Max-Planck-Institut für Astrophysik

SFB-TR7

TUM LMU Excellence Cluster Universe

NAVI Annual Meeting

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Supernovae and Neutron Star Mergers as Playground of Applied Nuclear Physics

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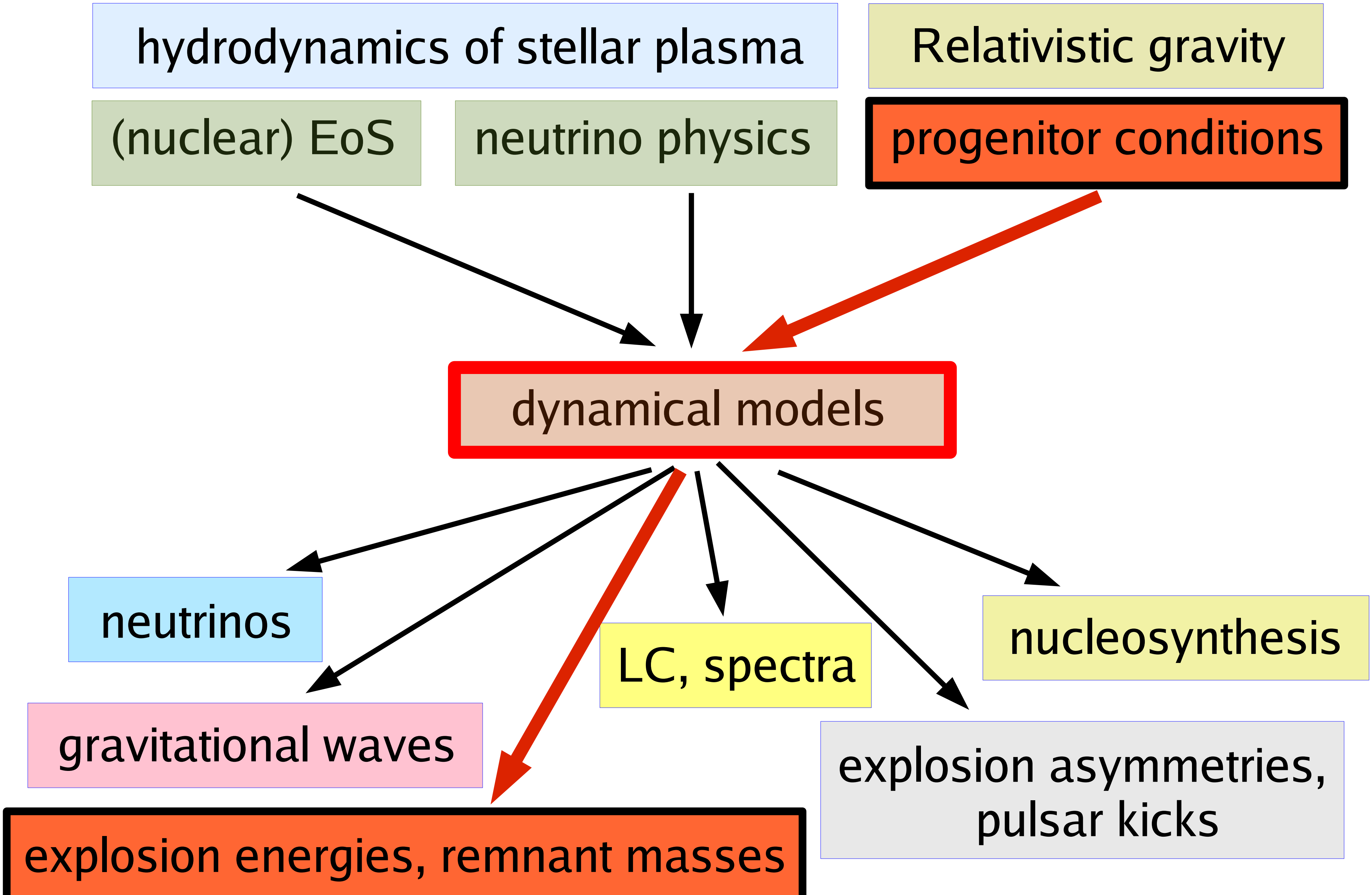
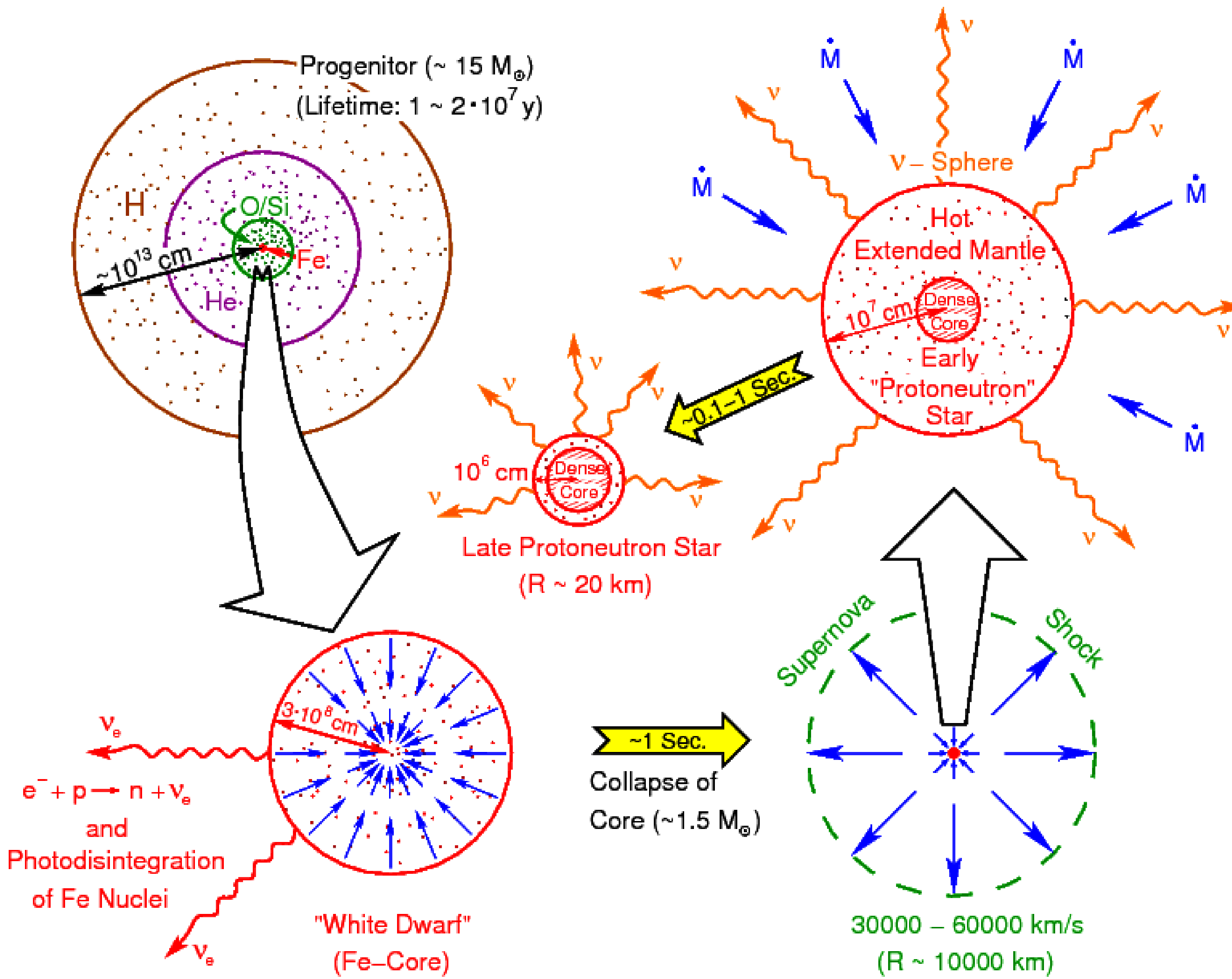
Predictions of Signals from SNe & NSs



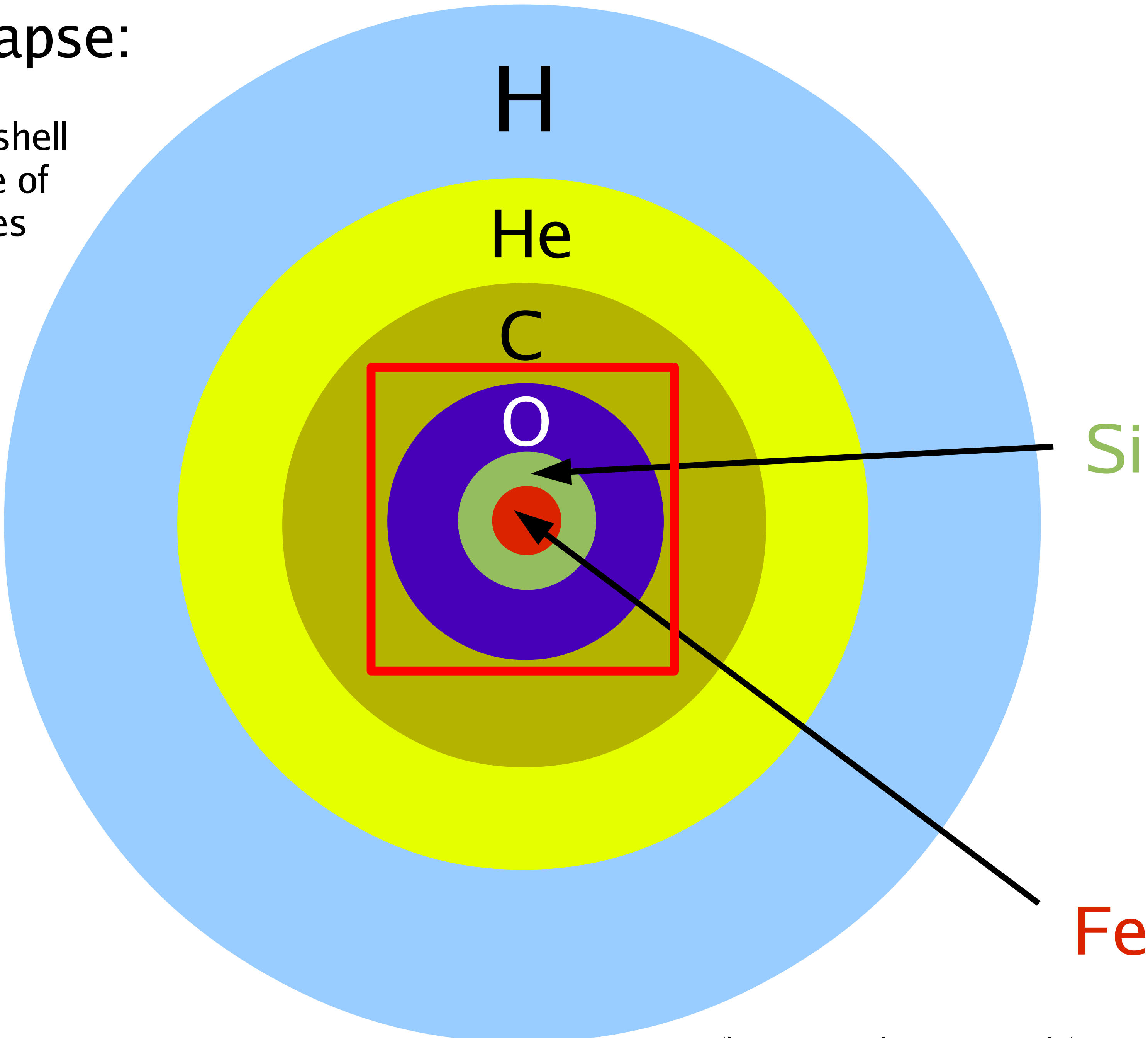
Stellar Collapse and Supernova Stages



adapted from A. Burrows (1990)

Evolved massive star prior to its collapse:

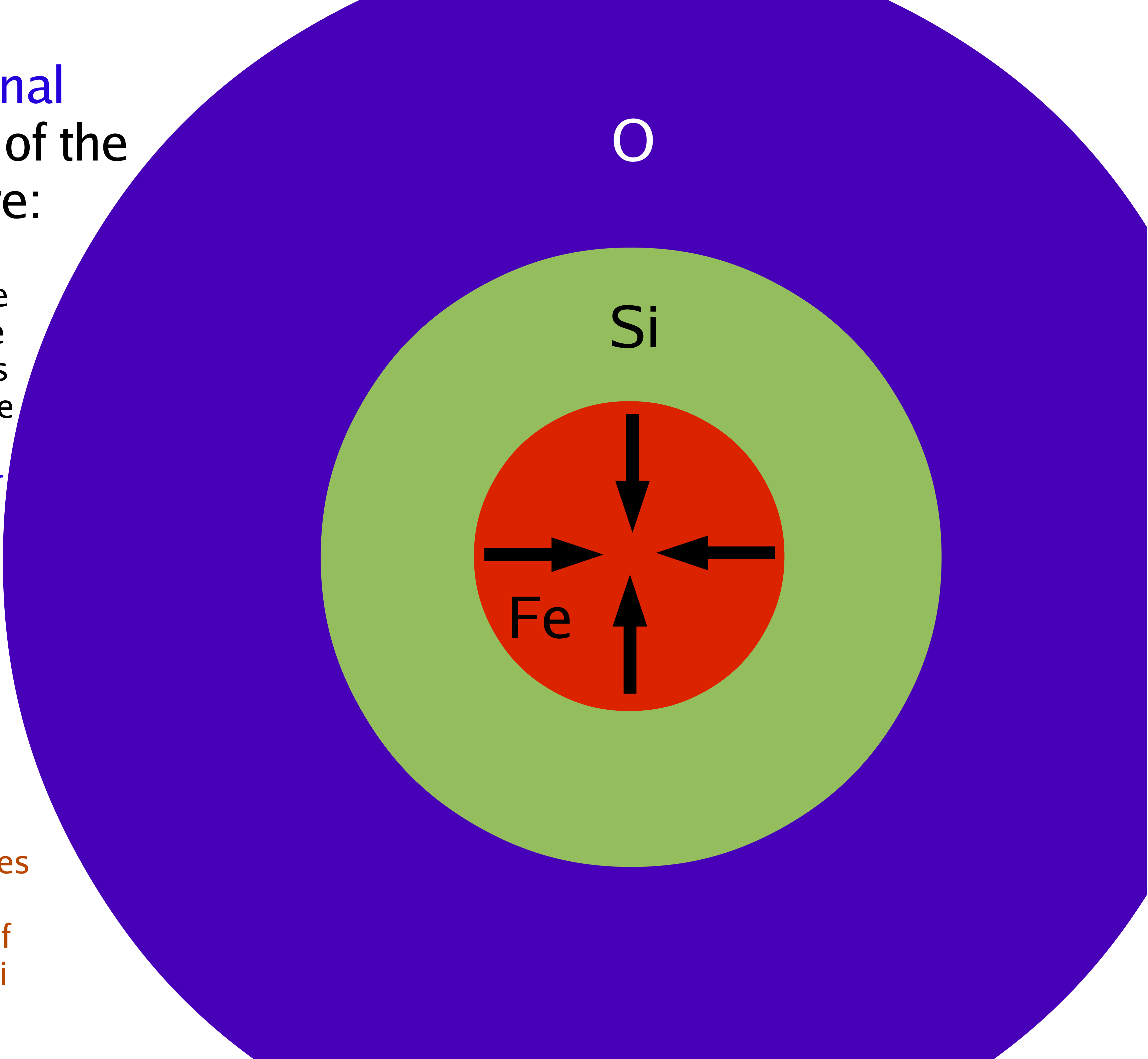
Star develops onion-shell structure in sequence of nuclear burning stages over millions of years



(layers not drawn to scale)

Gravitational instability of the stellar core:

Stellar iron core begins collapse when it reaches a mass near the critical Chandrasekhar mass limit



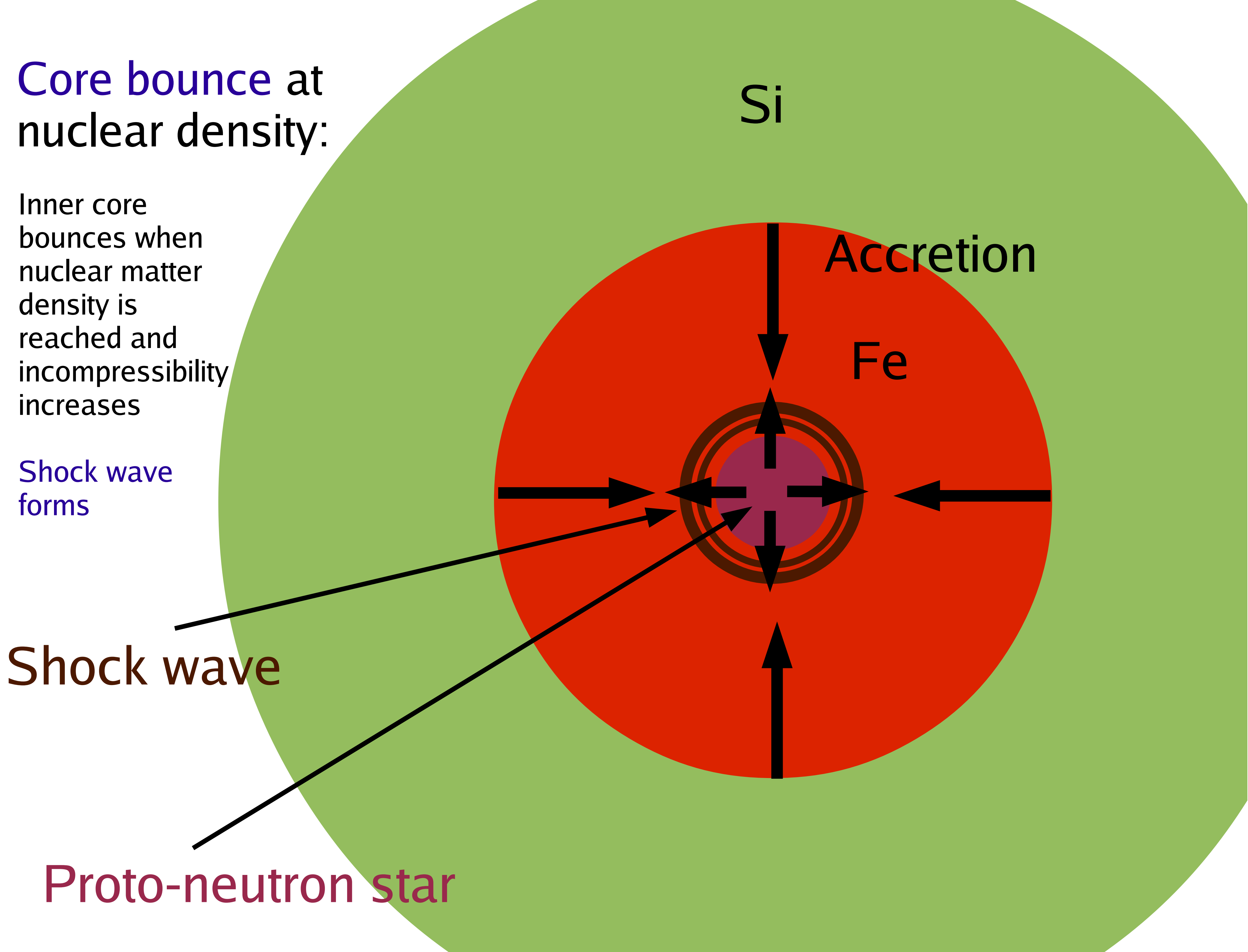
Collapse

becomes dynamical because of electron captures and photo-disintegration of Fe-group nuclei

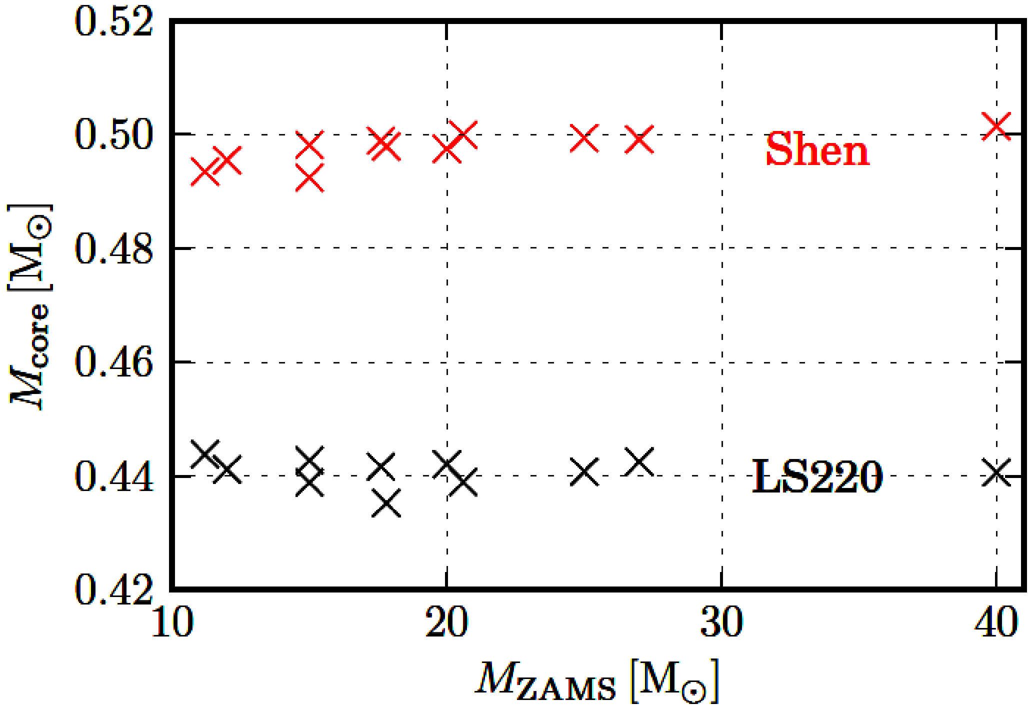
Core bounce at nuclear density:

Inner core bounces when nuclear matter density is reached and incompressibility increases

Shock wave forms

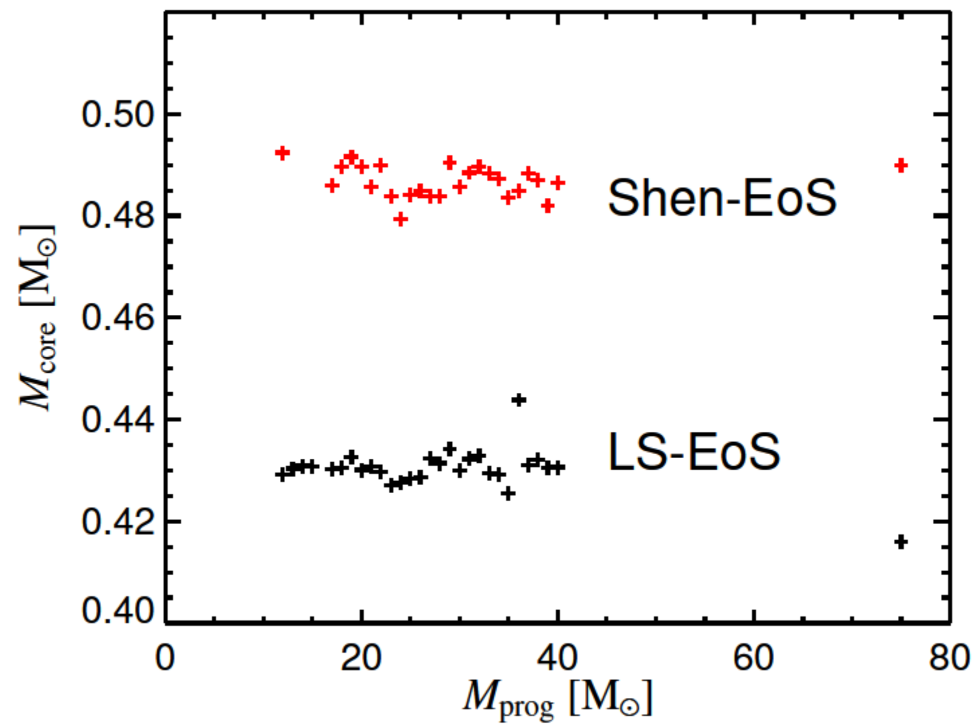


EOS dependence of inner-core mass at bounce



L. Hüdepohl, PhD Thesis (2013)

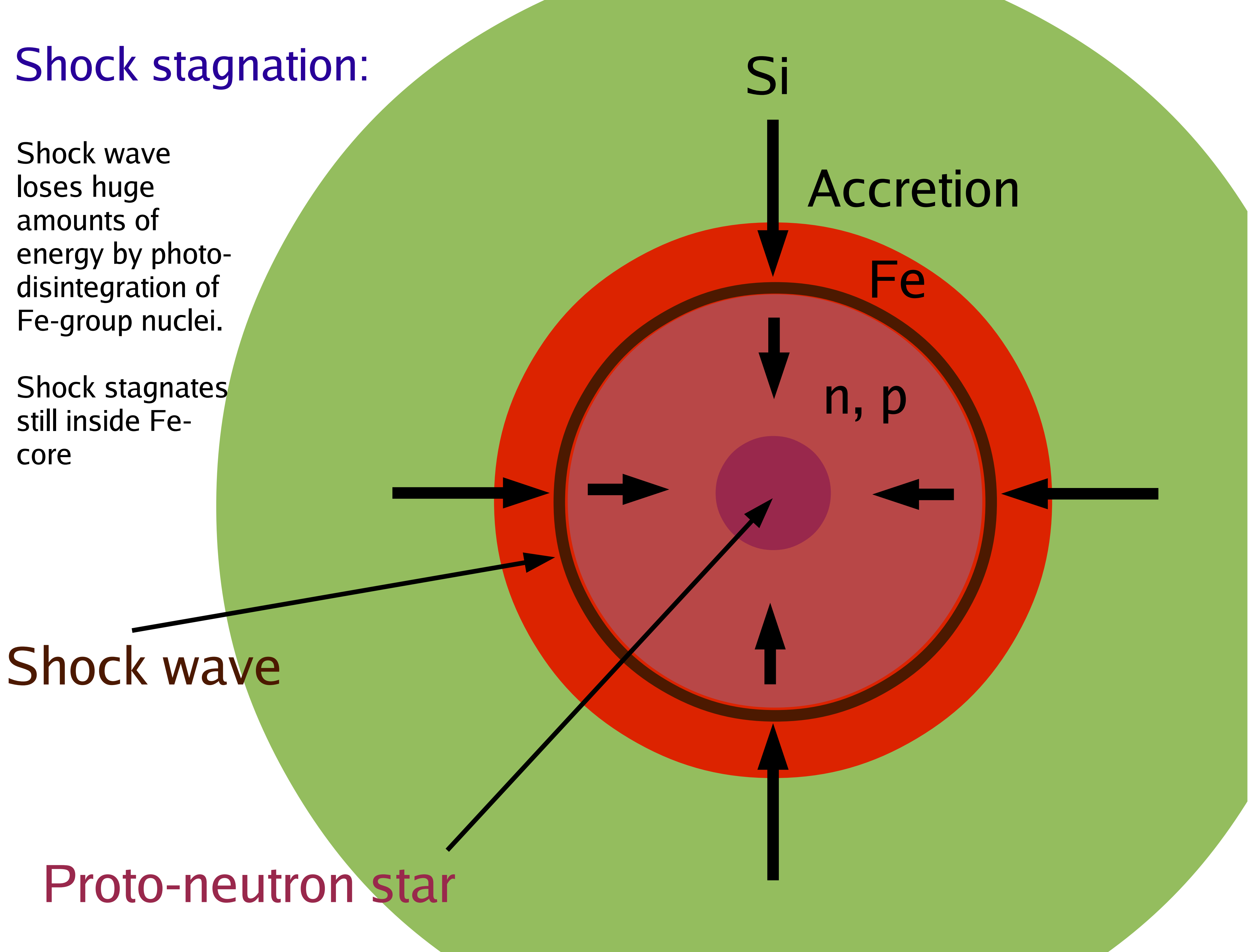
Janka et al., PTEP (2012)
(from A. Marek, PhD Thesis)



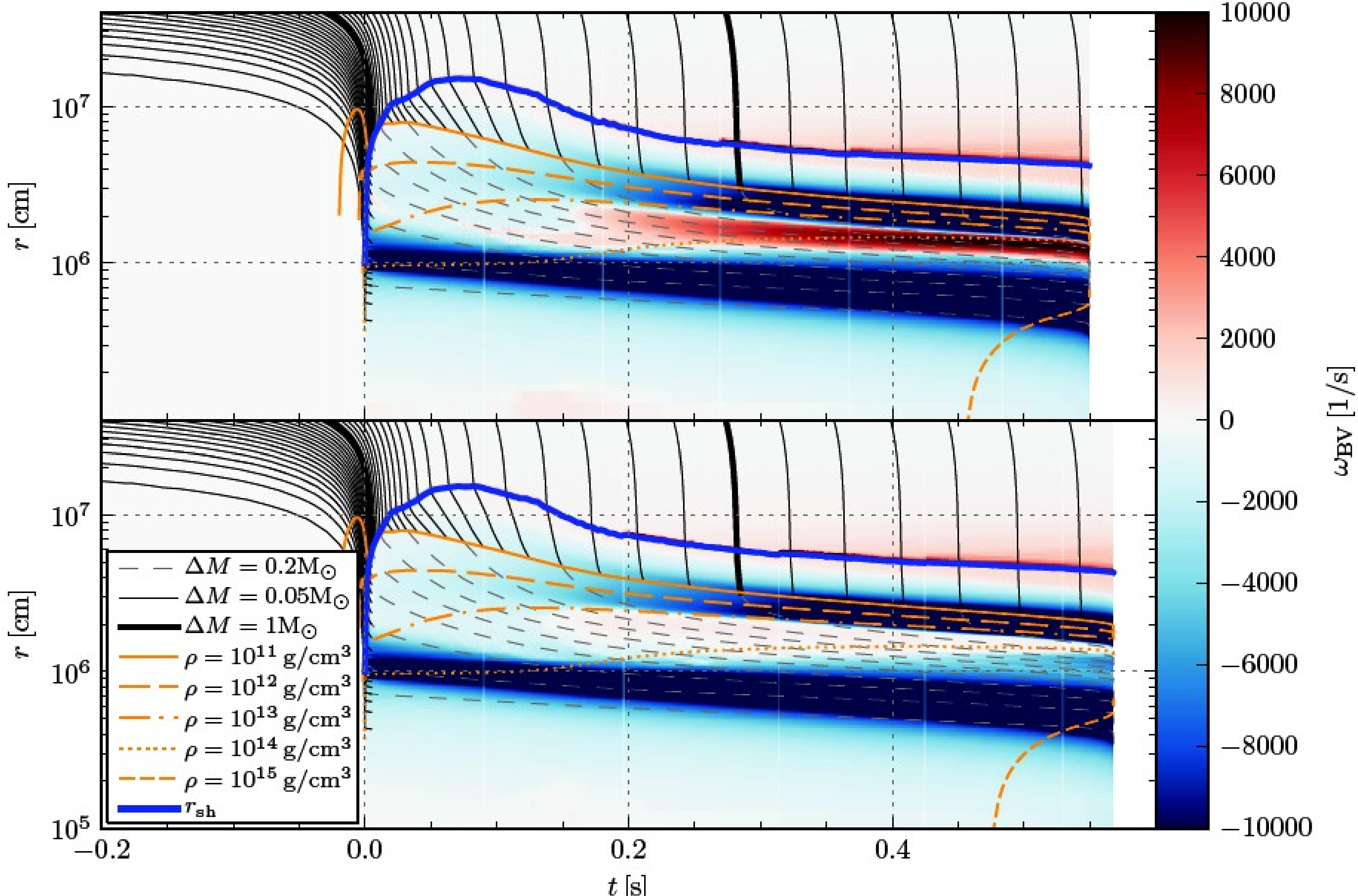
Shock stagnation:

Shock wave loses huge amounts of energy by photo-disintegration of Fe-group nuclei.

Shock stagnates still inside Fe-core



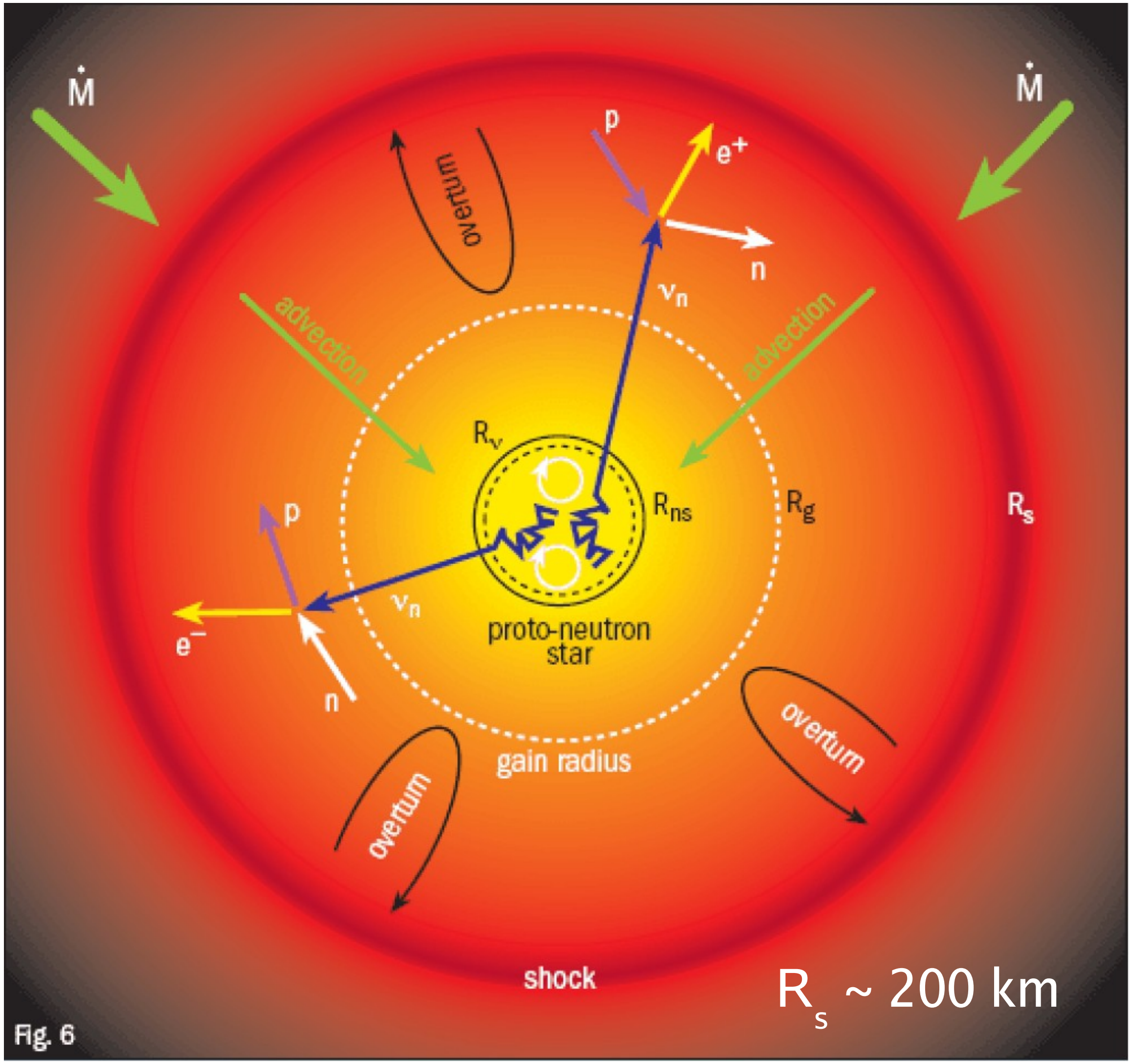
Shock evolution in 1D
without and with PNS convection



L. Hüdepohl, PhD Thesis (2013)

Neutrinos & SN Explosion Mechanism

Explosions powered by neutrino heating, supported by violent, large-scale hydrodynamic instabilities in the postshock layer

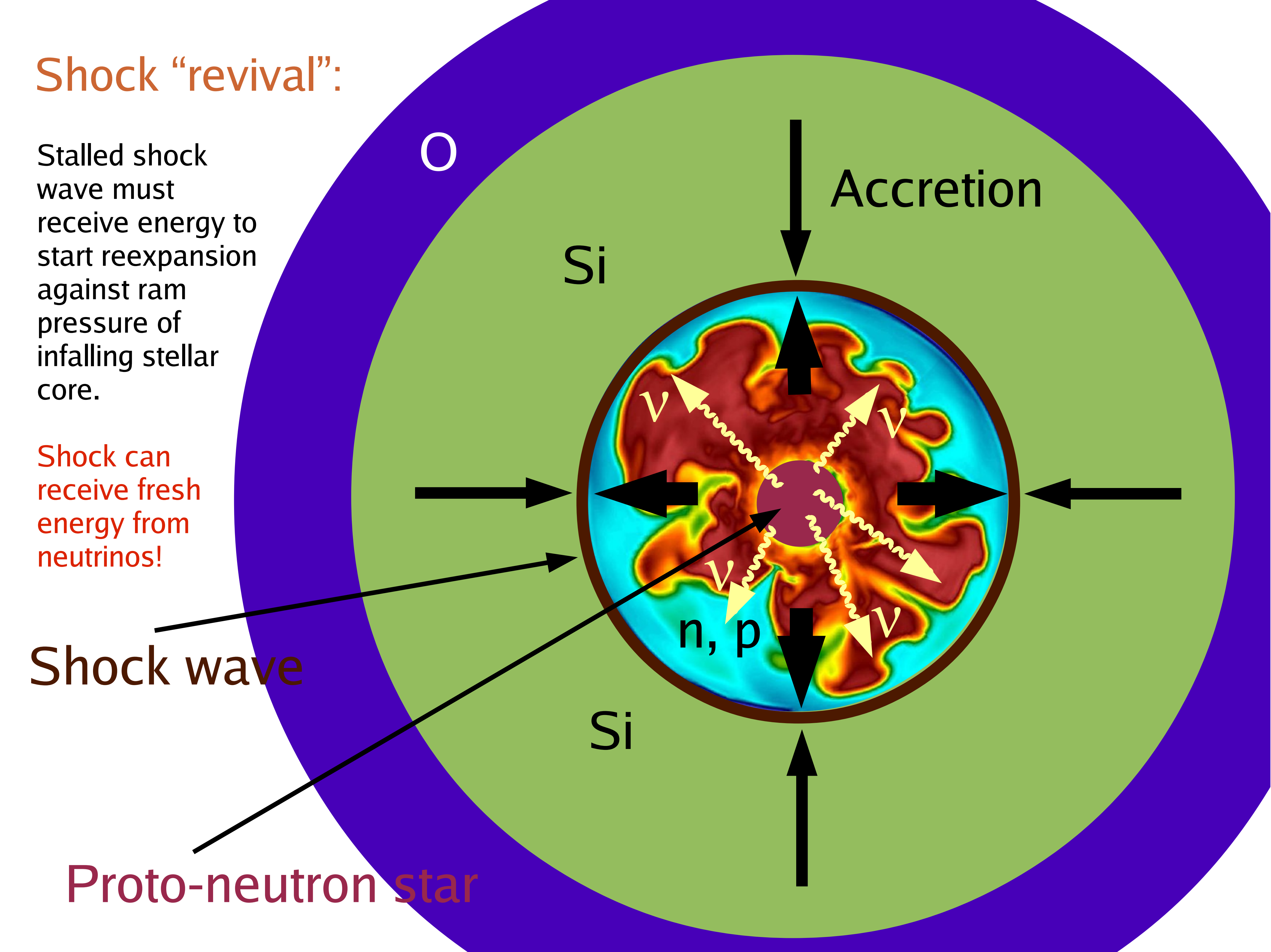


- "Neutrino-heating mechanism": Neutrinos `revive' stalled shock by energy deposition (Colgate & White 1966, Wilson 1982, Bethe & Wilson 1985);
- Convective processes & hydrodynamic instabilities support the heating mechanism (Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996; Fryer & Warren 2002, 2004; Blondin et al. 2003; Blondin & Mezzacappa 2007, Scheck et al. 2004,06,08, Iwakami et al. 2008, 2009, Ohnishi et al. 2006).

Shock "revival":

Stalled shock wave must receive energy to start reexpansion against ram pressure of infalling stellar core.

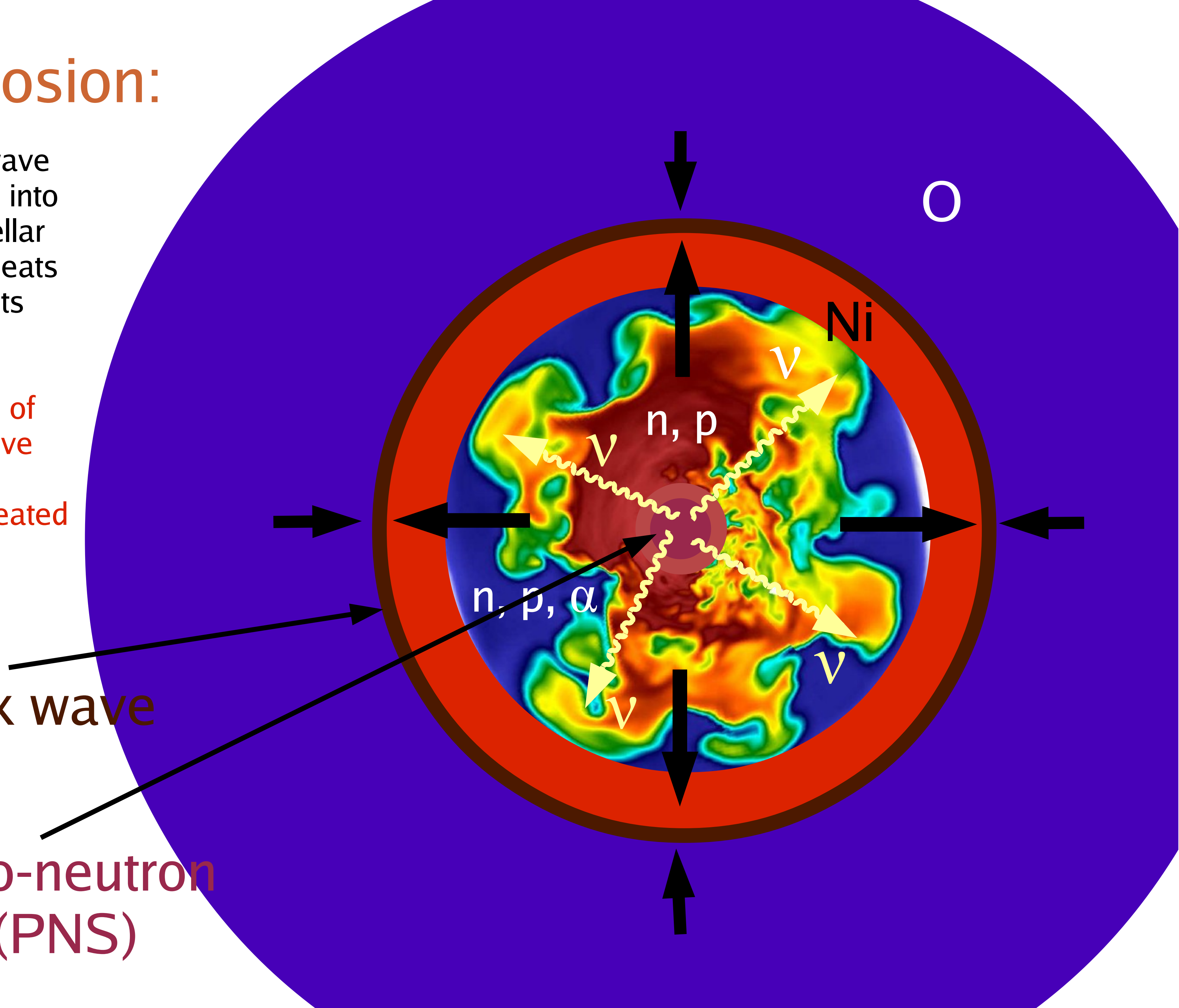
Shock can receive fresh energy from neutrinos!



Explosion:

Shock wave expands into outer stellar layers, heats and ejects them.

Creation of radioactive nickel in shock-heated Si-layer.



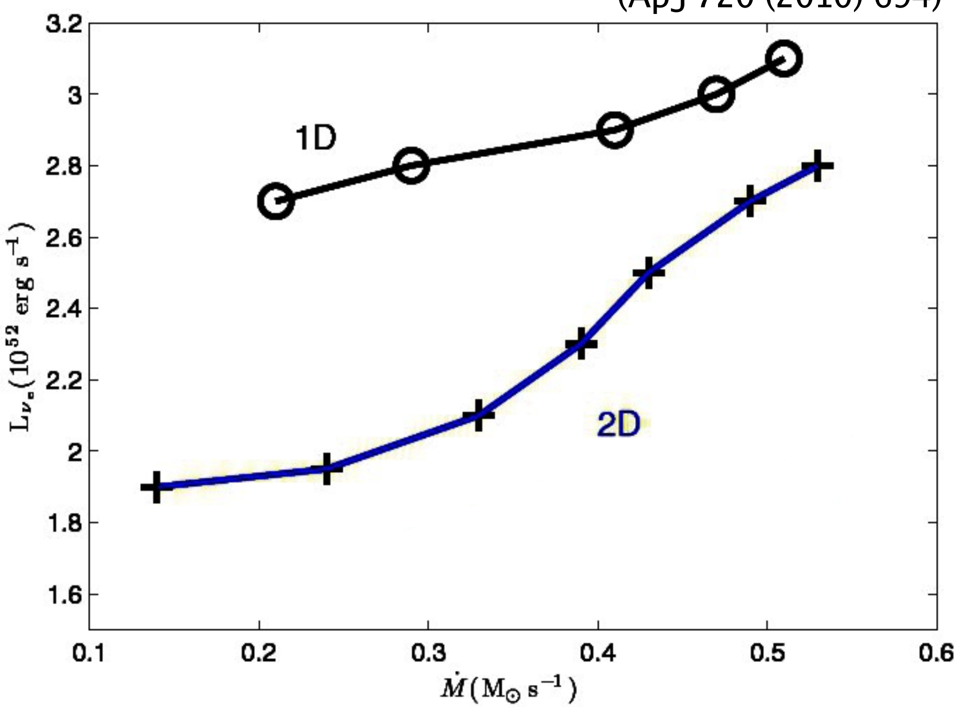
1D-2D Differences in Parametric Explosion Models

- Nordhaus et al. (ApJ 720 (2010) 694) and Murphy & Burrows (2008) performed 1D & 2D simulations with simple neutrino- heating and cooling terms (no neutrino transport but lightbulb) and found up to ~30% improvement in 2D for 15 M_{sun} progenitor star.

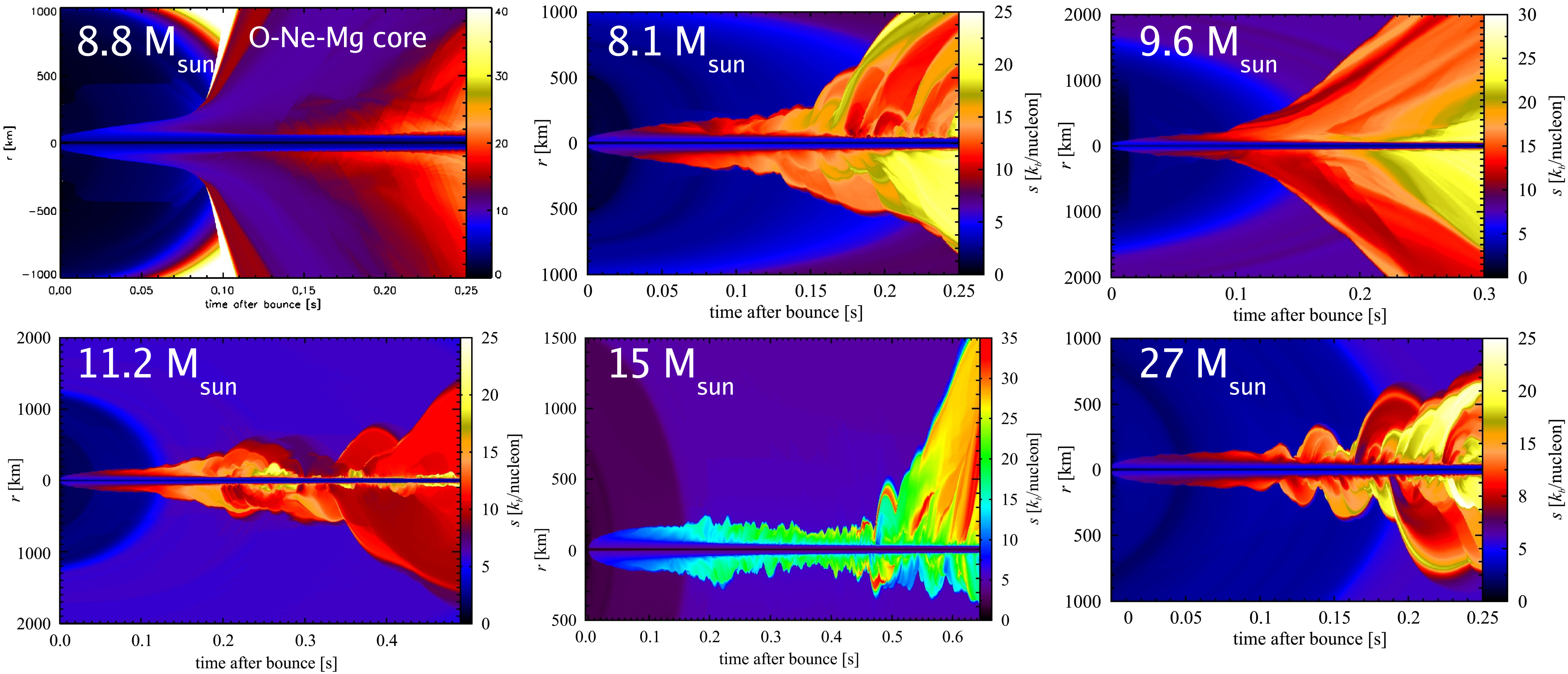
$$\mathcal{H} = 1.544 \times 10^{20} \left(\frac{L_{\nu_e}}{10^{52}\ \mathrm{erg\ s^{-1}}}\right)\left(\frac{T_{\nu_e}}{4\ \mathrm{MeV}}\right)^2 \times \left(\frac{100\,\mathrm{km}}{r}\right)^2 (Y_\mathrm{n} + Y_\mathrm{p}) e^{-\tau_{\nu_e}} \left[\frac{\mathrm{erg}}{\mathrm{g\ s}}\right]$$

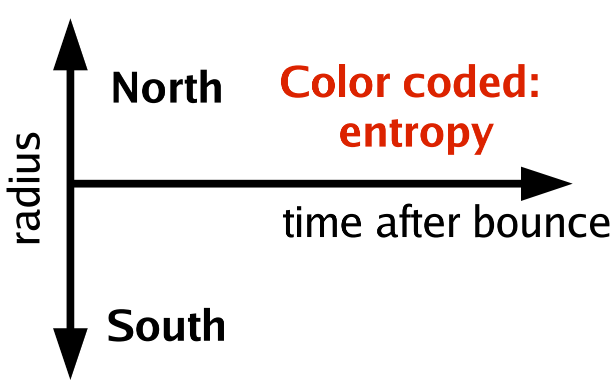
$$\mathcal{C} = 1.399 \times 10^{20} \left(\frac{T}{2\ \mathrm{MeV}}\right)^6 (Y_\mathrm{n} + Y_\mathrm{p}) e^{-\tau_{\nu_e}} \left[\frac{\mathrm{erg}}{\mathrm{g\ s}}\right]$$

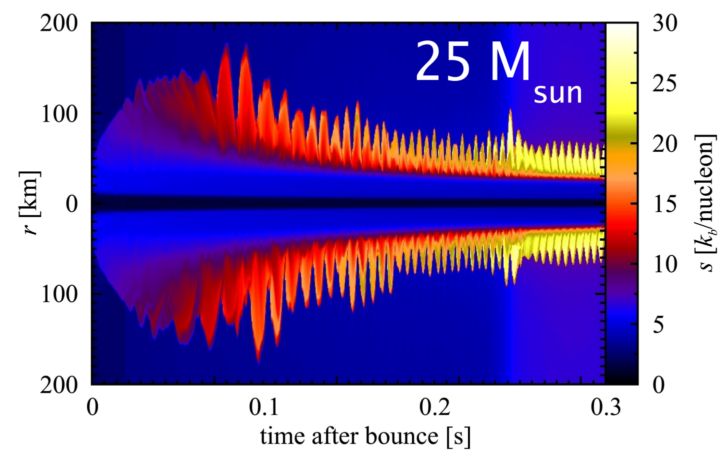
(ApJ 720 (2010) 694)



Relativistic 2D CCSN Explosion Models







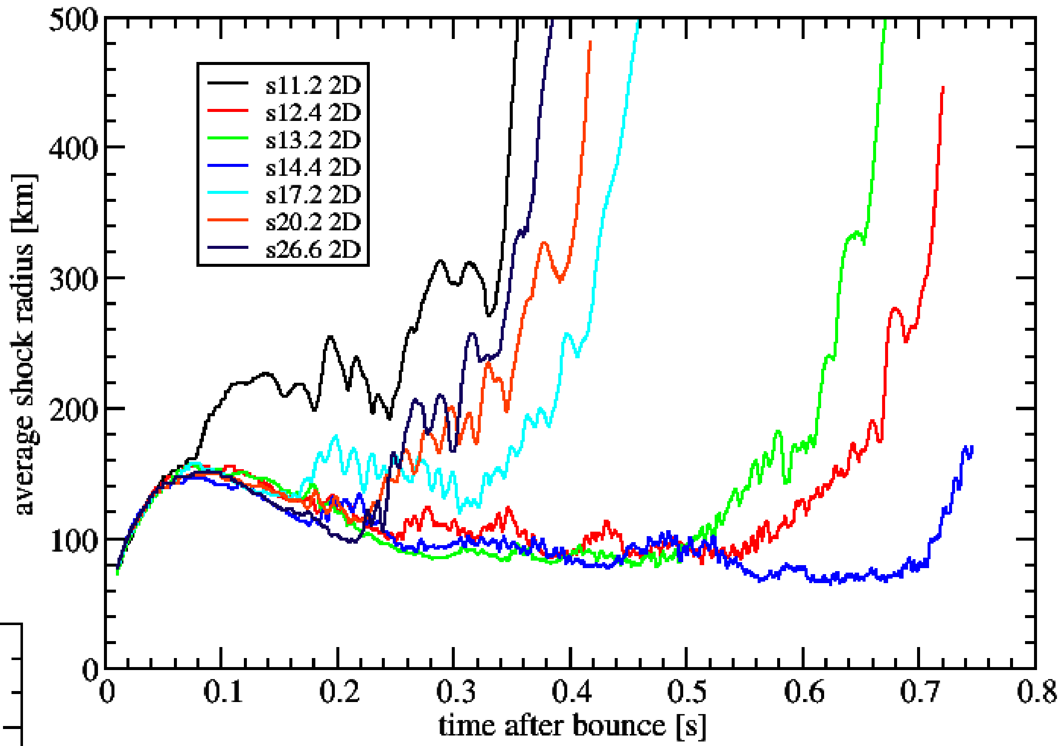
Bernhard Müller, THJ, et al. (ApJ 756, ApJ 761, ApJ 766

Basic confirmation of previous explosion models for 11.2 and 15 M_{sun} stars by Marek & THJ (2009)

Growing Set of 2D CCSN Explosion Models

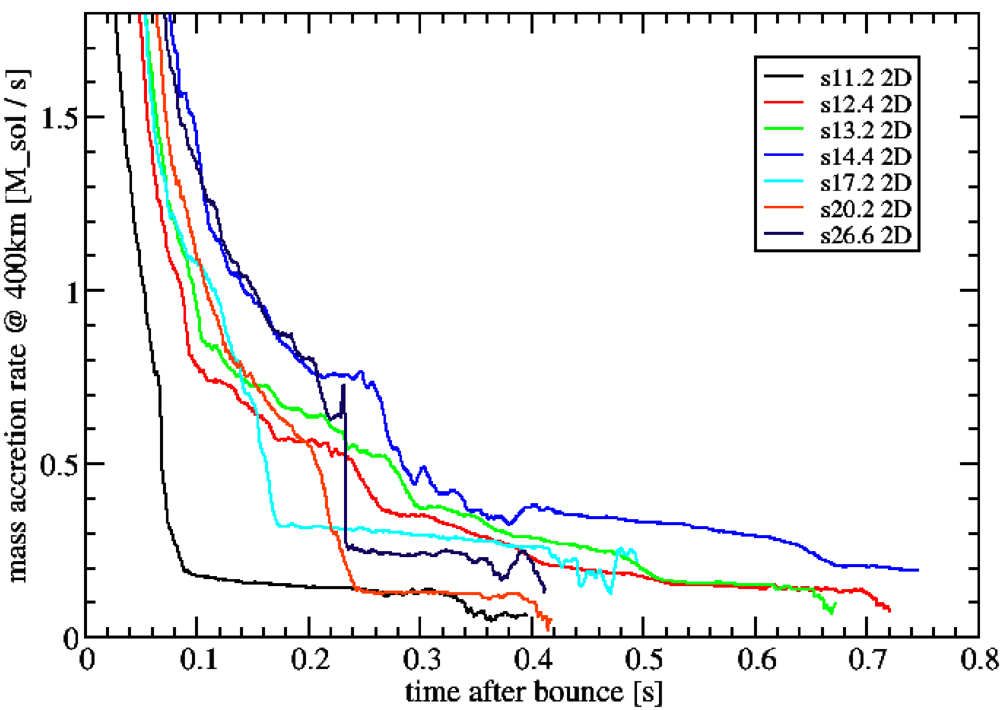
Decrease of mass-accretion rate at composition-shell interfaces allows for onset of explosions.

Florian Hanke (PhD project)



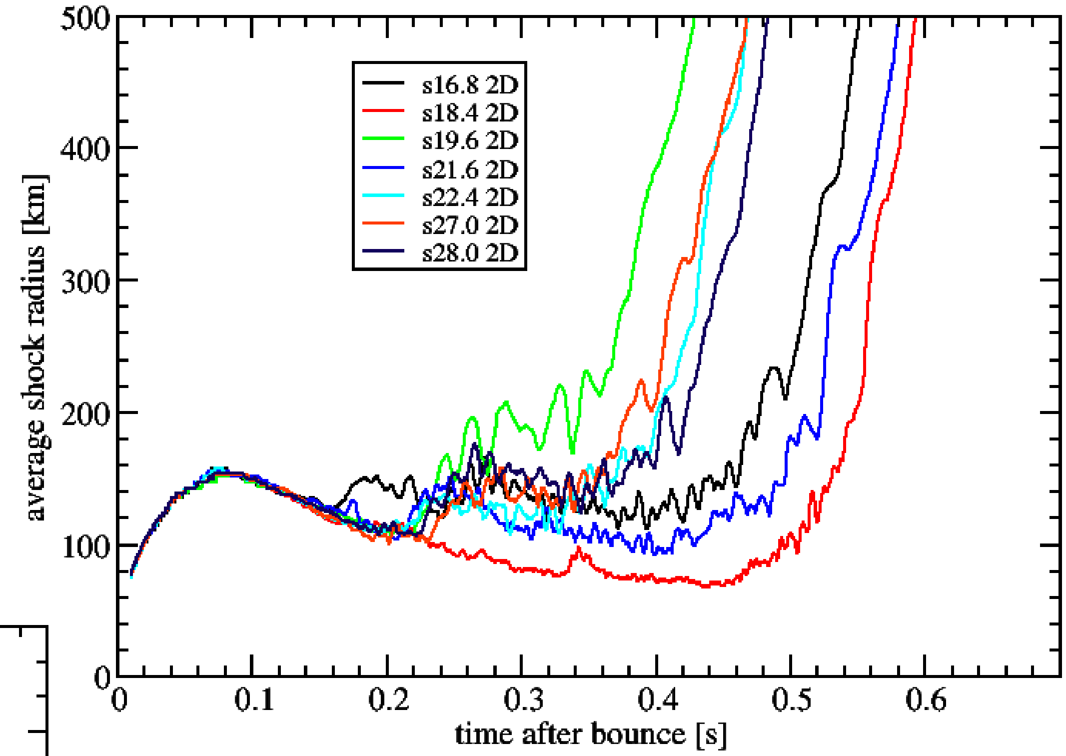
Average shock radius

Mass accretion rate



Progenitor models: Woosley et al. RMP (2002)

Growing Set of 2D CCSN Explosion Models



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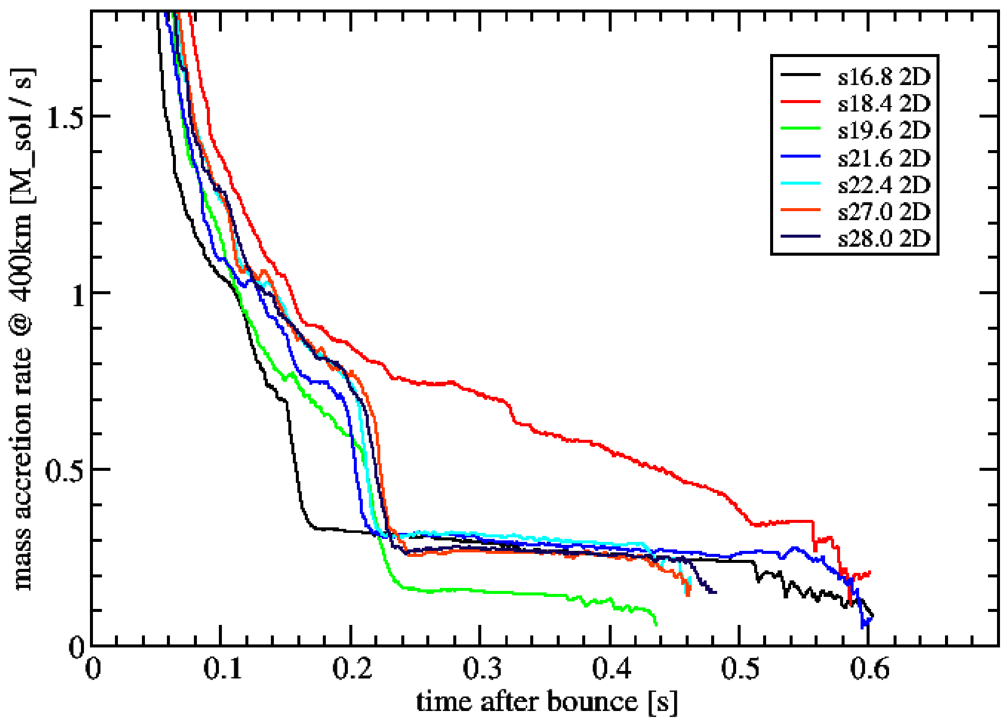
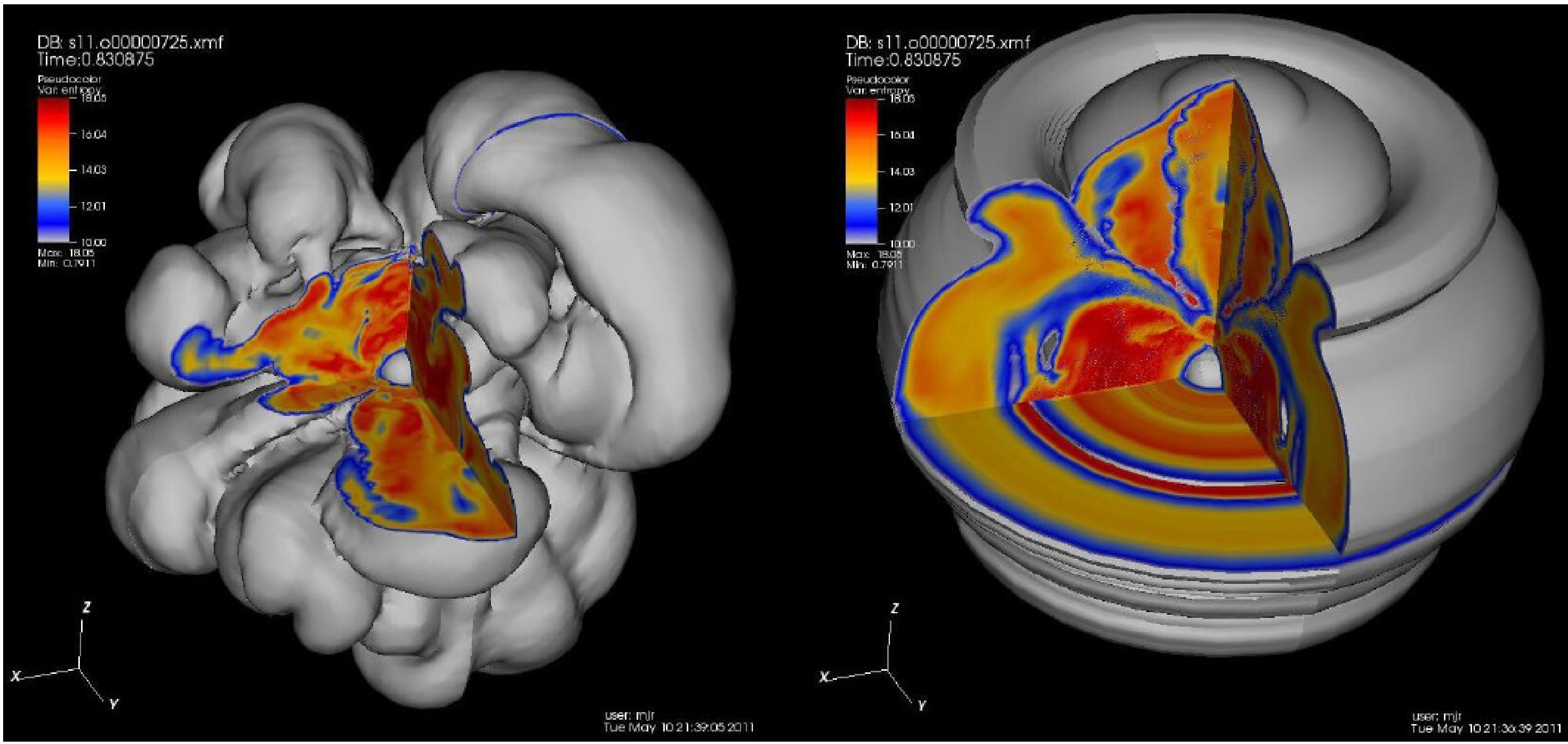
Mass accretion rate



Average shock radius

Progenitor models: Woosley et al. RMP (2002)

2D vs. 3D Morphology



(Images from Markus Rampp, RZG)

2D-3D Differences in Parametric Explosion Models

- Nordhaus et al. (ApJ 720 (2010) 694) performed 2D & 3D simulations with simple neutrino- heating and cooling terms (no neutrino transport but lightbulb) and found 15–25% improvement in 3D for 15 M_{sun} progenitor star (ApJ 720 (2010) 694)

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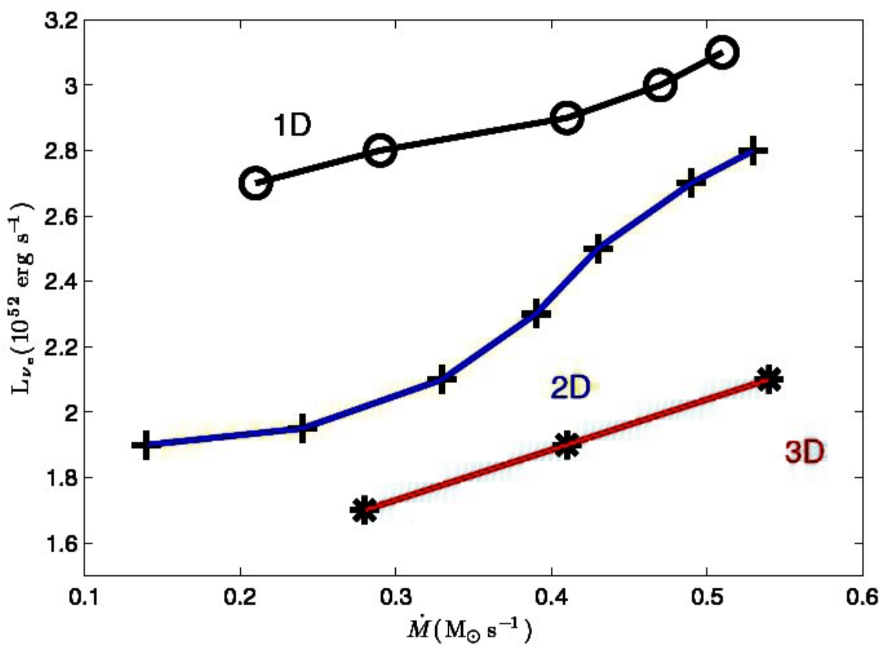

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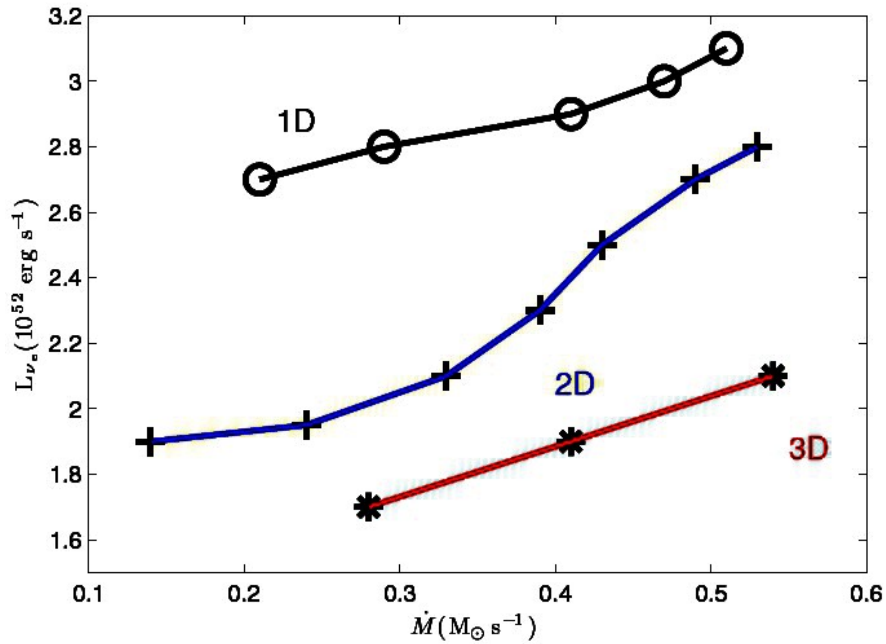
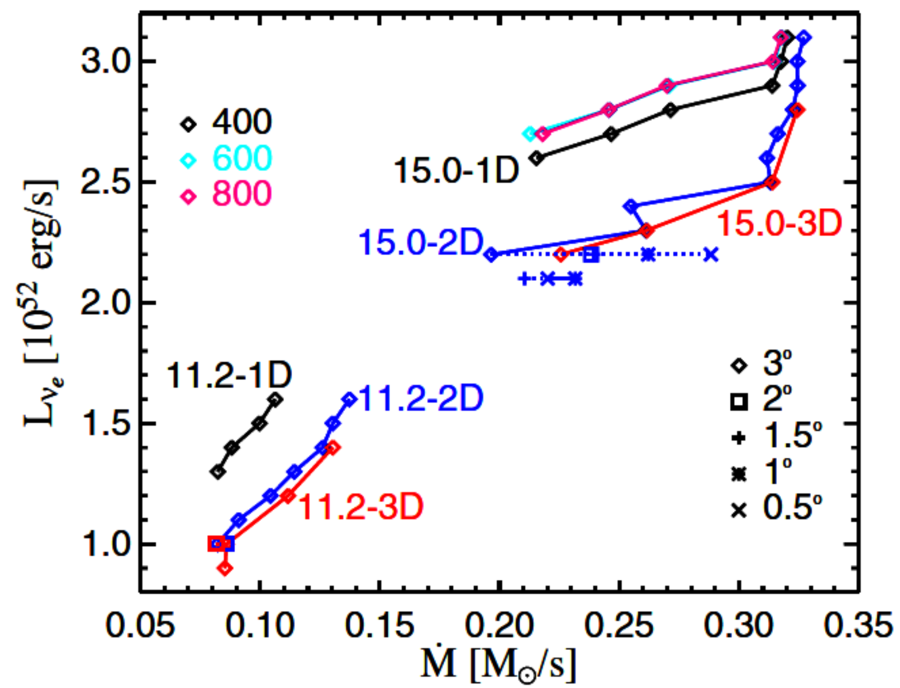


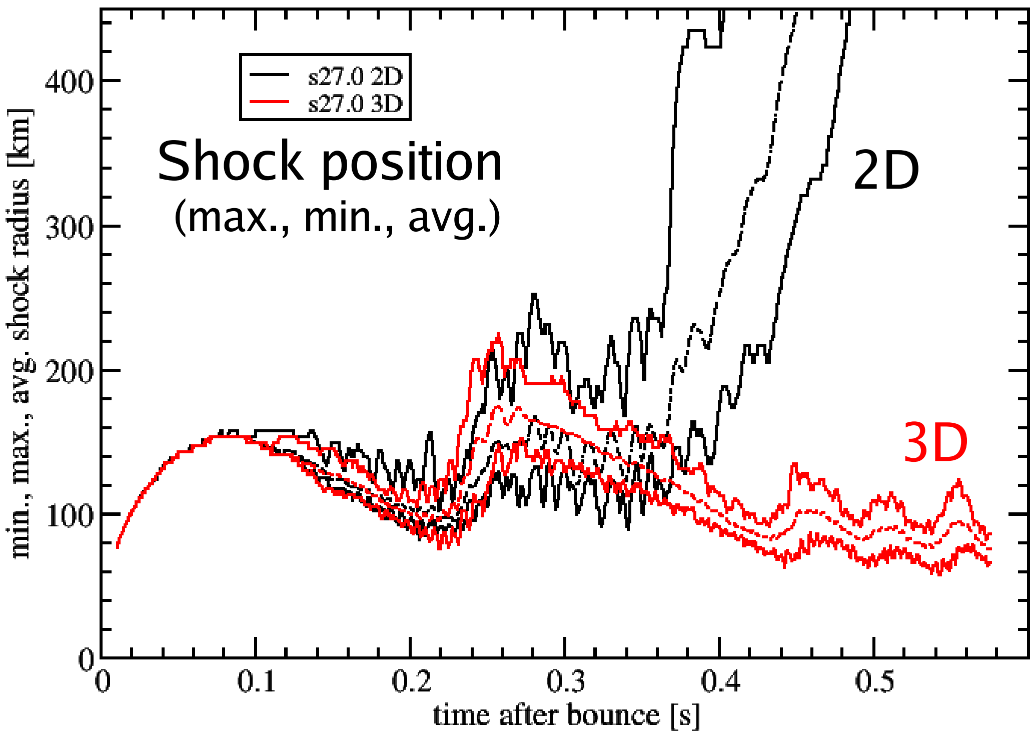
Nordhaus et al. (ApJ 720 (2010) 694)

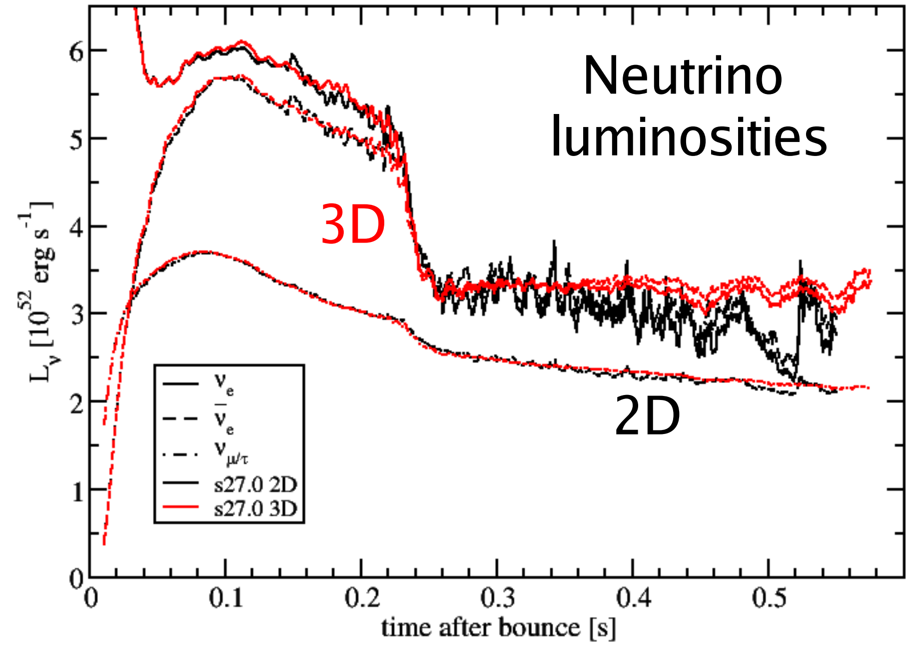


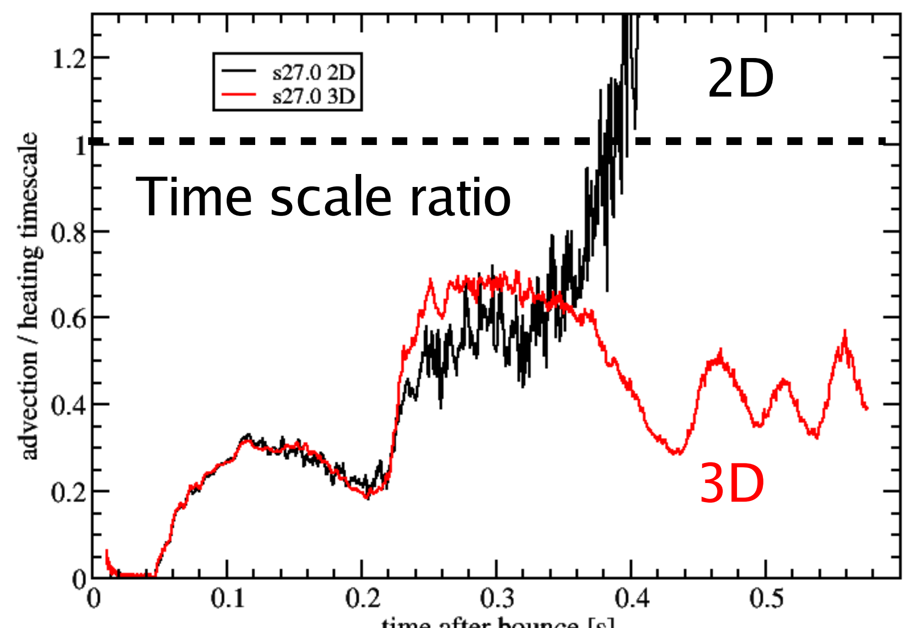
No confirmation by Hanke et al., ApJ 755 (2012) 138, Couch (2012), and Takiwaki et al. (2013), Couch & O'Connor (2013)

3D SNCC Models with Neutrino Transport

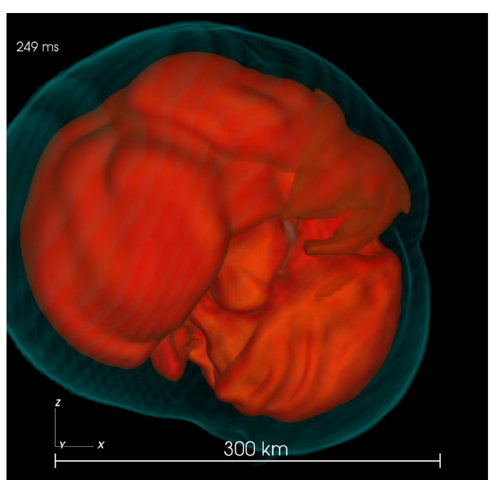
27 M_{sun} progenitor (WHW 2002)





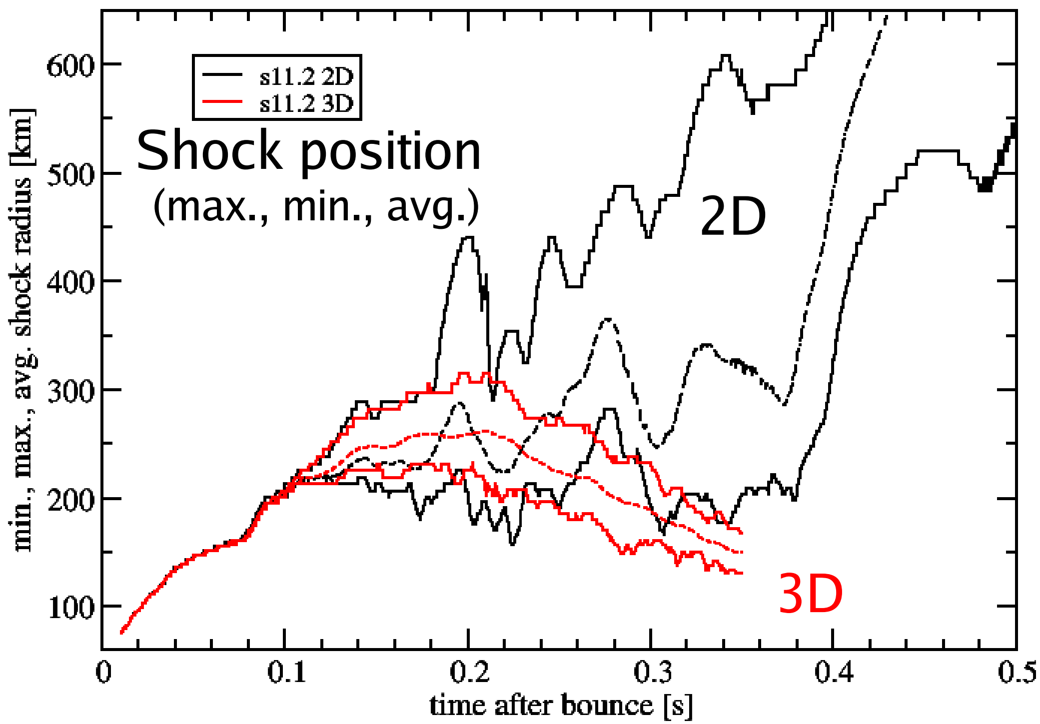


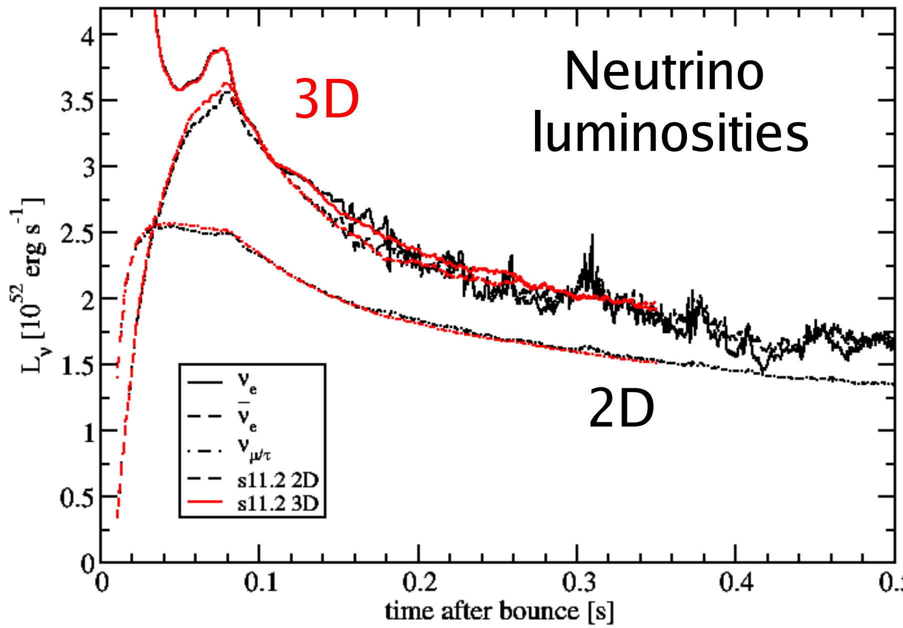
F. Hanke et al.,
ApJ 770 (2013) 66

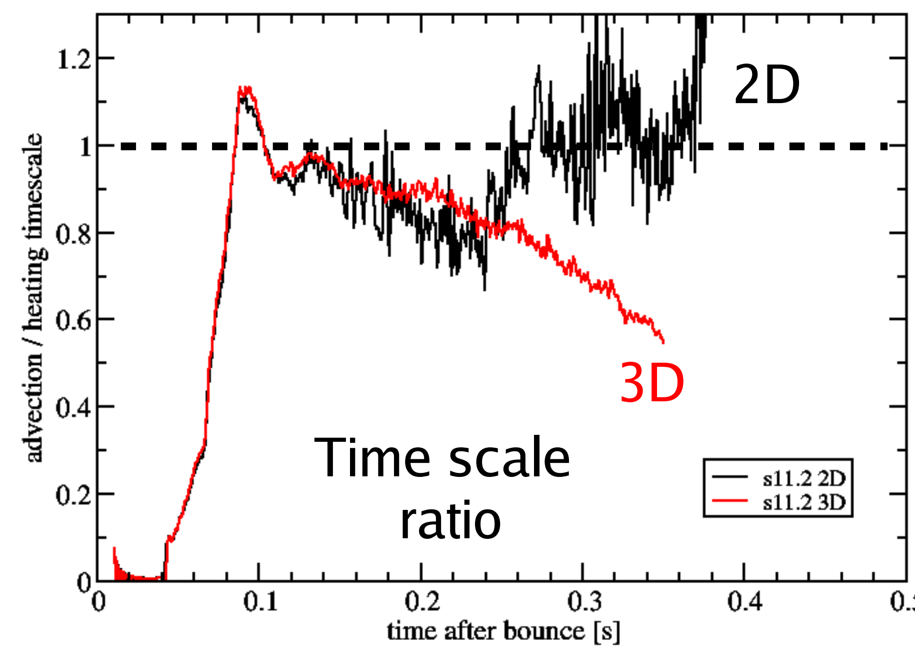


3D SNCC Models with Neutrino Transport

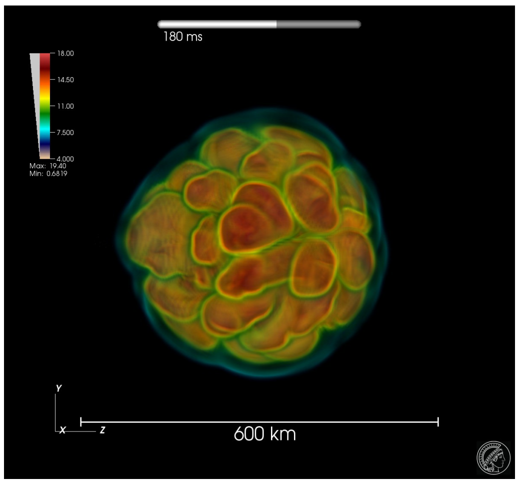
11.2 M_{sun} progenitor (WHW 2002)





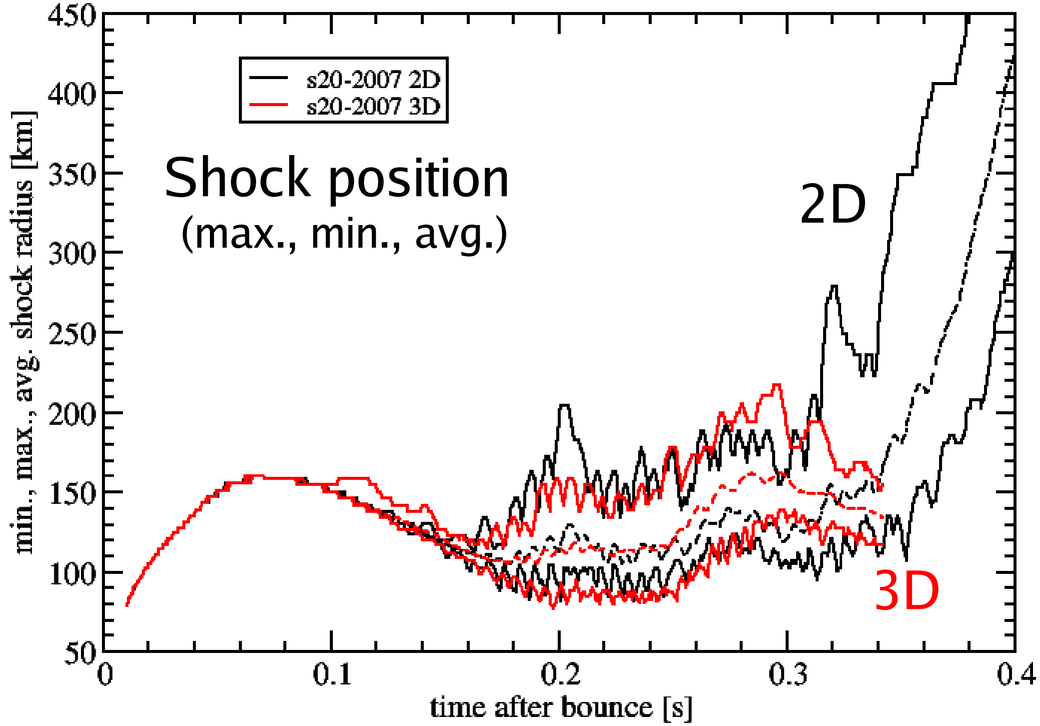


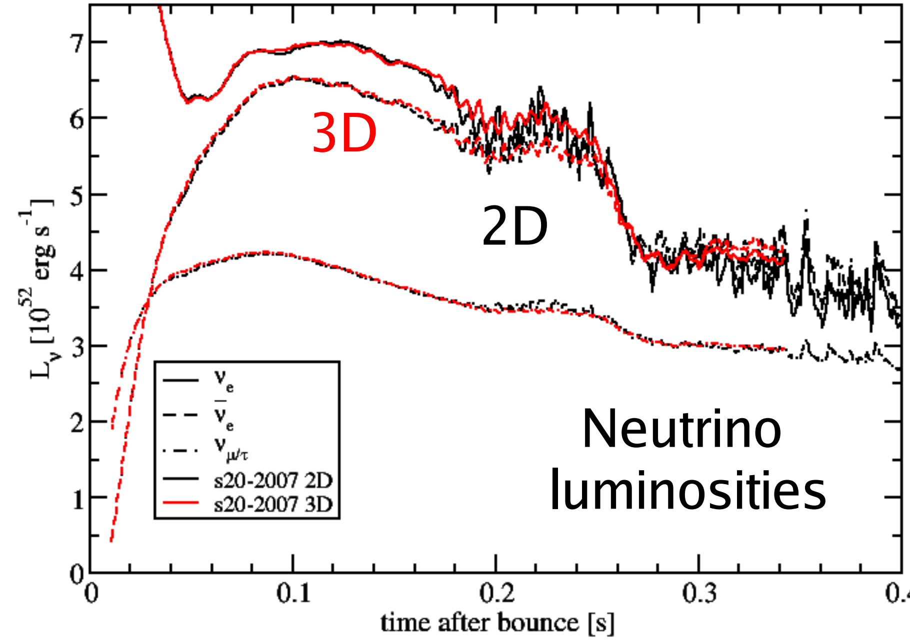
Florian Hanke, PhD project

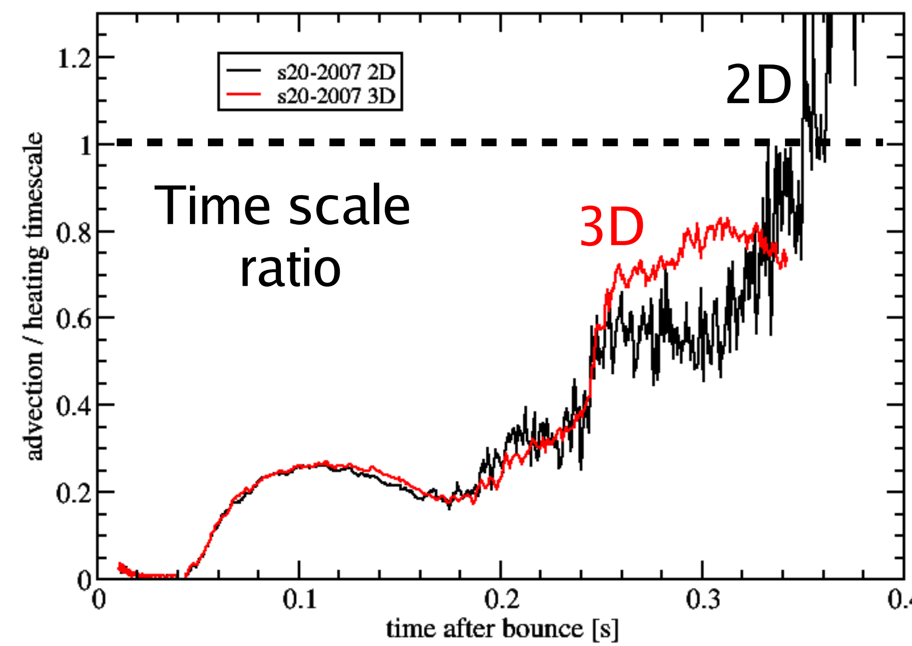


3D SNCC Models with Neutrino Transport

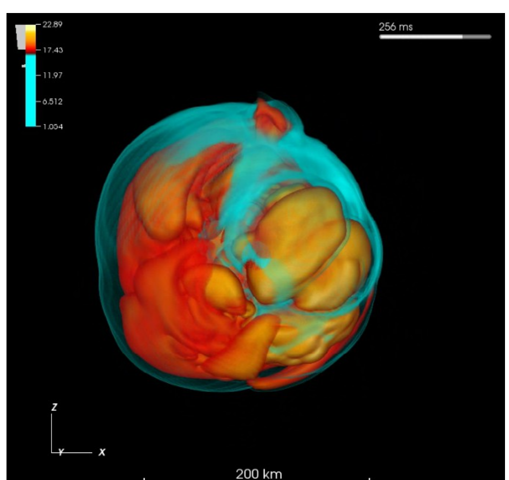
20 M_{sun} progenitor (WH 2007)







Florian Hanke, PhD project



Numerical Convergence?

Hanke et al., ApJ 755 (2012) 138; arXiv:1108.4355

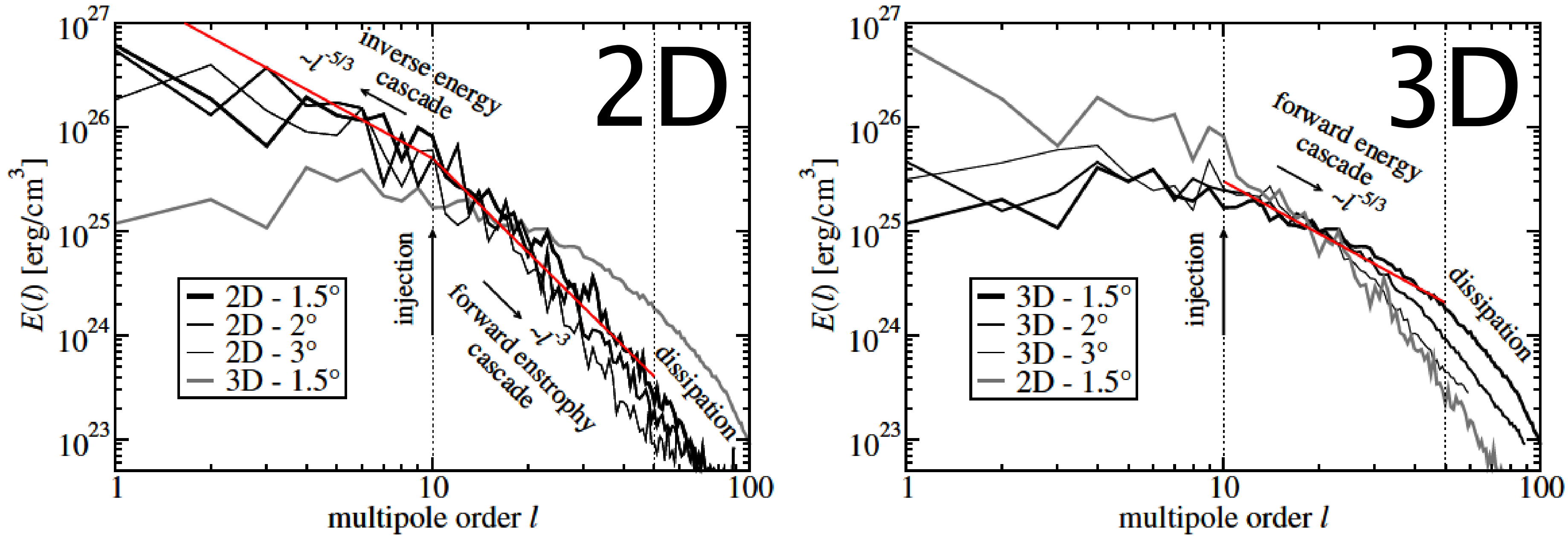


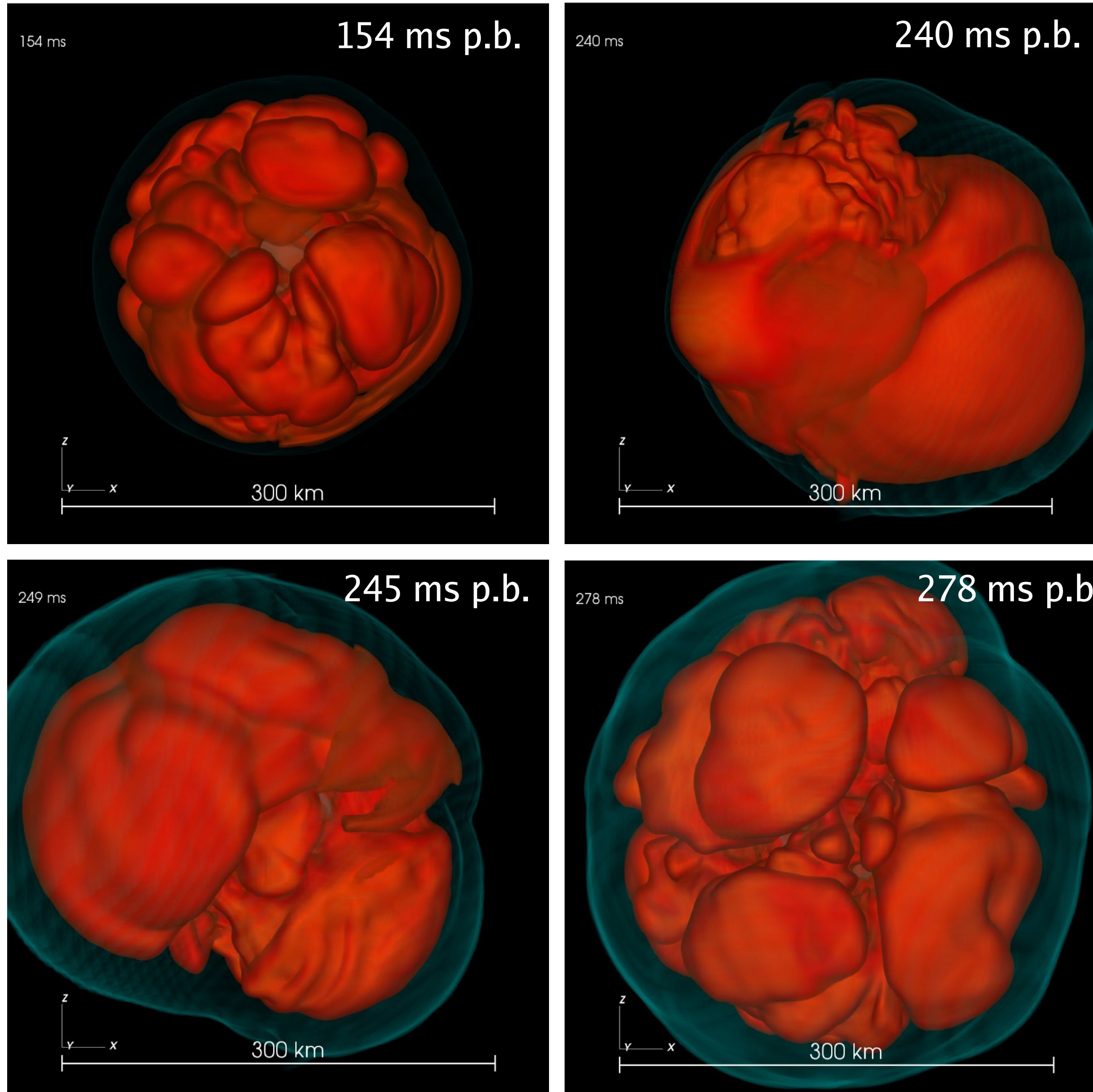
Figure 16. Turbulent energy spectra $E(l)$ as functions of the multipole order l for different angular resolution. The spectra are based on a decomposition of the azimuthal velocity v_θ into spherical harmonics at radius $r = 150$ km and 400 ms post-bounce time for 15 $M_\odot$ runs with an electron–neutrino luminosity of $L_{\nu_e} = 2.2 \times 10^{52}$ erg s^{-1}. Left: 2D models with different angular resolution (black, different thickness) and, for comparison, the 3D model with the highest employed angular resolution (gray). Right: 3D models with different angular resolution and, for comparison, the 2D model with the highest employed angular resolution (gray). The power-law dependence and direction of the energy and enstrophy cascades (see the text) are indicated by red lines and labels for 2D models in the left panel and 3D models in the right panel. The left vertical, dotted line roughly marks the energy-injection scale, and the right vertical, dotted line denotes the onset of dissipation at high l for the best-displayed resolution.

Turbulent energy cascade in 2D from small to large scales, in 3D from large to small scales!   =====>   **More than 2 degree resolution needed in 3D!**

3D Core-Collapse Models

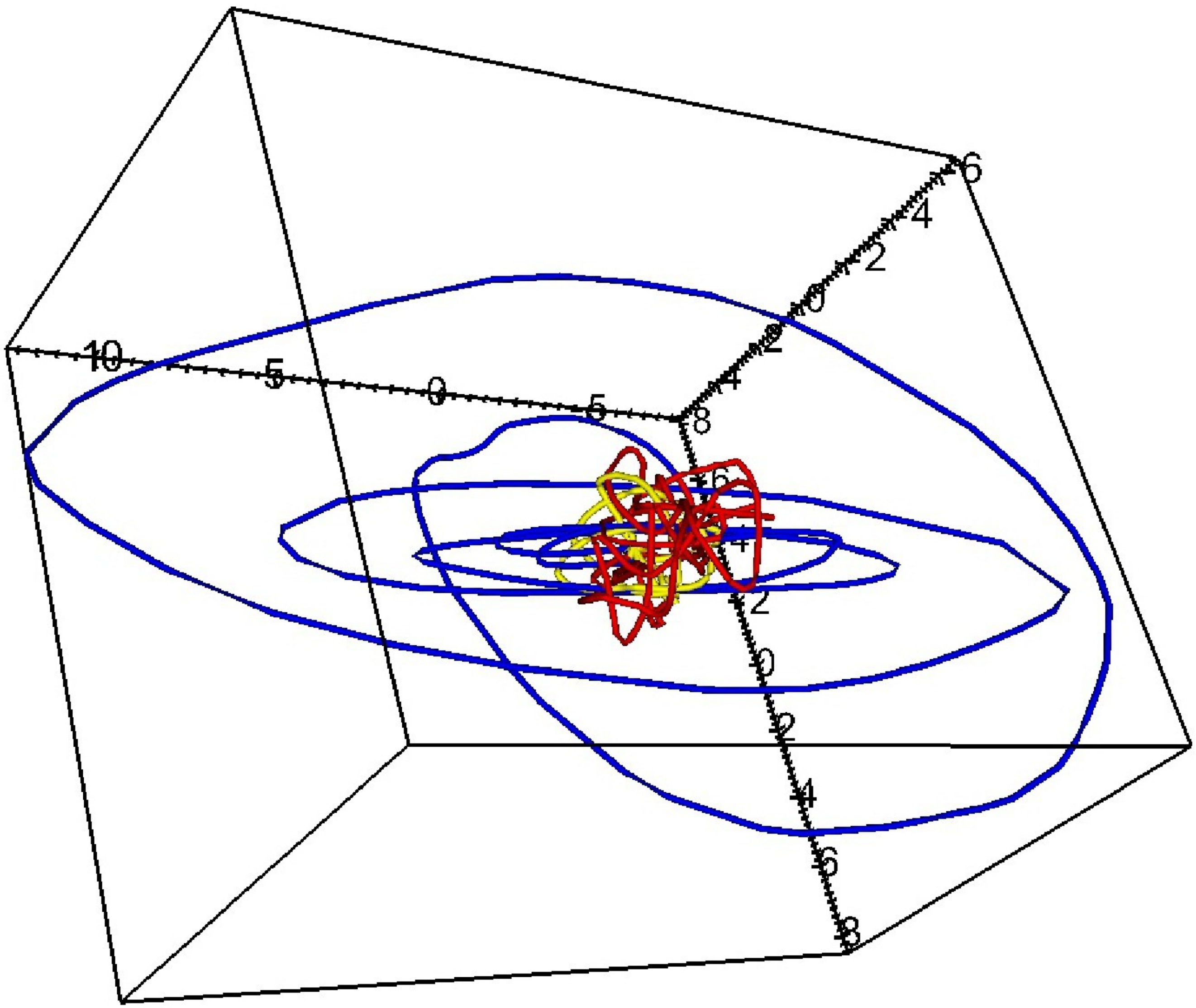
27 M_{sun} progenitor (WHW 2002)

27 M_{sun} SN model with neutrino transport develops spiral SASI as seen in idealized, adiabatic simulations by Blondin & Mezzacappa (Nature 2007)



F. Hanke et al., ApJ 770 (2013) 66

3D Core-Collapse Models



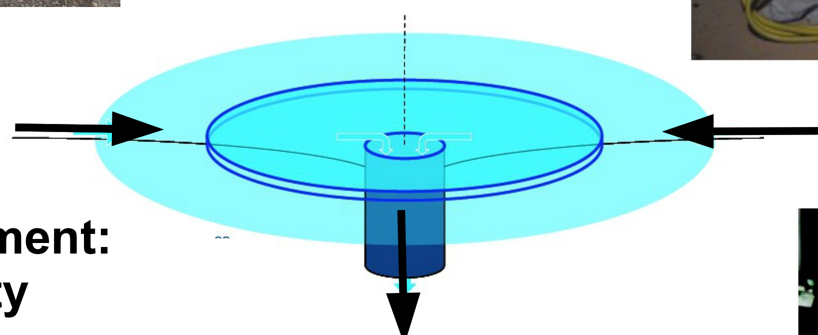
F. Hanke et al., ApJ 770 (2013) 66

27 M_{sun} progenitor (WHW 2002): Spiral mode axis

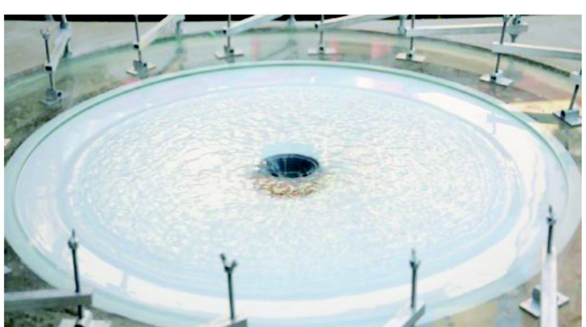
Laboratory Astrophysics

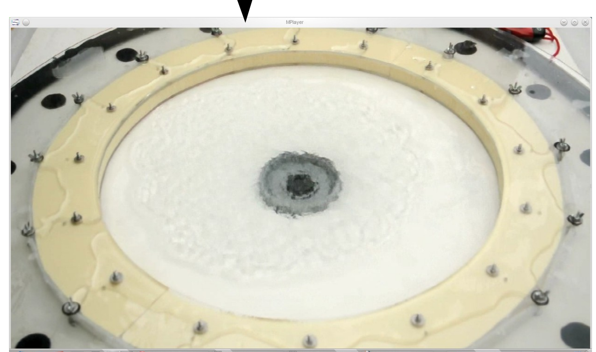
"SWASI" Instability as an analogue of SASI in the supernova core

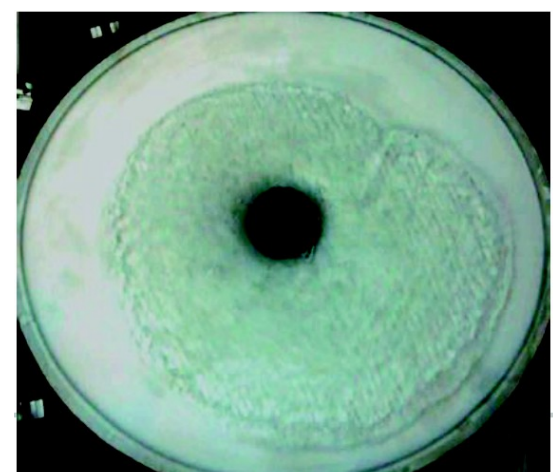
Foglizzo et al., PRL 108 (2012) 051103



Constraint of experiment:
No convective activity







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

- 2D models with relativistic effects (2D GR and approximate GR) yield explosions for "soft" EoSs, but explosion energies tend to be low.

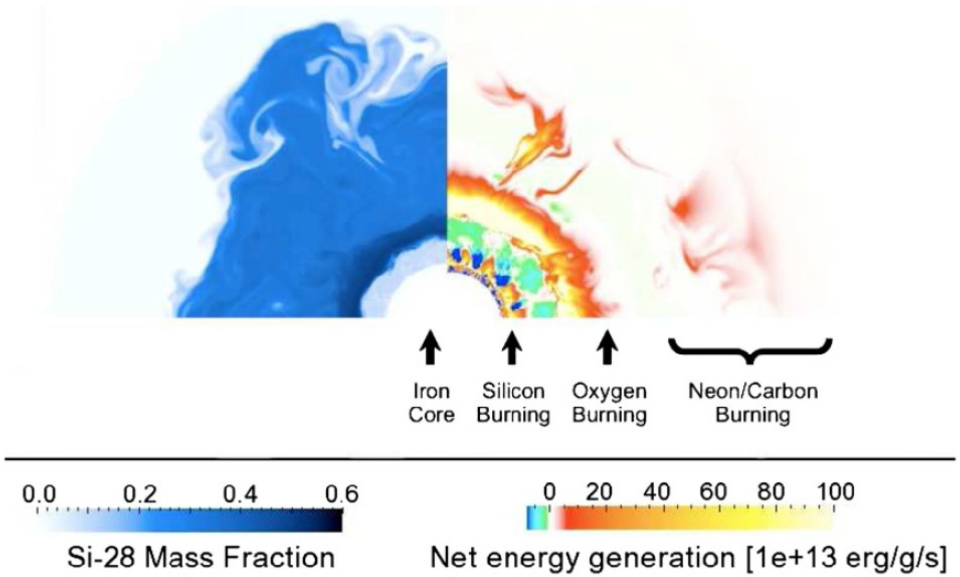
- 3D modeling has only begun. No finally clear picture of 3D effects yet. **SASI can dominate (certain phases) also in 3D models!**

- 3D models do not yet show explosions, but **still need higher resolution** for convergence.

- **Missing physics ?????**

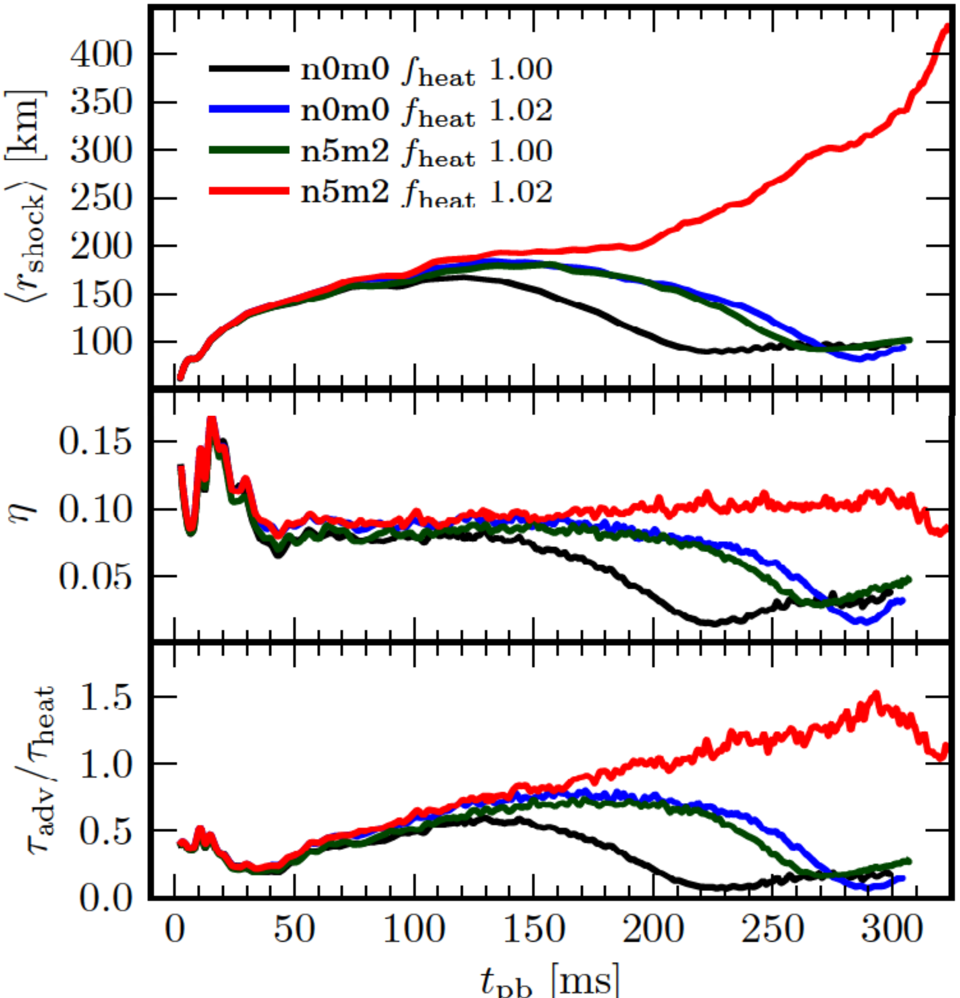
- **Progenitors are 1D**, but shell structure and initial progenitor-core asymmetries can affect onset of explosion (cf. Couch & Ott, ApJL778:L7 (2013))! How important is slow rotation for SASI growth?

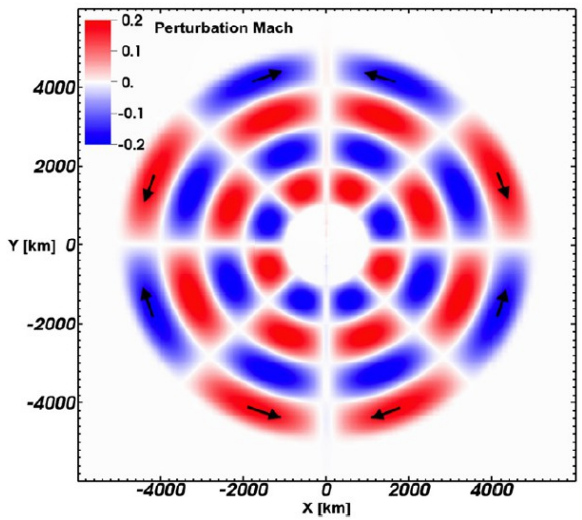
Large-scale Progenitor-Core Asymmetries?



Arnett & Meakin, ApJL 733:78 (2011)

Couch & Ott, ApJL 778:L7 (2013)





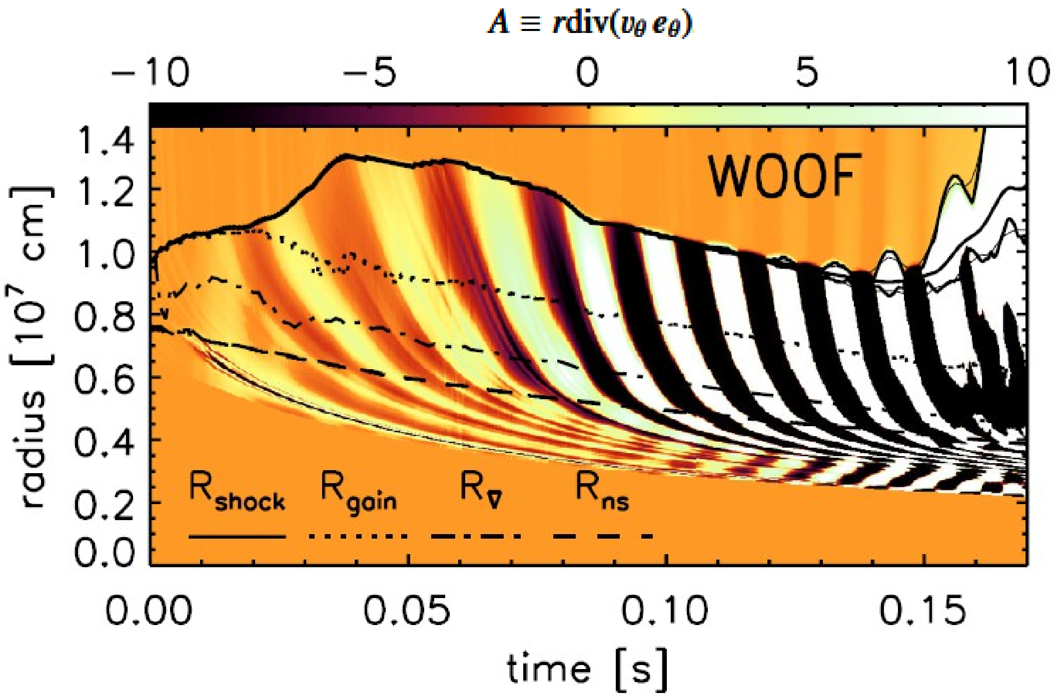
Couch & Ott, ApJL 778:L7 (2013)

$$\delta v_\theta = M_{pert} c_S \sin[(n-1)\theta] \sin[(n-1)\zeta] \cos(n\phi)$$

SASI: Standing Accretion Shock Instability

Nonradial, oscillatory shock-deformation modes (mainly l = 1, 2) caused by an amplifying cycle of advective-acoustic perturbations.

Blondin et al., ApJ (2003), Foglizzo (2002), Foglizzo et al. (2006,2007)



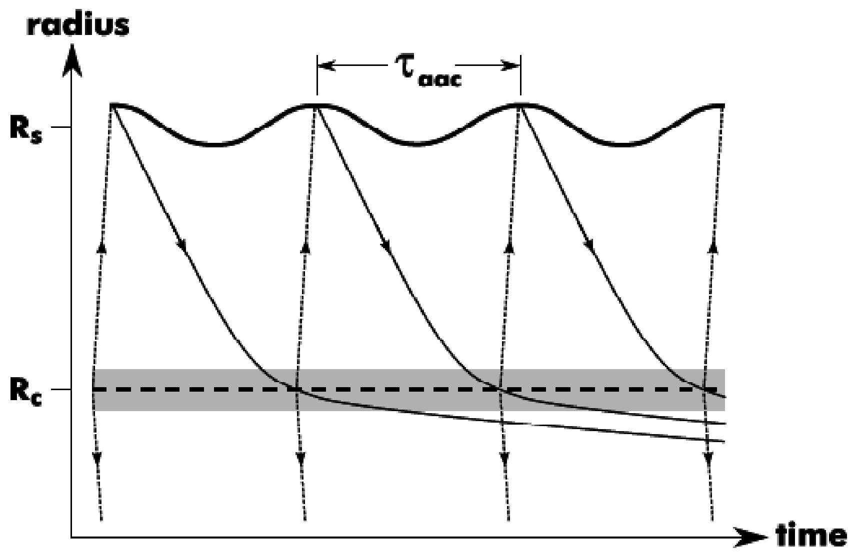


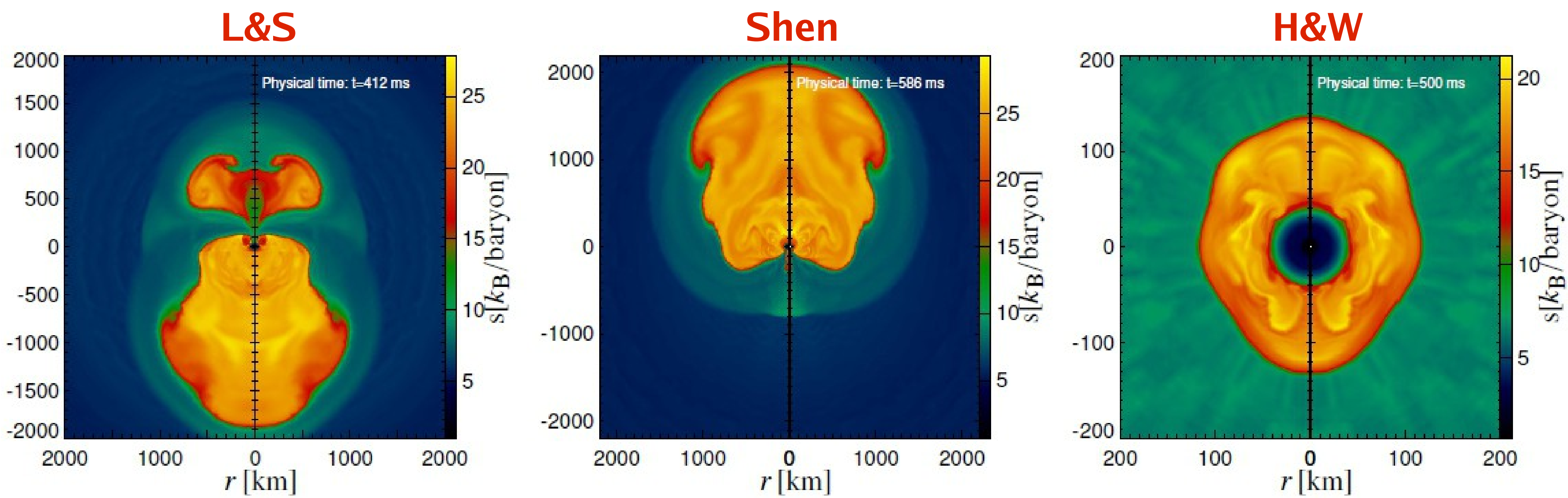
Fig. 1. Schematic view of the advective-acoustic cycle between the shock at R_s (thick solid line) and the coupling radius, R_c (thick dashed line), in the linear regime, shown for the case where the oscillation period of the shock (τ_{osc}) equals the cycle duration, τ_{aac}. Flow lines carrying vorticity perturbations downwards are drawn as solid lines, and the pressure feedback corresponds to dotted lines with arrows. In the gray shaded area around R_c the flow is decelerated strongly.

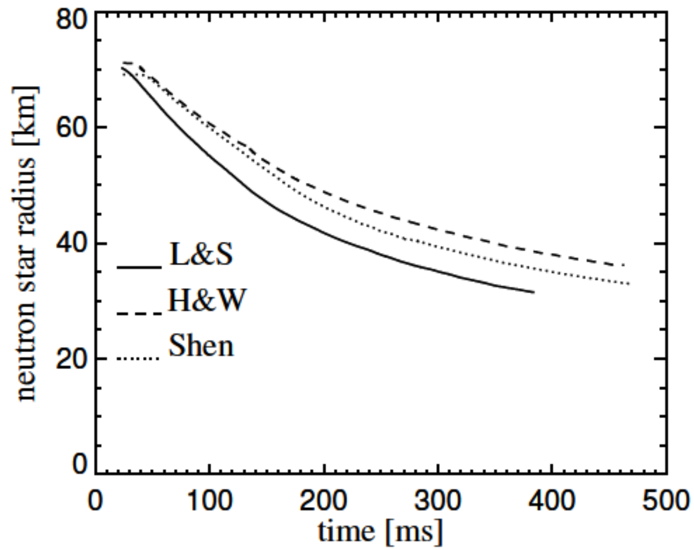
$$\tau_{aac}^{\nabla} \equiv \int_{R_\nabla}^{R_{sh}} \frac{dr}{|v|} + \int_{R_\nabla}^{R_{sh}} \frac{dr}{c - |v|}$$

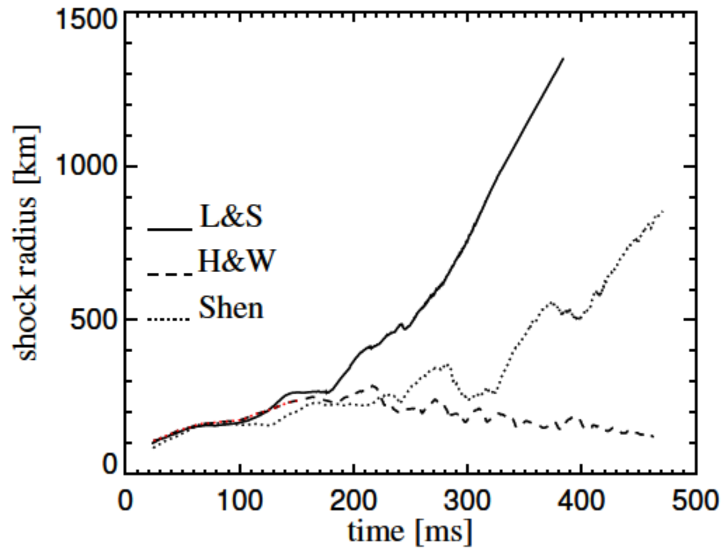
Scheck et al., A&A 447, 931 (2008)

Hadronic EOS and Supernova Explosion

Neutron star contraction has influence on the development of neutrino-driven explosions.

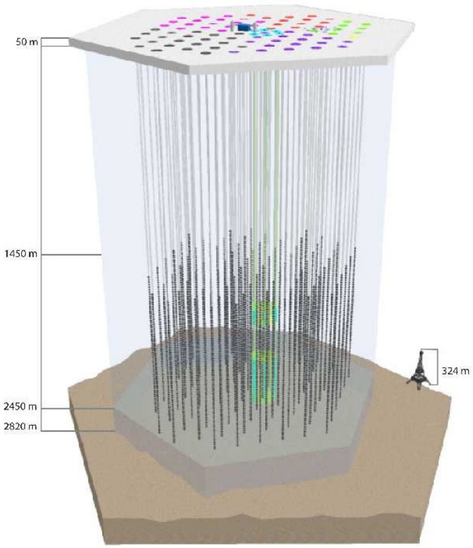






Detecting Core-Collapse SN Signals

Superkamiokande



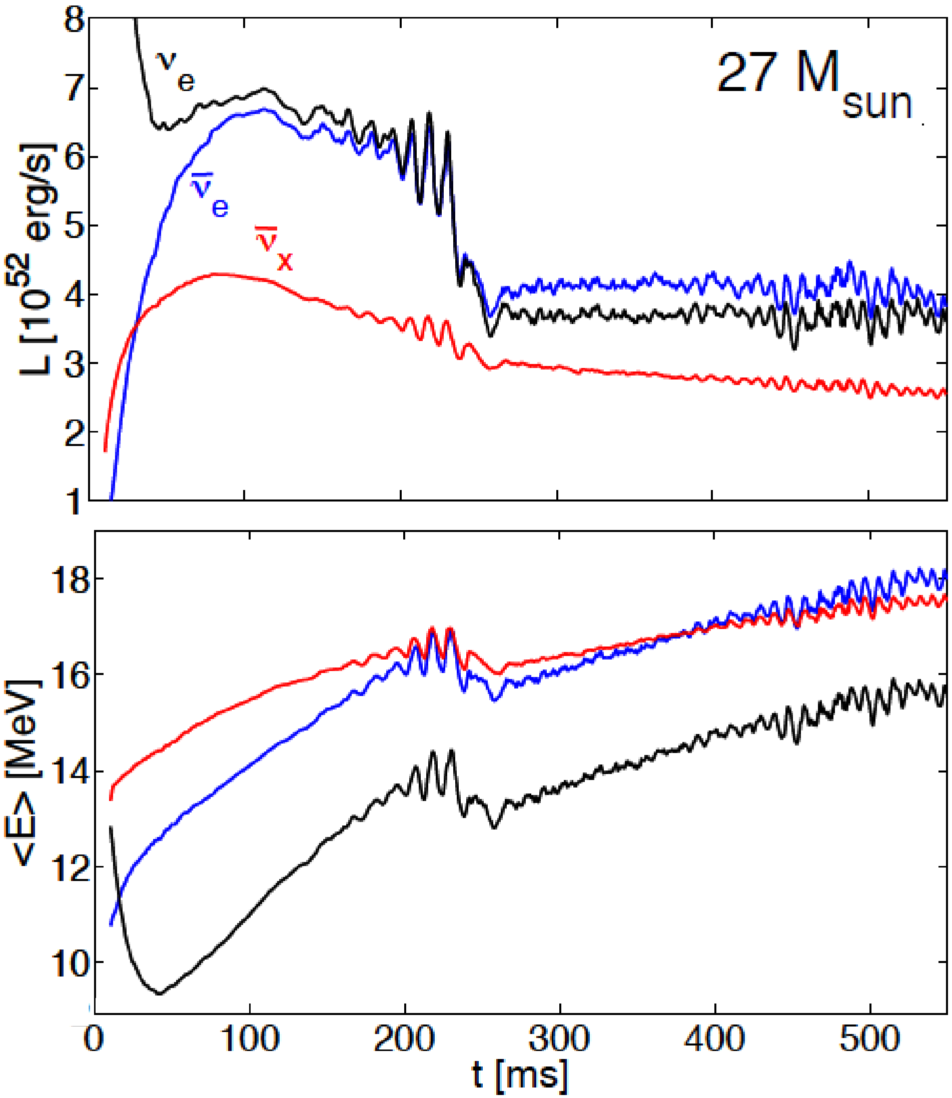
IceCube

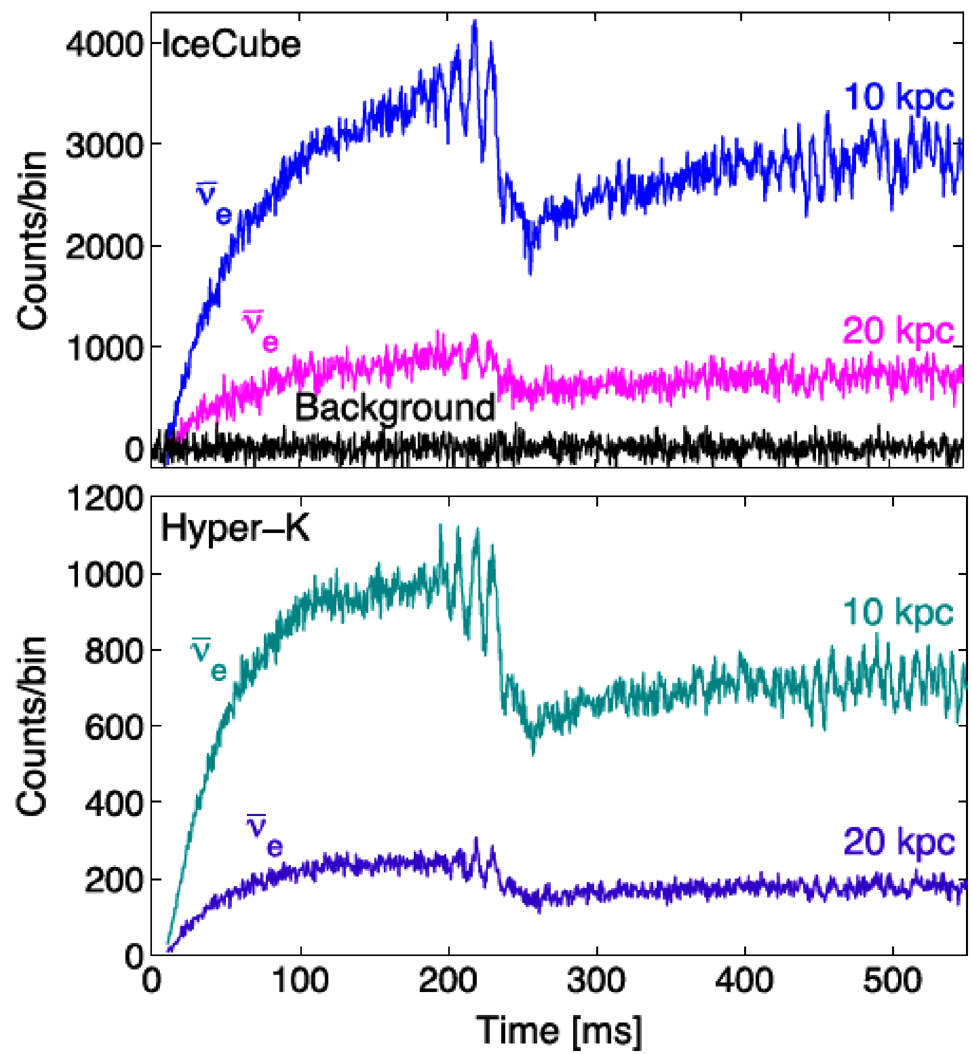
VIRGO

3D Core-Collapse Models: Neutrino Signals

11.2, 20, 27 M_{sun} progenitors (WHW 2002)

SASI produces modulations of neutrino emission and gravitational-wave signal.





(Tamborra et al., PRL 111, 121104 (2013); arXiv:1307.7936)

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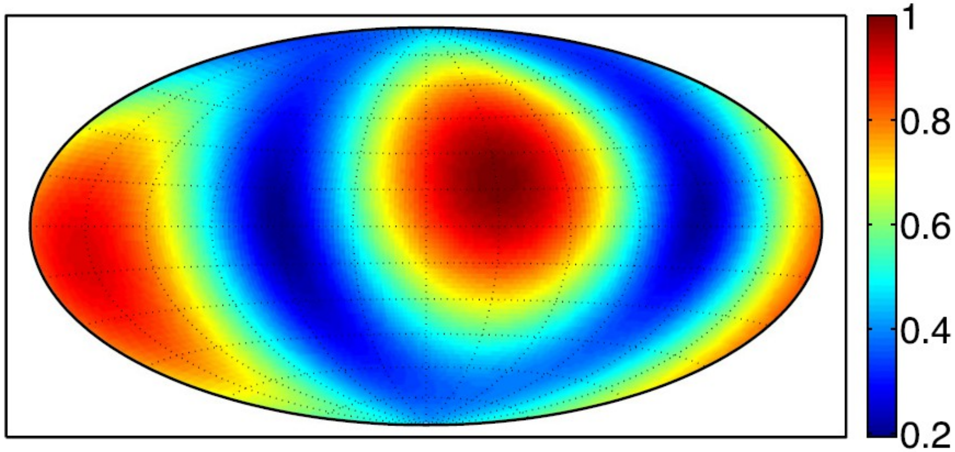
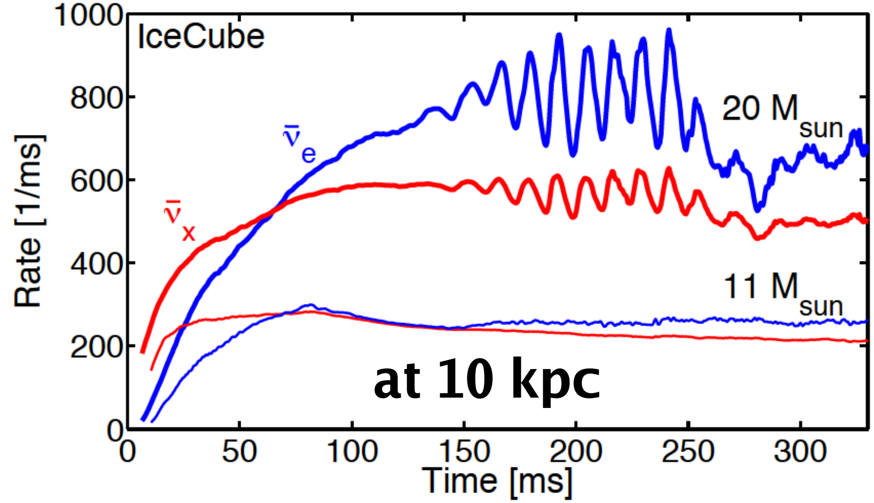
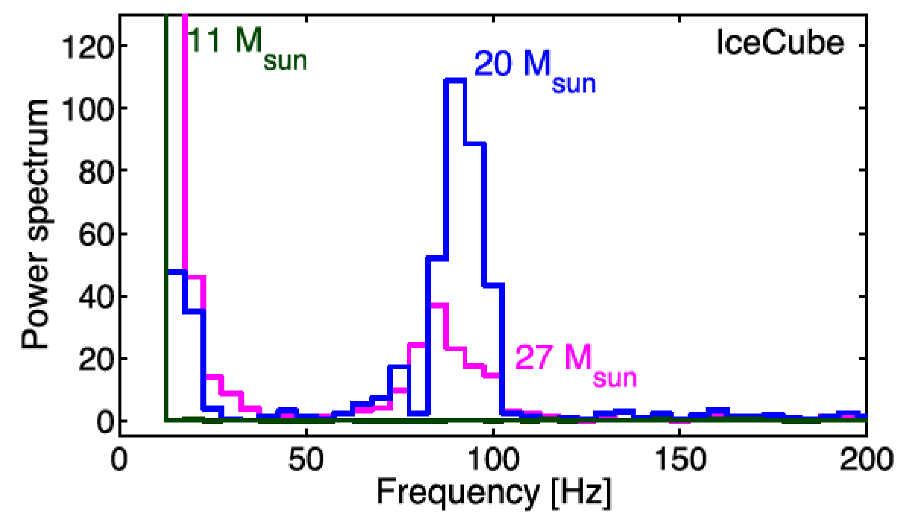


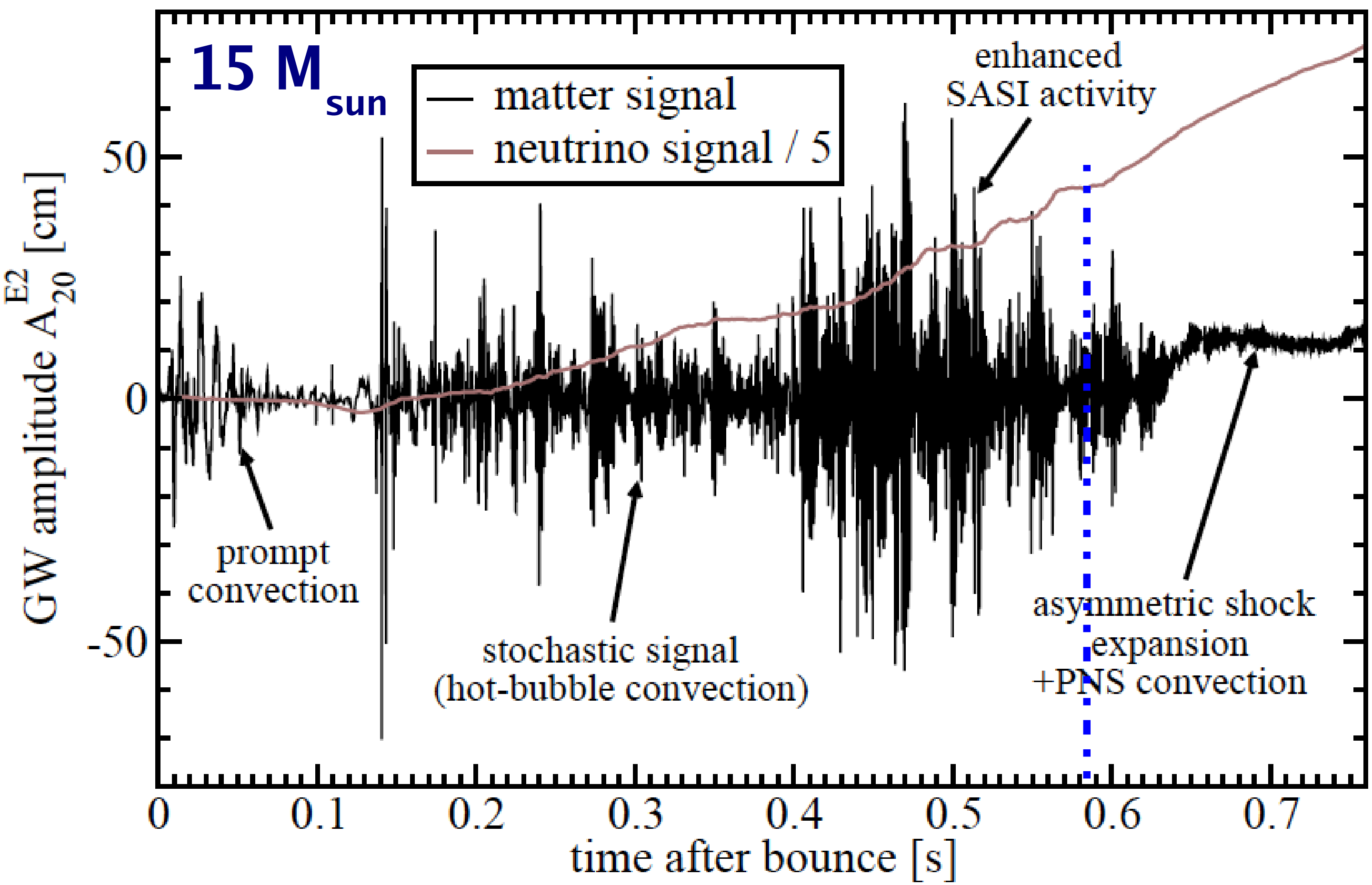


$$f_{\mathrm{SASI}}^{-1} \sim \int_{R_{\mathrm{NS}}}^{R_{\mathrm{S}}} \frac{dr}{|v|} + \int_{R_{\mathrm{NS}}}^{R_{\mathrm{S}}} \frac{dr}{c_{\mathrm{s}} - |v|}$$



(Tamborra et al., PRL 111, 121104 (2013); arXiv:1307.7936)

Gravitational Waves for 2D SN Explosions



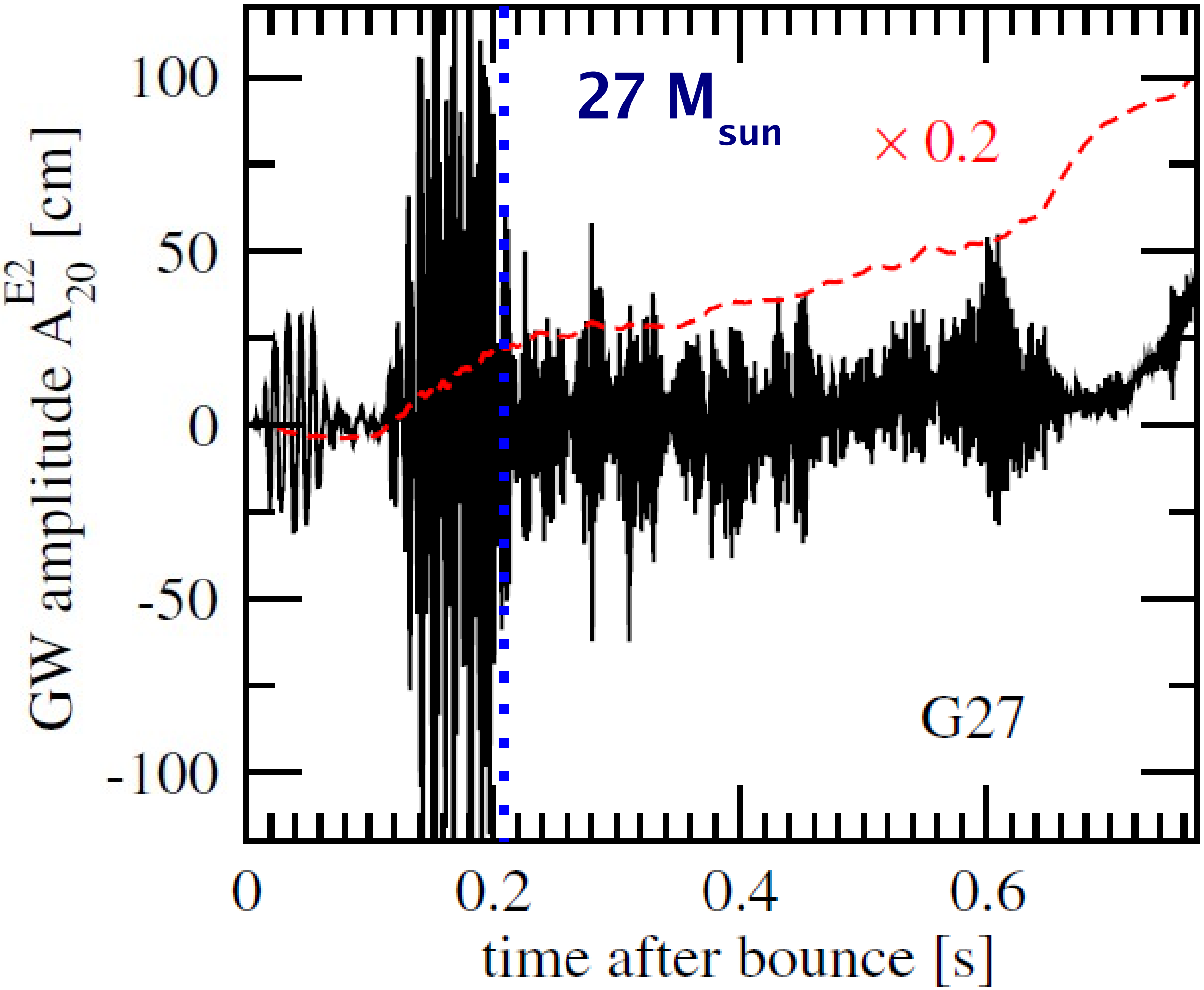
(Müller, THJ, & Marek, ApJ 766 (2013) 43)

$$h = \frac{1}{8}\sqrt{\frac{15}{\pi}}\sin^2\Theta\frac{A_{20}^{E2}}{R}$$

$$h_\nu = \frac{2G}{c^4 R}\int_0^t L_\nu(t')\alpha_\nu(t')\,dt'$$

$$\alpha_\nu = \frac{1}{L_\nu}\int \pi\sin\theta\,(2|\cos\theta| - 1)\,\frac{dL_\nu}{d\Omega}d\Omega$$

Gravitational Waves for 2D SN Explosions



(Müller, THJ, & Marek, ApJ 766 (2013) 43)

GW amplitudes in 2D are considerably larger than in 3D.
No template character, in 3D strongly direction dependent.

Need of sophisticated neutrino treatment

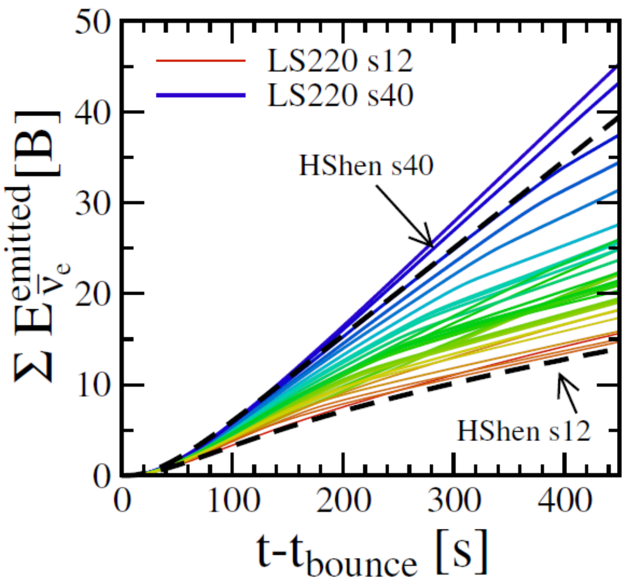
to conclude on EOS effects

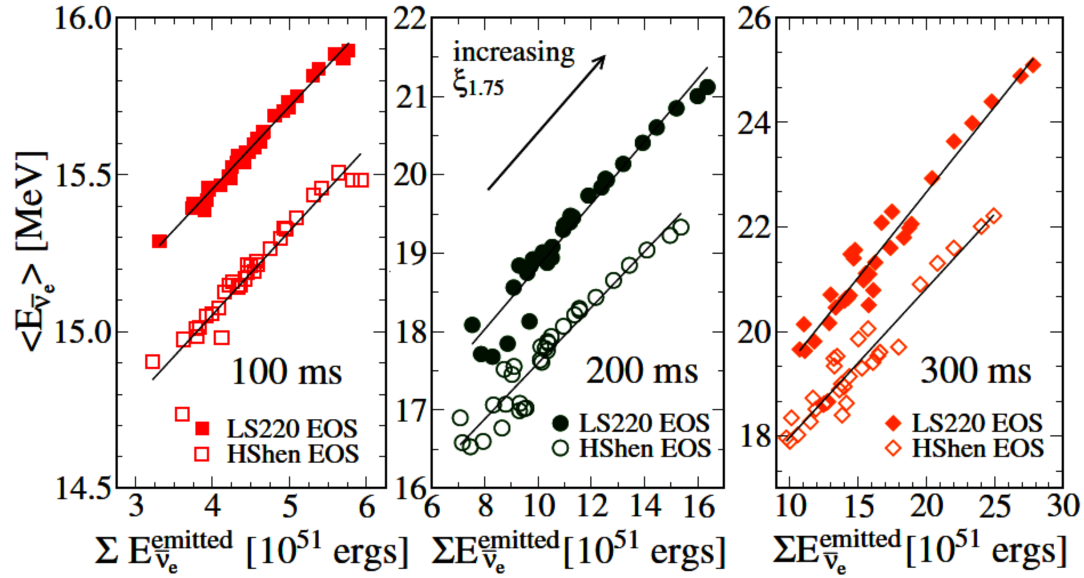
Neutrino Reactions in Supernovae

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:	• $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$ $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{ or } \bar{\nu}_\tau)$ • $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

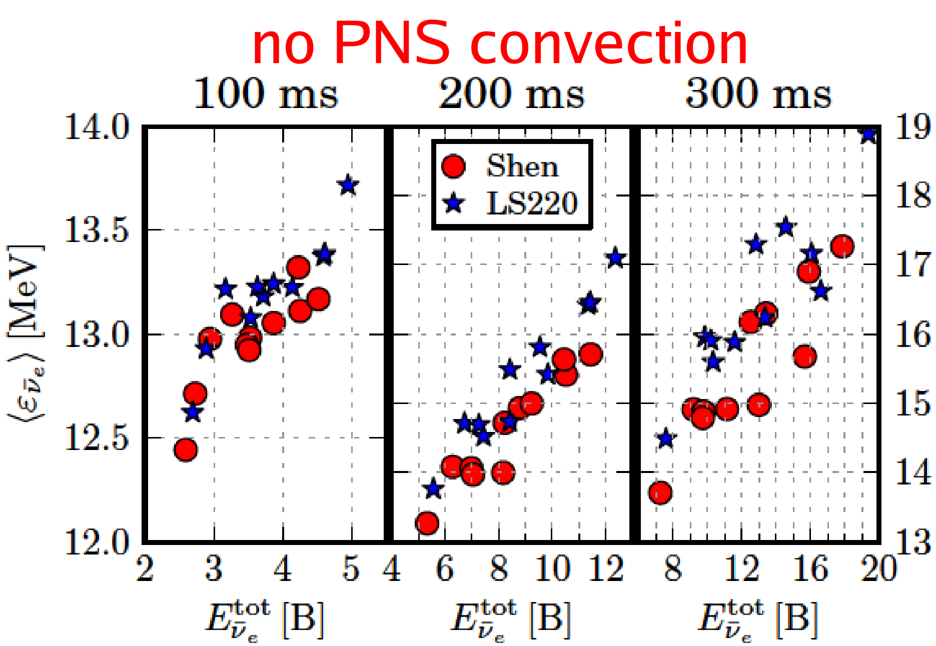
Neutrino Signal Dependence on Progenitor and EOS

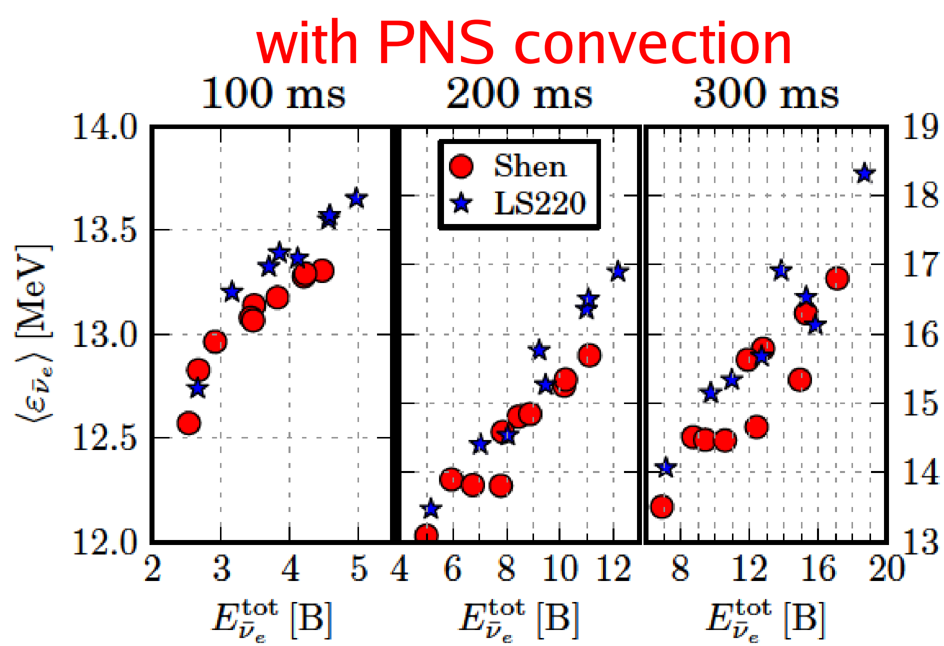
O'Connor & Ott, ApJ 762: 126 (2013)





L. Hüdepohl, PhD Thesis (2013)





Nucleosynthesis in Supernovae Ejecta

Crucial parameters for nucleosynthesis in neutrino-driven outflows:

* Electron-to-baryon ratio Y_e (<---> neutron excess)
* Entropy (<----> ratio of (temperature)^3 to density)
* Expansion timescale

Determined by the interaction of stellar gas with neutrinos from nascent neutron star:

$$\nu_e + n \rightarrow e^- + p$$
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

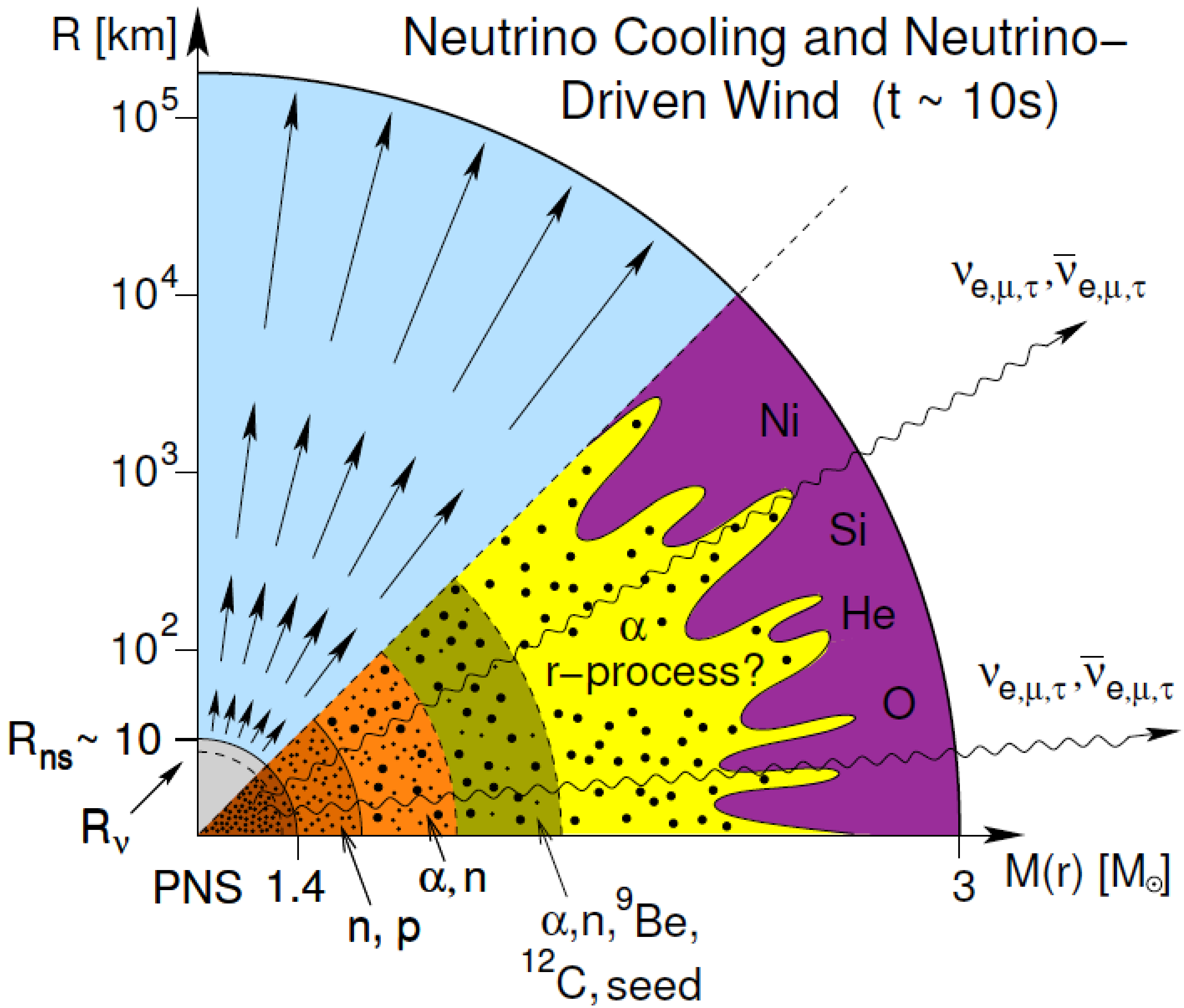
$$Y_e \sim \left[1 + \frac{L_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e} - 2\Delta)}{L_{\nu_e}(\epsilon_{\nu_e} + 2\Delta)}\right]^{-1}$$

with $\epsilon_\nu = \frac{\langle \epsilon_\nu^2 \rangle}{\langle \epsilon_\nu \rangle}$ and $\Delta = (m_n - m_p)c^2 \approx 1.29\,\mathrm{MeV}$.

If $L_{\bar{\nu}_e} \approx L_{\nu_e}$, one needs for $Y_e < 0.5$ (i.e. neutron excess):

$$\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} > 4\Delta.$$

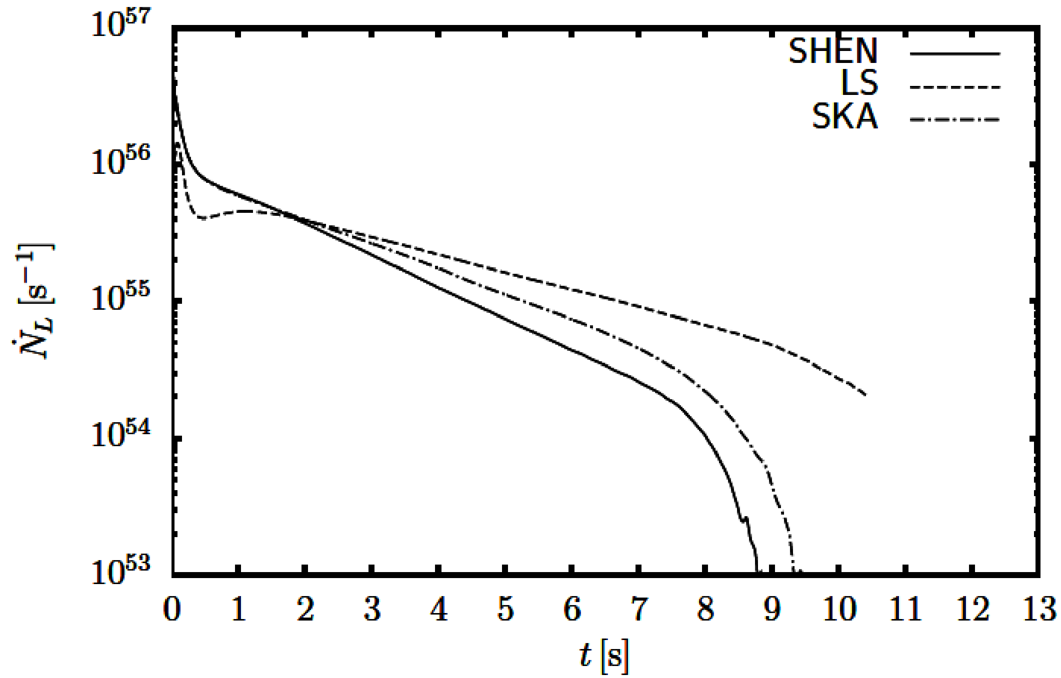
Neutrino-Driven Wind From Proto-Neutron Stars



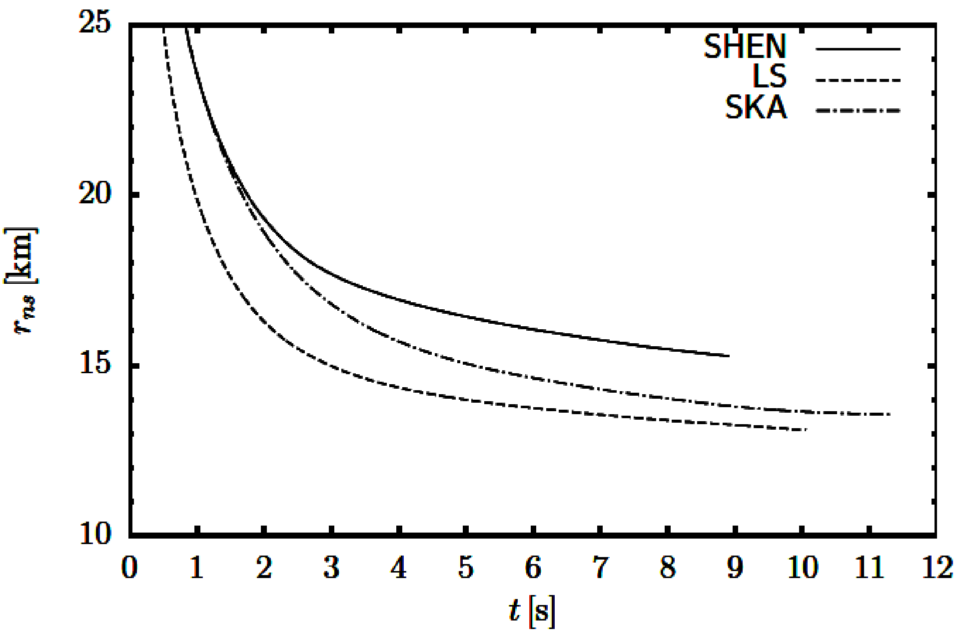
Proto-Neutron Star Neutrino-Cooling

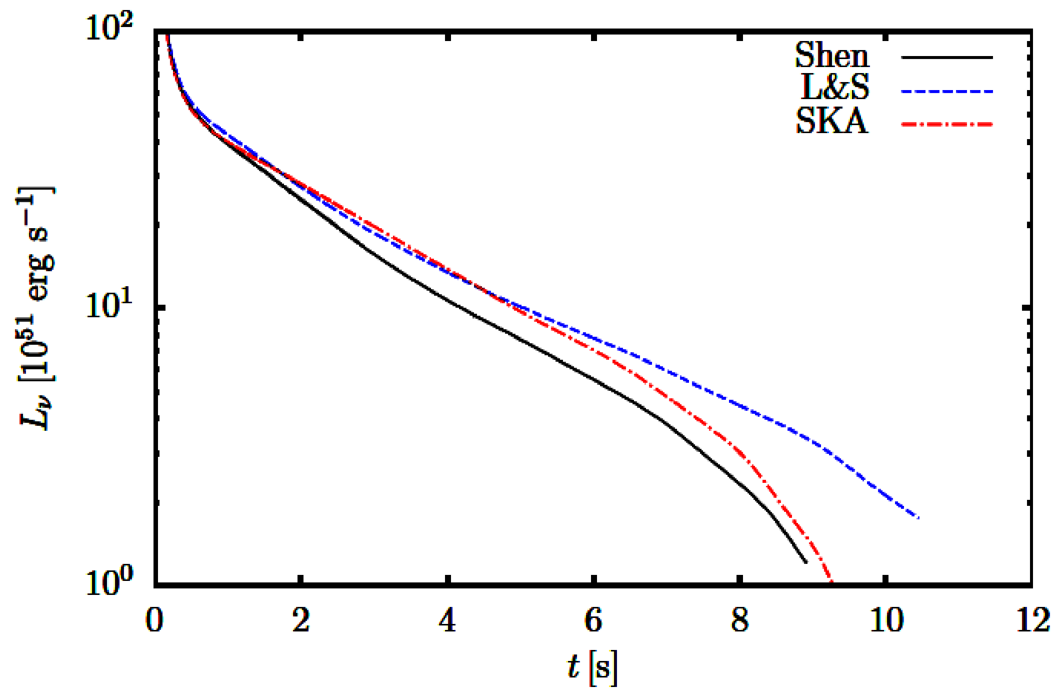
Signal from O-Ne-Mg cores

Signal duration and decline depends on the nuclear equation of state and NS properties.

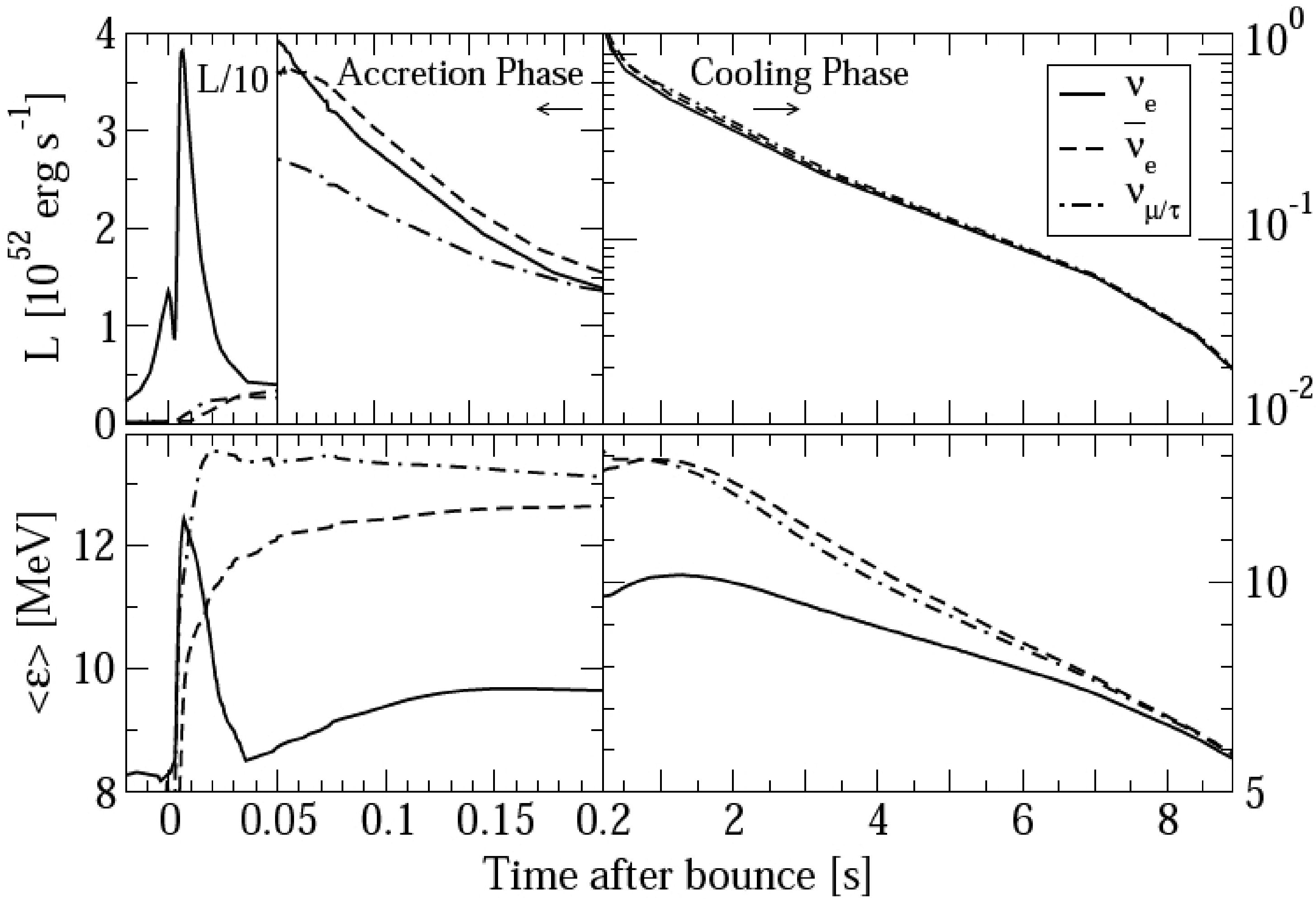


L. Hüdepohl, Diploma Thesis, TUM (2009)





PNS Cooling in O-Ne-Mg-Core SNe



Hüdepohl et al. (PRL 104 (2010)); arXiv:0912:0260

Luminosities and mean energies very similar for all neutrinos during the proto-neutron star (PNS) cooling evolution.

Nucleosynthesis in O-Ne-Mg Core Winds

- Neutrino-driven wind remains p-rich for >10 seconds!
- No r-process in the late neutrino-driven wind!
- Holds also for more massive progenitos (Fischer et al. 2009)

Hüdepohl (Diploma Thesis 2009);
Hüdepohl et al. (PRL 104 (2010);
arXiv:0912:0260)

No favorable conditions for a strong r-process in ONeMg-core explosions and neutrino-driven winds of PNSs!

Influence of convection and nucleon potentials????