ν-driven wind in the Aftermath of Neutron Star Merger

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Outline of the presentation

- Introduction: ejected matter from binary neutron star merger
- The model
  - initial conditions
  - ASL neutrino treatment
- Preliminary results
- Conclusion and outlook

Matter ejecta from BNS mergers

BNS mergers are among the most promising candidates to explain short gamma-ray bursts (GRBs).

- observations: good compatibility with observed rates, redshifts and host galaxies
- modelling: intense energy deposition in a relatively baryon-free region as driving mechanism, due to matter accretion on a stellar compact object (SMNS or BH)

Possible ejecta from BNS mergers

- dynamical ejecta (e.g. Rosswog 13, Bauswein et al 13, Hotokezaka et al 13)
- delayed disc evaporation (e.g. Fernandez & Metzger 2013)
- neutrino-driven ejecta (e.g. Dessart et al. 2009)

The model

Goal: extensive study the aftermath of BNSM

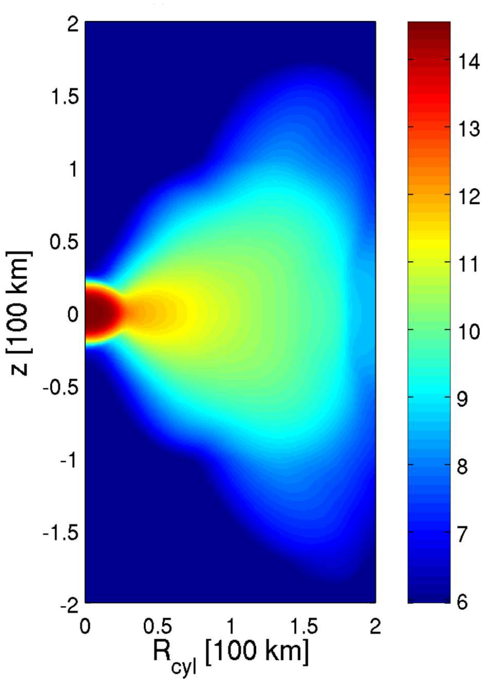
- ν emission
- disk dynamics and ν-driven wind formation
- nucleosynthesis in the wind
- baryonic pollution and GRB engine

Model ingredients:

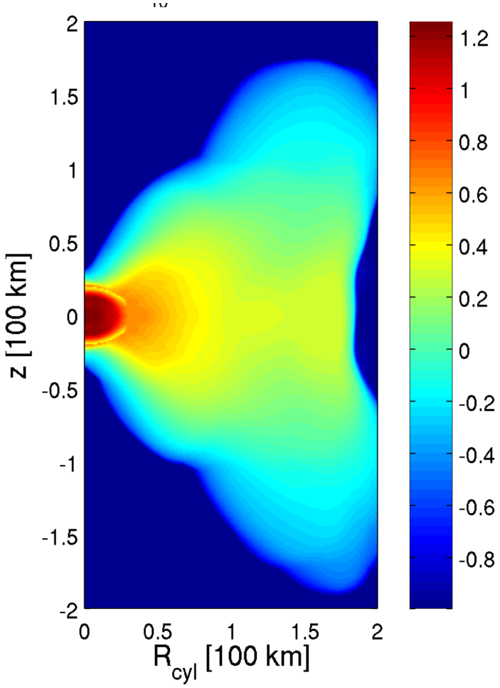
- data from Newtonian SPH BNS merger simulations (Price & Rosswog (2006))
- `FISH` 3D (M)HD Cartesian code (Käppeli et al. (2011))
- TM1 nuclear EoS (Hempel et al. (2012))
- ν treatment: Advanced Spectral Leakage (ASL) scheme (Perego et al., in preparation)

Initial conditions

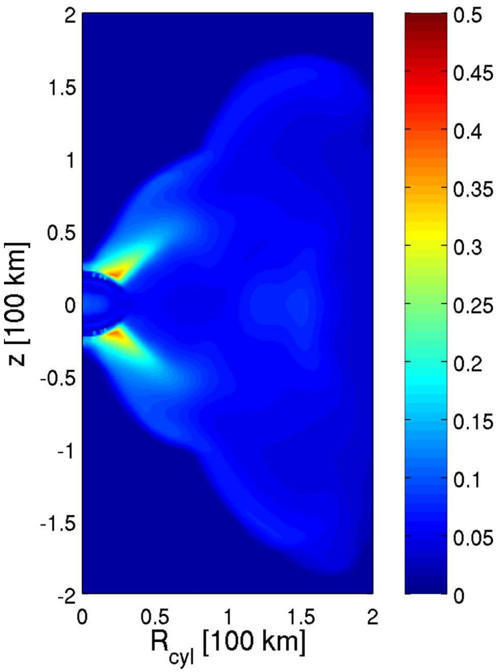
- 3D SPH data mapped on 3D `FISH` grid
- 1 km resolution: SMNS treated as stationary object
- data relaxation: $\Delta t \approx 10\mathrm{ms}$, hydro + ν emission



Matter density (2D avg)



Temperature (2D avg)



Electron fraction (2D avg)

Relevant timescales

- disc lifetime:

$$t_{\rm visc} \sim \alpha^{-1}\left(\frac{H}{R}\right)^{-2}\Omega_K^{-}1 \sim 0.31\,{\rm s}\left(\frac{\alpha}{0.05}\right)^{-1}\left(\frac{H/R}{1/3}\right)^{-2}\left(\frac{R}{100\,{\rm km}}\right)^{3/2}\left(\frac{M}{2.5M_\odot}\right)^{-1/2}$$

α: viscosity coefficient
H: disc typical height
R: radial position in the disc
Ω_K: Keplerian angular velocity

M: SMNS mass

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- disc dynamical time:

$$t_{\rm dyn\,disc} \sim \frac{2\pi}{\Omega_K} \sim\sim 0.0109\,{\rm s}\left(\frac{R}{100\,{\rm km}}\right)^{3/2}\left(\frac{M}{2.5 M_\odot}\right)^{-1/2}$$

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- disc cooling time:

$$t_{\rm cool} \sim \frac{\Delta E_{\rm disc,t=0}}{\sum_\nu L_\nu} \sim 0.20\,{\rm s}\left(\frac{\Delta E_{\rm disc,t=0}}{2\times 10^{52}{\rm erg}}\right)\left(\frac{\sum_\nu L_\nu}{10^{53}{\rm erg/s}}\right)^{-1}$$

$\Delta E_{\rm disc,t=0} = E_{\rm int,disc,t=0} + \frac{1}{2}\,E_{\rm grav,disc,t=0}$

L_ν: neutrino luminosity

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- wind time:

$$t_{\rm wind} \sim \frac{e_{\rm grav}}{\dot{e}_{\rm heat}} \sim 0.10\,{\rm s}\left(\frac{M}{2.5M_\odot}\right)\left(\frac{R}{80\,{\rm km}}\right)\left(\frac{E_\nu}{13\,{\rm MeV}}\right)^{-2}\left(\frac{(L_\nu)_{{\rm iso},\theta\approx\pi/4}}{4\times 10^{52}\,{\rm erg/s}}\right)^{-1}$$

$e_{\rm grav} = G\,M\,/\,R$: specific gravitational energy
$\dot{e}_{\rm heat} = E_\nu\,\chi_{\rm abs}\,n_\nu\,/\,\rho$: heating specific energy rate
$(L_\nu)_{\rm iso}$: isotropized neutrino luminosity
$\chi_{\rm abs}$: neutrino absorptivity

n_ν : neutrino density

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$$t_{\rm dyn\,disc} < t_{\rm wind} < t_{\rm cool,disc} < t_{\rm visc}$$

but there is something missing …

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but there is something missing . . .

- SMNS → BH time (e.g. Bauswein's and Metzger's talk) :

$$t_{\rm BH} \sim 0.01 - 10\,{\rm s}$$

The ASL scheme

- based on previous grey leakage schemes

  (Ruffert et al. 1997, Rosswog & Liebendörfer 2003, Aloy's talk)

- spectral scheme (12 bins, $2-200$ MeV)
- 3 flavors: ν_e,$\bar{\nu}_e$, $\nu_{\mu,\tau}$ ($\nu_{\mu,\tau} \equiv \nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$)
- ν reactions: ($\nu \equiv \nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$)

$e^- + p \rightarrow n + \nu_e$	O,T,P	$(A,Z) + \nu \rightarrow (A,Z) + \nu$	O
$e^+ + n \rightarrow p + \bar{\nu}_e$	O,T,P	$e^+ + e^- \rightarrow \nu + \bar{\nu}$	T,P
$e^- + (A,Z) \rightarrow \nu_e + (A,Z-1)$	T,P	$N + N \rightarrow N + N + \nu + \bar{\nu}$	T,P
$N + \nu \rightarrow N + \nu$	O		

major roles: O → opacity, T → thermalization, P → production

Bruenn 1985, Mezzacappa & Bruenn 1993, Hannestad & Raffelt 1998

- treatment developed and tested in Core Collapse Supernova context

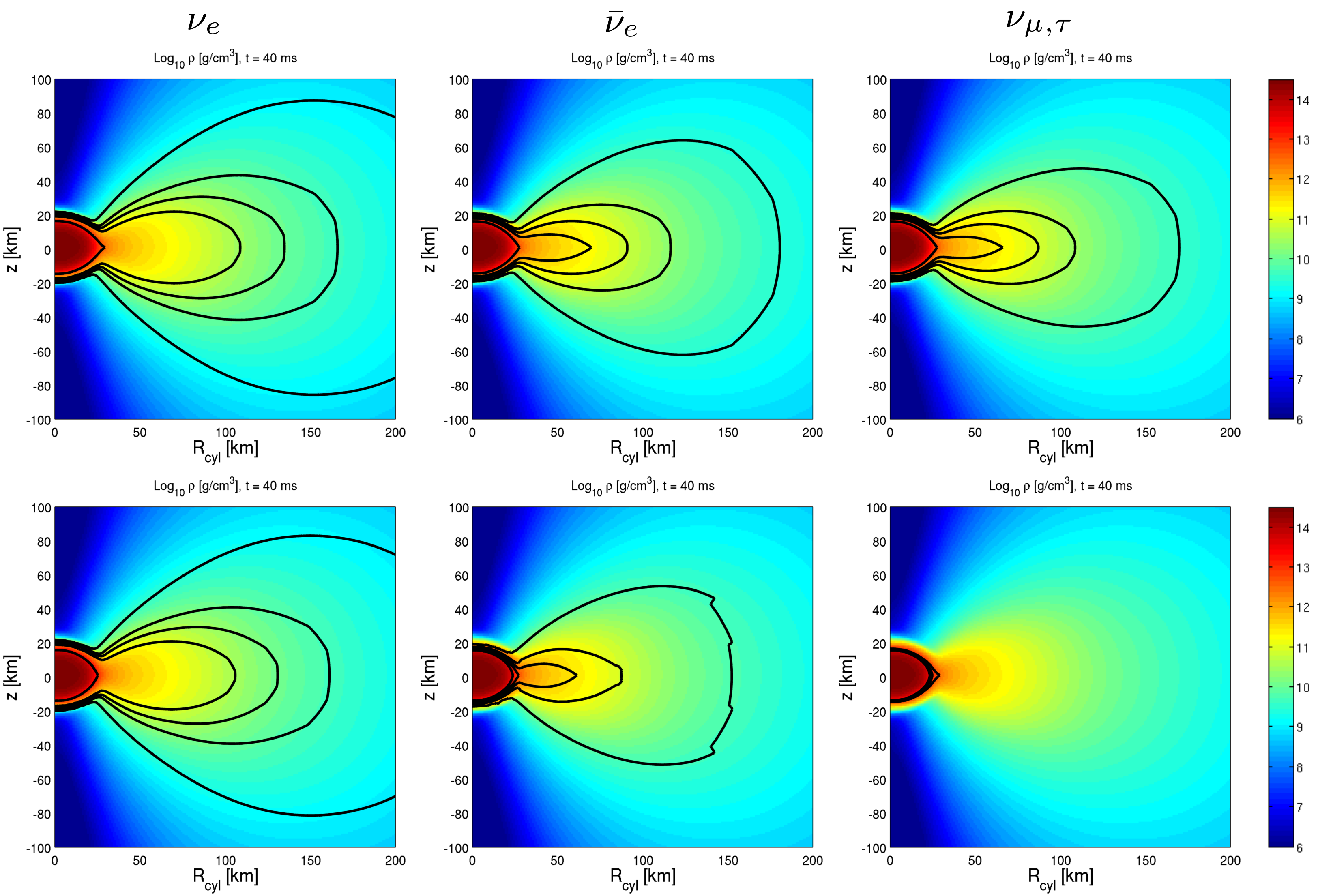
Neutrino treatment

- effective scheme: ASL mimics known solutions
- cooling part:
  - smooth interpolation between diffusion and production (spectral) rates
  - reproduction of the correct limits: diffusive ($\tau_\nu \gg 1$) and free streaming ($\tau_\nu \lesssim 1$)

    (τ_ν neutrino optical depth)
- heating part (for $\tau_\nu \lesssim 1$):
  - effective treatment of diffusion process in the opaque region
  - n_ν (neutrino density) calculated with ray-tracing from cooling rates, emitted at neutrino surfaces
  - $r_{\text{heat}} \propto \chi_{\text{ab}} \cdot n_\nu \qquad (\chi_{\text{ab}}\ \text{absorptivity})$

Neutrino Surfaces

$\tau_\nu = 2/3 \Rightarrow \nu$ surfaces, for $E_\nu = 4.6, 10.6, 16.2, 24.6, 57.0\,\mathrm{MeV}$, at 40 ms



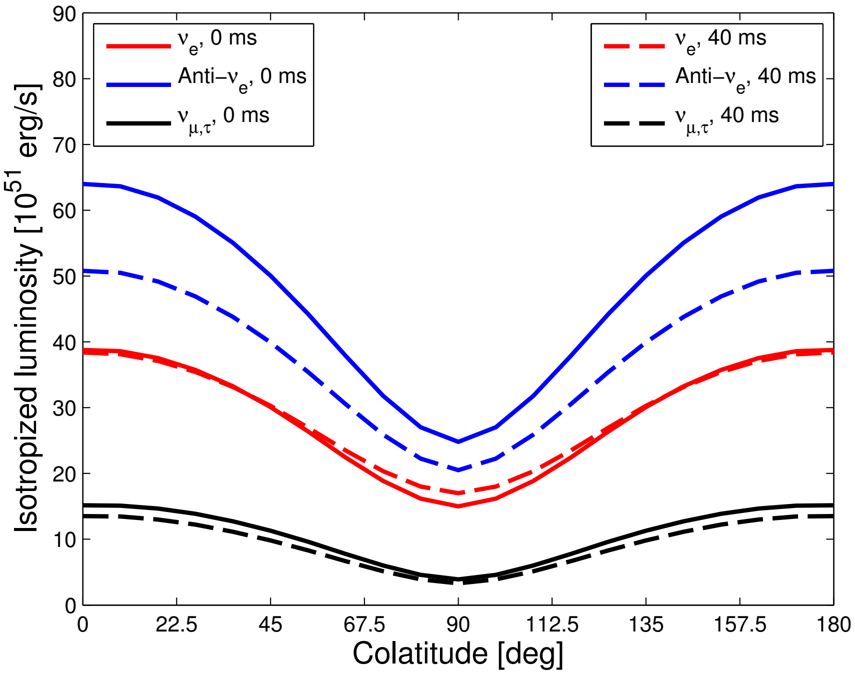
ν_e $\bar{\nu}_e$ $\nu_{\mu,\tau}$

$\tau_{\nu,\mathrm{scat}}$

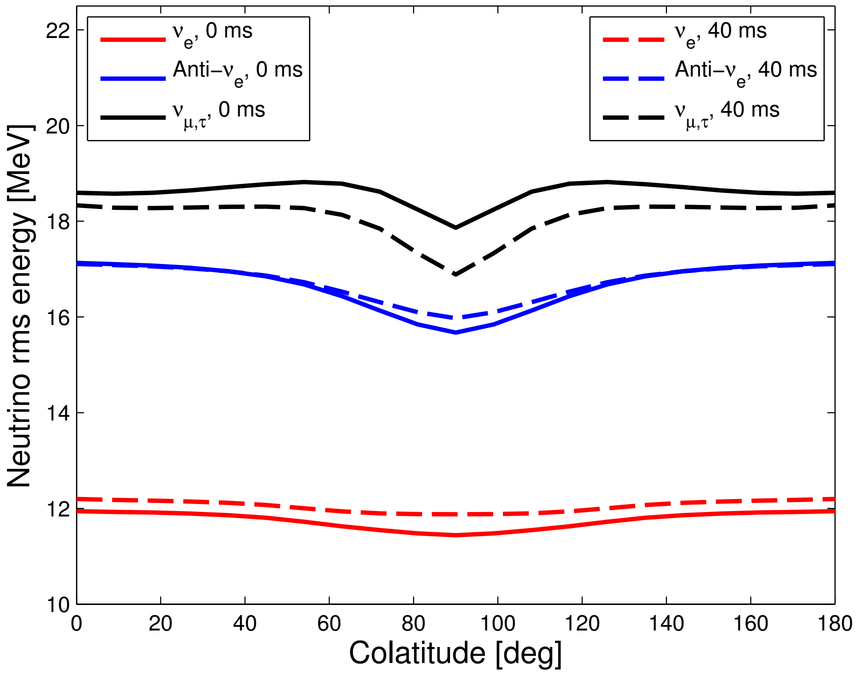
$\tau_{\nu,\mathrm{eff}}$

Neutrino luminosities

Isotropized ν luminosity
emerging from ν-surfaces



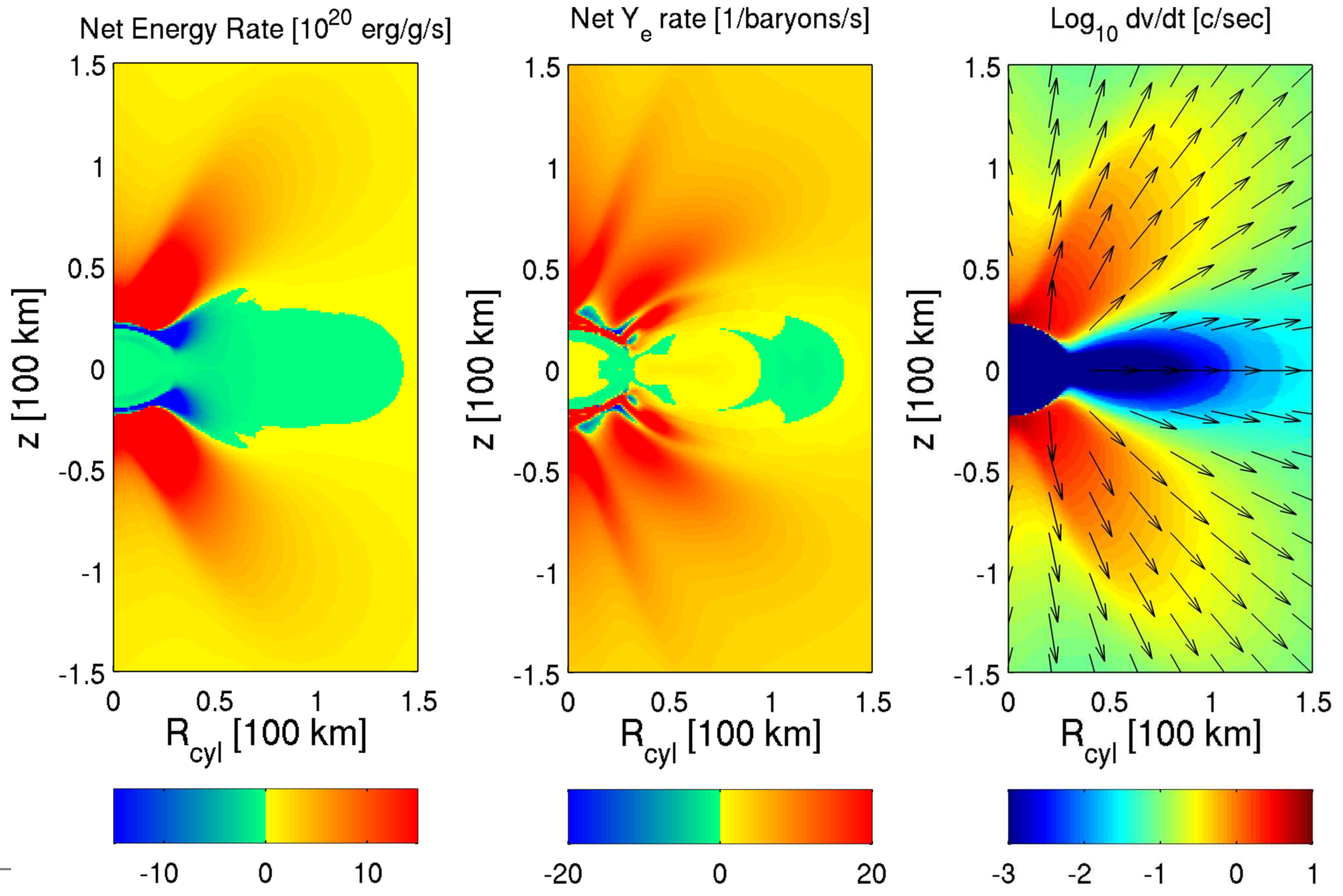
ν rms energy
emerging from ν-surfaces



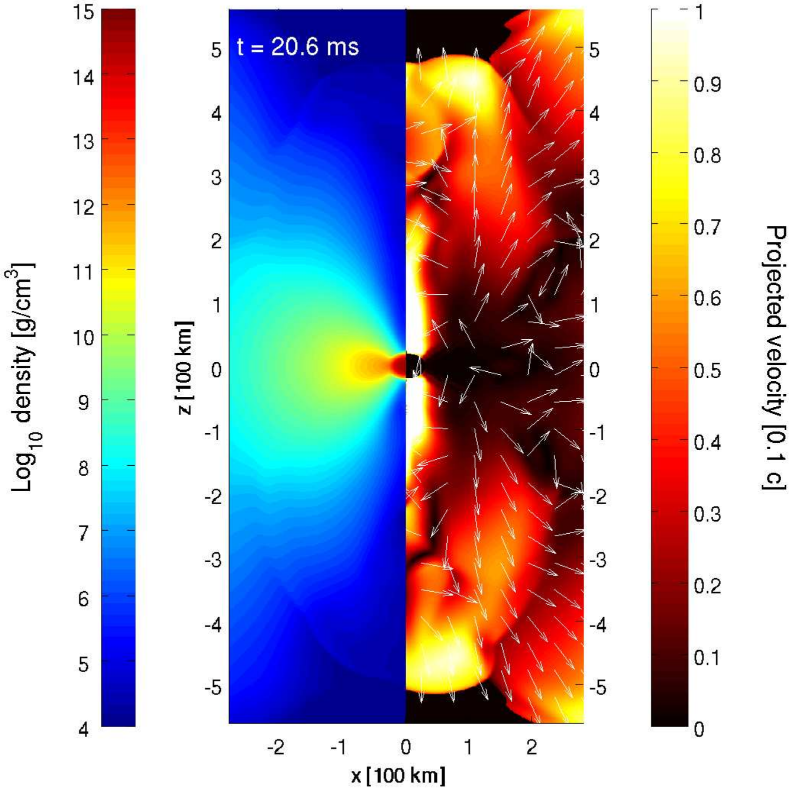
- θ angular dependence at $t = 0\,\mathrm{ms}$ and $t = 40\,\mathrm{ms}$
- luminosity hierarchy: $L_{\bar{\nu}_e} > L_{\nu_e} > L_{\nu_{\mu,\tau}}$
- mean energy hierarchy: $\langle E_{\nu_{\mu,\tau}} \rangle > \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$

Neutrino net rates

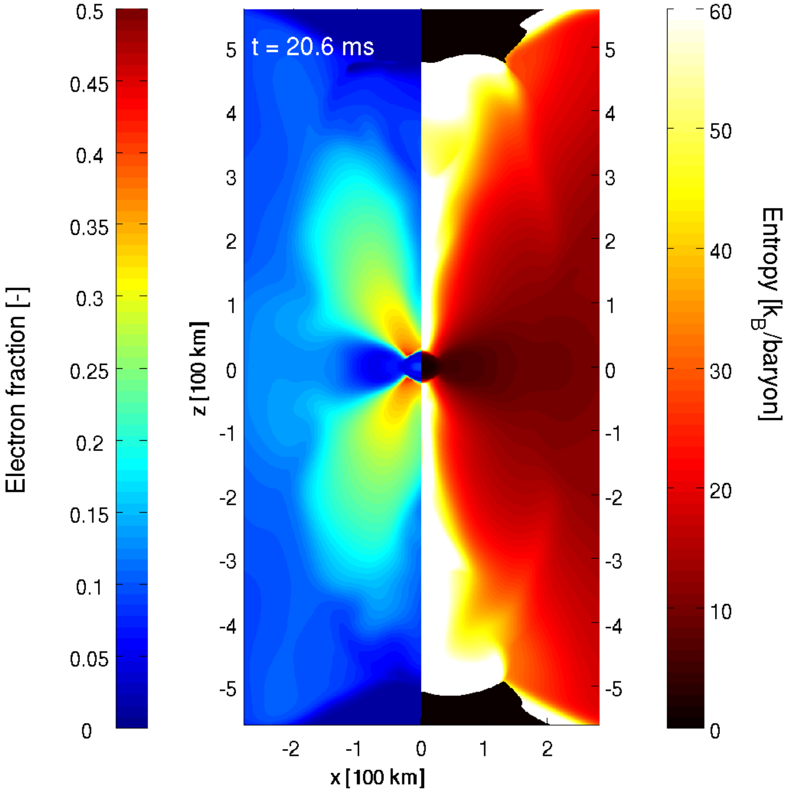
$\dot{e}_\nu$ @ 35 ms $\quad$ $\left(\dot{Y}_e\right)_\nu$ @ 35 ms $\quad$ $\dot{\mathbf{v}}_\nu$ @ 35 ms



Disc dynamics



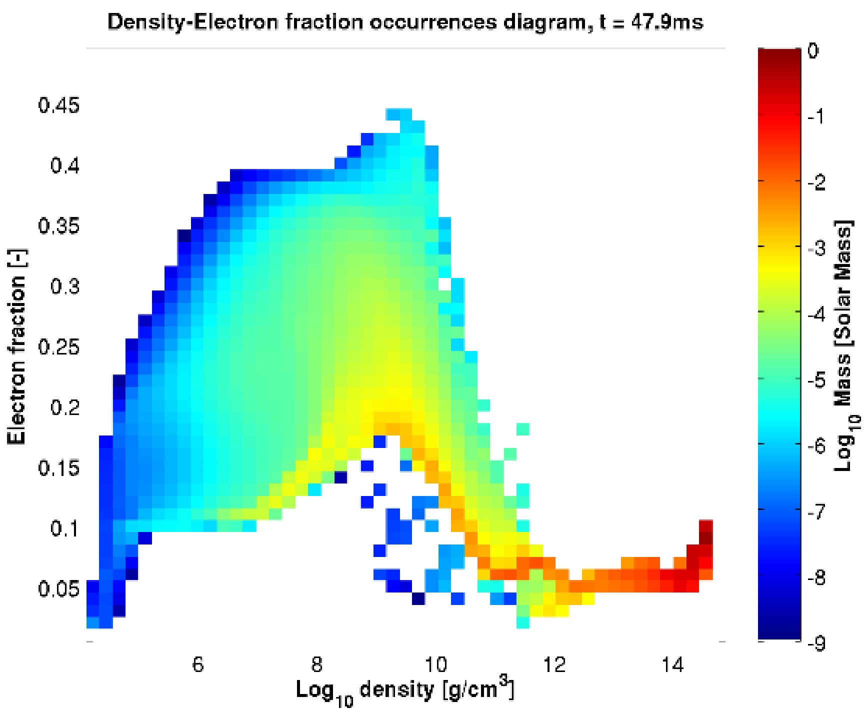
Movie I
left: matter density
right: projected velocity

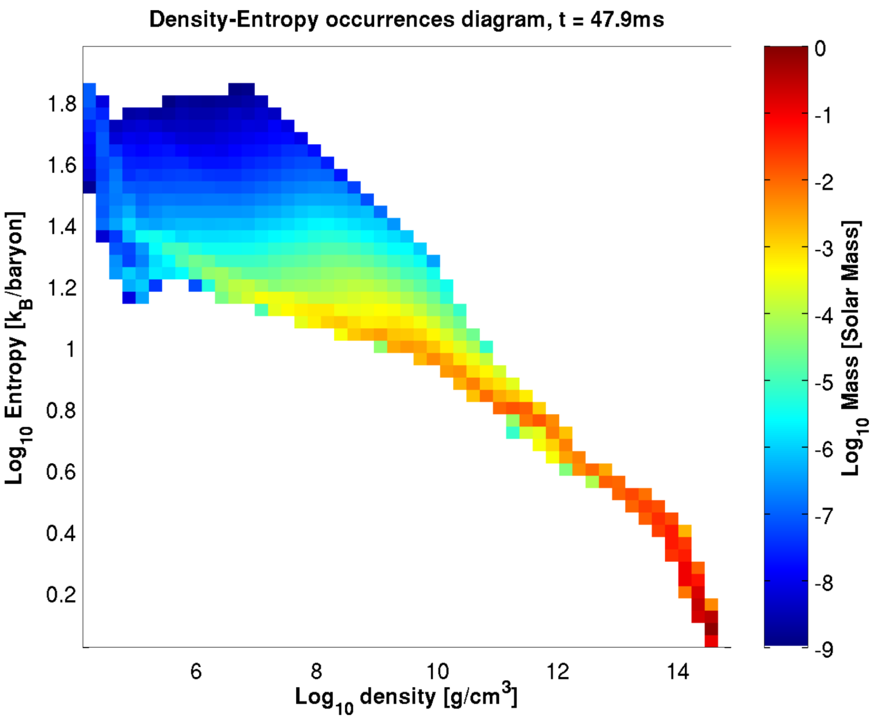


Movie II
left: electron fraction
right: entropy

Wind properties

- occurrence diagrams
- large variation for Y_e: $0.1 \lesssim Y_e \lesssim 0.35$
- small variation in entropy: $15 \lesssim s\ [\mathrm{k_B/bar}] \lesssim 25$





Conclusions & Outlook

- FISH + ASL approximate, suitable tool to model the aftermath of BNS merger
- obtained neutrino signature compatible with expected one
- relatively quick ν-driven wind development
- wind properties:
  - low entropy: $15 \lesssim s[\mathrm{k_B/baryon}] \lesssim 25$
  - mildly low Ye: $0.1 \lesssim Y_e \lesssim 0.35$

Outlook:

- ejecta properties? → nucleosynthesis, macro/kilo-nova
- $\nu - \bar{\nu}$ annihilation rate and baryonic pollution? → SGRB mechanism