Max–Planck–Institut
für Astrophysik

SFB-TR7

TUM LMU Excellence Cluster Universe

# The Supernova Mechanism and its Multi-messenger Astrophysics

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TAUP 2013

13th International Conference on Topics in Astroparticle and Underground Physics

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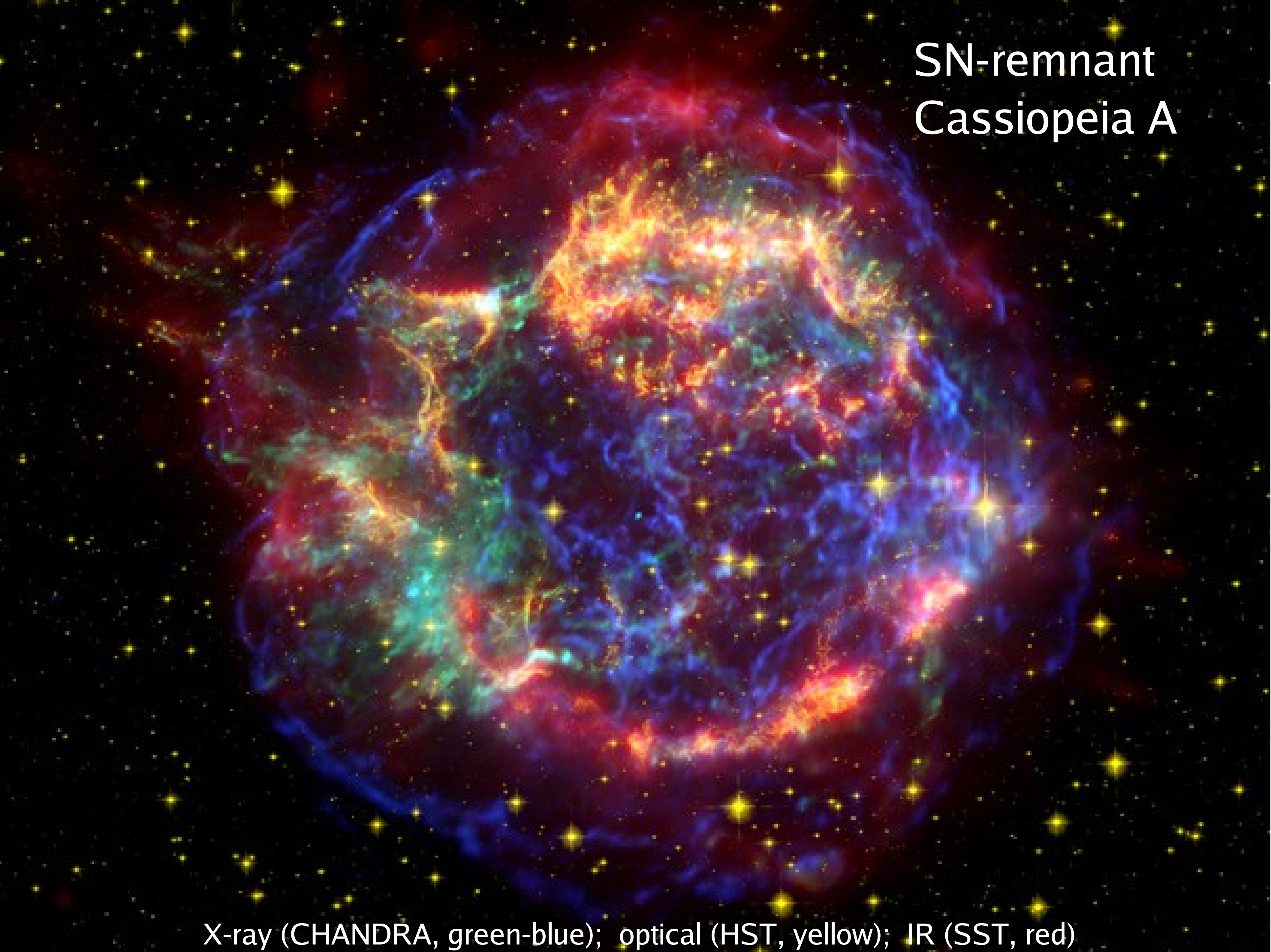
SN-remnant
Cassiopeia A



X-ray (CHANDRA, green-blue); optical (HST, yellow); IR (SST, red)

# Outline

- **Introduction:  The neutrino-driven explosion mechanism**
- **Status of self-consistent models in two dimensions**
- **The question of dimensions: How does 3D differ from 2D?**
- **Observational consequences of neutrino-driven explosions**

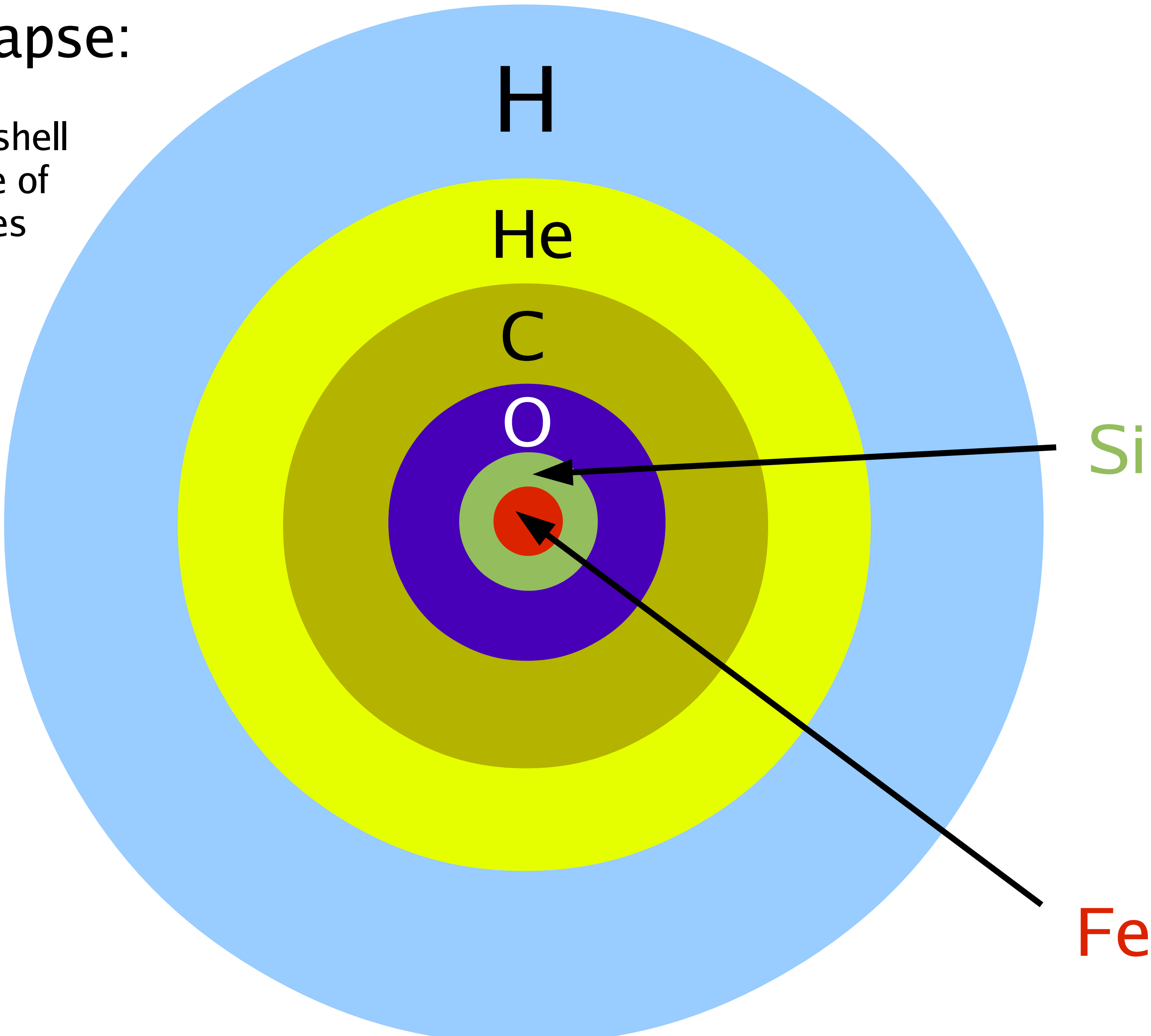
**Apologies to experts!**
This talk is a brief, general overview for a broad conference audience
but cannot account for individual contributions by all groups.

For more special and detailed presentations, see talks by
Irene Tamborra (Wed.) and Kei Kotake, Ernazar Abdikamalov (Thu.)

# Stellar Core Collapse and Explosion

# Evolved massive star prior to its collapse:

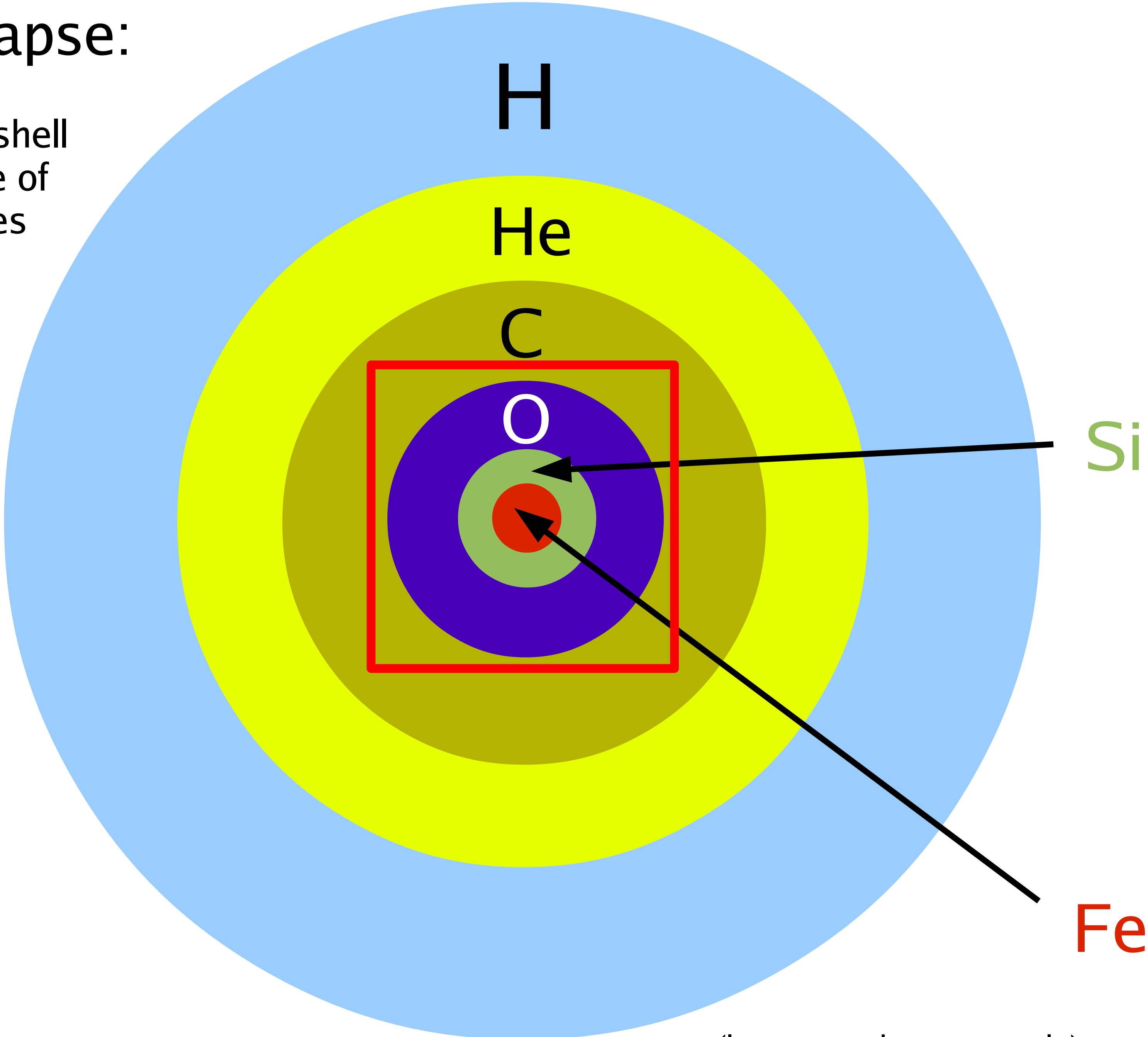
Star develops onion-shell structure in sequence of nuclear burning stages over millions of years




(layers not drawn to scale)

# Evolved massive star prior to its collapse:

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

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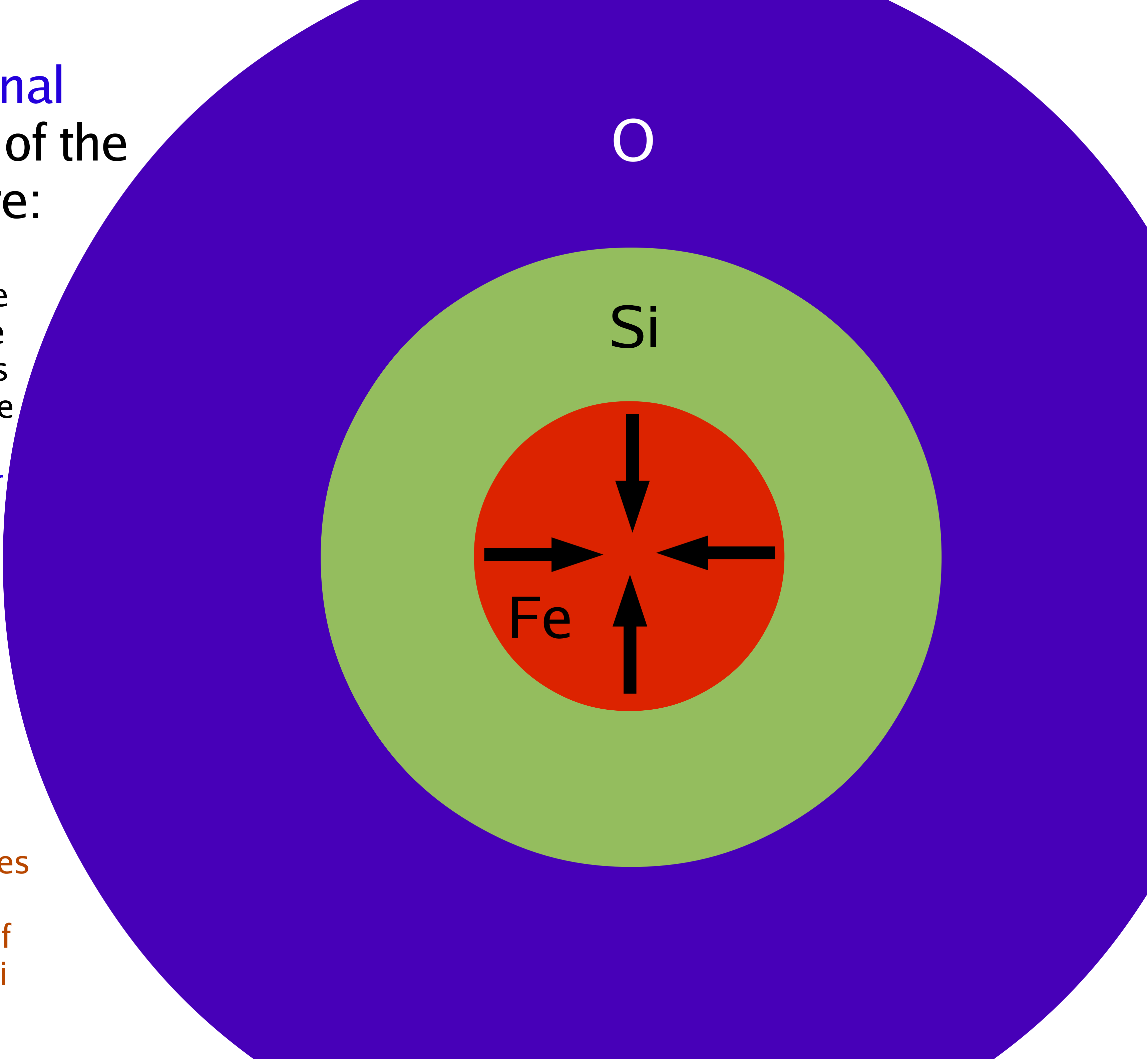
## Gravitational instability of the stellar core:

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

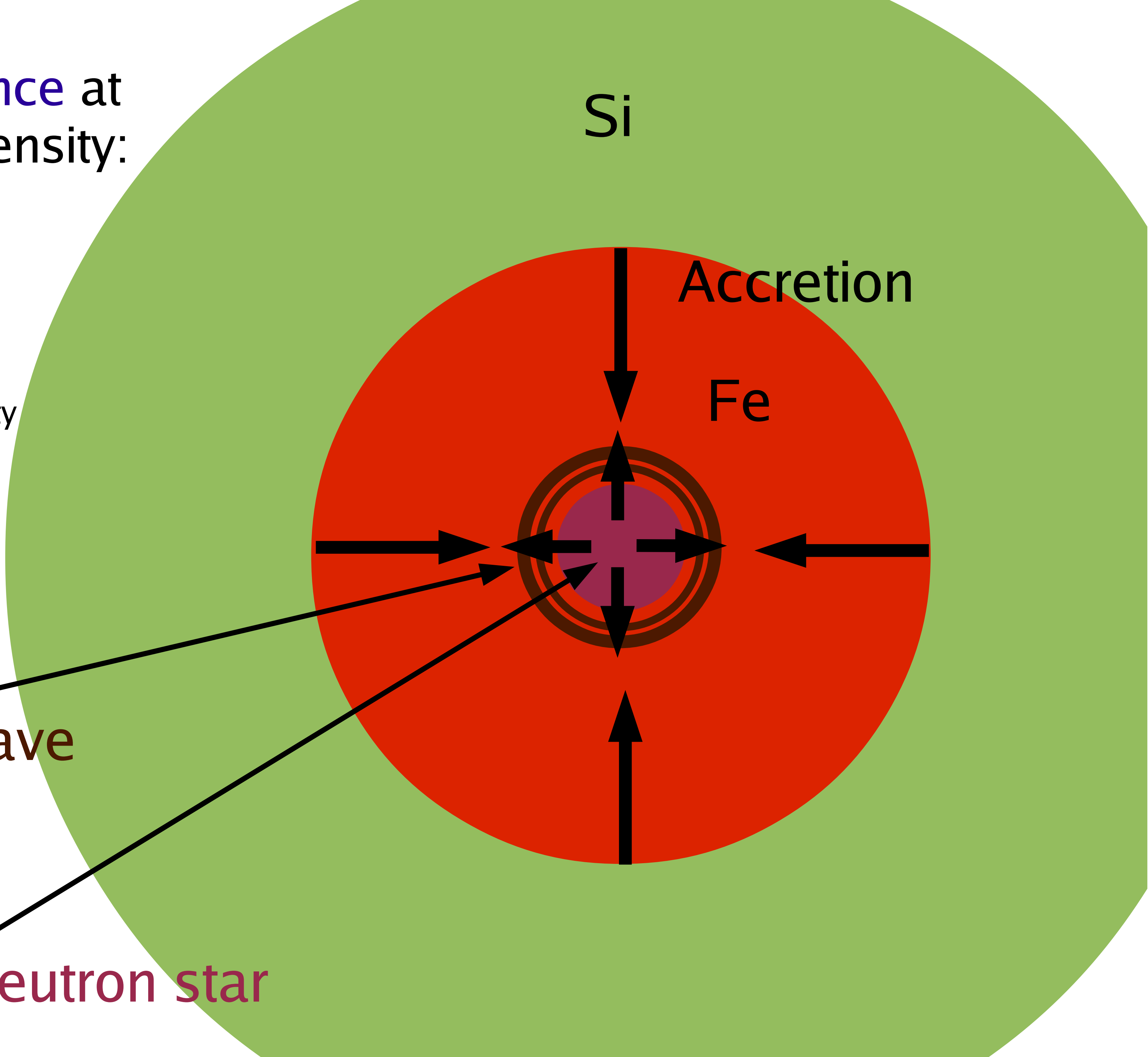
**Collapse** becomes dynamical because of electron captures and photo-disintegration of Fe-group nuclei



# Core bounce at nuclear density:

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

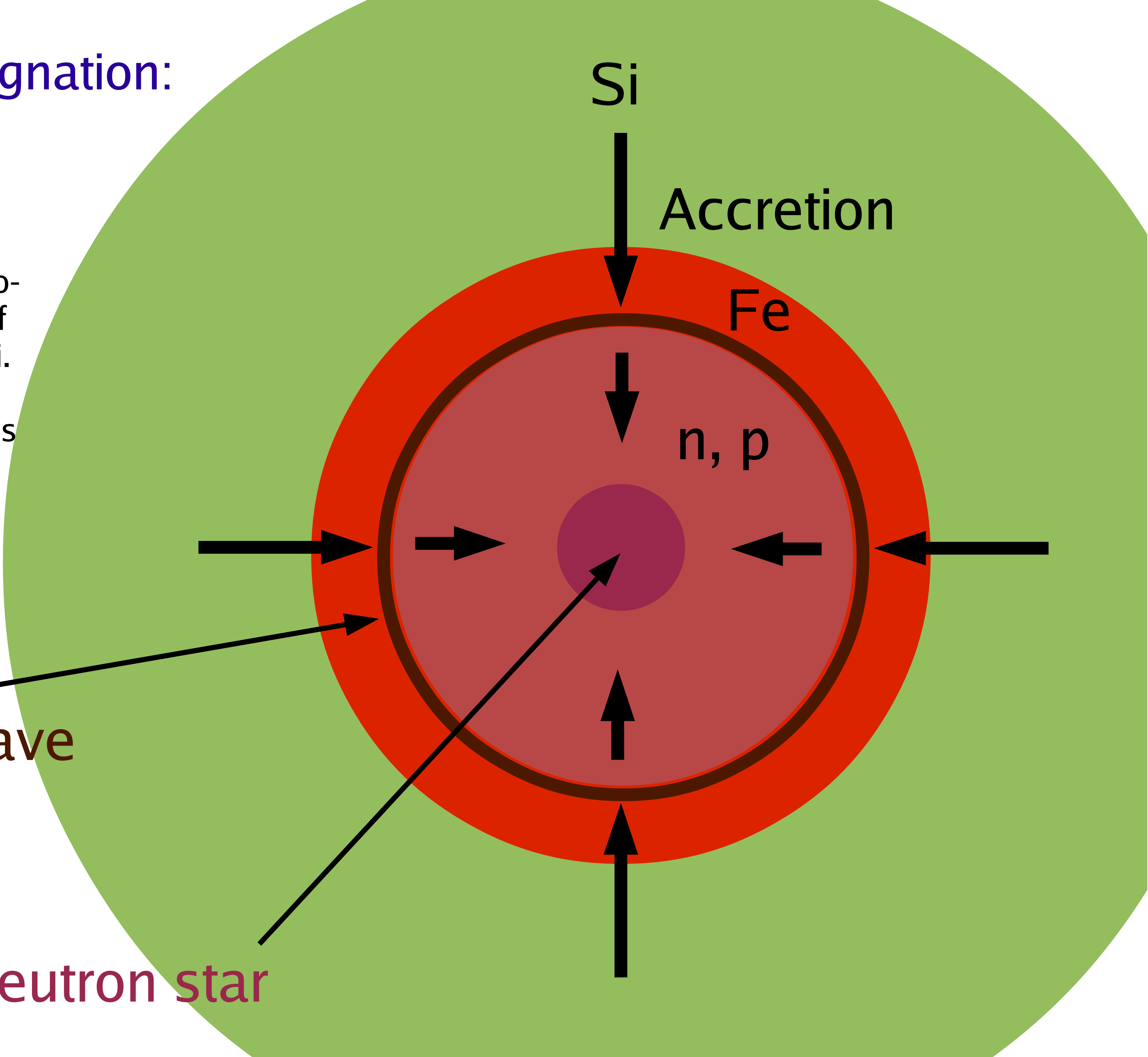
Shock wave forms



# Shock stagnation:

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

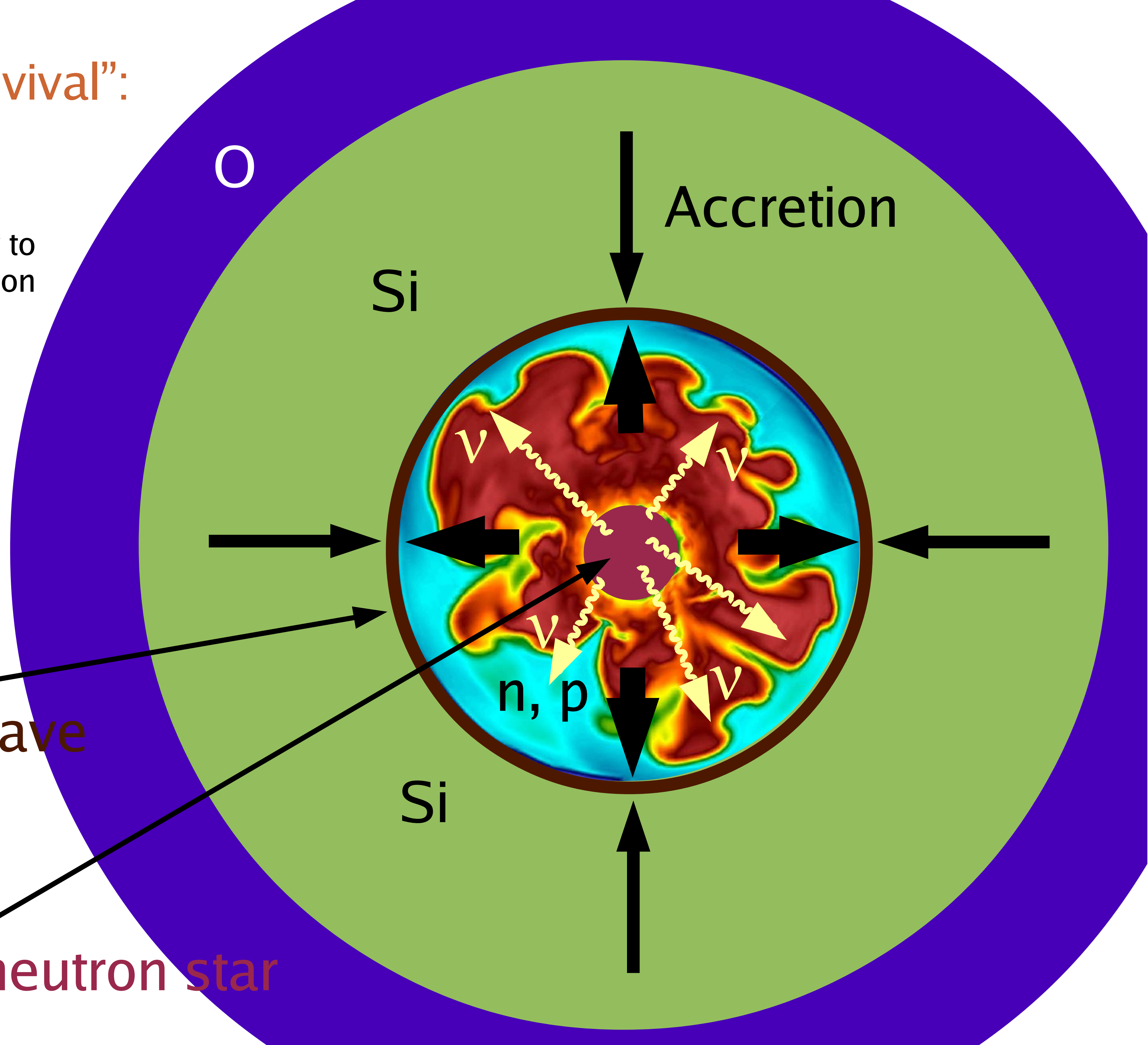
Shock stagnates still inside Fe-core



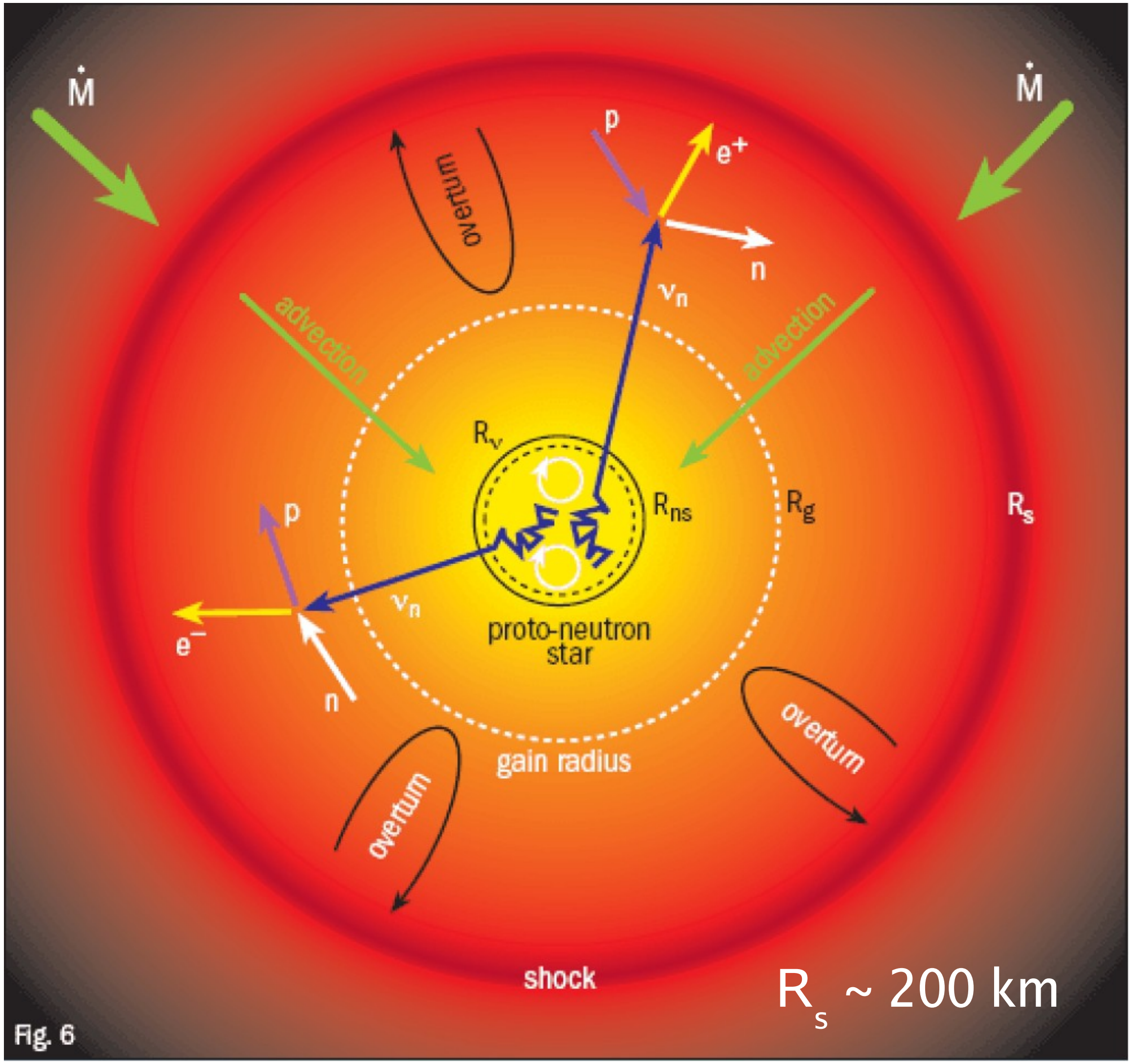
# Shock "revival":

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

Shock can receive fresh energy from neutrinos!



# Neutrinos & SN Explosion Mechanism



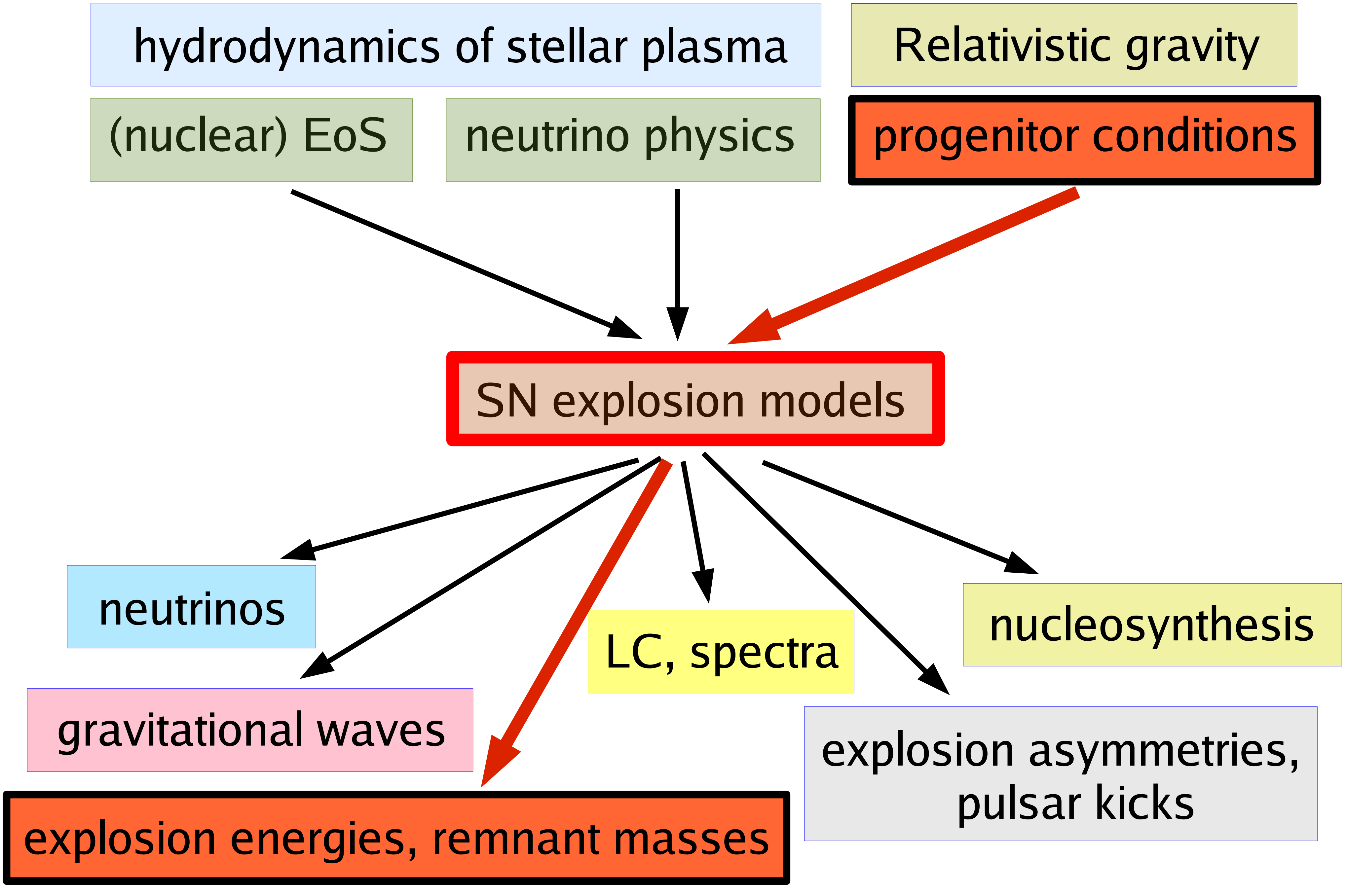

Paradigm: Explosions by the neutrino-heating mechanism, supported by hydrodynamic instabilities in the postshock layer

- "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).

**But: Is neutrino heating strong enough to initiate the explosion against the ram pressure of the collapsing stellar shells?**

Most sophisticated, self-consistent numerical simulations of the explosion mechanism in 2D and 3D are necessary!

# Predictions of Signals from SN Core



# General-Relativistic 2D Supernova Models of the Garching Group

(Müller B., PhD Thesis (2009); Müller et al., ApJS, (2010))

**GR hydrodynamics (CoCoNuT)**

$$\frac{\partial\sqrt{\gamma}\rho W}{\partial t}+\frac{\partial\sqrt{-g}\rho W\hat{v}^i}{\partial x^i} = 0, \quad (2.5)$$

$$\frac{\partial\sqrt{\gamma}\rho h W^2 v_j}{\partial t}+\frac{\partial\sqrt{-g}\left(\rho h W^2 v_j \hat{v}^i+\delta^i_j P\right)}{\partial x^i} = \frac{1}{2}\sqrt{-g}T^{\mu\nu}\frac{\partial g_{\mu\nu}}{\partial x^j}+\left(\frac{\partial\sqrt{\gamma}S_j}{\partial t}\right)_C, \quad (2.6)$$

$$\frac{\partial\sqrt{\gamma}\tau}{\partial t}+\frac{\partial\sqrt{-g}\left(\tau\hat{v}^i+Pv^i\right)}{\partial x^i} = \alpha\sqrt{-g}\left(T^{\mu 0}\frac{\partial\ln\alpha}{\partial x^\mu}-T^{\mu\nu}\Gamma^0_{\mu\nu}\right)+\left(\frac{\partial\sqrt{\gamma}\tau}{\partial t}\right)_C. \quad (2.7)$$

$$\frac{\partial\sqrt{\gamma}\rho W Y_e}{\partial t}+\frac{\partial\sqrt{-g}\rho W Y_e\hat{v}^i}{\partial x^i} = \left(\frac{\partial\sqrt{\gamma}\rho W Y_e}{\partial t}\right)_C, \quad (2.8)$$

$$\frac{\partial\sqrt{\gamma}\rho W X_k}{\partial t}+\frac{\partial\sqrt{-g}\rho W X_k\hat{v}^i}{\partial x^i} = 0. \quad (2.9)$$

**CFC metric equations**

$$\hat{\Delta}\Phi = -2\pi\phi^5\left(E+\frac{K_{ij}K^{ij}}{16\pi}\right), \quad (2.10)$$

$$\hat{\Delta}(\alpha\Phi) = 2\pi\alpha\phi^5\left(E+2S+\frac{7K_{ij}K^{ij}}{16\pi}\right), \quad (2.11)$$

$$\hat{\Delta}\beta^i = 16\pi\alpha\phi^4 S^i+2\phi^{10}K^{ij}\hat{\nabla}_j\left(\frac{\alpha}{\Phi^6}\right)-\frac{1}{3}\hat{\nabla}^i\hat{\nabla}_j\beta^j, \quad (2.12)$$

**Neutrino transport (VERTEX)**

$$\begin{aligned}
&\frac{\partial W\left(\hat{J}+v_r\hat{H}\right)}{\partial t}+\frac{\partial}{\partial r}\left[\left(W\frac{\alpha}{\phi^2}-\beta_r v_r\right)\hat{H}+\left(W v_r\frac{\alpha}{\phi^2}-\beta_r\right)\hat{J}\right]- \quad (2.28)\\
&\frac{\partial}{\partial\varepsilon}\left\{W\varepsilon\hat{J}\left[\frac{1}{r}\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)+2\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right]+\right.\\
&W\varepsilon\hat{H}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right)-\frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r}+\alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r}-\frac{\partial v_r}{\partial t}\right)\right]-\\
&\left.\varepsilon\hat{K}\left[\frac{\beta_r W}{r}-\frac{\partial\beta_r W}{\partial r}+W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right)+W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r}+v_r\frac{\partial v_r}{\partial t}\right)\right]\right\}-\\
&W\hat{J}\left[\frac{1}{r}\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)+2\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right]-\\
&W\hat{H}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right)-\frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r}+\alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r}-\frac{\partial v_r}{\partial t}\right)\right]+\\
&\hat{K}\left[\frac{\beta_r W}{r}-\frac{\partial\beta_r W}{\partial r}+W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right)+W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r}+v_r\frac{\partial v_r}{\partial t}\right)\right]=\alpha\hat{C}^{(0)},
\end{aligned}$$

$$\begin{aligned}
&\frac{\partial W\left(\hat{H}+v_r\hat{K}\right)}{\partial t}+\frac{\partial}{\partial r}\left[\left(W\frac{\alpha}{\phi^2}-\beta_r v_r\right)\hat{K}+\left(W v_r\frac{\alpha}{\phi^2}-\beta_r\right)\hat{H}\right]- \quad (2.29)\\
&\frac{\partial}{\partial\varepsilon}\left\{W\varepsilon\hat{H}\left[\frac{1}{r}\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)+2\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right]+\right.\\
&W\varepsilon\hat{K}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right)-\frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r}+\alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r}-\frac{\partial v_r}{\partial t}\right)\right]-\\
&\left.\varepsilon\hat{L}\left[\frac{\beta_r W}{r}-\frac{\partial\beta_r W}{\partial r}+W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right)+W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r}+v_r\frac{\partial v_r}{\partial t}\right)\right]\right\}+\\
&\left(\hat{J}-\hat{K}\right)\left[v_r\left(\frac{\beta_r}{r}-\frac{\partial\beta_r}{\partial r}\right)+\frac{\partial}{\partial r}\left(\frac{W\alpha}{\phi^2}\right)-\frac{W\alpha}{r\phi^2}+W^3\left(\frac{\partial v_r}{\partial t}-\beta_r\frac{\partial v_r}{\partial r}\right)\right]+\\
&\left(\hat{H}-\hat{L}\right)\left[\frac{W^3\alpha}{\phi^2}\frac{\partial v_r}{\partial r}+\frac{\beta W}{r}-\frac{\partial\beta W}{\partial r}-W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right)+\frac{\partial W}{\partial t}\right]-\\
&W\hat{H}\left[\frac{1}{r}\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)+2\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right]-\\
&W\hat{K}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right)-\frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r}+\alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r}-\frac{\partial v_r}{\partial t}\right)\right]+\\
&\hat{L}\left[\frac{\beta_r W}{r}-\frac{\partial\beta_r W}{\partial r}+W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right)+W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r}+v_r\frac{\partial v_r}{\partial t}\right)\right]=\alpha\hat{C}^{(1)}.
\end{aligned}$$

# 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:

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

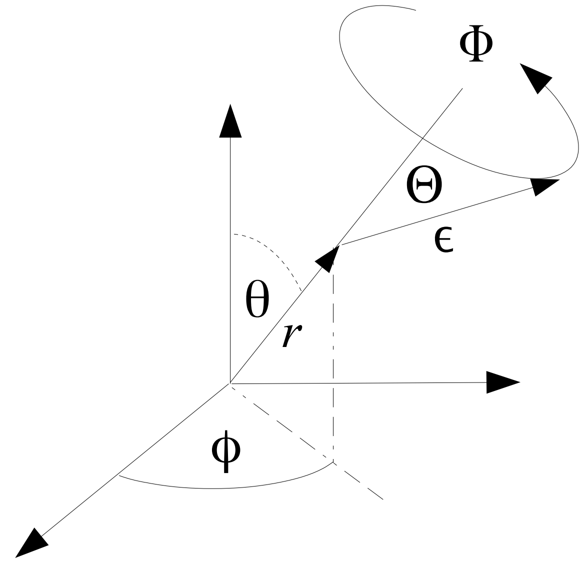
# The Curse and Challenge of the Dimensions

Boltzmann equation determines neutrino distribution function in 6D phase space and time

$$f\left(r,\theta,\phi,\Theta,\Phi,\epsilon,t\right)$$

Integration over 3D momentum space yields source terms for hydrodynamics

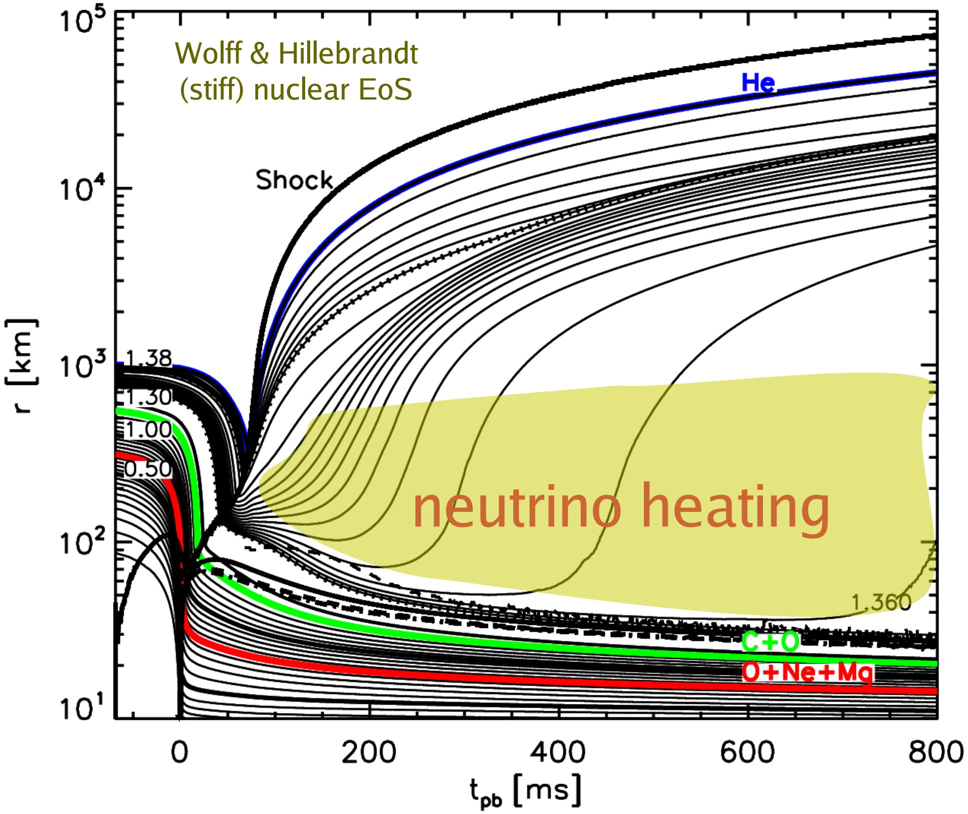
$$Q\left(r,\theta,\phi,t\right),\dot{Y}_e\left(r,\theta,\phi,t\right)$$




| **Solution approach** | **Required resources** |
|---|---|
| • **3D** hydro + **6D** direct discretization of Boltzmann Eq. (code development by Sumiyoshi & Yamada '12) | • ≥ 10–100 PFlops/s (sustained!) |
| • **3D** hydro + two-moment closure of Boltzmann Eq. (next feasible step to full 3D; O. Just et al. 2013) | • ≥ 1–10 Pflops/s, TBytes |
| • **3D** hydro + "**ray-by-ray-plus**" variable Eddington factor method (method used at MPA/Garching) | • ≥ 0.1–1 PFlops/s, Tbytes |
| • **2D** hydro + "**ray-by-ray-plus**" variable Eddington factor method (method used at MPA/Garching) | • ≥ 0.1–1 Tflops/s, < 1 TByte |

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

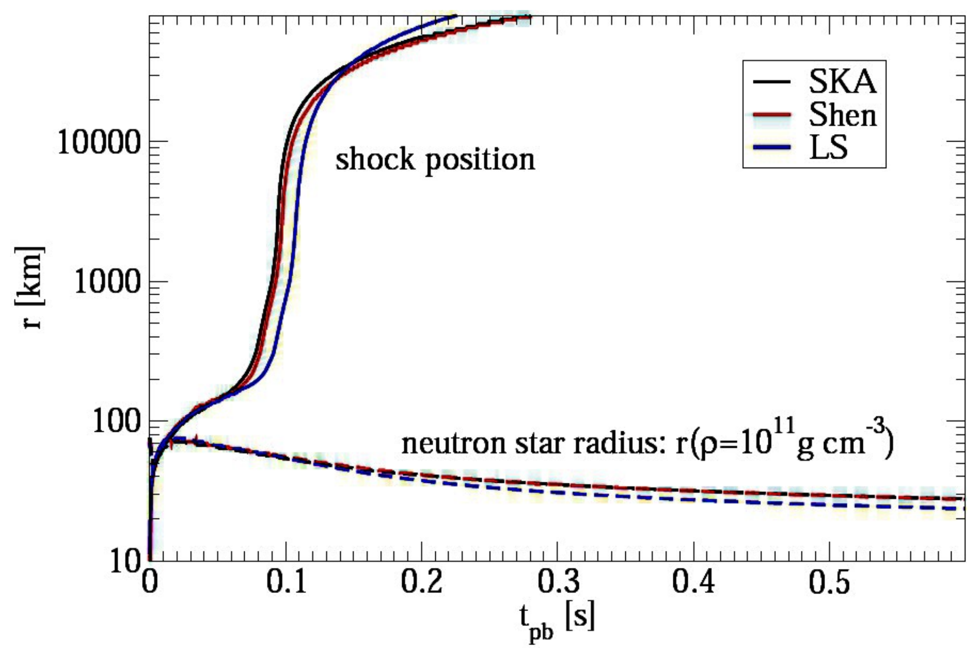
"Electron-capture supernovae"
or "ONeMg core supernovae"




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

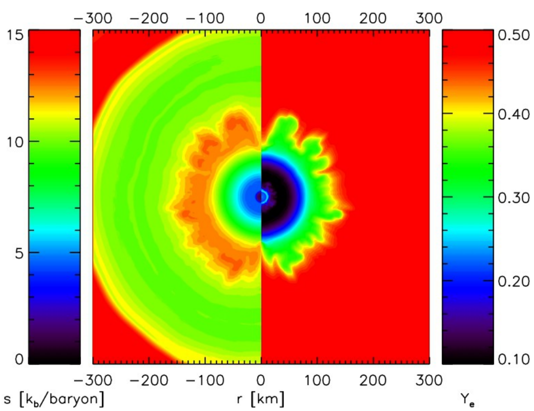
- No prompt explosion !
- Mass ejection by "neutrino-driven wind"
  (like Mayle & Wilson 1988
  and similar to AIC of WDs;
  see Woosley & Baron 1992, Fryer et al. 1999;
  Dessart et al. 2006)
- Explosion develops in similar way for soft nuclear EoS (i.e. compact PNS) and stiff EoS (less compact PNS)



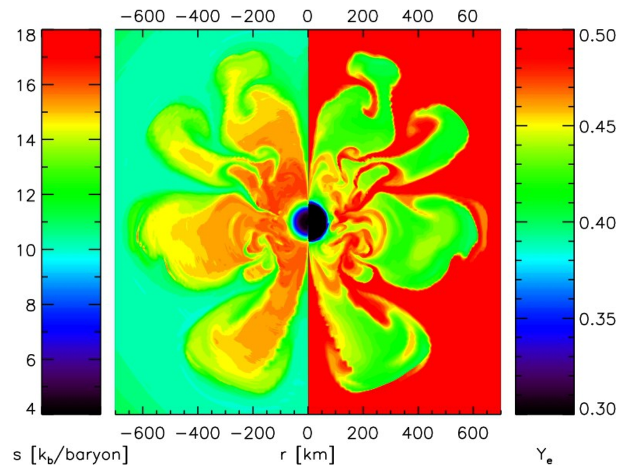
# 2D SN Simulations: $M_{star} \sim 8 \ldots 10\ M_{sun}$

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

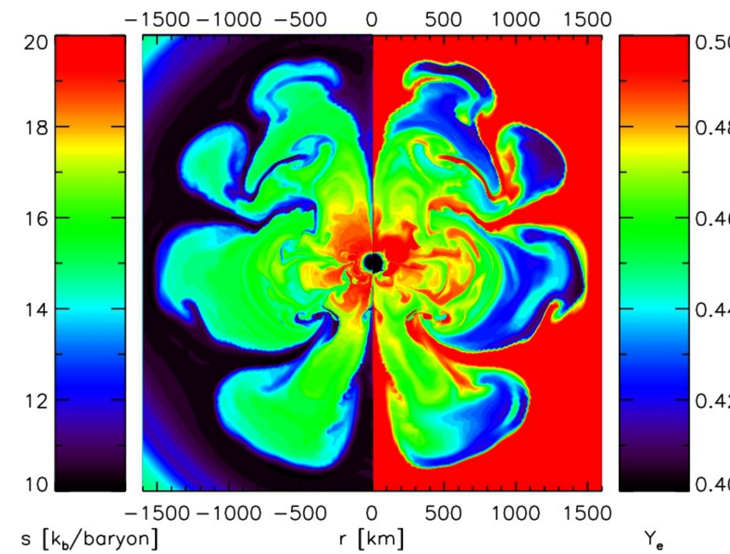
Entropy $Y_e$



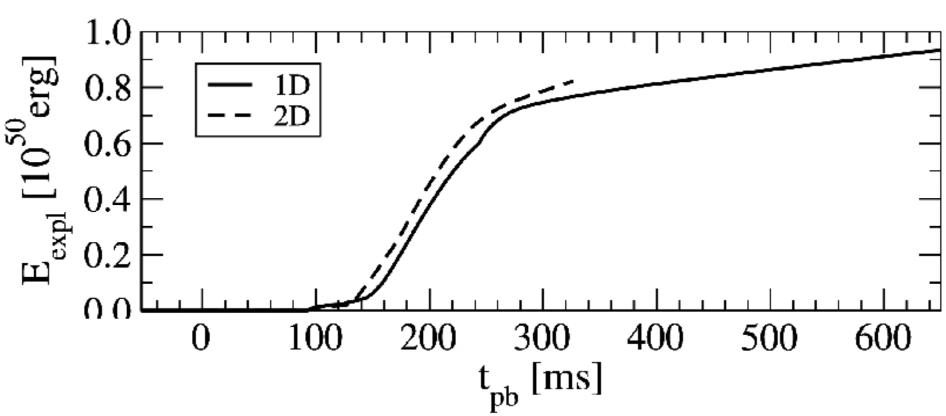

t = 0.097 s after core bounce

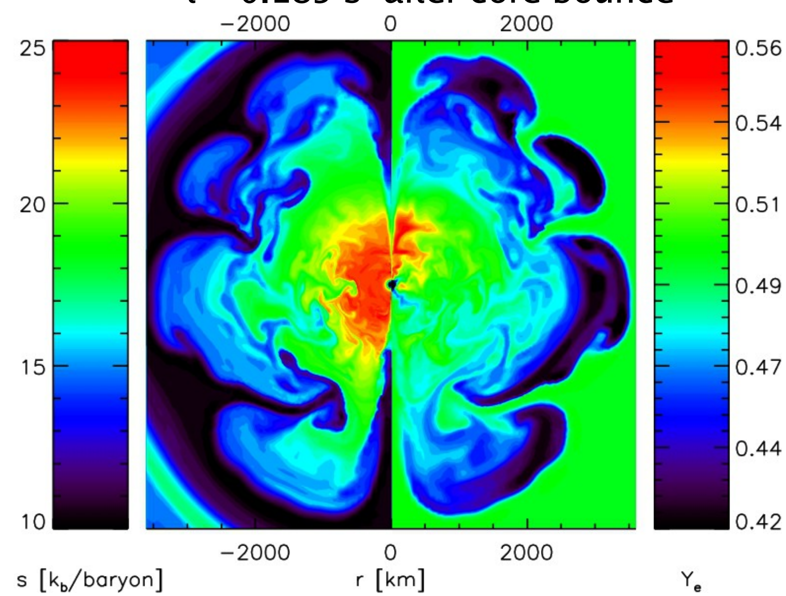



t = 0.144 s after core bounce




t = 0.185 s after core bounce

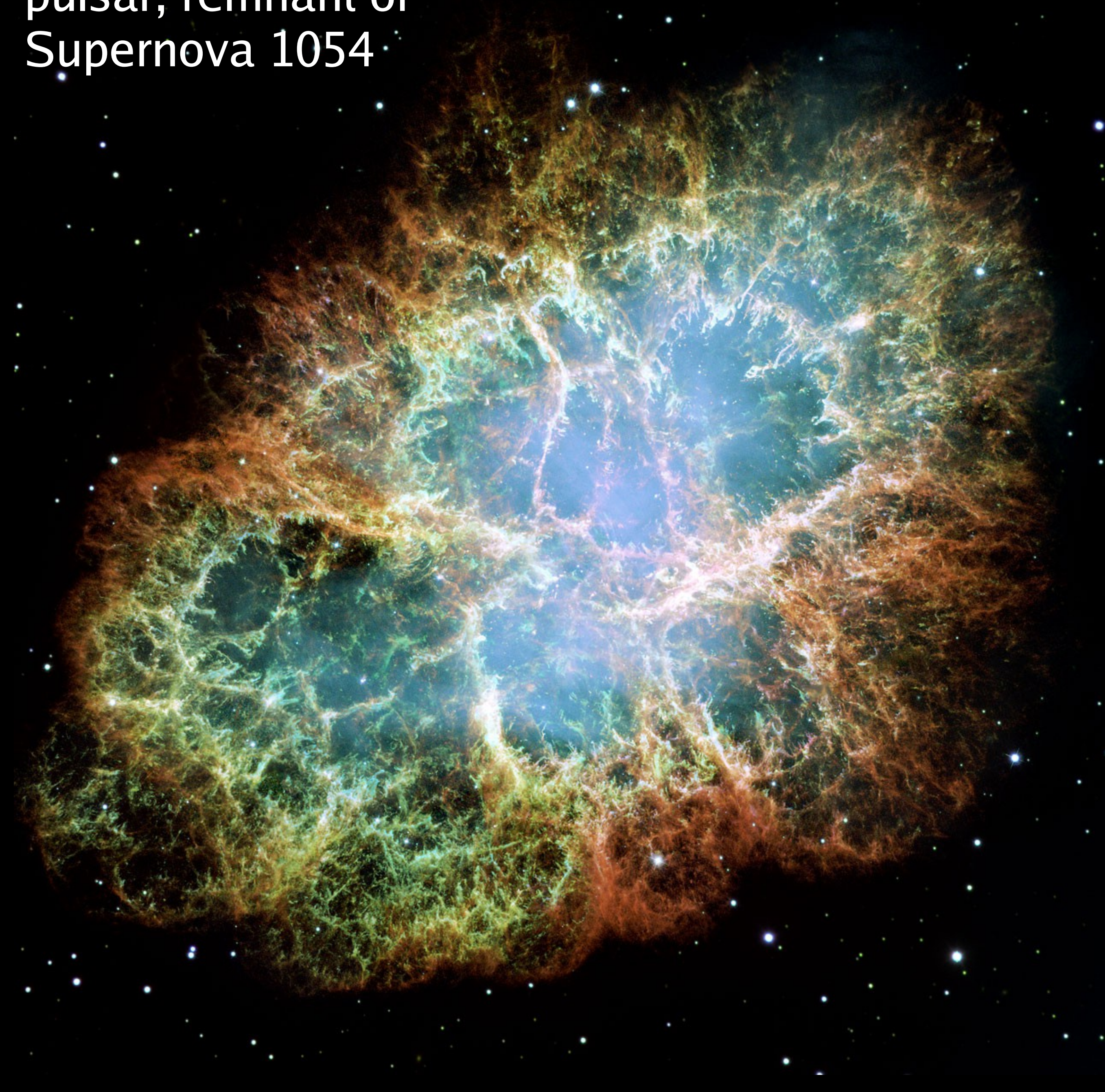



t = 0.262 s after core bounce

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

CRAB Nebula with pulsar, remnant of Supernova 1054



## Explosion properties:

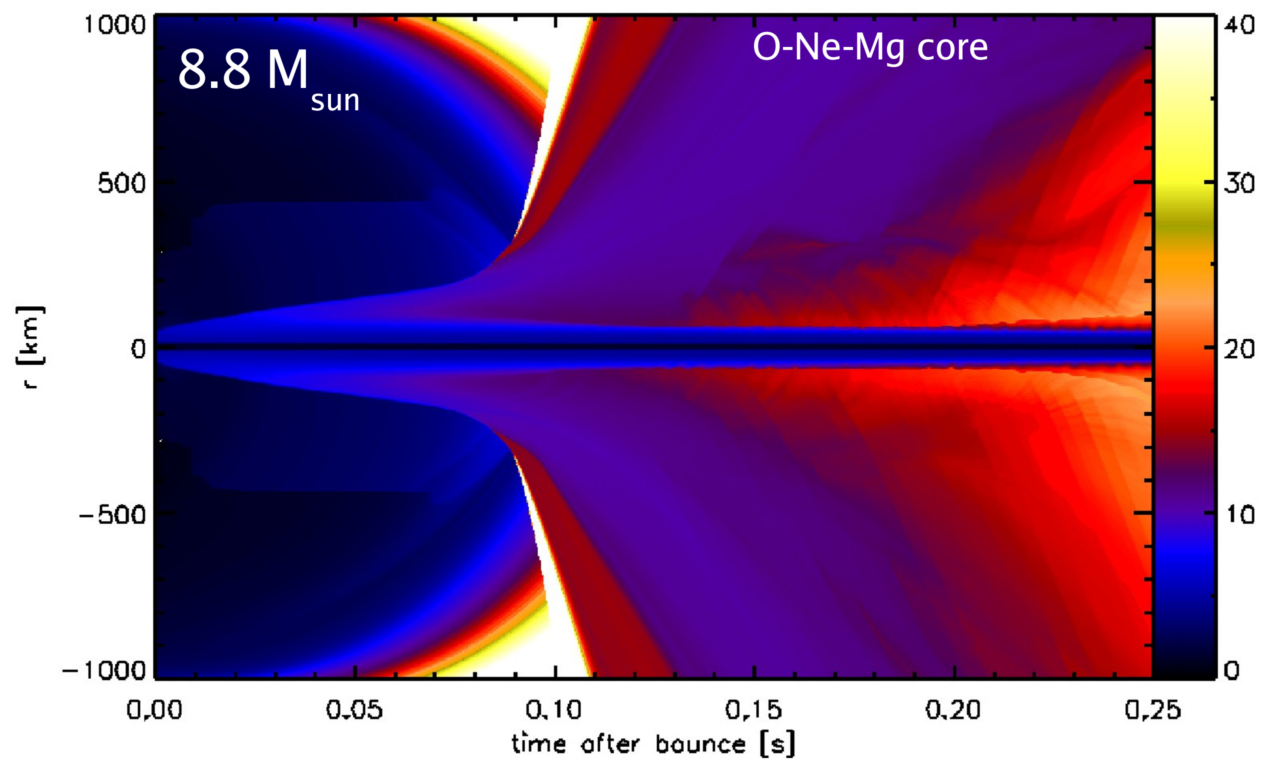
$E_{exp}$ ~ $10^{50}$ erg = 0.1 bethe
$M_{Ni}$ ~ 0.003 $M_{sun}$

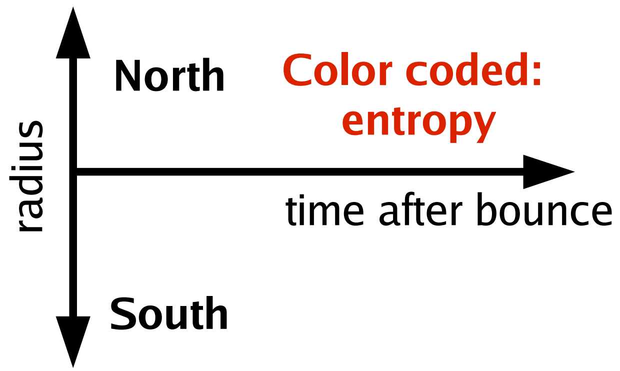
Low explosion energy and ejecta composition (little Ni, C, O) of ONeMg core explosion are compatible with CRAB (SN1054)

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

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

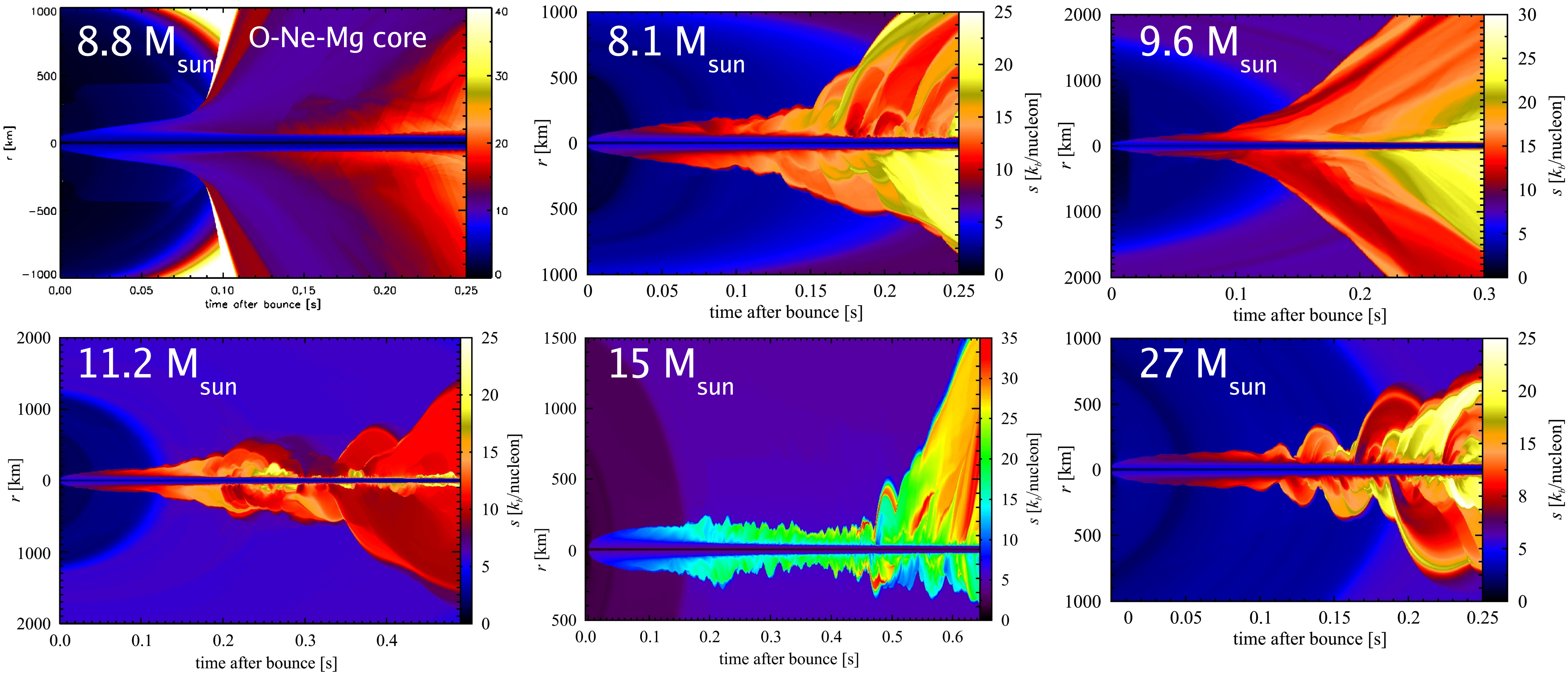
# 2D SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

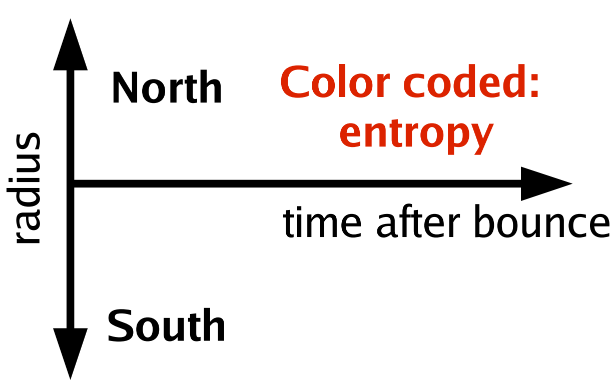


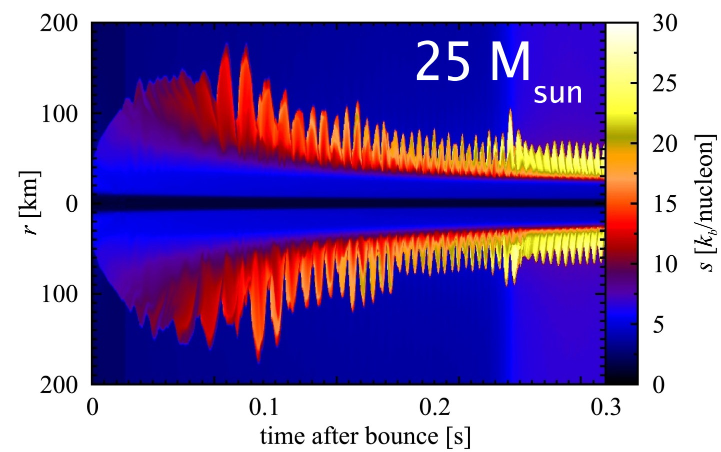




**Color coded: entropy**

# Relativistic 2D CCSN Explosion Models

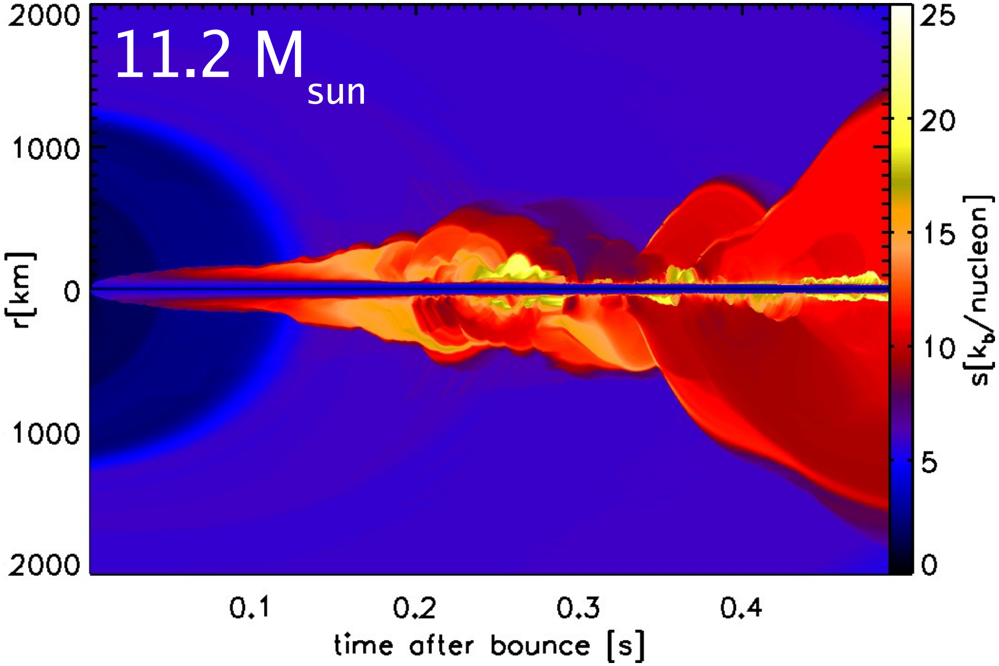


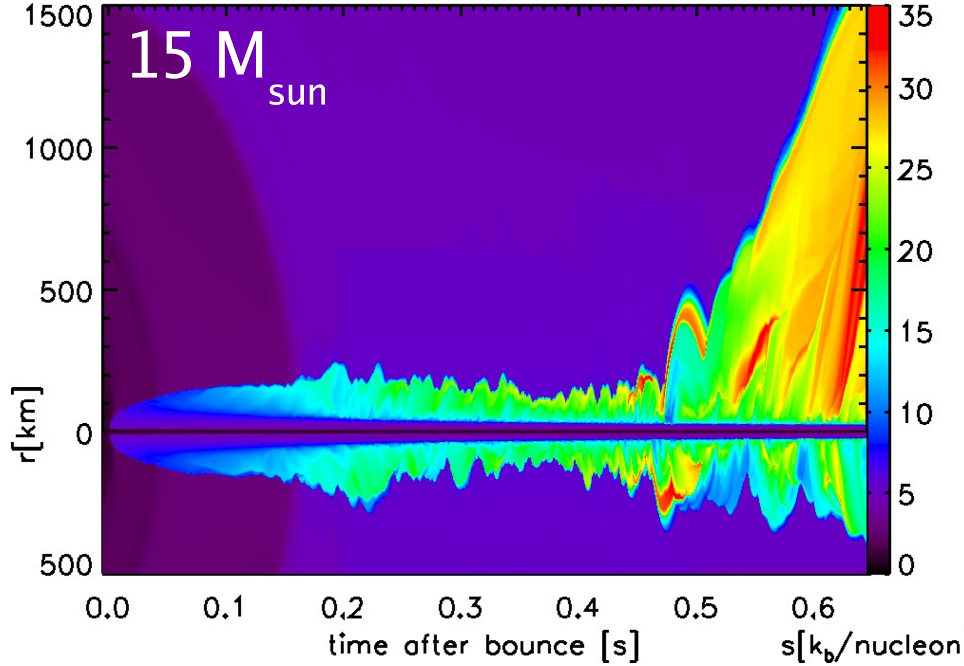




Bernhard Müller, THJ, et al. (ApJ 756, ApJ 761, arXiv:1210.6984

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



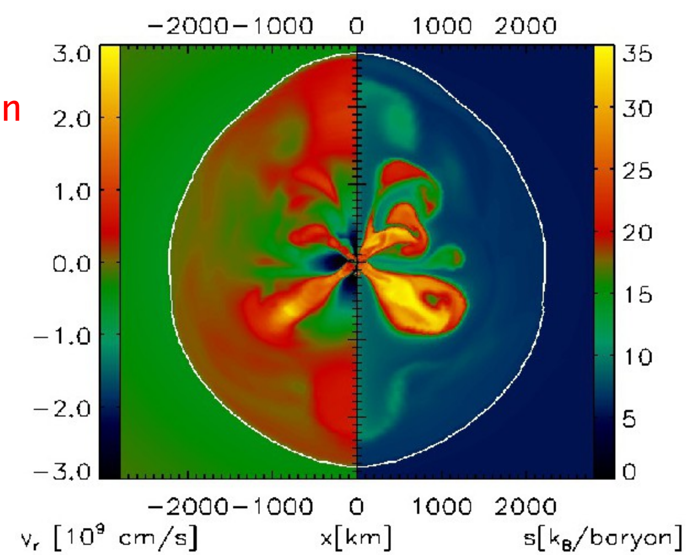




Violent, quasi-periodic, large-amplitude shock oscillations (by SASI) can lead to runaway and onset of explosion.

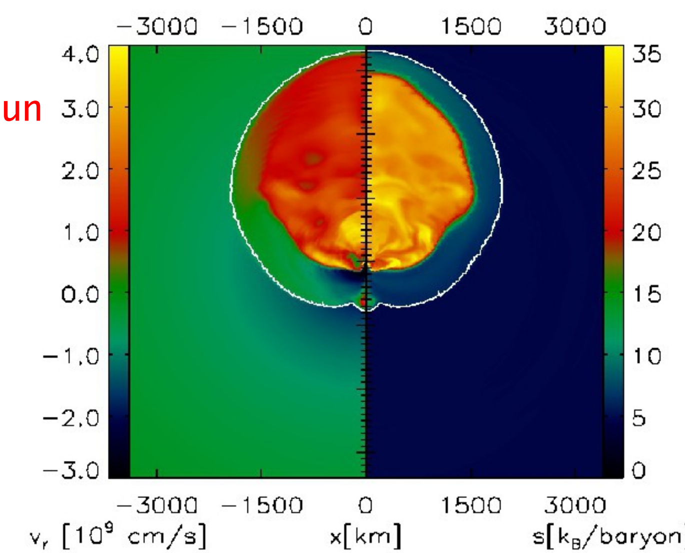
They also produce variations of neutrino emission and gravitational-wave signal.

(Müller, THJ, & Marek, ApJ 756 (2012) 84)

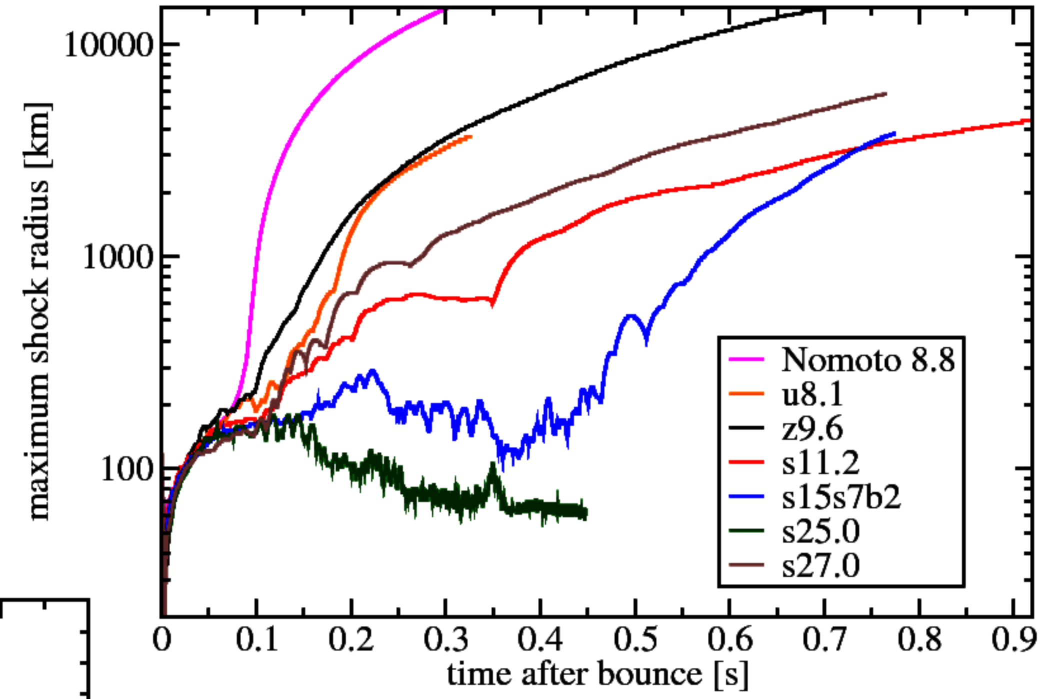
11.2 $M_{sun}$




15 $M_{sun}$

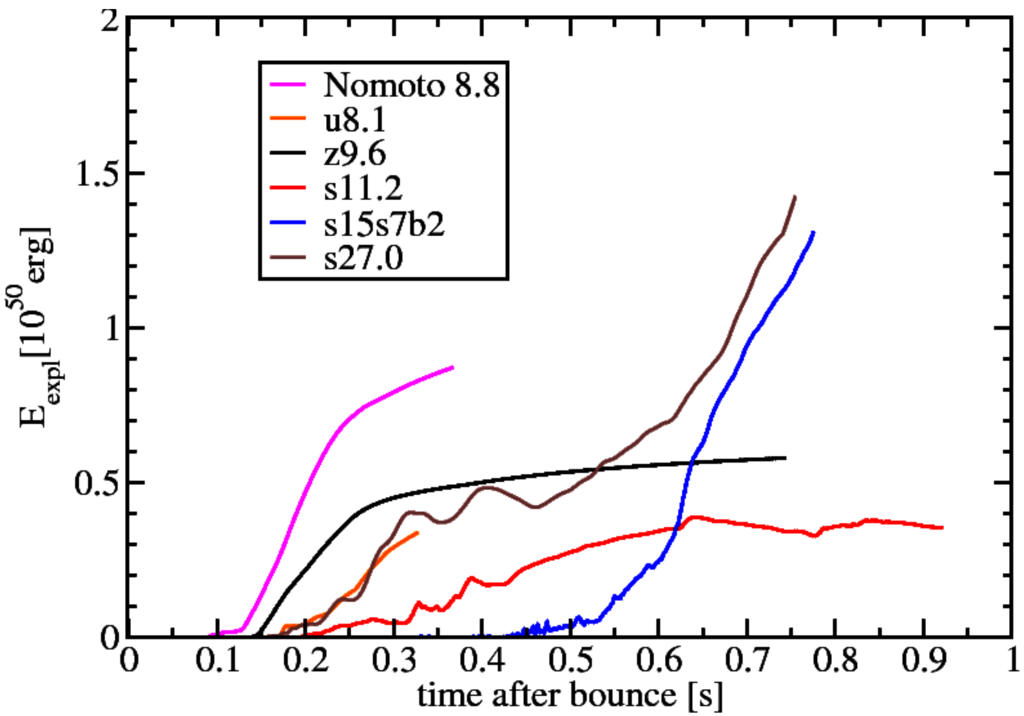


# Relativistic 2D CCSN Explosion Models




Maximum shock radius

"Diagnostic energy" of explosion



# 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)

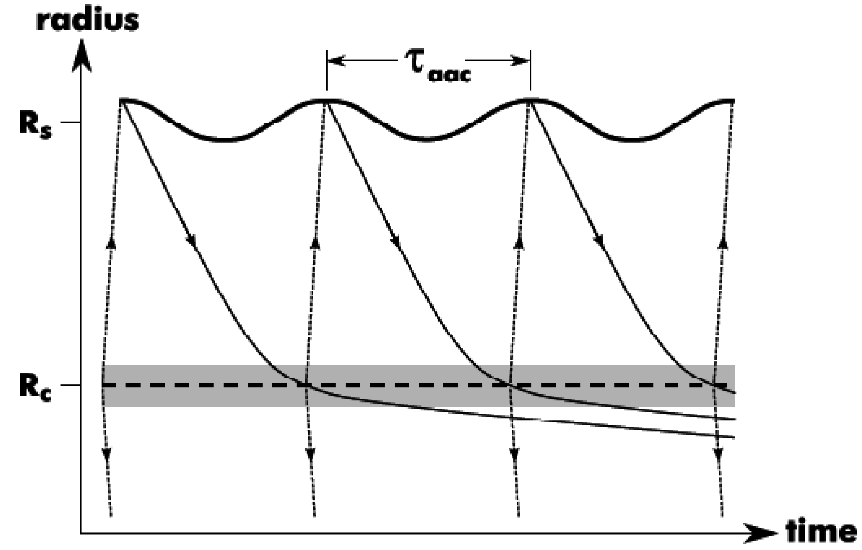
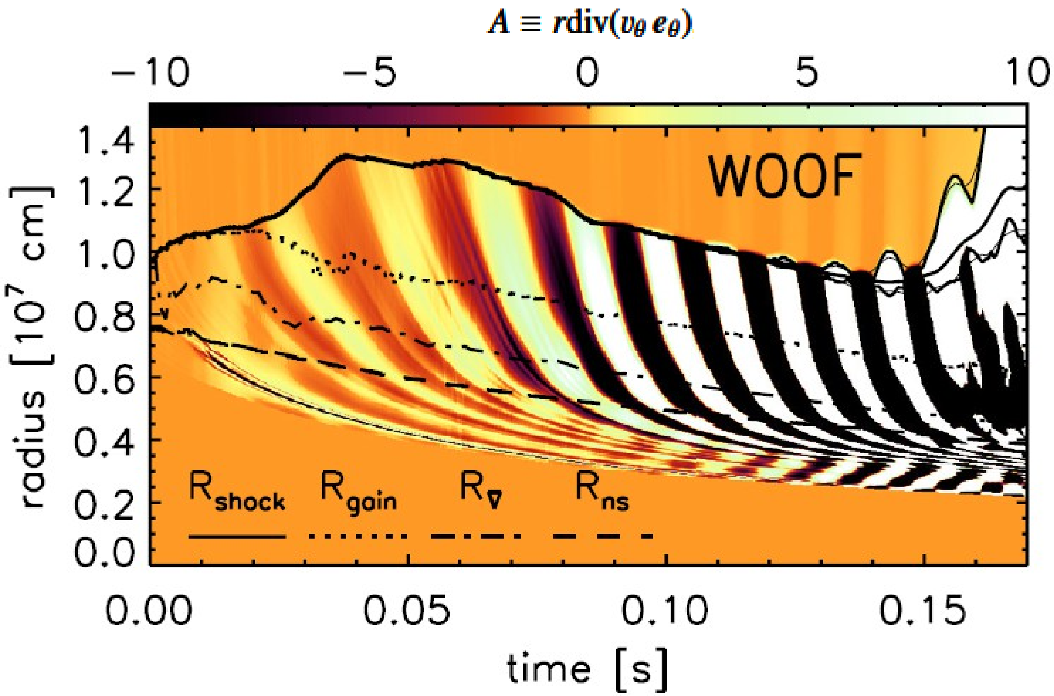



**Fig. 1.** Schematic view of the advective-acoustic cycle between the shock at $R_s$ (thick solid line) and the coupling radius, $R_c$ (thick dashed line), in the linear regime, shown for the case where the oscillation period of the shock ($\tau_{osc}$) equals the cycle duration, $\tau_{aac}$. Flow 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.

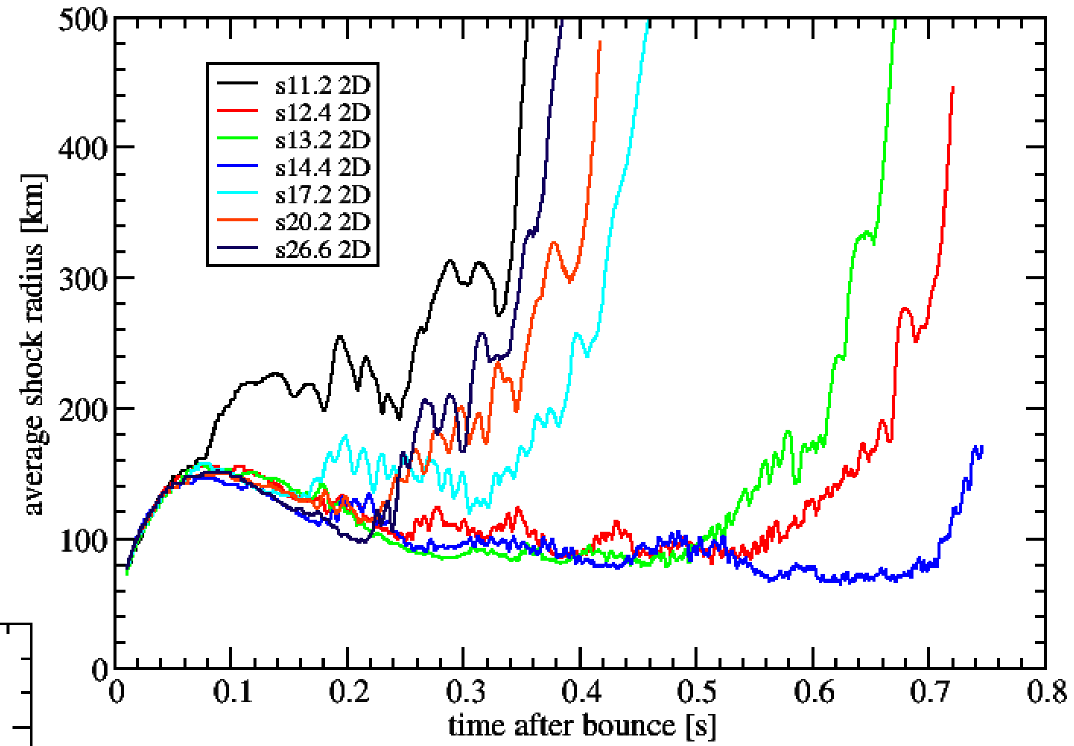



$$\tau_{aac}^{\nabla} \equiv \int_{R_\nabla}^{R_{sh}} \frac{dr}{|v|} + \int_{R_\nabla}^{R_{sh}} \frac{dr}{c - |v|}$$

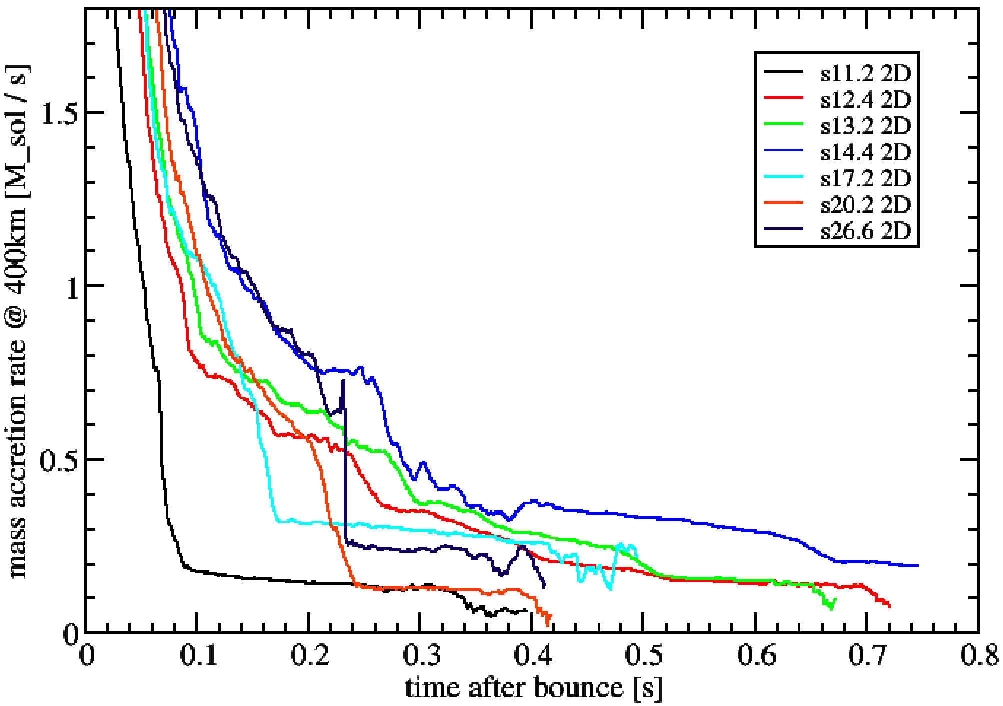
Scheck et al., A&A 447, 931 (2008)

# Growing set of 2D CCSN Explosion Models

**Florian Hanke**
**(PhD project)**




**Mass accretion rate**

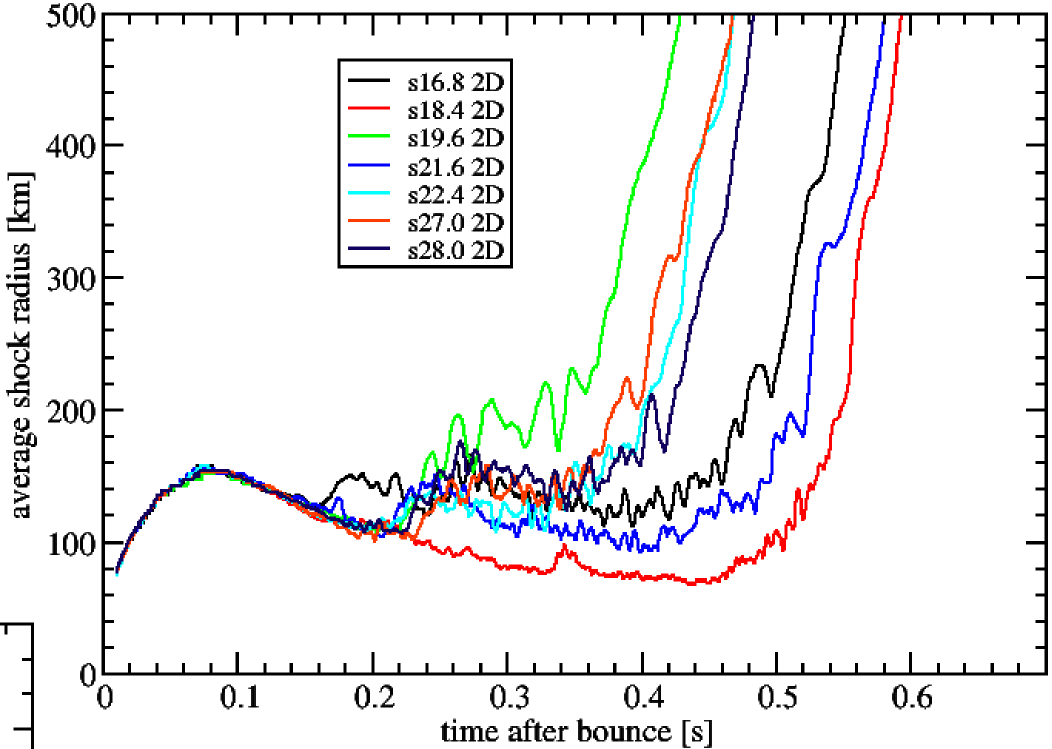



**Average shock radius**

**Progenitor models:**
**Woosley et al. RMP (2002)**

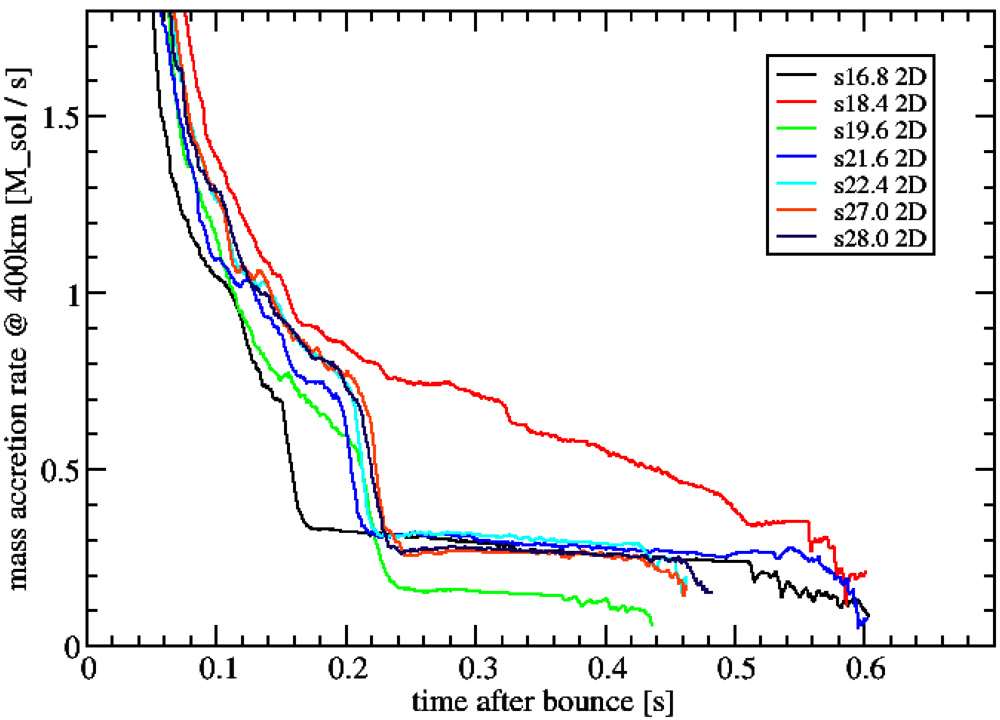
# Growing set of 2D CCSN Explosion Models

**Florian Hanke**
**(PhD project)**




**Average shock radius**

**Mass accretion rate**




**Progenitor models:**
**Woosley et al. RMP (2002)**

# 2D SN Explosion Models

- **Basic confirmation of the neutrino-driven mechanism**
- **Confirmation of reduction of the critical neutrino luminosity for explosions in self-consistent 2D treatments compared to 1D**

Explosions in 2D simulations were also obtained recently by Suwa et al. (2010, 2012), Takiwaki et al. (2013) [—> K. Kotake's talk on Thursday afternoon] and Bruenn et al. (ApJL, 2013) Important quantitative differences between all models.

Many numerical aspects, in particular also neutrino transport treatment, are different; code comparisons are needed!

# Challenge and Goal:  3D

- 2D explosions seem to be “marginal”, at least for some progenitor models and in some of the most sophisticated simulations.
- Nature is three dimensional, but 2D models impose the constraint of axisymmetry (—> toroidal structures).
- Turbulent cascade in 3D transports energy from large to small scales, which is opposite to 2D.
- Does SASI also occur in 3D?
- 3D models are needed to confirm explosion mechanism suggested by 2D simulations!

# Computing Requirements for 2D & 3D Supernova Modeling

**Time-dependent simulations: t ~ 1 second, ~ $10^6$ time steps!**

CPU-time requirements for one model run:

- **In 2D with 600 radial zones, 1 degree lateral resolution:**

  **~ $3*10^{18}$ Flops, need ~$10^6$ processor-core hours.**

- **In 3D with 600 radial zones, 1.5 degrees angular resolution:**

  **~ $3*10^{20}$ Flops, need ~$10^8$ processor-core hours.**

PRACE Partnership for Advanced Computing in Europe

NIC

John von Neumann Institut für Computing

HLRS

rzg IPP Rechen-Zentrum Garching

Leibniz-Rechenzentrum der Bayerischen Akademie der Wissenschaften

# 3D Supernova Simulations

**EU PRACE and GAUSS Centre grants of ~360 million core hours allow us to do the first 3D simulations on 16.000 cores.**

PRACE — Partnership for Advanced Computing in Europe

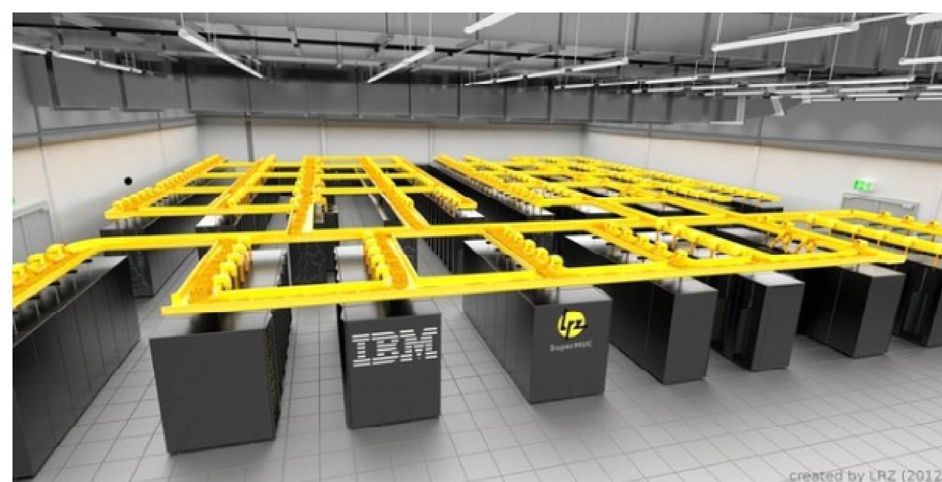
GCS — Gauss Centre for Supercomputing

DE LA RECHERCHE À L'INDUSTRIE cea — HPC CALCUL HAUTES PERFORMANCES — TGCC

Leibniz-Rechenzentrum der Bayerischen Akademie der Wissenschaften

TGCC Curie

SuperMUC Petascale System

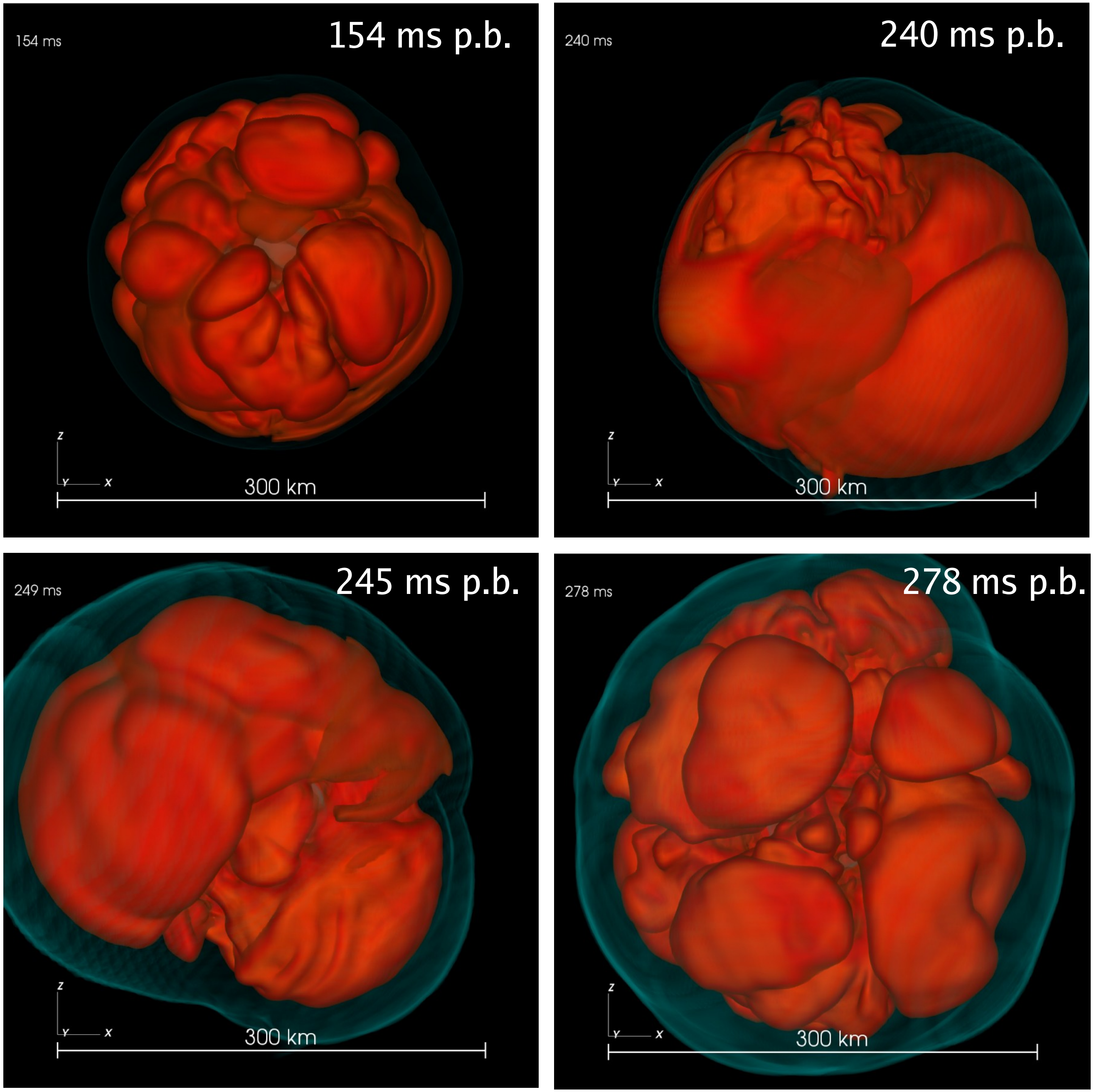


# 3D Core-Collapse Models

**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., arXiv:1303.6269

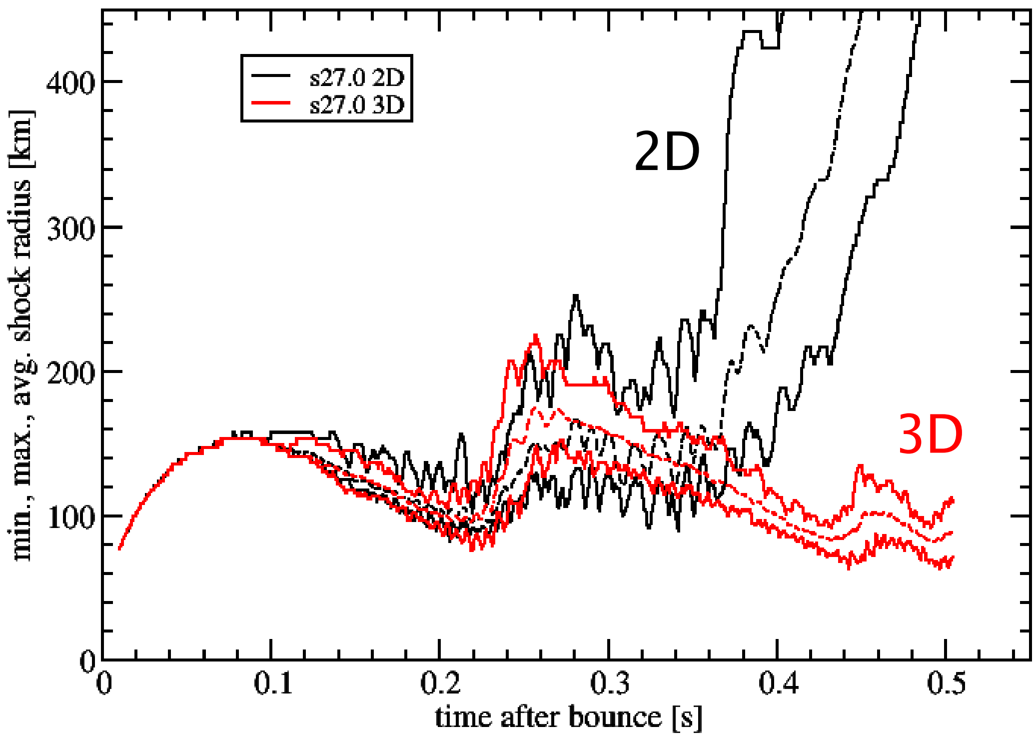


# 3D Explosions ?

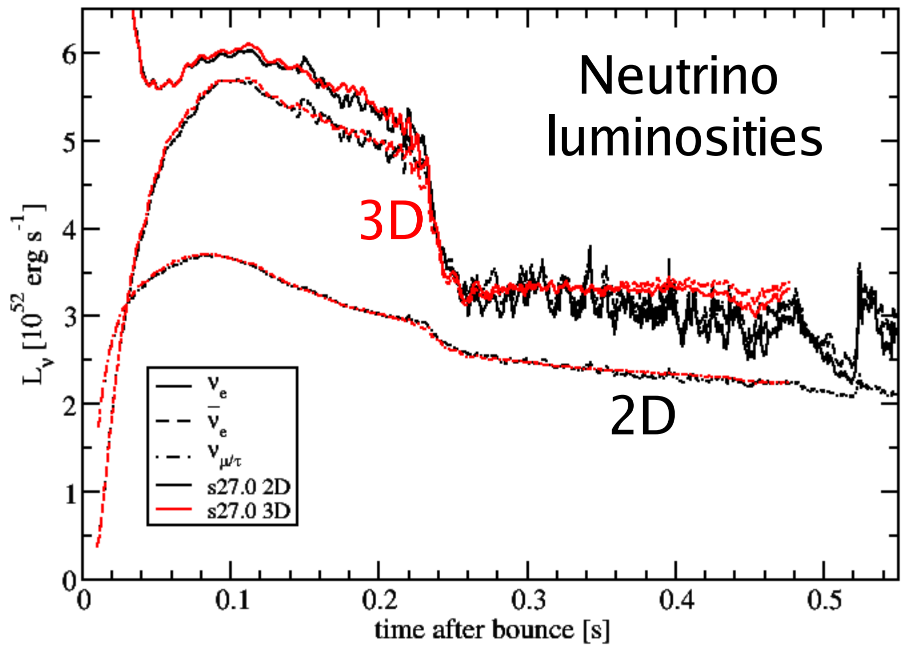
# 3D Core-Collapse Models

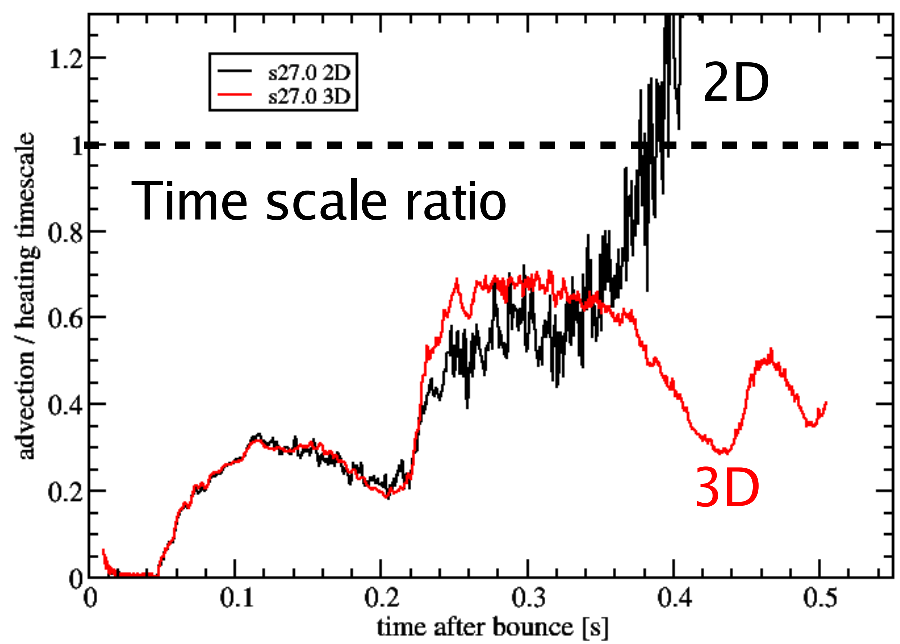
**27 $M_{sun}$ progenitor**
**(WHW 2002)**

Shock position (max., min., avg.)




Florian Hanke, PhD project



# Summary I

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

- Considerable quantitative differences compared to Bruenn et al. (arXiv:1212.1747) demand detailed comparison.

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

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

- Progenitors are 1D, but shell structure and initial asymmetries may depend on 3D effects! How important is slow rotation for SASI growth?

- Missing physics ?????

# Some Observable Consequences of Neutrino-driven Explosions

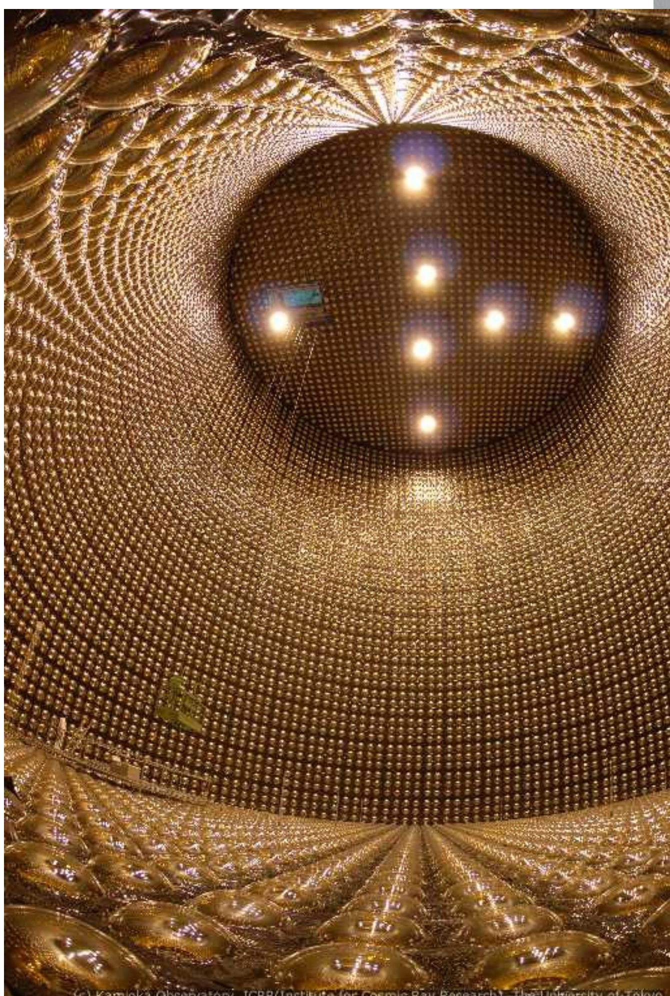
# Observational consequences and indirect evidence for neutrino heating and hydrodynamic instabilities at the onset of stellar explosions:

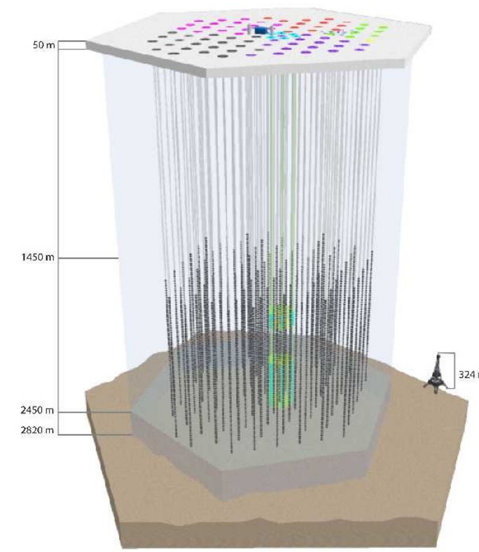
- Neutrino signals (characteristic modulations)
  (Marek et al. 2009; Müller E. et al. 2012; Lund et al. 2010, 2012; Tamborra et al. 2013)
- Gravitational-wave signals
  (Marek et al. 2009; Müller E. et al. 2012; Müller B. et al. 2012)
- Neutron star kicks (Scheck et al. 2004, 2006; Wongwathanat et al. 2010, 2012)
- Asymmetric mass ejection & large-scale radial mixing
  (Kifonidis et al. 2005, Hammer er al. 2010, Wongwathanat et al., in prep.)
- Progenitor – explosion – remnant connection (Ugliano et al. 2012)

- Lightcurve shape, spectral features (electromagnetic emission)
- Nucleosynthesis (e.g., Pruet et al. 2006, Wanajo et al. 2011,2013)

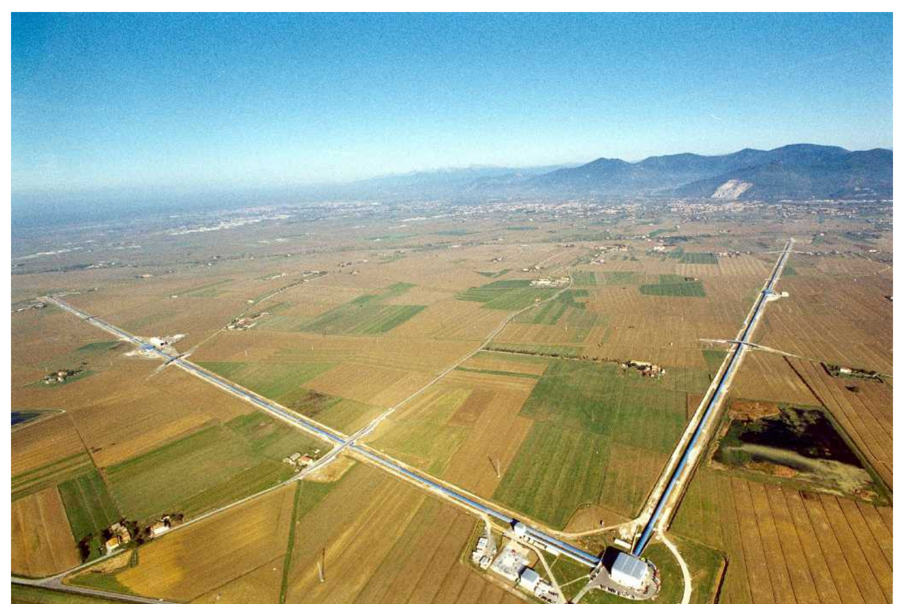
# Detecting Core-Collapse SN Signals

Superkamiokande




IceCube

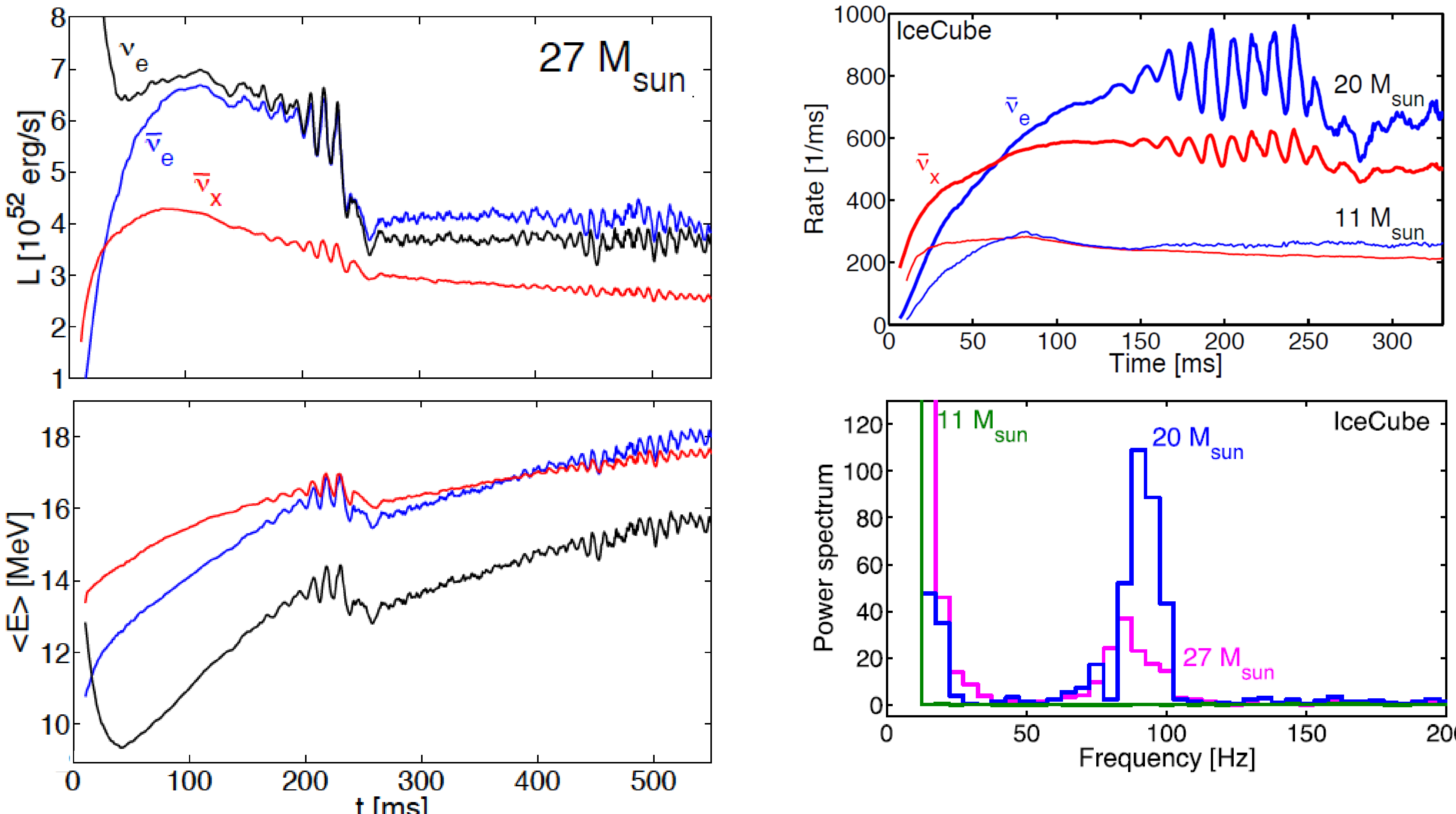


VIRGO

# 3D Core-Collapse Models: Neutrino Signals

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

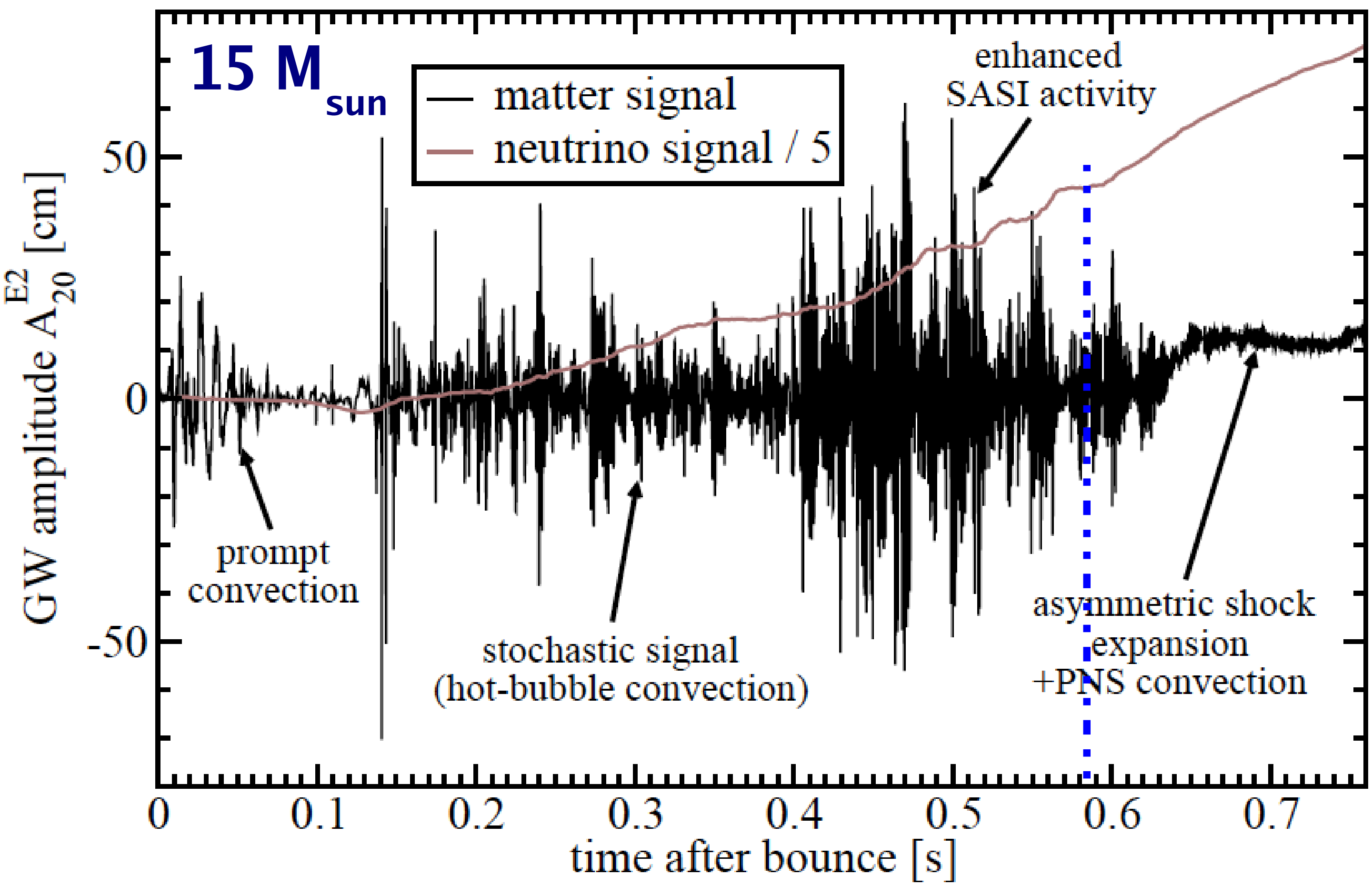
SASI produces modulations of neutrino emission and gravitational-wave signal.




(Tamborra et al., PRL, in press; arXiv:1307.7936)

—> I. Tamborra's talk in the afternoon!

# Gravitational Waves for 2D SN Explosions



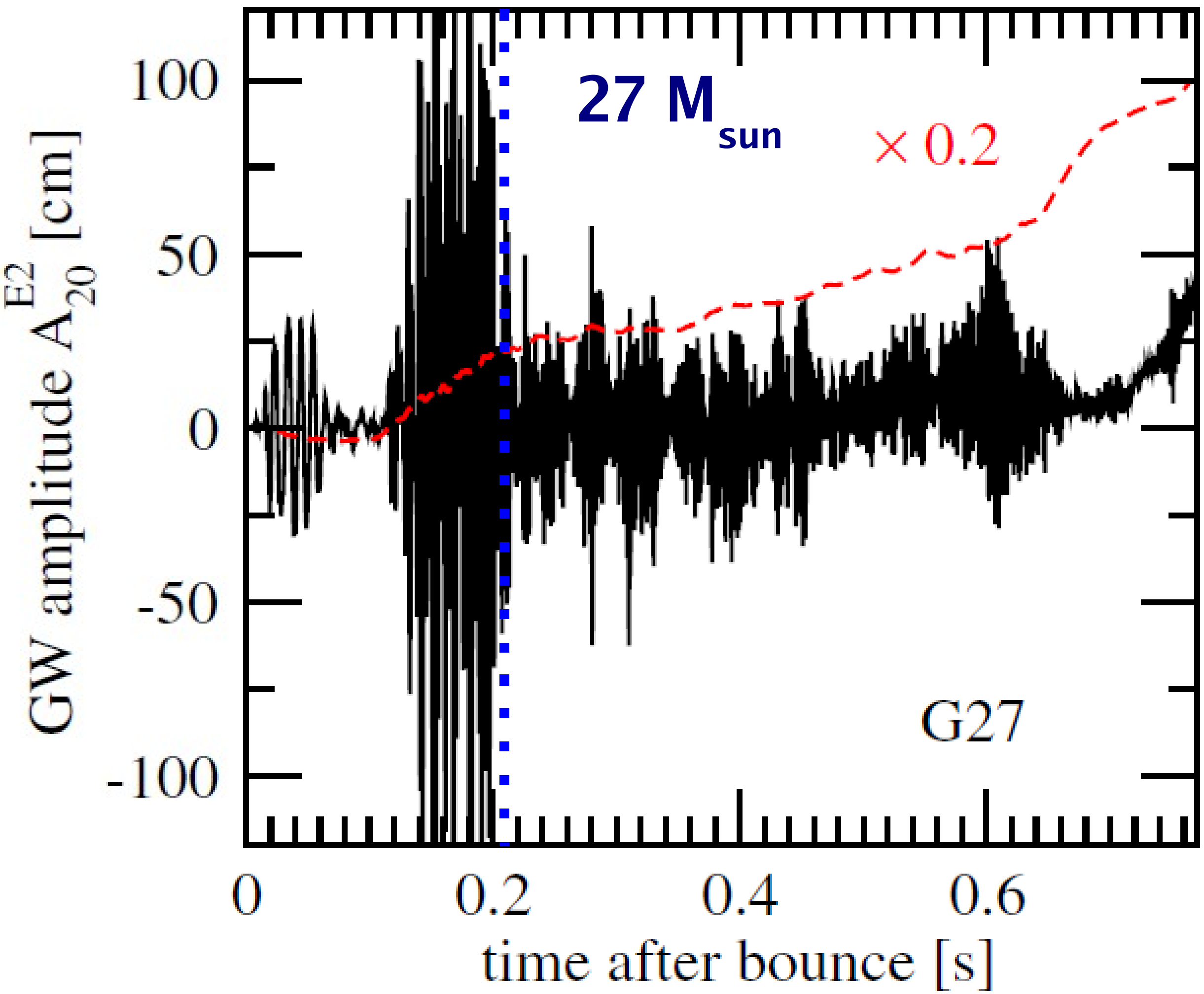

(Müller, THJ, & Marek, ApJ 766 (2013) 43)

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

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

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

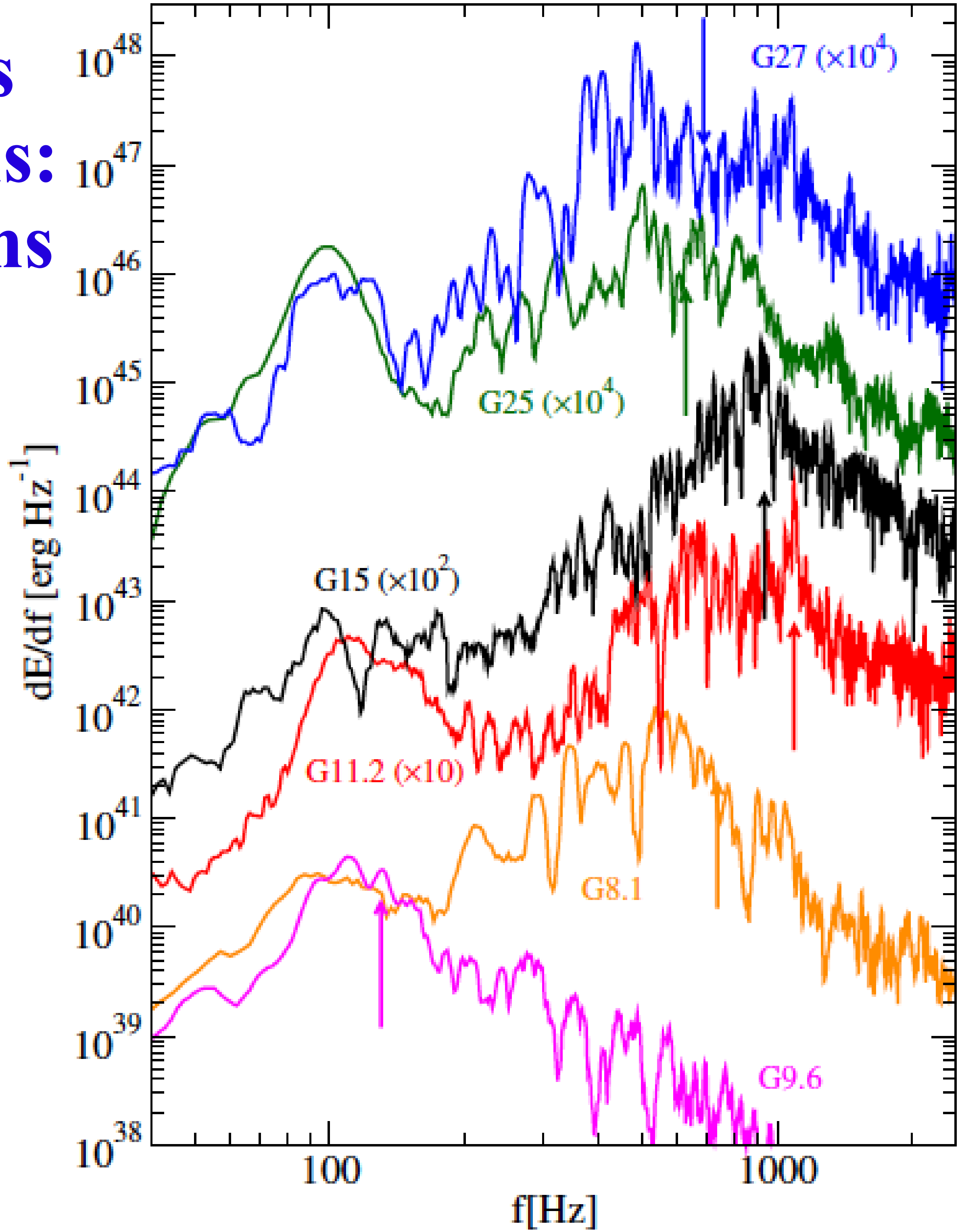
# Gravitational Waves for 2D SN Explosions




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

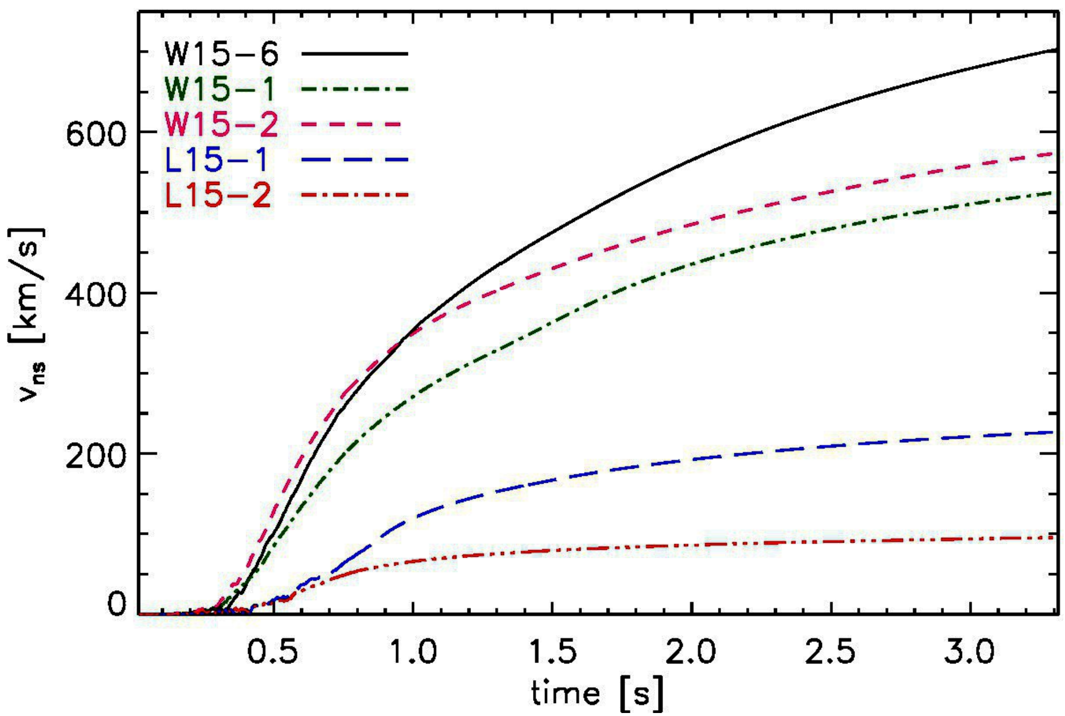
GW amplitudes in 2D are considerably larger than in 3D.
No template character, in 3D strongly direction dependent.

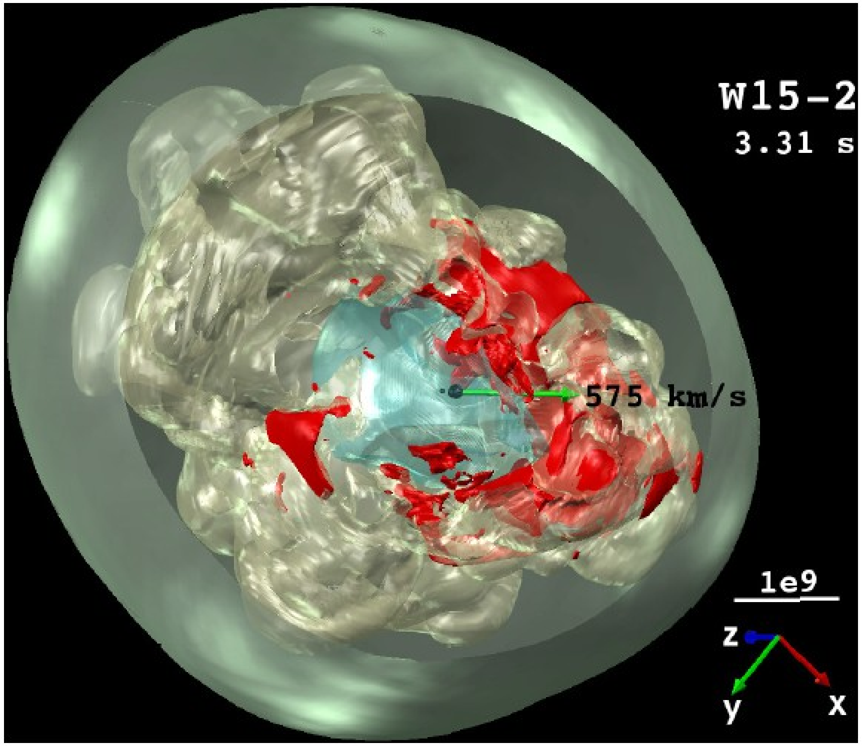
# Gravitational Waves for 2D SN Explosions: Progenitor Variations

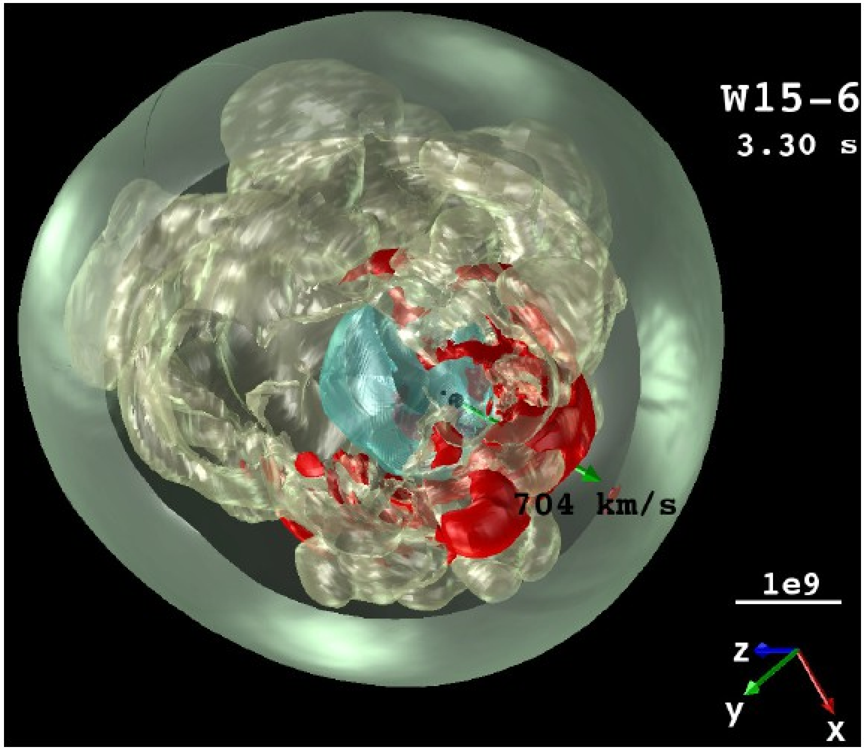



**(Müller, THJ, & Marek, ApJ 766 (2013) 43)**

# Neutron Star Recoil by "Gravitational Tug-Boat" Mechanism




(Wongwathanarat, Janka, Müller, ApJL 725 (2010) 106; A&A (2013), arXiv:1210.8148)

# Neutron Star Recoil by "Gravitational Tug-Boat" Mechanism

@ t = 1.4 s  @ t = 3.3 s

| Model | $M_{ns}$ [$M_\odot$] | $t_{exp}$ [ms] | $E_{exp}$ [B] | $v_{ns}$ [km/s] | $a_{ns}$ [km/s$^2$] | $v_{ns,\nu}$ [km/s] | $\alpha_{k\nu}$ [°] | $v_{ns}^{long}$ [km/s] | $a_{ns}^{long}$ [km/s$^2$] | $J_{ns,46}$ [$10^{46}$ g cm$^2$/s] | $\alpha_{sk}$ [°] | $T_{spin}$ [ms] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| W15-1 | 1.37 | 246 | 1.12 | 331 | 167 | 2 | 151 | 524 | 44 | 1.51 | 117 | 652 |
| W15-2 | 1.37 | 248 | 1.13 | 405 | 133 | 1 | [illegible] | 575 | 49 | 1.56 | 58 | 632 |
| W15-3 | 1.36 | 250 | 1.11 | 267 | 102 | 1 | 160 | - | - | 1.13 | 105 | 864 |
| W15-4 | 1.38 | 272 | 0.94 | 262 | 111 | 4 | 162 | - | - | 1.27 | 43 | 785 |
| W15-5-lr | 1.41 | 289 | 0.83 | 373 | 165 | 2 | [illegible] | - | - | 1.63 | 28 | 625 |
| W15-6 | 1.39 | 272 | 0.90 | 437 | 222 | 2 | 136 | 704 | 71 | 0.97 | 127 | 1028 |
| W15-7 | 1.37 | 258 | 1.07 | 215 | 85 | 1 | 81 | - | - | 0.45 | 48 | 2189 |
| W15-8 | 1.41 | 289 | 0.72 | 336 | 168 | 3 | 160 | - | - | 4.33 | 104 | 235 |
| L15-1 | 1.58 | 422 | 1.13 | 161 | 69 | 5 | 135 | 227 | 16 | 1.89 | 148 | 604 |
| L15-2 | 1.51 | 382 | 1.74 | 78 | 14 | 1 | 150 | [illegible] | [illegible] | 1.04 | 62 | 1041 |
| L15-3 | 1.62 | 478 | 0.84 | 31 | 27 | 1 | 51 | - | - | 1.55 | 123 | 750 |
| L15-4-lr | 1.64 | 502 | 0.75 | 199 | 123 | 4 | 120 | - | - | 1.39 | 93 | 846 |
| L15-5 | 1.66 | 516 | 0.62 | 267 | 209 | 3 | 147 | 542 | 106 | 1.72 | 65 | 695 |
| N20-1-lr | 1.40 | 311 | 1.93 | 157 | 42 | 7 | 118 | - | - | 5.30 | 122 | 190 |
| N20-2 | 1.28 | 276 | 3.12 | 101 | 12 | 4 | 159 | - | - | 7.26 | 43 | 127 |
| N20-3 | 1.38 | 299 | 1.98 | 125 | 15 | 5 | 138 | [illegible] | [illegible] | 4.42 | 54 | 225 |
| N20-4 | 1.45 | 334 | 1.35 | 98 | 18 | 1 | 98 | 125 | 9 | 2.04 | 45 | 512 |
| B15-1 | 1.24 | 164 | 1.25 | 92 | 16 | 1 | 97 | 102 | 1 | 1.03 | 155 | 866 |
| B15-2 | 1.24 | 162 | 1.25 | 143 | 37 | 1 | 140 | - | - | 0.12 | 162 | 7753 |
| B15-3 | 1.26 | 175 | 1.04 | 85 | 19 | 1 | 24 | 99 | 3 | 0.44 | 148 | 2050 |

(Wongwathanarat, Janka, Müller, A&A (2013), arXiv:1210.8148)

# Neutron Star Recoil by Hydrodynamical "Gravitational Tug-Boat" Mechanism

This mechanism can explain also with observed black hole kick velocities of Galactic BH-binaries, in contrast to kicks by asymmetric neutrino emission:
BH kick velocities are NOT reduced by ratio of NS/BH mass!

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS 434, 1355–1361 (2013) doi:10.1093/mnras/stt1106
Advance Access publication 2013 July 11

## Natal kicks of stellar mass black holes by asymmetric mass ejection in fallback supernovae

Hans-Thomas Janka★
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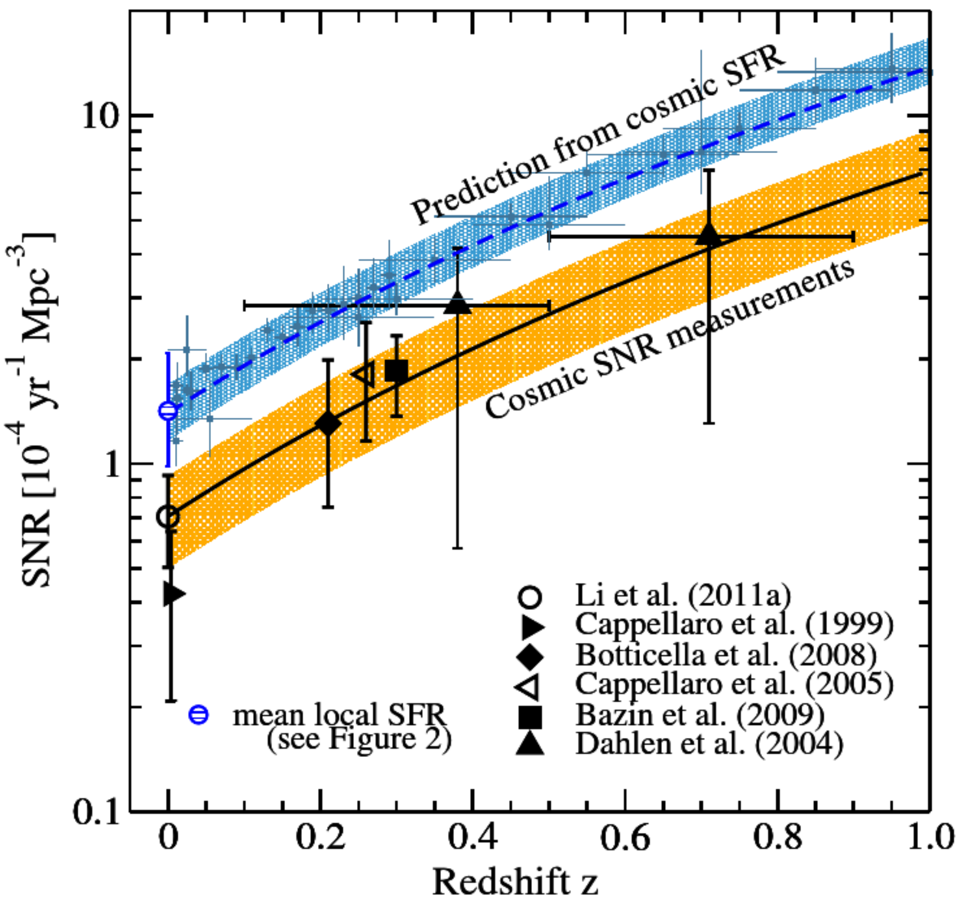
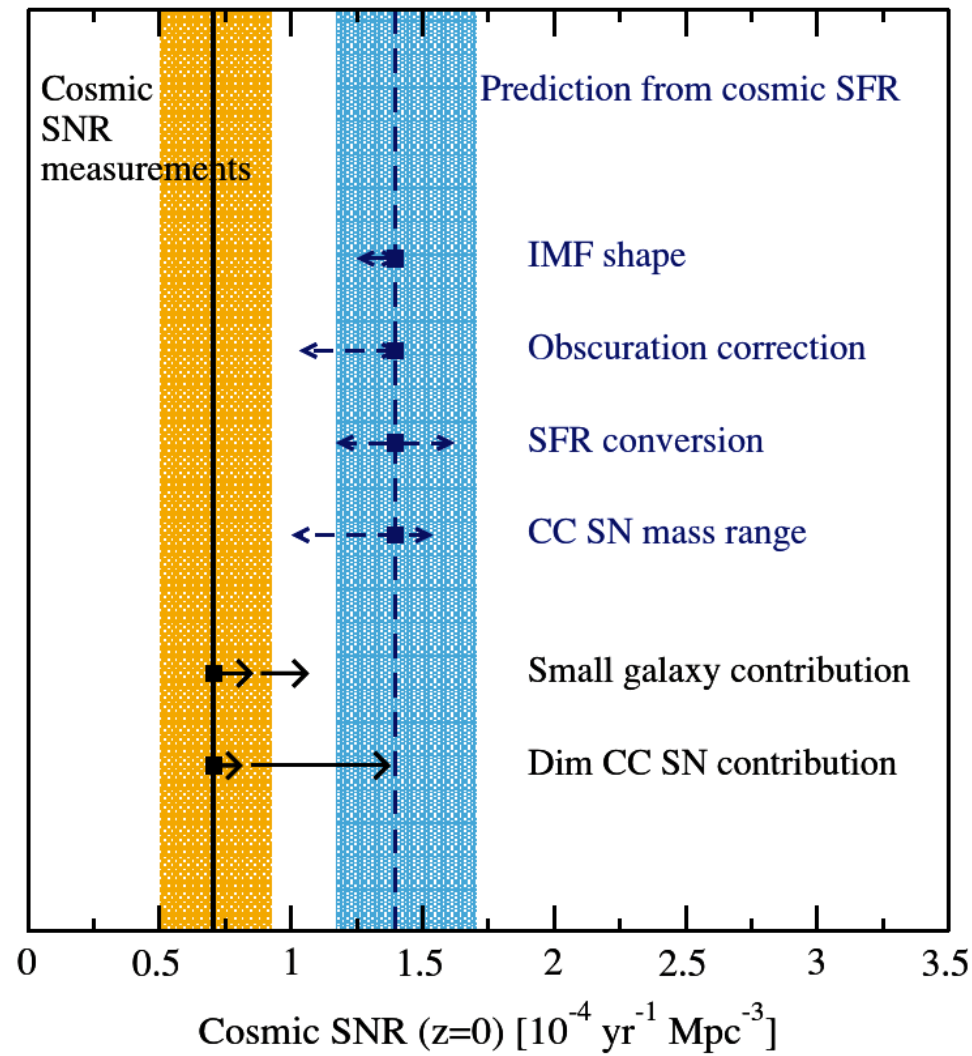
Accepted 2013 June 15. Received 2013 May 31

# Cosmic CCSN and Star Formation Rates

Horiuchi et al., ApJ 738 (2011) 154

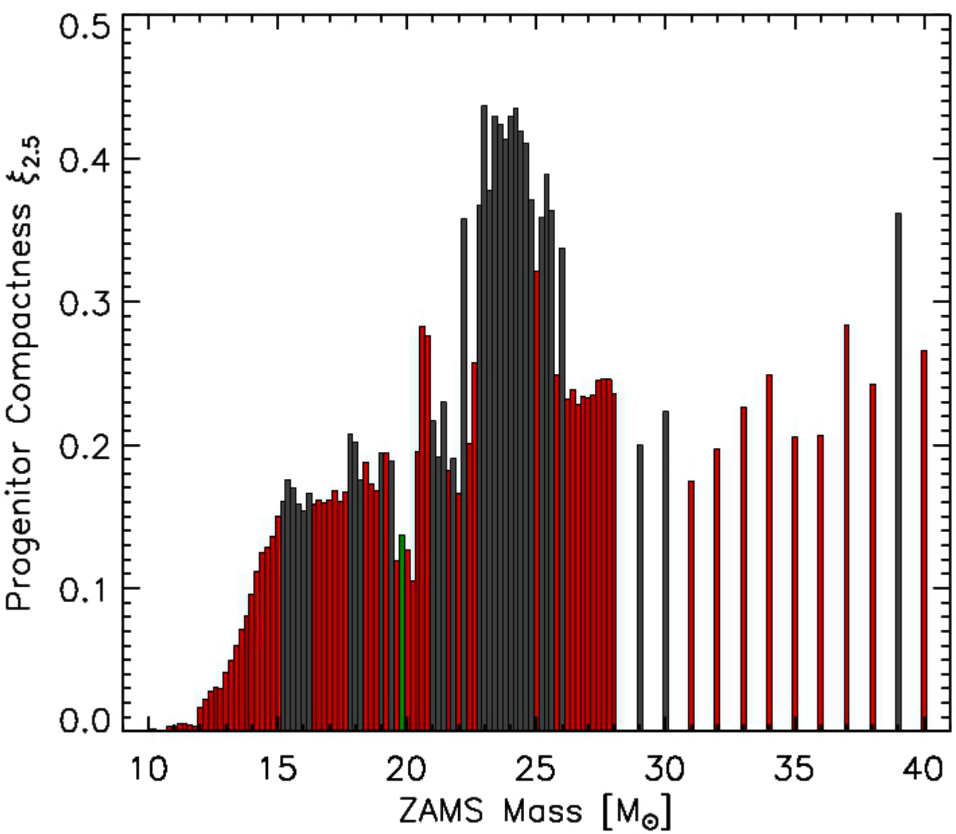


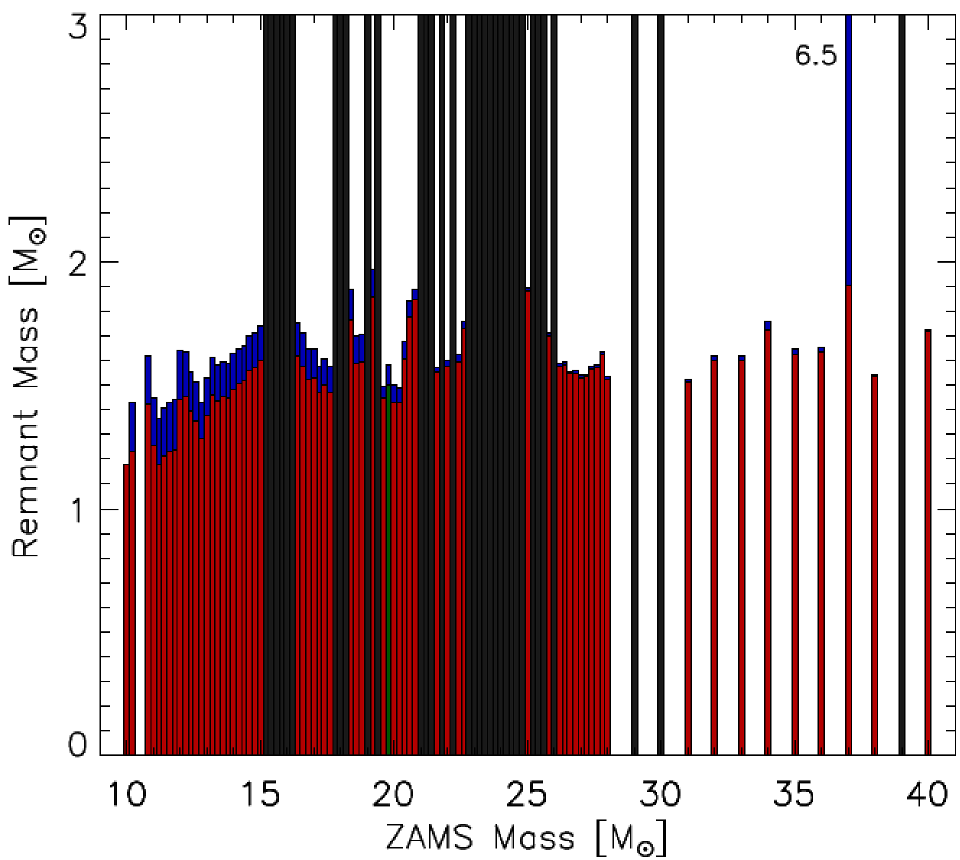



# Stellar Compactness and Explosion

Core compactness can be nonmonotonic function of ZAMS mass

Progenitor models: Woosley et al. (RMP 2002)



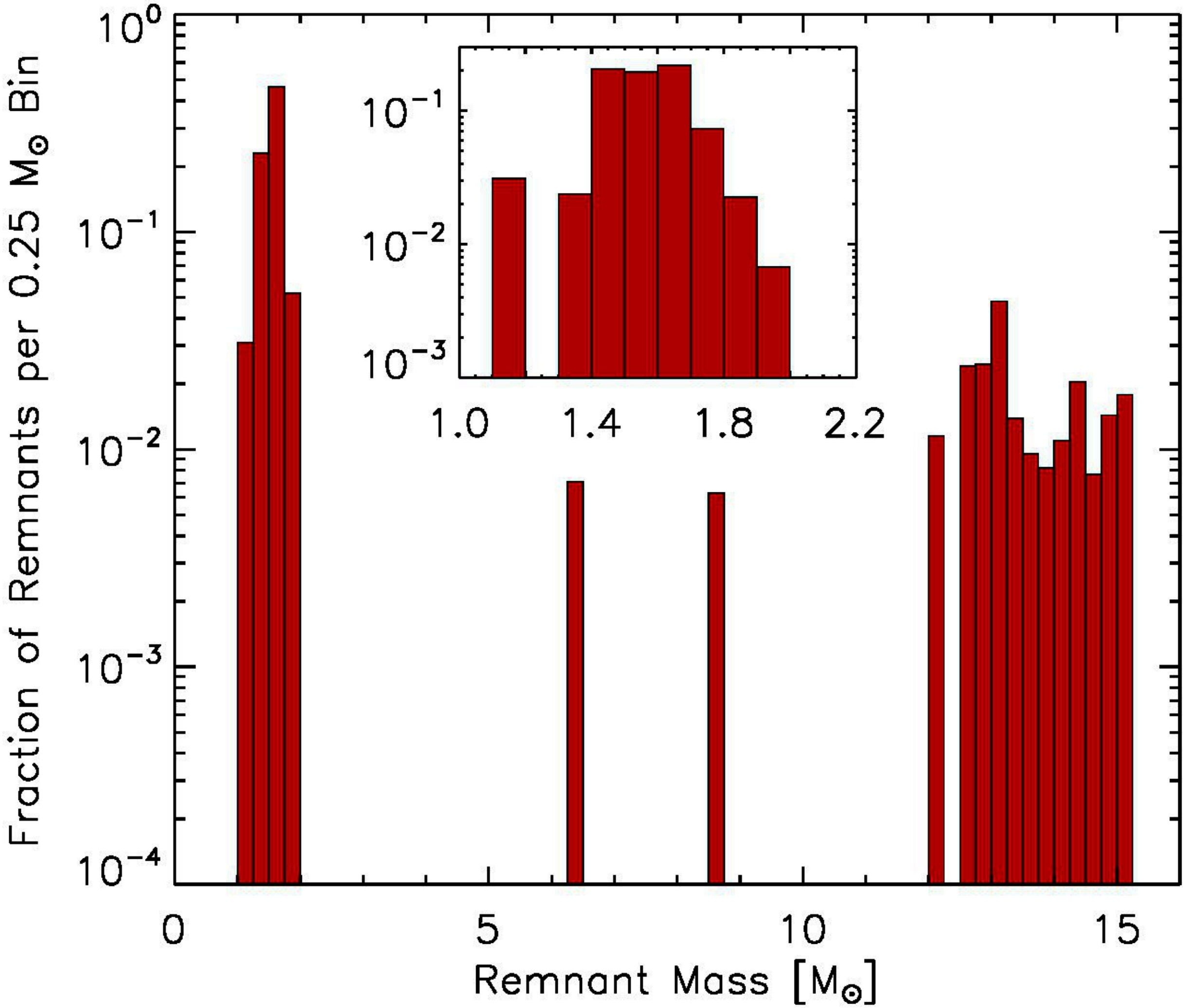

$$\xi_{2.5} \equiv \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}}\,, \quad \text{mass } M = 2.5\ M_\odot$$

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

(Ugliano, THJ, Marek, Arcones, ApJ 757, 69 (2012))

# Remnant Mass Distribution

Model results folded with Salpeter IMF:
23% of all stellar core collapses produce BHs

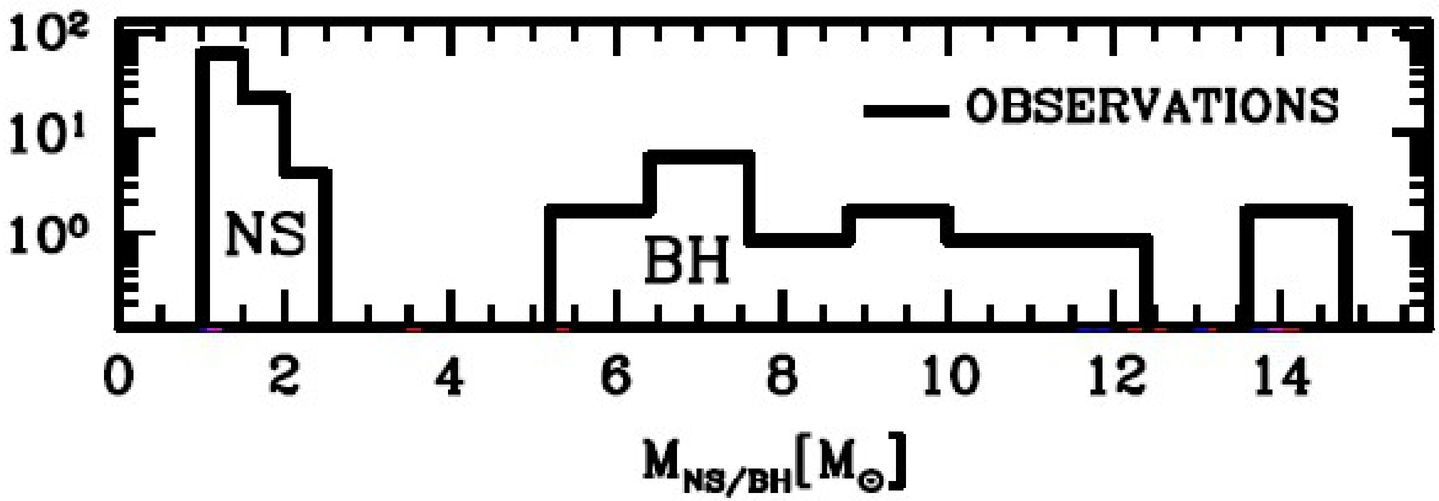



**Baryonic Remnant Mass**

(Ugliano, THJ, Marek, Arcones, ApJ 757, 69 (2012))

# Observed Remnant Mass Distribution

Our model results reproduce possible gap
in the observed distribution of NS and BH masses




**Belczynski et al., ApJ (2012)**

# Summary II

- Neutrino emission of SASI phases shows quasi-periodic modulation that will be easily detectable for a galactic supernova by IceCube or HyperK.

- Supernova core instabilities produce GWs of several 100~1000 Hz. Different emission phases from core bounce until after explosion. Strong dependence on progenitor and direction of observation. No template character. 3D models yield much (~10 times) smaller GW amplitudes than 2D simulations, even when violent, global nonradial shock instability (SASI) develops. Will it be detectable for galactic supernova?

- Neutrino-driven explosions naturally explain pulsar and BH kicks as well as SN explosion asymmetries.

- Failure of neutrino-heating mechanism may explain considerable rates of BH formation and/or weak and faint SNe.

# Munich Institute for Astro- and Particle Physics

www.munich-iapp.de

Submission of proposals for 2015 is open!

## MIAPP Workshops 2014

**Please register NOW!**

**The Extragalactic Distance Scale**
26 May – 20 June 2014
L. Macri, W. Gieren, W. Hillebrandt, R. Kudritzki

**Neutrinos in Astro- and Particle Physics**
30 June – 25 July 2014
S. Schönert, G. Raffelt, A. Smirnov, T. Lasserre

**Challenges, Innovations and Developments in Precision Calculations for the LHC**
28 July – 22 Aug. 2014
M. Krämer, S. Dittmaier, N. Glover, G. Heinrich

**Cosmology after Planck**
25 Aug . – 19 Sept. 2014
N. Aghanim, E. Komatsu, B. Wandelt, J. Weller

**Submission of proposals/application for workshop participation:**
**www.munich-iapp.de**

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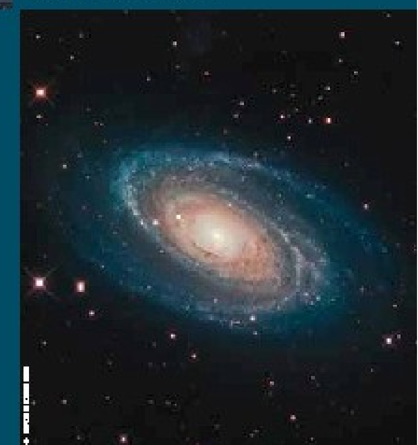
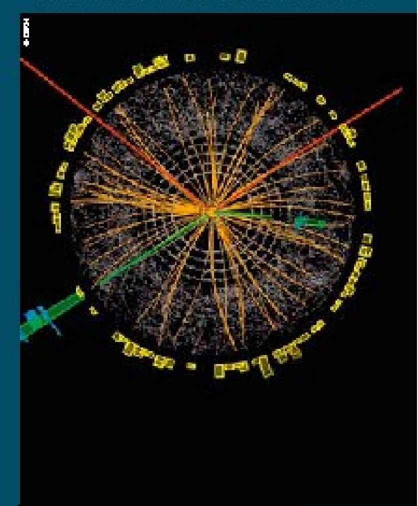
Excellence Cluster Universe

ASTROPHYSICS



PARTICLE & NUCLEAR PHYSICS



For concise reviews of most of what I will say, see

**ARNPS 62 (2012) 407, arXiv:1206.2503**
**and**
**PTEP 2012, 01A309, arXiv:1211.1378**

REVIEWS IN ADVANCE

# Explosion Mechanisms of Core-Collapse Supernovae

Hans-Thomas Janka

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email: thj@mpa-garching.mpg.de