Quark Matter And Its Impact On The Mass–Radius Relation Of Compact Stars

International Symposium "The QCD Phase Diagram: From Theory to Experiment"

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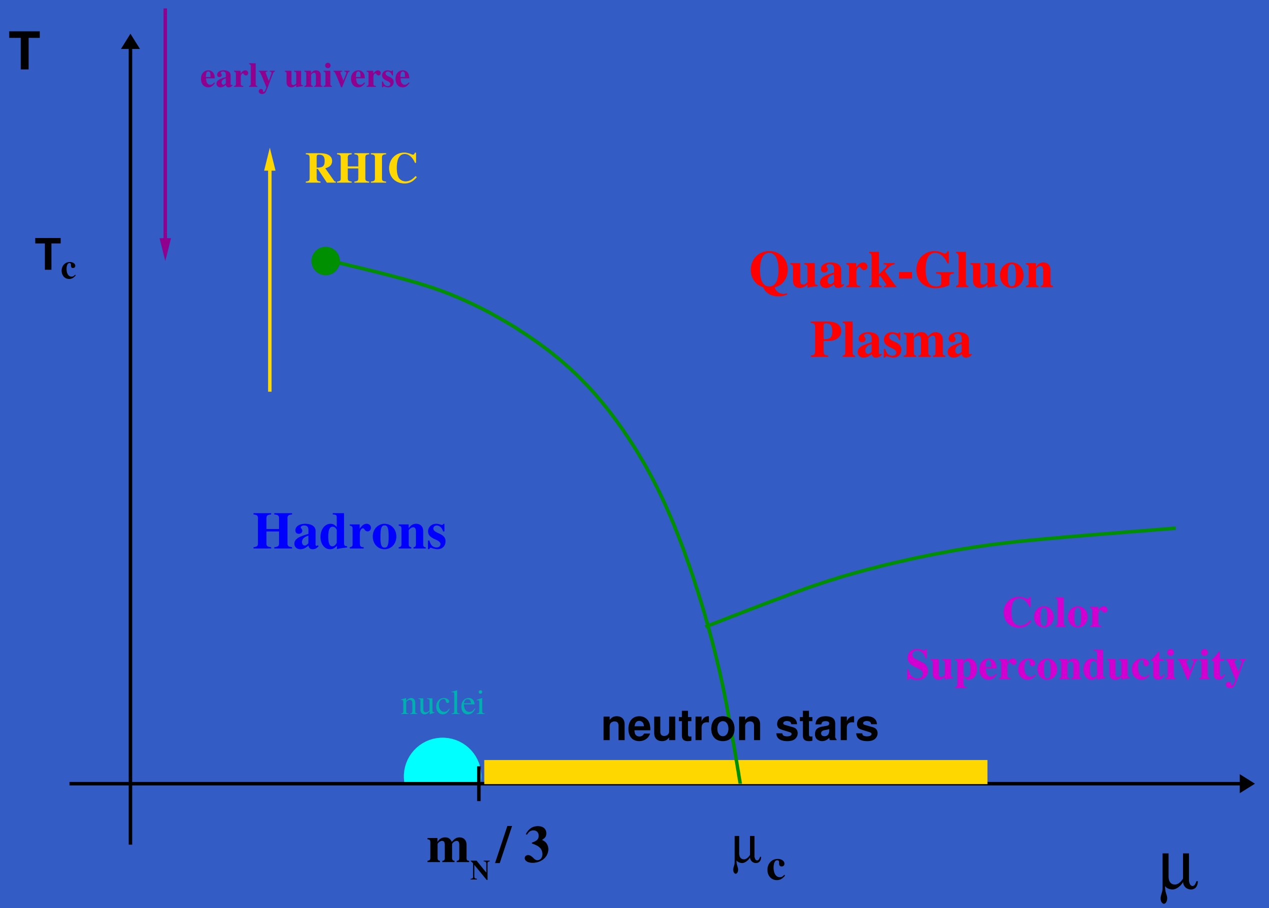
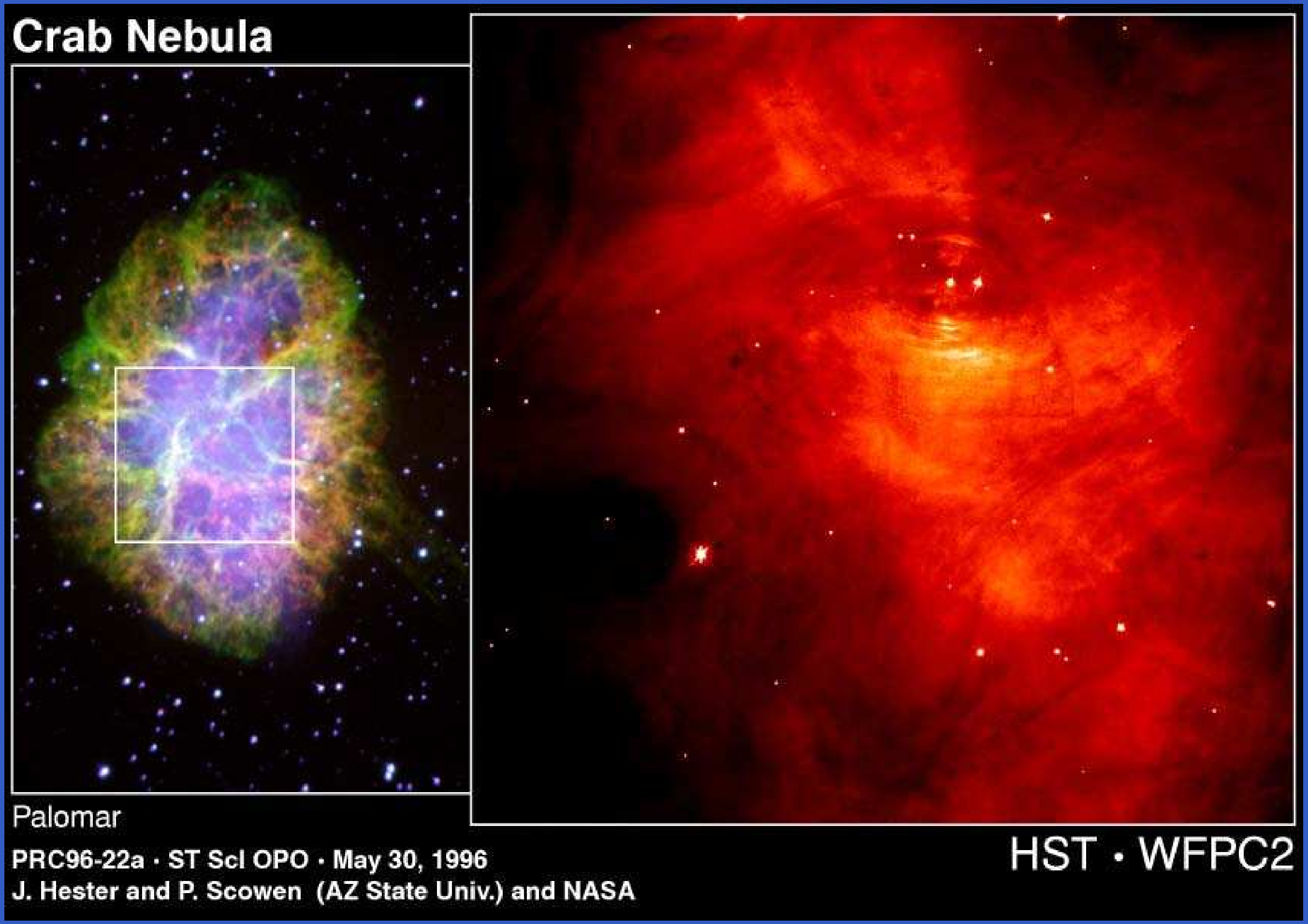
Phase Diagram of QCD



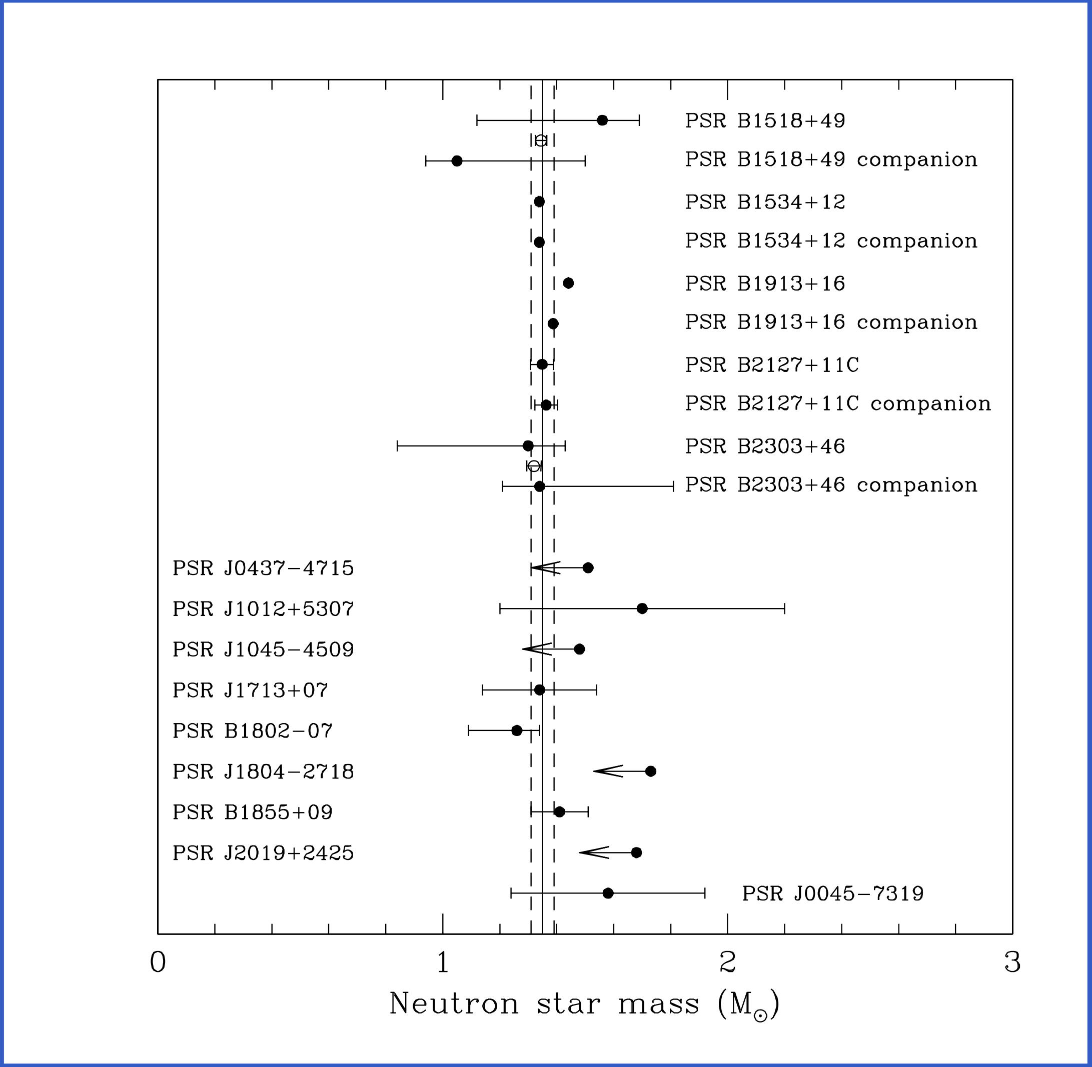
- Early universe at zero density and high temperature
- neutron star matter at zero temperature and high density
- lattice gauge simulations at $\mu = 0$:
  phase transition at $T_c \approx 170$ MeV

Neutron Stars



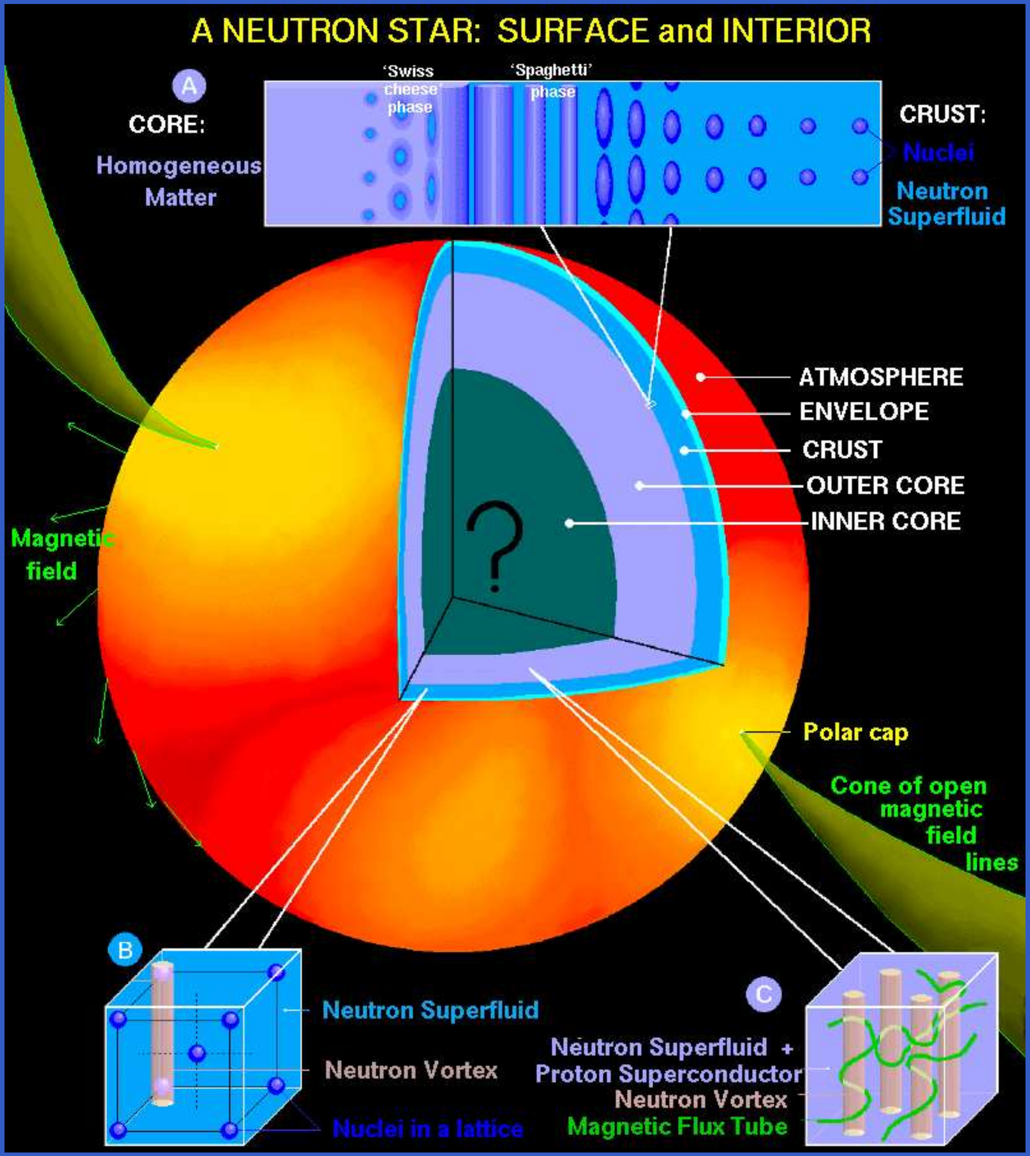
- produced in supernova explosions (type II)
- compact, massive objects: radius $\approx$ 10 km, mass $1 - 2M_\odot$
- extreme densities, several times nuclear density: $n \gg n_0 = 3 \cdot 10^{14}$ g/cm^3

Masses of Pulsars (Thorsett and Chakrabarty (1999))



- more than 1200 pulsars known
- best determined mass: $M = (1.4411 \pm 0.00035) M_\odot$ (Hulse-Taylor-Pulsar)
- shortest rotation period: 1.557 ms (PSR 1937+21)

Structure of Neutron Stars — the Crust



- $n \leq 10^4$ g/cm^3: atmosphere (atoms)

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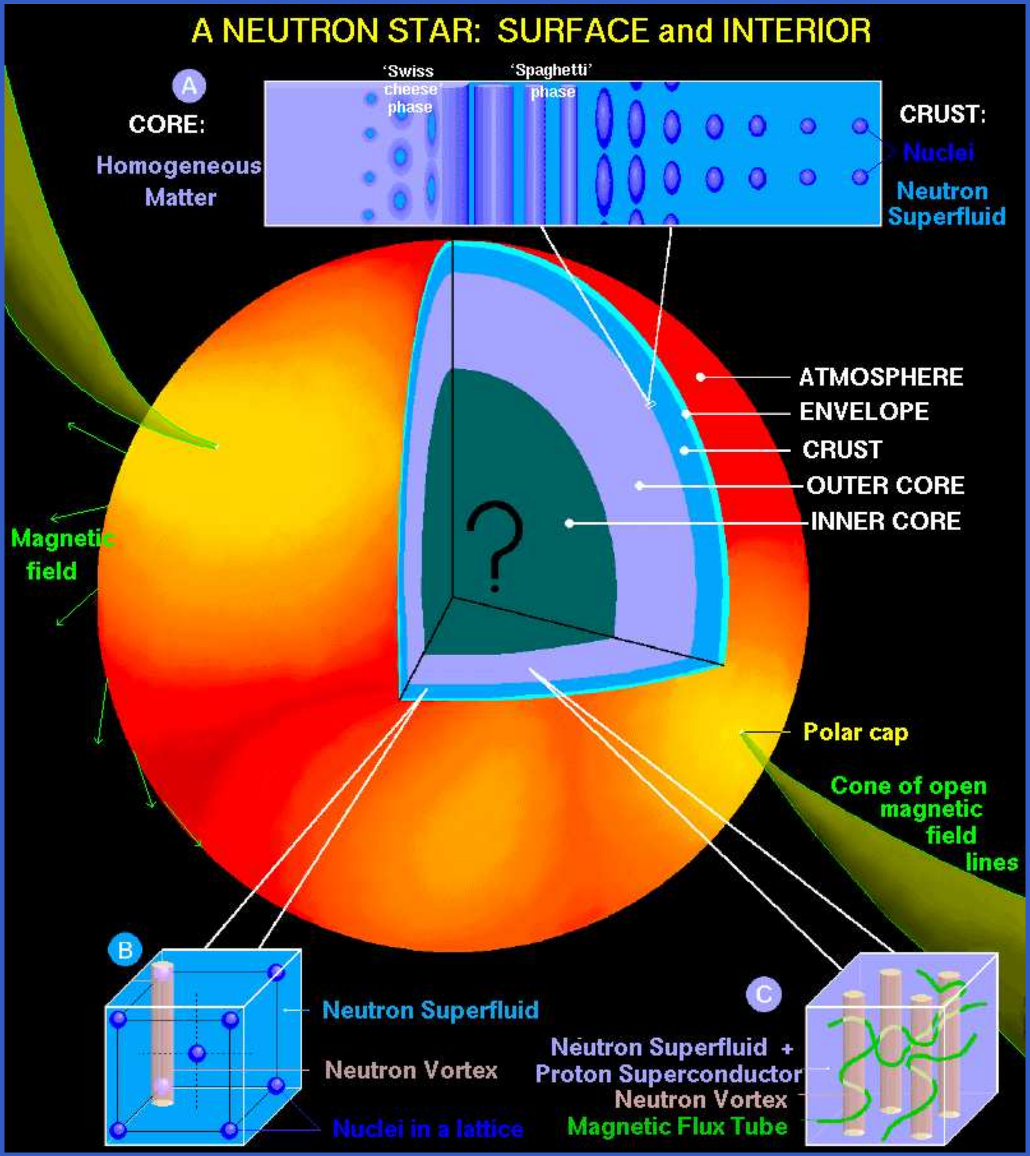

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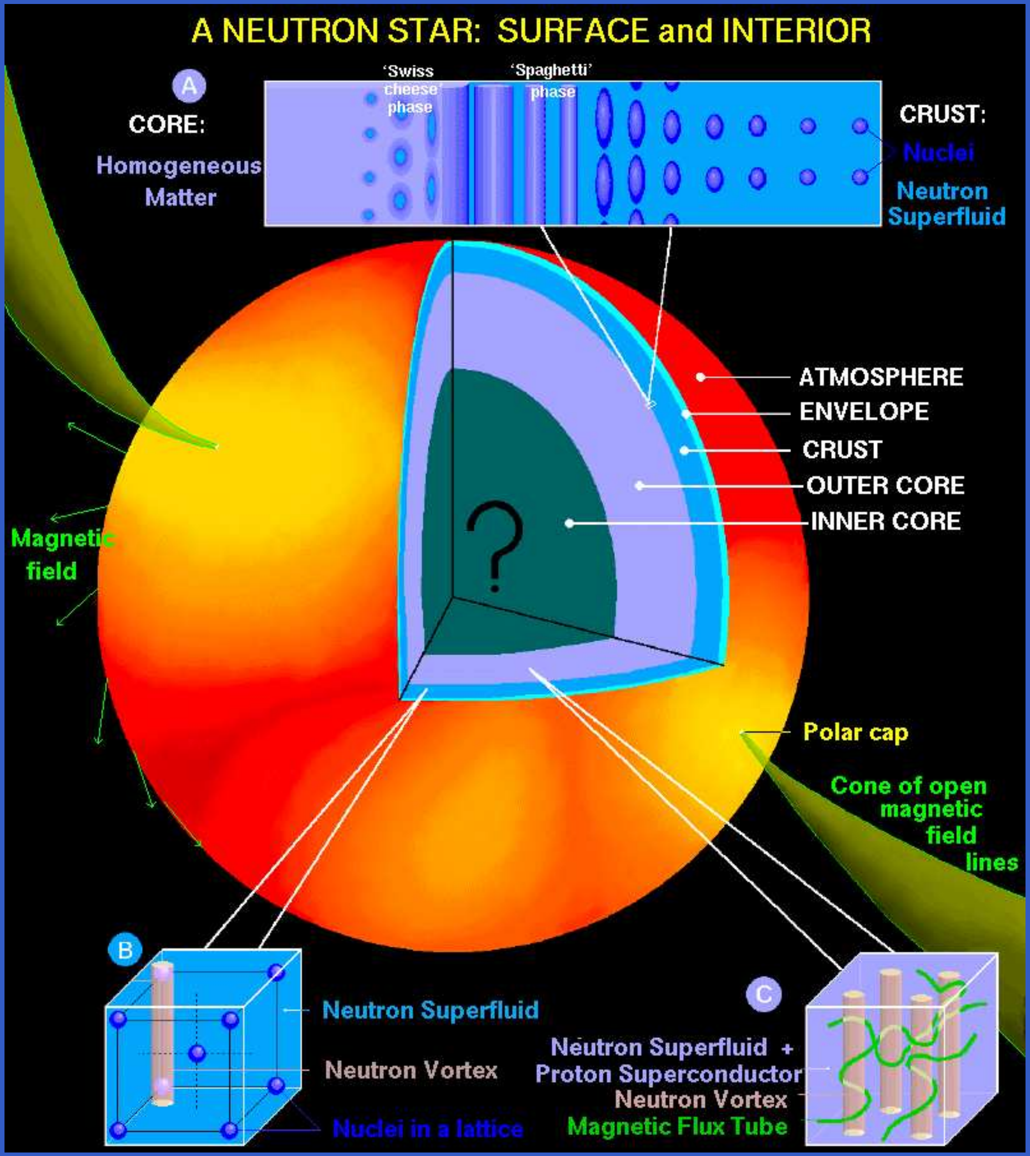

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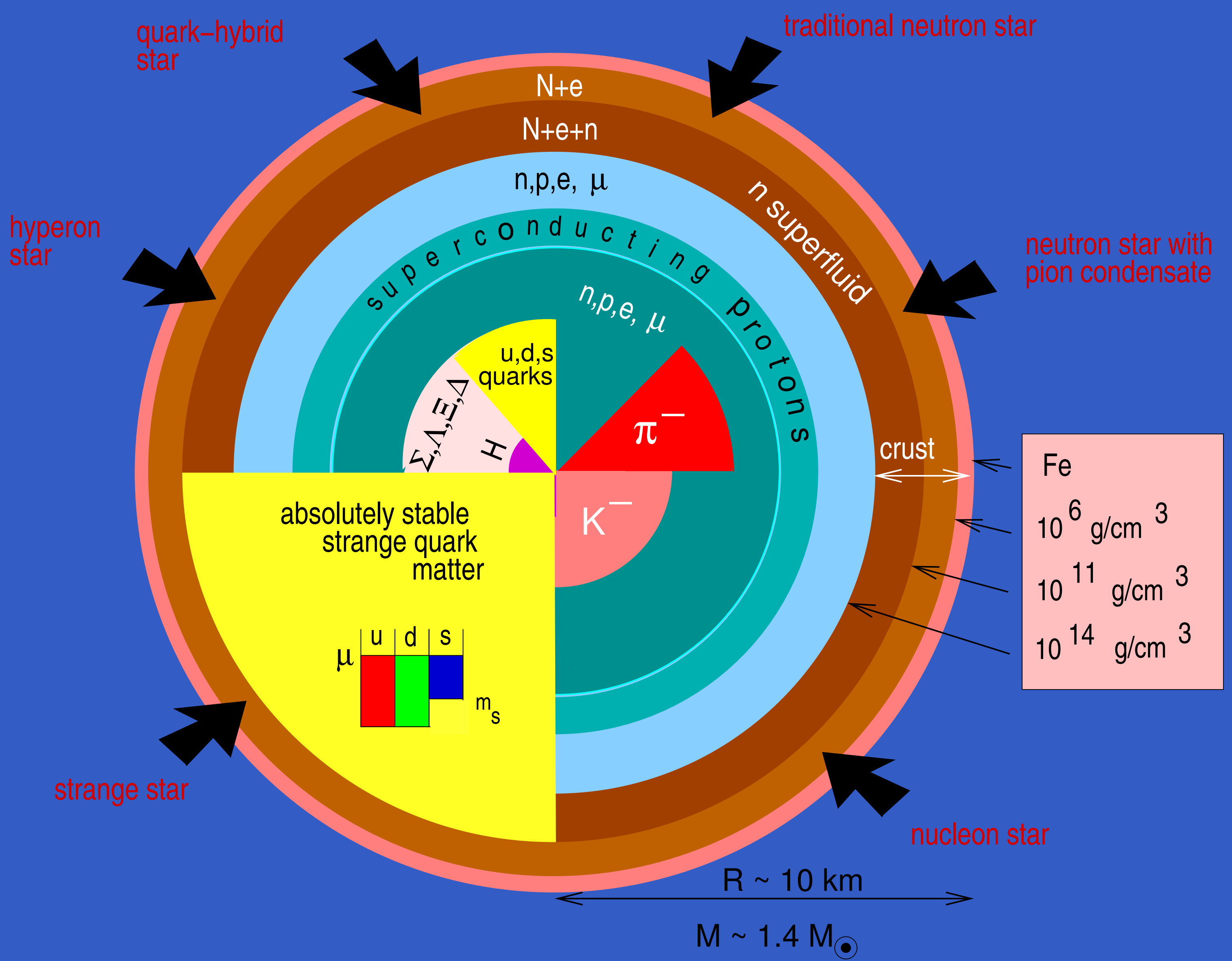
- $n = 4 \cdot 10^{11} - 10^{14}$ g/cm^3: Inner crust (lattice of nuclei with free neutrons and e^-)

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



Neutron Star Matter for a Free Gas

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

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

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

Baryon–Baryon Interactions

NΛ: attractive $\rightarrow$ Λ-hypernuclei for $A = 3 - 209$
$U_\Lambda = -30$ MeV at $n = n_0$

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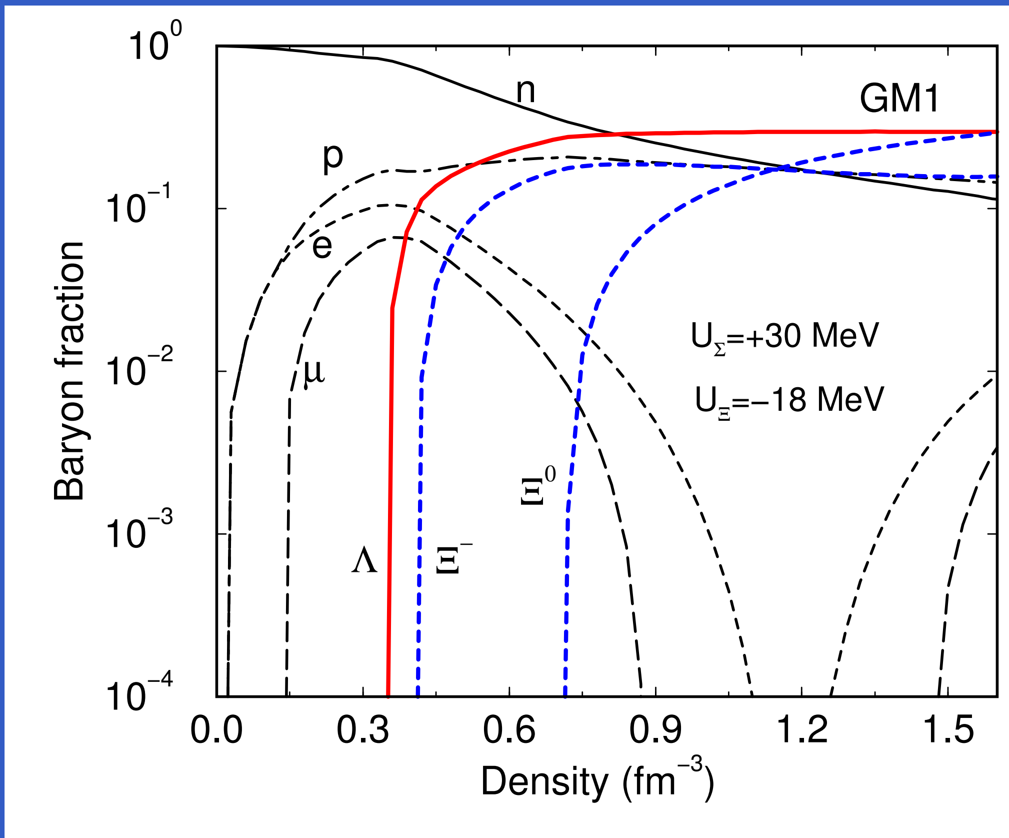
YY: Y$= \Lambda, \Sigma, \Xi$, unknown!

Neutron Star Matter and Hyperons

Hyperons appear at $n \approx 2n_0$!

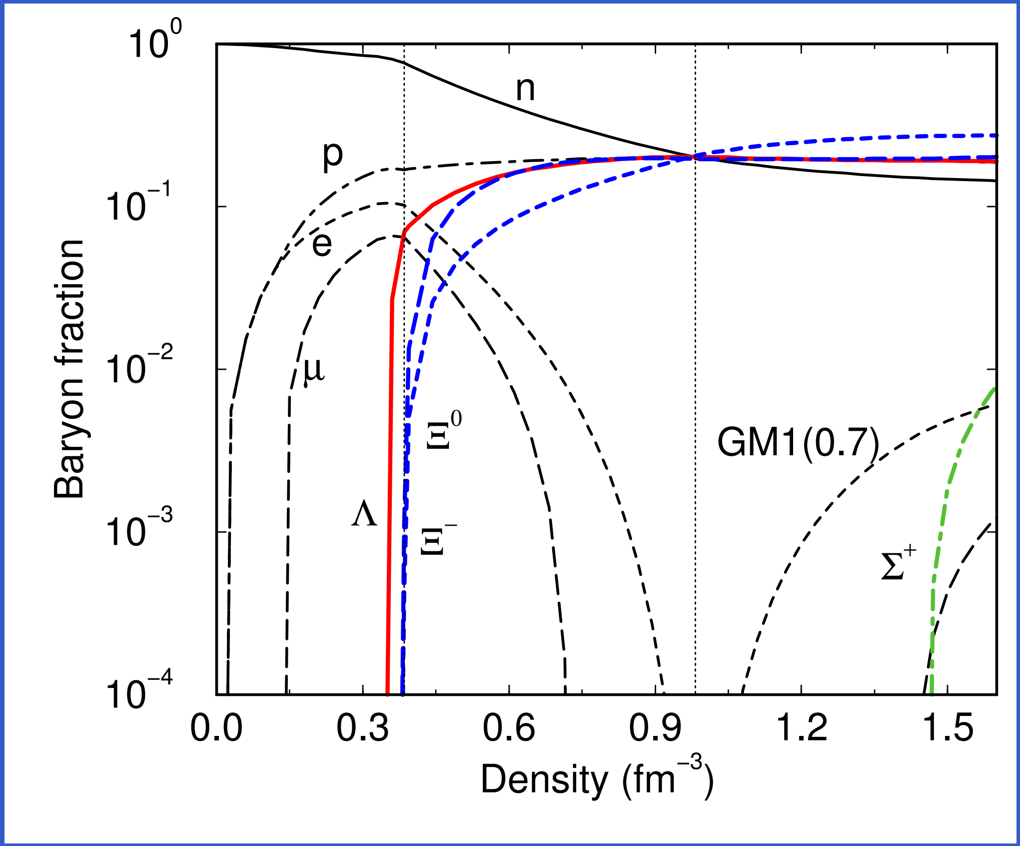
- nonrelativistic potential model (Balberg and Gal, 1997)
- quark-meson coupling model (Pal et al., 1999)
- relativistic mean–field models (Glendenning, 1985; Knorren, Prakash, Ellis, 1995; JS and Mishustin, 1996)
- relativistic Hartree–Fock (Huber, Weber, Weigel, Schaab, 1998)
- Brueckner–Hartree–Fock (Baldo, Burgio, Schulze, 2000; Vidana et al., 2000)
- chiral effective Lagrangian's (Hanauske et al., 2000)

Composition of Neutron Star Matter



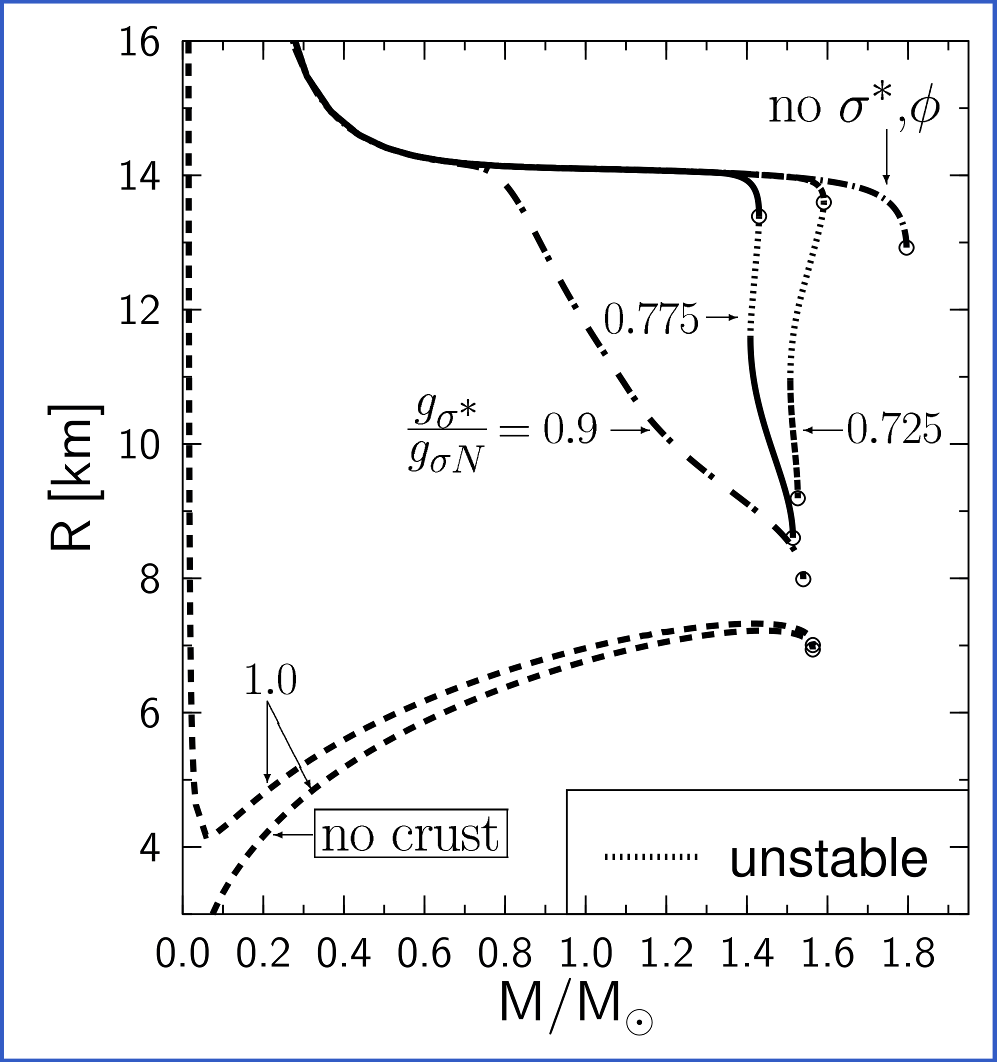
- Λs are present around $n = 2n_0$
- repulsive potential for Σs: Σ hyperons do not appear at all!
- Ξ^- present in matter before $n = 3n_0$

Phase Transition to Hypermatter



- first order phase transition
- mixed phase for a wide range of densities
- all hyperons (Λ, Ξ^0, Ξ^-) appear at the start of the mixed phase

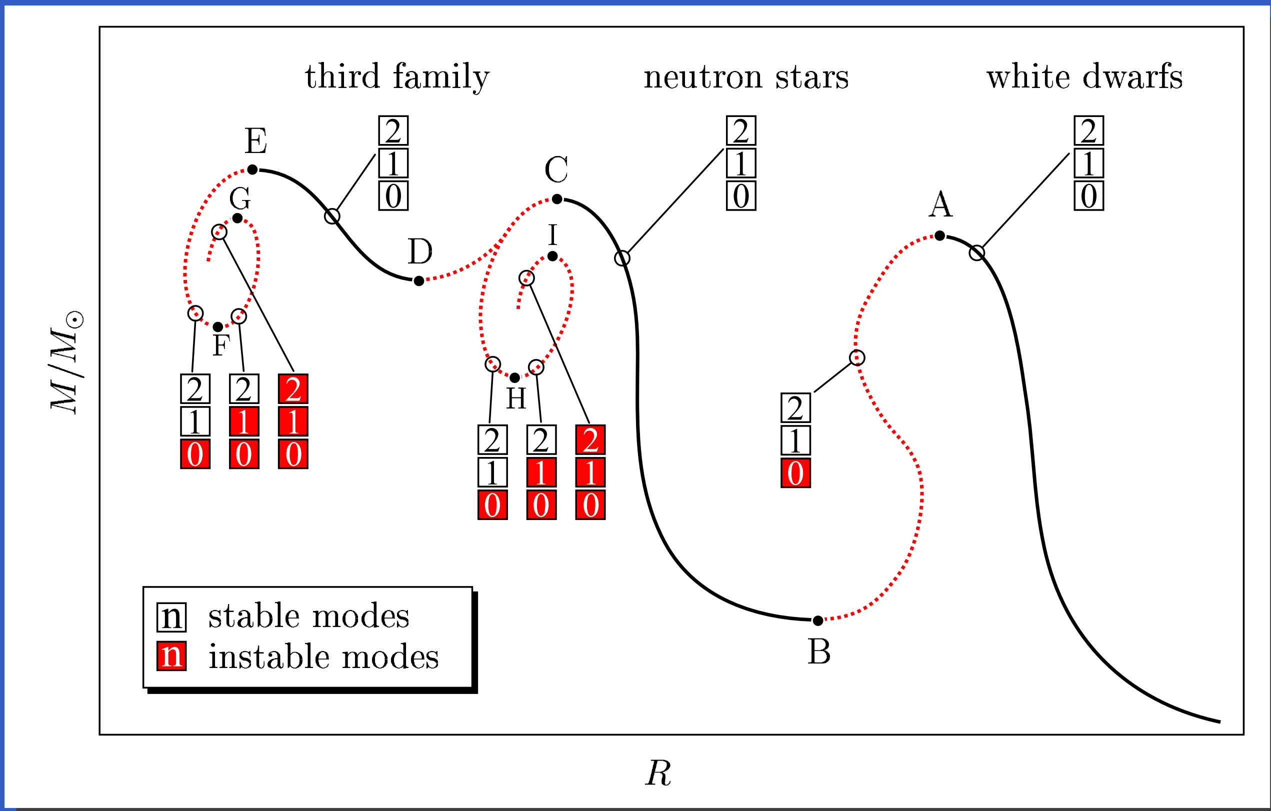
Hypercompact Neutron Stars



(JSB, Hanauske, Stöcker, Greiner, PRL 89, 171101 (2002))

- new stable solution in the mass–radius diagram!
- neutron star twins: $M_{\rm hyp} \sim M_n$ but $R_{\rm hyp} < R_n$
- selfbound compact stars for strong attraction with $R = 7 - 8$ km

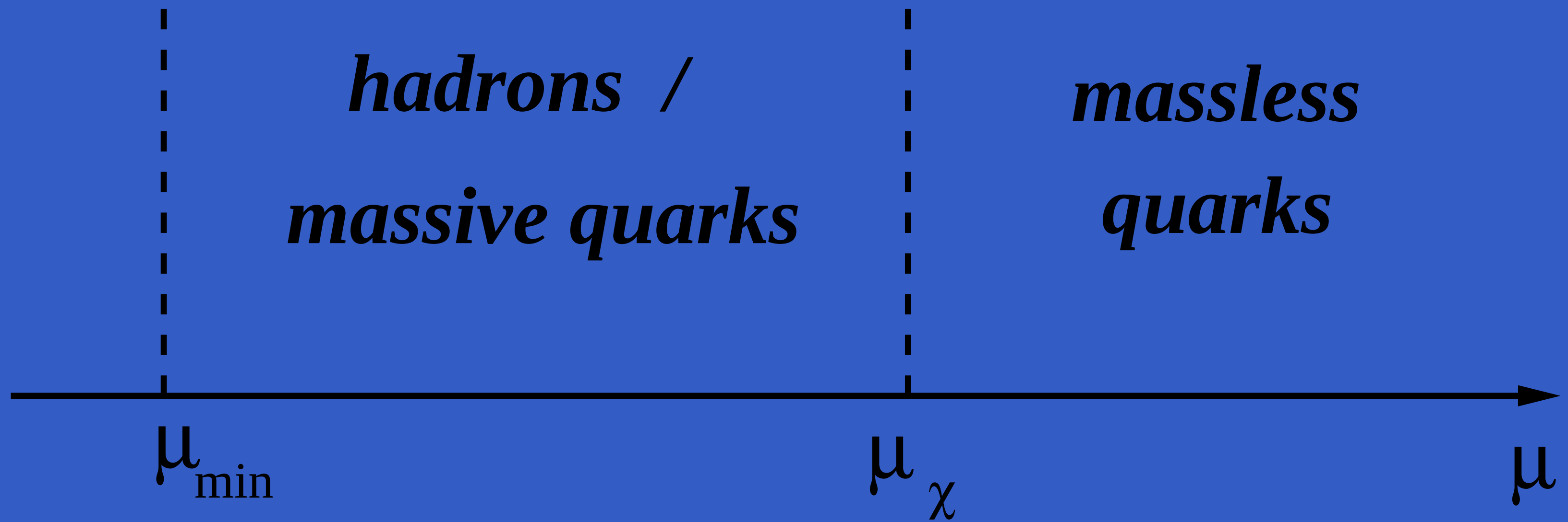
Third Family of Compact Stars



(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!

A Model For Cold And Dense QCD



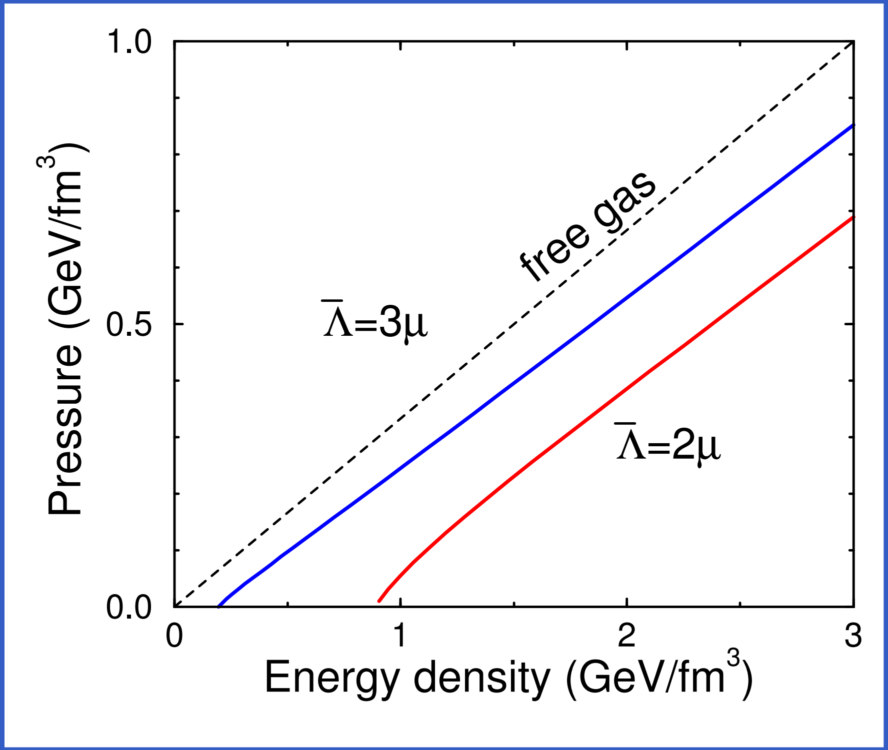
Two possibilities for first-order chiral phase transition:

- 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

A Simple Model of Dense QCD

- star made of a gas of u, d and s quarks
- interaction taken into account perturbatively up to α_s^2 ; $\alpha_s = g^2/4\pi$
- α_s runs according to the renormalization group equation
- No bag constant is introduced!
- star temperature $\ll$ typical chemical potentials $\longrightarrow$ zero temperature
- $m_s = 100$ MeV $\ll \mu_{\min} = m_N/3$ $\longrightarrow$ three flavor massless quarks
- charge neutrality and β equilibrium: $\mu_s = \mu_d = \mu_u \equiv \mu$

Equation of State in pQCD



Nearly linear behavior of the pressure with the energy density

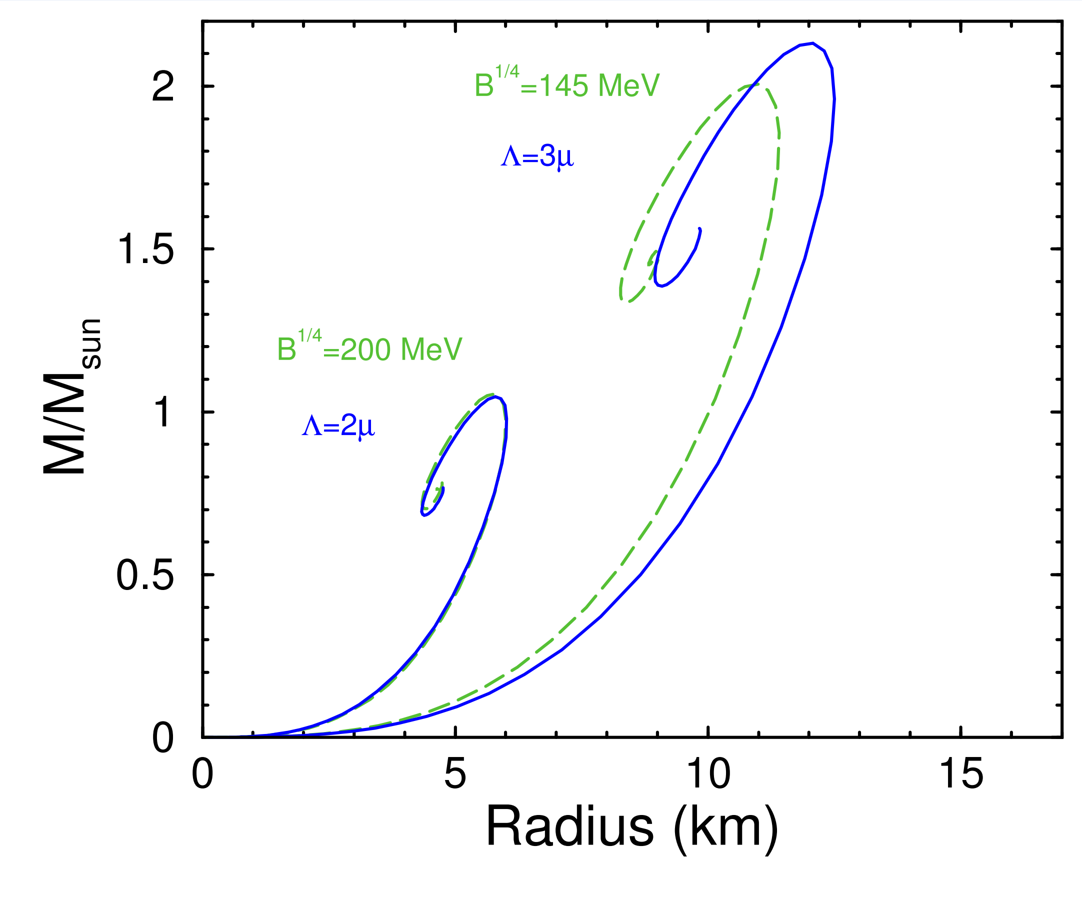
$\Rightarrow$ approximation with an effective nonideal bag model:

$$\Omega(\mu) = -\frac{N_f}{4\pi^2}\, a_{\rm eff}\, \mu^4 + B_{\rm eff}$$

case 2: $B_{\rm eff}^{1/4} = 199$ MeV, $a_{\rm eff} = 0.628$ ($\leq 4\%$)

case 3: $B_{\rm eff}^{1/4} = 140$ MeV, $a_{\rm eff} = 0.626$ ($\leq 2\%$)

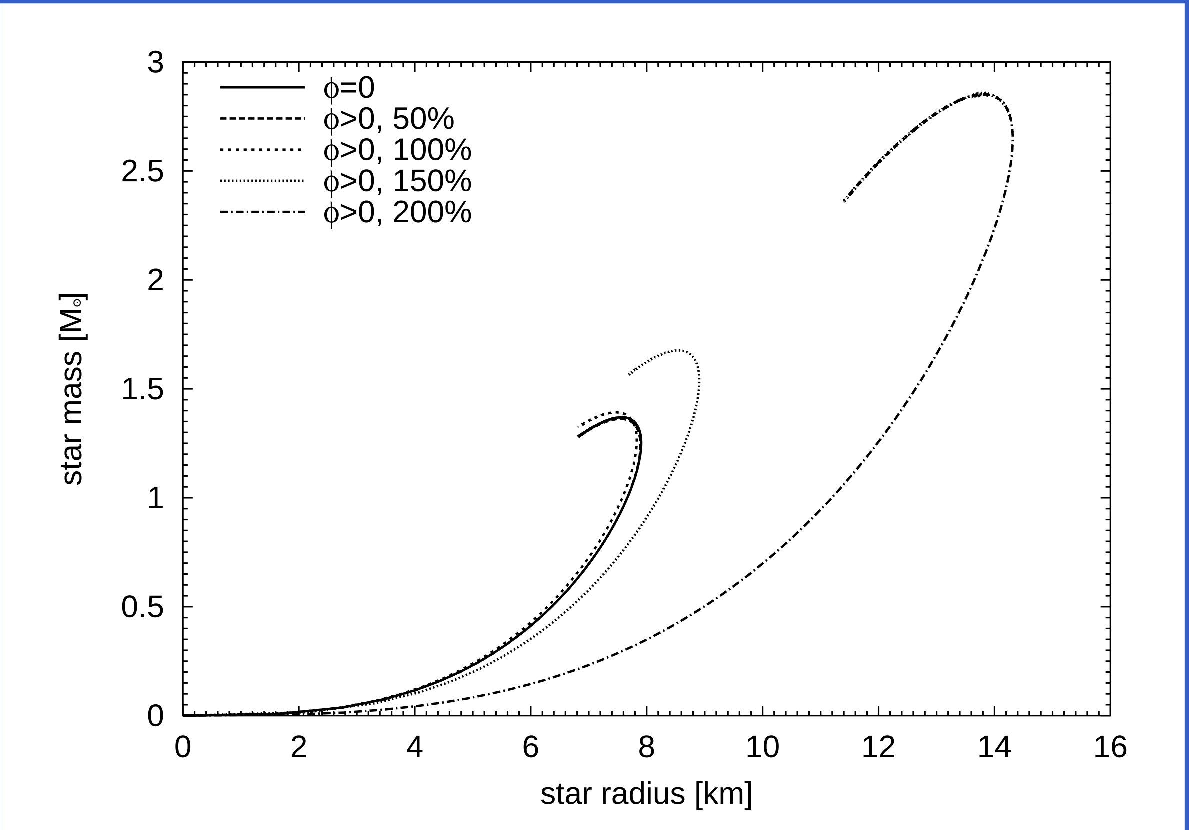
Mass-radius and maximum density of pure quark stars



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

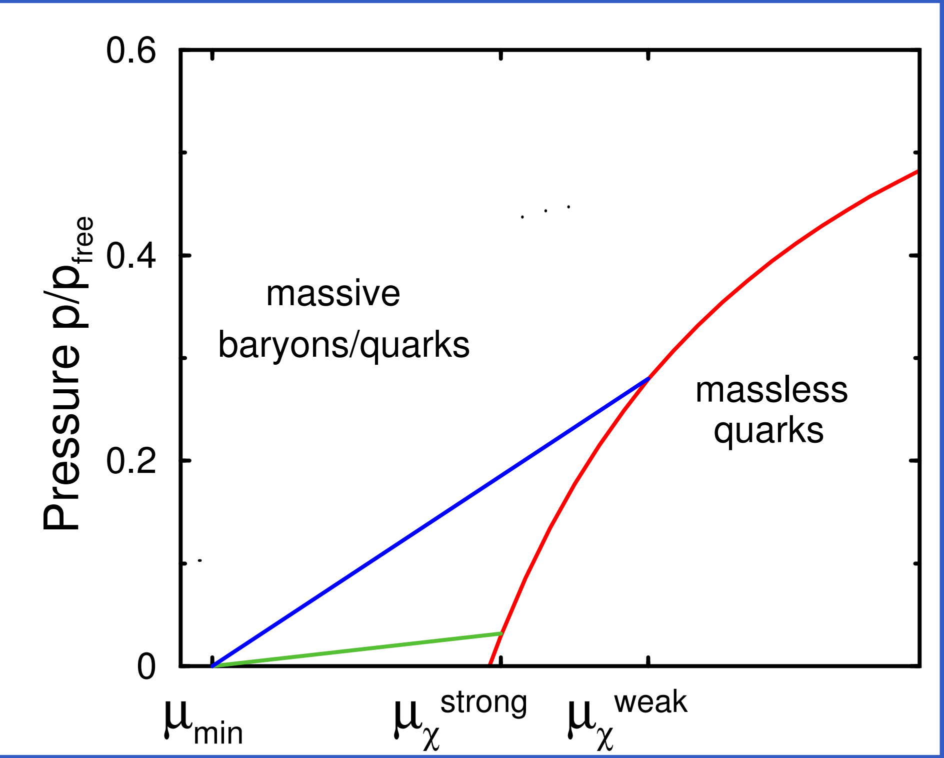
Heavy Quark Stars?

(Rüster and Rischke (2004))



- quark star with color–superconducting quarks
- uses NJL model for pairing quarks
- increased interactions gives heavy quark stars
- heavy quark stars also for HDL calculation (Strickland and Andersen (2002))

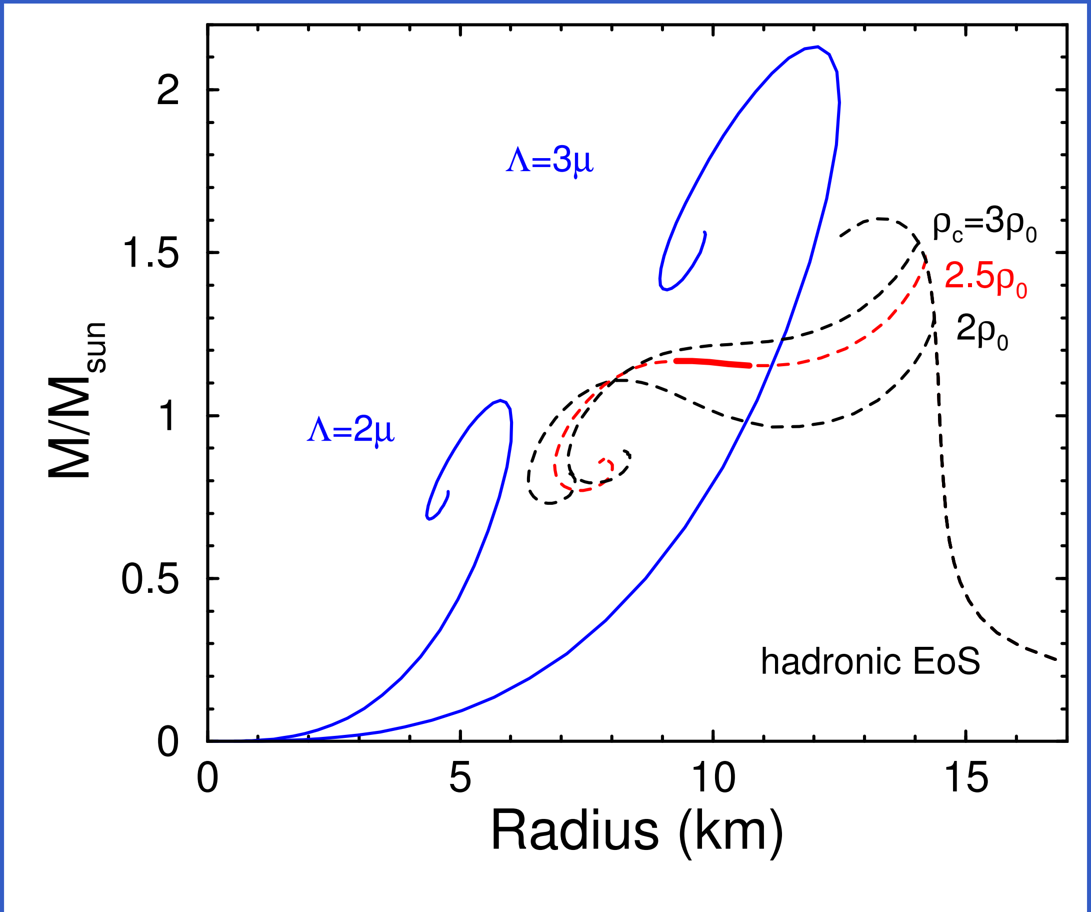
The two possible scenarios



- 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 $\sim 2n_0$: [Akmal,Pandharipande,Ravenhall (1998)]

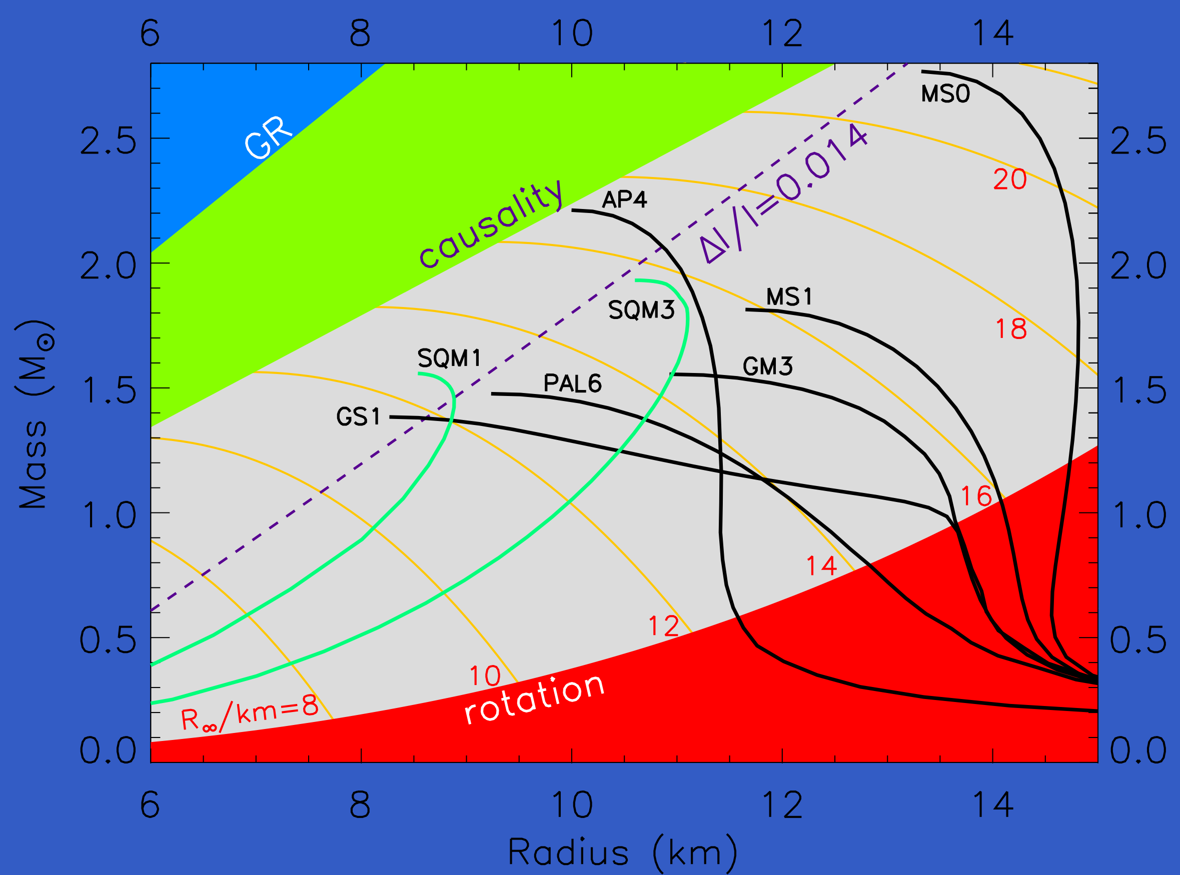
$$E/A \sim 15\ \text{MeV}\ (n/n_0) \rightarrow p_B \sim 0.04 \left(\frac{n}{n_0}\right)^2 \left(\frac{m_q}{\mu}\right)^4 \cdot p_{\text{free}}$$

Quark star twins?



- Weak: ordinary neutron star with quark core (hybrid star)
- Strong: 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

Constraints on the Mass–Radius Relation



(Lattimer and Prakash (2004))

- spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4 M_\odot$
- observed giant glitch from Vela pulsar: moment of inertia changes by 1.4%
- implies a mass-radius relation for glitches from the crust
- problematic, constraint not fulfilled by most EoS!

How To Measure Masses and Radii of Compact Stars

- mass from binary systems (pulsar with a companion star)
- radius and mass from thermal emission, for a blackbody:

$$F_\infty = \frac{L_\infty}{4\pi d^2} = \sigma_{\rm SB} T^4_{\rm eff,\infty} \left(\frac{R_\infty}{d}\right)^2$$

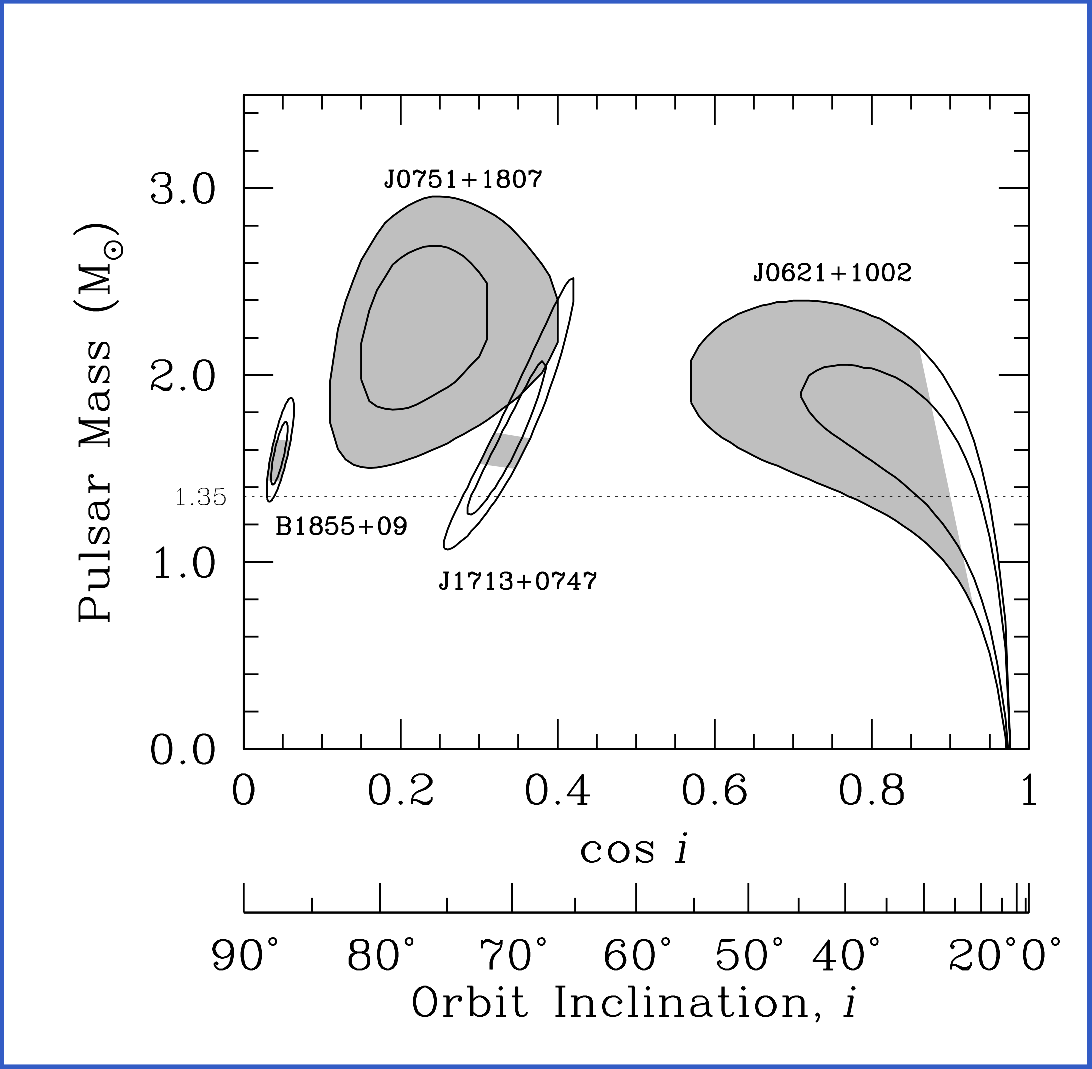
  with $T_{\rm eff,\infty} = T_{\rm eff}/(1+z)$ and $R_\infty = R/(1+z)$
- redshift:

$$1 + z = \left(1 - \frac{2GM}{R}\right)^{-1/2}$$

- need to know distance and effective temperature to get R_∞
- radius measured depends on true mass and radius of the star
- additional constraint from redshift measurement from e.g. redshifted spectral lines fixes mass and radius uniquely

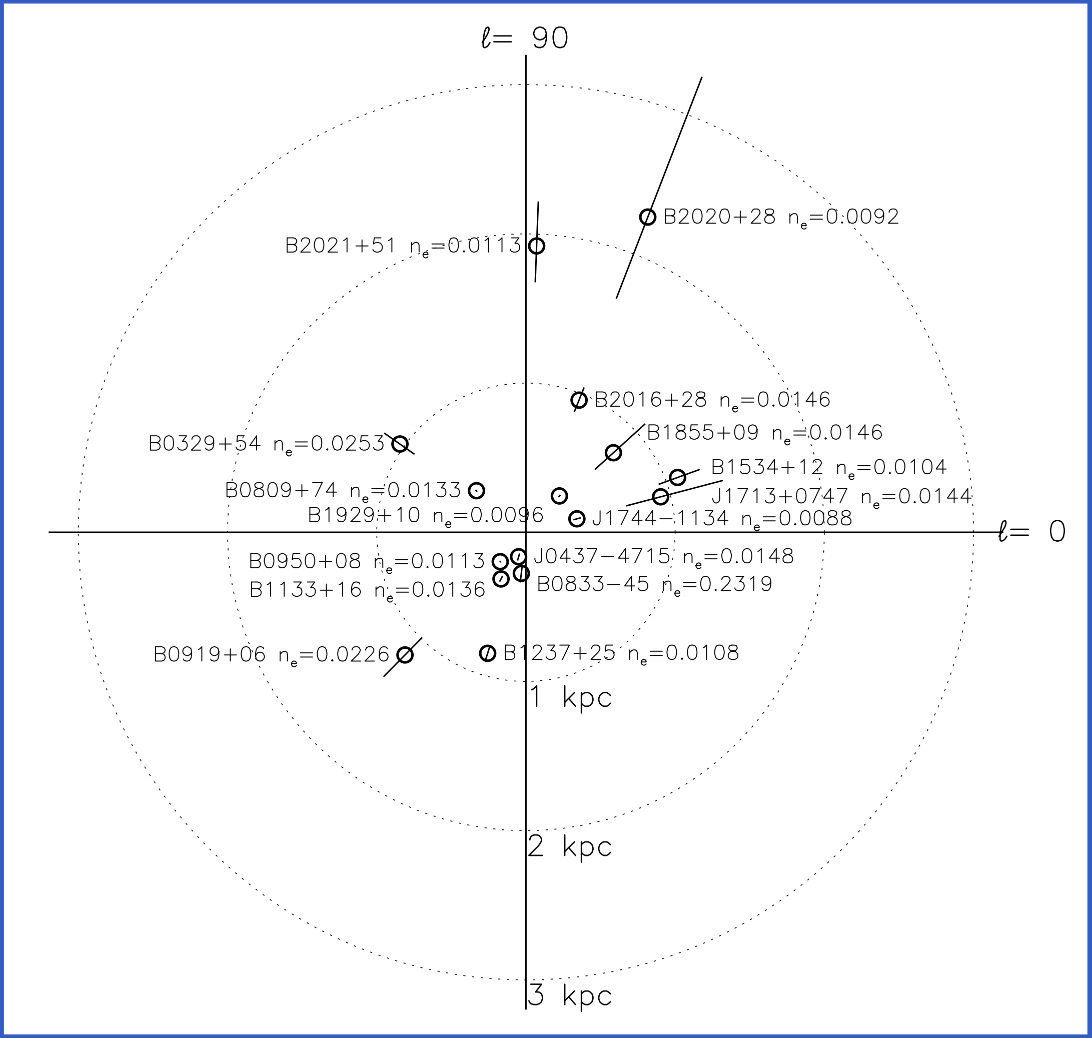
Heavy Neutron Stars in Pulsar–White Dwarfs Systems?

(Nice, Splaver, Stairs (2003))



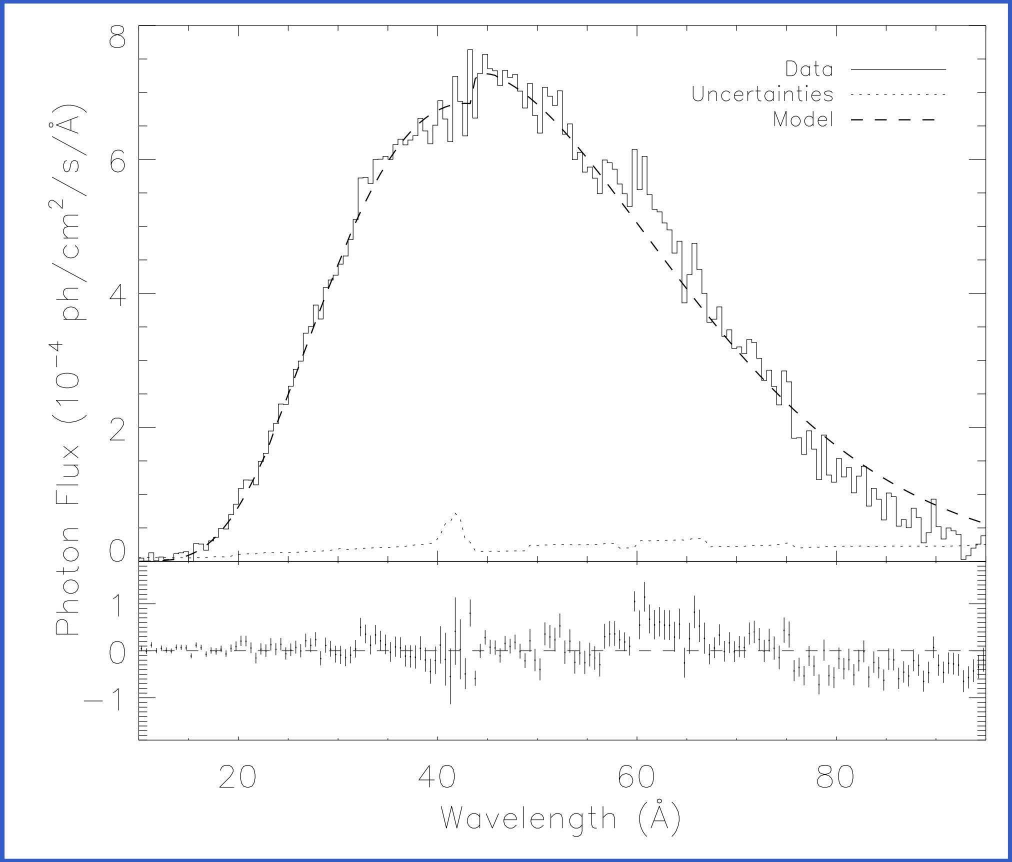
- four pulsars with a white dwarf companion
- measure masses by changes in the pulsar signal
- shaded area: from theoretical limits for white–dwarf companion
- massive pulsar J0751+1807: $M = 1.6 - 2.8 M_\odot$ (2σ!)
- independent of the inclination angle!

Pulsar Parallax Measurement via VLBA (Brisken et al. (2002))



- Very Long Baseline Array (VLBA) of 10 radio antennas
- parallax measurements with an accuracy of 2% for the distance!
- distances determined for more than 10 pulsars

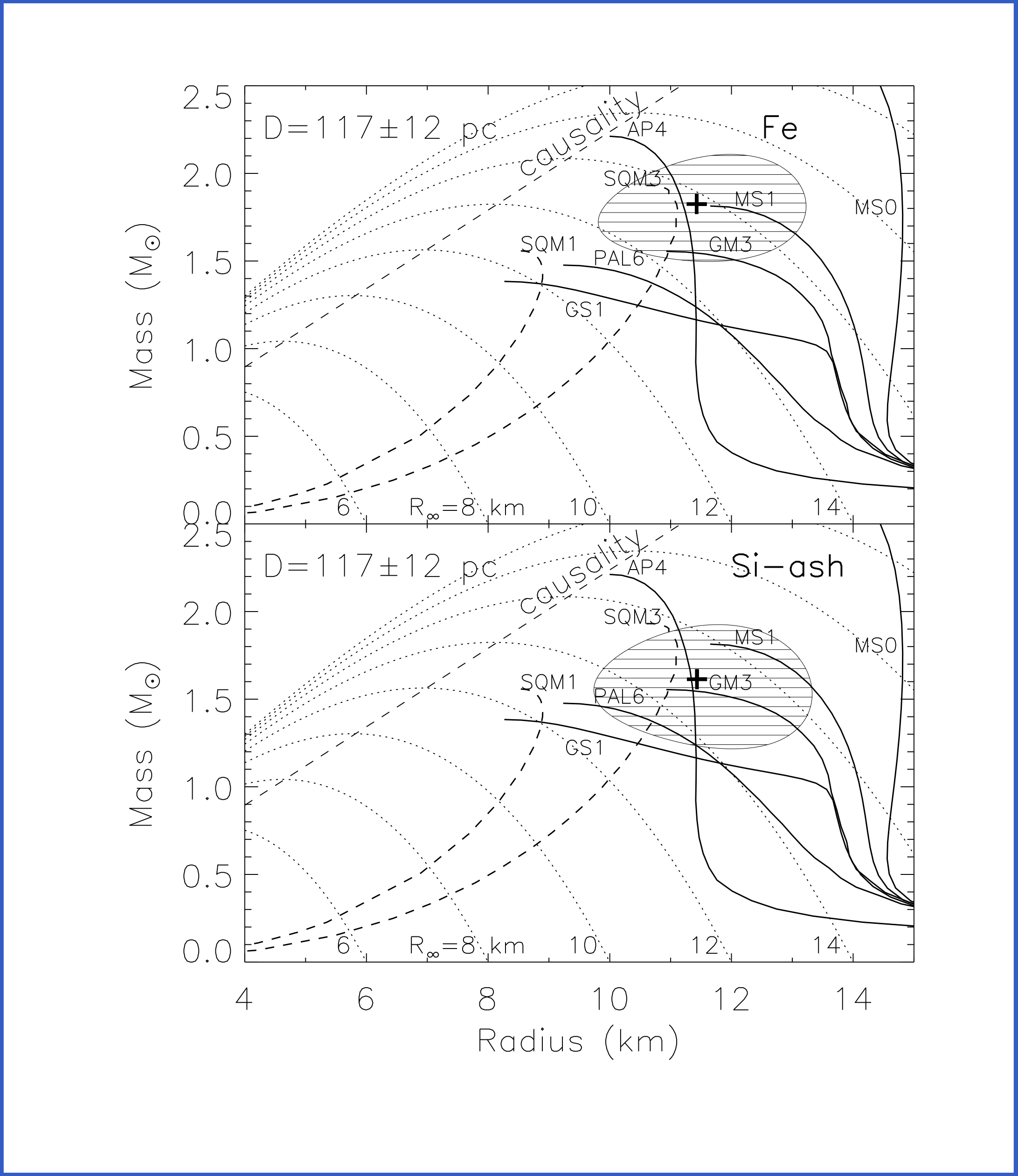
Isolated Neutron Star RX J1856



(Drake et al. (2002))

- closest known neutron star
- perfect black–body spectrum, no spectral lines!
- for black-body emission: $T = 60$ eV and $R_\infty = 4 - 8$ km!

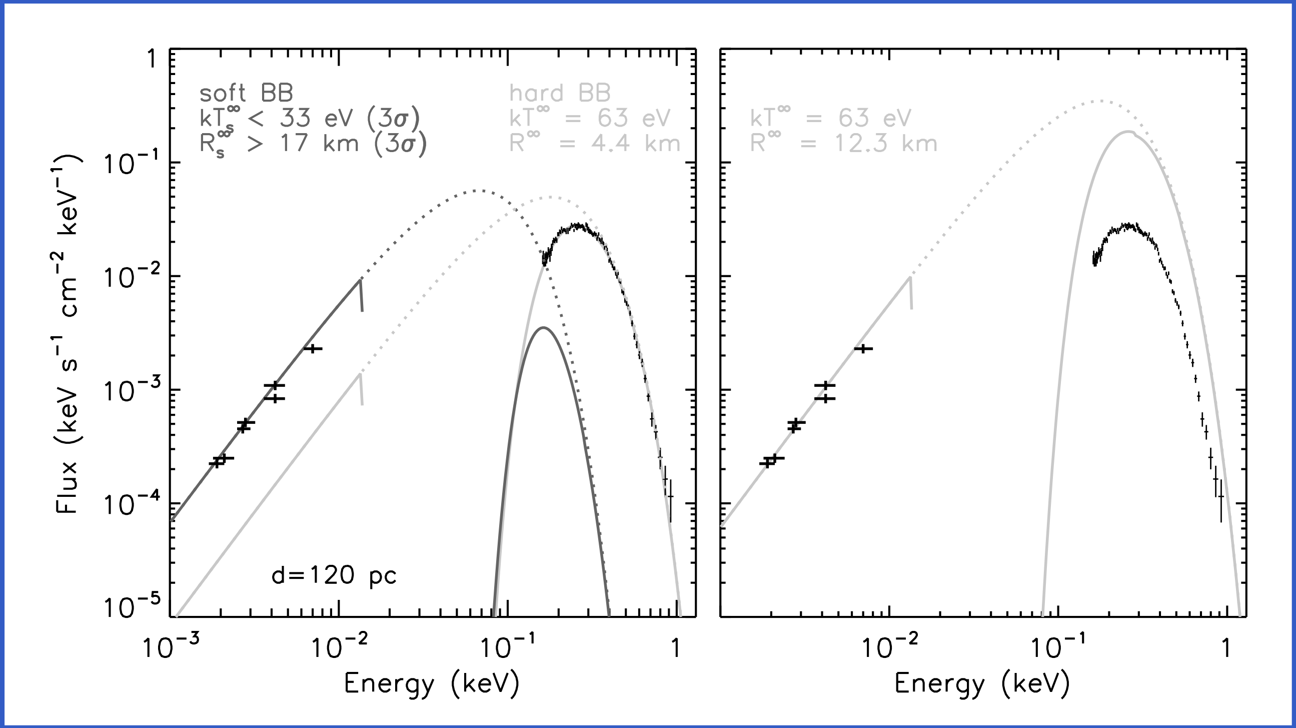
Parallax Measurement from Hubble



(Lattimer and Walter (2002))

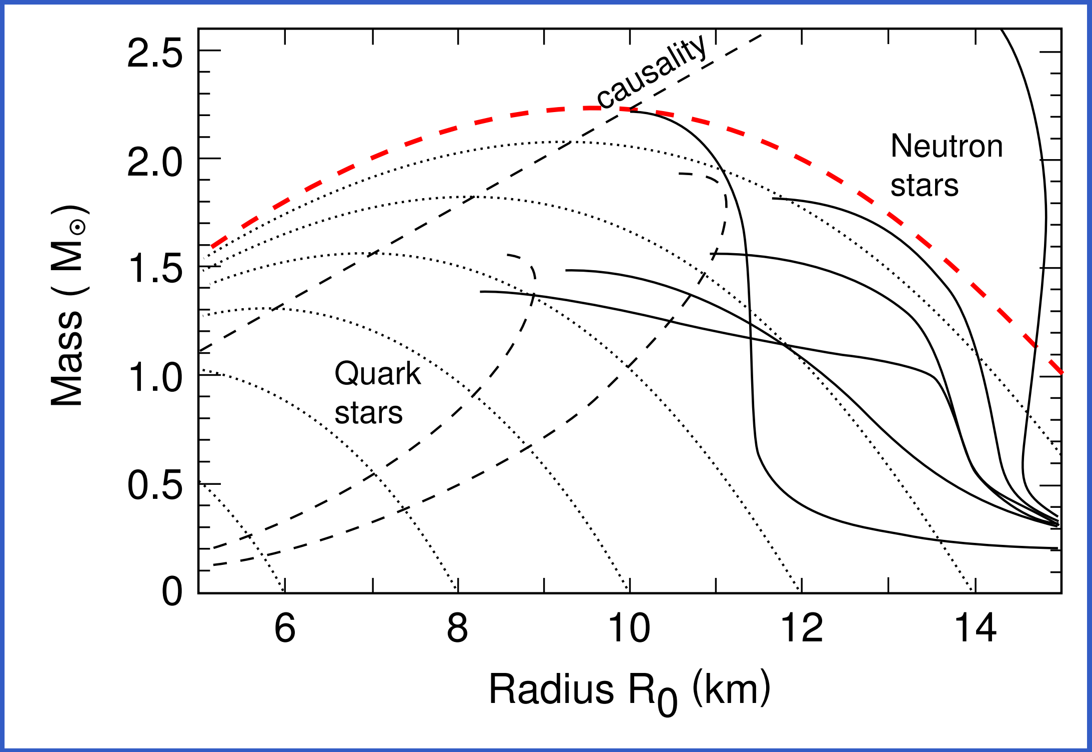
- corrected parallax measurement with Hubble: $D = 117 \pm 12$ pc
- Hubble measures only $T = 49$ eV in the optical band!
- refined modeling of the atmosphere needed

Modeling the Atmosphere of Neutron Stars (Burwitz et al. (2003))



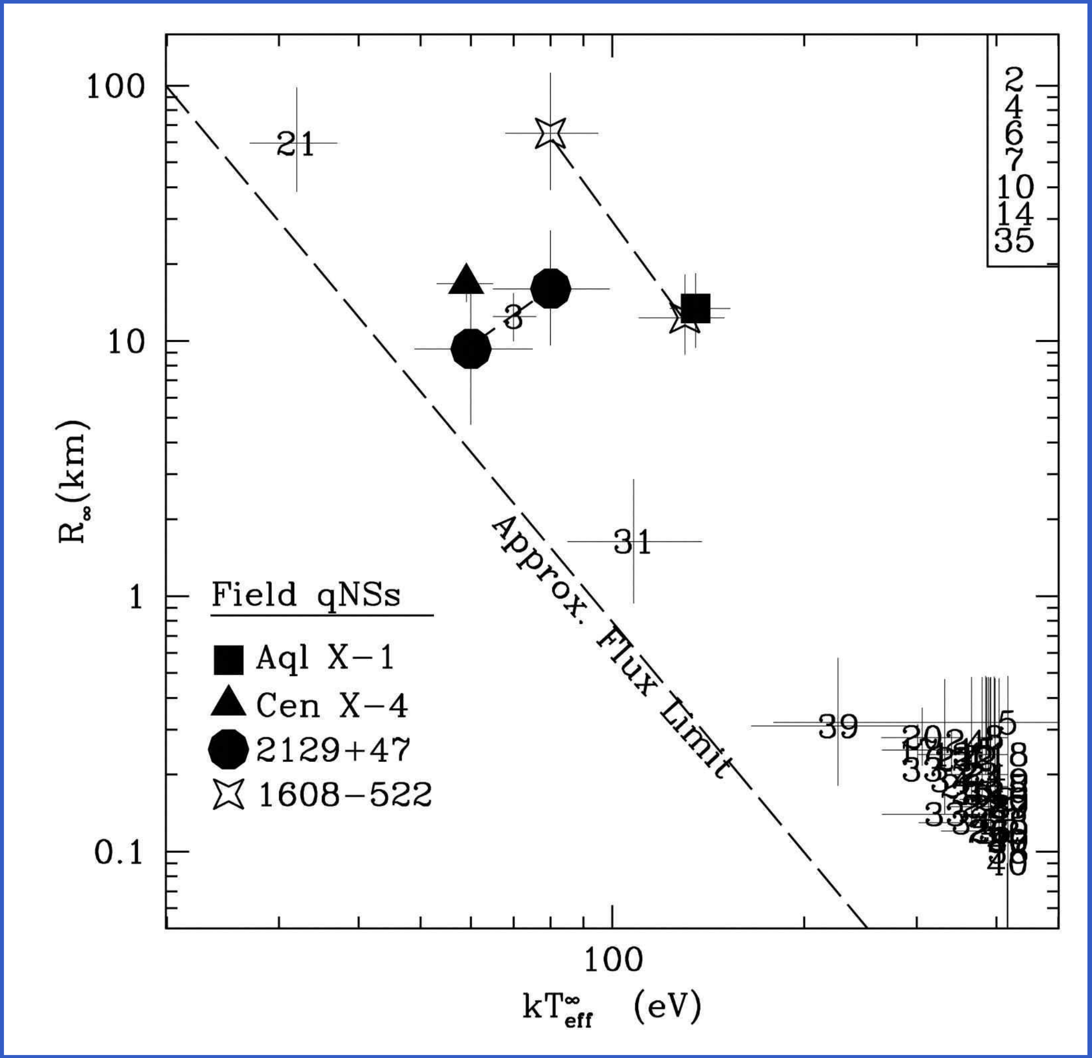
- H atmospheres ruled out, they over-predict the optical flux!
- heavy element atmospheres ruled out, as there are no spectral lines!
- all classic neutron star atmosphere models fail!
- alternatives: two-component blackbody model (left plot)
- or condensed matter surface for low $T < 86$ eV and high $B > 10^{13}$ G (right plot) — greybody with a suppression of a factor 7!

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



- two-component blackbody: small soft temperature, so as not to spoil the x-ray band
- this implies a rather LARGE radius so that the optical flux is right!
- conservative lower limit: $R_\infty = 16.5$ km (d/117 pc)
- excludes quark stars and even neutron stars with a quark core!

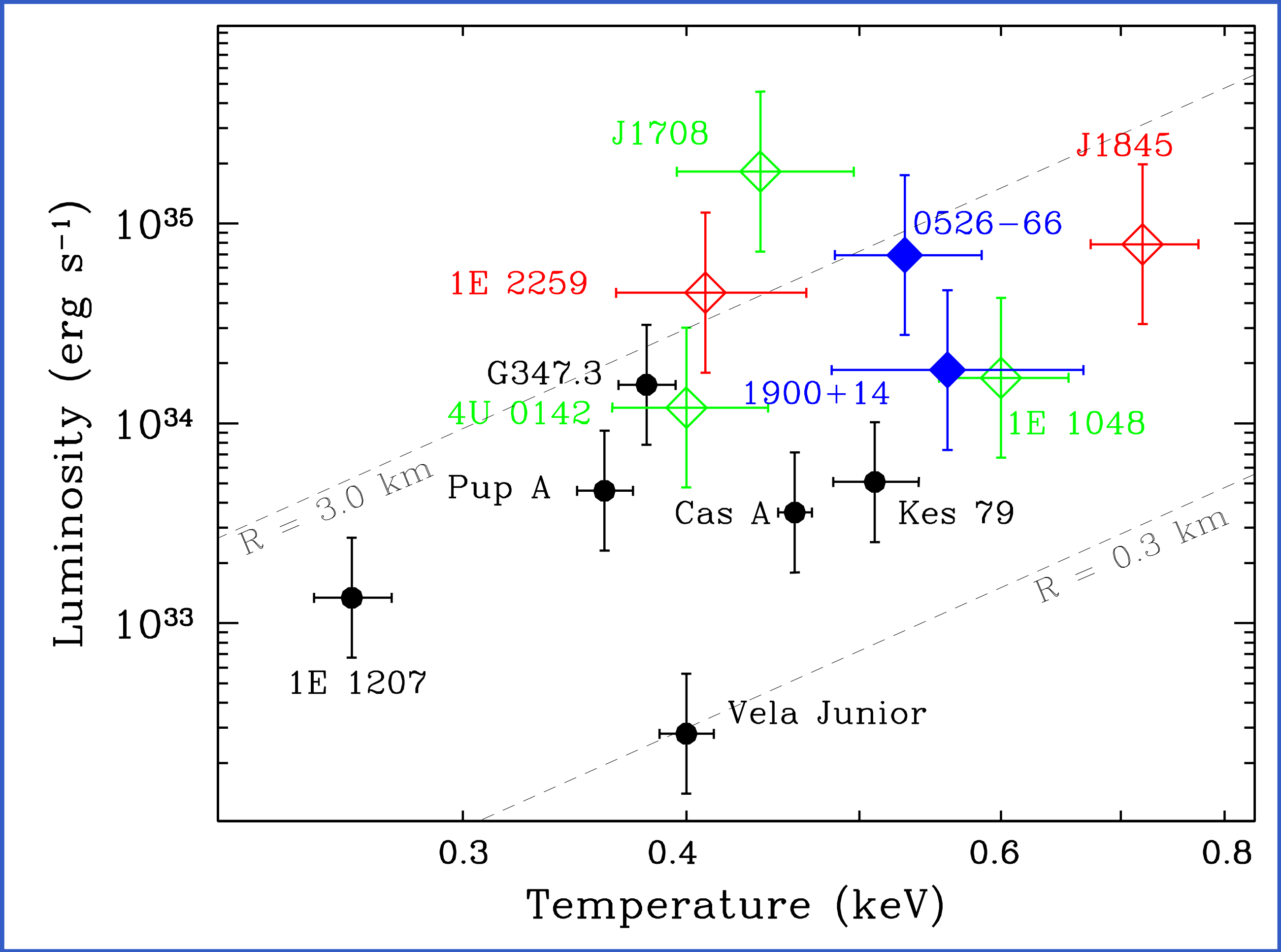
Neutron Stars in Globular Cluster (Rutledge et al. (2002))



- X-ray observations with the Chandra satellite of globular cluster (NGC5139)
- spectra fitted with H atmosphere
- most sources show a hot spot from accretion (extremely small radii)
- quiescent neutron stars found (qNSs): thermal emission from whole surface measurable
- allows to constrain the EoS: $R_\infty = 14.3 \pm 2.5$ km

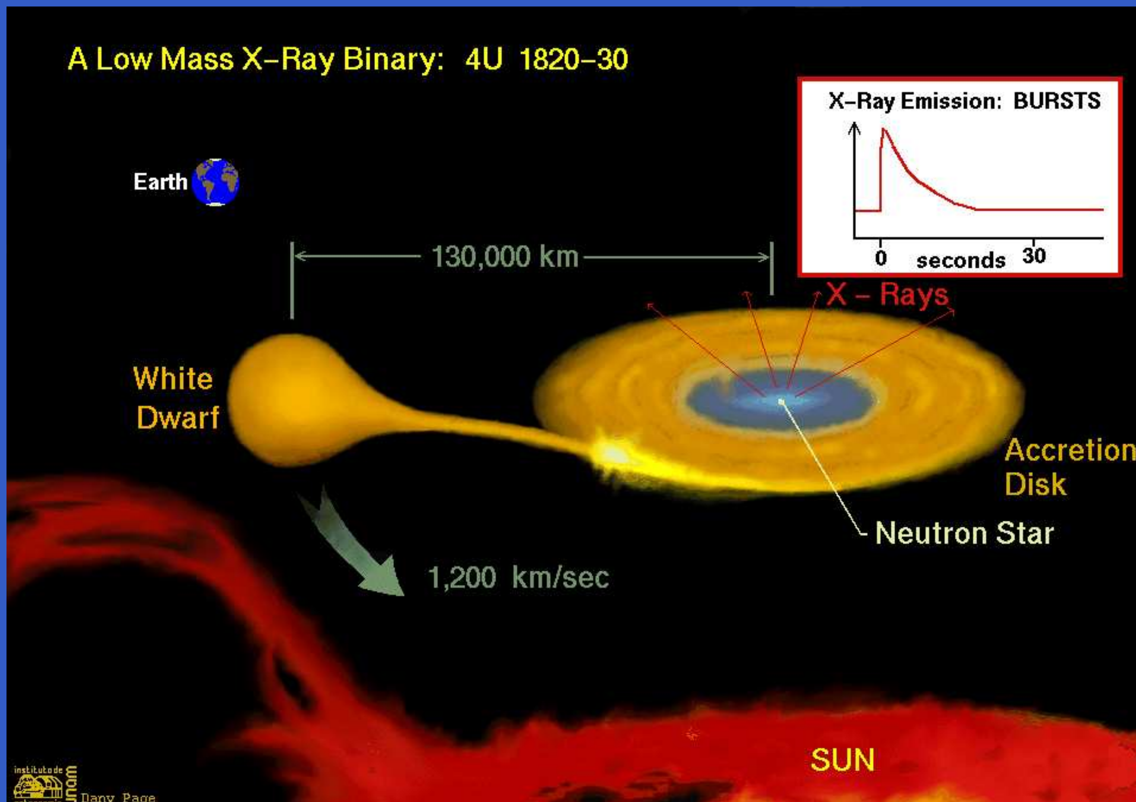
Central Compact Objects (CCOs) in Supernova Remnants

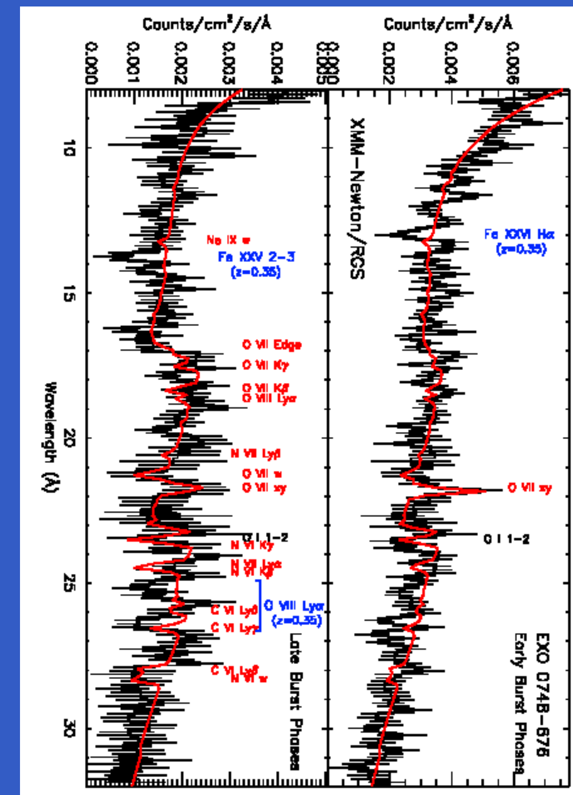
(Pavlov, Sanwal, Teter (2003))



- CCOs: point–like sources in the center of supernova remnants
- only observed in x–rays, radio–quiet, no pulsations seen
- temperatures of 0.2–0.5 keV and sizes of only 0.3–3 km!?!

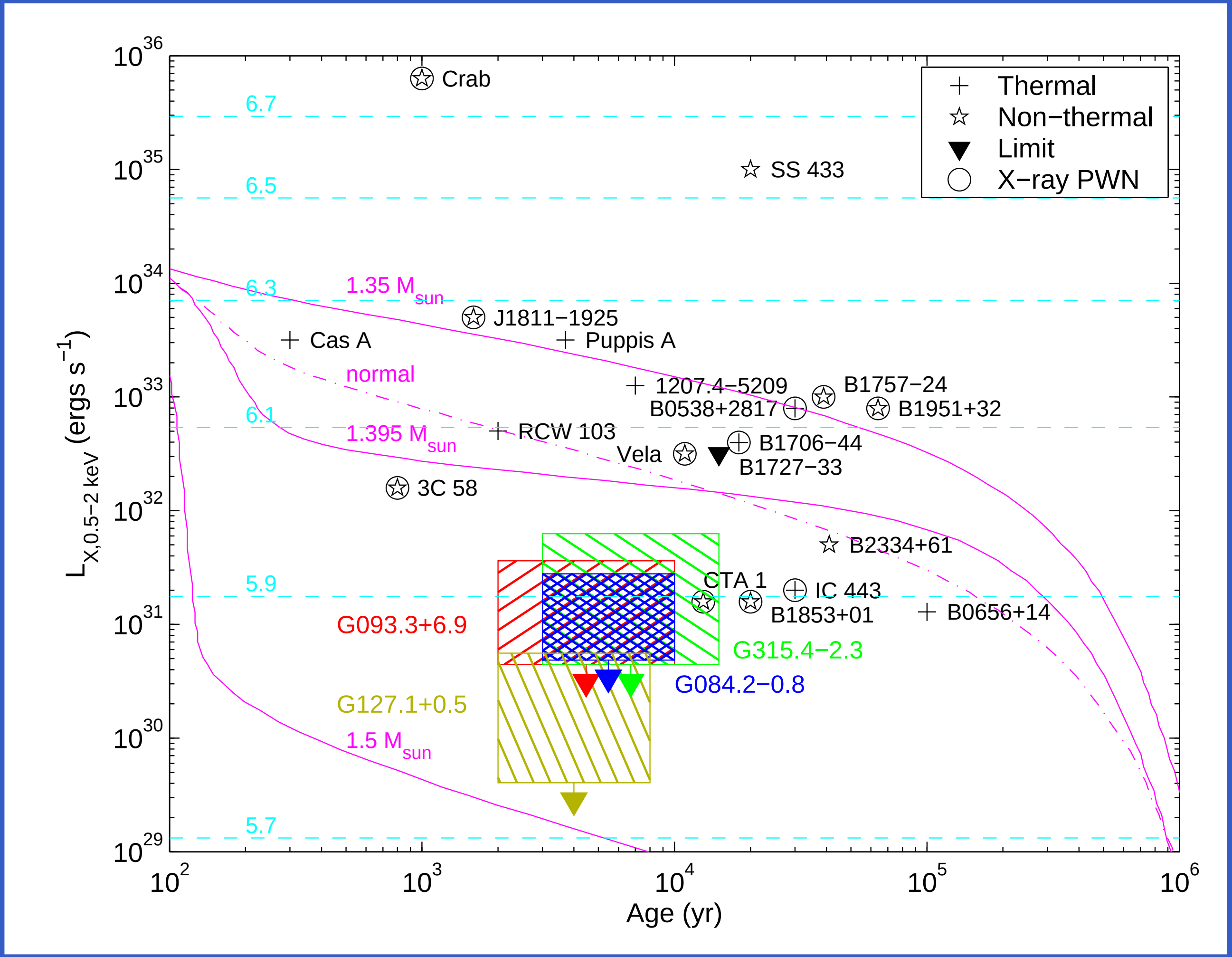
X-Ray burster





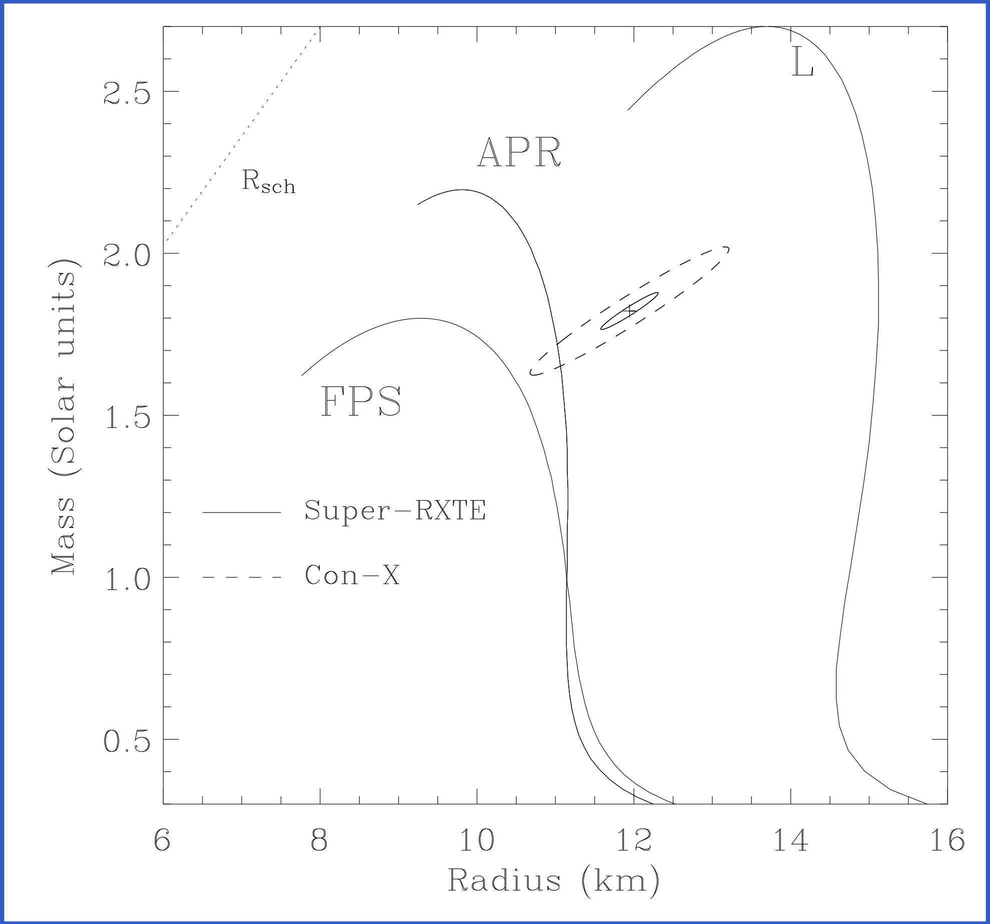
- binary systems of a neutron star with an ordinary star
- accreting material on the neutron star ignites nuclear burning
- explosion on the surface of the neutron star: x-ray burst
- red shifted spectral lines measured!
  ($z = 0.35 \rightarrow M/M_{\odot} = 1.5$ (R/10 km))
  (Cottam, Paerels, Mendez (2002))

Cooling of Supernova Remnants



- known age of the neutron star constrains cooling curves
- newest data from four neutron stars suggest fast cooling
- standard cooling curves are too high!
- signature for exotic matter in the core?

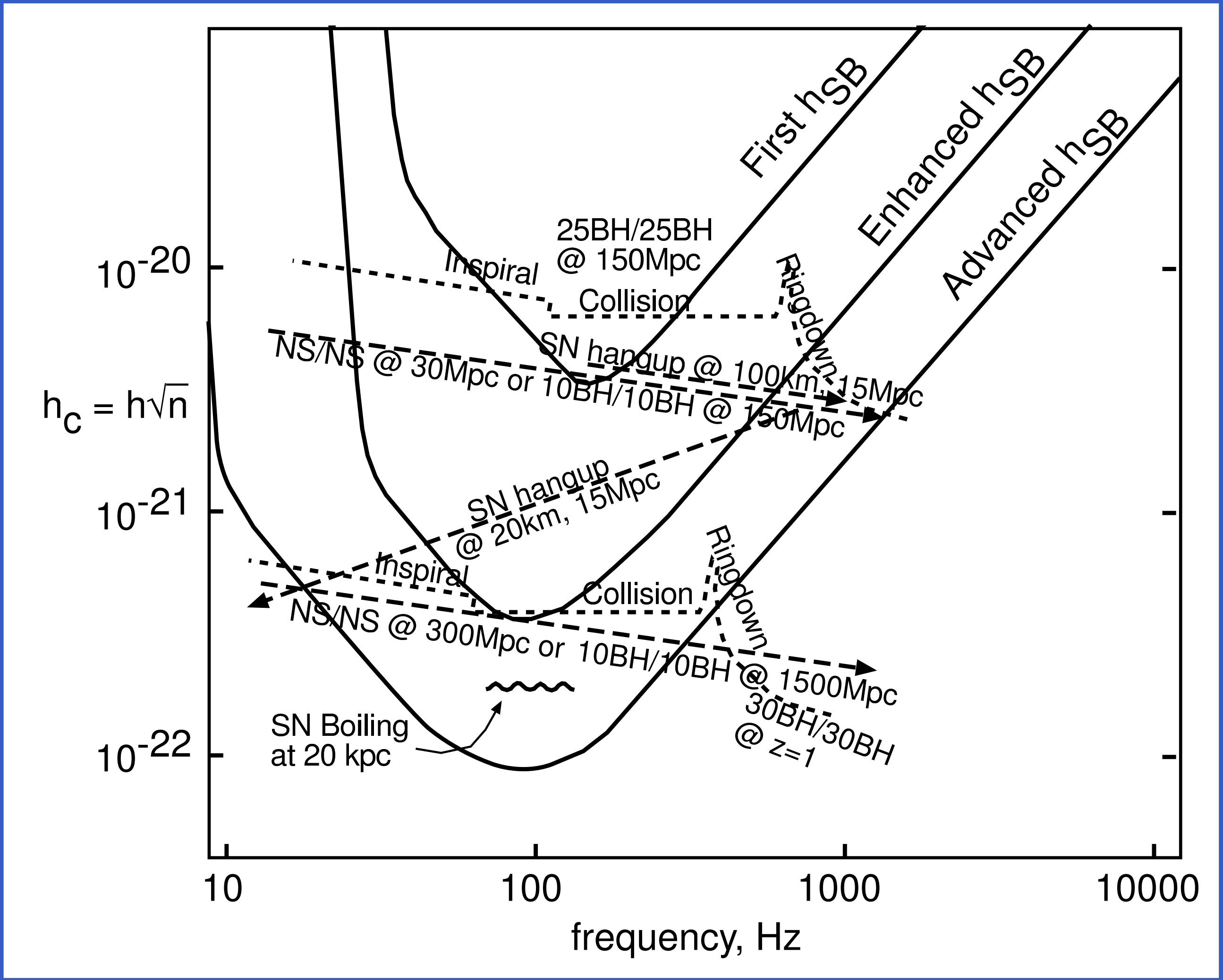
Future Probes Using X–Ray Bursts



(Strohmayer (2004))

- X-ray bursts from accreting neutron stars originating from the surface
- measure profile of emitted spectral lines
- spectral profile is modified from space-time warpage
- $\rightarrow$ gives a model independent mass and radius!

Future Probes Using Gravitational Waves



(Thorne (1997))

- sources of gravitational waves: nonspherical rotating neutron stars, colliding neutron stars and black-holes
- gravitational wave detectors are running now (LIGO,GEO600,VIRGO,TAMA)
- future: LISA, satellite detector!

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- present data about compact stars is still puzzling and full of surprises
- but the future is bright for determining the EoS from compact stars!