Nuclear theory for the *r*-process: masses, fission and β decays

Samuel A. Giuliani

Universidad Autónoma de Madrid, Madrid, Spain

January 21st, 2025

Nucleosynthesis of Heavy Elements: r-process

January 20 – 24, 2025

Hirschegg, Austria

Universidad Autónoma de Madrid

Centro de Investigación Avanzada en Física Fundamental

Universidad Autónoma de Madrid Departamento de Física Teórica

MINISTERIO DE CIENCIA E INNOVACIÓN

Financiado por la Unión Europea NextGenerationEU

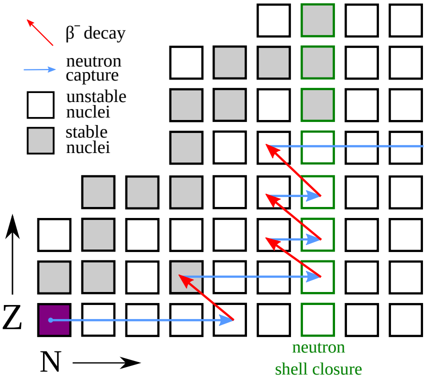
Plan de Recuperación, Transformación y Resiliencia

AGENCIA ESTATAL DE INVESTIGACIÓN

The r process

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

r(apid neutron capture) process: $\tau_{(n,\gamma)} \ll \tau_{\beta-}$; $\tau \sim 1\,\mathrm{s}$; $n_n \sim 10^{24-34}\,\mathrm{cm}^{-3}$

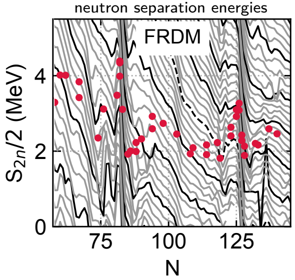


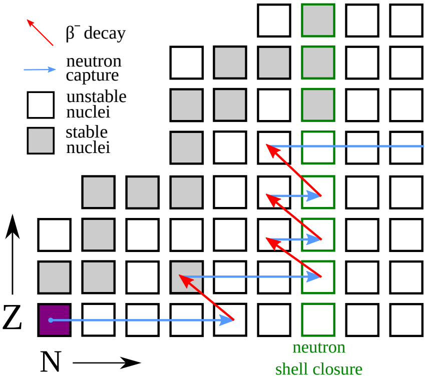
- The neutron-to-seed ratio determine how far the r-process can proceed.
- Astrophysical site with high neutron fluxes → transient object.

The r process

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

r(apid neutron capture) process: $\tau_{(n,\gamma)} \ll \tau_{\beta-}$; $\tau \sim 1\,\text{s}$; $n_n \sim 10^{24-34}\,\text{cm}^{-3}$



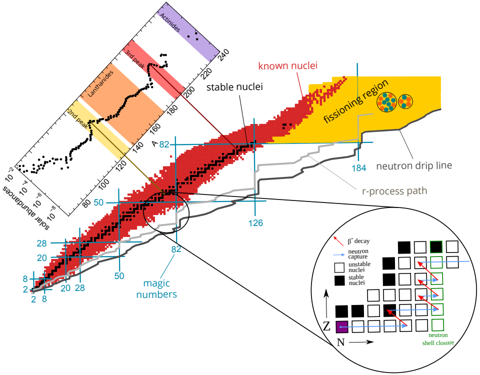


- The neutron-to-seed ratio determine how far the r-process can proceed.
- Astrophysical site with high neutron fluxes → transient object.

The r process

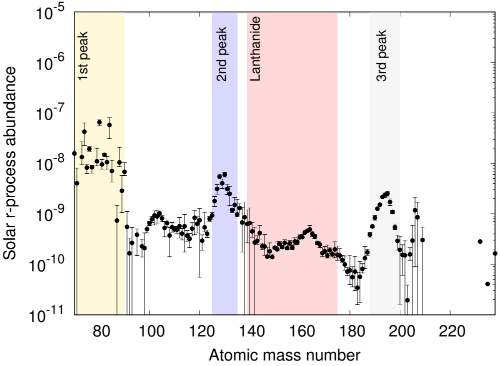
B[2]FH, Rev. Mod. Phys. 29, 547 (1957) ; A. Cameron, Report CRL-41 (1957)

r(apid neutron capture) process: $\tau_{(n,\gamma)} \ll \tau_{\beta-}$; $\tau \sim 1\,\mathrm{s}$; $n_n \sim 10^{24-34}\,\mathrm{cm}^{-3}$



- The neutron-to-seed ratio determine how far the r-process can proceed.
- Astrophysical site with high neutron fluxes → transient object.

Modeling *r*-process abundances



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

Astrophysical site

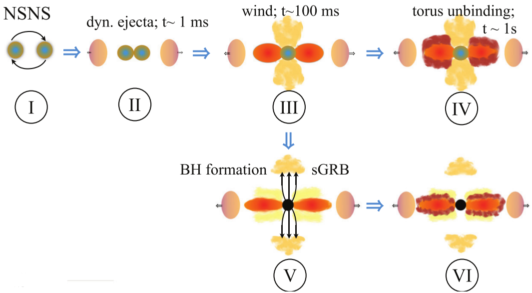
Sets thermodynamic conditions

Nuclear physics

Shapes abundances distribution

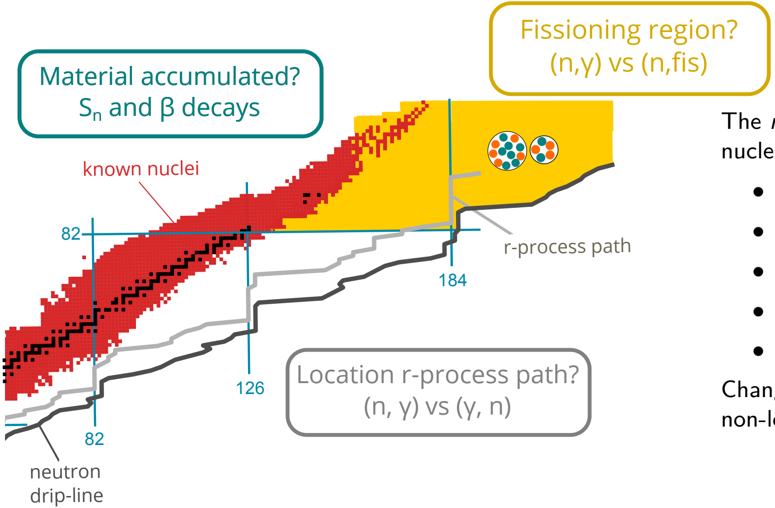
Neutron star mergers (NSM)

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



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

Nuclear inputs

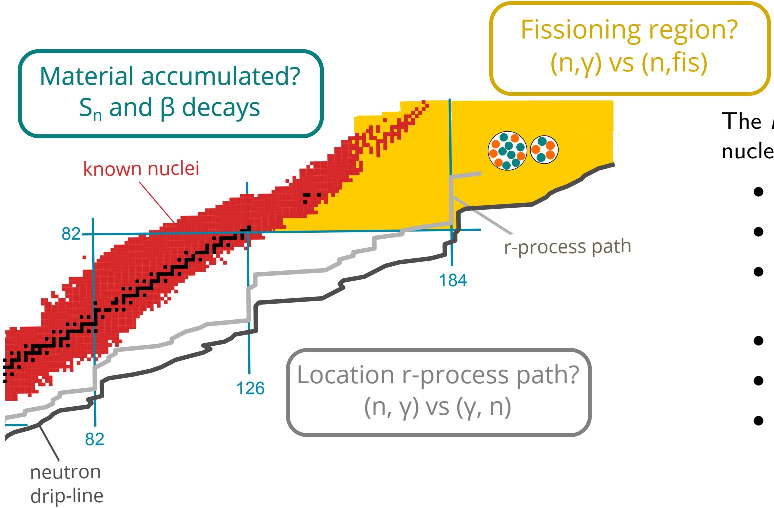


The *r*-process requires the knowledge of nuclear properties of neutron-rich nuclei:

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

Changes in nuclear properties result in non-local effects.

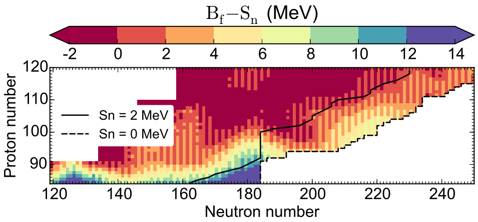
Nuclear inputs



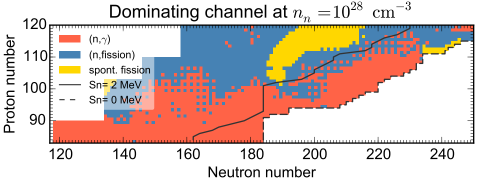
The *r*-process requires the knowledge of nuclear properties of neutron-rich nuclei:

- **nuclear masses** Kankanien talk
- **β-decay rates** Li and Kowacs talks
- neutron capture rates Muecher, Spyrous, and Domingo talks
- **fission rates** and yields Lenske talk
- β-delayed neutron emission Pallas talk
- α neutron capture rates Kiss talk.

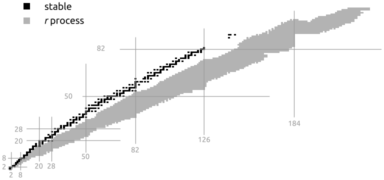
1) Compute relevant properties of *r*-process nuclei.



2) Calculate stellar reaction rates from Hauser-Feshbach theory.



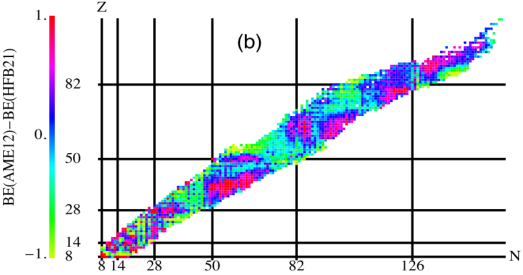
3) Obtain *r*-process abundances and light curve using nuclear network calculations.



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.

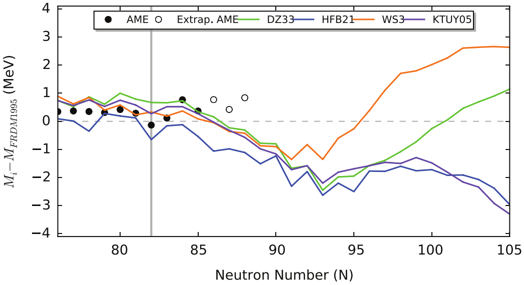
J. J. Mendoza-Temis, PhD Thesis (2014)



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.
- Far from stability: **large spread** in the predicted nuclear masses.

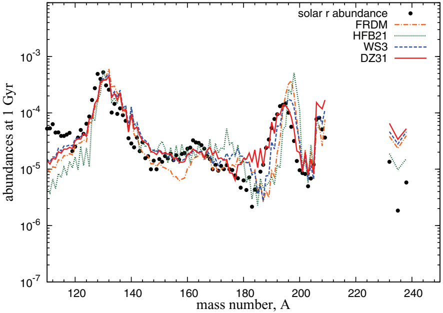
M. R. Mumpower et al., PPNP 86 (2016)



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

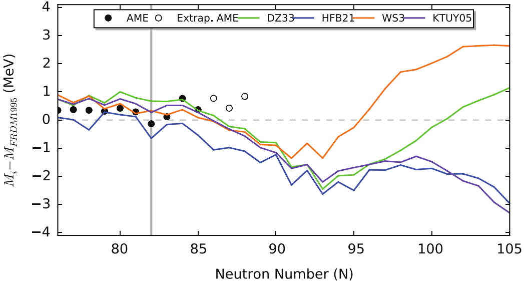
J. J. Mendoza-Temis et al., PRC 92 (2015)



Nuclear masses

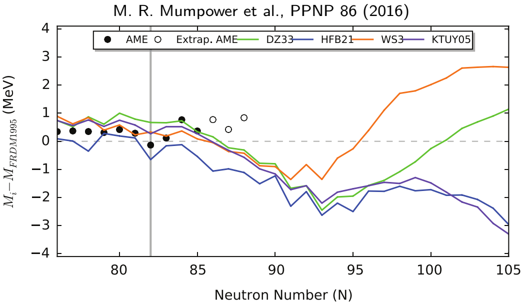
- Nuclear masses are an **essential ingredient**:
  i) energy budget of *n* captures, β decays and fission;
  ii) location of the *r*-process path;
  iii) accumulation of material.
- Global models with rms errors below 700 keV.
- Far from stability: **large spread** in the predicted nuclear masses.
- The predicted abundances and kilonova light curve suffer from **large uncertainties**.

M. R. Mumpower et al., PPNP 86 (2016)



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

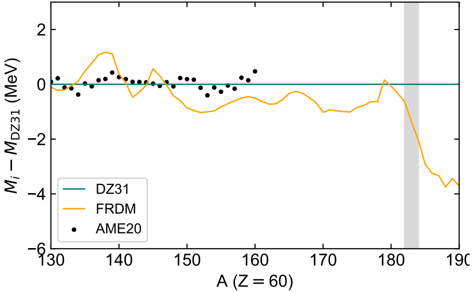


Which nuclear mass differences are relevant, and which differences are negligible?

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:

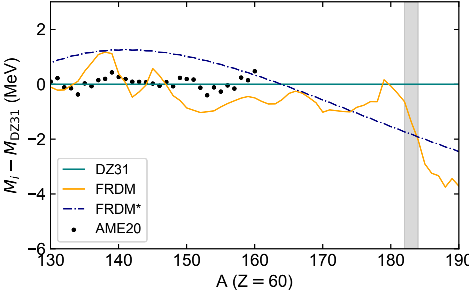
$$E(\mathrm{FRDM}^*) = E_{\mathrm{bulk}}^{\mathrm{FRDM}} + E_{\mathrm{shell}}^{\mathrm{DZ31}}$$

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

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:

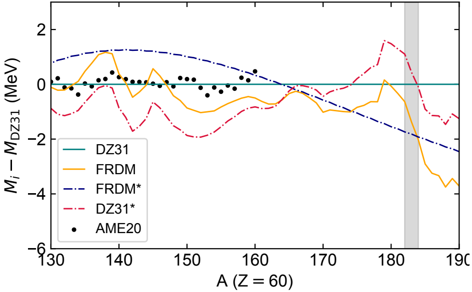
$$E(\mathrm{FRDM}^*) = E_{\mathrm{bulk}}^{\mathrm{FRDM}} + E_{\mathrm{shell}}^{\mathrm{DZ31}}$$

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

Nuclear masses - Global and local changes

SAG+ arXiv:2412.03243

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



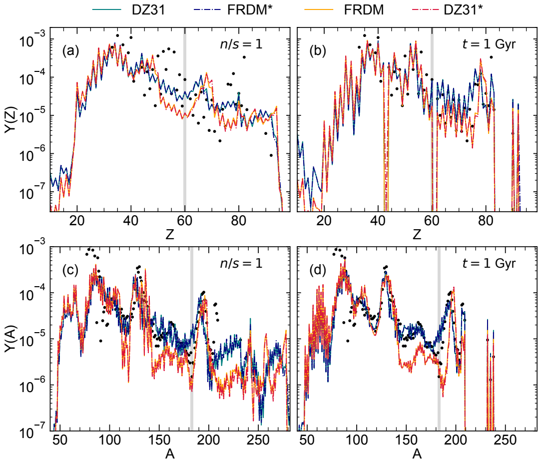
Starting from the DZ31 and FRDM models, we construct two new mass tables by mixing their bulk and the quantum shell parts:

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

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

Nuclear masses - Global and local changes

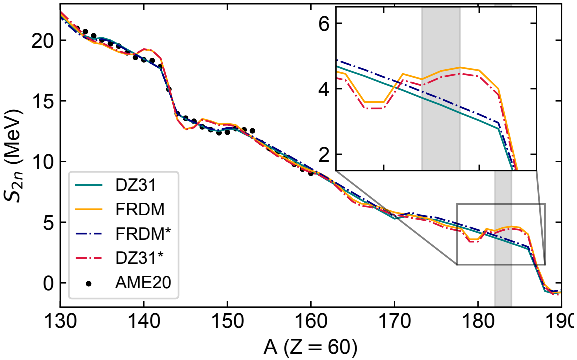
∼2000 NSM trajectories from Collins *et al.*, MNRAS 101093 (2023)



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

Nuclear masses - Global and local changes

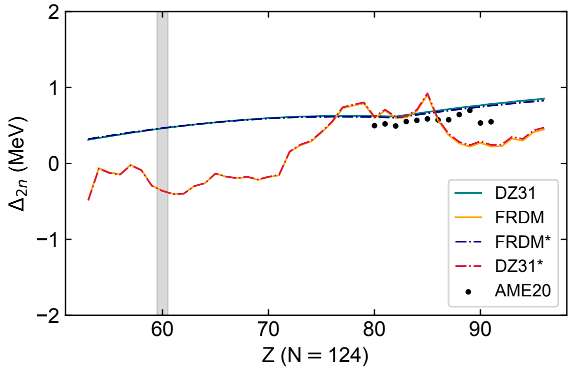
SAG+ arXiv:2412.03243



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

Nuclear masses - Global and local changes

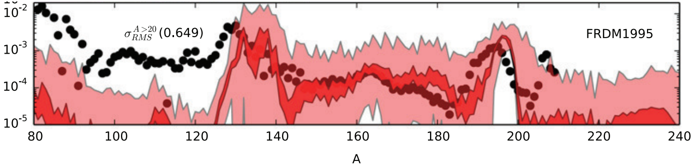
SAG+ arXiv:2412.03243



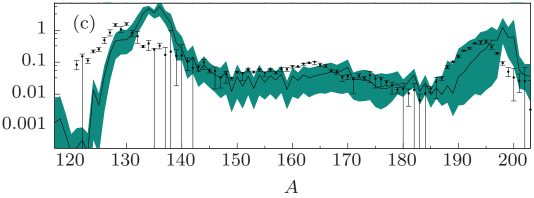
Abundance mostly related to local changes on S_{2n} (rather than bulk properties of masses) $\rightarrow$ $\Delta_{2n}(N,Z) = S_{2n}(N,Z) - S_{2n}(N+2,Z)$.

Sensitivity studies

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



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



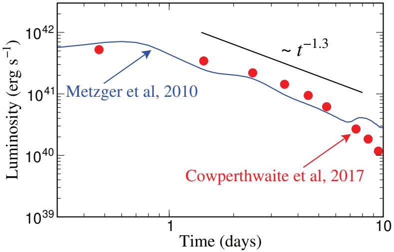
Kilonova

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

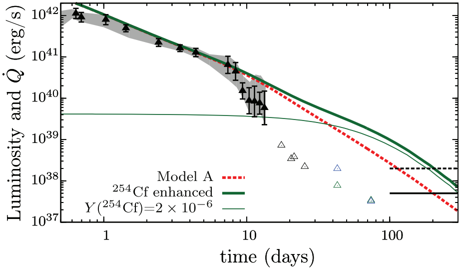
- Decay of *r*-process nuclei emits energy $\rightarrow$ electromagnetic transient (kilonova).
- Shape and magnitude depend on the properties forming the ejecta: detectable fingerprints?

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)



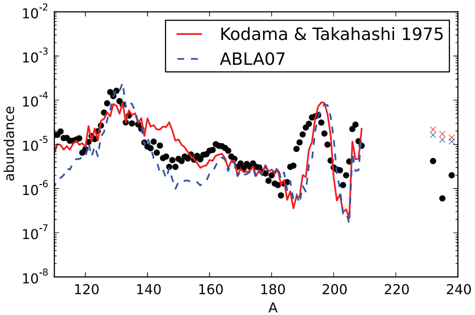
- The presence of fissioning nuclei and translead α emitters at $t \sim$ weeks impacts the lightcurve shape

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

Fission and *r* process

- Fission plays a crucial role during the *r*-process nucleosynthesis

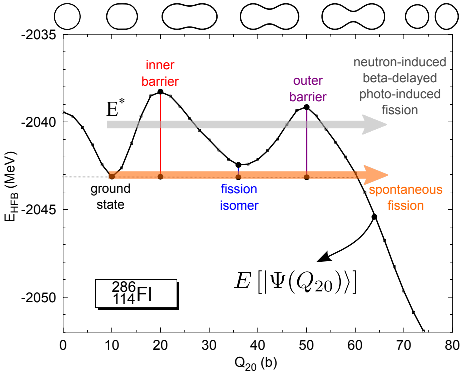
  Thielemann+(1983), Panov+(2005), Martinez-Pinedo+(2007), Korobkin+(2012), Petermann+(2012), Eichler+(2015), Goriely(2015), Mumpower+(2018), Vassh+(2019), Giuliani+(2020), Wang+(2020), Vassh+(2020), Lemaître+(2021), Mumpower+(2022), Roederer+(2023)...



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

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

The fission process



Potential Energy Surface $\mathcal{V}$

Energy evolution from the initial state to the scission point.

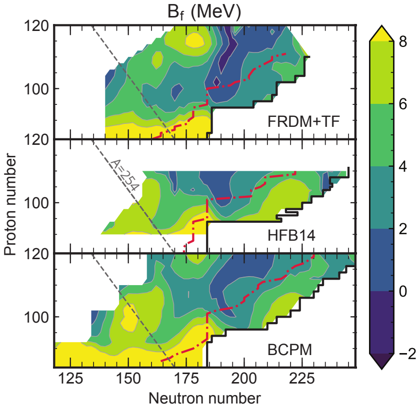
Collective inertias $\mathcal{M}$

Resistance of the nucleus against the deformation forces.

B_f: highest fission barrier height $\rightarrow$ stability against fission.

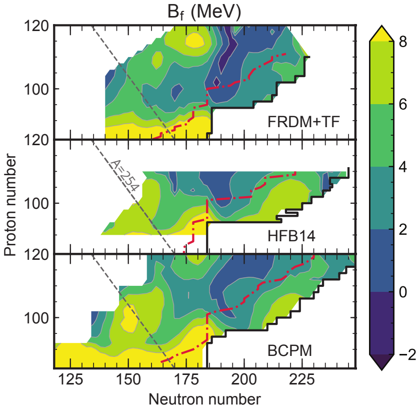
Impact of fission on the *r*-process

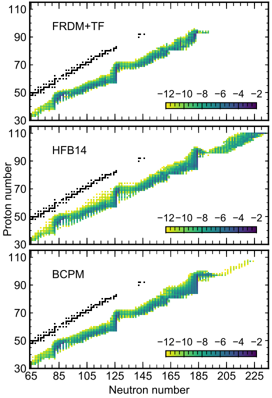
SAG *et al.*, Phys. Rev. C 102, 045804 (2020)



Impact of fission on the r-process

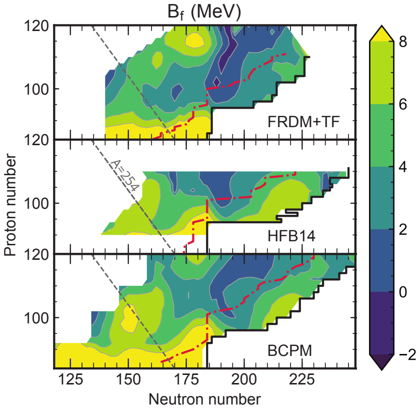
SAG *et al.*, Phys. Rev. C 102, 045804 (2020)

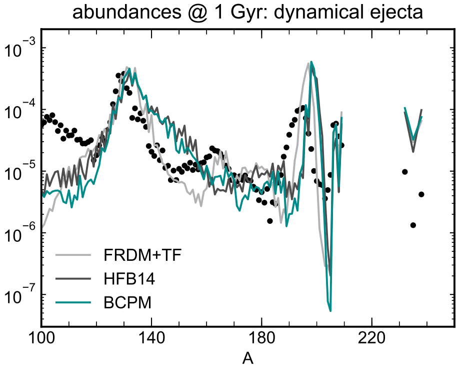




Impact of fission on the *r*-process

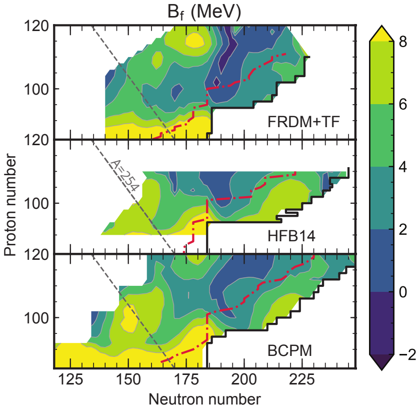
SAG *et al.*, Phys. Rev. C 102, 045804 (2020)

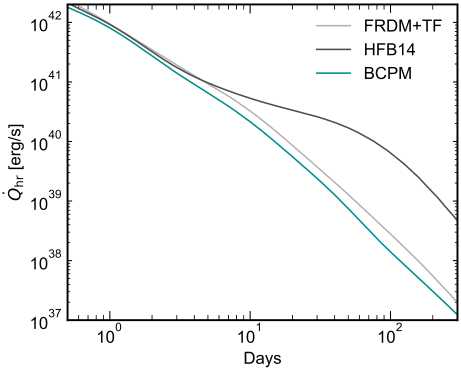




Impact of fission on the *r*-process

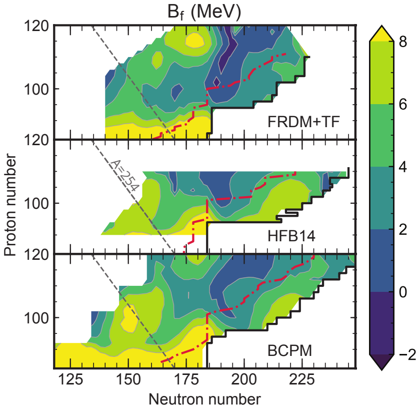
SAG *et al.*, Phys. Rev. C 102, 045804 (2020)

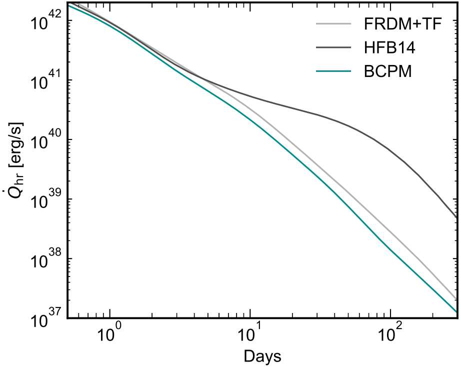




Impact of fission on the *r*-process

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



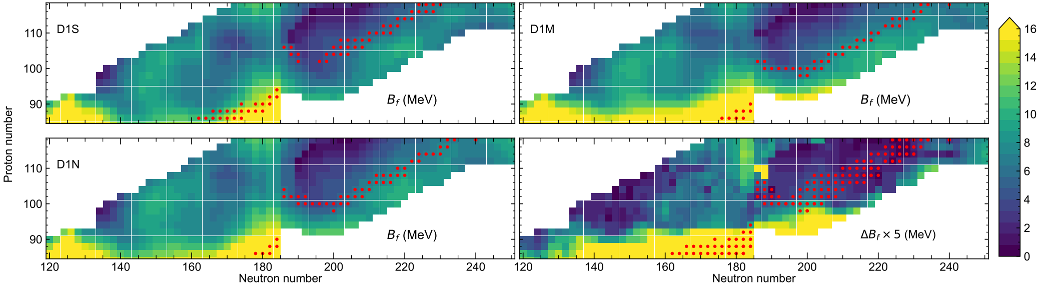


Kilonova sensitive to nuclear properties at $N = 184$

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

Systematic of fission barriers B_f

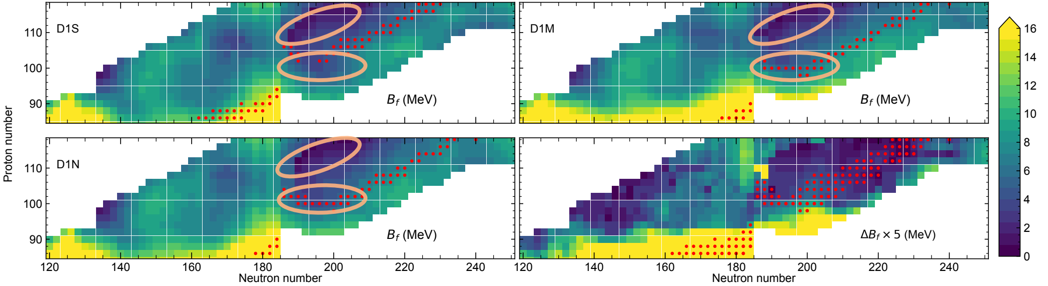
Three different parametrizations (D1S, D1N, and D1M) of the same nuclear interaction (Gogny EDF).



- B_f deviations tend to decrease with Z:
  - $Z \leq 94$: deviations up to 10 MeV (but very high B_f).
  - $Z > 94$: systematic deviations $\sim$ 1–2 MeV.
- After $N = 184$ r-process path pushed into a region of **low** $B_f - S_n$.
- Path towards stability interrupted by region of **low** $B_f - Q_\beta$.

Systematic of fission barriers B_f

Three different parametrizations (D1S, D1N, and D1M) of the same nuclear interaction (Gogny EDF).

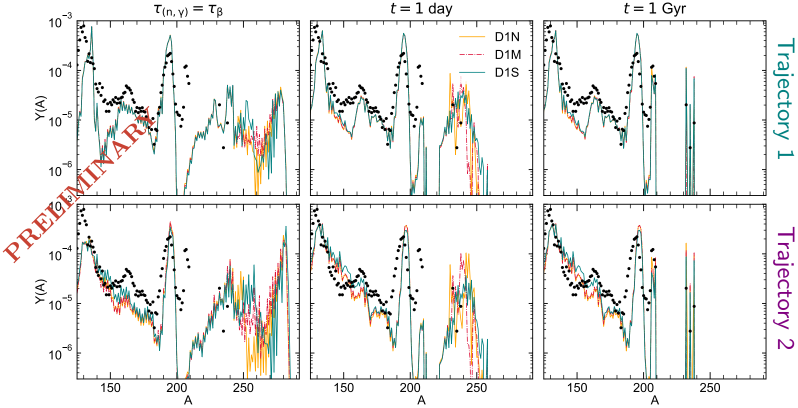


- B_f deviations tend to decrease with Z:
  - $Z \leq 94$: deviations up to 10 MeV (but very high B_f).
  - $Z > 94$: systematic deviations $\sim$ 1–2 MeV.
- After $N = 184$ r-process path pushed into a region of **low** $B_f - S_n$.
- Path towards stability interrupted by region of **low** $B_f - Q_\beta$.

Impact of fission on the r-process: abundances Y

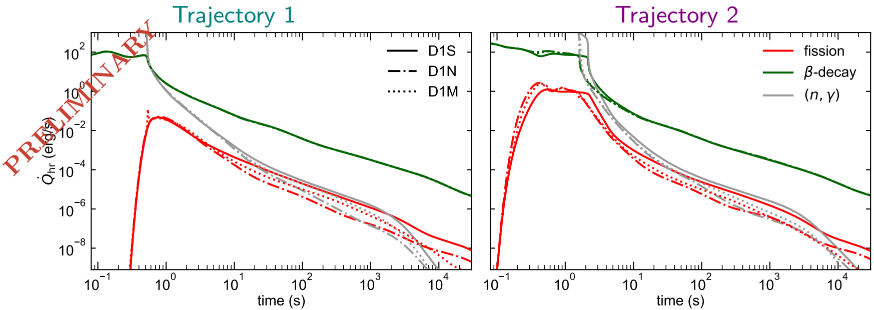
Dynamical ejecta from neutron star merger (C. E. Collins *et al.*, MNRAS 101093 (2023)):

- Trajectory 1: $Y_e = 0.151$; $n/s = 105$;
- Trajectory 2: $Y_e = 0.027$; $n/s = 1100$.



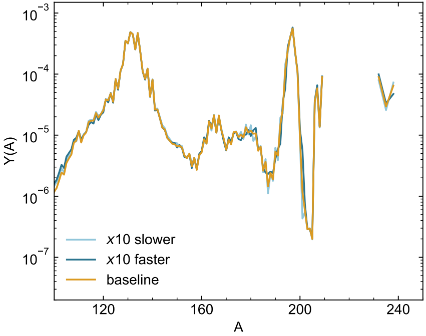
Impact of fission on the *r*-process: heating rates

- Trajectory 1: $Y_e = 0.151$; $n/s = 105$
- Trajectory 2: $Y_e \lesssim 0.027$; $n/s \approx 1100$



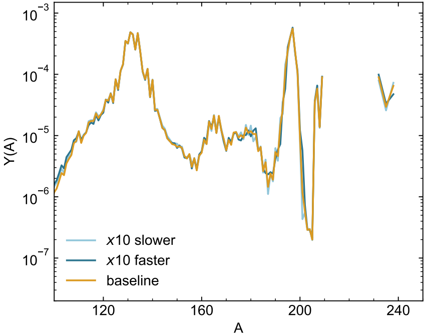
Impact of β-decay rates on fission

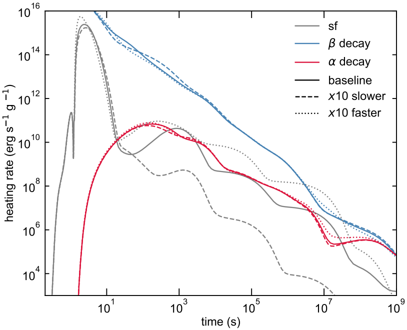
- Impact of β-decay half-lives varies with the observable.
- We modified $t_{1/2}^{\beta}$ (FRDM) ≥ 3 s and study the impact on abundances and heating rates.



Impact of β-decay rates on fission

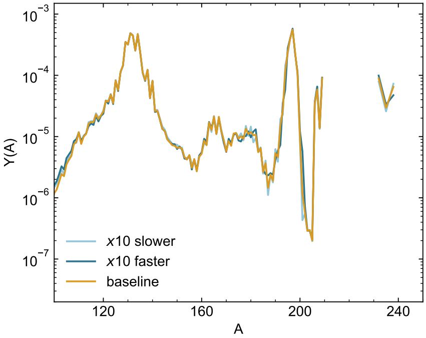
- Impact of β-decay half-lives varies with the observable.
- We modified $t_{1/2}^{\beta}$ (FRDM) ≥ 3 s and study the impact on abundances and heating rates.

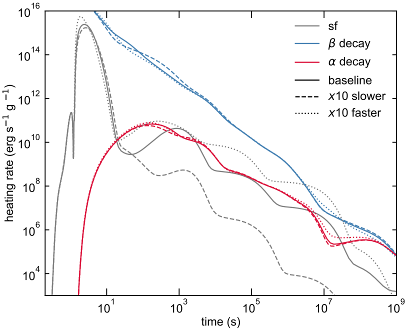




Impact of β-decay rates on fission

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

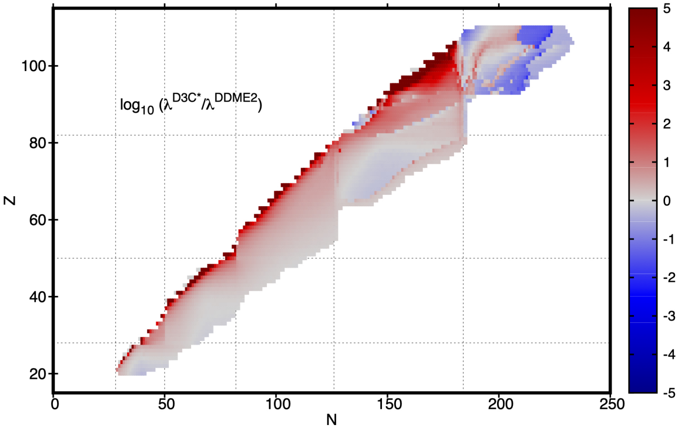




Fission heating rate sensitive to "slow" β-decay rates
($\tau_\beta \gtrsim$ few seconds)

Systematic of β-decay rates

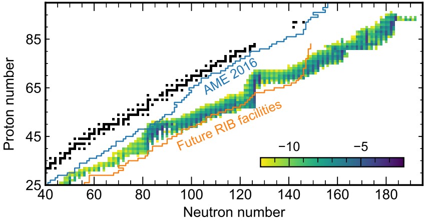
credit: Caroline Robin (U. Bielefeld)



- 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)).

Conclusions & Outlook

- GW170817 pushed *r*-process studies into an exciting era.
- Reliable estimations of nuclear properties are crucial for proper nucleosynthesis calculations and kilonova modeling.
- *r*-process abundances mostly determined by shell effects producing local changes in S_n.
- *r* process sensitive to fission rates properties at $N = 184 \rightarrow$ more (better...) input data is required.
- "slow" β decays can shape kilonova light curve if competing with fission.



Collaborators

UAM (Madrid)

L. M. Robledo

GSI (Darmstadt)

A. Bauswein
G. Martínez Pinedo
V. Vijayan

Sinica Institute (Taiwan)

M.-R. Wu

Universität Bielefeld

C. Robin

Funding