Expected impact on neutrino signal by modified nucleon-nucleon bremsstrahlung rates

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Flavor observations with SN Neutrinos
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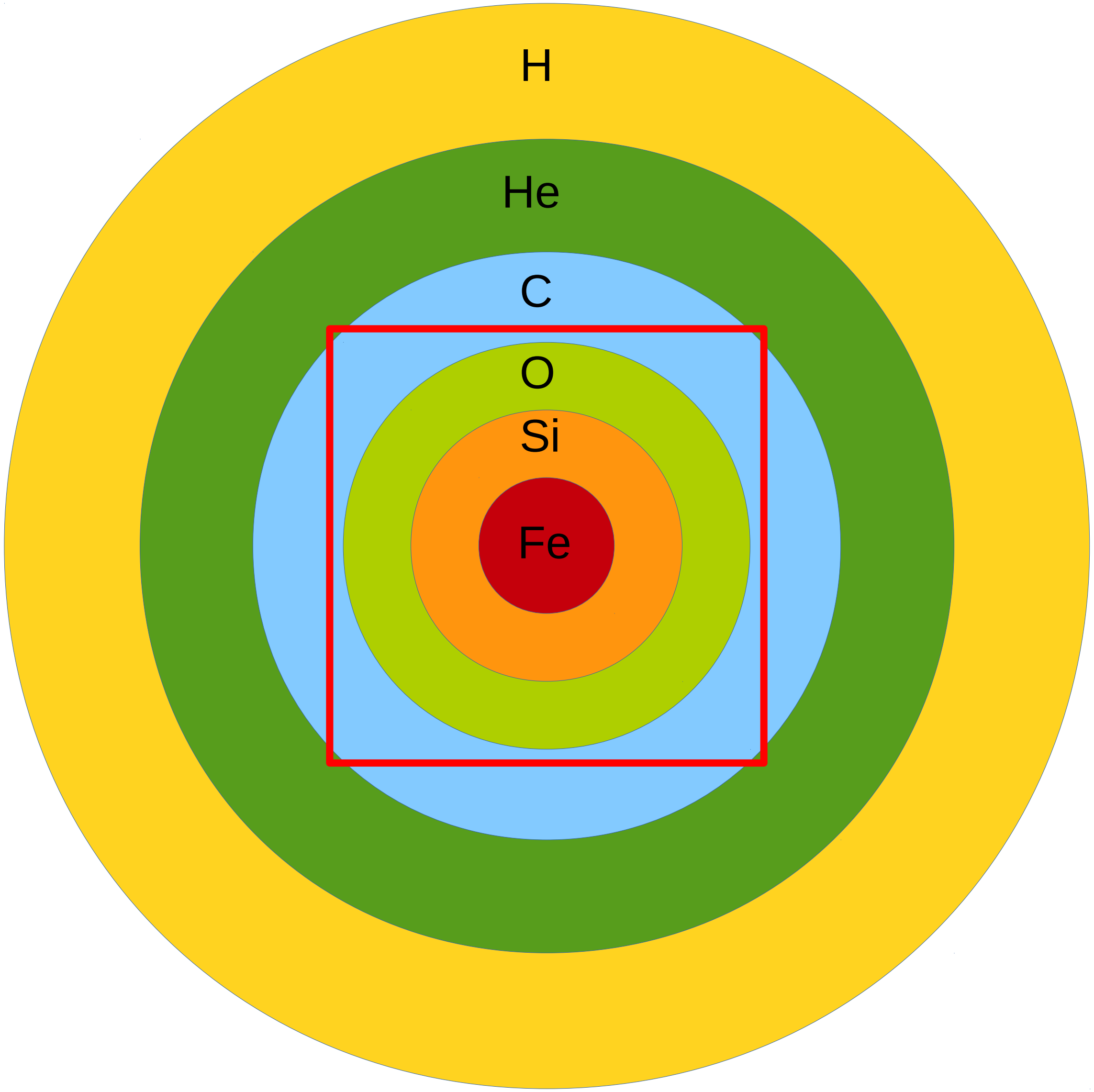
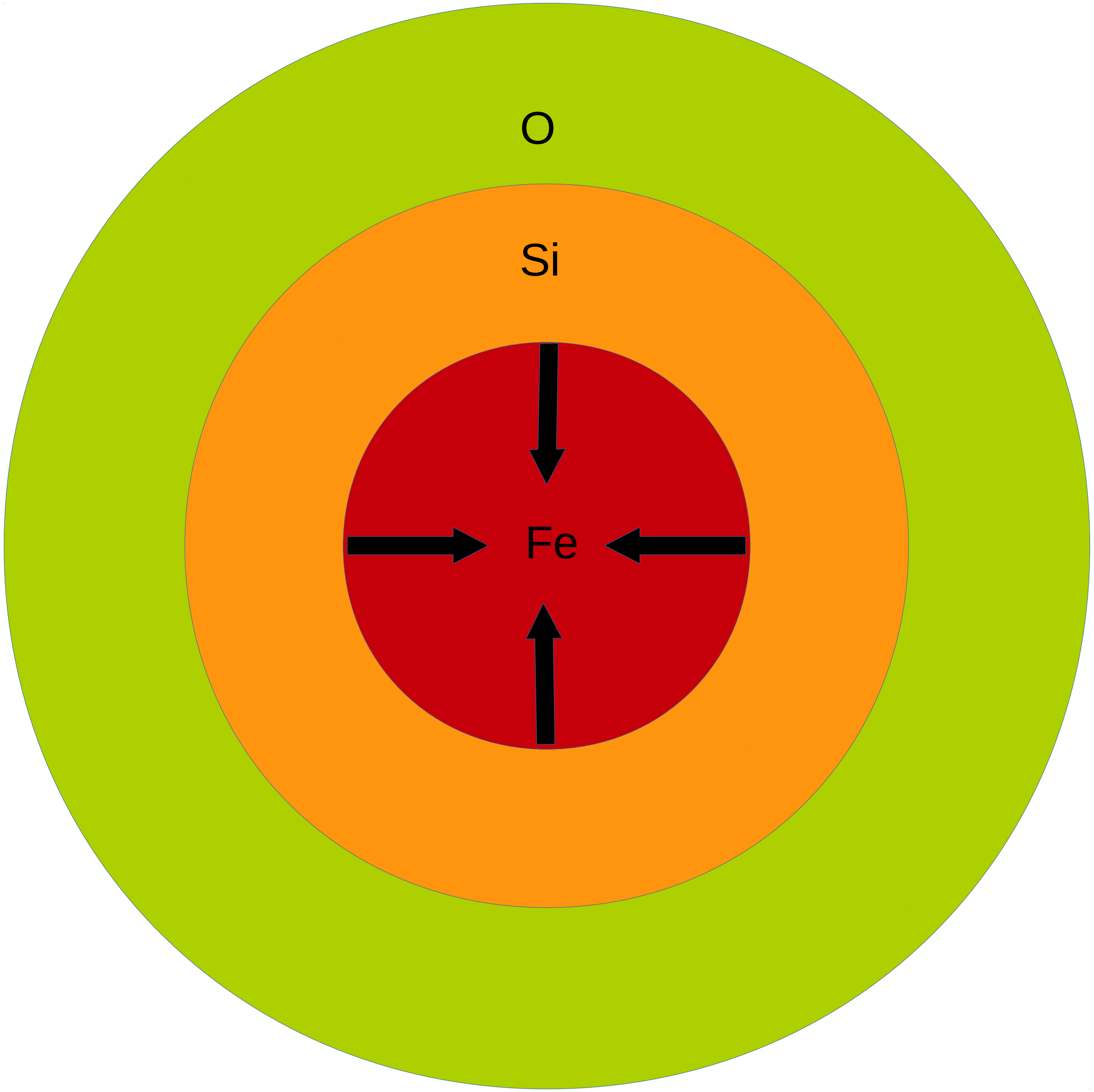
Introduction to core-collapse supernovae

Stellar structure prior to collapse



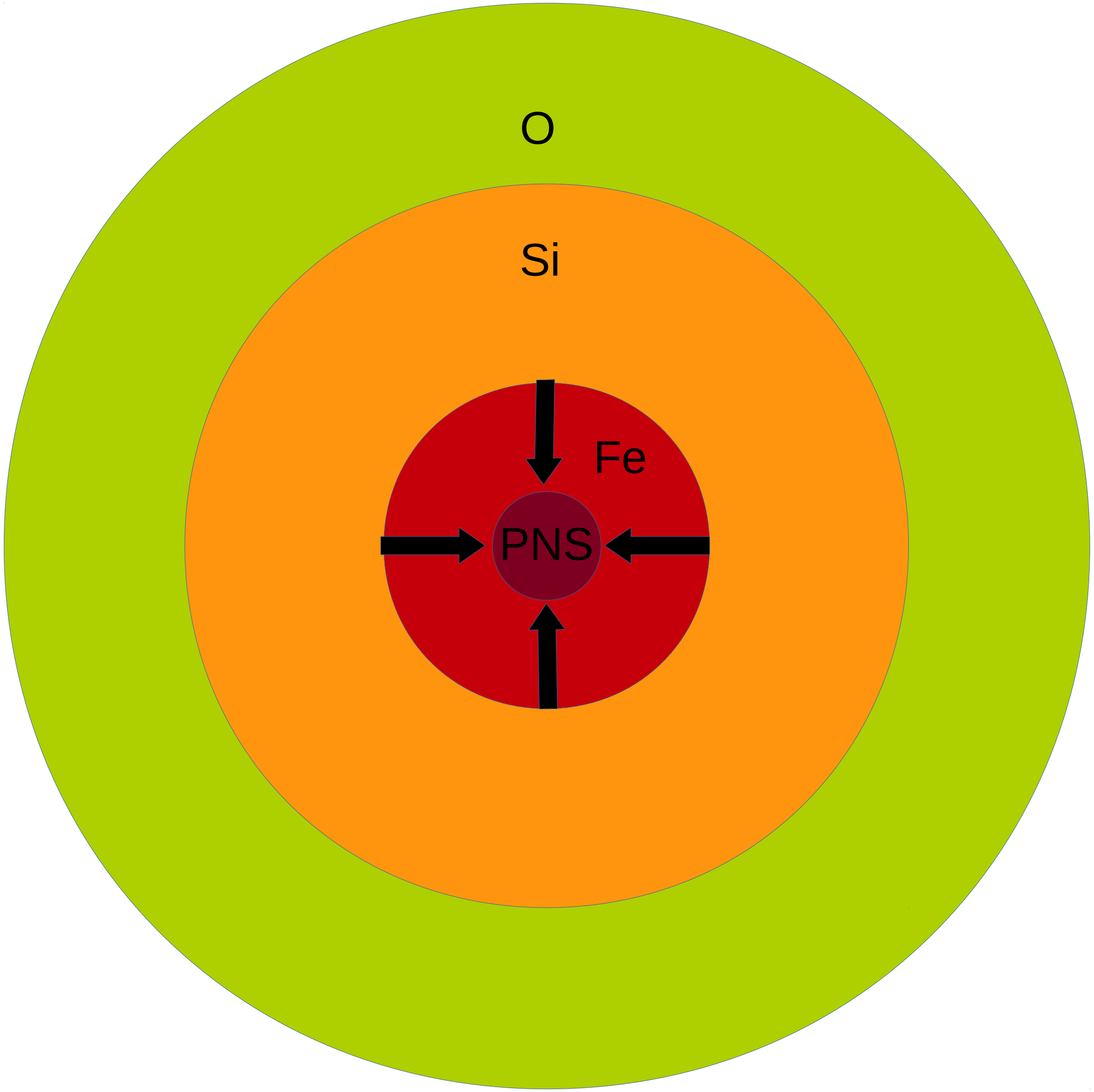
Introduction to core-collapse supernovae

Iron core becomes gravitationally unstable to collapse



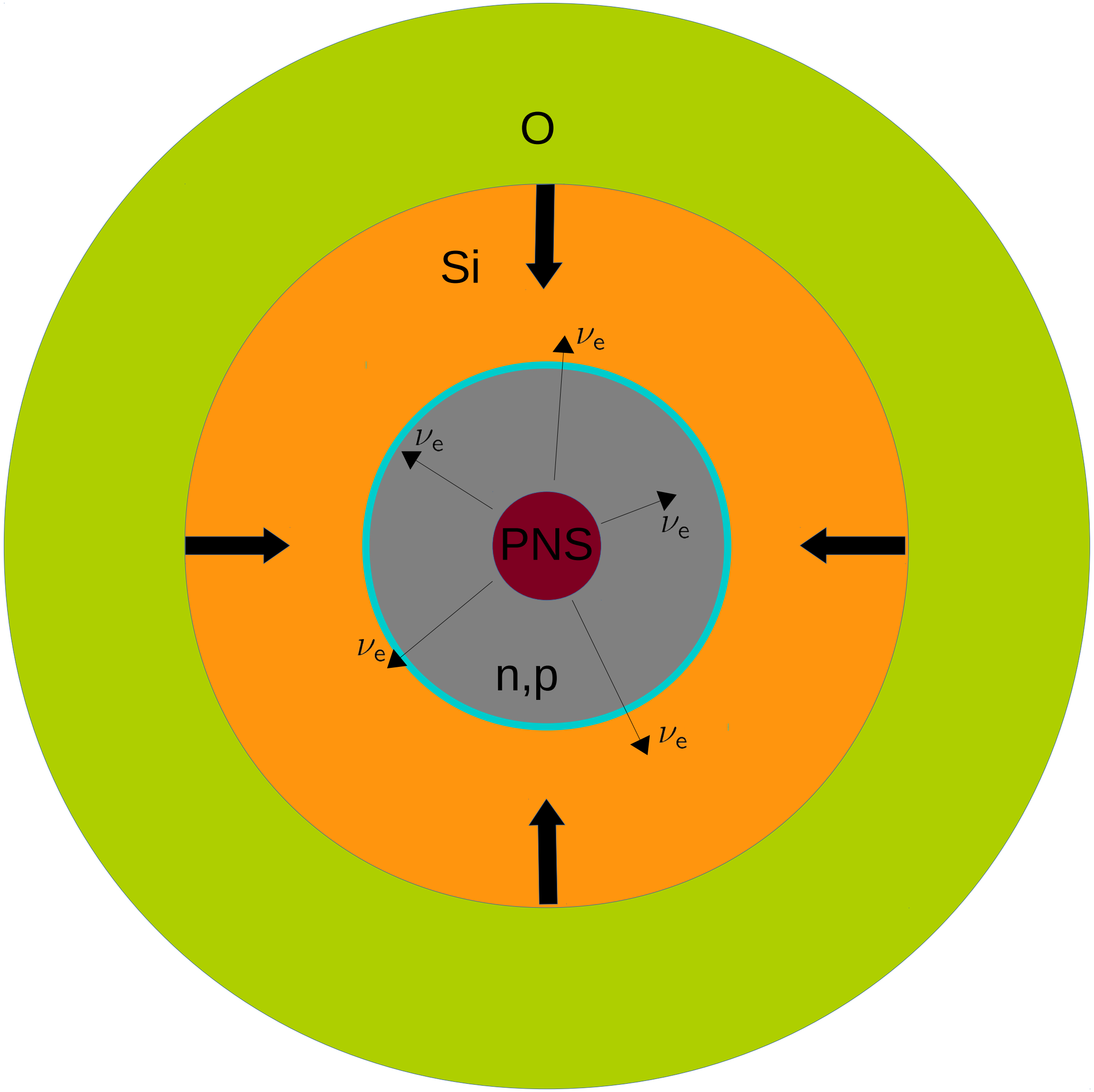
Introduction to core-collapse supernovae

Core bounces and protoneutron star begins to form



Introduction to core-collapse supernovae

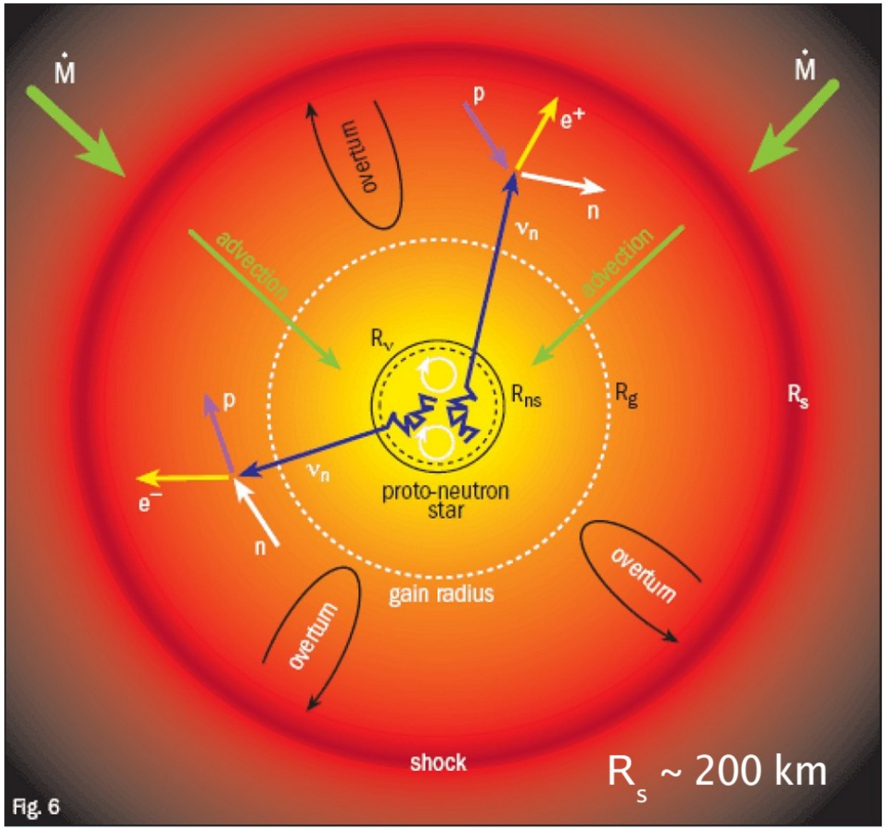
- Shock from rebounding core stalls and turns into an accretion shock
- Gravitational energy is radiated away in the form of neutrinos.



Introduction to core-collapse supernovae

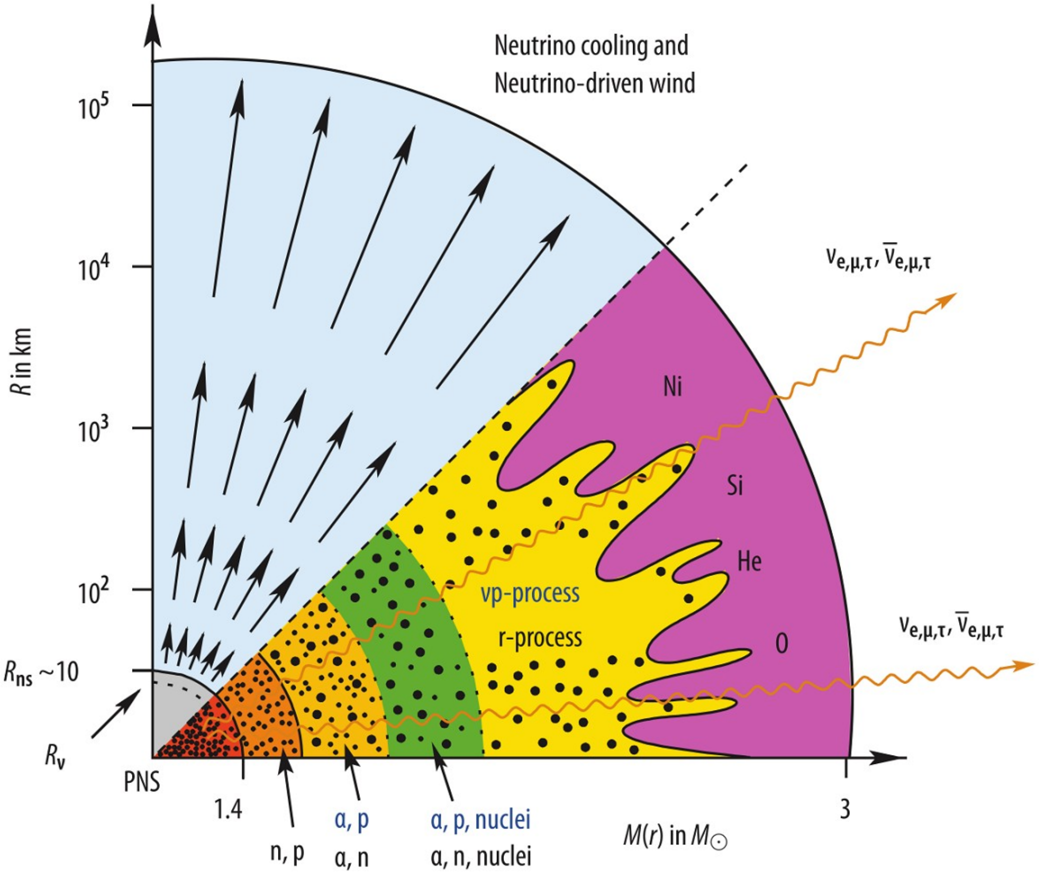
- Behind the shock a cooling layer and gain layer forms, separated by the gain radius.
- A fraction of neutrinos emitted by cooling layer are reabsorbed in the gain layer.
- Heating by neutrinos and increased dwell time by convective overturn, as well as other instabilities like SASI lead to an eventual shock revival.

→ **Classical neutrino-driven shock revival scenario**

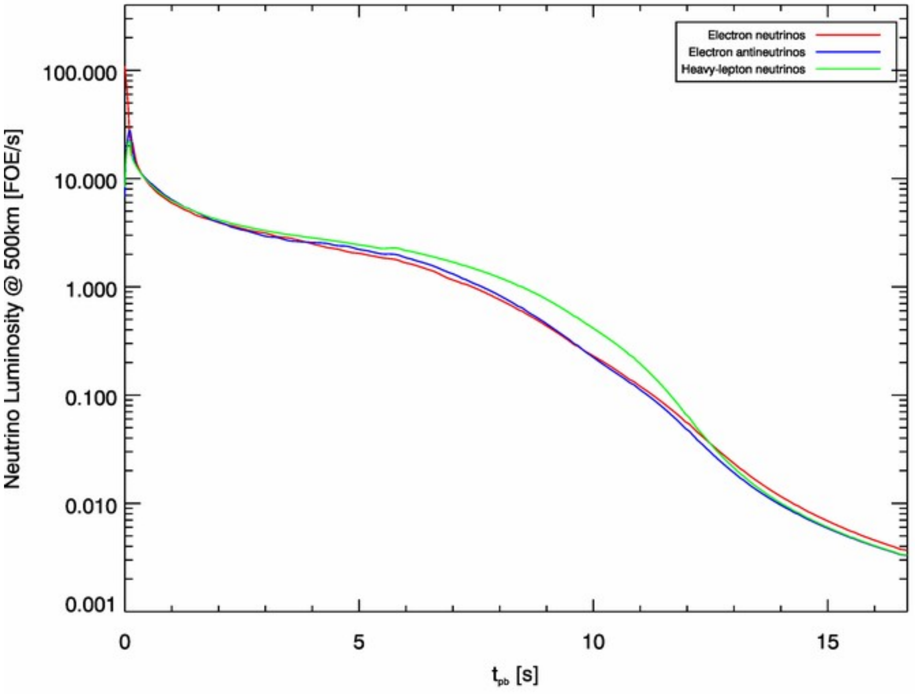


Introduction to core-collapse supernovae

- A successful explosion leads to the protoneutron star cooling phase with initial neutrino-driven wind outflow.
- The following neutrino signal and wind properties are mostly determined by neutrinos diffusing out of the dense core as well as convection inside the protoneutron star.



Example cooling curve



Prometheus-VERTEX

- Hydro module **Prometheus**
  - PPM method, Godunov-type exact solver
  - Newtonian self-gravity with effective GR potential corrections
  - Tabulated equations of state for HD and analytical eos for LD
- Neutrino transport module **VERTEX**
  - Implicit two-moment scheme with variable eddington factor closure
  - “Model Boltzmann equation” is solved using a tangent-ray angular discretization and the moment equations by the “ray-by-ray plus” method
  - comprehensive set of neutrino interactions

➔ VERTEX is ideally suited for 1D simulations where an accurate transition from diffusion limited to free streaming conditions is critical.

Introduction to neutrino interactions

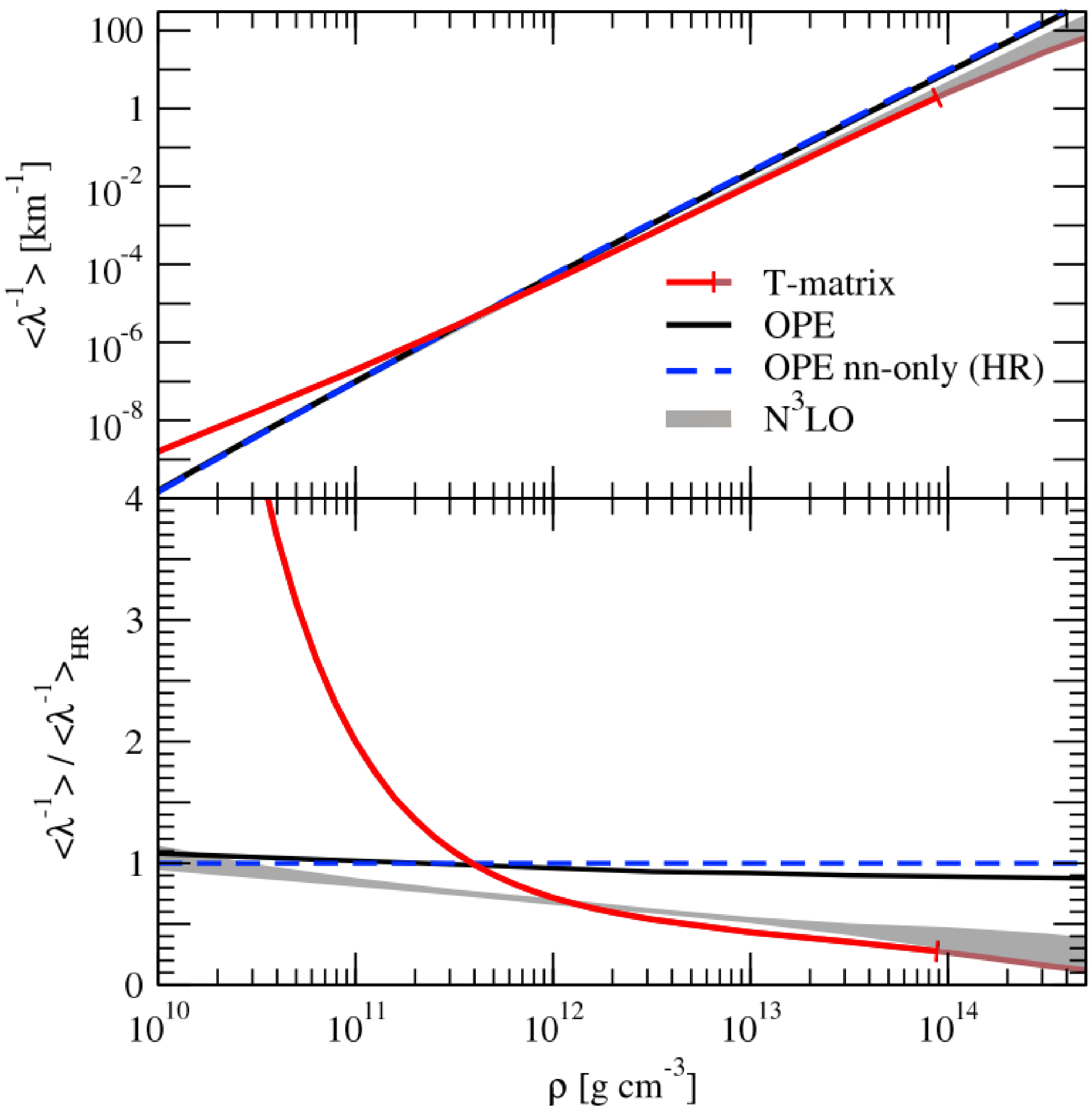
Included neutrino interaction rates in VERTEX

β-Processes	$\nu_e + n \leftrightharpoons e^- + p$	Burrows&Sawyer(1999); Horowitz(2002)
	$\bar{\nu}_e + p \leftrightharpoons e^+ + n$	Burrows&Sawyer(1999); Horowitz(2002)
	$\nu_e + A' \leftrightharpoons e^- + A$	Langanke et al (2003)
Scattering	$\nu + A \leftrightharpoons \nu + A$	Horowitz(1997); Bruenn&Mezzacappa(1997); Langanke et al.(2008)
	$\nu + N \leftrightharpoons \nu + N$	Burrows&Sawyer(1998); Horowitz(2002)
	$\nu + e^{\pm} \leftrightharpoons \nu + e^{\pm}$	Mezzacappa&Bruenn(1993b); Cernohorsky(1994)
	$\nu_{\mu,\tau} + \nu_e \leftrightharpoons \nu_{\mu,\tau} + \nu_e$	Buras et al.(2003)
Pair production	$e^- e^+ \leftrightharpoons \nu\bar{\nu}$	Bruenn(1985); Pons et al (1998)
	$\nu_\mathrm{e}\bar{\nu}_\mathrm{e} \leftrightharpoons \nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$	Buras et al.(2003)
Bremsstrahlung	$NN \leftrightharpoons NN + \nu\bar{\nu}$	Hannestad&Raffelt(1998)

Bremsstrahlung rates beyond one-pion exchange

- Nucleon-nucleon bremsstrahlung is caused by nucleons scattering against each other in conditions of extremely high density.
  - Very efficient production process for $\nu_{\mu/\tau}$
- One-pion-exchange (OPE) approximation (Hannestad&Raffelt 1998)
  - Nucleon-nucleon interactions mediated by a single pion
- T-Matrix approach (Bartl et al. 2014)
  - Nucleon interactions modeled by T-matrix, consistent with chiral EFT results, including N-N-correlations, and non-degenerate neutron-proton mixtures
  - See preceding talk by Achim Schwenk

Bremsstrahlung rates beyond one-pion exchange



(Bartl et al. 2014)

Bremsstrahlung rates beyond one-pion exchange

- Fully consistent calculation of T-matrix rates computationally challenging “on the fly”
- Possible solution are tabulated rates, but would require interpolation in a 5 dimensional table, $\rho,T,Y_e,\varepsilon,\bar{\varepsilon},\Phi_l$
- For first approach tackle this complexity using a simple fit formula

Bremsstrahlung rates beyond one-pion exchange

- Fit method
  - Define T as a function of density with

$$T(\rho) = T_{\rm SN}(\rho) = 3{\rm MeV}\left(\frac{\rho}{10^{11}{\rm g\ cm}^{-3}}\right)^{1/3}$$

(Bacca et al 2012)

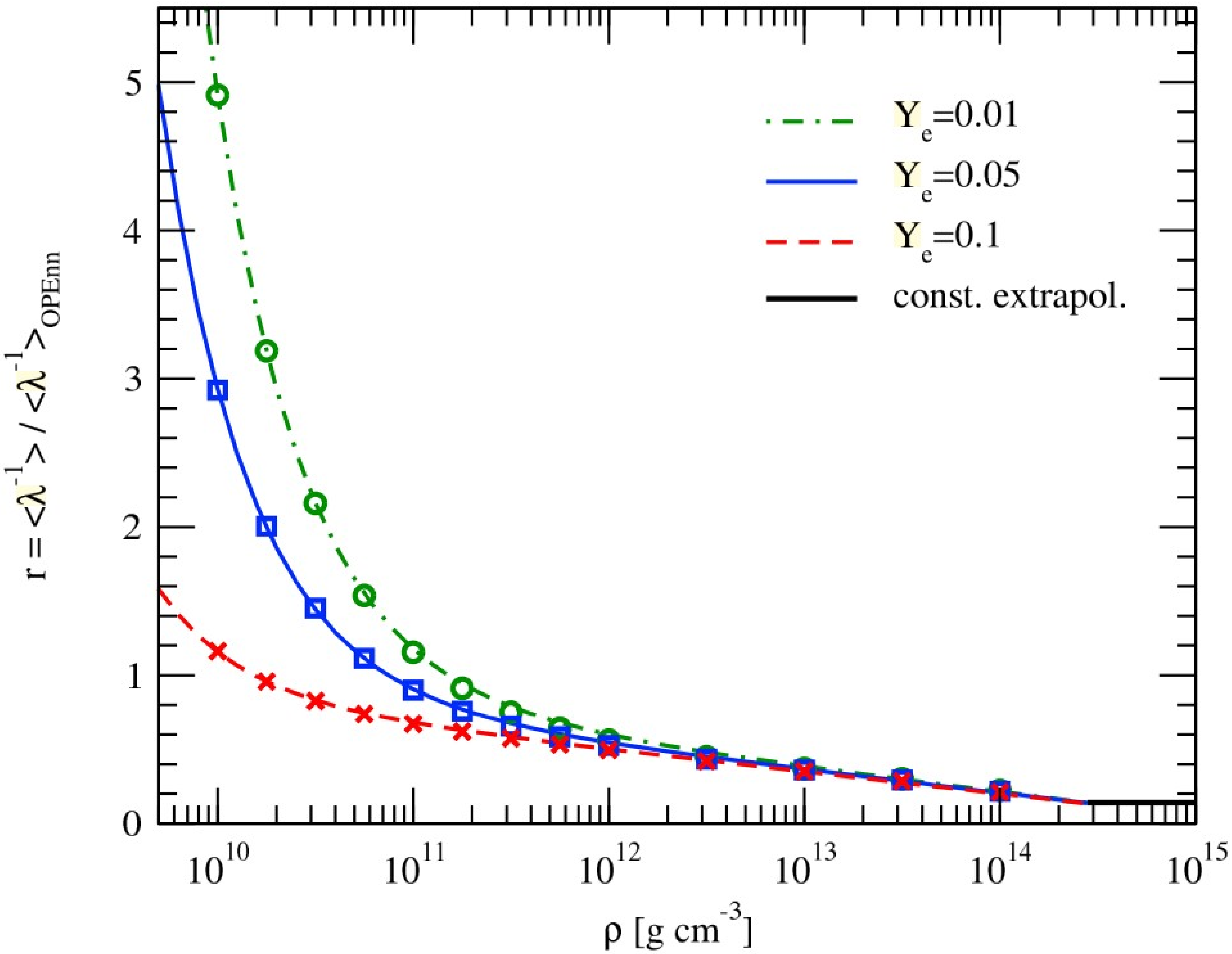
  - Average mean free path over Boltzmann distributed neutrino and antineutrino spectra
  - Define purely density dependent correction factors from HR results to T-matrix results

$$r_{\rm Y_e}(\rho) = \frac{\langle\lambda^{-1}\rangle\,(\rho, Y_e, T(\rho))}{\langle\lambda^{-1}\rangle_{\rm OPE}\,(\rho, T(\rho))}$$

Bremsstrahlung rates beyond one-pion exchange

- Fit function for fixed Y_e

$$r_{Y_e}(\rho) = a\ln(\rho) + 10^{10}/\rho^b + c$$



PNS cooling simulations
Numerical Setup

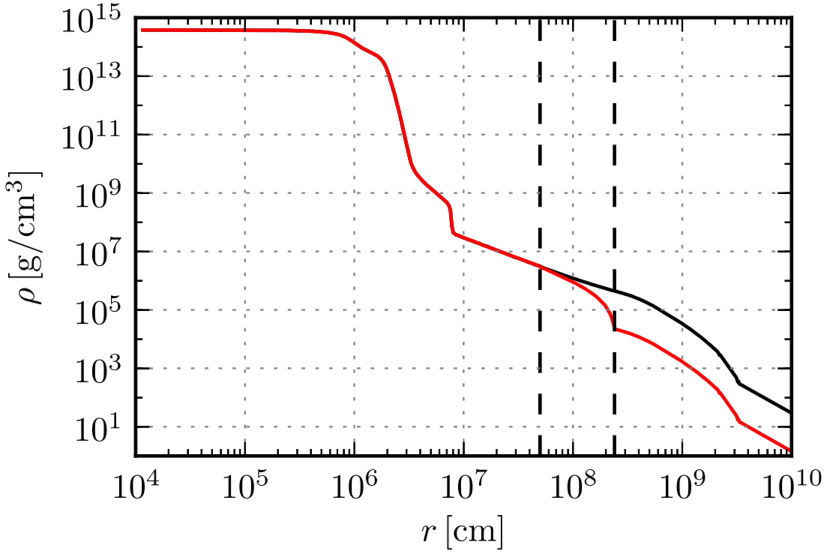
- Chosen progenitors
  - s27.0 (Woosley & Heger & Weaver 2002) with $M_{grav} = 1.59 M_\odot$
  - z9.6 (Woosley & Heger 2015) with $M_{grav} = 1.25 M_\odot$
- Chosen EOS
  - s27.0 : LS220 EOS (Lattimer&Swesty 1991)
  - z9.6 : SFHo EOS (Hempel et al 2013)
- 21 neutrino energy bins from 0.2 to 380 MeV with ν_e, $\nu_{\bar{e}}$, ν_x and $\nu_{\bar{x}}$
- 1D radially remapping grid to maintain high spatial resolution at protoneutron star mantle
- Protoneutron star convection included in 1D by mixing-length convection approach

PNS cooling simulations
Numerical Setup

- Transition from stalled accretion shock to shock-revival in 1D a well-known problem
- Several methods used to artificially induce an explosion
  - Push-method (Perego et al. 2015)
  - Increased heating by ν_e and $\bar{\nu}_e$ in gain layer (Fischer 2010)
  - Artificial quenching of the accretion flow by density reduction (Mirizzi 2015)
  - Defining a mass-cut (see Robert's talk)
  - Parametrized and calibrated neutrino flux models (Ertl et al. 2015)

PNS cooling simulations
Numerical Setup

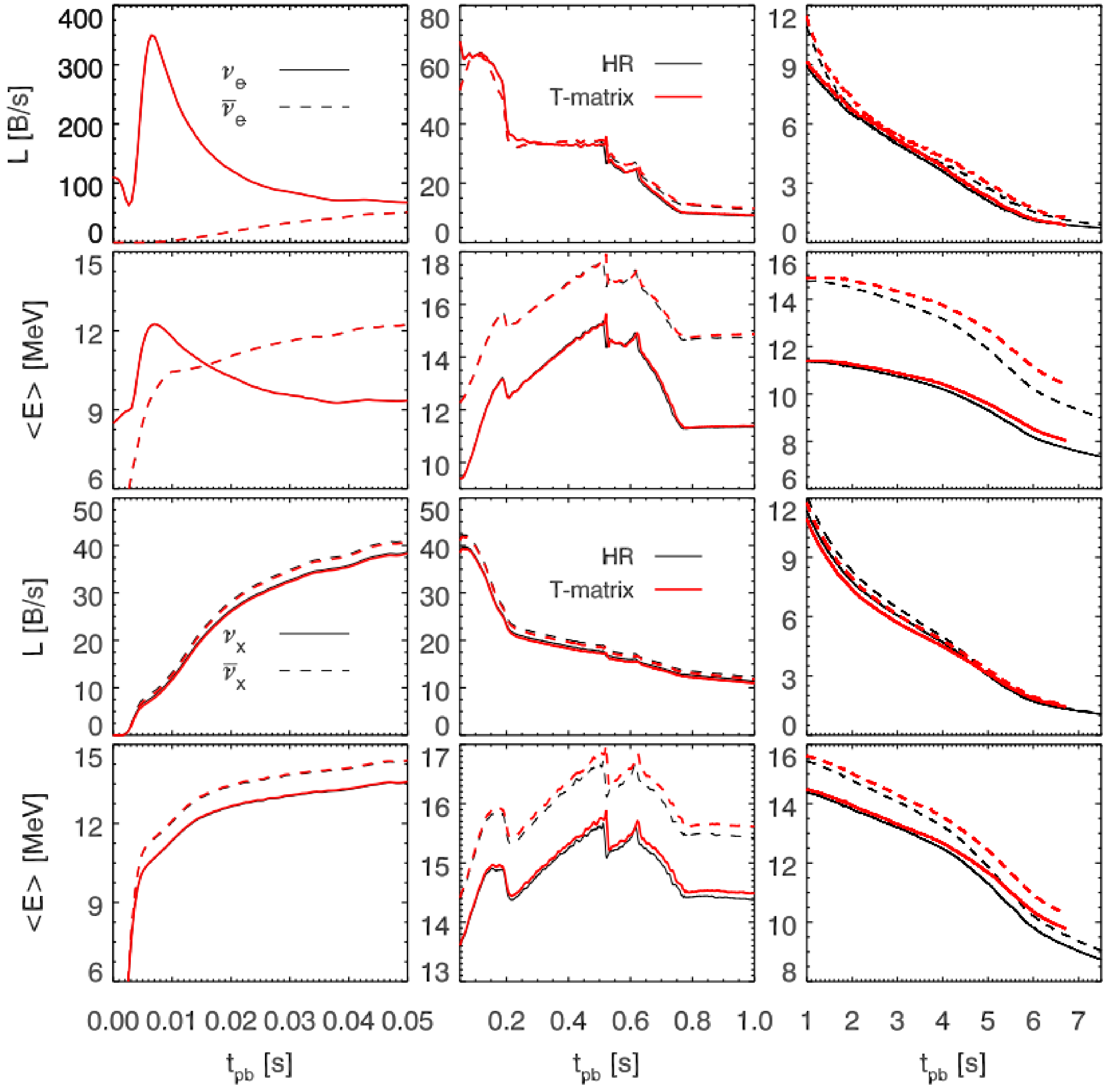
- s27.0 is artificially exploded at 500ms t_{pb} by gradually decreasing matter density from 500km to 2500km by a factor of 1/30



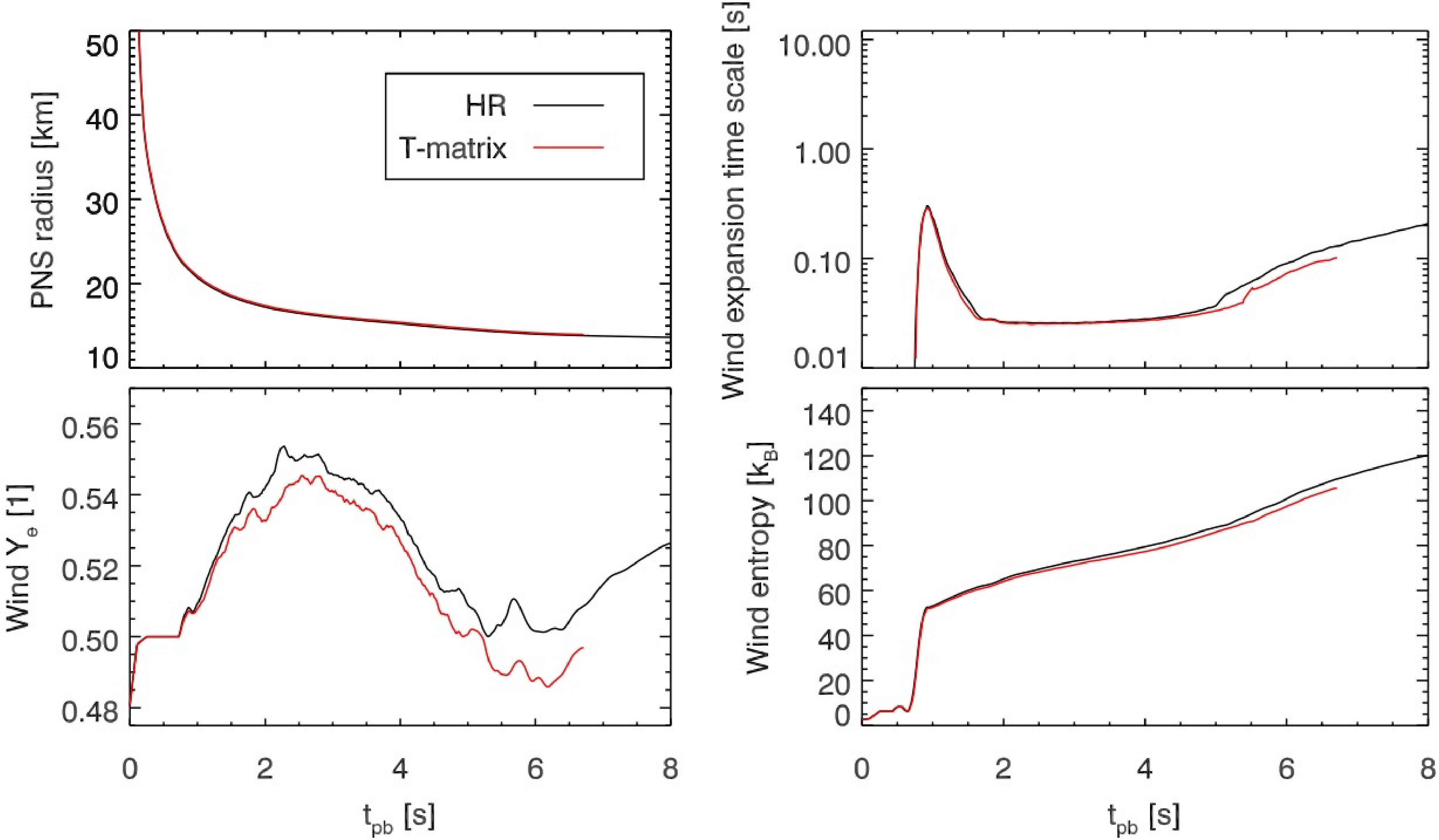
Here: s11.2-2002
Hüdepohl
(PHD Thesis 2013)

- z9.6 is unique in that it self-consistently explodes nearly simultaneously in 1D, 2D and 3D (Melson 2015)

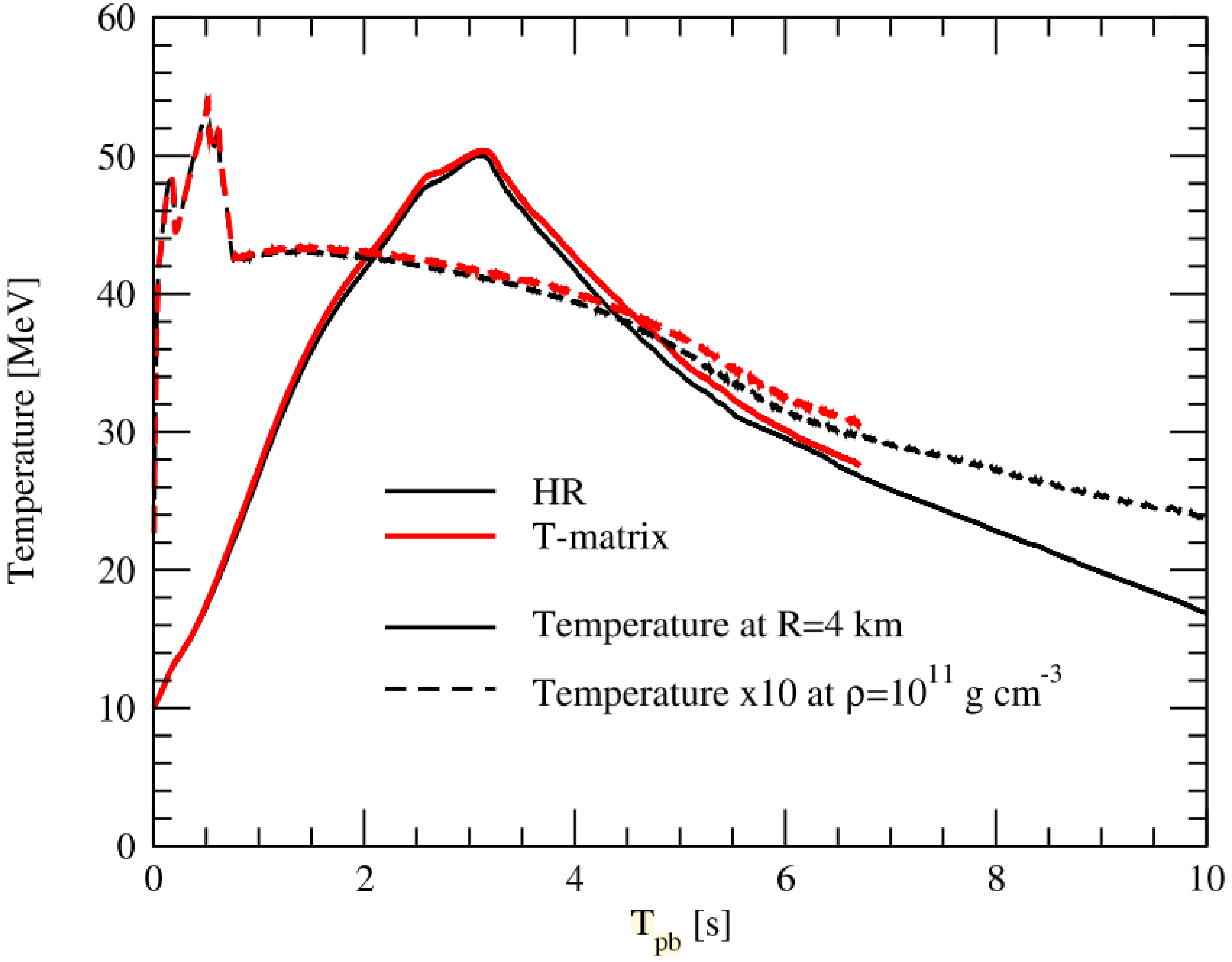
PNS cooling simulations
Neutrino signal



PNS cooling simulations
Neutrino signal



PNS cooling simulations
Neutrino signal

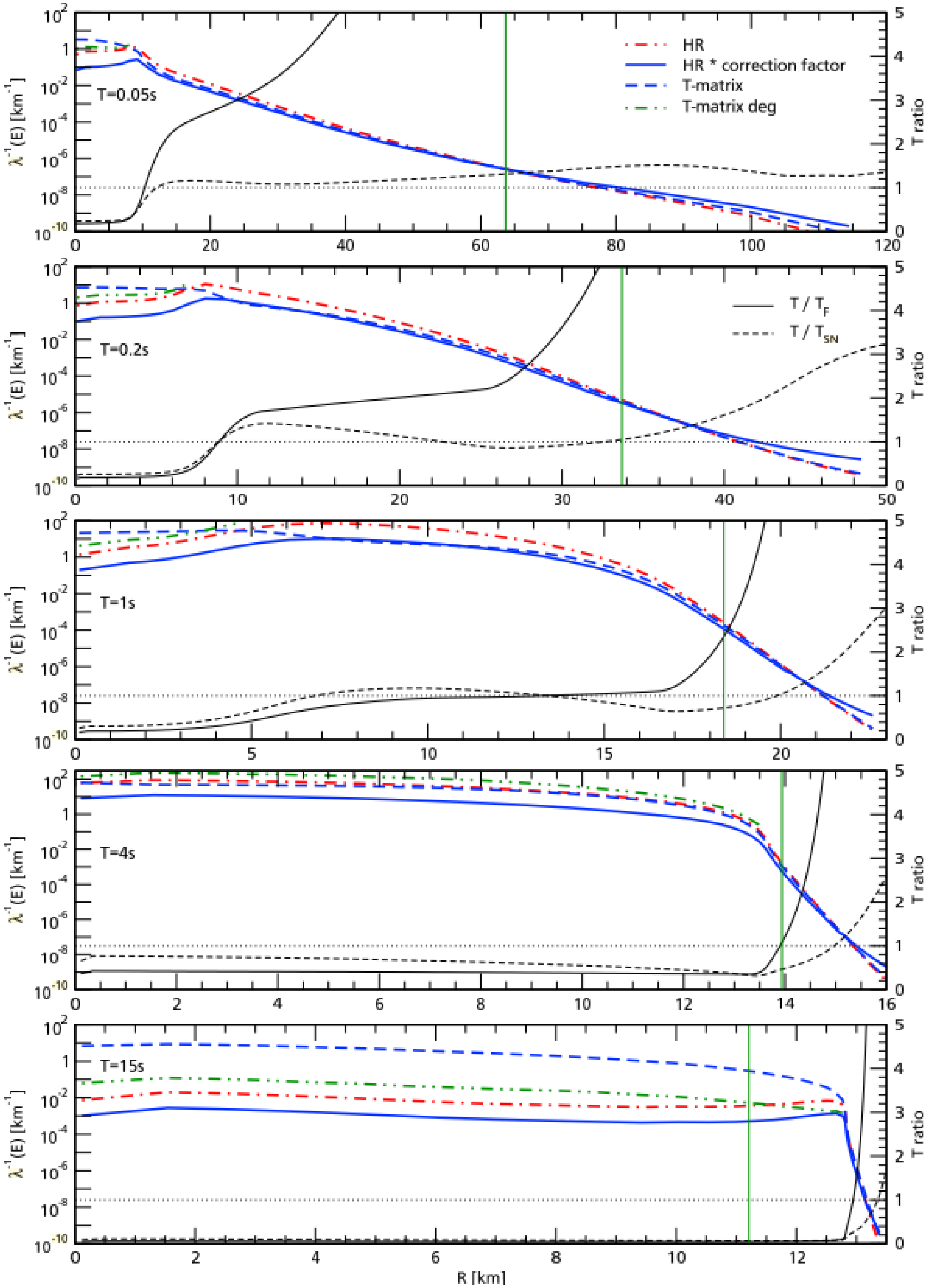


PNS cooling simulations
T-Matrix fit dependability

Possible concerns:

  - T-matrix fit assumes a fixed temperature along any density profile
  - Variable degeneracy of nucleons not fully taken into account

- Caveats of the fit method are present and dependability of results is most affected at cold and degenerate conditions.
- Modified HR results are over-suppressed compared to realistic values at very late times → T-matrix fit gives an upper bound on effect.



Conclusions

- T-matrix results generally reduce annihilation and production opacity of neutrino pairs inside PNS
- Reduced emission of heavy-lepton neutrinos and therefore reduced cooling of the PNS
- Diffusion time scale of neutrinos remain unchanged, bremsstrahlung is not a dominant transport opacity source
- Reduction of bremsstrahlung is partly compensated by $e^{\pm}$ and $\nu_e\bar{\nu}_e$-pair annihilation for $\nu_x\bar{\nu}_x$ production
- Reduction of PNS cooling by ν_x ,$\bar{\nu}_x$ is partly compensated by increased emission of ν_e,$\bar{\nu}_e$
- Direct influence of modified rates is small but time-integrated effect is measurable
- Results confirmed by an independent study made by Tobias Fischer (2016), but without convection treatment
- Paper about our results has been submitted to arXiv today!

PNS cooling simulations
mixing-length convection

Simulations in spherical symmetry are very efficient for long simulation times but lack crucial multi-dimensional effects.

- Convection inside the hot bubble between PNS and shock
- Hydrodynamical instabilities like SASI
- Convection inside the PNS (see also Robert's talk)

PNS convection is a quasi stationary state that can be very well represented by a mixing-length convection treatment

➔ One can define a convective Flux of energy and lepton number by thermodynamic derivatives and radial gradients

$$F_{\mathrm{conv}}^{\mathrm{lep}} = \rho v_c \lambda_c \frac{\mathrm{d}Y_{\mathrm{lep}}}{\mathrm{dr}}$$

$$F_{\mathrm{conv}}^{\mathrm{erg}} = \rho v_c \lambda_c \left(\frac{\mathrm{d}\epsilon}{\mathrm{d}r} + P \frac{\mathrm{d}(\rho^{-1})}{\mathrm{d}r} \right)$$

$$\text{Pressure scale height: } \lambda_c = \zeta P |\mathrm{d}P/\mathrm{d}r|^{-1}$$

$$\text{Convective velocity: } v_c = \sqrt{2 g \lambda_c C_{\mathrm{Ledoux}} \rho^{-1} \lambda_c}$$

PNS cooling simulations
mixing-length convection

Convective instability is given by Ledoux-criterion

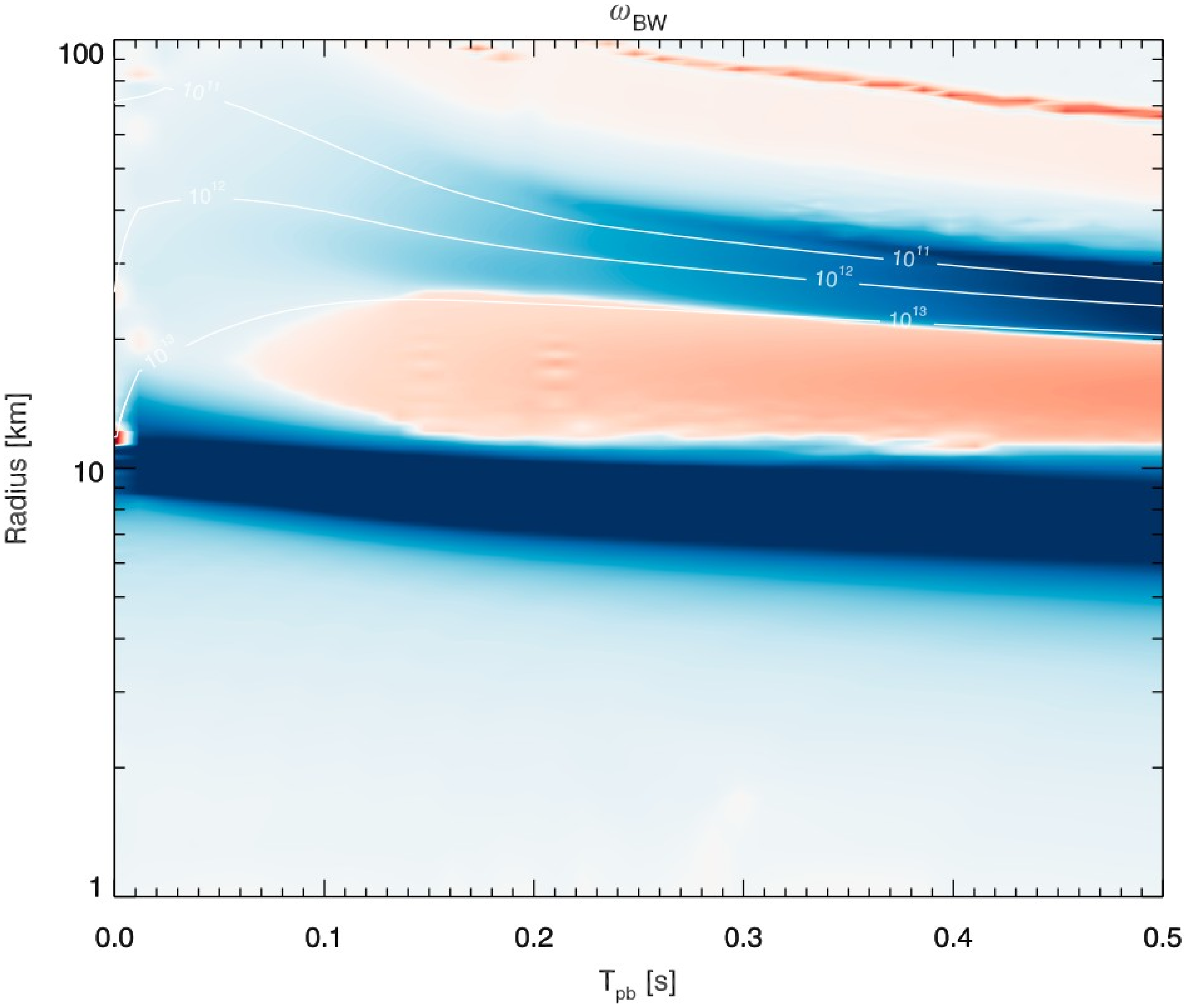
$$C_{\mathrm{Ledoux}} = \left(\frac{\partial\rho}{\partial s}\right)_{\mathrm{P,Y_{lep}}} \frac{\mathrm{d}s}{\mathrm{d}r} + \left(\frac{\partial\rho}{\partial Y_{\mathrm{lep}}}\right)_{\mathrm{P,s}} \frac{\mathrm{d}Y_{\mathrm{lep}}}{\mathrm{d}r} > 0$$

$$C_{\mathrm{Ledoux}} = \frac{\mathrm{d}\rho}{\mathrm{d}r} - \frac{1}{c_s^2}\frac{\mathrm{d}P}{\mathrm{d}r} > 0$$

With adiabatic sound speed $c_s = \sqrt{(\partial P/\partial\rho)_{s,\mathrm{Y_{lep}}}}$

PNS cooling simulations mixing-length convection

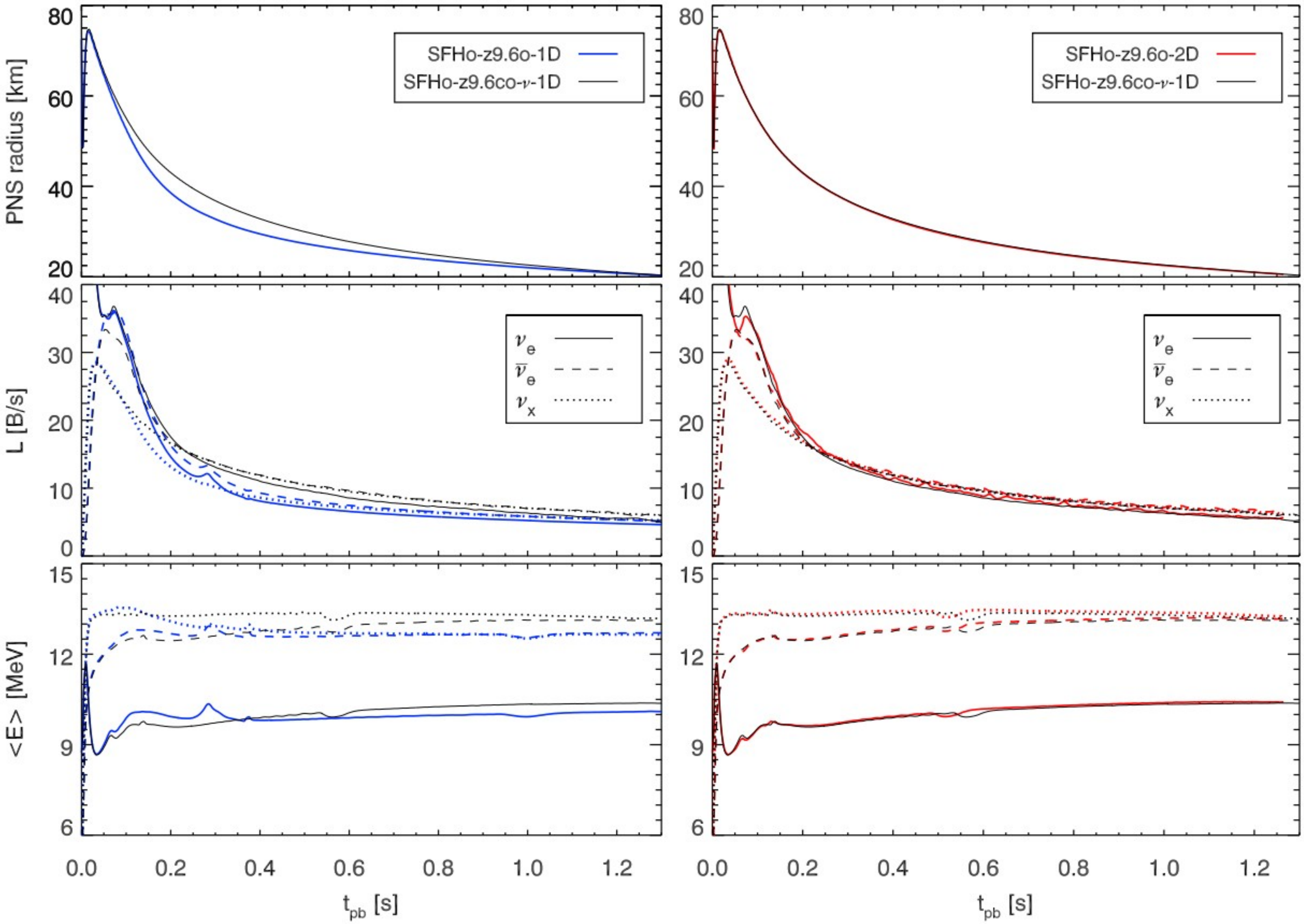
Convectively unstable region in red



s27.0-2002

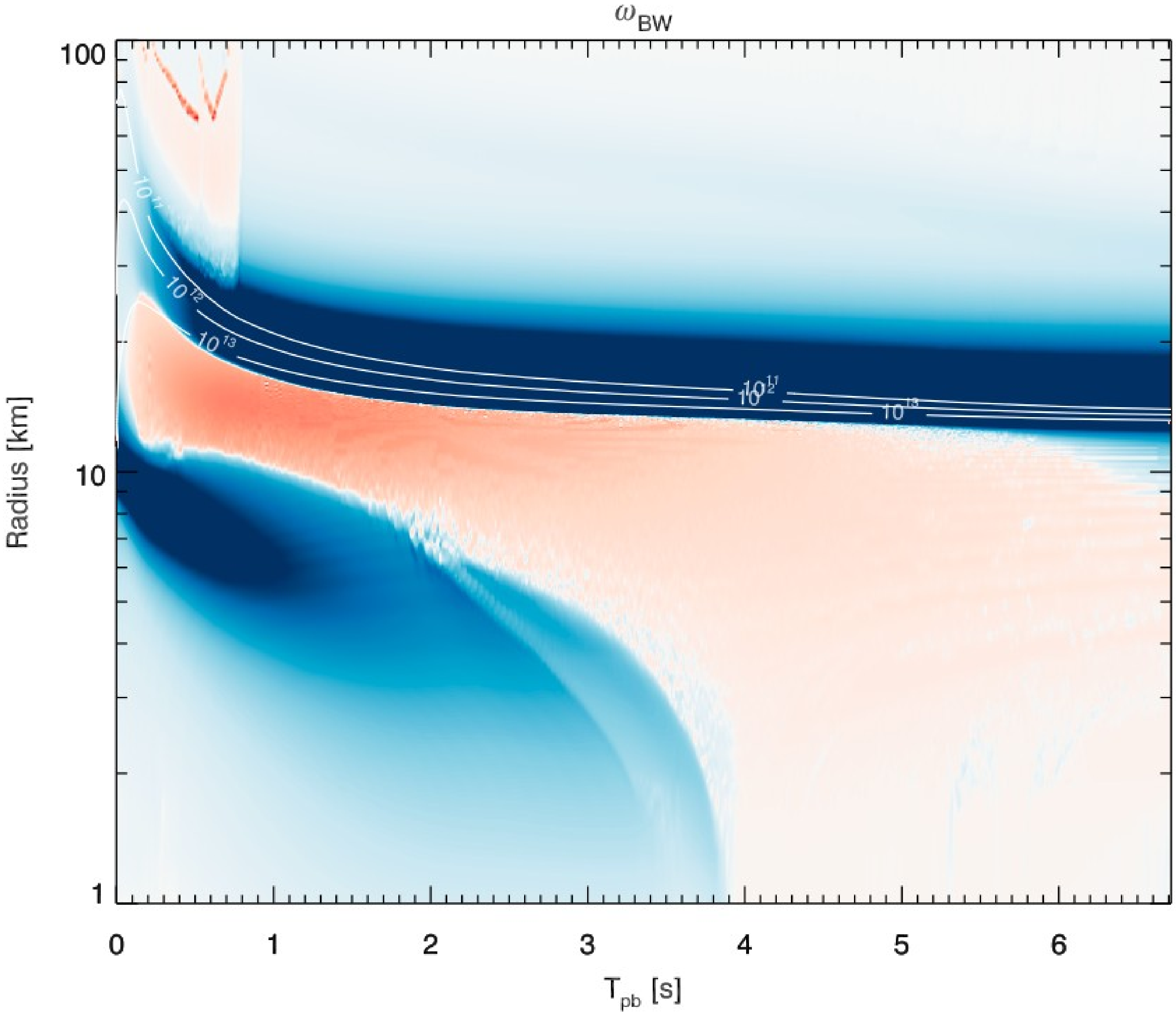
PNS cooling simulations
mixing-length convection

We find excellent agreement between PNS convection in 1D mixing-length and 2D simulations



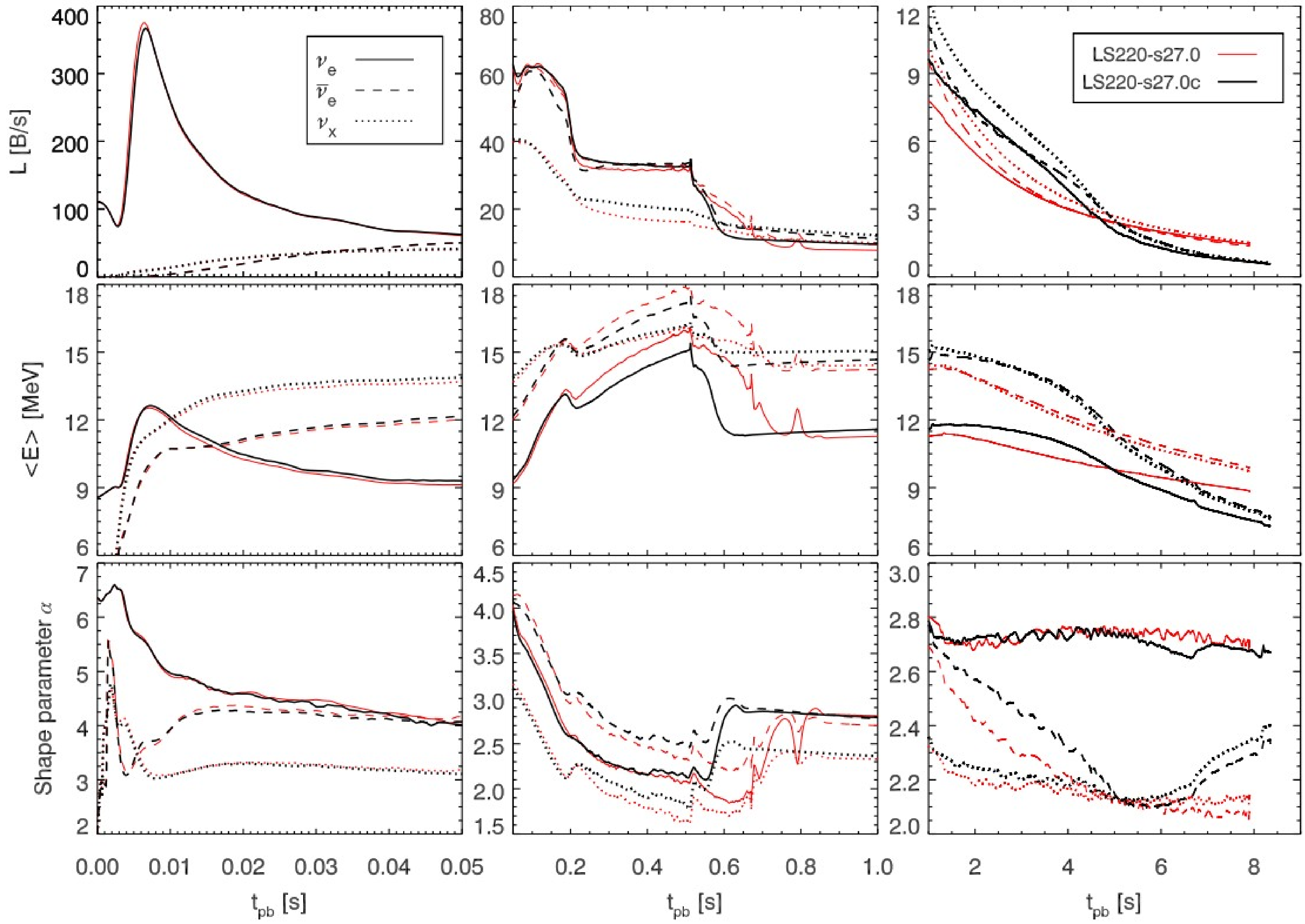
PNS cooling simulations
mixing-length convection

PNS becomes fully convective after 4 seconds



s27.0-2002

PNS cooling simulations
mixing-length convection



PNS cooling simulations 2nd conclusion

- Mixing-length convection gives accurate prediction for PNS cooling signals, if a reasonable explosion time can be defined
- Convection significantly decreases the PNS cooling timescale and strongly modifies the neutrino spectra
- Including neutrino contribution into Y_{lep} is necessary to give full strength of convection → Treat neutrinos as fully trapped leptons inside convection region