

Sonne, Mond ... und Quarksterne!

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RUPRECHT-KARLS-
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HEIDELBERG



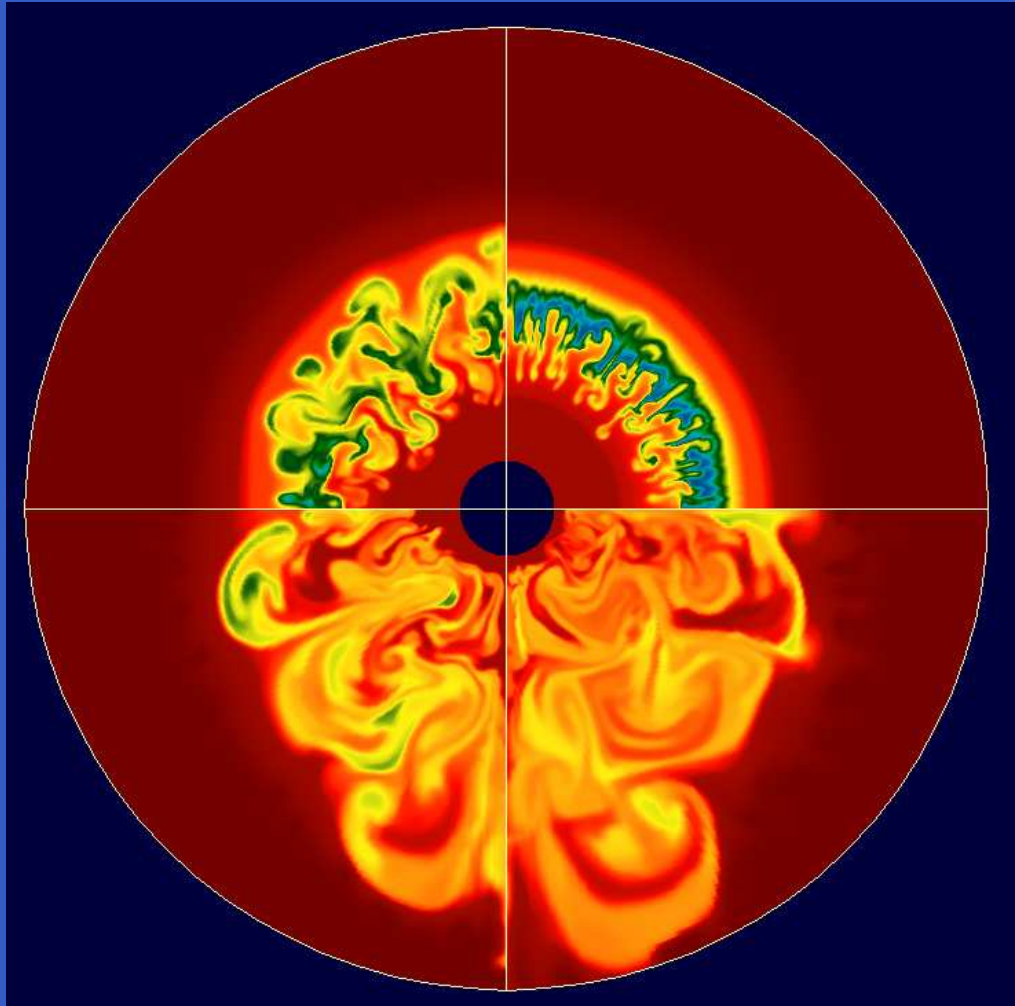
PIZZA Night

Ruprechts-Karl-Universität, Heidelberg, 08. Juli 2009

- Introduction: Quark stars
- Connecting Quarks with the Cosmos:
 - QCD phase transition and neutron stars
 - QCD phase transition in supernovae
 - QCD phase transition in the early universe
- Outlook

Introduction: Quark Stars

Supernova Explosions



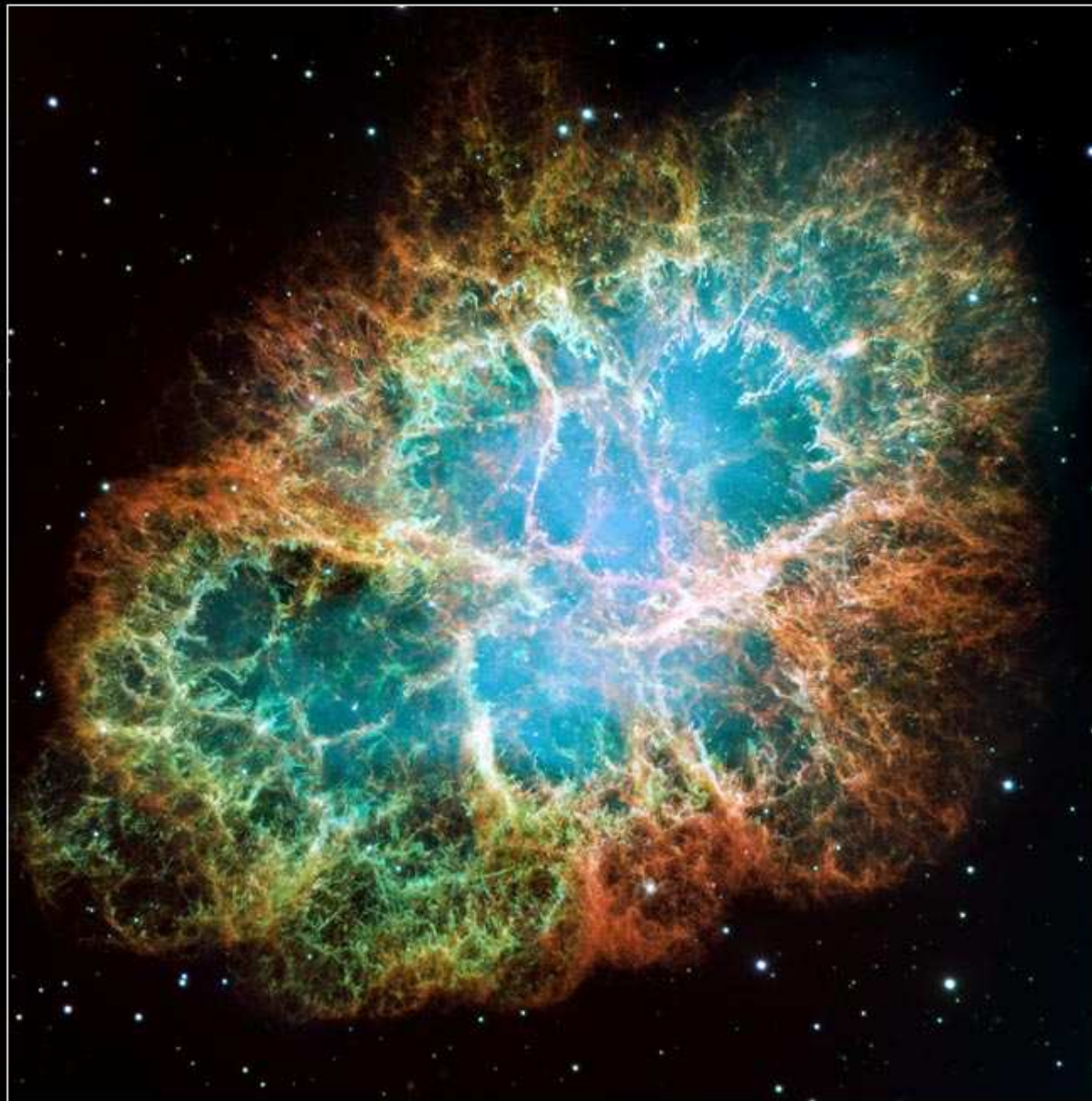
(supernova simulation by Janka et al.,
MPA Garching)

- stars with a mass of more than 8 solar masses end in a (core collapse) supernova (type II)
- Supernova of AD 1054 was visible for three weeks during daytime (crab nebula)!
- supernovae are several thousand times brighter than a whole galaxy!
- last supernova explosion for the last 400 years in our local group: SN1987A
- most prominent candidate in the universe for producing the heavy elements (r-process)

Neutron Stars

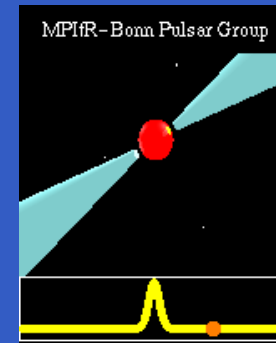
Crab Nebula ■ M1

HST ■ WFPC2



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

STScI-PRC05-37



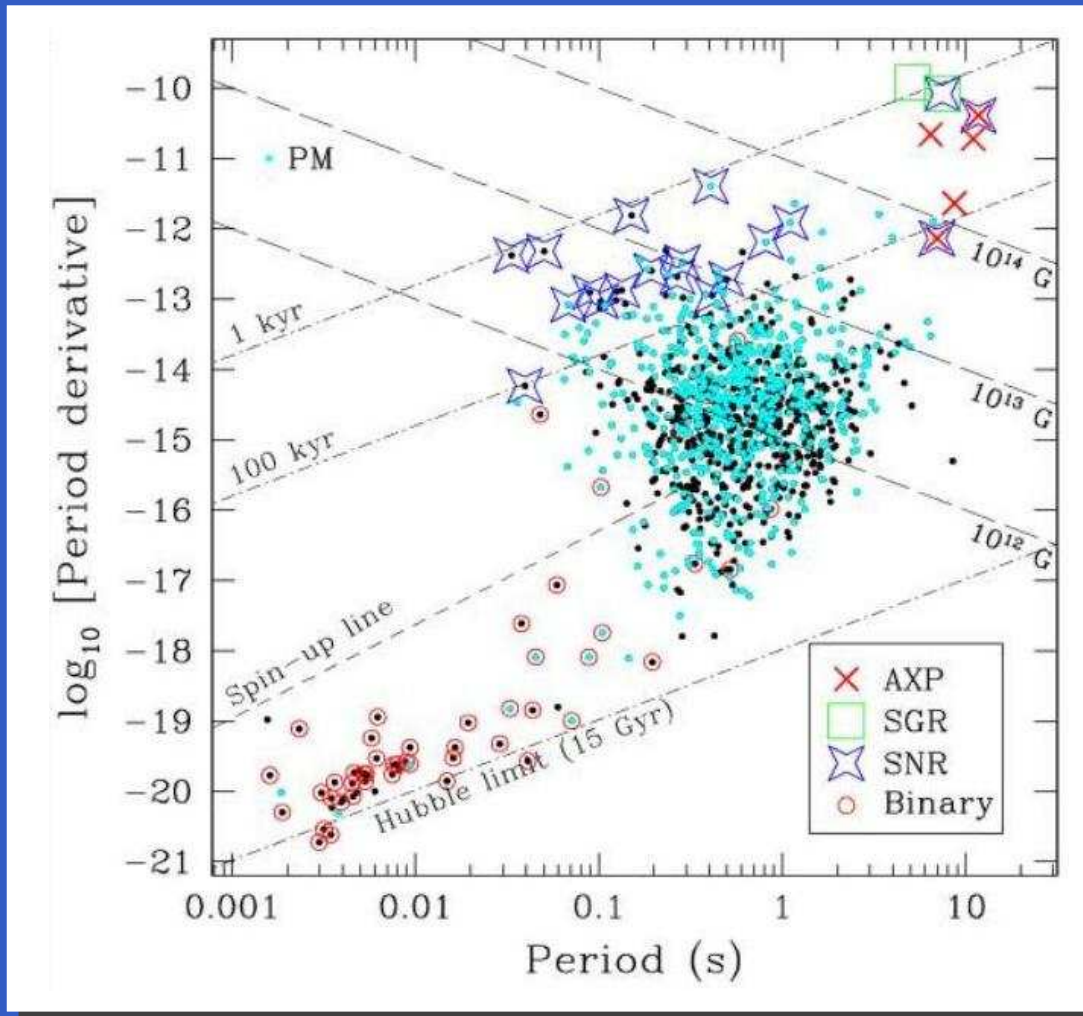
- produced in core collapse supernova explosions
- compact, massive objects: radius ≈ 10 km, mass $1 - 2M_{\odot}$
- extreme densities, several times nuclear density: $n \gg n_0 = 3 \cdot 10^{14}$ g/cm³
- in the middle of the crab nebula: a pulsar, a rotating neutron star!

Movie (seven still images in 11/2000–04/2001)

The Sounds of Pulsars

- PSR B0329+54: typical pulsar with a period of 0.7145519 s (1.4 pulses per second)
- PSR B0833-45 (Vela pulsar): in Vela supernova remnant, period of 89 ms (11 pulses per second)
- PSR B0531+21 (crab pulsar): youngest known pulsar, in crab nebula (M1), period: 33 ms (30 pulses per second)
- PSR J0437-4715: recently discovered pulsar, period of 5.7 ms (174 pulses per second)
- PSR B1937+21: second fastest known pulsar with a period of 1.56 ms (642 pulses per second)

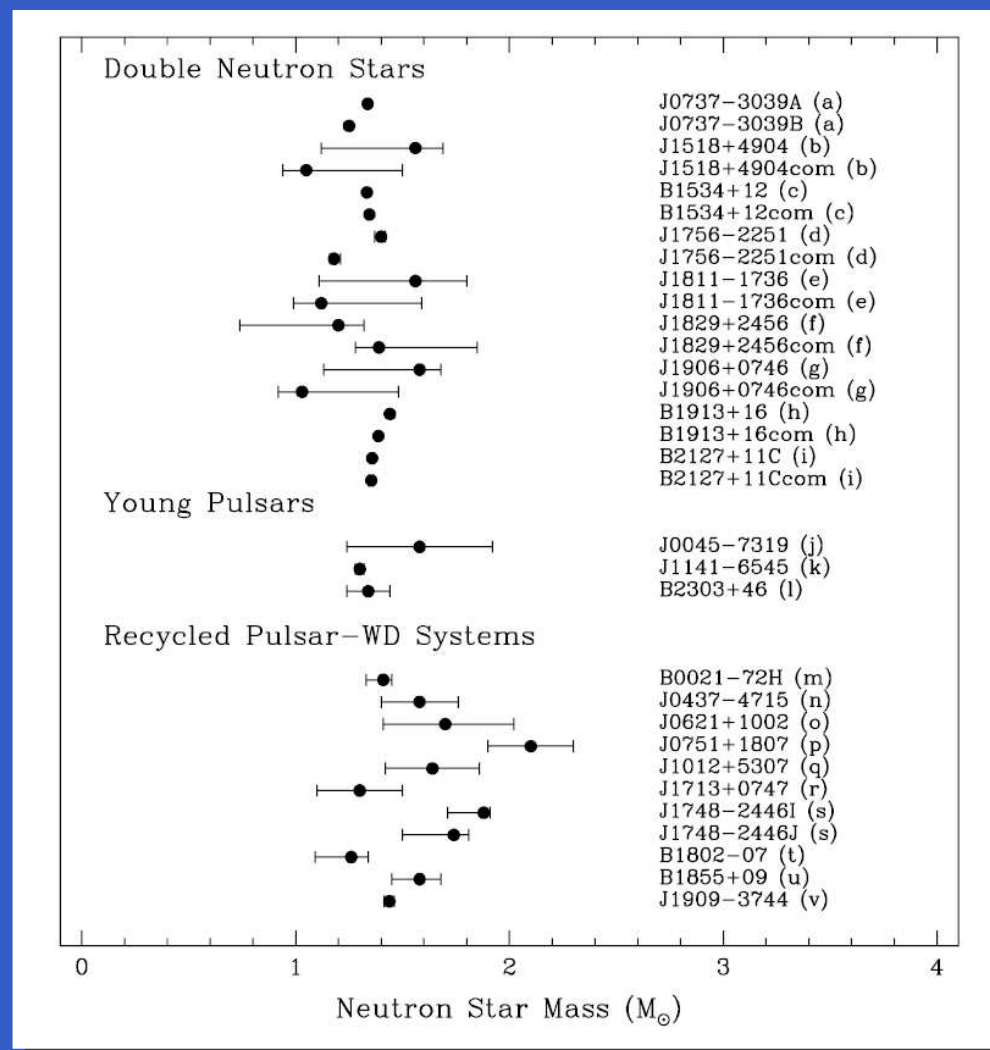
The Pulsar Diagram



(ATNF pulsar catalog)

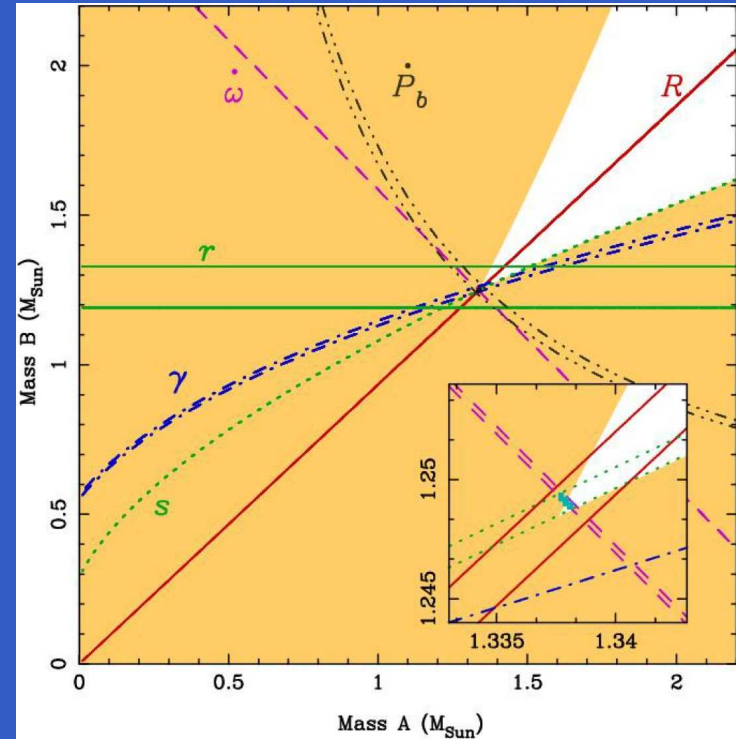
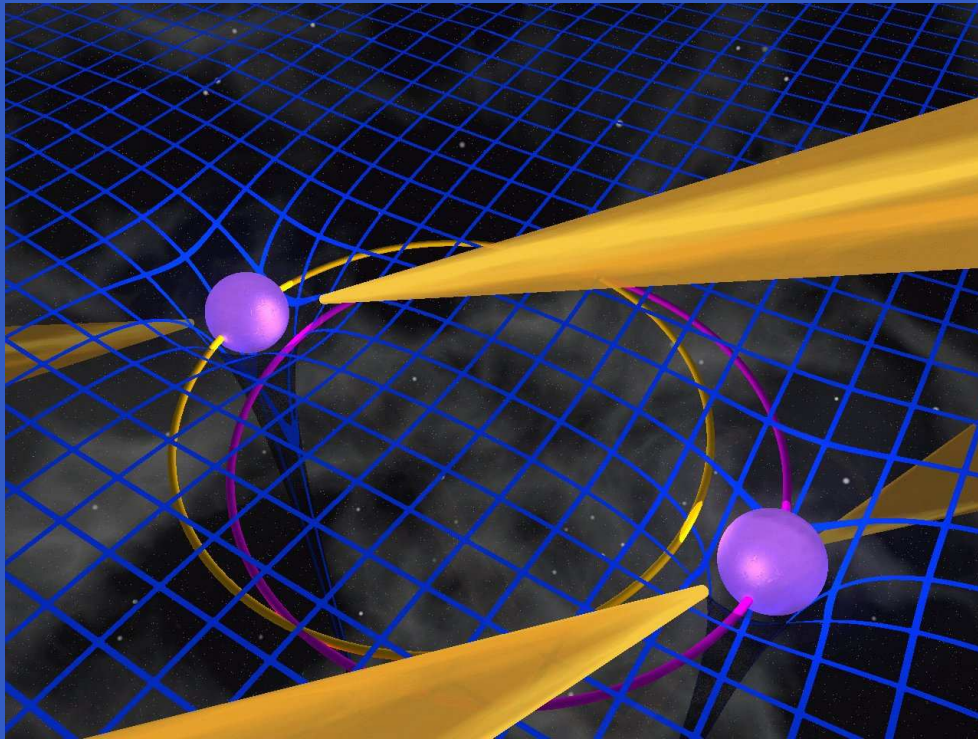
- the diagram for pulsars: period versus period change ($P-\dot{P}$)
- dipole model for pulsars:
characteristic age: $\tau = P/(2\dot{P})$
and magnetic field
 $B = 2 \cdot 10^{19} (P \cdot \dot{P})^{1/2}$ Gauss
- anomalous x-ray pulsars: AXP,
soft-gamma ray repeaters:
SGR, young pulsars in
supernova remnants: SNR
- rapidly rotating pulsars (millisecond pulsars): mostly in binary systems (old recycled pulsars!)

Masses of Pulsars (Stairs, 2006)



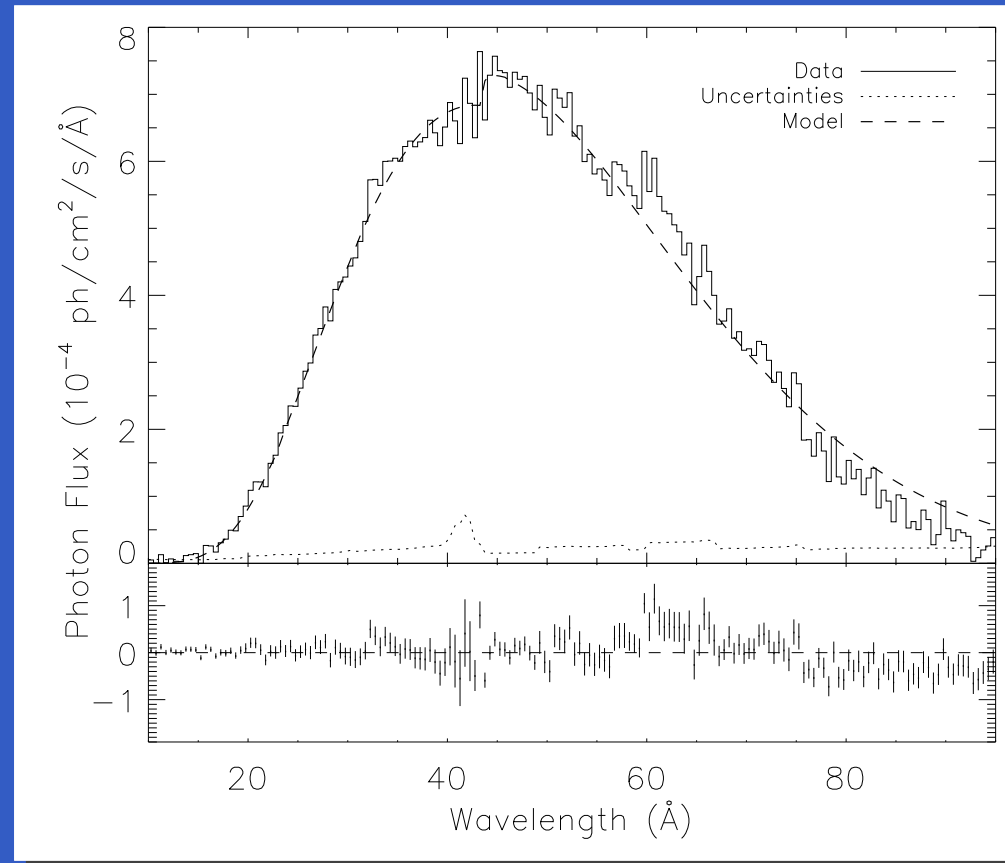
- more than 1700 pulsars known
- best determined mass:
 $M = (1.4414 \pm 0.0002)M_{\odot}$
 for the Hulse-Taylor pulsar
 (Weisberg and Taylor, 2004)
- smallest known mass:
 $M = (1.18 \pm 0.02)M_{\odot}$ for
 pulsar J1756-2251
 (Faulkner et al., 2005)
- PSR J0751+1807 corrected
 from $M = 2.1 \pm 0.2M_{\odot}$ to
 $M = 1.14 - 1.40M_{\odot}$
 (Nice et al. 2008)

The Double Pulsar PSR J0737-3039



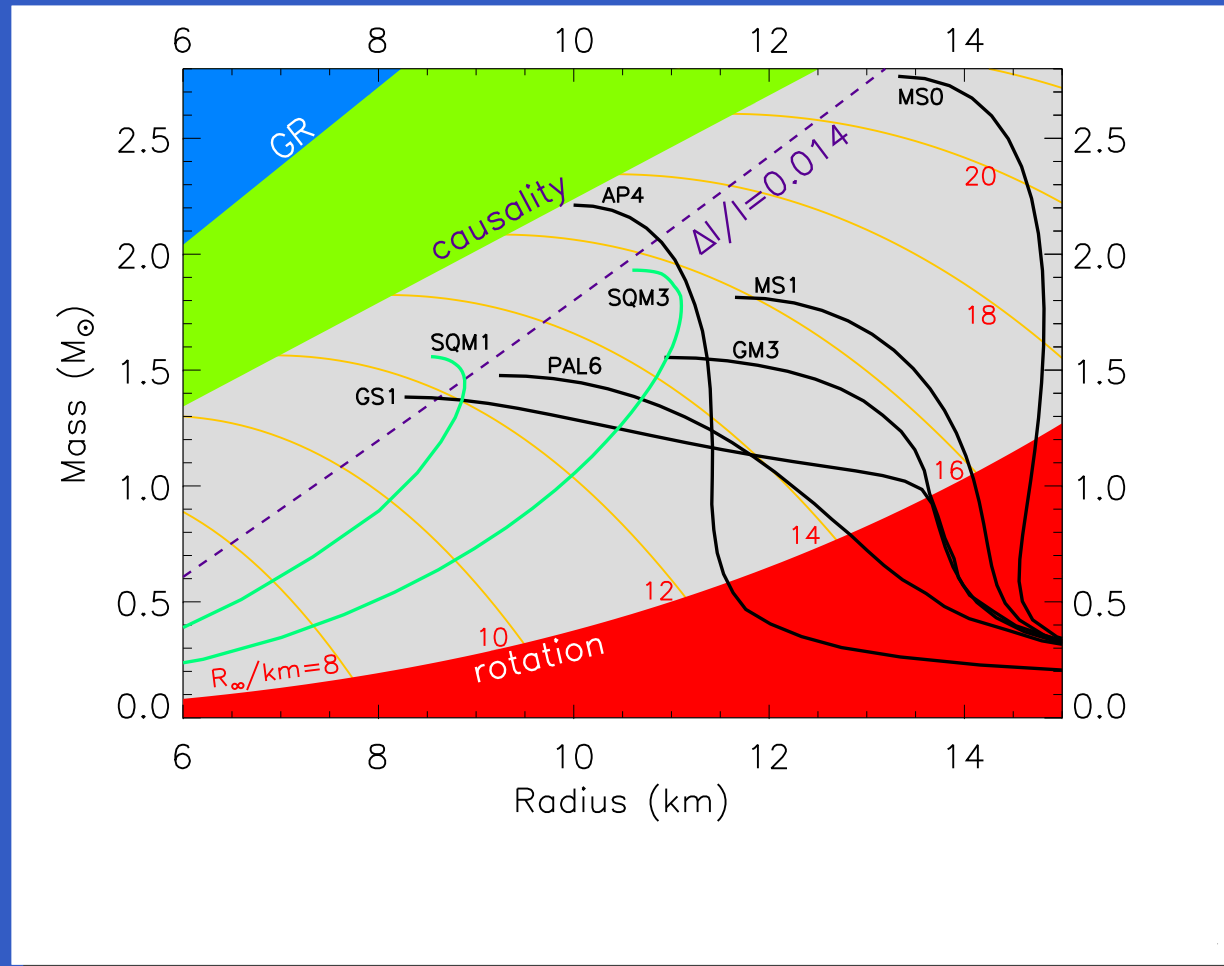
- sensational discovery of two pulsars orbiting each other (Lyne et al. 2004)
- measured five post-Keplerian parameters: Shapiro delay r and s , redshift γ , periastron advance $\dot{\omega}$, decrease in orbital period \dot{P}_b (Kramer et al. 2006)
- all in agreement with the prediction of GR to within 0.05% !
- fundamental tests of General Relativity in STRONG fields

Isolated Neutron Star RX J1856 (Drake et al. (2002))



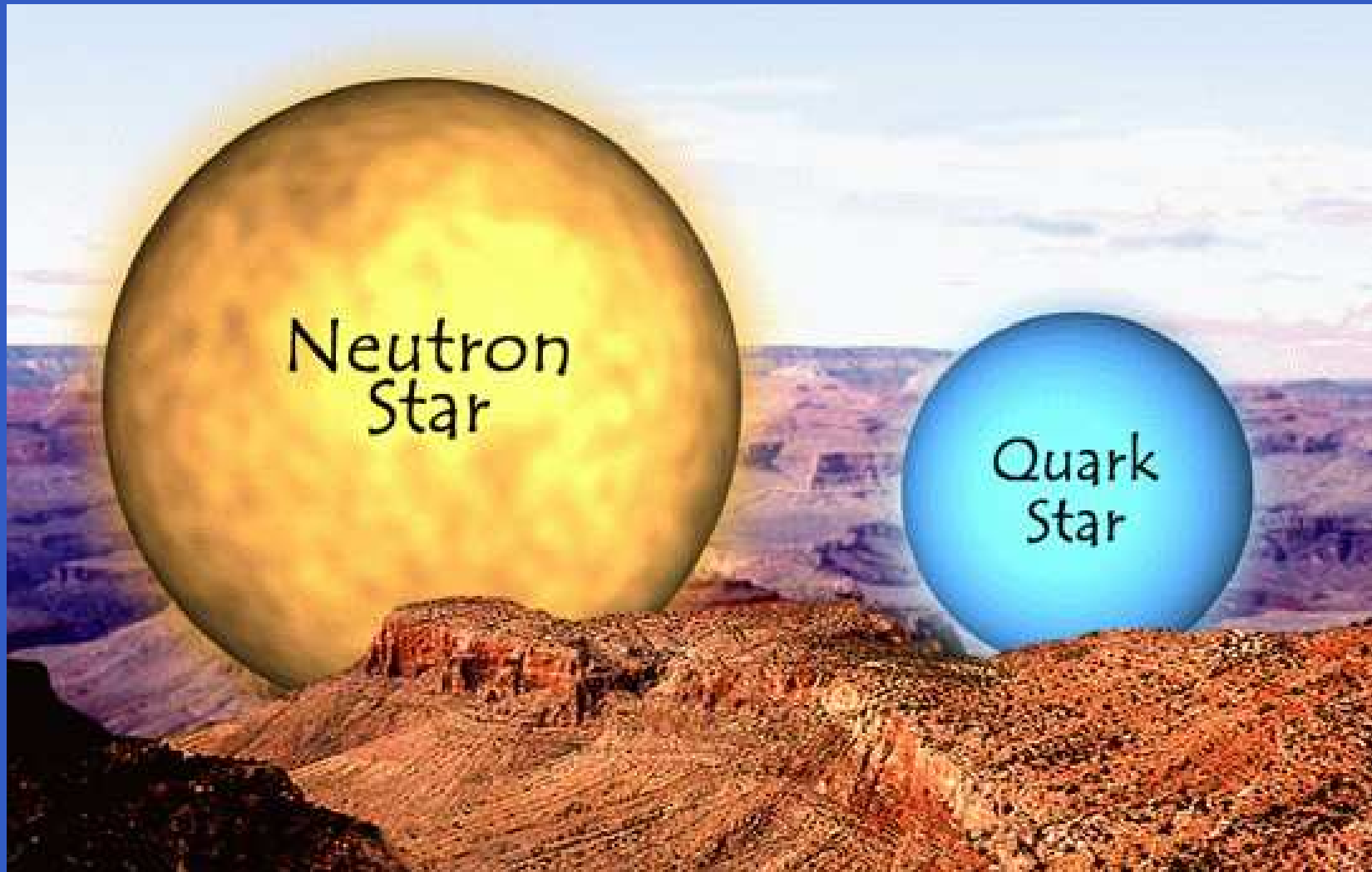
- closest known neutron star, parallax measurement with HST:
 $D = 117 \pm 12$ pc (Lattimer and Wolter 2002), $D = 140 \pm 40$ pc (van Kerkwijk and Kaplan 2004), $D = 161 \pm 18$ pc (Kaplan 2007)
- perfect black-body spectrum, no spectral lines!
- for black-body emission (x-ray part only): $T = 60$ eV and $R_\infty = 4 - 8$ km!

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



- spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4M_{\odot}$
- Schwarzschild limit (GR): $R > 2GM = R_s$
- causality limit for EoS: $R > 3GM$
- only quark stars can have small radii!

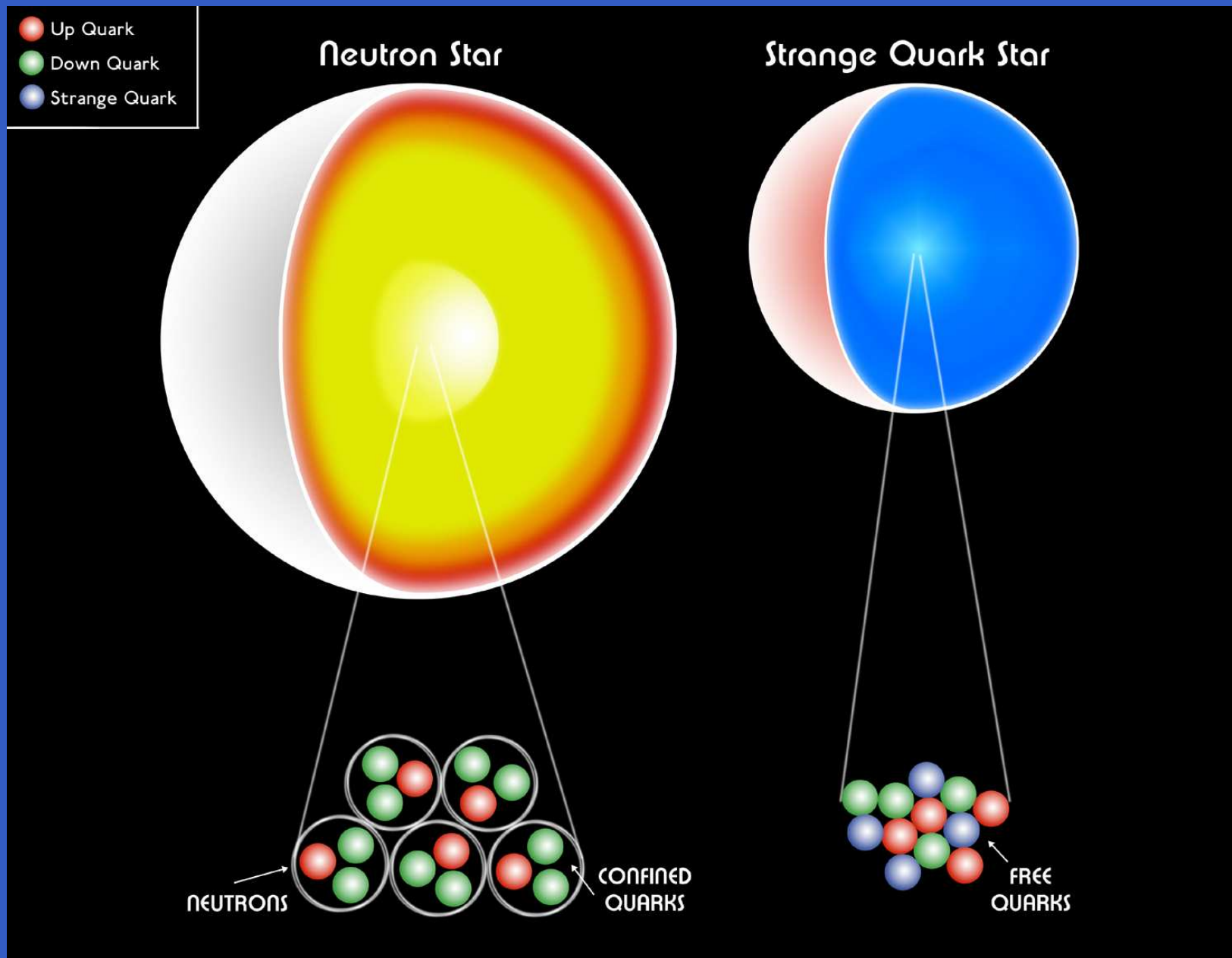
A Quark Star? (NASA press release 2002)



NASA news release 02-082:

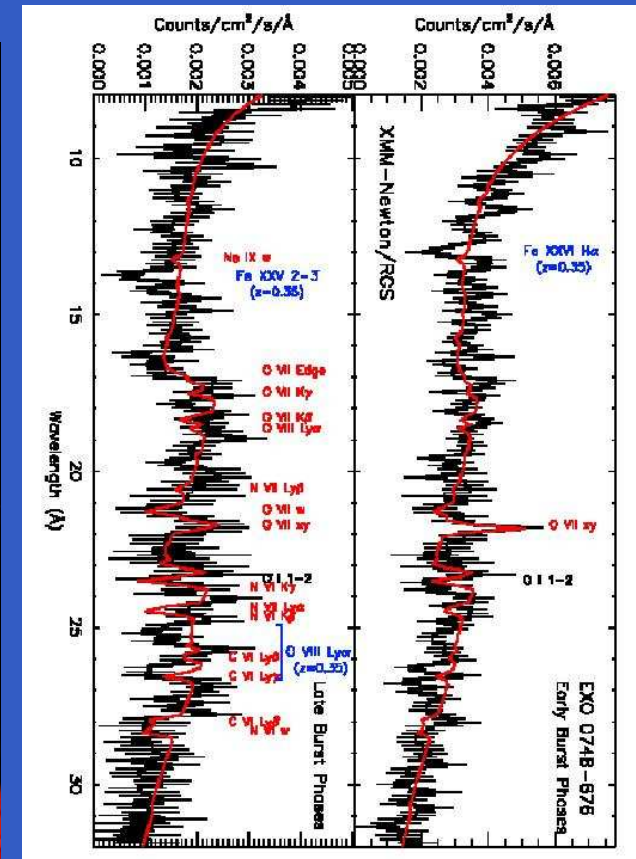
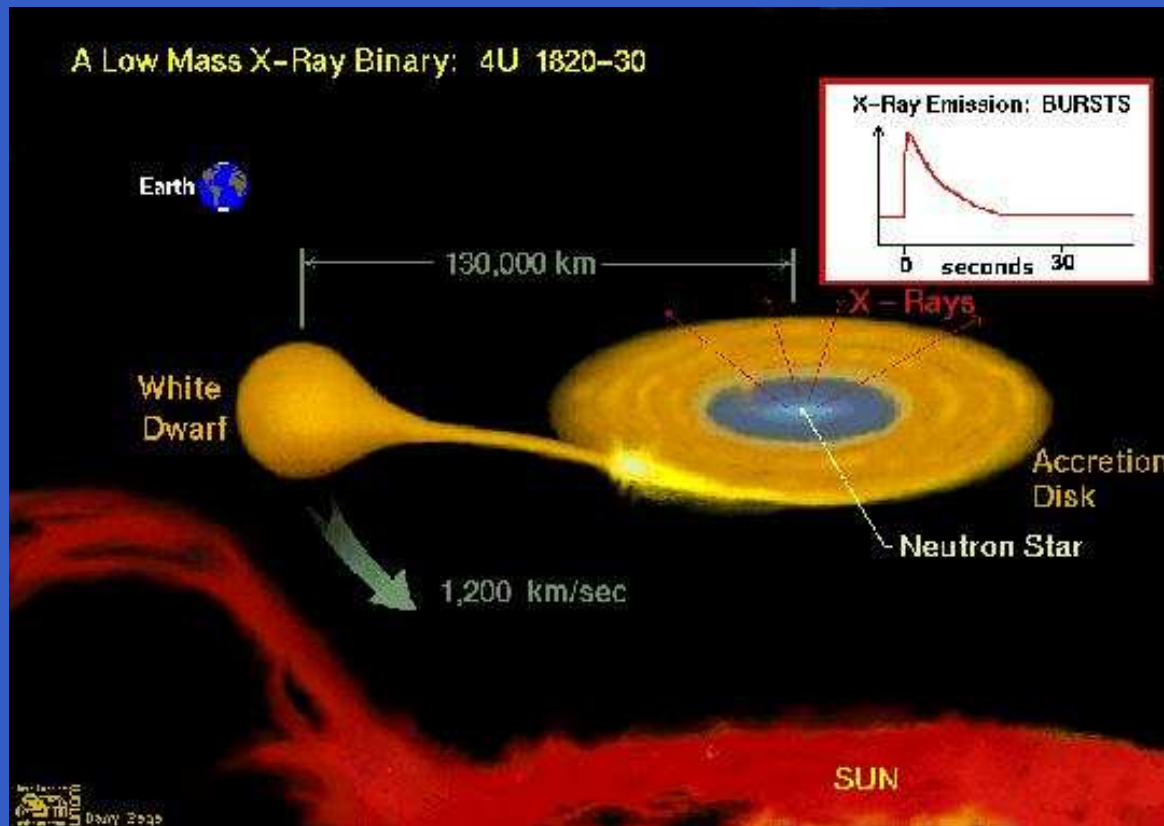
“Cosmic X-rays reveal evidence for new form of matter”
— a quark star?

Neutron Star versus Strange Quark Star



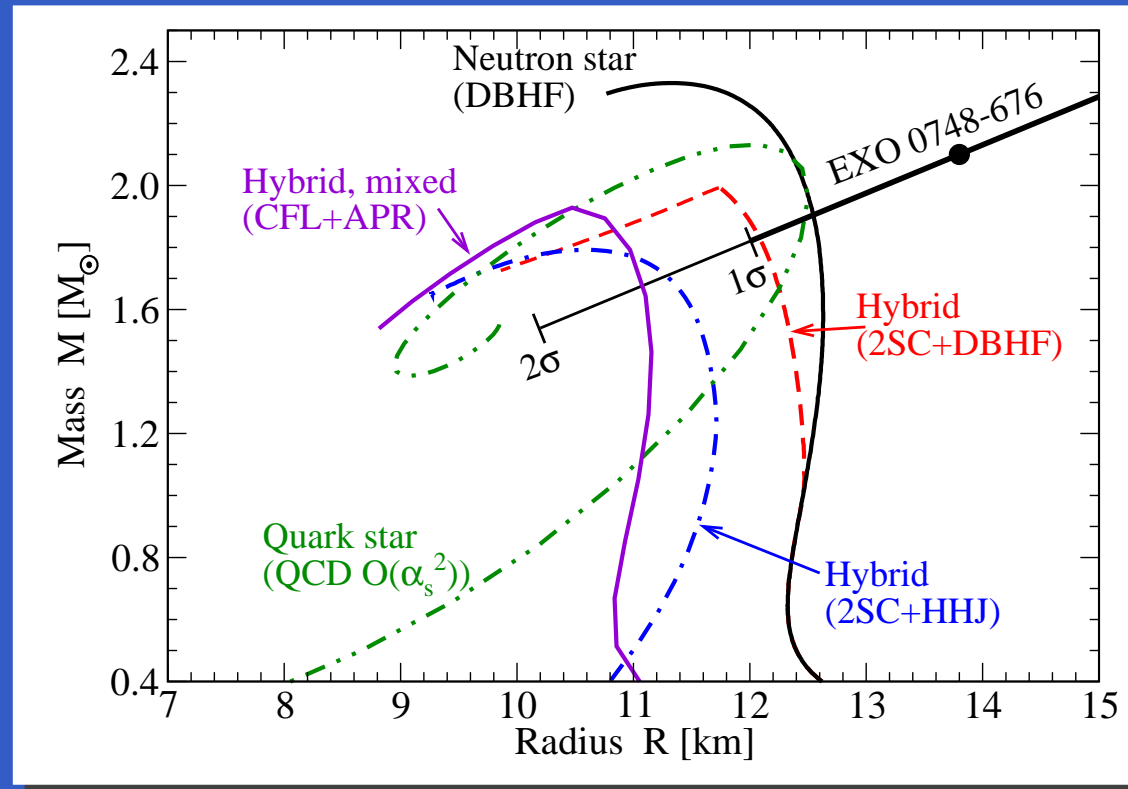
(Chandra X-Ray Center, 2002)

X-Ray burster



- binary systems of a neutron star with an ordinary star
- accreting material on the neutron star ignites nuclear burning
- red shifted spectral lines measured!
($z = 0.35 \rightarrow M/M_{\odot} = 1.5$ (R/10 km)) (Cottam, Paerels, Mendez (2002))
- Cottam et al. (2008): not confirmed with burst data from 2003

X-Ray burster EXO 0748–676



- analysis of Özel (Nature 2006): $M \geq 2.10 \pm 0.28M_{\odot}$ 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 $M = 1.35M_{\odot}$ than with $M = 2.1M_{\odot}$

Future: Square Kilometer Array (SKA)



- receiving surface of 1 million square kilometers
- 1 billion dollar international project
- potential to discover:
 - 10,000 to 20,000 new pulsars
 - up to 6,000 millisecond pulsars
 - at least 100 compact relativistic binaries!
- probing the equation of state at extreme limits!
- cosmic gravitational wave detector by using pulsars as clocks!
- design and location not fixed yet

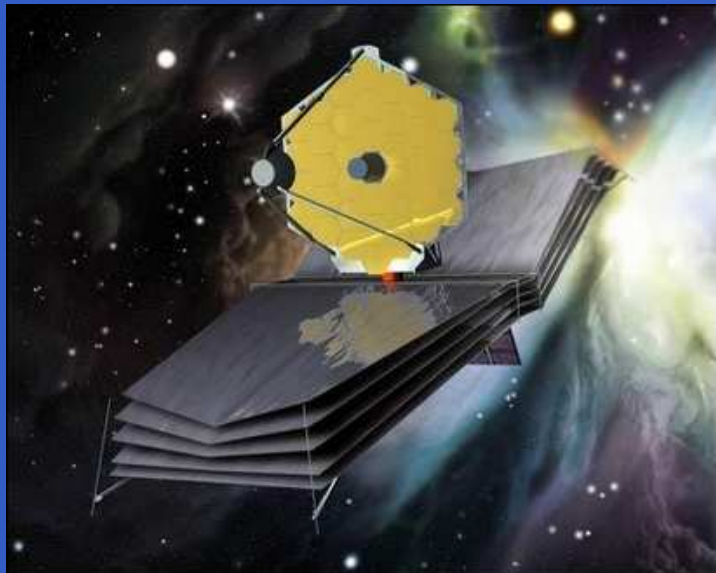
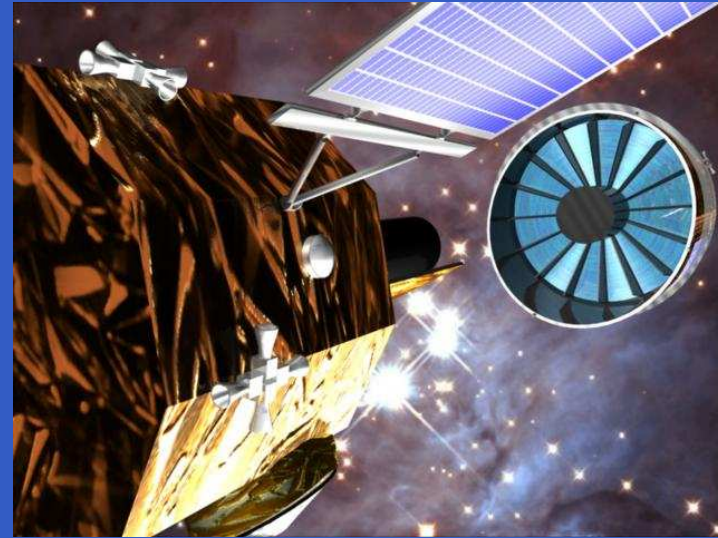
movie

Future Telescopes and Detectors in Space

Constellation-X (Photo: NASA)



XEUS (Photo: ESA)

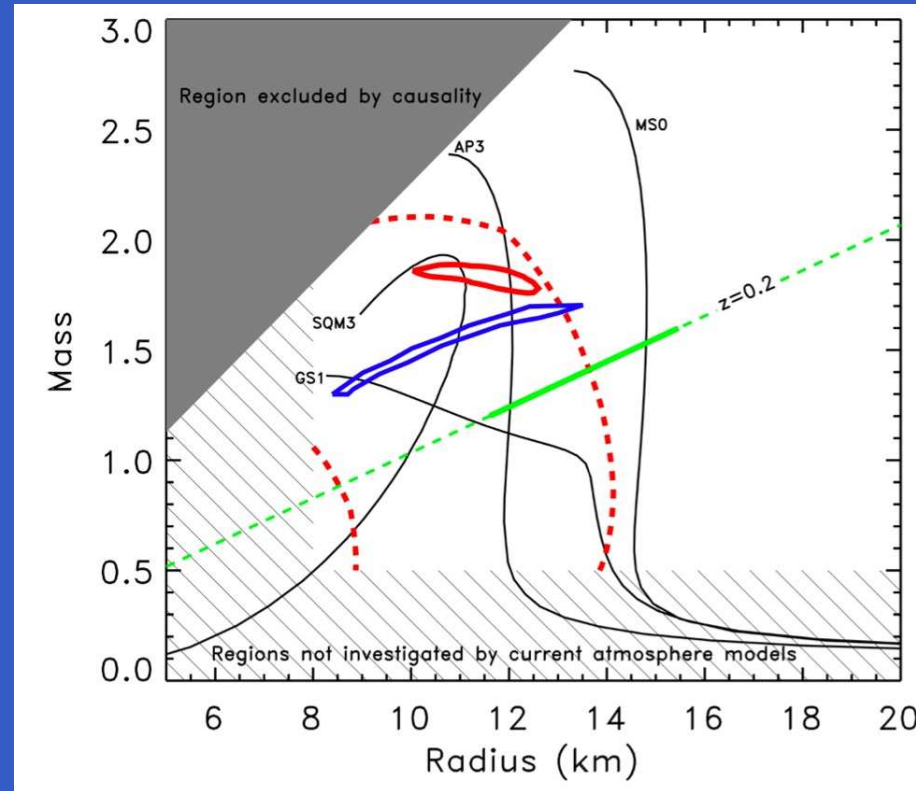


James Webb Space Telescope (Photo: ESA)



LISA (Photo: NASA)

Probes Using the International X-Ray Observatory (IXO)

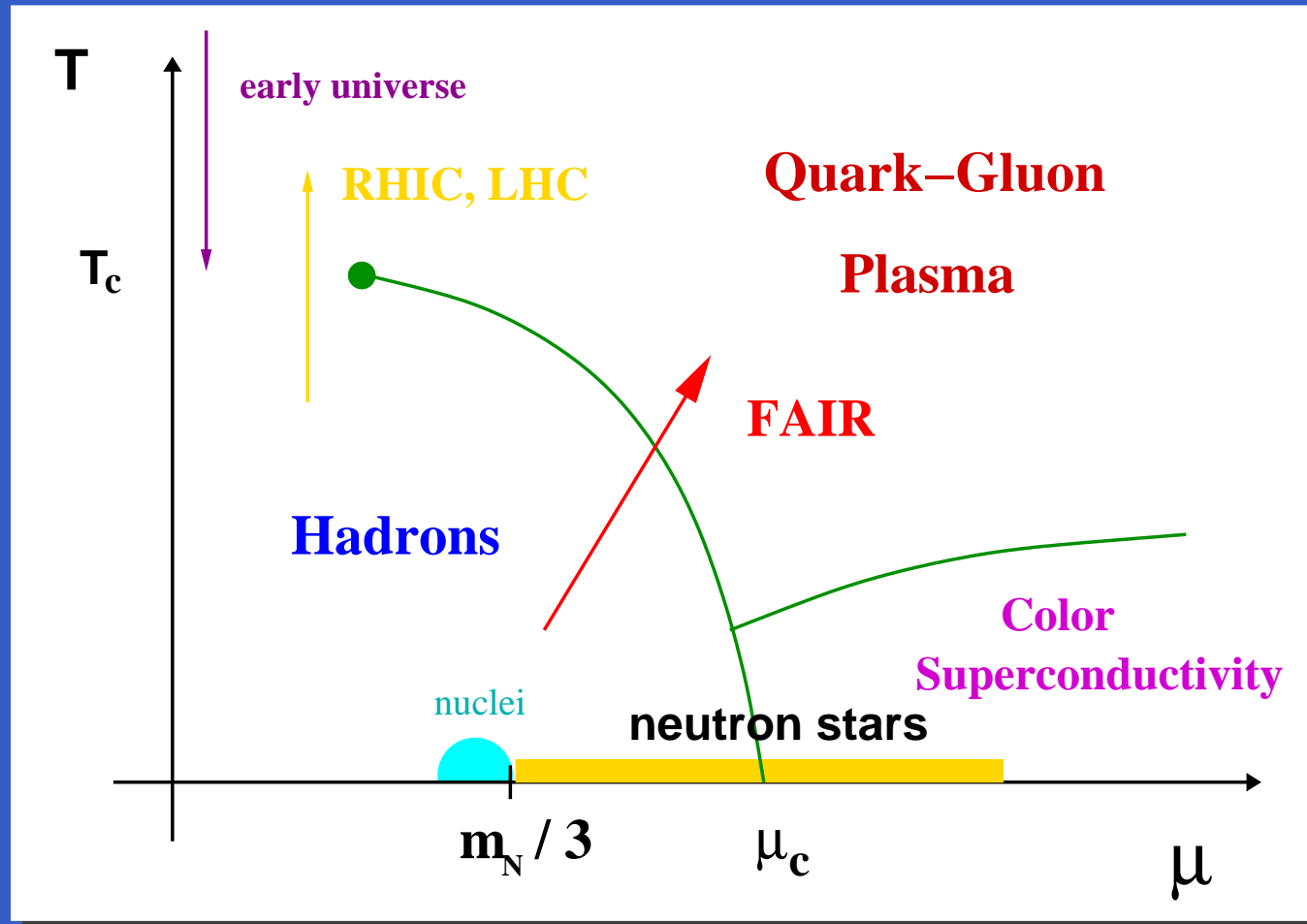


(Cackett et al., IXO Extreme States of Matter Working Group (2009))

- hydrogen atmosphere model fitting of quiescent neutron stars (red)
- waveform fitting of pulsations of accreting millisecond pulsar (spectral profile is modified from space-time warpage) (blue)
- X-ray bursts spectroscopy, gravitationally redshifted absorption lines (green)
- IXO can provide strong constraints on the mass-radius ratio

Connecting quarks with the cosmos

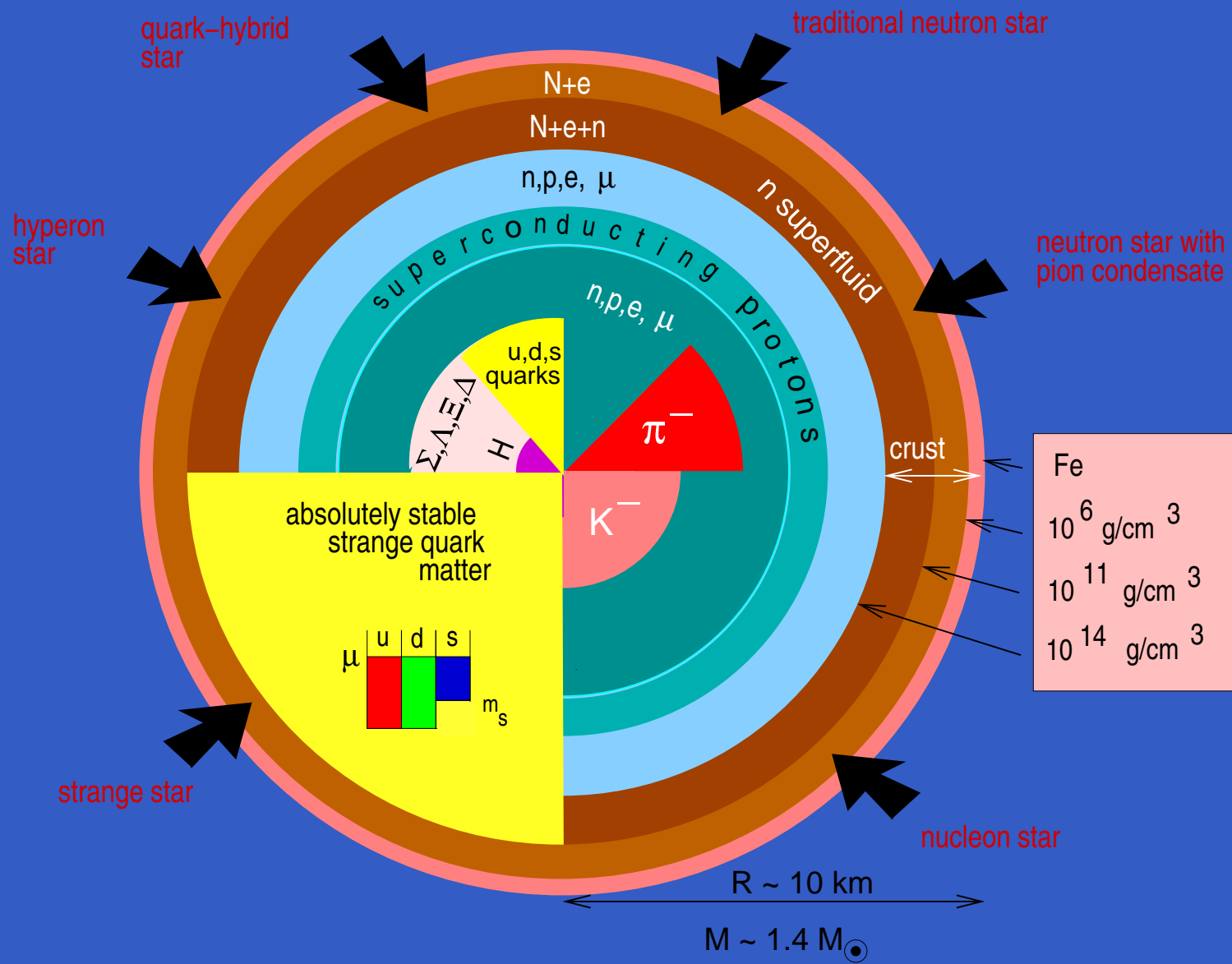
Phase Transitions in Quantum Chromodynamics QCD



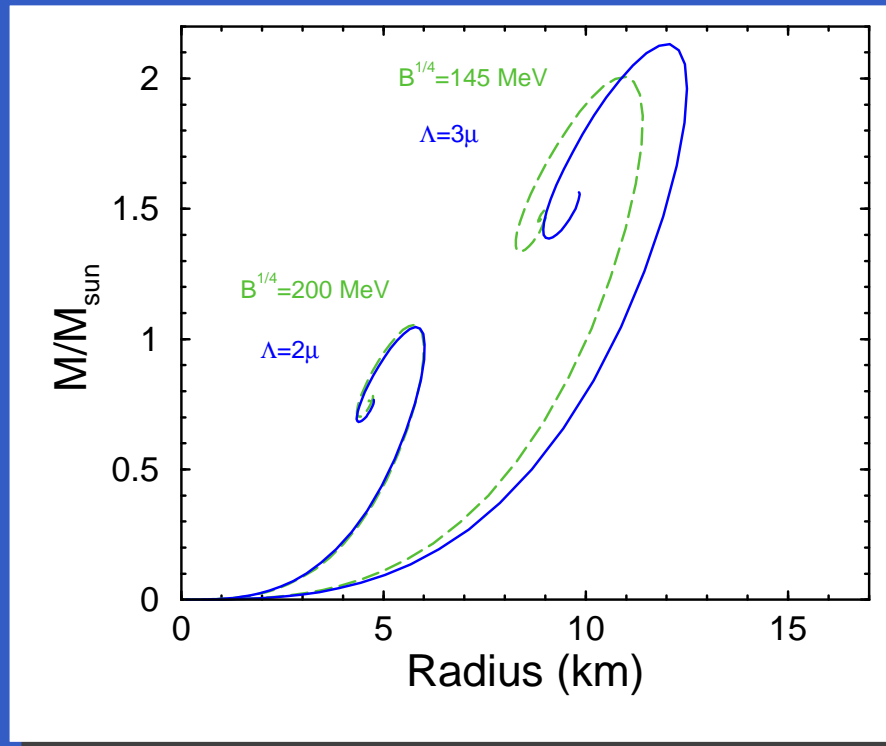
- Early universe at zero density and high temperature
- neutron star matter at small temperature and high density
- first order phase transition at high density (not deconfinement)!
- probed by heavy-ion collisions at GSI, Darmstadt (FAIR!)

QCD Phase Transition and Neutron Stars

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



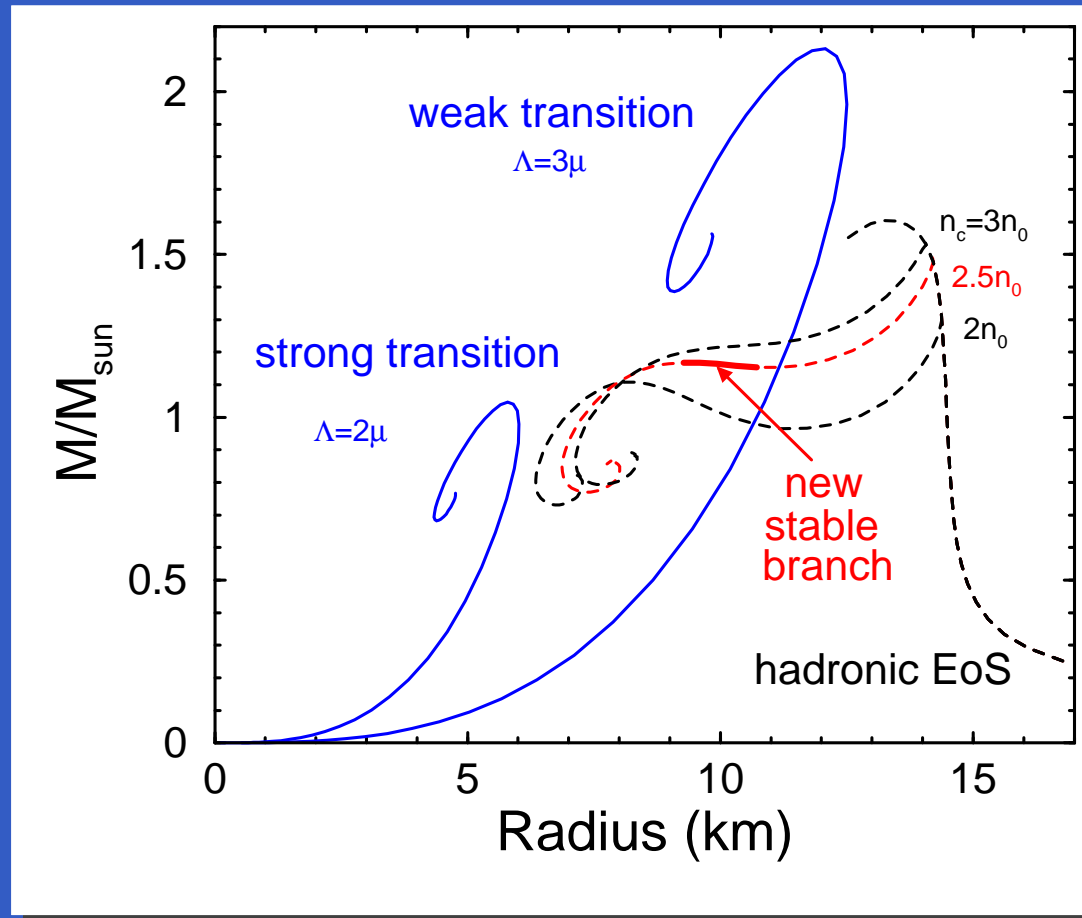
Mass-radius and maximum density of pure quark stars



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

- case $\Lambda = 2\mu$: $M_{\max} = 1.05 M_{\odot}$, $R_{\max} = 5.8 \text{ km}$, $n_{\max} = 15 n_0$
- case $\Lambda = 3\mu$: $M_{\max} = 2.14 M_{\odot}$, $R_{\max} = 12 \text{ km}$, $n_{\max} = 5.1 n_0$
- 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!

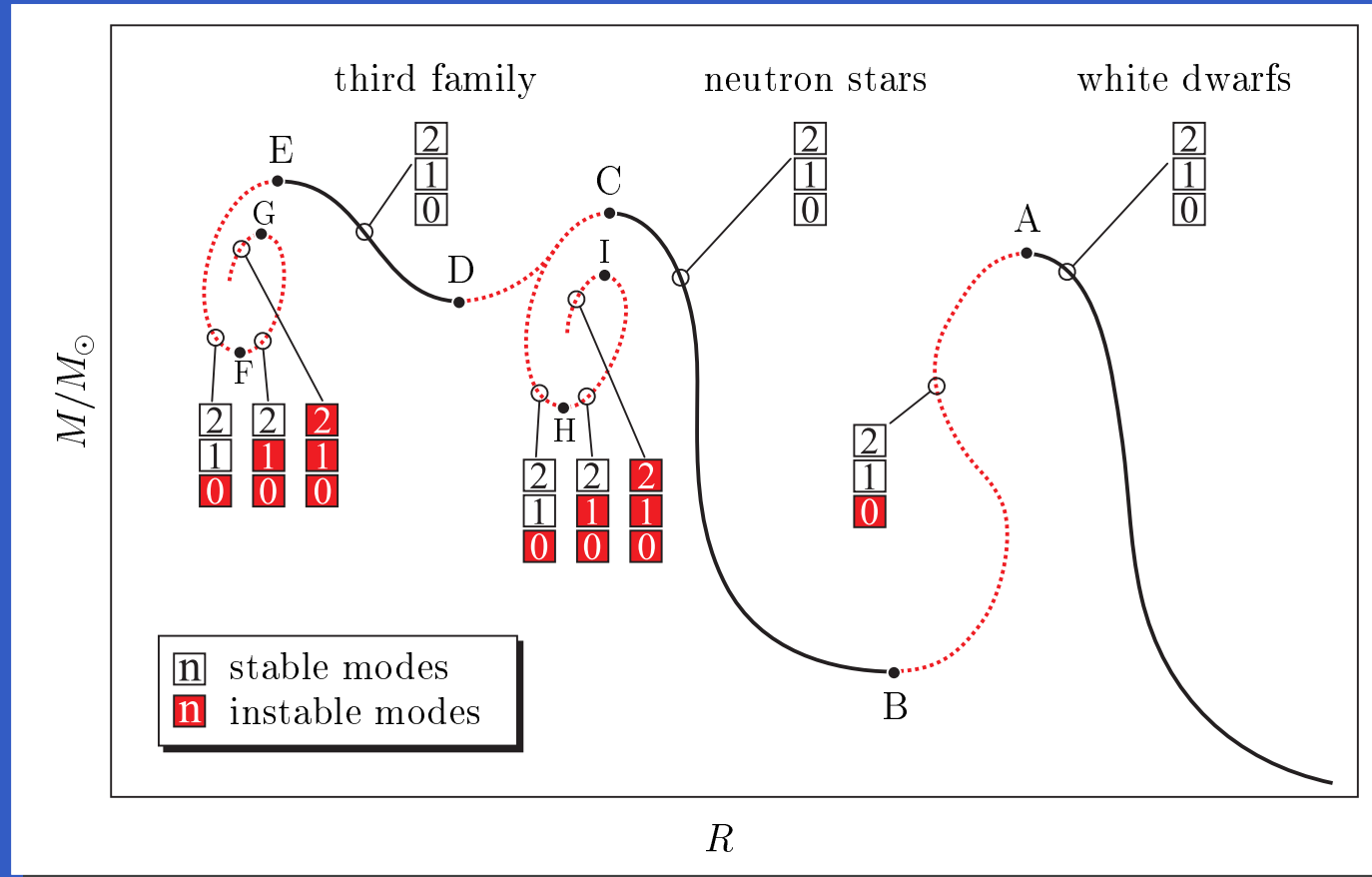
Quark star twins?



- 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)

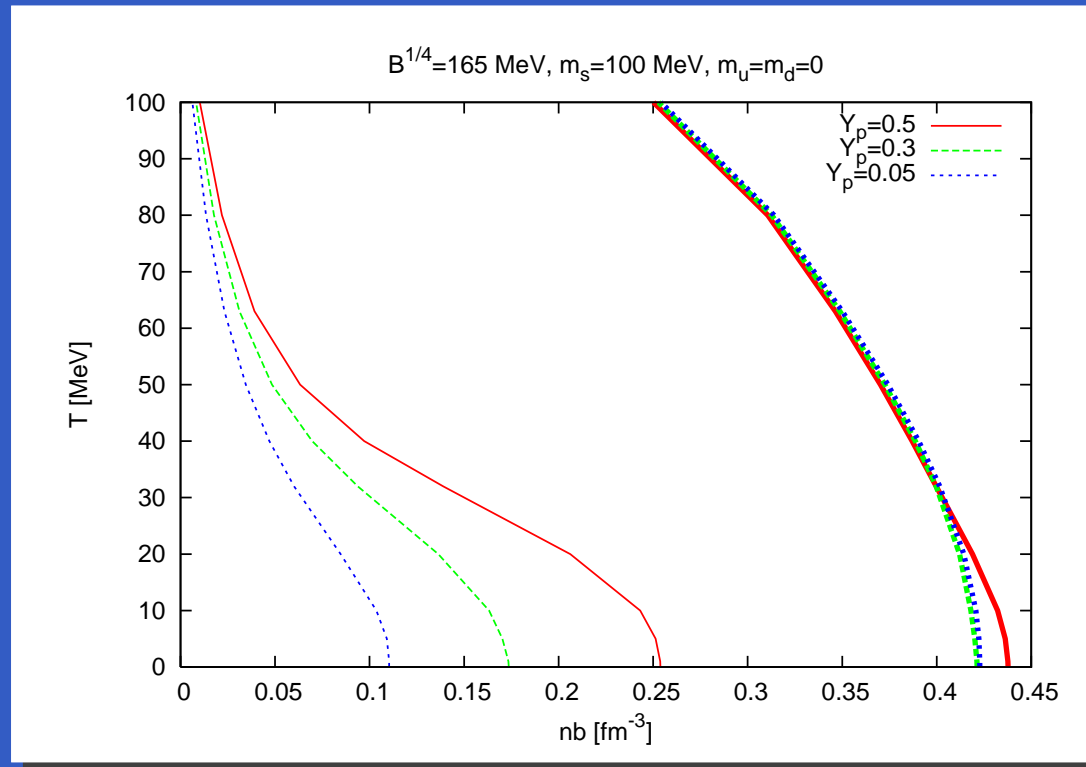
(Glendenning, Kettner 2000; Schertler, Greiner, JSB, Thoma 2000)



- 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!

QCD phase transition in supernovae

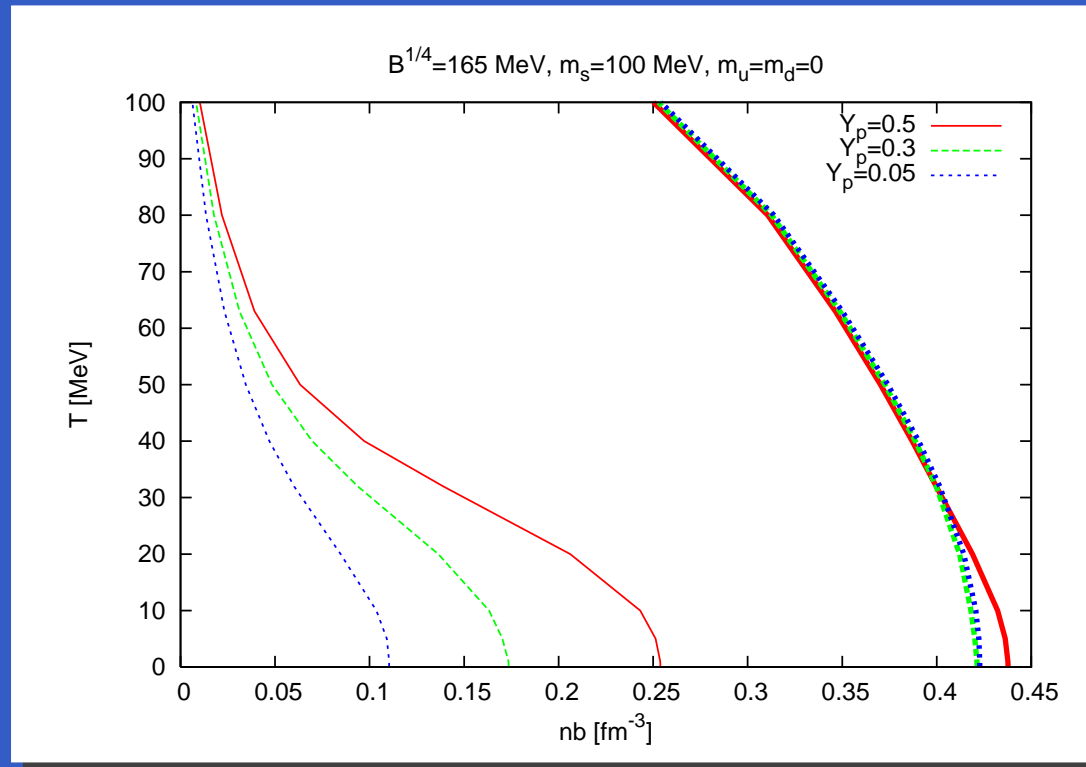
Phase Transition to Quark Matter for Astros



(Irina Sagert and Giuseppe Pagliara)

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

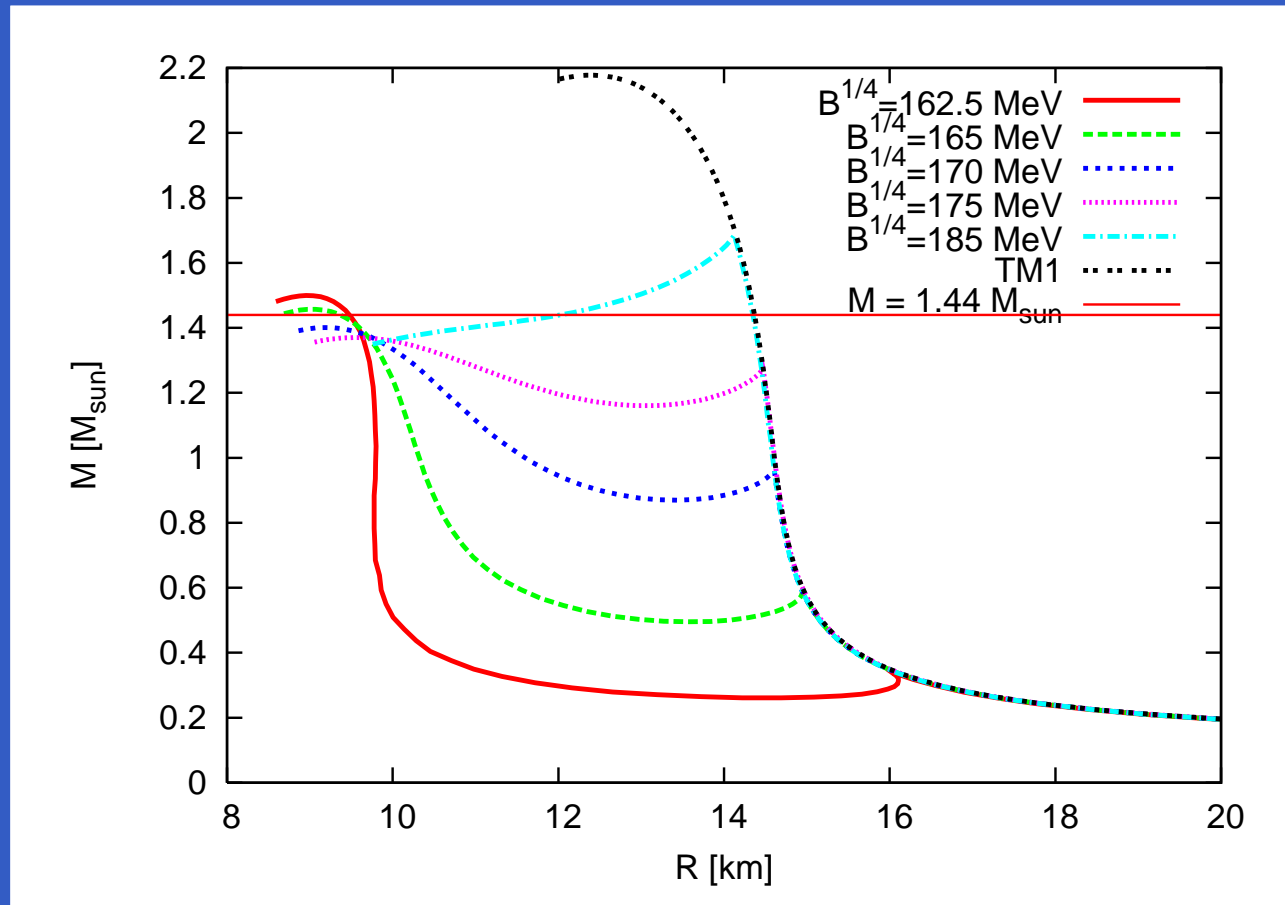
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- quark matter favoured at finite temperature
- supernova matter at bounce: $T = 10 - 20$ MeV, $Y_p = 0.2 - 0.3$, $\epsilon \sim (1 - 1.5)\epsilon_0$
- production of quark matter in supernovae at bounce possible!

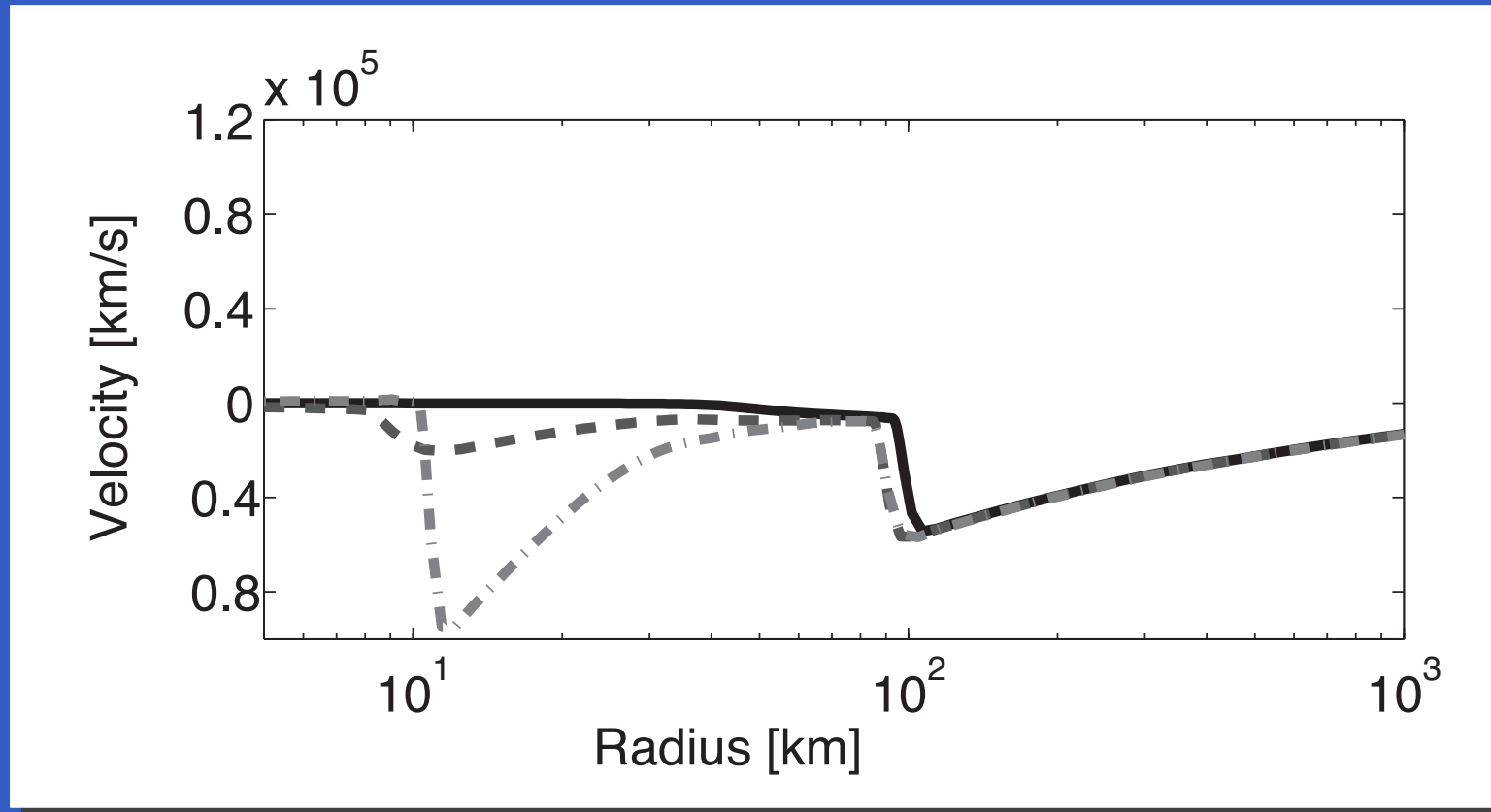
Check: Mass-Radius Diagram of Cold Neutron Stars



(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: $1.56M_{\odot}$ ($B^{1/4} = 162$ MeV), $1.5M_{\odot}$ ($B^{1/4} = 165$ MeV)

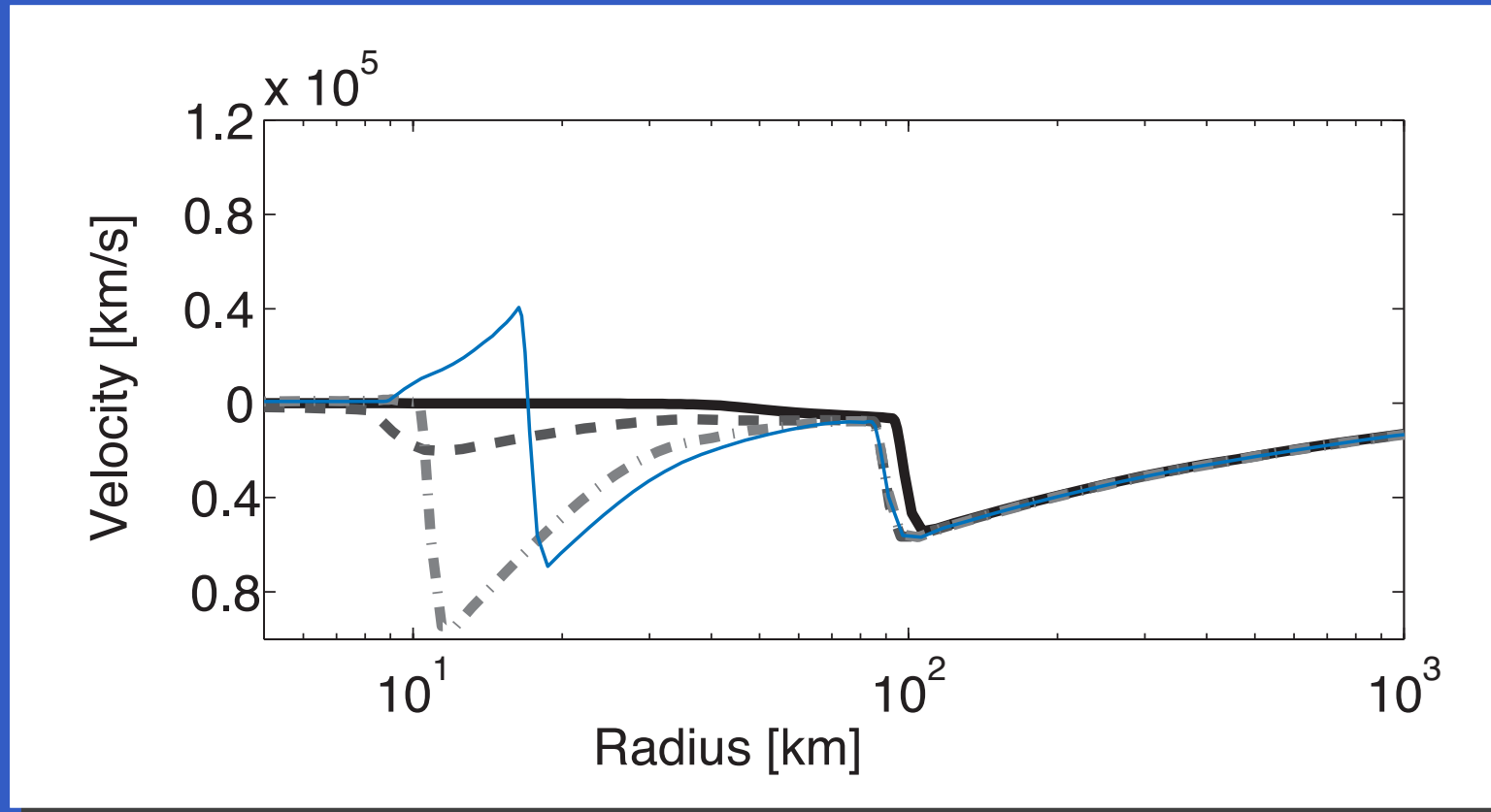
Implications for Supernovae – Explosion!



(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

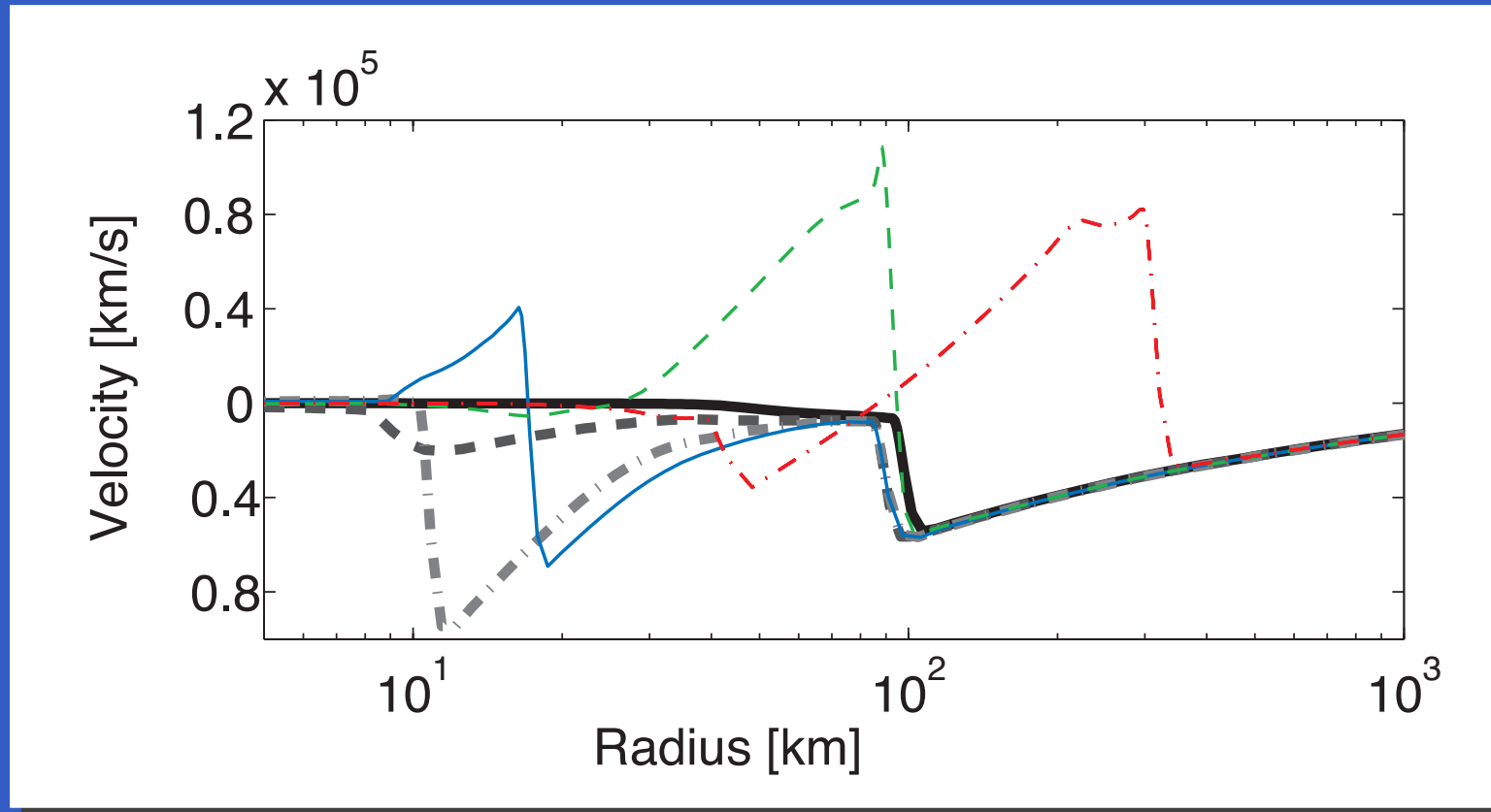
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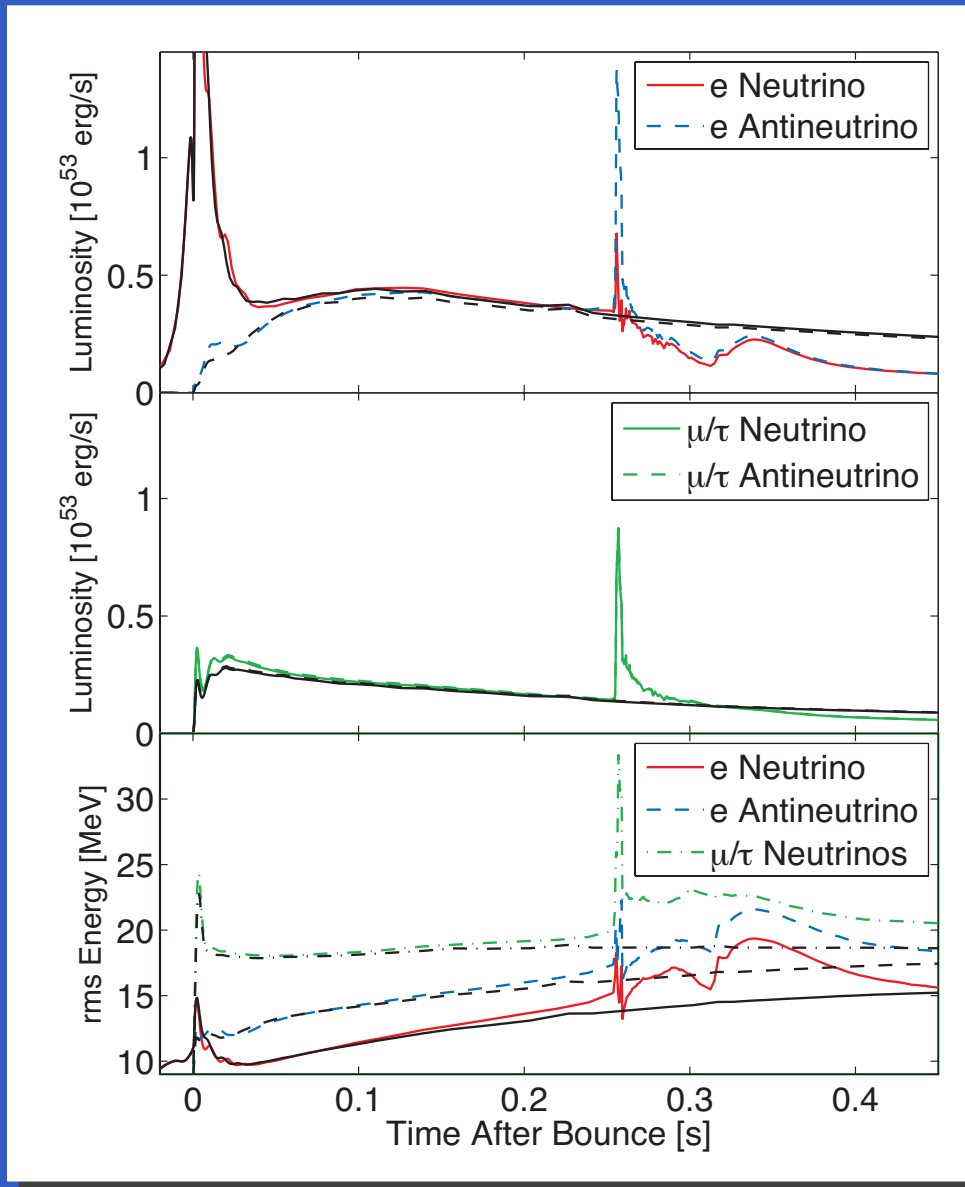
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- velocity profile of a supernova for different times (around 250ms)
- formation of a core of pure quark matter produces a second shock wave
- leads to an explosion!

Implications for Supernova – Neutrino-Signal!

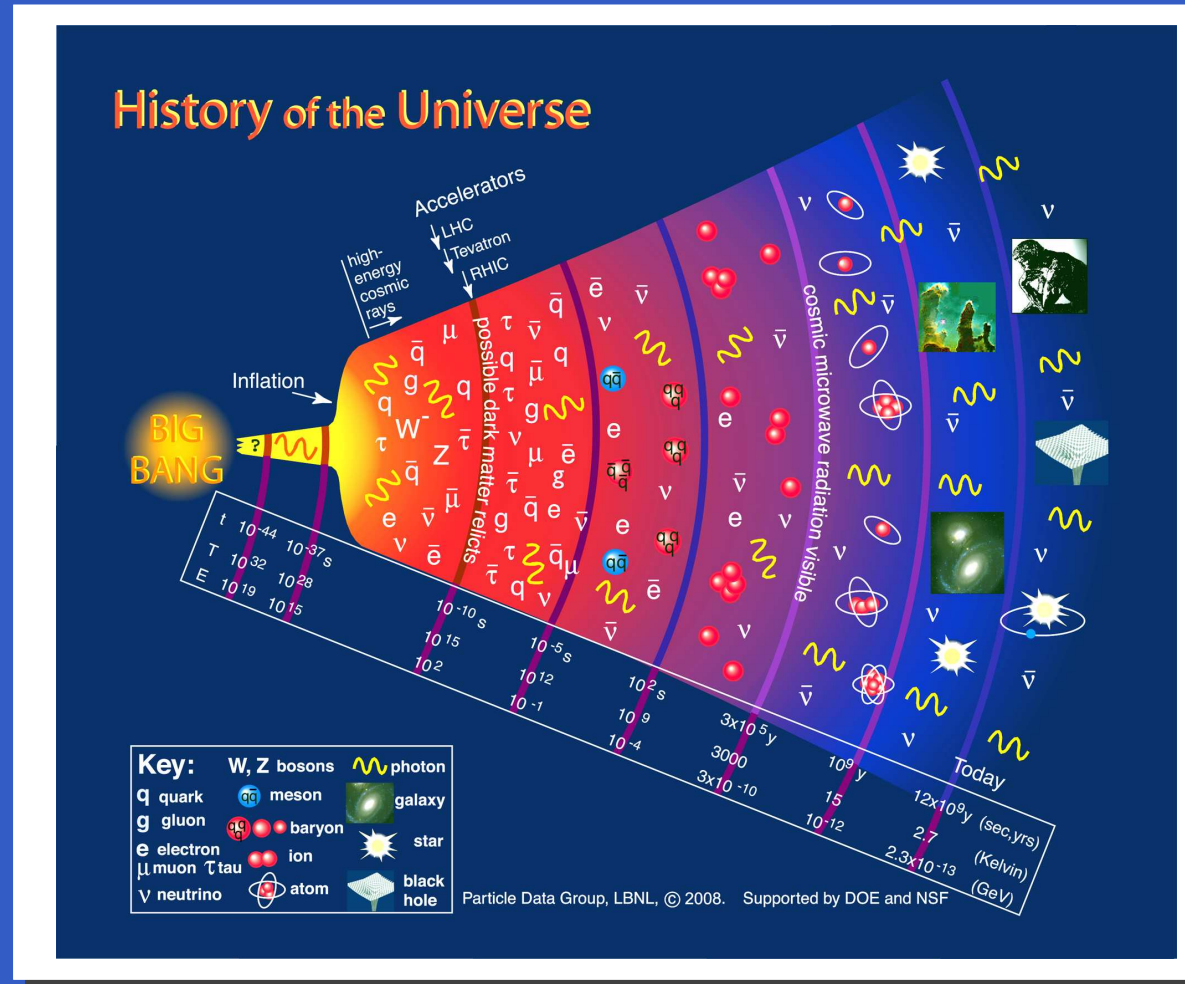


- temporal profile of the emitted neutrinos out of the supernova
- thick lines: without, thin lines: with a phase transition
- pronounced second peak of anti-neutrinos due to the formation of quark matter
- peak location and height determined by the critical density and strength of the QCD phase transition!

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

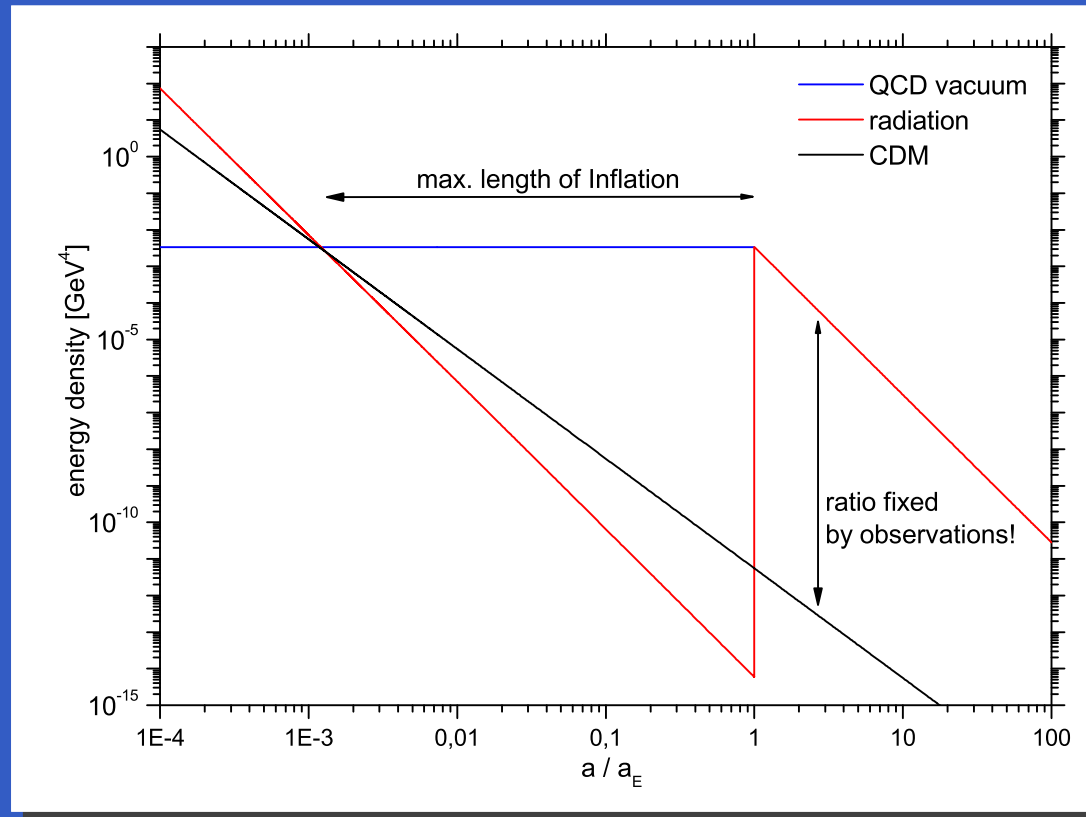
QCD phase transition in the early universe

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)

A little inflation at the QCD phase transition



(Boeckel and JSB, arXiv:0906.4520)

- universe trapped in false vacuum at *large* baryon density
- strong first order phase transition possible!
- possible with Affleck-Dine baryogenesis (baryon-to-photon ratio of one)
- cosmological signals!?! lots of opportunities . . .

Outlook

- quark matter can be present in the core of neutron stars and can lead to a new family of compact stars
- quark matter can be formed in supernovae, even shortly after the first bounce
 - leads to an explosion (with enough explosion energy in the shock)
 - forms a second peak in the (anti-)neutrino signal
 - implications for gravitational wave signal?
 - and r-process nucleosynthesis?
- quark matter is present in the early universe
 - would influence the relic densities of cold dark matter?
 - can have an impact on structure formation on small scales?
 - can form gravitational waves?
- a FAIR chance for exploring exotic matter on Earth and in the sky

- Interacting dark matter (Rainer Stiele): Friedmann equation with selfinteraction terms, constraints from BBN, WMAP, Lyman- α forest (to be prepared for publication)
- Dark matter with a finite chemical potential (Till Boeckel): solving the Friedmann equation numerically, using quantum statistics, integrals with general Fermi-Dirac distributions functions (published in PRD 2007)
- Equation of state of the outer crust of neutron stars (Matthias Hempel): calculating thermodynamic ensembles, solving for the nuclear equation of state (interacting nucleon gas), deriving distributions of the compositions with lattice corrections (PRC 2006)
- Pulsar kicks and cooling neutron stars (Irina Sagert): weak interaction rates in hot nuclear and quark matter, calculating Landau levels and magnetization, estimating kick velocities of quark stars (A& A 2008)

Summer projects (extended)

- Fermi stars with selfinteraction (Gaurav Narain): numerical solution of the Tolman-Oppenheimer-Volkoff (TOV) equations for arbitrary masses and interaction strengths (PRD 2009)
- Bose stars with selfinteraction (Pratik Agnihotri): solving the rescaled TOV equations for bosons with interaction terms (PRD 2006)
- Phase transition in compact stars and neutron star twins (Jean Macher): solving the TOV equations, parameterized phase transition, mass-radius relation for neutron star twins (EJP 2005)

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)
- Dipl.-Phys. Rainer Stiele (effective field theory of phase transitions in the early universe)
- Simon Schettler (gravitational wave emission from the QCD phase transition)

in Frankfurt:

- Alessandro Brillante (gravitational wave emission from the collapse to quark stars)
- Daniel Yueker (chiral effective model and phase transitions)