.

Fusion in stellar interiors

- Star mass and composition dictate the evolution.
- Successive thermonuclear burning stages (composition change) and gravitational contractions (temperature increase).
- Duration of burning phases decreases due to decreasing energy and increasing neutrino production.
- Charged particle reactions → tunneling probability → exponential decrease in abundance.
- After Si burning: gravitational collapse and catastrophic explosion.

S. Goriely, EPJA (2023) 59:16



T_c(K)	6×10^7	2×10^8	9×10^8	1.7×10^9	2.3×10^9	4×10^9
ρ_c(g/cm^3)	5	700	2×10^5	4×10^6	10^7	3×10^7
Time-scale	7×10^6 y	5×10^5 y	600 y	0.5 y	6 d	1 d

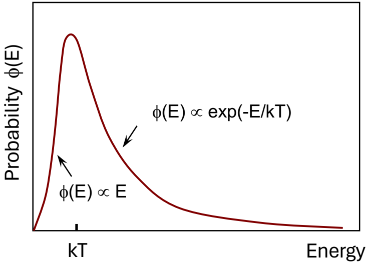
Thermonuclear reactions in stars

In stellar plasmas, nuclei in thermodynamic equilibrium → follow a Maxwell-Boltzmann distribution.
Reaction rate per particle pair:

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) \exp\left(-\frac{E}{kT}\right) E dE$$

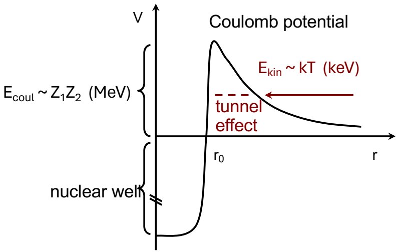
- $\langle \sigma v \rangle$ key quantity to determine energy production and change in abundances.
- From experiments and/or theory.
- T changes with star evolution → $\langle \sigma v \rangle$ over the relevant T range (analytical expression).

Credit: M. Aliotta



Coulomb barrier tunneling

Credit: M. Aliotta



- Charged-particle reactions hindered by Coulomb repulsion.
- Reactions initiated by thermal motion:

$$kT \sim 100\ T_9\ (\mathrm{keV})$$

Sun: $T \sim 1.5 \times 10^{-2}$ GK $\rightarrow kT \sim 1$ keV.

During quiescent burnings: $kT \ll E_{\mathrm{Coul}} \rightarrow$ reactions through tunnel effect (with $l = 0$):

$$P \propto \exp\left(-2\pi\eta(E)\right) = \exp\left(-\frac{b}{E^{1/2}}\right) \quad \text{with} \quad \eta = \left(\frac{\mu}{2E}\right)^{1/2} \frac{Z_1 Z_2 e^2}{\hbar}$$

Exponential drop in abundances curve. . .

Gamow peak

Cross section given in terms of the astrophysical $S(E)$ factor (non-resonant reactions):

$$\sigma(E) = \underbrace{\frac{1}{E}\exp(-2\pi\eta)}_{\text{strong } E \text{ dependence}} S(E)$$

Reaction rate given by a competition between MB distribution and tunneling probability:

$$\langle \sigma v \rangle \propto \int S(E) \exp\left(-\frac{E}{kT} - \frac{b}{\sqrt{E}}\right) dE$$

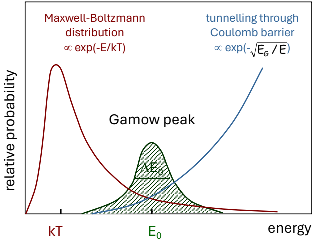
Maximum rate at Gamow Peak:

$$E_0 = 0.1220 \left(Z_1^2 Z_2^2 \mu\right)^{1/3} T_9^{2/3} \text{ MeV}$$

$$\Delta E_0 = 4 \left(\frac{E_0 kT}{3}\right)^{1/2}$$

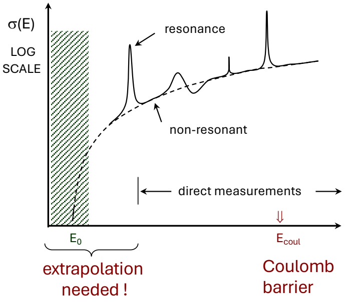
E window of astrophysical interest well below Coulomb barrier.

Credit: M. Aliotta



Stellar burning

Credit: M. Aliotta



- For stellar burning stages $T = 10^6 - 10^8$ K $\rightarrow E_0 \sim 100$ keV
- Gamow peak: $kT \ll E_0 \ll E_{\rm Coul} \rightarrow 10^{-18}\, b < \sigma < 10^{-9}\, b$ (tunneling)
- Average interaction time: $\tau \sim \langle \sigma v \rangle^{-1} \sim 10^9$ y $\rightarrow$ only stable species play a relevant role.

Charged particle reactions for stellar burning

Ab initio informed evaluation of the radiative capture of protons on ^{7}Be

K. Kravvaris [a,*], P. Navrátil [b], S. Quaglioni [a], C. Hebborn [c,a], G. Hupin [d]

https://doi.org/10.1038/s41586-018-0149-4

An increase in the ^{12}C + ^{12}C fusion rate from resonances at astrophysical energies

A. Tumino[1,2*], C. Spitaleri[2,3], M. La Cognata[2], S. Cherubini[2,3], G. L. Guardo[2,4], M. Gulino[1,2], S. Hayakawa[2,5], I. Indelicato[2], L. Lamia[2,3], H. Petrascu[4], R. G. Pizzone[2], S. M. R. Puglia[2], G. G. Rapisarda[2], S. Romano[2,3], M. L. Sergi[2], R. Spartá[2] & L. Trache[4]

PHYSICAL REVIEW LETTERS **127,** 152702 (2021)

Editors' Suggestion Featured in Physics

Direct Measurement of the Astrophysical ^{19}F($p,\alpha\gamma$)^{16}O Reaction in the Deepest Operational Underground Laboratory

L. Y. Zhang,[1] J. Su,[1] J. J. He,[1,*] M. Wiescher,[2,†] R. J. deBoer,[2] D. Kahl,[3] Y. J. Chen,[1] X. Y. Li,[1] J. G. Wang,[4]

PHYSICAL REVIEW C **110**, L061601 (2024)

Letter

^{19}F(p, γ)^{20}Ne reaction rate and the puzzling calcium abundance in metal-poor stars

G. X. Dong,[1] X. B. Wang,[1] N. Michel,[2,3] and M. Płoszajczak[4,*]

PHYSICAL REVIEW LETTERS **131,** 162701 (2023)

Proton-Capture Rates on Carbon Isotopes and Their Impact on the Astrophysical ^{12}C/^{13}C Ratio

J. Skowronski,[1,2] A. Boeltzig,[3,4,5,*] G. F. Ciani,[6,7] L. Csedreki,[8] D. Piatti,[1,2] M. Aliotta,[9] C. Ananna,[5,10]

Article

Measurement of ^{19}F(p, γ)^{20}Ne reaction suggests CNO breakout in first stars

https://doi.org/10.1038/s41586-022-05230-x

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Check for updates

Liyong Zhang[1], Jianjun He[1✉], Richard J. deBoer[2], Michael Wiescher[2✉], Alexander Heger[3], Daid Kahl[4], Jun Su[1], Daniel Odell[5], Yinji Chen[1], Xinyue Li[1], Jianguo Wang[6], Long Zhang[7], Fuqiang Cao[7], Hao Zhang[1], Zhicheng Zhang[8], Xinzhi Jiang[1], Luohuan Wang[1], Ziming Li[1], Luyang Song[1], Hongwei Zhao[6], Liangting Sun[6], Qi Wu[6], Jiaqing Li[6], Baoqun Cui[7], Lihua Chen[7], Ruigang Ma[7], Ertao Li[8], Gang Lian[7], Yaode Sheng[1], Zhihong Li[7], Bing Guo[7], Xiaohong Zhou[6], Yuhu Zhang[6], Hushan Xu[6], Jianping Cheng[1] & Weiping Liu[7,9✉]

PHYSICAL REVIEW C **103**, 055815 (2021)

Editors' Suggestion Featured in Physics

^{19}F(p, γ)^{20}Ne and ^{19}F(p, α)^{16}O reaction rates and their effect on calcium production in Population III stars from hot CNO breakout

R. J. deBoer,[1,*] O. Clarkson,[2,3,4] A. J. Couture,[5] J. Görres,[1] F. Herwig,[2,3,4] I. Lombardo,[6] P. Scholz,[1] and M. Wiescher[1]

PHYSICAL REVIEW LETTERS **129,** 102701 (2022)

Extending the Hoyle-State Paradigm to ^{12}C + ^{12}C Fusion

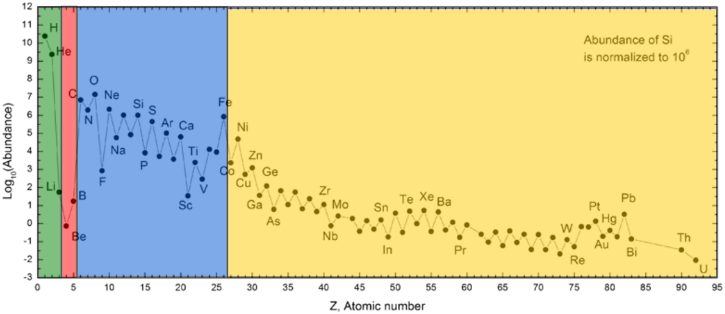
P. Adsley,[1,2,*,†] M. Heine,[3,4] D. G. Jenkins,[5,6,7] S. Courtin,[3,4,6] R. Neveling,[2] J. W. Brümmer,[8] L. M. Donaldson,[2]

PHYSICAL REVIEW C **110**, 035809 (2024)

^{16}O(e, $e'\alpha$) ^{12}C measurements and the ^{12}C(α, γ) ^{16}O astrophysical reaction rate

D. H. Potterveld,[1,*] B. W. Filippone,[2,†] R. J. Holt,[2,‡] and I. Friščić[3,§]

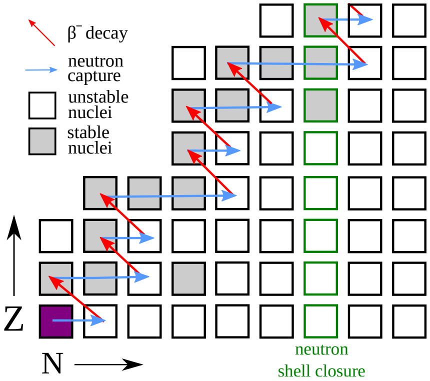
Solar system elemental abundances



- Nuclei heavier than ^{56}Fe (except *p* nuclei): neutron capture processes.

The *s* process

s(low neutron capture) process: $\tau_n \gg \tau_{\beta-}$; $\tau \sim 10 - 1000\,\mathrm{y}$; $n_n \sim 10^8\,\mathrm{cm}^{-3}$



- The path to heavier nuclei stays close to stability.
- Astrophysical site: He-burning in low and intermediate mass stars.

The s process

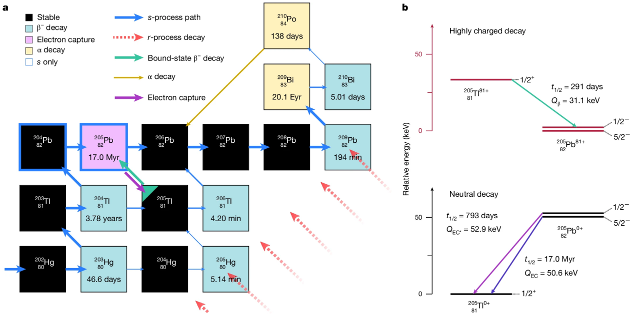
Generally, nuclear uncertainties are subdominant compared to than astrophysical uncertainties.

- Neutron source?
  - $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(\alpha,n)^{16}O$
  - $^{22}Ne(\alpha,n)^{25}Mg$
- At branching points
  - Neutron capture cross sections?
  - Astrophysical β decay rates?

High T β decay and ^{205}Pb dating in SS

- ^{205}Pb is the heaviest short-lived *s*-process (only) radionuclide.
- At *s*-process temperatures, ^{205}Pb EC competes with ^{205}Tl (bound) β^-.

G. Leckenby *et al.*, Nature **635**, 321-326 (2024)



- ^{205}Pb and ^{205}Tl astrophysical decay rates constrained by measuring β^- decay of ^{205}Tl^{81+}.
- ^{205}Pb as cosmochronometer of Sun formation.

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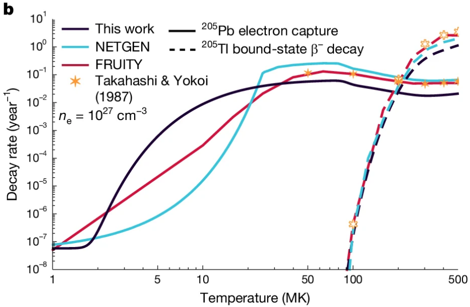
G. Leckenby *et al.*, Nature **635**, 321-326 (2024)



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The *r* process

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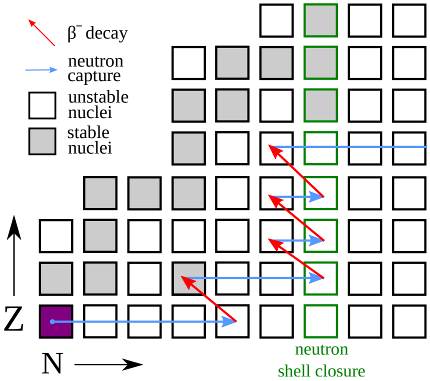

- The path to heavier nuclei goes through neutron-rich nuclei.
- Astrophysical site with high neutron fluxes → transient object.

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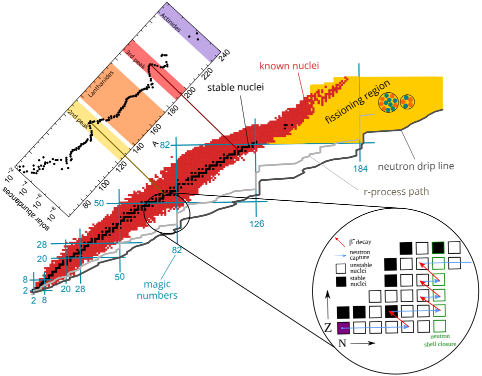

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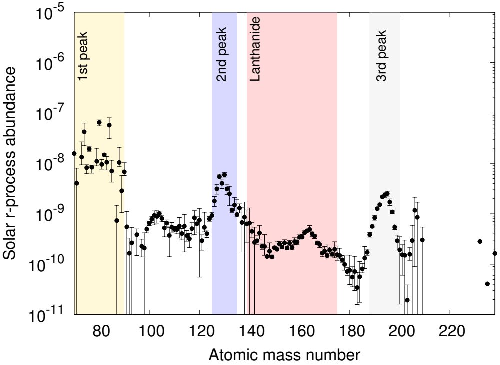
Modeling *r*-process abundances

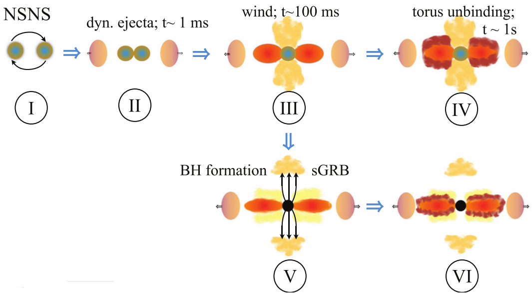


K. Hotokezaka *et al.*, Int. J. Mod. Phys. D 27, 1842005 (2018)

Astrophysical site	Nuclear physics
Sets thermodynamic conditions	Shapes abundances distribution

Neutron star mergers (NSM)

Rosswog *et al.*, Class. Quantum Grav. **34**, 104001 (2017)



Large variety of ejection channels in NSM, with different thermodynamic conditions.

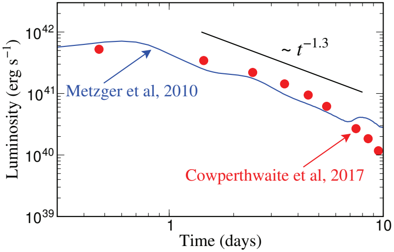
Kilonova

Li and Paczýnski (1998), Metzger+(2010), Roberts+(2011)...

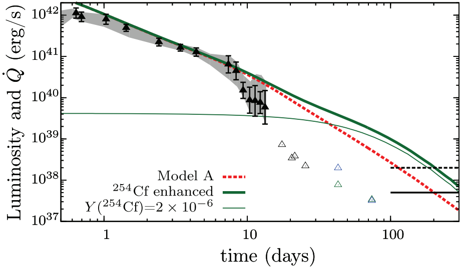
- Decay of r-process nuclei emits energy $\rightarrow$ electromagnetic transient (kilonova).
- Shape and magnitude depend on the properties forming the ejecta.
- At late times few nuclei dominate the heating: are there detectable fingerprints?

D. Watson *et al.*, Nature 574 (2019).

J. J. Cowan *et al.*, RMP 93, 015002 (2021)



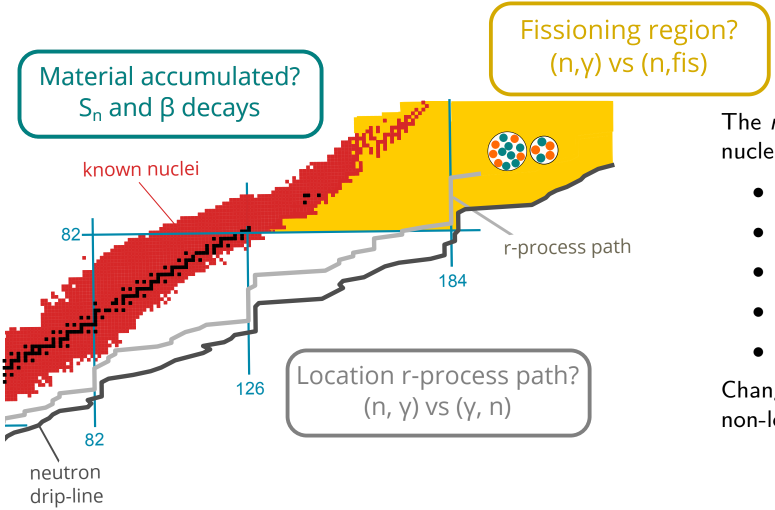
M.-R. Wu *et al.*, Phys. Rev. Lett. **122**, 062701 (2019)



- The presence of fissioning nuclei and translead α emitters at $t \sim$ weeks impacts the lightcurve shape

Y. Zhu+ ApJL (2018); S. Wanajo ApJ (2018); M.-R. Wu+ PRL (2019).

Nuclear inputs



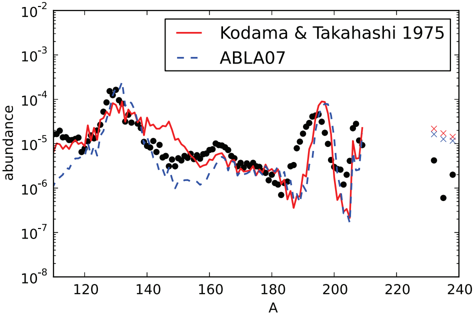
The *r*-process requires the knowledge of nuclear properties of neutron-rich nuclei:

- nuclear masses;
- β-decay rates;
- neutron capture rates;
- fission rates and yields;
- . . .

Changes in nuclear properties result in non-local effects.

Fission and *r* process

- Fission plays a crucial role during the *r*-process nucleosynthesis
  Thielemann+(1983), Panov+(2005), Martinez-Pinedo+(2007), Korobkin+(2012), Petermann+(2012), Eichler+(2015), Goriely(2015), Mumpower+(2018), Vassh+(2019), Giuliani+(2020), Wang+(2020), Vassh+(2020), Lemaître+(2021), Mumpower+(2022), Roederer+(2023)...

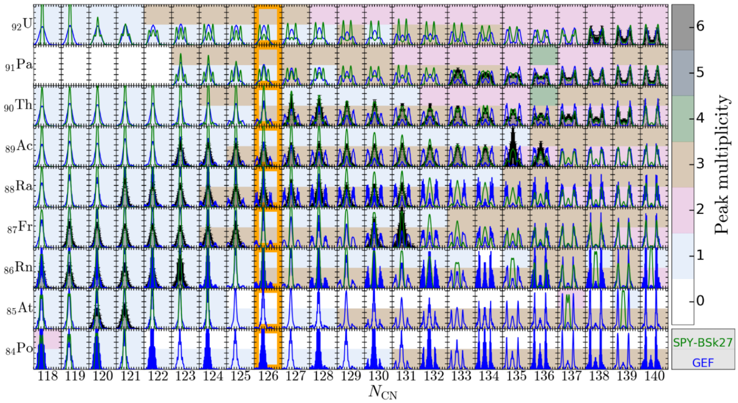


M. Eichler *et al.*, Astrophys. J. **808**, 30 (2015).

- Few fission data sets are available, mainly parametrizations/phenomenological → validity far from stability?

Fission and the *r*-process

J.-F.Lemaitre *et al.*, Phys. Rev. C 103, 025806 (2021)



- SPY: Fission yields obtained from scission-point model using BSk27 EDFs.
- Symmetric and asymmetric fission transition depends on deformed shell structure.
- Largest impact for neutron-rich ejecta .

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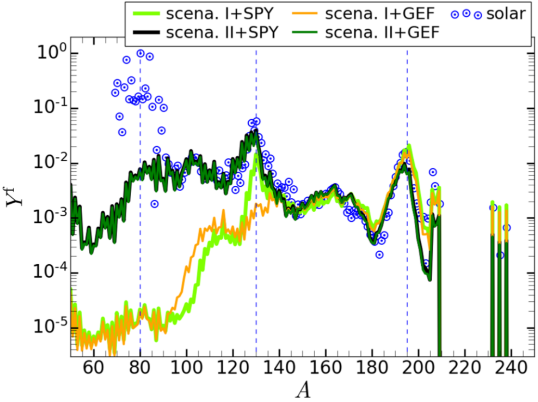

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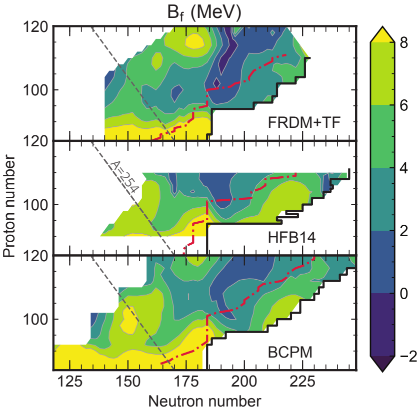

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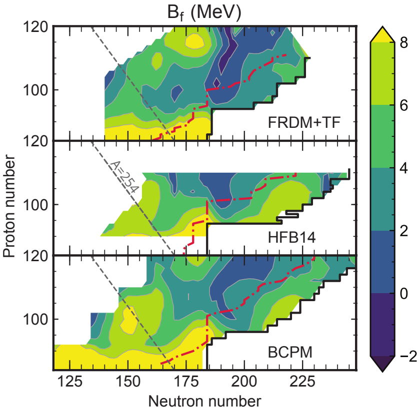

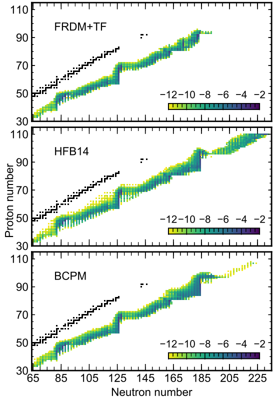

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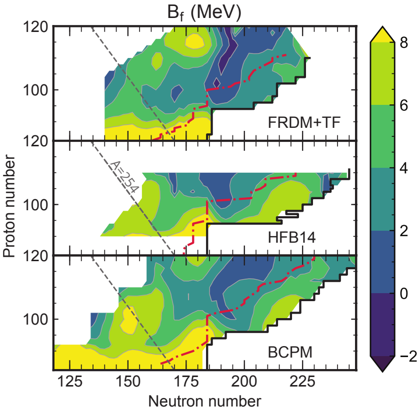
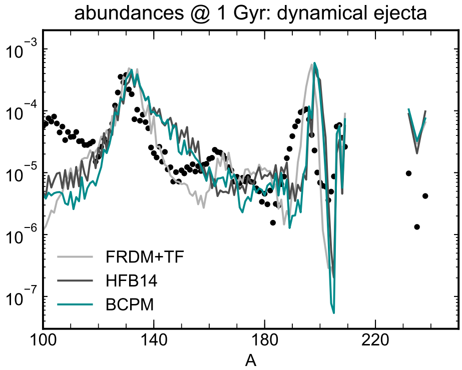
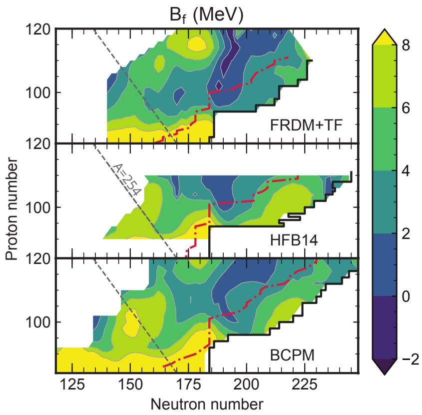
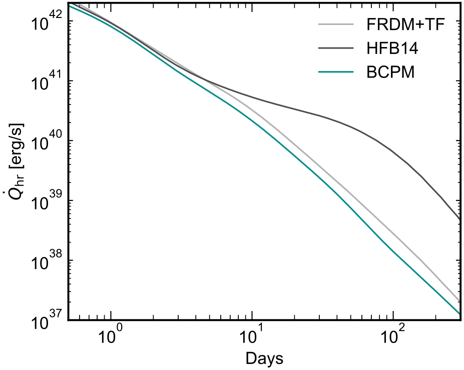




Fission and the r-process

SAG *et al.*, Phys. Rev. C 102, 045804 (2020)





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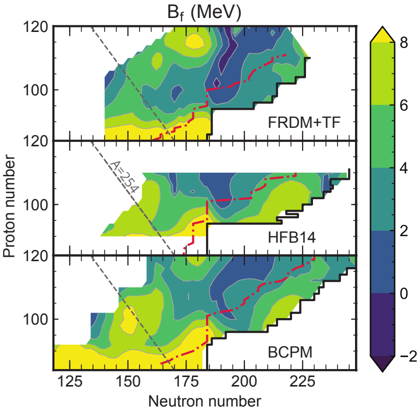
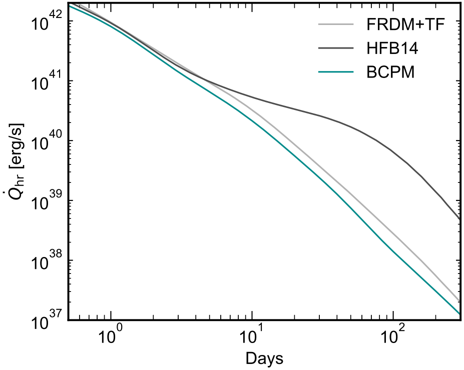


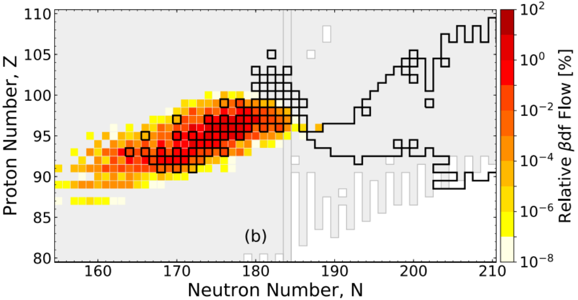


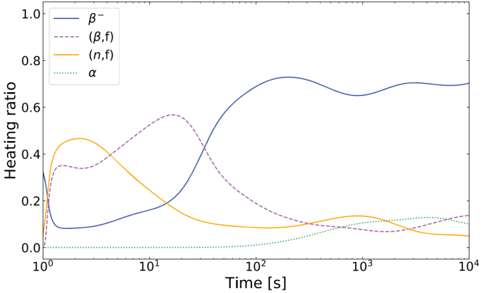
Kilonova sensitive to nuclear properties at $N = 184$

see also N. Vassh *et al.*, J. Phys. G **46**, 065202 (2019)

β-delayed fission and the r process

M. R. Mumpower *et al.*, Astrophys. J. **869**, 14 (2018)

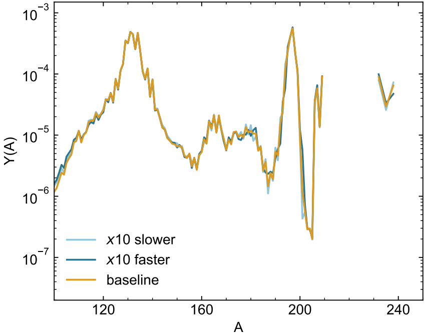


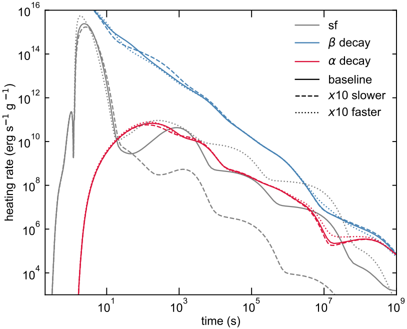


- β-delayed (and spontaneous) fission can dominate at late times.
- Extremely challenging: coupling between β strength, neutron emission and fission.

Impact of β decays and fission

- Impact of β-decay half-lives varies with the observable.
- We modified $t_{1/2}^{\beta}$ (FRDM) ≥ 3 s and study the impact on abundances and heating rates.





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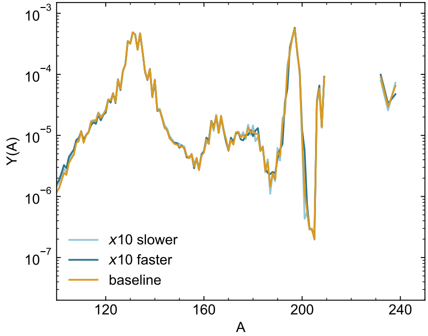
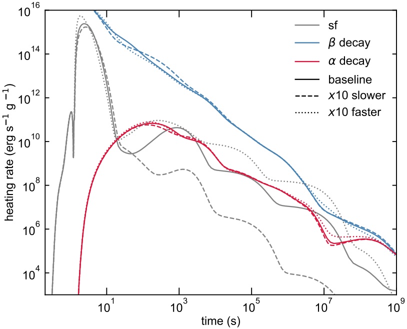
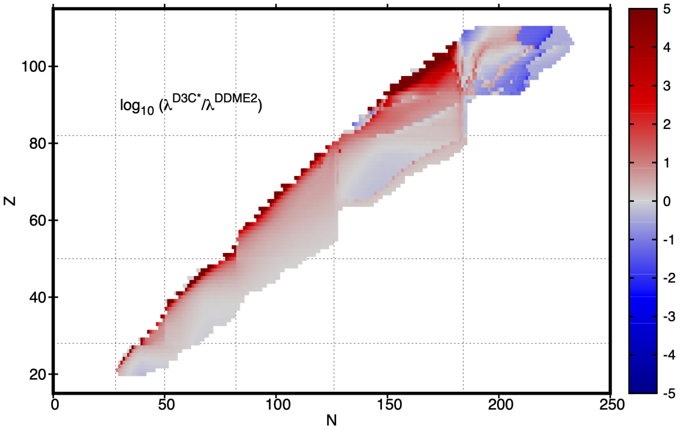




Fission heating rate sensitive to "slow" β-decay rates
($\tau_\beta \gtrsim$ few seconds)

Systematic of β-decay rates

credit: Caroline Robin (U. Bielefeld)



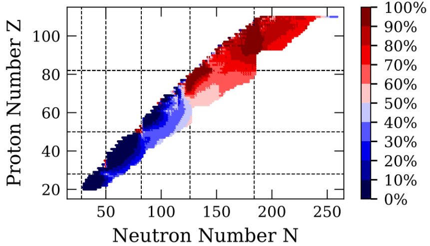
- β-decay rates closer to stability show larger uncertainties $\rightarrow$ more systematic studies are required (see also E. M. Ney *et al.*, Phys. Rev. C **102**, 034326 (2020)).

β decay and r process

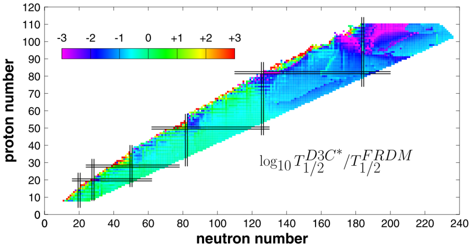
...Mumpower+(2016),Shafer+(2016),Marketin+(2016),Kajino+(2017),Lund+(2023),Kullmann+(2023)...

- Models: Interacting shell model (near neutron shell closure), FRDM+QRPA, HFB+QRPA (Diana's talk).
- Rates at $N = 50$ and 82 dominated by GT transitions, but forbidden transitions relevant for $N = 126$.

E. M. Ney *et al.*, PRC **102**, 034326 (2020).



T. Marketin *et al.*, PRC **93**, 025805 (2016)



- Global studies show large variations for medium heavy nuclei.
- Shorter half-lives for $Z > 80$ shift the third peak and increase the material available to fission.
- β-delayed neutron emission strongly impacts the abundances after freeze-out (Futoshi's talk).

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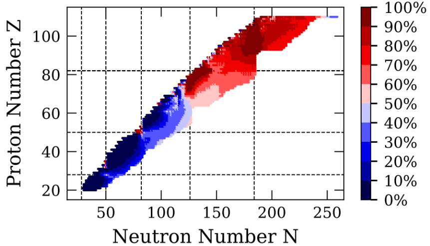

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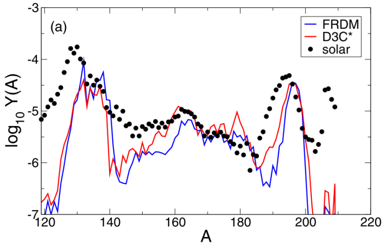

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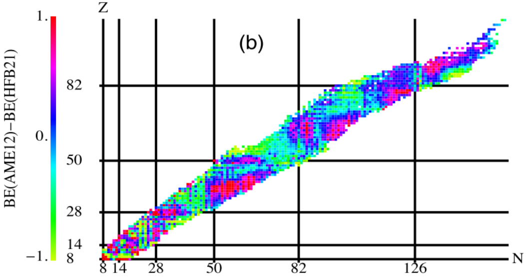
Nuclear masses

- Nuclear masses are an **essential ingredient**:
  i) energy budget of n captures, β decays and fission;
  ii) location of the r-process path;
  iii) accumulation of material.
- Global models with rms errors below 700 keV.

J. J. Cowan *et al.*, RMP 93, 015002 (2021)



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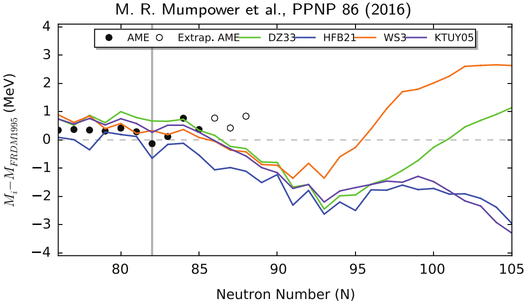

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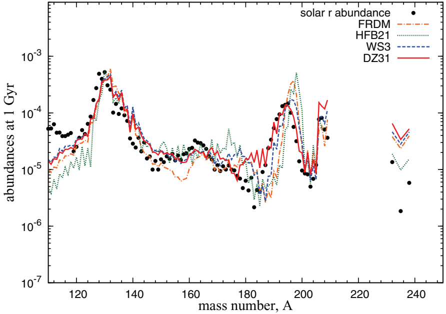
- Far from stability: **large spread** in the predicted nuclear masses.
- The predicted abundances and kilonova light curve suffer from **large uncertainties**.

J. J. Mendoza-Temis et al., PRC 92 (2015)



Impact of nuclear mass model uncertainties

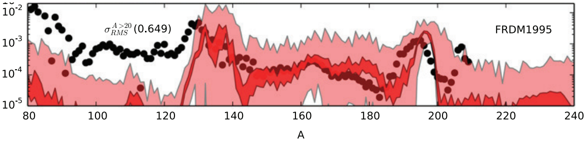
Monte Carlo variation on single nuclei

- Loose nuclear correlations ⇒ impact of masses can be overestimated. . .

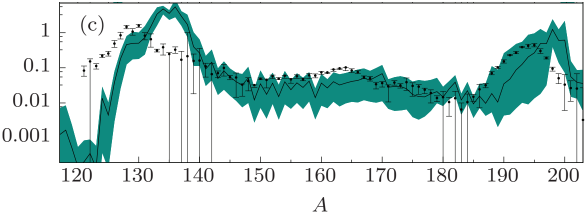
Propagation of nuclear models uncertainties

- Keep nuclear correlations ⇒ reduced impact of nuclear masses (good correlations?).

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



T. Sprouse *et al.*, Phys. Rev. C **101**, 055803 (2020)



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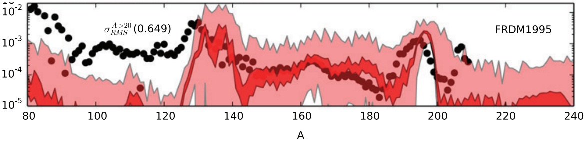

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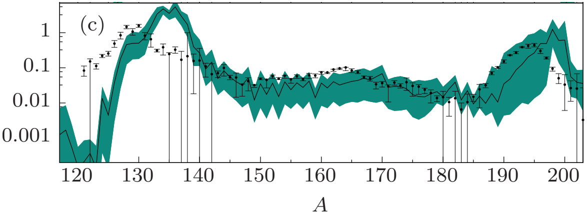
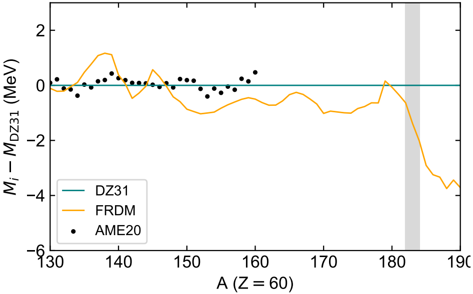


Which nuclear mass differences are relevant, and which differences are negligible?

Nuclear masses - Global and local changes

SAG+, arXiv:2412.03243

Masses = homogeneous part (global, LDM) + quantum shell-correction (local)



Starting from the DZ31 and FRDM models, we construct two new mass tables by mixing their bulk and the quantum shell parts:

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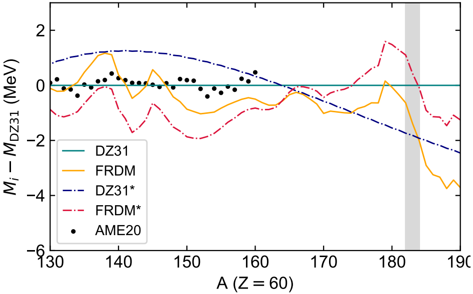

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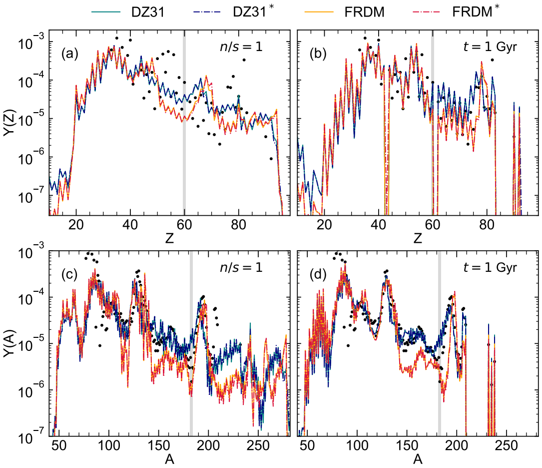
$$E(\text{DZ31*}) = E_{\text{bulk}}^{\text{FRDM}} + E_{\text{shell}}^{\text{DZ31}}$$

$$E(\text{FRDM*}) = E_{\text{bulk}}^{\text{DZ31}} + E_{\text{shell}}^{\text{FRDM}}$$

Nuclear masses - Global and local changes

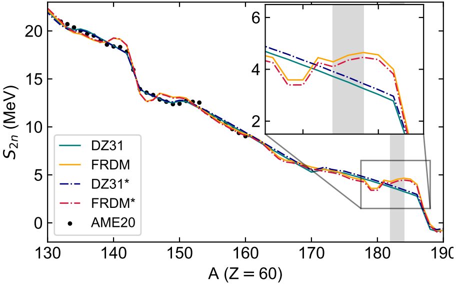
∼2000 NSM trajectories from Collins *et al.*, MNRAS 101093 (2023)

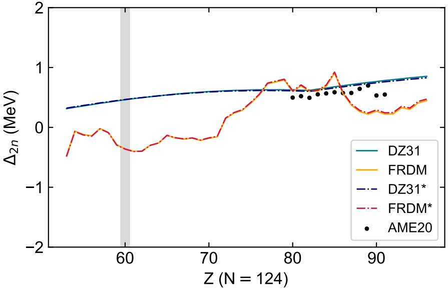


Abundances insensitive to global changes in masses (e.g., symmetry energy).

Nuclear masses - Global and local changes

SAG+, arXiv:2412.03243

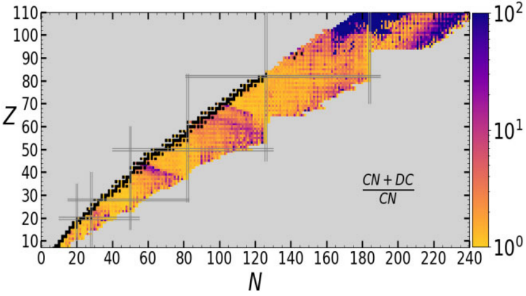


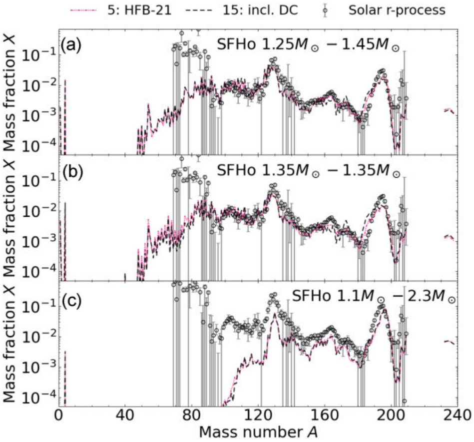


Abundance mostly related to local changes on S_{2n} (rather than bulk properties of masses) $\rightarrow$ $\Delta_{2n}(N, Z) = S_{2n}(N, Z) - S_{2n}(N + 2, Z)$.

Neutron capture rates

- If number of states available to compound nucleus (CN) is small, direct capture (DC) may dominate the neutron capture rate.



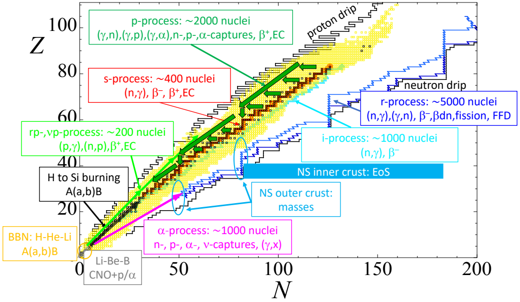


- Including DC affects the distribution around the third peak ($A \sim 160$) I. Kullman+, MNRAS **523**, 2551–2576 (2023).
- Results sensitive to masses, level densities, GRSF, optical model, . . .

Summary

- Stellar nucleosynthesis of chemical elements probes nuclear physics across the nuclear chart.

M. Arnould and S. Goriely, PPNP 112 103766 (2020)



- Nuclear uncertainties can reduce our capability to interpret astrophysical observations.
- Not all uncertainties may have an impact...
- Same problem tackled using different theoretical frameworks: complementary answers.

Collaborators

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Sinica Institute (Taiwan)

M.-R. Wu

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