Large scale fission calculations for stellar nucleosynthesis

Samuel A. Giuliani

Instituto de Estructura de la Materia – CSIC, Madrid, Spain
Universidad Autónoma de Madrid and CIAFF, Madrid, Spain

May 14, 2026

International Workshop on Fission Dynamics
May 11-15, 2026
Chongqing, China

MINISTERIO
DE CIENCIA, INNOVACIÓN
Y UNIVERSIDADES

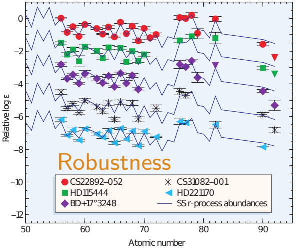
CSIC

IEM

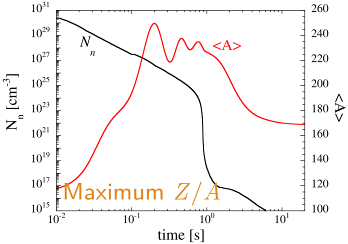
MaX
MARCO DE
AUTOEVALUACIÓN DE LA
EXCELENCIA

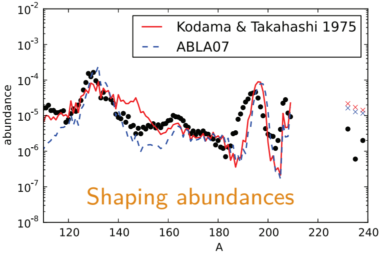
Fission and the r-process

Cowan and Sneden, Nature 440 1151 (2006)

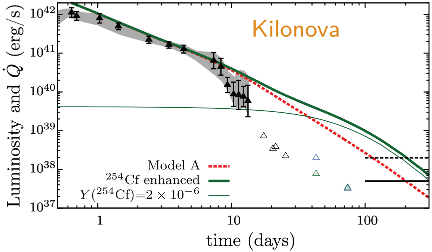


S. Goriely, EPJA 51, 22 (2015)





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

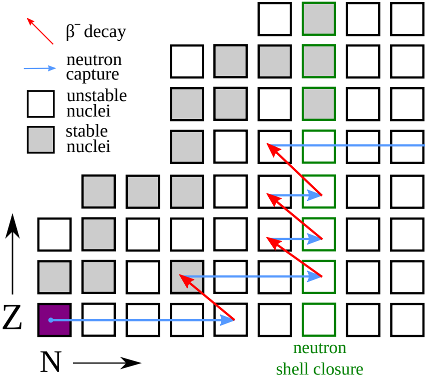


M.-R. Wu *et al.*, Phys. Rev. Lett. **122**, 062701 (2019).

The r process

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

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

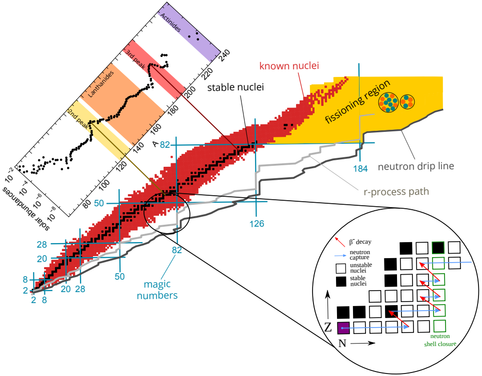


- The neutron-to-seed ratio determine how far the r-process can proceed.

The r process

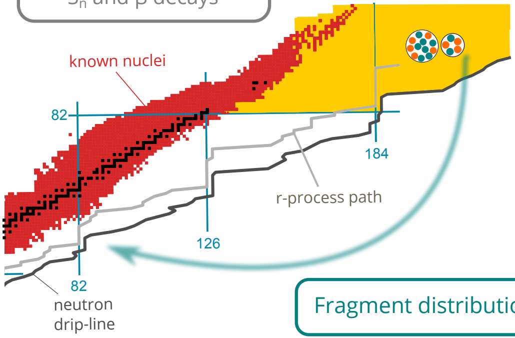
B^{2}FH, Rev. Mod. Phys. 29, 547 (1957) ; A. Cameron, Report CRL-41 (1957)

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.

Nuclear inputs for the r-process



Material accumulated?
S_n and β decays

Fissioning region?
(n,γ) vs (n,fis)

Fragment distributions?

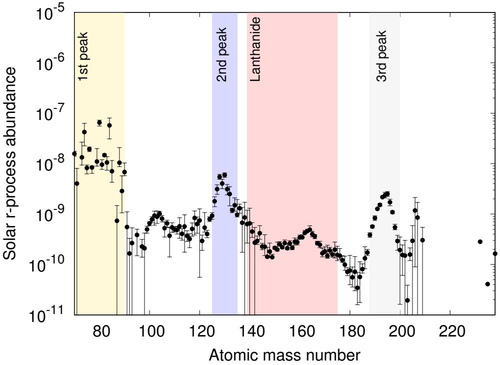
Assessing the impact of fission on the r-process requires the global calculations of

- fission rates, fragments distributions, neutron multiplicities for all the fission channels (n-induced, β-delayed, spontaneous, . . .)
- nuclear masses,
- β-decay rates,
- neutron-capture rates,
- . . .

of heavy neutron-rich nuclei.

In this talk: r-process sensitivity to fission properties from different parametrizations of the same energy density functional (EDF).

Modeling r-process abundances



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

Astrophysical site

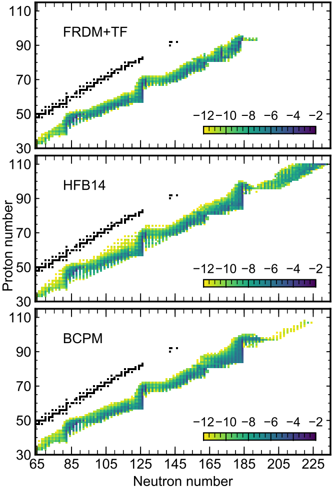
Sets thermodynamic conditions

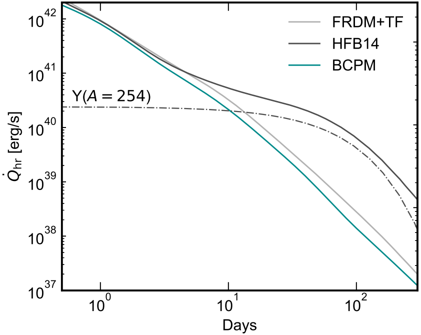
Nuclear physics

Shapes abundances distribution

Nuclear inputs and non-local effects

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



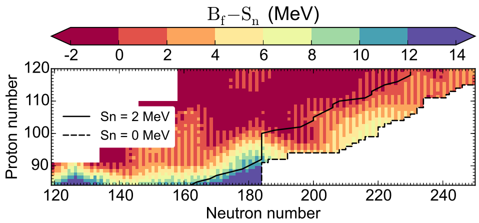


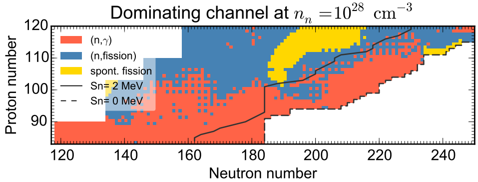
Kilonova sensitive to nuclear properties at $N = 184$

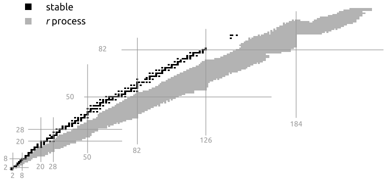
1) Compute relevant properties of r-process nuclei.

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

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







The Hartree-Fock-Bogolyubov (HFB) formalism

The ground-state wavefunction is obtained by minimizing the total energy:

$$\delta E[|\Psi\rangle] = 0\,,$$

where $|\Psi\rangle$ is a quasiparticle (β) vacuum:

$$|\Psi\rangle = \prod_{\mu} \beta_{\mu}|0\rangle \quad \Rightarrow \quad \beta_{\mu}|\Psi\rangle = 0\,.$$

The energy landscape is constructed by constraining the quadrupole deformation of the nucleus $\langle\Psi(q)|\hat{Q}_{20}|\Psi(q)\rangle = Q_{20}$.

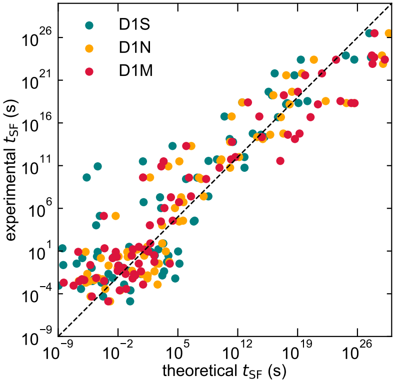
$$\mathcal{V}(Q_{20}) = E_{\mathrm{HFB}}(Q_{20}) - \varepsilon_{\mathrm{rot}}(Q_{20}) - \varepsilon_{\mathrm{vib}}(Q_{20})$$

The energy density functionals (EDF) provide a phenomenological ansatz of the effective nucleon-nucleon interaction:

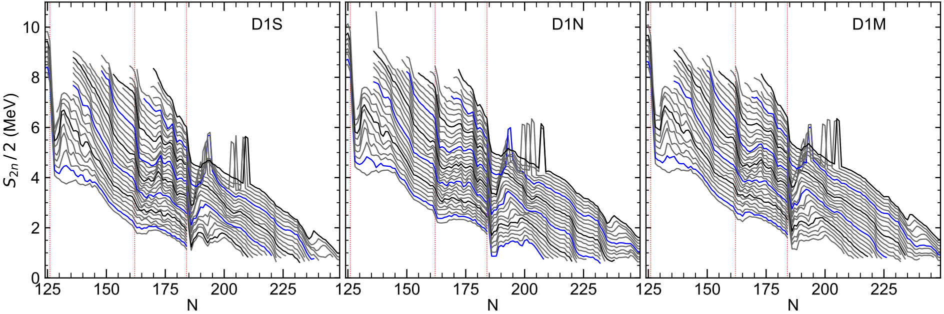
- D1S, D1N and D1M Gogny EDF;
- Skyrme, Barcelona-Catania-Paris-Madrid (BCPM), RMF. . .

Spontaneous fission half-lives: theory vs experiment

- $t^{\mathrm{sf}}_{1/2} \propto (1+\exp(2S(L)))$ with $S(L)=\int dQ_{20}\sqrt{2\mathcal{M}[\mathcal{V}(Q_{20})-E_0]}$.
- $t^{\mathrm{sf}}_{1/2}$ are systematically overpredicted (pairing as dof, collective inertias, triaxiality...) → collective inertias/fission barriers are renormalized in order to reproduce experimental $t^{\mathrm{sf}}_{1/2}$.

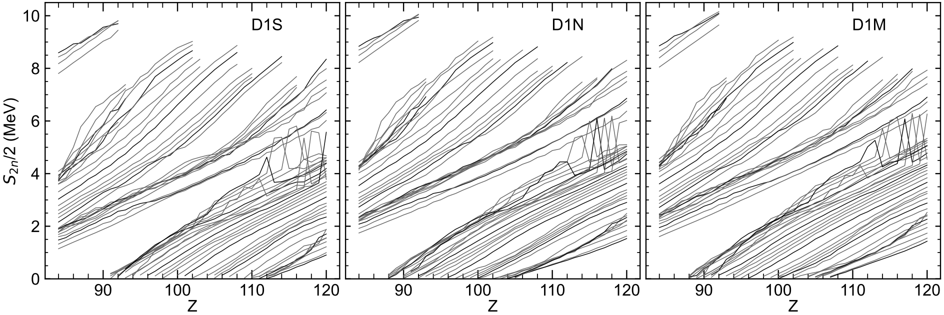


Neutron separation energies



- Neutron separation energies determine the probability of capturing a neutron.
- Trends in S_n (neutron-shell gaps) shape r-process abundance distribution SAG+, PRC (2026).

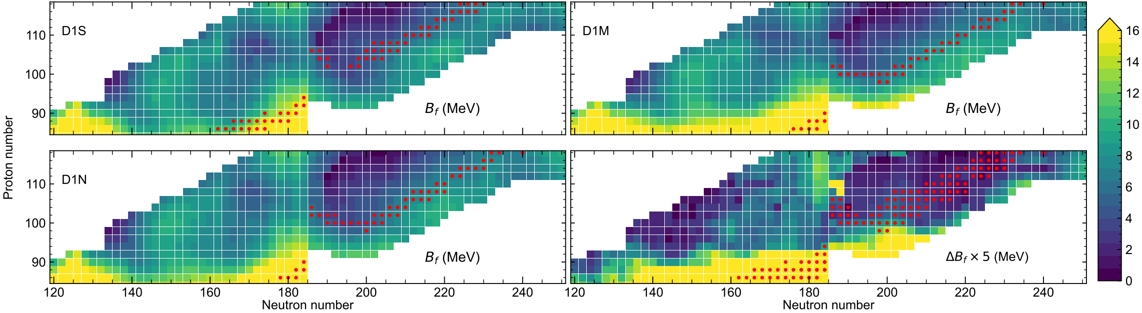
Neutron shell gaps



- Neutron separation energies determine the probability of capturing a neutron.
- Trends in S_n (neutron-shell gaps) shape r-process abundance distribution SAG+, PRC (2026).

Systematic of fission barriers B_f

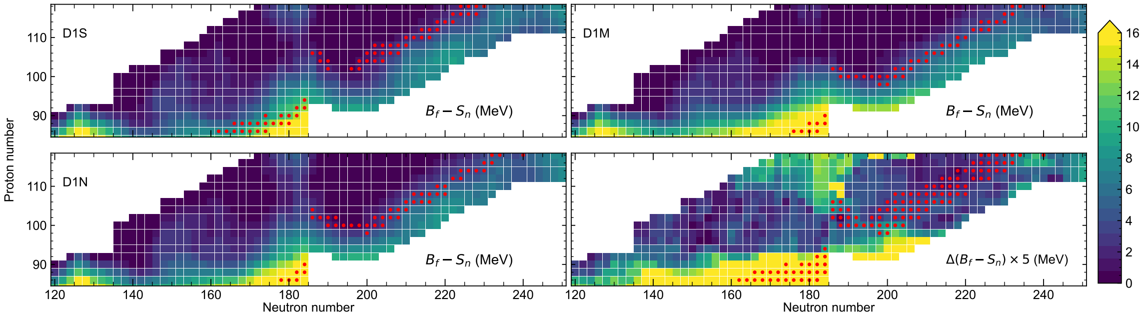
- Nuclei with $S_n \sim 2$ MeV (●): approximate r-process path.



- B_f trends qualitatively similar across different Gogny interactions:
  - $Z > 94$: systematic deviations $\sim$ 1–2 MeV $\rightarrow m^*/m \sim 0.7 - 0.75$.
  - $Z \leq 94$: deviations up to 10 MeV (but very high B_f).
- Location of the r process differ above $N = 184$.

Systematic of $B_f - S_n$

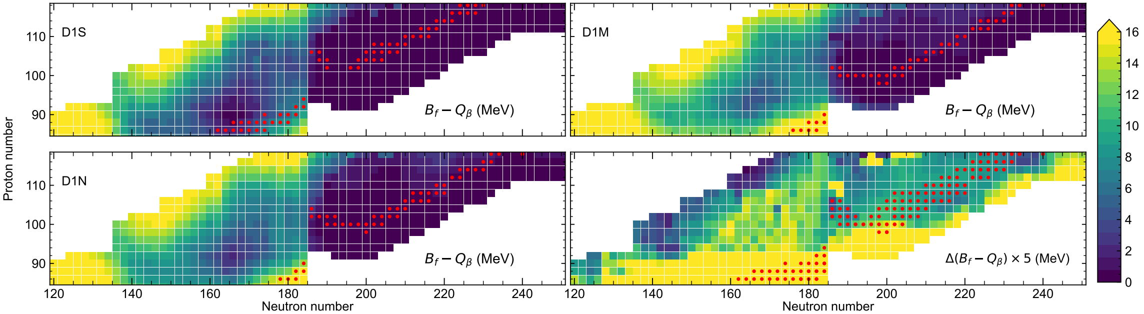
- For $B_f - S_n \lesssim 2\,\text{MeV}$ (n, fis) dominates over (n, γ).



- Production of (super)heavy nuclei requires the overcoming of neutron shell closure at $N = 184$.
- r-process path pushed into a region of low $B_f - S_n$.

Systematic of $B_f - Q_\beta$

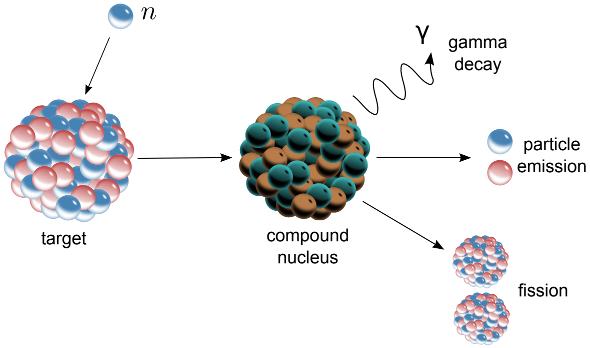
- $B_f - Q_\beta \rightarrow$ competition between fission and β-decay.



- Path towards stability interrupted by region of low fission barriers.

Hauser-Feshbach formalism

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



Based on the Bohr independence hypothesis: the decay of the compound nucleus is independent from its formation dynamics.

Nuclear reaction network

Abundances evolution modeled through a set of differential equations (reaction network equations):

$$\frac{dY_i}{dt} = \sum_j P_j^i \lambda_j Y_j + \sum_{jk} P_{jk}^i \frac{\rho}{m_u} \langle \sigma v \rangle_{jk} Y_j Y_k + \sum_{jkl} P_{jkl}^i \left(\frac{\rho}{m_u} \right)^2 \langle \sigma v \rangle_{jkl} Y_j Y_k Y_l$$

P^i describe how often the nucleus i is created or destroyed, and whether two or more identical nuclei are involved in the reactions.

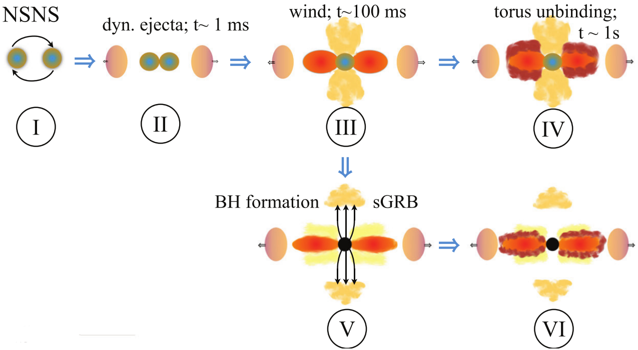
- Large nuclear reaction network up to $Z = 120$.
- Two sets of fission properties:
    - D1?-r: inertias/barriers renormalized
    - D1?-o: original Gogny values
- β-decay rates: FRDM2012 (P. Möller *et al.*, ADNDT 125, 1 (2019)).
- $n-$induced rates for $Z \leq 84$ based on FRDM 1995 (Mendoza *et al.* PRC92, 055805 (2015)).

Astrophysical site: neutron star mergers (NSM)

- Variety of ejection channels in NSM.
- Large amount of dynamical ejecta (0.001-0.01 $\mathrm{M}_\odot$).
- Material extremely neutron rich.

- Other r-process sites: CCSne, collapsars, MR supernovae, . . . dominant source?

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

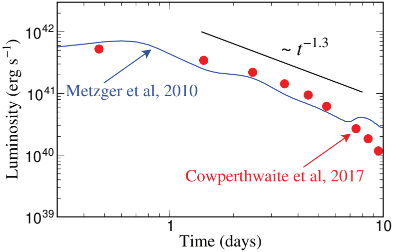


Kilonova

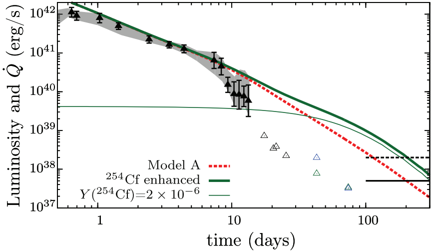
Li and Paczýnski (1998), Metzger+(2010), Roberts+(2011). . .

- Decay of r-process nuclei emits energy → electromagnetic transient (kilonova).
- The shape and magnitude of the light curve depend on the properties of nuclei forming the ejecta → direct information about ejecta composition!

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

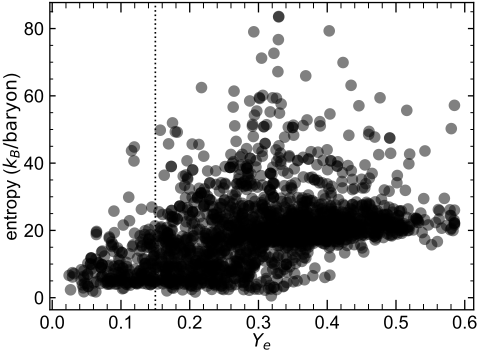
Y. Zhu+ ApJL (2018); S. Wanajo ApJ (2018); M.-R. Wu+ PRL (2019).

Hydrodynamical simulations

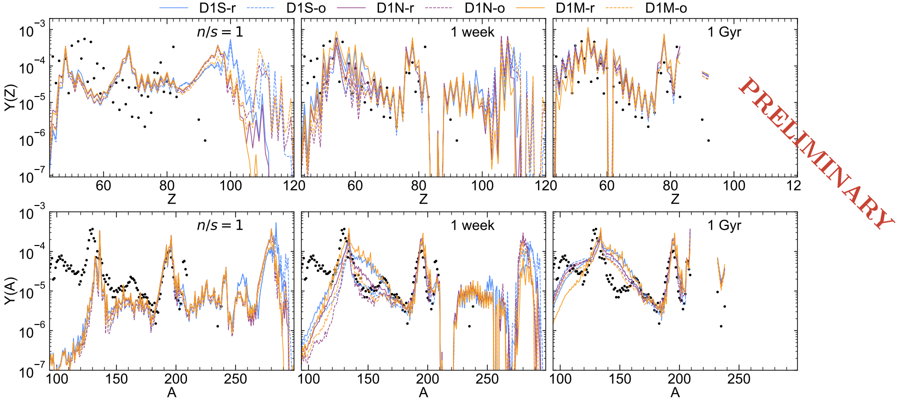
Collins *et al.*, MNRAS 101093 (2023)

- ~ 2000 trajectories simulating dynamical ejecta in NSM (0.5% $\mathrm{M}_\odot$).
- Equal mass NSs 1.35 $\mathrm{M}_\odot$.
- Broad range of thermodynamical conditions.
- Fission expected to be more relevant for more neutron-rich conditions:

$$Y_e = \frac{n_p}{n_n + n_p} \lesssim 0.15\,.$$



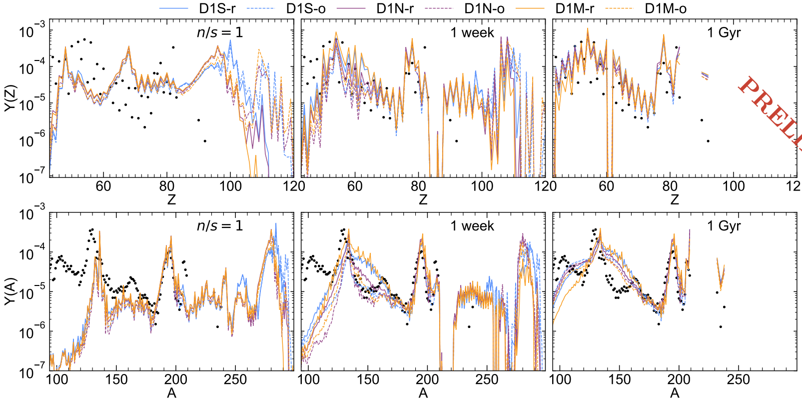
r-process abundances: $Y_e \leq 0.15$ trajectories



At $n/s = 1$:

- Gogny renormalized: r-process flow stops at $Z/N = 100/184$.
- Gogny original: accumulation of material at $Z = 110$ (subdominant).

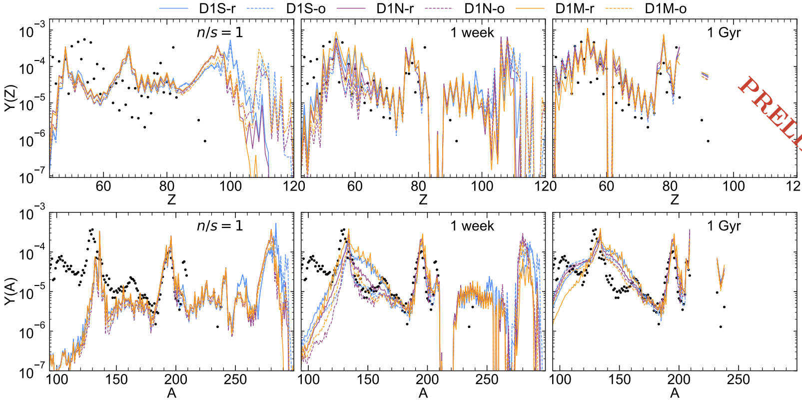
r-process abundances: $Y_e \leq 0.15$ trajectories



At $t = 1$ week:

- D1S/D1M renormalized: efficient β-delayed fission populates $A \approx 150$.
- Gogny original: pile up at $A \sim 280$

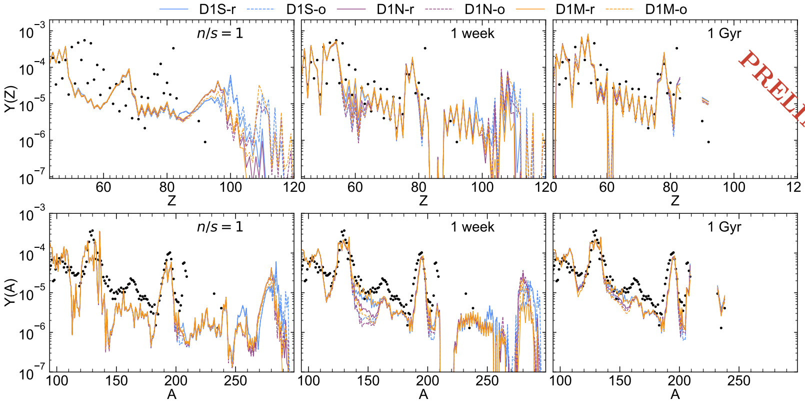
r-process abundances: $Y_e \leq 0.15$ trajectories



At $t = 1$ Gyr:

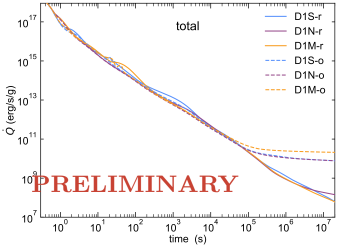
- Gogny original: more symmetric distribution around second peak.
- D1N: high lead peak.

r-process abundances: all trajectories



- Largest differences above the second peak ($Z/A \approx 62/150$), lead peak and U/Th.
- Fitting $t_{1/2}^{\mathrm{sf}}$ close to stability does not reduce sensitivity to fission. . .

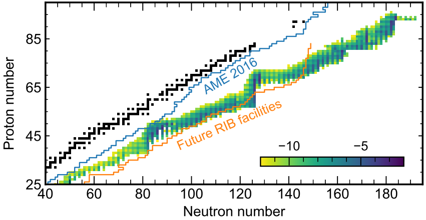
r-process radioactive energy



- Presence of fission (and α-decaying) at late times can strongly modify the heating rates (larger Q-values and thermalization efficiency).
- Larger amount of fissioning nuclei increases the radioactive energy emitted after ~110 days.

Conclusions & Outlook

- Fission plays a crucial role during the r-process.
- We study the sensitivity of r-process abundances and heating rates to variations in the predicted fission barriers by different Gogny EDFs.
- Renormalizing the barriers/inertias to reproduce experimental $t_{1/2}^{\mathrm{sf}}$ reduces the flow beyond $Z = 100$, increasing the abundances above the second peak. But $N = 184$ difficult to overcome. . .
- Large sensitivity around the lead peak and cosmochronometers U and Th.
- Strong impact in the radioactive energy emitted after ∼110 days.



Collaborators

GSI (Darmstadt)

A. Bauswein
G. Martínez Pinedo
V. Vijayan

UAM (Madrid)

UAM
Universidad Autónoma
de Madrid

L. M. Robledo

Sinica Institute (Taiwan)

M.-R. Wu

Funding

MINISTERIO
DE CIENCIA
E INNOVACIÓN

Financiado por
la Unión Europea
NextGenerationEU

Plan de Recuperación,
Transformación y
Resiliencia

AGENCIA
ESTATAL DE
INVESTIGACIÓN

PID2024-159559NB-C21
PID2021-127890NB-I00