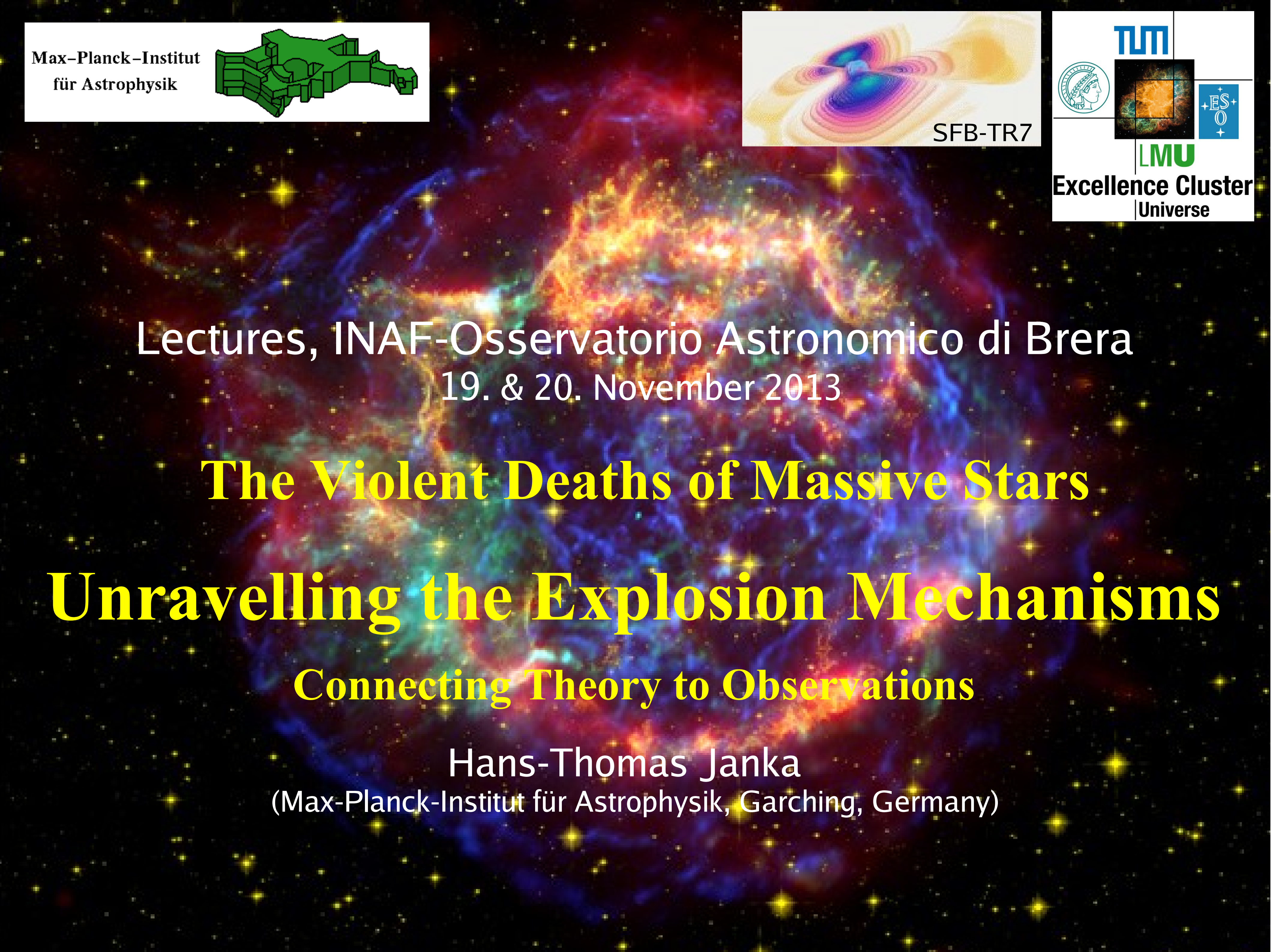

Max-Planck-Institut
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TUM
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Excellence Cluster
Universe

Lectures, INAF-Osservatorio Astronomico di Brera
19. & 20. November 2013

The Violent Deaths of Massive Stars

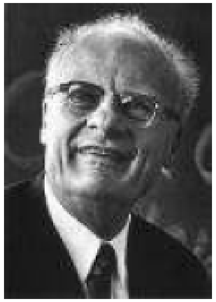
Unravelling the Explosion Mechanisms

Connecting Theory to Observations

Hans-Thomas Janka
(Max-Planck-Institut für Astrophysik, Garching, Germany)

Things that blow up

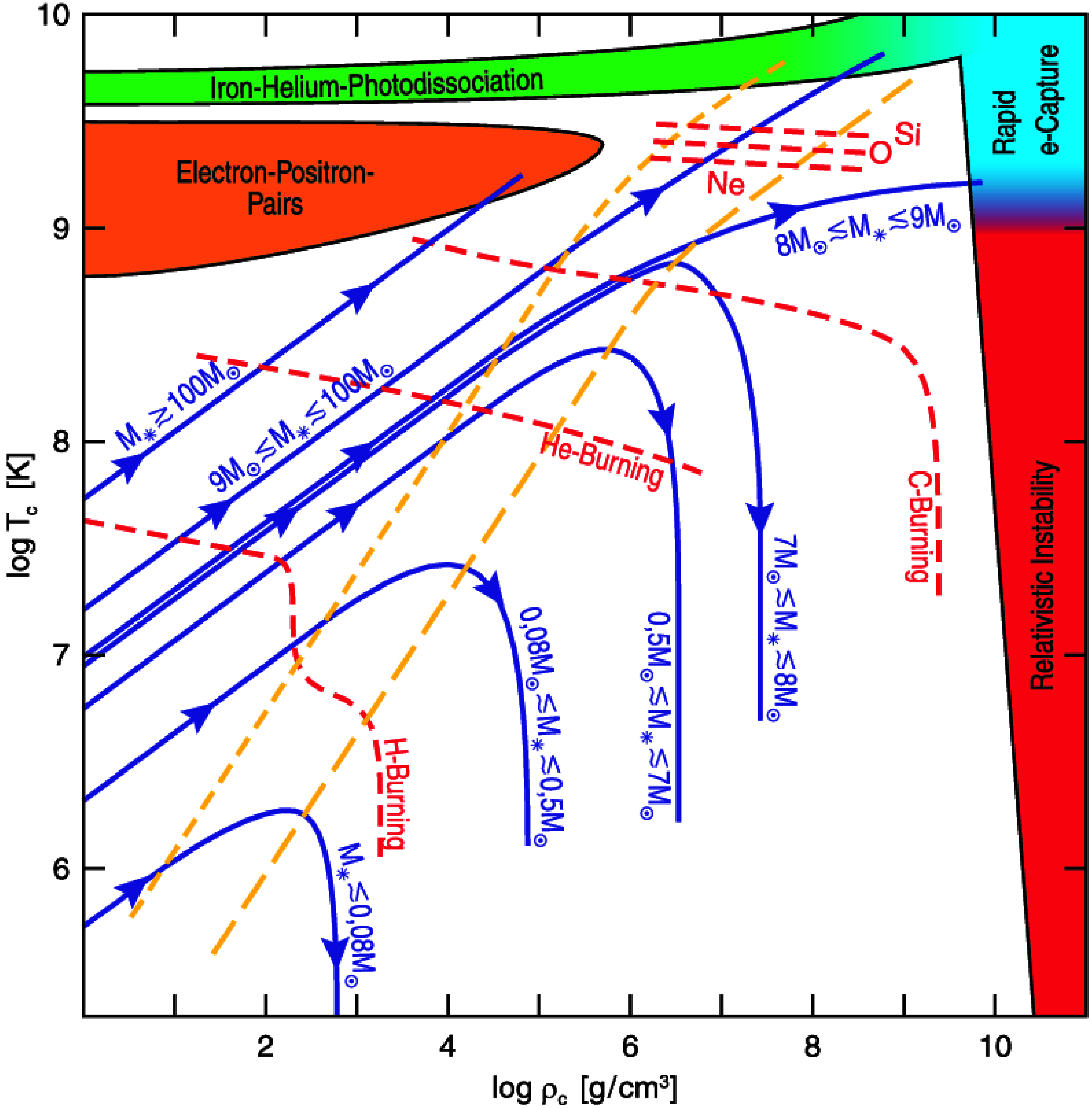
supernovae


1B=10^{51} erg

- CO white dwarf ➔ Type Ia SN, E$\approx$1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- "SAGB" star (AGB, then SN) ➔ EC SN
- "normal" SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- "Collapsar", GRB ➔ broad line Ib/a SN, "hypernova"
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN,$\lesssim$100B (1B=10^{51} erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- GR He instability ➔ >100 B SN+SMBH, or 10,000 B
- Supermassive stars ➔ $\gtrsim$100000 B SN or SMBH

A. Heger (2011)

Final Stages of Massive Star Evolution



Contents

Lecture I:

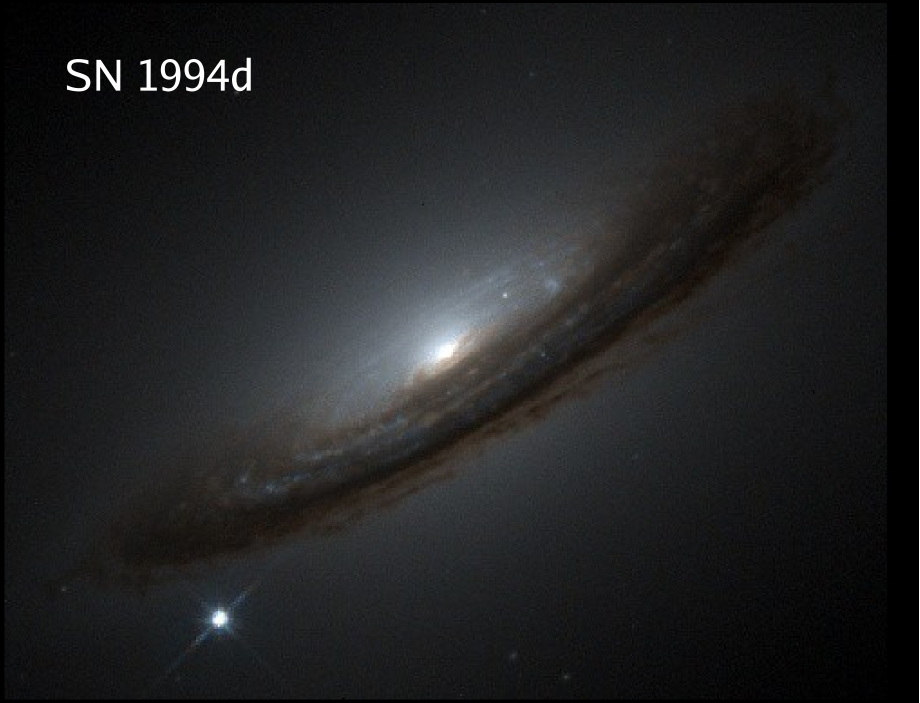
- Supernovae: classification and phenomenology
- Basics of stellar evolution & death scenarios in overview
- White dwarfs and thermonuclear supernovae

Lecture II:

- Gravitational (core-collapse) supernovae: evolution stages
- SN modeling: some technical aspects
- Status of 2D and 3D SN modeling

Lecture III:

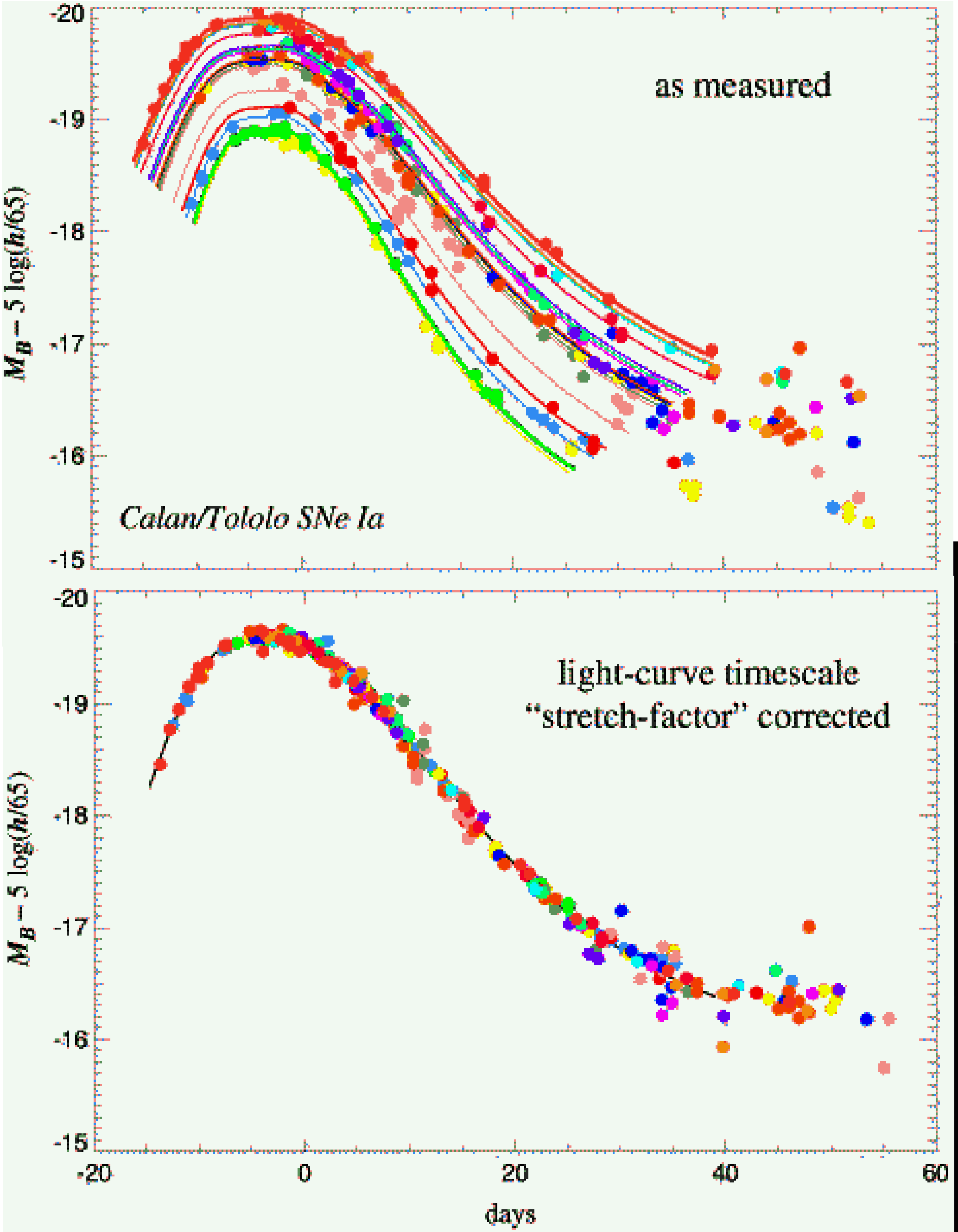
- Supernova models: Predictions of observable signals
- Neutron stars: birth and death
- Black holes and gamma-ray bursts: Sources of heavy elements



Thermonuclear (Type Ia) Supernovae

Standard candles for measuring the universe

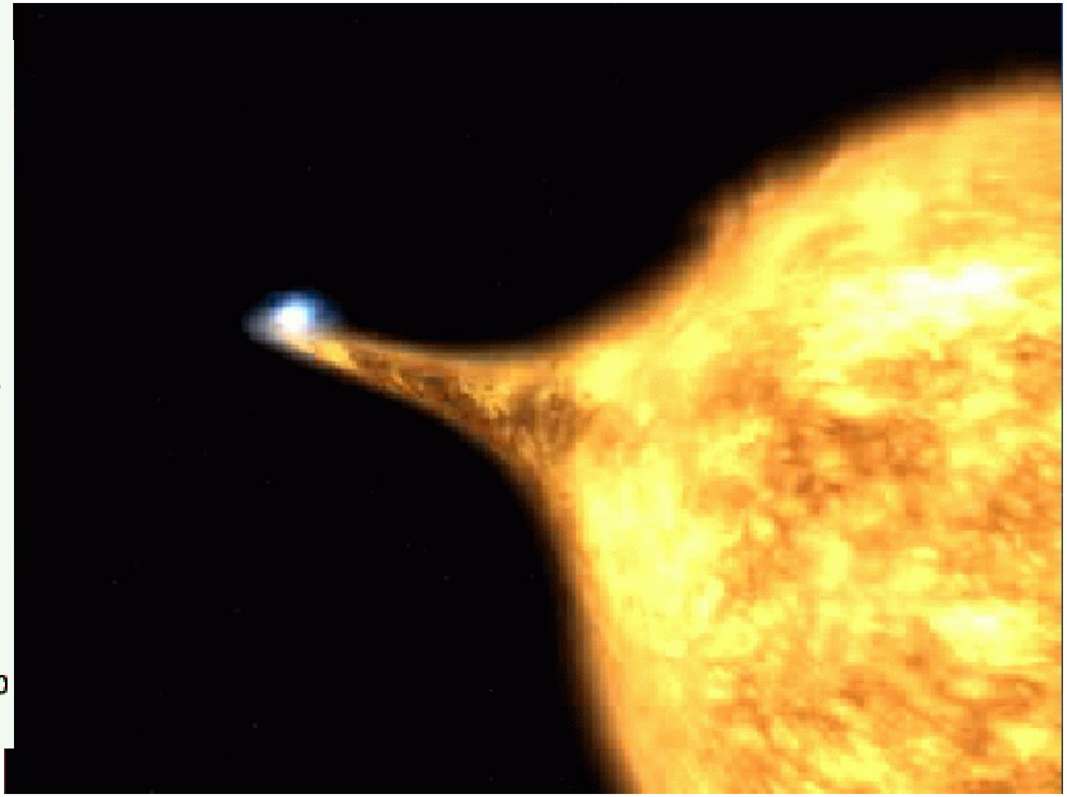
Type Ia Supernovae



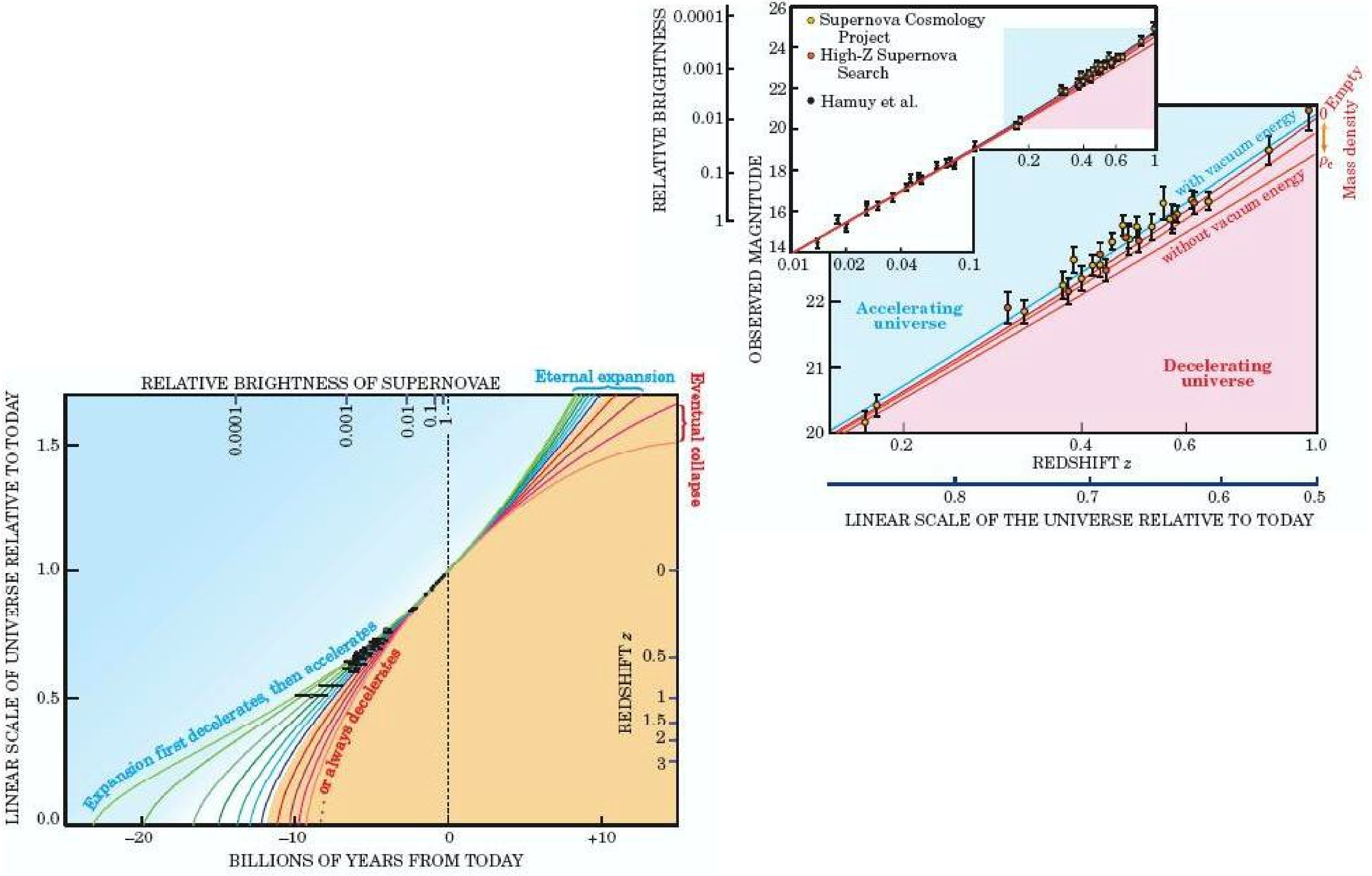
Recalibration with Phillips relation

Exploding accreting white dwarfs in binary systems

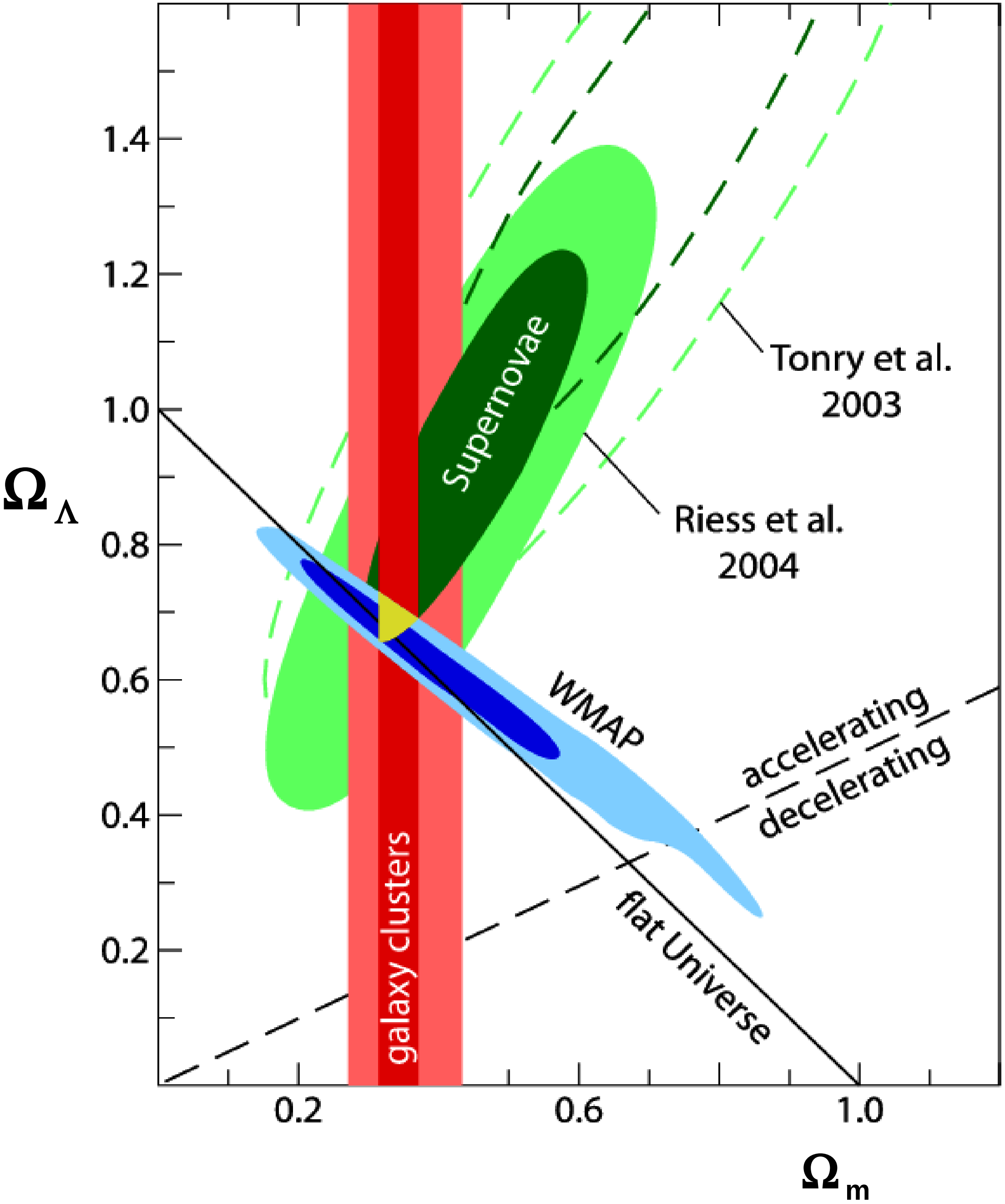
"standard candles"



Type Ia SNe and Cosmology



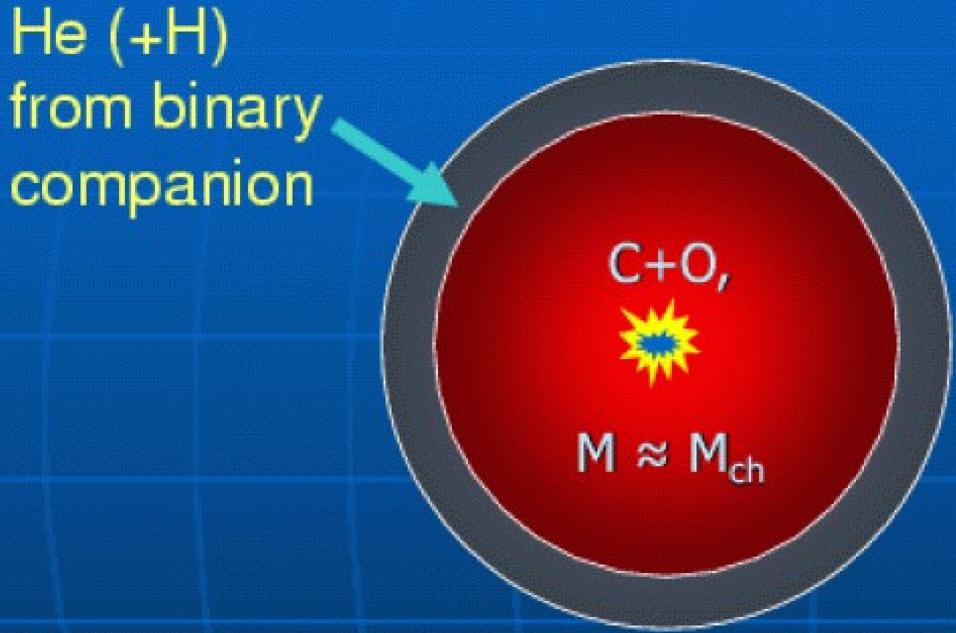
Observational Constraints of Cosmic Parameters



WMAP results from Spergel et al. 2003

REFLEX results from Schuecker et al. 2003 (three weeks before WMAP publication)

How does the model work?



Density ~ 10^9 - 10^{10} g/cm

Temperature: a few 10^9 K

Radii: a few 1000 km

Explosion energy:

Fusion C+C, C+O, O+O → "Fe"

Laminar burning velocity:

$U_L \sim 100$ km/s $<< U_S$

Too little is burned!

What is the mode of nuclear burning in SNe Ia?

"Detonation":

(Super-) Sonic front;

heating to ignition by a shock wave.

"Deflagration":

Subsonic front;

heating to ignition by heat diffusion.

Strong Si-lines at maximum light:

Pure detonations are excluded!

(But possibly at lower densities???)

The physics of turbulent combustion

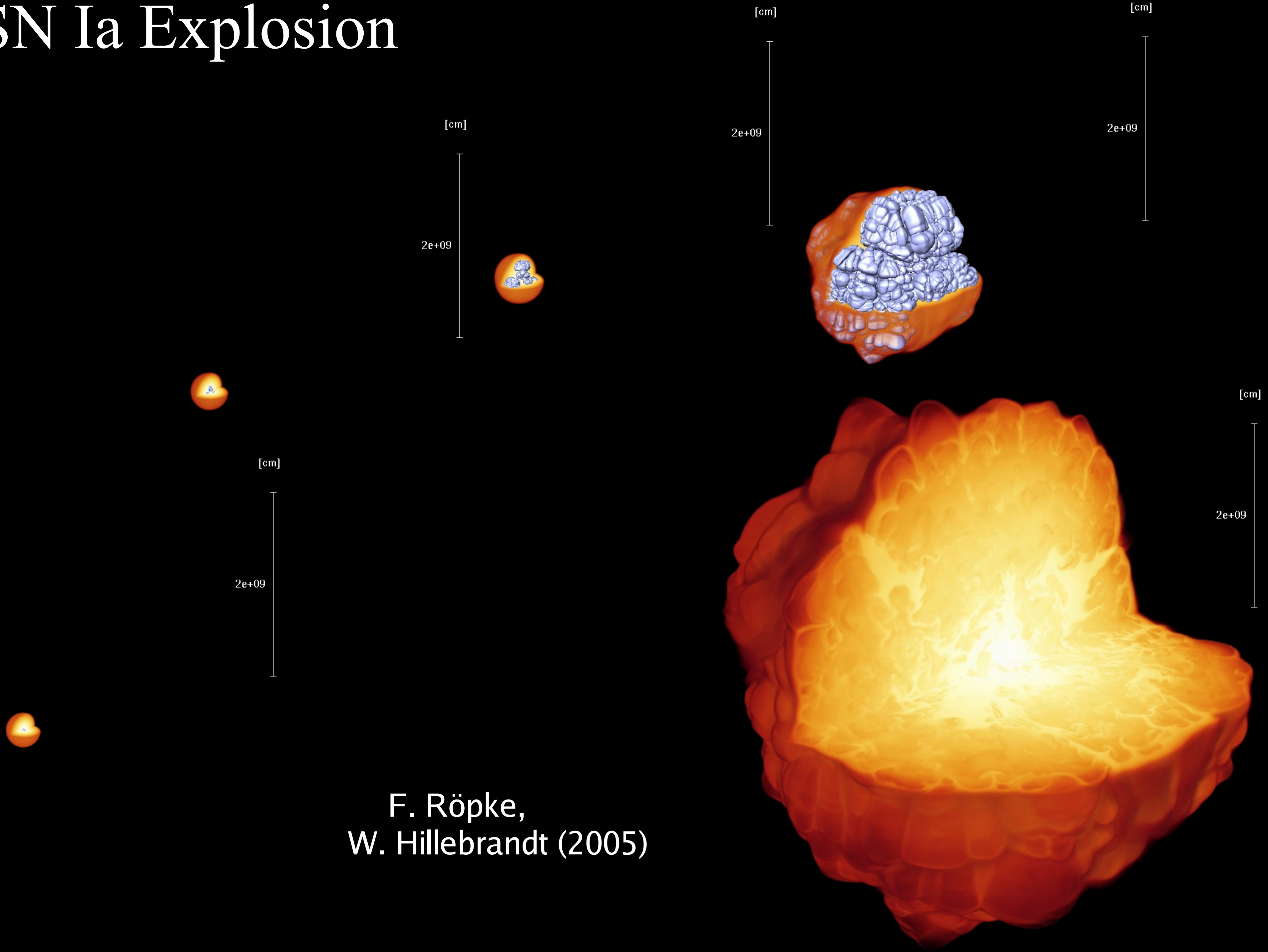
Everydays experience: *Turbulence increases the burning velocity*.

In a star: Reynoldsnumber ~ 10^{14} !

In the limit of strong turbulence: $U_B \sim V_T$!

Physics of thermonuclear burning is very similar to premixed chemical flames.

SN Ia Explosion

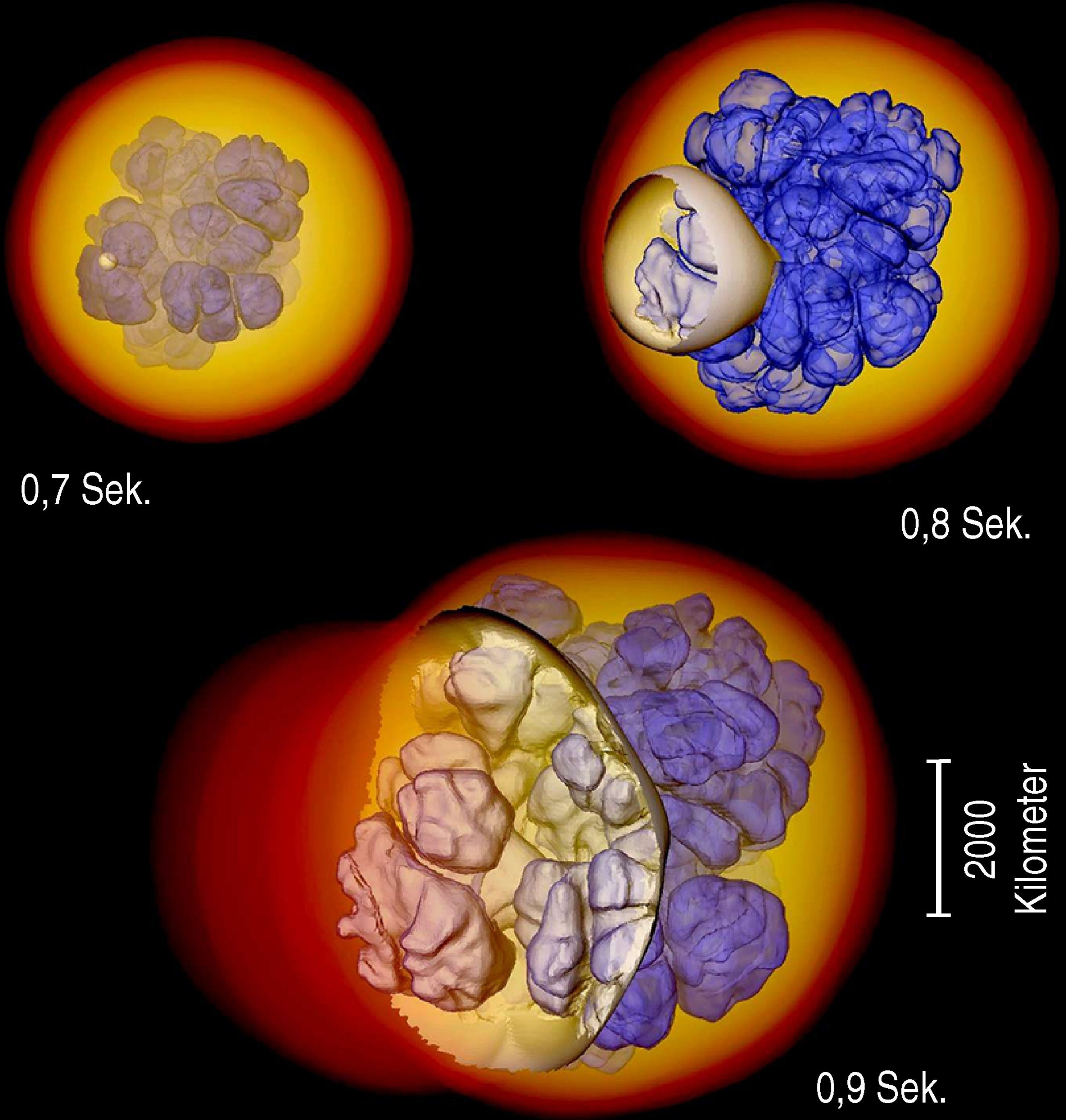


F. Röpke,
W. Hillebrandt (2005)

Type Ia Supernovae – Achievements and Insights

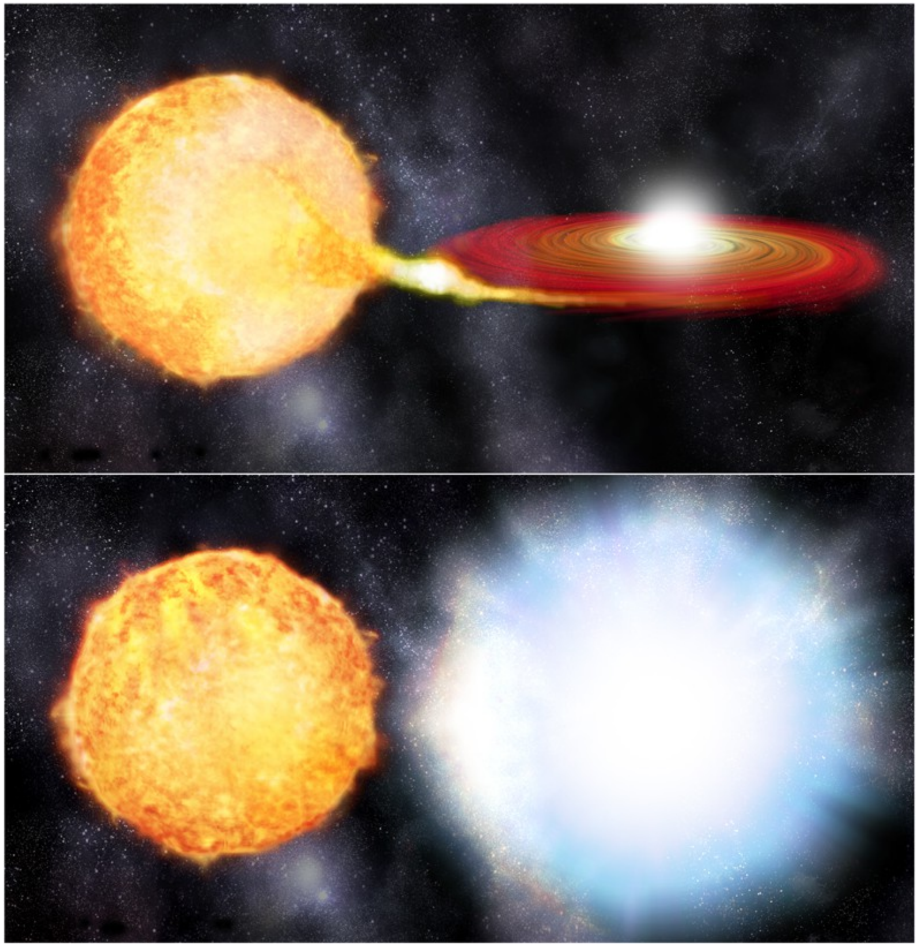
- Deflagration models explode.
- Explosion energy ~0.8*10^{51} ergs (a bit low), too much unburned C+O left.
- Need of deflagration to detonation transition.
- Explosion energy and produced Ni depends on ignition conditions but not on initial composition.
- Brightness depends on amount of Ni produced, but only weakly on C+O composition.

Deflagration-Detonation Transition

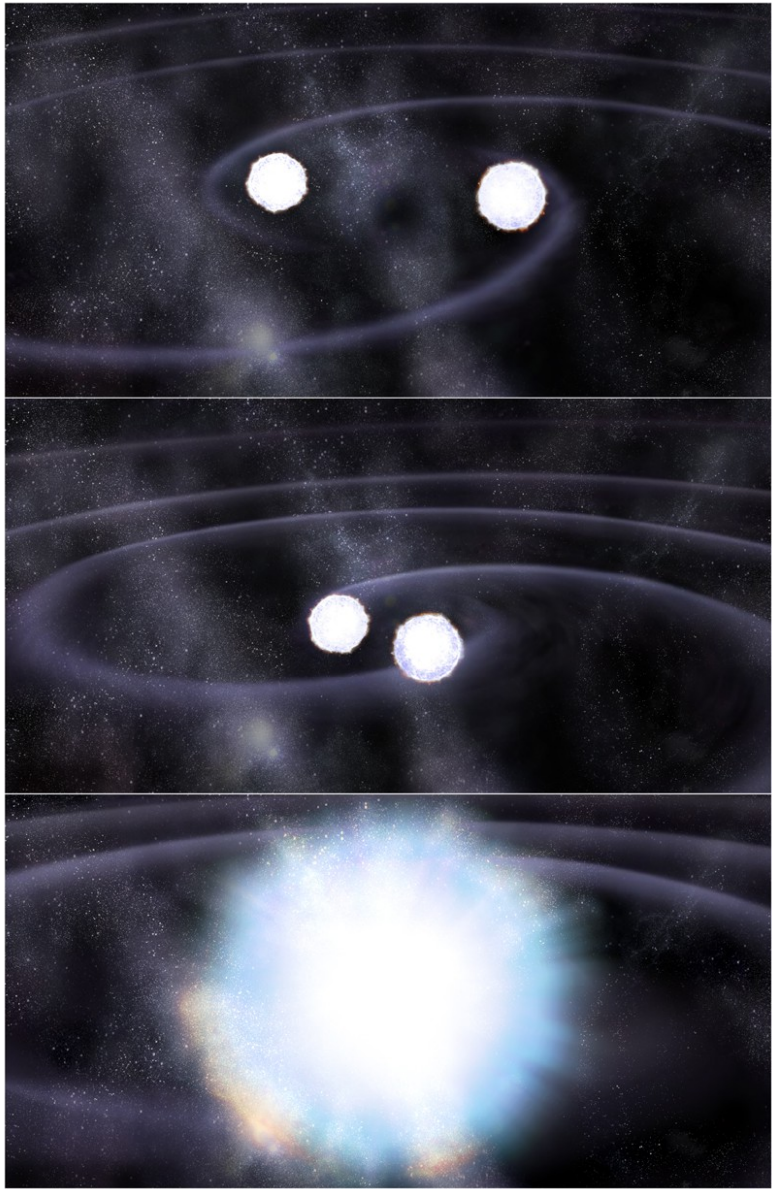


Single Degenerate vs. Double Degenerate Scenario

Interaction with companion star can "revive" dead, old white dwarf.

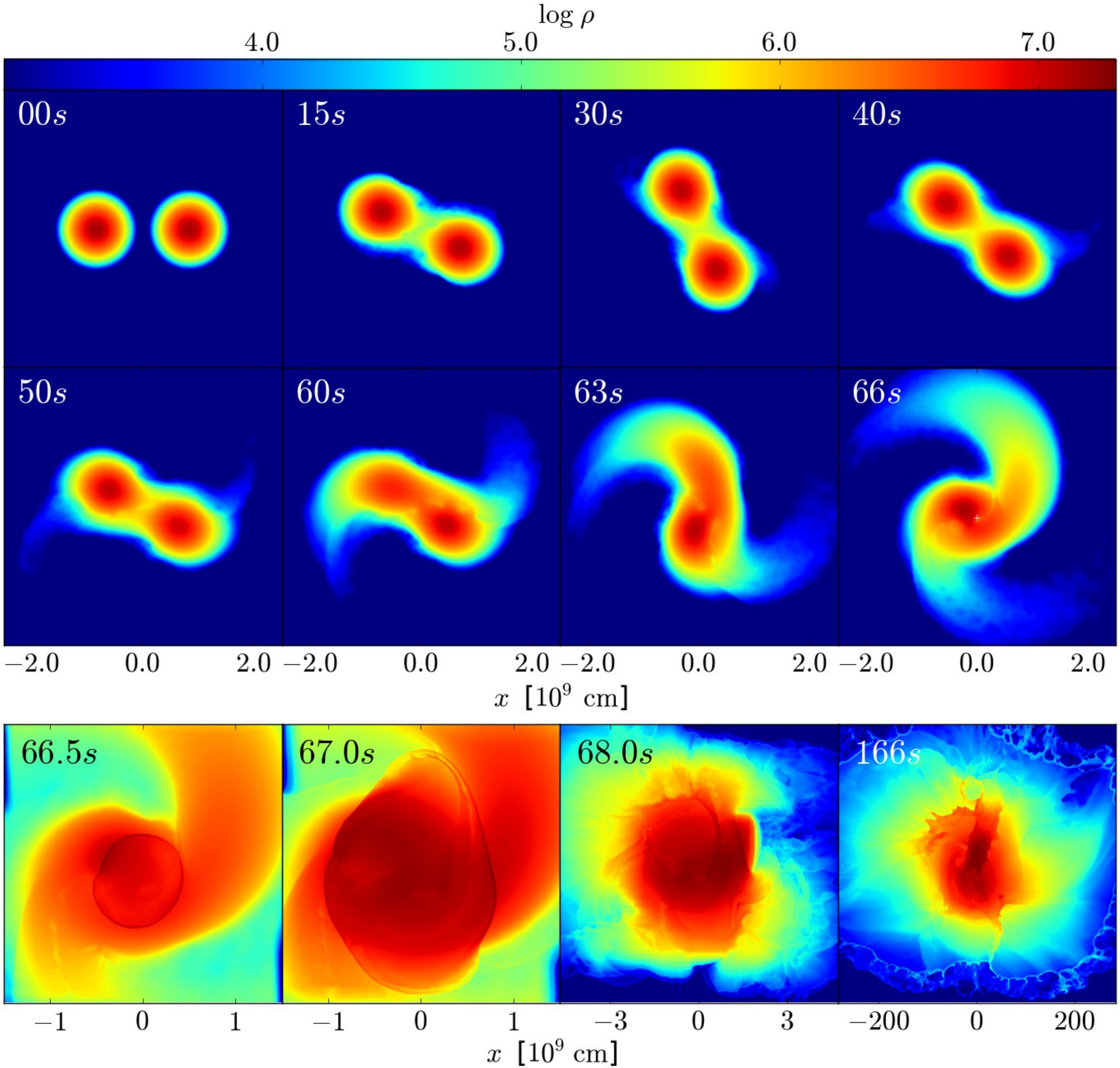


SD scenario: Gas accretion from close companion



DD scenario: Merging of two white dwarfs

WD Mergers



(Pakmor et al., Nature, 2010)

Type Ia Supernovae – Open Questions and Problems

- Probably there exist different types of progenitors.
  Progenitor systems have not been observed yet !

- Double-degenerate scenario seems favored over single-degenerate scenarios because of
  - delay-time distribution
  - X-ray luminosity of galaxies too low for SD systems
  - WD merger rates can account for SNIa rate,
    accreting MCh Wds too rare
  - SNIa environments?

- How does thermonuclear ignition of white dwarf start?

- Where and how does transition from deflagration to detonation occur?

- What is the reason for the Phillips relation?
  Are there any systematic uncertainties?

Type Ia Supernovae

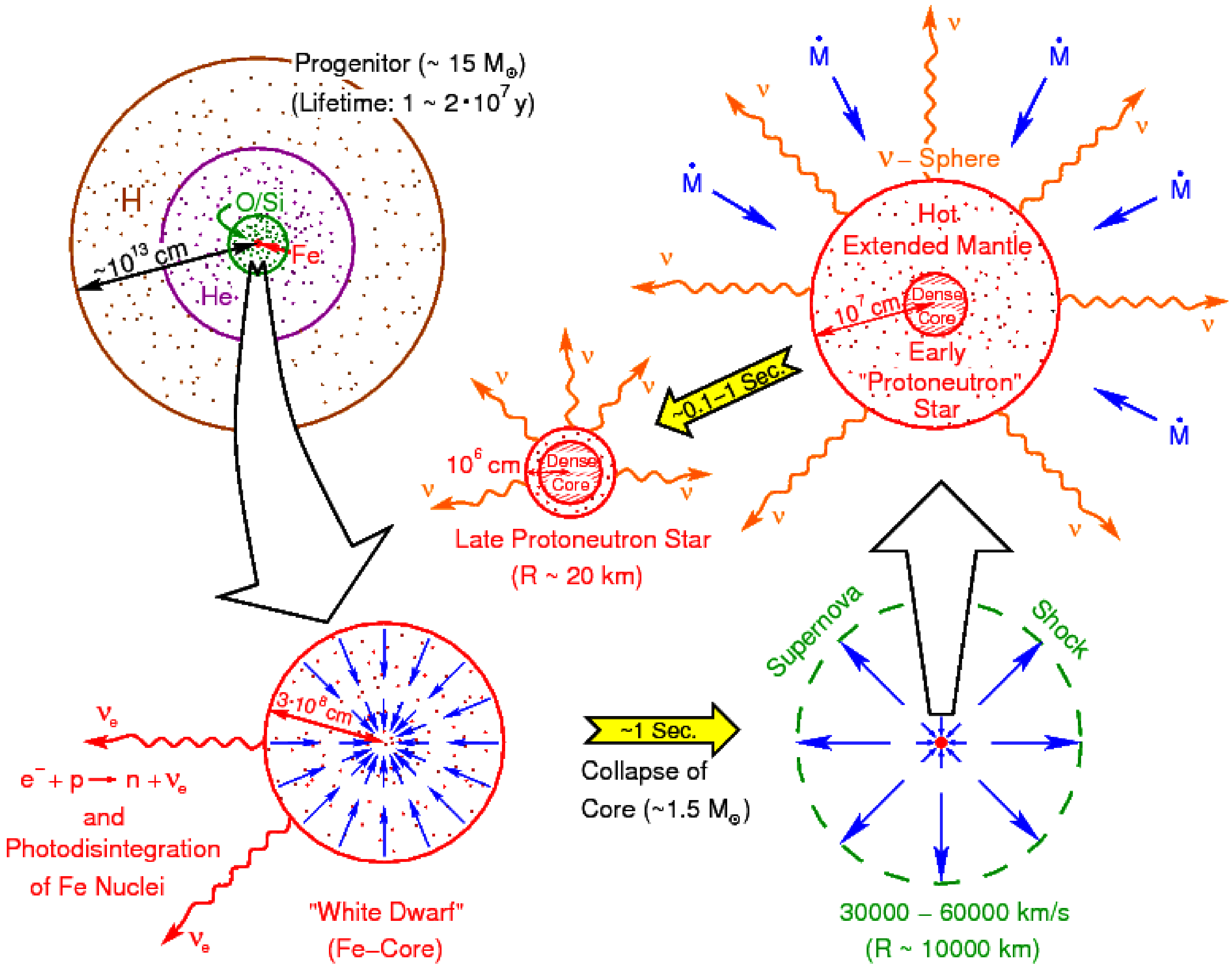
Exploding accreting or merging white dwarfs in binary systems

Used as "standard candles" for measuring distances in the Universe

"Ordinary" Supernovae

Gravitational collapse and explosions of stars with $8\ M_{sun} < M_* < 100\ M_{sun}$

Stellar Collapse and Supernova Stages

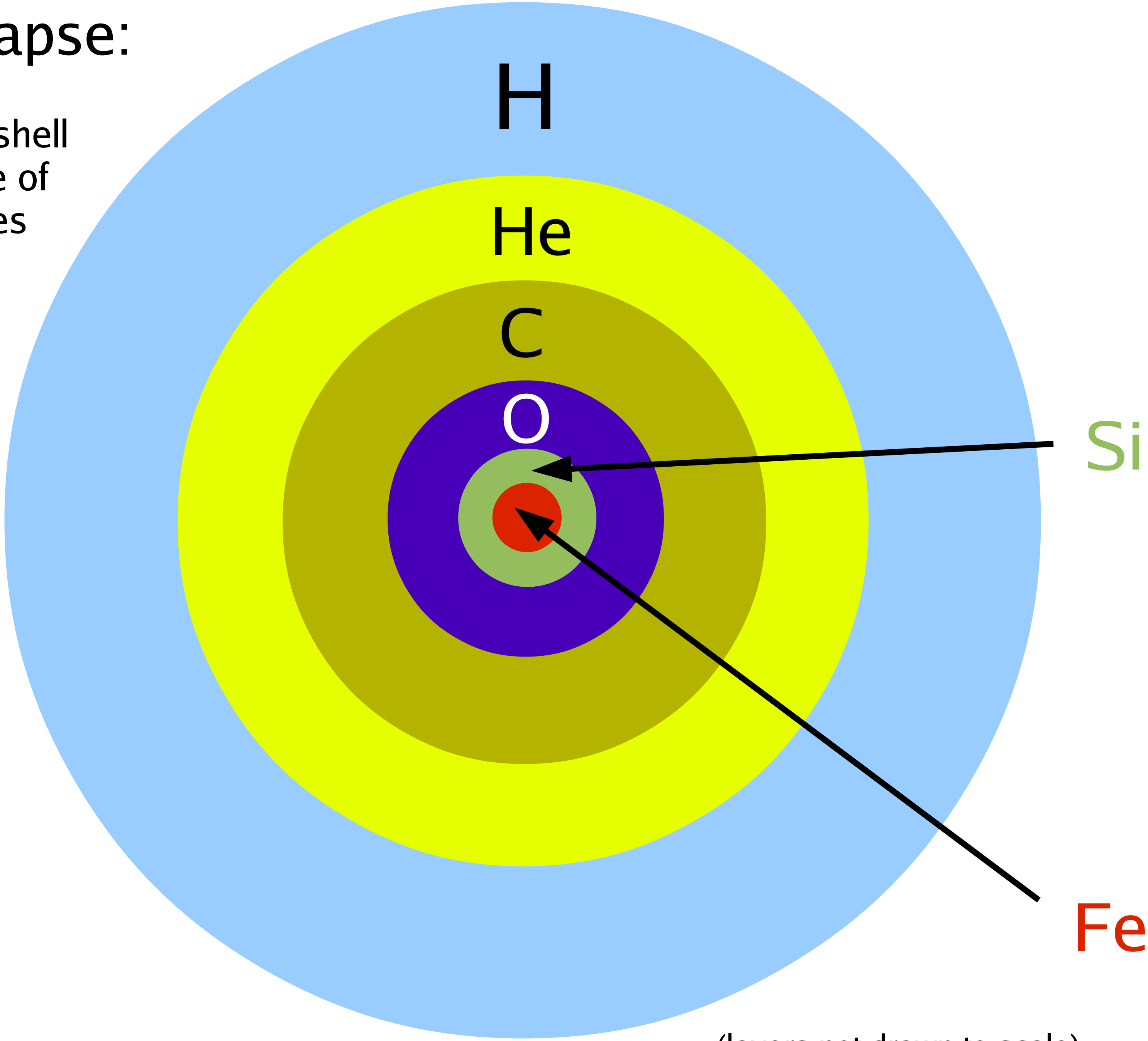


adapted from A. Burrows (1990)

Stellar Core Collapse and Explosion

Evolved massive star prior to its collapse:

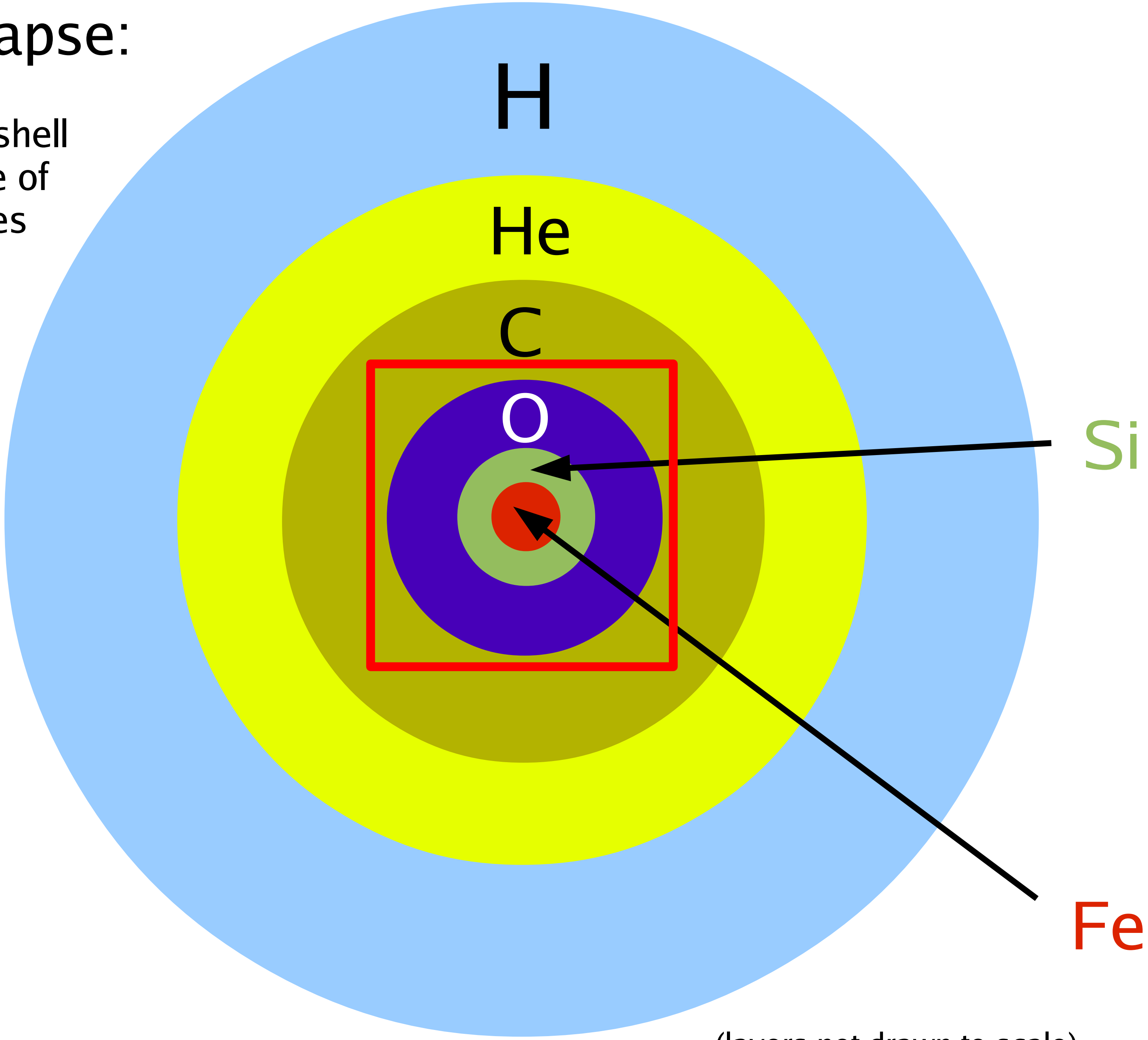
Star develops onion-shell structure in sequence of nuclear burning stages over millions of years



(layers not drawn to scale)

Evolved massive star prior to its collapse:

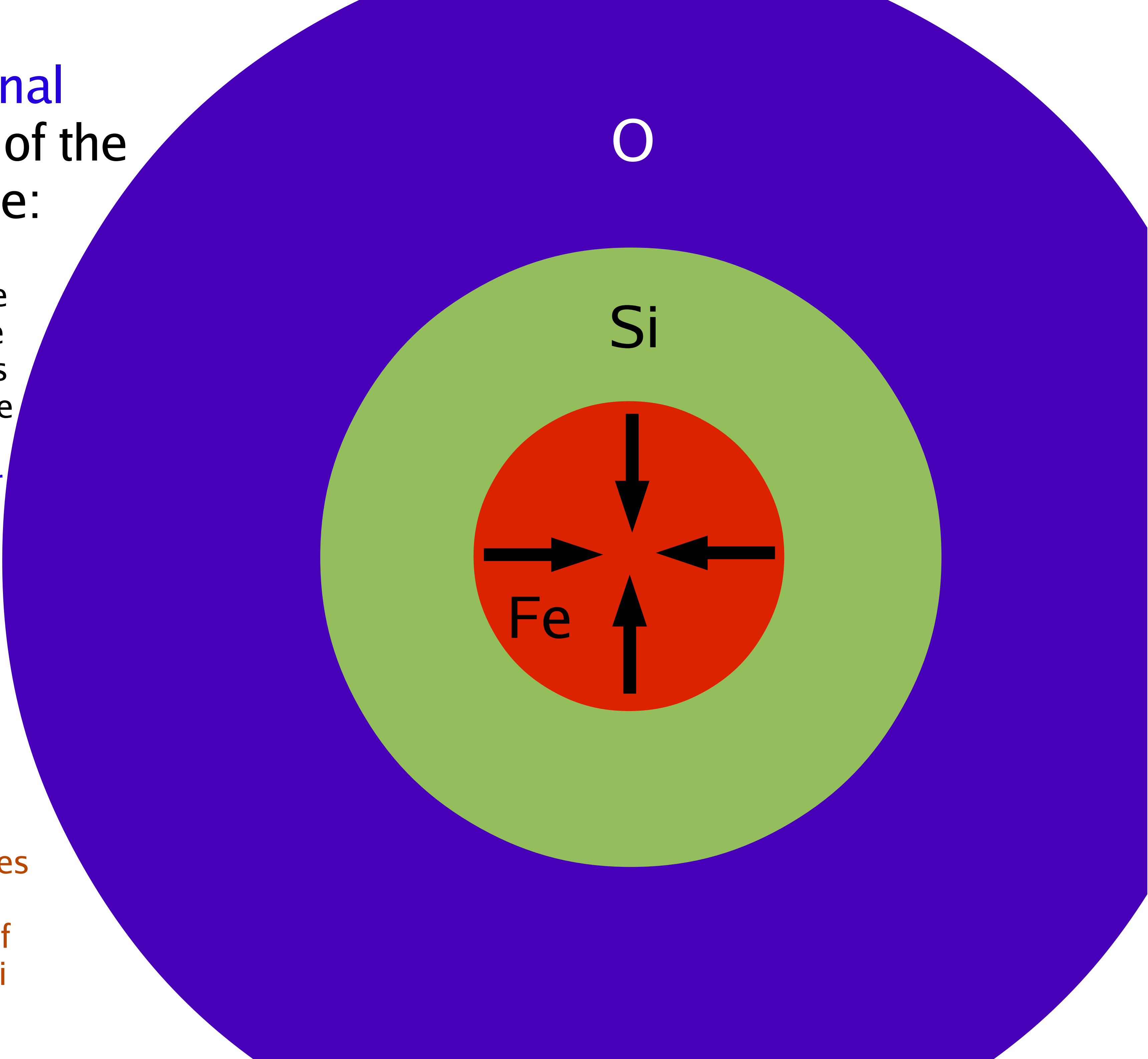
Star develops onion-shell
structure in sequence of
nuclear burning stages
over millions of years



(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

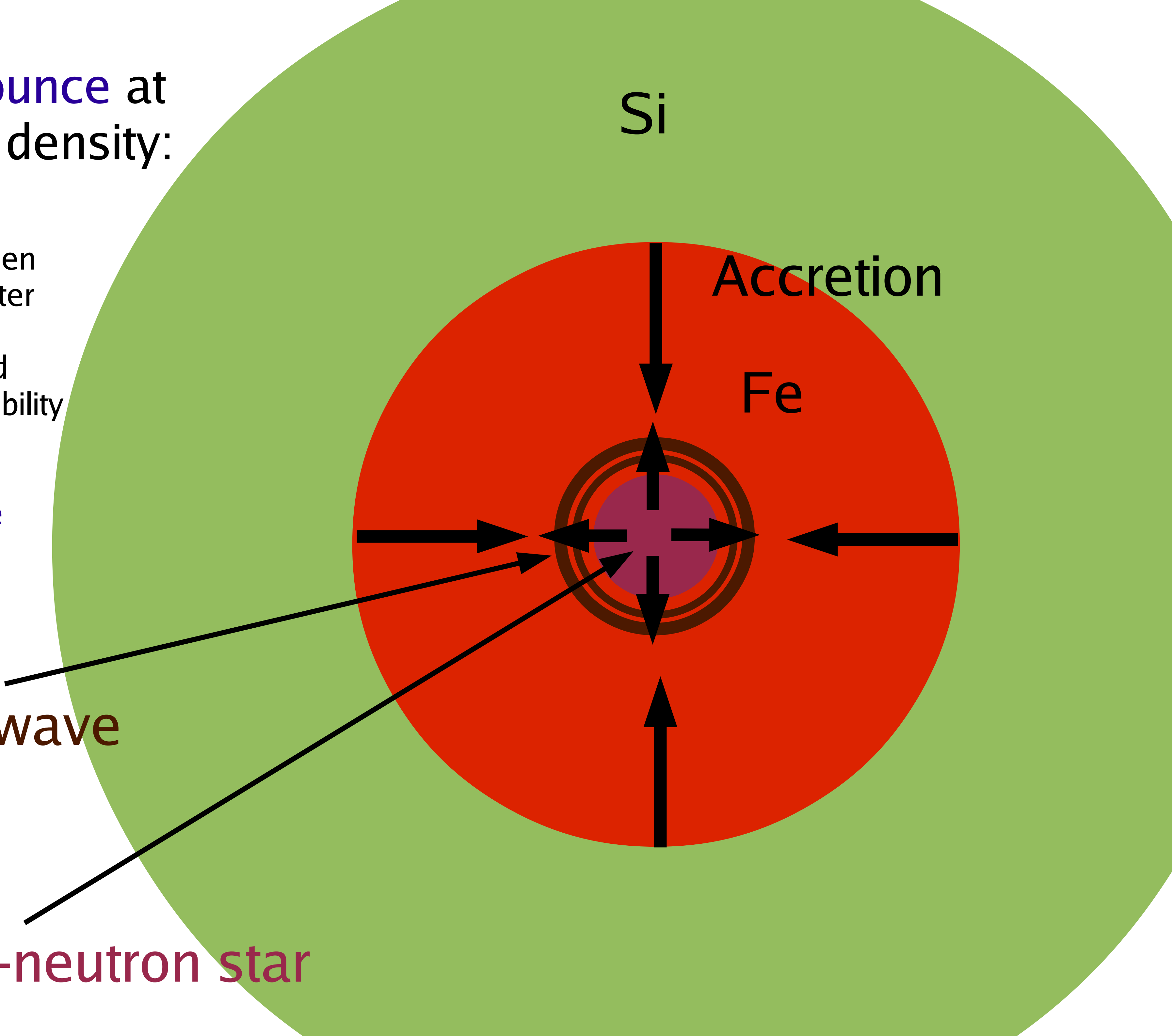


Collapse becomes dynamical because of electron captures and photo-disintegration of Fe-group nuclei

Core bounce at nuclear density:

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

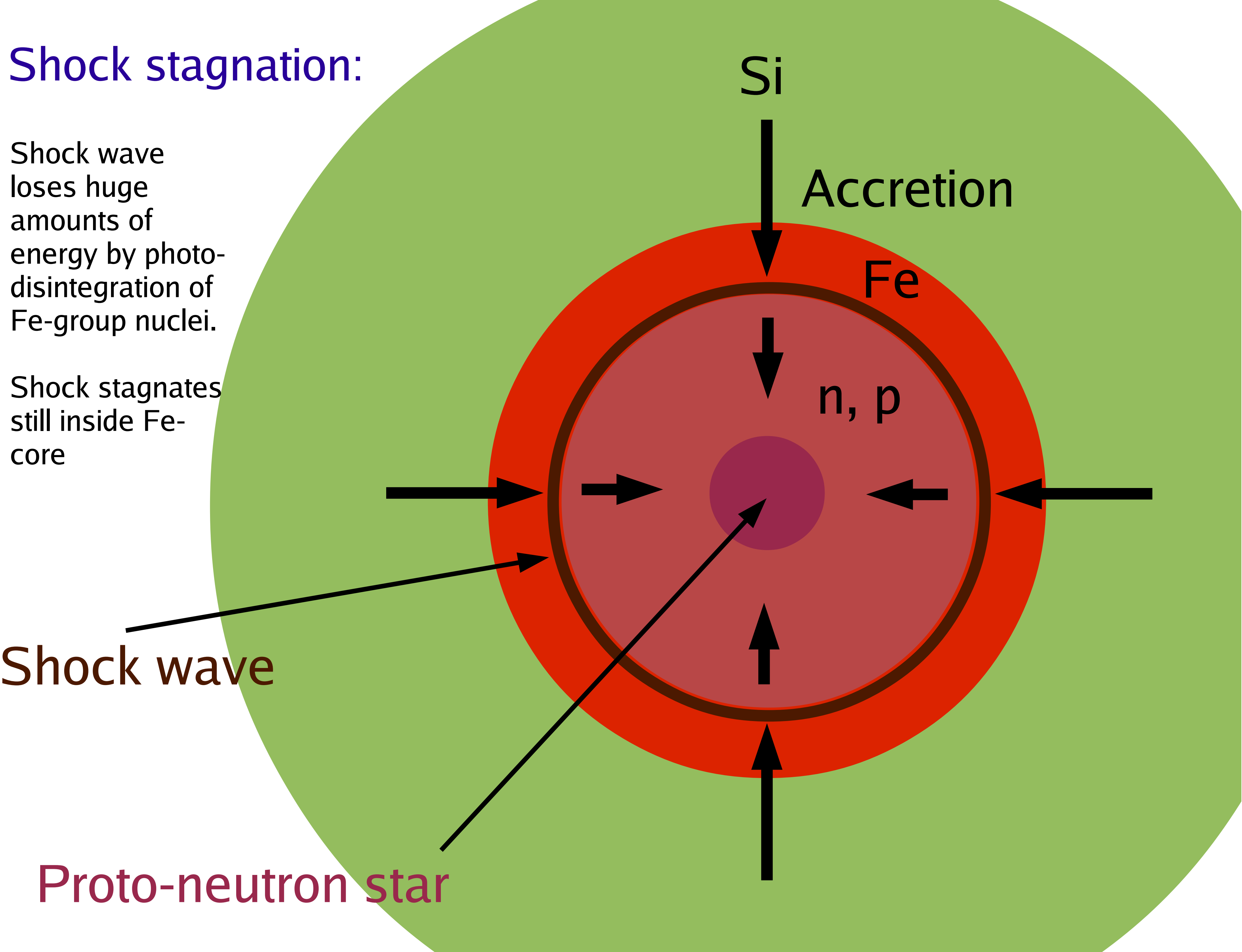
Shock wave forms



Shock stagnation:

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

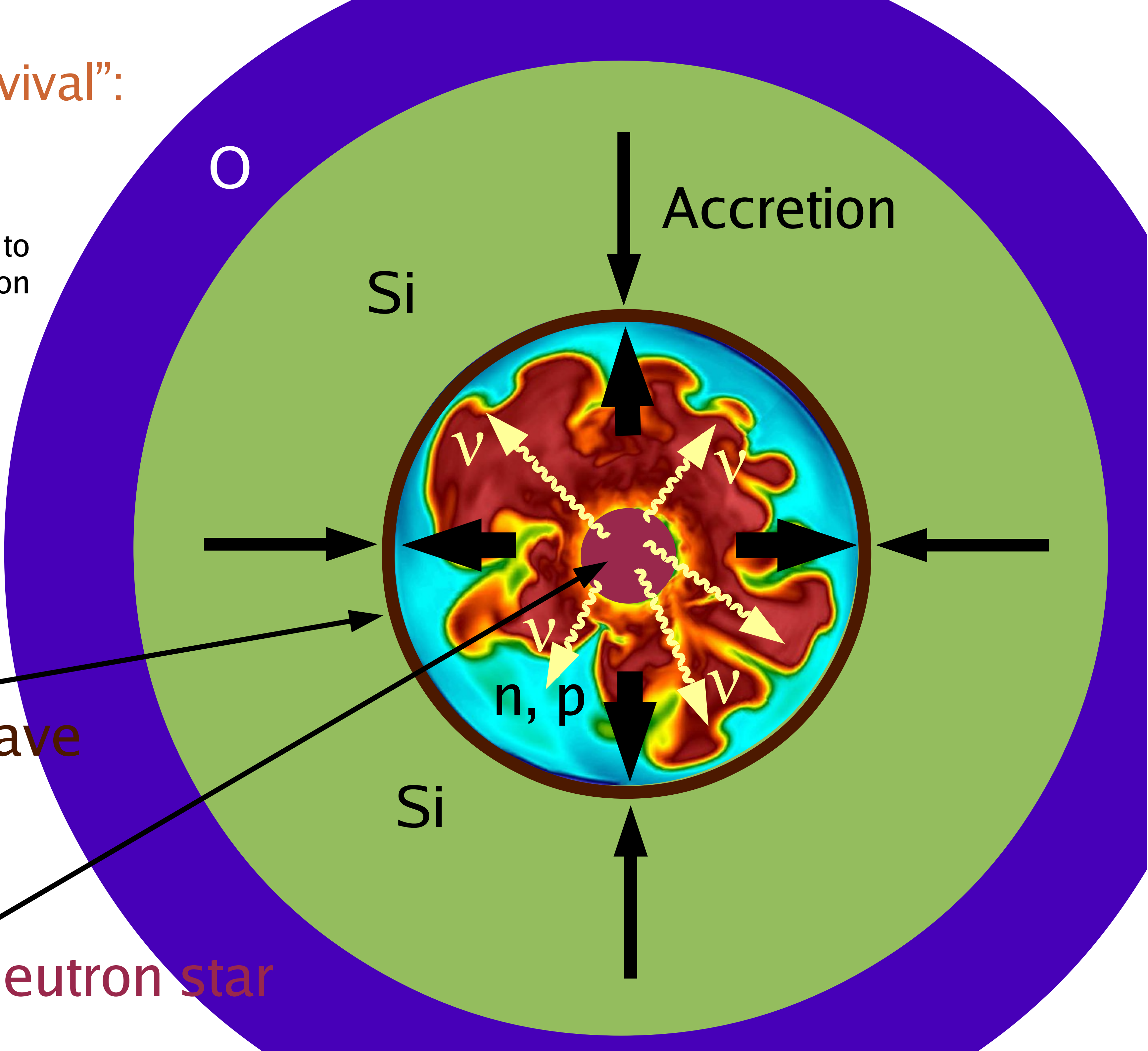
Shock stagnates still inside Fe-core



Shock “revival”:

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

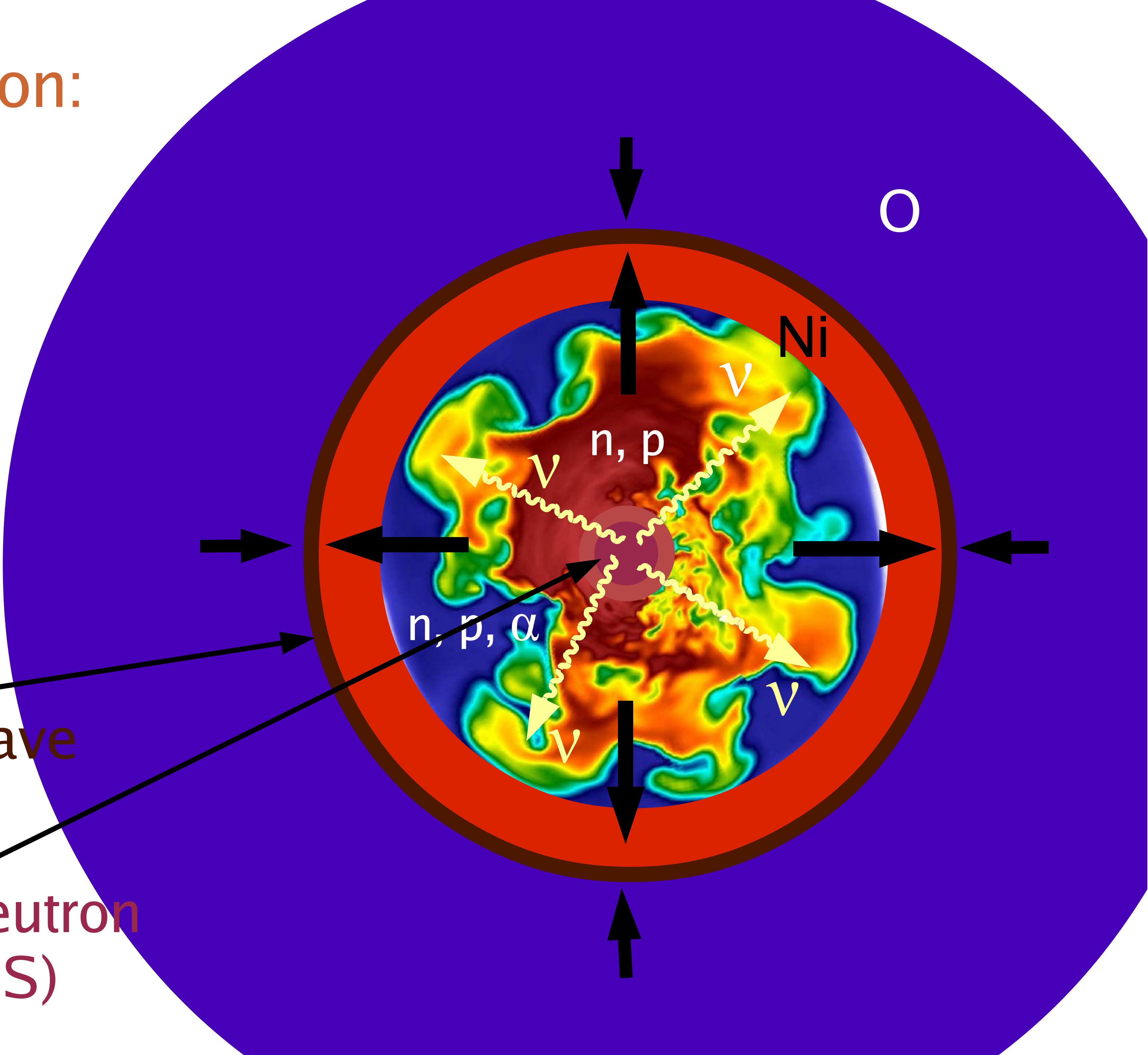
Shock can receive fresh energy from neutrinos!



Explosion:

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

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

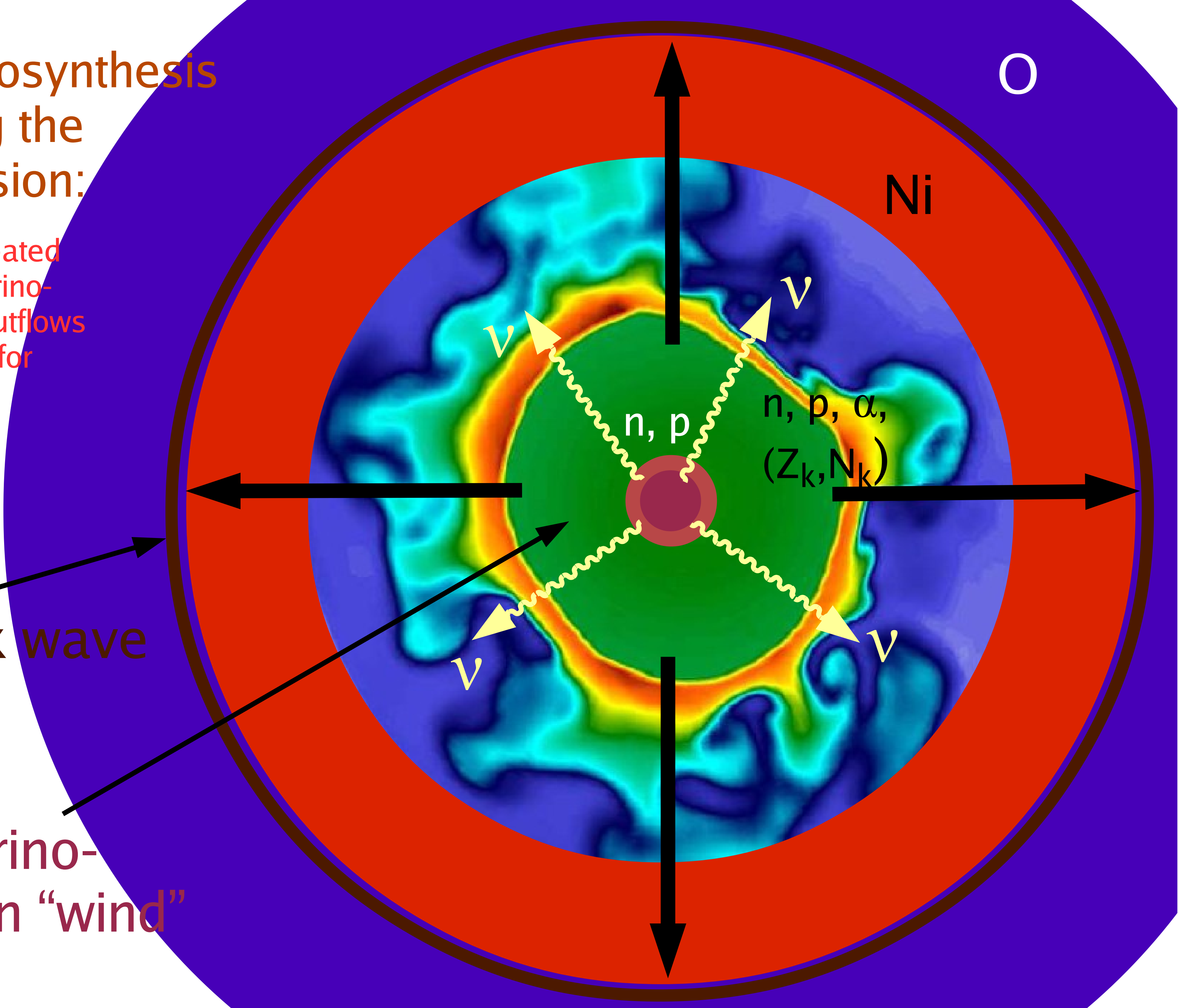


Shock wave

Proto-neutron star (PNS)

Nucleosynthesis during the explosion:

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



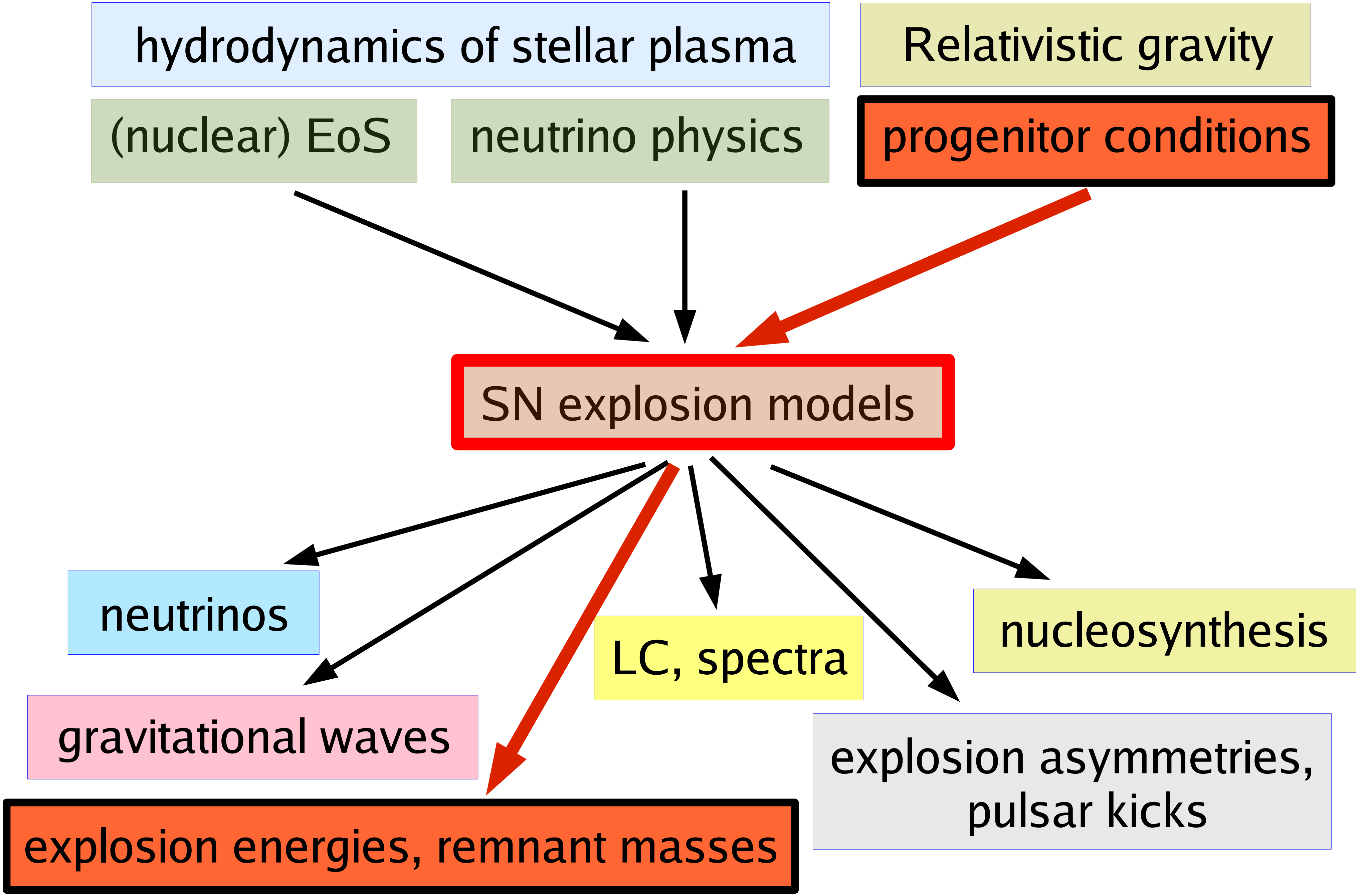
Shock wave

Neutrino-driven “wind”

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



hydrodynamics of stellar plasma

Relativistic gravity

(nuclear) EoS

neutrino physics

progenitor conditions

SN explosion models

neutrinos

gravitational waves

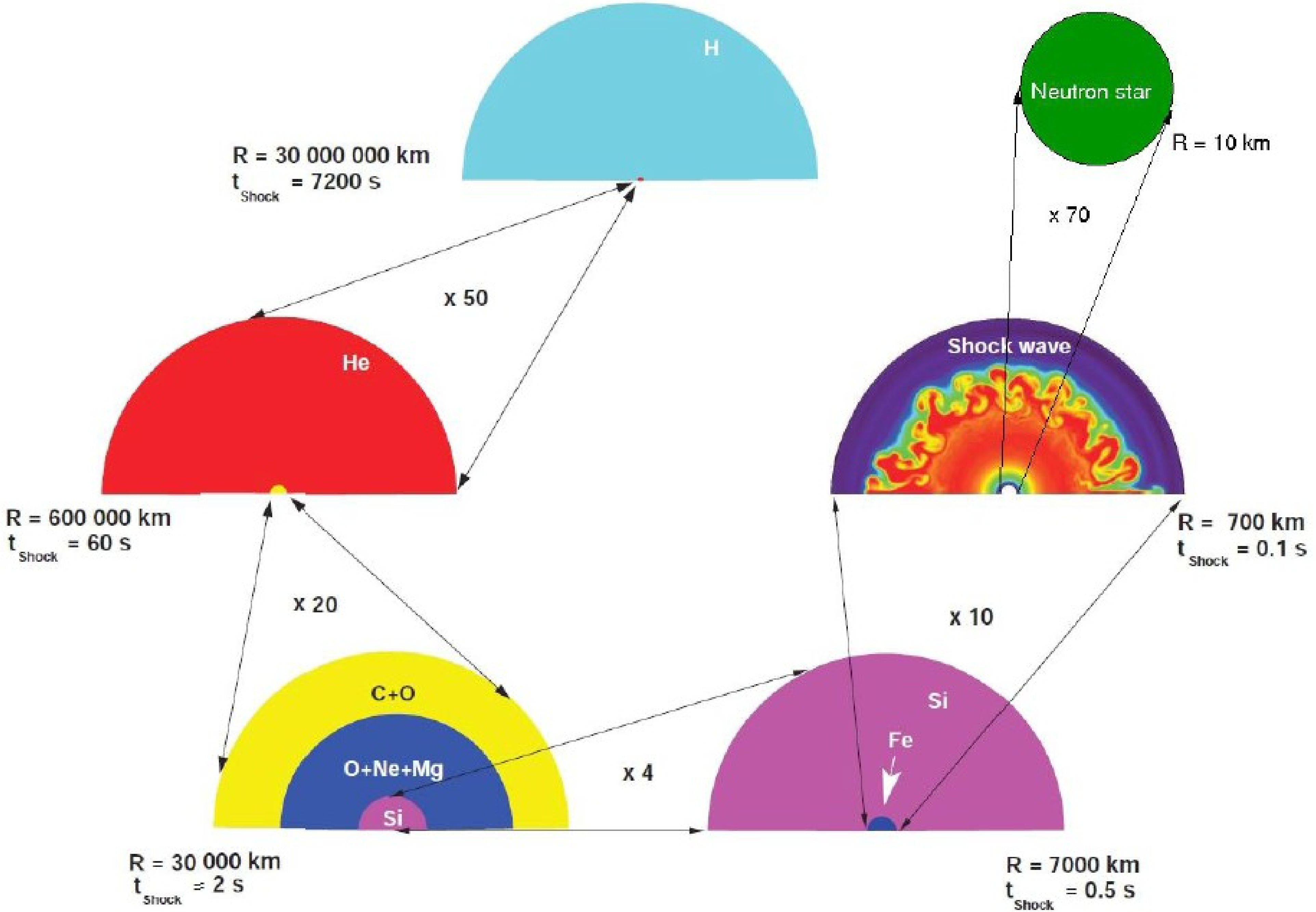
explosion energies, remnant masses

LC, spectra

nucleosynthesis

explosion asymmetries,
pulsar kicks

Supernova Scales



General-Relativistic 2D Supernova Models of the Garching Group

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

GR hydrodynamics (CoCoNuT)

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

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

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

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

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

CFC metric equations

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

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

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

Neutrino transport (VERTEX)

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

$$\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\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. \\
&\quad 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]- \\
&\quad\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\}+ \\
&\quad\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]+ \\
&\quad\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]- \\
&\quad 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]- \\
&\quad 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]+ \\
&\quad\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} \tag{2.29}$$

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

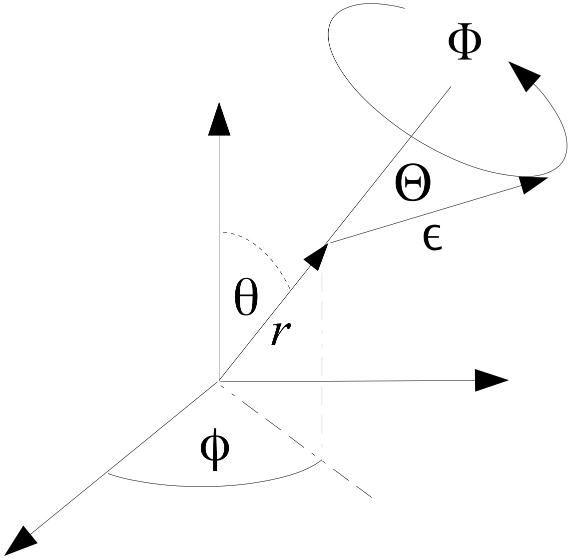
The Curse and Challenge of the Dimensions

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

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

Integration over 3D momentum space yields source terms for hydrodynamics

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



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

Explosion Mechanism: Most Sophisticated Current Models

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

SN Progenitors: Core density profiles

~8–10 M_{sun} (super-AGB) stars have ONeMg cores with a very steep density gradient at the surface

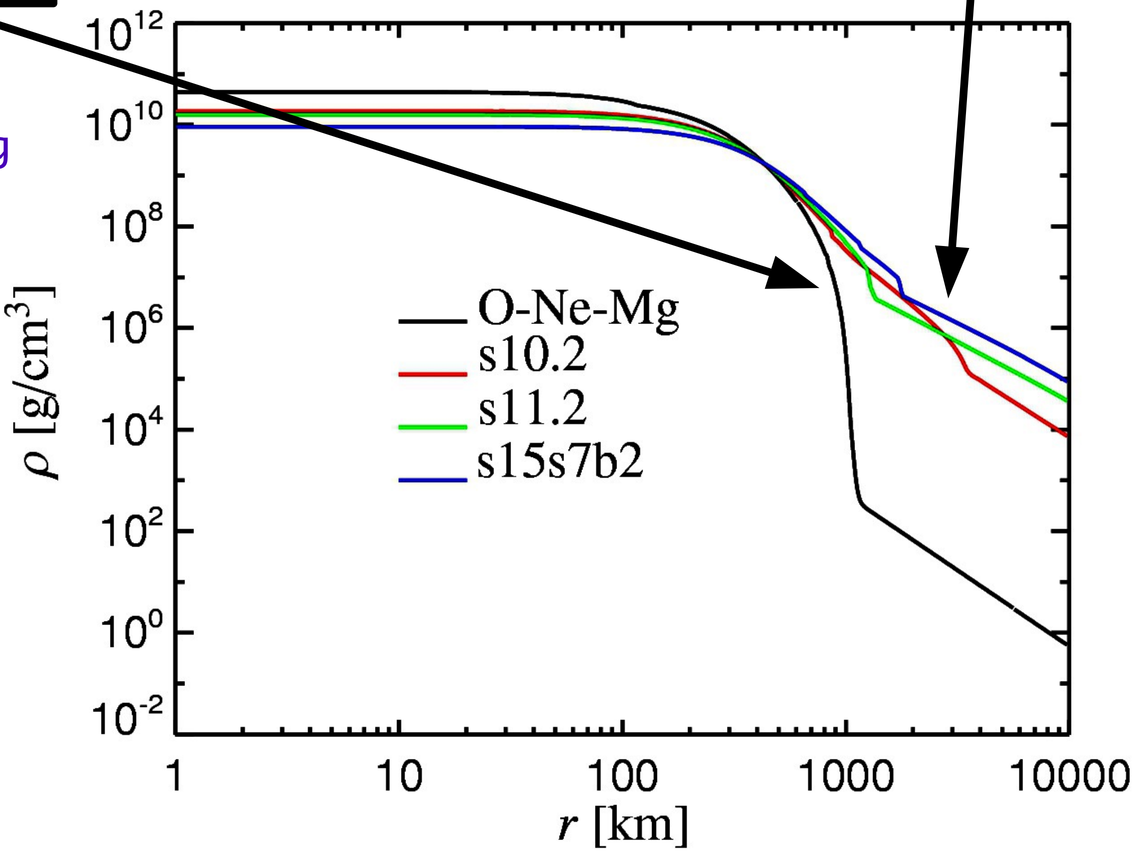
(====> rapidly decreasing mass accretion rate after core bounce)

>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

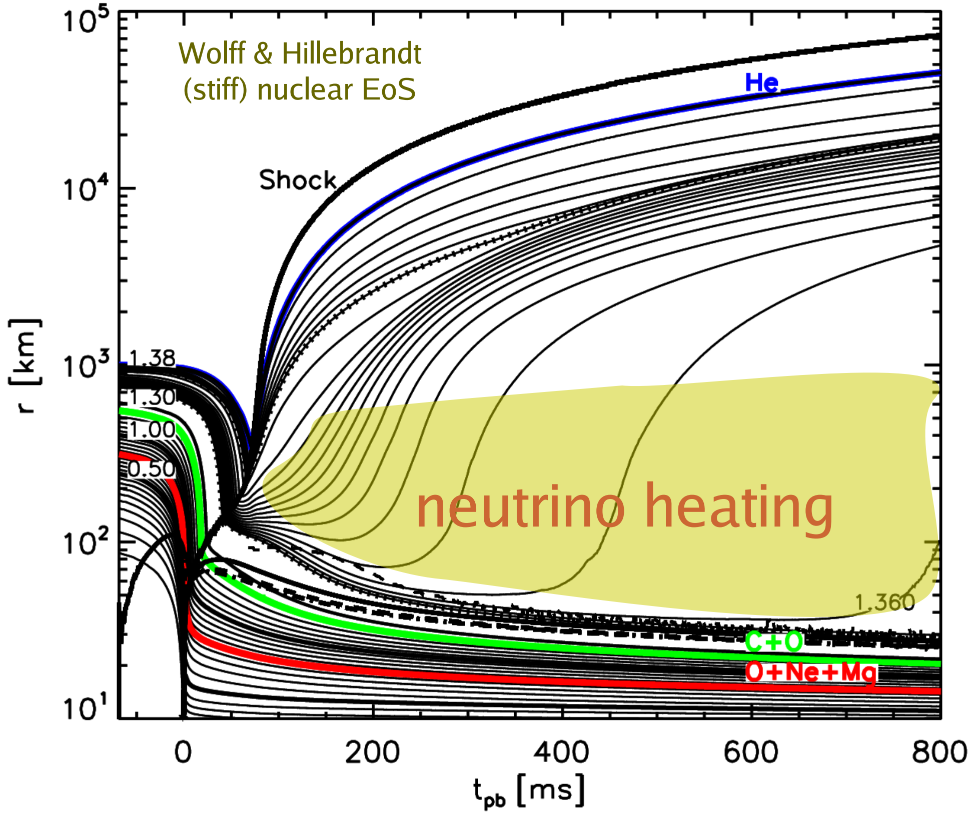


~30% of all SNe (Nomoto et al. 1981, 84, 87)

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.)

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

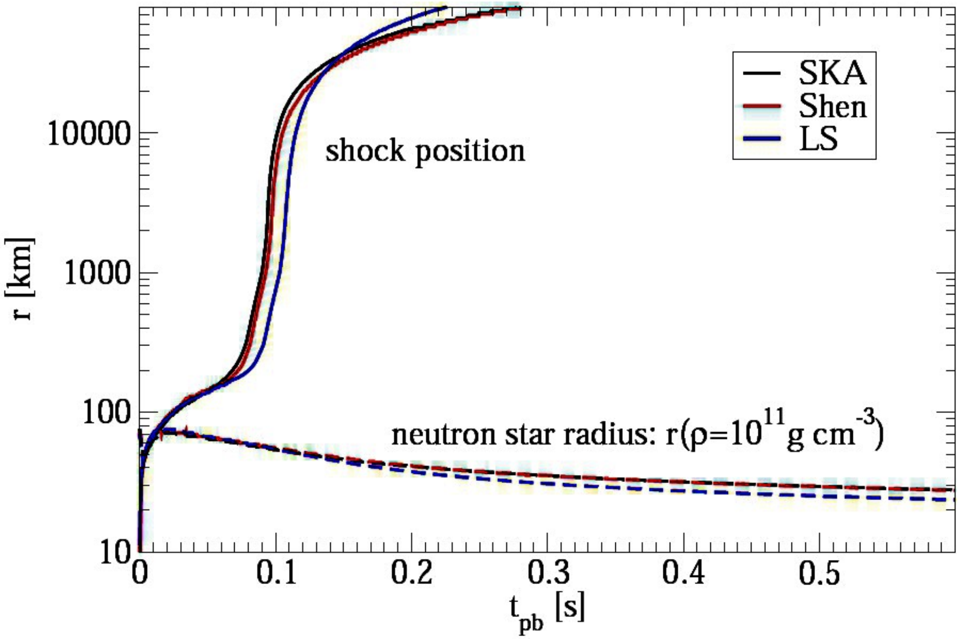
"Electron-capture supernovae"
or "ONeMg core supernovae"



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

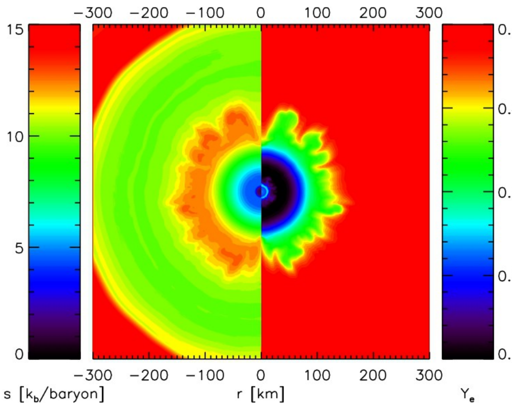
- No prompt explosion !
- Mass ejection by "neutrino-driven wind"
  (like Mayle & Wilson 1988
  and similar to AIC of WDs;
  see Woosley & Baron 1992, Fryer et al. 1999;
  Dessart et al. 2006)
- Explosion develops in similar way for soft nuclear EoS (i.e. compact PNS) and stiff EoS (less compact PNS)



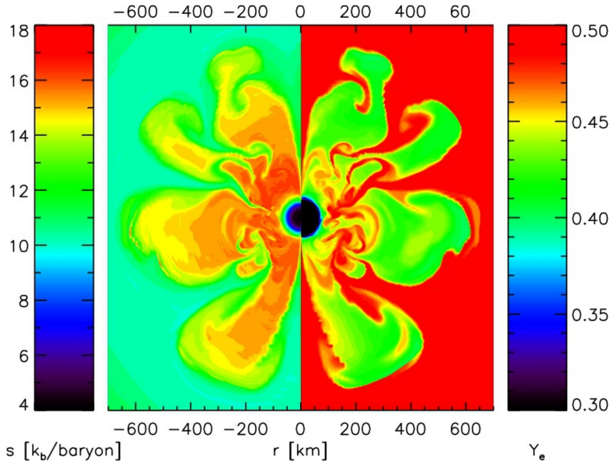
2D SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

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

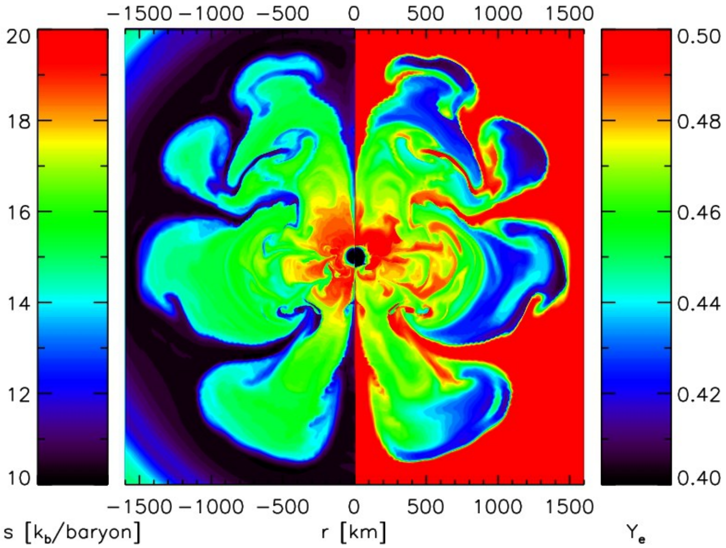
Entropy Y_e



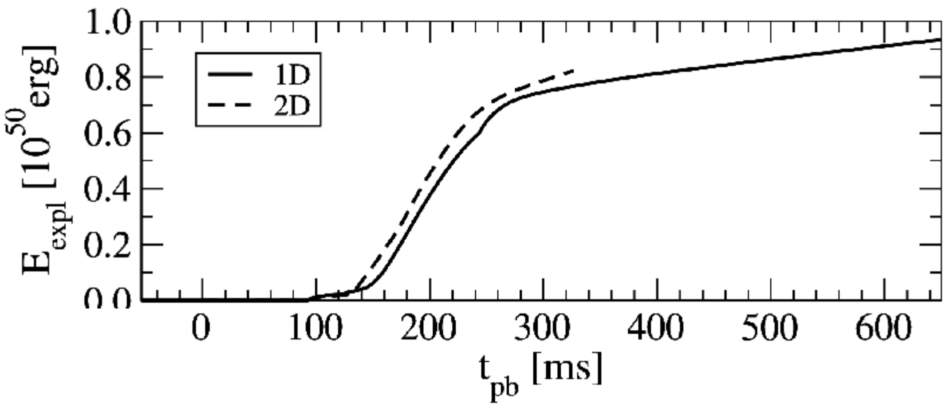
t = 0.097 s after core bounce



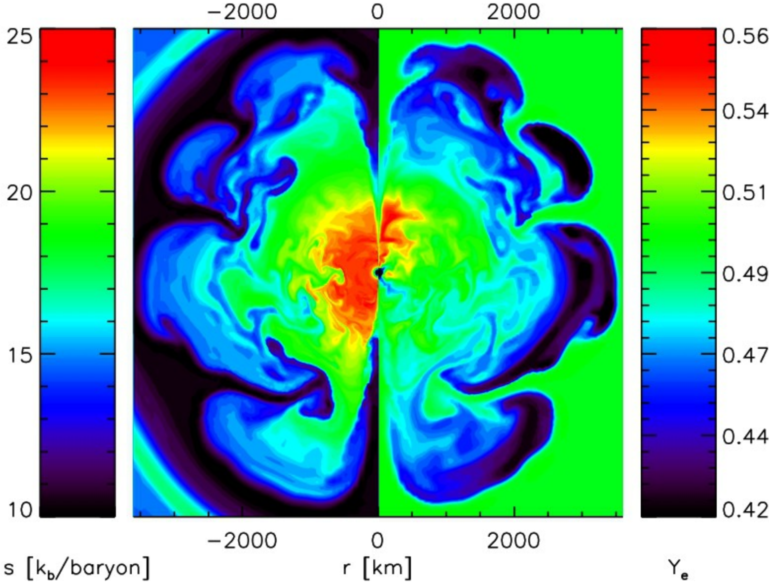
t = 0.144 s after core bounce



t = 0.185 s after core bounce

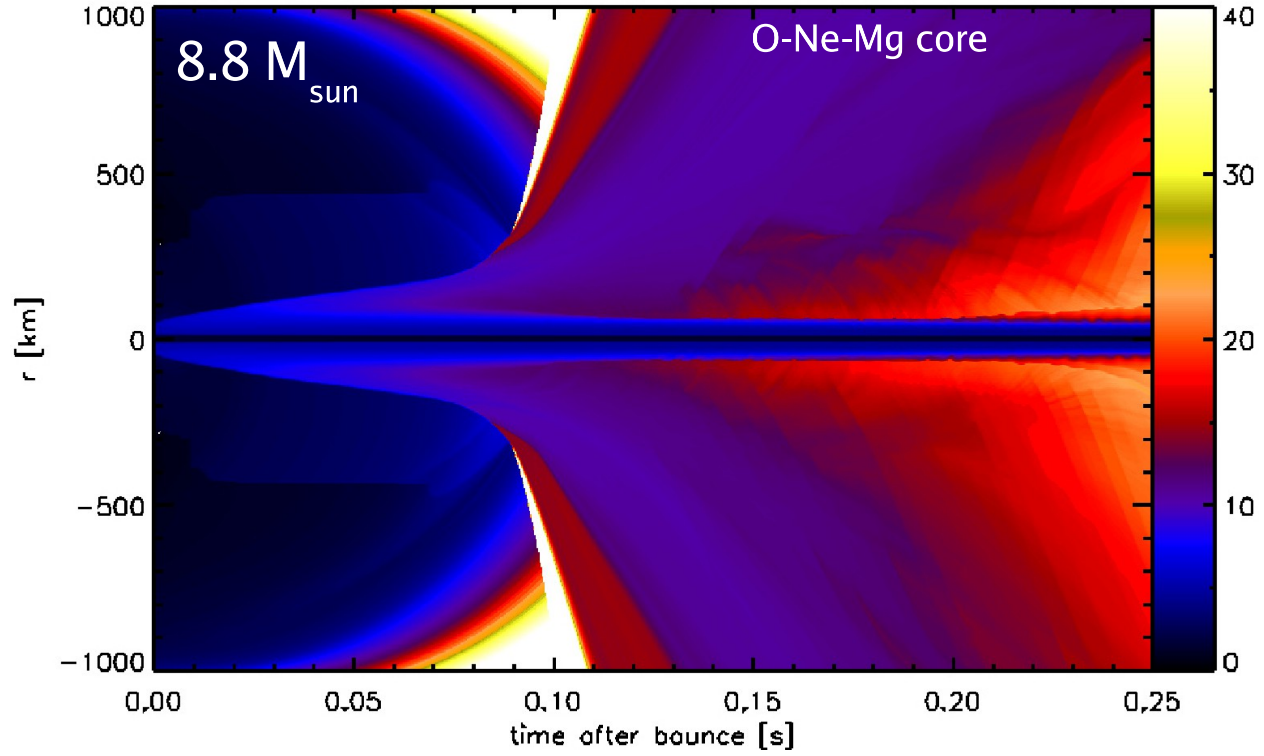


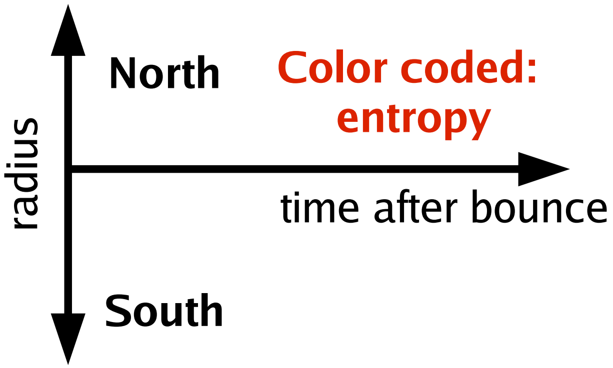
Janka et al. (2008), Wanajo et al. (2011), Groote et al. (in preparation)



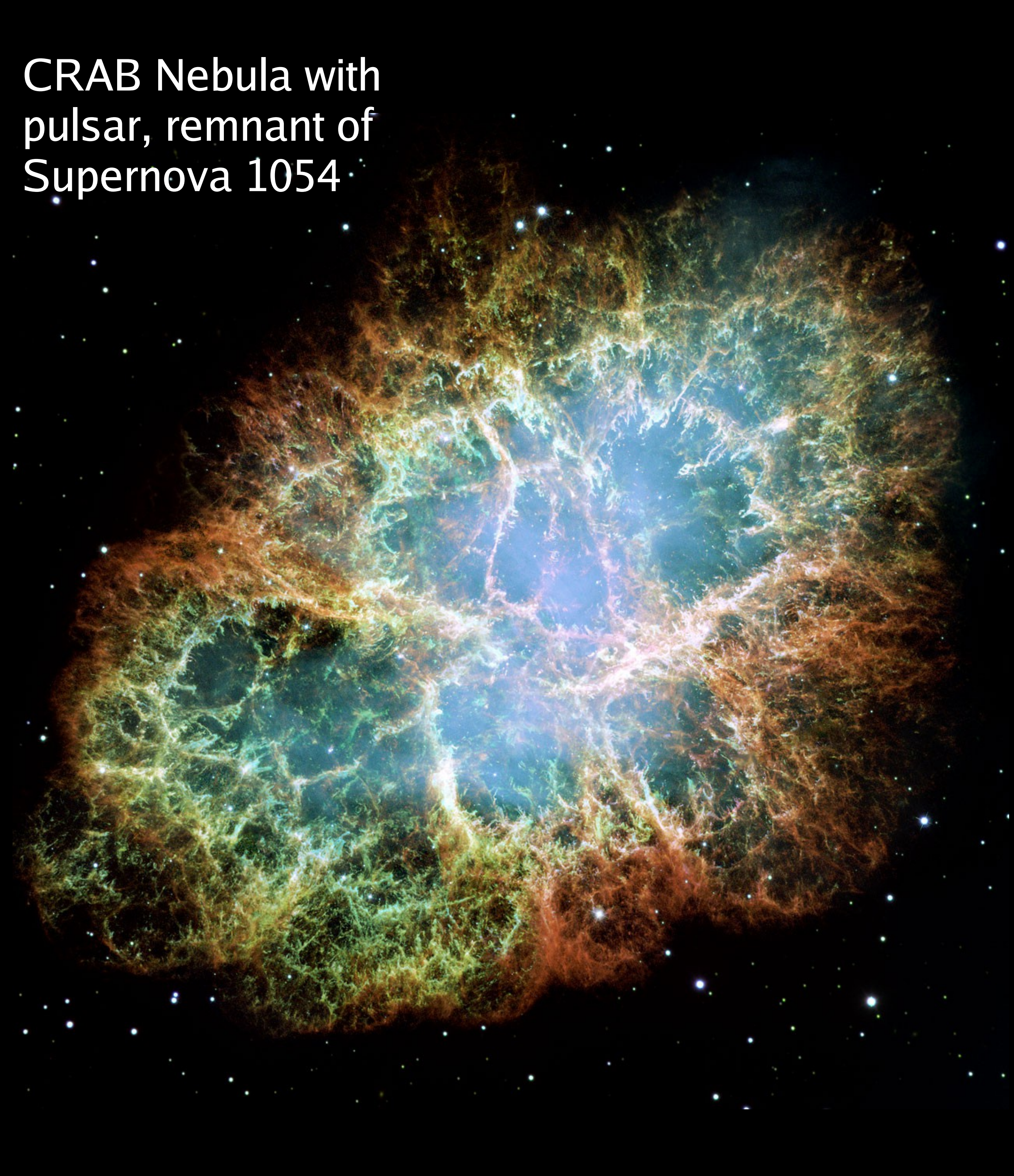
t = 0.262 s after core bounce

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





Color coded: entropy



CRAB Nebula with pulsar, remnant of Supernova 1054

Explosion properties:

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

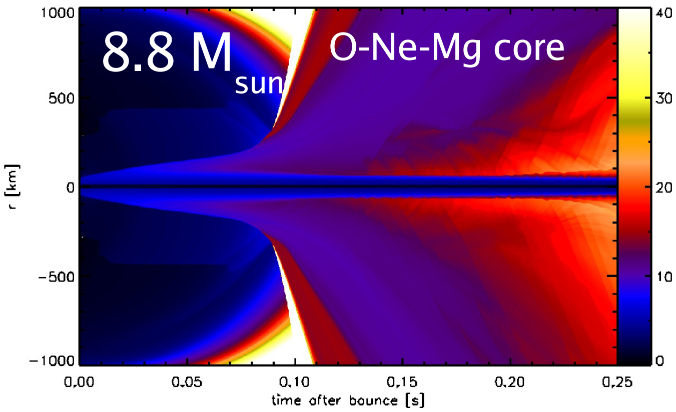
Low explosion energy and ejecta composition (little Ni, C, O) of ONeMg core explosion are compatible with CRAB (SN1054)

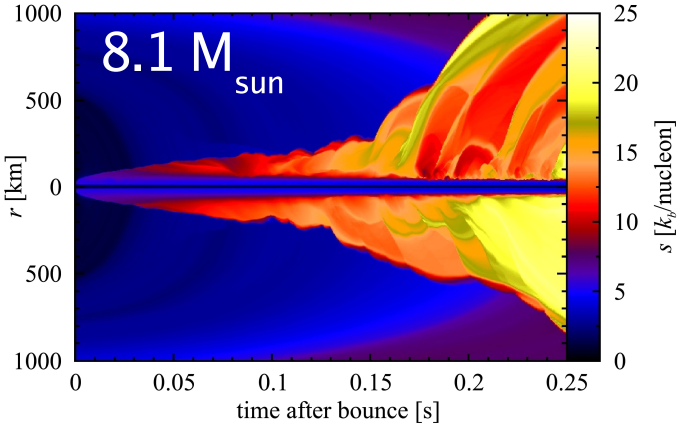
(Nomoto et al., Nature, 1982;
Hillebrandt, A&A, 1982)

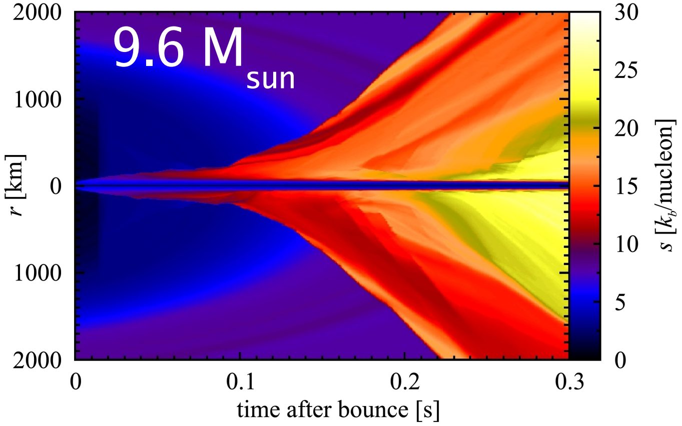
Might also explain other low-luminosity supernovae (e.g. SN1997D, 2008S, 2008HA)

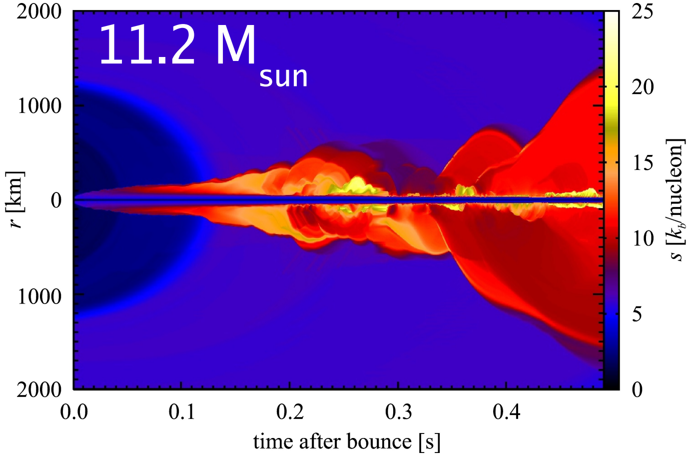
Explosions of Stars with $M_{star} > 10\ M_{sun}$

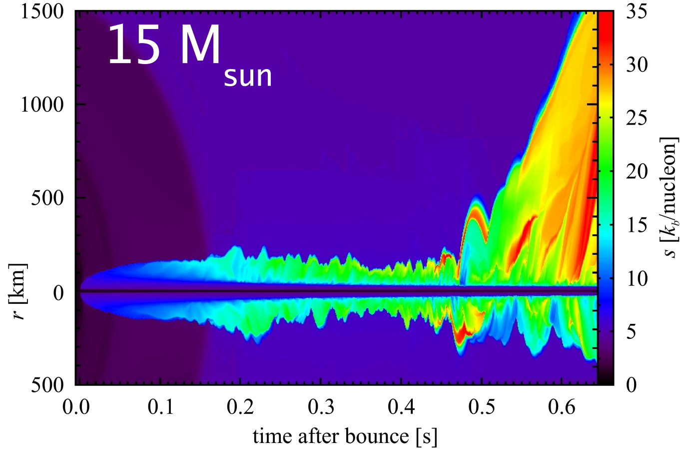
Relativistic 2D CCSN Explosion Models

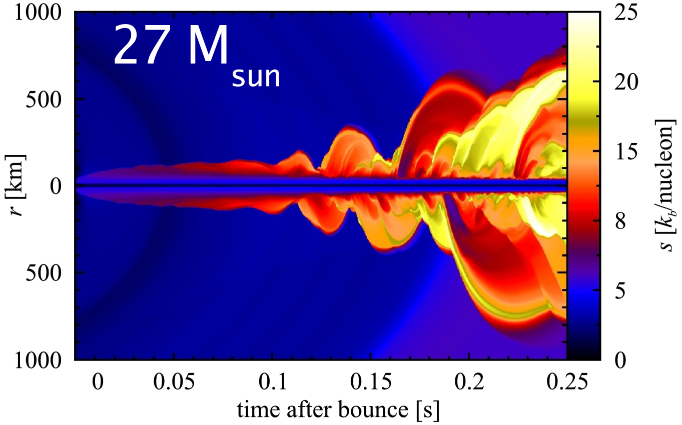


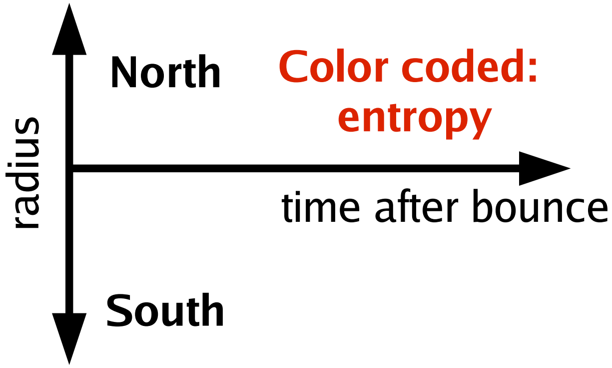












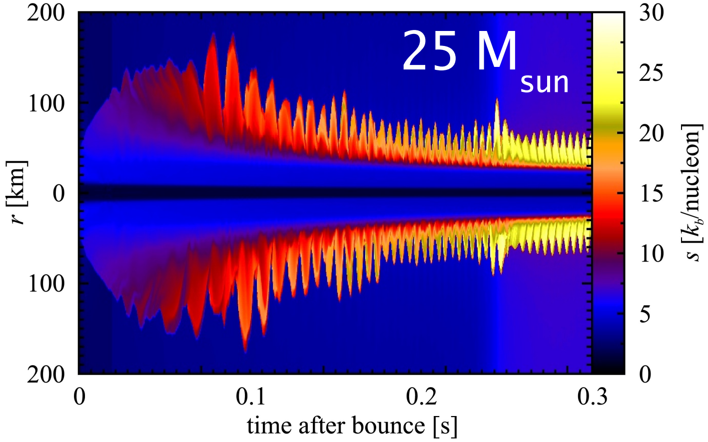
North

South

radius

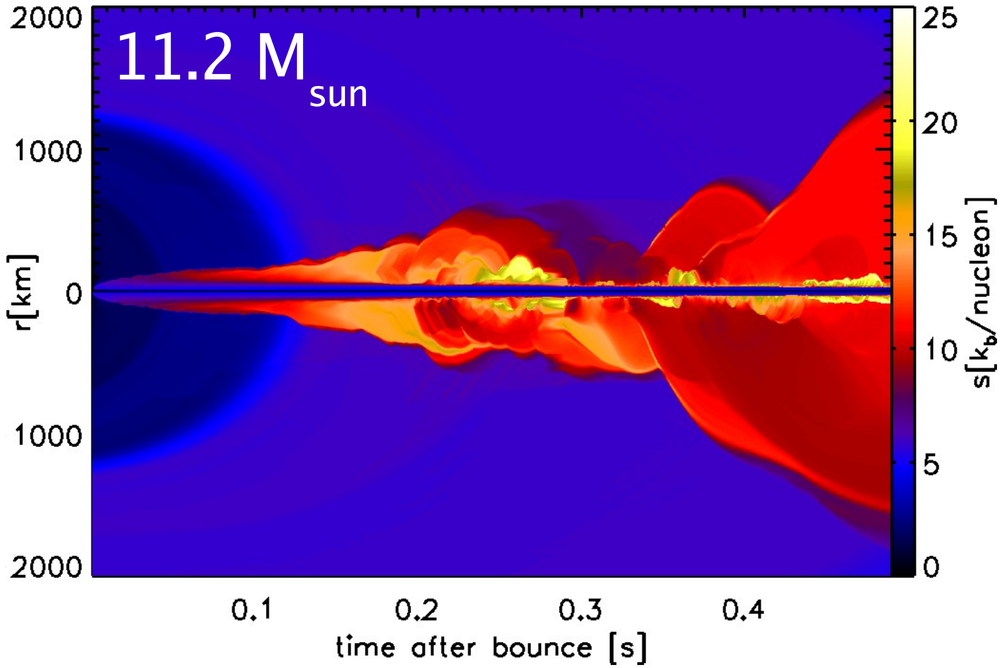
time after bounce

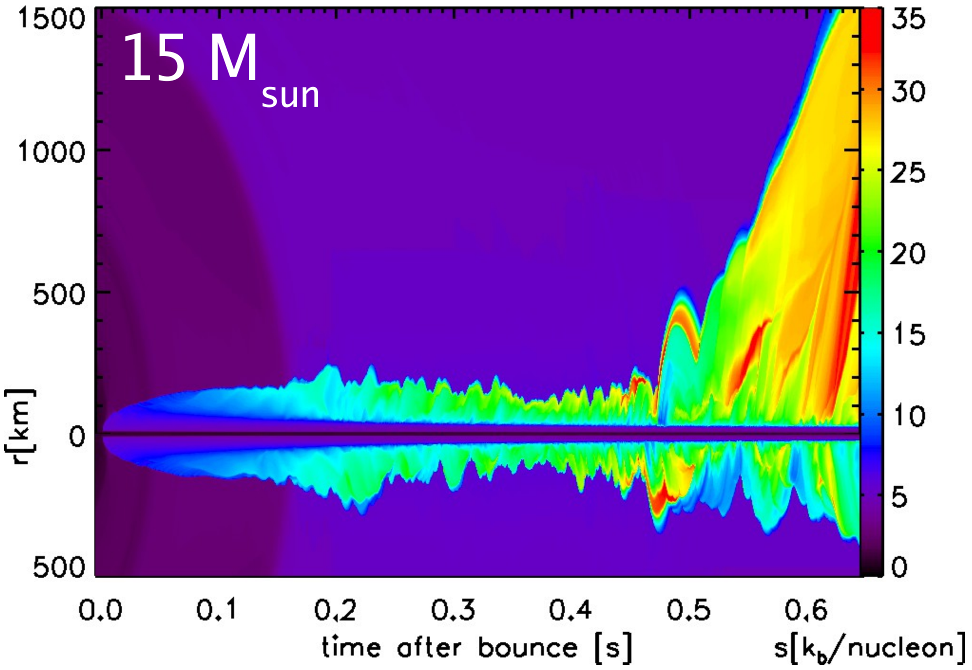
Color coded: entropy



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)



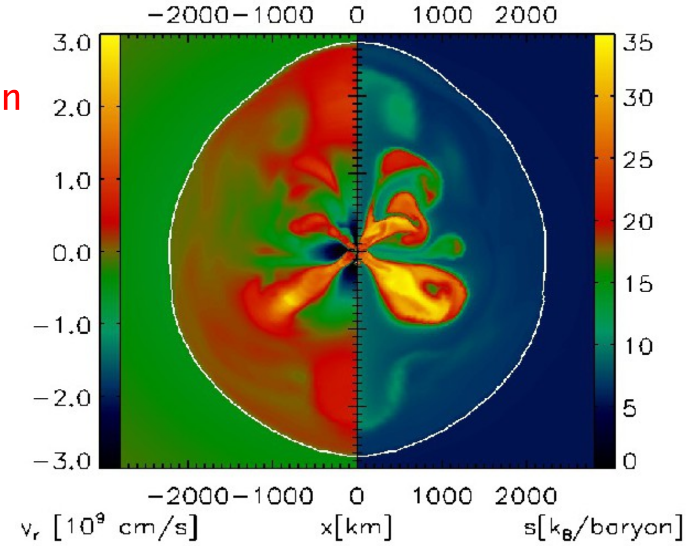


Violent, quasi-periodic, large-amplitude shock oscillations (by SASI) can lead to runaway and onset of explosion.

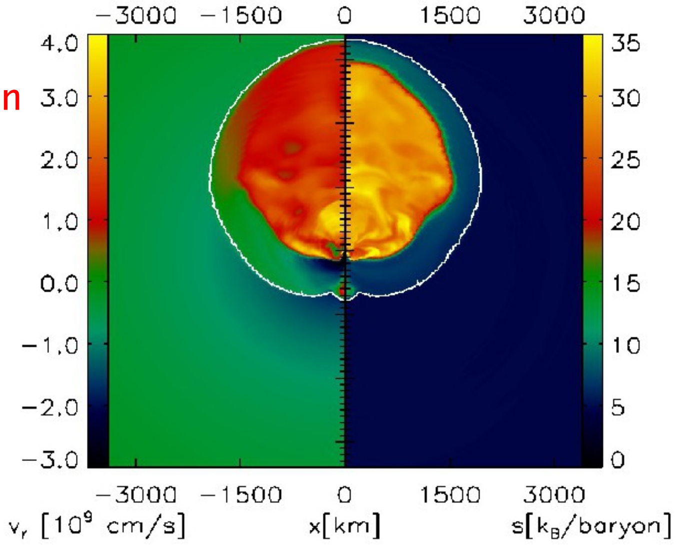
They also produce variations of neutrino emission and gravitational-wave signal.

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

$11.2\ M_{sun}$



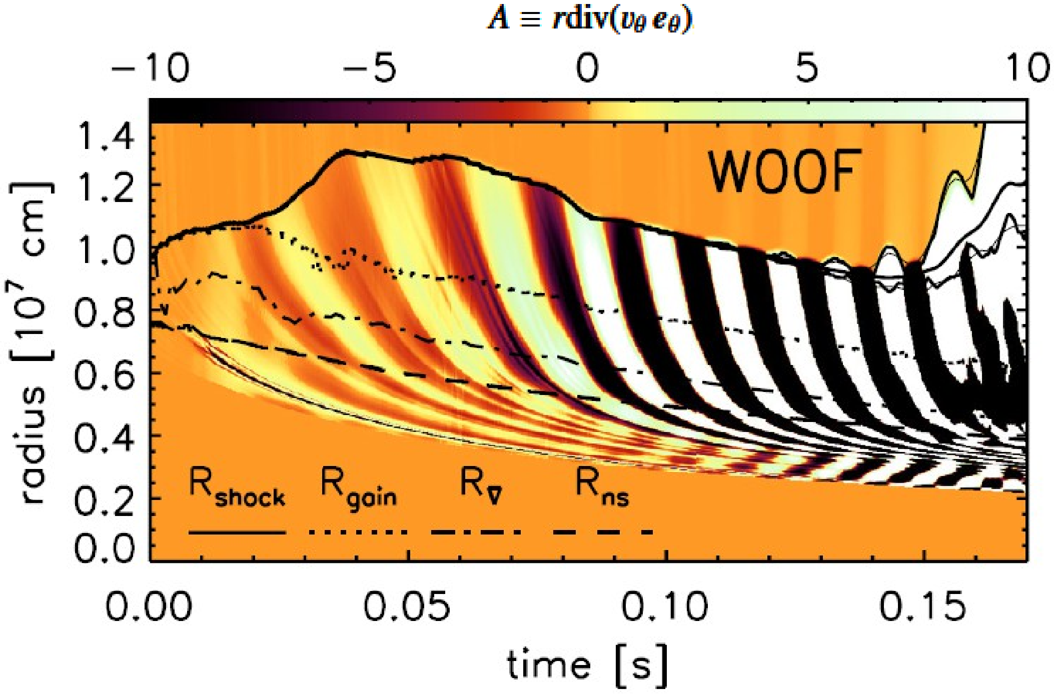
$15\ M_{sun}$



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)



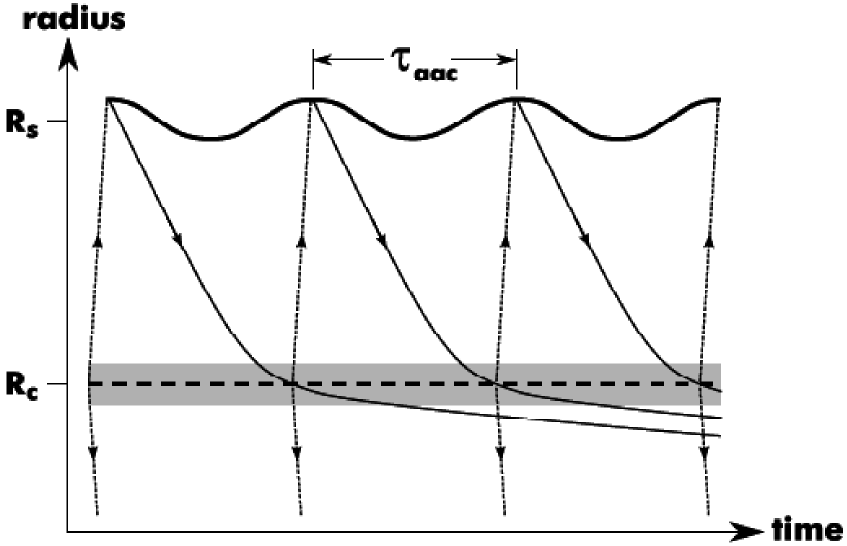


Fig. 1. Schematic view of the advective-acoustic cycle between the shock at R_s (thick solid line) and the coupling radius, R_c (thick dashed line), in the linear regime, shown for the case where the oscillation period of the shock ($\tau_{\rm osc}$) equals the cycle duration, $\tau_{\rm aac}$. Flow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

$$\boxed{\tau^{\nabla}_{\rm aac} \equiv \int_{R_\nabla}^{R_{\rm sh}} \frac{\mathrm{d}r}{|v|} + \int_{R_\nabla}^{R_{\rm sh}} \frac{\mathrm{d}r}{c-|v|}}$$

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

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**

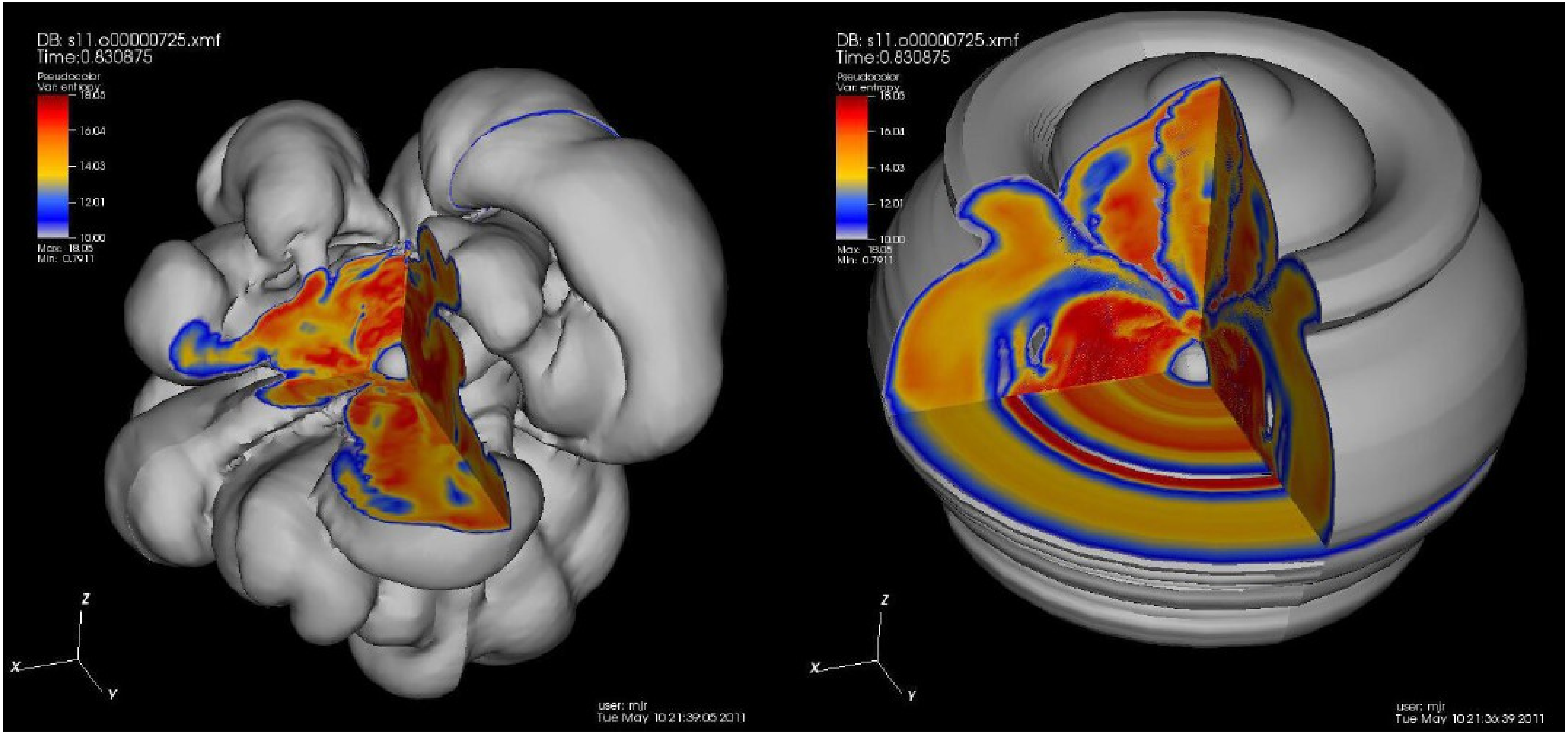
Explosions in 2D simulations were also obtained recently by
Suwa et al. (2010, 2012), Takiwaki et al. (2013) and
Bruenn et al. (ApJL, 2013).
BUT: There are important quantitative differences between all models.

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!

2D vs. 3D Morphology



(Images from Markus Rampp, RZG)

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.

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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.

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TGCC Curie

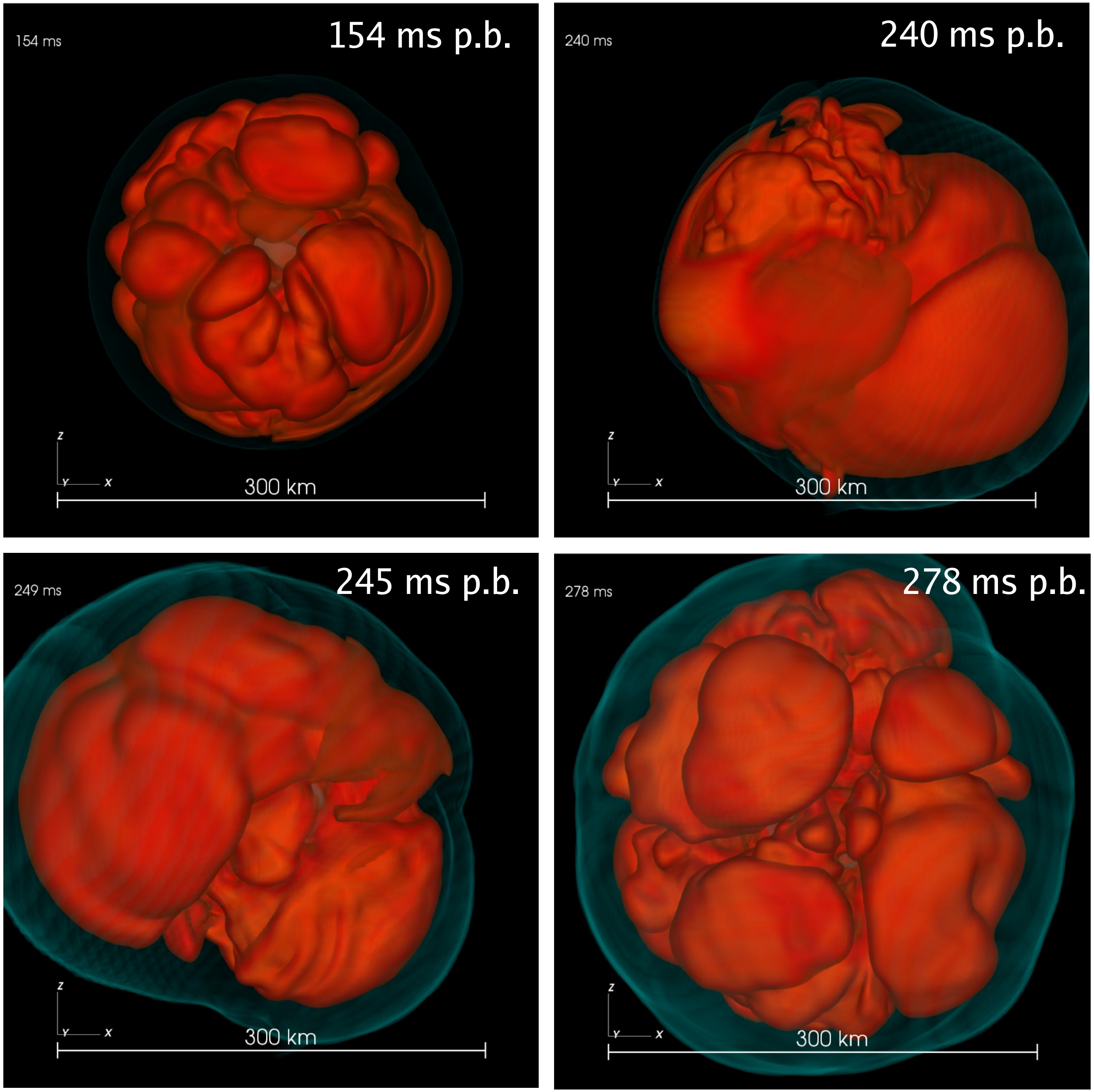
SuperMUC Petascale System

created by LRZ (2012)

3D Core-Collapse Models

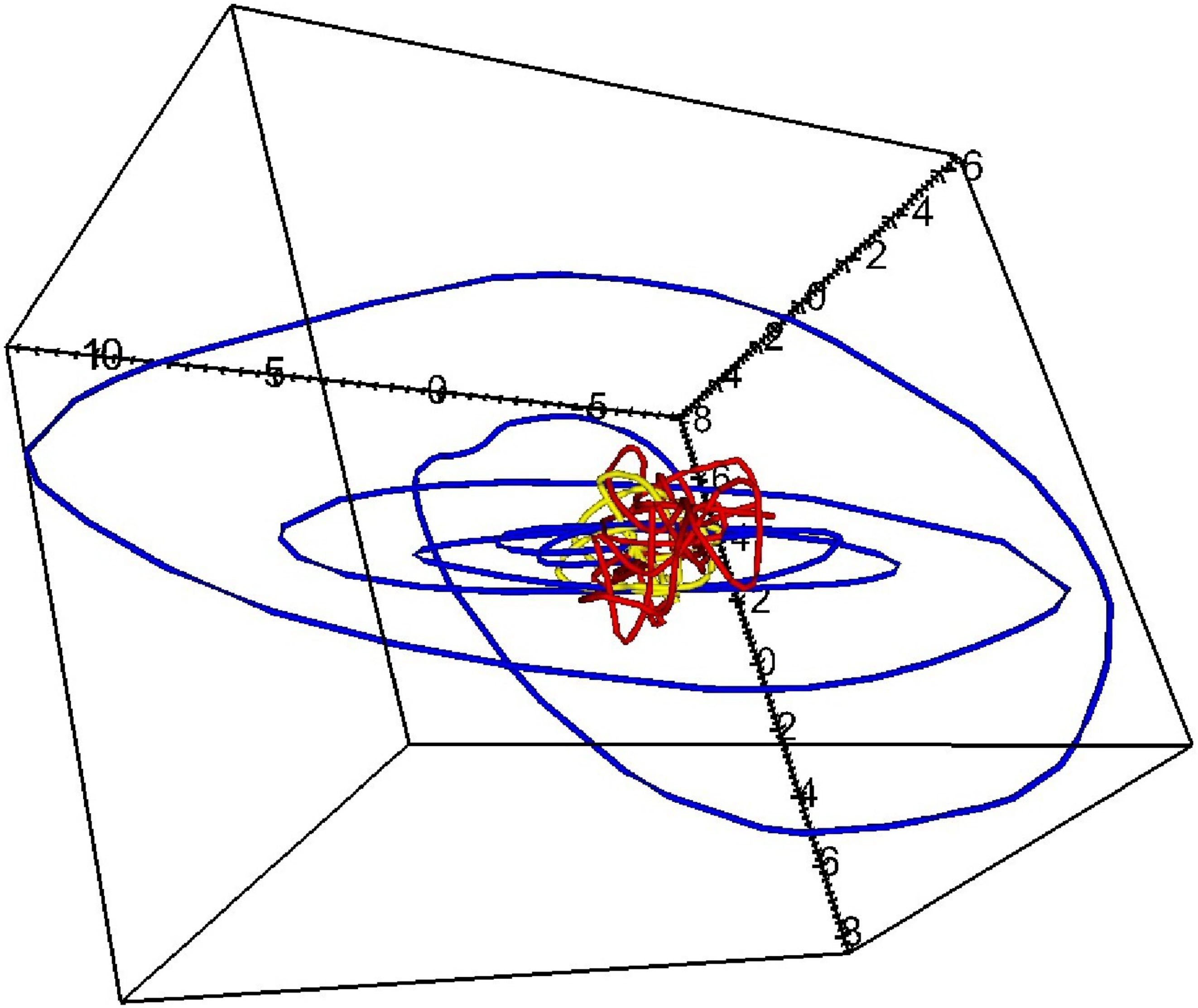
27 M_{sun} progenitor (WHW 2002)

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 Core-Collapse Models



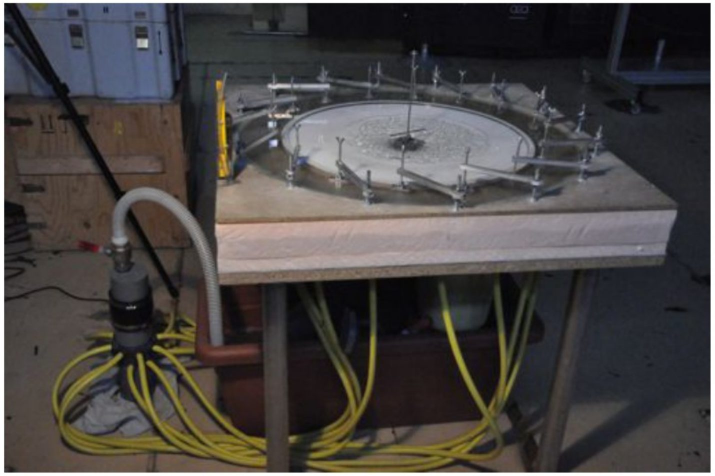
F. Hanke et al., arXiv:1303.6269

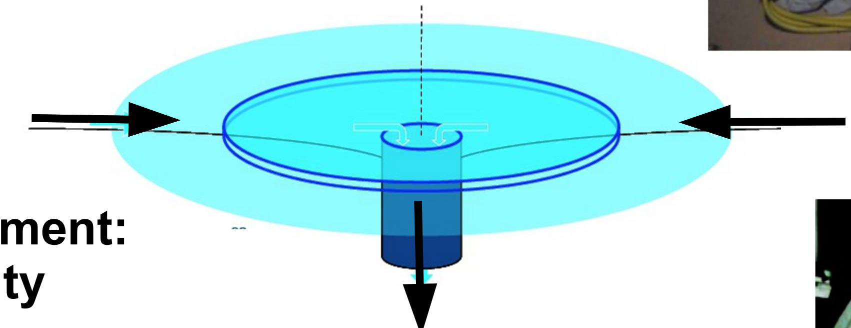
27 M_{sun} progenitor (WHW 2002): Spiral mode axis

Laboratory Astrophysics

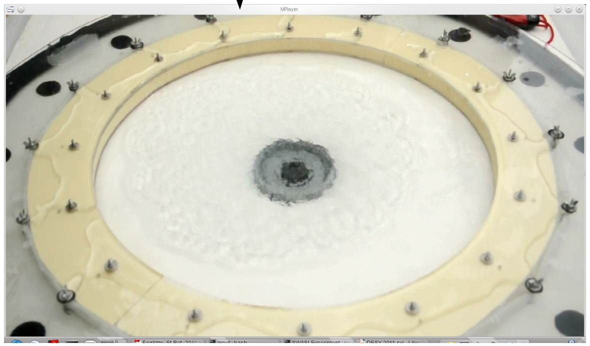
"SWASI" Instability as an analogue of SASI in the supernova core

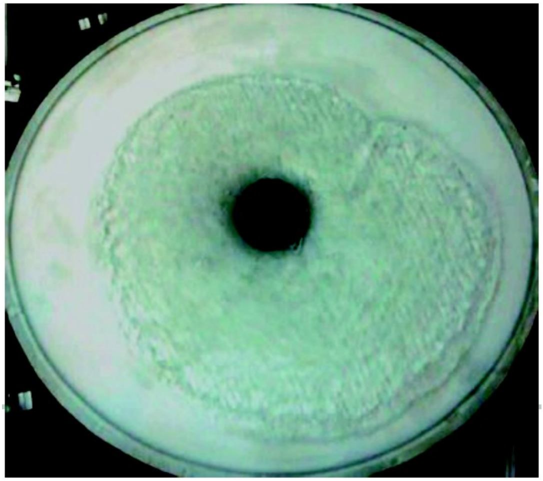
Foglizzo et al., PRL 108 (2012) 051103





Constraint of experiment:
No convective activity





Summary

- 2D models with relativistic effects (2D GR and approximate GR) yield explosions for “soft” EoSs, but explosion energy may tend to be low.
- 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 progenitor-core asymmetries can affect onset of explosion (cf. Couch & Ott, arXiv:1309.2632)! How important is slow rotation for SASI growth?
- Missing physics ?????