ν emission from the aftermath of neutron star merger

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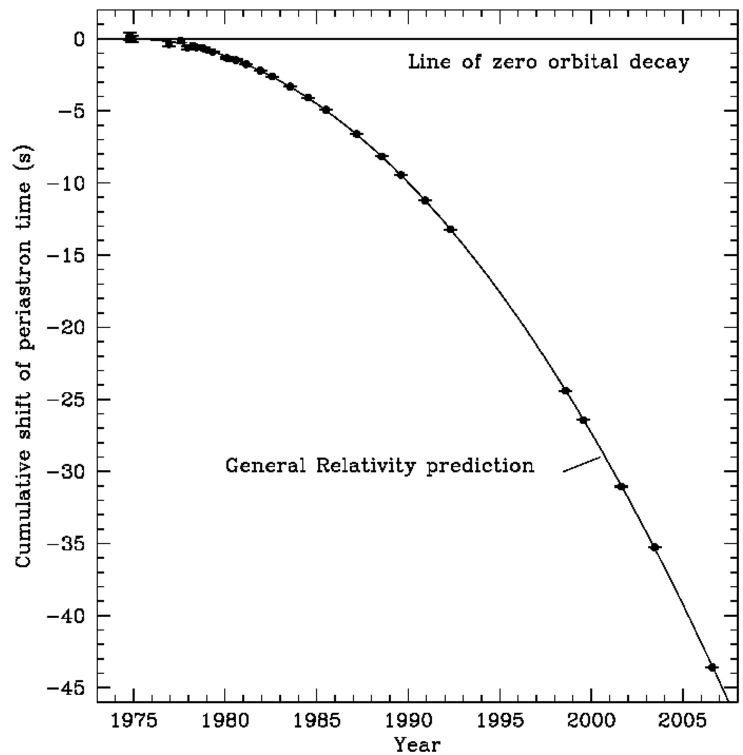
Outline of the presentation

- Introduction
  - neutrinos in the context of Binary Neutron Star (BNS) mergers
- Presentation of the simulation
  - neutrino treatment
- First results
- Conclusion and outlook

BNS merger in a nutshell

Final stage of a BNS system evolution:

- double BNS systems do exist (e.g. PSR1913+16)



(Weisberg et al., 2010)

BNS merger in a nutshell

Final stage of a BNS system evolution:

- double BNS systems do exist (e.g. PSR1913+16)
- inspiral phase, driven by GW emission

$$t_{\rm insp} \approx 10^7 {\rm yr} \left(\frac{T_{\rm orb}}{1 {\rm h}} \right) \left(\frac{M}{M_\odot} \right)^{-2/3} \left(\frac{\mu}{M_\odot} \right)^{-1} \left(1 - e^2 \right)^{-7/2} .$$

(see, e.g., Lorimer 2005)

BNS merger in a nutshell

Final stage of a BNS system evolution:

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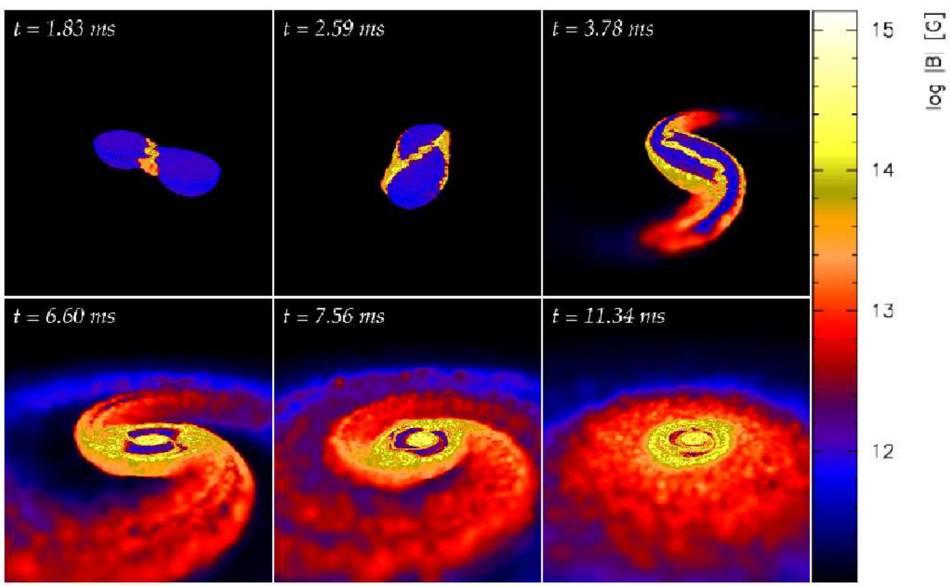
- coalescence phase



B field from a SPH simulations of BNS merger with 2 NS of $1.4 M_\odot$

Price & Rosswog 2006

BNS merger in a nutshell

Final stage of a BNS system evolution:

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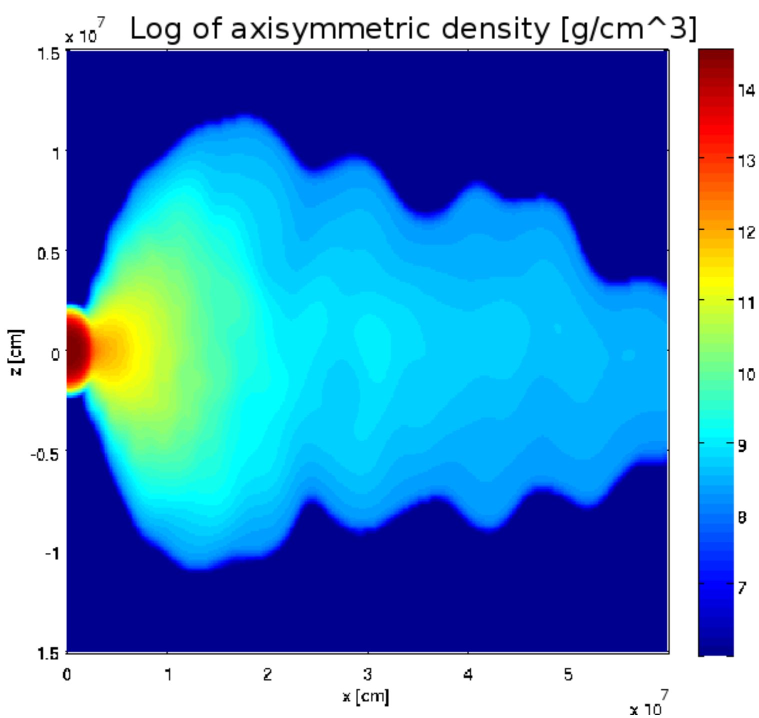
- inspiral phase, driven by GW emission
- coalescence phase
- NS merger aftermath



- hot SMNS $\rightarrow$ BH
  $\sim 2.7 M_\odot\,,\ T \sim 15\mathrm{MeV}$
- thick torus of accreting matter
  $\sim 0.1 M_\odot\,,\ Y_e \lesssim 0.05$
- intense ν emission
  $L_\nu \sim 10^{53}\mathrm{erg/s}$

BNS mergers and short GRBs

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
- modeling: intense energy deposition in a relatively baryon-free region as driving mechanism, due to matter accretion on a stellar compact object (SMNS or BH)

Open questions for this possible short GRB engine:

- pollution from ν-driven baryonic wind (e.g. Dessart et al. 2009)
- nucleosynthesis in ν-driven wind (e.g. Wanajo & Janka 2012)
- role of B field and GR (e.g. Rezzolla et al. 2011)

Neutrino transport

ν's role in BNS merger:

- exchange energy with matter (heating and cooling)
- release energy out of the system
- influence explosive nucleosynthesis

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ν's behaviour in this scenario:

- ν's are copiously produced in hot and dense matter
- where matter is opaque, ν's thermalize and diffuse out on the diffusion timescale $t_{\rm diff}$
- where matter is transparent, ν's stream out freely
- interaction rates are energy&angle dependent ($\sigma_\nu \propto E_\nu^2$)

$\Rightarrow$ radiation transport problem, $f_\nu(t, \mathbf{x}, \mathbf{p})$

Modeling BNS merger

- astrophysical plasma $\rightarrow$ MHD equations
- wide ranges of scales
- extreme matter conditions (nuclear EOS)
- necessity to include all fundamental interactions
  - gravity: true driving interaction
  - strong: nuclear matter properties and reactions
  - EM: matter properties and magnetic fields
  - weak: matter composition and neutrino interaction
- important role played by ν (radiation MHD)

$$\Downarrow$$

large multi-dimensional numerical models and computational simulations required!

The model

- data from SPH BNS merger simulations
  (Price & Rosswog (2006))
- FISH 3D (M)HD Cartesian code (Käppeli et al. (2011))
- Shen nuclear EoS (Shen et al. (1998))
- ν treatment: Advanced Spectral Leakage (ASL)
  (Perego et al., in preparation)

Goal: to study the aftermath of BNSM

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

The ASL scheme

- based on previous grey leakage schemes

  (Ruffert et al. 1997, Rosswog & Liebendörfer 2003)

- spectral scheme
- 3 flavors: ν_e,$\bar{\nu}_e$, $\nu_{\mu,\tau}$ ($\bar{\nu}_{\mu,\tau}$)
- ν reactions:

$e^- + p \rightarrow n + \nu_e$	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 $\rightarrow$ opacity, T $\rightarrow$ thermalization, P $\rightarrow$ production

- treatment developed and tested in Core Collapse Supernova context

ν optical depth

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

$$\tau_\nu = \int_\gamma \frac{1}{\lambda} \, \mathrm{d}s$$

- distinction between scattering ($\tau_{\nu,s}$) and energy ($\tau_{\nu,E}$) ν optical depths:
  - $\tau_{\nu,s} \gg 1$: diffusive regime
  - $\tau_{\nu,E} \gg 1$: diffusive regime & thermal equilibrium

ν rates

- effective scheme: it mimics known solutions
- particles and energy effective rates: smooth interpolation between diffusion and production rates

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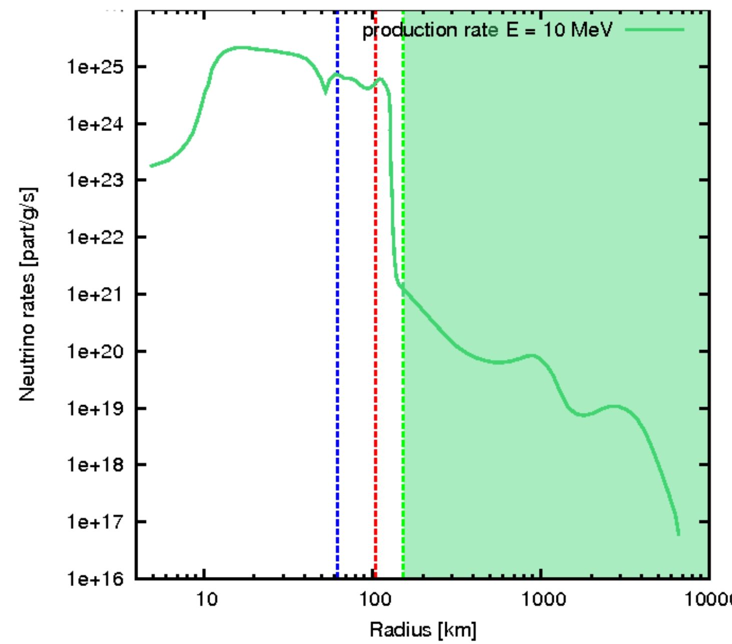
$\tau_\nu \lesssim 1$, production rate

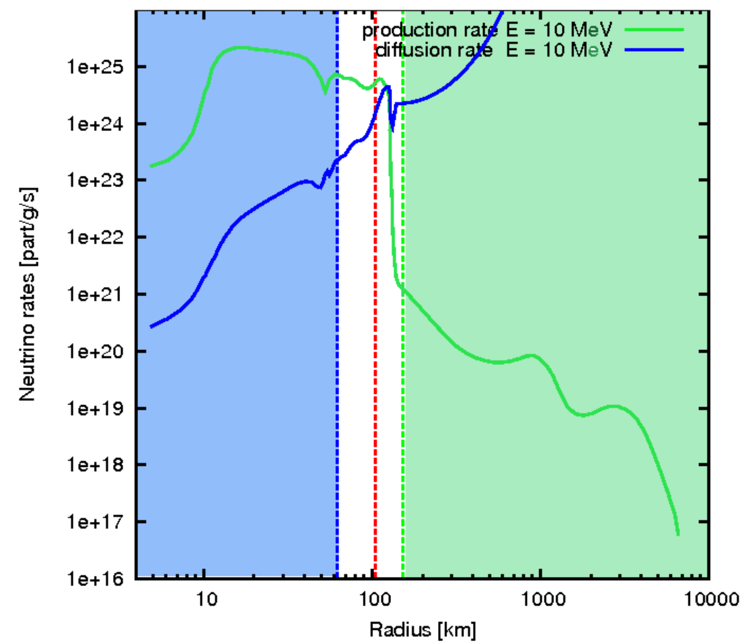


rates in CCSN model, just after bounce

ν rates

- effective scheme: it mimics known solutions
- particles and energy effective rates: smooth interpolation between diffusion and production rates

$\tau_\nu \lesssim 1$, production rate
$\tau_\nu \gg 1$, diffusion rate



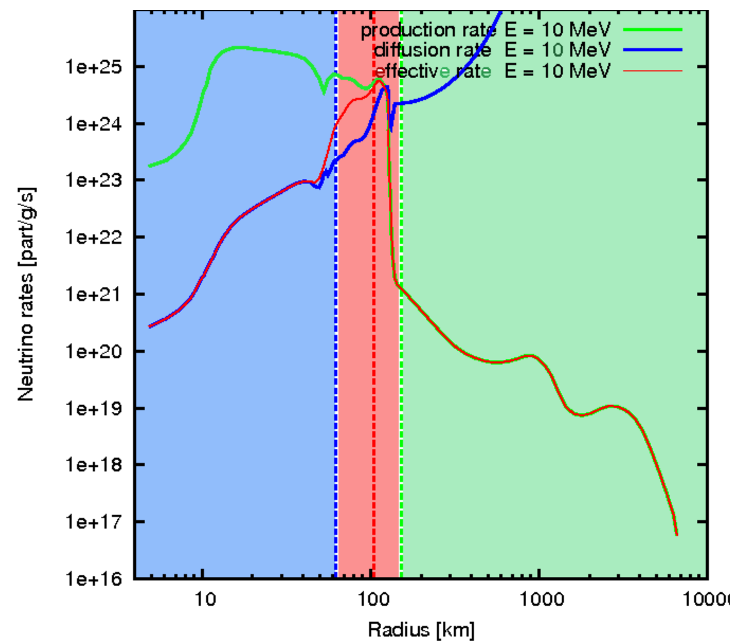
rates in CCSN model, just after bounce

ν rates

- effective scheme: it mimics known solutions
- particles and energy effective rates: smooth interpolation between diffusion and production rates

$\tau_\nu \lesssim 1$, production rate
$\tau_\nu \gg 1$, diffusion rate

$\tau_\nu \sim 1$, interpolation



rates in CCSN model, just after bounce

ν heating term

- inclusion of a heating rate (for $\tau_\nu \lesssim 1$)
  - $r_{\rm heat} \propto \chi_{\rm ab} \cdot \rho_\nu$ where $F_\nu \to \rho_\nu$

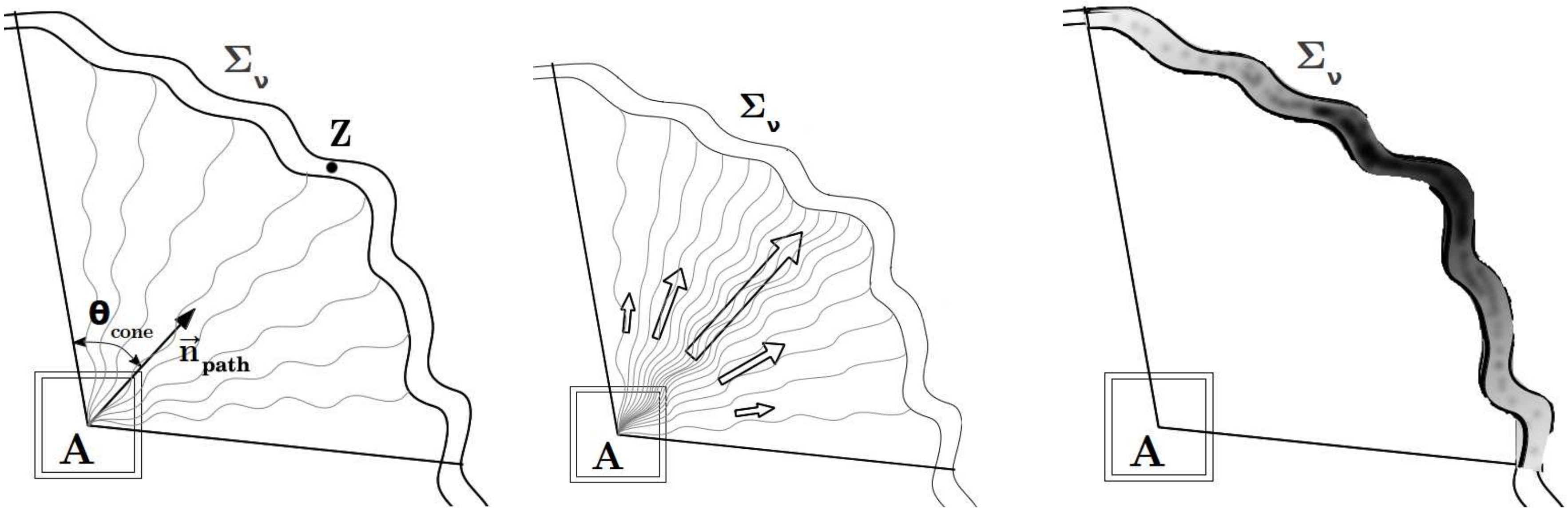
    $\chi_{\rm ab}$ absorptivity, ρ_ν neutrino density, F_ν neutrino flux
  - F_ν from cooling rates: spectrum too hard
  - effective implementation of thermalization:

$$r_{\rm cool} \to \tilde{r}_{\rm cool} = \beta_{\rm cut}\, r_{\rm cool}\, \exp\left(-\frac{\tau_{\rm eff}}{\alpha_{\rm cut}}\right)$$

    - $\beta_{\rm cut}$: $\int_0^\infty r_{\rm cool} E^2\, {\rm d}E = \int_0^\infty \tilde{r}_{\rm cool} E^2\, {\rm d}E$
    - $\alpha_{\rm cut}$: free parameter (~ 20)

- everything 3D, apart from axisymmetric τ_ν, L_ν and ρ_ν

Multi-D diffusion

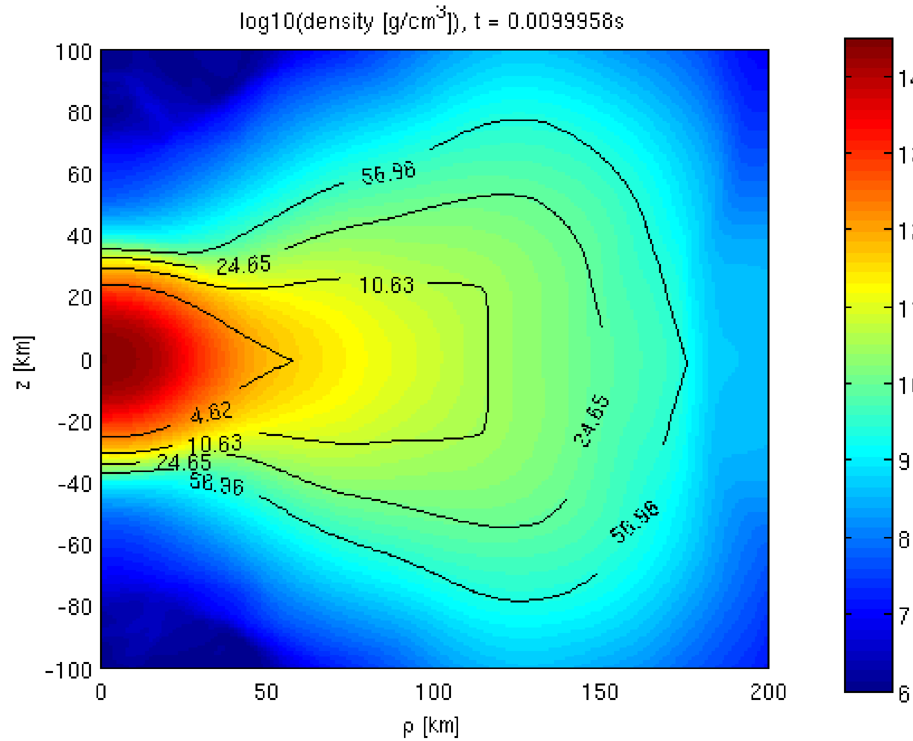


- Σ_ν: ν-surface
- $\mathbf{n}_{\rm path}$: $A \to Z$ "shortest" τ-path towards Σ_ν
- $F_\nu(\mathbf{n}) \propto \cos\theta$, where $\cos\theta = \mathbf{n} \cdot \mathbf{n}_{\rm path}$
- isotropic emission from $\Sigma_\nu \Rightarrow F_\nu$ and ρ_ν

Neutrino surfaces

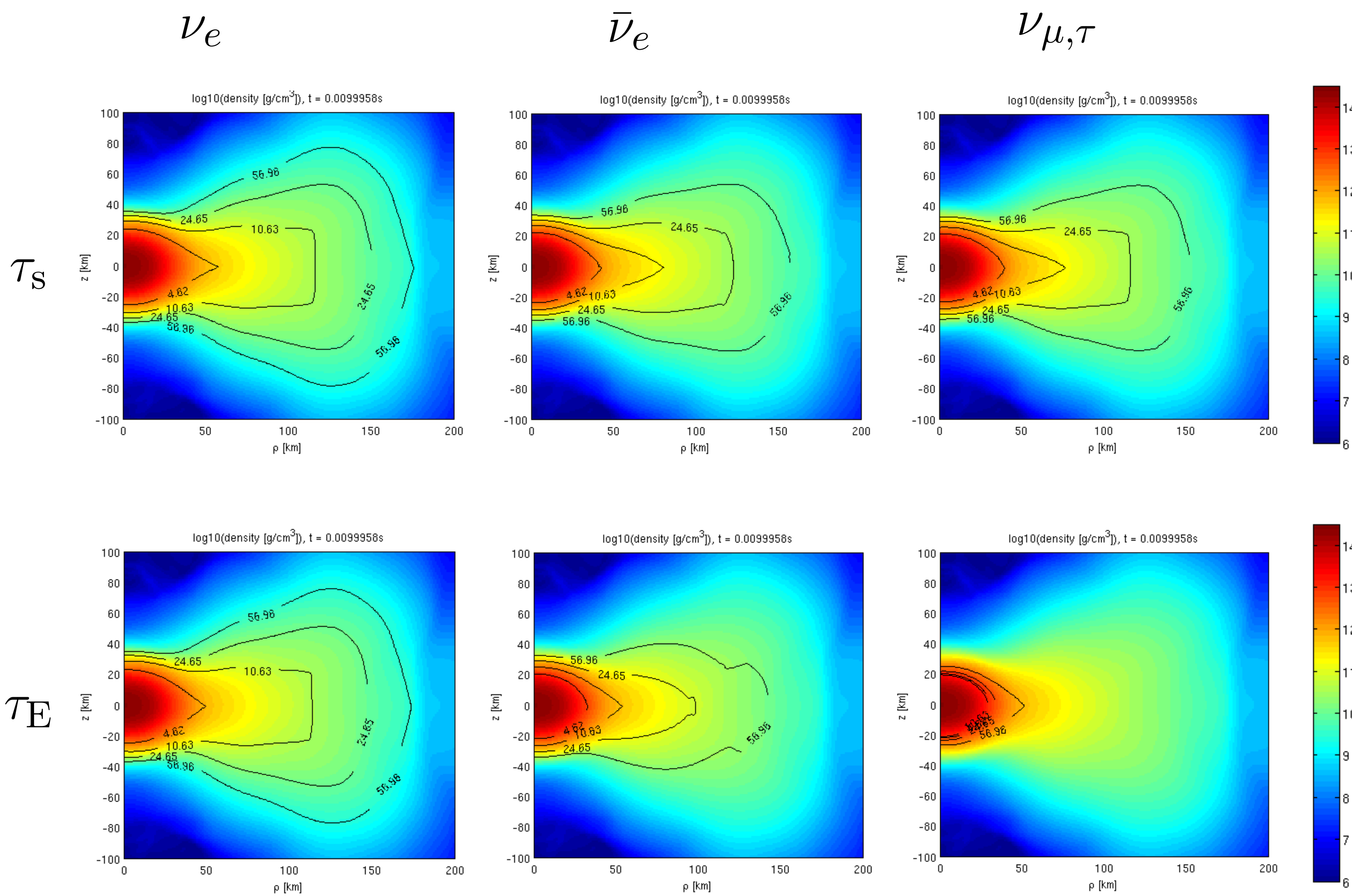
$\tau_\nu = 2/3 \rightarrow \nu$-surface ($\Sigma_\nu$)

- $\tau_{\nu,s} = 2/3$
  last (any) interaction surface
- $\tau_{\nu,E} = 2/3$
  last inelastic interaction surface



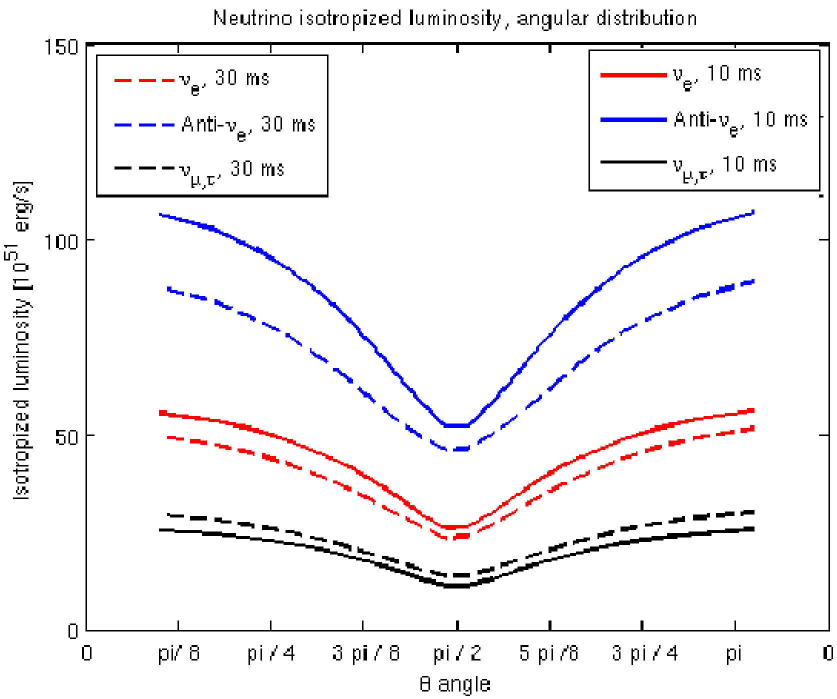
$\tau_{\nu,s}$ surfaces, for ν_e and different E_ν

Neutrino surfaces

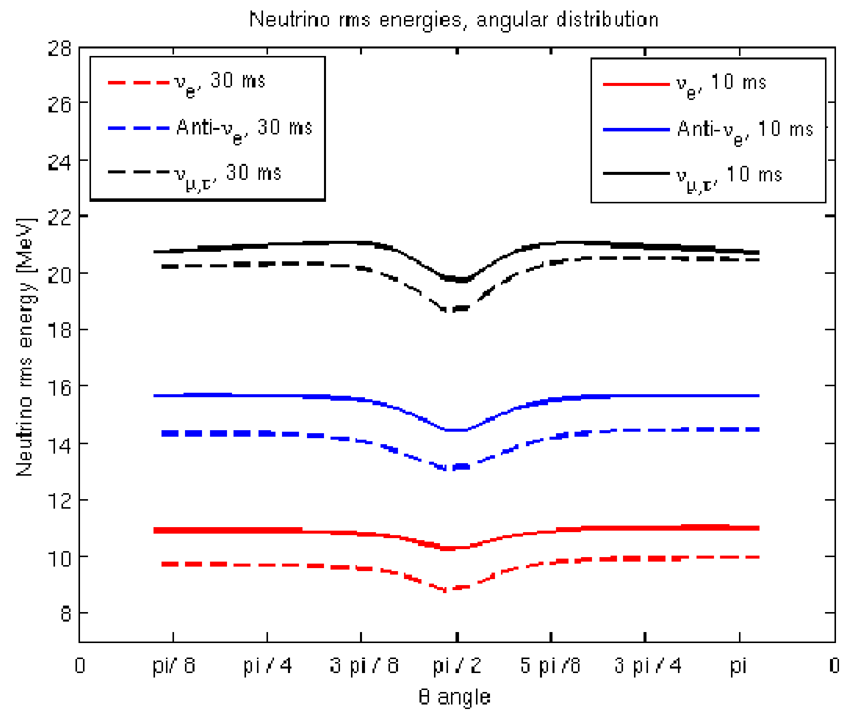


Neutrino luminosities

Isotropized ν luminosity

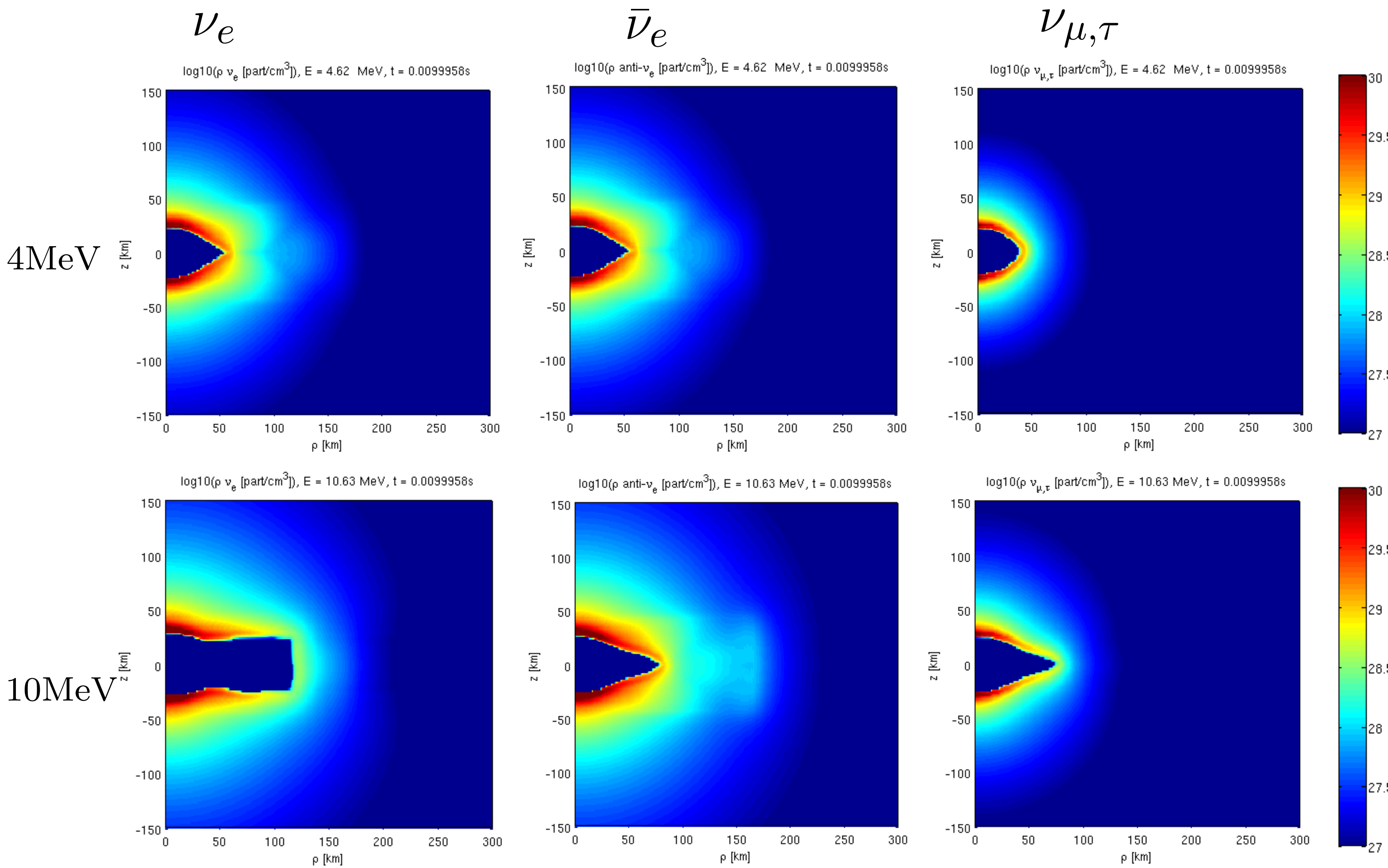


ν rms energy



- θ angular dependence at 10 ms and 30 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 densities



Conclusion and outlook

- First results from 3D Cartesian simulations of the aftermath of BNS merger, with neutrino multi-flavor spectral treatment
- ν results consistent with results in literature

  (e.g. axisym.: Dessart et al. 2009, SPH: Rosswog et al. 2012 ... Ruffert et al. 1997)

Outlook:

- study disk dynamics and effects of the ν heating
- perform nucleosynthesis calculation for the ejected matter
- set constraints for short-GRB mechanism

Multi-D streaming

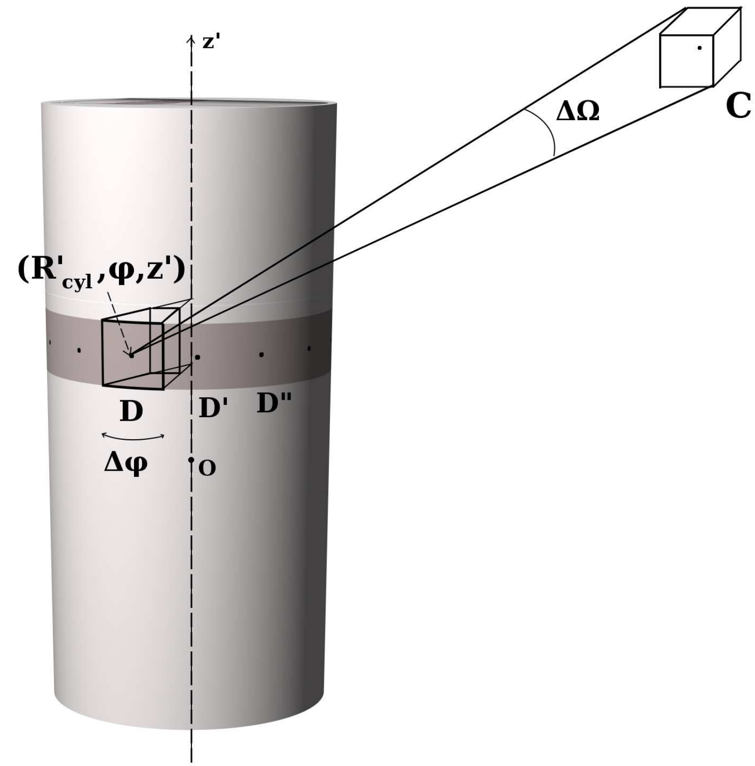
model for ρ_ν calculation:

Modeling free streaming ν:

- axisymmetric rates
- isotropic emission from Σ_ν and transparent region

$\Downarrow$

- axisymmetric luminosity
- axisymmetric ρ_ν



D source position

C evaluation point

Neutrino properties

According to our current knowledge,

- ν are fermions ($s = 1/2$), with very small masses ($m_\nu \lesssim 1\,\mathrm{eV}$)
- ν (and $\bar{\nu}$) exist in 3 flavors ν_e, ν_μ and ν_τ
- ν and $\bar{\nu}$ interact via weak interaction ($W^\pm$ and Z) with quarks and other leptons
- typical neutrino cross section:

$$\sigma_\nu \propto \sigma_0 \left(\frac{E_\nu}{m_e c^2} \right)^2$$

- $\sigma_0 \propto G_F^2$
- (relatively) very low: $\sigma_0 = 10^{-44}\mathrm{cm}^2 \sim 10^{-20}\sigma_{\mathrm{nuc}}$
- highly energy dependent (especially for $E \lesssim 50\mathrm{MeV}$)

Neutrinos in astrophysics

ν play a central role in many astrophysical scenarios

- Cosmic Neutrino Background:

  CνB with $T_\nu \approx 1.95\mathrm{K}$

- Neutrinos from the Sun:

  Production rate: $\sim 1.86 \times 10^{38}\mathrm{s}^{-1}$, $E_\nu \lesssim 0.420\mathrm{MeV}$
  Flux on Earth: $\sim 6 \times 10^{10}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

- ν-cooling of the core of massive stars, after He burning

  $$Q_{\nu-\mathrm{cooling}} \propto T^9$$

- Core Collapse SuperNova (CCSN)
- Binary Neutron Star Merger (BNSM)

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BNSM simulations

Evolution of simulations (from 80s' up to now)

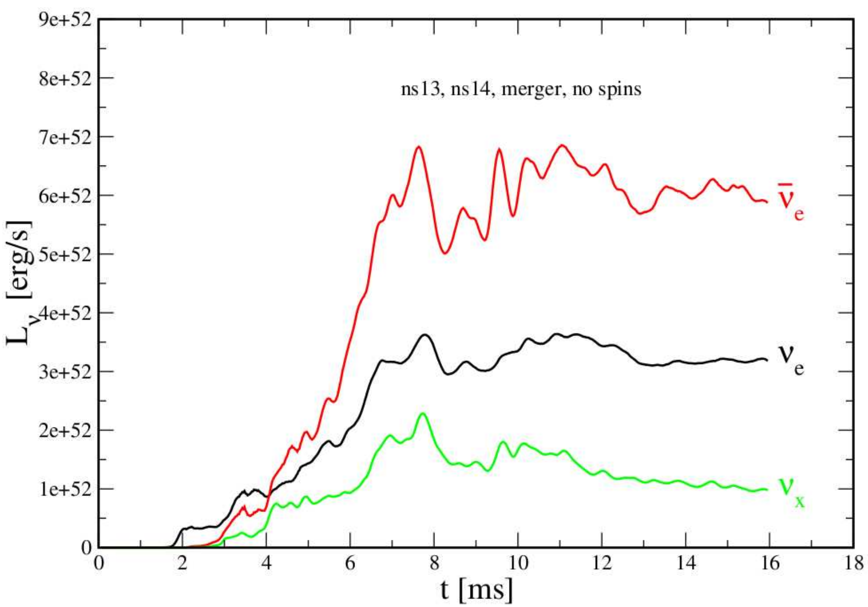
- dimensions: axisymmetry and 3D
- ν: from simple leakage scheme to approx transport
- gravity: from Newtonian to General Relativity
- microphysics: from polytropic EOS to nuclear EOS

State-of-the-art:

- 3D Newtonian models, with detailed ν treatment and microphysics input
- 3D GR models, with simplified microphysics input (e.g. polytropic EOS)

NS merger: neutrino signature

- NS coalescence heats high density matter up
- SMNS and inner disk emit ν of all flavors
- ν provide efficient way to release gravitational energy



- total luminosity: $L_\nu \sim 10^{53}\mathrm{erg/s}$
- luminosity hierarchy: $L_{\bar{\nu}_e} > L_{\nu_e} > L_{\nu_{\mu,\tau}}$
- mean energy hierarchy: $\langle E_{\nu_{\mu,\tau}} \rangle > \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$

ASL applications and drawbacks

Applications

- broad parameter space exploration

CCSN

- progenitor mass
- progenitor metallicity
- rotation rates
- B strength and configuration
- microphysics input

BNSM

- NS masses
- NS spins
- orbital parameters
- B strength and configuration
- microphysics input

ASL applications and drawbacks

Applications

- broad parameter space exploration
- scenarios where details of ν transport are less relevant
- complicated geometries, where detailed ν transport is still not available
- code development and testing phase

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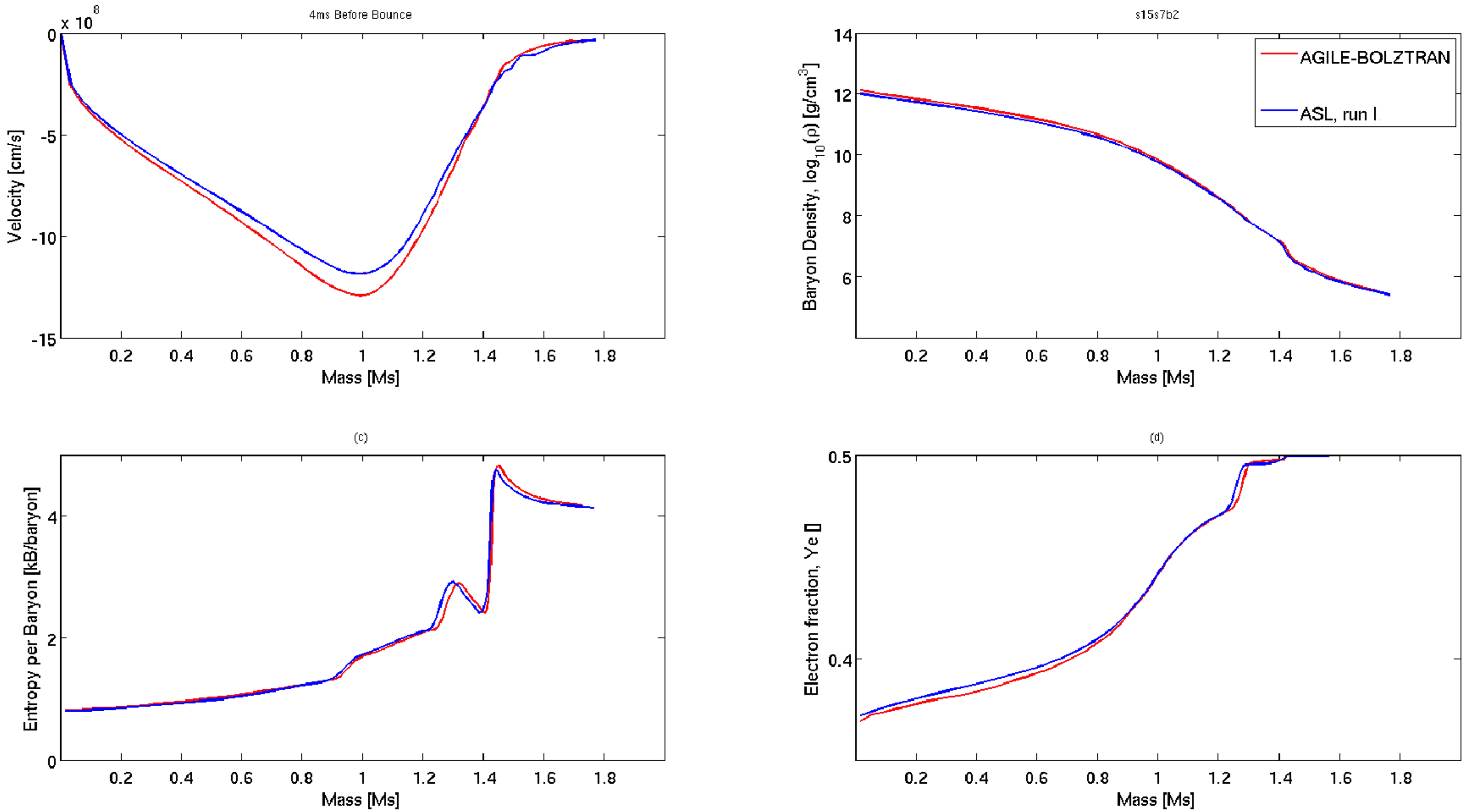
Drawbacks

- reduced accuracy
- reduced reliability far from tested configurations
- high sensitivity to single parts of the scheme
- presence of free parameters

Collapse phase

Test of type I (only ν_e and $\bar{\nu}_e$, with most relevant reactions)

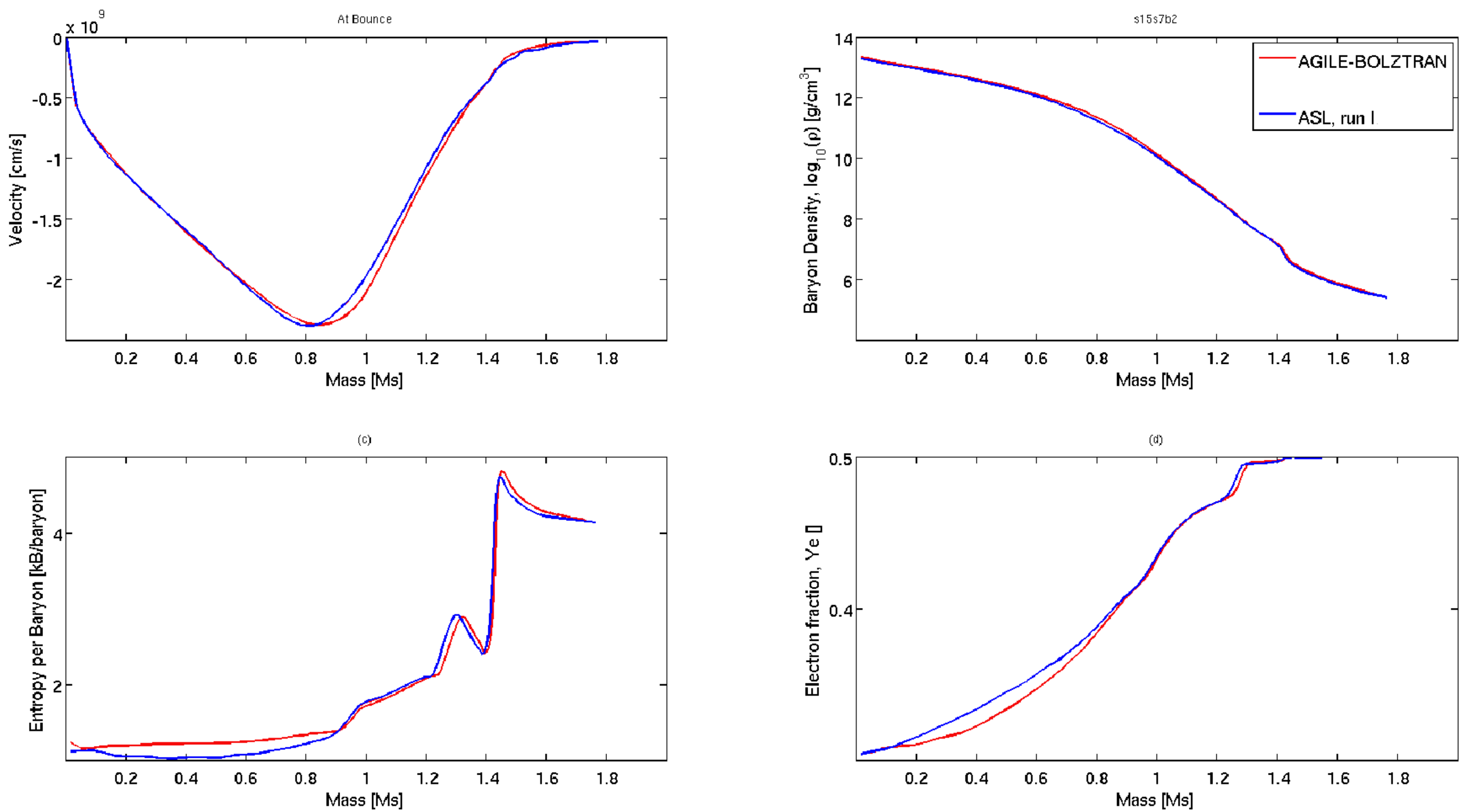
$$t_{\rm bb} = 5{\rm ms}$$



Collapse phase

Test of type I (only ν_e and $\bar{\nu}_e$, with most relevant reactions)

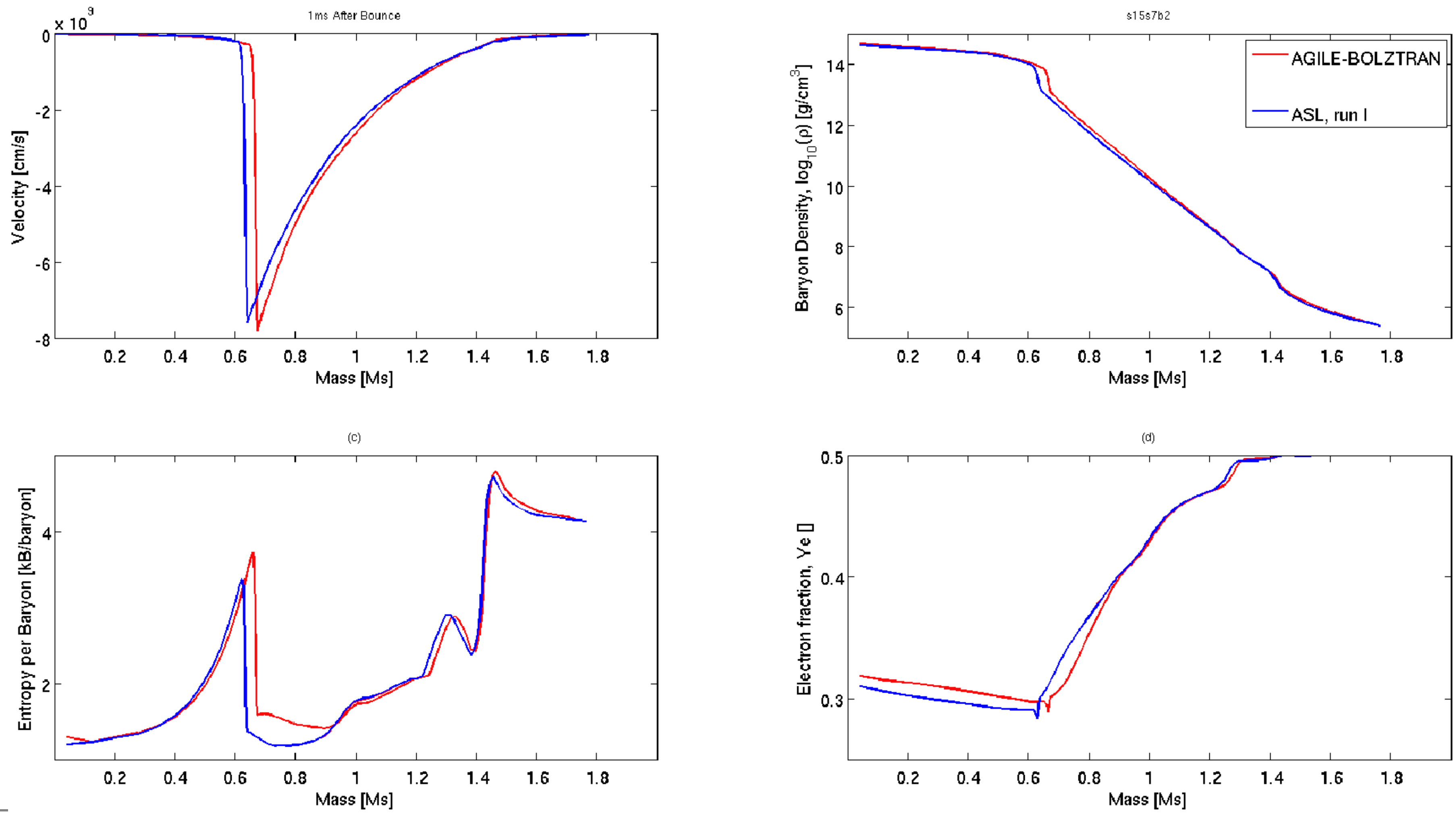
$$t_{\rm bb} = 1{\rm ms}$$



Collapse phase

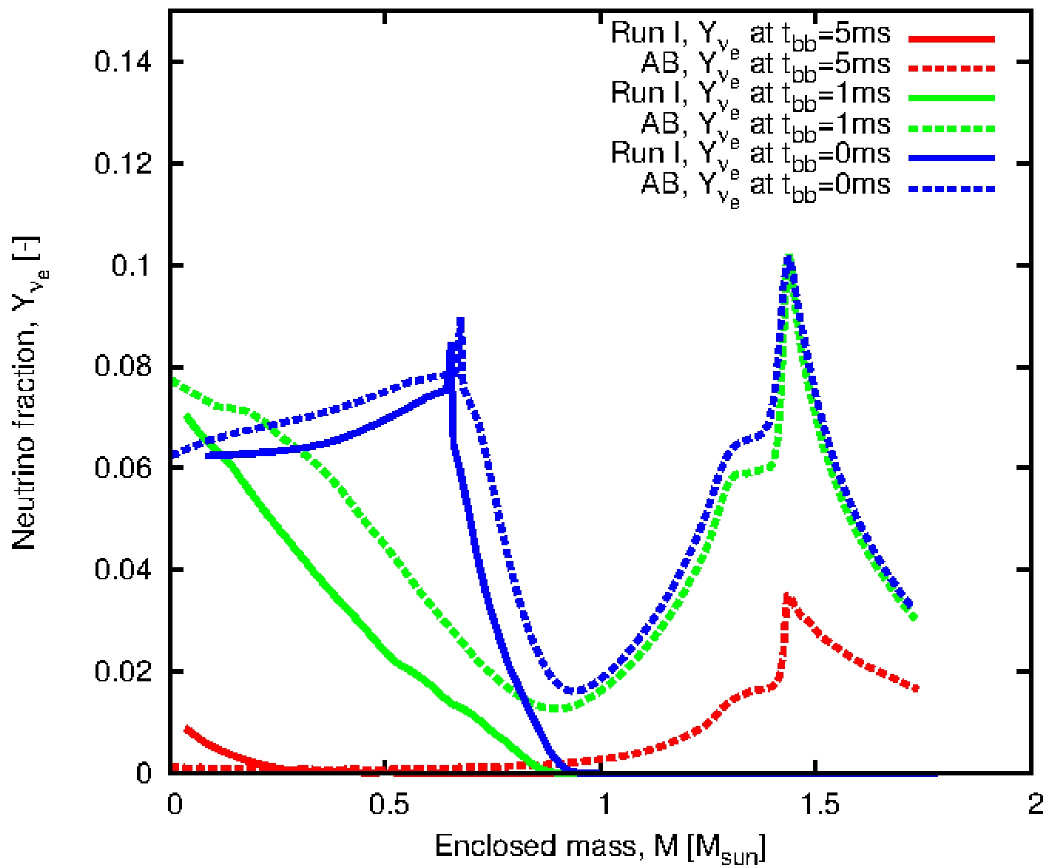
Test of type I (only ν_e and $\bar{\nu}_e$, with most relevant reactions)

$$t_{\rm bb} = 0{\rm ms}$$



Collapse phase

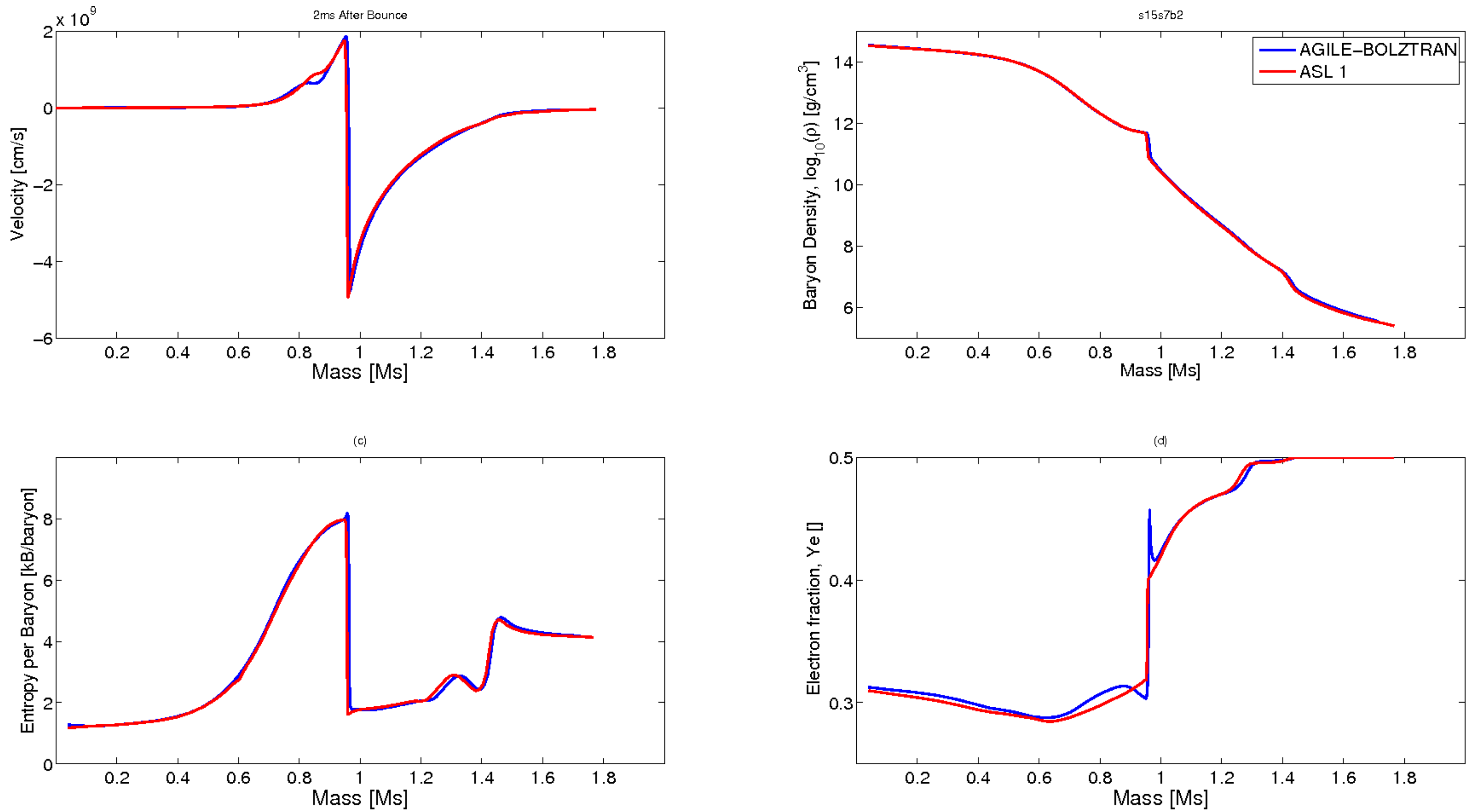
Test of type I (only ν_e and $\bar{\nu}_e$, with most relevant reactions) evolution of neutrino trapped component, Y_ν^T



Early post bounce phase, dynamics

Test of type I (only ν_e and $\bar{\nu}_e$, with most relevant reactions)

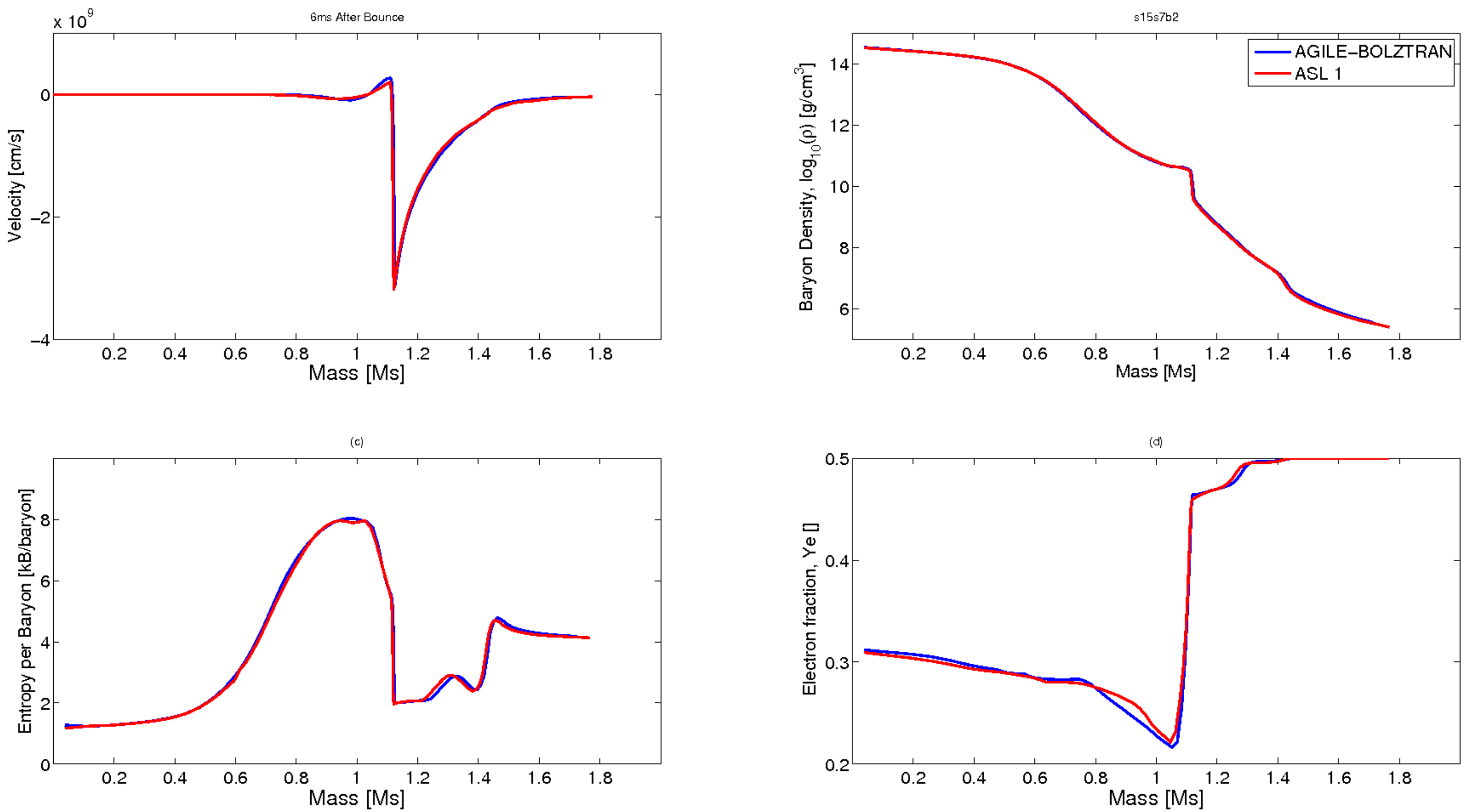
$$t_{\rm pb} = 1\rm ms$$



Early post bounce phase, dynamics

Test of type I (only ν_e and $\bar{\nu}_e$, with most relevant reactions)

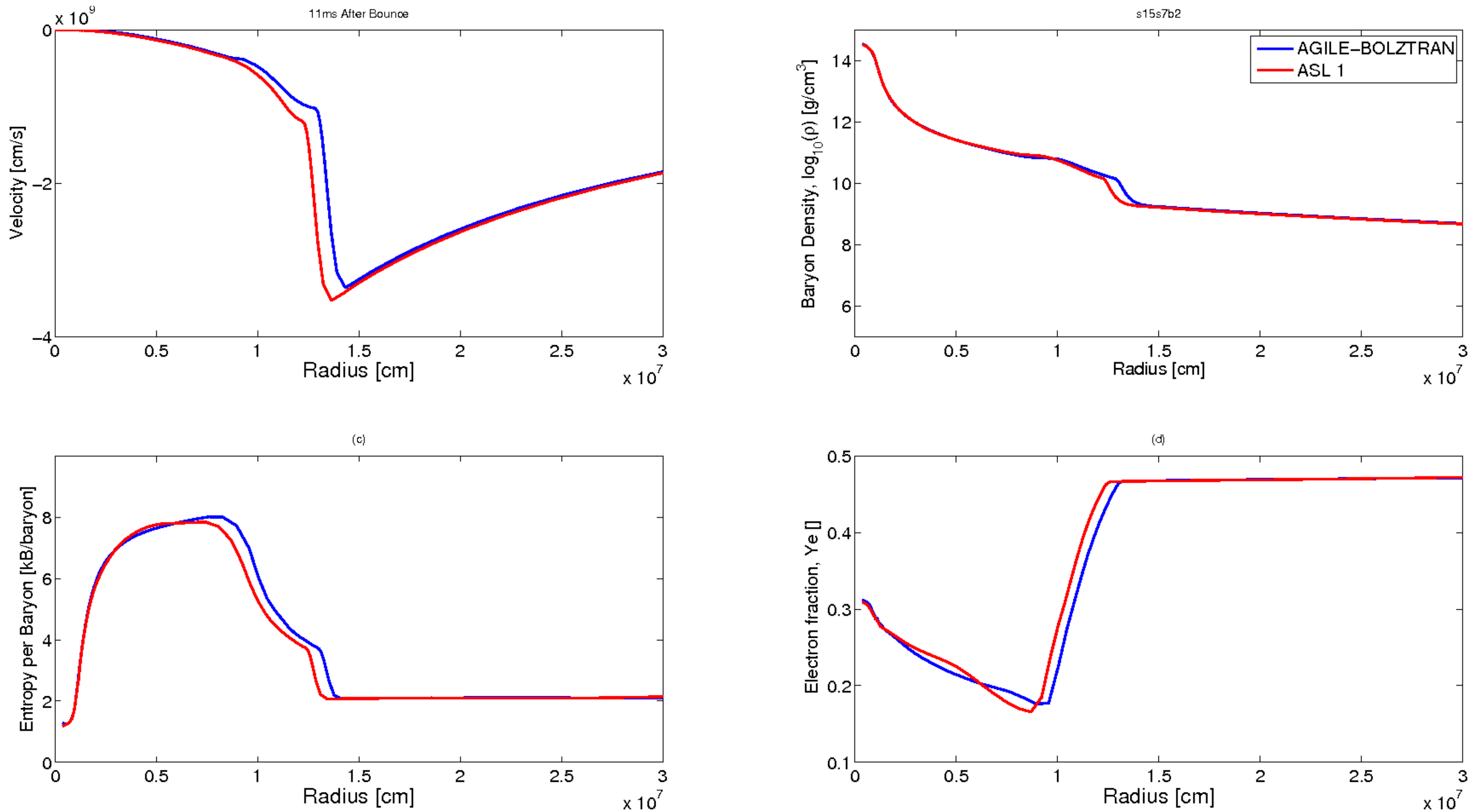
$$t_{\rm pb} = 5{\rm ms}$$



Early post bounce phase, dynamics

Test of type I (only ν_e and $\bar{\nu}_e$, with most relevant reactions)

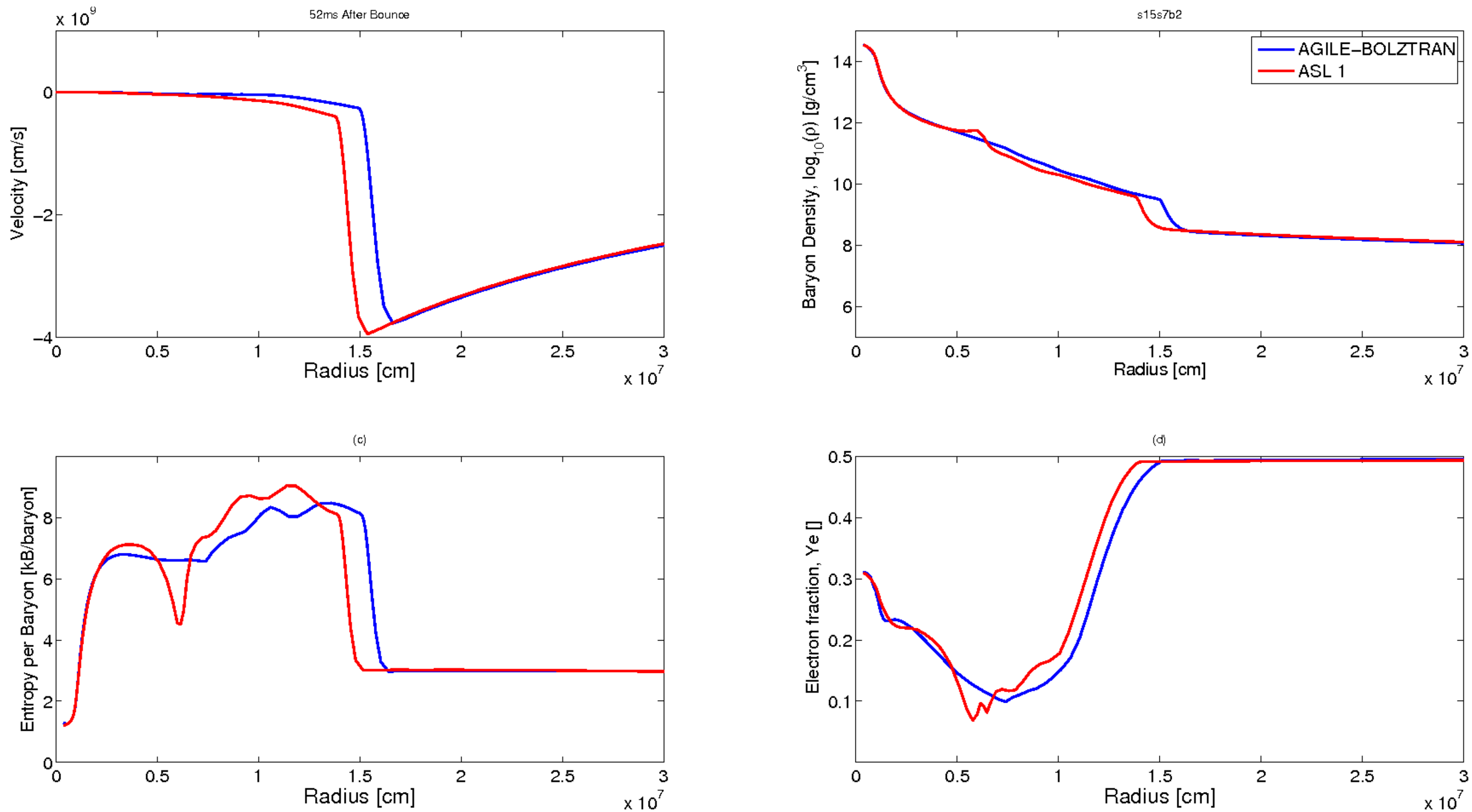
$$t_{\rm pb} = 10{\rm ms}$$



Early post bounce phase, dynamics

Test of type I (only ν_e and $\bar{\nu}_e$, with most relevant reactions)

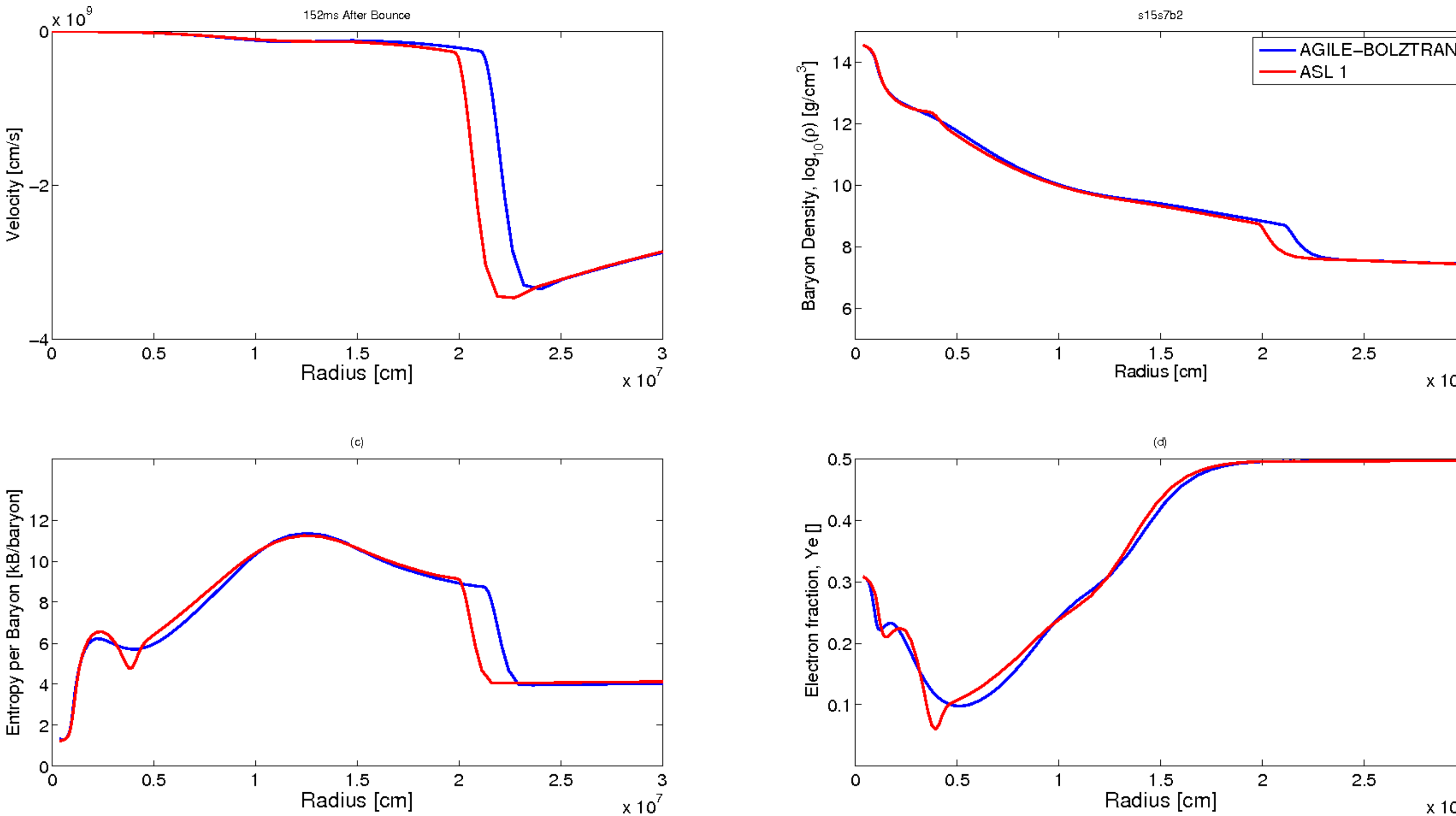
$$t_{\rm pb} = 50{\rm ms}$$



Late bounce phase, dynamics

Test of type I (only ν_e and $\bar{\nu}_e$, with most relevant reactions)

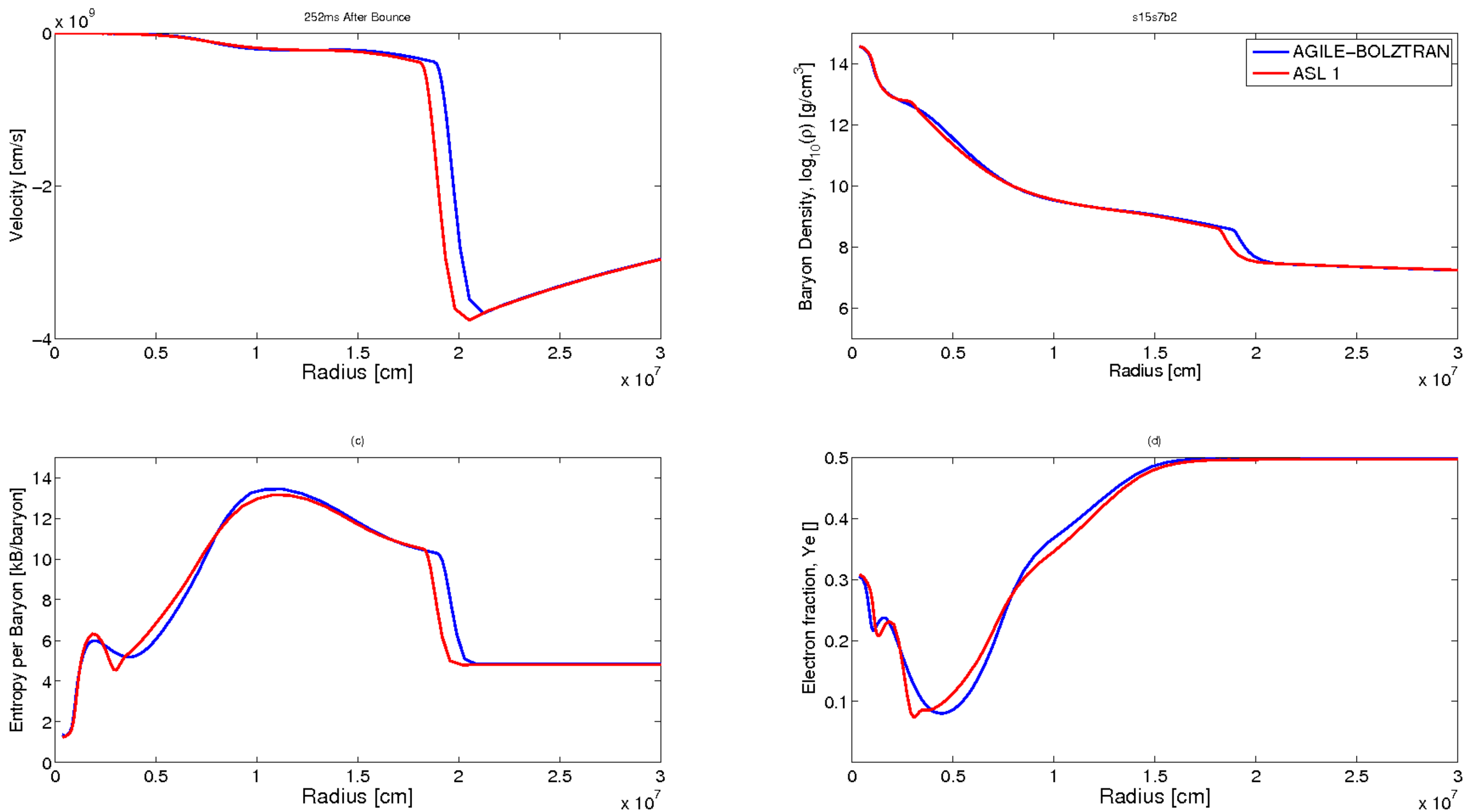
$$t_{\mathrm{pb}} = 150\mathrm{ms}$$



Late bounce phase, dynamics

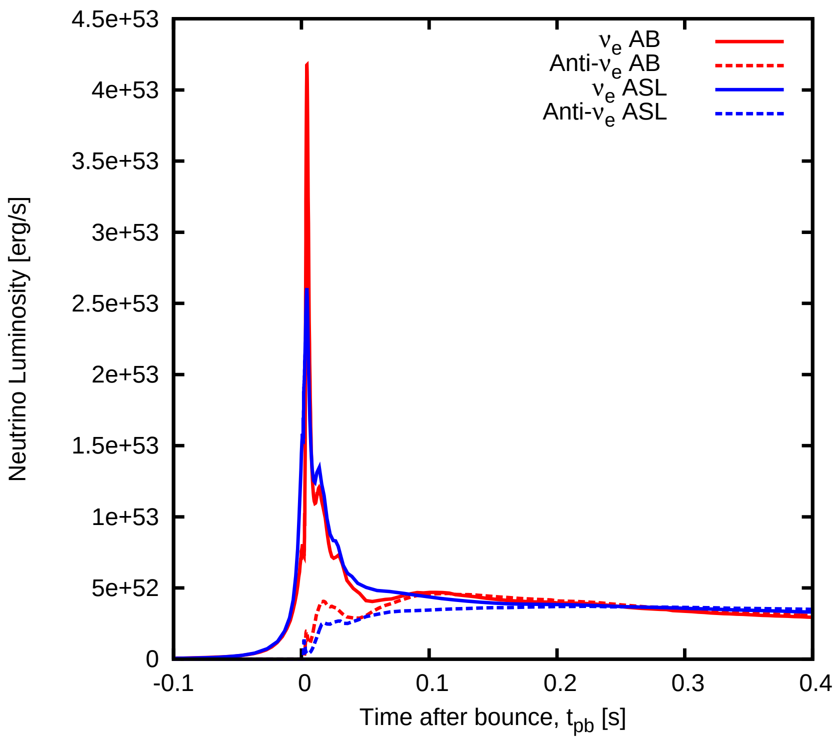
Test of type I (only ν_e and $\bar{\nu}_e$, with most relevant reactions)

$$t_{\rm pb} = 250{\rm ms}$$

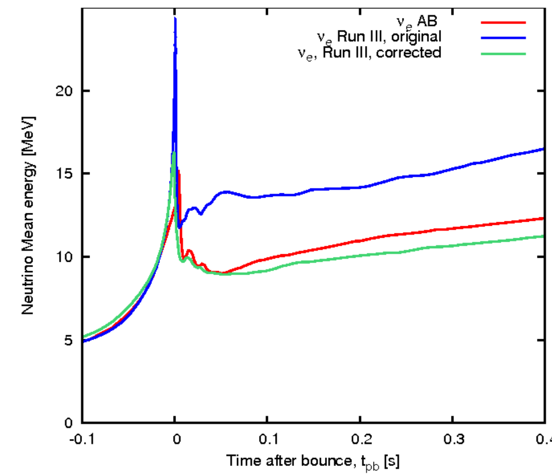


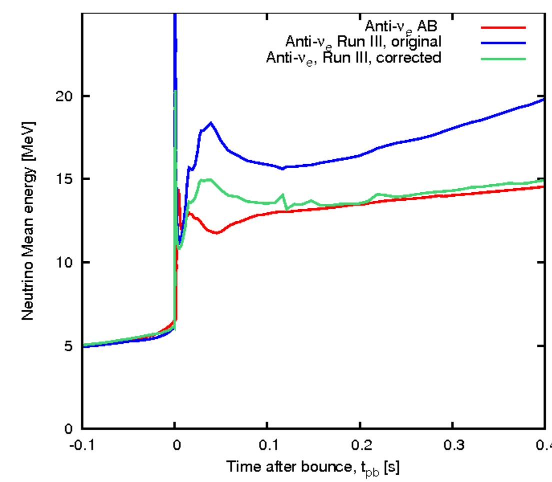
ν luminosities and mean energies

Test of type I (only ν_e and $\bar{\nu}_e$, with most relevant reactions)



$\nu_e, \bar{\nu}_e$ luminosity





$\langle E_{\nu_e} \rangle$ (MeV), up; $\langle E_{\bar{\nu}_e} \rangle$ (MeV), down