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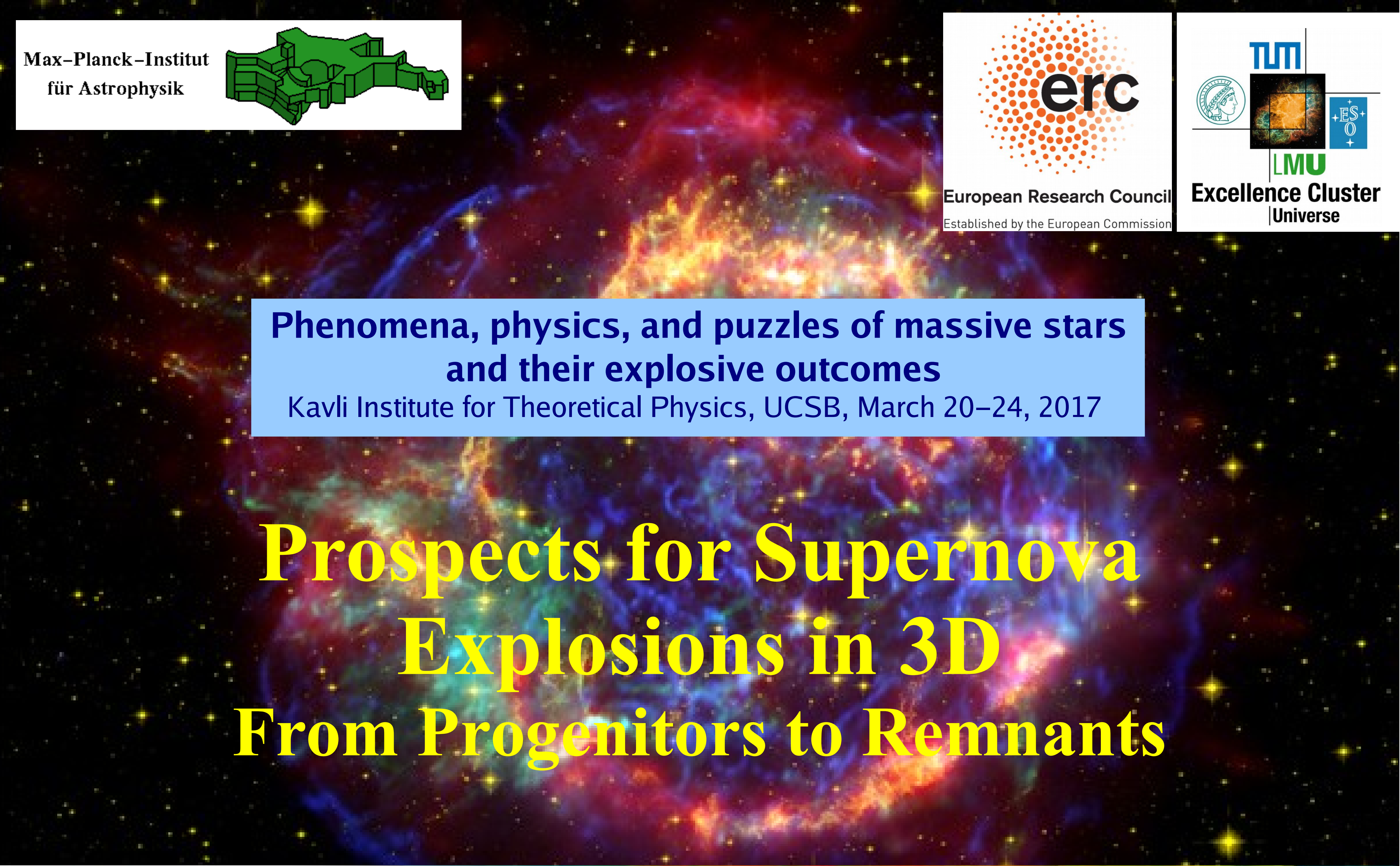

Phenomena, physics, and puzzles of massive stars and their explosive outcomes
Kavli Institute for Theoretical Physics, UCSB, March 20–24, 2017

Prospects for Supernova Explosions in 3D

From Progenitors to Remnants

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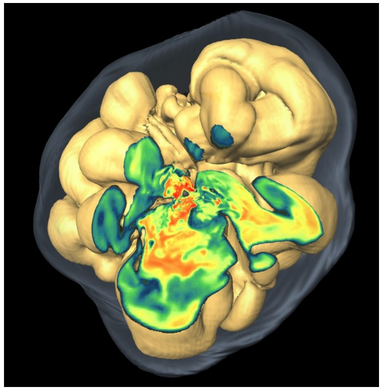
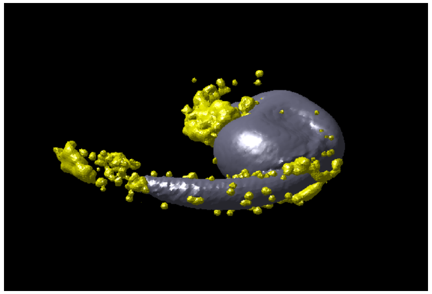
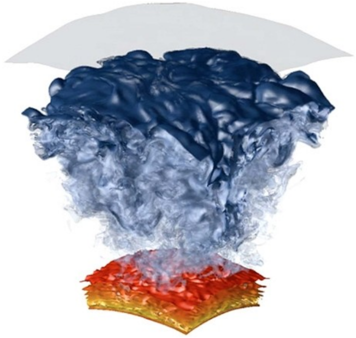
**Hans-Thomas Janka
for the Team**

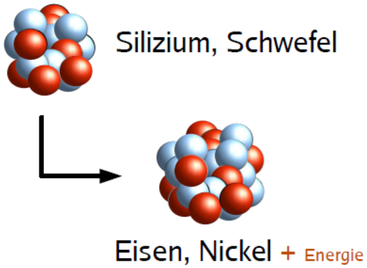
COCO2CASA

Supernovae, neutron star mergers, stellar evolution, neutrino astrophysics and nucleosynthesis: Team effort









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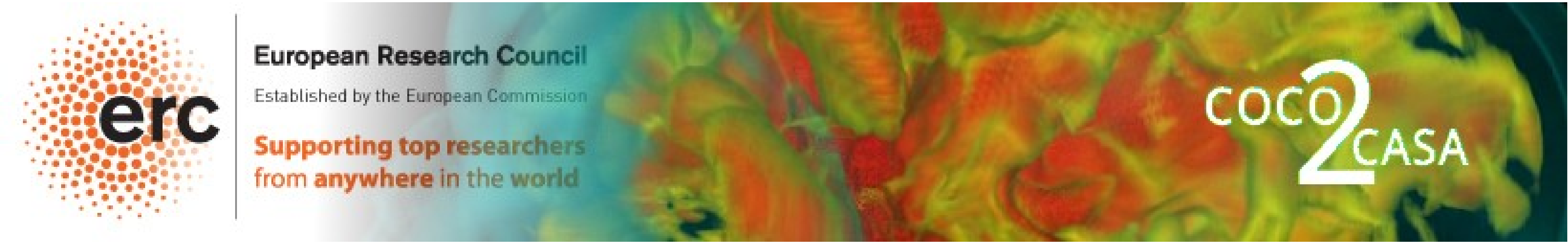


COCO2CASA: Goals

Connecting Supernova Progenitors with Supernova Remnants

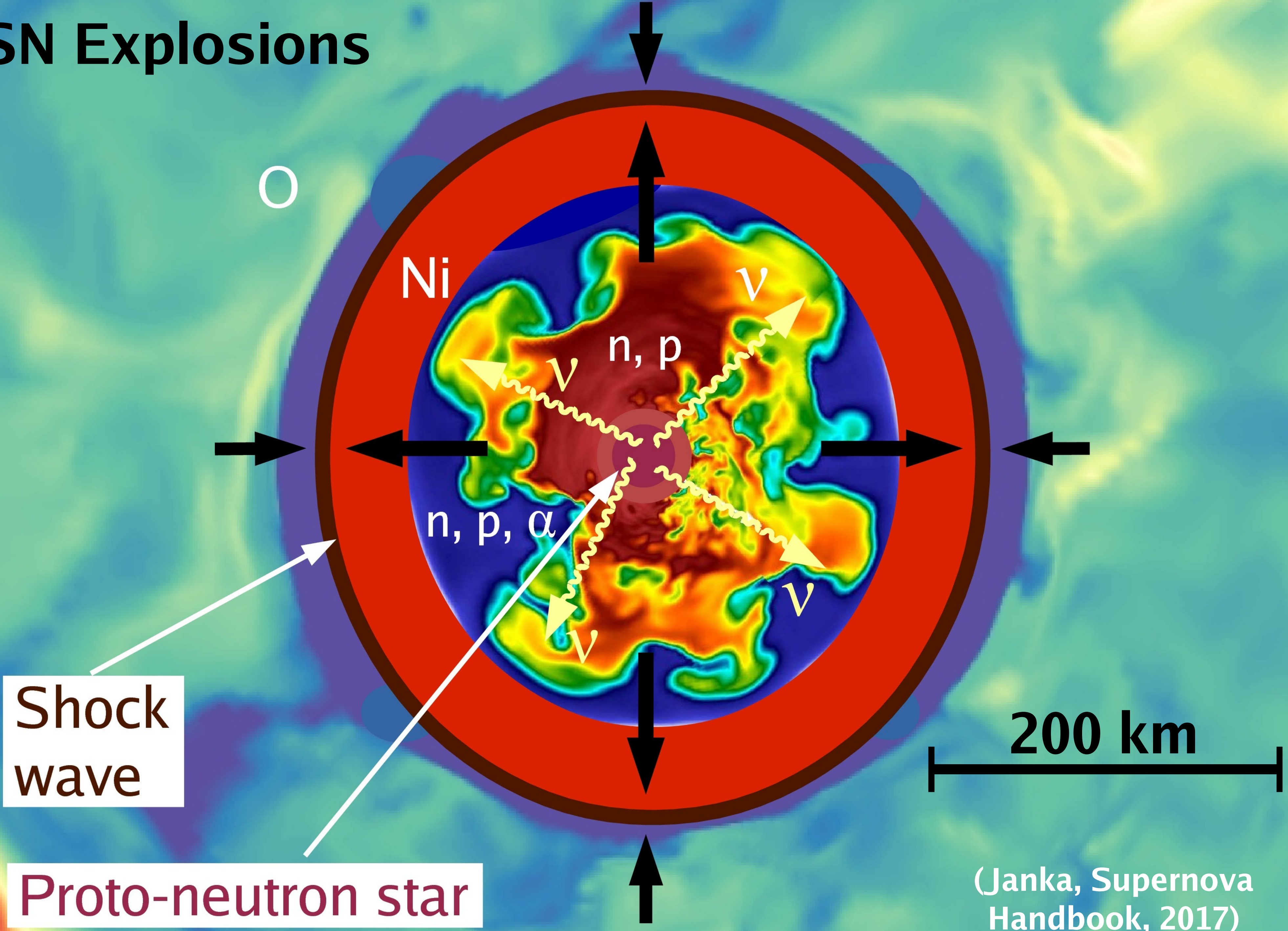
- 3D modeling of latest burning stages of pre-collapse stars
- 3D modeling of SN explosion mechanism
- 3D modeling of evolution from SN explosion to SN-remnant phase

Dedicated targets:

- Explanation of morphological and chemical properties of young, nearby, well studied SN remnants, e.g., Crab, Cas A, SN 1987A
- Collecting indirect evidence of neutrino-driven explosion mechanism

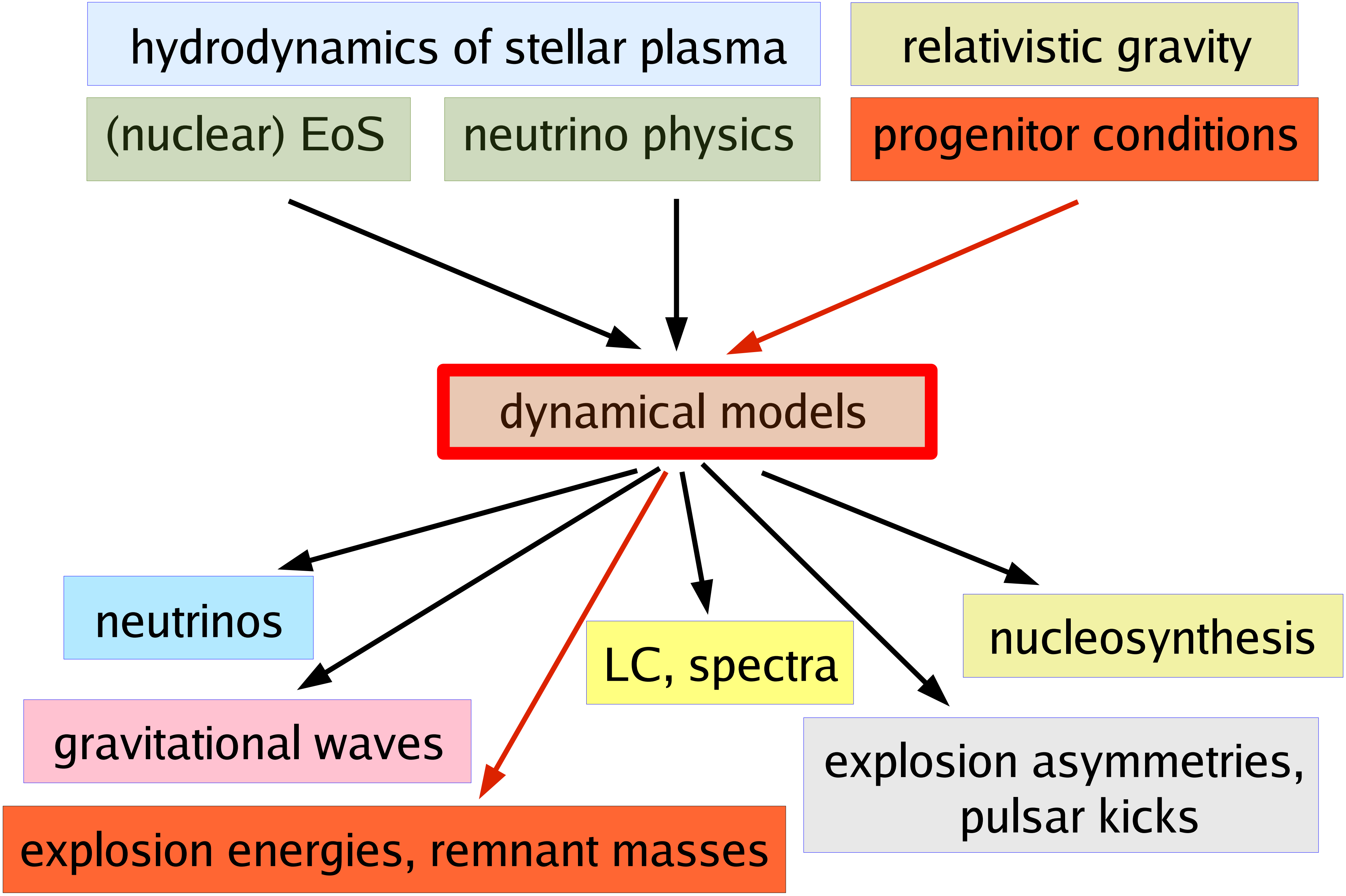
Neutrino-driven SN Explosions

Shock revival



(Janka, Supernova Handbook, 2017)

Predictions of Signals from SNe & NSs



hydrodynamics of stellar plasma

relativistic gravity

(nuclear) EoS

neutrino physics

progenitor conditions

dynamical models

neutrinos

gravitational waves

explosion energies, remnant masses

LC, spectra

explosion asymmetries, pulsar kicks

nucleosynthesis

The Simulation Code

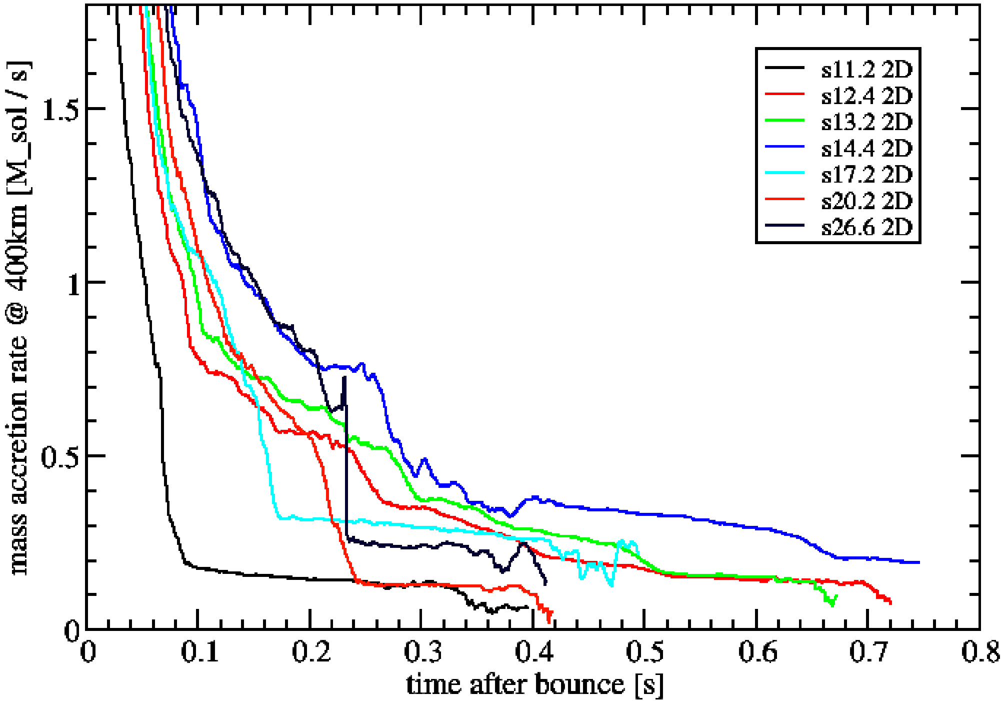
Prometheus/CoCoNuT – VERTEX: 1D, 2D, 3D

- Hydro modules:
  Newtonian: *Prometheus* + effective relativistic grav. potential.
  General relativistic: *CoCoNuT*
  Higher-order Godunov solvers, explicit.
- Neutrino Transport: *VERTEX*
  Two-moment closure scheme with variable Eddington factor based on model Boltzmann equation; fully energy-dependent, O(v/c), implicit, ray-by-ray-plus in 2D and 3D.
- Most complete set of neutrino interactions applied to date.
- Different nuclear equations of state.
- Spherical polar grid or axis-free Yin-Yang grid.

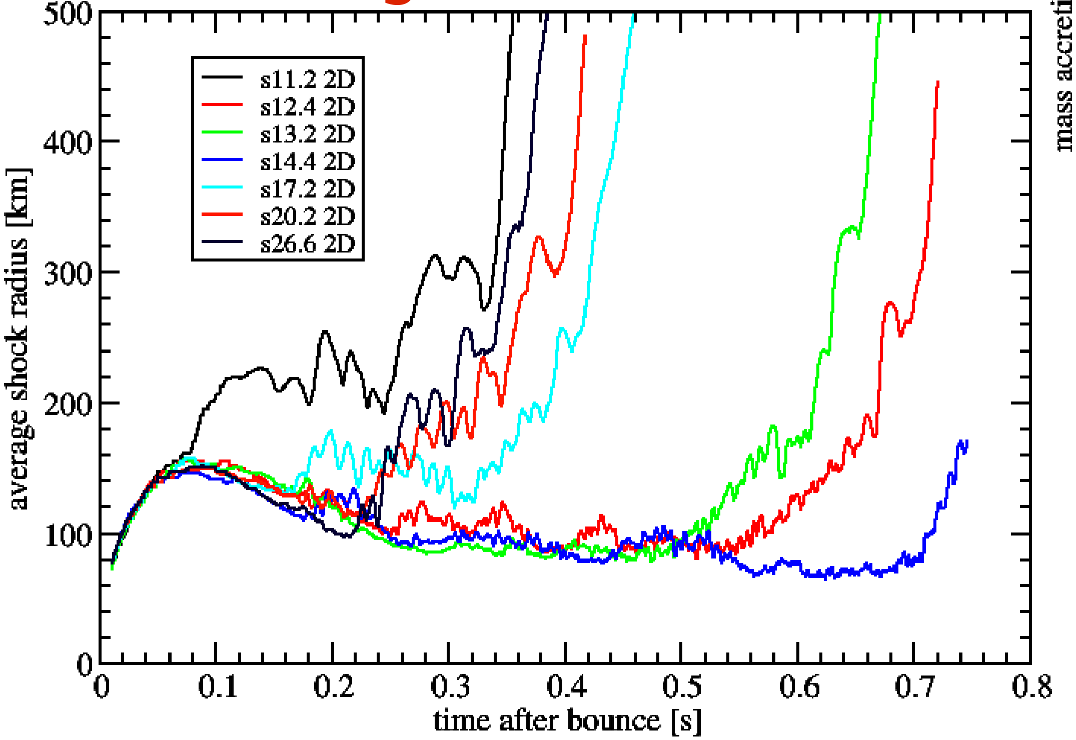
Growing Set of 2D CCSN Explosion Models

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

Mass accretion rate



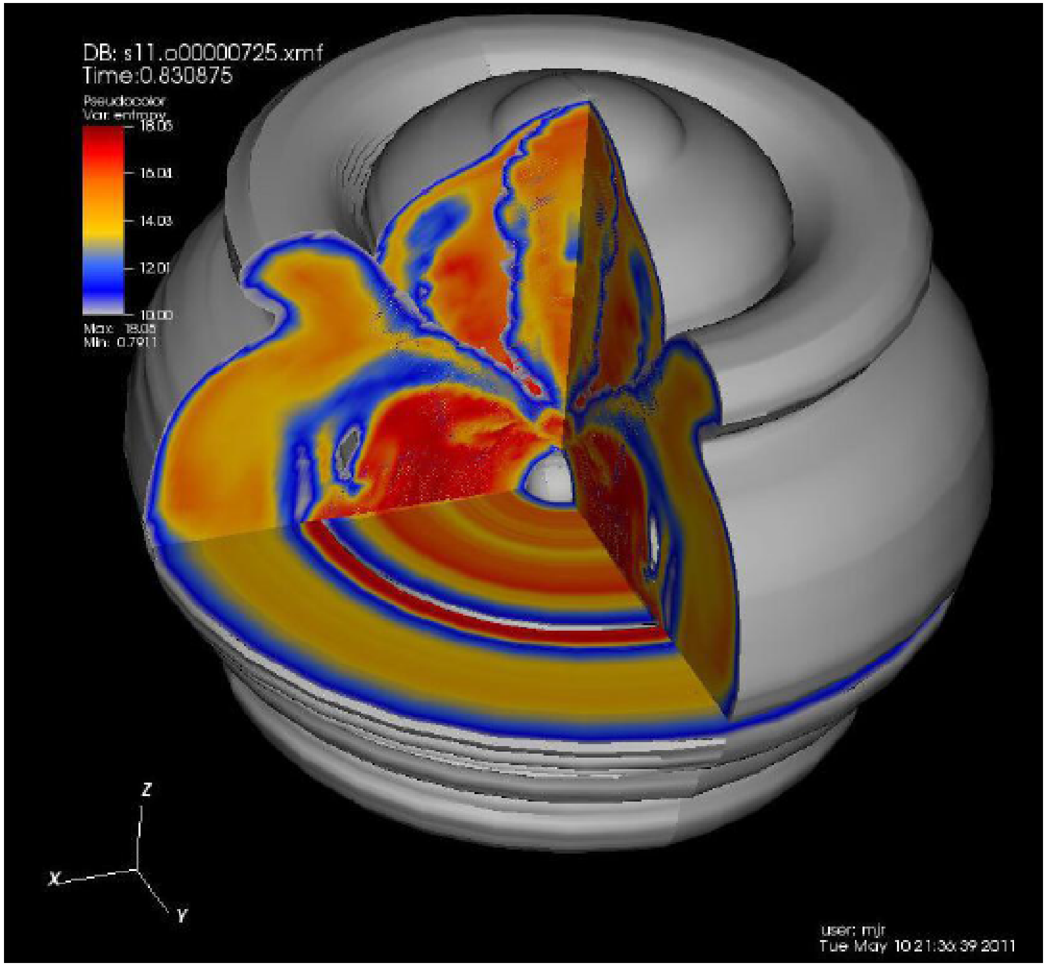
Average shock radius

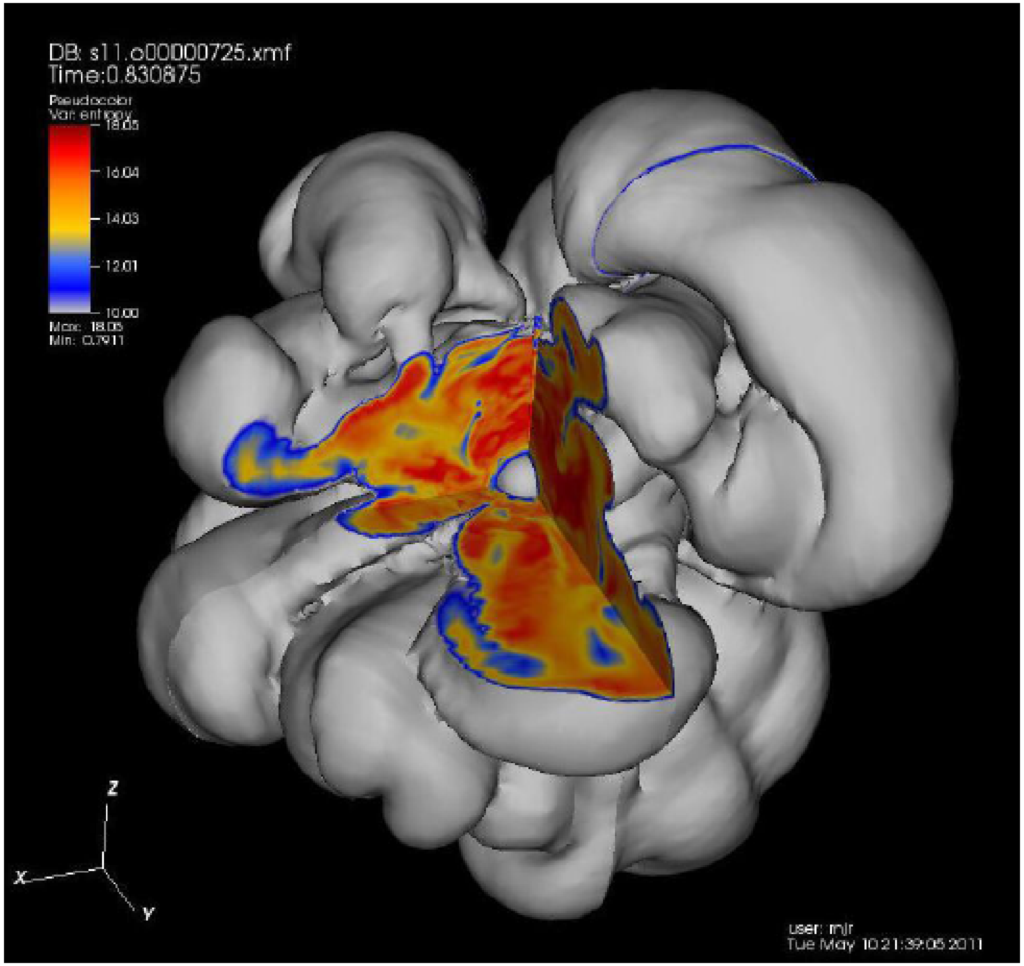


F. Hanke (2014, PhD Thesis, TUM);
A. Summa, F. Hanke, HTJ, et al., ApJ 825, 6 (2016)

Progenitor models: Woosley et al. RMP (2002)

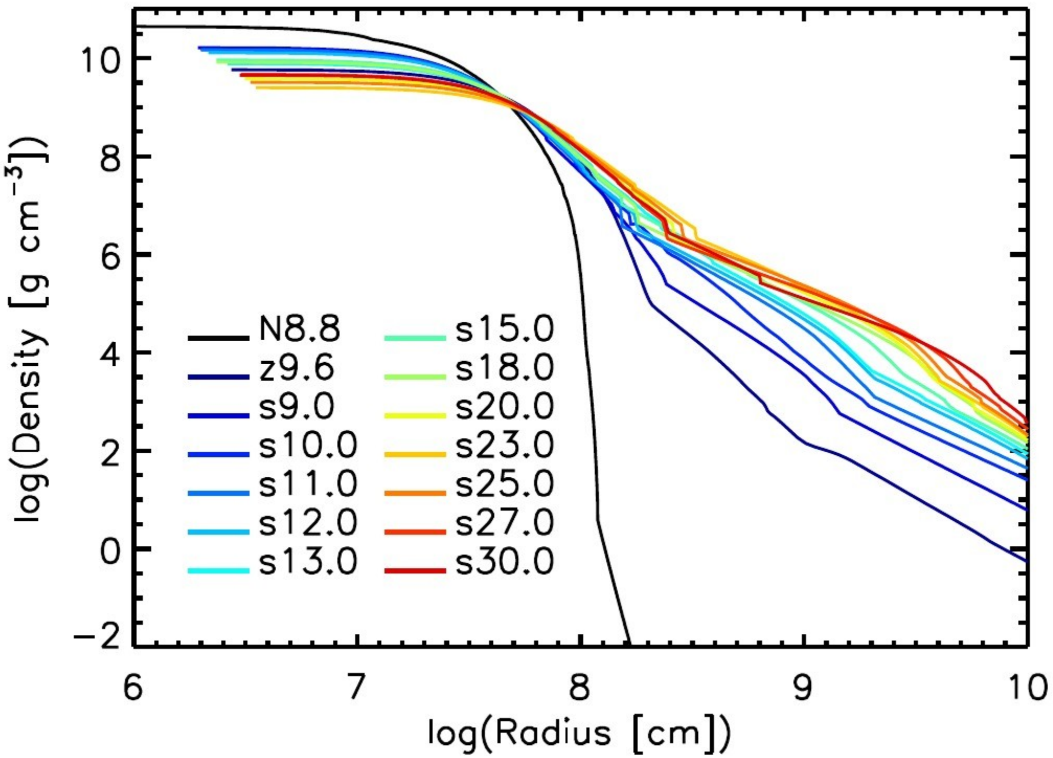
2D and 3D Morphology

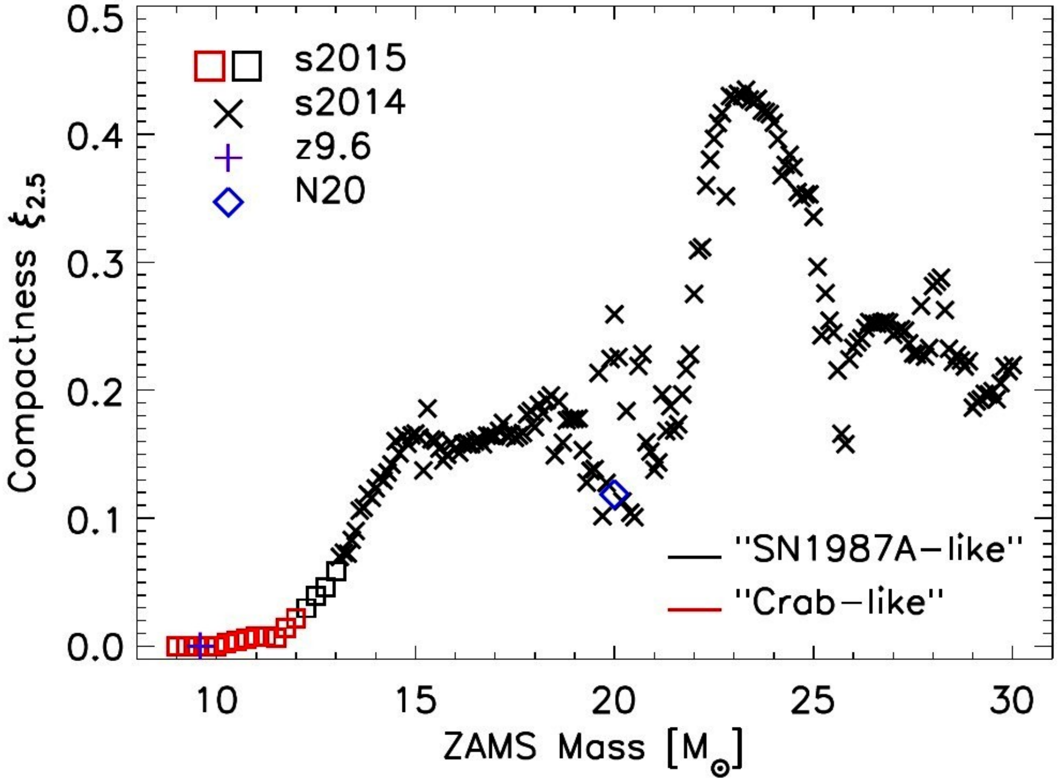




(Images from Markus Rampp, RZG)

Progenitor Density Profiles





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

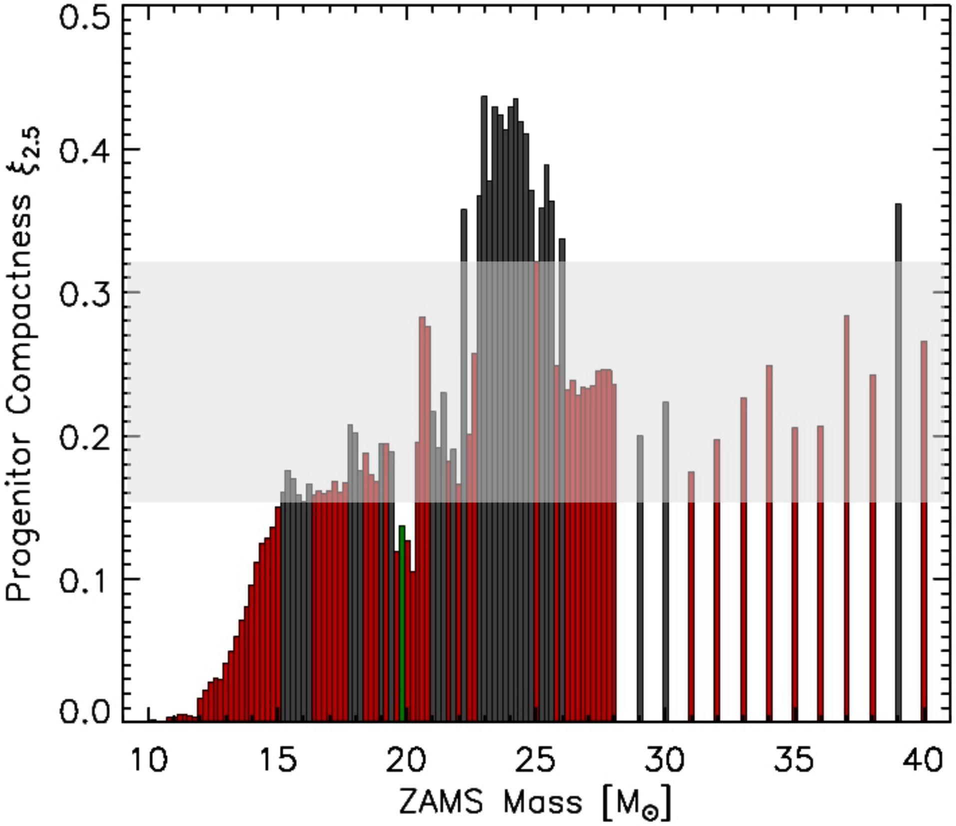
mass $M = 2.5\ M_\odot$

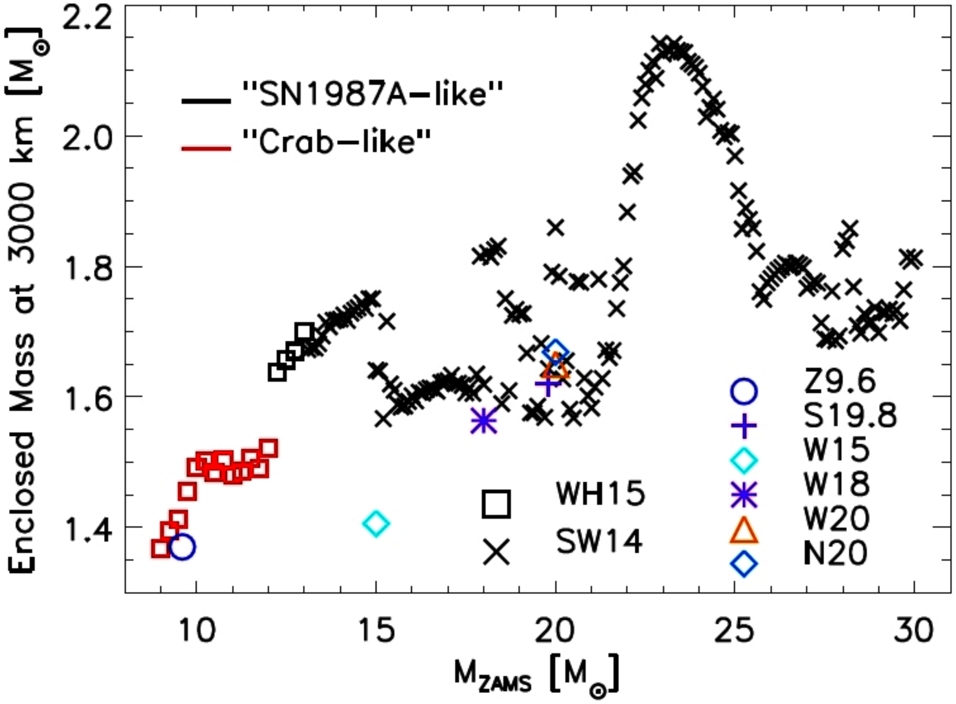
O'Connor & Ott, ApJ 730:70 (2011)

Stellar Compactness and Explosion

Core compactness can be nonmonotonic function of ZAMS mass

Progenitor models:
Woosley et al. (RMP 2002), Sukhbold & Woosley (2014), Woosley & Heger (2015)



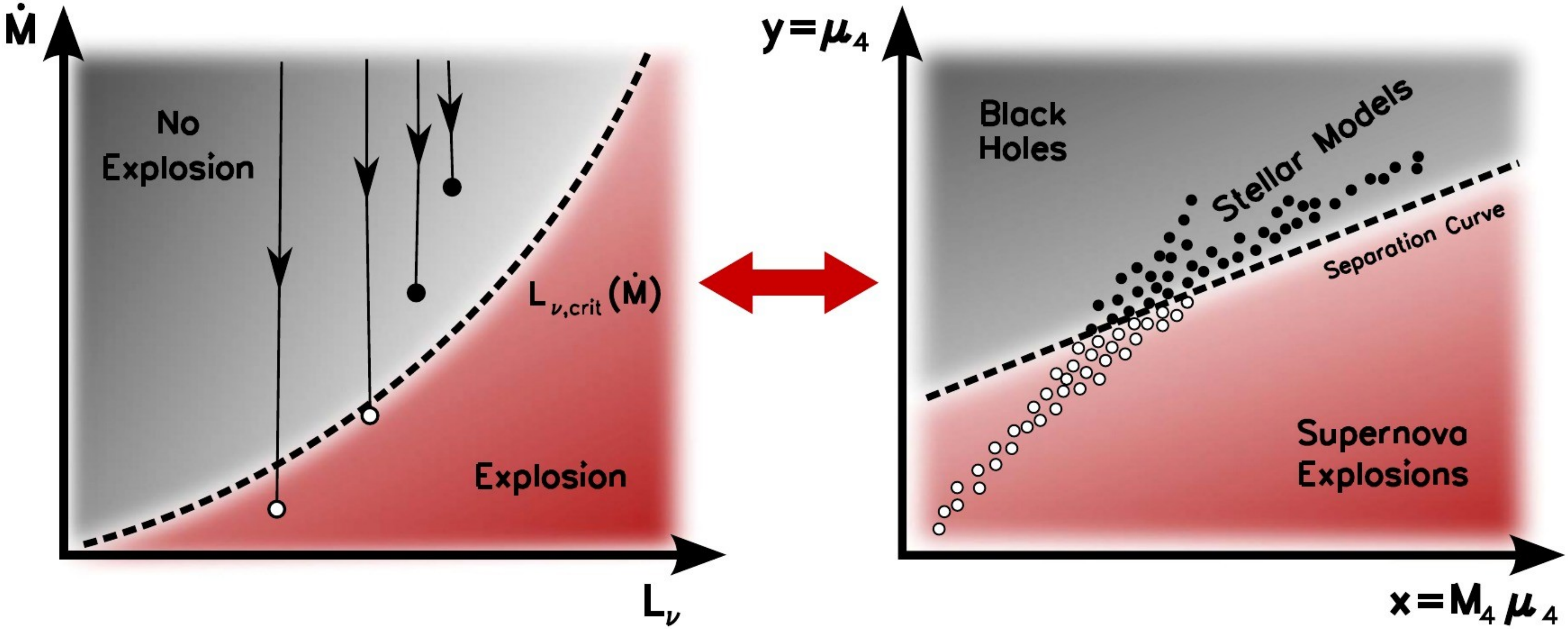


$$\xi_{2.5} \equiv \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}}\,, \qquad \text{mass } M = 2.5\ M_\odot$$

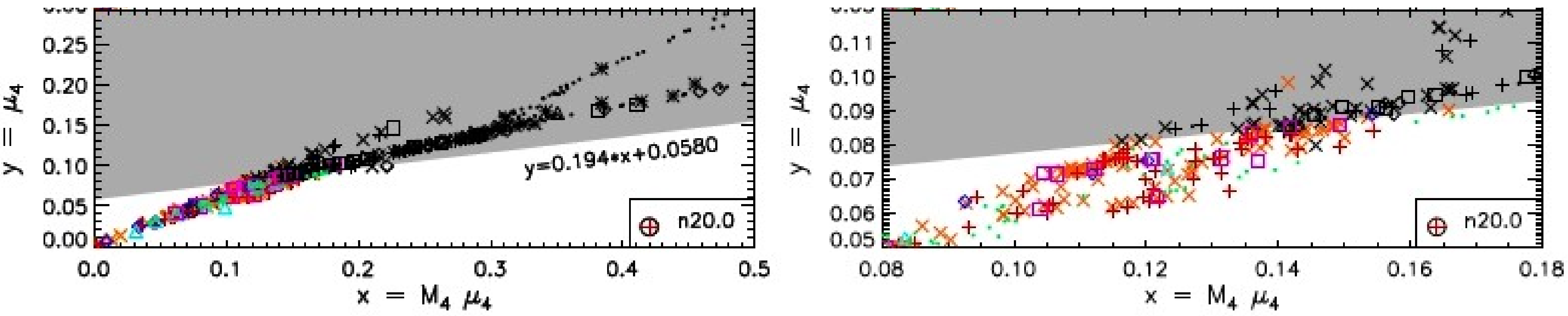
O'Connor & Ott, ApJ 730:70 (2011)

(Ugliano et al., ApJ 757 (2012) 69;
Ertl et al., ApJ 818 (2016) 124;
Sukhbold, Ertl et al., ApJ 821 (2016) 38)

Two-Parameter Criterion for Explodability



$$M_4 \equiv m(s=4)/M_\odot \qquad \mu_4 \equiv \left.\frac{dm/M_\odot}{dr/1000\ \mathrm{km}}\right|_{s=4}$$



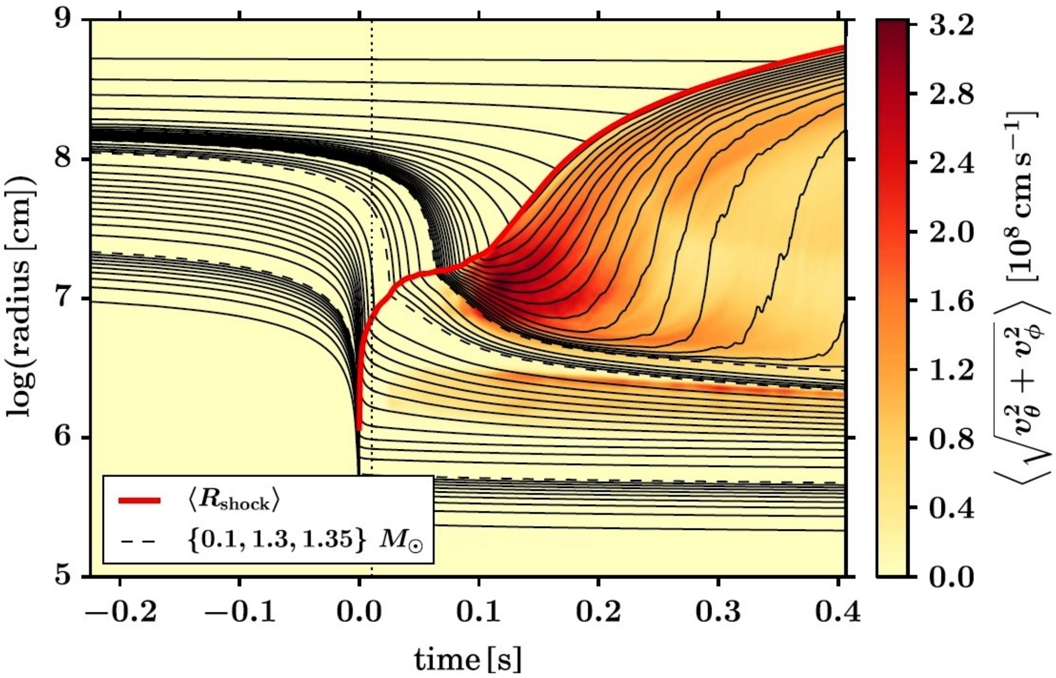
(Ertl, Janka, et al., ApJ 818, 124 (2016); arXiv:1503.07522)

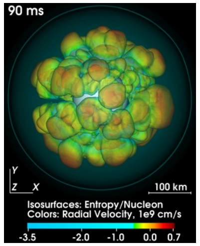
3D Core-Collapse SN Explosion Models

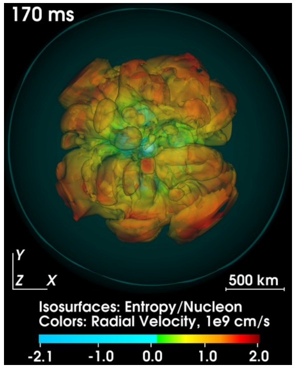
9.6 M_{sun} (zero-metallicity) progenitor (Heger 2010)

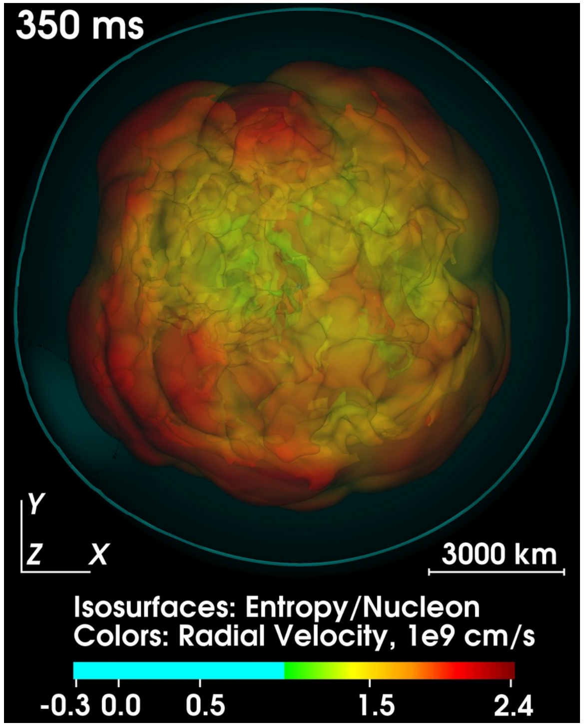
Fe-core progenitor (Heger 2012) with ECSN-like density profile and explosion behavior.

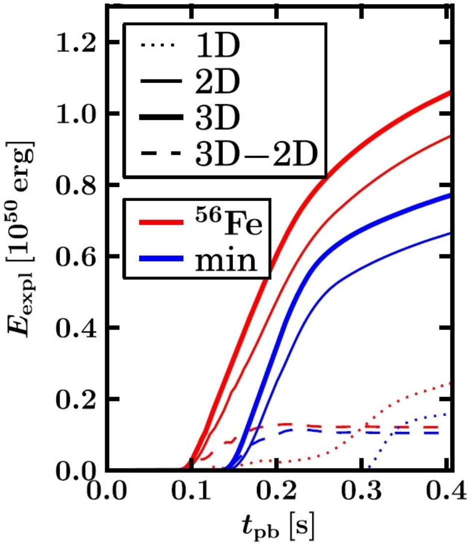
**Melson et al.,
ApJL 801 (2015) L24**

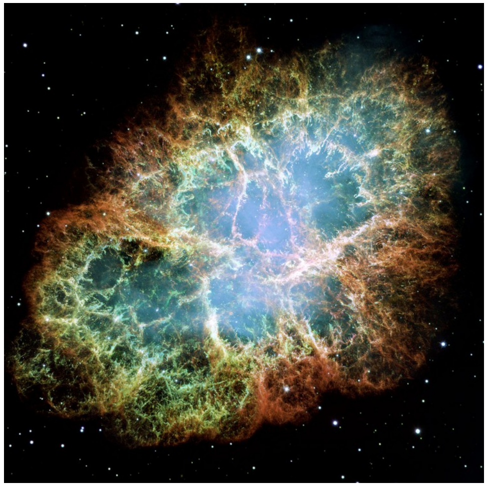








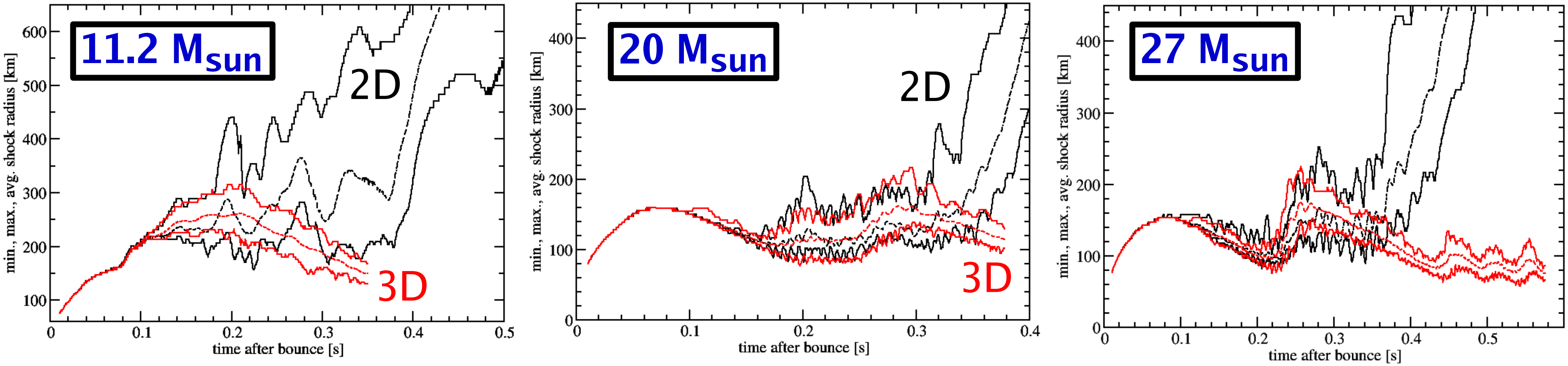




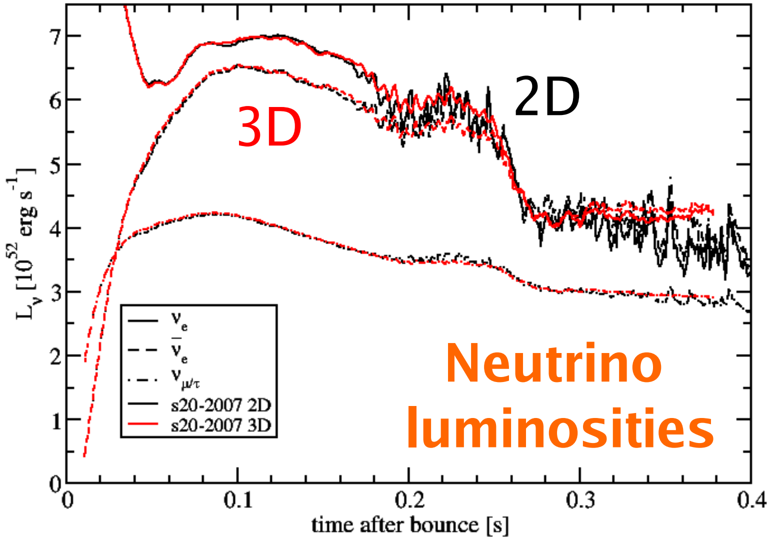
3D Core-Collapse SN Explosion Models

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

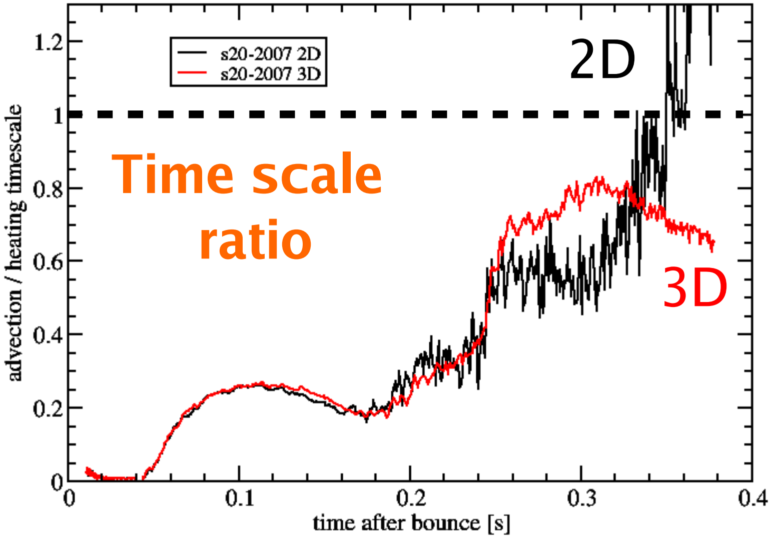
Shock radii (max., min., avg.) vs. time



Florian Hanke,
PhD project (2014)



Neutrino luminosities



Time scale ratio

What could facilitate robust explosions in 3D?

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

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

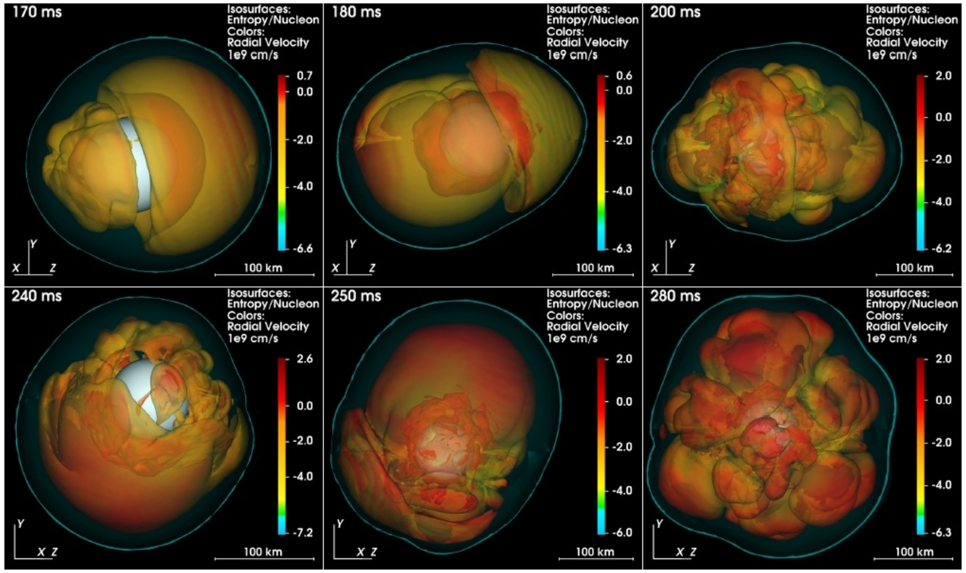
$$\sigma_0^t = \int_{4\pi} d\Omega\, \frac{d\sigma_0}{d\Omega}(1-\cos\theta) = \frac{2G_F^2\epsilon^2}{3\pi}\left(c_v^2+5c_a^2\right). \qquad (2)$$

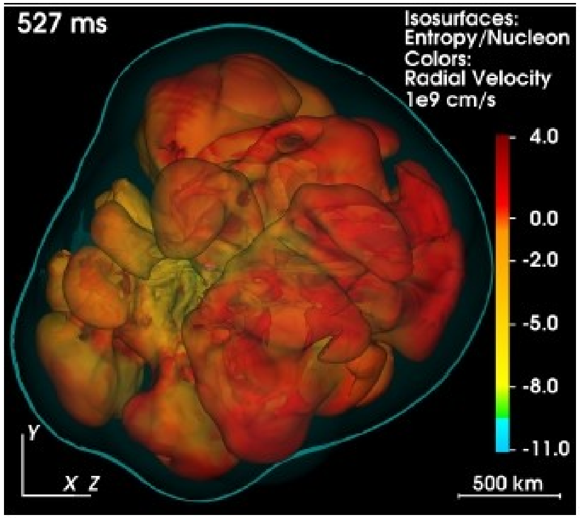
$$c_a = \frac{1}{2}\left(\pm g_a - g_a^s\right), \qquad (3)$$

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%

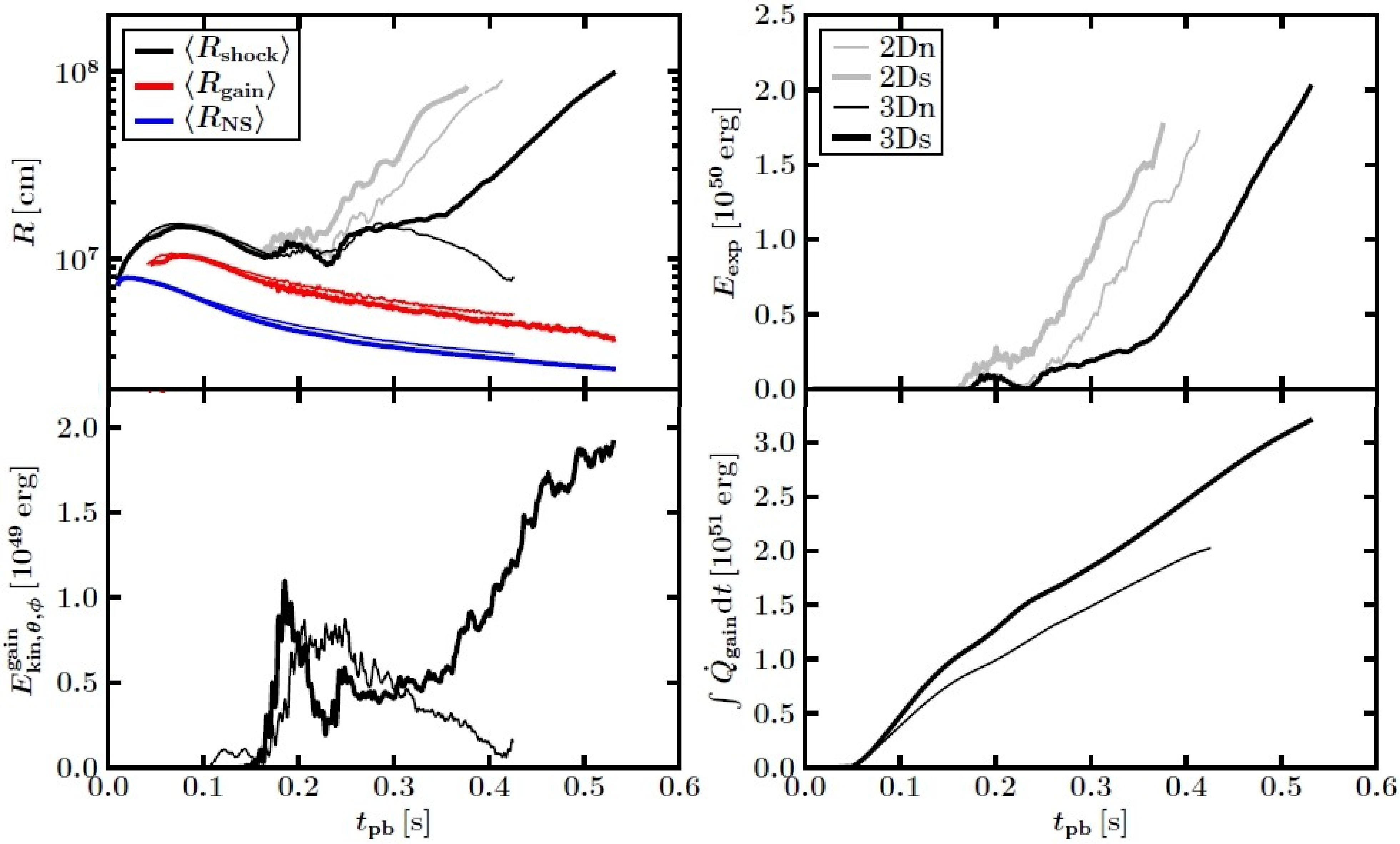




Melson et al., ApJL 808 (2015) L42

3D Core-Collapse SN Explosion Models

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



Melson et al., ApJL 808 (2015) L42

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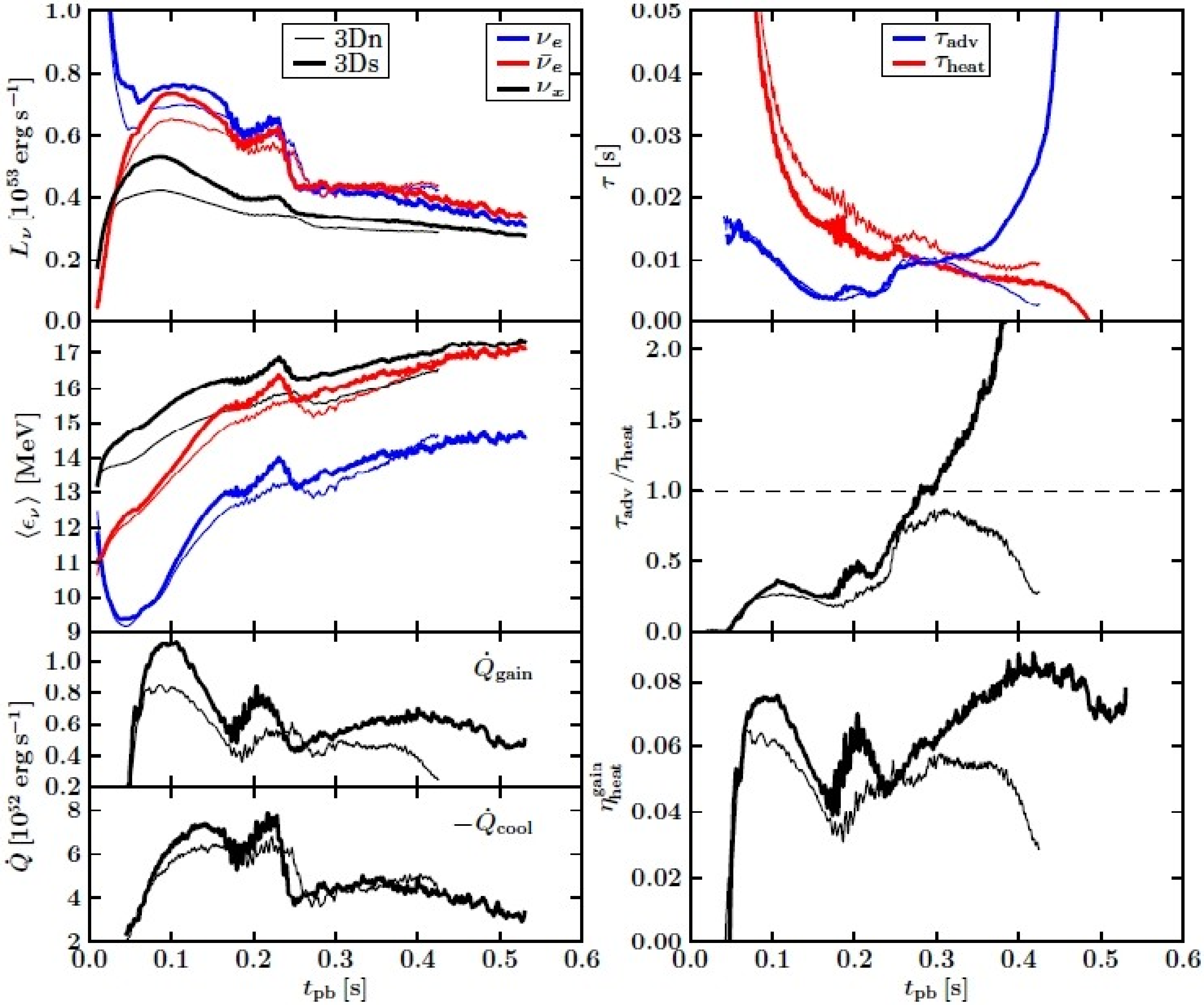


Melson et al., ApJL 808 (2015) L42

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 et al., ApJL 2015a,b; Müller 2016; Janka et al. 2016):

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)

3D CCSN Explosion Model with Rotation

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

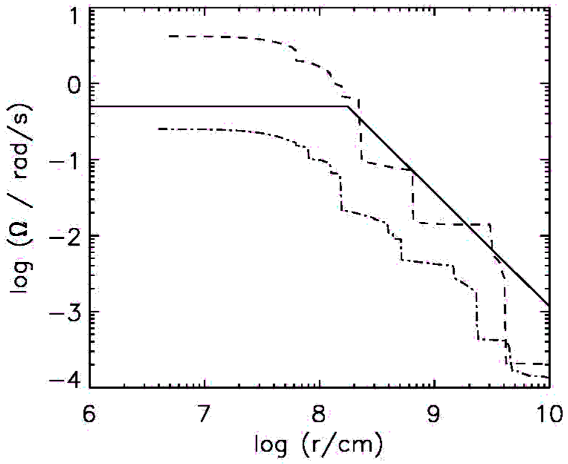
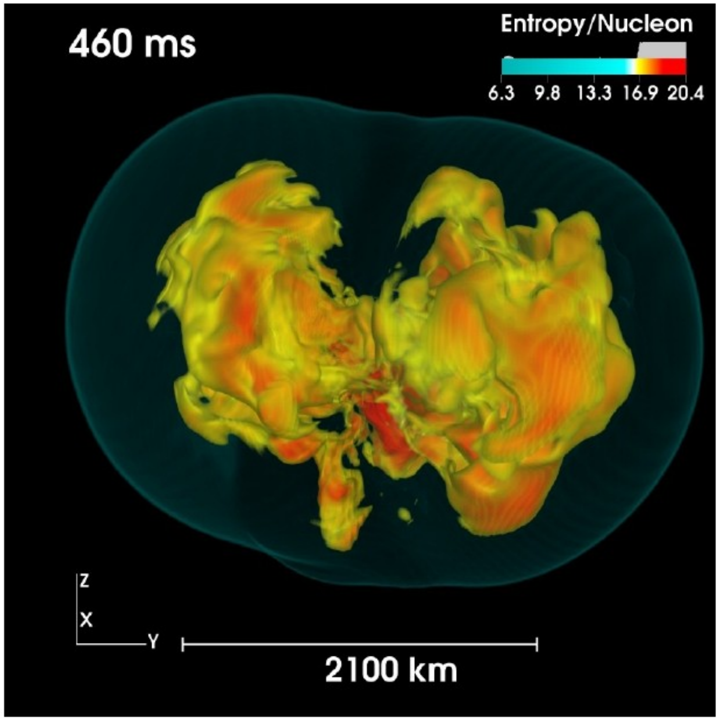
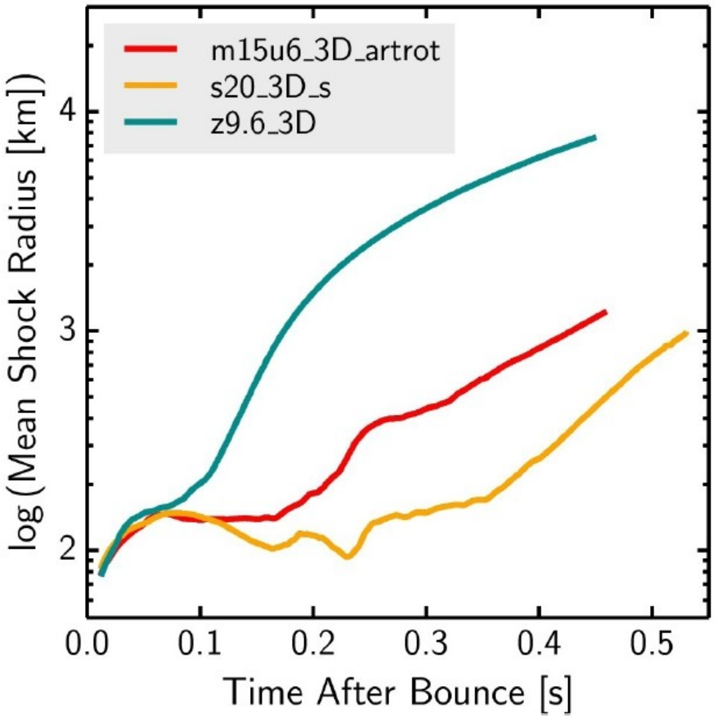


Fig. 1.—Angular velocity Ω as a function of radius *r* for the rotating 15 $M_{\odot}$ presupernova model (*dashed curve*) of Heger, Langer, & Woosley (2000), for the magnetic rotating 15 $M_{\odot}$ presupernova model (*dash-dotted curve*) of Heger et al. (2004), and for our rotating model s15r (*solid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

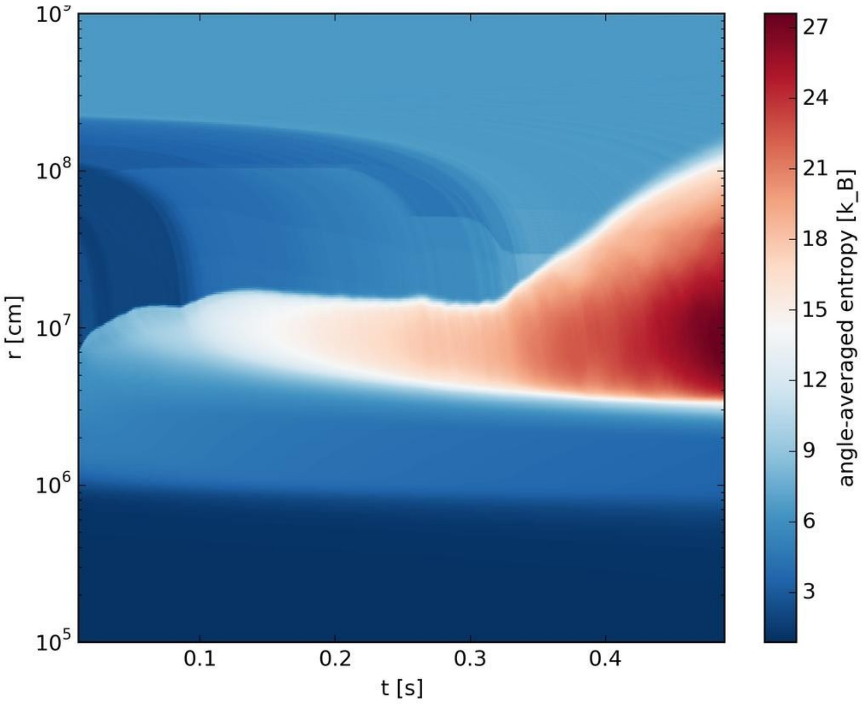


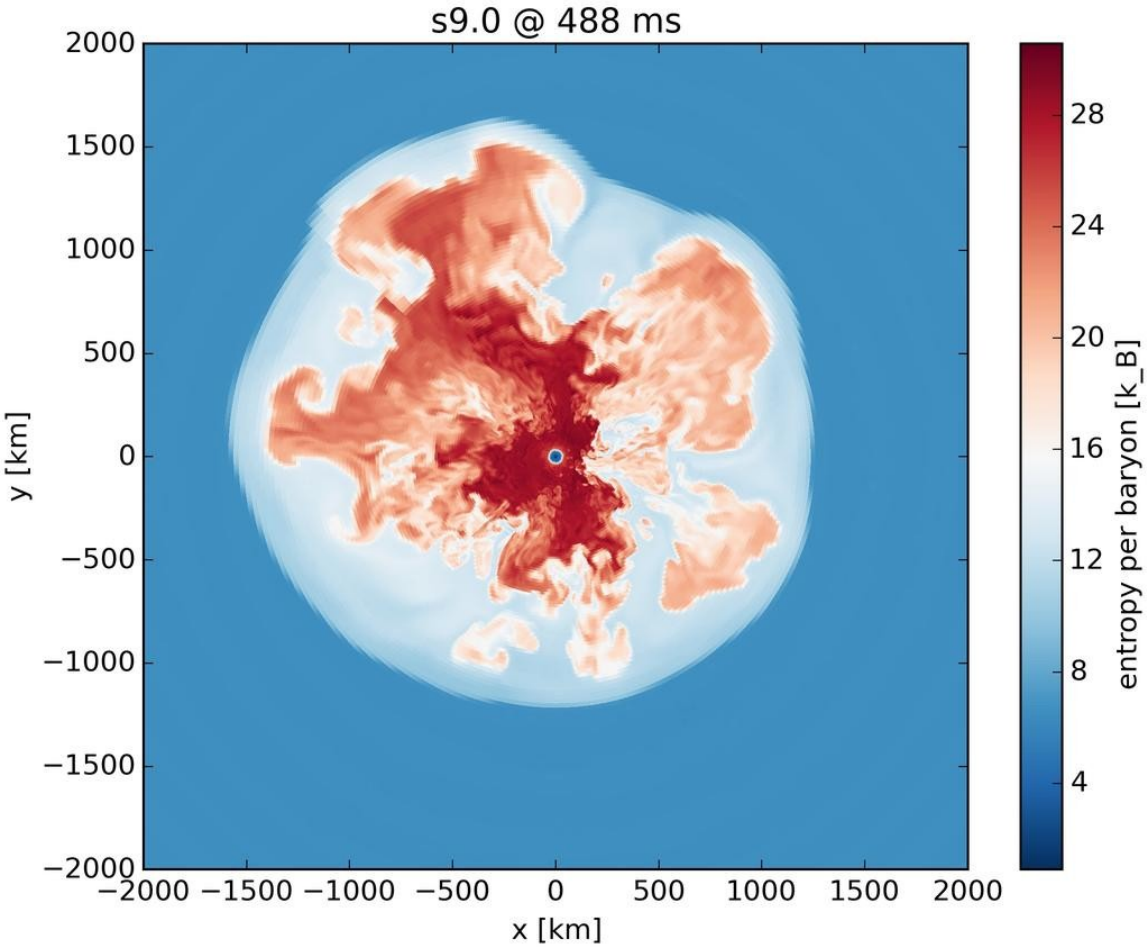


A. Summa (2015);
Janka, Melson & Summa,
ARNPS 66 (2016),
arXiv:1601.05576

3D CCSN Explosion Model of Low-Mass Star

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





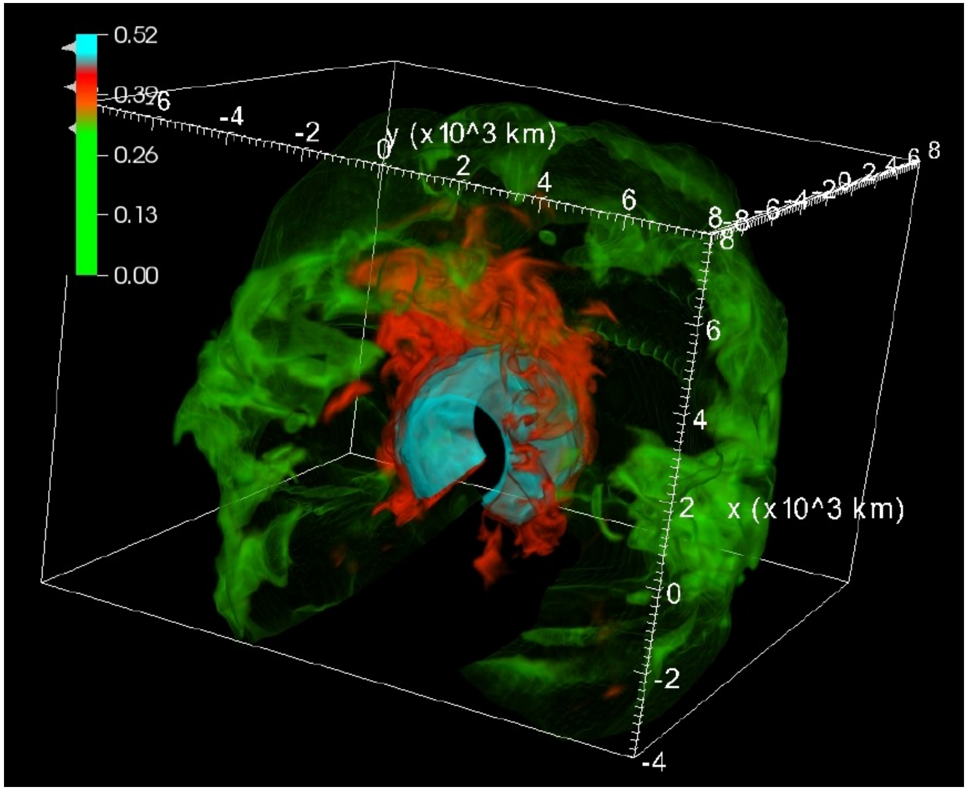
T. Melson et al., in preparation

3D Core-Collapse SN Progenitor Model

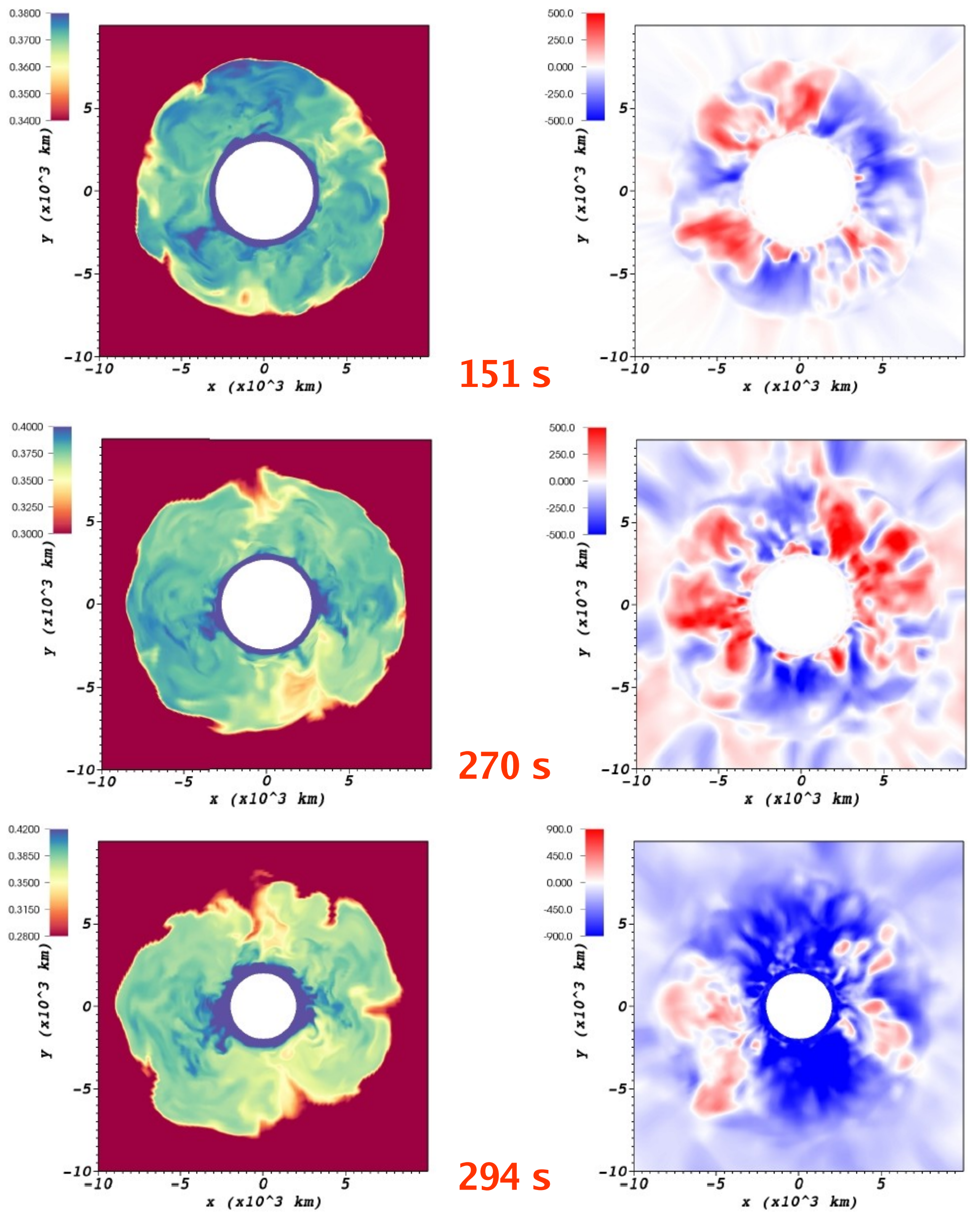
18 M_{sun} (solar-metallicity) progenitor (Heger 2015)

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)



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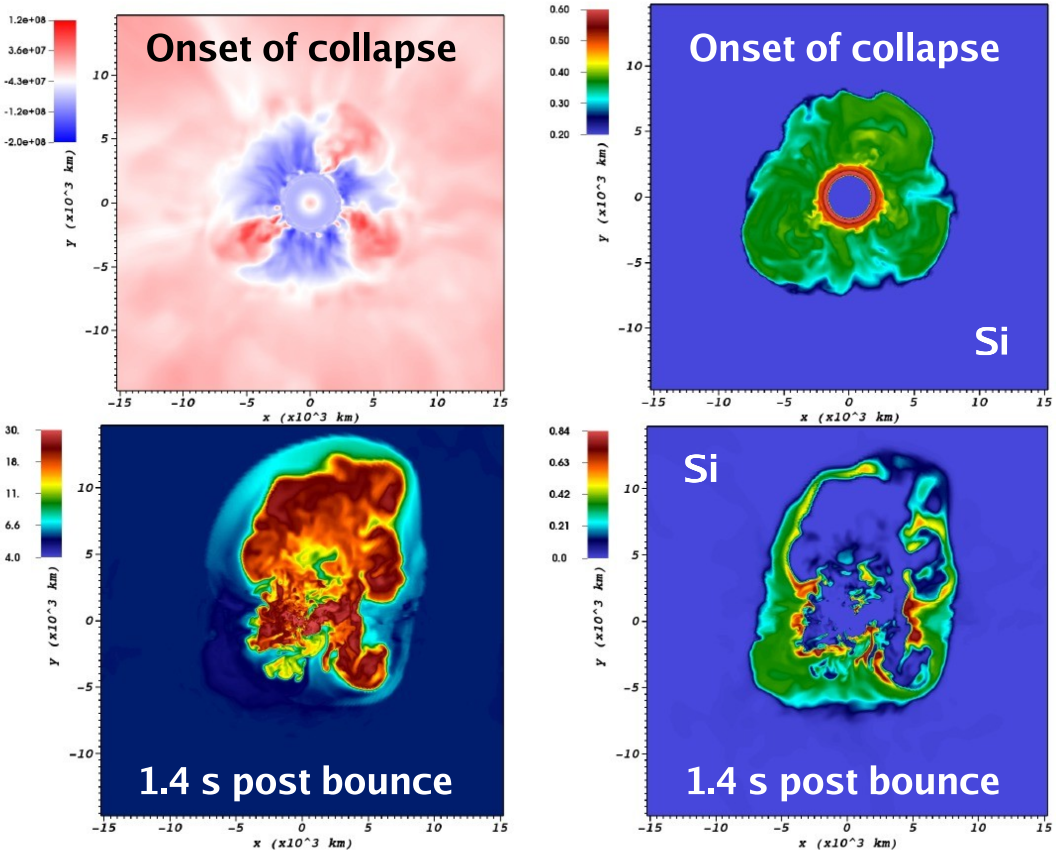
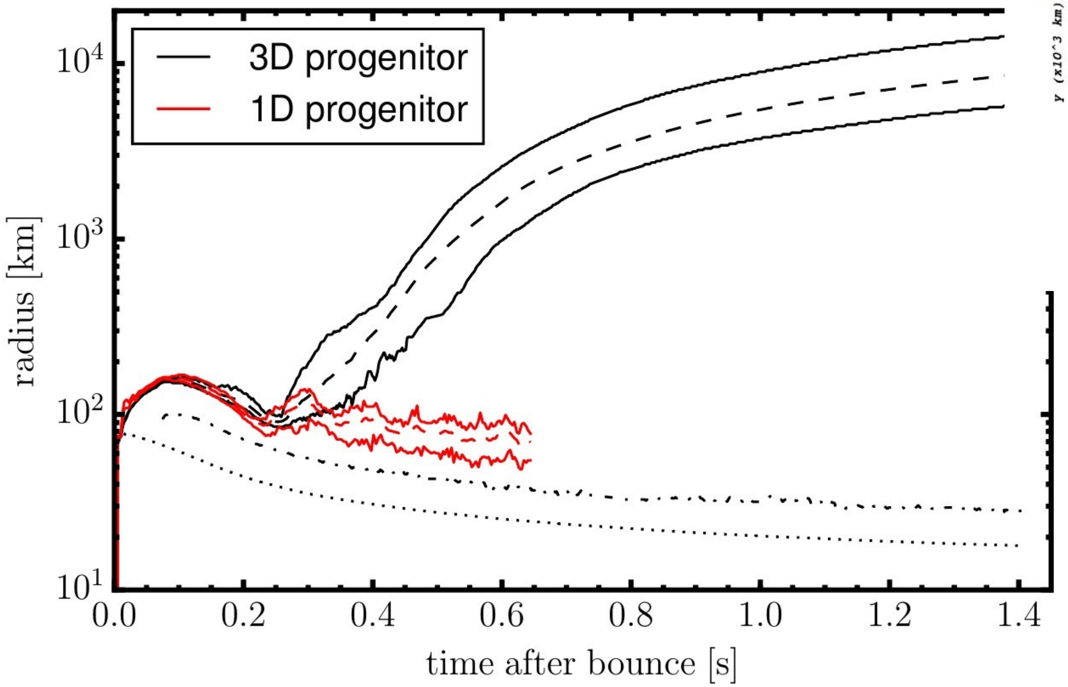
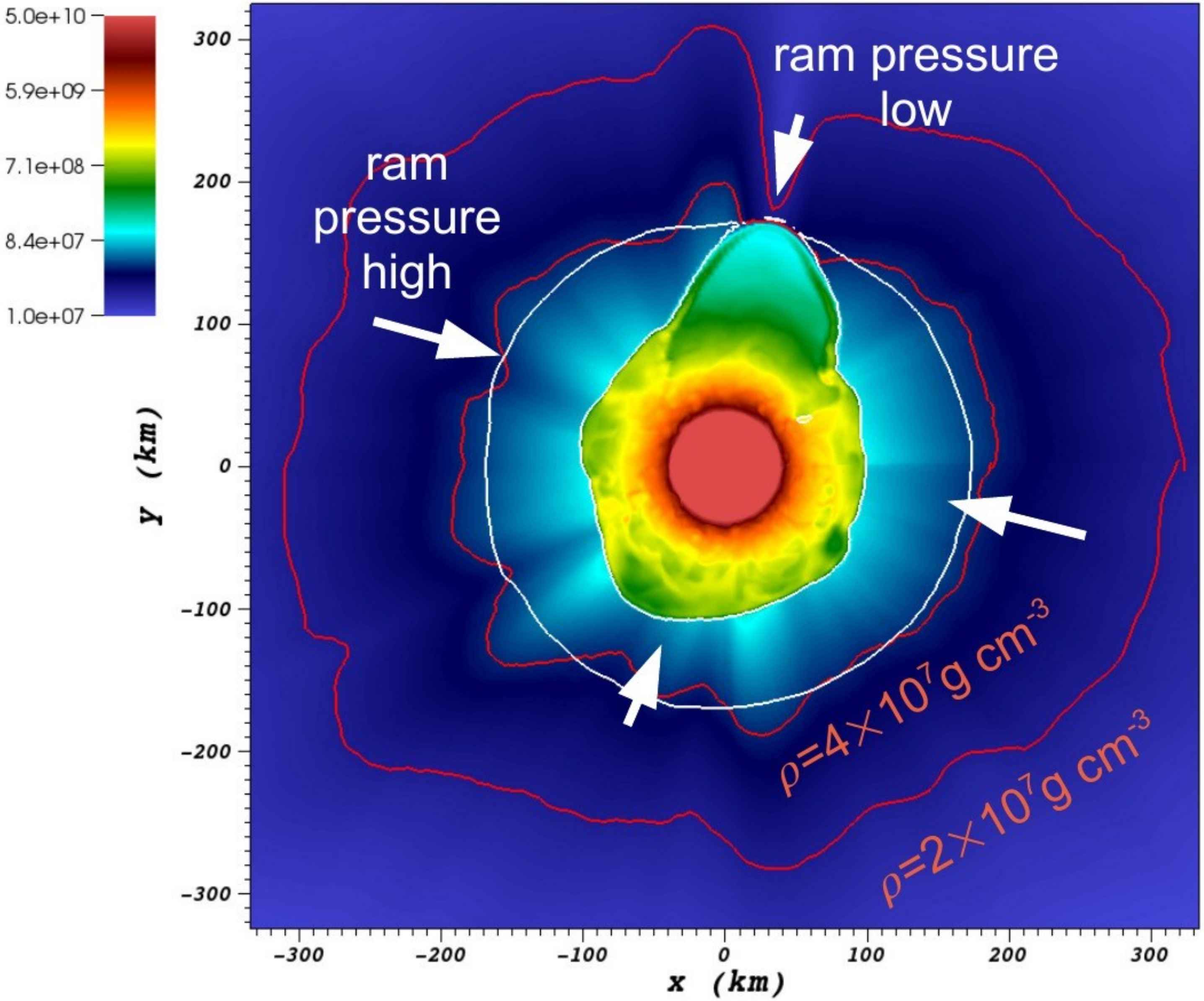




$$\delta\rho/\rho \sim \text{Ma}_{\text{conv}}$$

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

B. Müller, PASA 33, 48 (2016)



B. Müller, arXiv:1702.06940

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 ?????**

Universal Critical Neutrino Luminosity for Explosion

$$\left(L_\nu\langle E_\nu^2\rangle\right)_{\rm crit} \propto \left(\dot{M}M\right)^{3/5} \left|\bar{e}_{\rm tot,g}\right|^{3/5} R_{\rm g}^{-2/5}\,\xi_{\rm turb}^{-3/5}\,\xi_{\rm rot}^{6/5}$$

$$\equiv \left(\dot{M}M\right)^{3/5} \xi_{\rm g}$$

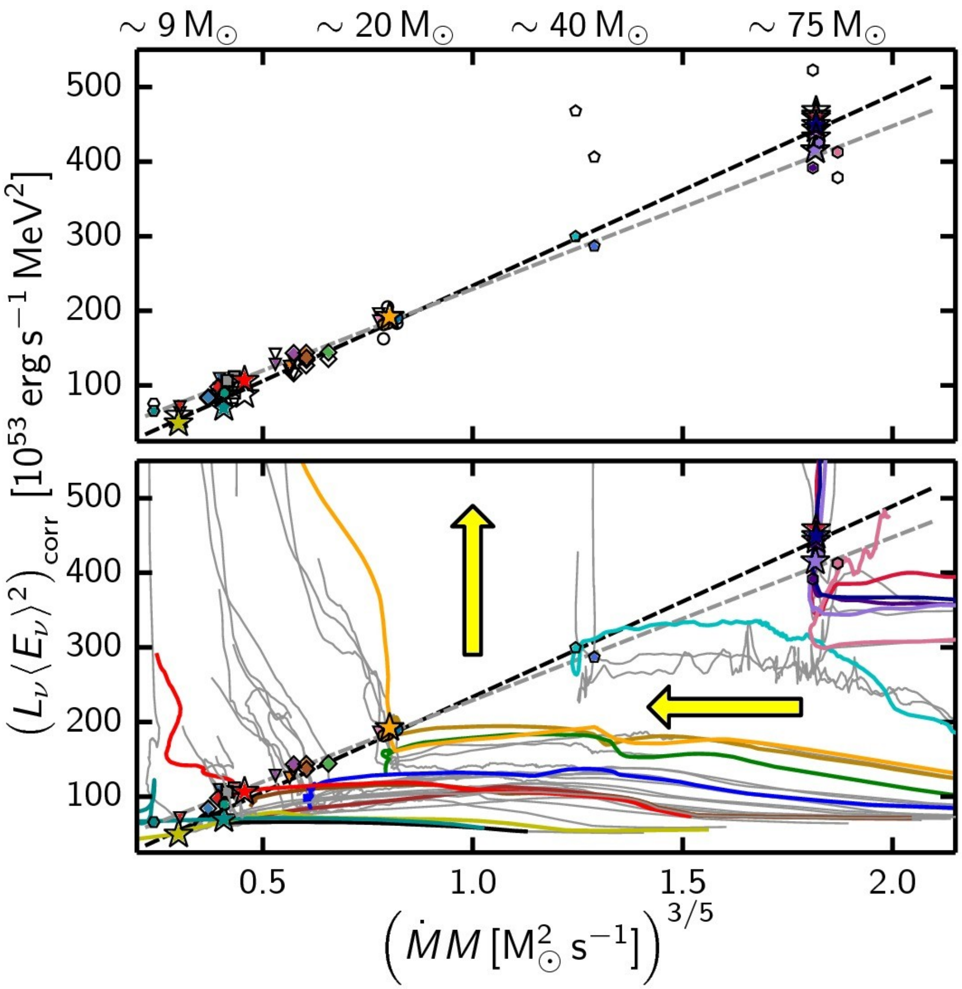
$$\xi_{\rm g} \equiv \left|\bar{e}_{\rm tot,g}\right|^{3/5} R_{\rm g}^{-2/5}\,\xi_{\rm turb}^{-3/5}\,\xi_{\rm rot}^{6/5}$$

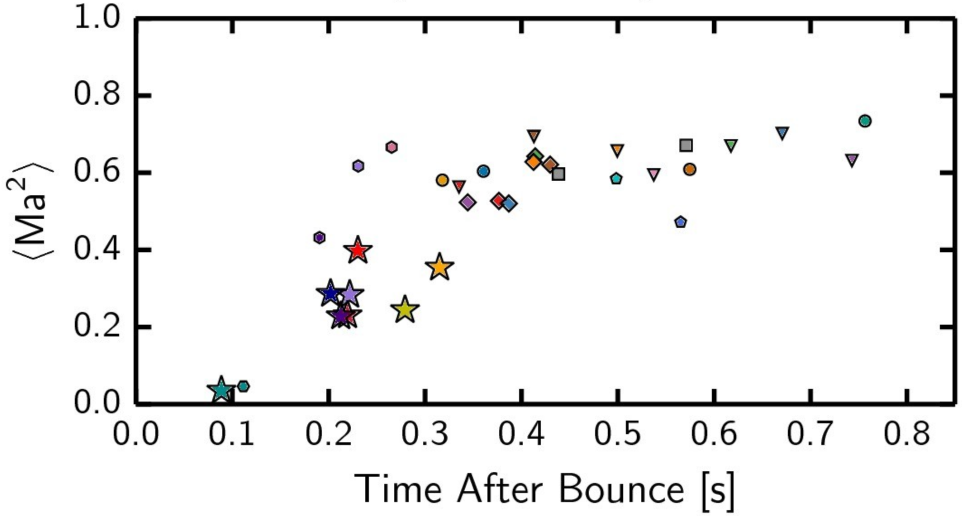
$$\xi_{\rm turb} = 1 + \frac{4}{3}\langle {\rm Ma}^2\rangle \geq 1$$

$$\xi_{\rm rot} = \sqrt{1 - \frac{j_0^2}{2GMR_{\rm s}}} \leq 1$$

$$\bar{e}_{\rm tot,g} = \frac{E_{\rm tot,g}}{M_{\rm g}}$$

$$\left(L_\nu\langle E_\nu^2\rangle\right)_{\rm crit,corr} \equiv \frac{1}{\xi_{\rm g}/\xi_{\rm g}^*}\left(L_\nu\langle E_\nu^2\rangle\right)_{\rm crit} \propto \left(\dot{M}M\right)^{3/5}$$





Ringberg Workshop on

Progenitor – Supernova – Remnant Connection

Ringberg Castle, Tegernsee

July 24–28, 2017

http://www.mpa-garching.mpg.de/conf/psrc/