The nuclear equation of state in core-collapse supernovae

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11th Russbach School, 14.3.2014

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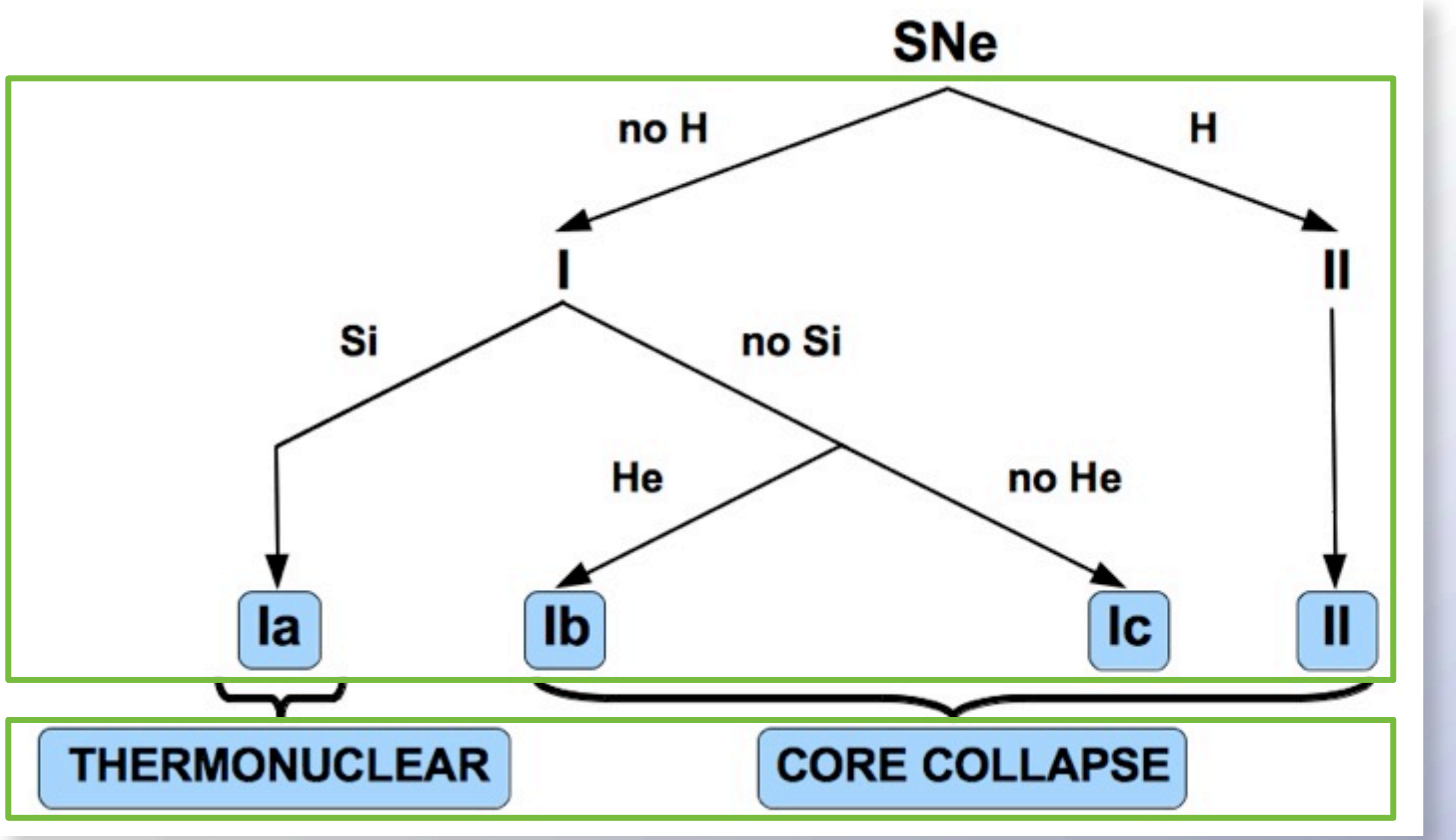
The nuclear equation of state in core-collapse supernovae

Outline

1) introduction
2) supernova EOS
3) supernova simulations in spherical symmetry
4) supernova simulations in 3D
5) conclusions

Introduction

Classification of supernovae

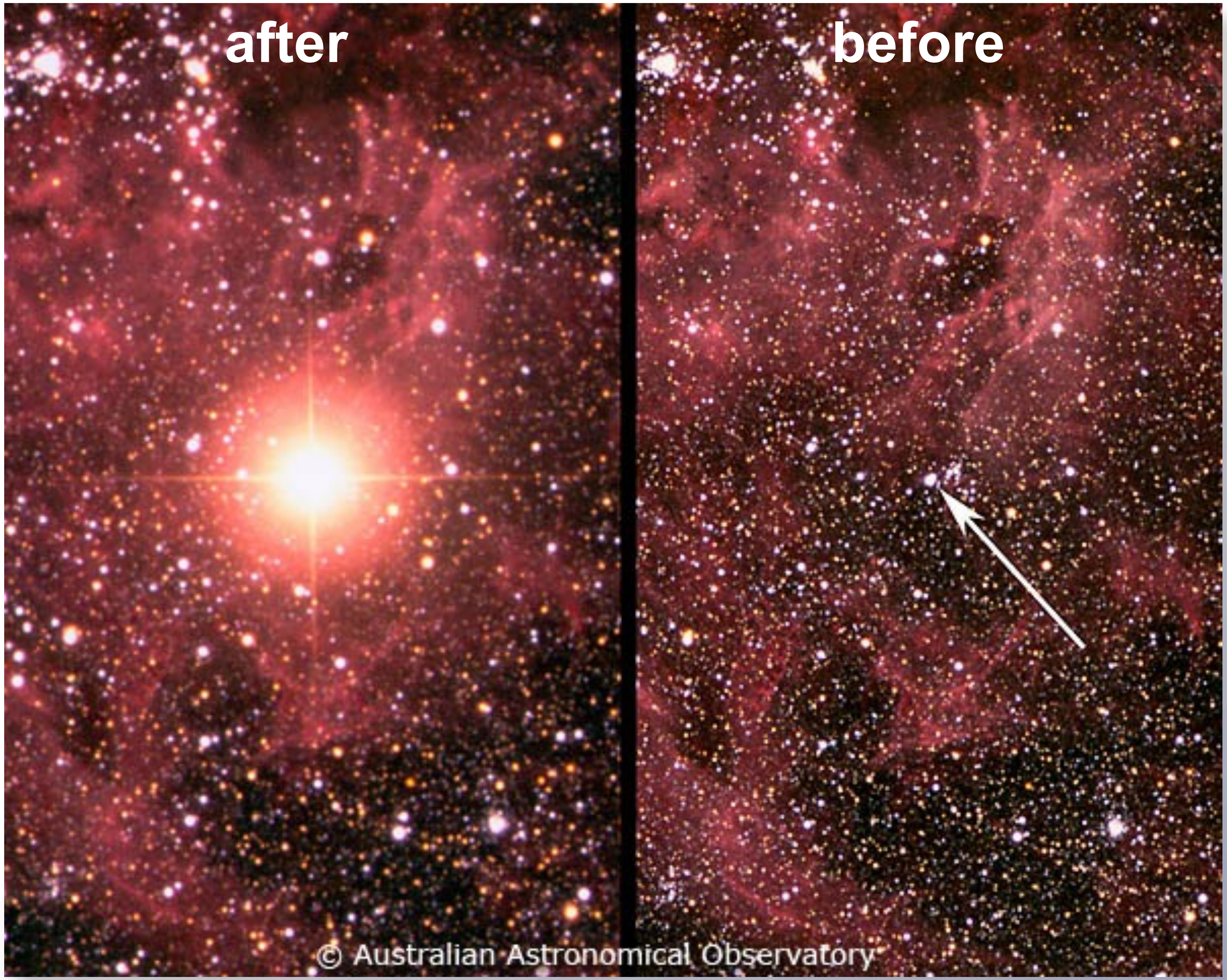


observations (elemental lines in spectra)

mechanism

- type Ia: thermonuclear explosions of white dwarfs
- all others: core-collapse
- Ib, Ic, II, IIp, IIn, ...: astronomical classification by spectra

SN1987a



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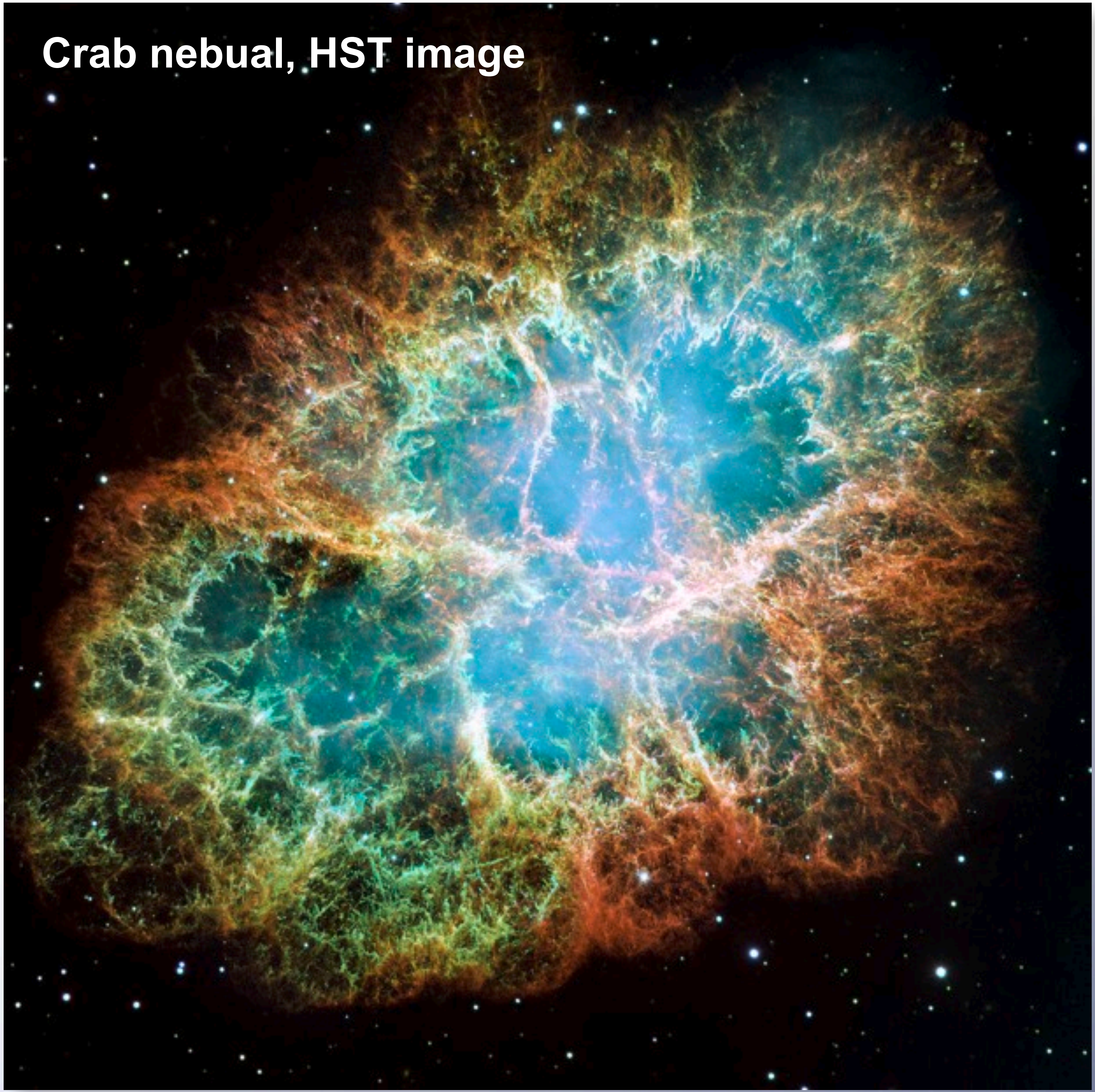
- 24.2.1987: last close-by core-collapse supernova (CCSN)
- distance: 150,000 light years in Large Magellanic Cloud
- galactic SN-rate: ~ 3/100 year
- thousands of observations of extragalactic SN
- observable in:
  - electro-magnetic
  - neutrinos
  - gravitational waves (?)

Supernova remnant

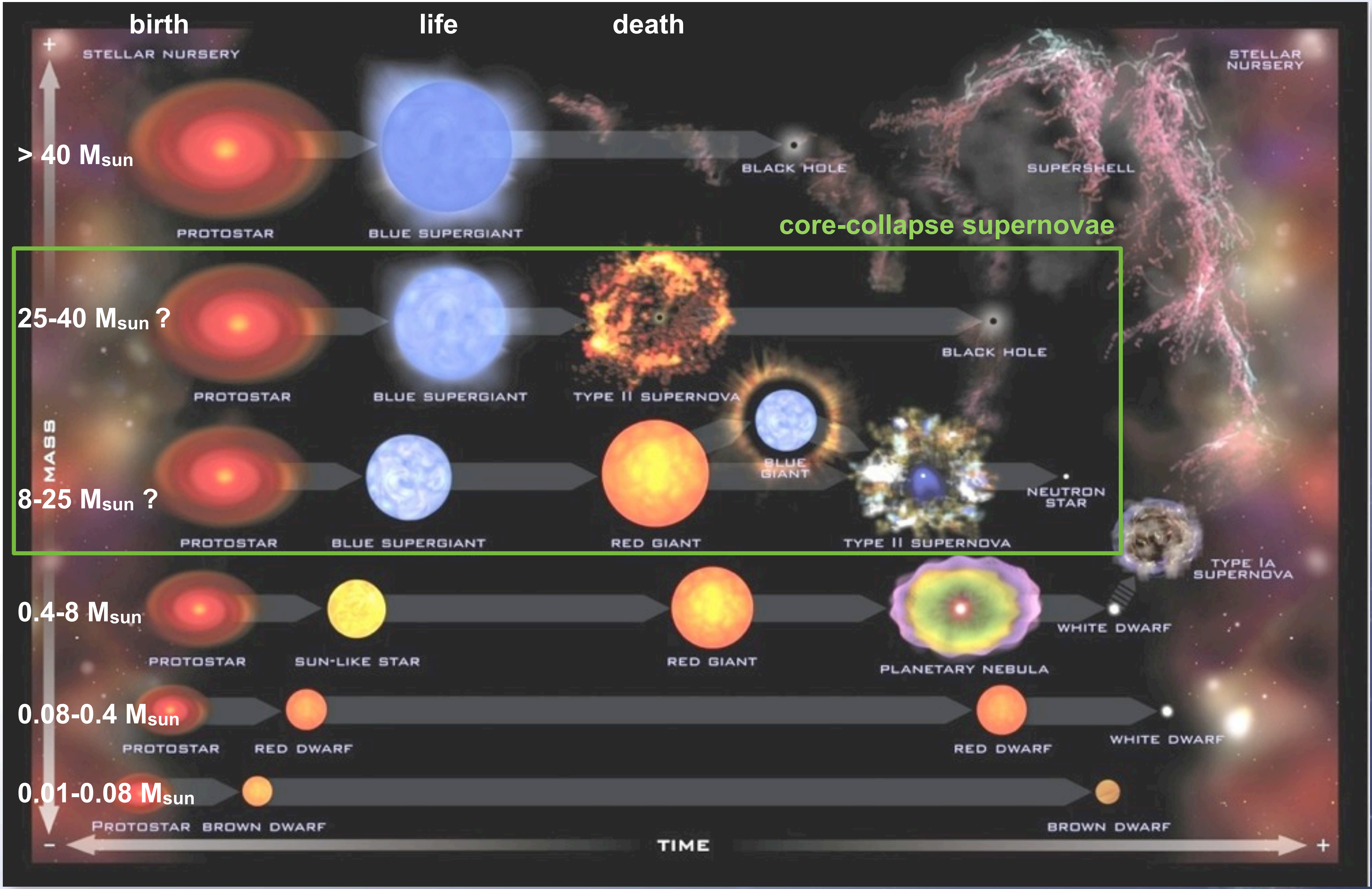

Crab nebual, HST image

- supernova of 1054 AD
- 6,000 light years distance

- roughly the mass of the iron core remains as a newly born neutron star
- CCSNe are birth places of neutron stars

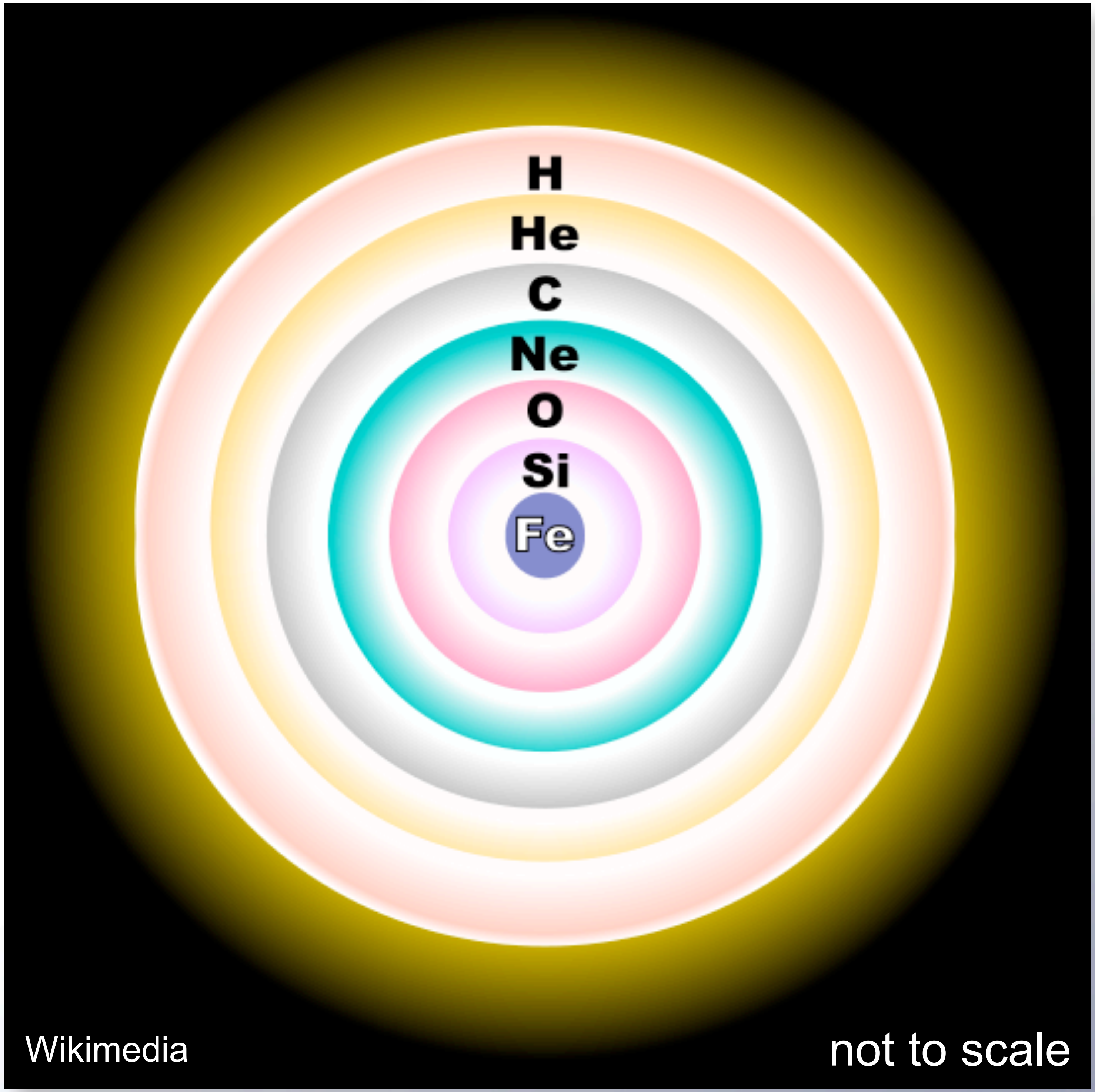
- neutron star in center “Crab pulsar“

Stellar evolution



Chandra

Shell burning of massive stars at the end of their evolution



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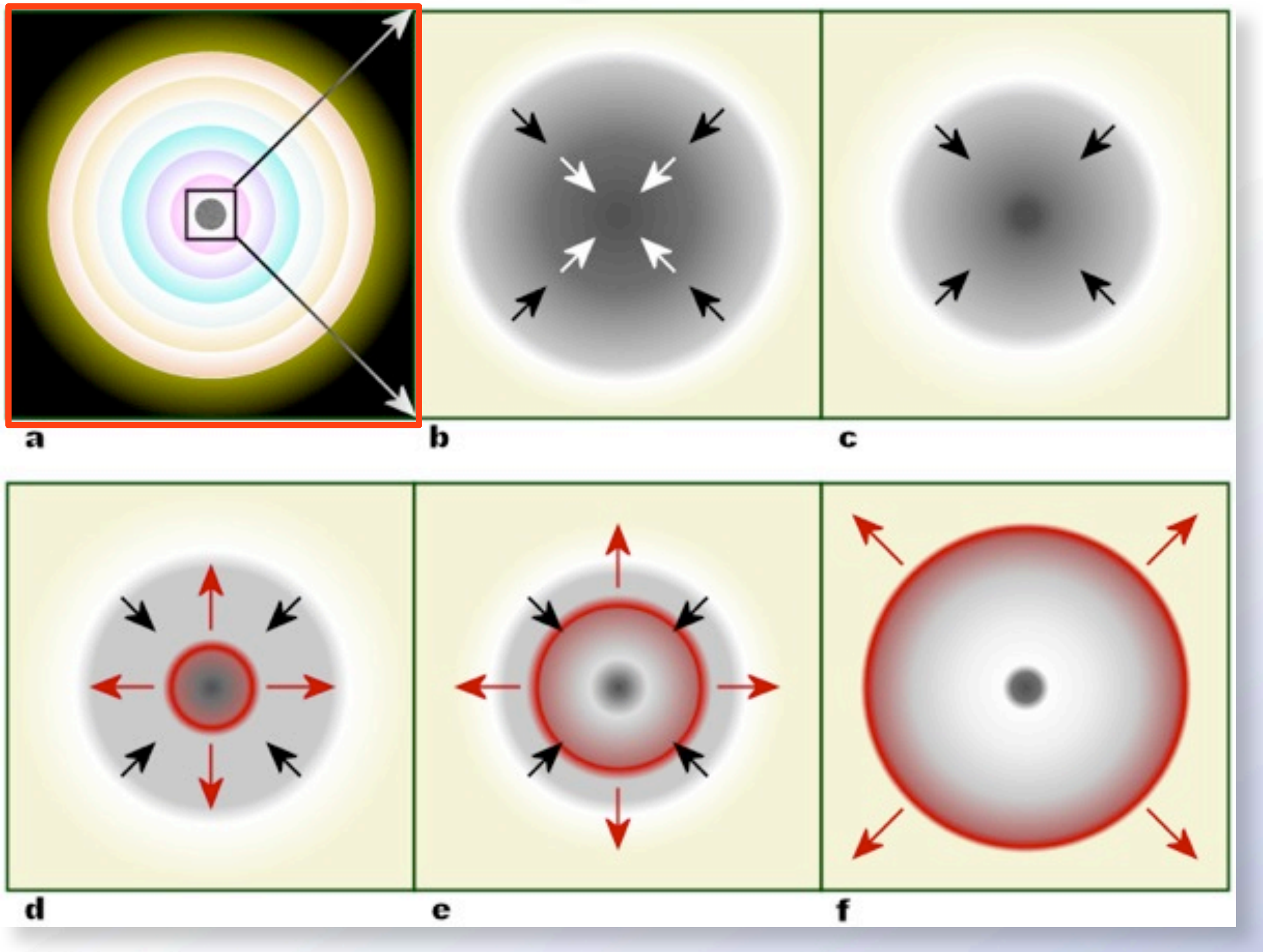
not to scale

- mass > 8-10 M_{sun}
- shell burning in outer layers
- formation of an iron core
- progenitor of a core-collapse supernova

Core-collapse supernova



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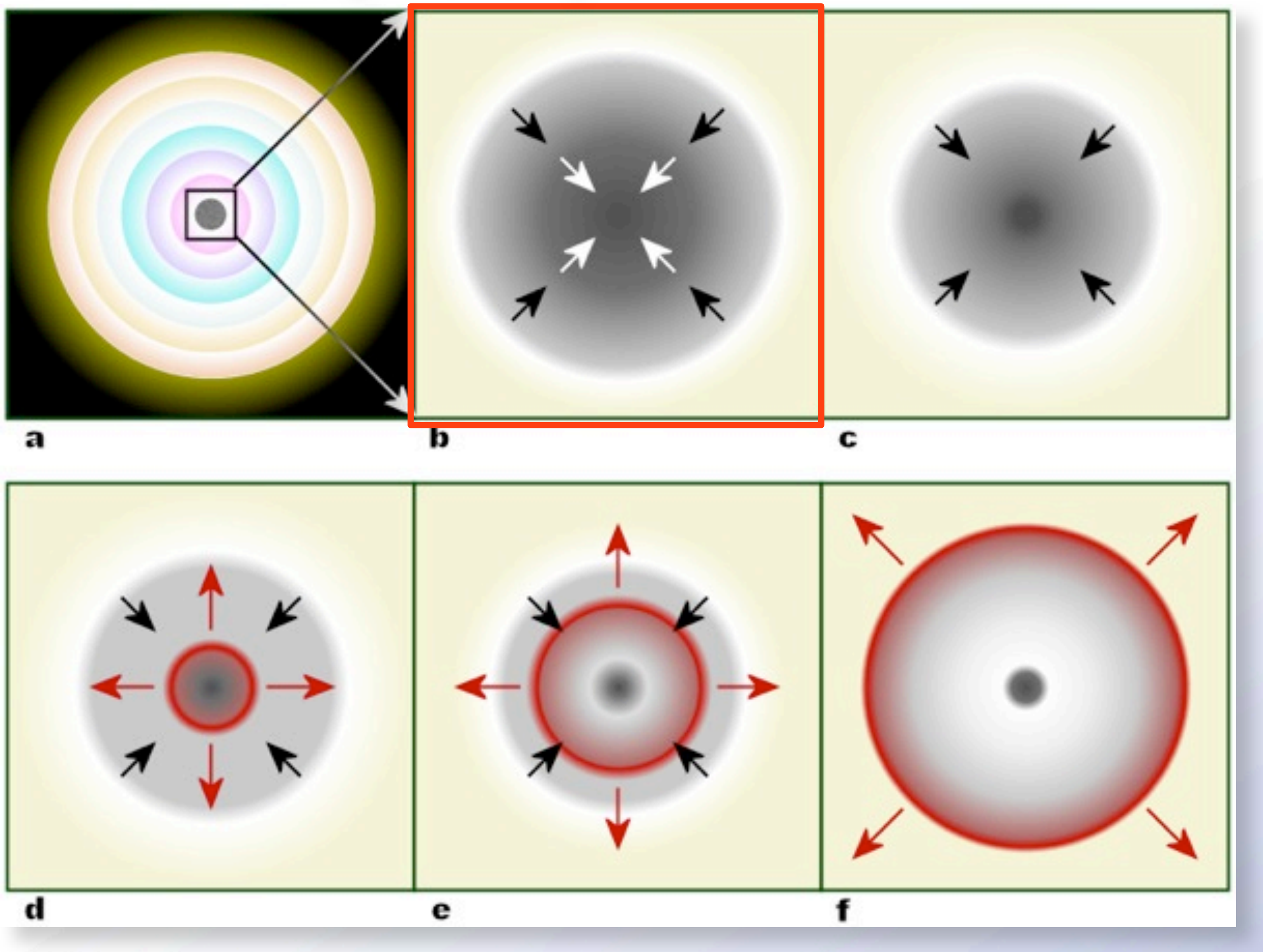
a:

- no further fusion in the iron core
- stabilization of the iron core by Fermi-pressure of electrons
- upper mass limit of stability: Chandrasekhar-limit ~1.4 M_{sun}

Core-collapse supernova



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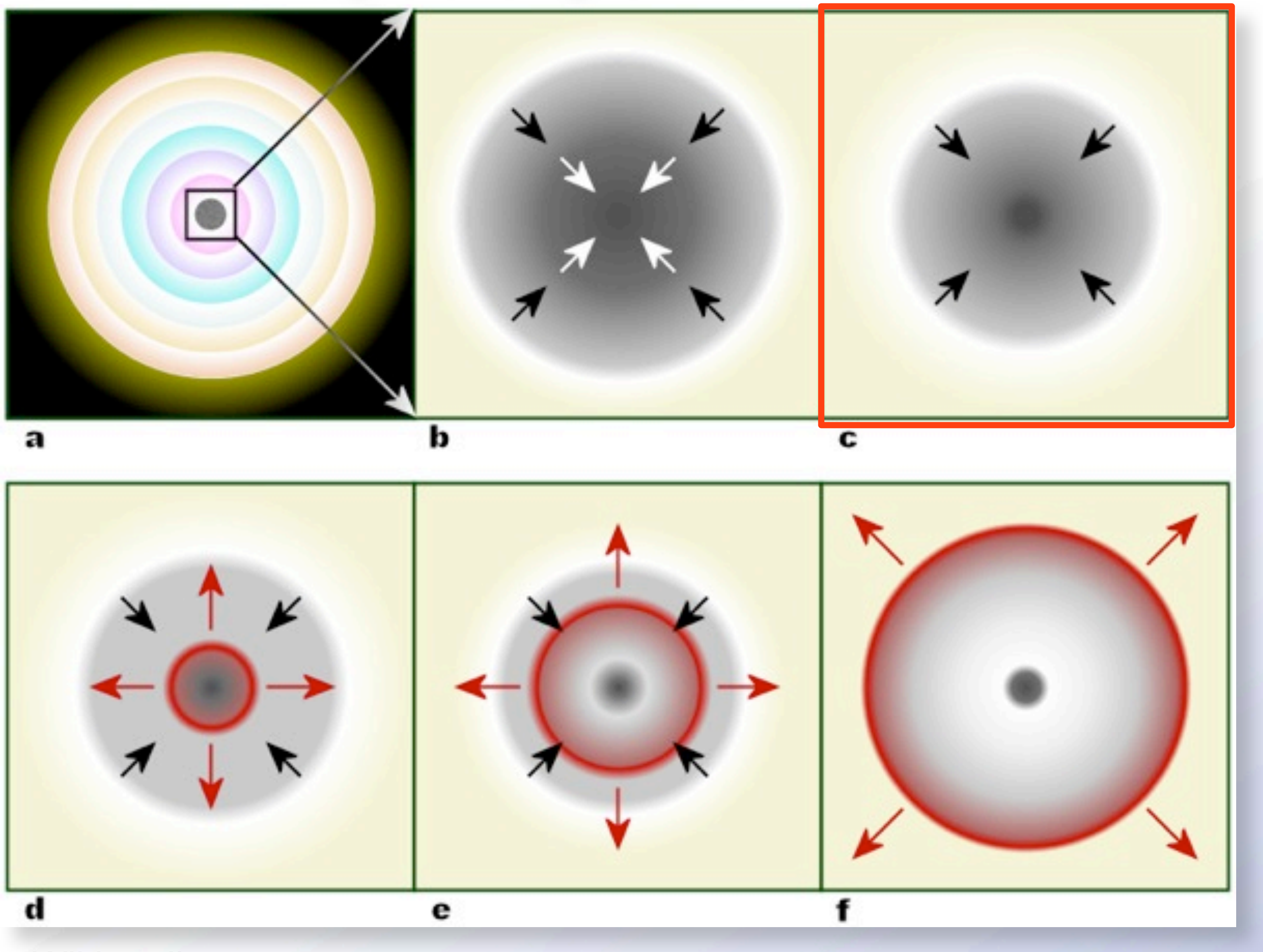
b:

- critical mass → collapse
- electron capture reactions and dissociation of heavy nuclei accelerate collapse

Core-collapse supernova



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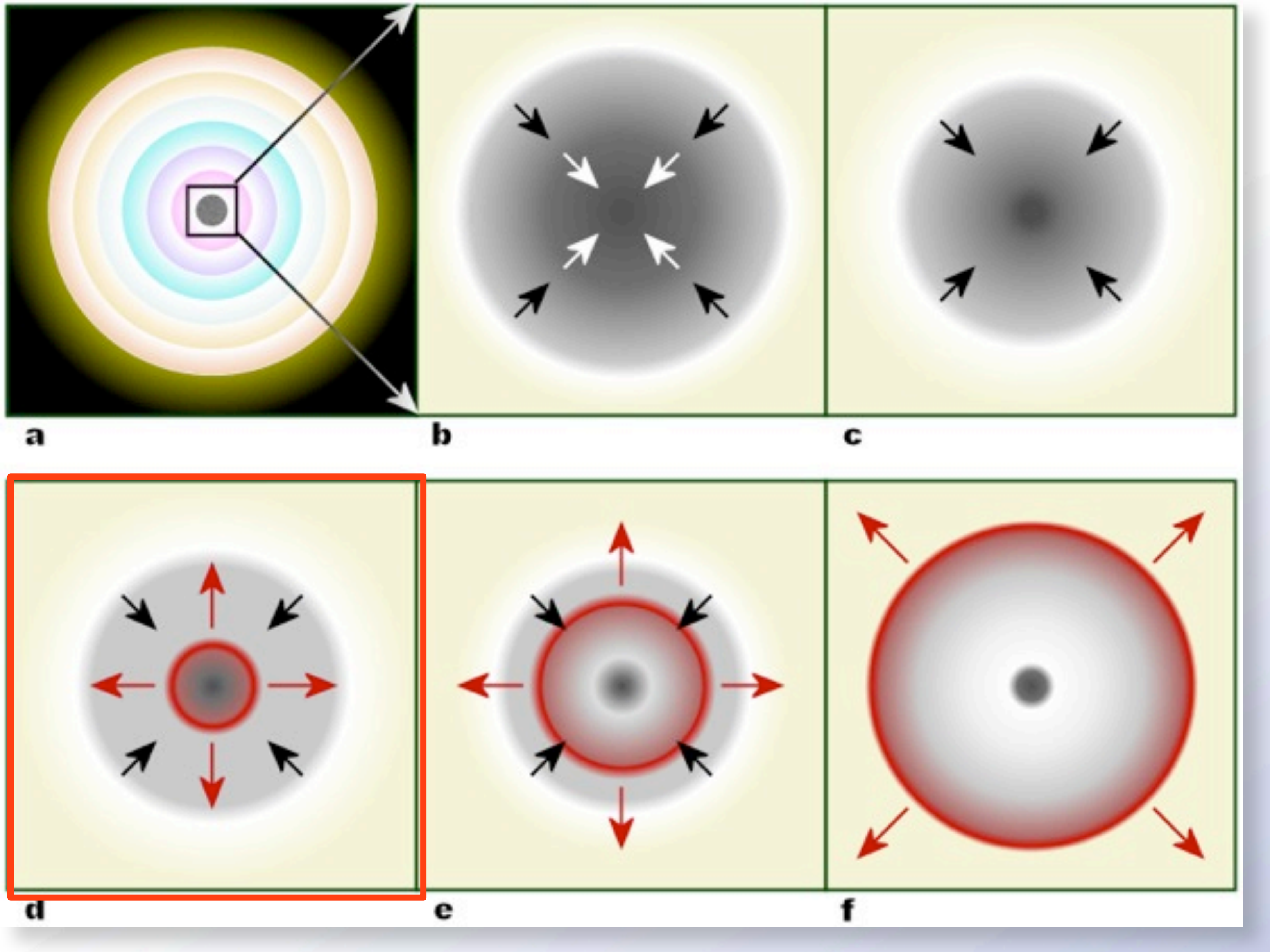
c:

- at densities of ρ_0: nuclear interactions become extremely repulsive
- sudden slow down of the collapse

density in atomic nuclei: $\rho_0 \approx 3 \cdot 10^{14}$ g/cm^3

Core-collapse supernova



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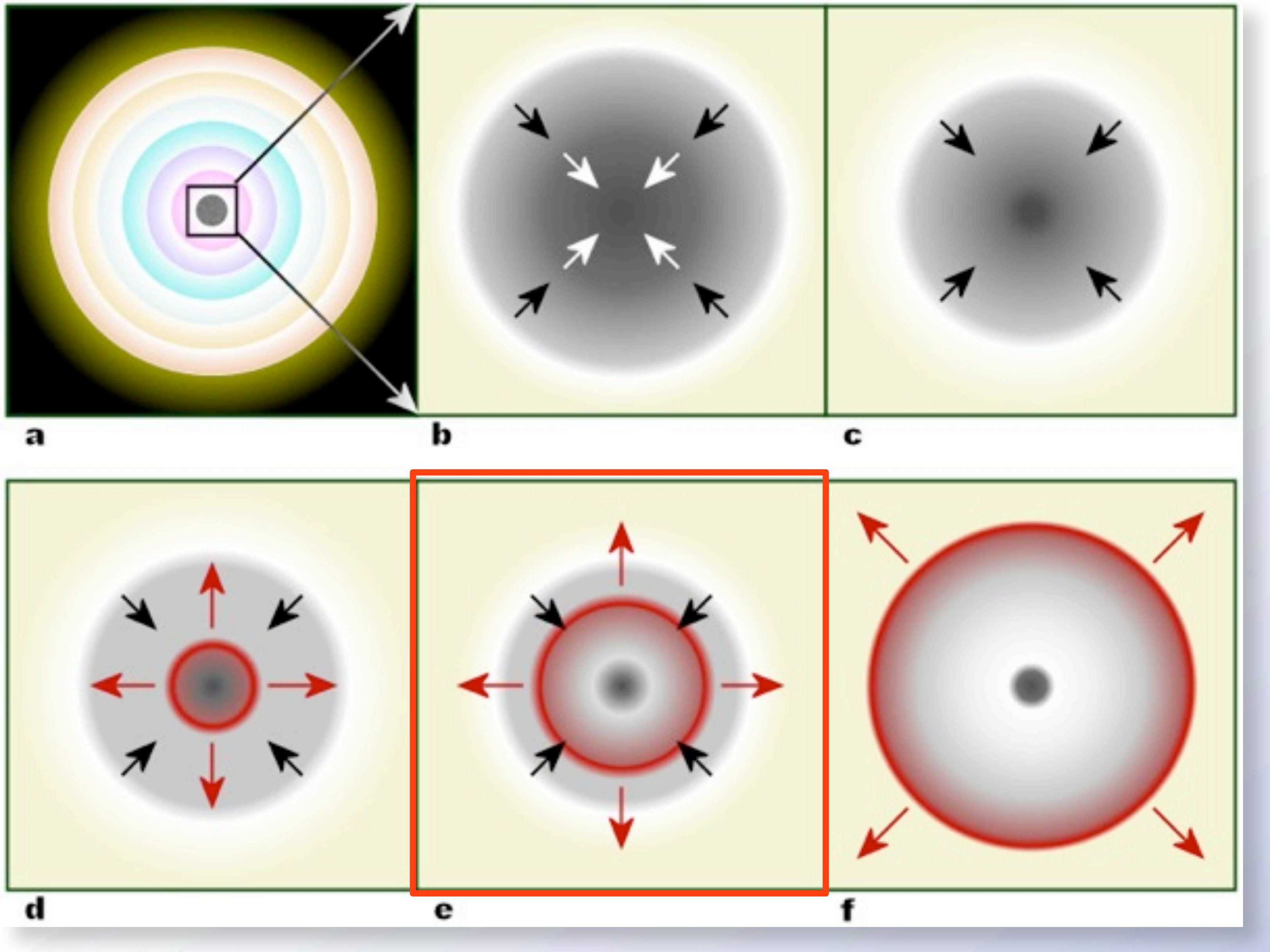
d:

- “bounce“ of the core, reexpansion
- formation of an outgoing shockwave
- shock wave moving into matter of the core which is still infalling

Core-collapse supernova



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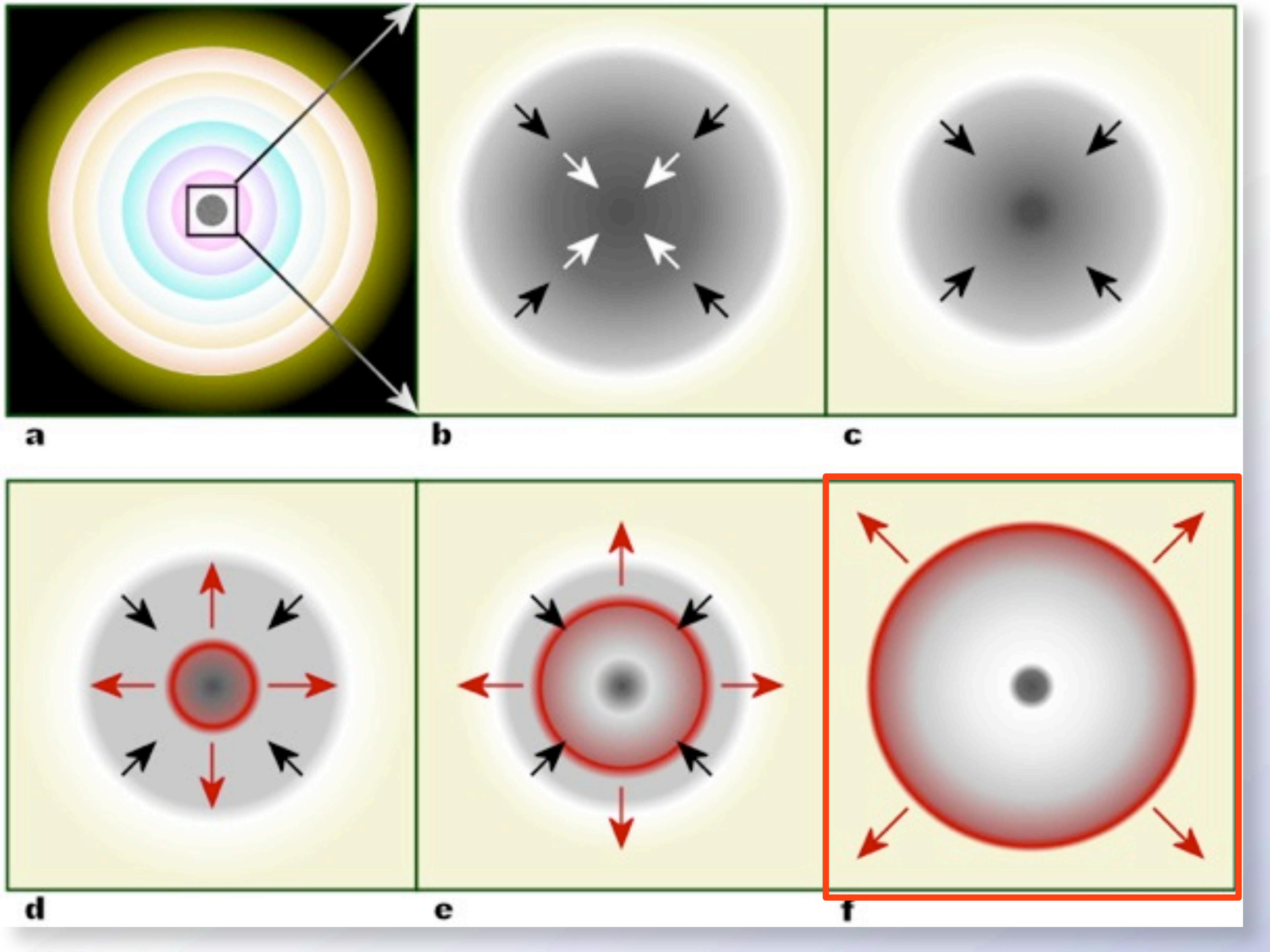
e:

- accretion of matter from collapsing layers onto the shock
- weakening of the shock by dissociation of heavy nuclei and neutrino losses

Core-collapse supernova



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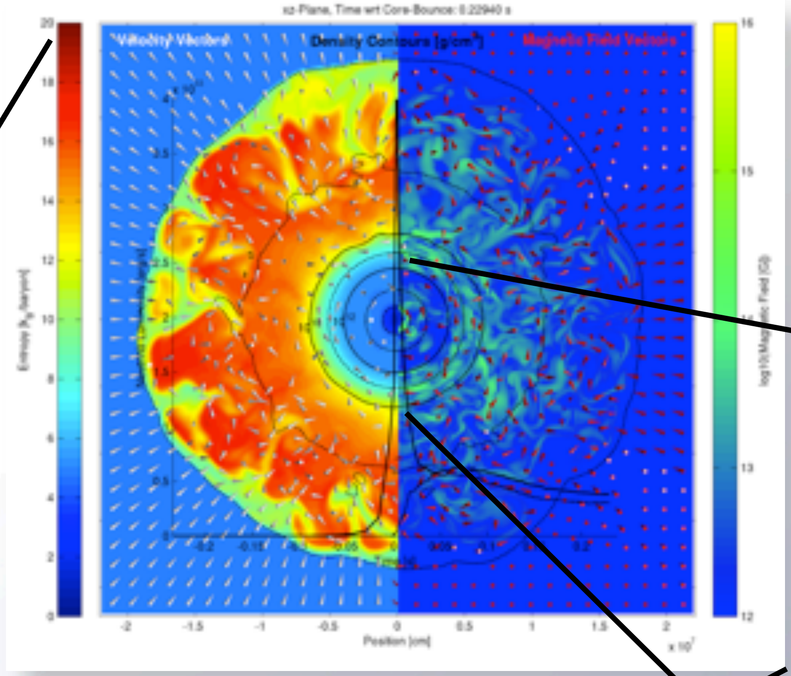
f:

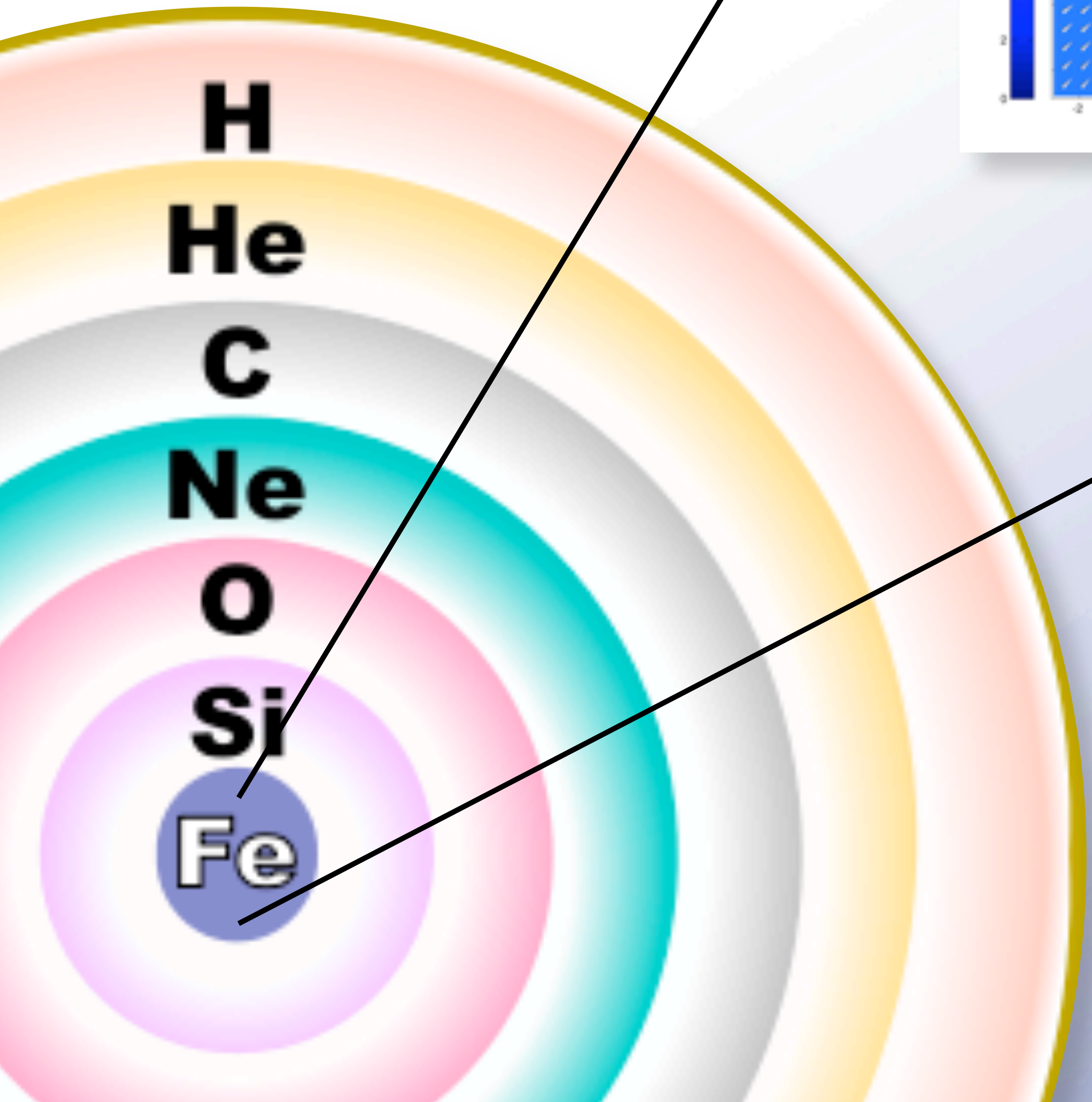
- the shock wave is (somehow) reaccelerated and leaves the core
- nuclear reactions are initiated
- ejection of the entire outer part of the star
- leftover in the center: a hot, young proto-neutron star

From progenitor stars via CCSNe to neutron stars

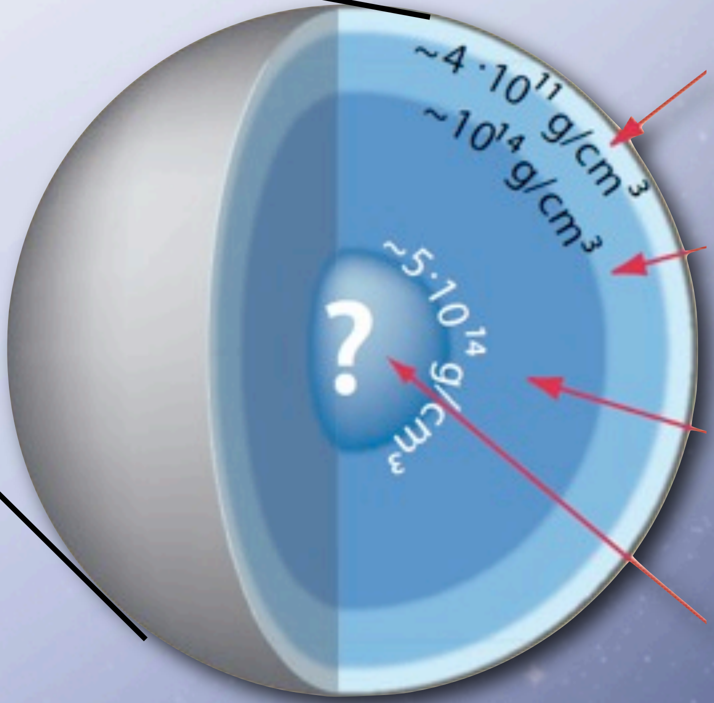
core-collapse
supernova explosion



progenitor star at
onset of collapse



cold neutron star



- what is the state of matter during all these stages?

Supernova EOS

Supernova EOS – introduction

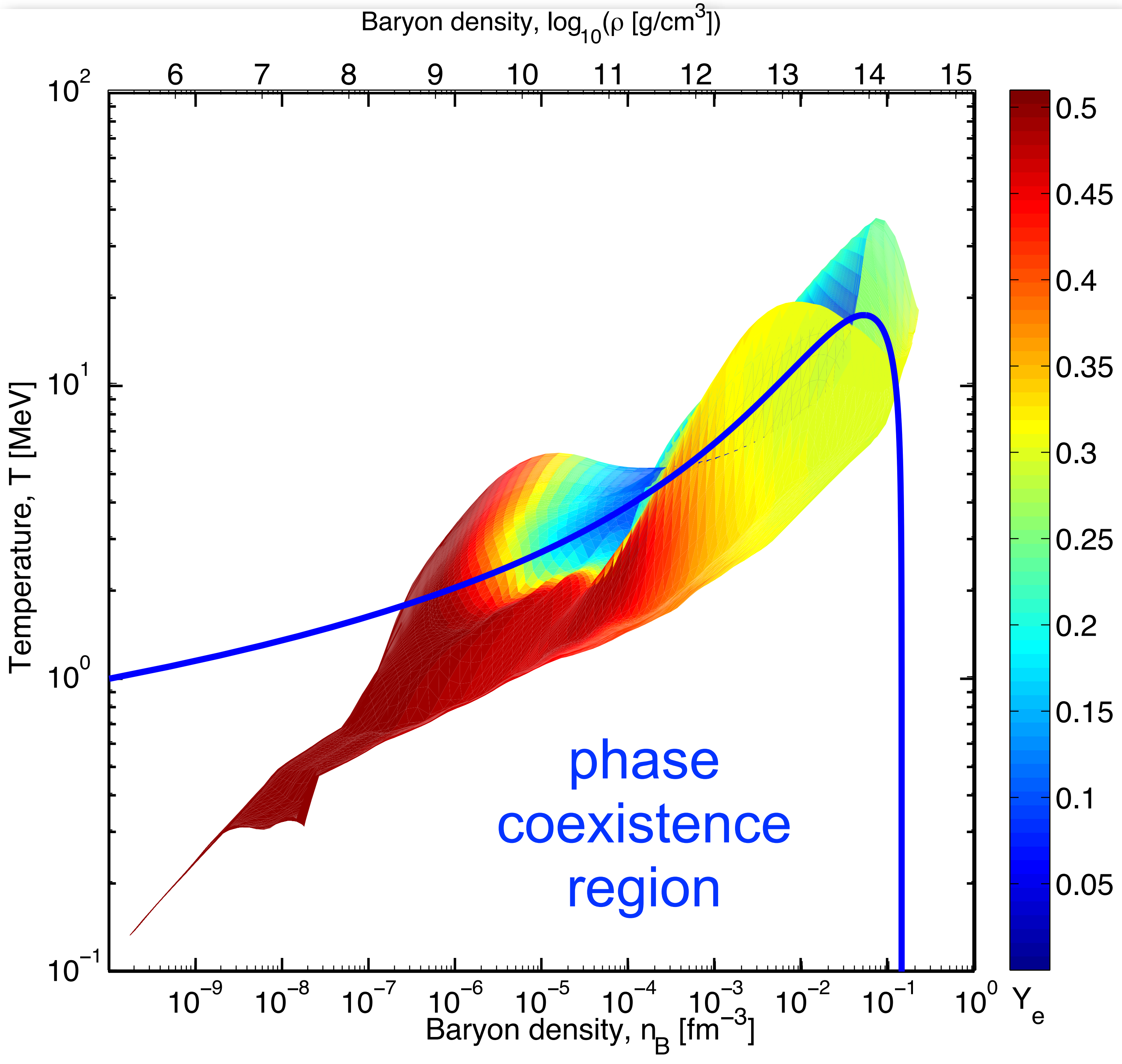
- EOS provides the nuclear physics input for astrophysical simulations

- commonly used EOS:
  - Shen et al. (STOS), 1998: Thomas-Fermi, relativistic TM1 interactions
  - Lattimer and Swesty (LS), 1991: non-relativistic liquid drop

- SN EOS: multi-purpose EOS, e.g., also (proto-) neutron stars, mergers of neutron stars, ...
  - finite temperature: $T = 0 – 100$ MeV
  - no weak equilibrium, electron fraction: $Y_e = 0 – 0.6$
  - wide density range: $\rho = 10^4 – 10^{15}$ g/cm^3
  - EOS in tabular form, ~1 million points in (T, Y_e, ρ)
- only limited number of models available

1 MeV ~ 10^{10} K

State of matter in core-collapse supernovae



based on: *[Fischer, MH, et al., ApJS 2010]*

- first order liquid-gas phase transition below T_c~15 MeV
- phase coexistence region

- with finite size effects:
→ non-uniform nuclear matter, mixture of nuclei and nucleons

General composition of matter in SN

- photons (trivial)

- neutrons and protons
- light and heavy nuclei, thermal ensemble
- hyperons, quark matter, ... (not considered as standard)

- electrons, positrons, (muons usually ignored)
- neutrinos: all flavors
  - trapped in the core, degenerate Fermi-Dirac gas
  - free streaming in outer layers
  - → not part of the EOS, but of (Boltzmann) transport

a model for the nuclear interactions **and** an approach for the many-body problem (e.g. formation of nuclei) is needed

EOS model: excluded volume NSE with interactions

MH, J. Schaffner-Bielich; NPA 837 (2010) (HS)

- chemical mixture of nuclei and interacting nucleons in nuclear statistical equilibrium
- nucleon interactions: relativistic mean-field (RMF)
- description of nuclei and medium effects: experimentally measured binding energies and nuclear mass tables, Coulomb screening, excited states, excluded volume, ...
- smooth and continuous change of composition and thermodynamic quantities

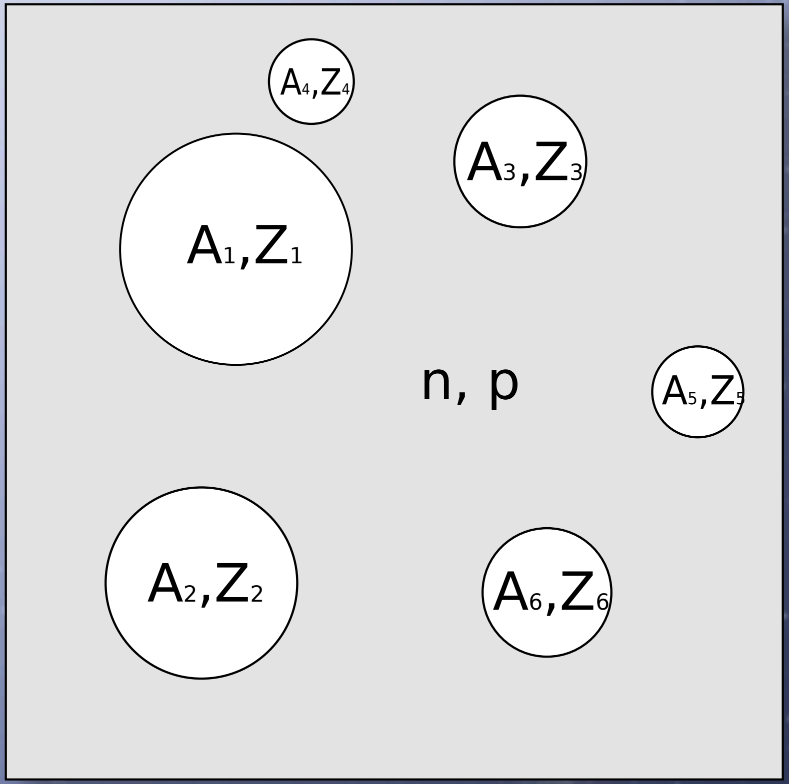
- eight EOS tables for different RMF interactions:

  NL3, TM1, TMA, FSUgold, DD2, SHFo, SHFx, IUFSU

  http://phys-merger.physik.unibas.ch/~hempel/eos.html

  http://www.stellarcollapse.org/

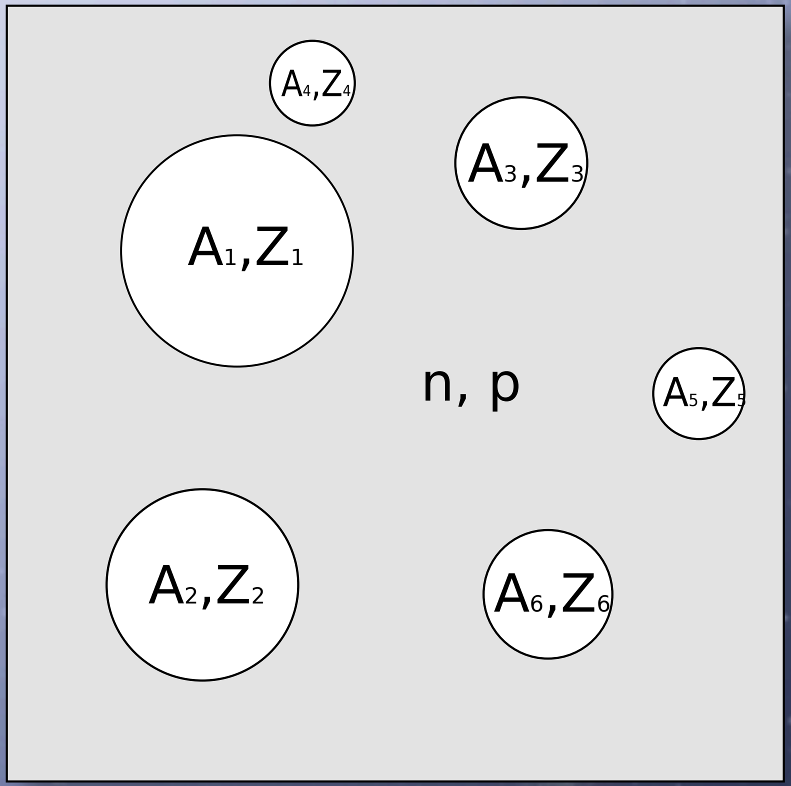
  http://compose.obspm.fr/ CompOSE CompStar Online Supernovæ Equations of State comp star



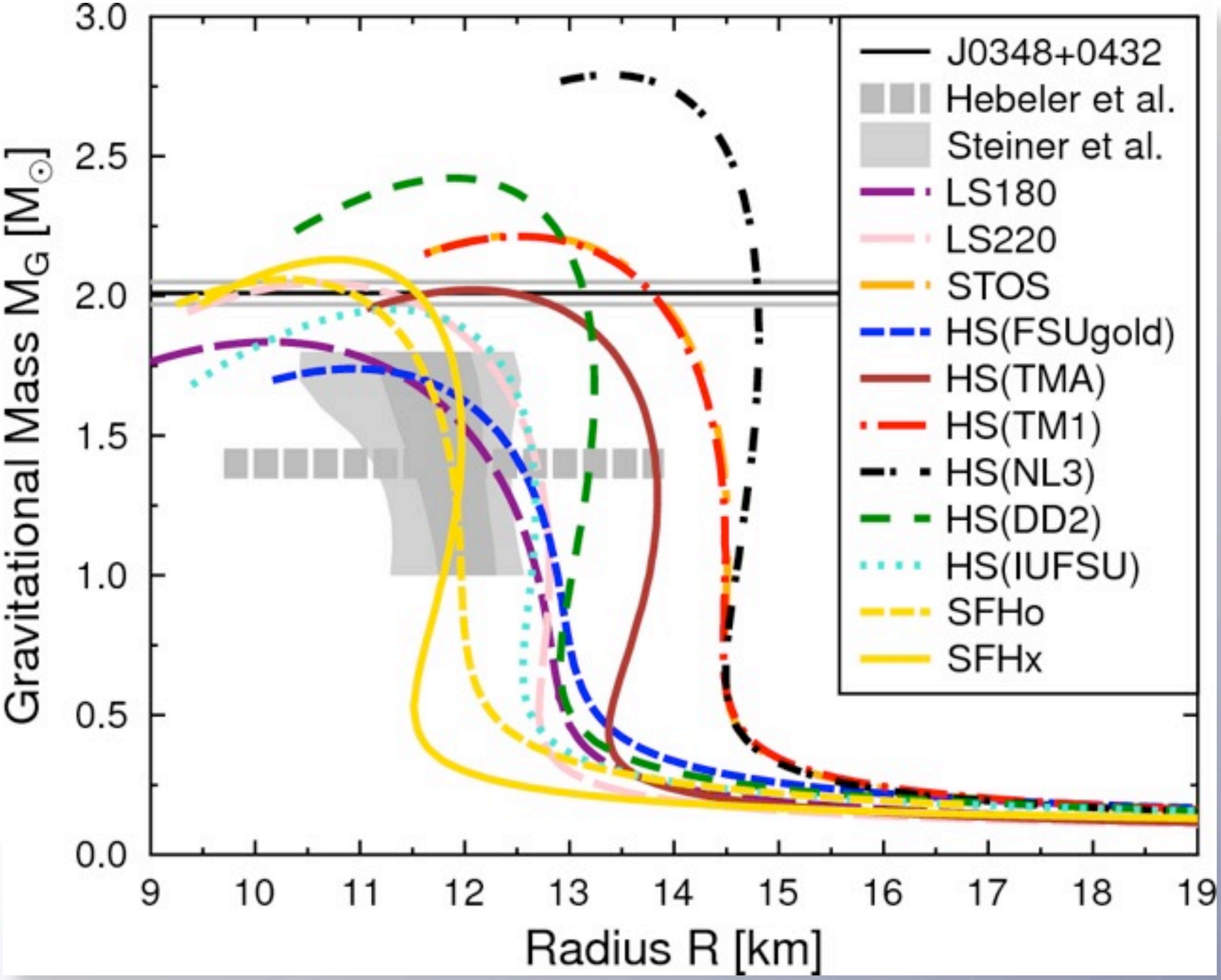
EOS model: excluded volume NSE with interactions

MH, J. Schaffner-Bielich; NPA 837 (2010) (HS)

- main differences to LS and STOS:
  - not only alpha particles, but also other light nuclei
  - thermal ensemble of heavy nuclei, not just one representative
  - variety of different nucleon interactions
  - “correct“ low-density limit, experimental binding energies and shell effects included



EOS constraints – neutron star mass-radius relation



T. Fischer, MH, et al.; Eur. Phys. J. A 50, 46 (2014)

- Pulsar J0348+0432: Antoniadis et al. Science 2013
- Steiner et al. ApJ 2010, Steiner et al. ApJ 2013: bayesian analysis of NS observations
- similar results from Chiral EFT (Hebeler et al. 2010)
- SFHo and SFHx: fitted to low radii (A. Steiner, MH, T. Fischer; ApJ 2013)

Supernova simulations in spherical symmetry

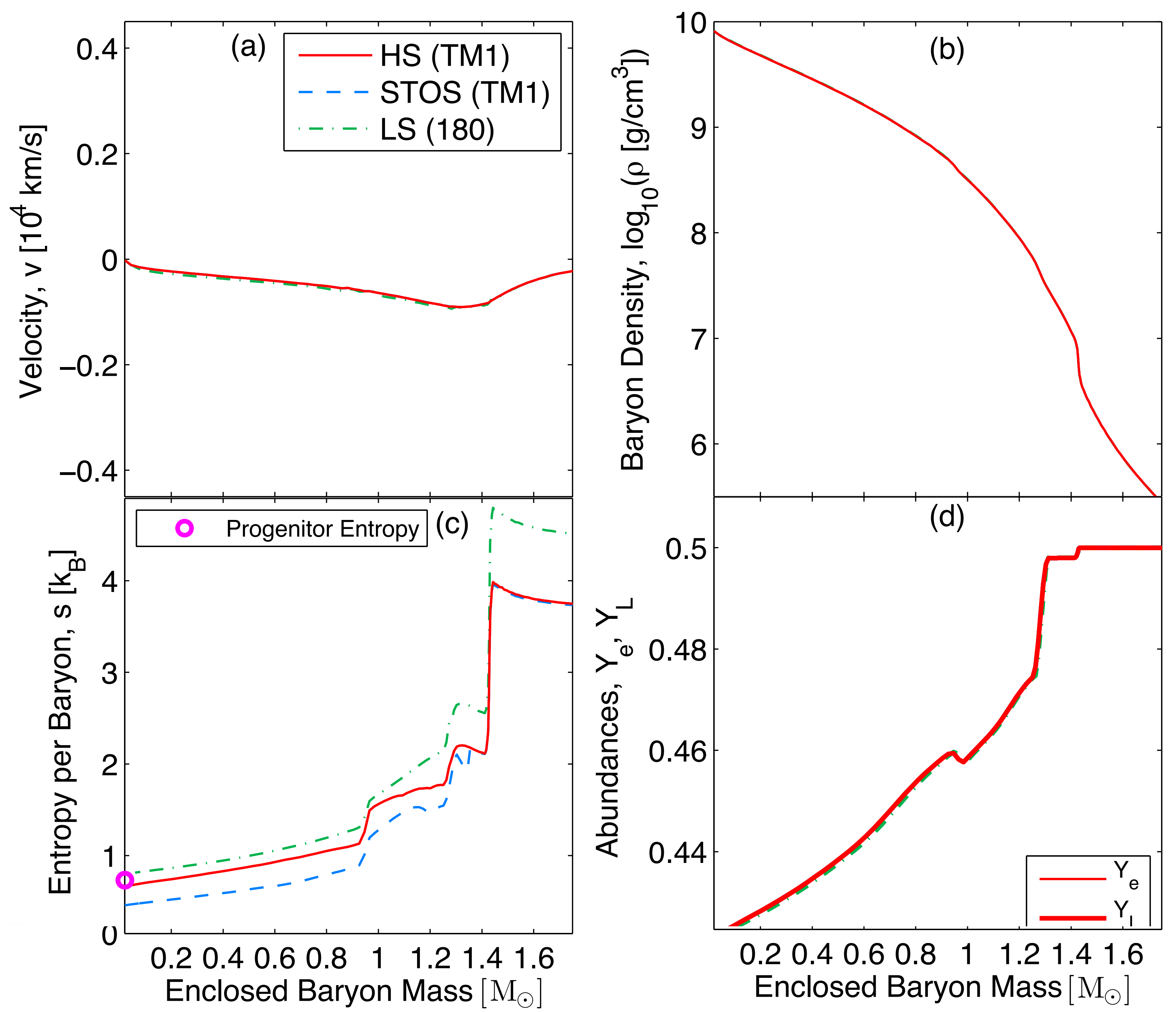
Supernova simulations – setup

MH, T. Fischer, J. Schaffner-Bielich, M. Liebendörfer, ApJ 748, 70 (2012),
A. Steiner, MH, T. Fischer; ApJ 774, 17 (2013),
T. Fischer, MH, et al.; Eur. Phys. J. A 50, 46 (2014)

- simulations by Tobias Fischer, University of Wroclaw
  - general relativistic radiation hydrodynamics in spherical symmetry
  - detailed Boltzmann neutrino transport
- 15 M_{sun} progenitor of Woosley and Weaver 1995
  - regular core-collapse supernova expected
- comparison of different EOSs: LS, STOS, HS
- weak reactions included:

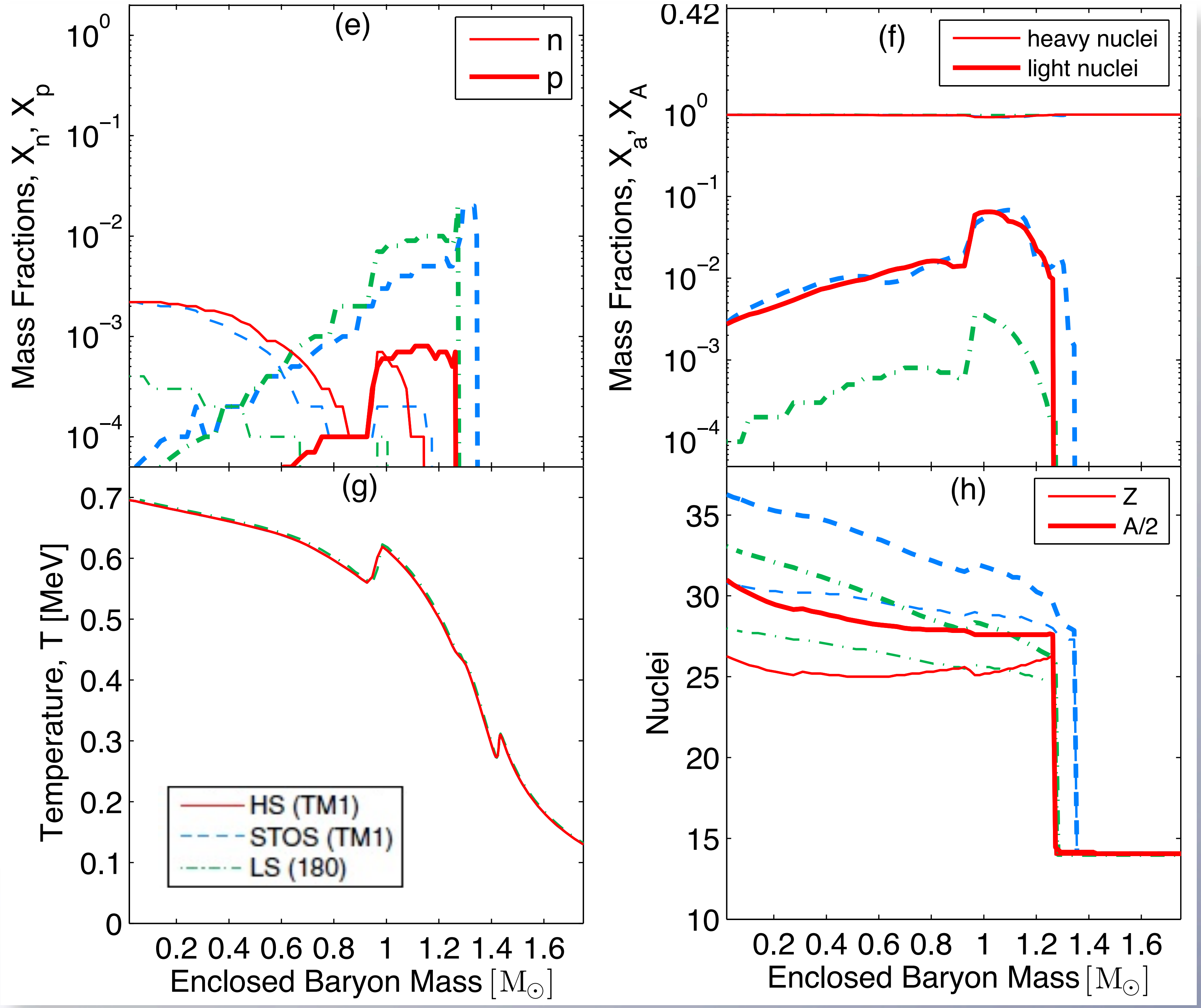
$$\begin{aligned}
e^- + < A,Z > \quad &\longleftrightarrow \quad < A,Z-1 > + \nu_e \\
e^- + p \quad &\longleftrightarrow \quad n + \nu_e \\
e^+ + n \quad &\longleftrightarrow \quad p + \bar{\nu}_e \\
\nu + e^\pm \quad &\longleftrightarrow \quad \nu + e^\pm \\
\nu + N \quad &\longleftrightarrow \quad \nu + N \\
N + N \quad &\longleftrightarrow \quad N + N + \nu + \bar{\nu} \\
\nu_e + \bar{\nu}_e \quad &\longleftrightarrow \quad \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}
\end{aligned}$$

Progenitor stage



- onset of collapse
- densities up to 10^{10} g/cm^3
- from symmetric to moderately neutron rich ($Y_{e,min}$ ~ 0.42)
- entropies from 1 to 4 k_B

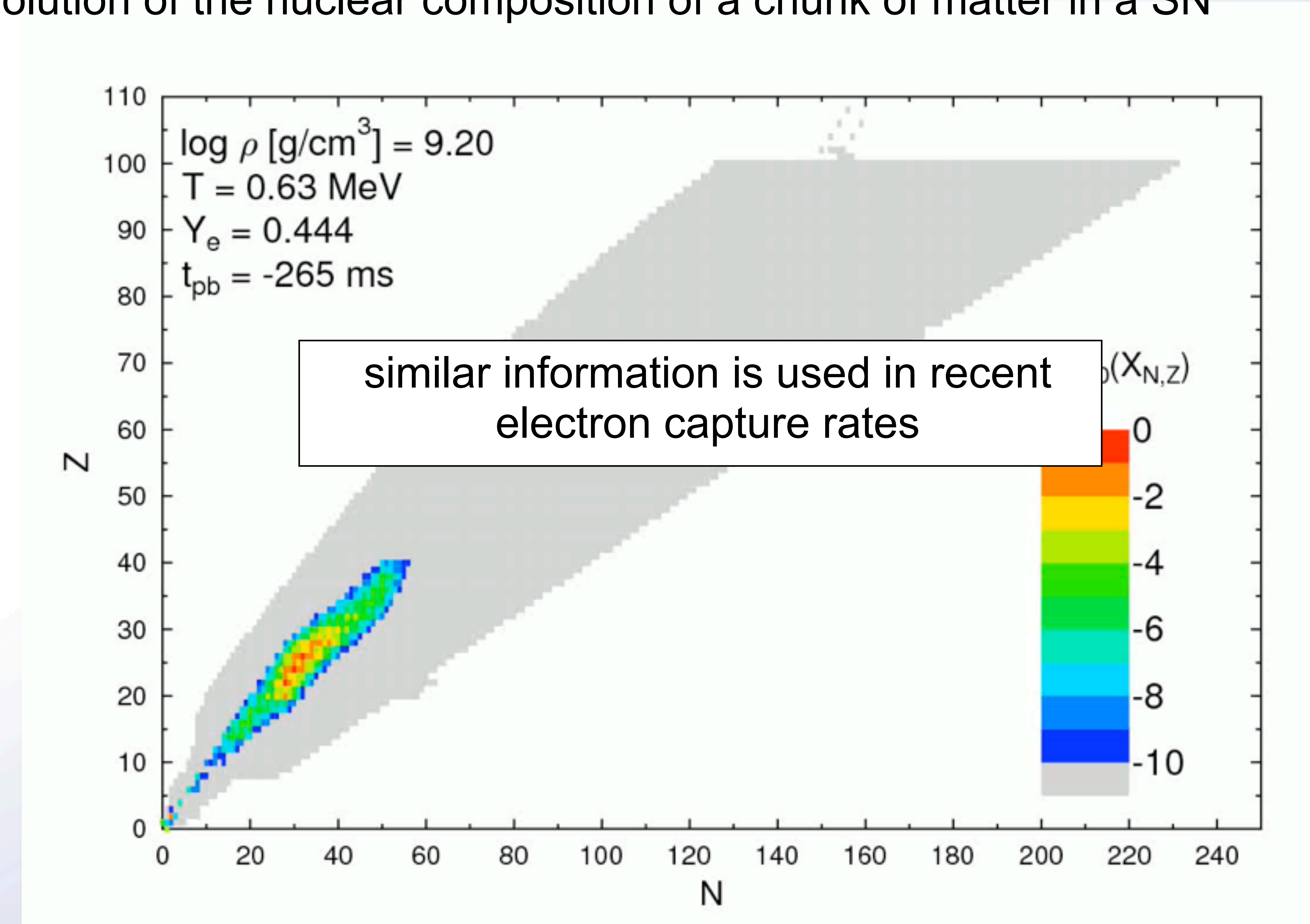
Progenitor stage



- composition dominated by heavy nuclei (iron group)
- above iron core: pure Si-gas assumed
- moderate EOS effects

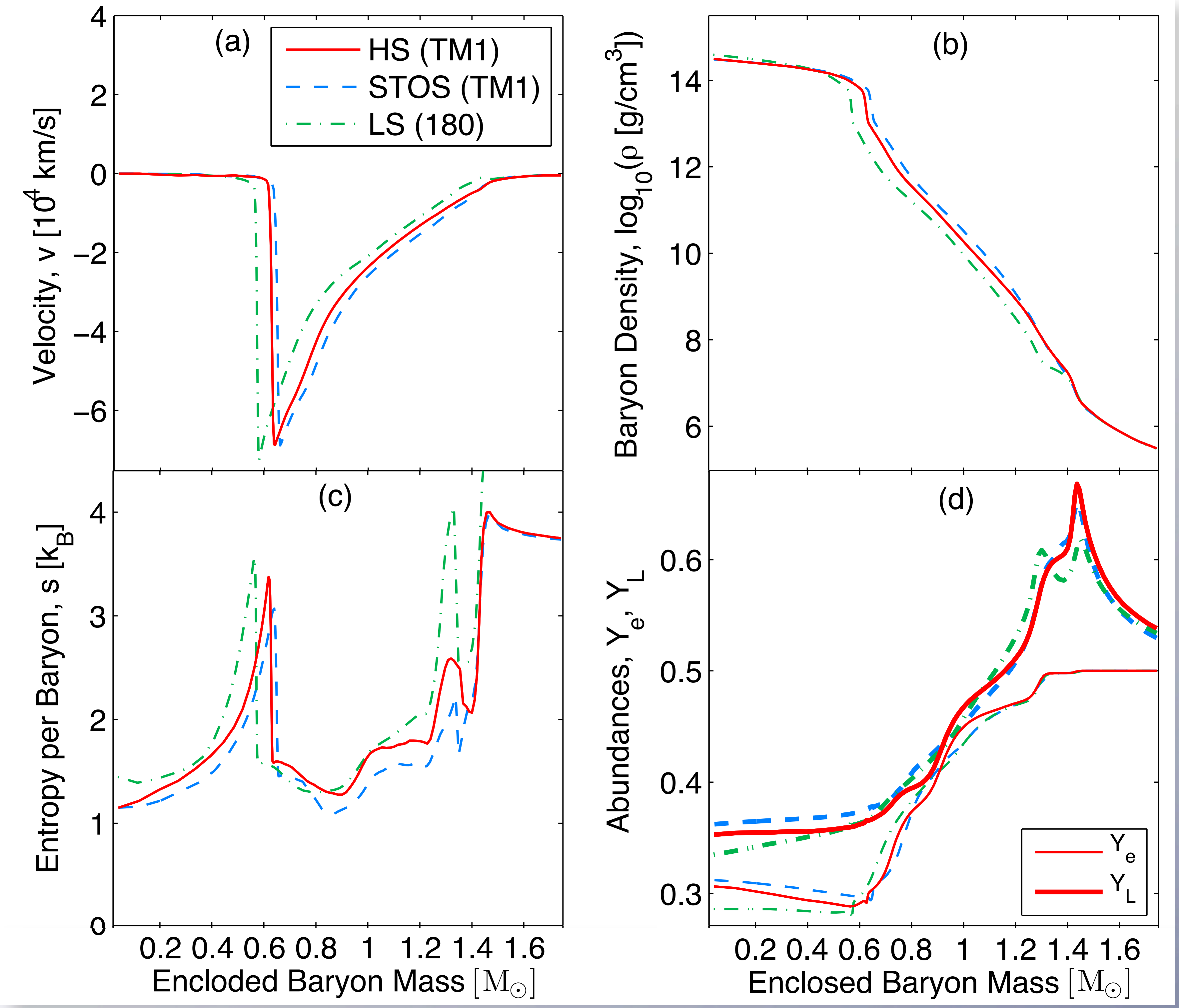
Nuclear distributions in the SN – prebounce

- nuclear distributions/chemical ensemble due to finite temperature
- evolution of the nuclear composition of a chunk of matter in a SN



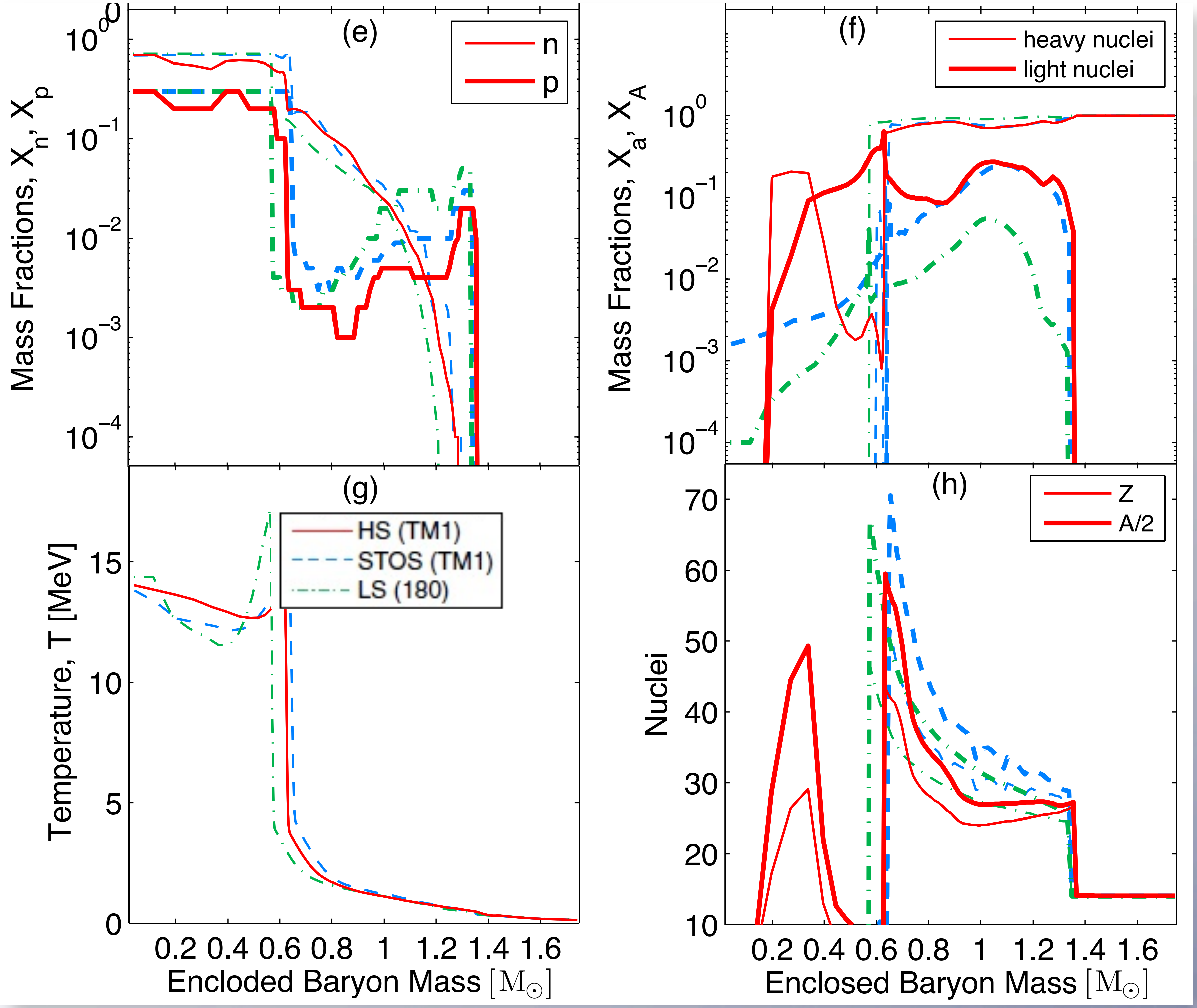
similar information is used in recent electron capture rates

Bounce



- densities around ρ_0
- core is not collapsing any more
- shock wave generates entropy, heats matter
- neutrinos trapped in the center

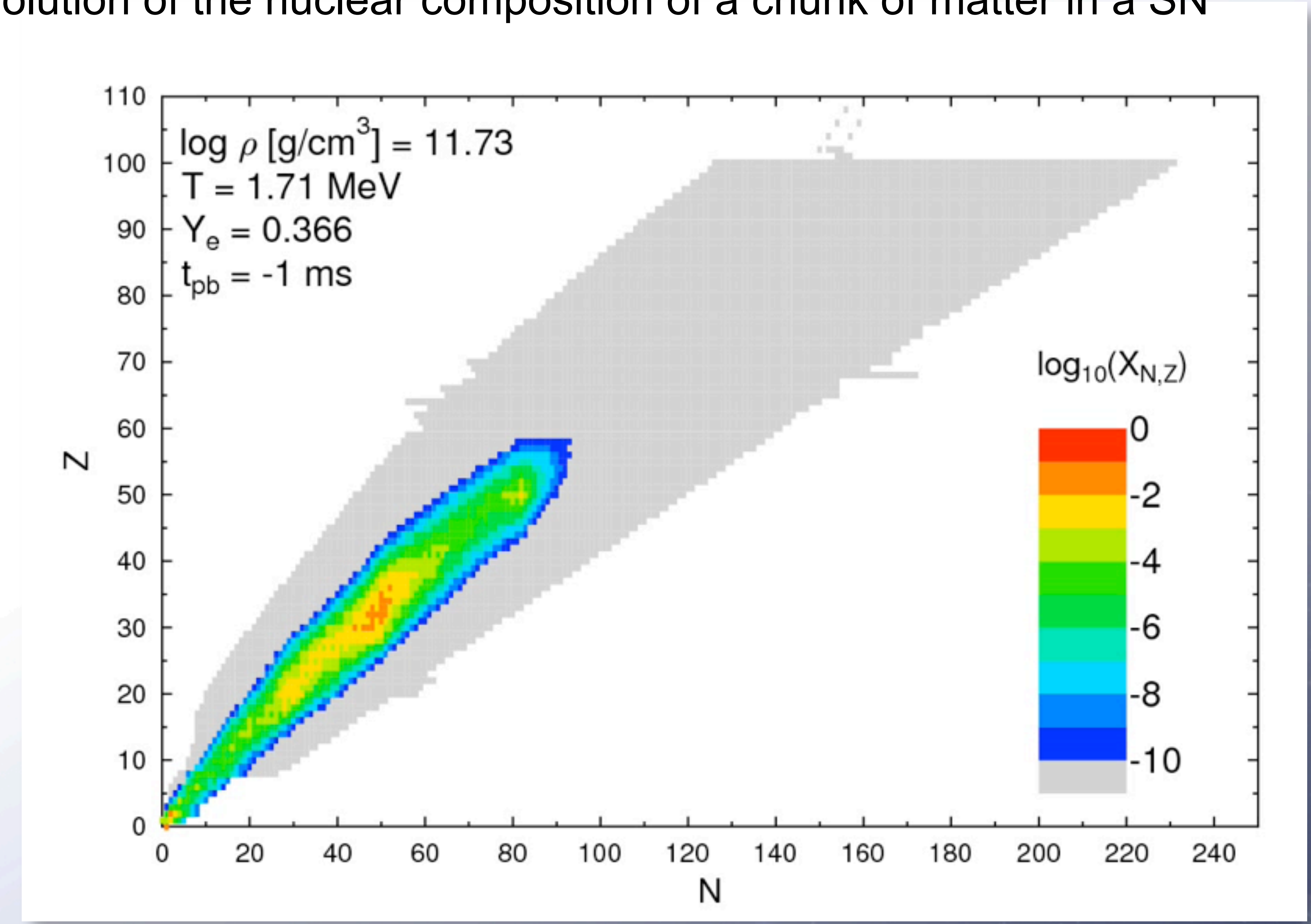
Bounce



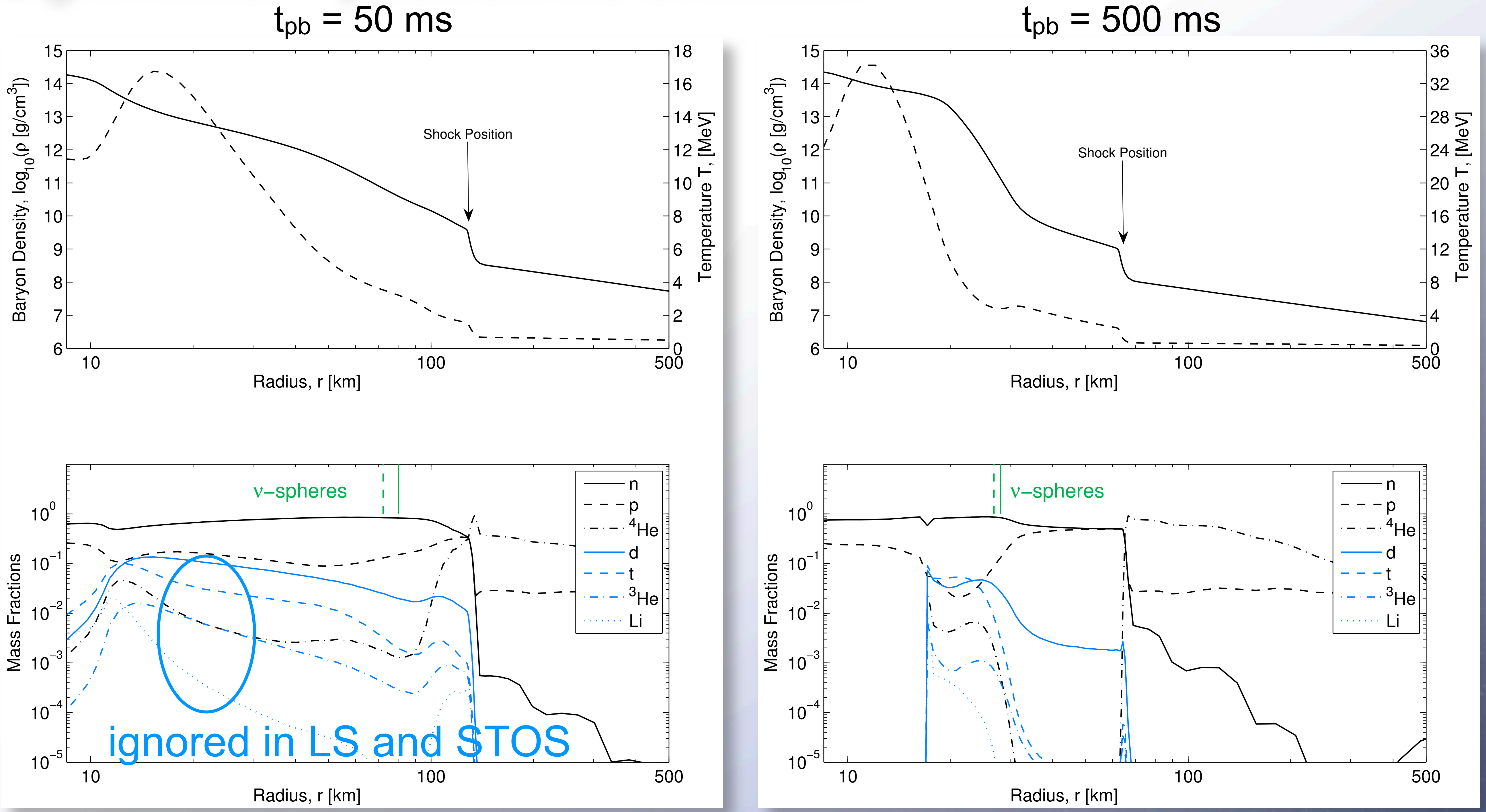
- high temperatures after shock passage
- shock heated matter: mostly neutrons, protons, some light nuclei

Nuclear distributions in the SN – bounce and post-bounce

- nuclear distributions/chemical ensemble due to finite temperature
- evolution of the nuclear composition of a chunk of matter in a SN



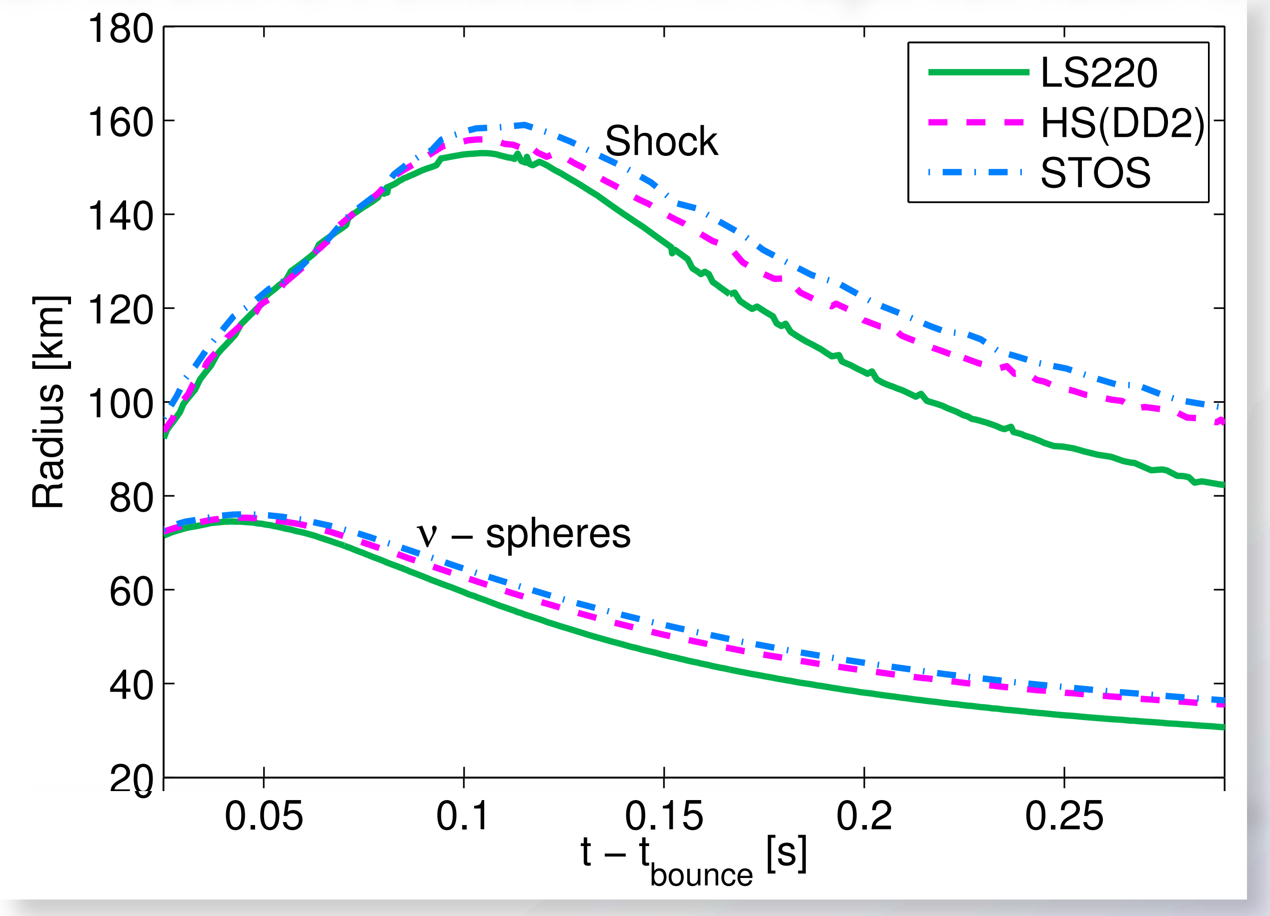
Light nuclei – postbounce evolution



ignored in LS and STOS

- proto-neutron star core: nucleons
- proto-neutron star envelope & shock heated matter: light nuclei
- infalling matter: heavies, alphas, nucleons

Shock evolution in spherical symmetry



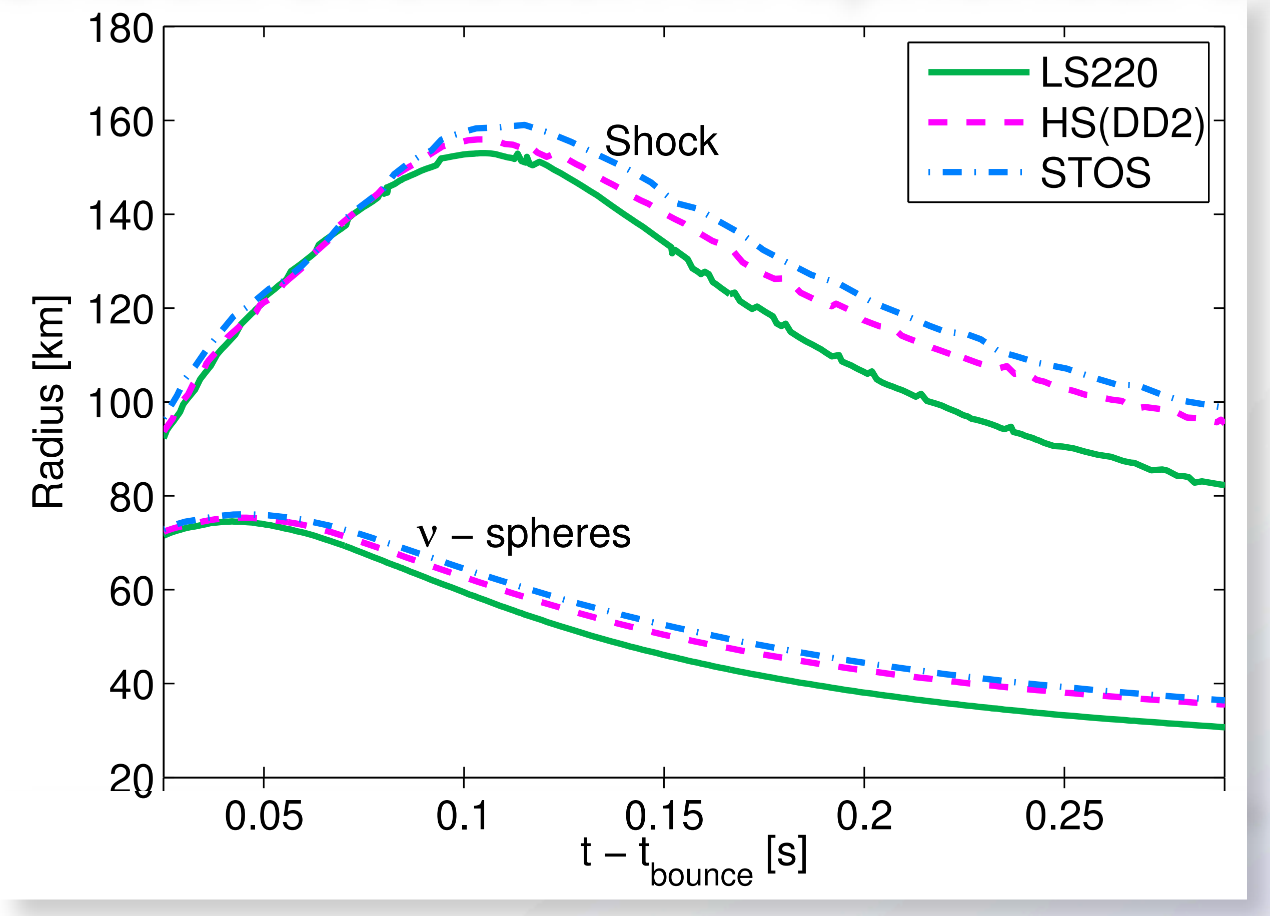
- detailed 1D simulations with realistic microphysics: no explosions!
- shockexpansion stalls, “standing accretion shock“
- energy loss of the shock:

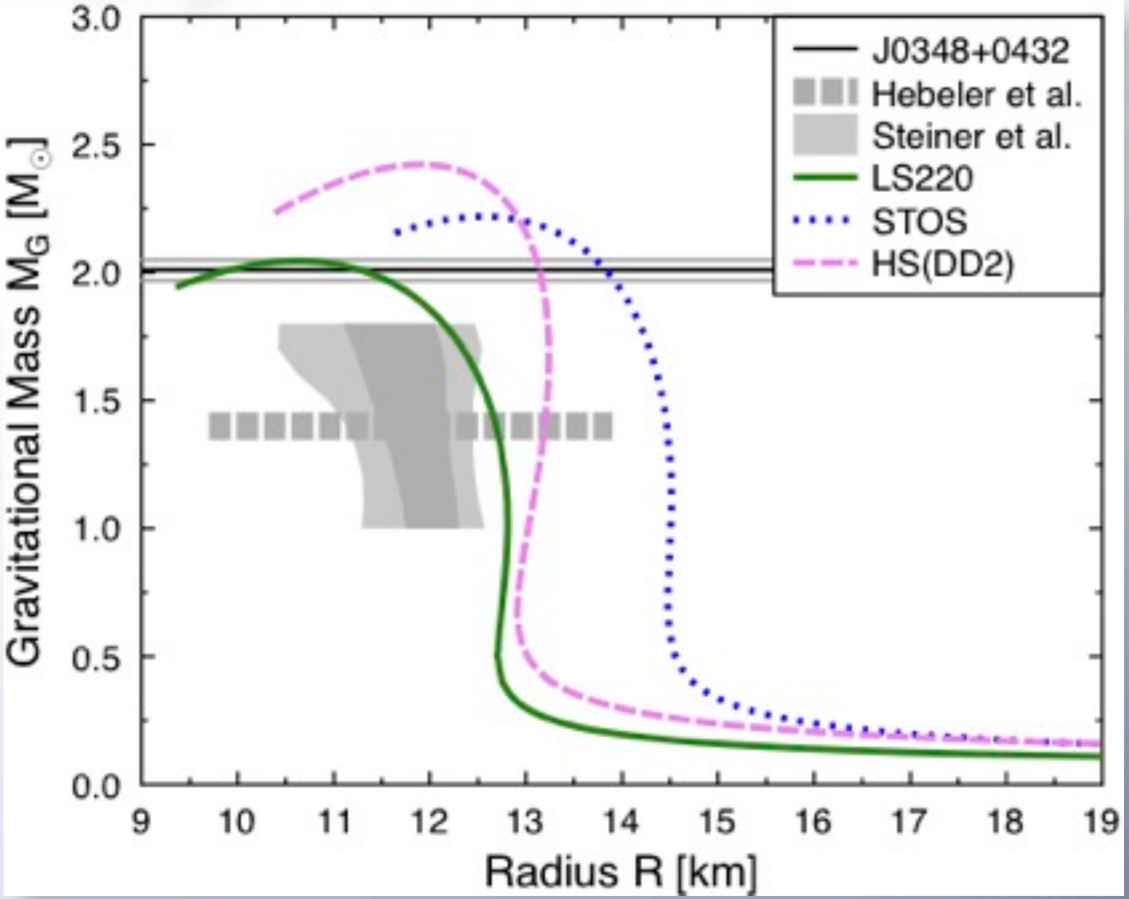
– dissociation of heavy nuclei

– neutrino emission

Matthias Hempel
Russbach, 14.3.2014

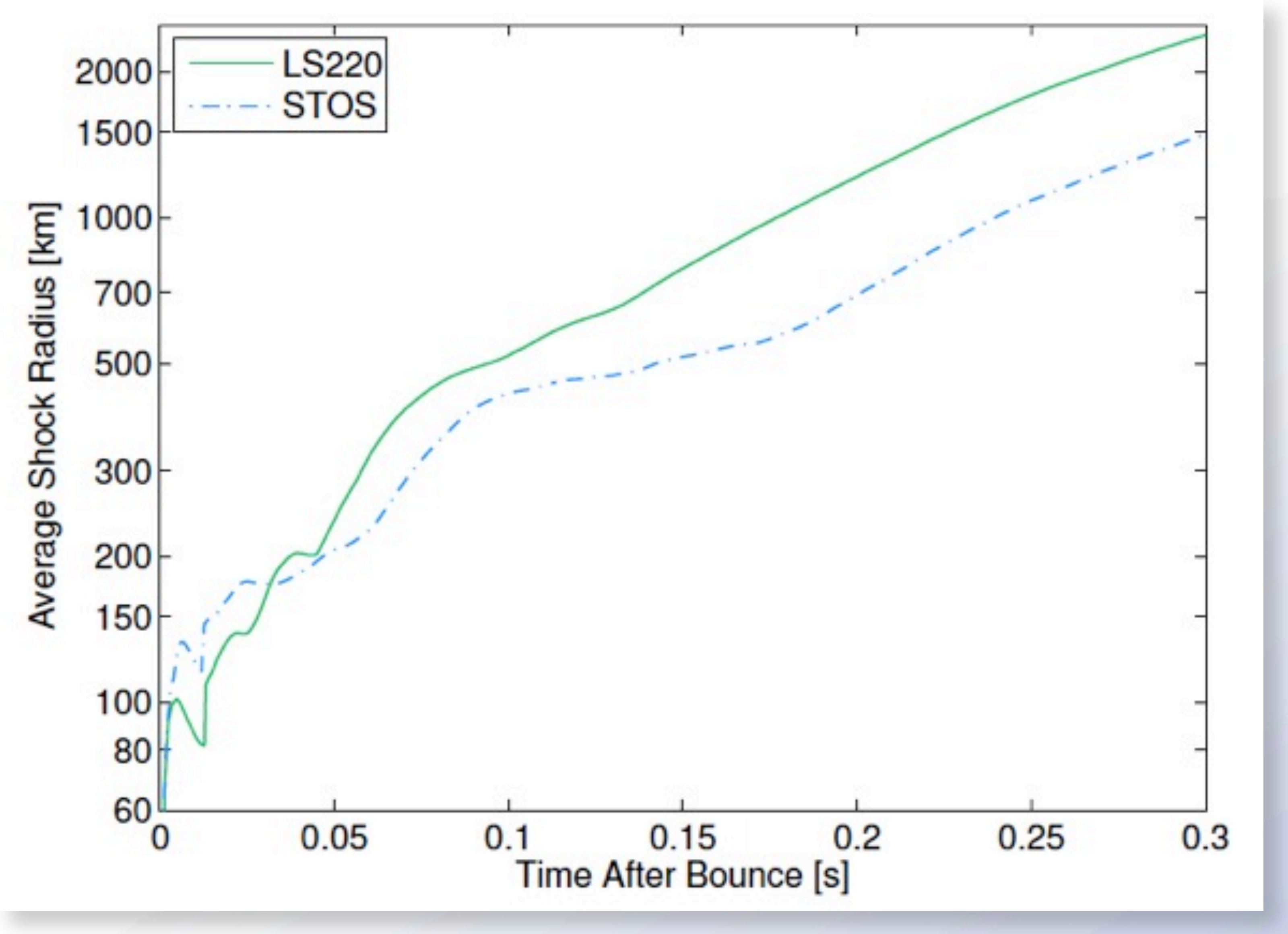
Shock evolution in spherical symmetry





- proto-neutron star contraction determined by EOS, faster for LS220
- DD2 between the more extreme cases of STOS and LS
- leading to higher mean energies of LS220
- radius evolution in agreement with TOV solutions
- small differences, but shown to be amplified in Multi-D (Suwa et al. 2013, Marek et al, 2009, Couch 2013)

Shock evolution in 2D, axisymmetric simulation (Suwa et al.)



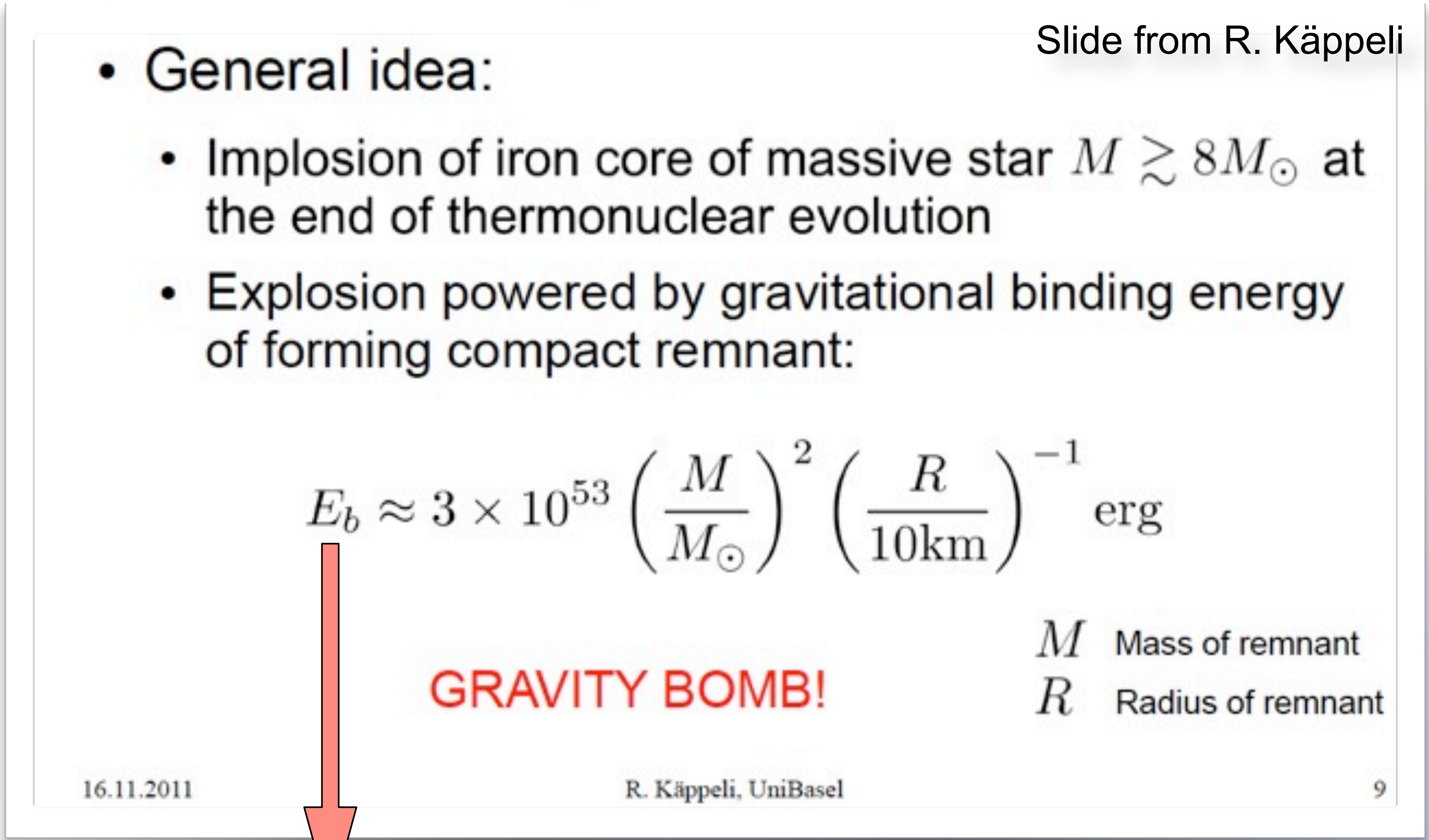
T. Fischer, MH, et al.; Eur. Phys. J. A 50, 46 (2014)

- faster shock expansion for LS220
- also for other progenitors: LS220 easier to explode than STOS
- see also: Marek et al. 2009, Suwa 2013, Couch 2013

STOS too pessimistic, LS220 too optimistic for explosion models

Supernova simulations in 3D - the supernova explosion mechanism

Supernova-energetics



Slide from R. Käppeli

- General idea:
  - Implosion of iron core of massive star $M \gtrsim 8M_\odot$ at the end of thermonuclear evolution
  - Explosion powered by gravitational binding energy of forming compact remnant:

$$E_b \approx 3 \times 10^{53} \left(\frac{M}{M_\odot}\right)^2 \left(\frac{R}{10\text{km}}\right)^{-1} \text{erg}$$

GRAVITY BOMB!

M Mass of remnant

R Radius of remnant

16.11.2011 R. Käppeli, UniBasel 9

1 erg = 10^{-7} J

- 10^{41} erg: visible spectrum
- 10^{48} erg: entire em-spectrum
- 10^{51} erg: kinetic energy
- 10^{53} erg: neutrinos

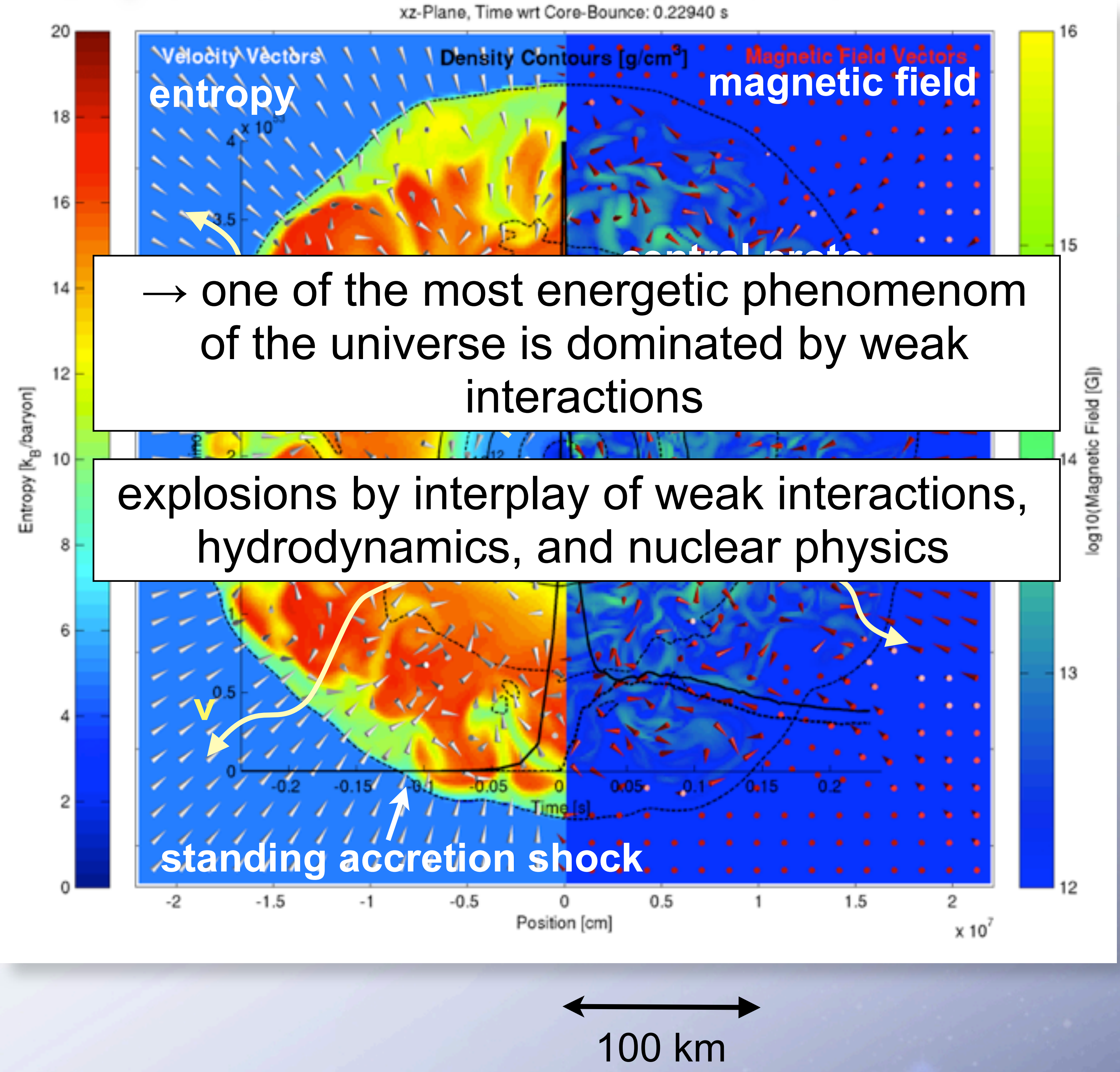
comparison:

- sun: 10^{41} erg/y
- worldwide energy consumption: 10^{27} erg/y

→ only 1% of the available energy required

→ “surface problem“, delicate numerics

Supernova neutrino-mechanism



→ one of the most energetic phenomenom of the universe is dominated by weak interactions

explosions by interplay of weak interactions, hydrodynamics, and nuclear physics

- snaphot of a 3D simulation by M. Liebendörfer
- trapped neutrinos inside the proto-neutron star

- neutrino-driven SN:
- neutrinos revive the shock
- sufficient neutrino heating requires fluid instabilities → multi-D

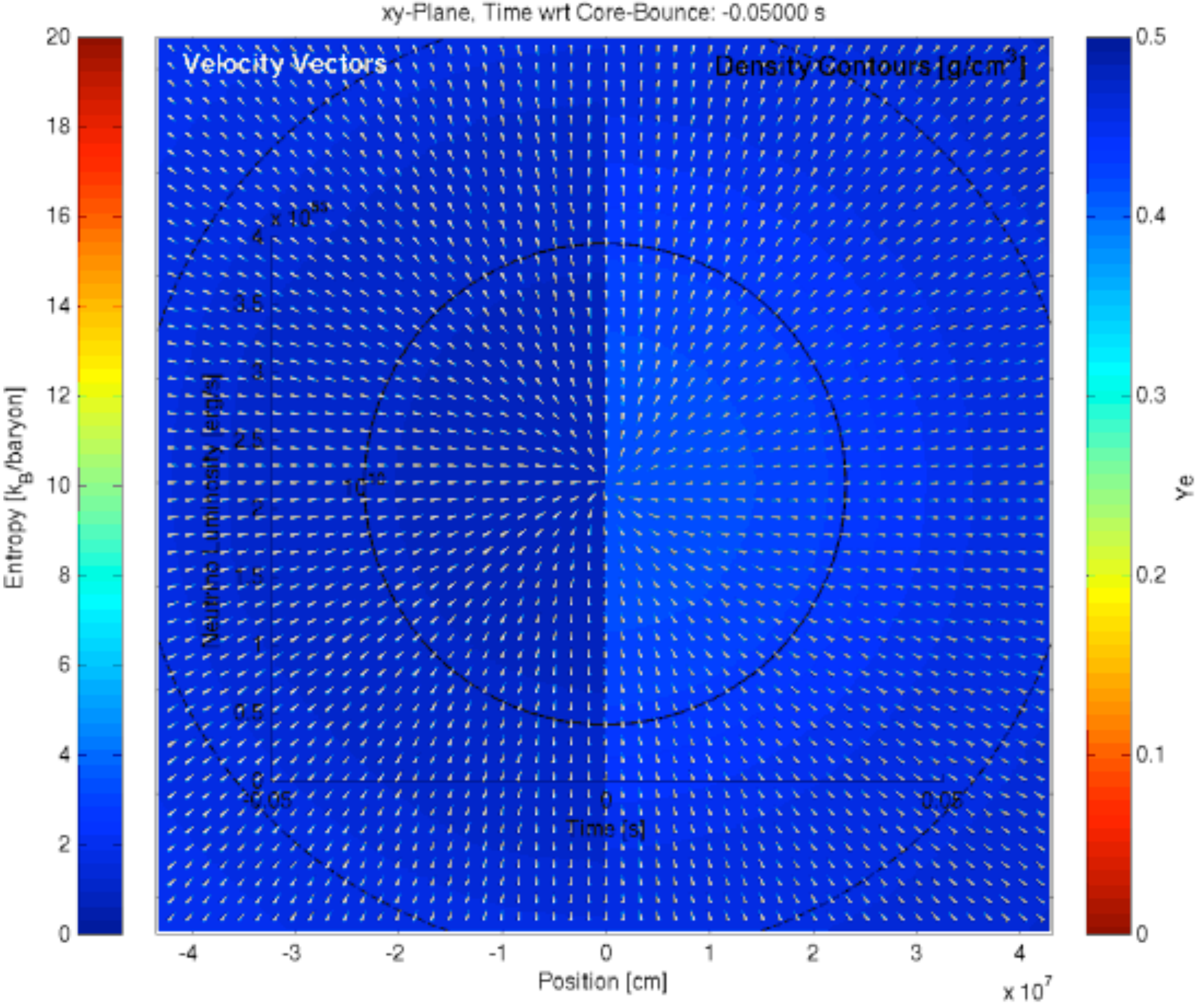
Basel 3D simulations

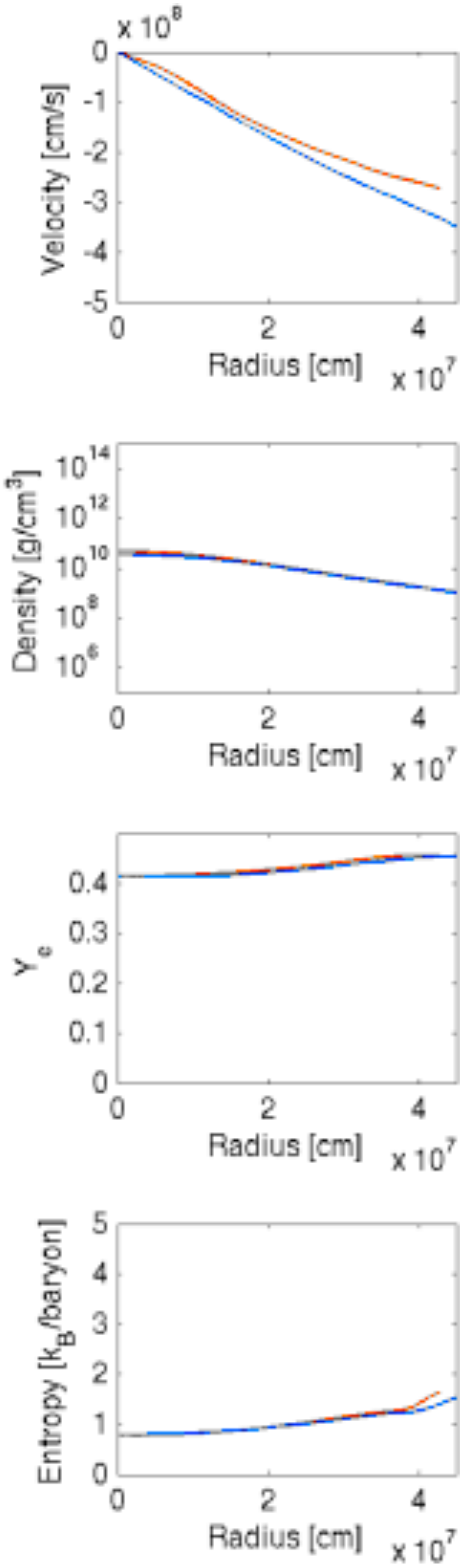
- Basel Supernova-group:

  Prof. Matthias Liebendörfer, Prof. Friedel Thielemann, Ruben Cabezon, Takami Kuroda, Kuo-Chuan Pan, Maik Frenzel, Kevin Ebinger, Roger Käppeli, MH
- 3D ELEPHANT code: **Ele**gant **P**arallel **H**ydrodynamics with **A**pproximate **N**eutrino **T**ransport
- one simulation ~ 1 MCPUh → 100 years on a regular CPU
- performed at Swiss supercomputer center CSCS, top 6 worldwide

CSCS

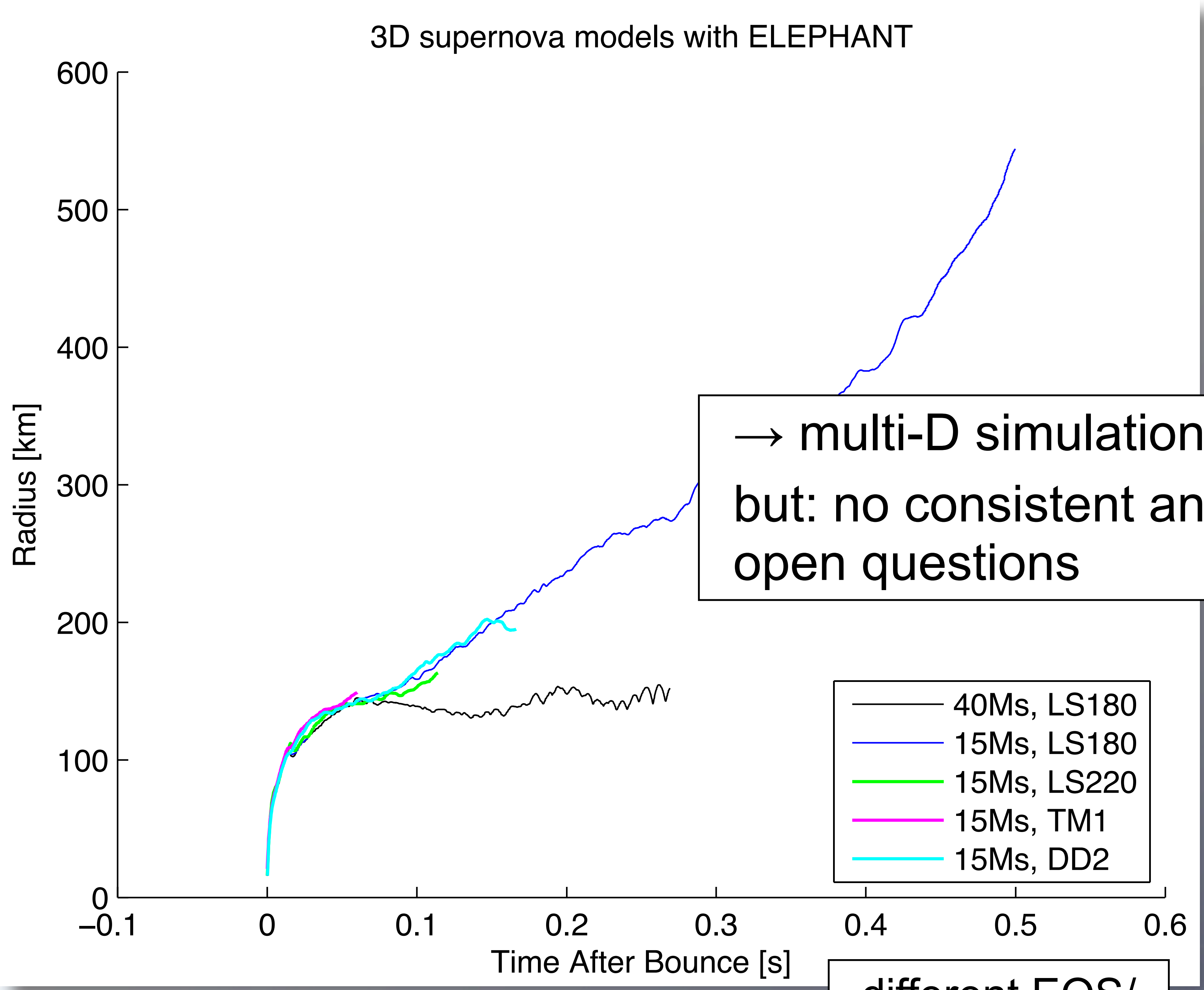
3D Elephant code, PoS(NIC X)243, arXiv:0711.2929, arXiv:0910.2854 (s15s7b2, red profiles -->)





Comparison with 1D GR Boltzmann ν transport: ApJ 620 (2005) 840, (Model G15, blue profiles -->)

Basel 3D simulations



- hydrodynamic instabilities increase heating efficiency
- slowly developing explosion

→ multi-D simulations (can) lead to explosions

but: no consistent answers yet, remaining open questions

different EOS/ progenitors

Conclusions

- states of matter in CCSN are extremely diverse (distributions of heavy nuclei, light nuclei, uniform nuclear matter, exotica, ...)

- the SN EOS is very complex, there are still uncertainties, especially at highest densities

- important constraints from astrophysical observations, nuclear experiments and theory
- new (and more realistic) supernova EOS available, quickly developing field

- multi-D simulations of CCSN (can) lead to explosions
- still remaining open questions, including the role of the EOS in CCSN