Thermodynamics conditions of matter in binary neutron star mergers

Albino Perego

Trento University & TIFPA

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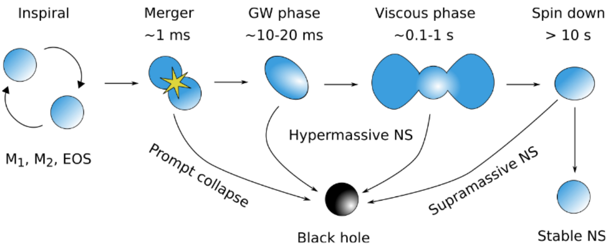
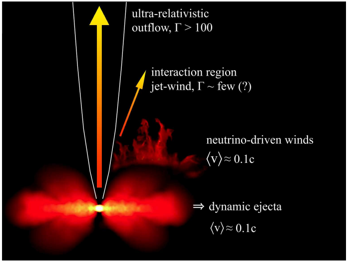
"The first compact star merger event: Implications for nuclear and particle physics", Trento

BNS merger in a nutshell



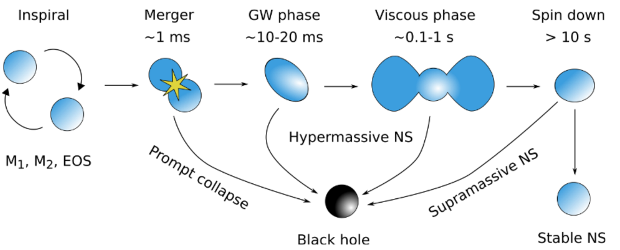
Credit: D. Radice; see Rosswog IJMP 2015 for a recent review



- Massive NS ($\rightarrow$ BH)
  $\rho \gtrsim 10^{12}\mathrm{g\,cm^{-3}}$, $T \sim$ a few 10 MeV
- thick accretion disk
  $M \sim 10^{-2} - 0.2 M_{\odot}$, $\mathrm{Y_e} \lesssim 0.20$
  $T \sim$ a few MeV
- intense ν emission
  $L_{\nu,\mathrm{tot}} \sim 10^{53}\mathrm{erg\,s^{-1}}$, $E_\nu \gtrsim 10\,\mathrm{MeV}$

$(\mathrm{Y_e} = \mathrm{n_e}/\mathrm{n_B} \approx \mathrm{n_p}/\left(\mathrm{n_p} + \mathrm{n_n}\right))$

BNS merger in a nutshell (II)



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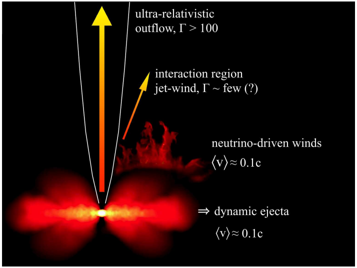


Rosswog 2015

- ejection of *n*-rich matter
  - a few % of M_{tot}
  - different ejection mechanisms acting on different timescales
  - possible ν's influence

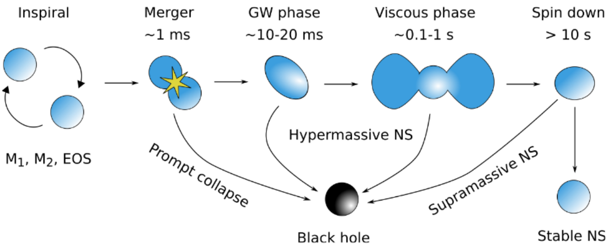
$$p + e^- \rightarrow n + \nu_e \quad (1)$$

$$n + e^+ \rightarrow p + \bar{\nu}_e \quad (2)$$

  - *r*-process nucleosynthesis

e.g. Lattimer & Schramm ApjL 73, for a recent review: Thielemann+ ARAA 17

BNS merger in a nutshell (II)



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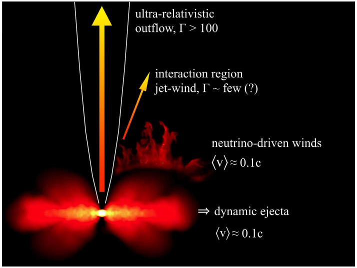

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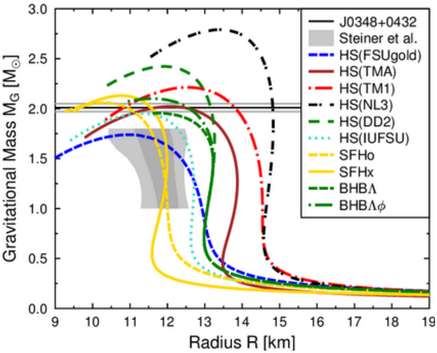
NS equation of state

Equation of state (EOS) of NS matter still affected by large uncertainties

- nucleon interaction
- many-body treatment
- thermodynamical degrees of freedom (hyperons, quarks?)
- EOS influences:
  - NS deformation
  - remnant fate
  - GW emission at merger and post-merger
  - ejecta amount and properties

Lattimer 2012



Set of M-R relations for spherically symmetric NSs, for different RMF EOS.

Courtesy of M. Hempel

Role of neutrinos in BNS mergers

Neutrinos: key players in BNS mergers

- exchange energy and momentum with matter
  - mainly cooling, but also heating
  - ν-$\bar{\nu}$ annihilation and GRBs?

Eichler+ 87

- form trapped gas
  - impact on massive NS stability?

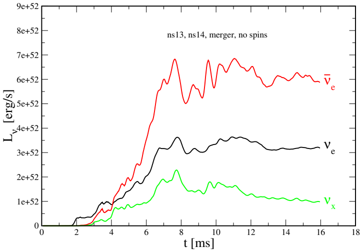
Kaplan+ 14

- set n-to-p ratio $\rightarrow \mathrm{Y_e}$
  - $p + e^- \leftrightarrow n + \nu_e$ (EC)
    $n + e^+ \leftrightarrow p + \bar{\nu}_e$ (PC)
- ν luminosities
  - n-richness $\rightarrow L_{\bar{\nu}_e} \gtrsim L_{\nu_e}$
  - EOS dependence

e.g. Sekiguchi+15

- ν oscillations
  - matter-neutrino resonance (MNR)

e.g. Malkus+ 2012, Zhu+ 2017



Rosswog+ 2017; First calculations: Ruffert+ 97, Rosswog & Liebendoerfer 03

Relevance & Challenges in NS merger modelling

- relevance:
  - astrophysical key players & prototype of MM astrophysics
  - BNS mergers as cosmic laboratory for fundamental physics
- challenges:
  - quantitative statements require sophisticated numerical models
- uncertainties
  - state-of-the-art models contains many uncertainties and approximations, for example in the EOS and neutrino microphysics

Given a large set of NR BNS merger simulations including finite T, composition dependent EOSs and approximated ν treatment

e.g. Radice,Perego, *et al* ApJ 2018; Dietrich *et al* CQG 2018

- Which are the thermodynamics conditions of matter during the merger?

Perego,Bernuzzi,Radice 2019 EPJ A 2019

- Which are the thermodynamics conditions of matter where neutrino-matter decoupling occurs?

Endrizzi,Perego, *et al.* arXiv 1908.04952

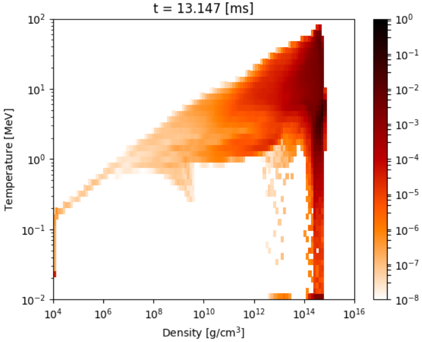
Thermodynamics conditions of matter in neutron star mergers

BNS mergers on thermodynamics diagrams

- set of BNS merger simulations in NR: different NS masses and microphysical EOSs (DD2, LS220, SFHo)
- ν-physics: leakage scheme (optically thick) + M0 transport (opt. thin)
- possibly, turbulent viscosity (GRLES)

Radice 2017

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



WhiskyTHC NR code

Radice+ 12,14,15

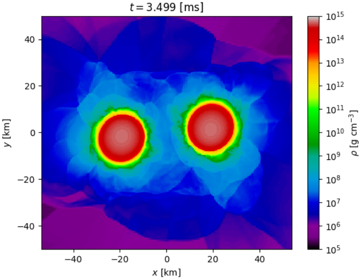
$$M_1 = M_2 = 1.364\ M_\odot$$

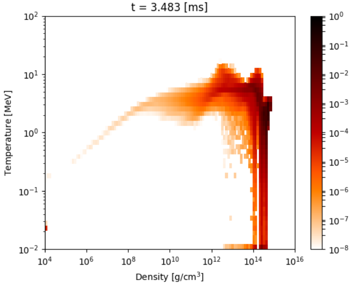
DD2 EOS

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

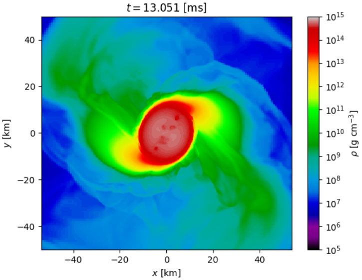
BNS mergers on thermodynamics diagrams II

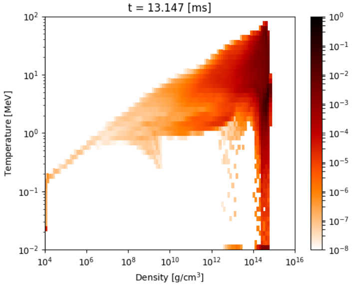
inspiral





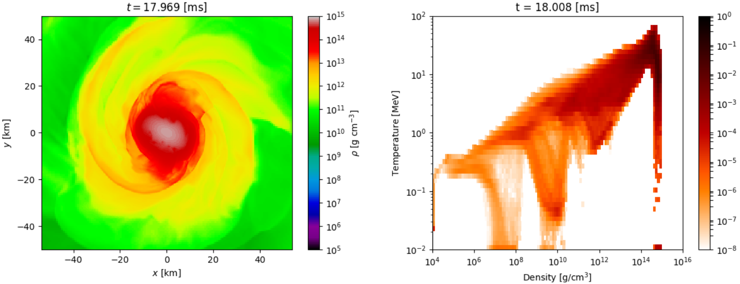
$t(T_{\rm peak})$



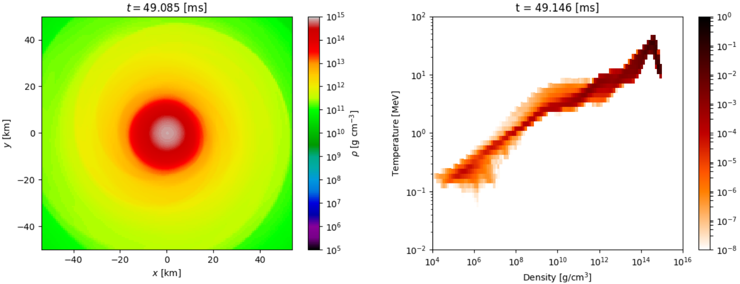


BNS mergers on thermodynamics diagrams III

$t \gtrsim t_{\rm dyn}$

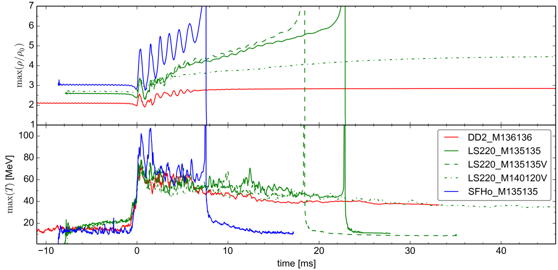


$t \gg t_{\rm dyn}$



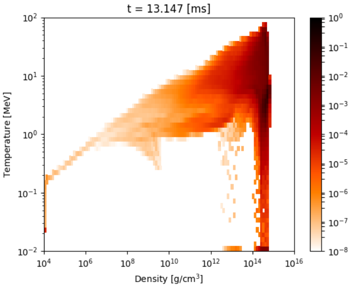
Perego,Bernuzzi,Radice 2019 arXiv:1903.07898

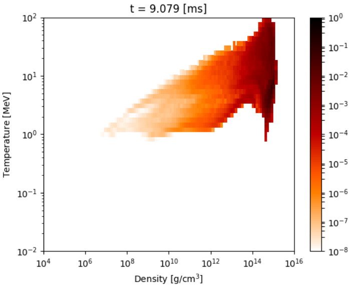
Thermodynamics diagrams: soft VS stiff EOS



DD2 (stiff), $M_1 = M_2 = 1.364 M_\odot$ SFHo (soft),, $M_1 = M_2 = 1.35 M_\odot$

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





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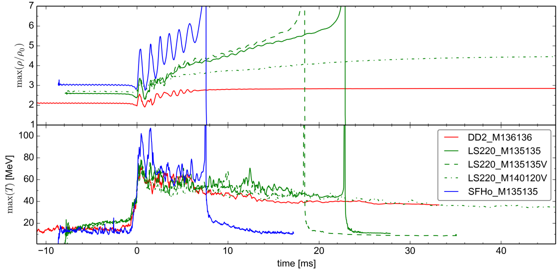
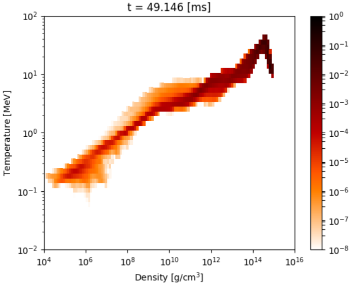
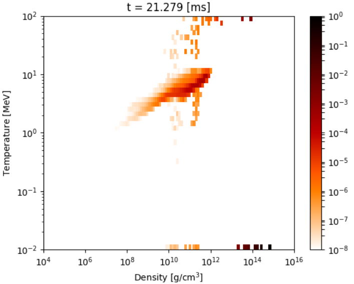


DD2 EOS (stiff)

SFHo EOS (soft)

$t \gg t_{\rm dyn}$





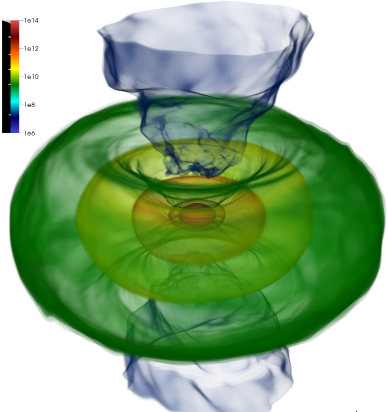
Disk properties: BH vs MNS remnant

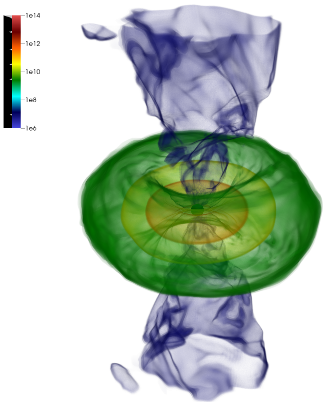
Disk harboring a MNS are ...

- ... less compact
- ... less entropic ($\Delta s \approx 2\, k_{\rm B}$)
- ... more neutron rich

Disk harboring a BH are ...

- ... more compact
- ... more entropic ($\Delta s \approx 2\, k_{\rm B}$)
- ... less neutron rich





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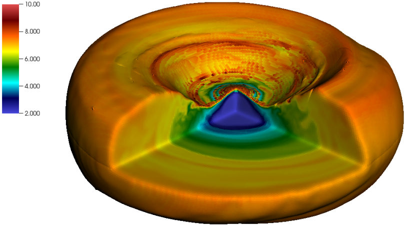

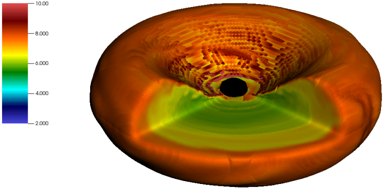

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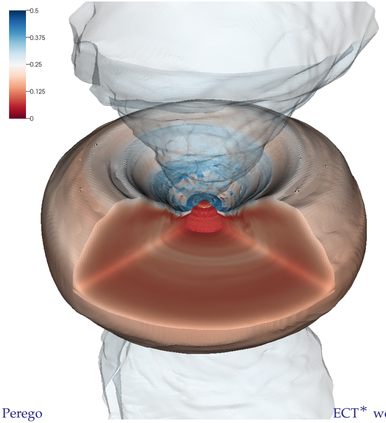
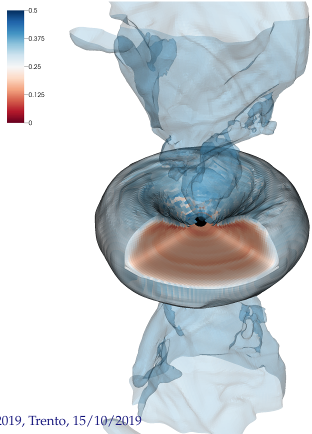


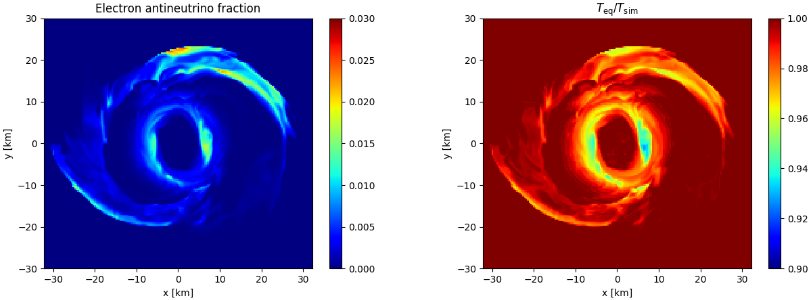


Influence of trapped neutrinos

- BNS simulations did not include trapped neutrinos
- post processing analysis:
  $Y_e \to Y_l = Y_e + Y_\nu \quad e \to u = e + e_\nu$

$$
\begin{aligned}
Y_l &= Y_{e,\mathrm{eq}} + Y_{\nu_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) - Y_{\bar{\nu}_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) \\
u &= \quad e(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + \frac{\rho}{m_{\mathrm{b}}}\left[Z_{\nu_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + \right. \\
&\qquad \left. + Z_{\bar{\nu}_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + 4 Z_{\nu_x}(T_{\mathrm{eq}})\right] \\
0 &= \quad \eta_{\nu_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) - \eta_e(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + \\
&\qquad - \eta_{\mathrm{p}}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + \eta_{\mathrm{n}}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) \, .
\end{aligned}
$$

- baryon degeneracy favors $\bar{\nu}_e$ over ν_e, but overall small effect
- $\delta T/T \lesssim 8\%$, $\delta P/P \lesssim 5\%$



Thermodynamics conditions at the neutrino decoupling surfaces

Neutrino optical depth

- Optical depth along a path γ (κ: ν opacity, λ: ν mean free path)

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

- given a matter distribution, for any point $\mathbf{x}$,

$$\tau(\mathbf{x}) = \min_{\gamma:\mathbf{x}\to\infty} \{\tau_\gamma\}$$

  How to minimize τ_γ?
  - local ray-by-ray
  - dedicated algorithms, e.g. `MODA`

Perego *et al.* A& A 2014

- physical interpretation: # of interactions for diffusing/escaping ν's:
  - $\tau(\mathbf{x}) \gg 1$: optically thick/diffusive conditions
  - $\tau(\mathbf{x}) \ll 1$: optically thin/ free streaming conditions
  - $\tau(\mathbf{x}) \sim 1$: semi-transparent regime &
    $\tau(\mathbf{x}) = 2/3$: neutrino surfaces (Eddington approximation)

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

Neutrino opacities

- Set of relevant neutrino-matter interactions:
  - charged-current absorption on nucleons
    - $n + \nu_e \to p + e^-$ $\quad p + \bar{\nu}_e \to n + e^+$
    - weak magnetism & recoil effects — Horowitz PRD 2001
    - no stimulated absorption
    - publicly available library: `NuLib` — O'Connor PhD thesis 2011
  - quasi-elastic scattering on nucleons (N) and nuclei (A)
    - $N + \nu \to N + \nu$ $\quad A + \nu \to A + \nu$
    - publicly available library: `NuLib` — O'Connor PhD thesis 2011
  - neutrino pair processes
    - $\nu + \bar{\nu} \to e^- + e^+$ $\quad N + N + \nu + \bar{\nu} \to N + N$
    - energy and flavor dependent kernels — Mezzacappa & Bruenn 1993, Hannestadt & Raffelt 1998
- strong ν-energy dependence, e.g.:

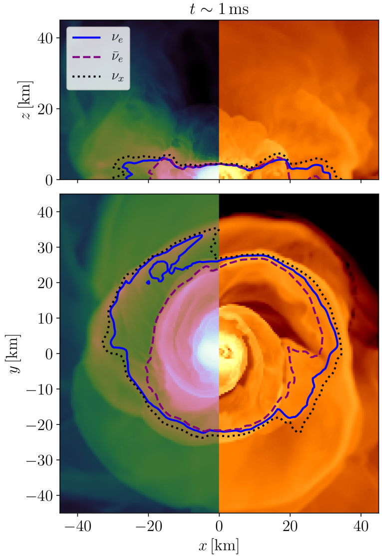
$$\kappa_{N+\nu} \propto \sigma_{N+\nu} \sim E_\nu^2 \Rightarrow \tau_\nu(\mathbf{x}, E_\nu)$$

Analysis strategy

post-processing outcome of BNS simulations

- THC code Radice *et al* 2012,14,15
- $M_1 = M_2 = 1.364 M_\odot$ (cf $\mathcal{M}_{\rm chirp}$ of GW170817)
- inspiral, merger, post-merger w ν cooling and heating (M0)
- 2 EOS:
  - DD2 (stiff) $\rightarrow$ MNS
  - SLy4 (soft) $\rightarrow$ BH @ 10ms
- selection of 3 timesteps

$$t \approx 1\text{ms},\ 10\text{ms},\ 20\text{ms}$$



Analysis strategy II

post-processing outcome of BNS simulations

- $(\rho, T, Y_e) \to \kappa \to \tau$
- calculations of $\tau_{\rm diff}$ and $\tau_{\rm eq}$ for:
  - average ν energies (at infinity):

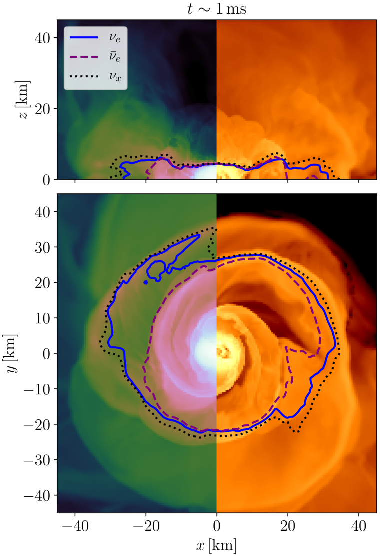
$$\langle E_{\nu_e} \rangle \approx 9 \text{ MeV} \quad \langle E_{\bar{\nu}_e} \rangle \approx 15 \text{ MeV}$$
$$\langle E_{\nu_x} \rangle \approx 24 \text{ MeV}$$

  - large set of energies:

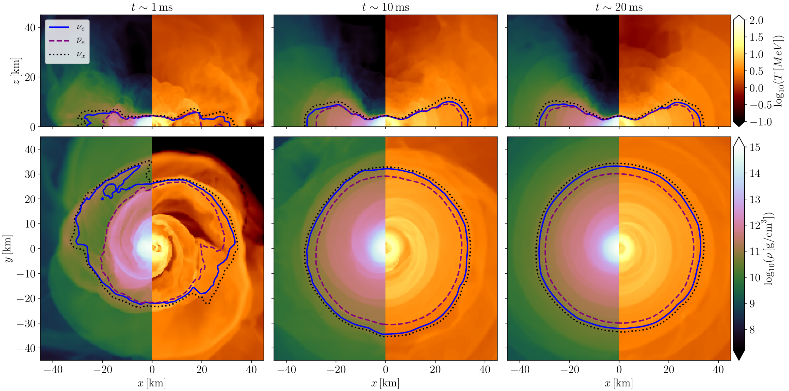
$$1 \text{ MeV} \lesssim E_\nu \lesssim 100 \text{ MeV}$$

  - for $q = \log_{10}(\rho),\ \log_{10}(T),\ Y_e$:

$$\langle q \rangle \pm \sigma_q |_{0.5 \le \tau \le 0.85}$$

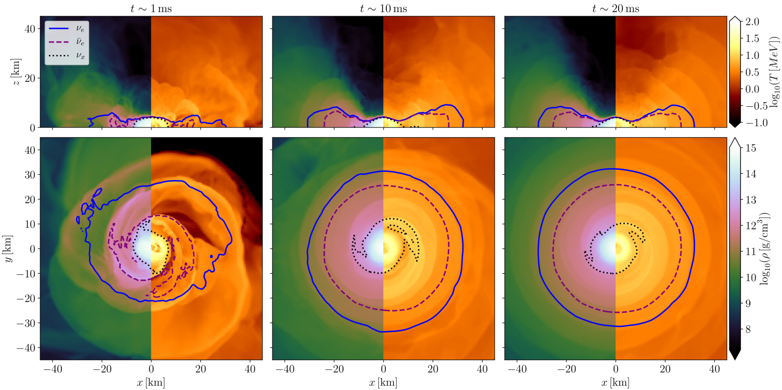


Scattering surfaces for average ν energies



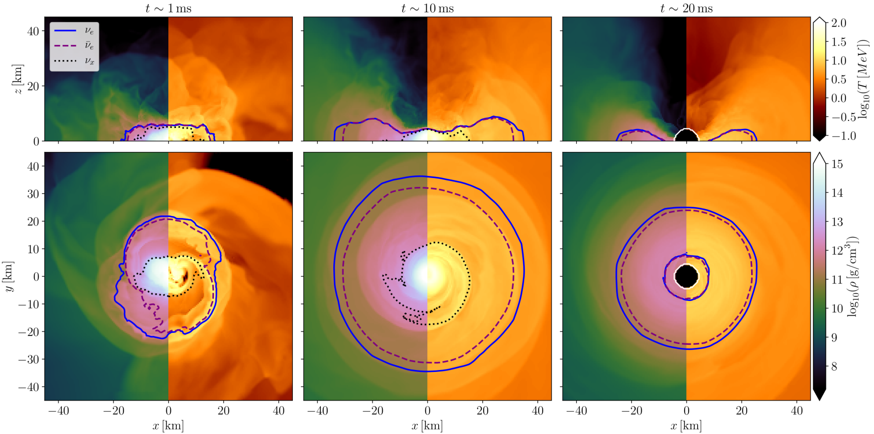
- $\tau_{\rm diff}(\langle E \rangle) = 2/3$ for DD2 simulation
- ρ dominant factor: $\rho \sim 10^{11}$g cm^{-3} at diffusion decoupling
- $\langle E_{\nu_x} \rangle > \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle \rightarrow \nu_x$'s free-stream at lower ρ & T

Equilibrium surfaces for average ν energies



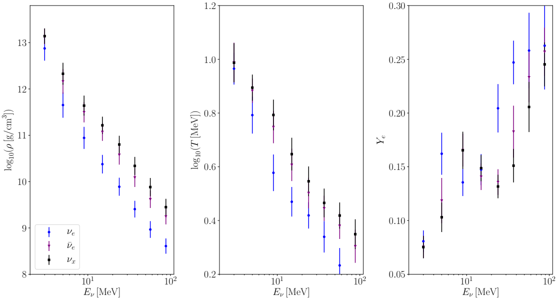
- $\tau_{\rm eq}(\langle E \rangle) = 2/3$ for DD2 simulation
- equilibrium decouplig: $\rho(\nu_e) \sim 10^{11}\mathrm{g\ cm^{-3}}$, $\rho(\bar{\nu}_e) \sim$ several $10^{11}\mathrm{g\ cm^{-3}}$, $\rho(\nu_x) \sim 10^{13}\mathrm{g\ cm^{-3}}$, $\langle E_\nu \rangle \approx (F_3(0)/F_2(0))\,T$
- n richness: stronger ν_e coupling
- pair processes: strong dependence on $T \Rightarrow$ quick ν_x decoupling

Equilibrium surfaces: BH formation



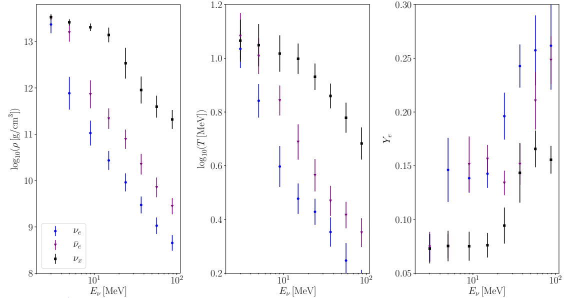
- $\tau_{\text{eq}}(\langle E \rangle) = 2/3$ for Sly4 simulation
- softer EOS: larger decoupling T
- BH-torus remnant: no decouplig surface for average energy ν_x

ν surfaces for MNS remnants: energy dependency

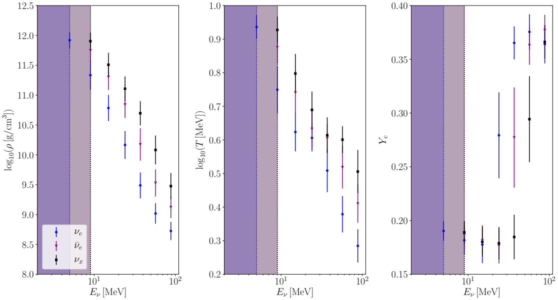


- DD2, $\tau_{\rm diff}(E_\nu) = 2/3$ at 20ms
- dominant $\sigma_\nu \propto \rho E_\nu^2$ contribution
- relevant neutrino decoupling: 10^{9-13}gcm^{-3}

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

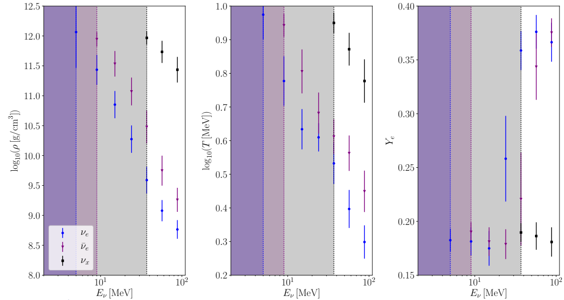


ν surfaces for BH remnants: energy dependency



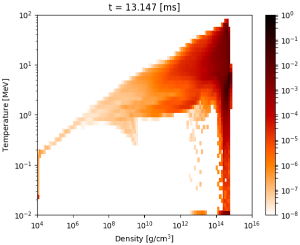
- Sly4, $\tau_{\rm diff}(E_\nu) = 2/3$ at 20ms
- soft $\bar{\nu}_e$'s and ν_x's do not diffuse

- most of ν_x and even soft ν_e do not thermalize
- effect of dramatic decrease of ρ after BH formation

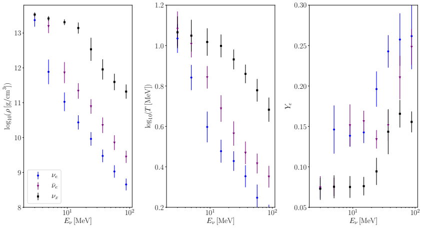


Conclusions

- during BNS merger event, matter reaches extreme conditions: up to several tens of MeV for $\rho \gtrsim \rho_0 \Rightarrow$ relevance of thermal effects
- trapped neutrinos: subdominant dynamical role inside cores
- density and neutrino energies: most relevant parameters for ν_e and $\bar{\nu}_e$ in determining ν-matter decoupling, while T relevant for ν_x equilibrium decoupling
- $\rho \sim 10^{11}$g cm^{-3} typical diffusion decoupling condition for $\langle E_\nu \rangle$, while $\rho \sim 10^{9-13}$g cm^{-3} decoupling range for $1 \lesssim E_\nu \lesssim 100$ MeV
- significant relevance of remnant nature (BH or MNS)



Perego, Bernuzzi, Radice EPJ A 2019



Endrizzi,Perego,*et al* arXiv 1908.04952