Astrophysical and cosmological explorations of the QCD phase diagram

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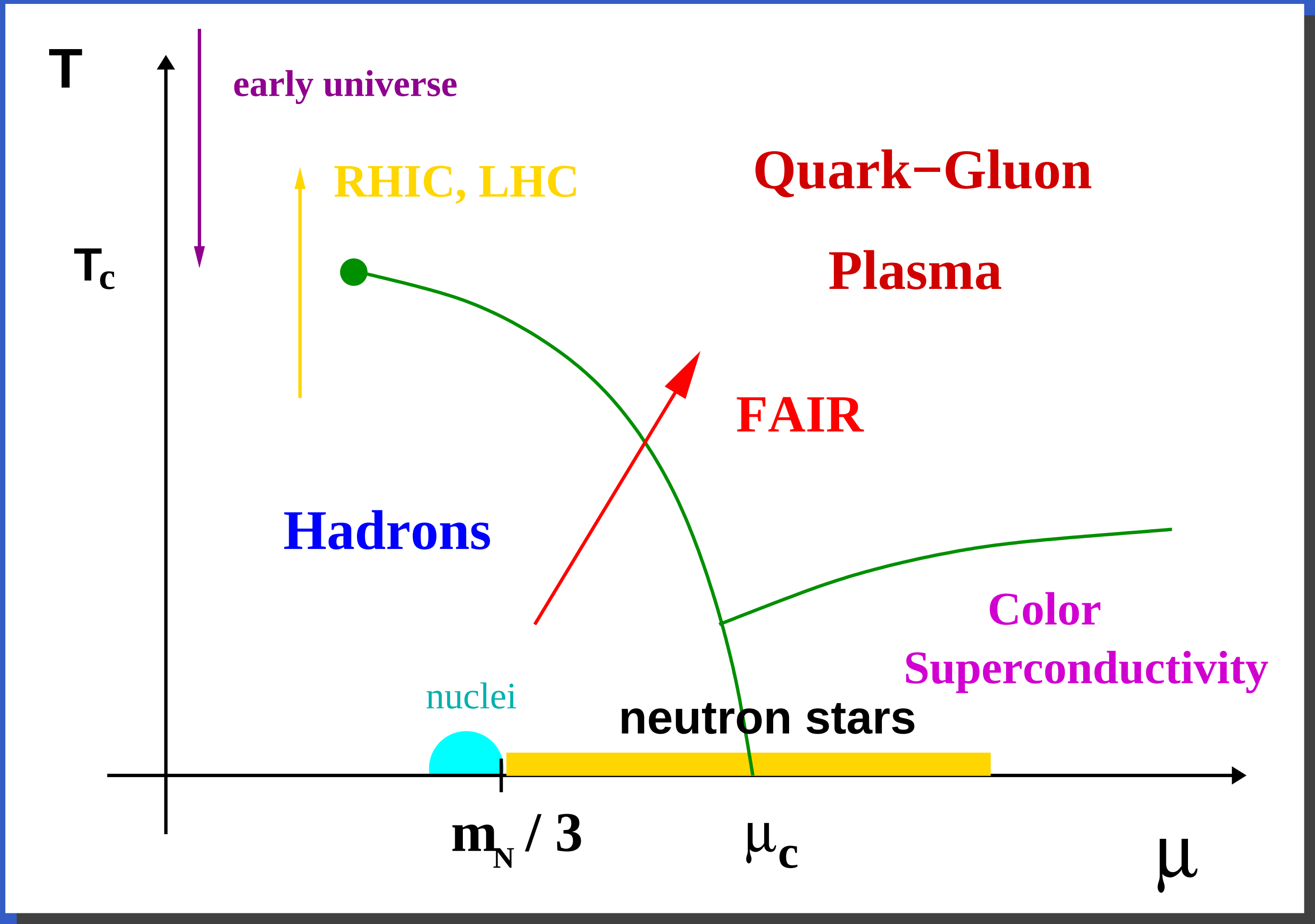
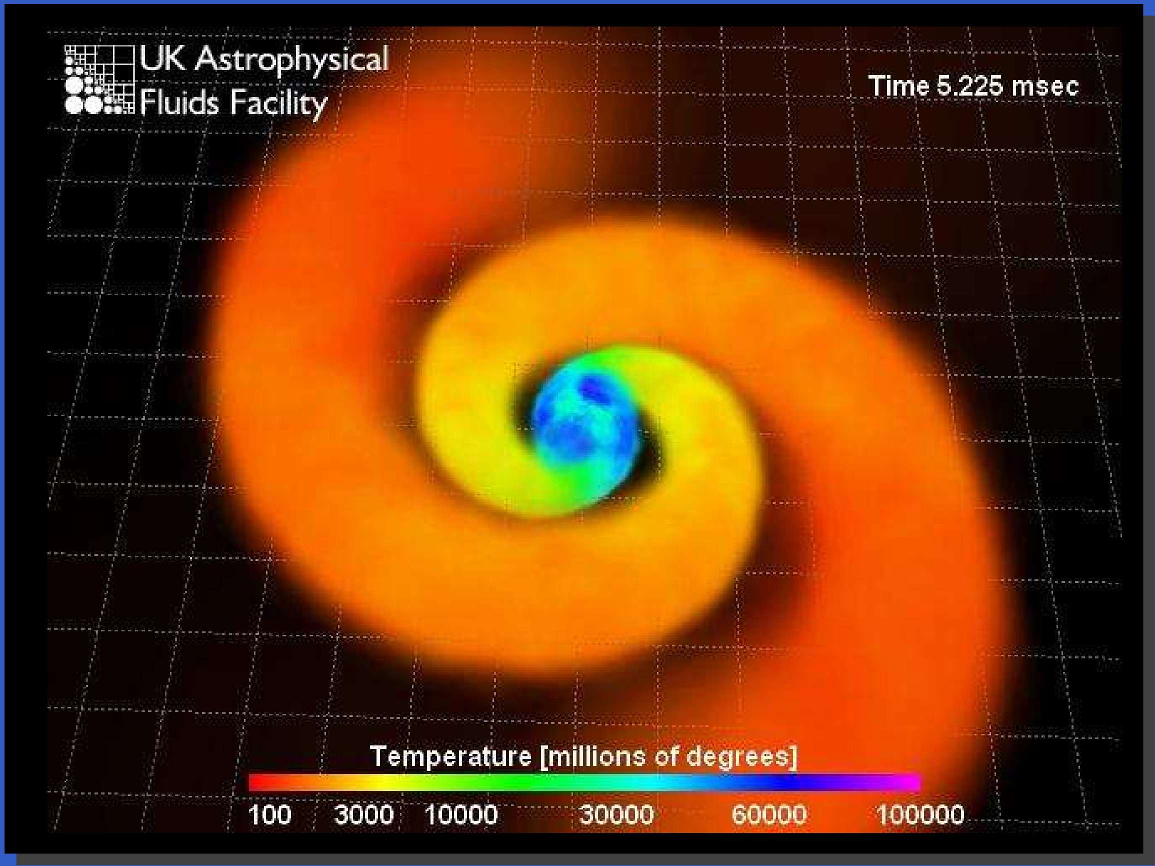
Quarks, Hadrons, and the Phase Diagram of QCD
St. Goar, August 31 – September 3, 2009

Phase Transitions in Quantum Chromodynamics QCD



- Early universe at zero density and high temperature
- supernova and neutron star matter at small temperature and high density
- first order phase transition at high density
- probed by heavy-ion collisions at GSI, Darmstadt (FAIR!)

QCD Equation of State as Input in Astrophysics



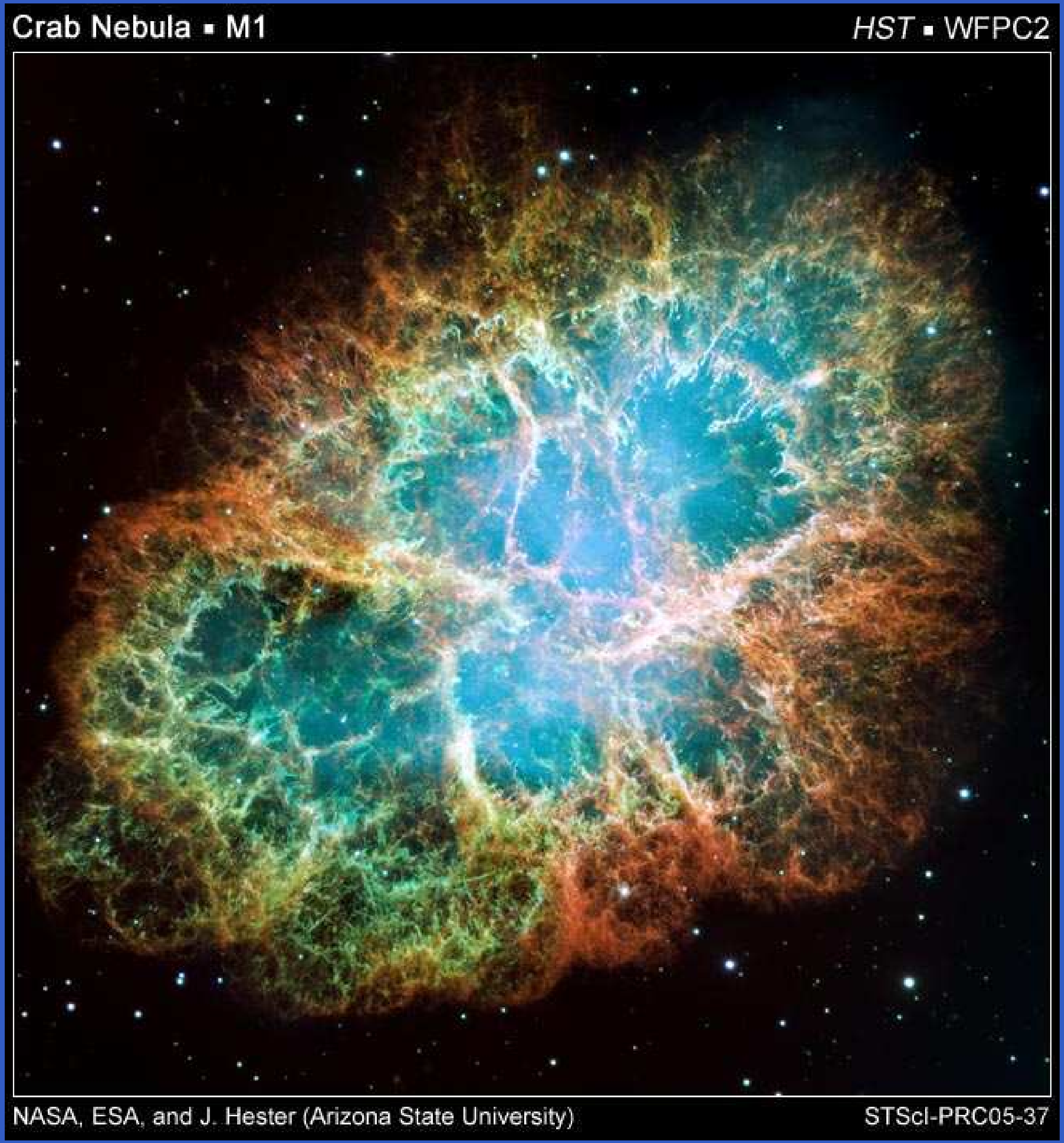
- supernovae simulations: $T = 1$–50 MeV, $n = 10^{-10}$–$2n_0$
- proto-neutron star: $T = 1$–50 MeV, $n = 10^{-3}$–$10n_0$
- global properties of neutron stars: $T = 0$, $n = 10^{-3}$–$10n_0$
- neutron star mergers: $T = 0$–175 MeV, $n = 10^{-10}$–$10n_0$

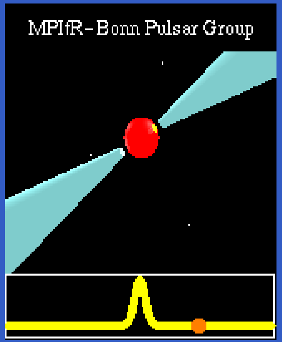
Outline

- Introduction: Pulsars, neutron stars and quark stars
- Connecting the QCD phase diagram with the cosmos:
  - QCD phase transition in neutron stars
  - QCD phase transition in supernovae
  - QCD phase transition in the early universe
- Summary and Outlook

Introduction: Pulsars, neutron stars and quark stars

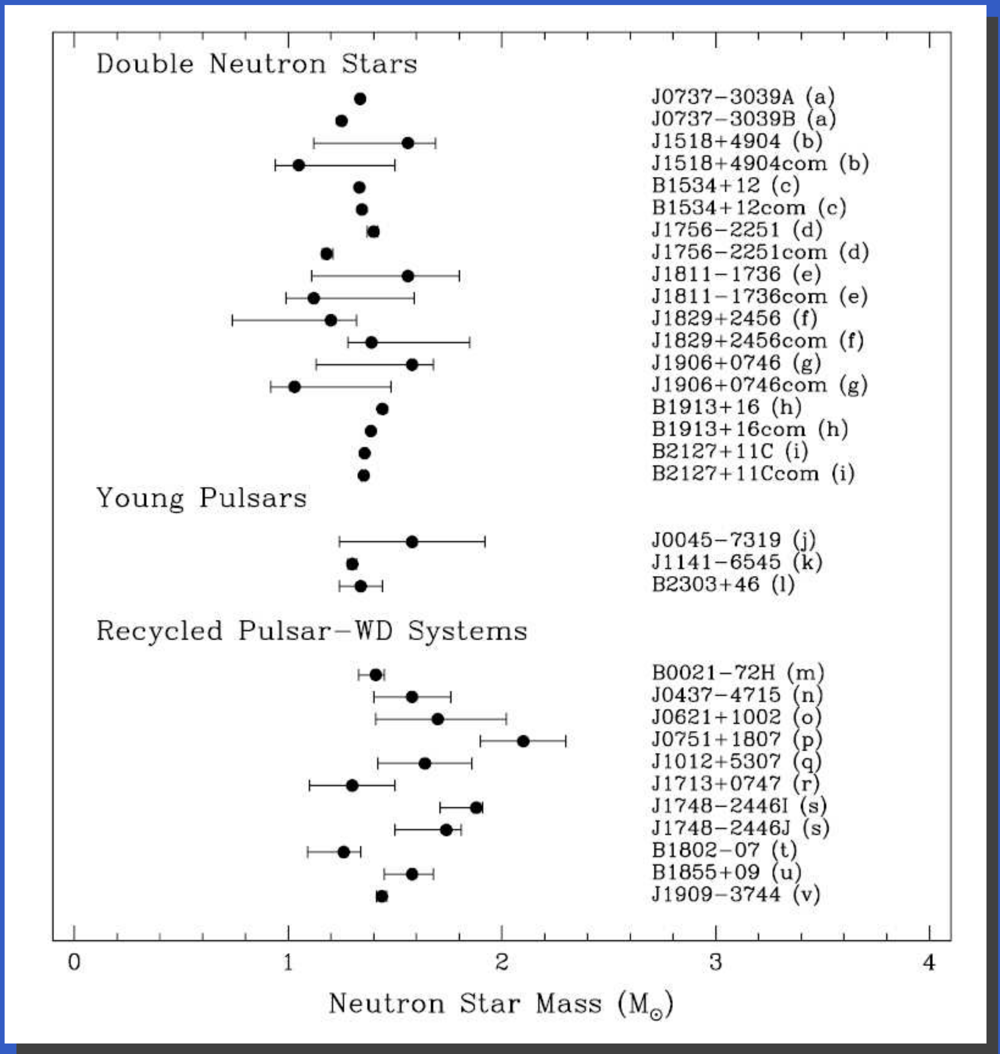
Neutron Stars





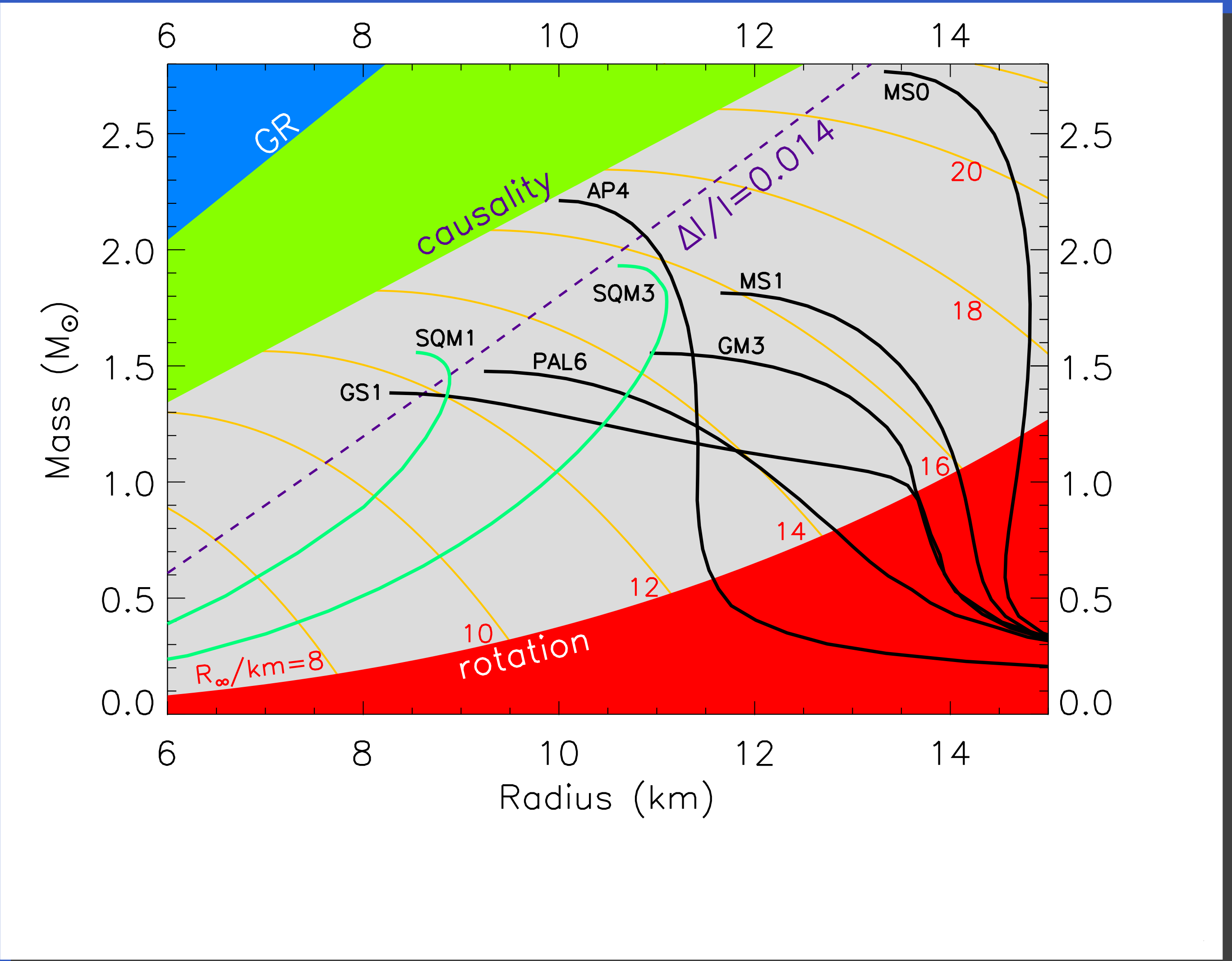
- produced in core collapse supernova explosions
- compact, massive objects: radius $\approx$ 10 km, mass $1 - 2M_{\odot}$
- extreme densities, several times nuclear density: $n \gg n_0 = 3 \cdot 10^{14}$ g/cm^3
- in the middle of the crab nebula: a pulsar, a rotating neutron star!

Masses of Pulsars (Stairs, 2006)



- >1700 pulsars known
- best determined mass: $M = (1.4414 \pm 0.0002) M_\odot$ for the Hulse-Taylor pulsar (Weisberg and Taylor, 2004)
- mass of PSR J0751+1807 corr. from $M = (2.1 \pm 0.2) M_\odot$ to $M = (1.14 - 1.40) M_\odot$ (Nice et al. 2008)
- mass of PSR J1903+0327 (not finalized yet): $M = (1.67 \pm 0.01) M_\odot$ (Freire et al. 2009)

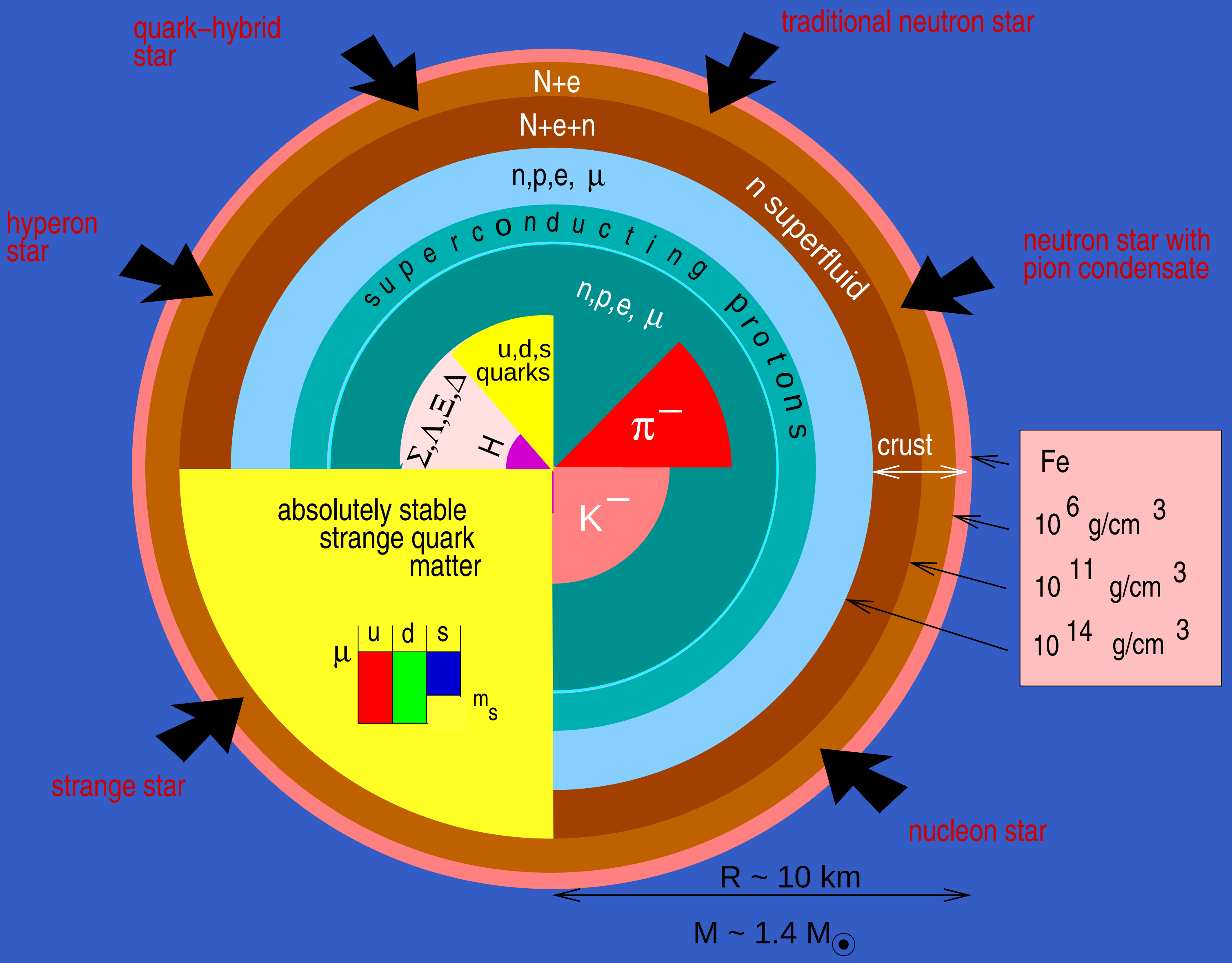
Constraints on the Mass–Radius Relation (Lattimer and Prakash (2004))



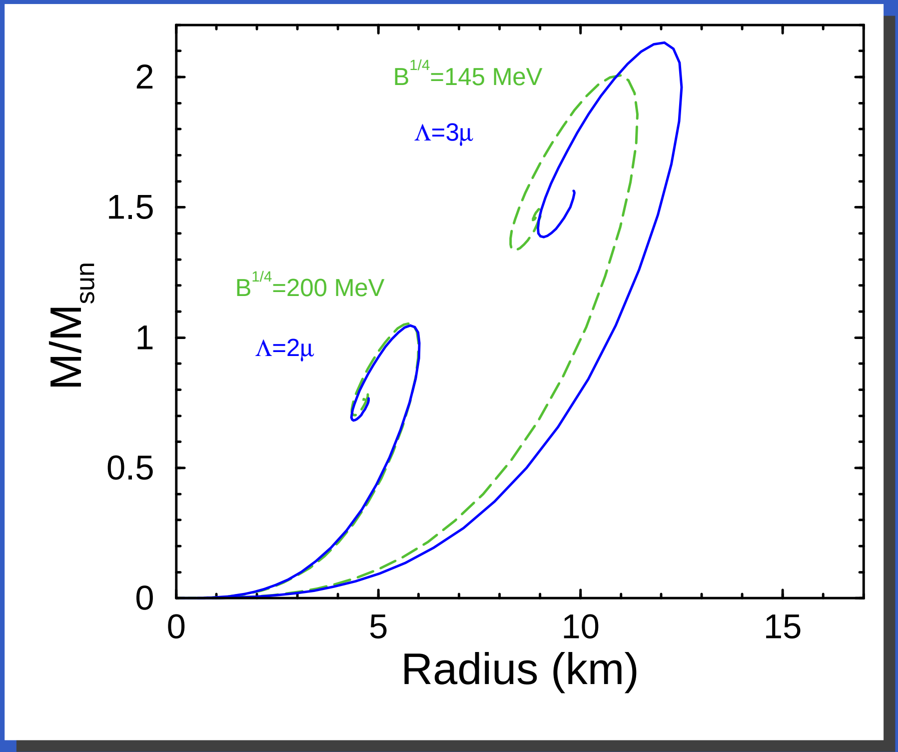
- spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4 M_\odot$
- Schwarzschild limit (GR): $R > 2GM = R_s$
- causality limit for EoS: $R > 3GM$

QCD Phase Transition in Neutron Stars

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



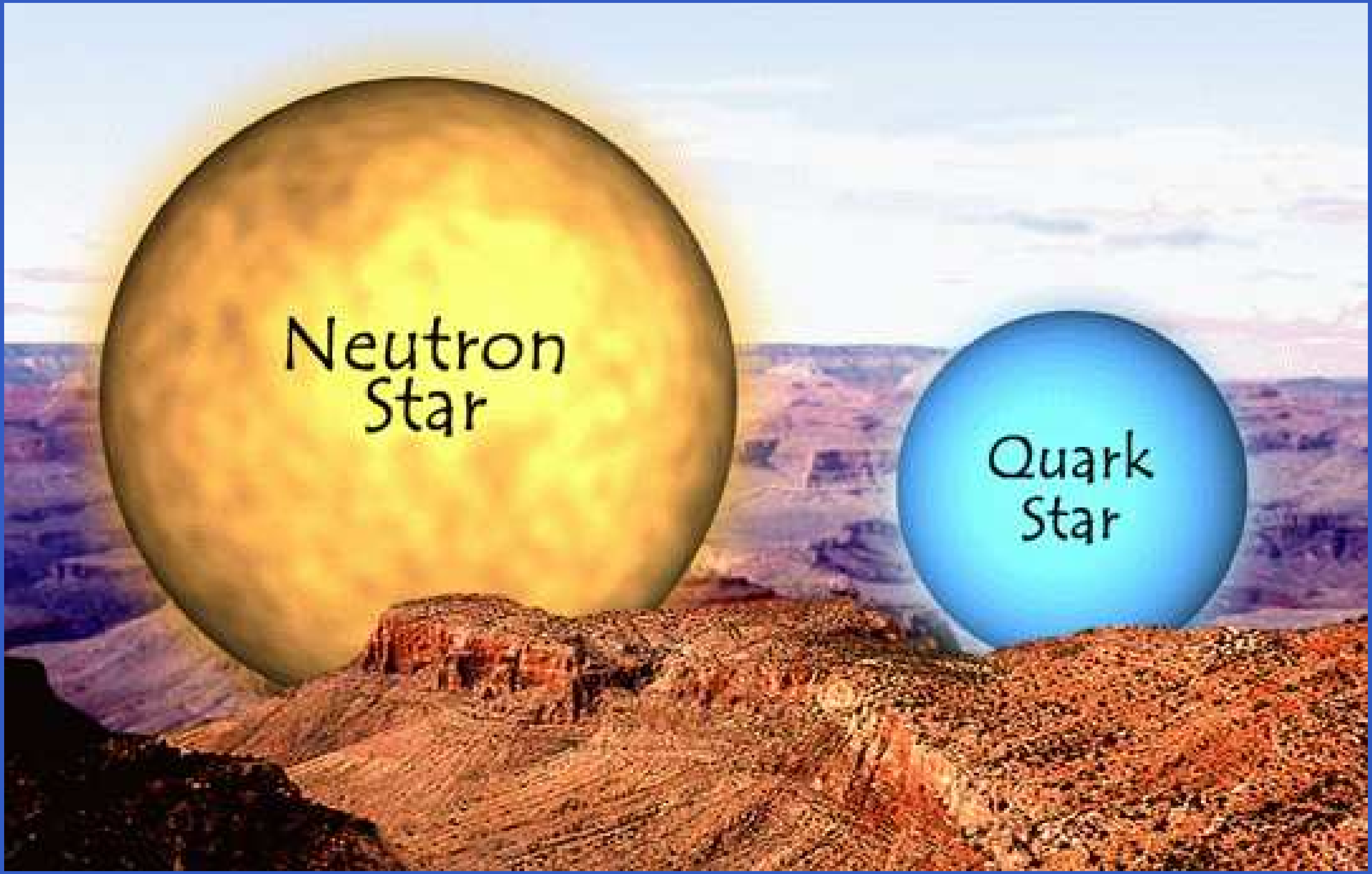
Pure quark(yonic) stars



- green curves: MIT bag model (Witten 1984, Haensel, Zdunik, Schaeffer 1986, Alcock, Farhi, Olinto 1986, see also Baym and Chin 1976)
- blue curves: perturbative QCD calculations to $\mathcal{O}(\alpha_s^2)$ (Freedman and McLerran 1978, Fraga, JSB, Pisarski 2001)

- case $\Lambda = 2\mu$: $M_{\max} = 1.05\,M_\odot$, $R_{\max} = 5.8$ km, $n_{\max} = 15\,n_0$
- case $\Lambda = 3\mu$: $M_{\max} = 2.14\,M_\odot$, $R_{\max} = 12$ km, $n_{\max} = 5.1\,n_0$
- other nonperturbative approaches: Schwinger–Dyson model (Blaschke et al.), massive quasiparticles (Peshier, Kämpfer, Soff), NJL model (Hanauske et al.), HDL (Andersen and Strickland), ...
- note: pure quark stars can be very similar to ordinary neutron stars!

A Quark Star? (NASA press release 2002)

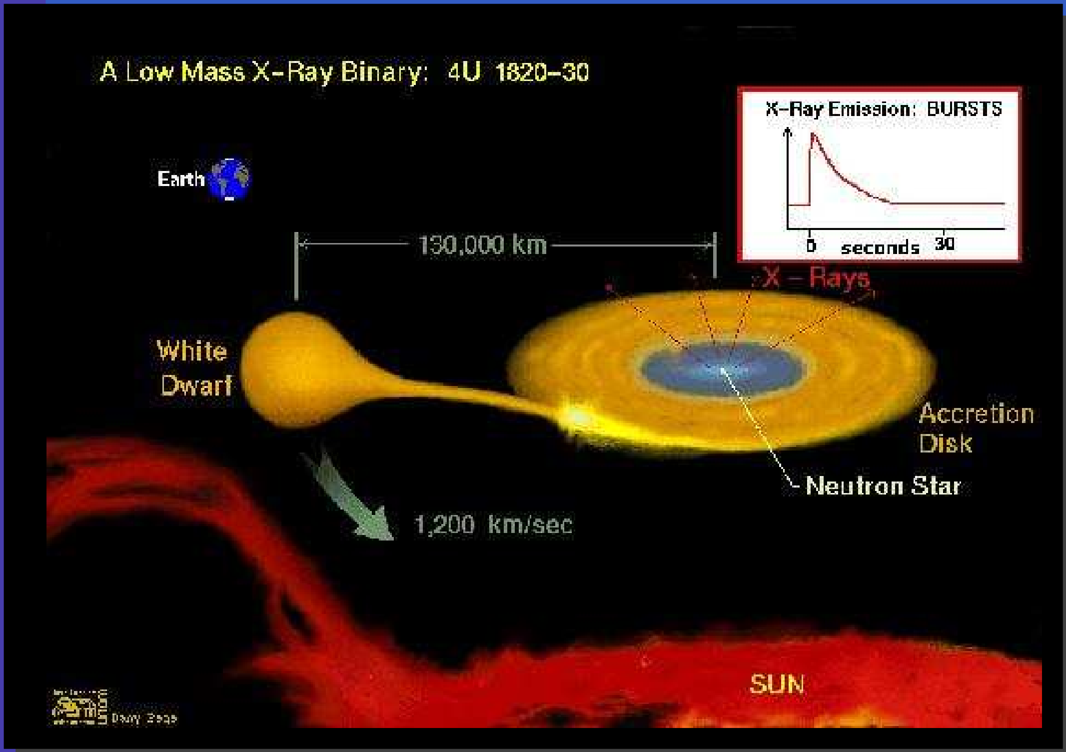


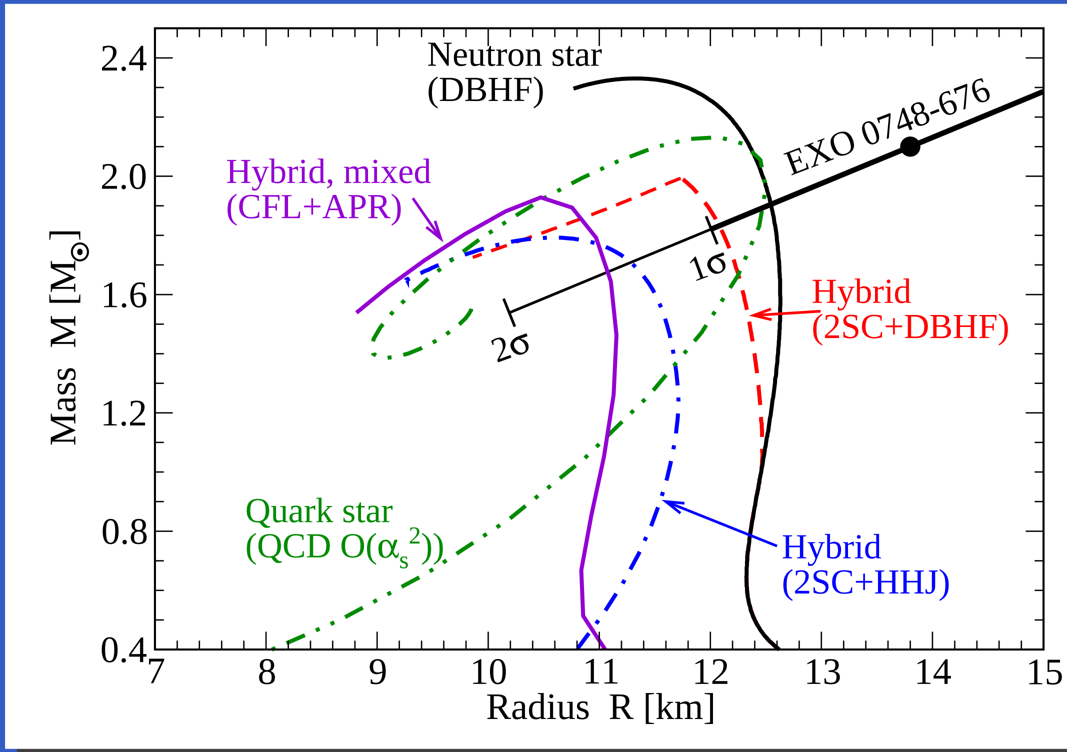
NASA news release 02-082:

“Cosmic X-rays reveal evidence for new form of matter”

— a quark star?

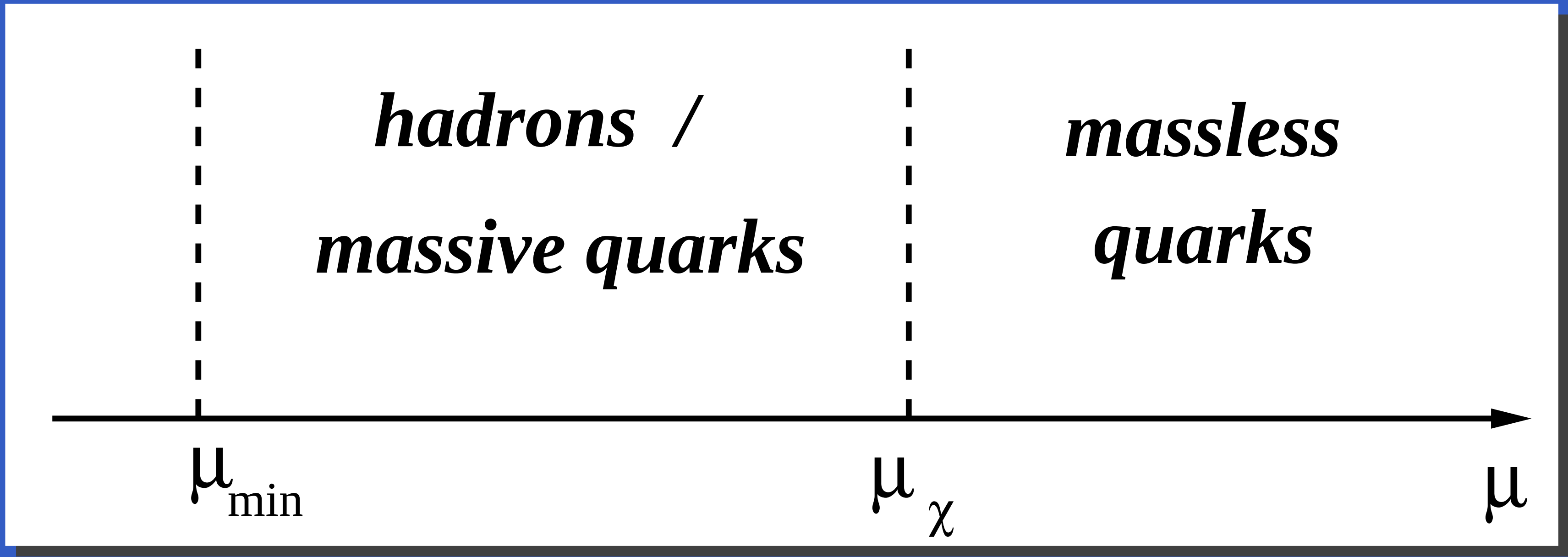
X-Ray burster EXO 0748–676 and Quark Matter





- analysis of Özel (Nature 2006): $M \geq 2.10 \pm 0.28 M_\odot$ and $R \geq 13.8 \pm 1.8$ km, claims: 'unconfined quarks do not exist at the center of neutron stars'!
- reply by Alford, Blaschke, Drago, Klähn, Pagliara, JSB (Nature 445, E7 (2007)): limits rule out soft equations of state, not quark stars or hybrid stars!
- multiwavelength analysis of Pearson et al. (2006): data more consistent with $M = 1.35 M_\odot$ than with $M = 2.1 M_\odot$

Matching to low density EoS

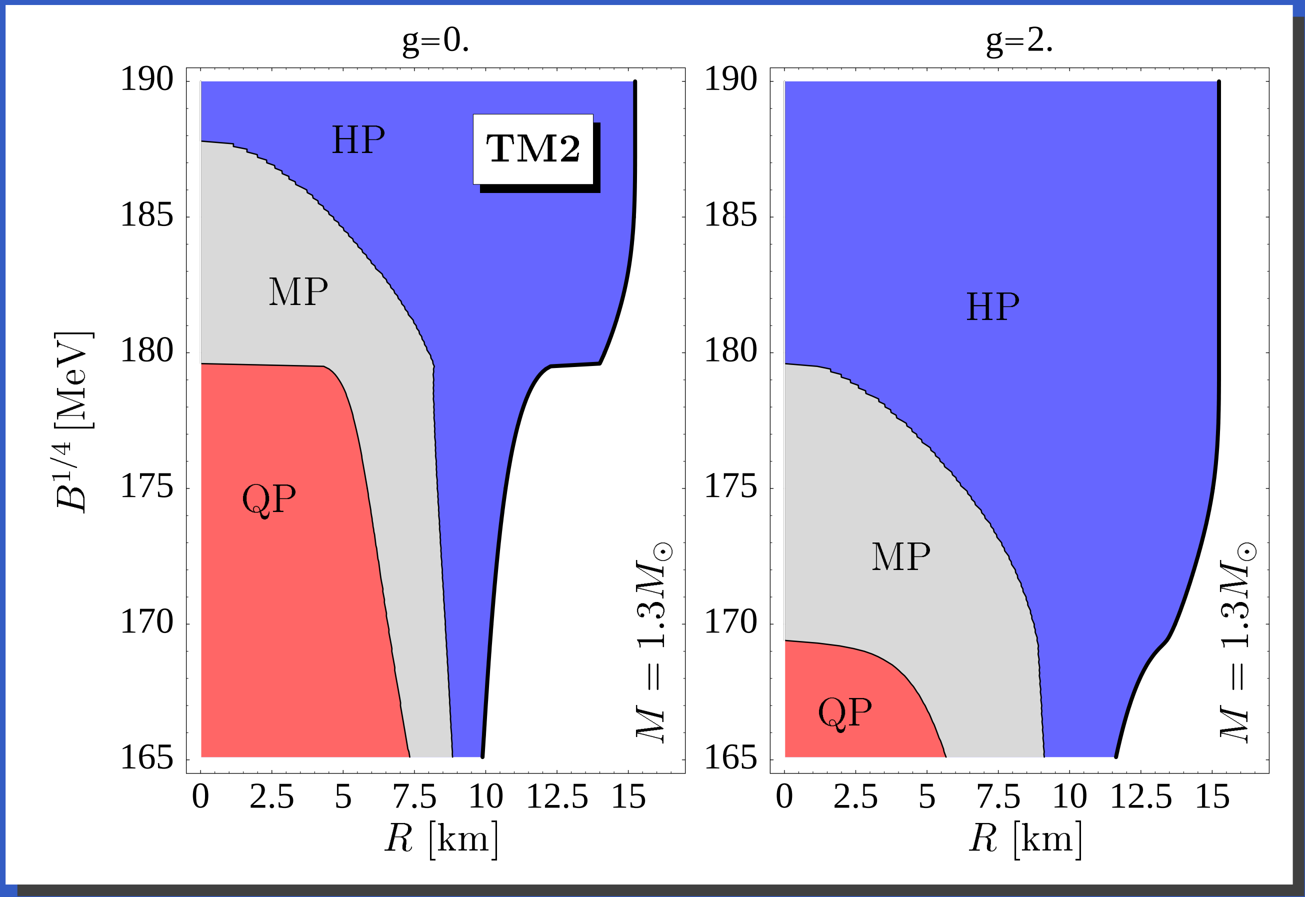


Two possibilities for a first-order chiral phase transition:

- A weakly first-order chiral transition (or no true phase transition),
  $\Longrightarrow$ one type of compact star:
  hybrid stars masquerade as neutron stars
- A strongly first-order chiral transition
  $\Longrightarrow$ two types of compact stars:
  a new stable solution with smaller masses and radii

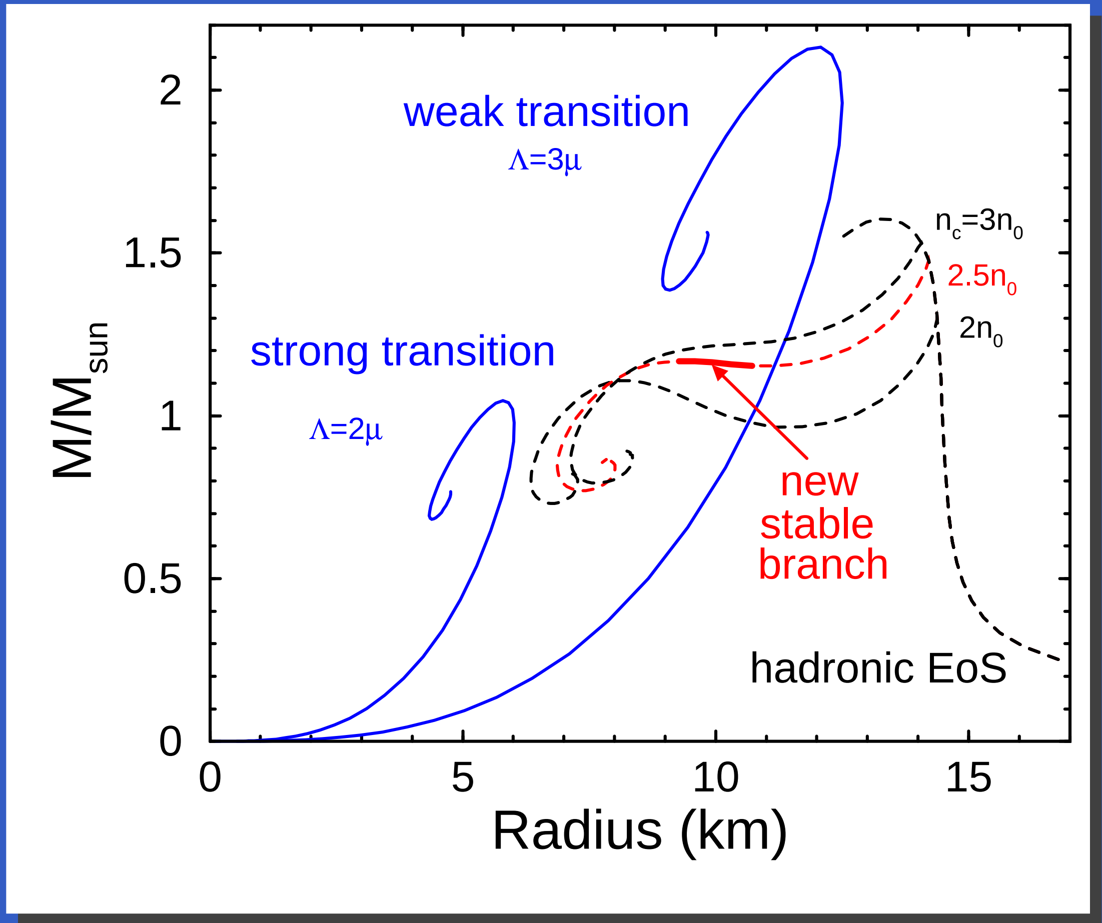
Hybrid Stars in the effective mass bag model

(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!)

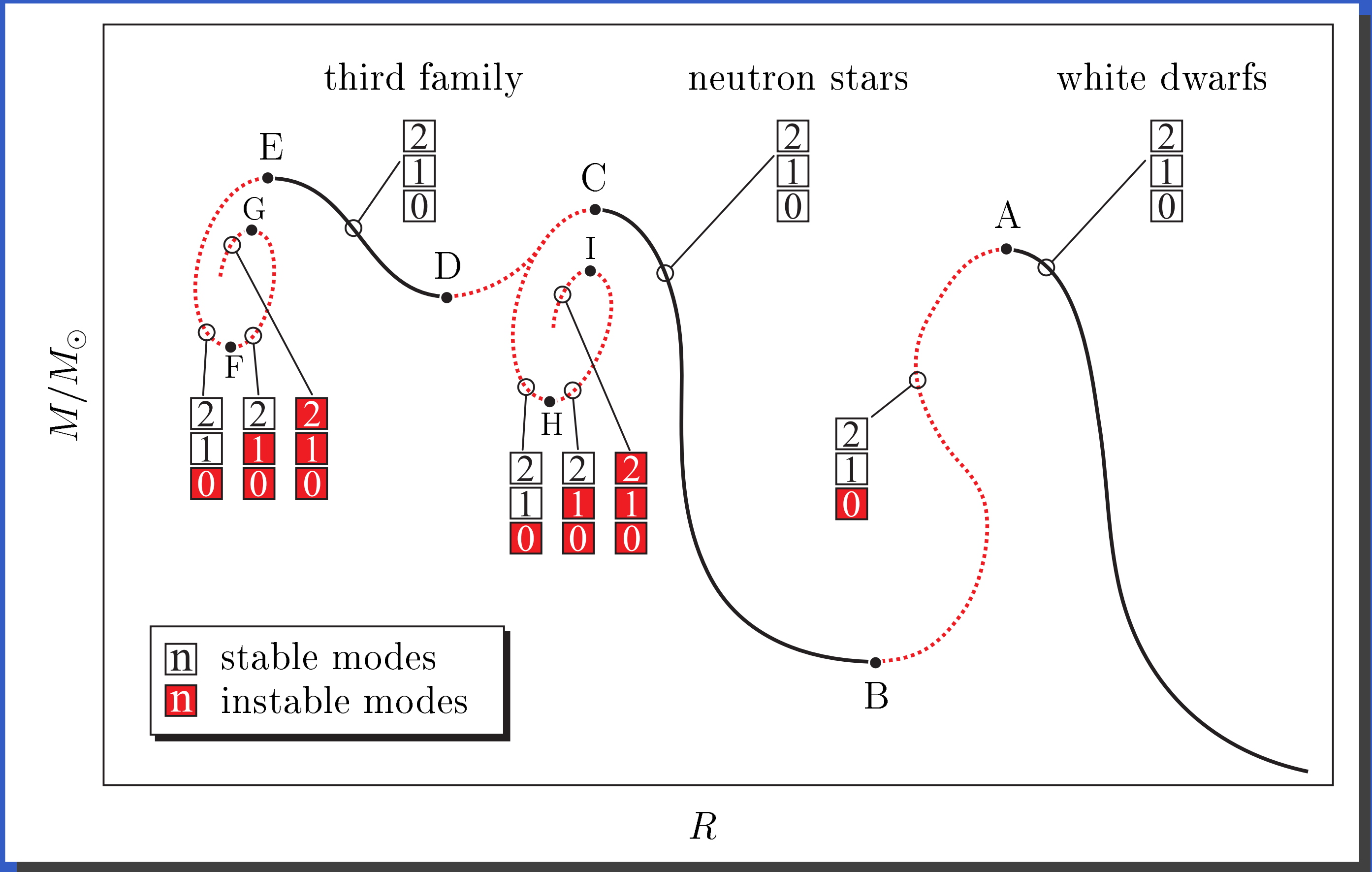
Quark star twins? (Fraga, JSB, Pisarski 2001)



- Weak transition: ordinary neutron star with quark core (hybrid star)
- Strong transition: third class of compact stars possible with maximum masses $M \sim 1\, M_\odot$ and radii $R \sim 6$ km
- Quark phase dominates ($n \sim 15\, n_0$ at the center), small hadronic mantle

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?

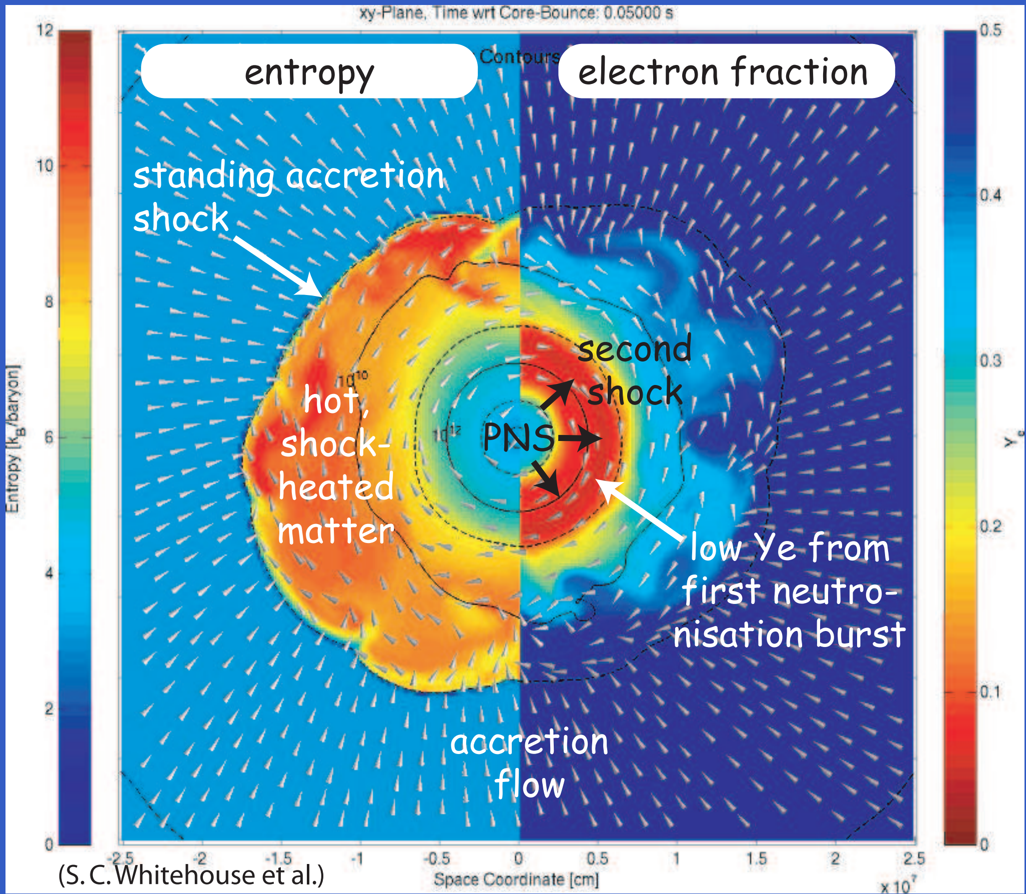
- spontaneous spin-up of pulsars (Glendenning, Pei, Weber, 1997)
- mass-radius relation: rising twins (Schertler et al., 2000)
- collapse of a neutron star to a quark star? (gravitational waves, γ-rays, neutrinos)
- r-mode instabilities: millisecond pulsars, gravitational wave burst (Drago, Pagliara, Berezhiani, 2006), . . .
- gamma-ray bursts with late x-ray emission, long quiescent times (Drago and Pagliara, 2007), . . .
- gravitational waves from neutron star mergers
- secondary shock wave in supernova explosions?

QCD phase transition in supernovae

Irina Sagert, Matthias Hempel, Giuseppe Pagliara, JSB, Tobias Fischer, Anthony Mezzacappa, Friedel Thielemann, Matthias Liebendörfer, PRL 102, 081101 (2009)

Supernova Explosions

(Liebendörfer et al.)

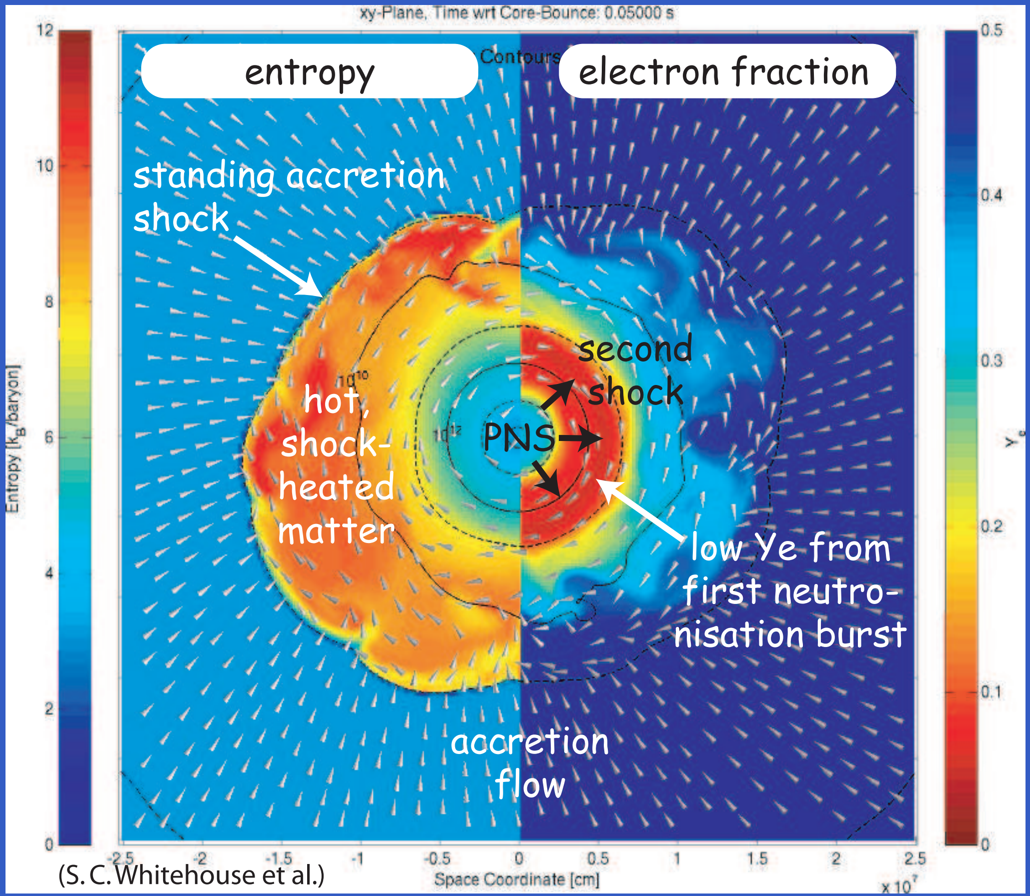


- stars with a mass of more than 8 solar masses end in a (core collapse) supernova (type II)
- new generation of simulation codes: 3D, Boltzmann neutrino transport
- Improved Models of Stellar Core Collapse and Still no Explosions: What is Missing? (Buras, Rampp, Janka, Kifonidis, PRL 2004)

'. . . the models do not explode. This suggests missing physics, possibly with respect to the nuclear equation of state . . . ' !

Supernova Explosions

(Liebendörfer et al.)



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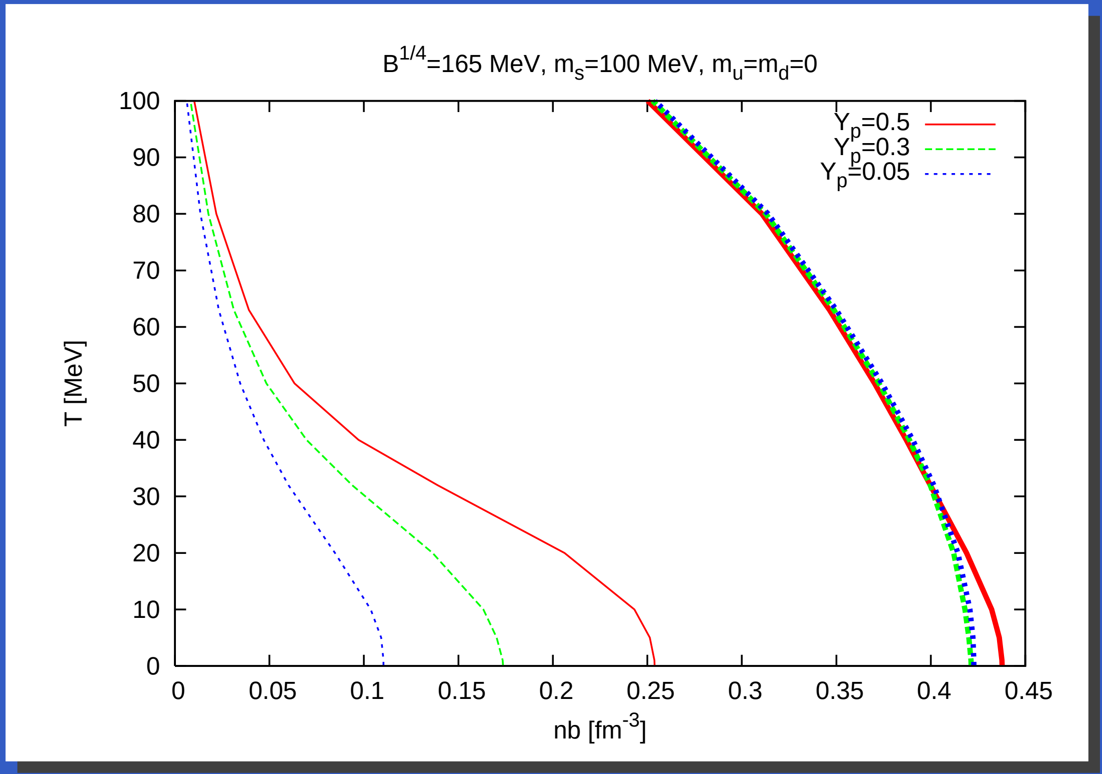
SASI: standing accretion shock instability, the models *do* explode after 600ms! (Marek and Janka, 2009)

Phase Transition to Quark Matter for Astros



(Irina Sagert and Giuseppe Pagliara)

- quark matter appears at low density due to β-equilibrium
- low critical density for low protn fraction (Y_p) due to nuclear asymmetry energy
- quark matter favoured at finite temperature
- supernova matter at bounce: $T = 10 - 20$ MeV, $Y_p = 0.2 - 0.3$, $\epsilon \sim (1 - 1.5)\epsilon_0$

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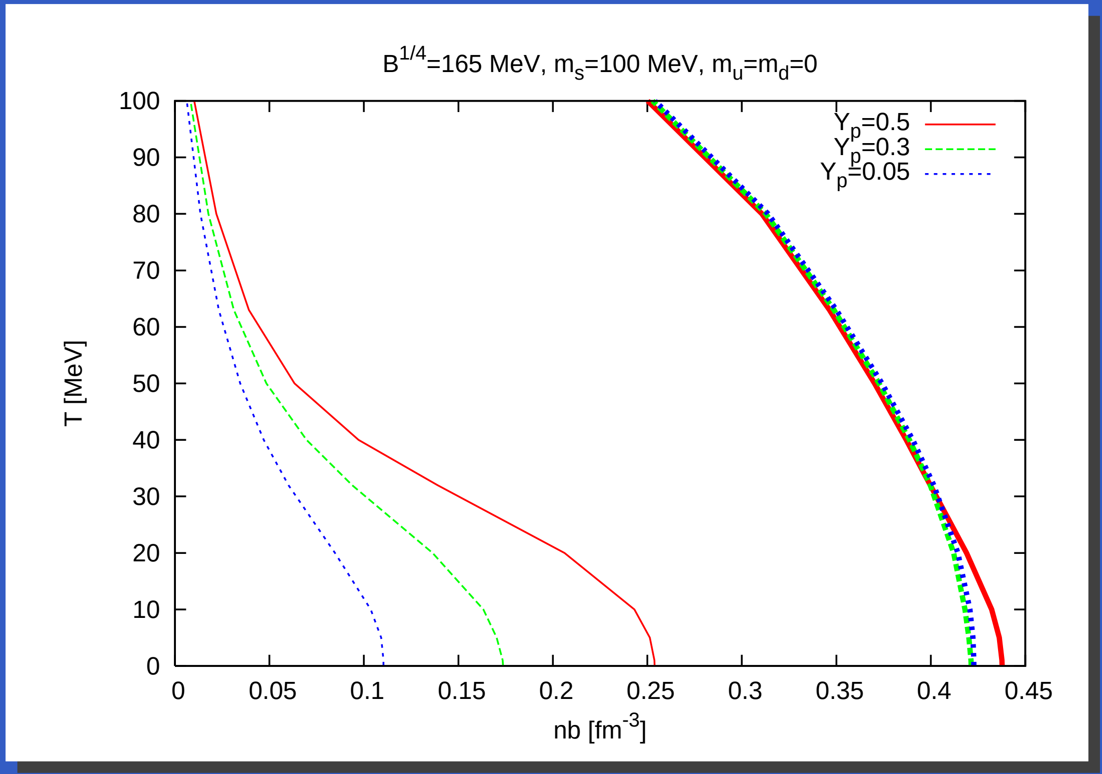

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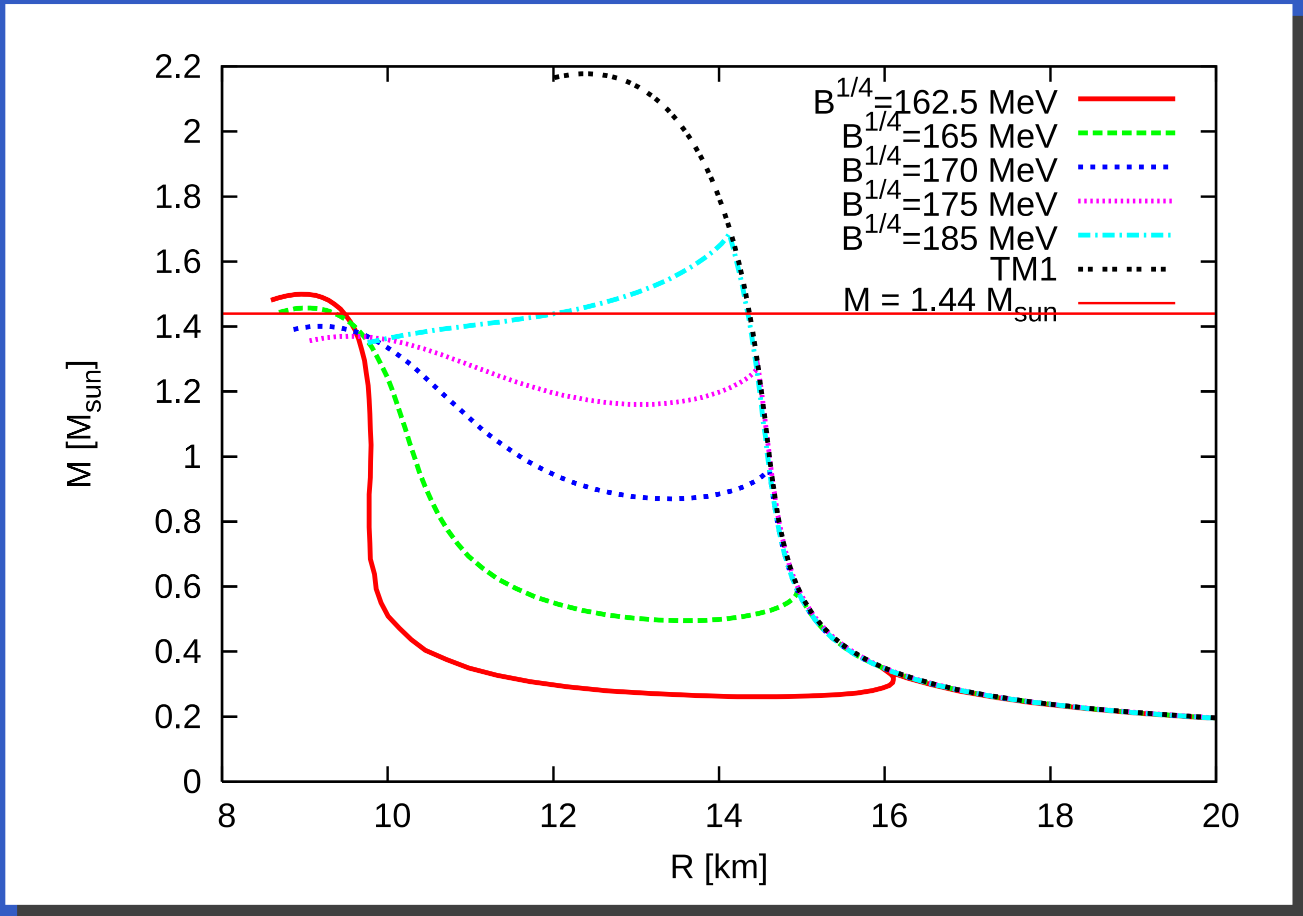
- supernova matter at bounce: $T = 10 - 20$ MeV, $Y_p = 0.2 - 0.3$, $\epsilon \sim (1 - 1.5)\epsilon_0$
- production of quark matter in supernovae at bounce possible!

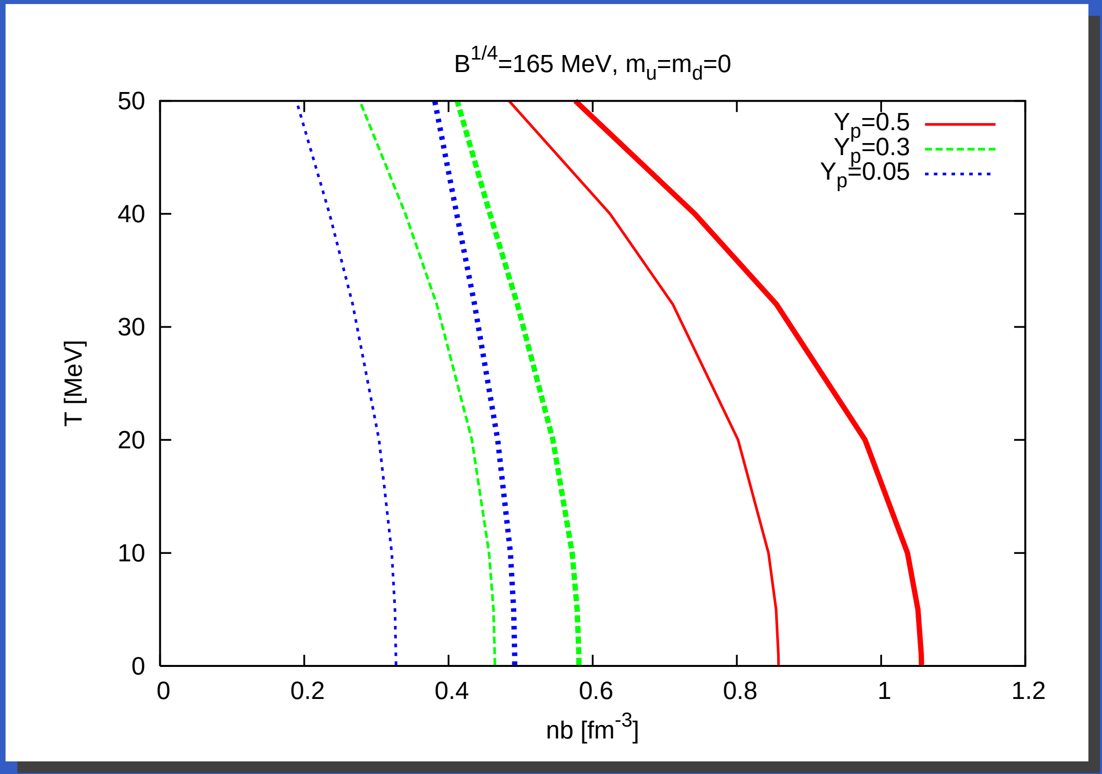
Check: Mass-Radius Diagram of Cold Neutron Stars



(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)

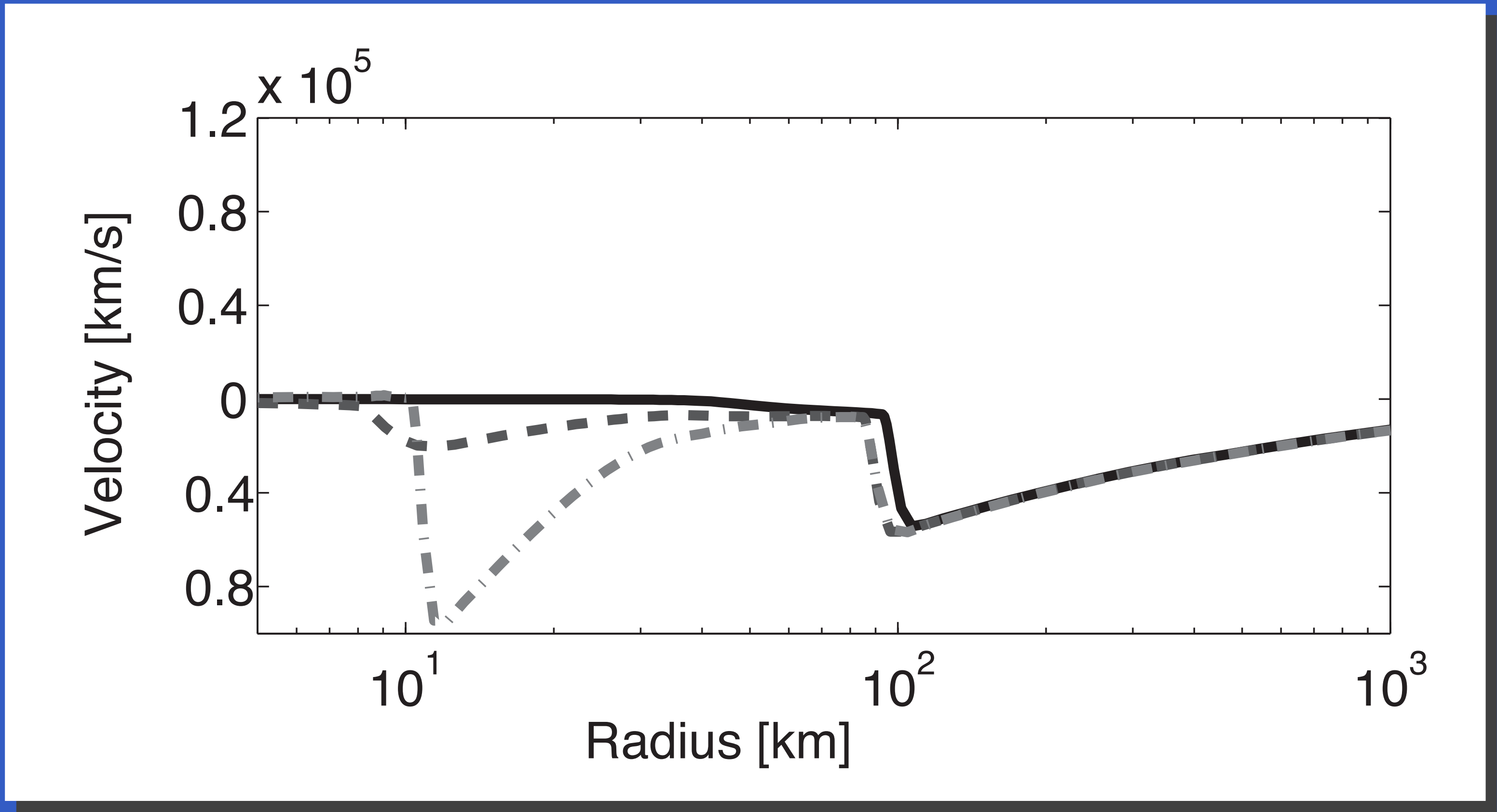
Check: Phase Transition for Heavy-Ion Collisions



(Irina Sagert and Giuseppe Pagliara)

- no β-equilibrium (just up-/down-quark matter)
- large critical densities in particular for isospin-symmetric matter (proton fraction $Y_p = 0.5$)
- production of ud-quark matter unfavoured for HICs at small T and high density
- no contradiction with heavy-ion data!

Implications for Supernovae – Explosion!



(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2009)

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

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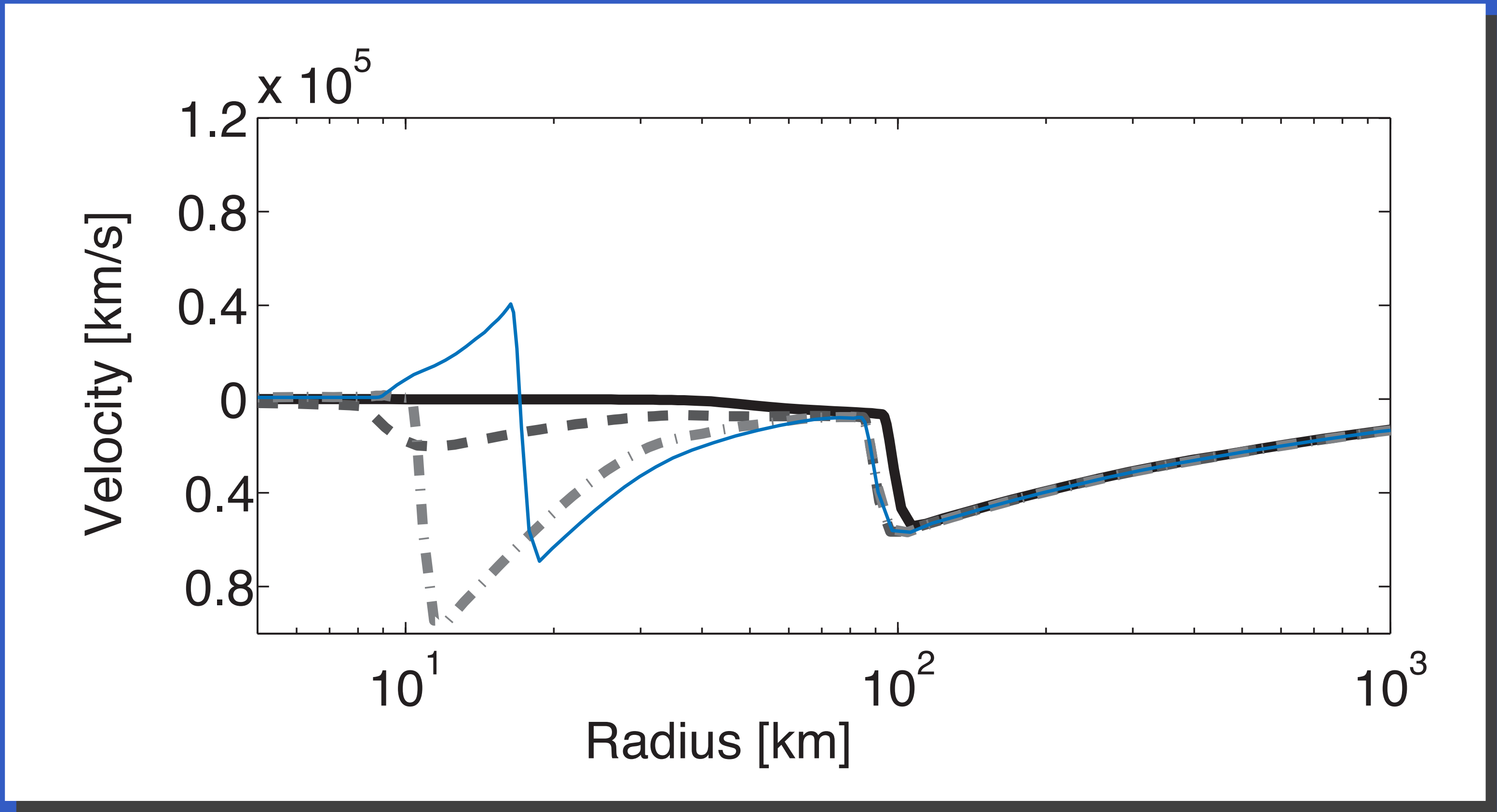

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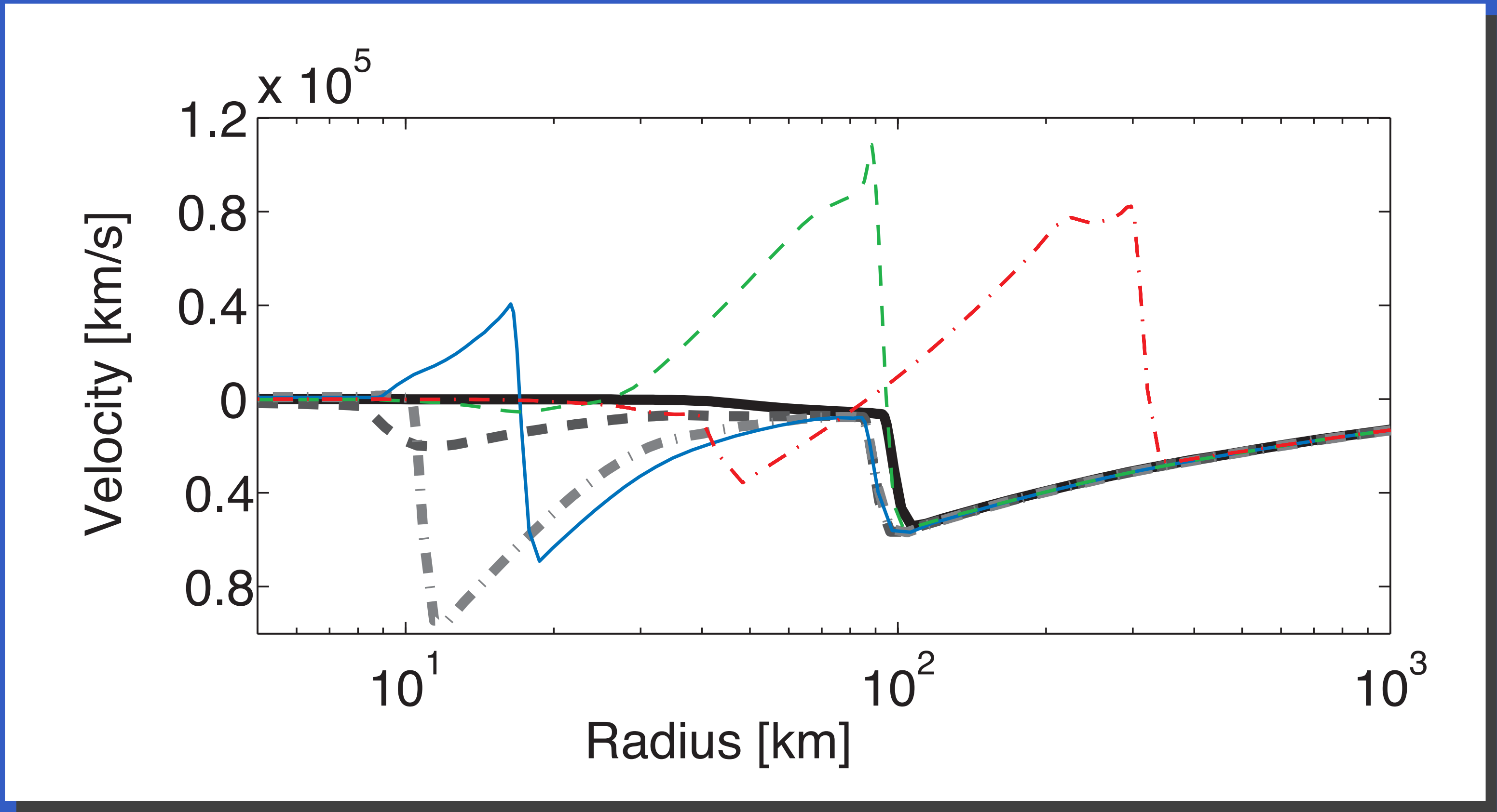

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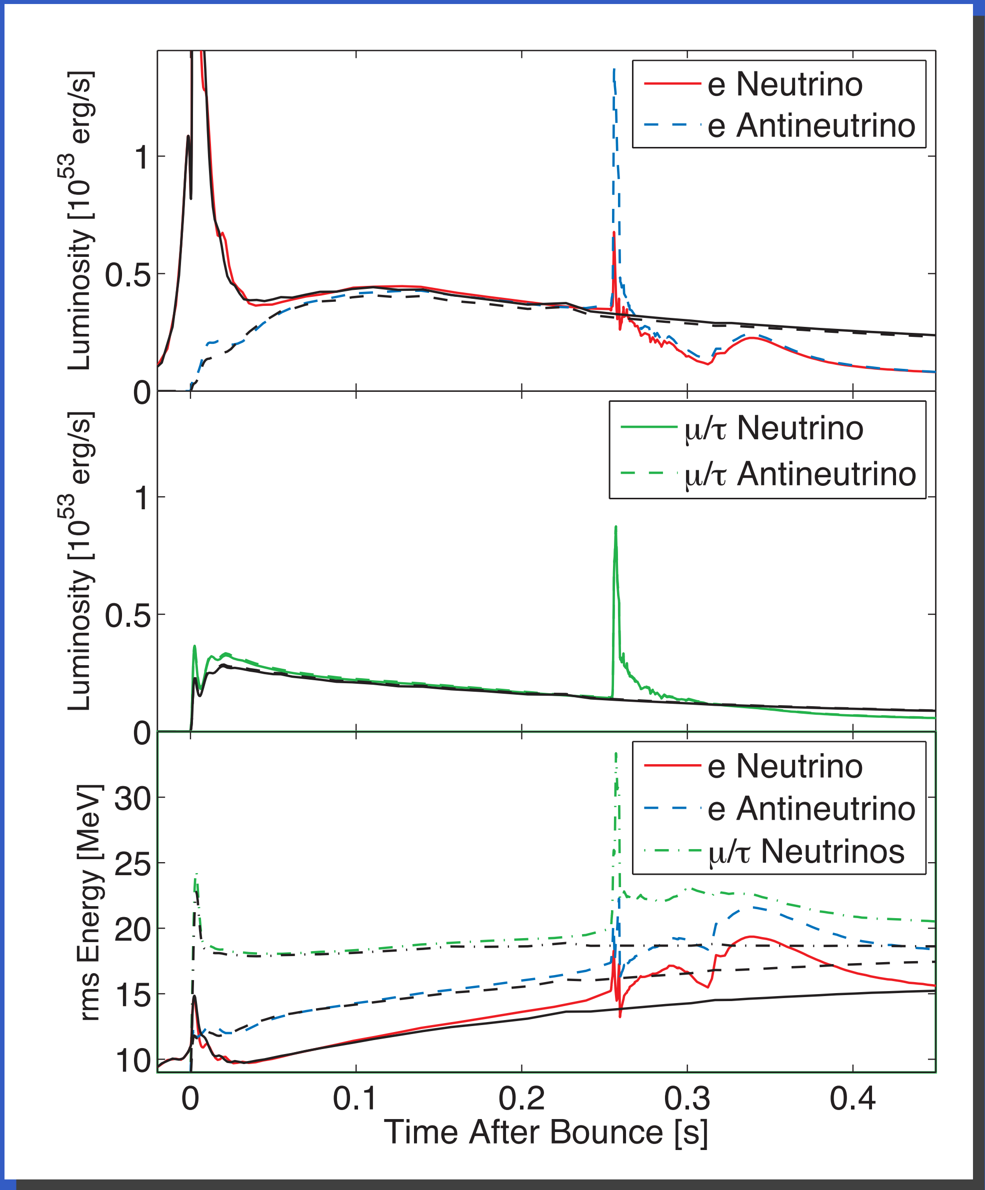
- velocity profile of a supernova for different times (around 250ms)
- formation of a core of pure quark matter produces a second shock wave
- leads to an explosion!

Implications for Supernova – Neutrino-Signal!

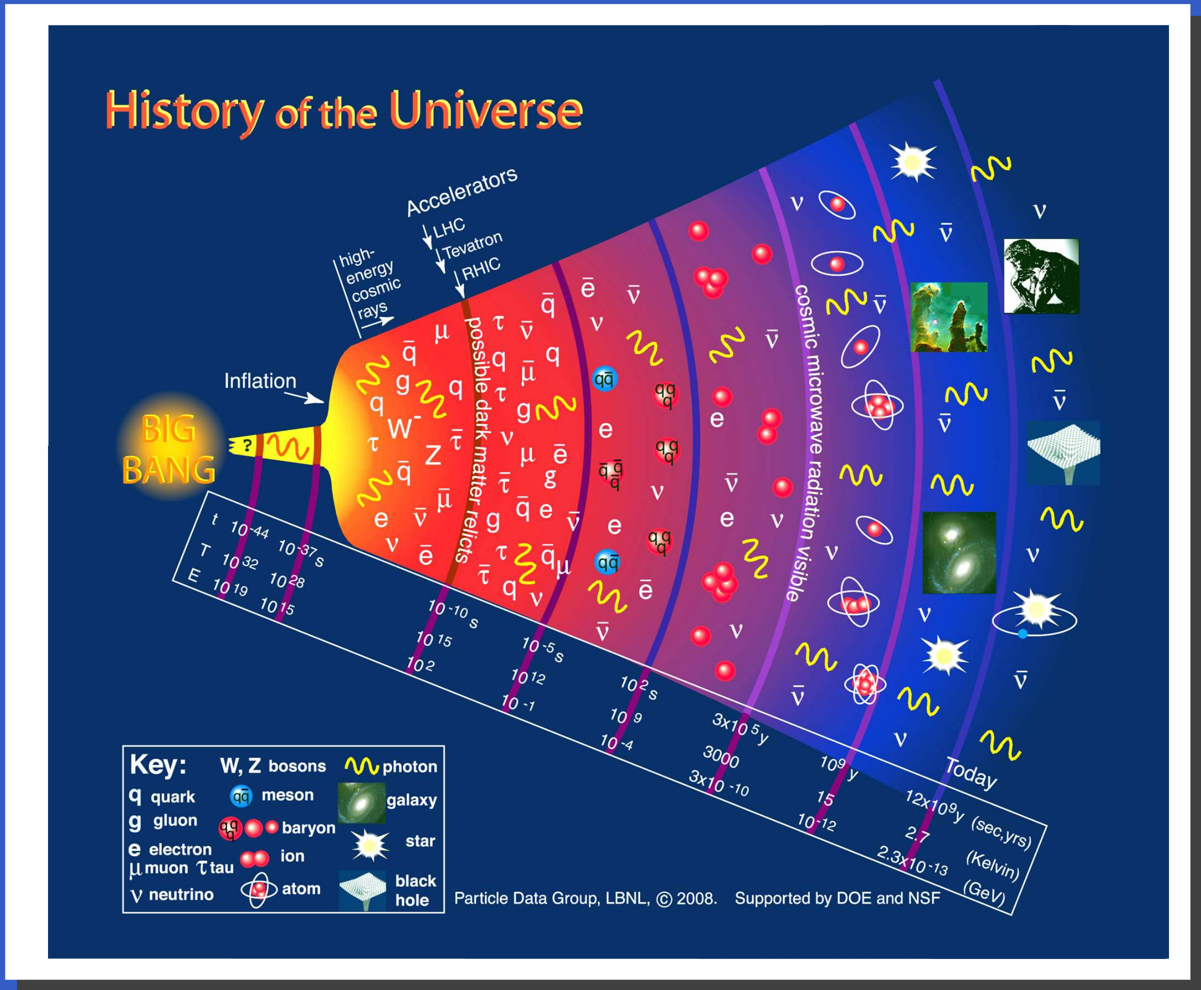


(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2009)

- 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!!

QCD phase transition in the early universe

History of the early universe



- Early universe: temperature increases with scale parameter as a^{-1}
- at $t = 1$s to 3 minutes: BBN ($T = 0.1$ to 1 MeV)
- at $t \approx 10^{-5}$s: QCD phase transition ($T \approx 170$ MeV)
- at $t \approx 10^{-10}$s: electroweak phase transition ($T \approx 100$ GeV)

Standard cosmology

from microwave background radiation and big bang nucleosynthesis:

$$n_B/s \sim n_B/n_\gamma \sim \mu/T \sim 10^{-9}$$

note: baryon number per entropy is conserved

$\Longrightarrow$ early universe evolves along $\mu \sim 0$

$\Longrightarrow$ crossover transition, nothing spectacular, no cosmological signals

Friedmann equation for radiation dominated universe:

$$H^2 = \frac{8\pi G}{3}\rho \sim g(T)\frac{T^4}{M_p^2}$$

$g(T)$: effective number of relativistic degrees of freedom at T

Hubble time (true time $t = 3t_H$ for radiation dominated universe):

$$t_H = \frac{1}{H} \sim g^{-1/2}\frac{M_P}{T^2} \Longrightarrow \frac{t}{1\text{ sec}} \sim \left(\frac{1\text{ MeV}}{T}\right)^2$$

A little inflation at the QCD phase transition

what happens if the early universe passes through a first order phase transition?

- is this possible? $\Longrightarrow$ Yes! no contradiction with present data
- could this be observable? $\Longrightarrow$ Yes! by gravitational waves

1st order phase transition $\Longrightarrow$ false metastable vacuum
$\Longrightarrow$ de Sitter solution $\Longrightarrow$ (additional small) inflationary period

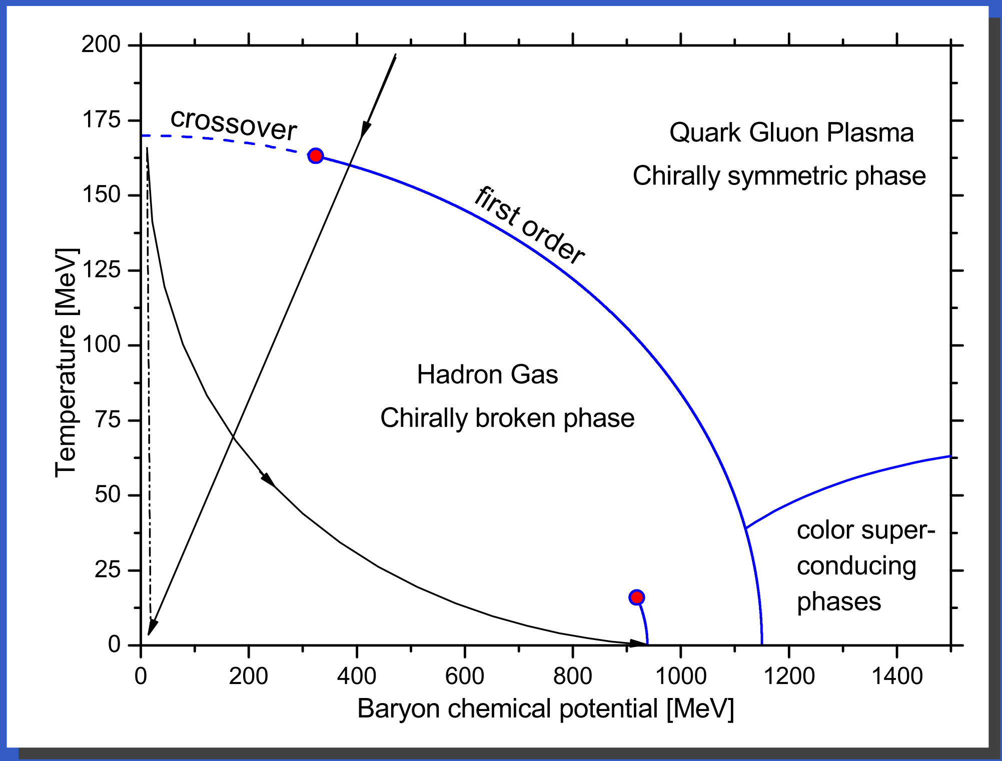
$$H = \dot{a}/a \sim M_p^{-1} \rho_{\mathrm{v}}^{1/2} = H_{\mathrm{v}} = const. \rightarrow a \sim \exp(H_{\mathrm{v}} \cdot t)$$

just a few e-folds is enough (standard inflation needs $N \sim 50$):

$$\left(\frac{\mu}{T}\right)_f \approx \left(\frac{a_i}{a_f}\right)^3 \left(\frac{\mu}{T}\right)_i$$

Hence $(\mu/T)_i \sim \mathcal{O}(1)$ for just $N = \ln\left(a_f/a_i\right) \sim \ln(10^3) \sim 7$

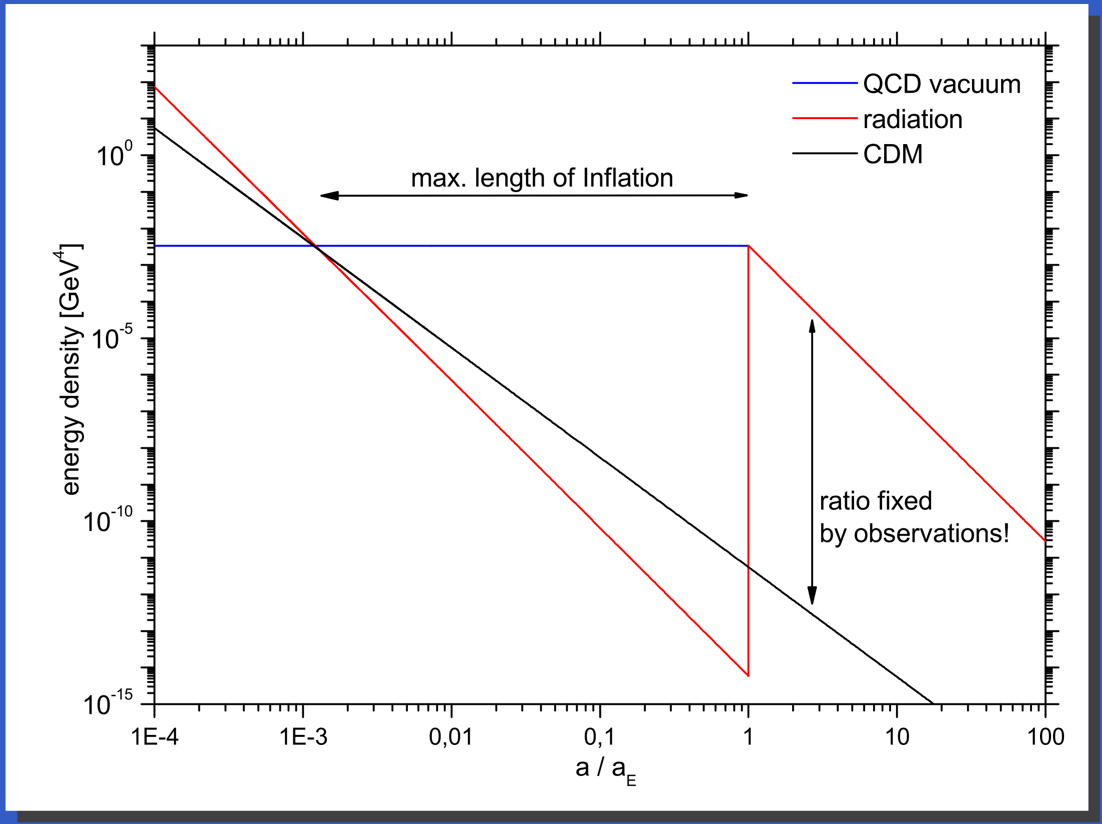
A little inflation in the QCD phase diagram



(Boeckel and JSB, arXiv:0906.4520)

- start with $\mu/T \sim 1$ (possible for e.g. Affleck-Dine baryogenesis)
- universe trapped in false vacuum at the transition line
- supercooling and dilution with $\mu/T = const.$
- decay to the true vacuum state $\rightarrow$ reheating to $T \sim T_c$ so that $\mu/T \sim 10^{-9}$
- then standard cosmological evolution to BBN

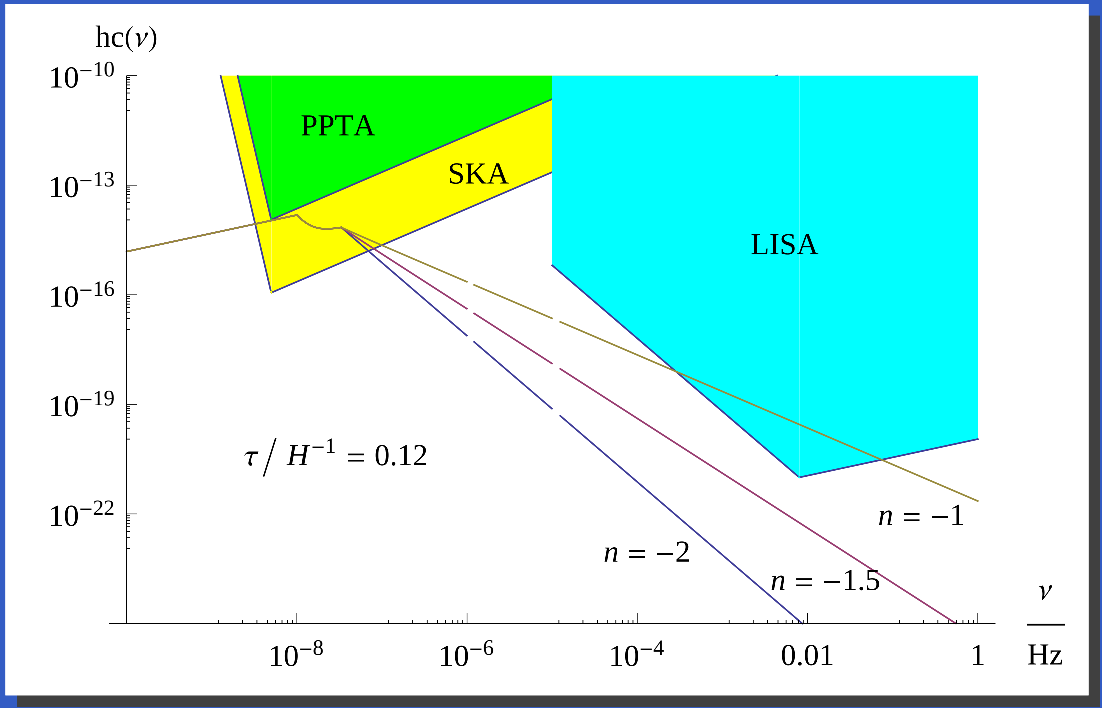
A little inflation – evolution of densities



(Boeckel and JSB, arXiv:0906.4520)

- energy density falls as a^{-4} until $\rho \sim \Lambda_{\rm QCD}^4$
- then $\rho = const. \rightarrow$ inflationary period starts
- reheating at the end of inflation
- maximum length of inflation for scale parameter a from CDM density $\sim 10^3$

Cosmological signal in gravitational waves!



(Till Boeckel)

- first order transition produces tensor perturbations → gravitational waves
- frequency scale given by (redshifted) horizon scale at the transition point $\nu_{\rm peak} \sim H \cdot T_{\gamma,0}/T \sim T/M_p \cdot T_{\gamma,0} \sim 10^{-7}$ Hz, amplitude $h \sim a/a_0 \sim 10^{-12}$
- amplitude scales as $h(\nu) \propto \nu^{-1/2}$ for $\nu < H$ (white noise) and as $h(\nu) \propto \nu^{-2\ldots-1}$ for $\nu > H$ (multi bubble collisions) (Kamionkowski, Kosowsky, Turner 1994, Huber, Konstandin 2008)

Cosmological implications of a first order transition

- gravitational wave background:
  observable with pulsar timing and LISA
- cold dark matter density is diluted by 10^{-9}
  $\rightarrow$ need different WIMP annihilation cross section as
  $\Omega_{\text{CDM}} \sim \sigma_{\text{weak}}/\sigma_{\text{ann}}$ or larger WIMP mass (probed by LHC!)
- large-scale structure modified up to $M \sim 10^9 M_\odot$
  (without QCD inflation only up the horizon mass $\sim 10^{-9} M_\odot$)
- generation of the seeds of (extra)galactic magnetic fields:
  observed today in our galaxy $B \sim 10^{-5}$ G,
  extragalactic $B \sim 10^{-7}$ G
  need primordial seed fields of $B = 10^{-30} \ldots 10^{-10}$ G
  $\rightarrow$ possible within the standard model again!

Summary and Outlook

- QCD phase transition can occur in the core of neutron stars
  $\Longrightarrow$ new family of compact stars possible, explosive phenomena
- transition can be present during a supernova, shortly after the first bounce
  $\Longrightarrow$ second shock forms, visible in a a second peak in the (anti-)neutrino signal, gravitational waves, r-process nucleosynthesis . . .
- 1st order transition could have happened in the early universe
  $\Longrightarrow$ impact on gravitational wave background, structure formation, cold dark matter densities . . .
- input needed from QCD: effective potential and nucleation timescales!

Thanks to:

my research group in Heidelberg:

- Giuseppe Pagliara
- Basil Sa'd
- Till Boeckel
- Matthias Hempel
- Irina Sagert
- Rainer Stiele
- Simon Schettler