The role of neutrinos in the ejection of matter from binary neutron star mergers.

Albino Perego

in collaboration with A. Arcones and D. Martin (TU Darmstadt), O. Korobkin and S. Rosswog (U. Stockholm), R. Cabezon, M. Liebendörfer and F.-K. Thielemann (U. Basel), R. Käppeli (ETH Zürich)

`albino.perego@physik.tu-darmstadt.de`

Technische Universität Darmstadt

Institute for Nuclear Physics, Theory

Introduction

BNS mergers and their aftermaths

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

- double BNS systems do exist
- merger rate: $\sim 1\,\mathrm{events}\,\mathrm{Myr}^{-1}\mathrm{galaxy}^{-1}$

BNS mergers and their aftermaths

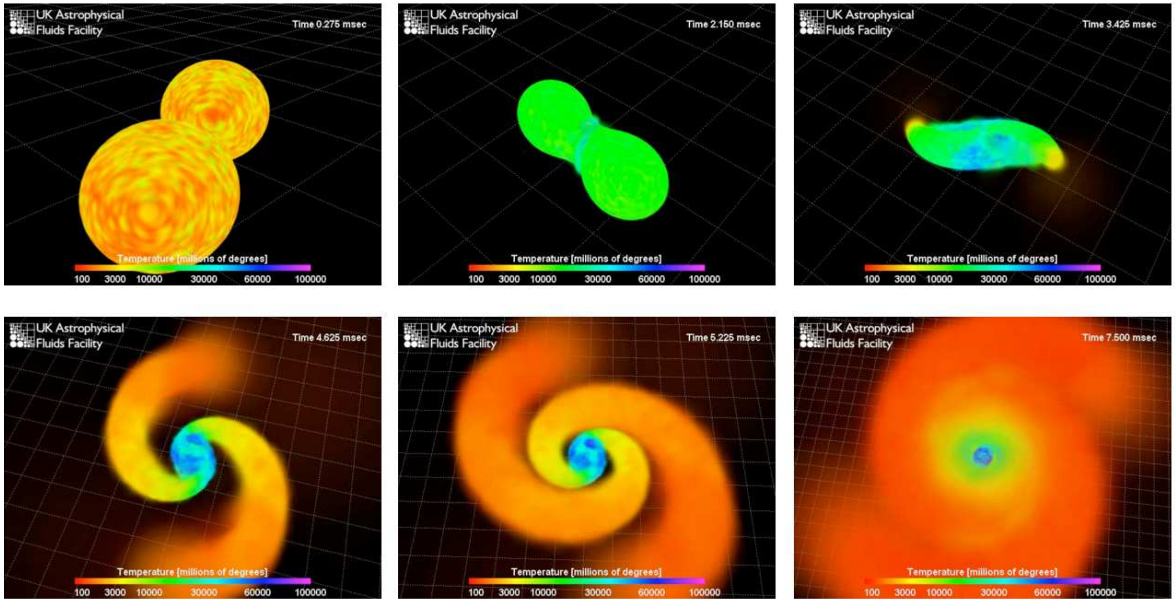
Final stage of a binary NS (BNS) system evolution:

- double BNS systems do exist
- merger rate: $\sim 1\,\mathrm{events}\,\mathrm{Myr}^{-1}\mathrm{galaxy}^{-1}$
- inspiral phase, driven by GW emission

BNS mergers and their aftermaths

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

- double BNS systems do exist
- merger rate: $\sim 1\,\mathrm{events}\,\mathrm{Myr}^{-1}\mathrm{galaxy}^{-1}$
- inspiral phase, driven by GW emission
- coalescence phase

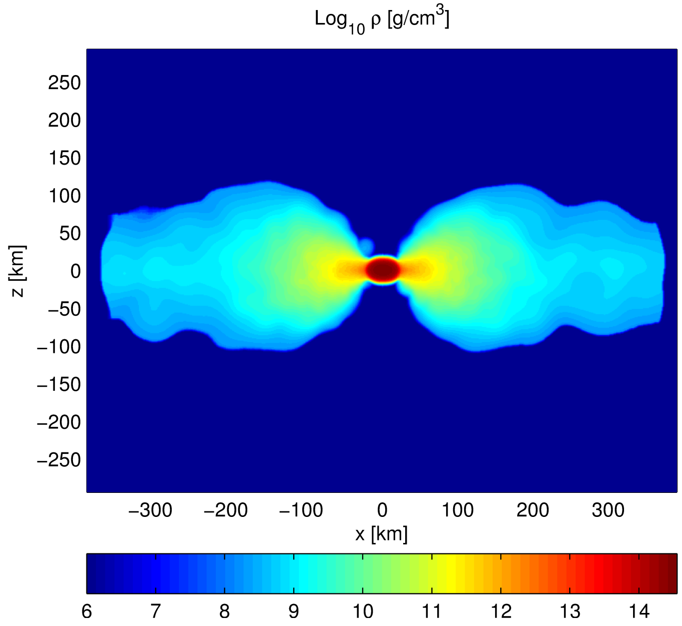


Matter temperature from a SPH simulations. Credit: S. Rosswog.

BNS mergers and their aftermaths

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

- double BNS systems do exist
- merger rate: $\sim 1\,\mathrm{events\,Myr^{-1} galaxy^{-1}}$
- inspiral phase, driven by GW emission
- coalescence phase
- NS merger aftermath



- (Hyper) Massive NS (→ BH)
  $\sim 2.6 M_\odot, \rho \gtrsim 10^{12}\mathrm{g\,cm^{-3}}$
- thick accreting disk
  $\sim 0.15 M_\odot$, neutron rich matter
- intense ν emission
  $L_{\nu,\mathrm{tot}} \sim 10^{53}\mathrm{erg\,s^{-1}}$

← figure: matter density

Astrophysical relevance

NS-NS (& BH-NS) mergers: multimessenger scenarios

e.g. Rosswog 12, more in Piran's talk

- GW emission e.g. Bernuzzi's, Kastaun's talk
- ν emission Ruffert&Janka98,Rosswog&Liebenörfer03
  - emission properties e.g. Rosswog+12,Foucart+14,Sekiguchi+15
- nucleosynthesis yields
  - r-process nucleosynthesis Lattimer&Schramm74,Eichler+89
  - different channels, with different properties
- e.m. emission
  - precursors and radio emission e.g. Troja+10, Nakar&Piran11
  - short GRB projenitors Paczynski86; Just's, Richers', Drago's talks
  - Kilo/Macro-nova emission Li&Paczynski98; Korobkin's, Lippuner's talk

Astrophysical relevance

NS-NS (& BH-NS) mergers: multimessenger scenarios

e.g. Rosswog 12, more in Piran's talk

- GW emission e.g. Bernuzzi's, Kastaun's talk
- ν emission Ruffert&Janka98,Rosswog&Liebenörfer03
  - emission properties e.g. Rosswog+12,Foucart+14,Sekiguchi+15
- nucleosynthesis yields
  - r-process nucleosynthesis Lattimer&Schramm74,Eichler+89
  - different channels, with different properties
- e.m. emission
  - precursors and radio emission e.g. Troja+10, Nakar&Piran11
  - short GRB projenitors Paczynski86; Just's, Richers', Drago's talks
  - Kilo/Macro-nova emission Li&Paczynski98; Korobkin's, Lippuner's talk

Matter conditions and ν reactions

relevant questions:

1. system dynamics and ejection mechanism?
2. ejecta properties (mass, thermodynamics evolution)?
3. nucleosynthesis yields?

Matter conditions and ν reactions

relevant questions:

1. system dynamics and ejection mechanism?
2. ejecta properties (mass, thermodynamics evolution)?
3. nucleosynthesis yields?

- Initial conditions:
  - 2 cold ($T \approx 0$) NS in weak equilibrium
- Merger:
  - increase in T and matter decompression
  - activation of weak reactions and intense ν emission
- Merger aftermath:
  - ν cooling, T and ρ decrease
  - persistent, decreasing weak reactions

Ejection channels

At least three relevant ejection channels

- dynamic ejecta
  - gravitational torques and shock during merger, time scale: a few ms
  - robust heavy r-process (Newtonian simul with ν cooling, approx GR without ν) or even full r-process (GR simul with ν, Sekiguchi's talk)

    e.g. Freiburghaus+99,Korobkin+12,Bauswein+13,Hotokezaka+13,Wanajo+14

Ejection channels

At least three relevant ejection channels

- dynamic ejecta
  - gravitational torques and shock during merger, time scale: a few ms
  - robust heavy r-process (Newtonian simul with ν cooling, approx GR without ν) or even full r-process (GR simul with ν, Sekiguchi's talk)

    e.g. Freiburghaus+99,Korobkin+12,Bauswein+13,Hotokezaka+13,Wanajo+14
- ν-driven ejecta
  - ν absorption in the disk, time scale: a few 10 ms e.g. Dessart+09, Perego+14
  - light r-process

    e.g. Metzger&Fernandez14,Just+14,Martin+15

Ejection channels

At least three relevant ejection channels

- dynamic ejecta
  - gravitational torques and shock during merger, time scale: a few ms
  - robust heavy r-process (Newtonian simul with ν cooling, approx GR without ν) or even full r-process (GR simul with ν, Sekiguchi's talk)

e.g. Freiburghaus+99,Korobkin+12,Bauswein+13,Hotokezaka+13,Wanajo+14

- ν-driven ejecta
  - ν absorption in the disk, time scale: a few 10 ms e.g. Dessart+09, Perego+14
  - light r-process

e.g. Metzger&Fernandez14,Just+14,Martin+15

- viscosity- and recombination-driven ejecta
  - disk viscosity and nuclear recombination, time scale: a few 100 ms
  - full r-process e.g. Fernandez&Metzger13,Just+14

Caveat:

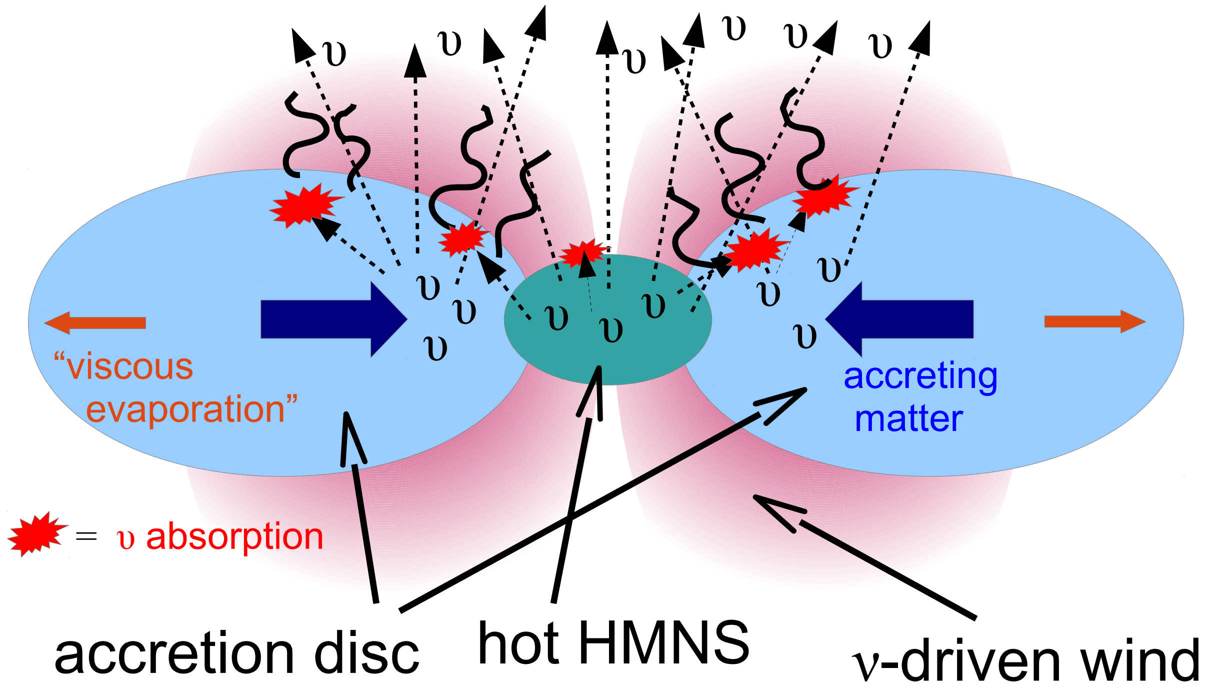
- continuous picture
- magnetic field role? magnetically-driven outflows?

ν-driven wind

Neutrino-driven wind

Physical origin of the ν-driven wind:

- HMNS ($\rightarrow$ BH)
  $\sim 2.60 M_\odot$
- thick accreting disk
  $\sim 0.17 M_\odot$, $Y_e \sim 0.1$
- intense neutrino (ν) emission
  $L_{\nu,\mathrm{tot}} \sim 10^{53} \mathrm{erg\,s^{-1}}$
- ν-disk interaction: wind formation



e.g. Ruffert&Janka 96, Rosswog+03

Goals of this study

Perego, Rosswog, Cabezon, Korobkin, Käppeli, Arcones, Liebendörfer, MNRAS 2014

Martin, Perego, Arcones, Thielemann, Korobkin, Rosswog, submitted to ApJ

- to characterize the neutrino emission
- to study the wind development
- to analyze the ejecta and to perform nucleosynthesis calculations
- to compute electromagnetic counterparts

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

what's new/different:

- first wind study in 3D
- disc and wind evolution over ~ 200 ms
- high spatial resolution in the wind $(\Delta x = 1\,\mathrm{km}, \Delta x/L \sim 5 \times 10^{-4})$

Model ingredients

- initial conditions:
  final stages of high resolution SPH simulation of binary NS merger, with multi-flavor ν cooling and Shen EOS

  e.g. Rosswog&Price07
- Hydrodynamics:
  `FISH` 3D Grid Cartesian code Käppeli+11
- ν treatment:
  Advanced Spectral Leakage (ASL) scheme

  dominant ν cooling & heating processes
- Nuclear equation of state:
  HS EoS, with TM1 parametrization Hempel+12
- Tracers:
  Lagrangian particles advected in the fluid ($100k$)

ASL: overview

- based on previous grey leakage schemes

(Ruffert+97, Rosswog & Liebendörfer03, O'Connor&Ott11)

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

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

ν optical depth

- optical depth: average number of interactions for a ν, before leaving the system

$$\tau_\nu = \int_\gamma \frac{1}{\lambda}\,\mathrm{d}s \qquad \lambda = \frac{1}{n_{\rm target}\;\sigma_{\nu-{\rm target}}} \propto E_\nu^{-2}$$

- scattering optical depth, $\tau_{\nu,\rm s}$:
  - $\lambda_{\rm s}^{-1} = \lambda_{\rm scat}^{-1} + \lambda_{\rm abs}^{-1}$ (all possible reactions)
  - $\tau_{\nu,\rm s} \gg 1$: diffusive regime
- energy optical depths, $\tau_{\nu,\rm e}$:
  - $\lambda_{\rm e}^{-1} = \sqrt{\left(\lambda_{\rm scat}^{-1} + \lambda_{\rm abs}^{-1}\right)\lambda_{\rm abs}^{-1}}$ (geometrical mean)
  - $\tau_{\nu,\rm e} \leq \tau_{\nu,s}$
  - $\tau_{\nu,\rm e} \gg 1$: diffusive regime & thermal equilibrium

ASL: basics

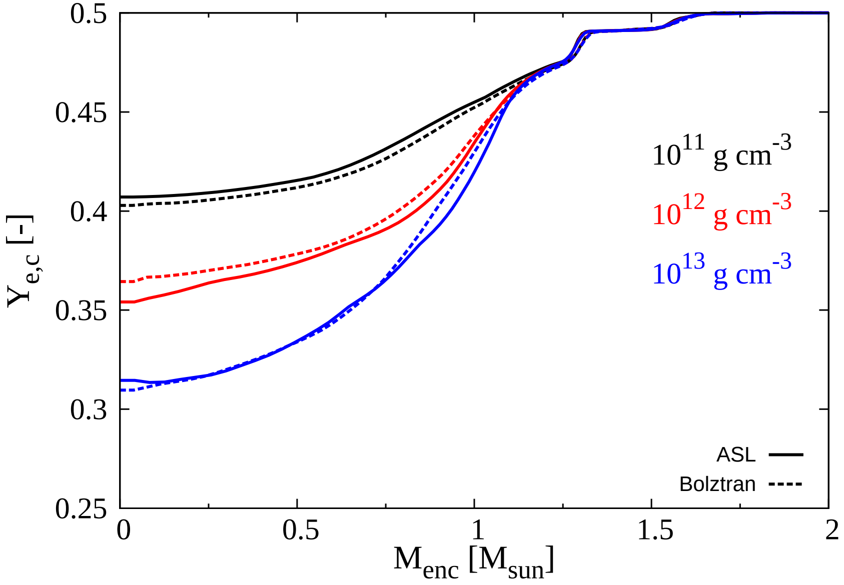
- effective scheme: ASL mimics known solutions of radiative transfer
- cooling part:
  - smooth interpolation between diffusion and production (spectral) rates
  - reproduction of the correct limits: diffusive ($\tau_\nu \gg 1$) and free streaming ($\tau_\nu \lesssim 1$) (τ_ν neutrino optical depth)
- heating part (for $\tau_\nu \lesssim 1$):
  - n_ν (neutrino density) calculated by ray-tracing algorithm; input: emission rates at ν-surfaces
  - $r_{\rm heat} \propto \chi_{\rm ab} \cdot n_\nu \qquad (\chi_{\rm ab}\ \text{absorptivity})$
- modeling of ν trapped component (for $\tau_\nu \gtrsim 1$)
  - Fermi-Dirac gas in thermal and weak equilibrium

ASL: CCSN 1D tests

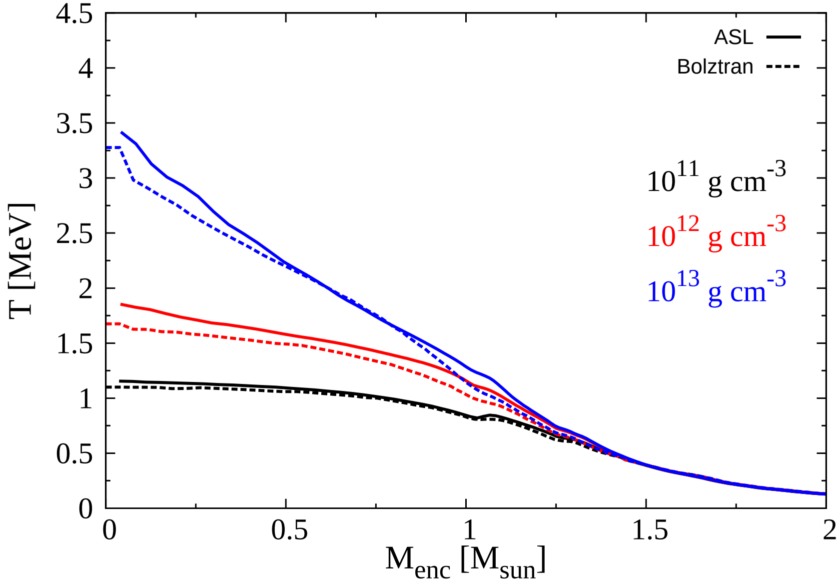
ASL developed and tested in CCSN context

comparison with spherically symmetric Boltzmann ν-transport (BOLZTRAN) for 15 $M_\odot$ progenitor, from collapse to several 100 ms (AB data: courtesy of M. Liebendörfer)

Y_e during collapse



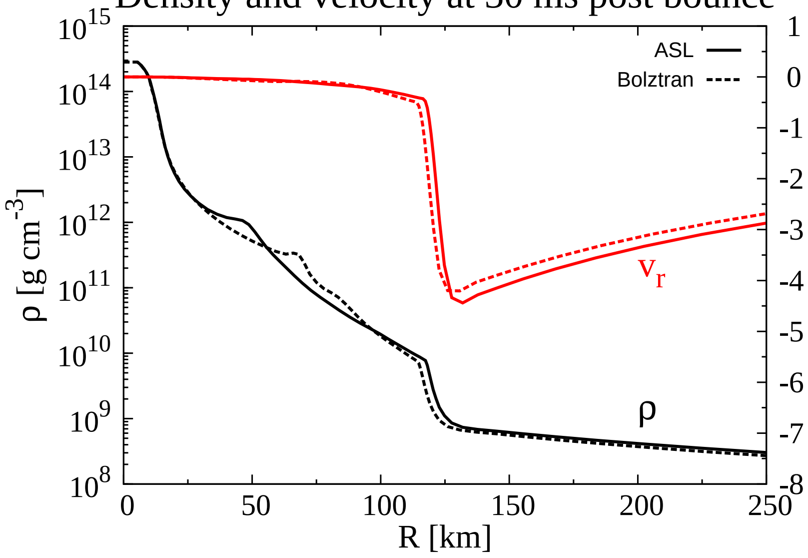
T during collapse

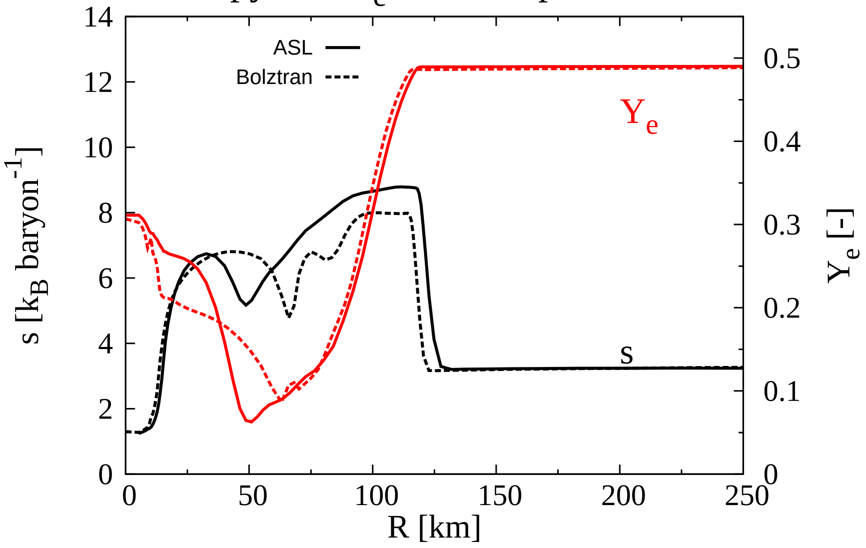


ASL: CCSN 1D tests

ASL developed and tested in CCSN context

comparison with spherically symmetric Boltzmann ν-transport (BOLZTRAN) for 15 $M_\odot$ progenitor, from collapse to several 100 ms (AB data: courtesy of M. Liebendörfer)

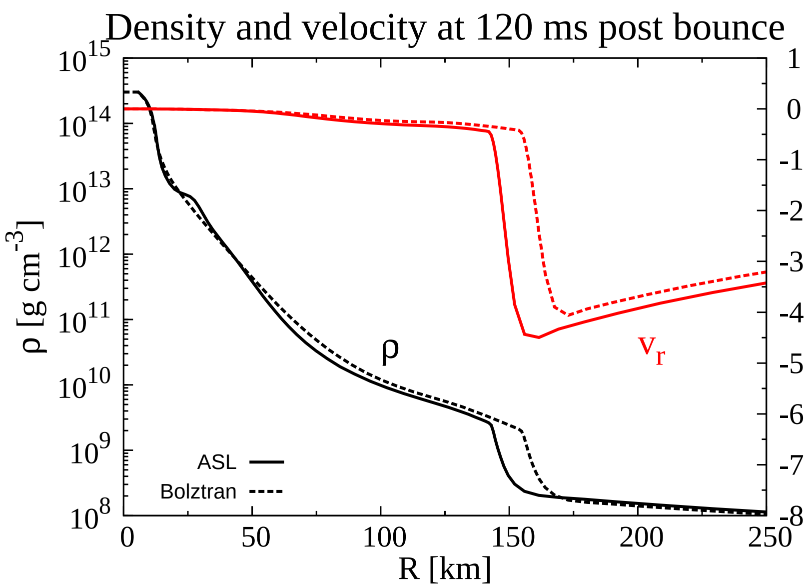

Density and velocity at 30 ms post bounce

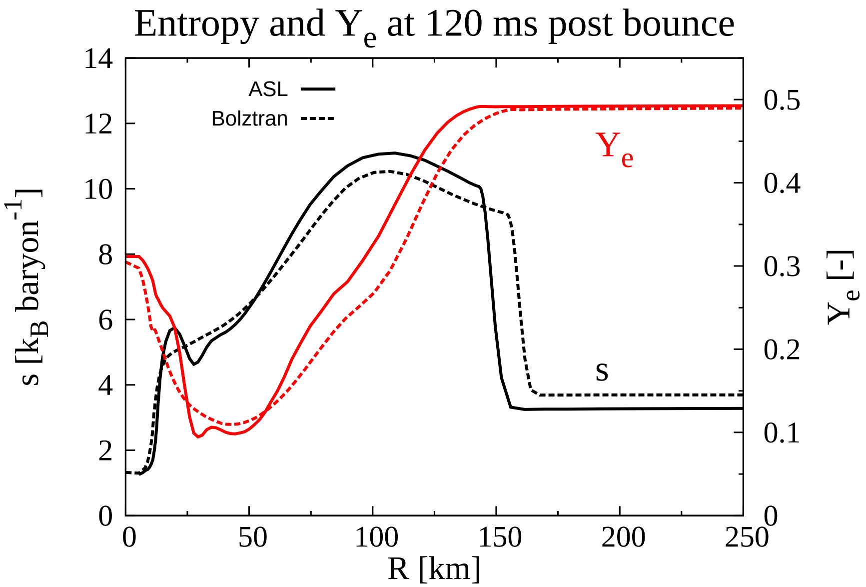

Entropy and Y_e at 30 ms post bounce

ASL: CCSN 1D tests

ASL developed and tested in CCSN context

comparison with spherically symmetric Boltzmann ν-transport (BOLZTRAN) for 15 $M_\odot$ progenitor, from collapse to several 100 ms (AB data: courtesy of M. Liebendörfer)





good qualities:

- computationally inexpensive
- flexibility and adaptivity

limitations:

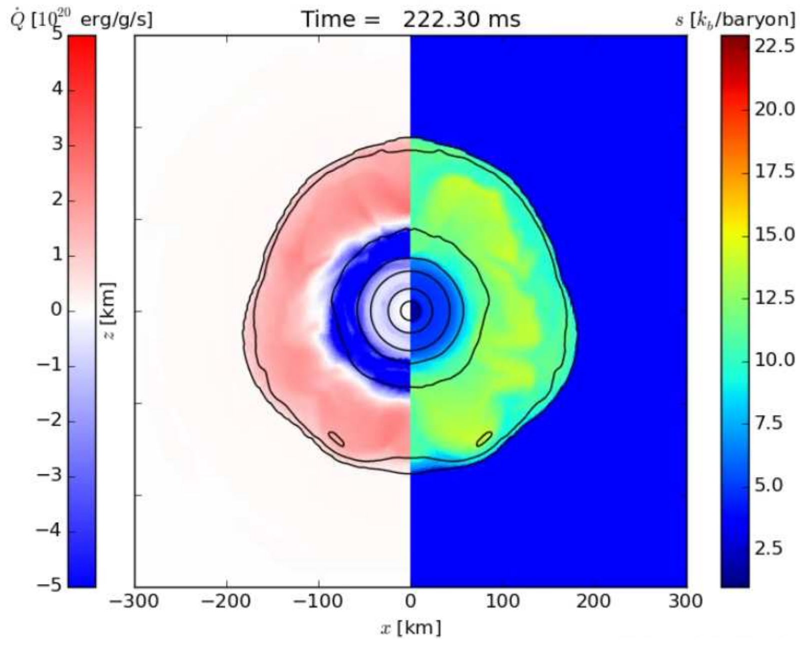
- reduced accuracy
- calibration required

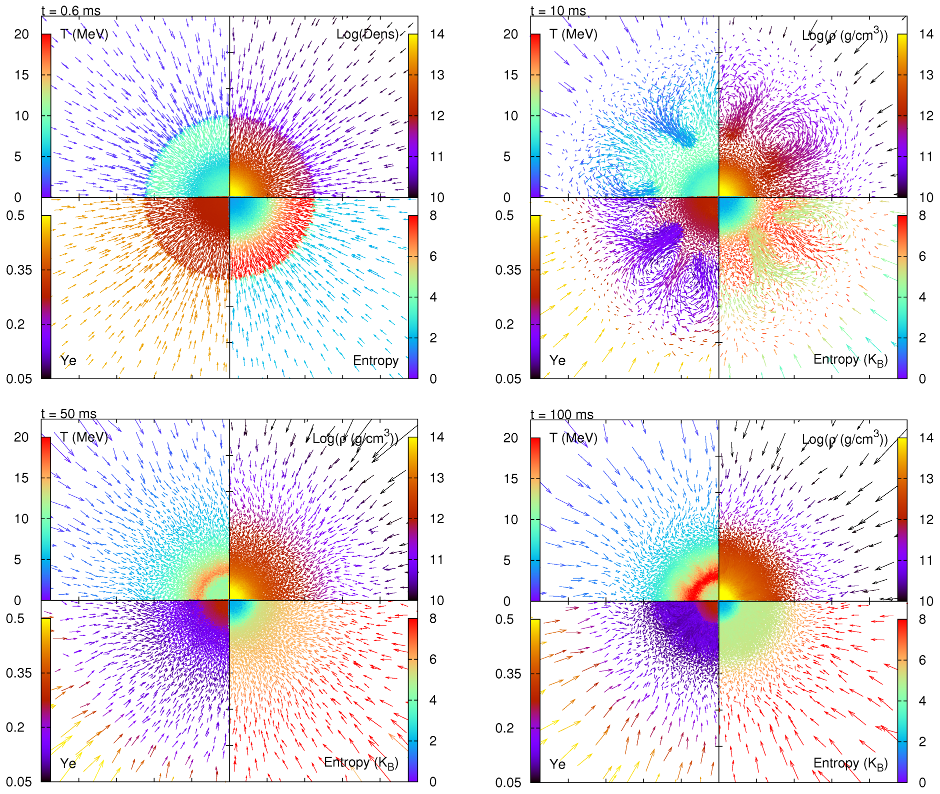
ASL: CCSN multi-D tests

ASL implemented in multi-D CCSN models:

3D SPH code

2D Eulerian code





preliminary, courtesy of R. Käppeli

preliminary, courtesy of R. Cabezon

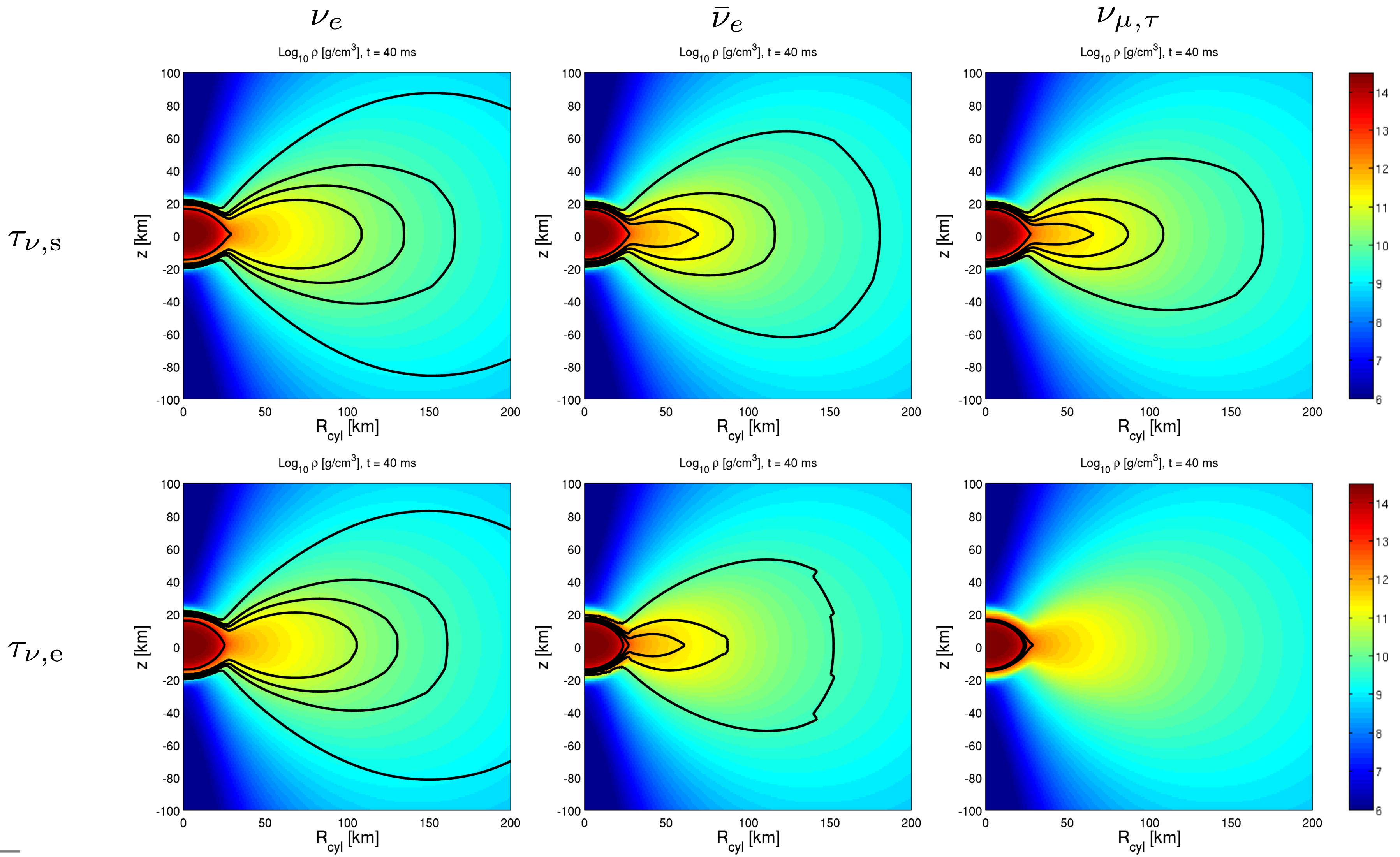
Other ASL applications:

3D MHD-driven explosions Winteler,Käppeli,Perego et al 2012

1D CCSN exploding models Perego,Hempel,Fröhlich et al 2015

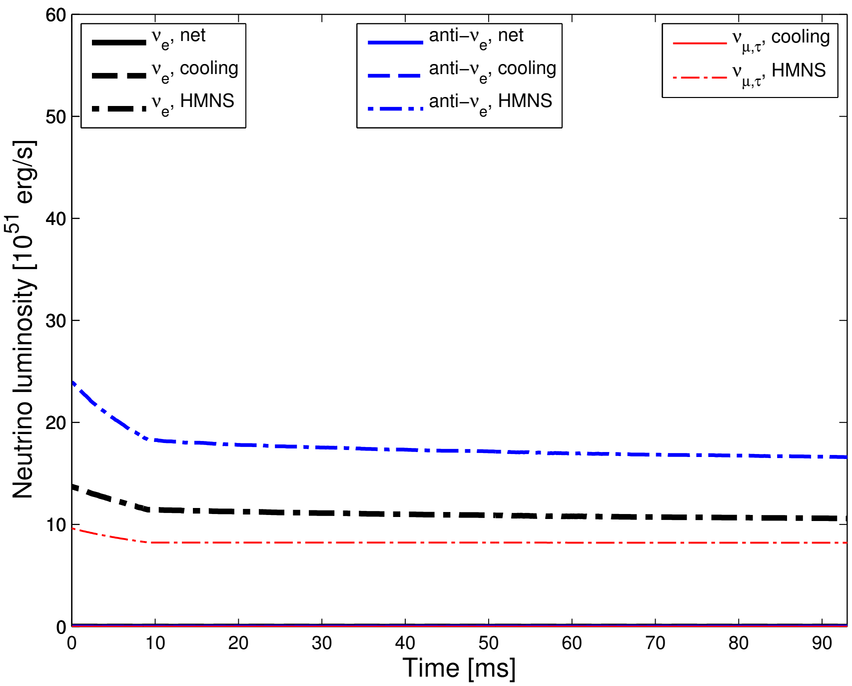
Neutrino Surfaces

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



Neutrino luminosities

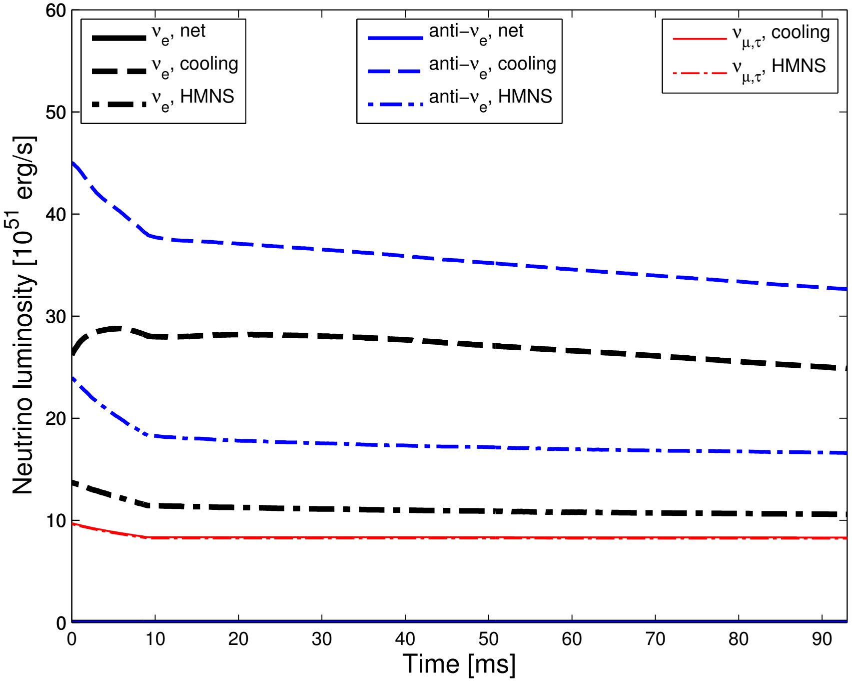
dependence on time



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

Neutrino luminosities

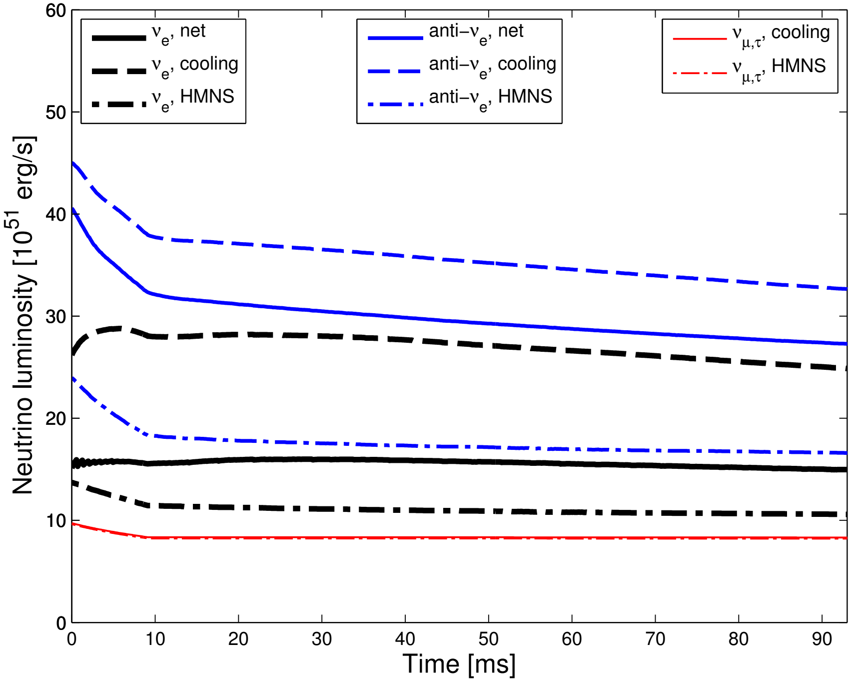
dependence on time



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

Neutrino luminosities

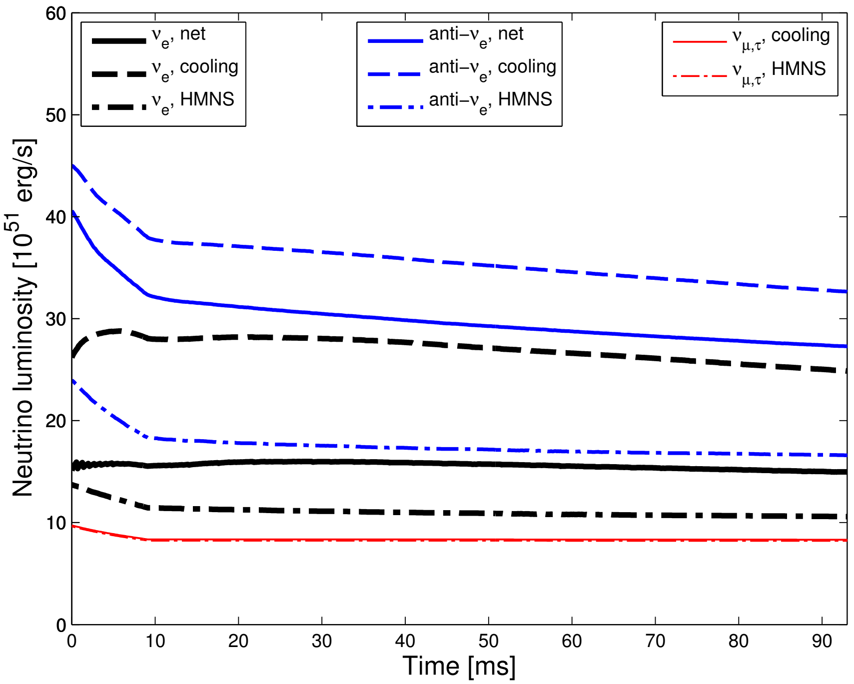
dependence on time



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

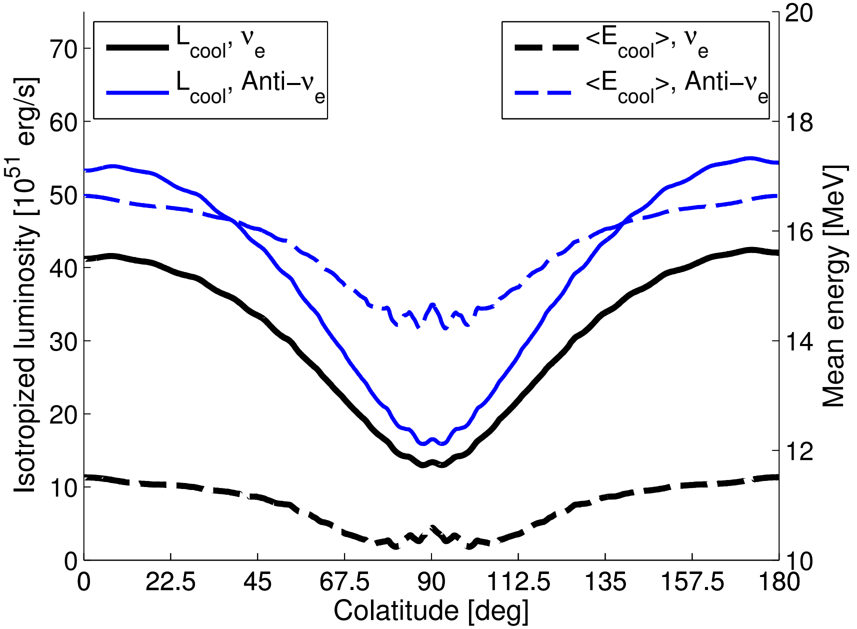
Neutrino luminosities

dependence on time



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

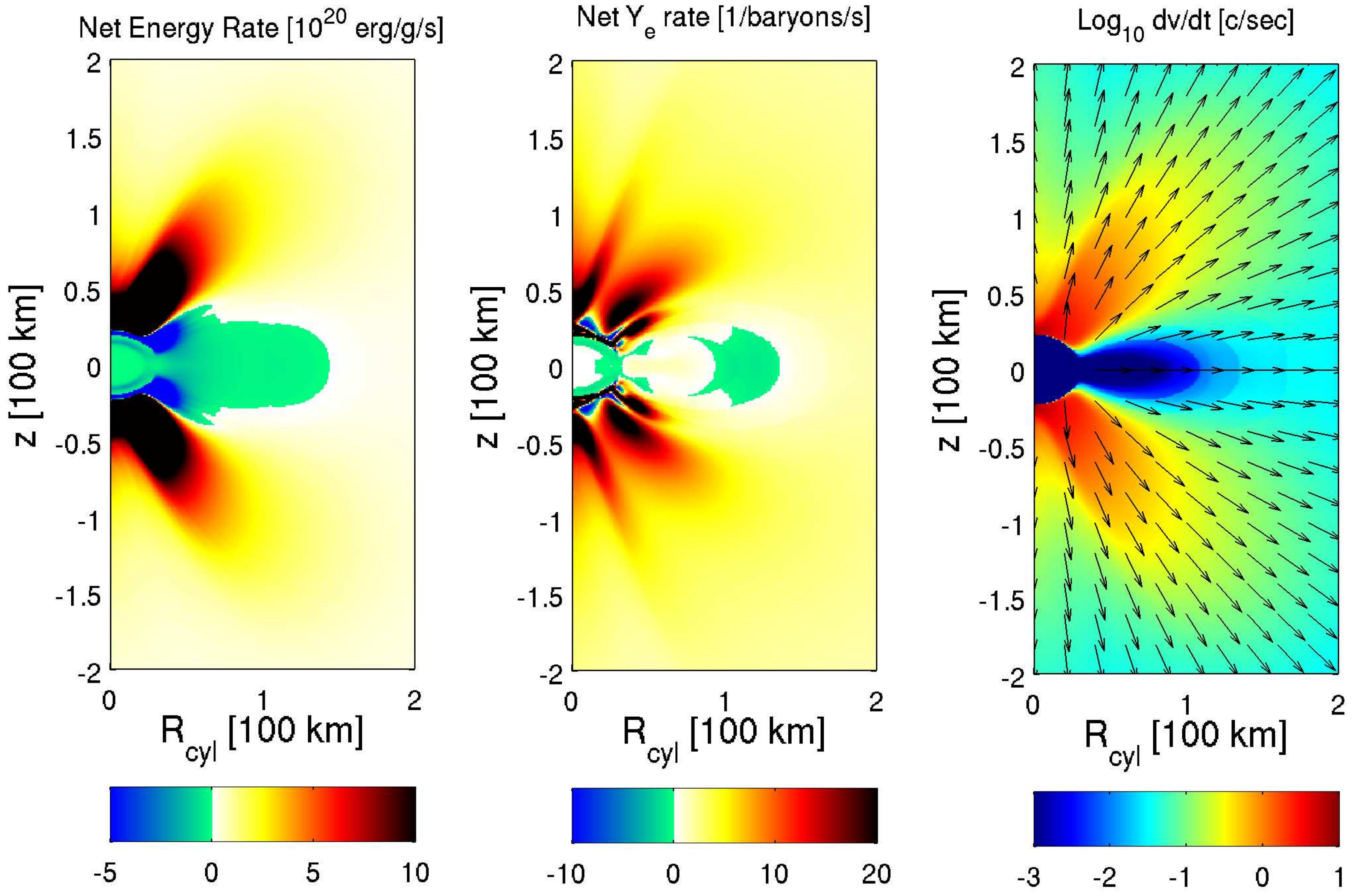
dependence on θ ($t = 40\mathrm{ms}$)



- mean energy hierarchy: $E_{\nu_{\mu,\tau}} > E_{\bar{\nu}_e} > E_{\nu_e}$
- $E_{\nu_e} \approx 11\,\mathrm{MeV}$, $E_{\bar{\nu}_e} \approx 15\,\mathrm{MeV}$, $E_{\nu_{\mu,\tau}} \approx 18\,\mathrm{MeV}$
- disk-shadow effect

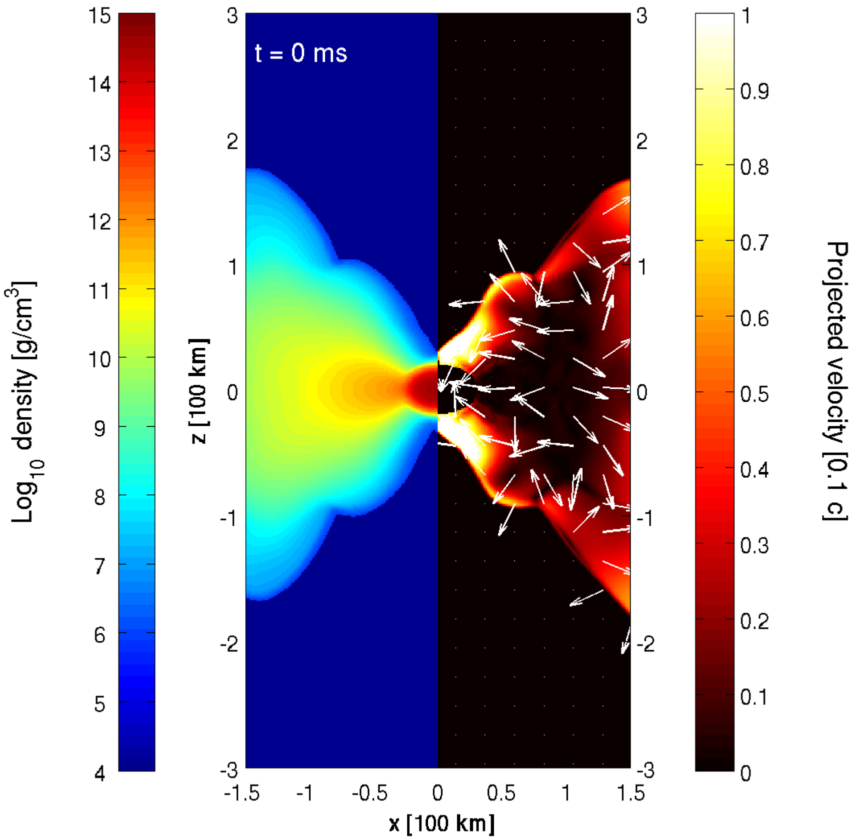
Neutrino net rates

2D averaged profiles at 40ms



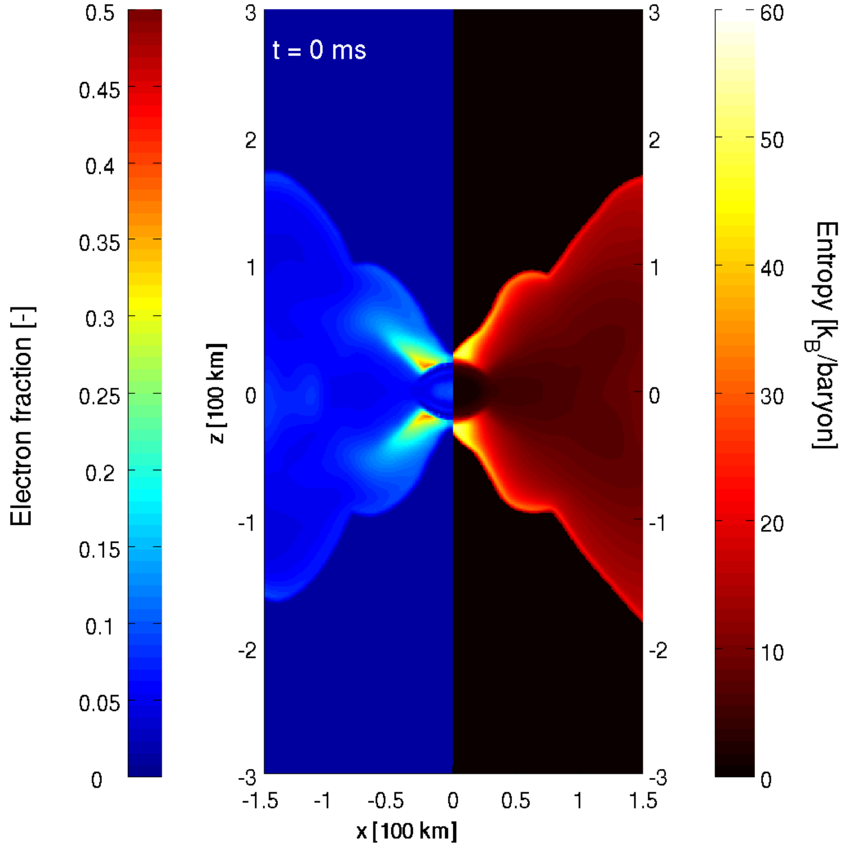
Disc and wind dynamics

t = 0 ms



left: matter density

right: projected velocity



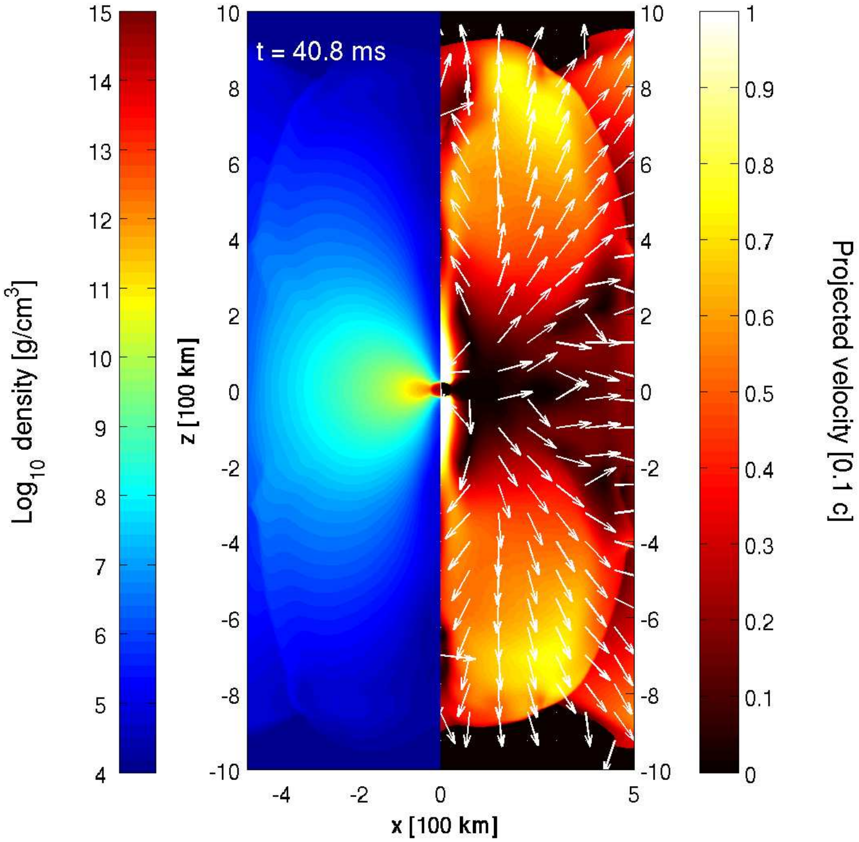
left: electron fraction

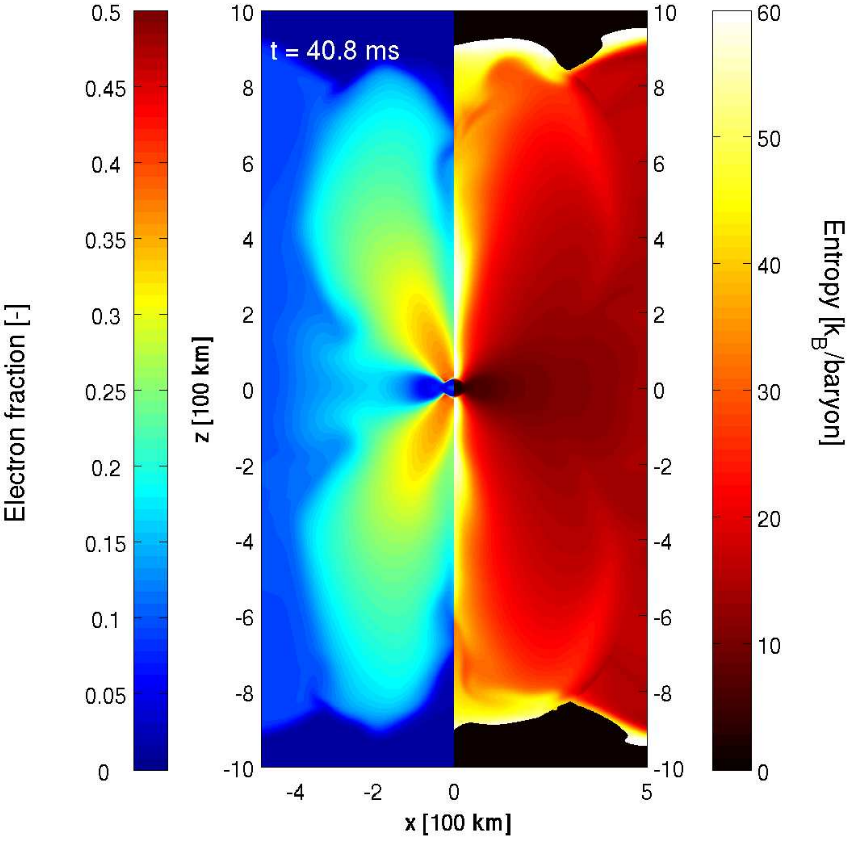
right: entropy

✓

Disc and wind dynamics

t = 40 ms





left: matter density

right: projected velocity

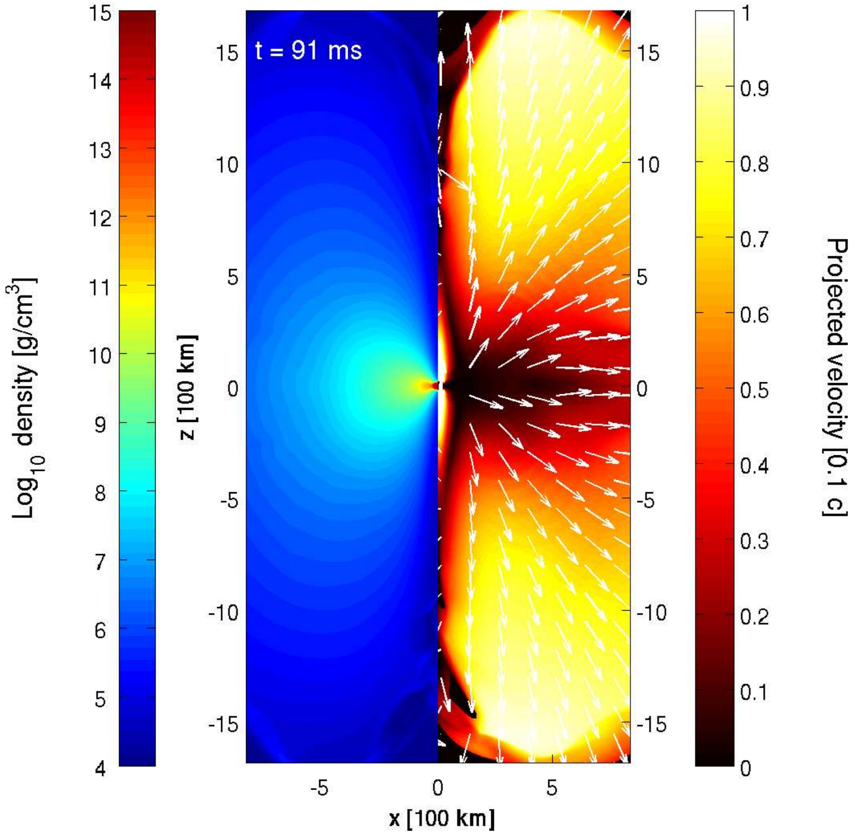
left: electron fraction

right: entropy

✓

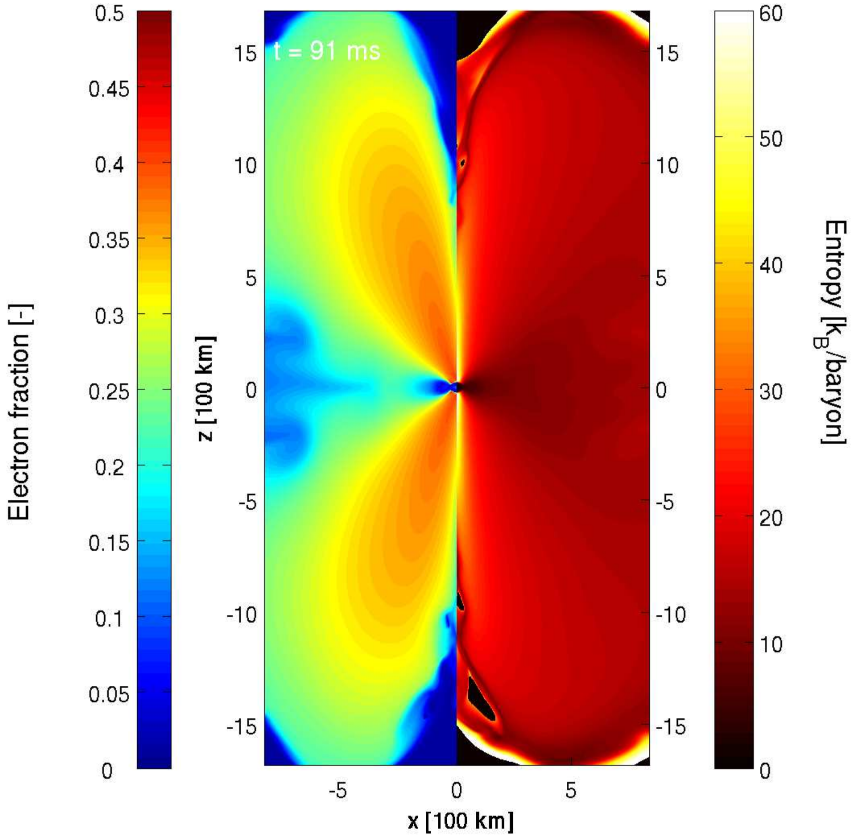
Disc and wind dynamics

t = 90 ms



left: matter density

right: projected velocity

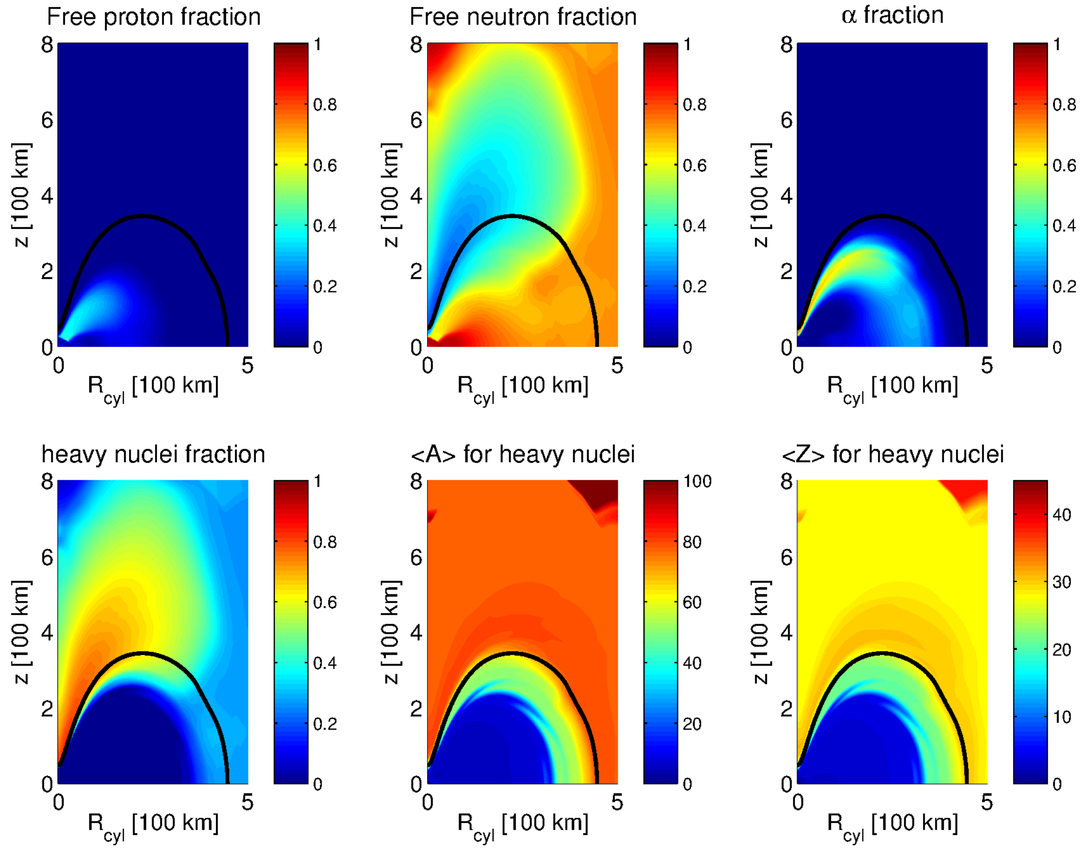


left: electron fraction

right: entropy

✓

Disc & wind composition



- mass fractions in the disk & wind

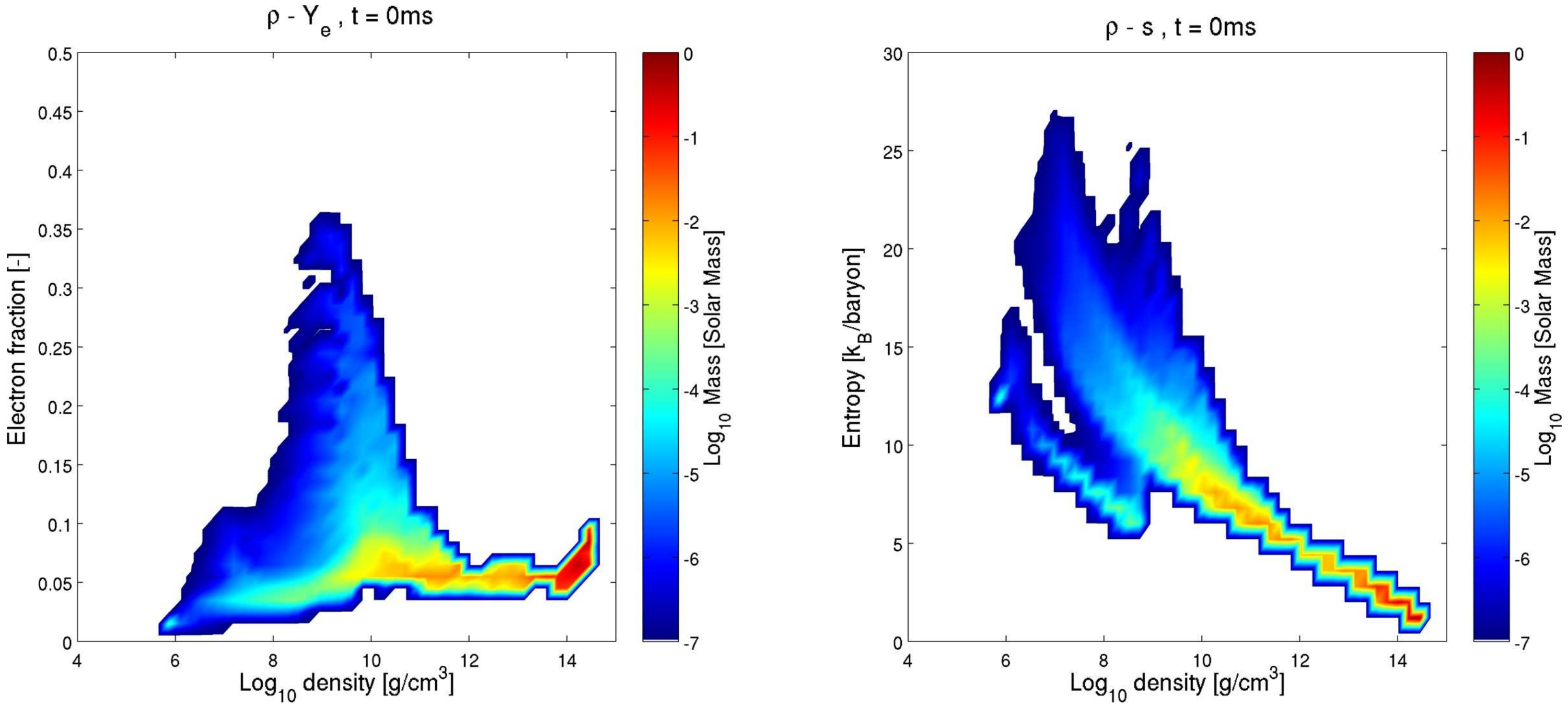
  (as predicted by NSE EOS)
- black line: NSE freeze-out (T=5GK)

- Relevant changes in nuclear composition:
  - n,p $\rightarrow$ n,α (still within NSE)
  - n,α $\rightarrow$ n,(A,Z) (at NSE-freezout)

Wind properties

2D mass-histograms of (ρ, Y_e) and (ρ, s)

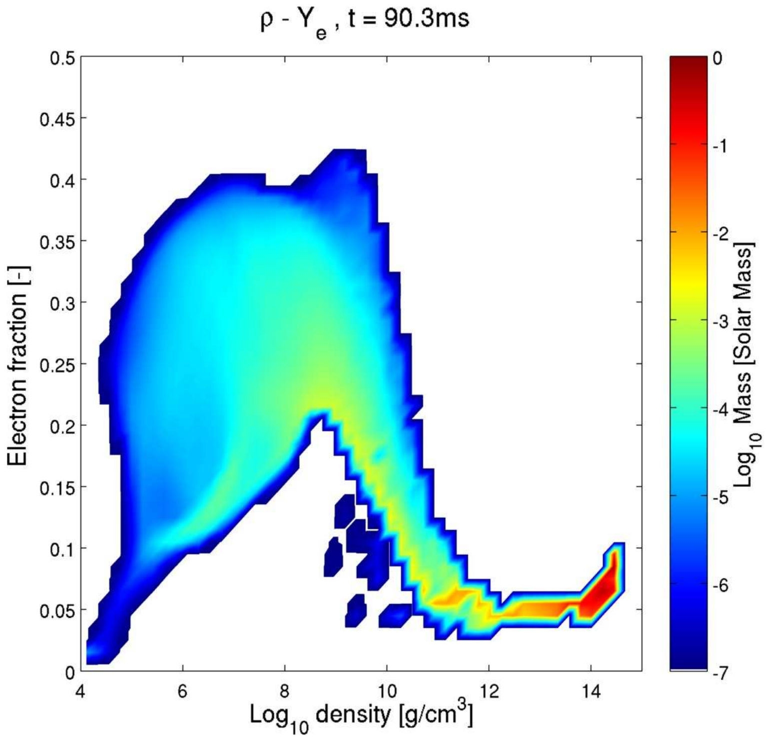
$t \approx 0$ ms

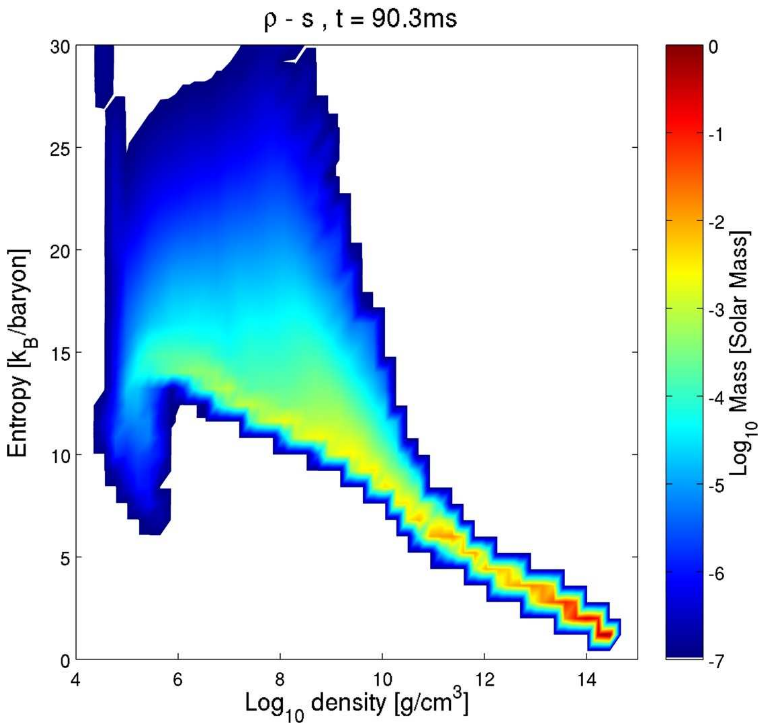


Wind properties

2D mass-histograms of (ρ, Y_e) and (ρ, s)

$t \approx 90$ ms





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

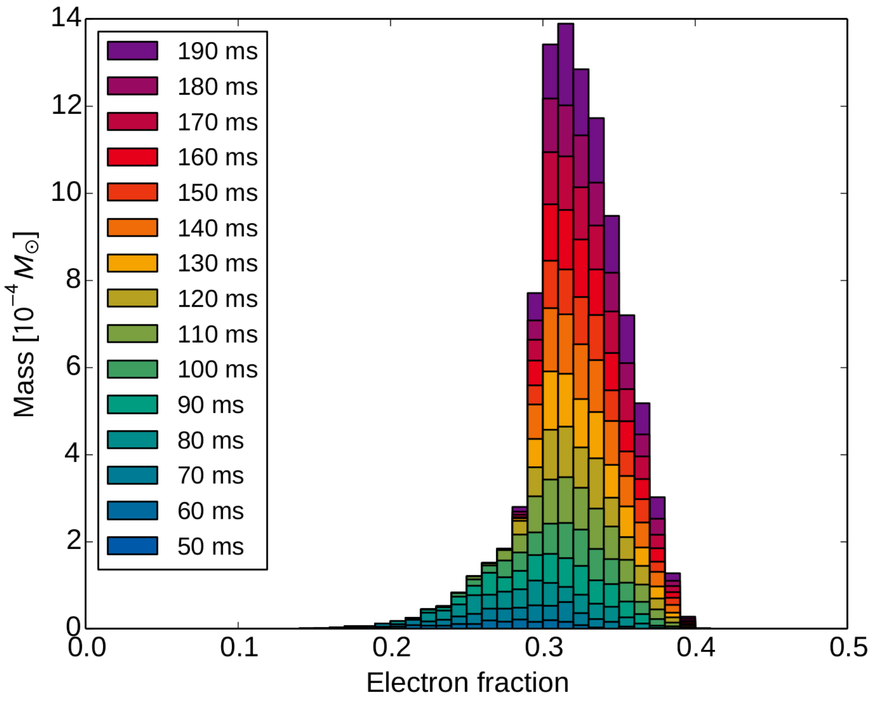
Wind ejecta

- $m_{\rm ej}(t \approx 100\,{\rm ms}) \approx 1.7 \times 10^{-3} M_{\odot}$
  $m_{\rm ej}(t \approx 200\,{\rm ms}) \approx 9.6 \times 10^{-3} M_{\odot}$
  $(\sim 0.05 M_{\rm disk}(t=0))$
- geometrical properties:
  - non-equatorial emission: $\theta < 60^{o}$
  - larger Y_e in the polar regions
- thermodynamical properties:
  - Y_e increase with time towards $(Y_e)_{\rm eq} \approx 0.35 - 0.40$

$$(Y_e)_{\rm eq} \approx \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{E_{\bar{\nu}_e} - 2\Delta}{E_{\nu_e} + 2\Delta} \right)^{-1}$$

Qian & Woosley 96

  - s: 15-20 $k_{\rm B}/{\rm baryon}$
  - v_r: 0.06-0.09 c



ejected mass: cumulative histogram

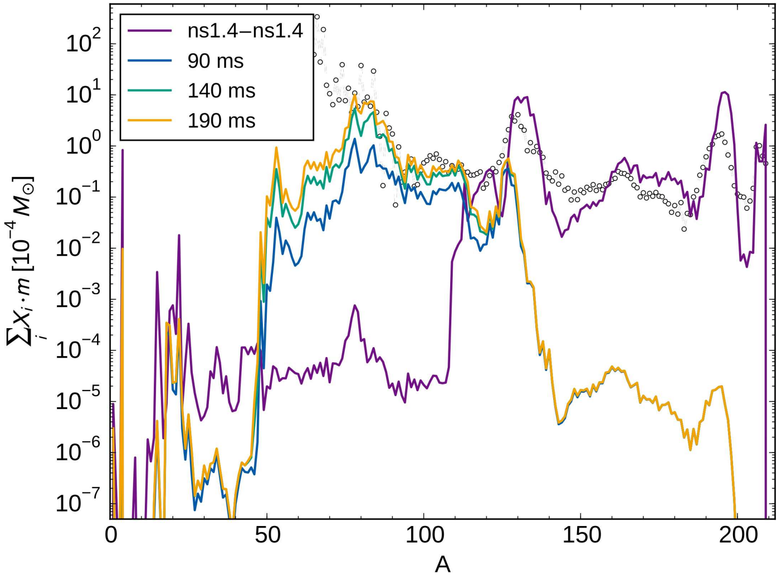
Martin et al. 2015

Nucleosynthesis from the wind

Postprocessing of ejected tracers $(\sim 17k)$

- `Winnet` nuclear network
- weak r-process: 80<A<130
- complementary to robust r-process nucleosynthesis from dynamic ejecta
- possible differences between high and low latitude ejecta

our wind ejecta + dynamical ejecta $(m_{\rm dyn} \approx 10^{-2} M_\odot)$ from Korobkin+12



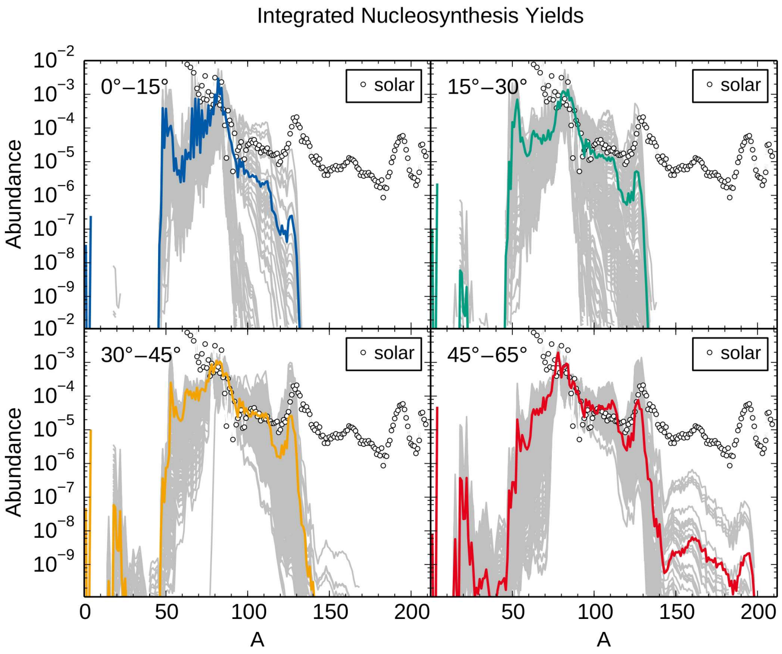
Martin et al 2015

Nucleosynthesis from the wind

Postprocessing of ejected tracers ($\sim 17k$)

- `Winnet` nuclear network
- weak r-process: 80<A<130
- complementary to robust r-process nucleosynthesis from dynamic ejecta
- possible differences between high and low latitude ejecta

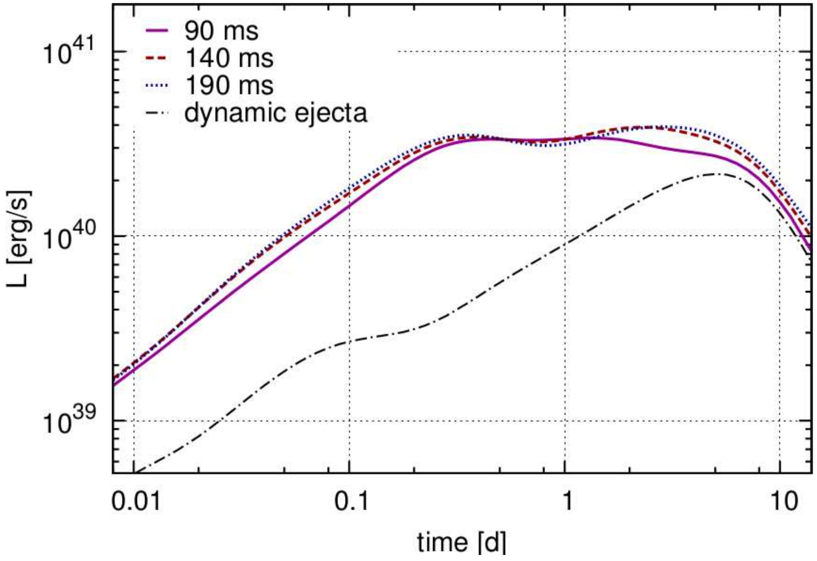
nucleosynthesis at different angles



Martin et al 2015

Electromagnetic transient

γ emission powered by radioactive material in the ejecta



bolometric luminosity (dynamic + wind), computed by O. Korobkin

Martin et al 2015

- model application for photon propagation and emission

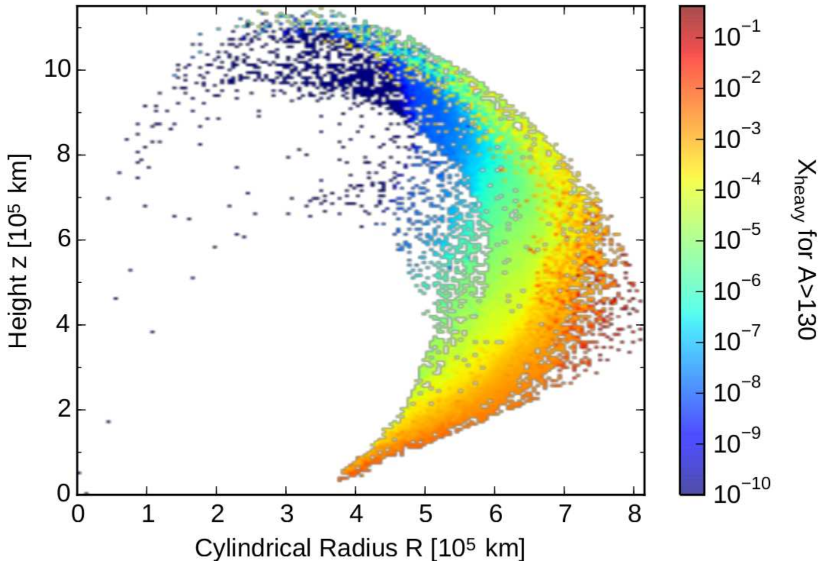
  e.g. Kulkarni05,Grossman+13
- potentially different from emission coming from dynamical/viscous ejecta
  - earlier and bluer
  - less contaminated by lanthanides and actinides

  cf Metzger&Fernandez14
- possible dependence from viewing angle and obscuration effects

  cf Fernandez+15

Electromagnetic transient

γ emission powered by radioactive material in the ejecta



Lanthanides and Actinides mass fraction, Martin et al. 2015

cf Korobkin's and Lippuner's talk

- model application for photon propagation and emission

  e.g. Kulkarni05,Grossman+13

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

  cf Metzger&Fernandez14

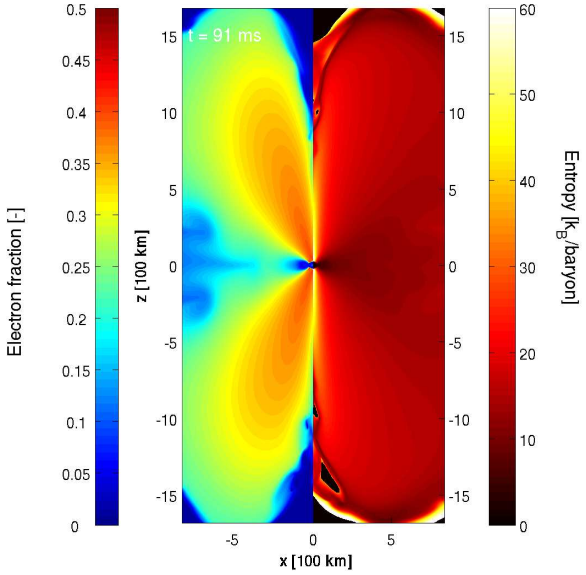
- possible dependence from viewing angle and obscuration effects

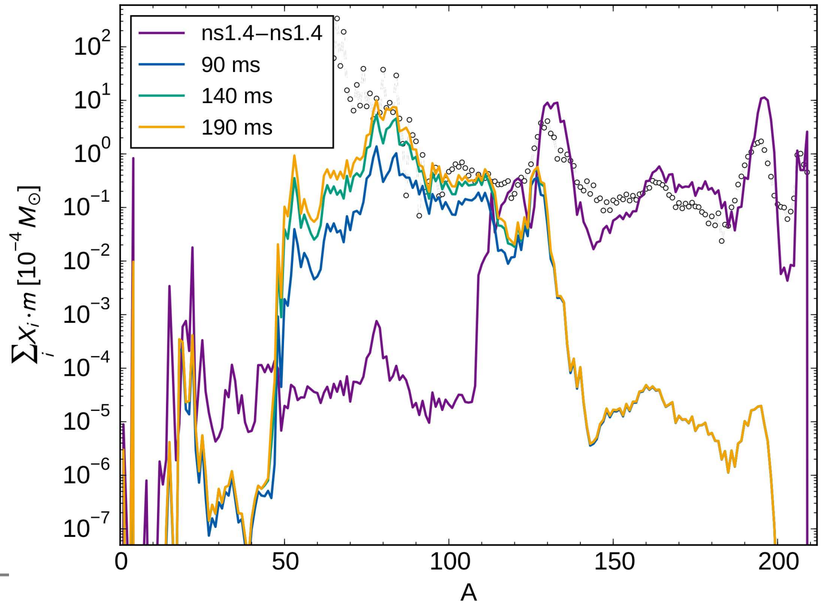
  cf Fernandez+15

Conclusions

Neutrinos matter in driving and setting properties of ejecta in BNS mergers.

- genuine ν-driven wind from ν heating in the disk
  $t_{\rm wind} \sim {\rm tens\,ms}$
- wind contributes substantially to BNS merger ejecta:
  $\sim 2 \times 10^{-3} M_{\odot}$ @ 100 ms
  $\sim 9 \times 10^{-3} M_{\odot}$ @ 200 ms





- mildly neutron-rich ejecta
  $(0.2 \lesssim Y_{\rm e,ejecta} \lesssim 0.4)$;
  weak r-process nucleosynthesis
  $(A \sim 80-130)$
- wind electromagnetic transient
  potentially different from dynamical ejecta transient