Binary neutron star mergers: neutrinos, ejecta and kilonovae

Albino Perego

Trento University & TIFPA-INFN

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DTP/Talent School: "Nuclear Theory for Astrophysics"

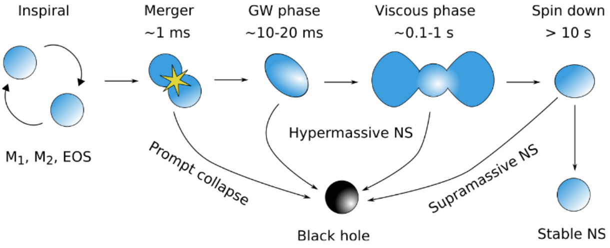
questions? albino.perego@unitn.it

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

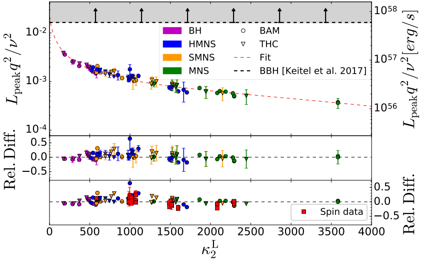


Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS, Bernuzzi 2020 for recent reviews

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

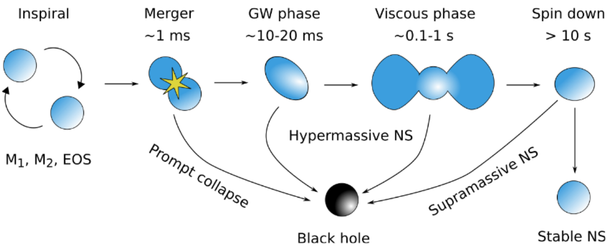
$$L_{\mathrm{GW,peak}} \sim 10^{55} - 10^{56} \mathrm{erg/s}$$

- 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



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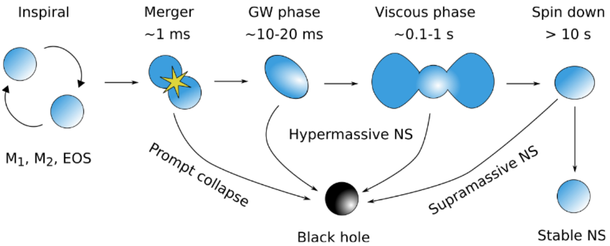
- speed at merger ($d = R_1 + R_2$)

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

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

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

BNS merger in a nutshell: merger



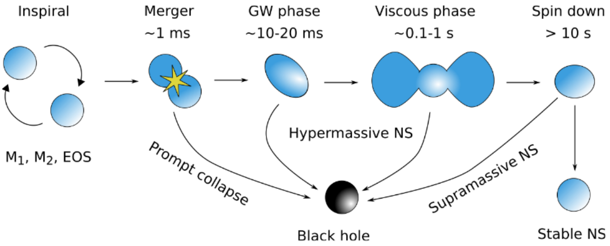
Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS, Bernuzzi 2020 for recent reviews

- dynamical timescales:

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

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

How hot is a merger remnant?



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

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

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

- hot nuclear matter → copious neutrino production

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

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

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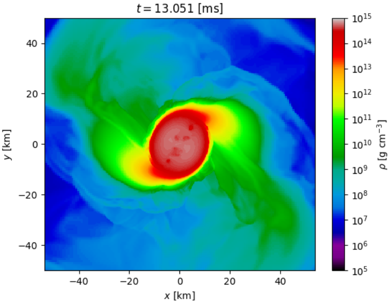
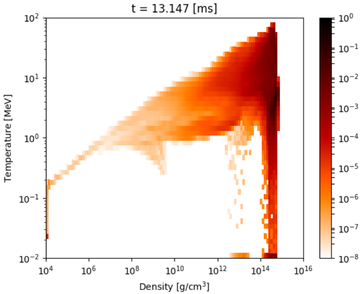
BNS simulation performed with the WhiskyTHC code Radice+ 12,14,15

$$M_1 = M_2 = 1.364\, M_\odot$$

DD2 EOS, leakage+M0 scheme for neutrinos

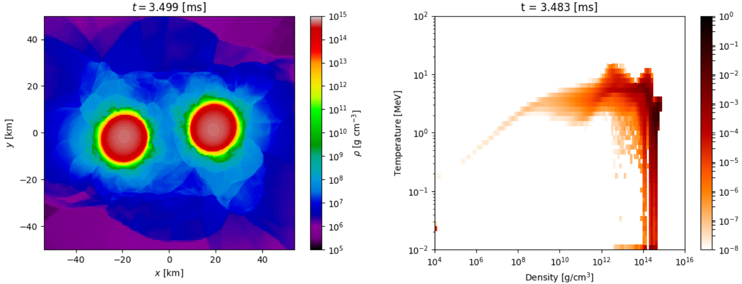
at each time, mass weighted histograms in the ρ-T-Y_e or ρ-s-Y_e plane



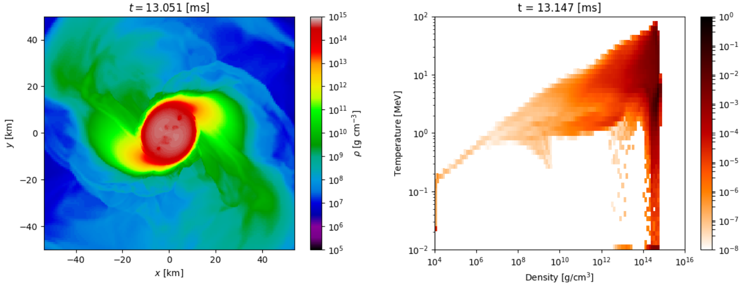


BNS mergers on thermodynamics diagrams II

inspiral



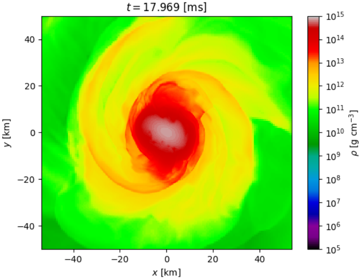
$t(T_{\rm peak})$

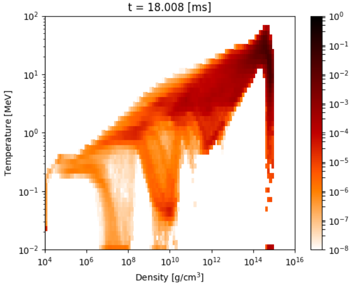


Perego,Bernuzzi,Radice EPJA 2019

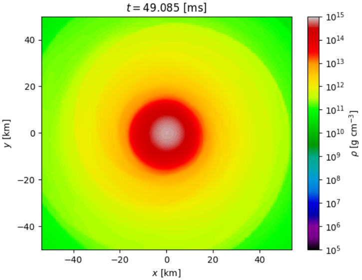
BNS mergers on thermodynamics diagrams III

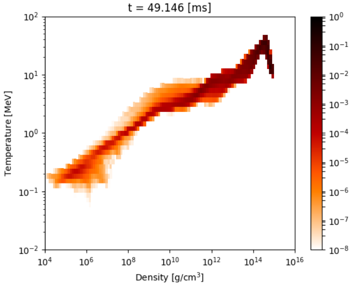
$t \gtrsim t_{\rm dyn}$





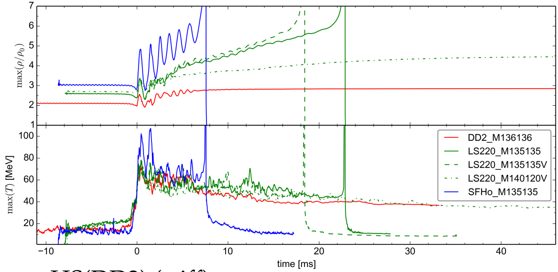
$t \gg t_{\rm dyn}$





Perego,Bernuzzi,Radice EPJA 2019

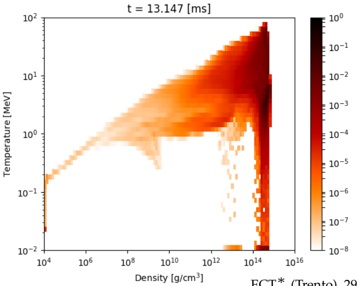
Thermodynamics diagrams: soft VS stiff EOS

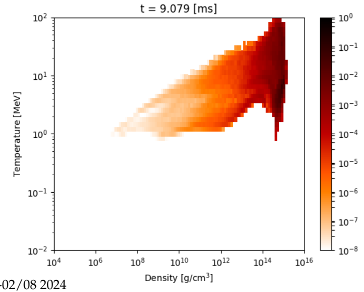


HS(DD2) (stiff),
$M_1 = M_2 = 1.364 M_\odot$

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

$t(T_{\rm peak})$





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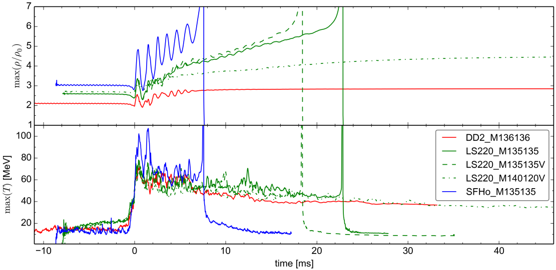
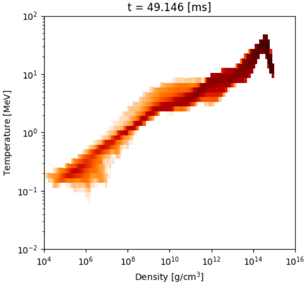
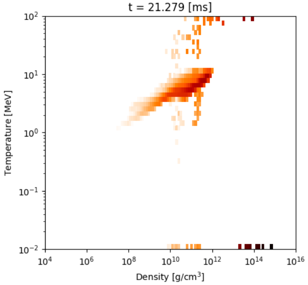


DD2 EOS (stiff)

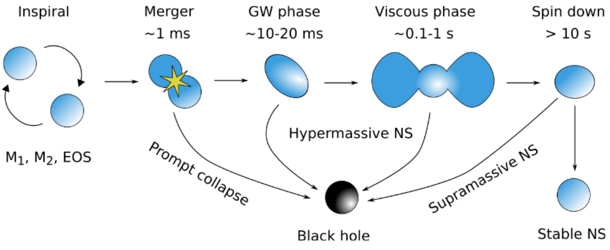
SFHo EOS (soft)

$t \gg t_{\rm dyn}$





BNS merger in a nutshell: GW-dominated phase



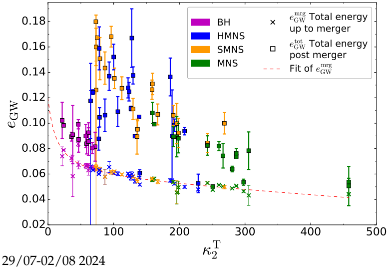
Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS, Bernuzzi 2020 for recent reviews

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

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

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

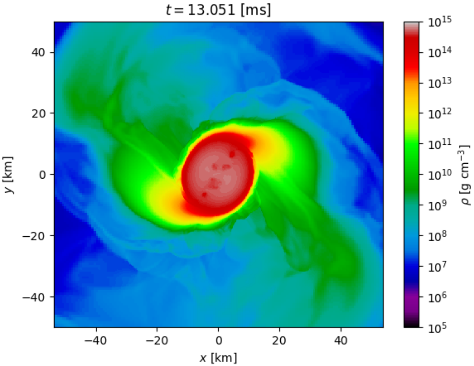
$$\sim 0.11 M_\odot c^2 \left(\frac{\langle L_{\rm GW}\rangle}{10^{55}\,{\rm erg/s}}\right)\left(\frac{t_{\rm GW}}{20{\rm ms}}\right)$$



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 $\rightarrow$ decompression & expansion of hot nuclear matter



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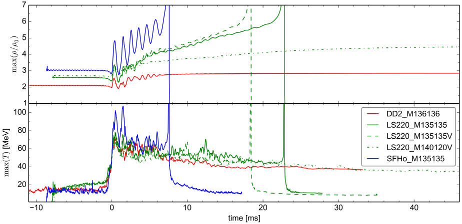
- core bounces
- hot spots $\rightarrow$ hot ring
- differential rotation: slowly rotating core ($\sim$ 1kHz) & fast envelope ($\sim$ 2kHz)



Perego+ EPJA, 55, 8 2019

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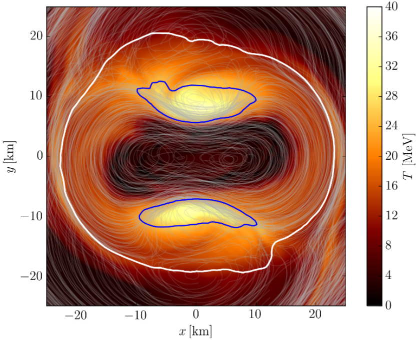


Kastaun+ PRD, 94, 4, 2016

BNS merger in a nutshell: disk formation

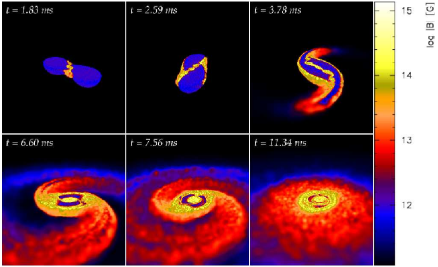
- tidal tails
- hot matter ejection
- angular momentum conservation

$\Rightarrow$ accretion disk formation

- what is the disk?
  - BH+torus: $\rho_{\rm torus} \lesssim 10^{12} \mathrm{g/cm^3}$
  - MNS+disk: $\rho_{\rm disk} \lesssim 10^{13} \mathrm{g/cm^3}$
- formation process:

  $t_{\rm form} \sim 10 - 20 \mathrm{ms}$ several $t_{\rm dyn,orb}$

- BH formation:
  more than 50% of disk immediately shallowed by BH



Price & Rosswog+ Science ,2006

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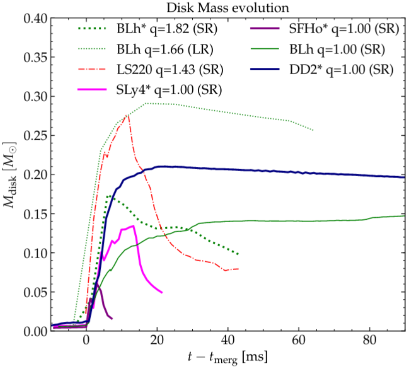


Nedora+ ApJ 906, 2,2021

BNS merger in a nutshell: disk properties

- (possibly) massive:

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

- typical lengthscale

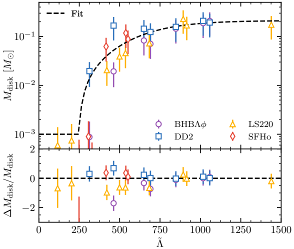
$$R_{\rm disk} \sim \text{several } 100\text{km}$$

- thick disks:

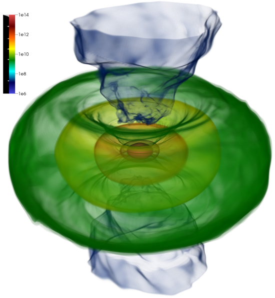
$$\frac{H}{R} \sim \frac{c_s}{v_{\rm orb}} \sim 0.2 - 0.7$$

- fix ratio between $J_{\rm disk}$ and $M_{\rm disk}$
  - $J_{\rm disk} \sim 7 - 10 \frac{G}{c} M_\odot M_{\rm disk}$
  - constant specific angular momentum:

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



Radice+ ApJ 2018



Perego,Bernuzzi,Radice EPJA 2019

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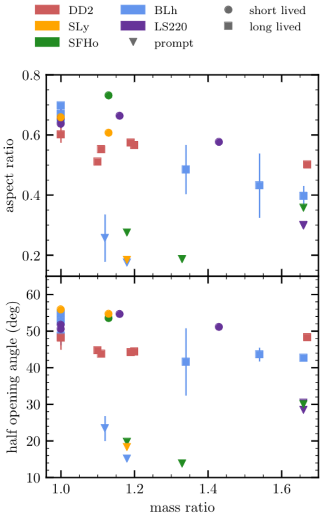

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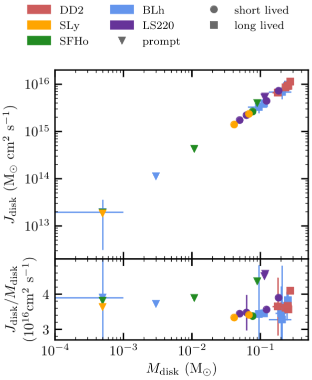

BNS merger in a nutshell: disk properties

- (possibly) massive:

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

- typical lengthscale

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

- thick disks:

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

- fix ratio between $J_{\rm disk}$ and $M_{\rm disk}$
  - $J_{\rm disk} \sim 7 - 10 \frac{G}{c} M_\odot M_{\rm disk}$
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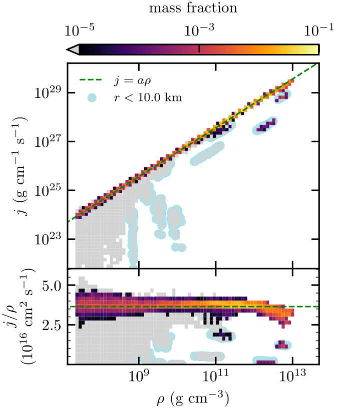
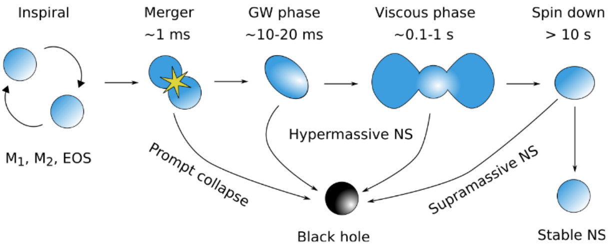


Camilletti *et al* MNRAS 2023

BNS merger in a nutshell: viscous phase

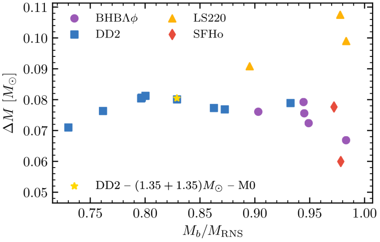


Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS, Bernuzzi 2020 for recent reviews

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

$$\Delta E_\nu \sim 5\times10^{52}\mathrm{erg}\left(\frac{\langle L_\nu\rangle}{5\times10^{52}\mathrm{erg/s}}\right)\left(\frac{t_\nu}{1\mathrm{s}}\right)$$

$$= 0.03 M_\odot c^2 \left(\frac{\langle L_\nu\rangle}{5\times10^{52}\mathrm{erg/s}}\right)\left(\frac{t_\nu}{1\mathrm{s}}\right)$$



Radice,Perego+ MNRAS 2018

Neutrinos in BNS mergers

Kinetic theory description of neutrinos

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

  $\frac{g_J\, f(t, \mathbf{x}, \mathbf{p})\, \mathrm{d}^3x\, \mathrm{d}^3p}{h^3}$ number of particles inside a volume d^3x around $\mathbf{x}$, with momentum between $\mathbf{p}$ and $\mathbf{p} + \mathrm{d}\mathbf{p}$, 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:

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

- density of energy:

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

- stress tensor (pressure):

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

Neutrino transport and moments

- time evolution of $f(x,p)$ $\quad\rightarrow\quad$ GR transport equation:

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

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

$$\frac{\mathrm{d}x^\alpha}{\mathrm{d}\tau}=p^\alpha=\omega\,(u^\alpha+l^\alpha)\qquad l^\alpha l_\alpha=1\qquad l^\alpha u_\alpha=0$$

- calculation of momenta of f:

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

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

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

all evaluated in fluid frame

From energy dependent to energy integrated transport

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

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

- stress-energy tensor in fluid frame

$$T^{\alpha\beta}_{\mathrm{rad}} = \int_0^{+\infty} \left(J_{(\omega)} u^\alpha u^\beta + H^\alpha_{(\omega)} u^\beta + H^\beta_{(\omega)} u^\alpha + K^{\alpha\beta}_{(\omega)} \right) \mathrm{d}\omega =$$

$$= J u^\alpha u^\beta + H^\alpha u^\beta + H^\beta u^\alpha + K^{\alpha\beta}$$

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

$$T^{\mu\nu}_{\mathrm{rad}} = E n^\mu n^\nu + F^\mu n^\nu + F^\nu n^\mu + P^{\mu\nu}$$

- coupling with GR-hydrodynamics

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

Moment transport equations

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

$$\partial_t(\sqrt{\gamma}E) + \partial_j[\sqrt{\gamma}(\alpha F^j - \beta^j E)] \\ = \alpha\sqrt{\gamma}[P^{ij}K_{ij} - F^j\partial_j \ln\alpha - S^\alpha n_\alpha],$$

$$\partial_t(\sqrt{\gamma}F_i) + \partial_j[\sqrt{\gamma}(\alpha P_i{}^j - \beta^j F_i)] \\ = \sqrt{\gamma}\left[-E\partial_i\alpha + F_k\partial_i\beta^k + \frac{\alpha}{2}P^{jk}\partial_i\gamma_{jk} + \alpha S^\alpha \gamma_{i\alpha}\right]$$

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

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

$$D_t\, f(\omega) = j(\omega) - \left(j + \frac{1}{\lambda(\omega)} \right) f(\omega)$$

$$D_t\, f(\omega) = j(\omega) - \kappa(\omega)\, f(\omega)$$

- $\kappa = (j + \lambda^{-1})$: (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 $\bar{\nu}_e$:

$$p + e^- \rightarrow n + \nu_e \text{ (EC)}$$
$$n + e^+ \rightarrow p + \bar{\nu}_e \text{ (PC)}$$

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

$$e^- + e^+ \rightarrow \nu + \bar{\nu}$$
$$N + N \rightarrow N + N + \nu + \bar{\nu}$$

- scattering for all ν's:

$$N + \nu \rightarrow N + \nu \text{ (quasi-elastic)}$$
$$e^\pm + \nu \rightarrow e^\pm + \nu \text{ (inelastic)}$$

- all neutrino flavor relevant, but with different physics

A qualitative overview of reactions (part 1)

$$e^- + p \leftrightarrow n + \nu_e \qquad e^+ + n \leftrightarrow p + \bar{\nu}_e$$

- $m_n c^2 \gtrsim m_p c^2 \gg E_e$ and $E_\nu \Rightarrow \delta_{(4)}(p_{\mathrm{i}} - p_{\mathrm{f}})$ 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

$$e^- + e^+ \leftrightarrow \nu + \bar{\nu} \qquad N + N \leftrightarrow N + N + \nu + \bar{\nu}$$

- $\rightarrow$: 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)

$$\nu + p \to \nu' + p \qquad \nu + n \to \nu' + n$$

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

$$e^\pm + \nu \to e^\pm + \nu$$

- since $\omega \sim E_e \quad \Rightarrow \quad \omega' \neq \omega$
- 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)

$$e^- + p \to n + \nu_e$$

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

Electron neutrino emissivity

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

$$e^- + p \to n + \nu_e$$

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

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

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

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

- let's rewrite it in the following way:

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

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

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

Total electron capture rates

- plasma $(n, p, e^{\pm}, \gamma)$ in thermal and NSE (NS matter EOS)

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

$$F_k(\eta) = \int_0^\infty \frac{x^k}{1+\exp(x-\eta)}\, \mathrm{d}x$$

- ν_e production rates: boosted by high temperatures & densities

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

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

Neutrino production mean energy

- neutrinos carry energy. For EC,

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

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

- 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

$$e^+ + n \to p + \bar{\nu}_e$$

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

$$j \propto n_n (k_B T)^5 F_4 \left(-\frac{\mu_e}{T} \right) \quad \eta \propto n_n (k_B T)^6 F_5 \left(-\frac{\mu_e}{T} \right) \quad \langle \omega \rangle = k_B T \frac{F_5 \left(-\frac{\mu_e}{k_B T} \right)}{F_4 \left(-\frac{\mu_e}{k_B T} \right)}$$

- pair annihilation

$$e^- + e^+ \to \nu + \bar{\nu}$$

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

- N-N bremsstrahlung

$$N + N \to N + N + \nu + \bar{\nu}$$

  - $j \propto \rho^2 \, (k_{\rm B} T)^{9/2} \qquad \langle \omega + \omega' \rangle \approx 4.36 \, (k_{\rm B} T) \qquad \eta \propto \rho^2 \, (k_{\rm B} T)^{11/2}$

Neutrino opacity in merger remnants

$$n + \nu_e \rightarrow e^- + p$$

forward and backward reactions related by detailed balance

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

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

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

- $p + \bar{\nu}_e \rightarrow e^+ + n$ $\quad \rightarrow \frac{1}{\lambda(\omega)} \approx n_p \sigma_0 \left(\frac{\omega - \Delta}{m_e c^2}\right)^2 (1 - f_{e^+}(\omega - \Delta))$
- $N + \nu \rightarrow N + \nu$ $\quad \rightarrow \frac{1}{\lambda(\omega)} \approx n_b \sigma_0 \left(\frac{\omega}{m_e c^2}\right)^2$

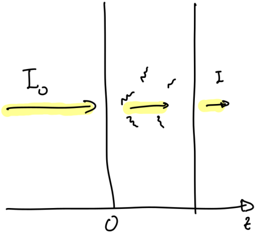
$$\Rightarrow \quad \lambda_\nu \sim \frac{1}{n_{\rm B}\sigma_\nu} \approx 2.36 \times 10^3 {\rm cm} \left(\frac{\rho}{10^{14}\,{\rm g/cm^3}}\right)^{-1} \left(\frac{\omega}{10\,{\rm MeV}}\right)^{-2}$$

Optical depth

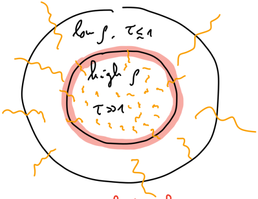
- optical depth τ along a path γ (λ: ν mean free path)

$$\tau_\gamma = \int_\gamma \lambda^{-1}\, \mathrm{d}s$$

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



$$I(z>0) = I_0 \exp\left(-\int \frac{dz}{\lambda}\right)$$
$$= I_0 \exp(-\tau)$$



$\tau \approx 1$ photosphere

↓

ν - sphere

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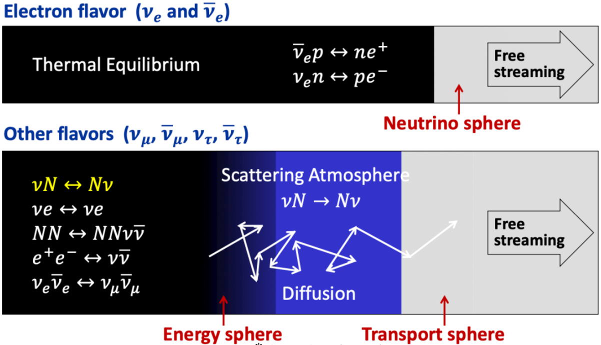


Optical depth: scattering VS equilibrium

- neutrino matter interactions
  - processes very effecient in coupling radiation to matter: e.g. absorption
  - processes very inefficient in coupling matter to radiation:
    e.g. elastic scattering
- *diffusion* optical depth: $\tau_{\rm diff}$

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

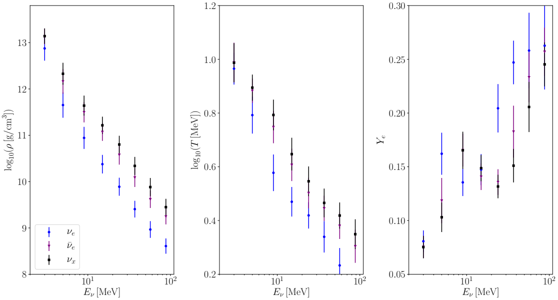
- *equilibrium* optical depth: $\tau_{\rm eq}$

$$\kappa_{\rm eq} = \sqrt{\kappa_{\rm diff}\,\kappa_{\rm ab}}$$

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

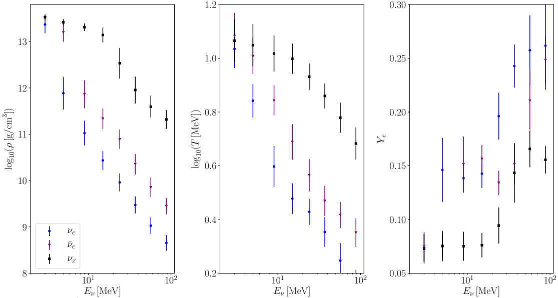
- $\sigma_\nu \propto \omega^2 \to$ optical depth and decoupling significantly depend on neutrino energy!

ν surfaces for MNS remnants: energy dependency

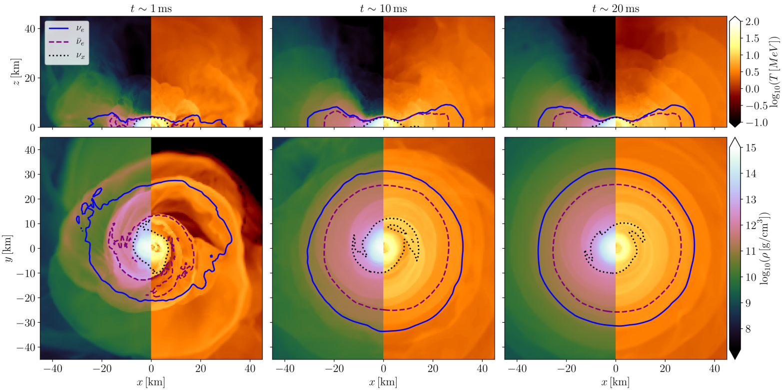


- DD2, $\tau_{\rm diff}(E_\nu) = 2/3$ at 20ms
- dominant $\sigma_\nu \propto \rho\omega^2$ contribution
- relevant neutrino decoupling: $10^{9-13}\mathrm{gcm}^{-3}$

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



Equilibrium surfaces for average ν energies



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

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

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

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

- 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
  - $\delta T/T \lesssim 8\%$, $\delta P/P \lesssim 5\%$

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

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

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

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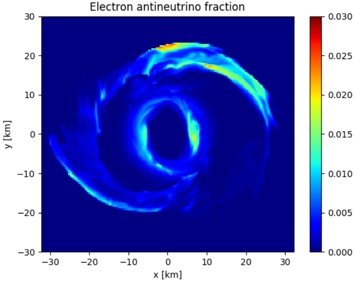
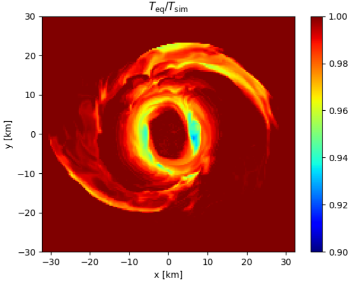




Neutrino diffusion & trapping

- diffusion timescale

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

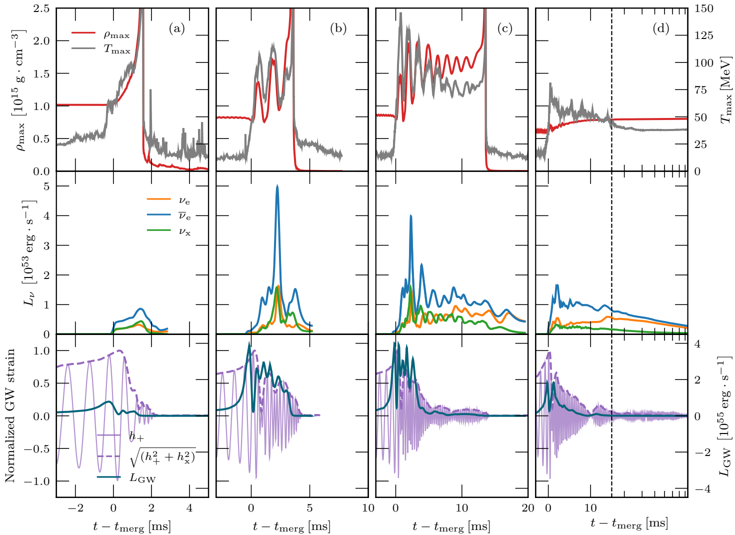
- $t_{\rm diff}$ from the remnant: $\ell = R_{\rm rem}$

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

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

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

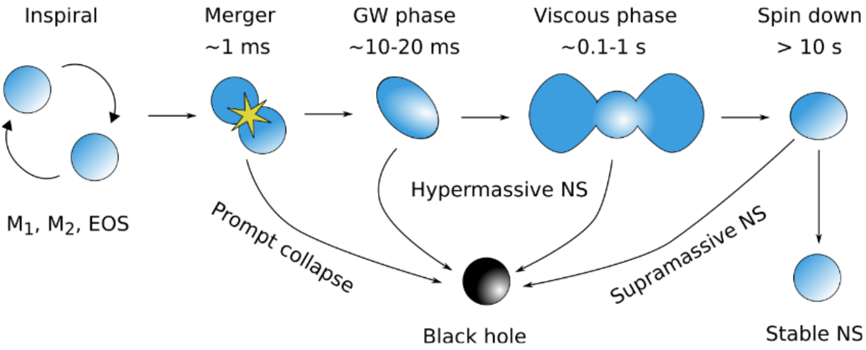
Neutrino emission: qualitative overview



a) PC b) short lived c) delayed collapse d) long lived

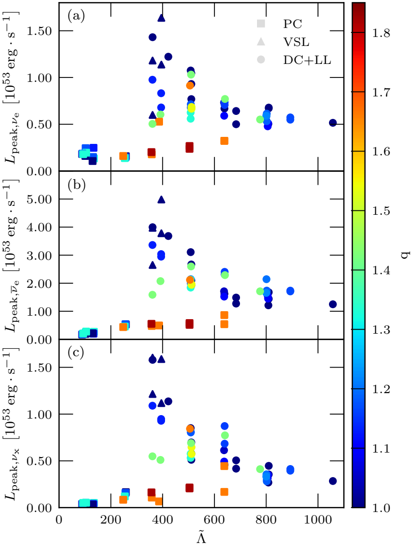
Cusinato *et al*, EPJA 2022

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 brench with weaker dependence on $\tilde{\Lambda}$
  - $L_{\nu,\mathrm{peak}}$ increases for increasing $\tilde{\Lambda}$, probably related with q
- similar dependence for $\langle L_\nu \rangle_{10\ \mathrm{ms}}$

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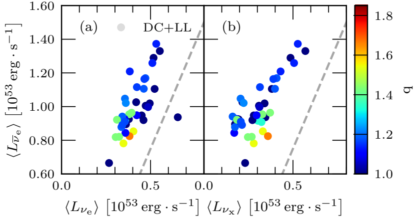
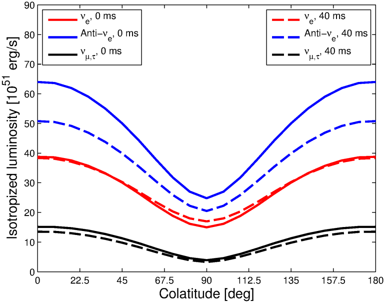
Neutrino emission: additional properties



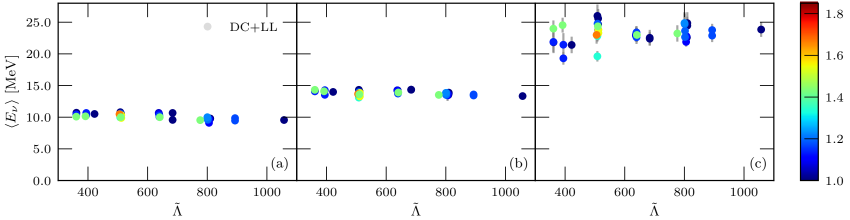


Top: Cusinato *et al*, EPJA 2022; Bottom: Perego+ 2014 MNRAS

- (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
  - $L_{\nu,\mathrm{pole}} \sim 3\, L_{\nu,\mathrm{equator}}$

e.g., Dessart+2009, Perego+14 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 looses 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:

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

- Bernoulli criterion:

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

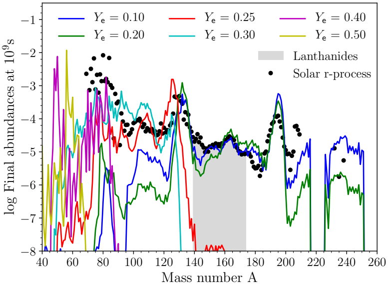
r-process nucleosynthesis in BNS ejecta

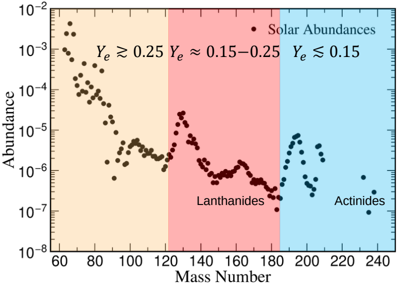
ideal conditions for r-process nucleosynthesis

- after dynamical phase, ejecta expand homologously

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

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

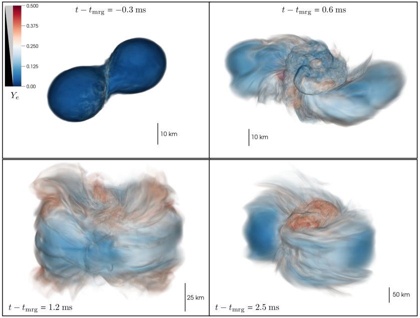




left: Perego, Thielemann & Cescutti 2021; right: Courtesy of G. Martinez-Pinedo

Dynamical ejecta from BNS merger

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



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

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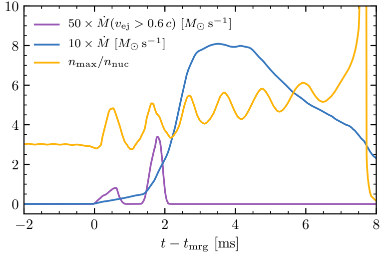

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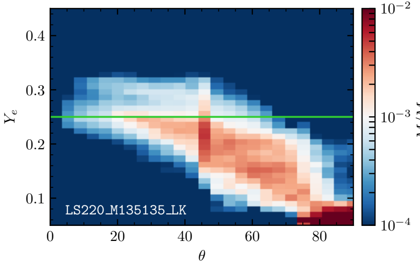
← Radice+ ApJ 18

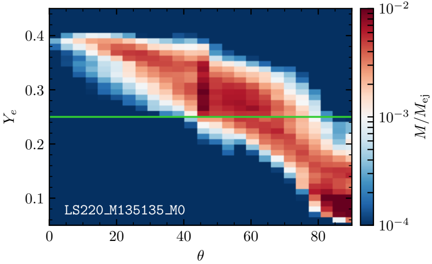
Impact of ν processes on BNS merger ejecta

- 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: $n + \nu_e \to p + e^-$
  - 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

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

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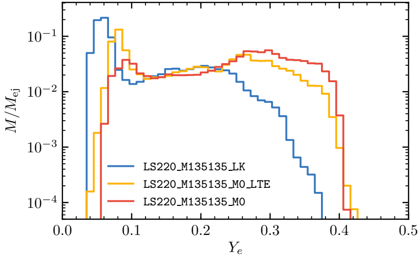
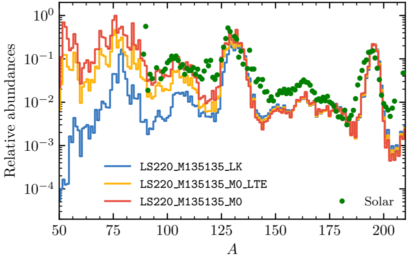


w neutrino absorption



Radice+ ApJ 2018

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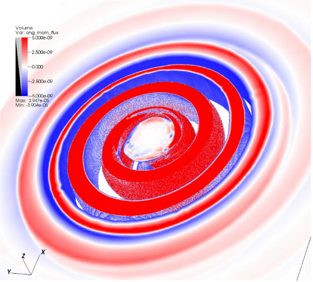
Spiral-wave wind

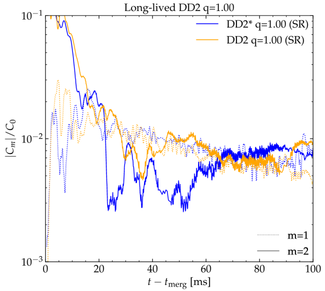
- development of GW-quiet $m = 1$ (long-lived) mode in addition to GW-loud $m = 2$ (short-lived) mode
- $m = 1, 2$ modes produce spiral arms in the disk, trasporting angular momentum outwards
- production of a fast wind from the disk outer layers
- robust hydrodynamics mechanism, depending on MNS lifetime

ϕ-angular momentum radial flux



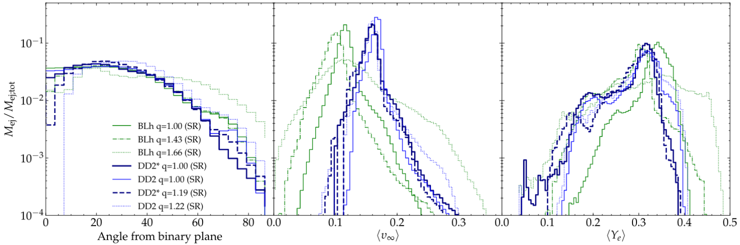
Nedora *et al* ApjL 2019

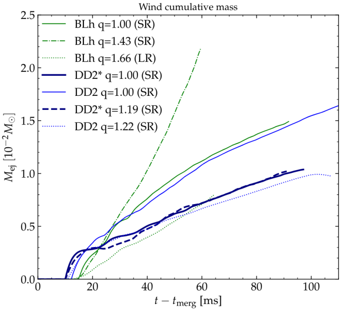
ρ azimuthal mode decomposition



Nedora *et al* ApJ 2021

Spiral-wave wind ejecta

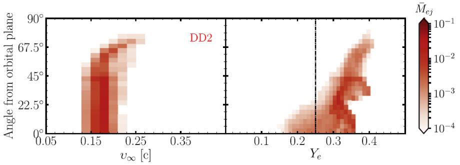




- Bernoulli criterion

Nedora *et al* ApJ 2021

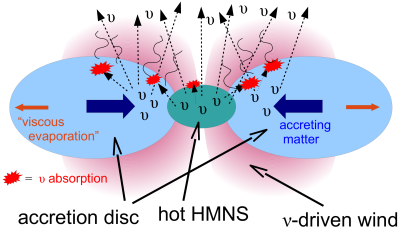
- $\dot{M}_{\rm wind} \sim 0.05 - 0.15\ M_\odot\ s^{-1}$
- mostly equatorial, fast, broad Y_e

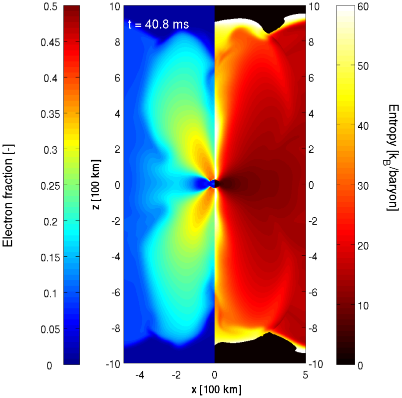


Nedora *et al* ApjL 2019

Neutrino-driven winds from BNS merger

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





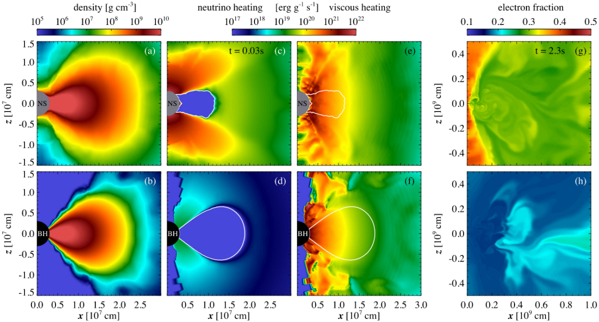
Perego+14, MNRAS, Martin+15 ApJ, see also Fujibajashi+18 ApJ, Nedora+21 ApJ

Viscous ejecta from accretion disks

- MHD viscosity inside the disk
- remnant expansion $\rightarrow$ nuclear recombination in the disk

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

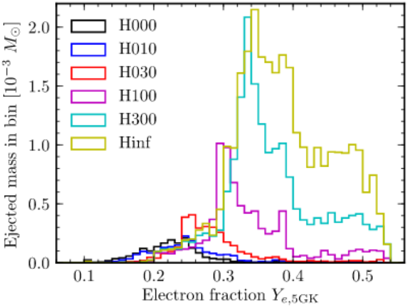
- $t_{\mathrm{ej,sec}} \sim$ few 100's ms and $v_{\mathrm{ej,sec}} \lesssim 0.1c$
- $M_{\mathrm{ej,sec}} \sim (0.1 - 0.4)\, M_{\mathrm{disk}}$
- $s_{\mathrm{ej,sec}} \sim 10 - 100\ k_B/\mathrm{baryon}$

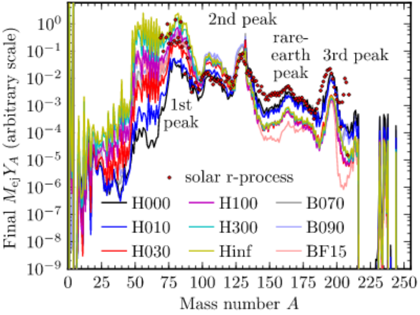


Figures from Metzger & Fernandez MNRAS 14, Wu+ MNRAS 16, see e.g. Just+ MNRAS 15, Siegel& Metzger PRD 17

Neutrino effect on viscosity-driven ejecta

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





$\mathrm{Y_e}$ histograms (and nucleosynthesis) of viscous ejecta depending on HMNS lifetime. Lippuner+ MNRAS 2016

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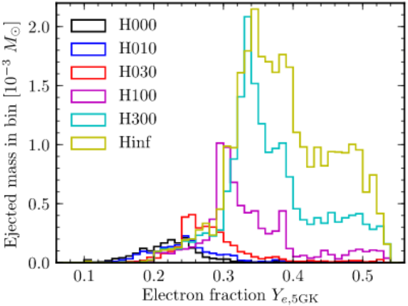

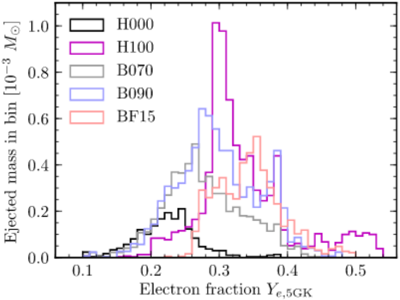

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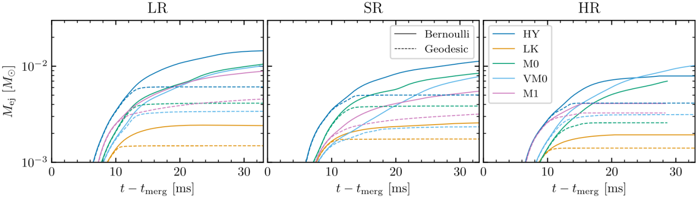
How robust is ejecta modelling?

- 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)

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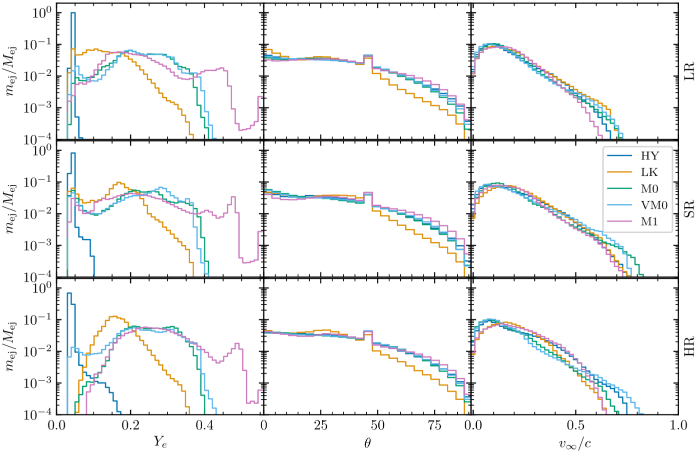
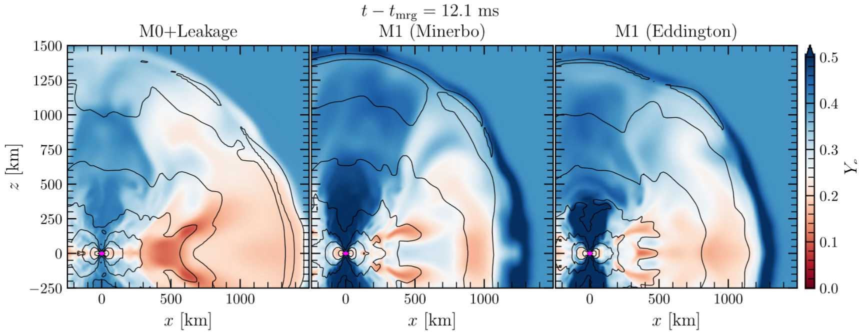


Zappa *et al* MNRAS (2023)

How robust is neutrino modelling?

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



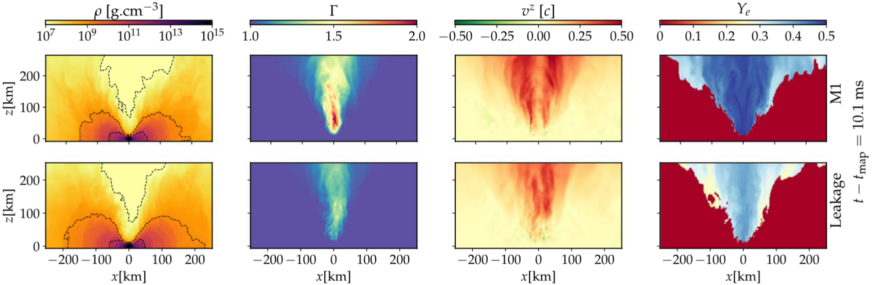
Radice *et al* MNRAS (2022)

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



Curtis *et al* ApJL (2024)

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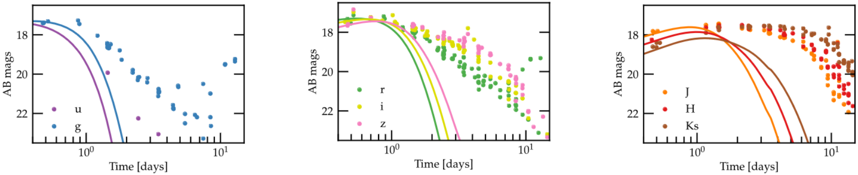
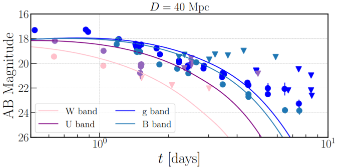


Curtis *et al* ApJL (2024)



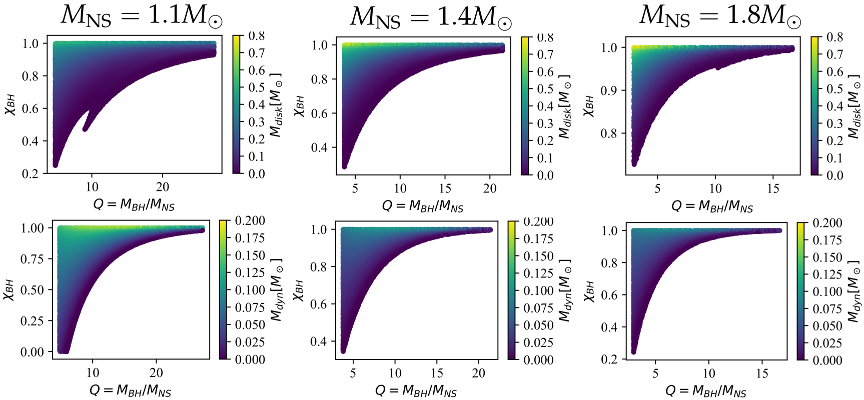
Combi & Siegel PRL (2023)

Disk and ejecta from BH-NS mergers

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

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

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

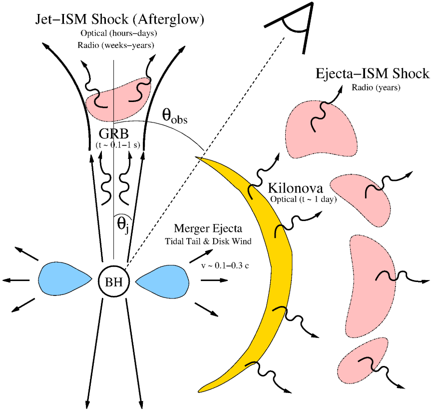


Mass in the disk and in dynamical ejecta after a BH-NS merger. NS EOS: SFHo. Fitting formulas from Foucart+ Arxiv 2018 & Kawaguchi+ PRD 2016.

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

Kilonova emission

Electromagnetic counterparts: kilonova



Berger & Metzger ARAA 12

- radioactive decay of freshly sinthetized *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

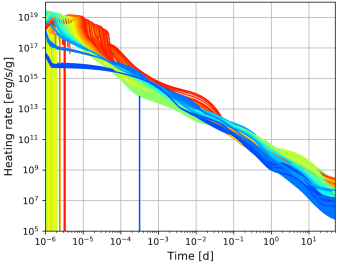
Radioactive decays of *r*-process elements release nuclear energy

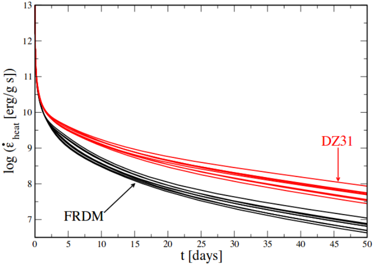
$$\dot{e}_{r-\mathrm{process}} = \sum_{i \in \mathrm{reactions}} Q_i \lambda_i \qquad Q = M_{\mathrm{initial}} - M_{\mathrm{final}}, \ \lambda : \text{decay rate}$$

- nuclear heat computed by detailed nuclear network

  mainly β − decay $\Rightarrow \dot{e}_{r-\mathrm{process}} = \dot{e}_0 t^{-\alpha} \qquad \alpha \approx 1.3, \ \dot{e}_0 \gtrsim 10^{16}\mathrm{erg/g/s}$

- $Y_e \gtrsim 0.25$: weak *r*-process: shorter β decays lifetimes
- strong dependence on trajectory and mass model





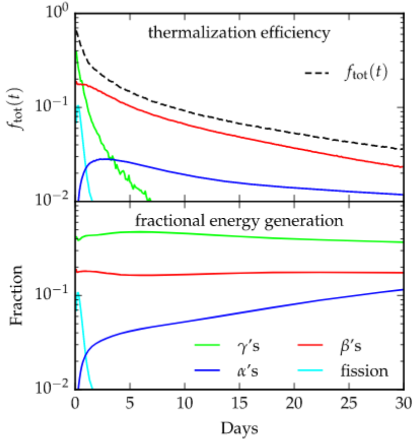
red: low Y_e, blue: high Y_e Wu, Ricigliano+ 22

Rosswog+ JphG 2017

Thermalization efficiency

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

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



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

Barnes+ ApJ 2016

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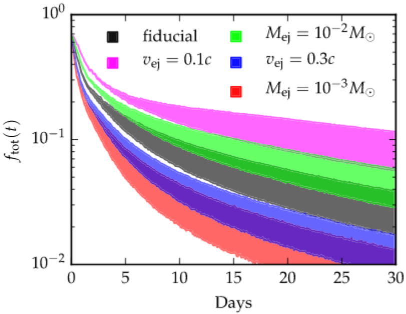


Barnes+ ApJ 2016

- thermalization efficiency depends on:
  - matter density
  - matter temperature
  - decay modes
  - decay product spectra
  - ...

$\Downarrow$

both nuclear and astrophysical uncertainties

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

A spherical model kilonova model

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

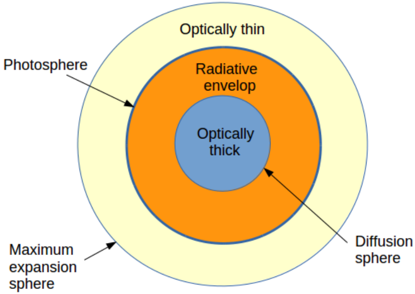
$$m_{\rm ej} = \int_0^{v_{\rm max}} \left(\int_\Omega \frac{1}{4\pi} \xi(v,\theta,\phi)\, \mathrm{d}\Omega \right) \mathrm{d}v$$

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

$$\begin{aligned}
\xi(v) &= \xi_0 \left(1 - \left(\frac{v}{v_{\rm max}} \right)^2 \right)^3 \\
v_{\rm rms} &= \left(\frac{1}{m_{\rm ej}} \int_0^{v_{\rm max}} v^2 \xi(v) \mathrm{d}v \right)^{1/2} = \frac{v_{\rm max}}{3} \\
m_{>v}(\tilde{v}) &= \int_{\tilde{v}}^{v_{\rm max}} \xi(v) \mathrm{d}v
\end{aligned}$$

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

Photon diffusion model



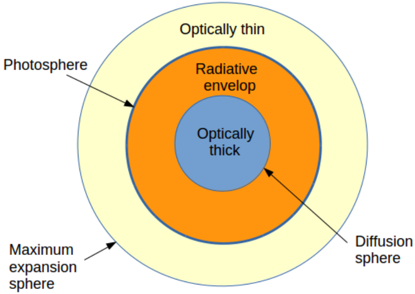
- let's suppose to consider a time $t = \tilde{t}$ after the merger
- the ejecta has maximally expanded up to $R_{\rm max} = v_{\rm max}\tilde{t}$
- diffusion radius $R_{\rm diff}(\tilde{t})$ (at which matter is moving at $\tilde{v}(\tilde{t})$):

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

clearly

  - $R_{\rm diff}(\tilde{t}) = \tilde{v}(\tilde{t})\,\tilde{t}$
  - 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:

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

where

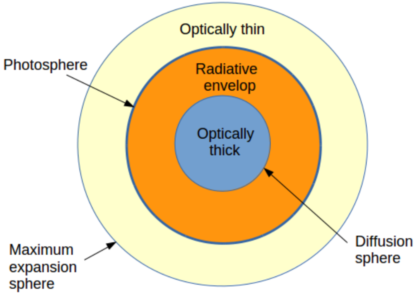
- $v_{\rm eff} = c/\tau$ is the photon effective (diffusion) speed
- τ is the optical depth:

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

$\Rightarrow$ 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:

- $R_{\rm ph}(\tilde{t})$ where

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

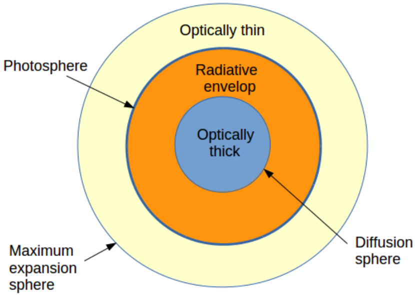
- matter at $R_{\rm ph}(\tilde{t})$ expands with velocity $v_{\rm ph}(\tilde{t})$:

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

$\Rightarrow$ implicit equation for $v_{\rm ph}(\tilde{t})$

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

Photon diffusion model



Photon luminosity:
emitted at the photosphere as a blacl body

$$
\begin{aligned}
L_\gamma(\tilde{t}) &= m_{\rm rad,env}(\tilde{t})\, \dot{e}_{r-{\rm proc}}(\tilde{t})\, f_{\rm th}(\tilde{t}) \\
m_{\rm rad,env}(\tilde{t}) &= \left(m_{>v}(\tilde{v}) - m_{>v}(v_{\rm ph}) \right)
\end{aligned}
$$

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

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

Peak properties: dependencies

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

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

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

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

Peak properties: dependencies

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

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

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

$$L_{\rm peak} \sim 2.4\times10^{40}\,{\rm erg/s}\left(\frac{\kappa}{10\,{\rm cm^2 g^{-1}}}\right)^{-13/20}\left(\frac{m_{\rm ej}}{0.01\,M_\odot}\right)^{7/20}\left(\frac{v}{0.1c}\right)^{13/20}\left(\frac{\dot{e}_0}{5\times10^{16}{\rm erg/g/s}}\right)\left(\frac{f_{\rm th}}{0.5}\right)$$

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

$$R_{\rm ph,peak} \sim 1.26\times10^{15}\,{\rm cm}\left(\frac{\kappa}{10\,{\rm cm^2 g^{-1}}}\right)^{1/2}\left(\frac{m_{\rm ej}}{0.01\,M_\odot}\right)^{1/2}\left(\frac{v}{0.1c}\right)^{1/2}$$

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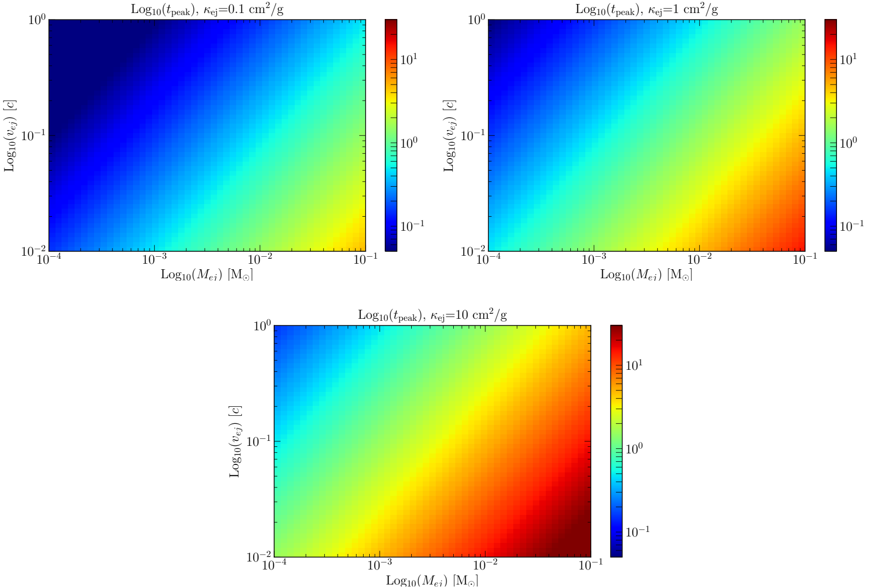
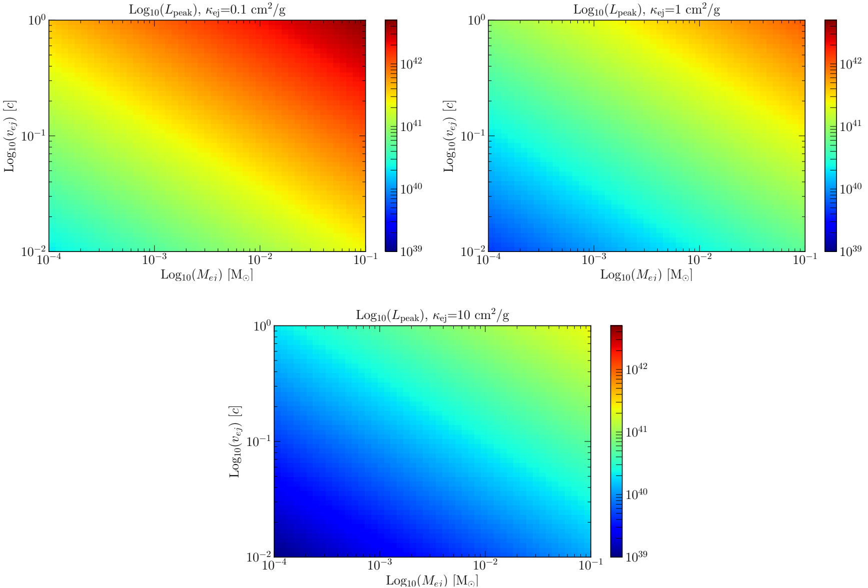
$$\frac{L_\gamma}{4\pi\,R_{\rm ph}^2} = \sigma_{\rm SB} T^4 \Rightarrow T_{\rm peak} \sim \left(\frac{L_{\rm peak}}{4\pi R_{\rm ph,peak}^2\,\sigma_{\rm SB}}\right)^{1/4}$$

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

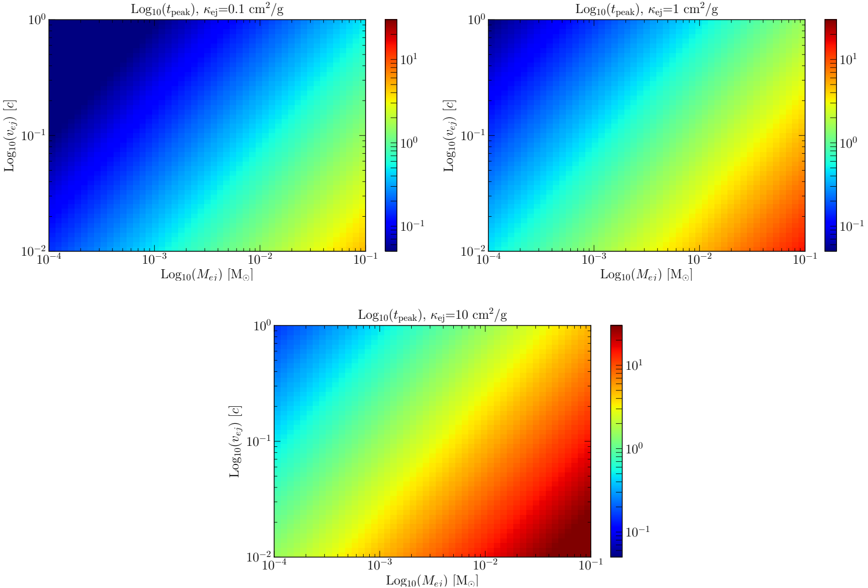
Peak properties: exploration of $t_{\rm peak}$(days)



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



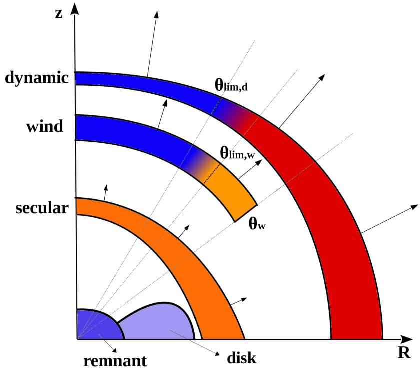
Peak properties: exploration of T_{peak}(K)



Multi-Component Anisotropic Kilonova Model

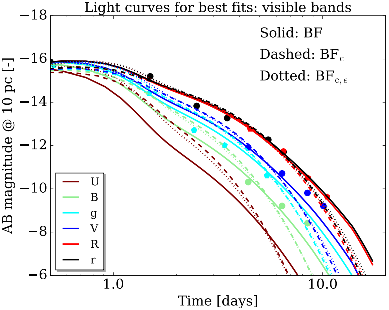
- kilonova model that includes our present knowledge about ejecta
- different ejection channels → multi-component
- explicit dependency on polar angle → anisotropic
  - multi-angle (polar angle discretization)
  - explicit dependence on observer viewing angle

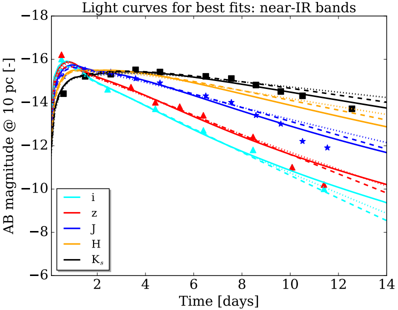
Perego, Radice, Bernuzzi 17, ApjL



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

Kilonova light curves





prompt BH

short-lived MNS

long-lived MNS