Neutrinos in neutron star mergers

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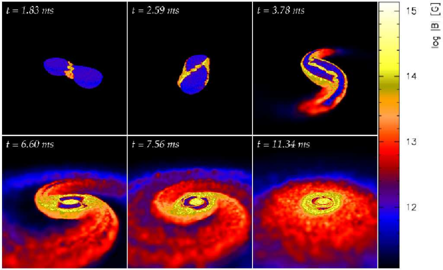
01 June 2016
XXVIII Rencontres de Blois

BNS mergers and their aftermaths

Final stage of a binary NS (BNS) system evolution:

- coalescence phase



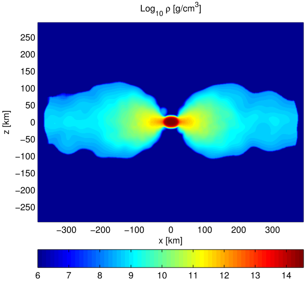
B field from a Newtonian SPH simulations of BNS merger (2 x $1.4M_{\odot}$)

Credit: Price&Rosswog 2006

BNS mergers and their aftermaths

Final stage of a binary NS (BNS) system evolution:

- coalescence phase
- NS merger aftermath



axisymmetric matter density

- Massive NS (→ BH) $\sim 2.6 M_\odot,\ \rho \gtrsim 10^{12}\,\mathrm{g\,cm^{-3}}$
- thick accreting disk $\sim 0.15 M_\odot,\ \mathrm{Y_e} \lesssim 0.20$ $\mathrm{Y_e} = \frac{\mathrm{n_e}}{\mathrm{n_B}} \approx \frac{\mathrm{n_p}}{\mathrm{n_p}+\mathrm{n_n}}$
- intense ν emission $L_{\nu,\mathrm{tot}} \sim 10^{53}\,\mathrm{erg\,s^{-1}}$

BNS in the multimessenger era

dynamical encounter of neutron-rich, stellar compact object

- intense emitter of GWs and ν's e.g. Read+13
- ejecta and heavy elements nucleosynthesis

  Lattimer&Schramm74

- possible short γ-ray burst progenitors e.g. Paczynski86
- e.m. counterpart from radioactive decay

  Li&Paczynski98

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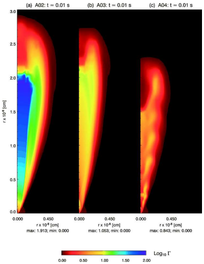

Aloy+05

BNS in the multimessenger era

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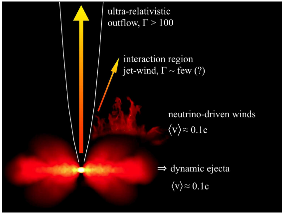
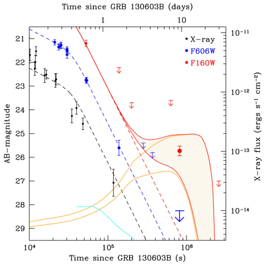
Lattimer&Schramm74



Rosswog 12

- possible short γ-ray burst progenitors e.g. Paczynski86
- e.m. counterpart from radioactive decay

Li&Paczynski98



Tanvir+13, Berger+13

ν emission from BNS mergers

Most relevant reactions:

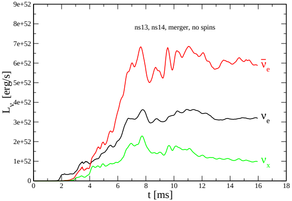
$$p + e^- \rightarrow n + \nu_e \qquad e^- + e^+ \rightarrow \nu + \bar{\nu}$$
$$n + e^+ \rightarrow p + \bar{\nu}_e \qquad N + \nu \rightarrow N + \nu$$

Role of ν's

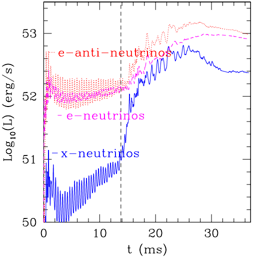
- release energy
- set n-to-p ratio $(\mathrm{Y_e} = \frac{\mathrm{n_e}}{\mathrm{n_B}} \approx \frac{\mathrm{n_p}}{\mathrm{n_p}+\mathrm{n_n}})$
- exchange energy and momentum with matter

ν luminosities $(\Delta E/\Delta t)$

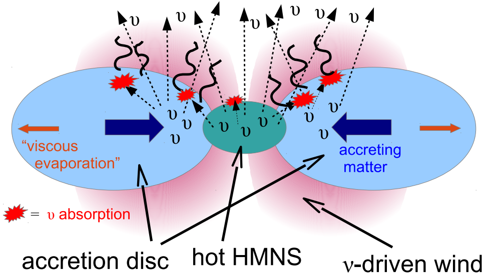
- negligible during inspiral $(T < 0.1\mathrm{MeV})$
- incresed during merger ($T \lesssim$ tens of MeV)
- ν gas formation and diffusion
- n-richness $\rightarrow L_{\bar{\nu}_e} \gtrsim L_{\nu_e}$



Rosswog+13 (up), Neilsen+15 (down)



Neutrino-driven wind



← physical sketch

Perego et al. MNRAS 2014

Martin, Perego et al. ApJ 2015

Goals

- characterize ν emission
- study wind development
- perform nucleosynthesis on ejecta
- compute e.m. counterpart

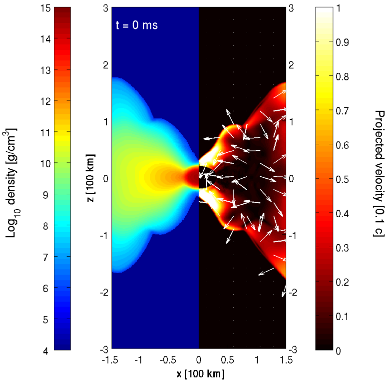
Model

- 3D hydro Käppeli+11
- ν leakage scheme Perego+16
- nuclear EoS Hempel+12
- initial conditions: end of merger simul. Rosswog&Price07

see also Dessart+09,Metzger&Fernandez14,Just+14,Sekiguchi+15

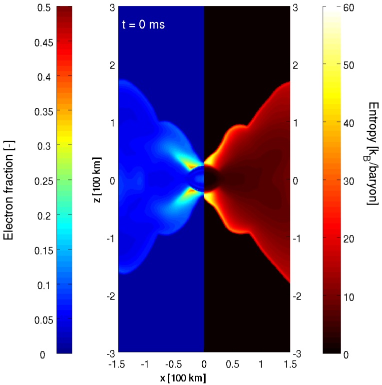
Disc and wind dynamics

t = 0 ms



left: matter density

right: projected velocity

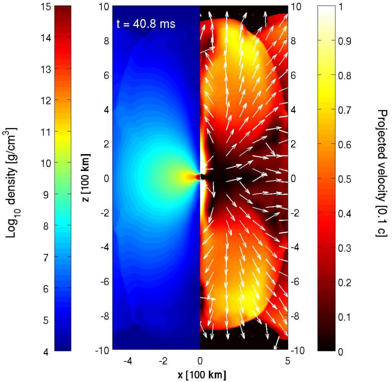


left: electron fraction

right: entropy

Disc and wind dynamics

t = 40 ms



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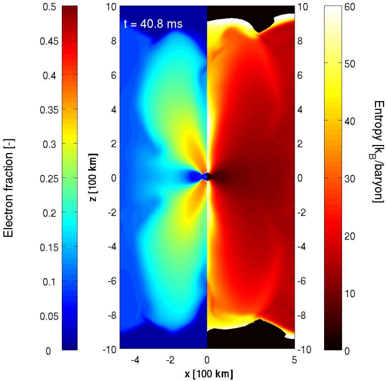
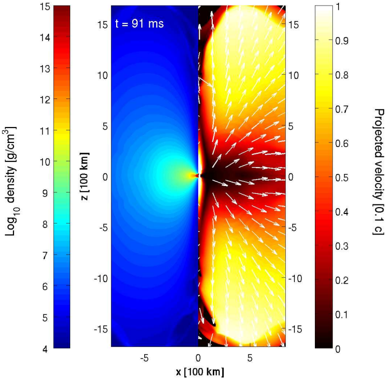


left: electron fraction

right: entropy

Disc and wind dynamics

t = 90 ms



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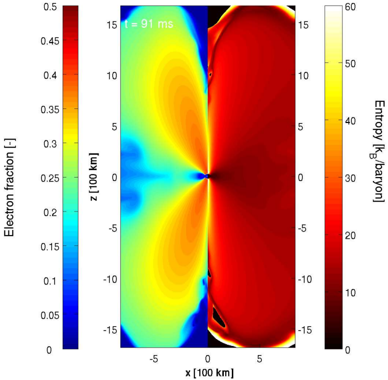

left: electron fraction

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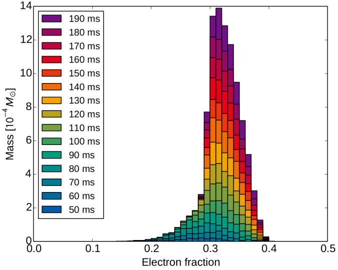
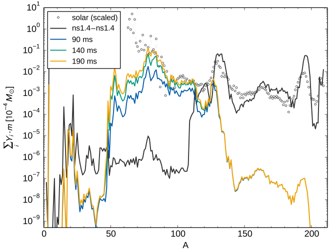
Wind ejecta and nucleosynthesis

- $m_{\mathrm{ej}} \approx 0.05\,M_{\mathrm{disc}} @ 200\,\mathrm{ms}$
- non-equatorial emission: $\theta < 60^o$
- larger $\mathrm{Y_e}$ in the polar regions
- thermodyn properties as input for nuclear network $\rightarrow$ nucleosynthesis abundances



ejected mass: cumulative histogram

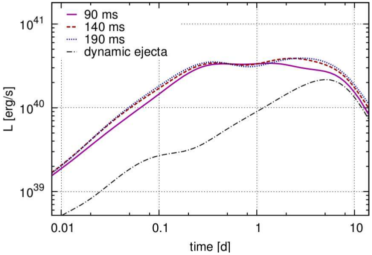


wind ejecta (color lines) + dynamical ejecta (black lines)

from Korobkin+12

Electromagnetic transient

γ emission powered by radioactive material in the ejecta



bolometric luminosity (dynamic + wind)

- 1D model for photon propagation and emission

  e.g. Kulkarni 05,Tanaka&Hotokezaka+14

- potentially different from emission coming from dynamical/viscous ejecta
  - earlier and bluer
  - less contaminated by lanthanides and actinides

  cf Metzger&Fernandez14

- possible dependence from viewing angle

Electromagnetic transient

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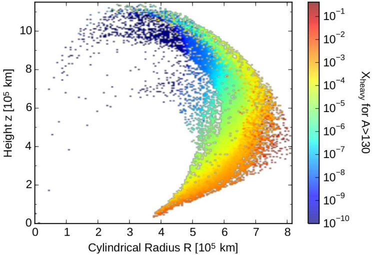

Lanthanides and Actinides mass fraction,

$$\kappa_{A>130} \approx 10\,\mathrm{cm}^2/\mathrm{g} \sim 100\kappa_{Ni}$$

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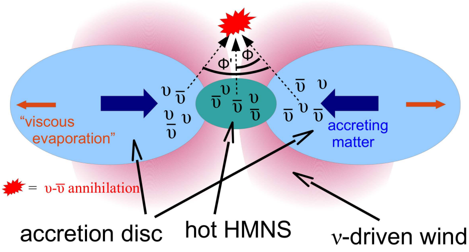
Outlook: ν-$\bar{\nu}$ annihilation

ν-$\bar{\nu}$ annihilation rate as sGRB central engine? Eichler et al. 1989



$$\nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau} \rightarrow e^- + e^+$$

net effect: ν energy deposition in plasma

← physical sketch

$$Q_{\rm ann}(t,\mathbf{x}) = \frac{1}{6}\frac{\sigma_0\left(C_A^2+C_V^2\right)}{c(m_e c^2)} \int I_\nu I_{\bar{\nu}} \left(E_\nu + E_{\bar{\nu}}\right)(1-\cos\Phi)^2 \, \mathrm{d}\Omega_\nu \mathrm{d}\Omega_{\bar{\nu}} \mathrm{d}E_\nu \mathrm{d}E_{\bar{\nu}}$$

where

- $\sigma_0 \approx 1.705 \times 10^{-44}\,\mathrm{cm}^2$ and $C_A, C_V \sim 1$
- $I_\nu(\mathbf{x}, E_\nu, \Omega_\nu)$: ν intensity, E_ν: ν energy, Ω_ν: solid angle
- $\cos\Phi = \mathbf{n}_\nu \cdot \mathbf{n}_{\bar{\nu}}$ ($\mathbf{n}_\nu \equiv \nu$ propagation direction)

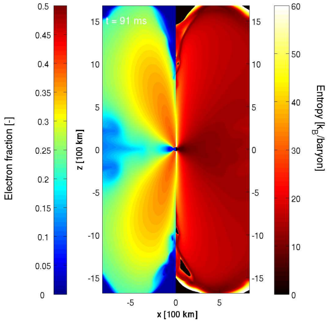
ν-$\bar{\nu}$ annihilation: open questions

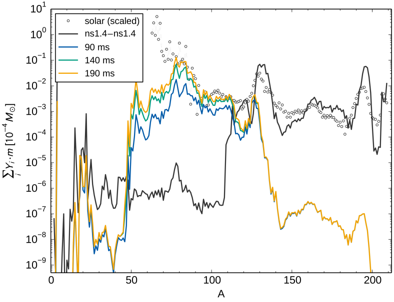
- why plausible mechanism?
  - large energy reservoir (accretion + remnant cooling)
  - high ν luminosities ($L_\nu \sim 10^{53}\,\mathrm{erg/s}$)
  - $\Delta t_{L_\nu} \gtrsim \Delta t_{\mathrm{disc}} \sim T_{90} \sim 0.3\,\mathrm{s}$
- why relevant in the funnel?
  - high intensity I_ν close to MNS
  - good collision angle Φ
  - lower baryonic pollution
- previous results (mainly BH-disc systems)
  - energy enough to explain SGRBs ($\sim 10^{49}\mathrm{erg}$)
  - however, baryonic pollution can prevent relativistic jet formation
  - role of MNS?

e.g. Dessart+09,Zalamea&Beloborodov+11,Richter+15,Just+16

Conclusions

- genuine ν-driven wind from ν heating in the disk
  $t_{\rm wind} \sim$ tens ms
- substantial wind ejecta:
  $\sim 0.05 M_{\rm disc}$ @ 200 ms
- mildly neutron-rich ejecta
  $0.2 \lesssim {\rm Y}_{\rm e,ejecta} \lesssim 0.4)$



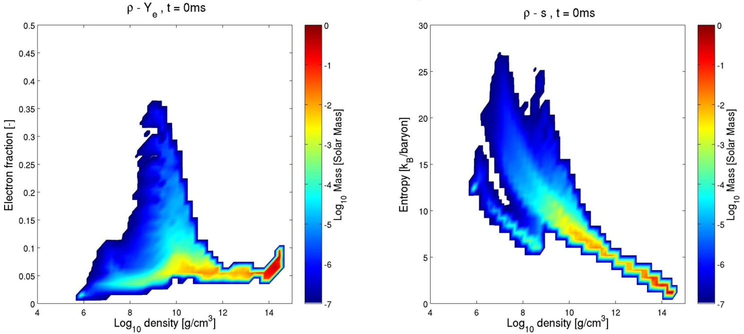


- weak r-process nucleosynthesis
  $(A \sim 80 - 130)$
- wind e.m. transient
  different from dynamical ejecta transient
- outlook:
  $\nu - \bar{\nu}$ annihilation above MNS

Wind properties

2D mass-histograms of $(\rho, \mathrm{Y_e})$ and (ρ, s)

$t \approx 0$ ms



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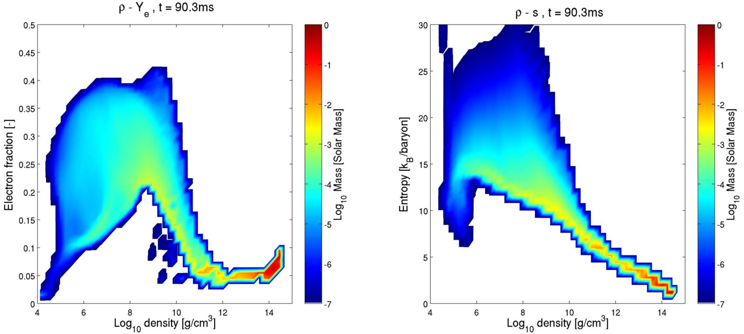

- large variation for $\mathrm{Y_e}$: $0.1 \lesssim \mathrm{Y_e} \lesssim 0.40$
- small variation in entropy: $10 \lesssim s\ [\mathrm{k_B/bar}] \lesssim 22$

BNS mergers as GW sources

BNS mergers (together with BH-NS mergers) are …

- …primary target of ground based GW detectors
  - aLIGO, VIRGO e.g. Acernese+08, Abbott+09, cf. Abbott+16 for BBH detection
  - calculation of GW signal from inspiral/merger/post-merger phases e.g. Duez+10, Read+13
  - constraint on nuclear EoS e.g. Bauswein+14

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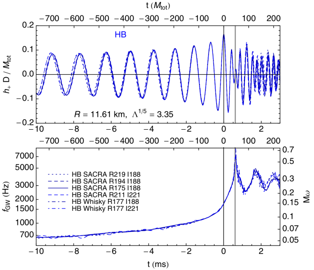
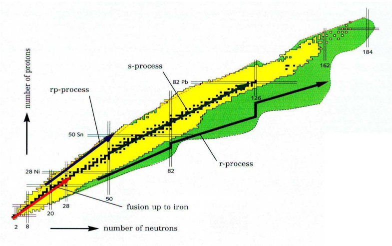
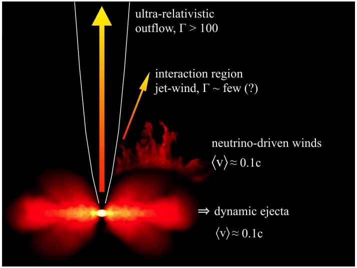


Read+13

BNS mergers & Nucleosynthesis

- massive stars produce elements up to Fe group
- where and how are heaviest elements formed?
  - high neutron densities $\Rightarrow t_{\mathrm{n-capture}} < t_{\beta\mathrm{decay}} \Rightarrow$ r-process
  - core collapse supernovae $\Rightarrow$ theoretically challenged
  - compact binary mergers, with different ejection channels:
    - dynamical ejecta e.g., Korobkin+12, Bauswein+13, Hotokezaka+13, Wanajo+14
    - viscous ejecta e.g., Fernandez&Metzger 13, Just+14
    - ν-driven wind e.g. Dessart+09, Metzger&Fernandez 14, Perego+14

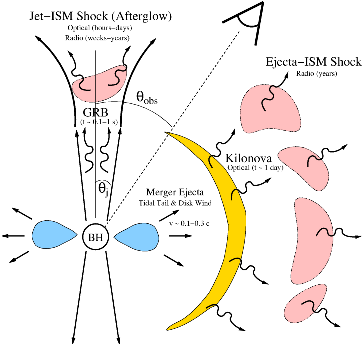




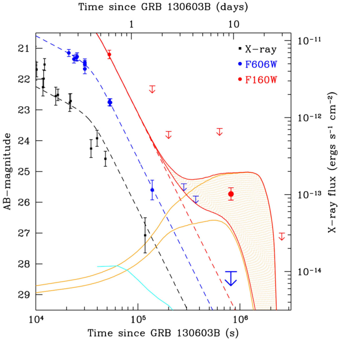
Rosswog 12

BNS mergers & e.m. counterparts

- late optical transient associated with short GRBs
  - radioactively-powered transient e.g. Li&Paczynski98
  - possible first kilo/macro-nova observations, associated with GRB130603B and GRB060614



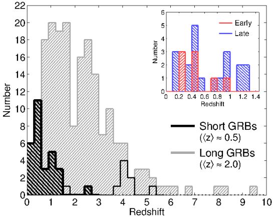
Metzger&Berger 12



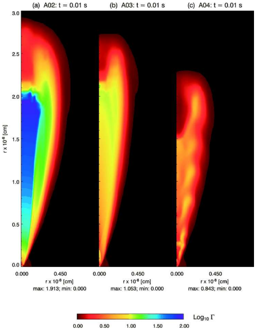
Tanvir+13, Berger+13 (cf. Bin Yang+15)

BNS mergers & GRBs

- promising progenitors of short/hard GRBs e.g. Paczynski86
  - compatibility with observation constraints e.g. Berger 14
  - massive (magnetized) compact object (MNS or BH) surrounded by accretion disc
  - possible central engine
    - $\nu - \bar{\nu}$ annihilation Eichler+ 89
    - BZ mechanism (with BH)
    - magnetar model (MNS) Metzger 08
    - magnetic ejection



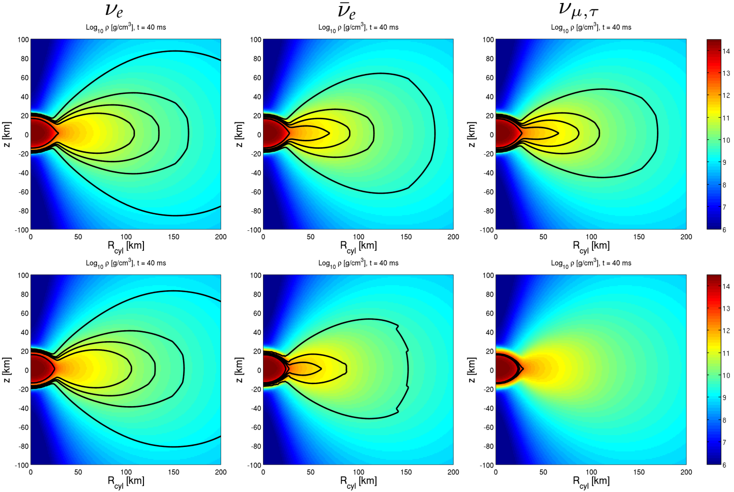
Berger 14



Aloy+05

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

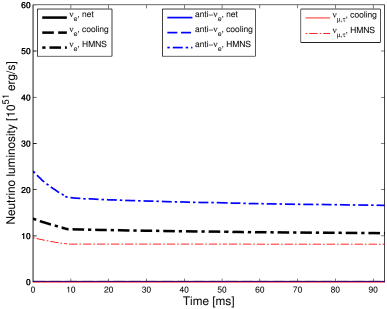


$\tau_{\nu,\mathrm{s}}$
scatt.

$\tau_{\nu,\mathrm{e}}$
therm.

Neutrino luminosities

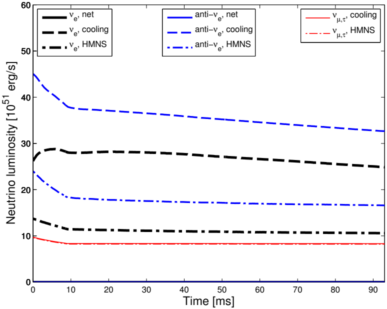
dependence on time



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

Neutrino luminosities

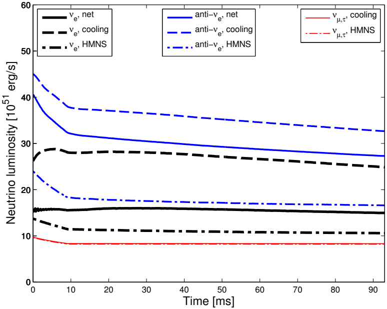
dependence on time



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

Neutrino luminosities

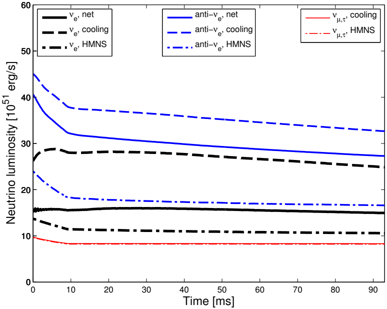
dependence on time



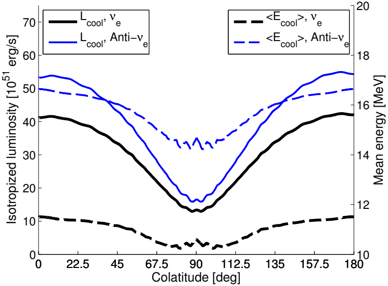
- MNS ($\rho > 5 \times 10^{11} \mathrm{g\,cm}^{-3}$) + disc
- luminosity hierarchy: $L_{\bar{\nu}_e} > L_{\nu_e} > L_{\nu_{\mu,\tau}}$
- disc luminosity powered by accretion: $\dot{M} \sim 0.6 - 0.4\, M_\odot\, \mathrm{s}^{-1}$ & $\alpha_{\mathrm{num}} \approx 0.05$

Neutrino luminosities

dependence on time



dependence on θ ($t = 40\mathrm{ms}$)



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