

μ and τ neutrinos in Supernova simulations

Albino Perego, Matthias Liebendorfer

`albino.perego@unibas.ch`

University of Basel

Department of Physics

EUROGRAD workshop

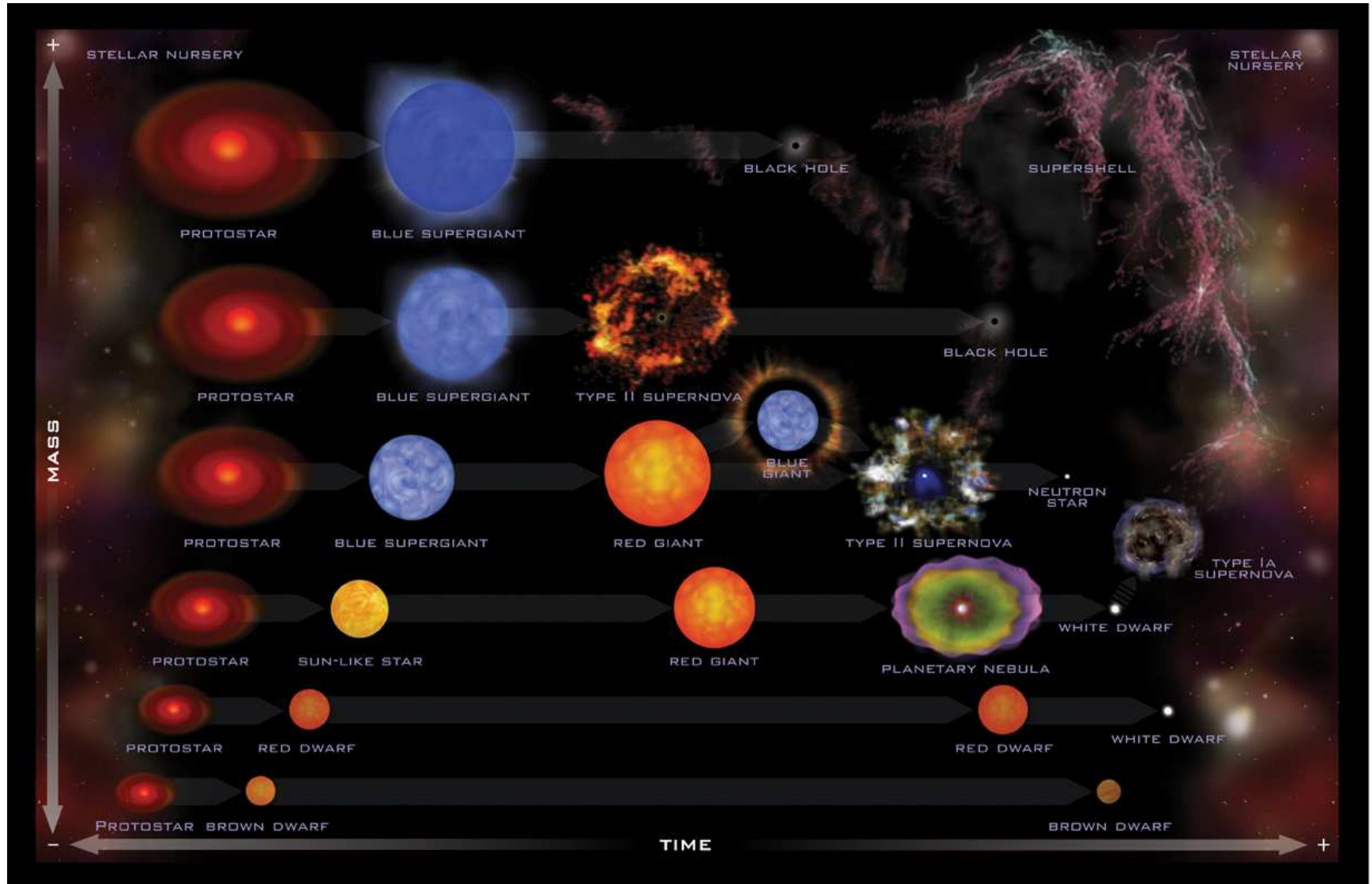
Hallstatt 27-29 September 2009

Outline

- Introduction: μ and τ neutrinos in SN explosion
- Leakage scheme
 - Motivations
 - What is a leakage scheme?
 - Implementation and comparison
- Conclusions

Introduction

Life of a star



Core collapse SN in a nutshell

- Core collapse SN explosion is the fate of a massive star ($8M_{\odot} \lesssim M_* \lesssim 90M_{\odot}$) before becoming a NS or a BH

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- dynamics:
 - *Collapse phase*

at the end of the nuclear burning phases, the iron core of the star collapses due to gravity;

timescale:

$$t_{\text{collapse}} \sim t_{\text{freefall}} \sim 1/\sqrt{G\bar{\rho}} \approx 30\text{ms}$$

initial iron core properties:

$$R \sim 3000 \text{ km}, \rho_c \sim 10^{10} \text{ g/cm}^3, T_c \sim 9 \times 10^9 \text{ K}$$

Core collapse SN in a nutshell

- Core collapse SN explosion is the fate of a massive star ($8M_{\odot} \lesssim M_* \lesssim 90M_{\odot}$) before becoming a NS or a BH
- dynamics:
 - *Collapse phase*
 - *Bounce phase*

when nuclear density is reached, the core bounces because of nuclear repulsive interaction;

central properties at bounce:

$$\rho_c \sim 5 \times 10^{14} \text{ g/cm}^3, T_c \sim 1.5 \times 10^{11} \text{ K}, Y_e \approx 0.3$$

where $Y_i = n_i/n_{\text{barions}}$ and n_i is the particles number density

Core collapse SN in a nutshell

- Core collapse SN explosion is the fate of a massive star ($8M_{\odot} \lesssim M_* \lesssim 90M_{\odot}$) before becoming a NS or a BH
- dynamics:
 - *Collapse phase*
 - *Bounce phase*
 - *Post-bound phase*

an outgoing shock wave forms, expands and stops, because it loses energy dissociating matter; later, the wave is somehow revived (neutrino heating or sound mechanism or 3D MHD effects or ...) and the star is destroyed.

timescale: $t_{\text{expl}} \sim 300\text{ms} - 1.5\text{s}$

Neutrinos in SN explosion

Neutrinos (of all flavours) are fundamental ingredients in core collapse SN; they ...

- exchange energy with matter (heating and cooling)
- release energy out of the system
- influence explosive nucleosynthesis
- give us important informations about dense matter

ν_e and $\bar{\nu}_e$ differ from $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$

- origin:
- at the on-set of the collapse, $Y_e \neq 0$ while $Y_\mu = Y_\tau = 0$
 - $m_e \ll m_\mu \ll m_\tau$

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 - $m_e \ll m_\mu \ll m_\tau$

$\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ production

- the production is due to neutral current weak processes in the stellar plasma:

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

$$N + N \leftrightarrow N' + N' + \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$

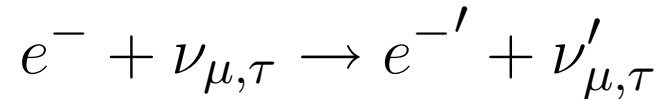
$$\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$

all these processes depend strongly on matter temperature T and density ρ

- during the collapse phase, ρ and T are too small to produce a relevant amount of $\nu_{\mu,\tau}$
- in the post-bounce phase (when $\rho \sim \rho_0$ and $T \gtrsim 10\text{MeV}$) $\nu_{\mu,\tau}$ production rates rise between the forming neutron star and the shock wave

$\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ thermalization

Production processes and neutrino scattering on electrons



are effective exchanging energy and creating or destroying neutrino pairs



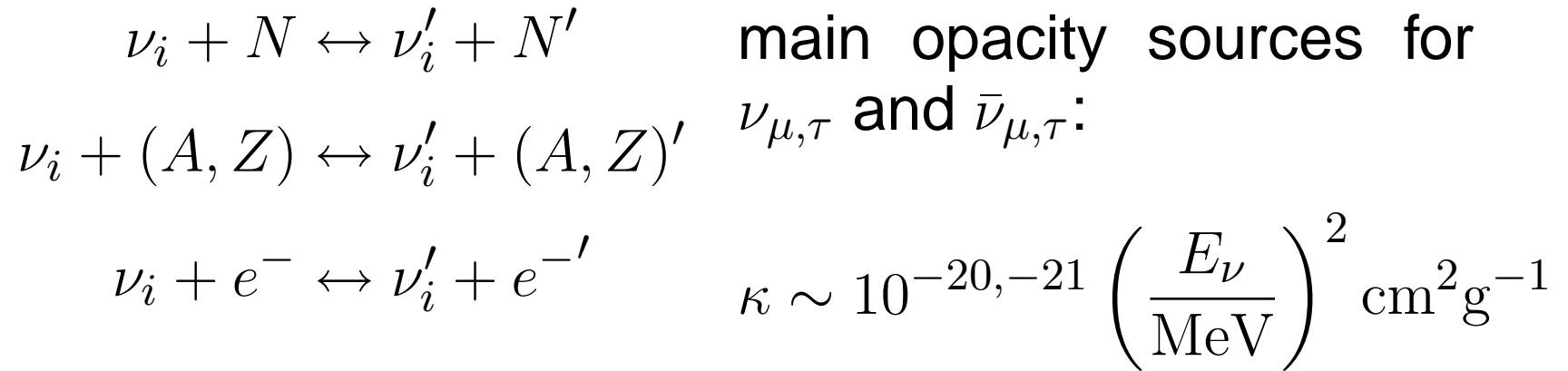
where these reaction are significantly active, they keep μ and τ neutrinos in local thermal equilibrium with matter



where thermalization is effective, $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ can be described as Fermi gases, with $T_{\nu} \approx T_{\text{matter}}$ and $\mu_{\nu} = 0$

$\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ diffusion

- neutral current weak processes allow neutrinos to diffuse far from their production site:



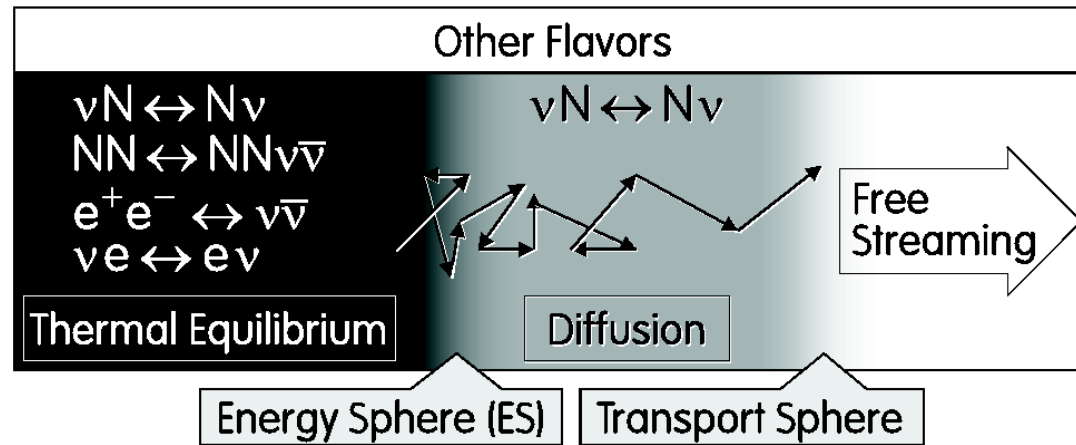
- Post-bounce phase: high E_ν in high ρ region

$$\Downarrow$$
$$\lambda_{\nu_{\mu,\tau}}(t, \mathbf{r}, E_\nu) \text{ can be short and } \tau_{\nu_{\mu,\tau}}(t, \mathbf{r}, E_\nu) \gg 1$$

\Downarrow
 μ and τ neutrinos diffuse out on a timescale

$$t_{\text{diff}} \sim \left(\frac{R}{c} \right) \tau_\nu$$

$\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ in SN environment



Raffelt 2001

- inside the energy sphere, $\nu_{\mu,\tau}$'s are produced and thermalize: they form a Fermi gas on a timescale shorter than t_{diff} and t_{dyn}
- inside transport sphere, $\nu_{\mu,\tau}$'s scatter mainly on nucleons and nuclei (isoenergetics scattering)
- out of transport sphere, $\nu_{\mu,\tau}$'s escape almost freely, leaking out energy

$\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ in SN simulations

- dynamical process
 - macrophysics phenomena
 - microphysics input
 - multi-component fluid (matter and radiation)
- numerical simulations required, with MHD + neutrino transport + EOS

In core collapse SN simulations we need:

- accurate and reliable treatment of neutrino-nuclear matter interaction at high density and high temperature
Implementation of improved ν bremsstrahlung, in collaboration with C. Pethick and A. Schwenk
- efficient and reliable implementation of $\nu_{\mu,\tau}$ transport in 1D, 2D and 3D codes

Leakage scheme for $\nu_{\mu,\tau}$

Motivations

ELEPHANT: 3D MHD core collapse SN code, with IDSA neutrino transport for electron flavour, ν_e and $\bar{\nu}_e$ (see, e.g., Liebendorfer et al. 2009 for IDSA)

simulation without $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$:

- missing cooling due to those neutrinos
- too energetic shock wave, compared with 1D simulations

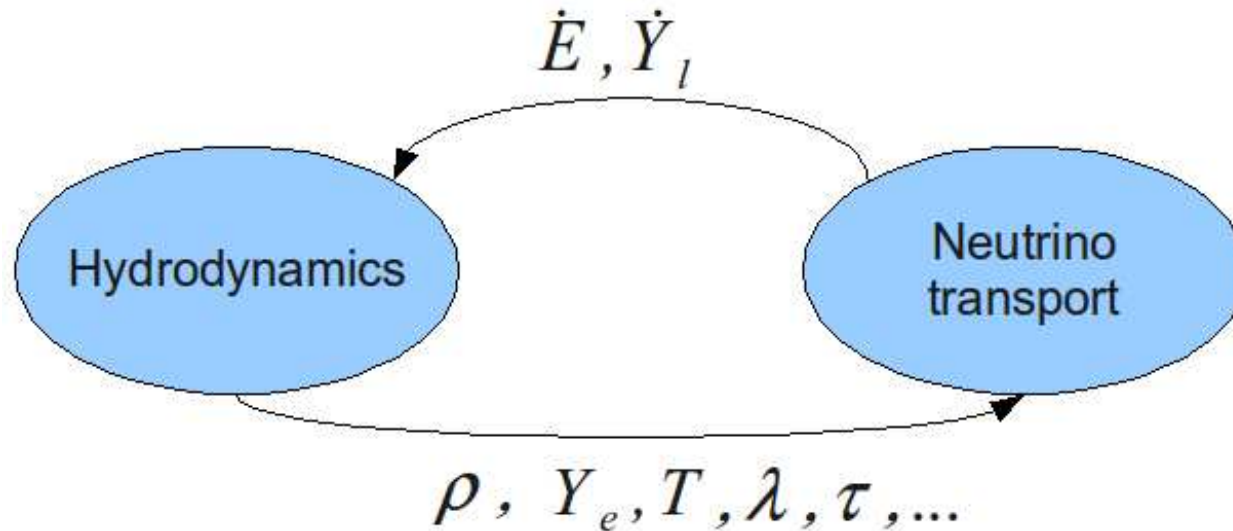
How to include the cooling contribution due to μ and τ neutrinos, using a computationally cheap implementation?

Leakage scheme

Battle plan

- to develop a simple leakage scheme for ν_μ and ν_τ
- to test the scheme against full Boltzmann transport in 1D simulations
- to include the scheme in 3D simulations
- to improve and extend the scheme

Leakage scheme: basic idea I



- cheap and easy estimation of $\dot{E}_{\mu,\tau} = Q$, considering only the loss of energy (no heating) due to neutrino production, thermalization, diffusion and free streaming
- $\dot{Y}_{\mu,\tau} = 0$

Ruffert et al. 1996, Rosswog&Liebendorfer 2003

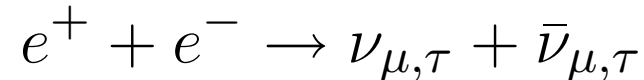
Leakage scheme: basic idea II

- transparent regime ($\tau \lesssim 1$)
 - $t_{\text{diff}} \approx t_{\text{free stream}}$
 - all the produced neutrinos can stream out freely
 - $Q \approx Q_{\text{prod}}$
- opaque regime ($\tau \gg 1$)
 - $t_{\text{diff}} \gg t_{\text{free stream}}$
 - neutrinos form a Fermi gas in equilibrium with matter and leak out on the diffusion time-scale
 - $Q \approx Q_{\text{diff}} \sim \frac{E_{\nu \text{ gas}}}{t_{\text{diff}}}$
- interpolation formula:

$$Q_{\text{eff}} = \frac{Q_{\text{diff}} Q_{\text{prod}}}{Q_{\text{diff}} + Q_{\text{prod}}}$$

Leakage scheme: ingredients

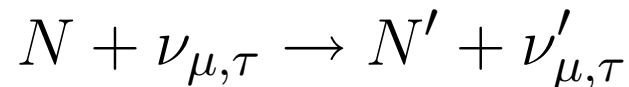
- Production mechanism: pair production



energy production rate depends on thermodynamic conditions:

$$Q_{\text{prod}} = Q_{\text{prod}}(\rho, T, Y_e)$$

- Diffusion mechanism: elastic scattering on nucleons



local diffused energy depends on local (temperature, mean free path) and global (optical depth) properties

$$Q_{\text{diff}} = Q_{\text{diff}}(T, \lambda_{\nu_{\mu,\tau}}, \tau_{\nu_{\mu,\tau}})$$

Comparison

We set up our comparison as follow:

- AGILE-BOLTZTRAN:
1D relativistic code

- ν_e transport provided
by Boltzmann
transport

- $\nu_{\mu,\tau}$ transport provided
by Boltzmann trans-
port

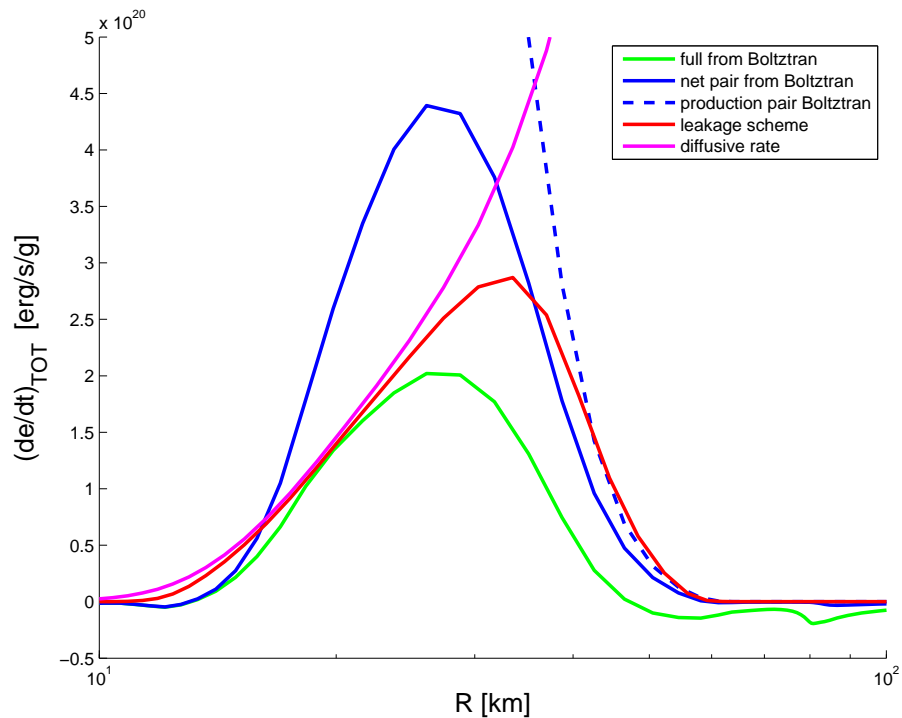
VS

- AGILE-BOLTZTRAN:
1D relativistic code

- ν_e transport provided
by Boltzmann
transport

- $\nu_{\mu,\tau}$ transport provided
by developed leakage
scheme

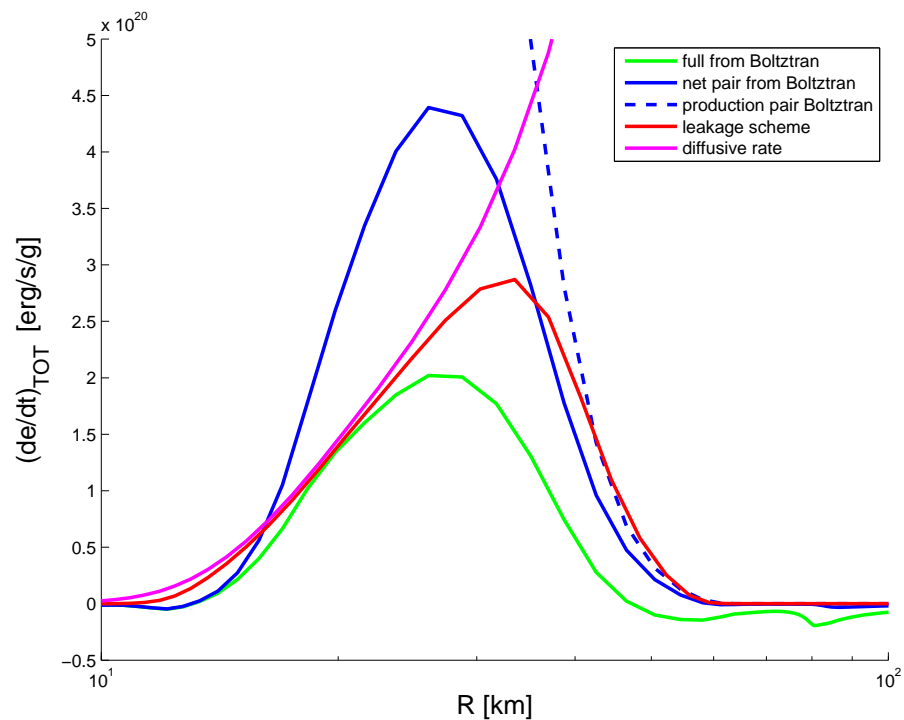
Energy released: 10 ms post-bounce



● Globally, qualitatively good agreement

Bolztran total results VS
leakage total results

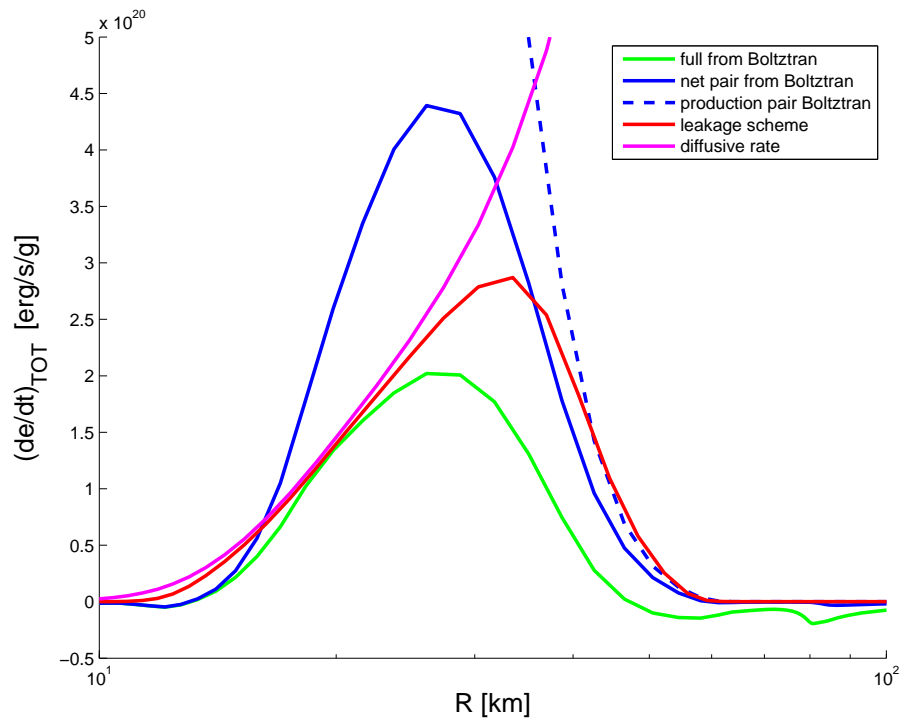
Energy released: 10 ms post-bounce



- Globally, qualitatively good agreement
- very good agreement for the streaming regime

Bolztran pair results VS
leakage total results

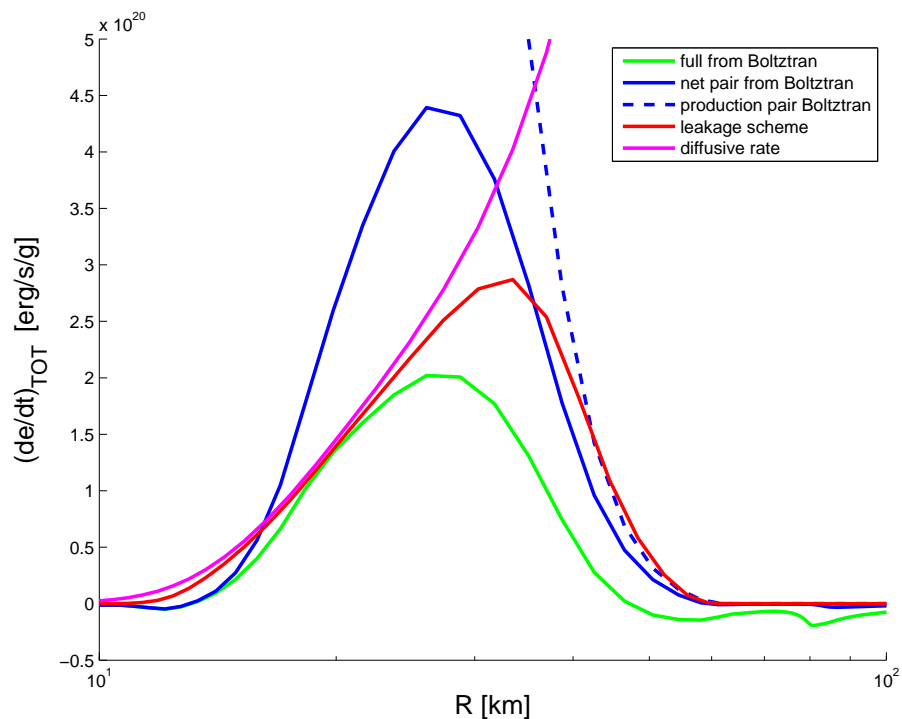
Energy released: 10 ms post-bounce



- Globally, qualitatively good agreement
- very good agreement for the streaming regime
- quiet good agreement for the diffusive regime

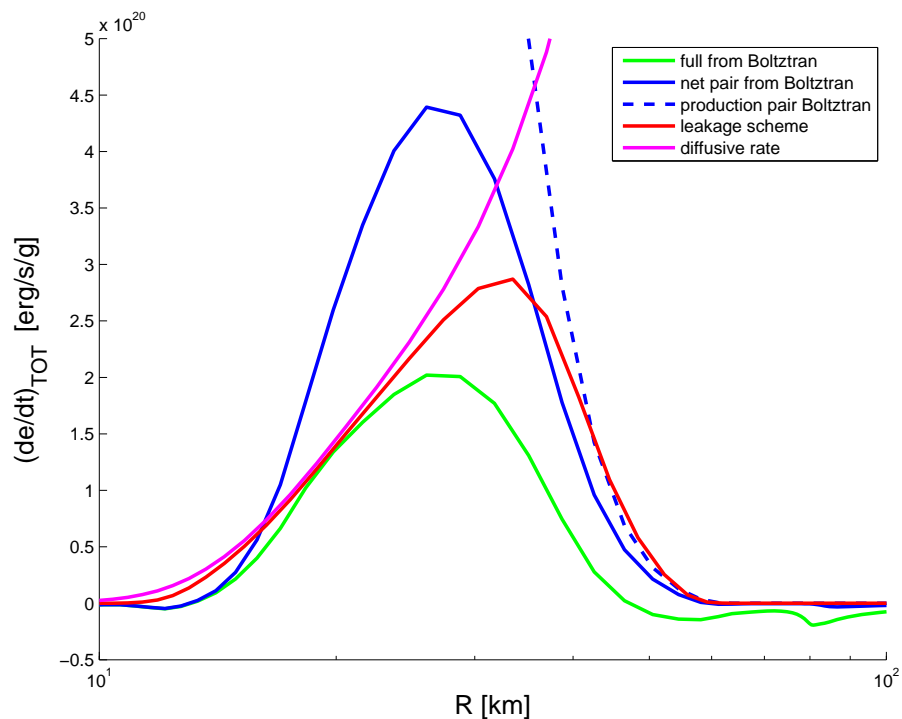
Bolztran total results VS
leakage diffusion rate

Energy released: 10 ms post-bounce



- Globally, qualitatively good agreement
- very good agreement for the streaming regime
- quiet good agreement for the diffusive regime
- the tail for $R \sim 10\text{km}$ seems to be artificial

Energy released: 10 ms post-bounce



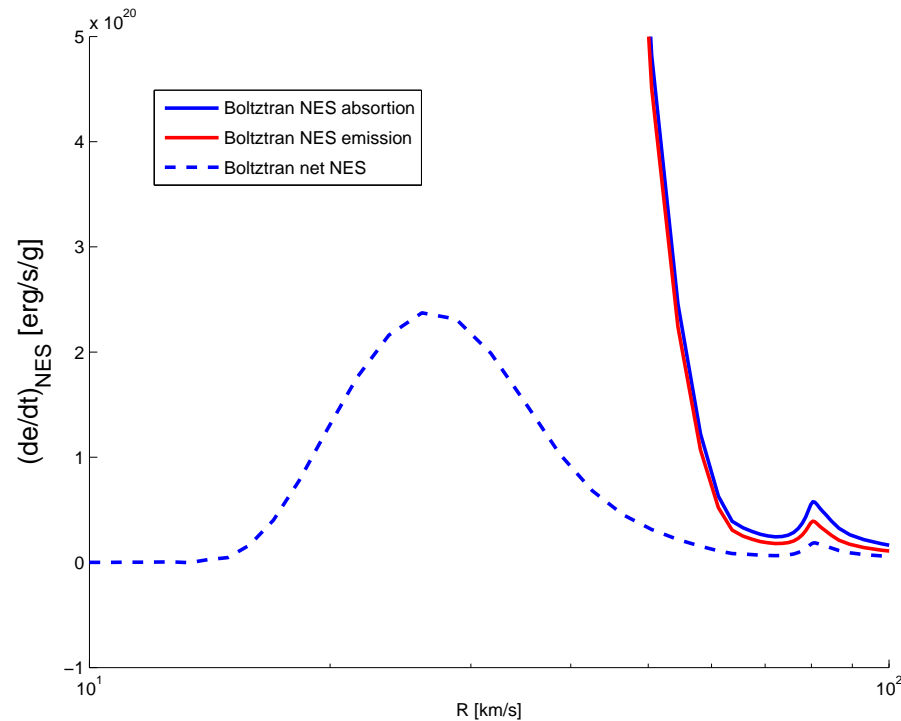
- Globally, qualitatively good agreement
- very good agreement for the streaming regime
- quiet good agreement for the diffusive regime
- the tail for $R \sim 10\text{km}$ seems to be artificial
- there is something missing in the semi-transparent regime

Missing NES

missing element in the semi-transparent regime: we are neglecting neutrino-electron scattering (NES)

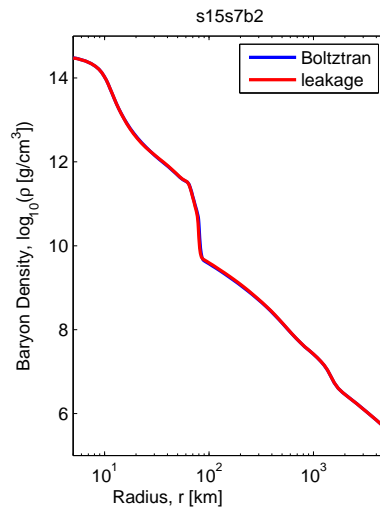
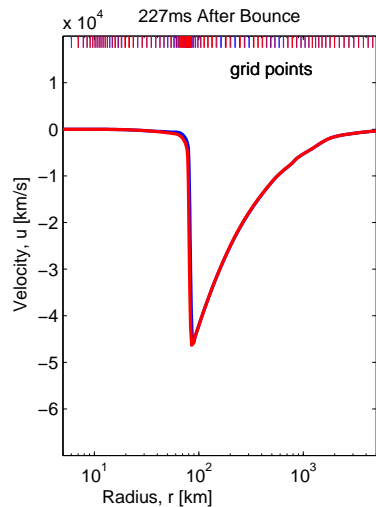


non-negligible heating for matter in the semi-transparent regime:



$$\left. \frac{d}{dt} E_{\text{NES}} \right|_{\text{abs}} - \left. \frac{d}{dt} E_{\text{NES}} \right|_{\text{em}} > 0$$

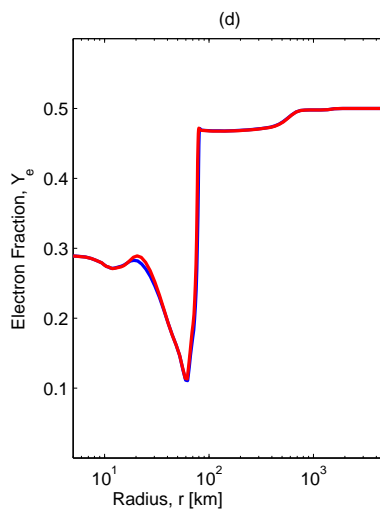
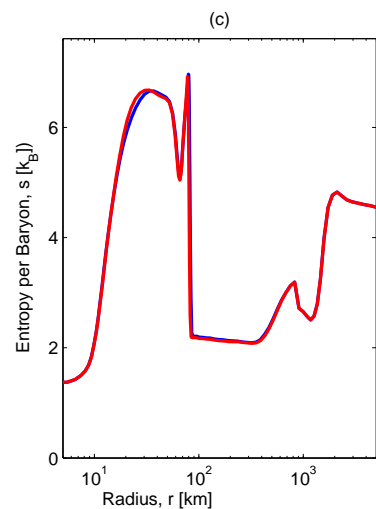
Profiles evolutions



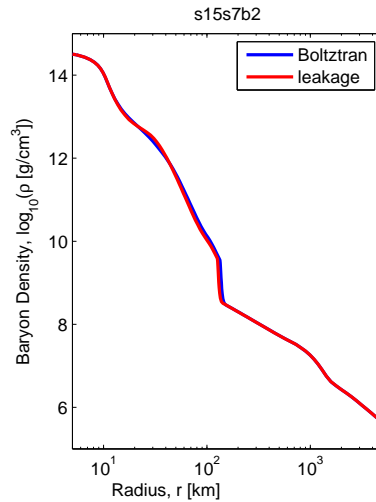
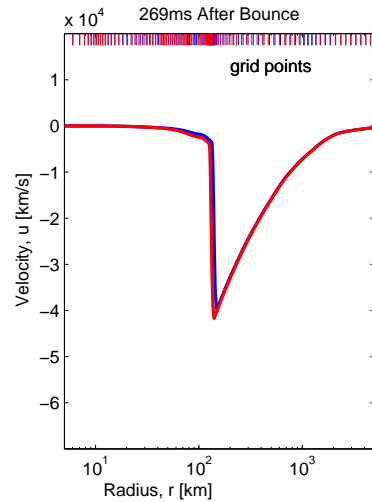
$t=10$ ms

Boltztran results VS
leakage results

very close to bounce:
good agreement, but
probably because the
cooling has not affected
the dynamics yet!



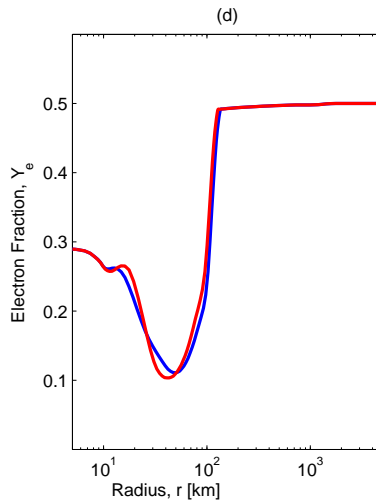
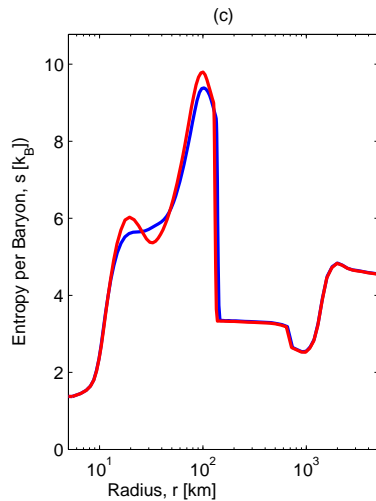
Profiles evolutions



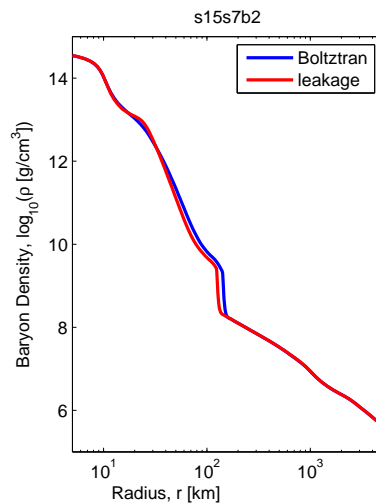
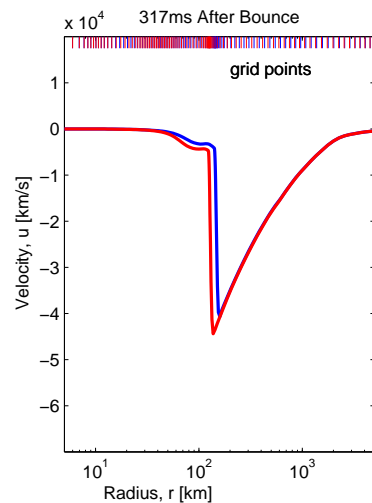
$t=50$ ms

Boltztran results VS
leakage results

Qualitatively good agreement, but the entropy shows some different features



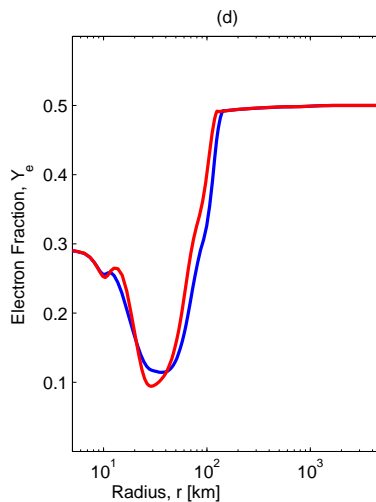
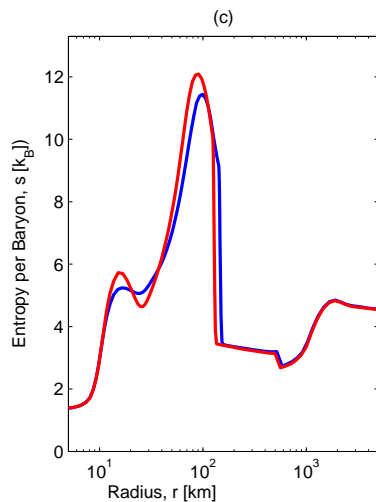
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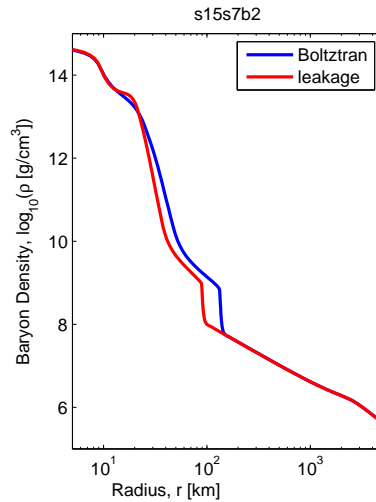
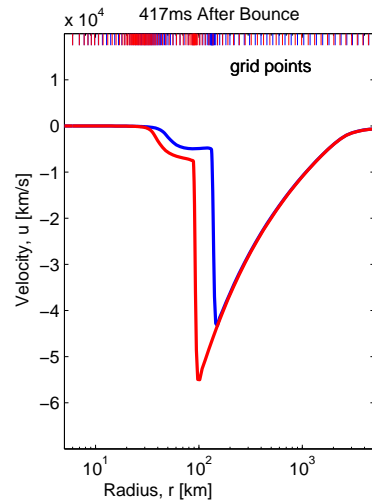
$t=100$ ms

Boltztran results VS
leakage results

Qualitatively good agreement, but the entropy shows some different features and the position of the shock is becoming different



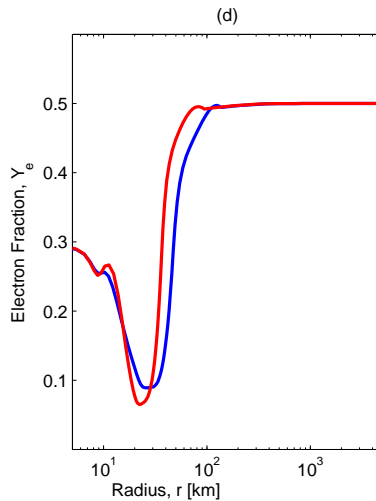
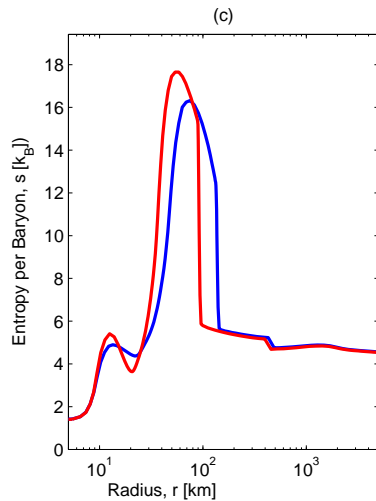
Profiles evolutions



$t=200$ ms

Boltztran results VS
leakage results

Qualitatively good agreement, but the entropy shows some different features and the position of the shock is becoming different

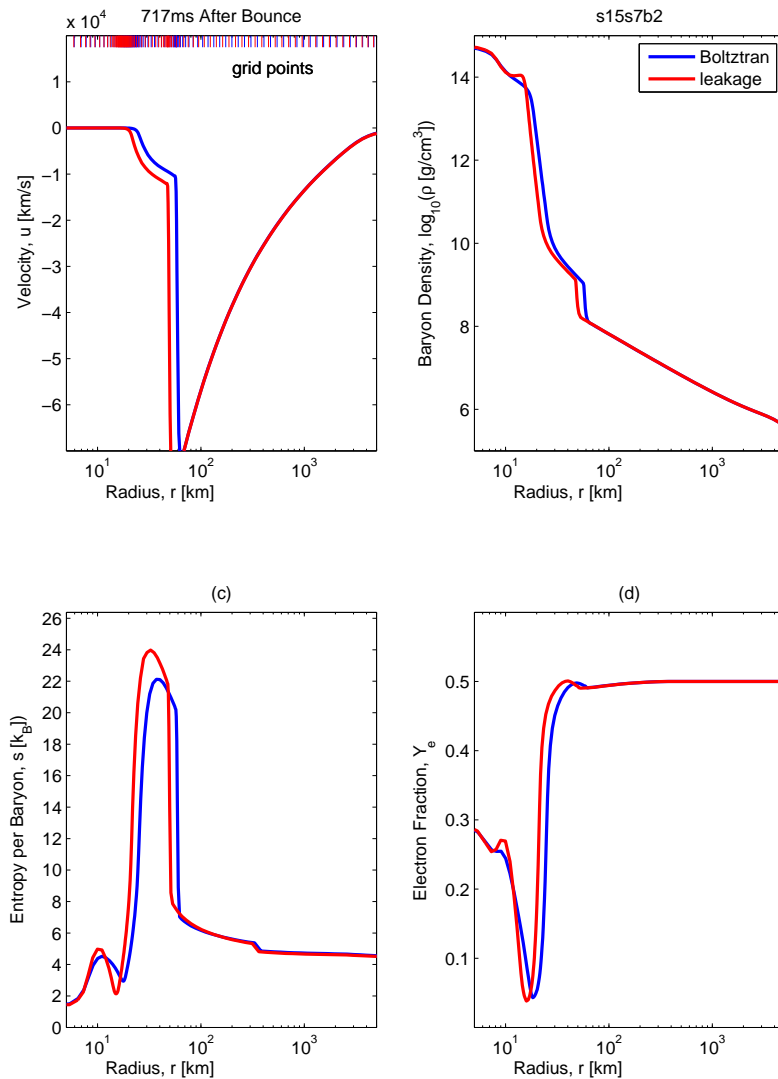


Profiles evolutions

t=500 ms

Boltztran results VS
leakage results

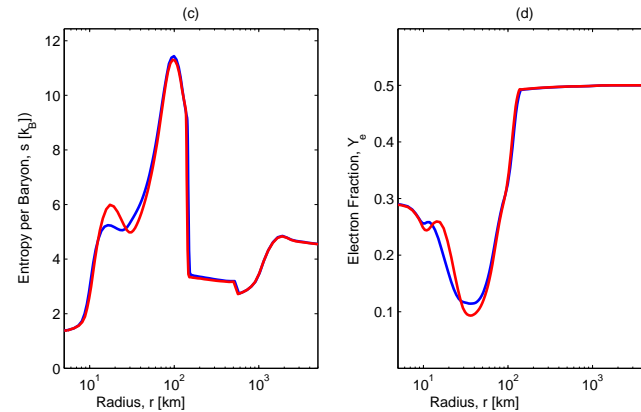
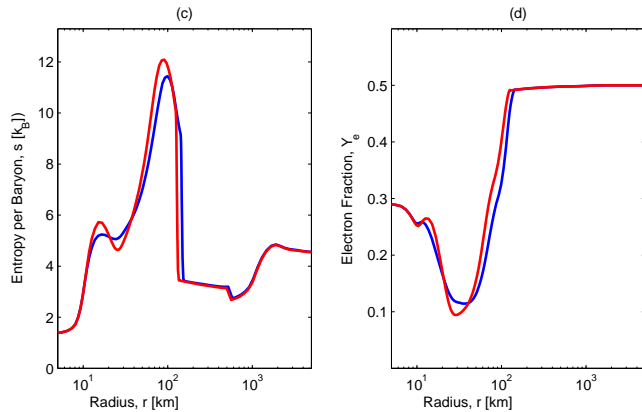
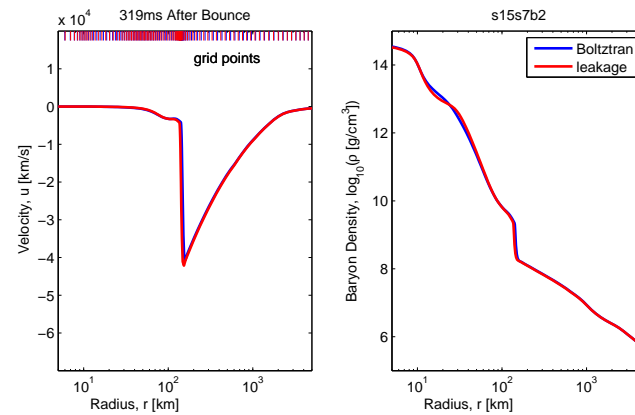
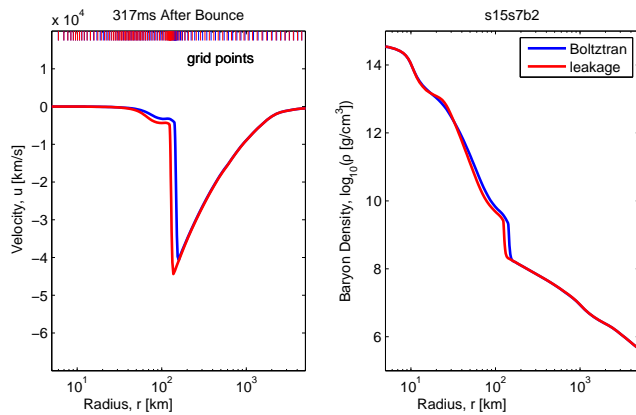
Qualitatively good agree-
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Refinement

$$T_{\text{diff}} \propto 3\tau_{\nu_{\mu,\tau}}; t = 100\text{ms}$$

$$T_{\text{diff}} \propto 6\tau_{\nu_{\mu,\tau}}; t = 100\text{ms}$$



Conclusions and improvements

1D comparison show a good agreement with refined leakage scheme



we can implement it in 3D simulations and see what happens ...

... but there are things we can do better:

- to include more reactions for productions and diffusion
- to perform a spectral analysis
- to give a more reliable treatment of NES
- to extend the scheme to electron flavour

Appendix:

Improved ν bremsstrahlung

A. Perego, C. Pethick, A. Schwenk, M. Liebendorfer

Motivations

AGILE-BOLTZTRAN: 1D relativistic core collapse SN code, with transport for all leptonic flavours (e, μ, τ) (see, e.g., Liebendorfer et al. 2001)

In this code, neutrino-pair bremsstrahlung and absorption were implemented according to Hannestad & Raffelt (1998) (implemented by Bruenn&Messer)

Recently, a more consistent treatment of neutrino emission from dense nucleon matter has been performed (Lykasov et al. 2008, Bacca et al. 2008)

Which is the impact of this improvement on core collapse SN simulation?

Battle plan (I part)

- compare the two approaches in the same limits
- if they are consistent, introduce all the improvements and point out the differences in the emission and absorption rates
- implement the new rates inside AGILE-BOLTZTRAN and check for meaningful differences for
 - dynamics of the post-bounce phase
 - $\nu_{\mu,\tau}$ luminosities and spectra

Bremsstrahlung rate expression

Rate for neutrino bremsstrahlung in one species nucleon medium:

$$\Gamma_{NN \leftrightarrow N'N'\nu\bar{\nu}} \approx 2\pi n_n G_F^2 C_A^2 (3 - \cos \theta) S_A(\omega, \mathbf{q} \rightarrow 0)$$

- n_n neutron number density (assuming only neutrons)
- θ angle between ν and $\bar{\nu}$ momenta
- (ω, \mathbf{q}) total neutrinos quadrimomenta
- $S_A(\omega, \mathbf{q} \rightarrow 0)$ axial structure function, in the long wavelength limit:

$$S_{A,ij}(\omega, \mathbf{q}) = \frac{1}{n_n} \int_{-\infty}^{+\infty} dt e^{i\omega t} (s_i(t, \mathbf{q}) s_j(0, -\mathbf{q})) \approx \delta_{ij} S_A(\omega, \mathbf{q})$$

Evaluation of S_A : theory

Hannestad&Raffelt 1998

- long wavelength limit ($q \rightarrow 0$)
- perturbative approach for the nuclear potential (OPE)
- inclusion of intermediate degrees of nucleon degeneracy in free-free transitions
- inclusion of multiple scattering effects
- inclusion of non-zero m_π

Lykasov, Bacca et al. 2008

- $|q| < p_F$
- perturbative approach for chiral effective field theory (until N^3LO)
- degenerate neutron matter
- one and two-particle-hole-pair state and mean field effects, calculated consistently
- inclusion of non-zero m_π

Evaluation of S_A : practice

Hannestad&Raffelt 1998

Ansatz:

$$S_A = \frac{2}{3\pi} \frac{\Gamma_\sigma}{\omega^2 + \Gamma^2/4} s\left(\frac{\omega}{T}\right)$$

- $\Gamma_\sigma \propto \rho T^{1/2}$, spin fluctuation rate
- $s(\omega/T)$ dimensionless scattering kernel, interpolation between degenerate and non-degenerate limits
- $\Gamma = \Gamma_\sigma g/2$, where g is set by normalization condition and accounts for multiple scattering effects

Lykasov, Bacca et al. 2008

Fluctuation-dissipation theorem

$$S_A = \frac{1}{\pi n_n} \frac{1}{1 - e^{-\omega/T}} \text{Im}\chi_\sigma(\omega, \mathbf{q})$$

- χ_σ spin response function, from quasiparticle transport equation (Landau Fermi-liquid):

$$\text{Im}\chi_\sigma(\omega, \mathbf{q} \rightarrow 0) \propto \frac{\omega\tau_\sigma}{(1 + G_0)^2 + (\omega\tau_\sigma)^2}$$

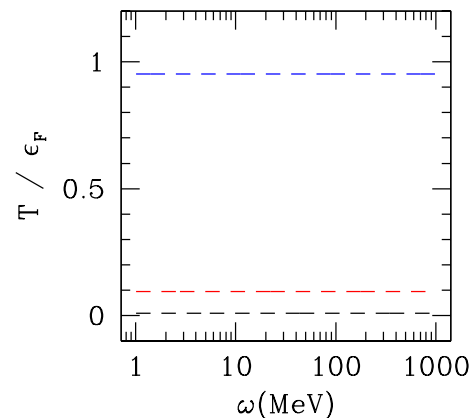
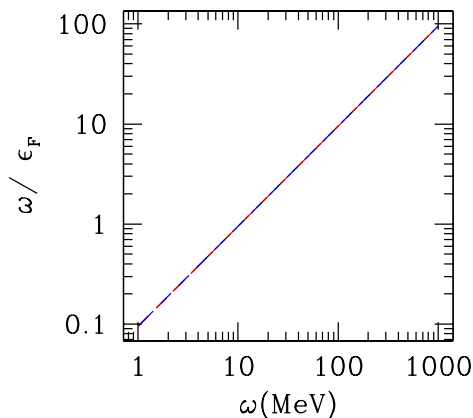
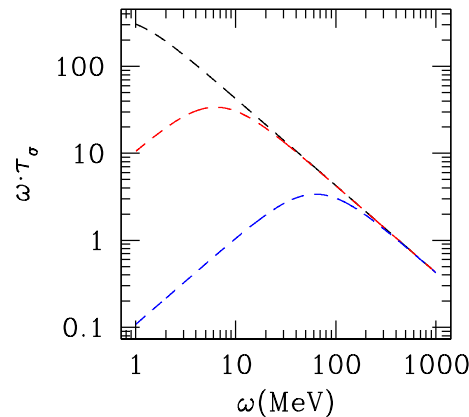
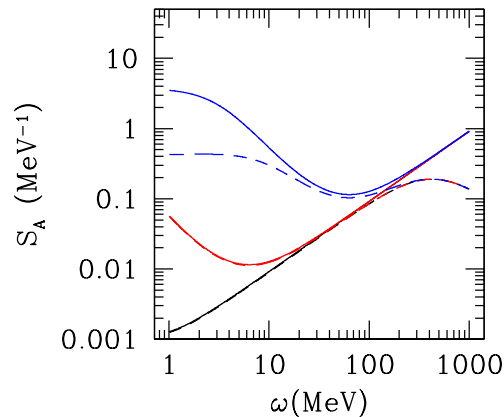
- for relaxation time $\omega\tau_\sigma \gg 1$,

$$1/\tau_\sigma = C_\sigma [T^2 + (\omega/2\pi)^2]$$

C_σ depends on NN interaction

Degenerate limit comparison I

$\rho = 2 \times 10^{13} \text{ g/cm}^3$ $T = 0.1 \text{ MeV}$, $T = 1 \text{ MeV}$, $T = 10 \text{ MeV}$



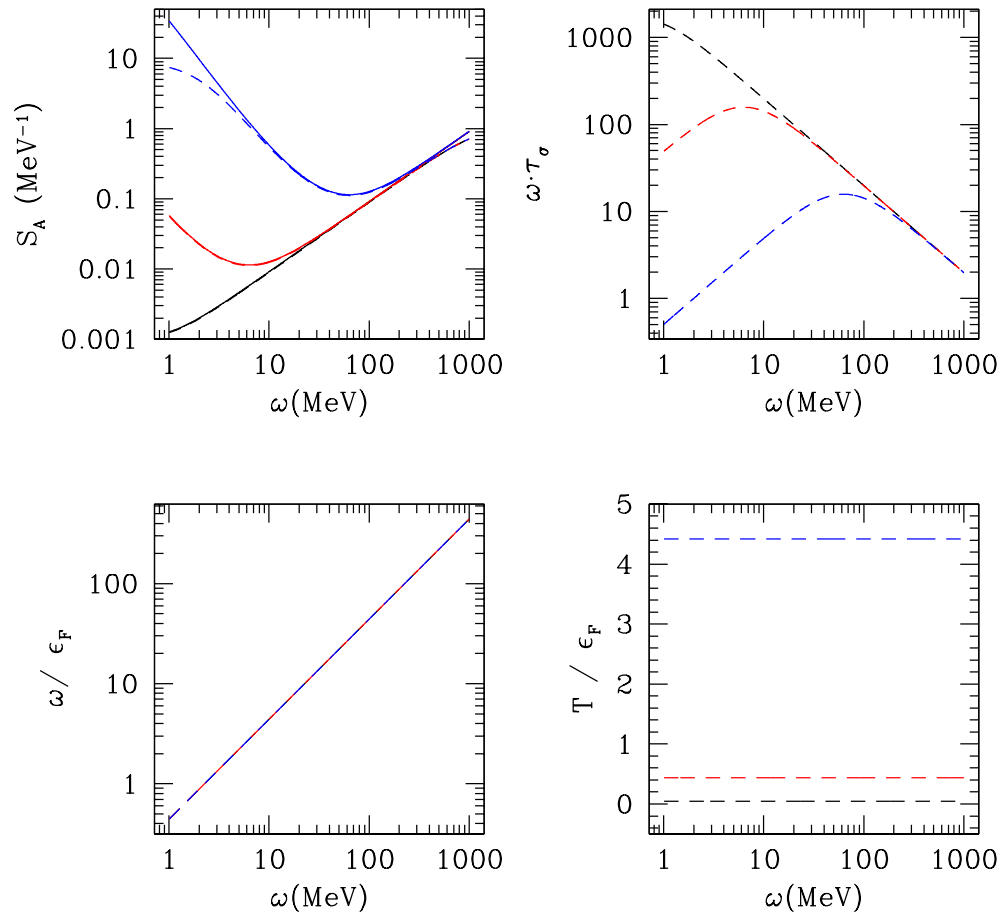
- comparison of S_A from Bacca et al. 08 (dashed) and the degenerate limit of S_A from Hannestad&Raffelt 98 (solid)

- S_A evaluated in the same limit:

- OPE
- no mean-field effects, $G_0 = 0$
- no effective mass correction

Degenerate limit comparison II

$\rho = 2 \times 10^{12} \text{ g/cm}^3$ $T = 0.1 \text{ MeV}$, $T = 1 \text{ MeV}$, $T = 10 \text{ MeV}$



- comparison of S_A from Bacca et al. 08 (dashed) and the degenerate limit of S_A from Hannestad & Raffelt 98 (solid)

- S_A evaluated in the same limit:
 - OPE
 - no mean-field effects, $G_0 = 0$
 - no effective mass correction

Conclusions and improvements

The degenerate expressions, considered in the same limits, show a good agreement as long as $\omega T_\sigma \gg 1$, but improvements are necessary:

- extension of the new approach to the non-degenerate limit and interpolation with the degenerate one (matter behind the shock wave is usually in non-degenerate condition ($\mu_n \lesssim -k_B T$))
- to switch on recent improvements in NN interactions (mean field effect, chiral EFT ...)
- inclusion of proton-neutron interaction ($0.7 \lesssim X_n \lesssim 0.9$)
- evaluation of inelastic scattering on nucleons in CCSN context and, eventually, its inclusion in simulations
- ...

Reviewed battle plan (I part)

- compare the two approaches in the same limit . . .



. . . we are working for you!

- if they are consistent, introduce all the improvements and . . .

Core collapse SN in a nutshell II

- energetics:
explosion energy comes from gravitational energy released by forming compact remnant
(e.g. NS of $M_{\text{NS}} \sim 1.5 M_{\odot}$ and $R_{\text{NS}} \sim 10$ km)

$$E_{\text{SN expl}} \sim \frac{GM_{\text{NS}}^2}{R_{\text{NS}}} - \frac{GM_{\text{NS}}^2}{R_{\text{core}}} \sim 6 \times 10^{53} \text{ergs}$$

where is this energy deposited?

$$E_{\text{SN expl}} \gg E_{\text{kin matter}} \sim 10^{51} \text{ergs} \gg E_{\gamma} \sim 10^{48} \text{ergs}$$

... but to produce a NS from ordinary matter we need to neutronize matter:

$$p + e^{-} \rightarrow n + \nu_e$$

estimated neutronization energy: $E_{\text{neut}} \sim 1.2 \times 10^{53} \text{ergs}$