Muon creation in supernova matter facilitates neutrino-driven explosions

Ringberg Workshop on the Progenitor-Supernova-Remnant connection

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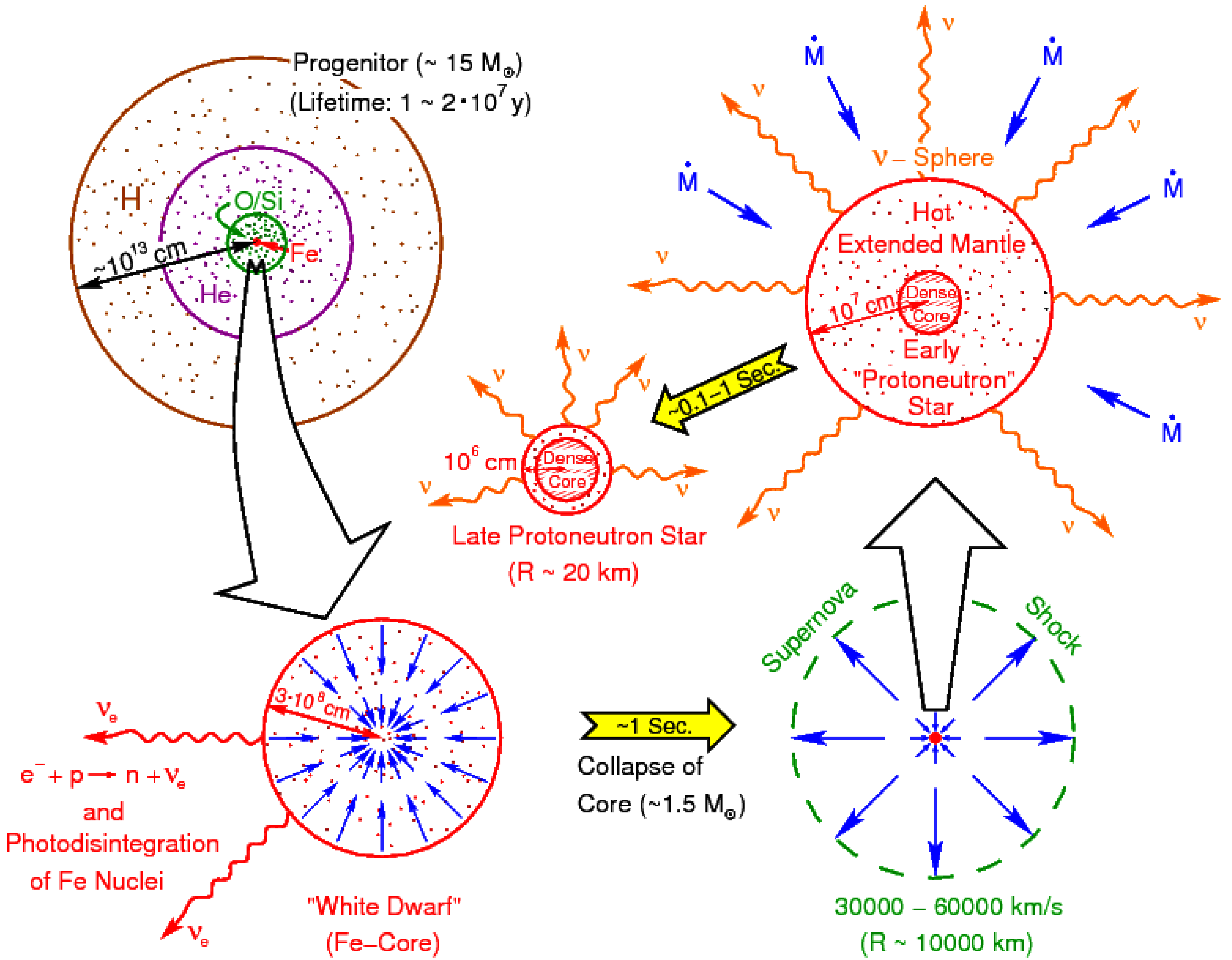
Schloss Ringberg

Robert Bollig

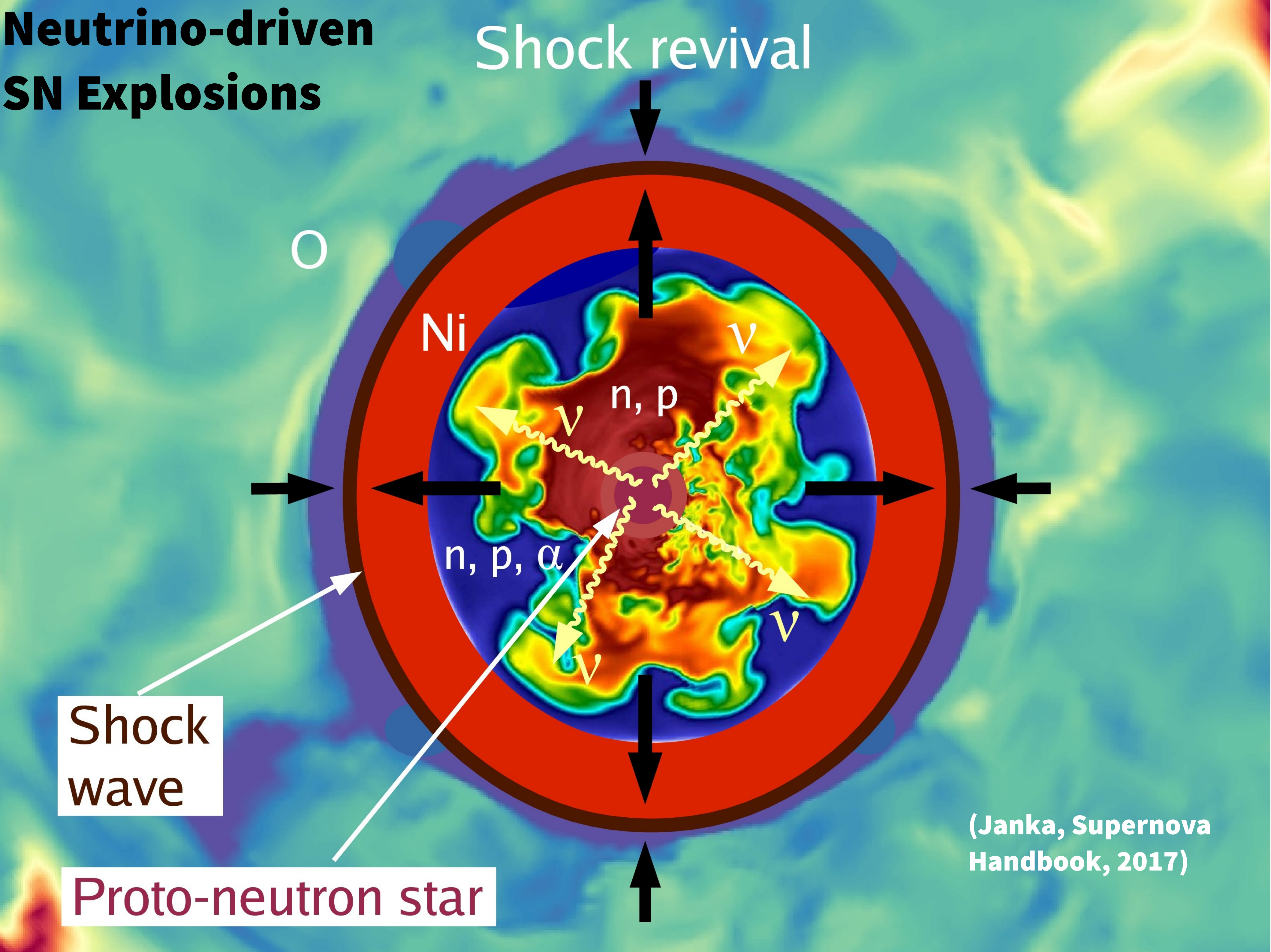
MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Astrophysik

Stellar Collapse and Supernova Stages



adapted from A. Burrows (1990)


Neutrino-driven
SN Explosions
Shock revival
O
Ni
n, p
ν
ν
n, p, α
ν
ν
Shock
wave
Proto-neutron star
(Janka, Supernova
Handbook, 2017)

Status of Neutrino-driven Mechanism in 2D & 3D Supernova Models

- 2D models including GR effects explode for “soft” EoS, but explosions are low in energy and late in general.
- 3D modeling is only in its initial stages and no final conclusion can be drawn yet.
- Several groups achieved 3D explosions but less robustly than in otherwise identical 2D simulations.
- Robustness of explosions increase by adding additional ingredients, e.g. rotation, 3D progenitor perturbations or slightly reduced neutrino-nucleon scattering opacities
  - 3D results are however not converged in terms of spatial resolution yet

What could facilitate robust explosions in 3D?

Uncertain microphysics in neutrinospheric region

- Strangeness contribution to nucleon spin affecting axial-vector neutral-current scattering on nucleons

$$\frac{d\sigma_o}{d\Omega} = \frac{G_F^2\epsilon^2}{4\pi^2}\left[c_v^2(1+\cos\theta) + c_a^2(3-\cos\theta)\right]$$

$$\sigma_0^t = \int_{4\pi} d\Omega \frac{d\sigma_0}{d\Omega}(1-\cos\theta) = \frac{2G_F^2\epsilon^2}{3\pi}\left(c_v^2 + 5c_a^2\right)$$

$$c_a = \frac{1}{2}\left(\pm g_a - g_a^s\right)$$

see Melson et al, ApJL 808 (2015) L42
Successful 3D explosion of a $20M_{sun}$ (W&H 2007) progenitor using a strange contribution of $g_a^s = -0.2$

Uncertain microphysics in neutrinospheric region

- Virial correction to neutral-current scattering
  - Modification of the axial vector response due to spin correlation effects in the virial expansion

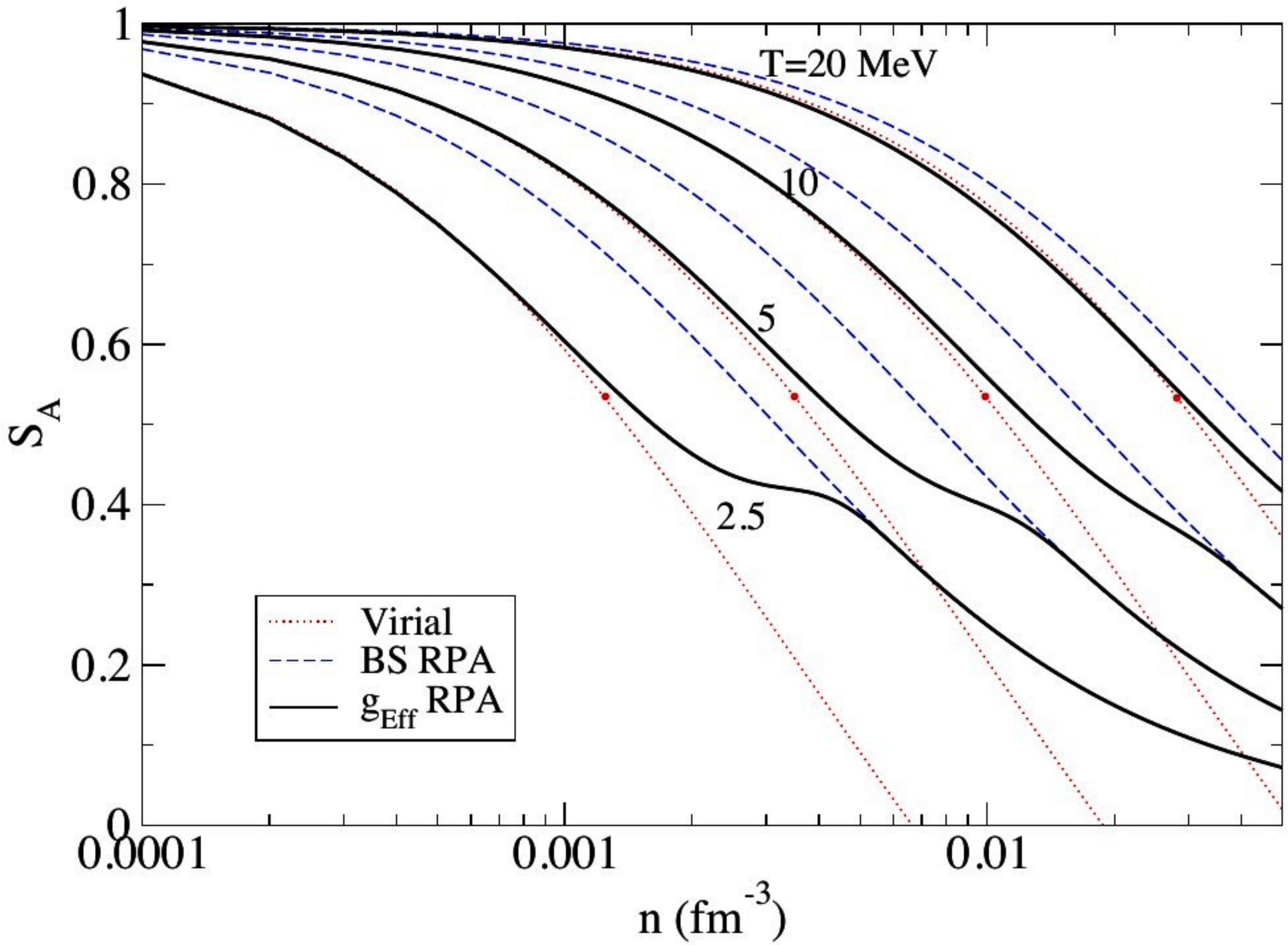
    see Horowitz et al, Phys. Rev. C 95, 025801 (2017)

    $$\frac{1}{V}\frac{d\sigma}{d\Omega} \approx \frac{G_F^2 E_\nu^2}{16\pi^2}\left(c_a^2(3 - cos\theta)S_A + c_v^2(1 + \cos\theta)S_V\right)$$

    $$S_V \approx 1 \quad S_A \leq 1$$

  - Reduces neutrino-nucleon scattering opacity around neutrinospheric region but is strongly temperature dependent

Uncertain microphysics in neutrinospheric region



Can lead to easier explosions

see Burrows, arXiv:1611.05859

Uncertainties in high density equation of state

- Hyperons
  - Strong interactions between hyperon-hyperon and hyperon-nucleon are poorly constrained
  - Reduction of cold maximum neutron star mass due to loss of neutron degeneracy pressure is significant
- Quarks
  - Exotic physics and problems with maximum neutron star mass

Uncertainties in high density equation of state

- Muons
  - Ideal Fermi-gas of muons analogous to electrons
  - Only classical physics needed
  - Maximum cold neutron star mass is only weakly affected
  - Weak interactions and lepton number conservation require integration into neutrino transport
  - Theoretical presence of muons not disputed, but typically neglected except in Kelvin-Helmholtz phase of PNS cooling, cf. Pons et al., Astrophys.J. 513 (1999) 780

Muons in hot neutron-star medium

Arxiv:1706.04630

Bollig, R.; Janka, H.-Th.; Lohs, A.; Martinez-Pinedo, G.; Horowitz, C. J.; Melson, T.

- Muon rest mass much larger than electron rest mass $m_\mu c^2 \approx 105.66\mathrm{MeV}$
- But: Temperatures in PNS mantle become hotter than 30 MeV and electron chemical potential μ_e > 100 MeV can be reached easily

Muons in hot neutron-star medium

- T > 30 MeV leads to mean particle energies of the order of the muon restmass and allows abundant production by pair conversion processes → EoS component of muon gas

$$e^- + e^+ \leftrightharpoons \mu^- + \mu^+ \quad \gamma + \gamma \leftrightharpoons \mu^- + \mu^+$$

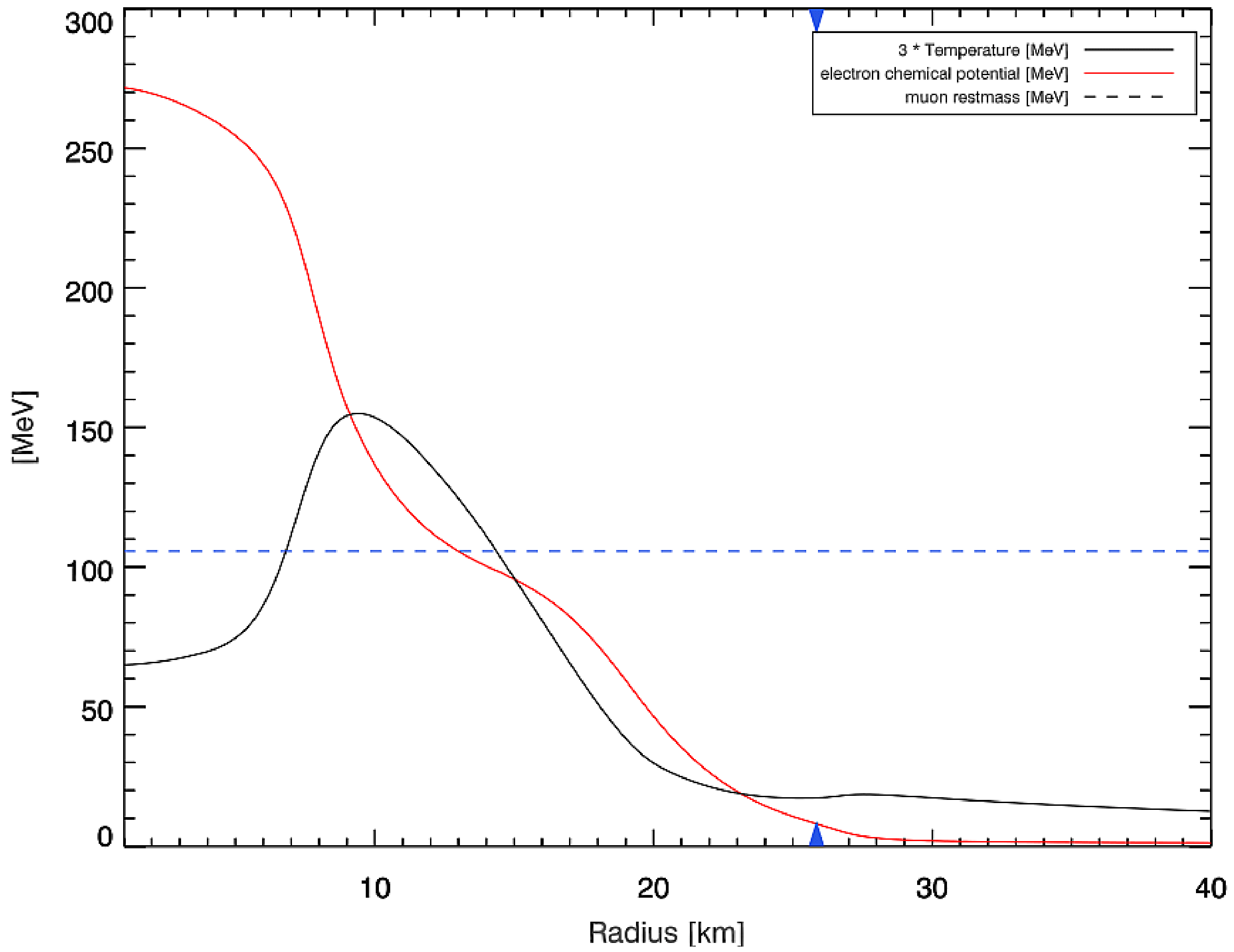
- Electron and muon chemical potential are coupled by beta equilibrium → neutrino transport dependent component of muon gas

$$\hat{\mu} = \mu_n - \mu_p = \mu_e - \mu_{\nu_e} = \mu_\mu - \mu_{\nu_\mu}$$

$$\mu_{\nu_e} = \mu_{\nu_\mu} = 0 \rightarrow \mu_n - \mu_p = \mu_e = \mu_\mu$$

Muons in hot neutron-star medium

- Example PNS conditions at 400ms after core-bounce: s20.0-SFHo



Muons in hot neutron-star medium

- Muons participate in weak equilibrium by a variety of neutrino processes, in particular charged-current reactions with nucleons:

$$\nu_\mu + n \leftrightharpoons p + \mu^-$$

$$\overline{\nu}_\mu + p \leftrightharpoons n + \mu^+$$

- In contrast to electrons the muon restmass can not be neglected $\rightarrow$ All involved opacities need to be generalized to finite lepton mass
- In particular: Weak magnetism correction of Horowitz (2002) can not be applied to muonic beta-processes

Muons in hot neutron-star medium

- Additional reactions of neutrinos with electrons produce muons and couple neutrinos of different flavors:

TABLE I. Neutrino reactions with muons.

$\nu + \mu^- \leftrightharpoons \nu' + \mu^{-\prime}$	$\nu + \mu^+ \leftrightharpoons \nu' + \mu^{+\prime}$
$\nu_\mu + e^- \leftrightharpoons \nu_e + \mu^-$	$\overline{\nu}_\mu + e^+ \leftrightharpoons \overline{\nu}_e + \mu^+$
$\nu_\mu + \overline{\nu}_e + e^- \leftrightharpoons \mu^-$	$\overline{\nu}_\mu + \nu_e + e^+ \leftrightharpoons \mu^+$
$\overline{\nu}_e + e^- \leftrightharpoons \overline{\nu}_\mu + \mu^-$	$\nu_e + e^+ \leftrightharpoons \nu_\mu + \mu^+$
$\nu_\mu + n \leftrightharpoons p + \mu^-$	$\overline{\nu}_\mu + p \leftrightharpoons n + \mu^+$

see PhD Thesis (A.Lohs 2015)

Prometheus-VERTEX

- Hydro module **Prometheus**
  - PPM method, Godunov-type exact solver
  - Newtonian self-gravity with effective GR potential corrections
  - Tabulated EoS 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

Prometheus-VERTEX

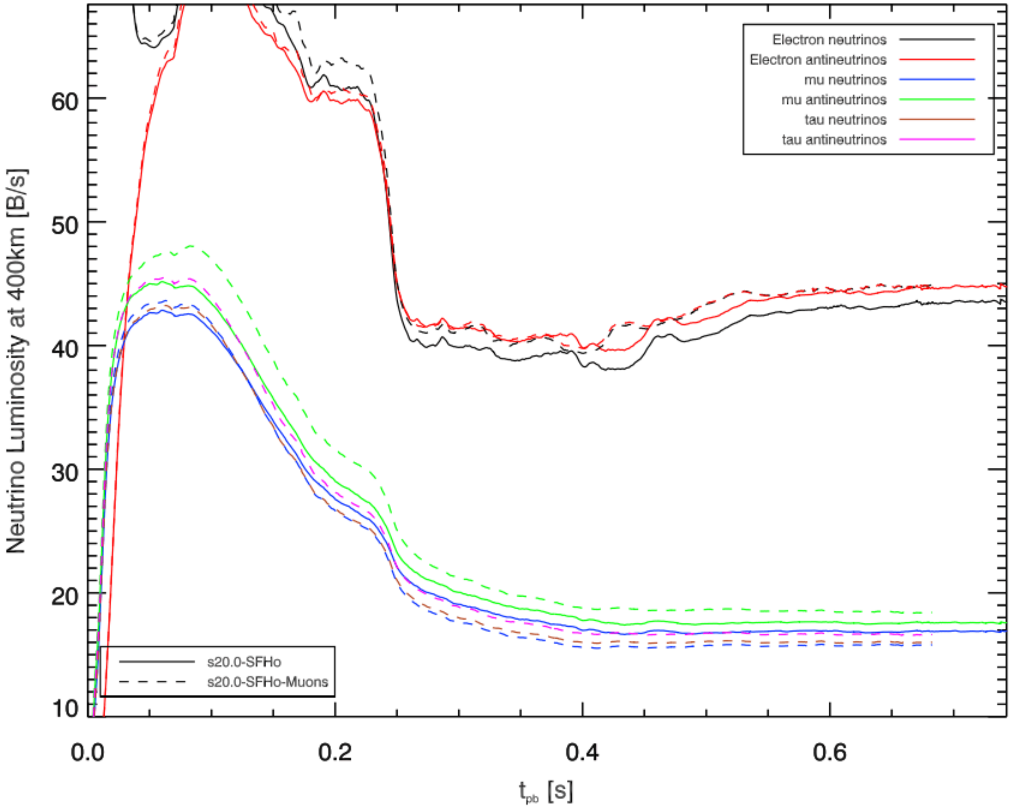
β-Processes	$\nu_e + n \leftrightharpoons e^- + p$	Burrows&Sawyer(1999); Horowitz(2002)
	$\bar{\nu}_e + p \leftrightharpoons e^+ + n$	Burrows&Sawyer(1999); Horowitz(2002)
	$\nu_e + A' \leftrightharpoons e^- + A$	Langanke et al (2003)
Scattering	$\nu + A \leftrightharpoons \nu + A$	Horowitz(1997); Bruenn&Mezzacappa(1997); 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)

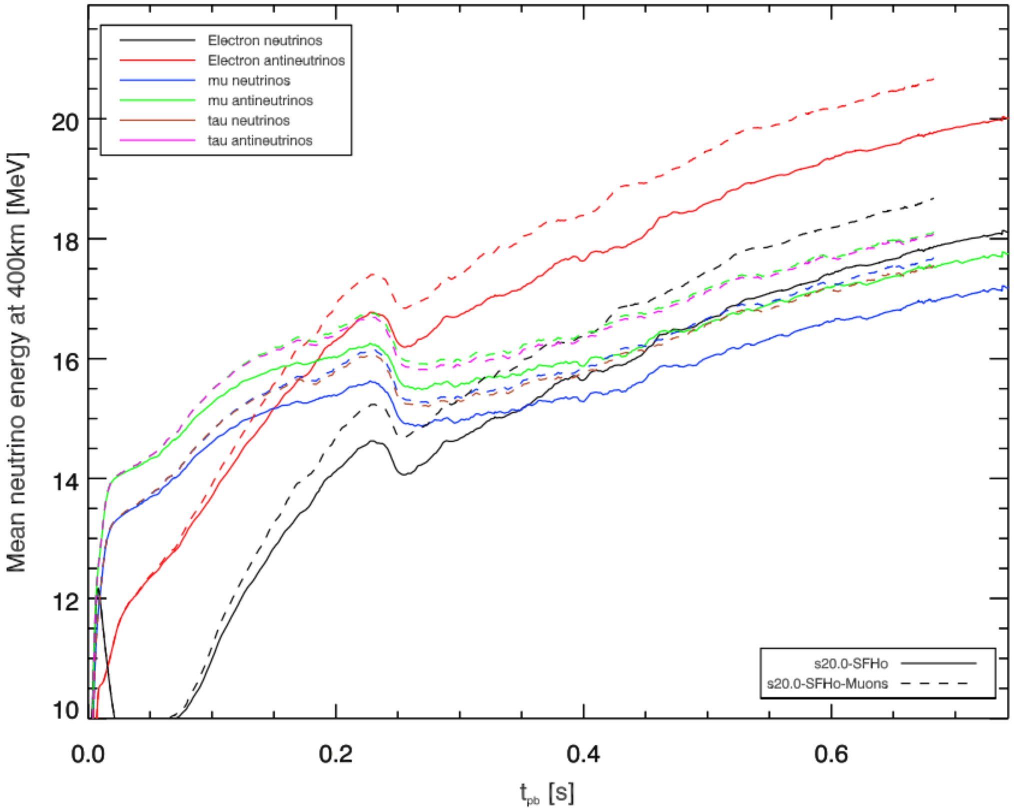
Prometheus-VERTEX

- Modifications to base code
  - Add additional evolution equation for muon number
    $$\frac{\partial(\rho Y_\ell)}{\partial t} + \vec{\nabla}(\rho Y_\ell \vec{v}) = Q_\ell$$
  - Generalize neutrino transport to evolve all six neutrino species individually
    $\nu_e,\ \bar{\nu}_e,\ \nu_\mu,\ \bar{\nu}_\mu,\ \nu_\tau, \bar{\nu}_\tau$
- Weak magnetism effects on neutral-scattering by itself leads to natural buildup of mu and tau neutrino number
- Additional muonic reactions lead to full coupling between $\nu_e,\ \bar{\nu}_e,\ \nu_\mu,\ \bar{\nu}_\mu$ and $Q_e,\ Q_\mu$

1D results

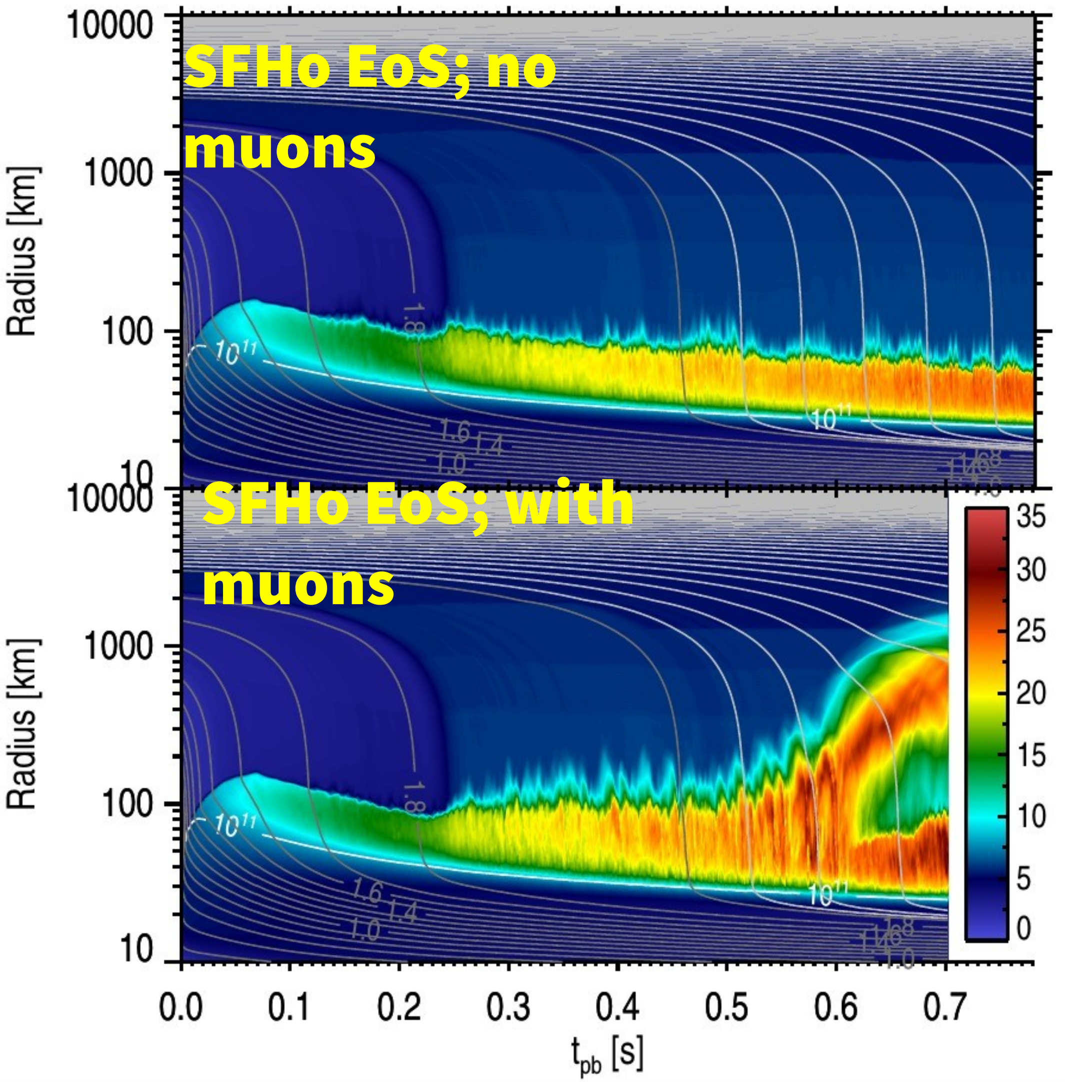
- s20.0 progenitor (Woosley & Heger 2007) with SFHo EoS





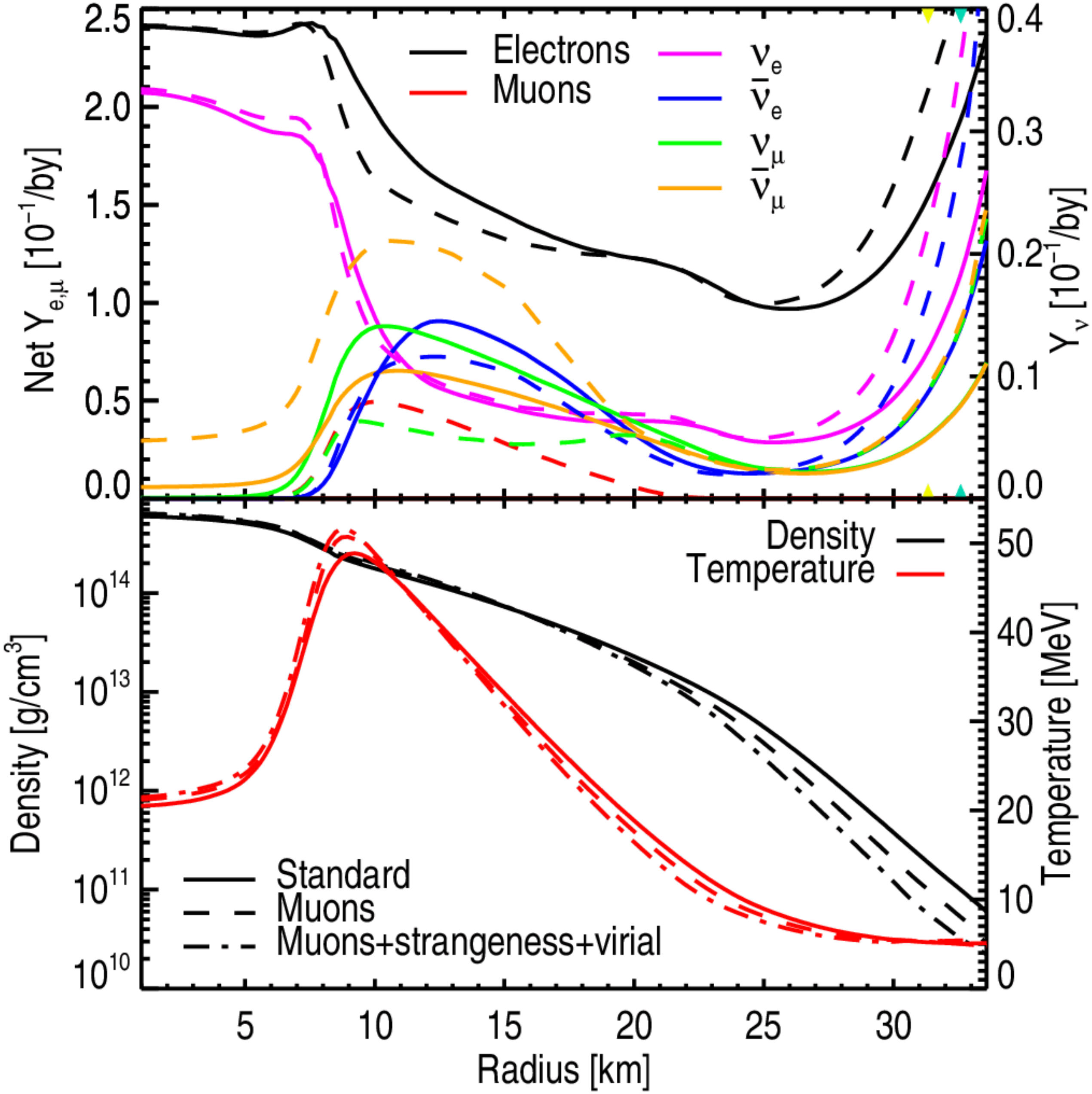
2D results

- Inclusion of muons can lead a non-exploding model to explosion in 2D



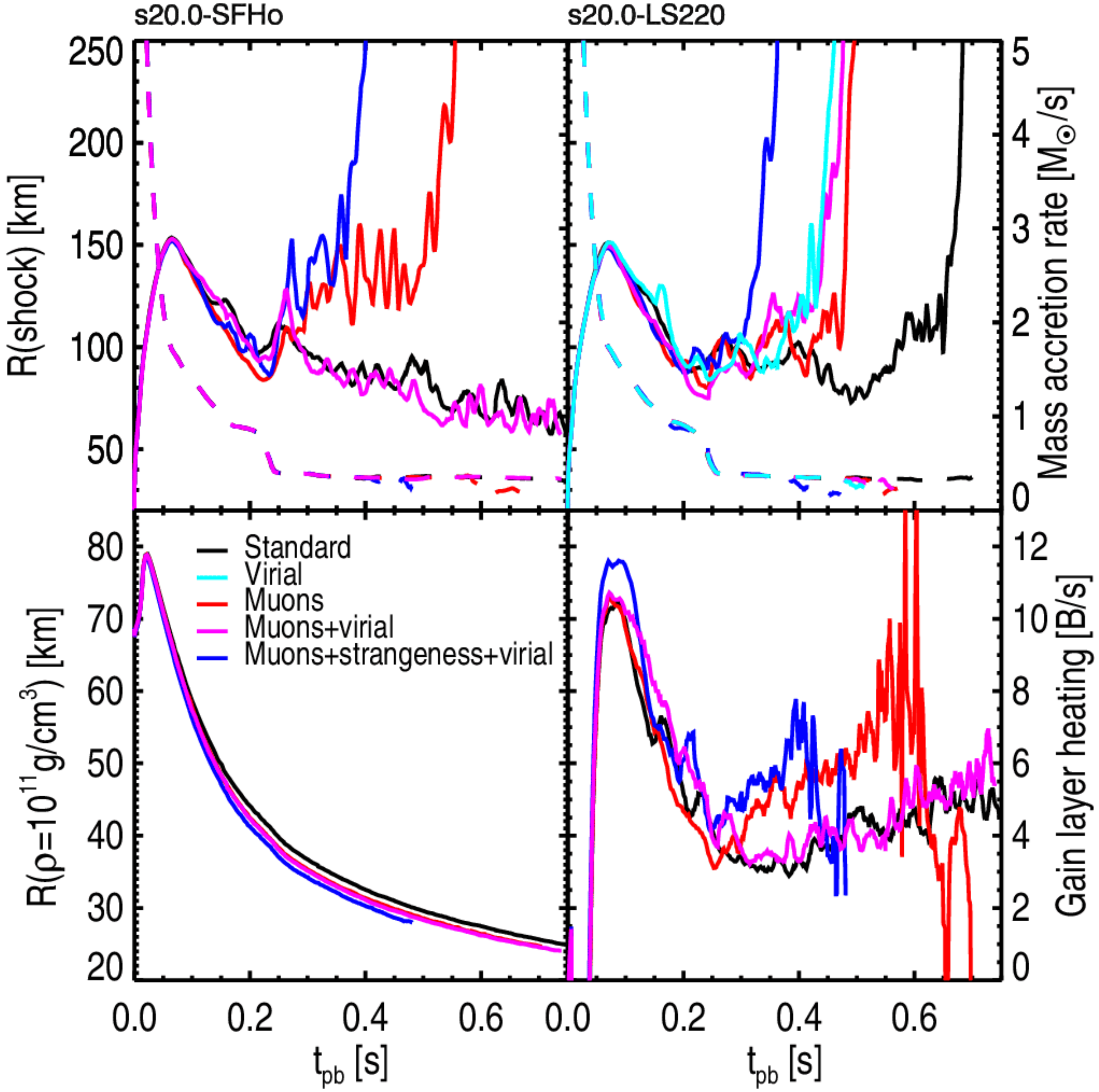
2D results

- Composition 400ms postbounce
- Thermal energy is converted to restmass energy and electron degeneracy pressure is reduced



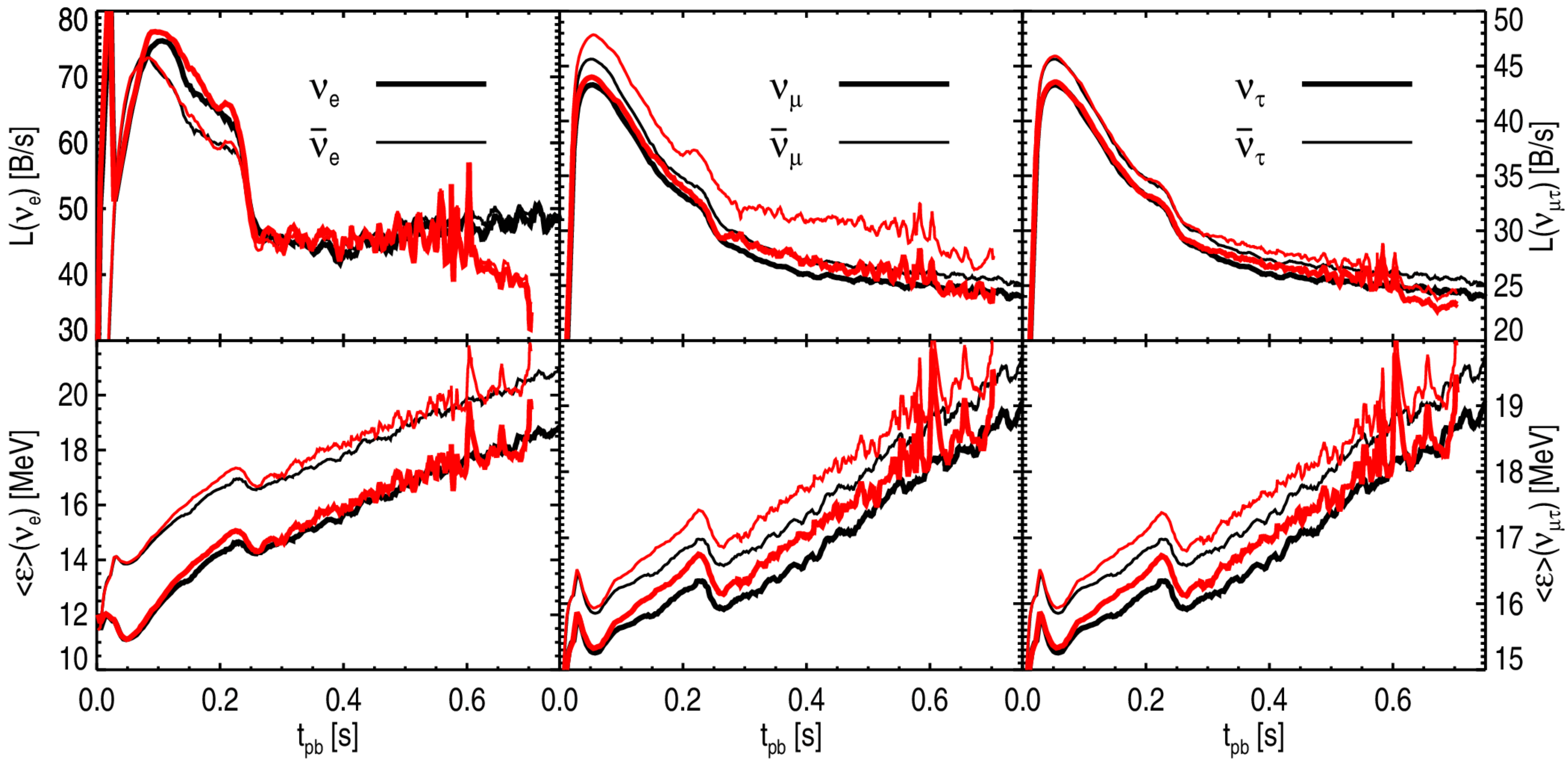
2D results

- Inclusion of muons facilitates the neutrino-driven mechanism
- PNS radius shrinks more rapidly



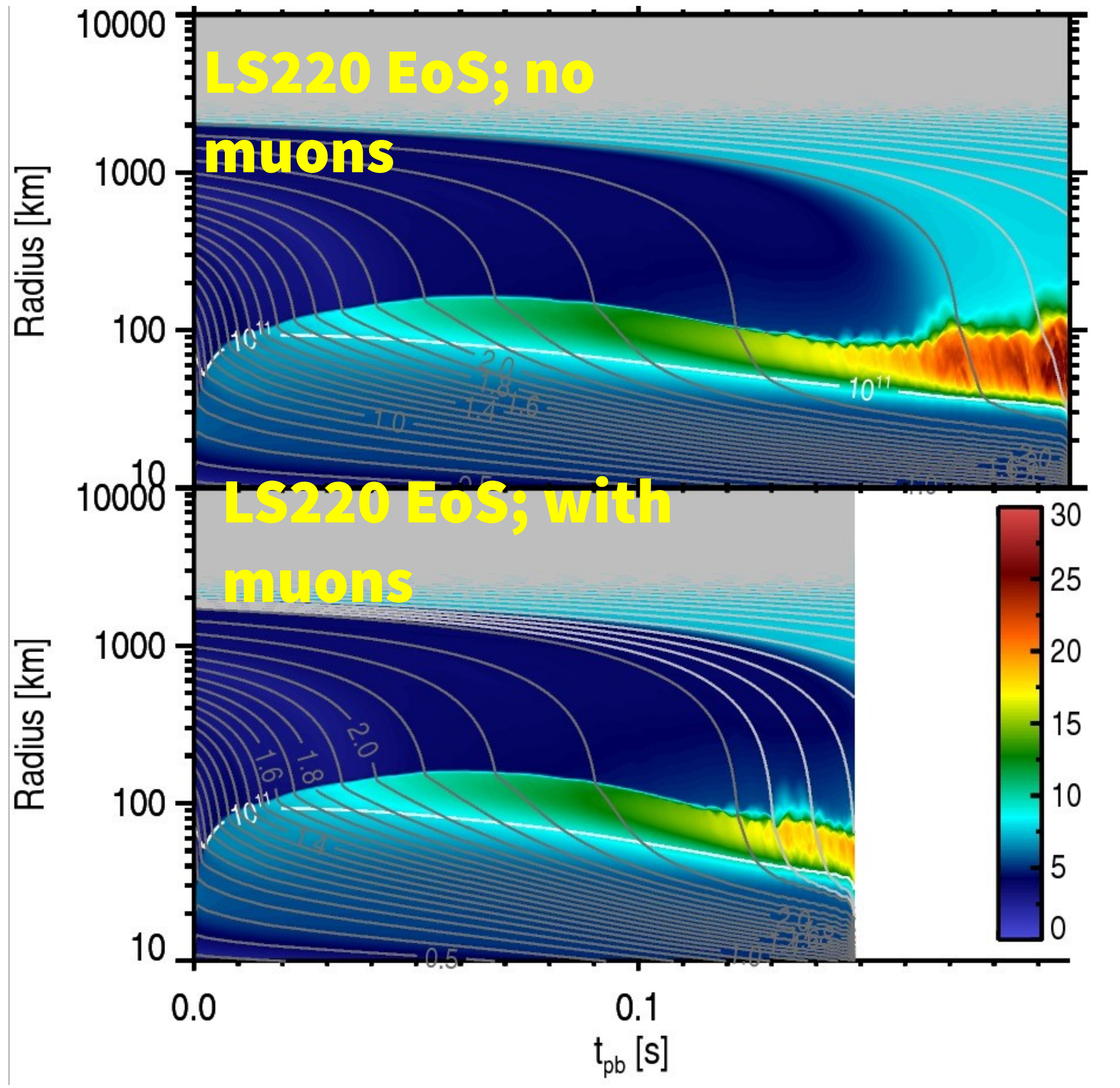
2D results

- More rapidly contracting NS leads to hotter neutrino emission, increasing gain layer heating



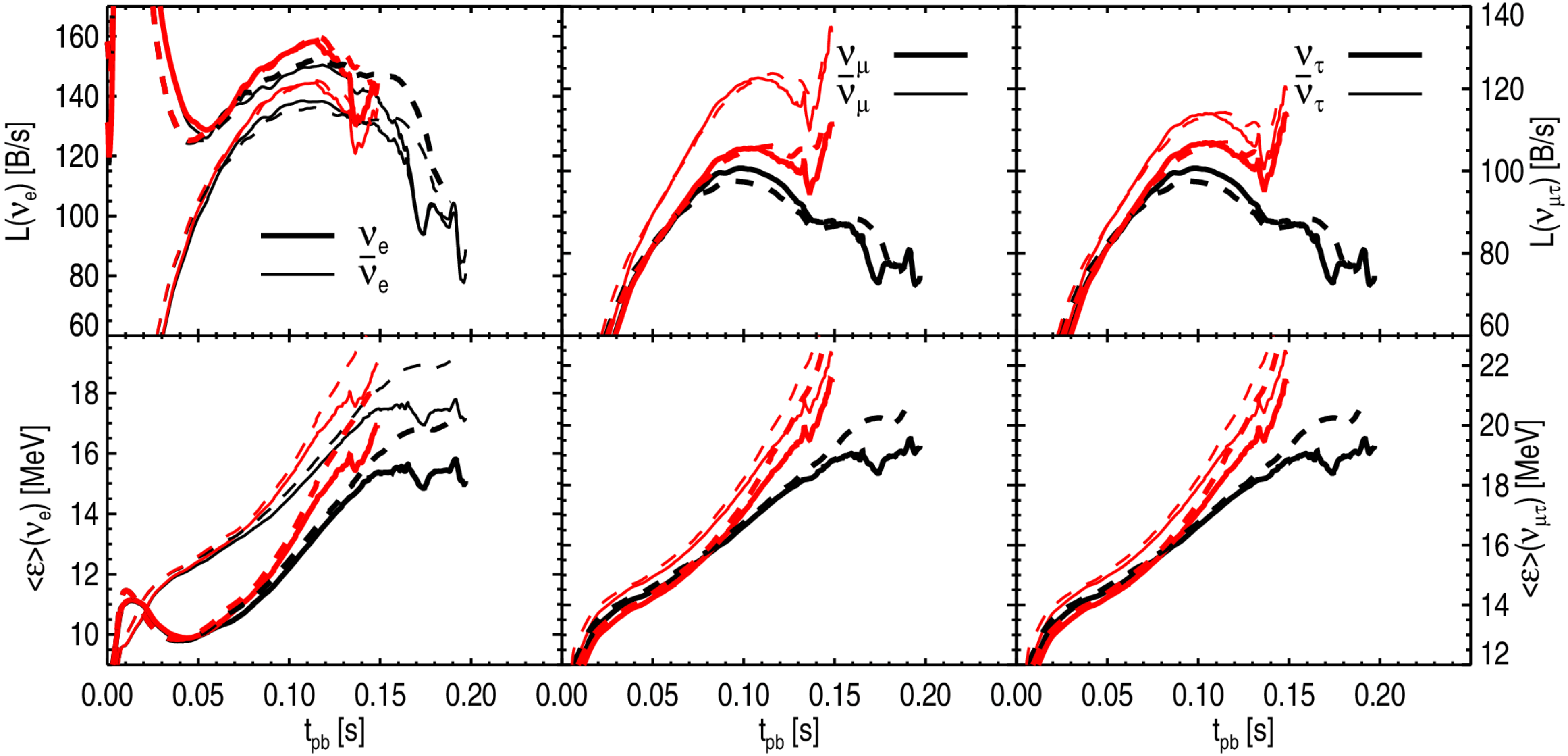
2D black hole collapse

- u75.0 (Woosley & Heger 2002)
- Collapse is significantly faster by inclusion of muons



2D black hole collapse

- Neutrino emission strongly increased by muon inclusion

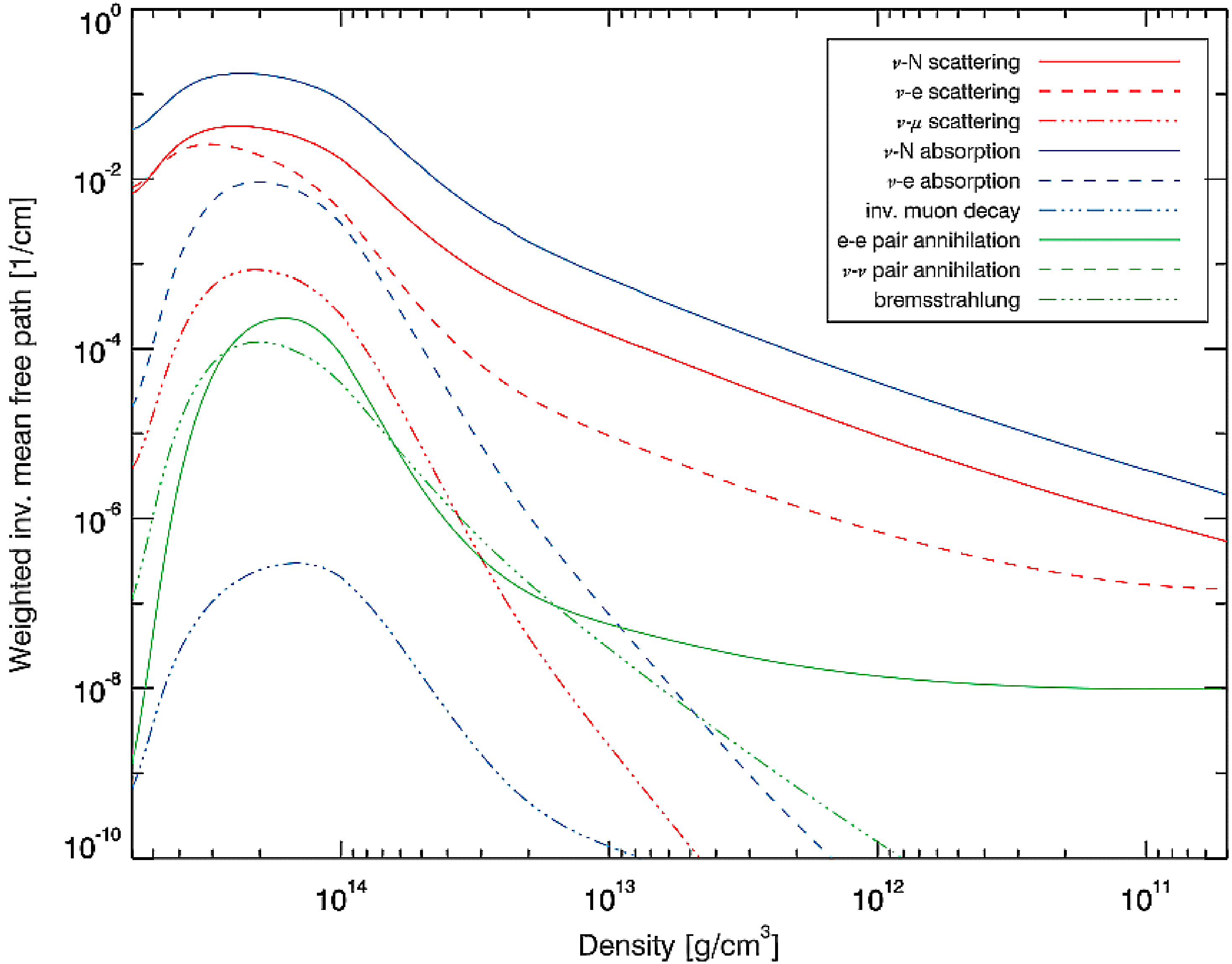


Consequences

- **Affect explosion mechanism of supernovae**
- **Affect gravitational instability of hot NSs to BHs**
- **Affect compactness of hot NSs**
- **Change neutrino emission**
- **May affect neutrino oscillations**
- **Should be included in SN and NS-NS/BH merger simulations**
- **Require full six-species neutrino transport with coupling of different neutrino flavors**

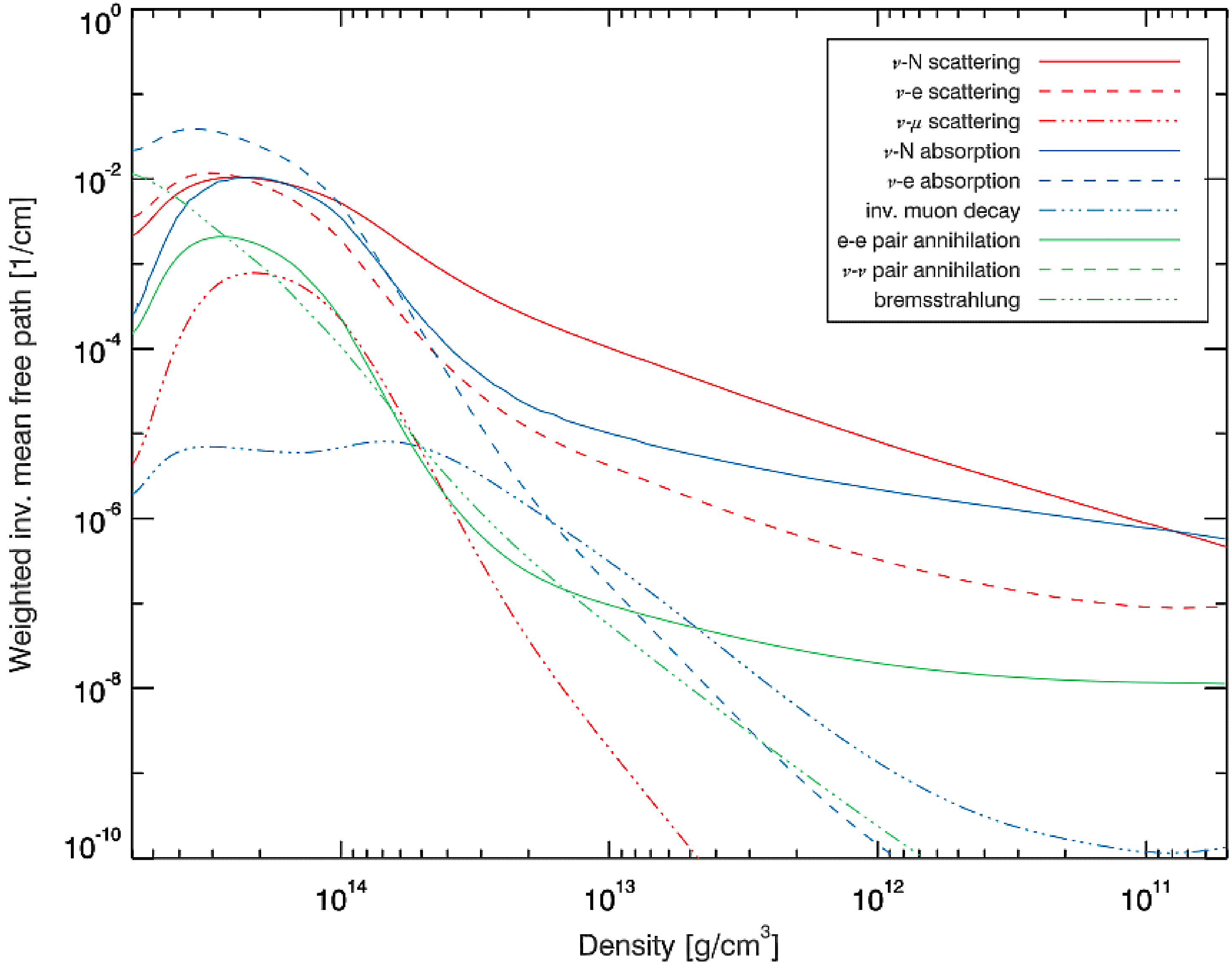
Appendix: Opacities

- ν_e opacities at 400ms postbounce: s20.0-SFHo



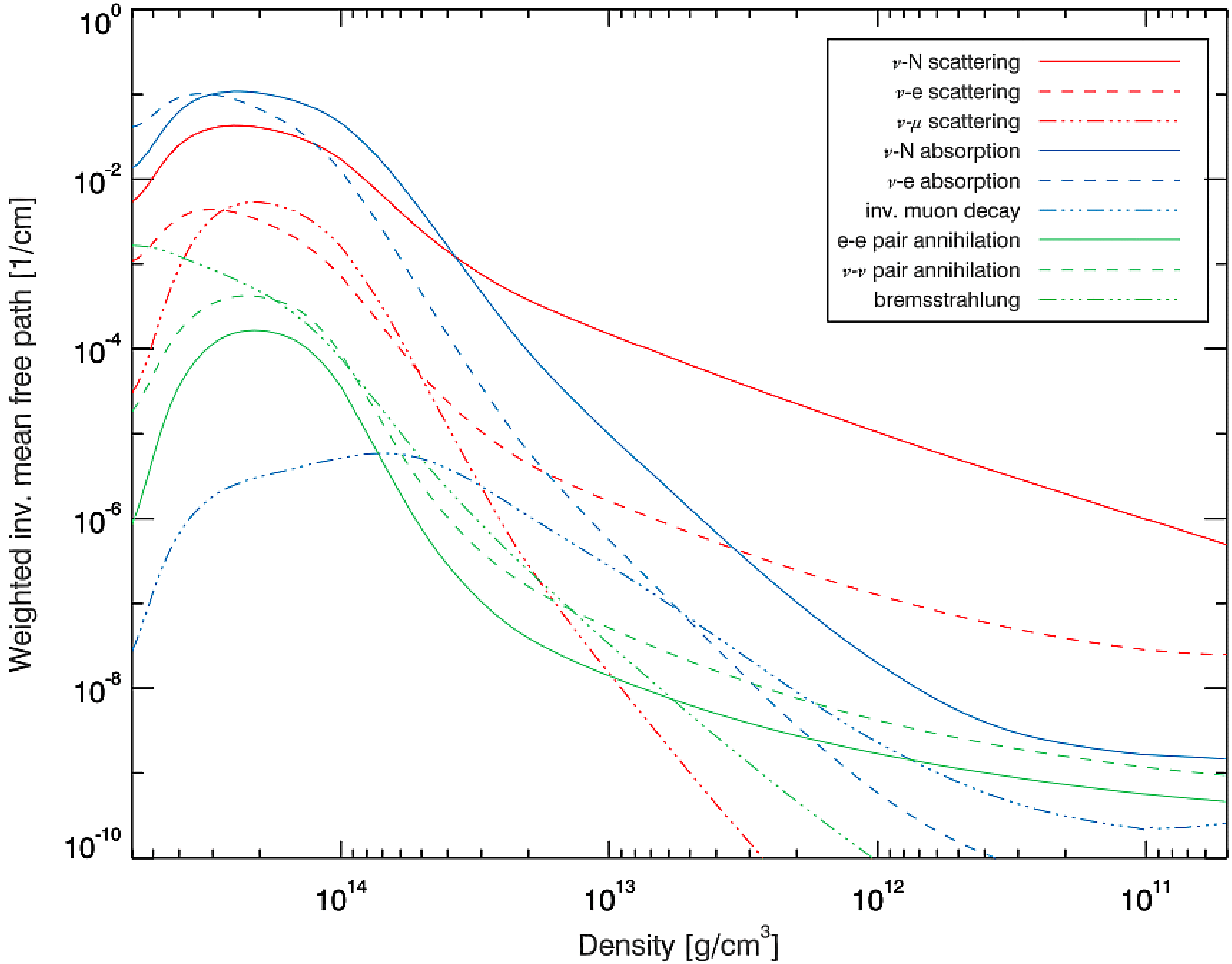
Appendix: Opacities

- $\bar{\nu}_e$ opacities at 400ms postbounce: s20.0-SFHo



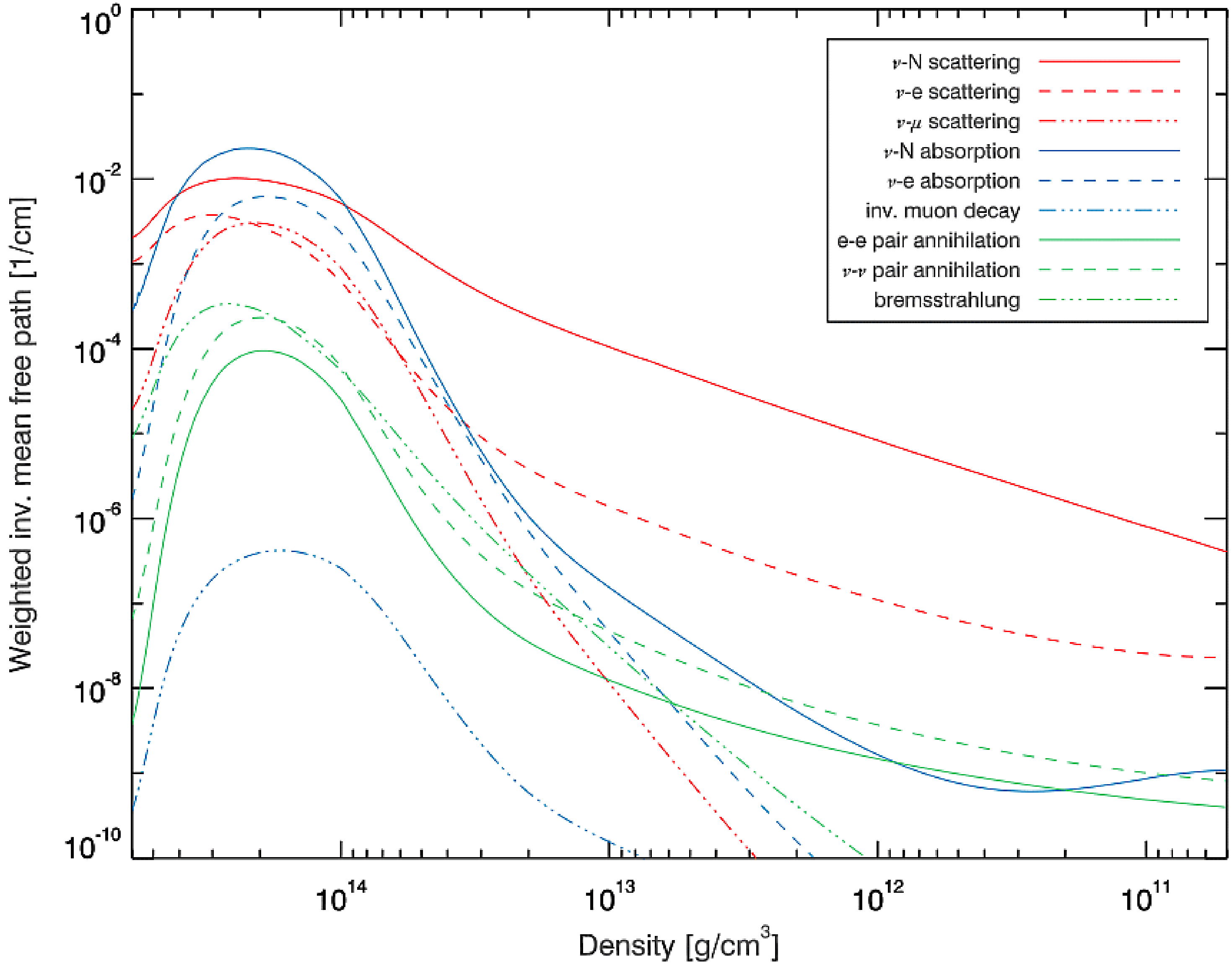
Appendix: Opacities

- ν_μ opacities at 400ms postbounce: s20.0-SFHo



Appendix: Opacities

- $\bar{\nu}_\mu$ opacities at 400ms postbounce: s20.0-SFHo



Appendix: Muonic opacities of ν_μ