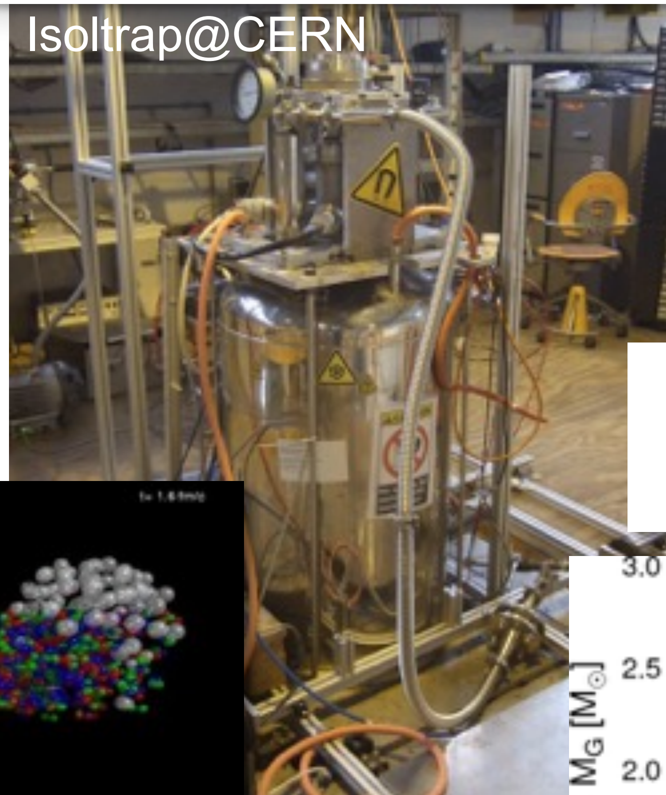
Clusters and phase transitions in supernova equations of state — part I

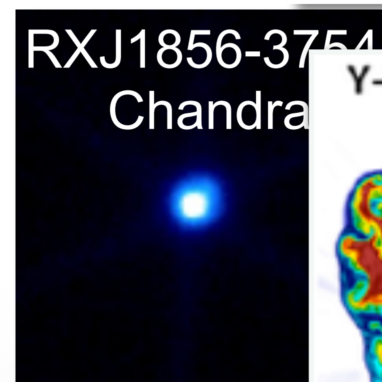
Matthias Hempel, Basel University
HISS Dubna „Dense Matter“, 29.6.2015

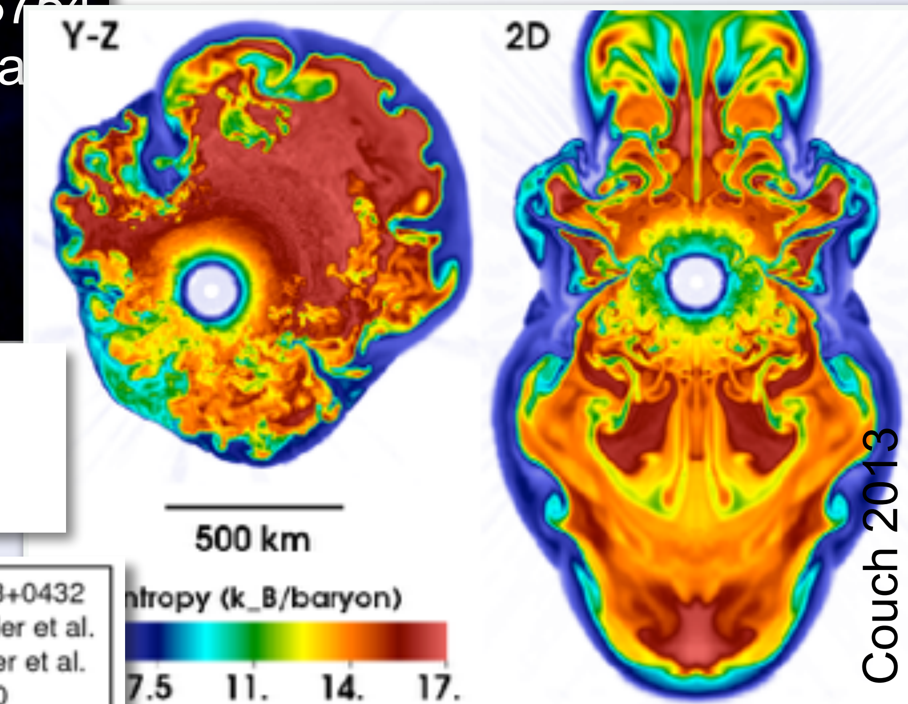
My research interests:

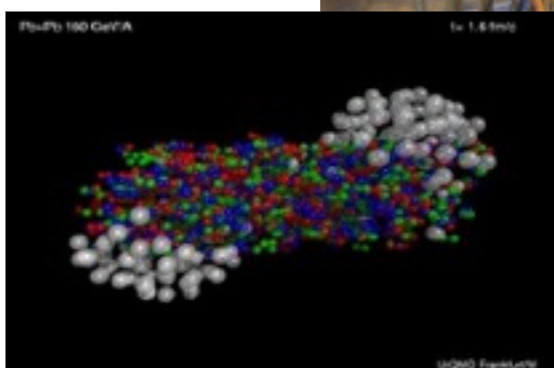
core-collapse supernovae
& neutron stars

nuclear experiments

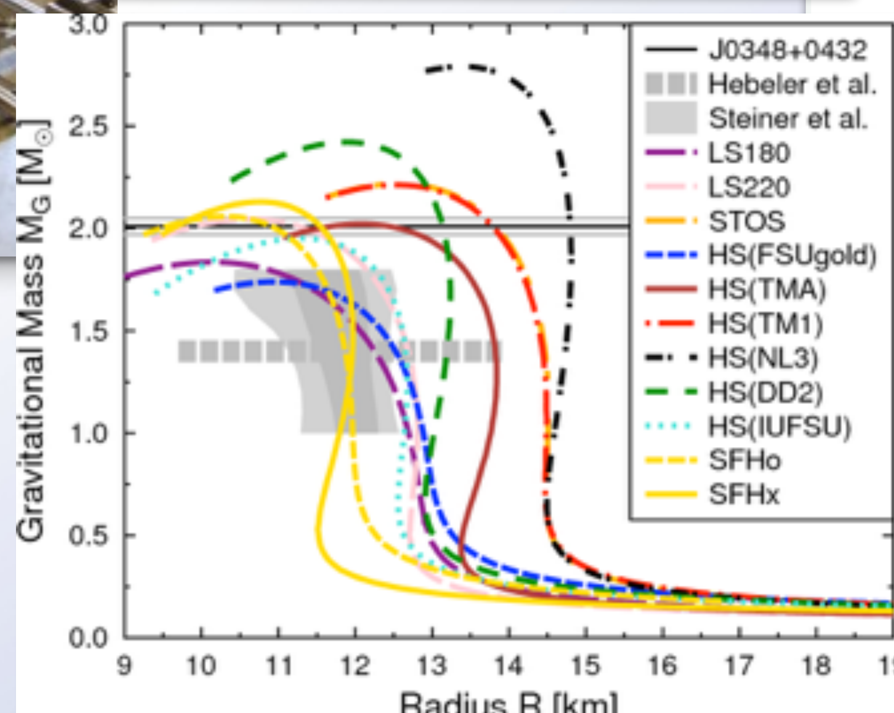


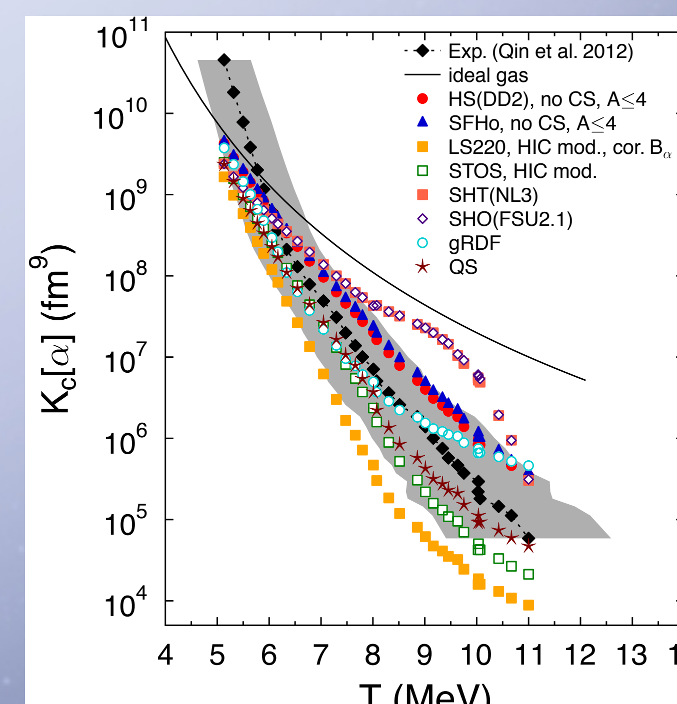


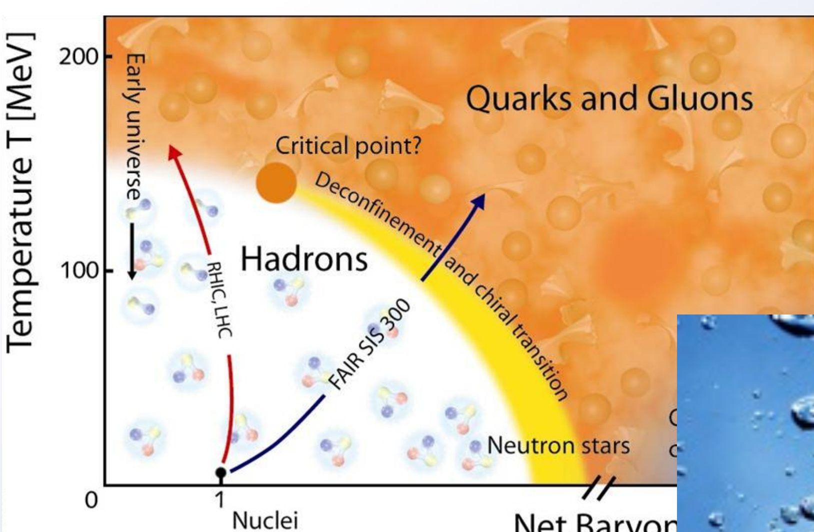




astrophysical
equation of state







phase transitions

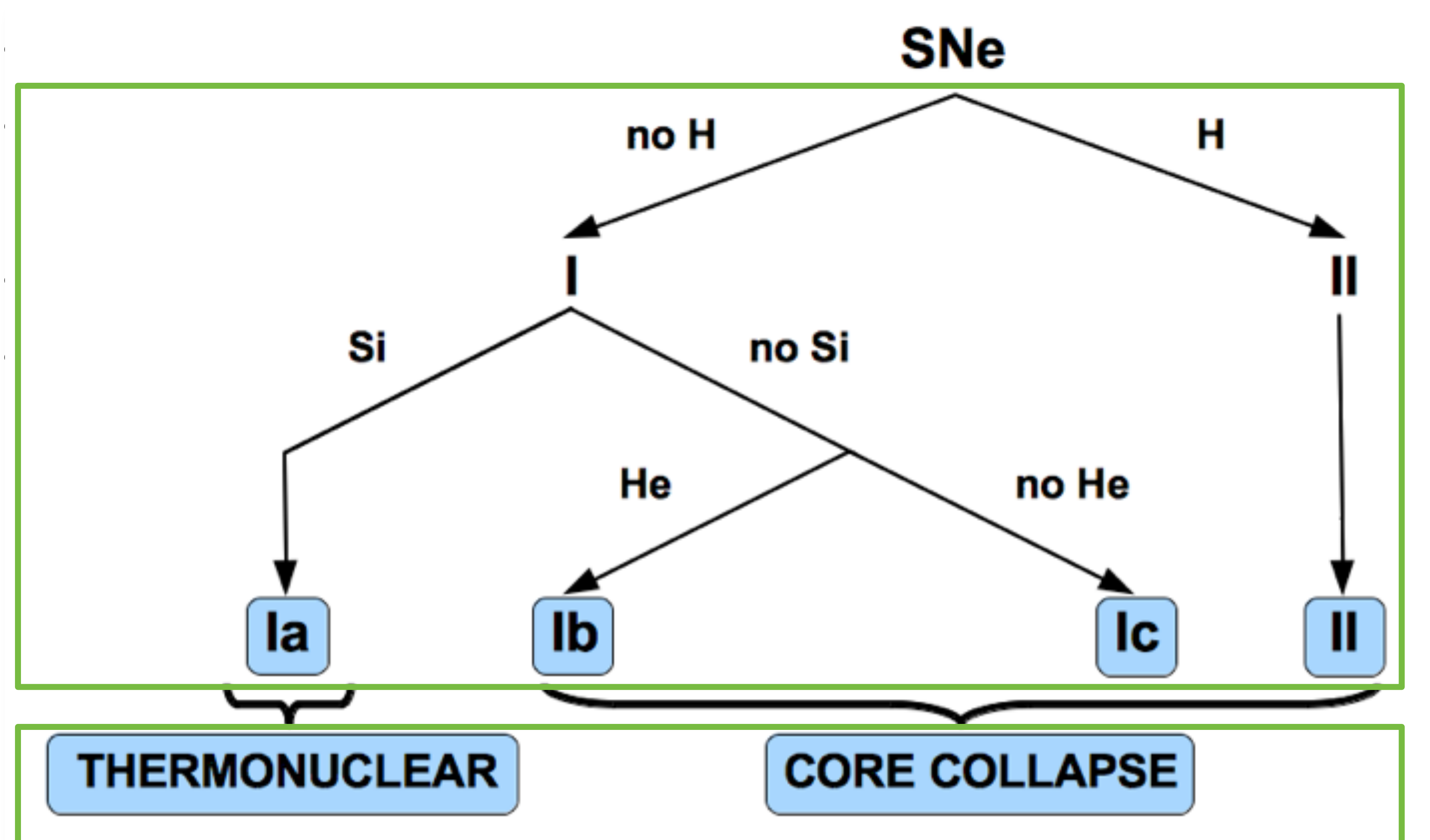
cluster formation

Outline

Monday	• brief astrophysical introduction • matter in supernovae, comparison with HICs • QCD phase transition in supernovae
Tuesday	• comparison liquid-gas with QCD phase transition, non-congruence • cluster in supernovae • cluster formation in nuclear matter, experimental probes

astrophysical background:
core-collapse supernovae

Classification of supernovae



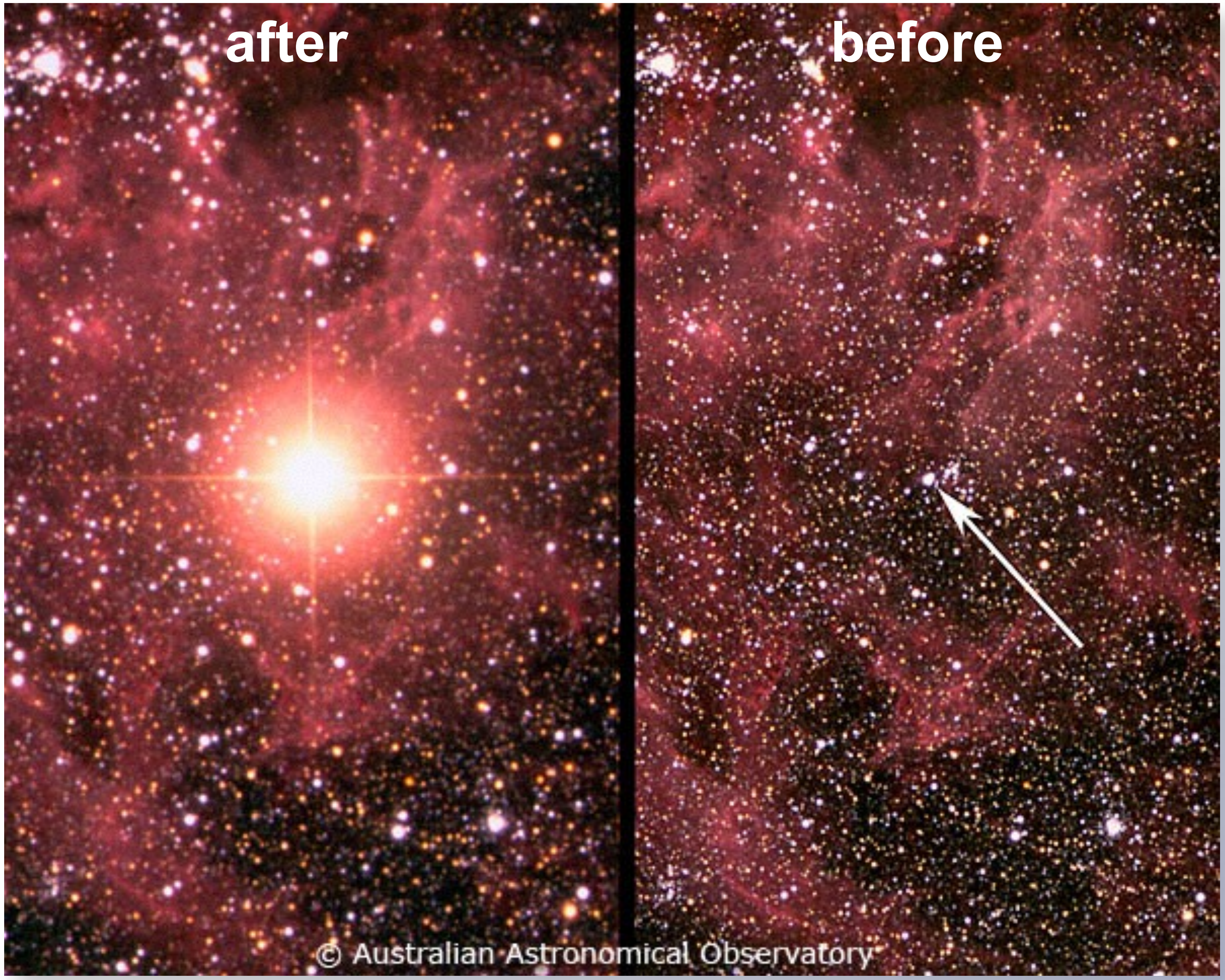
observations (elemental lines in spectra)

mechanism

- thermonuclear explosions of white dwarfs
- no remnant

- core collapse of massive progenitor stars
- remnant: neutron stars or black holes

SN1987A

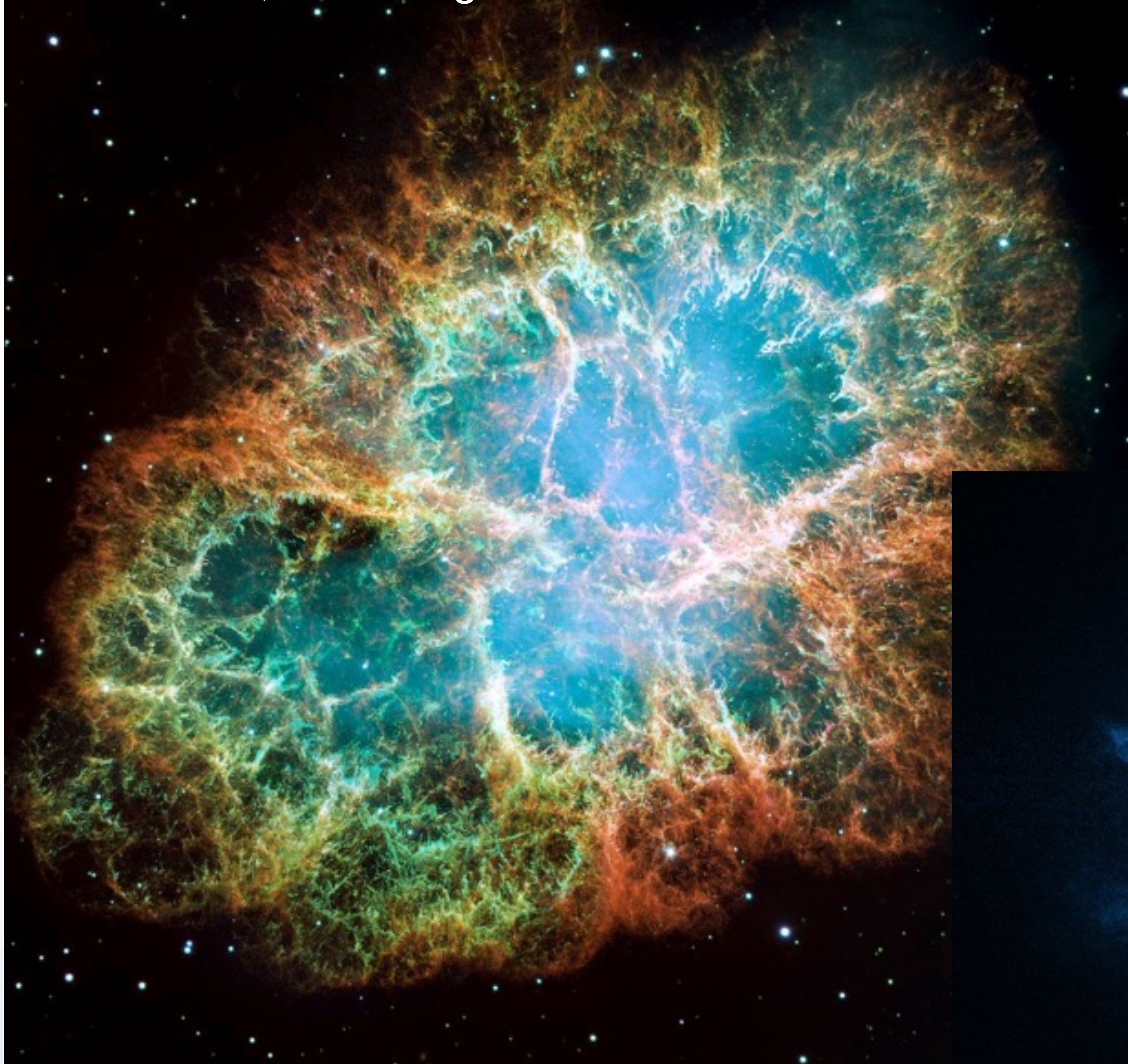


- 24.2.1987: last close-by CCSN
- distance: 150,000 light years in Large Magellanic Cloud
- explosion energy: ~10^{51}erg
- 20 neutrinos observed

- galactic SN-rate: ~ 3/100 years
- thousands of observations of extragalactic SN
- observable in:
  - electro-magnetic
  - neutrinos
  - gravitational waves (?)

1 erg = 10^{-7} J = 6.2×10^{5} MeV

Supernova remnant



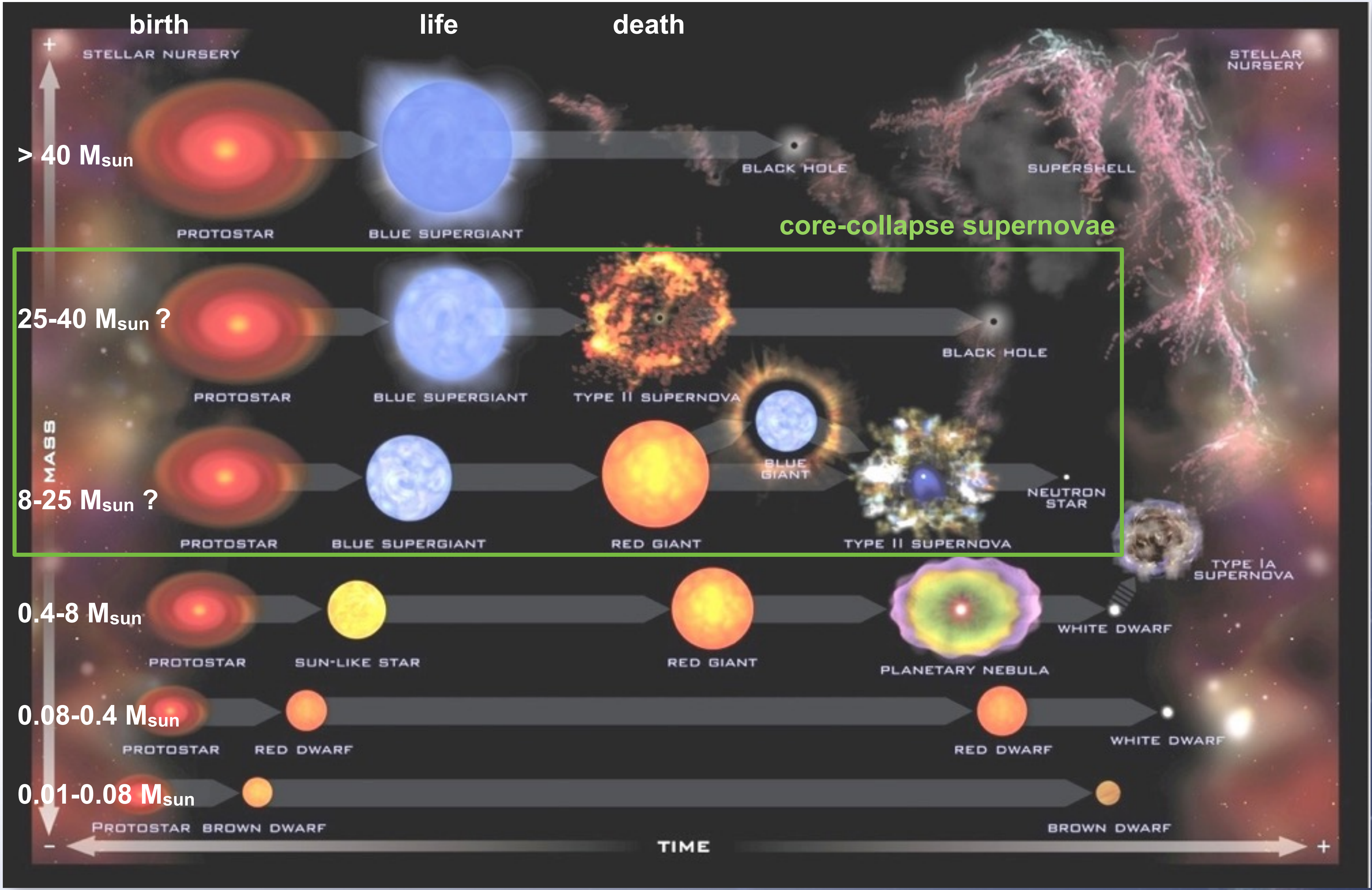
Crab nebula, HST image

- Supernova of 1054 AD
- 6,000 light years distance
- neutron star in center

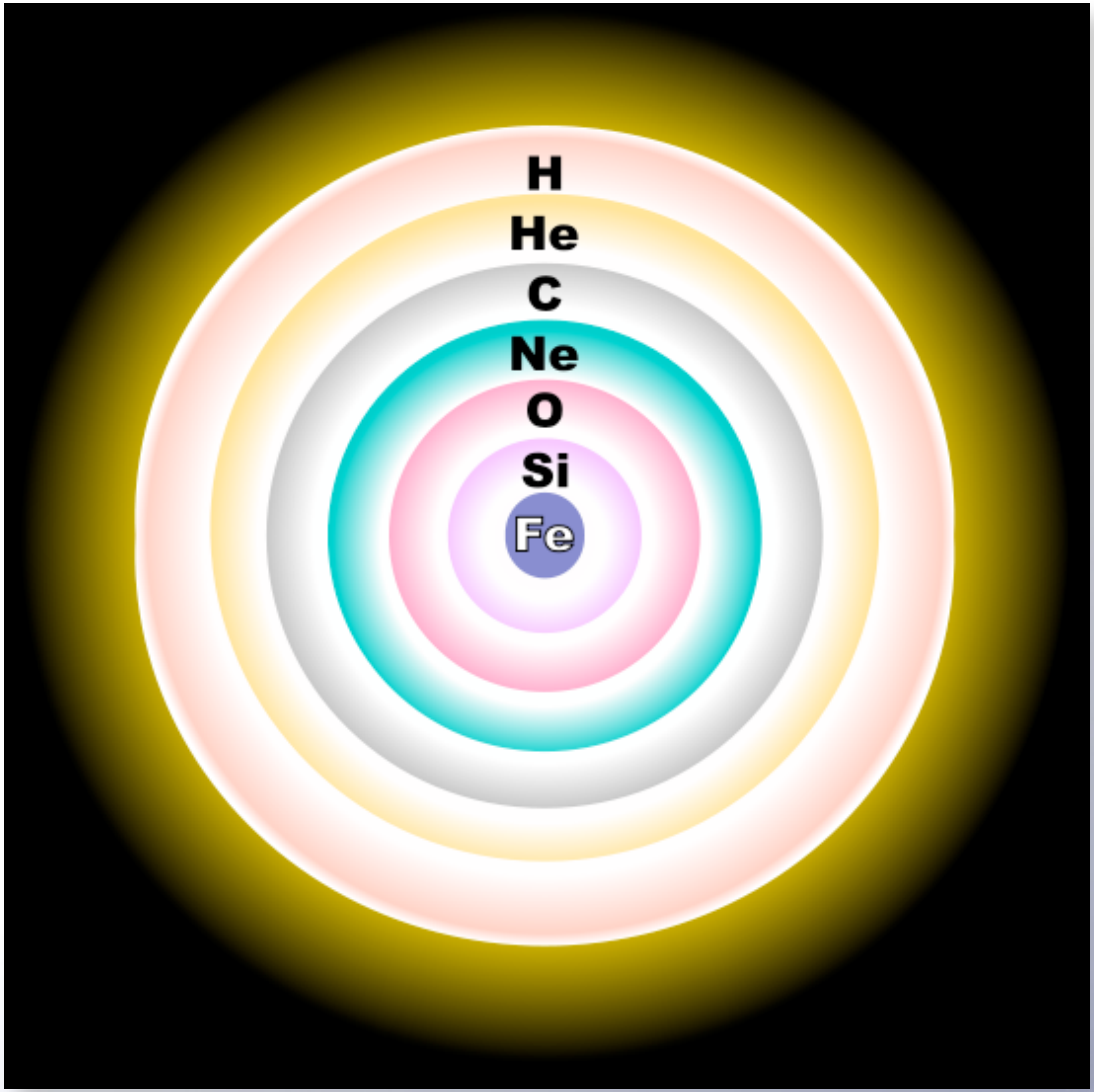
- CCSNe are birth places of neutron stars

Crab pulsar, Chandra X-ray image

Stellar evolution



Shell burning of massive stars at the end of their evolution

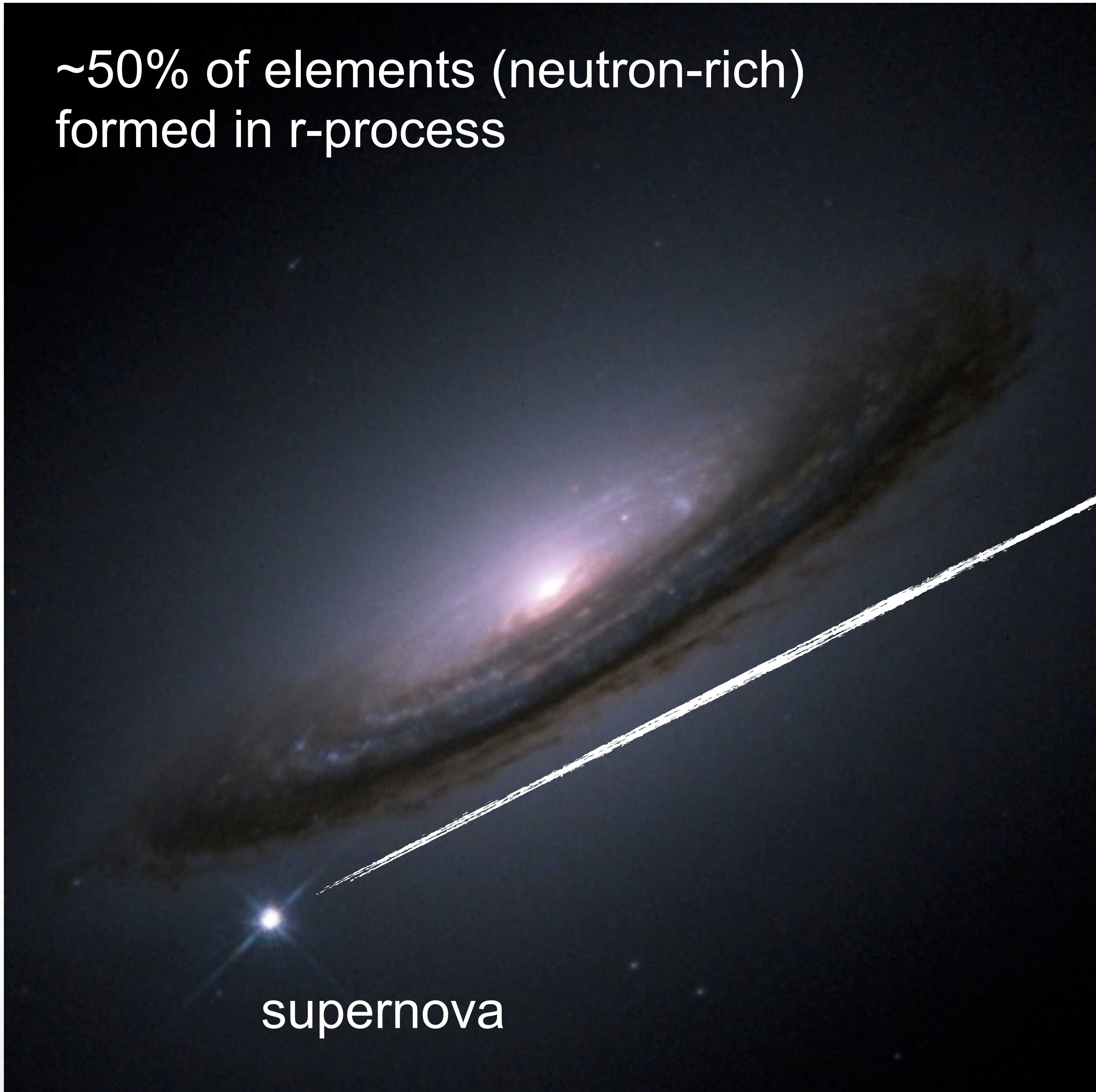


- mass > 8-10 M_{sun}
- shell burning in outer layers
- formation of an iron core
- progenitor of a core-collapse supernova

- gravitational collapse when Chandrasekhar mass limit of ~ 1.4 M_{sun} is reached
- after collapse: explosion as a core-collapse supernova
- how does it work? → *supernova mechanism*
- still not completely understood

solar mass: 1 M_{sun} = 2×10^{33} g = 1.4×10^{57} baryons

nucleosynthesis of heavy elements (r-process)



- paradigm: r-process occurs in core-collapse supernovae
- not supported by simulations (!)
- neutron star mergers: r-process possible, but: early/fast enough to explain old stars?

→ still open questions in r-process nucleosynthesis

Matthias Hempel
Dubna, 29.6.2015

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:

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

GRAVITY BOMB!

M Mass of remnant
R Radius of remnant

16.11.2011 R. Käppeli, UniBasel 9

1 erg = 10^{-7} J
= 6.2×10^{5} MeV

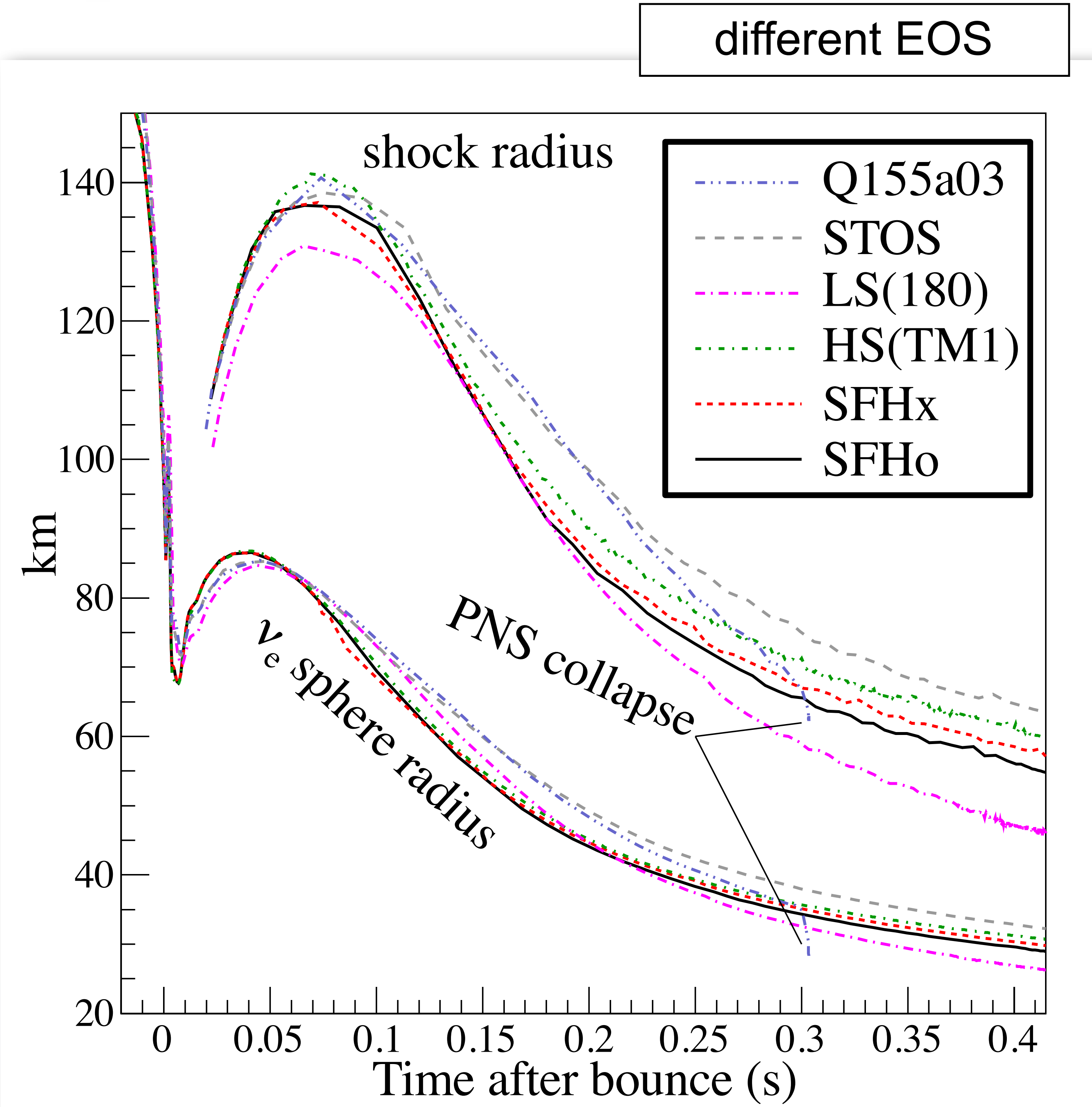
- 10^{41} erg: visible spectrum
- 10^{48} erg: entire em-spectrum
- 10^{51} erg: kinetic energy
- 10^{53} erg: neutrinos

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 simulations in spherical symmetry

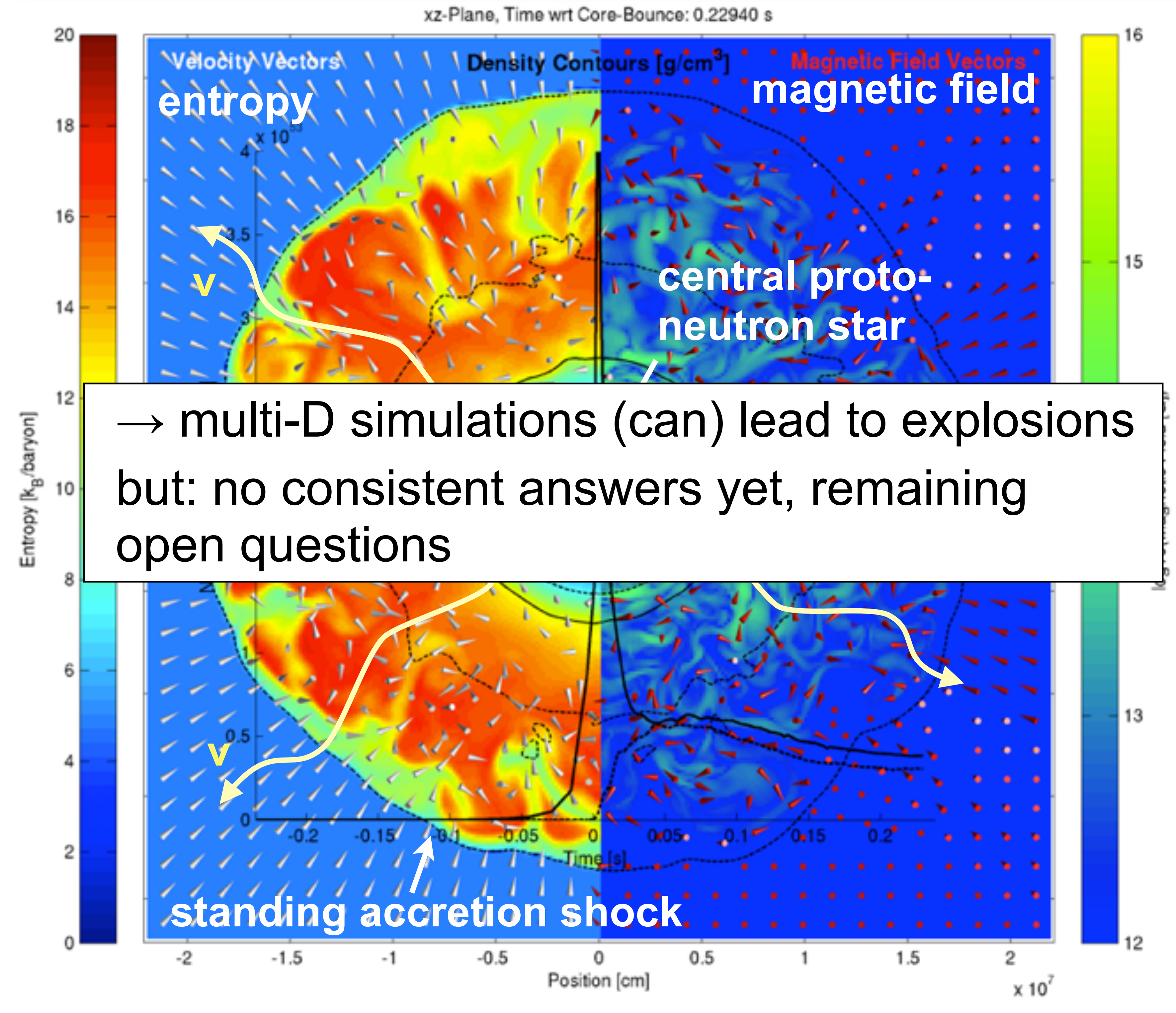


A. Steiner, MH, T. Fischer; ApJ 774 (2013) 17

- detailed 1D simulations with realistic microphysics: no explosions!
- shock expansion stalls, "standing accretion shock"
- energy loss of shock:
  - dissociation of heavy nuclei
  - neutrino emission

bounce: moment of highest density, end of collapse

Neutrino-driven supernova mechanism

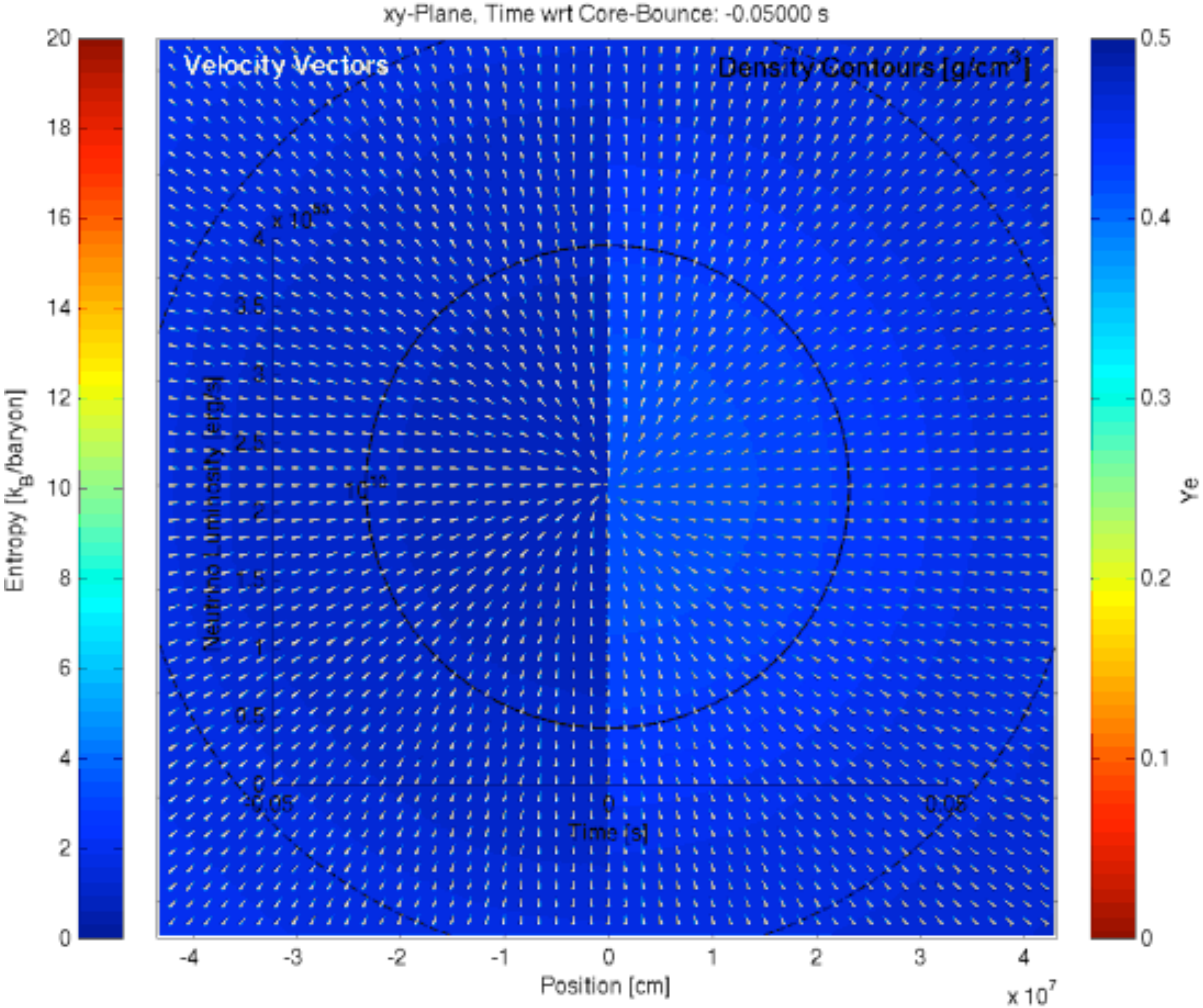


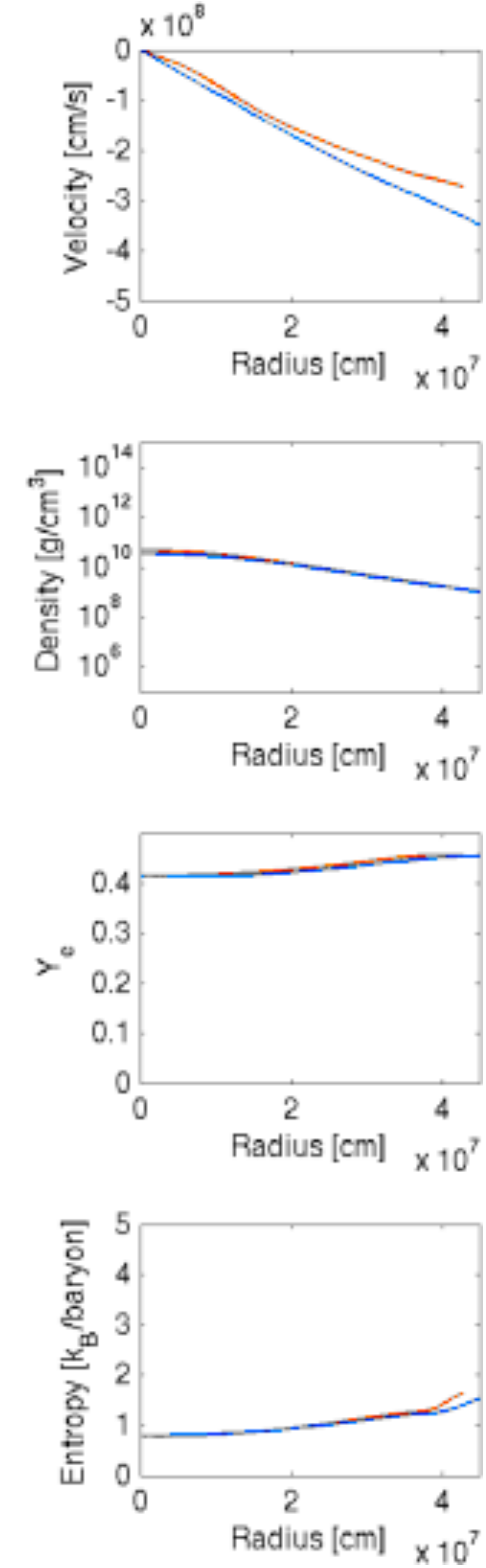
→ multi-D simulations (can) lead to explosions
but: no consistent answers yet, remaining open questions

100 km

- snapshot of a 3D simulation by M. Liebendörfer
- trapped neutrinos inside the PNS
- neutrino-driven SN:
- neutrinos revive the shock
- sufficient neutrino heating requires hydrodynamic instabilities → multi-D

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

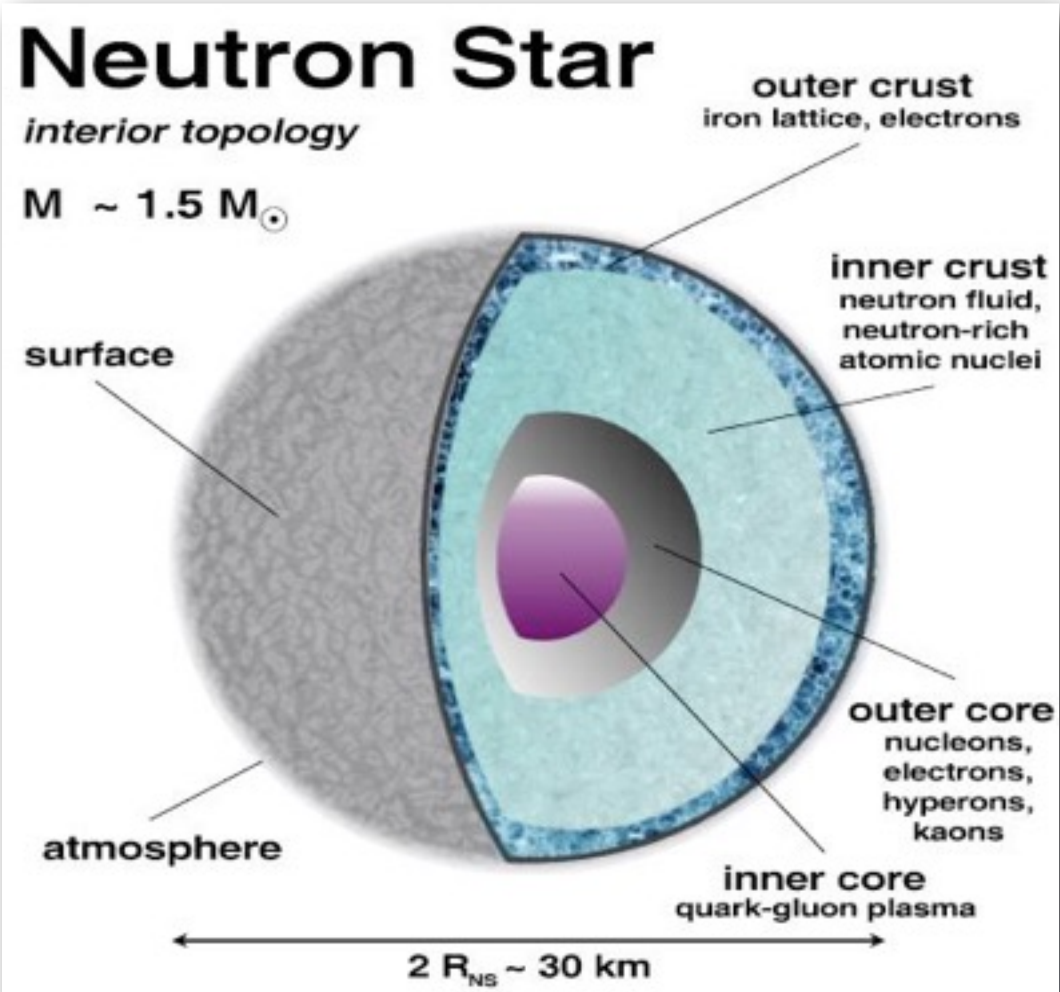




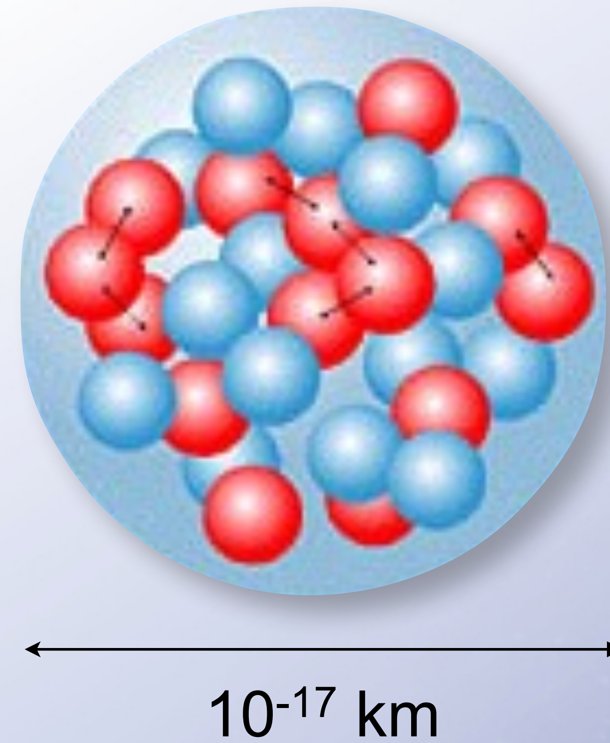
Comparison with 1D GR Boltzmann ν transport: ApJ 620 (2005) 840, (Model G15, blue profiles -->)

neutron stars

Neutron stars: giant atomic nuclei



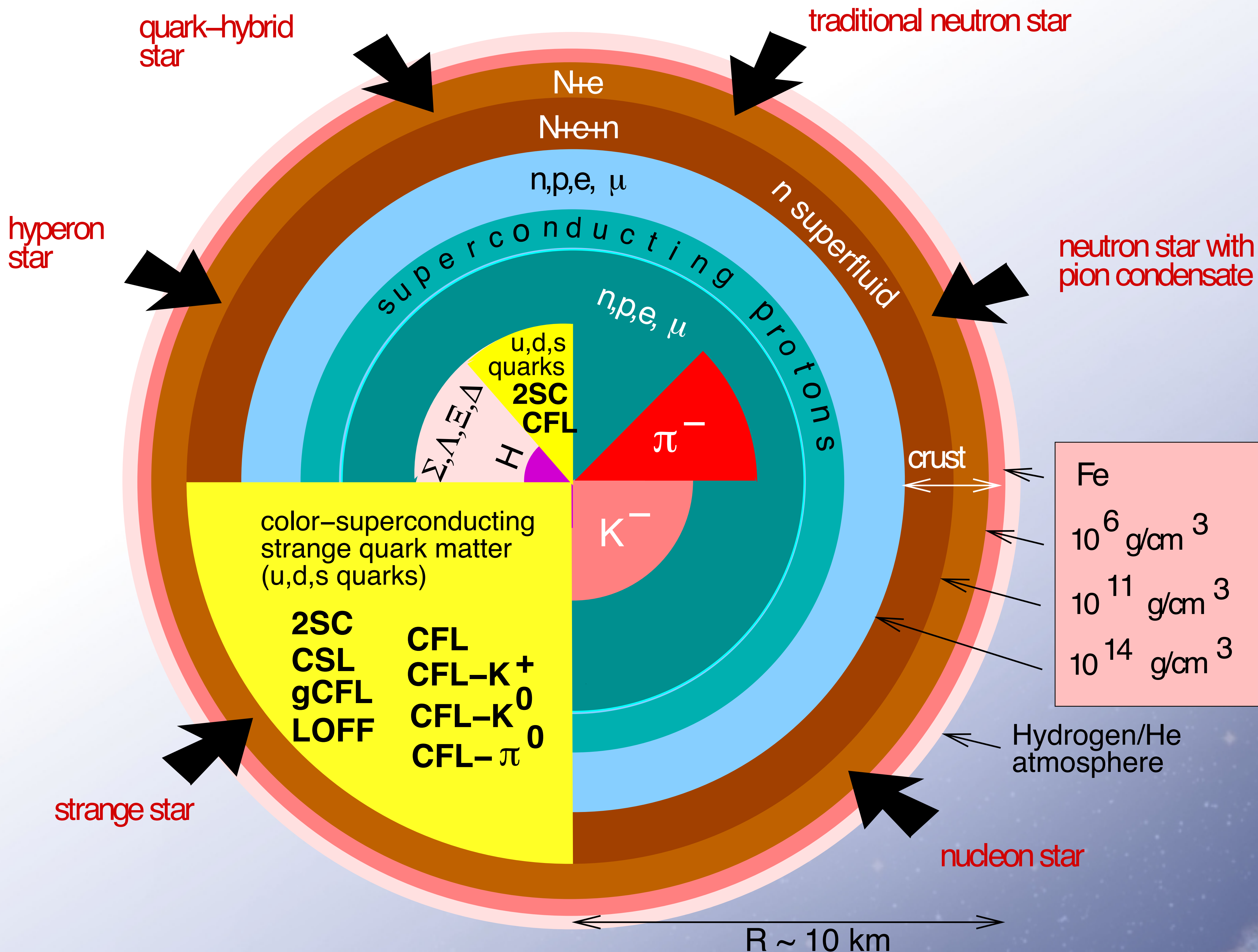
atomic nucleus



- $M = 3\text{x}10^{33}$ g
- $\rho \sim 5\text{x}10^{14}$ g/cm^3
- ~10^{57} neutrons and protons
- nuclear interactions repulsive
- bound by (self-)gravity (general relativity)

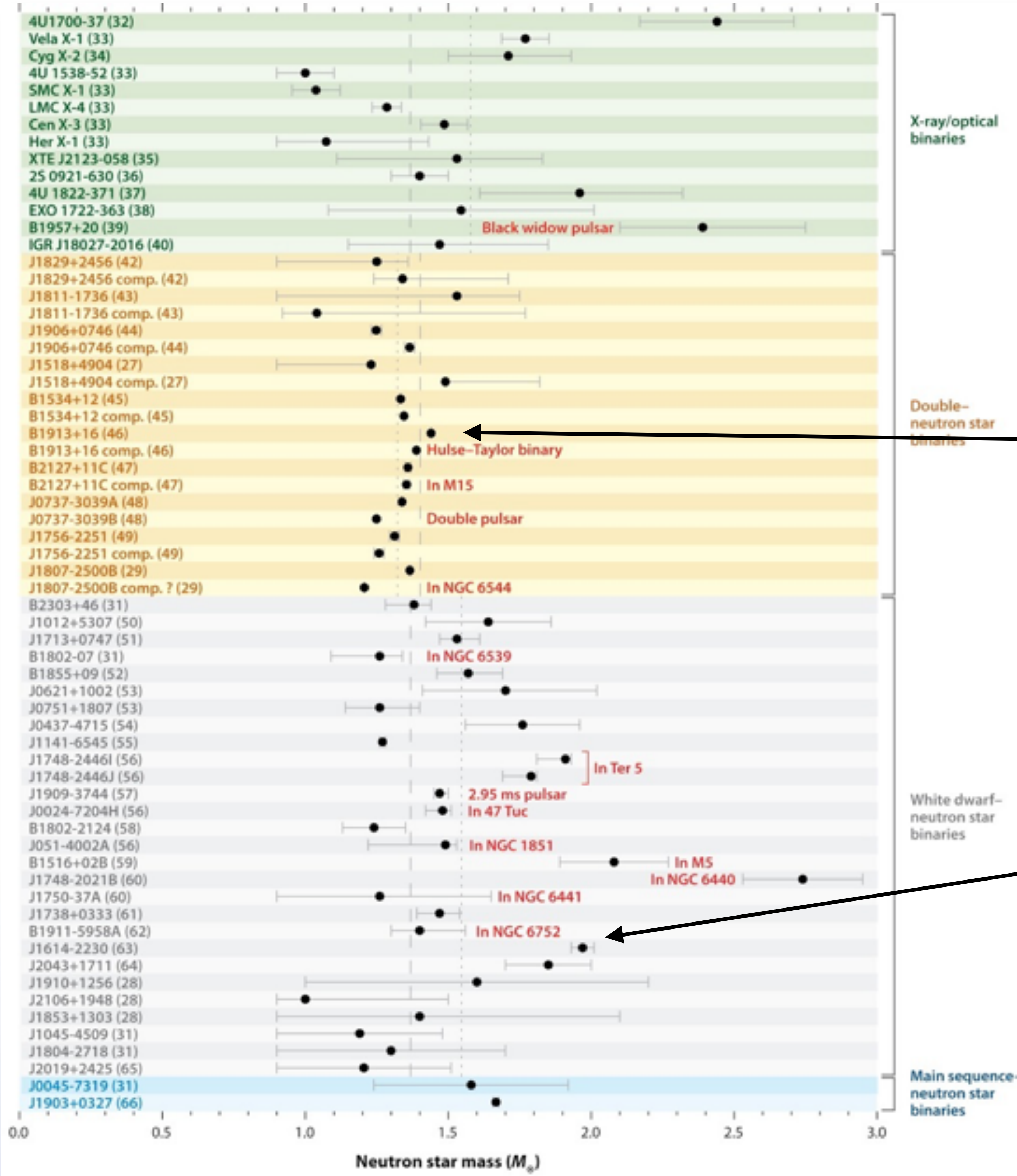
- $M = 10^{-22}$ g
- $\rho = \rho_0 \sim 3\text{x}10^{14}$ g/cm^3
- ~ 10^2 neutrons and protons
- nuclear interactions attractive
- self-gravity = 0

Exotic matter in neutron stars



F. Weber, Prog. Theor. Phys. 2005

Neutron star masses from observations



Lattimer JM. 2012.
Annu. Rev. Nucl. Part. Sci. 62:485–515

- mass measurements in binary systems
- most accurate: double-neutron star binaries

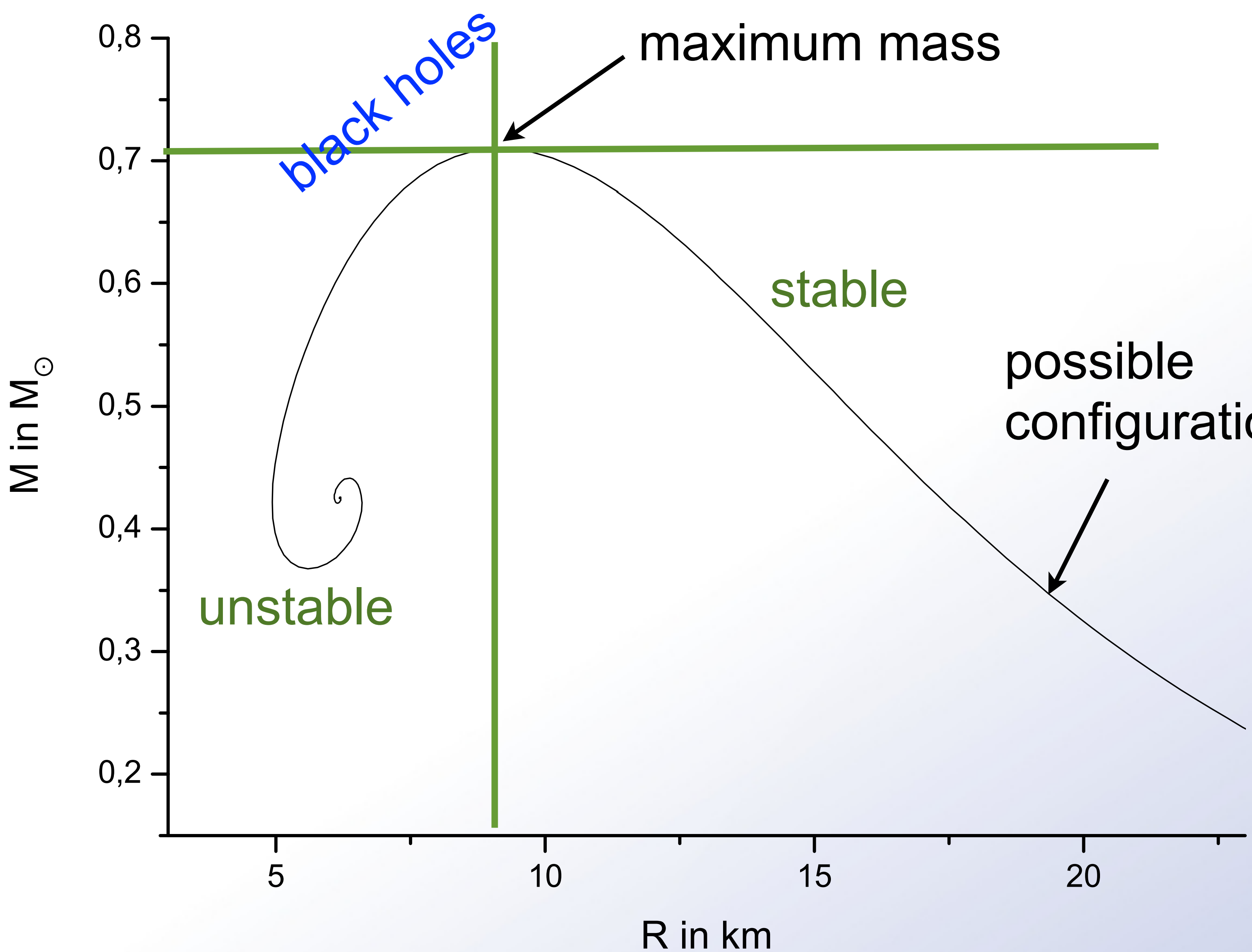
Hulse-Taylor Pulsar

- discovered 1974
- 21,000 light years distance
- M = 1.4411 ± 0.0007 M_{sun}
- Nobel price 1993, test of general relativity

Demorest Pulsar

- discovered 2006
- 4,000 light years distance
- M = 1.97 ± 0.04 M_{sun}
- 2nd heaviest known NS, heaviest: M = 2.01 ± 0.04 M_{sun}

The mass-radius relation of neutron stars

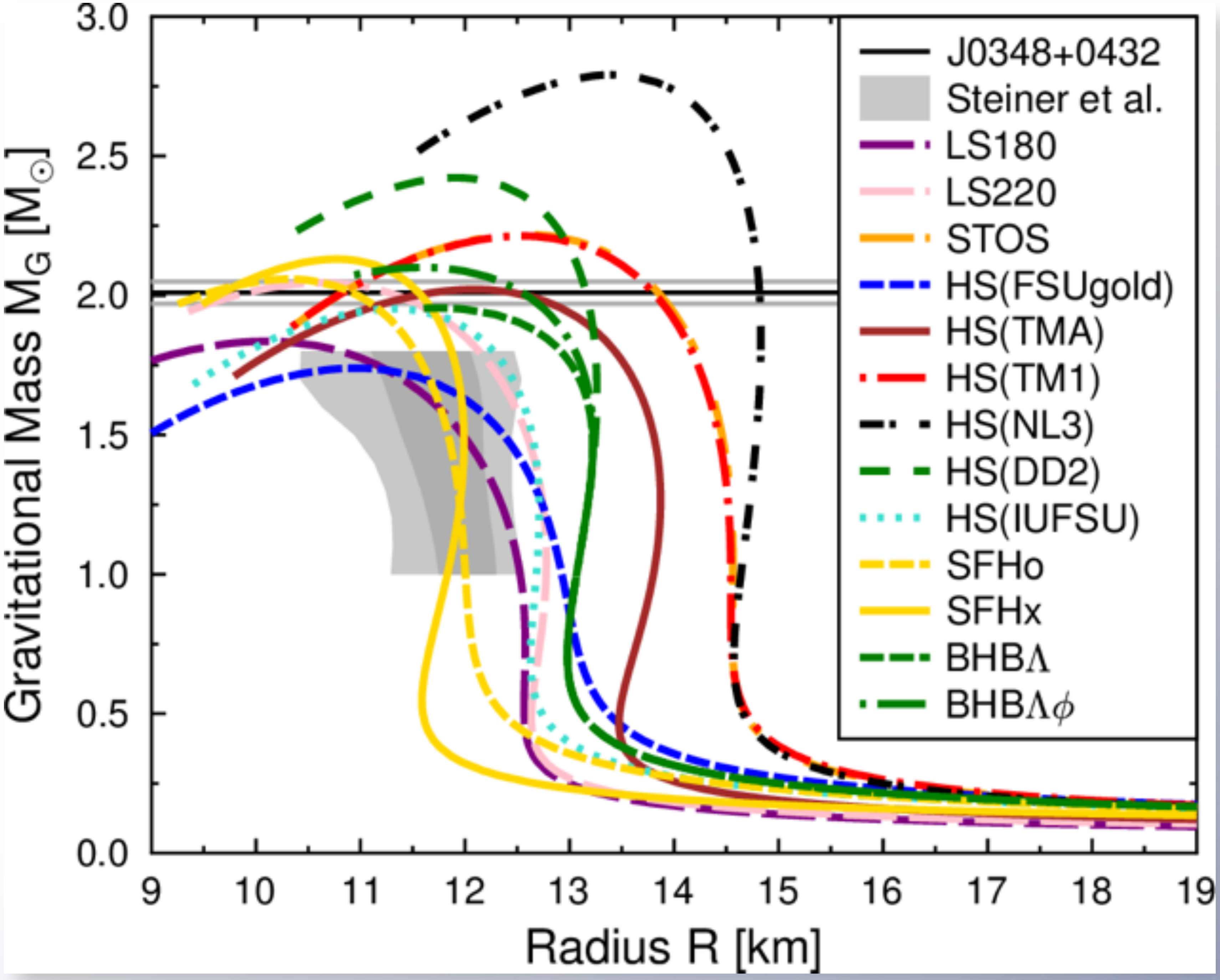


example: non-interacting neutron gas

- model for nuclear matter → equation of state (pressure vs. energy density)
- general relativity: Tolman-Oppenheimer-Volkoff equations for structure of neutron stars

masses and radii in hydrostatic equilibrium

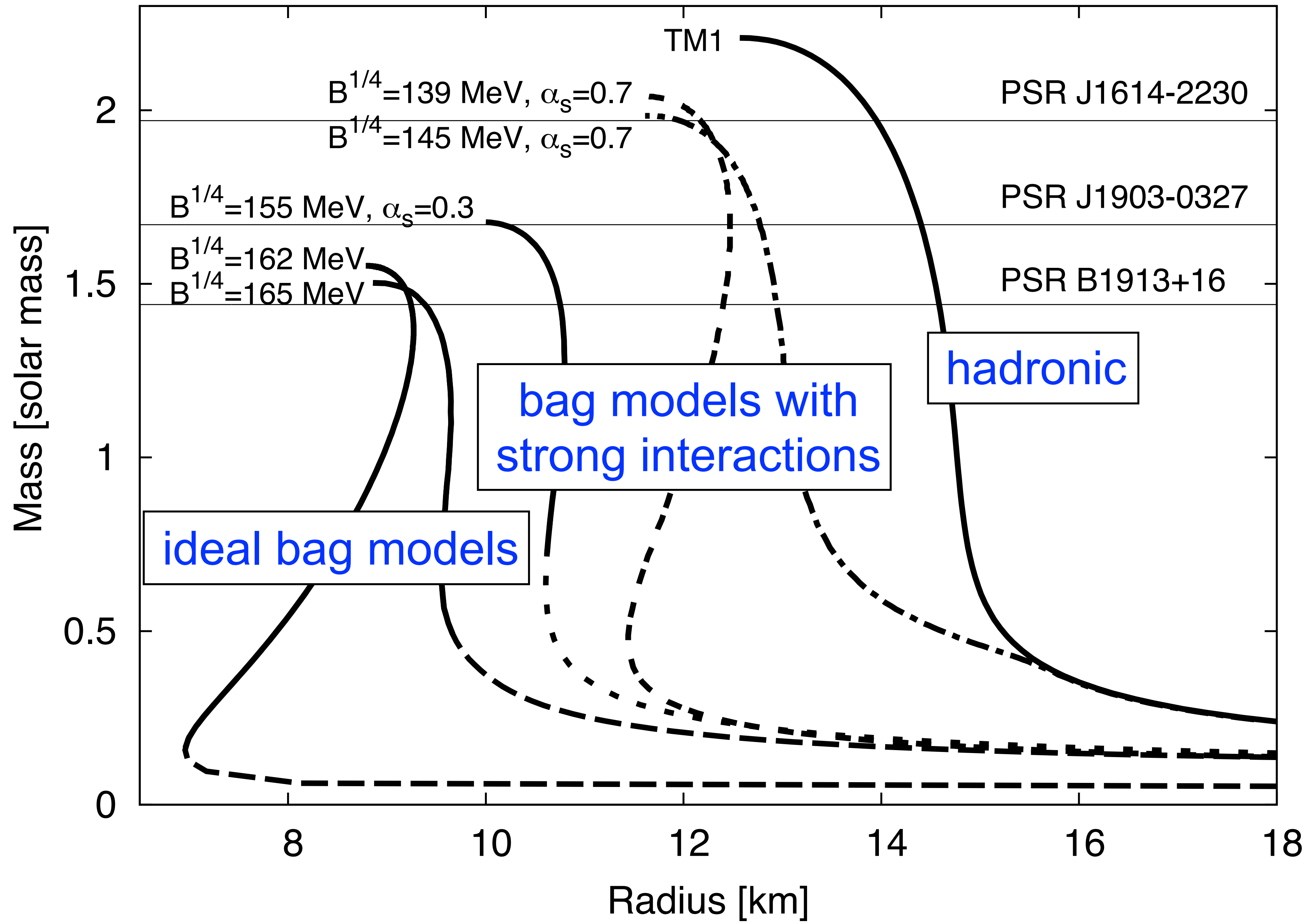
Mass-radius relations of hadronic EOS



- PSR J0348+0432: Antoniadis et al. Science 2013
- Steiner et al. ApJ 2010, Steiner et al. ApJ 2013: bayesian analysis of NS observations
- EOS shown here: „supernova“ EOS, only hadronic matter

[T. Fischer, MH, et al.; EPJA50 (2014)]
[S. Banik, MH, D. Bandyophadyay; APJS214 (2014)]

Mass-radius relations of hybrid EOS



[Sagert, et al. 2012]

- typical features: lower maximum mass, lower radii
- with interactions: quark matter behaves similarly as hadronic matter, „masquerade“

bag model:

ideal gas of quarks with confining bag pressure

Quark matter in neutron stars ruled out?

[Weissenborn et al., ApJL 740 (2011)]

QUARK MATTER IN MASSIVE COMPACT STARS

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ABSTRACT

The recent observation of the pulsar PSR J1614-2230 with a mass of $1.97 \pm 0.04\ M_{\odot}$ gives a strong constraint on the quark and nuclear matter equations of state (EoS). We explore the parameter ranges for a parameterized EoS for quark stars. We find that strange stars, made of absolutely stable strange quark matter, comply with the new constraint only if effects from the strong coupling constant and color-superconductivity are taken into account. Hybrid stars, compact stars with a quark matter core and a hadronic outer layer, can be as massive as $2\ M_{\odot}$, but only for a significantly limited range of parameters. We demonstrate that the appearance of quark matter in massive stars crucially depends on the stiffness of the nuclear matter EoS. We show that the masses of hybrid stars stay below the ones of hadronic and pure quark stars, due to the softening of the EoS at the quark–hadron phase transition.

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Nature **445**, E7-E8 (18 January 2007) | doi:10.1038/nature05582

Astrophysics: Quark matter in compact stars?

M. Alford[1], D. Blaschke[2,3], A. Drago[4,5], T. Klähn[3,6], G. Pagliara[4,5] and J. Schaffner-Bielich[7]

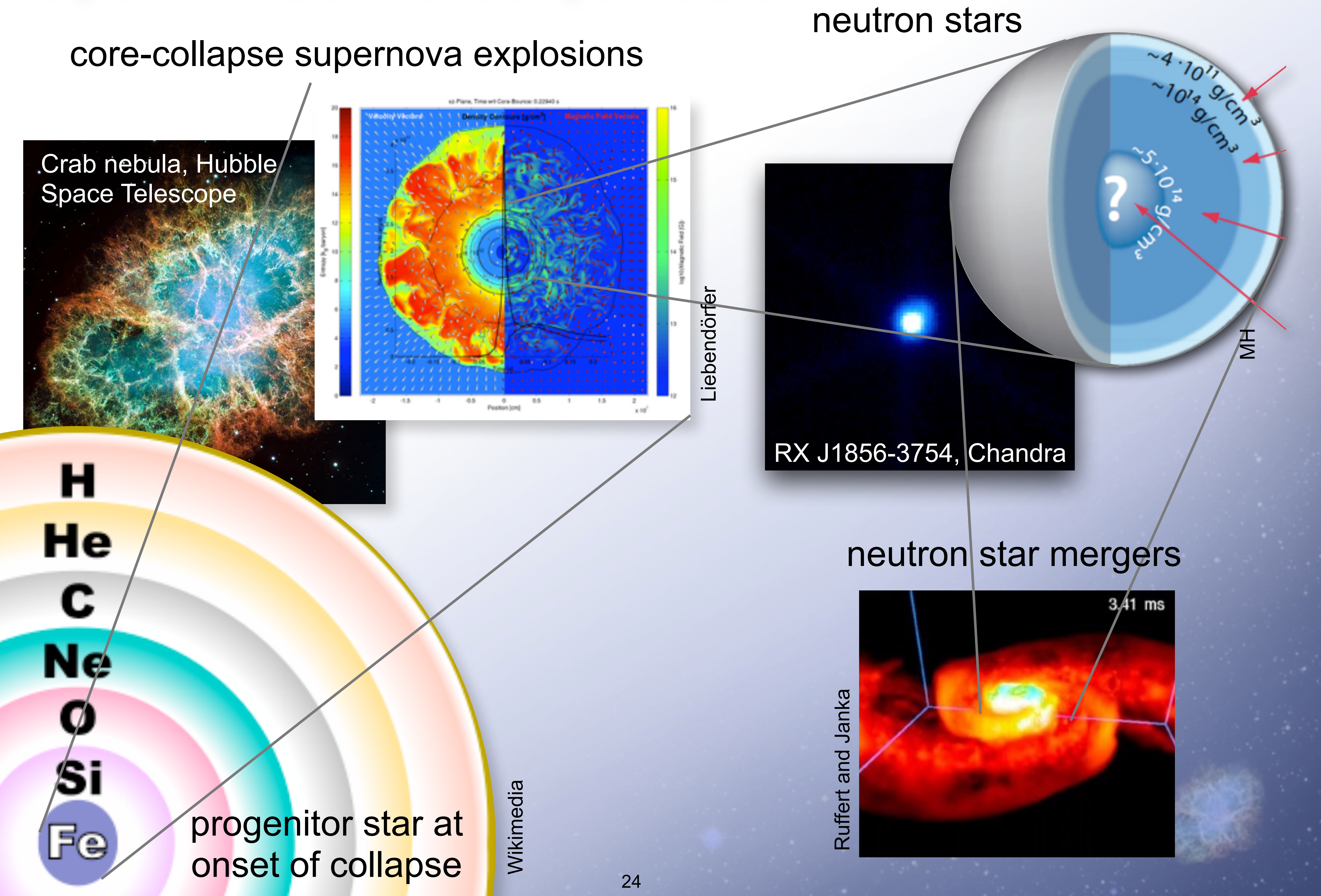
Arising from: F. Özel. *Nature* 441, 1115–1117 (2006); Özel replies Top

In a theoretical interpretation of observational data from the neutron star EXO 0748–676, Özel concludes that quark matter probably does not exist in the centre of neutron stars[1]. However, this conclusion is based on a limited set of possible equations of state for quark matter. Here we compare Özel's observational limits with predictions based on a more comprehensive set of proposed quark-matter equations of state from the literature, and conclude that the presence of quark matter in EXO 0748–676 is not ruled out.

no!

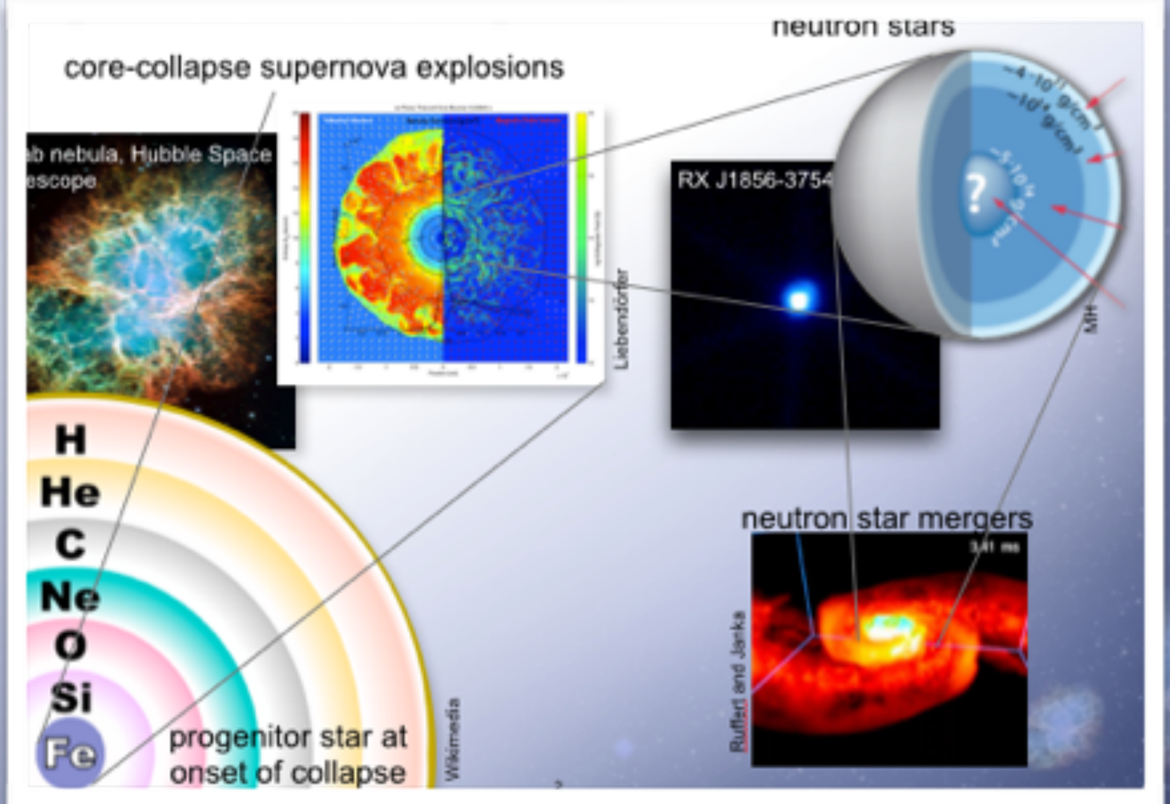
Supernova EOS

Equation of State for Compact Stars



„Supernova“ EOS – Introduction

- EOS provides the crucial nuclear physics input for astrophysical simulations: thermodynamic quantities and nuclear composition
- plenty of EOSs for cold neutron stars
- „supernova“ EOS: general-purpose EOS, at present only ~30 available
- challenge of the „supernova“ EOS:
  - finite temperature, $T = 0 - 100$ MeV
  - no weak equilibrium, fixed isospin, resp. charge fraction, $Y_Q = 0 - 0.6$
  - huge range in density, $\rho = 10^4 - 10^{15}$ g/cm^3
  - EOS in tabular form, ~1 million configurations (T, Y_Q, ρ)



$Y_Q = \Sigma n_i Q_i / n_B$

$n_B = \Sigma n_i B_i$

n_i: density of hadron/quark species i

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)
- neutrinos: all flavors
  - not always in equilibrium with matter
  - → not part of the EOS, but of (Boltzmann) transport

Comparison of conditions in NS, SN, and HIC

	neutron stars	supernovae	heavy ion collisions
dynamic timescales	(d - yrs)	ms	fm/c
equilibrium	full	weak eq. only partly	only strong eq.
temperatures	0	0 - 100 MeV	10 - 200 MeV
charge neutrality	yes	yes	no
asymmetry	high	moderate	low
highest densities	$< 9\ \rho_0$	$< 2\text{-}4\ \rho_0$	$< 4\text{-}5\ \rho_0$

weak equilibrium

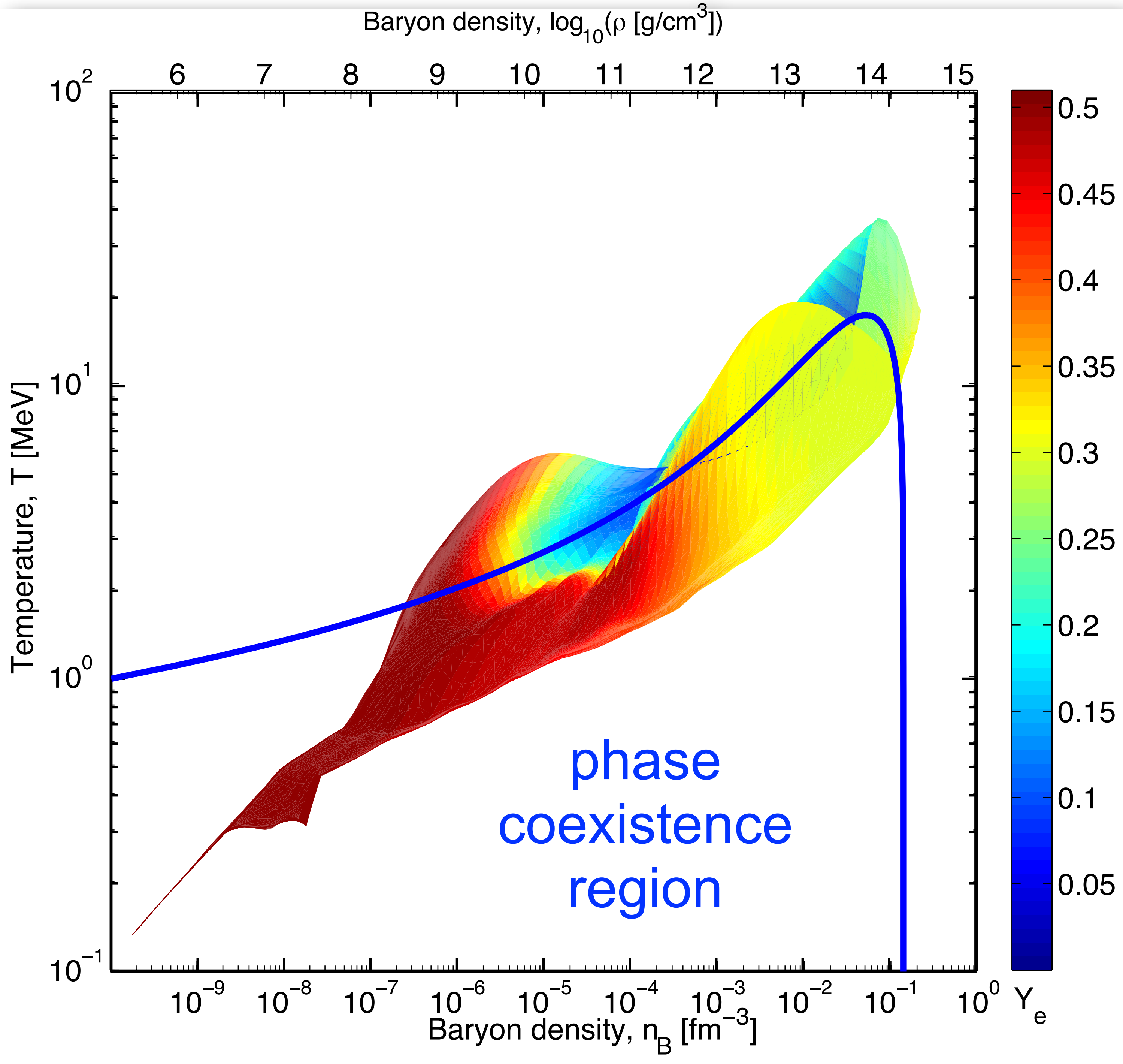
$\mu_i = B_i\mu_B + Q_i\mu_Q + L_i\mu_L$; $\mu_S=0$

charge neutrality:

$Y_Q = Y_e+Y_\mu \Leftrightarrow n_Q = n_e+n_\mu$

- matter in SN: no weak equilibrium, finite temperature
  → somewhere between cold neutron stars and heavy-ion collisions

State of matter in core-collapse supernovae I

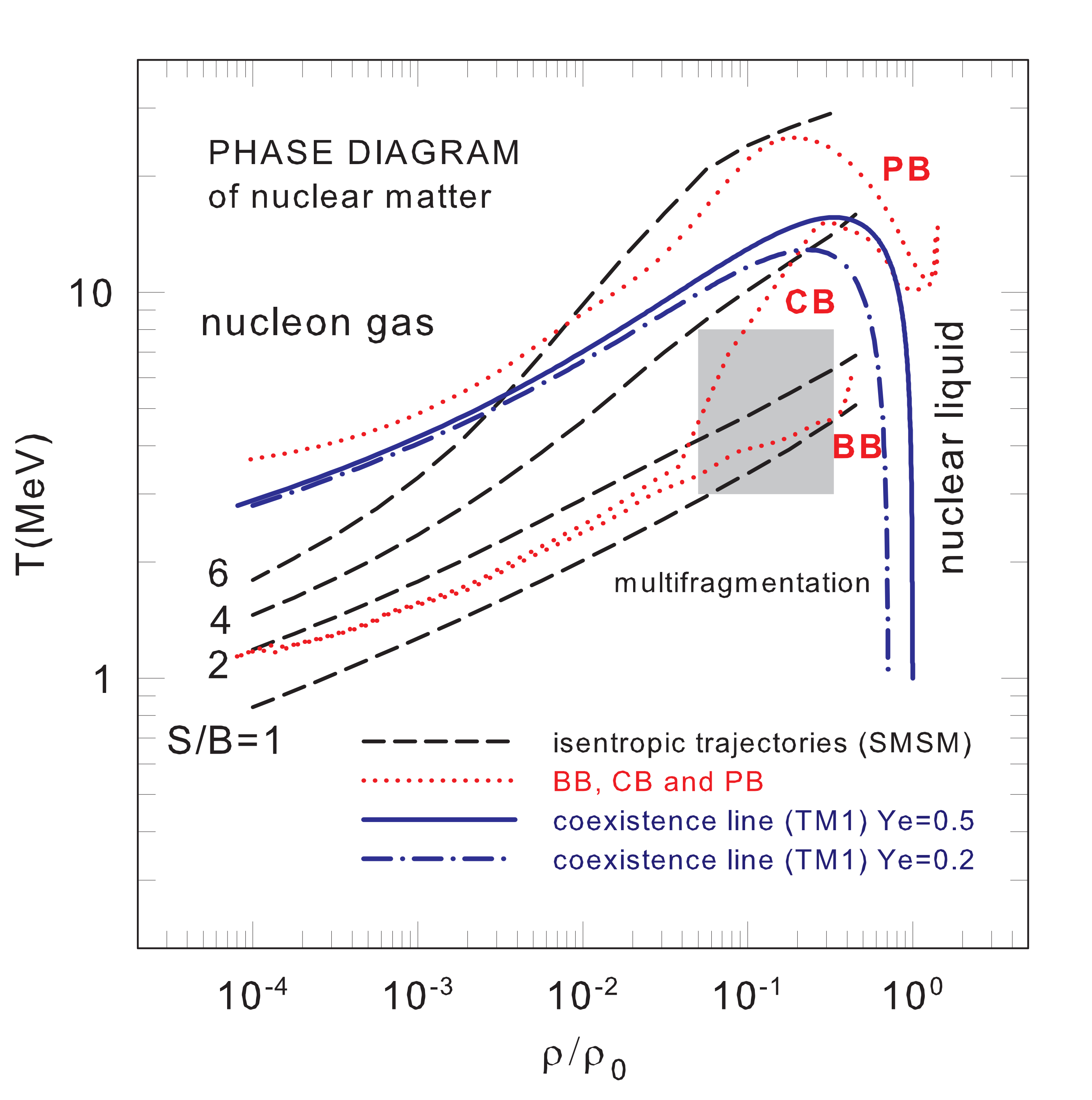


based on: *[Fischer et al., ApJS 2010]*

- without Coulomb, „bulk“: first order liquid-gas phase transition
- with finite size effects: → non-uniform nuclear matter, formation of nuclei

- ρ ~10^9 – 10^{12} g/cm³: crucial for supernova explosion mechanism

State of matter in core-collapse supernovae II

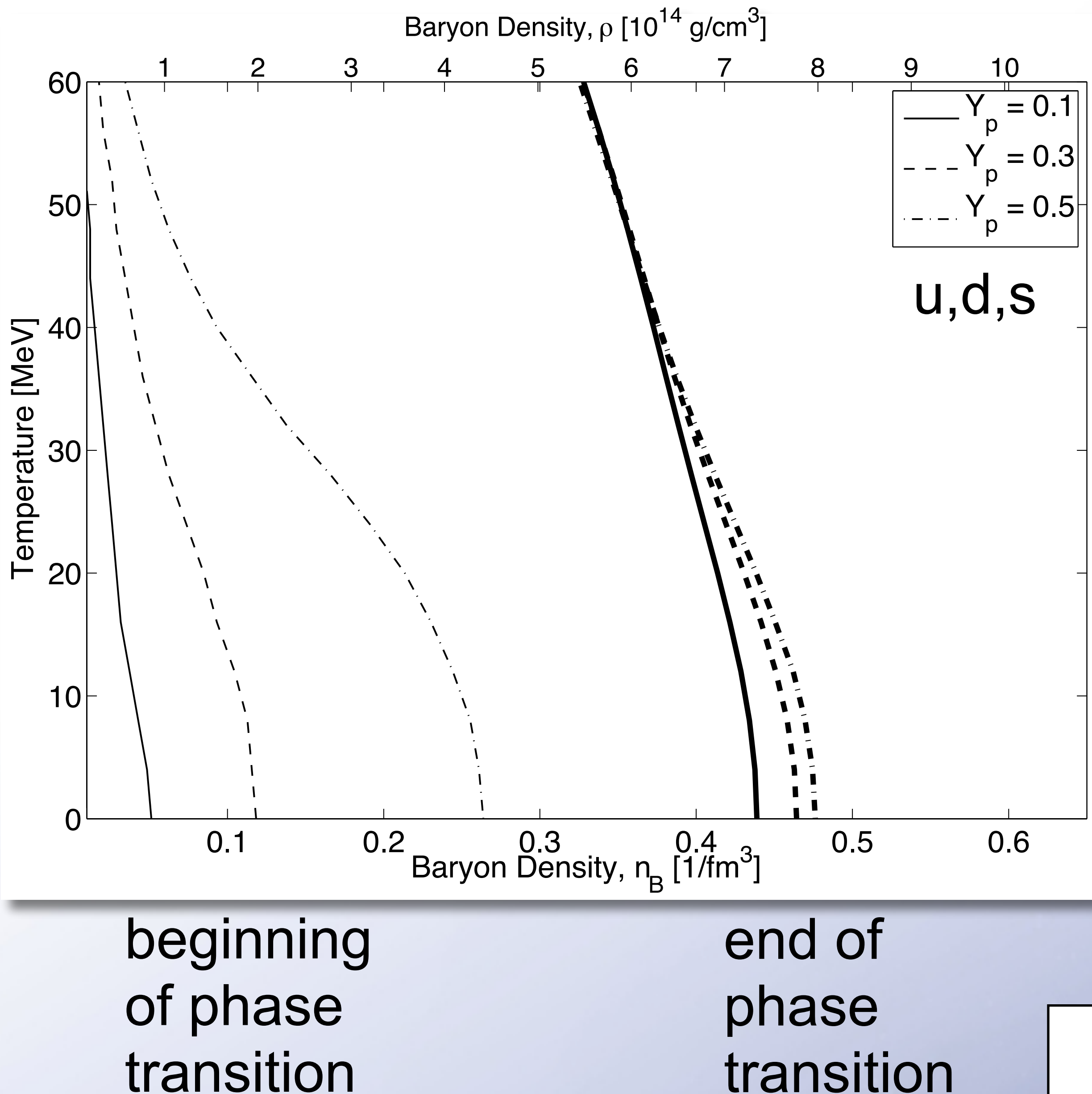


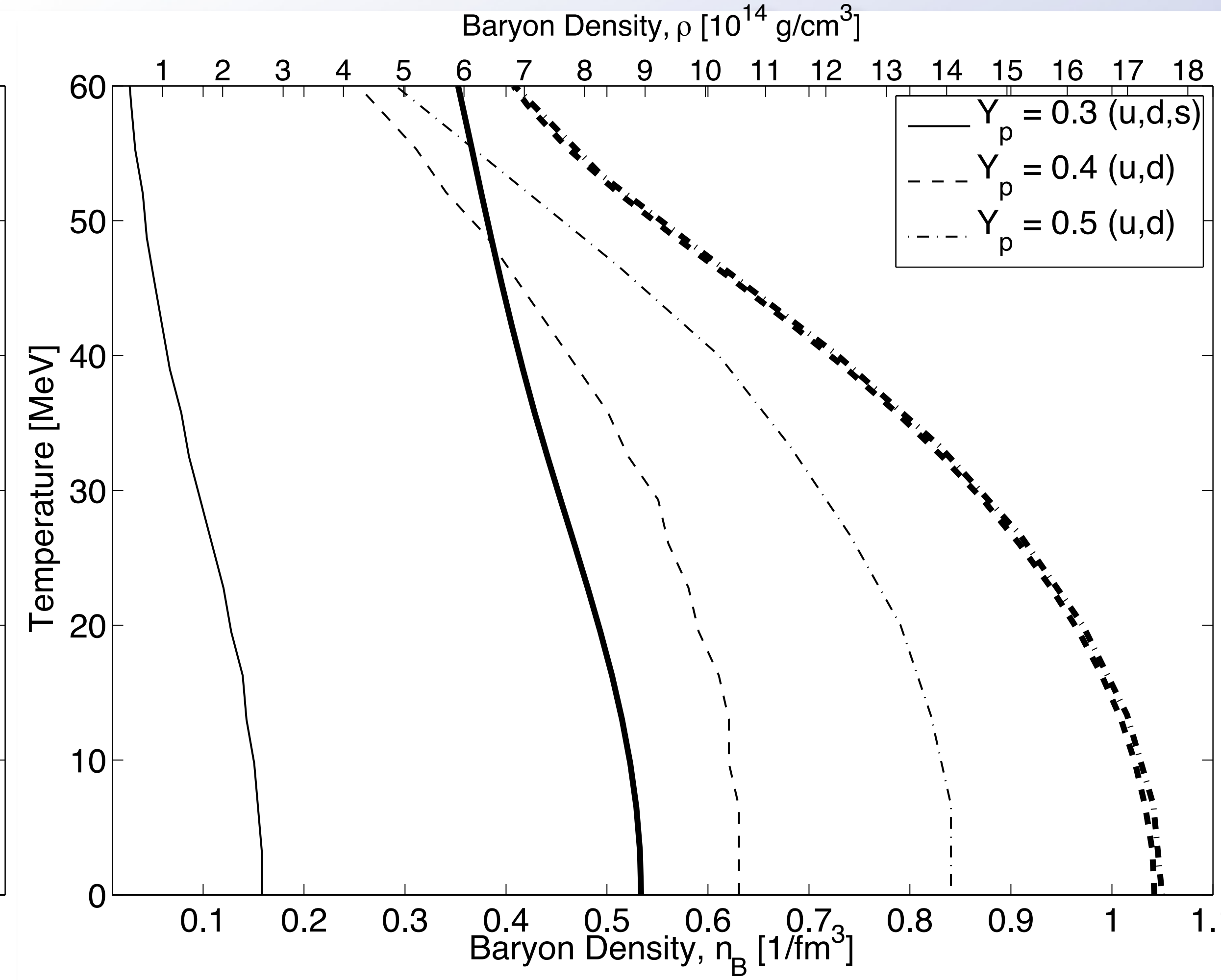
- multi-fragmentation reactions: heavy-ion collisions from several 10 to 100 MeV/A
- BB: before bounce
- CB: core bounce
- PB: post bounce

core-collapse supernova explosions induced by the QCD phase transition

Quark-hadron hybrid EOS for supernovae

- 2009/2011: Sagert, Pagliara, Schaffner-Bielich, MH
- simple bag model for quark matter
- STOS EOS from Shen et al. for hadronic matter
- low phase transition density for supernova matter

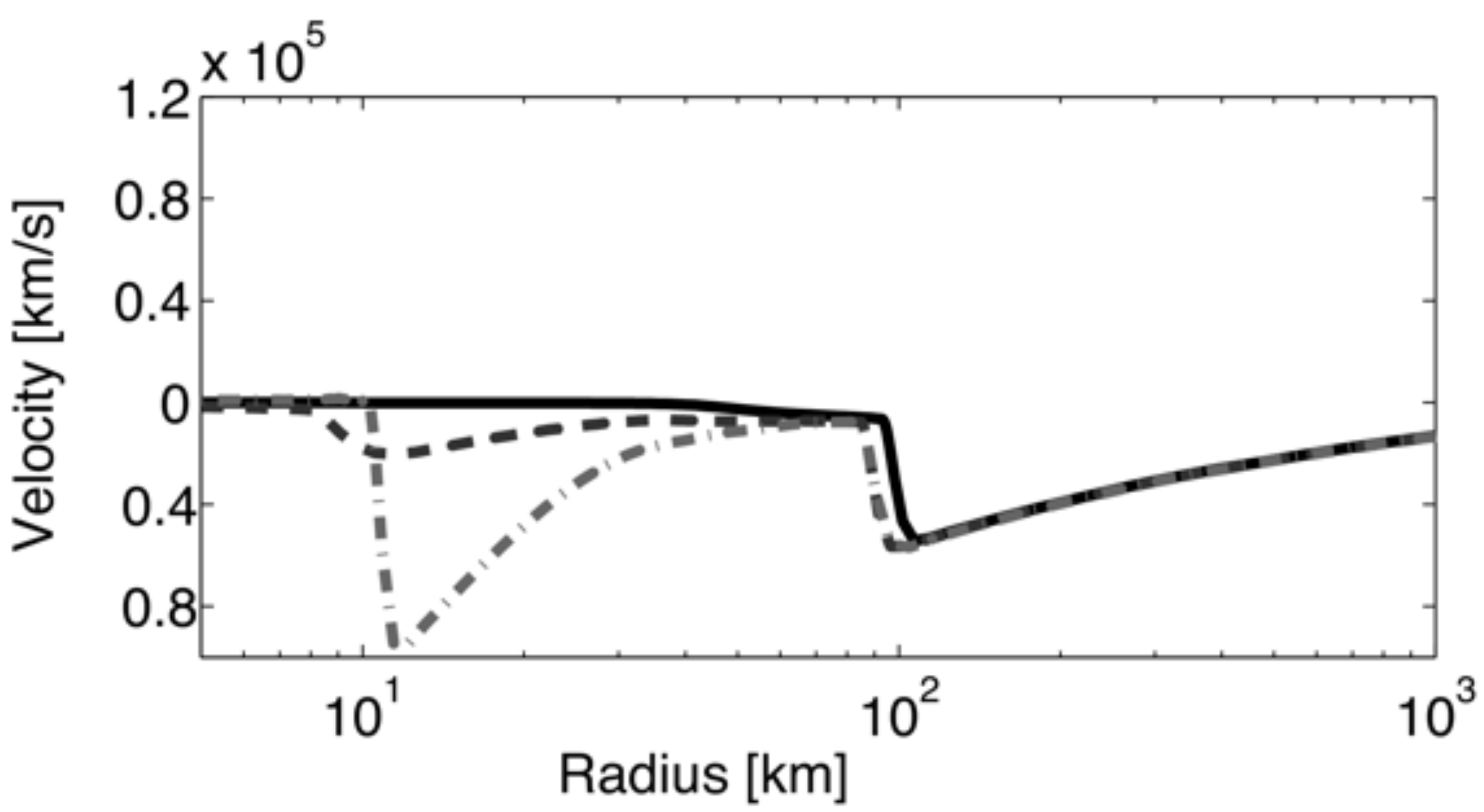




→ not in conflict with heavy-ion data

Implications for supernovae: explosions!

[Sagert, et al. PRL 2009]



t_{pb}= 240.5 ms

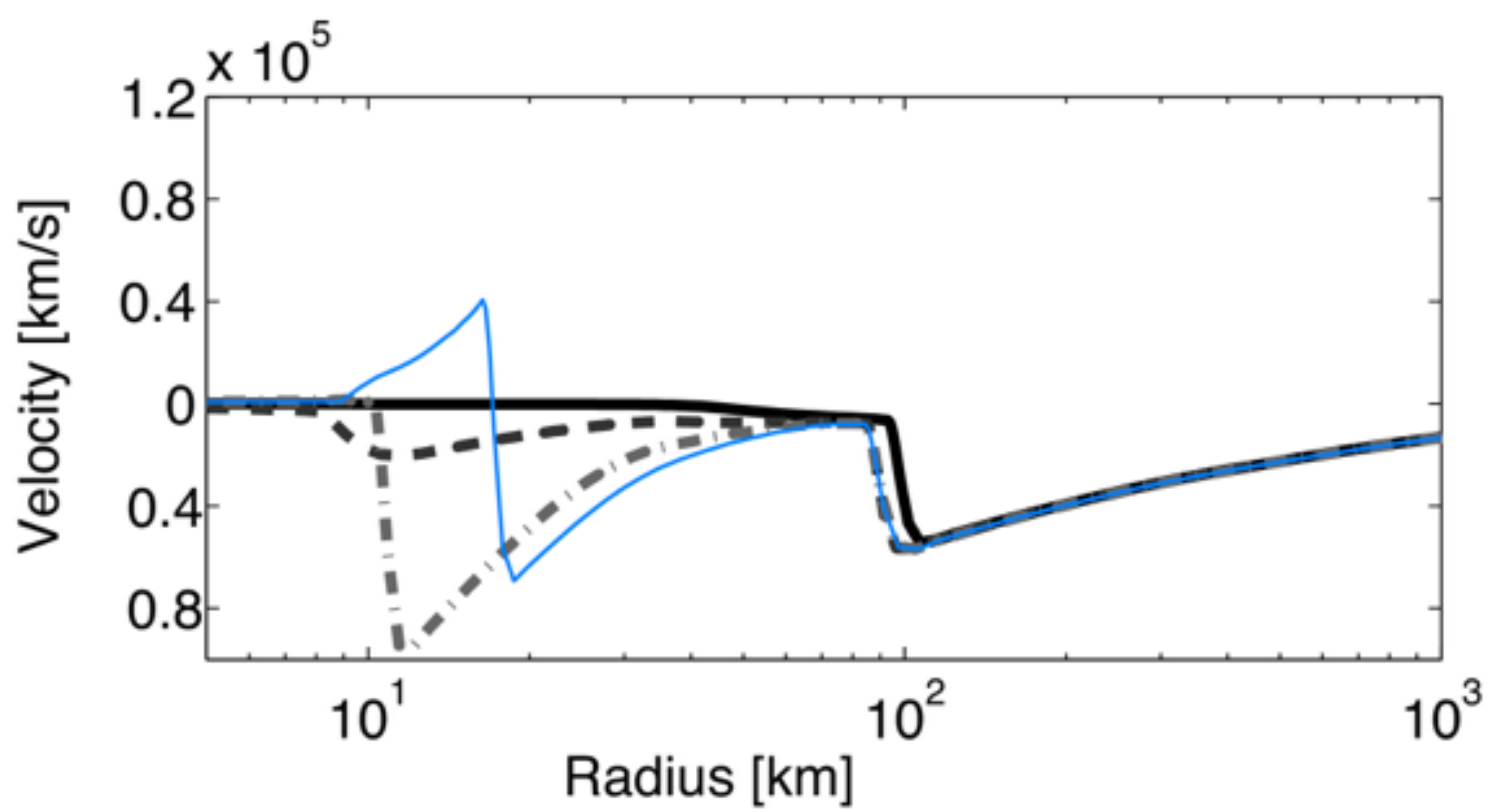
t_{pb}= 255.2 ms

t_{pb}= 255.4 ms

- phase transition induces collapse of the proto-neutron star
- once pure quark matter is reached, collapse halts
- formation of an accretion shock

Implications for supernovae: explosions!

[Sagert, et al. PRL 2009]



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t_{pb}= 255.2 ms

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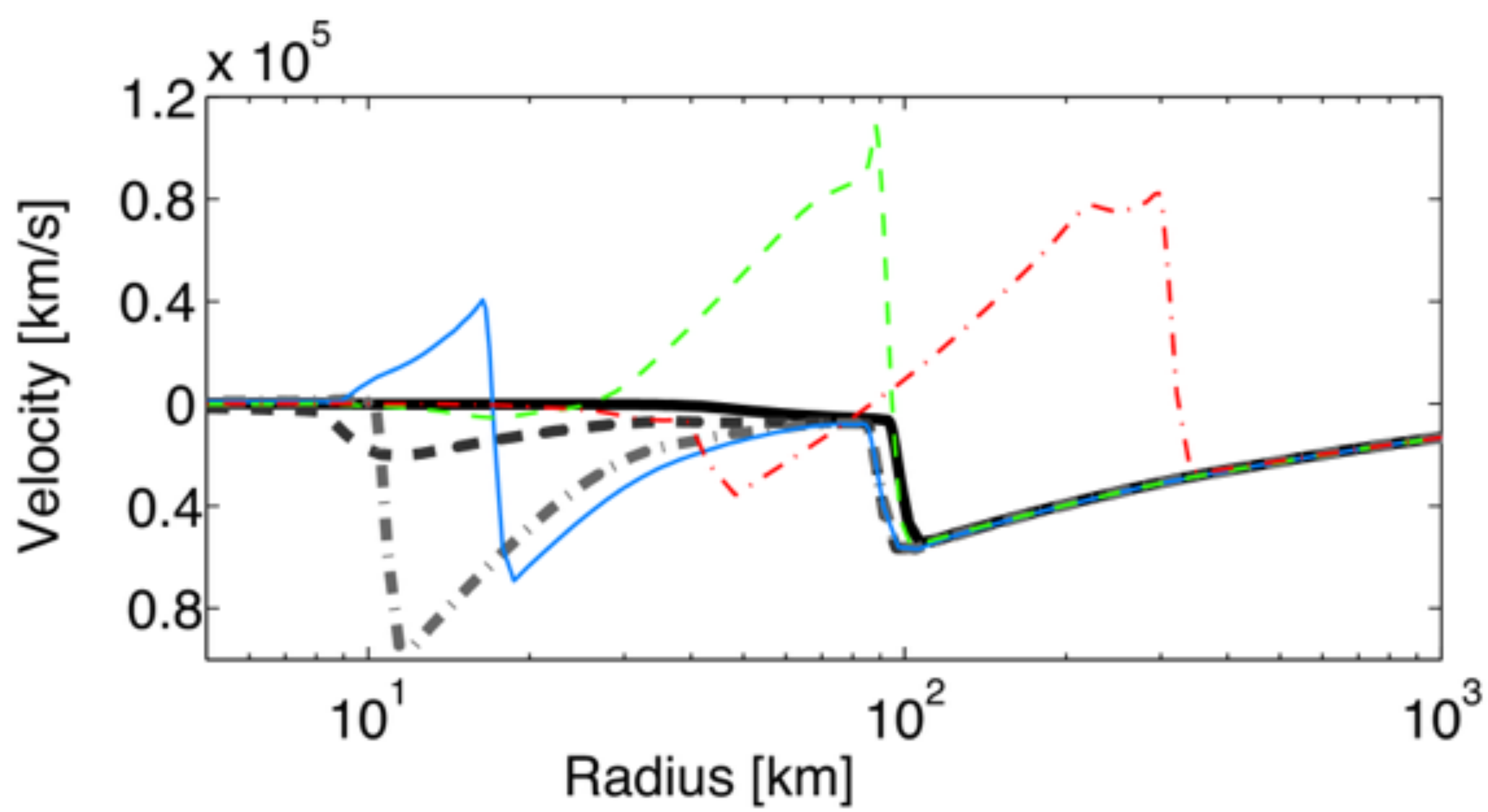
- phase transition induces collapse of the proto-neutron star
- once pure quark matter is reached, collapse halts
- formation of a second shock
- higher temperatures, increased neutrino heating → positive velocities

Implications for supernovae: explosions!

[Sagert, et al. PRL 2009]



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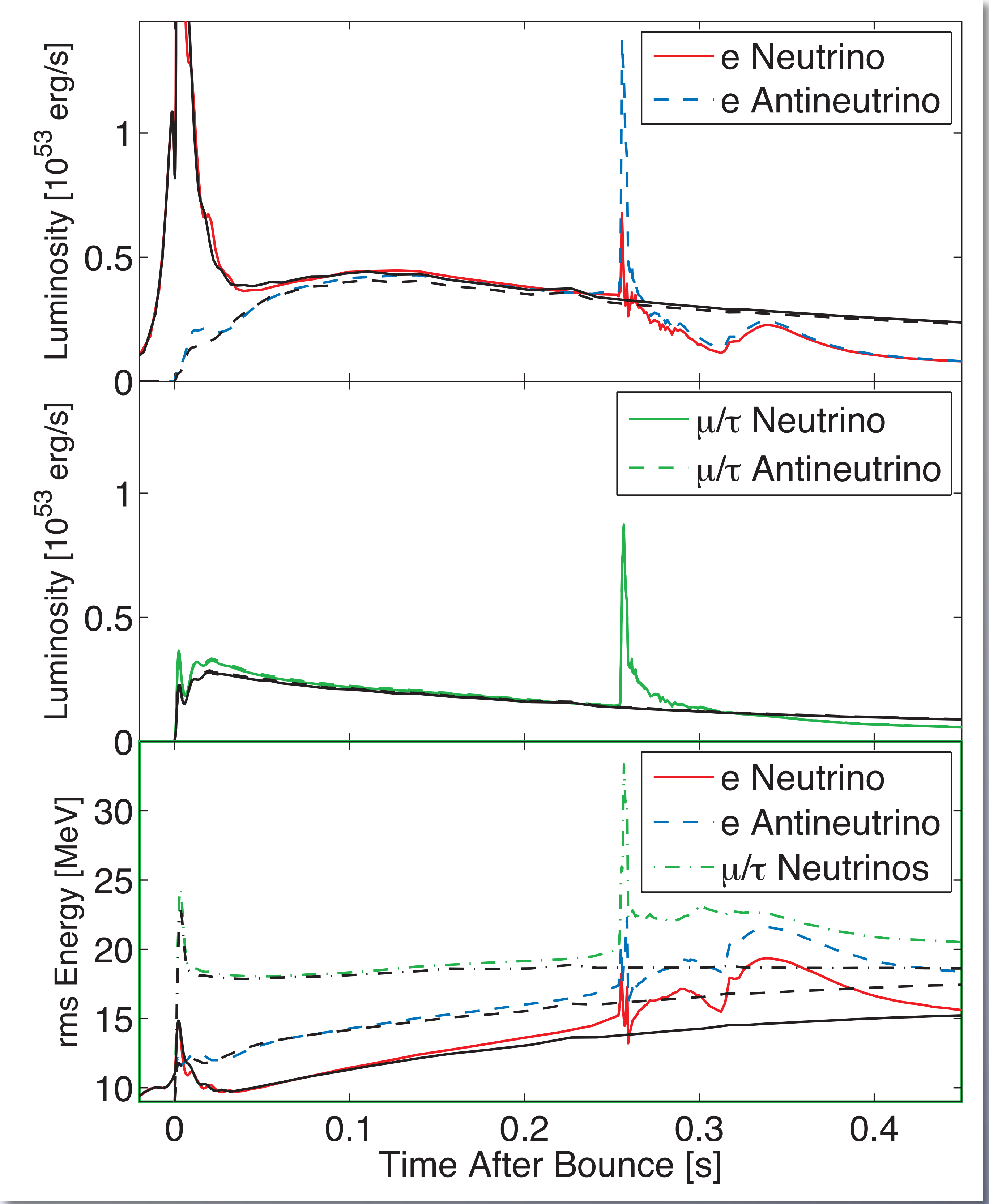
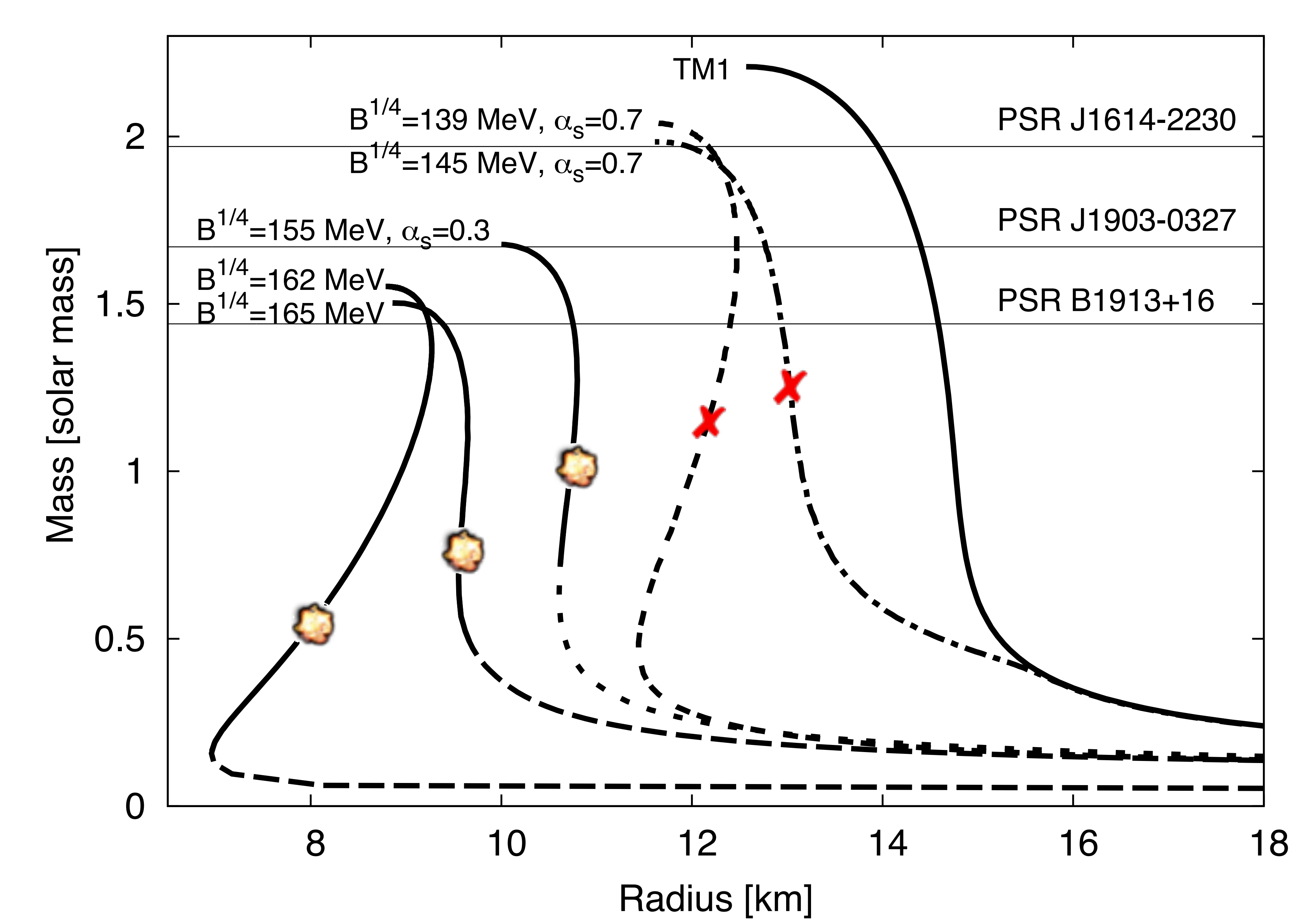
- phase transition induces collapse of the proto-neutron star
- once pure quark matter is reached, collapse halts
- formation of a second shock
- higher temperatures, increased neutrino heating → positive velocities
- shock merges with standing accretion shock
- explosion

Neutrino signal



- colored lines with phase transition, black without
- second neutrino burst due to quark matter
- peak and height determine density and strength of the phase transition
- measurable with present day neutrino detectors

Mass-radius relation of tested hybrid EOS

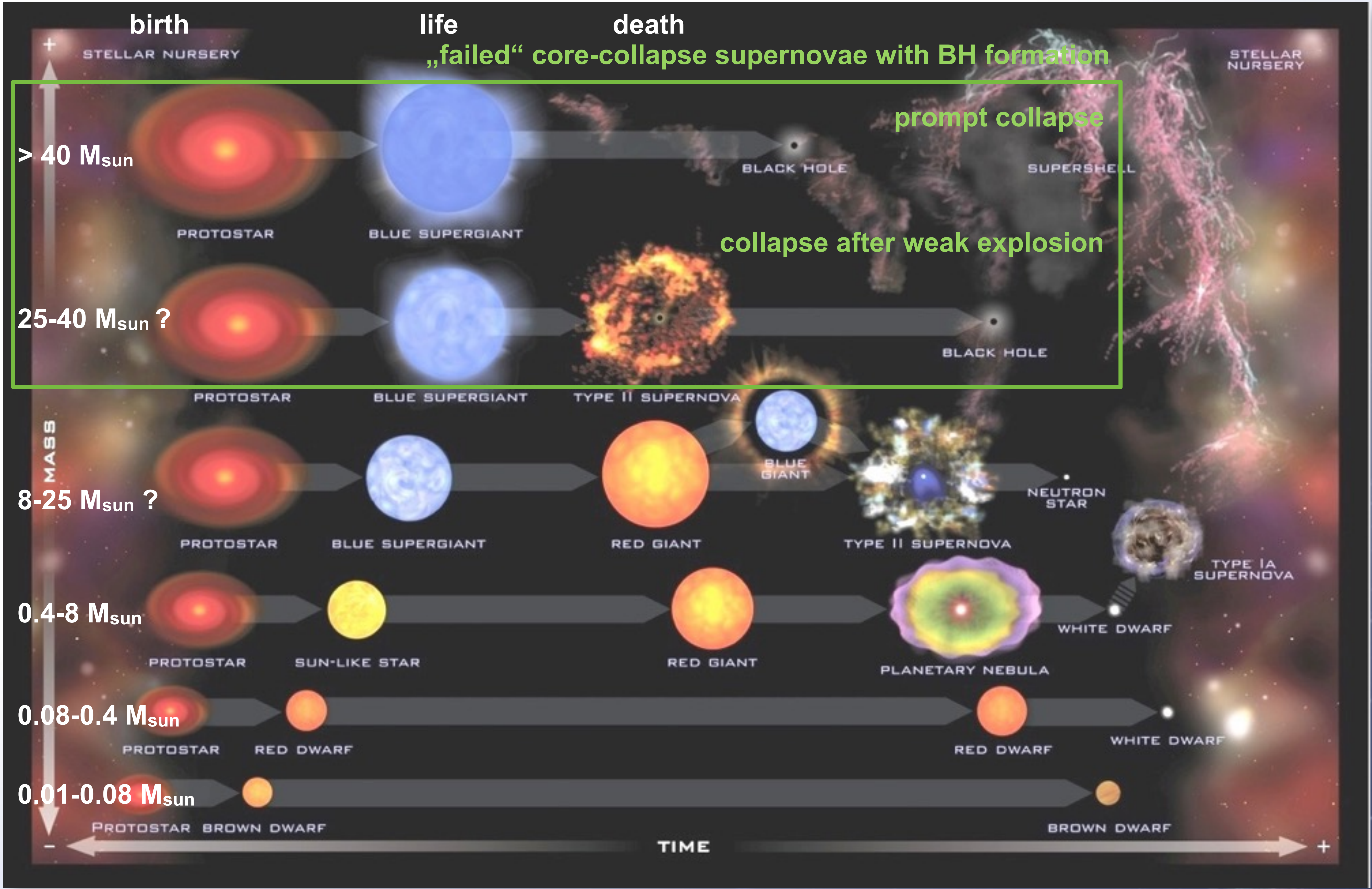


explosions in spherical symmetry (T. Fischer et al. ApJS 2011)

- no explosions for sufficiently high maximum mass
- weak phase transition
- quark matter behaves similarly as hadronic matter „masquerade“
- cf.: Fischer, Blaschke, et al. 2012: PNJL hybrid EOS
- only few models tested, mechanism still possible for others?

failed supernova with black hole formation

Stellar evolution



Supernova simulations – signal from black hole formation

MH, T. Fischer, J. Schaffner-Bielich, M. Liebendörfer; ApJ (2012)

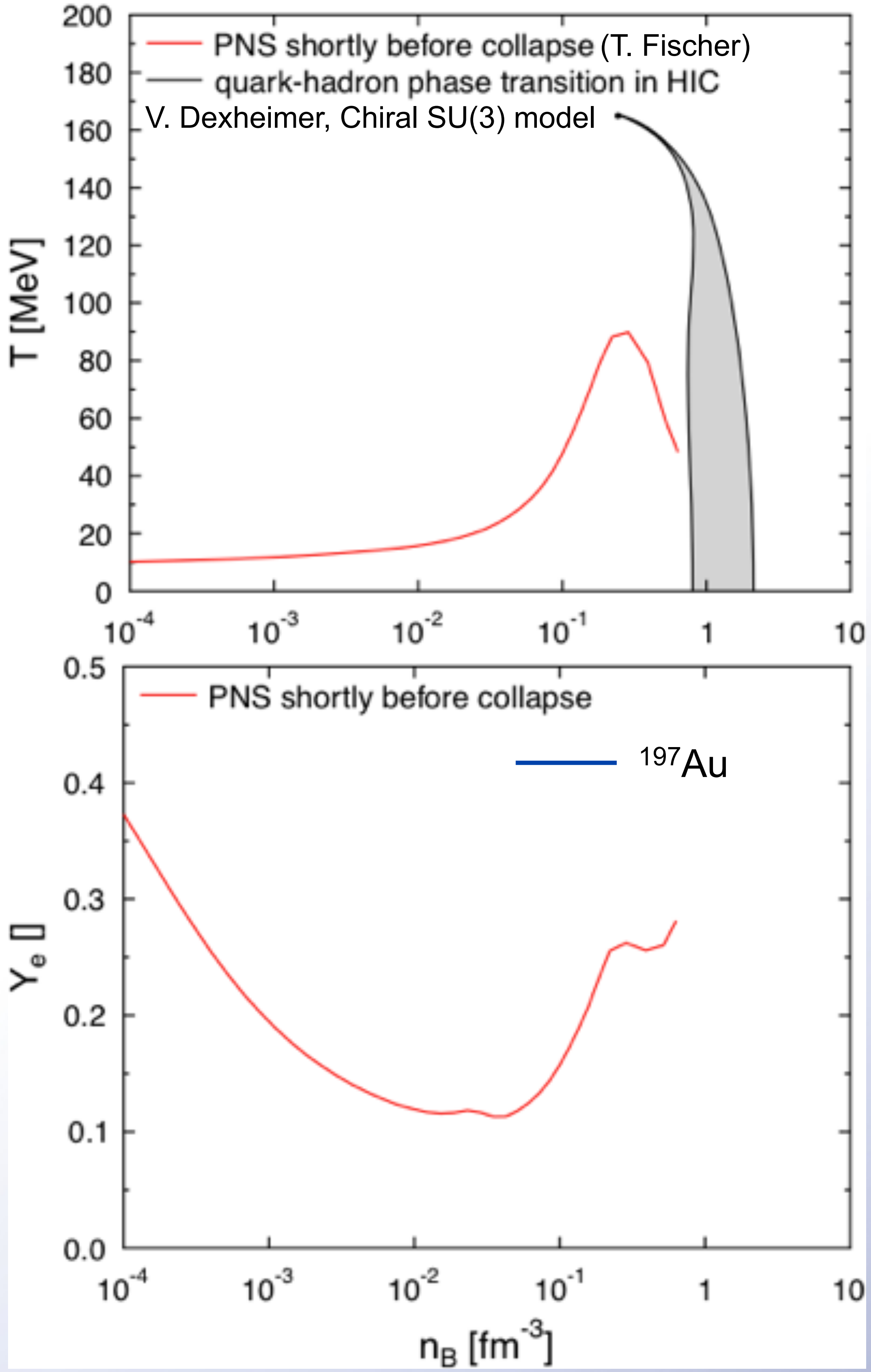
A. Steiner, MH, T. Fischer; ApJ

- simulations by Tobias Fischer, GSI/TU Darmstadt
  - general relativistic radiation hydrodynamics in spherical symmetry
  - three flavor Boltzmann neutrino transport

- 40 M_{sun} progenitor of Woosley & Weaver ApJS 101 (1995) (blue supergiant)
- “failed supernova“: core-collapse to stellar black hole

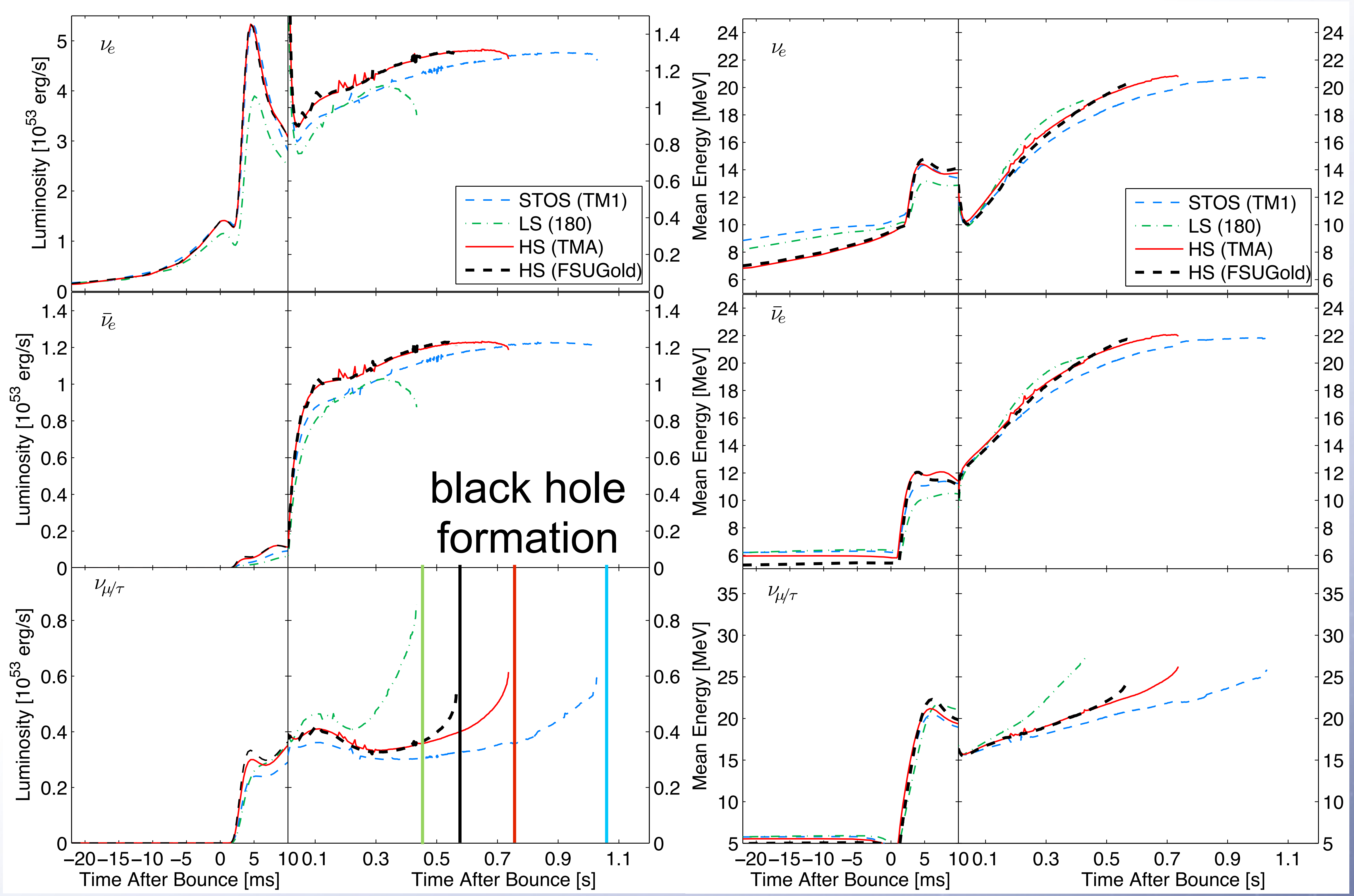
- neutrinos are emitted from the hot neutron star
- after BH formation: neutrino signal ceases

State of matter before black hole formation in a failed supernova



taken from a talk of J. Cleymans

Neutrino signal — different hadronic EOS

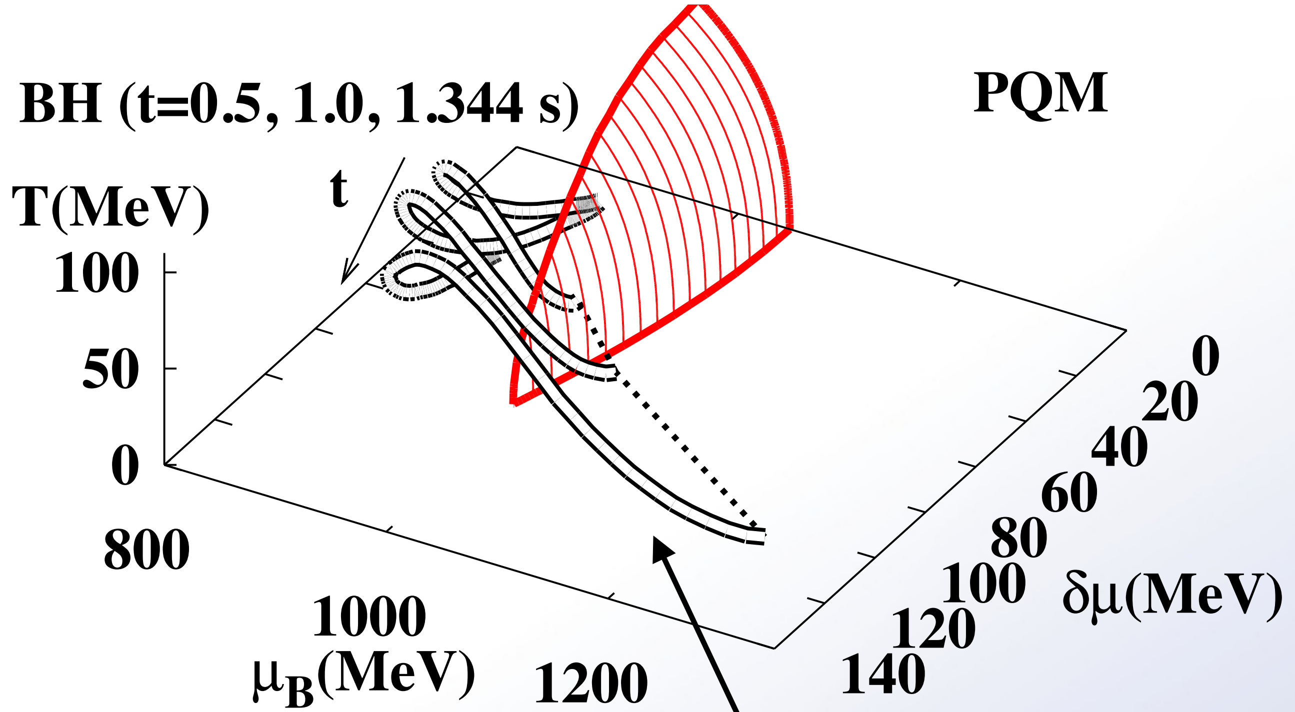


- μ/τ-neutrinos most sensitive to EOS because emitted from deeper layers

Reaching the critical point

[Onishi et al., PLB (2011)]

- phase diagrams from chiral effective models, taking into finite isospin chemical potential

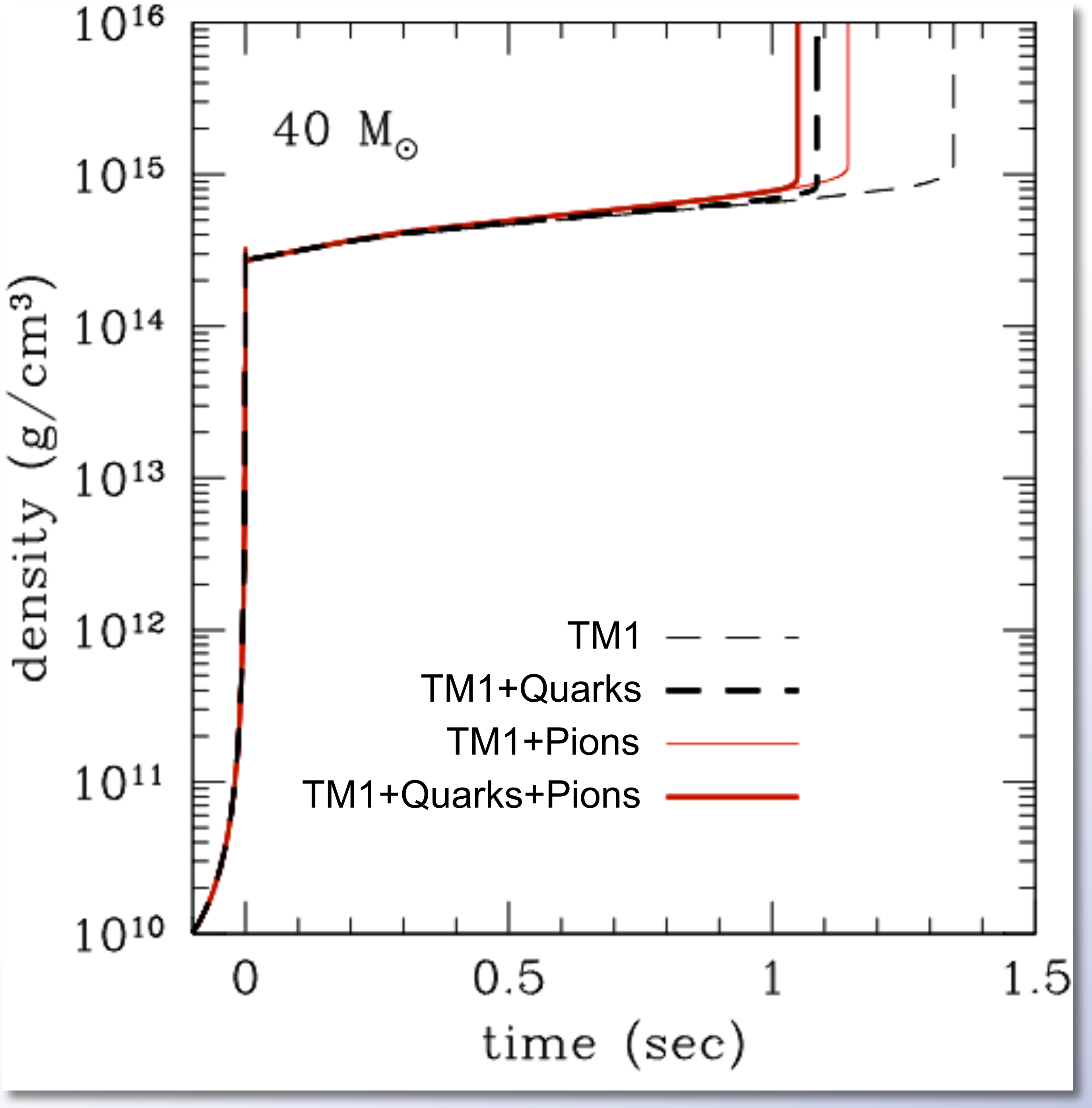


trajectories from supernova simulation

- 1st order PT, critical point, and/or crossover can be reached! „critical point sweep"

Effect of pions and/or quarks

[Nakazato et al. ApJ 721 (2010)]



- simple bag model, i.e., no critical point
- quarks reduce maximum mass and thus accelerate the collapse

Conclusions

- supernova matter: somewhere between matter in neutron stars and heavy-ion collisions, differences can be relevant
- quark matter in neutron stars and supernovae can lead to interesting phenomenology
- an astrophysical „smoking gun“ for quark matter has not been seen (yet)
- astrophysical observations allow to constrain the low temperature/high asymmetry part of the QCD phase diagram