B07: Equation of state and nucleosynthesis in neutron star mergers

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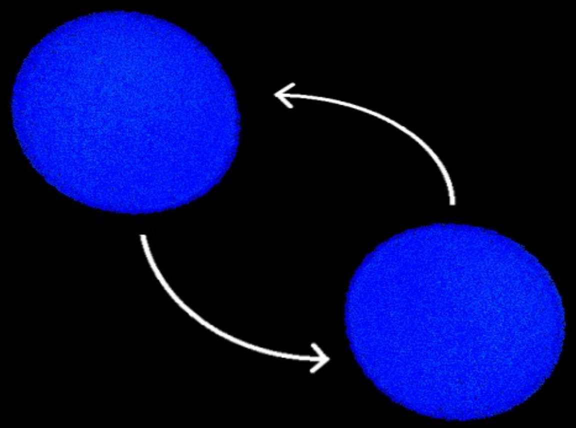
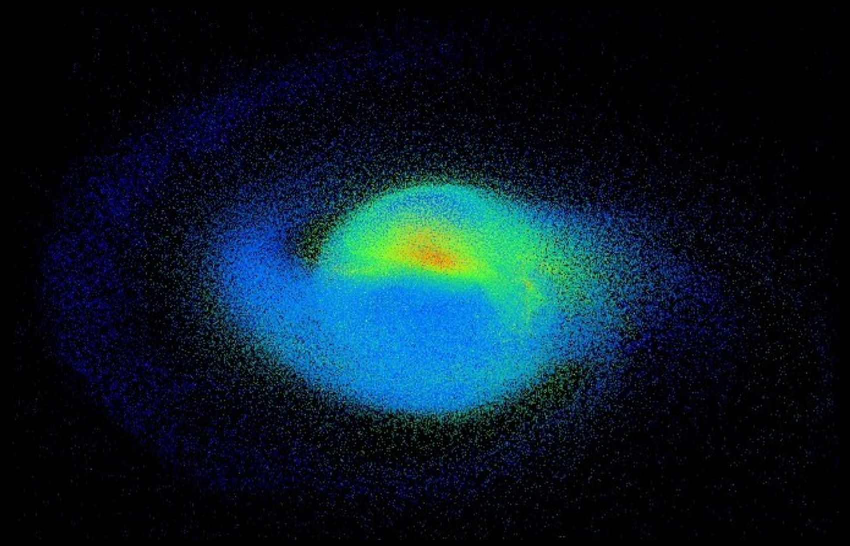




A break-through in astrophysics and beyond

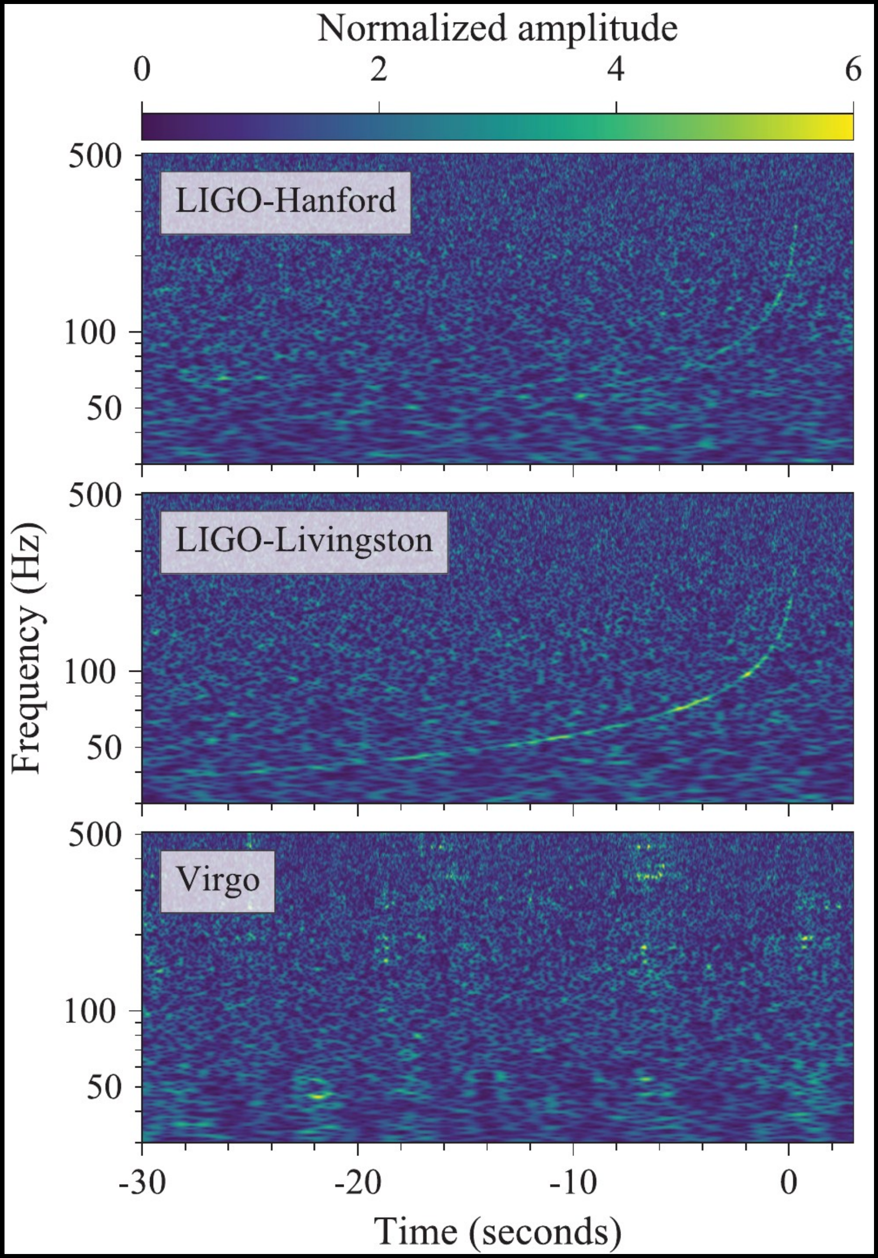
- GW170817 first unambiguously detected NS merger
- Mutli-messenger observations: gravitational waves, gamma, X-rays, UV, optical, IR, radio

Detection August 17, 2017 by LIGO-Virgo network

→ GW data analysis

→ follow-up observations - probably largest coordinated observing campaign in astronomy (observations/time)

Announcement October 2017



Abbott et al. 2017

	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)
Primary mass m_1	1.36–1.60 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$
Using NGC 4993 location	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800

Abbott et al. 2017

Chirp-like signal → compact binary merger

Shape reveals masses → only compatible with NSs

→ triggered some follow-up observations (approximate sky location by GWs)

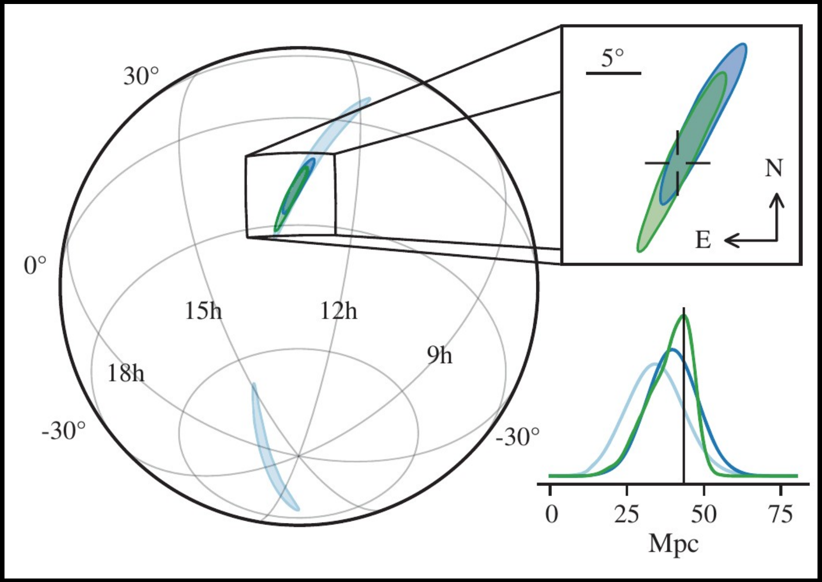
→ more detailed analysis of finite-size effects constrains EoS (later)

EM Observations

- Follow up observation (UV, optical, IR) starting ~12 h after merger (evolved over days)

  → ejecta masses, velocities, opacities

  → red and blue component fit data
- X-rays, radio several days after merger
- Gamma-rays 1.7 after merger



Abbott et al. 2017

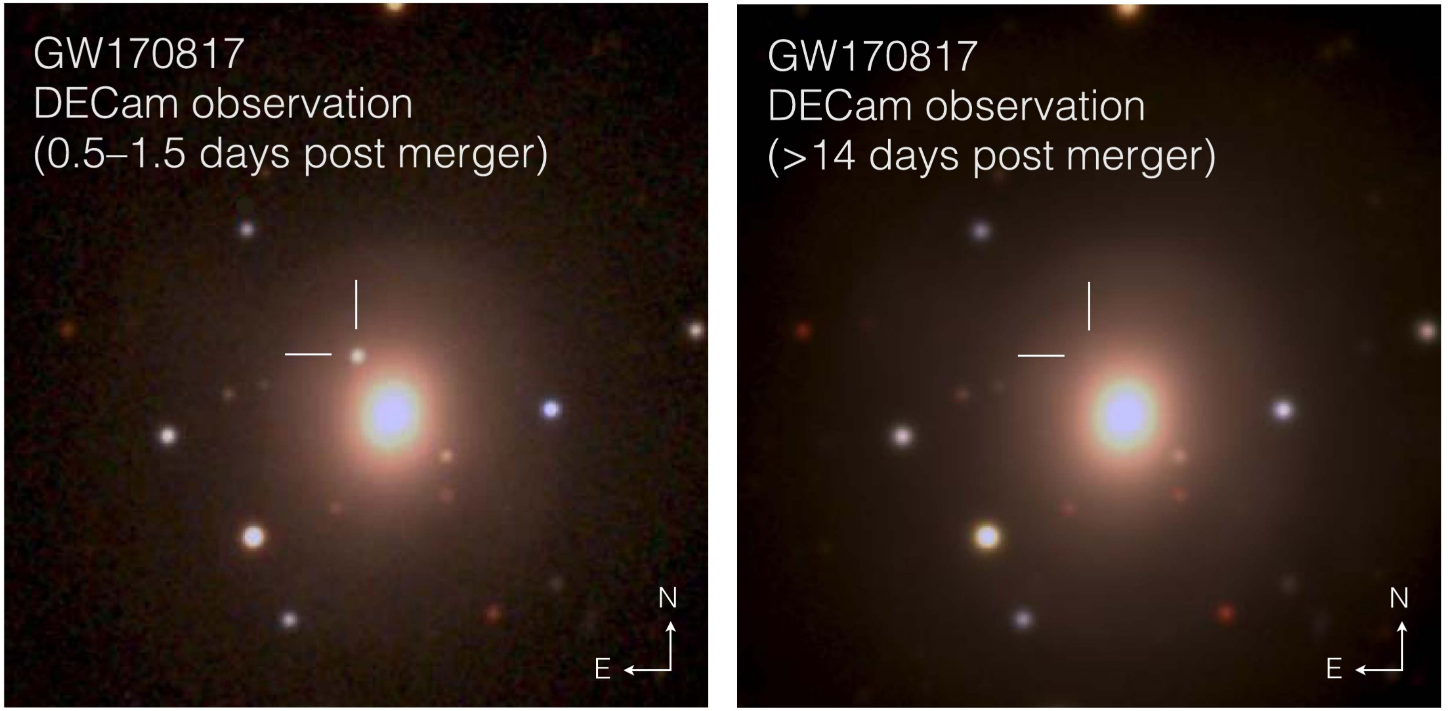


Figure 1. NGC4993 *grz* color composites (1′.5 × 1′.5). Left: composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374, −23.381495. Right: the same area two weeks later.

Soares-Santos et al 2017

Implications of em transient / kilonova

- Emission in IR, optical compatible with a few 0.01 Msun of ejecta heated by radioactive decays during/after r-process
- Generally, remarkable overall agreement between observations and theoretical expectations (from hydro-simulations + nuclear network + radiative transfer)
- Roughly estimated merger rate * ejected mass = compatible with mergers being main producers of heavy r-process elements

  (BUT: only order-of-magnitude accurate statement)

- Details unclear:

  - how much ejecta

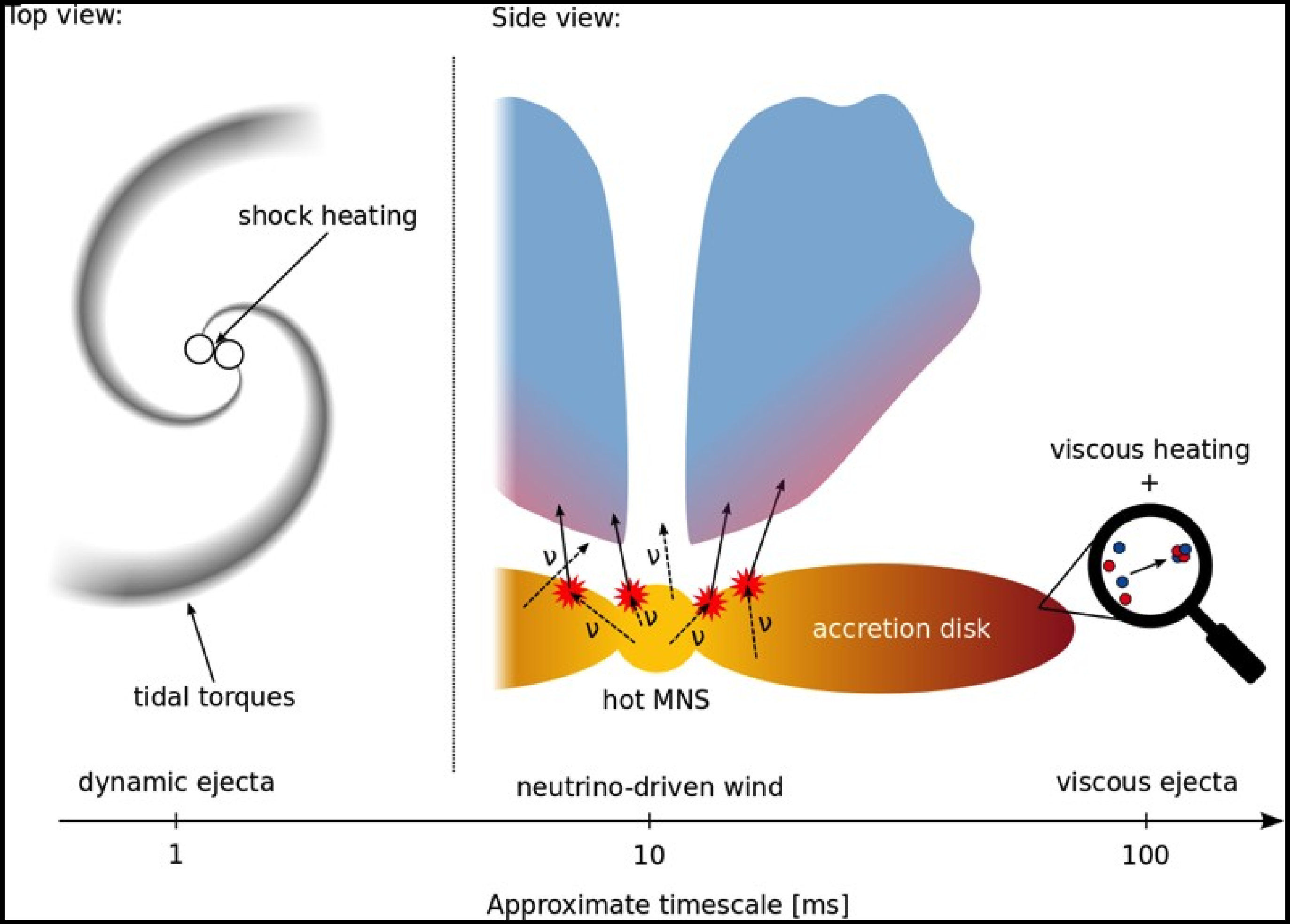
  - from which components of the merger (dynamical vs. wind/disk ejecta)

  - abundances

→ plenty of work required on the theory side for reliable interpretation of current and future data

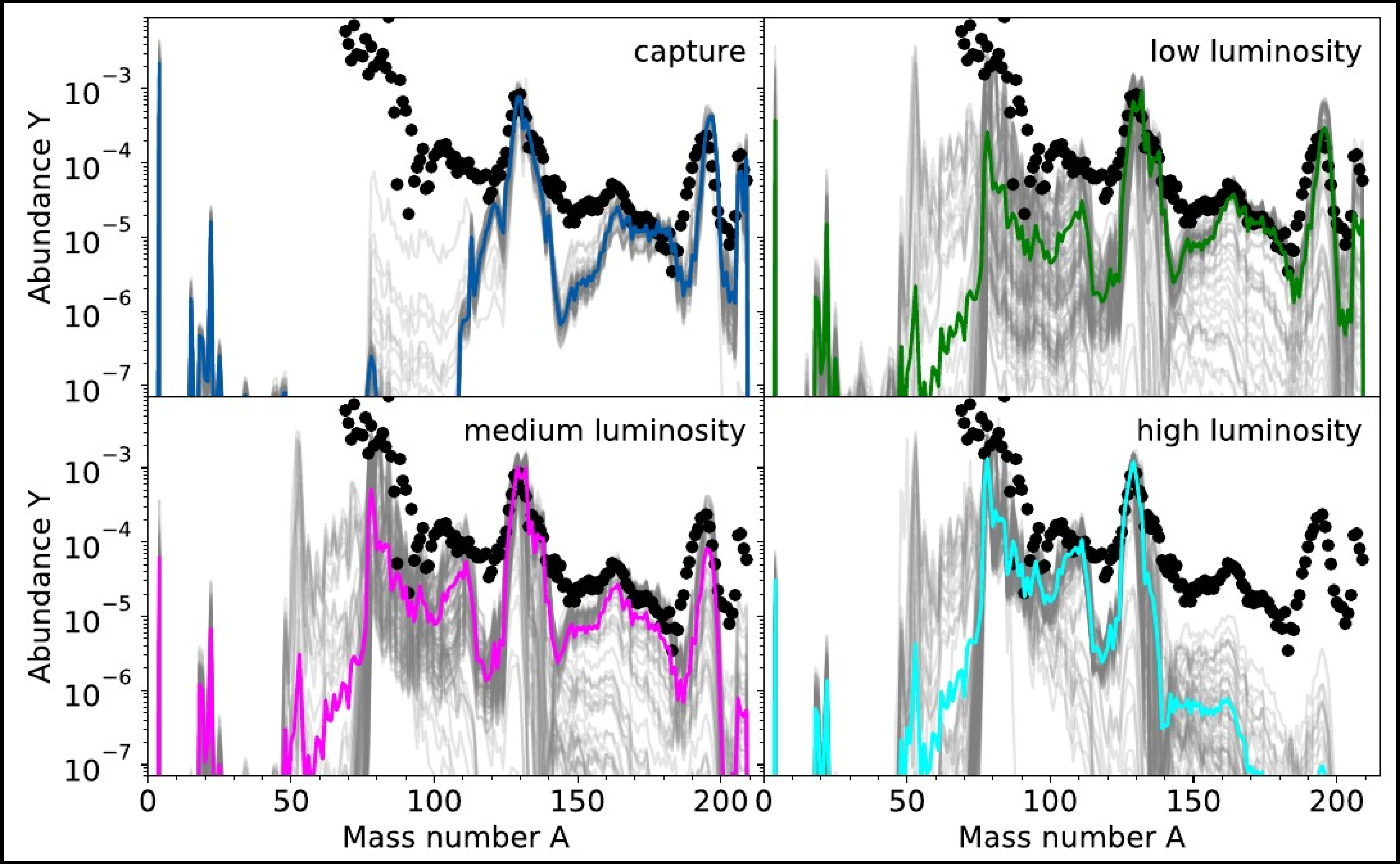
→ indispensable to judge overall contribution of mergers for Galactic enrichment and for detailed understanding of r-process nucleosynthesis

Ejecta and nucleosynthesis (subproject Arcones)



- Different ejection mechanisms → different ejecta components contributing to the r-process and em counterpart (can be comparable in mass)
- **Main goal:** Astro and nuclear physics uncertainties: astrophysical models challenging (e.g. neutrinos), impact of incompletely known EoSs, nuclear models of reactions of nuclei involved in r-process

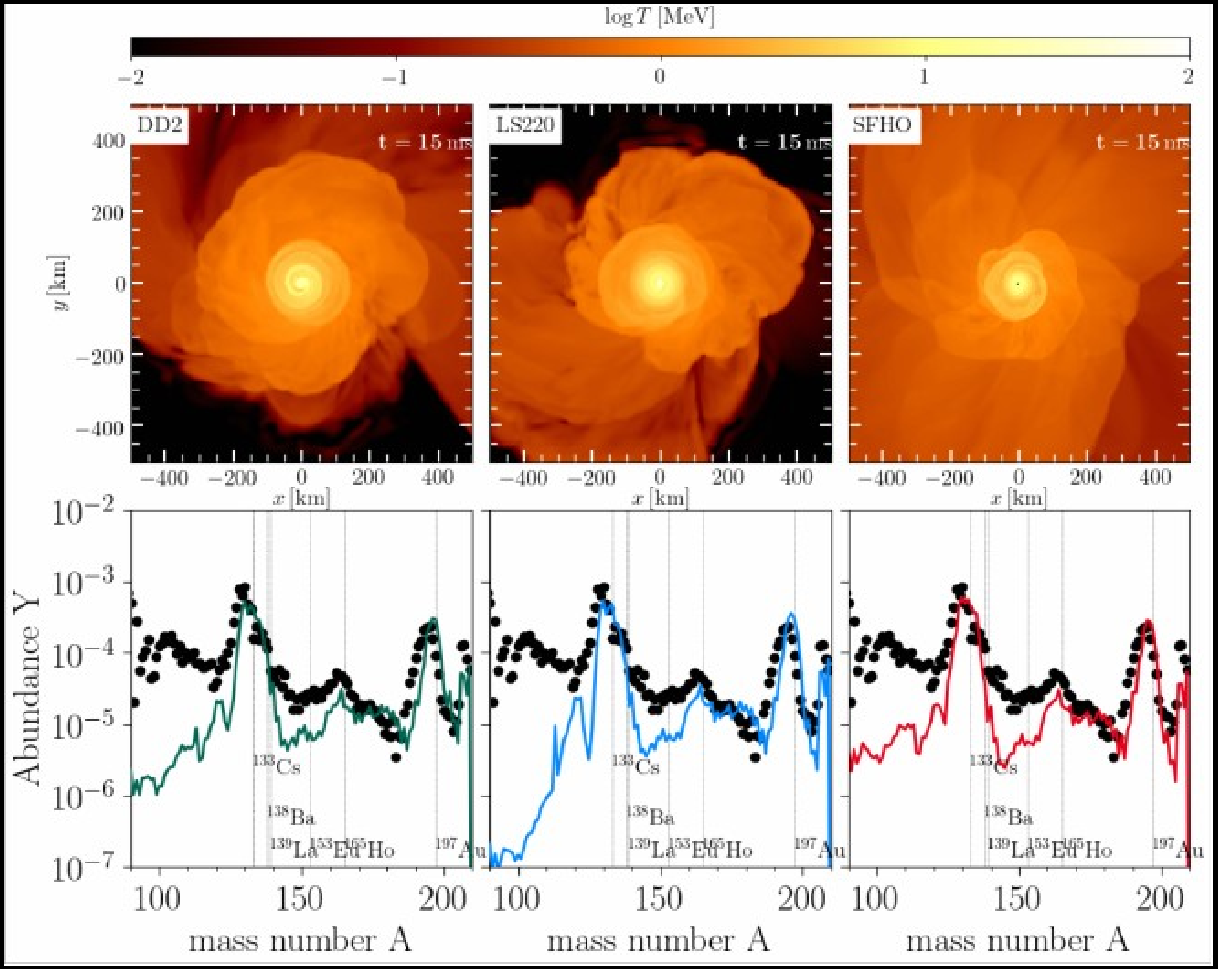
Astro uncertainties: neutrino impact on ejecta composition and r-process



Martin et al. 2018

- Impact on dynamical ejecta
- Extend study to other secular ejecta components

Astro uncertainties: EoS on mass ejection and r-process abundance



Bovard et al. 2017

- EoS strongly affects ejecta mass and thus kilonova brightness
- Smaller impact on abundances

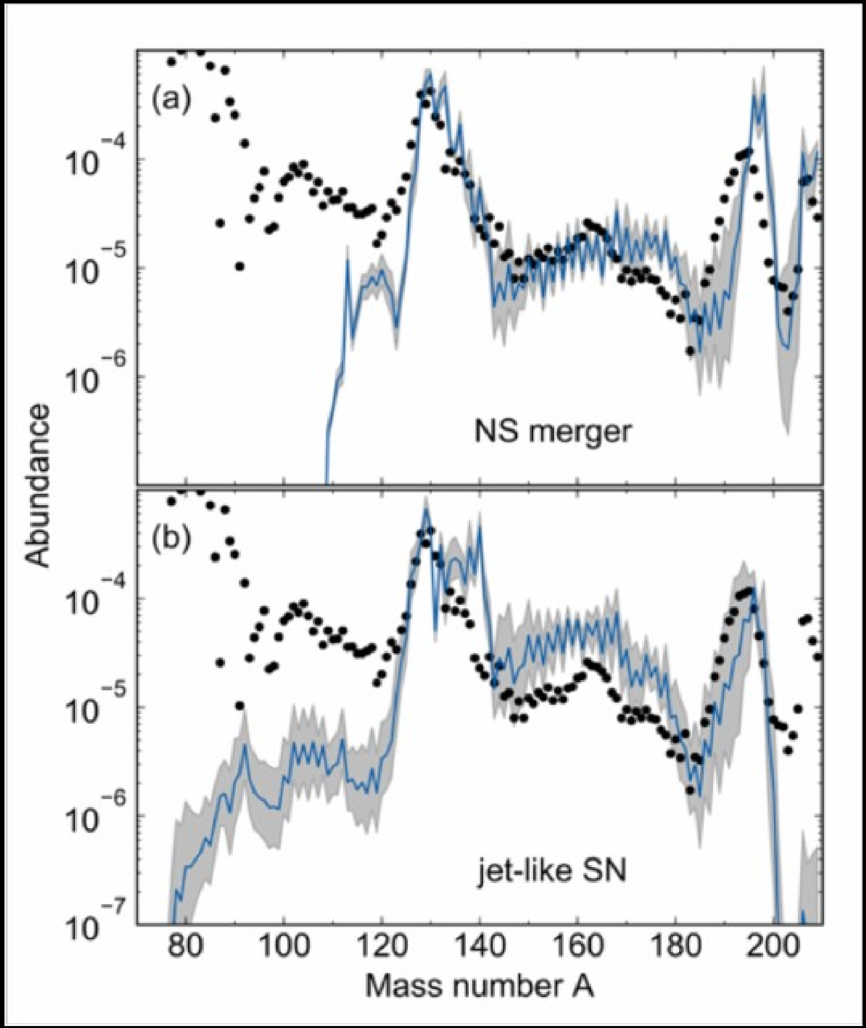
→ Plan for B07: use SFB EoSs to study impact on nucleosynthesis

Nuclear uncertainties

- Neutrino-driven wind: weak r-process up to second peak (A=130)

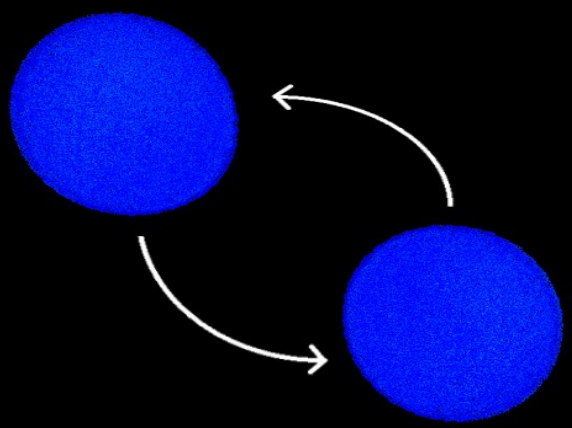
  → similar analysis to B06 for supernovae
- Dynamical ejecta → r-process up to uranium
- Abundances with uncertainties – comparison with observations
- Relevant nuclear physics input: nuclear masses, beta decays, fission

  Plan for B07: systematic study of neutron star merger nucleosynthesis (strong and weak r-process) exploring theoretical uncertainties from astrophysical conditions and nuclear physics input

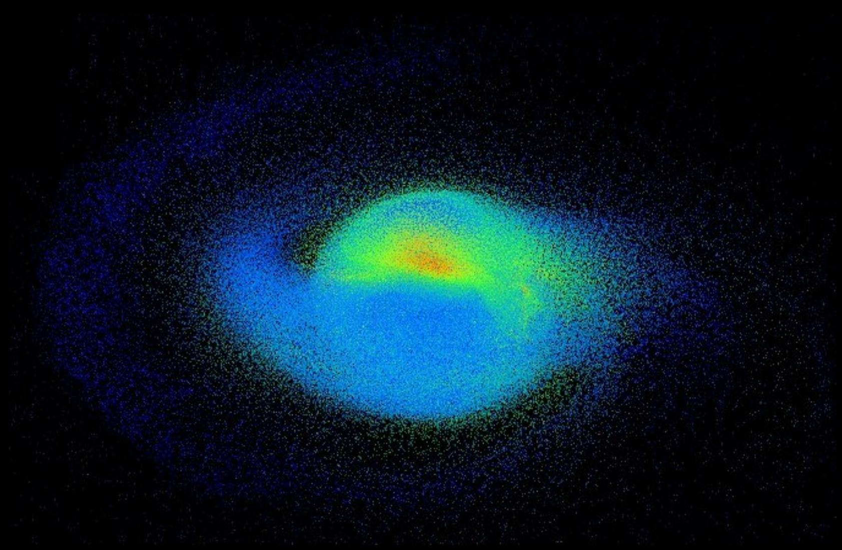


Martin et al. 2016, first systematic uncertainty band for r-process abundances

GWs and EoS constraints (subproject Bauswein)



Inspiral



Post-merger

Current EoS constraints by GW170817

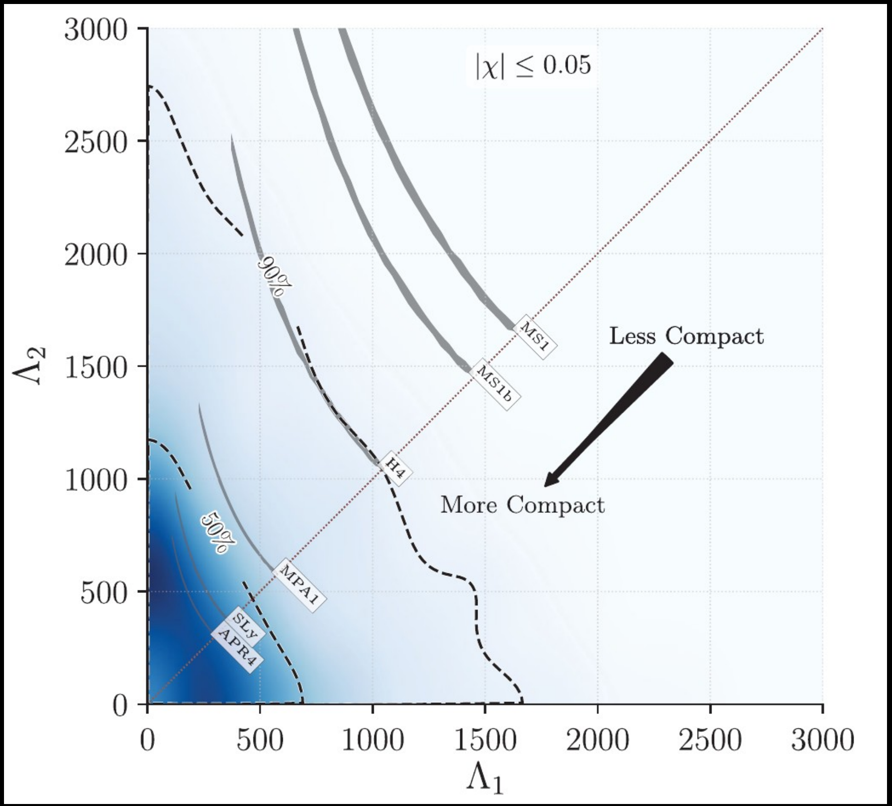
- Generally: EoS characterized by stellar parameters, e.g. radii
- Finite-size effects during inspiral:

  larger NSs → stronger tidal deformation → merge earlier
- encoded by tidal deformability

  upper limit → upper limit on NS radii 13.5 km → nuclear EoS not very stiff

$$\Lambda = \frac{2}{3} k_2 \left(\frac{c^2\, R}{G\, M} \right)^5$$

$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12 m_2) m_1^4 \Lambda_1 + (m_2 + 12 m_1) m_2^4 \Lambda_2}{(m_1 + m_2)^5}$$



Abbott et al. 2017 and follow-up studies

Current EoS constraints by GW170817

- Multi-messenger interpretation – several ideas relying on different assumptions
- high Mej → no direct BH formation (reasonable and simple assumption):

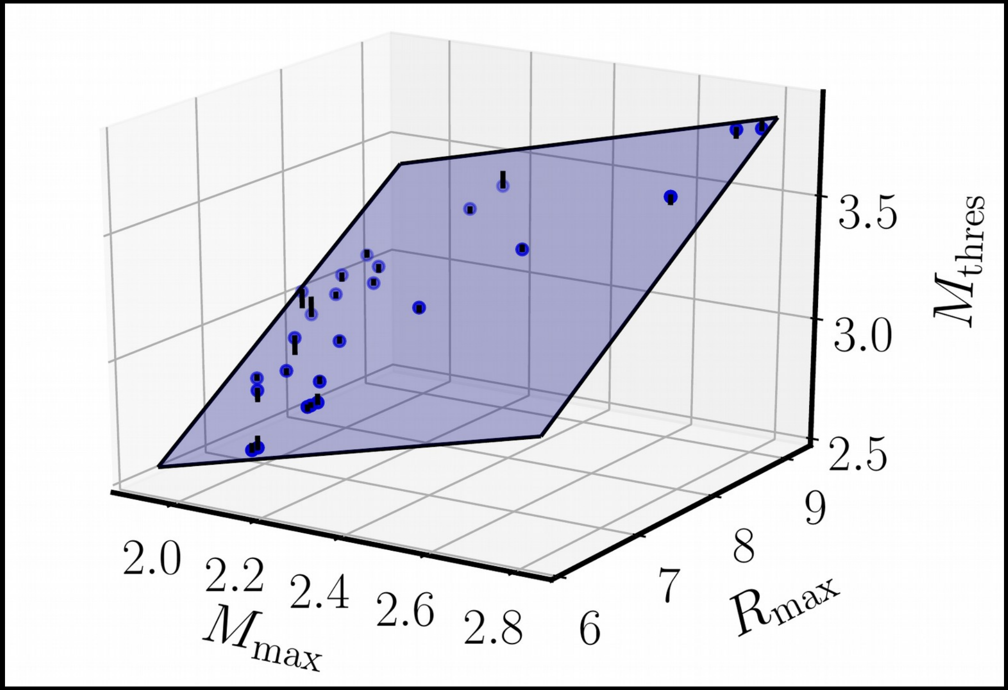
  $M_{tot} = 2.74\ M_{sun} < M_{thres,BH}$ (EoS)

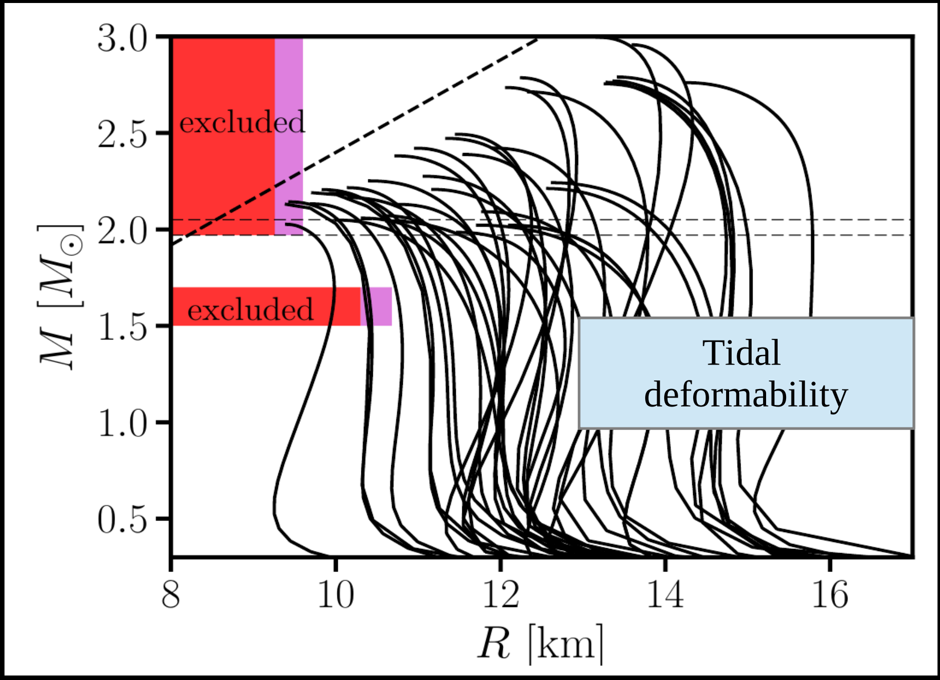
- Empirical relation based simulations

$$M_{\rm thres} = M_{\rm thres}(M_{\rm max}, R_{1.6}) = \left(-3.6\frac{G\,M_{\rm max}}{c^2\,R_{1.6}} + 2.38\right)\,M_{\rm max}$$

→ R1.6 > 10.7 km → nuclear EoS not extremely soft

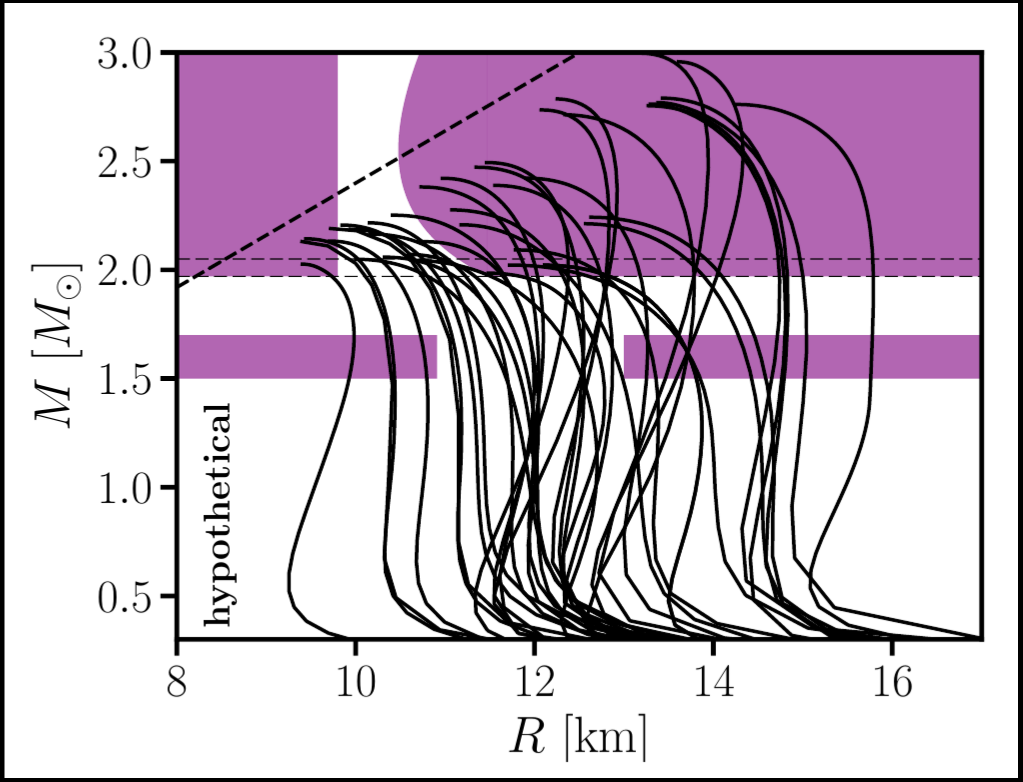
Bauswein et al. 2017



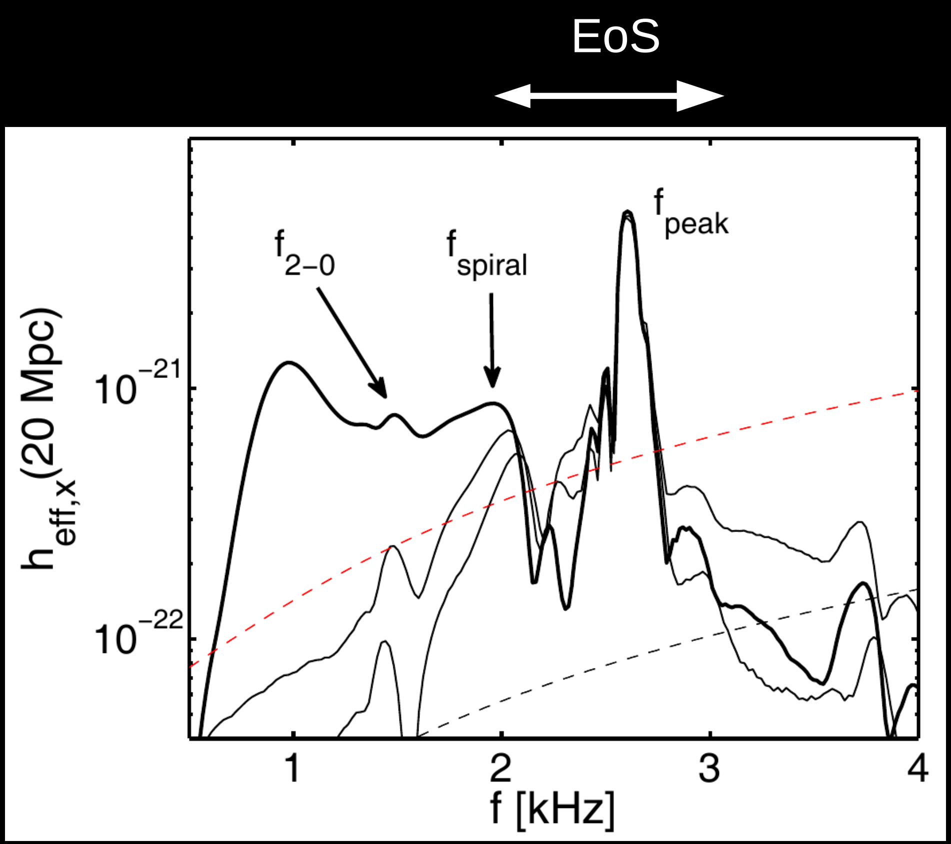


Future EoS constraints and plans within B07

- More accurate and robust measurements with current methods
- Collapse behavior → maximum mass of nonrotating NSs, stronger radius constraints
- Postmerger GW emission

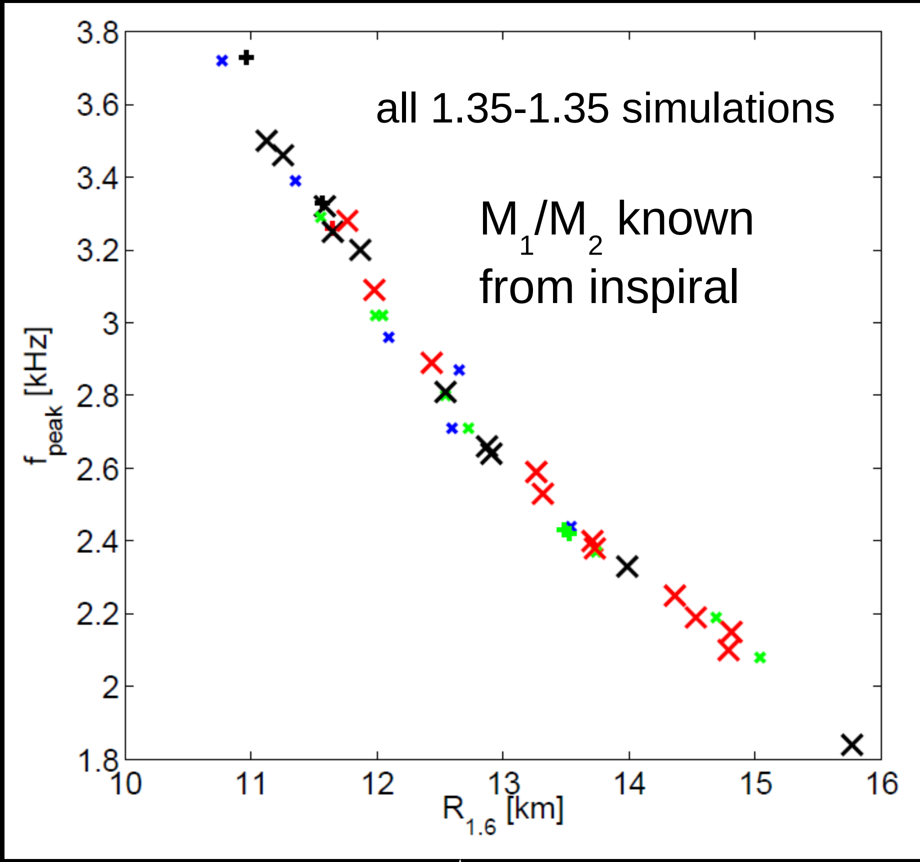


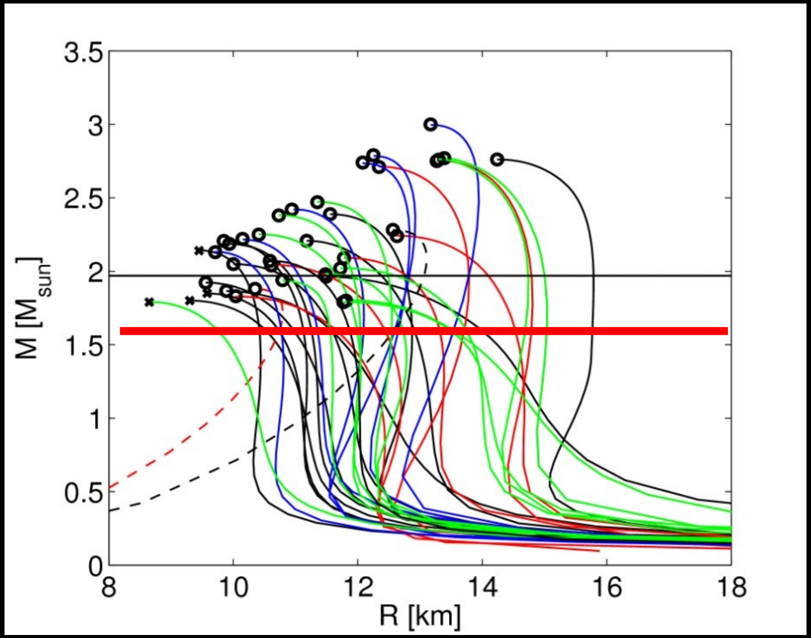
Bauswein et al. 2017



Bauswein et al. 2012/2015

Postmerger Gravitational Waves





characterize EoS by radius of nonrotating NS with 1.6 M_{sun}

Bauswein et al. 2012

Pure TOV/EoS property => Radius measurement via f_{peak}

GW data analysis: Clark et al 2014, Clark et al 2016, Chatziioannou et al 2017, …
→ detectable at a few 10 Mpc, i.e. in reach within the next years !!!

Plans for B07

- Relativistic hydrodynamics simulations of NS mergers (using two complementary tools including)
- Detailed investigation of collapse behavior

  - EoS dependence, mass ratio dependence

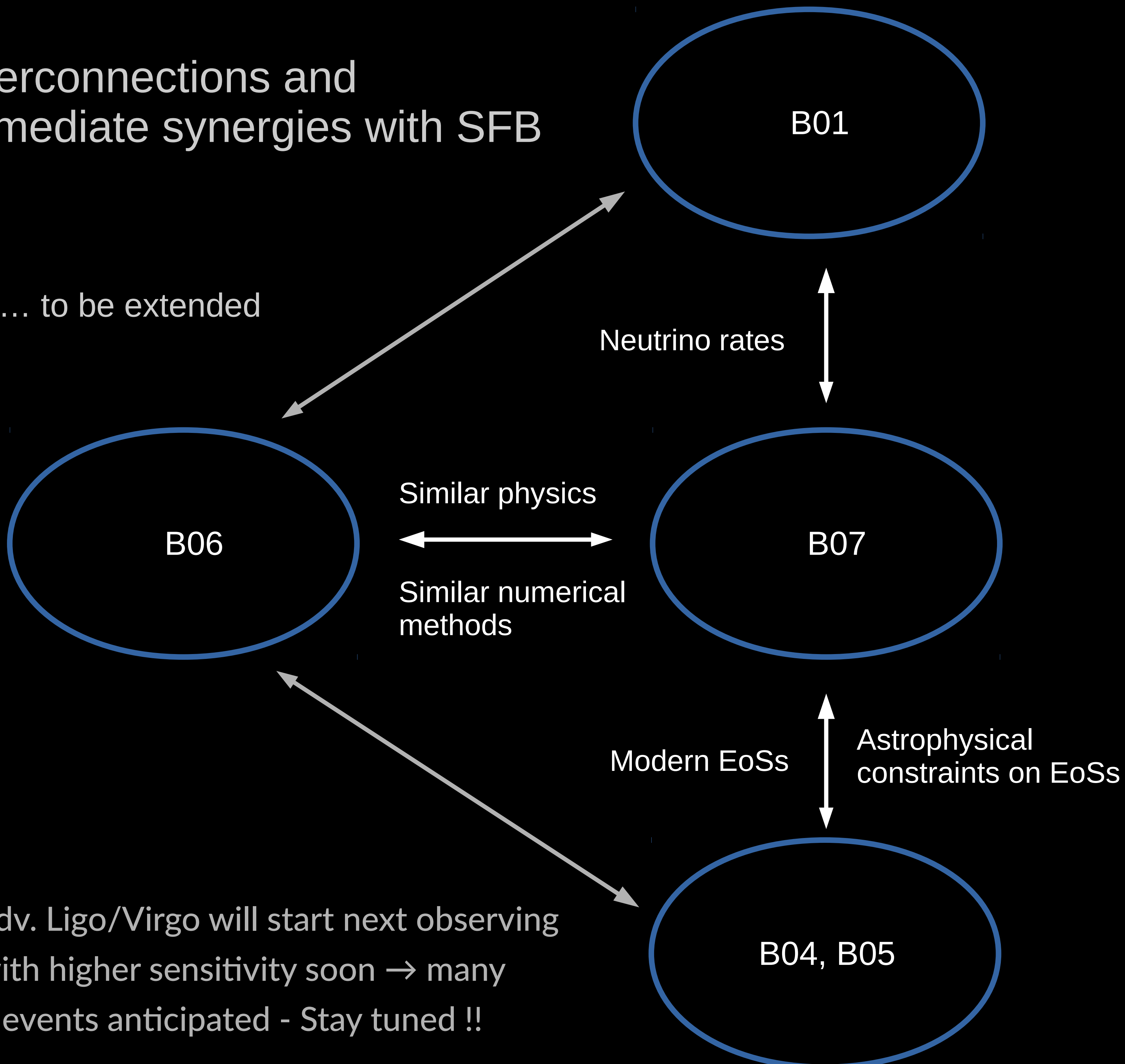
  - GW data analysis (with collaborators)
- Comprehensive analysis of postmerger spectrum

  - Origin and dependencies of spectral features

  - dependence on EoS and mass ratio

  - develop dedicated GW analysis to extract EoS effects

Interconnections and immediate synergies with SFB



… to be extended

PS: Adv. Ligo/Virgo will start next observing run with higher sensitivity soon → many more events anticipated - Stay tuned !!

Nuclear physics impact on NS mergers and vice versa

- Nuclear EoS → merger dynamics

  → GW emission (pre-merger and post-merger)

  → remnant stability and life time

  → conditions for short gamma-ray burst

  → mass ejection and conditions for long-term evolution → conditions r-process nucleosynthsis and nuclear-decay powered transient

  → neutrino emission → conditions r-process nucleosynthsis and nuclear-decay powered transient

- Nuclear models for r-process reaction rates

  → detailed path of the r-process and final abundance

  → heating by decays → properties of em transient

- In turn, observables which are affected by EoS reveal properties of EoS

  - if theoretical models allow reliable connection between input and observables

- Note: work within B07 goes in both directions