Astrophysics of Dense Matter and Neutron Stars

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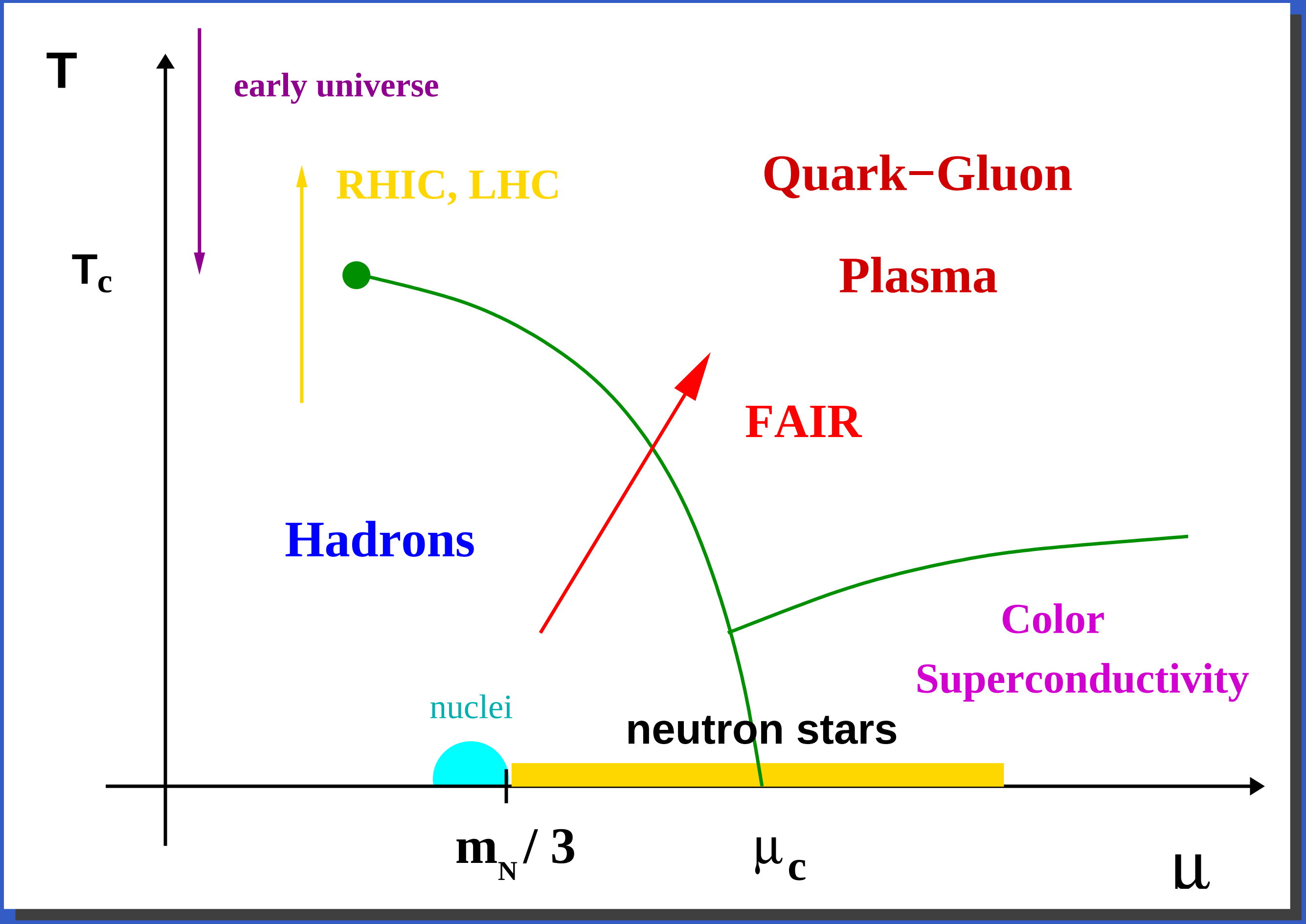
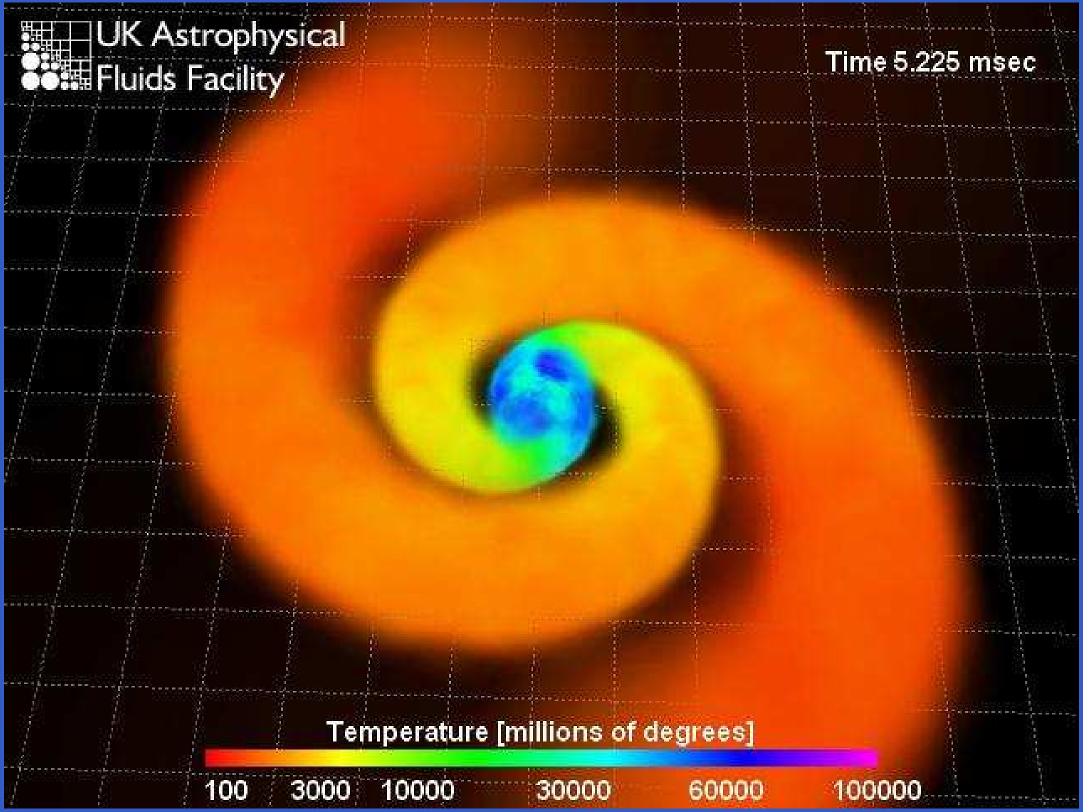
Phase Transitions in Quantum Chromodynamics QCD



- 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!)

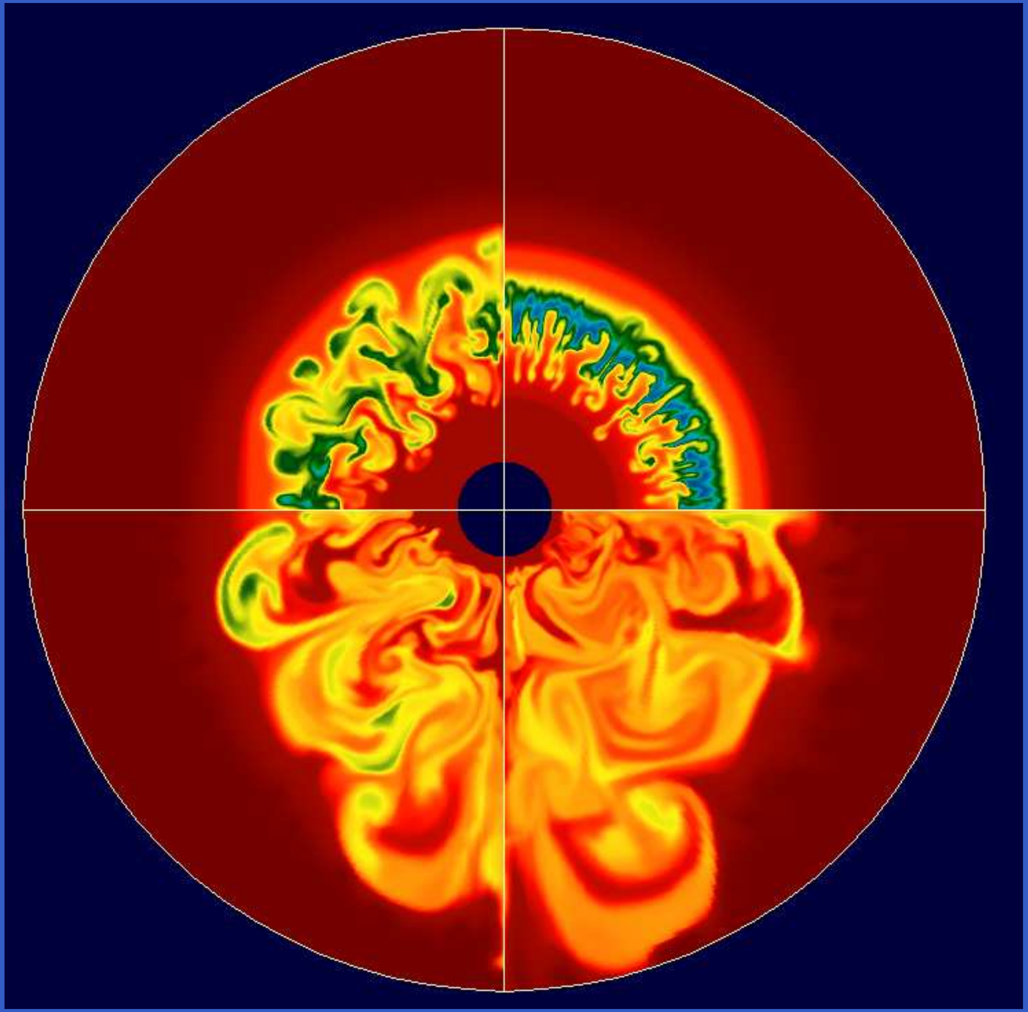
Astronomical Data on Neutron Stars

Nuclear Equation 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: $T = 0$–100 MeV, $n = 10^{-10}$–$10n_0$

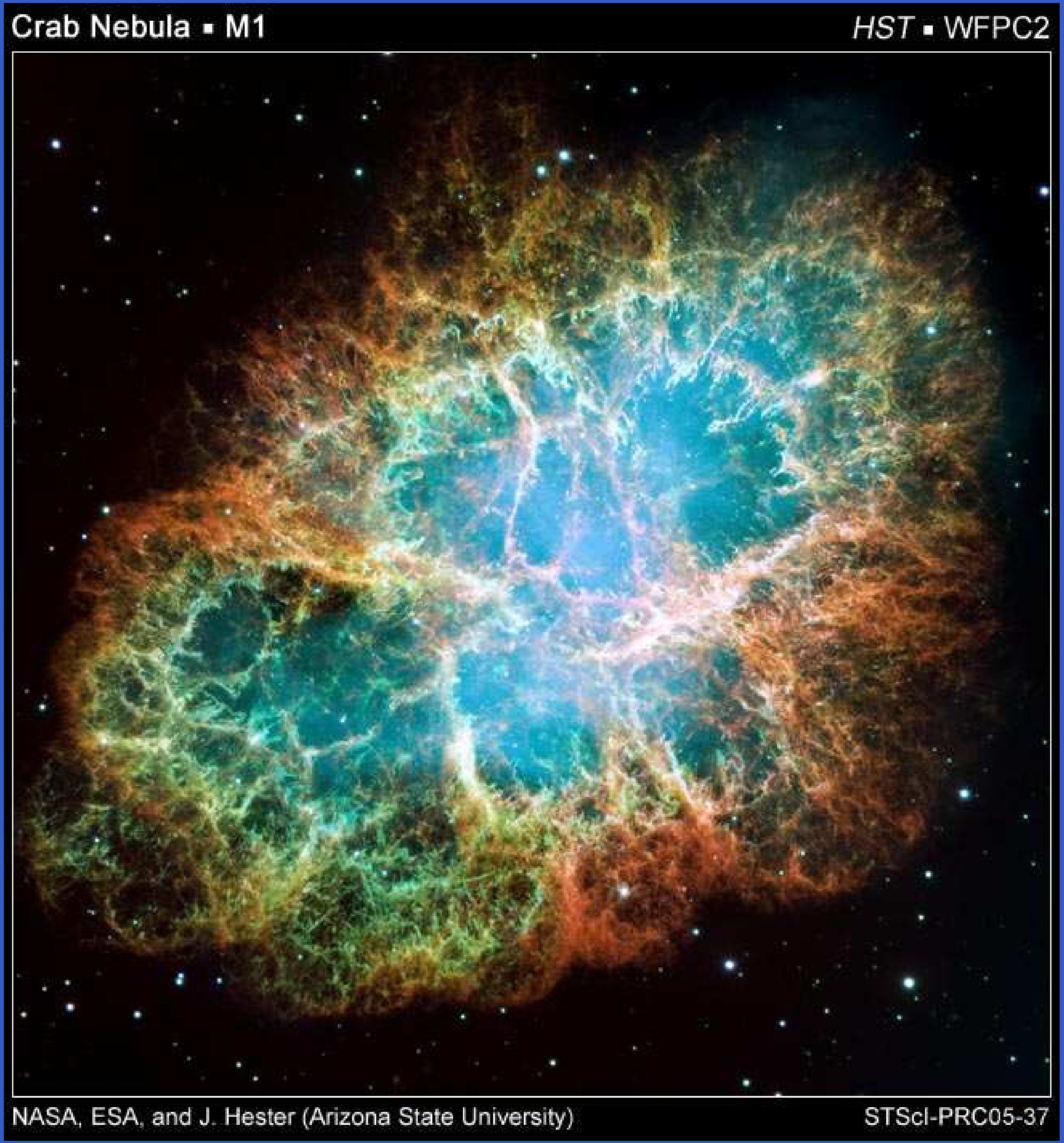
Supernova Explosions



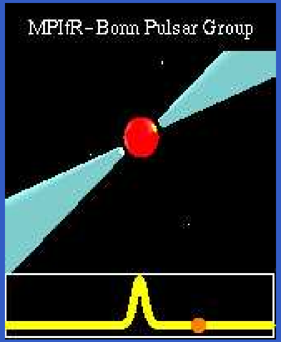
- stars with a mass of more than 8 solar masses end in a (core collapse) supernova (type II)
- Supernova of AD 1054 was visible for three weeks during daytime (crab nebula)!
- supernovae are several thousand times brighter than a whole galaxy!
- last supernova explosion for the last 400 years in our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

Animation of a supernova explosion (Chandra, NASA)

Neutron Stars



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



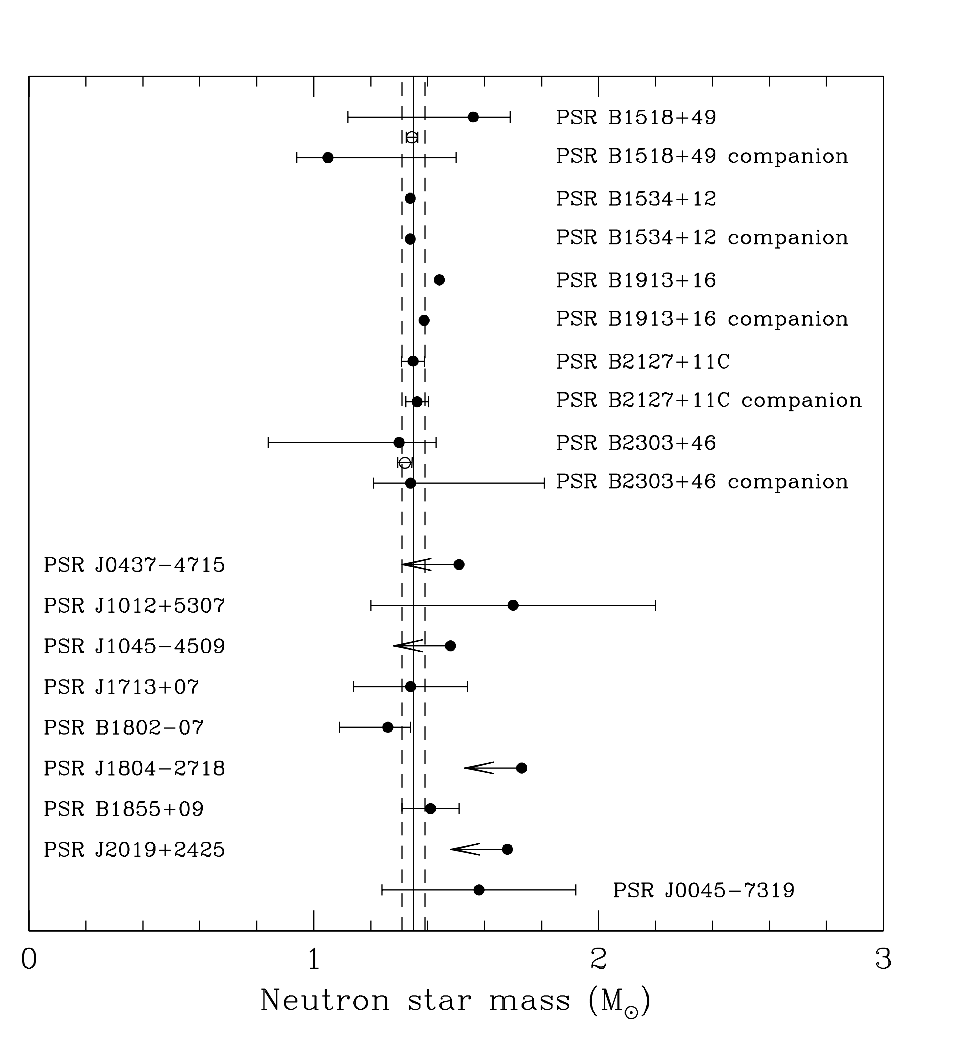
- produced in core collapse supernova explosions
- compact, massive objects: radius ≈ 10 km, mass $1 - 2M_\odot$
- extreme densities, several times nuclear density: $n \gg n_0 = 3 \cdot 10^{14}$ g/cm^3
- in the middle of the crab nebula: a pulsar, a rotating neutron star!

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)

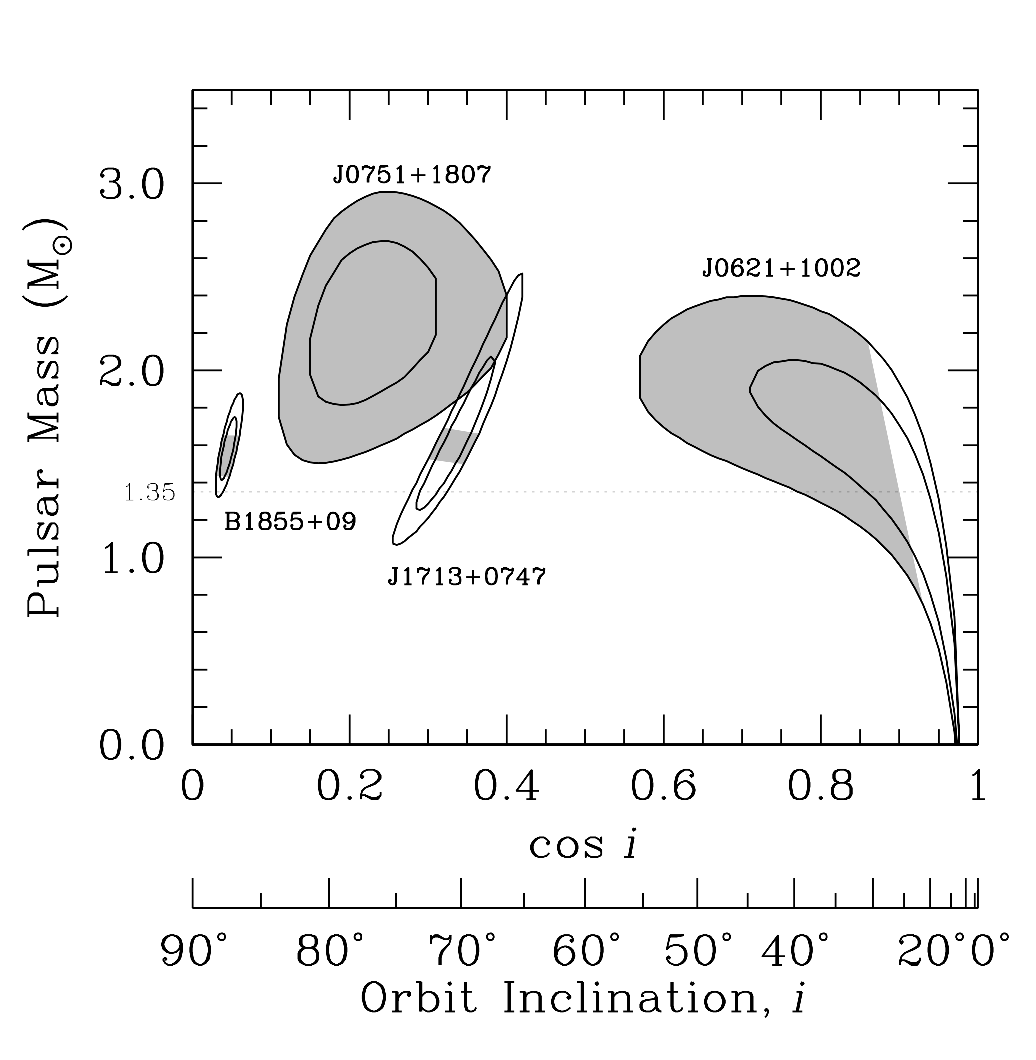
Masses of Pulsars (Thorsett and Chakrabarty (1999))



- more than 1600 pulsars known
- best determined mass: $M = (1.4411 \pm 0.00035) M_\odot$ (Hulse-Taylor pulsar)
- extremely rapid rotations: up to 716 Hz (1.397 ms) (PSR J1748-2446ad)

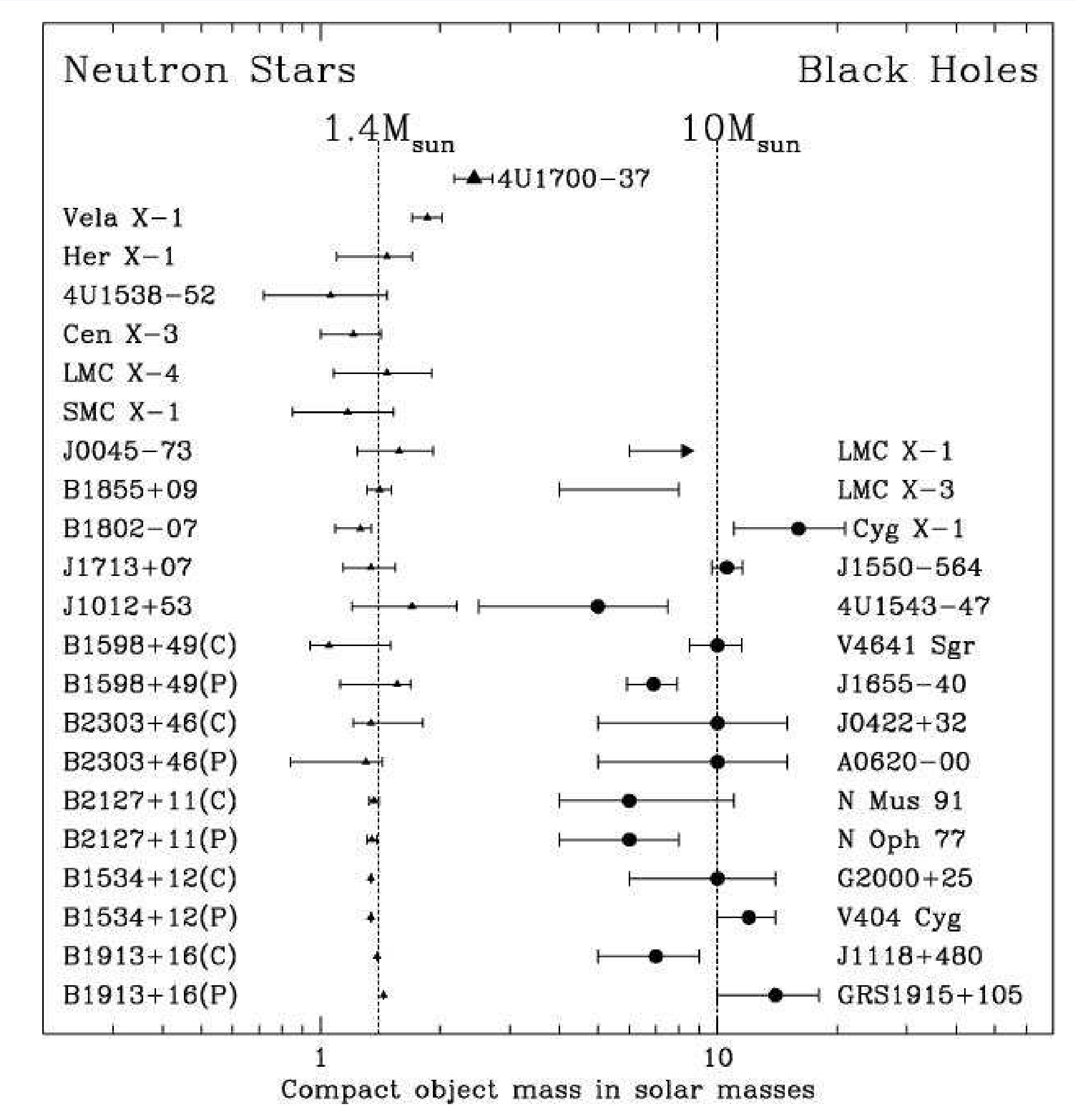
Massive Neutron Stars in Pulsar–White Dwarfs Systems?

(Nice, Splaver, Stairs (2003))



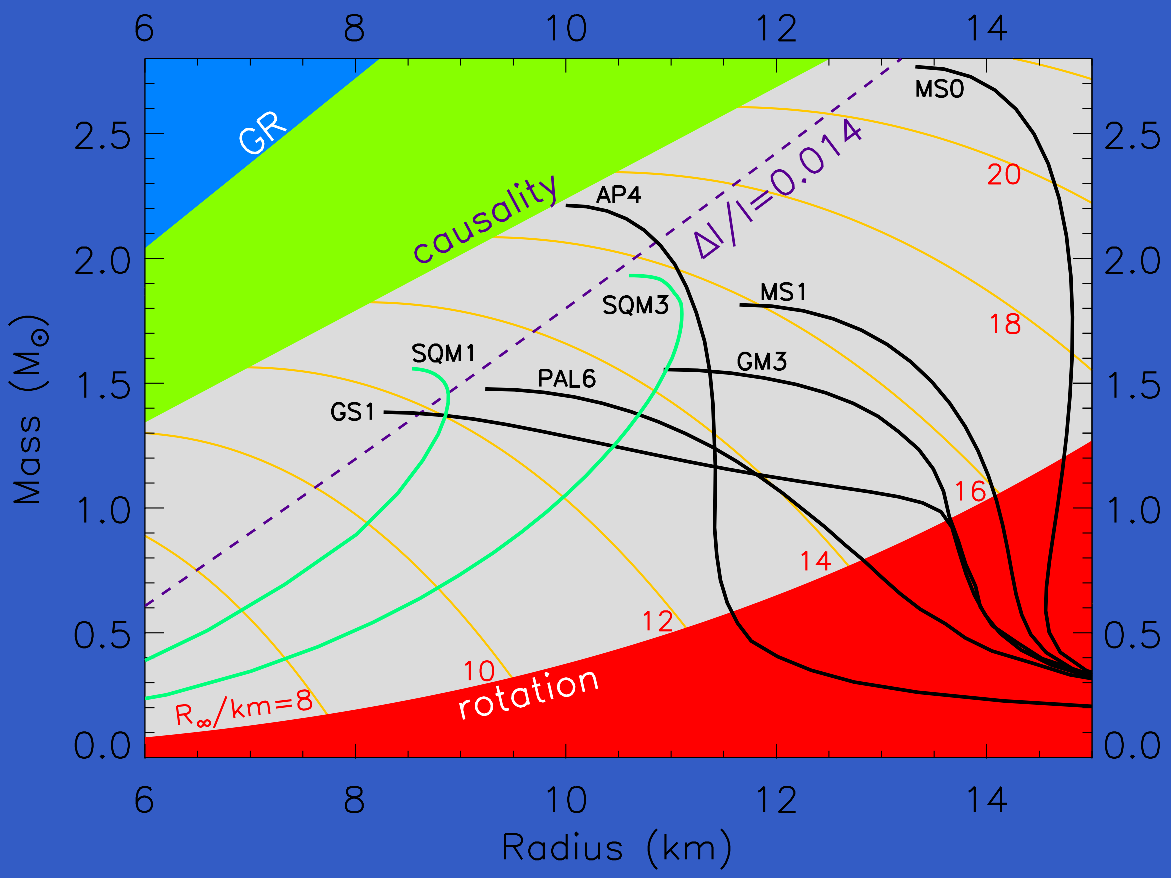
- four pulsars with a white dwarf companion
- measure masses by changes in the pulsar signal
- shaded area: from theoretical limits for white–dwarf companion
- massive pulsar J0751+1807: $M = 1.6 - 2.8 M_\odot$ (2σ!)
- Nice et al. (2005): $M = 2.1 \pm 0.2 M_\odot$ (1σ) and $M = 1.6 - 2.5 M_\odot$ (2σ)!!!

Massive Compact Objects In X-ray Binaries? (Clark et al. 2002)



- Vela X-1: X-ray pulsar, $M = 1.88 \pm 0.13 M_\odot$ (Quaintrell et al. 2003)
- Cygnus X-2: X-ray burster, $M = 1.78 \pm 0.23 M_\odot$ (Orosz and Kuulkers 1999), or $M = 1.44 \pm 0.06 M_\odot$ (Titarchuk and Shaposhnikov 2002)?
- U1700-37: High Mass X-ray Binary (HMXB), $M = 2.44 \pm 0.27 M_\odot$ with $M(2\sigma) > 2M_\odot$! (Clark et al. 2002), could be a black hole!

Constraints on the Mass–Radius Relation



(Lattimer and Prakash (2004))

- spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4M_\odot$
- observed giant glitch from Vela pulsar: moment of inertia changes by 1.4%
- Schwarzschild limit (GR): $R > 2GM = R_s$
- causality limit for EoS: $R > 3GM$

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:

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

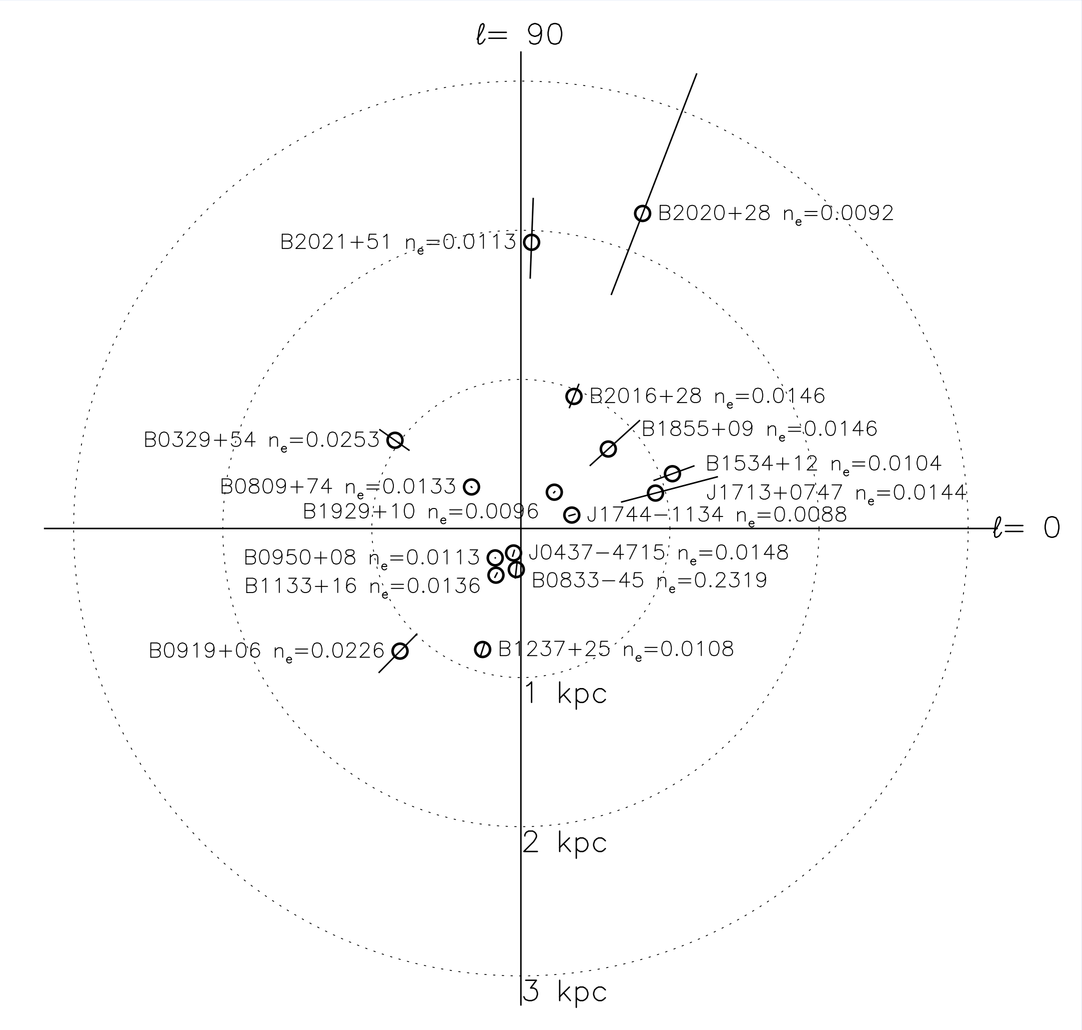
with $T_{{\rm eff},\infty} = T_{\rm eff}/(1+z)$ and $R_\infty = R/(1+z)$

- redshift:

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

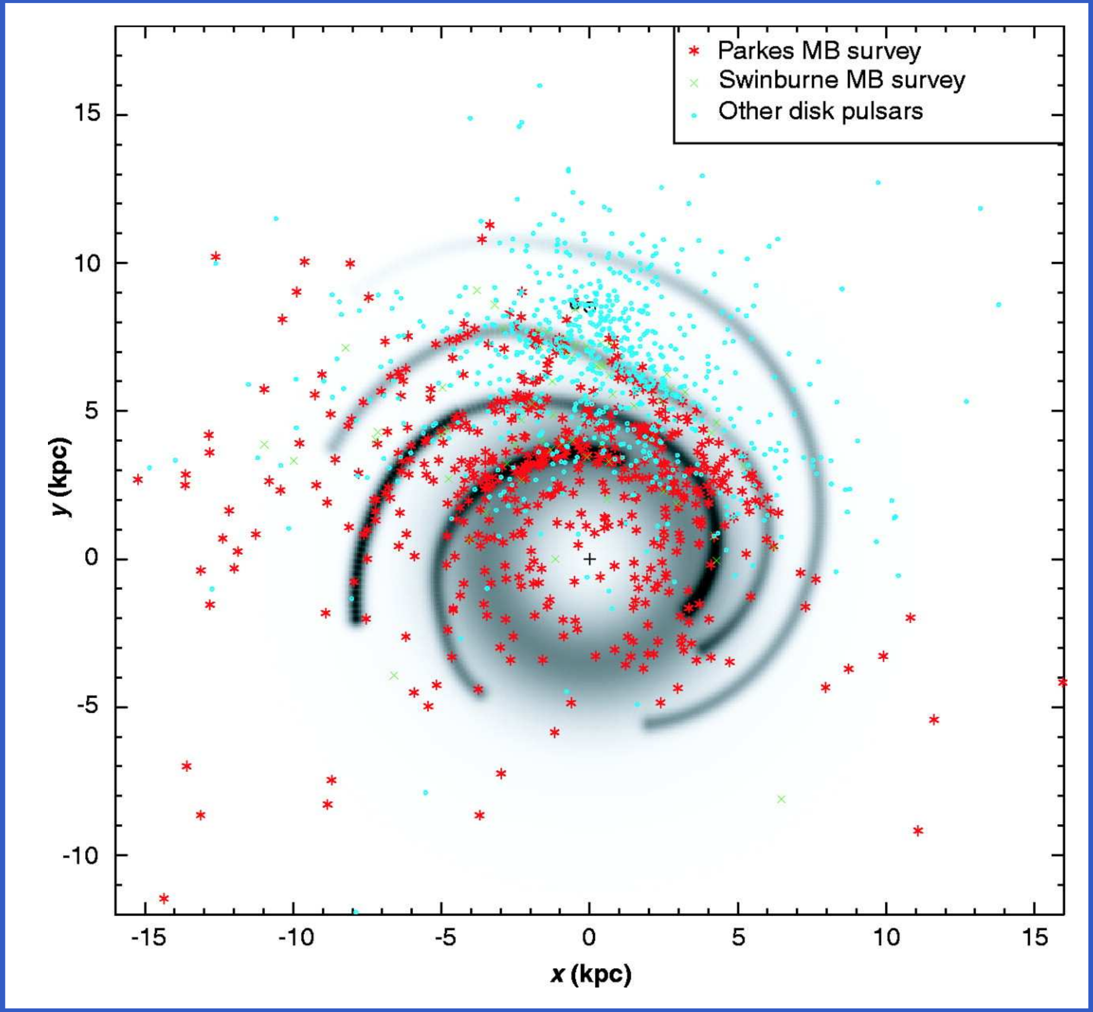
- need to know distance and effective temperature to get R_∞
- radius measured depends on true mass and radius of the star
- additional constraint from redshift measurement from e.g. redshifted spectral lines fixes mass and radius uniquely

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



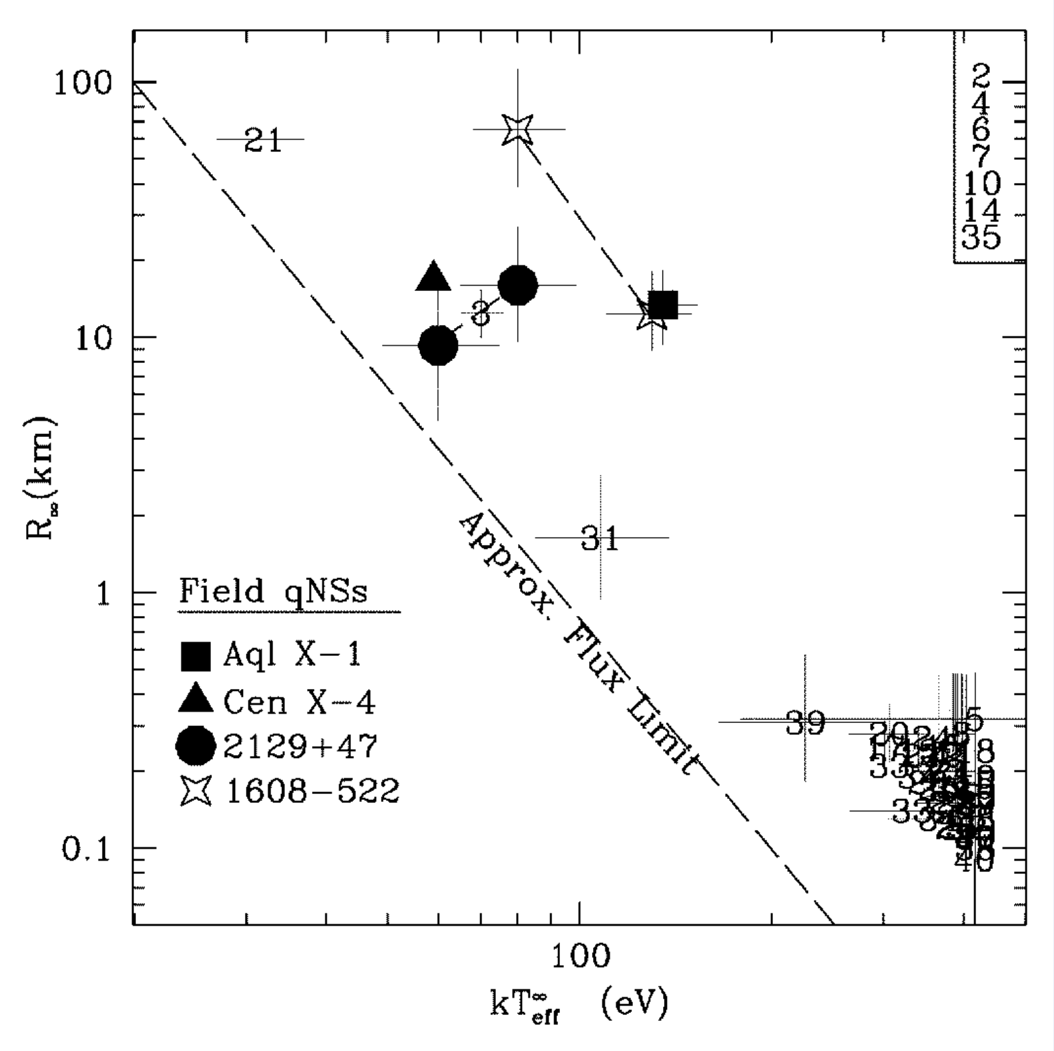
- Very Long Baseline Array (VLBA) of 10 radio antennas
- parallax measurements with an accuracy of 2% for the distance!
- distances determined for more than 10 pulsars

Pulsar Distribution in our Galaxy



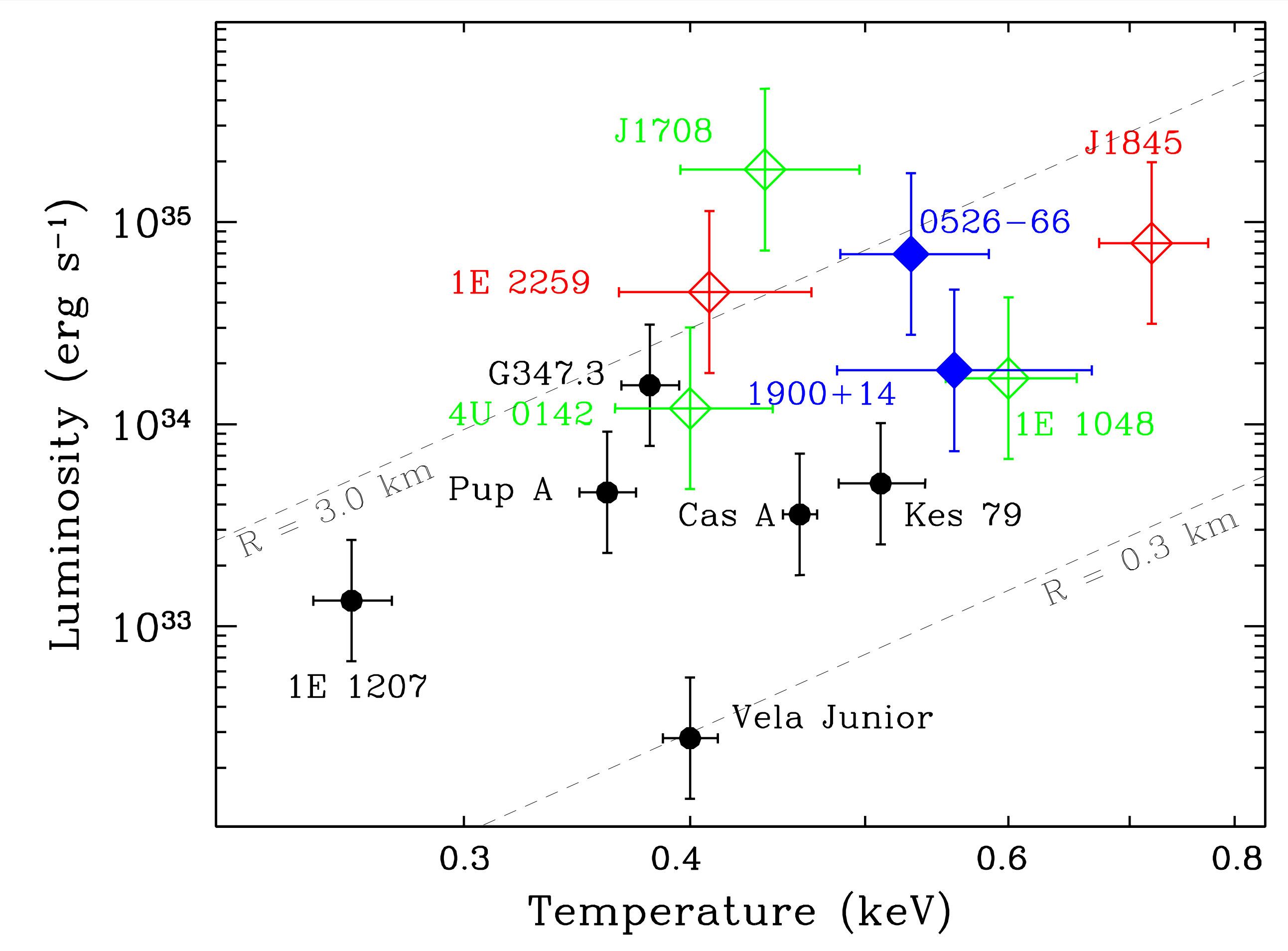
- distance estimate by dispersion measure (DM)
- dispersion due to conducting interstellar medium
- works for known electron number density distribution

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

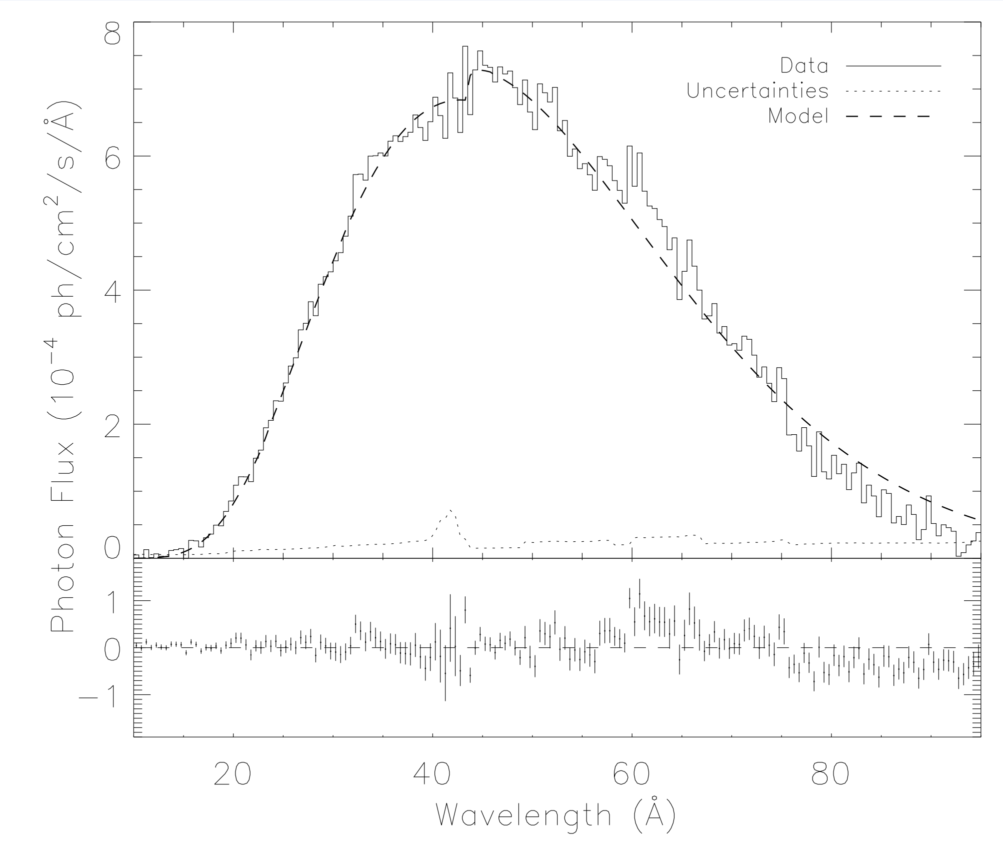
Central Compact Objects (CCOs) in Supernova Remnants



(Pavlov, Sanwal, Teter (2003))

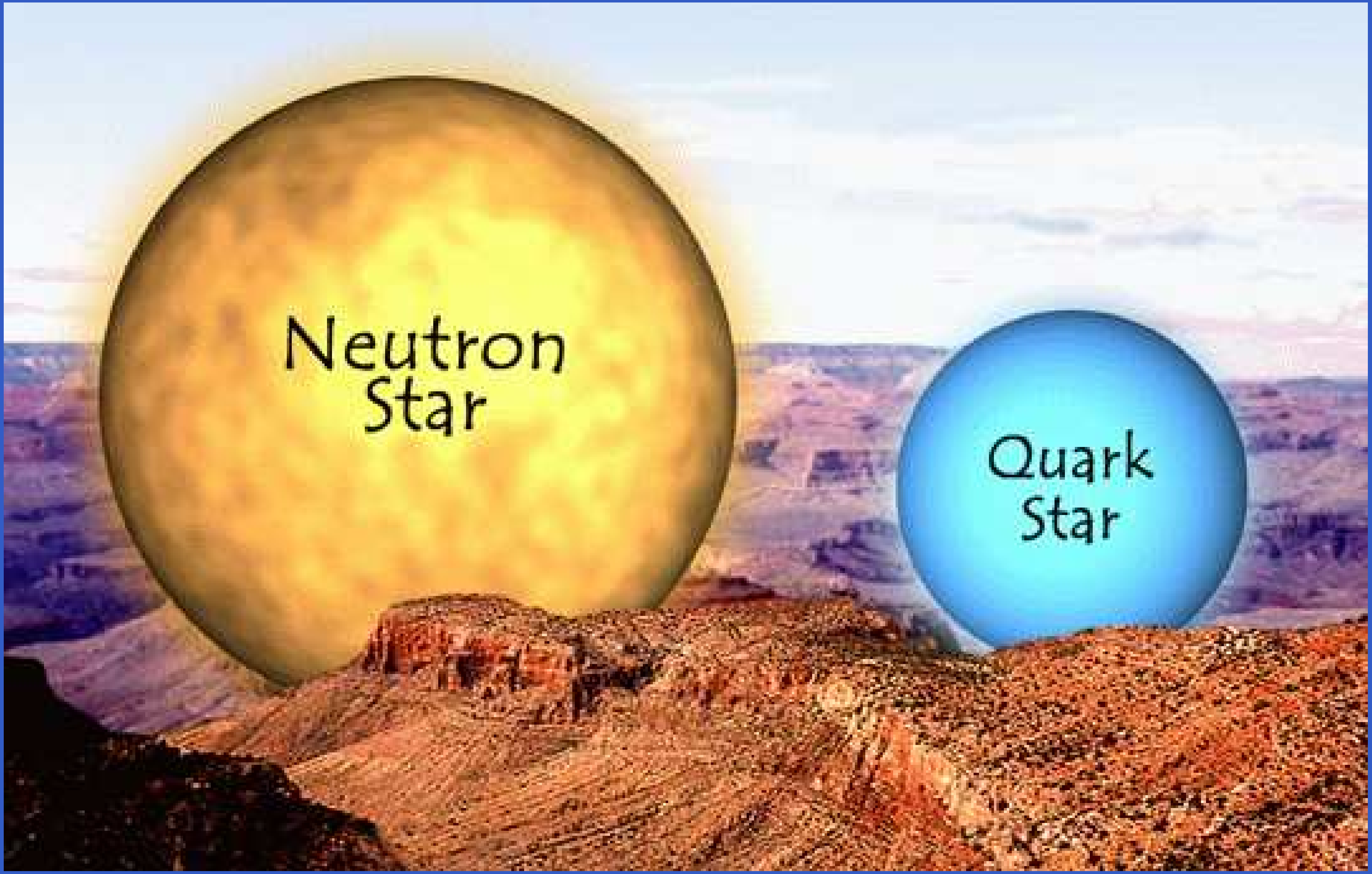
- CCOs: point–like sources in the center of supernova remnants
- only observed in x–rays, radio–quiet, no pulsations seen
- temperatures of 0.2–0.5 keV and sizes of only 0.3–3 km!?!

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!

A Quark Star? (NASA press release 2002)

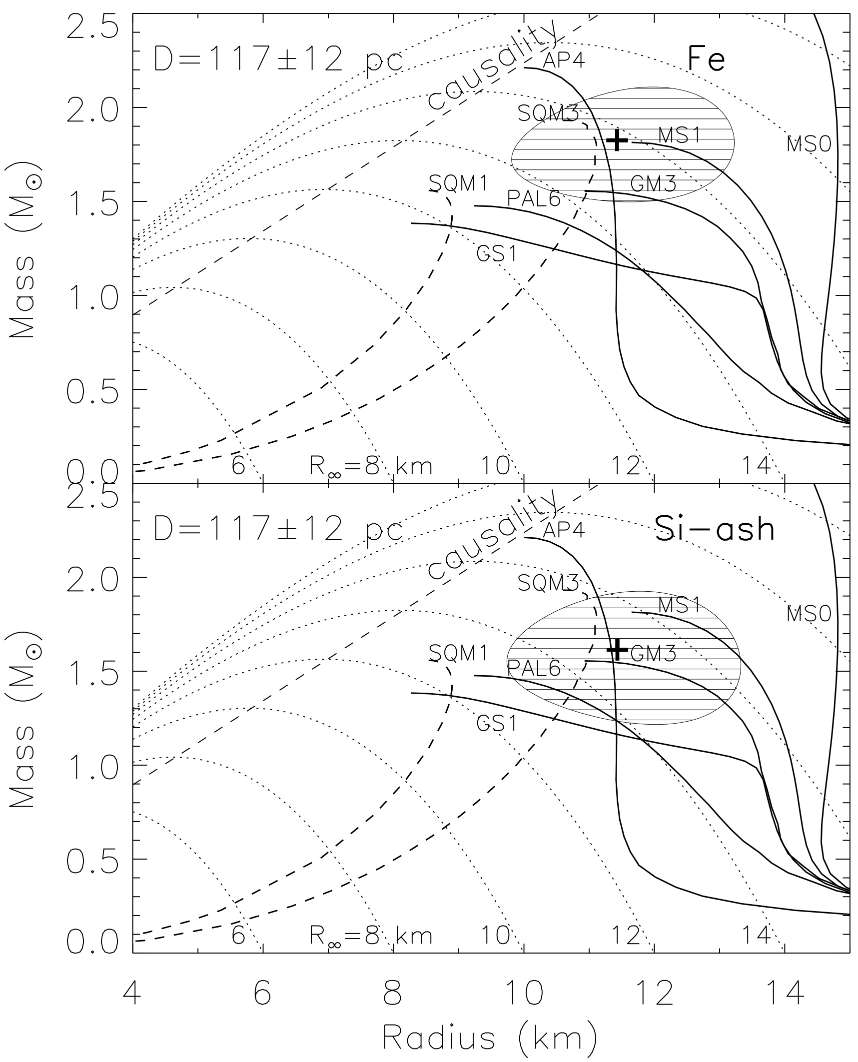


NASA news release 02-082:

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

— a quark star?

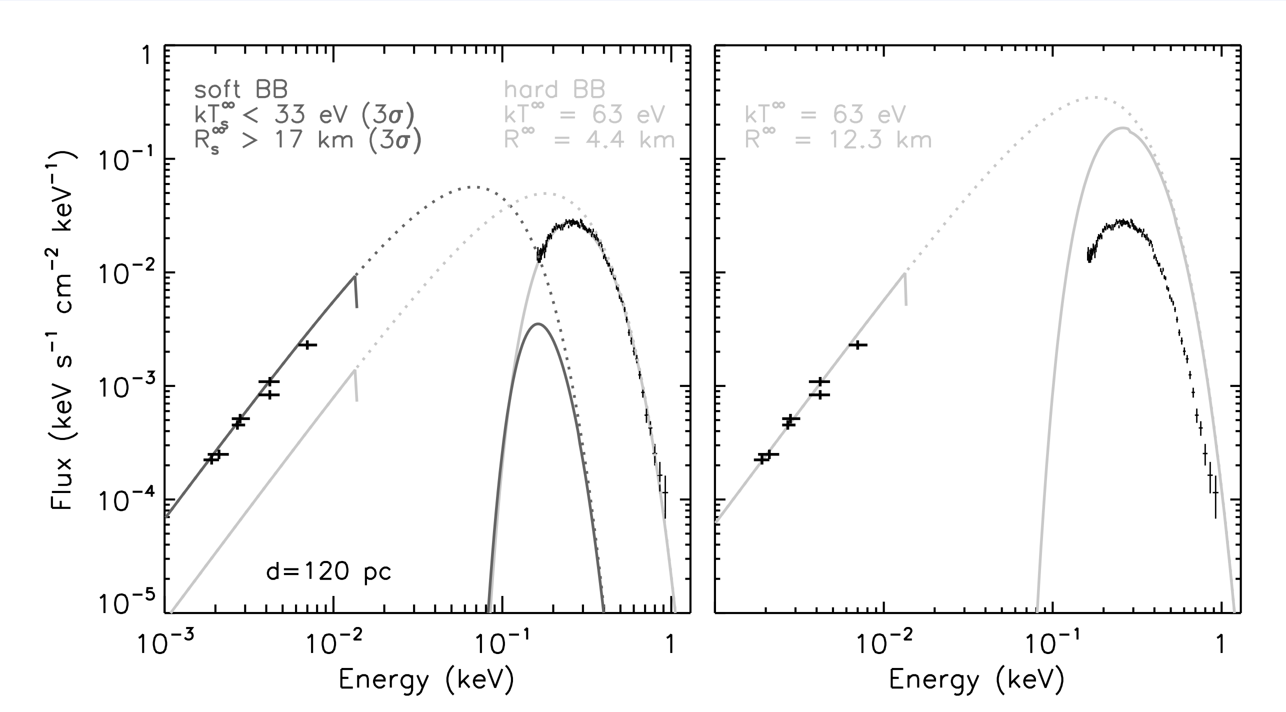
Parallax Measurement from Hubble



(Lattimer and Walter (2002))

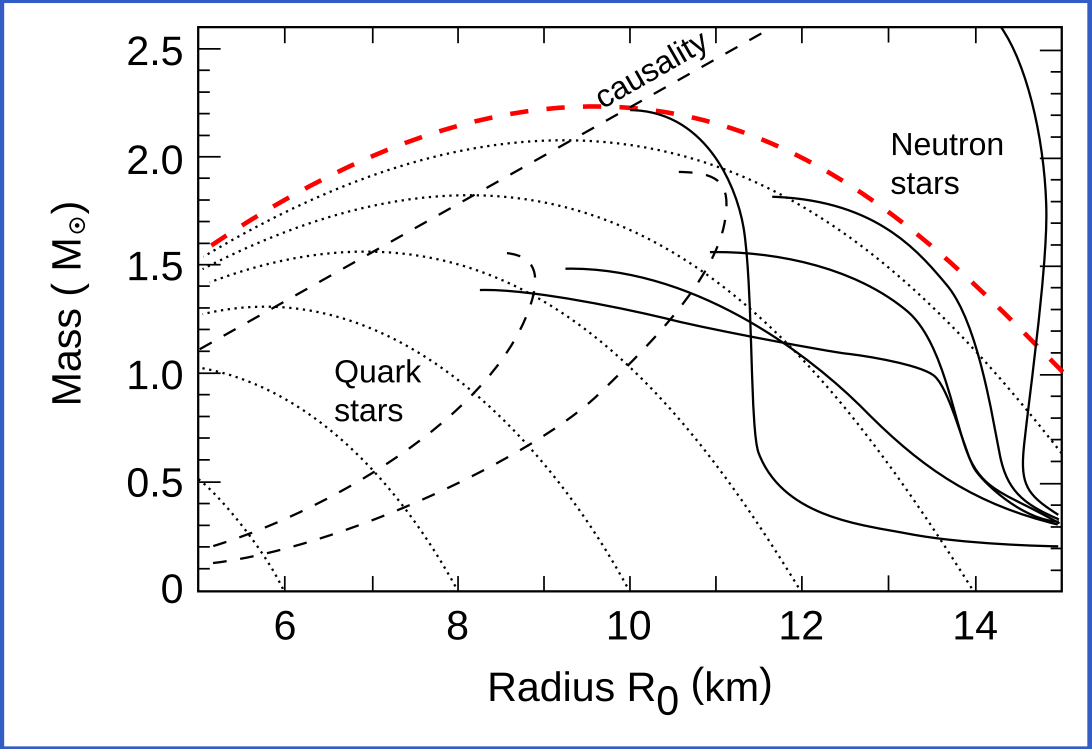
- corrected parallax measurement with Hubble: $D = 117 \pm 12$ pc
- Hubble measures only $T = 49$ eV in the optical band!
- refined modelling of the atmosphere needed

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



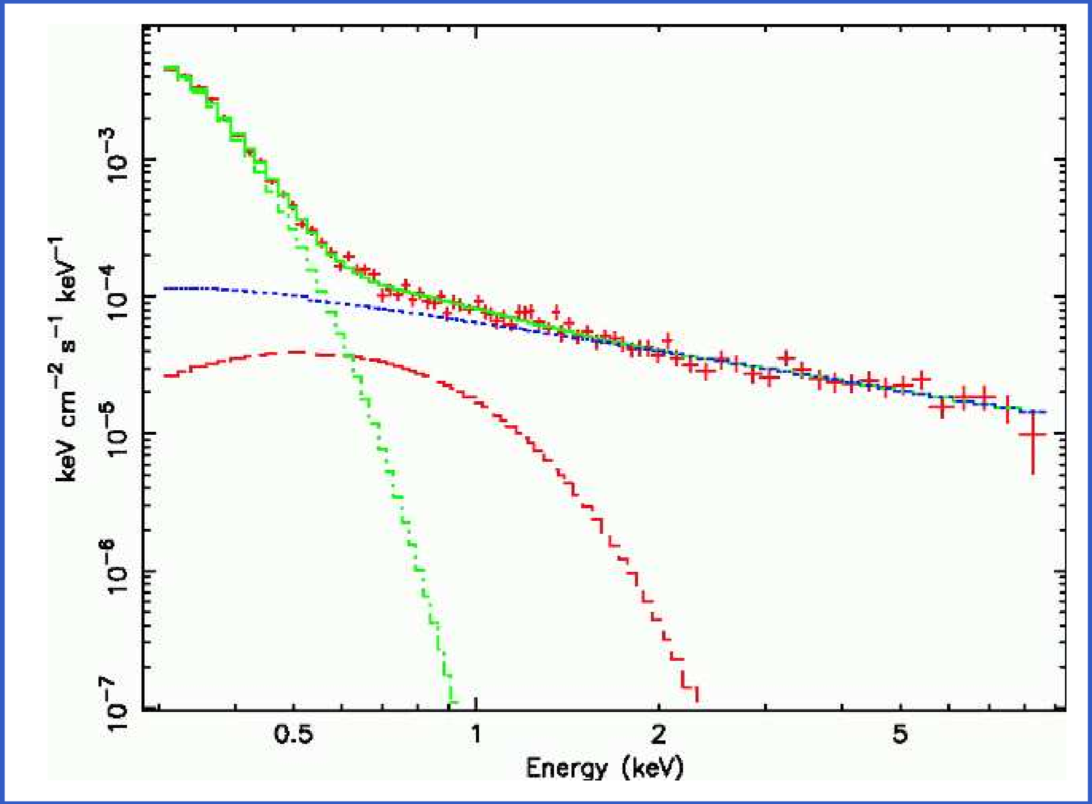
- H atmospheres ruled out, they over-predict the optical flux!
- heavy element atmospheres ruled out, as there are no spectral lines!
- all classic neutron star atmosphere models fail!
- alternatives: two-component blackbody model (left plot)
- or condensed matter surface for low $T < 86$ eV and high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

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



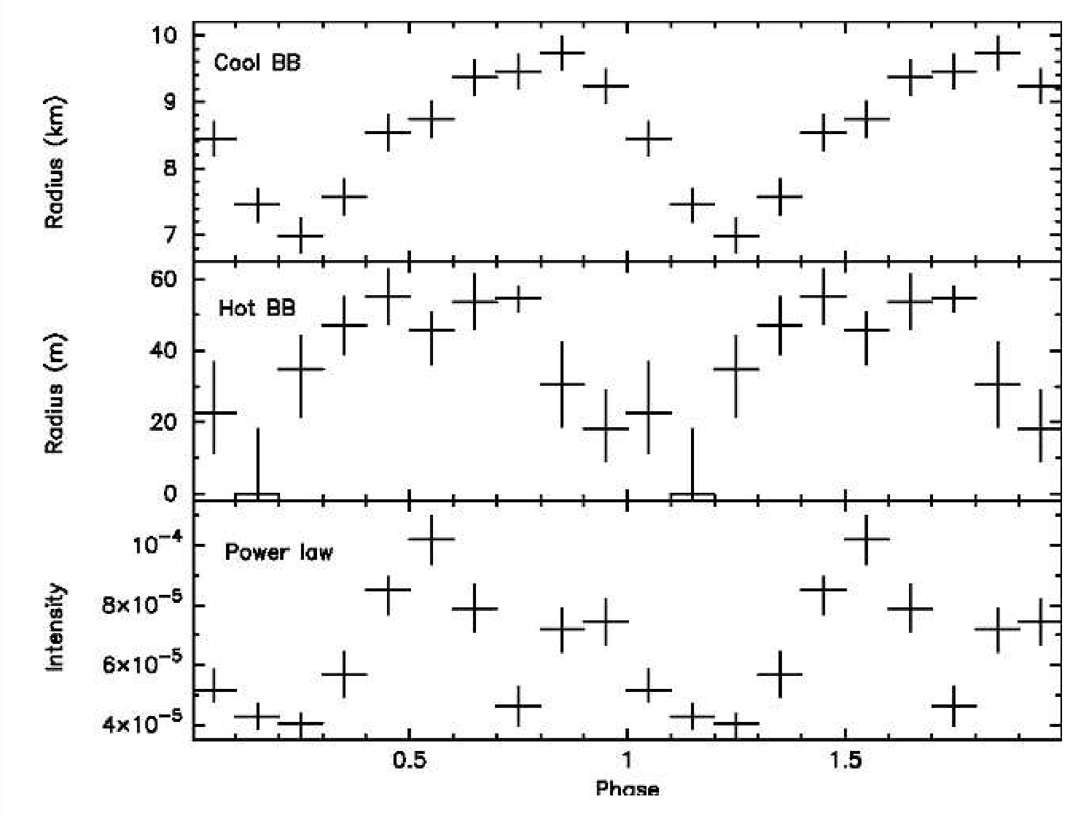
- two-component blackbody: small soft temperature, so as not to spoil the x-ray band
- this implies a rather LARGE radius so that the optical flux is right!
- conservative lower limit: $R_\infty = 16.5$ km (d/117 pc)
- excludes quark stars and even neutron stars with a quark core!

Spectra from Geminga (Caraveo et al. (2004))



- three component fit to spectra of the Geminga pulsar:
- power law tail at high energies (from magnetosphere)
- hot black-body with a size of only $R = 40 \pm 10$ m (from polar caps)
- cool black-body with a size of $R = 8.6 \pm 1$ km (from pulsar surface?)

Phase Resolved Spectra from Geminga (Caraveo et al. (2004))



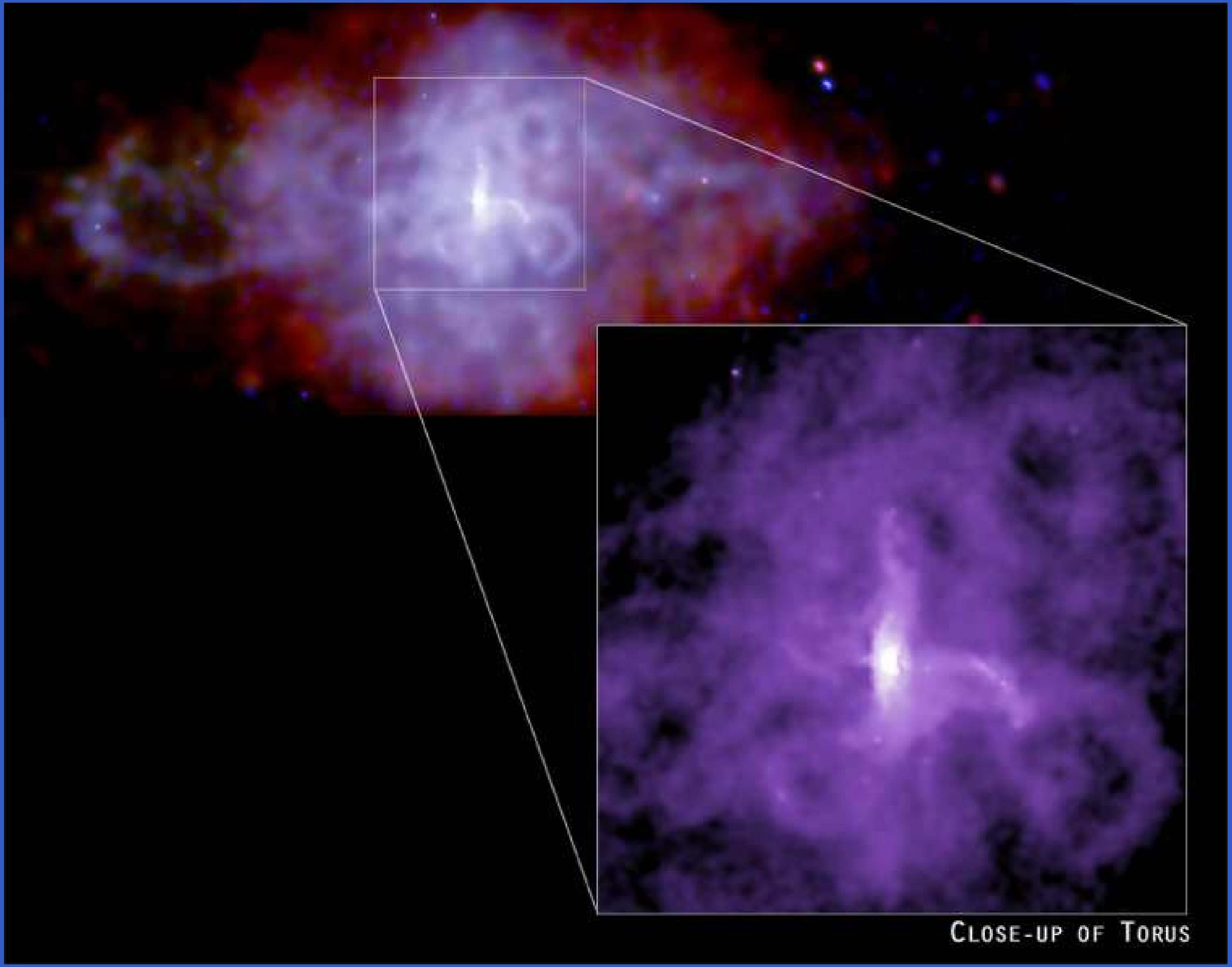
← radius of $T = 43$ eV emitting area (cool black–body)

← radius of $T = 170$ eV hot spot (hot black–body)

← power law flux at 1 keV

- power law tail at high energies (from magnetosphere)
- hot black-body with a size of only $R = 60$ m (from polar caps)
- cool black-body with a size of $R = 10$ km (from hot continent)
- varies with time, not from entire surface!

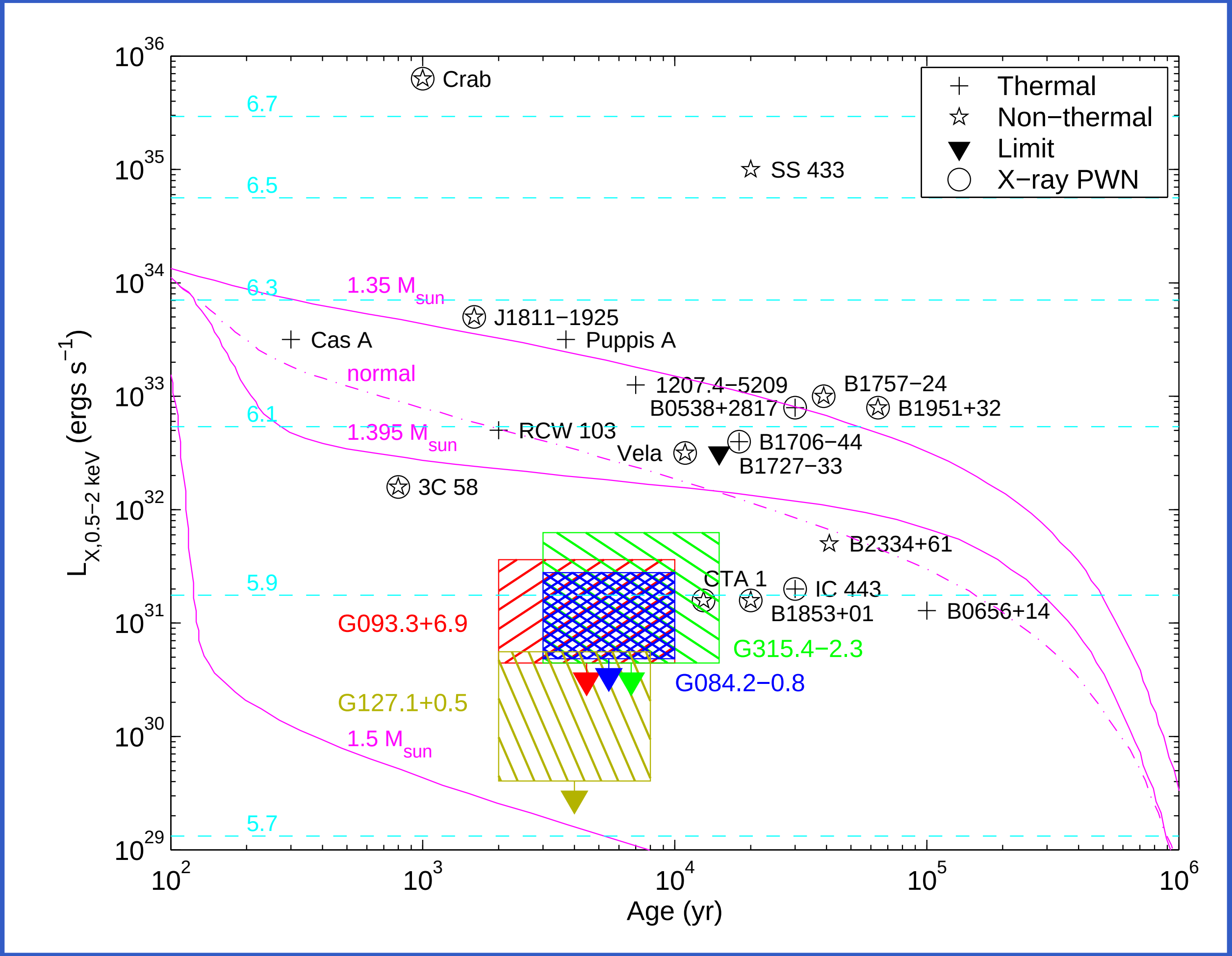
Supernova remnant 3C58 from 1181 AD (Slane et al. 2004)



CHANDRA press release 04-13:

“Going to Extremes: Pulsar Gives Insight on Ultra Dense Matter and Magnetic Fields” — rapid cooling due to unexpected conditions in the neutron star!

Cooling of Supernova Remnants (Kaplan et al. (2004))



- newest data from four neutron stars suggest fast cooling (direct URCA)
- standard cooling curves are too high!
- large nuclear asymmetry energy generates fast cooling!
- strange particles (exotic matter) generate fast cooling!

Cooling processes with neutrinos

modified URCA process (slow):

$N + p + e^- \longrightarrow N + n + \nu_e \qquad N + n \longrightarrow N + p + e^- + \bar{\nu}_e$

direct URCA process (fast):

$p + e^- \longrightarrow n + \nu_e \qquad n \longrightarrow p + e^- + \bar{\nu}_e$

can only proceed for $p_F^p + p_F^e \geq p_F^n$! Charge neutrality implies:

$$n_p = n_e \hookrightarrow p_F^p = p_F^e \hookrightarrow 2p_F^p = p_F^n \hookrightarrow n_p/n \geq 1/9$$

nucleon URCA only possible for a large fraction of protons!

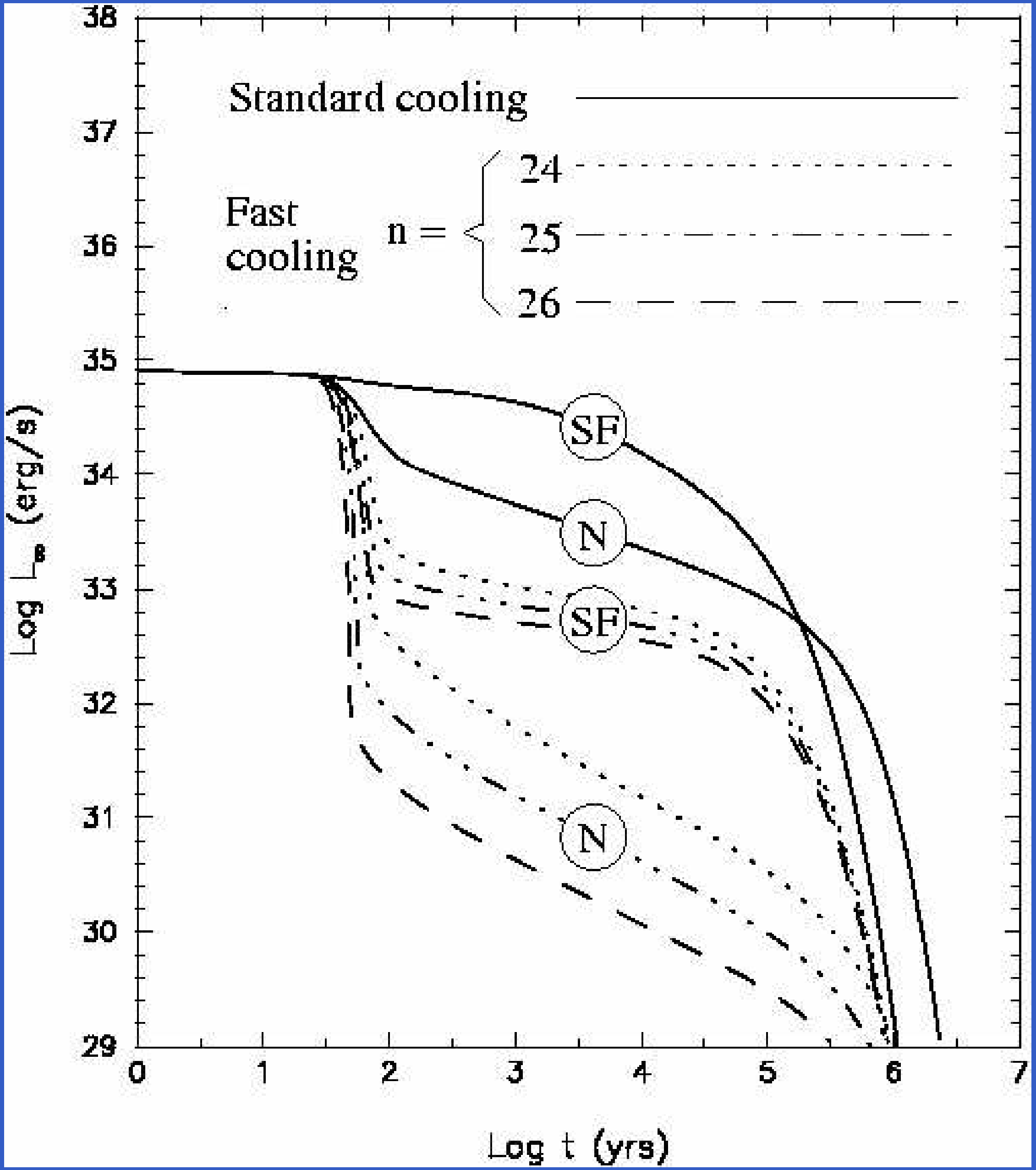
hyperon URCA process:

$$\Lambda \longrightarrow p + e^- + \bar{\nu}_e \quad , \quad \Sigma^- \longrightarrow n + e^- + \bar{\nu}_e \quad , \quad \ldots$$

happens immediately when hyperons are present!

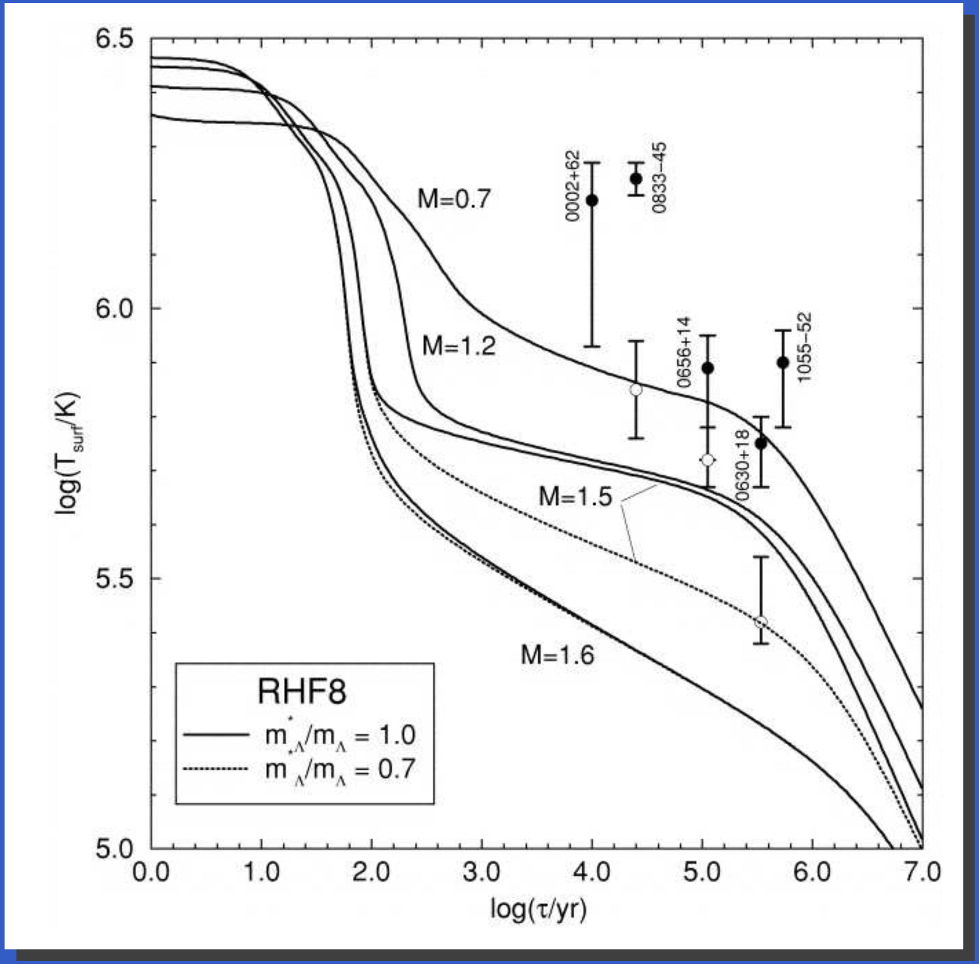
only suppressed by hyperon pairing gaps!

Basic cooling of neutron stars (Page and Reddy (2006))



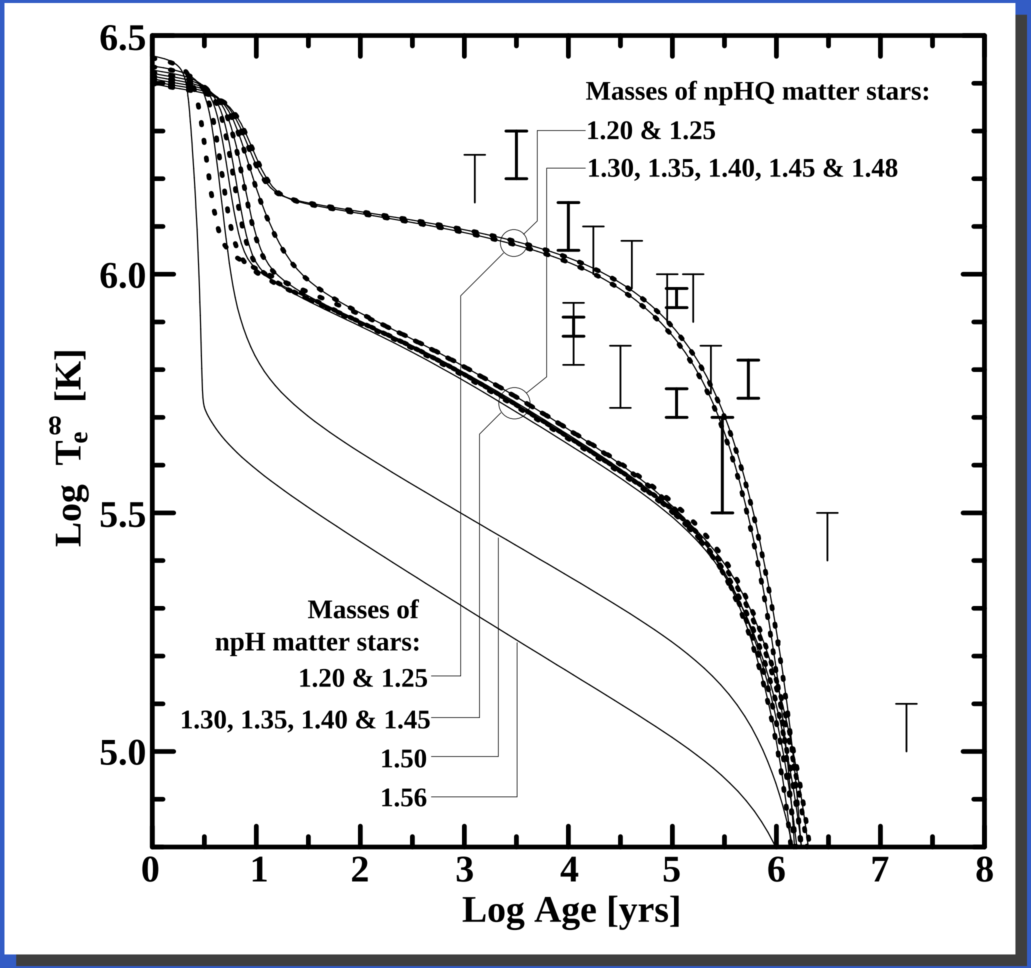
- slow standard cooling via the modified URCA process versus fast neutrino cooling (emissivities of $\epsilon_\nu = 10^n \times T_9^6 \text{ erg cm}^{-3} \text{ s}^{-1}$)
- normal neutron matter: N, superfluid neutron matter: SF
- fast cooling due to ’exotic’ processes as nucleon direct URCA or kaon condensation

Cooling with hyperon gaps (Schaab, JSB, Balberg 1998)



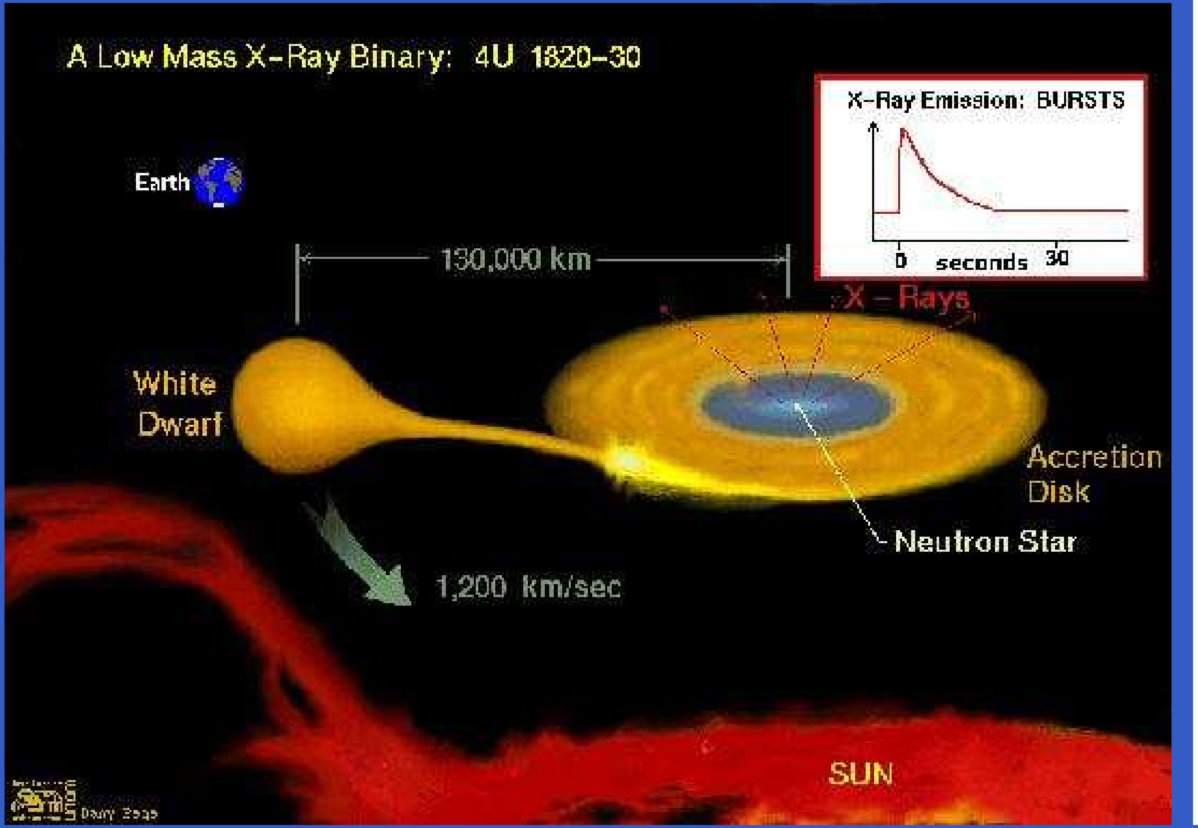
- slow cooling for low mass neutron stars
- fast cooling for heavier ones due to direct nucleon URCA!
- hyperons are present in the core for $M \geq 1.35 M_\odot$
- hyperon cooling suppressed by pairing gaps (same curve for $M = 1.6 M_\odot$)

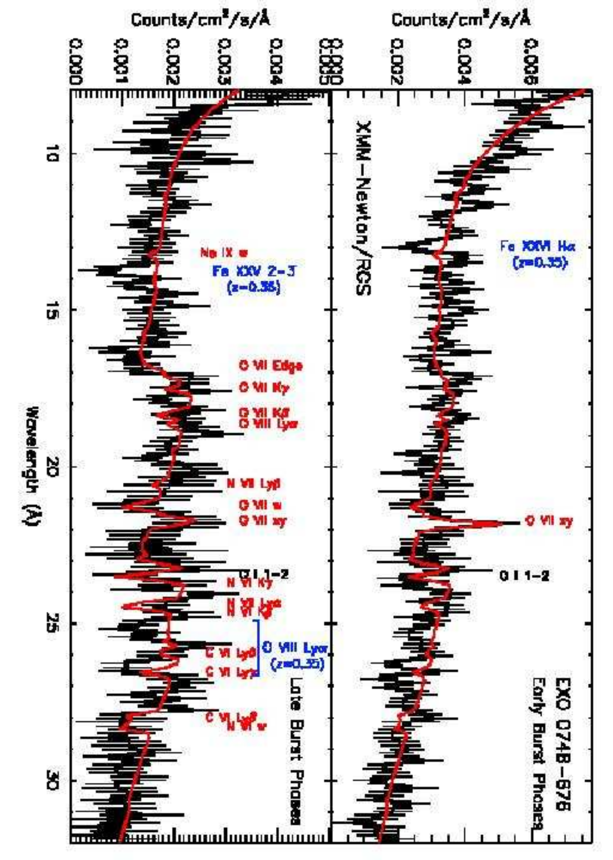
Cooling with hyperon gaps II (Page, Lattimer, Prakash, Steiner 2000)



- fast cooling for $M \geq 1.3 M_\odot$ stars via direct nucleon URCA
- even faster cooling for heavier stars via hyperon direct URCA
- hyperon cooling not suppressed by pairing gaps!
- tiny density range of unpaired Λ hyperons present as Σ hyperons appear later!

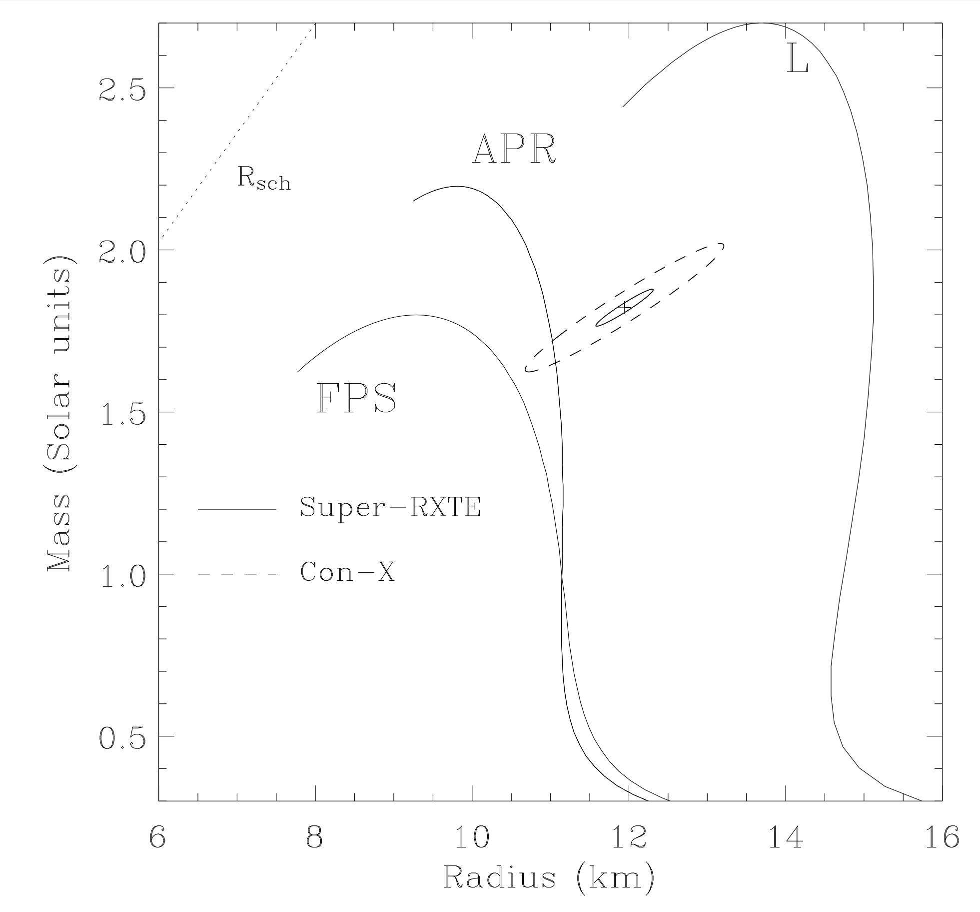
X-Ray burster





- 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))

Probes Using X–Ray Bursts

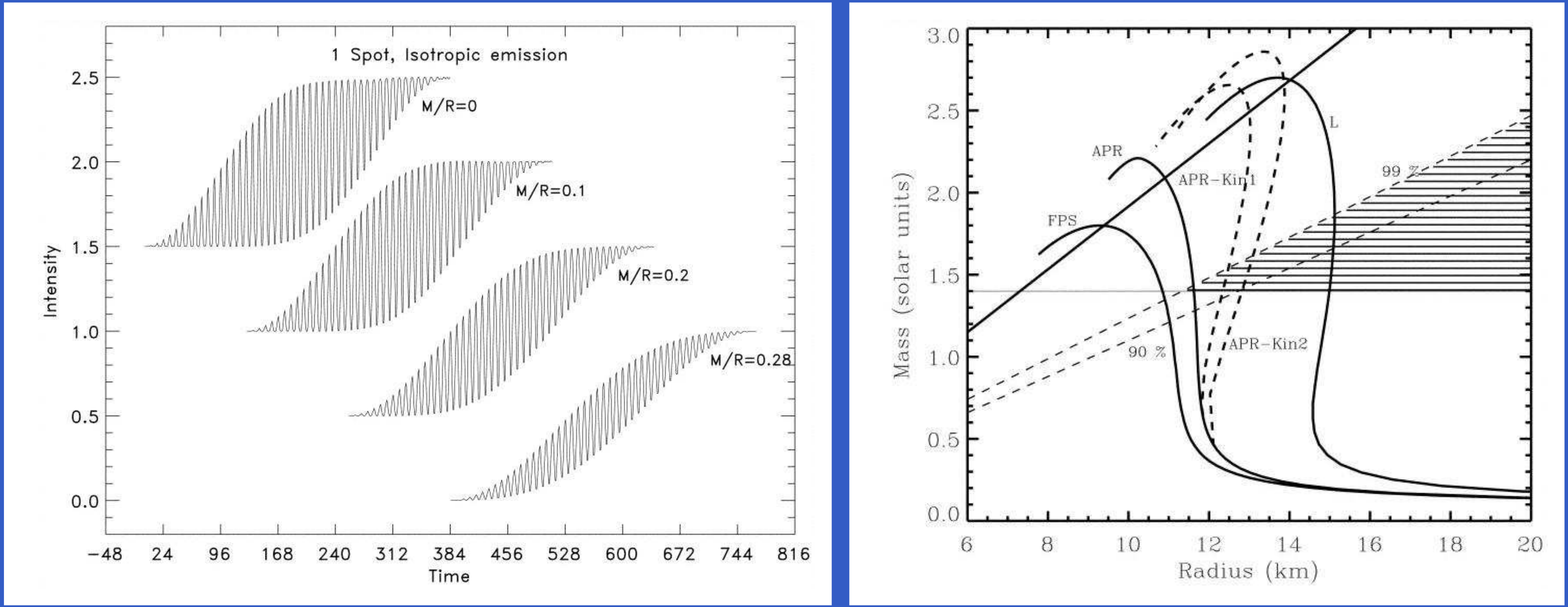


(Strohmayer (2004))

- 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
- → gives a model independent mass and radius!

Bounds on Compactness for LMXB neutron stars

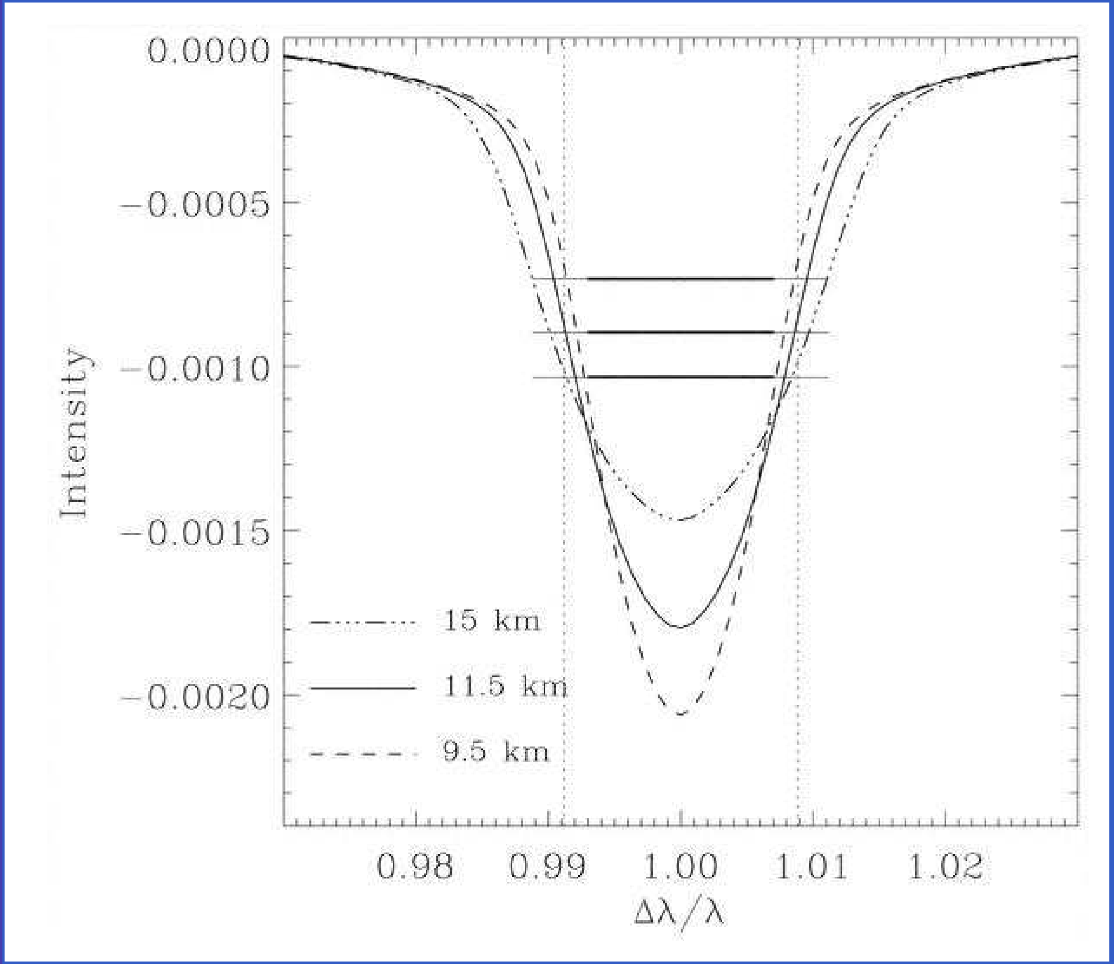
(Nath, Strohmayer, Swank, 2002)



- thermonuclear bursts from Low-Mass X-ray Binary (LMXB) 4U 1636-53 and 4U1728-34
- oscillations due to neutron star rotation
- burst hot spot spreads over entire neutron star surface!
- amplitude decreases with increasing compactness
- results: $M/R < 0.163$ (upper limit only due to unknown geometry)

Discovery of the Neutron Star Spin Frequency in EXO 0748-676

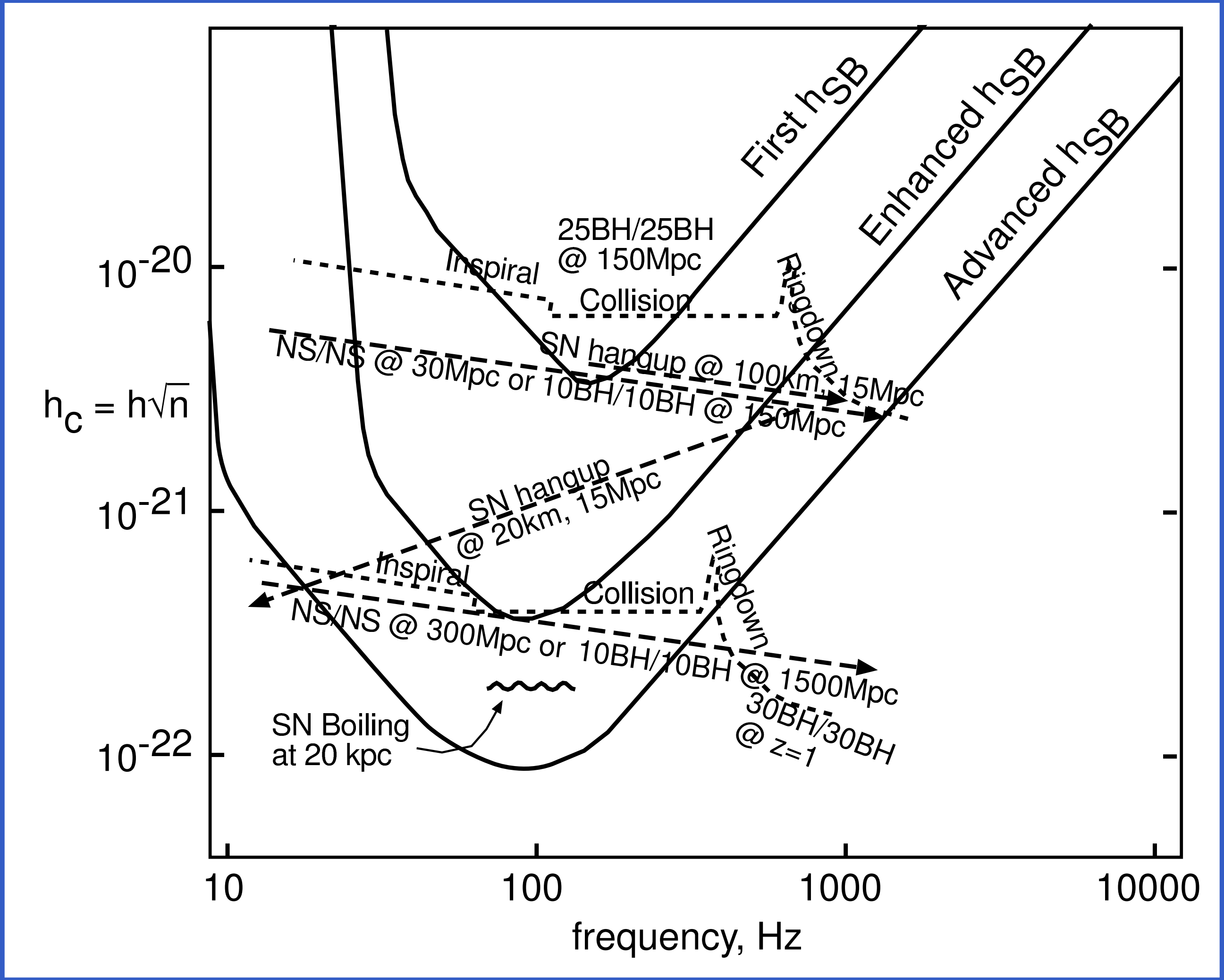
(Villarreal and Strohmayer, 2004)



animation of a superburst

- Low-Mass X-ray Binary (previously found red-shifted spectral lines!)
- detected 45 Hz oscillation in 38 thermonuclear bursts
- fit to line profile: width depends on surface rotational velocity $v_{rot} \propto \nu_{spin} R$
- determines radius for known spin frequency!
- constraint: $9.5 < R < 15$ km, with $Z = 0.35$ (Cottam et al.) $1.5 M_\odot < M < 2.3 M_\odot$

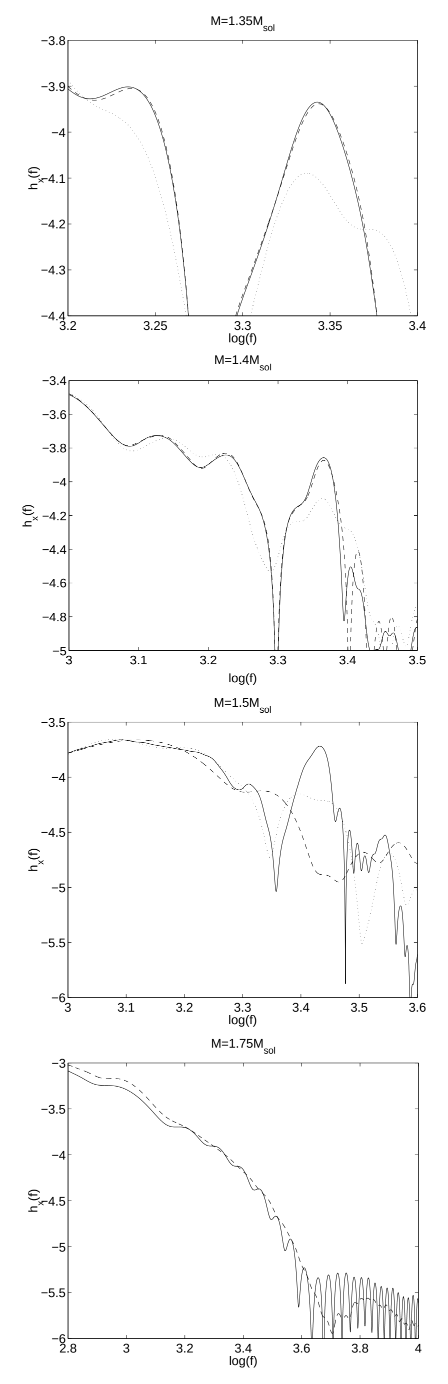
Future Probes Using Gravitational Waves

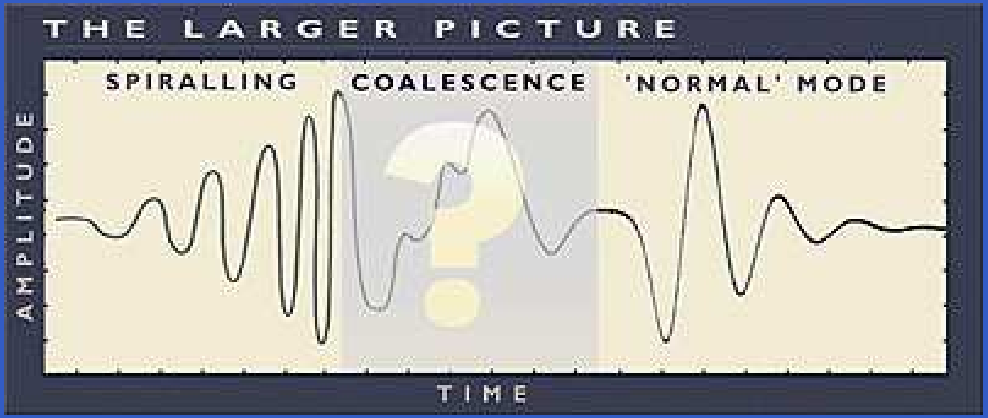


(Thorne (1997))

- 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!

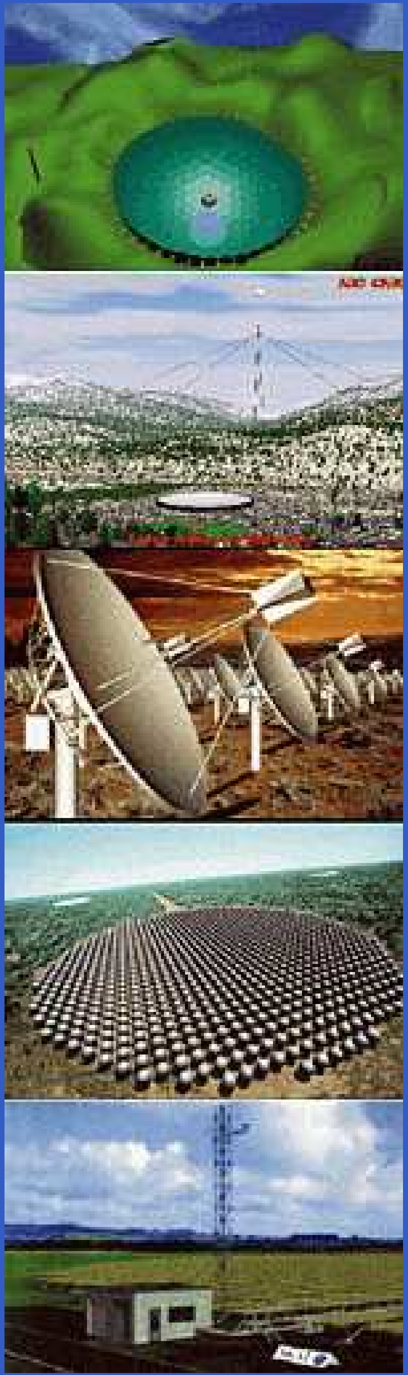
Gravitational wave signal from strange quark matter?





- binary neutron star mergers with a quark core: signal clearly seen in different Fourier spectrum!
  (Oechslin, Uryū, Pogosyan, Thielemann 2004)
- binary strange quark star collision: higher frequencies possible before 'touch-down' compared to normal neutron stars
  (Limousin, Gondek-Rosinska, Gourgoulhon 2005)
- collapse of neutron star to quark matter: sensitive to EoS
  (Lin, Cheng, Chu, Suen 2006)

Future: Square Kilometer Array (SKA)

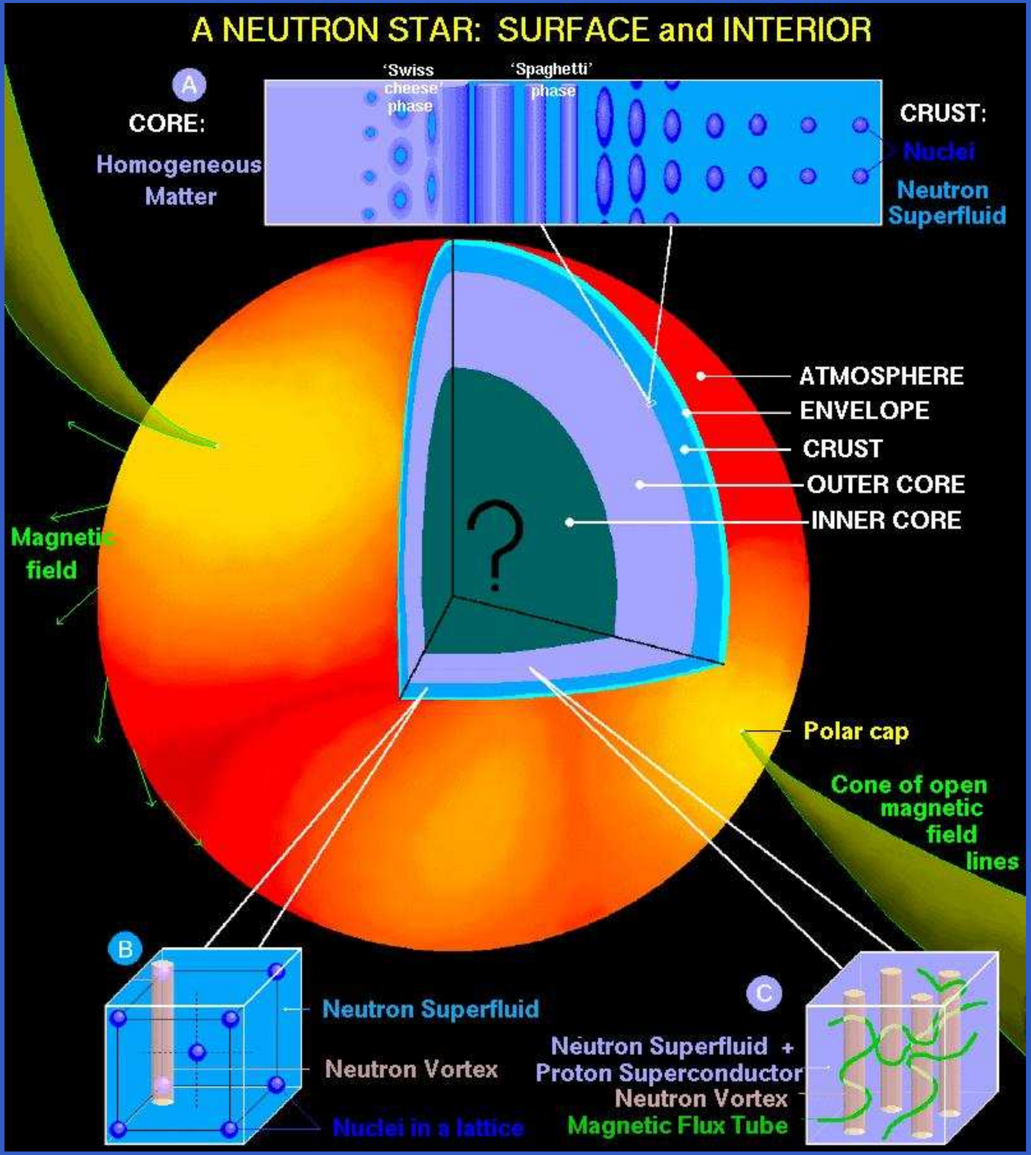


- receiving surface of 1 million square kilometers
- 1 billion dollar international project
- potential to discover:
  - 10,000 to 20,000 new pulsars
  - more than 1,000 millisecond pulsars
  - at least 100 compact relativistic binaries!
- probing the equation of state at extreme limits!
- cosmic gravitational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

movie

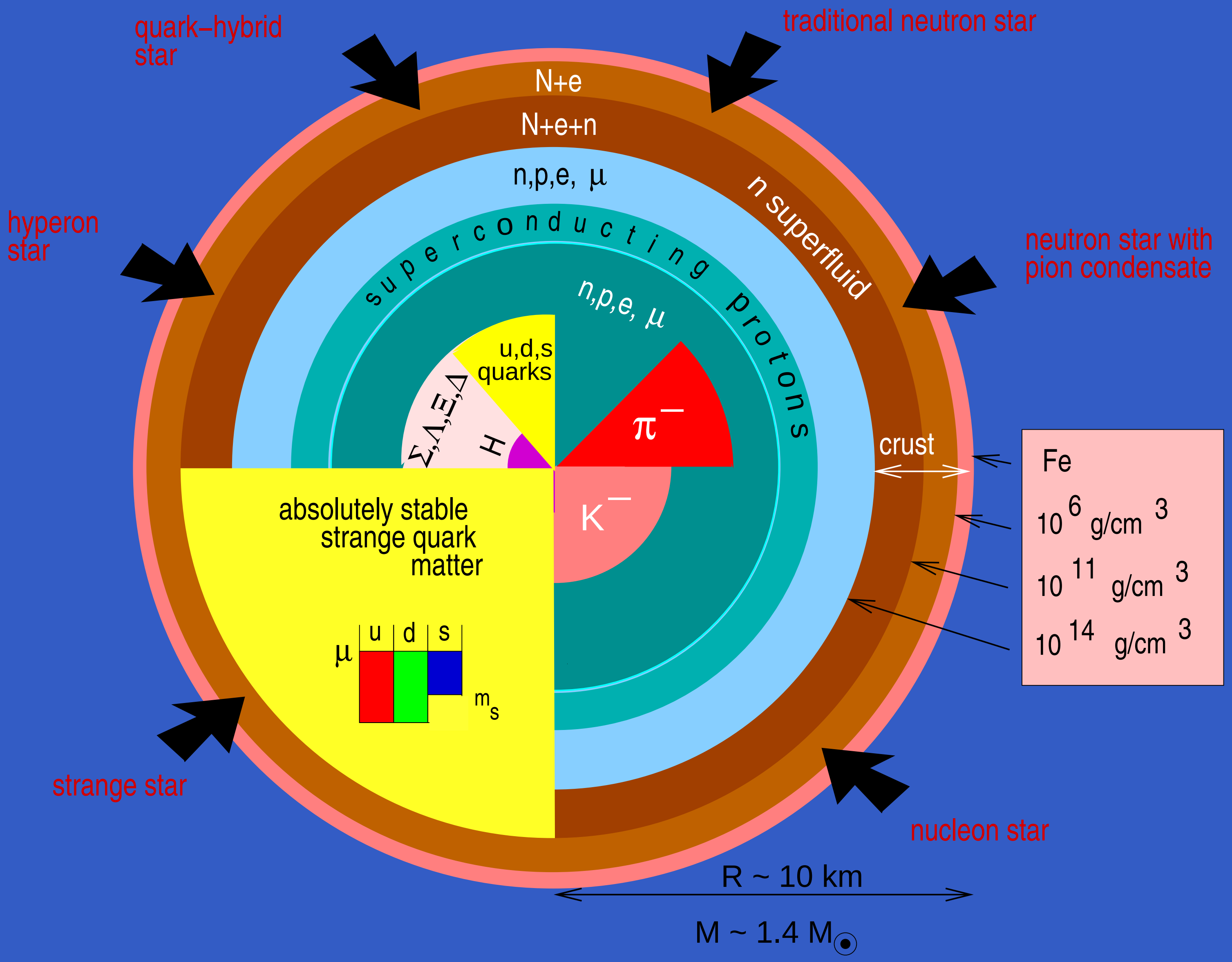
Modelling the Neutron Star

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^-)

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

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

(Oppenheimer and Volkoff, 1939)

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

Empirical Nucleon-Nucleon Interaction

Ansatz for the energy per particle:

$$\epsilon/n = m_N + E_0^{kin} + \frac{A}{2} \cdot u + \frac{B}{\sigma + 1} u^\sigma + S_0 \cdot u \cdot \left(\frac{n_n - n_p}{n} \right)^2$$

where $u = n/n_0$. The parameters A, B, σ are fixed by nuclear matter properties n_0, E/A, and the compression modulus K, the asymmetry term by the asymmetry energy S_0 at n_0.

The pressure is determined by the thermodynamic relation

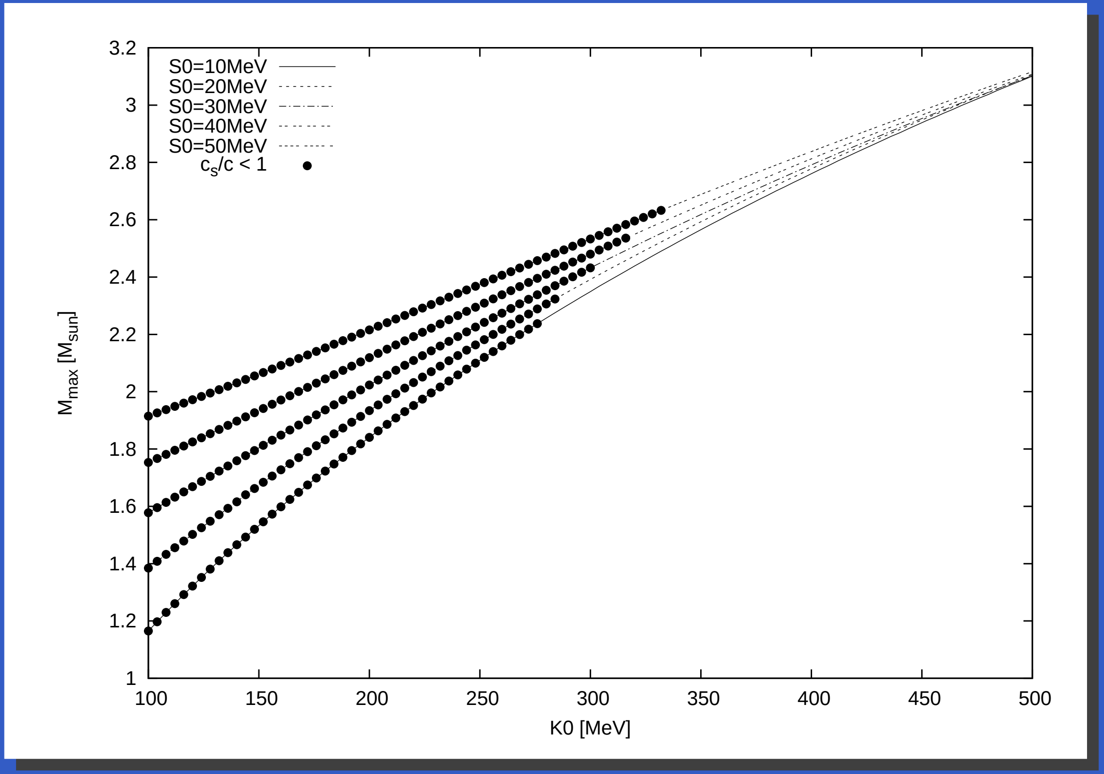
$$P = n^2 \frac{d}{dn} \left(\frac{\epsilon}{n} \right)$$

EoS used as input in transport model calculations.

(Note: the equation of state can become acausal for $\sigma > 2$.)

Check: are low compressibilities ruled out by neutron star mass measurements?

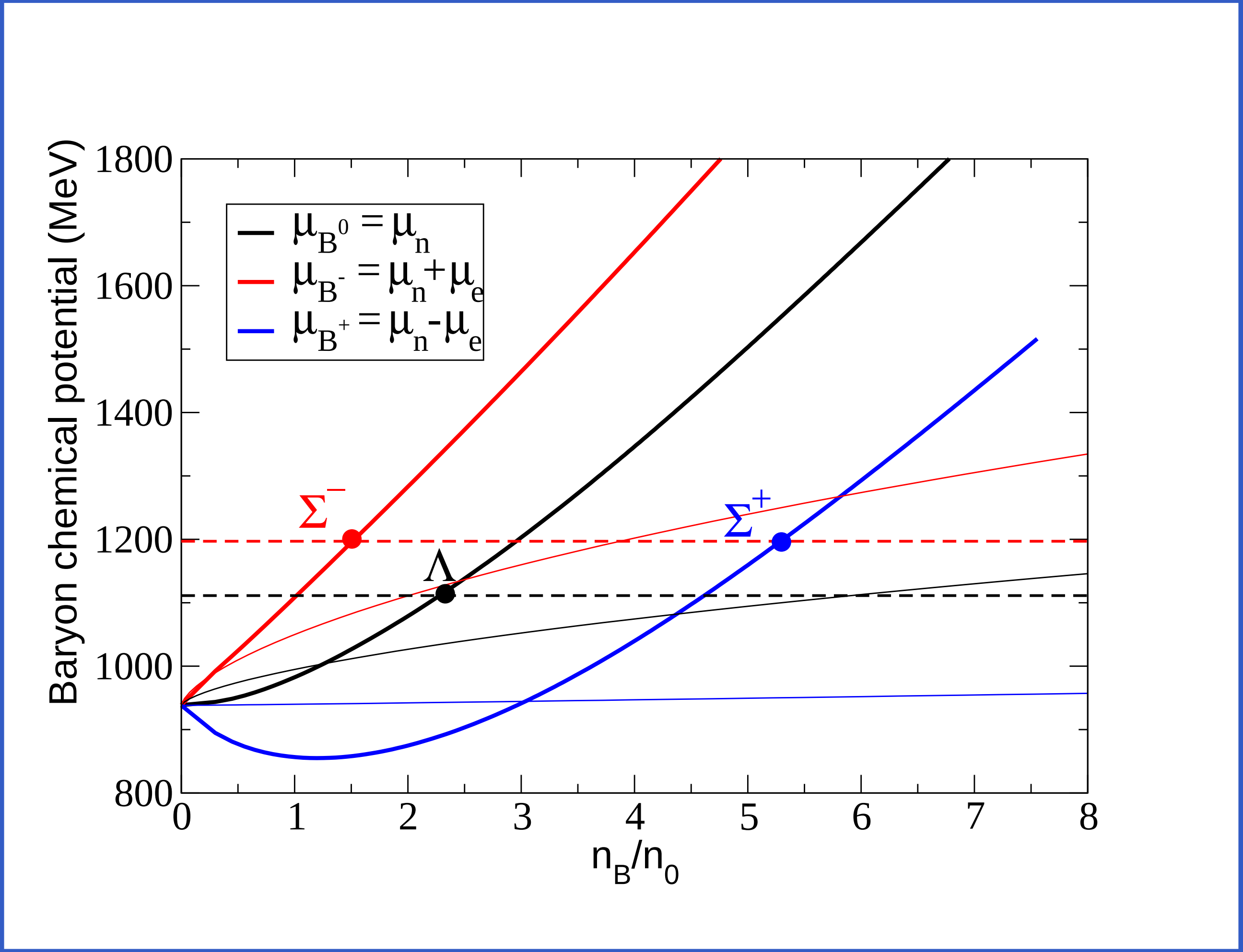
Empirical Nucleon-Nucleon Interaction: Masses



(Irina Sagert, 2006)

- maximum mass $M \geq 2M_\odot$ for $K_0 > 200$ MeV ($S_0 = 30$ MeV)!
- slight dependence on S_0, up to $\Delta M = \pm 0.2 M_\odot$ for low K_0 values
- EoS causal up to $M = 2.4 M_\odot$ ($K_0 = 300$ MeV)
- even 'soft' equations of state can give high neutron star masses!

At which density do new particles appear? (Page and Reddy (2006))

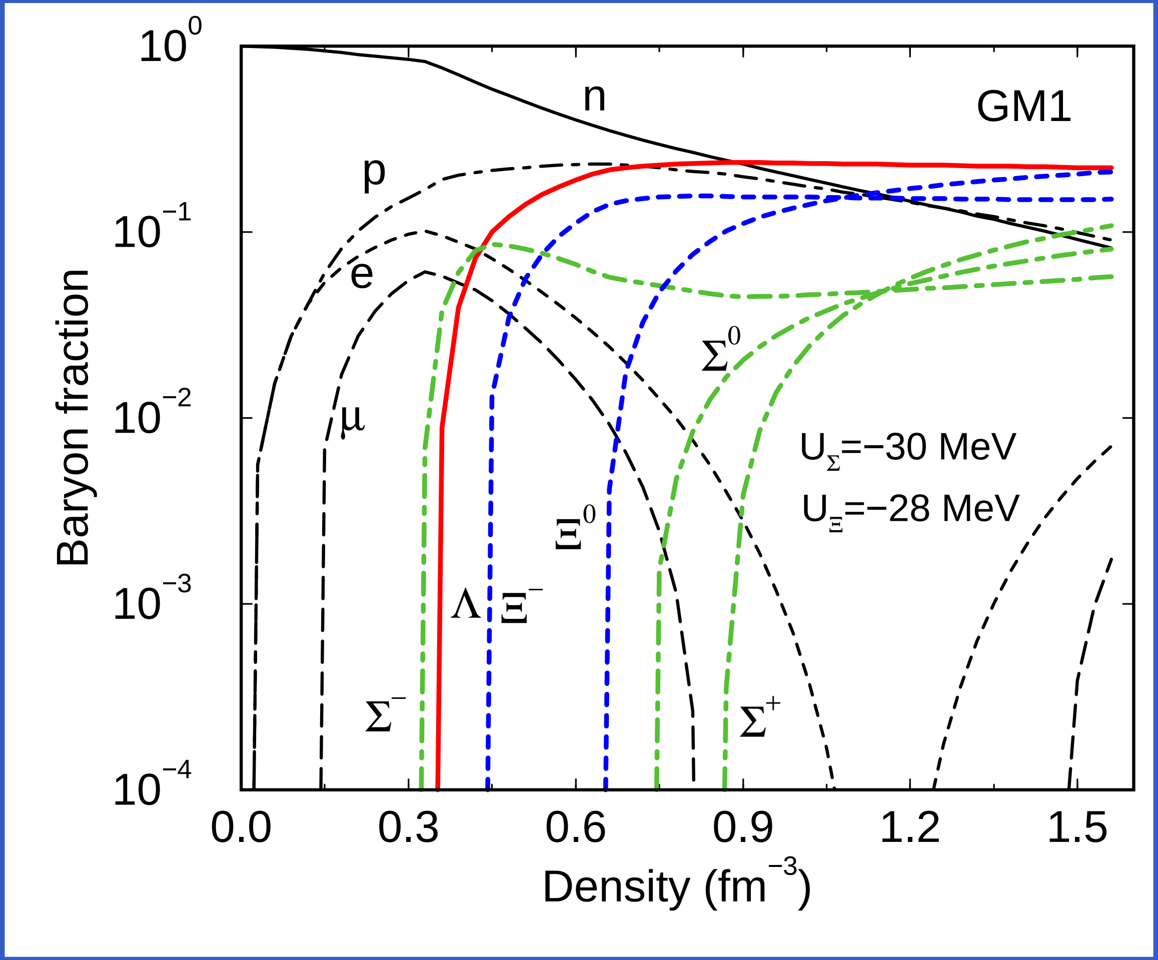


- hyperons appear, when its in-medium energy equals its chemical potential:

$$\mu(Y) = \omega(Y) = m_Y + U_Y(n)$$

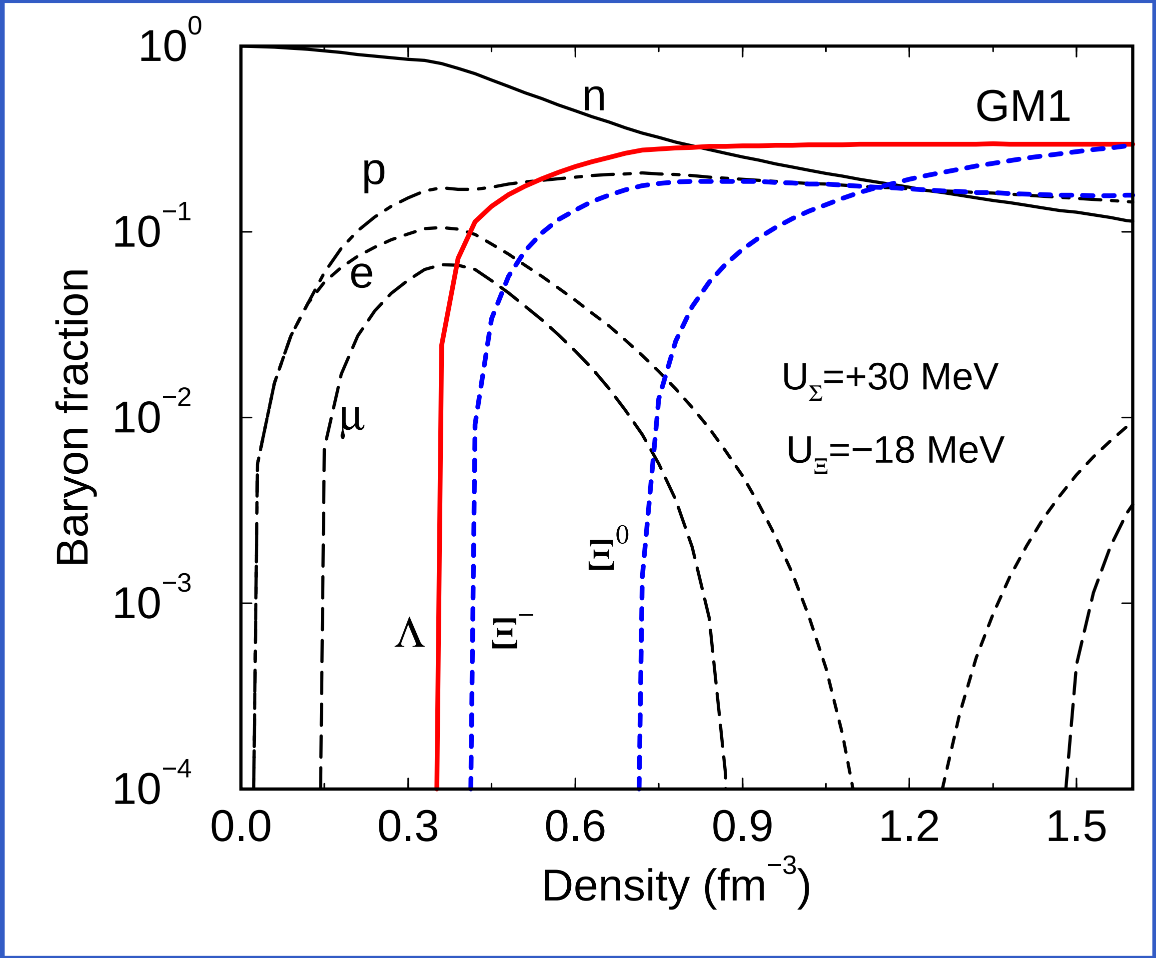
- thin lines: no potential, thick lines: with mean-field potential

Composition of Neutron Star Matter



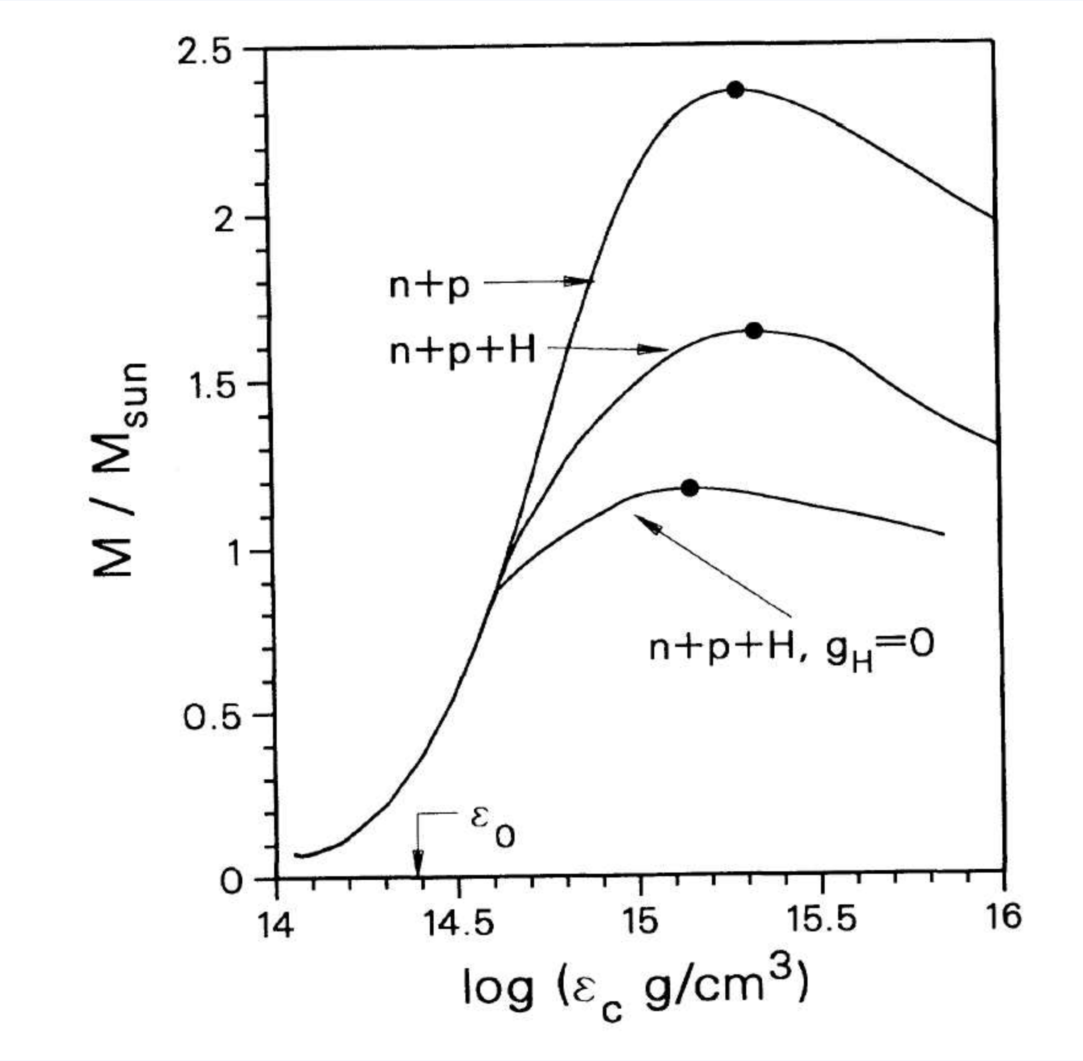
- attractive potential for Σs and Ξs
- Σ^- appear shortly before Λs around $n = 2n_0$
- Λs present in matter at $n = 2.5n_0$, Ξ^- before $n = 3n_0$

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!

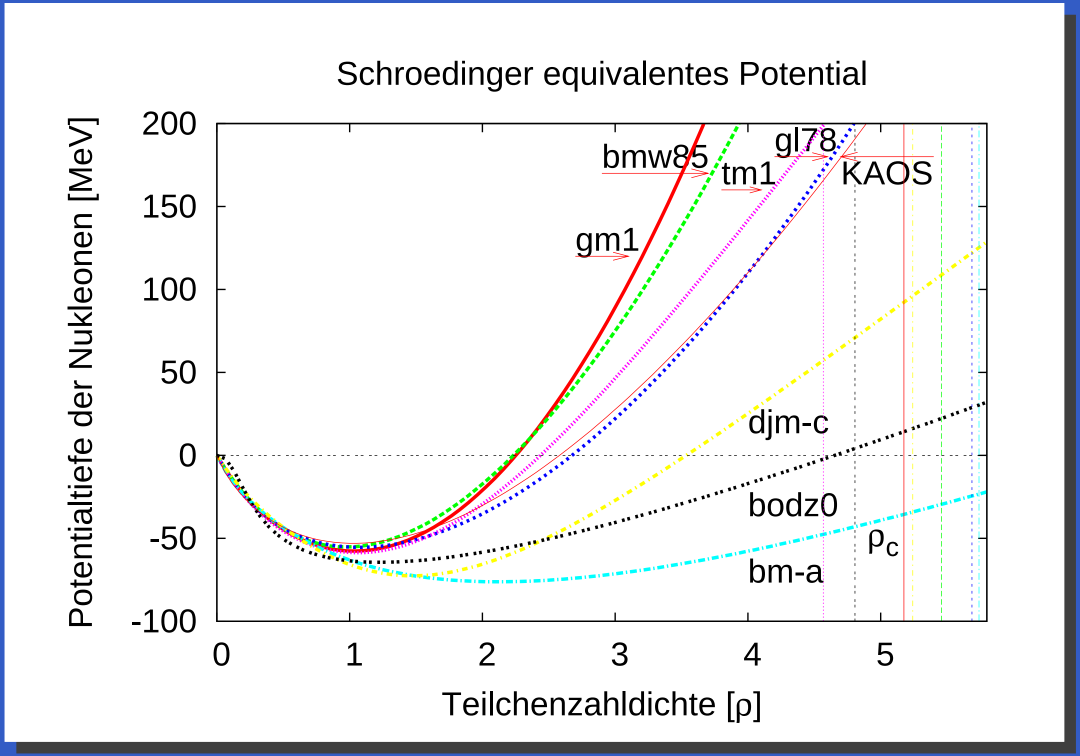
Impact of hyperons on the maximum mass of neutron stars



(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: $M < 1.4 M_\odot$!

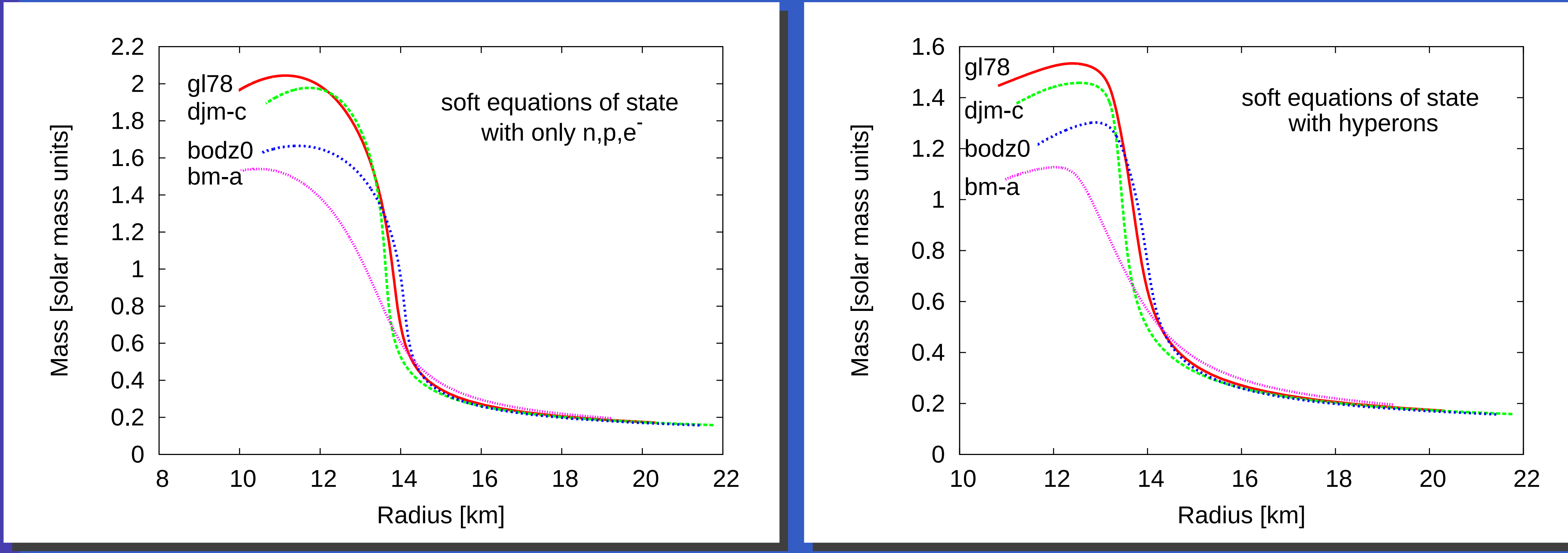
The EoS using Relativistic Mean–Field Models



(Mirjam Wietoska, 2006)

- sensitive to flow measurement: non-relativistic Schrödinger equivalent potential (SEV)
- compare effective model using $K = 200$ MeV with:
  standard nonlinear σ model (gl78, bmw85, gm1), with added nonlinear vector selfinteractions (bodz0) fitted to nuclei (tm1) or to many-body approaches (djm-c, bm-a)

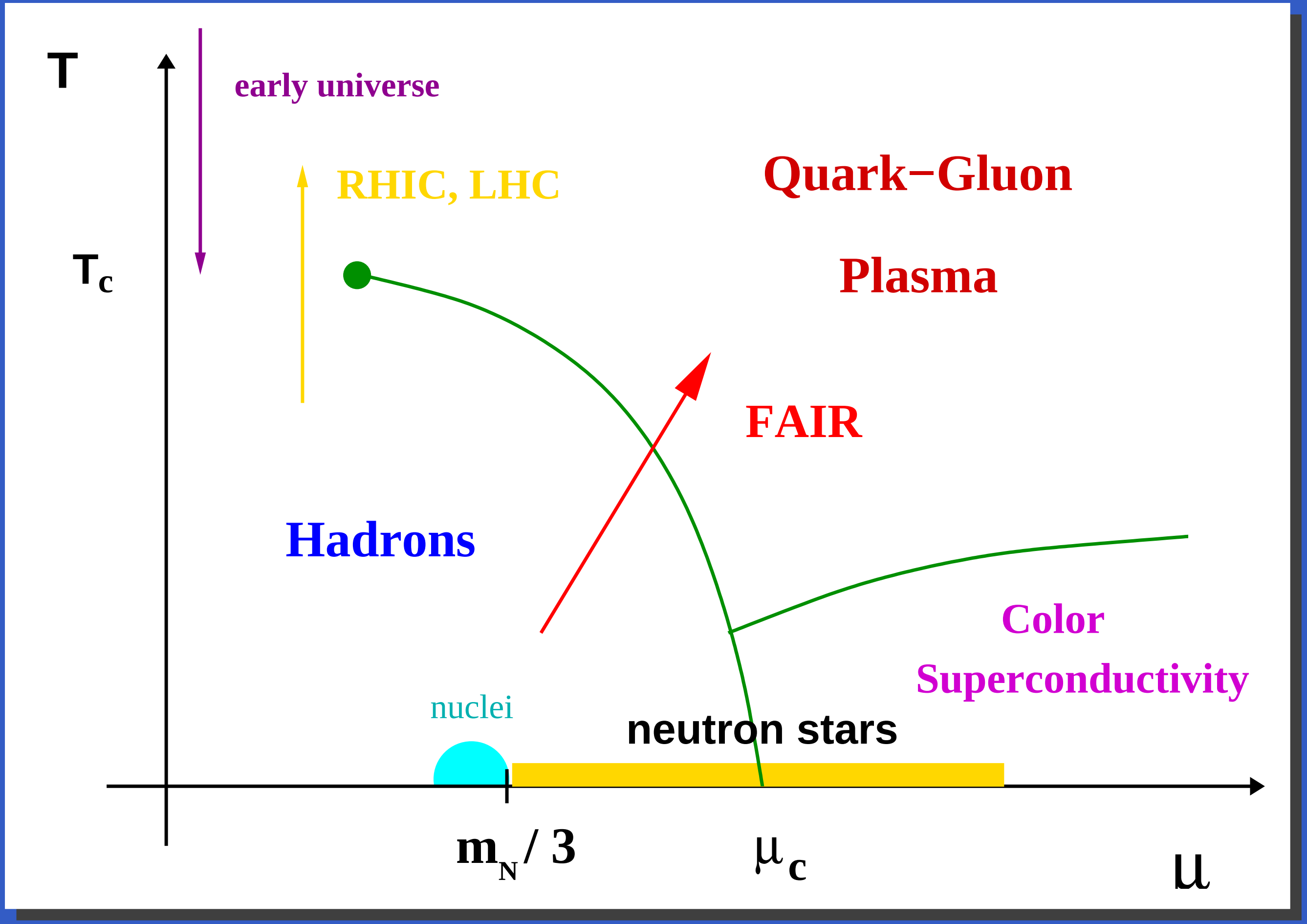
Relativistic Mean–Field Model: Masses



(Mirjam Wietoska, 2006)

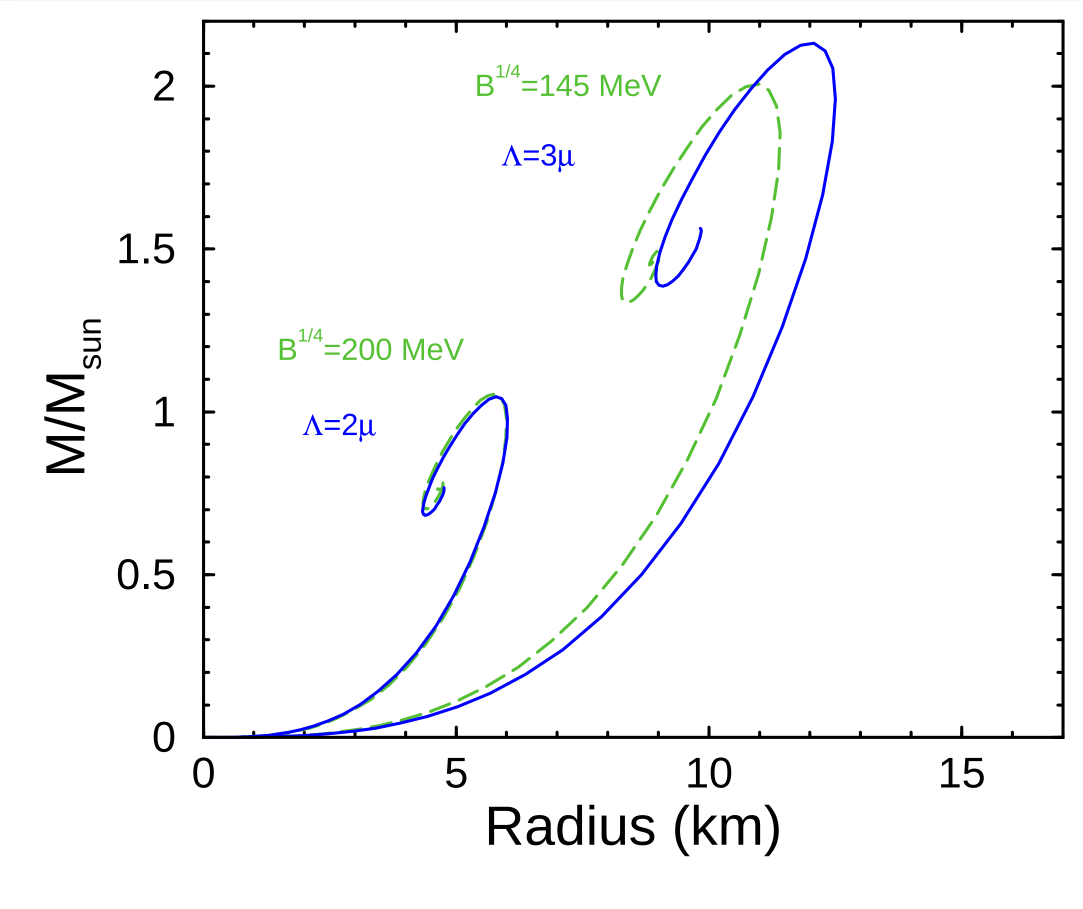
- maximum masses with nucleons and leptons only:
  all above $1.44M_\odot$!
- ultrasoft non-relativistic potentials compatible with pulsar data!
- but with hyperons: too soft! (in particular for sets bodz0 and bm-a)

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!)

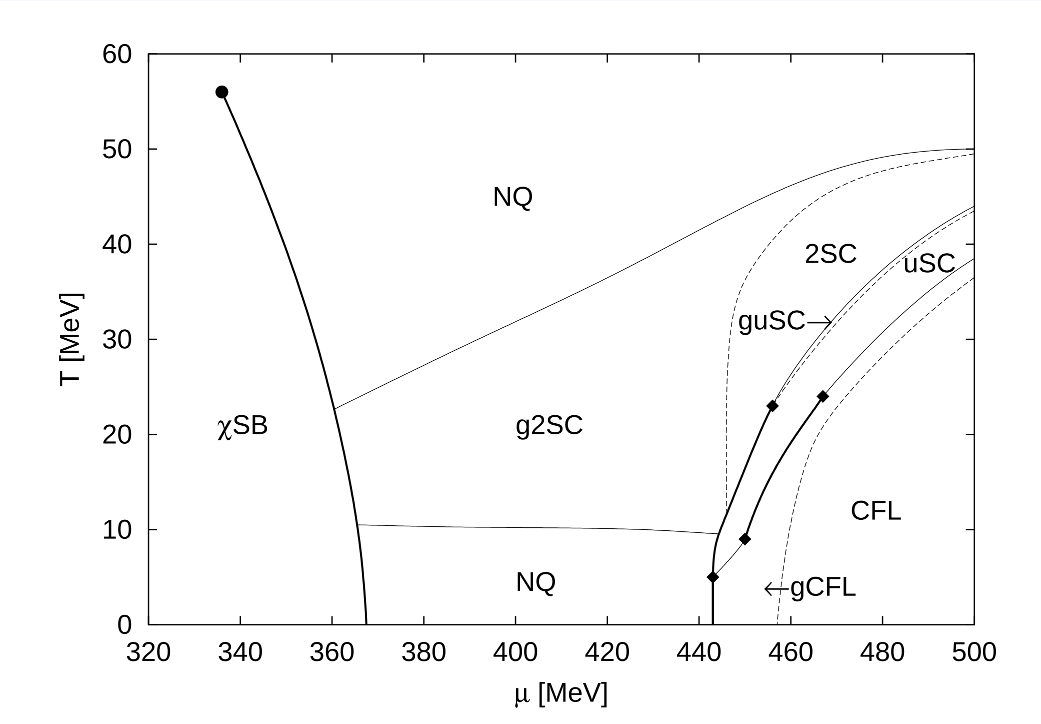
Mass-radius and maximum density of pure quark stars



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

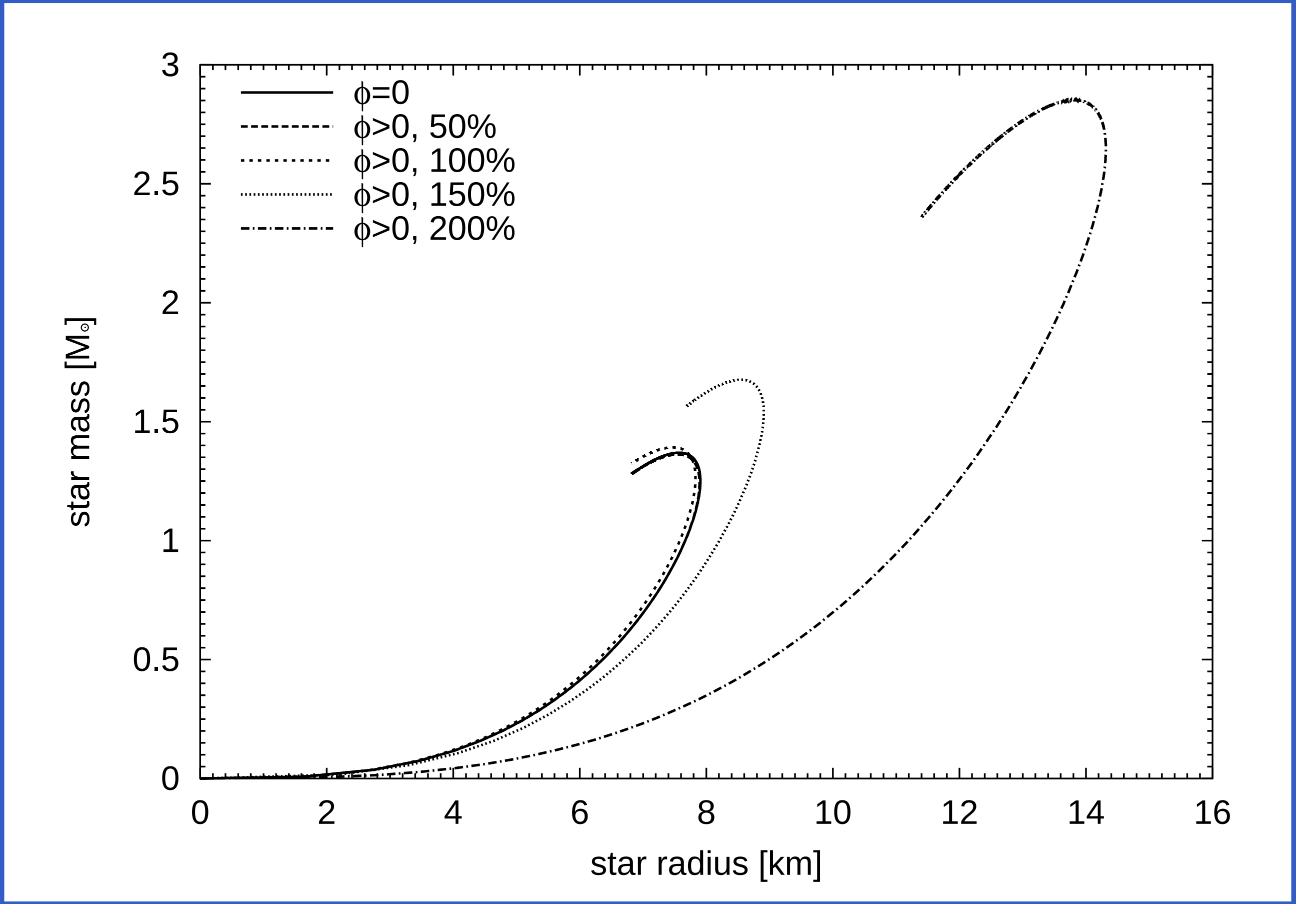
- case 2: $M_{\max} = 1.05\, M_\odot$, $R_{\max} = 5.8$ km, $n_{\max} = 15\, n_0$
- case 3: $M_{\max} = 2.14\, M_\odot$, $R_{\max} = 12$ km, $n_{\max} = 5.1\, n_0$

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



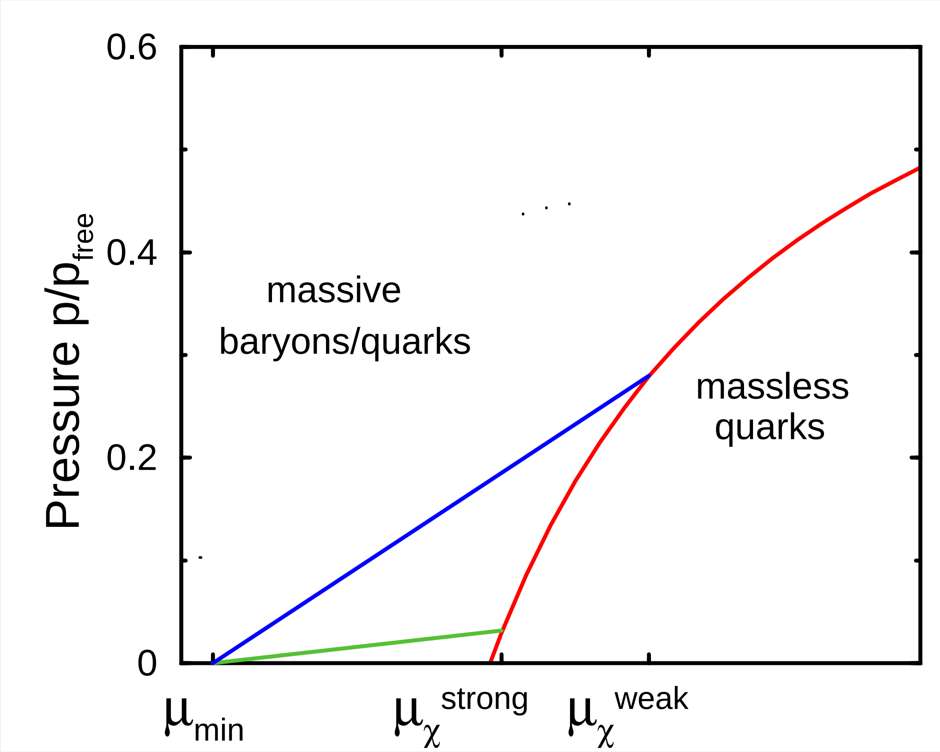
- first order phase transition based on symmetry arguments!
- phases of color superconducting quark matter in β equilibrium:
- normal (unpaired) quark matter (NQ)
- two-flavor color superconducting phase (2SC), gapless 2SC phase
- color-flavor locked phase (CFL), gapless CFL phase, metallic CFL phase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

Heavy Quark Stars? (Rüster and Rischke (2004))



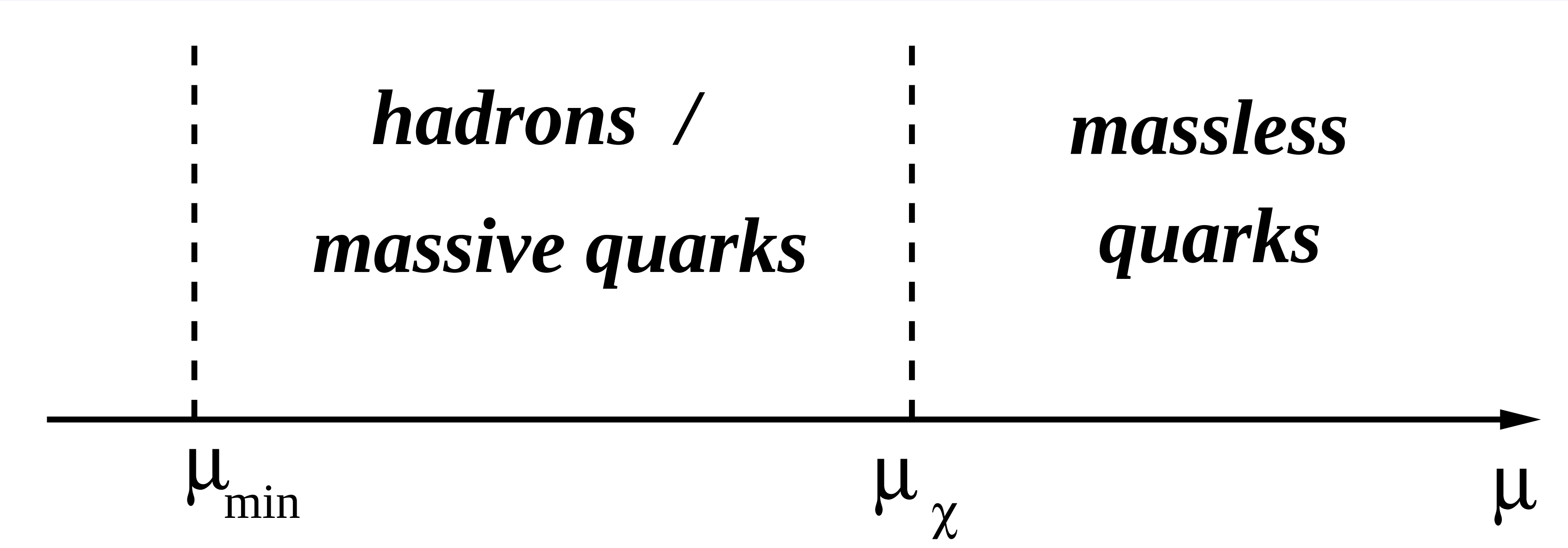
- quark star with color–superconducting quarks
- uses NJL model for pairing quarks
- increased interactions gives more massive quark stars

Matching the two phases: two possible scenarios



- Weak: phase transition is weakly first order or a crossover → pressure in massive phase rises strongly
- Strong: transition is strongly first order → pressure rises slowly with μ

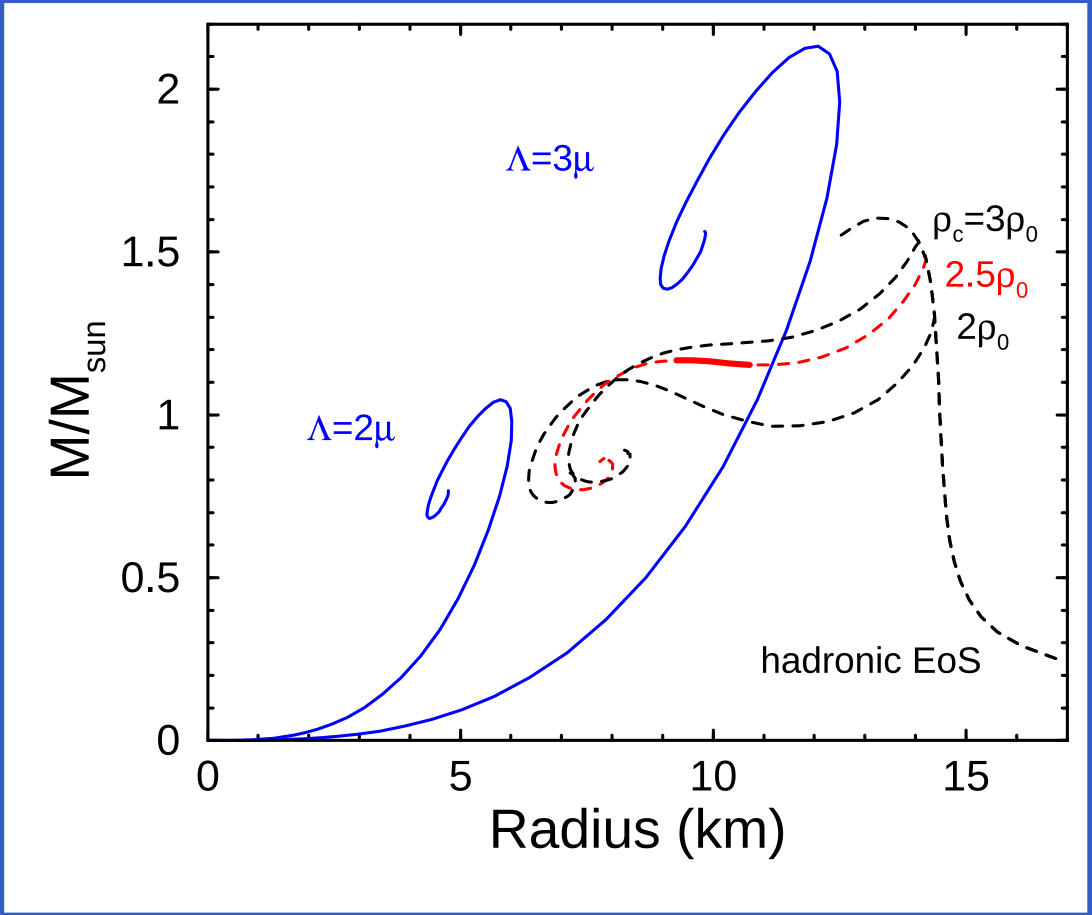
A Model For Cold And Dense QCD



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

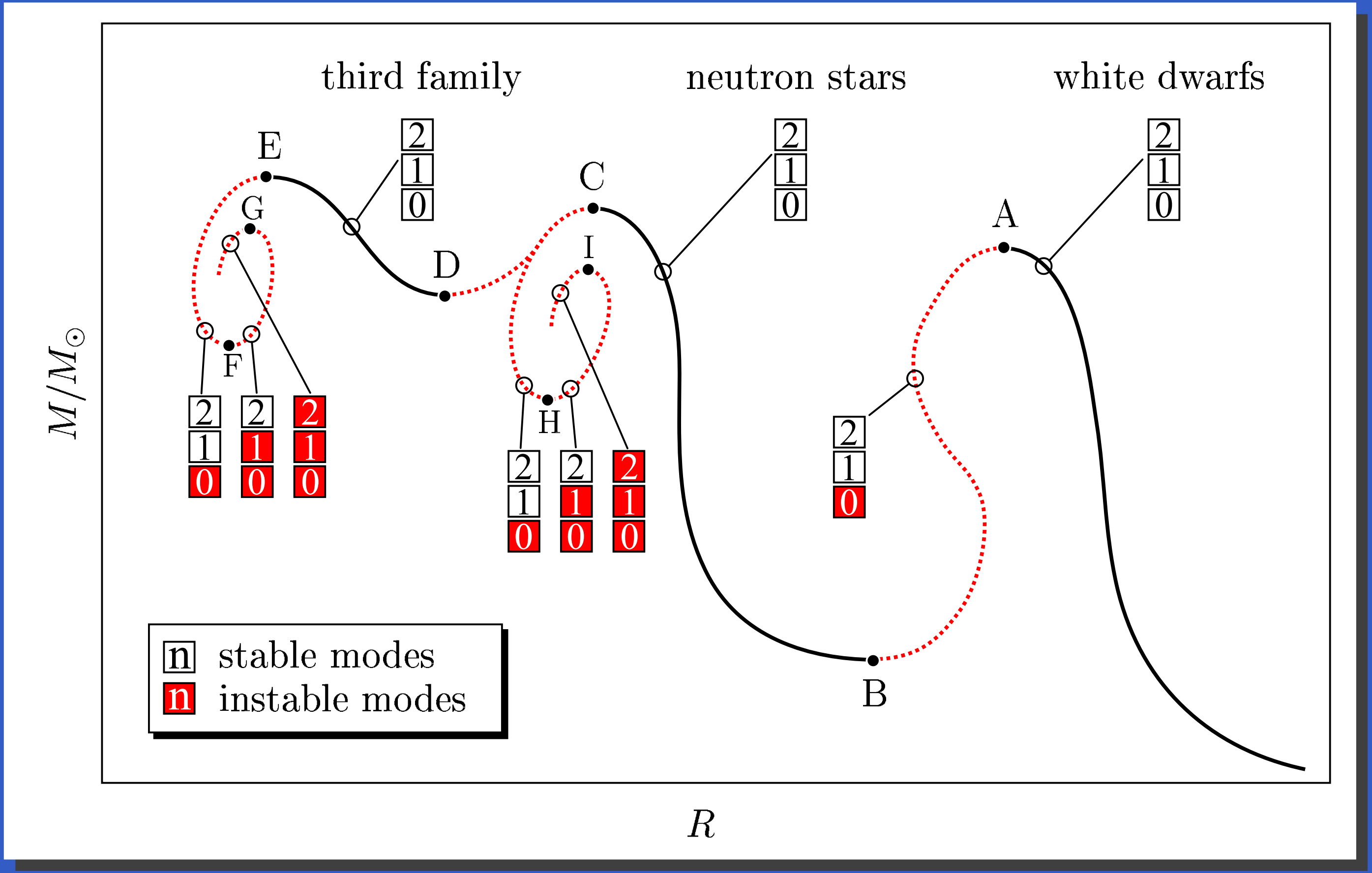
Quark star twins? (Fraga, JSB, Pisarski (2001))



- 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

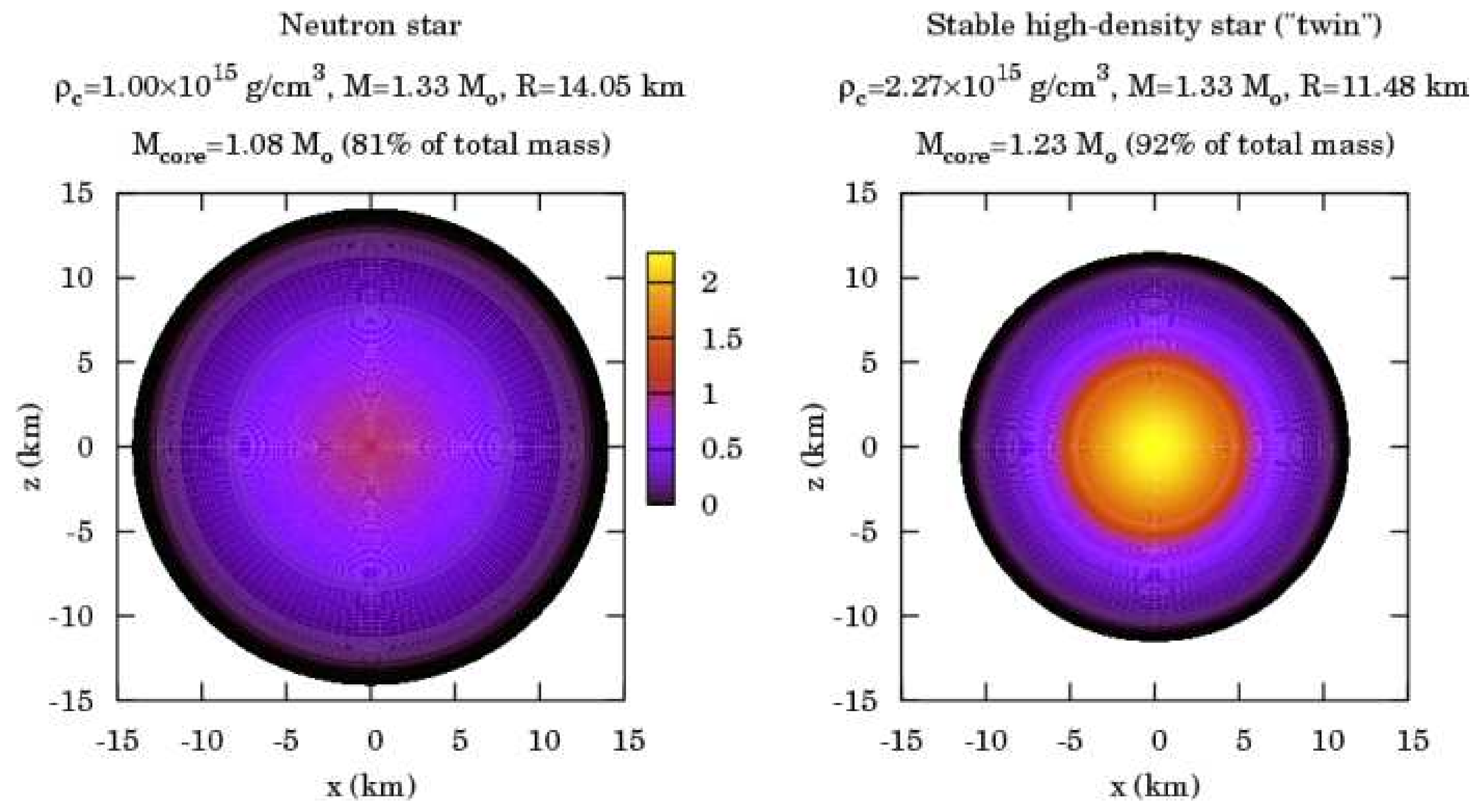
Third Family of Compact Stars (Gerlach 1968)

(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!

Density profile of quark star twins (Papasotiriou 2006)



Signals for a Third Family/Phase Transition?

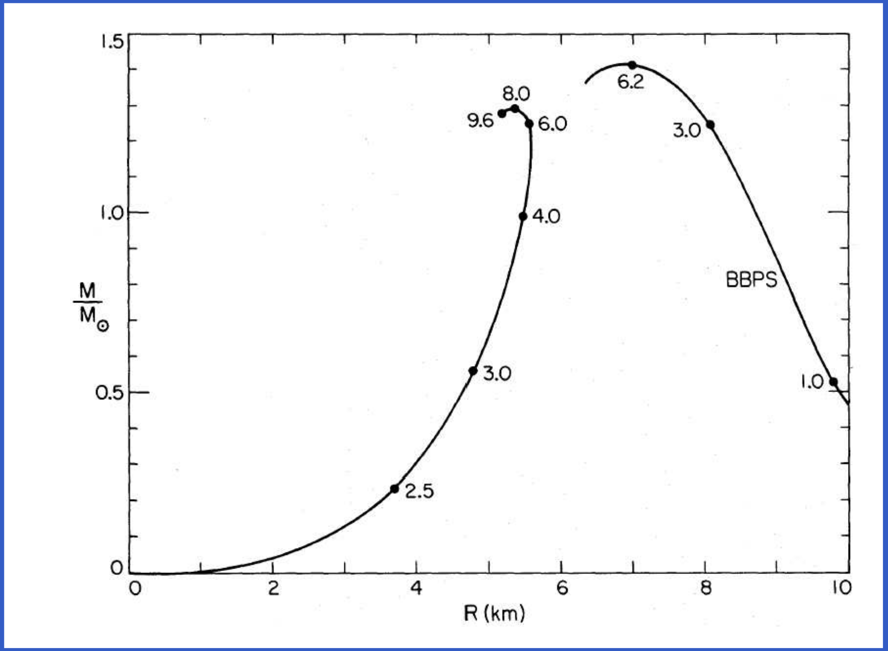
- mass-radius relation: rising twins (Schertler et al., 2000)
- spontaneous spin-up of pulsars (Glendenning, Pei, Weber, 1997)
- delayed collapse of a proto-neutron star to a black hole (Thorsson, Prakash, Lattimer, 1994)
- bimodal distribution of pulsar kick velocities (Bombaci and Popov, 2004)
- collapse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

Difference between quark stars, hybrid stars, etc?

- hybrid stars: neutron stars mixed with quark matter in the core
- quark star twins: special hybrid stars with a pure quark matter core
- strange stars or selfbound stars: consists of stable quark matter only, purely hypothetical!!!

Hypothetical Selfbound Star versus Ordinary Neutron Star

(Hartle, Sawyer, Scalapino (1975!))



selfbound stars:

- vanishing pressure at a finite energy density
- mass-radius relation starts at the origin (ignoring a possible crust)
- arbitrarily small masses and radii possible

neutron stars:

- bound by gravity, finite pressure for all energy density
- mass-radius relation starts at large radii
- minimum neutron star mass: $M \sim 0.1 M_\odot$ with $R \sim 200$ km

Summary

- equation of state (EoS) determines the maximum mass and its radius
- in-medium potentials of hadrons determine the population
- cooling is sensitive to the population
- new hadronic degrees of freedoms normally soften the EoS!
- but quark matter can also stiffen the EoS!
- strong chiral phase transition leads to a third family of compact stars
- sensitive to mass-radius relation, cooling, neutrinos, gravitational waves!