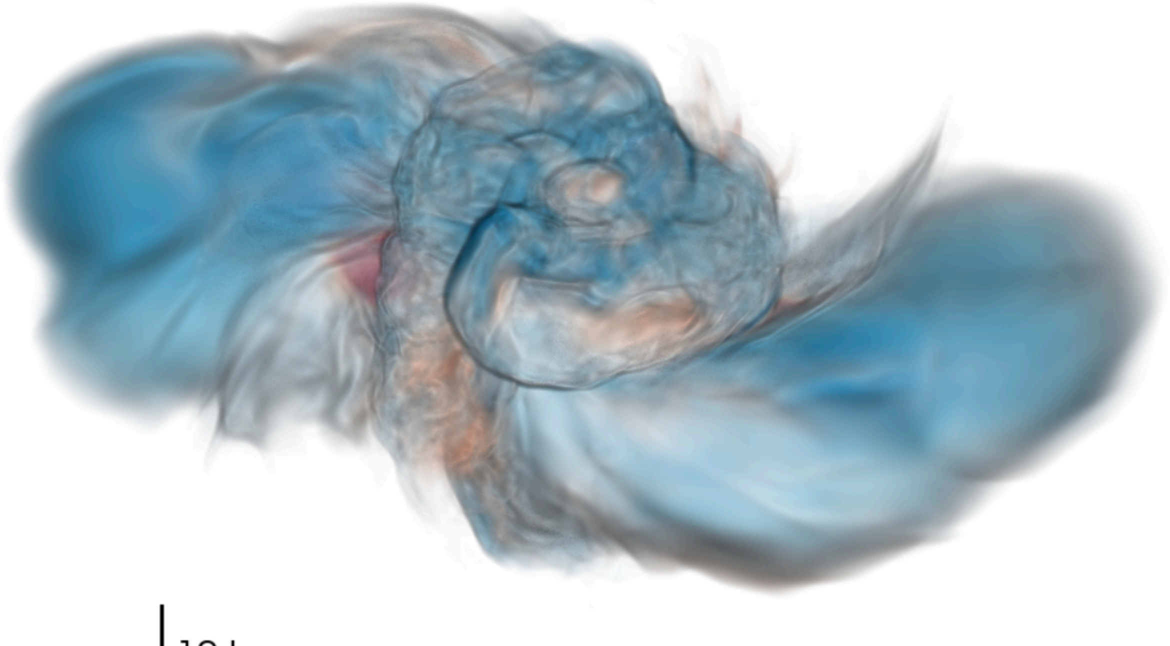
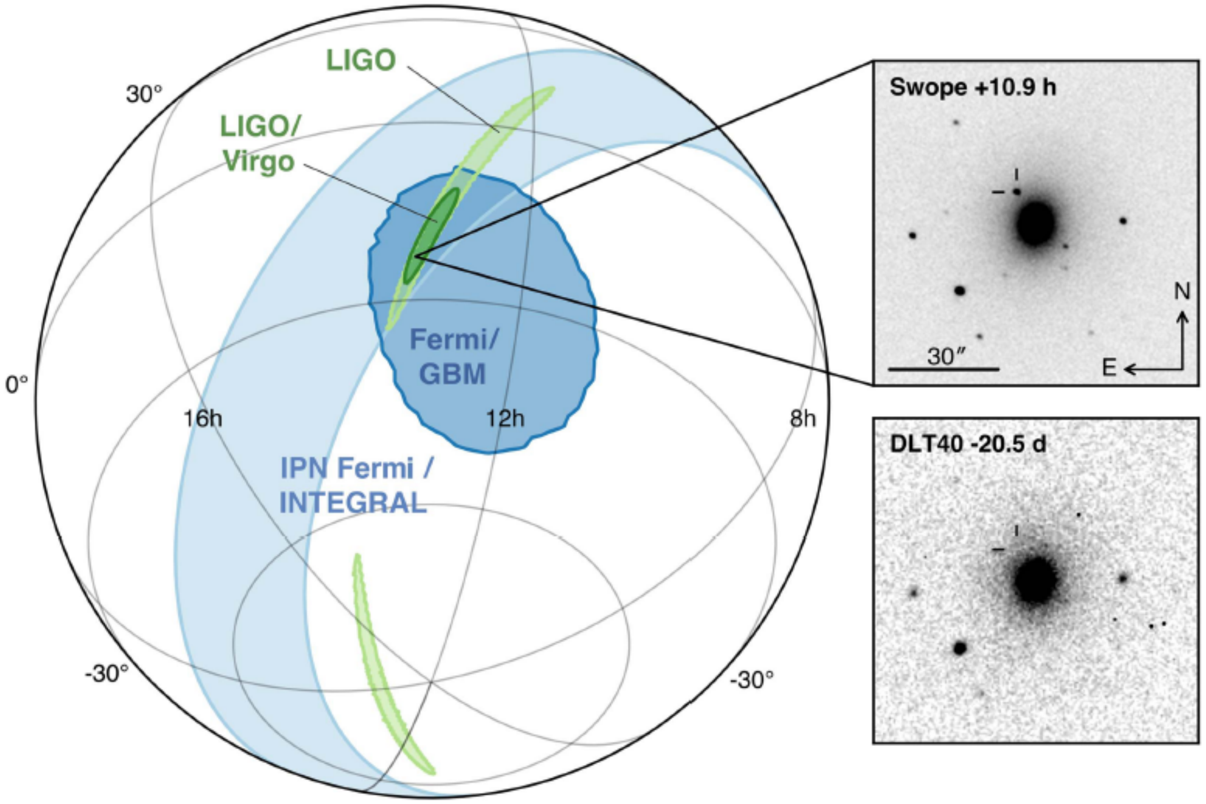
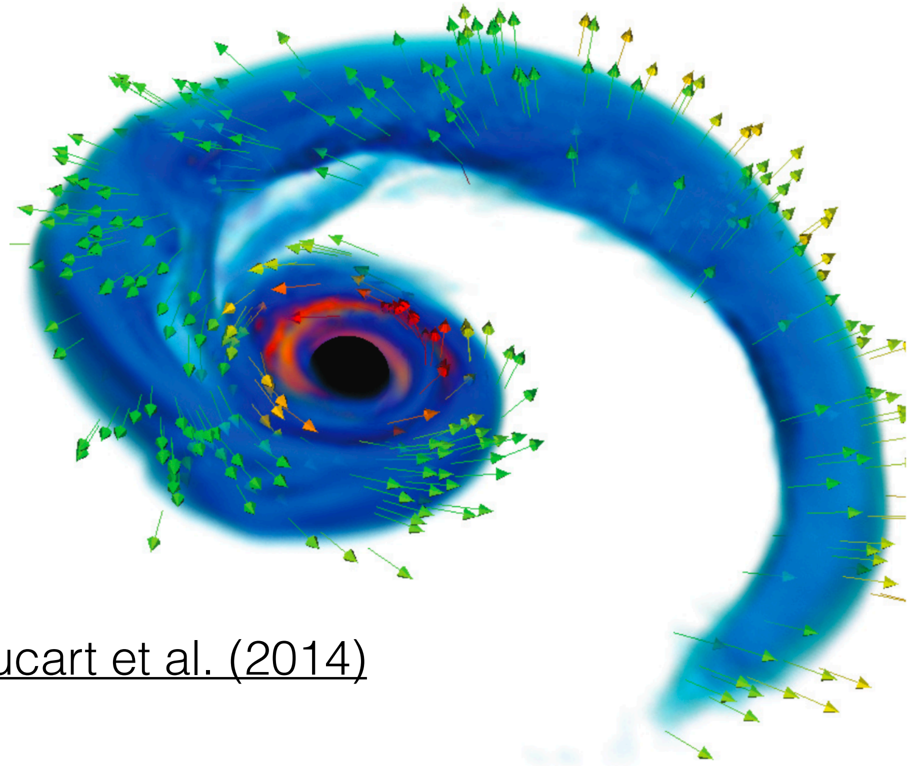


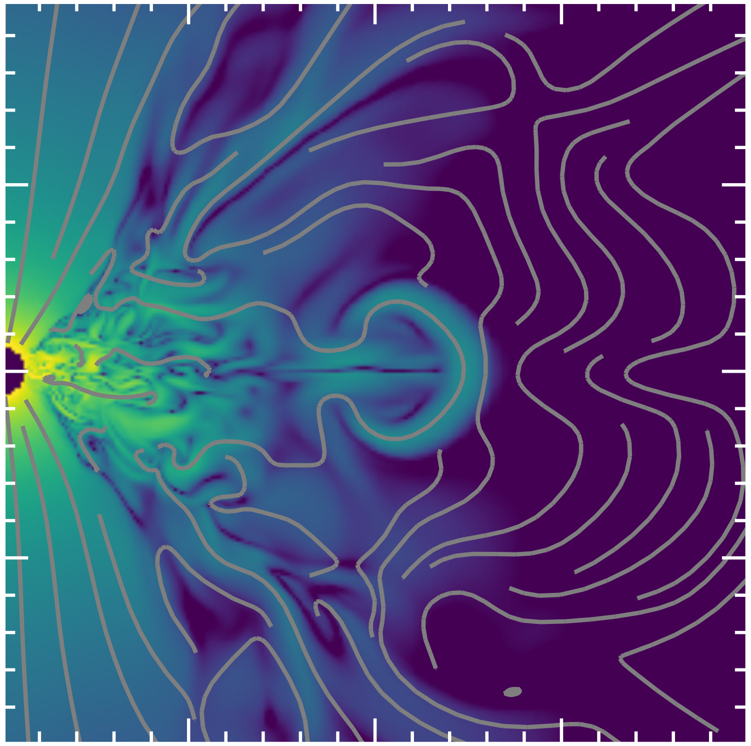
Radice et al. (2018)



Abbott et al. (2017) [LVC]: GW170817



Foucart et al. (2014)



RF et al. (2019)

Neutron Star Mergers I

Rodrigo Fernández (University of Alberta)

Outline

1) Neutron stars

2) Overview of Merger Phases

3) Inspiral Phase: GW & EM precursors

4) Dynamical Phase: Mass Ejection, NSNS vs NSBH

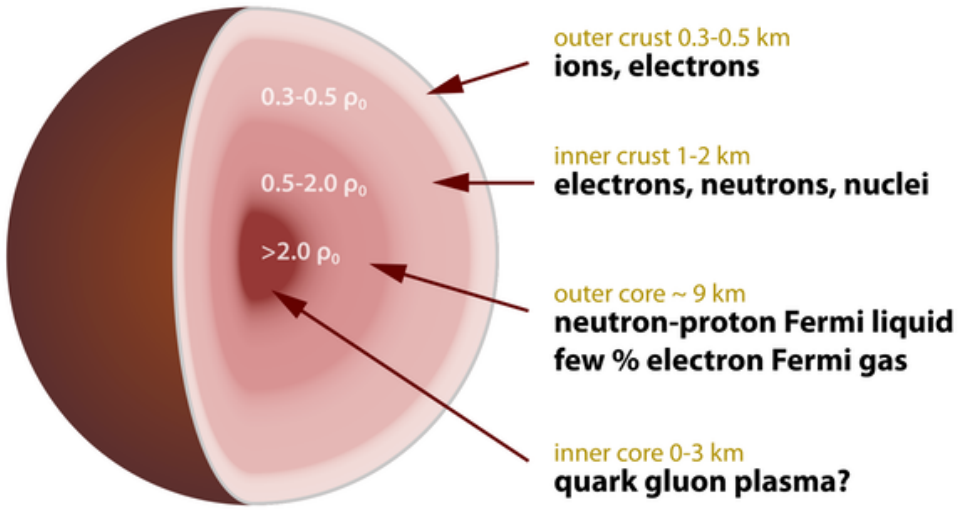
5) Merger Remnant: Post-merger GWs, EOS

6) Accretion Disk: evolution & mass ejection

7) EM Counterpart Overview: GRBs, Kilonovae, and more

8) r-process in a nutshell

Neutron Stars



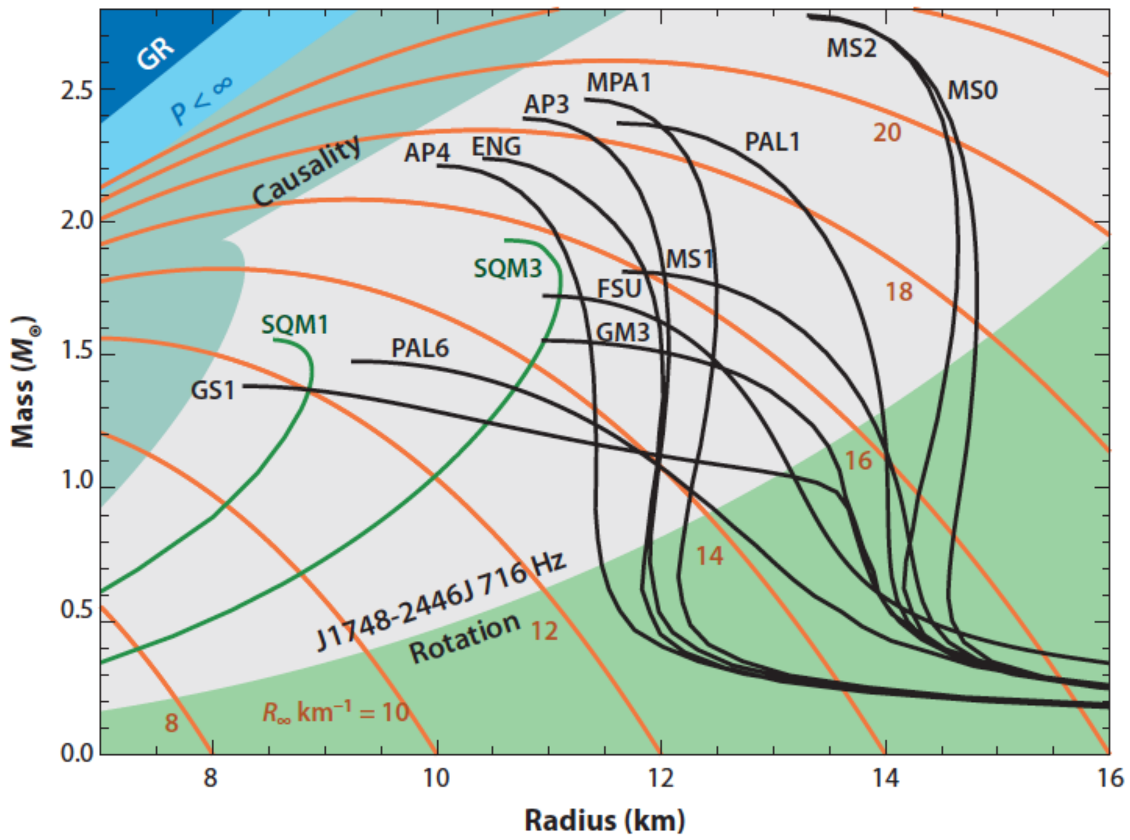
outer crust 0.3-0.5 km
ions, electrons

inner crust 1-2 km
electrons, neutrons, nuclei

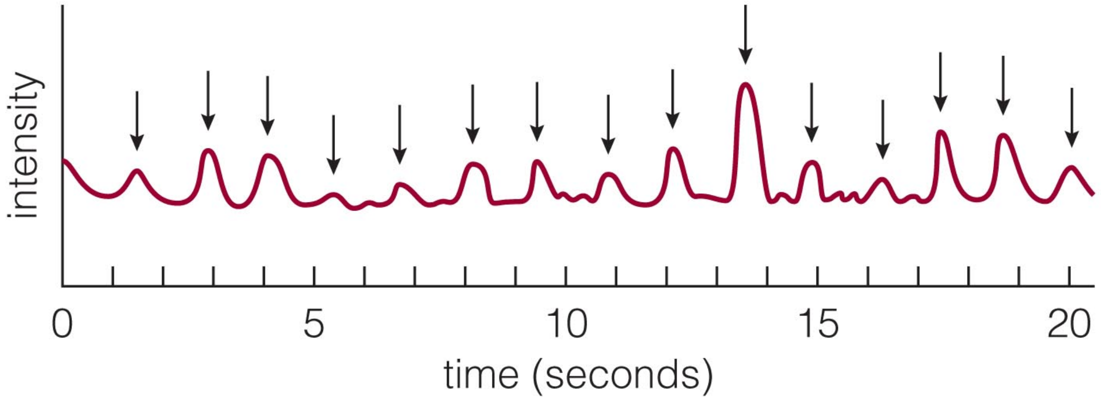
outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas

inner core 0-3 km
quark gluon plasma?

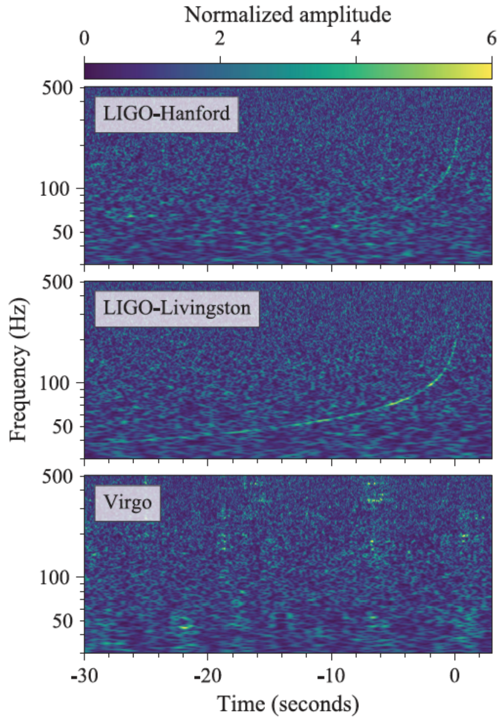
astro.puc.cl

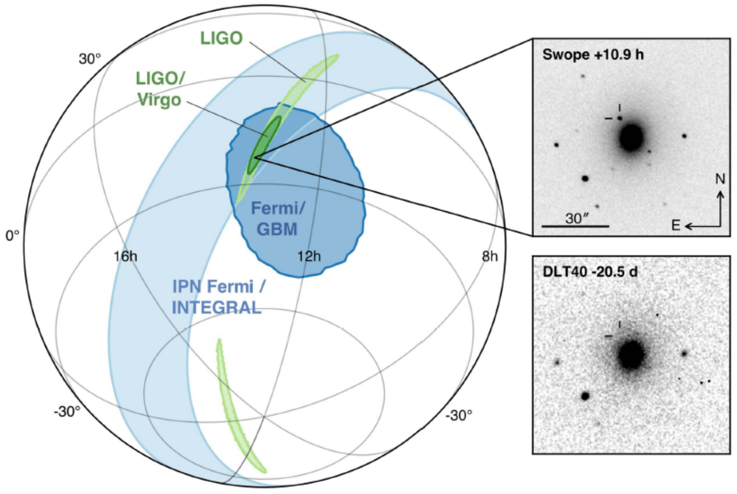


Lattimer (2012)



Pearson Education





Abbott et al. (2017) [LVC]

Supernovae in Binary Systems

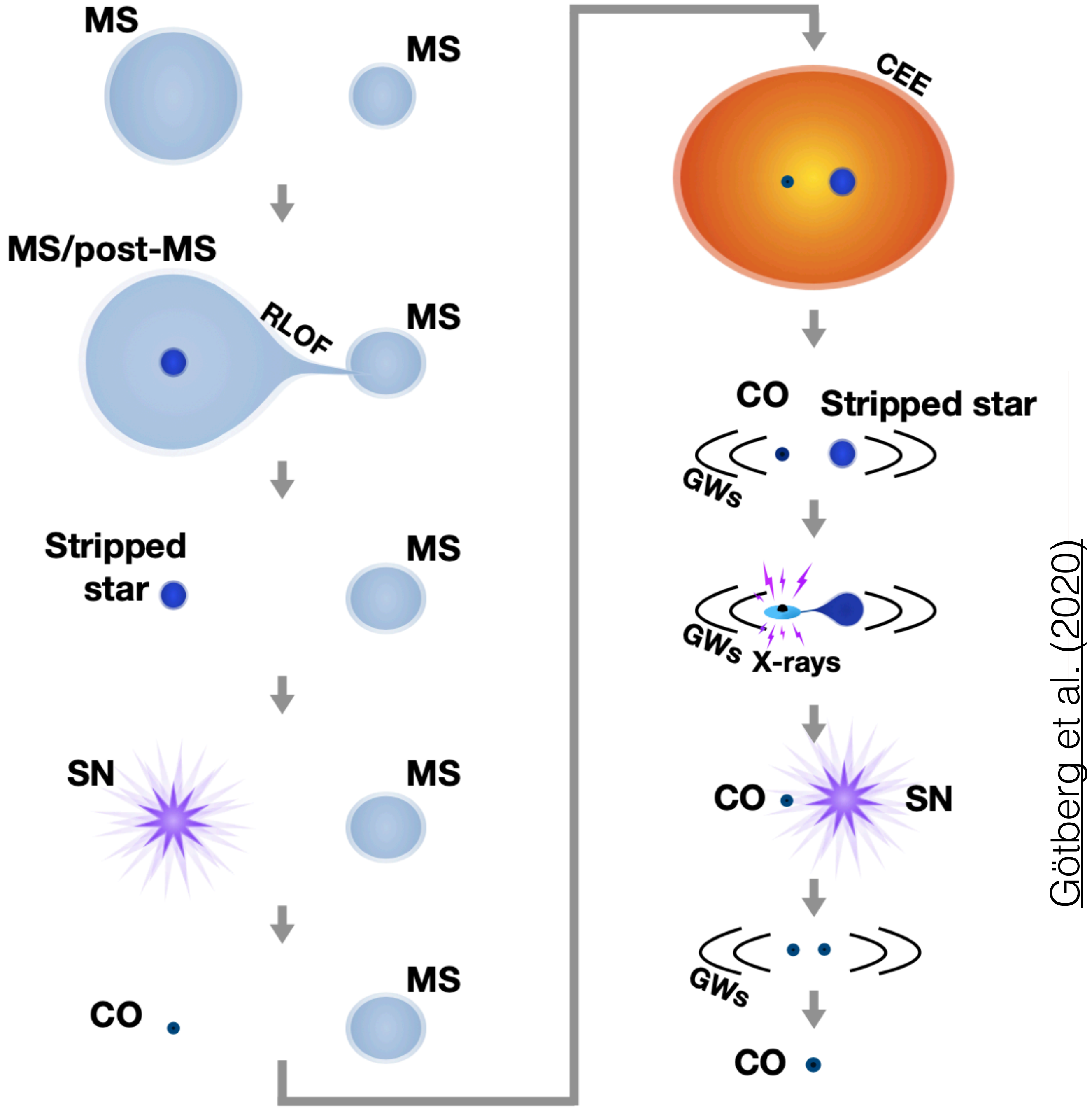
Significant fraction of massive stars live in binary systems

(e.g., Sana et al. 2012)

Interaction between stars leads to more complex evolution and interesting outcomes.

Binary black holes and/or neutron stars!

(e.g., Postnov & Yungelson 2014)



MS - main-sequence star • RLOF - Roche-lobe overflow • SN - compact object formation • CO - compact object • CEE - common envelope evolution • GW - gravitational waves

Götberg et al. (2020)

Double Neutron Star Systems

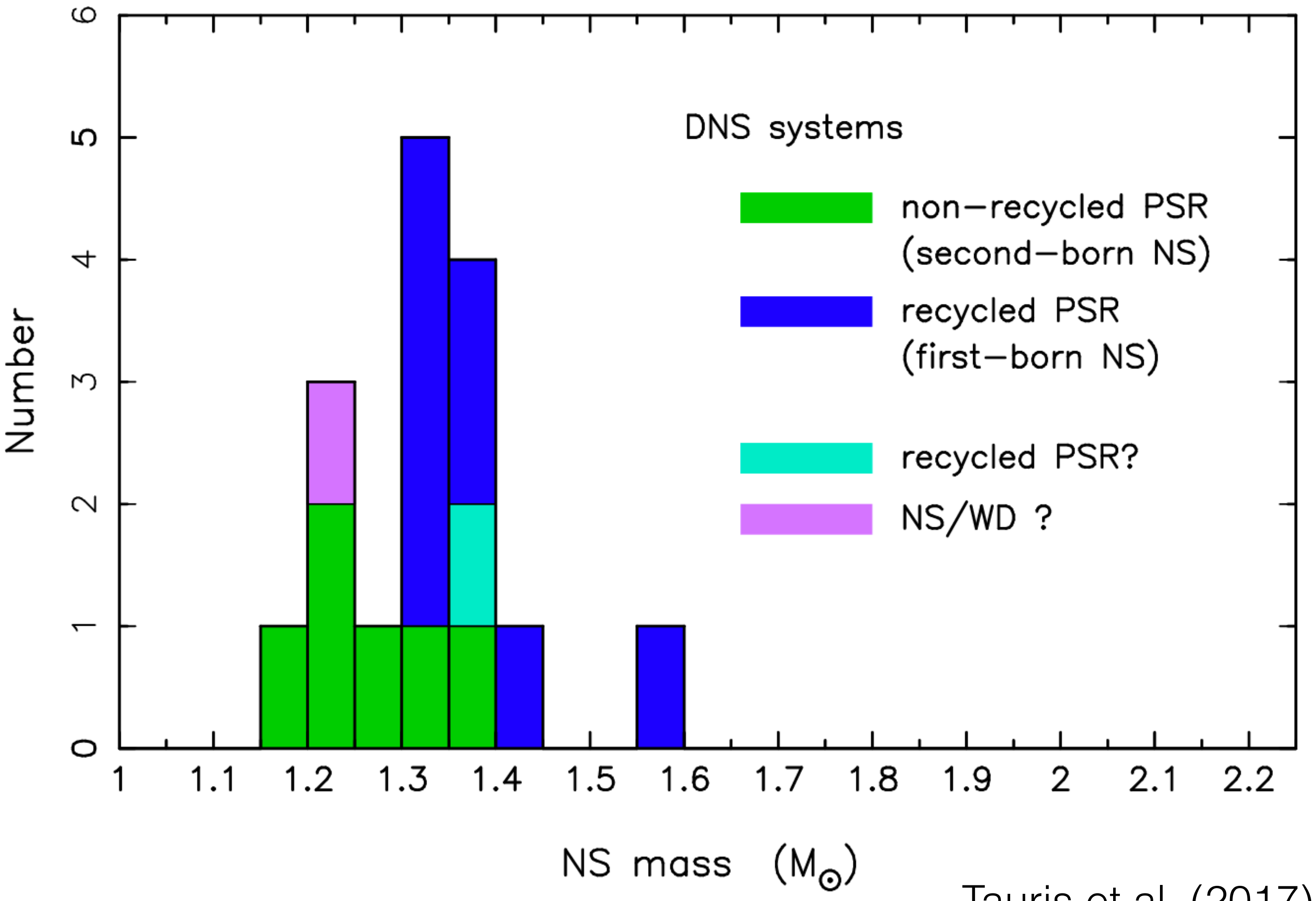
We know of at least 12 double NS (DNS) binary systems in the Milky Way, with 3 more that could also be WD-NS systems.

Out of these, only 7 will merge in less than a Hubble time due to GW emission and orbital decay.

The mass distribution is peaked around 1.35 M_{sun}.

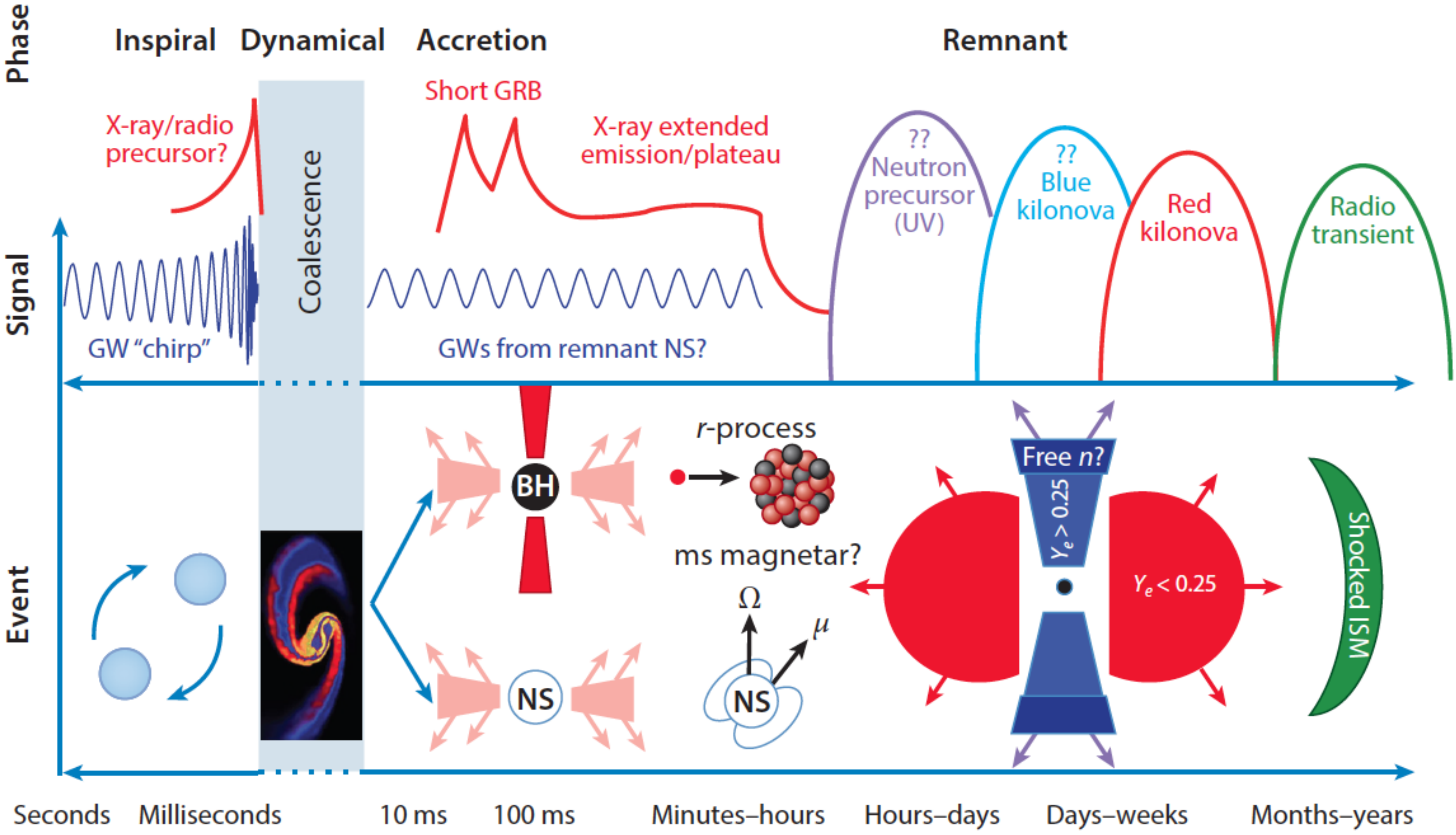
$$\tau_{\rm GW} = \frac{5}{64}\frac{a^4}{\mu M^2} = \frac{5}{64}\frac{a^4}{q(1+q)M_1^3}$$
$$= 2.2\times 10^8 q^{-1}(1+q)^{-1}\left(\frac{a}{R_\odot}\right)^4\left(\frac{M_1}{1.4\,M_\odot}\right)^{-3}\ \mathrm{yr}$$

Faber & Rasio (2012)



Tauris et al. (2017)

Neutron Star Mergers: Overview



RF & Metzger (2016)

Reference Numbers

$$M \sim M_\odot = 2 \times 10^{33}\ \mathrm{g}$$

GR:

$$r_g = \frac{GM}{c^2} \sim 1.5\ \mathrm{km}$$

$$R \sim 10\ \mathrm{km}$$

GWs:

$$t_{\mathrm{dyn}} = 2\pi \left(\frac{R^3}{GM} \right)^{1/2} \sim 10^{-3}\ \mathrm{s} \longrightarrow f_{\mathrm{GW}} \lesssim 1\ \mathrm{kHz}$$

$$\bar{\rho}_{\mathrm{NS}} \sim \frac{M}{R^3} \sim 10^{15}\ \mathrm{g\ cm}^{-3}$$

$$\frac{kT_{\mathrm{vir}}}{m_n} \sim \frac{GM}{R}$$

$$\downarrow$$

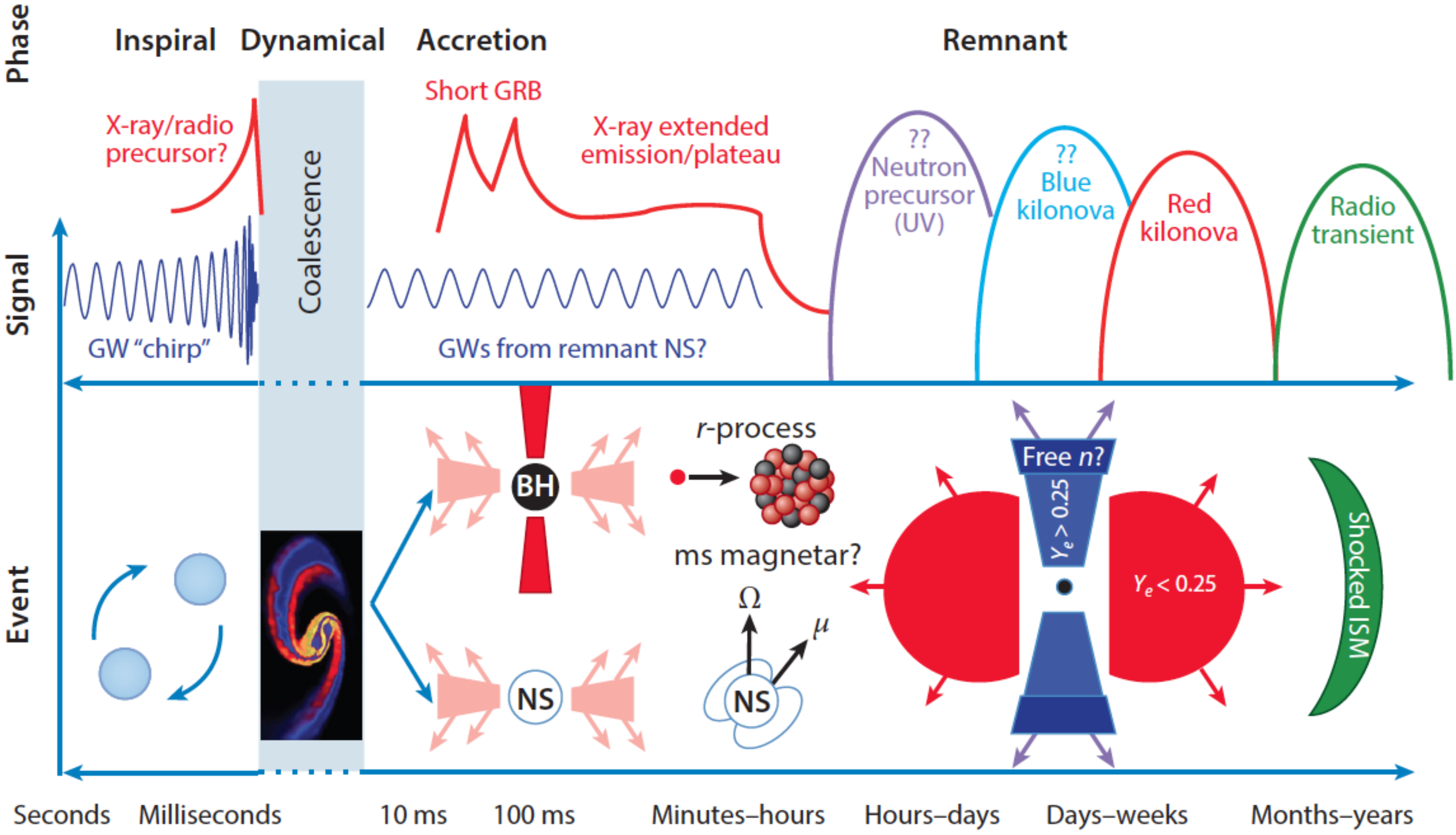
$$kT_{\mathrm{vir}} \sim 100\ \mathrm{MeV}$$

Nuclear physics

$$\tau_\nu \sim \frac{R}{\ell_\nu} \sim \left(\frac{\varepsilon_\nu}{15\ \mathrm{MeV}} \right)^2 \left(\frac{\rho}{10^{11} \mathrm{g\ cm}^{-3}} \right)$$

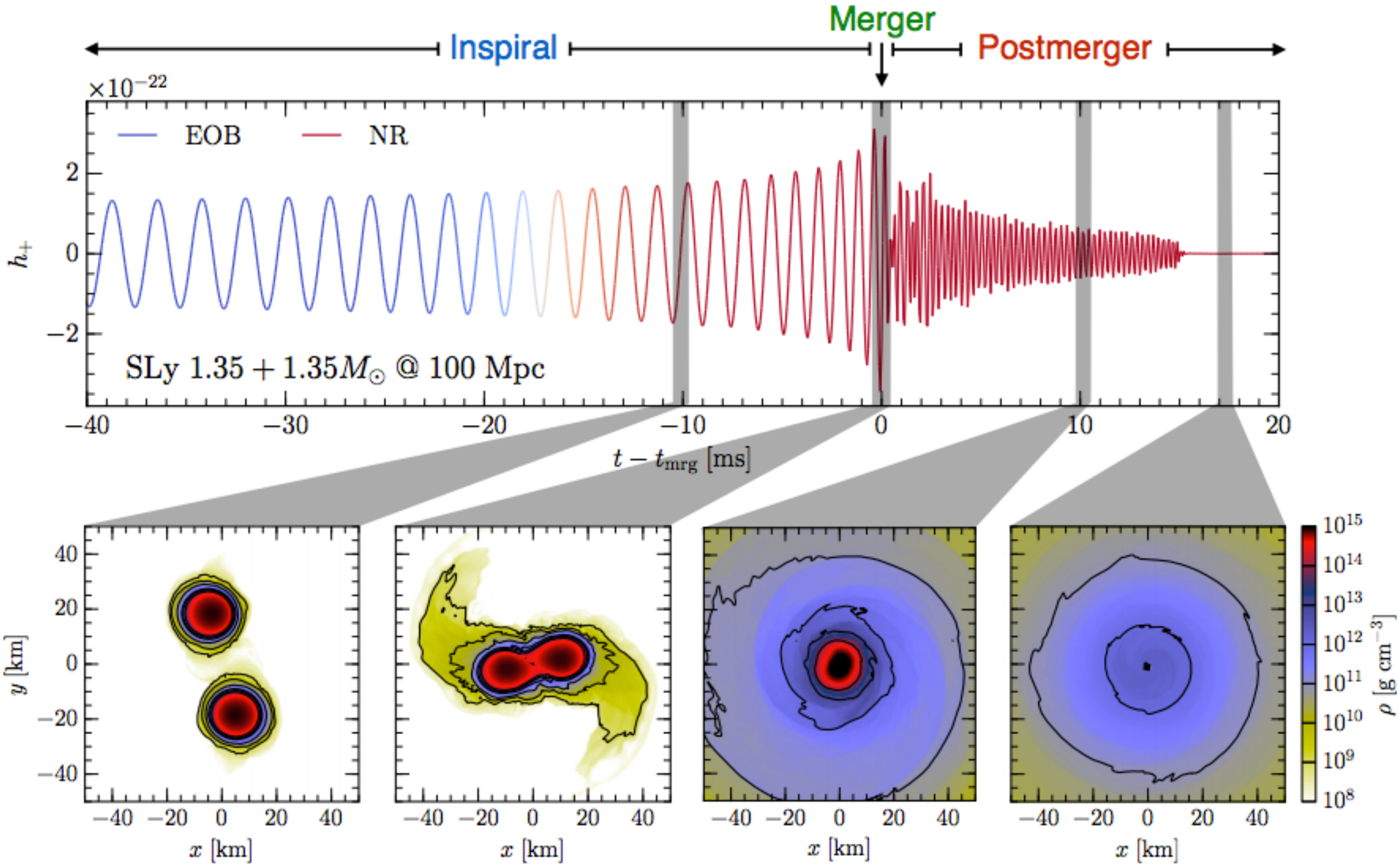
Neutrinos

Neutron Star Mergers: Overview



RF & Metzger (2016)

Inspiral Phase: Gravitational Waves



Slide from D. Radice

Radice et al. (2016)

Inspiral Phase: Gravitational Waves

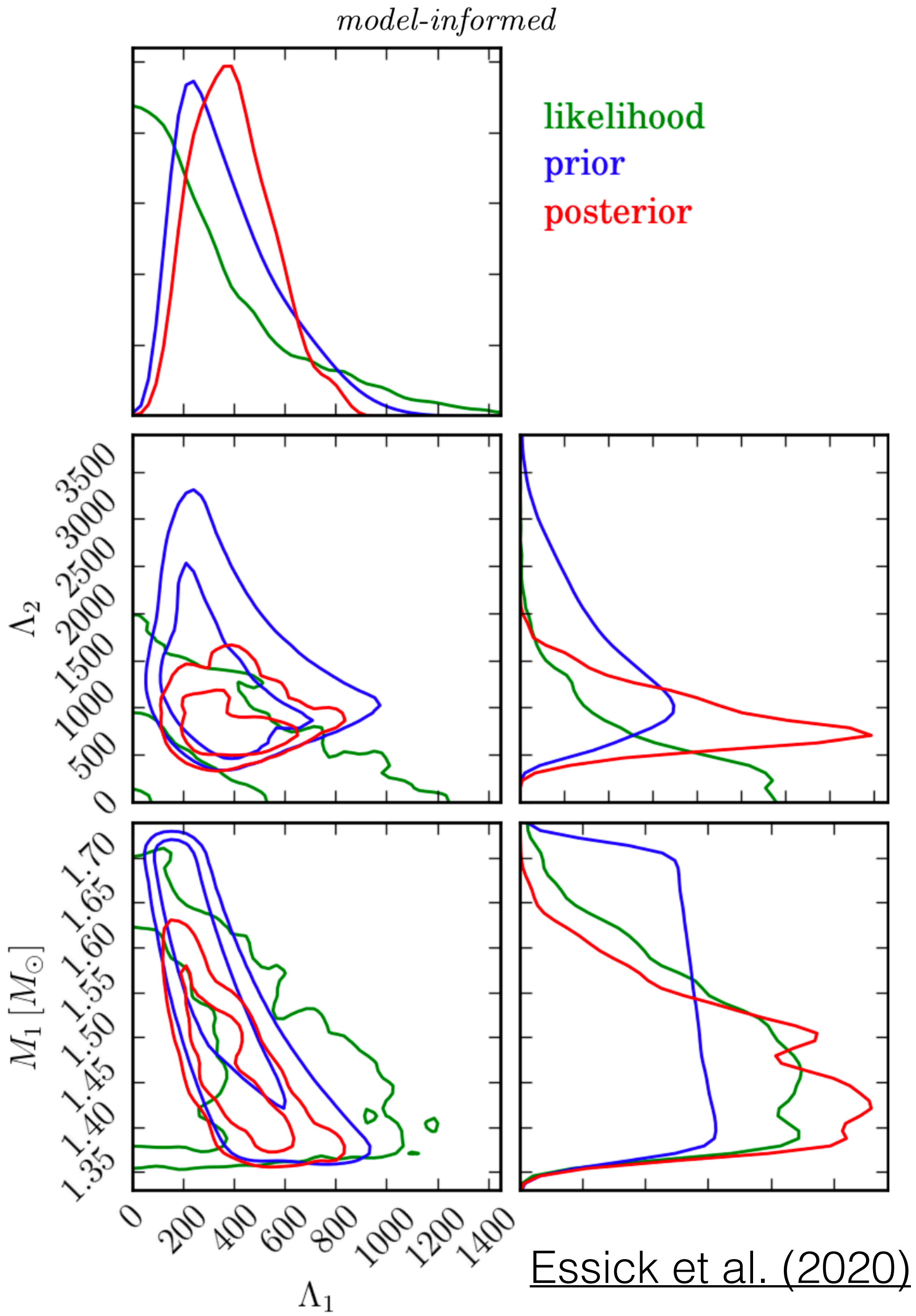
Ground-based interferometers are most sensitive to the inspiral phase, where GW signal is in the 100-1000 Hz range.

Key difference with BHBH waveform is the effects of tides due to the finite size of NSs: change in phase evolution.

e.g. Blanchet et al. (2006) Hinderer et al. (2016)

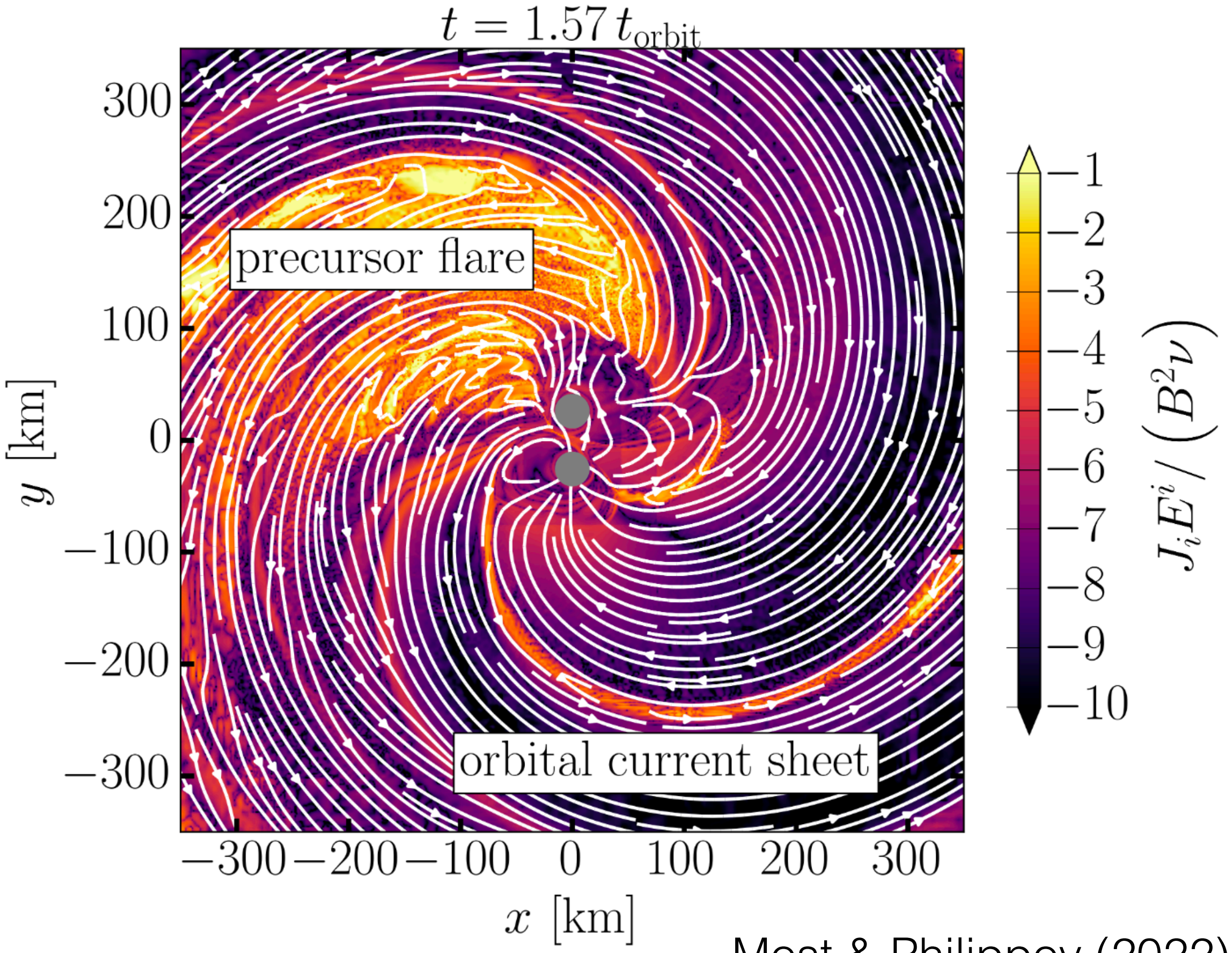
GW170817 yielded constraints on the tidal deformability parameter Λ of neutron stars, which constrains the EOS of neutron star matter.

Abbott et al. [LVC] (2017)



Essick et al. (2020)

Inspiral Phase:
EM Precursors



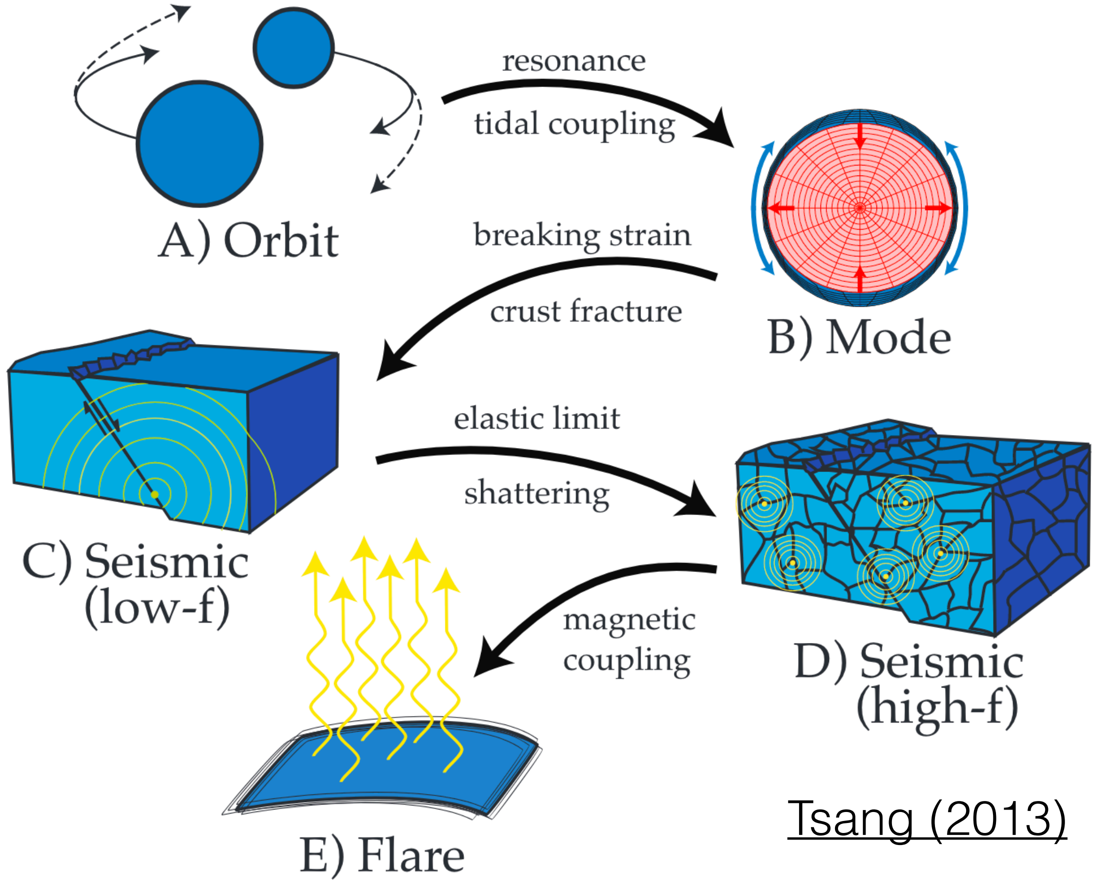
Magnetospheric interaction: emission due to magnetic reconnection and/or particle acceleration by induced electric fields.

Hansen & Lyutikov (2001), Lai (2012), Palenzuela et al. (2013)

Most & Philippov (2022)

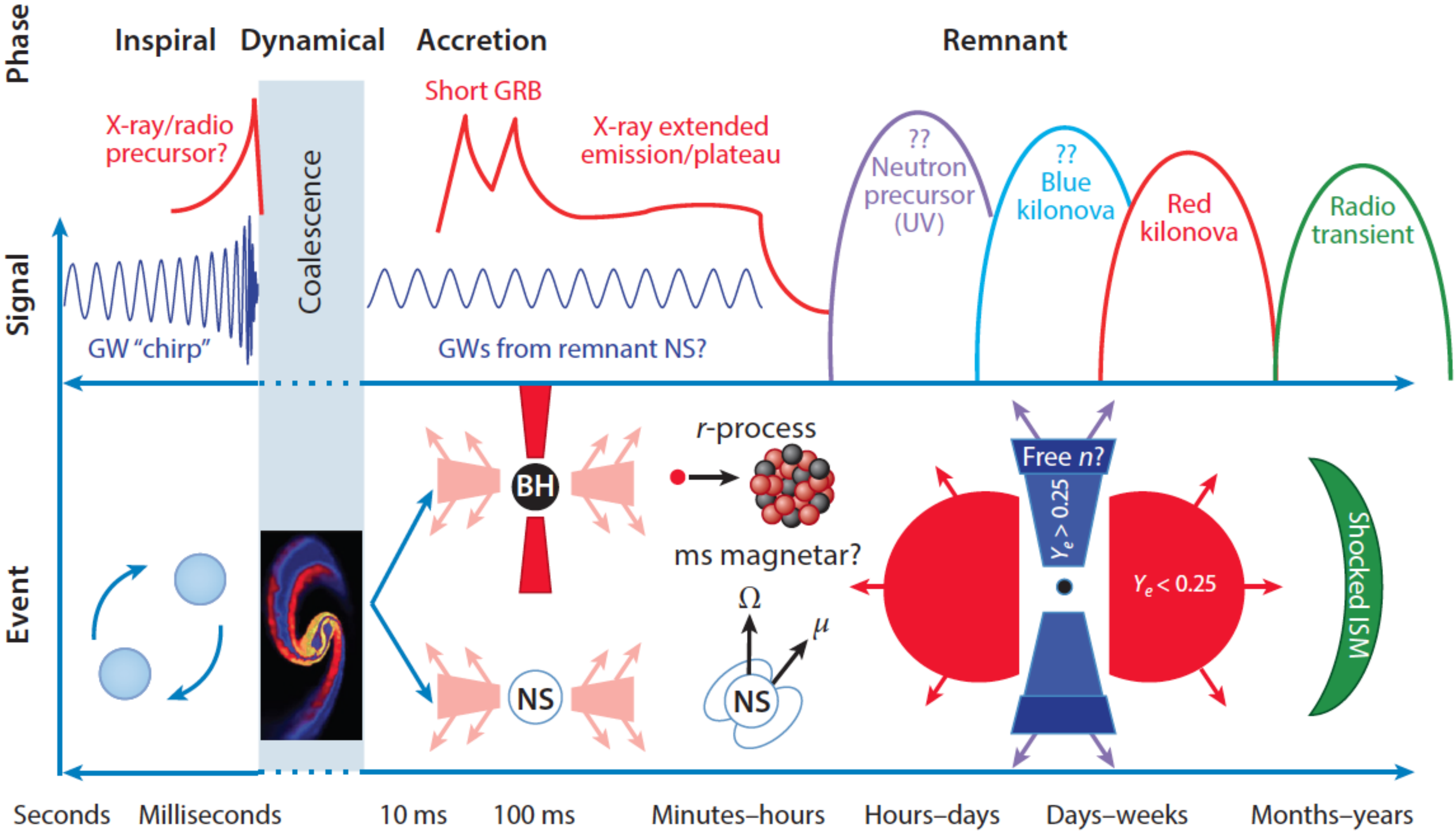
Crust-shattering flares: tidal interactions excite normal modes. If mode amplitude is sufficiently large, can cause deformation that exceeds breaking strain of crust. Seismic energy transferred to the magnetosphere.

Tsang et al. (2012)



Tsang (2013)

Neutron Star Mergers: Overview



RF & Metzger (2016)

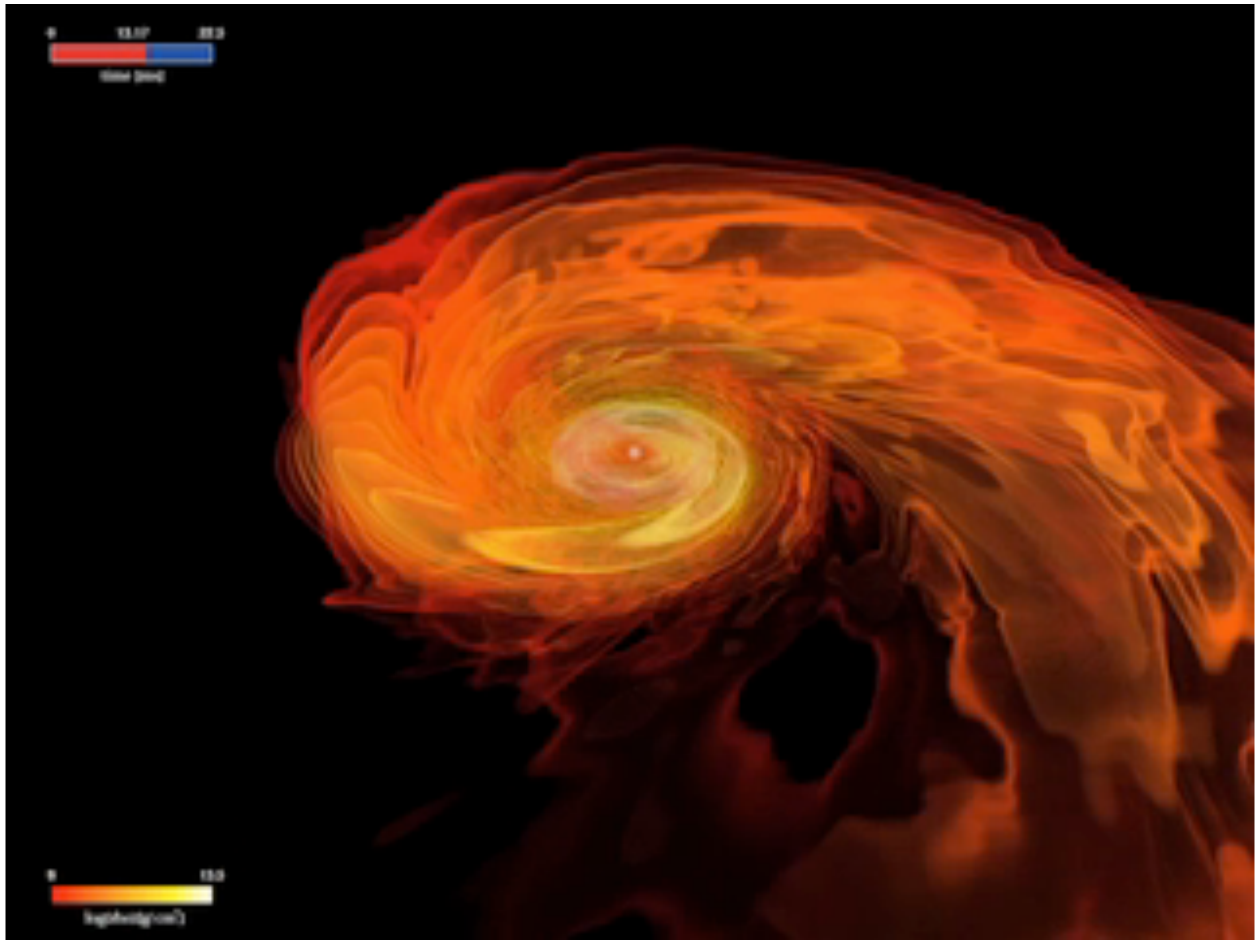
Dynamical Phase: Numerical Relativity

Spacetime evolves non-linearly: perturbative approach not possible, must solve numerically.

Nakamura et al. (1987), Shibata & Nakamura (1995), Baumgarte & Shapiro (1999), Pretorius (2005)

Long-history of efforts to include matter, focusing on GR with simple fluids, or on the microphysics with simple gravity.

e.g. Ruffert & Janka (1996), Shibata & Uryu (2000)



Rezzolla+ (2010)

State-of-the-art models focus on including GRMHD and neutrino transport with good accuracy for mass ejection and composition (GW emission not very sensitive to those effects).

Dynamical Phase: Mass Ejection

Material ejected on the orbital time is collectively called **dynamical ejecta**.

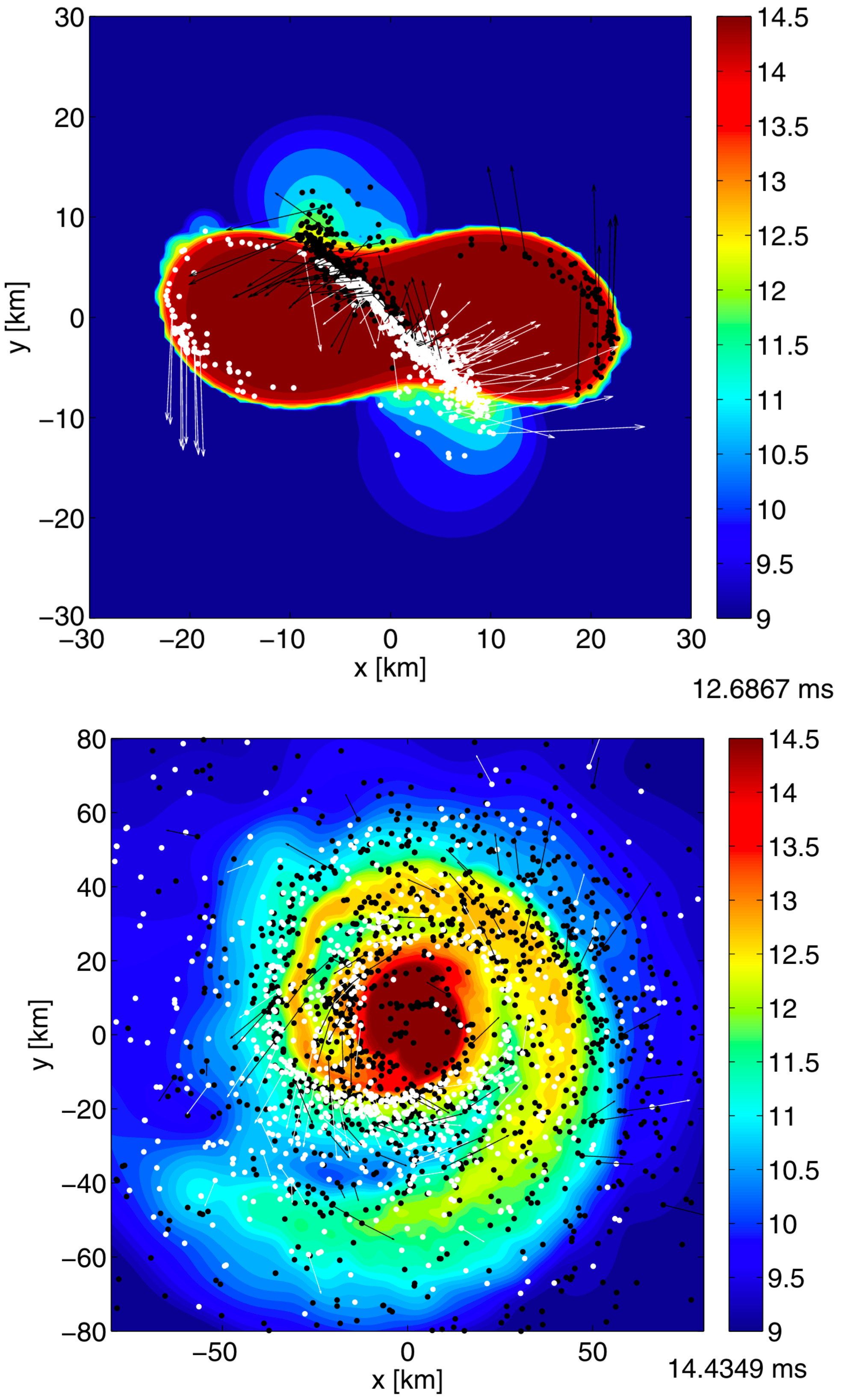
For NSNS mergers, there are two components:

1) Shock-heated material from the collision interface between stars

2) Colder material ejected in tidal tails and remnant oscillations

Depends on: total binary mass, mass ratio, initial spins, EOS, neutrino heating & cooling, and magnetic stresses.

(e.g., Radice et al. 2018, Shibata & Hotokezaka 2019)

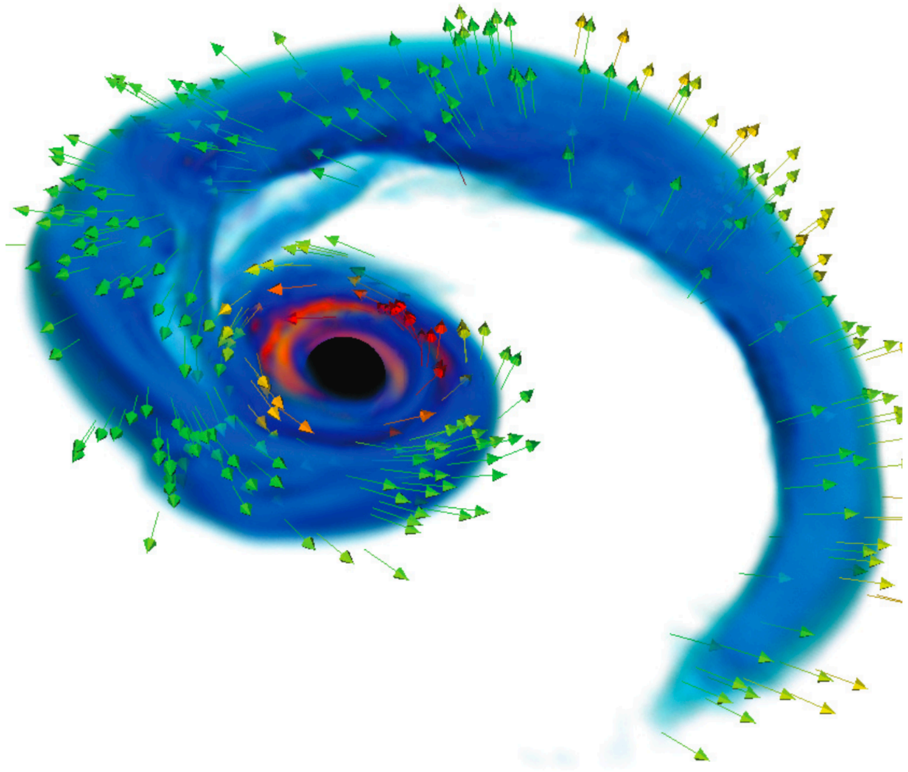


Bauswein et al. (2013)

Dynamical Phase: Mass Ejection

For BHNS models, there is only tidal tail dynamical ejecta.

(e.g., Shibata & Taniguchi 2000)



Foucart et al. (2014)

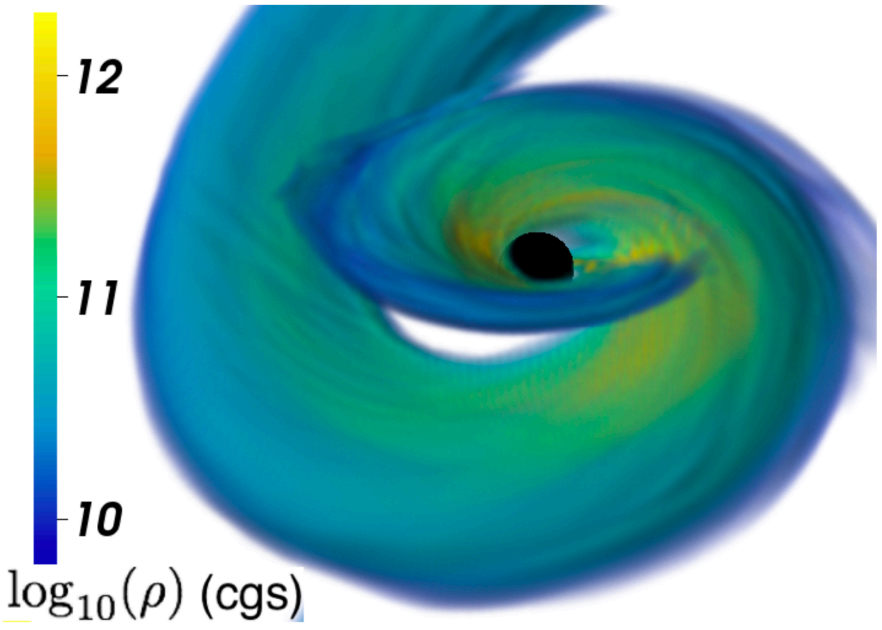
In addition, for BHNS systems there is a finite range in mass ratios and initial BH spins such that the NS is tidally disrupted and not swallowed.

Foucart et al. (2018)

Semianalytic formulae for mass ejection.

e.g., Krüger & Foucart (2020)

Additional complications include misalignment between BH spin and orbital spin (precession, etc.) →



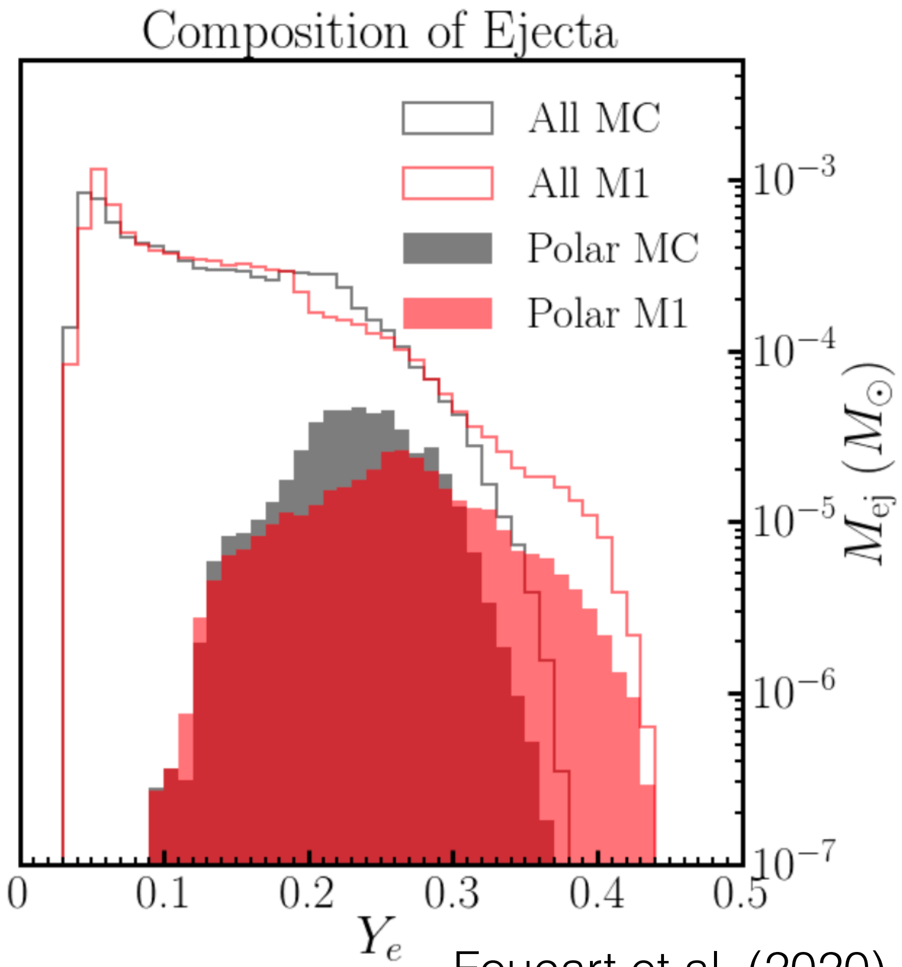
Foucart et al. (2017)

Dynamical Phase: Mass Ejection

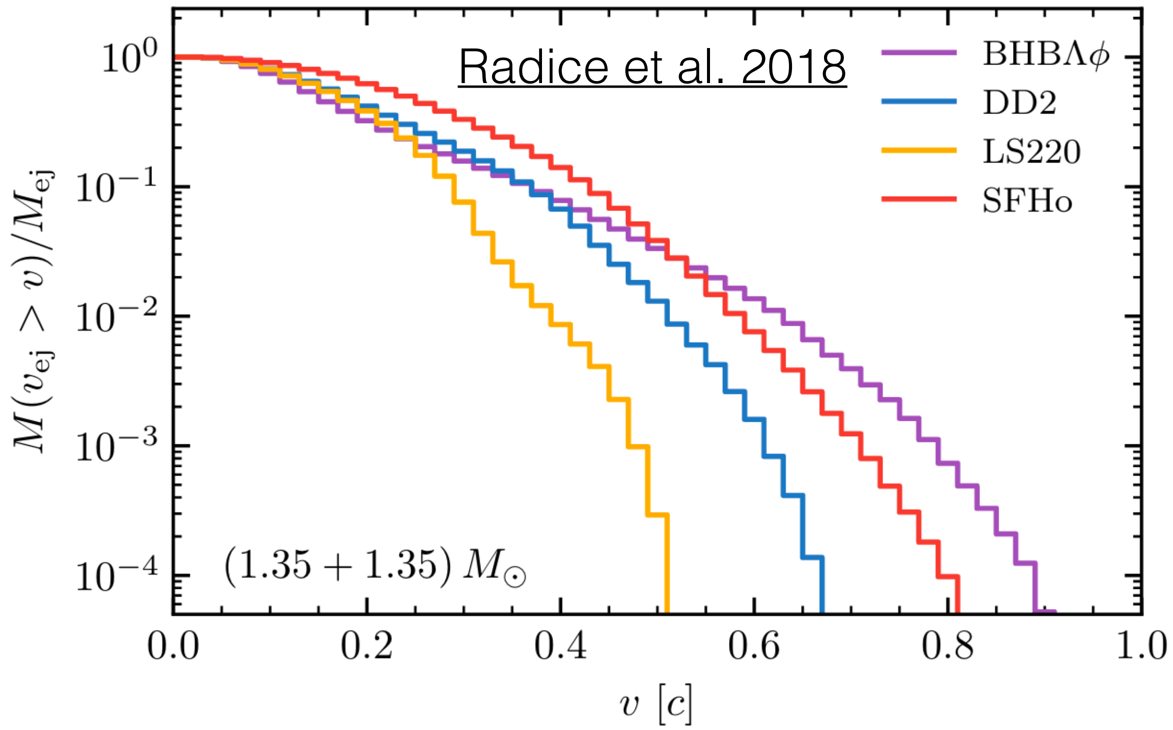
Not only the amount, but also the composition and velocity of the dynamical ejecta is important for EM counterpart predictions and nucleosynthesis calculations. **Ye definition**.

The composition is very sensitive to the quality of the approximations used to treat neutrino transport. State-of-the art is Monte Carlo approach.

The ejecta velocity is also sensitive to the equation of state, spatial resolution used, and to the treatment of magnetic fields.



Foucart et al. (2020)



Radice et al. 2018

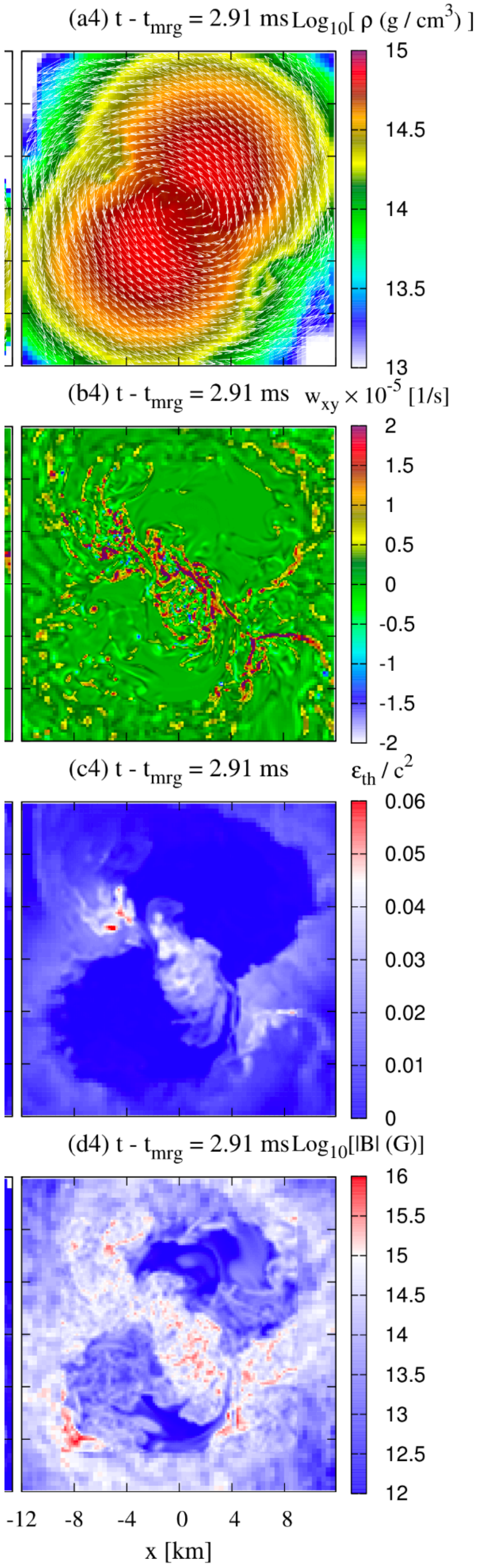
Dynamical Phase: Magnetic Field Amplification

The shear interface in NSNS mergers is subject to the Kelvin-Helmholtz instability, which can efficiently convert turbulent kinetic energy into small-scale magnetic fields.

Price & Rosswog (2006)

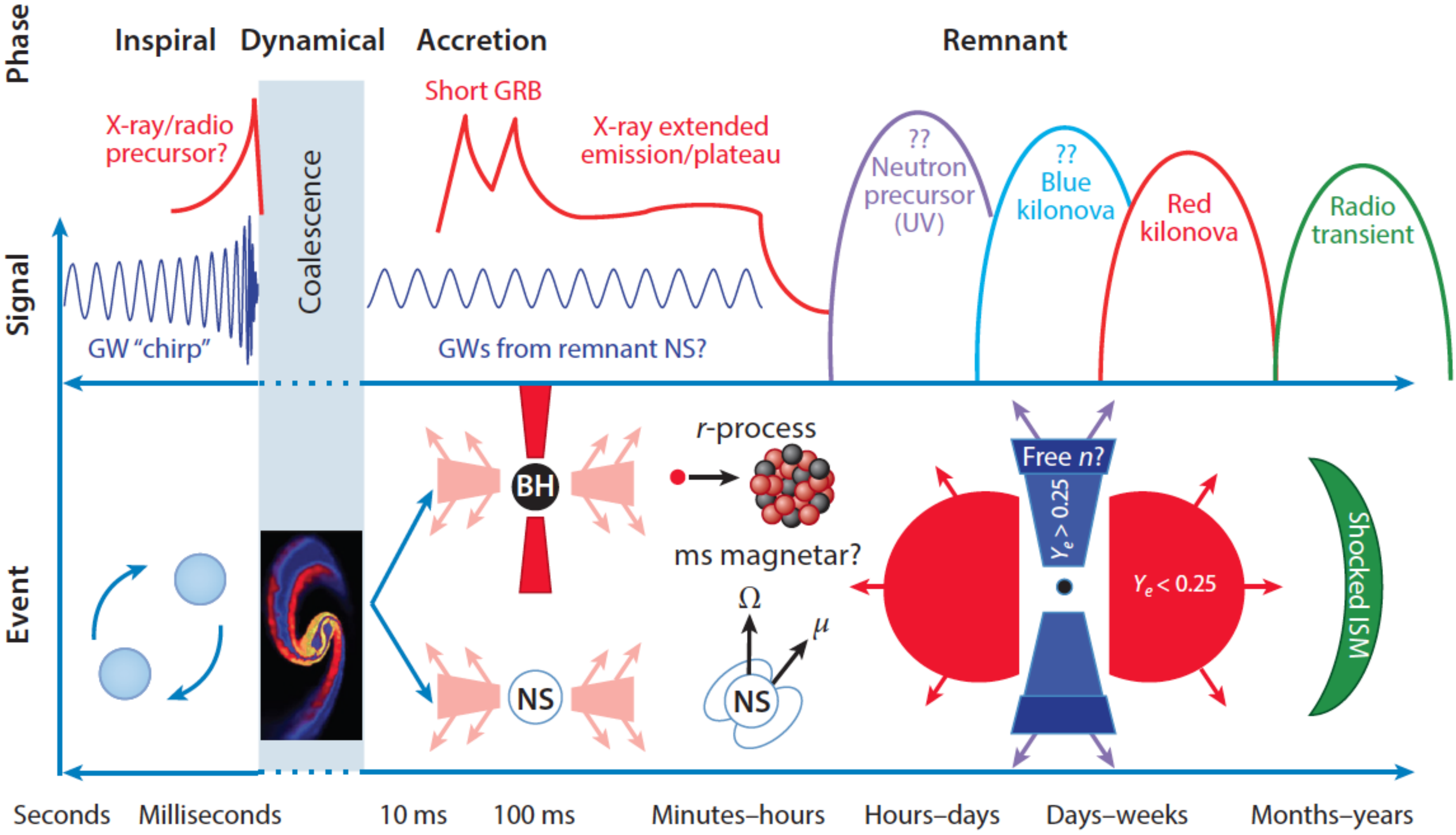
A current challenge is that numerical simulations cannot reach spatial resolutions that allow convergence and self-consistent production of large-scale fields through dynamo action. Sub-grid models have been developed.

e.g., Miravet-Tenés et al. (2022)



Kiuchi et al. (2015)

Neutron Star Mergers: Overview



RF & Metzger (2016)

Merger Remnant: Mass Limits

BHNS: remnant is always a BH, semianalytic formulate that connect initial binary mass with remnant BH mass, calibrated with Numerical Relativity simulations.

e.g., Pannarale (2014)

NSNS: depending on initial binary mass, remnant can be:

1) Promptly-formed BH (~ 1ms)

2) Hypermassive NS (HMNS): differential rotation, finite lifetime

3) Supermassive NS (SMNS): uniform rotation (low-mass cases)

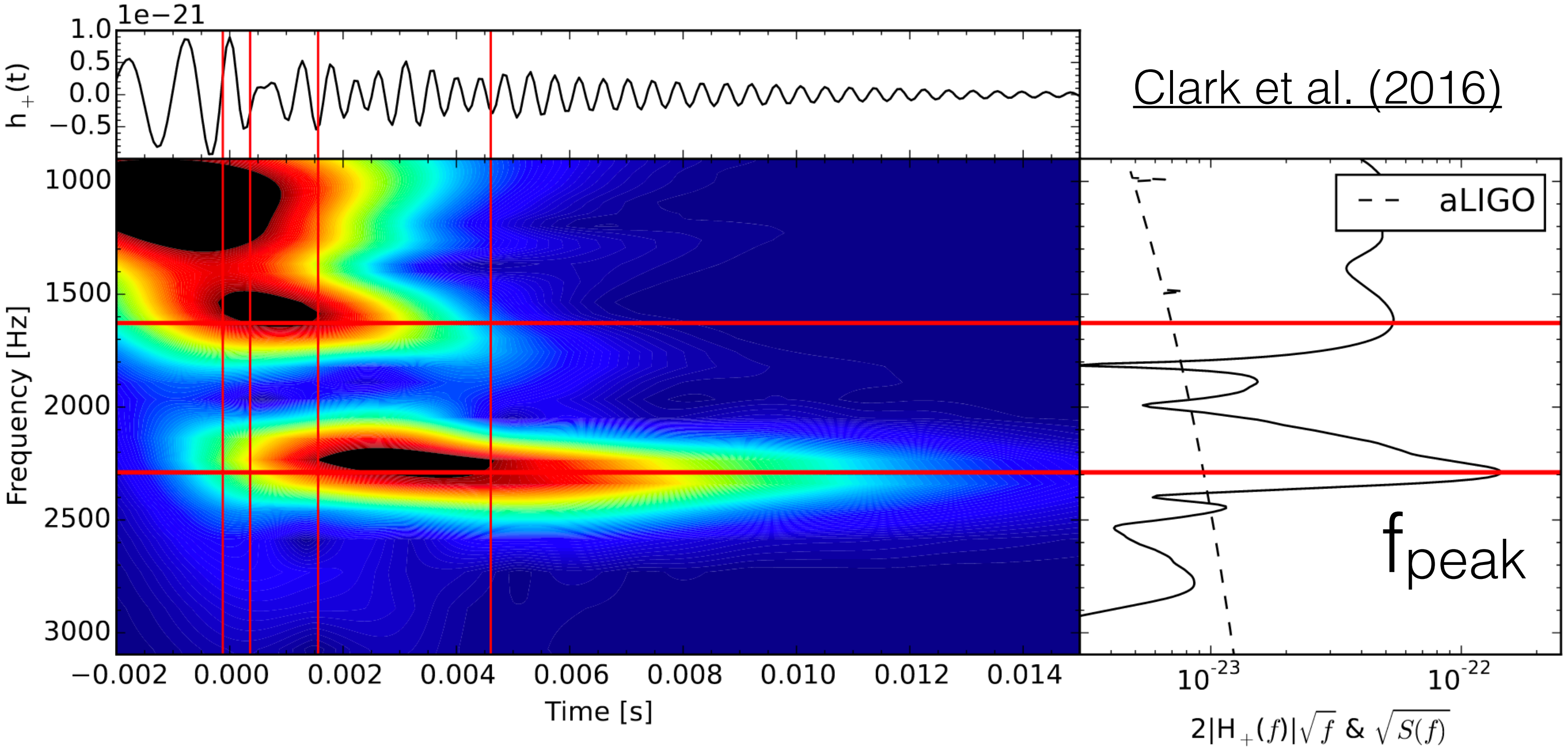
Mass limit for prompt BH formation, and lifetime of HMNS influenced by the EOS, as well as treatment of magnetic fields (which regulates differential rotation support) and neutrino transport (thermal support).

e.g., Anderson et al. (2008), Giacomazzo et al. (2011), Kaplan et al. (2014)

Merger Remnant: Gravitational Waves

The remnant of a NSNS merger executes oscillations at ~few kHz frequencies. Detectable out to ~20Mpc currently.

e.g. Shibata & Taniguchi (2006), Abbott et al. (2017)



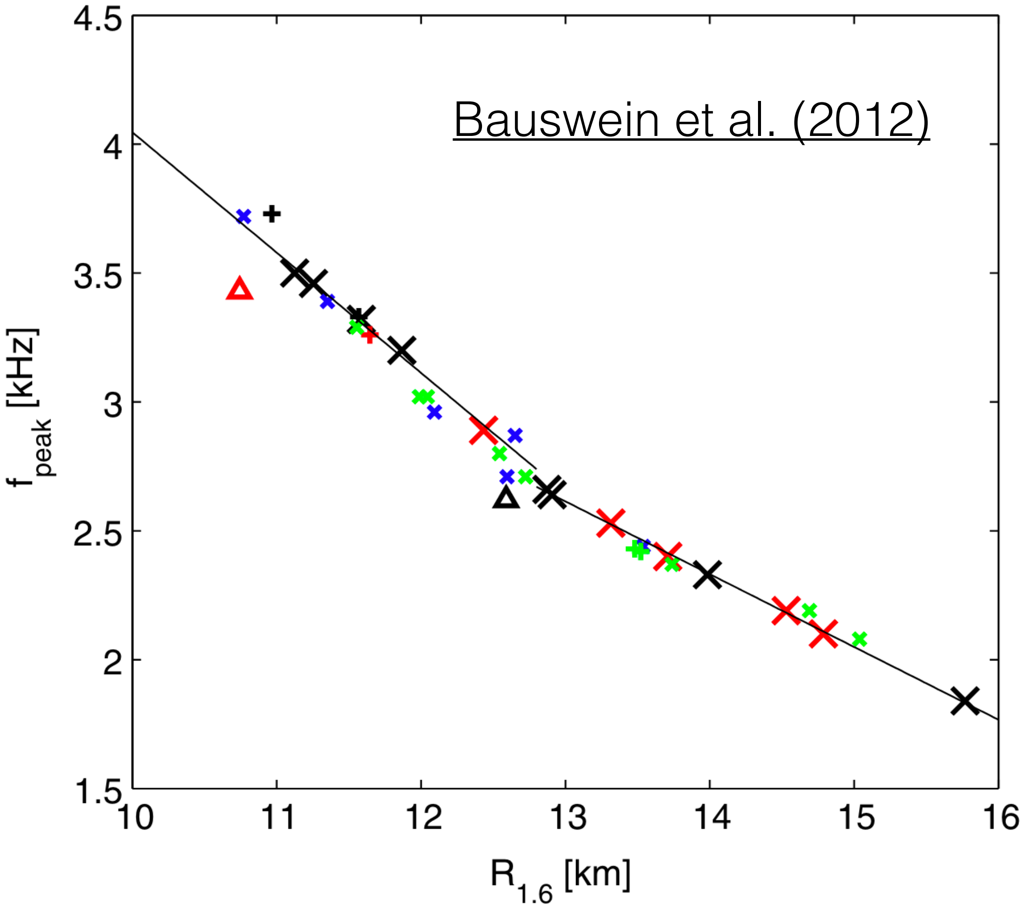
Clark et al. (2016)

The peak frequency is the ~ inverse dynamical time

$$f_{\mathrm{peak}} \sim t_{\mathrm{dyn}}^{-1} \propto \left(\frac{M}{R^3}\right)^{1/2}$$

Encodes information about the EOS.

e.g. Palenzuela et al. (2015), Breschi et al. (2022)



Bauswein et al. (2012)