Nuclear Structure and Astrophysics Theory:

Heavy element nucleosynthesis as a probe of matter at the extremes

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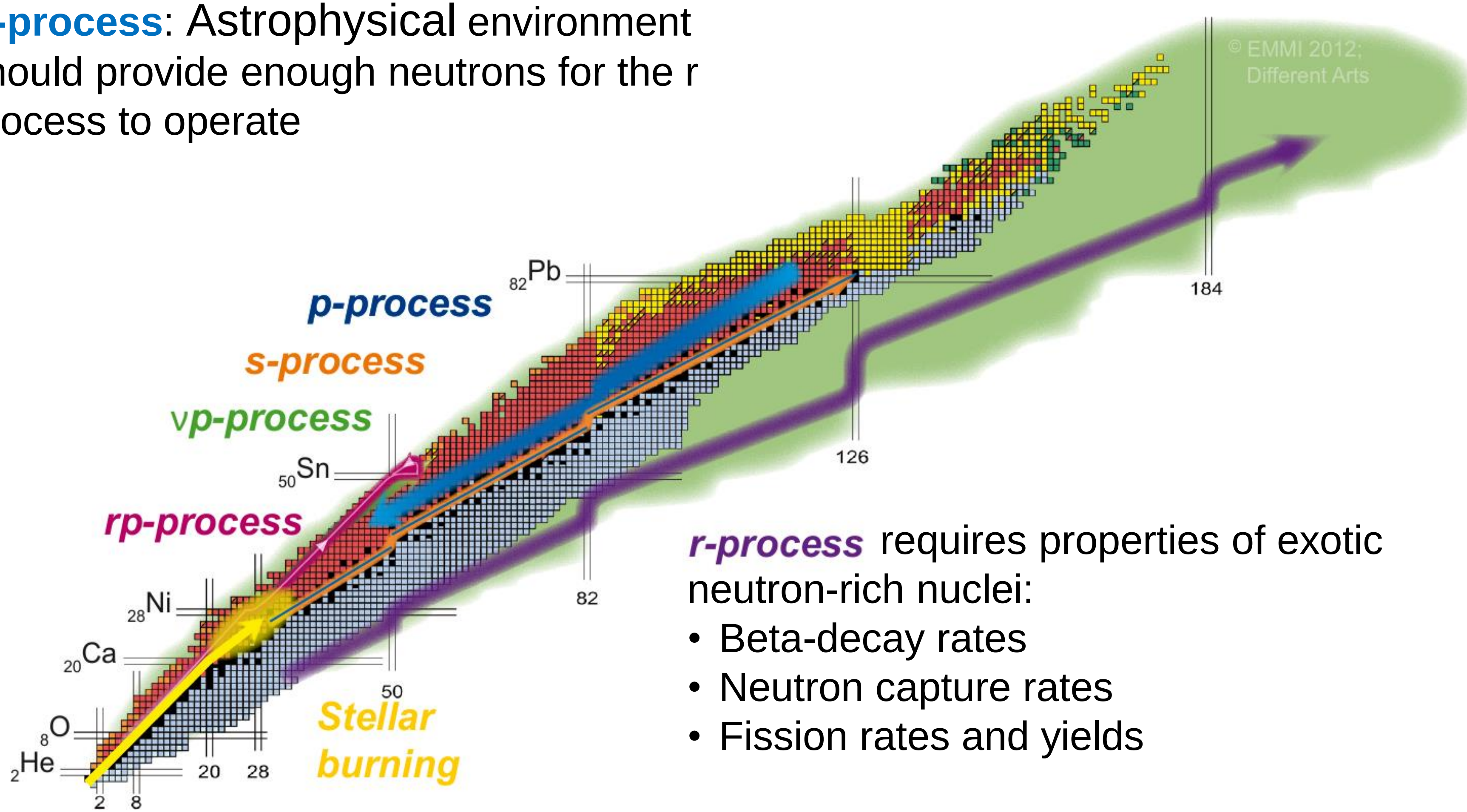
Nucleosynthesis heavy elements

R-process: Astrophysical environment should provide enough neutrons for the r process to operate



r-process requires properties of exotic neutron-rich nuclei:

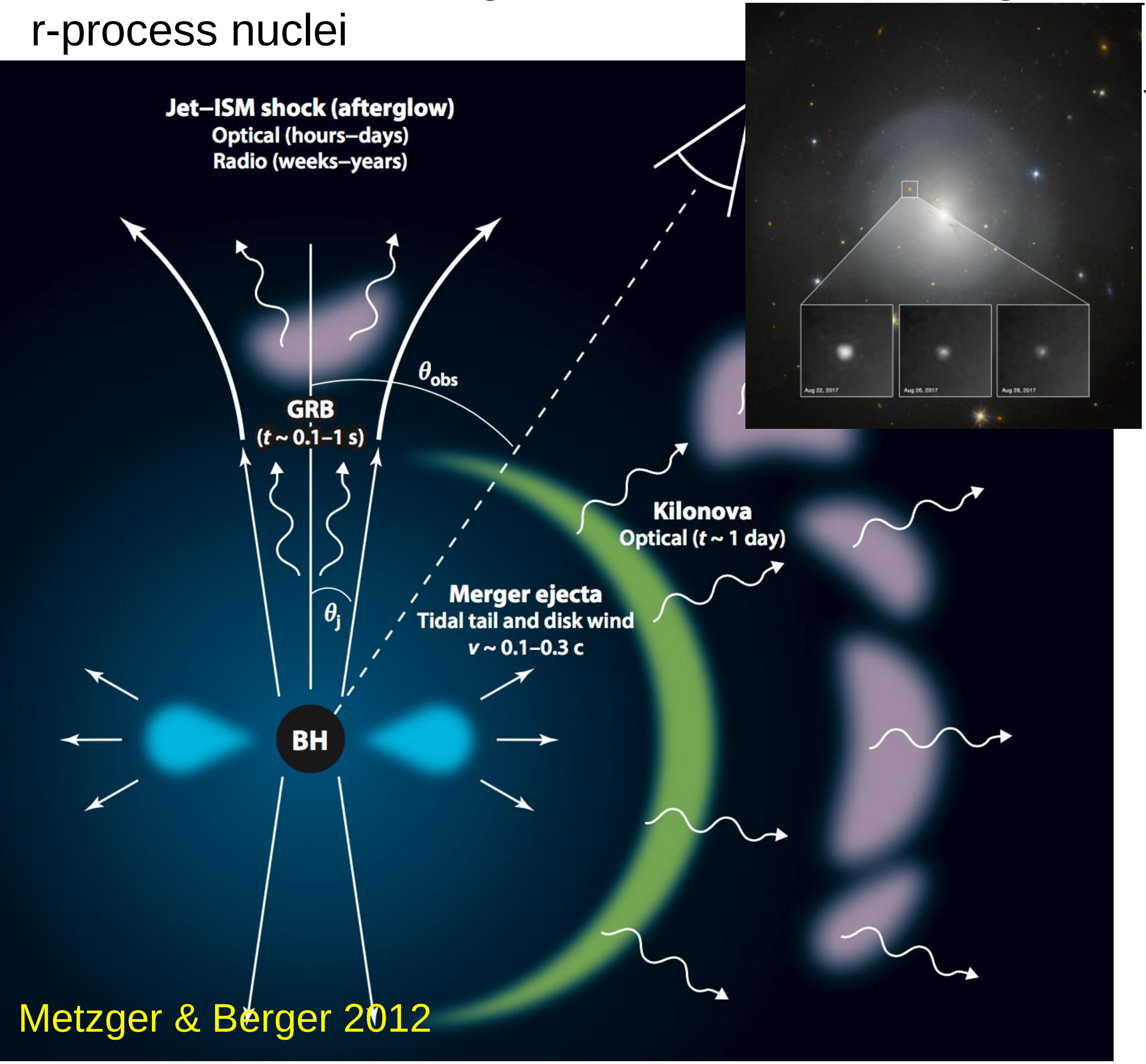
- Beta-decay rates
- Neutron capture rates
- Fission rates and yields

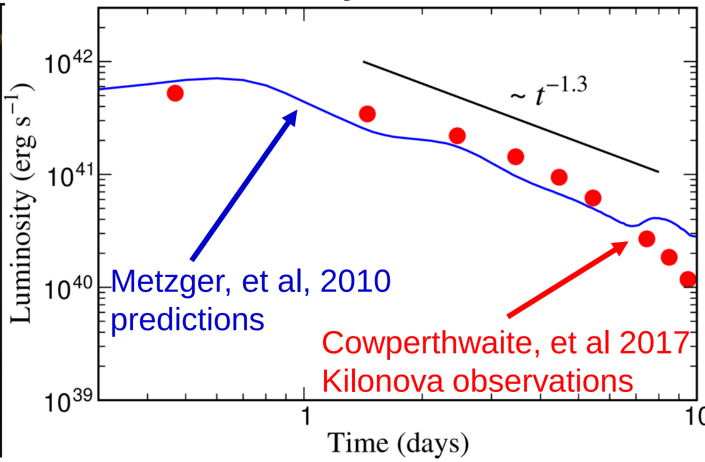
Benchmark against observations:

- Indirect: Solar and stellar abundances (contribution many events, chemical evol.)
- Direct: Kilonova electromagnetic emission (single event, sensitive Atomic and Nuclear Physics)

Kilonova: signature of the r-process

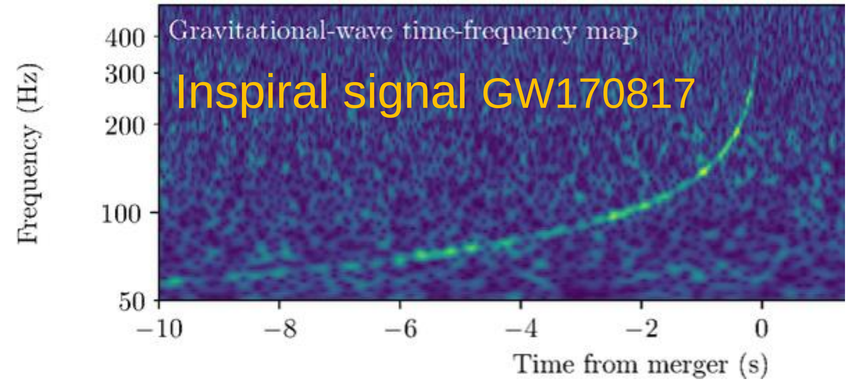
Kilonova: An electromagnetic transient due to long term radioactive decay of r-process nuclei



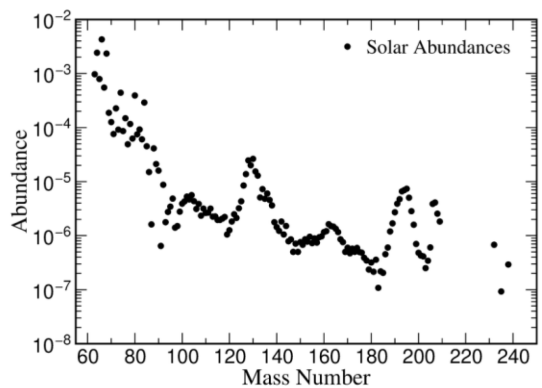


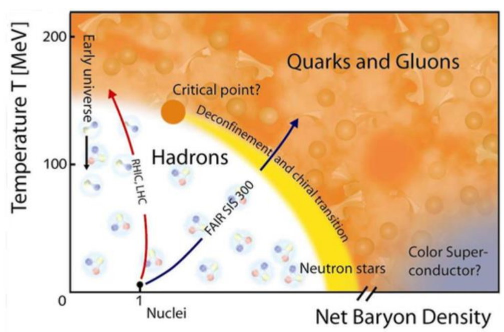
- Electromagnetic counterpart to Gravitational Waves
- Diagnostics physical processes at work during merger
- Direct probe of the formation r-process nuclei
- Information elements produced single event

Multiphysics picture of r-process

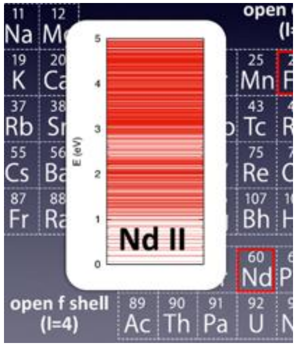


r-process: nucleosynthesis and electromagnetic transient

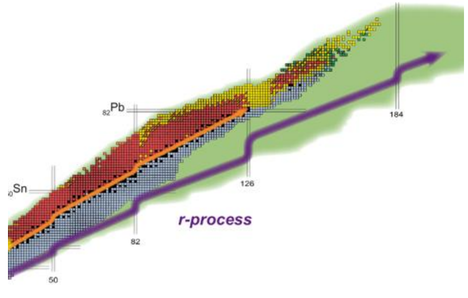




Phase diagram QCD matter



Atomic opacities



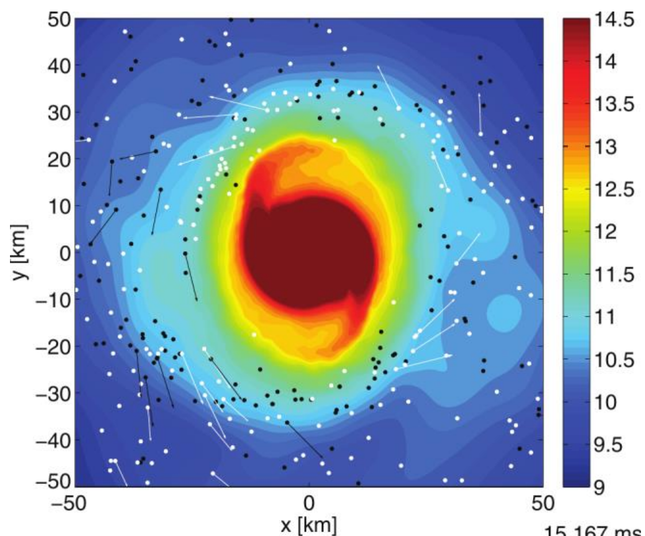
Neutron-rich exotic nuclei

Pipeline for r-process in mergers

- Properties ejecta: proton-to-nucleon ratio (Y_e)
- Role of equation of state
- Role of neutrinos

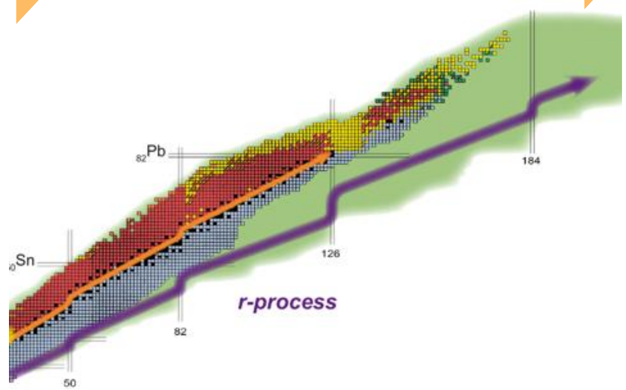
- Physics of neutron-rich and heavy nuclei

- Radioactive energy deposition
- Thermalization decay products (Barnes+ 2016, Kasen+ 2019)
- Spectra formation: atomic data depends on ejecta evolution (LTE vs NLTE)

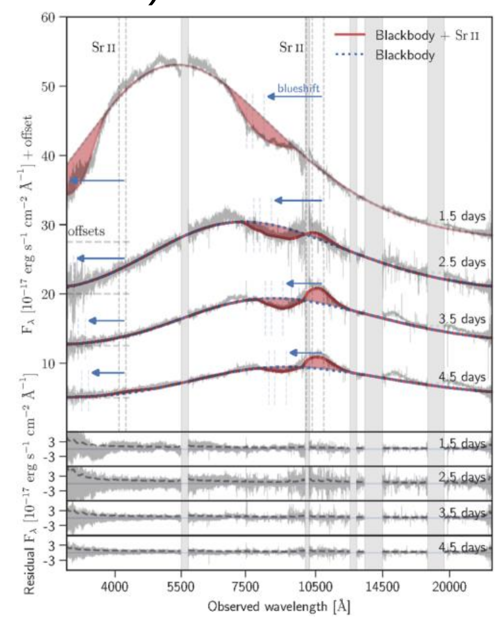


Bauswein et al, ApJ 773, 78 (2013)

forward modelling



backward modelling



Watson et al, Nature **574**, 497 (2019)

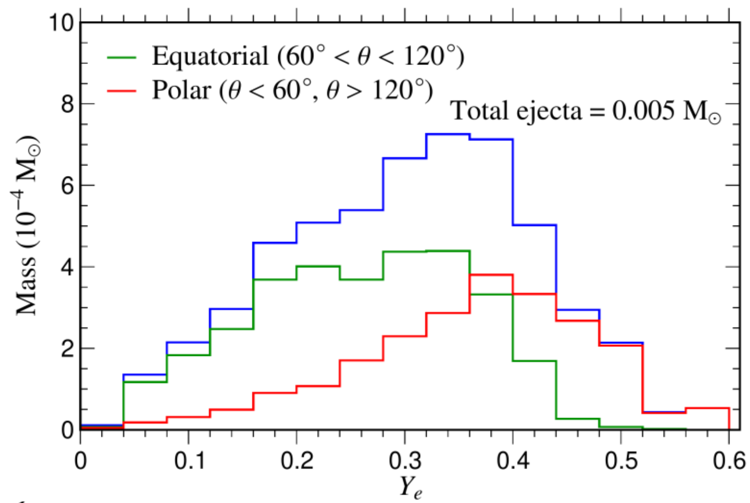
Infer components ejecta (Y_e)

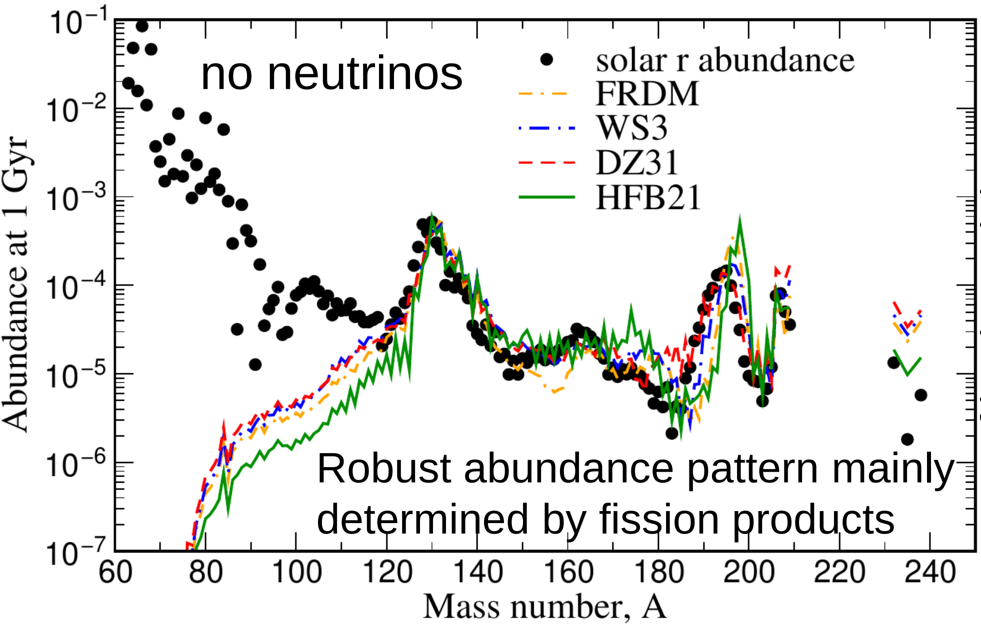
- Which r-process elements are produced in mergers?
- Are mergers the (main) r-process site?

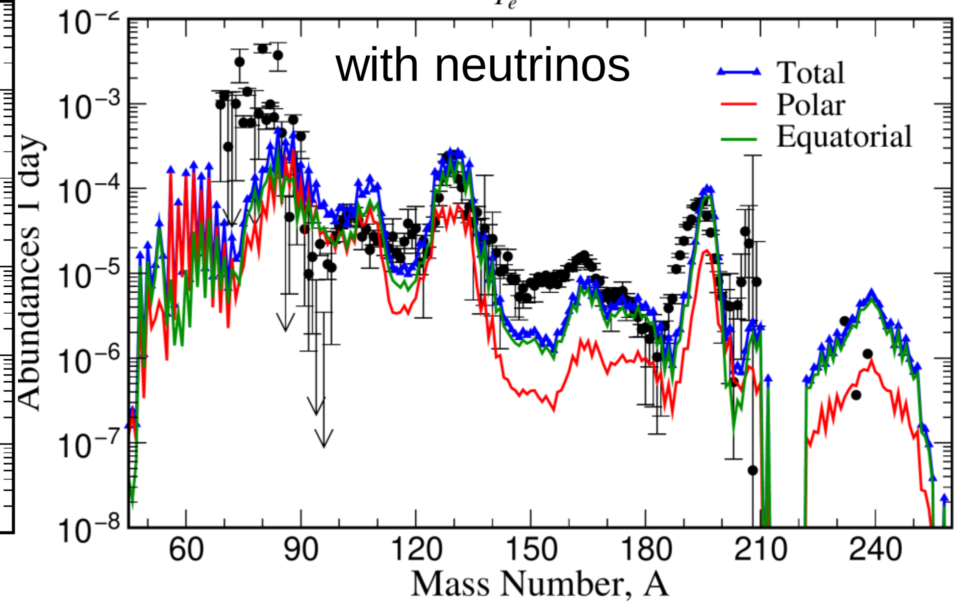
Dynamical ejecta (simulations): Weak-interaction

- Early simulations assumed dynamical ejecta was very neutron rich ($Y_e \lesssim 0.1$).
- However, weak processes modify the neutron-to-proton ratio increasing Y_e
- Largest impact in the polar regions

SPH Simulation **Vimal Vijayan**
Neutrino transport: ILEAS
1.35 – 1.35 $M_\odot$, SFHo EoS

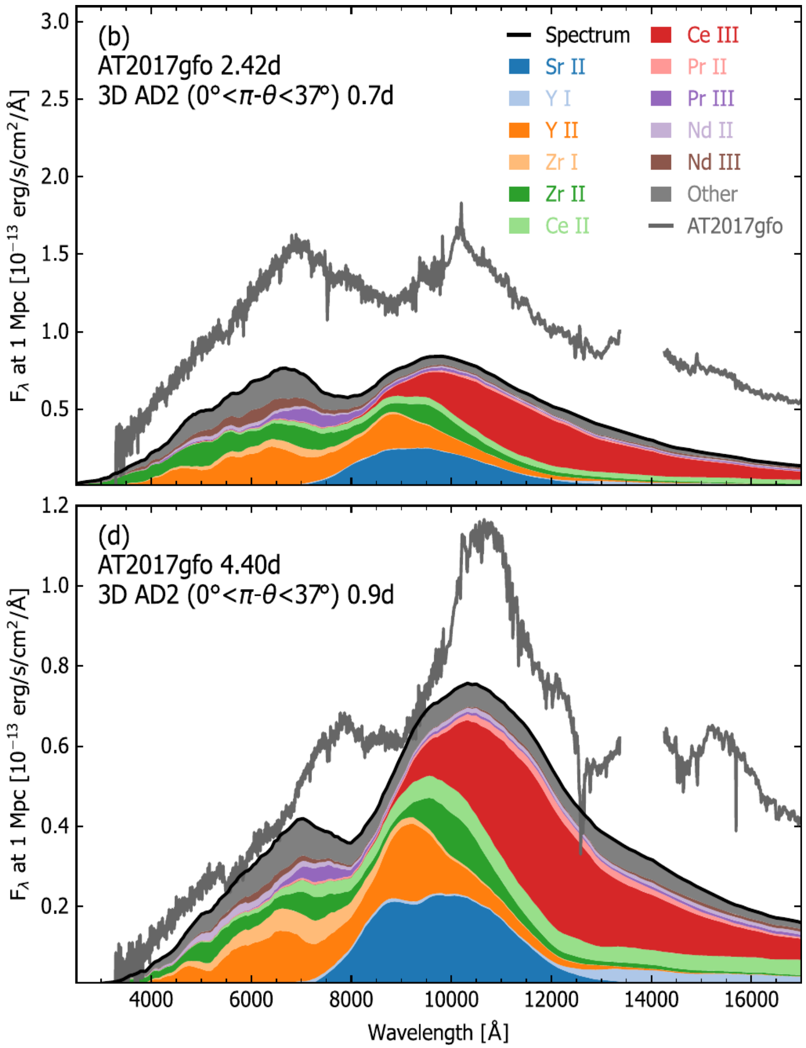


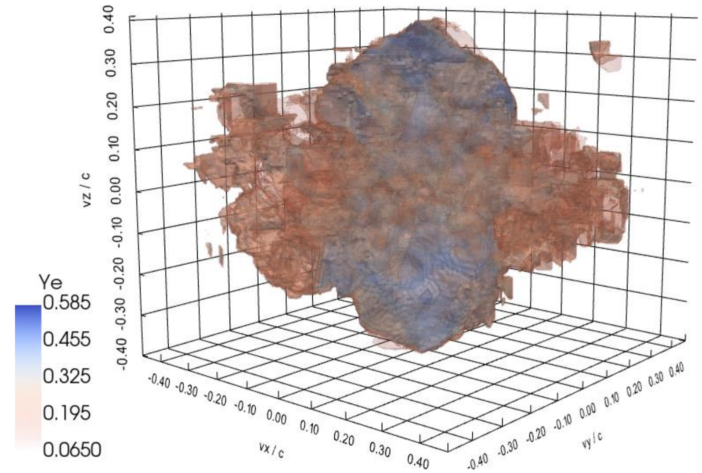




Mendoza-Temis, et al, PRC 92, 055805 (2015)

Self-consistent 3D radiative transfer



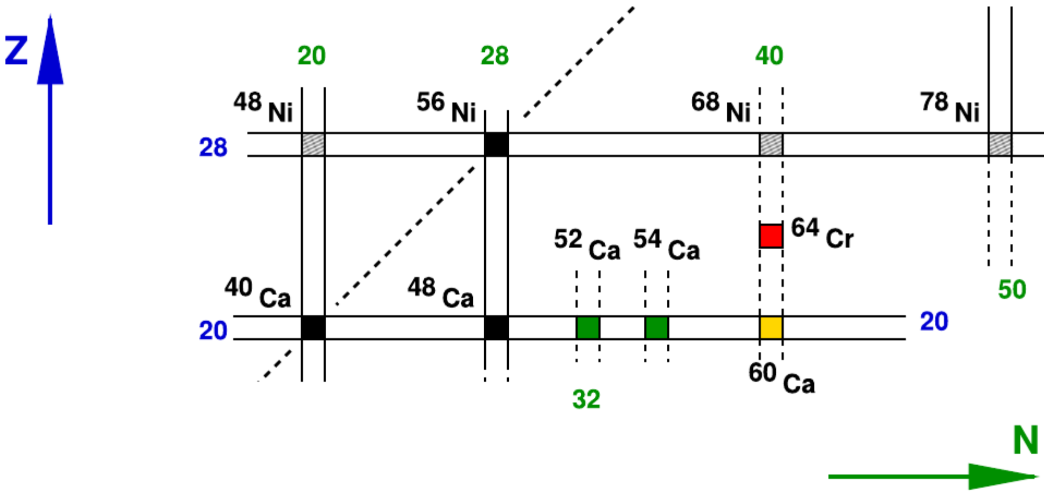


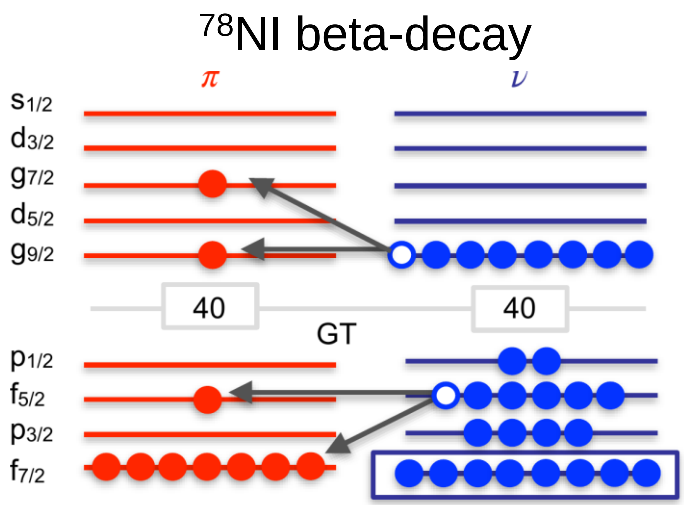
- Monte Carlo 3D radiative transfer using the ARTIS code. https://github.com/artis-mcrt/artis
- Matter distribution based on SPH Dynamical ejecta (0.005 $M_{\odot}$)
- Based on line-by-line bound-bound atomic opacities

Similar spectral evolution that AT2017gfo once differences in brightness are accounted

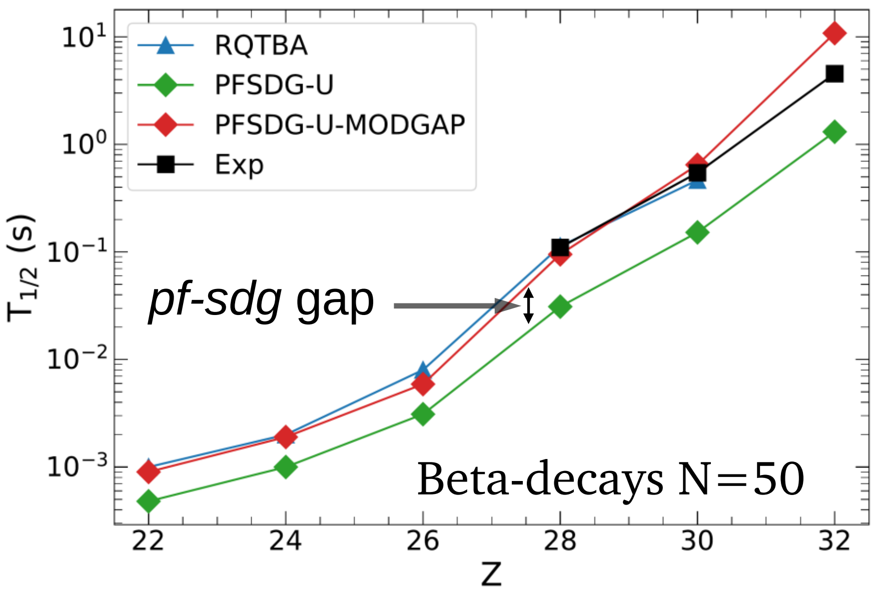
Shingles et al, ApJ 954, L41 (2023)

Structure around ^{78}Ni



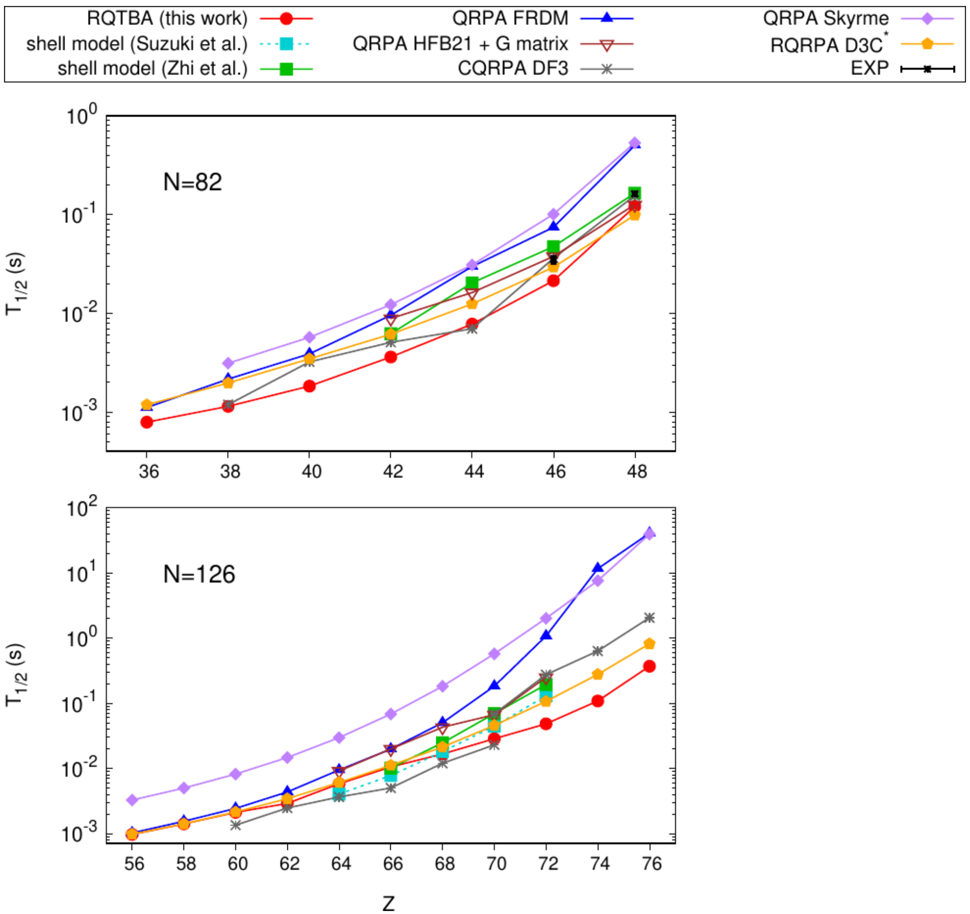


- Nuclei around 78Ni relevant for synthesis first r-process peak elements
- Coexistence deformed and spherical structures
- Shell-model calculations as benchmark of global calculations of beta-decay rates

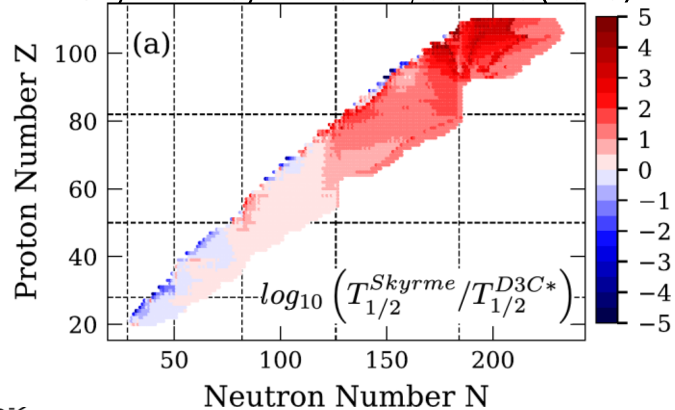


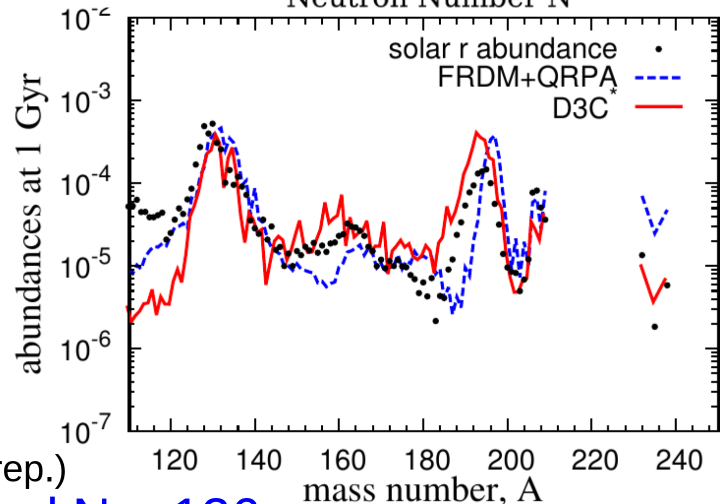
Nuclear physics input: beta-decay half-lives

- Develop Global beyond mean field methods for beta-decay half-lives
- N~126 Half-lives have a strong impact on the position of the A ~ 195 peak



DC3*: Marketin+PRC 93, 025805 (2016)
Skyrme: Ney+ PRC102, 034326 (2020)



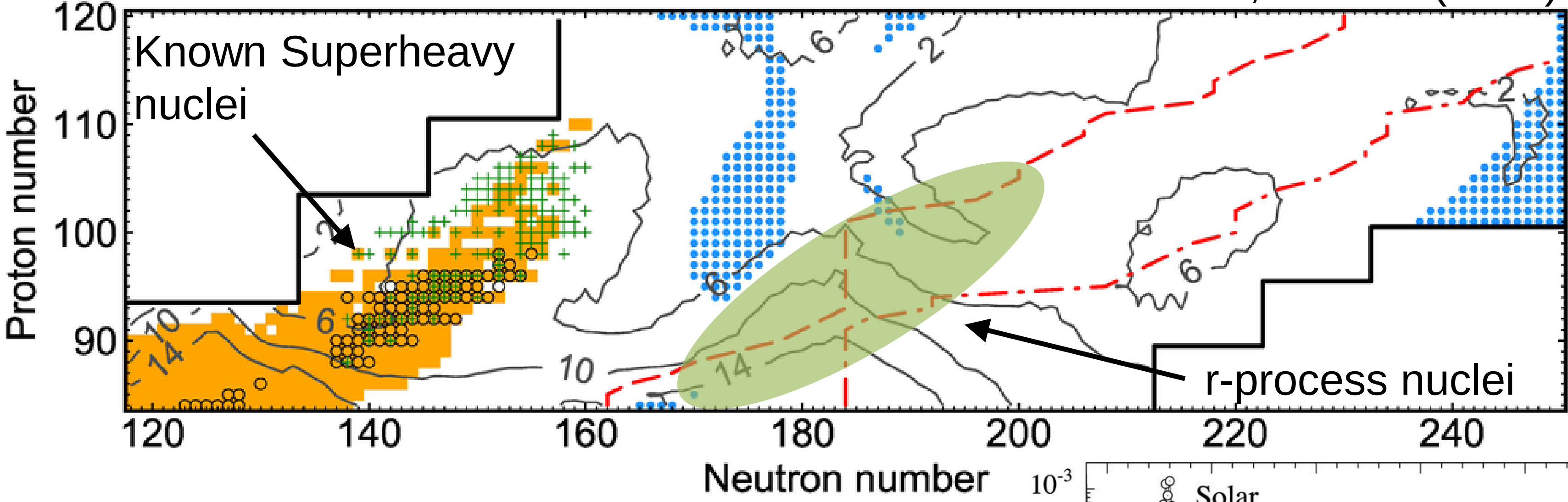


Beyond mean field for spherical nuclei (C. Robin, GMP, in prep.)

Need data for beta decay half-lives around N ~ 126

What is the role of fission in the r-process nucleosynthesis?

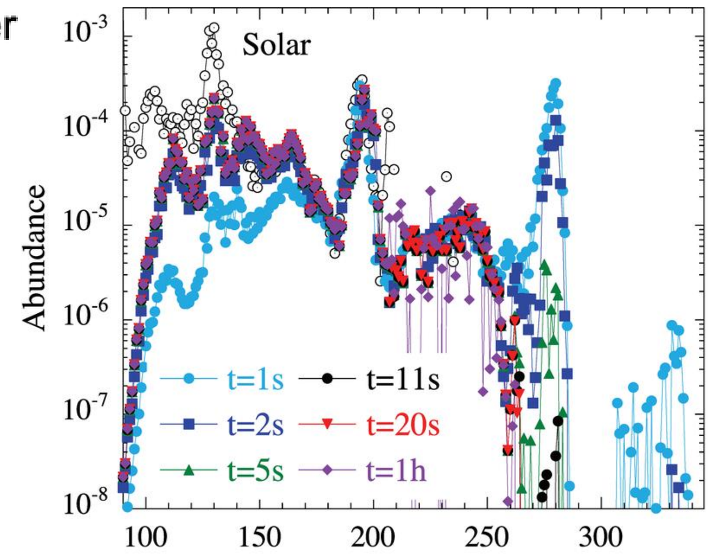
Giuliani et al PRC 97, 034323 (2018)



Current r-process modes predict substantial production of nuclei around A~ 280 (Z ~ 96 N ~ 184)

However during their decay to beta stability they fission on timescales of seconds to hours.

What are the heaviest elements that survive on kilonova timescales?

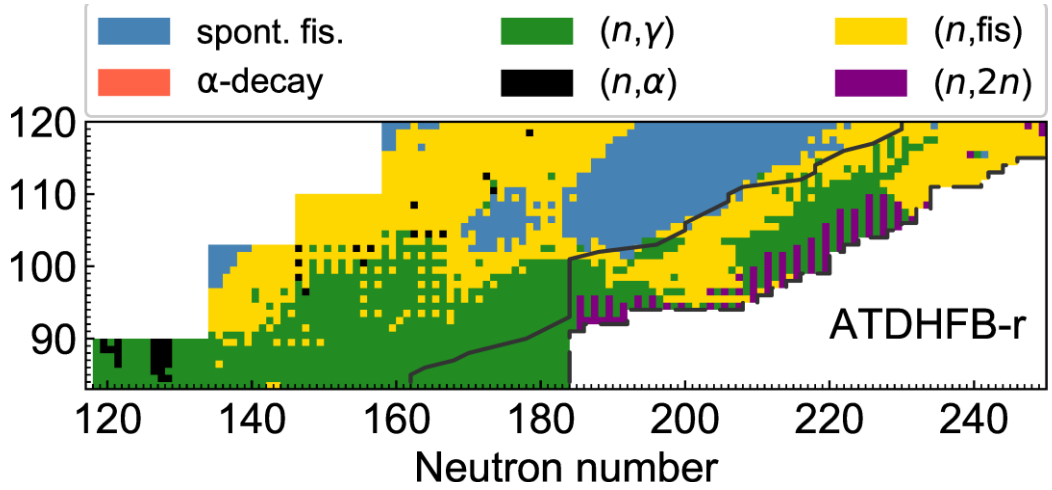


Goriely and GMP NPA **944**, 158 (2015).

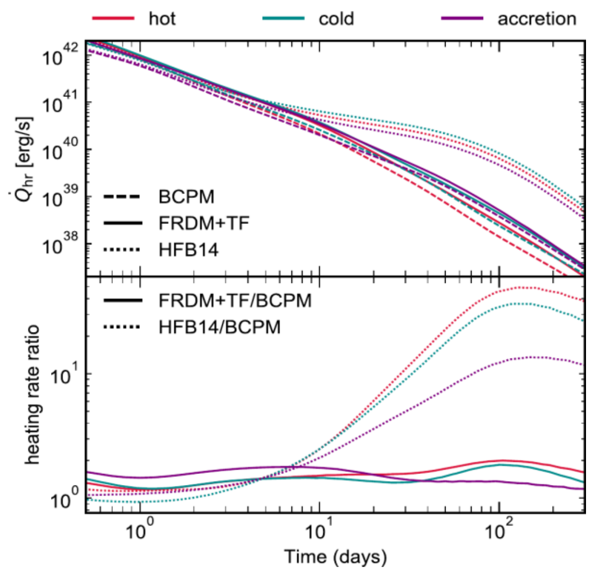
Superheavy region: mine-field due to low fission barriers

Giuliani, GMP, Robledo, PRC 97, 034323 (2018).

- During the r-process operation mainly (n,fiss) limits the production of superheavy nuclei
- After freeze-out a competition between beta-delayed, spontaneous and neutron induced fission.



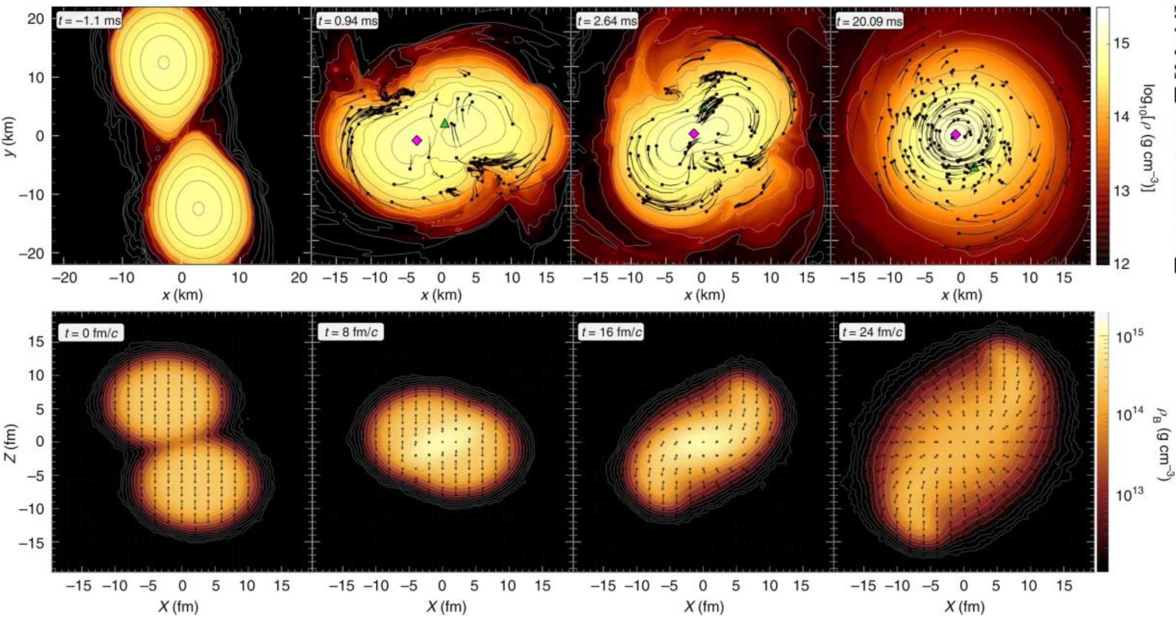
Fission may have a strong impact on heating rates for kilonova

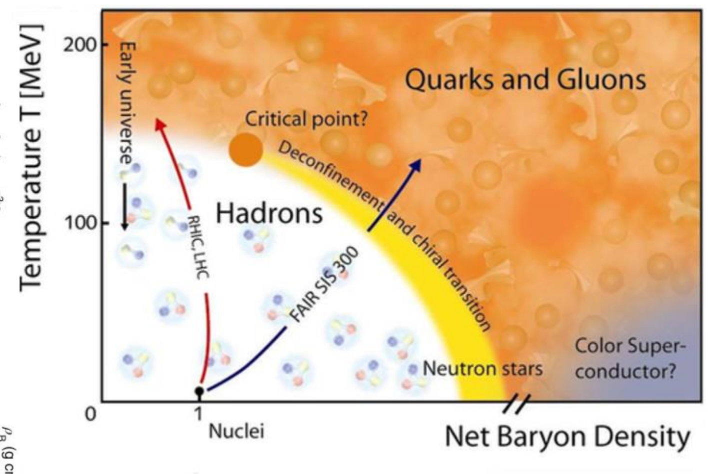


Giuliani, GMP, Wu, Robledo, PRC **102**, 045804 (2020)

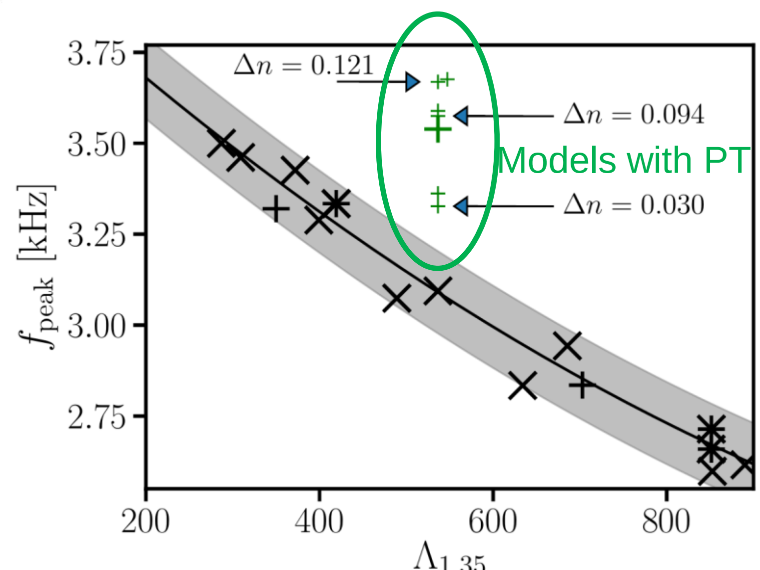
Gravitational Wave Signal from Neutron Star mergers (postmerger)

HADES collaboration, *Nat. Phys.* **15**, 1040–1045 (2019)





- Similarity between neutron star mergers and heavy ion collisions
- Postmerger signal characterized by a peak frequency.
- Simultaneous measurement tidal deformability and peak frequency may provide signature of a first order phase transition to QGP
- Impact on kilonova light curve?



Bauswein et al, PRL 122, 061102 (2018)

Summary:
The Universe in the Lab

- Connect Multi-messenger observations (Gravitational and Electromagnetic waves) to GSI/FAIR experiments:
  - Kilonova observations provide direct evidence of the “in situ operation of the r-process”
  - Gravitational Waves as probes of high density matter
- Challenges:
  - Impact of weak processes and EoS in the ejecta properties and GW signals
  - Improved nuclear and atomic input
  - 3D radiative transfer to benchmark simulations and nucleosynthesis predictions with observations.