

Quarks and Compact Stars

Jürgen Schaffner-Bielich

Institute for Theoretical Physics and
Heidelberg Graduate School for Fundamental Physics



RUPRECHT-KARLS-
UNIVERSITÄT
HEIDELBERG

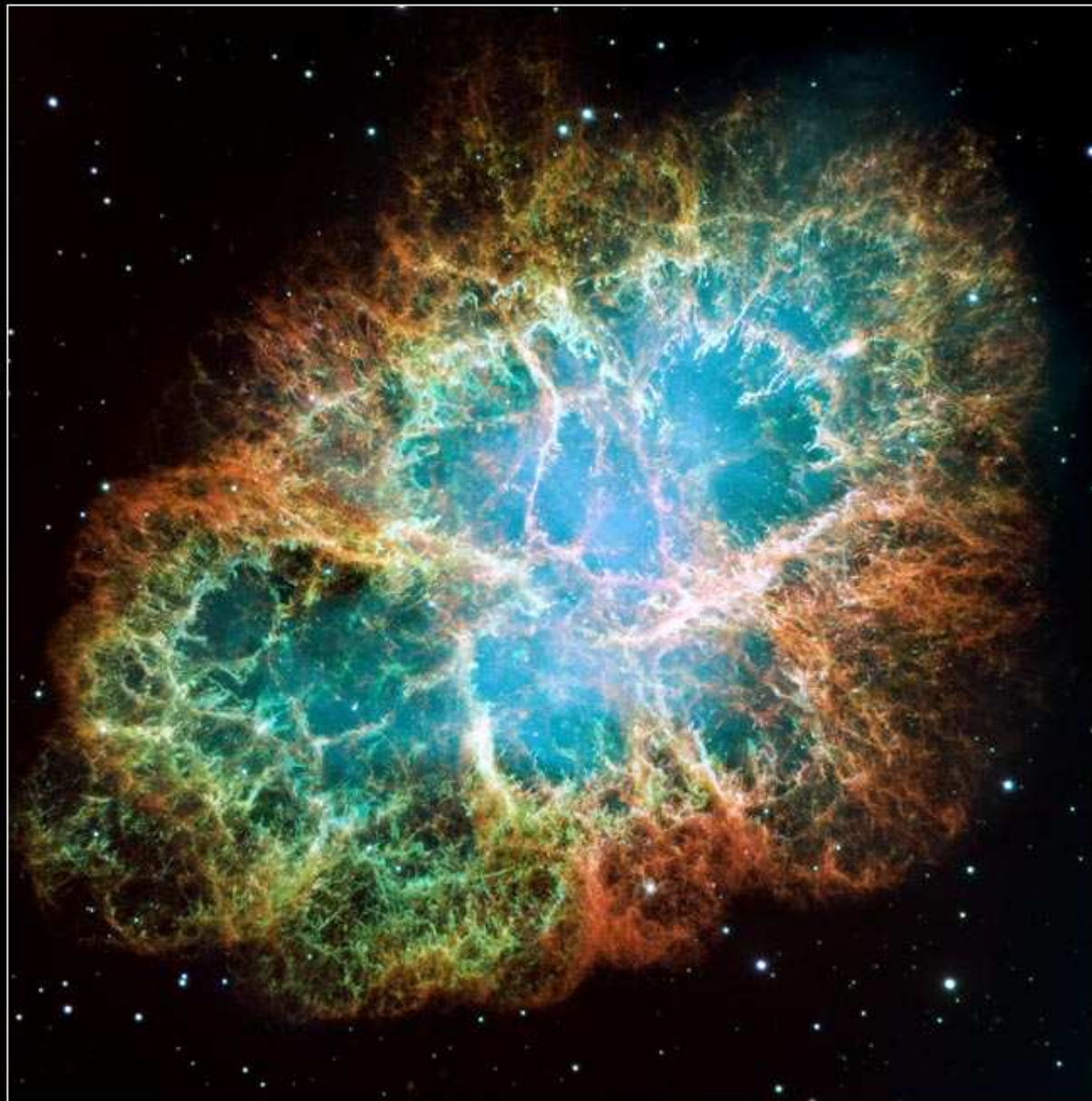


Landessternwarte
Heidelberg, 12.01.2009

Neutron Stars

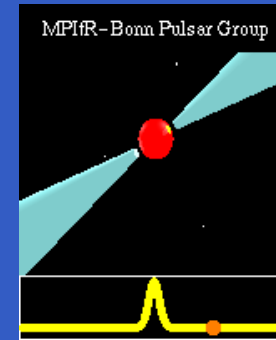
Crab Nebula ■ M1

HST ■ WFPC2



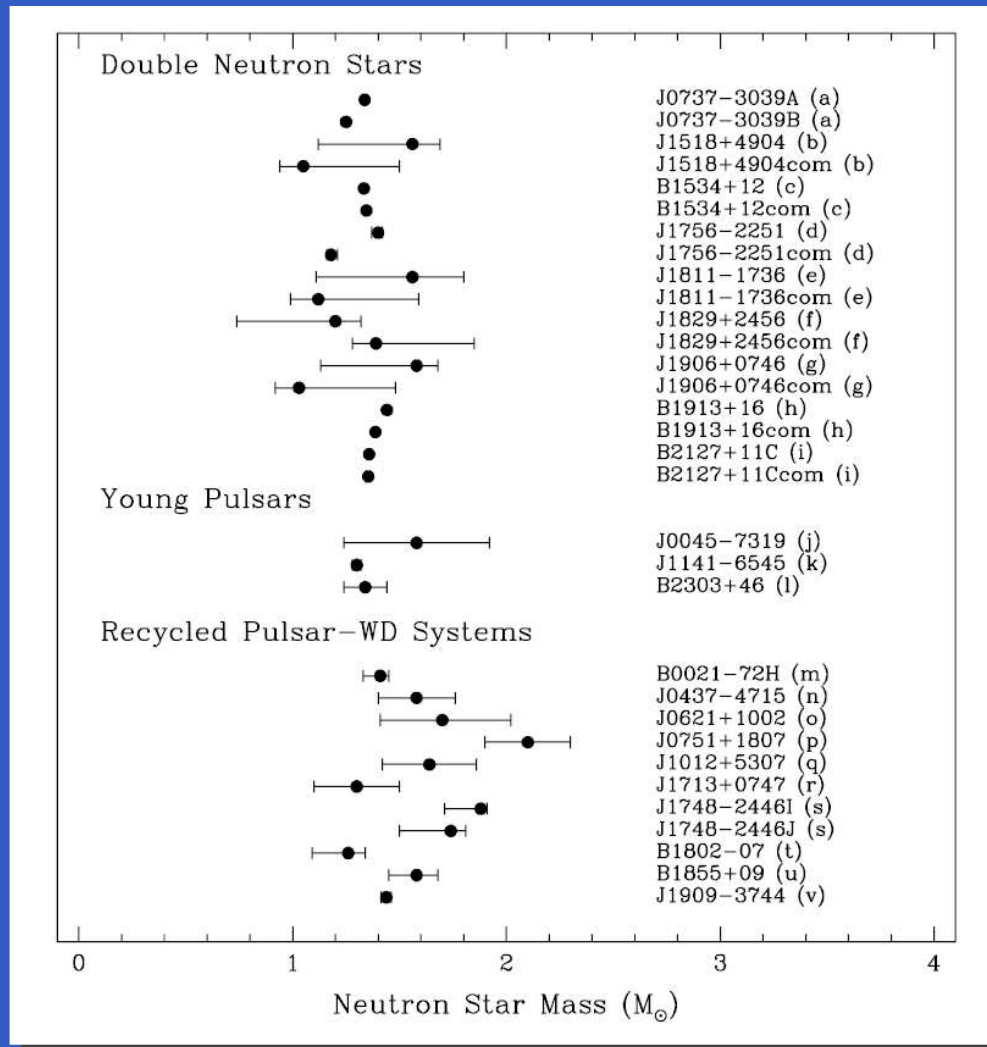
NASA, ESA, and J. Hester (Arizona State University)

STScI-PRC05-37



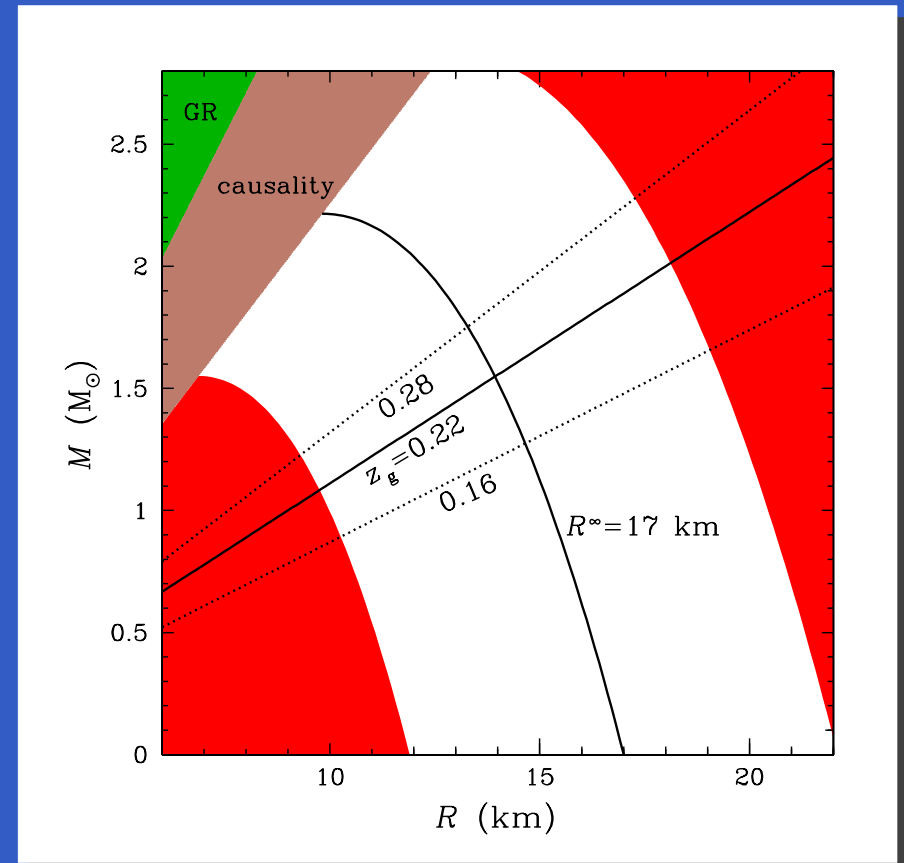
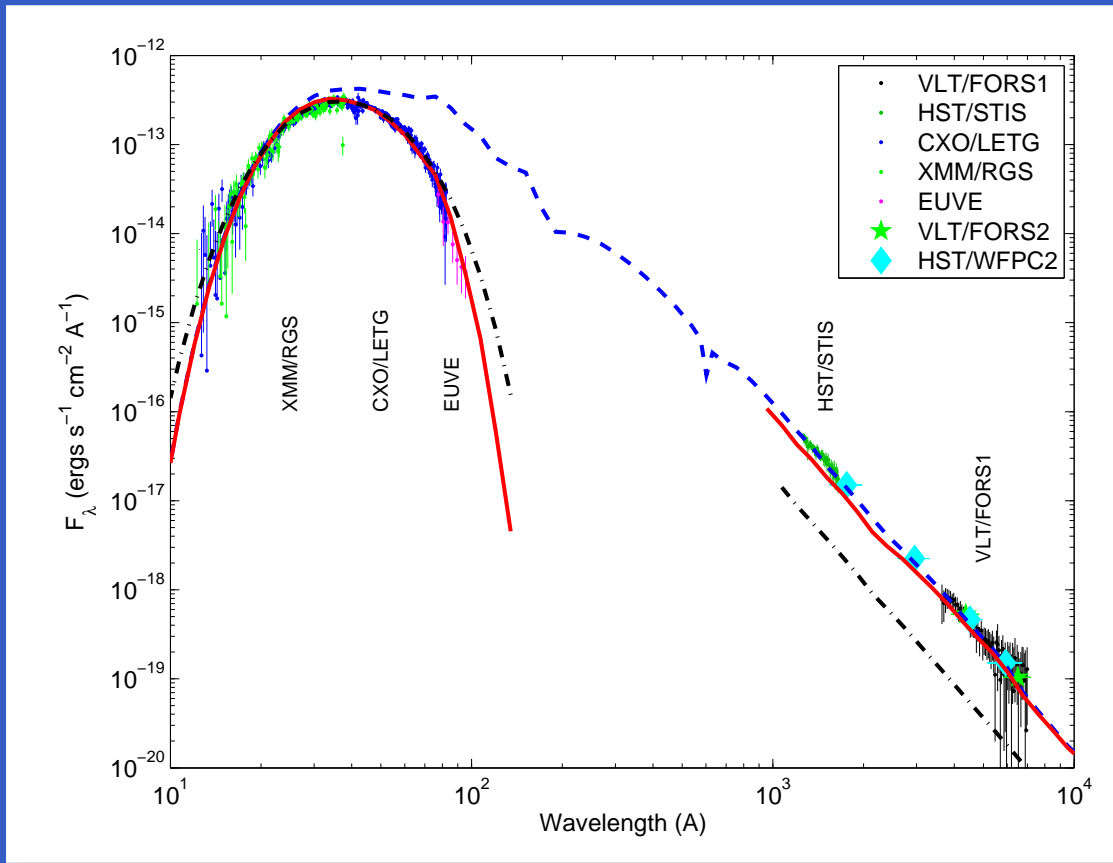
- produced in core collapse supernova explosions
- compact, massive objects: radius ≈ 10 km, mass $1 - 2M_{\odot}$
- extreme densities, several times nuclear density: $n \gg n_0 = 3 \cdot 10^{14} \text{ g/cm}^3$
- in the middle of the crab nebula: a pulsar, a rotating neutron star!

Masses of Pulsars (Stairs, 2006)



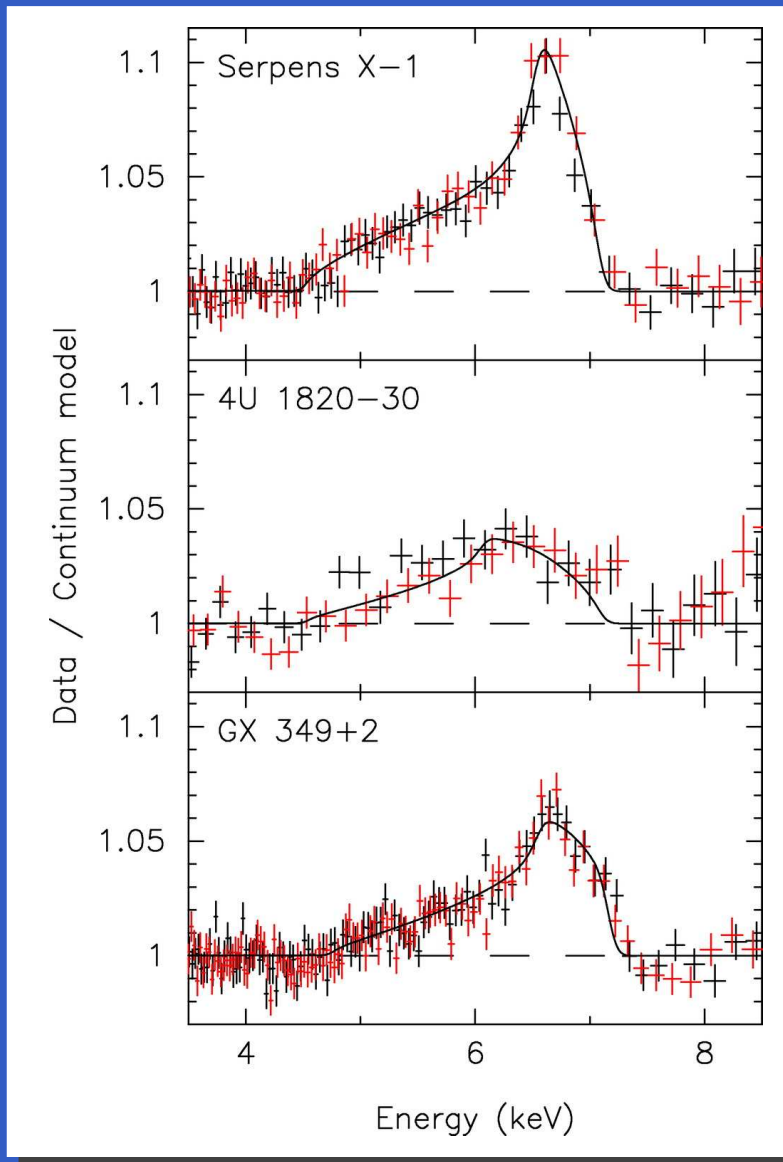
- more than 1600 pulsars known
- best determined mass:
 $M = (1.4414 \pm 0.0002)M_{\odot}$
for the Hulse-Taylor pulsar
(Weisberg and Taylor, 2004)
- smallest known mass:
 $M = (1.18 \pm 0.02)M_{\odot}$ for
pulsar J1756-2251 (Faulkner
et al., 2005)
- PSR J0751+1807 corrected
from $M = 2.1 \pm 0.2M_{\odot}$ to
 $M = 1.14 - 1.40M_{\odot}$ (Nice et
al. 2008)

RXJ 1856: Neutron Star or Quark Star? (Trümper et al. (2003), Ho et al. (2003))

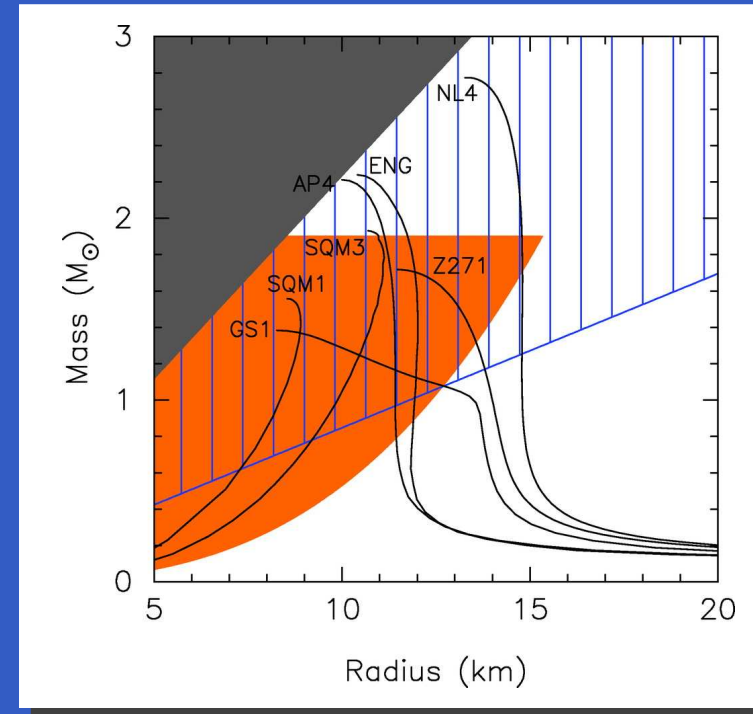


- two-temperature black-body fit (Trümper et al.) implies a lower limit for radiation radius: $R_\infty = R/\sqrt{1 - 2GM/R} \approx 17$ km (d/140 pc)
- thin magnetized H-atmosphere on condensed iron core (Ho et al.): redshift $z_g \approx 0.22$: $R \approx 14$ km and $M \approx 1.55M_\odot$
- largest uncertainty in distance d

Broadened Iron Lines from LMXBs

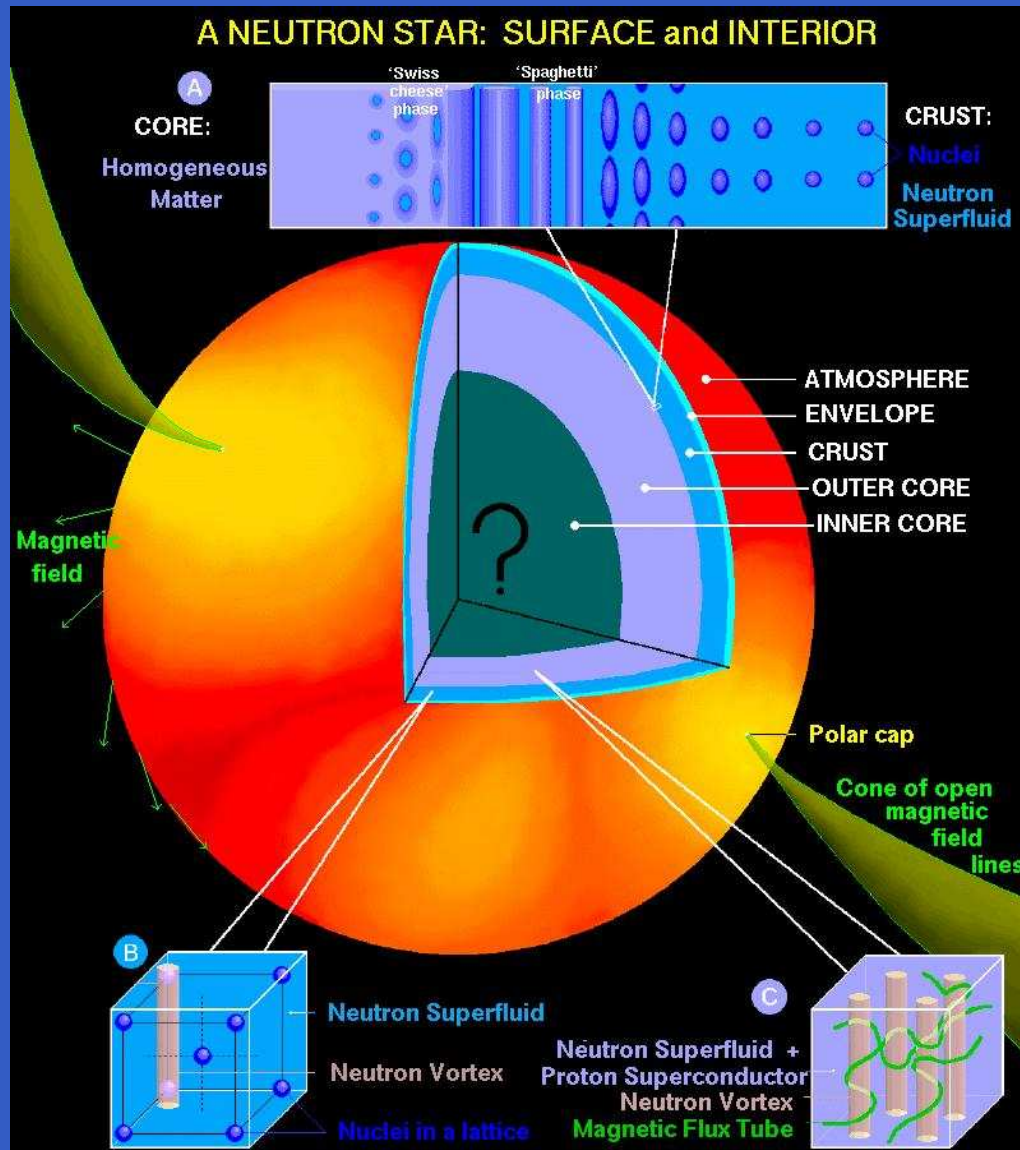


(Cackett et al. (2008))



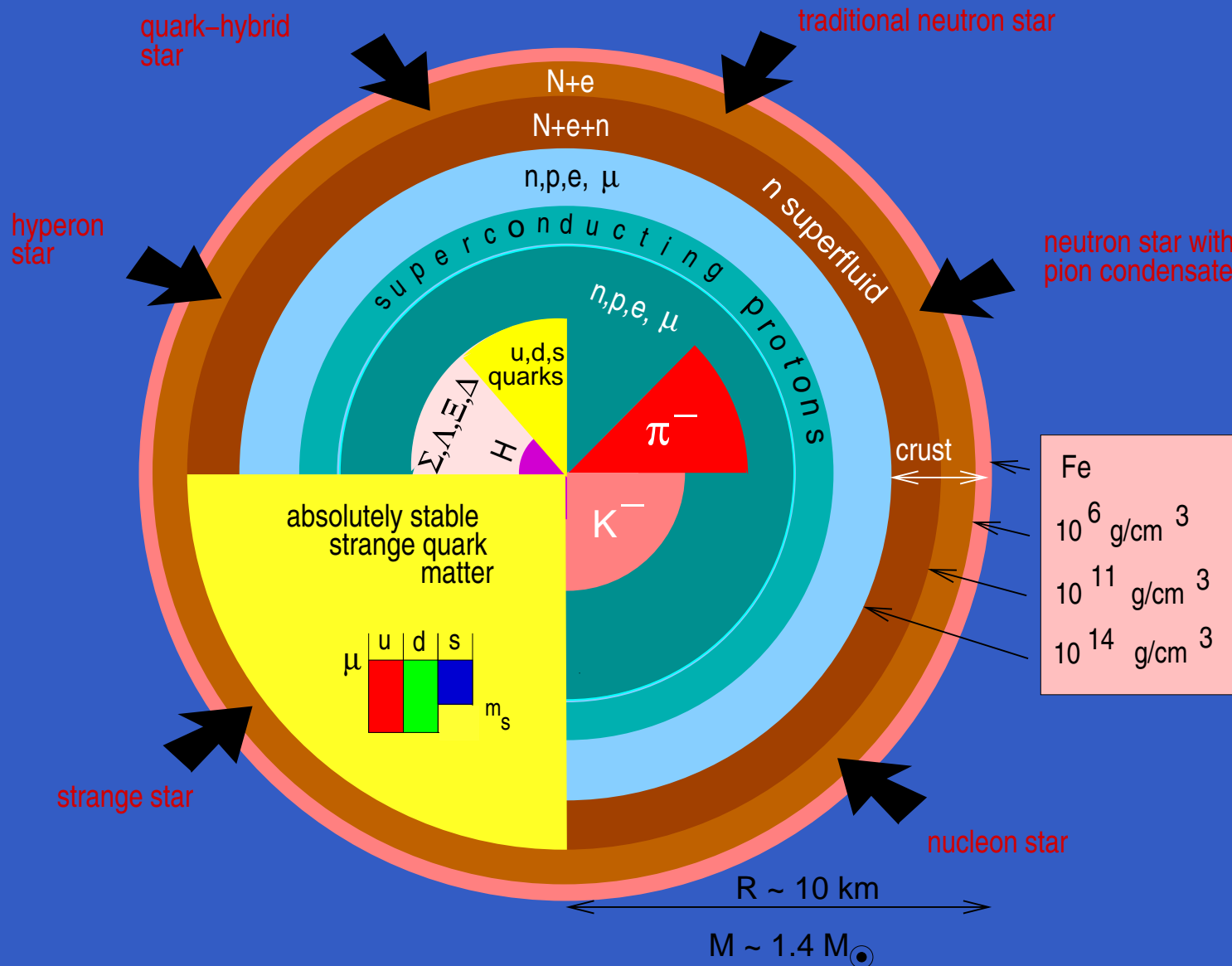
- broadened 6.4keV iron line measured for LMXBs (as seen in AGNs) measured with Suzaku (and XMM Newton)
- inner radius of the accretion disk at $R_{in} = (7 - 8)GM$ (14.5 – 16.5 km for $M = 1.4M_{\odot}$)
- neutron star radius must be smaller

Structure of Neutron Stars — the Crust (Dany Page)

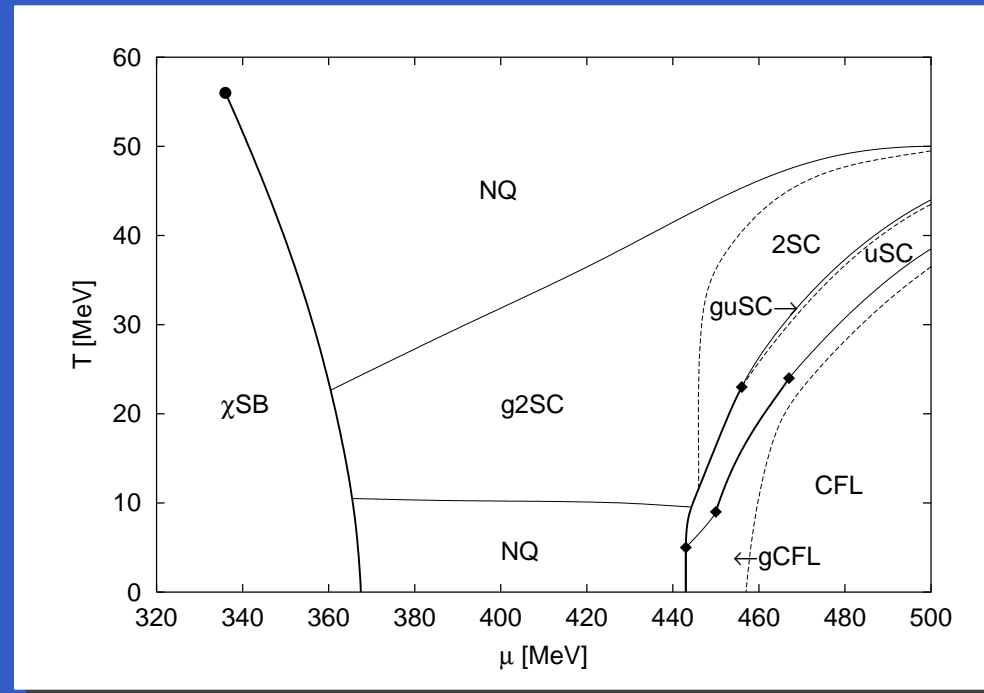


- $n \leq 10^4 \text{ g/cm}^3$:
atmosphere
(atoms)
- $n = 10^4 - 4 \cdot 10^{11} \text{ g/cm}^3$:
outer crust or envelope
(free e^- , lattice of nuclei)
- $n = 4 \cdot 10^{11} - 10^{14} \text{ g/cm}^3$:
Inner crust
(lattice of nuclei with free
neutrons and e^-)

Structure of a Neutron Star — the Core (Fridolin Weber)

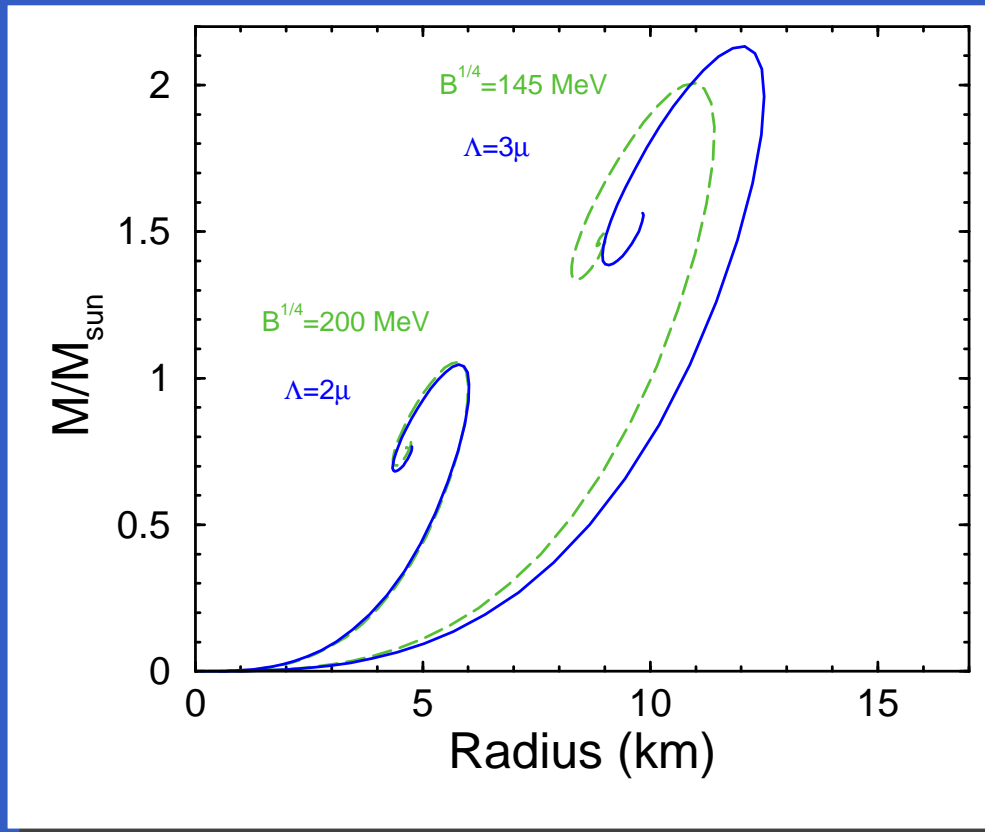


Phases in Quark Matter (Rüster et al. (2005))



- first order phase transition based on symmetry arguments!
- phases of color superconducting quark matter in β equilibrium:
- normal (unpaired) quark matter (NQ)
- two-flavor color superconducting phase (2SC), gapless 2SC phase
- color-flavor locked phase (CFL), gapless CFL phase, metallic CFL phase
- (Alford, Rajagopal, Wilczek, Reddy, Buballa, Blaschke, Shovkovy, Drago, Rüster, Rischke, Aguilera, Banik, Bandyopadhyay, Pagliara, ...)

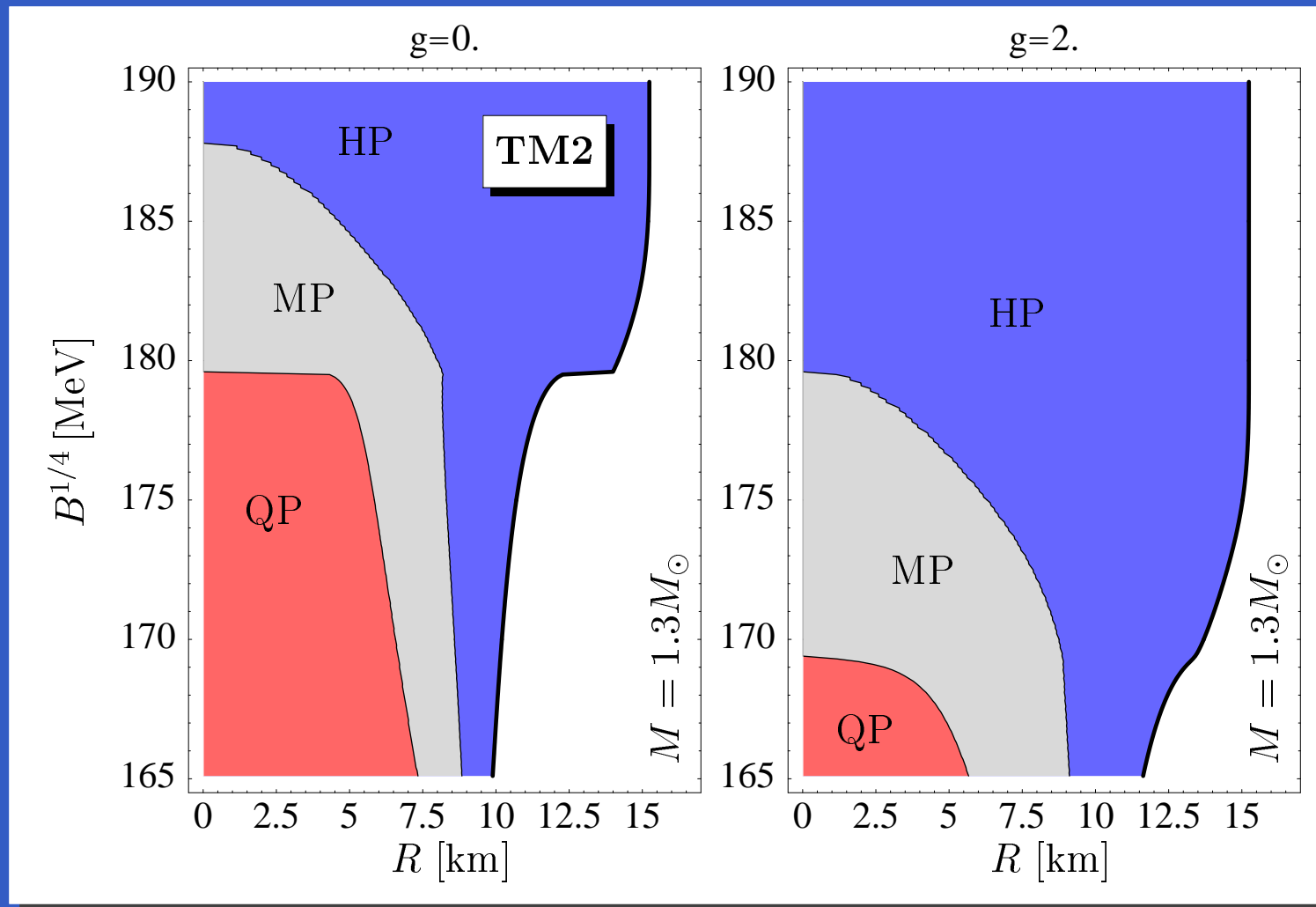
Mass-radius and maximum density of pure quark stars



- green curves: MIT bag model
- blue curves: perturbative QCD calculations
(Fraga, JSB, Pisarski 2001)

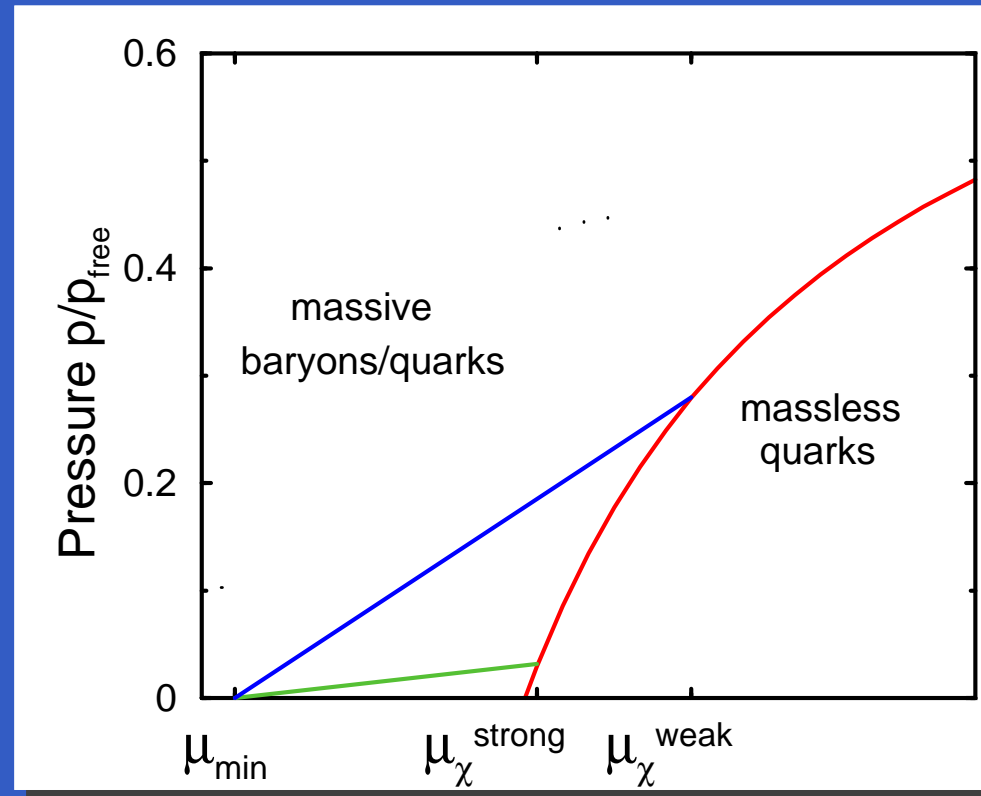
- case $\Lambda = 2\mu$: $M_{\text{max}} = 1.05 M_{\odot}$, $R_{\text{max}} = 5.8 \text{ km}$, $n_{\text{max}} = 15 n_0$
- case $\Lambda = 3\mu$: $M_{\text{max}} = 2.14 M_{\odot}$, $R_{\text{max}} = 12 \text{ km}$, $n_{\text{max}} = 5.1 n_0$
- note: pure quark stars can be very similar to ordinary neutron stars!

Hybrid Stars (Schertler et al. (2000))



- hybrid star: consists of hadronic and quark matter
- three phases possible: hadronic, mixed phase and pure quark phase
- composition depends crucially on the parameters as the bag constant B (and on the mass!)

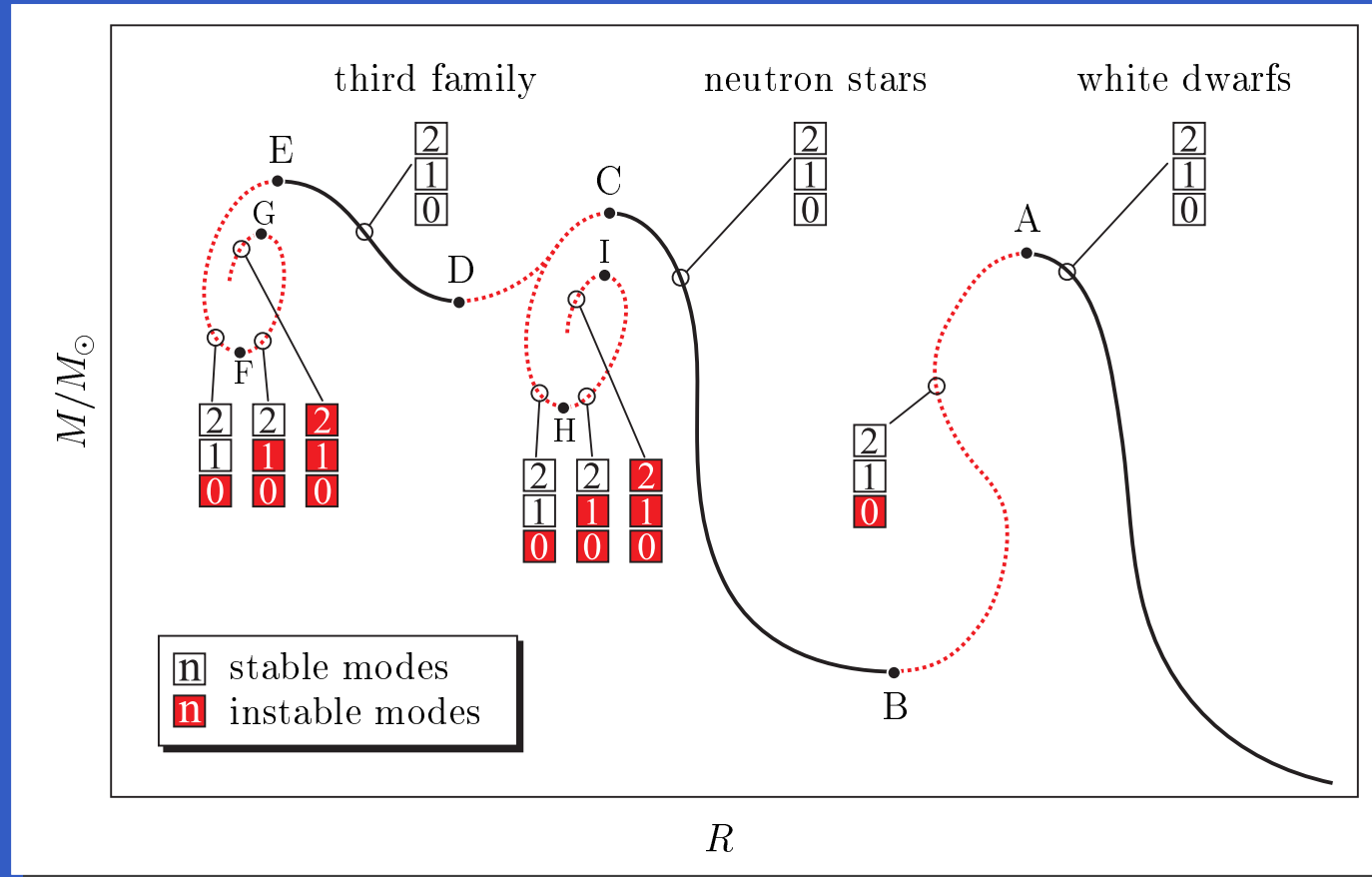
Matching the two phases: two possible scenarios



- Weak: phase transition is weakly first order or a crossover \rightarrow pressure in massive phase rises strongly
- Strong: transition is strongly first order \rightarrow pressure rises slowly with μ
- asymmetric matter up to $\sim 2n_0$: suggest a slow rise with density!
(Akmal, Pandharipande, Ravenhall (1998))

Third Family of Compact Stars (Gerlach 1968)

(Glendenning, Kettner 2000; Schertler, Greiner, JSB, Thoma 2000)

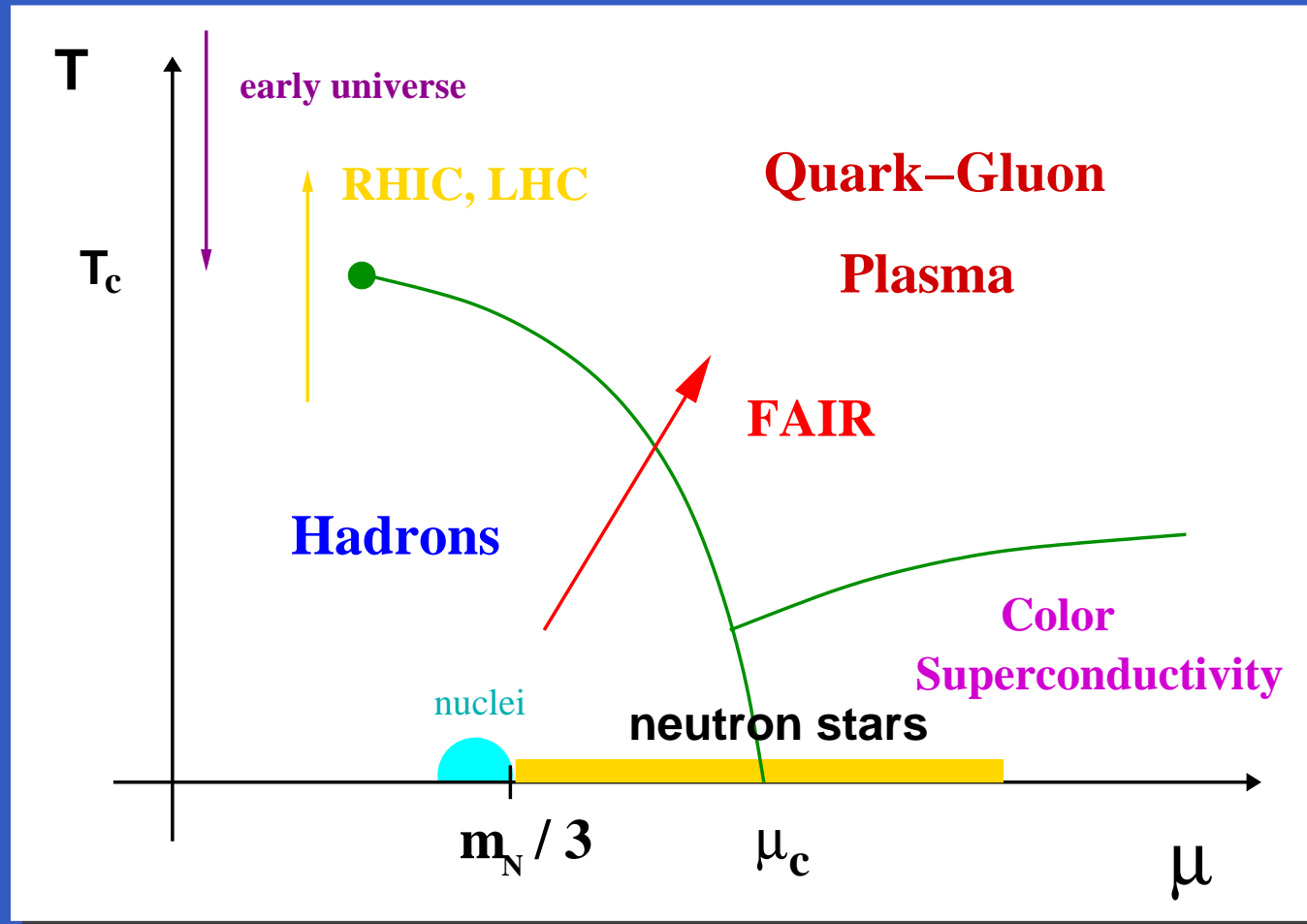


- third solution to the TOV equations besides white dwarfs and neutron stars, solution is stable!
- generates stars more compact than neutron stars!
- possible for any first order phase transition!

Signals for a Third Family/Phase Transition?

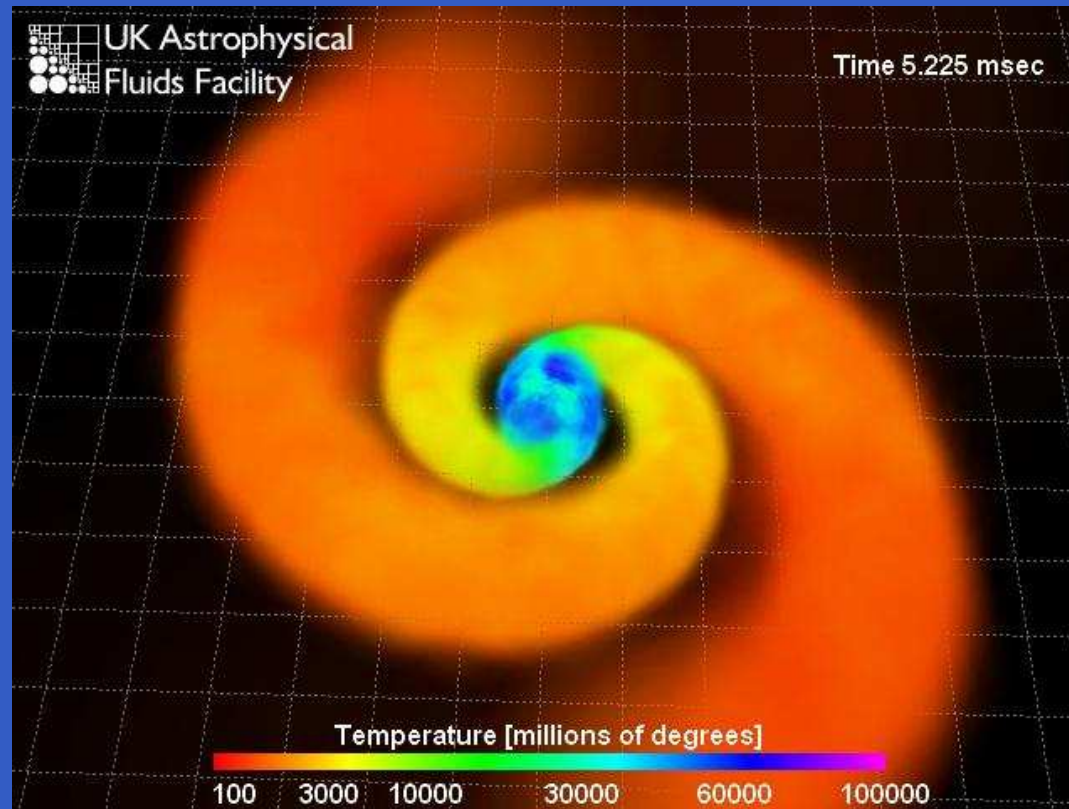
- mass-radius relation: rising twins (Schertler et al., 2000)
- spontaneous spin-up of pulsars (Glendenning, Pei, Weber, 1997)
- delayed collapse of a proto-neutron star to a black hole (Thorsson, Prakash, Lattimer, 1994)
- bimodal distribution of pulsar kick velocities (Bombaci and Popov, 2004)
- collapse of a neutron star to the third family? (gravitational waves, γ -rays, neutrinos)
- gravitational waves from colliding neutron stars?
- secondary shock wave in supernova explosions?

Phase Transitions in Quantum Chromodynamics QCD



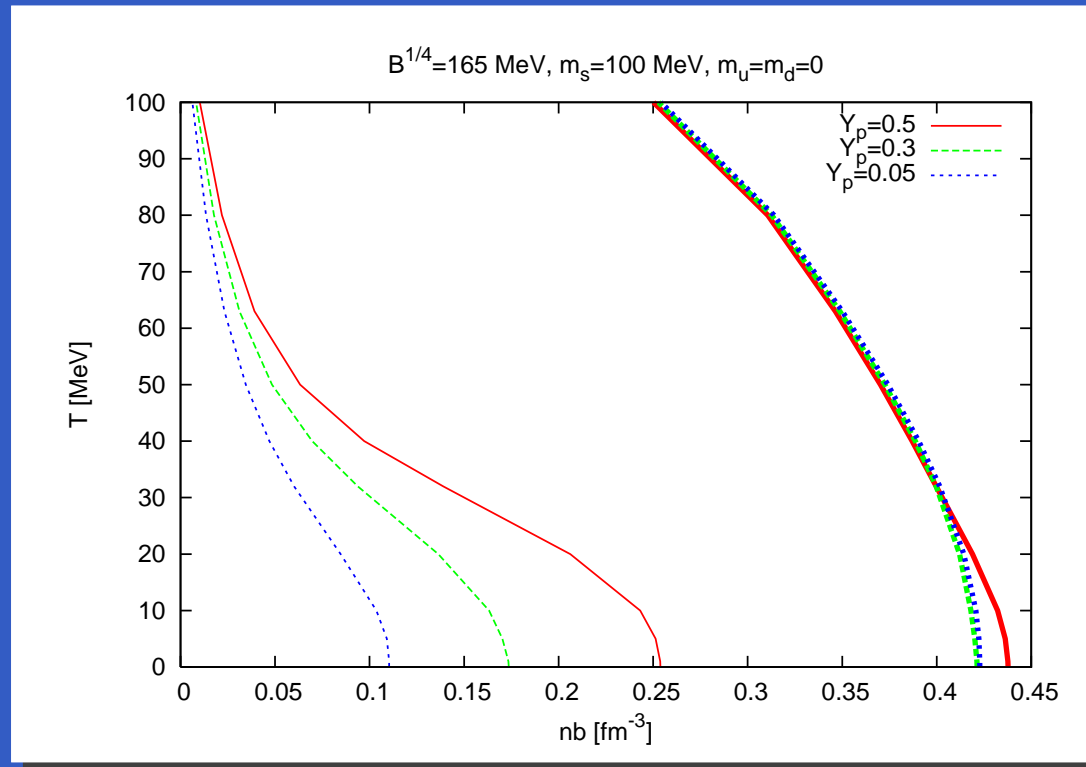
- Early universe at zero density and high temperature
- neutron star matter at small temperature and high density
- first order phase transition at high density (not deconfinement)!
- probed by heavy-ion collisions at GSI, Darmstadt (FAIR!)

Nuclear EoS in Astrophysics



- supernovae simulations: $T = 1\text{--}50$ MeV, $n = 10^{-10}\text{--}2n_0$
- proto-neutron star: $T = 1\text{--}50$ MeV, $n = 10^{-3}\text{--}10n_0$
- global properties of neutron stars: $T = 0$, $n = 10^{-3}\text{--}10n_0$
- neutron star mergers: $T = 0\text{--}100$ MeV, $n = 10^{-10}\text{--}10n_0$

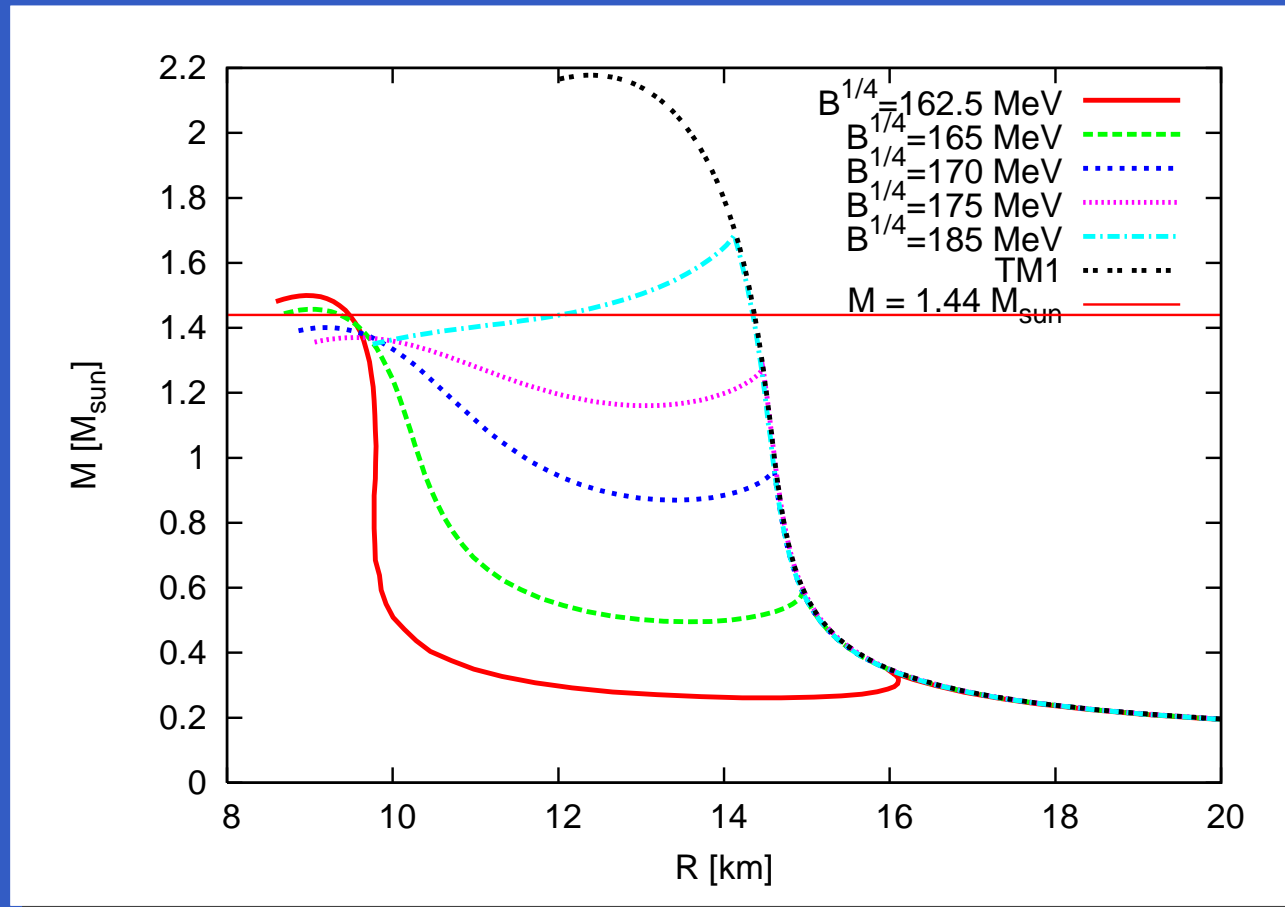
Phase Transition to Quark Matter for Astros



(Irina Sagert and Giuseppe Pagliara)

- start of the mixed phase at quite low densities due to β -equilibrium, strange quark matter is more stable than nucleon matter (using RMF model TMA)
- even lower critical densities for isospin-asymmetric matter (low proton fraction Y_p) due to asymmetry energy for nucleons
- quark matter favored in hot matter due to the QCD phase diagram
- production of quark matter in supernovae at bounce possible!

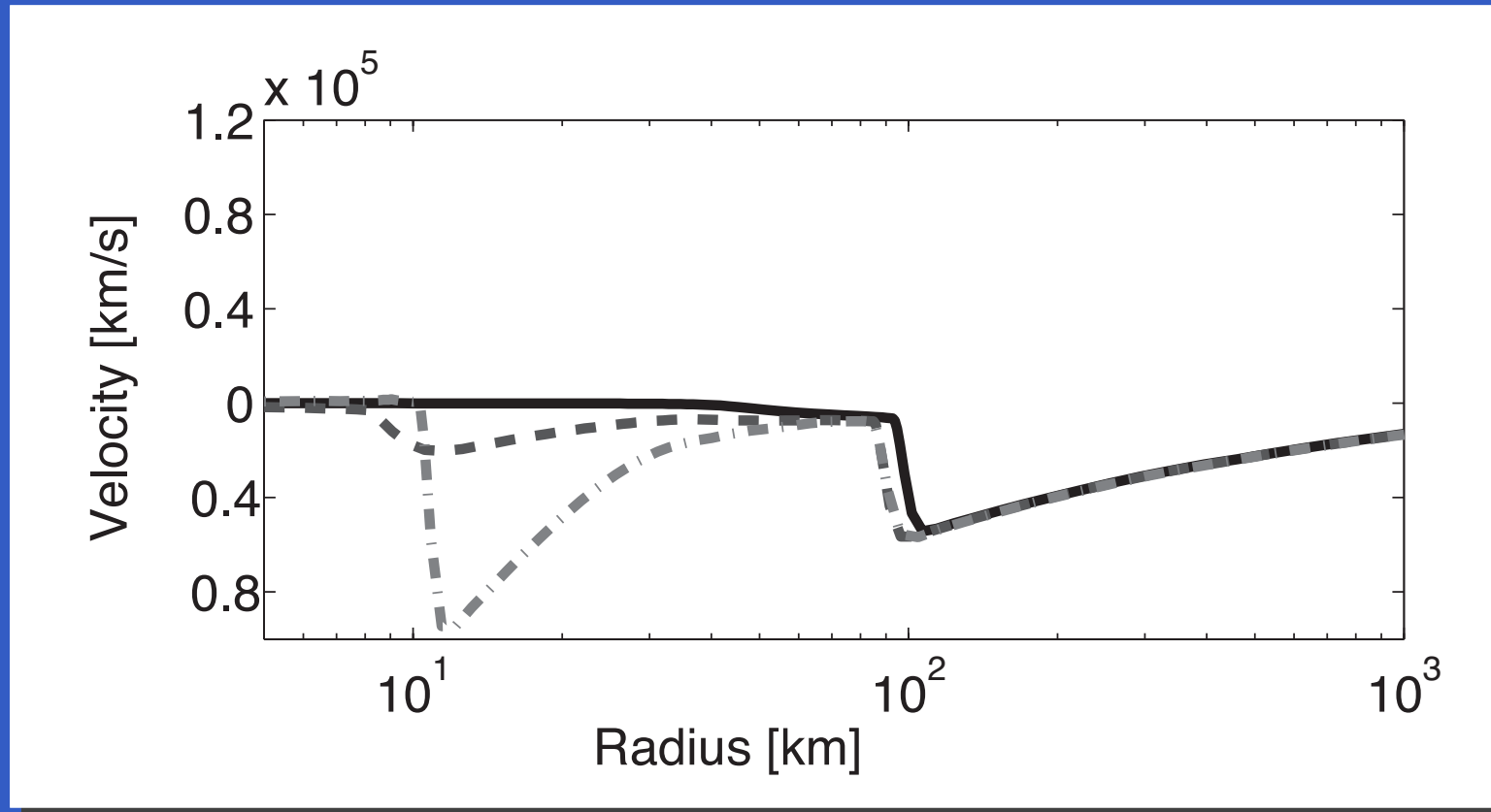
Check: Mass-Radius Diagram of Cold Neutron Stars



(Irina Sagert and Giuseppe Pagliara)

- presence of quark matter can change drastically the mass-radius diagram
- third family of solution for certain bag constants
- maximum mass: $1.56 M_{\odot}$ ($B^{1/4} = 162$ MeV), $1.5 M_{\odot}$ ($B^{1/4} = 165$ MeV)

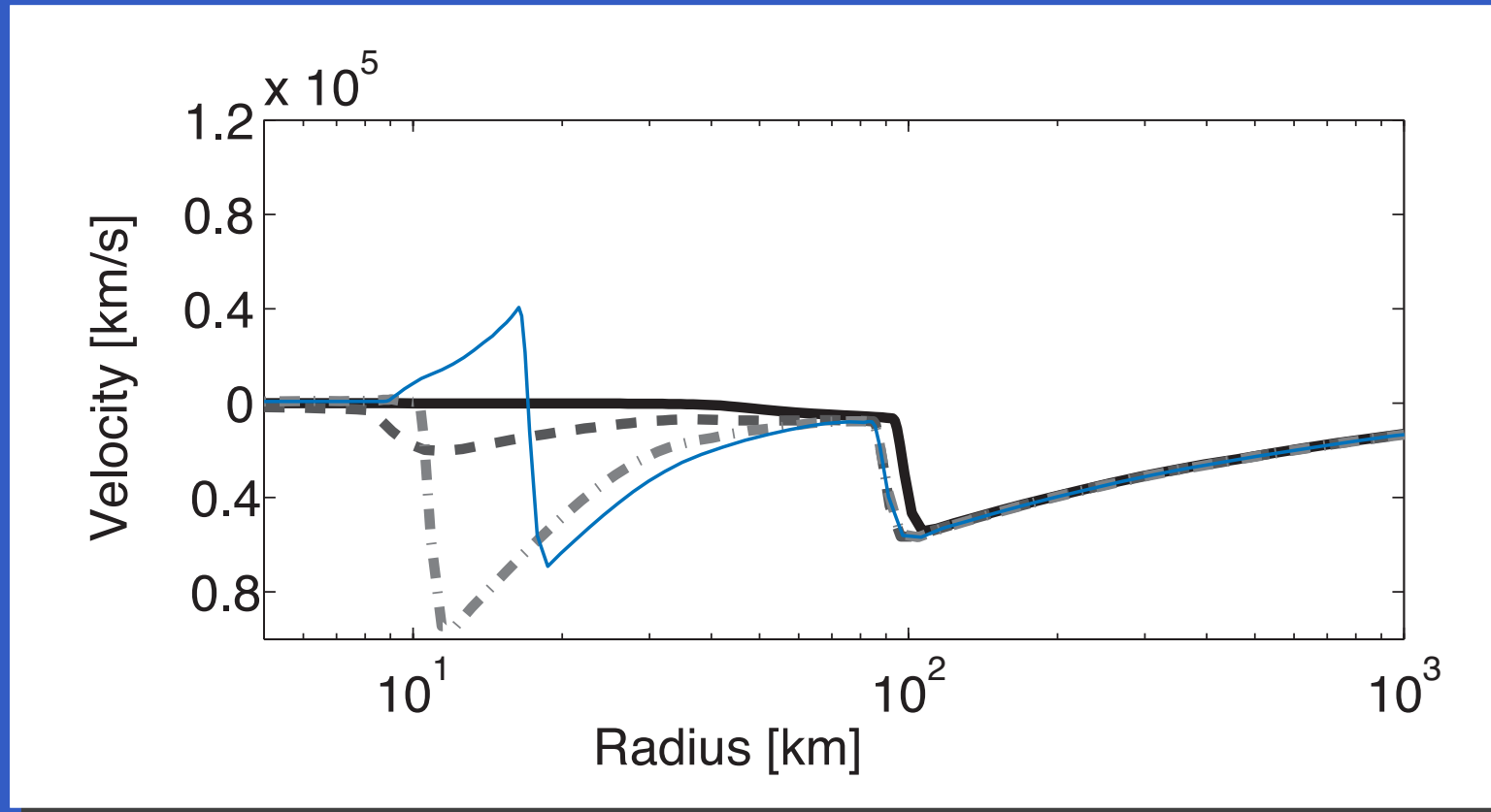
Implications for Supernovae – Explosion!



(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2008)

- velocity profile of a supernova for different times (around 250ms)
- formation of a core of pure quark matter produces a second shock wave

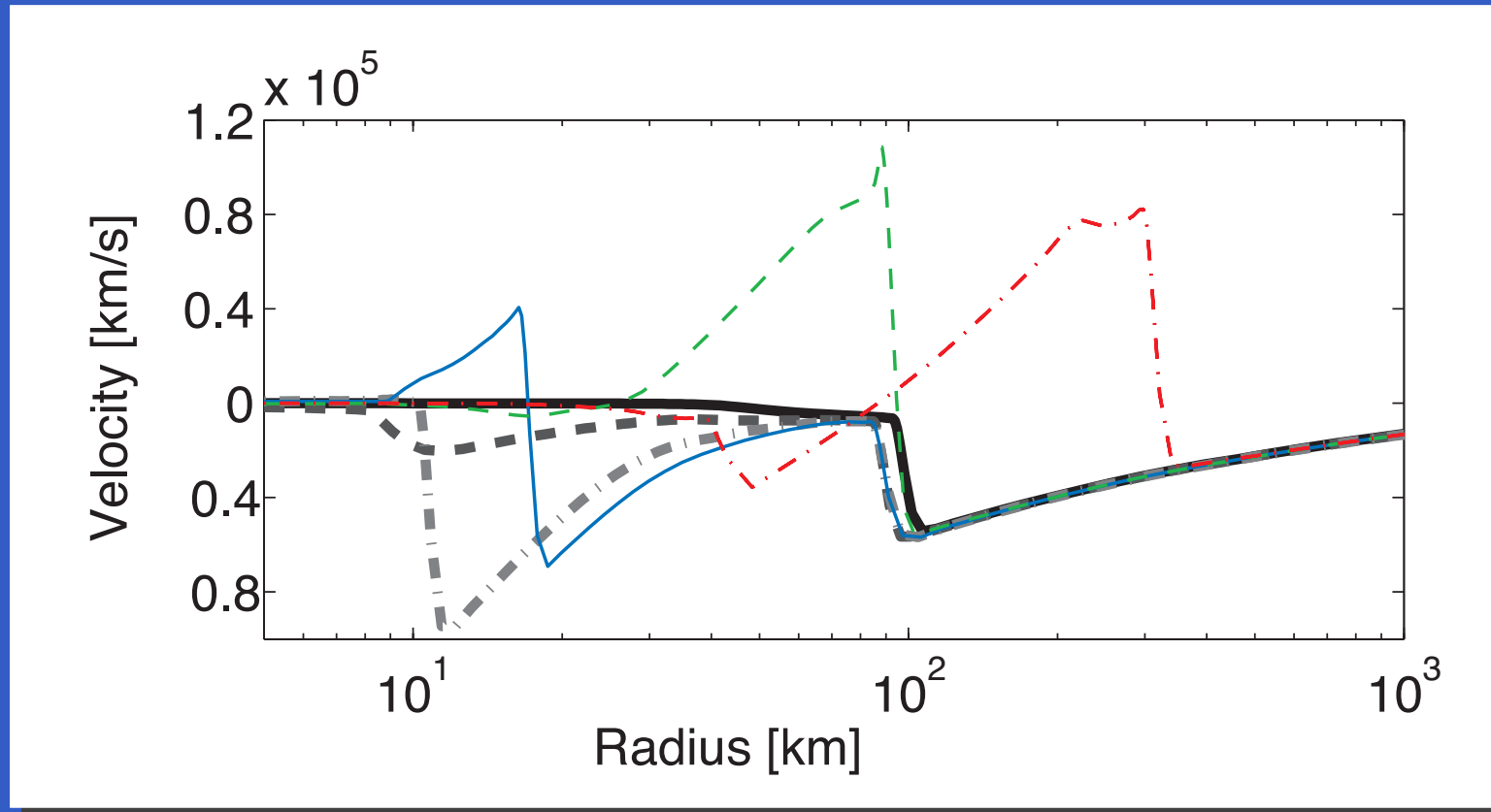
Implications for Supernovae – Explosion!



(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2008)

- velocity profile of a supernova for different times (around 250ms)
- formation of a core of pure quark matter produces a second shock wave

Implications for Supernovae – Explosion!



(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2008)

- velocity profile of a supernova for different times (around 250ms)
- formation of a core of pure quark matter produces a second shock wave
- leads to a successful explosion!

Successful Supernova Explosion – Parameter dependence

Prog.	B	t_{pb}	M_Q	M_{mixed}	$M_{PN S}$	E_{expl}
[M]	[MeV]	[ms]	[M]	[M]	[M]	[10^{51} erg]
10	162	255	0.850	0.508	1.440	0.44
10	165	448	1.198	0.161	1.478	1.64
15	162	209	1.146	0.320	1.608	0.42
15	165	330 ^a	1.496	0.116	1.700	unknown ^b

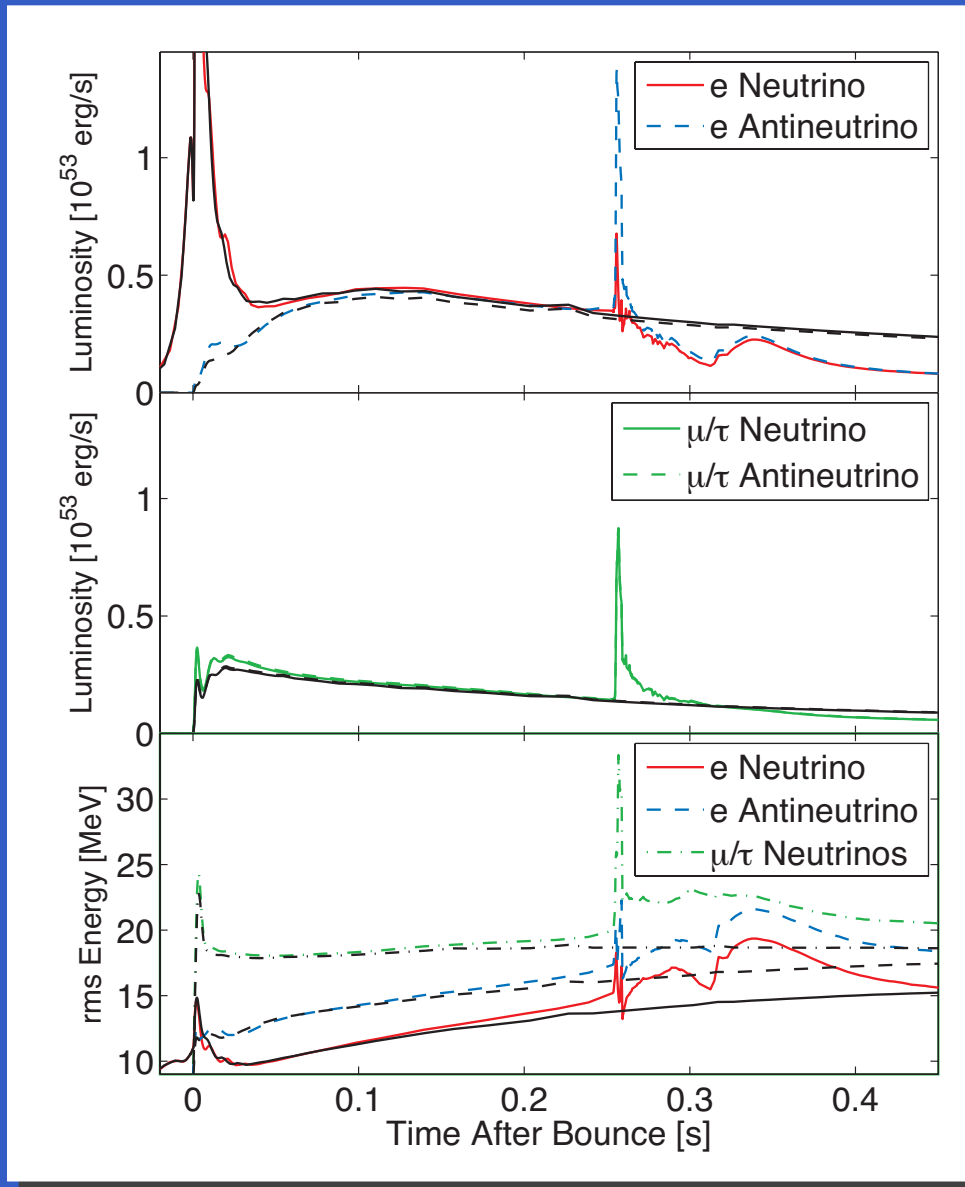
^a moment of black hole formation

^b black hole formation before positive explosion energy is achieved

(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2008)

- supernova simulation runs for different parameters
- appearance of the quark core at $t_{pb} = 200$ to 500 ms
- results (t_{pb} , baryonic mass and explosion energy) are significantly sensitive to the location of the QCD phase transition (bag constant)
- heavier progenitor masses can lead to the formation of a black hole

Implications for Supernova – Neutrino-Signal!



- temporal profile of the emitted neutrinos out of the supernova
- thick lines: without, thin lines: with a phase transition
- pronounced second peak of anti-neutrinos due to the formation of quark matter
- peak location and height determined by the critical density and strength of the QCD phase transition!!

(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2008)

Summary

- equation of state (EoS) determines the maximum mass and its radius
- phase transitions lead to a third family of compact stars
- implications for mass-radius relation, cooling, neutrino emission, gravitational waves emission
- and for supernovae!

Thanks to:

my research group in Heidelberg:

- Dr. Giuseppe Pagliara
(gamma-ray bursts, SN EoS, CFL quark stars)
- Dr. Basil Sa'd
(r-mode instability, gravitational wave emission, csc phases)
- Dipl.-Phys. Till Boeckel
(QCD phase transition and structure formation)
- Dipl.-Phys. Matthias Hempel
(full supernova equation of state)
- Dipl.-Phys. Irina Sagert
(EoS from heavy ion physics, SN EoS, proto-neutron stars)
- Rainer Stiele (starts his PhD 03/2009 in HD)
(interacting dark matter in the early universe)