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INT-16-2: "The Phases of Dense Matter"
INT @ UW, Seattle, WA, Week 5, August 8-12, 2016

Supernova Simulations
From Progenitors to Remnants

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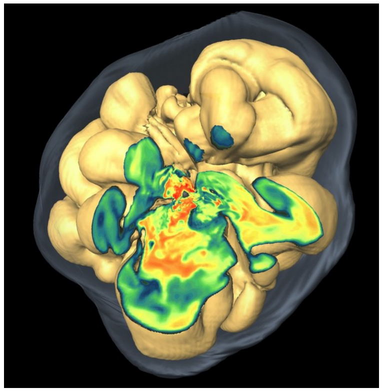
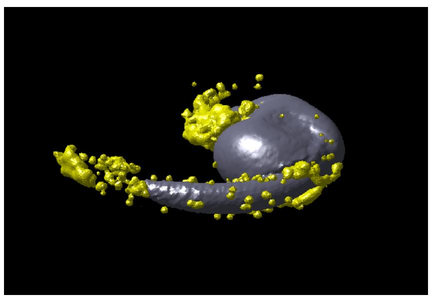
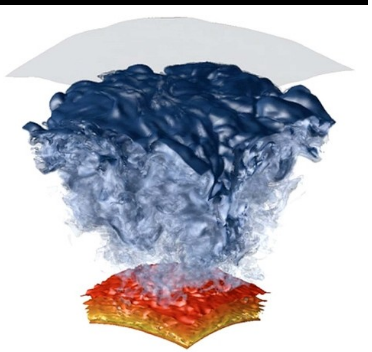
Hans-Thomas Janka
for the Team

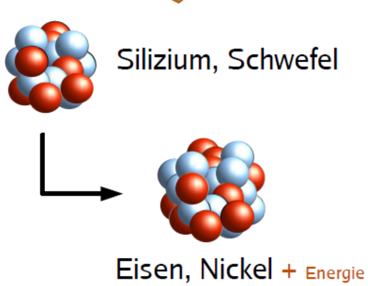
COCO2CASA

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









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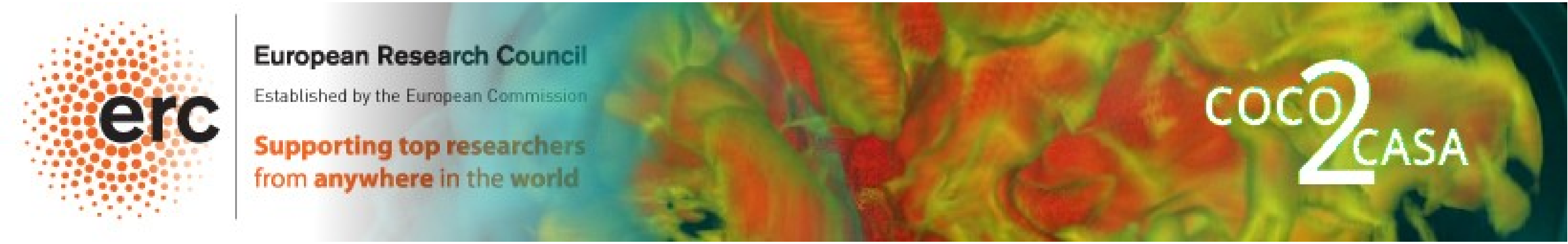


COCO2CASA: Goals

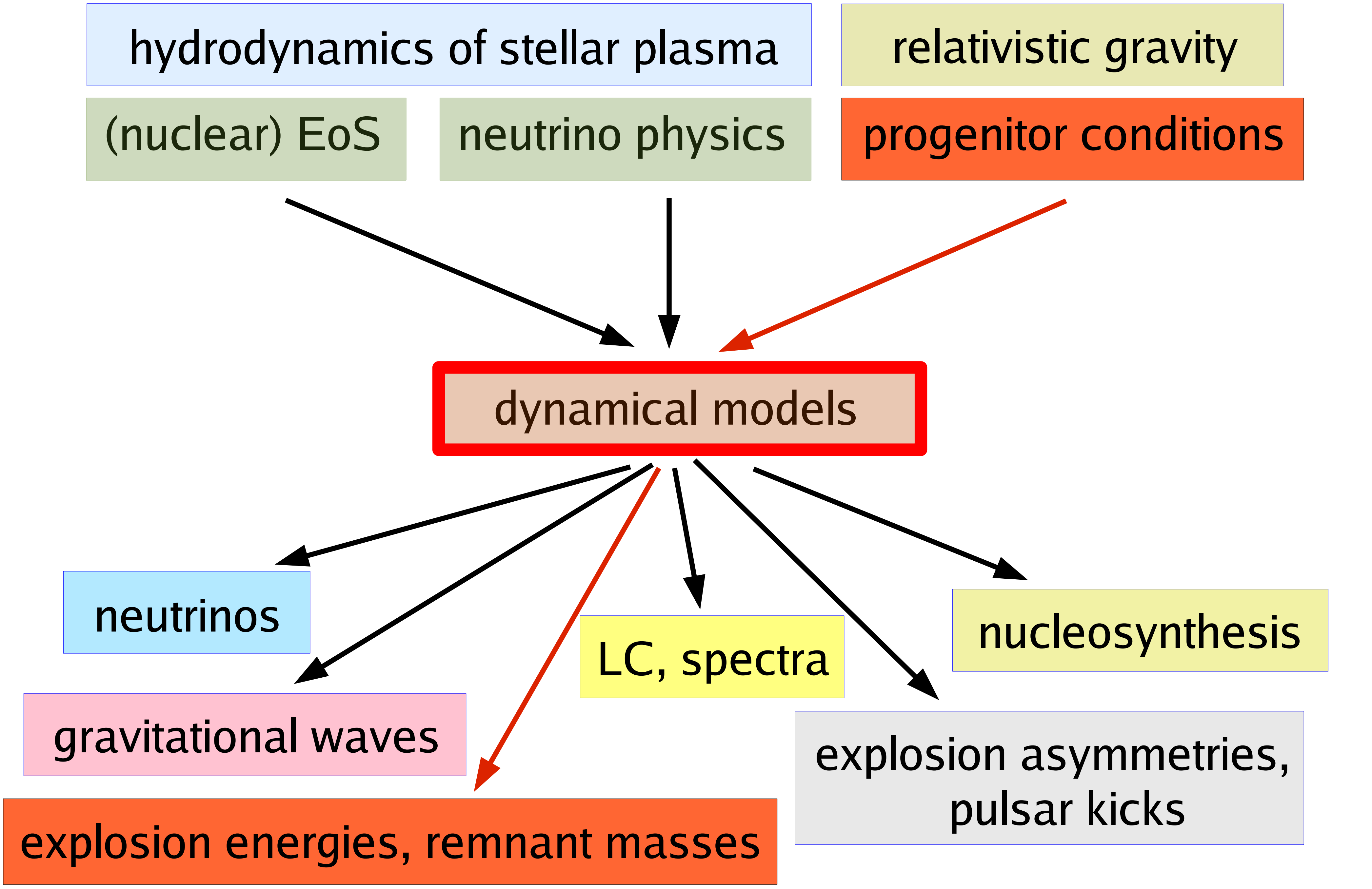
Connecting Supernova Progenitors with Supernova Remnants

- 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

Predictions of Signals from SNe & NSs



The Simulation Code

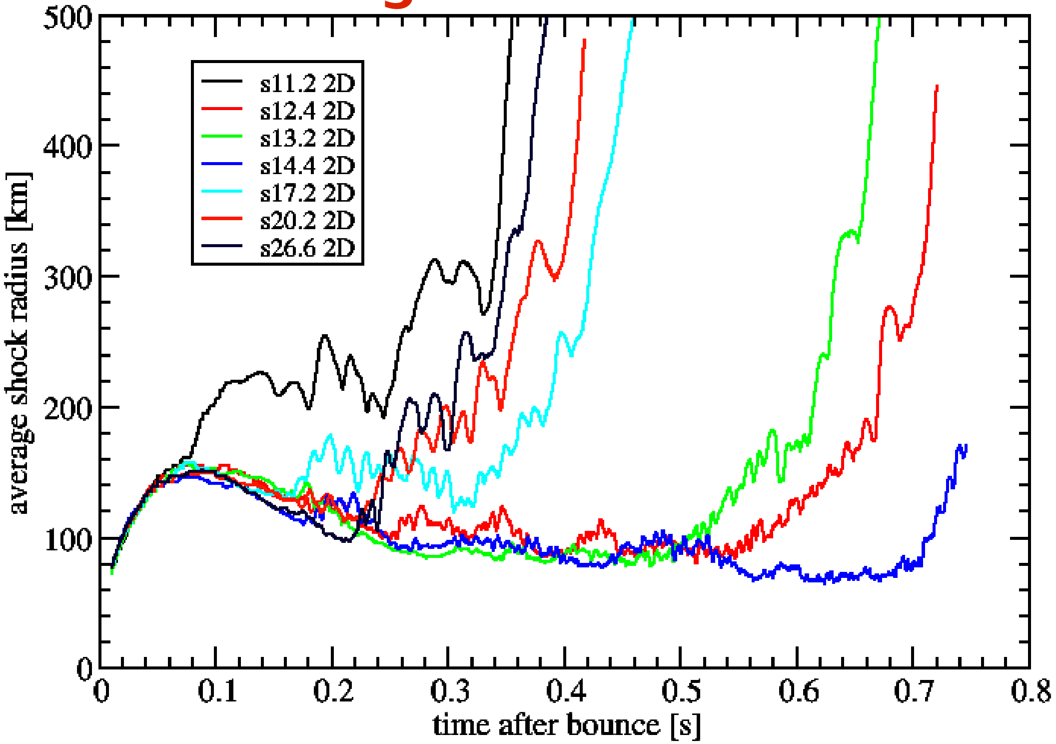
Prometheus/CoCoNuT – VERTEX: 1D, 2D, 3D

- **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.**

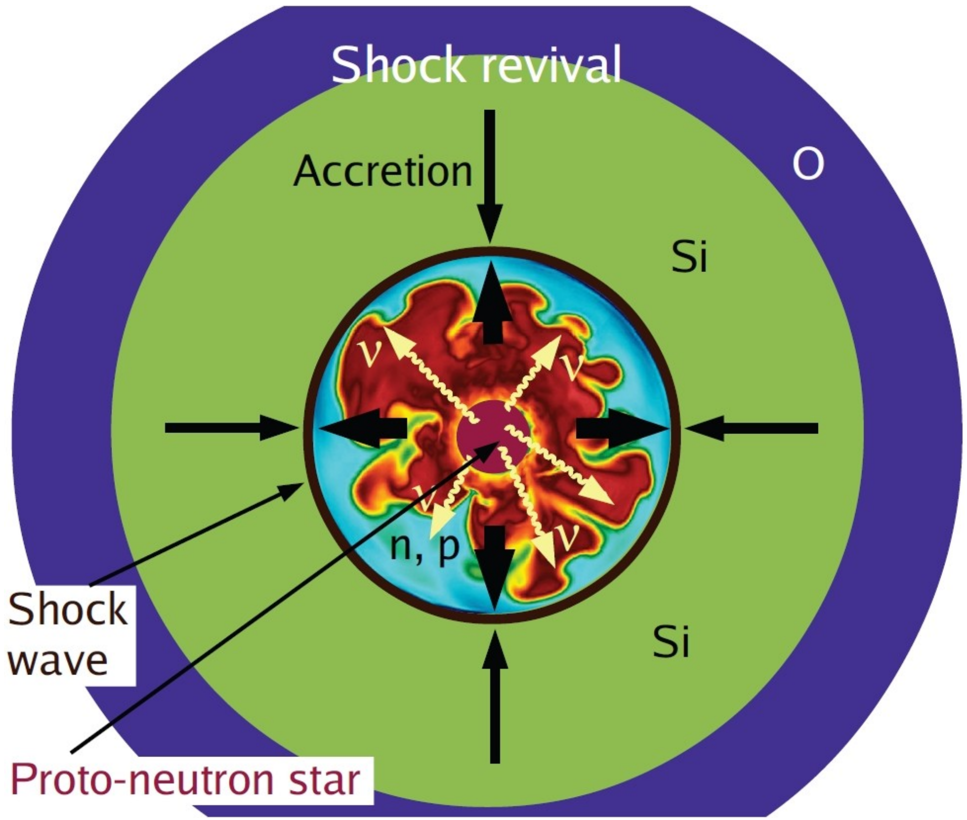
Growing Set of 2D CCSN Explosion Models

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

Average shock radius



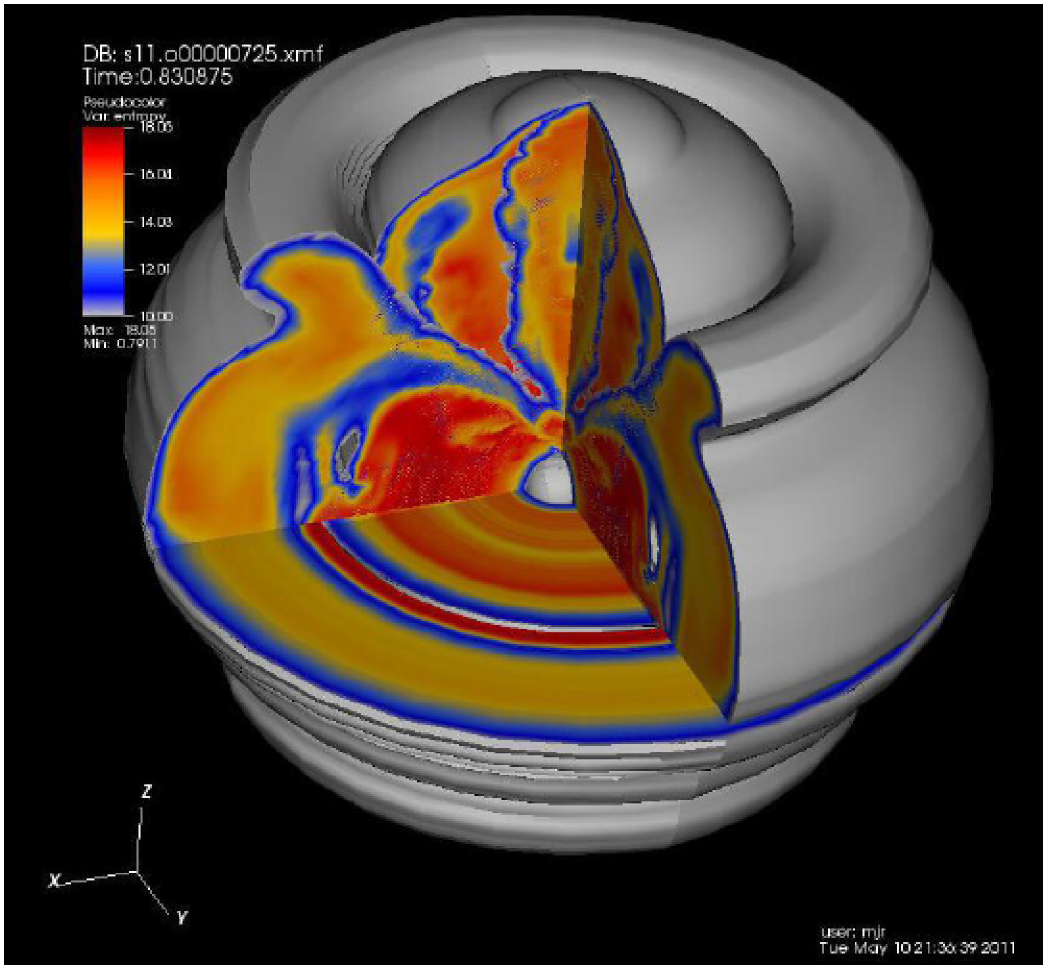
Shock "revival" by neutrino heating

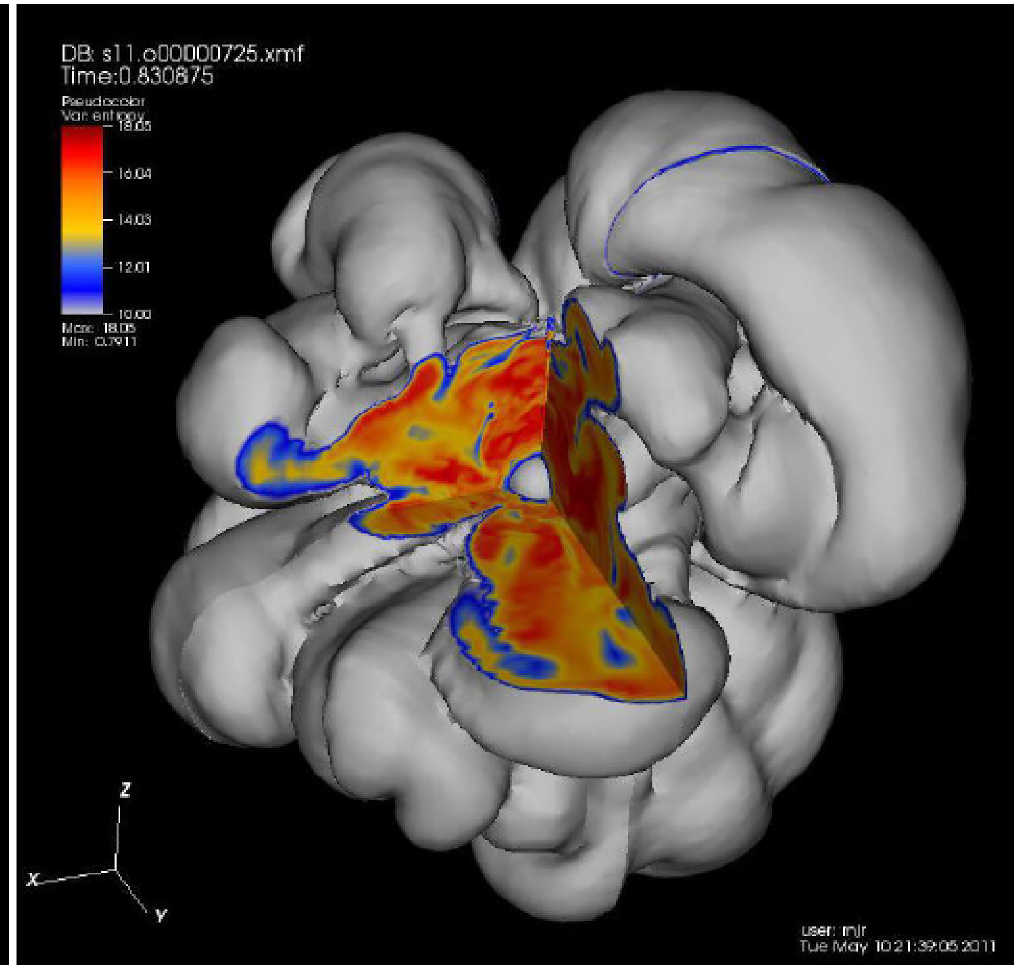


F. Hanke (2014, PhD Thesis, TUM);
A. Summa, F. Hanke, HTJ, et al., arXiv:1511.07871

Progenitor models: Woosley et al. RMP (2002)

2D and 3D Morphology





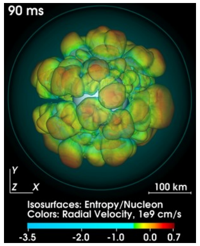
(Images from Markus Rampp, RZG)

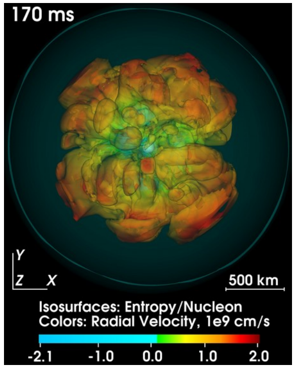
3D Core-Collapse SN Explosion Models

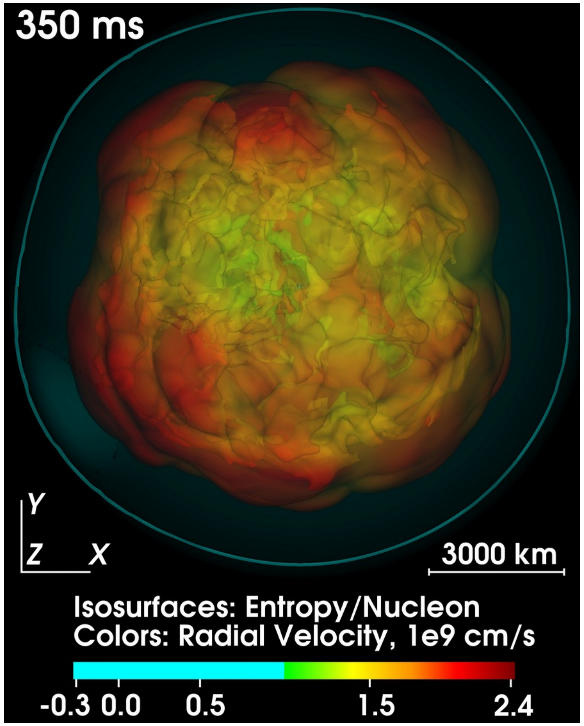
9.6 M_{sun} (zero-metallicity) progenitor (Heger 2010)

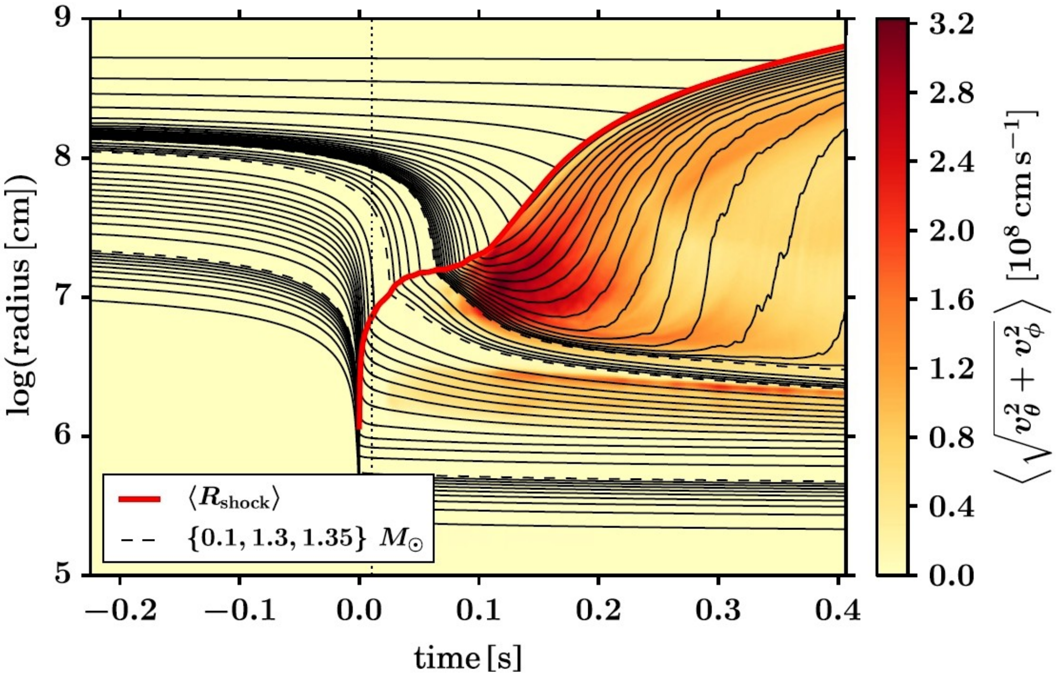
Fe-core progenitor (Heger 2012) with ECSN-like density profile and explosion behavior.

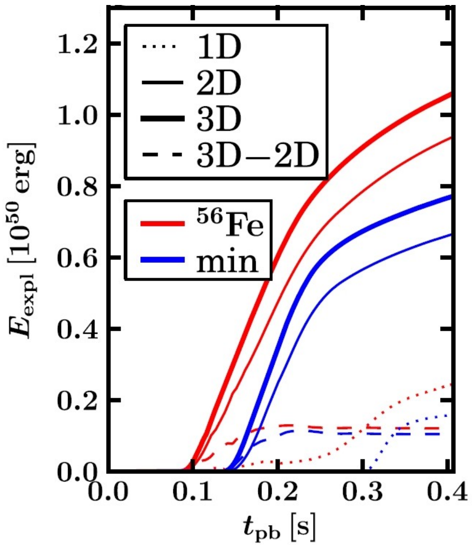
Melson et al., ApJL 801 (2015) L24

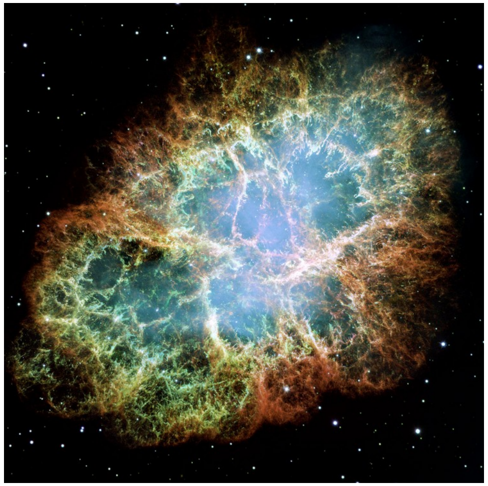








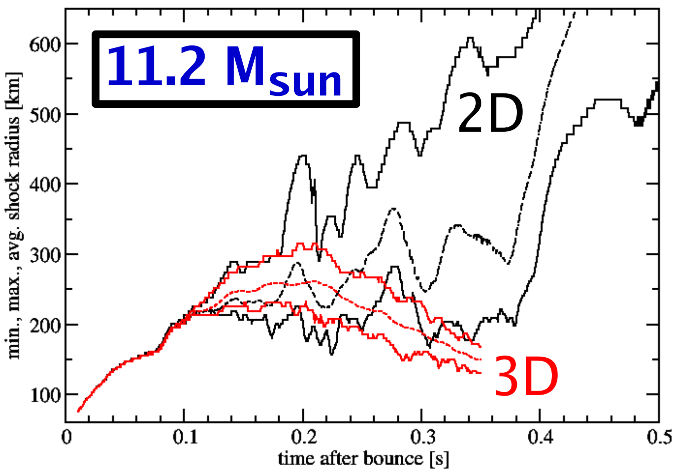


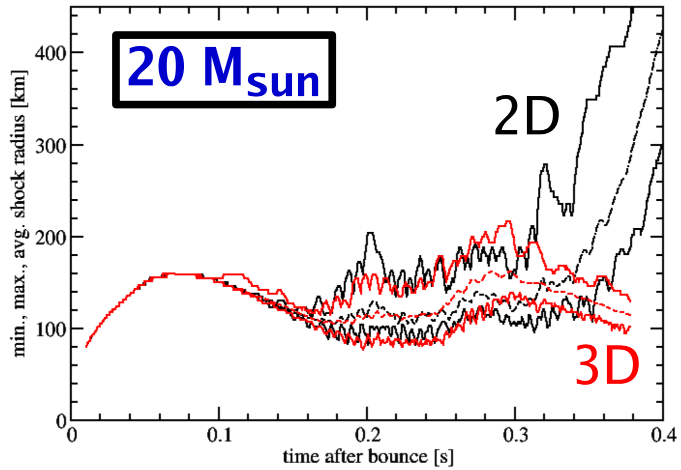


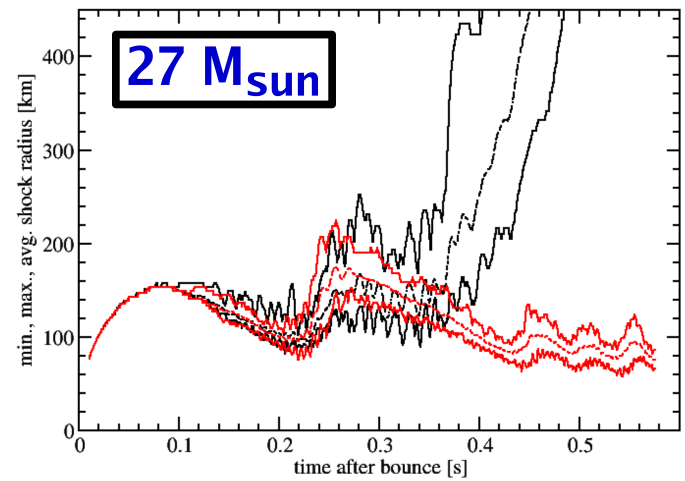
3D Core-Collapse SN Explosion Models

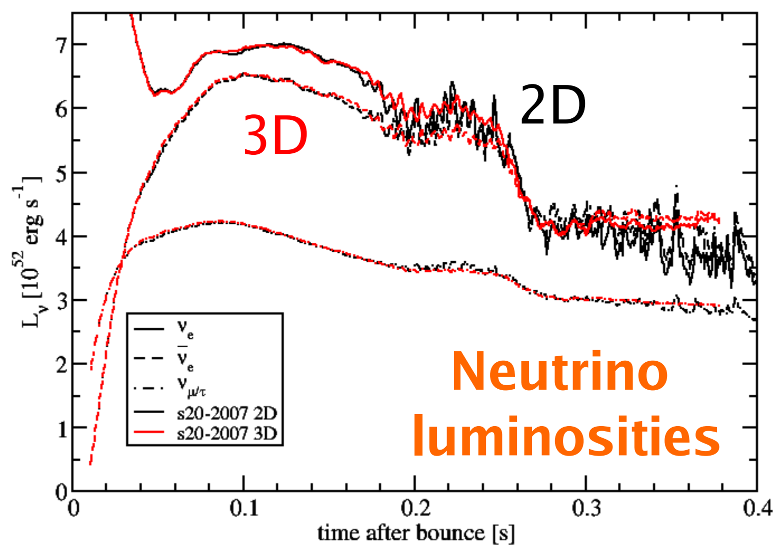
11.2, 20, 27 M_{sun} progenitors (WH 2007)

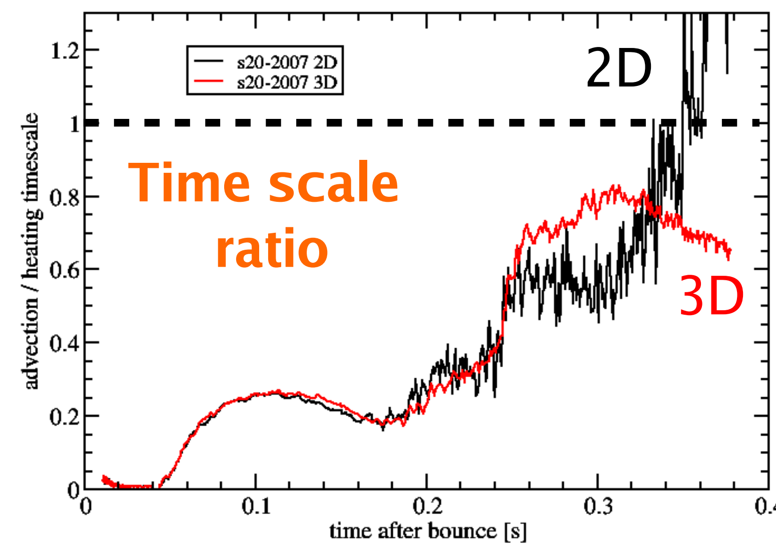
Shock radii (max., min., avg.) vs. time









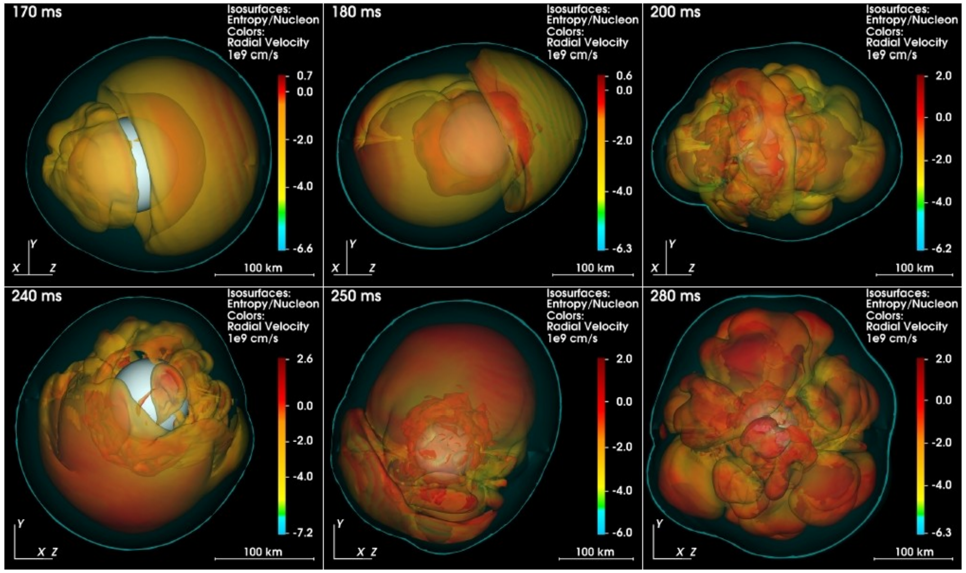


**Florian Hanke,
PhD project (2014)**

What could facilitate robust explosions in 3D?

3D Core-Collapse SN Explosion Models

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



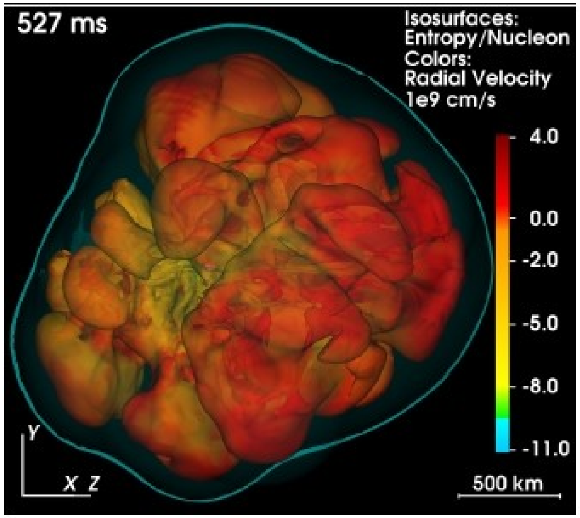
Explore uncertain aspects of microphysics in neutrinospheric region:

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

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

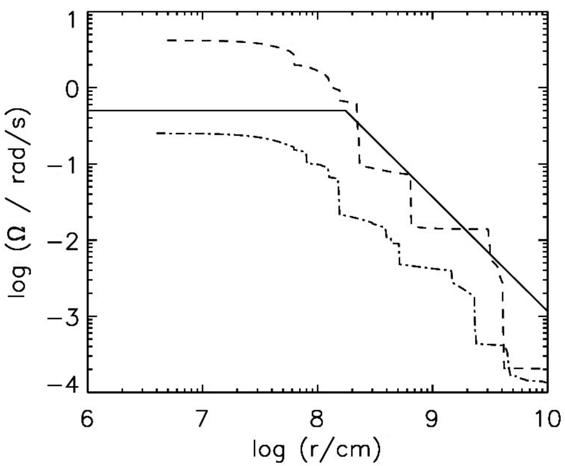
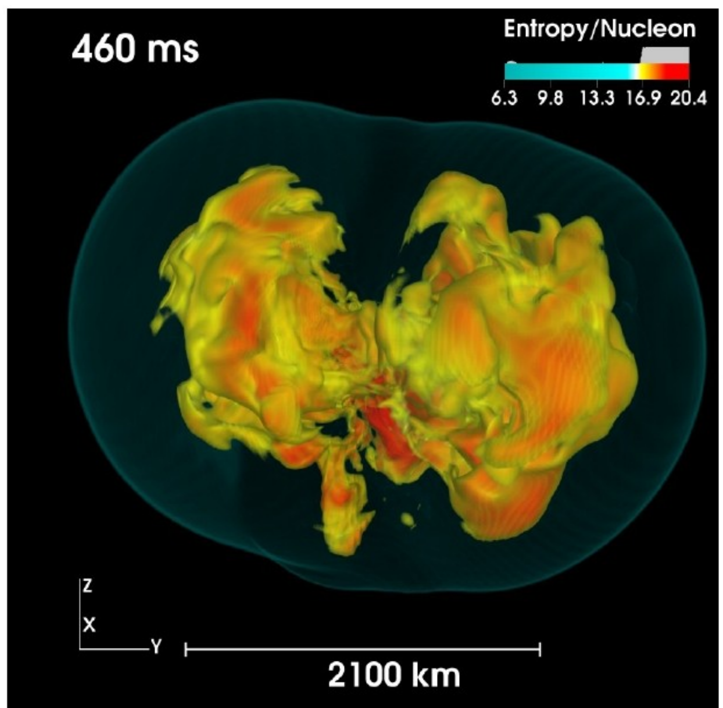
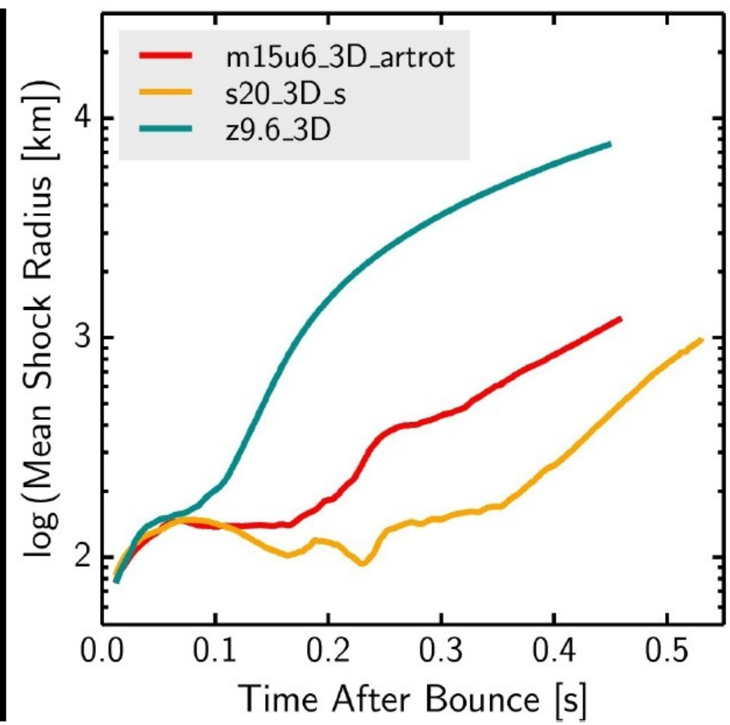


FIG. 1.—Angular velocity Ω as a function of radius r for the rotating 15 $M_\odot$ presupernova model (*dashed curve*) of Heger, Langer, & Woosley (2000), for the magnetic rotating 15 $M_\odot$ presupernova model (*dash-dotted curve*) of Heger et al. (2004), and for our rotating model s15r (*solid curve*).

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.



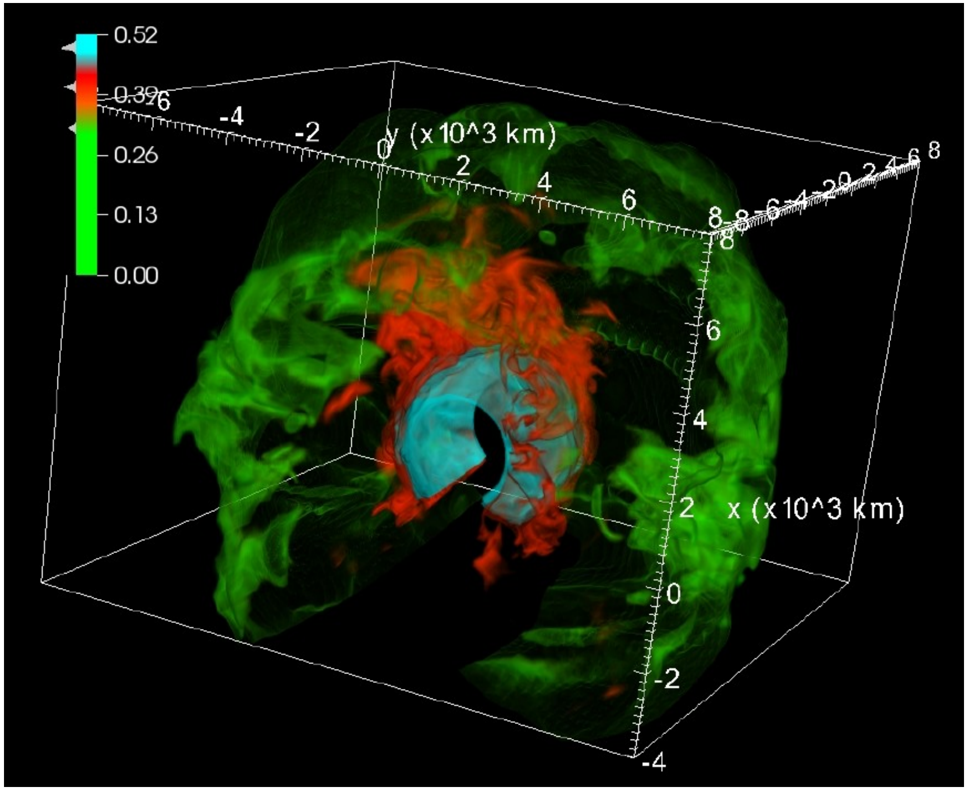


A. Summa (2015);
Janka, Melson & Summa, ARNPS 66 (2016), arXiv:1601.05576

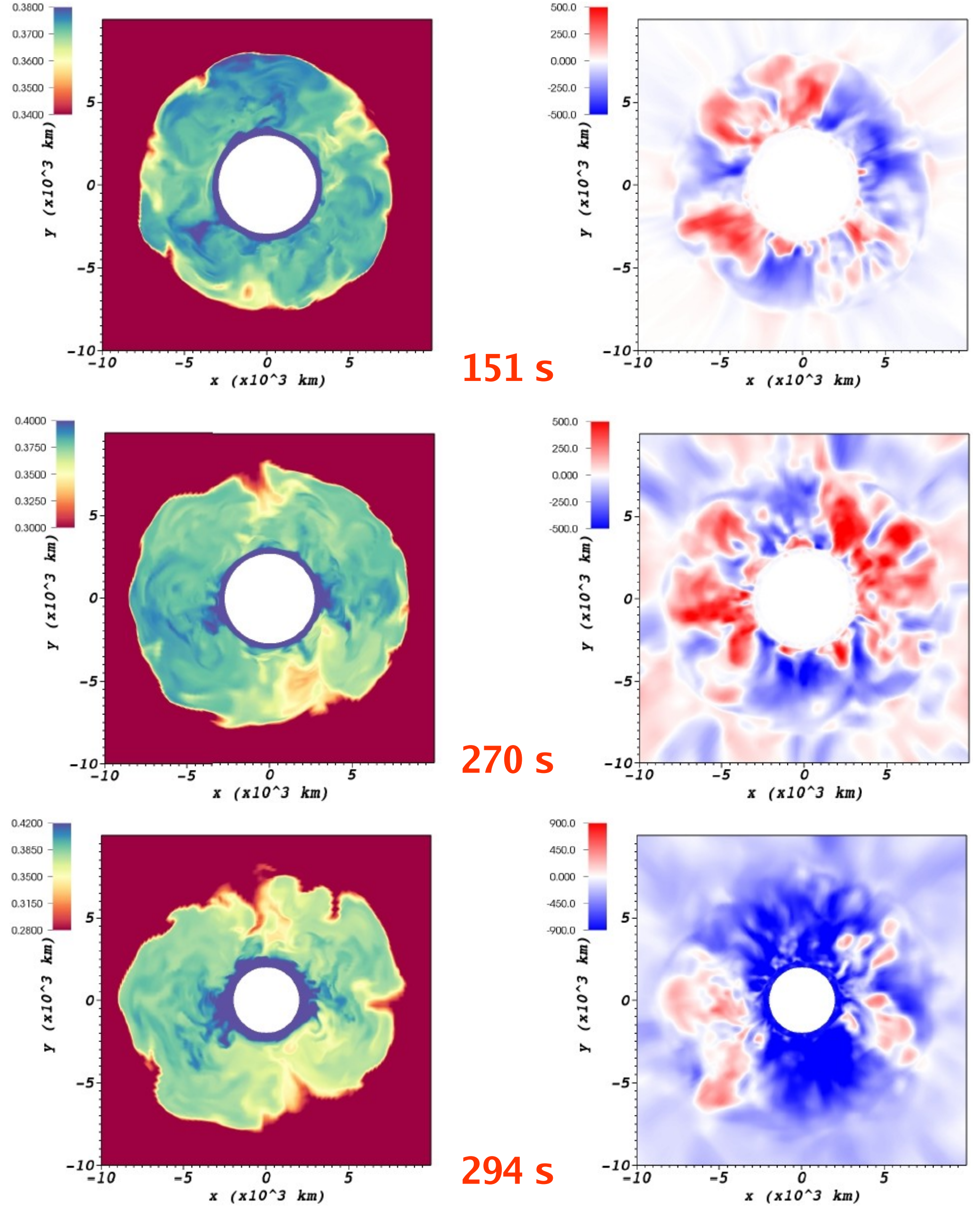
3D Core-Collapse SN Progenitor Model

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, arXiv:1605.01393



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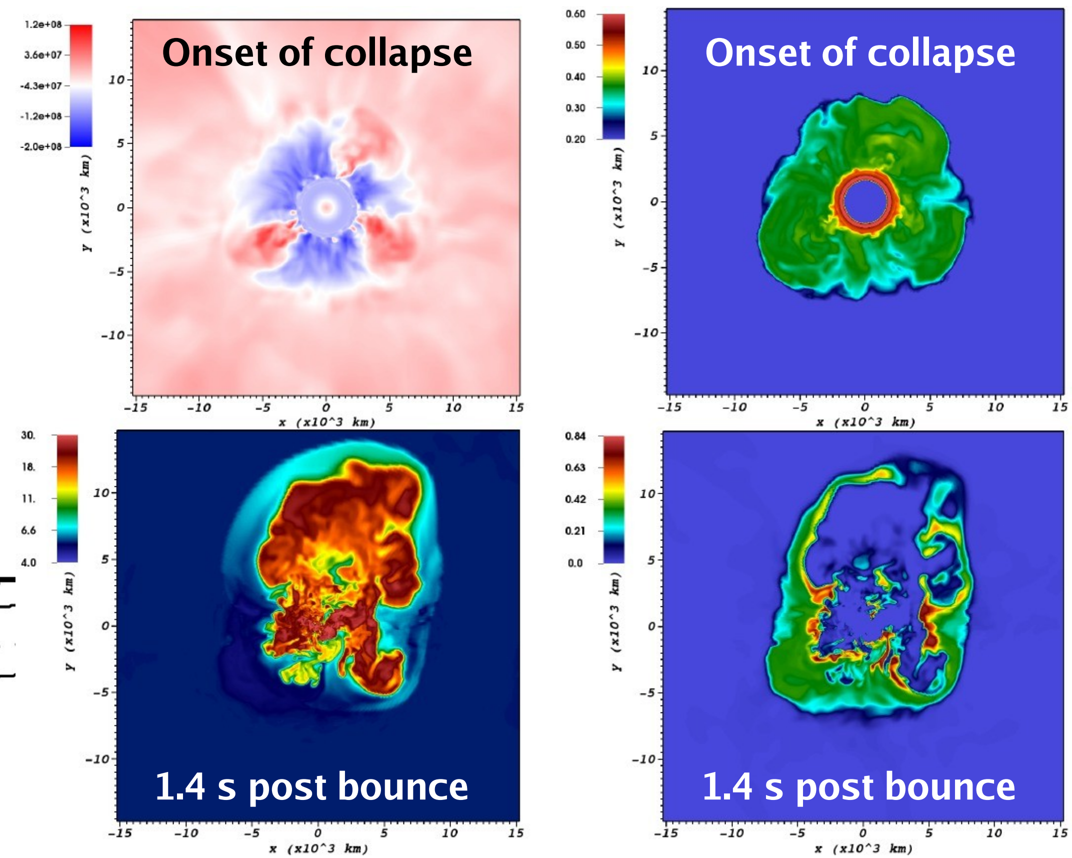

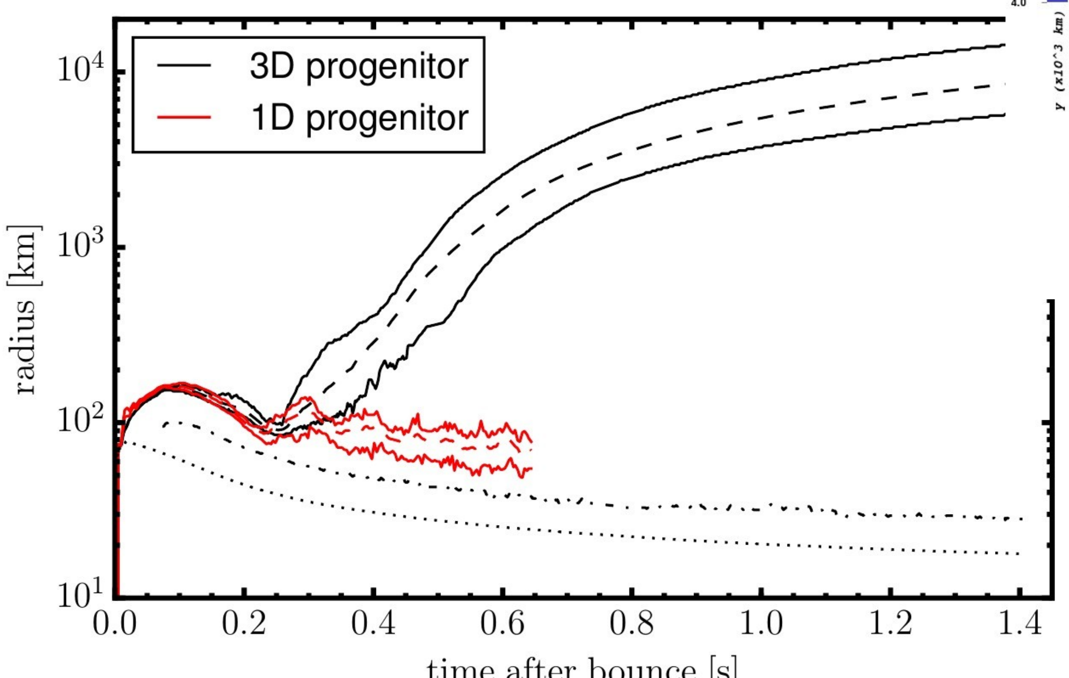

B. Müller, PASA review, arXiv:1608.03274