ν-driven wind in the Aftermath of Neutron Star Merger

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BNS mergers

NS-NS (BH-NS) mergers

- intense GW emitters and major targer of GW detectors — Luciano's talk
- candidates as central engine of short GRBs — e.g. Paczynski 86, Goodman 86
- nucleosynthesis from the ejecta: r-process — e.g. Lattimer&Schramm74, Eichler+89, …Surman+08
  - initial n-rich matter
  - dominant $\bar{\nu}_\mathrm{e}$ over ν_e
  - fast expansion timescales

Channels for matter ejection

see also Oliver's, Yuichiro's, Brian's talks

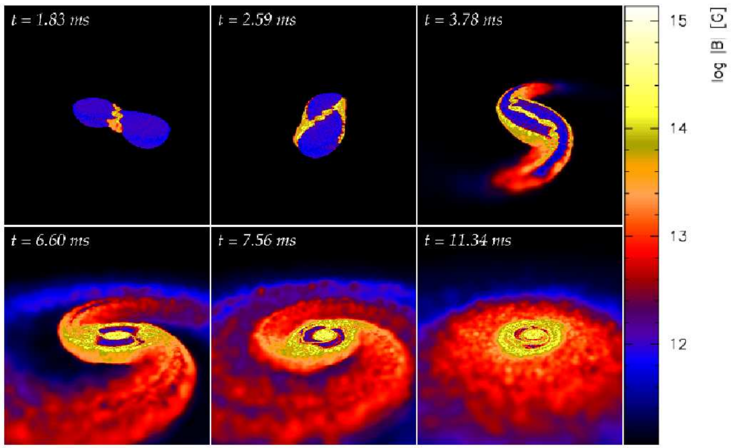
- dynamical ejecta — e.g., Korobkin+12, Bauswein+13, Hotokezaka+13, Wanajo+14
- viscous ejecta — e.g., Fernandez&Metzger 13, Just+14
- ν-driven wind ejecta — e.g. Dessart+09, Metzger&Fernandez 14, Perego+14, Just+14

kilo/macro- nova observation in (short) GRB130603B

compatible with production of r-process elements in sGRB events

e.g. Kasen+13, Grossman+14,Tanaka+14

Physical sketch

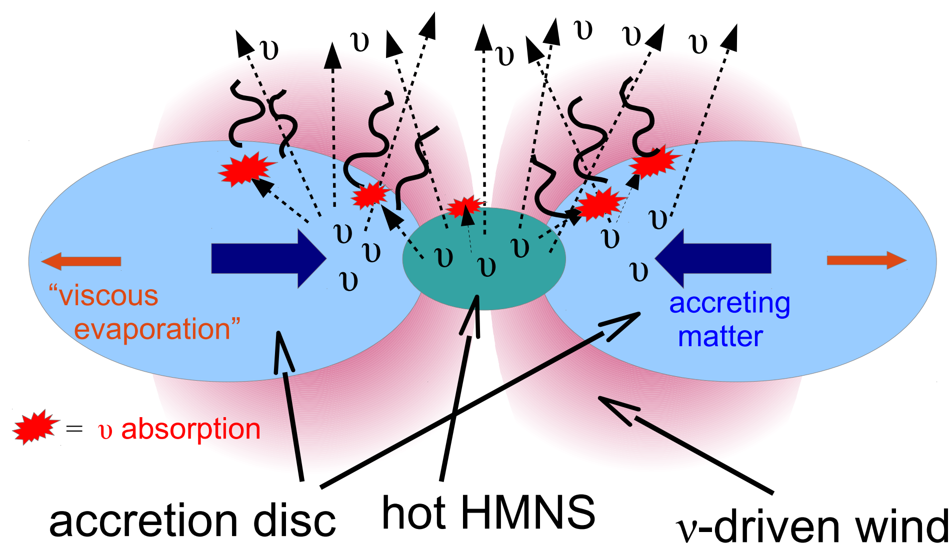


Final stages of a binary NS (2 x $1.4 M_\odot$) system evolution

- inspiral
- merger
- hypermassive NS (HMNS) + disc

Credit: Price&Rosswog 06

- HMNS ($\rightarrow$ BH) $\sim 2.55 M_\odot$
- thick accreting torus $\sim 0.17 M_\odot$, $Y_e \lesssim 0.05$
- intense ν emission $L_{\nu,\mathrm{tot}} \sim 10^{53} \mathrm{erg\,s^{-1}}$
- ν-disc interaction: wind



Relevant time scales

- disc lifetime:

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

α: viscosity coefficient
$R_{\rm disc}$: disc typical radius
H/R: disc aspect ratio
Ω_K: Keplerian angular velocity
$M_{\rm ns}$: HMNS mass

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- disc L:

$$L_{\nu,{\rm disc}} \sim \frac{\Delta E_{\rm grav}}{2\,t_{\rm disc}} \approx 8.35\times10^{52}\,{\rm erg\,s^{-1}}\left(\frac{M_{\rm ns}}{2.5\,M_{\odot}}\right)^{3/2}\left(\frac{M_{\rm disc}}{0.2\,M_{\odot}}\right)\left(\frac{R_{\rm disc}}{100\,{\rm km}}\right)^{-3/2} \times\left(\frac{\alpha}{0.05}\right)\left(\frac{R_{\rm ns}}{25\,{\rm km}}\right)^{-1}\left(\frac{H/R}{1/3}\right)^{2}$$

$\Delta E_{\rm grav}$: gravitational energy released during accretion

Relevant time scales

- disc lifetime: $t_{\rm disc} \sim 0.31\,{\rm s}\,\left(\frac{\alpha}{0.05}\right)^{-1}\left(\frac{H/R}{1/3}\right)^{-2}\left(\frac{R_{\rm disc}}{100\,{\rm km}}\right)^{3/2}\left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right)^{-1/2}$
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- HMNS L:

$$L_{\nu,{\rm ns}} \sim \frac{\Delta E_{\rm ns}}{t_{\rm cool,ns}} \approx 1.86 \times 10^{52}\,{\rm erg\,s^{-1}}\left(\frac{\Delta E_{\rm ns}}{3.5\times 10^{52}\,{\rm erg}}\right)\left(\frac{R_{\rm ns}}{25\,{\rm km}}\right)^{-2}\left(\frac{\rho_{\rm ns}}{10^{14}\,{\rm gcm^{-3}}}\right)^{-1}\left(\frac{k_{\rm B}T_{\rm ns}}{15\,{\rm MeV}}\right)^{-2}$$

$\Delta E_{\rm ns}$: thermal energy

$t_{\rm ns,cool} \sim 3\tau_{\nu,{\rm ns}}/\left(R_{\rm ns}c\right)$: diffusion time scale

$\tau_{\nu,{\rm ns}}$: ν optical depth in HMNS

Relevant time scales

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- HMNS L: $L_{\nu,{\rm ns}} \sim 1.86 \times 10^{52}\,{\rm erg\,s^{-1}} \left(\frac{\Delta E_{\rm ns}}{3.5\times 10^{52}\,{\rm erg}}\right) \left(\frac{R_{\rm ns}}{25\,{\rm km}}\right)^{-2} \ldots$
- wind time:

$$t_{\rm wind} \sim \frac{e_{\rm grav}}{\dot{e}_{\rm heat}} \approx 0.072\,{\rm s} \left(\frac{M_{\rm ns}}{2.5\,M_\odot}\right) \left(\frac{R_{\rm disc}}{100\,{\rm km}}\right) \left(\frac{E_\nu}{15\,{\rm MeV}}\right)^{-2} \left(\frac{\xi L_{\nu_e}}{4.5 \times 10^{52}\,{\rm erg\,s^{-1}}}\right)^{-1}$$

$e_{\rm grav}$: specific gravitational energy

$\dot{e}_{\rm heat}$: specific heating rate

ξL_{ν_e}: isotropized ν_e luminosity at $\theta \approx \pi/4$, $\xi \sim 1.5$ and $L_{\nu_e} \sim (L_{\rm ns} + L_{\rm disc})/3$

Relevant time scales

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$$t_{\rm wind} < t_{\rm disc}$$

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$$t_{\rm wind} < t_{\rm disc}$$

- HMNS $\rightarrow$ BH: EoS, $M_{\rm ns}$, $B_{\rm ns}$, ang. mom. transport, etc.

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

our assumption: $t_{\rm bh} \gtrsim 0.1\,{\rm s}$

Goals & model

Goal: study of the aftermath of BNSM under ν influence

- ν emission
- disc dynamics and ν-driven wind formation
- nucleosynthesis in the wind
- e.m. counterparts

Perego+14, to be published in MNRAS

Model ingredients:

- HD: `FISH` 3D Newtonian Cartesian code — Käppeli+11
- EoS: TM1 nuclear EoS — Hempel+12
  - stiff EoS, large NS radii — cf Wanajo+14
- ν treatment: Advanced Spectral Leakage (ASL) scheme
- initial conditions: final stage of 1.4-1.4 $M_{\odot}$ no-spin NS merger
  - high resolution Newt. SPH simulation + multi-flavor ν cooling — Rosswog&Price 06
- dynamical evolution: $\sim 100\,\mathrm{ms}$

Neutrino treatment: the ASL scheme

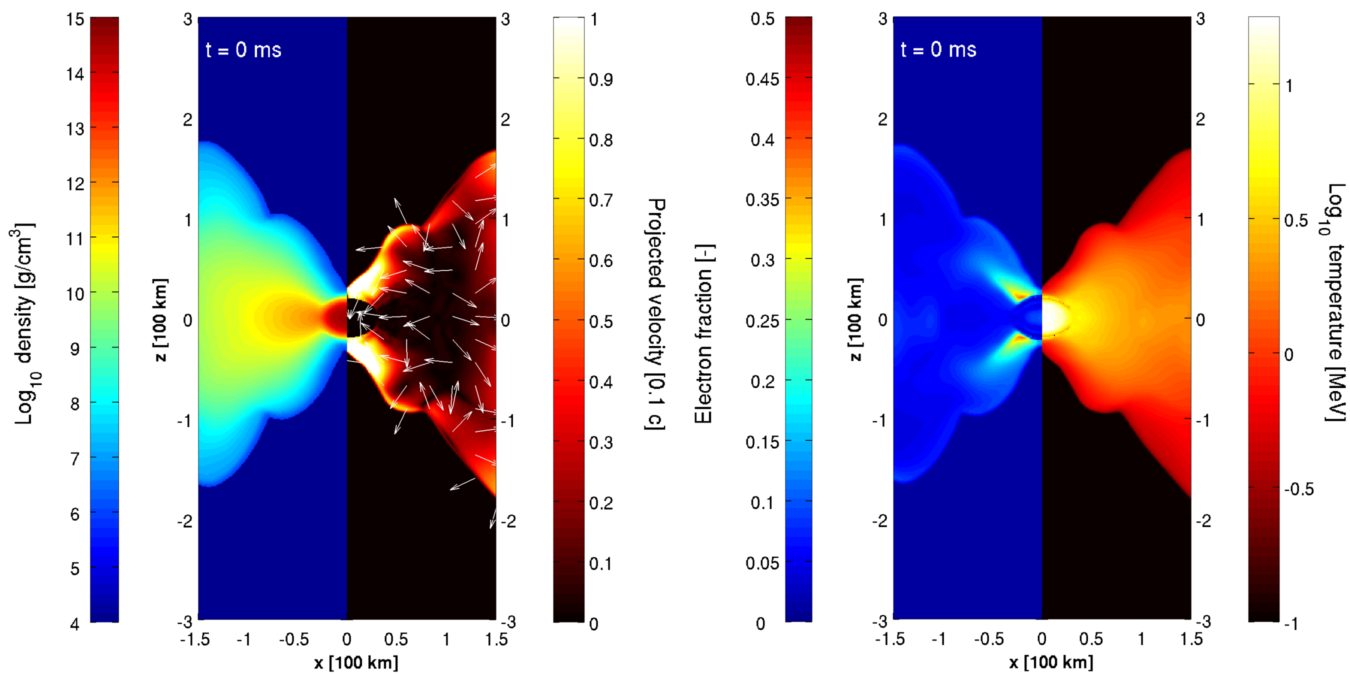
- effective scheme: ASL mimics known solutions
- 3-flavors, spectral scheme, based on previous grey leakage schemes

Ruffert+97, Rosswog&Liebendörfer 03

- cooling part
  - smooth interpolation between diffusion and production (spectral) rates
  - reproduction of the correct limits: diffusive ($\tau_\nu \gg 1$) and free streaming ($\tau_\nu \lesssim 1$)
- heating part (for $\tau_\nu \lesssim 1$):
  - n_ν (neutrino density) calculated by ray-tracing algorithm; input: emission rates at ν-surfaces
  - $r_{\rm heat} \propto \chi_{\rm ab} \cdot n_\nu$ ($\chi_{\rm ab}$ absorptivity)

Initial conditions

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

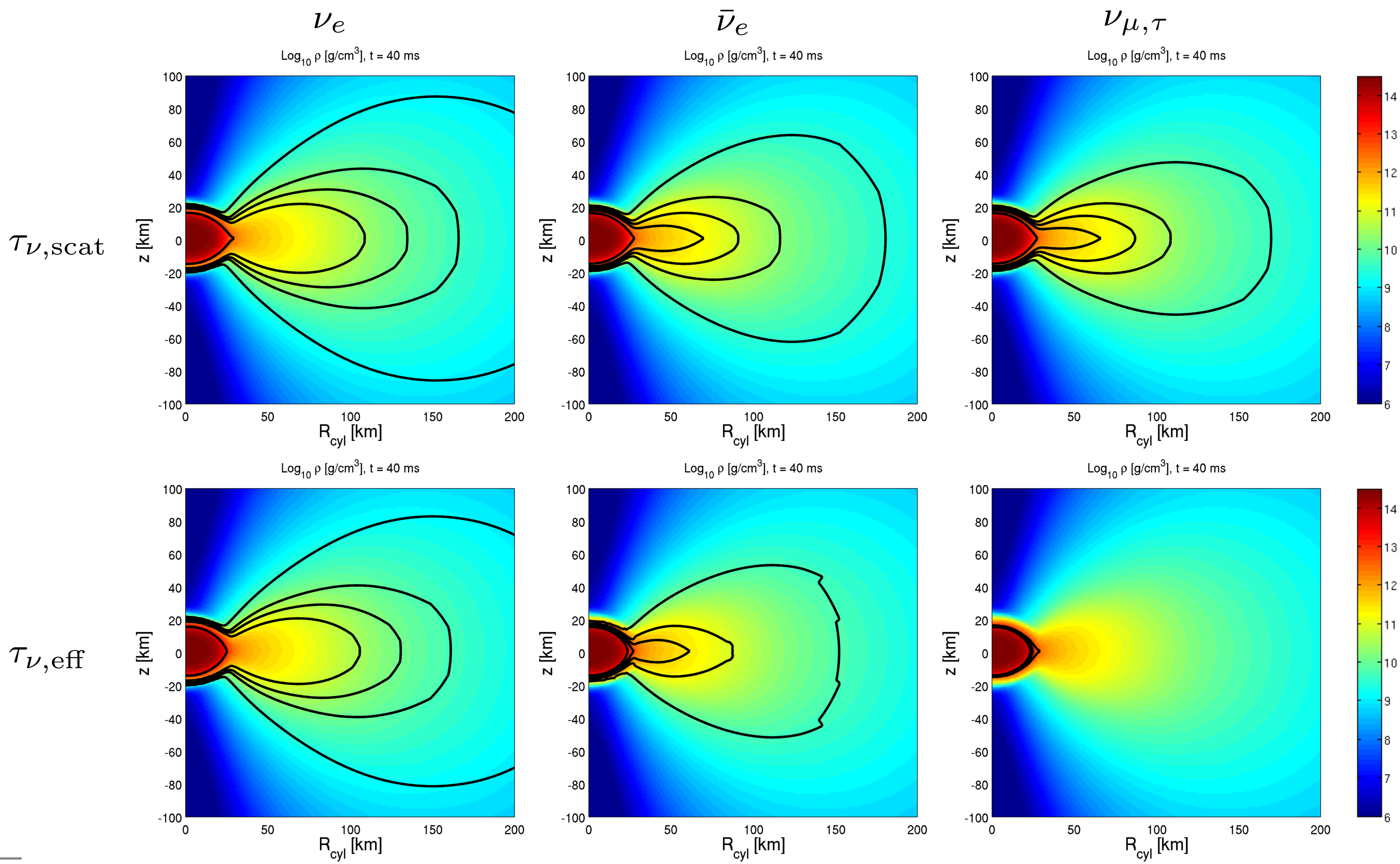


density, velocity, Y_e, temperature

2D slice of 3D domain, at $t = 0$

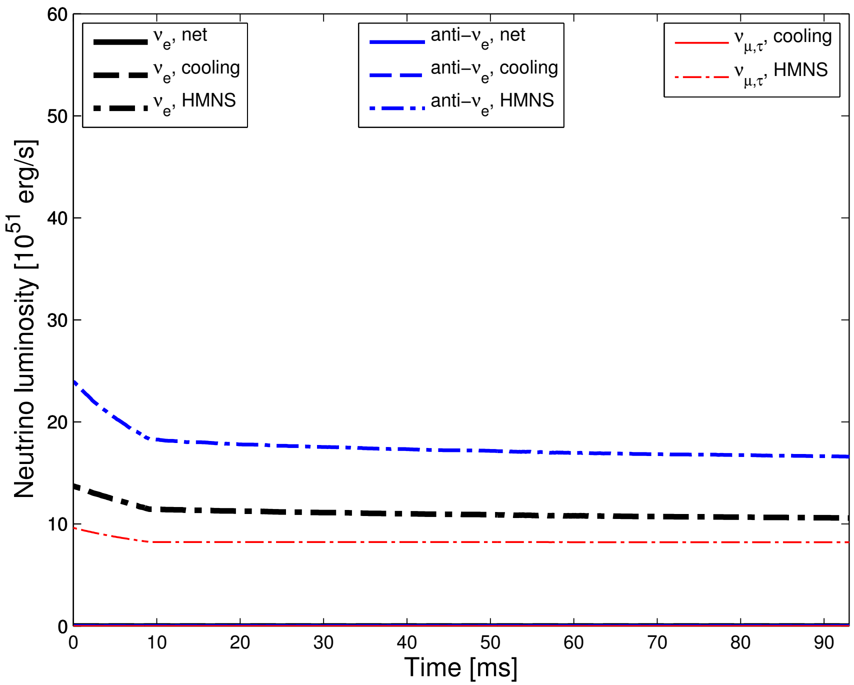
Neutrino Surfaces

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



Neutrino luminosities

dependence on time



- HMNS ($\rho > 5 \times 10^{11}\,\mathrm{g\,cm^{-3}}$)

Neutrino luminosities

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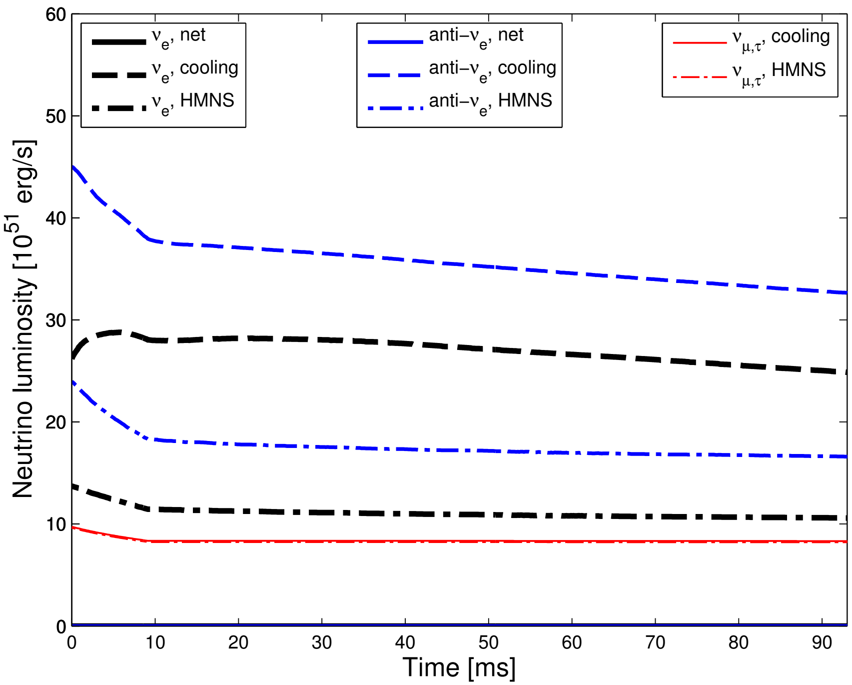
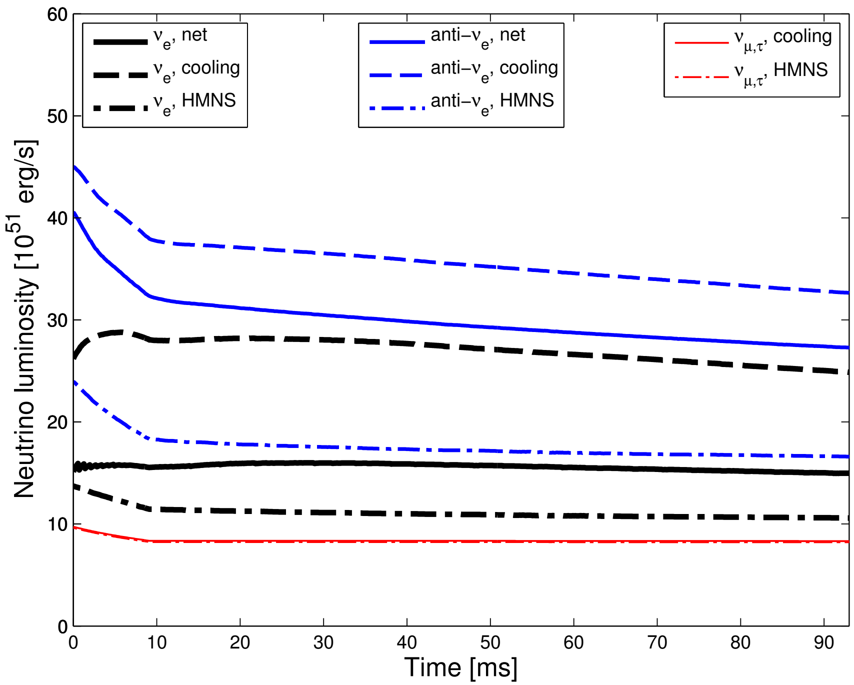


- HMNS ($\rho > 5 \times 10^{11}\,\mathrm{g\,cm^{-3}}$) + disc

Neutrino luminosities

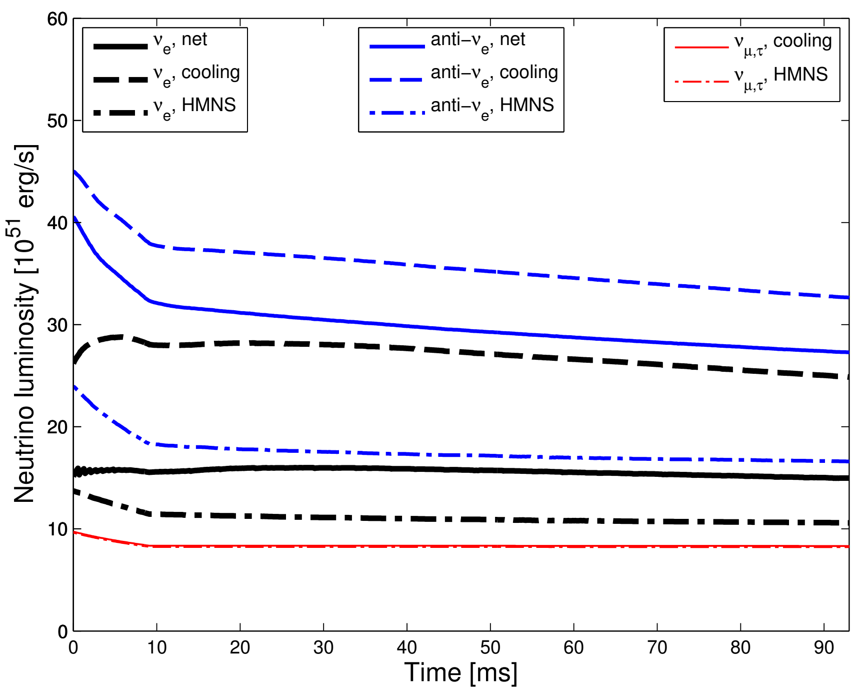
dependence on time



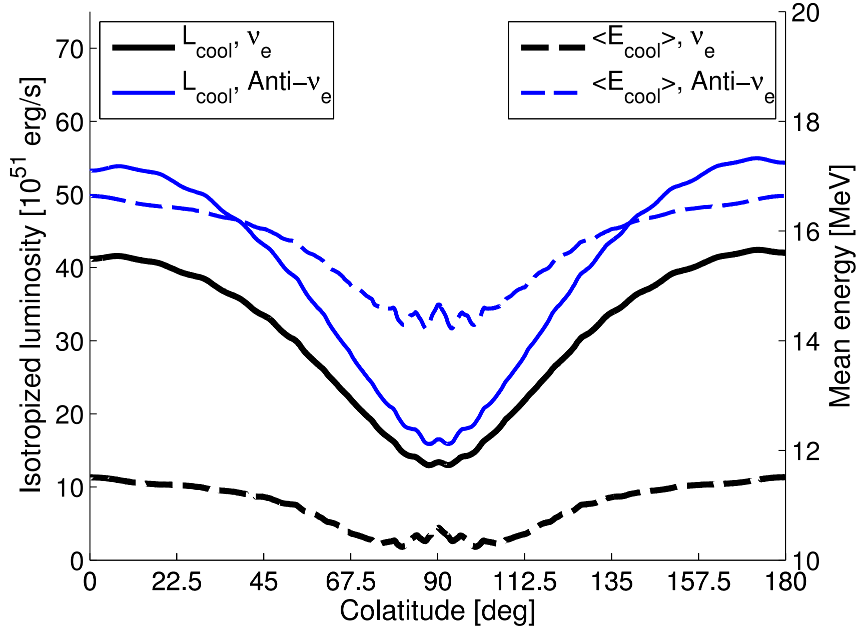
- HMNS ($\rho > 5 \times 10^{11}\,\mathrm{g\,cm^{-3}}$) + disc
- luminosity hierarchy:
  $L_{\bar{\nu}_e} > L_{\nu_e} > L_{\nu_{\mu,\tau}}$
- disc luminosity powered by accretion:
  $\dot{M} \sim 0.6 - 0.4\,M_\odot\,\mathrm{s}^{-1}$ & $\alpha_{\mathrm{num}} \approx 0.05$

Neutrino luminosities

dependence on time

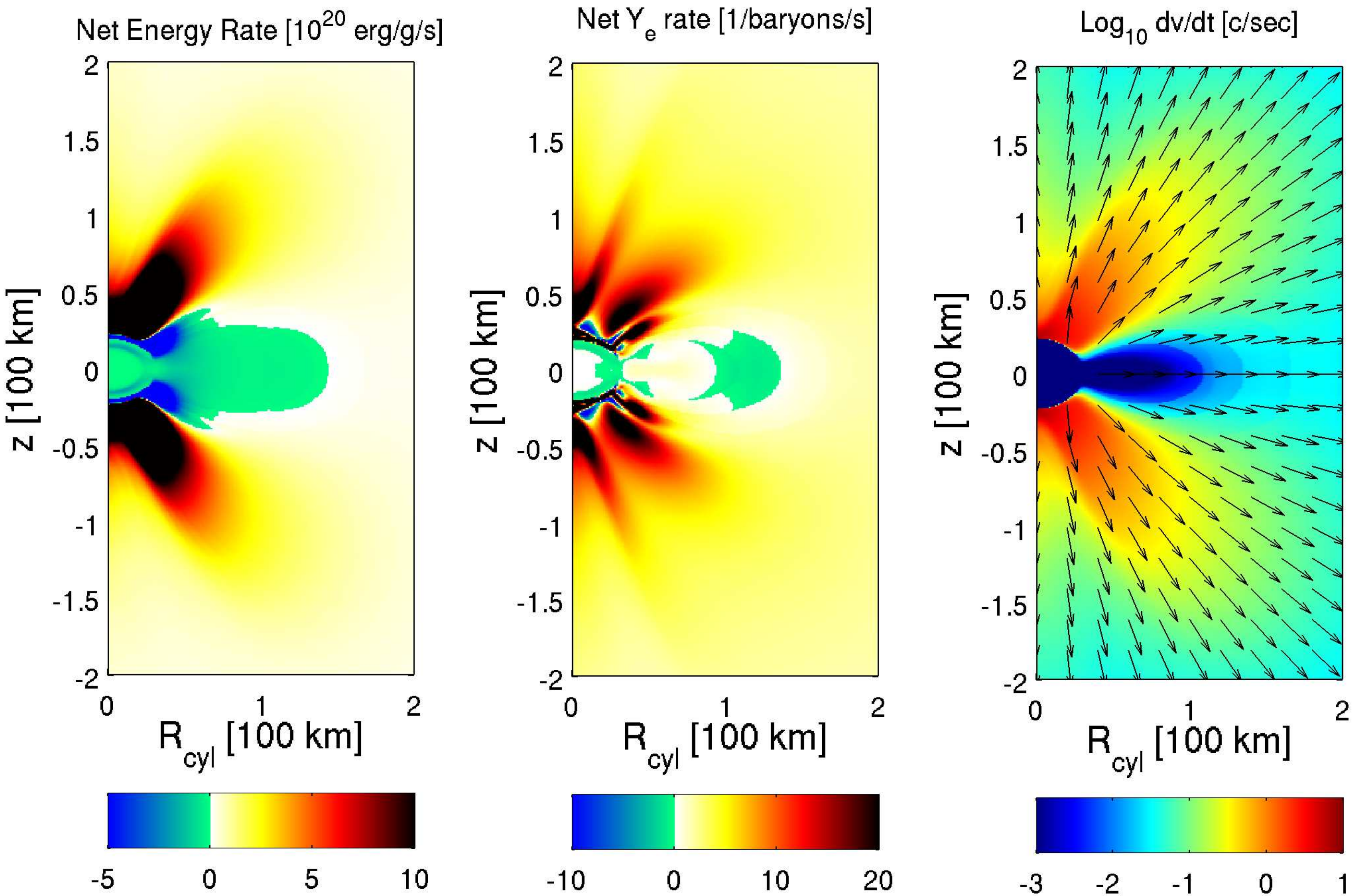


dependence on θ ($t = 40$ms)

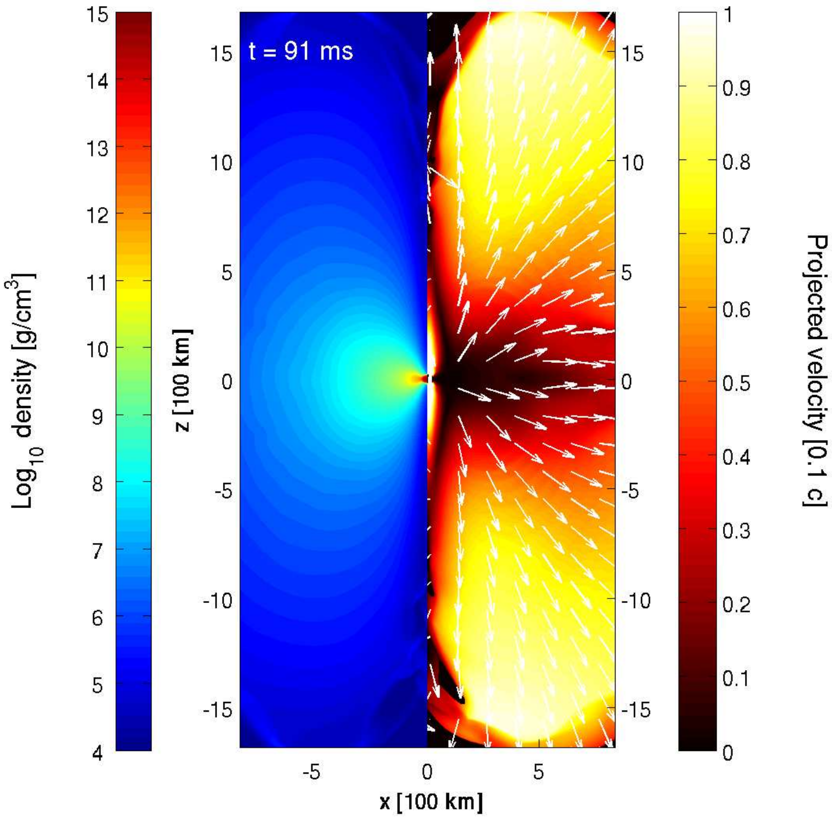


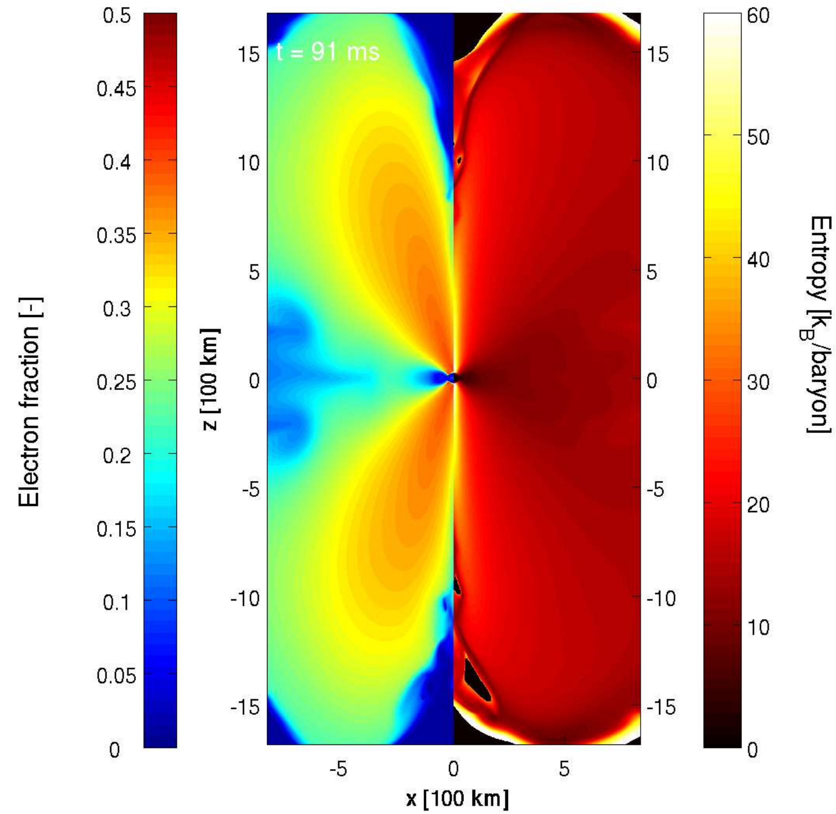
- HMNS ($\rho > 5 \times 10^{11}\,\mathrm{g\,cm^{-3}}$) + disc
- luminosity hierarchy:
  $L_{\bar{\nu}_e} > L_{\nu_e} > L_{\nu_{\mu,\tau}}$
- disc luminosity powered by accretion:
  $\dot{M} \sim 0.6 - 0.4\, M_\odot\,\mathrm{s}^{-1}$ & $\alpha_{\mathrm{num}} \approx 0.05$
- mean energy hierarchy:
  $E_{\nu_{\mu,\tau}} > E_{\bar{\nu}_e} > E_{\nu_e}$
- $E_{\nu_e} \approx 11\,\mathrm{MeV}$, $E_{\bar{\nu}_e} \approx 15\,\mathrm{MeV}$,
  $E_{\nu_{\mu,\tau}} \approx 18\,\mathrm{MeV}$
- disc-shadow effect

Neutrino net rates



Disc and wind dynamics





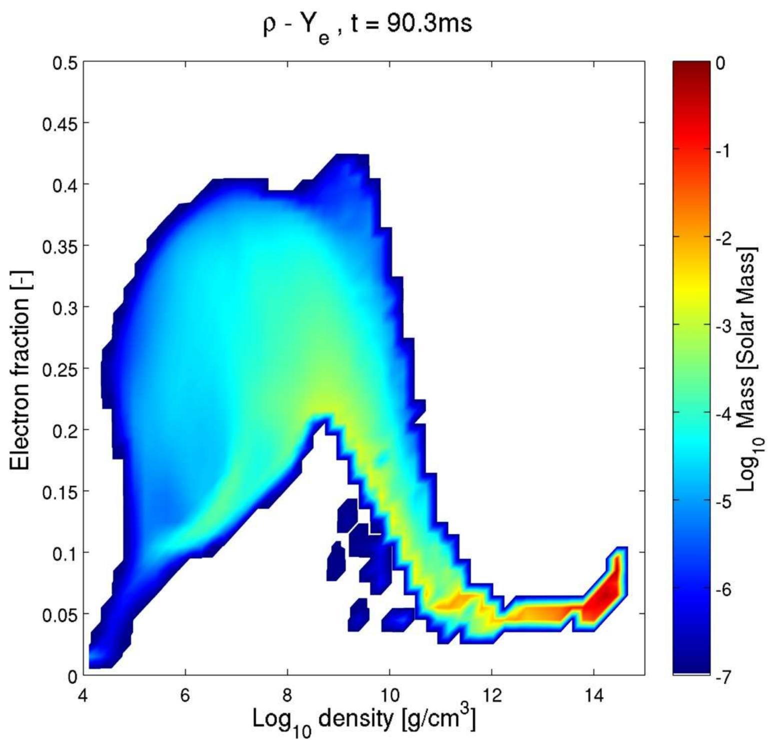
Picture I
left: matter density
right: projected velocity

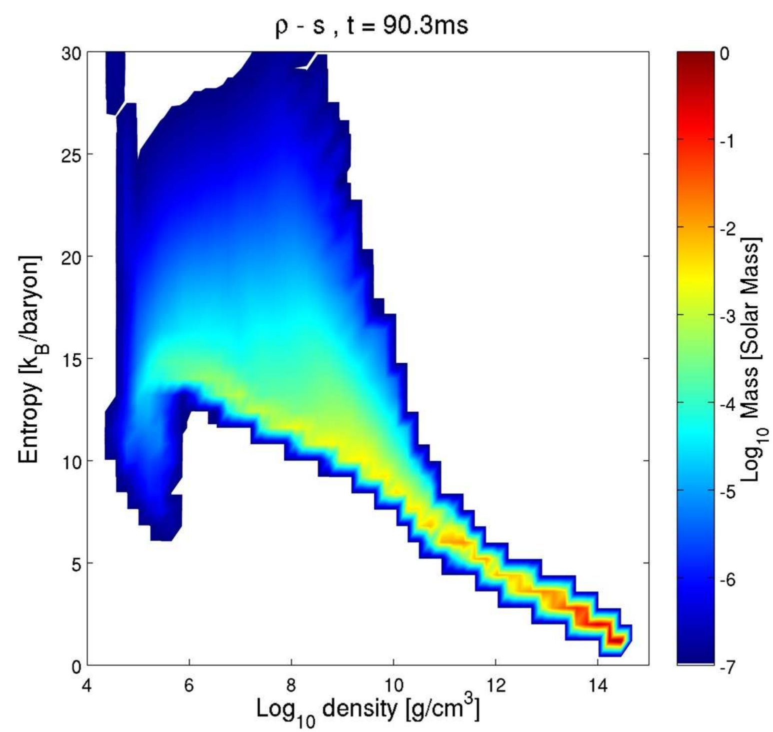
Picture II
left: electron fraction
right: entropy

Click here for the video

Wind properties

- 2D mass-histograms of (ρ, Y_e) and (ρ, s)
- large variation for Y_e: $0.1 \lesssim Y_e \lesssim 0.40$
- small variation in entropy: $10 \lesssim s\ [\mathrm{k_B/bar}] \lesssim 22$

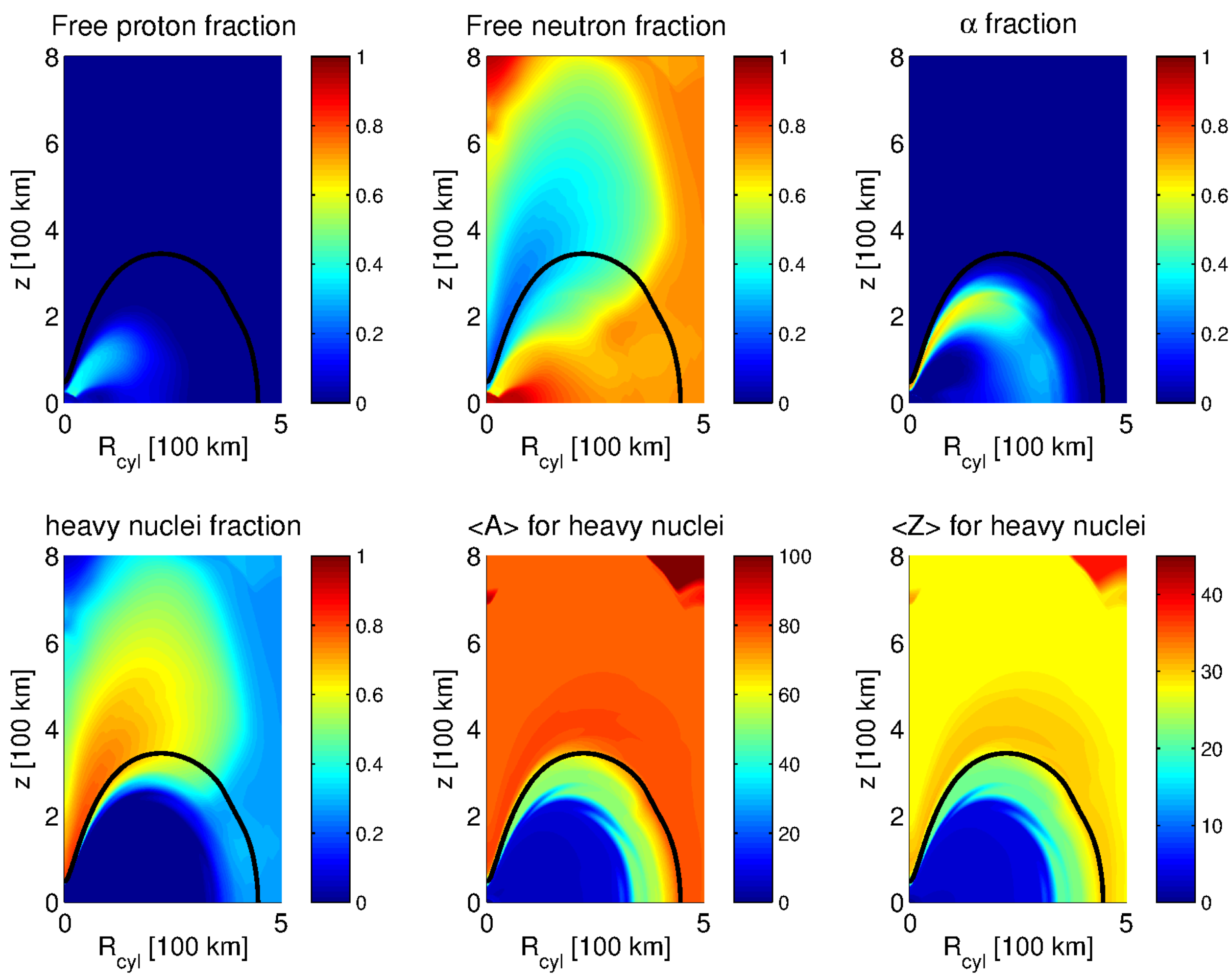




Click here for the video

Ejecta

- criteria: 1) $e_{\rm tot} = e_{\rm kin} + e_{\rm th} + e_{\rm pot} > 0$ & 2) $v_r > 0$ & 3) $\theta < 60^o$
- nuclear recombination energy included



Ejecta

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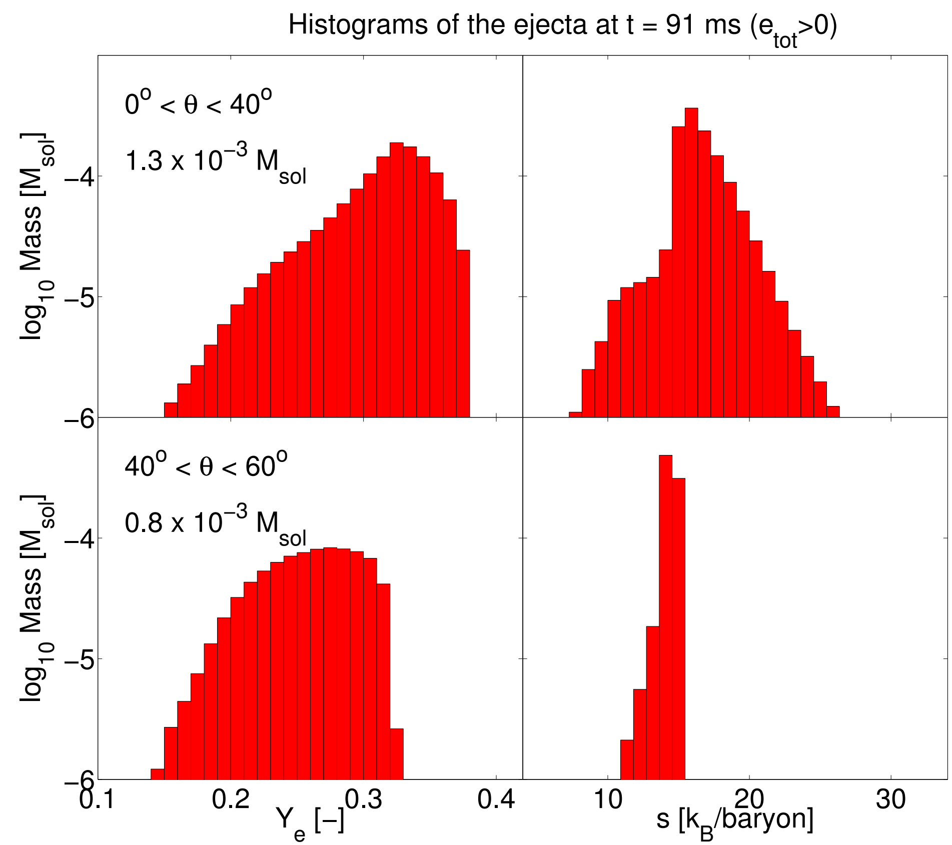
- nuclear recombination energy included

high latitudes ($0^o < \theta < 40^o$)

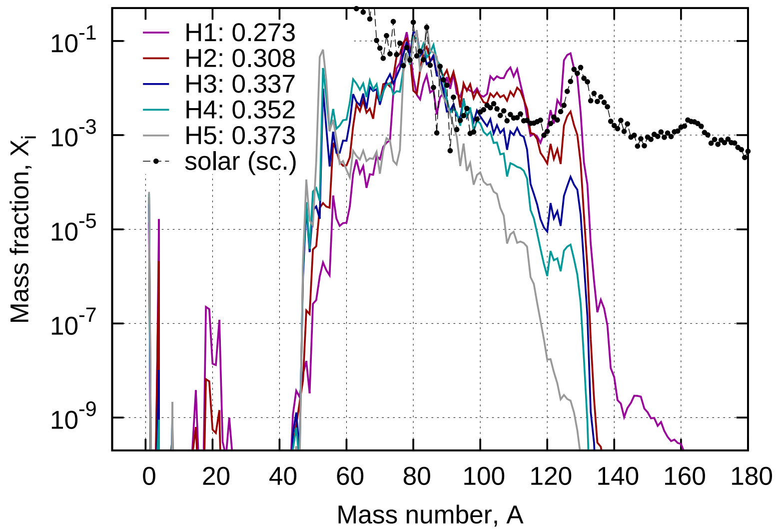
- $m_{\rm ej}(t = 91\,{\rm ms}) \approx 1.3 \times 10^{-3} M_\odot$
  $m_{\rm ej}(t = t_{\rm disc}) \approx 2 - 3 \times 10^{-3} M_\odot$
- $Y_{\rm e}$: 0.31-0.35
  s: 15-20 $k_{\rm B}$ baryon^{-1}
  v_r: 0.08-0.09 c

low latitudes ($40^o < \theta < 60^o$)

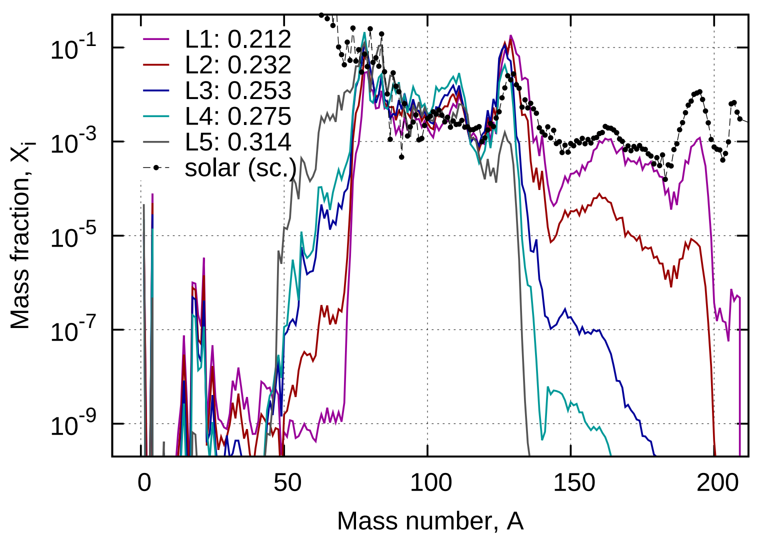
- $m_{\rm ej}(t = 91\,{\rm ms}) \approx 0.8 \times 10^{-3} M_\odot$
  $m_{\rm ej}(t = t_{\rm disc}) \approx 1 - 2 \times 10^{-3} M_\odot$
- $Y_{\rm e}$: 0.23-0.31
  s: 14-15 $k_{\rm B}$ baryon^{-1}
  v_r: 0.06-0.07 c



nucleosynthesis: representative tracers



Tracer	Y_e	s [k_B/baryon]	$\langle A \rangle_{\rm final}$	$\langle Z \rangle_{\rm final}$	$X_{\rm La,Ac}$
L1	0.213	12.46	118.0	46.2	0.04
L2	0.232	11.84	107.1	42.5	0.009
L3	0.253	12.68	98.0	39.2	$7 \cdot 10^{-5}$
L4	0.275	12.73	90.2	36.4	$1 \cdot 10^{-7}$
L5	0.315	13.68	81.7	33.0	$3 \cdot 10^{-12}$
H1	0.273	13.57	93.0	37.4	$8 \cdot 10^{-7}$
H2	0.308	14.69	83.3	33.7	$6 \cdot 10^{-11}$
H3	0.338	15.36	79.4	32.1	$< 10^{-12}$
H4	0.353	16.40	78.4	31.7	$< 10^{-12}$
H5	0.373	18.35	76.8	31.0	$< 10^{-12}$

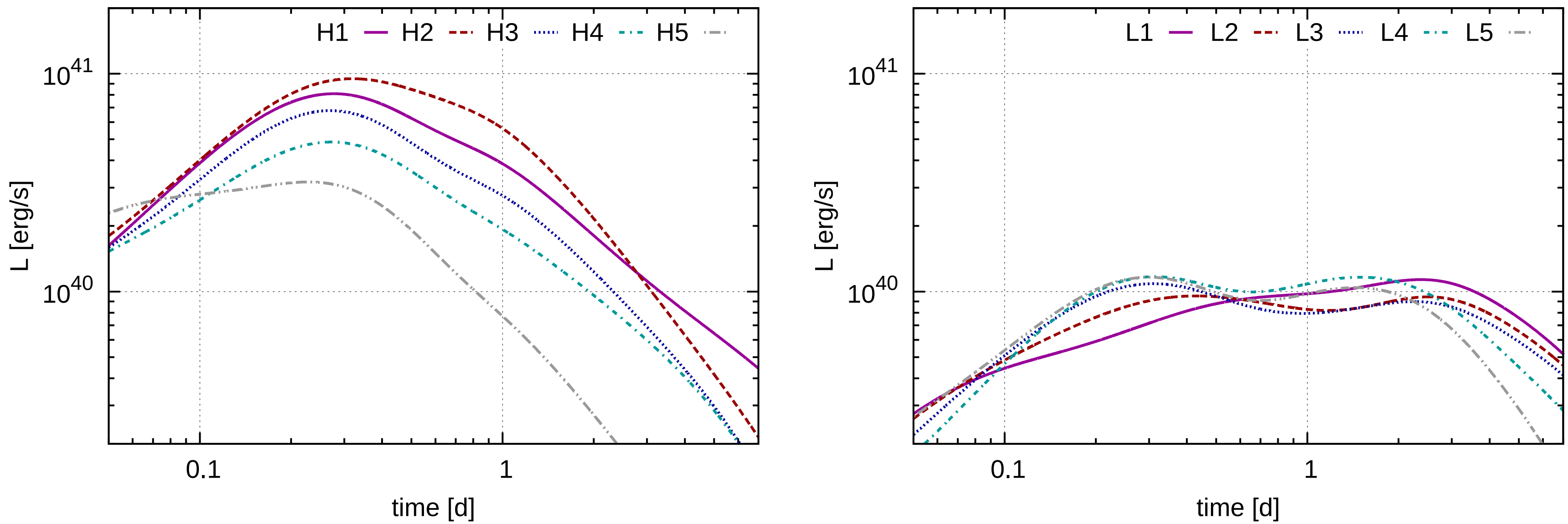


- post-processed with *WinNet*

  Winteler et al (2012)

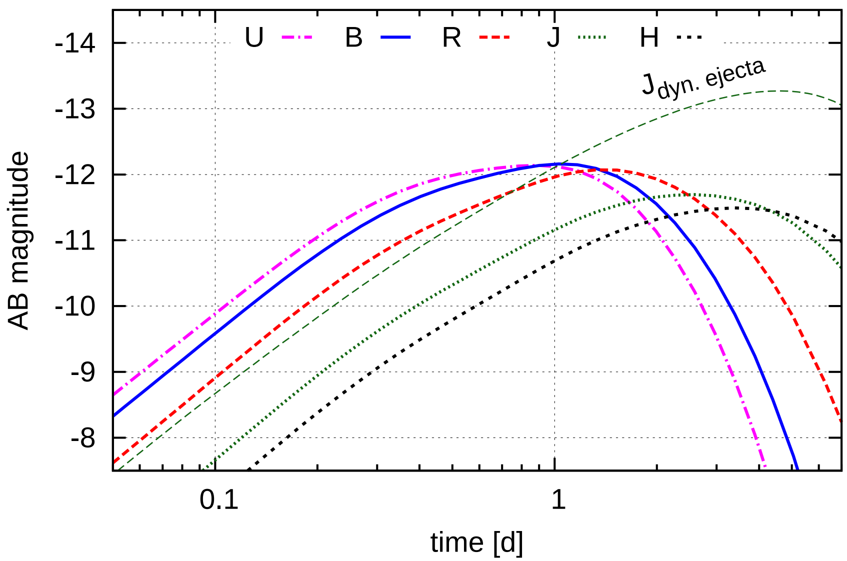
- no robust r-process
- weak r-process $(70 \lesssim A \lesssim 110)$
- significant differences between high and low latitudes

e.m. transient: bolometric luminosity

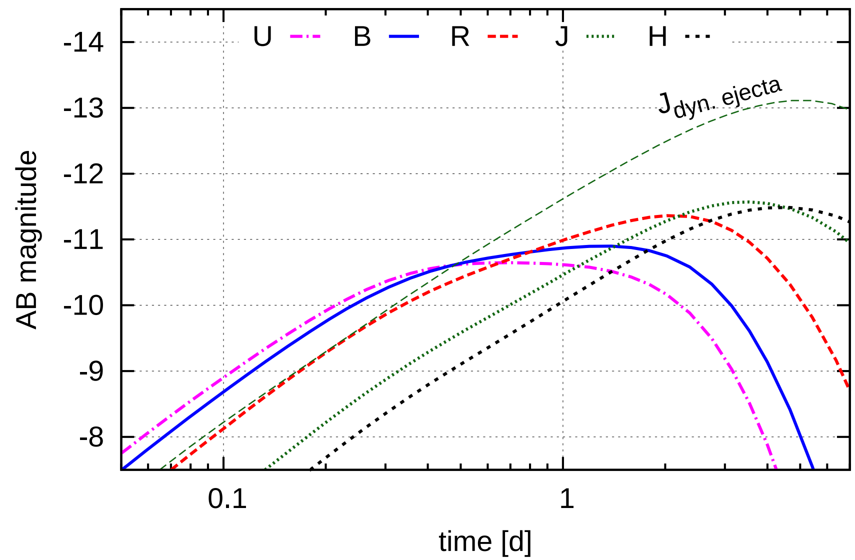


- L_γ powered by radioactive material in the wind — model by Kulkarni 05
- $m_{\rm ej} \approx 2 \times 10^{-3} M_\odot$
  $v_{\rm ej} \approx 0.08\, c$
- uniform grey opacity: $\kappa_h = 1\,{\rm cm}^2\,{\rm g}^{-1}$ VS $\kappa_l = 10\,{\rm cm}^2\,{\rm g}^{-1}$
  Tanaka&Hotokezaka 13, Grossmann+14
- different shapes reflect individual nuclear heating conditions

e.m. transient: broadband lightcurves



top/on-axis view



side/off-axis view

- AB broadband lightcurves
- high latitude: peak in B band at $t \sim 1.3\,\mathrm{d}$
  low latitude: dimmer, redder and delayed
- comparison with dynamical ejecta ($m_{\rm dyn} \approx 1.3 \times 10^{-2} M_\odot$)

Conclusions and outlook

- genuine ν-driven wind from ν heating in the disc ($t_{\rm wind} \sim {\rm tens\,ms}$)
  both HMNS (cooling) and disc (accretion) L_ν
- ν-driven wind contributes substantially ($\gtrsim 3.5 \times 10^{-3} M_\odot$) to ejecta in BNS mergers
- mildly neutron-rich ejecta ($0.2 \lesssim Y_{\rm e,ejecta} \lesssim 0.4$);
  high latitude wind: weak r-process nucleosynthesis ($A \sim 80 - 130$)
  stronger irradiations $\rightarrow$ larger $Y_{\rm e}, s, v_{\rm ej}$
  large $Y_{\rm e}$ range: no robust r-process
- wind e.m. transient depends on geometry and relative orientation
  high latitude outflow powers bluer and brighter lightcurve, that peaks $\approx 1\,{\rm d}$
  low latitude outflow redder and dimmer lightcurve, that peaks $\approx {\rm few\,ds}$

Outlooks

- ν-driven wind and GRB mechanism — e.g. Murguia-Berthier+14
- role of ν oscillations in wind-dynamics and nucleosynthesis — Malkus+14, Gail's talk
- role of GR on ν emission — Caballero+12
- detailed nucleosynthesis and e.m. transient