μ and τ neutrinos in supernova simulations

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Outline

- Introduction
- I part: improved neutrino bremsstrahlung
- II part: leakage scheme

Introduction

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

μ and τ neutrino fields are important in CCSN context because they ...

- ... exchange energy with matter (heating and thermalization processes)
- ... release energy out of the system (cooling process)
- ... give us precious informations about dense matter

then, in core collapse SN simulations we need

- accurate and reliable treatment of neutrino-nuclear matter interaction at high density and high temperature
- efficient and reliable implementation of $\nu_{\mu,\tau}$ transport in 1D, 2D and 3D codes

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

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

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

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

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

$$\ldots$$

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 ν_{μ}, τ
- in the post bounce phase (when $\rho_c \sim \rho_o$ and $T \gtrsim 10\,\mathrm{MeV}$) $\nu_{\mu,\tau}$ production rates rise below the shock wave

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

- neutral current weak processes causing neutrino diffusion:

$$\nu_i + (n, p) \rightarrow \nu_i' + (n', p')$$

$$\nu_i + e^- \rightarrow \nu_i' + e^{-\prime}$$

$$N + N + \nu_i \rightarrow N' + N' + \nu_i{}'$$

$$(\nu_i + A \rightarrow \nu_i' + A')$$

$$\ldots$$

opacity sources for $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$:

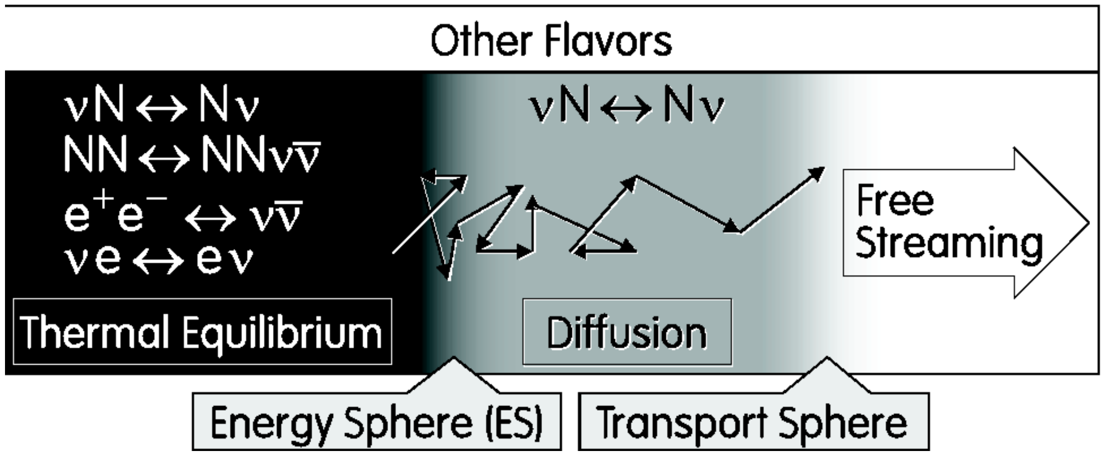
$$\kappa \sim 10^{-20,-21} \left(\frac{E_\nu}{\mathrm{MeV}} \right)^2 \mathrm{cm}^2 \mathrm{g}^{-1}$$

- Post-bounce phase: high energy ν's in high density region

$$\Downarrow$$

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

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



Raffelt, 2001

- inside the neutrino sphere, ν's form a Fermi gas on a timescale shorter than $t_{\rm diff}$ and $t_{\rm dyn}$, and they diffuse out
- during diffusion, ν's exchange energy with matter
- out from ν-spheres, ν's escape freely, leaking out energy

Part I:
Improved ν bremsstrahlung

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

Motivations

AGILE-BOLTZTRAN: 1D relativistic core collapse SN code, with Boltztrann ν 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 and Raffelt analysis
(implemented by Bruenn&Messer, based on Hannestad&Raffelt 1998)

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

- 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:

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

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

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

Evaluations of S_A

Hannestad&Raffelt 1998

- long wavelength limit ($\mathbf{q} \to 0$)
- perturbative approach for nuclear potential (OPE)
- inclusion of intermediate degrees of nucleon degeneracy in free-free transitions
- inclusion of multiple scattering effect
- inclusion of non-zero m_π

Lykasov et al., Bacca et al. 2008

- $\mathbf{q} < \mathbf{p}_F$
- 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

Evaluations of S_A (part II)

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 et al., Bacca et al. 2008

Fluctuation-dissipation theorem

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

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

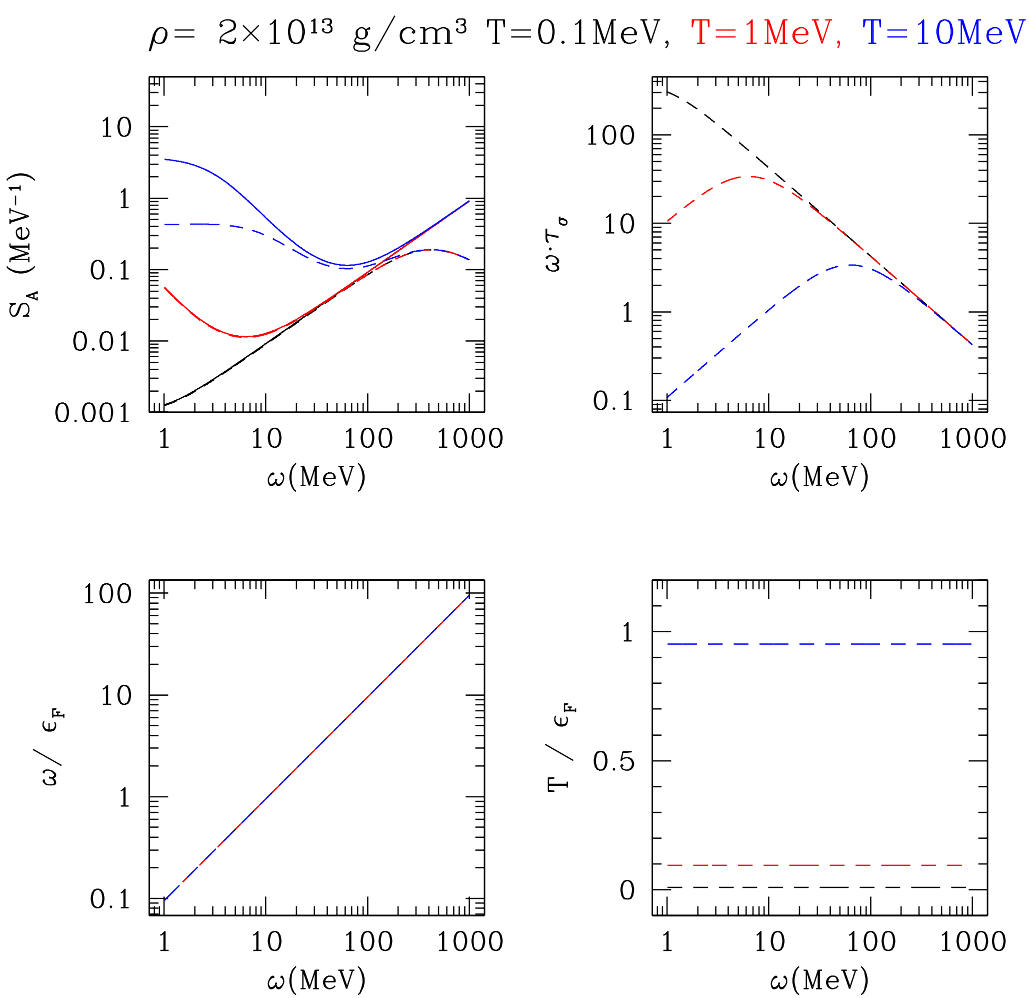
$$\mathrm{Im}\,\chi_\sigma(\omega, q\to 0) \propto \frac{\omega\tau_\sigma}{(1+G_0)^2+(\omega\tau_\sigma)^2}$$

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

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

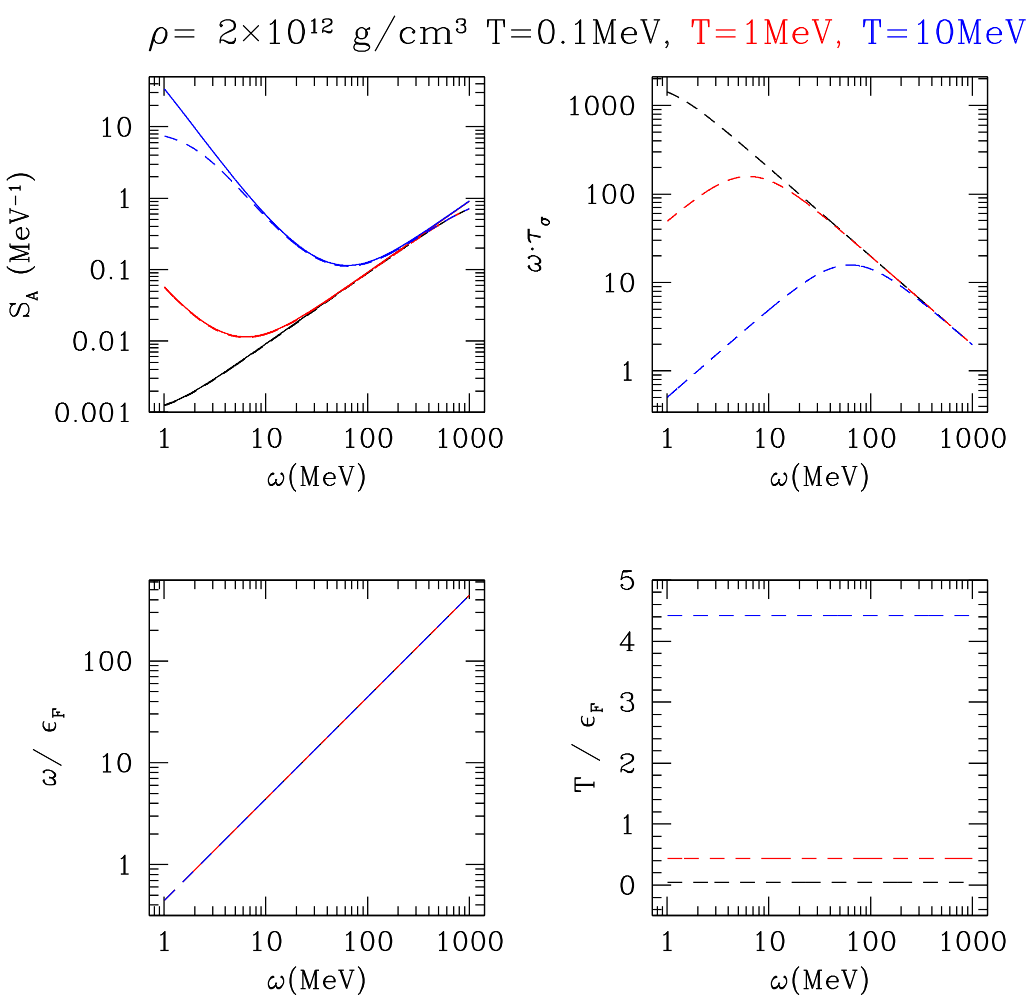
where C_σ depends on the nucleon interaction

Degenerate limit comparison I



- 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



- 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 $\omega\tau_\sigma \gg 1$, 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, $\mu_n < 0$ and $|\mu_n| > T$)
- to switch on recent improvement (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

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

. . . we are working for you!

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

Reviewed battle plan

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

. . . we are working for you!

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

My talk in a nutshell:
Achim and Chris, please, can you provide me the non-degenerate limit espression ?

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Part II:
Leakage scheme

A. Perego, M. Liebendorfer

Motivations

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

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

What's a leakage scheme?

. . . see on the black board . . .

Battle plan

- to develop a simple leakage scheme for ν_μ and ν_τ
- to test the scheme with full Boltztrann trasport in 1D simulations
- to include the scheme in 3D code
- to improve and extend the scheme

Ingredients

- Production regime: pair production (only. . .)

$$e^+ + e^- \to \nu_{\mu,\tau} + \nu_{\bar{\mu},\tau}$$

the rate for production is taken from Itoh et al. (1996):

$$(\rho(R), T(R), Y_e(R)) \to Q_{\text{pair prod}}(R)$$

- Diffusion regime: scattering on nucleons (and on nuclei) as sources of opacity

$$(\rho, T, Y_e, R) \to (T(R), \lambda_{\nu_{\mu,\tau}}(R), \tau_{nu_{\mu,\tau}}(R)) \to Q_{\text{diff}}(R)$$

- Effective energy rate:

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

Comparison

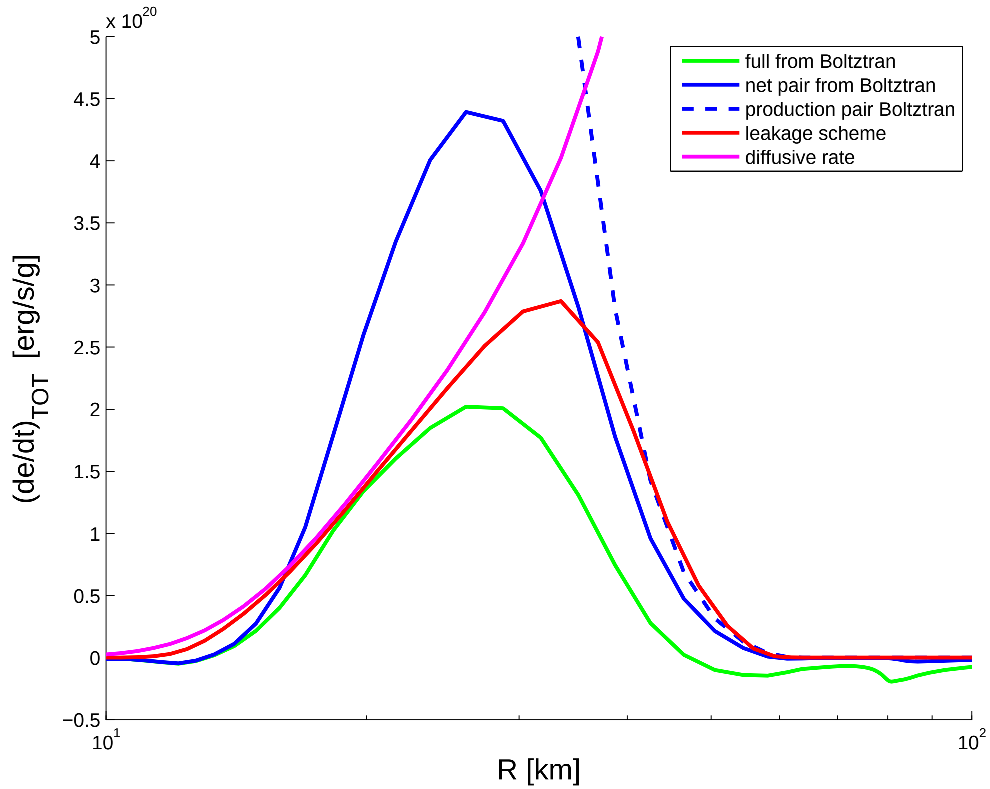
We set up our comparison:

- AGILE-BOLTZTRAN: 1D relativistic code
- ν_e transport provided by Boltztrann transport
- $\nu_{\mu,\tau}$ transport provided by Boltztrann transport

VS

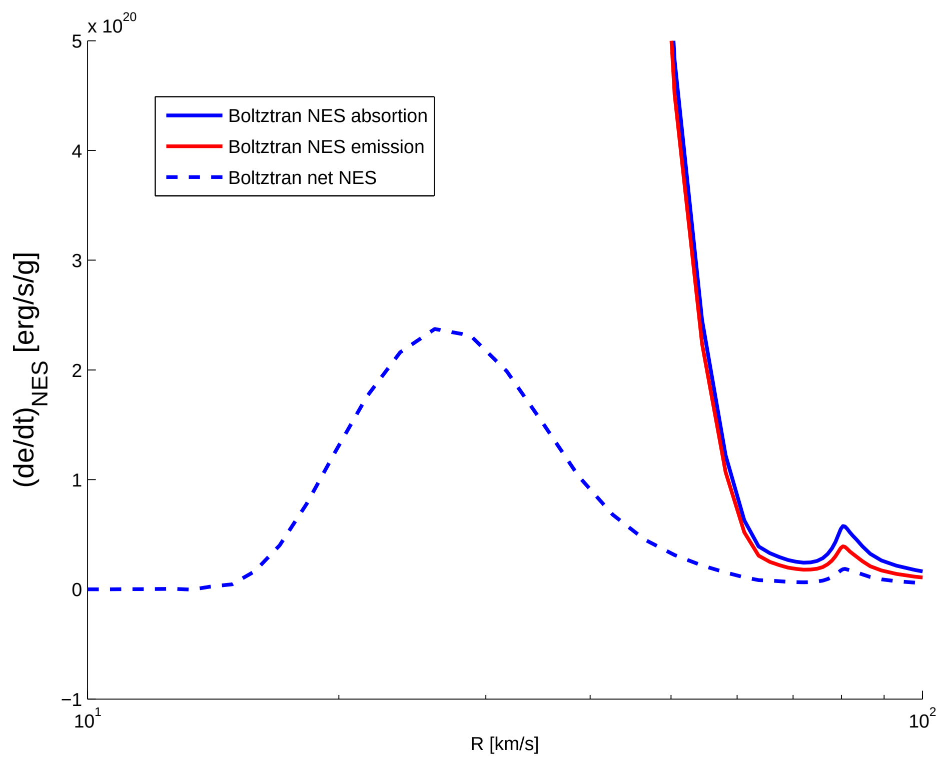
- AGILE-BOLTZTRAN: 1D relativistic code
- ν_e transport provided by Boltztrann transport
- $\nu_{\mu,\tau}$ transport provided by leakage scheme

Results: 10 ms post-bounce



- globally, qualitatively good agreement
- very good agreement for the streaming regime
- pretty good agreement for the diffusive regime, but . . .
- the tail for $R \sim 10\mathrm{km}$ seems to be artificial
- there is something missing in the intermediate part

Results: 10 ms post-bounce



missing element in the transition regime: neclection of neutrino-electron scattering

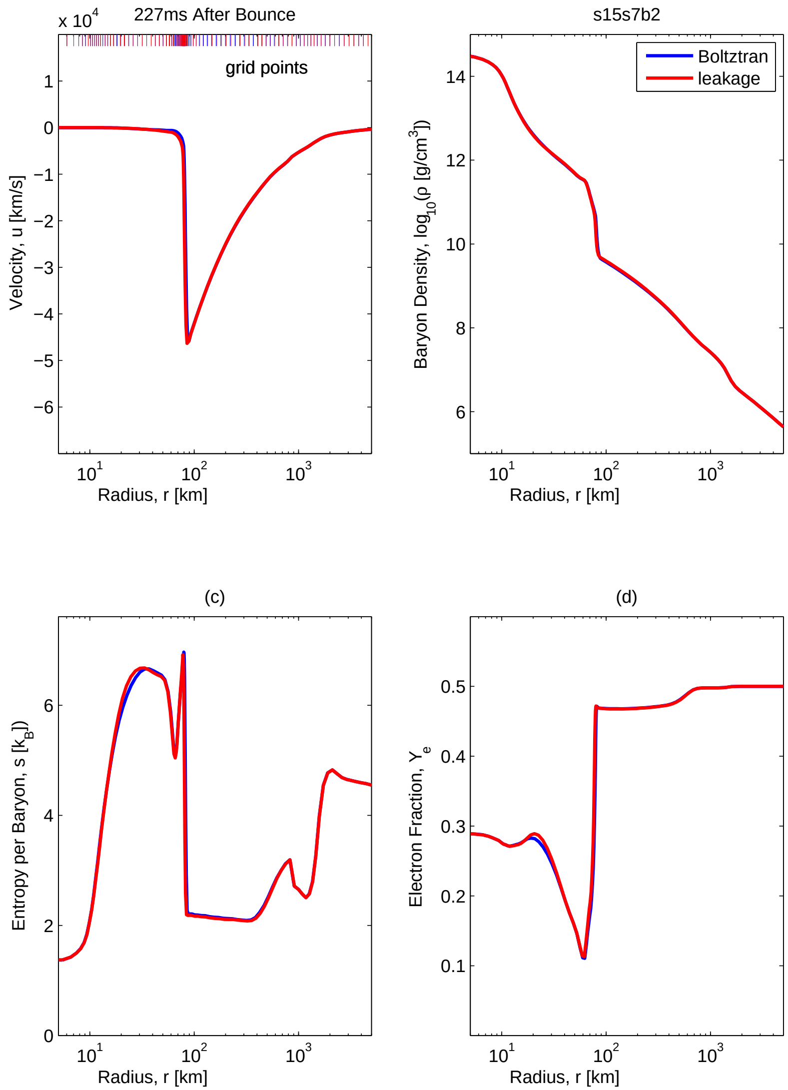
$\Downarrow$

it provides a non-negligible heating for matter:

$$\left.\frac{de_{NES}}{dt}\right|_{\mathrm{abs}} - \left.\frac{de_{NES}}{dt}\right|_{\mathrm{em}} > 0$$

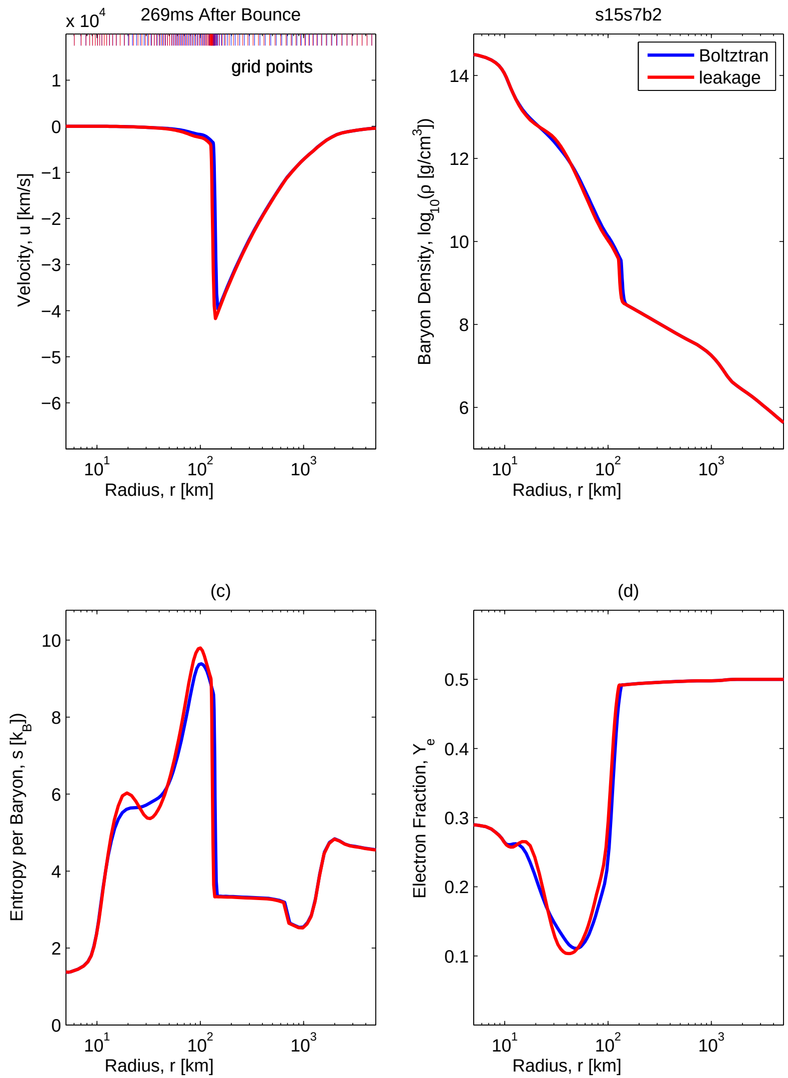
e_{NES}: energy exchange by $\nu - e$ scattering, per unit mass

Results: 10 ms post-bounce



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

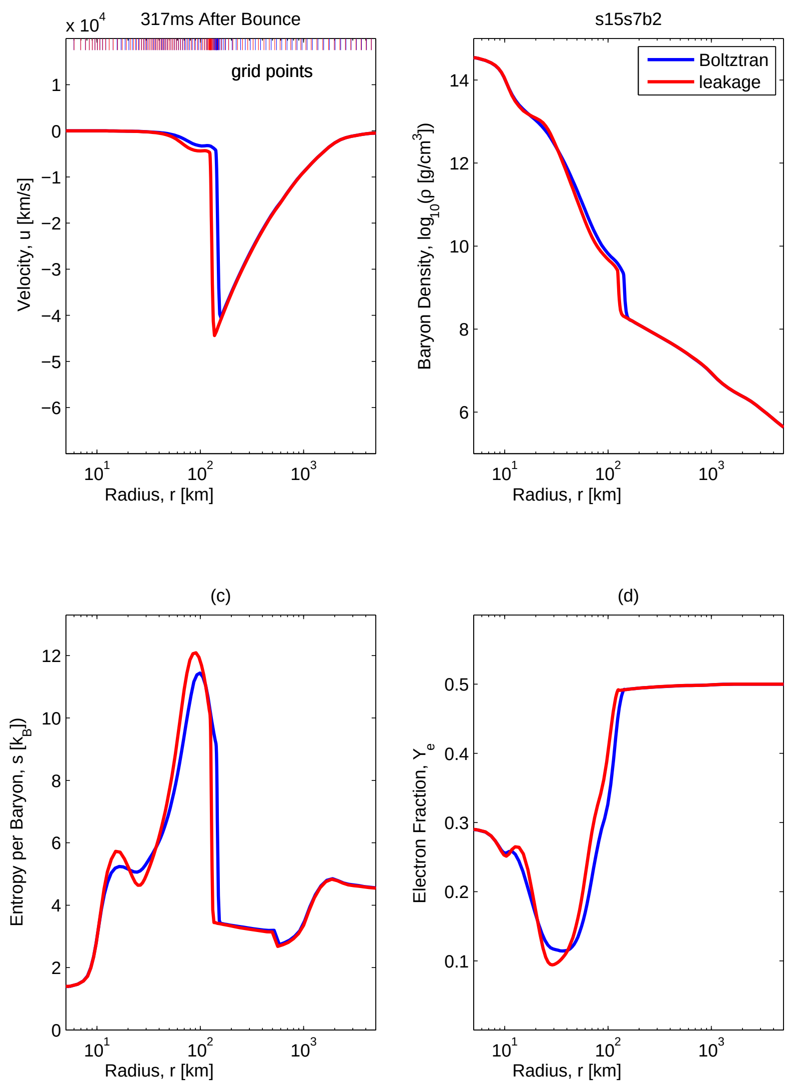
Results: 50 ms post-bounce



Qualitatively good agreement,

but the entropy shows some different features

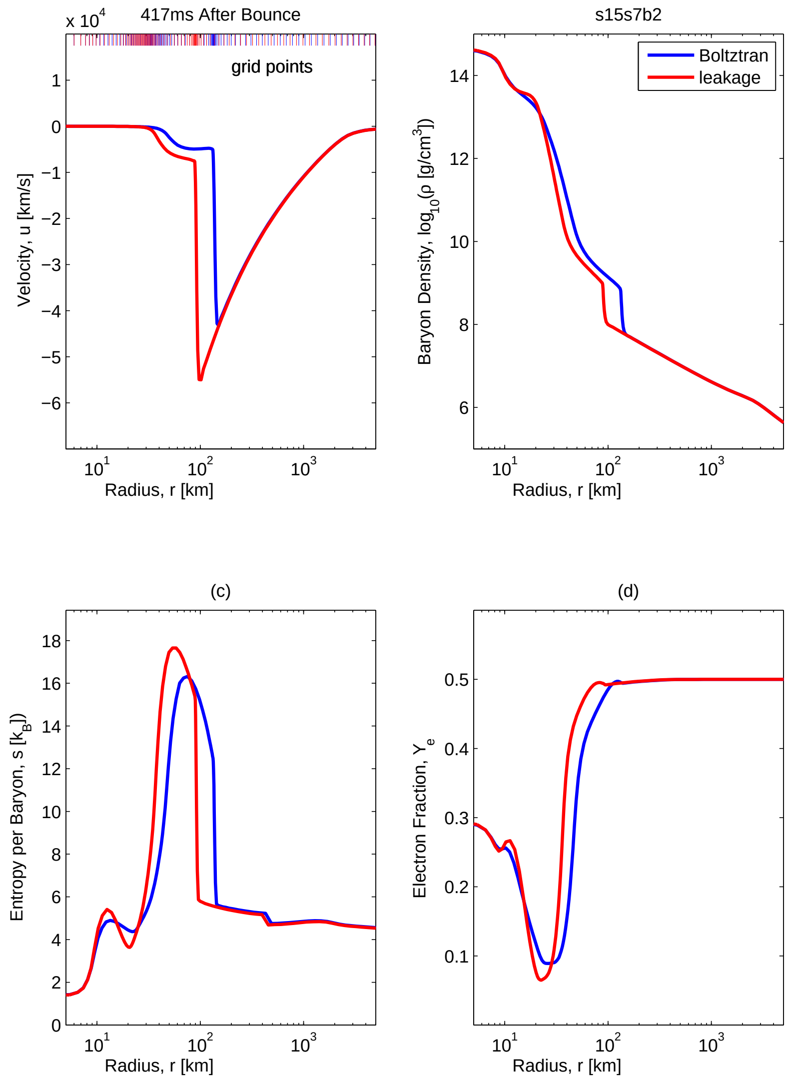
Results: 100 ms post-bounce



Qualitatively good agreement,

but the entropy shows some different features and the position of the shock is becoming different

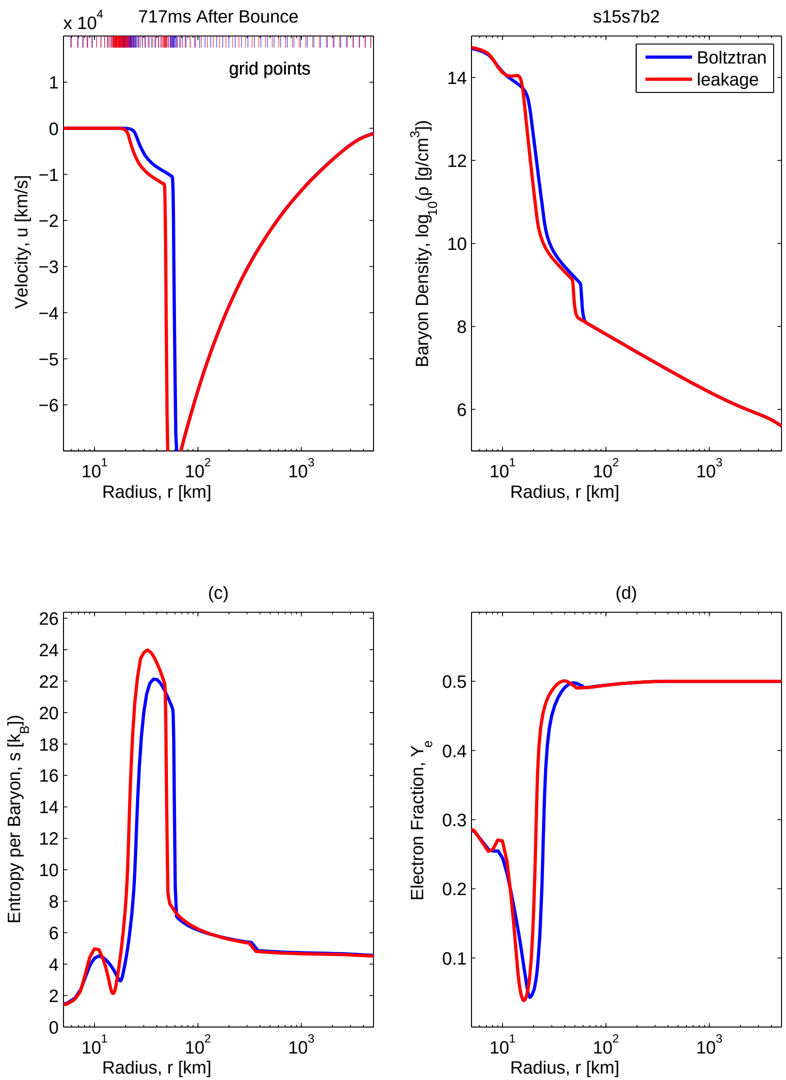
Results: 200 ms post-bounce



Qualitatively good agreement,

but the entropy shows some different features and the position of the shock is different

Results: 500 ms post-bounce

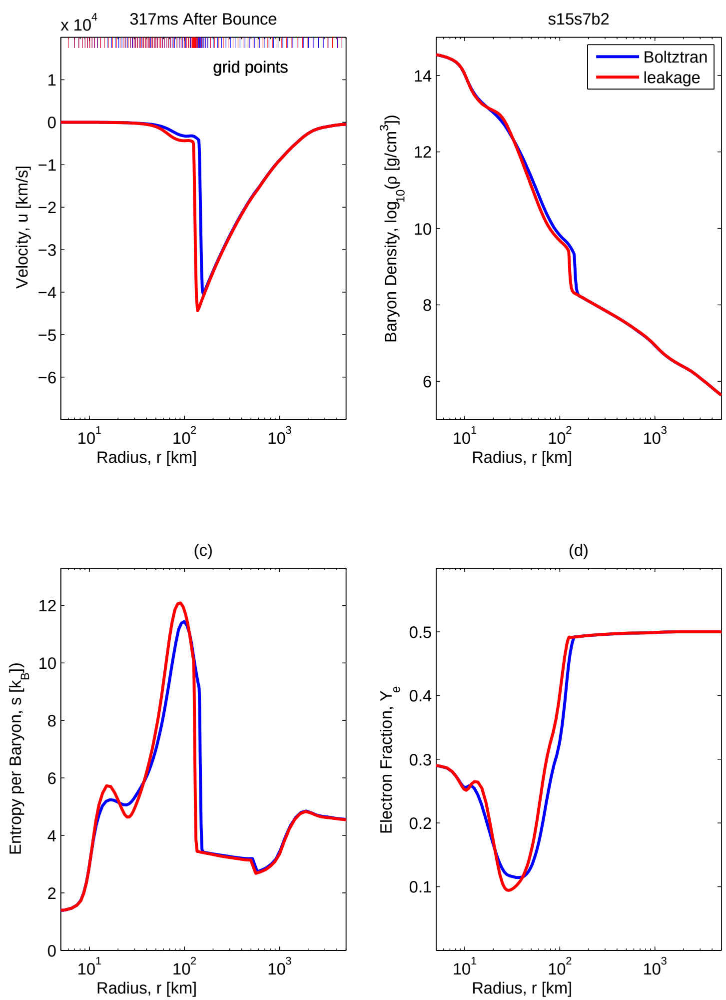


Qualitatively good agreement,

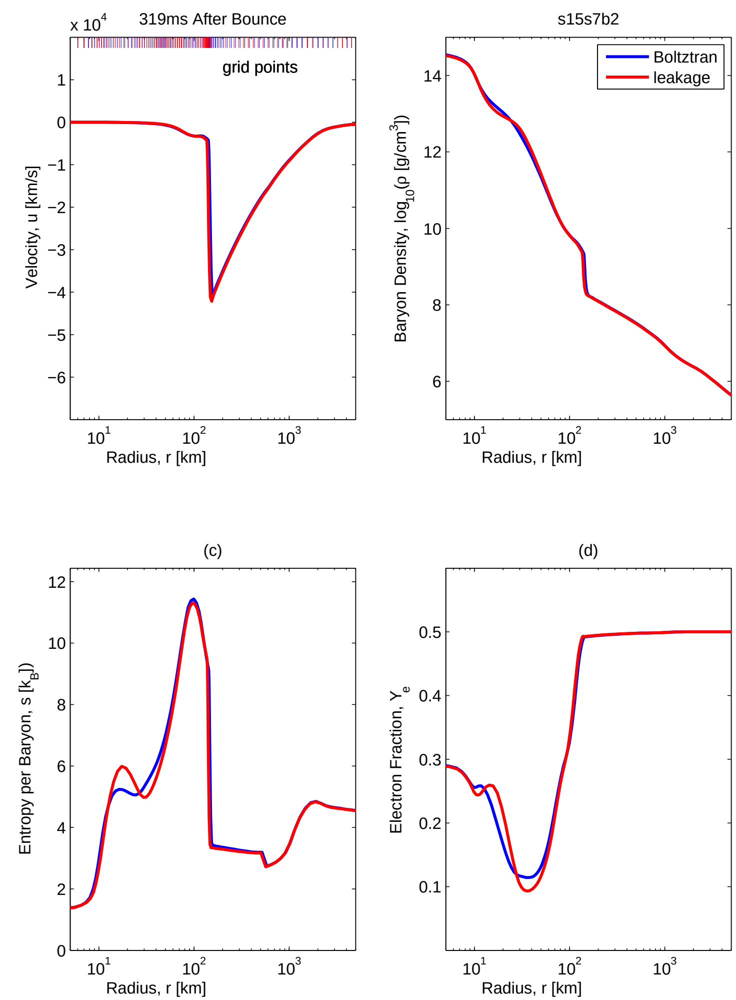
but the entropy shows some different features and the position of the shock is different

Refinement: 100 ms

$T_{\text{diff}} \propto 3\tau$



$T_{\text{diff}} \propto 6\tau$



Conclusion and improvements

We are quite satisfied by our refined leakage scheme in the 1D comparison

$$\Downarrow$$

we implemented it for the $\nu_{\mu,\tau}$ cooling in the 3D code
we look forward to having results (maybe, see next workshop!)

but, there are things we can do better:

- to include more reactions for productions and diffusione
- to perform a spectral analysis
- to give a more reliable treatment of $\nu_{\mu,\tau} - e$ scattering
- to extend the scheme to the electric flavour

Talk punchline

Talk punchline

No cheap ν_μ and ν_τ cooling? ... No party!