

Recent advances in nuclear inputs for r -process simulations

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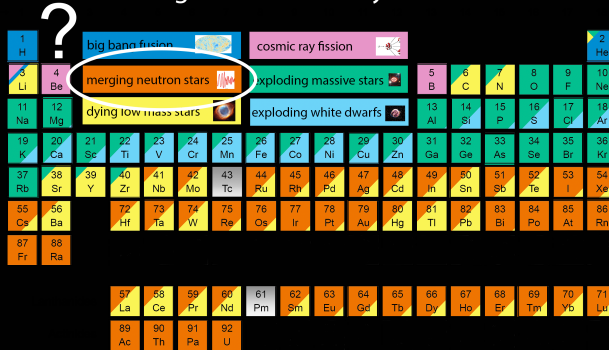
Lublin, Poland



CSIC



The Origin of the Solar System Elements



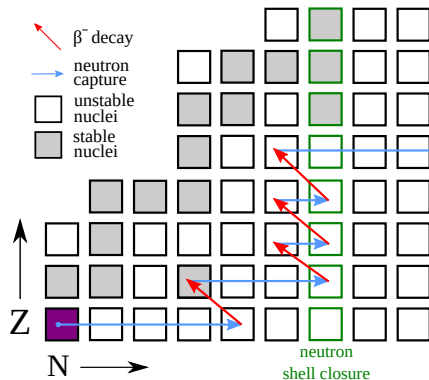
Graphic created by Jennifer Johnson

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The r process

B²FH, Rev. Mod. Phys. 29, 547 (1957) ; A. Cameron, Report CRL-41 (1957)

r (apid neutron capture) process: $\tau_{(n,\gamma)} \ll \tau_{\beta^-}$, $\tau \sim 1\text{ s}$; $n_n > 10^{26}\text{ cm}^{-3}$

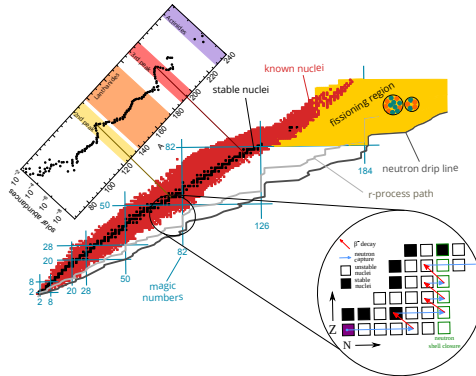


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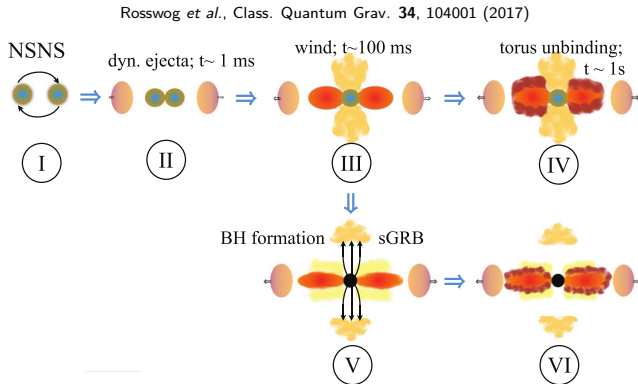
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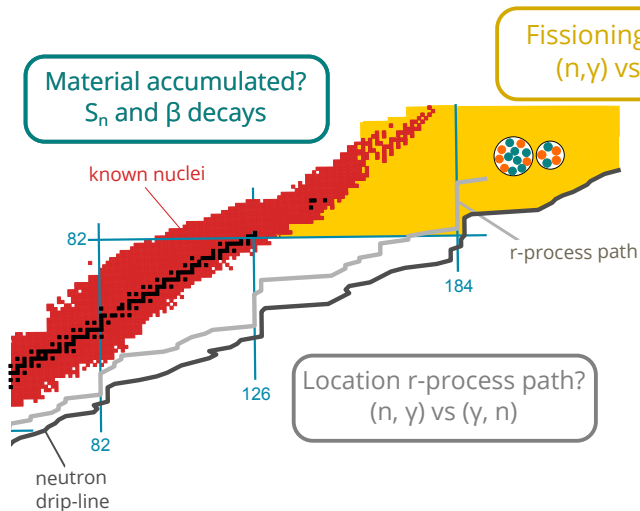
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Neutron star mergers (NSM)

- Variety of **ejection channels** in NSM.
- **Large amount** of dynamical ejecta ($0.001\text{--}0.01\ M_{\odot}$).
- Material **extremely neutron rich**.
- Direct evidence from AT2017gfo kilonova.
- Dominant source?
 - CCSne (produce first peak).
 - Collapsars
 - Magnetorotational supernovae
 - ...



Nuclear inputs

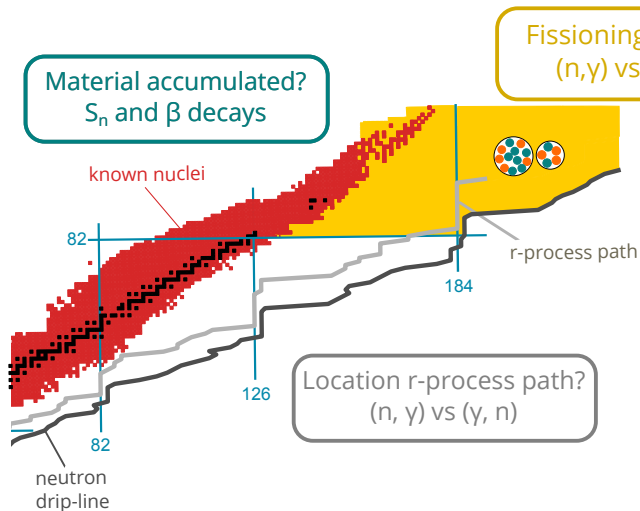


The r -process requires the knowledge of nuclear properties of **neutron-rich nuclei**:

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

from theory and experiment.

Nuclear inputs

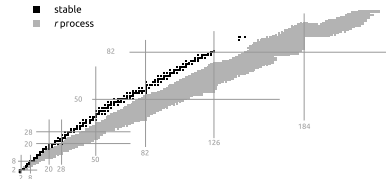
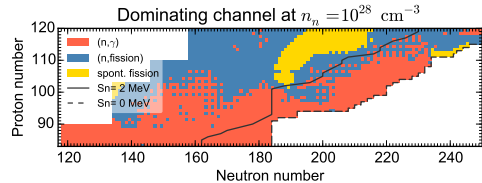
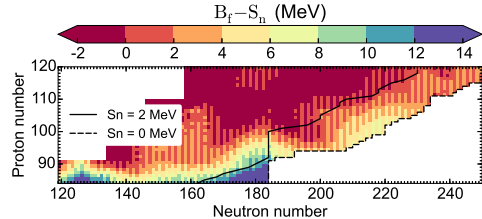


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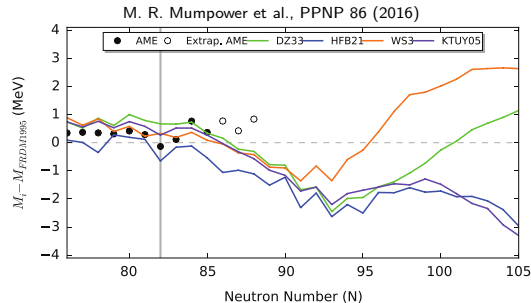
from **theory** and experiment.

- 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.



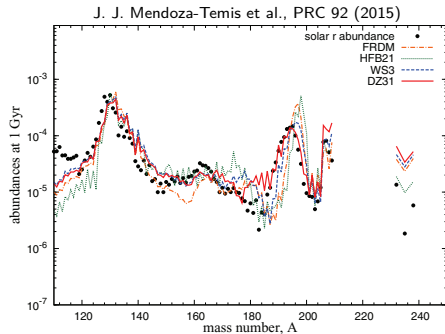
Nuclear masses

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



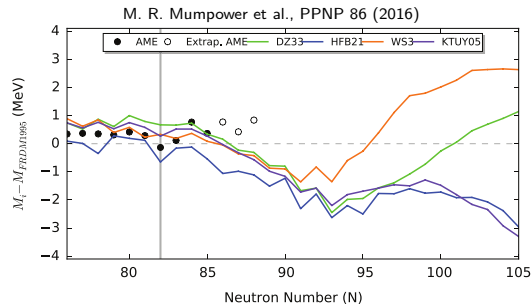
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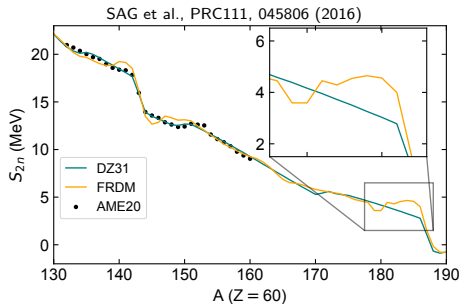


Question: What are the most relevant nuclear mass differences?

Answer:

Nuclear masses

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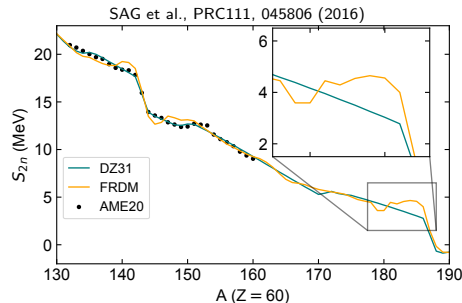


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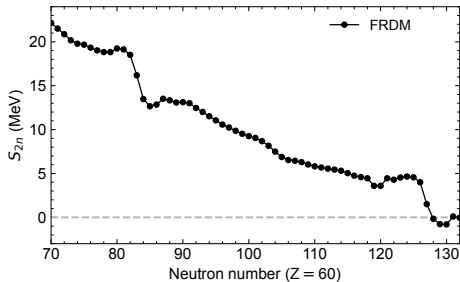
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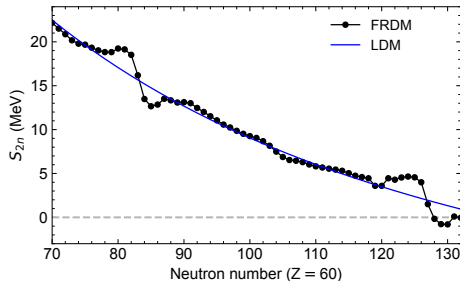
Answer: Local changes in S_{2n} (not global properties of nuclear masses or S_{2n}).

Nuclear masses - Global and local contributions



Binding energies can be decomposed into **two contributions**: $E = E_{\text{bulk}} + E_{\text{shell}}$

Nuclear masses - Global and local contributions

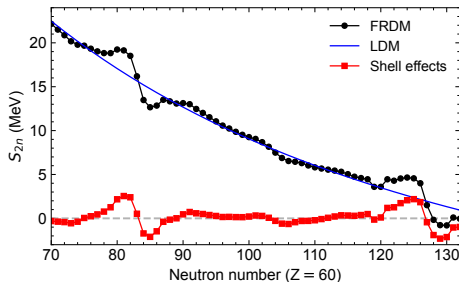


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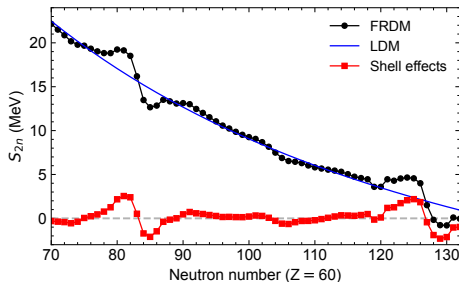
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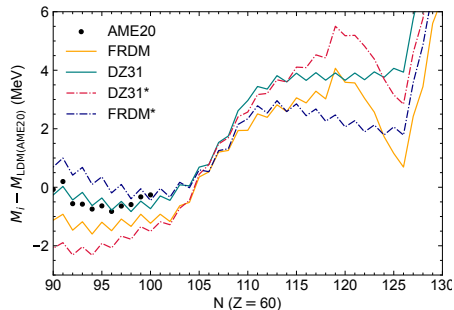
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ii) E_{shell} : **shell effects**, producing local changes in mass surfaces and $S_n \rightarrow$ **shape the abundances!**

Nuclear masses - Global and local changes

SAG+, PRC 113, 045806 (2026)



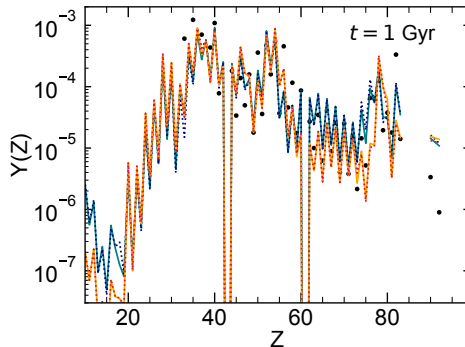
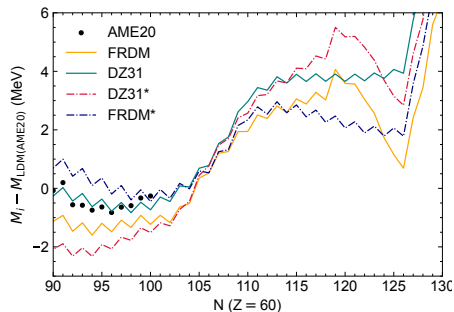
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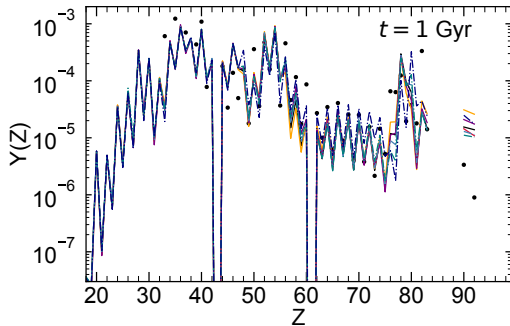
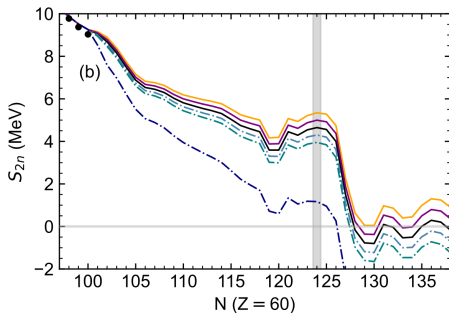
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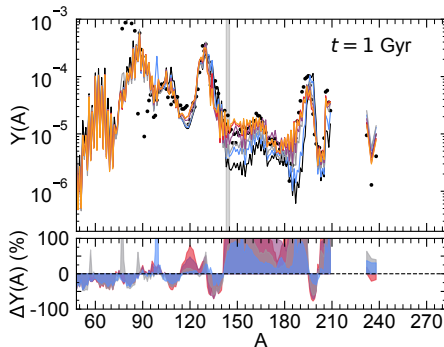
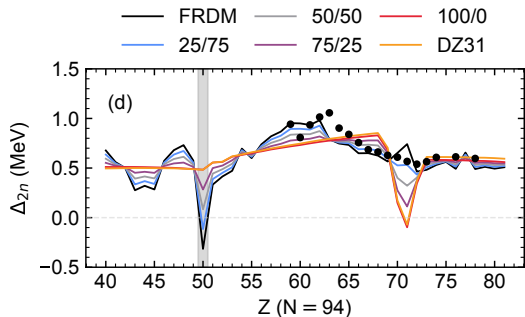
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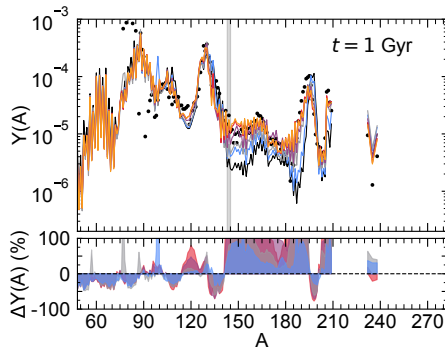
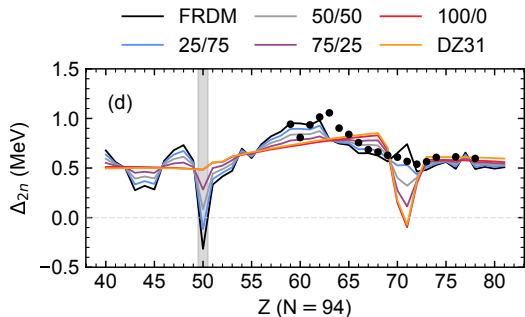


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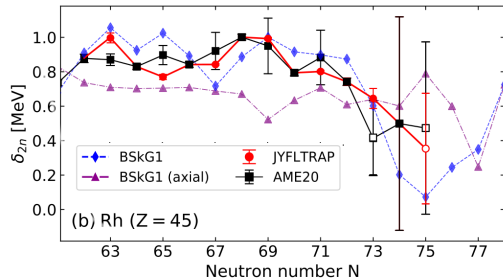
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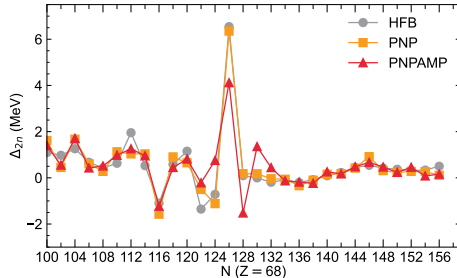
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Abundances insensitive to global changes in masses and S_{2n} !

Relevant for experimental campaigns

M. Hukkanen *et al.*, Phys. Rev. C **107**, 014306 (2023)

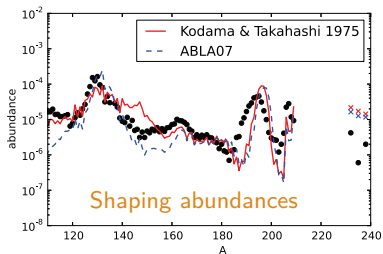
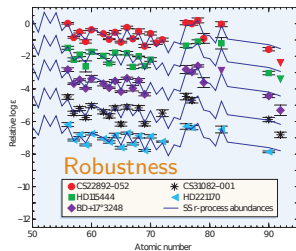
Relevant for theoretical calculations

J. García Santana *et al.* (in preparation)

- Study the impact of beyond mean-field calculations on S_{2n} and D_{2n} .
- In collaboration with L. Lotina, J. García Santana, T. Rodríguez,
- RES resources provided by CNS in Barcelona Supercomputing Center to FI-2026-1-0045.

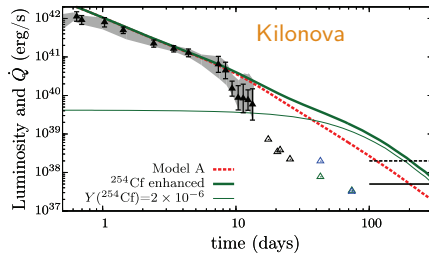
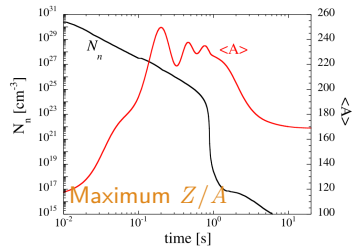
Fission and r process

Cowan and Sneden, Nature 440 1151 (2006)



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

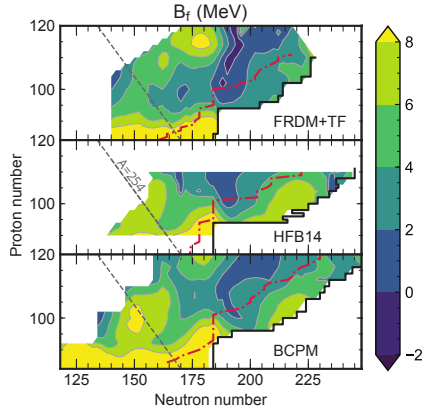
S. Goriely, EPJA 51, 22 (2015)



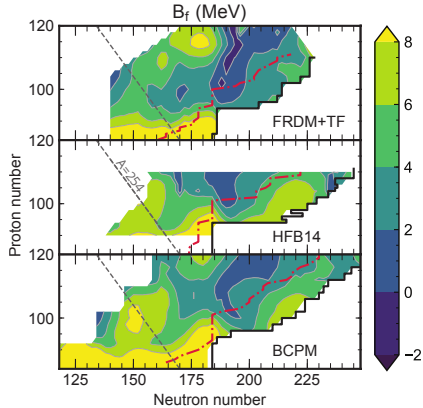
M.-R. Wu *et al.*, Phys. Rev. Lett. **122**, 062701 (2019).

Impact of fission on the r -process

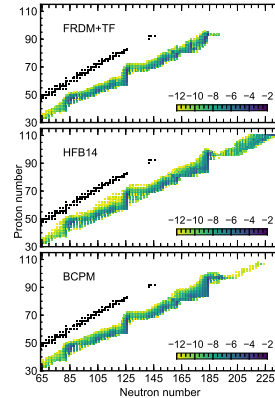
SAG *et al.*, Phys. Rev. C 102, 045804 (2020)



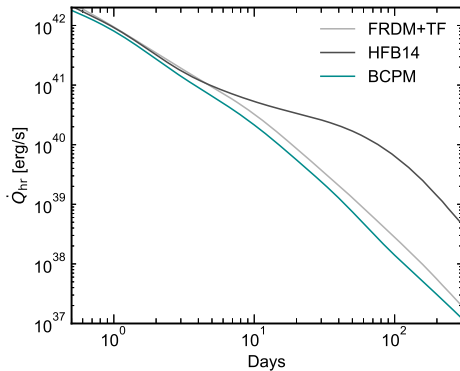
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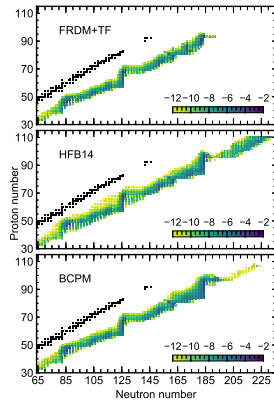
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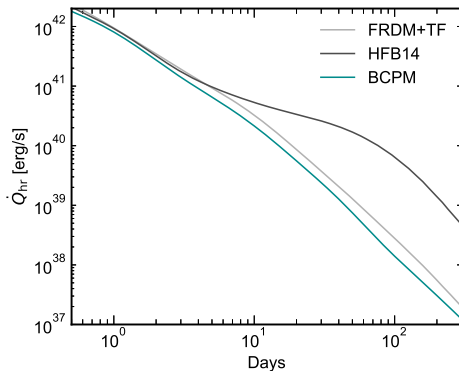
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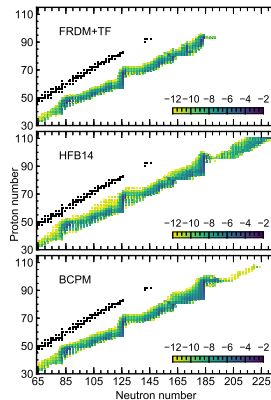
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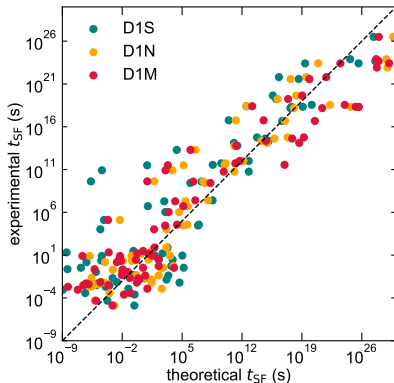


Kilonova sensitive to nuclear properties at $N = 184$

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

Sensitivity to EDF parametrizations

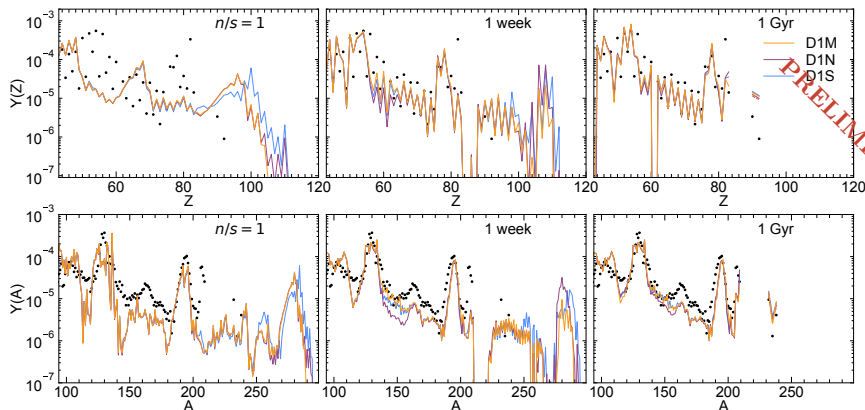
- Study the sensitivity to different parametrizations of the same EDF: D1S, D1N, and D1M.



- $t_{1/2}^{\text{sf}}$ systematically **overpredicted** (pairing as dof, collective inertias, triaxiality...) $\rightarrow$ collective inertias/fission barriers are renormalized in order to reproduce experimental $t_{1/2}^{\text{sf}}$.

Gogny r -process abundances

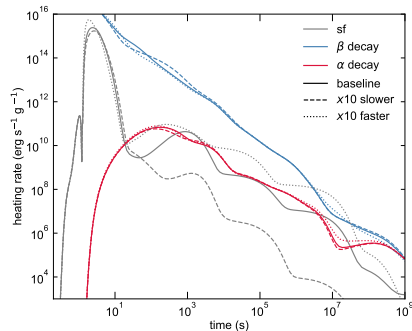
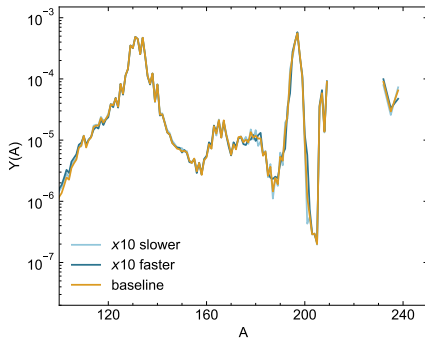
trajectories from Collins *et al.*, MNRAS 101093 (2023)



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

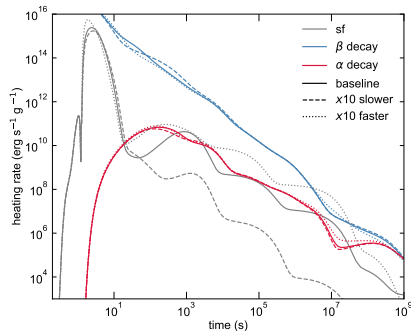
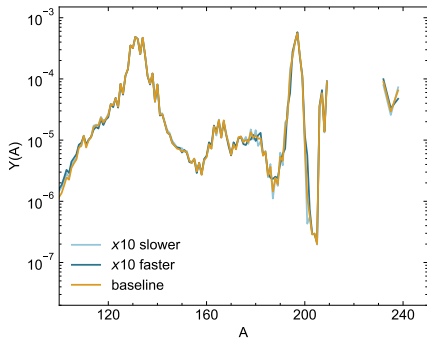
Impact of β -decay rates on fission

- 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.



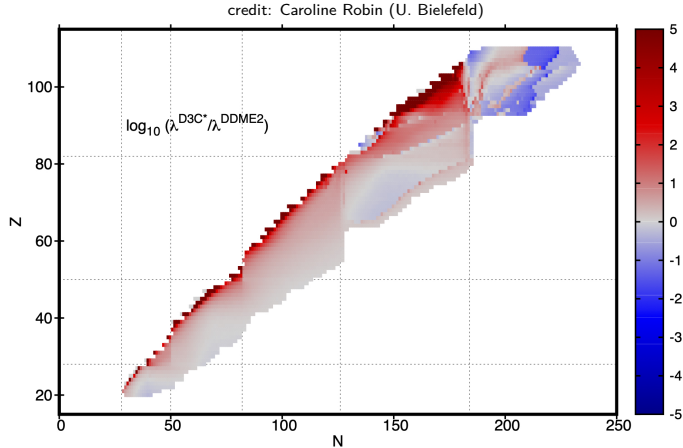
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Fission heating rate sensitive to “slow” β -decay rates
($\tau_{\beta} \gtrsim$ few seconds)

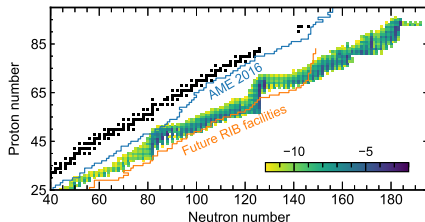
Systematic of β -decay rates



- 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

GSI (Darmstadt)



A. Bauswein
G. Martínez Pinedo
V. Vijayan

UAM (Madrid)



L. M. Robledo
J. García

Sinica Institute (Taiwan)



M.-R. Wu

IMROH



L. Lotina

US (Sevilla)



T. R. Rodríguez

Funding



CSIC



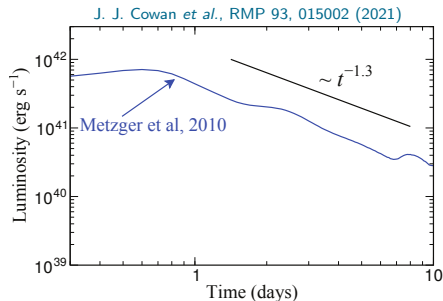
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Backup

Kilonova

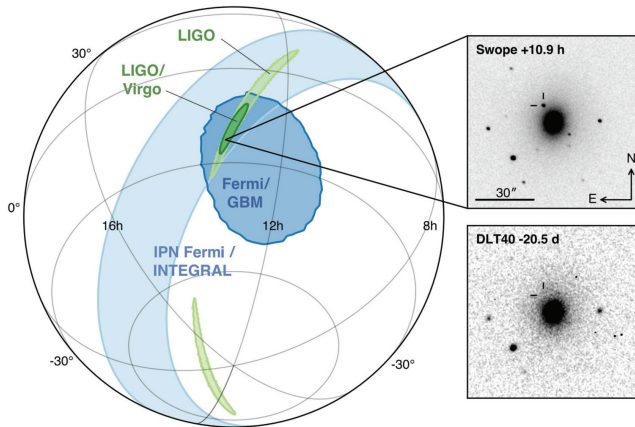
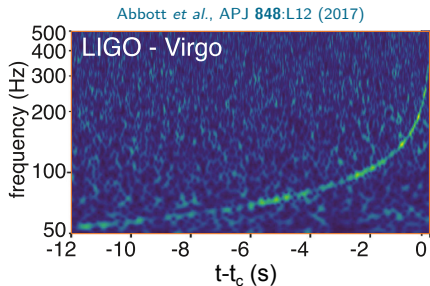
Li and Paczyński (1998), Metzger+(2010), Roberts+(2011)...

- Decay of r -process nuclei emits energy → **electromagnetic transient**.
- Peak luminosity thousand times brighter than a nova (**kilonova**).



- The **shape and magnitude** of the light curve depend on the properties of nuclei forming the ejecta → direct information about **ejecta composition**!

The AT2017gfo kilonova



- 10.9 hours after the NSM GW170817 its kilonova was observed.

Kilonova modeling

- Detected light curve in very good agreement with theoretical predictions.
- Fingerprints from individual elements? D. Watson *et al.*, Nature 574 (2019).

