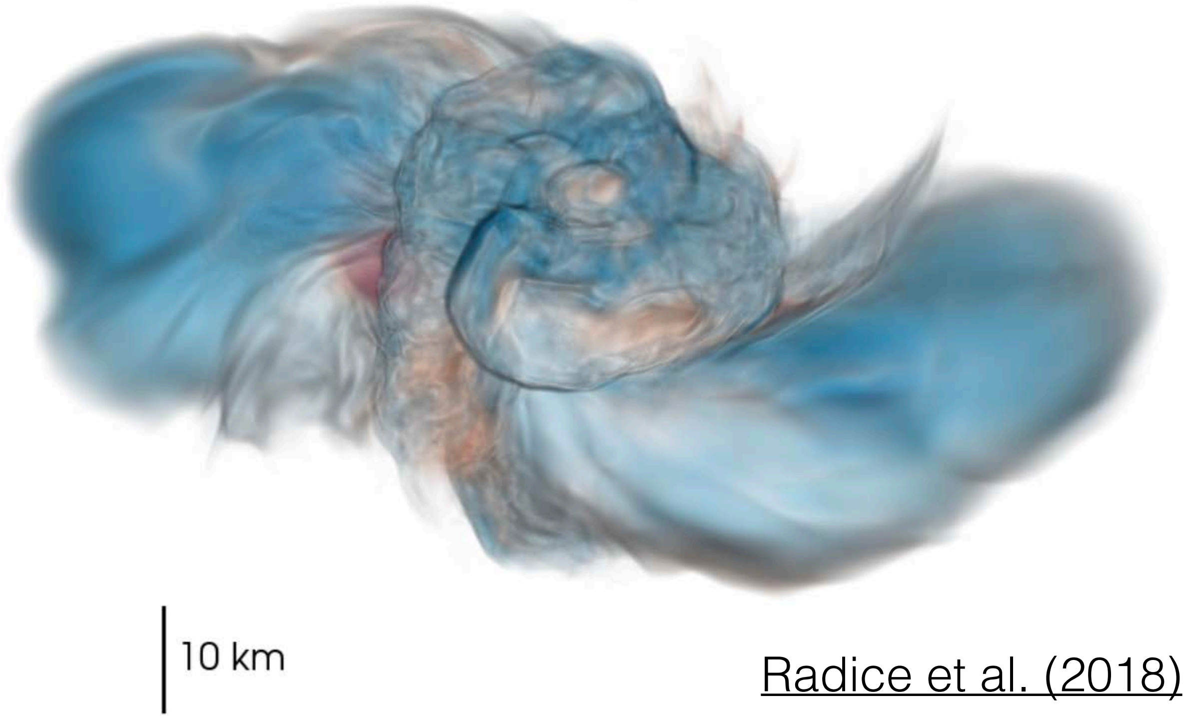
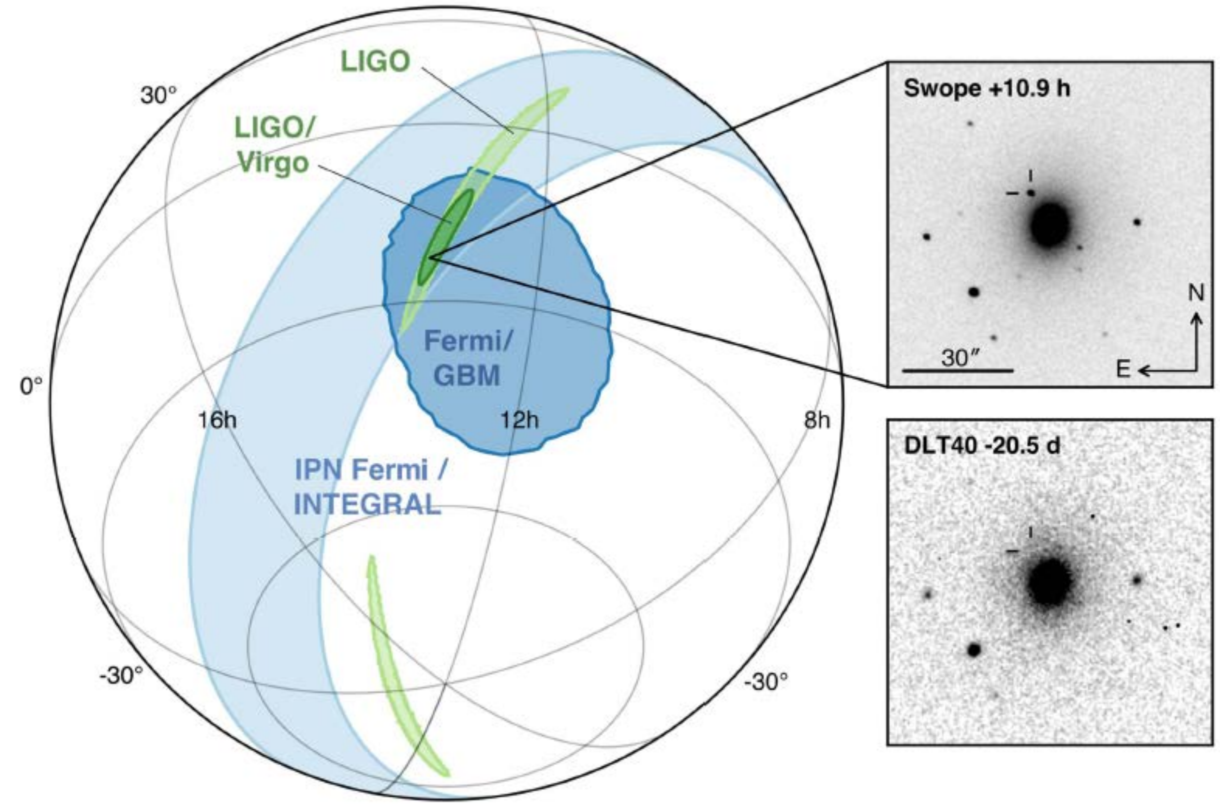
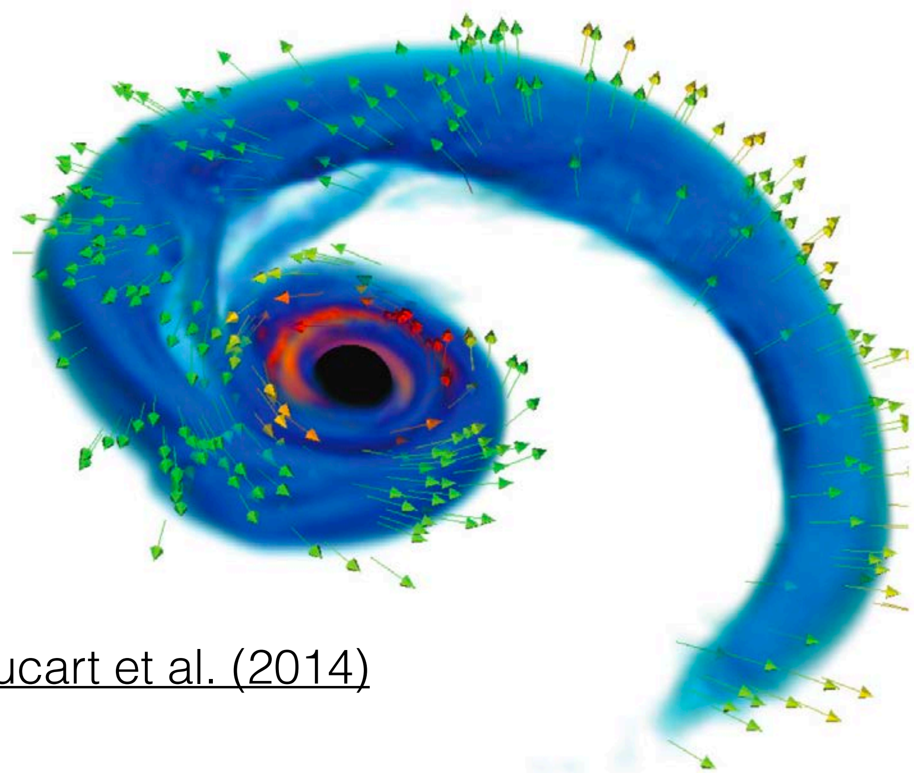


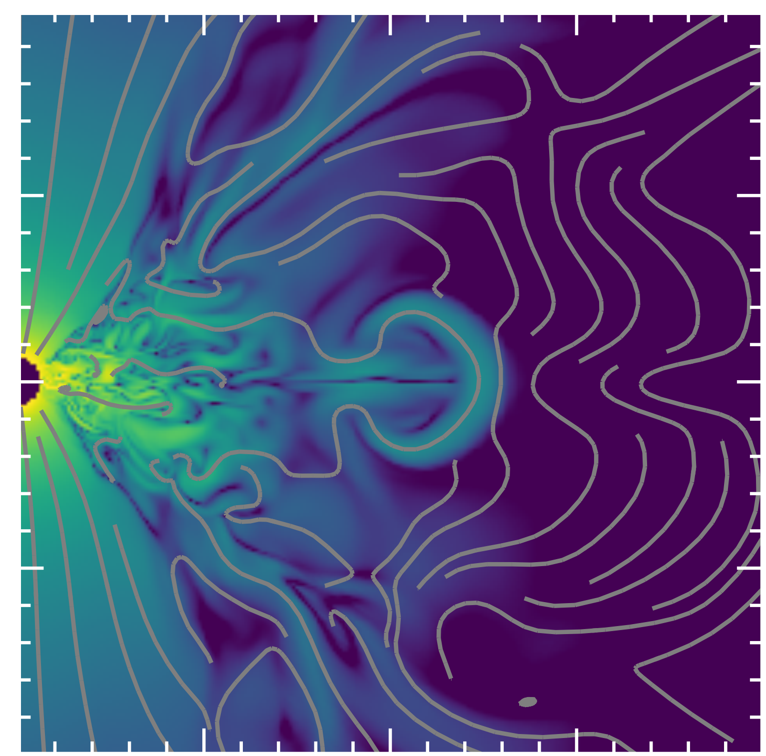
Radice et al. (2018)



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



Foucart et al. (2014)



RF et al. (2019)

Neutron Star Mergers & Supernovae

Rodrigo Fernández (University of Alberta)

Outline

1) Core-Collapse Supernovae & Neutron Star Formation

2) Overview of Neutron Star 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: Kilonovae, GRBs, and more

Supernovae: Classification

Core-Collapse

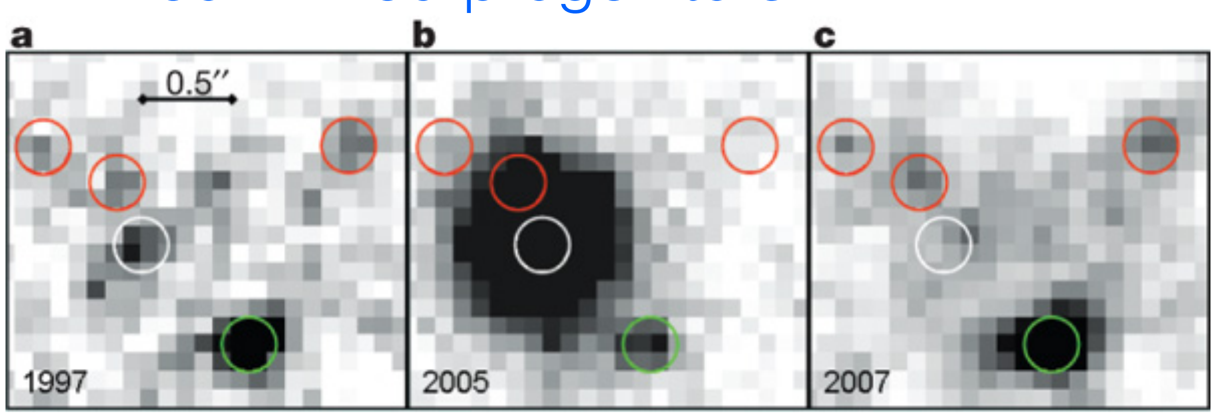
Type II

Type Ib,c

Associated with
massive stars

$M \gtrsim 8 M_{\odot}$

several systems with
confirmed progenitors:



SN 2005gl (Gal-Yam & Leonard 2009)

Thermonuclear

Type Ia

incineration
of white dwarf

$M \sim 1 M_{\odot}$

astrophysical
progenitors systems
not yet established

see Liu et al. (2023)

Pair Instability

predicted for very
massive stars

$140 \lesssim M/M_{\odot} \lesssim 260$

candidate objects

Pair Instability Supernovae

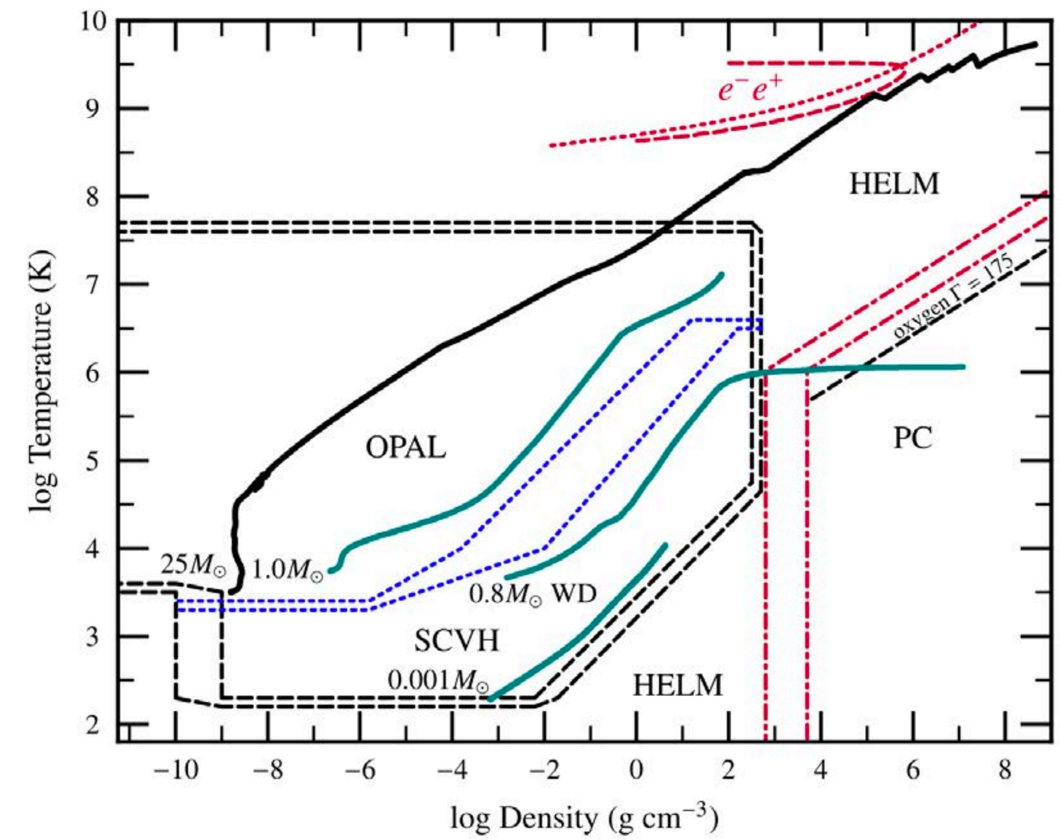
Stars in the ZAMS range:

$$140 \lesssim M/M_{\odot} \lesssim 260$$

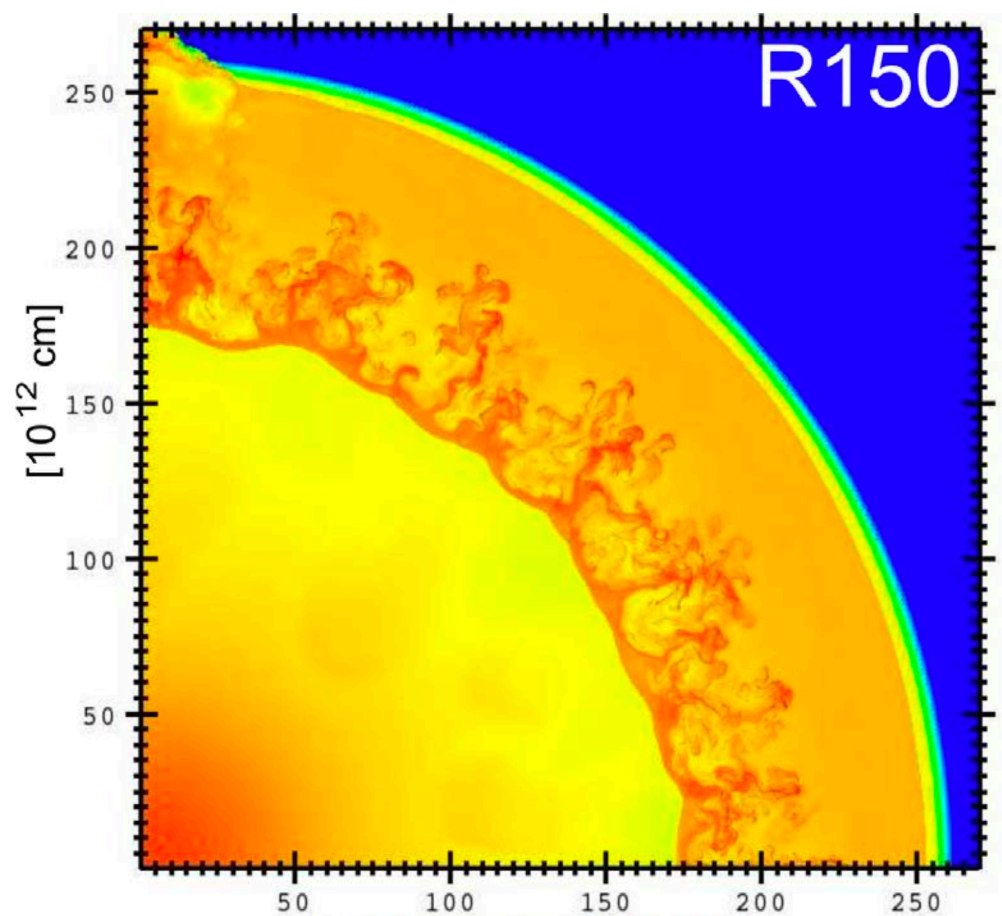
(for solar metallicity), encounter a region of thermodynamic space where it is energetically convenient to convert photons to e^+e^- pairs, which removes pressure support and causes the star to collapse (pc/E < 1 for non-zero m).

Explosive burning of oxygen or silicon (depending on mass) due to the temperature overshoot from hydrostatic equilibrium then explodes the star, leaving no remnant behind. For masses above the upper limit, explosive burning cannot reverse the collapse and a BH forms with no mass ejection.

Fryer et al. (2001)



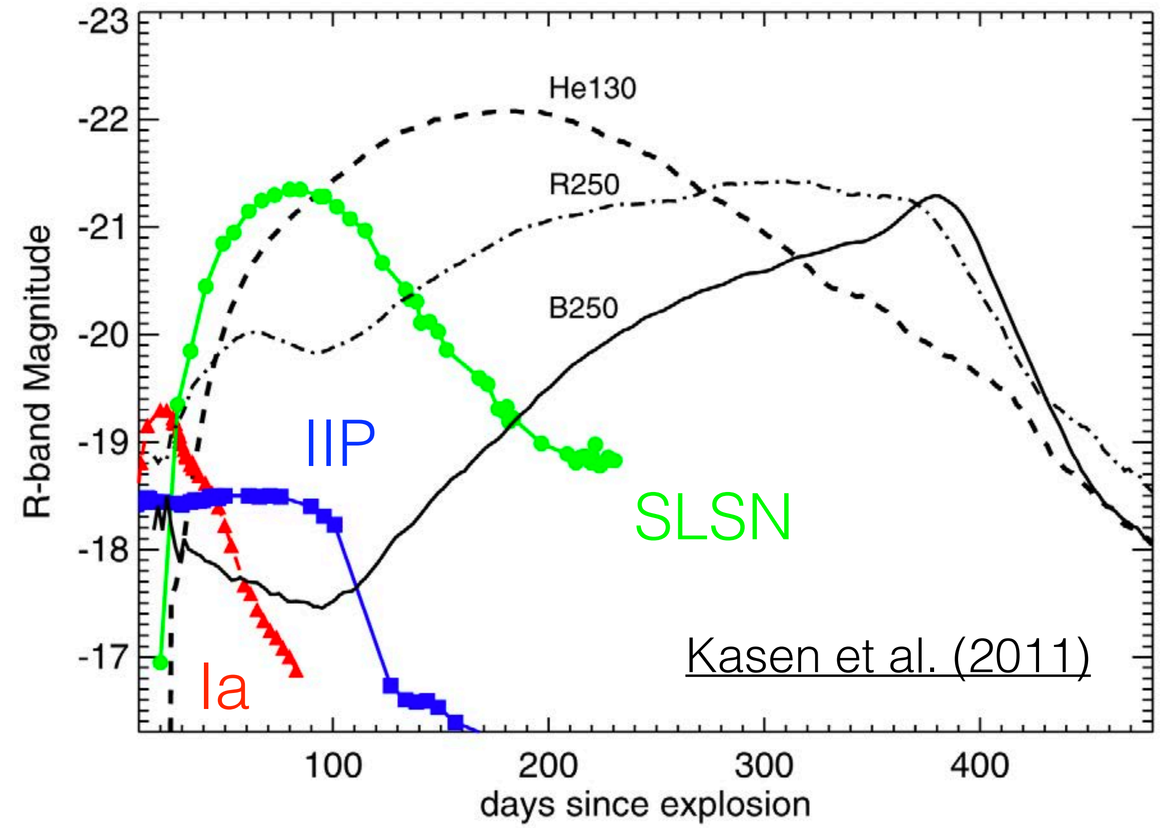
Paxton et al. (2011)



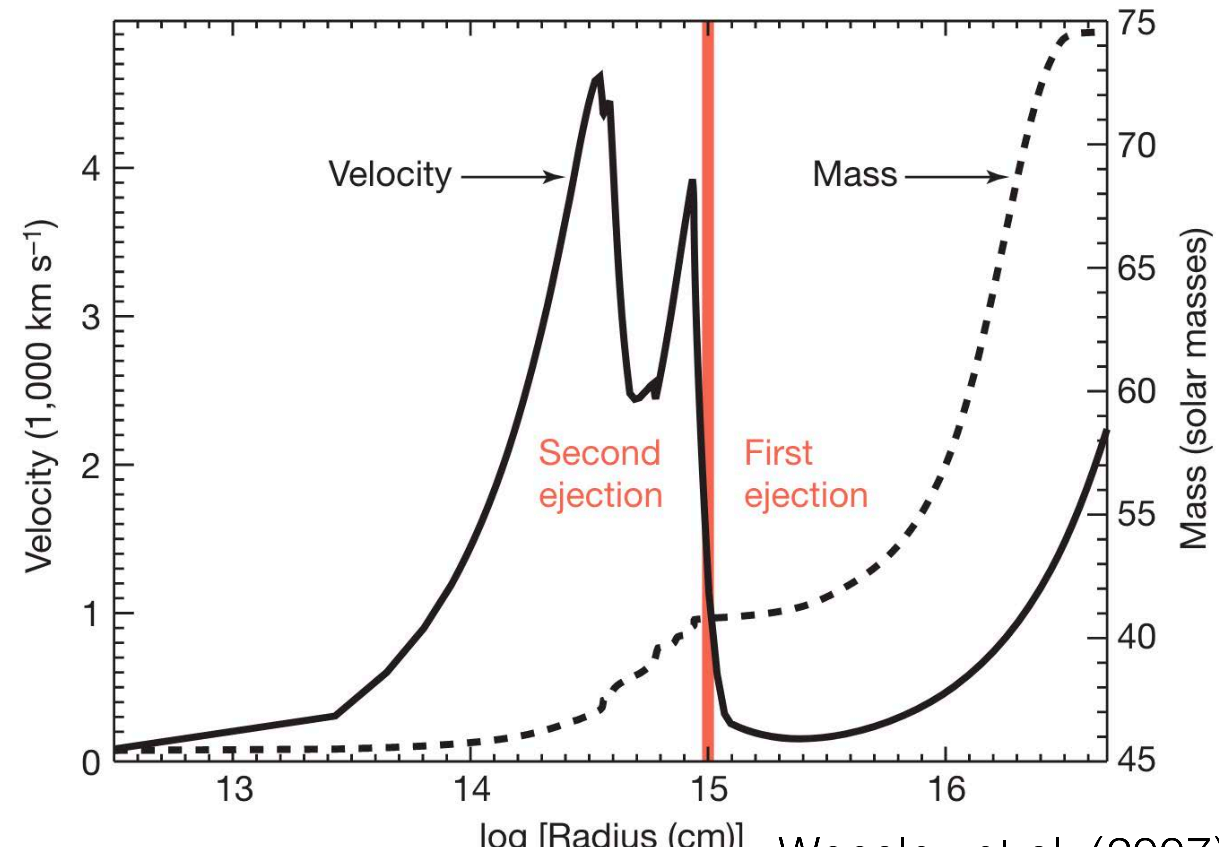
Chen et al. (2014)

Pair Instability Supernovae

PISN produce large ejecta masses (> 50M$_{sun}$) hence their light curves peak over a timescale of ~1yr. The ^{56}Ni mass ejected can range from zero to several 10M$_{sun}$, hence there is a very wide range in (predicted) luminosities, even exceeding the most luminous supernovae yet observed.



Around the lower mass end, explosive burning does not disrupt the star, leading to a subsequent collapse(s) due to pair instability, and more explosive burning. These are called **pulsational pair instability supernovae** when a terminal pulse occurs (stars can also move to regular core-collapse evolution).

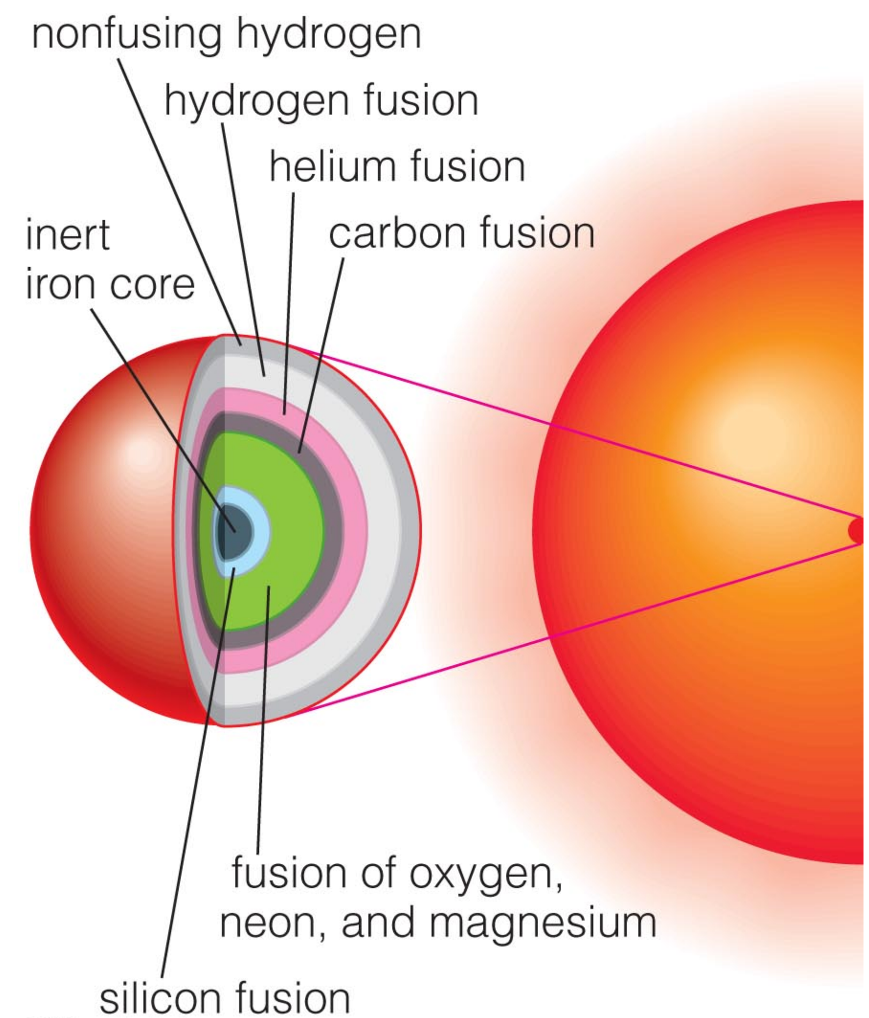


Pre-supernova Evolution

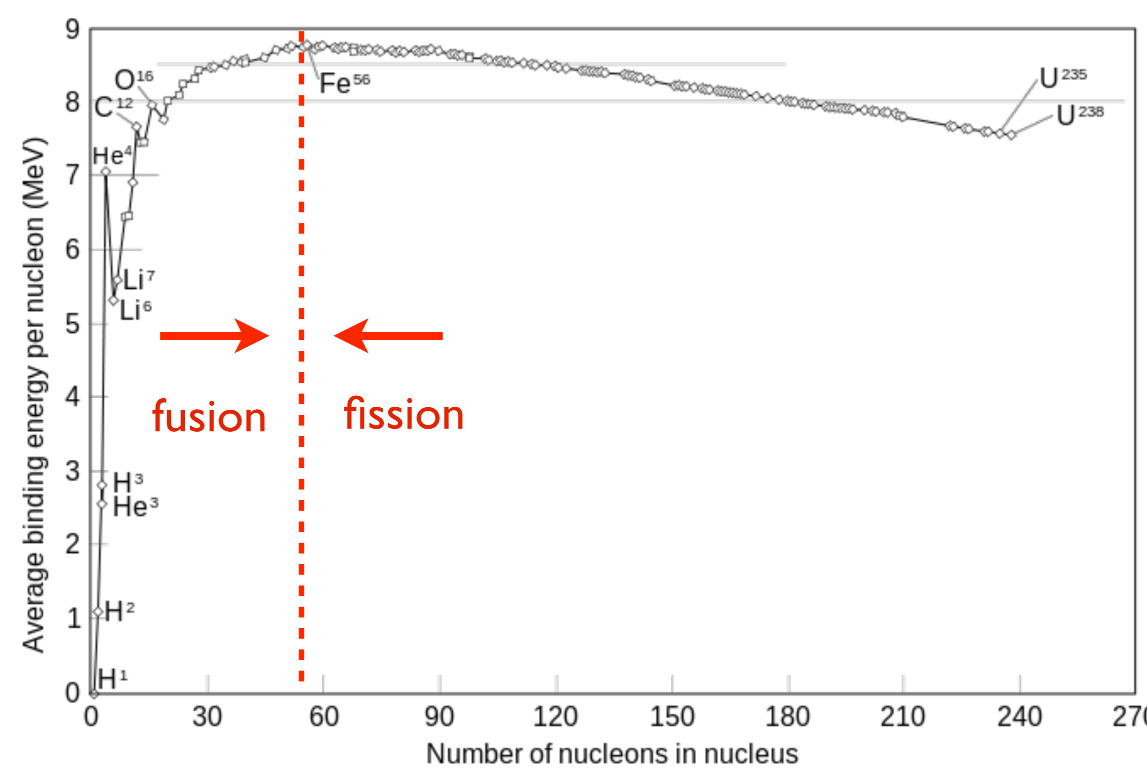
Stars that do not encounter the pair instability, go through advanced burning stages of increasingly heavier elements.

Stars more massive than about $10M_{sun}$ at solar metallicity reach silicon burning, generating a degenerate iron core.

Since iron and surrounding elements are the most tightly bound nuclei, no more energy can be produced by nuclear fusion, and the core grows in mass (due to continuous silicon burning), being supported against gravity by electron degeneracy pressure.



credit: Pearson Education



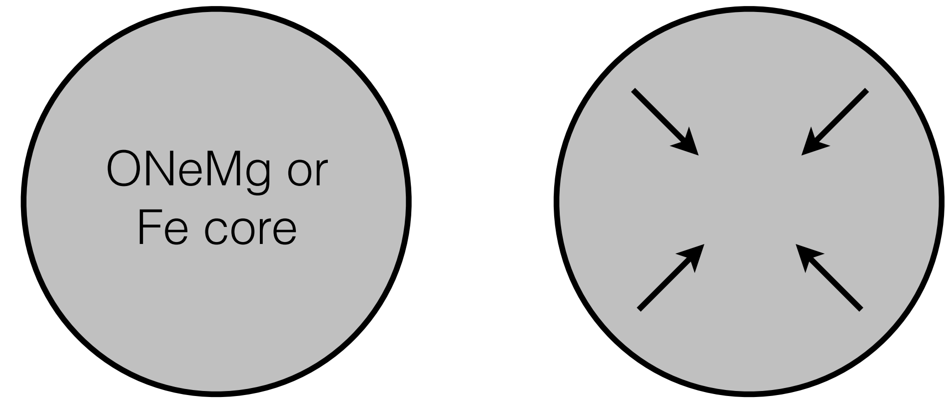
wikipedia.org

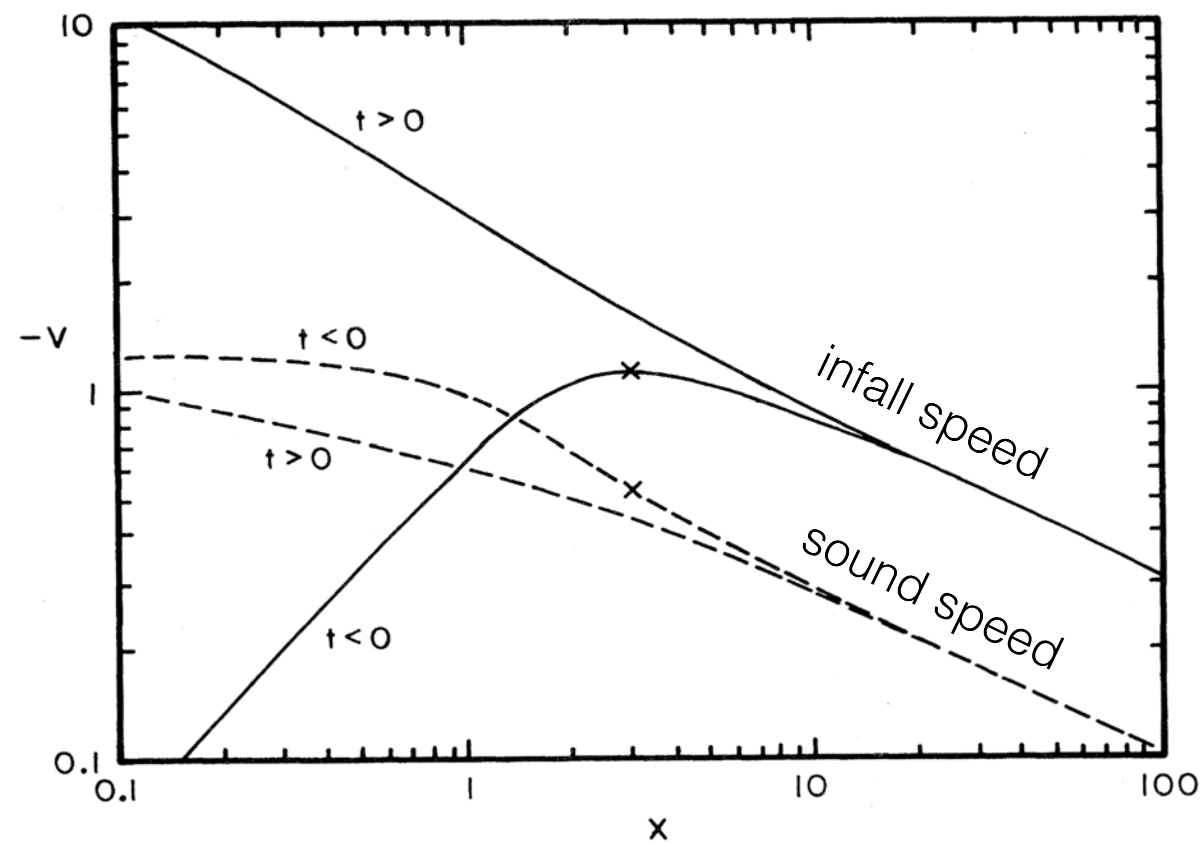
Core Collapse and Bounce

Once collapse sets in, the dynamics proceeds on the dynamical time for a core of mass ~1.4M$_{sun}$ and radius 2000km:

$$t_{\rm dyn} \sim 1\,{\rm s}\left(\frac{M}{1.4\,M_\odot}\right)^{-1/2}\left(\frac{R}{2000\,{\rm km}}\right)^{3/2}$$

Collapse proceeds self-similarly, with the inner regions contracting sub-sonically and with velocity proportional to radius ("homologous collapse"). The contraction speed reaches a peak above the sound speed: the outer core collapses supersonically.





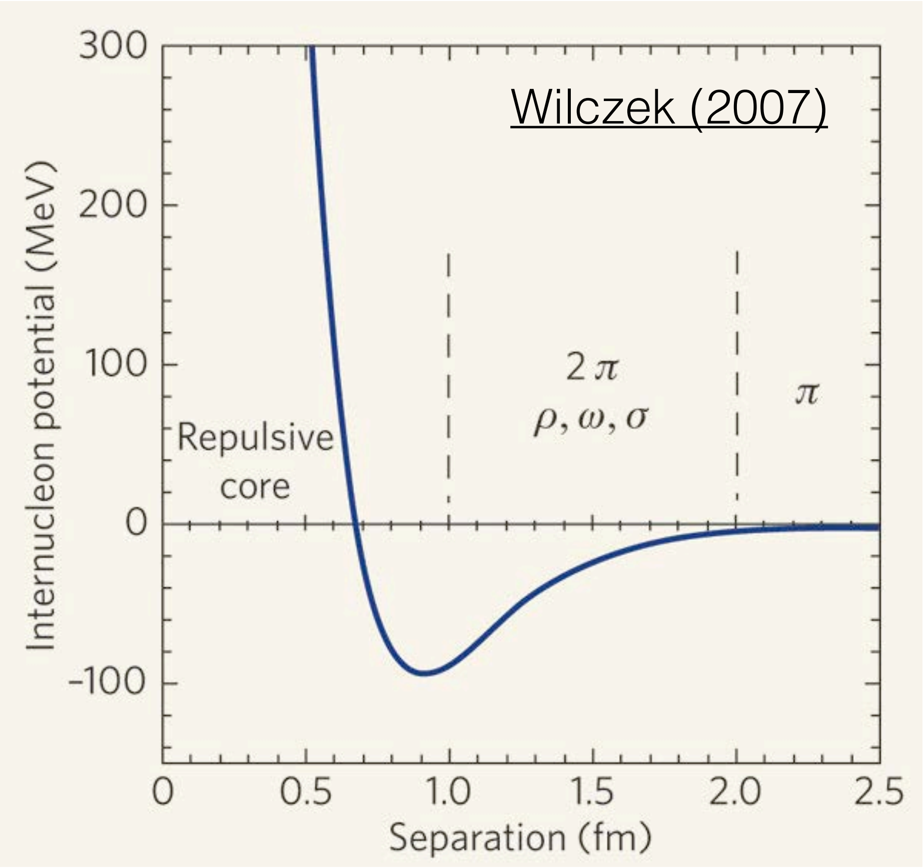
Yahil & Lattimer (1982)

Core Collapse and Bounce

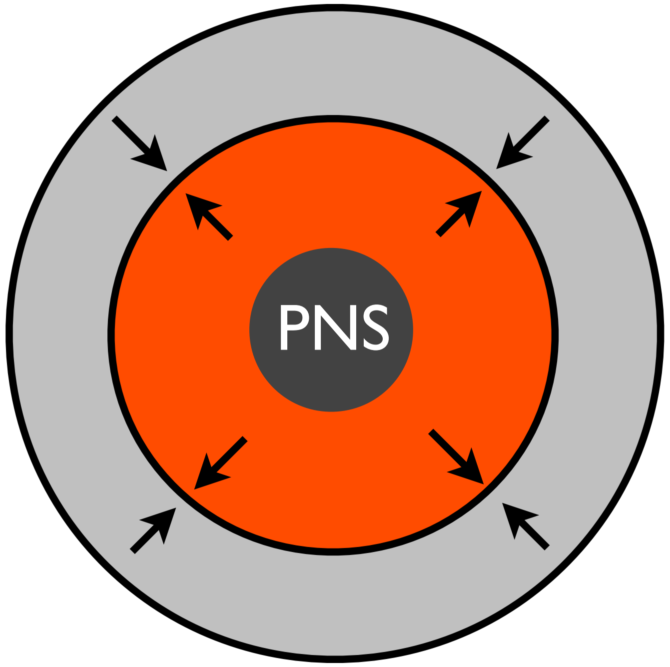
When the center of the core reaches densities around those of atomic nuclei

$$\rho_{\rm nuc} \simeq 2.5 \times 10^{14}\,{\rm g\,cm^{-3}}$$

the equation of state stiffens, increasing the pressure faster for a given density change, relative to lower densities. This is quantified by the adiabatic index $P \sim \rho^{\gamma}$. This stiffening is due to the fact that the strong interaction becomes repulsive at very short distances.



This results in a hydrodynamic pulse (sound wave) emerging from the core due to the slow down. The sound wave stiffens into a shock once it reaches the supersonically collapsing regions (the “bounce shock”).

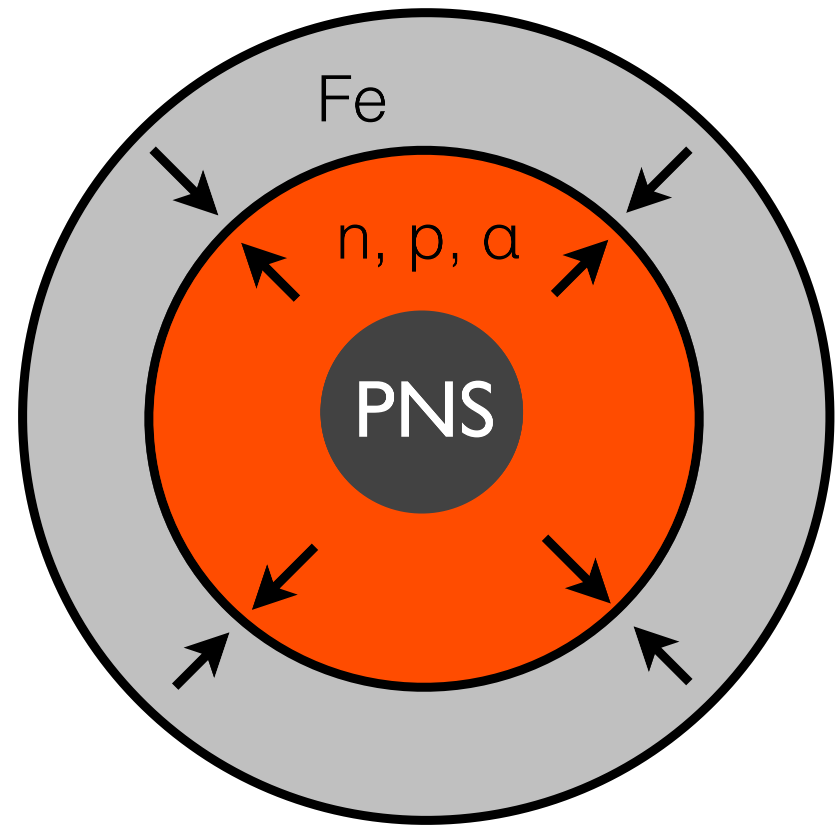


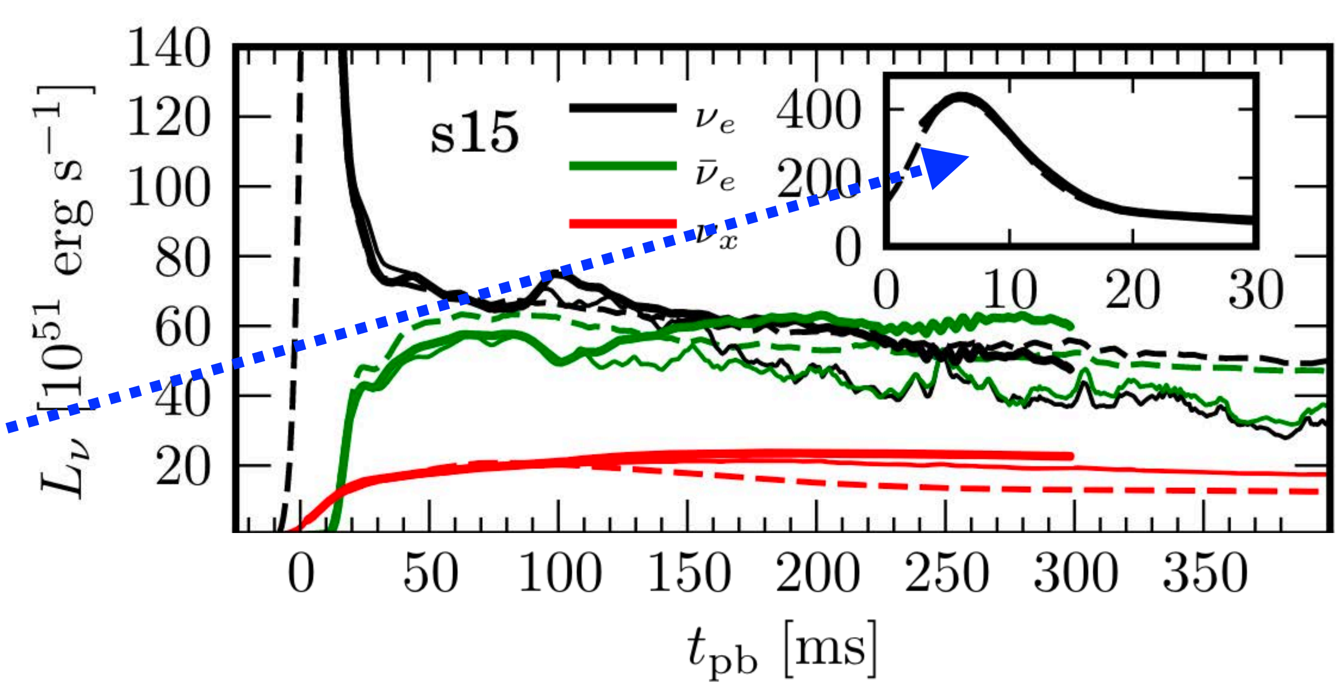
Core Collapse and Bounce

The outgoing shock stalls on its way out due to energy losses from dissociation of heavy nuclei falling through it and neutrino emission.

Dissociation of a heavy nucleus costs the nuclear binding energy of the nucleus (~8-9 MeV/ nucleon), which decreases the internal energy.

Electron neutrinos (produced by e- capture on p) initially trapped behind the shock, are suddenly released once the shock reaches optically thin regions: electron neutrino burst.





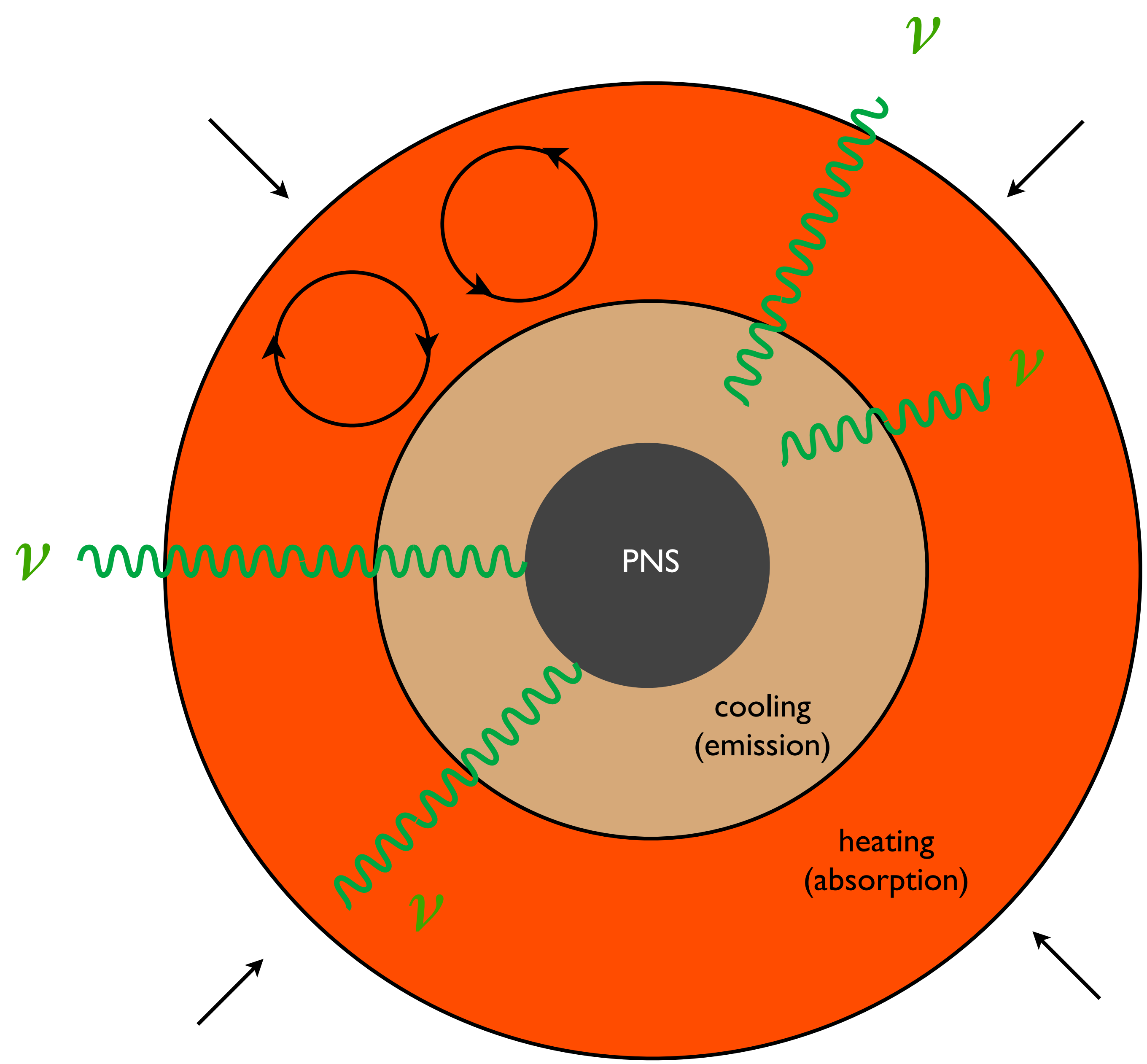
Couch & O'Connor (2014)

Delayed Neutrino Mechanism

The stalled shock needs additional energy to be revived in order for a successful explosion to occur.

In the absence of additional effects like rapid rotation, the default explosion mode is the **delayed neutrino mechanism.**

A fraction ~1% of neutrinos emitted by the dense core (protoneutron star) and by accretion, are re-absorbed in a layer just behind the shock where heating dominates cooling (the "gain" layer).



Bethe & Wilson (1985)

Delayed Neutrino Mechanism: Numbers

Available energy: $$\frac{GM_{\rm PNS}^2}{R_{\rm PNS}} \sim 10^{53}\left(\frac{M_{\rm PNS}}{M_\odot}\right)^2\left(\frac{30\,{\rm km}}{R_{\rm PNS}}\right)\,{\rm erg}$$ plenty!

Average density: $$\bar\rho \sim \frac{M_{\rm PNS}}{R_{\rm PNS}^3} \sim 10^{14}\left(\frac{M_{\rm PNS}}{M_\odot}\right)\left(\frac{30\,{\rm km}}{R_{\rm PNS}}\right)^3\,{\rm g\,cm^{-3}} \sim \rho_{\rm nuc}$$ nuclear physics

Neutrinos: $$\sigma_\nu \simeq 10^{-42}\left(\frac{\varepsilon_\nu}{10{\rm MeV}}\right)^2\,{\rm cm}^2$$

$$\tau_{\rm PNS} \sim \frac{R_{\rm PNS}}{\ell_{\rm mfp}} \sim \left(\frac{\bar\rho}{m_n}\right)\sigma_\nu\,R_{\rm PNS} \sim 100$$

neutrino transport
(radiation hydro)

$$\tau_{\rm shock} \sim 0.01\left(\frac{\rho_{\rm shock}}{10^9{\rm g\,cm^{-3}}}\right)\left(\frac{R_{\rm shock}}{150\,{\rm km}}\right)$$

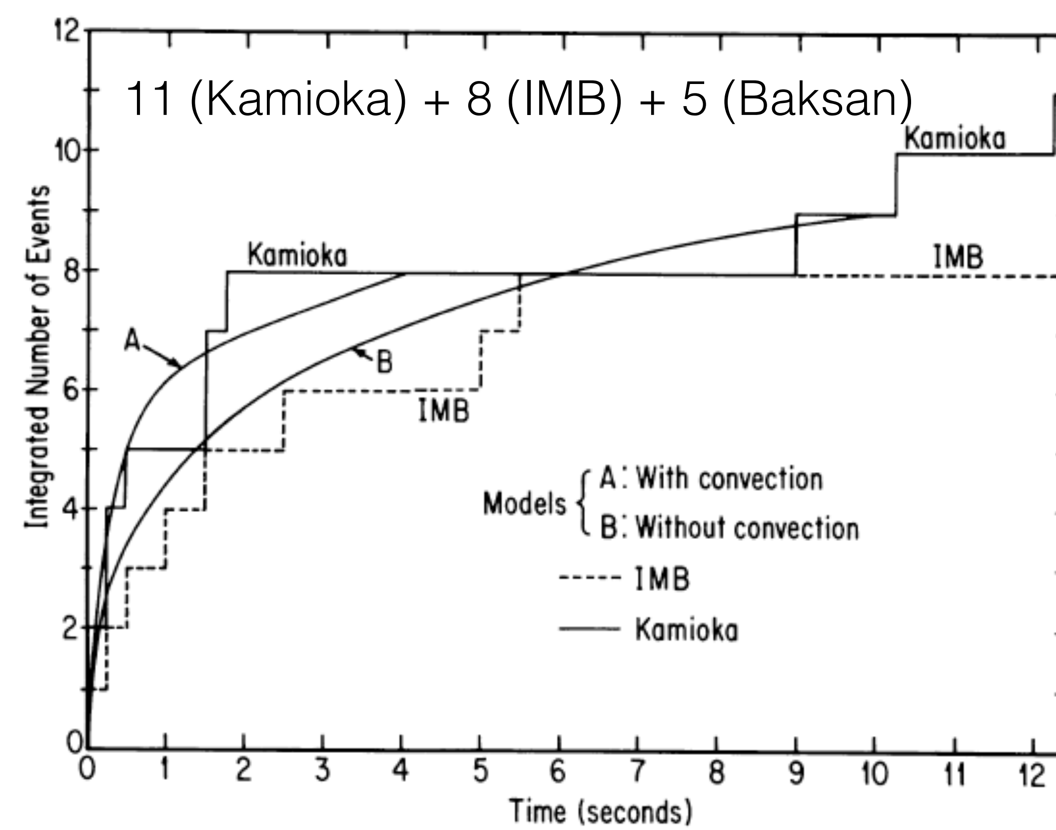
small number: sensitive to details

Delayed Neutrino Mechanism: Evidence

Evidence for the delayed neutrino mechanism comes from **SN 1987A**, the closest core-collapse supernova in the modern era, and the first multi-messenger astrophysical source (after the Sun)

SN 1987A (ESO)

A total of 24 neutrinos were detected, with a timing consistent with what is expected from the delayed neutrino mechanism (a few hours before electromagnetic detection when the shock breaks out of the stellar surface).



Burrows & Lattimer (1987)

Supernovae in Binary Systems

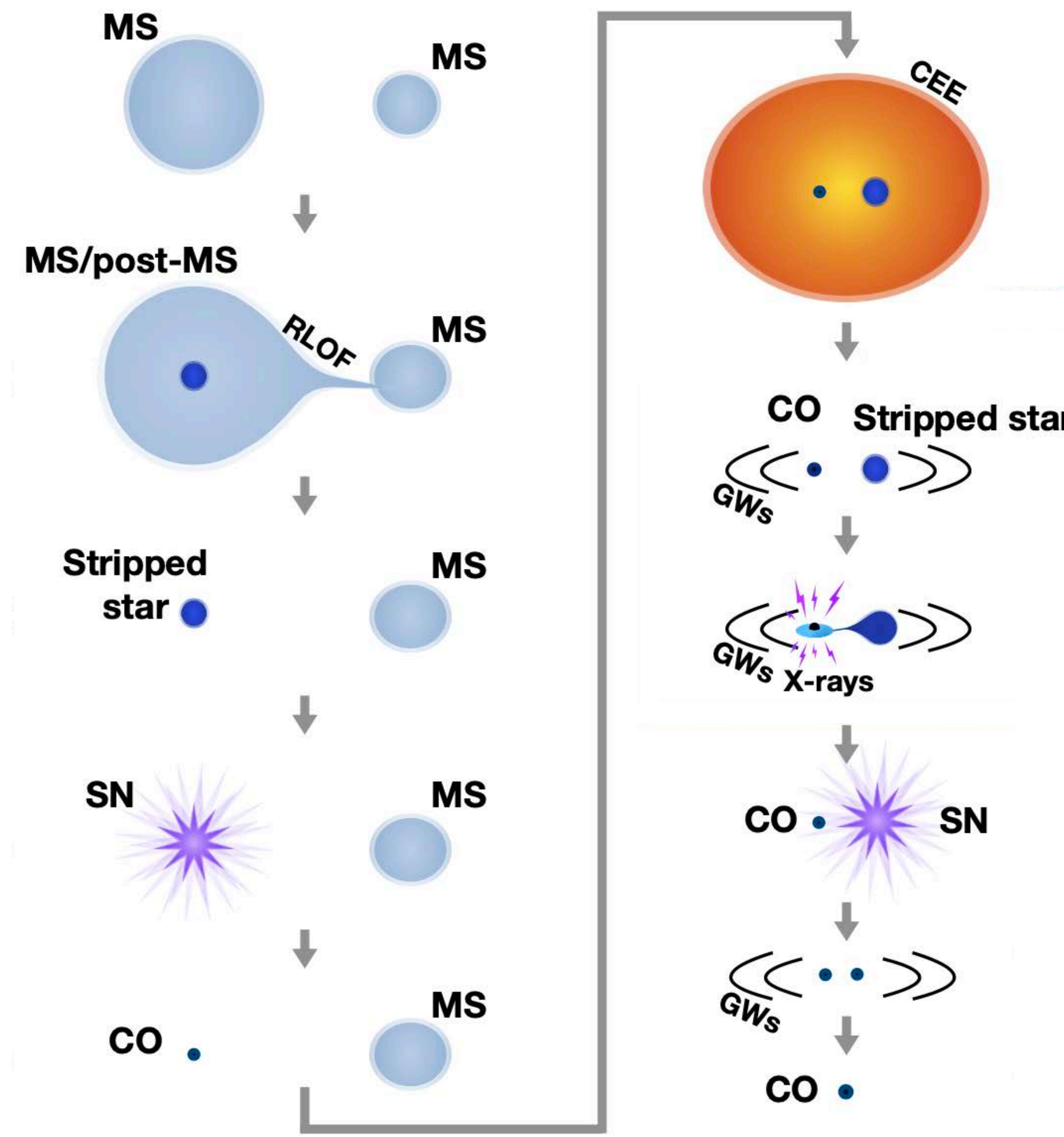
Significant fraction of massive stars live in binary systems

(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)



Götberg et al. (2020)

Double Neutron Star Systems

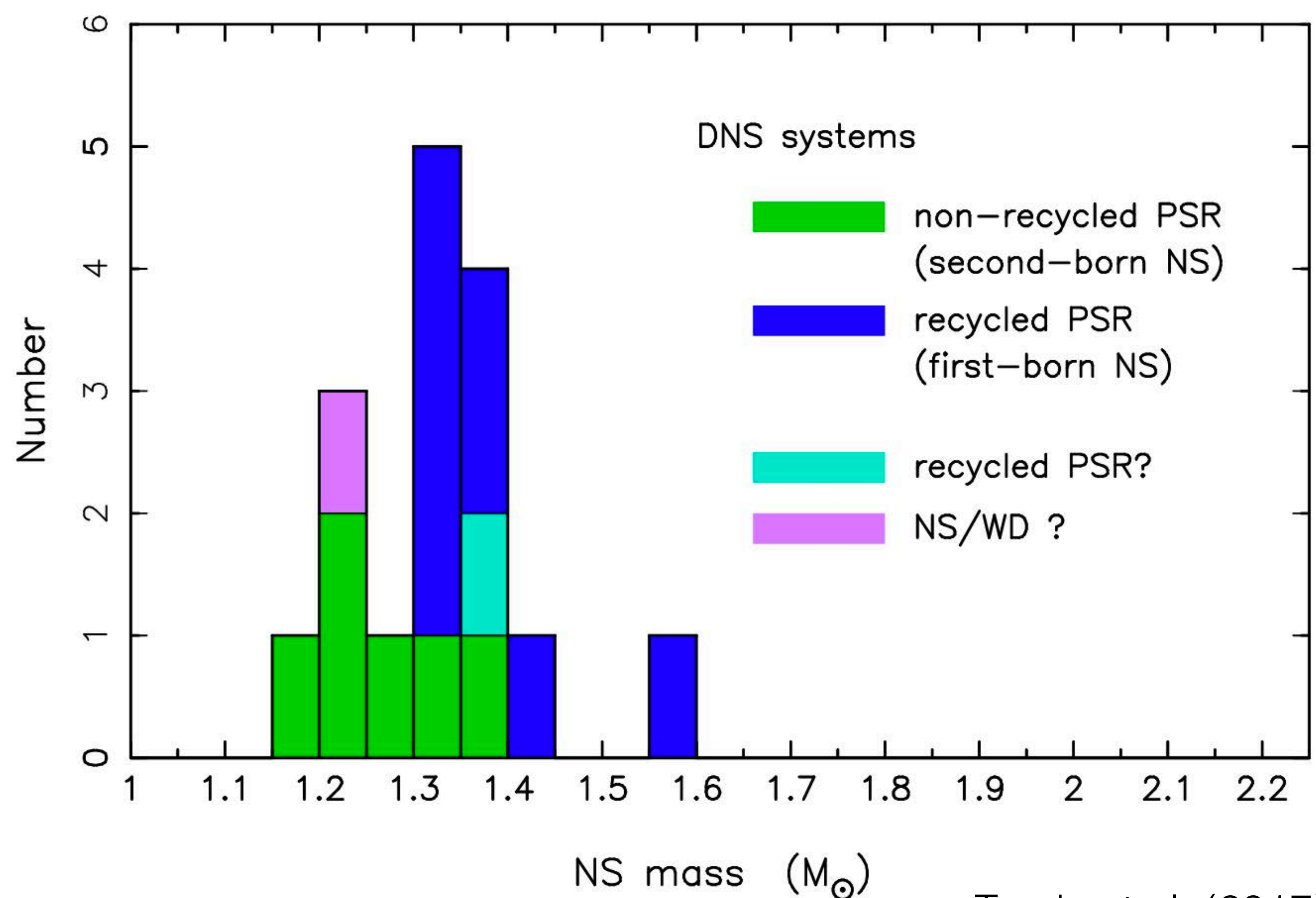
We know of at least 12 double NS (DNS) binary systems in the Milky Way, with 3 more that could also be WD-NS systems.

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}.

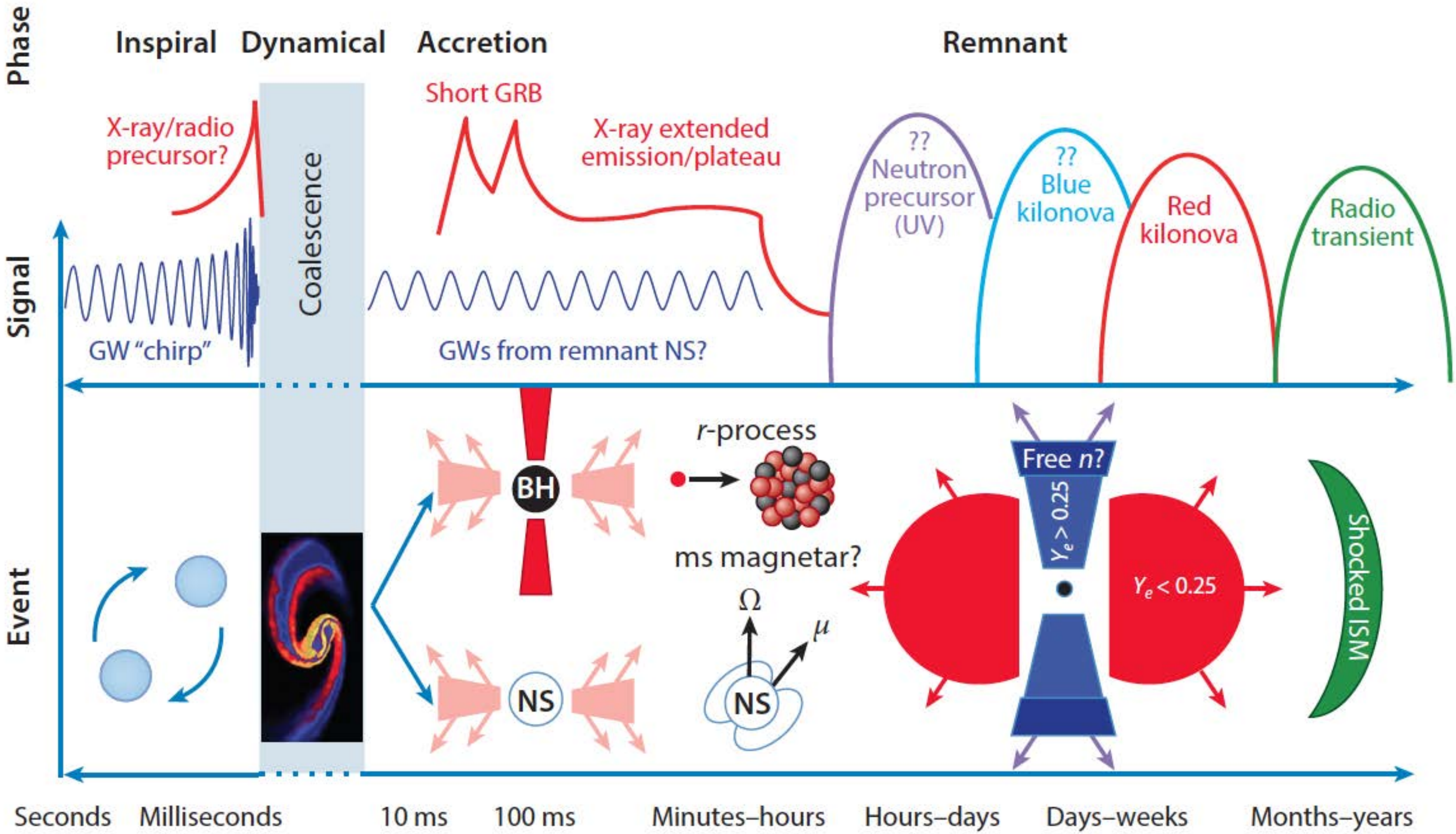
$$\tau_{\rm GW} = \frac{5}{64}\frac{a^4}{\mu M^2} = \frac{5}{64}\frac{a^4}{q(1+q)M_1^3}$$
$$= 2.2\times 10^8 q^{-1}(1+q)^{-1}\left(\frac{a}{R_\odot}\right)^4\left(\frac{M_1}{1.4\,M_\odot}\right)^{-3}\ \mathrm{yr}$$

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:

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

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

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

$$\downarrow$$

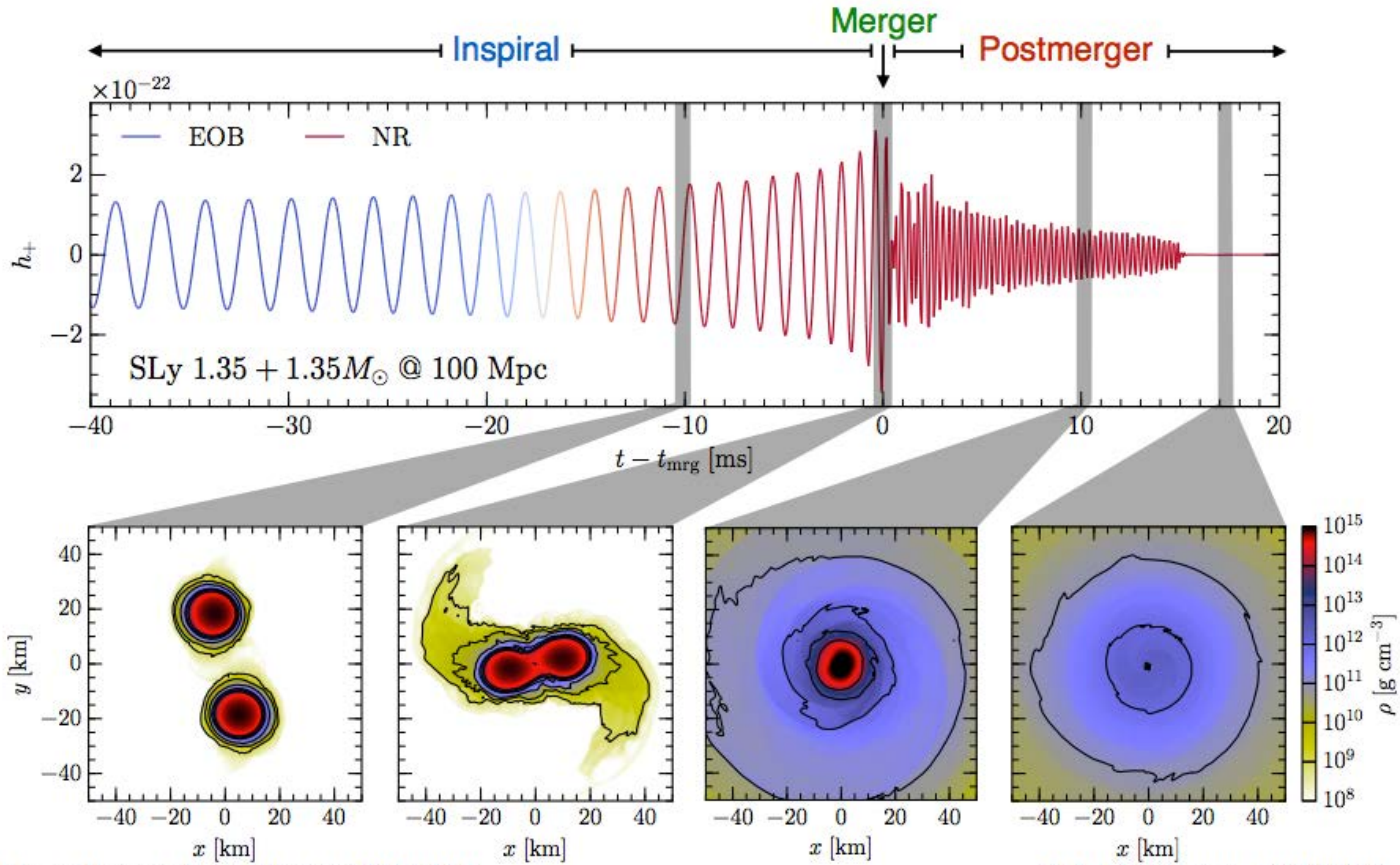
$$kT_{\mathrm{vir}} \sim 100\ \mathrm{MeV}$$

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

Inspiral Phase: Gravitational Waves



Slide from D. Radice

Radice et al. (2016)

Inspiral Phase: Gravitational Waves

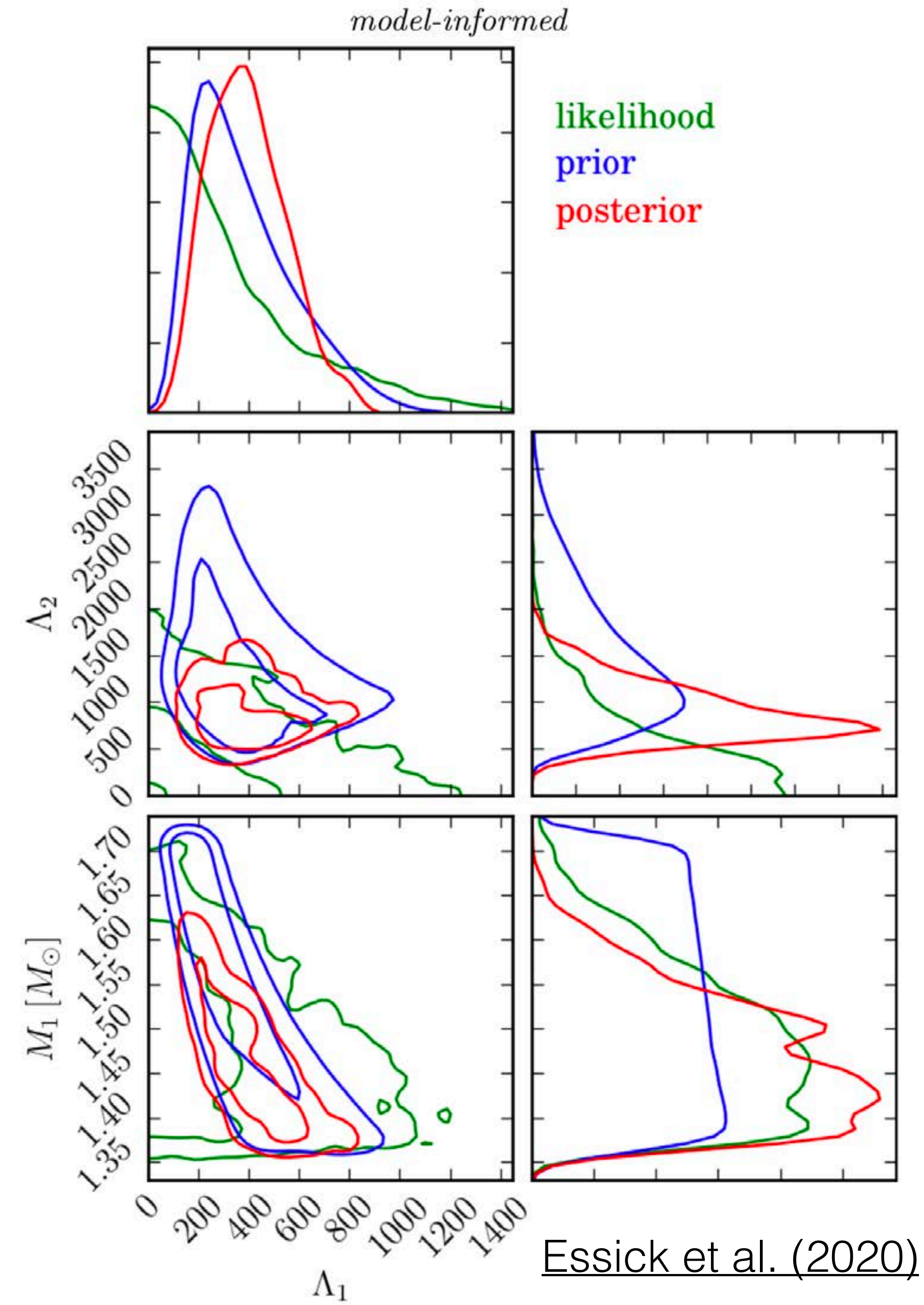
Ground-based interferometers are most sensitive to the inspiral phase, where GW signal is in the 100-1000 Hz range.

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)

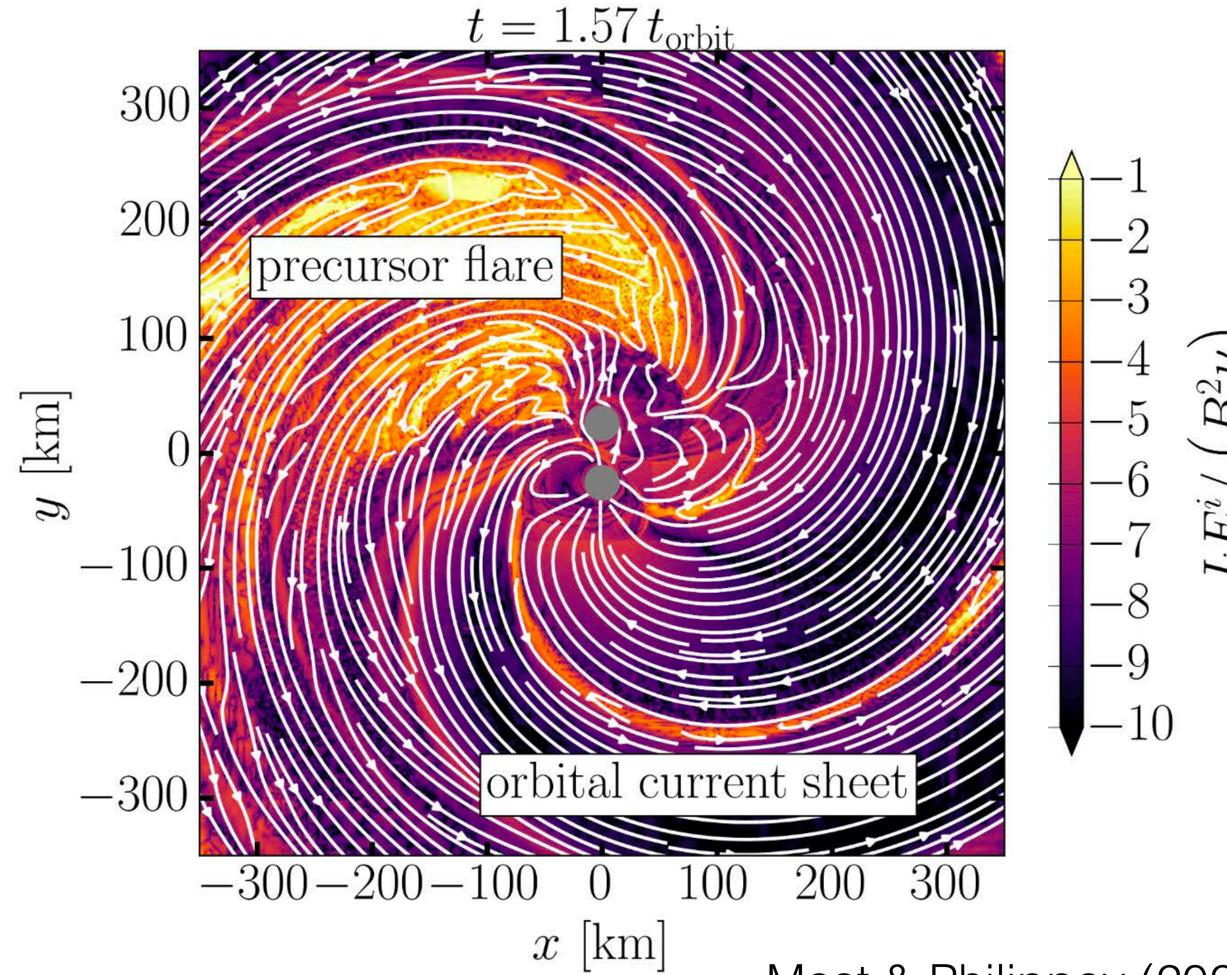
GW170817 yielded constraints on the tidal deformability parameter Λ of neutron stars, which constrains the EOS of neutron star matter.

Abbott et al. [LVC] (2017)



Essick et al. (2020)

Inspiral Phase: EM Precursors



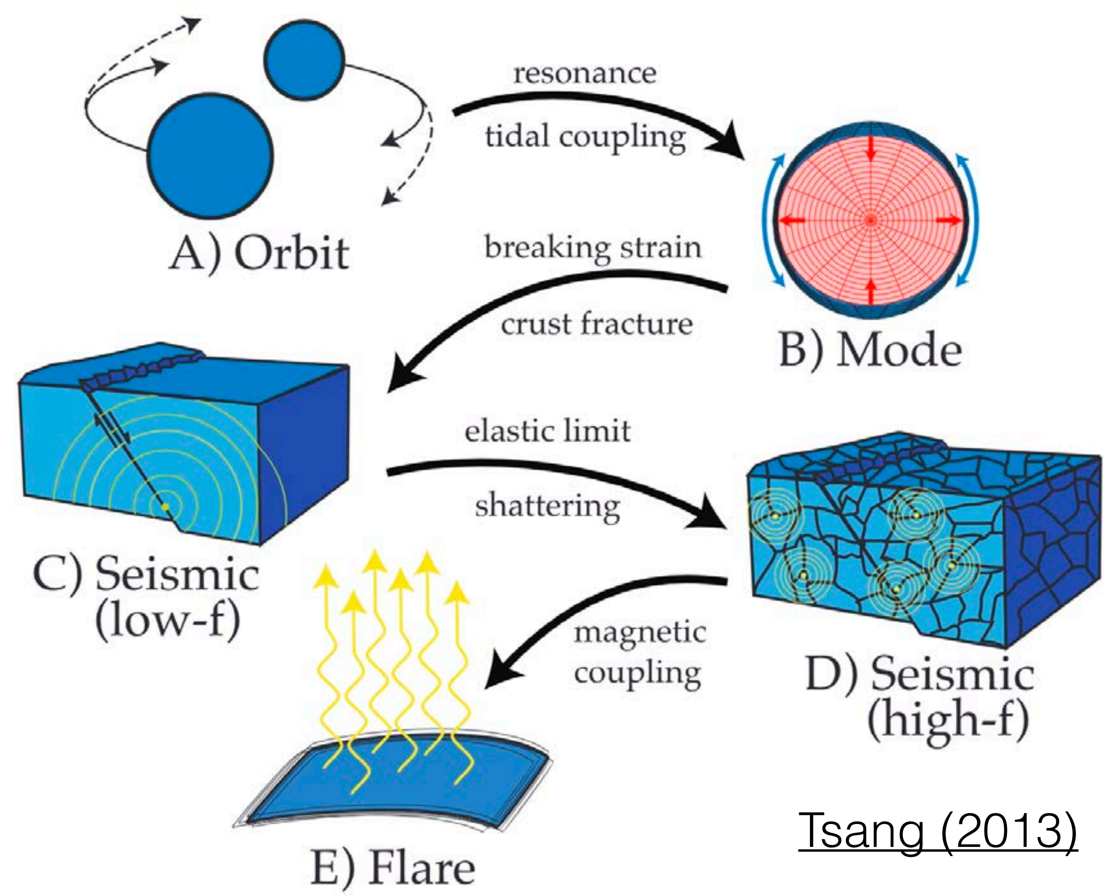
Most & Philippov (2022)

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

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

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)

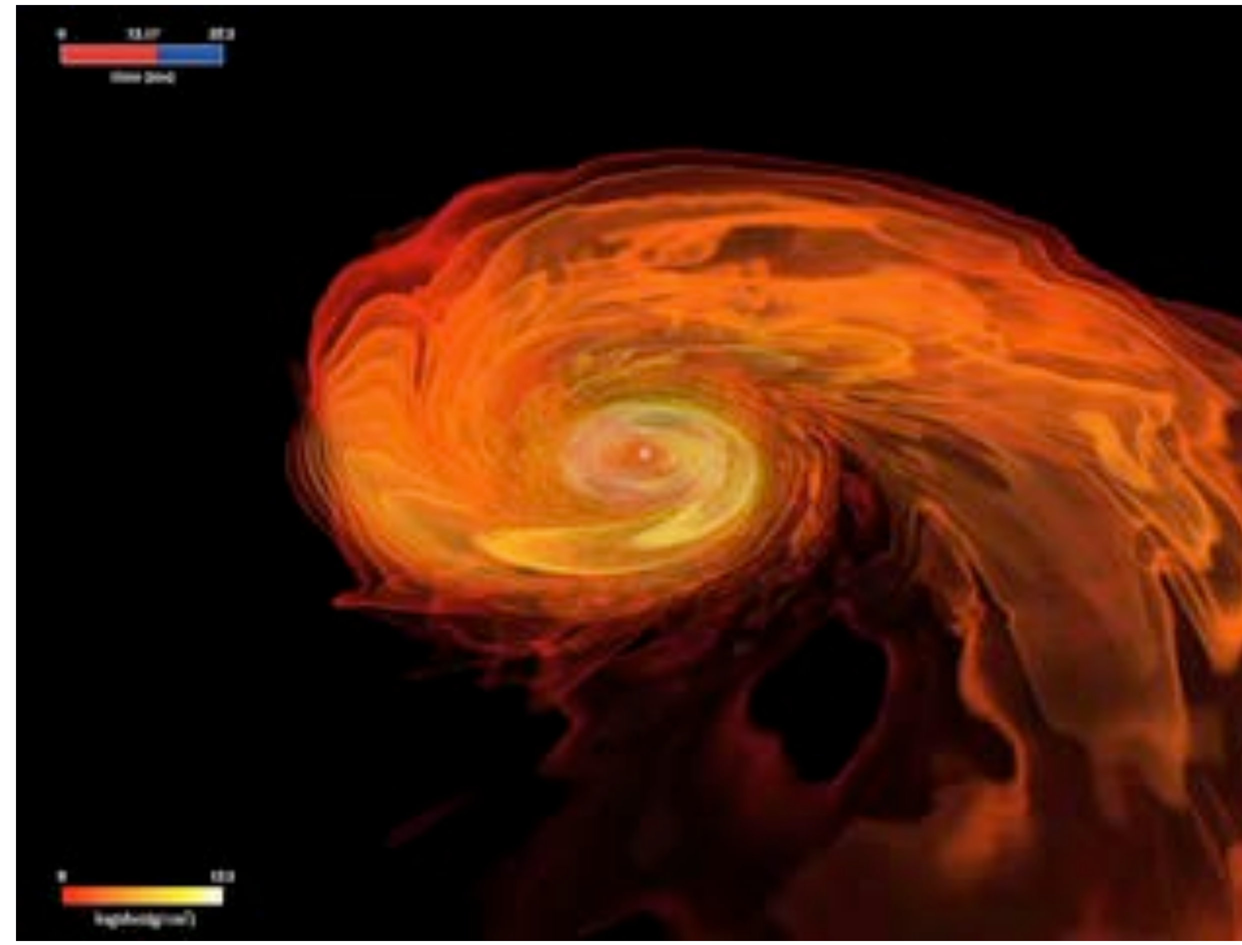
Dynamical Phase: Numerical Relativity

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**.

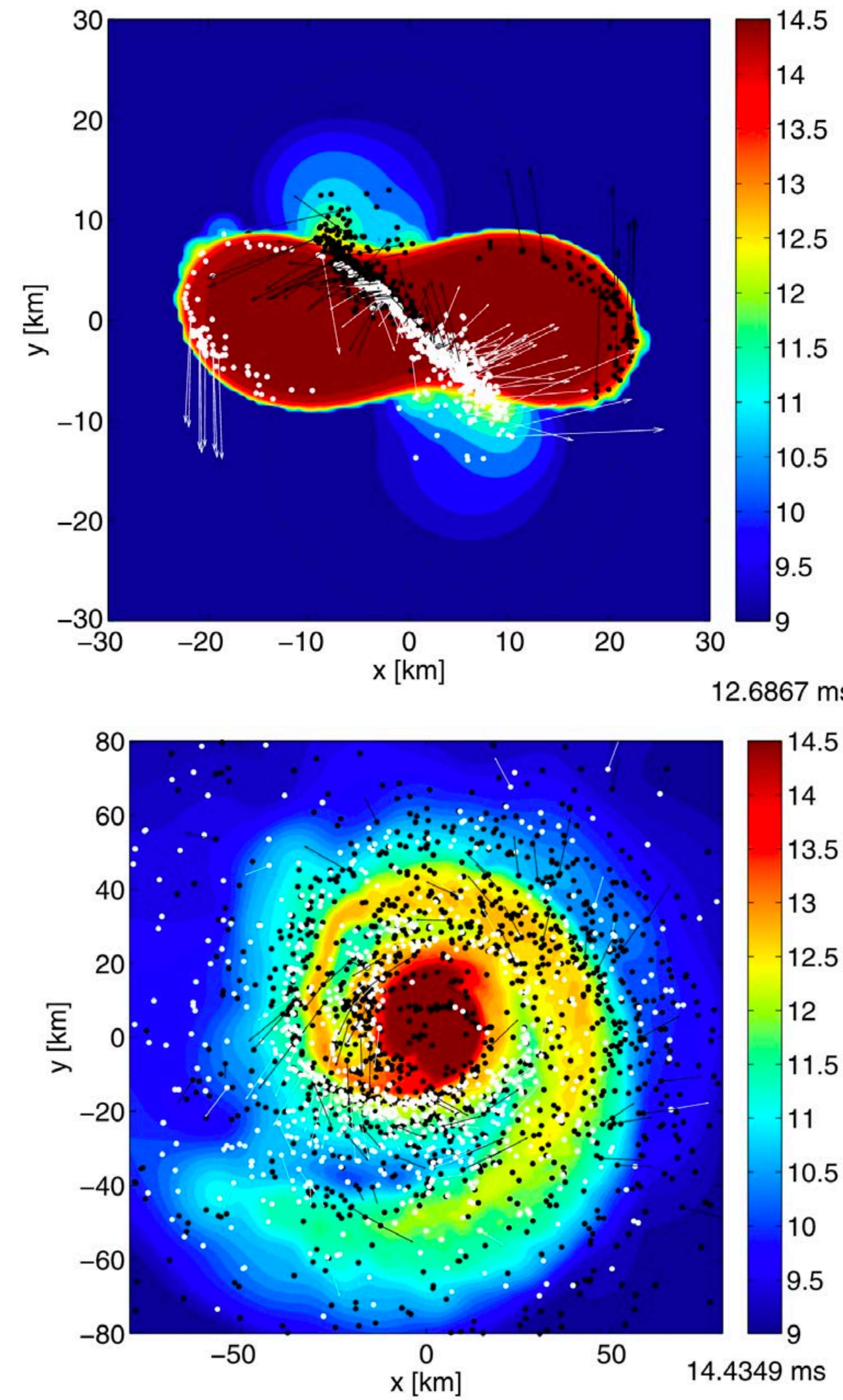
For NSNS mergers, there are two components:

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)

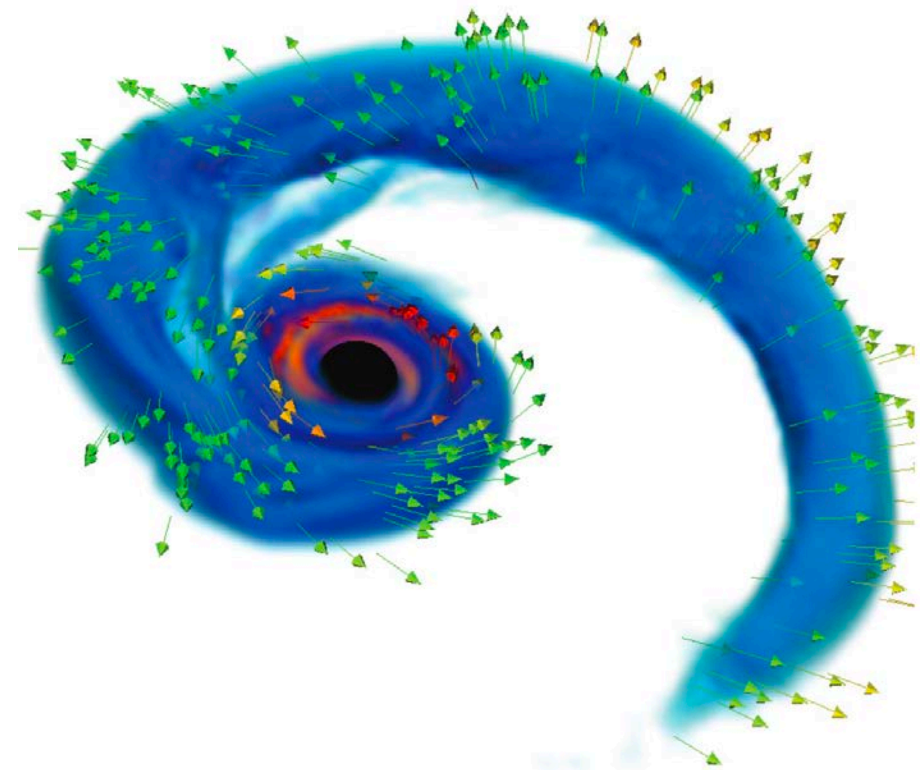


Bauswein et al. (2013)

Dynamical Phase: Mass Ejection

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

(e.g., Shibata & Taniguchi 2000)



Foucart et al. (2014)

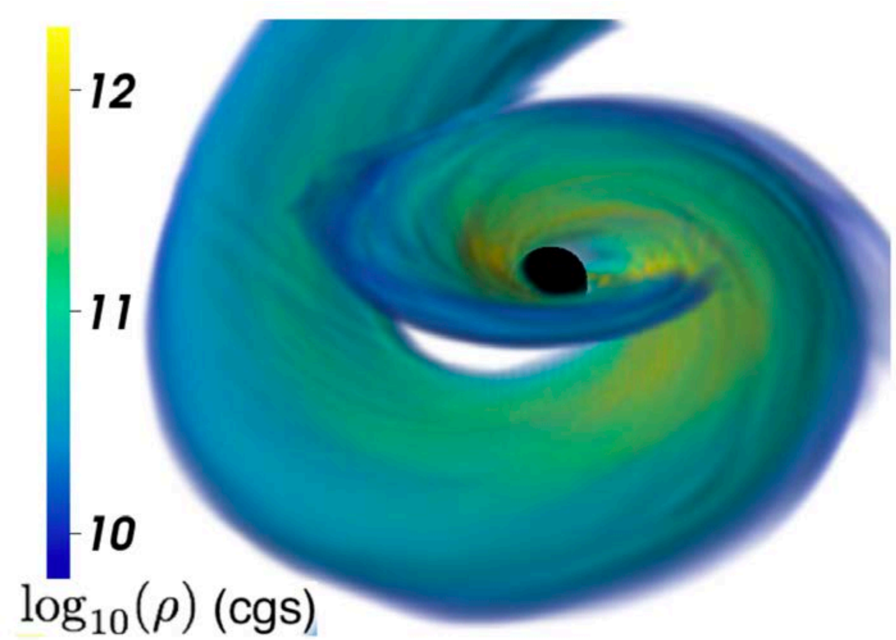
In addition, for BHNS systems there is a finite range in mass ratios and initial BH spins such that the NS is tidally disrupted and not swallowed.

Foucart et al. (2018)

Semianalytic formulae for mass ejection.

e.g., Krüger & Foucart (2020)

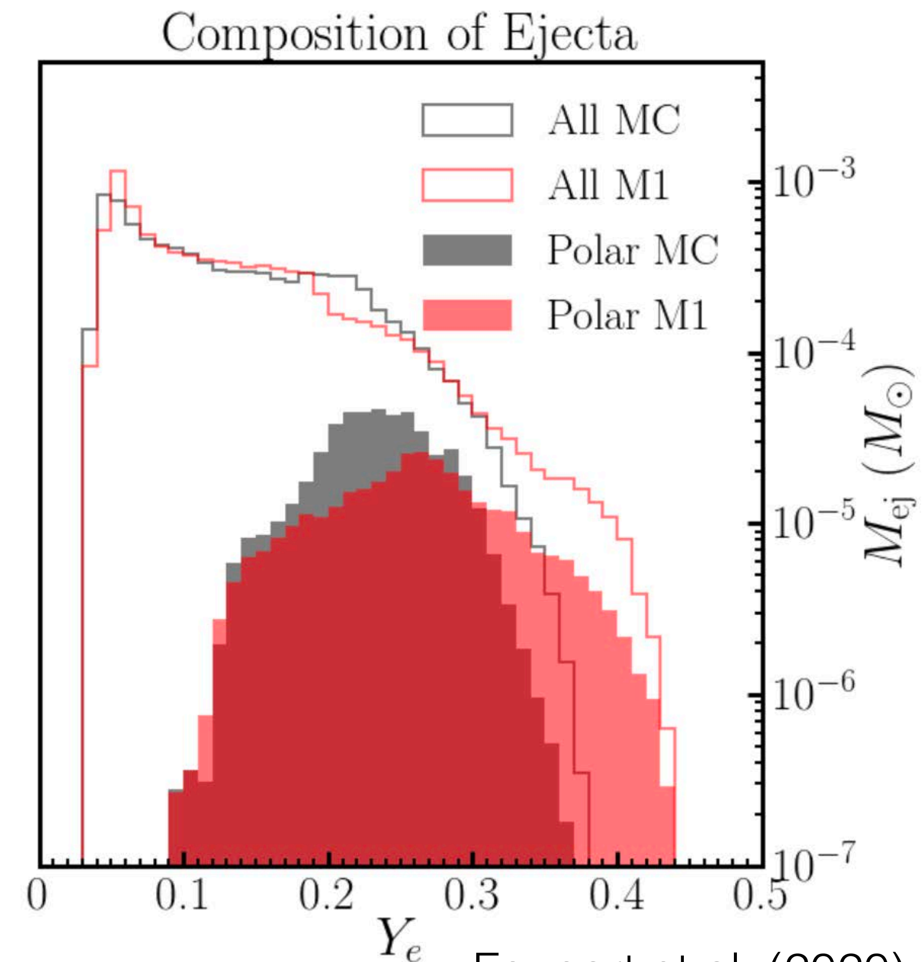
Additional complications include misalignment between BH spin and orbital spin (precession, etc.) →



Foucart et al. (2017)

Dynamical Phase: Mass Ejection

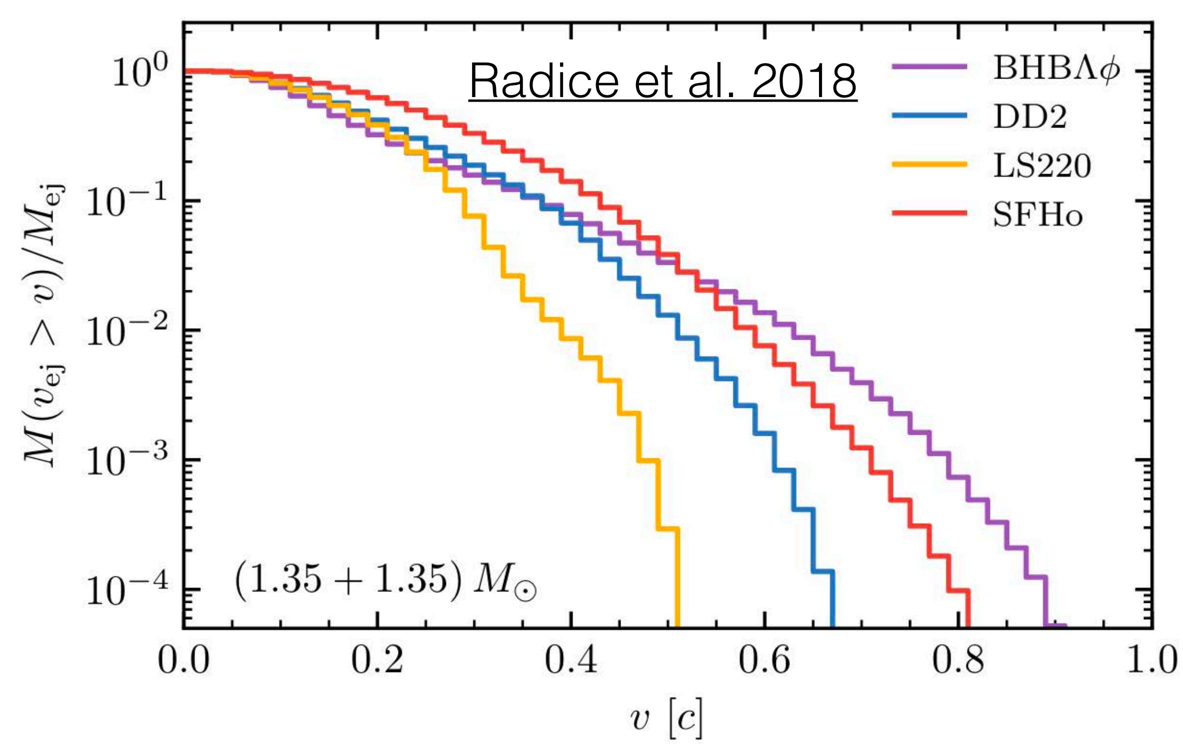
Not only the amount, but also the composition and velocity of the dynamical ejecta is important for EM counterpart predictions and nucleosynthesis calculations. **Ye definition**.



Foucart et al. (2020)

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.



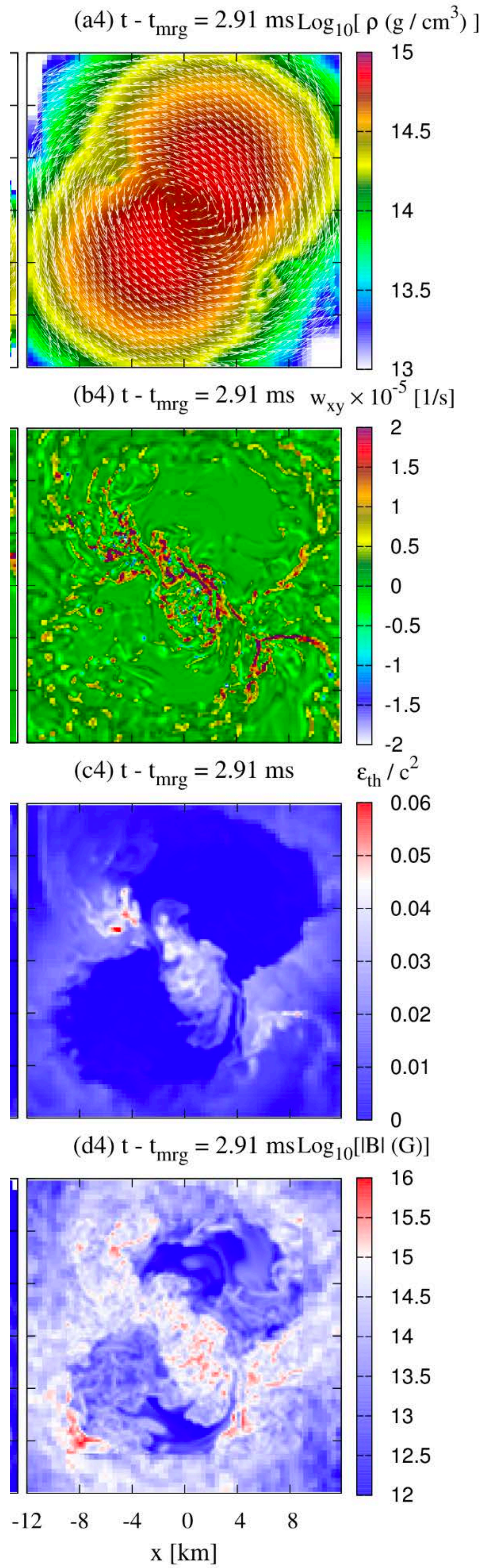
Dynamical Phase: Magnetic Field Amplification

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)