Max-Planck-Institut für Astrophysik

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Supernova Simulations in Three Dimensions: Models Confronting Observations

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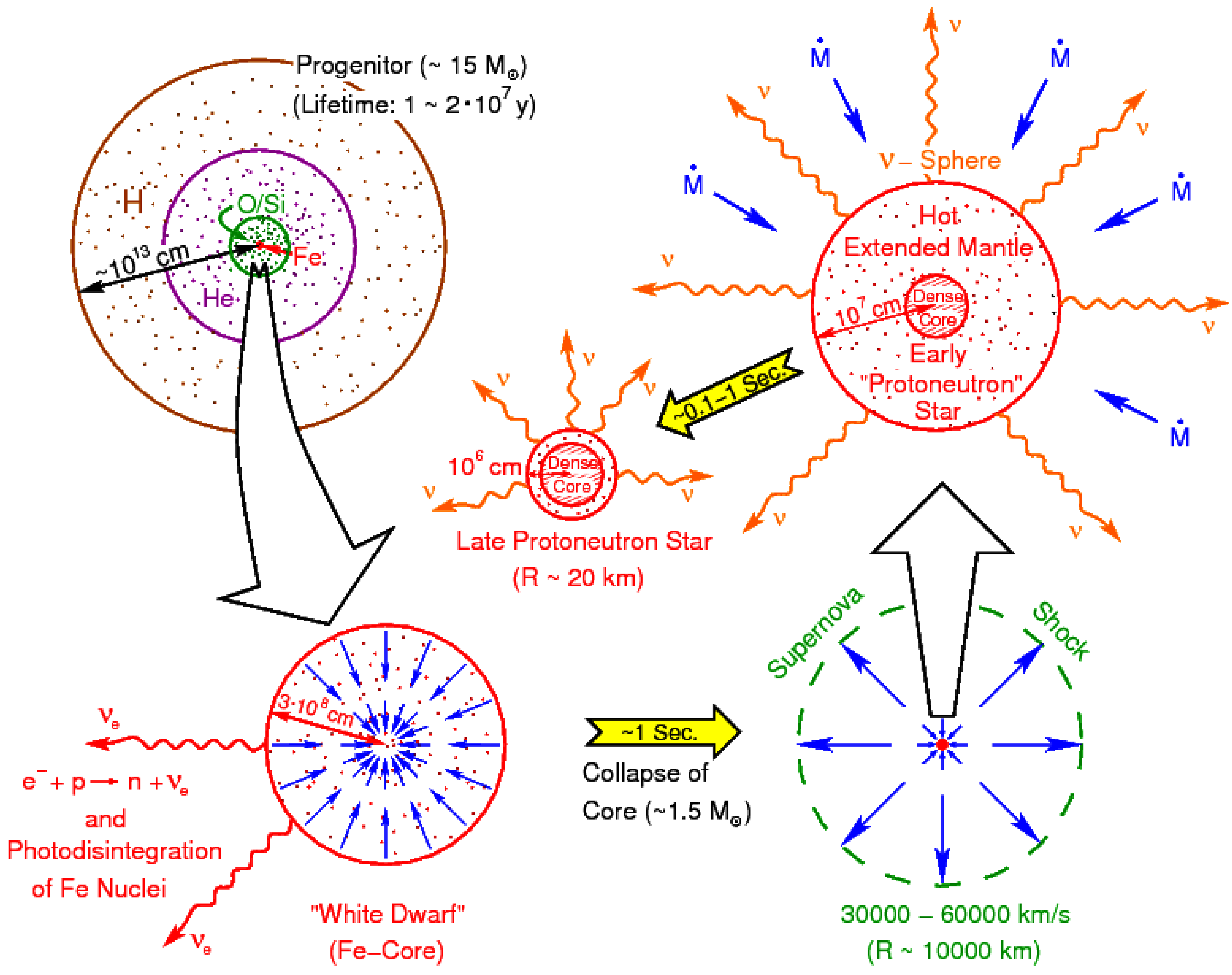
Problems & Questions

- Core collapse SN explosion mechanism(s)?
- NS/BH formation probabilities?
- SN explosion properties; explosion asymmetries, mixing, gaseous remnant properties
- NS birth masses, kicks, spins
- Neutrino and gravitational-wave signals
- Neutrino oscillations,
  impact of non-standard physics, e.g. sterile neutrinos
- Heavy-element formation;
  what are the sites of the r-process(es)?
- What is the equation of state (EOS) of ultra-dense matter?

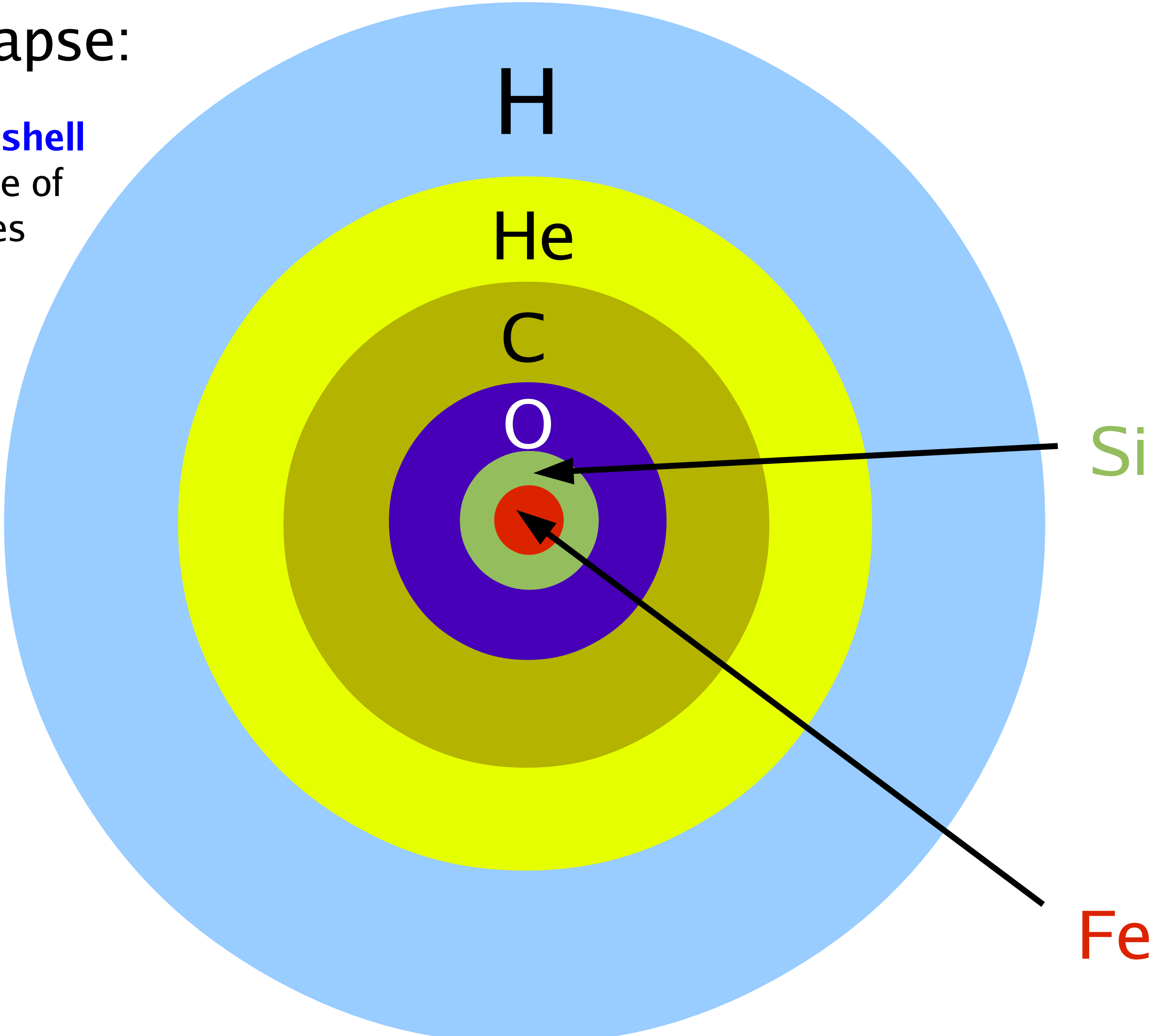
Stellar Collapse and Supernova Stages



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)

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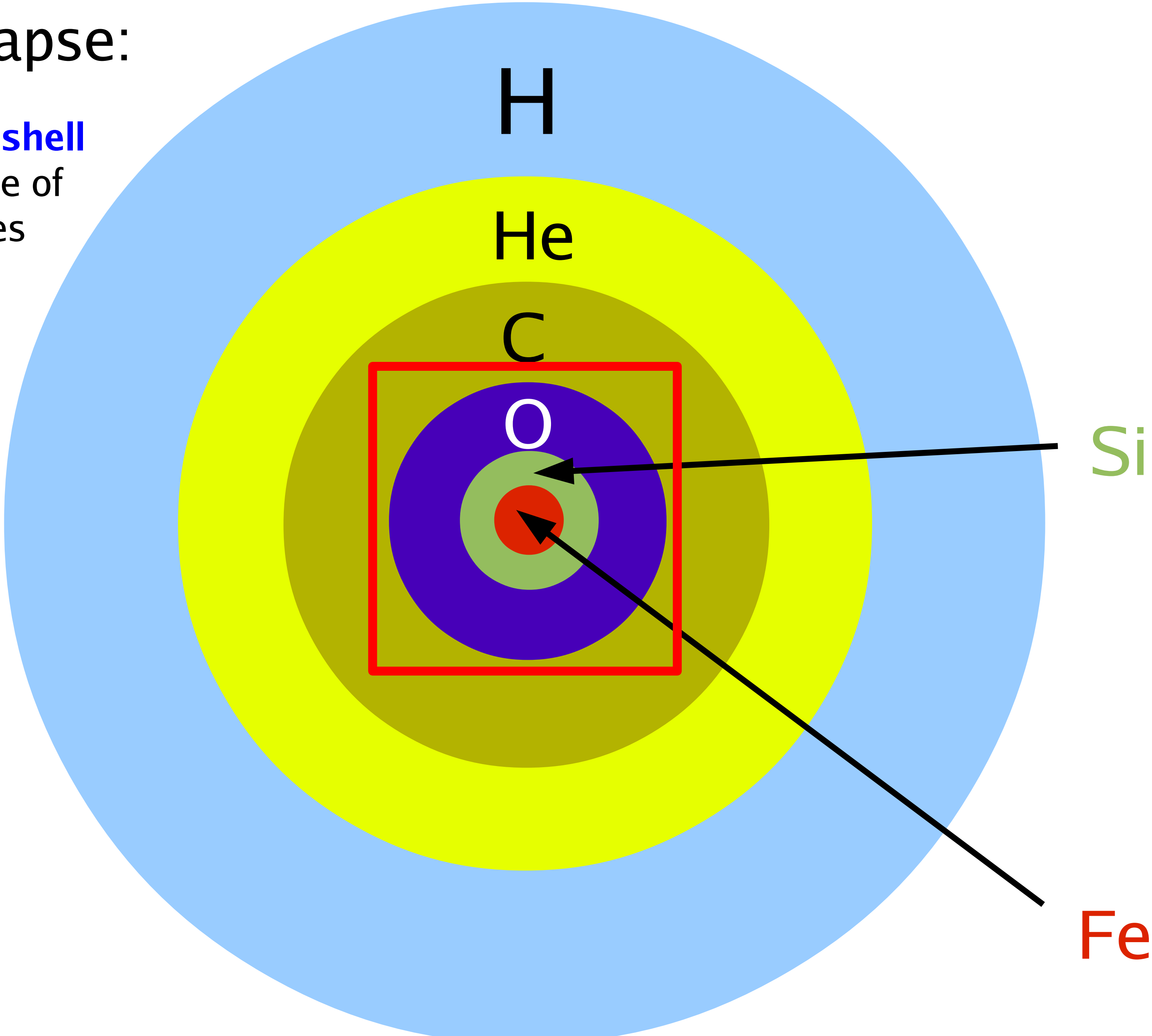


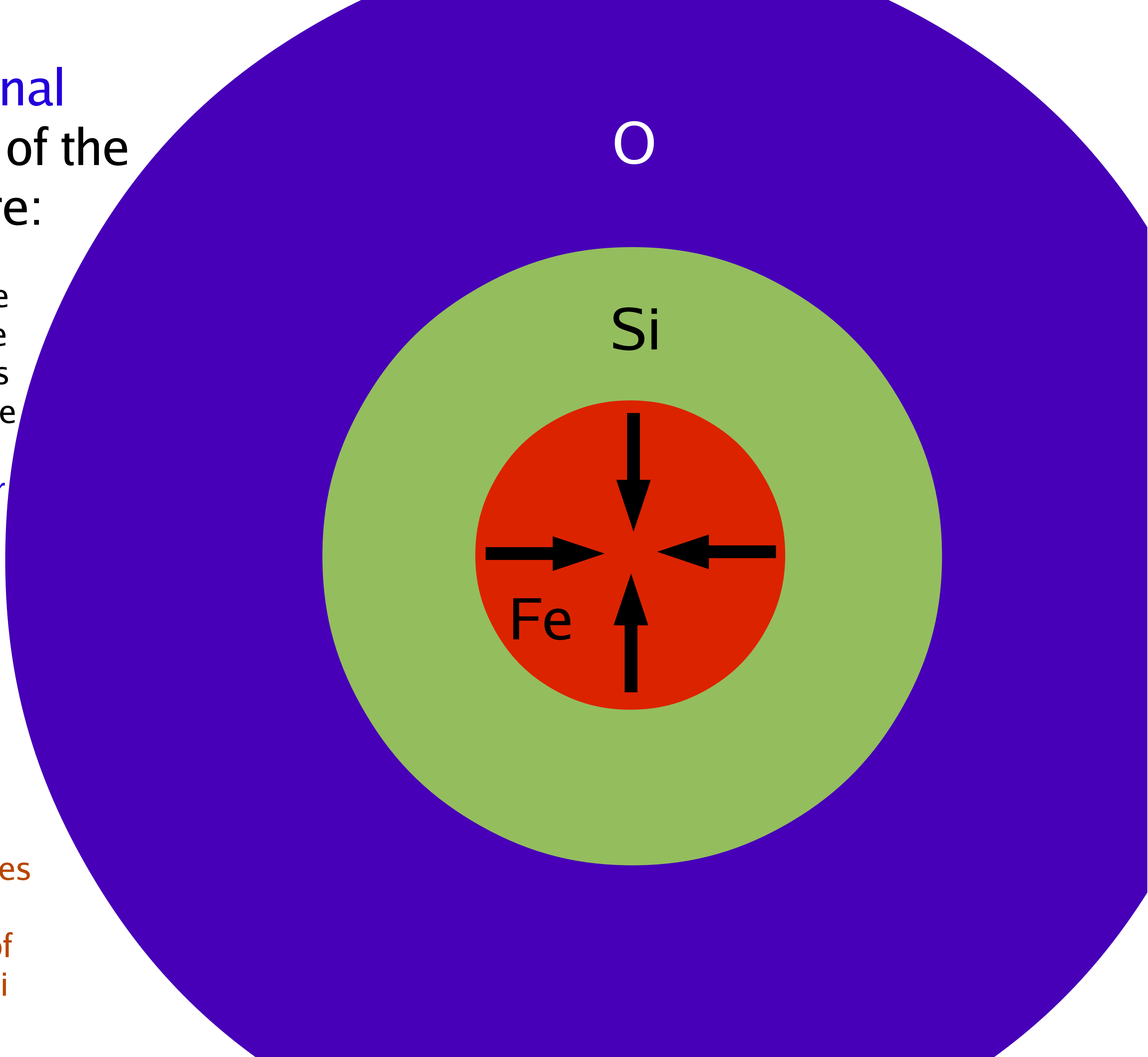
(layers not drawn to scale)

Gravitational instability of the stellar core:

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

Collapse

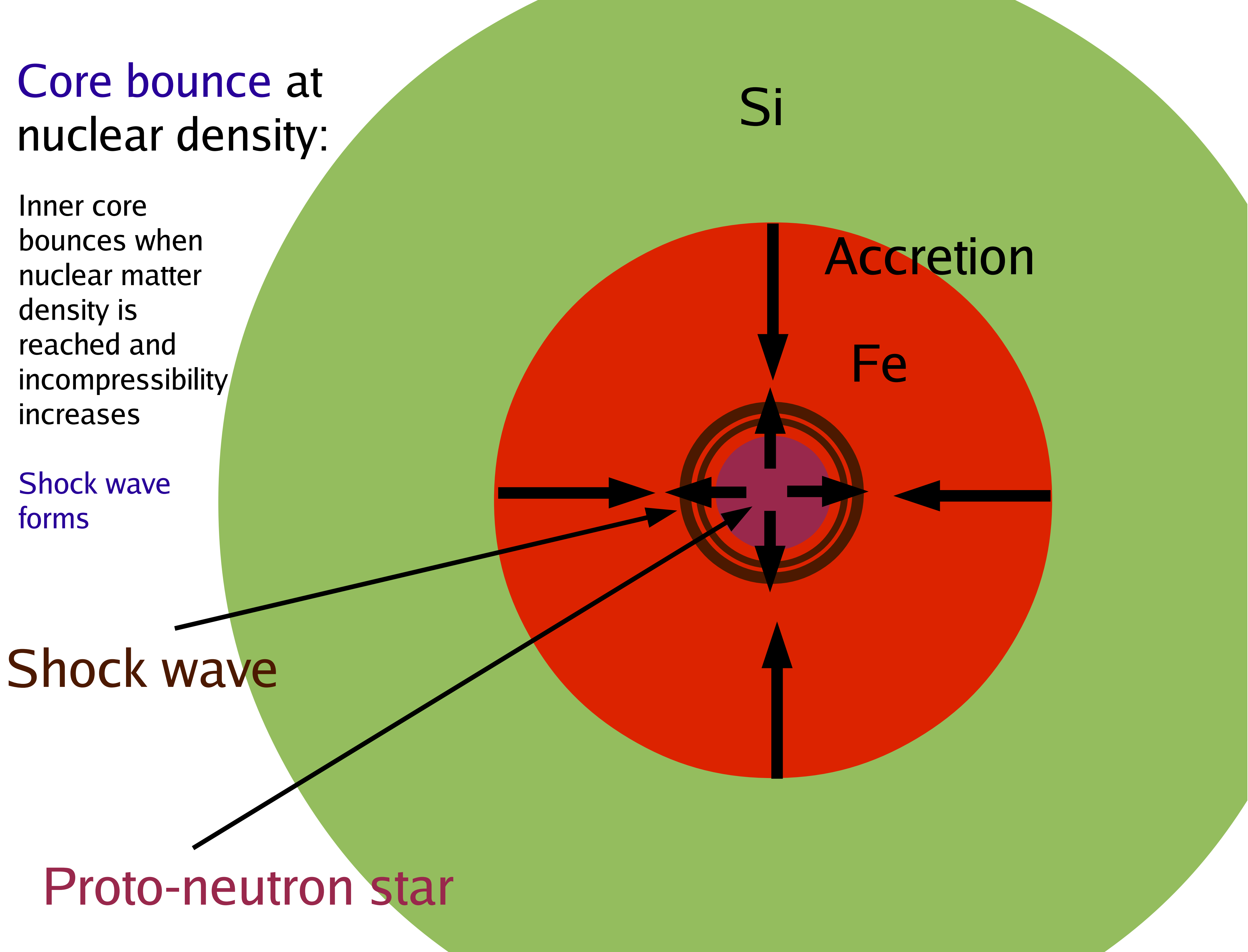
becomes dynamical because of electron captures and photo-disintegration of Fe-group nuclei



Core bounce at nuclear density:

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

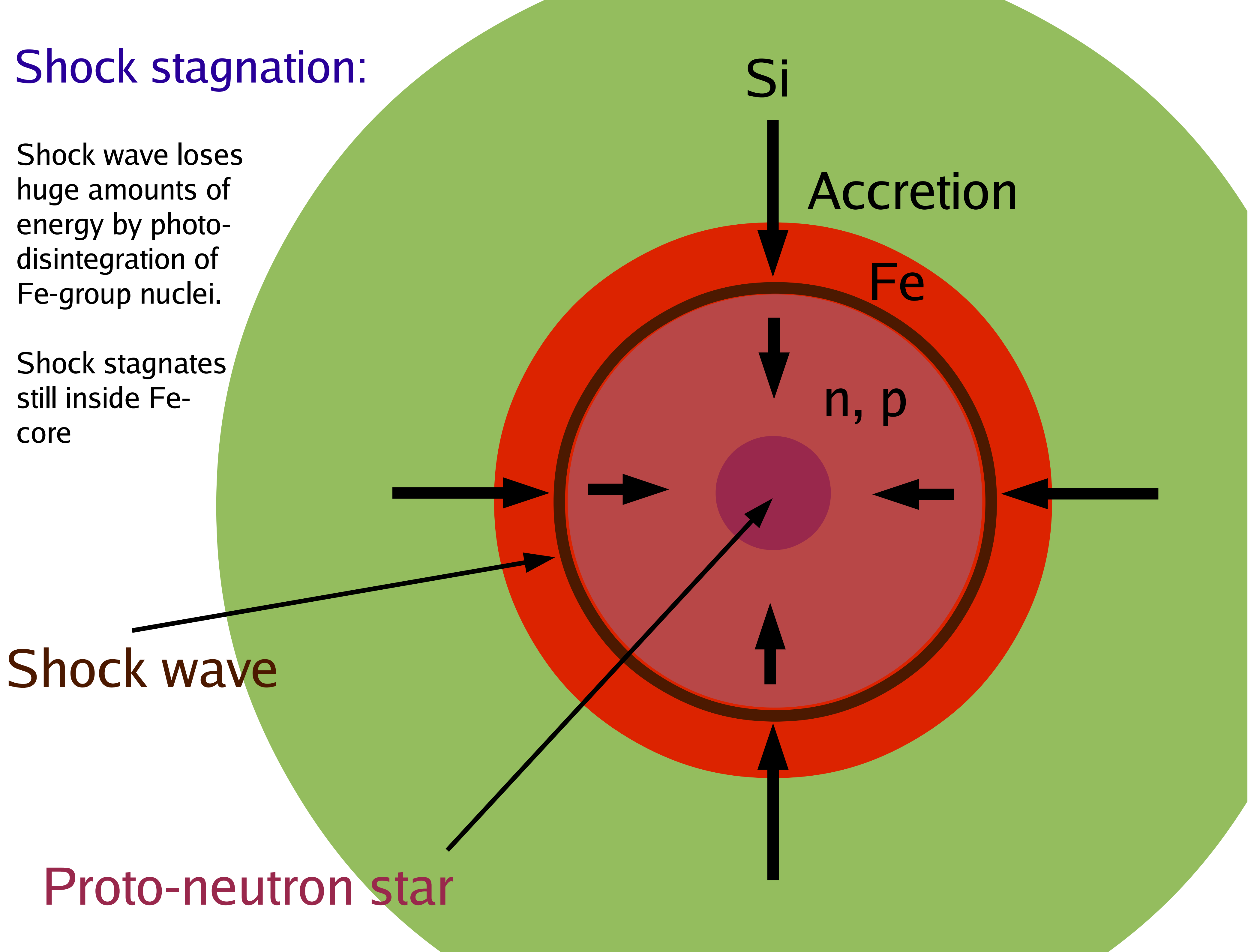
Shock wave forms



Shock stagnation:

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

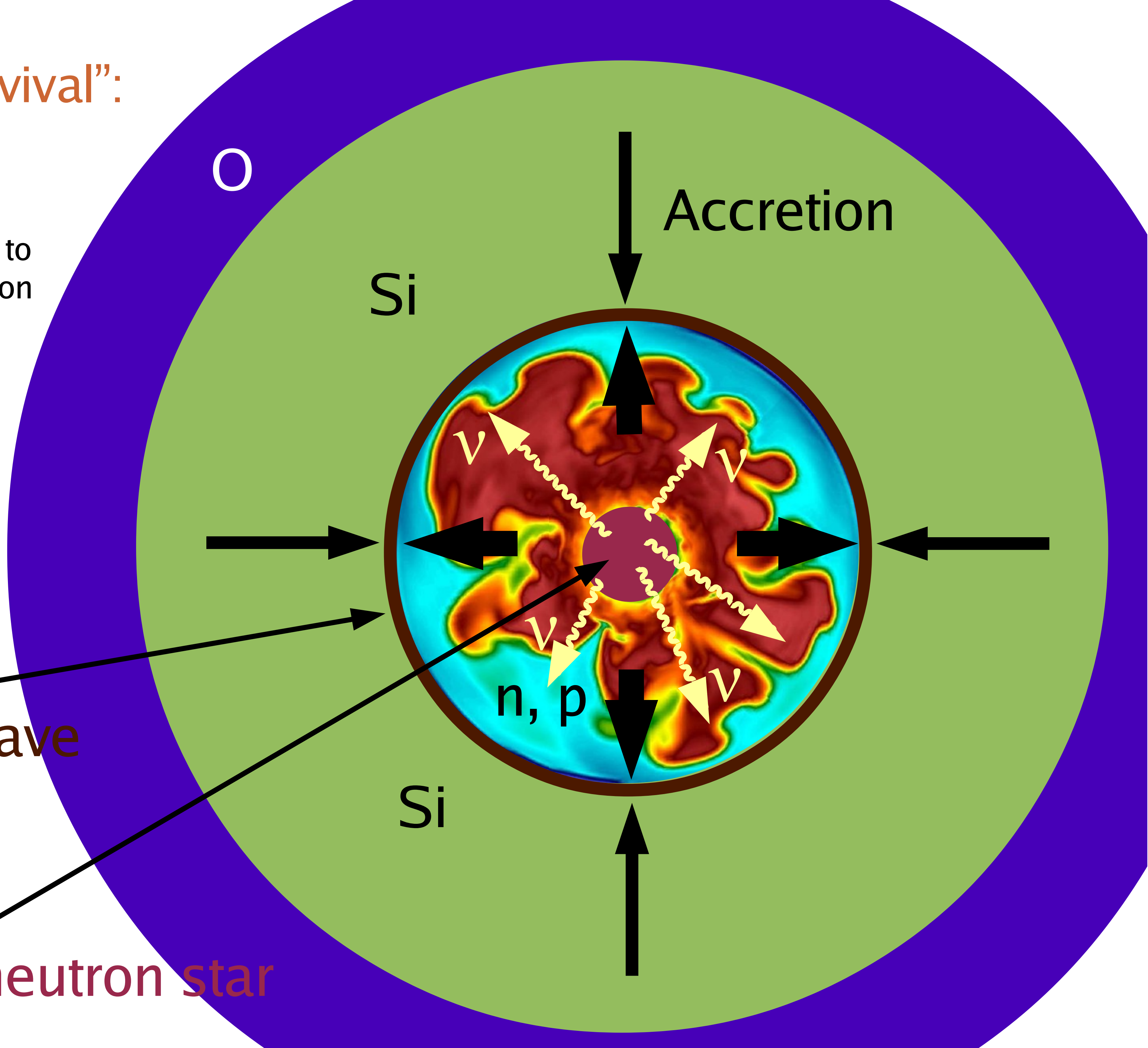
Shock stagnates still inside Fe-core



Shock "revival":

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

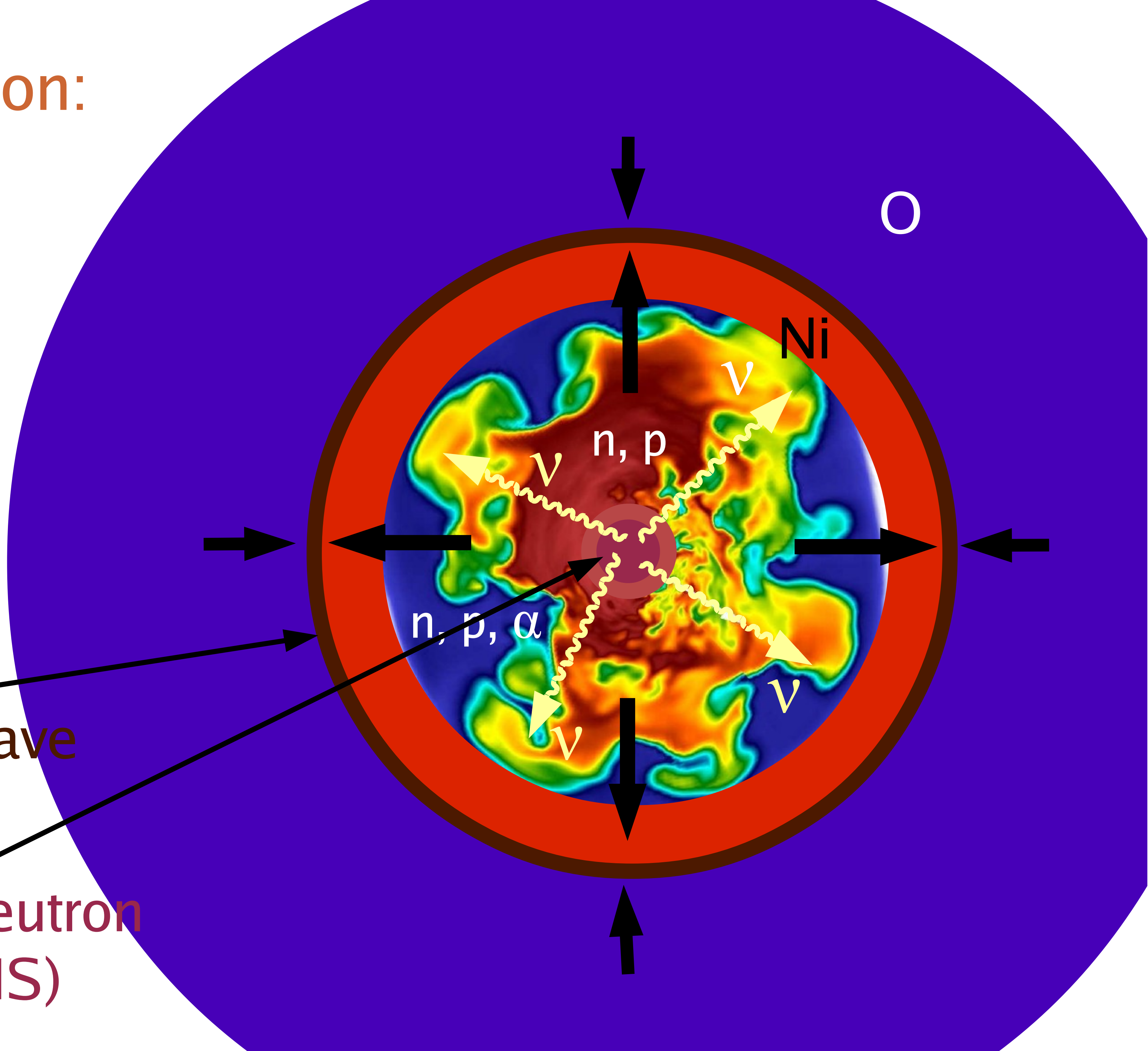
Shock can receive fresh energy from neutrinos!



Explosion:

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

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

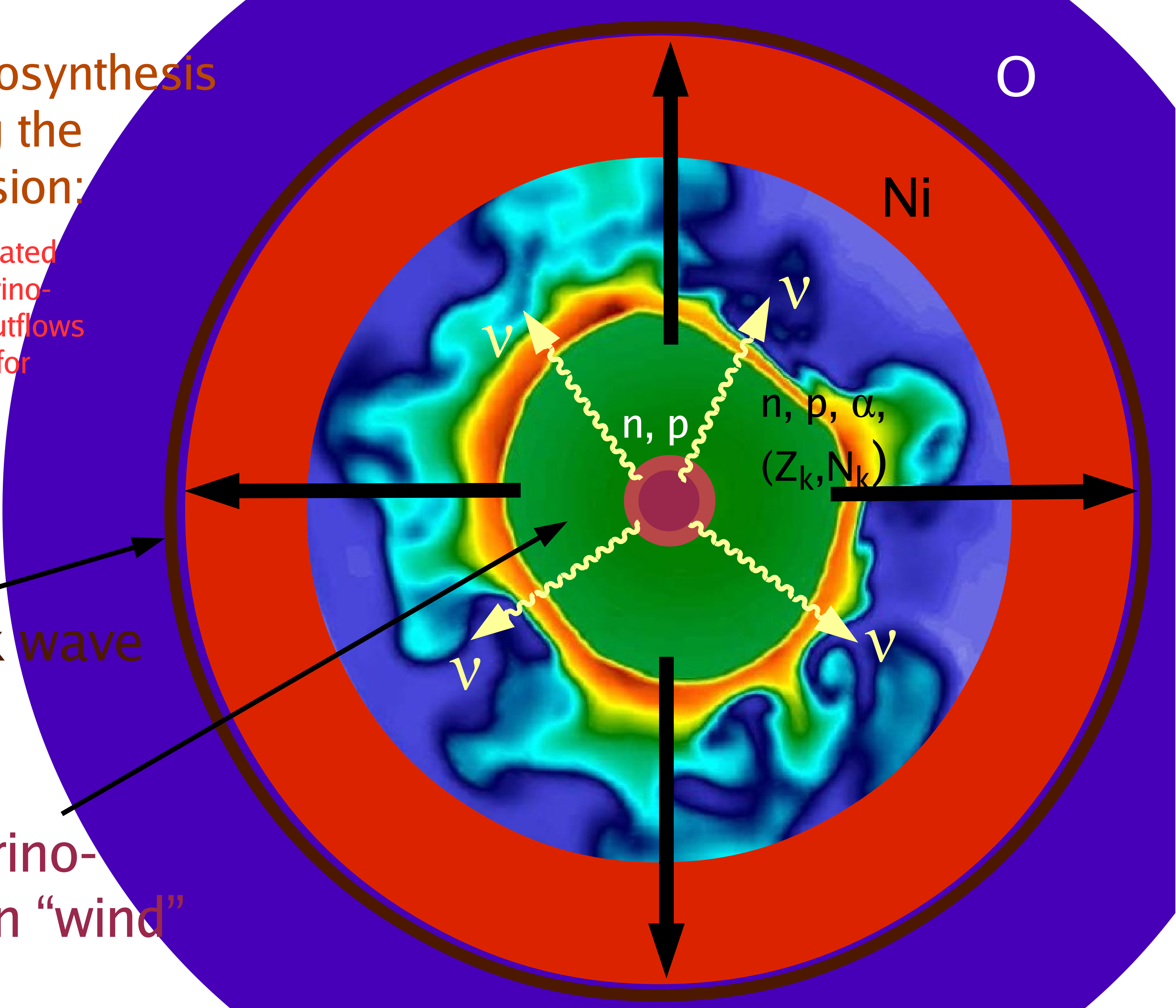


Shock wave

Proto-neutron star (PNS)

Nucleosynthesis during the explosion:

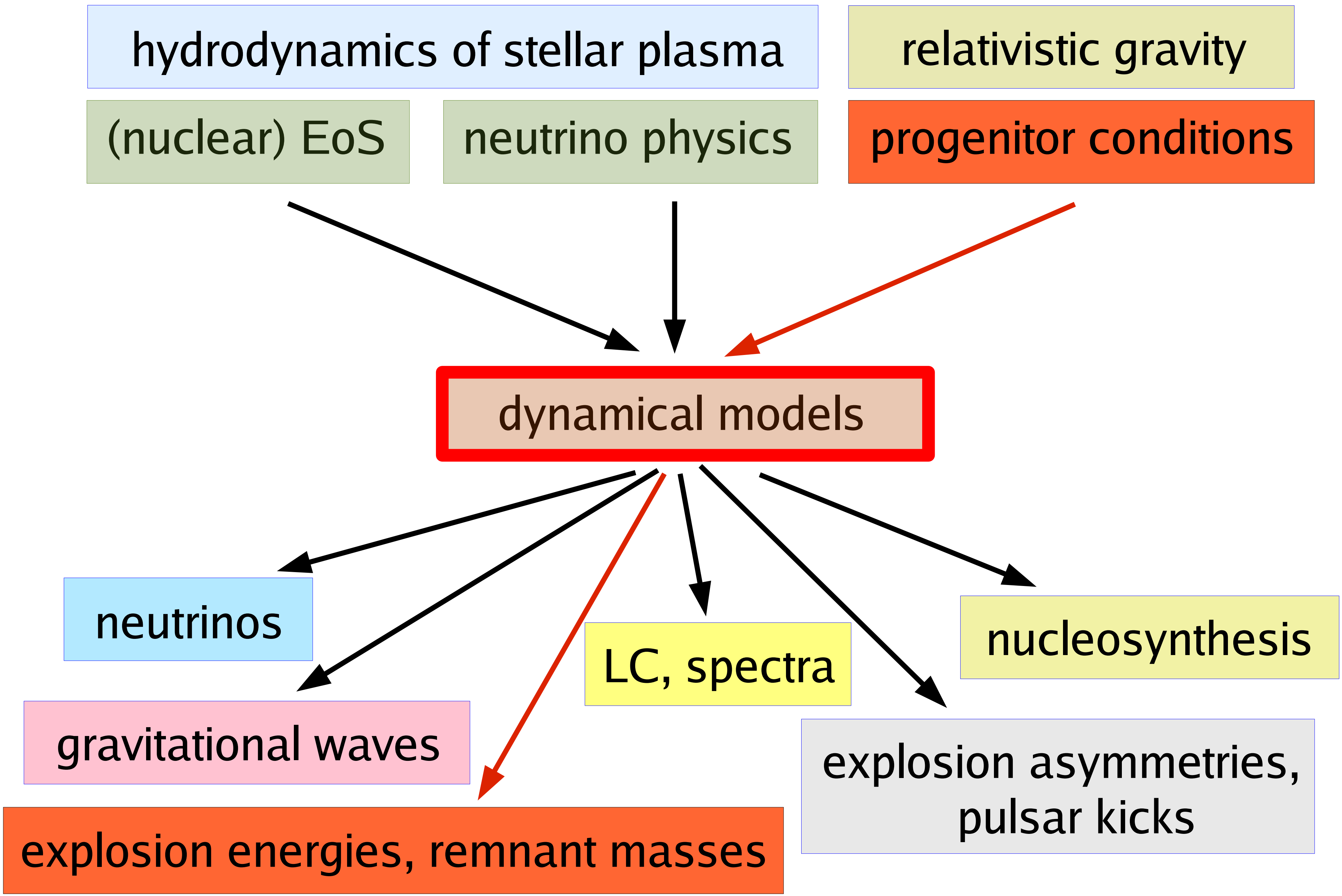
Shock-heated and neutrino-heated outflows are sites for element formation



Shock wave

Neutrino-driven "wind"

Predictions of Signals from SNe & NSs



The Simulation Code

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

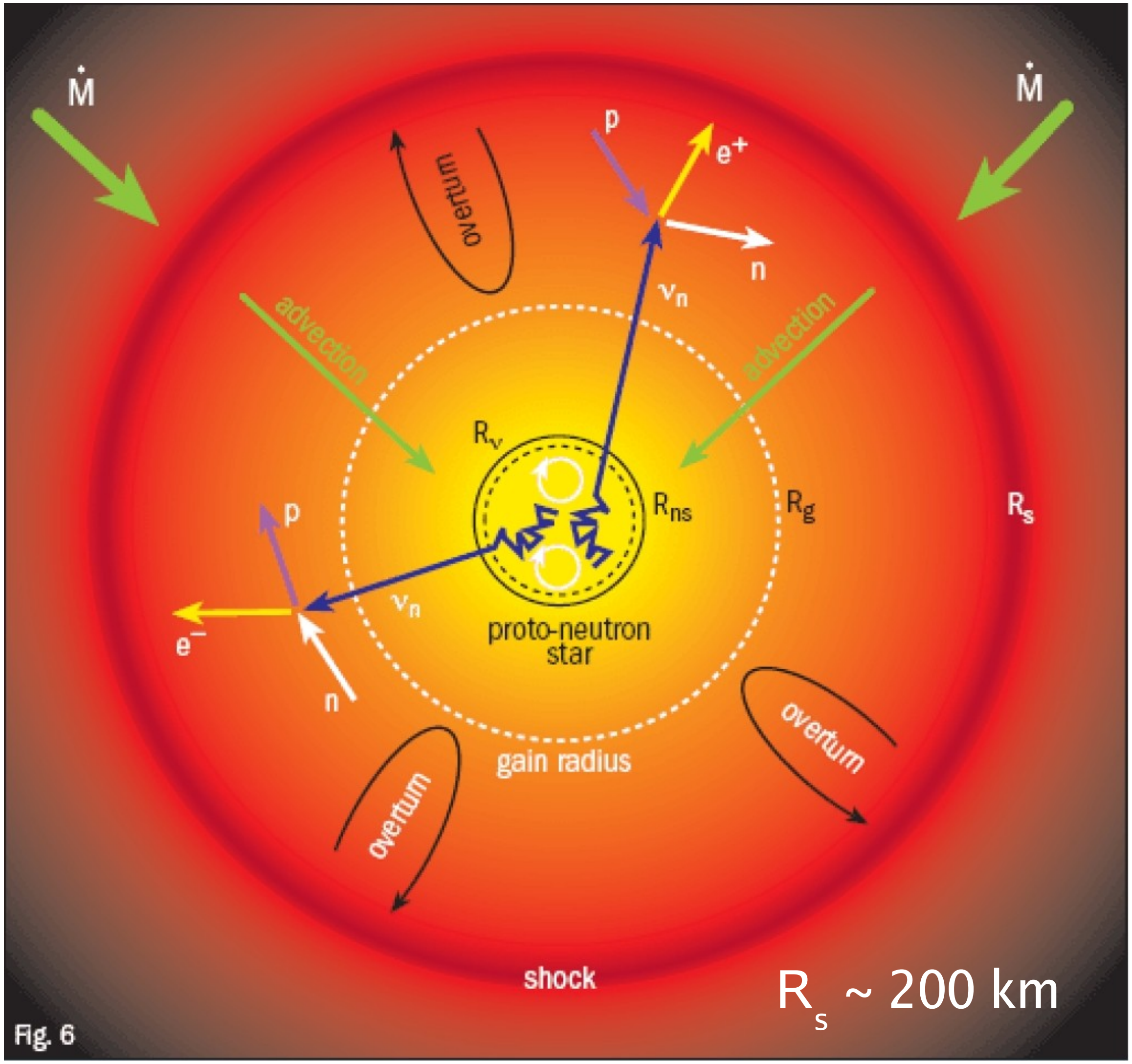
- **Hydro modules:**
  Newtonian: *Prometheus* + effective relativistic grav. potential.
  General relativistic: *CoCoNuT*
  Higher-order Godunov solvers, explicit.
- **Neutrino Transport: *VERTEX***
  Two-moment closure scheme with variable Eddington factor based on model Boltzmann equation; fully energy-dependent, 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.**

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

Neutrinos & SN Explosion Mechanism

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



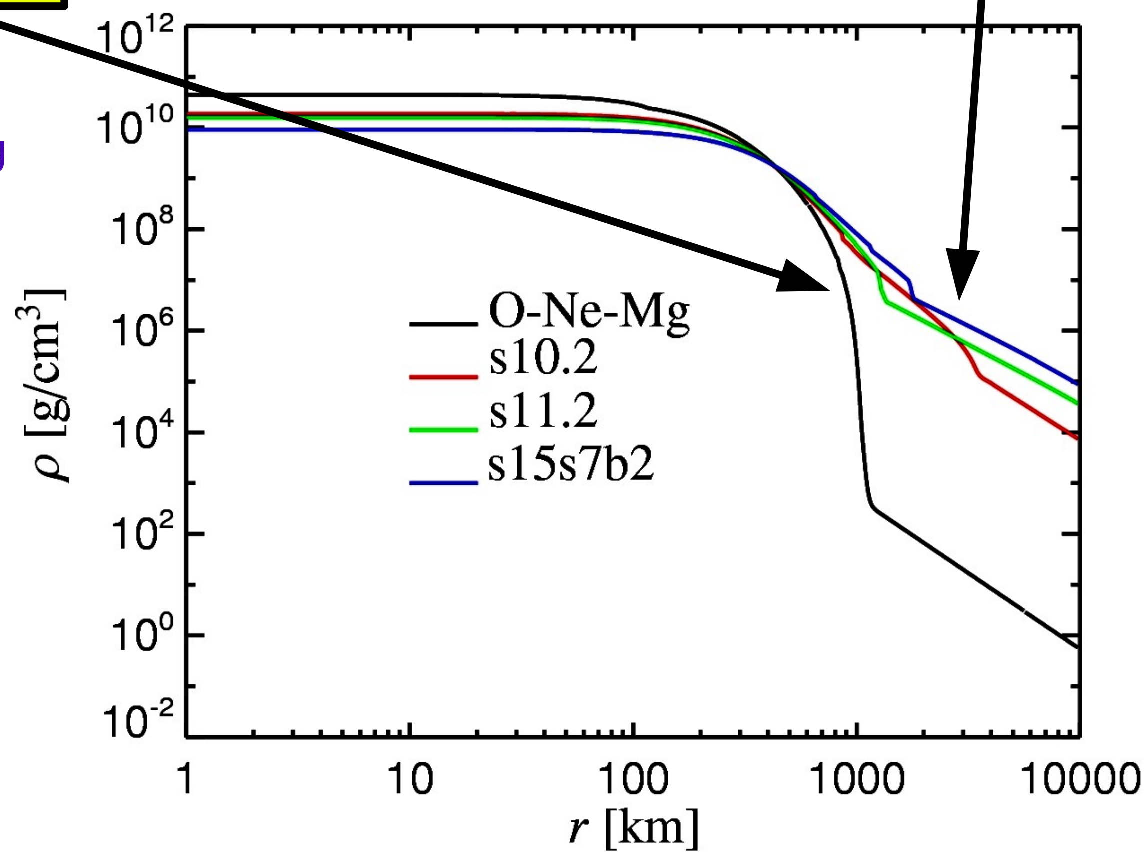
- "Neutrino-heating mechanism": Neutrinos `revive' stalled shock by energy deposition (Colgate & White 1966, Wilson 1982, Bethe & Wilson 1985);
- Convective processes & hydrodynamic instabilities support the heating mechanism (Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996; 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).

SN Progenitors: Core Density Profiles

~8–10 M_{sun} (super-AGB) stars have ONeMg cores with a very steep density gradient at the surface
(====> rapidly decreasing mass accretion rate after core bounce)

>10 M_{sun} stars have much higher densities outside of their Fe cores
(e.g. Heger et al., Limongi et al.,Nomoto et al., Hirschi et al.)
(====> ram pressure of accreted mass decreases slowly after core bounce)

8.8 M_{sun} progenitor model (Nomoto 1984):
2.2 M_{sun} H+He, 1.38 M_{sun} C+O, 1.28 M_{sun} ONeMg at the onset of core collapse



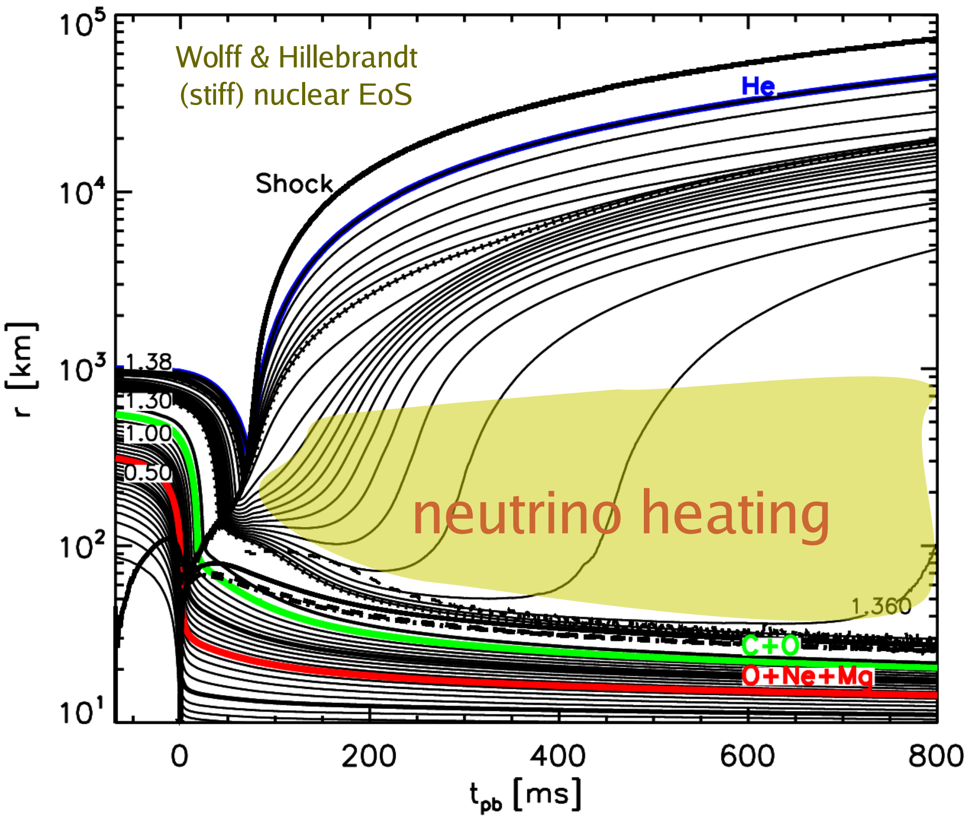
~30% of all SNe (Nomoto et al. 1981, 84, 87)

8.75 M_{sun} < M_{ZAMS} < 9.25 M_{sun}: < 20% of all SNe; (Poelarends et al., A&A 2006), but mass range much larger at metallicities less than solar (Langer et al.)

Explosions of $M_{star} \sim 8\text{–}10\ M_{sun}$ Stars

SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

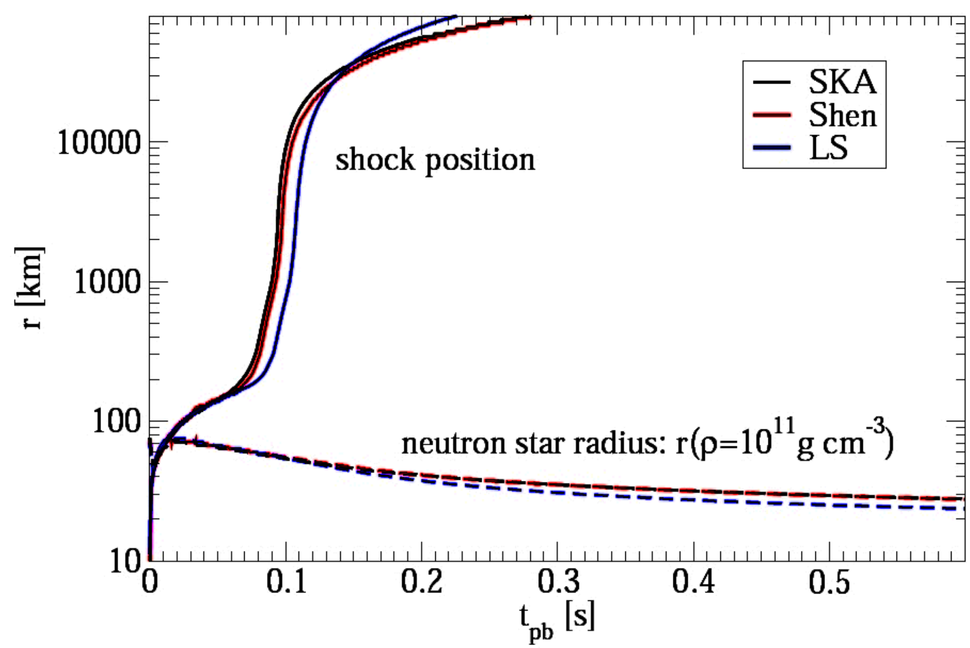
"Electron-capture supernovae"
or "ONeMg core supernovae"



Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199

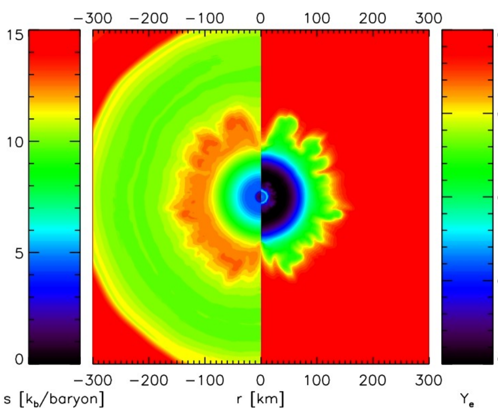
Convection is not necessary for launching explosion
but occurs in NS and in neutrino-heating layer

- No prompt explosion !
- Mass ejection by "neutrino-driven wind"
  (like Mayle & Wilson 1988
  and similar to AIC of WDs;
  see Woosley & Baron 1992, Fryer et al. 1999;
  Dessart et al. 2006)
- Explosion develops in similar way for soft nuclear EoS (i.e. compact PNS) and stiff EoS (less compact PNS)

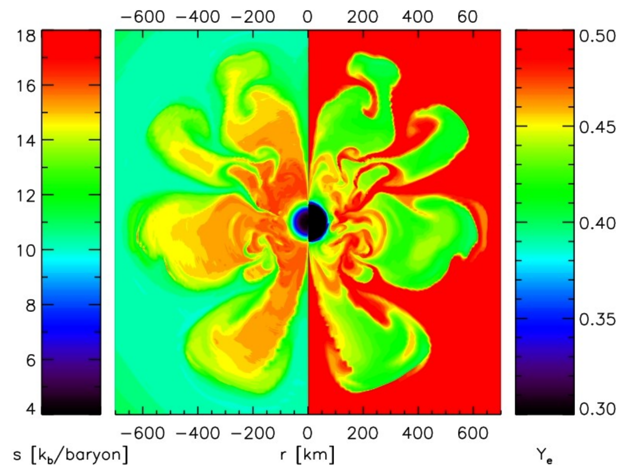


2D SN Simulations: $M_{star} \sim 8 \ldots 10\ M_{sun}$

Convection leads to slight increase of explosion energy, causes explosion asymmetries, and ejects n-rich matter!

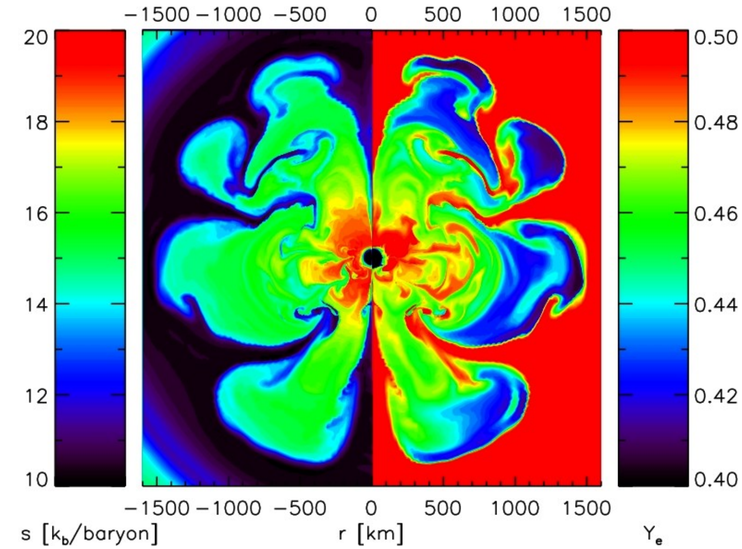


t = 0.097 s after core bounce

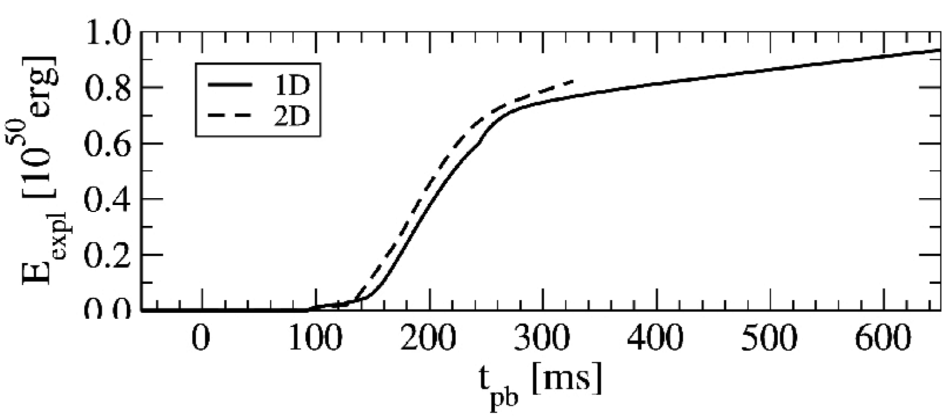


t = 0.144 s after core bounce

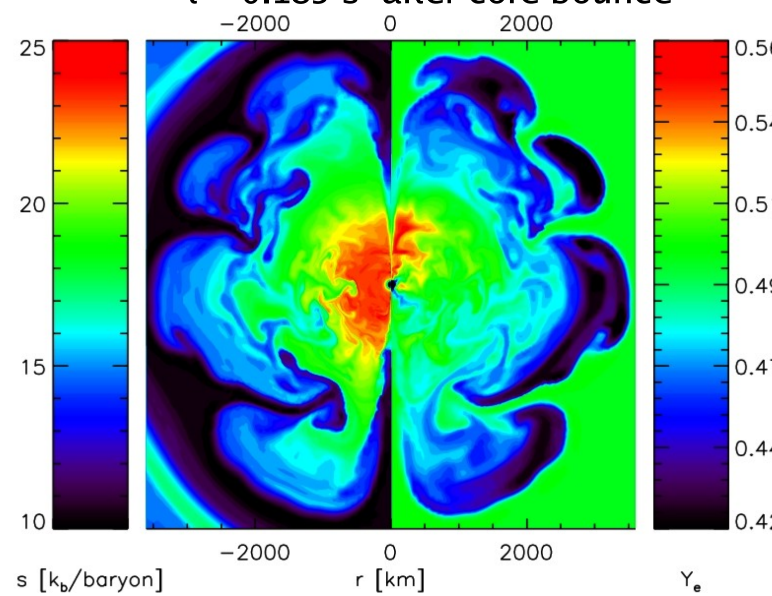
Entropy Y$_e$



t = 0.185 s after core bounce

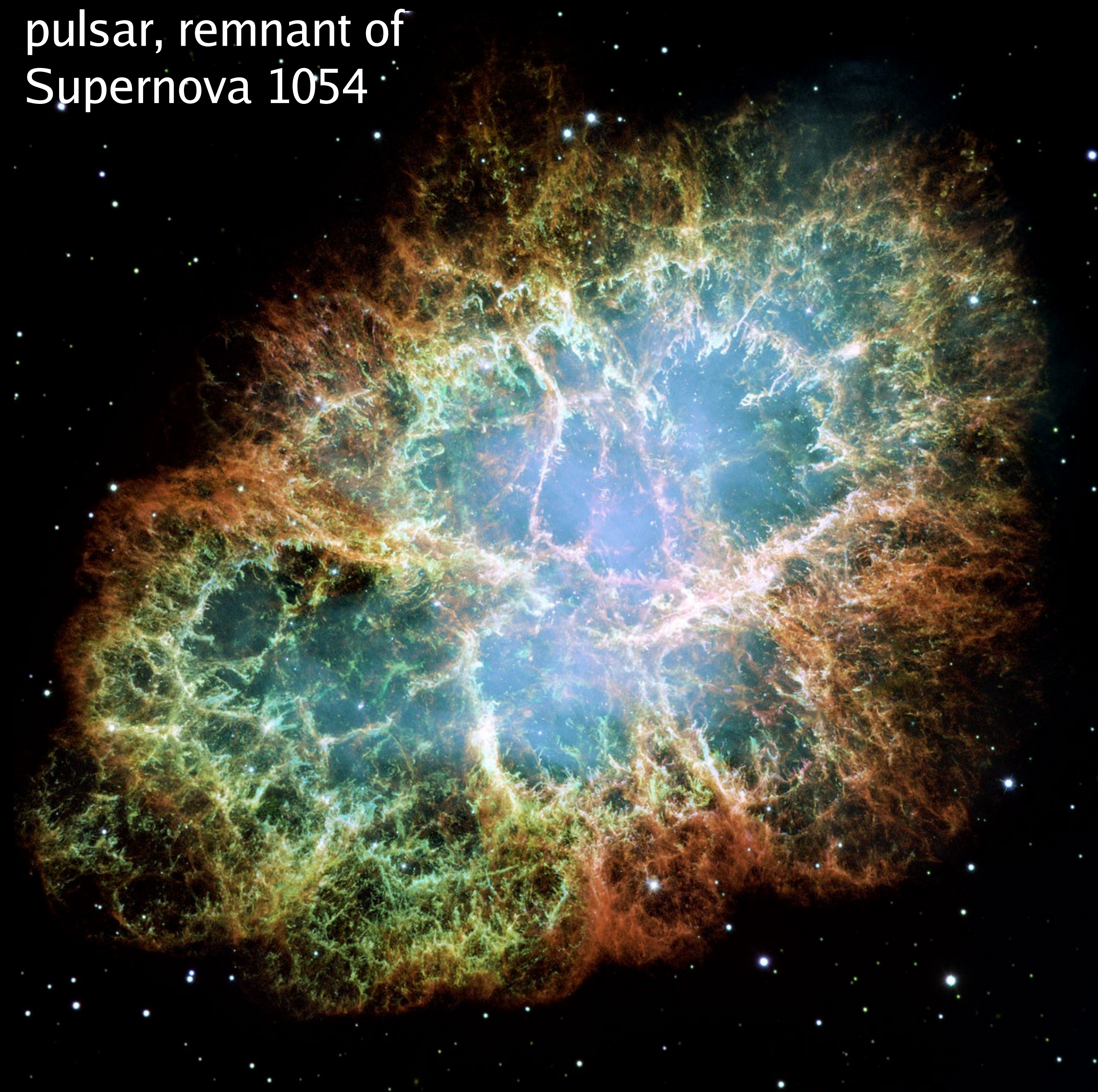


Janka et al. (2008), Wanajo et al. (2011), Groote et al. (in preparation)



t = 0.262 s after core bounce

CRAB Nebula with pulsar, remnant of Supernova 1054



Explosion properties:

$E_{exp} \sim 10^{50}$ erg $= 0.1$ bethe
$M_{Ni} \sim 0.003\ M_{sun}$

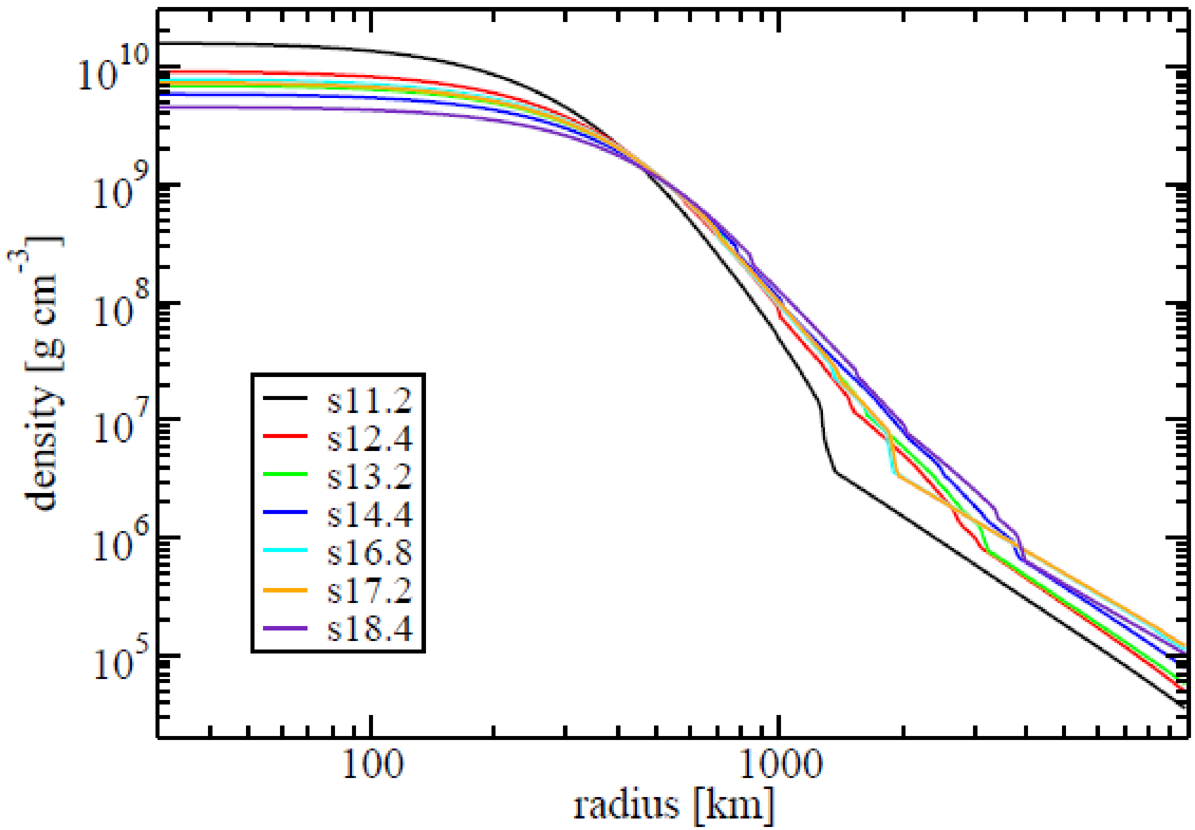
Low explosion energy and ejecta composition (little Ni, C, O) of ONeMg core explosion are compatible with CRAB (SN1054)

(Nomoto et al., Nature, 1982; Hillebrandt, A&A, 1982)

Might also explain other low-luminosity supernovae (e.g. SN1997D, 2008S, 2008HA)

Explosions of Stars with $M_{star} > 10\ M_{sun}$

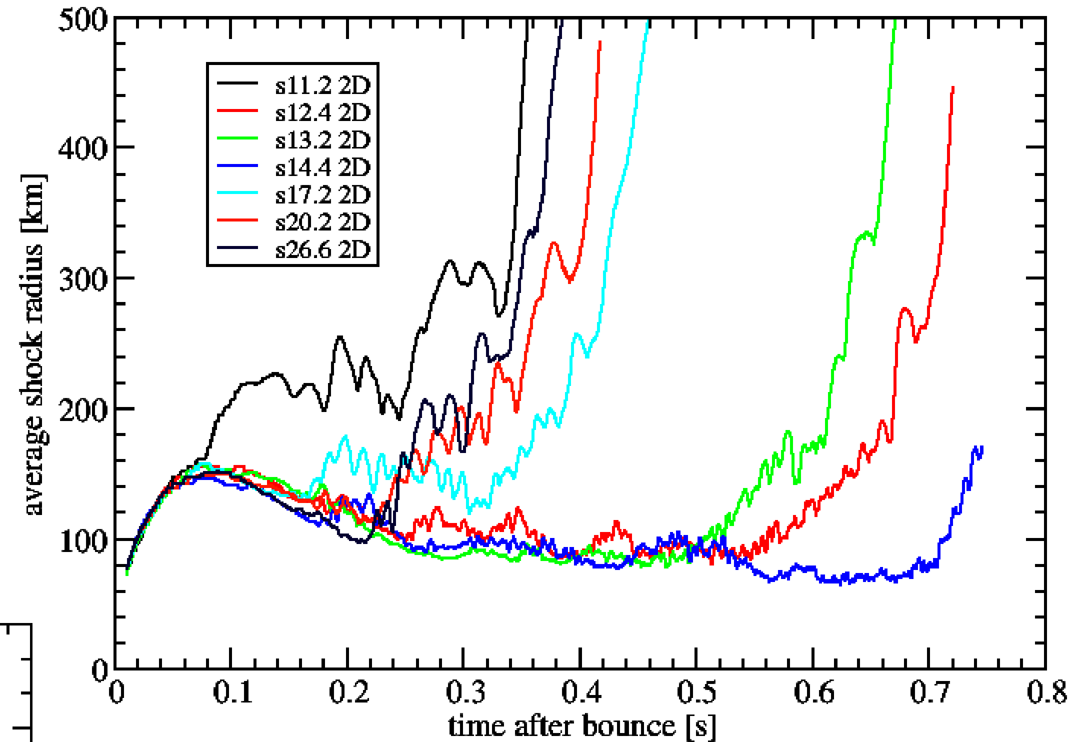
Progenitor Stars: Density Profiles



Progenitor models at onset of stellar core collapse:
Woosley, Heger & Weaver, RMP (2002)

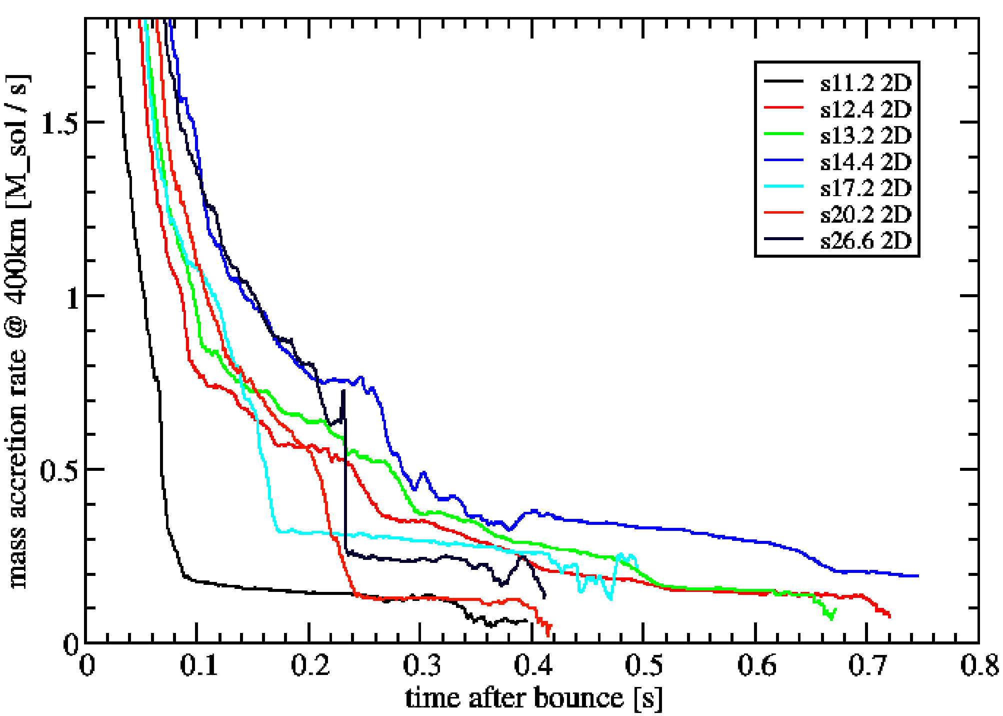
Growing Set of 2D CCSN Explosion Models

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



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

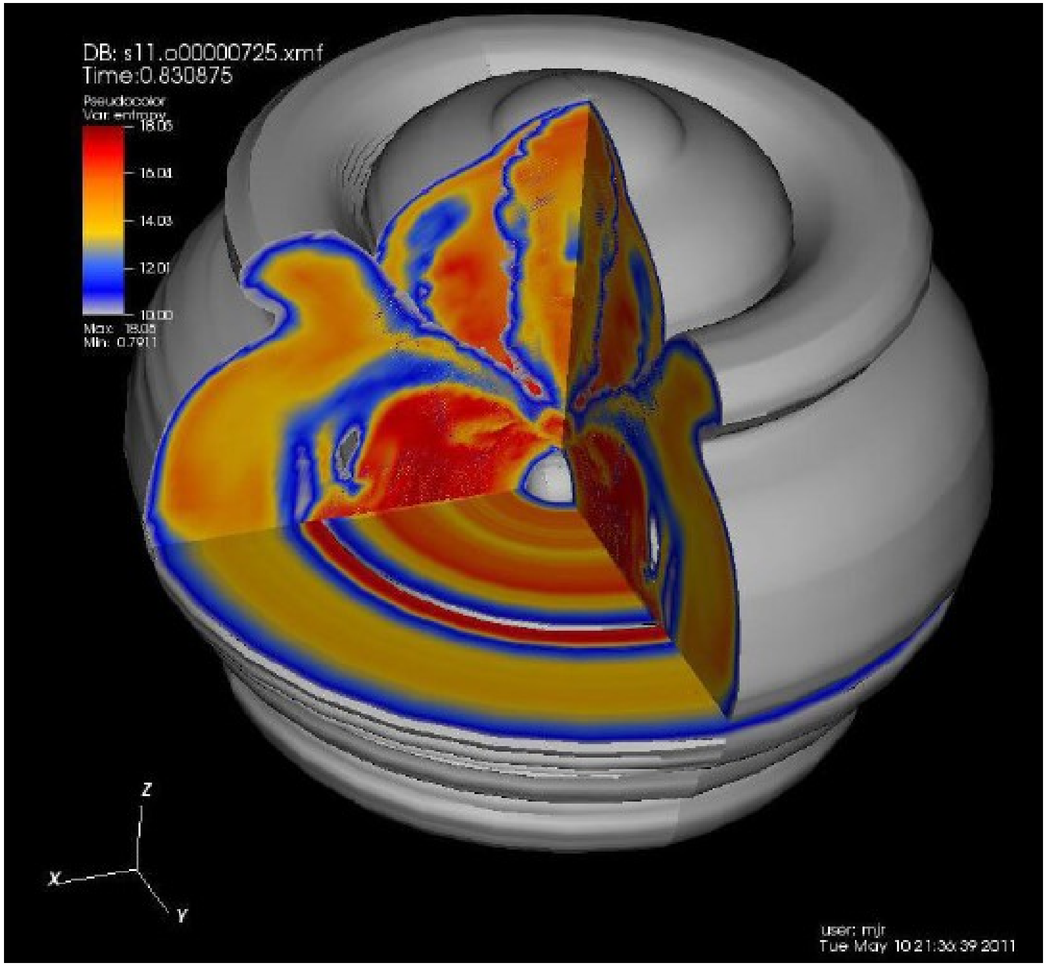
Mass accretion rate

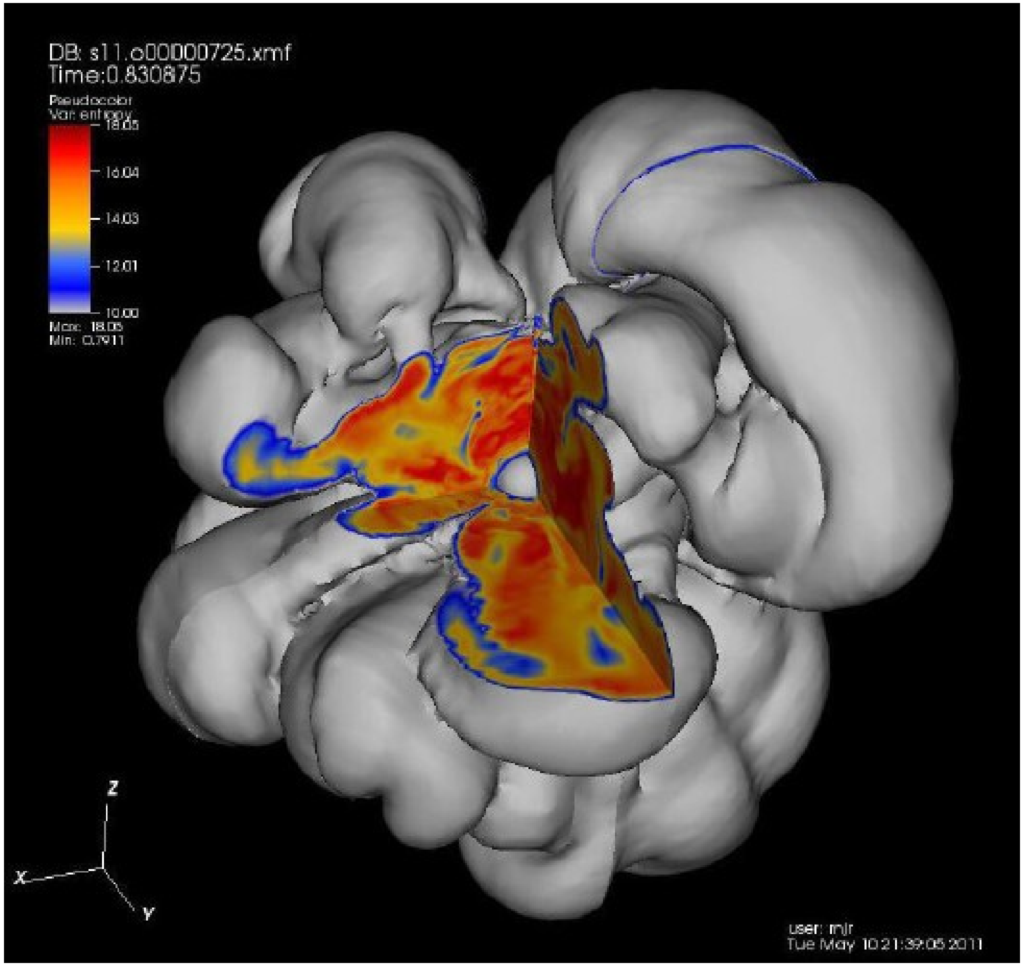


Average shock radius

Progenitor models:
Woosley et al. RMP (2002)

2D and 3D Morphology





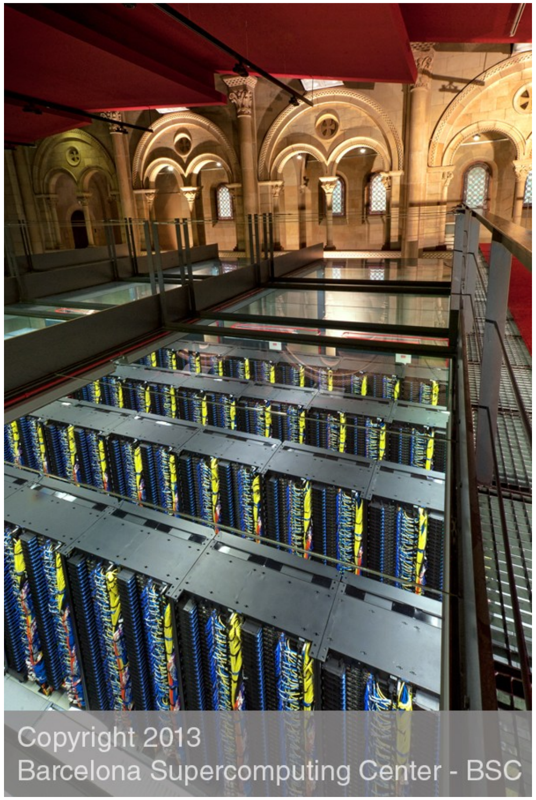
(Images from Markus Rampp, RZG)

3D Supernova Simulations

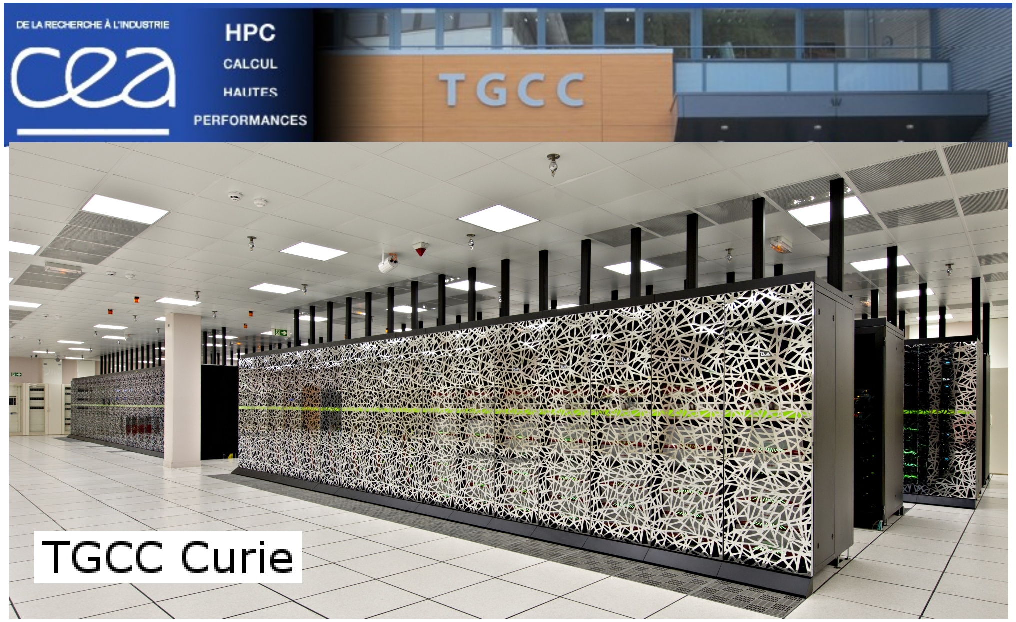
EU PRACE and GAUSS Centre grants of ~1 billion core hours allow(ed) us to do the first 3D simulations on 16.000 cores.

PRACE
PARTNERSHIP FOR ADVANCED COMPUTING IN EUROPE

GCS
Gauss Centre for Supercomputing



Mare Nostrum



TGCC Curie

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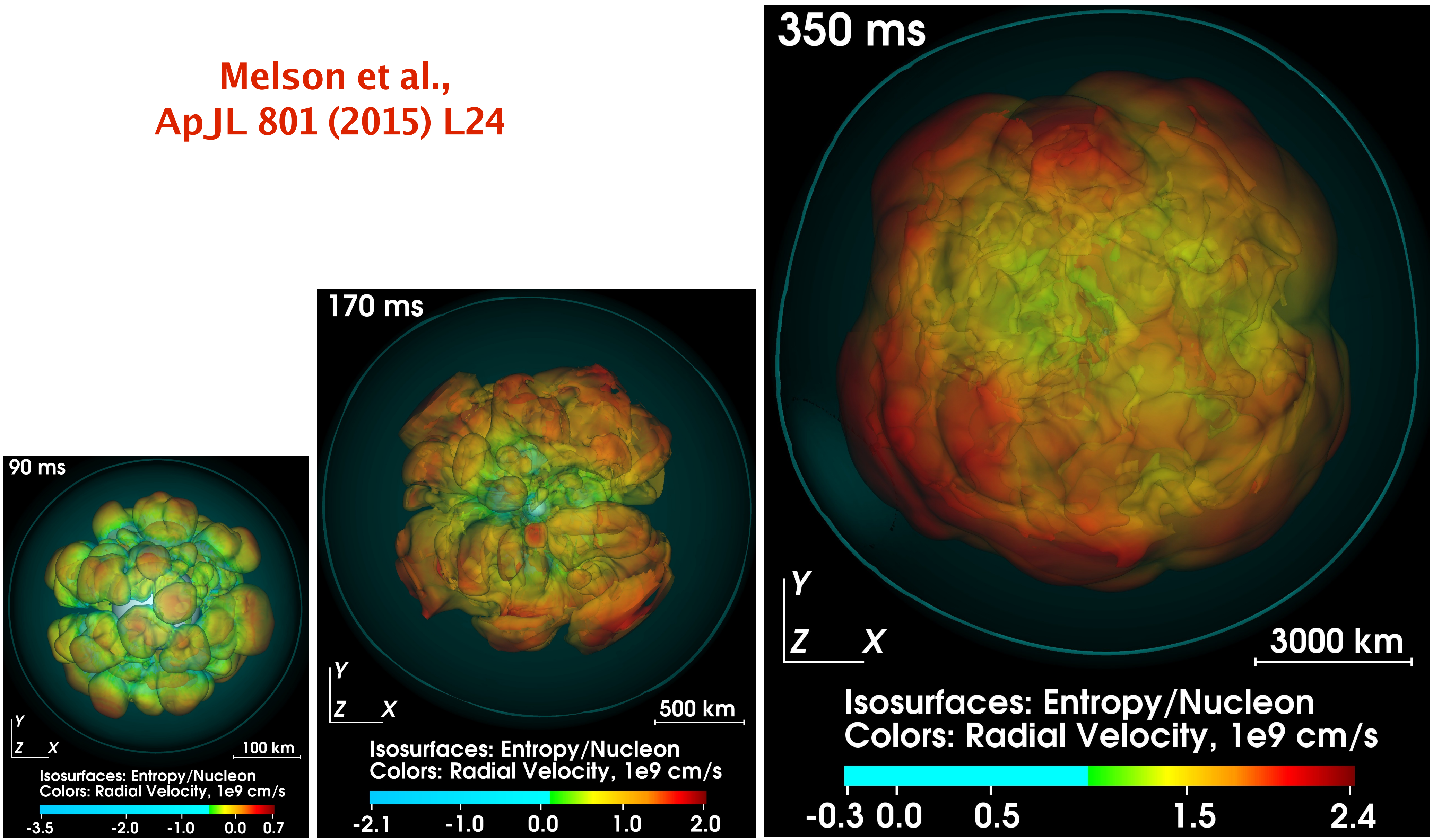
SuperMUC

3D Core-Collapse SN Explosion Models

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

Melson et al.,
ApJL 801 (2015) L24



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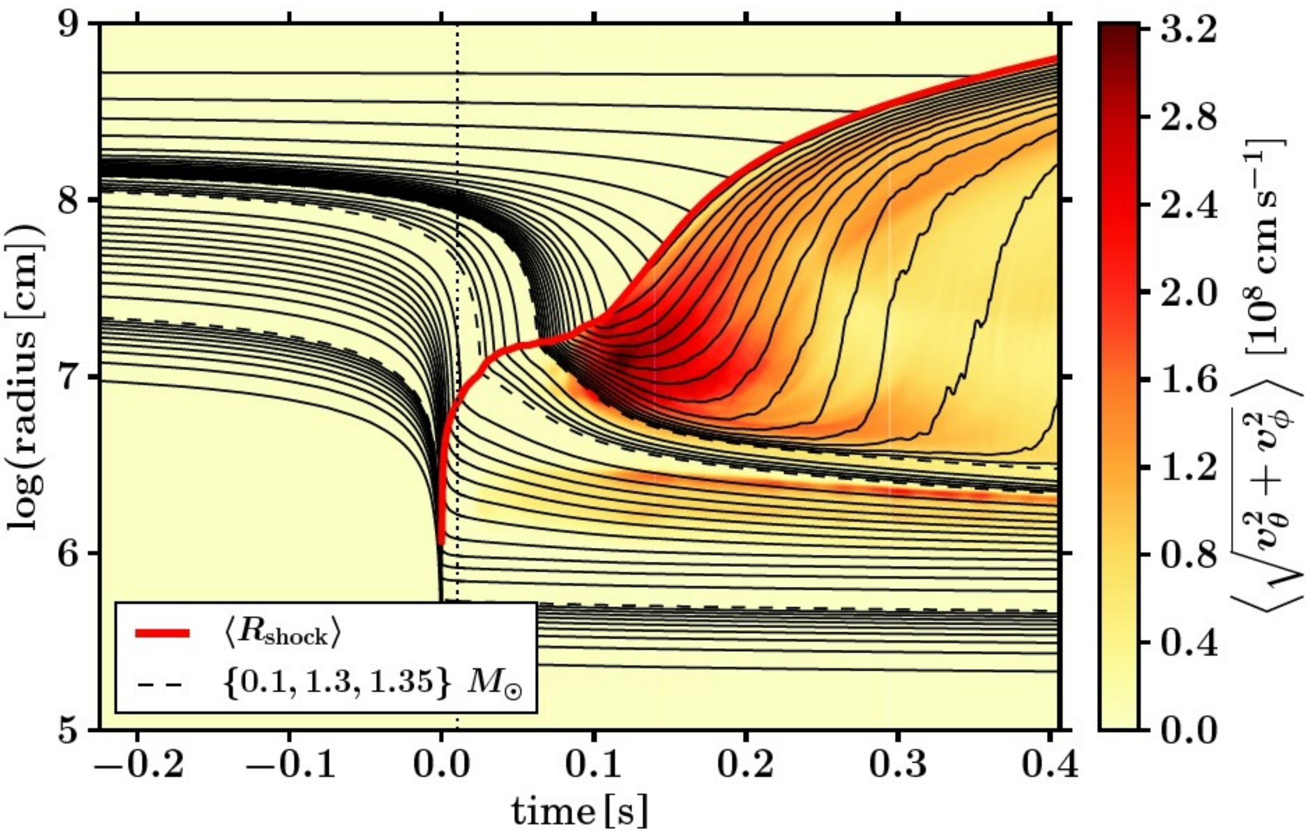

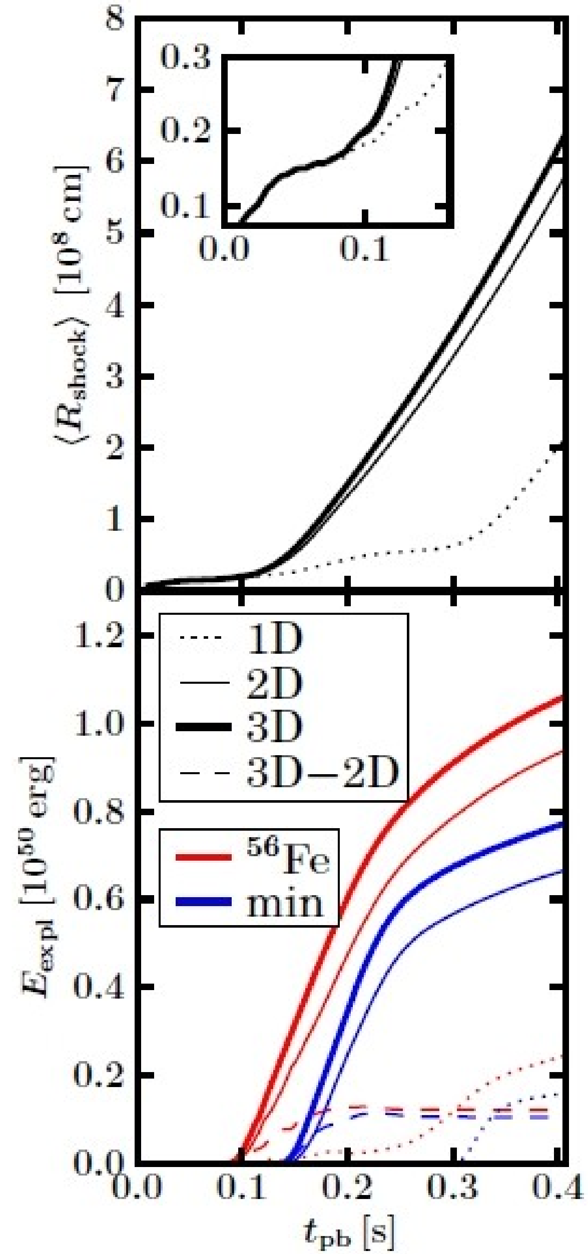

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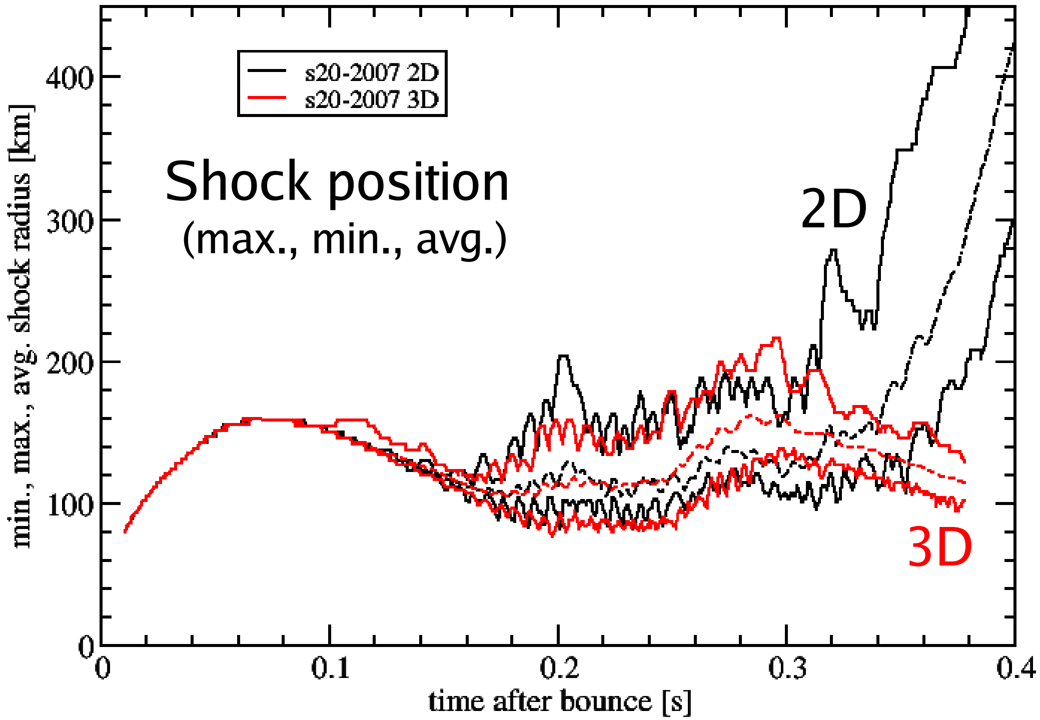
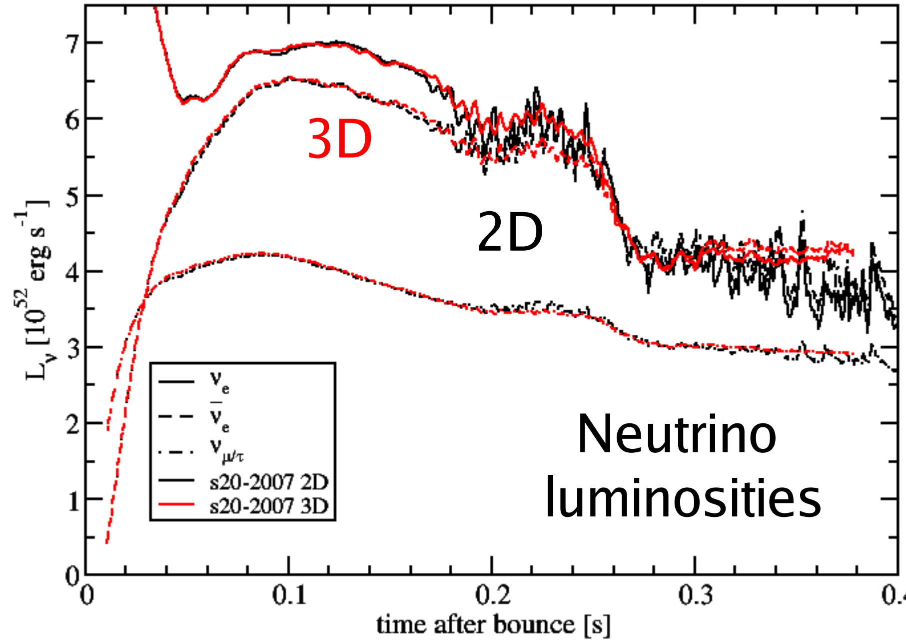
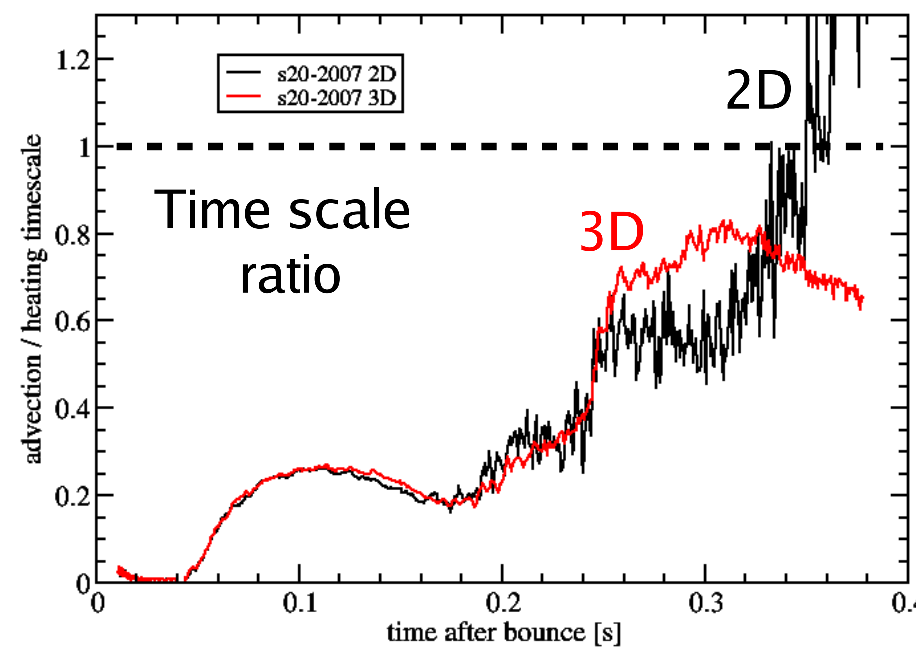
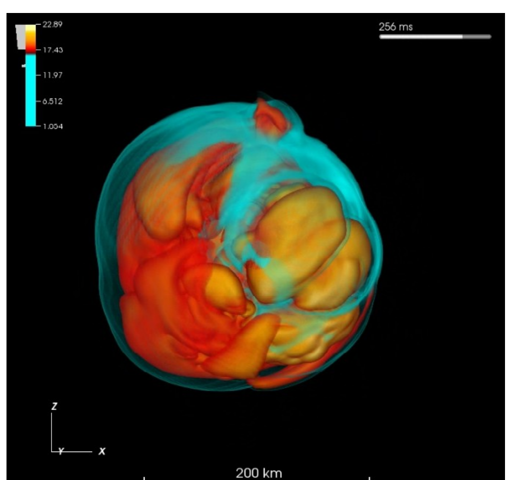
20 M_{sun} progenitor (WH 2007)







Florian Hanke,
PhD project



3D Core-Collapse SN Explosion Models

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

3. STRANGENESS CONTRIBUTIONS TO NEUTRINO-NUCLEON SCATTERING

The lowest-order differential neutrino-nucleon scattering cross section reads

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

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

While in our SN simulations corrections due to nucleon thermal motions and recoil, weak magnetism, and nucleon correlations at high densities are taken into account (Rampp & Janka 2002; Buras et al. 2006), Eqs. (1,2) provide good estimates. Strange quark contributions to the nucleon spin modify c_a according to

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

where the plus sign is for νp and the minus sign for νn scattering (see, e.g., Horowitz 2002; Langanke & Martínez-Pinedo 2003). Since $g_a^s \le 0$, the cross section for νp-scattering is increased and for νn-scattering decreased.

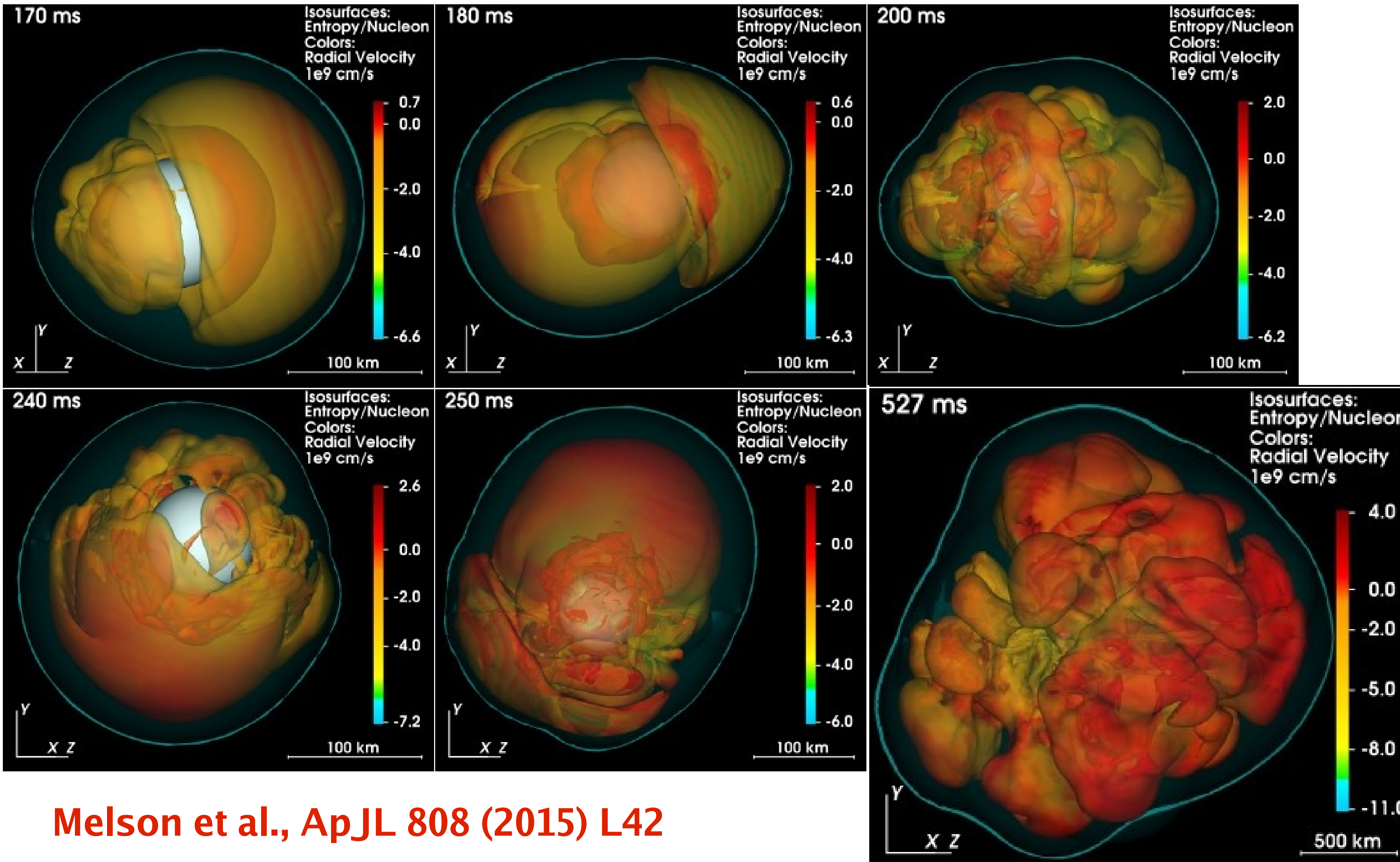
We use:
$g_a = 1.26$
$g_a^s = -0.2$

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

Melson et al., ApJL 808 (2015) L42

3D Core-Collapse SN Explosion Models

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



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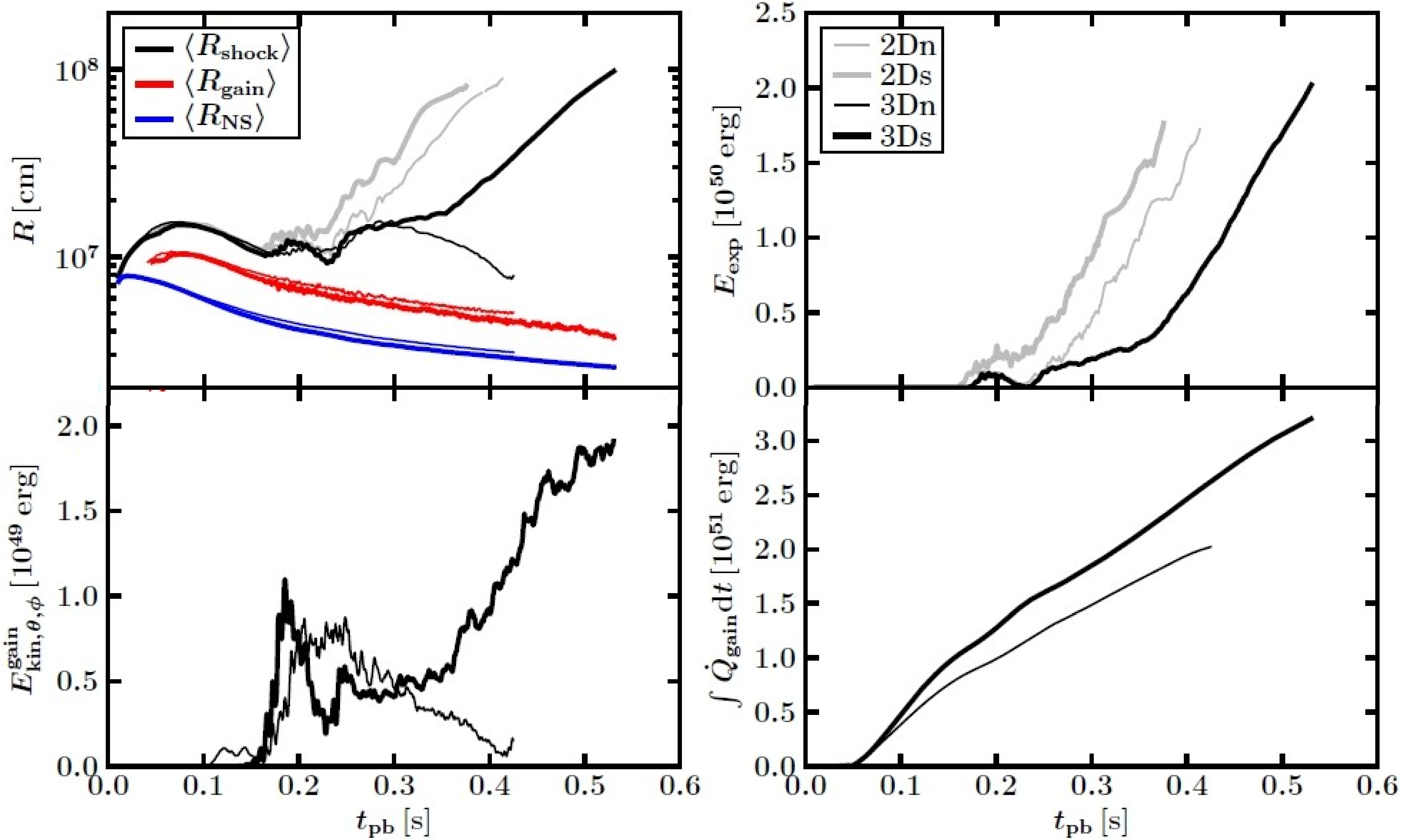

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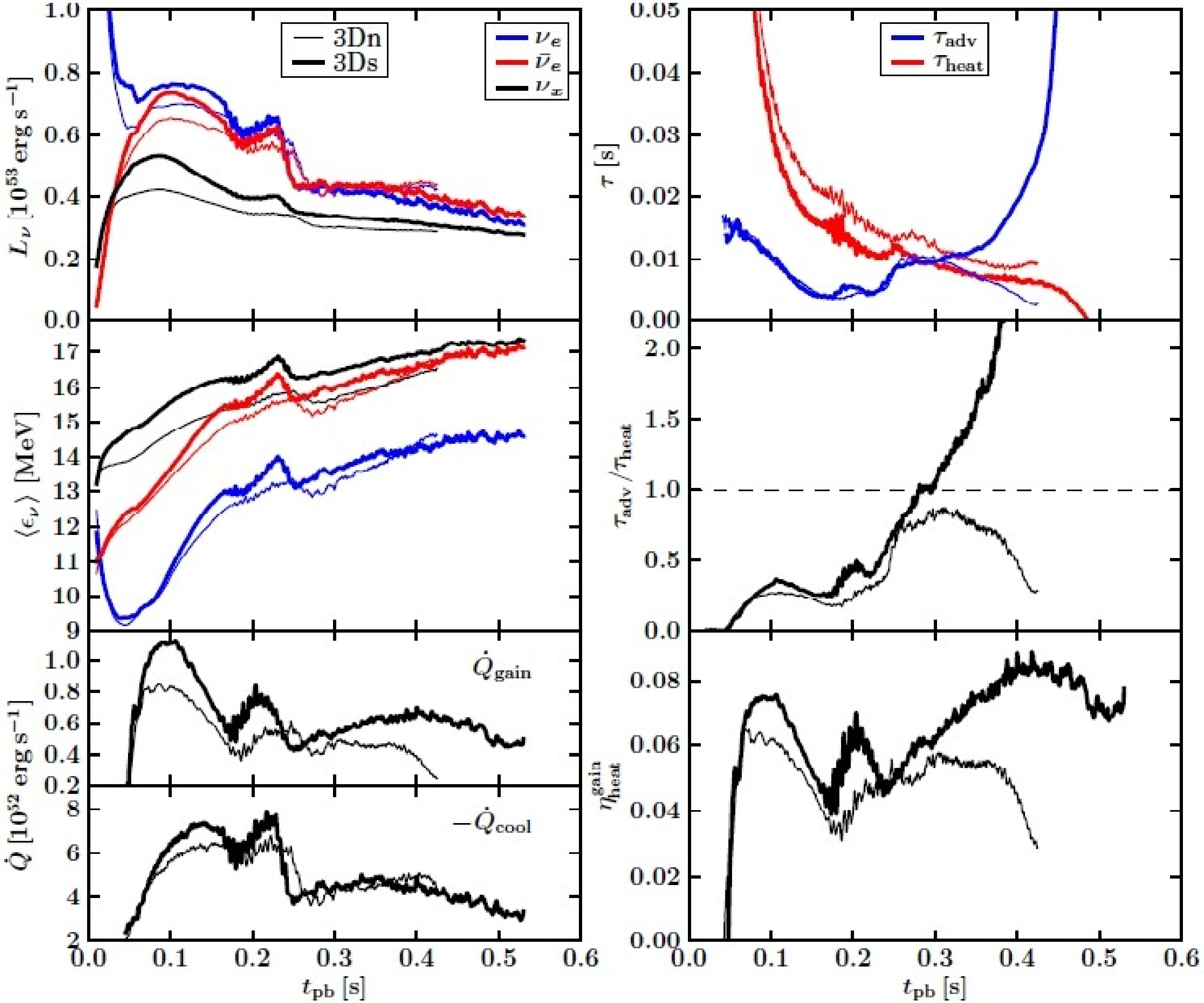


Melson et al., ApJL 808 (2015) L42

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.

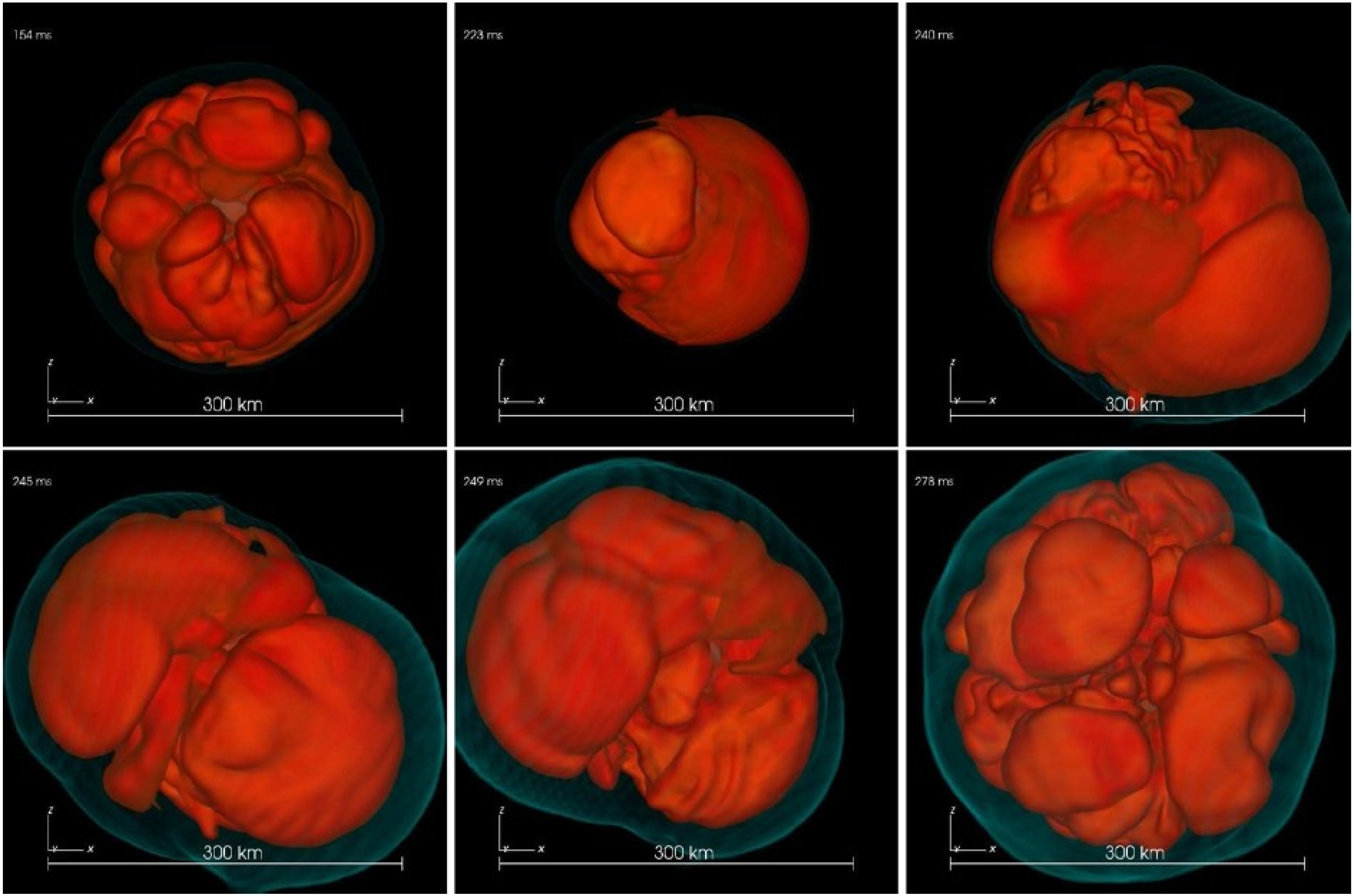
- 3D modeling has only begun. No final picture of 3D effects yet.

- **$M < 10\ M_{sun}$ stars explode in 3D.**
  First 3D explosion of 20 M_{sun} progenitor
  (for 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 ?????**

Some Observable Consequences of Neutrino-driven Explosions

SASI in the Postshock Accretion Layer



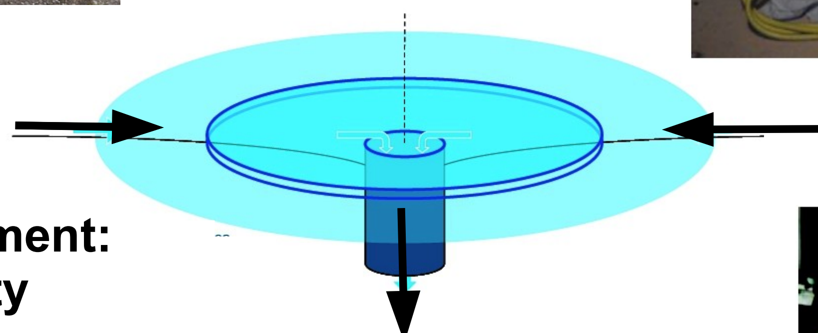
27 M_{sun} progenitor (WHW 2002)

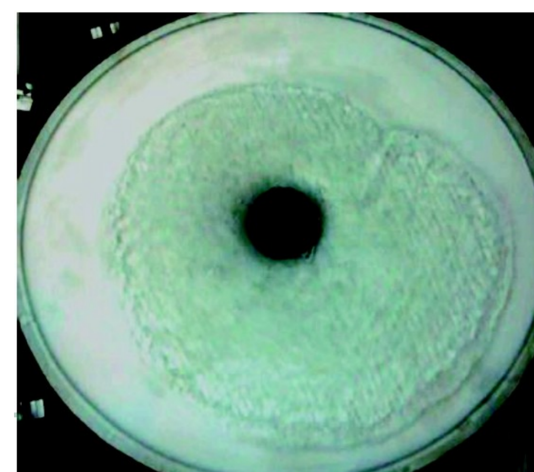
F. Hanke et al., ApJ 770 (2013) 66

Laboratory Astrophysics

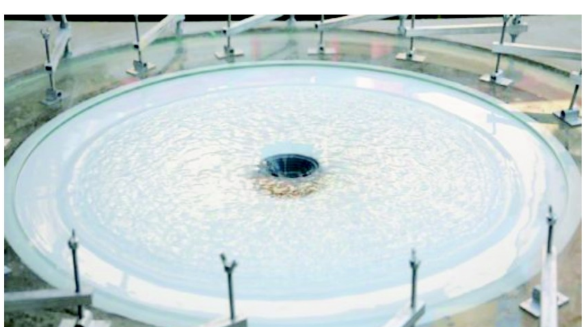
"SWASI" Instability as an analogue of SASI in the supernova core

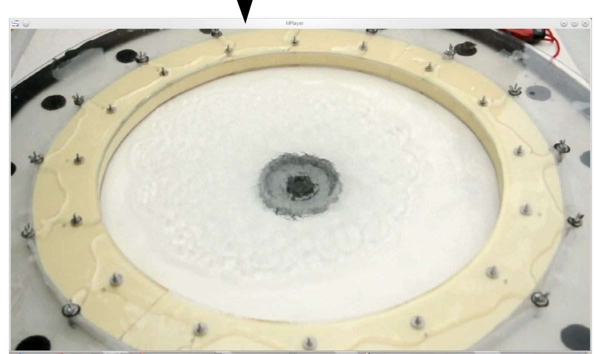
Foglizzo et al., PRL 108 (2012) 051103



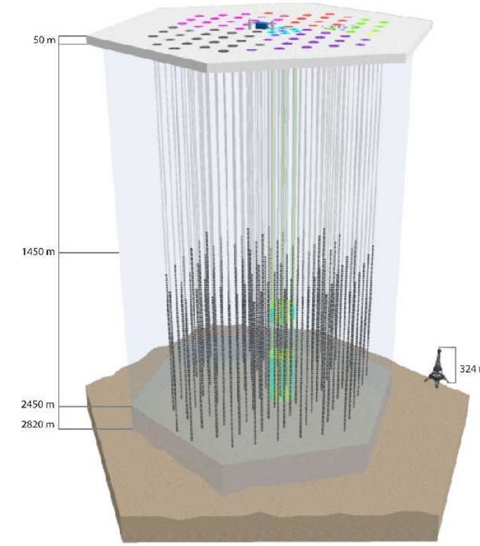


Constraint of experiment:
No convective activity



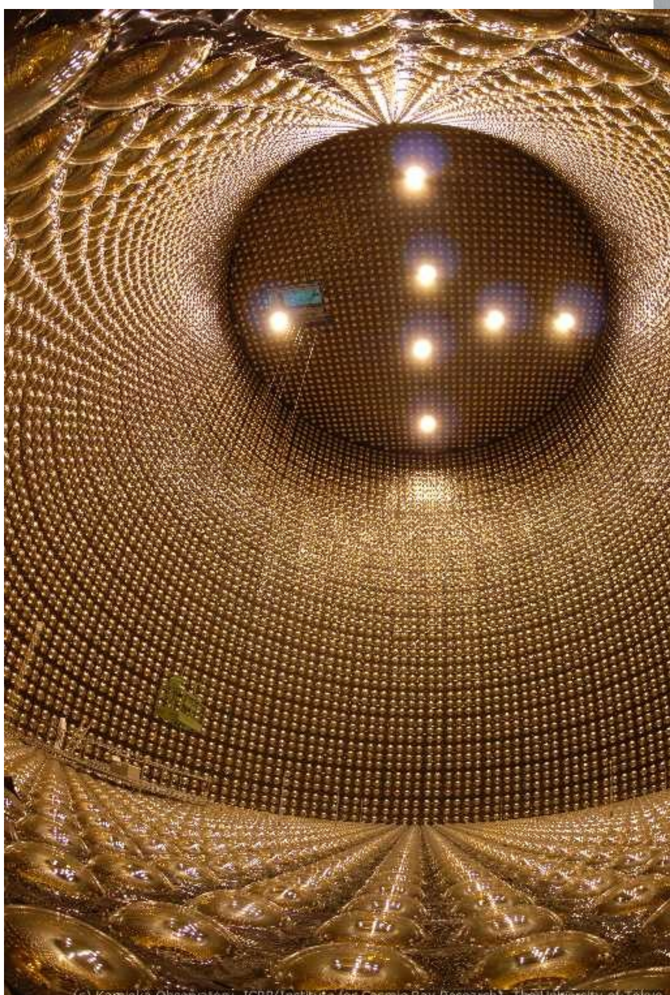


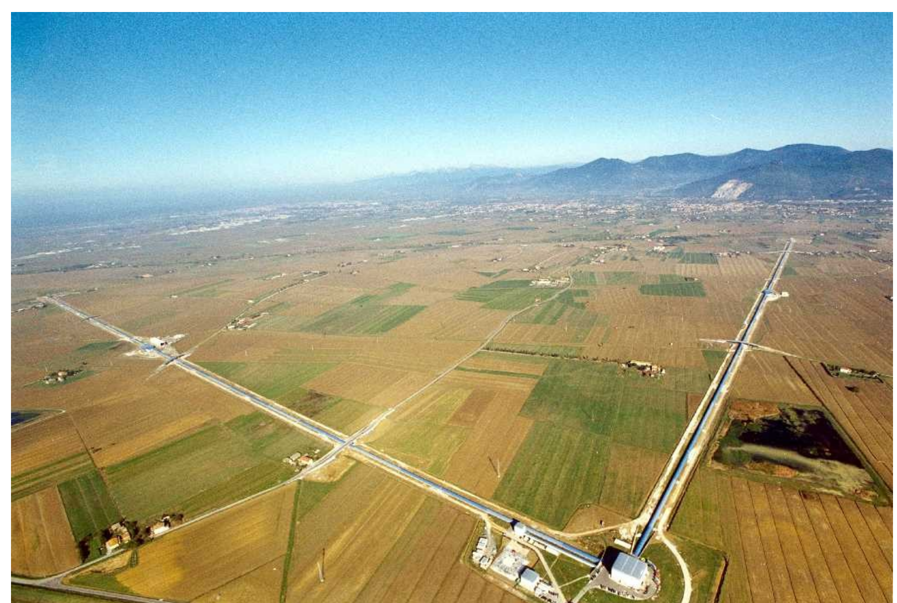
Detecting Core-Collapse SN Signals



IceCube

Superkamiokande



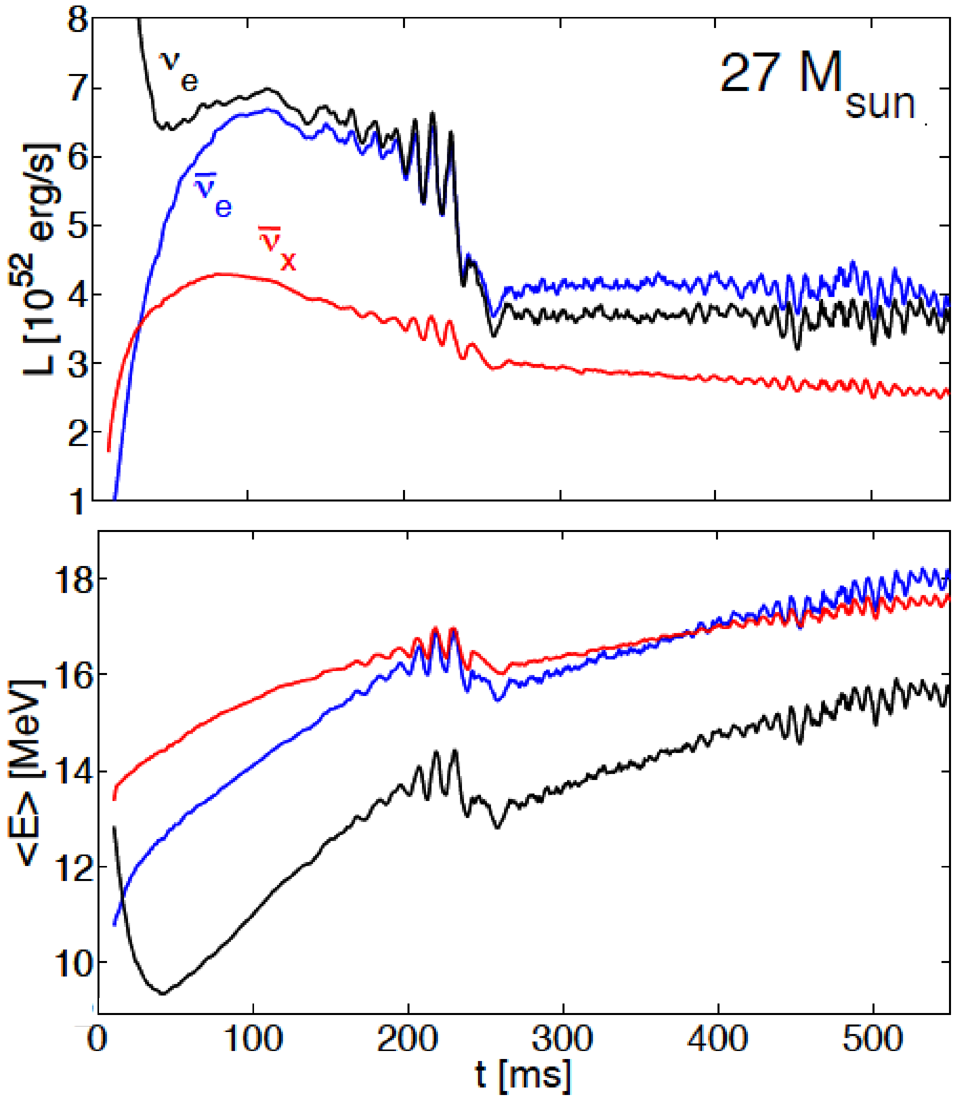


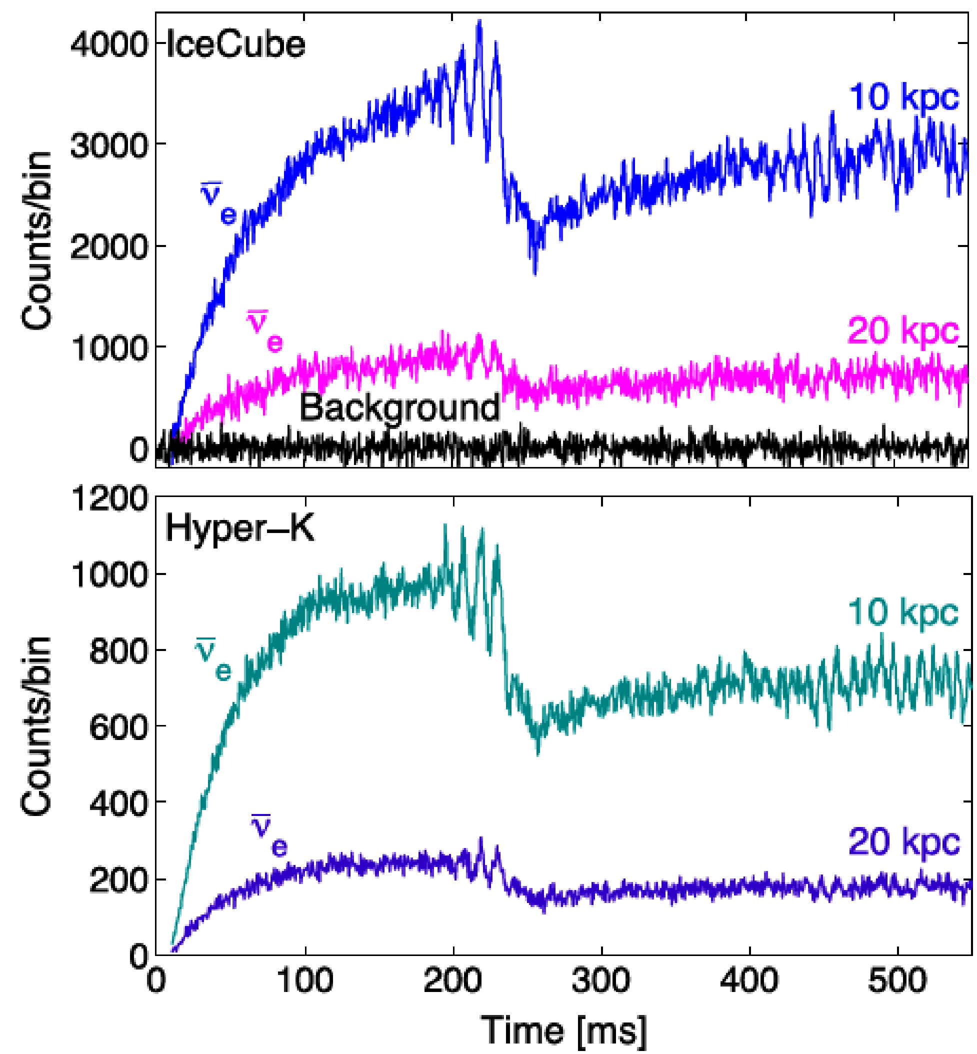
VIRGO

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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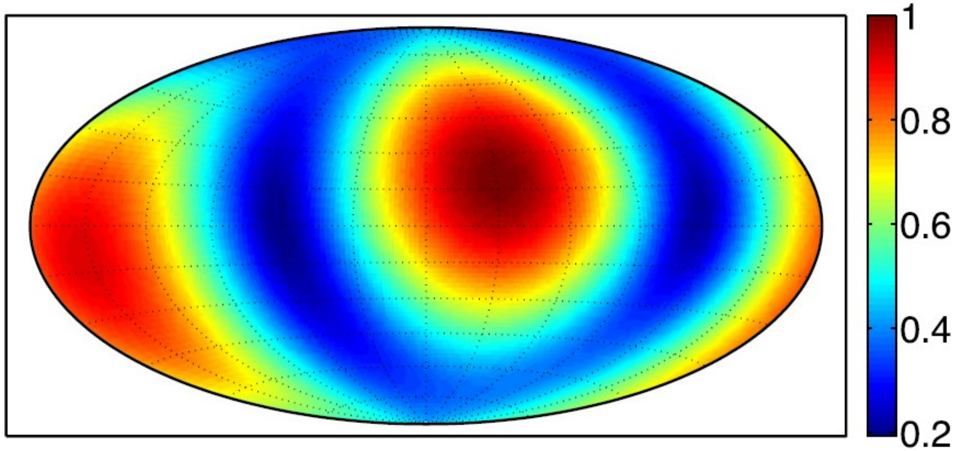
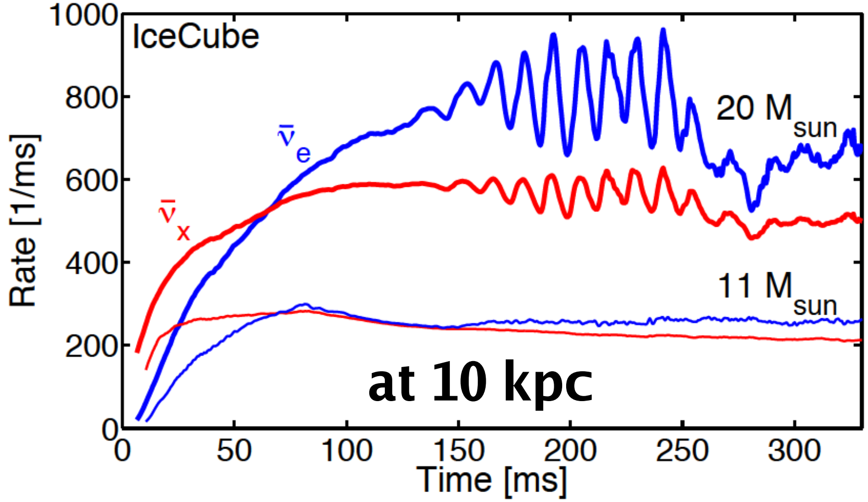
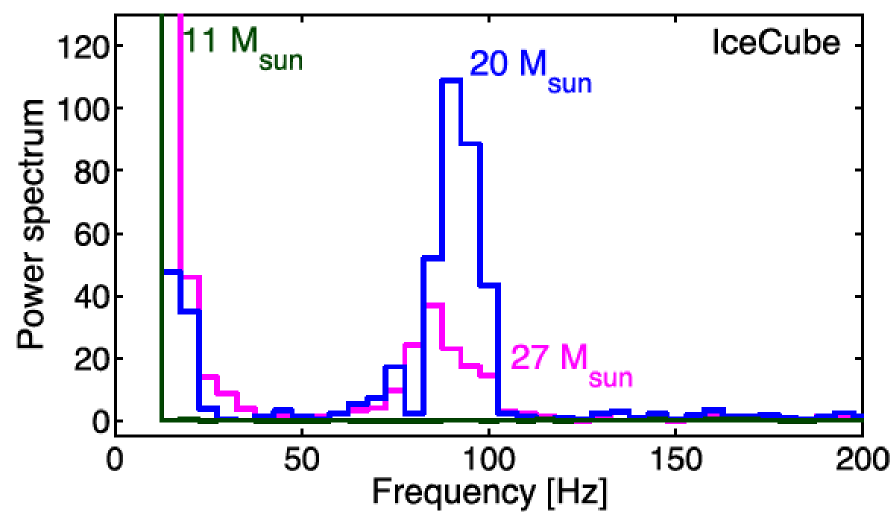


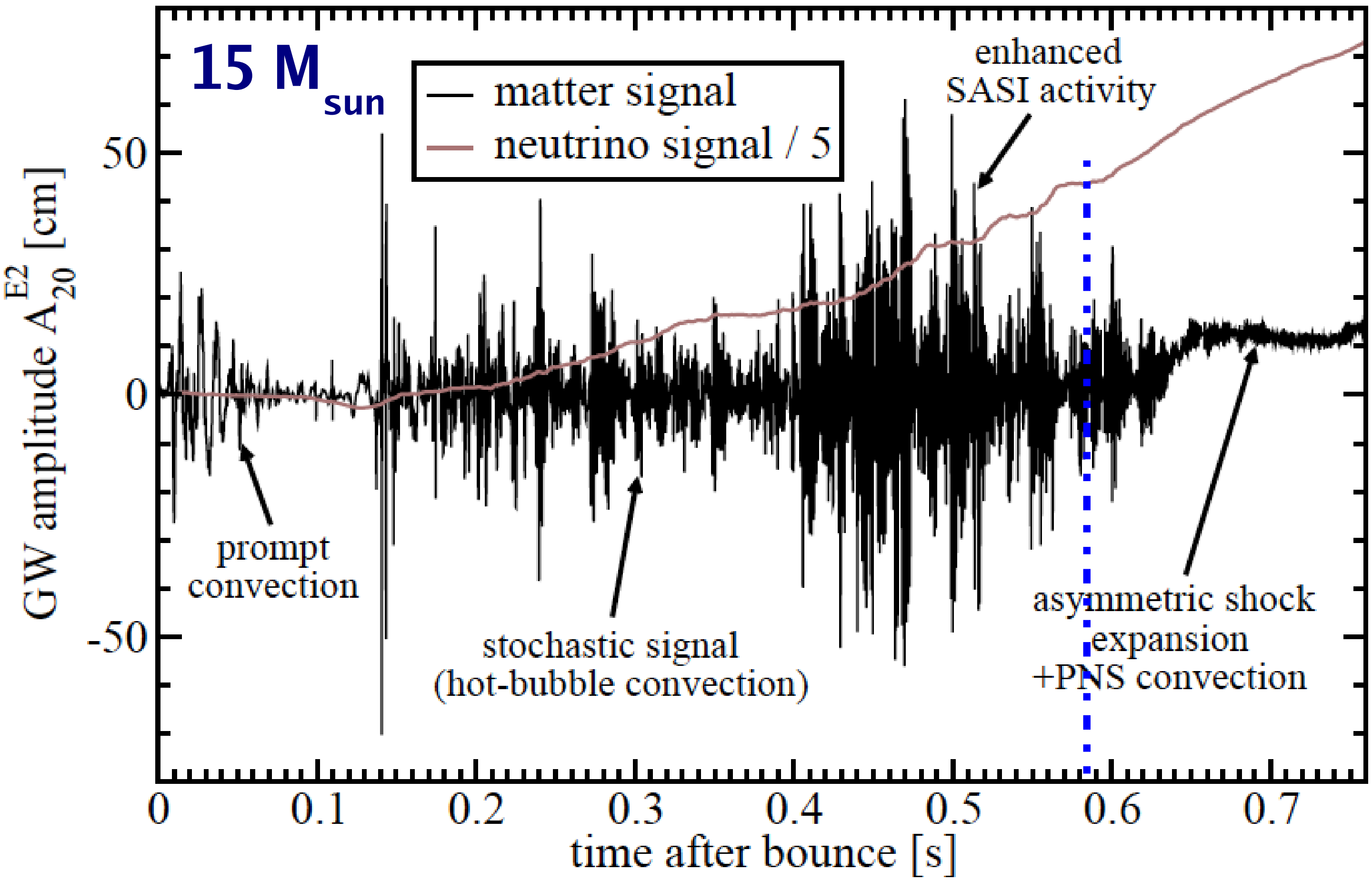


$$f_{\mathrm{SASI}}^{-1} \sim \int_{R_{\mathrm{NS}}}^{R_{\mathrm{S}}} \frac{dr}{|v|} + \int_{R_{\mathrm{NS}}}^{R_{\mathrm{S}}} \frac{dr}{c_{\mathrm{s}} - |v|}$$



Tamborra et al., PRL 111, 121104 (2013);
PRD 90, 045032 (2014)

Gravitational Waves for 2D SN Explosions



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

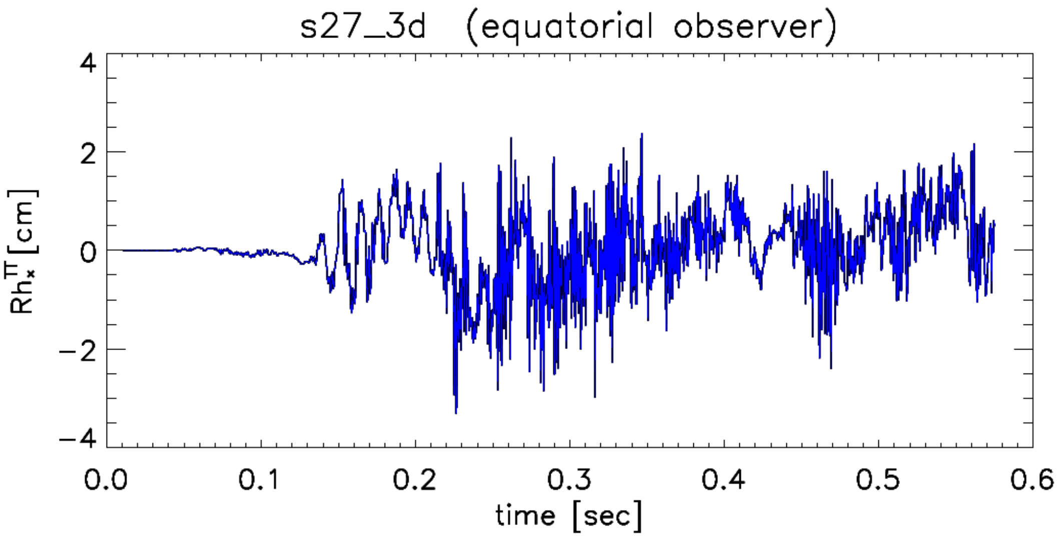
$$h = \frac{1}{8}\sqrt{\frac{15}{\pi}}\sin^2\Theta\,\frac{A_{20}^{E2}}{R}$$

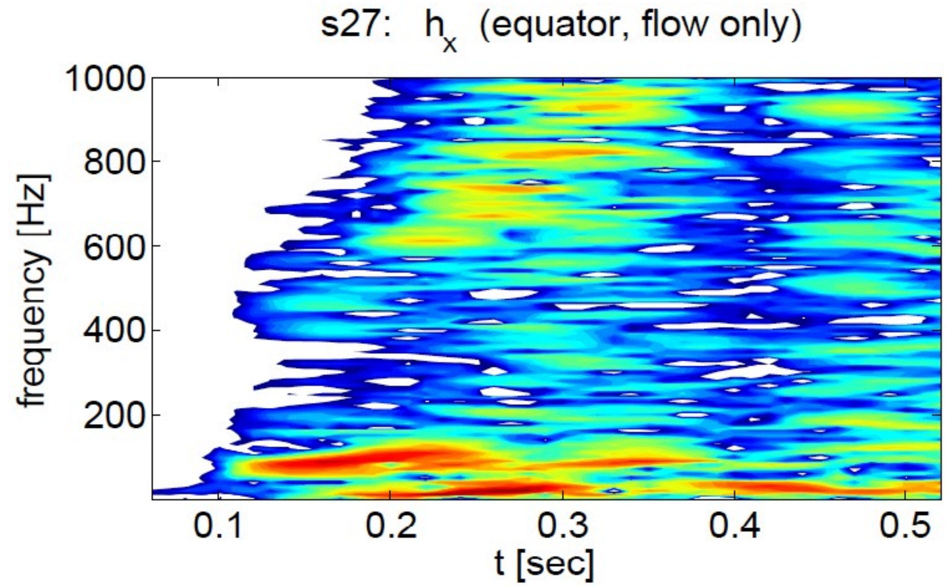
$$h_\nu = \frac{2G}{c^4 R}\int_0^t L_\nu(t')\alpha_\nu(t')\,dt'$$

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

3D Core-Collapse Models: Gravitational Waves

27 M_{sun} progenitor (WHW 2002)





Preliminary analysis
by E. Müller of
model from
F. Hanke et al.,
ApJ 770 (2013) 66