Max-Planck-Institut für Astrophysik

SFB 1258 Neutrinos Dark Matter Messengers

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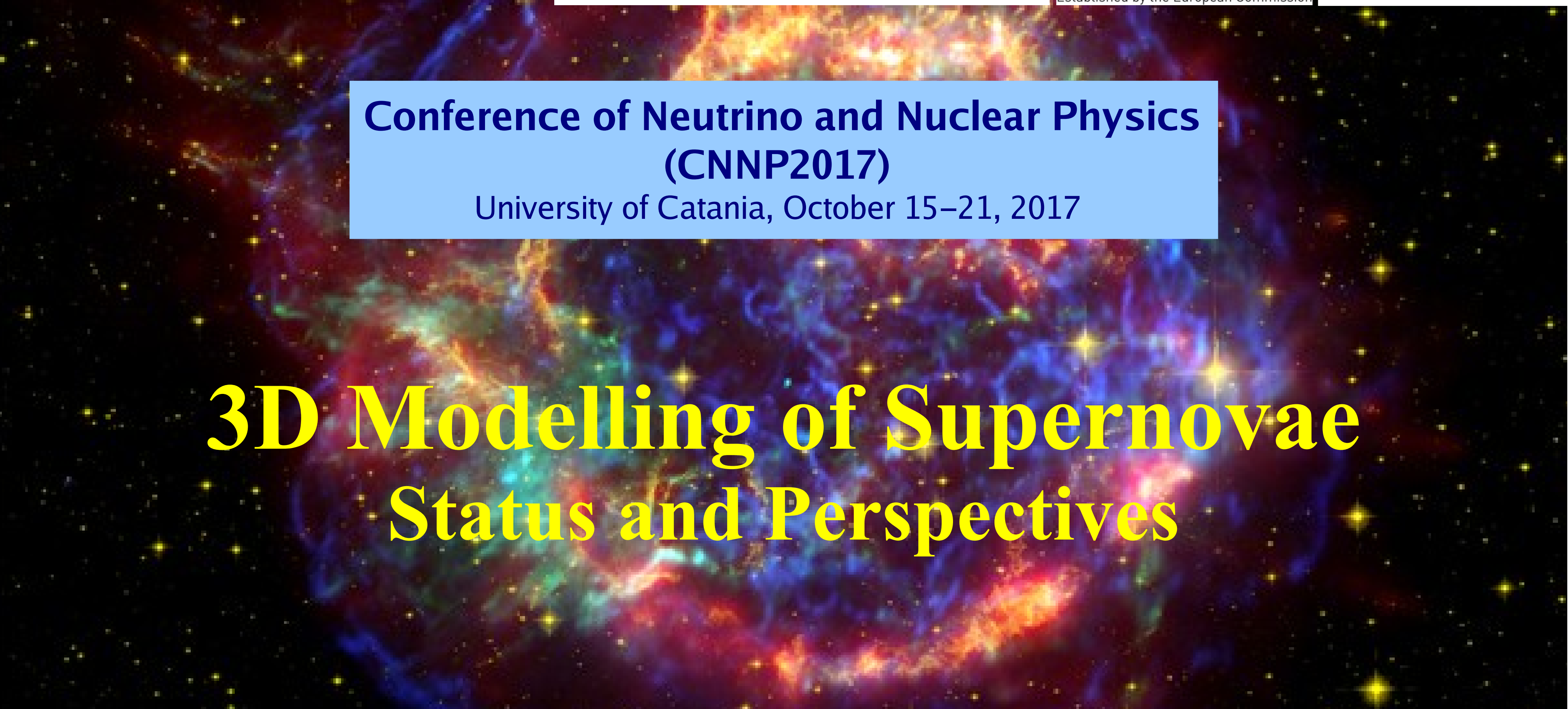
Excellence Cluster Universe



Conference of Neutrino and Nuclear Physics (CNNP2017)

University of Catania, October 15–21, 2017

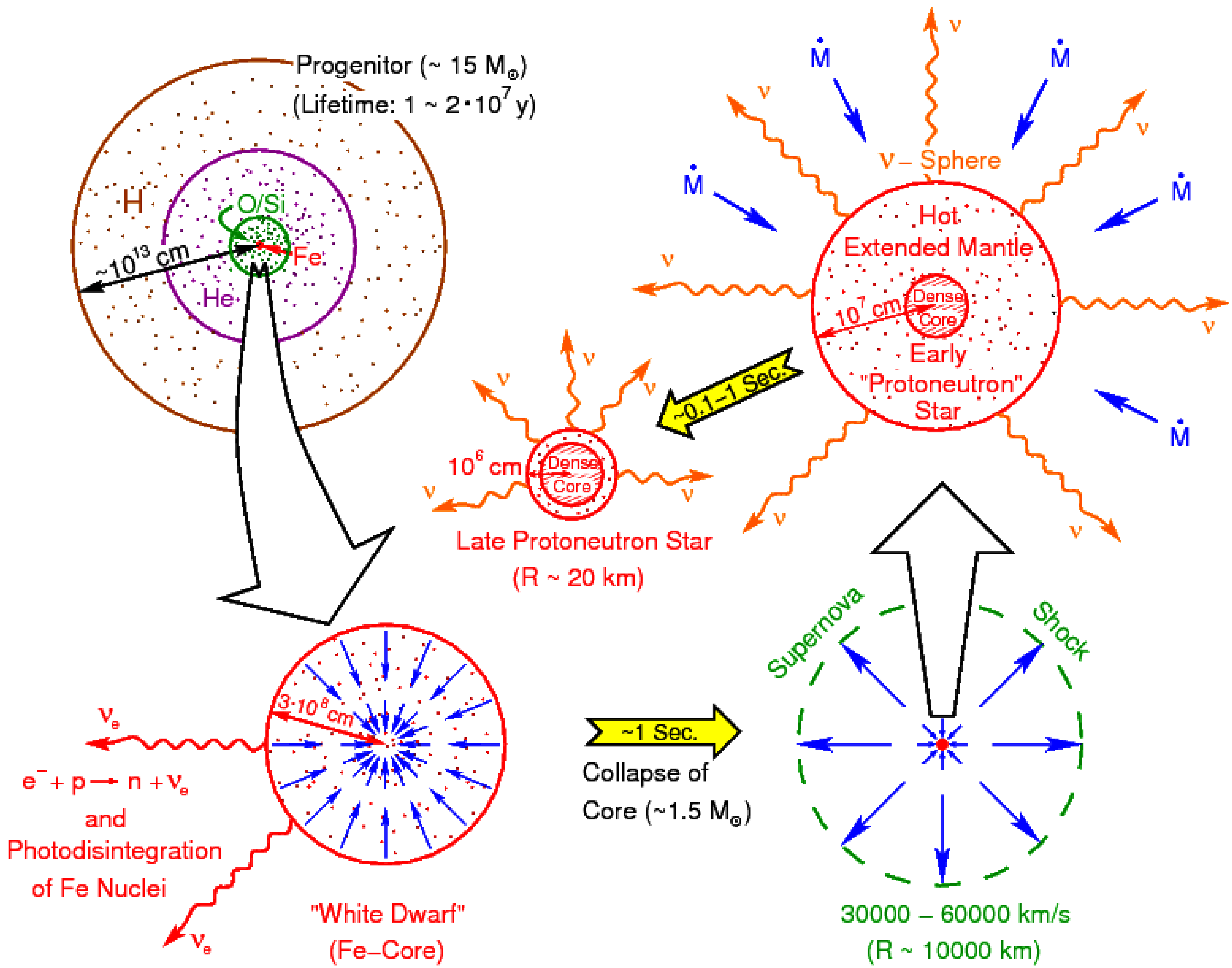
3D Modelling of Supernovae
Status and Perspectives

European Research Council
Established by the European Commission
Supporting top researchers from anywhere in the world

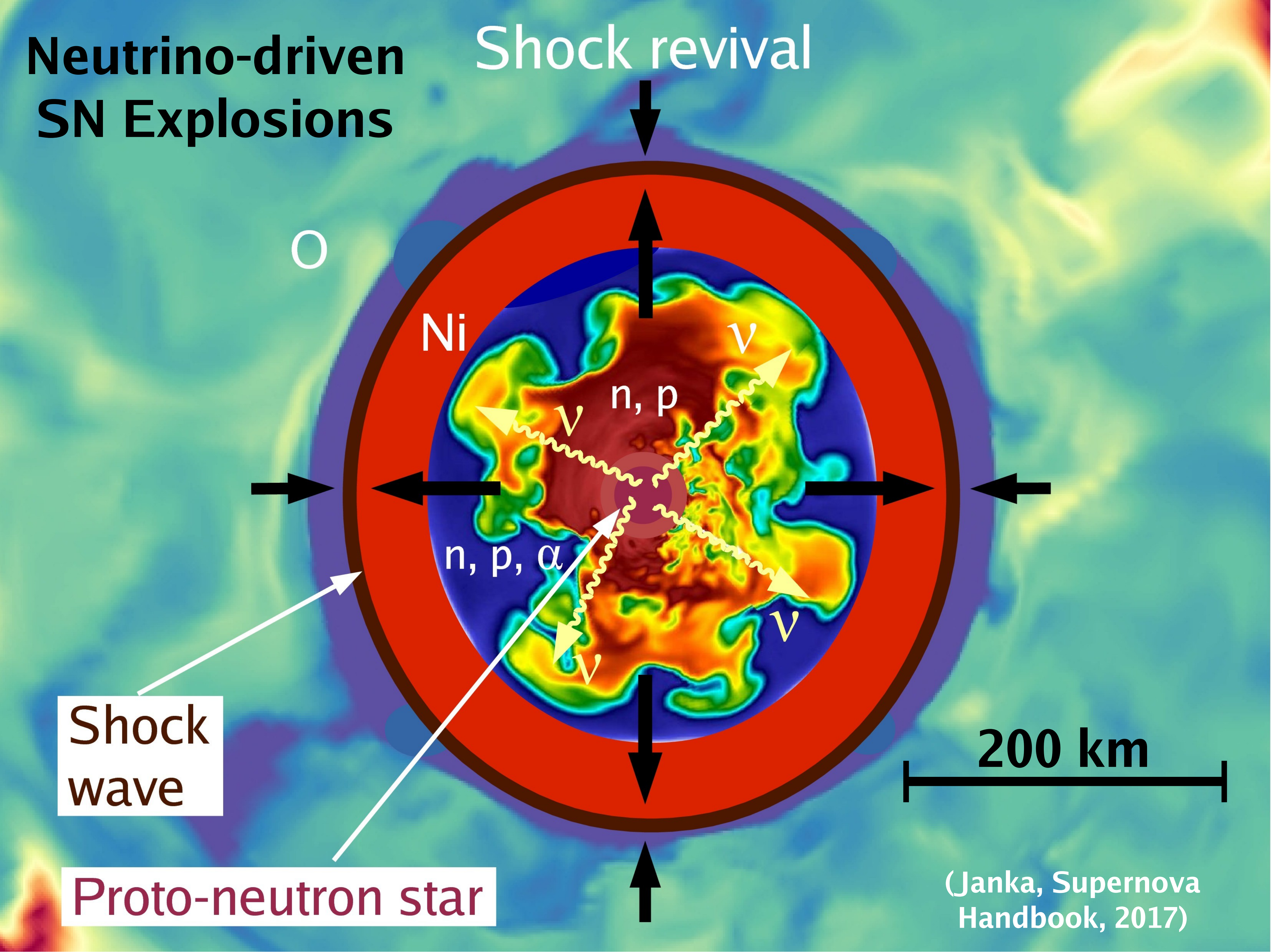
Hans-Thomas Janka
for the Team

COCO2CASA

Stellar Collapse and Supernova Stages

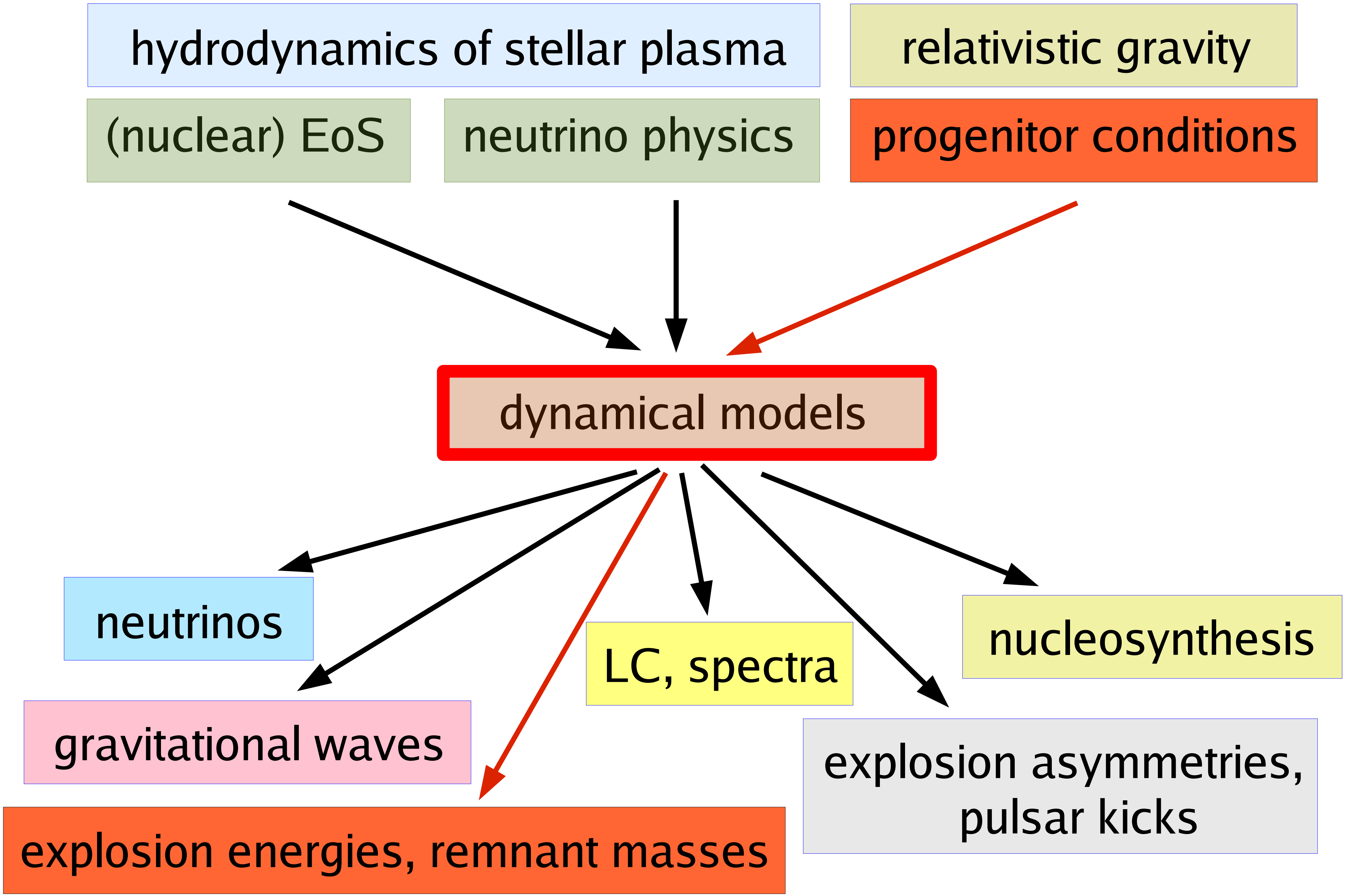


adapted from A. Burrows (1990)

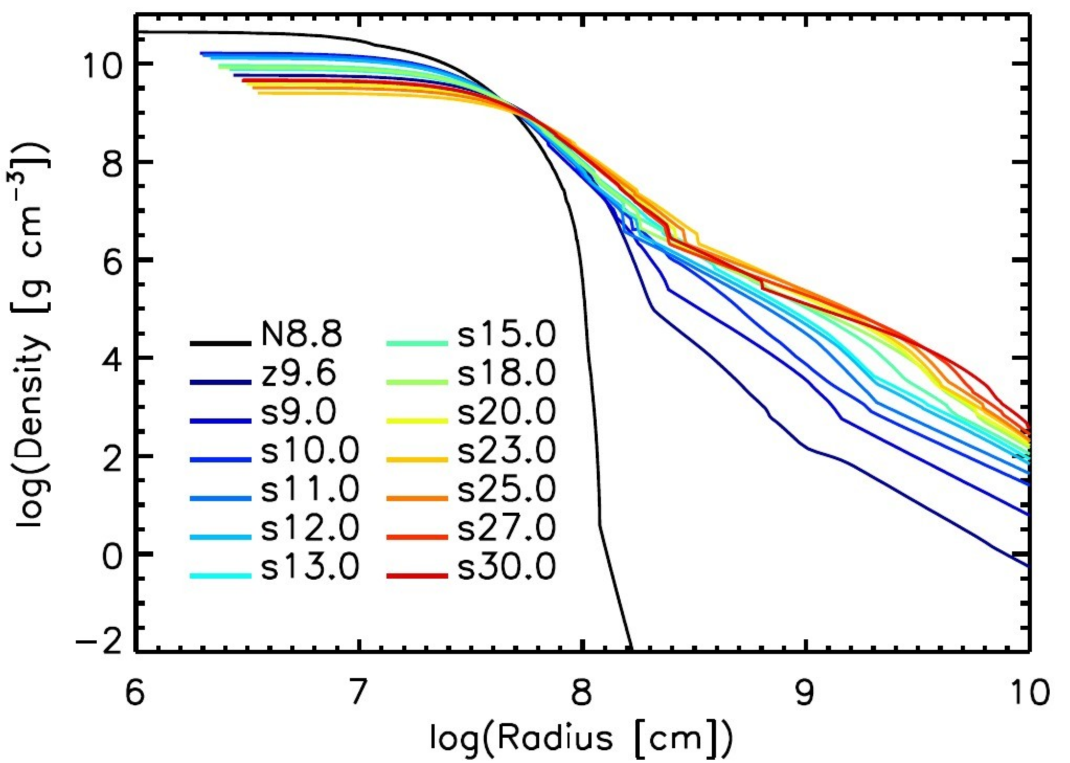


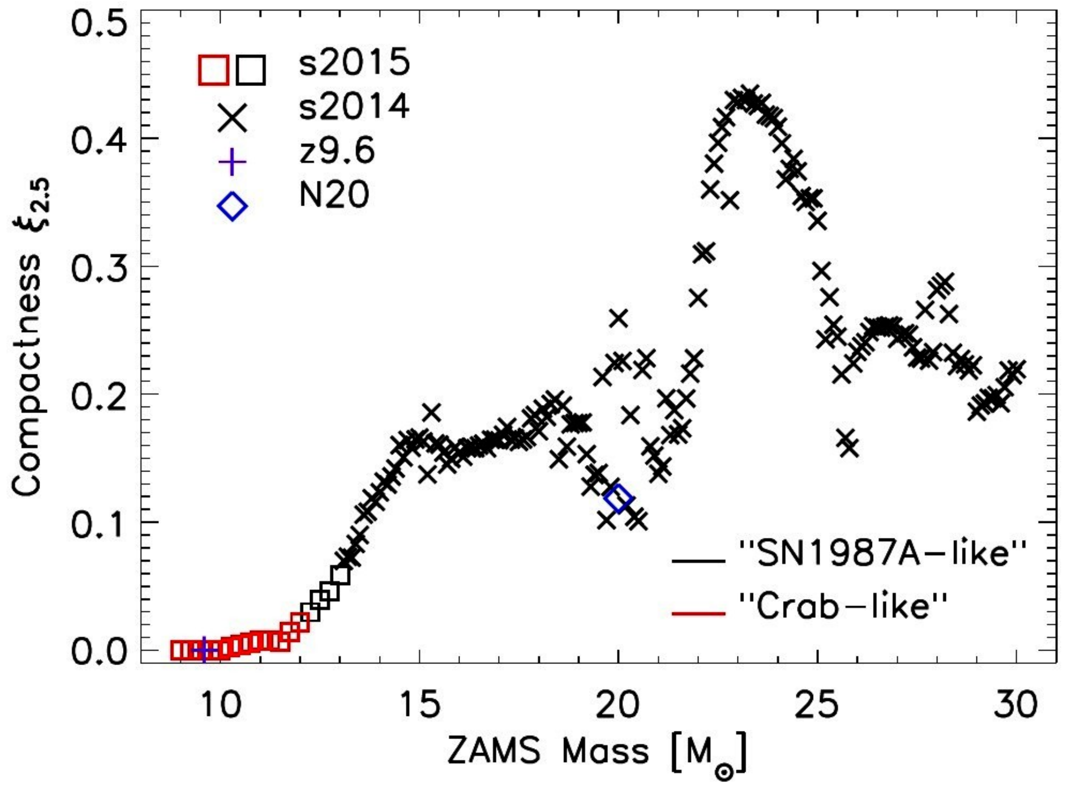
Neutrino-driven
SN Explosions
Shock revival
O
Ni
n, p
ν
ν
n, p, α
ν
ν
Shock
wave
Proto-neutron star
200 km
(Janka, Supernova
Handbook, 2017)

Predictions of Signals from SNe & NSs



Progenitor Density Profiles





$$\xi_{2.5} \equiv \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}},$$

mass $M = 2.5\ M_\odot$

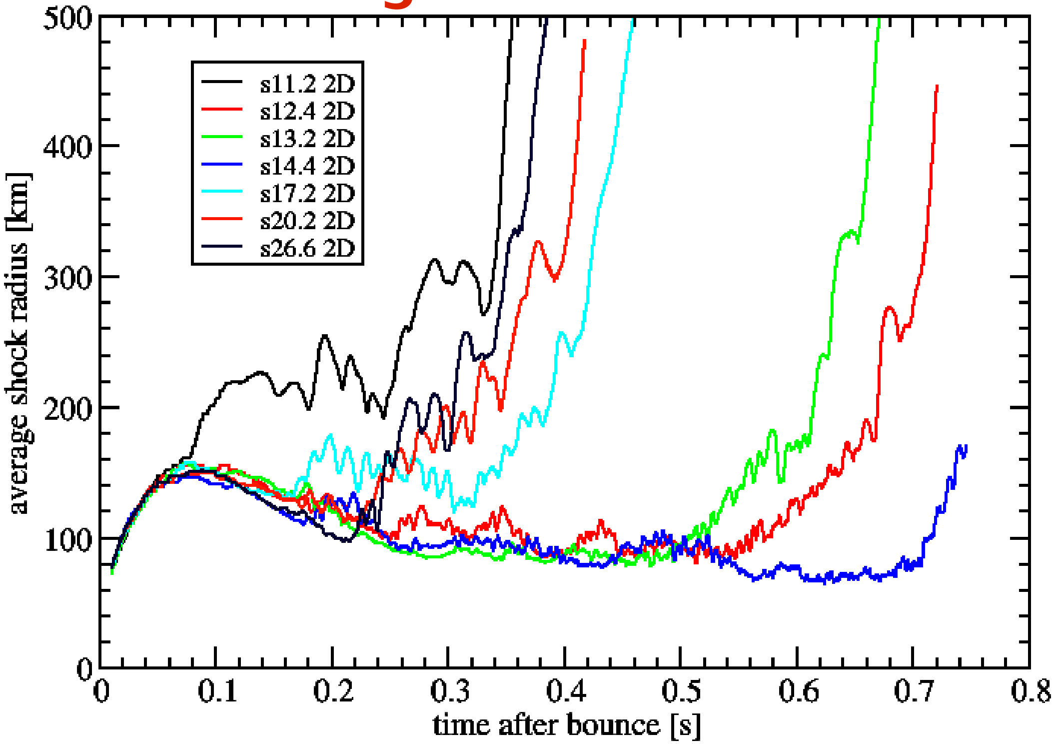
O'Connor & Ott, ApJ 730:70 (2011)

Growing Set of 2D CCSN Explosion Models

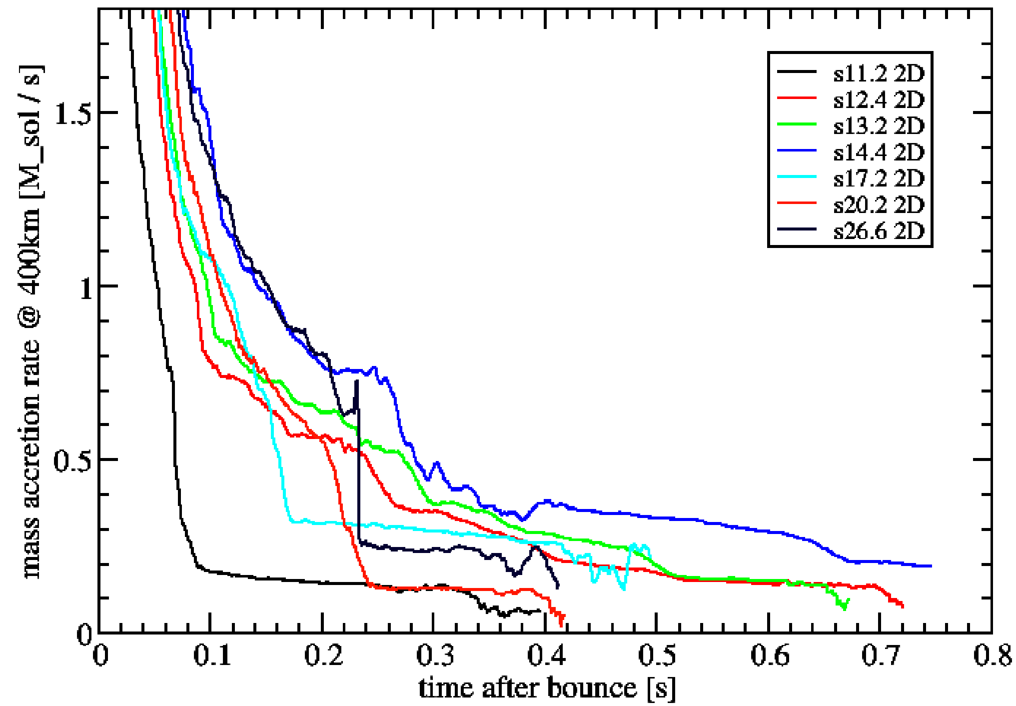
Decrease of mass-accretion rate at Si-O composition-shell interface allows for onset of explosions.

All cases computed with RPA NN correlations!

Average shock radius



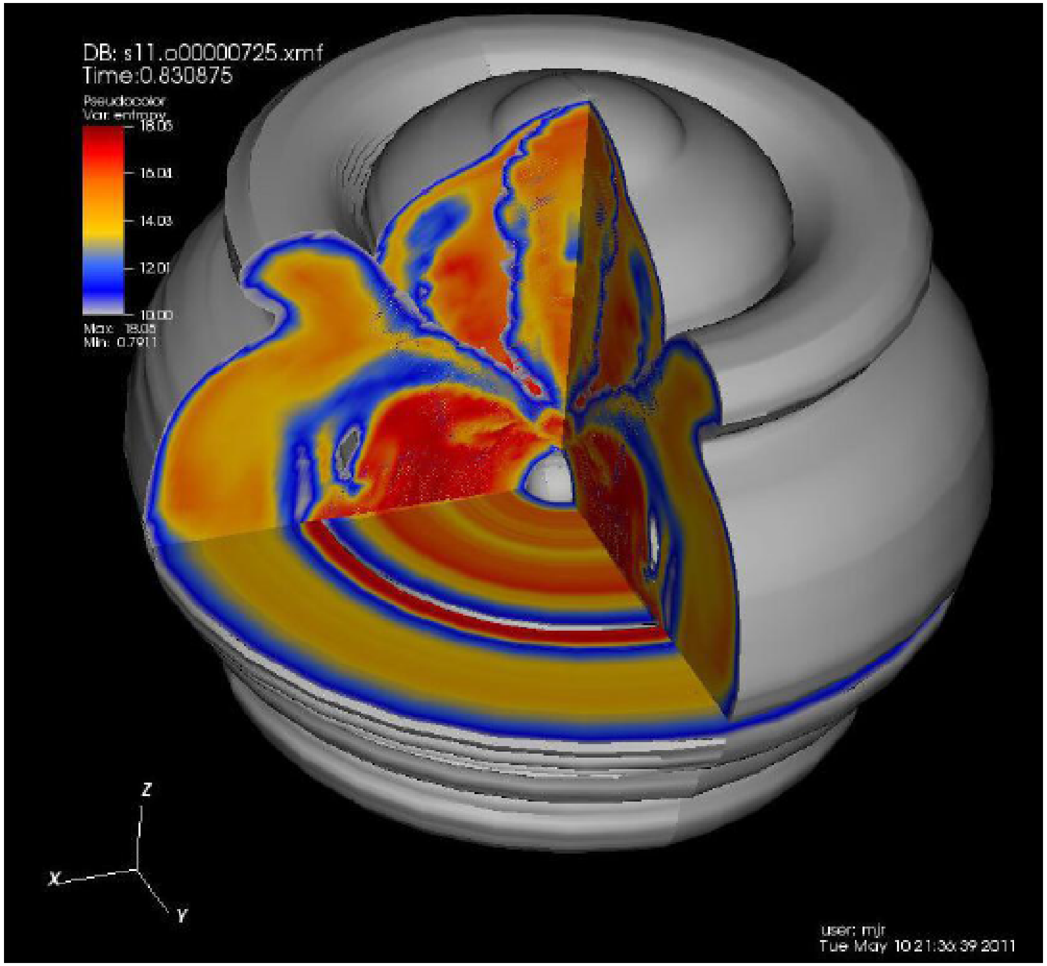
Mass accretion rate

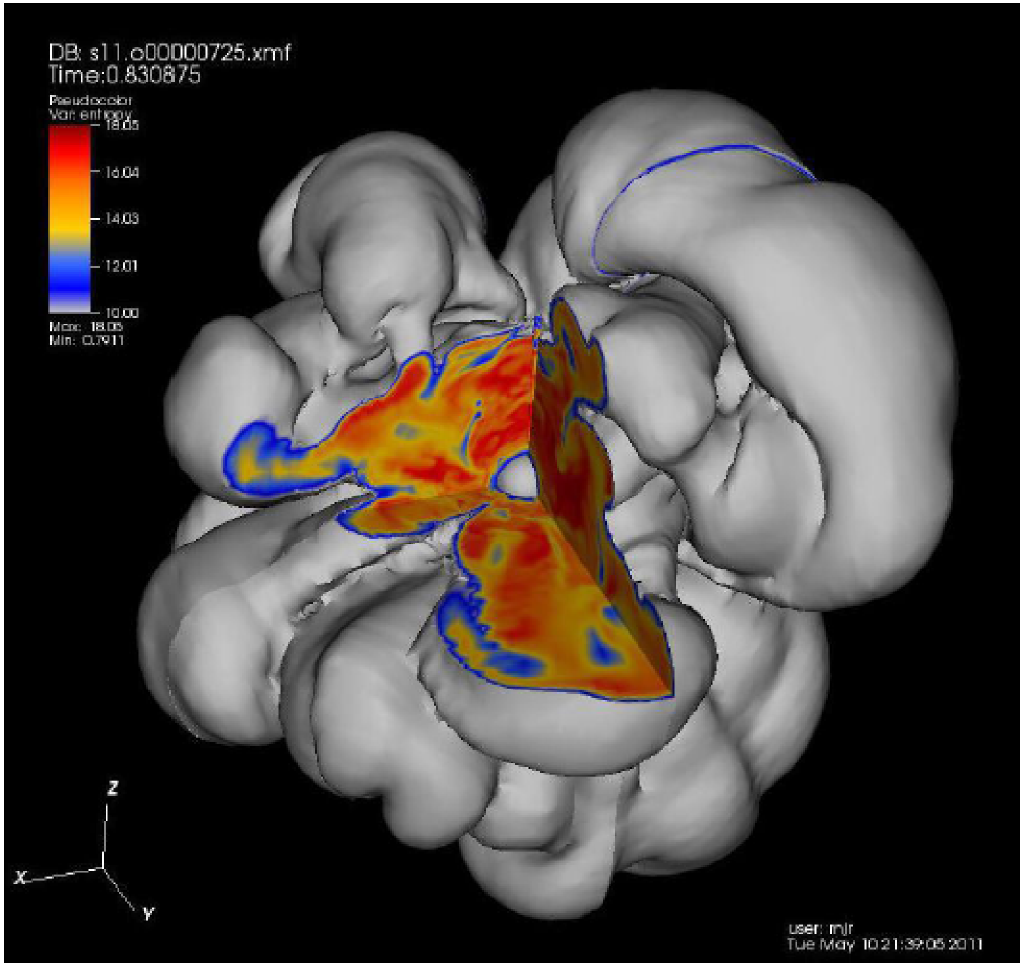


F. Hanke (2014, PhD Thesis, TUM);
A. Summa, F. Hanke, HTJ, et al., ApJ 825, 6 (2016)

Progenitor models: Woosley et al. RMP (2002)

2D and 3D Morphology



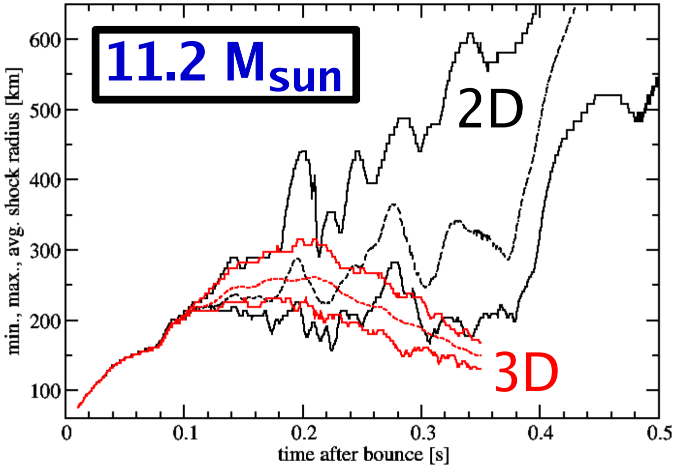


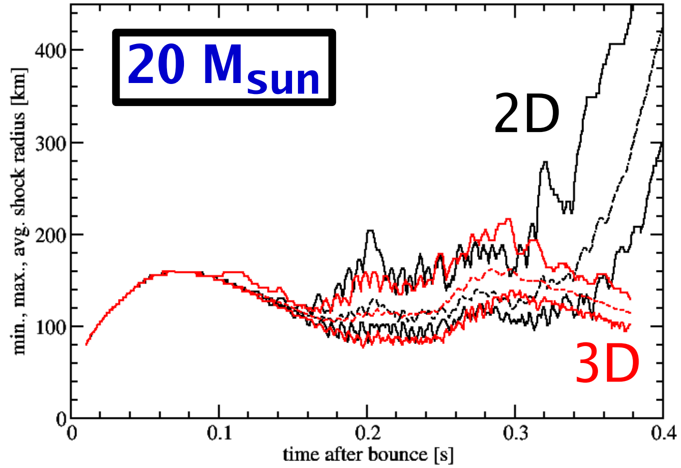
(Images from Markus Rampp, RZG)

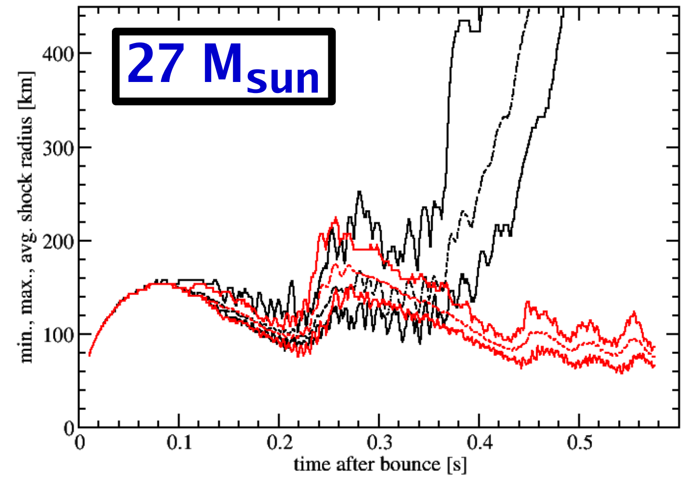
3D Core-Collapse SN Explosion Models

11.2, 20, 27 M_{sun} progenitors (WH 2007)

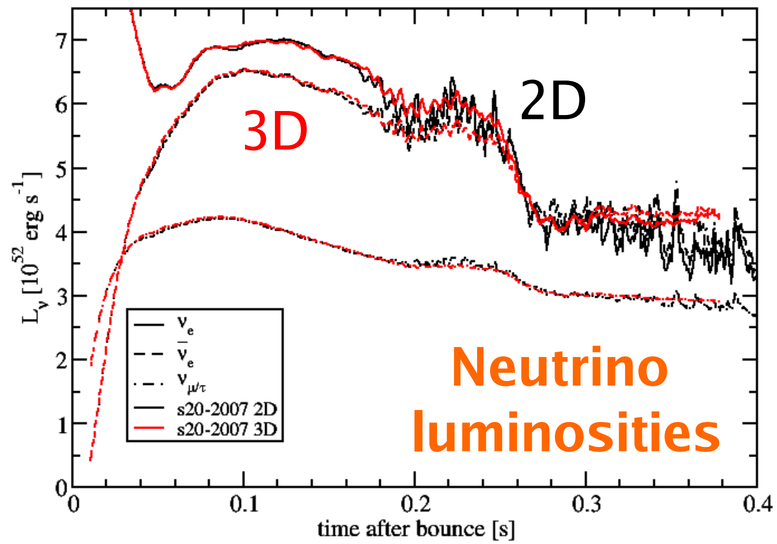
Shock radii (max., min., avg.) vs. time

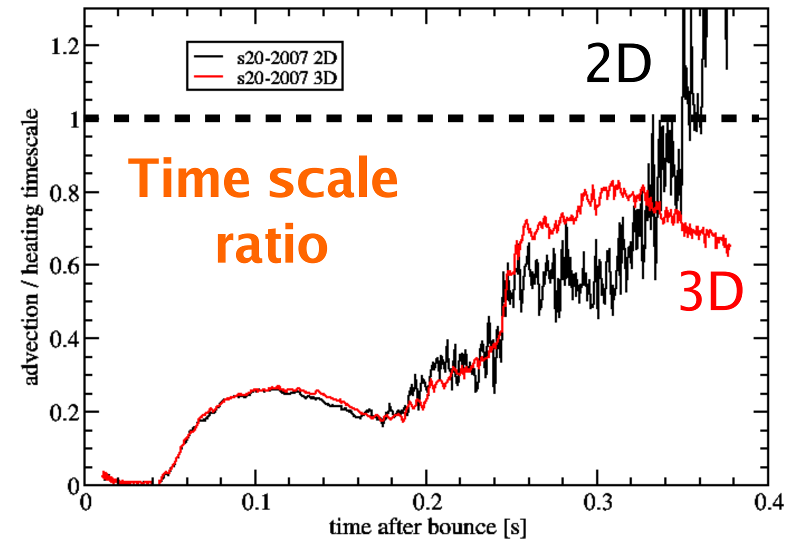






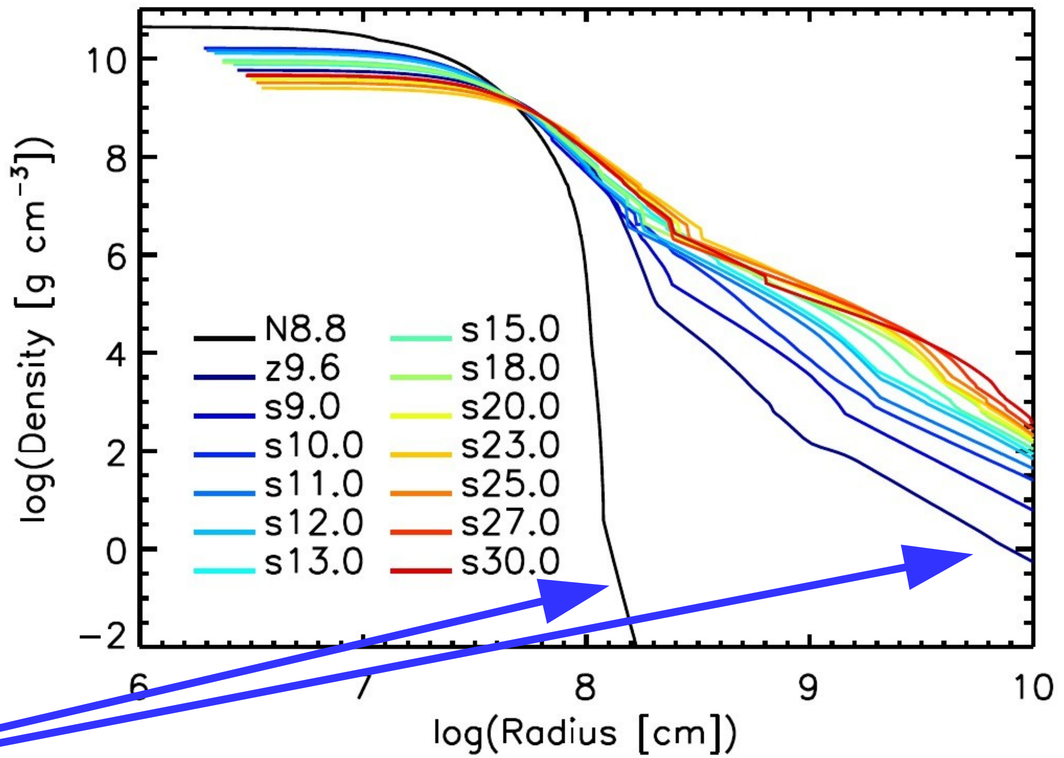
Florian Hanke,
PhD project (2014)



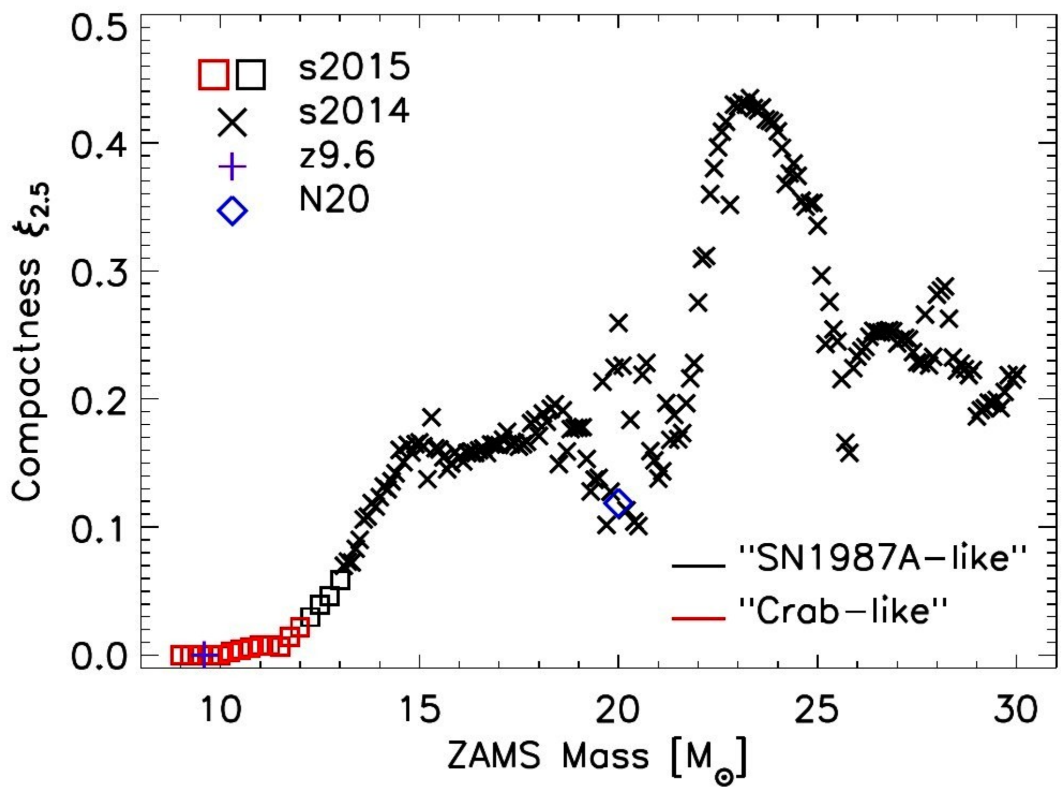


What can facilitate robust explosions in 3D?

Progenitor Density Profiles



Steep density gradients



$$\xi_{2.5} \equiv \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}},$$

$$\text{mass } M = 2.5\ M_\odot$$

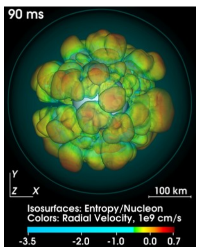
O'Connor & Ott, ApJ 730:70 (2011)

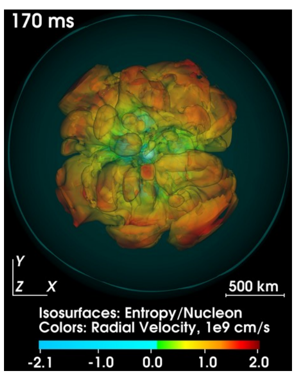
3D CCSN Explosion Models of Low-Mass Stars

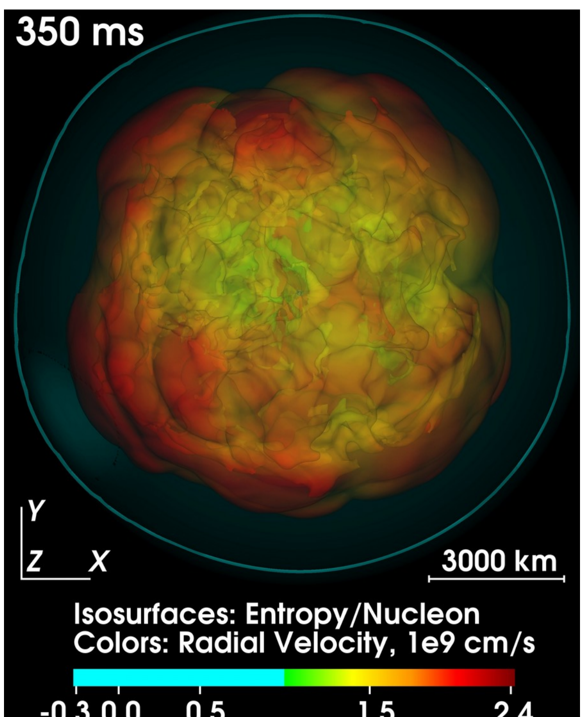
9.6 M_{sun} (zero-metallicity) progenitor (Heger 2010)

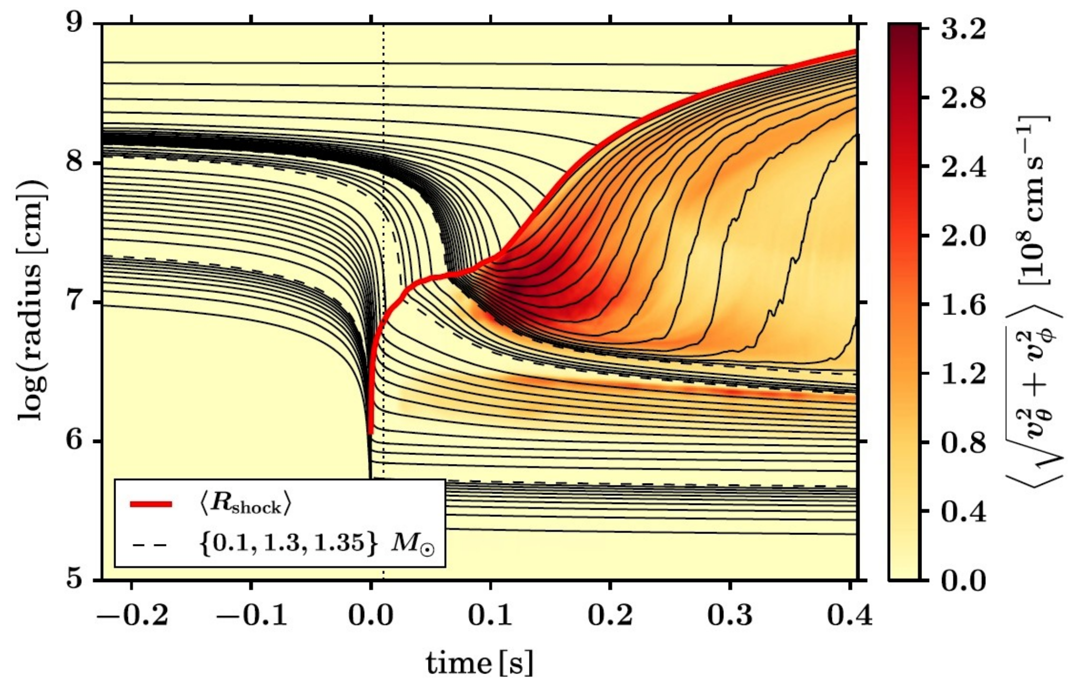
Fe-core progenitor (Heger 2012) with ECSN-like density profile and explosion behavior.

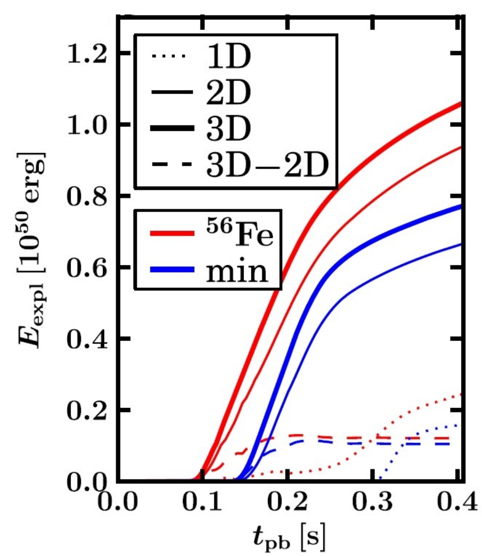
Melson et al., ApJL 801 (2015) L24





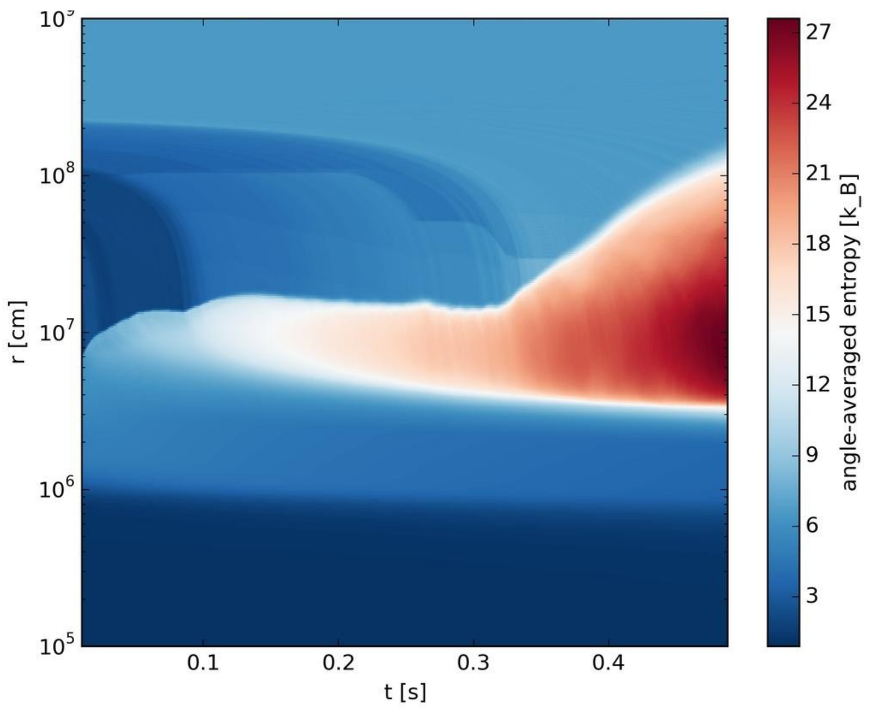


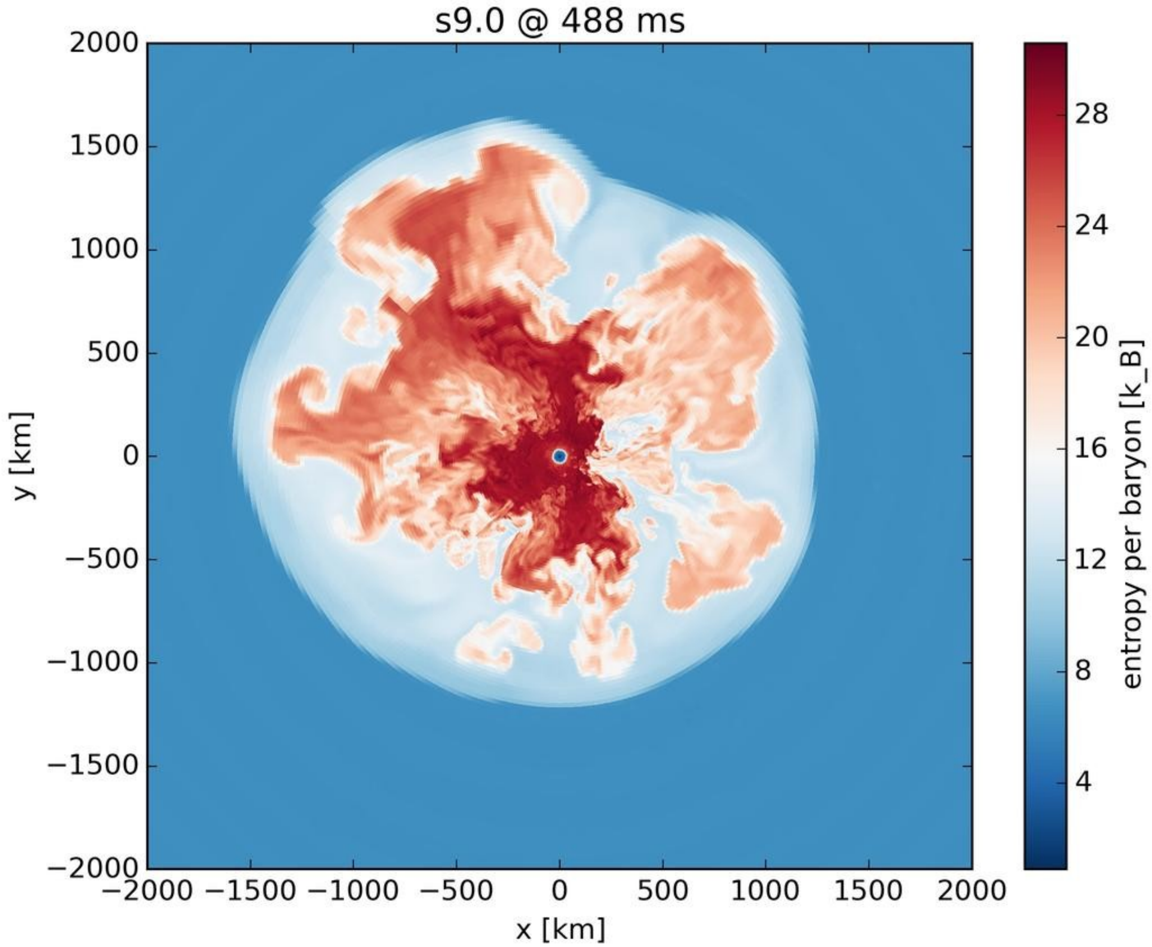




3D CCSN Explosion Models of Low-Mass Stars

9.0 M_{sun} progenitor (Wossley & Heger 2015)





T. Melson et al., in preparation

3D Core-Collapse SN Explosion Models

20 M_{sun} (solar-metallicity) progenitor (Woosley & Heger 2007)

Explore uncertain aspects of microphysics in neutrinospheric region:

Example: strangeness contribution to nucleon spin, affecting axial-vector neutral-current scattering of neutrinos on nucleons

$$\frac{d\sigma_0}{d\Omega} = \frac{G_F^2 \epsilon^2}{4\pi^2}\left[c_v^2(1+\cos\theta) + c_a^2(3-\cos\theta)\right], \quad (1)$$

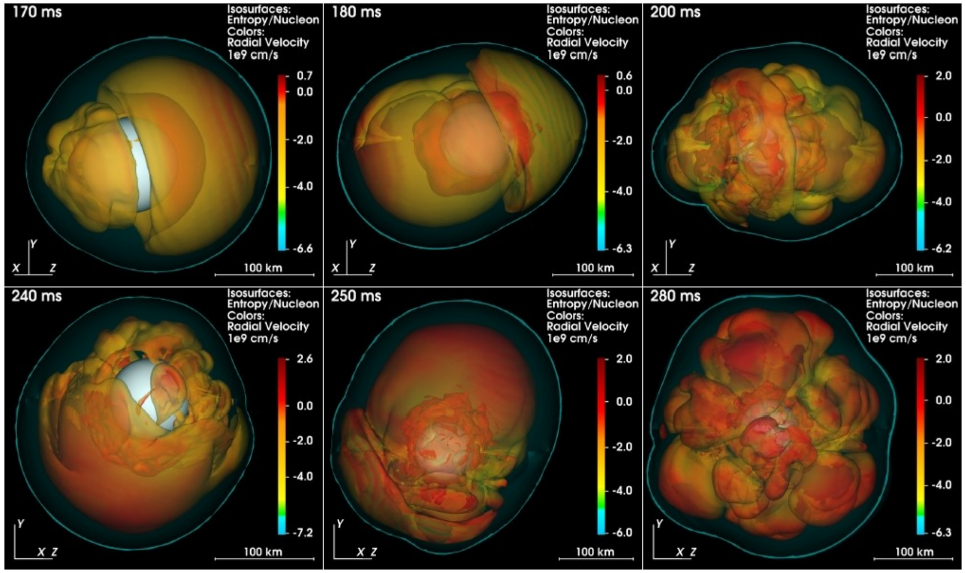
$$\sigma_0^t = \int_{4\pi} d\Omega \frac{d\sigma_0}{d\Omega}(1-\cos\theta) = \frac{2G_F^2\epsilon^2}{3\pi}\left(c_v^2 + 5c_a^2\right). \quad (2)$$

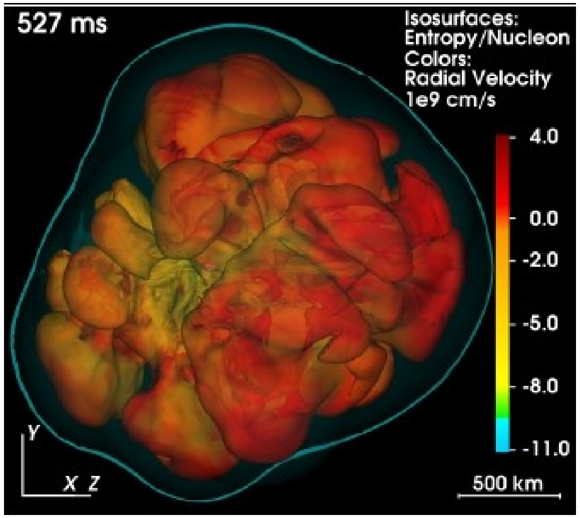
$$c_a = \frac{1}{2}\left(\pm g_a - g_a^s\right), \quad (3)$$

We use:
$g_a = 1.26$
$g_a^s = -0.2$

Currently favored theoretical & experimental (HERMES, COMPASS) value:
$g_a^s \sim -0.1$

Effective reduction of neutral-current neutrino-nucleon scattering by ~15%

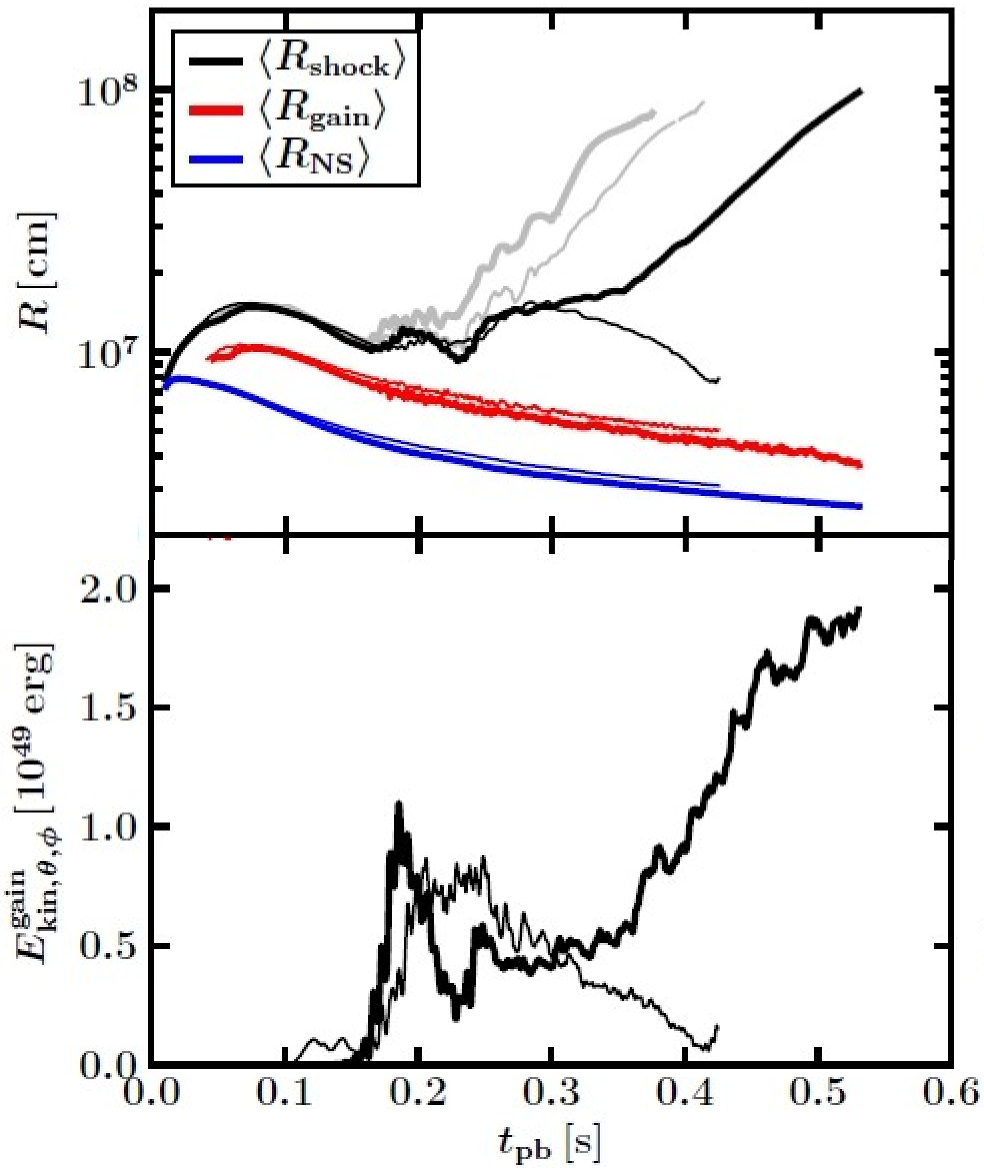


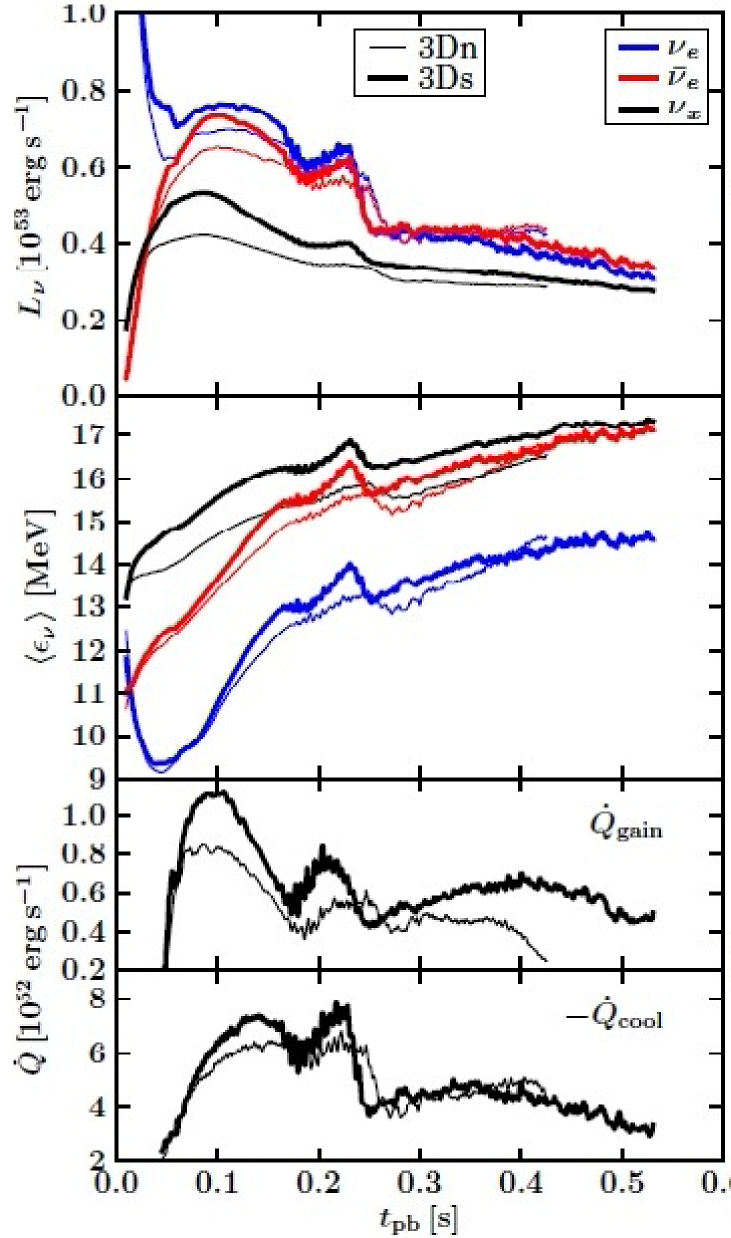


Melson et al., ApJL 808 (2015) L42

3D Core-Collapse SN Explosion Models

20 M_{sun} (solar-metallicity) progenitor (Woosley & Heger 2007)





Melson et al., ApJL 808 (2015) L42

3D CCSN Explosion Model with Rotation

15 M_{sun} rotating progenitor (Heger, Woosley & Spruit 2005)

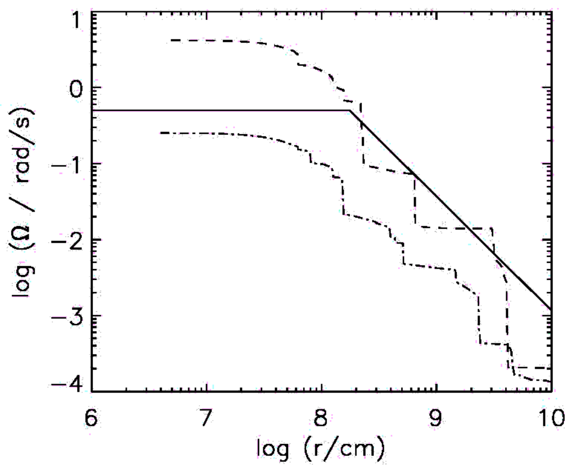
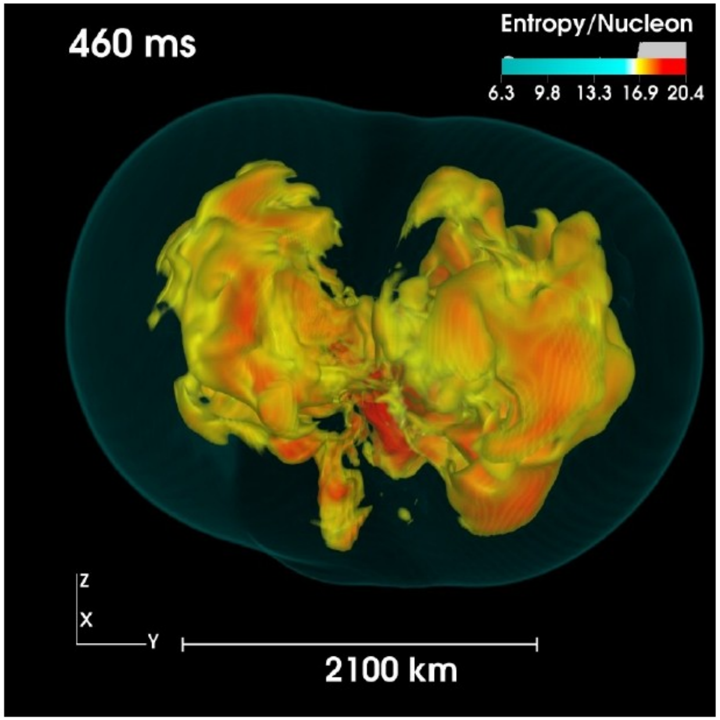
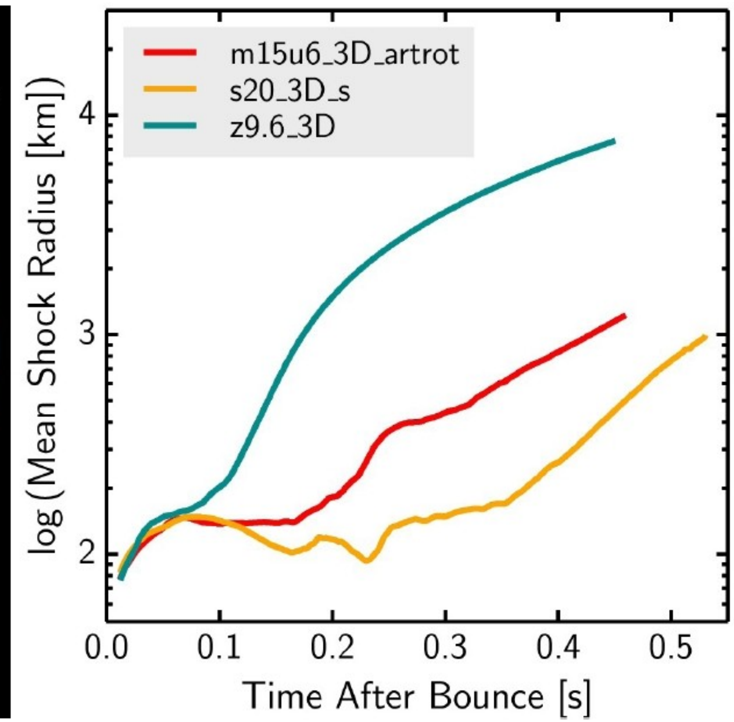


FIG. 1.—Angular velocity Ω as a function of radius *r* for the rotating 15 $M_\odot$ presupernova model (*dashed curve*) of Heger, Langer, & Woosley (2000), for the magnetic rotating 15 $M_\odot$ presupernova model (*dash-dotted curve*) of Heger et al. (2004), and for our rotating model s15r (*solid curve*).

Explosion occurs for angular velocity of Fe-core of 0.5 rad/s, rotation period of ~12 seconds (several times faster than predicted for magnetized progenitor by Heger et al. 2005).
Produces a neutron star with spin period of ~1–2 ms.



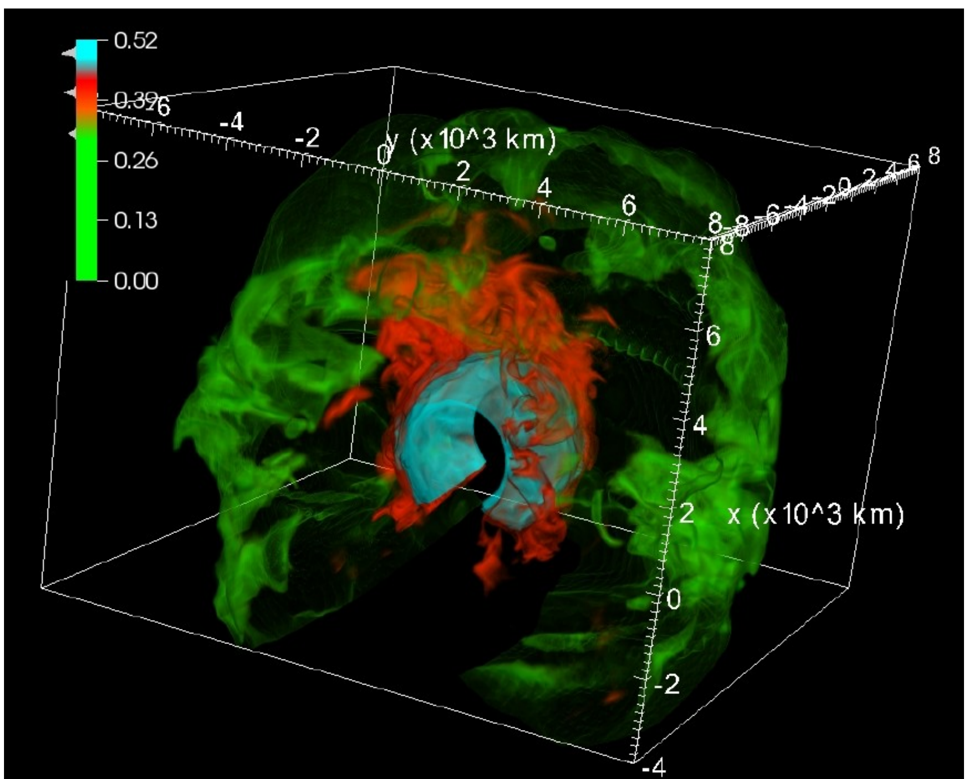


A. Summa (2015);
Janka, Melson & Summa,
ARNPS 66 (2016),
arXiv:1601.05576

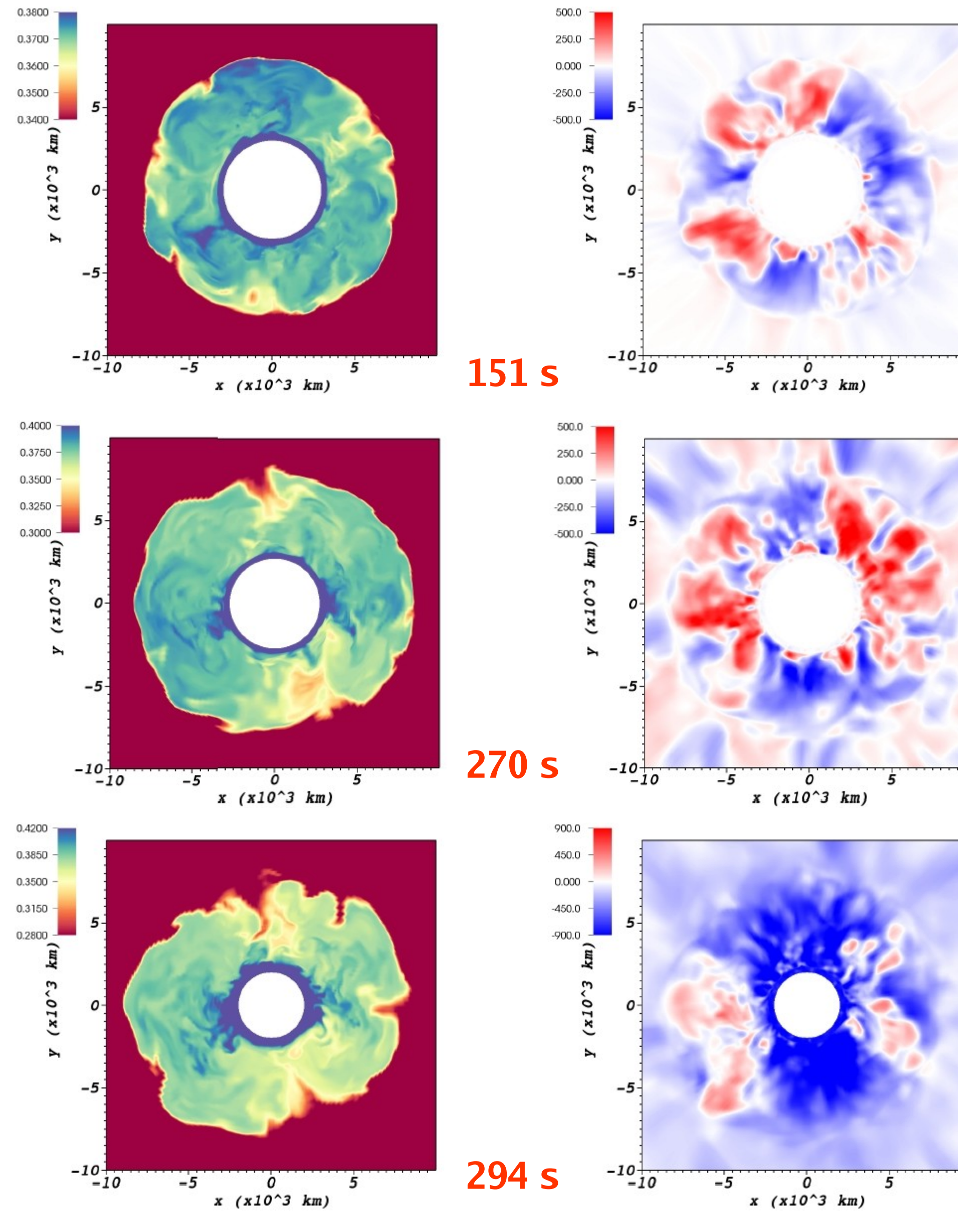
3D Core-Collapse SN Progenitor Model

18 M_{sun} (solar-metallicity) progenitor (Heger 2015)

3D simulation of last 5 minutes of O-shell burning. During accelerating core contraction a quadrupolar (l=2) mode develops with convective Mach number of about 0.1.
This will foster strong postshock convection and could thus reduce the criticial neutrino luminosity for explosion.



B. Müller, Viallet, Heger, & THJ, ApJ 833, 124 (2016)



3D Core-Collapse SN Explosion Model

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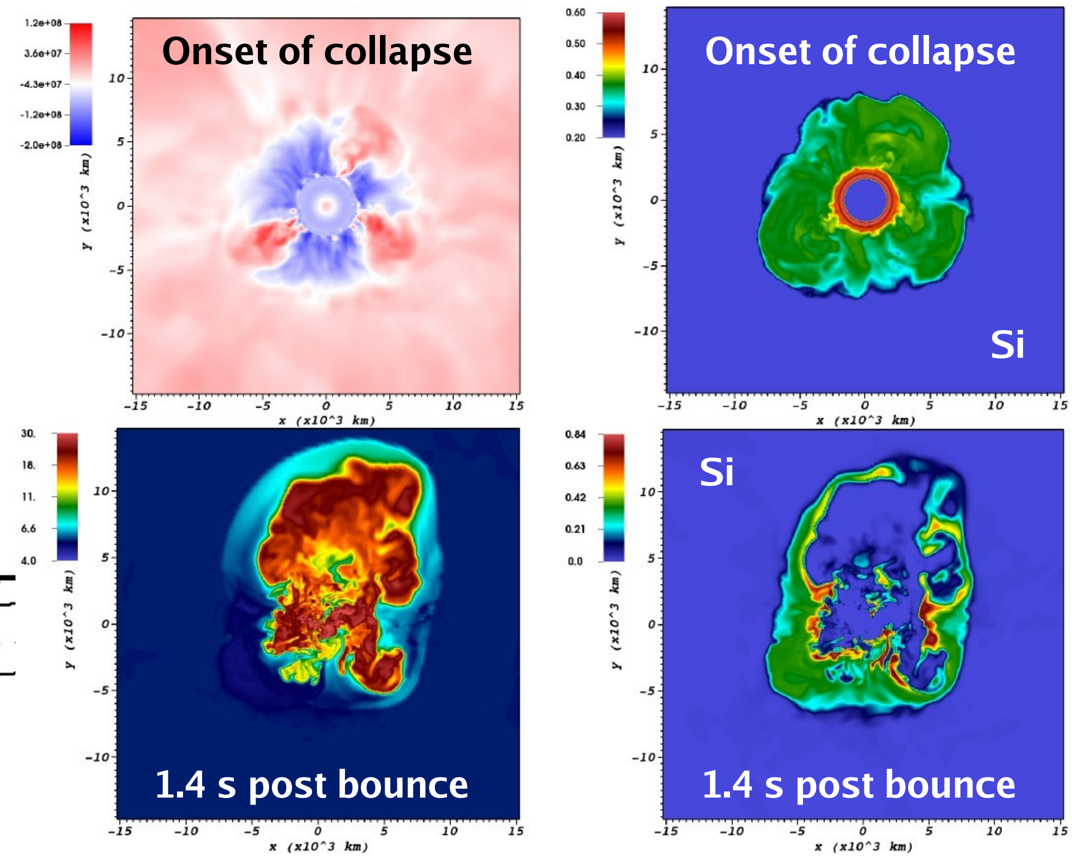
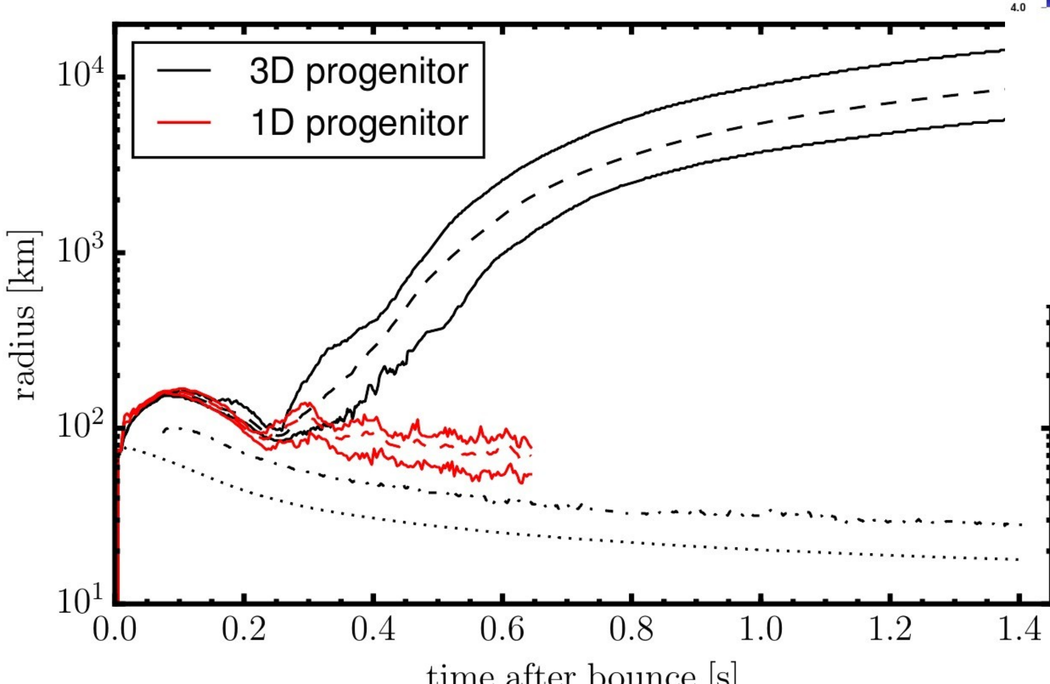
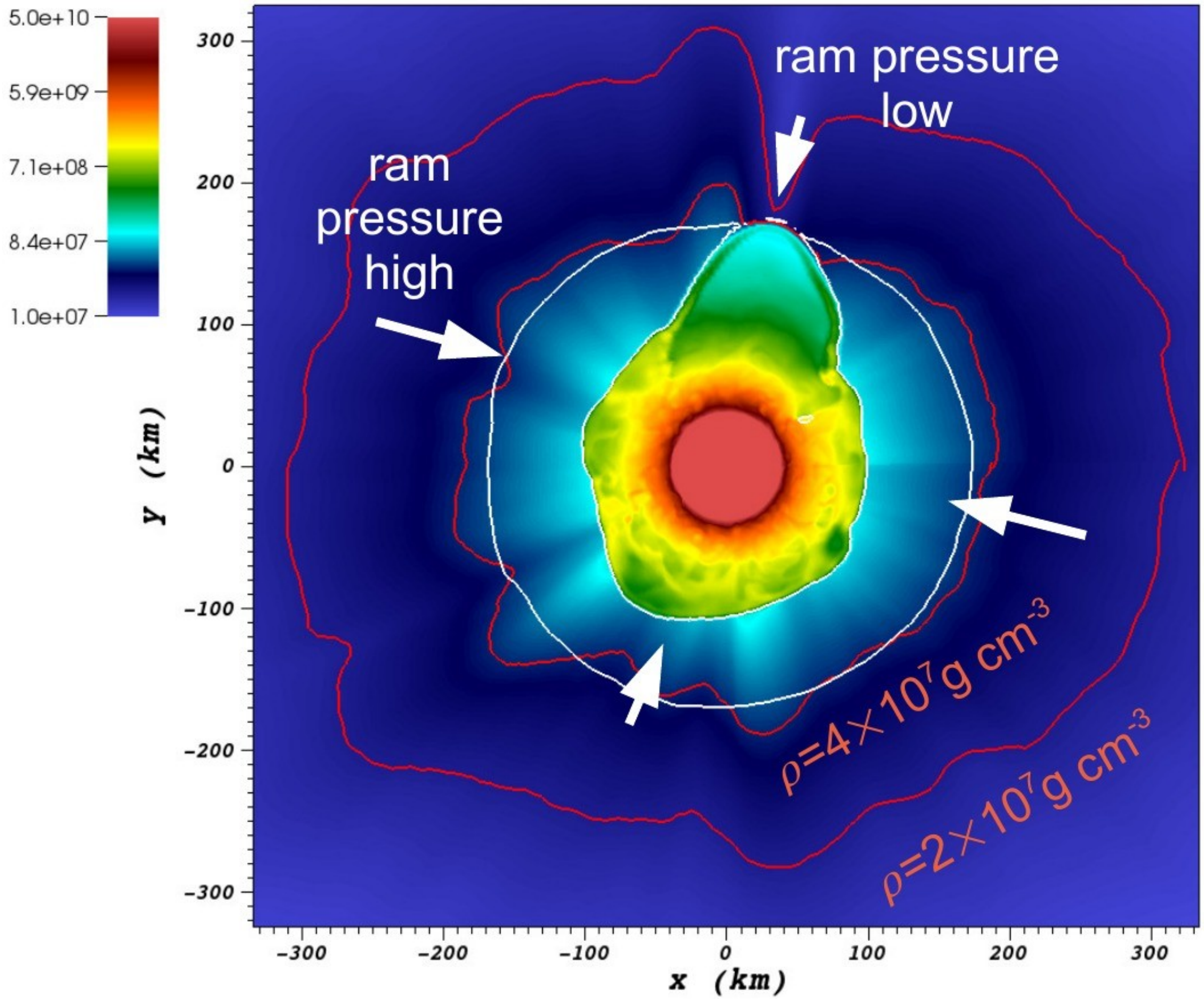




$\delta\rho/\rho \sim \mathrm{Ma}_{conv}$

$$(L_\nu E_\nu^2)_{\mathrm{crit,pert}} \approx (L_\nu E_\nu^2)_{\mathrm{crit,3D}} \left(1 - 0.47 \frac{\mathrm{Ma}_{\mathrm{conv}}}{\ell \eta_{\mathrm{acc}} \eta_{\mathrm{heat}}}\right)$$

B. Müller, PASA 33, 48 (2016);
Müller, Melson, Heger & THJ, arXiv:1705.00620



B. Müller, arXiv:1702.06940

3D Core-Collapse SN Explosion Models

Oak Ridge (Lentz et al., ApJL 2015):

15 M_{sun} nonrotating progenitor (Woosley & Heger 2007)

Tokyo/Fukuoka (Takiwaki et al., ApJ 2014):

11.2 M_{sun} nonrotating progenitor (Woosley et al. 2002)

Caltech/NCSU/LSU/Perimeter (Roberts et al., ApJ 2016):

27 M_{sun} nonrotating progenitor (Woosley et al. 2002)

Garching/QUB/Monash

(Melson+, ApJL 2015a,b; Müller 2016; Janka et al. 2016, Müller+ 2017):

9.6, 20 M_{sun} nonrotating progenitors (Heger 2012; Woosley & Heger 2007)

18 M_{sun} nonrotating progenitor (Heger 2015)

15 M_{sun} rotating progenitor (Heger, Woosley & Spuit 2005, modified rotation)

9.0 M_{sun} nonrotating progenitor (Woosley & Heger 2015)

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

- 2D models with relativistic effects (2D GR and approximate GR) explode for "soft" EoSs, but explosion energies tend to low side.
- 3D modeling has only begun. No final picture of 3D effects yet.

- **$M < 10\ M_{sun}$ stars explode in 3D.**
  First 3D explosions of 15–20 M_{sun} progenitors
  (with rotation, 3D progenitor perturbations or slightly reduced neutrino-nucleon scattering opacities).

- 3D simulations **still need higher resolution** for convergence.
- **Progenitors are 1D**, but shell structure and initial progenitor-core asymmetries can affect onset of explosion.
  (cf. Couch et al. ApJL778:L7 (2013), arXiv:1503.02199; Müller & THJ, MNRAS 448 (2015) 2141)
- **Uncertain/missing physics ?????**

Muons in Hot Neutron-Star Medium

arXiv:1706.04630

R. Bollig, THJ, G. Martinez-Pinedo, A. Lohs, C. Horowitz, & T. Melson

- Muon rest mass much larger than electron rest mass:

$$m_\mu c^2 \approx 105.66\,\mathrm{MeV}$$

- Therefore muons have traditionally been ignored in SN and NS-merger modeling.
- **But: Temperatures T > 30 MeV and electron chemical potentials μ_e > 100 MeV can be reached easily.**

- Consequence: muon abundance is **not** negligibly small.

$$e^- + e^+ \longrightarrow \mu^- + \mu^+ \,, \qquad \gamma + \gamma \longrightarrow \mu^- + \mu^+$$

Muons in Hot Neutron-Star Medium

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

$$\nu_\ell + n \longleftrightarrow p + \ell^- \,,$$
$$\bar{\nu}_\ell + p \longleftrightarrow n + \ell^+ \,,$$

with ℓ standing for electrons or muons.

- At equilibrium, the corresponding relation for between the chemical potentials holds for both electrons and muons:

$$\Delta\mu \equiv \mu_n - \mu_p = \mu_\ell - \mu_{\nu_\ell} \,.$$

Neutrino Reactions in Supernovae

Beta processes:	• $e^- + p \rightleftharpoons n + \nu_e$ • $e^+ + n \rightleftharpoons p + \bar{\nu}_e$ • $e^- + A \rightleftharpoons \nu_e + A^*$
Neutrino scattering:	• $\nu + n, p \rightleftharpoons \nu + n, p$ • $\nu + A \rightleftharpoons \nu + A$ • $\nu + e^\pm \rightleftharpoons \nu + e^\pm$
Thermal pair processes:	• $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$ • $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$
Neutrino-neutrino reactions:	• $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$ $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{ or } \bar{\nu}_\tau)$ • $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Muons in Hot Neutron-Star Medium

- Additional reactions of neutrinos with muons need to be included and couple neutrinos of different flavors:

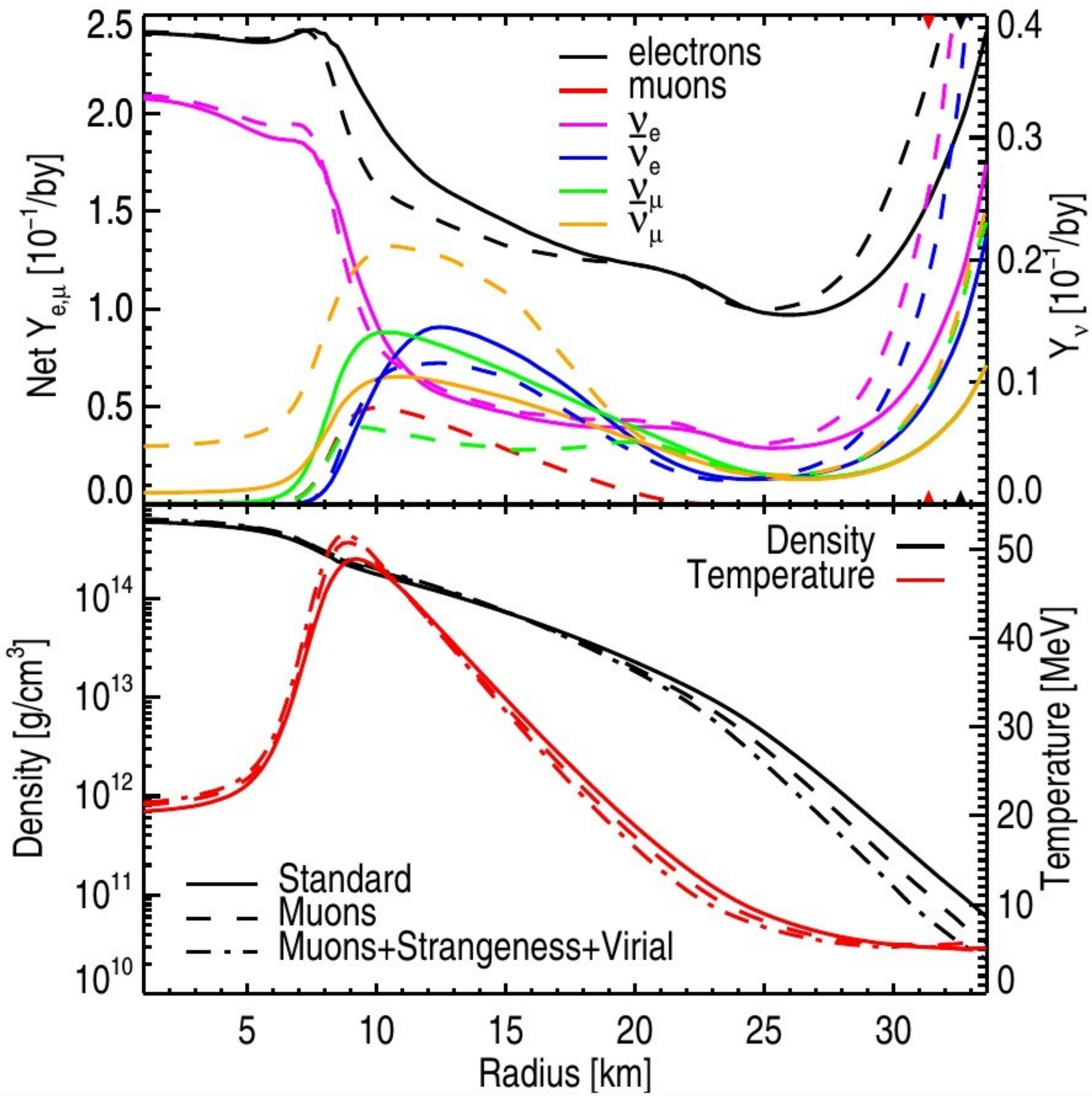
TABLE I. Neutrino reactions with muons.

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

Muons in Hot Neutron-Star Medium

Proto-neutron star at 400 ms after core bounce:

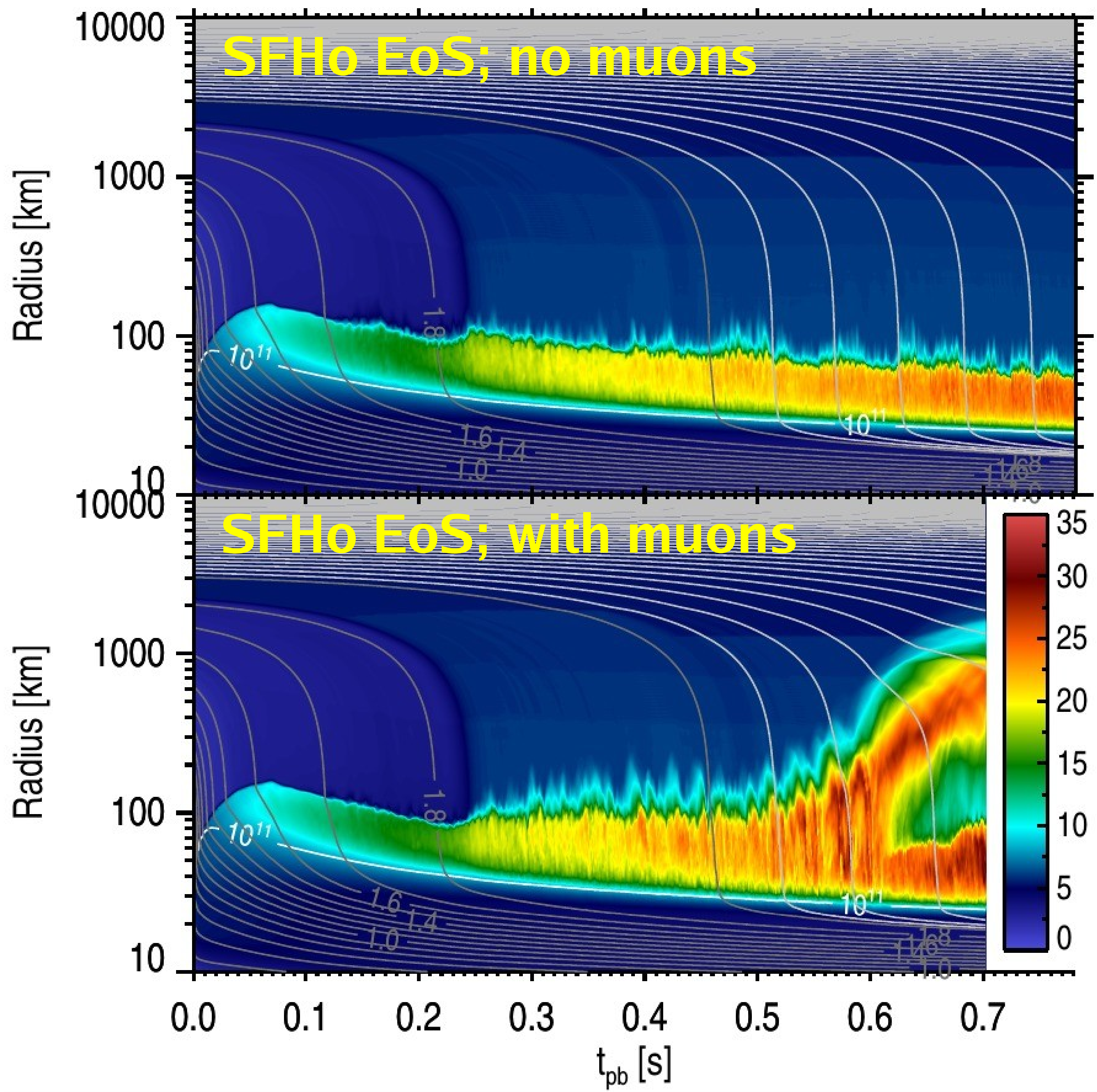
Due to presence of muons the EoS is softened and the NS radius shrinks



Muons in Hot Neutron-Star Medium

2D simulations of 20 Msun non-rotating progenitor

Neutrino-driven supernova explosions are favored by appearance of muons!

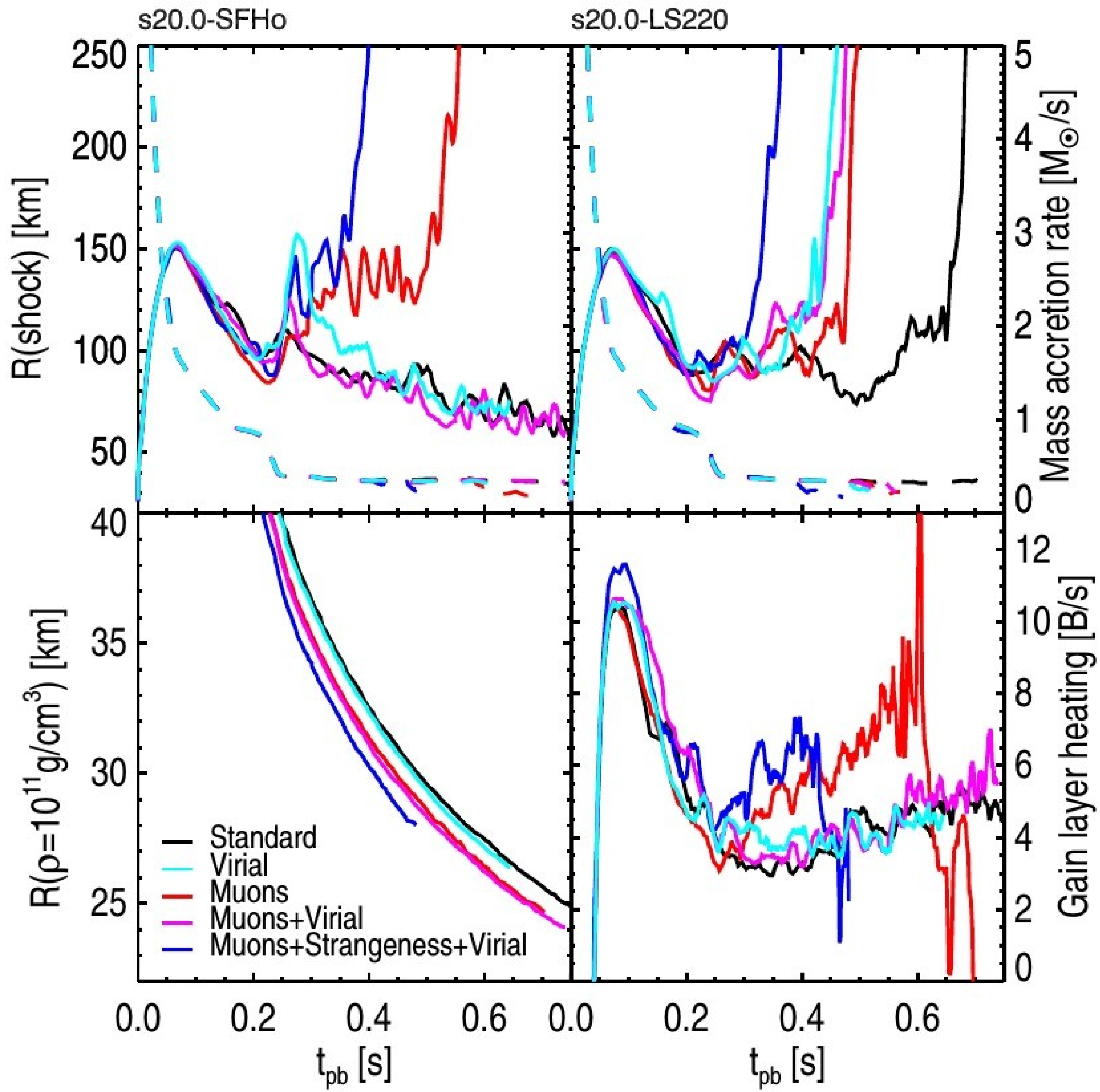


Muons in Hot Neutron-Star Medium

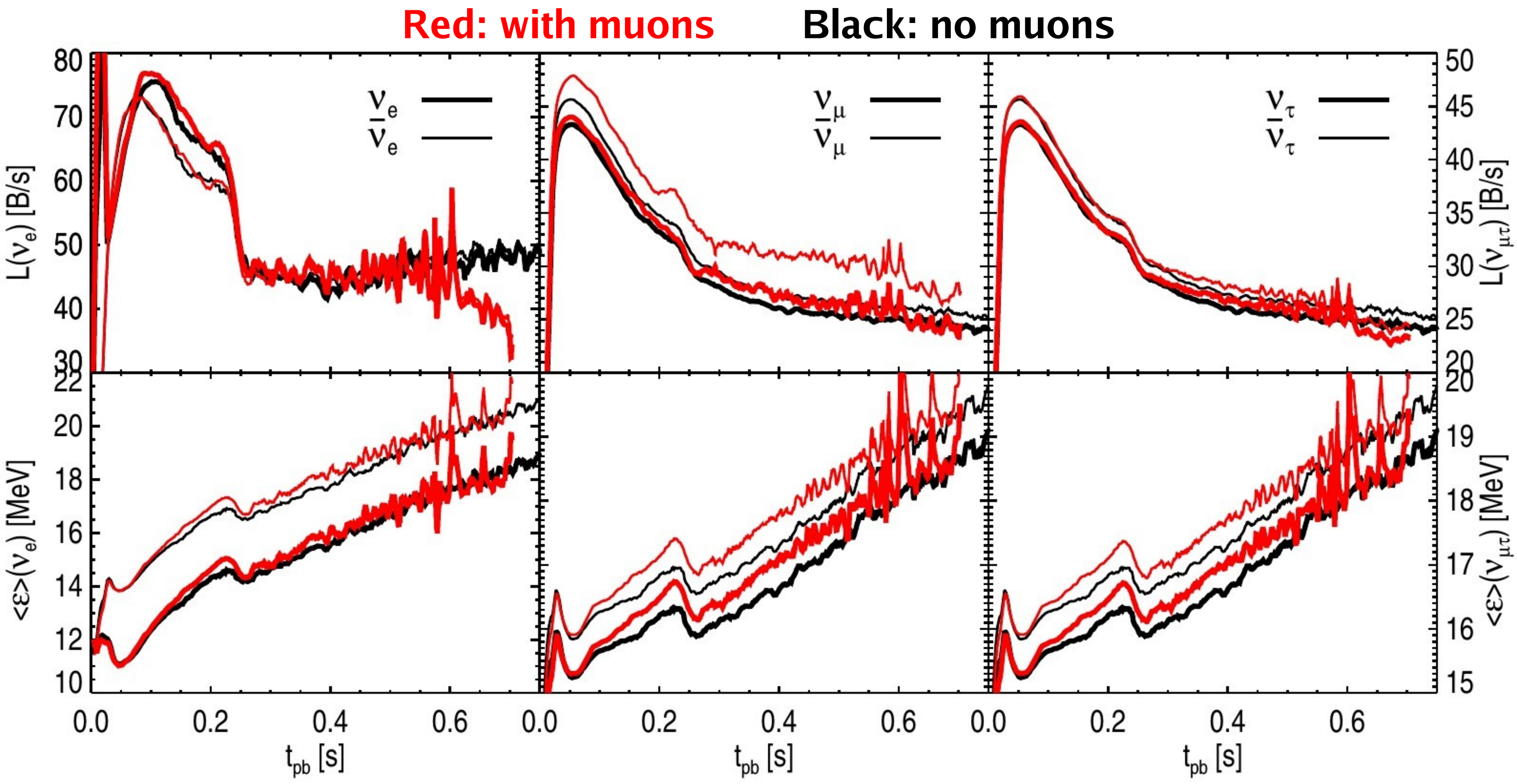
Neutrino-driven supernova explosions are favored by appearance of muons!

- **Here:**

  2D simulations of 20 Msun non-rotating progenitor



Muons in Hot Neutron-Star Medium



Muon formation softens EoS and NS radius shrinks:

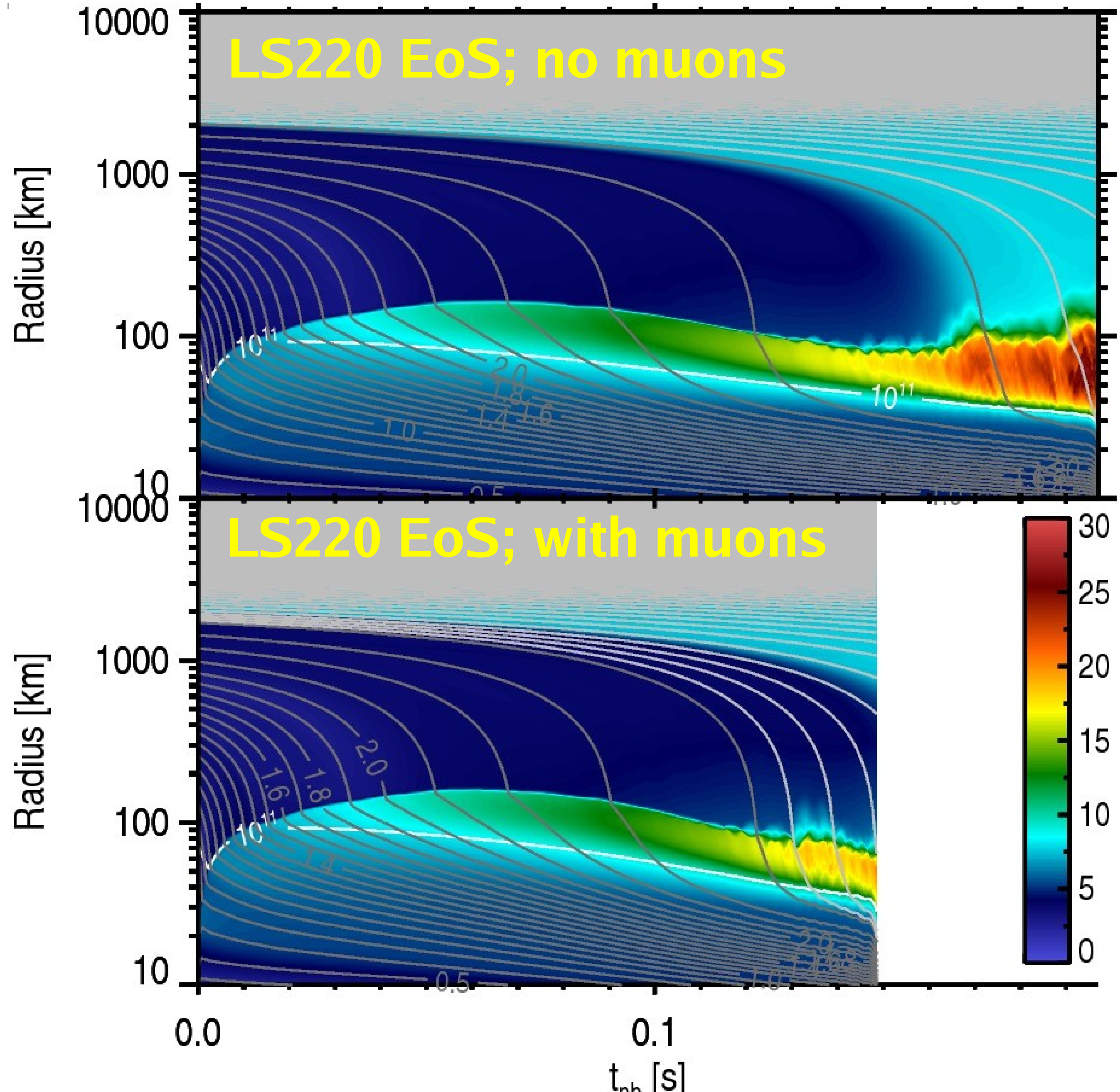
Therefore also electron neutrino and antineutrino luminosities and neutrino heating is enhanced, can trigger SN explosion.

Muons in Hot Neutron-Star Medium

75 M_{sun} star

Collapse of hot NS is much faster when muons are included!

Muons reduce maximum mass of hot neutron star by 0.05–0.1 M_{sun}



Muons in Hot Neutron-Star Medium: 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