Max–Planck–Institut für Astrophysik

SFB 1258 Neutrinos Dark Matter Messengers

Excellence Cluster Universe

57th International Winter Meeting on Nuclear Physics
Bormio, Italy, Jan. 21–25, 2019

Neutron-Star Merger Modelling after GW170817

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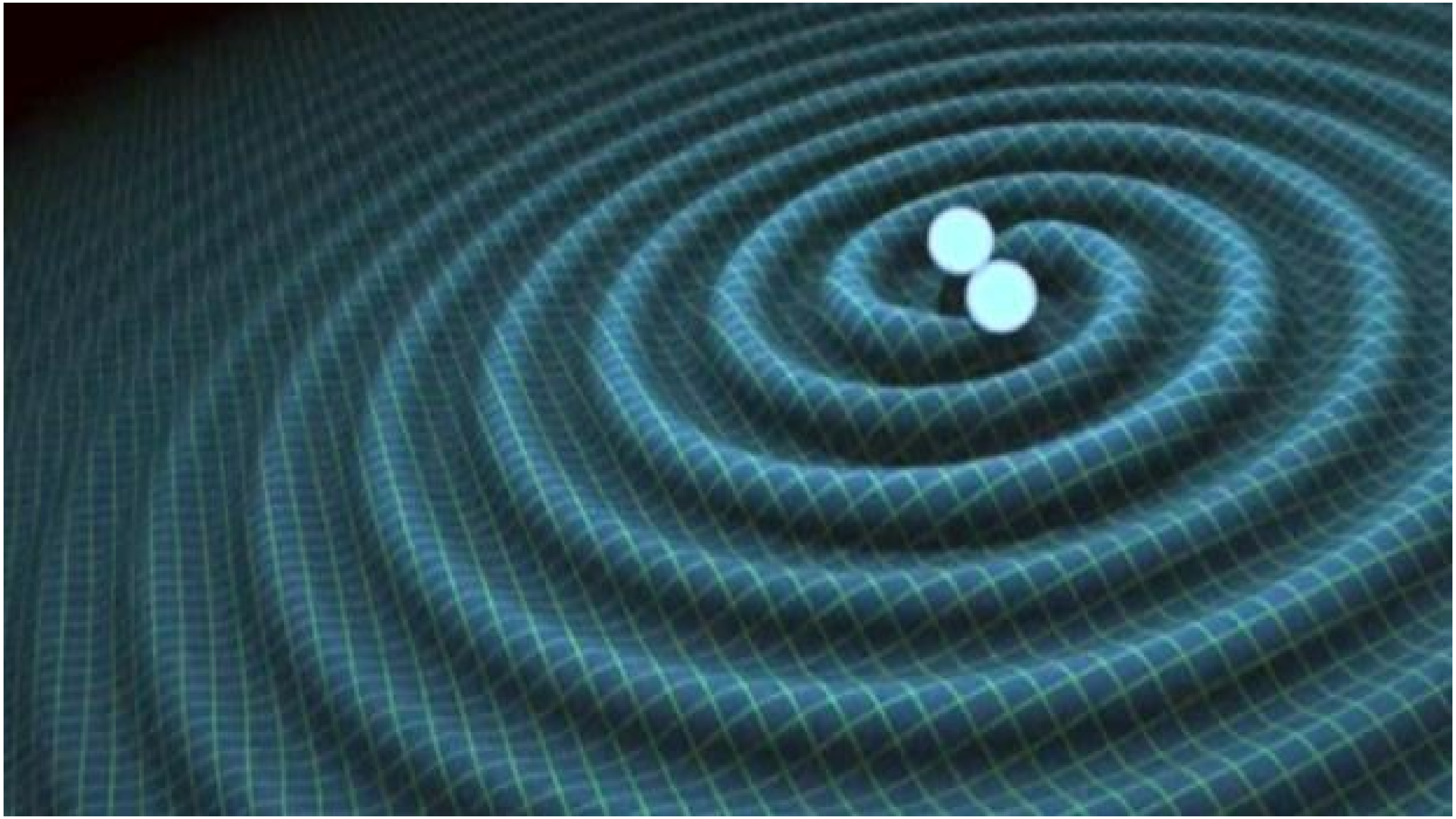
Outline

- **Observations: GW170817 as a NS+NS merger event**
- **Theoretical predictions and models for NS mergers**
- **NS mergers as sources of r-process elements**
- **Role of neutrinos for r-process production**
- **Constraints for NS and nuclear EOS properties from binary NS mergers**

NS+NS Binaries: Coalescence with Final Merger



17. August 2017:

First gravitational wave from merger event of two neutron stars:

GW170817

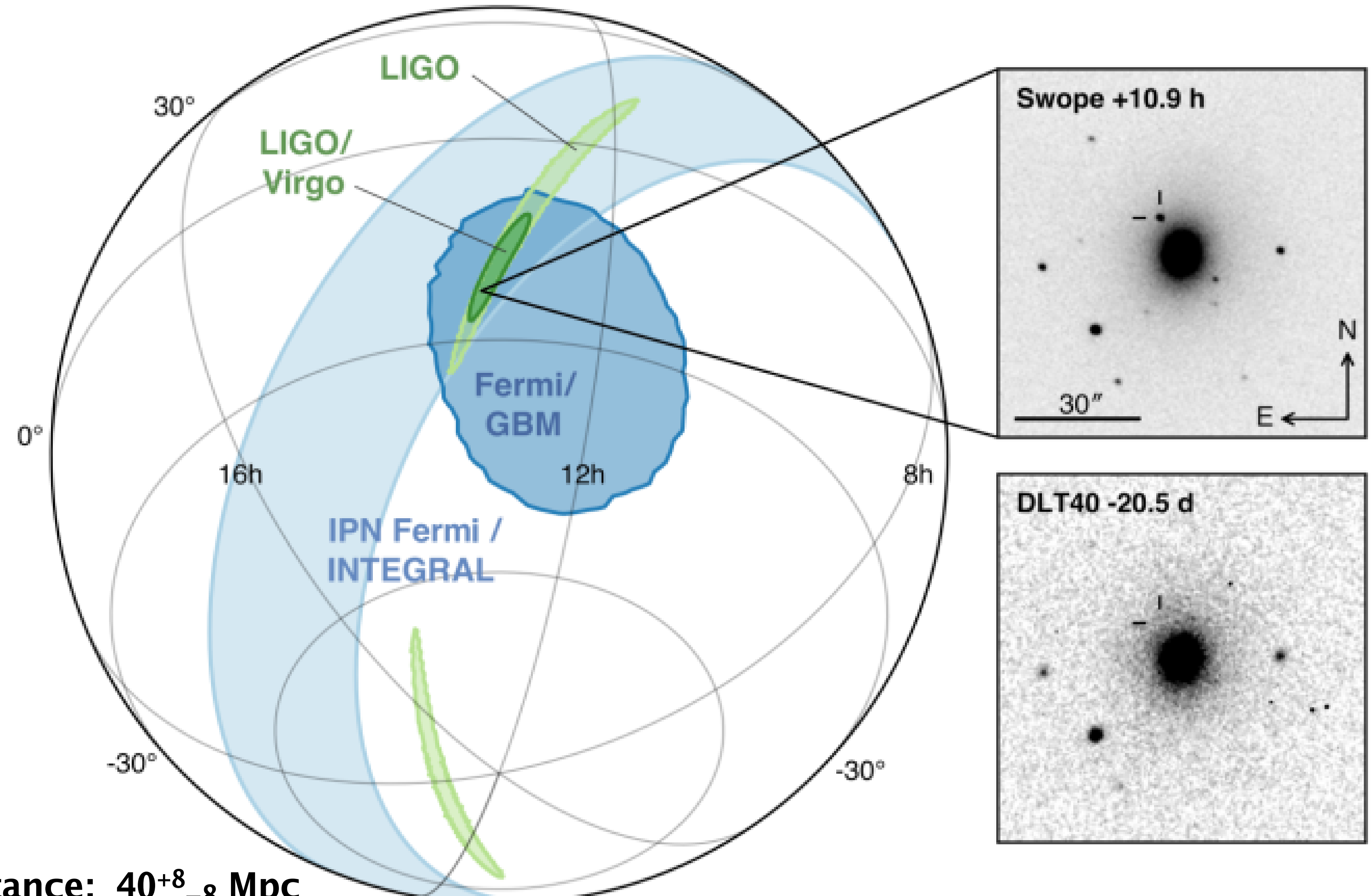
Closest ever short gamma-ray burst:

GRB170817A

First unambiguous detection of kilonova:

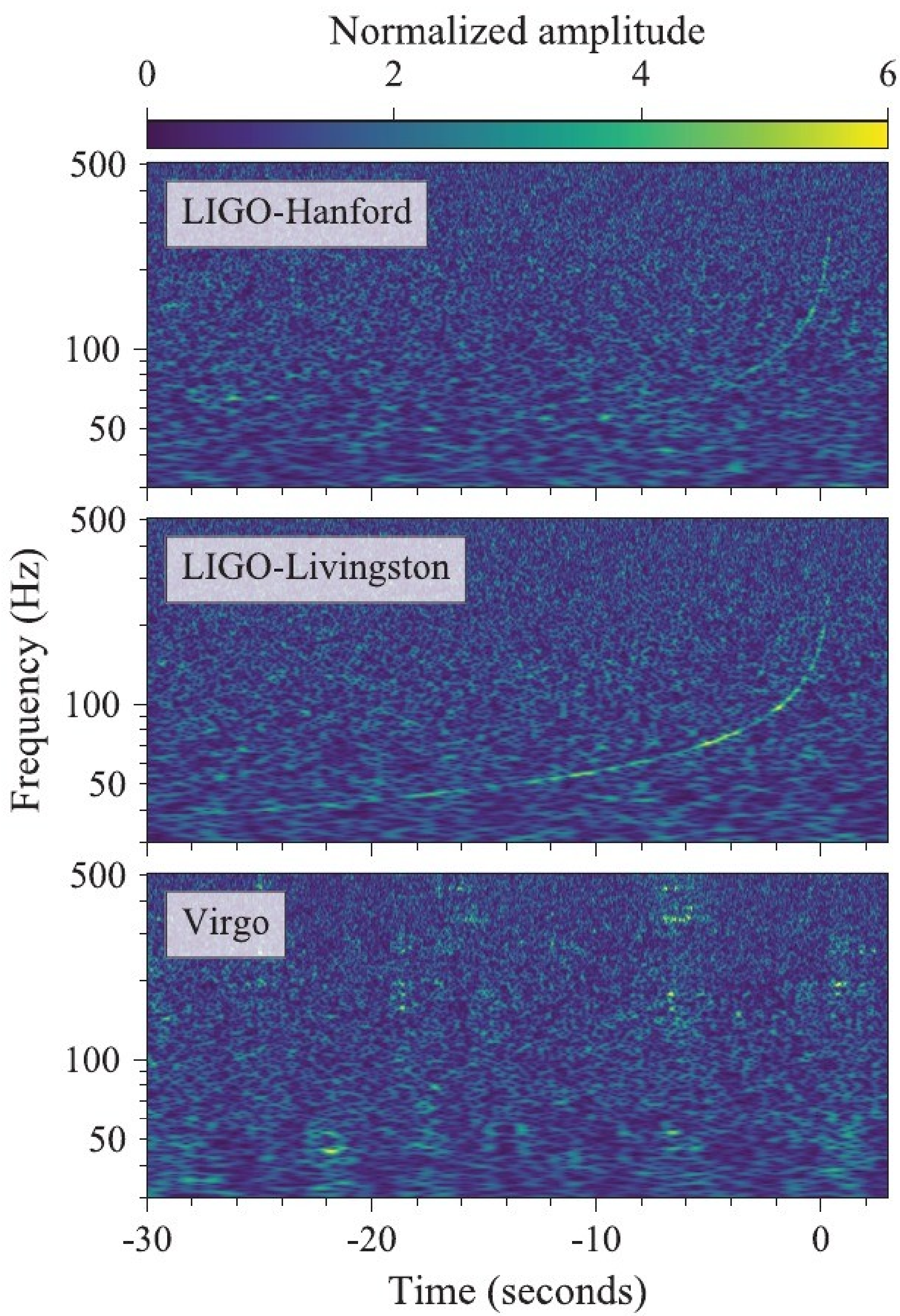
AT2017gfo

Celestial Position of Gravitational Wave Source



Distance: 40^{+8}_{-8} Mpc

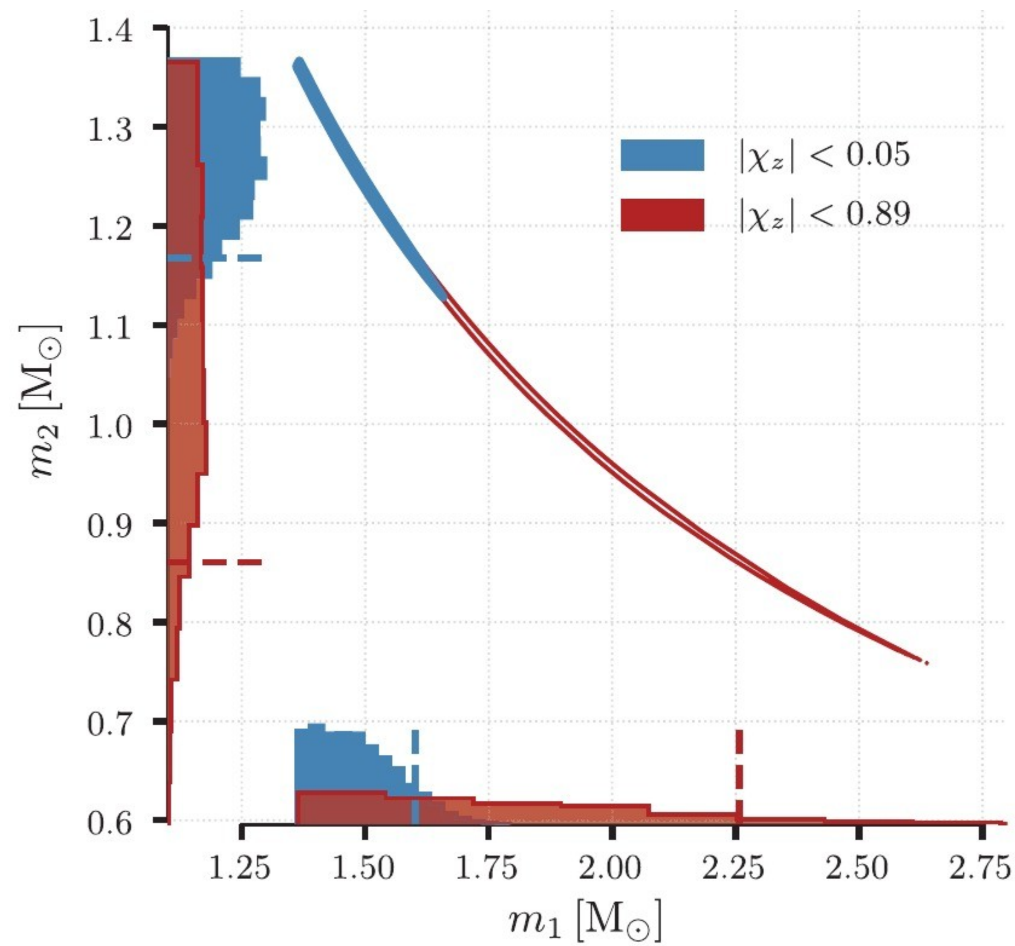
Gravitational Wave Detection



Chirp mass: 1.188

Total mass: ~2.74 M_{sun},

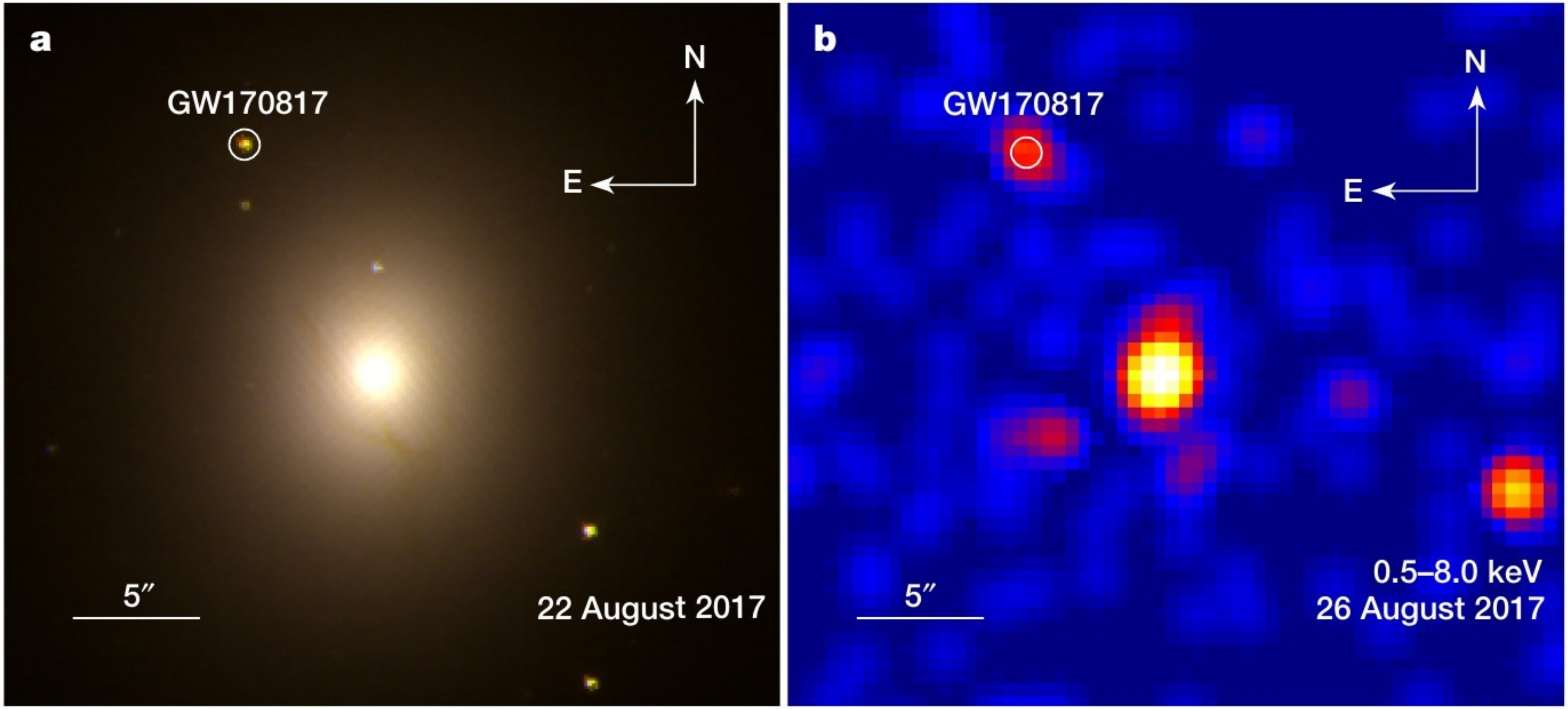
M_1 ~ 1.36–1.60 M_{sun}, M_2 ~1.17–1.36 M_{sun}



Abbott et al., PRL 119 (2017)

Optical and X-Ray Counterparts

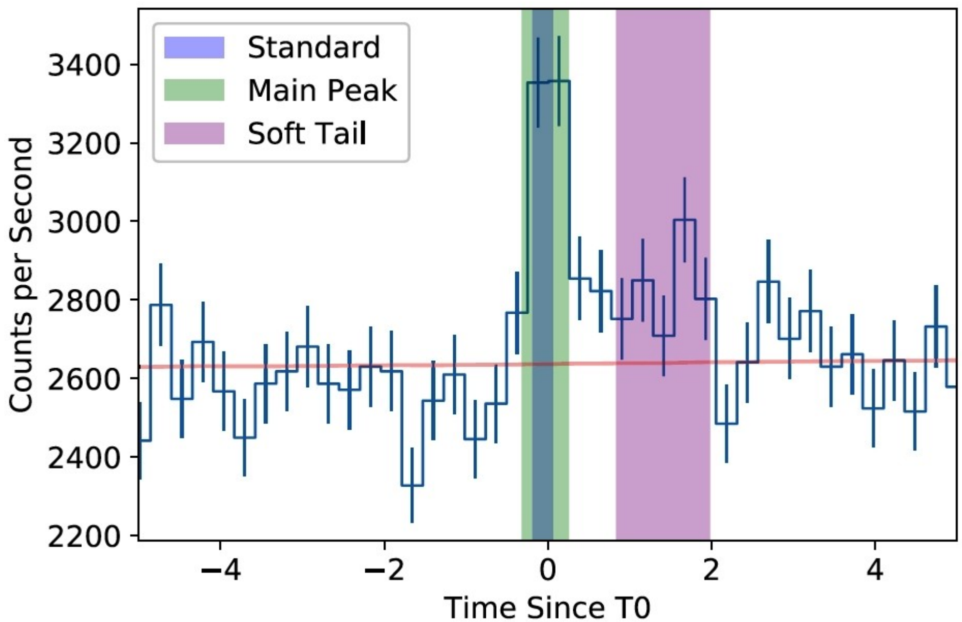
Optical/infrared and X-ray images of counterpart of GW170817



Distance of galaxy
NGC 4993 ~ 40 Mpc

Troja et al., Nature (2017)

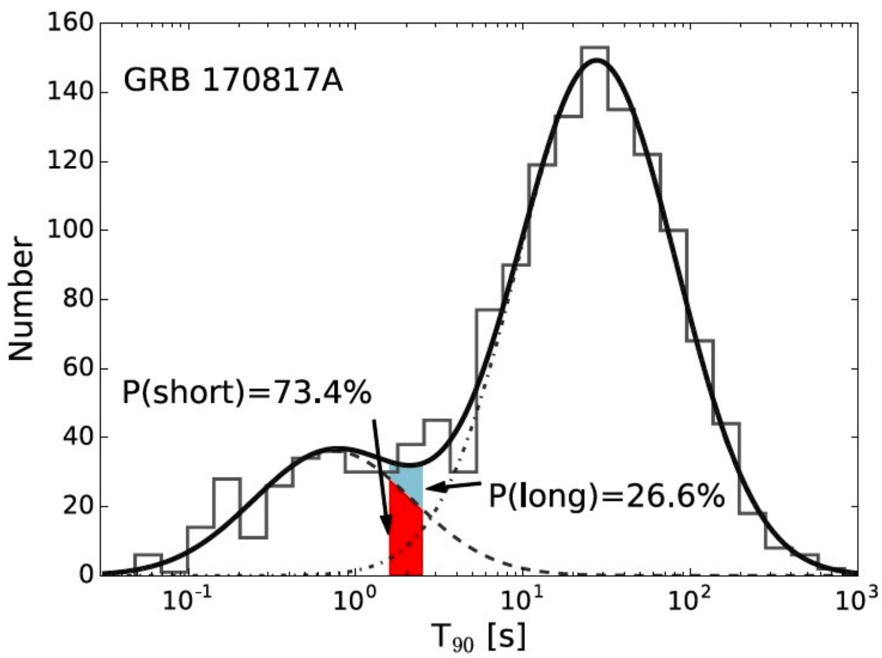
Gamma-Ray Burst Detection

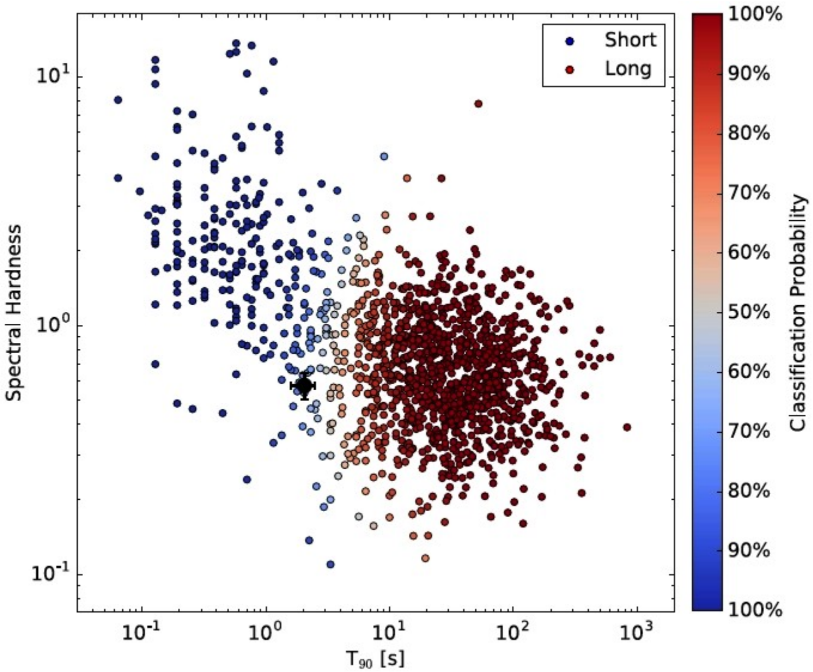


Short GRB ~1.7s after gravitational-wave measurement

Observed Energy: $E_\gamma \sim 10^{47}$ ergs,
~10000 times lower than typical short GRBs

Spectral peak: $E_p = 240^{+130}_{-70}$ keV,
on soft side of usual short GRBs

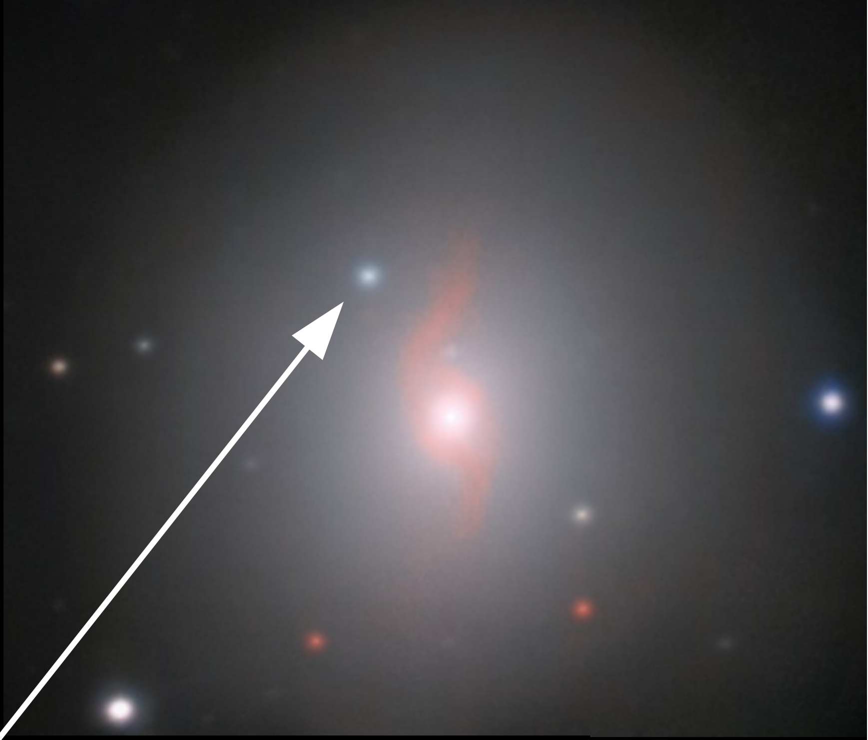


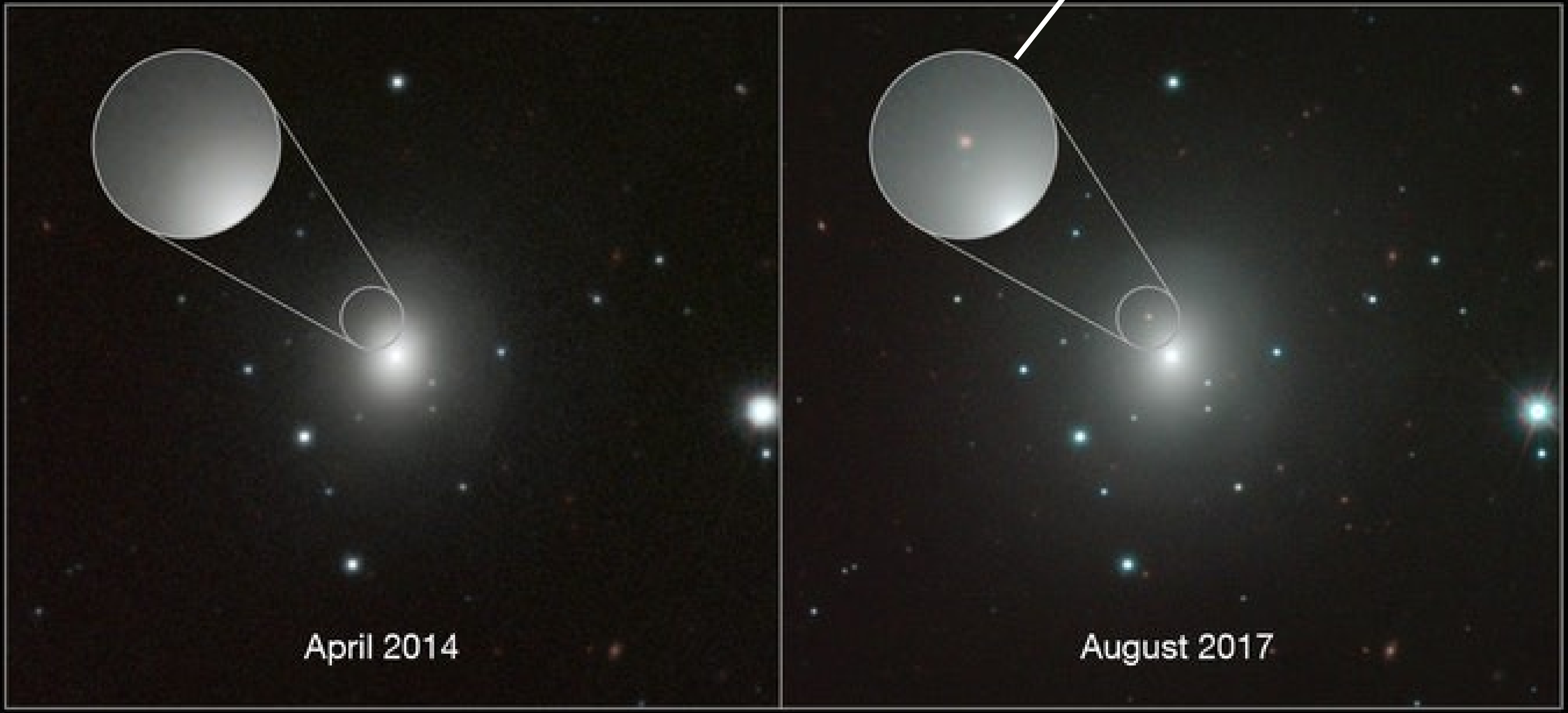


Goldstein et al., ApJL (2017)

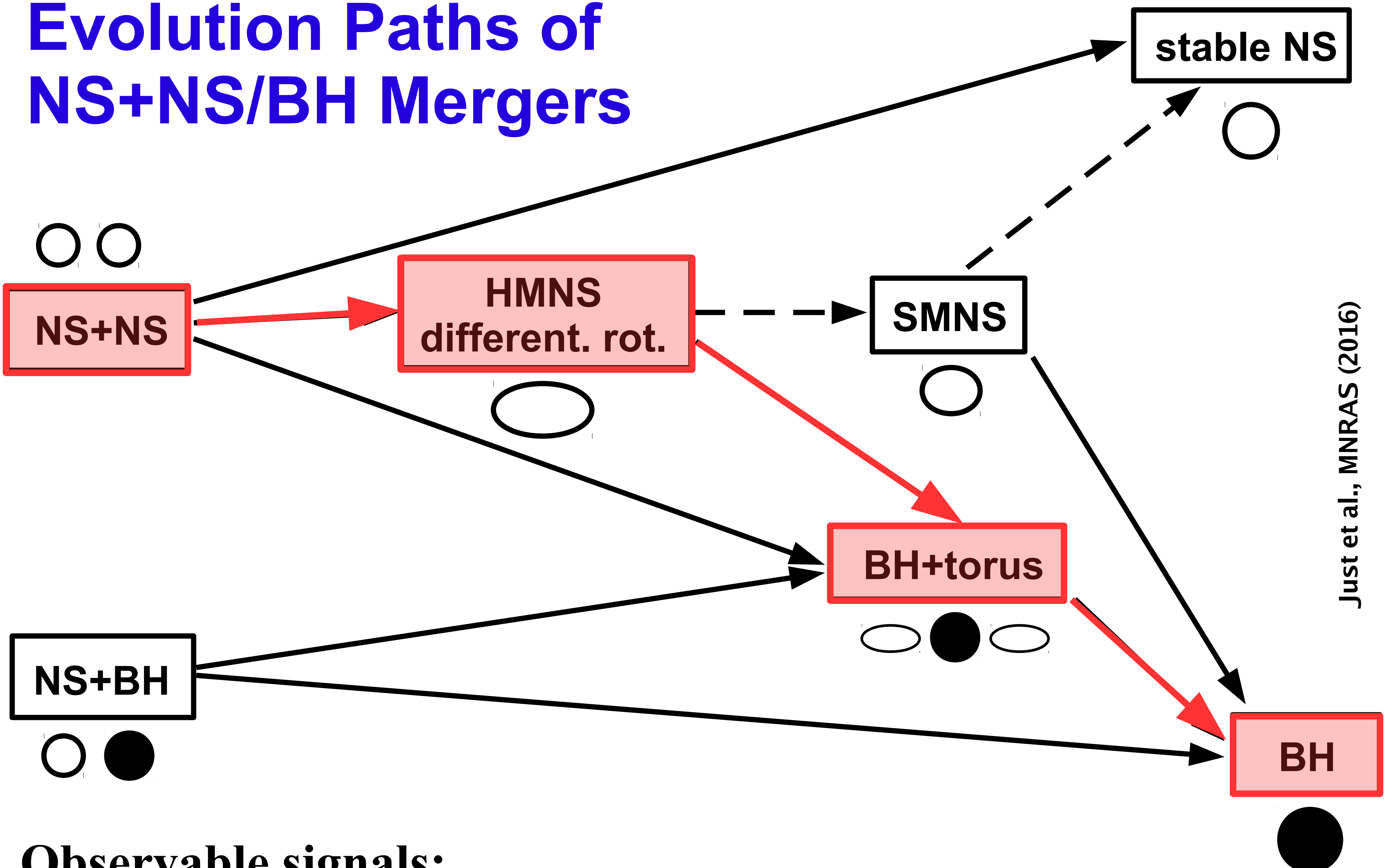
Kilonova in Elliptical Galaxy NGC 4993

Distance: “only” 130 million light years





Evolution Paths of NS+NS/BH Mergers



Observable signals:

Gravitational waves, neutrinos, gamma-ray bursts,
mass ejection, r-process elements, electromagnetic transients

Phases & Signals of NS+NS/BH Mergers

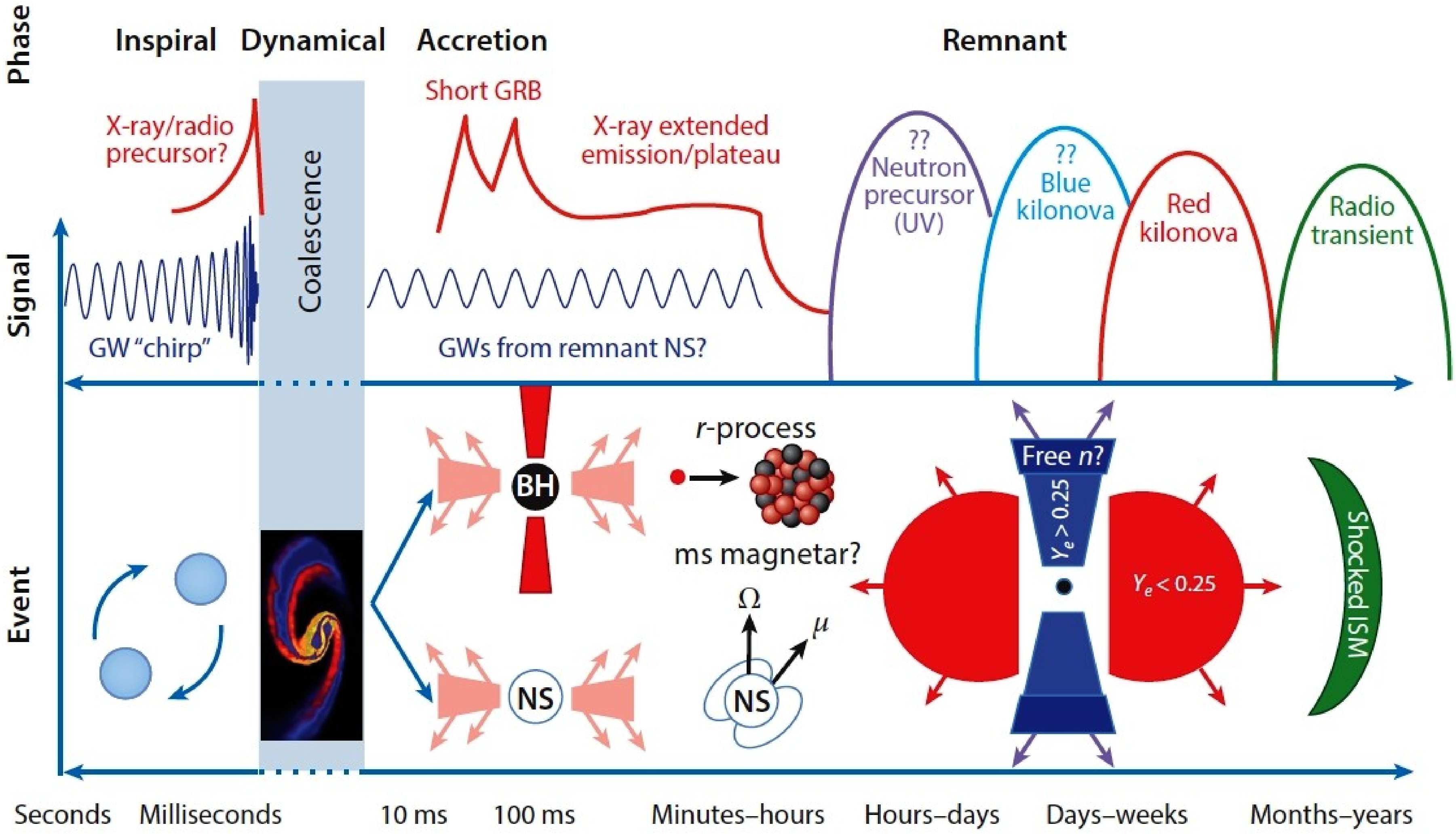


Figure 1

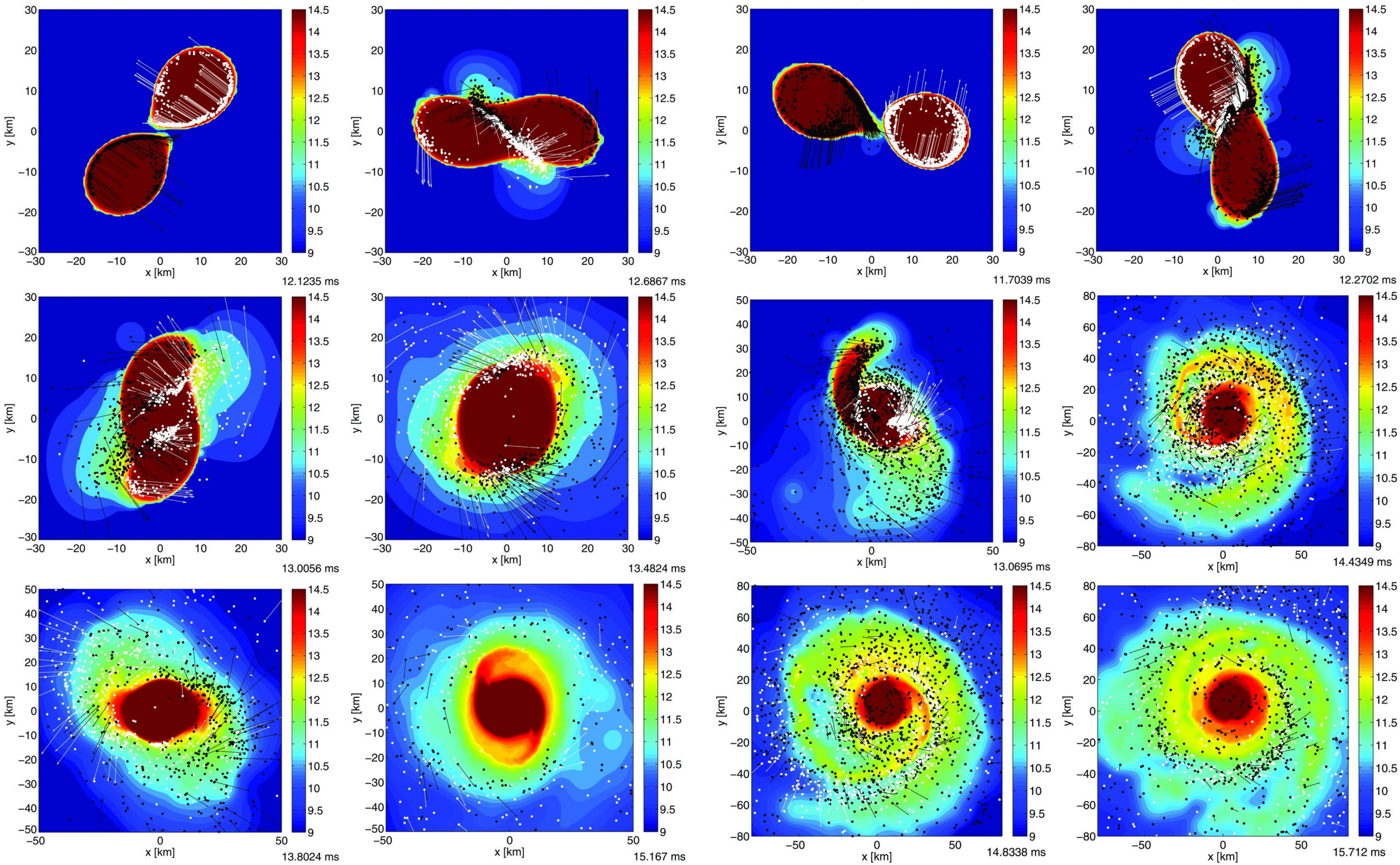
Phases of a neutron star (NS) merger as a function of time, showing the associated observational signatures and underlying physical phenomena. Abbreviations: BH, black hole; GRB, γ-ray burst; GW, gravitational wave; ISM, interstellar medium; n, neutron; UV, ultraviolet; Y_e, electron fraction. Coalescence inset courtesy of D. Price and S. Rosswog (see also Reference 15).

Fernández & Metzger, ARNPS (2016)

Dynamical Mass Ejection from NS+NS Mergers

Symmetric NS-NS merger

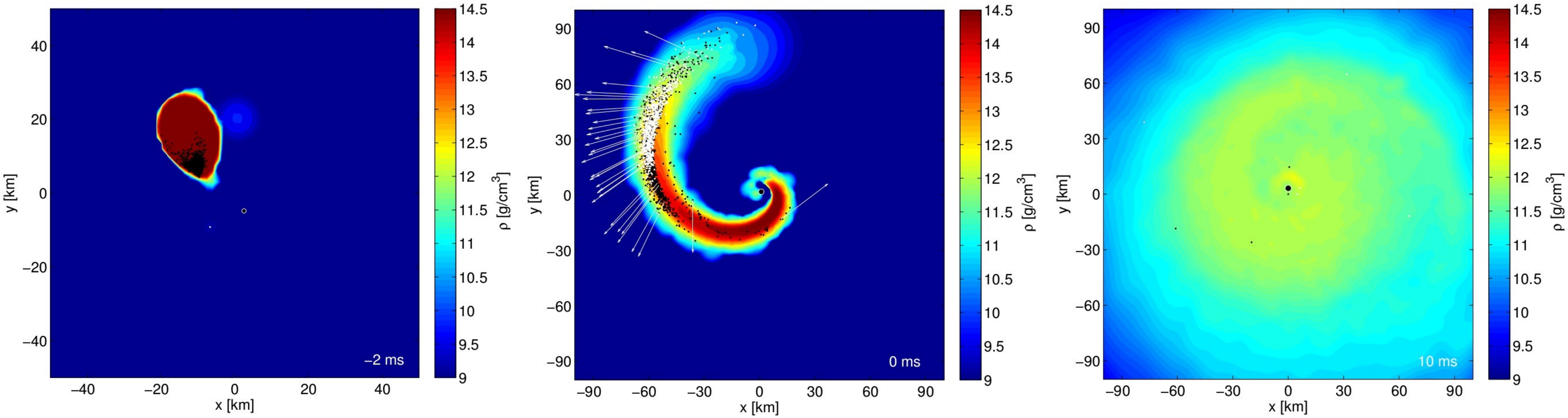
Asymmetric NS-NS merger



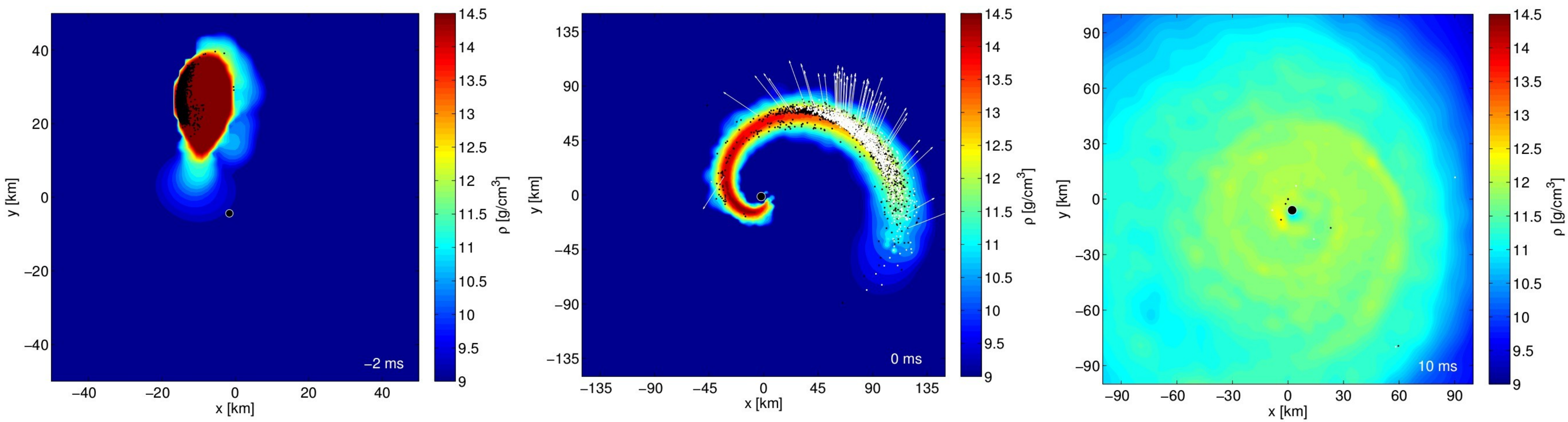
(Bauswein, Goriely, Janka, Marek; ApJ 773 (2013) 78)

Dynamical Mass Ejection from NS+BH Mergers

NS-BH merger: 1.45 M_{sun} + 2.9 M_{sun}

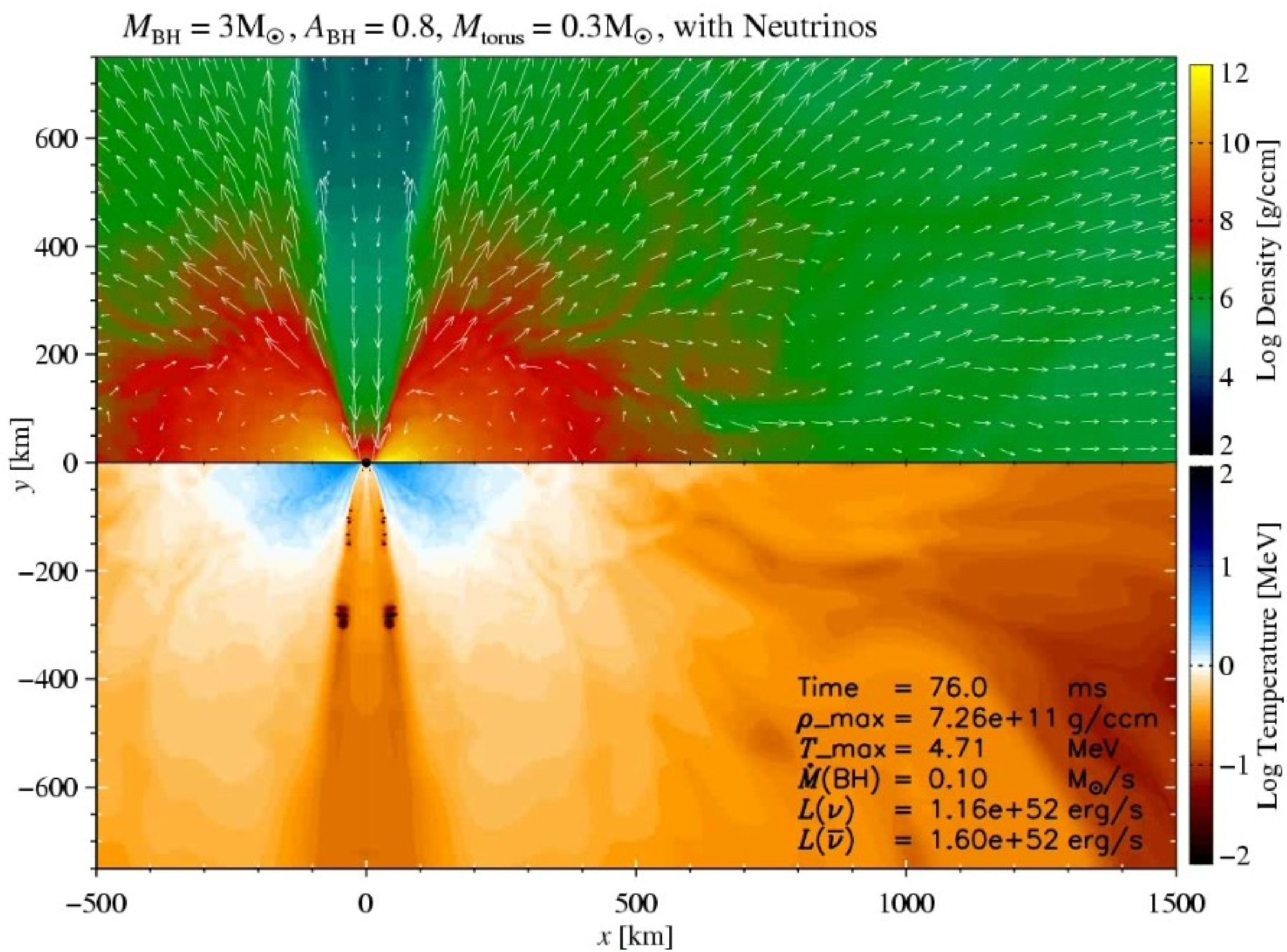


NS-BH merger: 1.40 M_{sun} + 5.1 M_{sun}



(Just et al, MNRAS 448 (2015) 541)

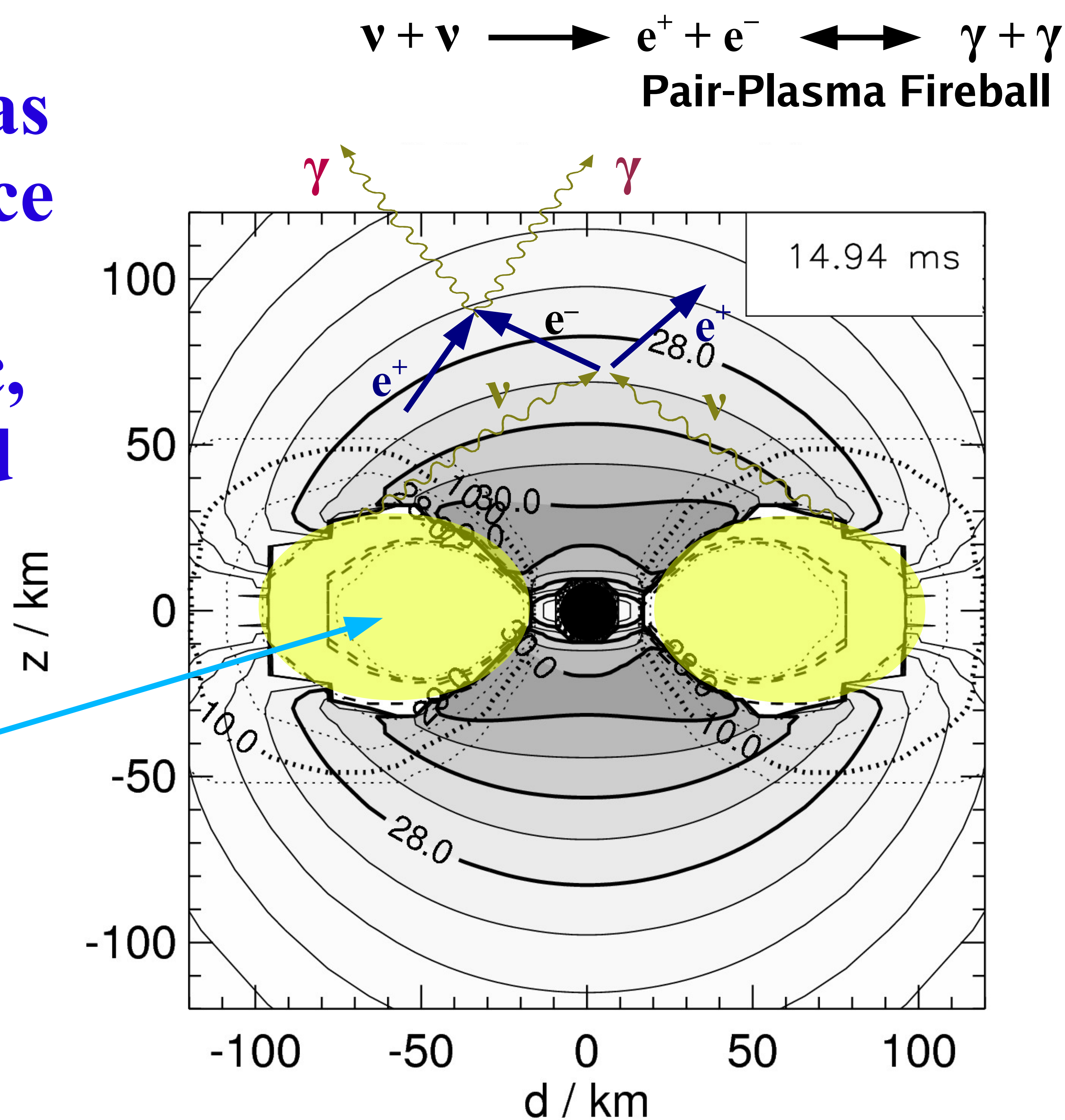
Outflows from Magnetized BH-torus



Magnetohydrodynamic simulation
With M1 ALCAR neutrino transport

(Just, PhD Thesis 2012)

Neutrinos as energy souce of ultra-relativistic, collimated outflow



Extremely hot torus radiates high neutrino luminosities into polar low-density funnels.

Can the Extreme Magnetic Fields Power Jet Outflows?

THE ASTROPHYSICAL JOURNAL LETTERS, 824:L6 (5pp), 2016 June 10 RUIZ ET AL.

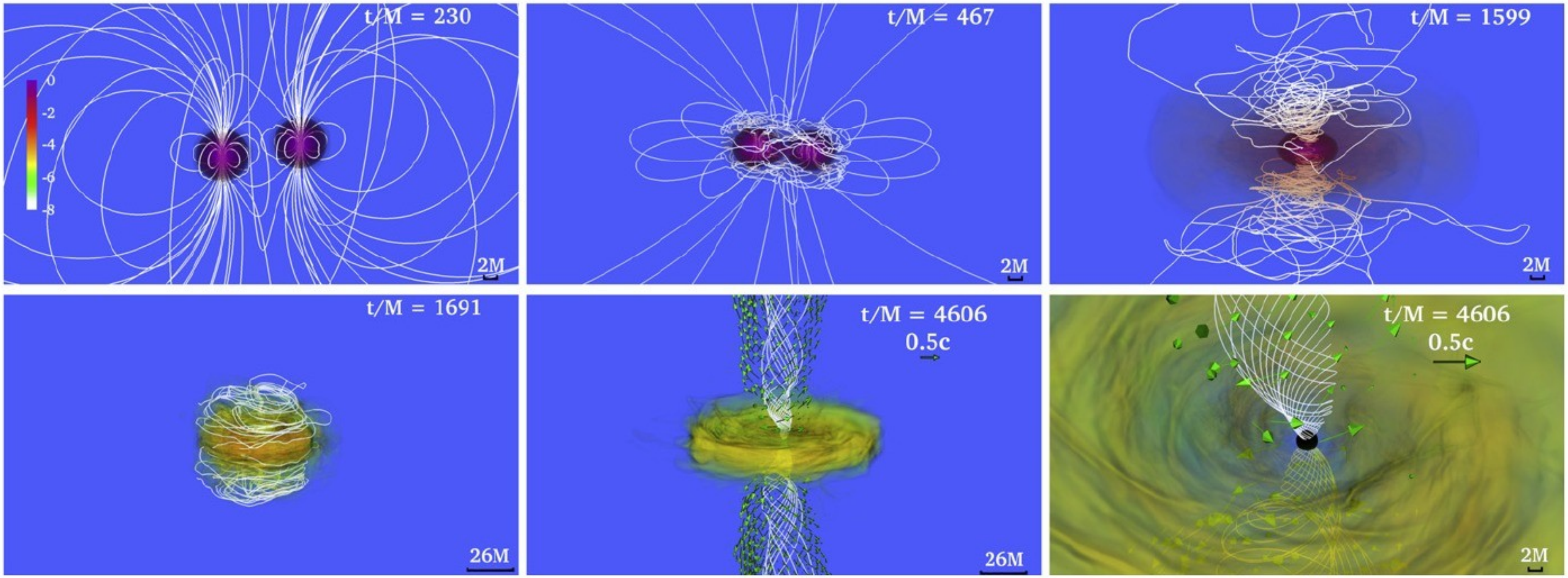


Figure 1. Snapshots of the rest-mass density, normalized to its initial maximum value $\rho_{0,\mathrm{max}} = 5.9 \times 10^{14}\,(1.625\,M_\odot/M_{\mathrm{NS}})^2\ \mathrm{g\,cm^{-3}}$ (log scale) at selected times for the P case. The arrows indicate plasma velocities, and the white lines show the B-field structure. The bottom middle and right panels highlight the system after an incipient jet is launched. Here $M = 1.47 \times 10^{-2}(M_{\mathrm{NS}}/1.625\,M_\odot)$ ms $= 4.43(M_{\mathrm{NS}}/1.625\,M_\odot)$ km.

Ruiz, Lang, Paschalidis, & Shapiro, ApJL 824 (2016) L6

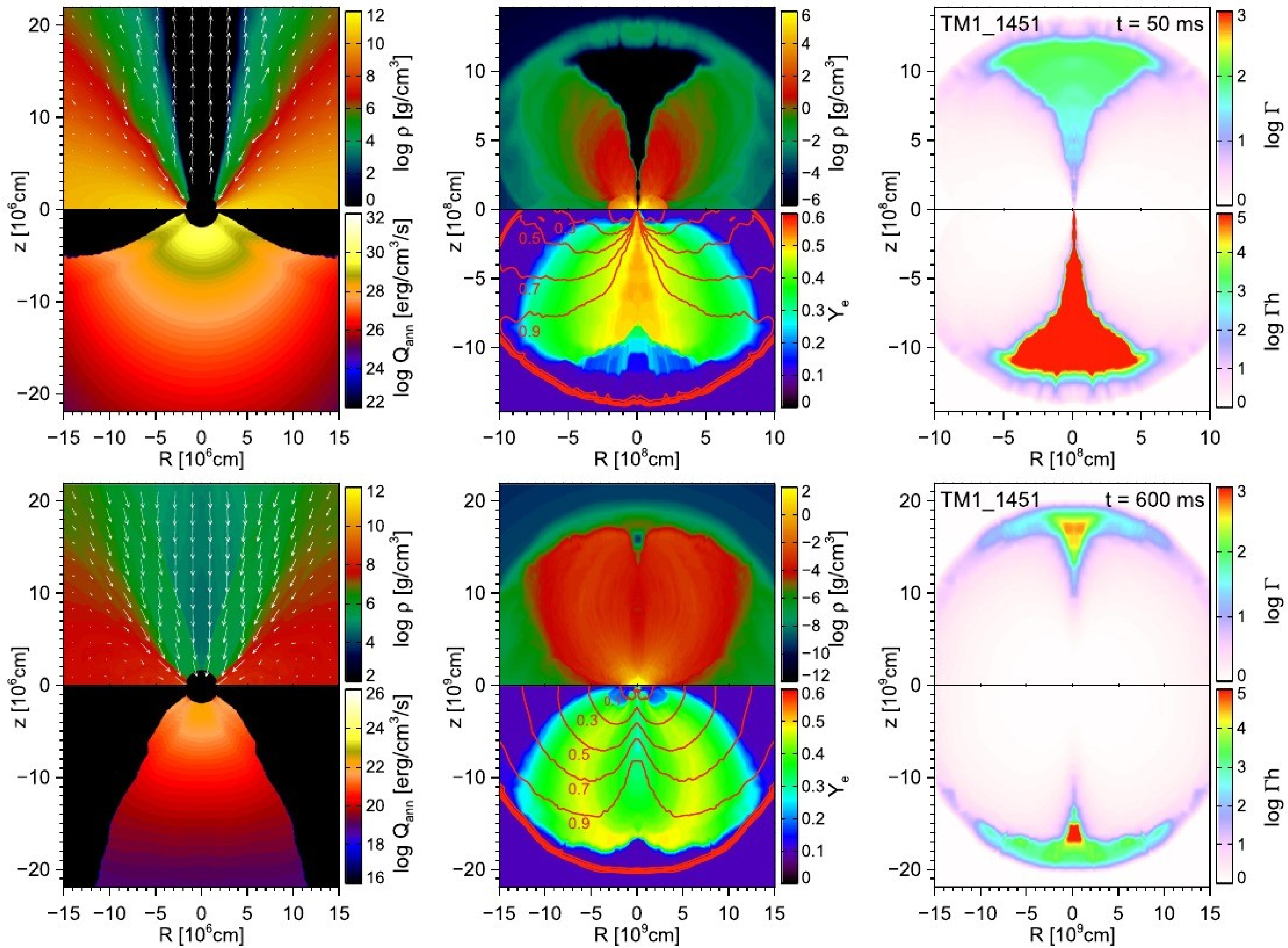


Figure 4. Same as Figure 2, but for NS–BH merger model TM1_1451 and with partially different spatial and color scales.

Just et al., ApJL 816 (2016) 30

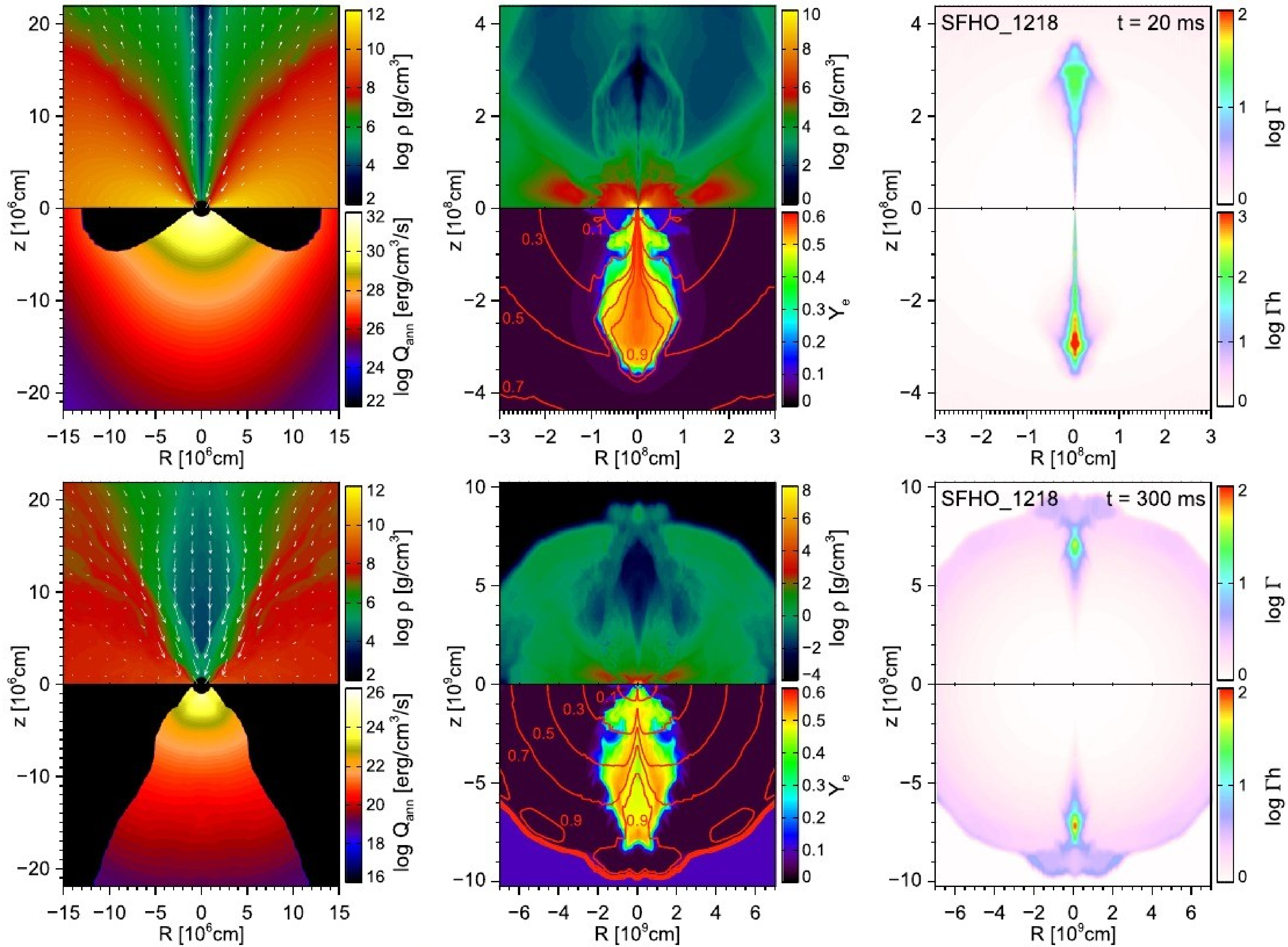
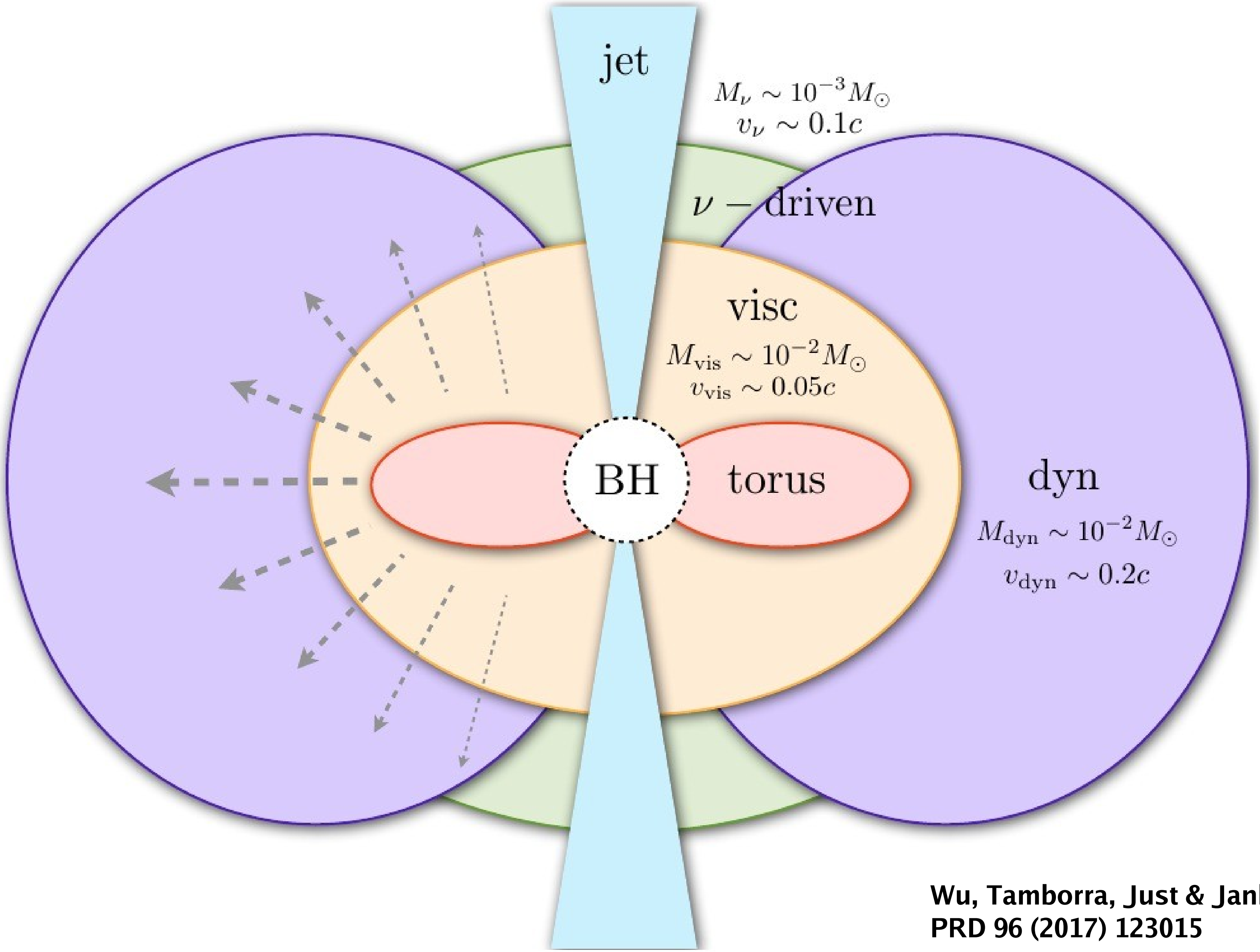


Figure 3. Same as Figure 2, but for model SFHO_1218 and with partially different spatial and color scales.

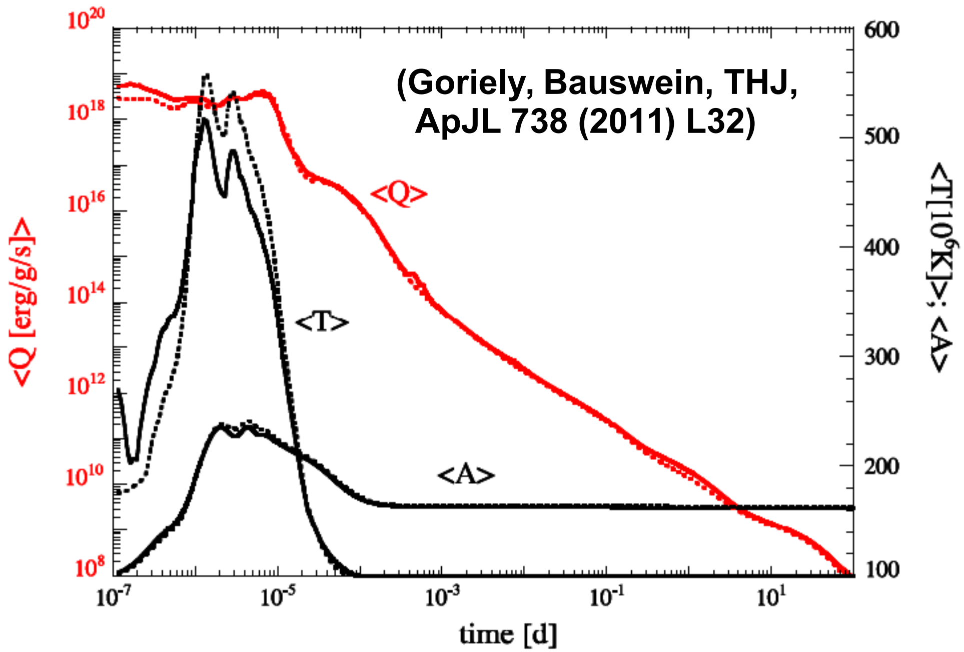
Just et al., ApJL 816 (2016) 30

Jets and Outflows from Compact Binary Mergers



Wu, Tamborra, Just & Janka,
PRD 96 (2017) 123015

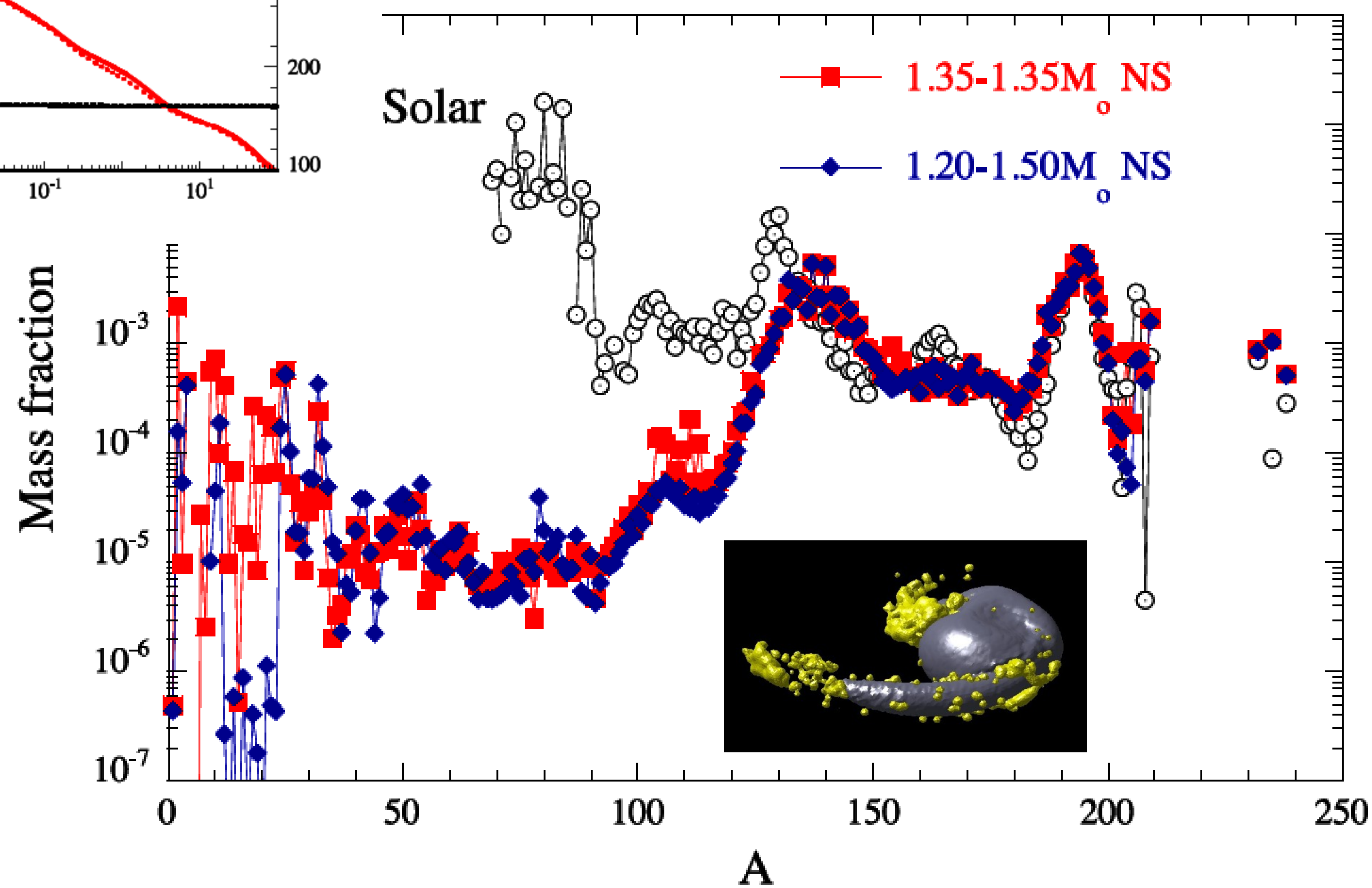
Nucleosynthesis in Dynamical Merger Ejecta



During r-processing fission recycling takes place and produces roughly solar abundances for A > 130.

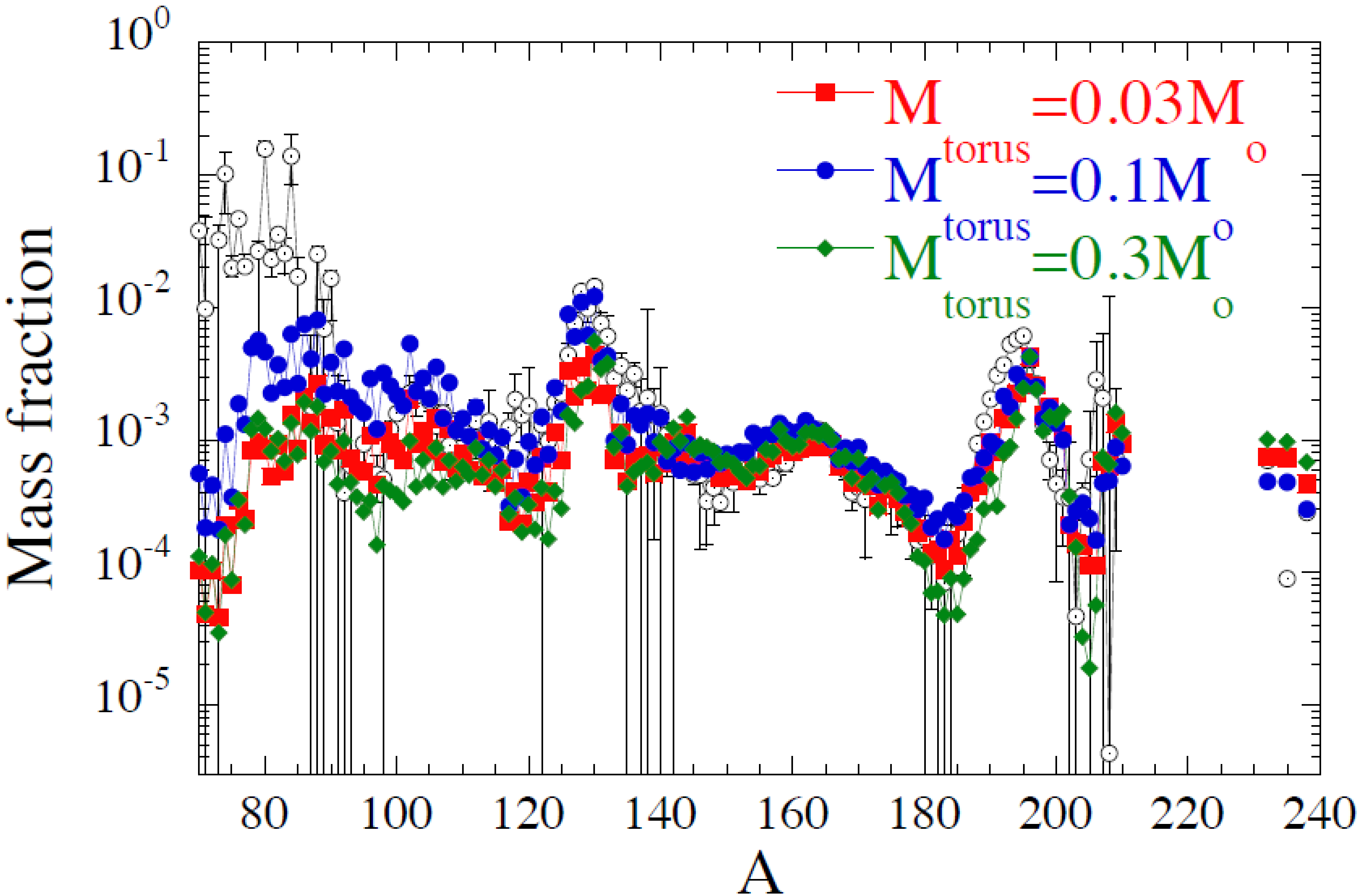
Per merger event 10^{-3}–10^{-2} M_{sun} are ejected.

With rate of 10^{-5} events per year and galaxy, NS mergers could be the main source of heavy r-process material.



r-process Nucleosynthesis

Ejecta from NS+NS merger + BH-torus remnant



(Just et al, MNRAS 448 (2015) 541)

For BH-disk ejecta, see also Wu+ (2016); for HMNS winds, see Perego+ (2014), Martin+ (2015)

Light Curve of Kilonova AT2017gfo

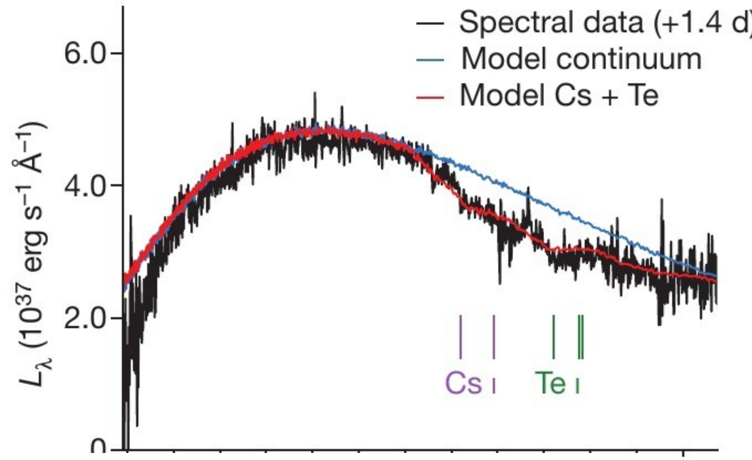
Theoretical models reproduce observation if heavy trans-iron elements dominate composition of ejecta

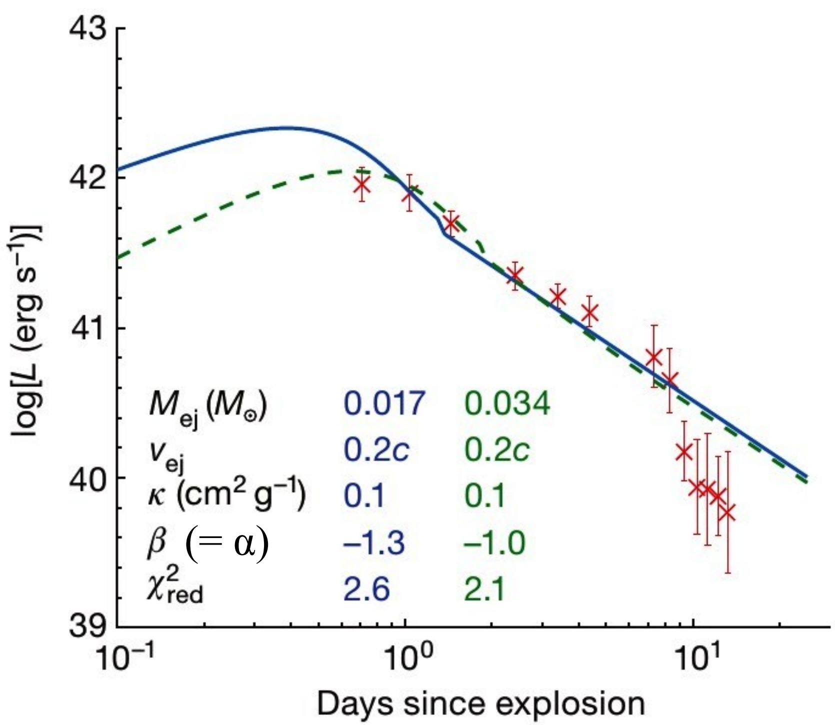
$$\dot{\varepsilon}_{\rm nuc} \approx 10^{10} t^{-\alpha}$$

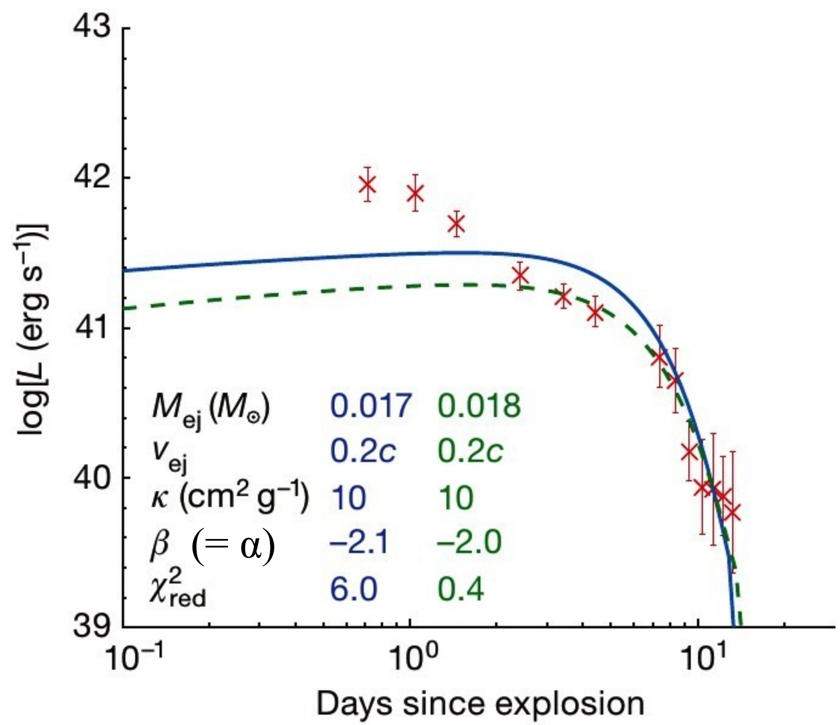
$$t_{\rm lc} \approx \left(\frac{3\kappa M}{4\pi c v}\right)^{\frac{1}{2}} \approx 2.7\,\text{days} \times \left(\frac{M}{0.01 M_\odot}\right)^{\frac{1}{2}} \left(\frac{v}{0.1c}\right)^{-\frac{1}{2}} \left(\frac{\kappa}{1\,\text{cm}^2\,\text{g}^{-1}}\right)^{\frac{1}{2}}$$

$$L_{\rm lc} \approx M \dot{\varepsilon}_{\rm nuc}(t_{\rm lc})$$

$$\approx 5 \times 10^{40}\,\text{erg s}^{-1} \times \left(\frac{M}{0.01 M_\odot}\right)^{1-\frac{\alpha}{2}} \left(\frac{v}{0.1c}\right)^{\frac{\alpha}{2}} \left(\frac{\kappa}{1\,\text{cm}^2\,\text{g}^{-1}}\right)^{-\frac{\alpha}{2}}$$







Smartt, Chen, Jerkstrand, et al., Nature (2017)

Components of Outflows from Compact Binary Mergers

(Kasen, Metzger et al., Nature 2017)

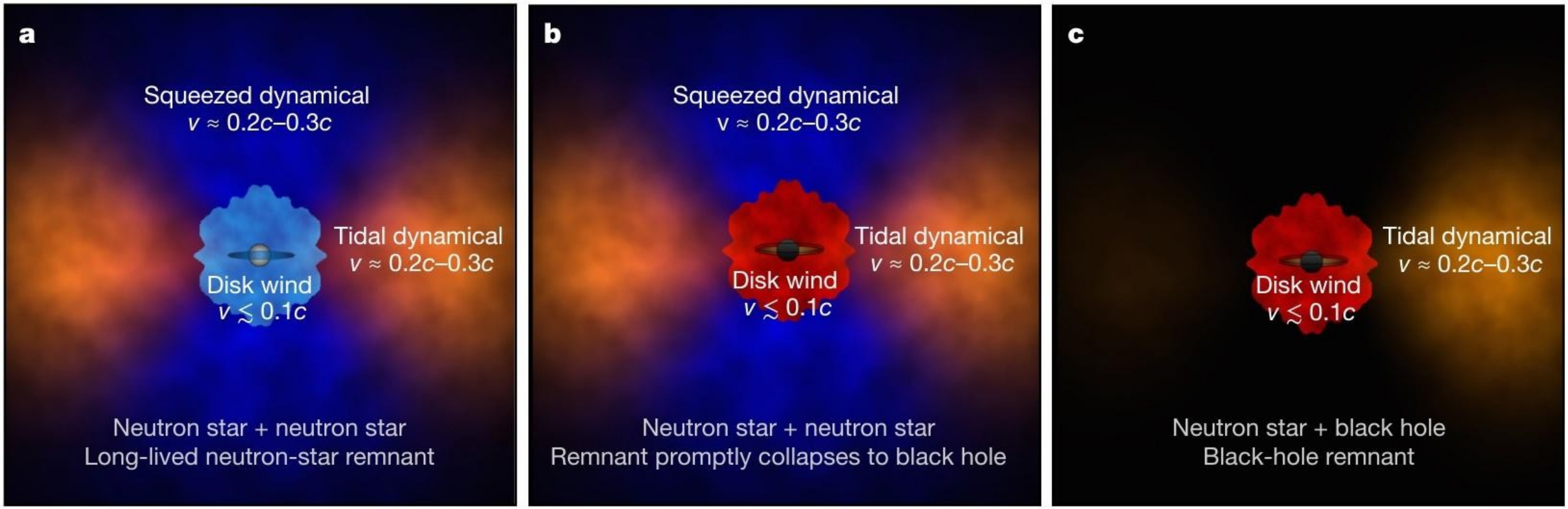


Figure 1 | Schematic illustration of the components of matter ejected from neutron-star mergers. Red colours denote regions of heavy r-process elements, which radiate red/infrared light. Blue colours denote regions of light r-process elements which radiate blue/optical light. During the merger, tidal forces peel off tails of matter, forming a torus of heavy r-process ejecta in the plane of the binary. Material squeezed into the polar regions during the stellar collision can form a cone of light r-process material. Roughly spherical winds from a remnant accretion disk can also contribute, and are sensitive to the fate of the central merger remnant. **a**, If the remnant survives as a hot neutron star for tens of milliseconds, its neutrino irradiation lowers the neutron fraction and produces a blue wind. **b**, If the remnant collapses promptly to a black hole, neutrino irradiation is suppressed and the winds may be red. **c**, In the merger of a neutron star and a black hole, only a single tidal tail is ejected and the disk winds are more likely to be red.

Ye > 0.25: Lanthanide-poor "blue" ejecta (low photon opacity)
Ye > 0.25: Lanthanide-rich "red" ejecta (high photon opacity)

Light Curve of Kilonova AT2017gfo

Kasen et al., Nature (2017)

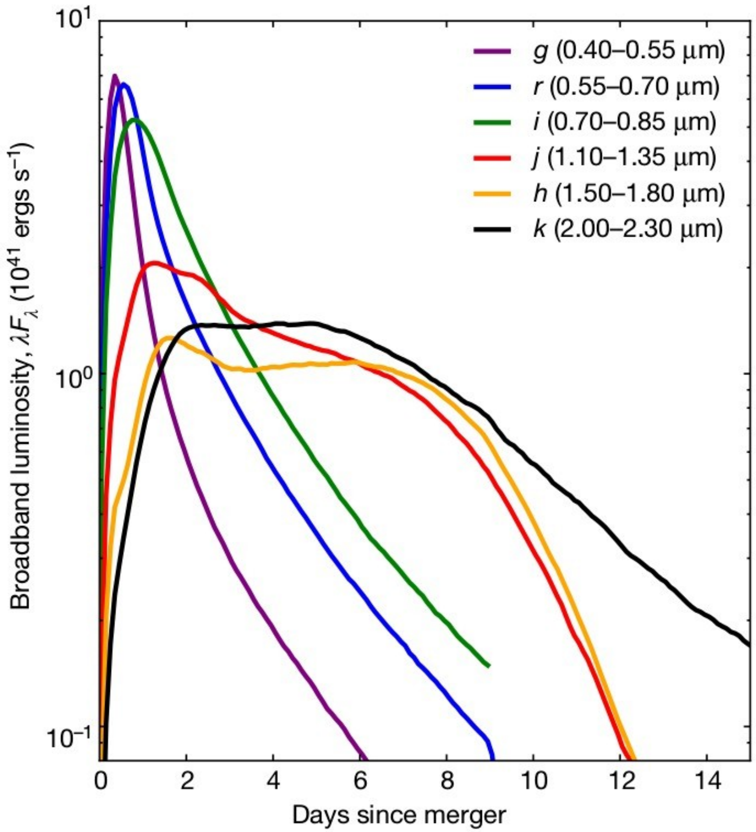
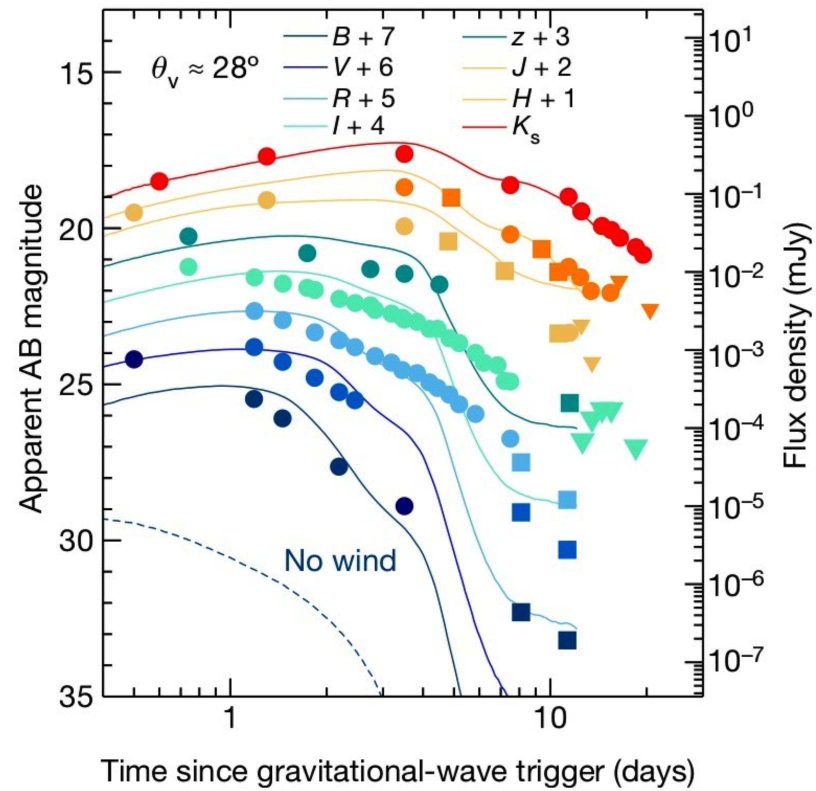


Figure 5 | A unified kilonova model explaining the optical/infrared counterpart of GW170817. The model is the superposition of the emission from two spatially distinct ejecta components: a 'blue' kilonova (light r-process ejecta with $M = 0.025M_{\odot}$, $v_k = 0.3c$ and $X_{lan} = 10^{-4}$) plus a 'red' kilonova (heavy r-process ejecta with $M = 0.04M_{\odot}$, $v_k = 0.15c$ and $X_{lan} = 10^{-1.5}$). Composite broadband light curves. The light r-process component produces the rapidly evolving optical emission while the heavy r-process component produces the extended infrared emission. The composite model predicts a distinctive colour evolution, spectral continuum shape and infrared spectral peaks, all of which resemble the properties of AT 2017gfo.

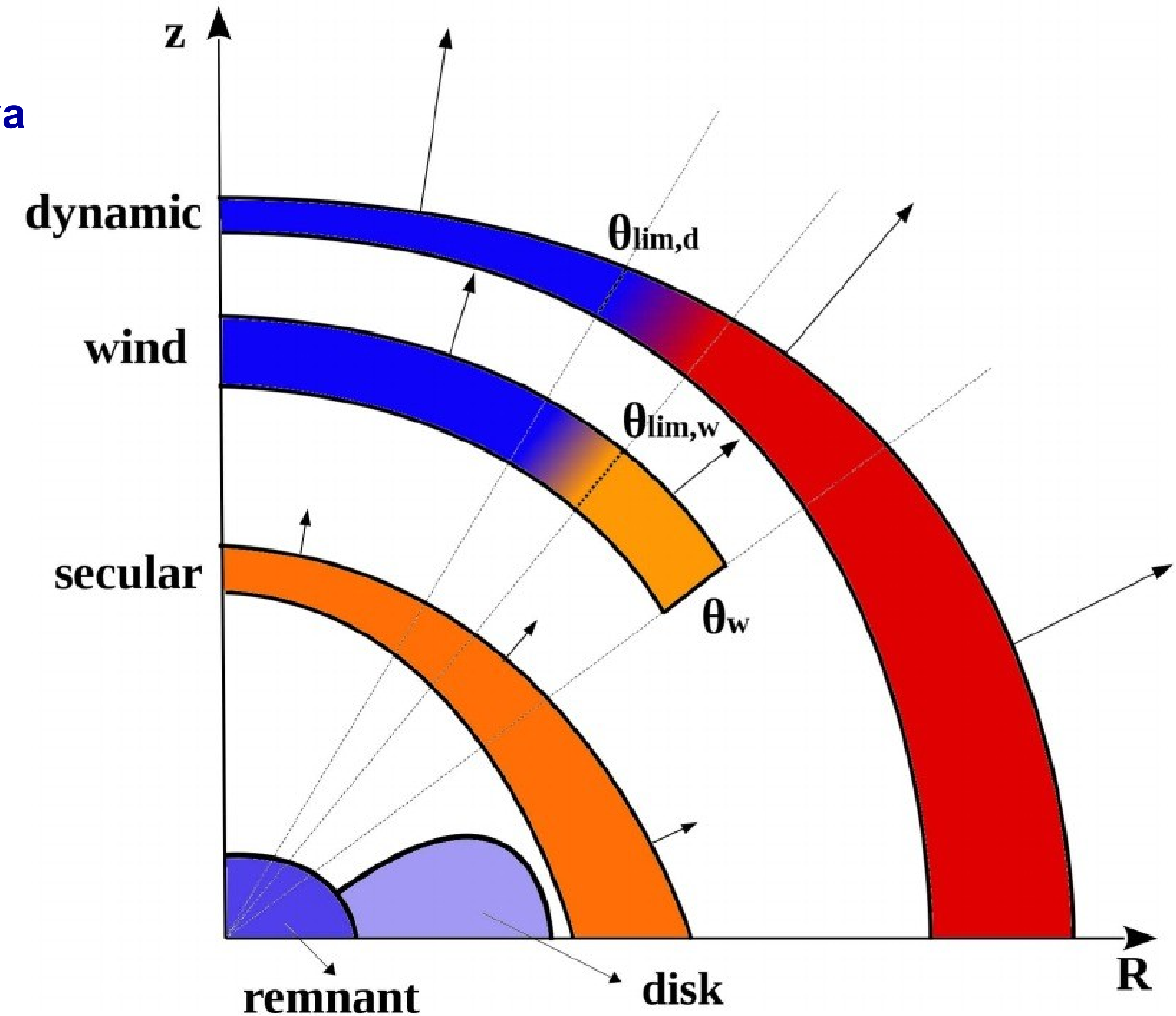
Troja et al., Nature (2017)



Temporal evolution of the optical and infrared transient AT 2017gfo compared with the theoretical predictions (solid lines) for a kilonova seen off-axis with viewing angle $\theta_v \approx 28°$. For comparison with the ground-based photometry, Hubble Space Telescope measurements (squares) were converted to standard filters. Our model includes the contribution from a massive, high-speed wind along the polar axis ($M_w \approx 0.015M_{\odot}$, $v \approx 0.08c$) and from the dynamical ejecta ($M_{ej} \approx 0.002M_{\odot}$, $v \approx 0.2c$). The presence of a wind is required to explain the bright and long-lived optical emission, which is not expected otherwise (see dashed line).

Interpretation of Kilonova AT2017gfo of GW170817

- Interpretation of kilonova signal is ambiguous.
- One, two or three components?
- Is very heavy r-process matter needed?
- All radiation emission calculations based on parametrized ejecta models, simplifications in the radiative transfer (LTE), and uncertain opacities.



(Perego, Radice, & Bernuzzi, ApJL 2017)

Nucleosynthesis in Neutrino-heated Ejecta

Crucial parameters for nucleosynthesis in neutrino-irradiated outflows:

- * Electron-to-baryon ratio Y_e (<---> neutron excess)
- * Entropy (<----> ratio of (temperature)^3 to density)
- * Expansion timescale

Determined by the interaction of neutrinos in the stellar gas and ejecta of merger remnant:

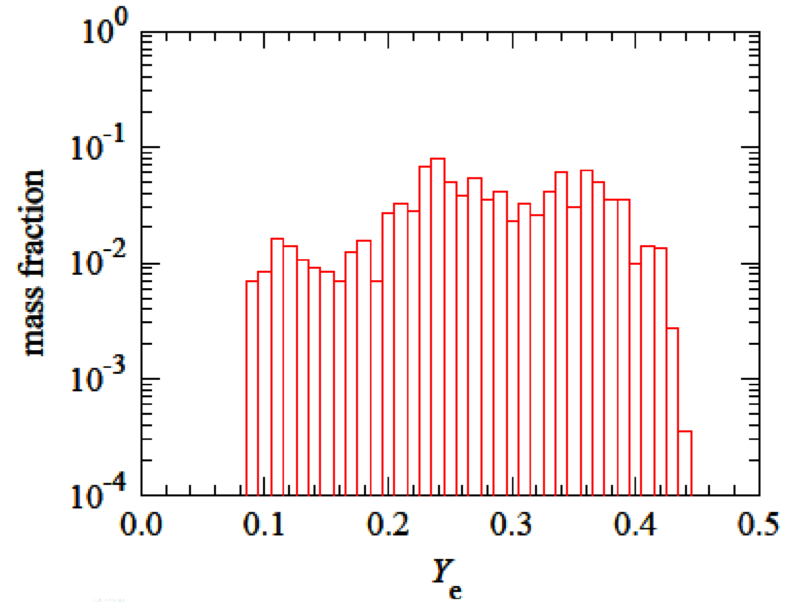
$$\boxed{\begin{aligned} \nu_e + n &\longleftrightarrow e^- + p \\ \bar{\nu}_e + p &\longleftrightarrow e^+ + n \end{aligned}}$$

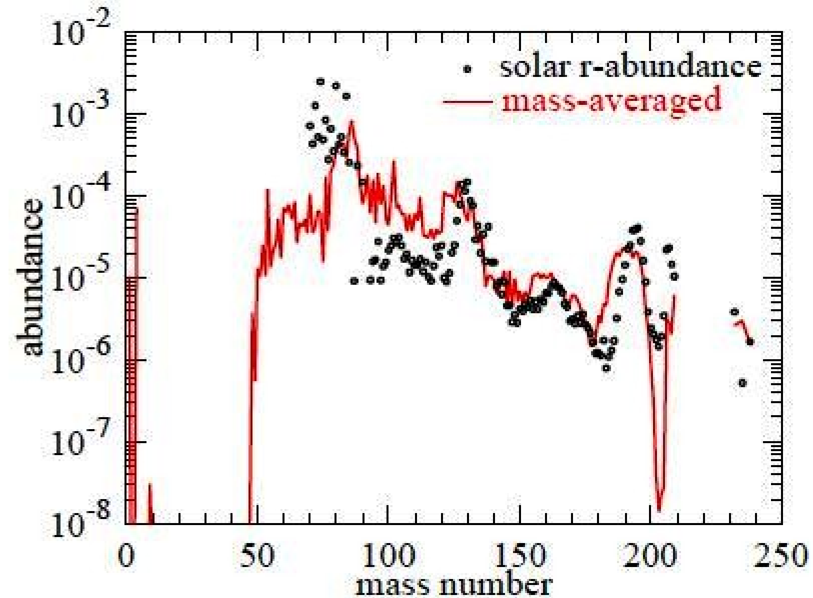
$$Y_e^\infty \simeq \frac{L_{\nu_e} \langle E_{\nu_e} \rangle f_{\nu_e}^{\mathrm{mr}}}{L_{\nu_e} \langle E_{\nu_e} \rangle f_{\nu_e}^{\mathrm{mr}} + L_{\bar{\nu}_e} \langle E_{\bar{\nu}_e} \rangle f_{\bar{\nu}_e}^{\mathrm{mr}}}$$

Nucleosynthesis in Neutrino-processed Merger Ejecta

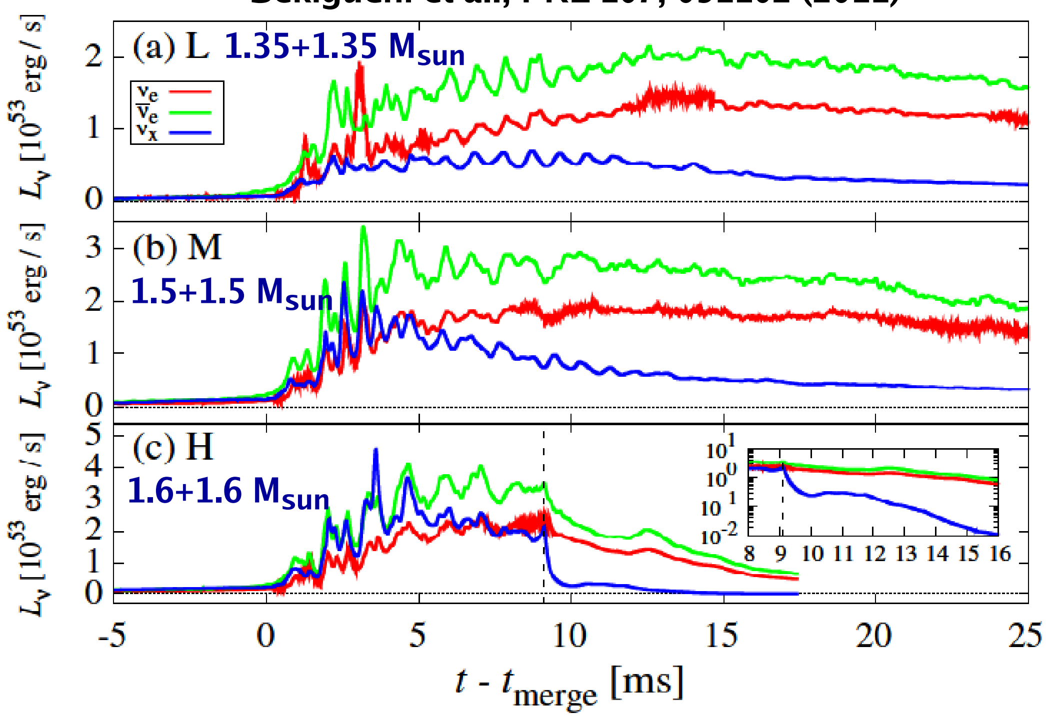
- **Compact NSs produce strongly shock-heated ejecta.**
- **Electron fraction increases considerably in hot ejecta, mostly due to positron capture.**
- **Heavy r-process is still produced, but also A < 130 nuclei.**

Wanajo et al., ApJL 789 (2014) L39

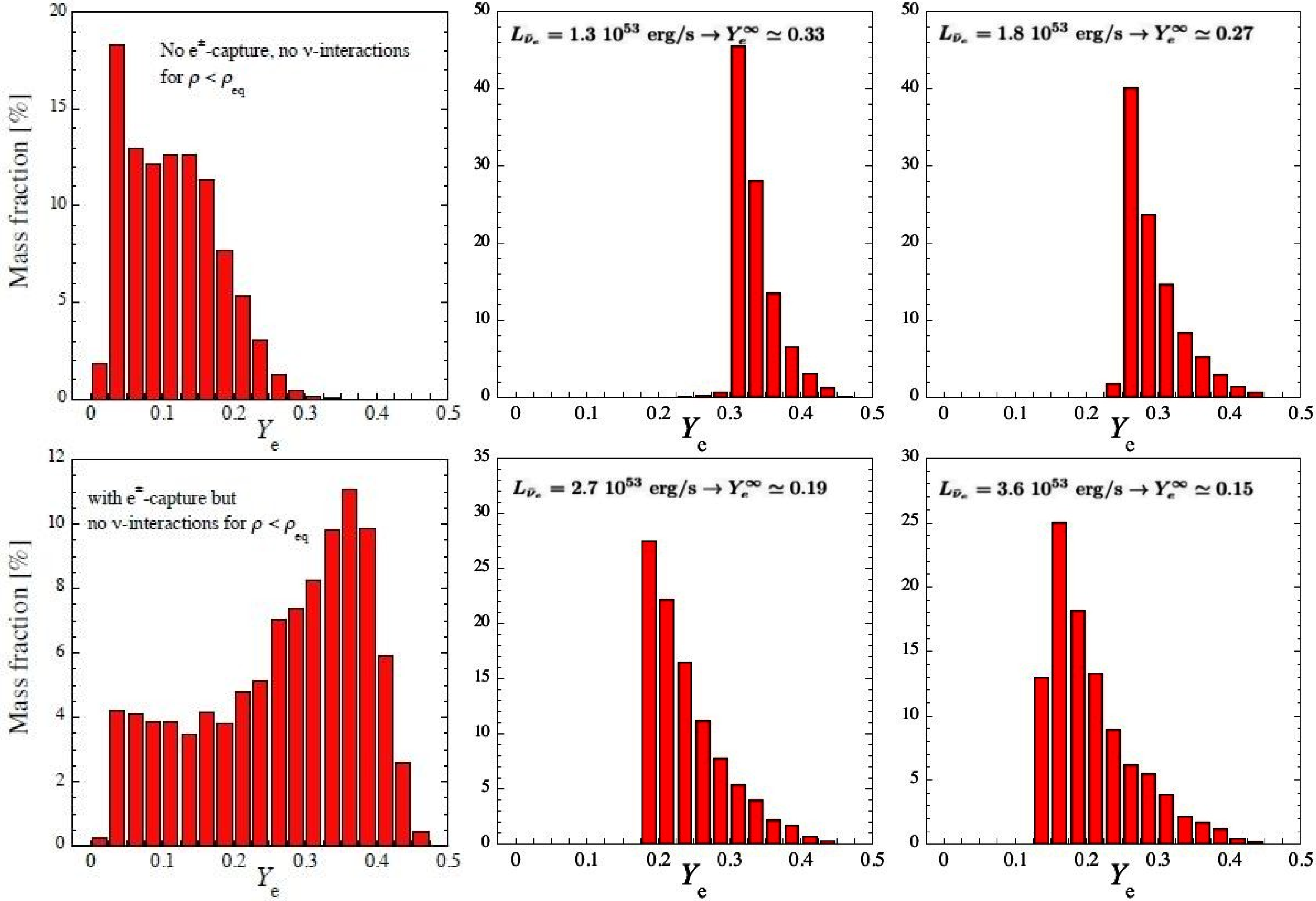




Sekiguchi et al., PRL 107, 051102 (2011)

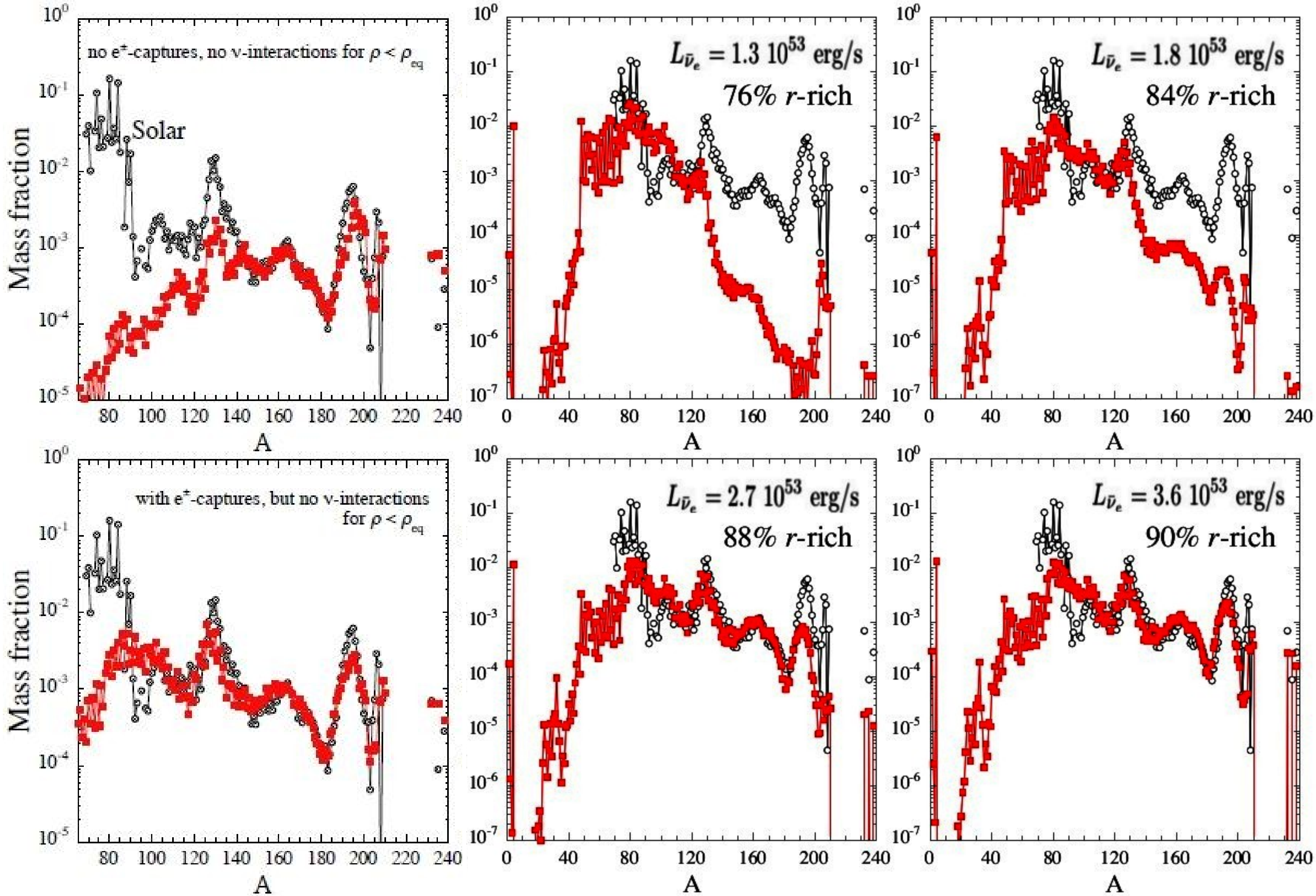


Nucleosynthesis in Neutrino-processed Dynamical NS-NS Merger Ejecta



(Goriely et al., MNRAS 452 (2015) 3894)

Nucleosynthesis in Neutrino-processed Dynamical NS-NS Merger Ejecta



(Goriely et al., MNRAS 452 (2015) 3894)

Strength of r-process depends on antineutrino luminosity

(also: Roberts et al. 2016, Foucart et al. 2016)

Improved Leakage-Equilibration-Absorption Scheme (ILEAS)

Leakage

- Effective local neutrino loss rates
- Interpolation: diffusion - free streaming
- Three species: ν_e , $\bar{\nu}_e$, ν_x

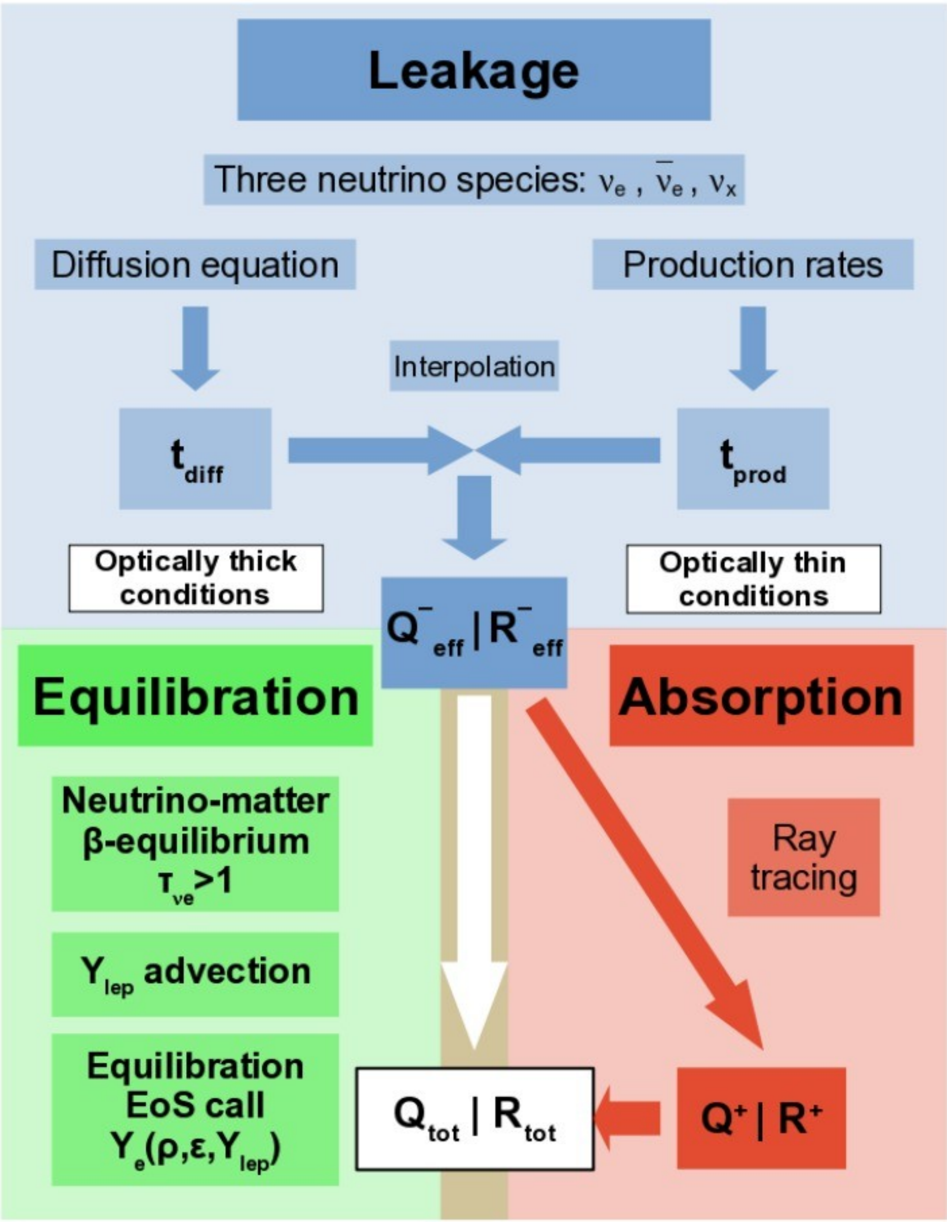
Equilibration

- Lepton fraction advection
- Neutrino β-equilibrium EoS
- Equilibration step

Absorption

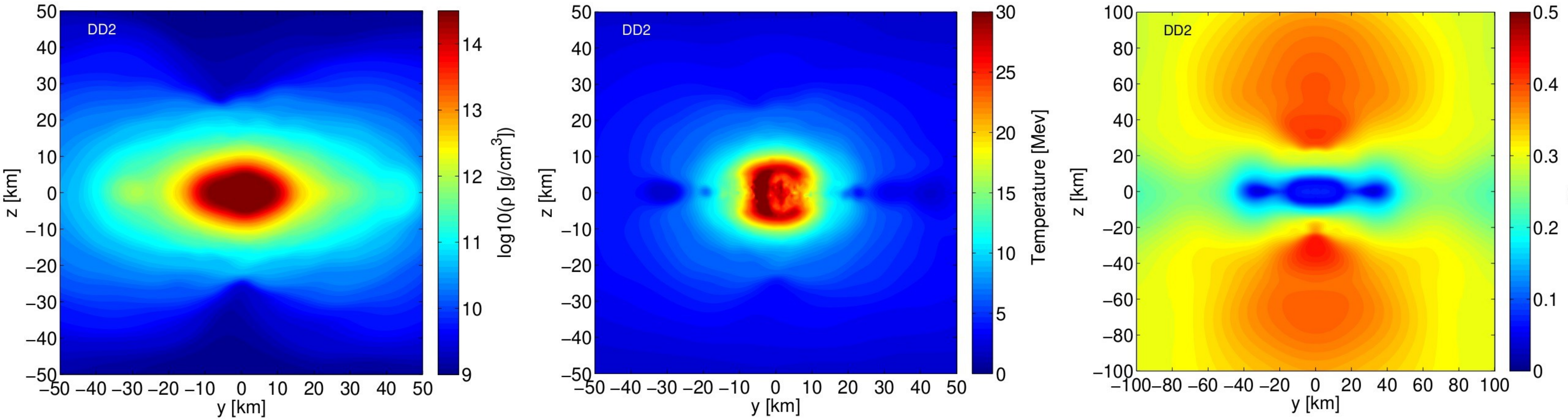
- Neutrino absorption rates
- Ray tracing

R. Ardevol-Pulpillo, PhD Thesis;
Ardevol-Pulpillo, Janka, Just & Bauswein (arXiv:1808.00006)

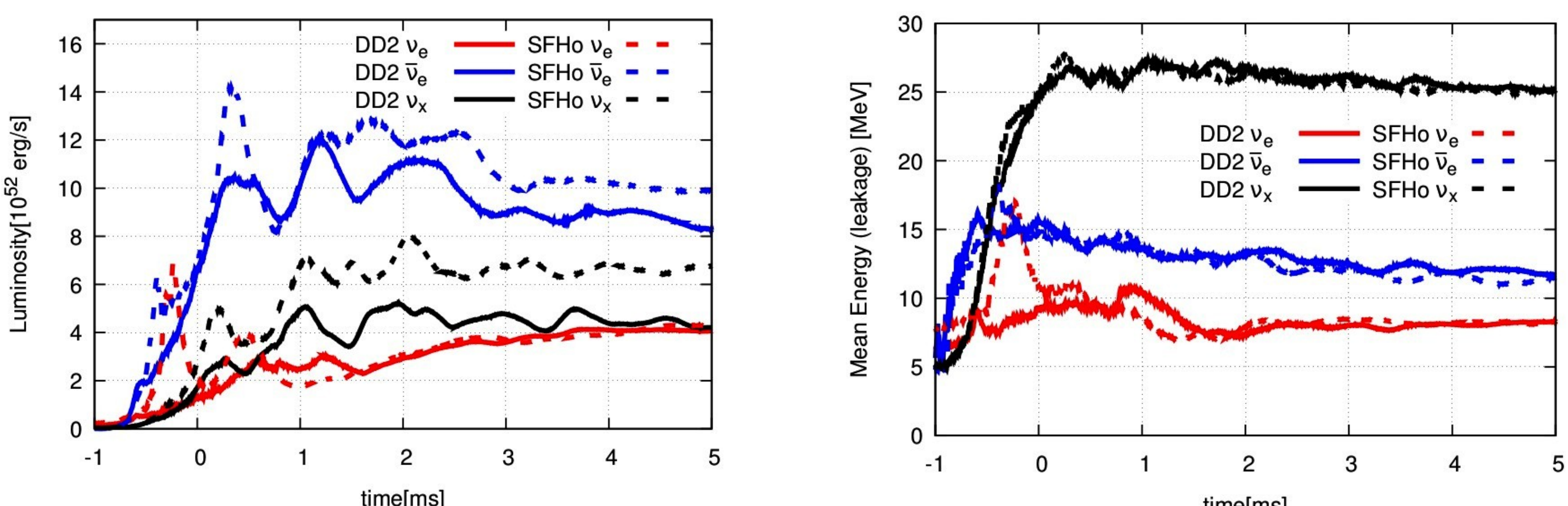


NS+NS Merger Results with ILEAS

Merger remnant 5 ms after collision of symmetric (1.35+1.35 M_{sun}) NS-NS binary



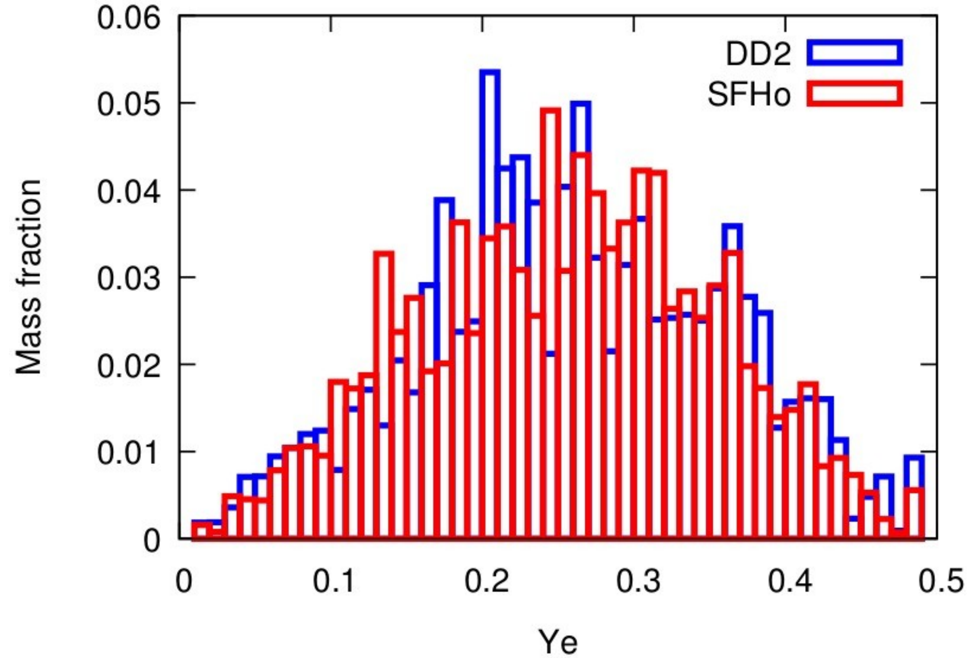
Neutrino emission



Ardevol-Pulpillo, Janka, Just & Bauswein (arXiv:1808.00006)

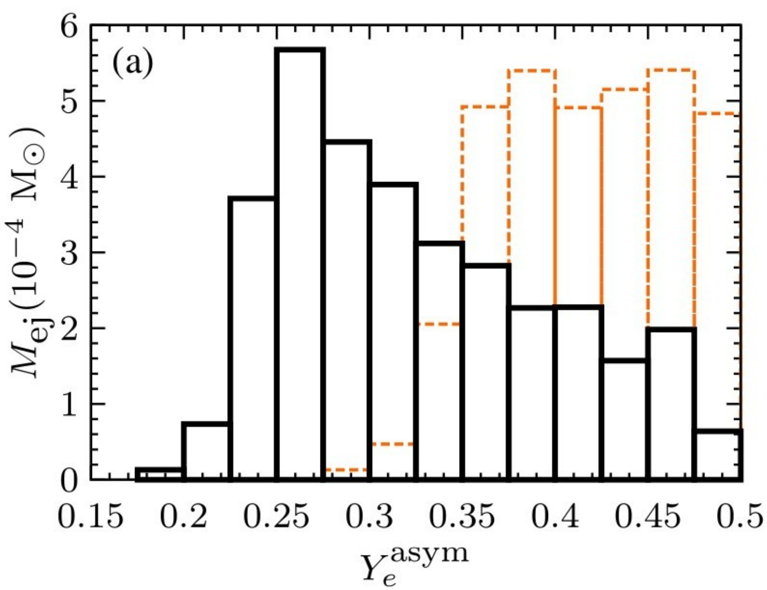
NS+NS Merger Results with ILEAS

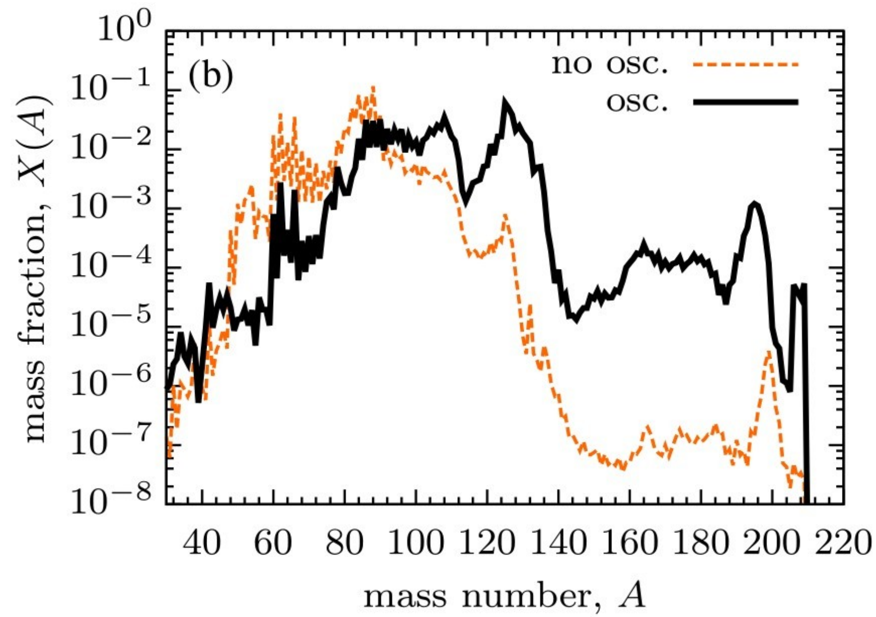
Y_e in dynamical ejecta from symmetric (1.35+1.35 M_{sun}) NS-NS merger



Ardevol-Pulpillo, Janka, Just & Bauswein (arXiv:1808.00006)

BUT: Neutrino-flavor oscillations might have an important impact

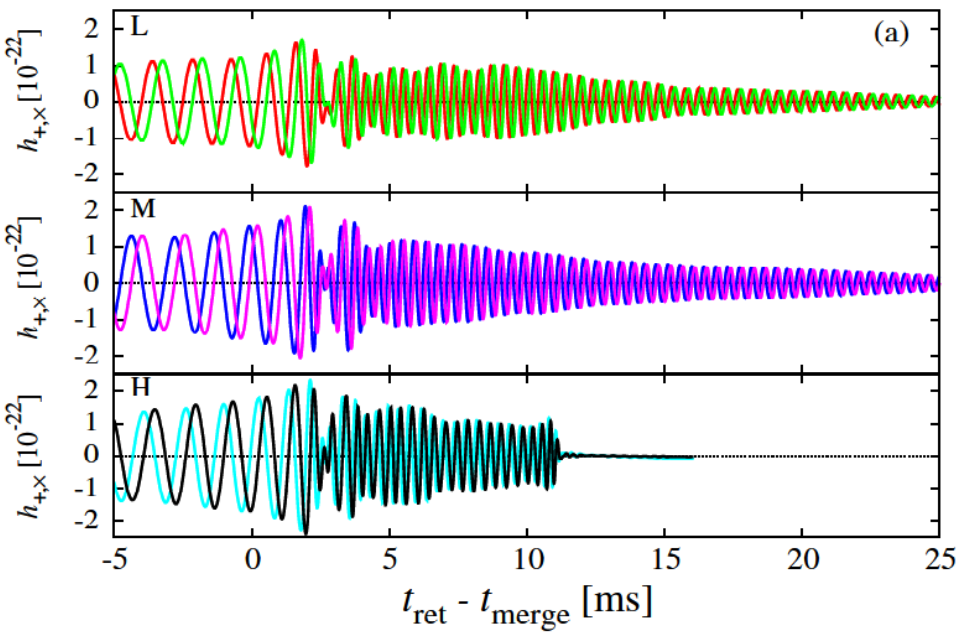




Wu, Tamborra, Just & Janka, PRD 96 (2017) 123015

Neutron-Star Binary Mergers for Constraining Neutron Star Masses, Radii, and EOS Properties

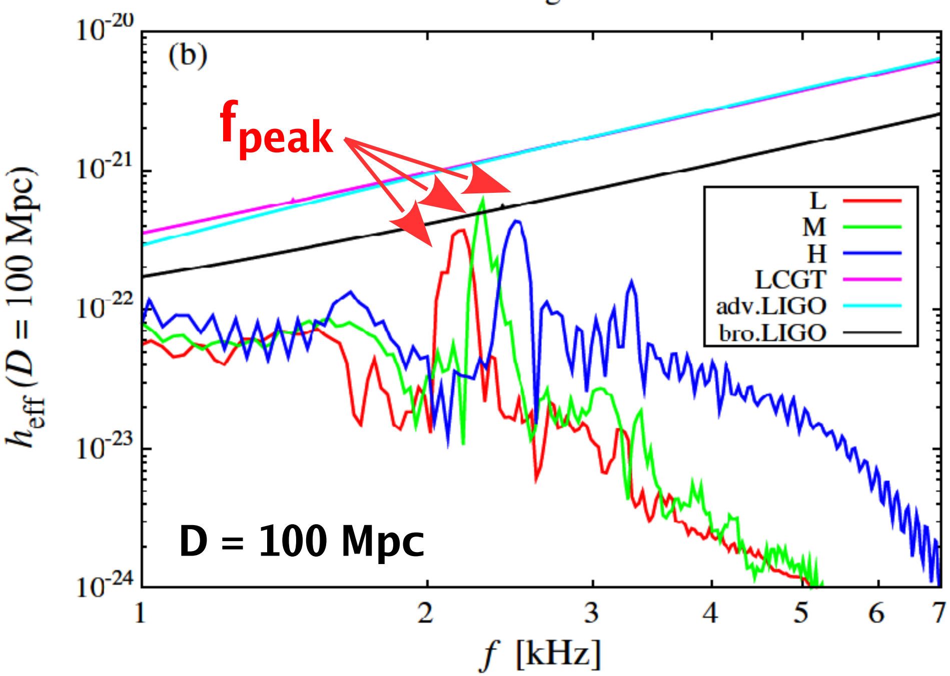
Gravitational Waves from NS+NS Mergers



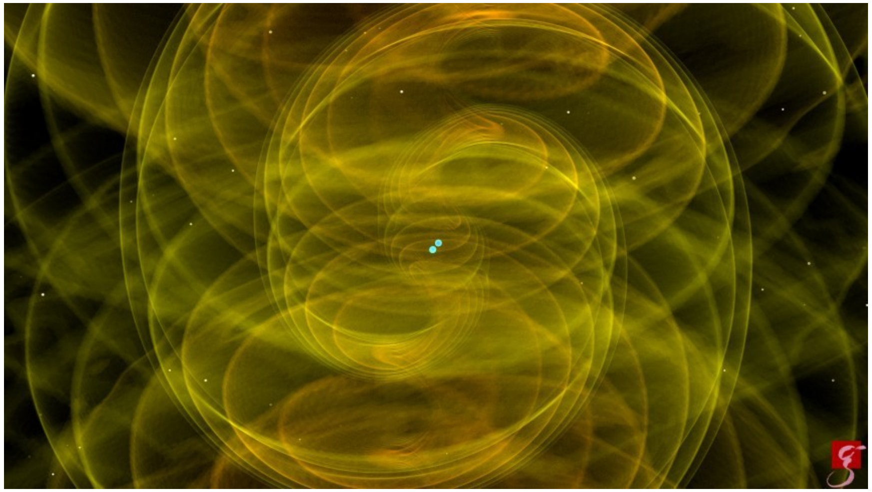
L: 1.35+1.35 M_{sun}

M: 1.5+1.5 M_{sun}

H: 1.6+1.6 M_{sun}



Sekiguchi et al., PRL 107, 051102 (2011)



(AEI Golm, Buonnano et al.)

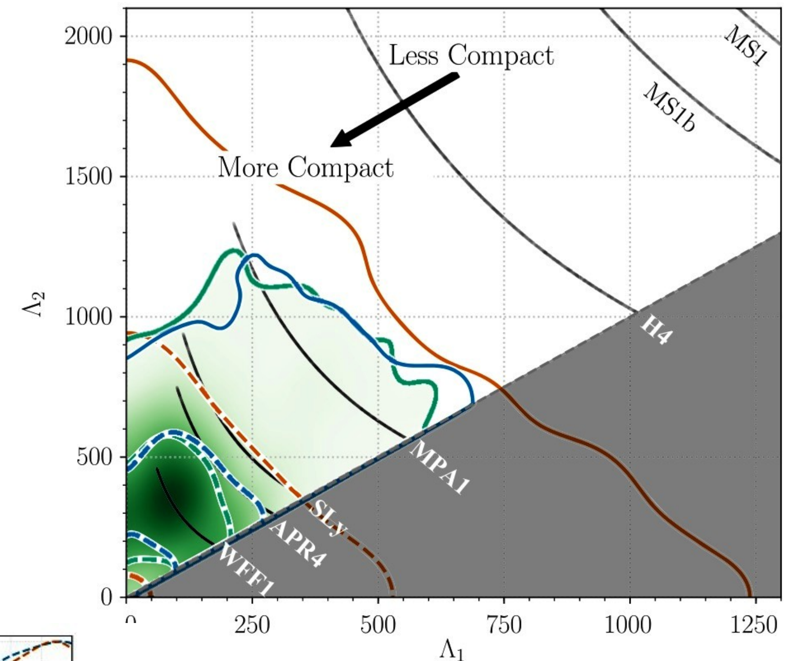
Present Constraints on NS Properties

$R_1 = 10.8^{+2.0}_{-1.7}$ $(11.9^{+1.4}_{-1.4})$ km

$R_2 = 10.7^{+2.1}_{-1.5}$ $(11.9^{+1.4}_{-1.4})$ km

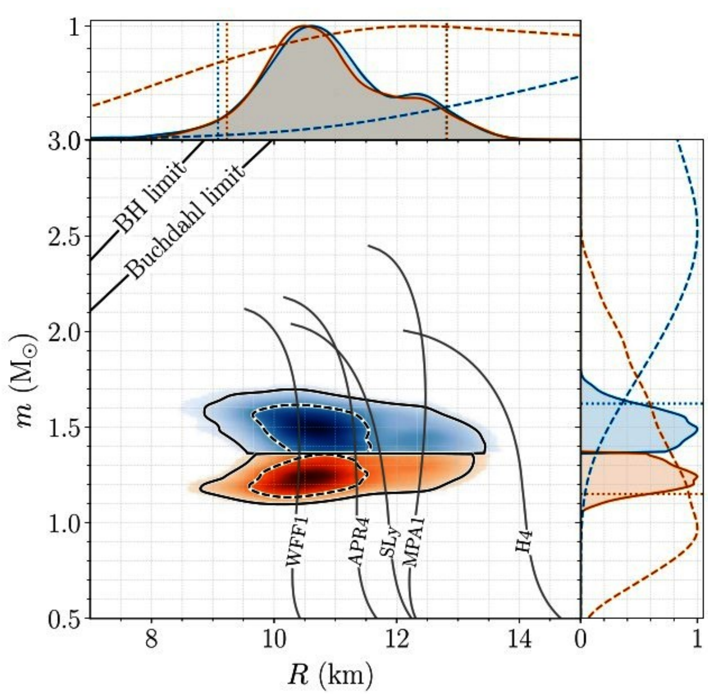
(EOS supports $M_{max} > 1.9\ M_{sun}$)

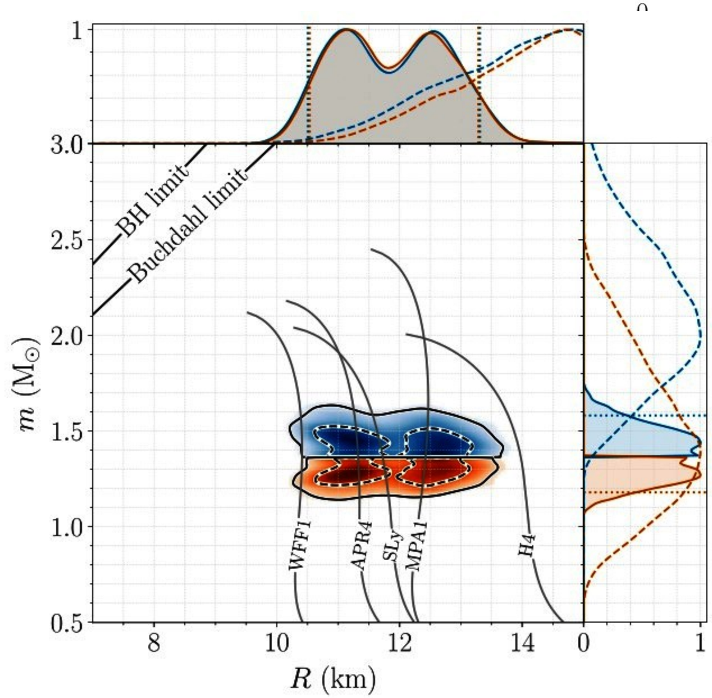
(Abbott et al., PRL 121 (2018) 161101)



M_{max} <~ 2.17 M_{sun} ?? (from kilonova)

(Margalit & Metzger (2017); Rezzolla+ (2018))





$$\tilde{\Lambda} = \frac{16}{13}\left[\frac{(M_A + 12M_B)M_A^4\tilde{\Lambda}_A}{(M_A + M_B)^5} + (A \leftrightarrow B)\right],$$

$$\tilde{\Lambda}_i = \frac{2}{3}k_2^{(i)}\left[\left(\frac{c^2}{G}\right)\left(\frac{R_i}{M_i}\right)\right]^5, \quad i = A, B$$

(Abbott et al., PRL 121 (2018) 161101)

Present Constraints on NS Properties

GW analysis consistent with astrophysical arguments based on KN observation

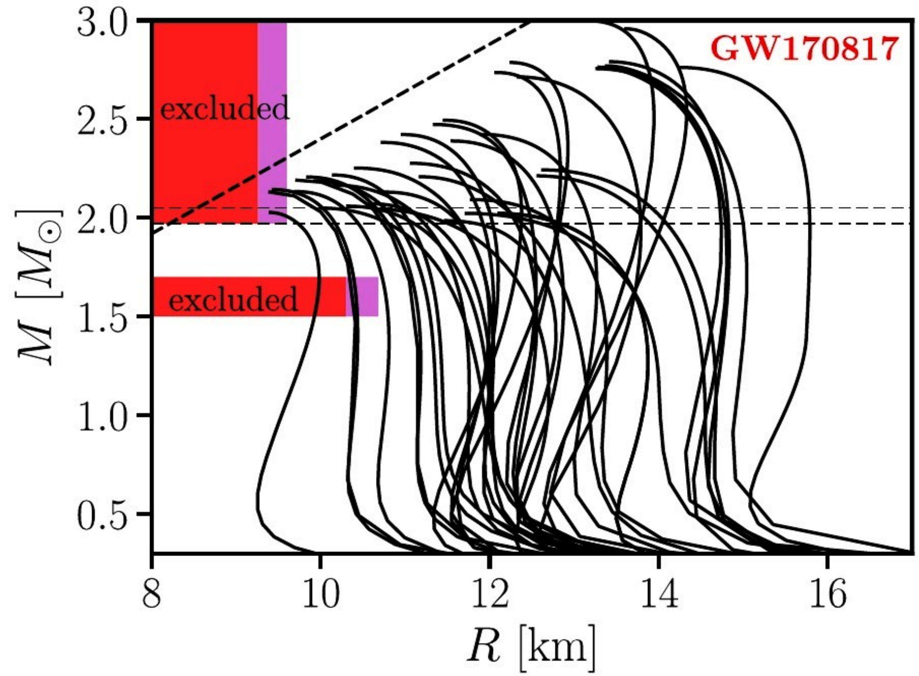
$$M_{\rm thres} = \left(-3.606\frac{GM_{\rm max}}{c^2 R_{1.6}} + 2.38\right)\cdot M_{\rm max}$$

$$M_{\rm thres} = \left(-3.38\frac{GM_{\rm max}}{c^2 R_{\rm max}} + 2.43\right)\cdot M_{\rm max},$$

$R_{1.6}$ > 10.3 (10.7) km

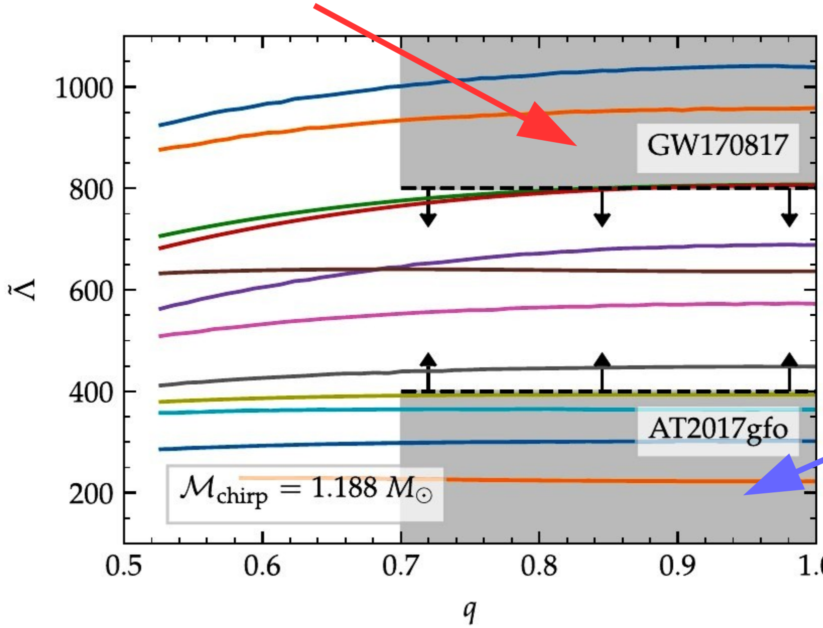
R_{max} > 9.3 (9.6) km

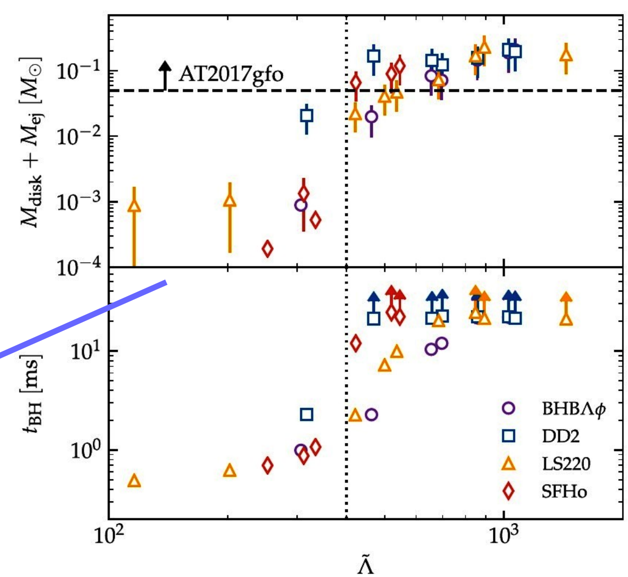
(No direct collapse (> 10 ms) to BH)



(Bauswein, Just, Janka, Stergioulas, ApJL 850 (2017) L34)

From GW179817 (Abbott et al., PRL (2017))



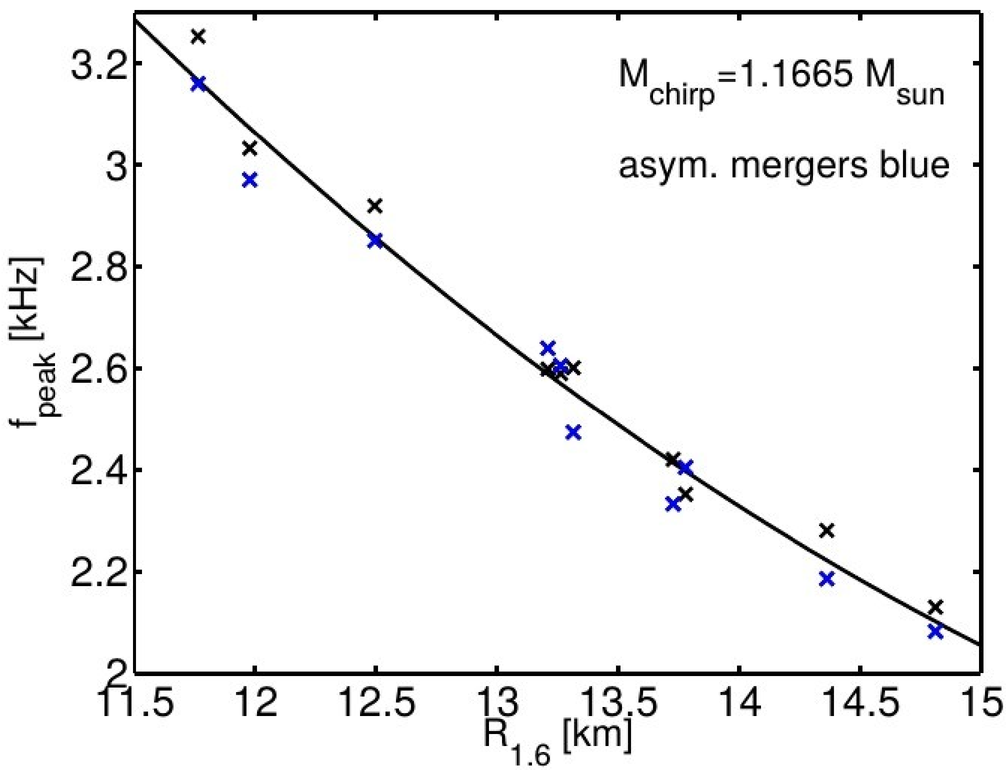


(Radice, Perego, et al., ApJL 852 (2018) L29)

Future Constraints on NS Properties

Peak frequency f_{peak} of merger ring-down GW emission will constrain NS radius to an accuracy of some 100 meters!

$R_{1.6}$ = radius of 1.6 M_{sun} neutron star



(Bauswein, THJ, et al. (2012, 2013, 2016); Takami & Rezzolla (2014, 2016)

Ring-down GW emission will also contain information on phase transitions in supranuclear medium (e.g. hyperons, quark phase).

(Sekiguchi et al. (2011), Radice et al. (2017), Bauswein et al. (2018), Most et al. (2018))

Summary

- GW170817: First GW detection from two merging neutron stars; first-ever identification of cosmic source of r-process elements
- Enormous diversity of phenomena in NS-NS/BH mergers
- Dependent on many degrees of freedom:
  total system mass, mass ratio, spins, nuclear EOS
- Large sets of computational models needed!
- One observed event is not enough to explore physics of mergers; do not generalize too quickly!
- Dynamical ejecta: $< 0.02–0.03\ M_{sun}$ for NS+NS
  Secular (remnant) ejecta: can be even more
- Y_e and its evolution and directional dependence are still uncertain
- More work is needed on the complex neutrino physics

Future Perspectives

- Advanced LIGO/VIRGO sensitivity will be increased by factor of ~2 until 2019/2020
  → ~10 times more sources out to distance of <~130 Mpc!

  Perspective: 1–50 NS-NS merger events per year!

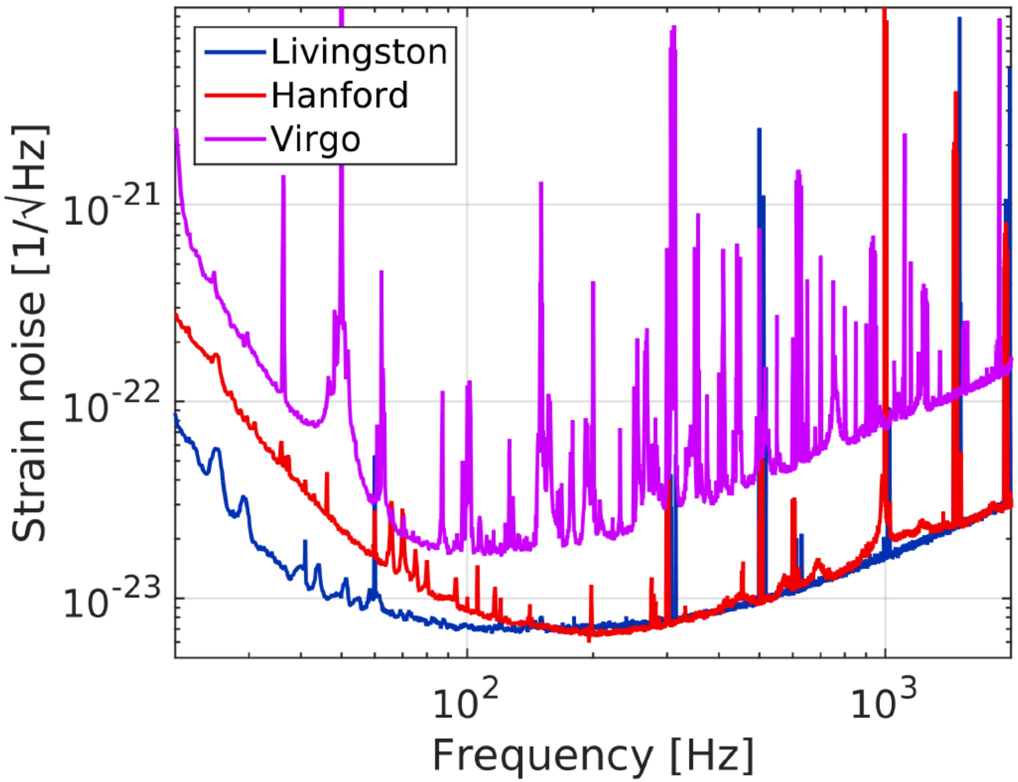
- Kilonovae will be detectable to distance of ~100–200 Mpc;

  good localization of GW source will be important.

- GRB detectable for maybe ~1/30 of all GW/KN cases;

  But: Searches in archival data for events similar to GW170817.

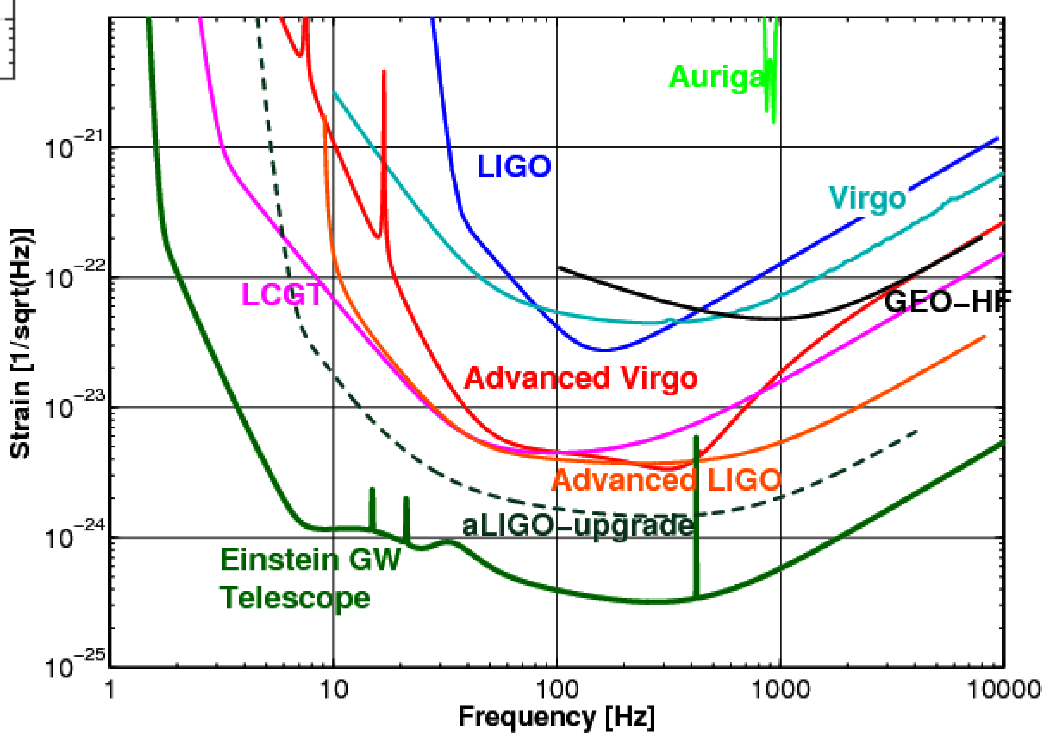
GW Detector Sensitivities



Current: O2

Future: O3+

LCGT: KAGRA



Source:
LIGO Collaboration and VIRGO Collaboration