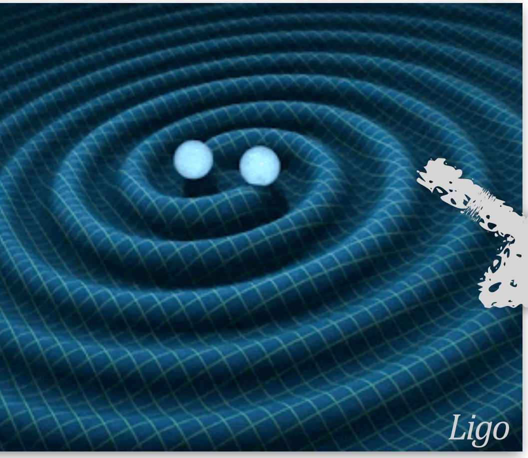
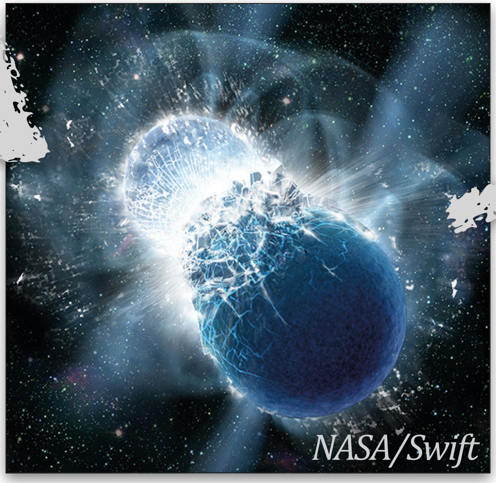
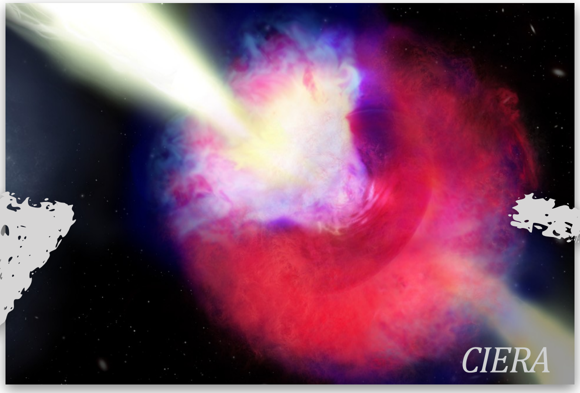
MU Days 2023, Karlsruhe, Sept. 14th

Using simulations of colliding neutron stars to investigate the origin of the heaviest elements







Oliver Just

Relativistic Astrophysics Group, GSI

with: A. Bauswein, C. Collins, A. Flörs, S. Goriely, J. Guilet, H.-Th. Janka, G. Leck, G. Martinez-Pinedo, L. Shingles, S. Sim, A. Sneppen, T. Soultanis, V. Vijayan, D. Watson, Z. Xiong, …

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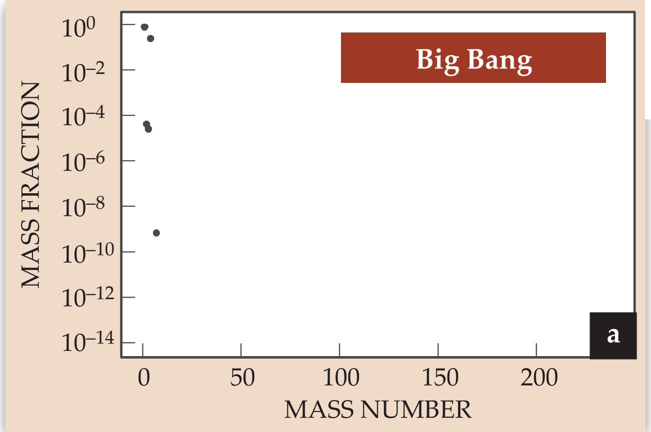
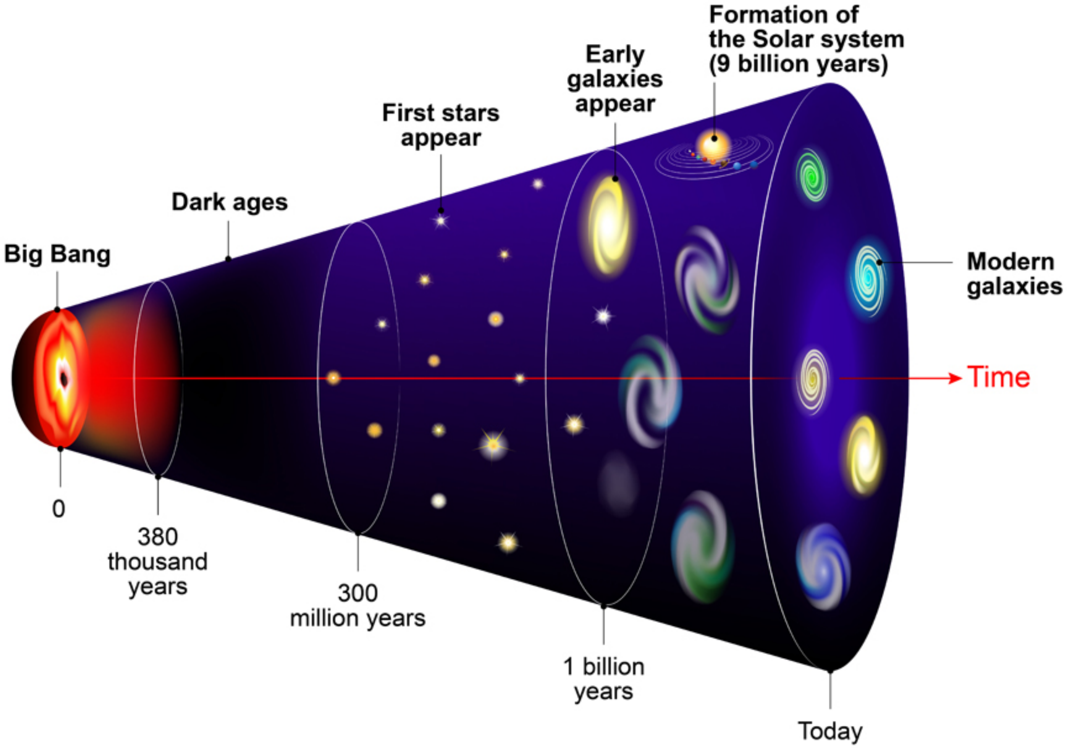
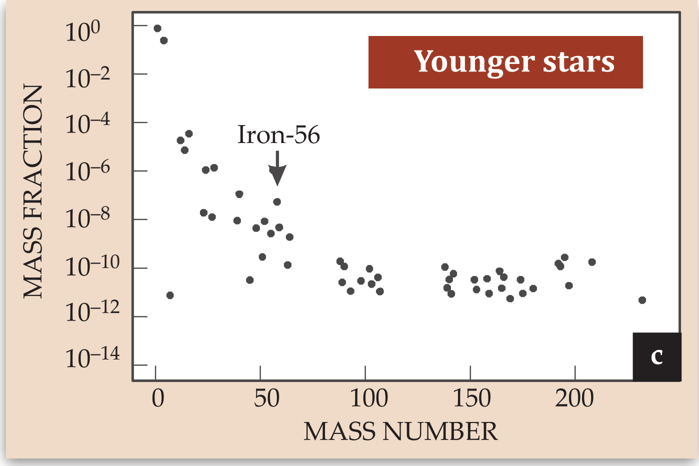
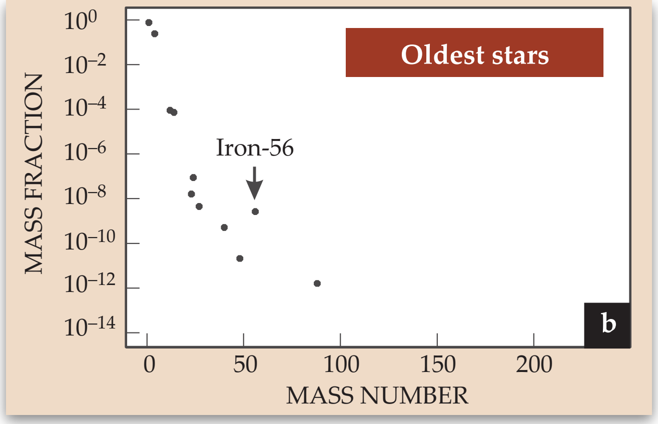
Chemical enrichment of the Universe

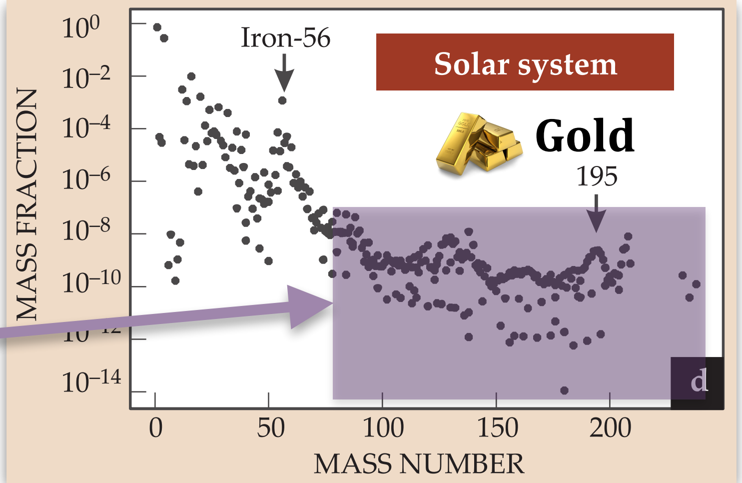








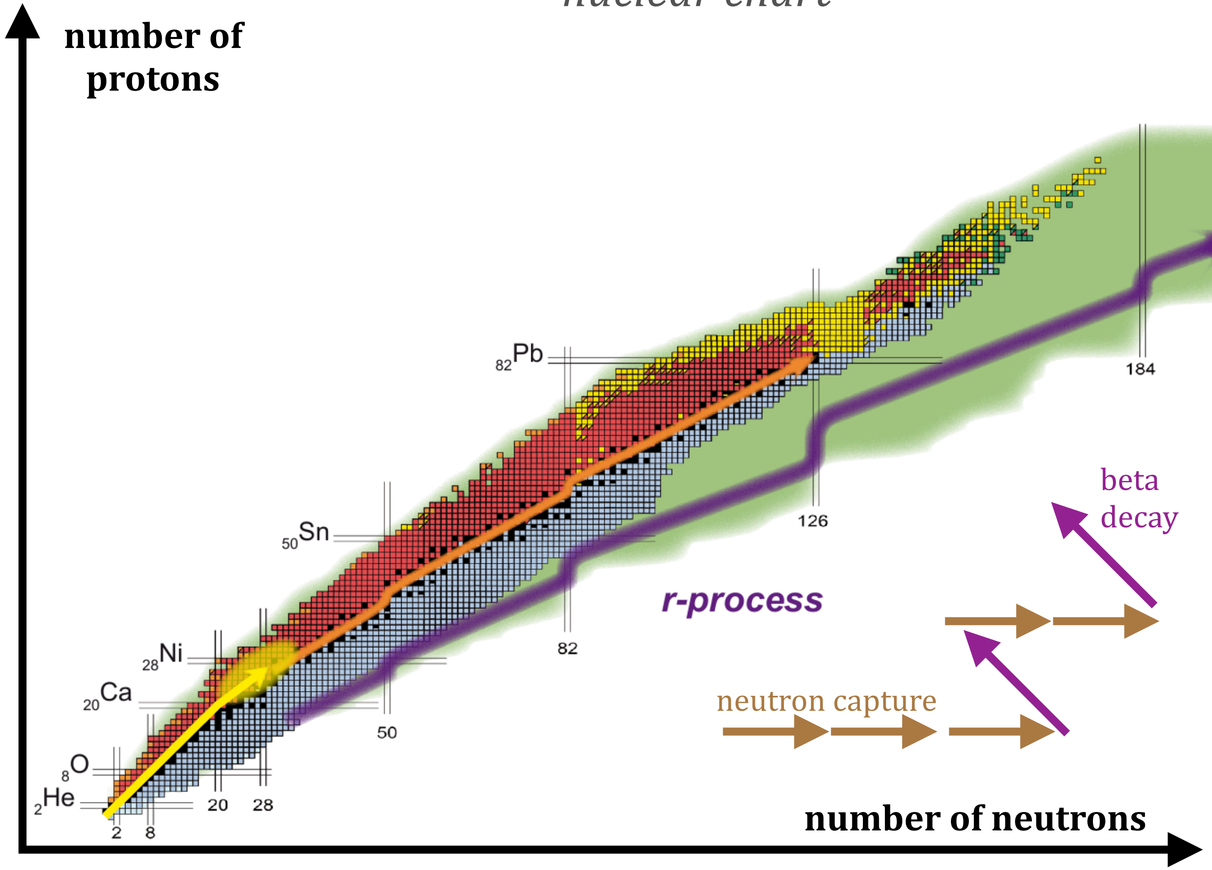
- stars of different age provide tracers of chemical enrichment history
- **but:** poor knowledge of elements produced by individual nucleosynthesis events
- elements heavier than Iron **must** be produced by neutron capture (Coulomb barrier)



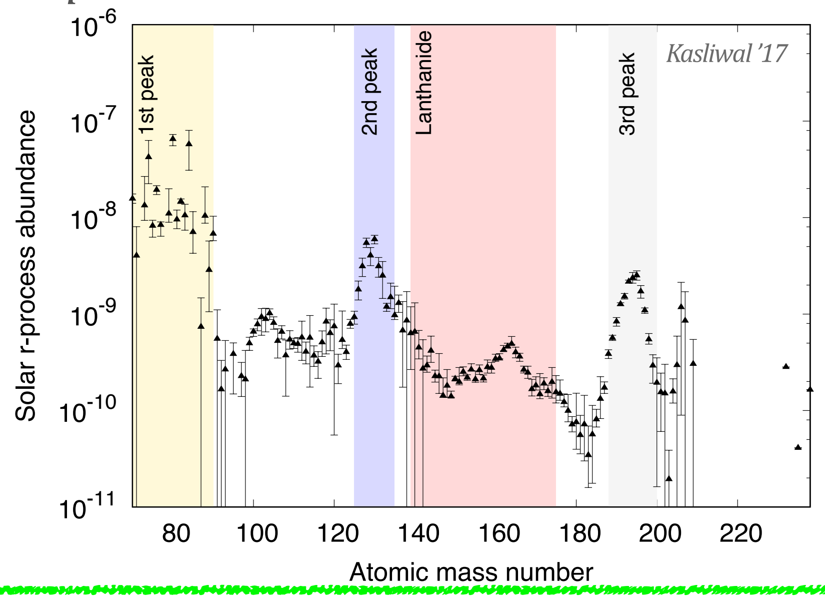
abundance plots from Schatz 2008

The rapid neutron-capture (or r-) process

nuclear chart



r-process abundances measured in the Sun



REQUIRED conditions on the astrophysical environment:

- ✓ high neutron richness
- ✓ fast expansion
- ✓ high temperatures

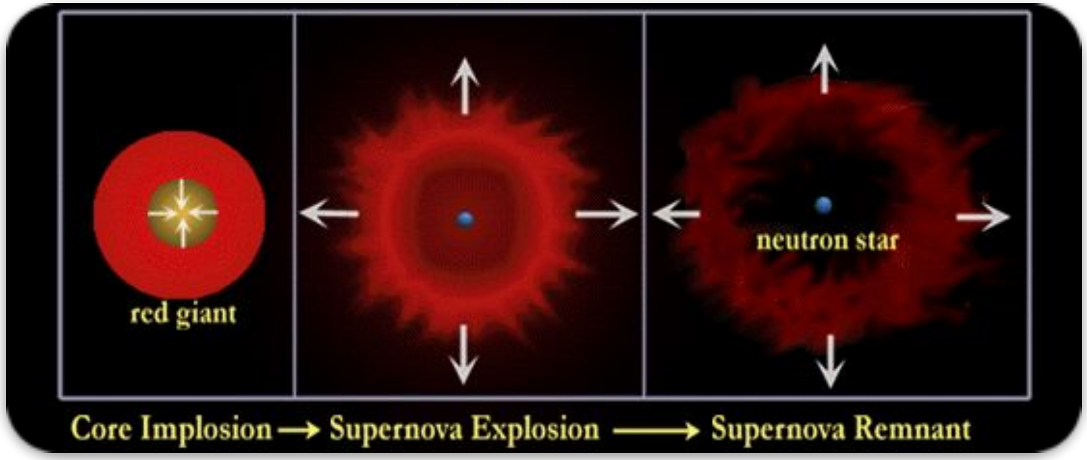
➡ **suggests outflows from astrophysical explosions**

Where does the r-process take place??? 🧐

(one of the longest-standing questions of nuclear astrophysics)

Main candidates for r-process sites

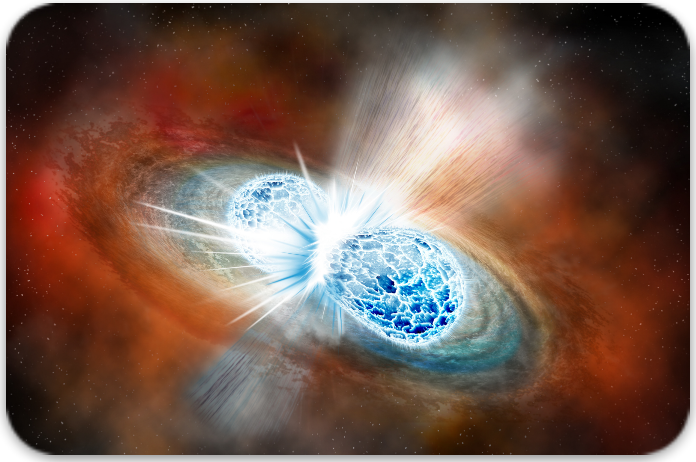
core-collapse supernova (CCSN)



ESO

- favored candidate for many decades
- core of massive star ($M > 8\ M_{sun}$) runs out of nuclear burning "fuel" —> implosion
- once core reaches nuclear densities —> implosion abruptly stops, bounce, explosion shock
- newly formed neutron star launches outflows ("neutrino-driven winds")
- **PROBLEM:** modern simulations predict proton-rich (not neutron-rich!) conditions

NS-NS (or NS-BH) merger

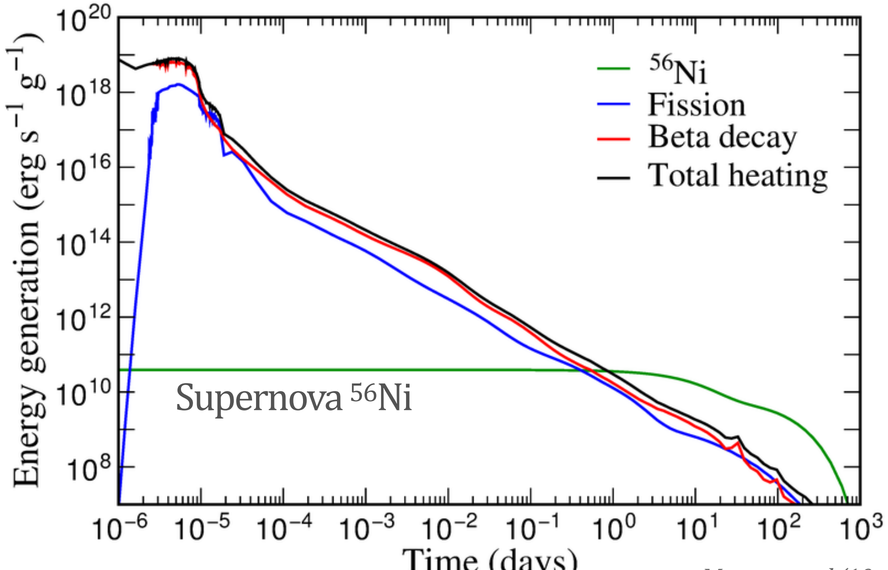


- massive stars born in binaries produce NS binaries
- ~O(10) NS binaries observed in our Galaxy (e.g. Hulse-Taylor pulsar)
- emission of gravitational waves —> decay of orbit —> coalescence
- ejection of few 0.01 M_{sun}
- **ejecta neutron-rich enough to enable r-process?**

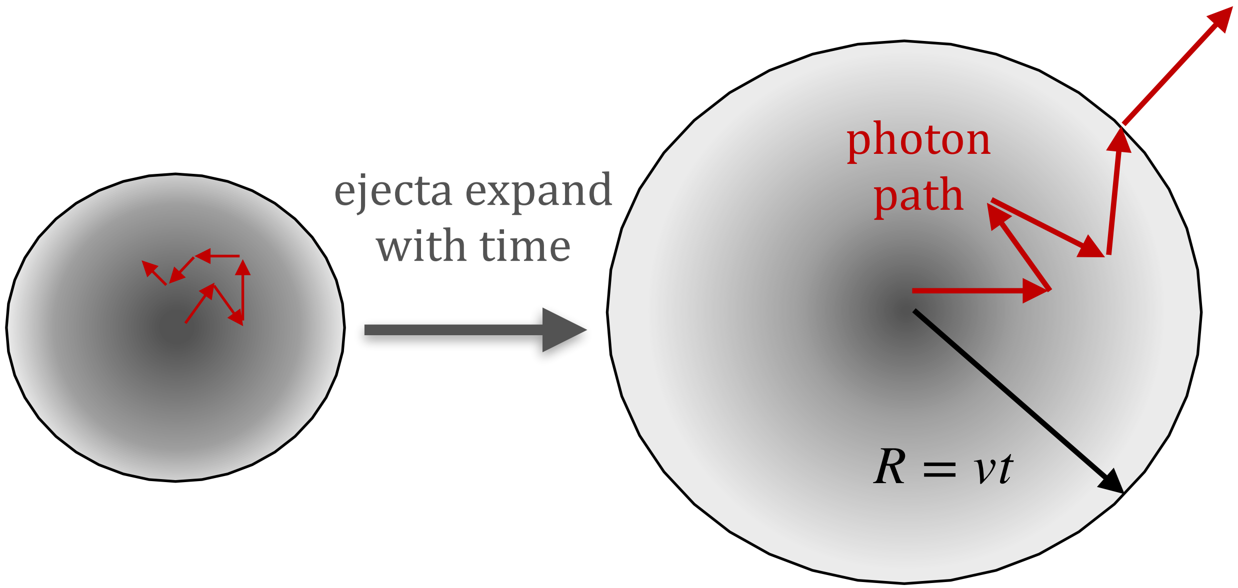
Kilonova: smoking gun for the r-process

("Kilo" because 1000 times brighter than a nova)

- radioactive decay of freshly synthesized material produces energy (= heat)
- heating rate typically declines as $t^{-1.3}$



Metzger et al. '10

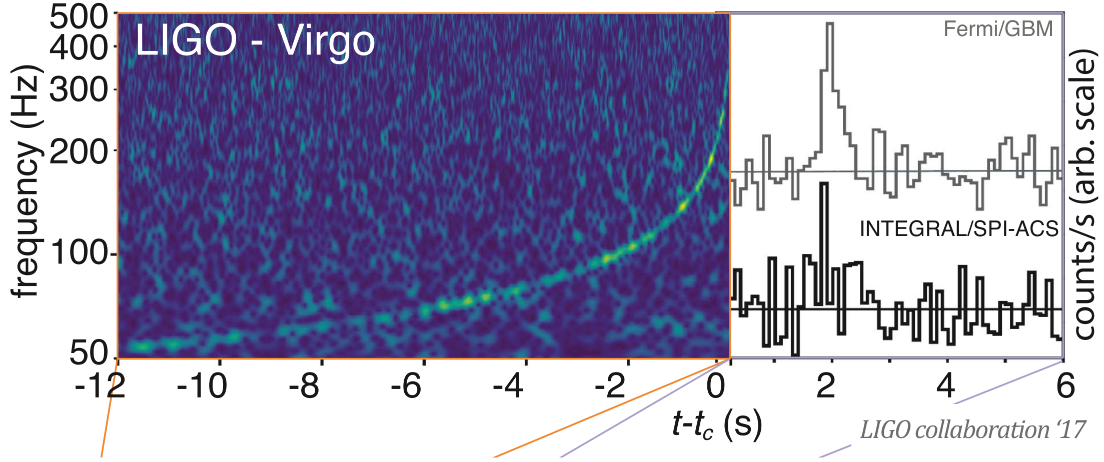


- radioactive heating creates photons —> random walk diffusion through expanding ejecta while density decreases
- photon opacity sensitive to detailed composition (very high for lanthanides)
- **allows in-situ observations of the r-process**

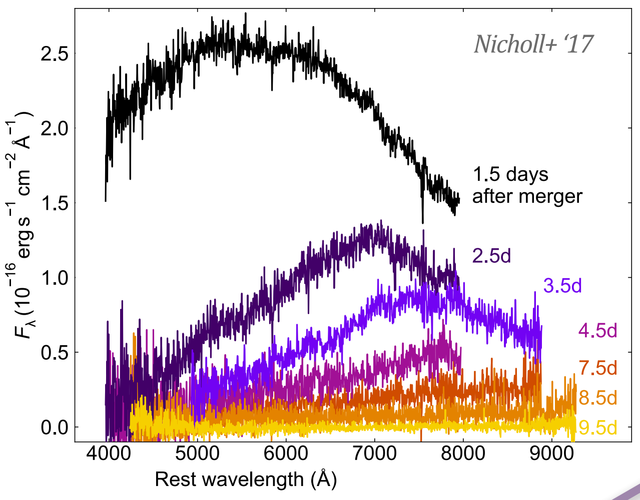
GW170817 - the first direct observation of a NS merger

(on August 17th, 2017)

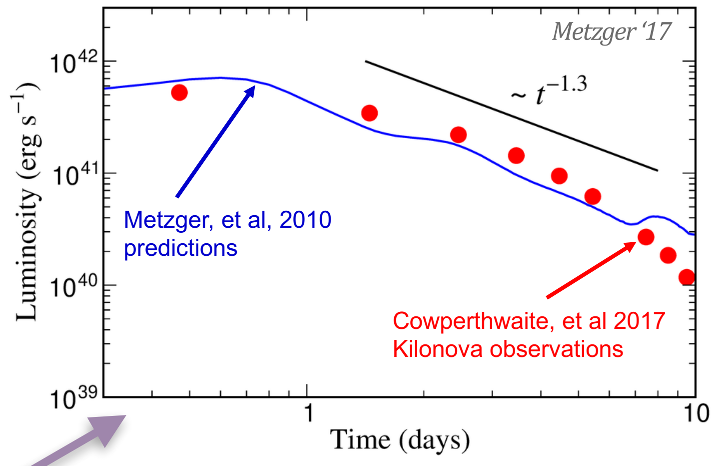
gravitational waves *gamma rays*



UV+optical+IR spectra



UV+optical+IR light curve



- dawn of new era of **multi-messenger** astronomy:
  - gamma-ray burst ~1.7 sec after GW signal
  - Kilonova ~1-10 days later
  - radio, optical, X-ray afterglow ~100-1000 days later

- light curve shows remarkable agreement with predicted $t^{-1.3}$ behavior
- strongly suggests that source of energy is radioactive decay of r-process elements

➡ ***confirmed long-standing idea that NS mergers are sites of heavy element nucleosynthesis***

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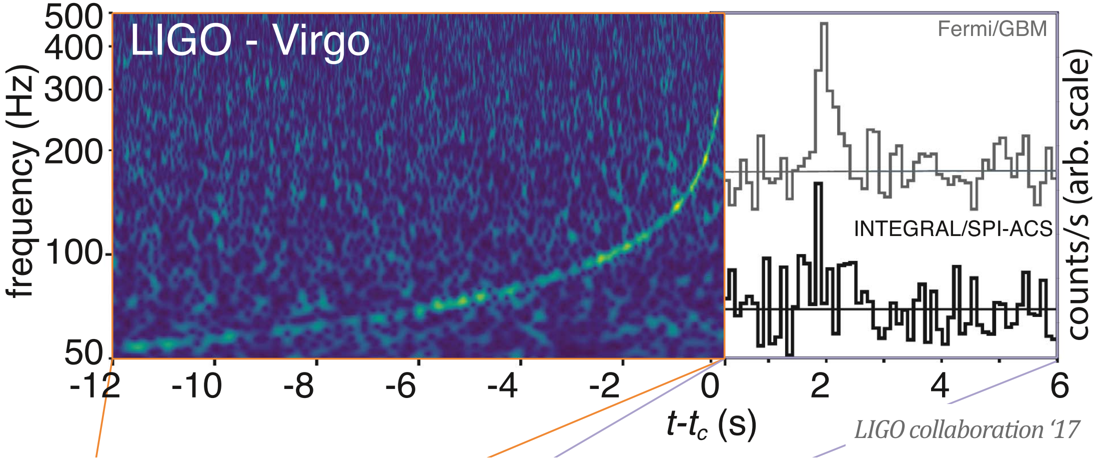
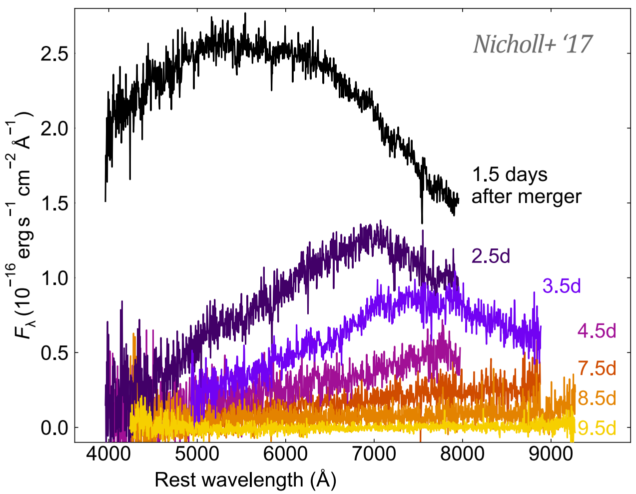
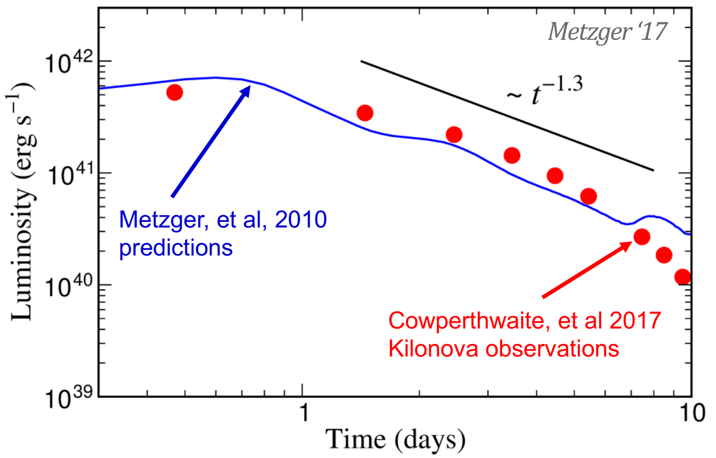
gravitational waves *gamma rays*



UV+optical+IR spectra



UV+optical+IR light curve

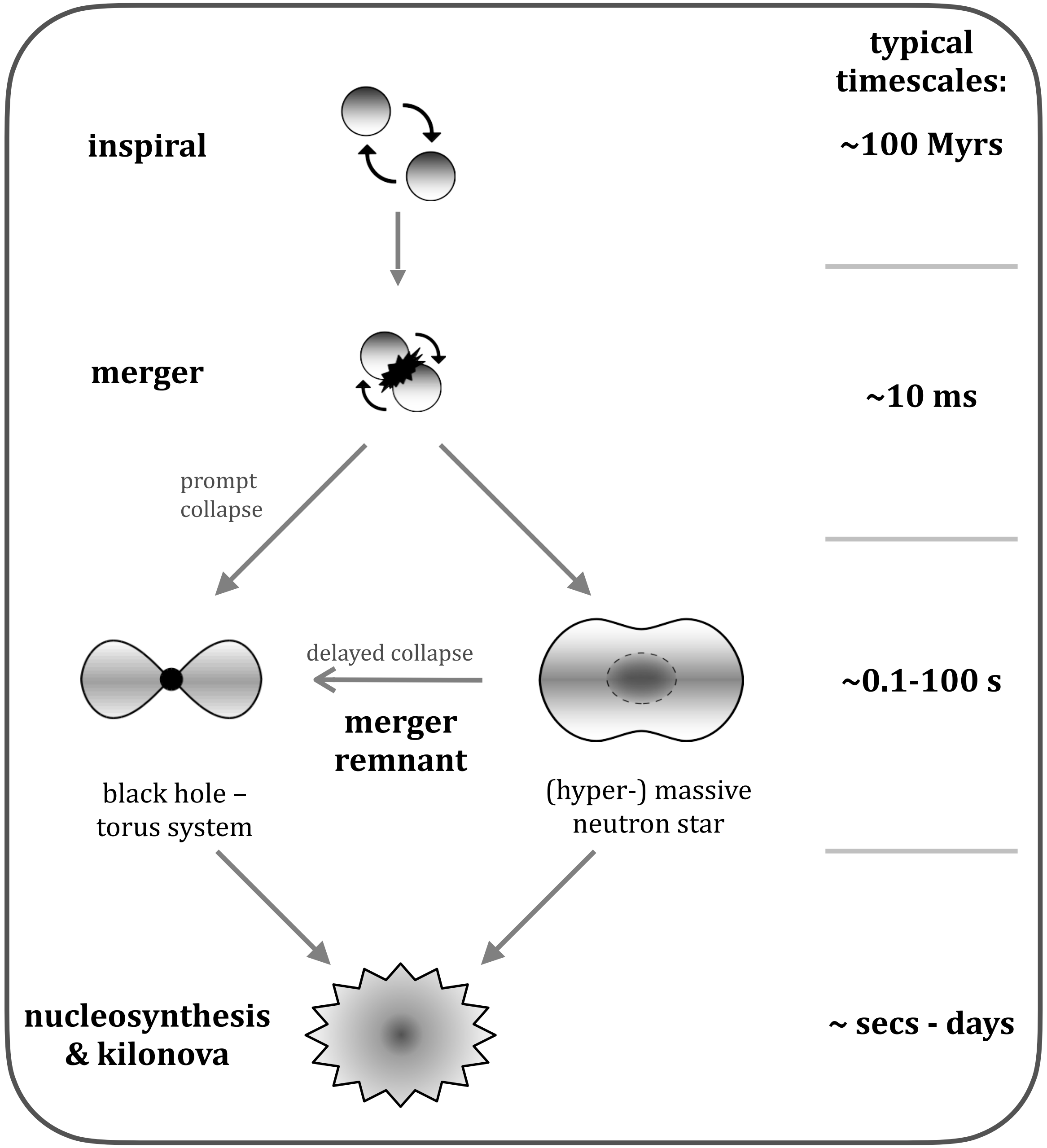


Many open questions:

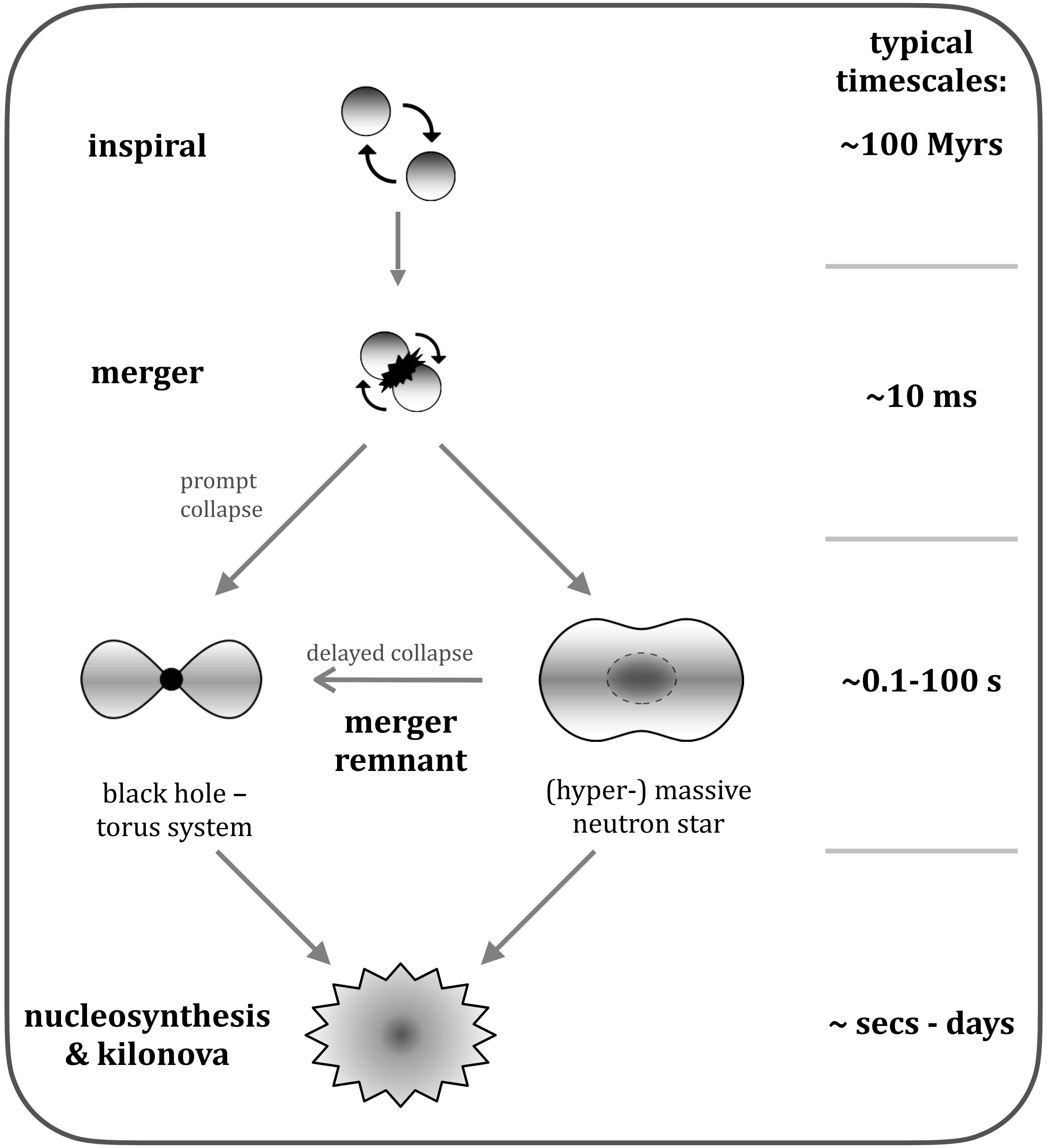
- Conditions in the outflow?
- How to infer composition and geometrical shape of outflows from kilonova signal?
- How to use kilonovae to measure cosmological distances?
- How to infer properties of high density matter?
- What are the detailed nuclear reactions? —> FAIR
- …

Call for reliable theoretical modeling of the merger process
in order to fully exploit future observations and experimental capabilities!

NS mergers: Overview



Physics ingredients



$$Y_e = \frac{N_{\mathrm{proton}}}{N_{\mathrm{proton}} + N_{\mathrm{neutron}}}$$

Neutrino transport
- crucial for predicting the weak reactions and composition ($\boldsymbol{Y_e}$)
- impact of neutrino oscillations at high densities

Magnetic fields and turbulence
- transport angular momentum
- trigger matter ejection

General/special relativistic effects
- velocities close to speed of light
- strong space-time curvature around a NS or BH

Nuclear physics
- govern the dynamics of the merger and its outflow
- determine the nucleosynthesis yields

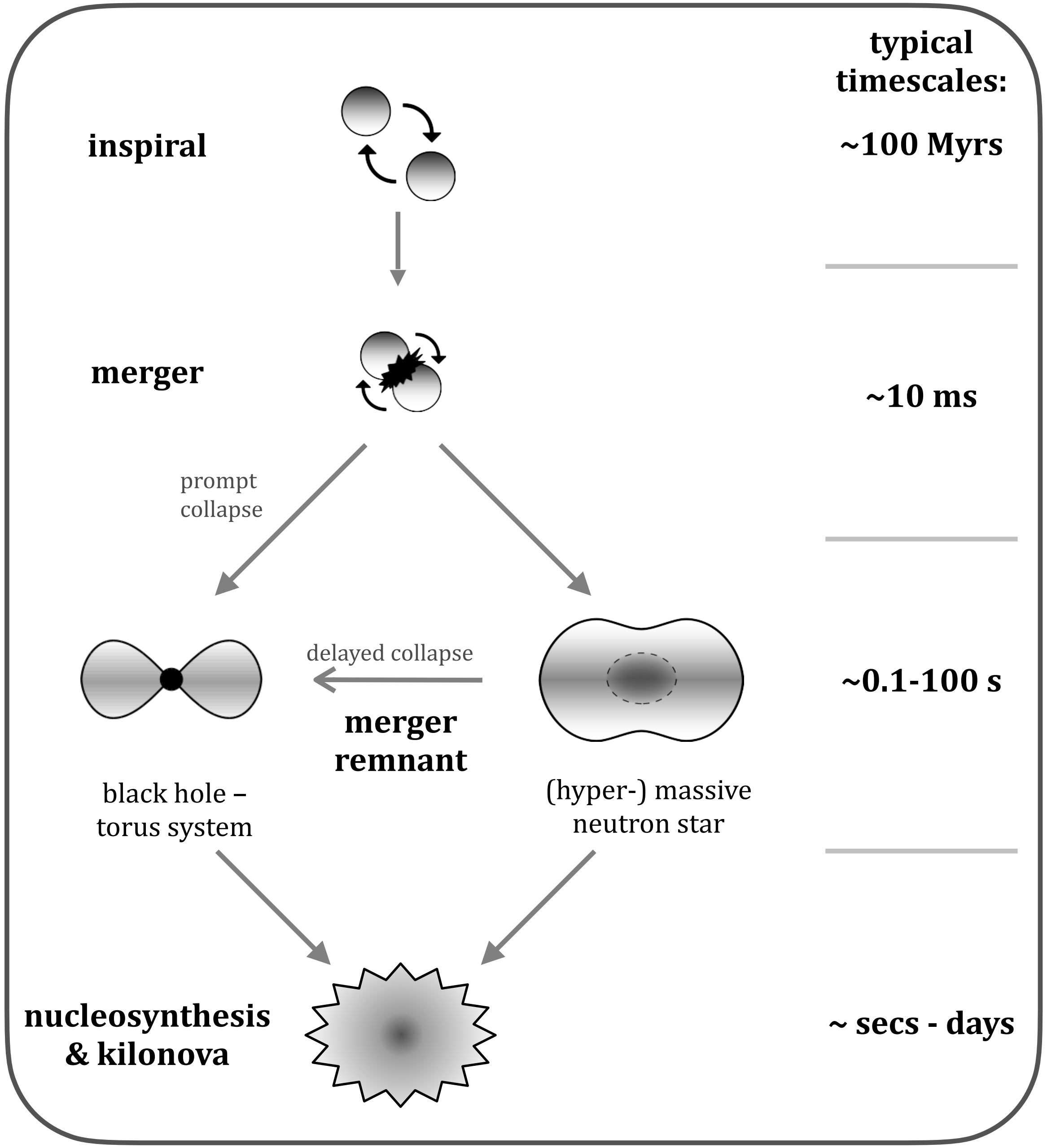
Atomic physics and photon transfer
- atomic line lists and opacities affect kilonova signal
- non-LTE effects

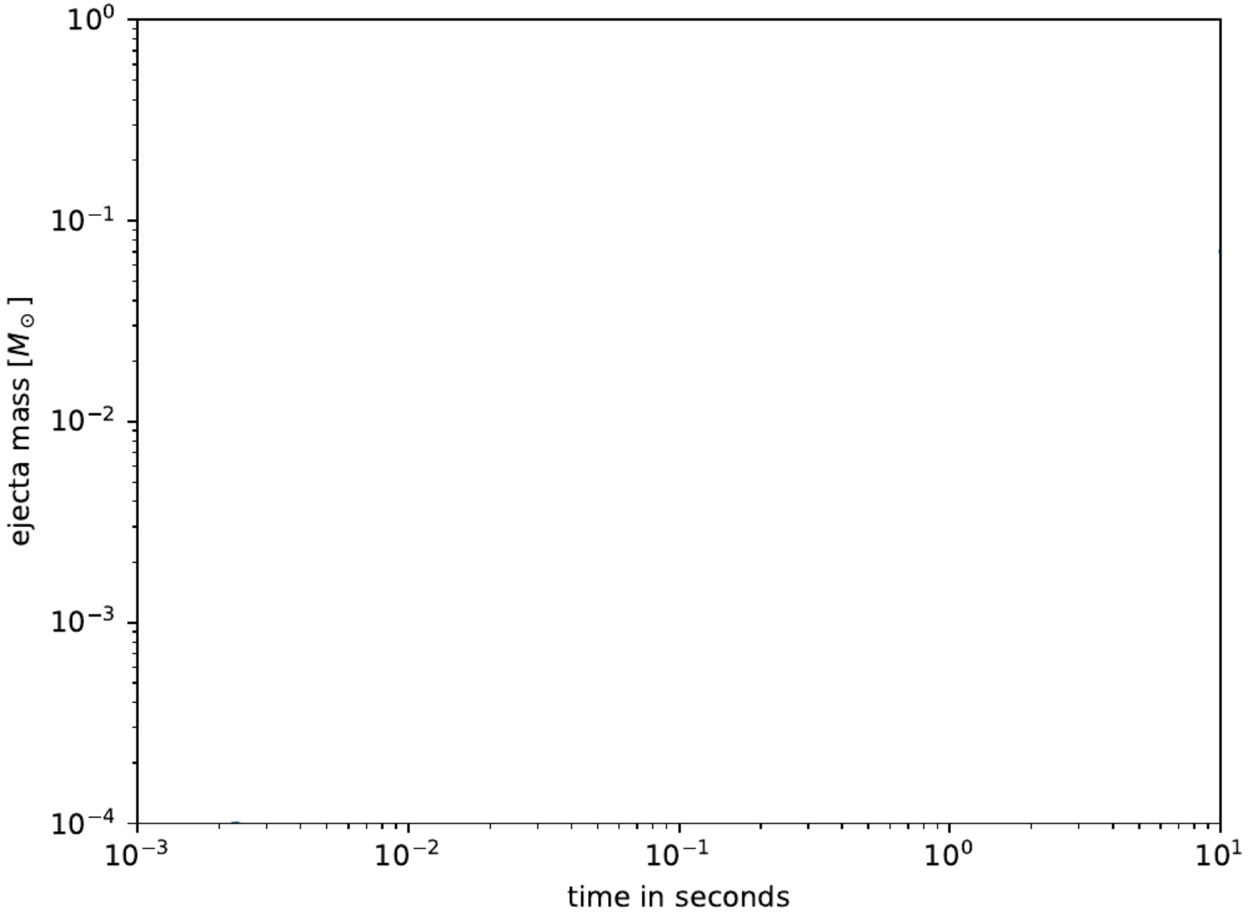
➡ **self-consistent modeling requires expensive, large-scale numerical simulations**

➡ ***most current simulations focus only on one, not all, merger phases…***

End-to-end models capturing all phases of matter ejection

(Just et al., ApJ Letters 951, L12, 2023)





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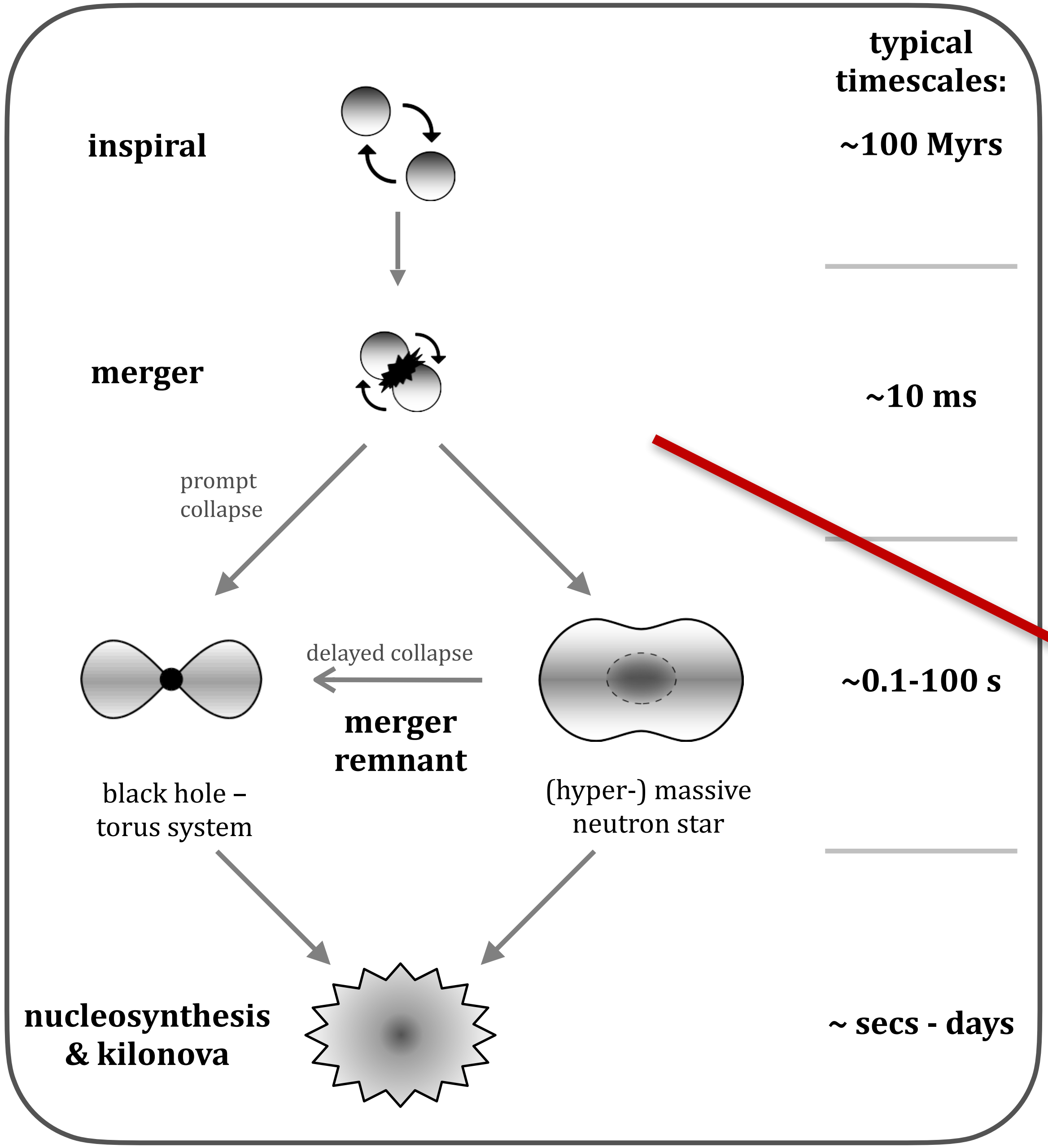

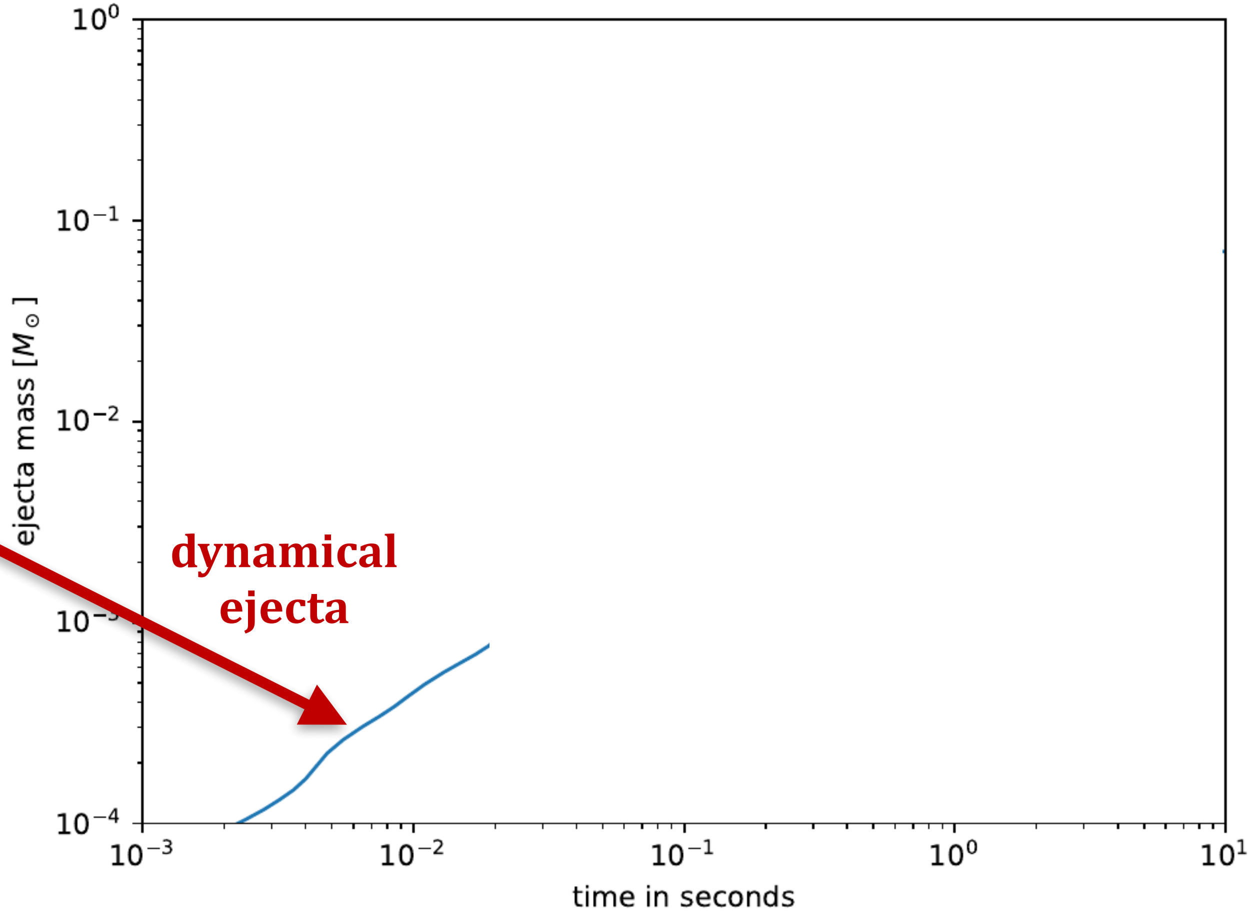

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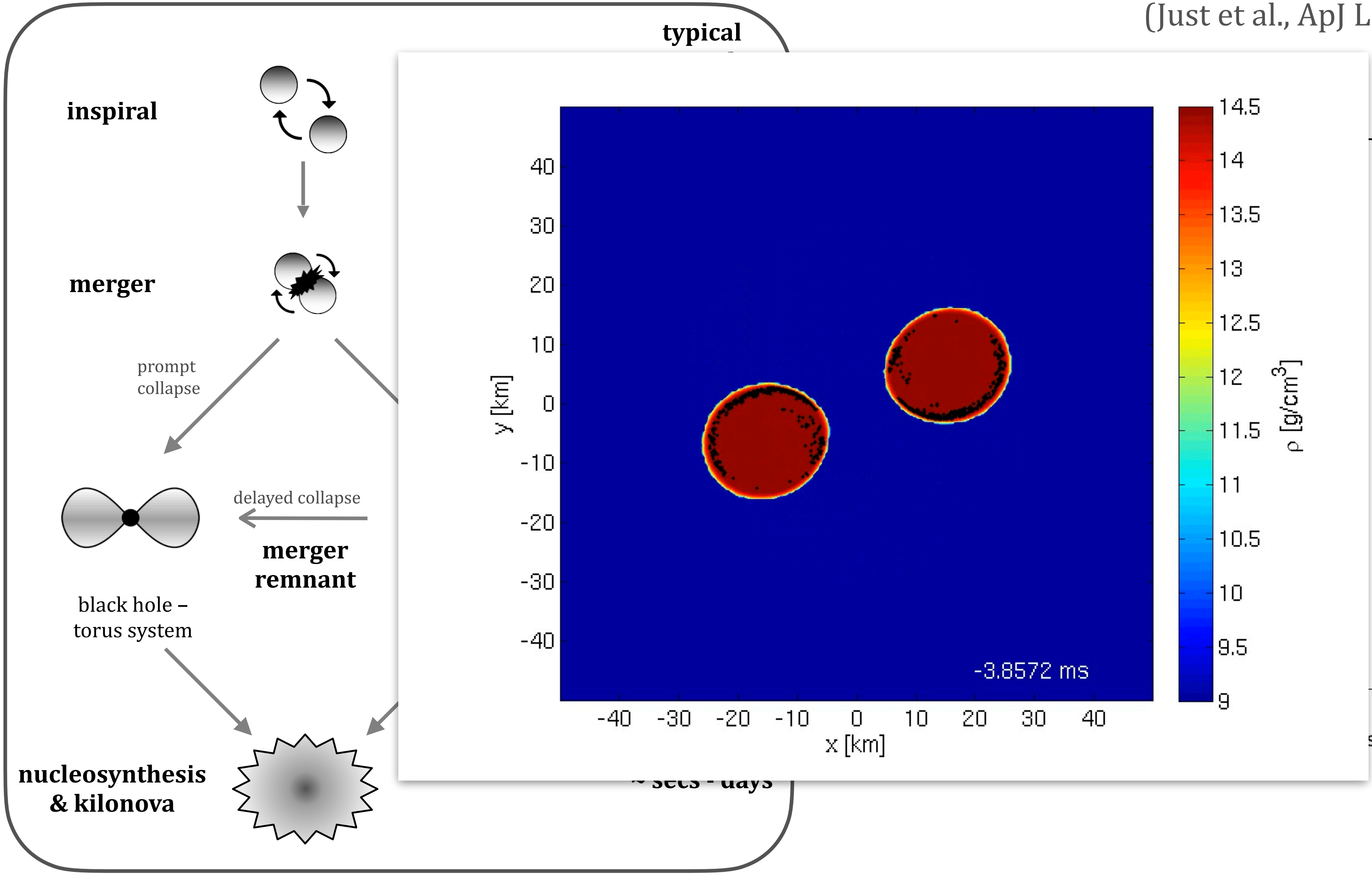

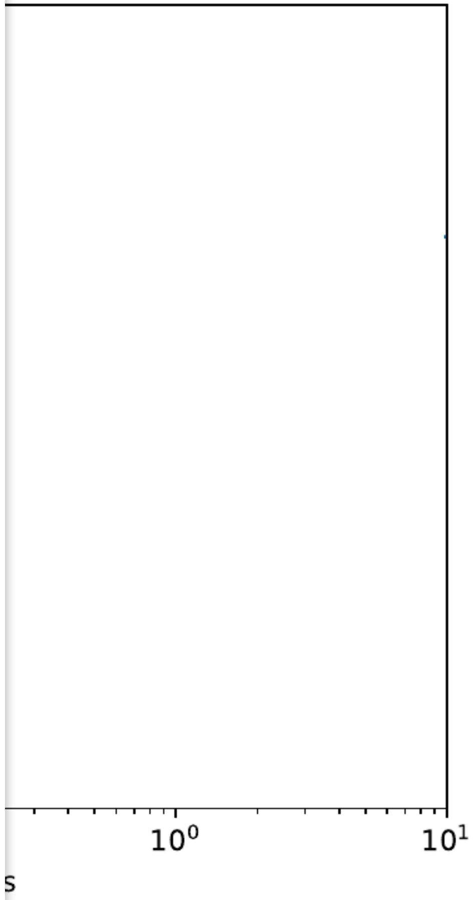

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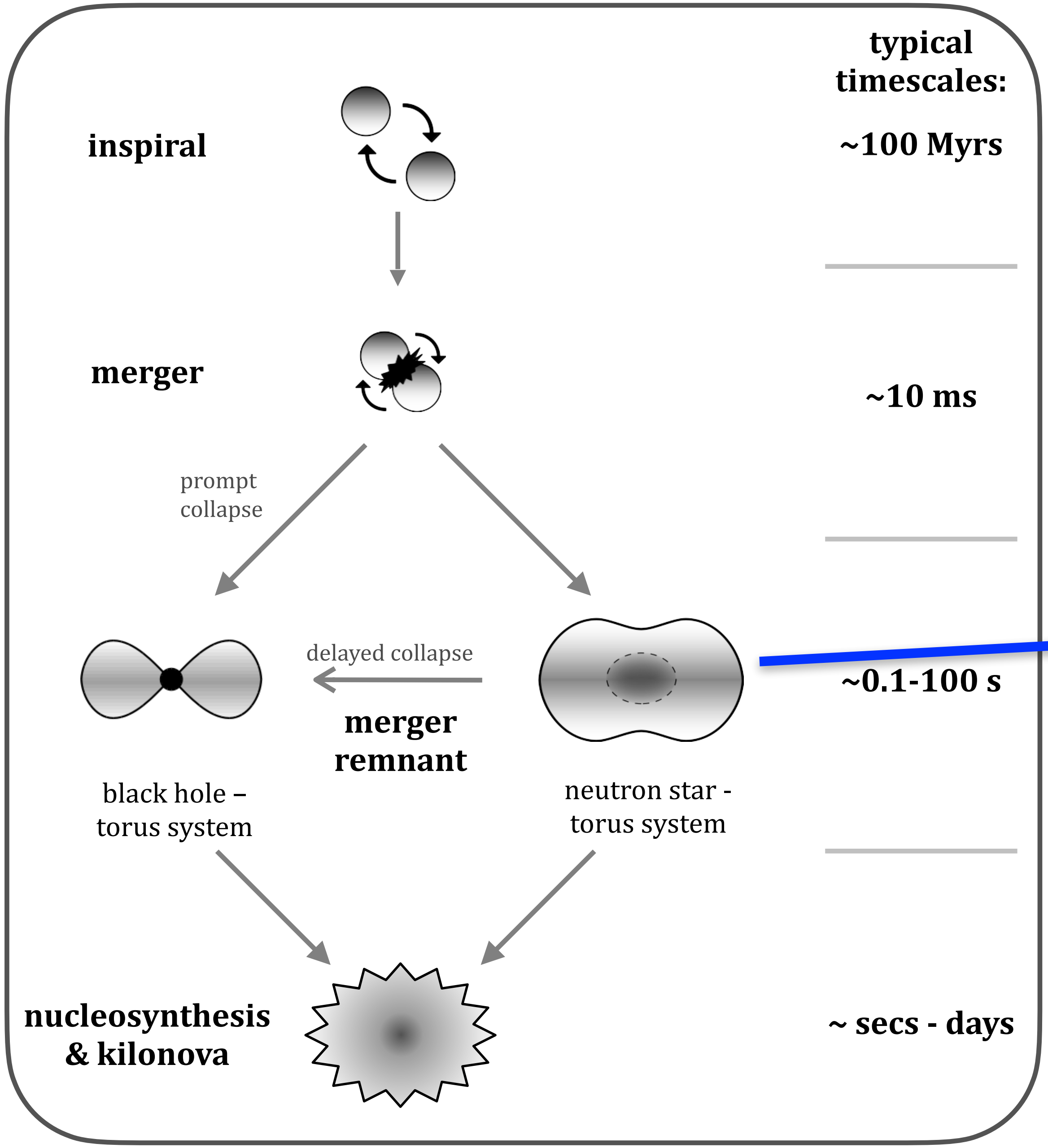

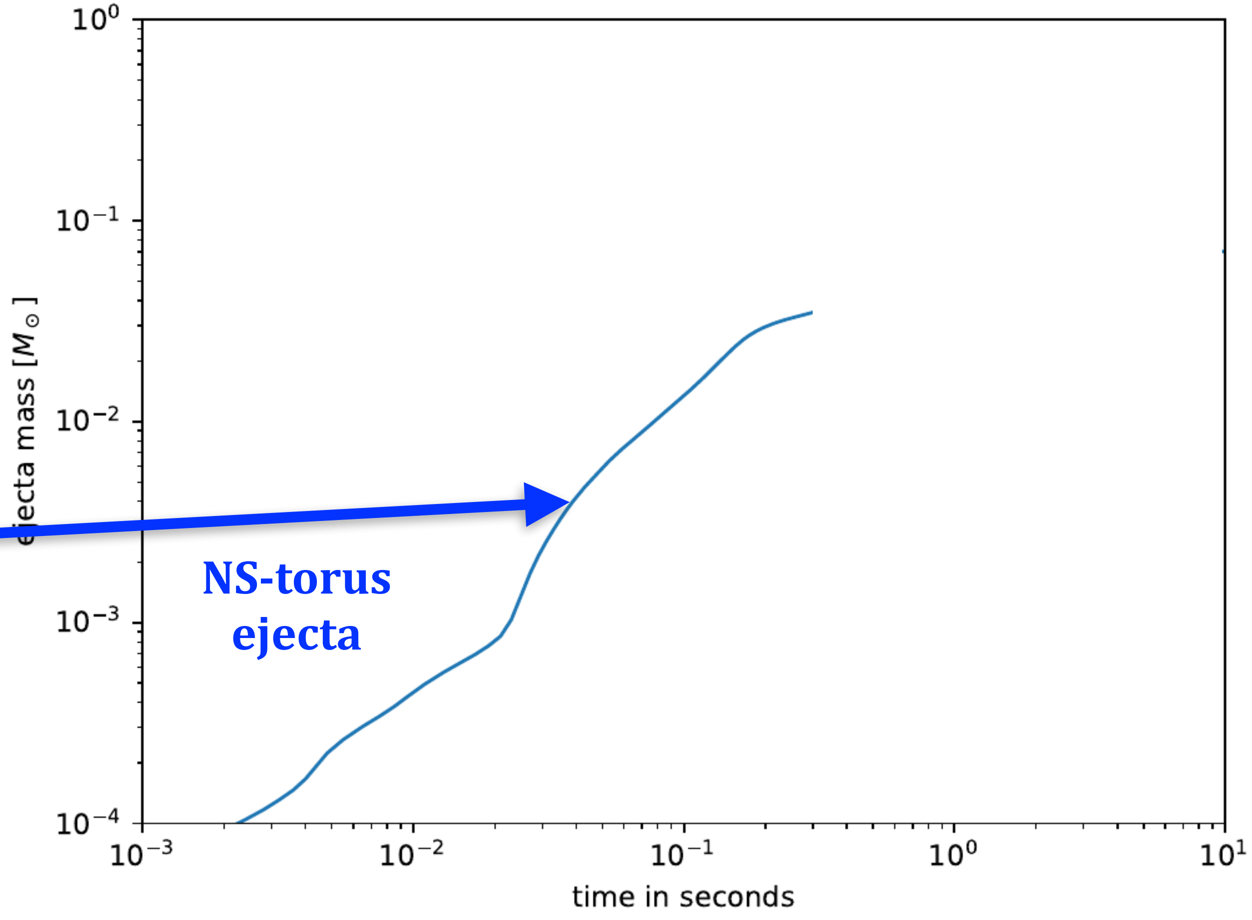

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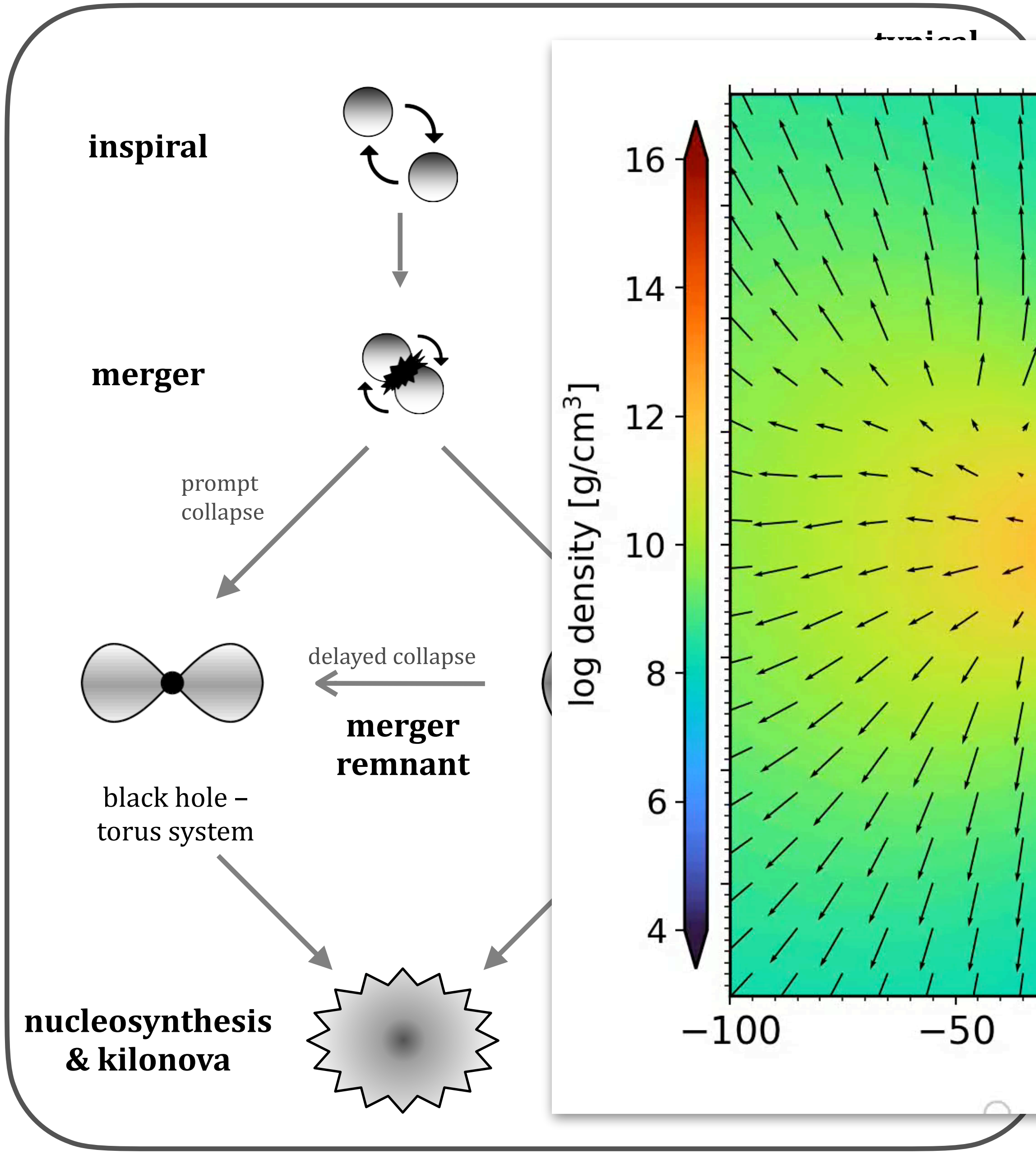

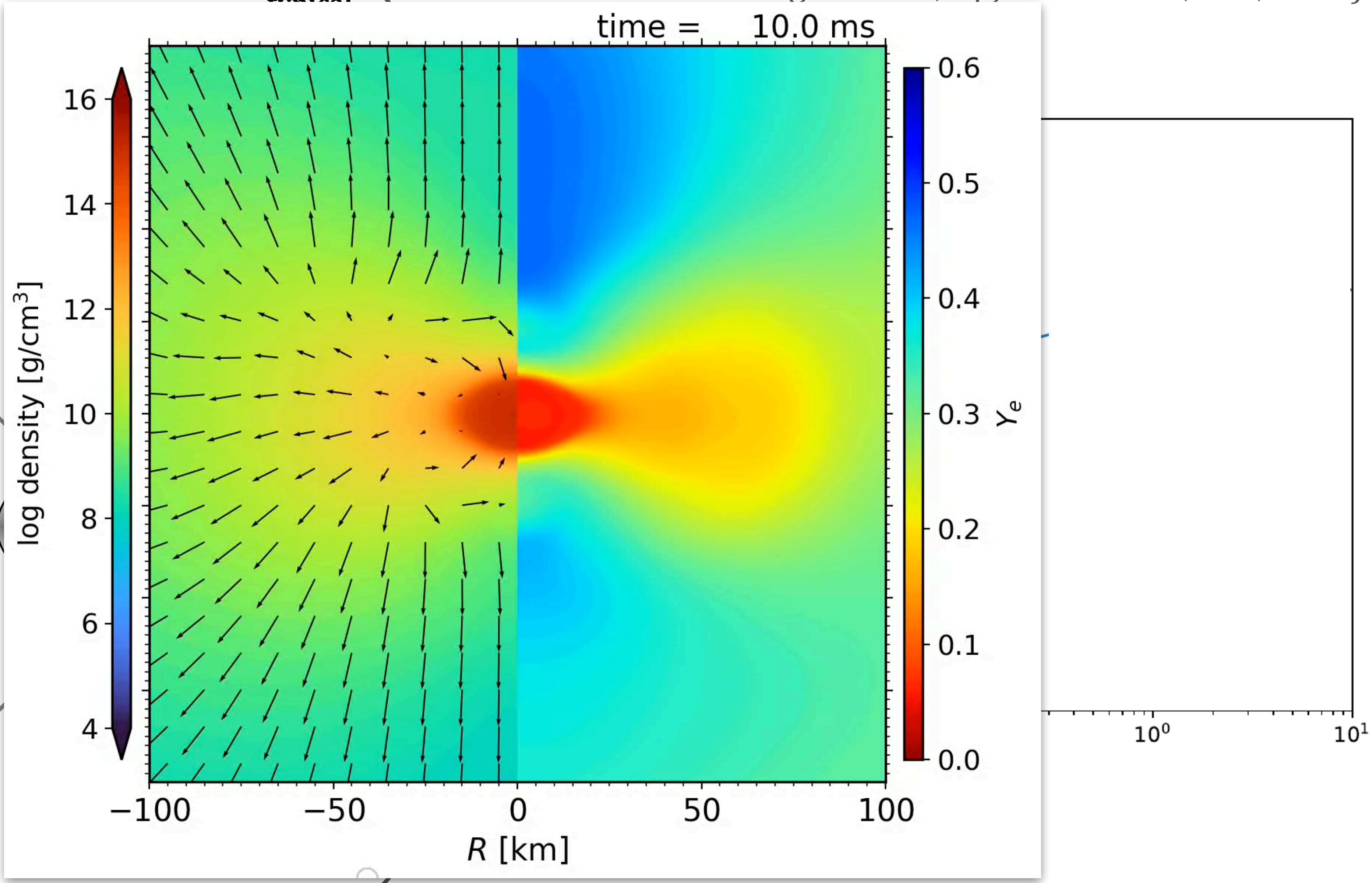

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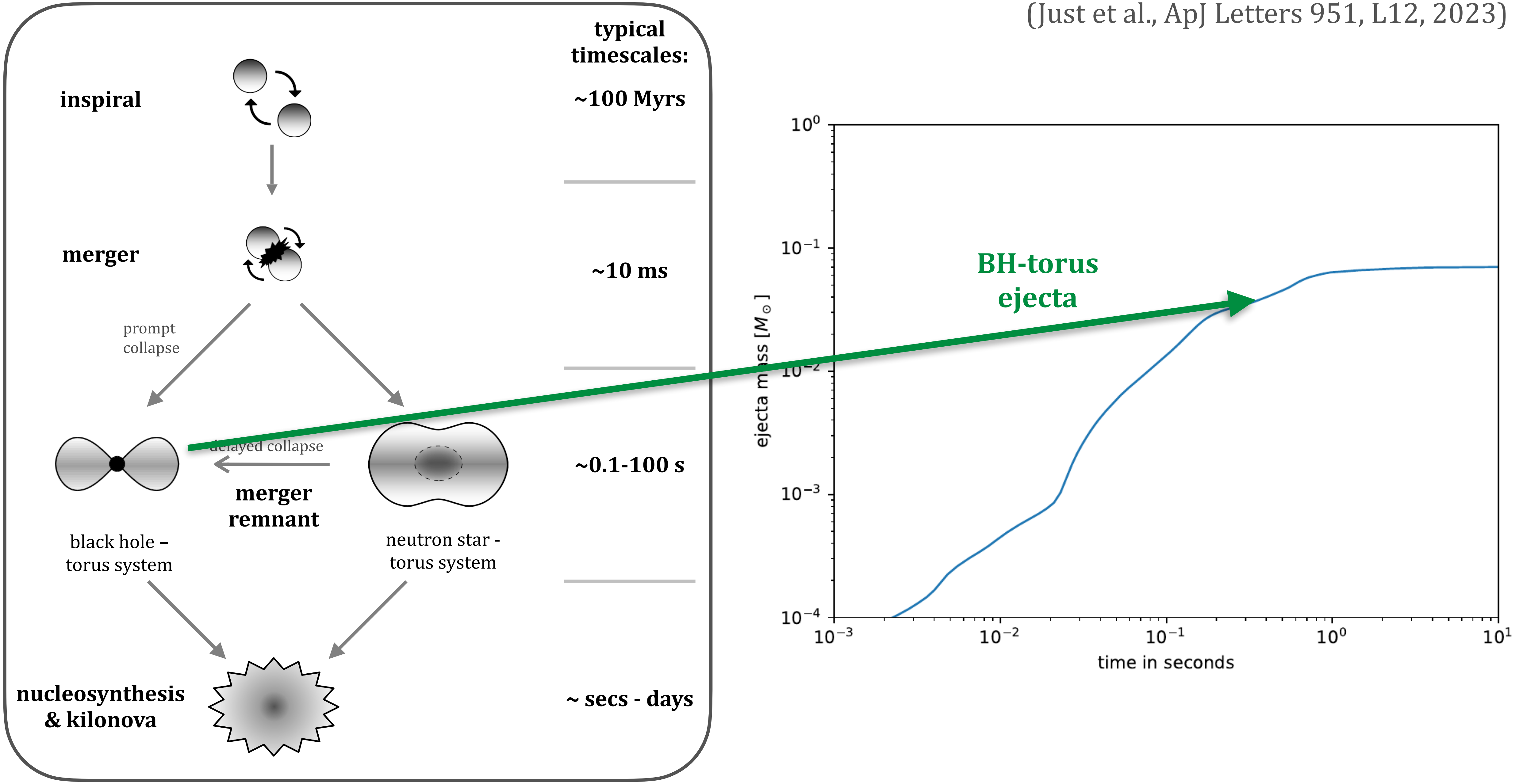

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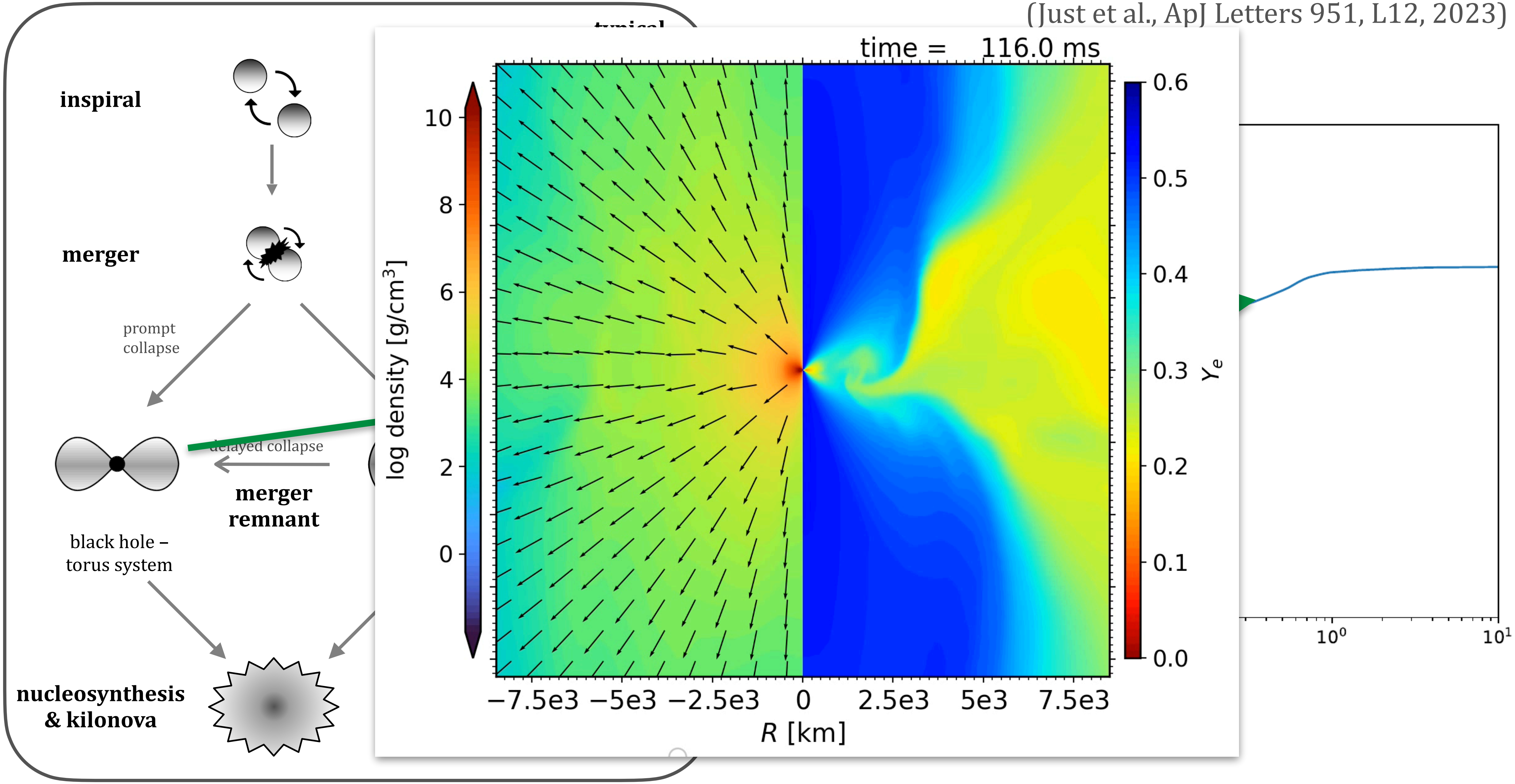
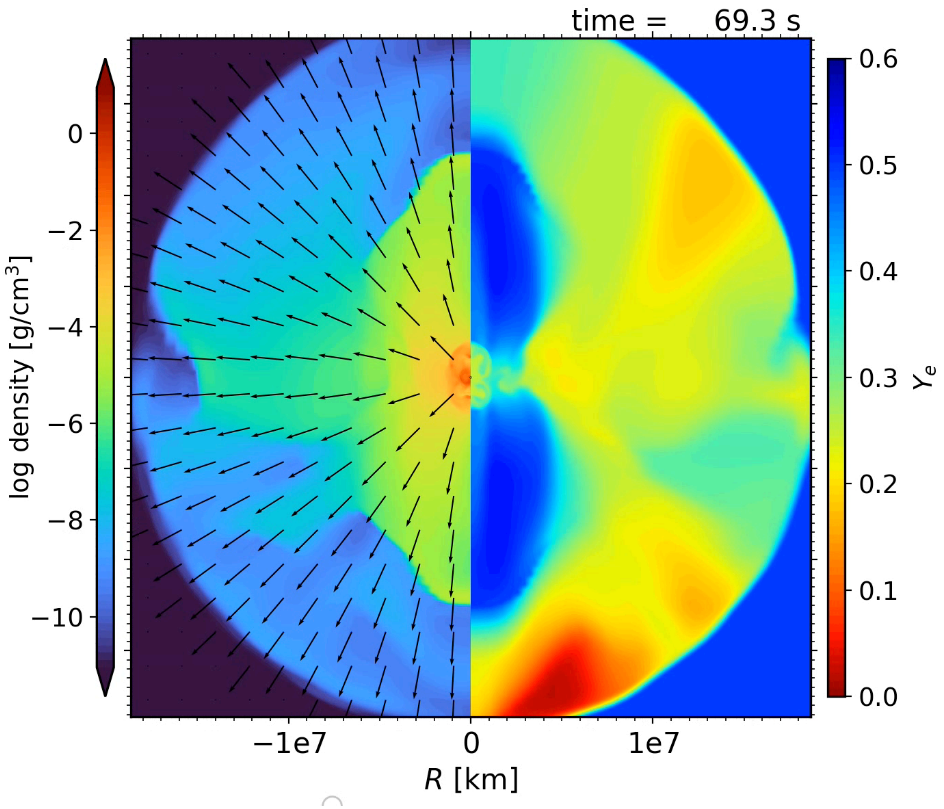
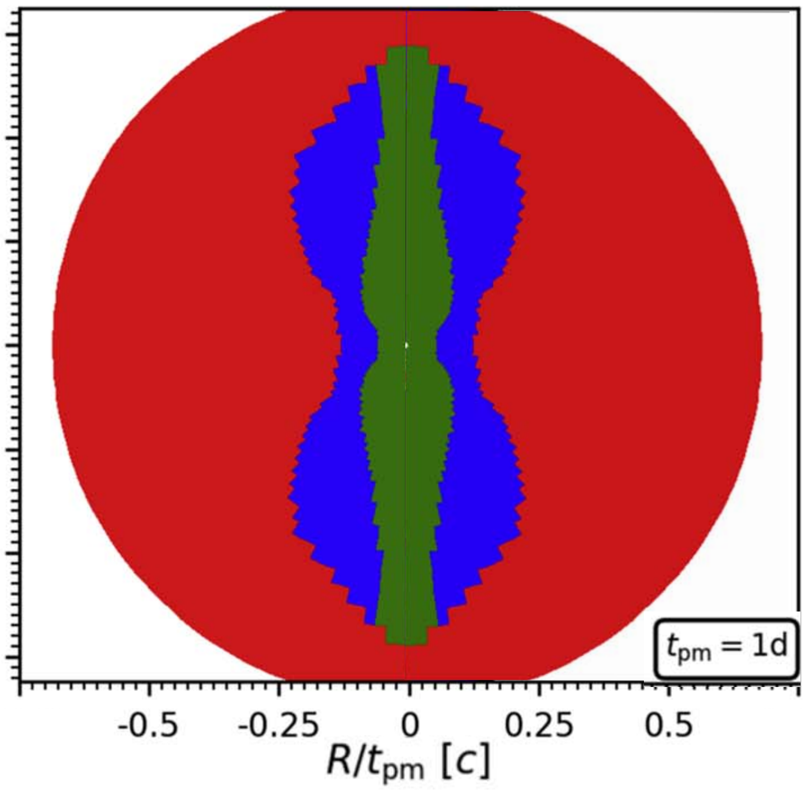
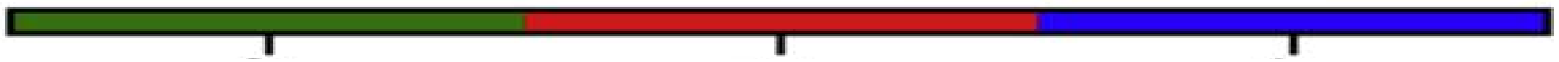


Final ejecta configuration





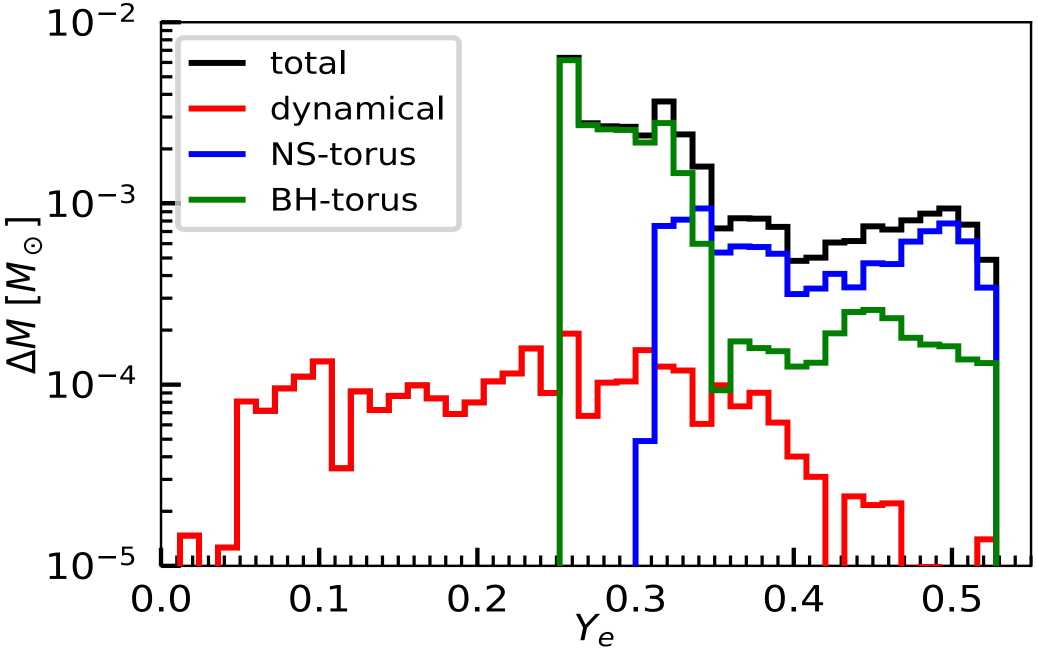


BH-torus ejecta dynamical ejecta NS-torus ejecta

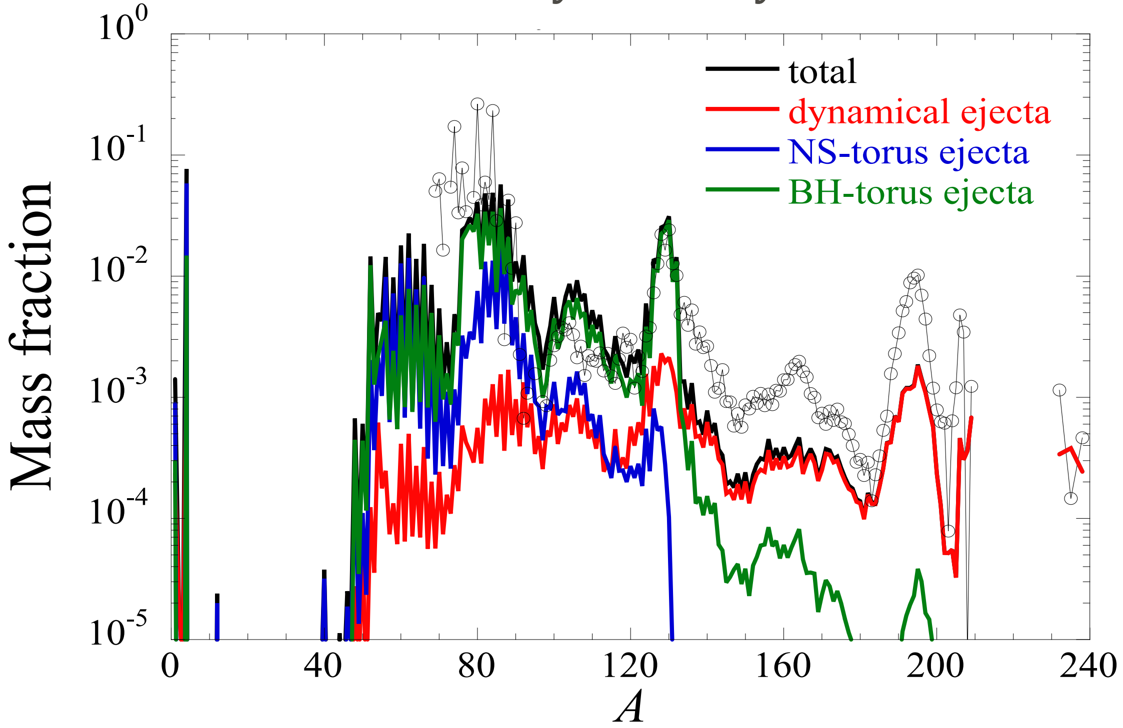
- ➡ characteristic geometric shape of each ejecta component
- ➡ end-to-end modeling **crucial** for reliable kilonova interpretation

Ejecta composition

Y_e histogram

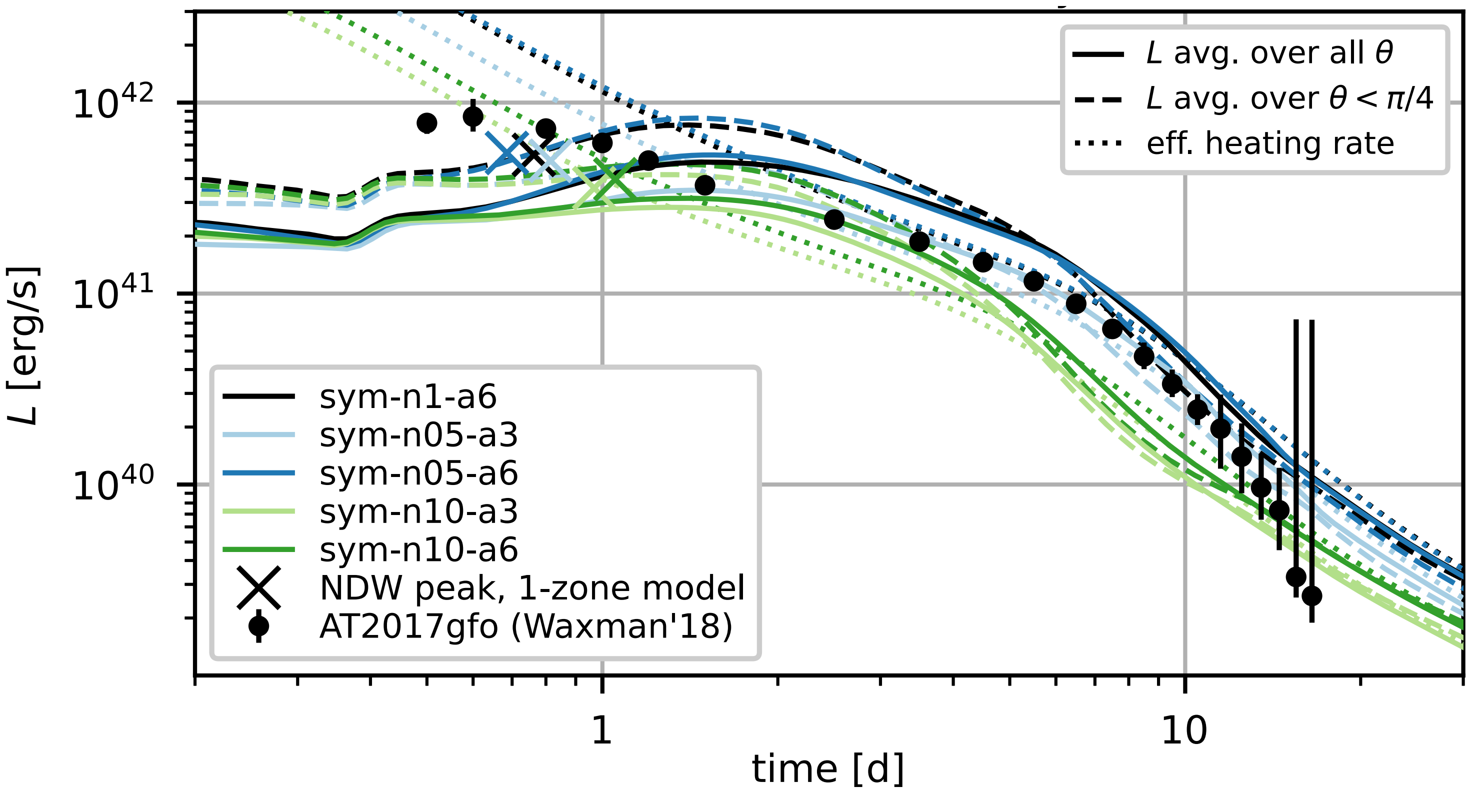


nucleosynthesis yields



- ➡ different Y_e and yields for each ejecta component
- ➡ relative contribution of each component only accessible through end-to-end modeling
- ➡ detailed distributions vary with initial NS masses and nuclear EOS

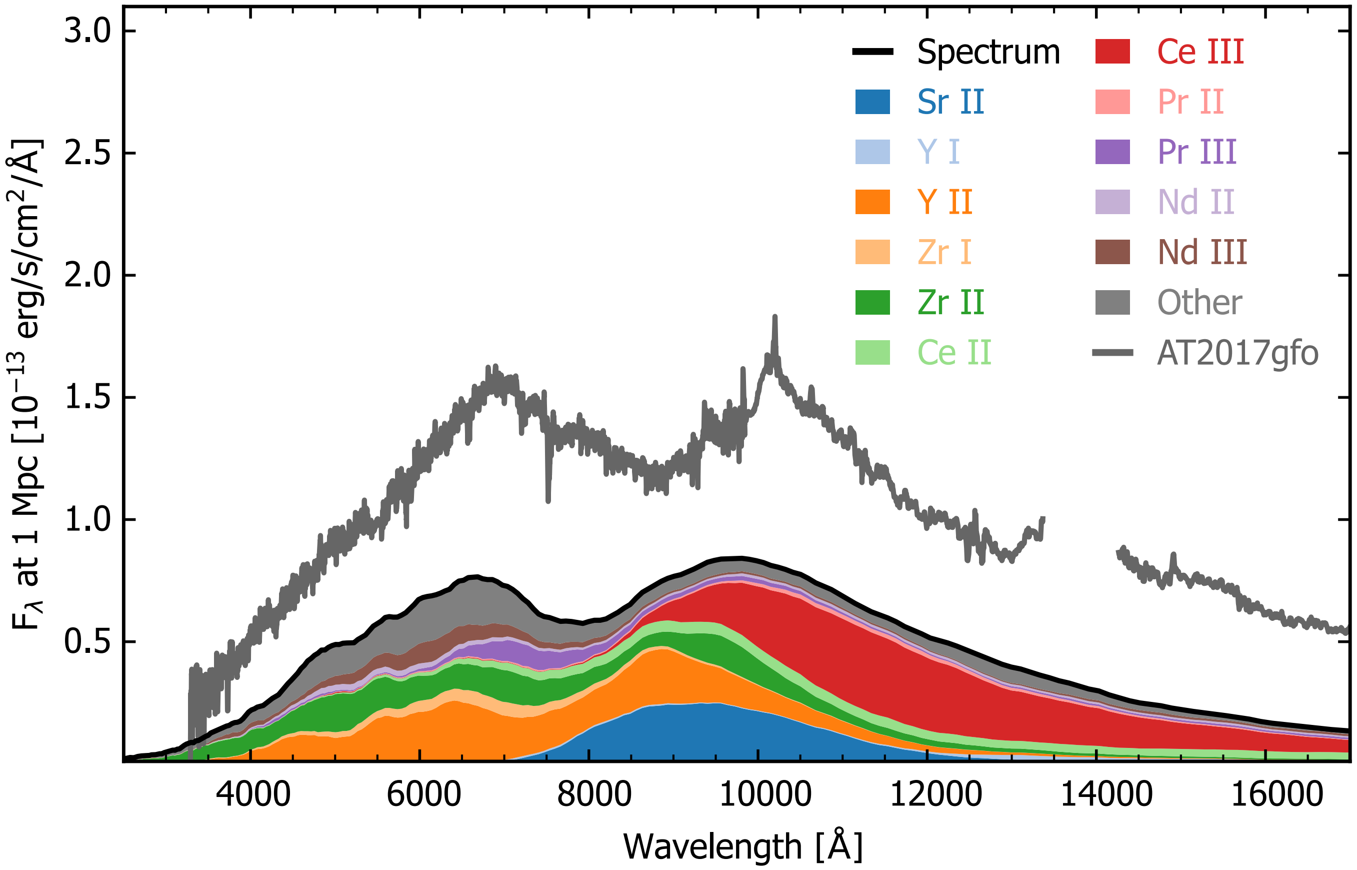
Kilonova light curve of end-to-end models — comparison with GW170817/AT2017gfo



- estimate of kilonova light curve using simplified radiative transfer algorithm
- **encouraging:** good agreement with GW170817

A step towards accurate kilonova radiative transfer modeling

(Shingles et al. ’23, ApJ Letters, accepted)

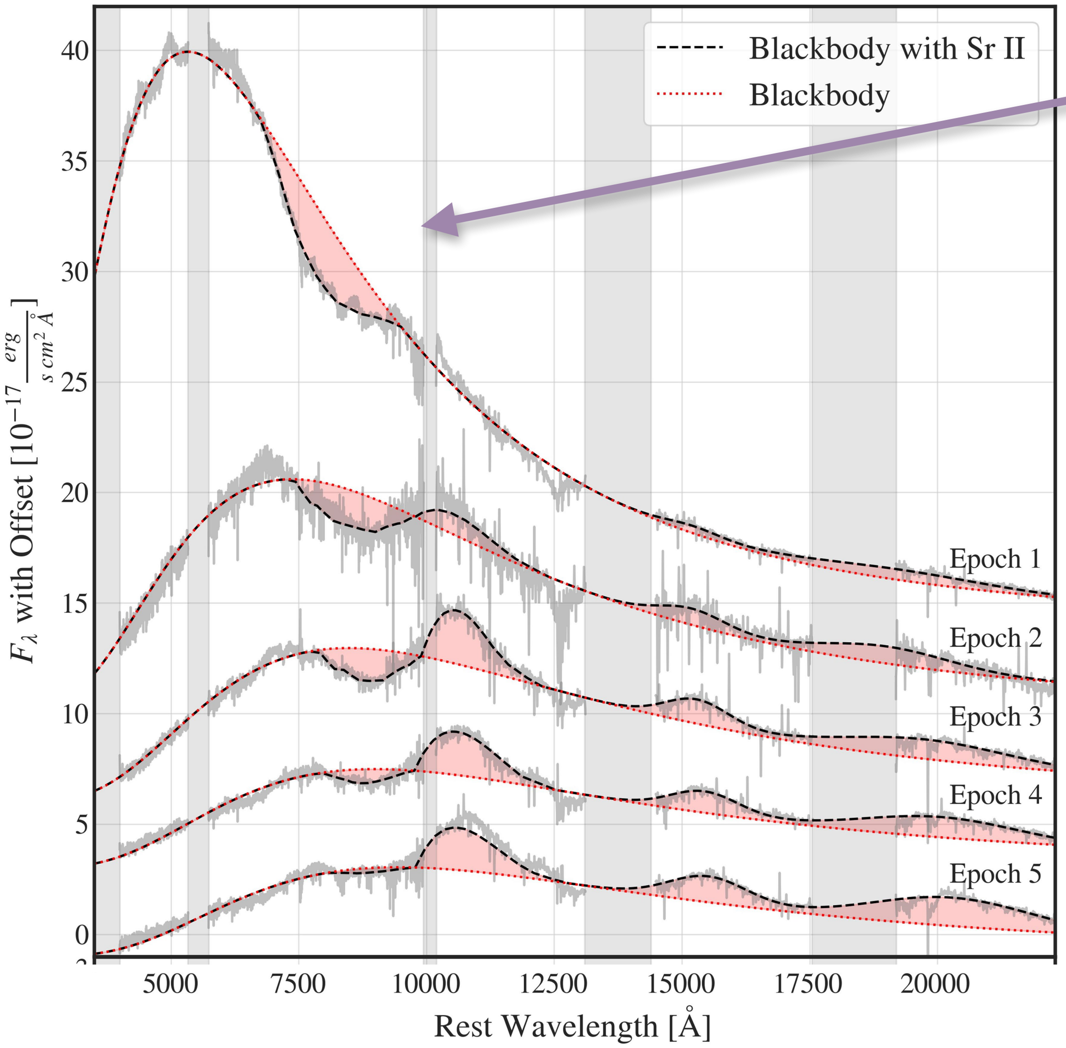


- 3D Monte-Carlo radiative transfer including millions of atomic lines + sophisticated thermalization treatment using ARTIS code (previously used for thermonucl. SNe)
- most detailed kilonova calculation performed so far
- only single ejecta component (i.e. not end-to-end models) —> total luminosity lower than AT2017gfo
- spectra look **remarkably similar** to AT2017gfo

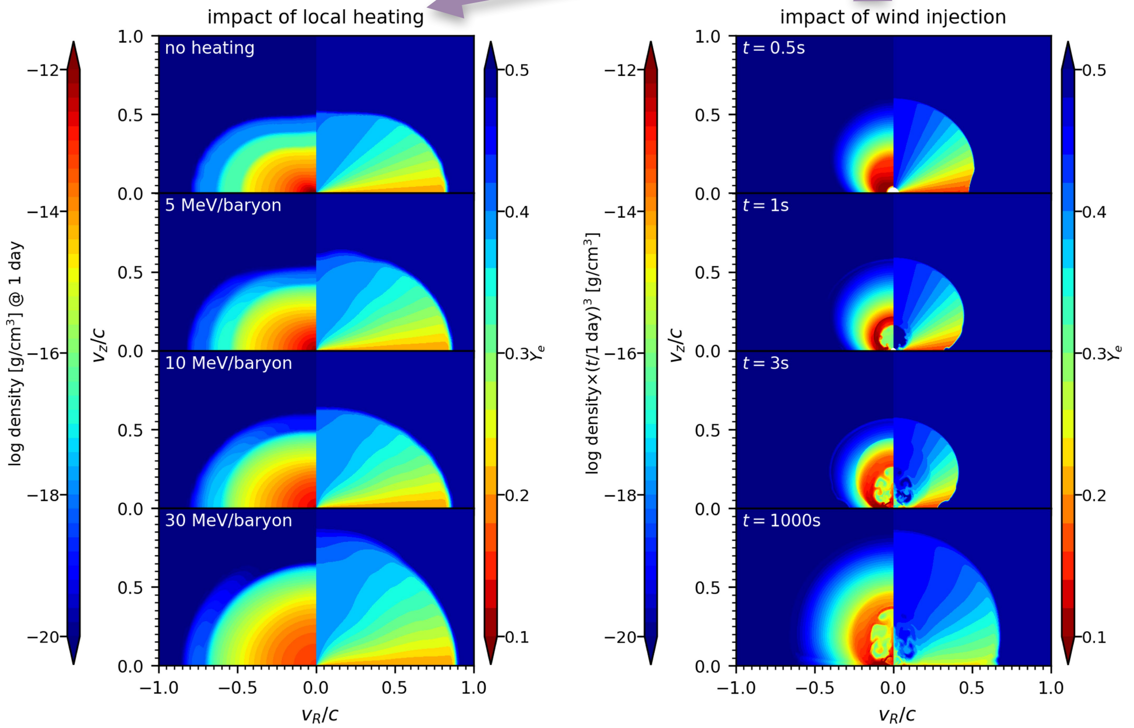
Inferring the ejecta geometry from observed kilonovae

(Sneppen et al., Nature 614, 7948, 2023)

observed spectra of AT2017gfo + fits

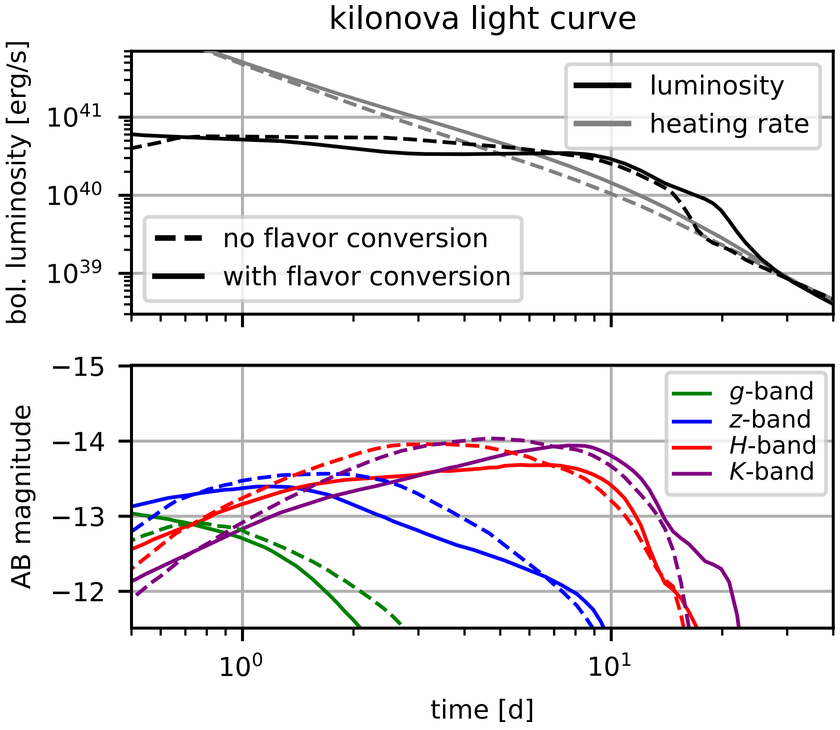


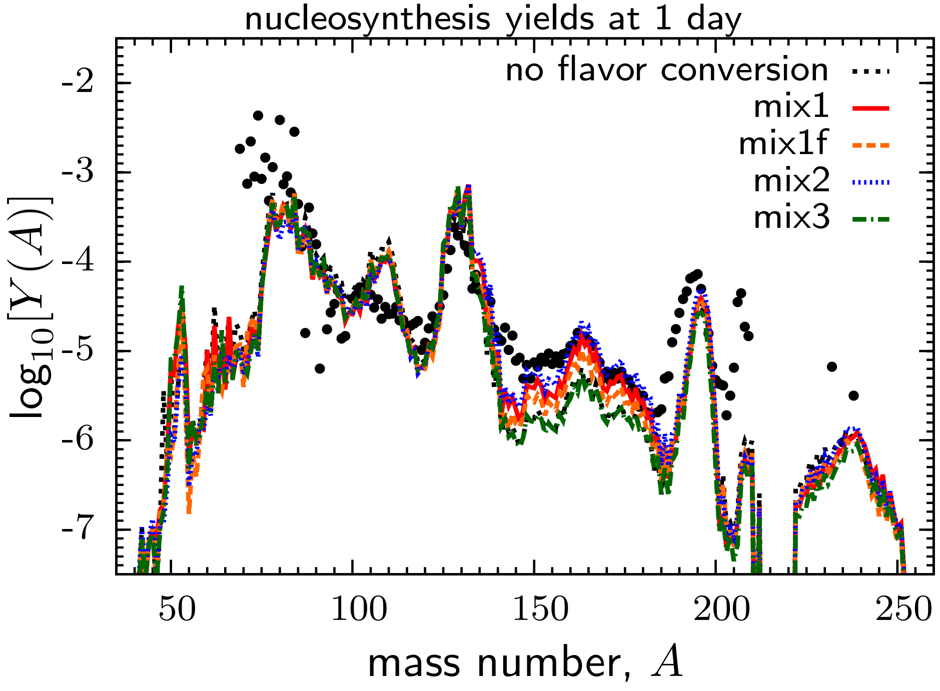
- spectral dip (due to absorption of strontium) used to constrain the geometry of the ejecta
- suggests (surprisingly) high degree of sphericity of ejecta (e.g. useful for constraining Hubble constant)
- difficult to explain with numerical simulations



Impact of neutrino fast flavor conversions

(Just et al. PRD 105, 2022)





- fast pairwise neutrino flavor instability grows on length scales of centimeters (!)
- may lead to complete flavor mixing, e.g.:

$$n_\nu = \frac{1}{6}\left(n^0_{\nu_e,q} + n^0_{\bar{\nu}_e,q} + 2n^0_{\nu_x,q} + 2n^0_{\bar{\nu}_x,q}\right)$$

- moderate boost of r-process yields
- slightly delayed kilonova signal

Summary and outlook

Kilonovae allow to address many fundamental physics questions

- Are NS mergers the (main) origin of r-process elements?
- How does the r-process operate and depend on nuclear physics properties?
- What are the properties of high-density matter?
- How to constrain the cosmic expansion rate?
- …

Interpretation of kilonova observations requires reliable modeling

- all ejecta components produced during and after merger can be important
- first models with kilonova radiative transfer including self-consistent nucleosynthesis and atomic data
- intriguing possibility to constrain ejecta geometry from spectral features
- nucleosynthesis yields and kilonova may be sensitive to neutrino flavor conversions

The future (kilonova) is bright…

- **plenty** more observations expected with upgraded and new GW detectors and EM telescopes
- develop robust theoretical understanding in order to maximize scientific output of observations and and nuclear physics facilities (e.g. FAIR)