Exotic Matter in Neutron Stars and Supernovae

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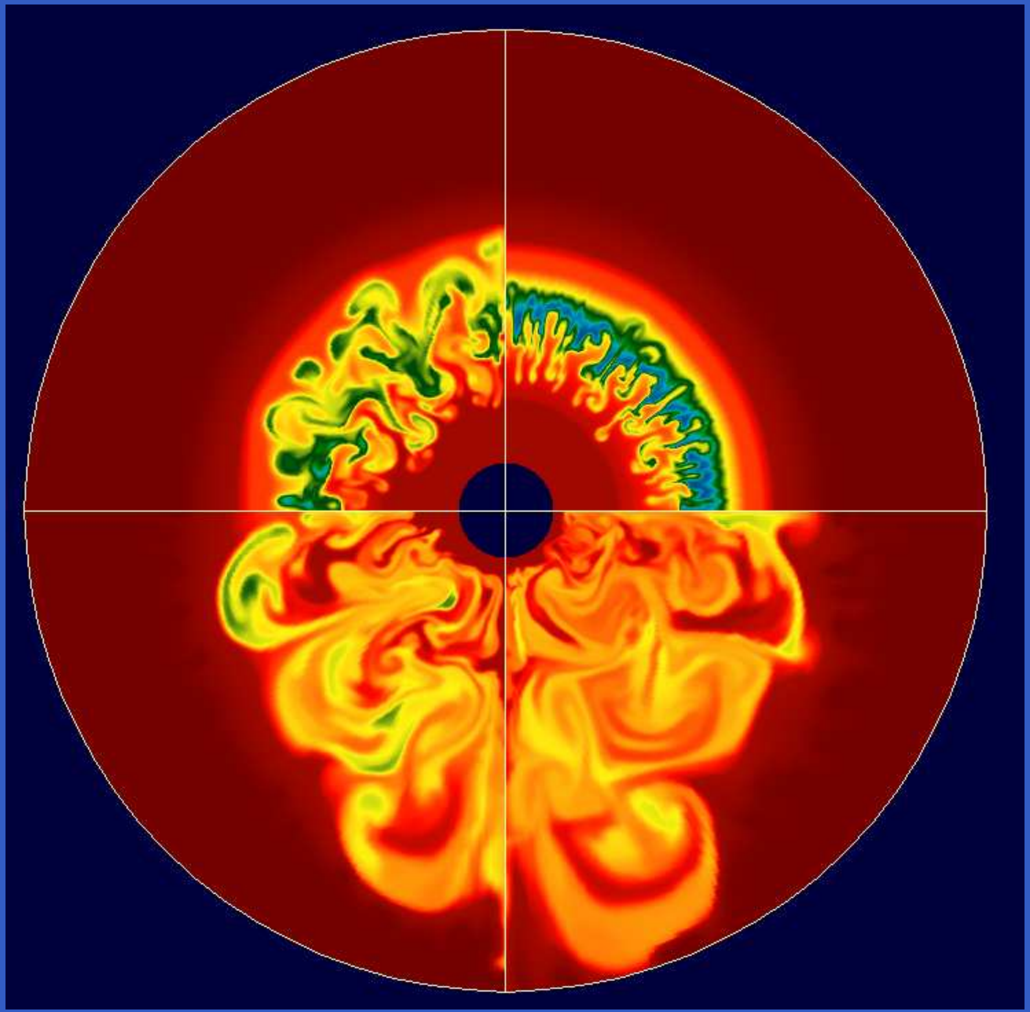
Outline

- Observations of neutron stars
- Modelling neutron stars
- The FAIR connection:
  - Constraints on the maximum mass of neutron stars from heavy-ion data
  - QCD phase transition and neutron stars
  - QCD phase transition in supernovae
- Summary

Observational Data of Neutron Stars

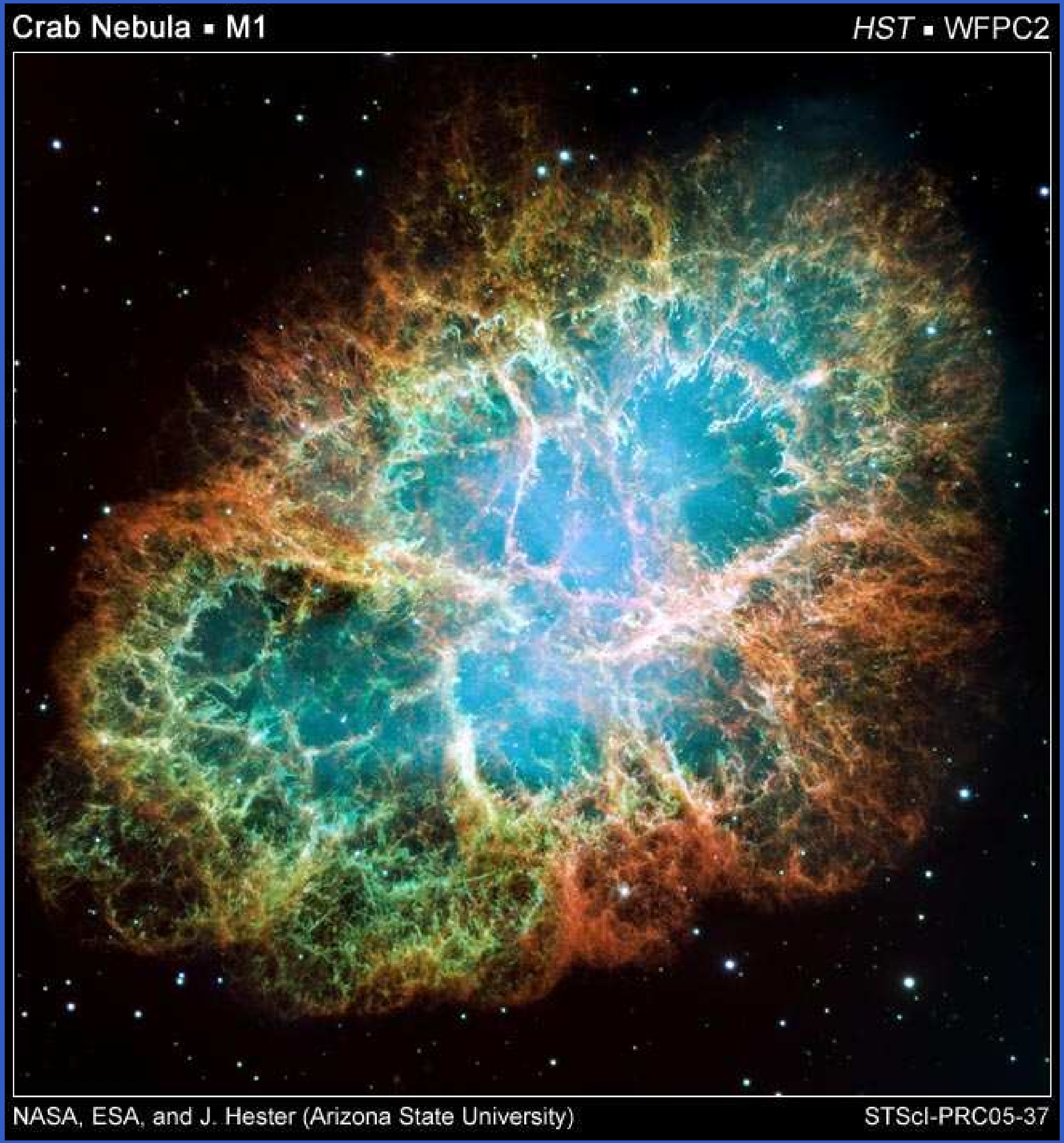
Supernova Explosions



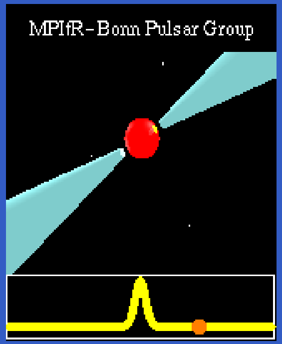
(supernova simulation by Janka et al., MPA Garching)

- 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



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



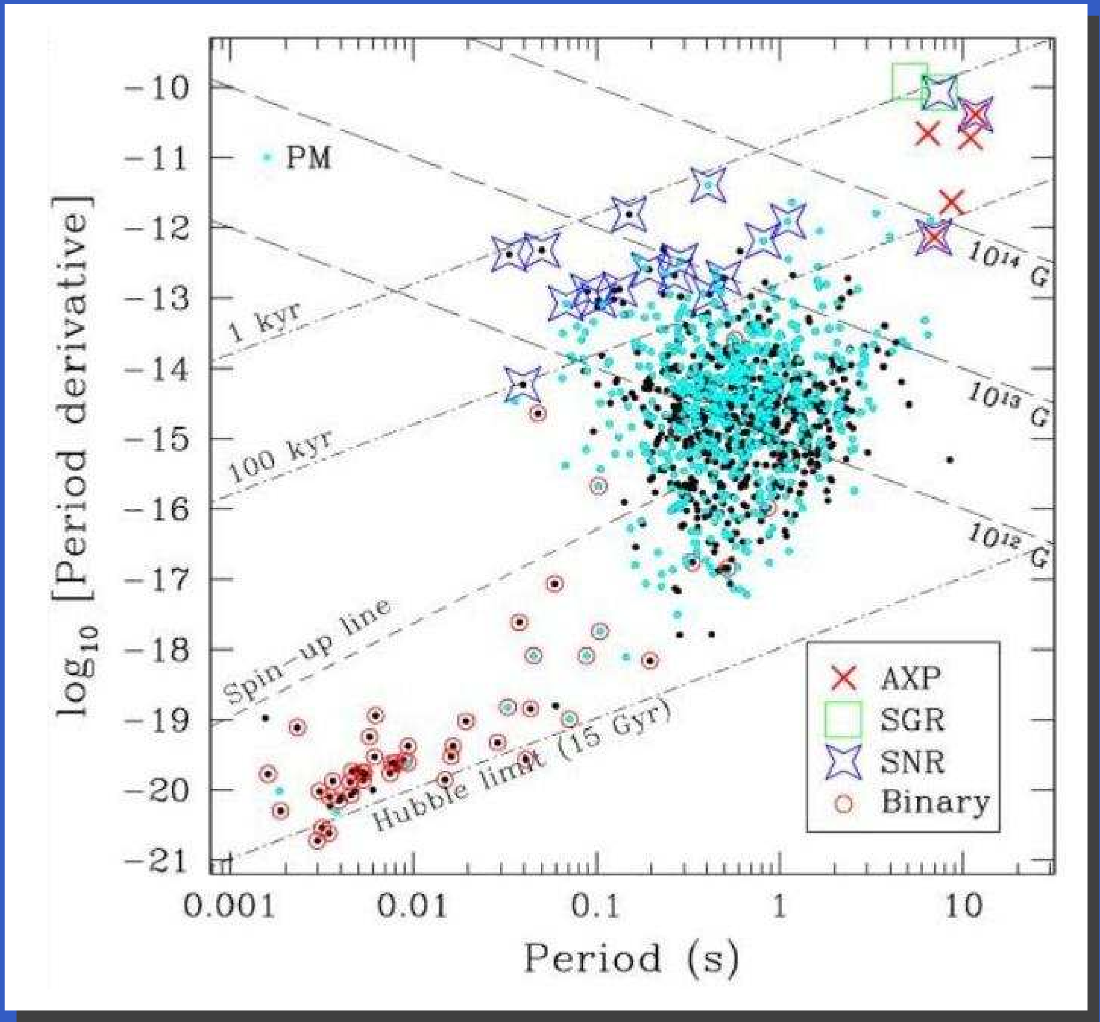
- produced in core collapse supernova explosions
- compact, massive objects: radius $\approx$ 10 km, mass $1 - 2M_\odot$
- extreme densities, several times nuclear density: $n \gg n_0 = 3 \cdot 10^{14}$ g/cm^3
- in the middle of the crab nebula: a pulsar, a rotating neutron star!

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)

(Jodrell Bank Observatory, University of Manchester)

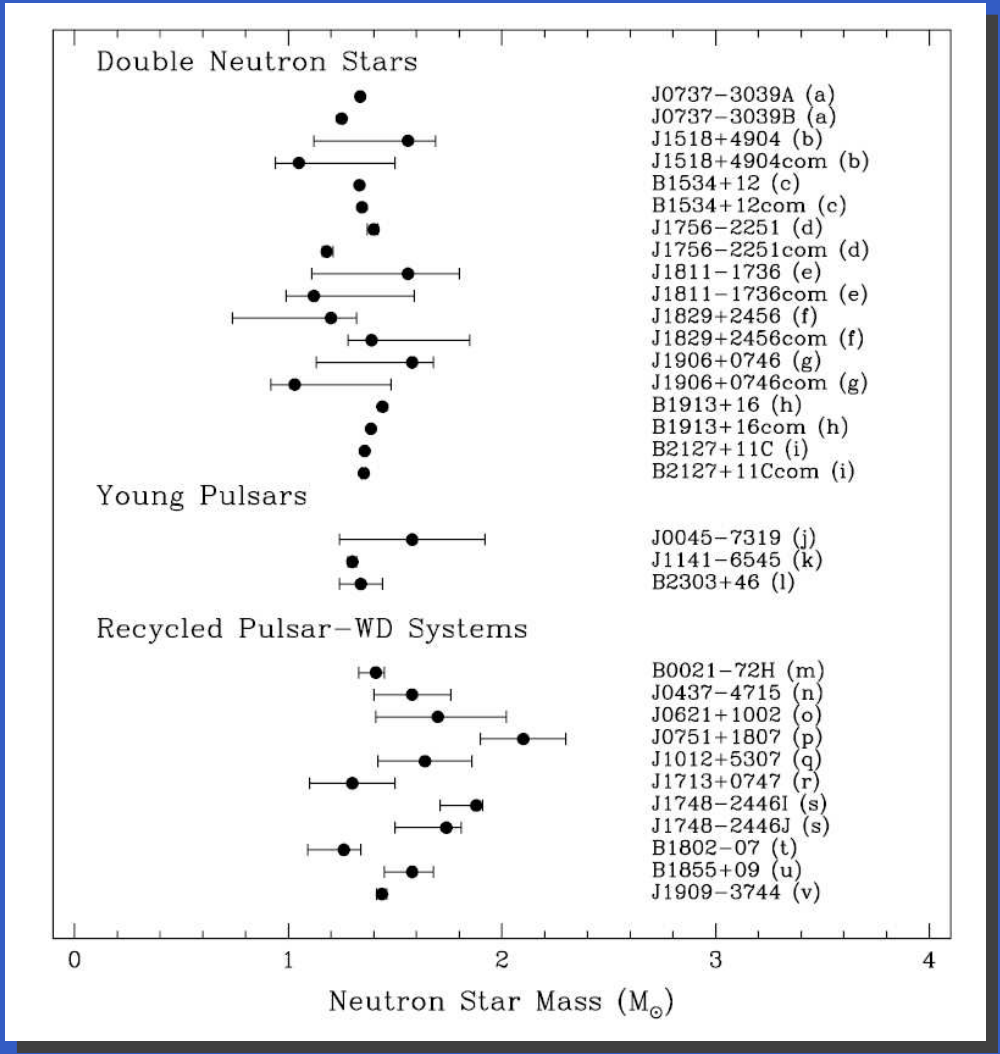
The Pulsar Diagram



(ATNF pulsar catalog)

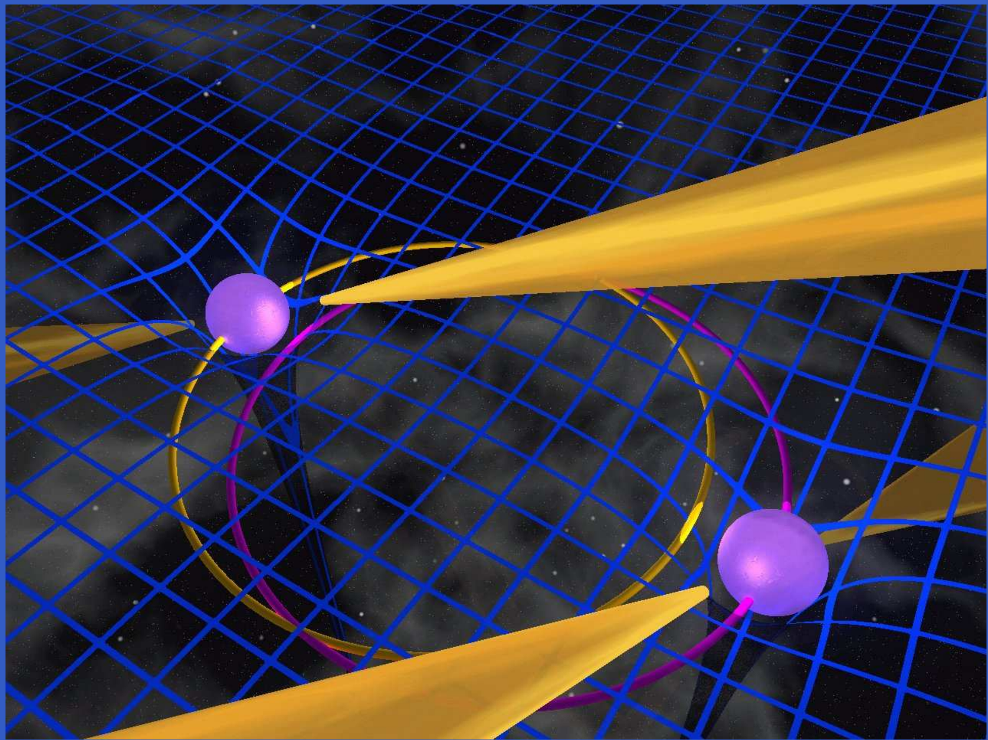
- the diagram for pulsars: period versus period change (P-$\dot{P}$)
- dipole model for pulsars: characteristic age: $\tau = P/(2\dot{P})$ and magnetic field $B = 2 \cdot 10^{19} (P \cdot \dot{P})^{1/2}$ Gauss
- anomalous x-ray pulsars: AXP, soft-gamma ray repeaters: SGR, young pulsars in supernova remnants: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

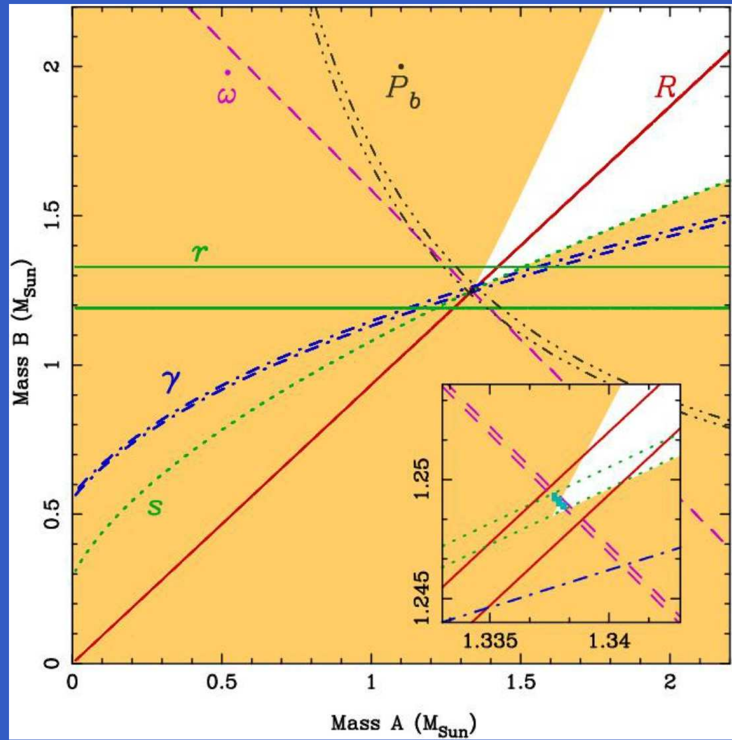
Masses of Pulsars (Stairs, 2006)



- 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 $M = 2.1 \pm 0.2 M_\odot$ to $M = 1.14 - 1.40 M_\odot$ (Nice et al. 2008)

The Double Pulsar PSR J0737-3039

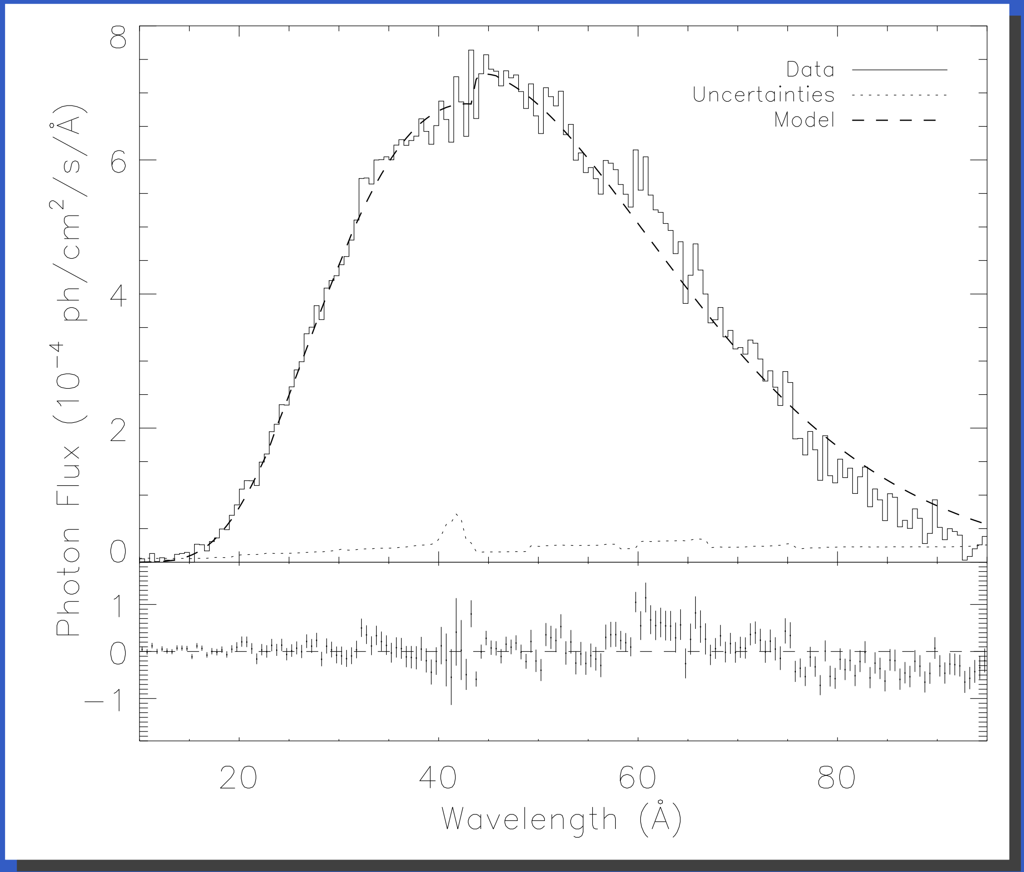




- sensational discovery of two pulsars orbiting each other (Lyne et al. 2004)
- measured five post-Keplerian parameters: Shapiro delay r and s, redshift γ, periastron advance $\dot{\omega}$, decrease in orbital period $\dot{P}_b$ (Kramer et al. 2006)
- all in agreement with the prediction of GR to within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

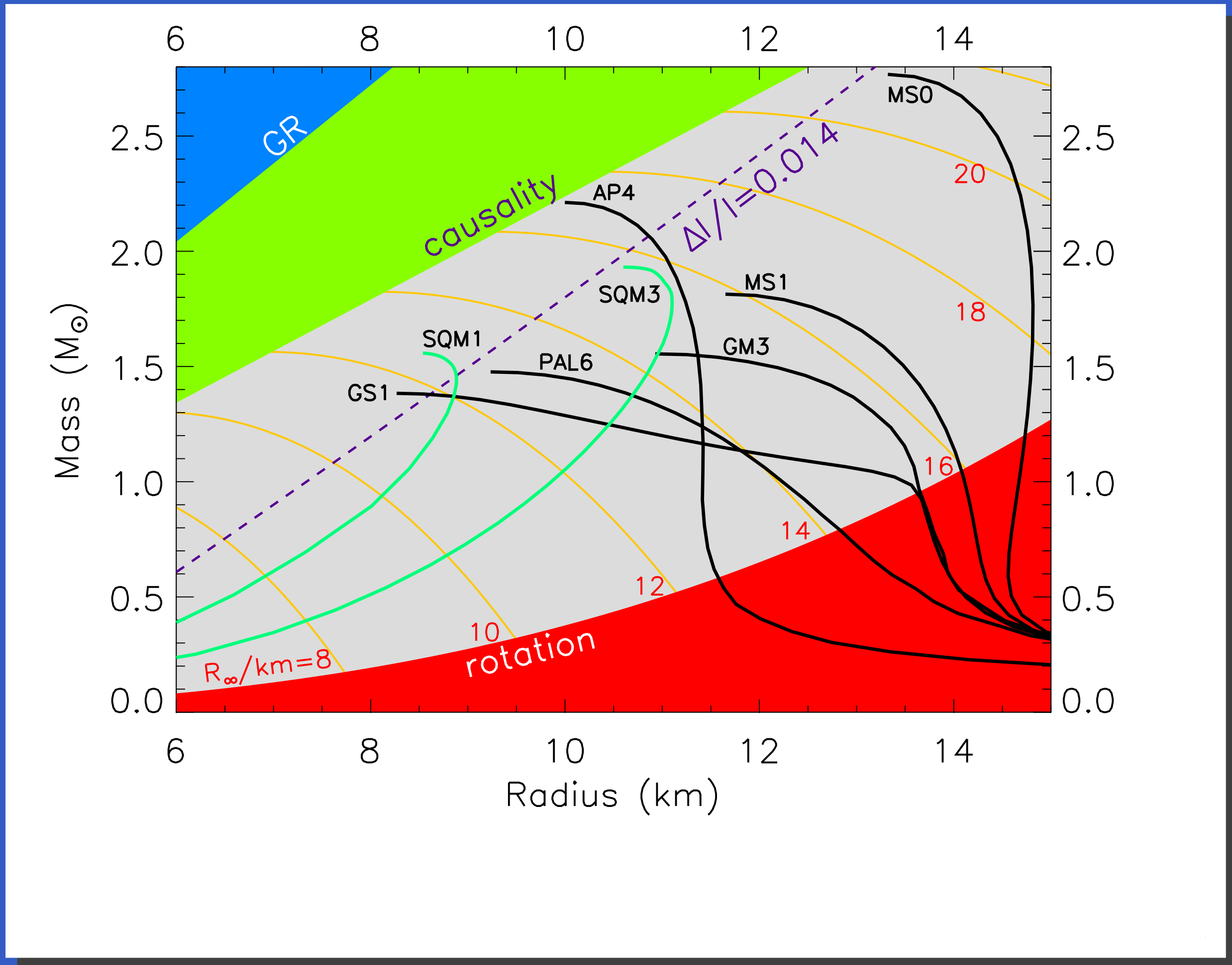
animation (credit: Michael Kramer)

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



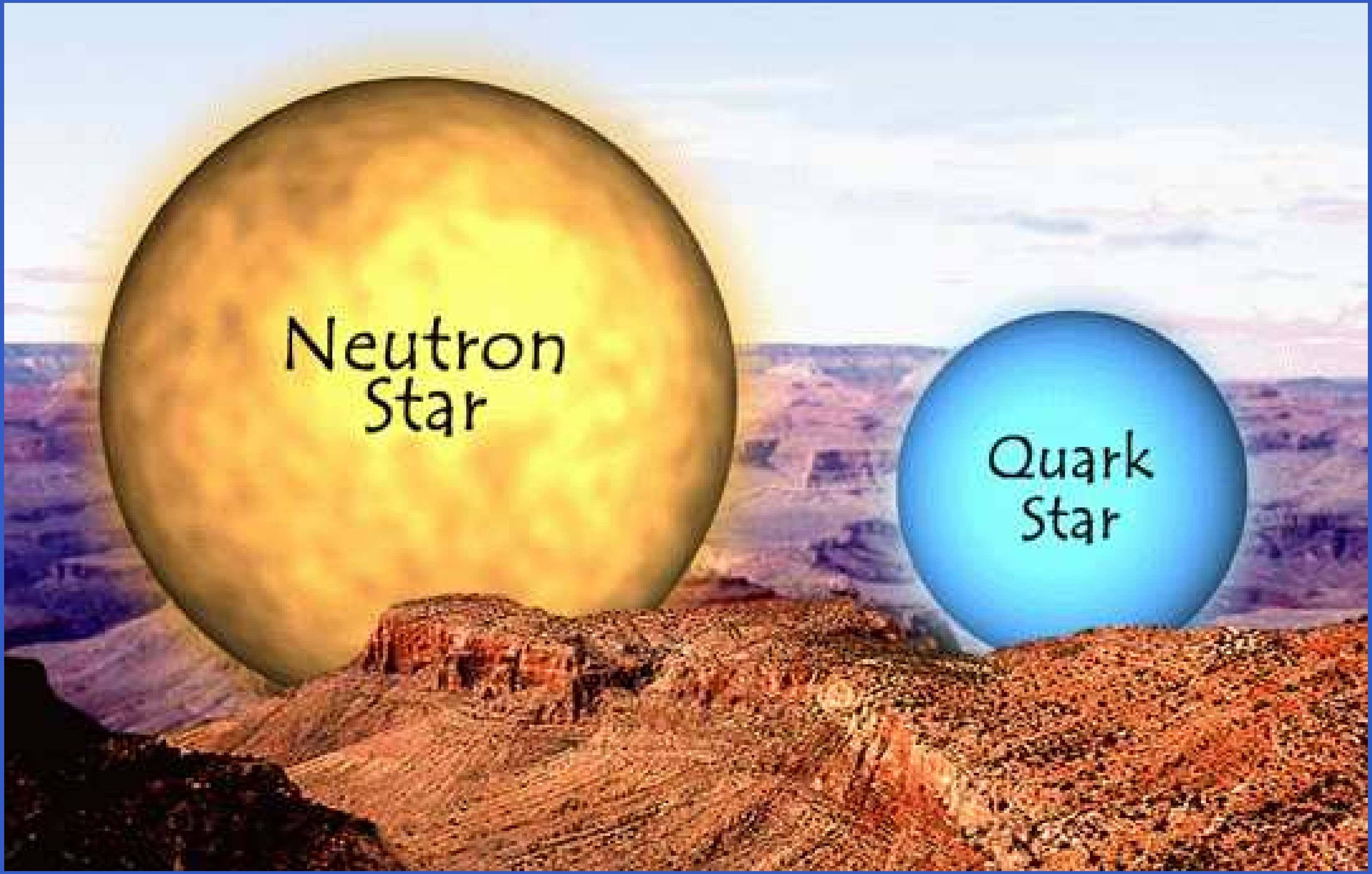
- closest known neutron star, parallax measurement with HST: $D = 117 \pm 12$ pc (Lattimer and Wolter 2002), $D = 140 \pm 40$ pc (van Kerkwijk and Kaplan 2004), $D = 161 \pm 18$ pc (Kaplan 2007)
- perfect black–body spectrum, no spectral lines!
- for black-body emission (x-ray part only): $T = 60$ eV 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 $M = 1.4 M_\odot$
- 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)

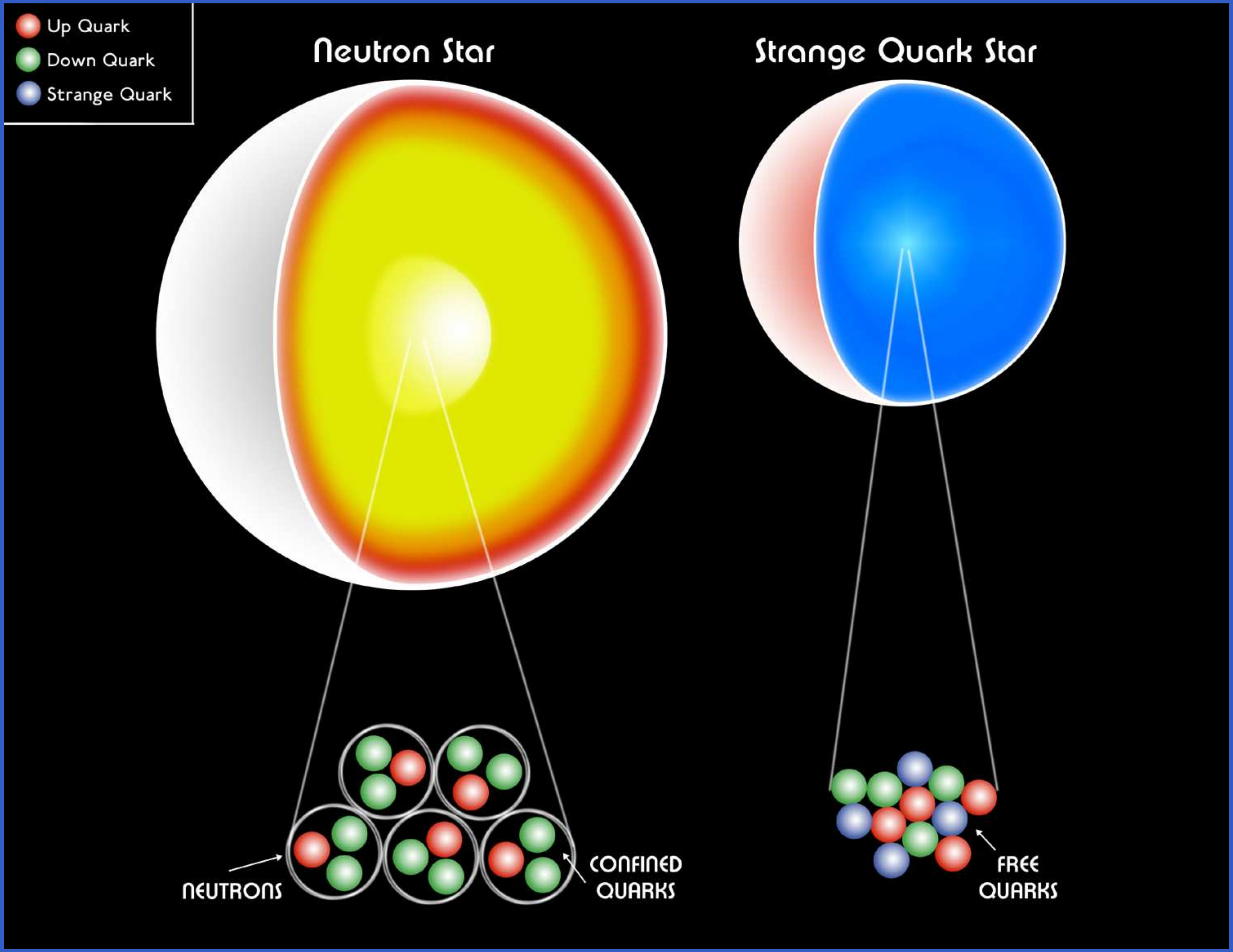


NASA news release 02-082:

"Cosmic X-rays reveal evidence for new form of matter"

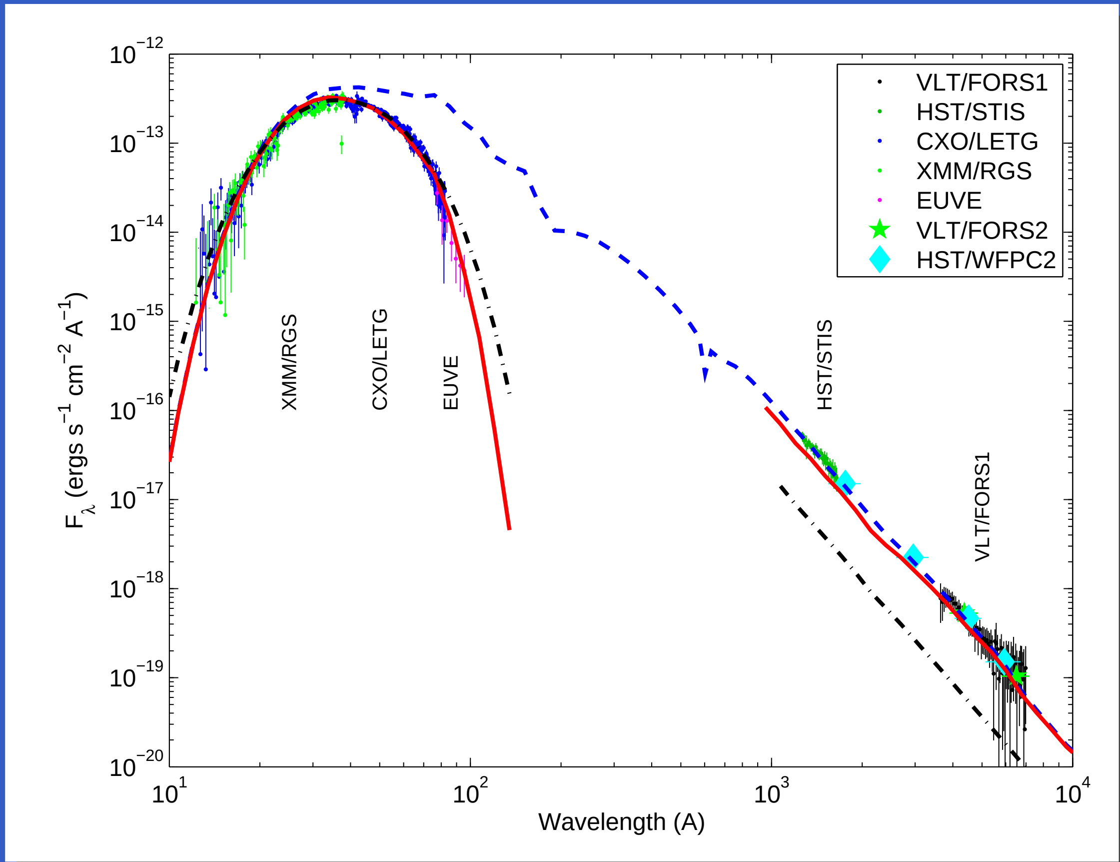
— a quark star?

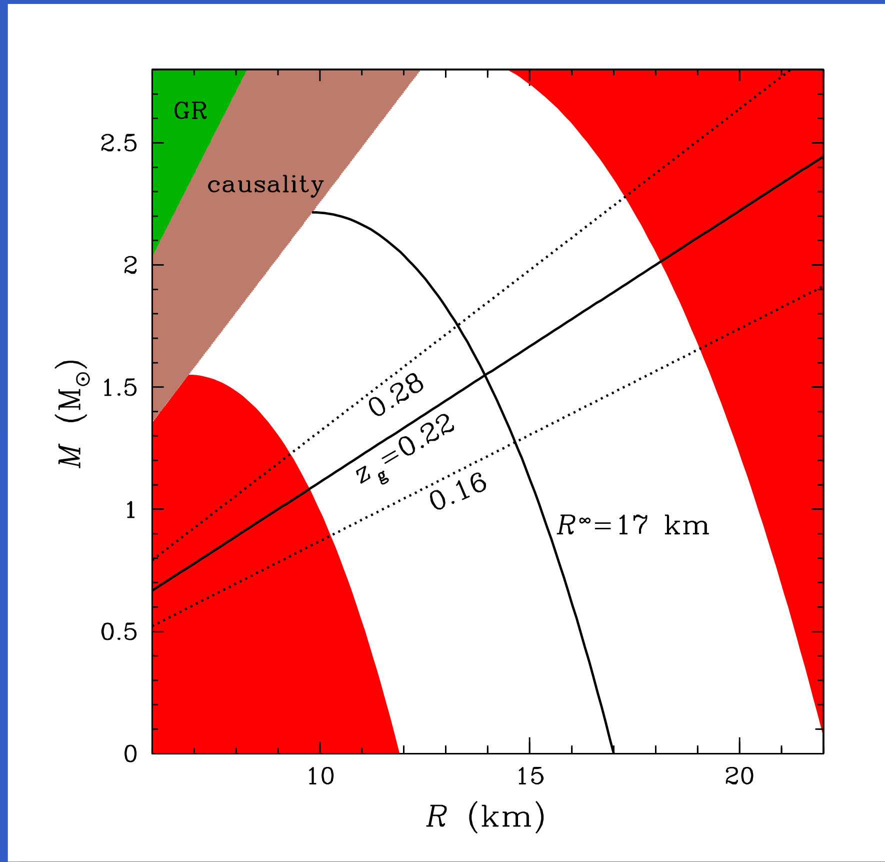
Neutron Star versus Strange Quark Star



(Chandra X-Ray Center, 2002)

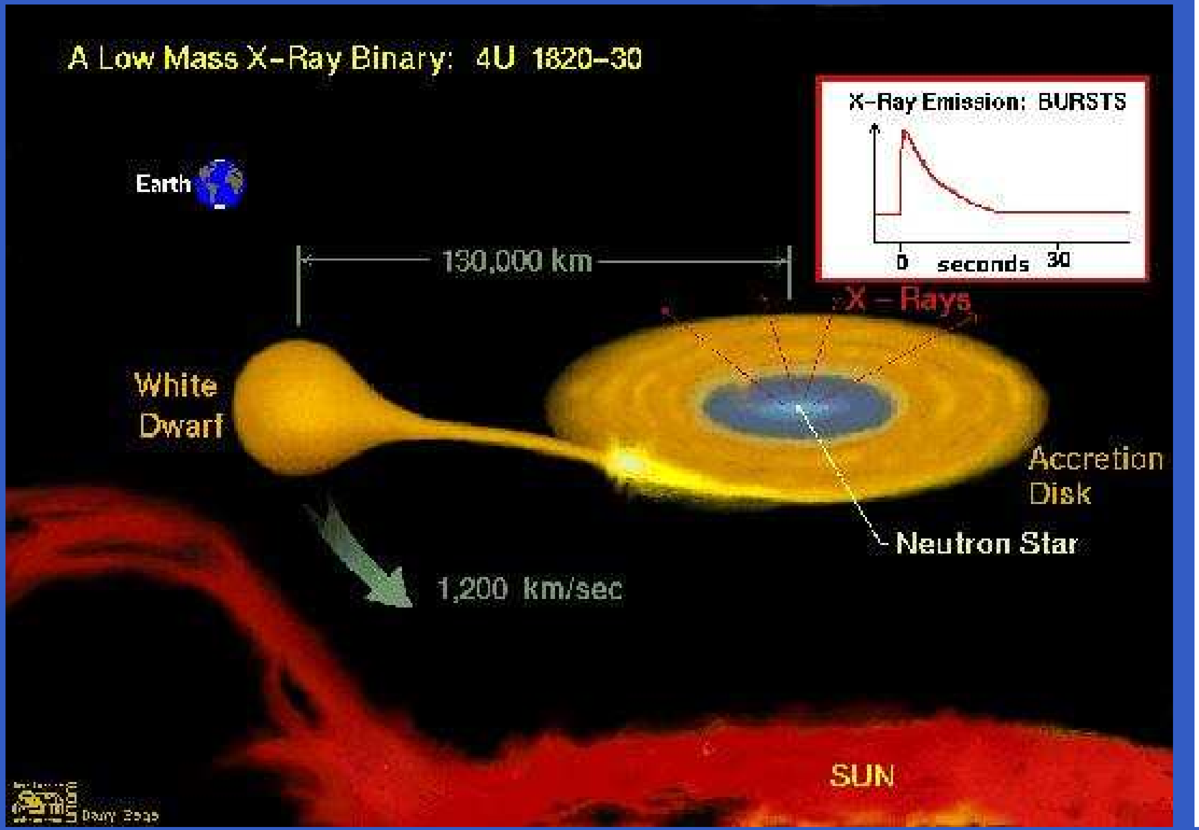
RXJ 1856: Neutron Star or Quark Star? (Ho et al. (2007))

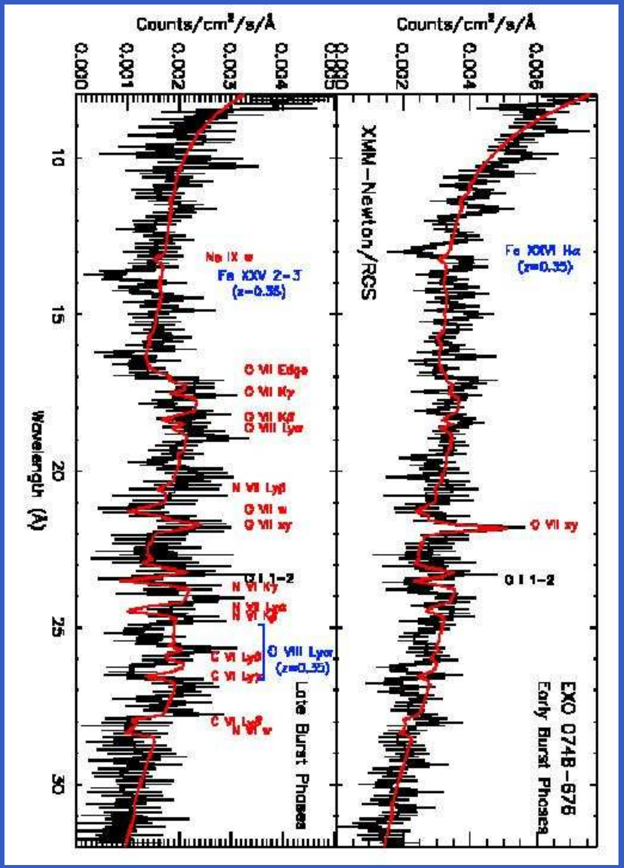




- two-temperature black-body fit implies a lower limit for radiation radius: $R_\infty = R/\sqrt{1-2GM/R} \approx 17$ km (d/140 pc)
- thin magmetized H-atmosphere on condensed iron core (Ho et al.): redshift $z_g \approx 0.22$: $R \approx 14$ km and $M \approx 1.55 M_\odot$
- not necessarily a quark star!

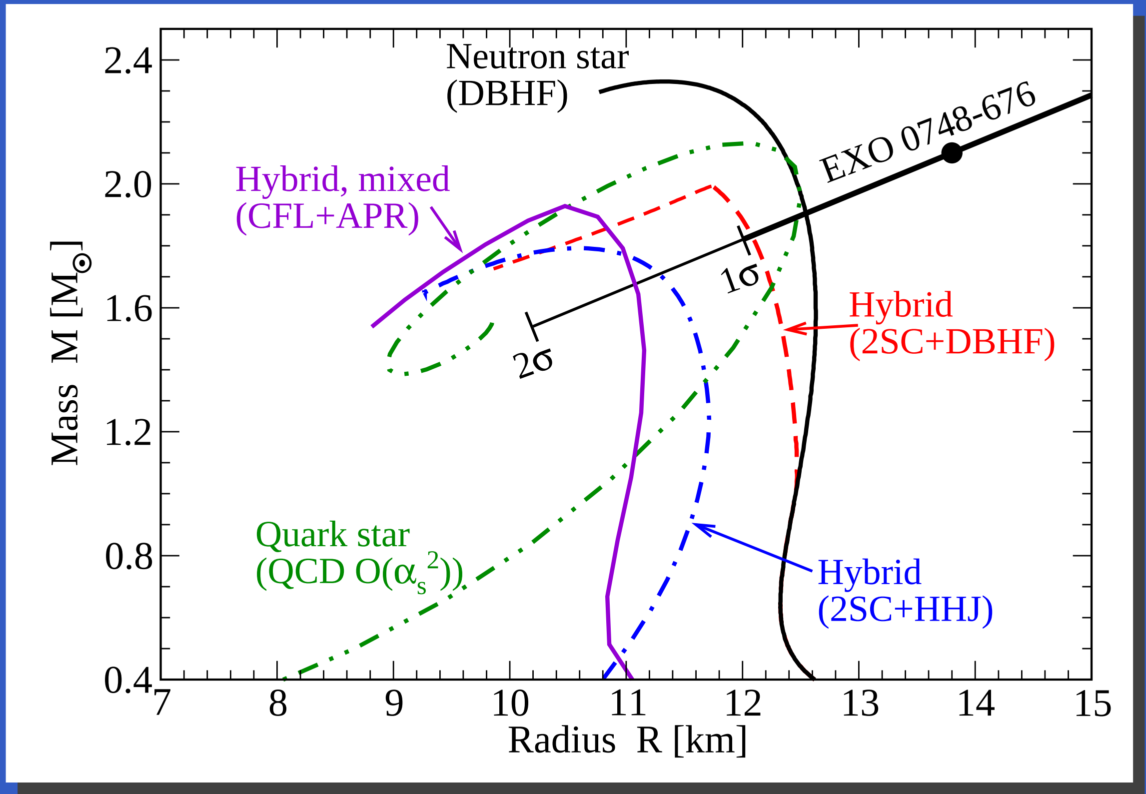
X-Ray burster





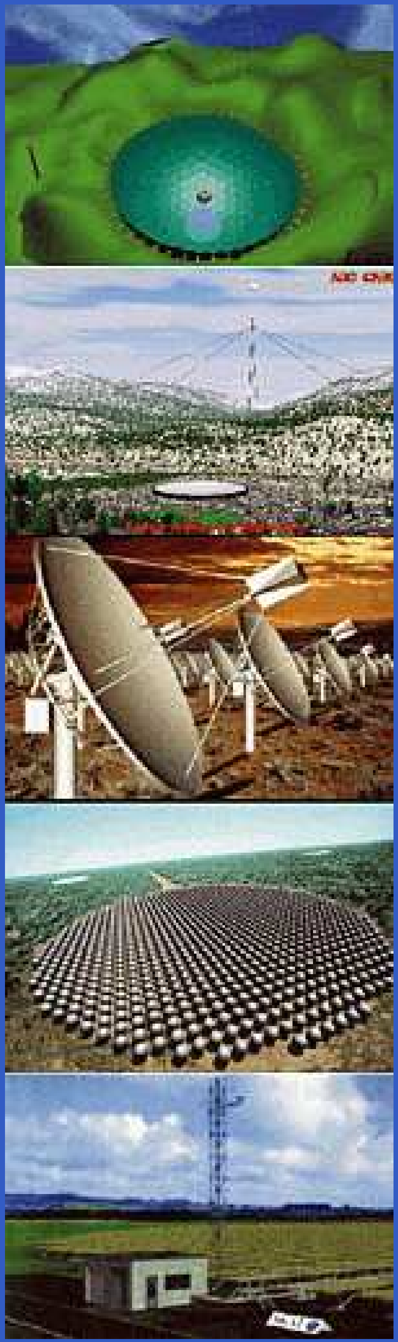
- binary systems of a neutron star with an ordinary star
- accreting material on the neutron star ignites nuclear burning
- red shifted spectral lines measured!
  ($z = 0.35 \rightarrow M/M_\odot = 1.5$ (R/10 km)) (Cottam, Paerels, Mendez (2002))
- Cottam et al. (2008): not confirmed with burst data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

X-Ray burster EXO 0748–676



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

Future: Square Kilometer Array (SKA)



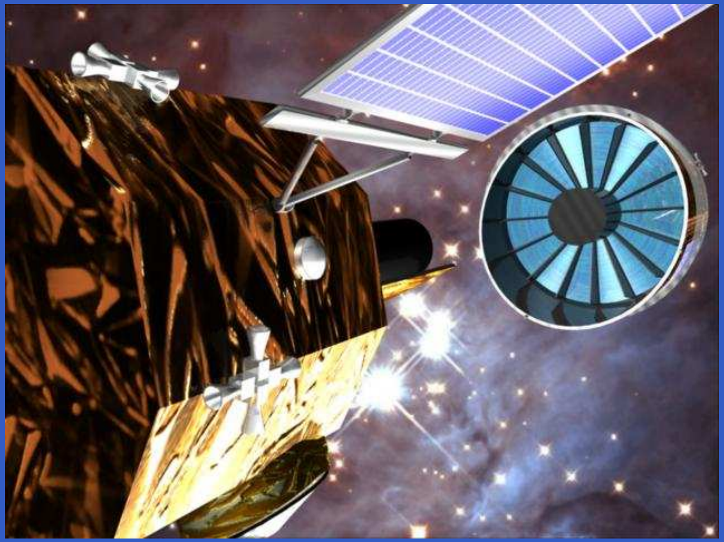
- receiving surface of 1 million square kilometers
- 1 billion dollar international project
- potential to discover:
  - 10,000 to 20,000 new pulsars
  - up to 6,000 millisecond pulsars
  - at least 100 compact relativistic binaries!
- probing the equation of state at extreme limits!
- cosmic gravitational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

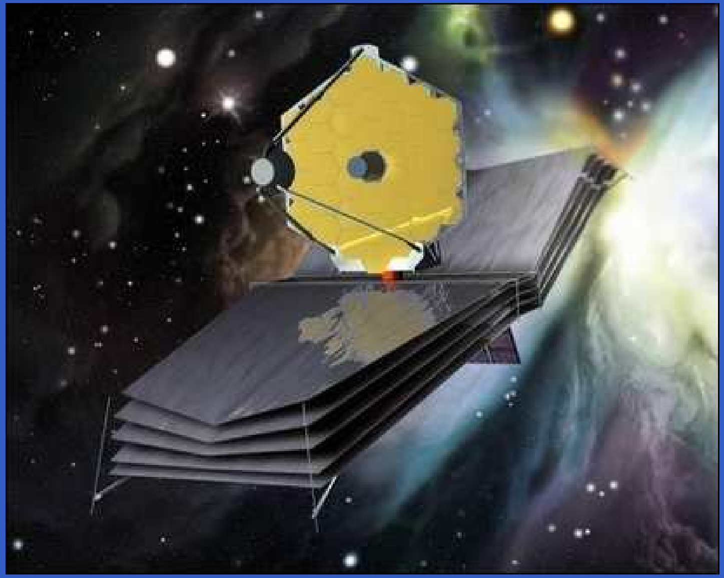
movie

Future Telescopes and Detectors in Space

Constellation-X (Photo: NASA)

XEUS (Photo: ESA)

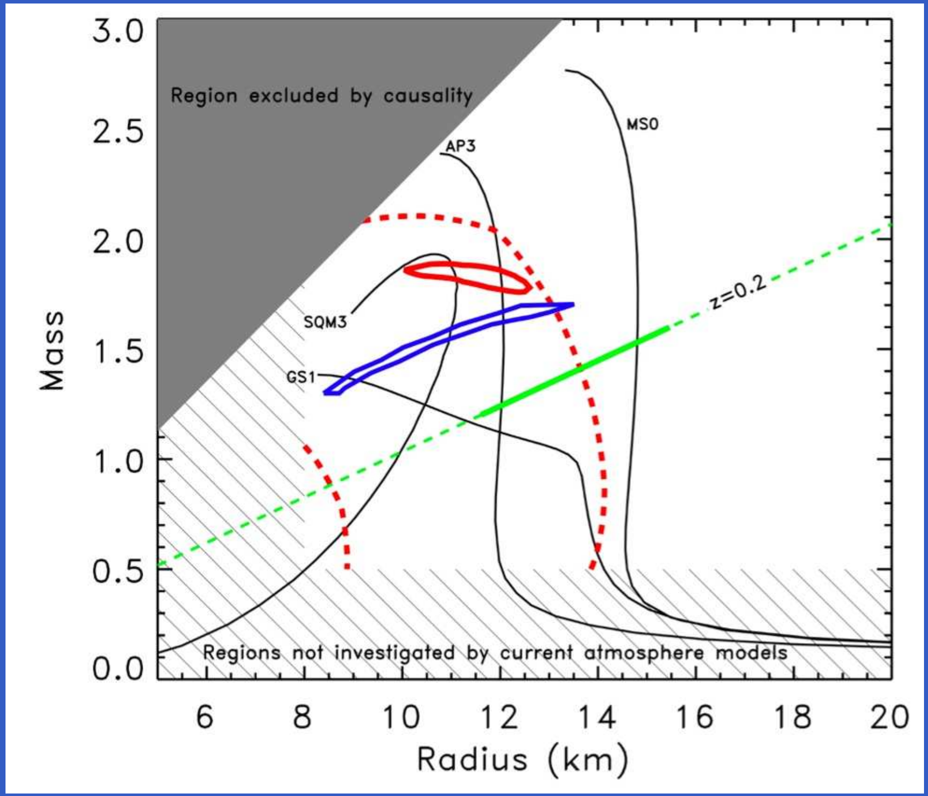




James Webb Space Telescope (Photo: ESA)

LISA (Photo: NASA)

Probes Using the International X–Ray Observatory (IXO)

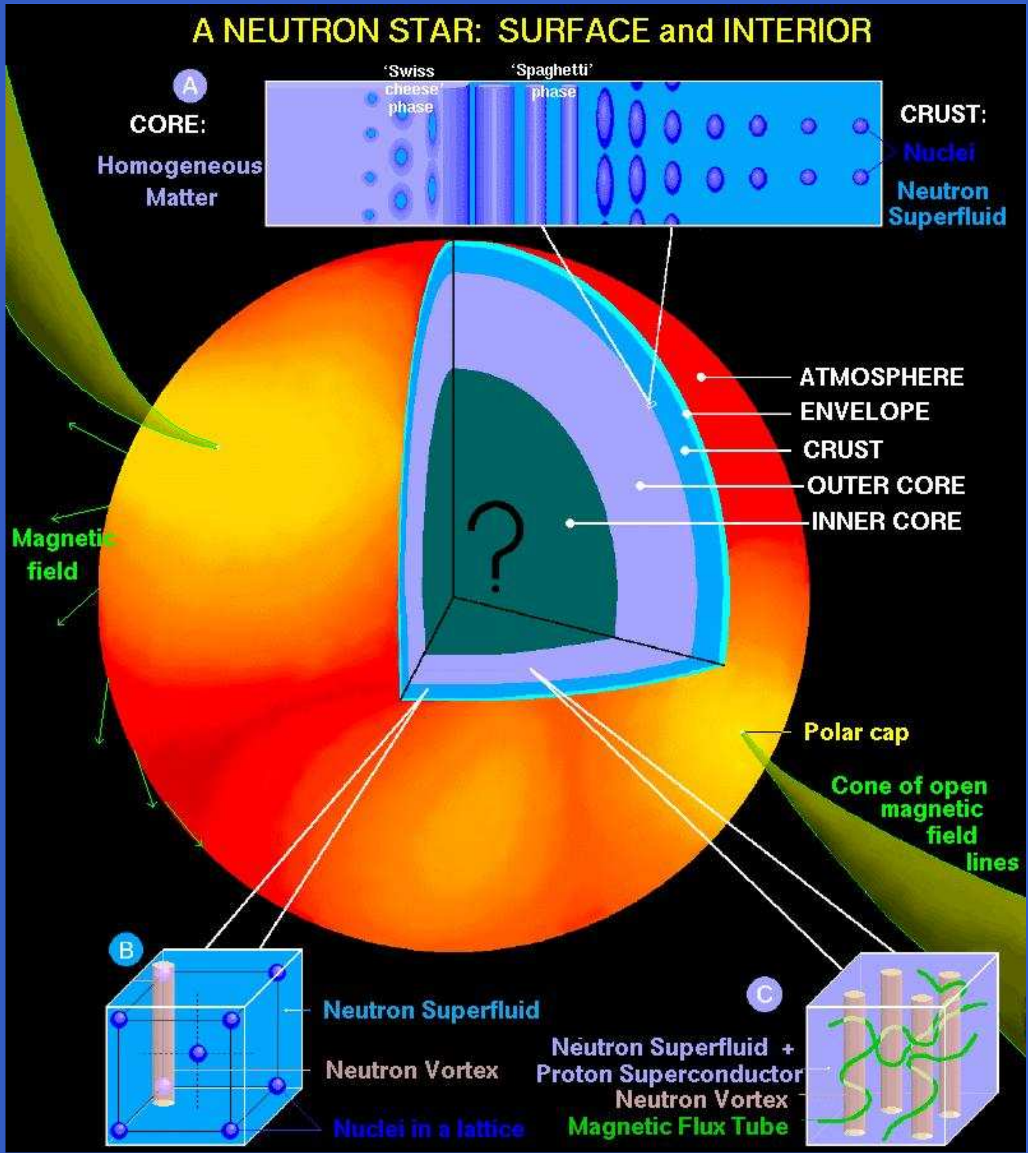


(Cackett et al., IXO Extreme States of Matter Working Group (2009))

- 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

Modelling the Neutron Star

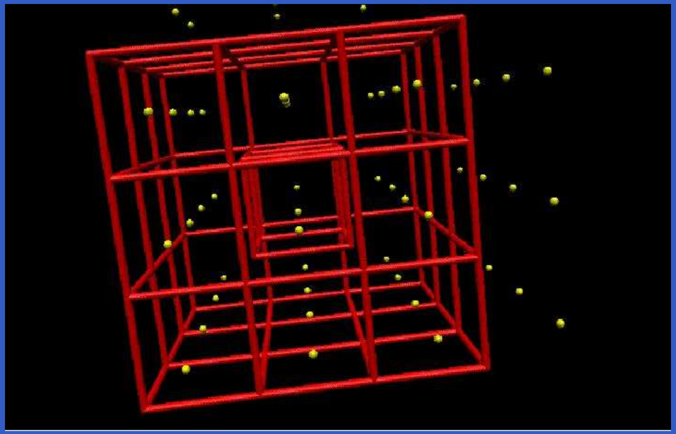
Structure of Neutron Stars — the Crust (Dany Page)



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

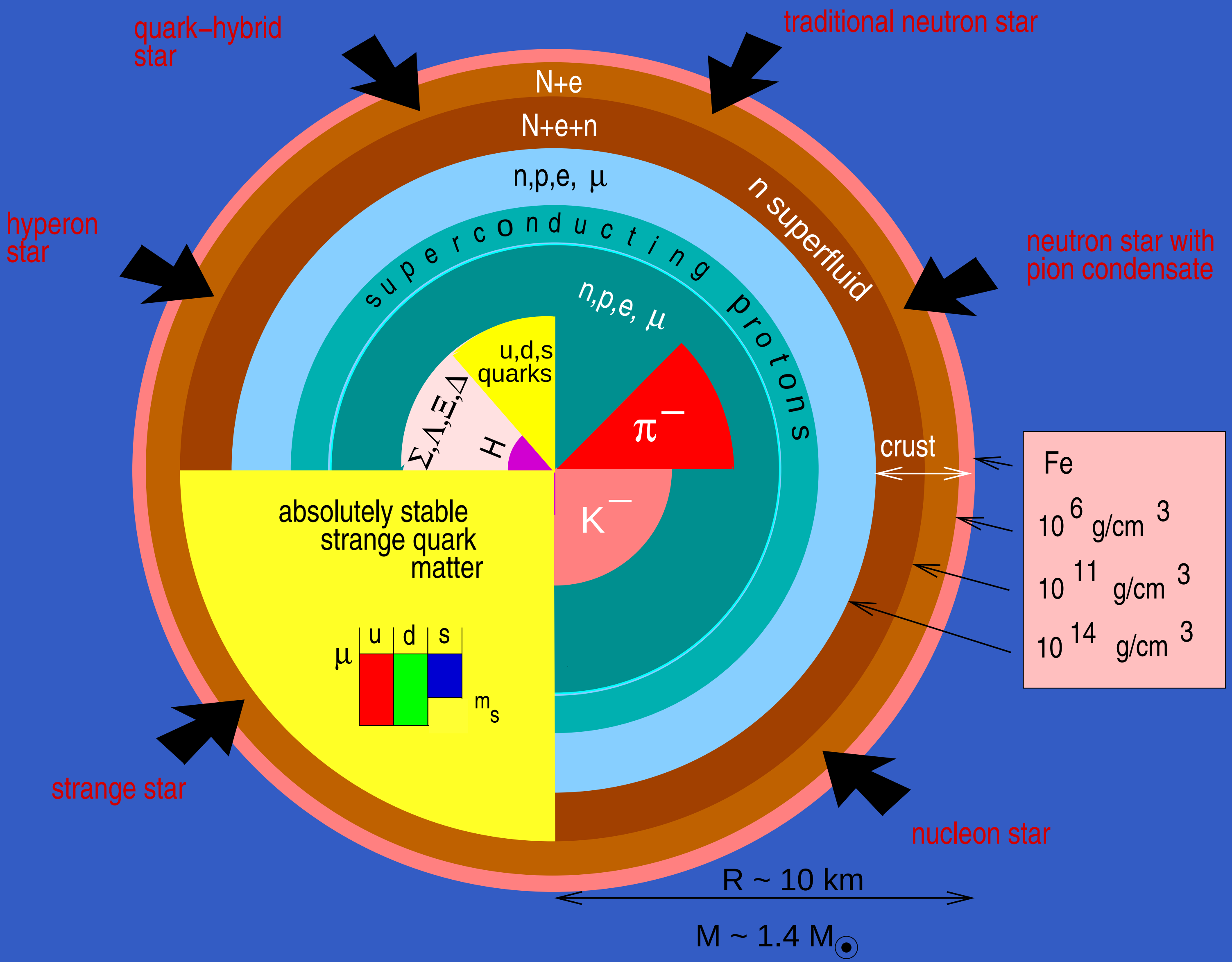
Composition of the crust of a neutron star

lattice of nuclei surrounded by free electrons



- Wigner–Seitz–cell, lattice structure is bcc
- minimize $E = E_{\text{nuclei}} + E_{\text{lattice}} + E_{\text{electrons}}$
- loop over all particle stable nuclei (up to 14.000)
- use atomic mass evaluation of 2003 by Audi, Wapstra, and Thibault
- extrapolate to the drip–line with various models
- $\Longrightarrow$ sequence of nuclei ${}^{A}Z$ as a function of density
  (Baym, Pethick, Sutherland 1971; Rüster, Hempel, JSB 2006)

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



Neutron Star Matter for a Free Gas

(Ambartsumyan and Saakyan, 1960)

Hadron	p,n	Σ^-	Λ	others
appears at:	$\ll n_0$	$4n_0$	$8n_0$	$> 20n_0$

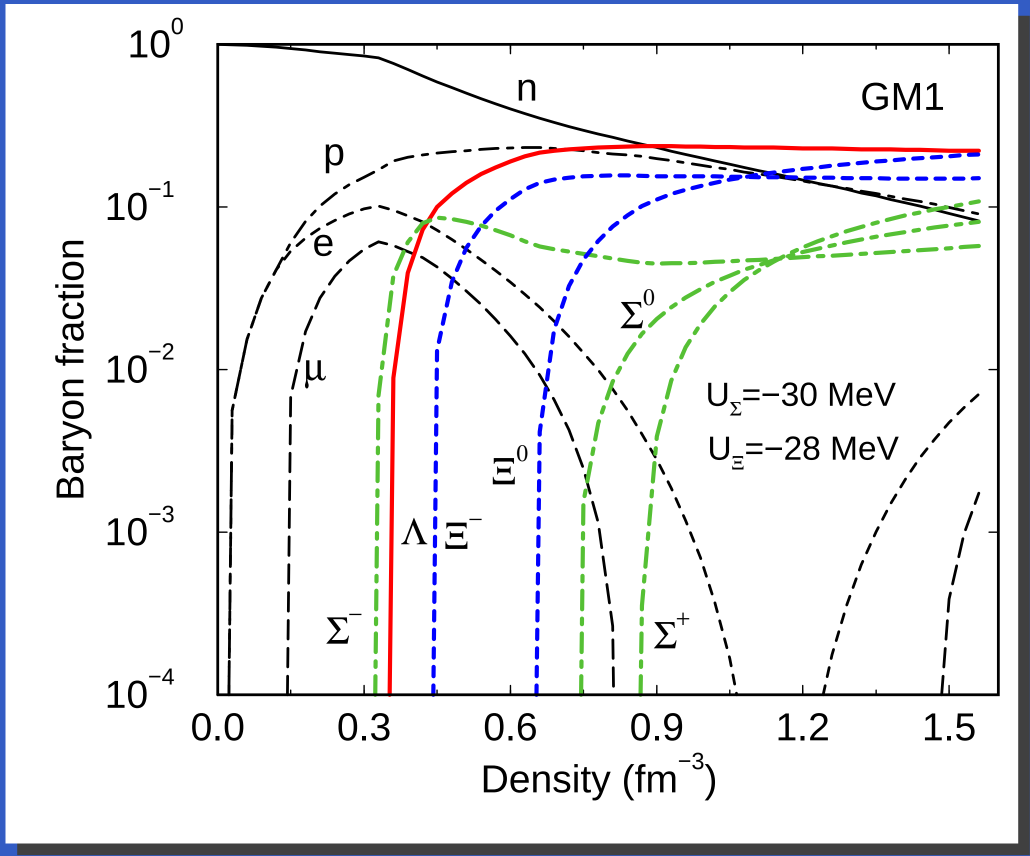
but the corresponding equation of state results in a maximum mass of only

$$M_{\rm max} \approx 0.7 M_\odot < 1.44 M_\odot$$

(Oppenheimer and Volkoff, 1939)

$\Longrightarrow$ effects from strong interactions are essential to describe neutron stars!

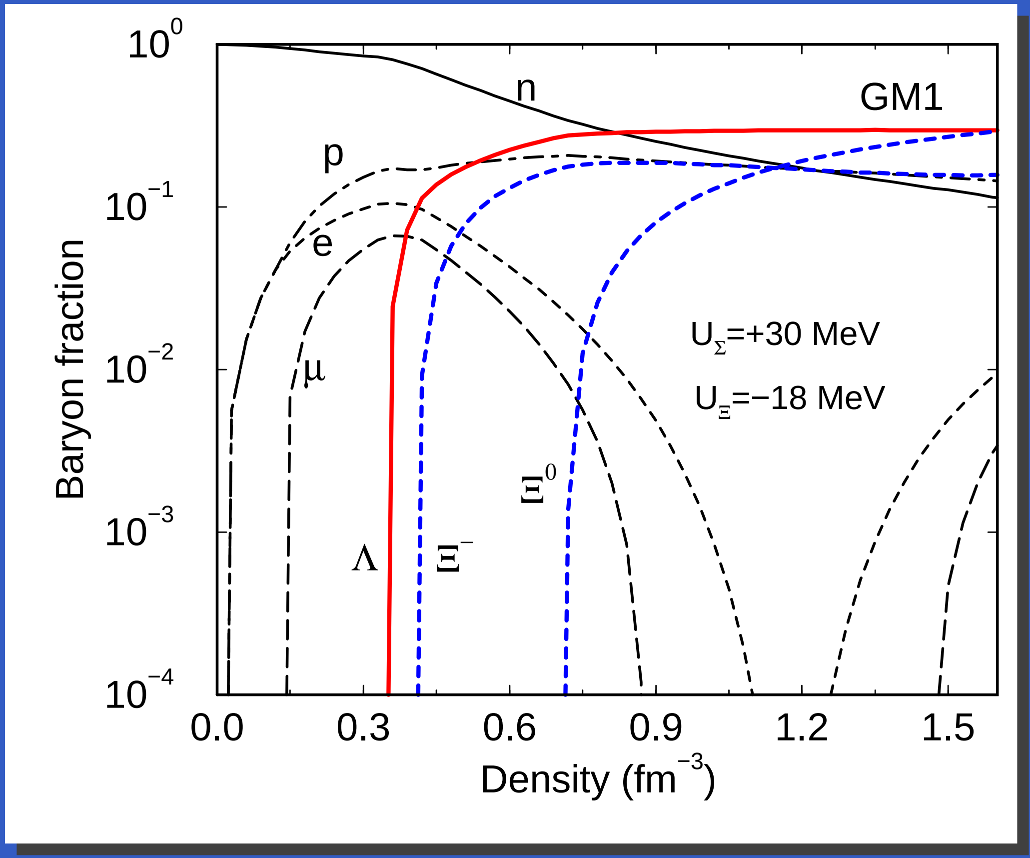
Composition of Neutron Star Matter



(JS and Mishustin 1996)

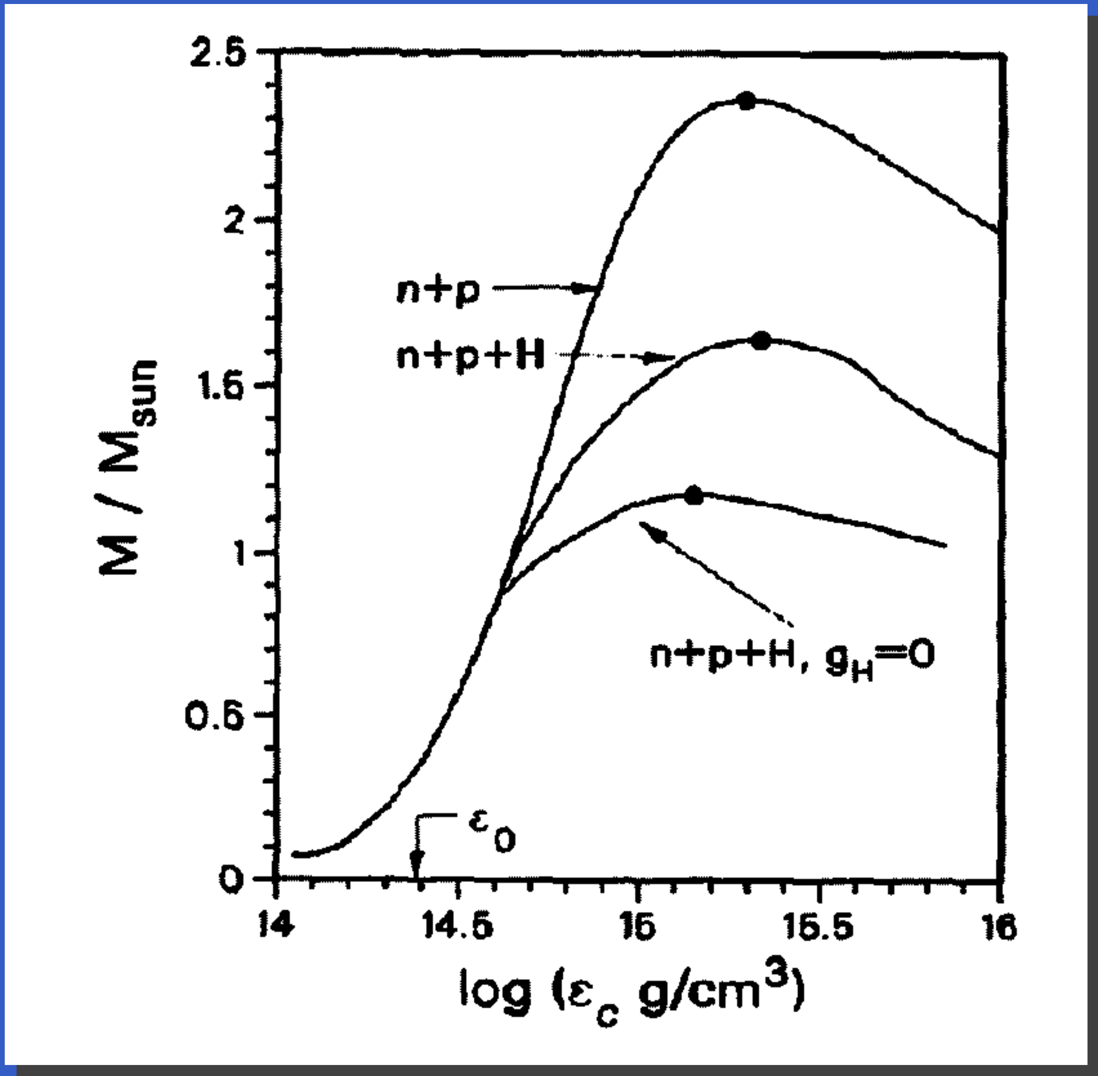
- hyperon potentials fixed to hypernuclear data
- attractive potential for Σs and Ξs
- Σ^- appear shortly before Λs around $n = 2n_0$
- Λs present in matter at $n = 2.5n_0$, Ξ^- before $n = 3n_0$

Composition of Neutron Star Matter



- Λs are present close to $n = 2n_0$
- repulsive potential for Σs: Σ hyperons do not appear at all!
- population is highly sensitive to the in-medium potential!

Impact of hyperons on the maximum mass of neutron stars



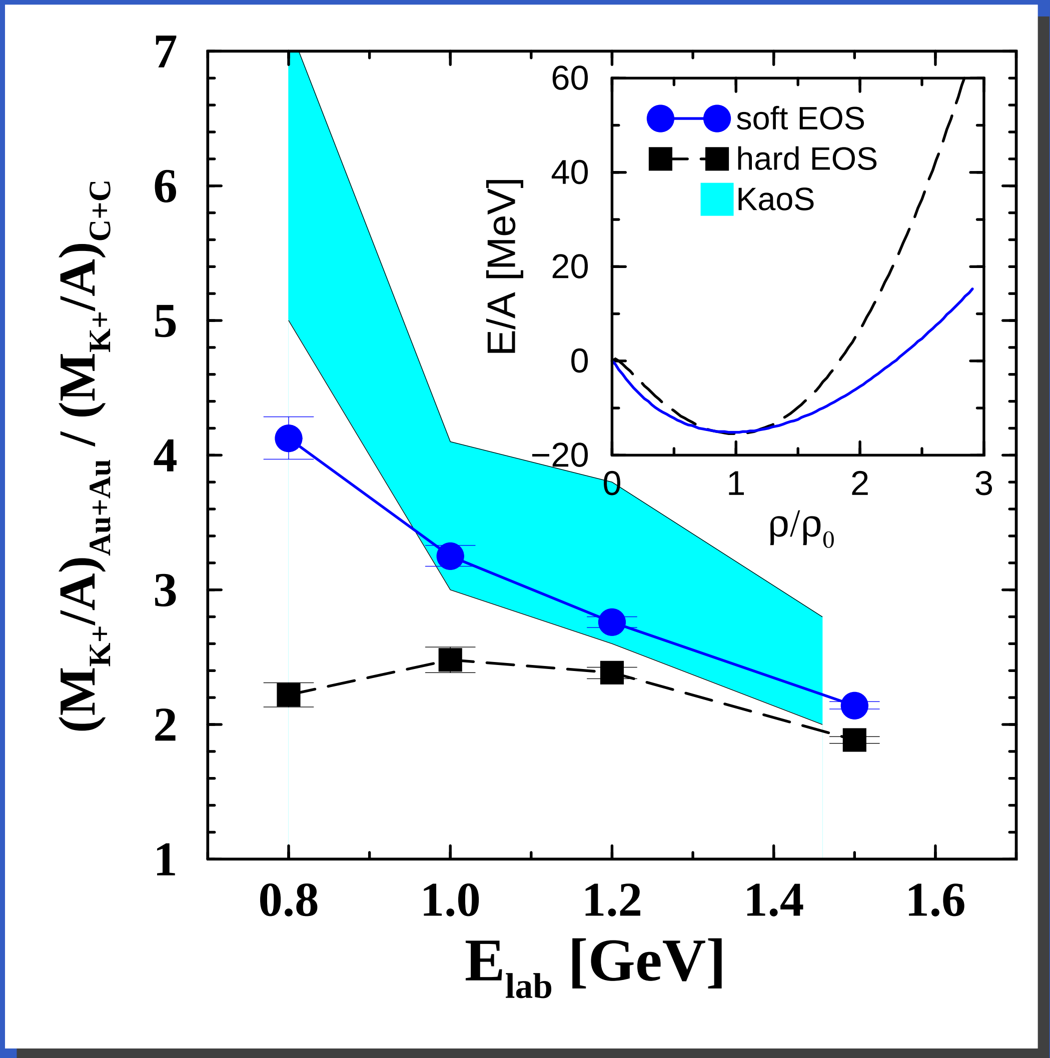
(Glendenning and Moszkowski 1991)

- neutron star with nucleons and leptons only: $M \approx 2.3 M_\odot$
- substantial decrease of the maximum mass due to hyperons!
- maximum mass for "giant hypernuclei": $M \approx 1.7 M_\odot$
- noninteracting hyperons result in a too low mass: $M < 1.4 M_\odot$!

Constraint on the maximum mass of neutron stars from heavy-ion data

(Irina Sagert, JSB, Christian Sturm, 2009)

Kaon production in heavy-ion collisions

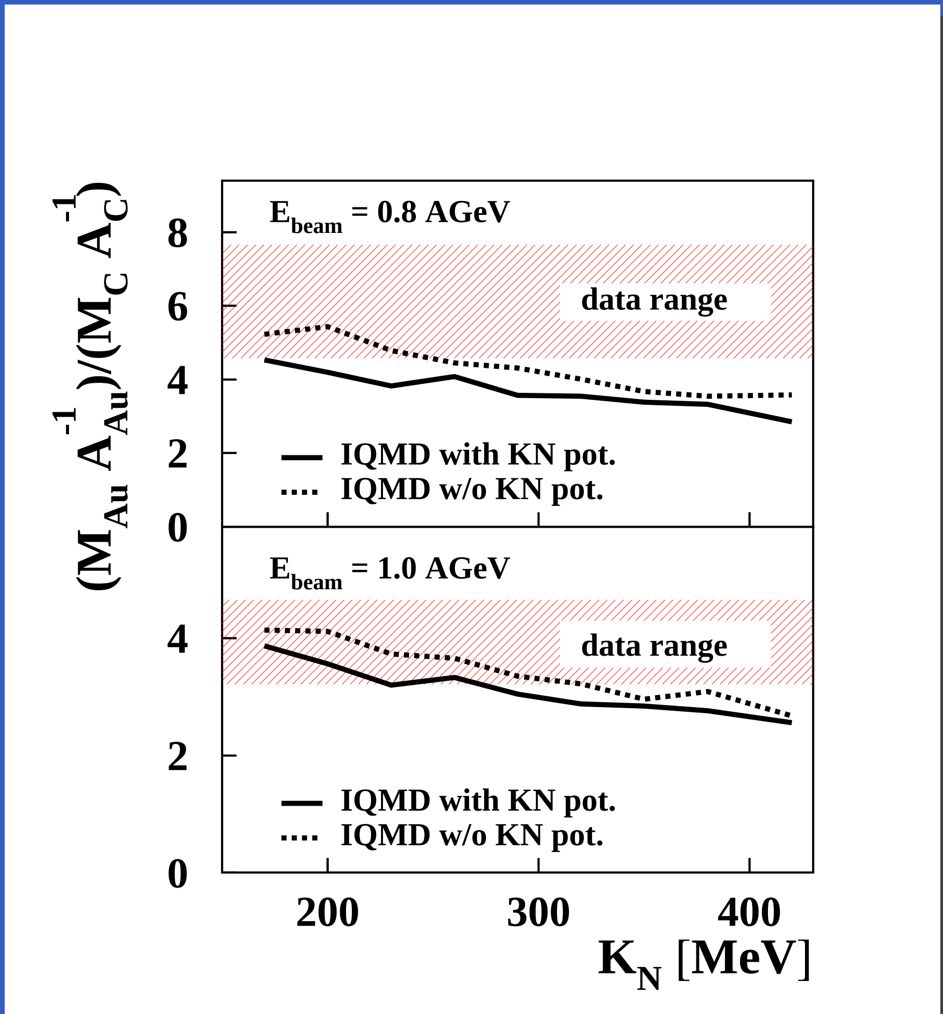


Sturm et al. (KaoS collaboration), PRL 2001

Fuchs, Faessler, Zabrodin, Zheng, PRL 2001

- Kaons produced by associated production: NN$\rightarrow$ NΛK, NN$\rightarrow$NNK$\overline{\mathrm{K}}$
- in-medium processes (rescattering): πN $\rightarrow$ ΛK, $\pi\Lambda$ $\rightarrow$ N$\overline{\mathrm{K}}$
- nuclear matter is compressed up to $3n_0$!
- long mean-free path of kaons: kaons can escape high density matter

Confirmed KaoS data analysis: the nuclear EoS is soft!

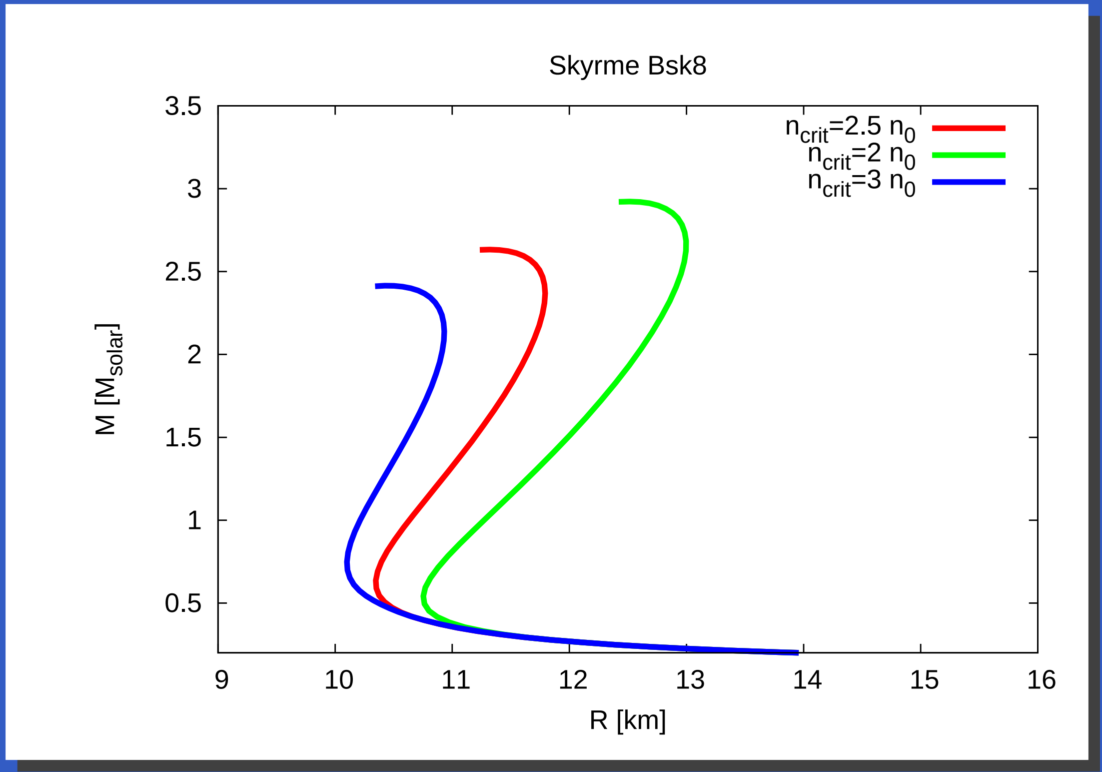


The KAOS Collaboration

- kaon production (K^+) in heavy-ion collisions at subthreshold energies
- double ratio: multiplicity per mass number for C+C collisions and Au+Au collisions at 0.8 AGeV and 1.0 AGeV (rather insensitive to input parameters)
- only calculations with a compression modulus of $K_N \approx 200$ MeV can describe the data (Hartnack, Oeschler, Aichelin, PRL 2006; KaoS collaboration, 2007)

$\Longrightarrow$ the nuclear equation of state is SOFT!

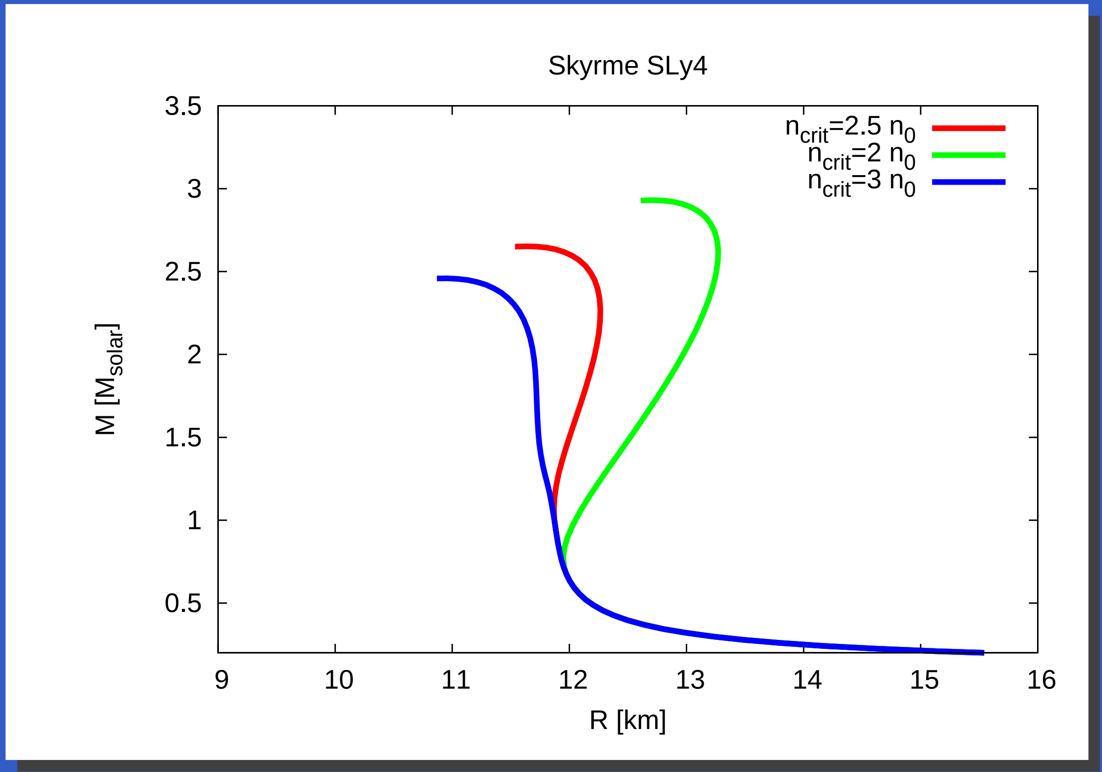
Maximum Masses of Neutron Stars – Causality



(Irina Sagert)

- Skyrme parameter set BSK8: fitted to masses of all known nuclei
- above a fiducial density (determined from the data analysis of the KaoS data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f
  Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\rm max} = 4.2 M_\odot (\epsilon_0/\epsilon_f)^{1/2}$
- $\Longrightarrow$ new upper mass limit of about $2.7 M_\odot$ from heavy-ion data!

Maximum Masses of Neutron Stars – Causality



(Irina Sagert)

- Skyrme parameter set Sly4: fitted to properties of spherical nuclei
- above a fiducial density (determined from the data analysis of the KaoS data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f
  Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\rm max} = 4.2 M_\odot (\epsilon_0/\epsilon_f)^{1/2}$
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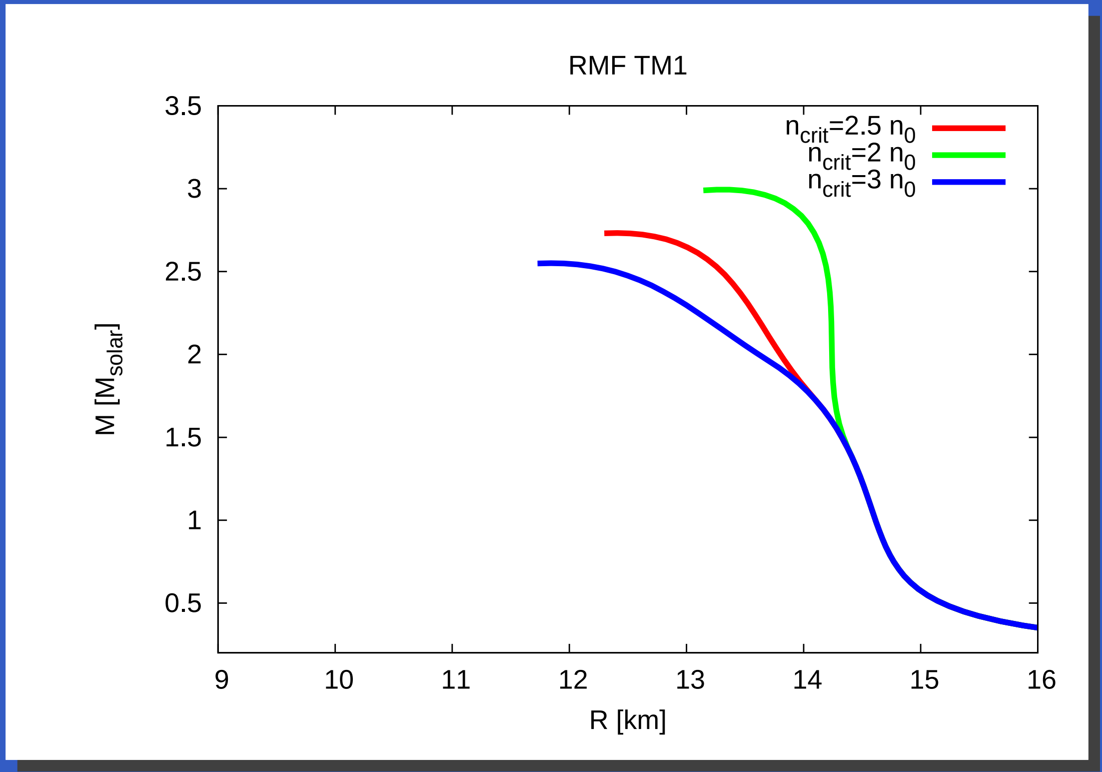
Maximum Masses of Neutron Stars – Causality

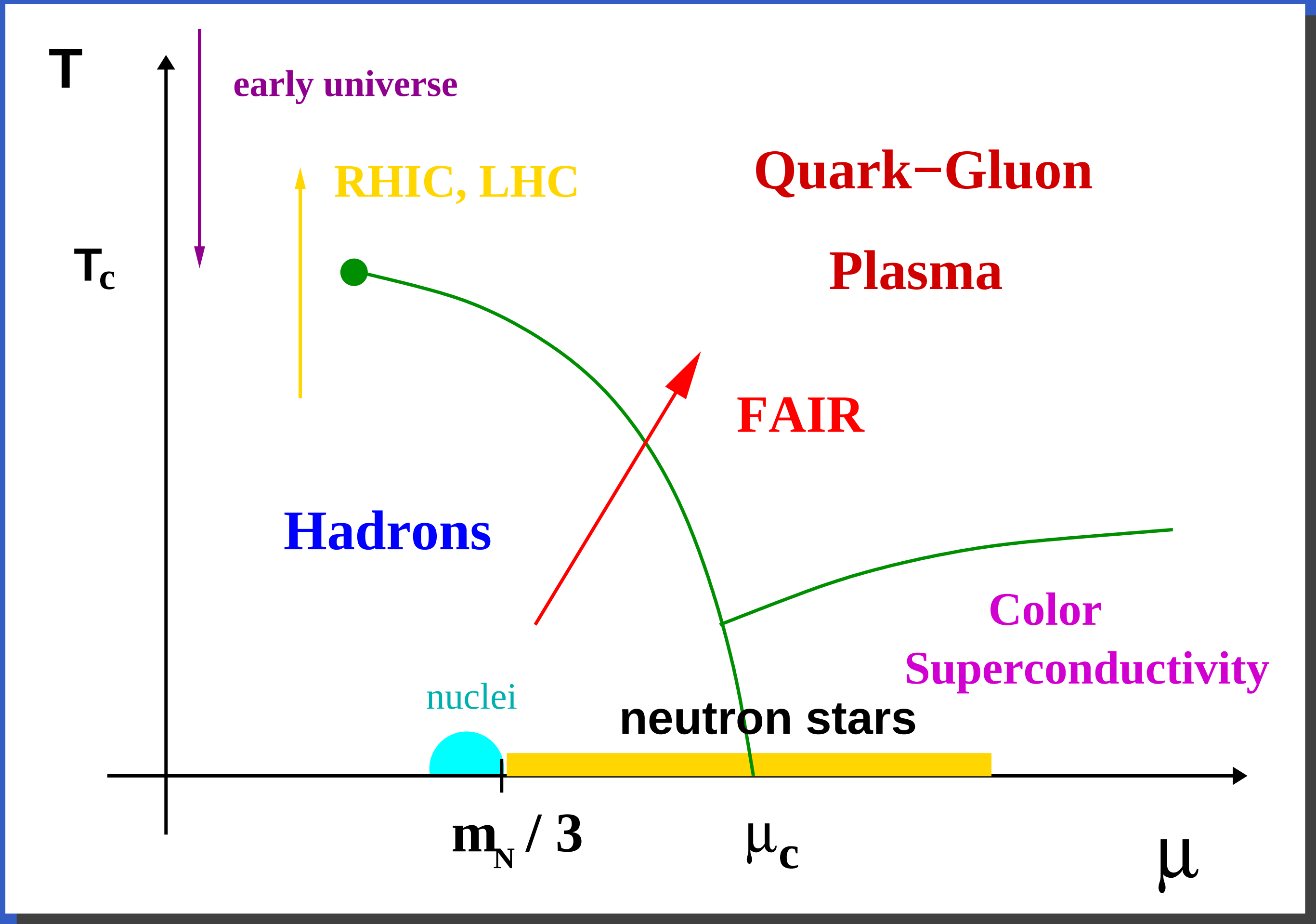


(Irina Sagert)

- RMF parameter set TM1: fitted to properties of spherical nuclei
- above a fiducial density (determined from the data analysis of the KaoS data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f
  Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\max} = 4.2 M_\odot (\epsilon_0/\epsilon_f)^{1/2}$
- $\Longrightarrow$ new upper mass limit of about $2.8 M_\odot$ from heavy-ion data!

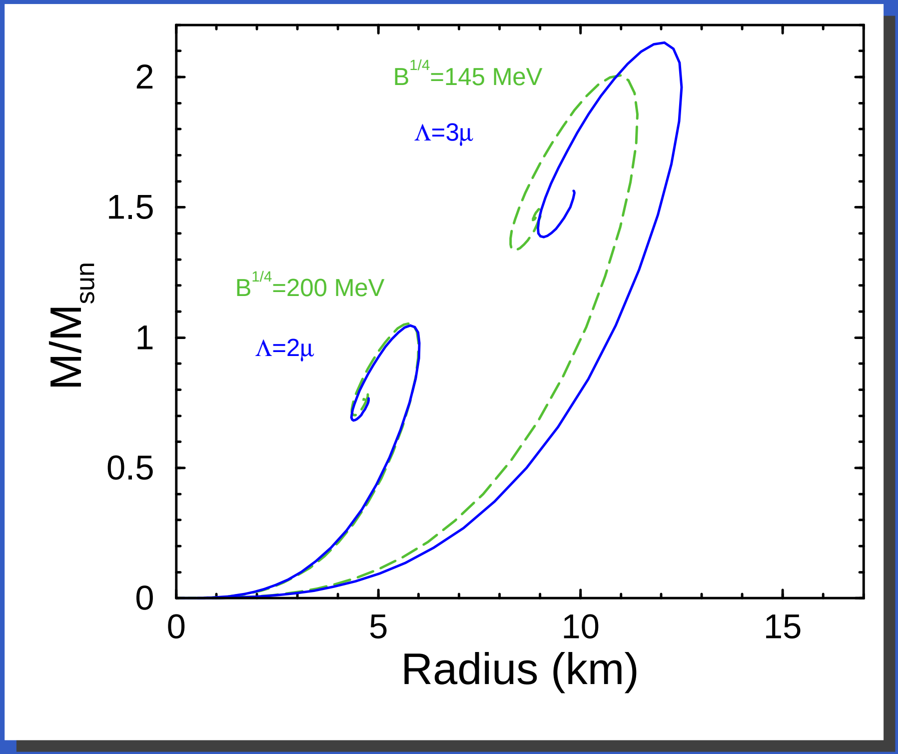
QCD Phase Transition and Neutron Stars

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!)

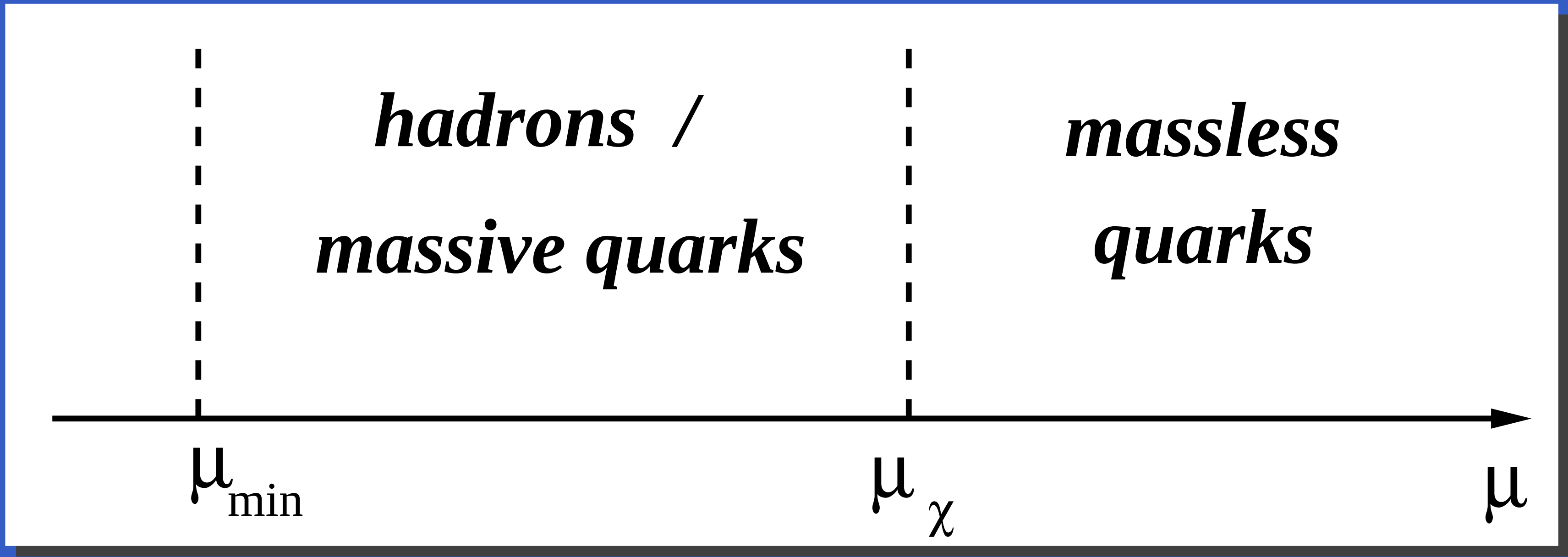
Mass-radius and maximum density of pure quark stars



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

- case $\Lambda = 2\mu$: $M_{\max} = 1.05\, M_{\odot}$, $R_{\max} = 5.8$ 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!

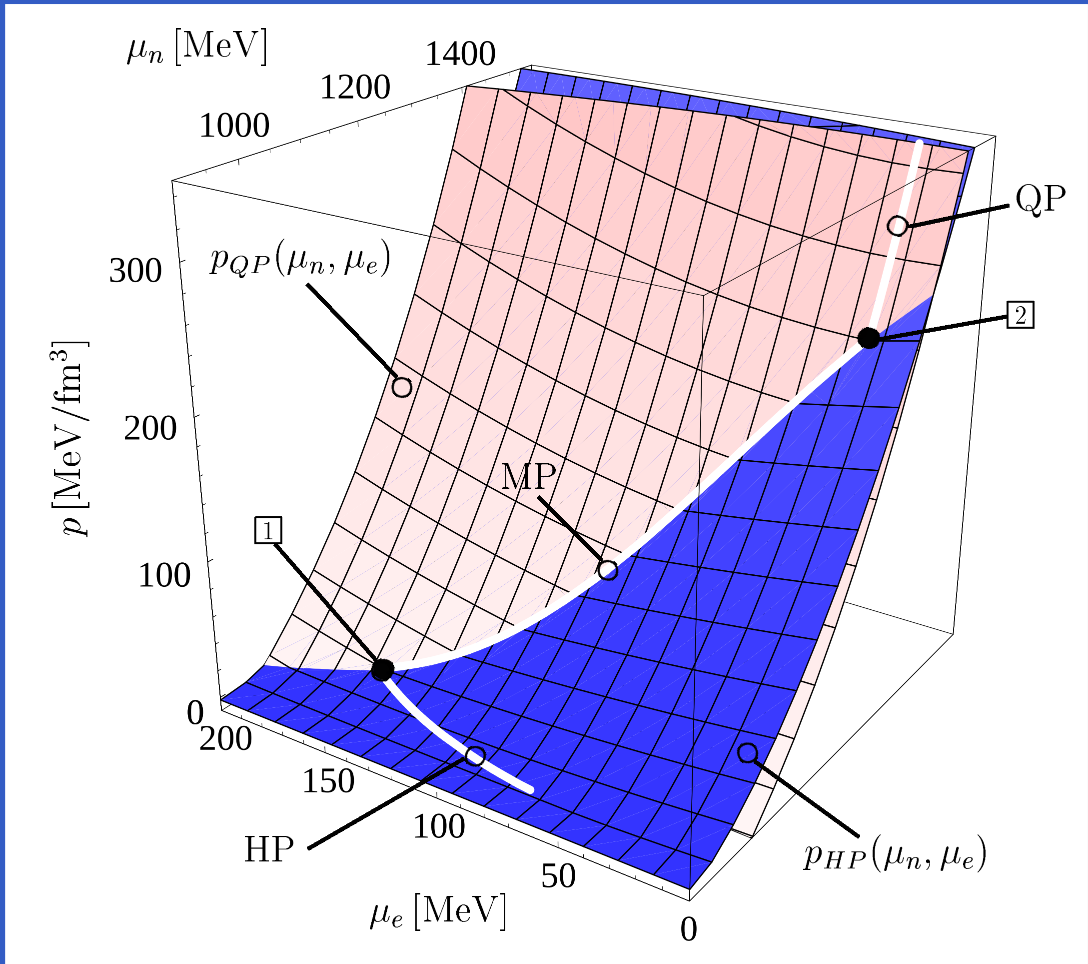
Matching to low density EoS



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 (neutron star)
- A strongly first-order chiral transition
  $\Longrightarrow$ two types of compact stars:
  a new stable solution with smaller masses and radii

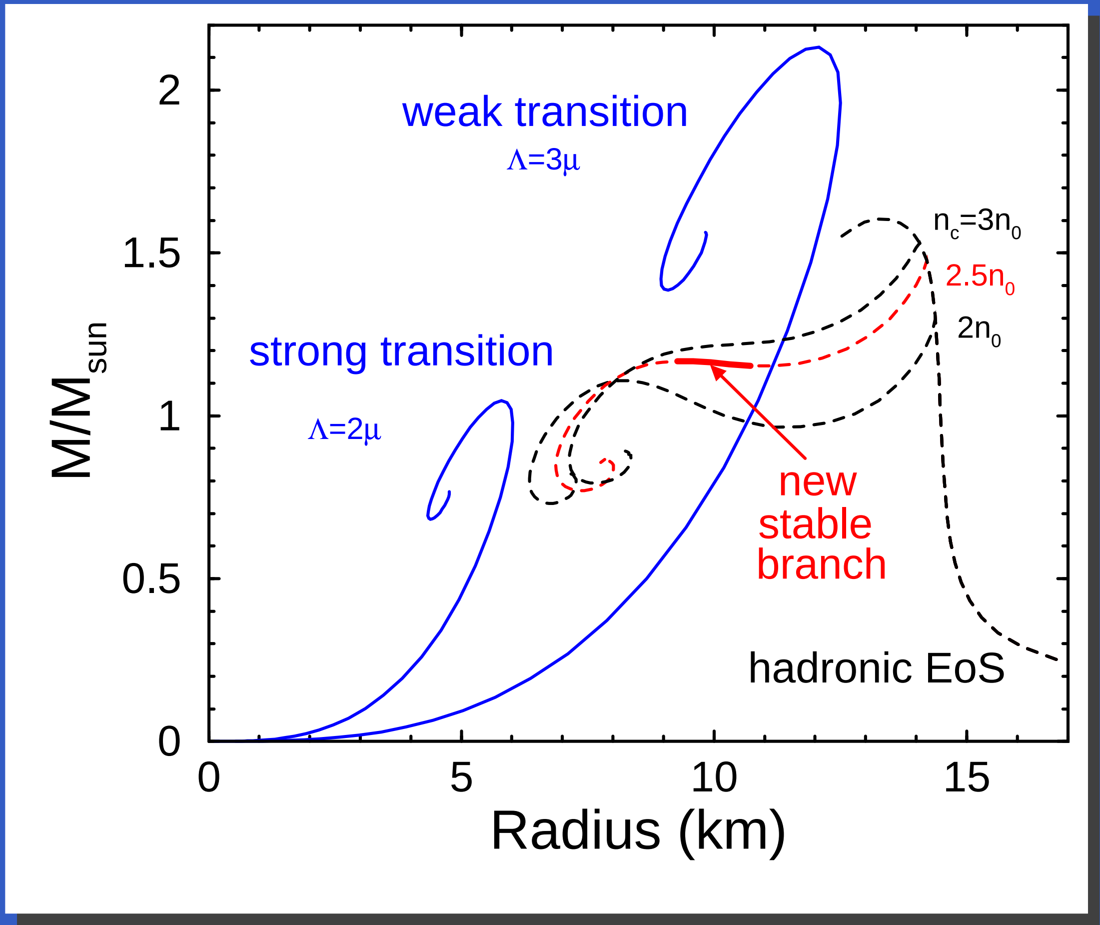
Gibbs Phase Construction (Glendenning 1992)



(Schertler et al. (2000))

- two conserved charges in β-equilibrium: baryon number and charge!
- Gibbs criterium for phase equilibrium: equal pressure for equal chemical potentials $P_I(\mu_B, \mu_e) = P_I I(\mu_B, \mu_e)$
- globally charge neutral matter: mixed phase with charged bubbles forms!

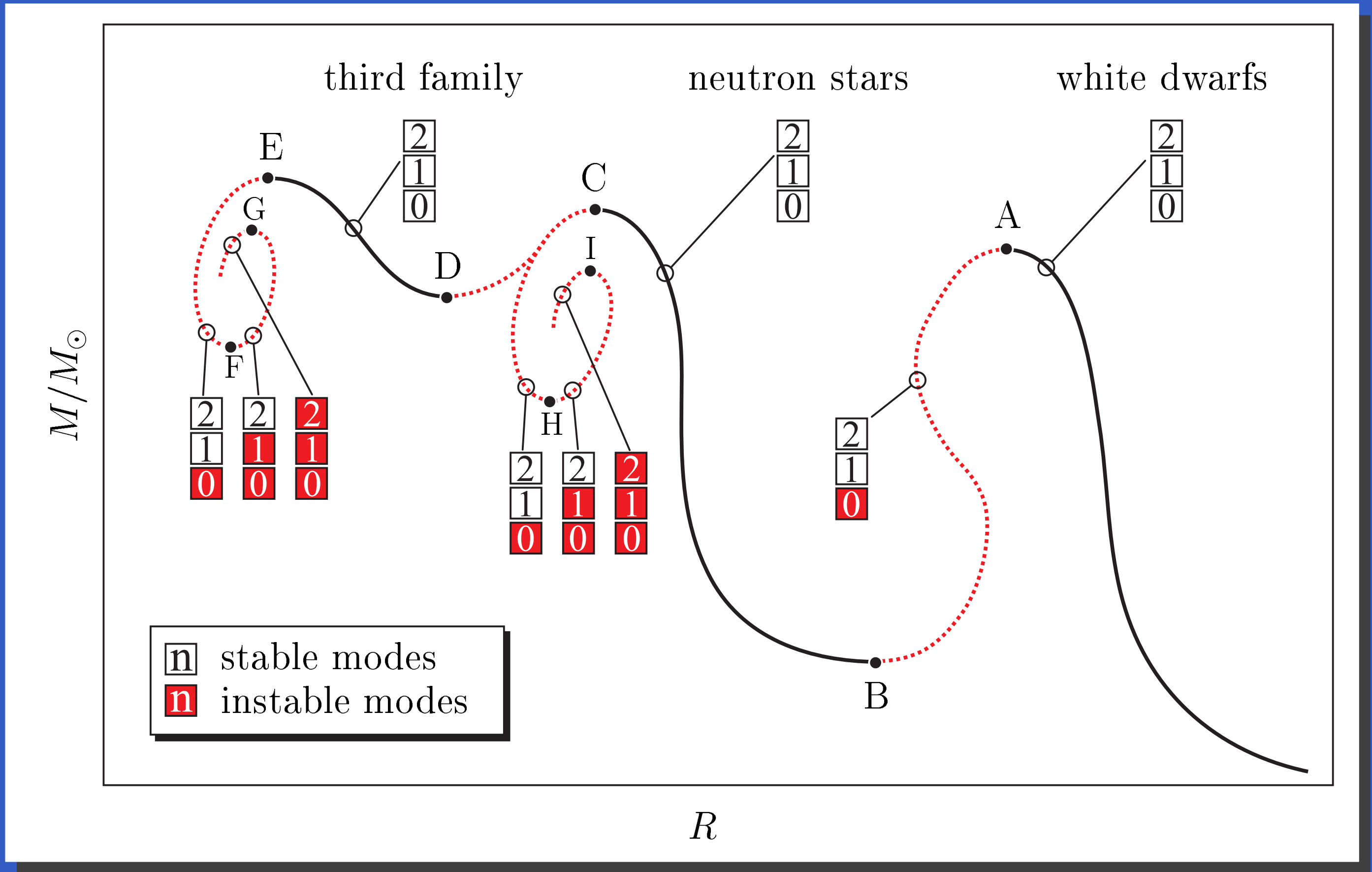
Quark star twins? (Fraga, JSB, Pisarski 2001)



- 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)

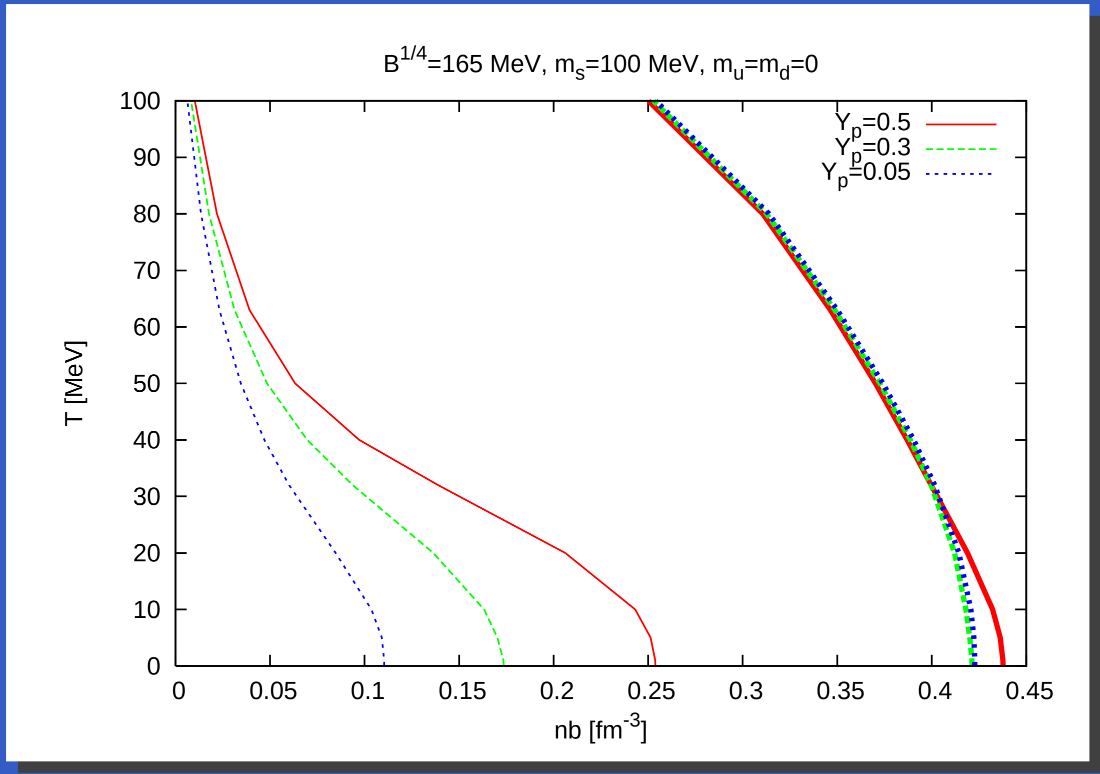


- third solution to the TOV equations besides white dwarfs and neutron stars, solution is stable!
- generates stars more compact than neutron stars!
- possible for any first order phase transition!

QCD phase transition in supernovae

Irina Sagert, Matthias Hempel, Giuseppe Pagliara, JSB, Tobias Fischer, Anthony Mezzacappa, Friedel Thielemann, Matthias Liebendörfer, arXive:0809.4225, PRL in press

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: $T = 10 - 20$ MeV, $Y_p = 0.2 - 0.3$, $\epsilon \sim (1 - 1.5)\epsilon_0$

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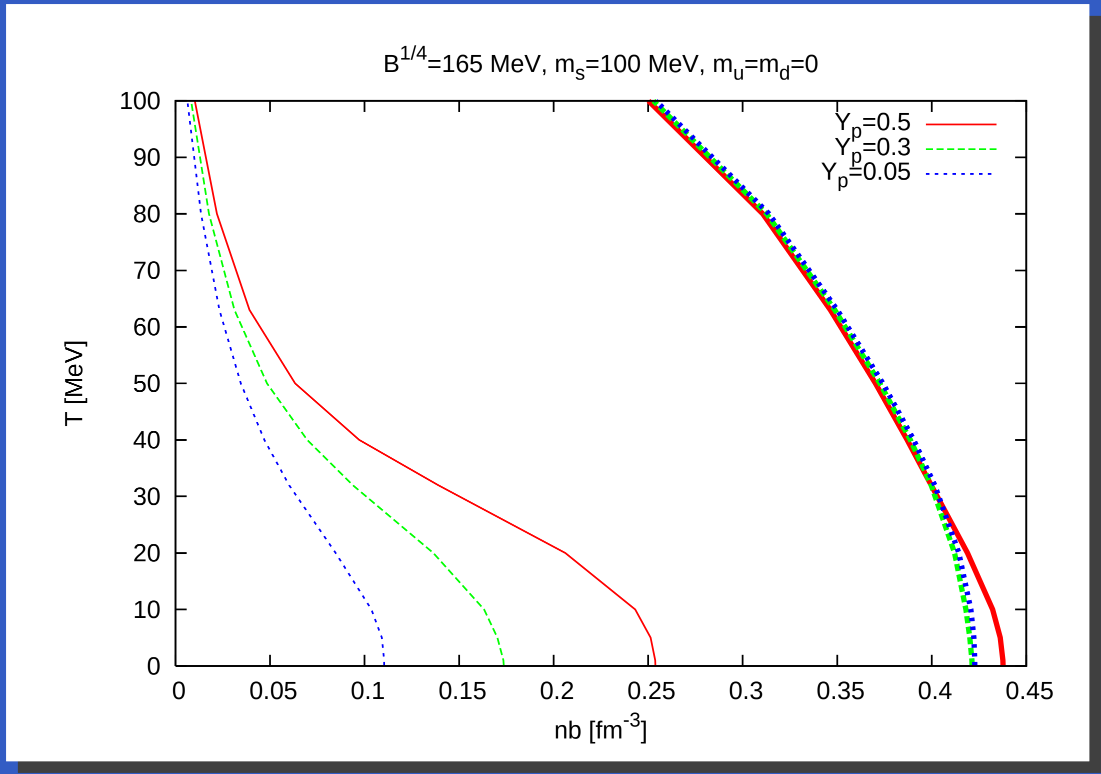

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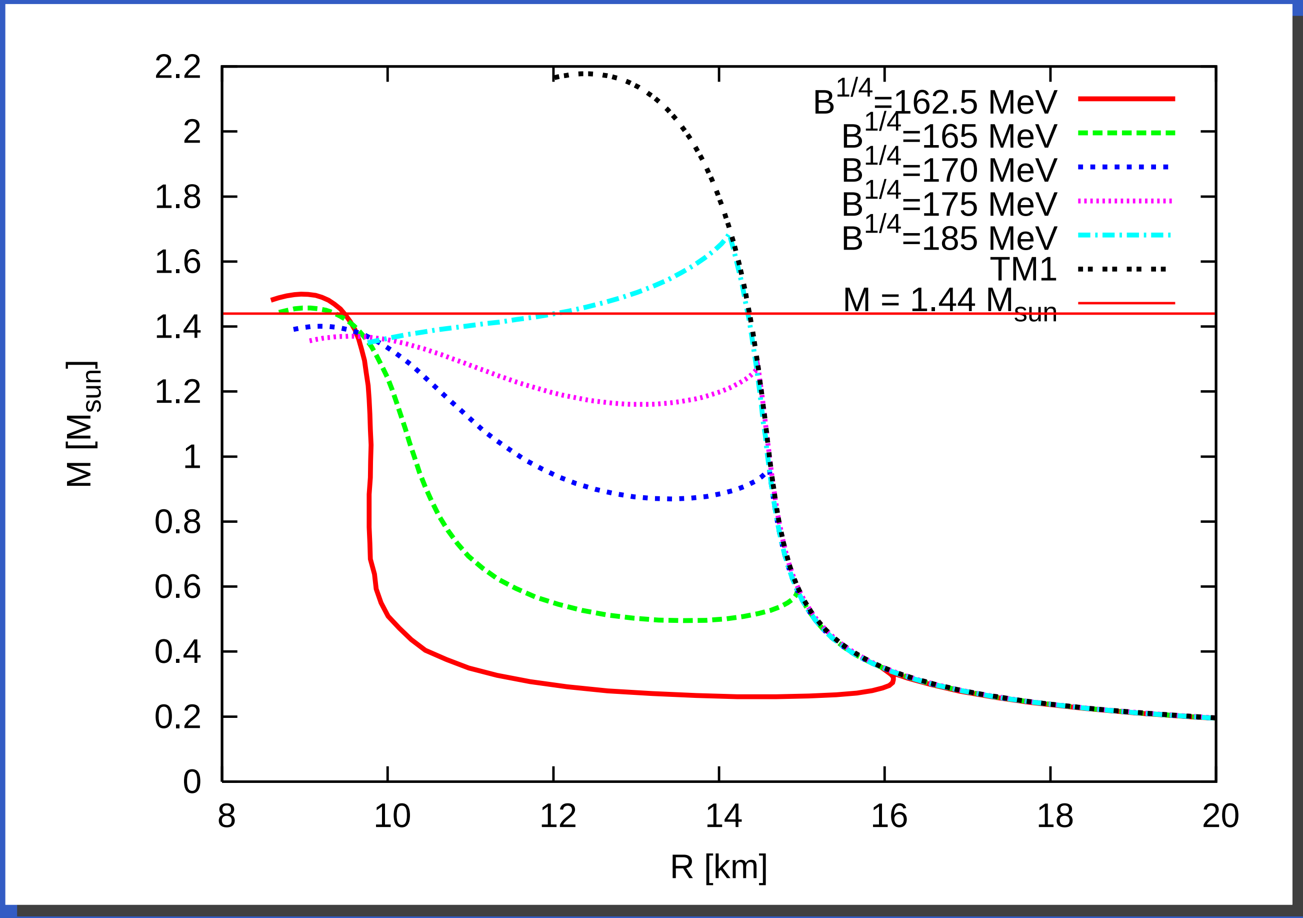
- supernova matter at bounce: $T = 10 - 20$ MeV, $Y_p = 0.2 - 0.3$, $\epsilon \sim (1 - 1.5)\epsilon_0$
- production of quark matter in supernovae at bounce possible!

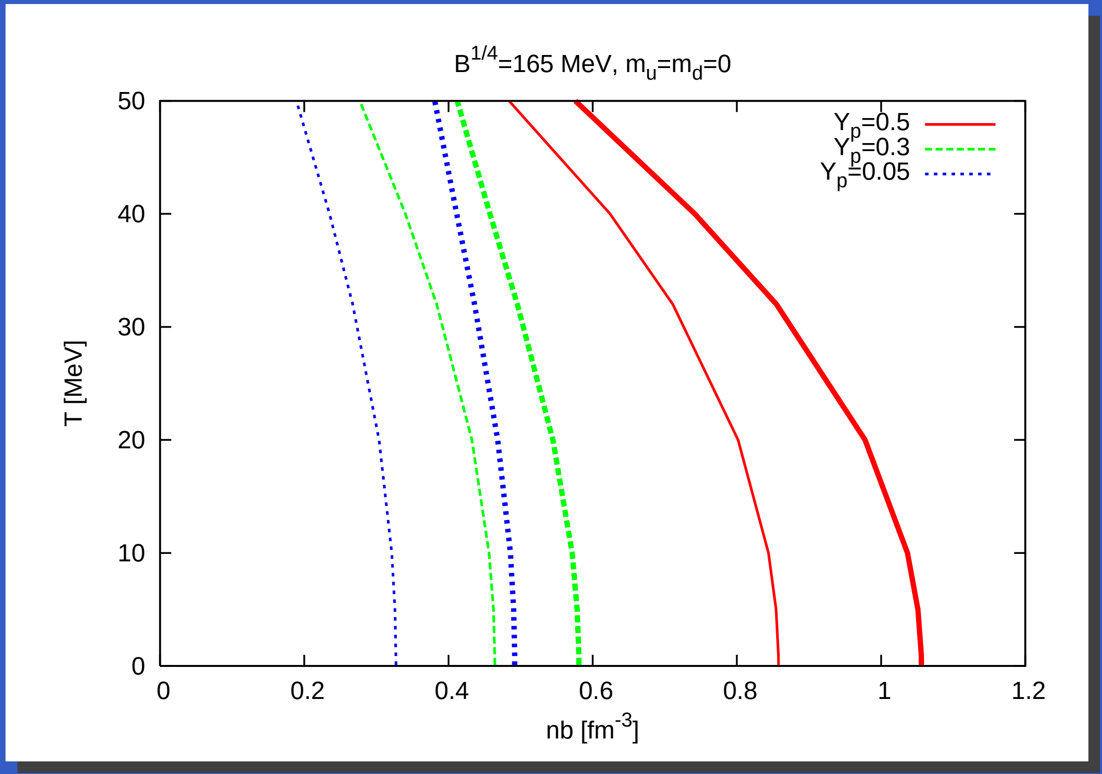
Check: Mass-Radius Diagram of Cold Neutron Stars



(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)

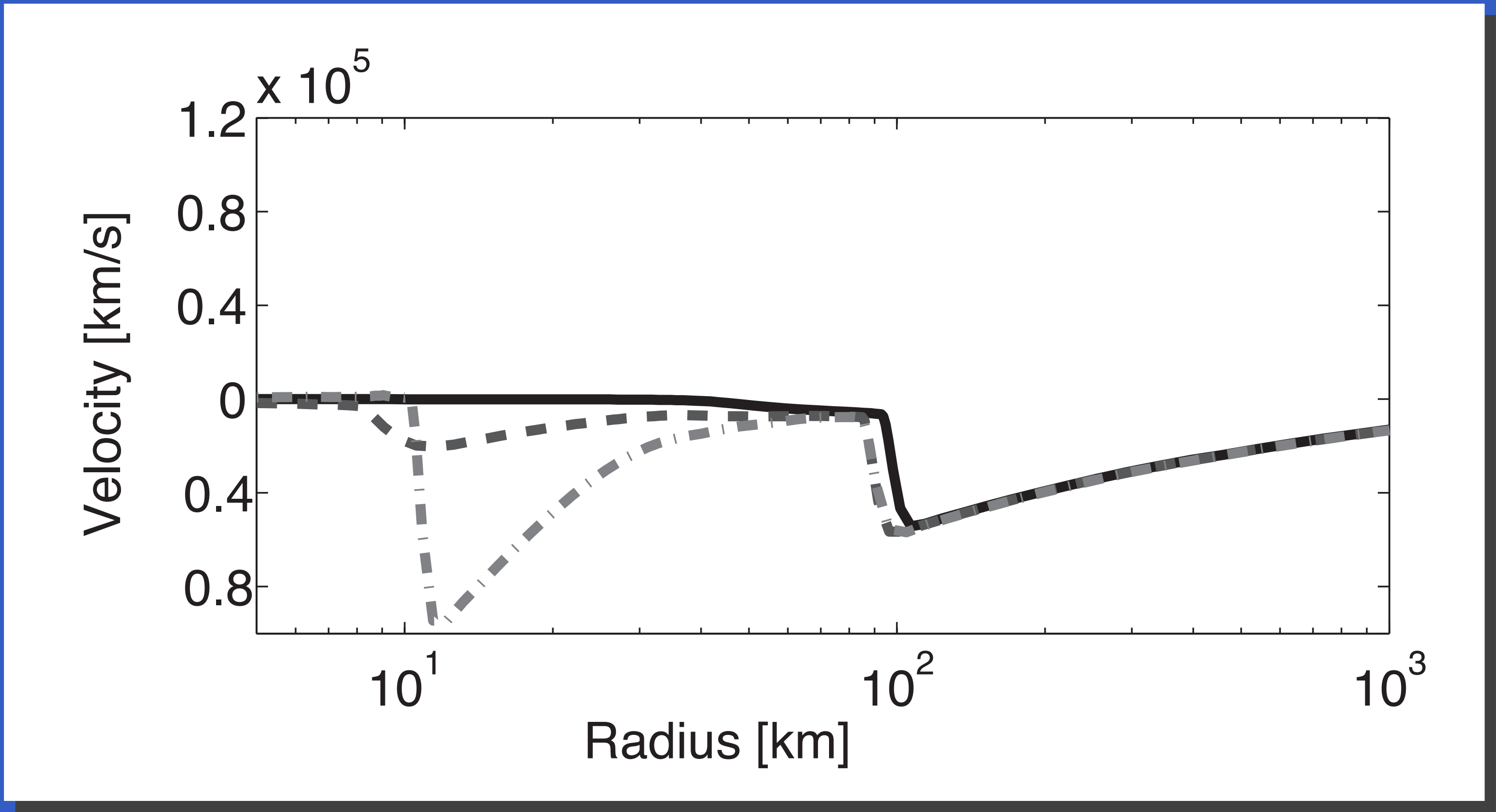
Check: Phase Transition for Heavy-Ion Collisions



(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, 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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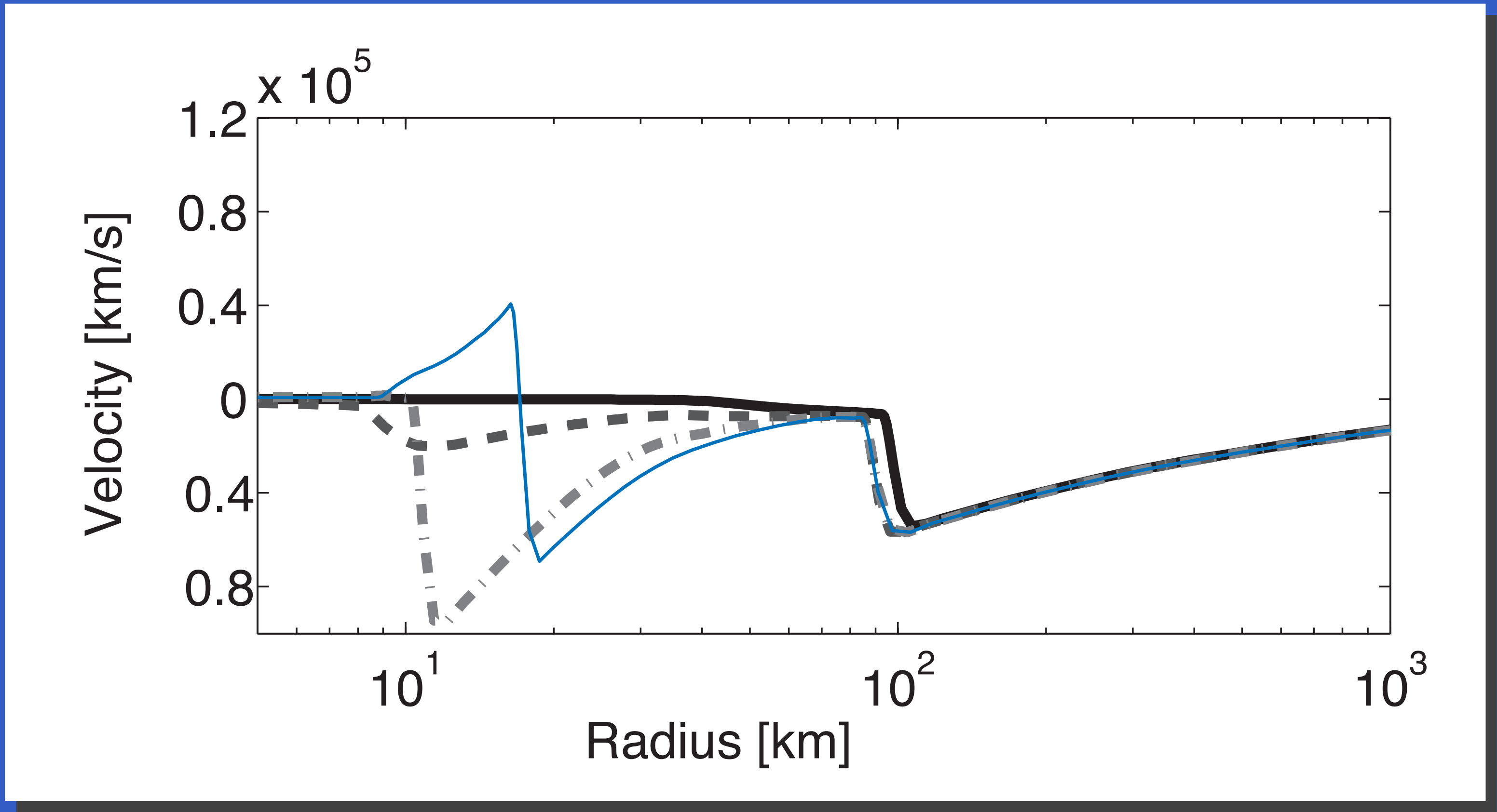

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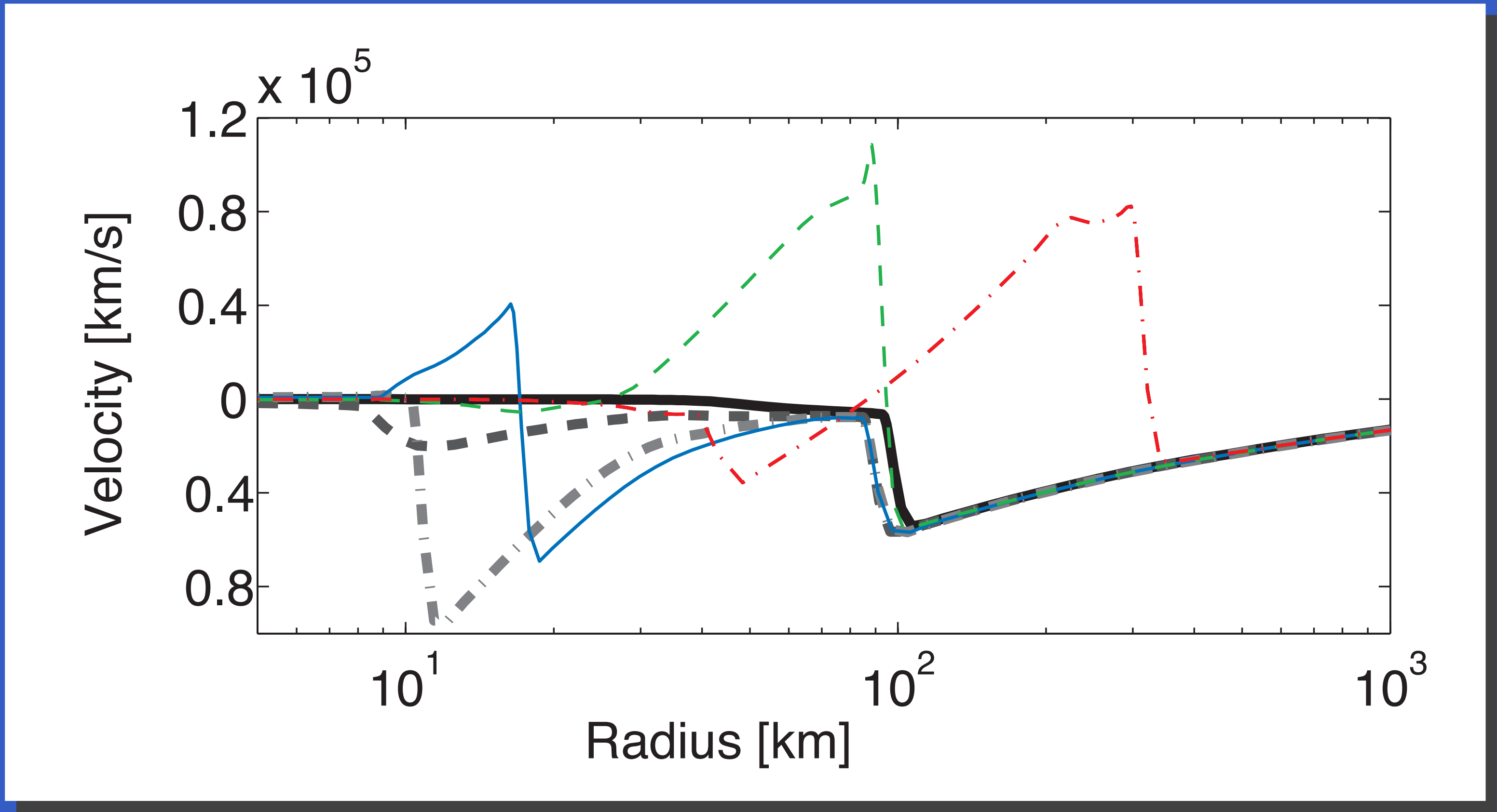
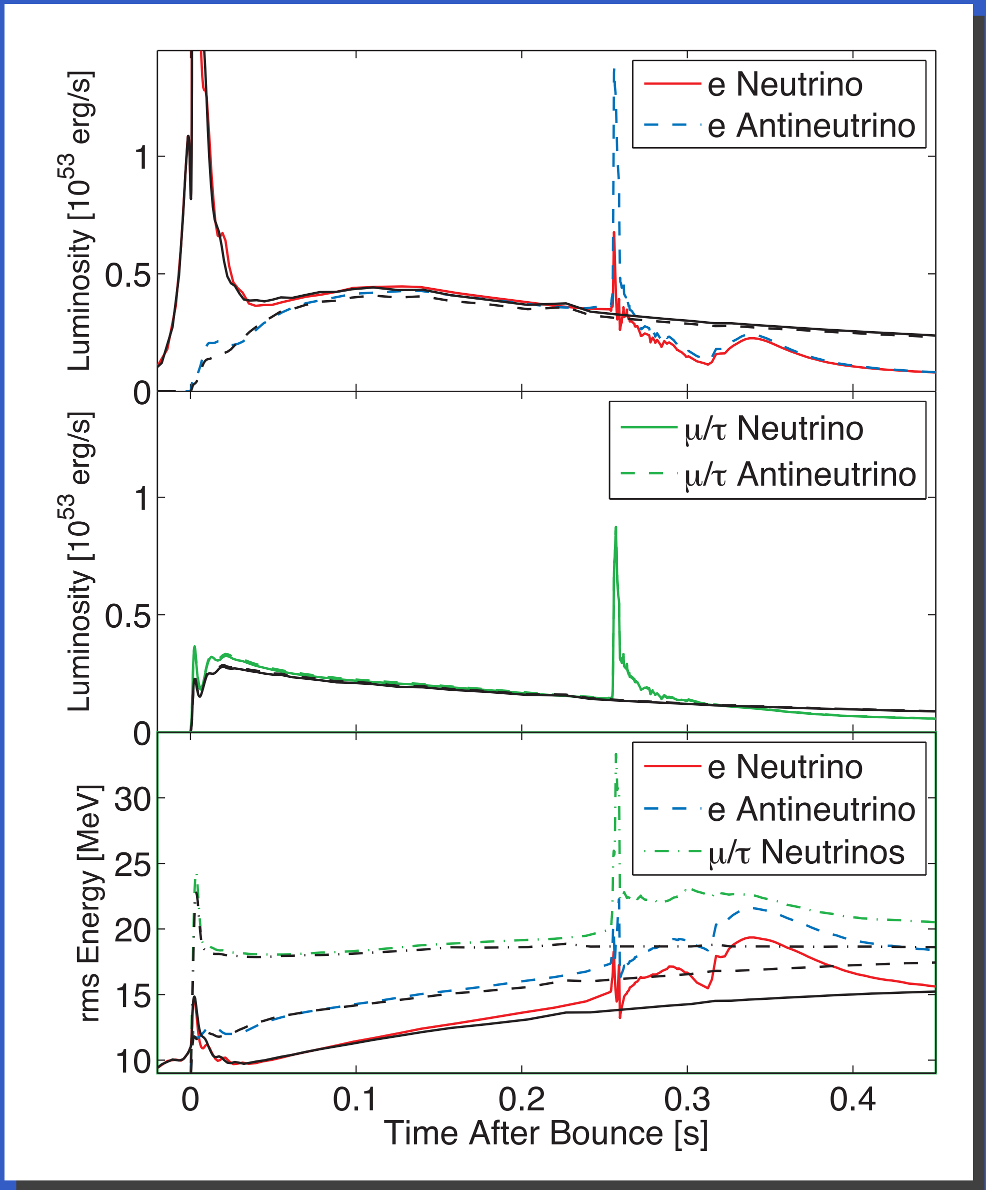


(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2008)

- 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 an explosion!

Implications for Supernova – Neutrino-Signal!



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

- 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!!

Summary

- heavy-ion data constrains the maximum mass of neutron stars to be less than $2.7 M_\odot$
- 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?
- a FAIR chance for exploring exotic matter on Earth and in the sky

Thanks to:

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- Dr. Giuseppe Pagliara
  (gamma-ray bursts, SN EoS, CFL quark stars)
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- 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)