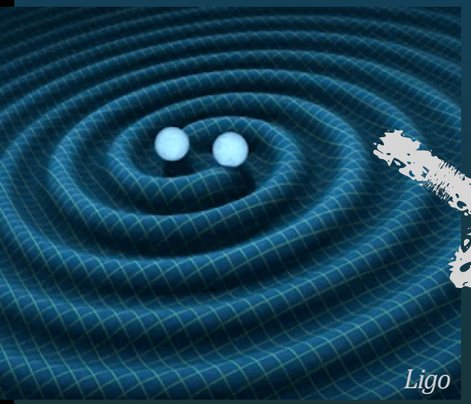
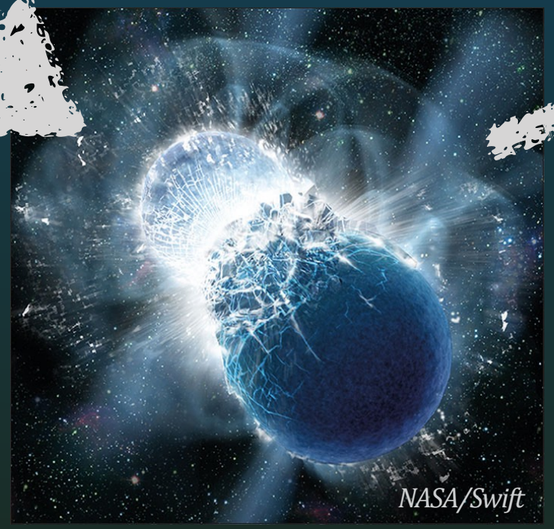
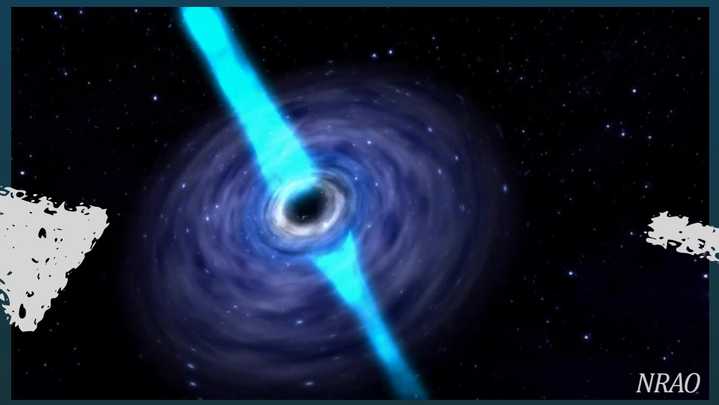
R-process nucleosynthesis in neutron-star mergers

(or How much Gold is produced?)







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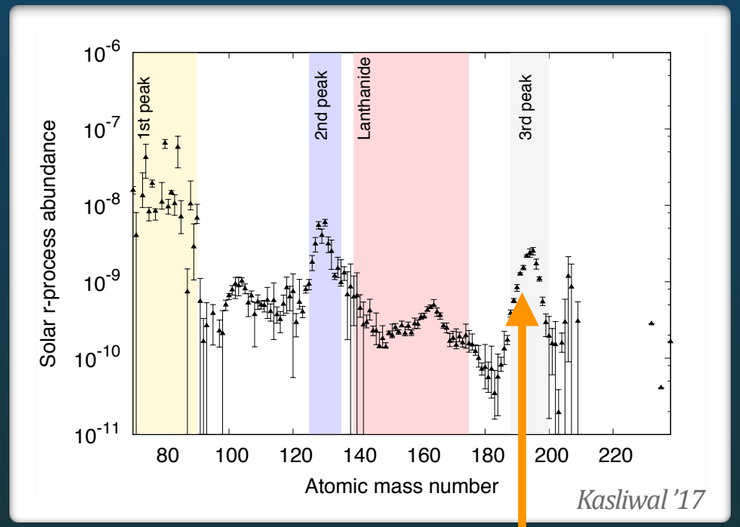
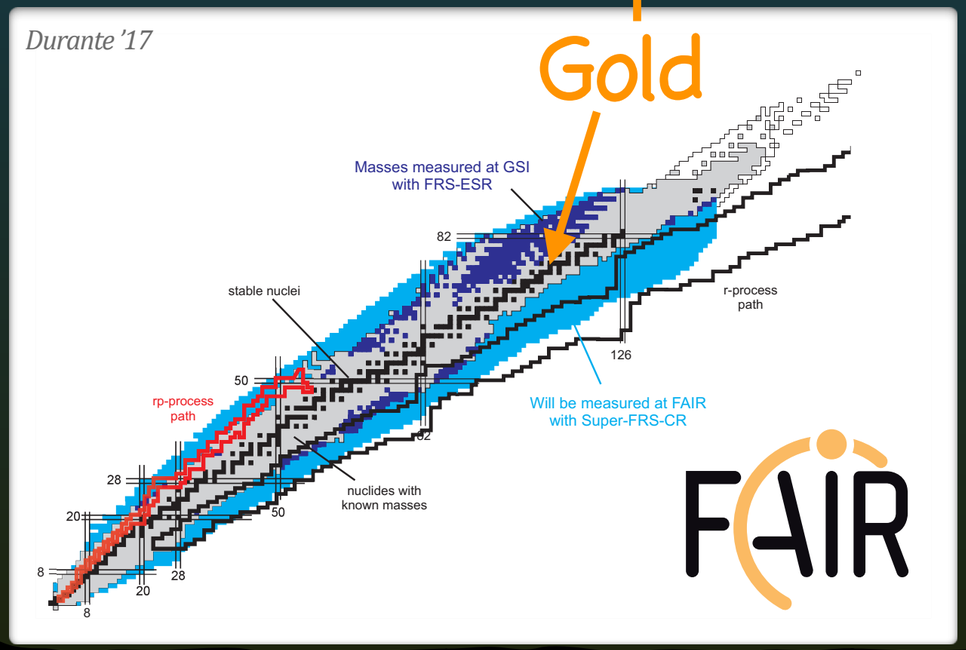
GSI Theory

- O. Just, I. Kullmann, S. Goriely, A. Bauswein, H.T. Janka, C.E. Collins, **arXiv:2109.14617**, accepted to MNRAS
- I. Kullmann, S. Goriely, O. Just, R. Ardevol-Pulpillo, A. Bauswein, H.T. Janka, arXiv:2109.02509, accepted to MNRAS
- O. Just, S. Goriely, H.T. Janka, S. Nagataki, A. Bauswein, MNRAS 509, 1377 (2022)

Long-standing question:
Where do heavy (r-process) elements come from?





rapid neutron capture process requires:

- ✓ high neutron richness
- ✓ fast expansion
- ✓ high temperature
- ➡ can only take place in outflows from astrophysical explosions

suggested environments:

- ★ core-collapse supernovae
- ★ magneto-rotational supernovae
- ★ ***neutron star mergers (only source confirmed so far in observed event on GW170817 on August 17th, 2017!)***

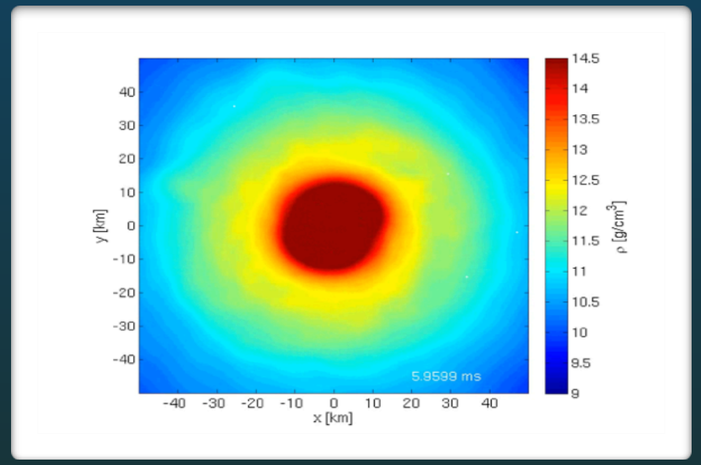
open questions:

- ✤ what elements are created in which ejecta component?
- ✤ what are properties of exotic nuclei and reaction rates far away from the valley of stability where the r-process proceeds?
- ✤ what is the electromagnetic signal called kilonova?
- ✤ are neutron star merger dominant sites of r-process?

Outflows during the first ~20 milliseconds: Dynamical ejecta

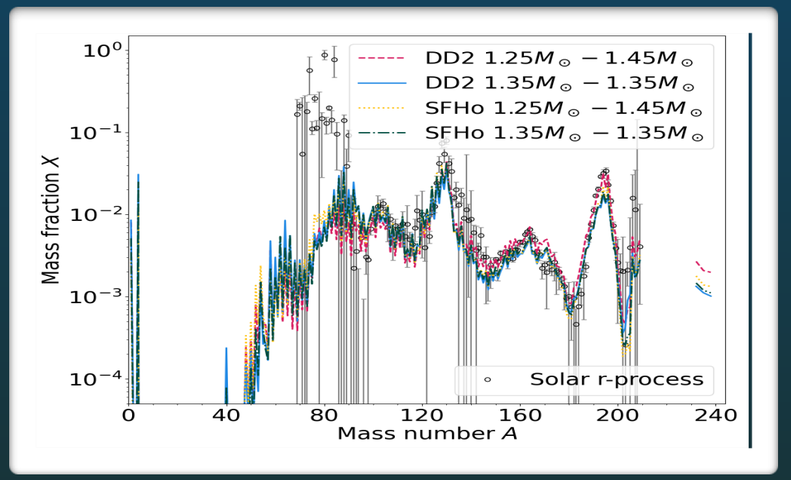
(arXiv:2109.14617, arXiv:2109.02509)

hydrodynamical simulations



- ✓ matter pushed out dynamically due to violent collision
- ✓ computationally very challenging to describe transport of neutrinos (E~10 MeV)

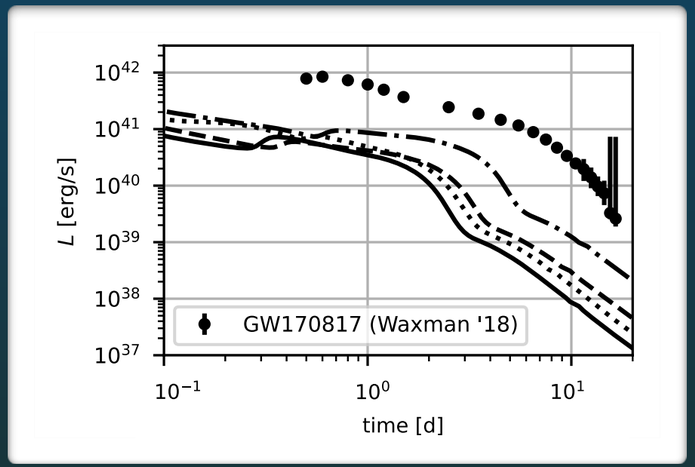
nucleosynthesis analysis



- ✓ robust r-process between $80 < A < 240$
- ✓ not very sensitive to stellar masses
- ✓ but sensitive to adopted nuclear input and to neutrino transport scheme

➡ suggests that dynamical ejecta are viable r-element sources

kilonova light curve



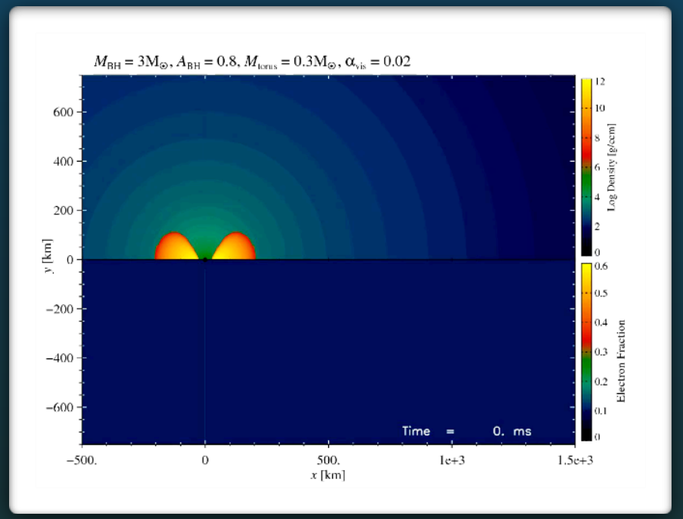
- ✓ powered by radioactive decay of newly synthesized elements
- ✓ requires detailed knowledge of r-process path
- ✓ light curve peaks at ~ 1 day in infra-red wavelengths

➡ challenging to explain kilonova of GW170817 with typical dynamical ejecta

Outflows during the next ~ 10 seconds from black-hole torus remnant

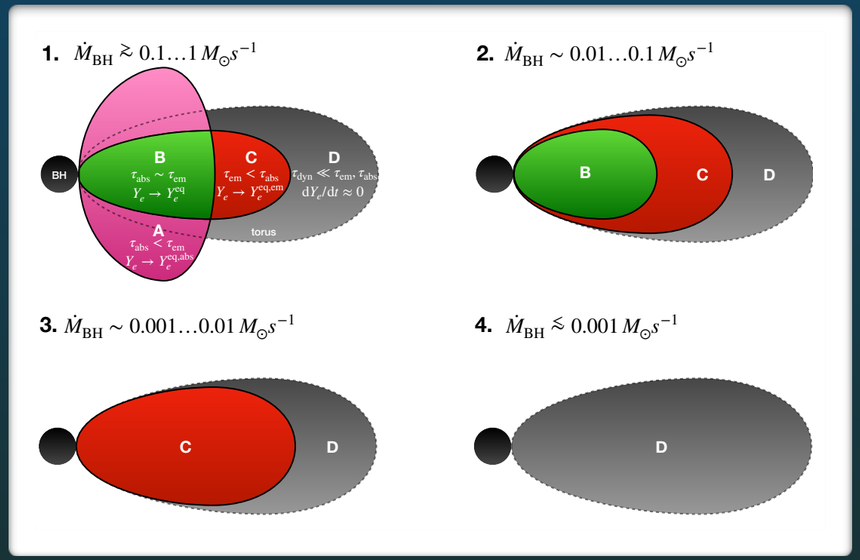
(MNRAS 509, 1377 ,2022)

hydrodynamical simulation



- ✓ matter ejected due to viscous heating in turbulent torus
- ✓ about 20-40% of initial torus can become ejected
- ✓ typically more mass ejected than in dynamical ejecta

analysis for different torus masses M_{torus}

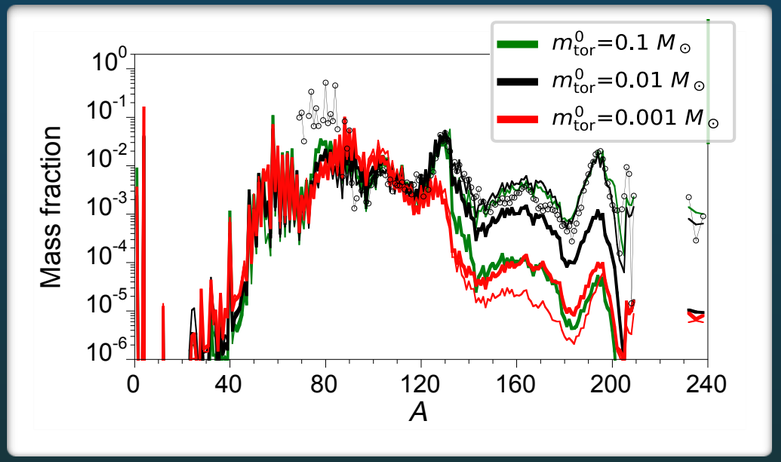


neutron richness tends to…

- ✓ … increase with M_{torus} due to electron degeneracy
- ✓ … decrease again for very high M_{torus} because of higher neutrino luminosities

➡ highest neutron density for **$0.01 < M_{torus}/M_{sun} < 0.1$**

nucleosynthesis analysis



- ✓ production of heavy elements strongly depends on M_{torus}
- ✓ sensitive to adopted nuclear models

➡ supports that black-hole tori in mergers are generic r-process sources

Conclusions

- ✓ outflows of mergers and their remnants appear as dominant/important sites of heavy element production
- ✓ quantitatively reliable models needed to interpret future observation of neutron star mergers
- ✓ many more kilonova events expected with upgraded GW detectors and new telescopes
- ✓ challenges:
  - ✳ self-consistent modeling including neutrino interactions, magnetic fields, turbulence
  - ✳ radiative transfer of kilonovae and atomic data of heavy elements
  - ✳ improved nuclear input from theoretical models and experiments (FAIR) critical to understand nucleosynthesis output and interpret kilonova
  - ✳ impact of "exotic" physics, e.g. neutrino oscillations, axions, dark matter?

Thank you for your attention!