

Binary neutron star mergers: neutrinos, ejecta and kilonovae

Albino Perego

Trento University & TIFPA-INFN

August 01 2024

DTP/Talent School: "Nuclear Theory for Astrophysics"
questions? albino.perego@unitn.it

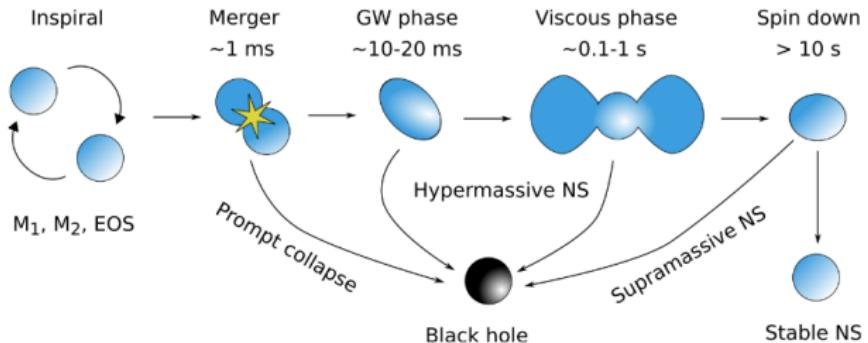


Outline

- ▶ An overview on BNS mergers
- ▶ Neutrinos in BNS merger
- ▶ Ejecta and nucleosynthesis from BNS mergers
- ▶ Kilonovae

A brief overview about BNS mergers

BNS merger in a nutshell: inspiral

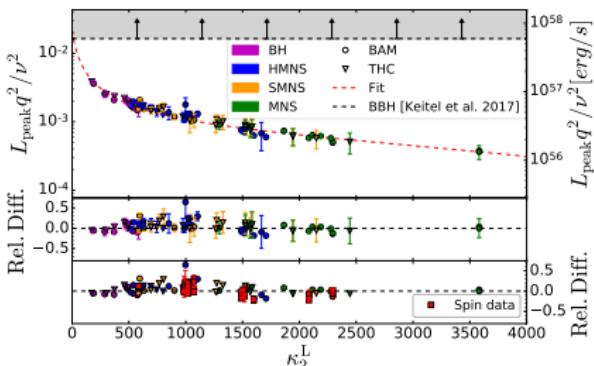


Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS, Bernuzzi 2020 for recent reviews

- ▶ driven by GW emission: GWs carry away energy and angular momentum

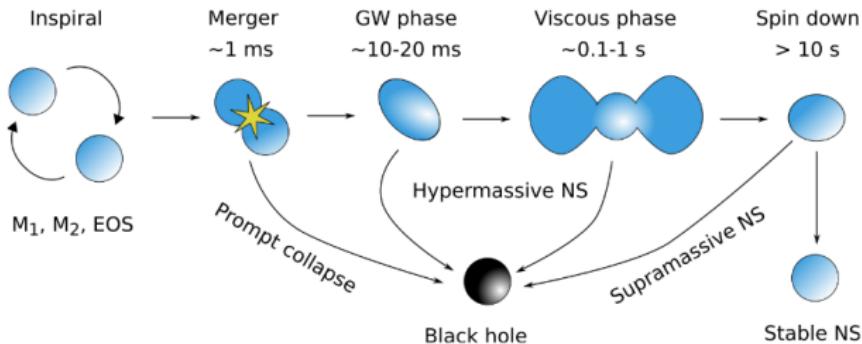
$$L_{\text{GW,peak}} \sim 10^{55} - 10^{56} \text{ erg/s}$$

- ▶ most relevant binary parameters: masses and EOS
- ▶ secondary parameters: spins, residual eccentricity, NS B field



Zappa et al PRL 2018

BNS merger in a nutshell: merger



Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS, Bernuzzi 2020 for recent reviews

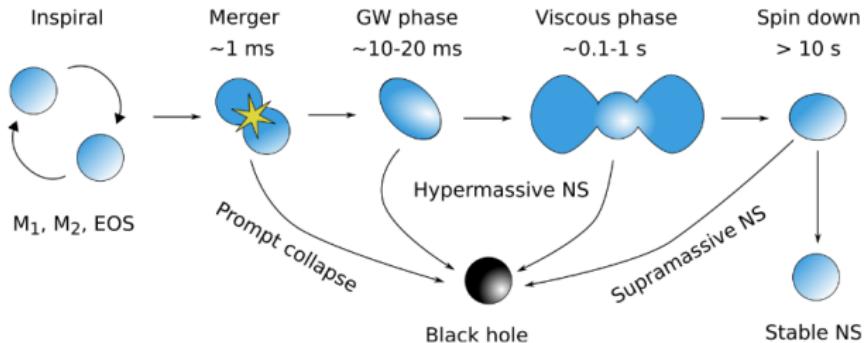
- ▶ speed at merger ($d = R_1 + R_2$)

$$\frac{v_{\text{orb}}}{c} \sim \frac{\Omega_{\text{Kep}} d}{c} \approx \sqrt{\frac{GM_{\text{tot}}}{c^2(R_1 + R_2)}}^q \stackrel{q \approx 1}{\approx} \sqrt{\mathcal{C}} \sim 0.39 \left(\frac{\mathcal{C}}{0.15} \right)^{1/2}$$

$$\frac{v_r}{c} \approx \frac{192\pi}{15} \frac{G^3 M_{\text{tot}}^3}{c^5 (R_1 + R_2)^5} \frac{q}{(1+q)^2} \stackrel{q \approx 1}{\approx} 0.034 \left(\frac{\mathcal{C}}{0.15} \right)^3$$

$$\left[\frac{v_r}{c} \sim \frac{2d}{3} \frac{\dot{\Omega}}{\Omega c} \quad \& \quad \dot{\Omega}_{\text{GW}}^3 = \frac{3456}{125} \left(\frac{G\mathcal{M}_c}{c^3} \right)^5 \Omega_{\text{GW}}^{11} \right]$$

BNS merger in a nutshell: merger



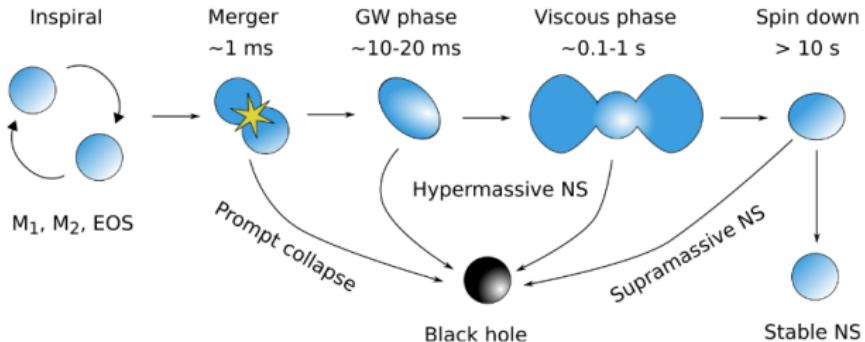
Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS, Bernuzzi 2020 for recent reviews

- ▶ dynamical timescales:

$$t_{\text{dyn,orb}} \sim \frac{1}{2f_{\text{GW,merger}}} \approx 1.50 \text{ ms} \left(\frac{M}{2.8M_\odot} \right)^{-3/2} \left(\frac{C}{0.15} \right)^{-1/2}$$

$$t_{\text{dyn,rad}} \sim \frac{R_{\text{rem}}}{c_s} \stackrel{R_{\text{rem}} = 2R_{\text{NS}}}{\approx} 0.4 \text{ ms} \left(\frac{R_{\text{NS}}}{12 \text{ km}} \right) \left(\frac{c_s}{0.2c} \right)$$

How hot is a merger remnant?



Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS, Bernuzzi 2020 for recent reviews

- ▶ kinetic NS energy \rightarrow remnant thermal energy
- ▶ efficient process, mediated by shock formation
- ▶ ξ : fraction of converted kinetic energy

$$\xi \left(\frac{1}{2} M v_{\text{orb}}^2 \right) \sim \frac{3}{2} N_{\text{bar}} k_B T_{\text{rem}} \quad \Rightarrow \quad k_B T_{\text{rem}} \sim 24 \text{ MeV} \left(\frac{\mathcal{C}}{0.15} \right) \left(\frac{\xi}{0.5} \right)$$

- ▶ hot nuclear matter \rightarrow copious neutrino production

$$L_{\nu, \text{peak}} \sim 10^{53} \text{ erg/s}$$

BNS mergers on thermodynamics diagrams

Which are the thermodynamics conditions of matter during the merger?

Perego,Bernuzzi,Radice 2019 EPJ A 2019

movies at www.youtube.com/channel/UChmn-JGNa9mfY5H5938jnig

BNS mergers on thermodynamics diagrams

Which are the thermodynamics conditions of matter during the merger?

Perego,Bernuzzi,Radice 2019 EPJ A 2019

movies at www.youtube.com/channel/UChmn-JGNa9mfY5H5938jnig

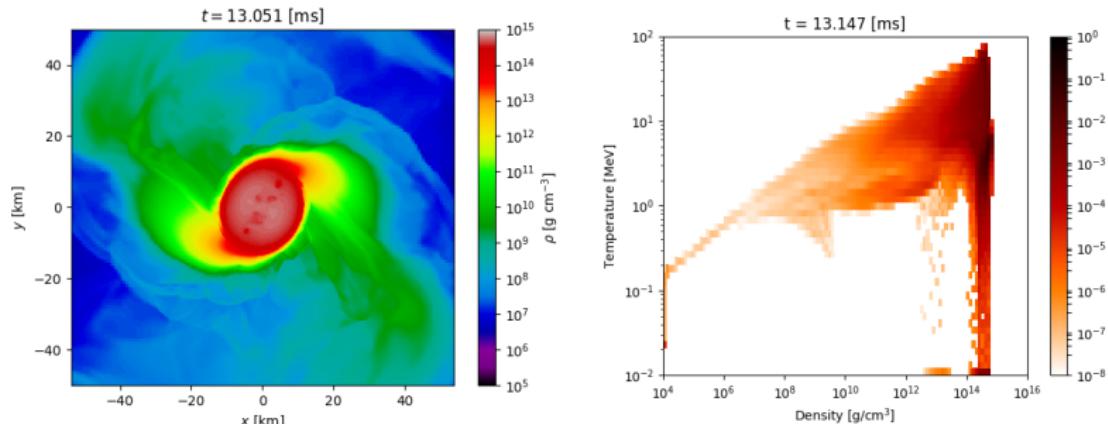
BNS simulation performed with the WhiskyTHC code

Radice+ 12,14,15

$$M_1 = M_2 = 1.364 M_{\odot}$$

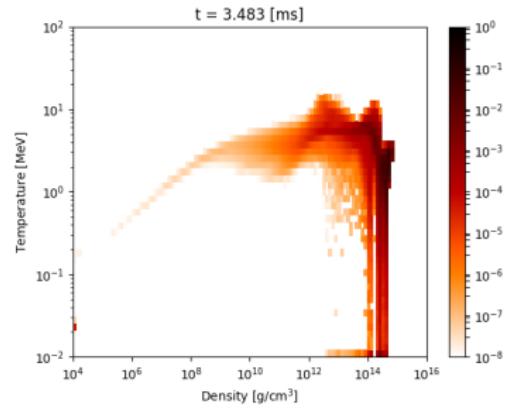
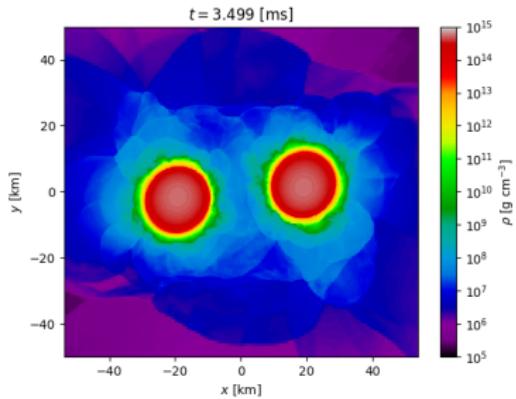
DD2 EOS, leakage+M0 scheme for neutrinos

at each time, mass weighted histograms in the ρ - T - Y_e or ρ - s - Y_e plane

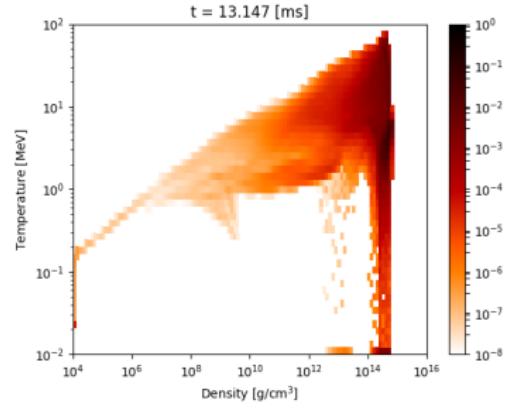
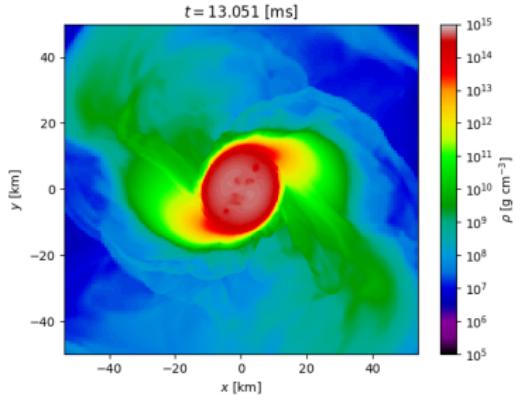


BNS mergers on thermodynamics diagrams II

inspiral

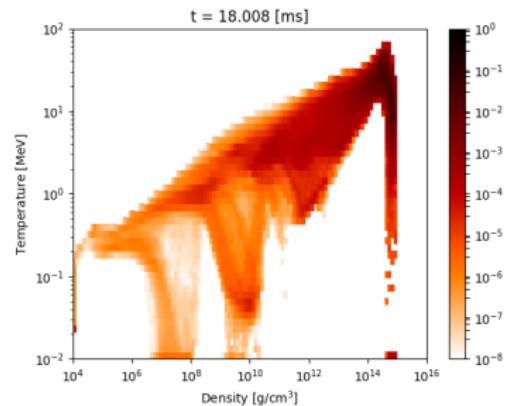
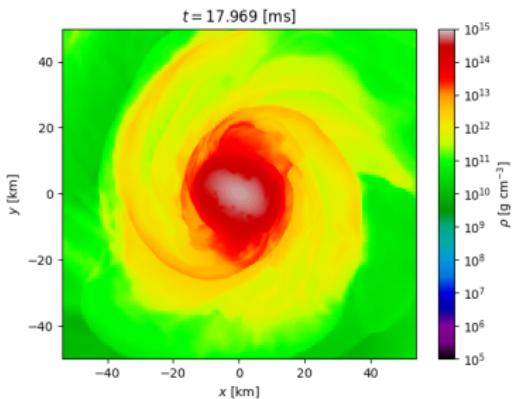


$t(T_{\text{peak}})$

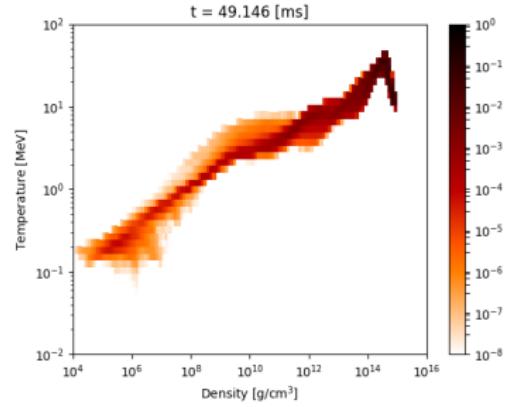
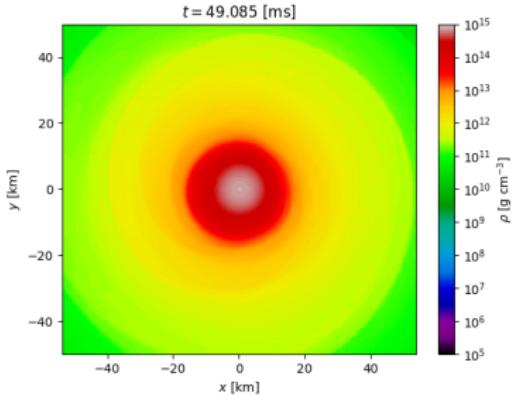


BNS mergers on thermodynamics diagrams III

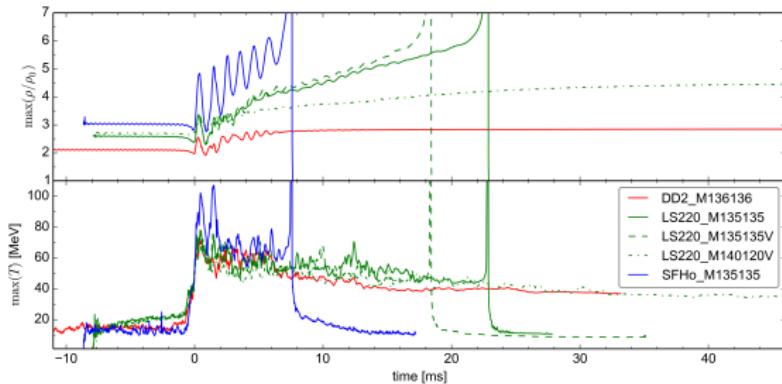
$$t \gtrsim t_{\text{dyn}}$$



$$t \gg t_{\text{dyn}}$$

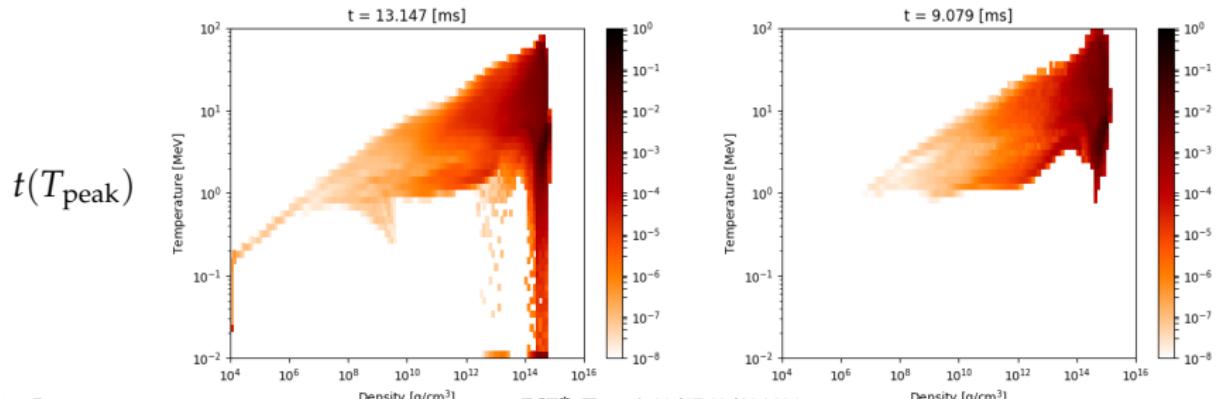


Thermodynamics diagrams: soft VS stiff EOS

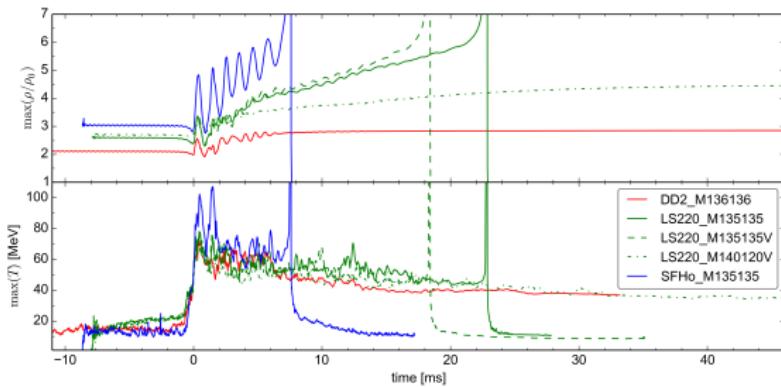


HS(DD2) (stiff),
 $M_1 = M_2 = 1.364M_\odot$

SFHo (soft), $M_1 = M_2 = 1.35M_\odot$



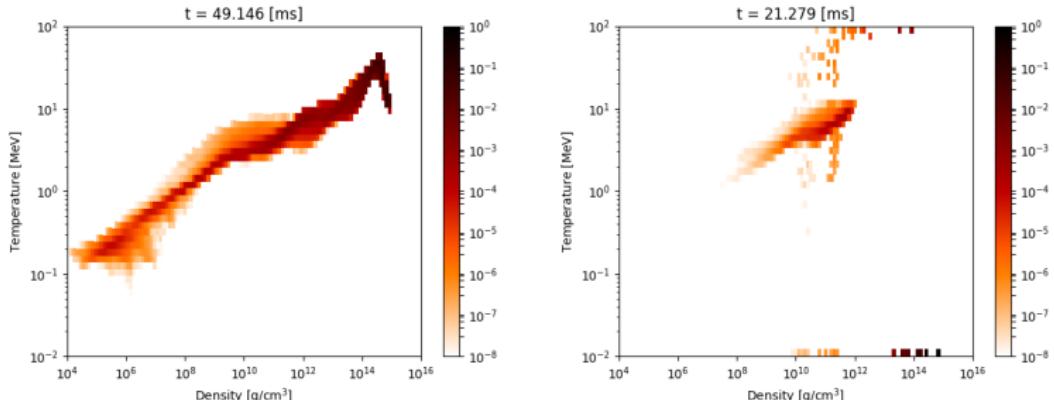
Thermodynamics diagrams: soft VS stiff EOS



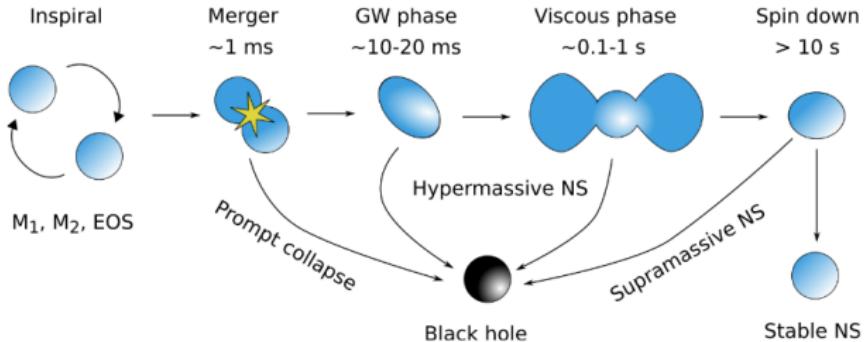
DD2 EOS (stiff)

SFHo EOS (soft)

$t \gg t_{\text{dyn}}$



BNS merger in a nutshell: GW-dominated phase



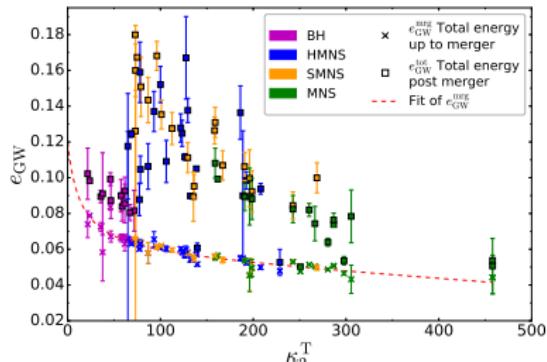
Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS, Bernuzzi 2020 for recent reviews

- GW emission from deformed, rotating remnant
- magnetic field amplification, disk formation, neutrino emission

$$L_{\text{GW}} \sim 10^{55} \text{ erg/s}$$

$$\Delta E_{\text{GW}} \sim 2 \times 10^{53} \text{ erg} \left(\frac{\langle L_{\text{GW}} \rangle}{10^{55} \text{ erg/s}} \right) \left(\frac{t_{\text{GW}}}{20 \text{ ms}} \right)$$

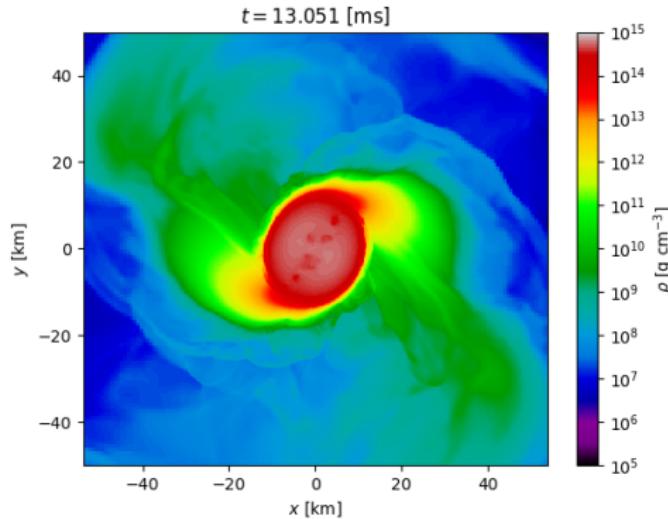
$$\sim 0.11 M_{\odot} c^2 \left(\frac{\langle L_{\text{GW}} \rangle}{10^{55} \text{ erg/s}} \right) \left(\frac{t_{\text{GW}}}{20 \text{ ms}} \right)$$



BNS merger in a nutshell: core remnant dynamics

remnant: out of equilibrium, self-gravitating, fast rotating object

- ▶ fusion of two cold (i.e. low entropy) NS cores
 - ▶ fusion timescale: several t_{dyn}
 - ▶ gravity compression VS nuclear repulsion (Pauli & short range force)
- ▶ squeezing and compression of matter at contact interface → decompression & expansion of hot nuclear matter

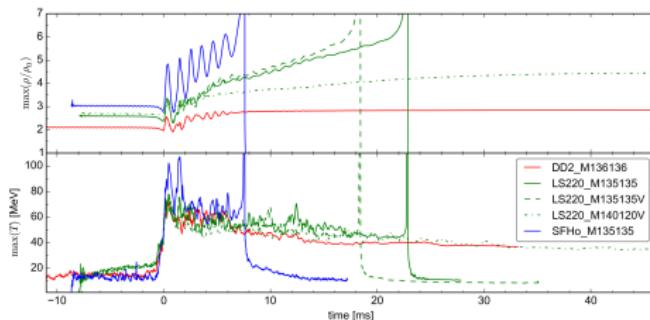


BNS merger in a nutshell: core remnant dynamics

remnant: out of equilibrium, self-gravitating, fast rotating object

- ▶ fusion of two cold (i.e. low entropy) NS cores
 - ▶ fusion timescale: several t_{dyn}
 - ▶ gravity compression VS nuclear repulsion (Pauli & short range force)
- ▶ squeezing and compression of matter at contact interface → decompression & expansion of hot nuclear matter

- ▶ core bounces
- ▶ hot spots → hot ring
- ▶ differential rotation: slowly rotating core ($\sim 1\text{kHz}$) & fast envelope ($\sim 2\text{kHz}$)

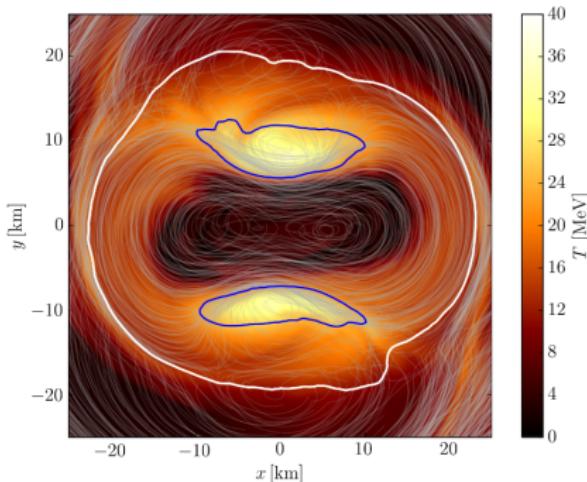


Perego+ EPJA, 55, 8 2019

BNS merger in a nutshell: core remnant dynamics

remnant: out of equilibrium, self-gravitating, fast rotating object

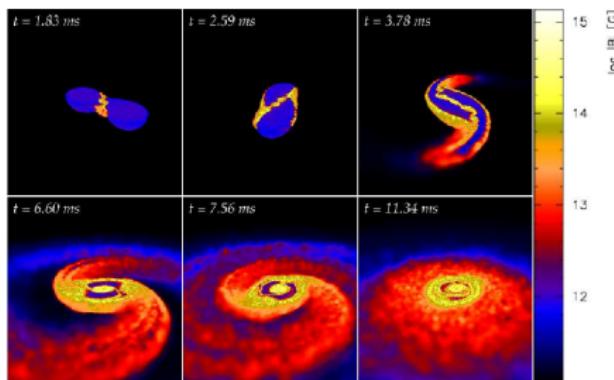
- ▶ fusion of two cold (i.e. low entropy) NS cores
 - ▶ fusion timescale: several t_{dyn}
 - ▶ gravity compression VS nuclear repulsion (Pauli & short range force)
- ▶ squeezing and compression of matter at contact interface → decompression & expansion of hot nuclear matter



- ▶ core bounces
- ▶ hot spots → hot ring
- ▶ differential rotation: slowly rotating core ($\sim 1\text{kHz}$) & fast envelope ($\sim 2\text{kHz}$)

BNS merger in a nutshell: disk formation

- ▶ tidal tails
- ▶ hot matter ejection
- ▶ angular momentum conservation
- ⇒ accretion disk formation
- ▶ what is the disk?
 - ▶ BH+torus: $\rho_{\text{torus}} \lesssim 10^{12} \text{ g/cm}^3$
 - ▶ MNS+disk: $\rho_{\text{disk}} \lesssim 10^{13} \text{ g/cm}^3$
- ▶ formation process:
 $t_{\text{form}} \sim 10 - 20 \text{ ms}$ several $t_{\text{dyn,orb}}$
- ▶ BH formation:
more than 50% of disk
immediately shallowed by BH

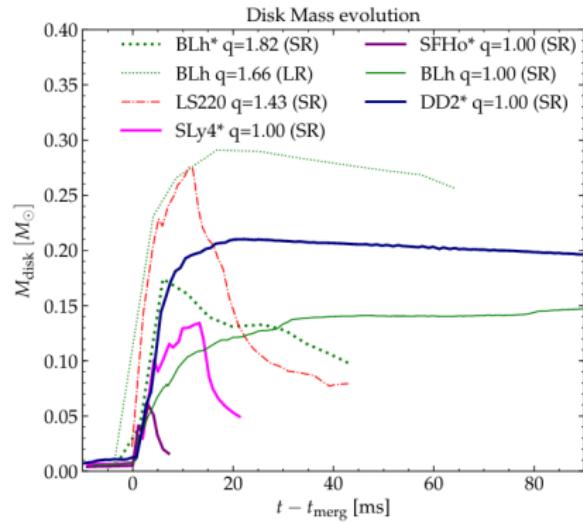


Price & Rosswog+ Science ,2006

BNS merger in a nutshell: disk formation

- ▶ tidal tails
 - ▶ hot matter ejection
 - ▶ angular momentum conservation
- ⇒ accretion disk formation

- ▶ what is the disk?
 - ▶ BH+torus: $\rho_{\text{torus}} \lesssim 10^{12} \text{ g/cm}^3$
 - ▶ MNS+disk: $\rho_{\text{disk}} \lesssim 10^{13} \text{ g/cm}^3$
- ▶ formation process:
 $t_{\text{form}} \sim 10 - 20 \text{ ms}$ several $t_{\text{dyn,orb}}$
- ▶ BH formation:
more than 50% of disk immediately shallowed by BH



Nedora+ ApJ 906, 2, 2021

BNS merger in a nutshell: disk properties

- ▶ (possibly) massive:

$$M_{\text{disk}} \sim 10^{-5} M_{\odot} - \text{a few } 0.1 M_{\odot}$$

- ▶ typical lengthscale

$$R_{\text{disk}} \sim \text{several } 100 \text{ km}$$

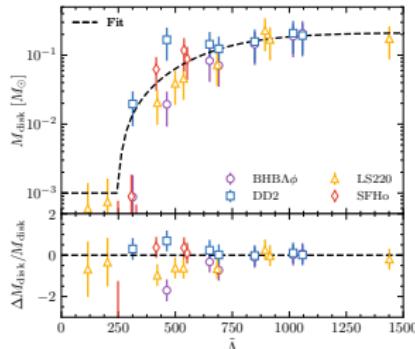
- ▶ thick disks:

$$\frac{H}{R} \sim \frac{c_s}{v_{\text{orb}}} \sim 0.2 - 0.7$$

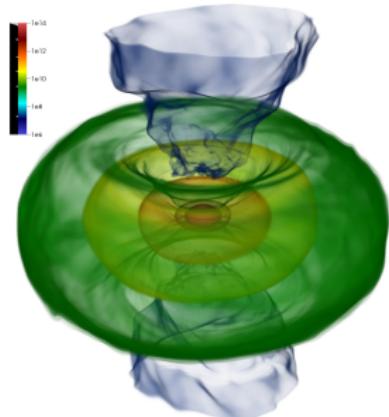
- ▶ fix ratio between J_{disk} and M_{disk}

- ▶ $J_{\text{disk}} \sim 7 - 10 \frac{G}{c} M_{\odot} M_{\text{disk}}$
- ▶ constant specific angular momentum:

$$\frac{j}{\rho} \approx \text{const} = 3.5 - 5 \times 10^{16} \text{ cm}^2 \text{s}^{-1}$$



Radice+ ApJ 2018



Perego,Bernuzzi,Radice EPJA 2019

BNS merger in a nutshell: disk properties

- ▶ (possibly) massive:

$$M_{\text{disk}} \sim 10^{-5} M_{\odot} - \text{a few } 0.1 M_{\odot}$$

- ▶ typical lengthscale

$$R_{\text{disk}} \sim \text{several } 100 \text{ km}$$

- ▶ thick disks:

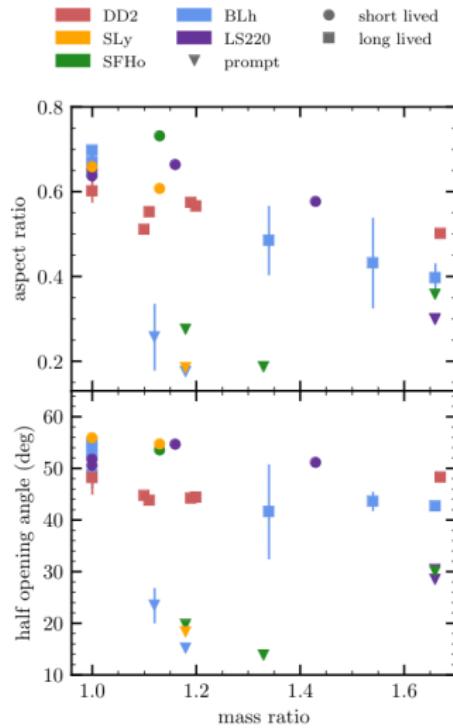
$$\frac{H}{R} \sim \frac{c_s}{v_{\text{orb}}} \sim 0.2 - 0.7$$

- ▶ fix ratio between J_{disk} and M_{disk}

- ▶ $J_{\text{disk}} \sim 7 - 10 \frac{G}{c} M_{\odot} M_{\text{disk}}$

- ▶ constant specific angular momentum:

$$\frac{j}{\rho} \approx \text{const} = 3.5 - 5 \times 10^{16} \text{ cm}^2 \text{s}^{-1}$$



BNS merger in a nutshell: disk properties

- ▶ (possibly) massive:

$$M_{\text{disk}} \sim 10^{-5} M_{\odot} - \text{a few } 0.1 M_{\odot}$$

- ▶ typical lengthscales

$$R_{\text{disk}} \sim \text{several } 100 \text{ km}$$

- ▶ thick disks:

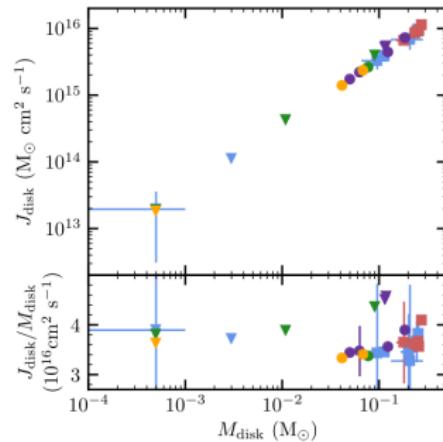
$$\frac{H}{R} \sim \frac{c_s}{v_{\text{orb}}} \sim 0.2 - 0.7$$

- ▶ fix ratio between J_{disk} and M_{disk}

- ▶ $J_{\text{disk}} \sim 7 - 10 \frac{G}{c} M_{\odot} M_{\text{disk}}$

- ▶ constant specific angular momentum:

$$\frac{j}{\rho} \approx \text{const} = 3.5 - 5 \times 10^{16} \text{ cm}^2 \text{s}^{-1}$$



BNS merger in a nutshell: disk properties

- ▶ (possibly) massive:

$$M_{\text{disk}} \sim 10^{-5} M_{\odot} - \text{a few } 0.1 M_{\odot}$$

- ▶ typical lengthscales

$$R_{\text{disk}} \sim \text{several } 100 \text{ km}$$

- ▶ thick disks:

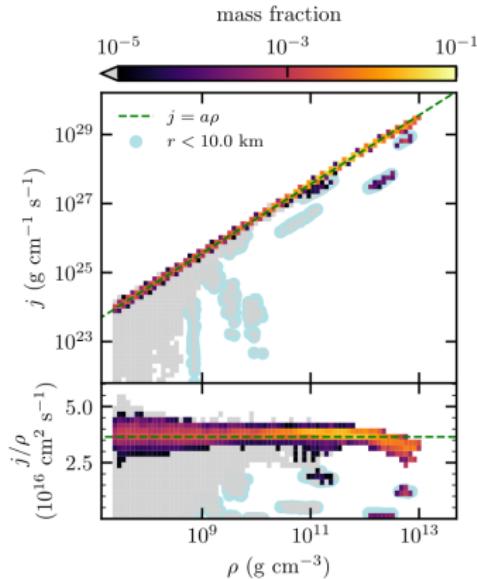
$$\frac{H}{R} \sim \frac{c_s}{v_{\text{orb}}} \sim 0.2 - 0.7$$

- ▶ fix ratio between J_{disk} and M_{disk}

- ▶ $J_{\text{disk}} \sim 7 - 10 \frac{G}{c} M_{\odot} M_{\text{disk}}$

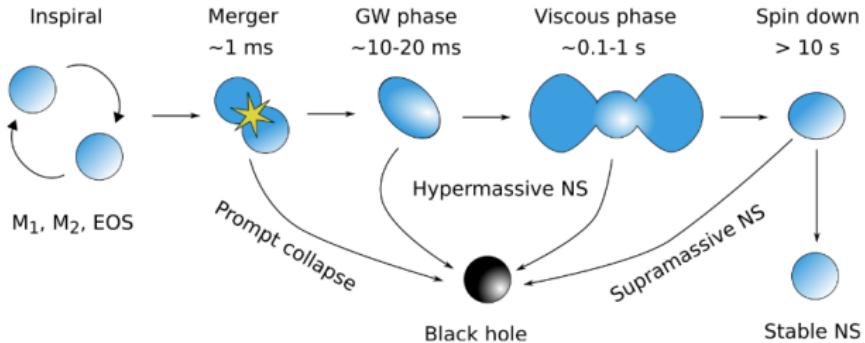
- ▶ constant specific angular momentum:

$$\frac{j}{\rho} \approx \text{const} = 3.5 - 5 \times 10^{16} \text{ cm}^2 \text{s}^{-1}$$



Camilletti et al MNRAS 2023

BNS merger in a nutshell: viscous phase

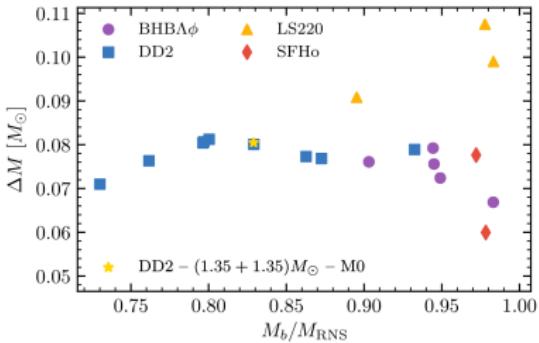


Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS, Bernuzzi 2020 for recent reviews

- viscous phase: MHD viscosity + ν emission + nuclear recombination

$$\Delta E_\nu \sim 5 \times 10^{52} \text{ erg} \left(\frac{\langle L_\nu \rangle}{5 \times 10^{52} \text{ erg/s}} \right) \left(\frac{t_\nu}{1 \text{ s}} \right)$$

$$= 0.03 M_\odot c^2 \left(\frac{\langle L_\nu \rangle}{5 \times 10^{52} \text{ erg/s}} \right) \left(\frac{t_\nu}{1 \text{ s}} \right)$$



Neutrinos in BNS mergers

Kinetic theory description of neutrinos

- distribution function: $f(t, \mathbf{x}, \mathbf{p})$

$\frac{g_J f(t, \mathbf{x}, \mathbf{p}) d^3x d^3p}{h^3}$ number of particles inside a volume d^3x around \mathbf{x} , with momentum between \mathbf{p} and $\mathbf{p} + d\mathbf{p}$, at time t
 g_J , spin/helicity multiplicity

- particles in UR limit: $m_\nu c^2 \ll \omega$ and $\omega \approx pc$
- density of particles:

$$n(t, \mathbf{x}) = \frac{g_J}{h^3} \int f(\mathbf{x}, \mathbf{p}, t) d^3p = \frac{g_J}{h^3} \int_0^{+\infty} d\omega \omega^2 \int_{\Omega} d\Omega f(t, \mathbf{x}, \omega, \Omega)$$

- density of energy:

$$J(t, \mathbf{x}) = \frac{g_J}{h^3} \int \omega f(\mathbf{x}, \mathbf{p}, t) d^3p = \frac{g_J}{h^3} \int_0^{+\infty} d\omega \omega^3 \int_{\Omega} d\Omega f(t, \mathbf{x}, \omega, \Omega)$$

- stress tensor (pressure):

$$K^{ij}(t, \mathbf{x}) = \frac{g_J}{h^3} \int n^i n^j \omega f(\mathbf{x}, \mathbf{p}, t) d^3p = \frac{g_J}{h^3} \int_0^{+\infty} d\omega \omega^3 \int_{\Omega} d\Omega n^i n^j f(t, \mathbf{x}, \omega, \Omega)$$

Neutrino transport and moments

- ▶ time evolution of $f(x, p)$ → GR transport equation:

$$\frac{dx^\alpha}{d\tau} \frac{df}{dx^\alpha} + \frac{dp^\alpha}{d\tau} \frac{df}{dp^\alpha} = (-p_\mu x^\mu) S(f, p, x)$$

- ▶ decomposition of 4-momentum, ω : particle energy in fluid frame

$$\frac{dx^\alpha}{d\tau} = p^\alpha = \omega (u^\alpha + l^\alpha) \quad l^\alpha l_\alpha = 1 \quad l^\alpha u_\alpha = 0$$

- ▶ calculation of momenta of f :

$$J_{(\omega)} = \omega^3 \int f(\omega, \Omega, x) d\Omega \quad \text{spectral density of energy}$$

$$H_{(\omega)}^\alpha = \omega^3 \int l^\alpha f(\omega, \Omega, x) d\Omega \quad \text{spectral density of energy flux}$$

$$K_{(\omega)}^{\alpha\beta} = \omega^3 \int l^\alpha l^\beta f(\omega, \Omega, x) d\Omega \quad \text{spectral density of energy stress}$$

all evaluated in fluid frame

From energy dependent to energy integrated transport

- ▶ from spectral (energy-dependent) to gray (energy-integrated) quantities

$$X = \int_0^{+\infty} X_{(\omega)} d\omega$$

- ▶ stress-energy tensor in fluid frame

$$\begin{aligned} T_{\text{rad}}^{\alpha\beta} &= \int_0^{+\infty} \left(J_{(\omega)} u^\alpha u^\beta + H_{(\omega)}^\alpha u^\beta + H_{(\omega)}^\beta u^\alpha + K_{(\omega)}^{\alpha\beta} \right) d\omega = \\ &= Ju^\alpha u^\beta + H^\alpha u^\beta + H^\beta u^\alpha + K^{\alpha\beta} \end{aligned}$$

- ▶ stress-energy tensor in lab (i.e. Eulerian) frame

$$T_{\text{rad}}^{\mu\nu} = En^\mu n^\nu + F^\mu n^\nu + F^\nu n^\mu + P^{\mu\nu}$$

- ▶ coupling with GR-hydrodynamics

$$\nabla_\mu \left(T_{\text{hydro}}^{\mu\nu} + T_{\text{rad}}^{\mu\nu} \right) = 0 \quad \rightarrow \quad \nabla_\mu T_{\text{hydro}}^{\mu\nu} = -\nabla_\mu T_{\text{rad}}^{\mu\nu}$$

Moment transport equations

transport equations in gray, two-moment (M1) formalism:

$$\begin{aligned}\partial_t(\sqrt{\gamma}E) + \partial_j[\sqrt{\gamma}(\alpha F^j - \beta^j E)] \\ = \alpha\sqrt{\gamma}[P^{ij}K_{ij} - F^j\partial_j \ln \alpha - S^\alpha n_\alpha], \\ \partial_t(\sqrt{\gamma}F_i) + \partial_j[\sqrt{\gamma}(\alpha P_i{}^j - \beta^j F_i)] \\ = \sqrt{\gamma}\left[-E\partial_i\alpha + F_k\partial_i\beta^k + \frac{\alpha}{2}P^{jk}\partial_i\gamma_{jk} + \alpha S^\alpha\gamma_{ia}\right]\end{aligned}$$

$$\partial_t(\alpha\sqrt{\gamma}nf^0) + \partial_i(\alpha\sqrt{\gamma}nf^i) = \alpha\sqrt{\gamma}(j - \kappa_a^0n) \quad f^\mu = \left(u^\mu + \frac{H^\mu}{J}\right)$$

Shibata *et al.* 2011, Foucart *et al* PRD 2016, Radice *et al* MNRAS 2023

- ▶ γ_{ij}, γ : 3D metric and its determinant
- ▶ K_{ij} : extrinsic curvature
- ▶ rhs: source + metric effects (e.g. grav. redshift, light bending)
- ▶ 2 equations with 3 unknowns. Need of a closure:

$$P^{ij} = P^{ij}(E, F^k)$$

A few words about closures

$$P^{ij} = P^{ij}(E, F^k)$$

- ▶ analytic closures
 - ▶ computationally cheaper
 - ▶ designed to reproduce some limits
 - ▶ possible artifacts far from these limits
- ▶ "consistent" closure (e.g. Monte Carlo)
 - ▶ computationally expensive
 - ▶ potentially "exact"
- ▶ popular analytical choice: Minerbo closure
 - ▶ interpolation between optically thin and thick limits
 - ▶ optically thick:

$$K^{\mu\nu} = \frac{1}{3}J(g^{\mu\nu} + u^\mu u^\nu)$$

- ▶ optically thin:

$$P^{\alpha\beta} = \frac{E}{F^2} F^\alpha F^\beta$$

Stimulated absorption

Source term in transport equation for $A + B \leftrightarrow C + \nu$

$$D_t [f(\omega)] = \mathcal{C}[f] \quad \Rightarrow \quad D_t [f(\omega)] = j(\omega)(1 - f(\omega)) - \frac{1}{\lambda(\omega)} f(\omega)$$

- ▶ j : spectral emissivity
- ▶ $1/\lambda$: spectral inverse mean free path

can be written as

$$\begin{aligned} D_t f(\omega) &= j(\omega) - \left(j + \frac{1}{\lambda(\omega)} \right) f(\omega) \\ D_t f(\omega) &= j(\omega) - \kappa(\omega) f(\omega) \end{aligned}$$

- ▶ $\kappa = (j + \lambda^{-1})$: (stimulated) spectral opacity

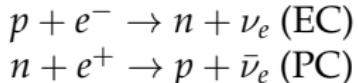
Back to M1 transport scheme, energy-integrated source term in energy equation:

$$S^\mu = (\eta - \kappa_a J) u^\mu - (\kappa_a + \kappa_s) H^\mu$$

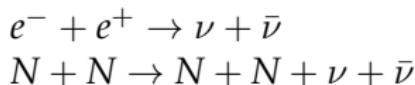
η : emissivities, $\kappa_{a,s}$: absorption & scattering (stimulated) opacities

Neutrino-matter interaction in hot and dense matter

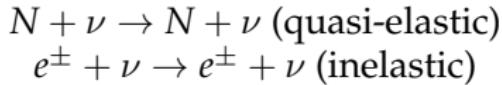
- ▶ ν 's are weakly interacting particles (NC & CC processes)
- ▶ production (\rightarrow , and possibly absorption, \leftarrow) of ν_e and $\bar{\nu}_e$:



- ▶ production (\rightarrow , and possibly absorption, \leftarrow) of all ν 's



- ▶ scattering for all ν 's:



- ▶ all neutrino flavor relevant, but with different physics

A qualitative overview of reactions (part 1)



- ▶ $m_n c^2 \gtrsim m_p c^2 \gg E_e$ and $E_\nu \Rightarrow \delta_{(4)}(p_i - p_f)$ implies $E_e \approx E_\nu$
- ▶ \rightarrow : efficient in producing ν_e and $\bar{\nu}_e$
- ▶ \leftrightarrow : relevant in keeping ν_e 's & $\bar{\nu}_e$'s in thermal contact with matter
- ▶ \leftarrow :
 - ▶ at high density: efficient in providing ν_e and $\bar{\nu}_e$ opacity
 - ▶ at low density: relevant in transferring energy and momentum from hot and dense to cold and dilute matter



- ▶ \rightarrow : efficient in producing ν_x and $\bar{\nu}_x$ ($x = \mu, \tau$), always in pairs
- ▶ \leftrightarrow : relevant in keeping ν_x 's & $\bar{\nu}_x$'s in thermal contact with matter
- ▶ \leftarrow : "early" freeze-out due to pair nature of the process

A qualitative overview of reactions (part 2)



- $m_n c^2 \gtrsim m_p c^2 \gg E_\nu$ and $E_{\nu'} \Rightarrow \delta_{(4)}(p_i - p_f)$ implies $E_{\nu'} \approx E_\nu$
- \rightarrow : efficient in providing scattering opacity, but not relevant in keeping ν in thermal contact with matter



- since $\omega \sim E_e \Rightarrow \omega' \neq \omega$
- relevant in keeping ν_x 's & $\bar{\nu}_x$'s in thermal contact with matter, even after pair freeze-out

Electron neutrino emissivity

- $j(\omega)$: amount of neutrinos with energy ω emitted per unit time
- electron captures (ECs)



$$\left\{ \begin{array}{l} j(\omega) \\ 1/\lambda^{(a)}(\omega) \end{array} \right\} = \int \frac{d^3 p_p}{(2\pi)^3} \int \frac{d^3 p_n}{(2\pi)^3} \int \frac{d^3 p_e}{(2\pi)^3} \left\{ \begin{array}{l} 2F_p(E_p)[1 - F_n(E_n)]2F_e(E_e)r(p_p + p_e \rightarrow p_n + q) \\ [1 - F_p(E_p)]2F_n(E_n)[1 - F_e(E_e)]r(p_n + q \rightarrow p_p + p_e) \end{array} \right\},$$

Electron neutrino emissivity

- ▶ $j(\omega)$: amount of neutrinos with energy ω emitted per unit time
- ▶ electron captures (ECs)



$$j(\omega) \approx \left[\frac{G_F^2}{\hbar^4 c^3} \frac{1}{\pi} \left(g_V^2 + 3g_A^2 \right) \right] \eta_{pn} f_{e^-}(\omega + \Delta) (\omega + \Delta)^2$$

$$\eta_{pn} \propto \int d^3p f_p(E_p) (1 - f_n(E_p)) \sim n_p$$

$f_{e^-}(\omega + \Delta)$ Fermi – Dirac dist for electrons

$\Delta = m_n c^2 - m_p c^2$ $\Delta \approx 1.29 \text{ MeV}$ Q value of reaction

- ▶ let's rewrite it in the following way:

$$j(\omega) \approx n_p \left[\frac{1}{g_j h^3} \frac{dn_e}{d^3p} \right] c \sigma_\nu(E_\nu)$$

$$\sigma_\nu(\omega) \approx \sigma_0 \left(\frac{\omega - \Delta}{m_e c^2} \right)^2,$$

$$\sigma_0 = \frac{G_F^2 (m_e c^2)^2 (g_V^2 + 3g_A^2)}{\pi (\hbar c)^4} \approx 2.43 \times 10^{-44} \text{ cm}^2 \sim 2 \times 10^{-20} \sigma_{\text{Thomson}, e}$$

Total electron capture rates

- plasma (n, p, e^\pm, γ) in thermal and NSE (NS matter EOS)

$$\begin{aligned} j &= \int \frac{d^3 p_\nu}{(2\pi\hbar c)^3} j_{\nu_e}(\omega) \\ &\approx n_p \frac{4\pi\sigma_0 c}{(2\pi\hbar c)^3} \int_0^\infty \left(\frac{\omega + \Delta}{m_e} \right)^2 f_{e^-}(\omega + \Delta) \omega^2 d\omega \\ F_k(\eta) &= \int_0^\infty \frac{x^k}{1 + \exp(x - \eta)} dx \end{aligned}$$

- ν_e production rates: boosted by high temperatures & densities

$$j \propto n_p (k_B T)^5 F_4 \left(\frac{\mu_e}{k_B T} \equiv \eta_e \right)$$

$$F_4(\eta) \sim \frac{\eta^5}{5} \text{ if } \eta \gg 1 \quad F_4(0) \approx 23.3 \quad F_4(\eta) \sim 24e^{-|\eta|} \text{ if } \eta \ll -1$$

Neutrino production mean energy

- neutrinos carry energy. For EC,

$$\begin{aligned}\eta &= \int \frac{d^3 p_\nu}{(2\pi\hbar c)^3} \omega j(\omega) \propto n_p \int_0^\infty \left(\frac{\omega + \Delta}{m_e} \right)^3 f_{e^-}(\omega + \Delta) \omega^2 d\omega \\ &\propto n_p (k_B T)^6 F_5 \left(\frac{\mu_e}{k_B T} \right)\end{aligned}$$

$$F_5(\eta) \sim \frac{\eta^6}{6} \text{ if } \eta \gg 1 \quad F_5(0) \approx 118.3 \quad F_5(\eta) \sim 120 e^{-|\eta|} \text{ if } \eta \ll -1$$

- neutrino production mean energy:

$$\langle \omega \rangle = \frac{\eta}{j} = k_B T \frac{F_5 \left(\frac{\mu_e}{k_B T} \right)}{F_4 \left(\frac{\mu_e}{k_B T} \right)}$$

- if $\eta_e \gg 1$, $\langle \omega \rangle \approx \frac{5}{6} \mu_e$; if $\eta_e \sim 0$, $\langle \omega \rangle \approx 5 k_B T$

Other neutrino production

- positron captures: dominant $\bar{\nu}_e$ source



$$j(\omega > \Delta) \approx \left[\frac{G_F^2}{\hbar^4 c^3} \frac{1}{\pi} \left(g_V^2 + 3g_A^2 \right) \right] \eta_{np} f_{e^+}(\omega - \Delta) (\omega - \Delta)^2$$
$$j \propto n_n (k_B T)^5 F_4 \left(-\frac{\mu_e}{T} \right) \quad \eta \propto n_n (k_B T)^6 F_5 \left(-\frac{\mu_e}{T} \right) \quad \langle \omega \rangle = k_B T \frac{F_5 \left(-\frac{\mu_e}{k_B T} \right)}{F_4 \left(-\frac{\mu_e}{k_B T} \right)}$$

- pair annihilation



- $j \sim \sigma_0 \langle E_{e^-} + E_{e^+} \rangle^2 n_{e^-} n_{e^+} \propto (k_B T)^2 (k_B T)^3 (k_B T)^3 f(\mu/k_B T) = (k_B T)^8 f(\mu/k_B T)$
- $\eta \sim j \langle \omega + \omega' \rangle \propto (k_B T)^8 (k_B T) = (k_B T)^9$

- $N-N$ bremsstrahlung



- $j \propto \rho^2 (k_B T)^{9/2} \quad \langle \omega + \omega' \rangle \approx 4.36 (k_B T) \quad \eta \propto \rho^2 (k_B T)^{11/2}$

Neutrino opacity in merger remnants



forward and backward reactions related by detailed balance

$$\frac{1}{\lambda(\omega)} = \frac{j(\omega)}{c} \exp\left(\frac{\omega - \mu_p + \mu_e - \mu_n}{k_B T}\right)$$

$$\frac{1}{\lambda(\omega)} \approx \left[\frac{G_F^2}{\hbar^4 c^4} \frac{1}{\pi} \left(g_V^2 + 3g_A^2 \right) \right] \eta_{np} (1 - f_{e^-}(\omega + \Delta)) (\omega + \Delta)^2$$

introducing again σ_0 ,

$$\frac{1}{\lambda(\omega)} \approx n_n \sigma_0 \left(\frac{\omega + \Delta}{m_e c^2} \right)^2 (1 - f_{e^-}(\omega + \Delta))$$

Similarly, for

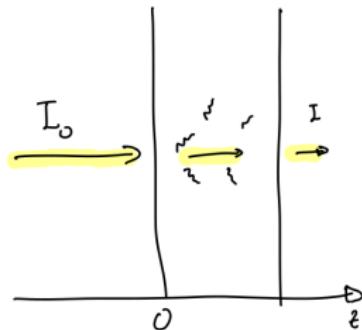
- $p + \bar{\nu}_e \rightarrow e^+ + n \rightarrow \frac{1}{\lambda(\omega)} \approx n_p \sigma_0 \left(\frac{\omega - \Delta}{m_e c^2} \right)^2 (1 - f_{e^+}(\omega - \Delta))$
- $N + \nu \rightarrow N + \nu \rightarrow \frac{1}{\lambda(\omega)} \approx n_b \sigma_0 \left(\frac{\omega}{m_e c^2} \right)^2$
$$\Rightarrow \lambda_\nu \sim \frac{1}{n_B \sigma_\nu} \approx 2.36 \times 10^3 \text{ cm} \left(\frac{\rho}{10^{14} \text{ g/cm}^3} \right)^{-1} \left(\frac{\omega}{10 \text{ MeV}} \right)^{-2}$$

Optical depth

- optical depth τ along a path γ ($\lambda: \nu$ mean free path)

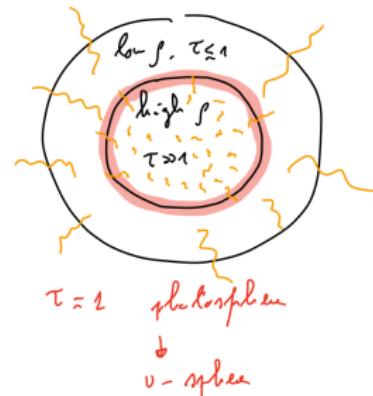
$$\tau_\gamma = \int_\gamma \lambda^{-1} ds$$

- physical interpretation: # number of interaction experienced by a radiation particle moving along a certain path
 - $\tau(x) \gg 1$: optically thick/diffusive conditions
 - $\tau(x) \sim 1$: semi-transparent regime
 - $\tau(x) \lesssim 1$: optically thin/ free streaming conditions



$$I(x>s) = I_0 \exp\left(-\int \frac{ds}{\lambda}\right)$$

$$= I_0 \exp(-\tau)$$



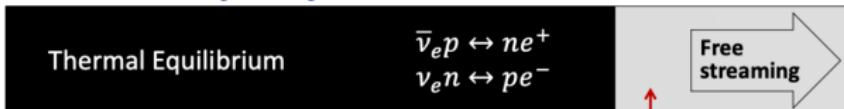
Optical depth

- optical depth τ along a path γ (λ : ν mean free path)

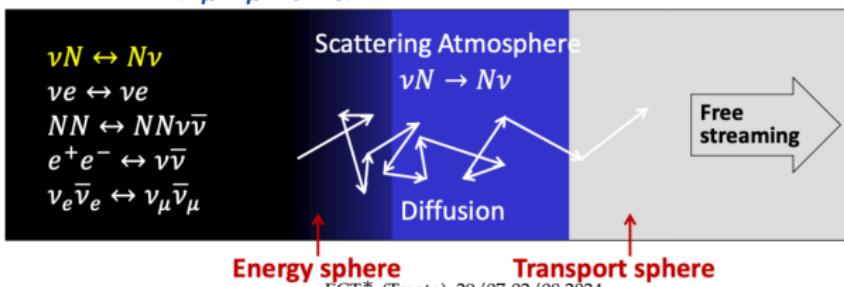
$$\tau_\gamma = \int_\gamma \lambda^{-1} ds$$

- physical interpretation: # number of interaction experienced by a radiation particle moving along a certain path
 - $\tau(x) \gg 1$: optically thick/diffusive conditions
 - $\tau(x) \sim 1$: semi-transparent regime
 - $\tau(x) \lesssim 1$: optically thin/ free streaming conditions

Electron flavor (ν_e and $\bar{\nu}_e$)



Other flavors ($\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$)



Optical depth: scattering VS equilibrium

- ▶ neutrino matter interactions
 - ▶ processes very efficient in coupling radiation to matter: e.g. absorption
 - ▶ processes very inefficient in coupling matter to radiation:
e.g. elastic scattering
- ▶ *diffusion* optical depth: τ_{diff}

$$\kappa_{\text{diff}} = \kappa_{\text{sc}} + \kappa_{\text{ab}}$$

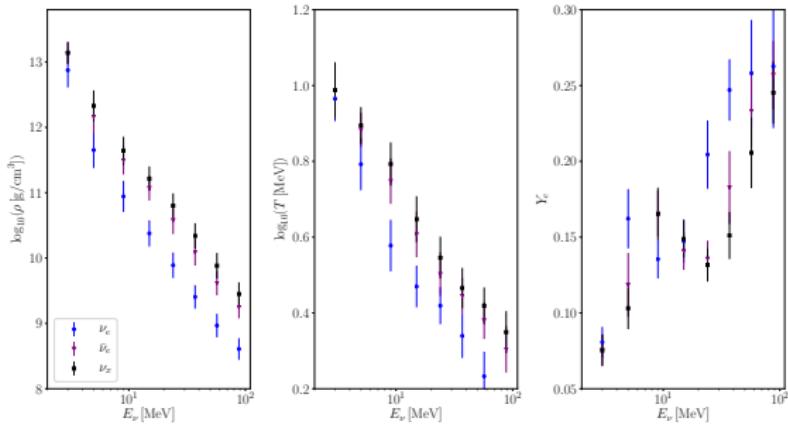
- ▶ *equilibrium* optical depth: τ_{eq}

$$\kappa_{\text{eq}} = \sqrt{\kappa_{\text{diff}} \kappa_{\text{ab}}}$$

e.g., Shapiro & Teukolsky 83, Raffelt 2001

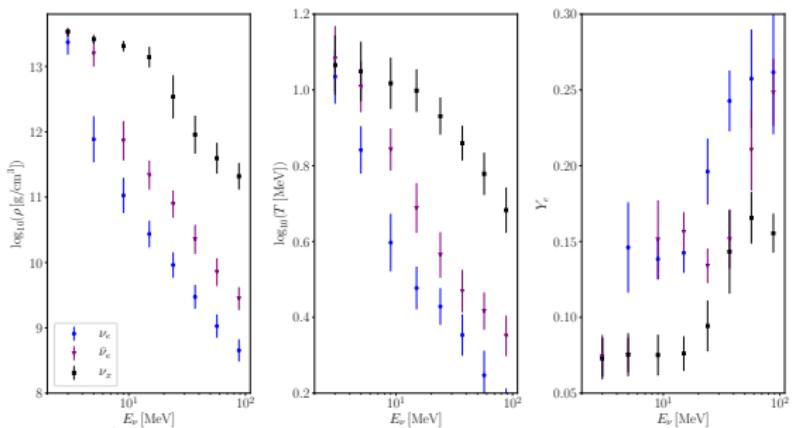
- ▶ $\sigma_\nu \propto \omega^2 \rightarrow$ optical depth and decoupling significantly depend on neutrino energy!

ν surfaces for MNS remnants: energy dependency

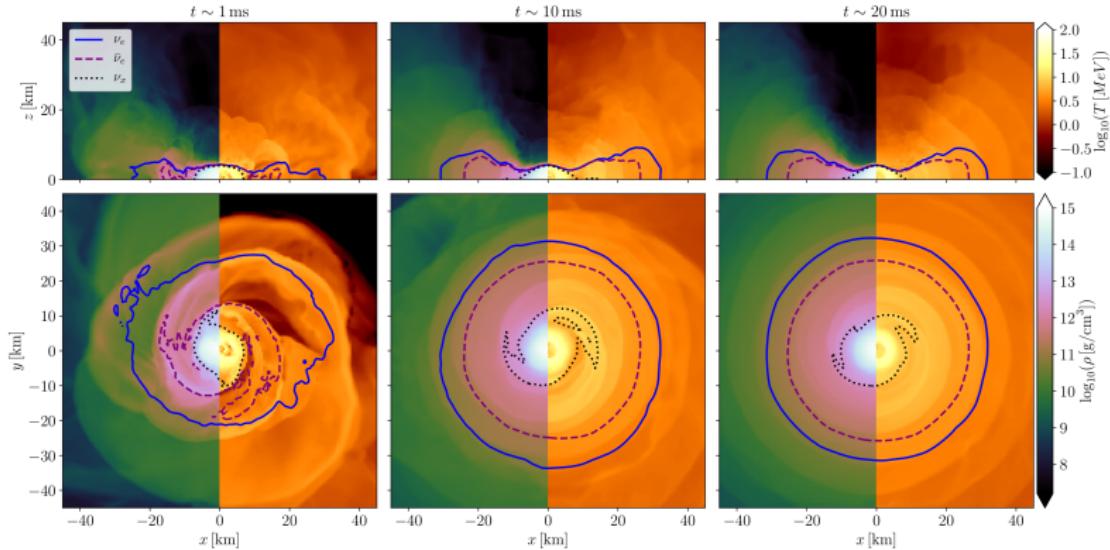


- DD2, $\tau_{\text{diff}}(E_\nu) = 2/3$ at 20ms
- dominant $\sigma_\nu \propto \rho \omega^2$ contribution
- relevant neutrino decoupling: $10^{9-13} \text{ g cm}^{-3}$

- DD2, $\tau_{\text{eq}}(E_\nu) = 2/3$ at 20ms
- ν_e diffuse & thermalize together
- ν_x : significant T dependence



Equilibrium surfaces for average ν energies



- ▶ equilibrium decoupling:
 $\rho(\nu_e) \sim 10^{11} \text{ g cm}^{-3}$, $\rho(\bar{\nu}_e) \sim \text{several } 10^{11} \text{ g cm}^{-3}$, $\rho(\nu_x) \sim 10^{13} \text{ g cm}^{-3}$
- ▶ richness: stronger ν_e coupling ($n + \nu_e \rightarrow p + e^-$)
- ▶ pair processes: strong dependence on $T \& \rho \Rightarrow$ quick ν_x decoupling
- ▶ $\langle E_\nu \rangle \approx (F_3(0)/F_2(0)) k_B T \sim 3.15 k_B T$

$$\langle E_{\nu_e} \rangle \approx 9 \text{ MeV} \quad \langle E_{\bar{\nu}_e} \rangle \approx 15 \text{ MeV} \quad \langle E_{\nu_x} \rangle \approx 24 \text{ MeV}$$

Trapped neutrinos & ν gas

- ▶ deep inside the remnant: $\tau_\nu \sim 10^3 \Rightarrow$ diffusive/trapping regime
- ▶ ν rates large enough to produce a ν gas in thermal and weak equilibrium with matter

$$\mu_{\nu_e} = \mu_p + \mu_{e^-} - \mu_n \quad \mu_{\bar{\nu}_e} = -\mu_{\nu_e} \quad \mu_{\nu_{\mu,\tau}} = \mu_{\bar{\nu}_{\mu,\tau}} \approx 0$$

- ▶ ν EOS: EOS of UR fermions at $T \neq 0$ ($g_j = 1$)
 - ▶ baryon degeneracy favors $\bar{\nu}_e$ over ν_e , but overall small effect
 - ▶ $\delta T/T \lesssim 8\%$, $\delta P/P \lesssim 5\%$

$$n_\nu = \frac{4\pi}{(hc)^3} (k_B T)^3 F_2 \left(\frac{\mu_\nu}{k_B T} \right)$$

$$J_\nu = \frac{4\pi}{(hc)^3} (k_B T)^4 F_3 \left(\frac{\mu_\nu}{k_B T} \right)$$

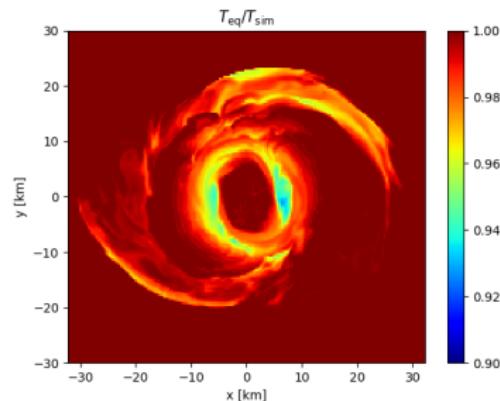
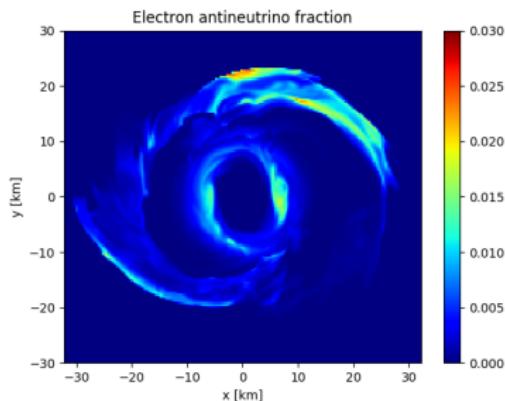
$$K_\nu = \frac{1}{3} J_\nu$$

Trapped neutrinos & ν gas

- deep inside the remnant: $\tau_\nu \sim 10^3 \Rightarrow$ diffusive/trapping regime
- ν rates large enough to produce a ν gas in thermal and weak equilibrium with matter

$$\mu_{\nu_e} = \mu_p + \mu_{e^-} - \mu_n \quad \mu_{\bar{\nu}_e} = -\mu_{\nu_e} \quad \mu_{\nu_{\mu,\tau}} = \mu_{\bar{\nu}_{\mu,\tau}} \approx 0$$

- ν EOS: EOS of UR fermions at $T \neq 0$ ($g_j = 1$)
 - baryon degeneracy favors $\bar{\nu}_e$ over ν_e , but overall small effect
 - $\delta T/T \lesssim 8\%$, $\delta P/P \lesssim 5\%$



Neutrino diffusion & trapping

- ▶ diffusion timescale

$$v_{\text{diff}} \sim \frac{c}{3\tau_\nu} \quad v_{\text{diff}} \sim \frac{\ell}{t_{\text{diff}}} \quad \tau_\nu \sim \frac{\ell}{\lambda_\nu} \quad \rightarrow \quad t_{\text{diff}} \sim \frac{3\ell^2}{c\lambda_\nu}$$

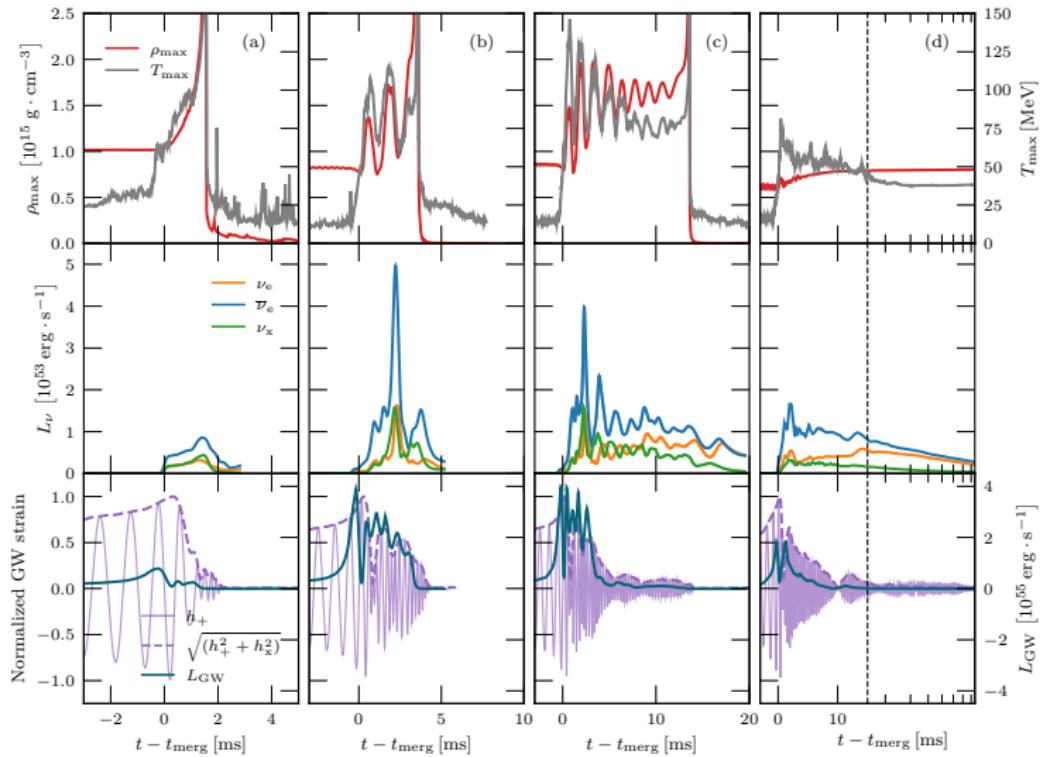
- ▶ t_{diff} from the remnant: $\ell = R_{\text{rem}}$

$$t_{\text{diff}} \sim 1.88 \text{ s} \left(\frac{R_{\text{rem}}}{25 \text{ km}} \right)^2 \left(\frac{\rho_{\text{rem}}}{10^{14} \text{ g cm}^{-3}} \right) \left(\frac{k_B T_{\text{rem}}}{15 \text{ MeV}} \right)^2$$

- ▶ t_{diff} from the disk: $\ell = H_{\text{disk}}$

$$t_{\text{diff}} \sim 6.8 \text{ ms} \left(\frac{H/R}{1/3} \right)^2 \left(\frac{R_{\text{disk}}}{50 \text{ km}} \right)^{-2} \left(\frac{\rho_{\text{disk}}}{10^{12} \text{ g cm}^{-3}} \right) \left(\frac{E_\nu}{15 \text{ MeV}} \right)^2$$

Neutrino emission: qualitative overview



a) PC

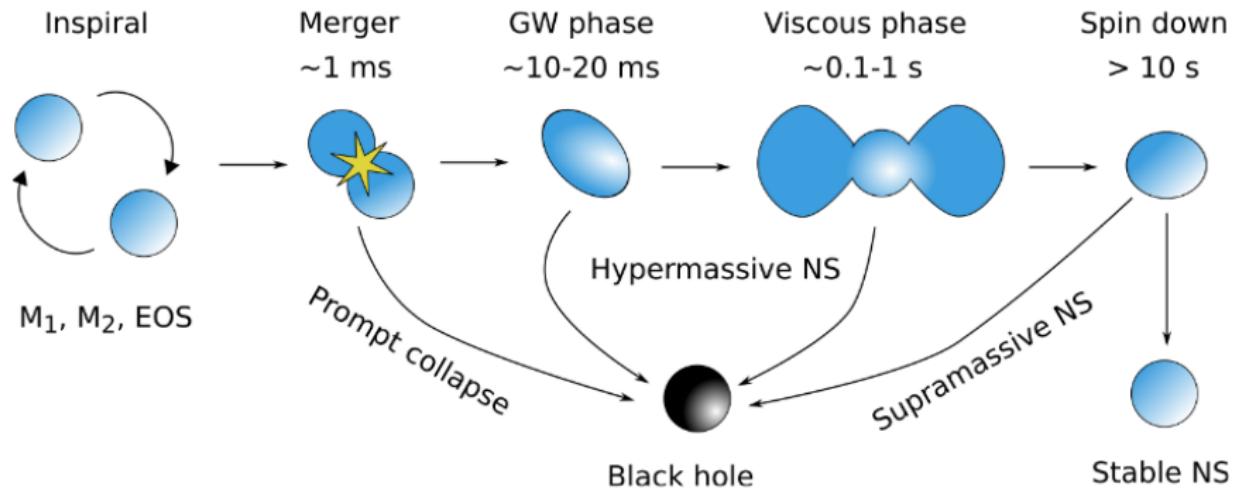
b) short lived

c) delayed collapse

d) long lived

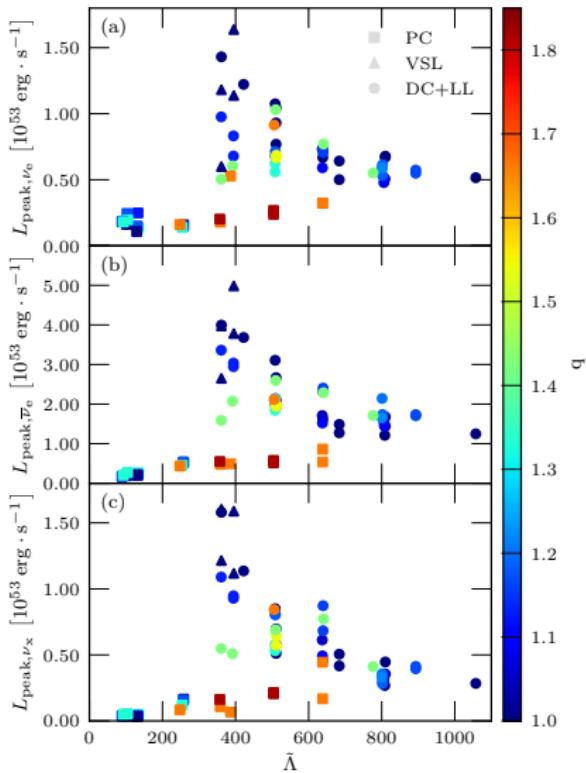
Casinato et al., EPJA 2022

Neutrino emission: qualitative overview



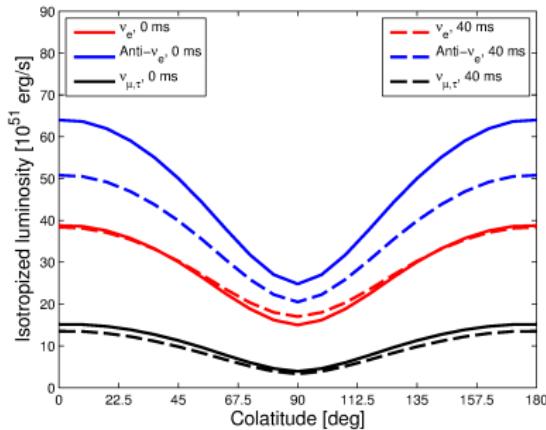
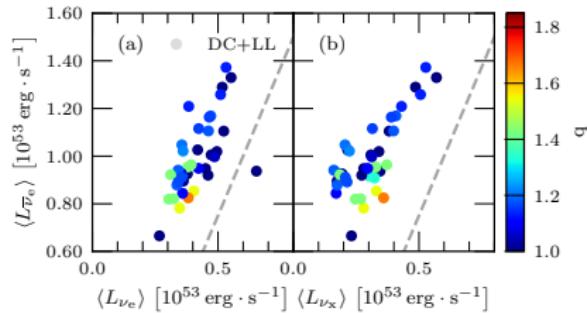
Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS

Neutrino emission: peak luminosity



- ▶ non-PC BNS mergers
 - ▶ main $\tilde{\Lambda}$ dependence: for $q \gtrsim 1$, L_{peak} decreases for increasing $\tilde{\Lambda}$
 - ▶ further influence on q
- ▶ PC mergers
 - ▶ separated branch with weaker dependence on $\tilde{\Lambda}$
 - ▶ $L_{\nu,\text{peak}}$ increases for increasing $\tilde{\Lambda}$, probably related with q
- ▶ similar dependence for $\langle L_{\nu} \rangle_{10 \text{ ms}}$

Neutrino emission: additional properties

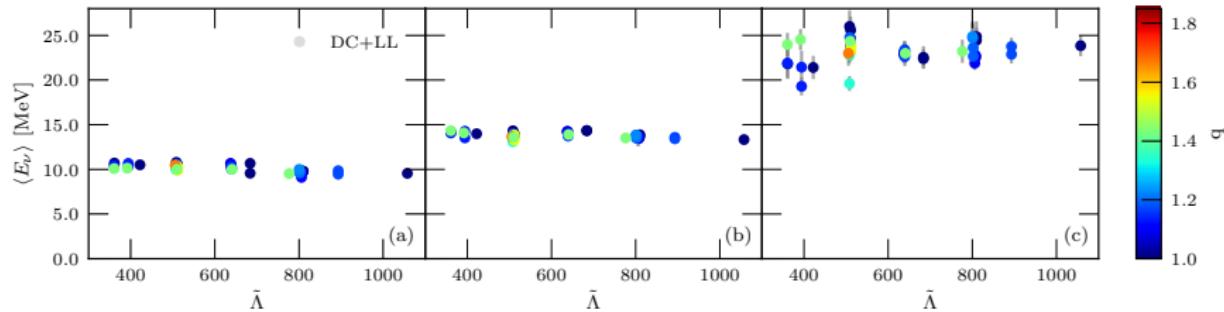


- ▶ (initial) $\bar{\nu}_e$ dominance over the other flavors
- ▶ good correlation between luminosities in different flavors
- ▶ **anisotropic ν emission**
 - ▶ disk: more opacity in equatorial direction
 - ▶ $L_{\nu, \text{pole}} \sim 3 L_{\nu, \text{equator}}$

e.g., Dessart+2009, Perego+14 MNRAS

Top: Cusinato *et al*, EPJA 2022; Bottom: Perego+ 2014 MNRAS

Neutrino emission: mean energies



Cusinato *et al*, EPJA 2022

- ▶ results compatible with previous outcomes

e.g. Ruffert+97 A&A, Rosswog & Liebendoerfer 03 MNRAS, Foucart+ 16 PRD

- ▶ mean ν energy at infinity: robust behavior wrt BNS parameters
- ▶ robust hierarchy, reflecting ν 's decoupling conditions

e.g. Endrizzi *et al* 2021 EPJA

- ▶ indication that post-merger remnant partially loses memory of the merging binary (for non-PC)

Nucleosynthesis in BNS mergers

Matter ejection from BNS mergers

ejecta:

- ▶ a few percent of $M = M_A + M_B$
- ▶ expelled by different mechanisms, acting on different timescales
- ▶ neutron rich, i.e. $Y_e < 0.5$ and typically $Y_e \ll 0.5$

How can we identify ejected matter from a BNS merger simulation?
Unbound fluid elements must satisfy ejection criterion:

- ▶ geodesic criterion:

$$-u_t \geq c \quad \Rightarrow \quad \text{NR} : v > v_{\text{escape}}$$

- ▶ Bernoulli criterion:

$$-hu_t > c \quad \Rightarrow \quad \text{NR} : e_{\text{kin}} + e_{\text{int}} + e_{\text{grav}} > 0$$

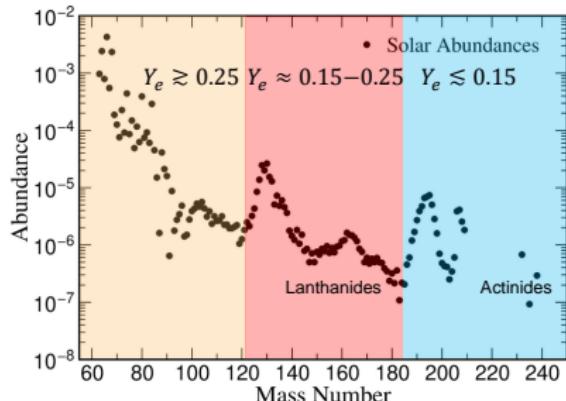
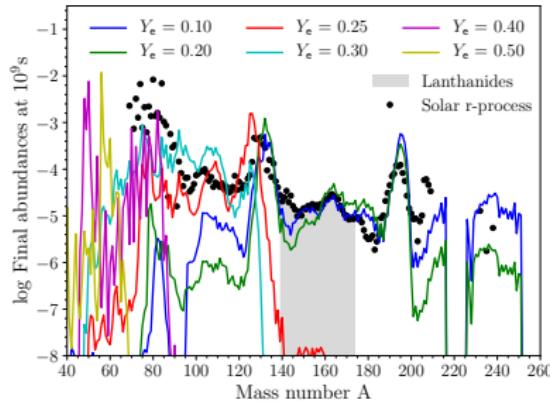
r-process nucleosynthesis in BNS ejecta

ideal conditions for *r*-process nucleosynthesis

- ▶ after dynamical phase, ejecta expand homologously

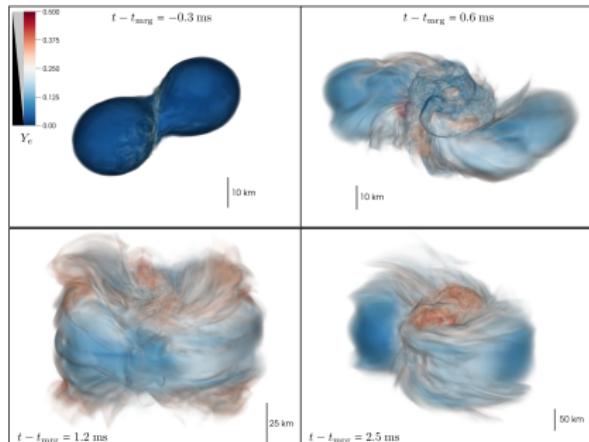
$$v \approx \text{const} \quad \rho = \rho_0 \left(\frac{t}{\tau} \right)^{-3}$$

- ▶ in these conditions, final abundances depends on :
 - ▶ electrons per baryon: $Y_e \in [0.01, 0.5]$
 - ▶ entropy per baryon: $s \in [1, 300] k_B/\text{baryon}$
 - ▶ expansion timescale, $\tau \in [0.1, 100] \text{ ms}$
- ▶ at low entropy ($s \lesssim 40 k_b/\text{baryon}$), Y_e dominant parameter



Dynamical ejecta from BNS merger

- ▶ $t_{\text{ej,dyn}} \sim \text{few ms}$
- ▶ $v_{\text{ej,dyn}} \sim 0.2 - 0.3 c$
- ▶ $M_{\text{ej,dyn}} \sim 10^{-4} - 10^{-3} M_{\odot}$, depending on M_{NS} , q and NS EOS
- ▶ $s_{\text{ej,dyn}} \sim 1 - 30 k_B/\text{baryon}$

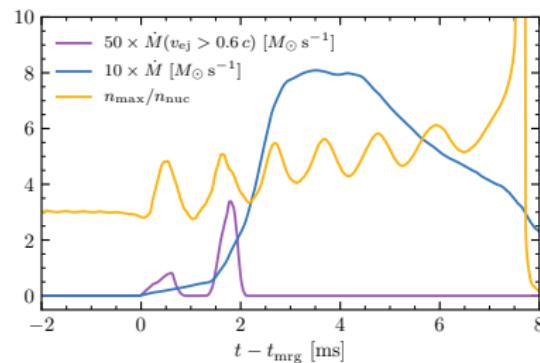


Radice+ 2018 ApJ

- ▶ **tidal component**
 - ▶ first to develop
 - ▶ equatorial
 - ▶ cooler (lower entropy)
 - ▶ relevant for asymmetric BNS
- ▶ **shock-heated component**
 - ▶ due to (H)MNS bounces
 - ▶ equatorial & polar
 - ▶ higher entropy
 - ▶ relevant for symmetric BNS

Dynamical ejecta from BNS merger

- $t_{\text{ej,dyn}} \sim \text{few ms}$
- $v_{\text{ej,dyn}} \sim 0.2 - 0.3 c$
- $M_{\text{ej,dyn}} \sim 10^{-4} - 10^{-3} M_{\odot}$, depending on M_{NS} , q and NS EOS
- $s_{\text{ej,dyn}} \sim 1 - 30 k_B/\text{baryon}$



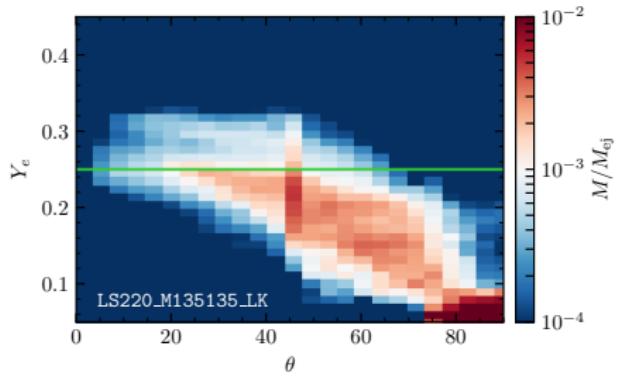
- tidal component
 - first to develop
 - equatorial
 - cooler (lower entropy)
 - relevant for asymmetric BNS
- shock-heated component
 - due to (H)MNS bounces
 - equatorial & polar
 - higher entropy
 - relevant for symmetric BNS

← Radice+ ApJ 18

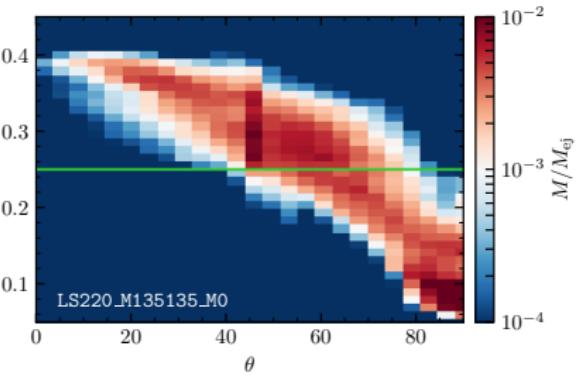
Impact of ν processes on BNS merger ejecta

- if ν absorption is neglected (e.g., for BH-NS mergers)
 - $Y_e \lesssim 0.1 \Rightarrow$ robust r -process ($Y_e = n_e/n_B = n_p/(n_n + n_p)$)
- however, ν -matter interactions increase Y_e , e.g. at polar latitudes
 - most relevant reaction: $n + \nu_e \rightarrow p + e^-$
 - possible angular dependence in r -process nucleosynthesis

w/o neutrino absorption



w neutrino absorption



Perego, Radice, Bernuzzi ApJL 17; Radice, Perego, Hotokezaka *et al* ApJ 2018

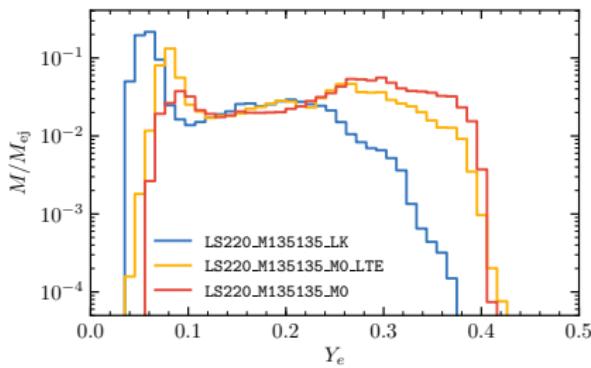
see also e.g. Wanajo+ ApJL 2014' Sekiguchi+ PRD 2015; Martin, Perego, Kastaun & Arcones CQG 2018

$$(Y_e)_{\text{eq}} \approx \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\epsilon_{\bar{\nu}_e} - 2\Delta}{\epsilon_{\nu_e} + 2\Delta} \right)^{-1} \sim 0.42 \quad \epsilon \approx 1.2 \langle E_\nu \rangle$$

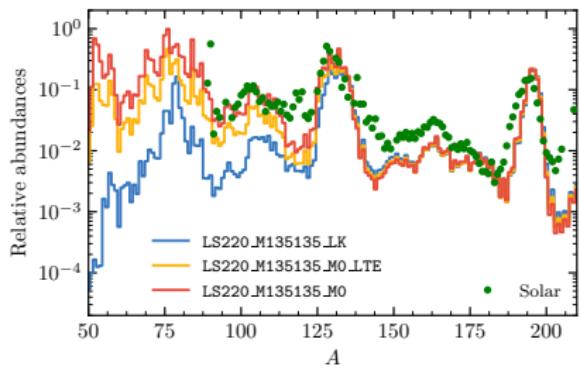
Impact of ν processes on BNS merger ejecta

- if ν absorption is neglected (e.g., for BH-NS mergers)
 - $Y_e \lesssim 0.1 \Rightarrow$ robust r -process ($Y_e = n_e/n_B = n_p/(n_n + n_p)$)
- however, ν -matter interactions increase Y_e , e.g. at polar latitudes
 - most relevant reaction: $n + \nu_e \rightarrow p + e^-$
 - possible angular dependence in r -process nucleosynthesis

w/o neutrino absorption



w neutrino absorption

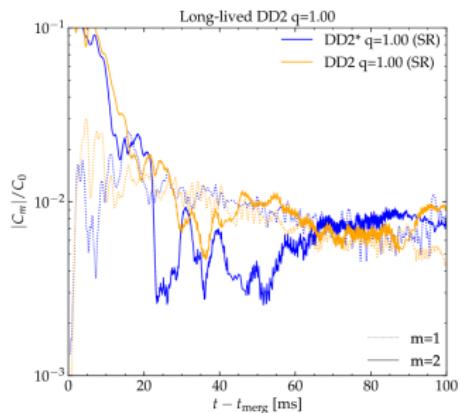
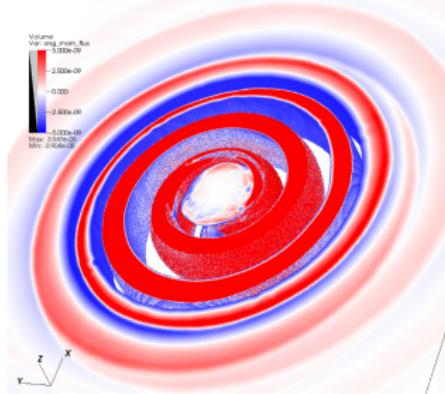


Radice+ ApJ 2018

$$(Y_e)_{eq} \approx \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\epsilon_{\bar{\nu}_e} - 2\Delta}{\epsilon_{\nu_e} + 2\Delta} \right)^{-1} \sim 0.42 \quad \epsilon \approx 1.2 \langle E_\nu \rangle$$

Spiral-wave wind

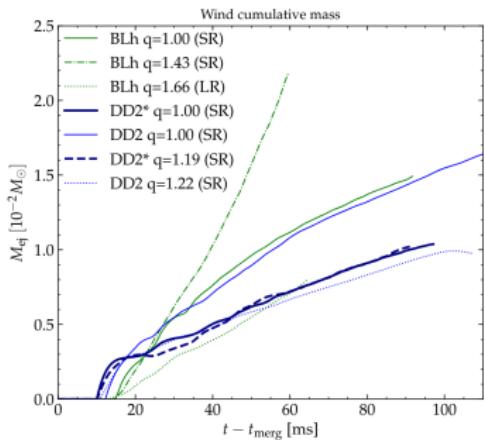
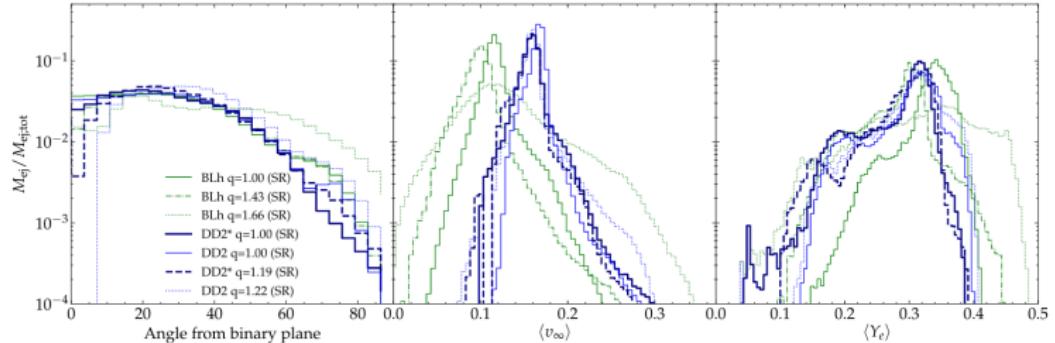
- ▶ development of GW-quiet $m = 1$ (long-lived) mode in addition to GW-loud $m = 2$ (short-lived) mode
 - ▶ $m = 1, 2$ modes produce spiral arms in the disk, transporting angular momentum outwards
 - ▶ production of a fast wind from the disk outer layers
 - ▶ robust hydrodynamics mechanism, depending on MNS lifetime
- ϕ -angular momentum radial flux ρ azimuthal mode decomposition



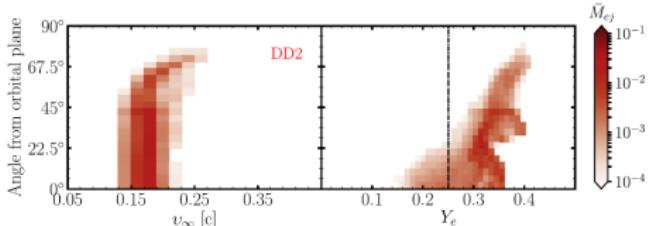
Nedora *et al* ApJL 2019

Nedora *et al* ApJ 2021

Spiral-wave wind ejecta



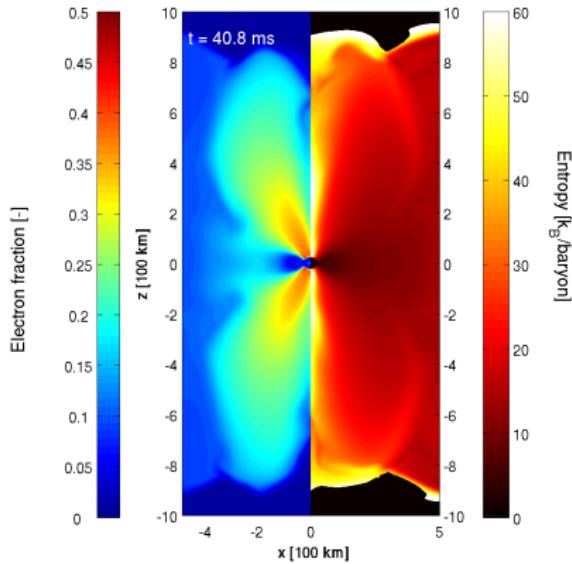
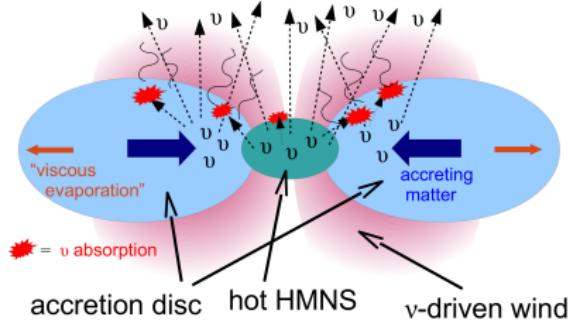
- ▶ Bernoulli criterion
- ▶ $\dot{M}_{\text{wind}} \sim 0.05 - 0.15 M_\odot s^{-1}$
- ▶ mostly equatorial, fast, broad Y_e



Nedora *et al* ApJL 2019

Neutrino-driven winds from BNS merger

- ▶ caused by neutrino energy and momentum deposition
- ▶ $t_{\text{ej,wind}} \sim \text{few 10's-100's ms}$ and $v_{\text{ej,wind}} \lesssim 0.1 c$
- ▶ $M_{\text{ej,wind}}$ up to a few $0.01 M_{\odot} \rightarrow$ possibly, relevant contribution!



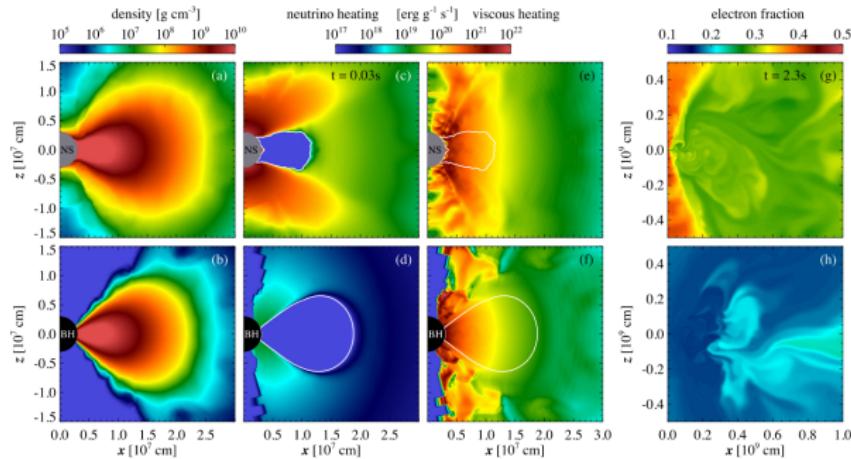
Perego+14, MNRAS, Martin+15 ApJ, see also Fujibayashi+18 ApJ, Nedora+21 ApJ

Viscous ejecta from accretion disks

- MHD viscosity inside the disk
- remnant expansion → nuclear recombination in the disk

$$(n, p) \rightarrow (\alpha, n) \rightarrow ((A, Z), n) \Rightarrow \dot{e} \approx 8 \text{ MeV/baryon}$$

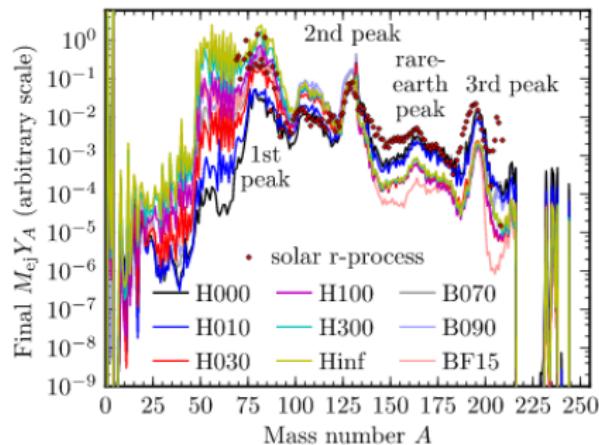
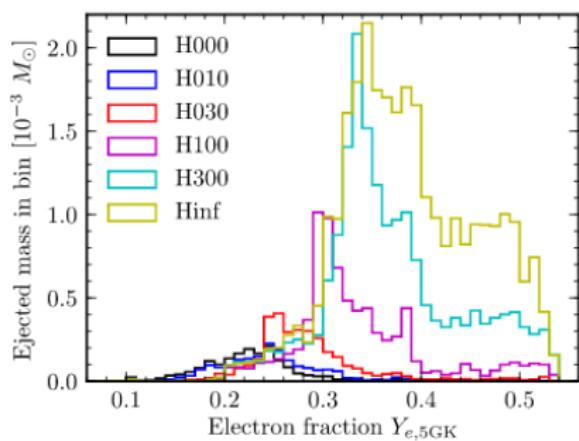
- $t_{\text{ej,sec}} \sim \text{few 100's ms}$ and $v_{\text{ej,sec}} \lesssim 0.1c$
- $M_{\text{ej,sec}} \sim (0.1 - 0.4) M_{\text{disk}}$
- $s_{\text{ej,sec}} \sim 10 - 100 k_B/\text{baryon}$



Figures from Metzger & Fernandez MNRAS 14, Wu+ MNRAS 16, see e.g. Just+ MNRAS 15, Siegel& Metzger PRD 17

Neutrino effect on viscosity-driven ejecta

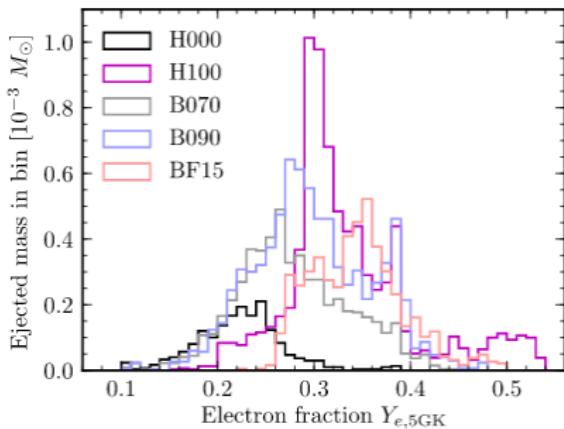
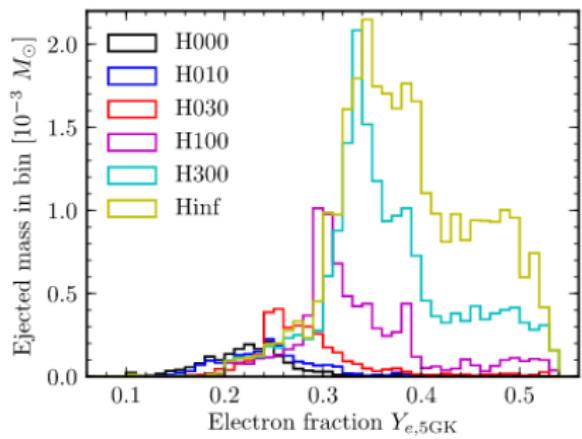
- ▶ ejecta: broad distribution of n -rich matter ($0.1 \lesssim Y_e \lesssim 0.4$)
- ▶ all solid angle ejection, intermediate opacity $\kappa_\gamma \approx 1 - 10 \text{ cm}^2 \text{g}^{-1}$
- ▶ key parameter: HMNS lifetime; long lived HMNS:
 - ▶ significantly larger ejecta
 - ▶ ejecta with larger Y_e



Y_e histograms (and nucleosynthesis) of viscous ejecta depending on HMNS lifetime. Lippuner+ MNRAS 2016

Neutrino effect on viscosity-driven ejecta

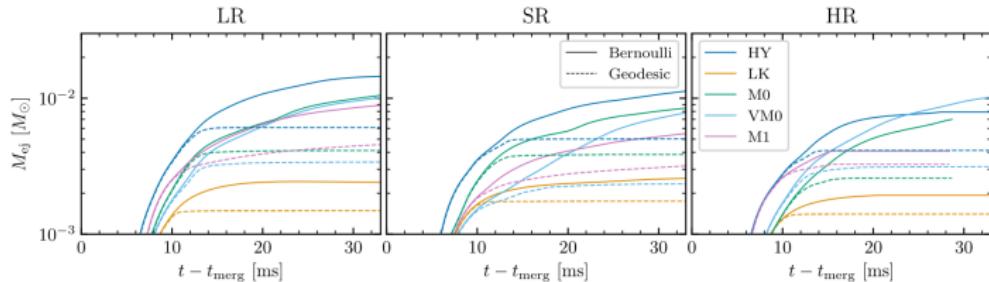
- ▶ ejecta: broad distribution of n -rich matter ($0.1 \lesssim Y_e \lesssim 0.4$)
- ▶ all solid angle ejection, intermediate opacity $\kappa_\gamma \approx 1 - 10 \text{ cm}^2 \text{g}^{-1}$
- ▶ key parameter: HMNS lifetime; long lived HMNS:
 - ▶ significantly larger ejecta
 - ▶ ejecta with larger Y_e



Y_e histograms (and nucleosynthesis) of viscous ejecta depending on HMNS lifetime. Lippuner+ MNRAS 2016

How robust is ejecta modelling?

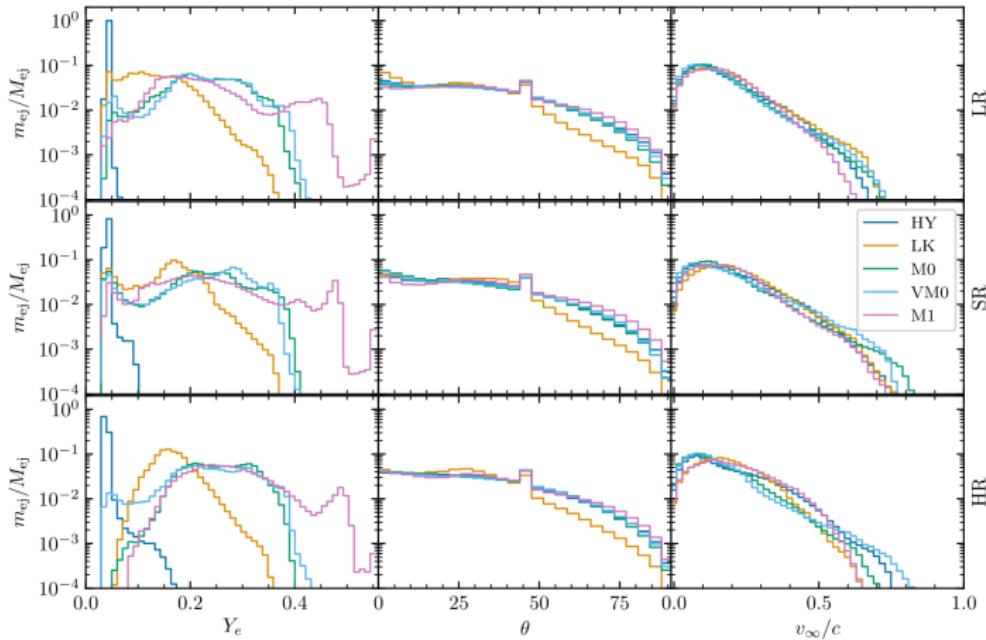
- ▶ numerical experiments show that numerical resolution is still the dominant source of uncertainties
- ▶ microphysics and neutrino transport are still very approximated



Zappa *et al* MNRAS (2023)

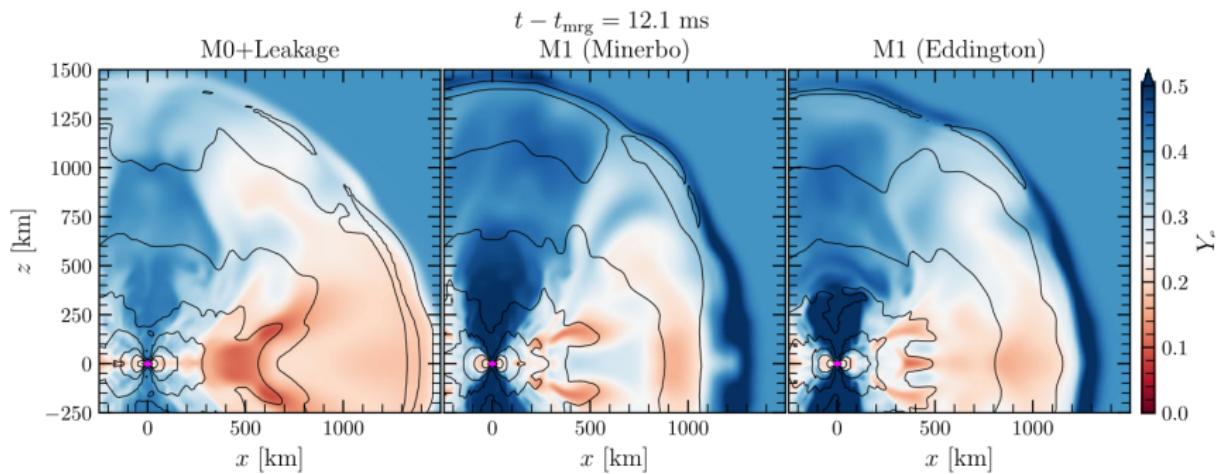
How robust is ejecta modelling?

- ▶ numerical experiments show that numerical resolution is still the dominant source of uncertainties
- ▶ microphysics and neutrino transport are still very approximated



How robust is neutrino modelling?

- ▶ gray M1 good transport, but not perfect & not spectral
- ▶ non negligible effects from scheme & closure
- ▶ approximated rates
- ▶ neutrino oscillations (!!?)



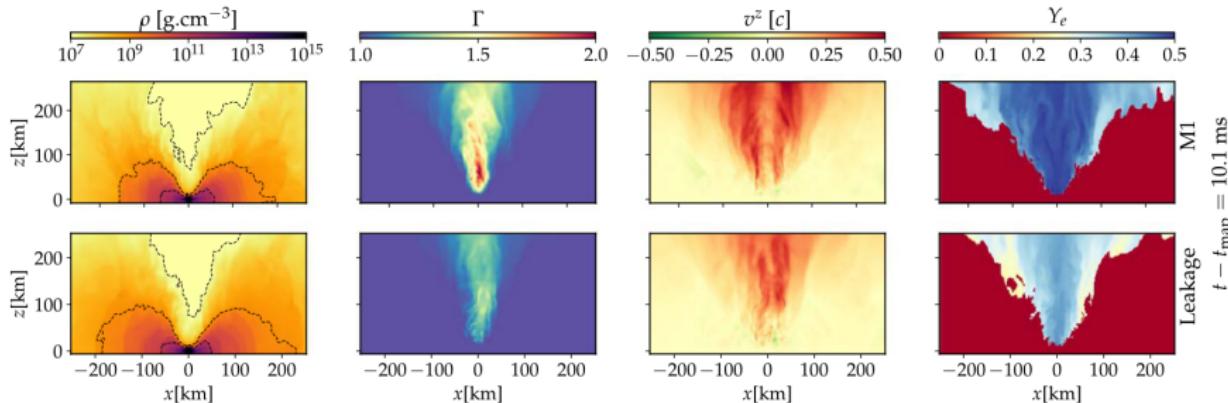
Radice *et al* MNRAS (2022)

What is the role of magnetic field?

Growing consensus that (ultra?)strong, larger scale B field can drive significant matter ejection

Ciolfi & Kalinani ApJL (2020), Combi & Siegel PRL (2023), Curtis+ ApJL (2024), Kiuchi+ 2024 (Nat Astr)

- ▶ very efficient: $0.1\text{-}1 M_{\odot}/\text{s}$
- ▶ on average, fast: $0.2\text{-}0.3 c$
- ▶ lanthanide free, if weak interactions are taken into account



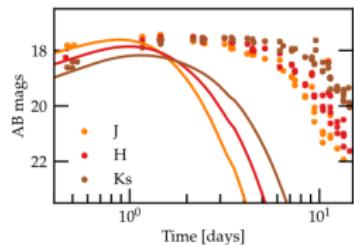
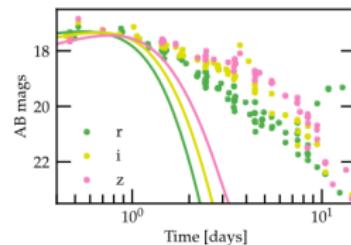
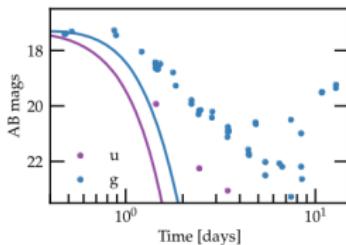
Curtis *et al* ApJL (2024)

What is the role of magnetic field?

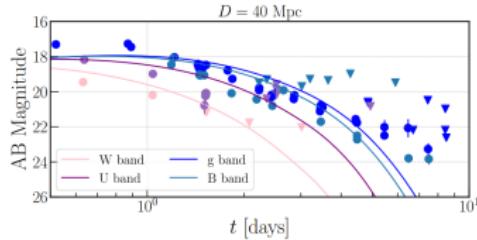
Growing consensus that (ultra?)strong, larger scale B field can drive significant matter ejection

Ciolfi & Kalinani ApJL (2020), Combi & Siegel PRL (2023), Curtis+ ApJL (2024), Kiuchi+ 2024 (Nat Astr)

- ▶ very efficient: $0.1\text{-}1 M_{\odot}/s$
- ▶ on average, fast: $0.2\text{--}0.3 c$
- ▶ lanthanide free, if weak interactions are taken into account



Curtis *et al* ApJL (2024)

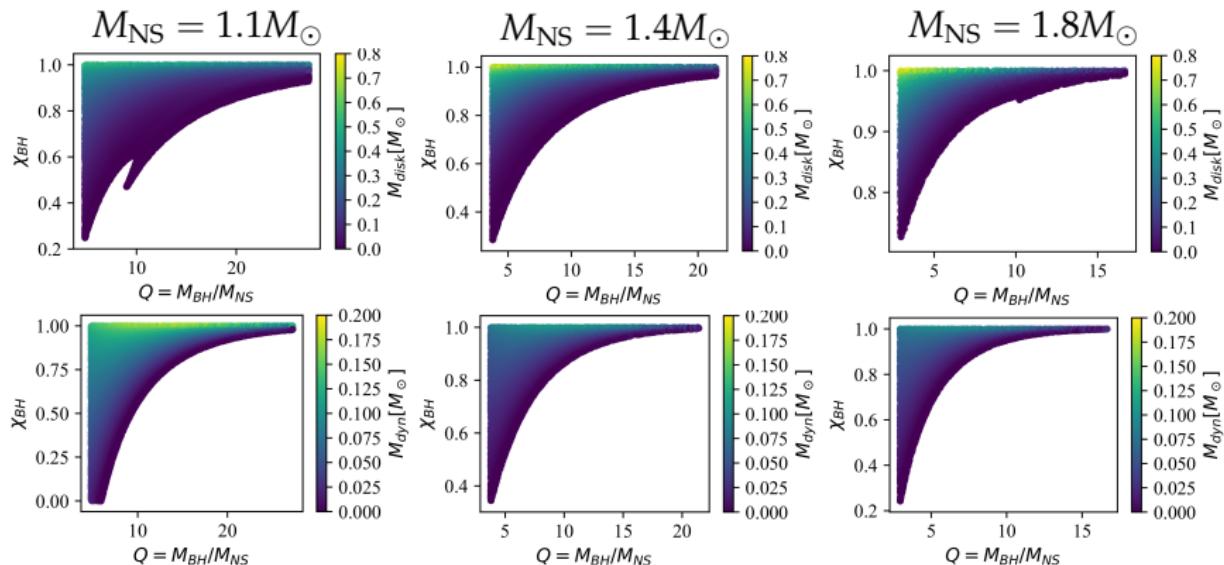


Disk and ejecta from BH-NS mergers

Mass outside the BH horizon: only if $R_{\text{tidal}} \gtrsim R_{\text{isco}}$

$$R_{\text{tidal}} \sim R_{\text{NS}} \left(2 \frac{M_{\text{BH}}}{M_{\text{NS}}} \right)^{1/3}$$

$$R_{\text{isco}} = \frac{GM_{\text{BH}}}{c^2} f(\xi_{\text{BH}}) \quad f(\chi_{\text{BH}} = 1) = 1; f(\chi_{\text{BH}} = 0) = 6; f(\chi_{\text{BH}} = -1) = 9$$

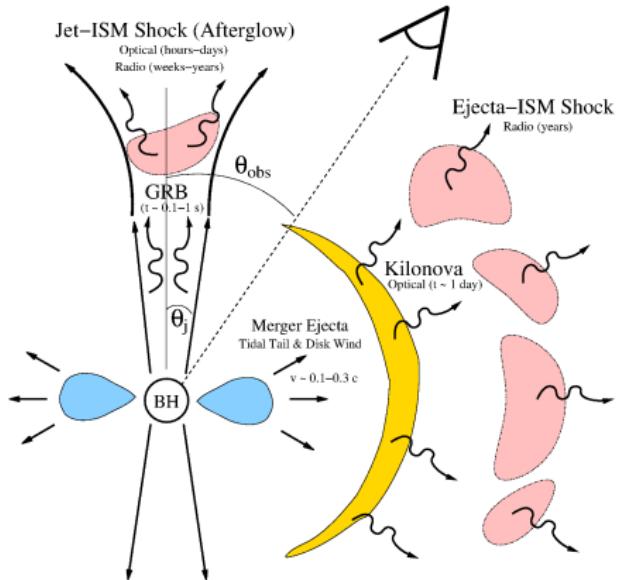


Mass in the disk and in dynamical ejecta after a BH-NS merger. NS EOS: SFHo. Fitting formulas from Foucart+ Arxiv 2018 & Kawaguchi+ PRD 2016.

Figures courtesy of Claudio Barbieri (PhD student Uni MiB).

Kilonova emission

Electromagnetic counterparts: kilonova



Berger & Metzger ARAA 12

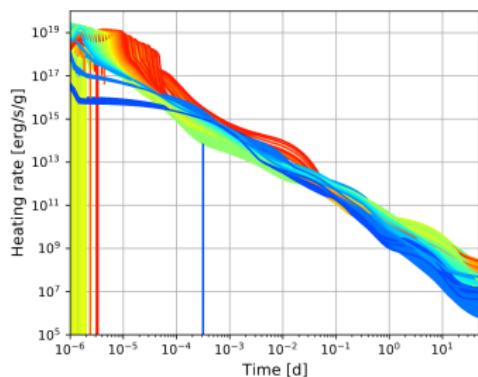
- ▶ radioactive decay of freshly synthesized r -process elements in ejecta: release of nuclear energy
- ▶ thermalization of high energy decay products with ejecta
- ▶ diffusion of thermal photons during ejecta expansion
- ▶ quasi-thermal emission of photons at photosphere

Nuclear heating rate

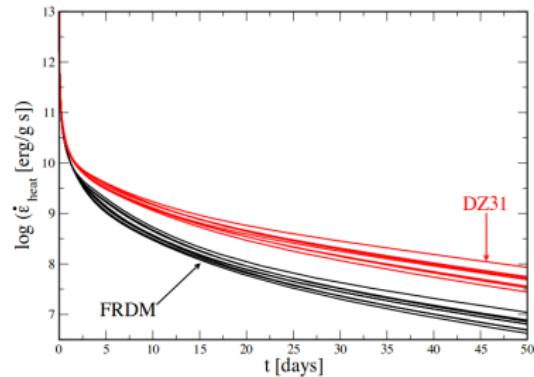
Radioactive decays of *r*-process elements release nuclear energy

$$\dot{e}_{r\text{-process}} = \sum_{i \in \text{reactions}} Q_i \lambda_i \quad Q = M_{\text{initial}} - M_{\text{final}}, \lambda : \text{decay rate}$$

- ▶ nuclear heat computed by detailed nuclear network
mainly β – decay $\Rightarrow \dot{e}_{r\text{-process}} = \dot{e}_0 t^{-\alpha} \quad \alpha \approx 1.3, \dot{e}_0 \gtrsim 10^{16} \text{ erg/g/s}$
- ▶ $Y_e \gtrsim 0.25$: weak *r*-process: shorter β decays lifetimes
- ▶ strong dependence on trajectory and mass model



red: low Y_e , blue: high Y_e Wu, Ricigliano+ 22

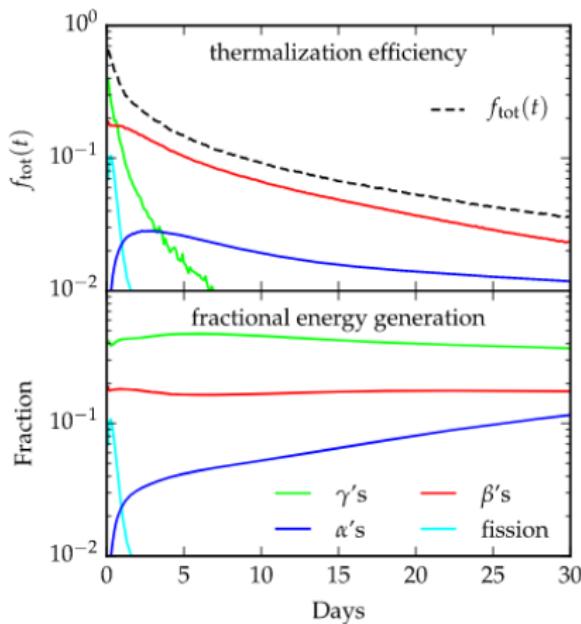


Rosswog+ JphG 2017

Thermalization efficiency

Not all the nuclear energy released by radioactive decay thermalize with ejecta:

$$\dot{e}_{\text{heat}} = \dot{e}_{\text{r-process}} f_{\text{th}} \quad 0 \leq f_{\text{th}} \leq 1$$

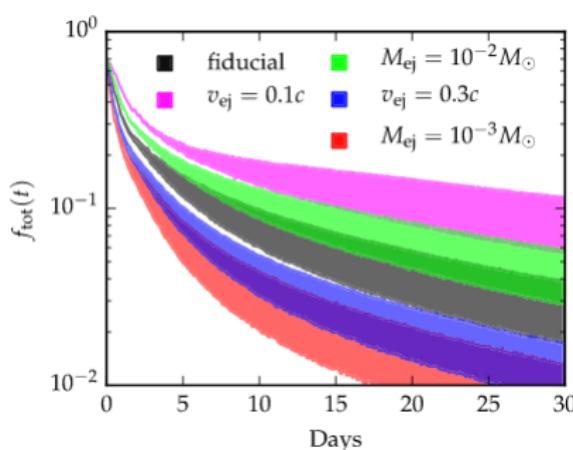


- ▶ $(A, Z) \rightarrow (A, Z + 1) + e^- + \bar{\nu}_e + \gamma$
- ▶ $(A, Z) \rightarrow (A - 4, Z - 2) + \alpha + \gamma$
- ▶ $(A, Z) \rightarrow (A', Z') + (A'', Z'') + n's + p's + \gamma's$

Thermalization efficiency

Not all the nuclear energy released by radioactive decay thermalize with ejecta:

$$\dot{e}_{\text{heat}} = \dot{e}_{\text{r-process}} f_{\text{th}} \quad 0 \leq f_{\text{th}} \leq 1$$



► thermalization efficiency depends on:

- matter density
- matter temperature
- decay modes
- decay product spectra
- ...



both nuclear and astrophysical uncertainties

(fiducial: $m_{\text{ej}} = 10^{-3} M_{\odot}$, $Y_e = 0.04$, $v = 0.2c$)

Barnes+ ApJ 2016

A spherical model kilonova model

- ▶ m_{ej} : amount of ejecta passing through a surface @ $R \gg R_{\text{NS}}$
- ▶ radial, homologous expansion: we label each mass element by its velocity

$$m_{\text{ej}} = \int_0^{v_{\max}} \left(\int_{\Omega} \frac{1}{4\pi} \xi(v, \theta, \phi) d\Omega \right) dv$$

- ▶ spherical symmetry: $\xi(v, \theta, \phi) \Rightarrow \xi(v)$
- ▶ homologous expansion:

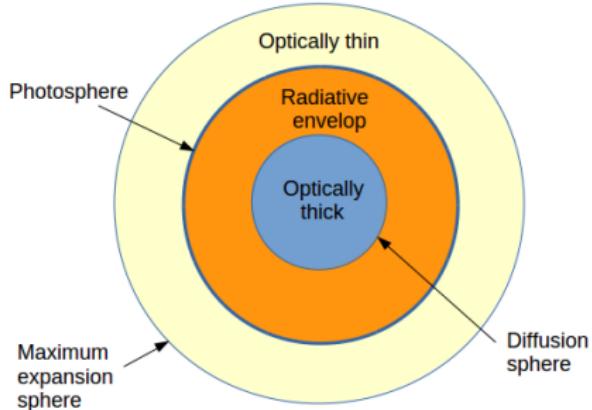
$$\xi(v) = \xi_0 \left(1 - \left(\frac{v}{v_{\max}} \right)^2 \right)^3$$

$$v_{\text{rms}} = \left(\frac{1}{m_{\text{ej}}} \int_0^{v_{\max}} v^2 \xi(v) dv \right)^{1/2} = \frac{v_{\max}}{3}$$

$$m_{>v}(\tilde{v}) = \int_{\tilde{v}}^{v_{\max}} \xi(v) dv$$

e.g., Grossman+ MNRAS 2014; see Metzger LRR 2017, Fernandez & Metzger ARAA 2016 for good reviews

Photon diffusion model



- ▶ let's suppose to consider a time $t = \tilde{t}$ after the merger
- ▶ the ejecta has maximally expanded up to $R_{\max} = v_{\max}\tilde{t}$
- ▶ diffusion radius $R_{\text{diff}}(\tilde{t})$ (at which matter is moving at $\tilde{v}(\tilde{t})$):

$$t_{\text{diff}} \approx t_{\text{dyn}}$$

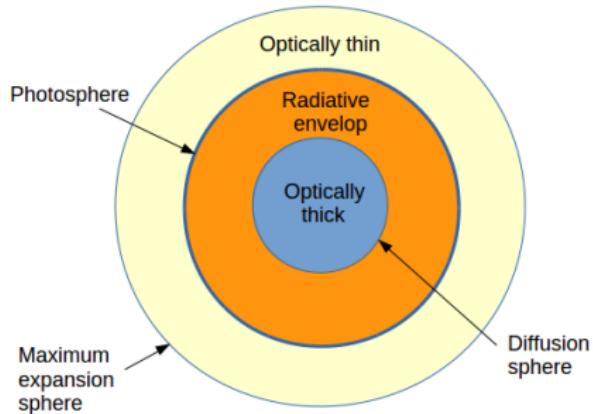
clearly

- ▶ $R_{\text{diff}}(\tilde{t}) = \tilde{v}(\tilde{t})\tilde{t}$
- ▶ **thermalizing photons outside this radius can be emitted at the photosphere carrying information about the present state of the system**

Photon diffusion model

Diffusion radius:

$$t_{\text{diff}} \approx t_{\text{dyn}} \Rightarrow \tilde{v} = v_{\text{eff}}$$



where

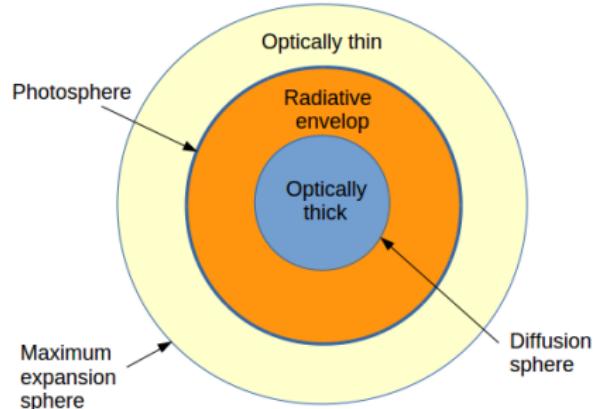
- ▶ $v_{\text{eff}} = c/\tau$ is the photon effective (diffusion) speed
- ▶ τ is the optical depth:

$$\tau \approx \langle \rho \rangle \Delta R \kappa \approx \frac{m_{>v}(\tilde{v}) \Delta R \kappa}{4\pi(\tilde{v}\tilde{t})^2 \Delta R}$$

⇒ implicit equation for $\tilde{v}(\tilde{t})$

$$c = \frac{m_{>v}(\tilde{v}) \kappa}{4\pi \tilde{v} \tilde{t}^2}$$

Photon diffusion model



Photospheric radius:

- ▶ $R_{\text{ph}}(\tilde{t})$ where

$$\tau(R_{\text{ph}}) = 2/3$$

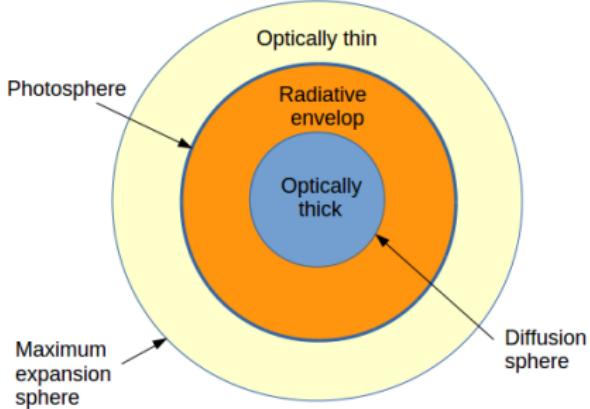
- ▶ matter at $R_{\text{ph}}(\tilde{t})$ expands with velocity $v_{\text{ph}}(\tilde{t})$:

$$R_{\text{ph}}(\tilde{t}) = v_{\text{ph}}(\tilde{t}) \tilde{t}$$

⇒ implicit equation for $v_{\text{ph}}(\tilde{t})$

$$\frac{m_{>v}(v_{\text{ph}}) \kappa}{4\pi (v_{\text{ph}} \tilde{t})^2} = \frac{2}{3}$$

Photon diffusion model



Photon luminosity:
emitted at the photosphere as a black body

$$L_\gamma(\tilde{t}) = m_{\text{rad,env}}(\tilde{t}) \dot{e}_{r-\text{proc}}(\tilde{t}) f_{\text{th}}(\tilde{t})$$

$$m_{\text{rad,env}}(\tilde{t}) = (m_{>v}(\tilde{v}) - m_{>v}(v_{\text{ph}}))$$

Emission at the photosphere with
black body temperature $T(\tilde{t})$

$$\frac{L_\gamma}{4\pi R_{\text{ph}}^2} = \sigma_{\text{SB}} T^4$$

Peak properties: dependencies

$$c = \frac{m_{>v}(\tilde{v}) \kappa}{4\pi \tilde{v} \tilde{l}^2} \Rightarrow t_{\text{peak}} \sim \sqrt{\frac{m_{\text{ej}} \kappa}{4\pi v_{\text{ej}} c}}$$

$$t_{\text{peak}} \sim 4.9 \text{ day} \left(\frac{\kappa}{10 \text{ cm}^2 \text{g}^{-1}} \right)^{1/2} \left(\frac{m_{\text{ej}}}{0.01 M_{\odot}} \right)^{1/2} \left(\frac{v}{0.1c} \right)^{-1/2}$$

Peak properties: dependencies

$$c = \frac{m_{>v}(\tilde{v}) \kappa}{4\pi \tilde{v} \tilde{l}^2} \Rightarrow t_{\text{peak}} \sim \sqrt{\frac{m_{\text{ej}} \kappa}{4\pi v_{\text{ej}} c}}$$

$$t_{\text{peak}} \sim 4.9 \text{ day} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2} \left(\frac{m_{\text{ej}}}{0.01 M_{\odot}} \right)^{1/2} \left(\frac{v}{0.1c} \right)^{-1/2}$$

$$L_{\gamma} = m_{\text{rad,env}} \dot{e}_{r-\text{proc}} f_{\text{th}} \Rightarrow L_{\text{peak}} \sim m_{\text{ej}} f_{\text{th}} \dot{e}_0 t_{\text{peak}}^{-\alpha}$$

$$L_{\text{peak}} \sim 2.4 \times 10^{40} \text{ erg/s} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{-13/20} \left(\frac{m_{\text{ej}}}{0.01 M_{\odot}} \right)^{7/20} \left(\frac{v}{0.1c} \right)^{13/20} \left(\frac{\dot{e}_0}{5 \times 10^{16} \text{ erg/g/s}} \right) \left(\frac{f_{\text{th}}}{0.5} \right)$$

Peak properties: dependencies

$$c = \frac{m_{>v}(\tilde{v}) \kappa}{4\pi \tilde{v} \tilde{l}^2} \Rightarrow t_{\text{peak}} \sim \sqrt{\frac{m_{\text{ej}} \kappa}{4\pi v_{\text{ej}} c}}$$

$$t_{\text{peak}} \sim 4.9 \text{ day} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2} \left(\frac{m_{\text{ej}}}{0.01 M_{\odot}} \right)^{1/2} \left(\frac{v}{0.1c} \right)^{-1/2}$$

$$L_{\gamma} = m_{\text{rad,env}} \dot{e}_{r-\text{proc}} f_{\text{th}} \Rightarrow L_{\text{peak}} \sim m_{\text{ej}} f_{\text{th}} \dot{e}_0 t_{\text{peak}}^{-\alpha}$$

$$L_{\text{peak}} \sim 2.4 \times 10^{40} \text{ erg/s} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{-13/20} \left(\frac{m_{\text{ej}}}{0.01 M_{\odot}} \right)^{7/20} \left(\frac{v}{0.1c} \right)^{13/20} \left(\frac{\dot{e}_0}{5 \times 10^{16} \text{ erg/g/s}} \right) \left(\frac{f_{\text{th}}}{0.5} \right)$$

$$R_{\text{ph,peak}} \sim v_{\text{ej}} t_{\text{peak}}$$

$$R_{\text{ph,peak}} \sim 1.26 \times 10^{15} \text{ cm} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2} \left(\frac{m_{\text{ej}}}{0.01 M_{\odot}} \right)^{1/2} \left(\frac{v}{0.1c} \right)^{1/2}$$

Peak properties: dependencies

$$c = \frac{m_{>v}(\tilde{v}) \kappa}{4\pi \tilde{v} \tilde{l}^2} \Rightarrow t_{\text{peak}} \sim \sqrt{\frac{m_{\text{ej}} \kappa}{4\pi v_{\text{ej}} c}}$$

$$t_{\text{peak}} \sim 4.9 \text{ day} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2} \left(\frac{m_{\text{ej}}}{0.01 M_{\odot}} \right)^{1/2} \left(\frac{v}{0.1c} \right)^{-1/2}$$

$$L_{\gamma} = m_{\text{rad,env}} \dot{e}_{r-\text{proc}} f_{\text{th}} \Rightarrow L_{\text{peak}} \sim m_{\text{ej}} f_{\text{th}} \dot{e}_0 t_{\text{peak}}^{-\alpha}$$

$$L_{\text{peak}} \sim 2.4 \times 10^{40} \text{ erg/s} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{-13/20} \left(\frac{m_{\text{ej}}}{0.01 M_{\odot}} \right)^{7/20} \left(\frac{v}{0.1c} \right)^{13/20} \left(\frac{\dot{e}_0}{5 \times 10^{16} \text{ erg/g/s}} \right) \left(\frac{f_{\text{th}}}{0.5} \right)$$

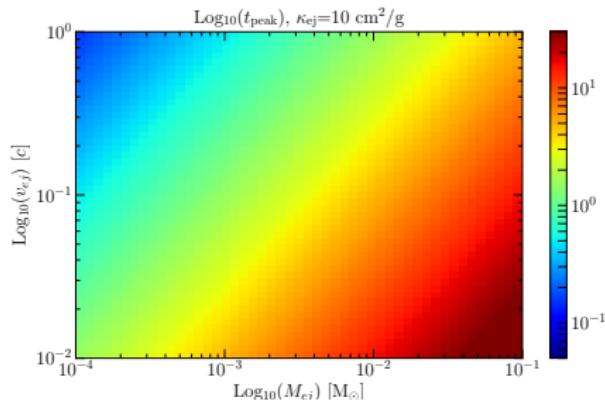
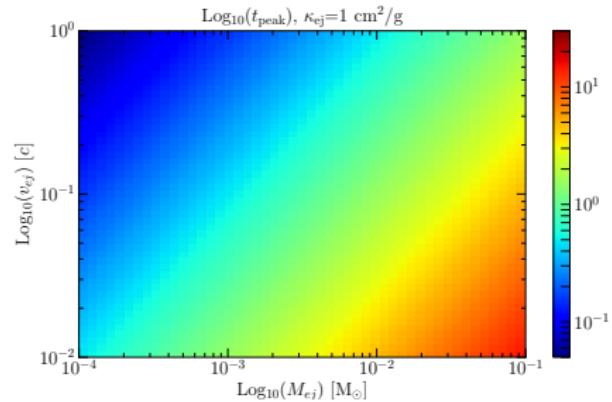
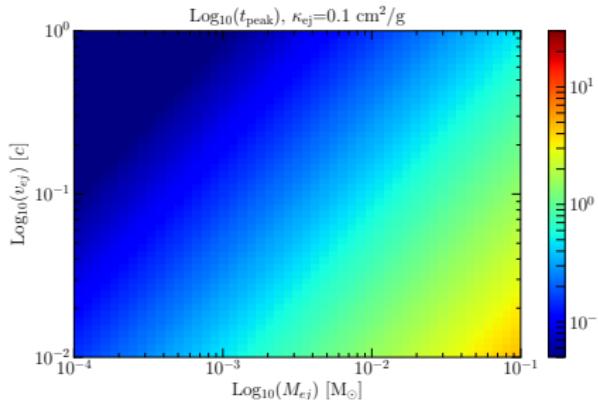
$$R_{\text{ph,peak}} \sim v_{\text{ej}} t_{\text{peak}}$$

$$R_{\text{ph,peak}} \sim 1.26 \times 10^{15} \text{ cm} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2} \left(\frac{m_{\text{ej}}}{0.01 M_{\odot}} \right)^{1/2} \left(\frac{v}{0.1c} \right)^{1/2}$$

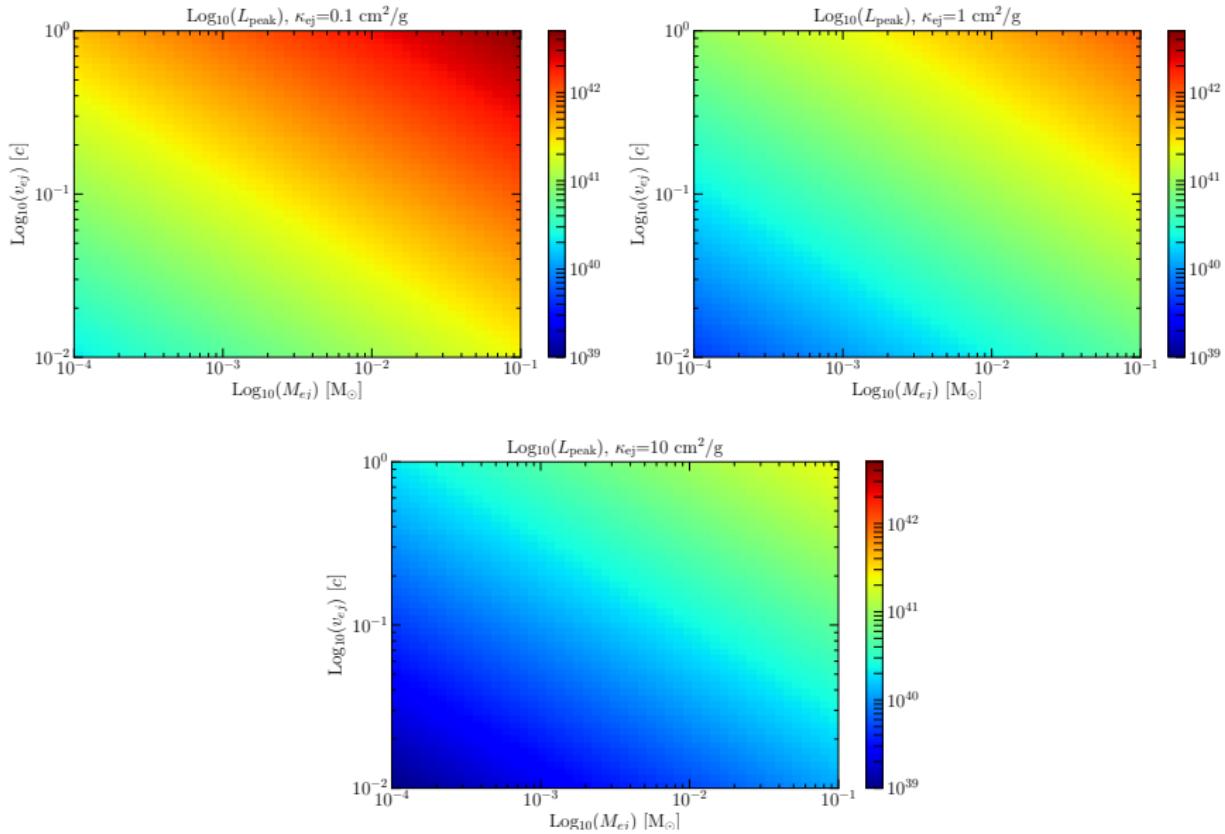
$$\frac{L_{\gamma}}{4\pi R_{\text{ph}}^2} = \sigma_{\text{SB}} T^4 \Rightarrow T_{\text{peak}} \sim \left(\frac{L_{\text{peak}}}{4\pi R_{\text{ph,peak}}^2 \sigma_{\text{SB}}} \right)^{1/4}$$

$$T_{\text{peak}} \sim 2.15 \times 10^3 \text{ K} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{-33/80} \left(\frac{m_{\text{ej}}}{0.01 M_{\odot}} \right)^{-13/80} \left(\frac{v}{0.1c} \right)^{-27/80} \left(\frac{\dot{e}_0}{5 \times 10^{16} \text{ erg/g/s}} \right)^{1/4} \left(\frac{f_{\text{th}}}{0.5} \right)^{1/4}$$

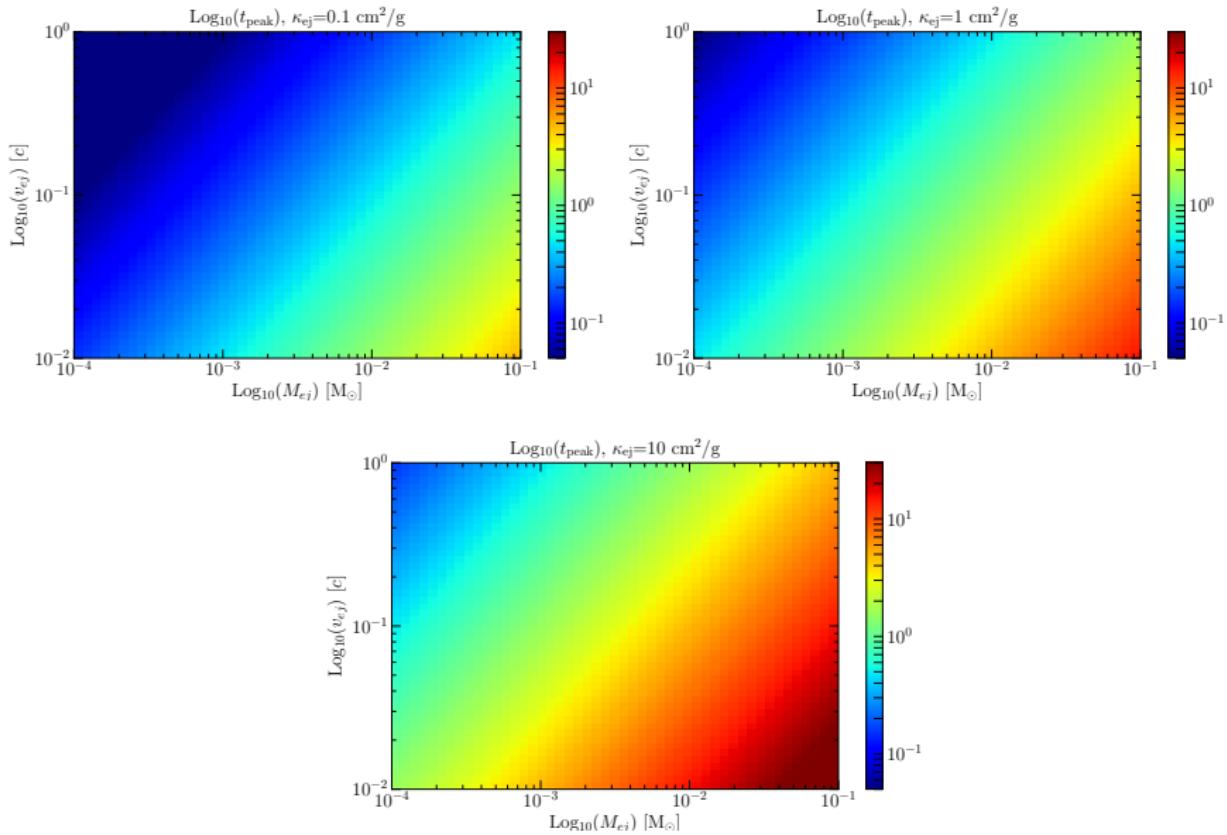
Peak properties: exploration of t_{peak} (days)



Peak properties: exploration of L_{peak} (erg/s)



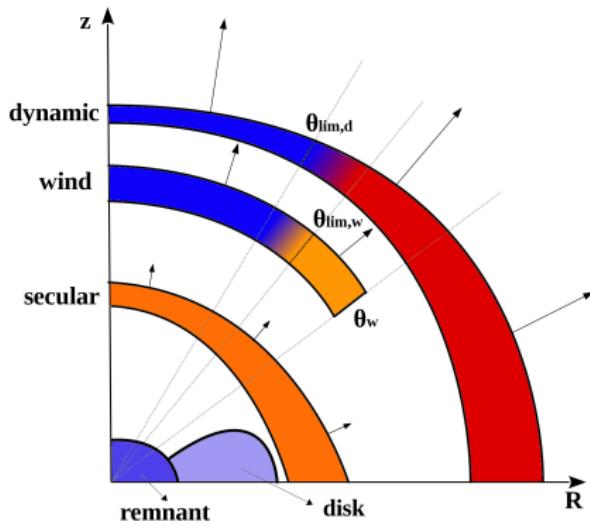
Peak properties: exploration of $T_{\text{peak}}(\text{K})$



Multi-Component Anisotropic Kilonova Model

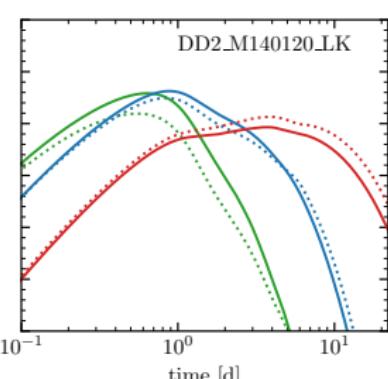
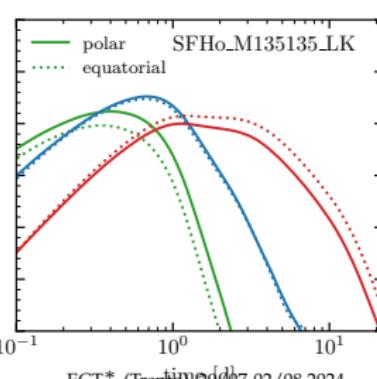
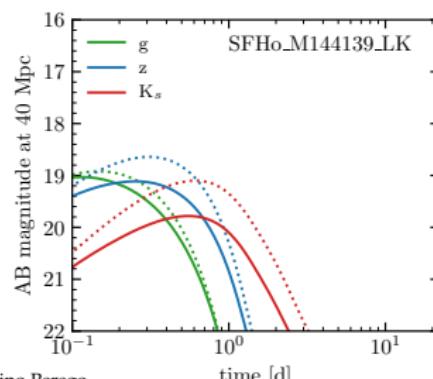
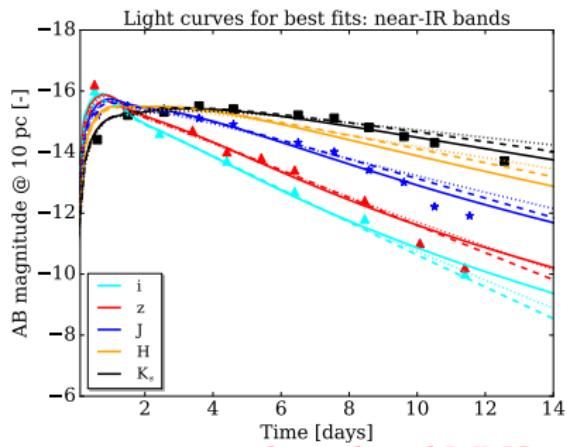
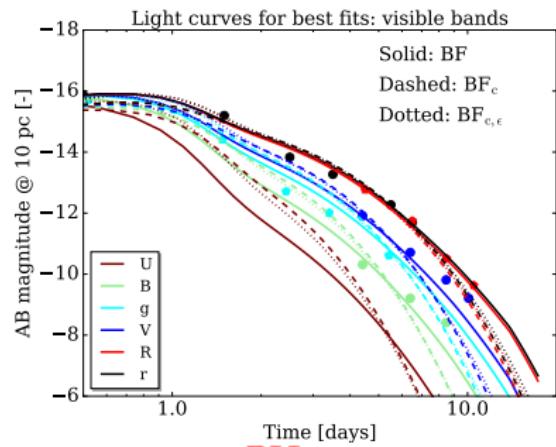
- ▶ kilonova model that includes our present knowledge about ejecta
- ▶ different ejection channels → multi-component
- ▶ explicit dependency on polar angle → anisotropic
 - ▶ multi-angle (polar angle discretization)
 - ▶ explicit dependence on observer viewing angle

Perego, Radice, Bernuzzi 17, ApJL



- ▶ $M_{\text{ej}}(\theta), v_{\text{ej}}(\theta), \kappa_{\text{ej}}(\theta)$
- ▶ 1D models along each ray
- ▶ homologous mass expansion

Kilonova light curves



Some useful references

- ▶ some recent reviews on BNS mergers:
 - ▶ Radice, Bernuzzi, Perego, *The Dynamics of Binary Neutron Star Mergers and GW170817*, Annual Review of Nuclear and Particle Science, vol. 70, p.95-119
 - ▶ Bernuzzi, *Neutron star merger remnants* General Relativity and Gravitation, Volume 52, Issue 11, article id.108
- ▶ neutrino physics and thermodynamics in BNS mergers:
 - ▶ Foucart, *Neutrino transport in general relativistic neutron star merger simulations*, Living Reviews in Computational Astrophysics, Volume 9, Issue 1, article id.1
 - ▶ Cusinato *et al*, *Neutrino emission from binary neutron star mergers: characterising light curves and mean energies*, The European Physical Journal A, Volume 58, Issue 5, article id.99
 - ▶ Perego *et al*, *Thermodynamics conditions of matter in neutron star mergers*, The European Physical Journal A, Volume 55, Issue 8, article id. 124, 21 pp.
 - ▶ Endrizzi *et al*, *Thermodynamics conditions of matter in the neutrino decoupling region during neutron star mergers*, The European Physical Journal A, Volume 56, Issue 1, article id.15

Some useful references, II

- ▶ some recent reviews and works on BNS mergers, r-process and kilonovae:
 - ▶ Cowan *et al*, *Origin of the heaviest elements: The rapid neutron-capture process*, Reviews of Modern Physics, Volume 93, Issue 1, article id.015002
 - ▶ Perego, Thielemann, Cescutti, *r-Process Nucleosynthesis from Compact Binary Mergers* Handbook of Gravitational Wave Astronomy. Edited by C. Bambi, S. Katsanevas and K.D. Kokkotas. ISBN: 978-981-15-4702-7, A Living Reference Work. Springer, 2021, id.13
 - ▶ Metzger, *Kilonovae*, Living Reviews in Relativity, Volume 23, Issue 1, id.1
 - ▶ Radice *et al*, *Binary Neutron Star Mergers: Mass Ejection, Electromagnetic Counterparts, and Nucleosynthesis*, The Astrophysical Journal, Volume 869, Issue 2, article id. 130, 31 pp. (2018)
 - ▶ Radice *et al*, *Long-lived remnants from binary neutron star mergers*, Monthly Notices of the Royal Astronomical Society, Volume 481, Issue 3, p.3670-3682