# $r$-process nucleosynthesis: fingerprints from fissioning nuclei

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March 27th, 2019

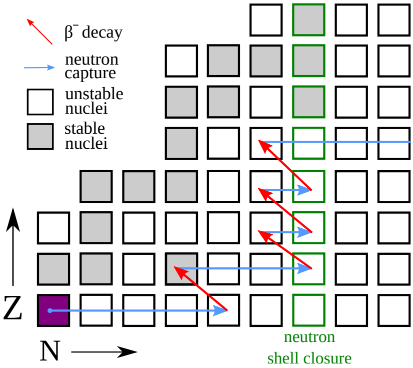
"Nuclear Fission and Structure of Exotic Nuclei"
ASRC International workshop Sakura-2019

Tokai, Japan

# The $r$ process

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

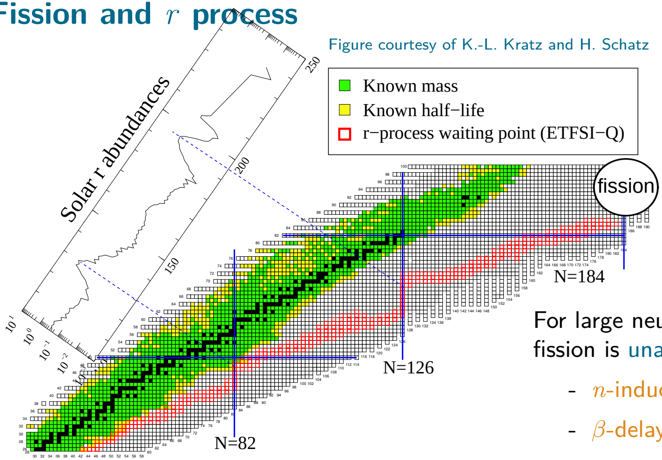
$r$(apid neutron capture) process: $\tau_n \ll \tau_{\beta^-}$




- How far can the $r$ process proceed? Number of free neutrons that seed nuclei can capture (neutron-to-seed ratio).

# Fission and $r$ process

Figure courtesy of K.-L. Kratz and H. Schatz

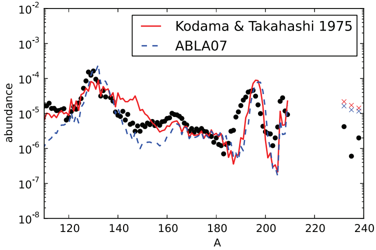



For large neutron-to-seed ratio fission is unavoidable

- $n$-induced fission
- $\beta$-delayed fission
- spontaneous fission

- Where does fission occur?
- How much material accumulates in fissioning region?
- What are the fission yields?

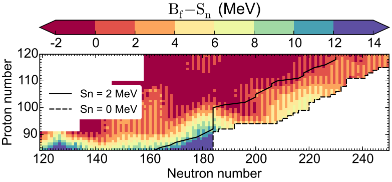
# Fission and $r$ process #2



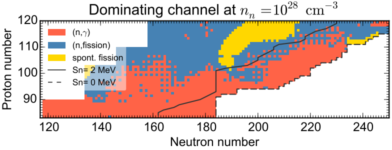

M. Eichler *et al.*, Astrophys. J. **808**, 30 (2015).

- Abundances and kilonova light curves strongly affected by fission rates and fragments. Eichler+(2015), Goriely (2015), Zhu+(2018), Mumpower+(2018), Wu+(2019)...
- Few fission data sets are available...
- Most of the models are parametrizations/phenomenological → validity far from stability?
- Long-term goal: compute reaction rates and fission properties from consistent (EDF) nuclear input.

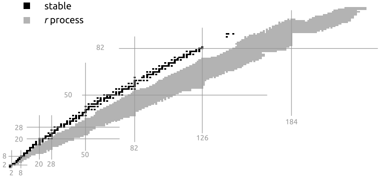
1) Compute fission properties and binding energies using EDF.



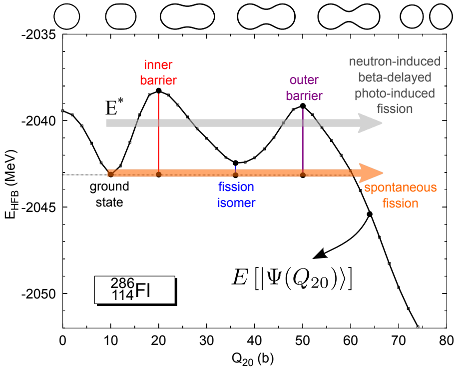

2) Calculate stellar reaction rates from Hauser-Feshbach theory.




3) Obtain $r$-process abundances using network calculations.



# The fission process




**Potential Energy Surface**

Energy evolution from the initial state to the scission point.

SAG+ PRC90 (2014); Sadhukhan+ PRC90 (2014)

**Collective inertias**

Resistance of the nucleus against the deformation forces.

Baran+ PRC84 (2011); SAG+ PLB787 (2018)

# 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 ($\beta$) 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 deformation of the nucleus $\langle\Psi(q)|\hat{Q}|\Psi(q)\rangle = q$:

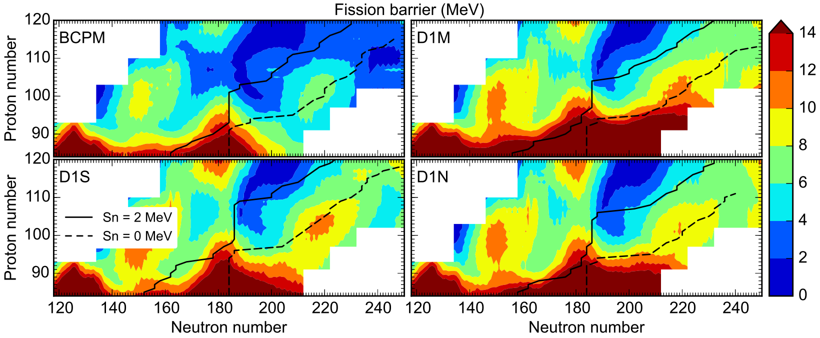
$$E[|\Psi(q)\rangle] = \langle\Psi(q)|\hat{\mathcal{H}} - \lambda_q \hat{Q}|\Psi(q)\rangle\,.$$

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

- Barcelona-Catania-Paris-Madrid (BCPM);
- Skyrme and Gogny interactions (UNEDF1, D1S);
- relativistic EDF.

## Fission barriers from EDF's

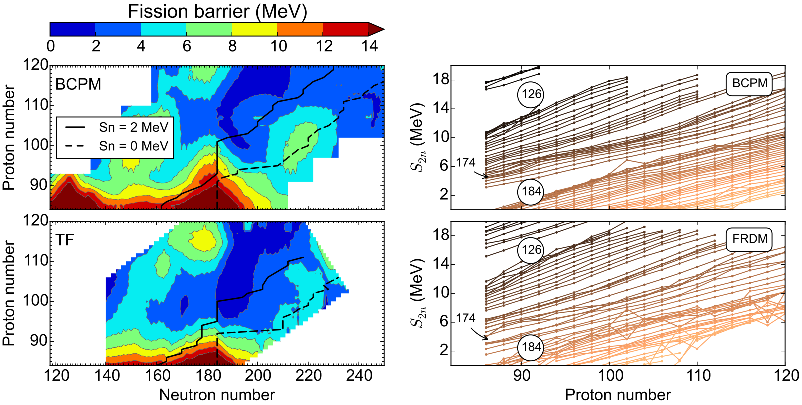
The EDF formalism provides neutron separation energies, fission barriers and collective inertias for reaction rates calculations.




Above $N = 184$ the $r$-process path ($S_n = 2$ MeV) enters in a region of low fission barriers $\Rightarrow$ neutron-induced fission dominates.

# Nuclear inputs from the BCPM EDF

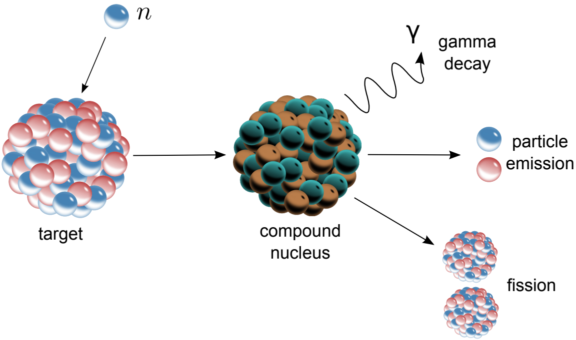
We study the impact of fission in the $r$ process by comparing BCPM with previous calculations based on Thomas-Fermi (TF) barriers and Finite Range Droplet Model (FRDM) masses.




**BCPM**: Giuliani *et al.* (2018); **TF**: Myers and Świątecky (1999); **FRDM**: Möller *et al.* (1995).

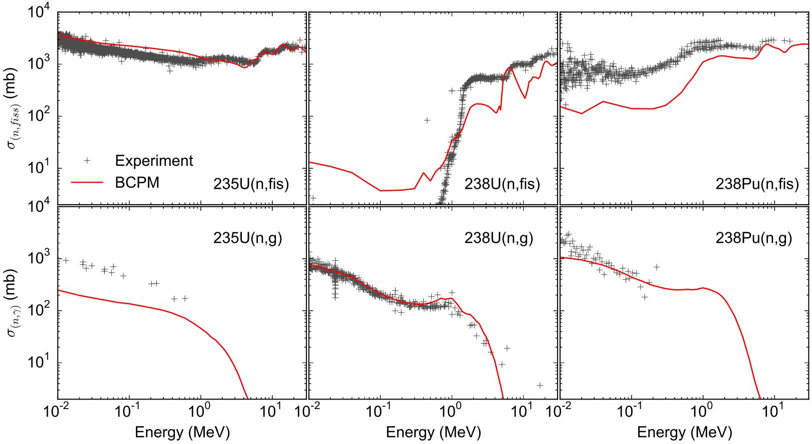
# Compound reactions

Reaction rates computed within the Hauser-Feshbach statistical model.

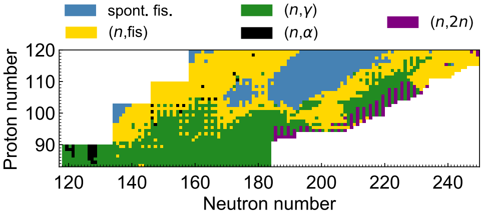



- Based on the Bohr independence hypothesis: the decay of the compound nucleus is independent from its formation dynamics.
- BCPM nuclear inputs implemented in TALYS reaction code to compute $n$-induced fission and $n$-capture rates.

# Cross sections from BCPM



# BCPM stellar reaction rates

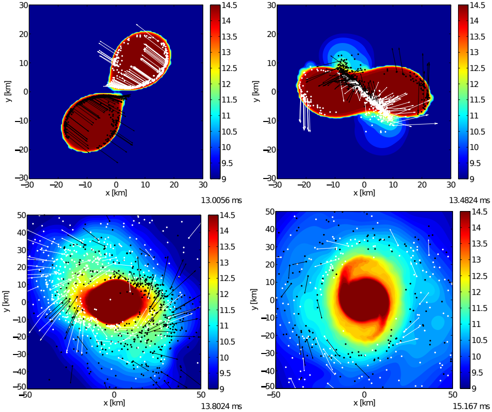



SAG *et al.*, Rev. Mod. Phys. **91**, 011001 (2019).

- Fission dominates above $N = 184 \rightarrow$ superheavy elements cannot be created?
- Path to stability crosses region of low fission barriers.

# The dynamical ejecta in neutron mergers

Trajectory from 3D relativistic simulations of $1.35\,\mathrm{M}_\odot$-$1.35\,\mathrm{M}_\odot$ NS mergers.

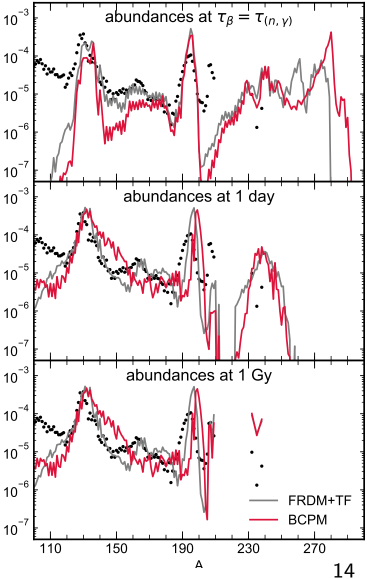



Bauswein et al., ApJ 773, 78 (2013).

- Large amount of ejecta ($0.001$-$0.01\ \mathrm{M}_\odot$).
- Material extremely neutron rich ($R_{n/s} \gtrsim 600$).
- Role of weak interactions?

# $r$-process abundances: BCPM vs FRDM+TF

- BCPM Giuliani+(2017) vs TF+FRDM Panov+(2010).
- We changed the rates of nuclei with $Z \geq 84$.
- Same $\beta$-decay rates [Möller *et al.* PRC67(2003)].



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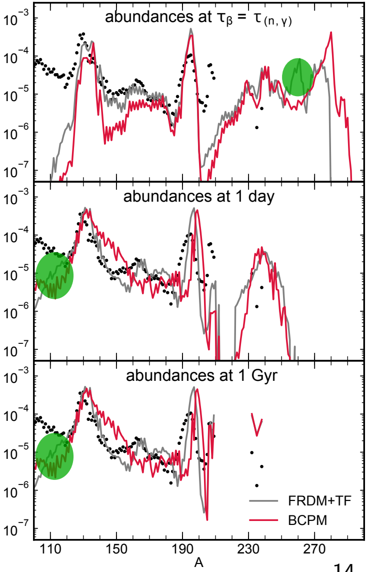
- BCPM shell gap smaller than FRDM at $N = 174$:
  - FRDM-TF peak at $A \sim 257$,
  - impact on final abundances at $A \sim 110$.



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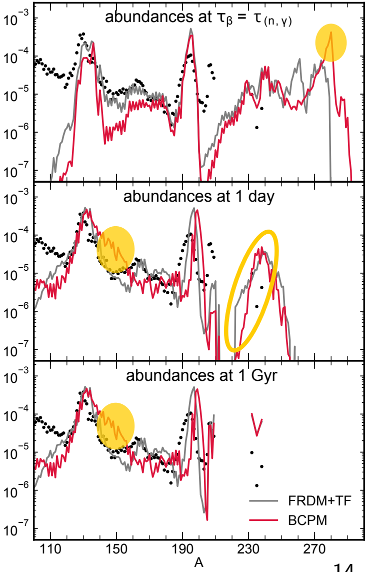
  - nuclei around $A > 280$ longer lifetimes,
  - accumulation above 2nd peak,
  - more free neutrons available at later stages $\Rightarrow$ impact for kilonova?



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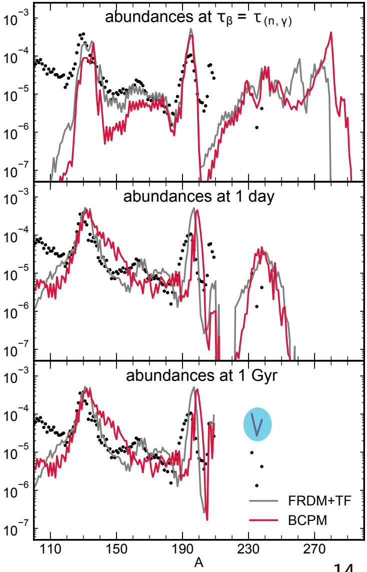
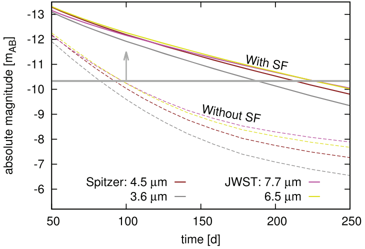
- Same $^{232}$Th/$^{238}$U ratio: progenitors of actinides have $Z < 84 \Rightarrow$ can initial nuclei with $Z \geq 84$ survive to fission?



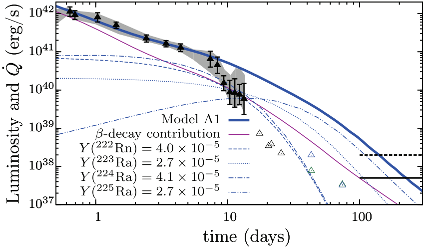
# Kilonova and nuclear physics: impact on light curves

- Kilonova: EM transient produced by radioactive decay of $r$-process nuclei.
  - $\rightarrow$ Observable!
- Composition of the ejecta impacts light curve's shape.

Y. Zhu *et al.*, Astrophys. J. Lett. **863**, 2 (2018).




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

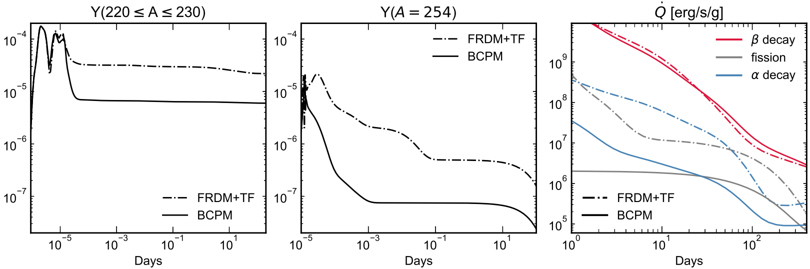



- At late times decay energy can be dominated by few nuclei:
  - Spontaneous fission of $^{254}$Cf.
  - $\alpha$ decay of Ra and Rn isotopes.

# Ejecta properties: BCPM vs FRDM+TF

The free neutrons produced by fission:

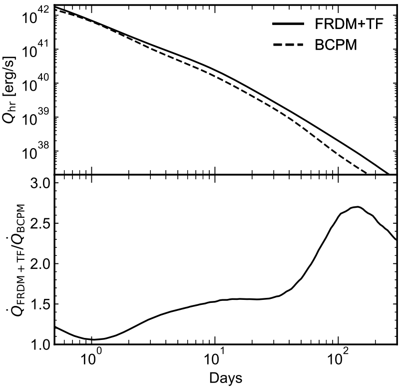
- Destroy progenitors of $^{254}$Cf via $n$-induced fission.
- Remove progenitors of Ra, Rn via neutron captures.




- BCPM leads to smaller radioactive energy emitted by $\alpha$ and fission.

# Kilonova light curves: BCPM vs FRDM+TF

SAG *et al.*, in preparation




Accumulation of fissioning nuclei at early stages strongly reduces the ejecta heating rate at late times!

# Conclusions & Outlook

- GW170817 pushed $r$-process studies into an exciting era.
- Reliable estimations of nuclear properties are crucial for proper nucleosynthesis calculations.
- Energy density functionals can be extremely valuable tools:
  - HFB + Hauser-Feshbach for reaction cross sections.
  - HFB + Langevin for fission yields.
- New set of stellar rates suited for $r$-process calculations:
  - Strong sensitivity to height of fission barriers and neutron separation energies around $A = 257$ and $A > 280$.
  - Progenitors of actinides have $Z < 84 \Rightarrow$ no nuclei with $Z \geq 84$ survive to fission?
  - Accumulation of fissioning nuclei at early stages reduces the ejecta heating rate at late times.
- **Future work:**
  - extend computation of fragments distributions;
  - explore different EDF;
  - compute $\beta$-decay rates.

## Cnollaborators

- Z. Matheson and W. Nazarewicz (NSCL/FRIB, East Lansing)
- G. Martínez Pinedo (TUD/GSI, Darmstadt)
- L. M. Robledo (UAM, Madrid)
- J. Sadhukhan (VECC, Kulkata)
- N. Schunck (LLNL, Livermore)
- M.-R. Wu (Sinica, Taiwai)

# Thank you!