Max-Planck-Institut
für Astrophysik

LMU TUM
ORIGINS
Excellence Cluster

SFB 1258
Neutrinos
Dark Matter
Messengers

## Guest Lecture

University Stockholm, November 22, 2022

# Core-collapse Supernova Theory

## The Final Fates of Massive Stars

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

# Contents

- Introduction to supernovae
- Final stages of stellar evolution
- Physics of stellar core collapse:

  Neutrinos, explosion mechanism, dynamics
- Supernova nucleosynthesis and diagnostics

  Cas A, SN 1987A, Crab

- Gamma-ray bursts and hypernovae (?)

# Concise reviews of much of what I will say:

H.-T. J., K. Langanke, A. Marek, et al., “Theory of core-collapse supernovae”, Physics Reports 442 (2007) 38; astro-ph/0612072

H.-T. J., “Explosion mechanisms of core-collapse supernovae”, ARNPS 62 (2012) 407;  arXiv:1206.2503

H.-T. J., F. Hanke, L. Hüdepohl, et al., “Core-Collapse Supernovae: reflections and directions”, PTEP 2012, 01A309;  arXiv:1211.1378

A. Mirizzi, I. Tamborra, H.-T. J., et al., “Supernova neutrinos: production, oscillations and detection, La Rivista del Il Nuovo Cimento 39 (2016) 1; arXiv::1508.00785

H.-T. J., T. Melson, and A. Summa, “Physics of core-collapse supernovae in three dimensions: a sneak preview”, ARNPS 66 (2016); arXiv:1602.05576

# Introduction

# Supernovae in the Universe

- 1–10 supernovae explode in the Universe every second
- ~2 per 100 years in the Milky Way (historical records of ~10 past events, several with visible remnants)
- Several 100 distant supernovae observed every year in surveys

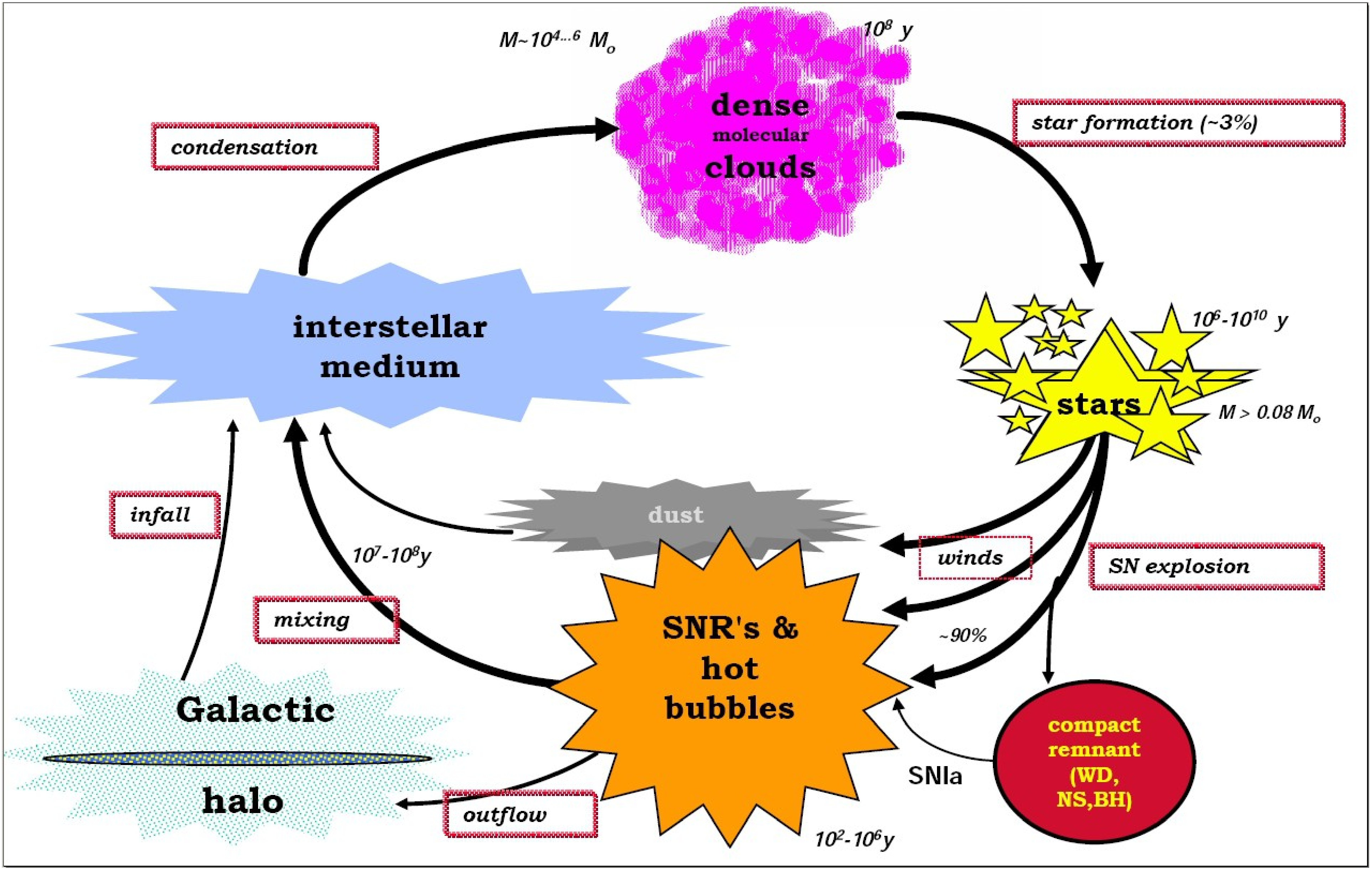
- Energy release in radiation: $10^{49}$ erg
  Release of kinetic energy of ejected gas: $10^{51}$ erg
  (1 erg = $10^{-7}$ J; $10^{51}$ erg = 1 bethe)

- Hypernovae and gamma-ray bursts (GRBs) can release up to 100 times more energy, but occur only in < 1% of all core collapses!

# Role of Supernovae

- strongest cosmic explosions
- sources of heavy elements
- driving force of cosmic cycle of matter
- sources of neutrinos and gravitational waves: fundamental physics
- acceleration of cosmic radiation
- birth sites of neutrons stars and black holes
-
-
-

# SNe in the Cosmic Cycle of Matter



$M \sim 10^{4 \ldots 6}\ M_o$

$10^8$ y

**dense**
**molecular**
**clouds**

*condensation*

*star formation (~3%)*

**interstellar medium**

**stars**

$10^6$-$10^{10}$ y

$M > 0.08\ M_o$

**dust**

*infall*

$10^7$-$10^8$y

*winds*

*SN explosion*

*mixing*

**SNR's & hot bubbles**

~90%

**Galactic**

**halo**

**compact remnant (WD, NS,BH)**

SNIa

*outflow*

$10^2$-$10^6$y

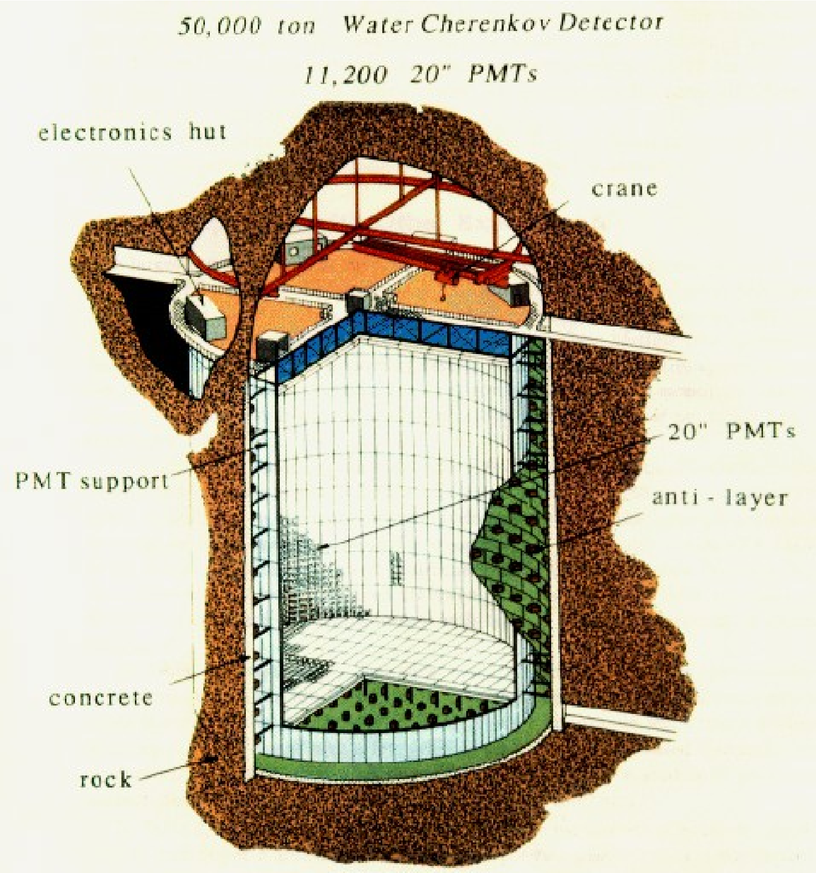
Sanduleak –69 202

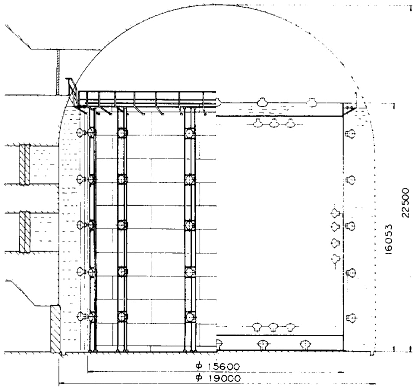
Supernova 1987A 23. Februar 1987

# Supernova 1987A

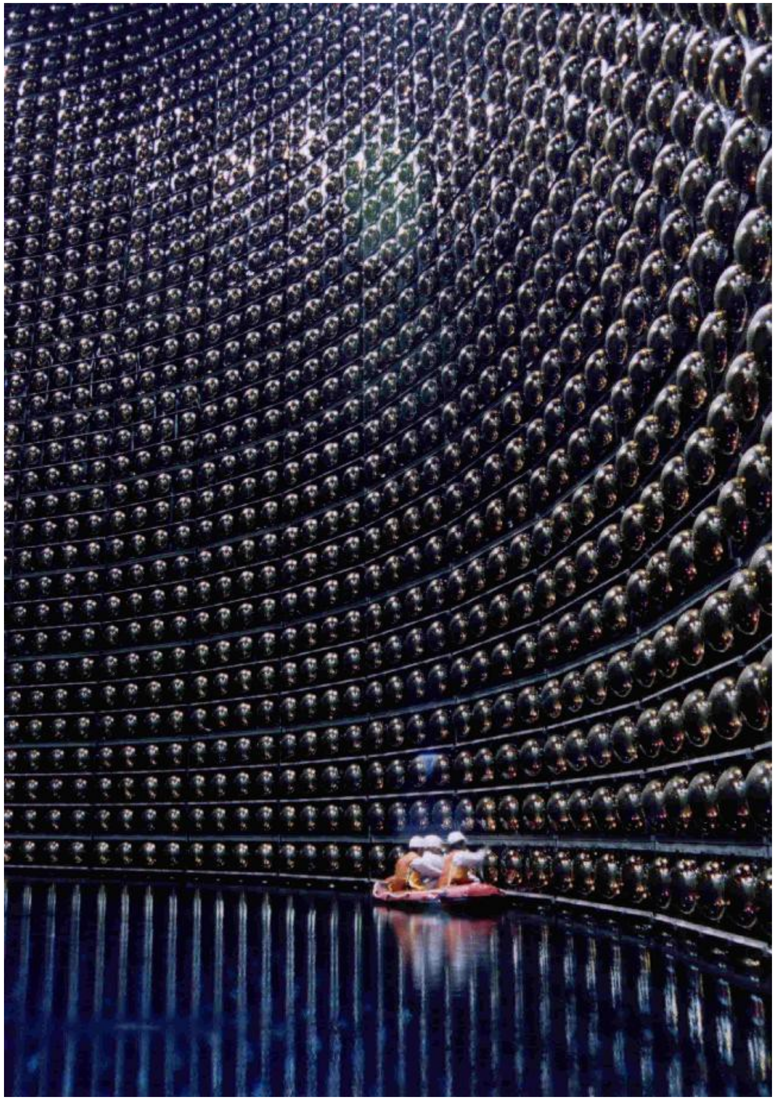
- Birthday: Februar 23rd, 1987
- Birth place: Large Magellanic Cloud
- Distance: about 170,000 lightyears
- Origin: blue supergiant star with about 20 solar masses
- Importance:
  - * only nearby supernova in the past 400 years that was visible to the naked eye
  - * unprecidented wealth of observational data
  - * first measurement of extragalactic neutrinos
  - * confirmation of neutron star birth theory
  - * unambiguous information about strongly turbulent processes during stellar explosions

# Supernova 1987A

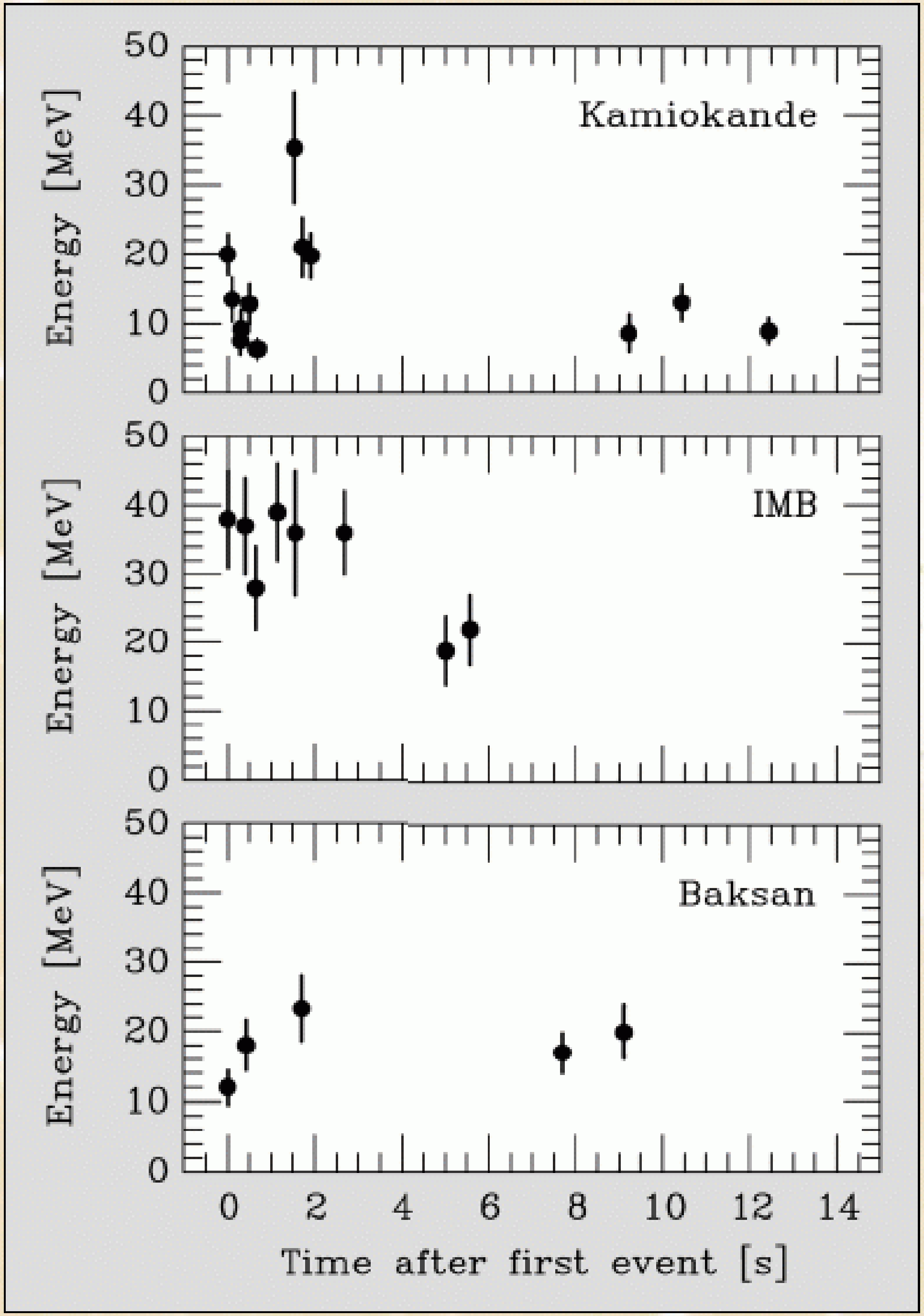




Two dozen (of $10^{58}$) neutrinos were captured in underground laboratories!



# Neutrino Burst of Supernova 1987A

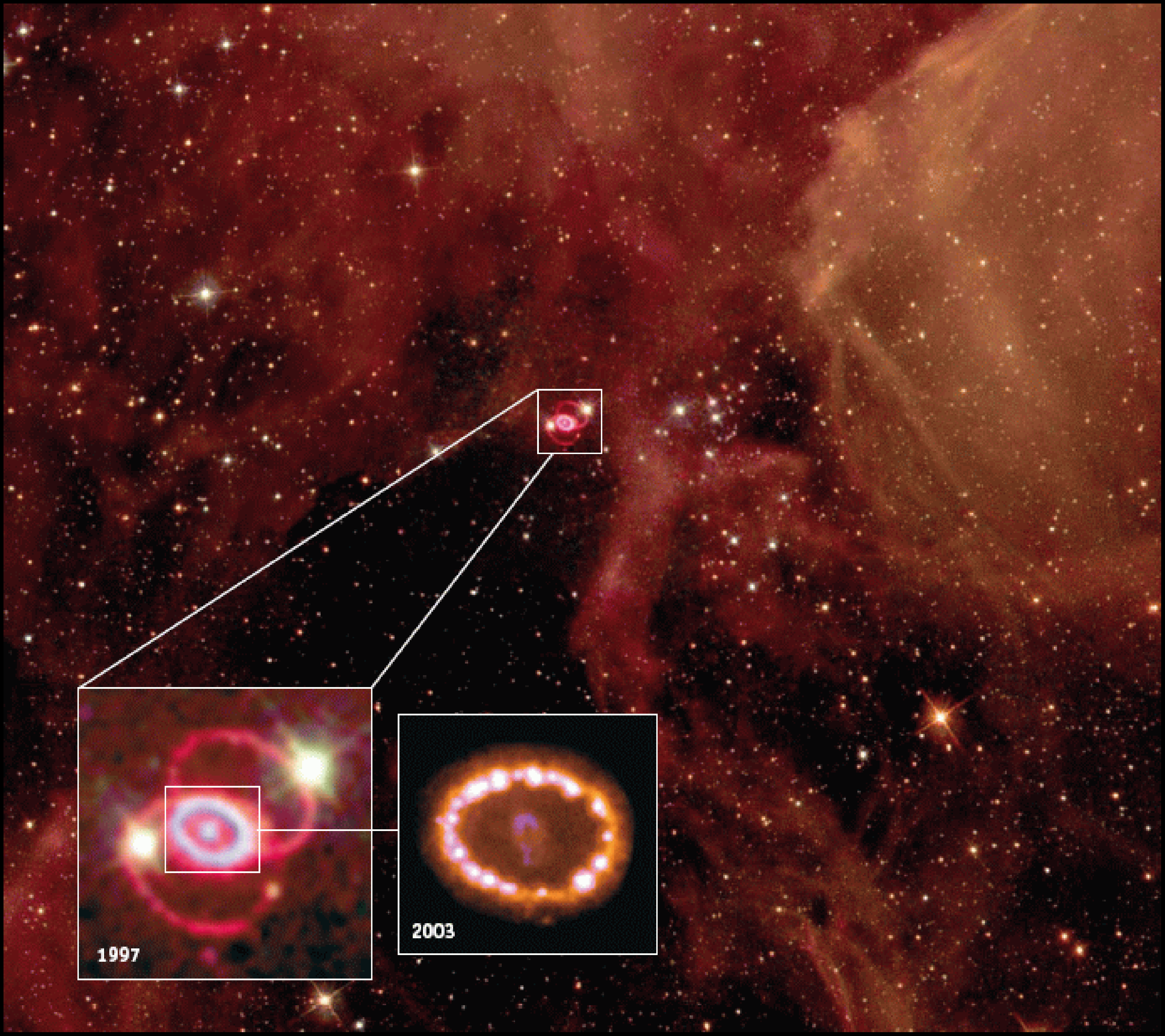


Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

**Within clock uncertainties, signals are contemporaneous**

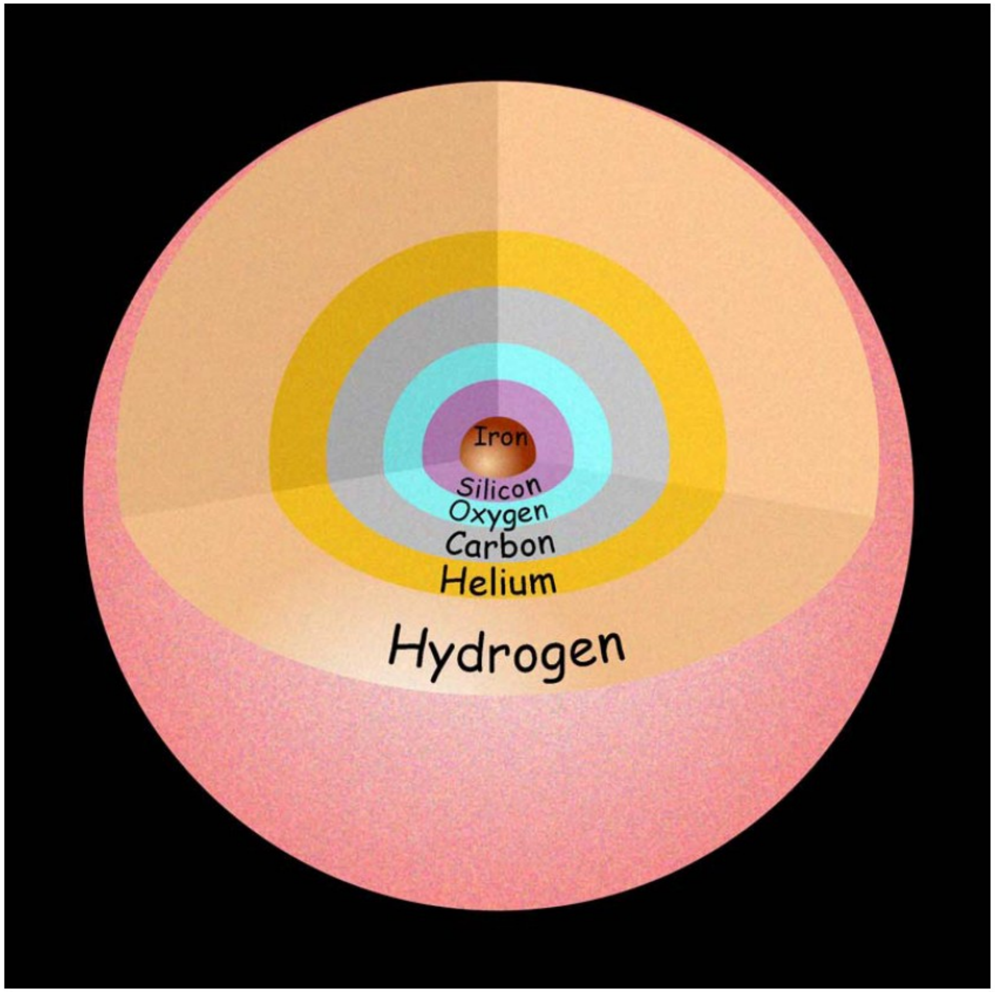


# Supernova 1987A as a teenager

# End Points of Massive-star Evolution

# Final Stages of Massive Star Evolution

## Onion-shell structure



# Final Stages of Stellar Evolution

- Stars with $M_* > 9\ M_{sun}$: approach gravitational instability:

  Hydrostatic (mechanical) equilibrium breaks down

  -----------> collapse of stellar core to neutron star or black hole

- Mechanical equilibrium impossible when adiabatic index of EoS

$$\boxed{\Gamma_{EoS} = (\partial \ln P/\partial \ln \rho)_s < \Gamma_{crit} = 4/3 + \delta_{GR} - \delta_{rot} + \delta_{\nu loss}}$$

(Reason: for $\Gamma_{EoS} = (4/3 + \varepsilon)$ with $\varepsilon < 0$ stabilizing pressure gradient increases less steeply with density than destabilizing gravitational force:

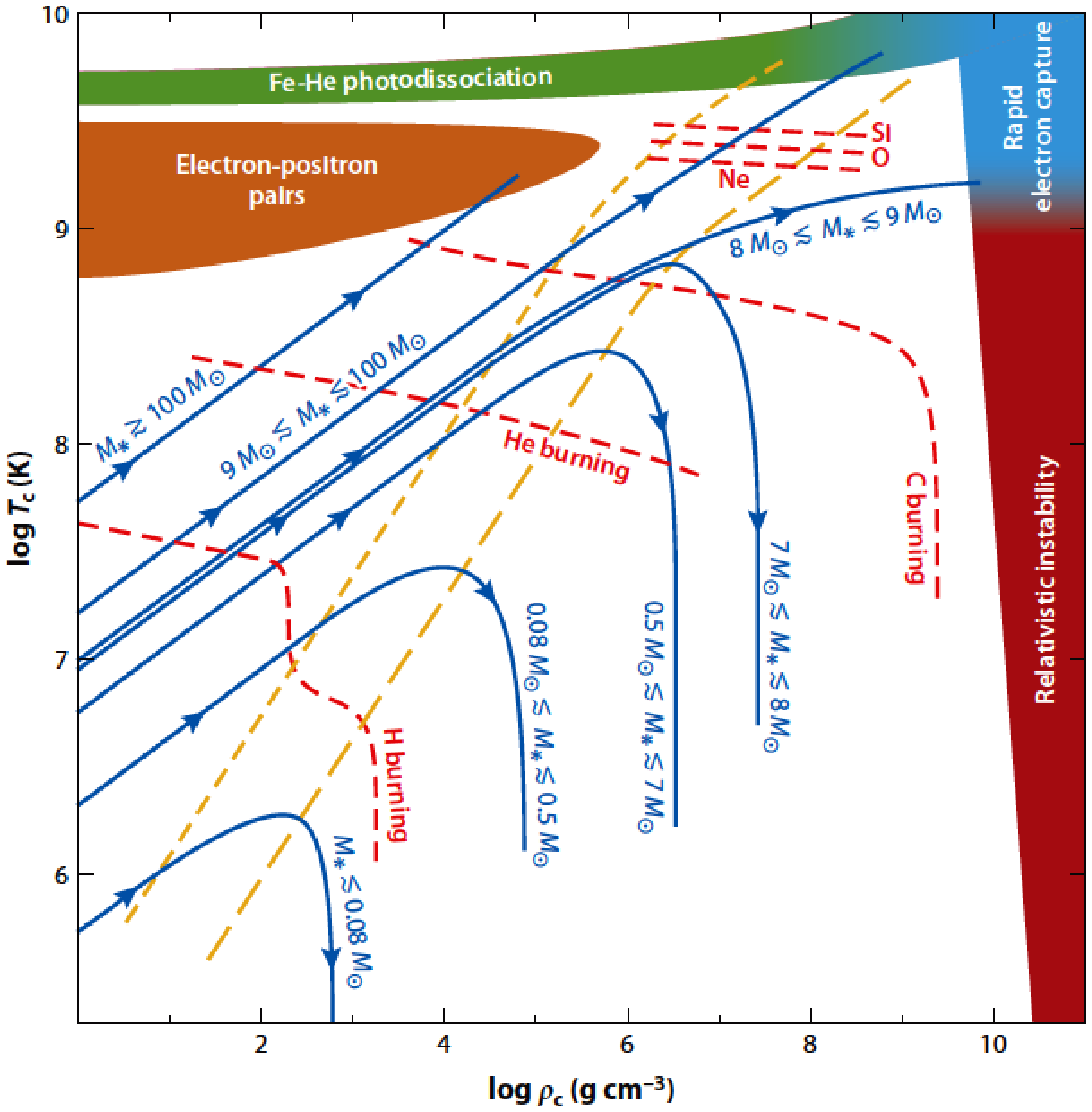
$P/R \propto \rho^{5/3+\varepsilon}$; $GM/R^2 \propto \rho^{5/3}$)

# Final Stages of Massive Star Evolution

Stars with ~8–9 $M_{sun}$ develop degenerate ONeMg cores
—> collapse by
rapid e-capture

Stars with ~9–100 $M_{sun}$ develop Fe cores
—> collapse by nuclear
photodisintegration

Stars with > 100 $M_{sun}$ approach gravitational instability before O-burning
—> collapse by
$e^+e^-$ pair fomation



(Janka, ARNPS 62. 2012)

# Final Stages of Massive Star Evolution

Stars with ~8–9 $M_{sun}$ develop degenerate ONeMg cores

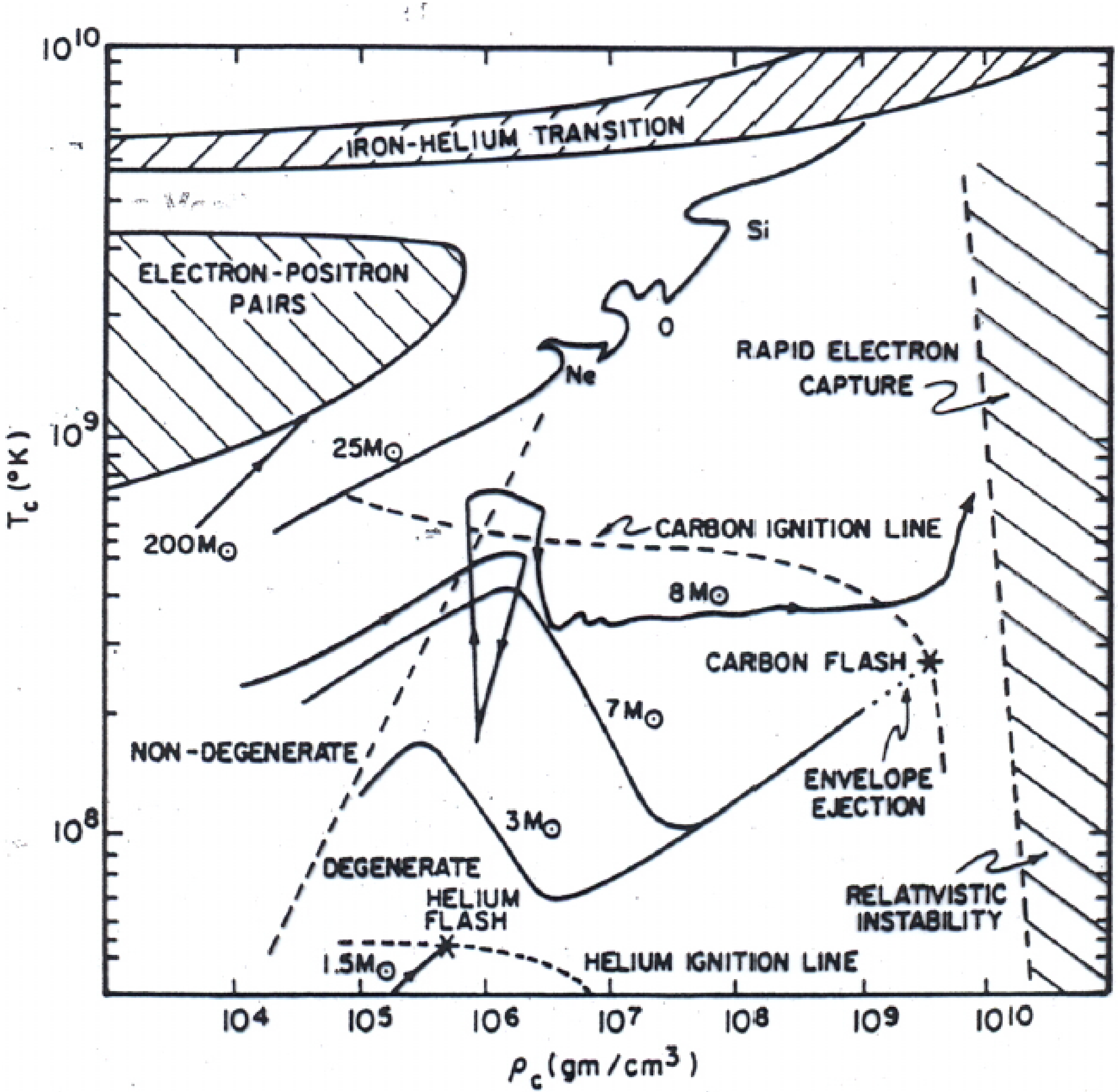
—> collapse by rapid e-capture

Stars with ~9–100 $M_{sun}$ develop Fe cores

—> collapse by nuclear photodisintegration

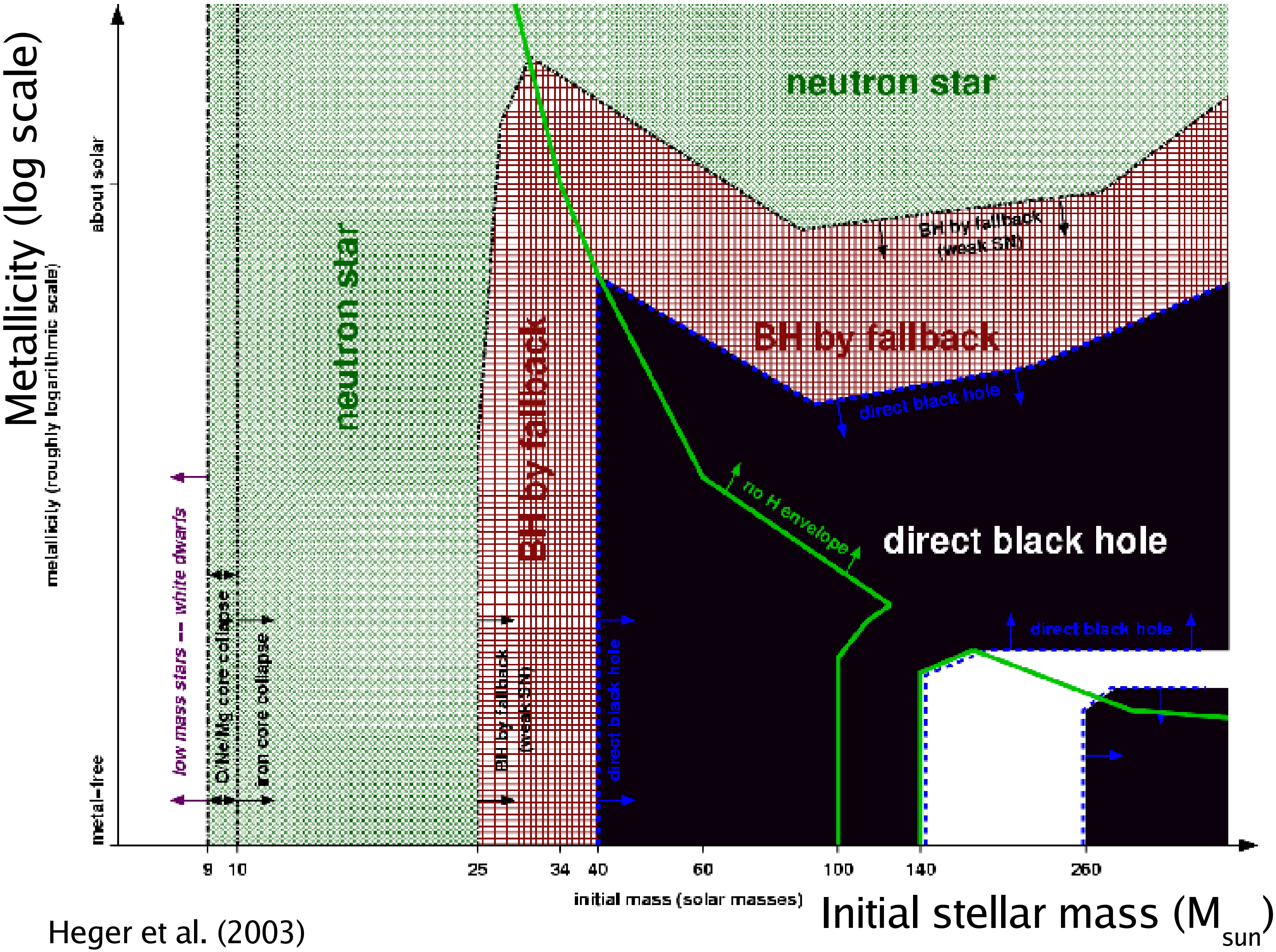
Stars with > 100 $M_{sun}$ approach gravitational instability before O-burning

—> collapse by $e^+e^-$ pair fomation



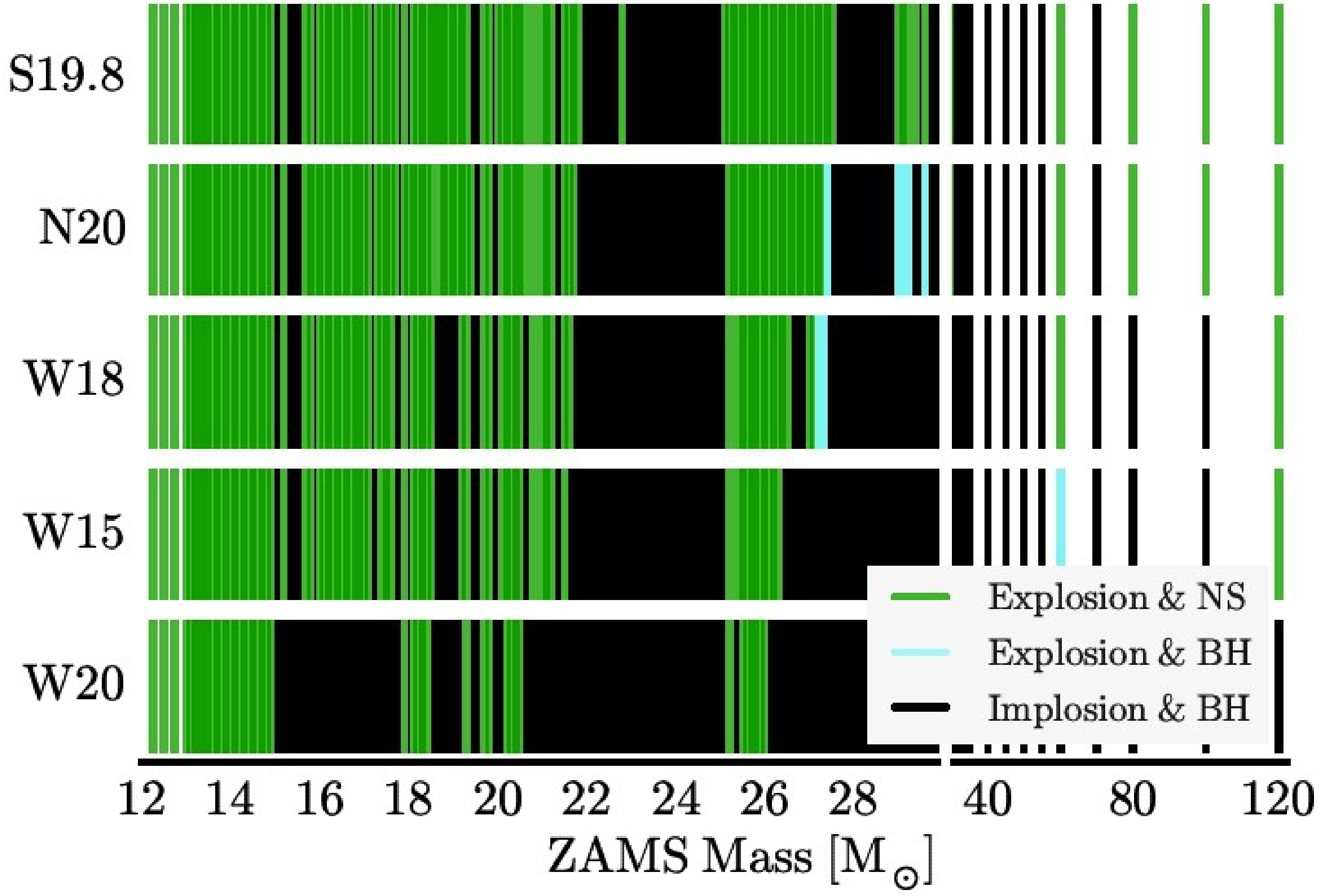
(Wheeler et al. 1990)

# Core Collapse Events and Remnants



Heger et al. (2003)

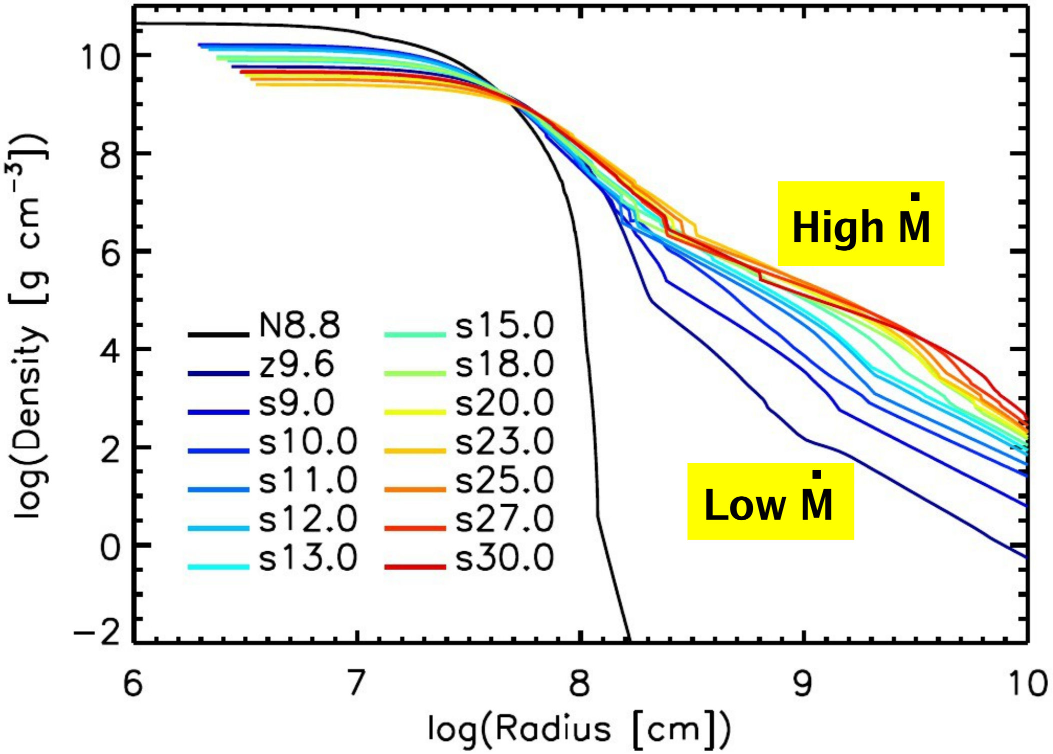
# BH Formation for Different SN 1987A Engines



(Sukhbold, Ertl, Woosley, Brown, and Janka, arXiv:1510.04643)

# Progenitors: Density Profiles

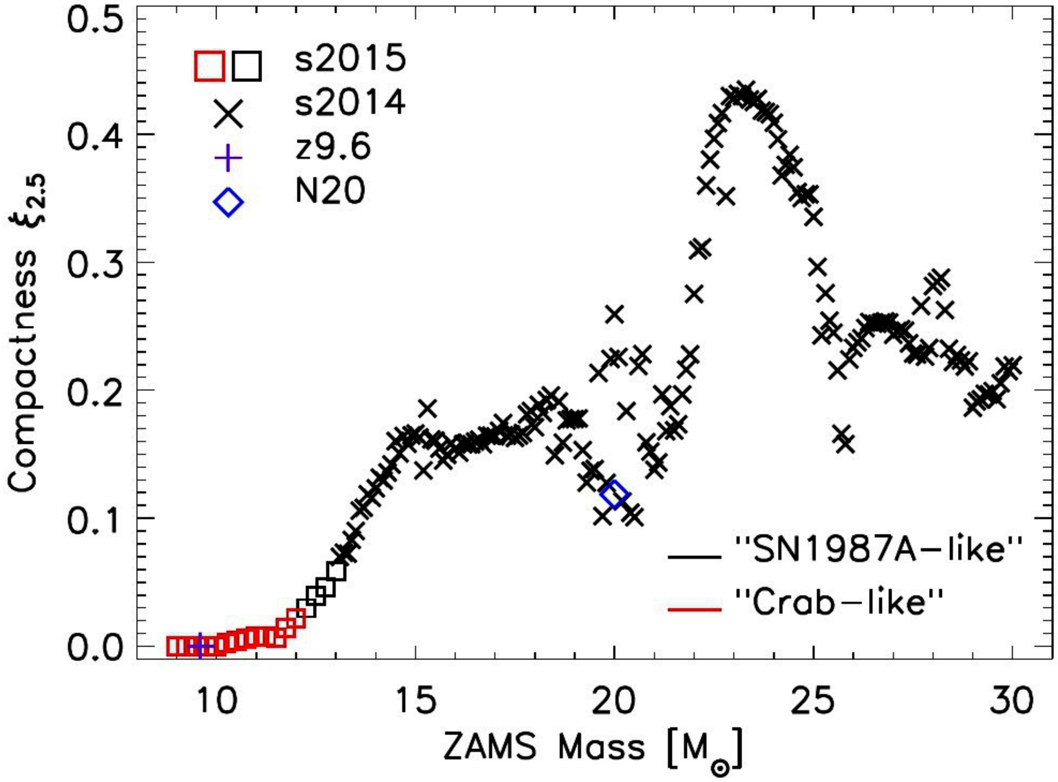
**Progenitor models:**
**Woosley et al. (RMP 2002), Sukhbold & Woosley (2014), Woosley & Heger (2015)**



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

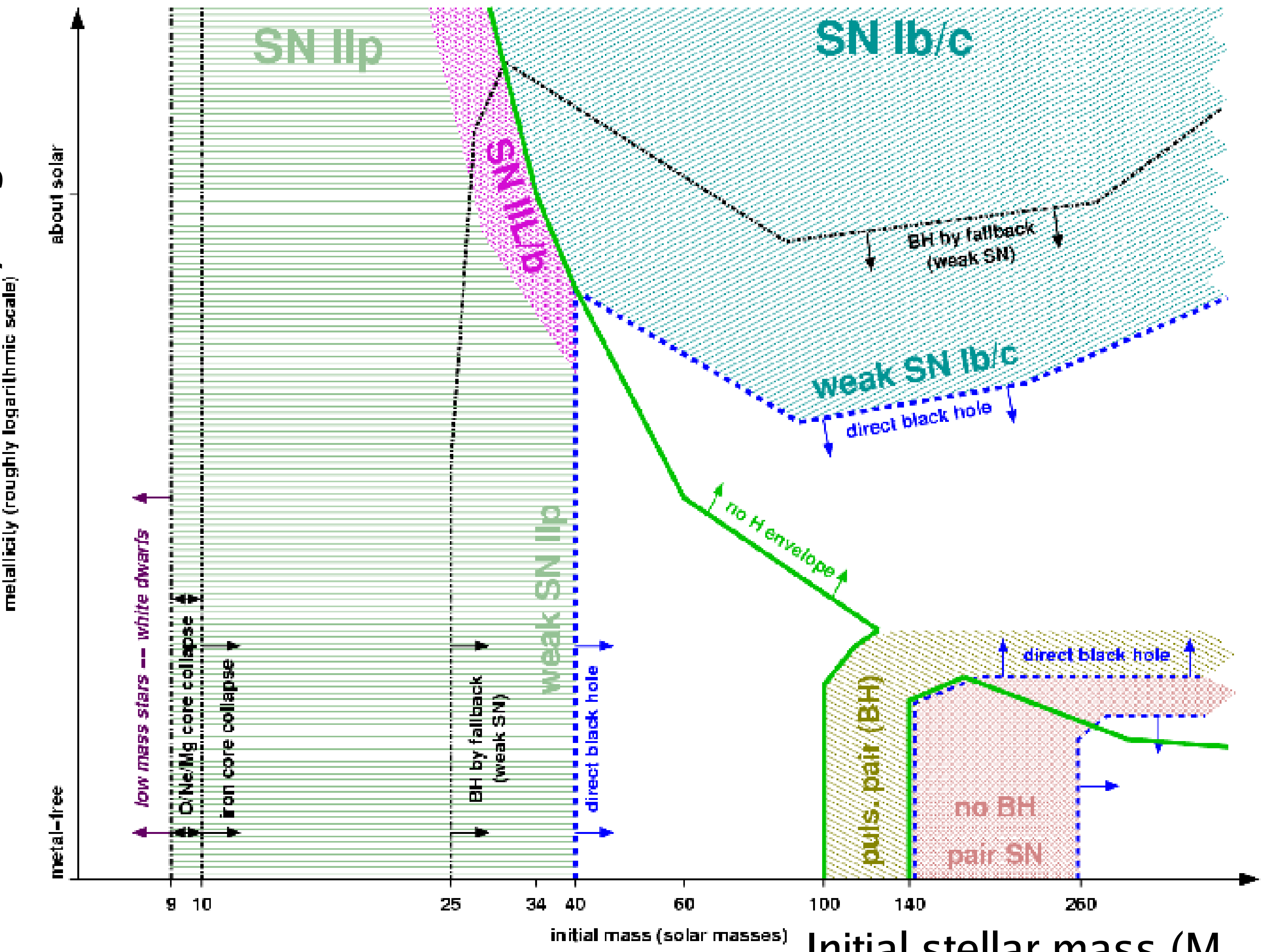
mass $M = 2.5\ M_\odot$

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



# Core Collapse Events and Remnants

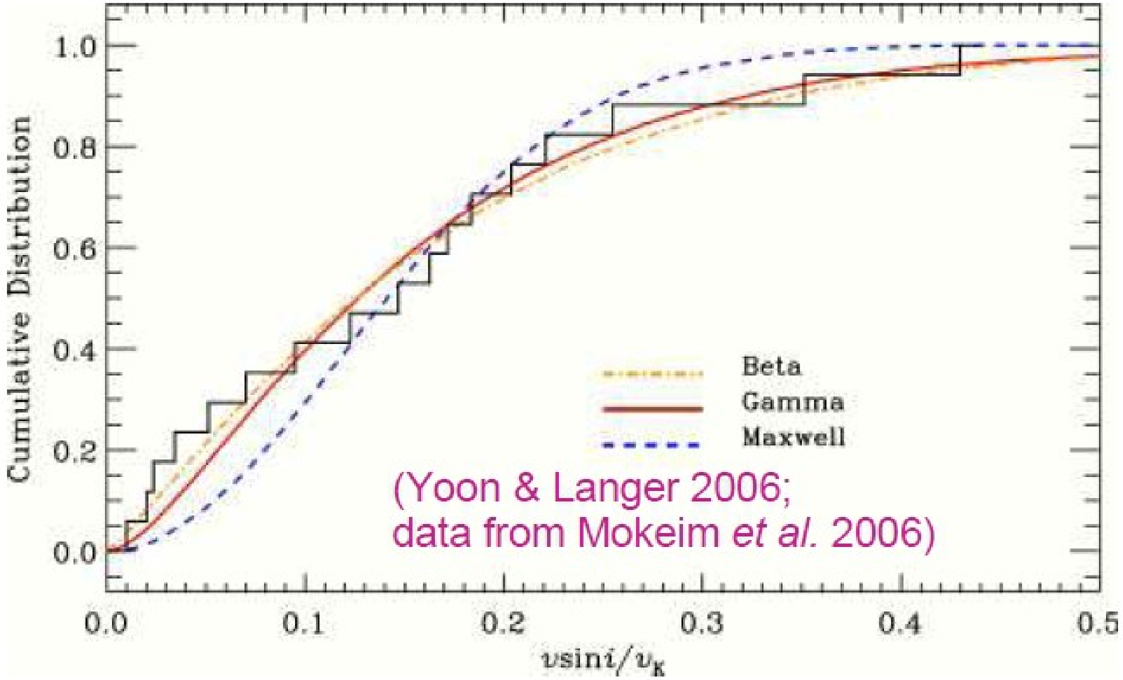
Metallicity (log scale)



Initial stellar mass ($M_{sun}$)

Heger et al. (2003)

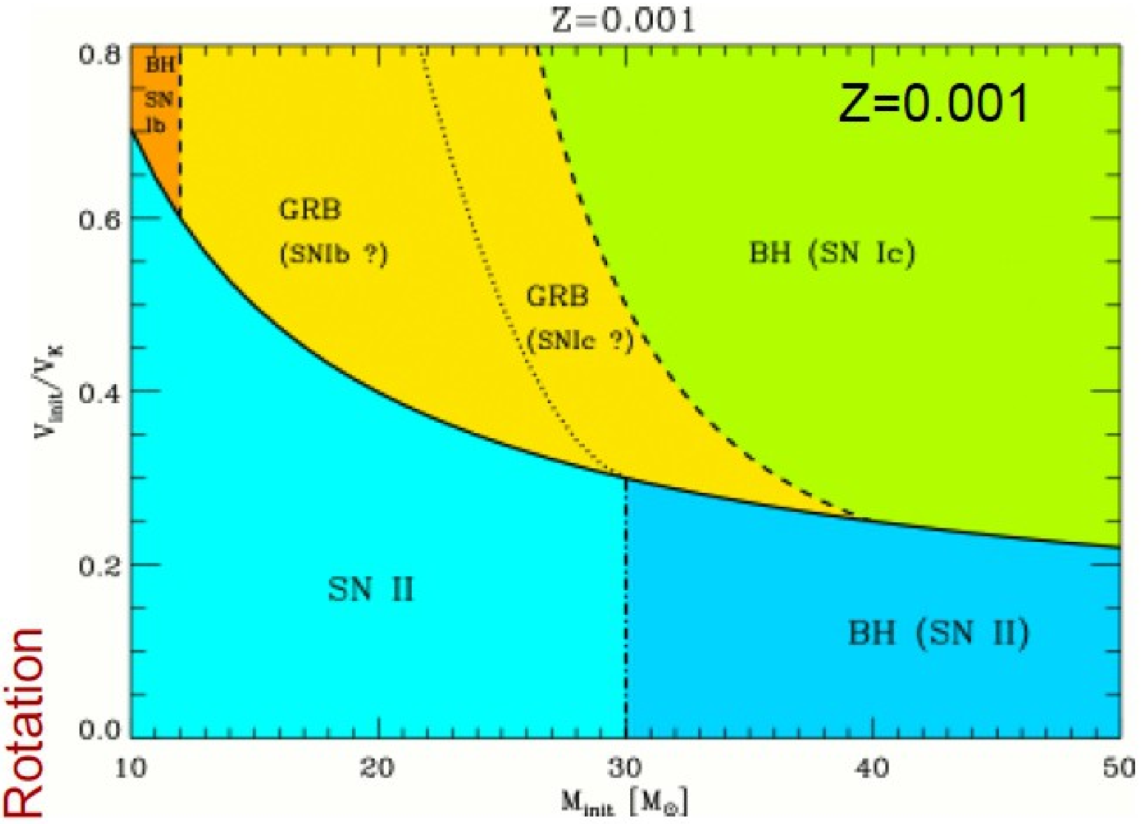
# Black Holes and GRBs from Rotating Stars



(Yoon & Langer 2006; data from Mokeim *et al.* 2006)

A small fraction of single stars is born rotating rapidly

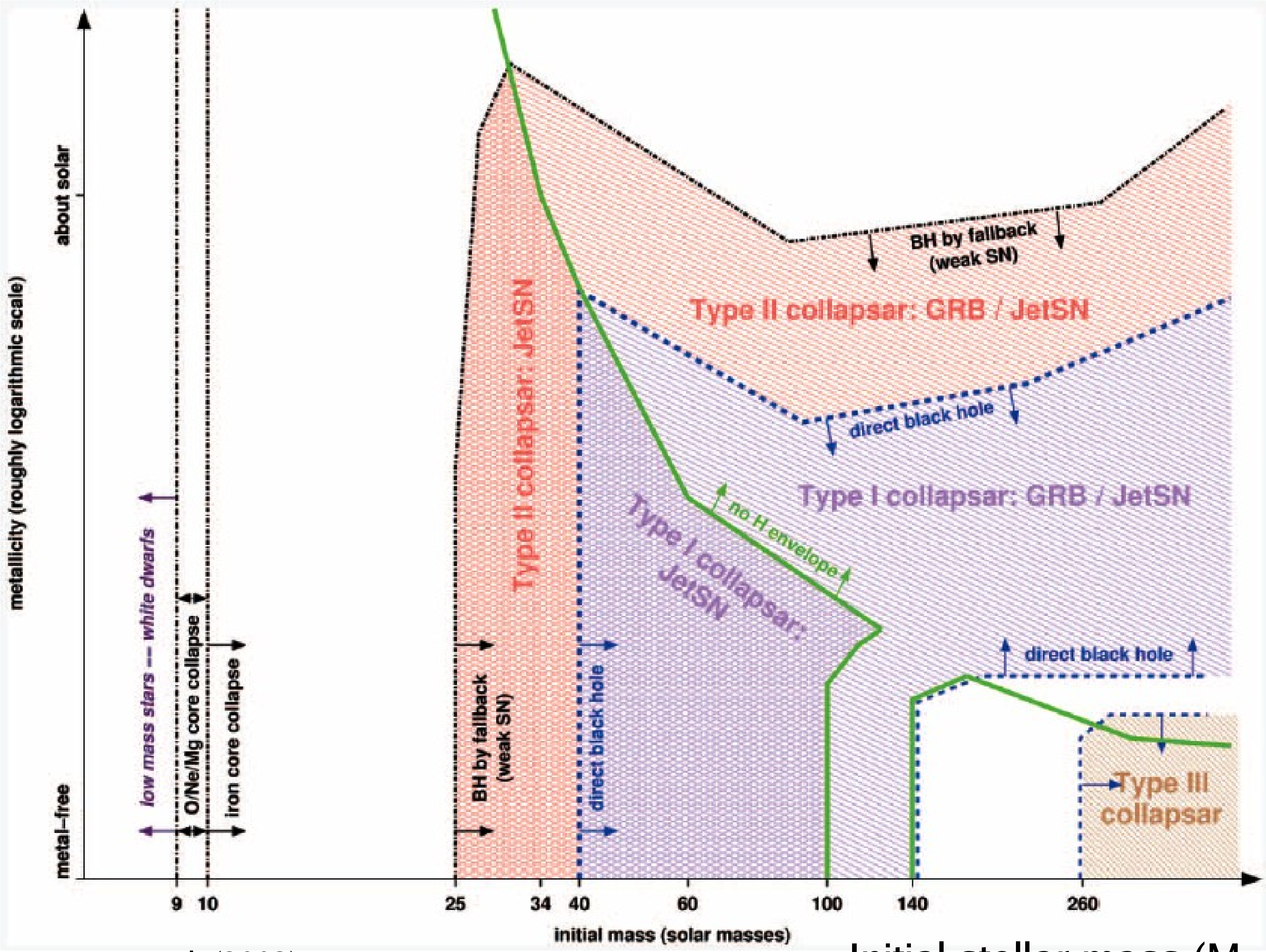
The fastest rotators evolve chemically homogeneously, become WR stars on the MS, and may lose less angular momentum.



Rotation

(Yoon & Langer 2006)

# Core Collapse Events and Remnants



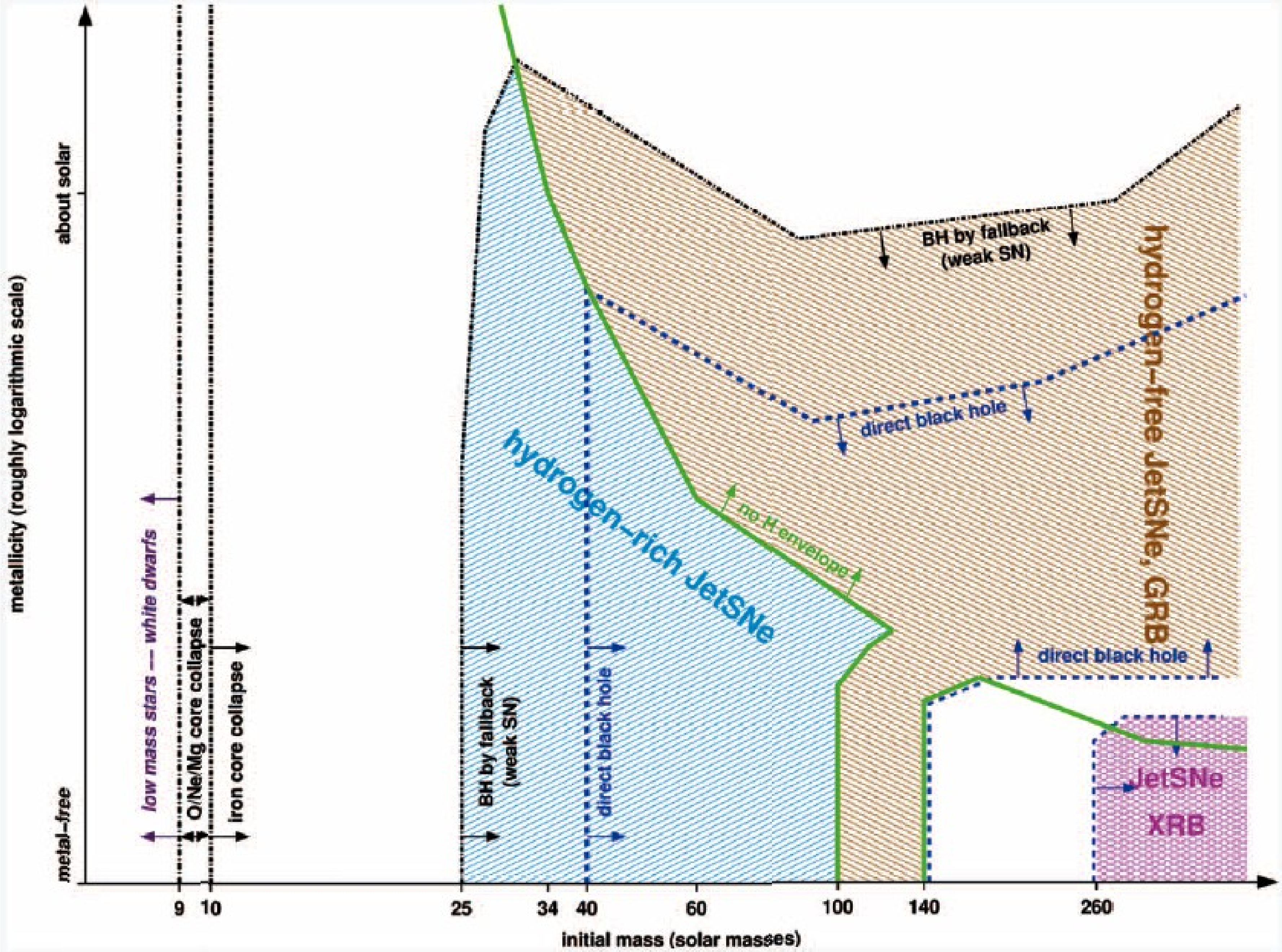
Metallicity (log scale)

Heger et al. (2003)

Initial stellar mass ($M_{sun}$)

# Core Collapse Events and Remnants

Metallicity (log scale)



Heger et al. (2003)

Initial stellar mass ($M_{sun}$)

# Core-Collapse Events

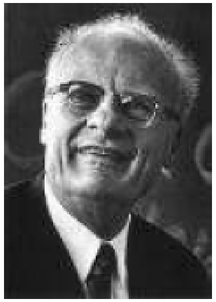
## A heterogeneous class with growing diversity

- Observational diversity: Large variability due to structure of stellar mantle and envelope at time of explosion, also on environment!
- Intrinsic explosion differences: Events also differ largely in energy and Ni production <--------> different explosions mechanisms?

- Determining factors of stellar evolution:
  - * mass of progenitor star
  - * "metallicity" (i.e., heavy element abundance of stellar gas at formation)
  - * binary effects
  - * mass loss during stellar evolution
  - * stellar rotation and magnetic fields
- These factors decide about:
  - * neutron star (NS) or black hole (BH) formation in collapse;
  - * explosion mechanism, explosion energy, & Ni production;
  - * lightcurve and spectral properties <—> SN classes;
  - * anisotropy of explosion

# Things that blow up

## supernovae



1B=$10^{51}$ erg

- CO white dwarf ➔ Type Ia SN, $E \approx 1$Bethe
- 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/c 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

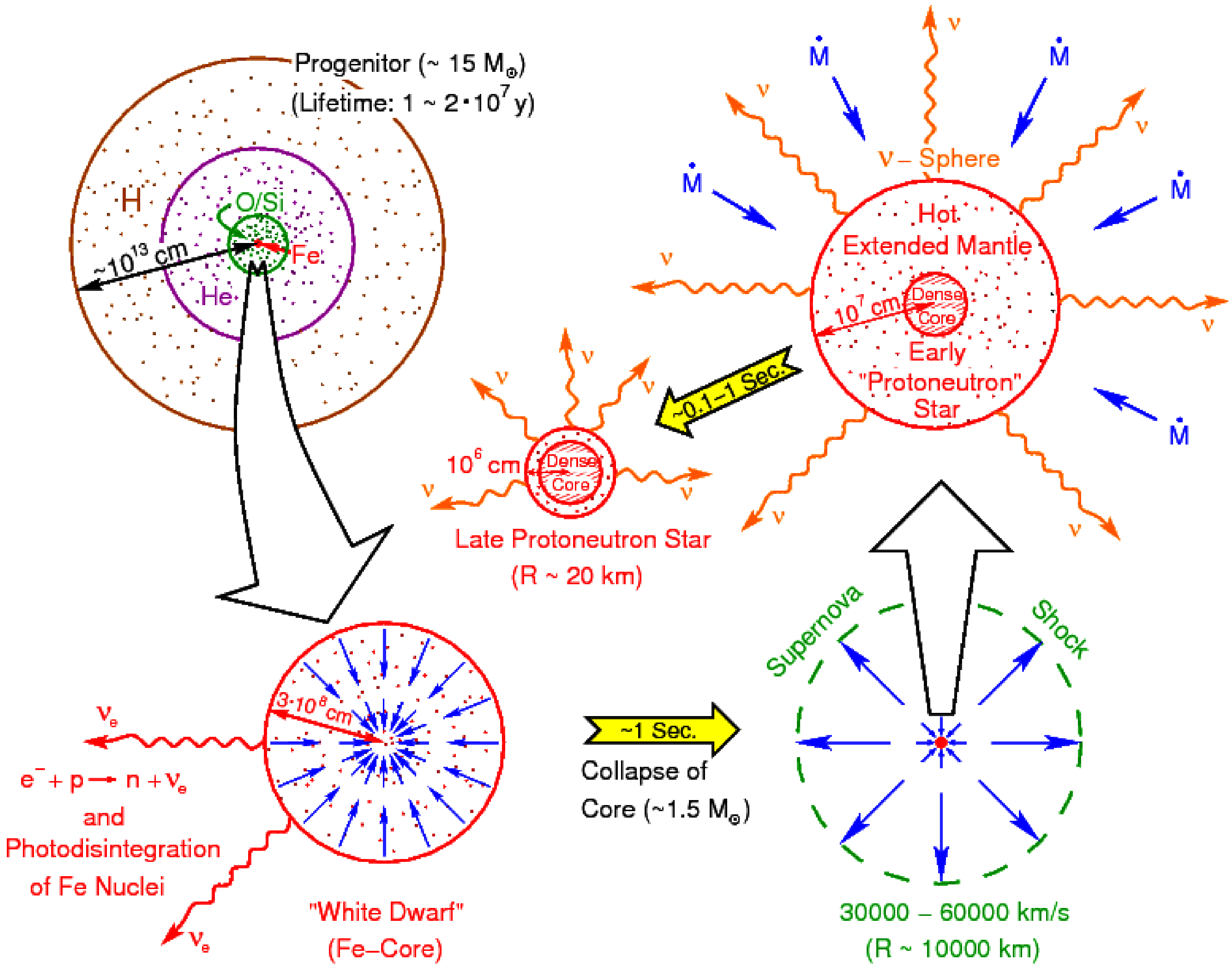
A. Heger (2011)

# Physics of
# Stellar Core Collapse and Explosion

# Problems & Questions

- Core collapse SN explosion mechanism(s)
- SN explosion properties; explosion asymmetries, mixing, gaseous remnant properties
- NS/BH formation paths and probabilities
- NS birth masses, kicks, spins
- Neutrino and gravitational-wave signals
- Neutrino flavor 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?

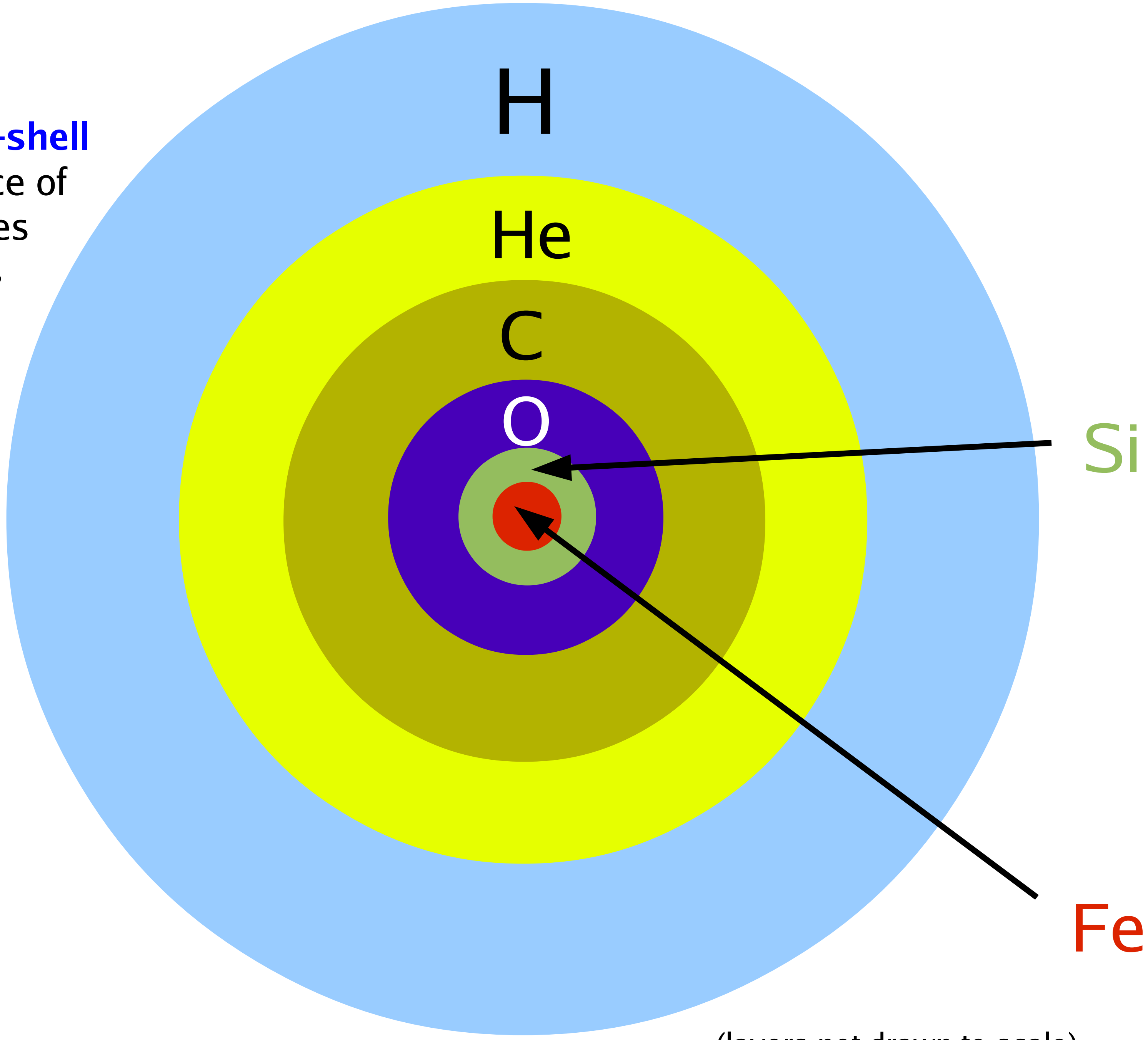
# Stellar Collapse and Supernova Stages



adapted from A. Burrows (1990)

# Onion-shell structure of pre-collapse star

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



(layers not drawn to scale)

# Onion-shell structure of pre-collapse star

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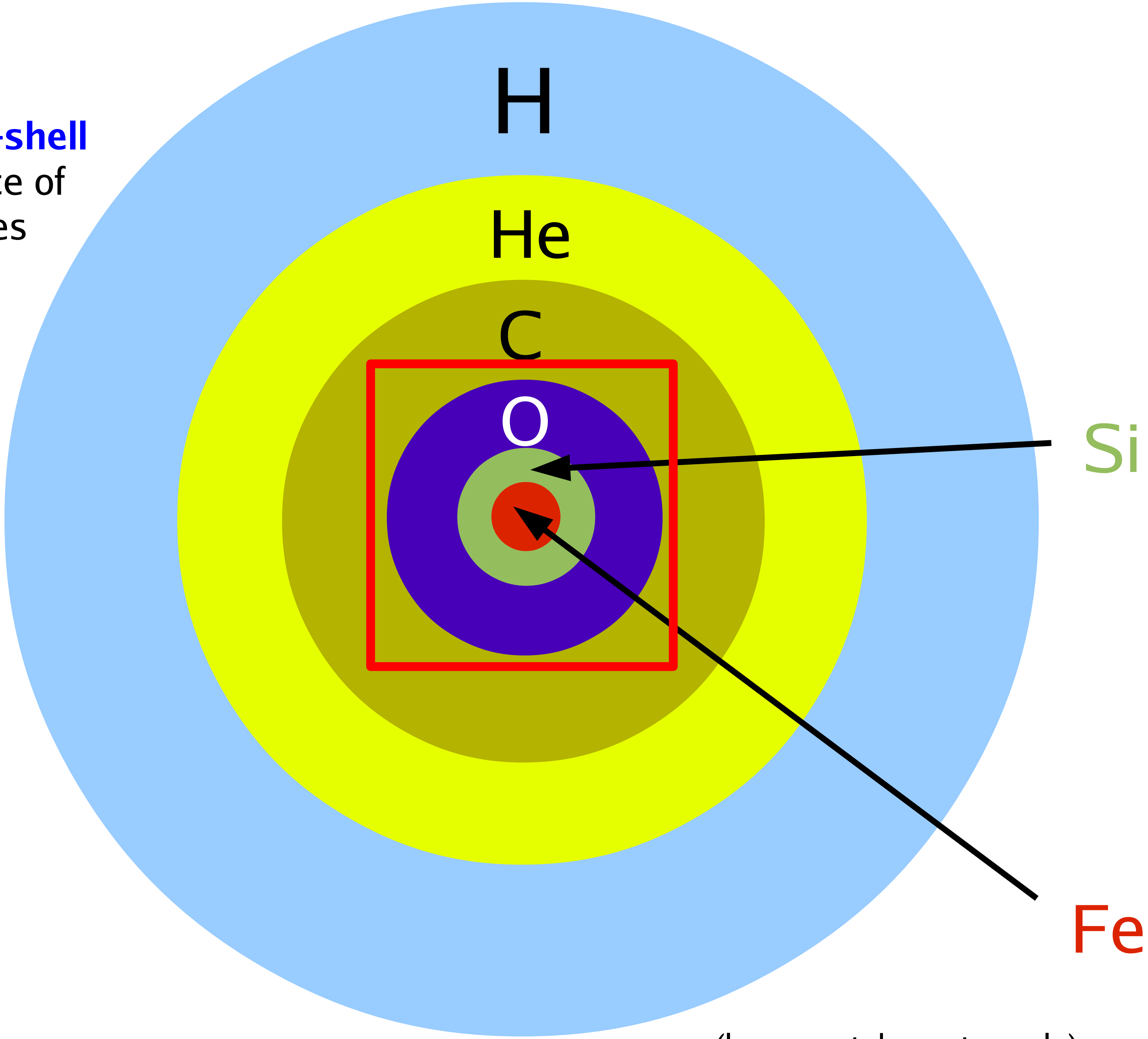
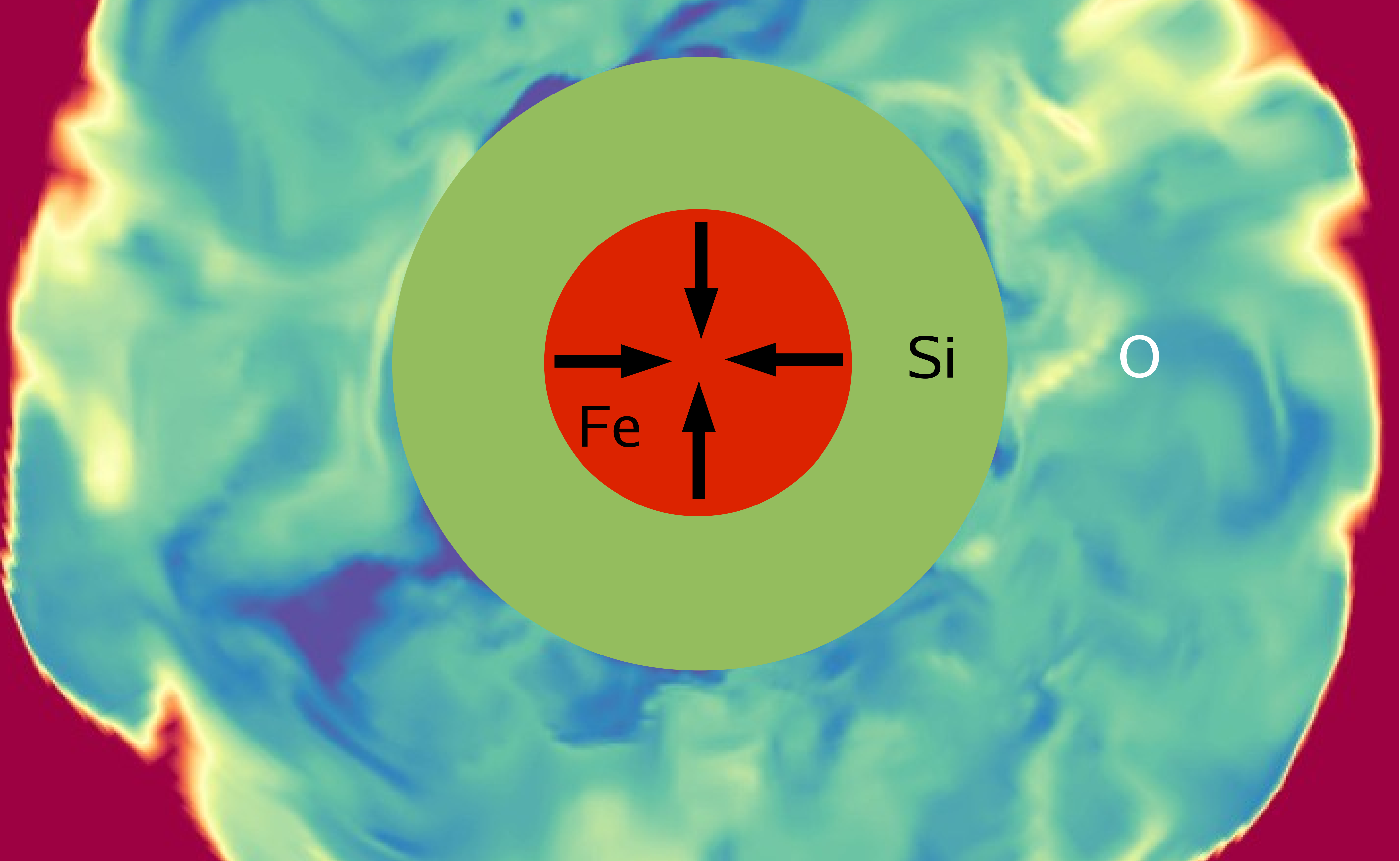
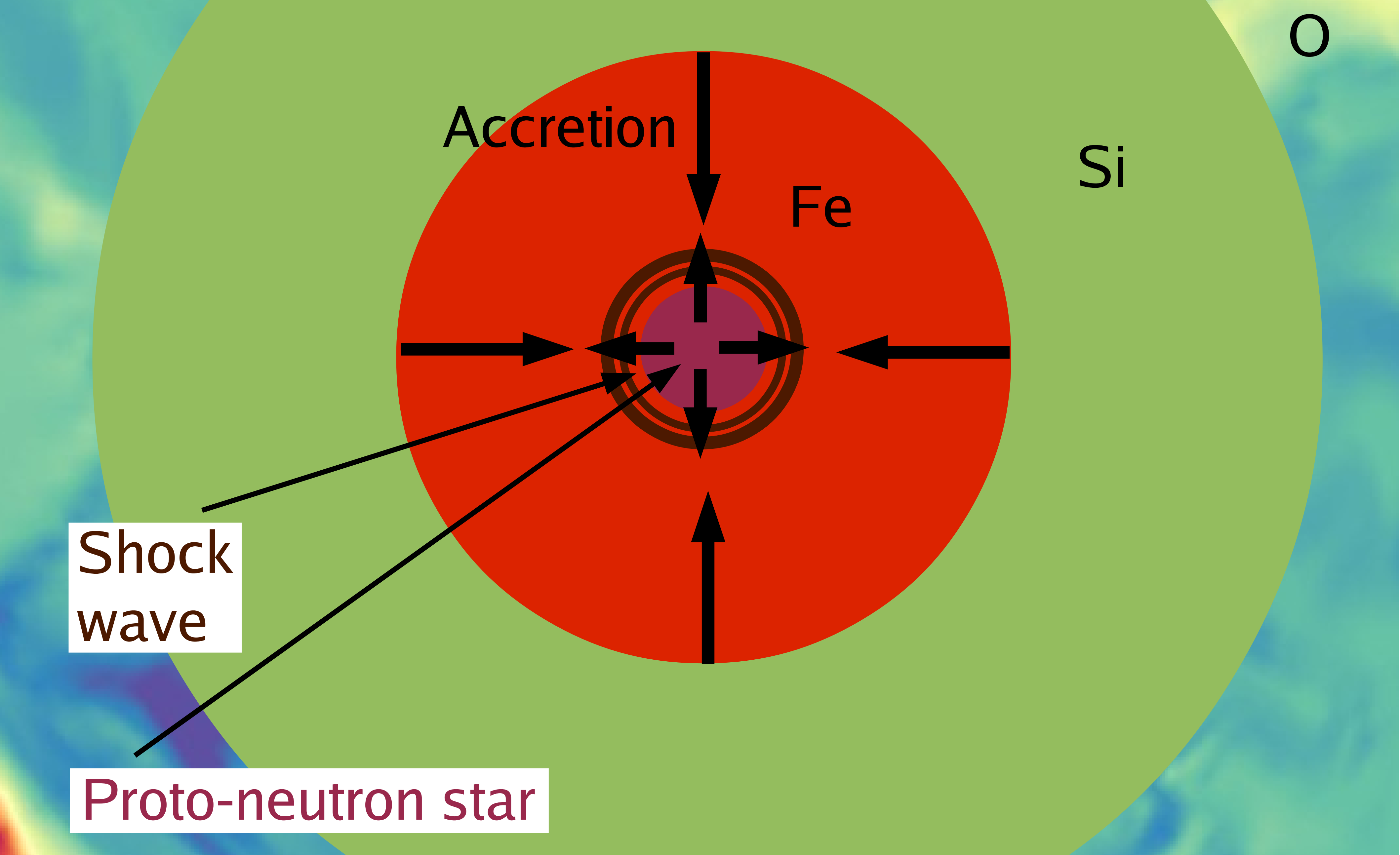


(layers not drawn to scale)

# Gravitational instability of stellar core



# Core bounce at nuclear density



O

Accretion

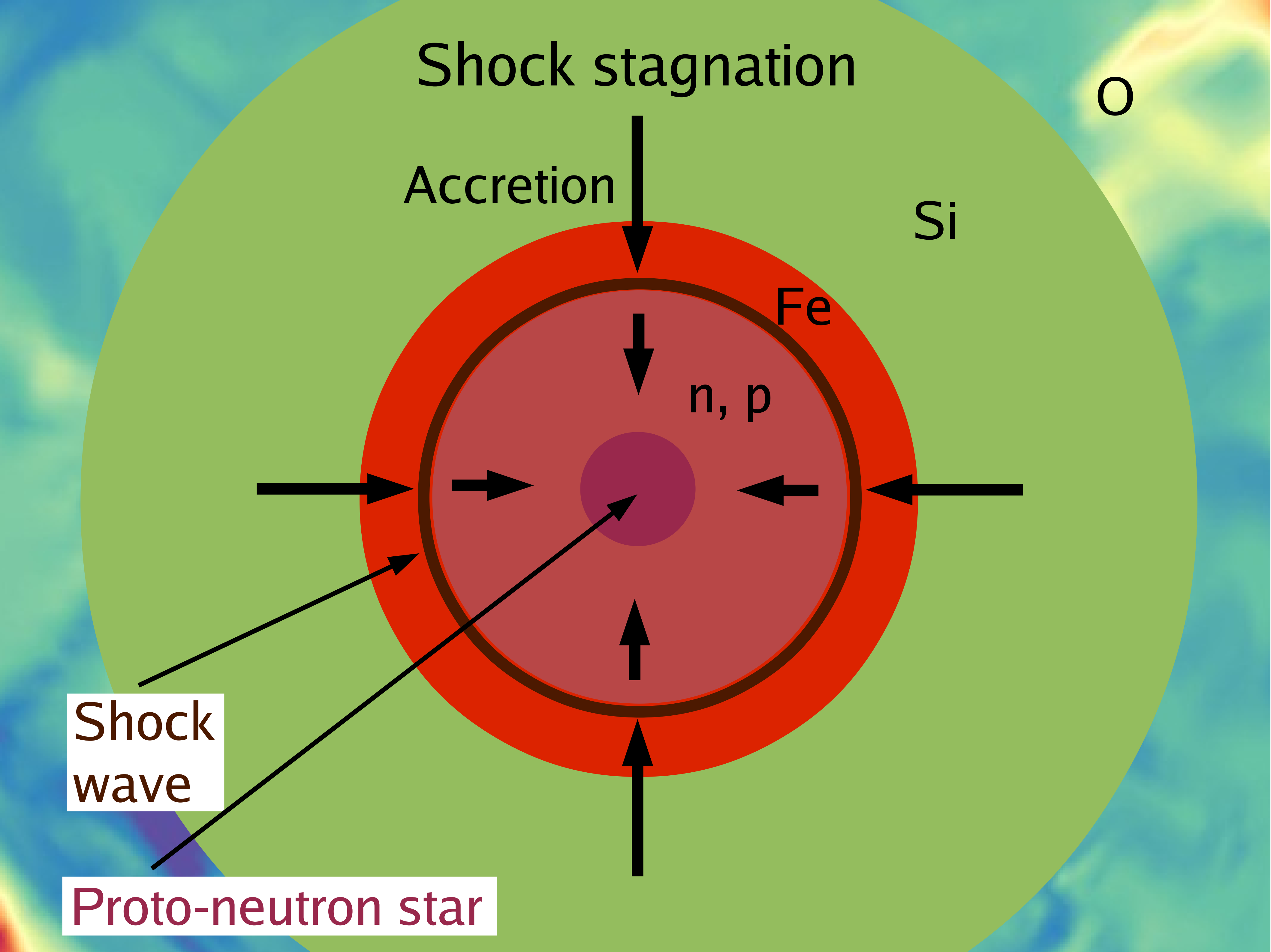
Si

Fe

Shock wave

Proto-neutron star

# Shock stagnation



Accretion

O

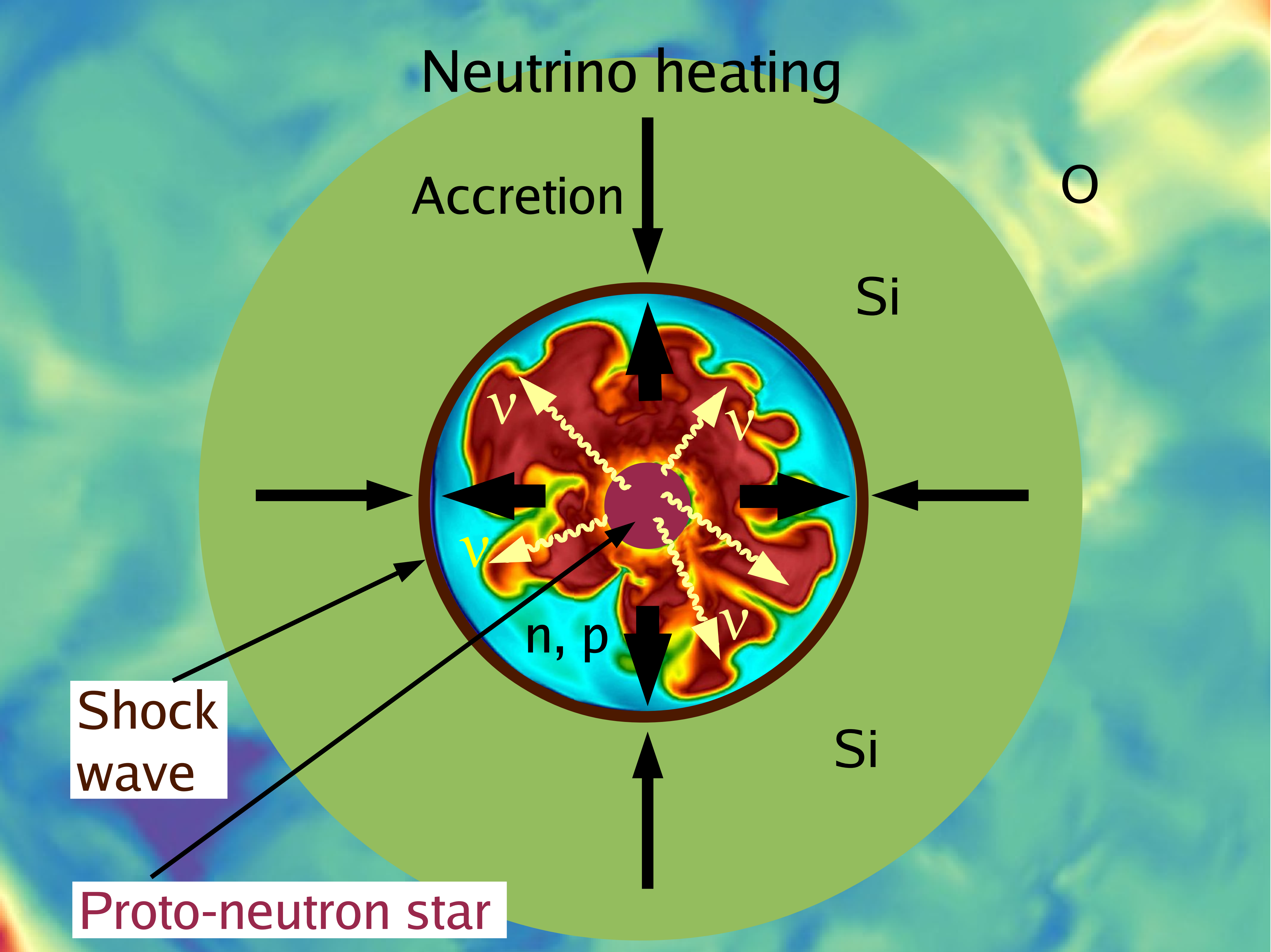
Si

Fe

n, p

Shock wave

Proto-neutron star



Neutrino heating

Accretion

O

Si

$\nu$

$\nu$

$\nu$

$\nu$

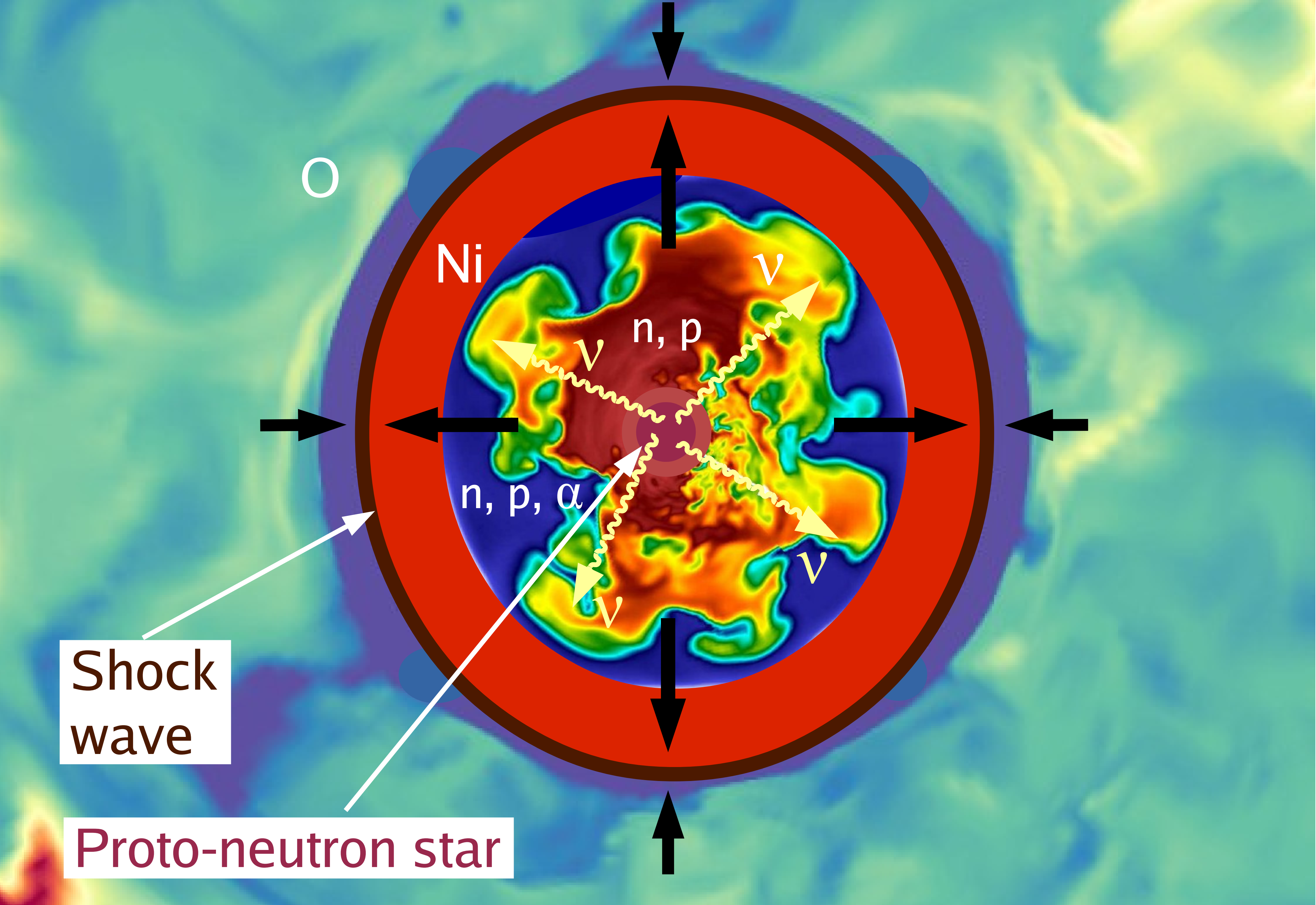
n, p

Si

Shock wave

Proto-neutron star

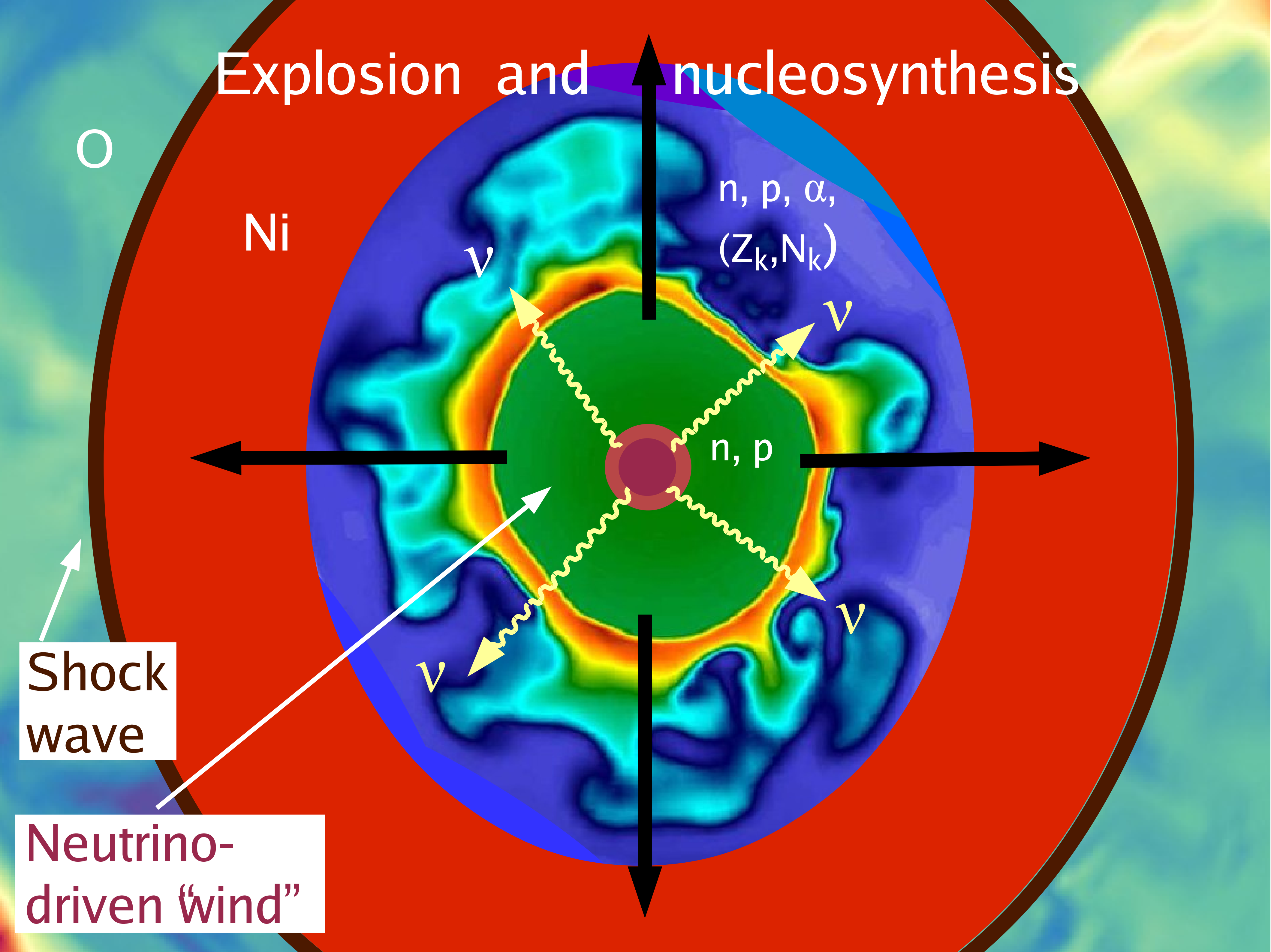
# Shock revival



Shock wave

Proto-neutron star

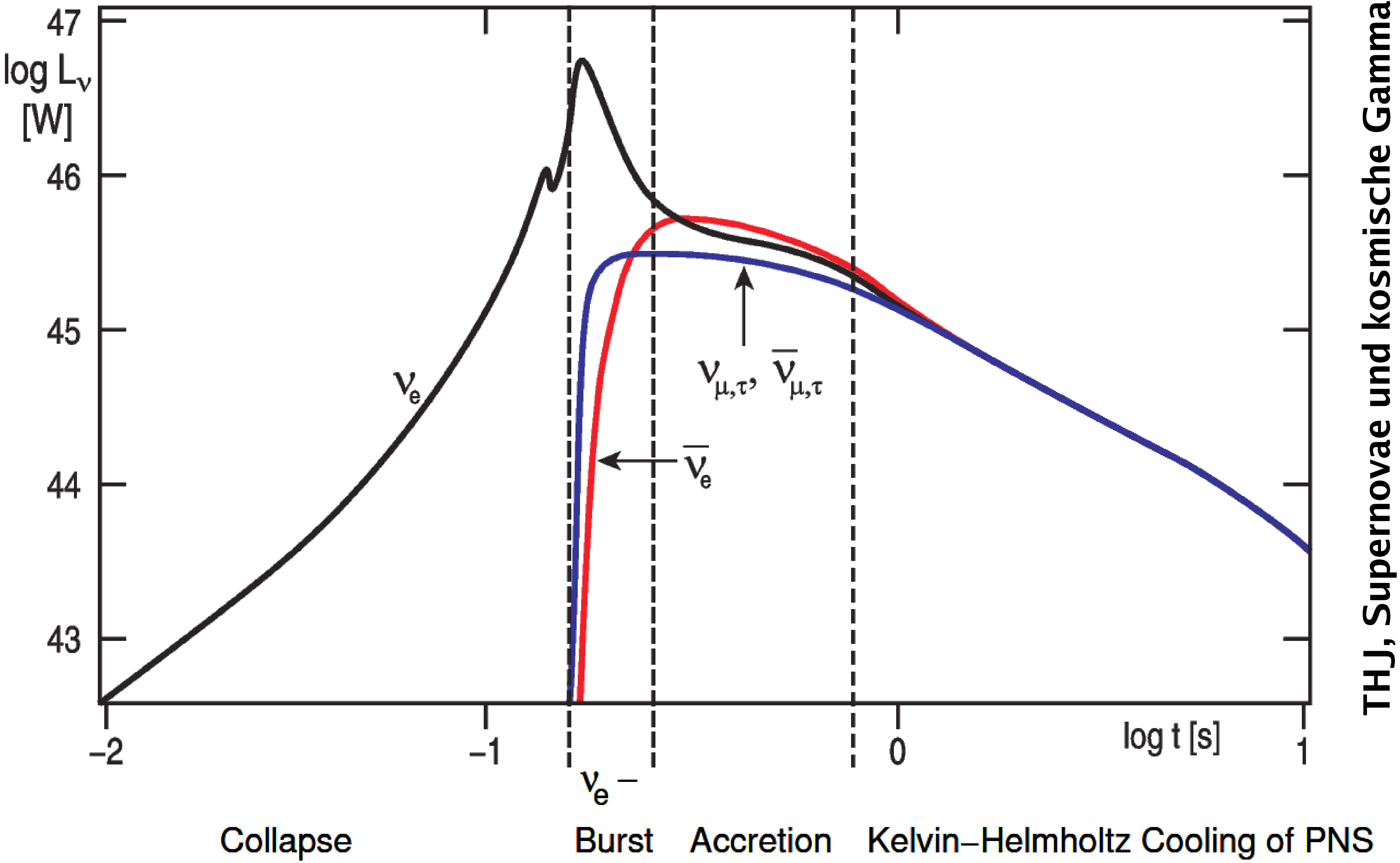
# Explosion and nucleosynthesis



Shock wave

Neutrino-driven "wind"

# Neutrino Emission Phases



THJ, Supernovae und kosmische Gammablitze,
Springer Spektrum (2011)

# Neutrino Heating and Cooling

$$\boxed{\begin{array}{lcl} \nu_{\mathrm{e}} + n & \rightarrow & e^{-} + p \\ \bar{\nu}_{\mathrm{e}} + p & \rightarrow & e^{+} + n \end{array}}$$

- Neutrino heating:

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

- Neutrino cooling:

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

See, e.g., Janka, ARNPS 62 (2012) 407

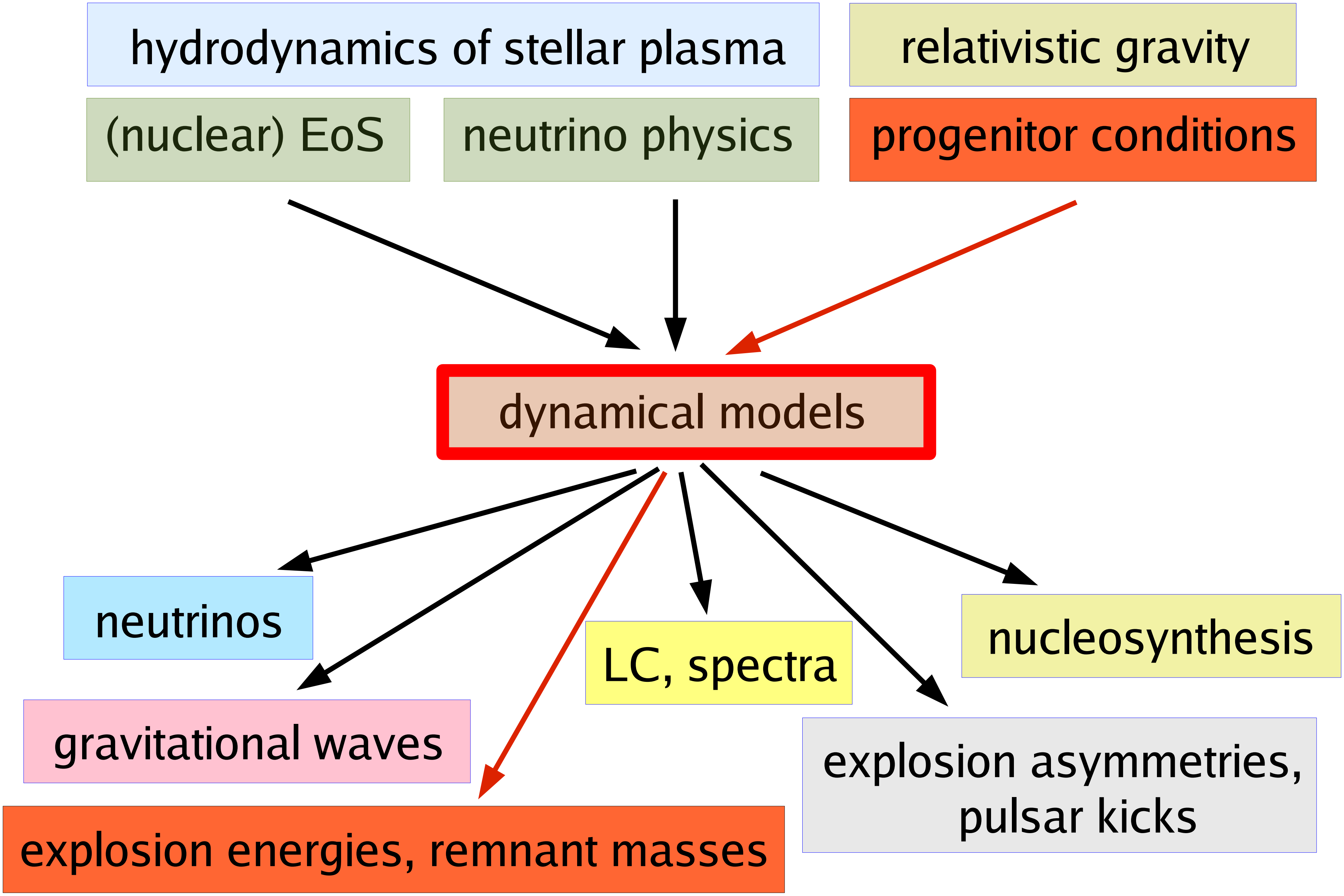
$$\begin{aligned} Q_{\nu}^{+} &= q_{\nu}^{+}\, M_{\mathrm{g}} \\ &\sim 9.4 \times 10^{51}\,\frac{\mathrm{erg}}{\mathrm{s}} \left(\frac{k_{\mathrm{B}} T_{\nu}}{4\ \mathrm{MeV}}\right)^{2} \left(\frac{L_{\nu}}{3 \cdot 10^{52}\,\mathrm{erg/s}}\right) \left(\frac{M_{\mathrm{g}}}{0.01\,M_{\odot}}\right) \left(\frac{R_{\mathrm{g}}}{100\,\mathrm{km}}\right)^{-2} \end{aligned}$$

$$\boxed{\begin{aligned} E_{N} &\sim Q_{\nu}^{+}\, t_{\mathrm{dwell}} \\ &\sim 9.4 \times 10^{50}\,\mathrm{erg} \left(\frac{k_{\mathrm{B}} T_{\nu}}{4\ \mathrm{MeV}}\right)^{2} \left(\frac{L_{\nu}}{3 \cdot 10^{52}\,\mathrm{erg/s}}\right) \times \\ &\qquad \left(\frac{M_{\mathrm{g}}}{0.01\,M_{\odot}}\right)^{2} \left(\frac{\dot{M}}{0.1\,M_{\odot}\,\mathrm{s}^{-1}}\right)^{-1} \left(\frac{R_{\mathrm{g}}}{100\,\mathrm{km}}\right)^{-2} \end{aligned}}$$

$$\boxed{t_{\mathrm{dwell}} \approx \frac{M_{\mathrm{g}}}{\dot{M}}}$$

Hydrodynamic instabilities

# Predictions of Signals from SNe & NSs



hydrodynamics of stellar plasma

relativistic gravity

(nuclear) EoS

neutrino physics

progenitor conditions

dynamical models

neutrinos

gravitational waves

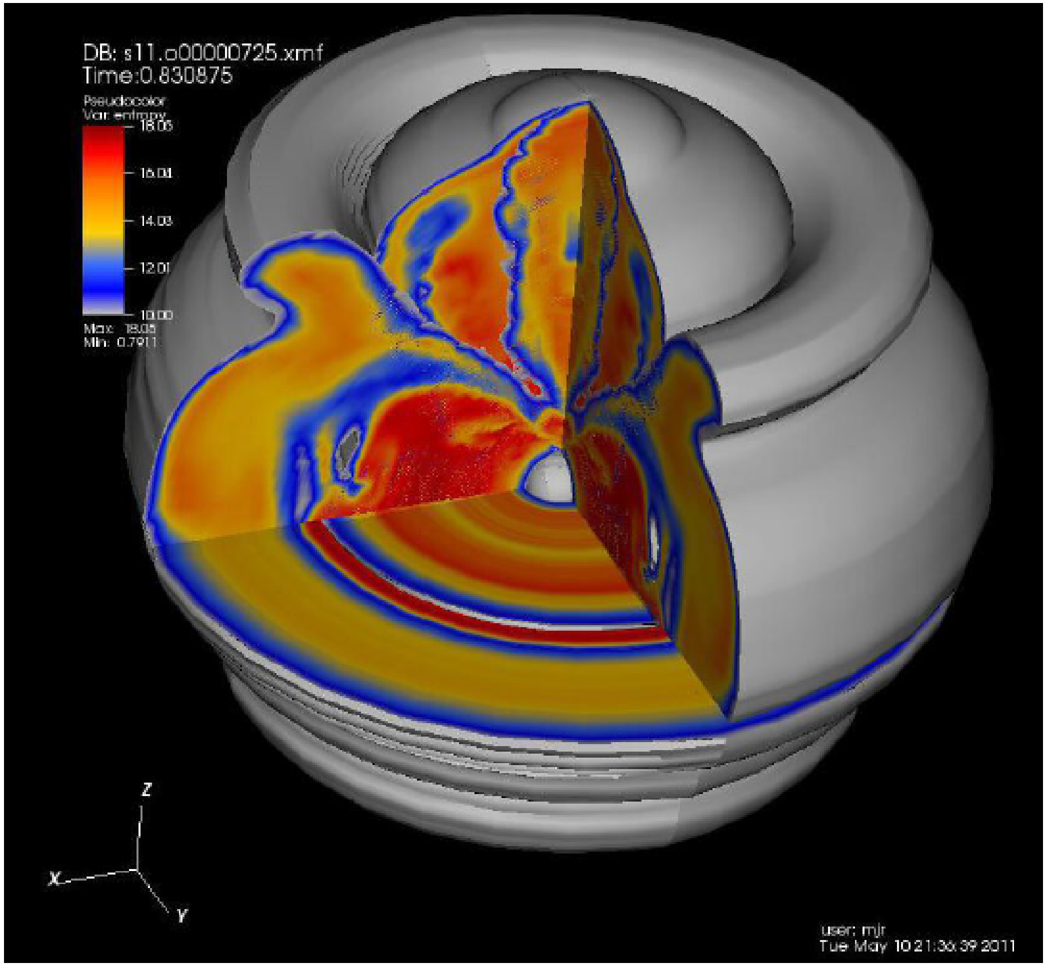
explosion energies, remnant masses

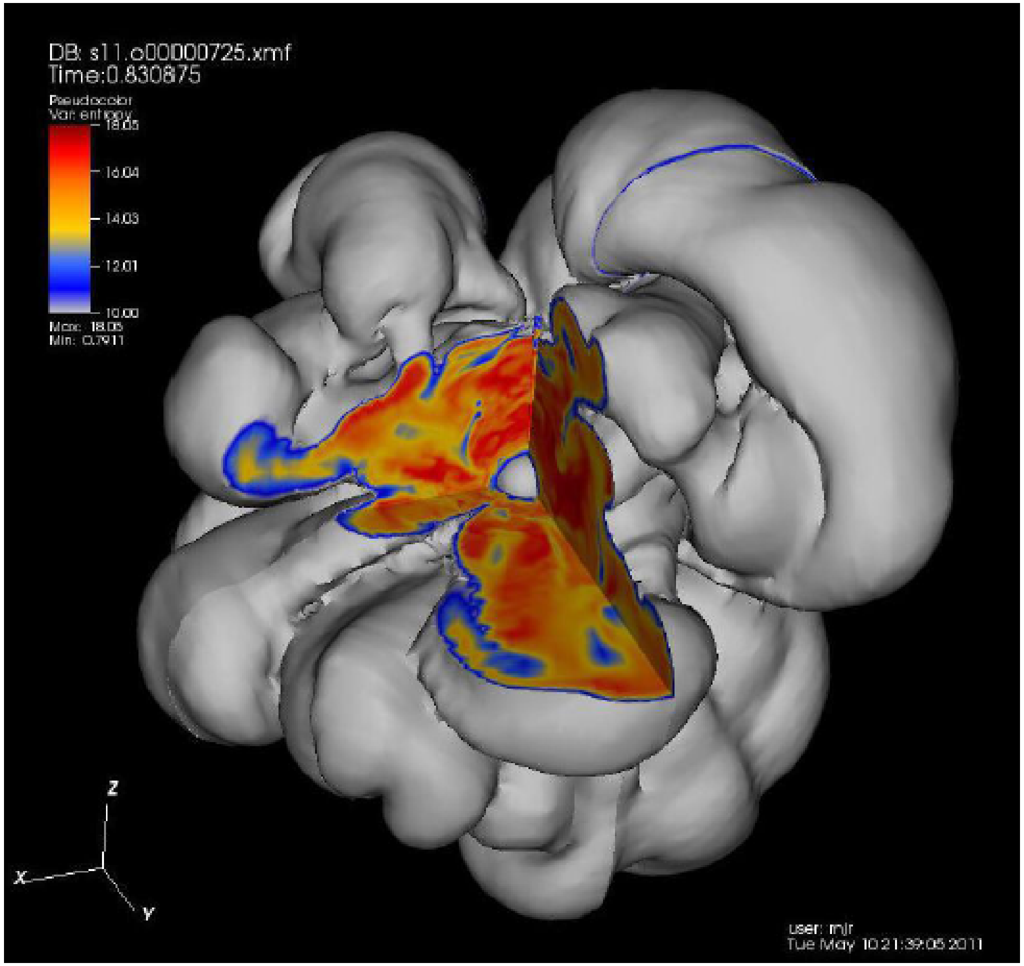
LC, spectra

explosion asymmetries, pulsar kicks

nucleosynthesis

# 2D and 3D Morphology





(Images from Markus Rampp, RZG)

# Explosions of $M_{star} \sim 8\text{–}9\ M_{sun}$ 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

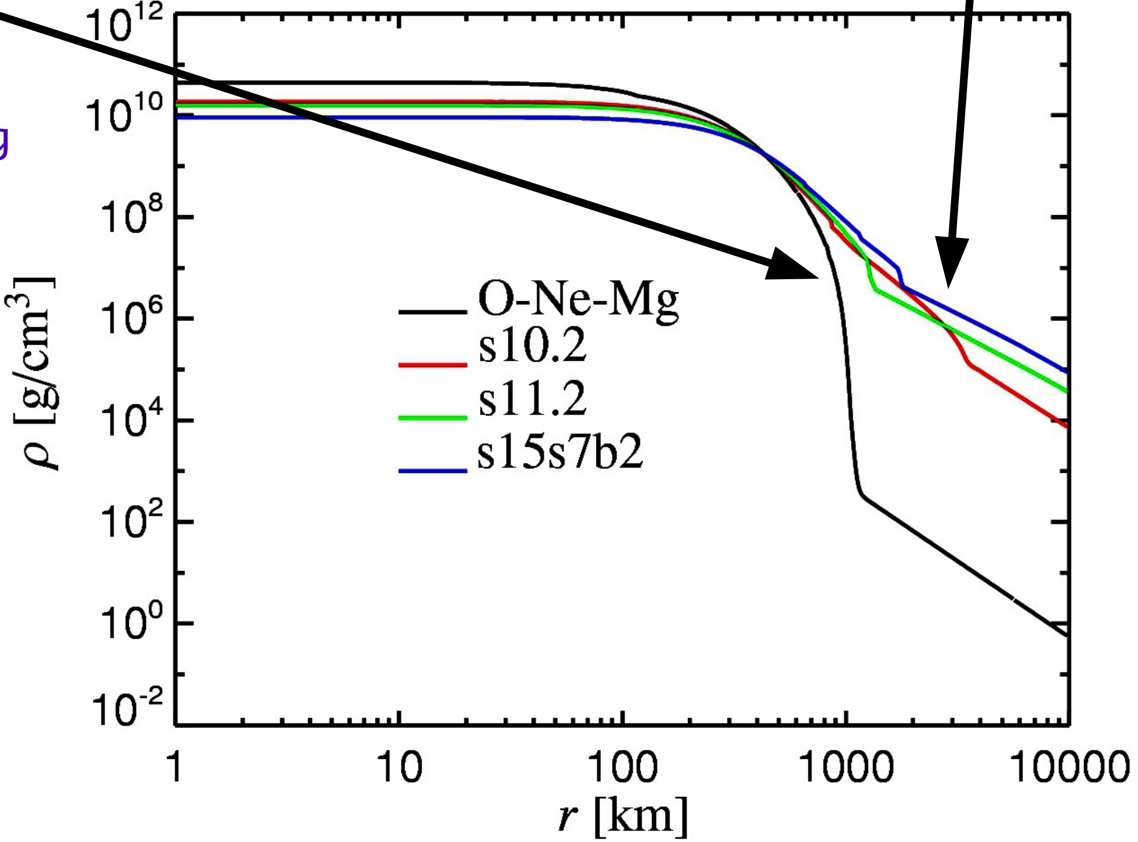
(====> rapidly decreasing mass accretion rate after core bounce)

>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

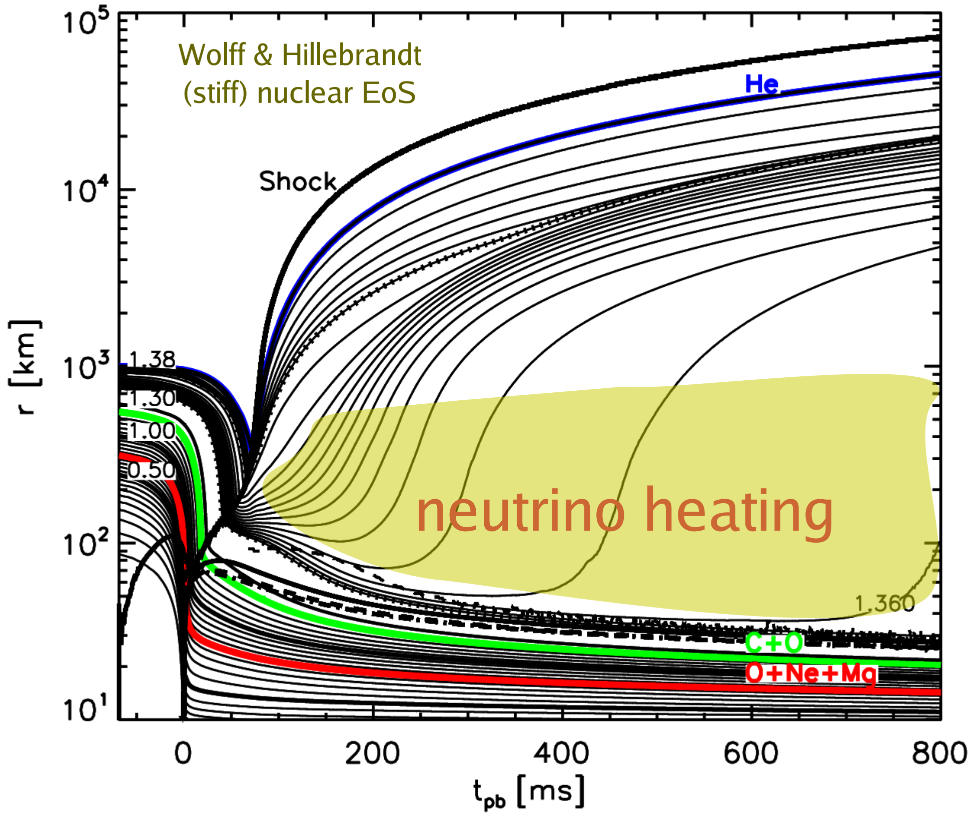


~30% of all SNe (Nomoto et al. 1981, 84, 87)

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: ECSN Explosions

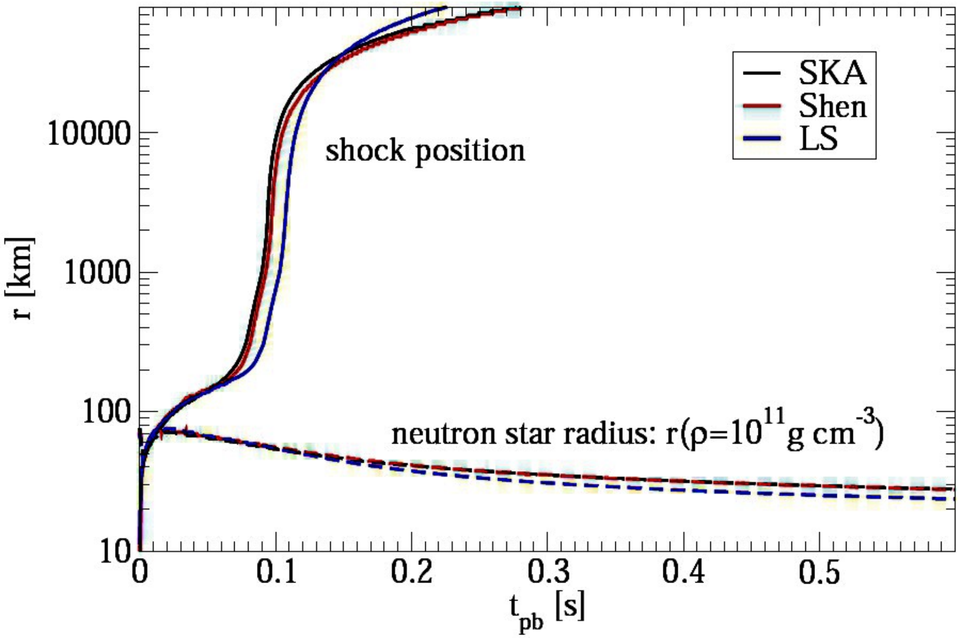
"Electron-capture supernovae"
or "ONeMg core supernovae"



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

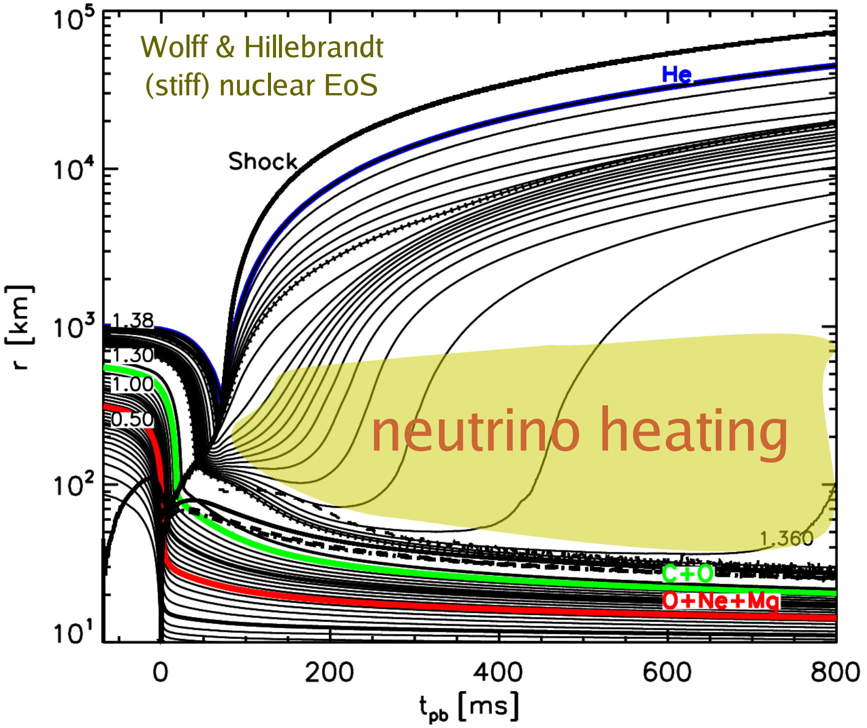
Convection is not necessary for launching explosion
but occurs in NS and in neutrino-heating layer

- 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)

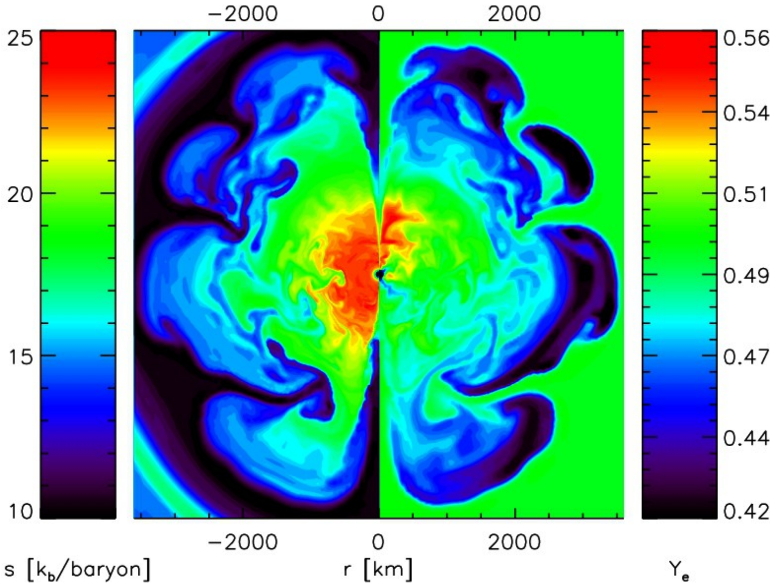


# 2D and 3D ECSN Models

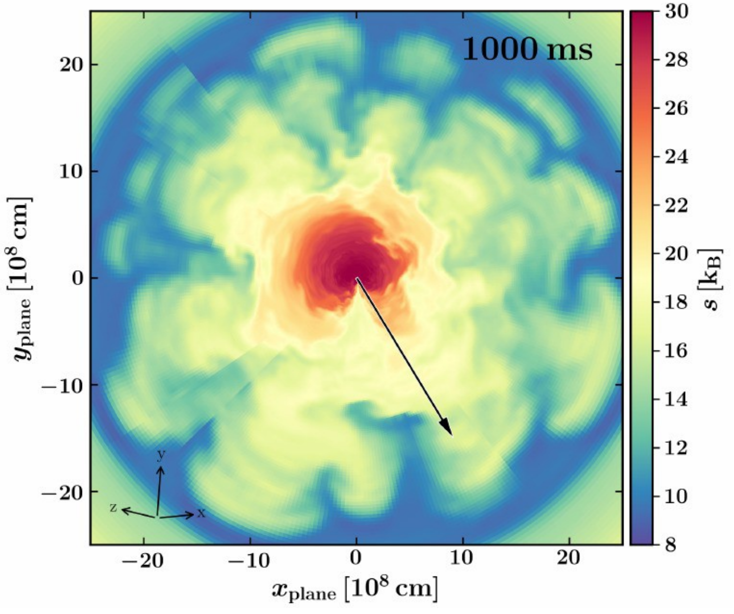
**ECSNe:**
**Explosions of low-mass stars ($\sim 9\ M_{sun}$) with O-Ne-Mg cores**

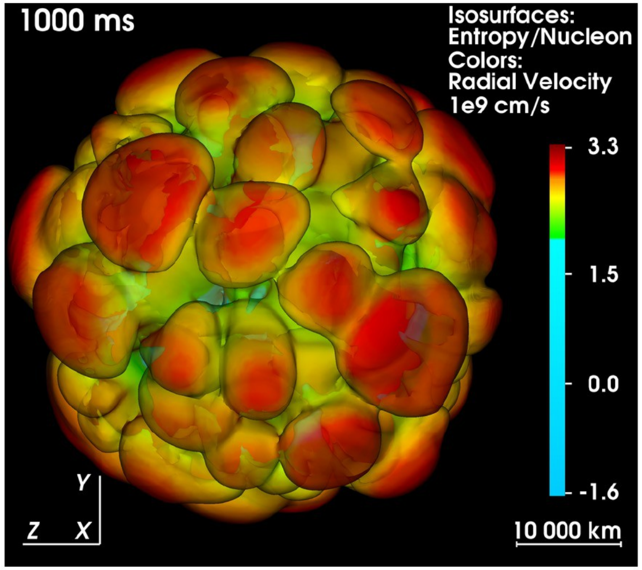


Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199



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



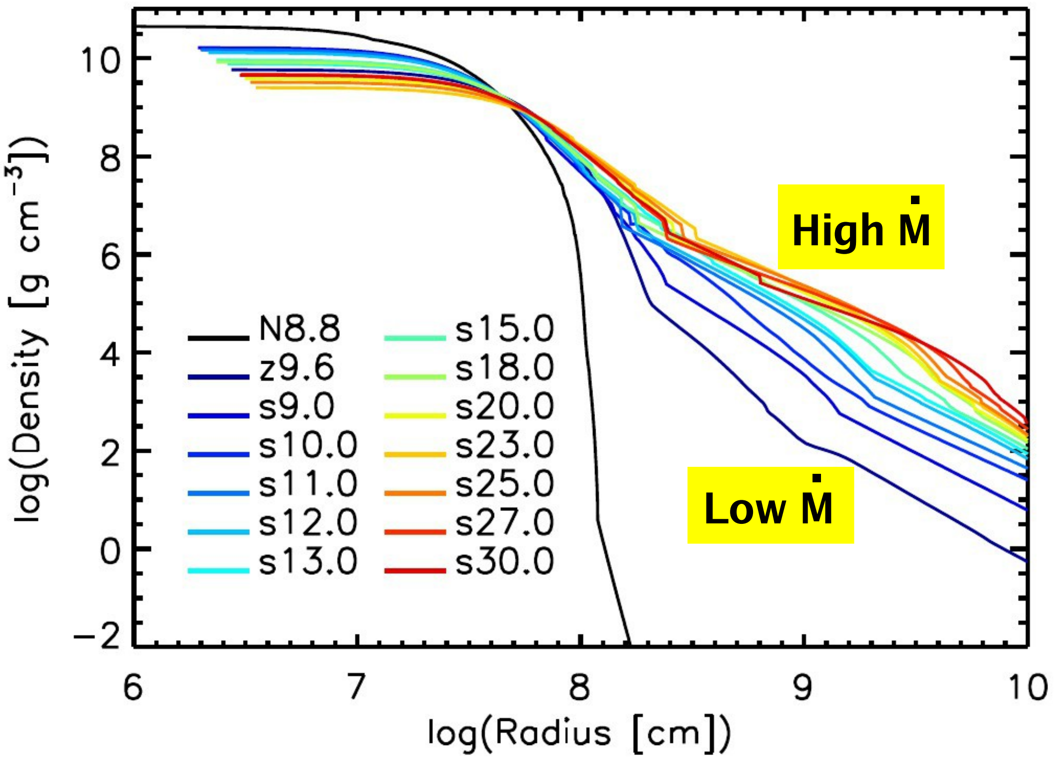


Gessner & Janka,
ApJ 865 (2018) 61

# Explosions of Stars with $M_{star} > 9\ M_{sun}$

# Progenitors: Density Profiles

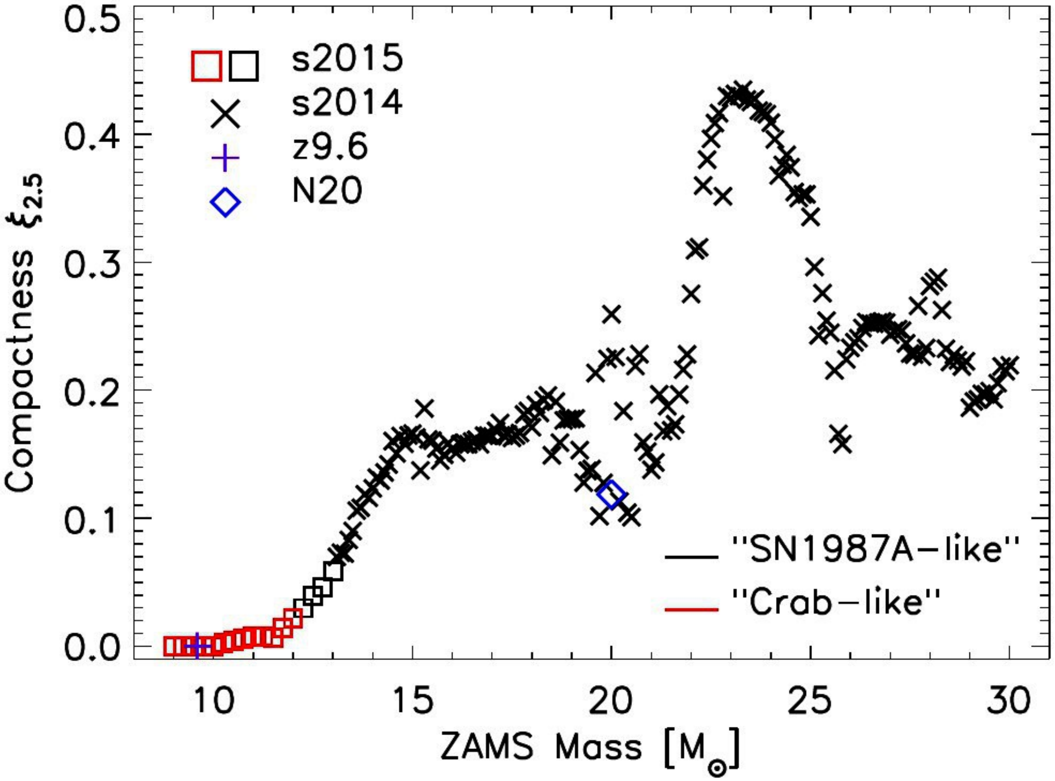
**Progenitor models:**
**Woosley et al. (RMP 2002), Sukhbold & Woosley (2014), Woosley & Heger (2015)**



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

mass $M = 2.5\ M_\odot$

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

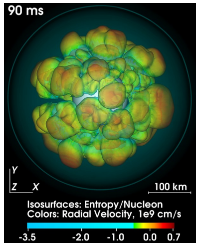


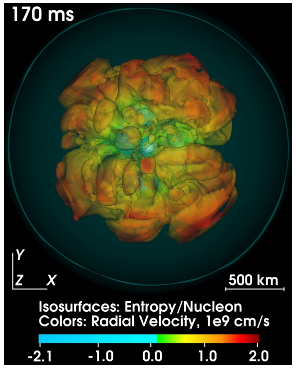
# 3D Core-Collapse SN Explosion Models

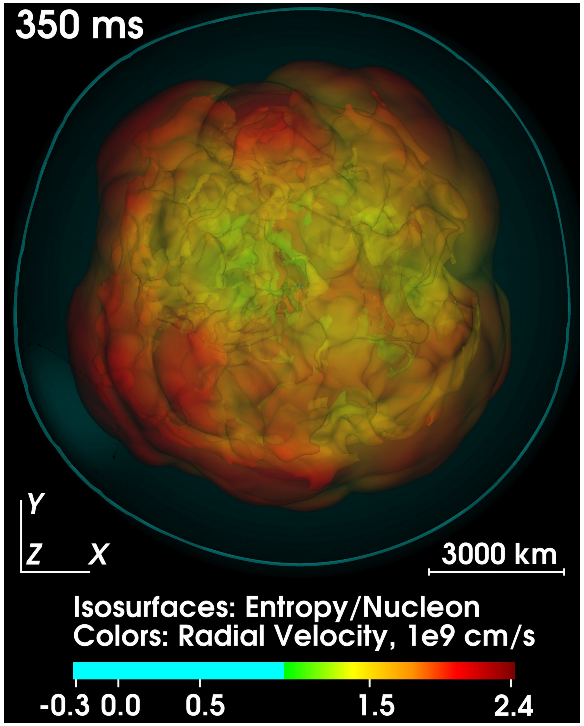
## 9.6 $M_{sun}$ (zero-metallicity) progenitor (Heger 2010)

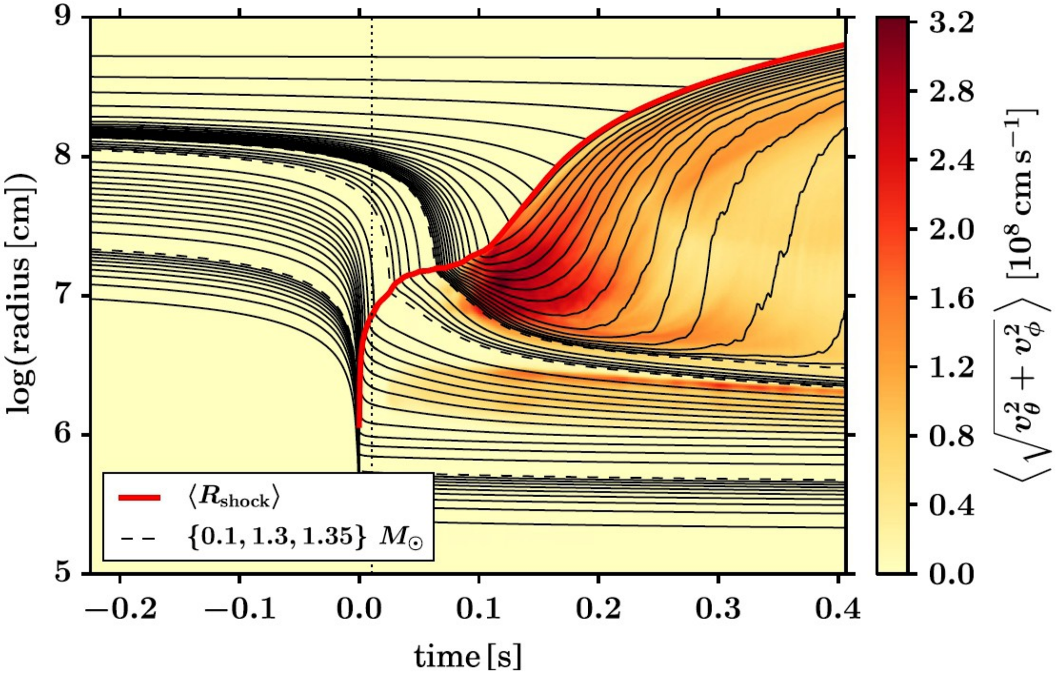
**Fe-core progenitor (Heger 2012) with ECSN-like density profile and explosion behavior.**

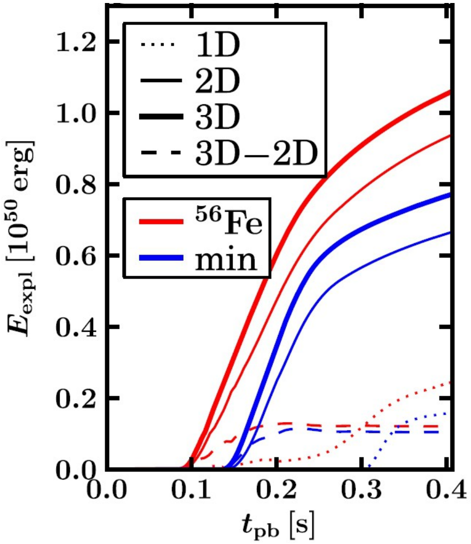
**Melson et al.,
ApJL 801 (2015) L24**

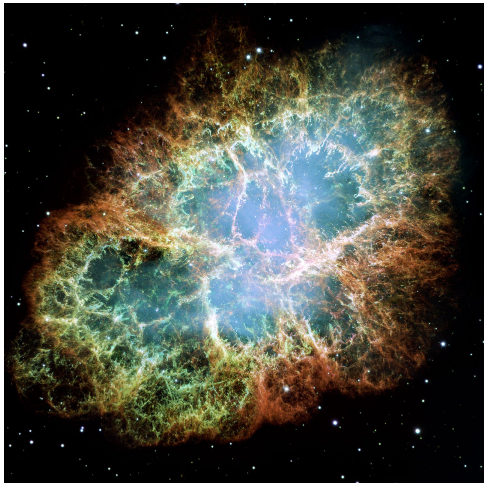






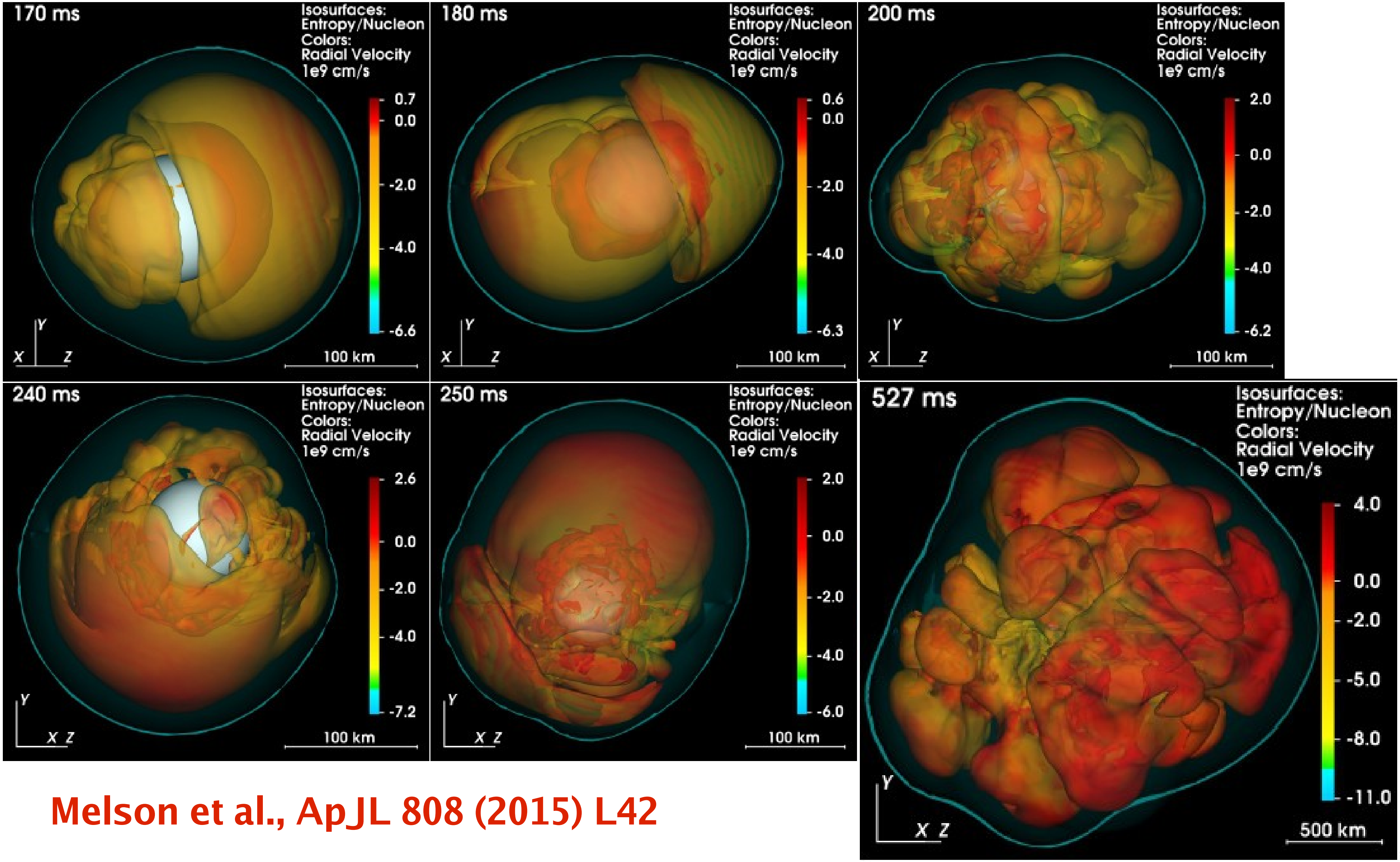






# 3D Core-Collapse SN Explosion Models

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

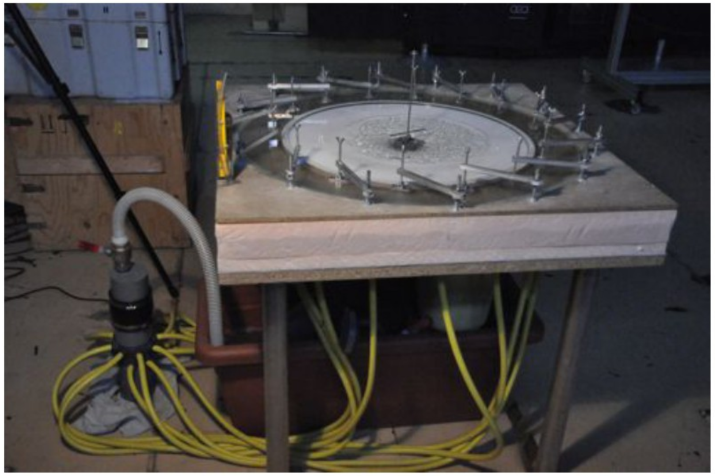


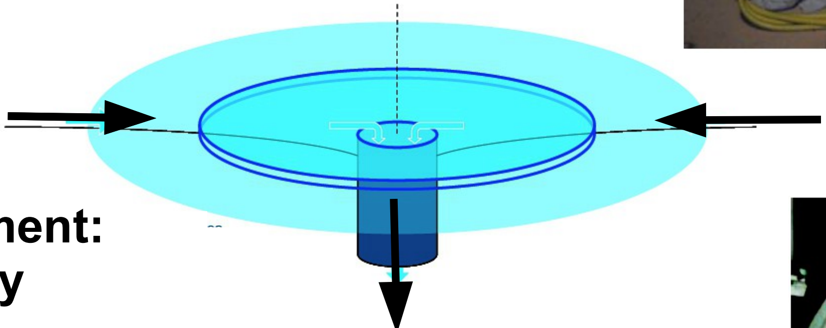
**Melson et al., ApJL 808 (2015) L42**

# Laboratory Astrophysics

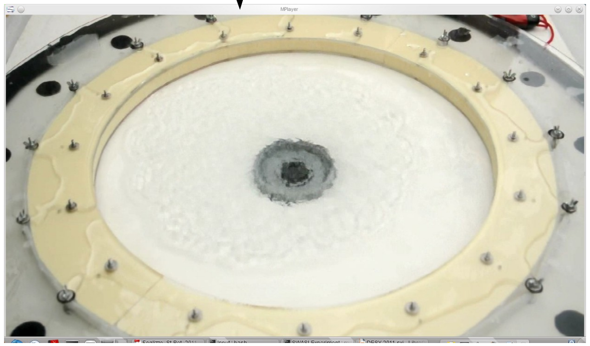
**"SWASI" Instability** as an analogue of SASI in the supernova core

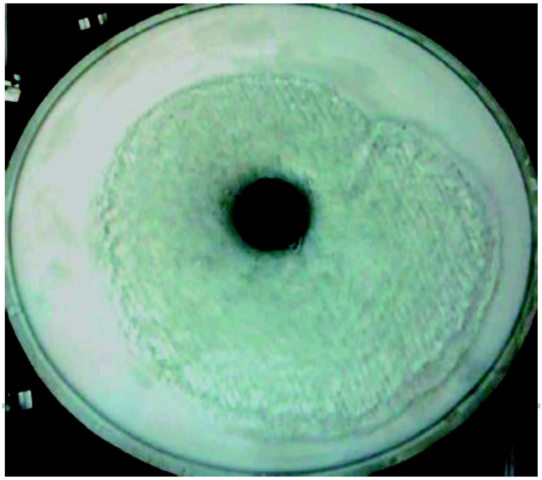
Foglizzo et al., PRL 108 (2012) 051103





**Constraint of experiment:**
**No convective activity**





# 3D CCSN Explosion Model with Rotation

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

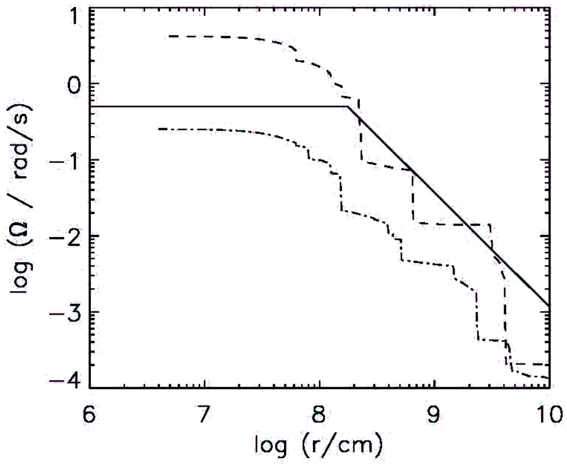
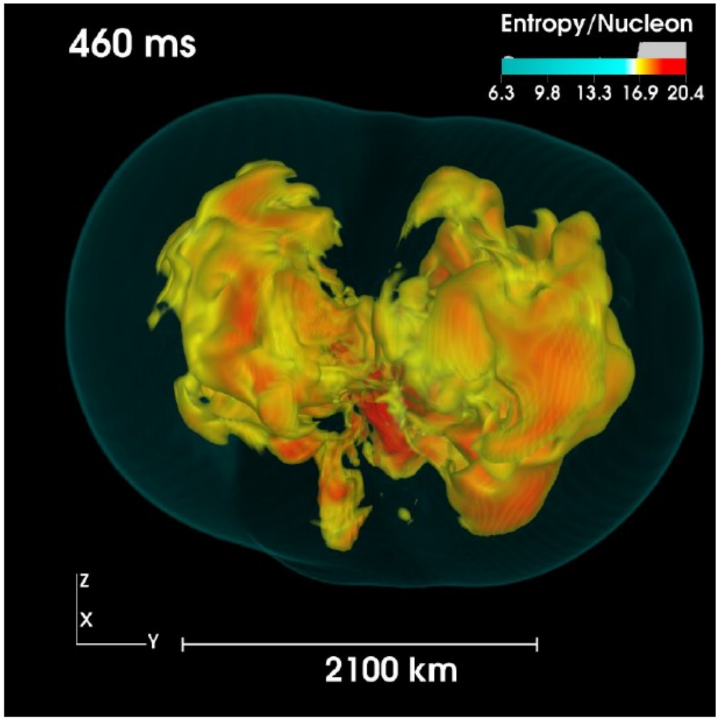
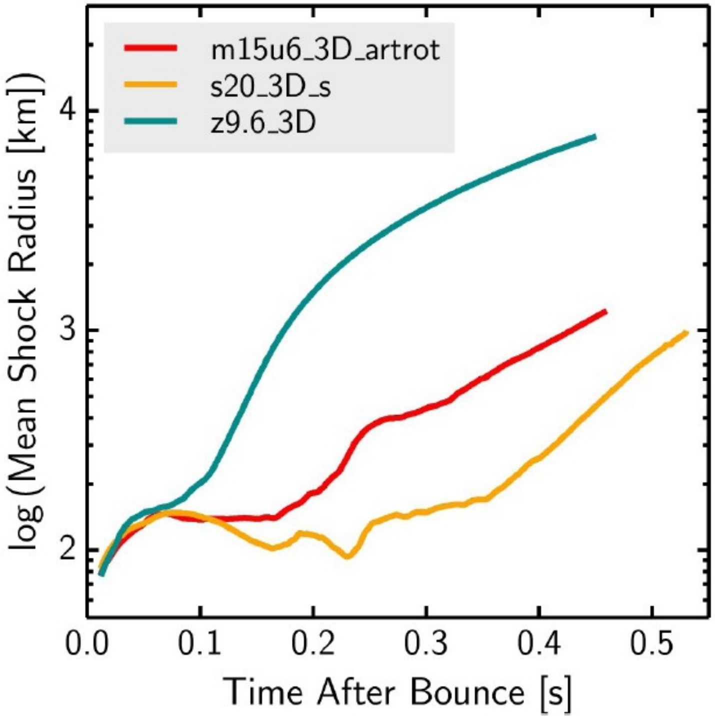


Fig. 1.—Angular velocity Ω as a function of radius *r* for the rotating 15 $M_\odot$ presupernova model (*dashed curve*) of Heger, Langer, & Woosley (2000), for the magnetic rotating 15 $M_\odot$ presupernova model (*dash-dotted curve*) of Heger et al. (2004), and for our rotating model s15r (*solid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

Explosion occurs for angular velocity of Fe-core of 0.5 rad/s, rotation period of ~12 seconds (several times faster than predicted for magnetized progenitor by Heger et al. 2005). Produces a neutron star with spin period of ~1–2 ms.





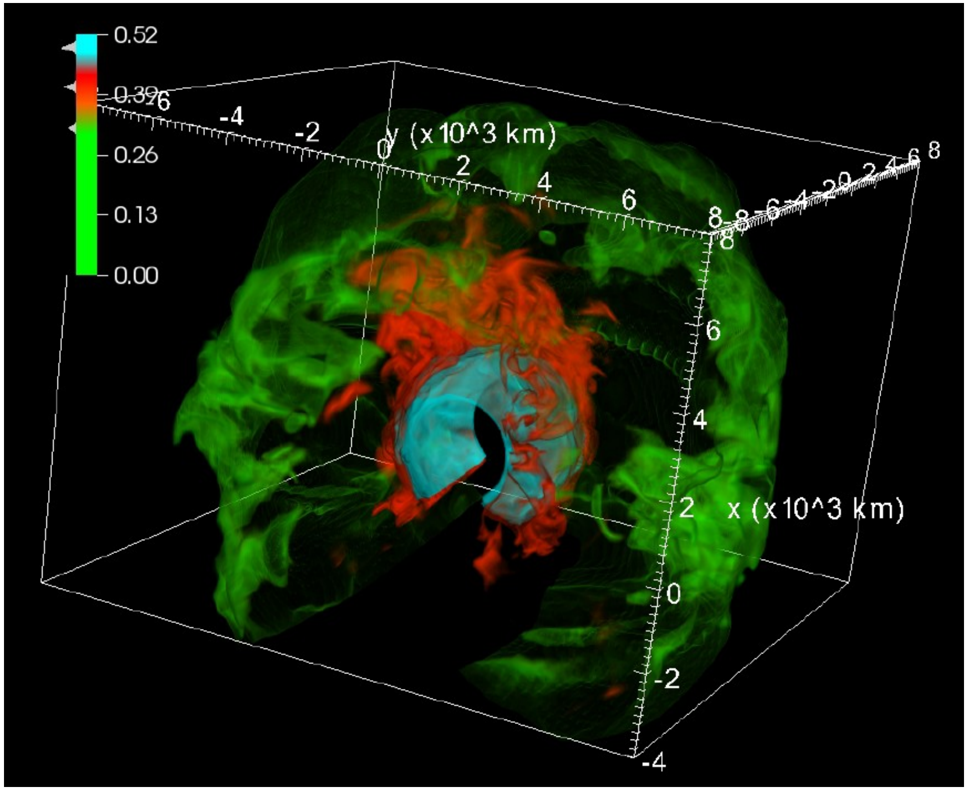
Janka, Melson & Summa, ARNPS 66 (2016);
Summa et al., ApJ 852 (2018) 28

# Pre-collapse
# 3D Asymmetries
# in Progenitors

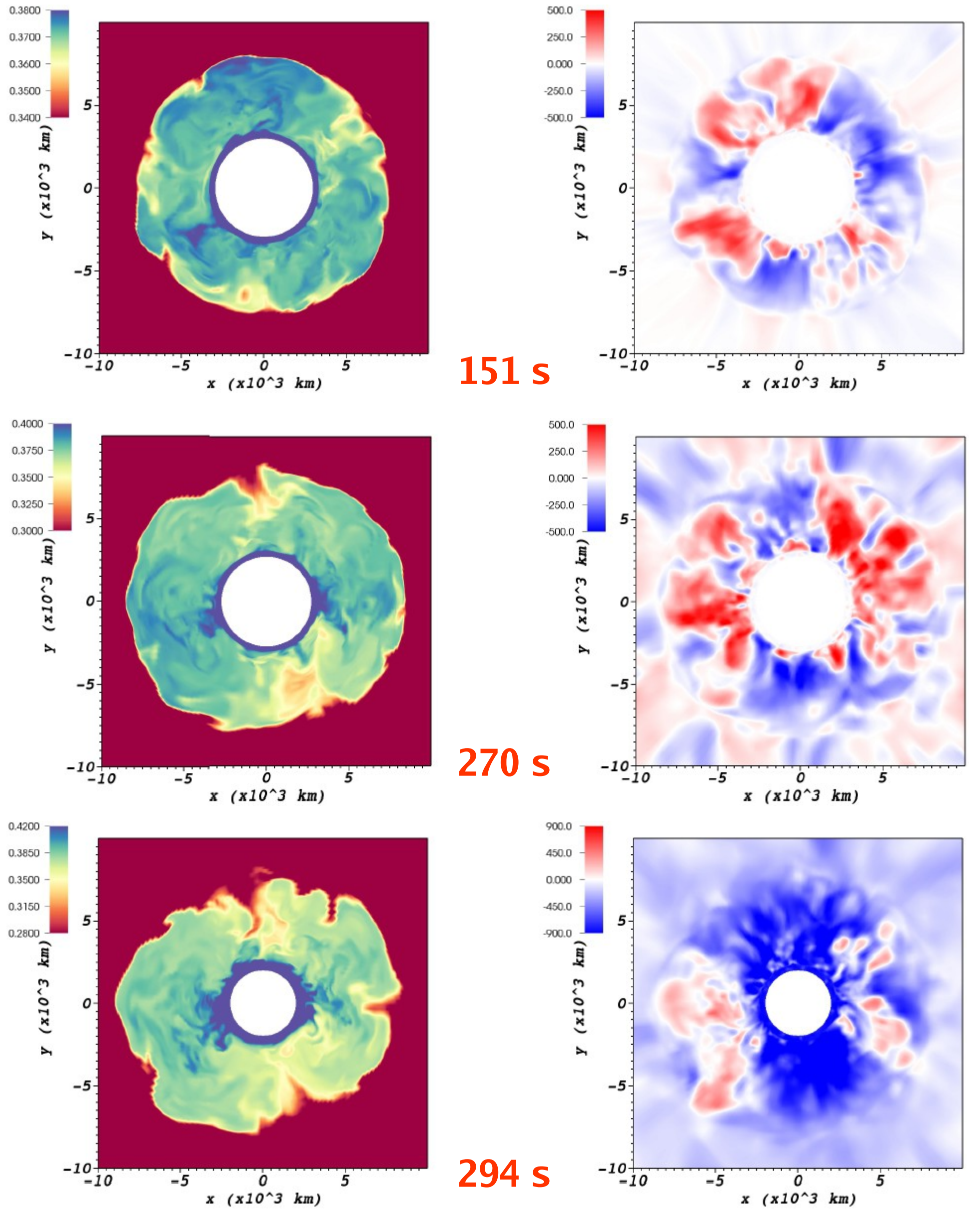
# 3D Core-Collapse SN Progenitor Model

## 18 $M_{sun}$ (solar-metallicity) progenitor (Heger 2015)

**3D simulation of last 5 minutes of O-shell burning. During accelerating core contraction a quadrupolar (l=2) mode develops with convective Mach number of about 0.1.**



B. Müller, Viallet, Heger, & THJ, ApJ 833, 124 (2016)

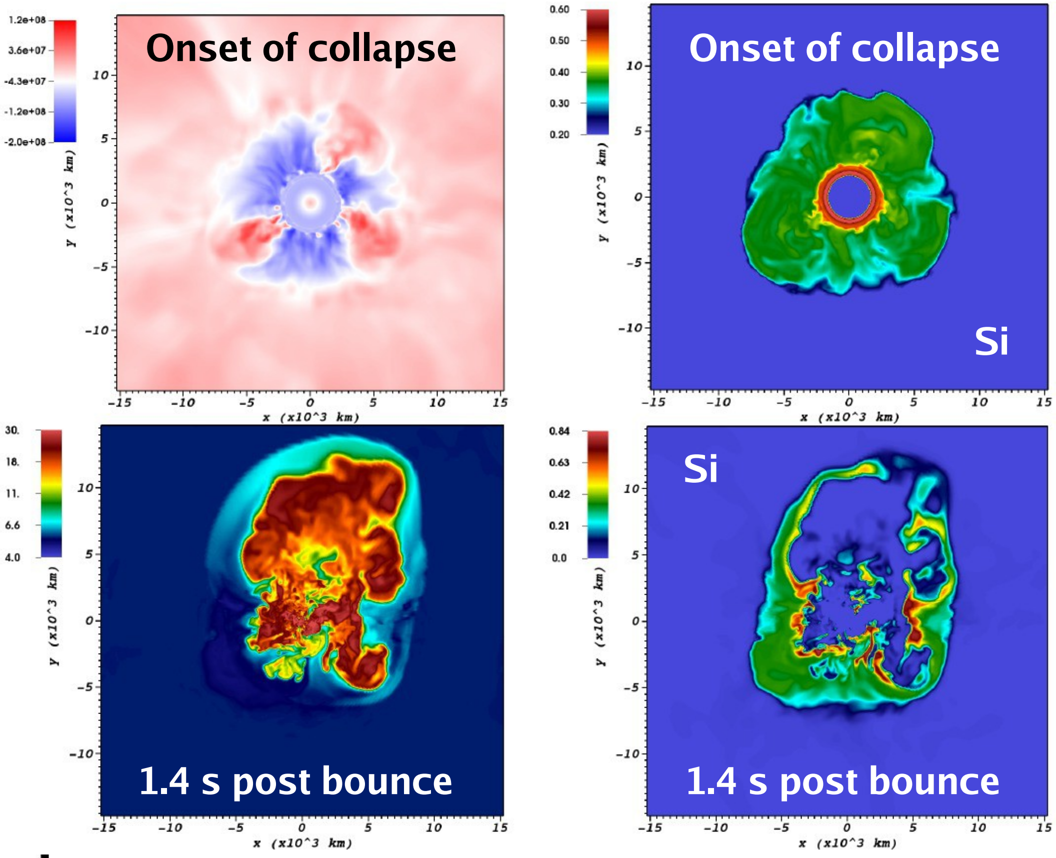


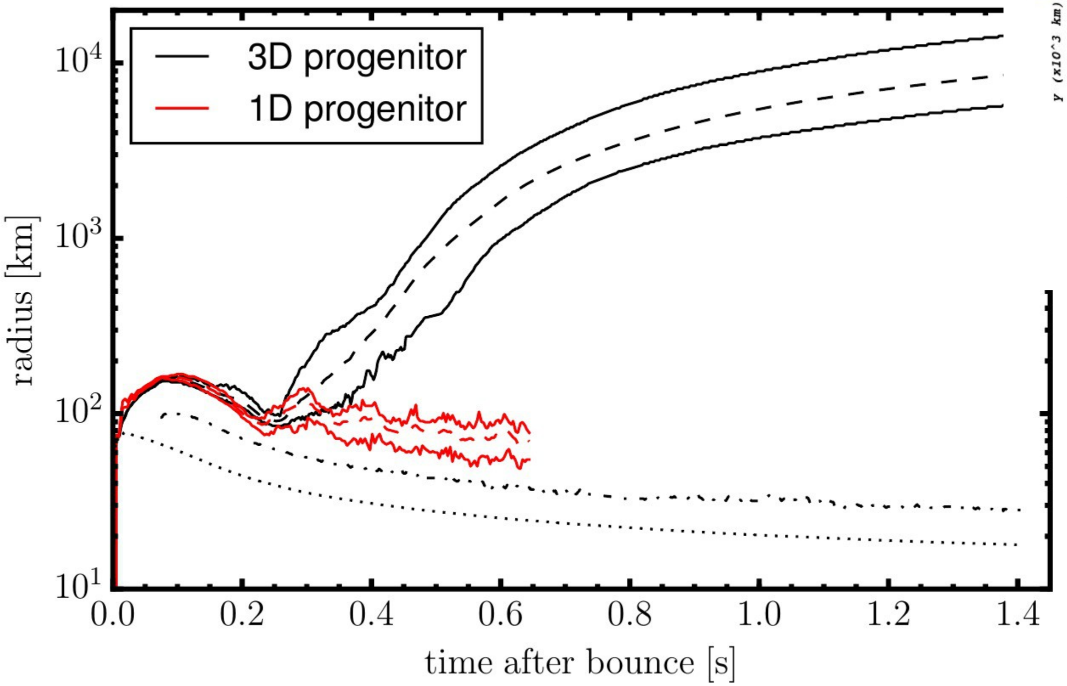
# 3D Core-Collapse SN Explosion Model

## 18 $M_{\rm sun}$ (solar-metallicity) progenitor (Heger 2015)

3D simulation of last 5 minutes of O-shell burning. During accelerating core contraction a quadrupolar (l=2) mode develops with convective Mach number of about 0.1.

This fosters strong postshock convection and could thus reduces the criticial neutrino luminosity for explosion.





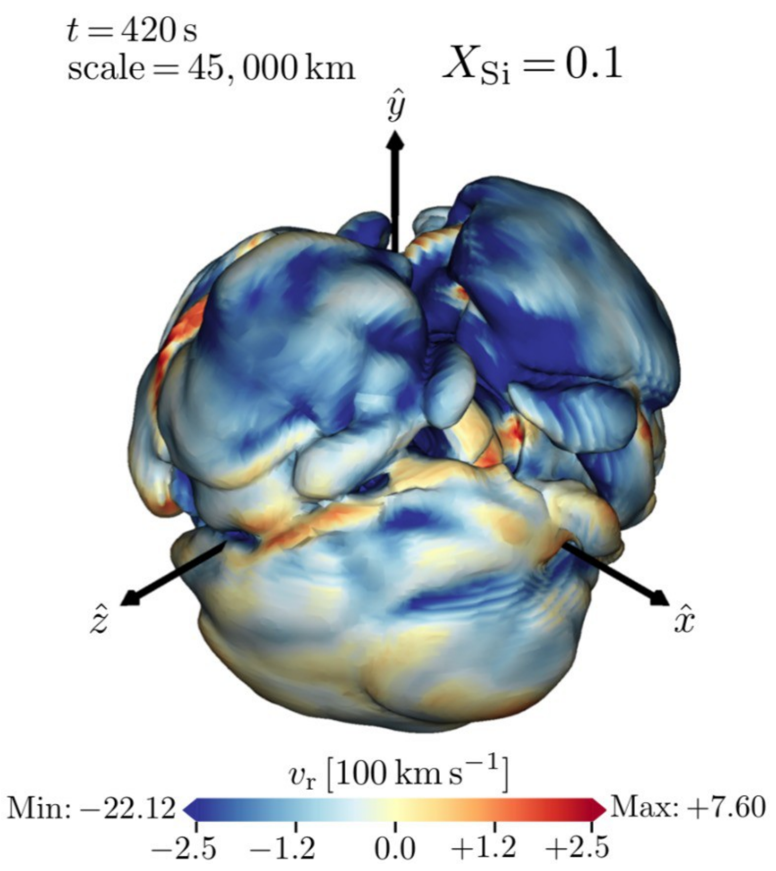
$$\delta\rho/\rho \sim \mathrm{Ma}_{\rm conv}$$

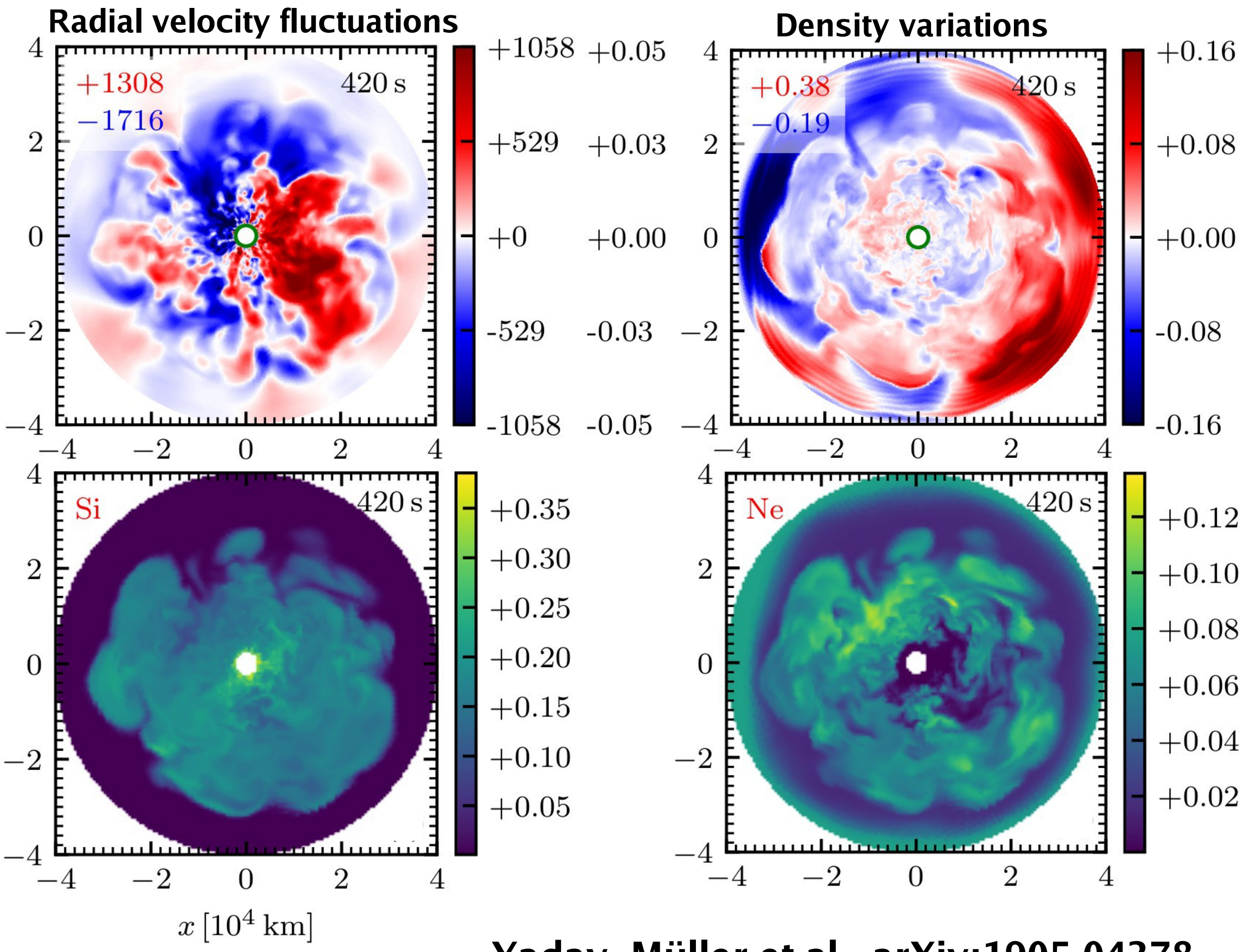
$$(L_\nu E_\nu^2)_{\rm crit,pert} \approx (L_\nu E_\nu^2)_{\rm crit,3D}\left(1-0.47\,\frac{\mathrm{Ma}_{\rm conv}}{\ell\,\eta_{\rm acc}\,\eta_{\rm heat}}\right)$$

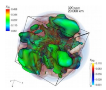
**B. Müller, PASA 33, 48 (2016);**
**Müller, Melson, Heger & THJ, MNRAS 472, 491 (2017)**

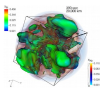
# Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 $M_{sun}$

## Flash of Ne+O burning creates large-scale asymmetries in density, velocity, Si/Ne composition



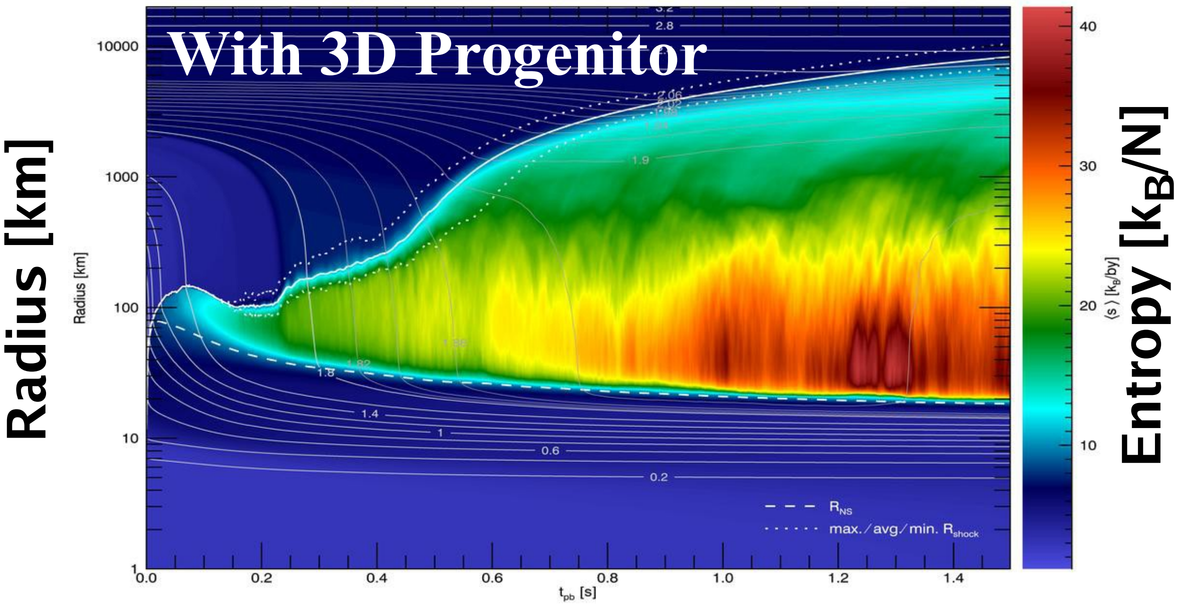


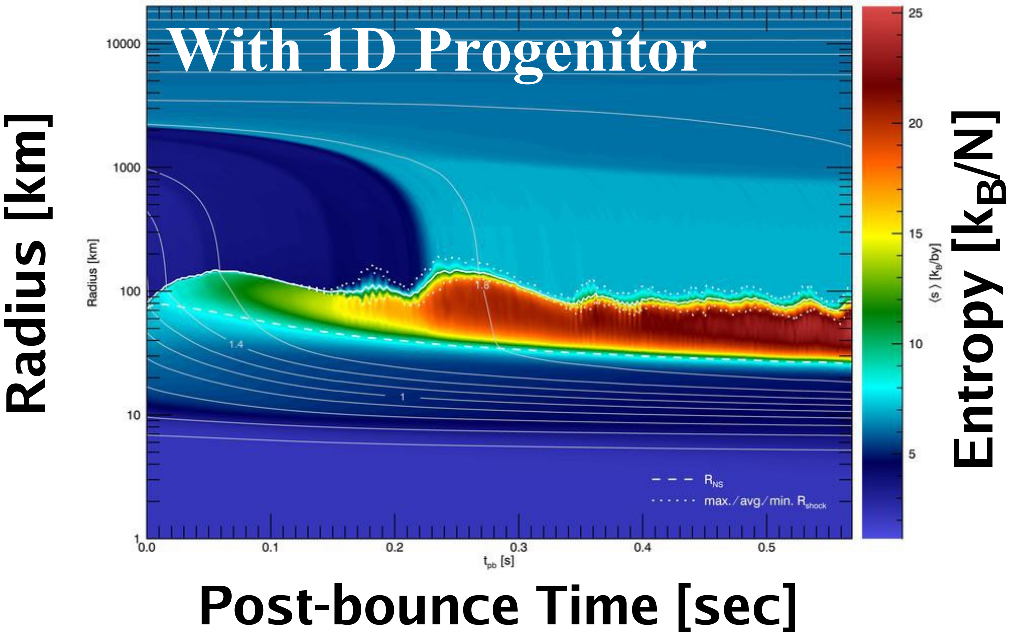


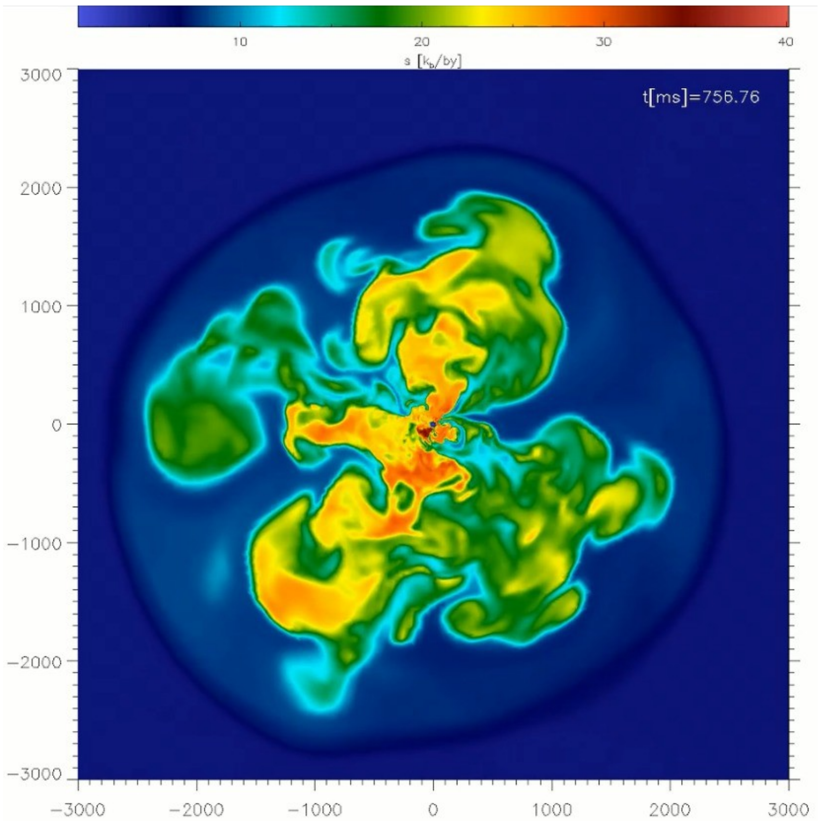


Yadav, Müller et al., arXiv:1905.04378

# 3D Explosion of ~19 $M_{sun}$ Star after Neon-oxygen-shell Merger







**Pre-collapse perturbations in convectively burning O-shell aid explosion because it stirs strong postshock convection.**

**R. Bollig et al., arXiv preprint**

# Observational consequences

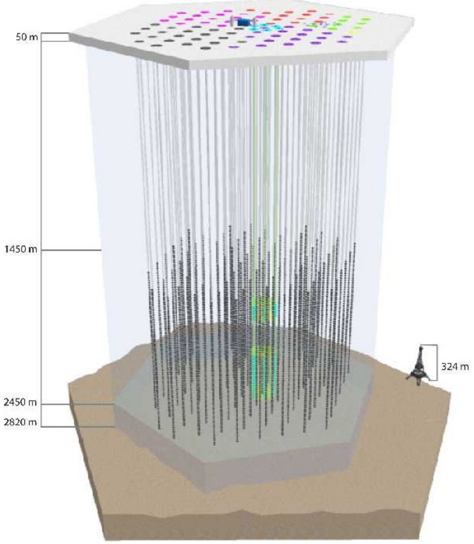
## and indirect evidence for neutrino heating and hydrodynamic instabilities at the onset of stellar explosions:

- Neutrino signals (characteristic modulations)
- Gravitational-wave signals
- Neutron star kicks
- Asymmetric mass ejection & large-scale radial mixing
- Light curve shape, spectral features (elmagn. emission)
- Progenitor – explosion – remnant connection
- Nucleosynthesis

# Detecting Core-Collapse SN Signals

Superkamiokande


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo



IceCube

VIRGO

# Observational consequences

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

- Neutrino signals (characteristic modulations)
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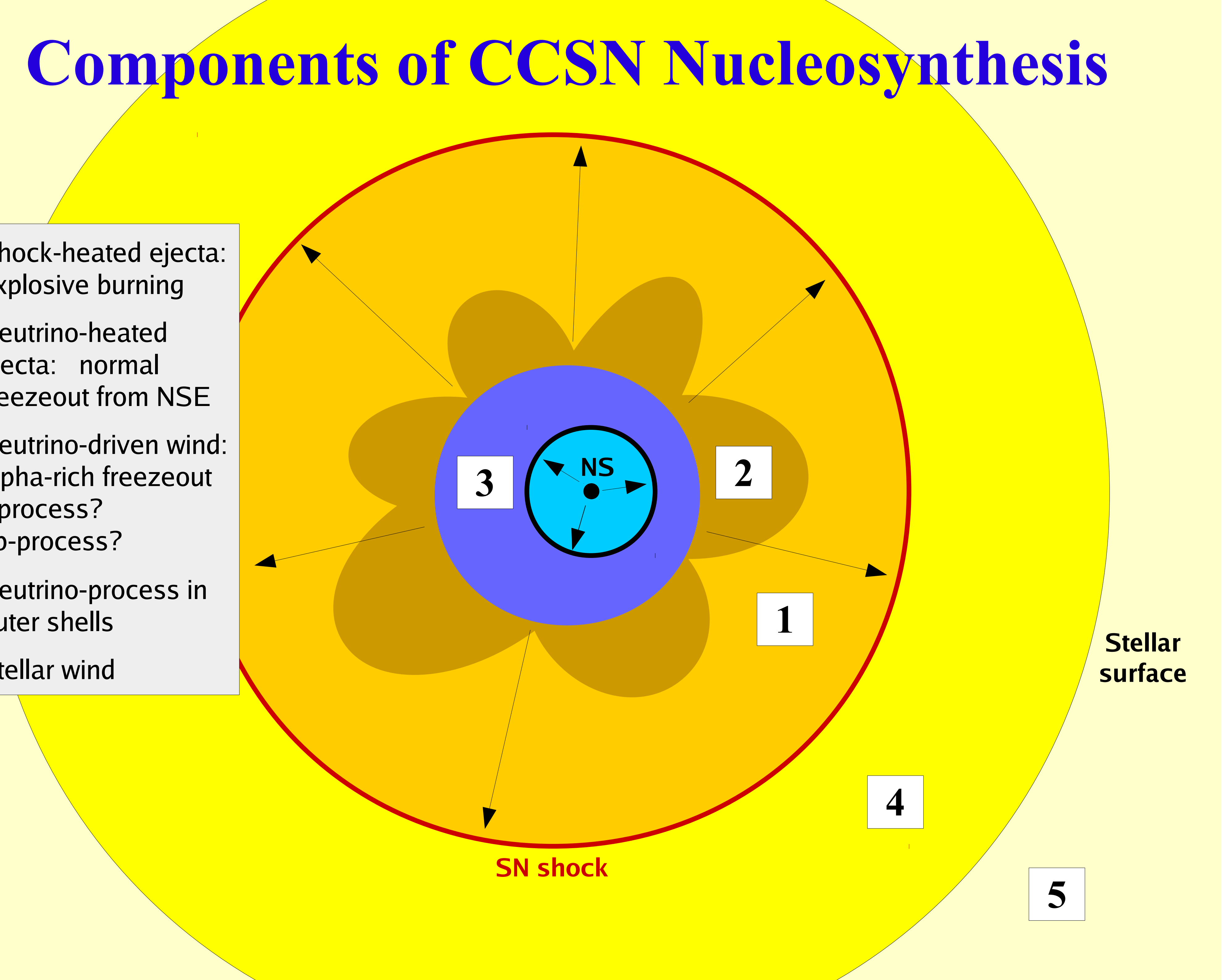
# Nucleosynthesis
# &
# Supernova Diagnostics

# Components of CCSN Nucleosynthesis



1. Shock-heated ejecta: explosive burning
2. Neutrino-heated ejecta: normal freezeout from NSE
3. Neutrino-driven wind: alpha-rich freezeout<br>r-process?<br>νp-process?
4. Neutrino-process in outer shells
5. Stellar wind

# Components of CCSN Nucleosynthesis

1. Shock-heated ejecta: explosive burning
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3. Neutrino-driven wind: alpha-rich freezeout r-process? νp-process?
4. Neutrino-process in outer shells
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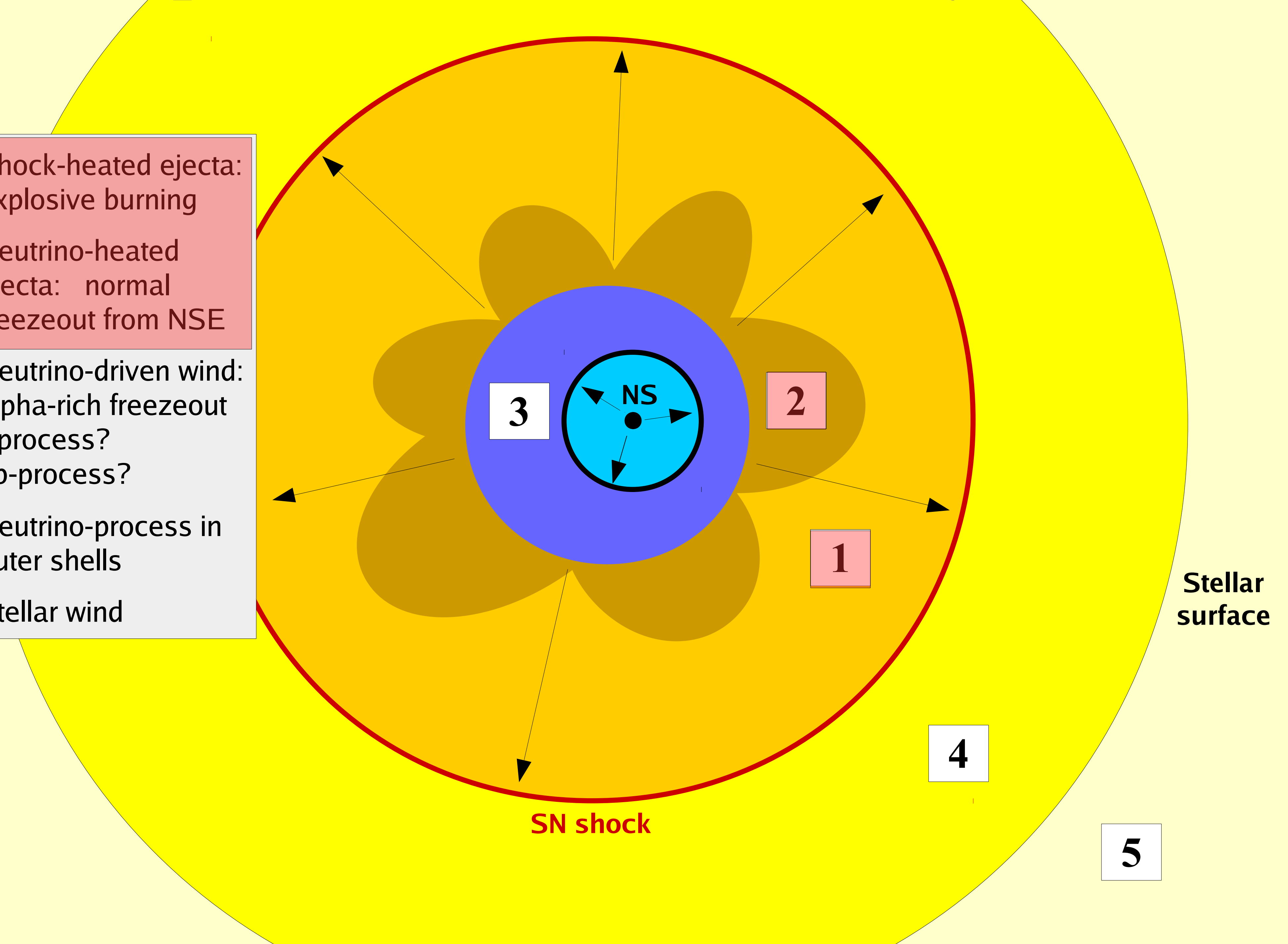


# Nucleosynthesis in Supernovae Ejecta

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:

$$\begin{aligned} \nu_e + n &\rightarrow e^- + p \\ \bar{\nu}_e + p &\rightarrow e^+ + n \end{aligned}$$

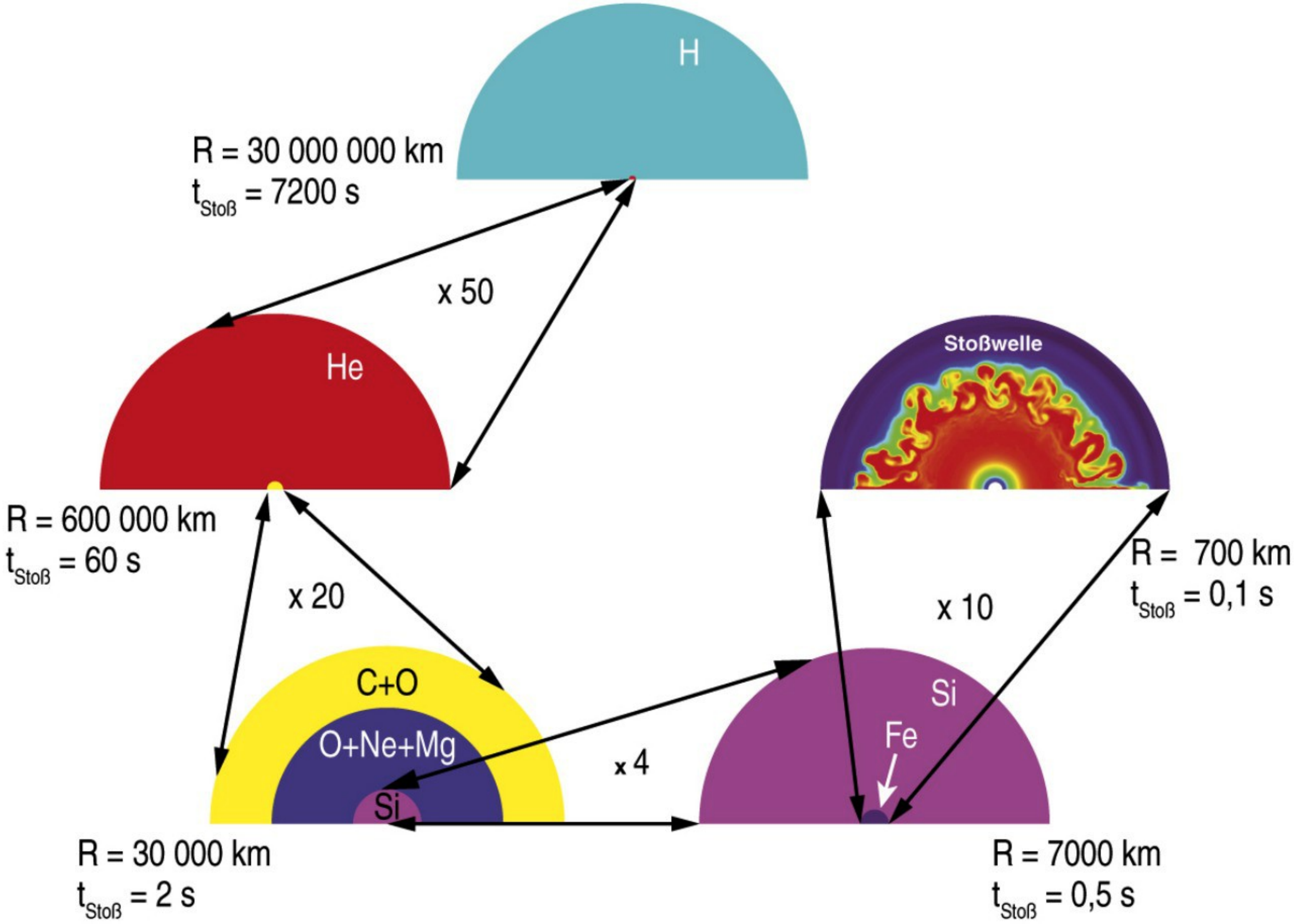
$$\boxed{Y_e \sim \left[1 + \frac{L_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e} - 2\Delta)}{L_{\nu_e}(\epsilon_{\nu_e} + 2\Delta)}\right]^{-1}}$$

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

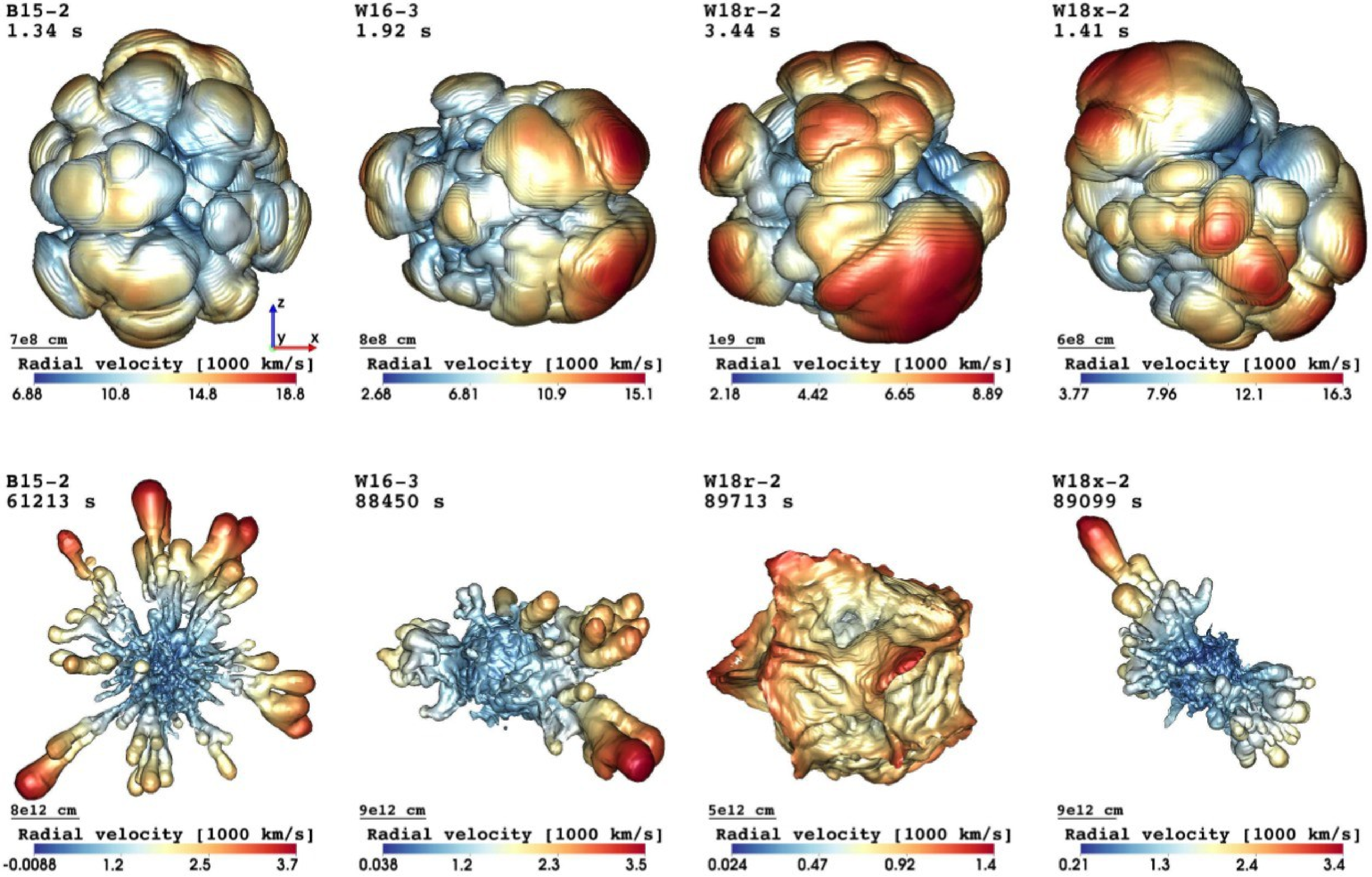
If $L_{\bar{\nu}_e} \approx L_{\nu_e}$, one needs for $Y_e < 0.5$ (i.e. neutron excess):

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

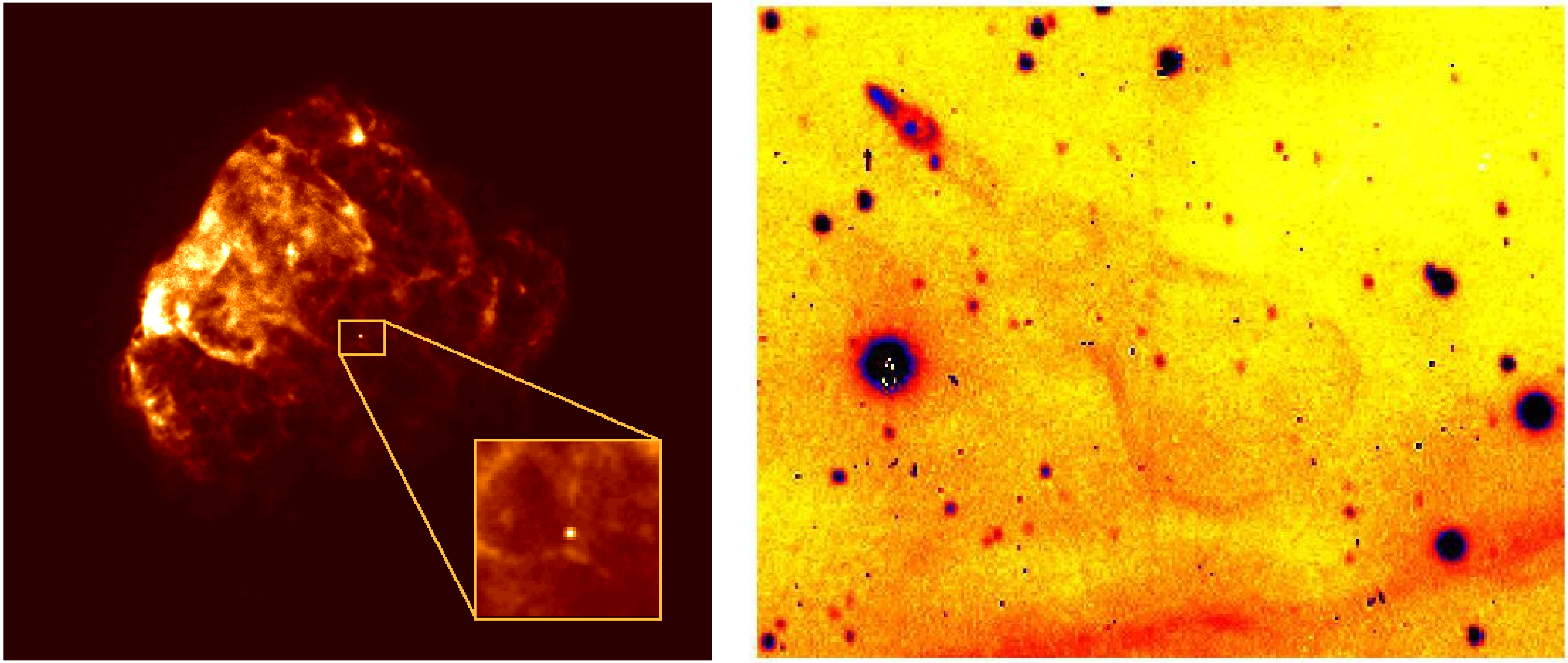
**3D asymmetries from the onset of the explosion determine asymmetry of the SN ejecta and SN remnant.**
**Modeling of the explosion has to be performed in 3D consistently from pre-collapse stage to SNR phase !**



# 3D SN Models: Different Morphologies

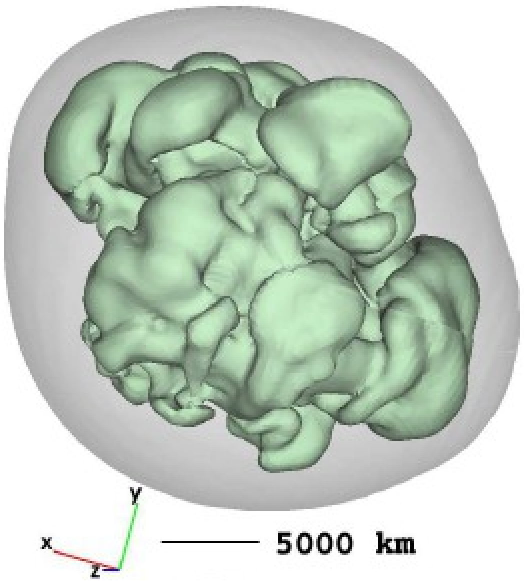


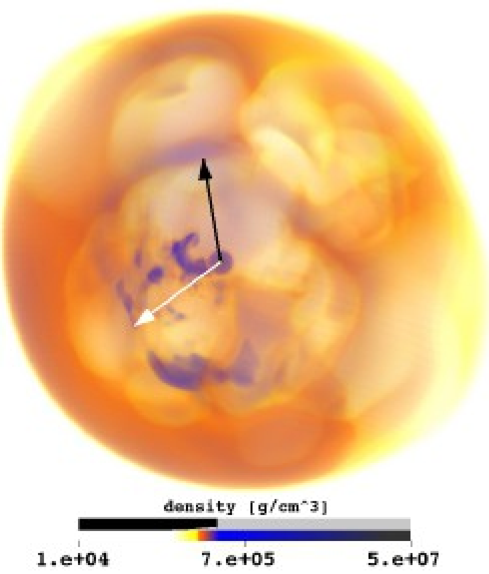
Utrobin et al., A&A 624 (2019) A116

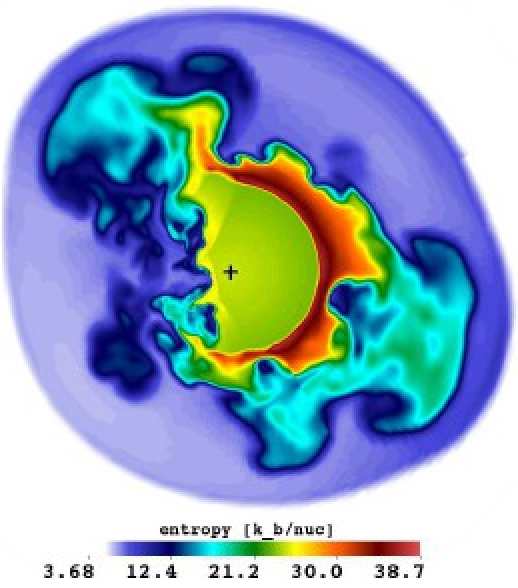


# Neutron Star Kicks in 3D SN Explosions

# Neutron Star Recoil in 3D Explosion Models





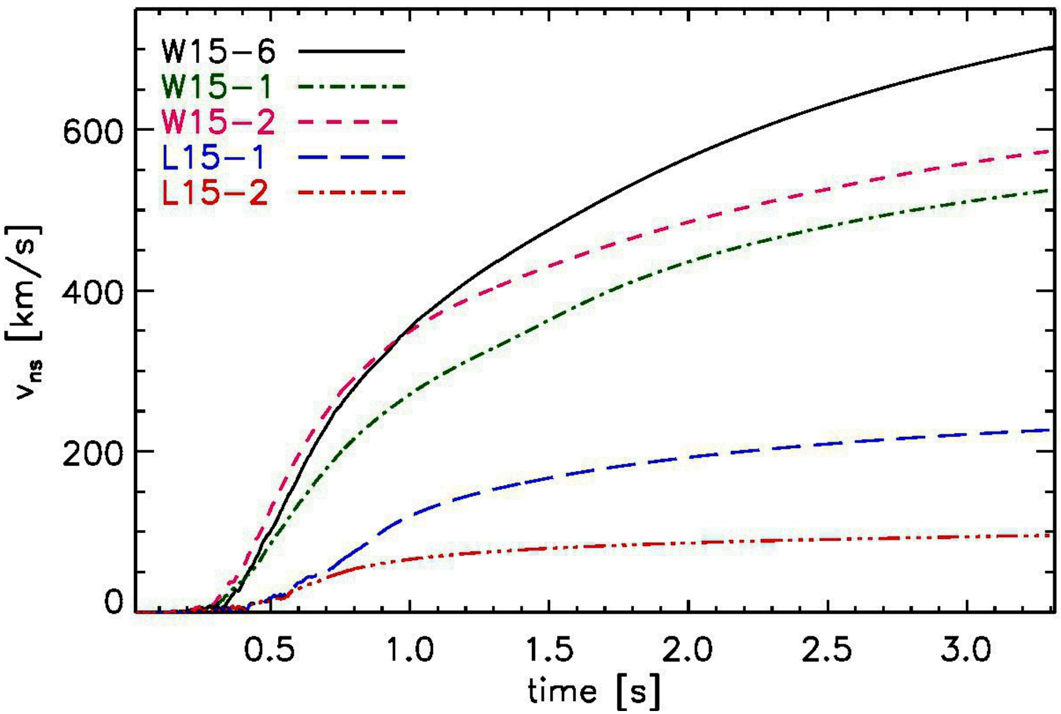


## Gravitational tug-boat mechanism

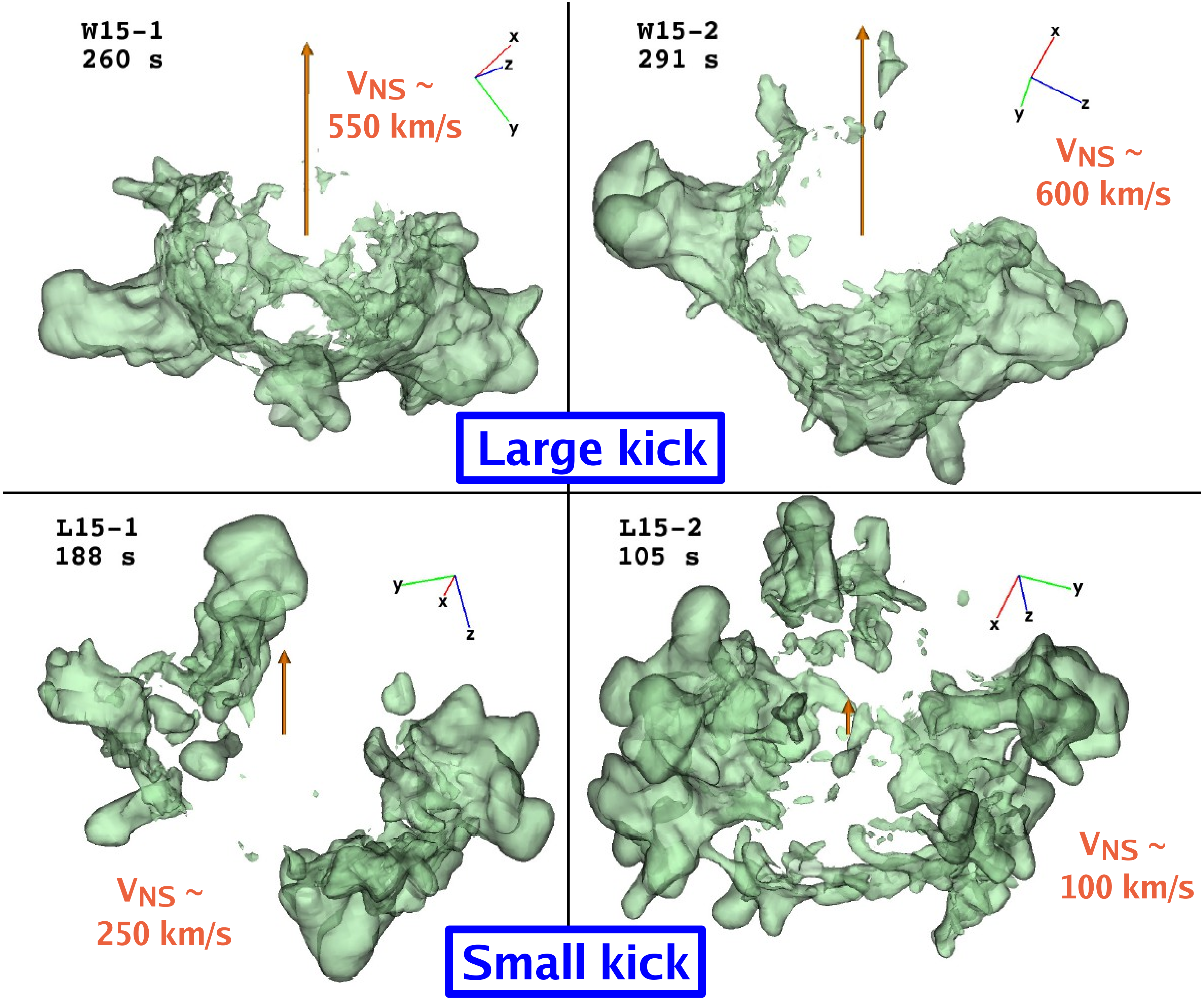
$$v_{\mathrm{ns}} \approx \frac{2G\Delta m}{r_{\mathrm{i}} v_{\mathrm{s}}} \approx 540 \left[\frac{\mathrm{km}}{\mathrm{s}}\right] \frac{\Delta m_{-3}}{r_{\mathrm{i},7}\, v_{\mathrm{s},5000}},$$

where $\Delta m$ is normalized by $10^{-3}\,M_{\odot}$, $r_{\mathrm{i}}$ by $10^{7}$ cm, and $v_{\mathrm{s}}$ by $5000\,\mathrm{km\,s^{-1}}$.

Wongwathanarat, Janka, Müller,
ApJL 725, 106 (2010); A&A 552, 126 (2013)



Wongwathanarat, Janka, Müller, A&A 552 (2013) A126



$V_{NS}$ ~ 550 km/s

$V_{NS}$ ~ 600 km/s

**Large kick**

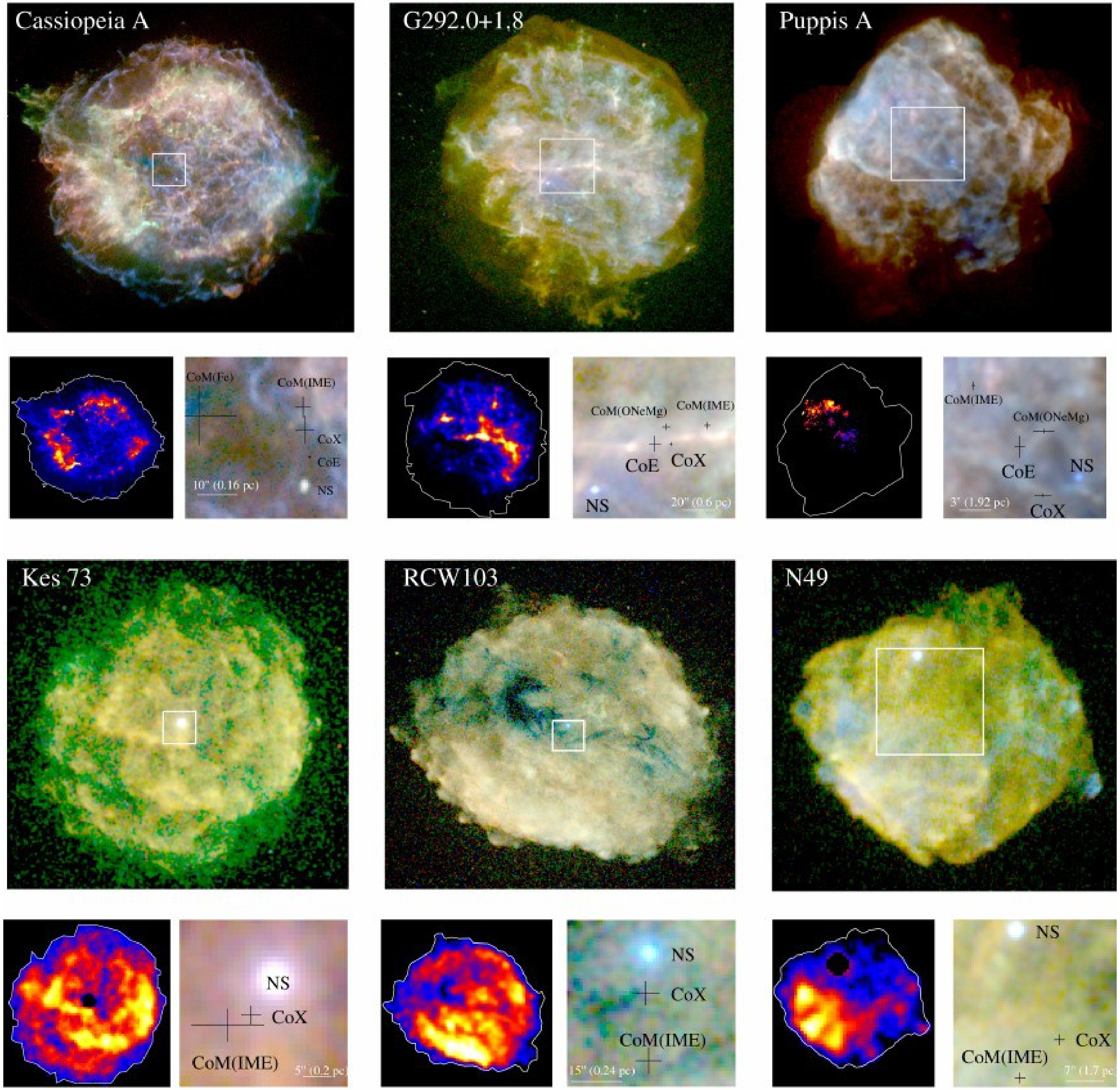
$V_{NS}$ ~ 250 km/s

$V_{NS}$ ~ 100 km/s

**Small kick**

# Neutron Star Kicks and Young SN Remnants

Analysis of spatial distribution of IMEs (from Ne to Fe-group) in young, nearby SNRs with known NS kick velocities.

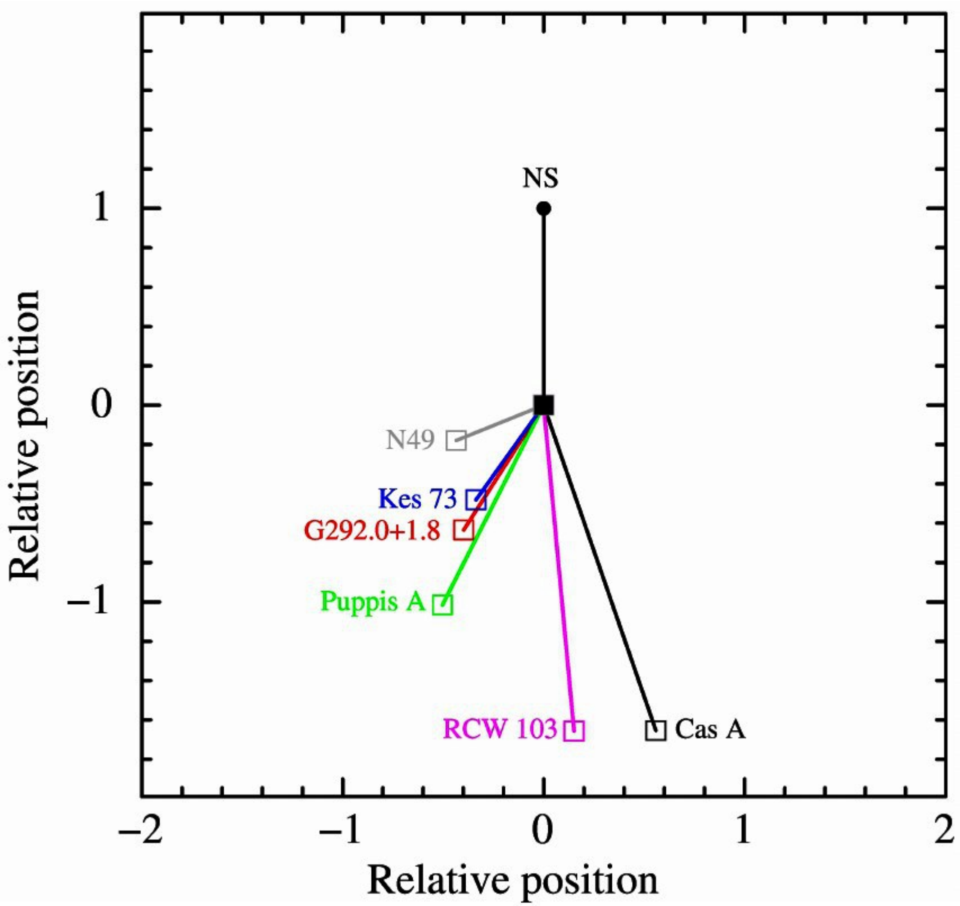


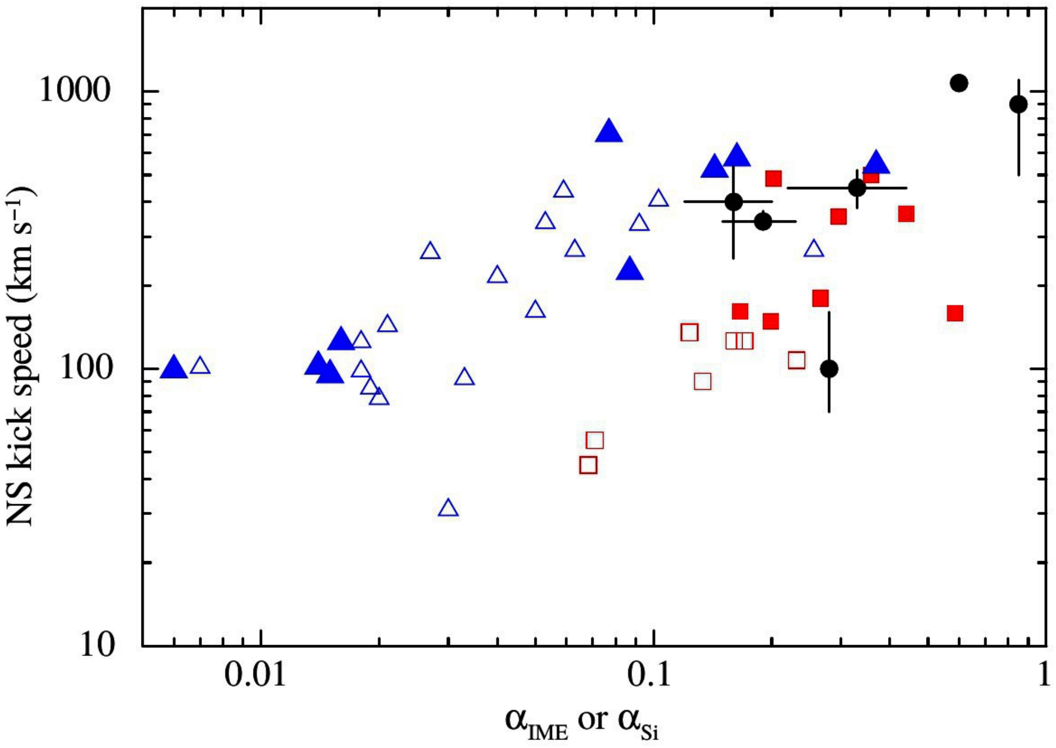
Katsuda, Morii, THJ, et al.
arXiv:1710.10372

see also:
Holland-Ashford, et al.,
ApJ 844 (2017) 84;
Bear & Soker, arXiv:1710.00819

# Neutron Star Kicks and Young SN Remnants

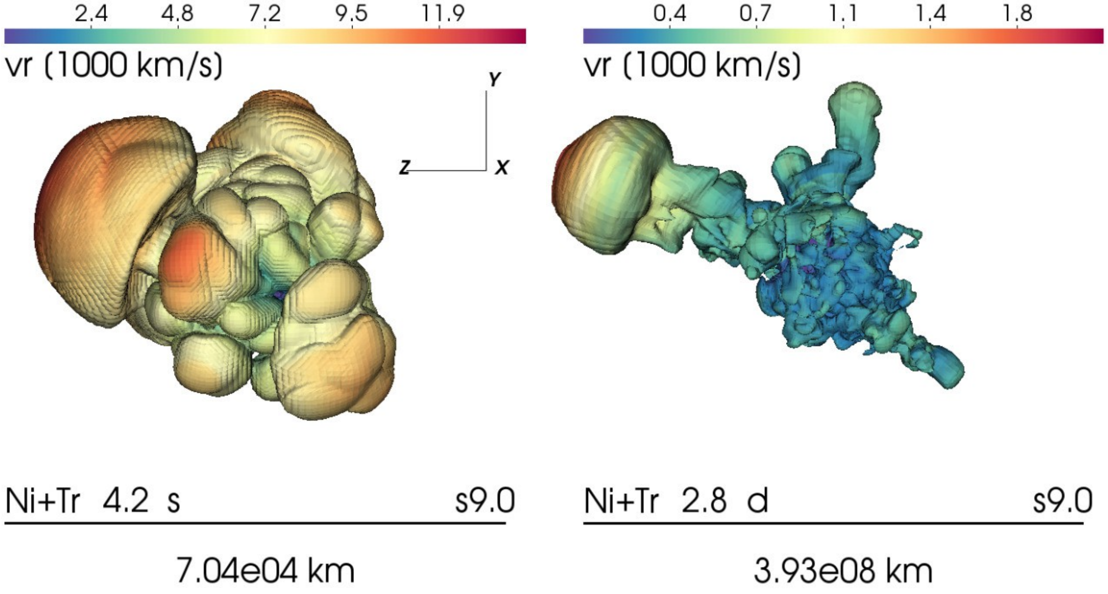
**Analysis of spatial distribution of IMEs (from Ne to Fe-group) in young, nearby SNRs with known NS kick velocities.**





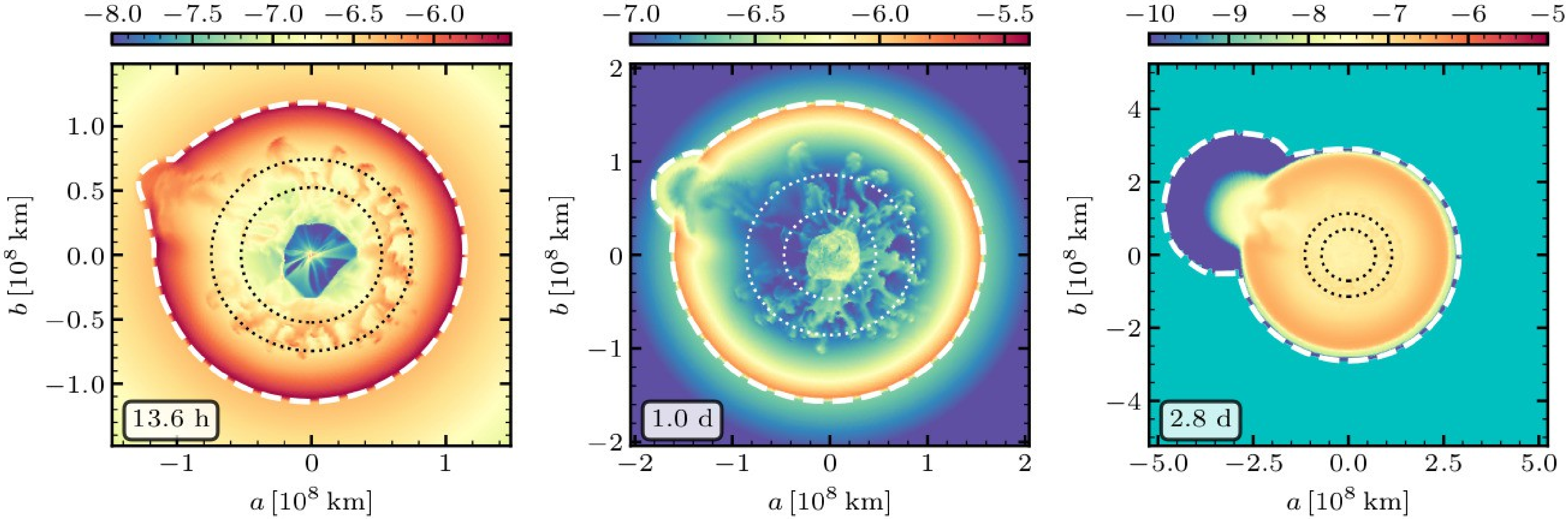
**Katsuda, Morii, THJ, et al. arXiv:1710.10372**

# CRAB: Remnant of low-mass Fe-core SN?



- **Explosion energy: $5*10^{49}$ erg** **OK**
- **Ni+Fe mass: $6*10^{-3}$ M $_{sun}$** **OK**
- **O+Ne+Mg mass: 0.11 $M_{sun}$** **OK?**
- **NS kick velocity: > 40 km/s** **(low)**
- **NS spin period: 30 ms** **OK**

**Stockinger, Janka, et al., to be submitted**



# Conclusions

## Neutrino-driven Explosions in 3D Supernova Models

- **Delayed neutrino-driven mechanism succeeds in 2D and 3D!**
- **Multi-D models of neutrino-driven explosions are sufficiently mature to test them against observations.**
- **3D geometry of neutrino-driven explosions seems to explain morphology of SNRs such as Cas A and SN 1987A.**
  *What are the Cas A 'jets'? How much Fe is unshocked in Cas A?*
- Pulsar kick in CRAB is hardly compatible with origin in ECSN !
  Crab could be remnant of exploding low-mass Fe-core progenitor.
  *Do core-collapse ECSNe exist?*

# Open Questions

- Can neutrino-driven mechanism provide explosion energies of $10^{51}$ erg and more?

  Can self-consistent "ab initio" models explain energies of SN 1987A and CAS A?

- "Details" of the physics in the core still need further studies. Can dense-matter effects be settled in near future?

  Neutrino flavor oscillations, high-density equation of state in hot neutron stars

- Progenitor-explosion-remnant systematics from 3D modeling.

  Population studies by 3D simulations including self-consistent 3D pre-collapse conditions; large model grid

- What is the relevance of stellar (core) rotation and magnetic-field amplification in new-born neutron stars?

  Exploration of links to magnetars, hypernovae, long-duration gamma-ray bursts, superluminous supernovae

# Gamma-ray Bursts and Hypernovae

# Observational Supernova-Progenitor Connection

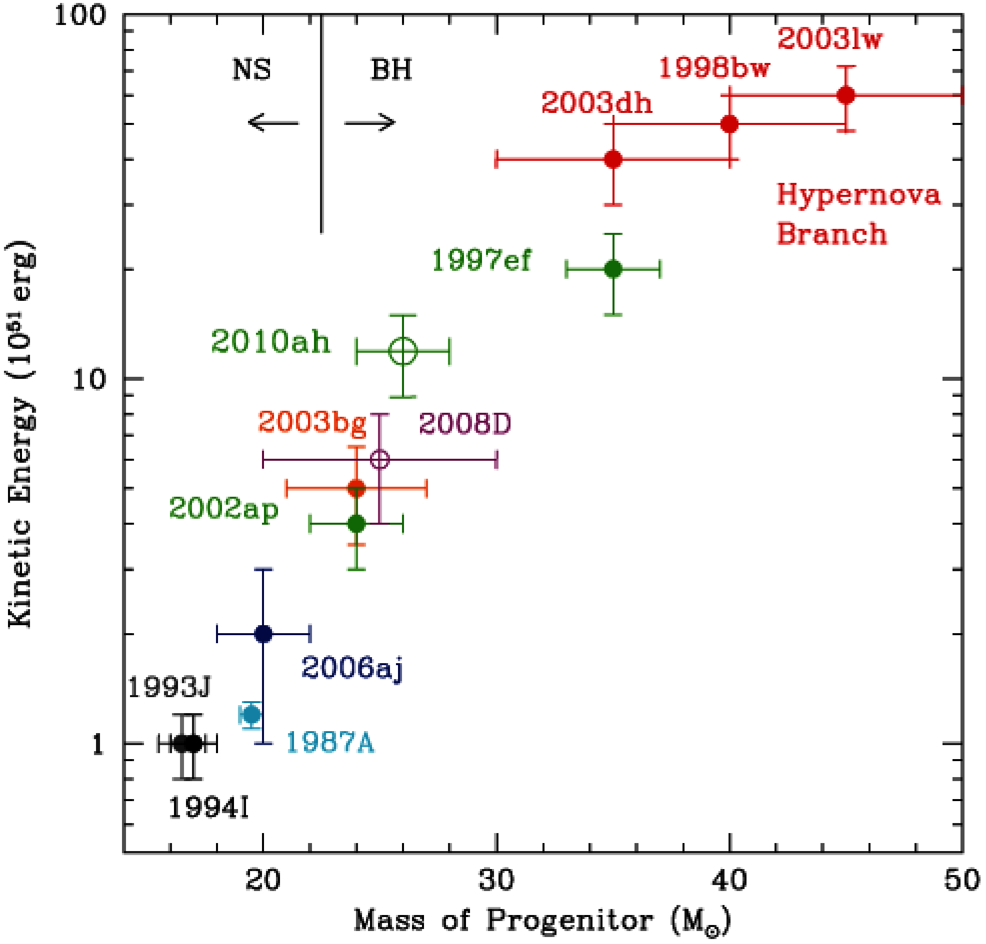


**Figure 11.** The $E_{\mathrm{kin}}$ derived from spectral/LC modelling of a number of SNe Ib/c plotted against the inferred ZAMS mass of the progenitor star using single-star evolutionary models. Colour coding is by spectral type, and it is the same as in Fig. 9.

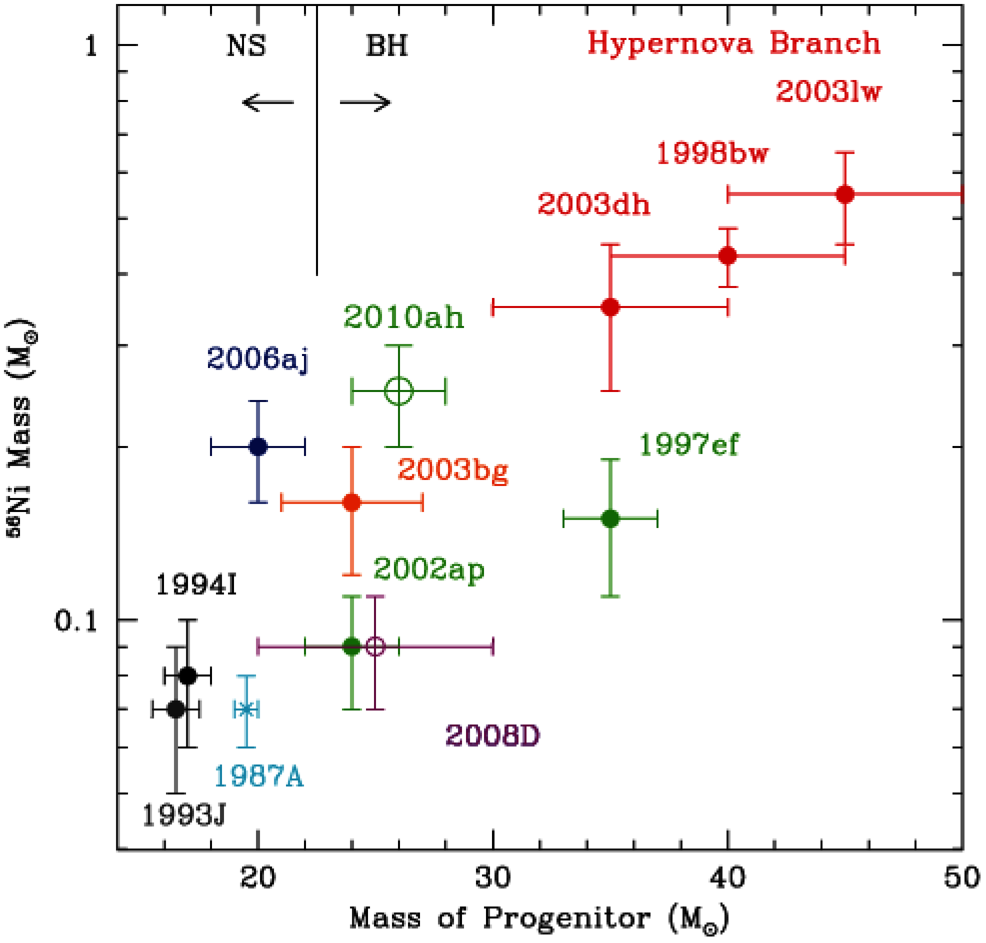
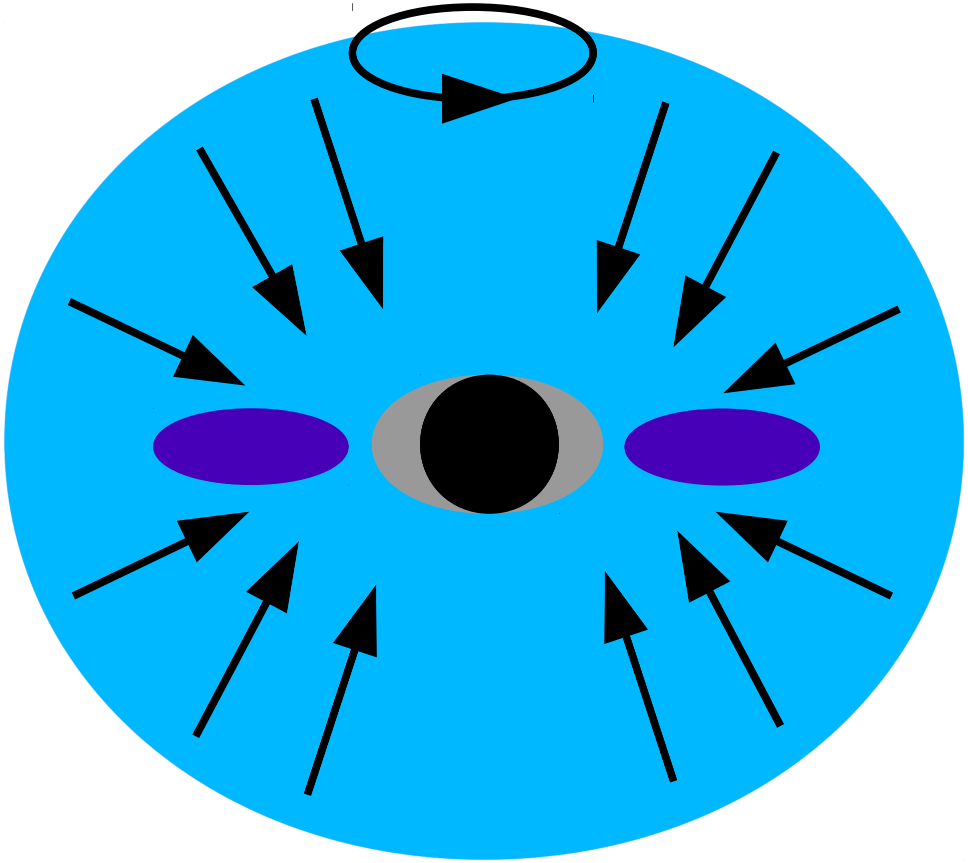


**Figure 10.** The mass of $^{56}$Ni derived from spectral/LC modelling of a number of SNe Ib/c plotted against the inferred zero-age main sequence (ZAMS) mass of the progenitor star using single-star evolutionary models. Colour coding is by spectral type, and it is the same as in Fig. 9.

Mazzali et al., MNRAS 432 (2013) 2463

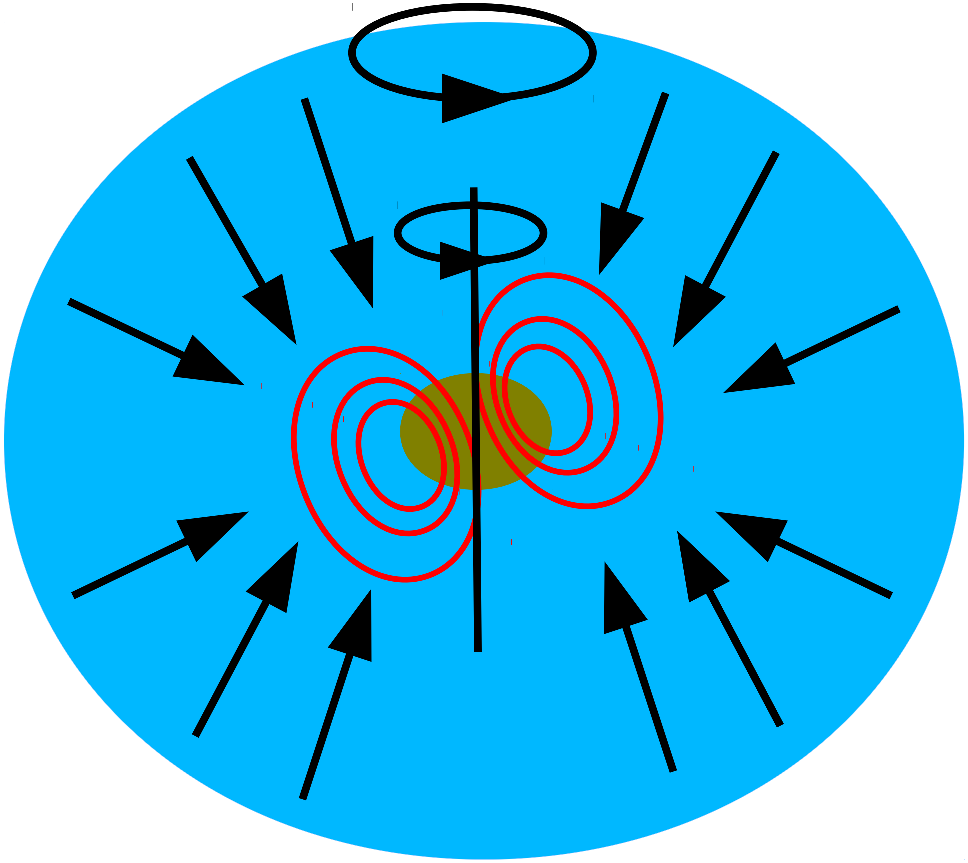
# GRB & Hypernova Central Engines

(Most popular, but not exclusive, scenarios)



**Collapsar: BH+torus**

Woosley (1993), MacFadyen
Woosley (1999), Lazzati et al. (2013)

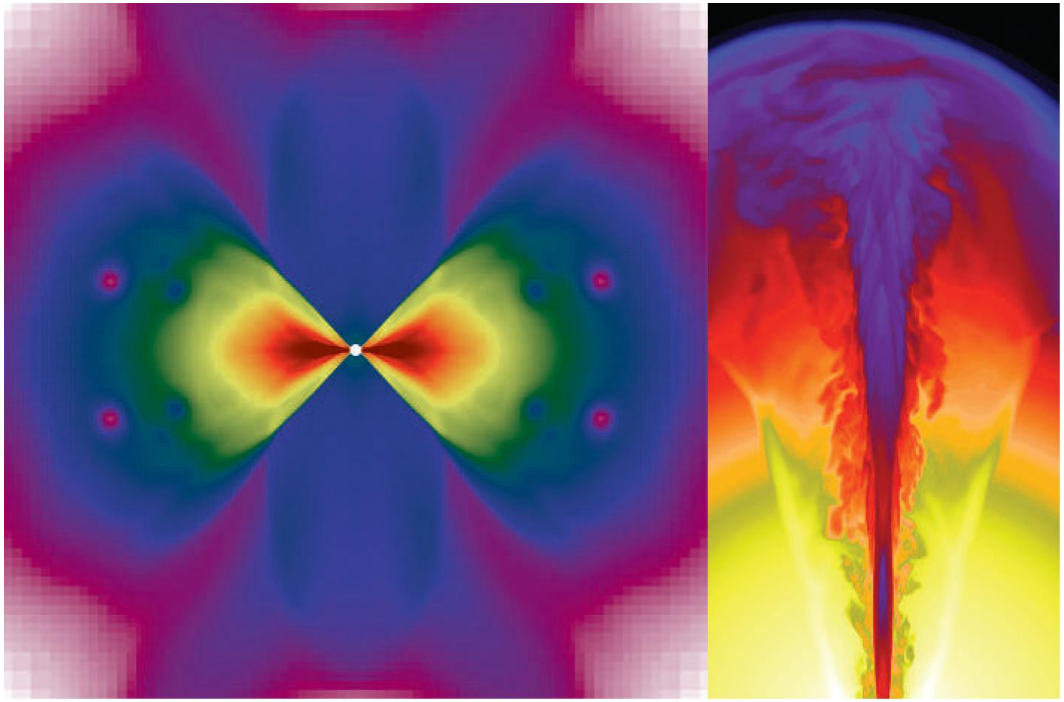


**Magnetar "engine"**

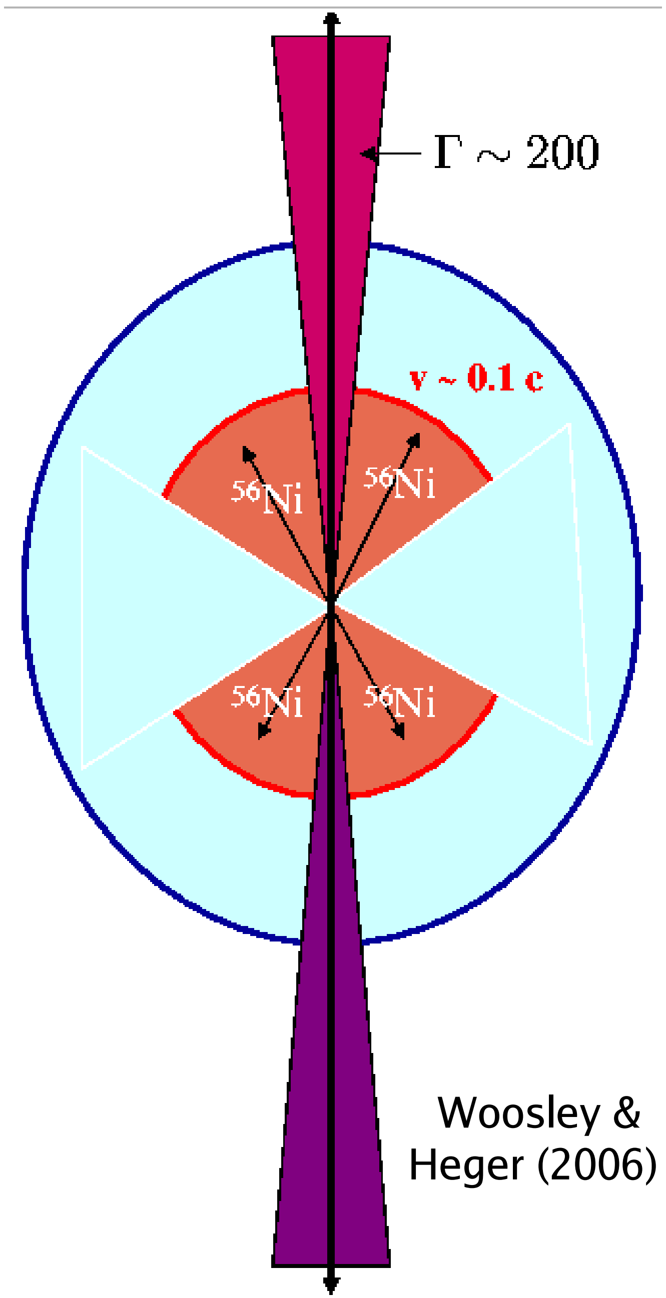
Usov (1992), Metzger et al. (2011),
Bucciantini et al. (2007, 2008, 2009)

# GRBs & Hypernovae: Collapsar Scenario

- Occur in rare cases of very rapidly rotating, very massive stars with sufficient mass loss until collapse.
- Black hole formation.
- BH accretion and ejection of very narrow, ultrarelativistic GRB jet, can be accompanied by hypernova explosion.
- Jet is driven by Poynting flux of disk and BH magnetic fields (Blandford-Znajek mechanism) and/or neutrino-antineutrino annihilation.
- Extremely energetic stellar explosion by magnetohydrodynamic (MHD) mechanism or nuclear energy release in accretion disk.



Zhang & Woosley (2005)



Woosley & Heger (2006)