Neutron stars and quark stars: Two coexisting families of compact stars?

363. Heraeus-Seminar: Neutron Stars and Pulsars

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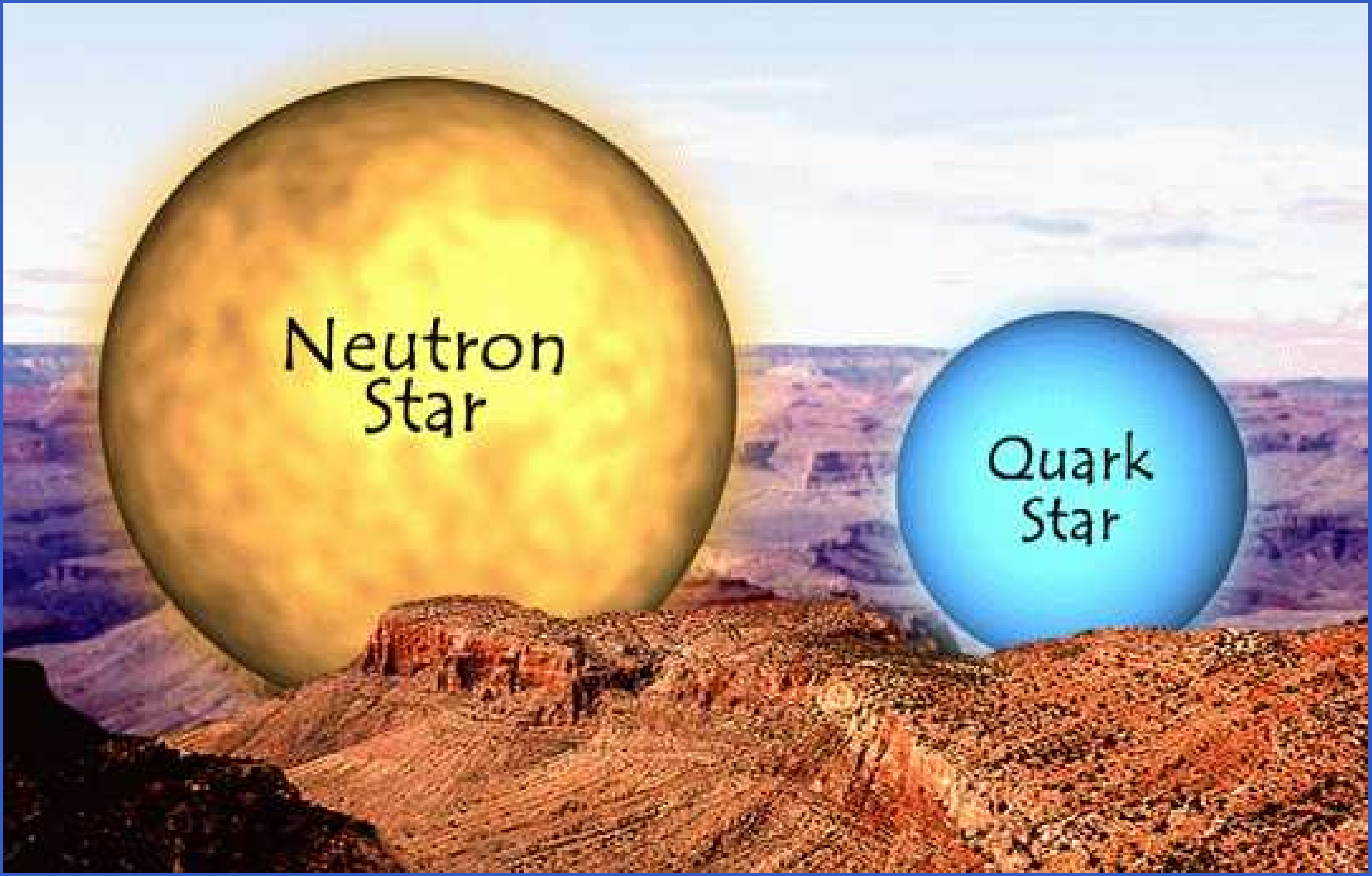
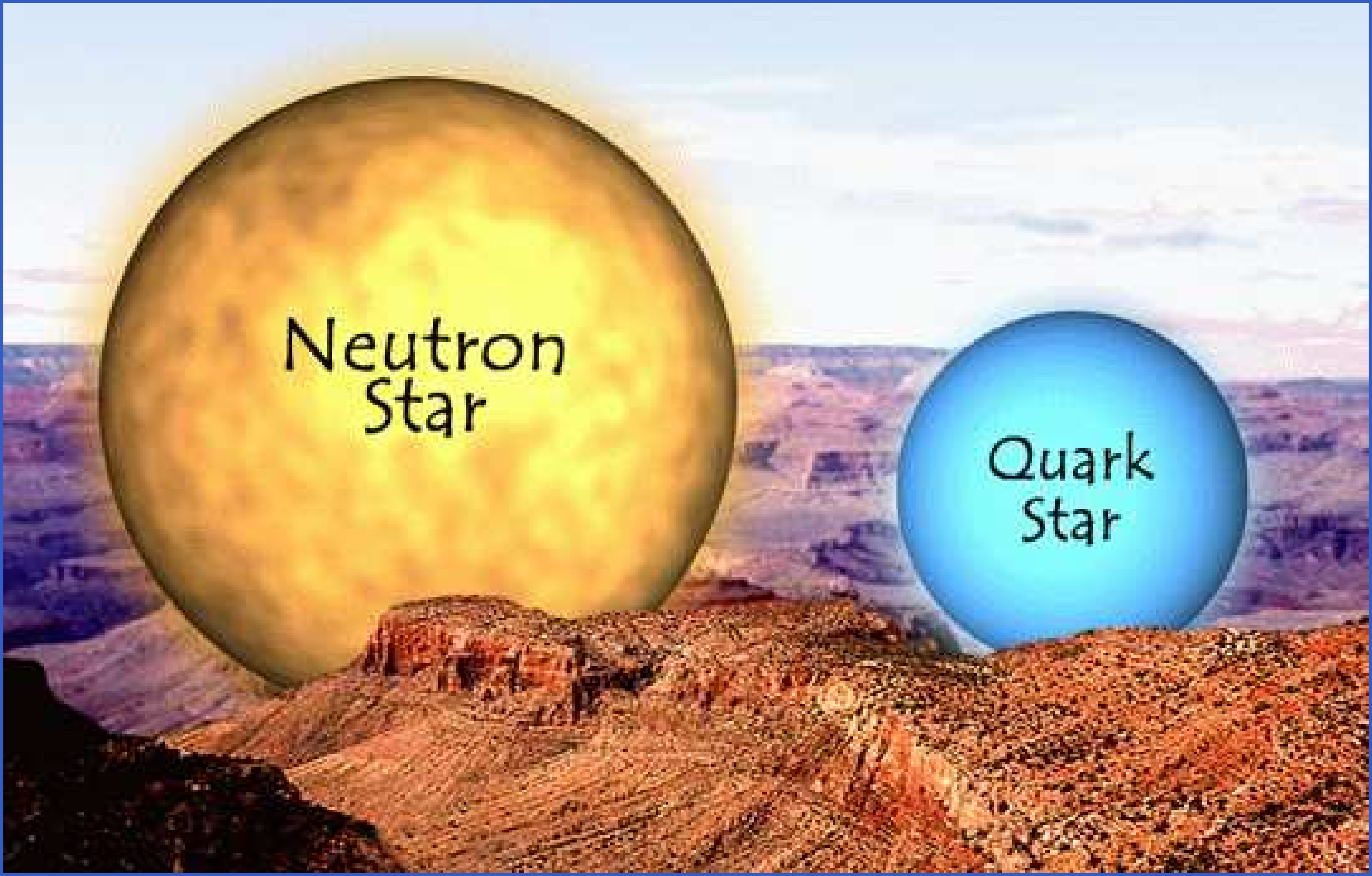
Quark Stars according to NASA



NASA press release 02-082, 2002: quark stars have a small radius

Quark Stars according to NASA



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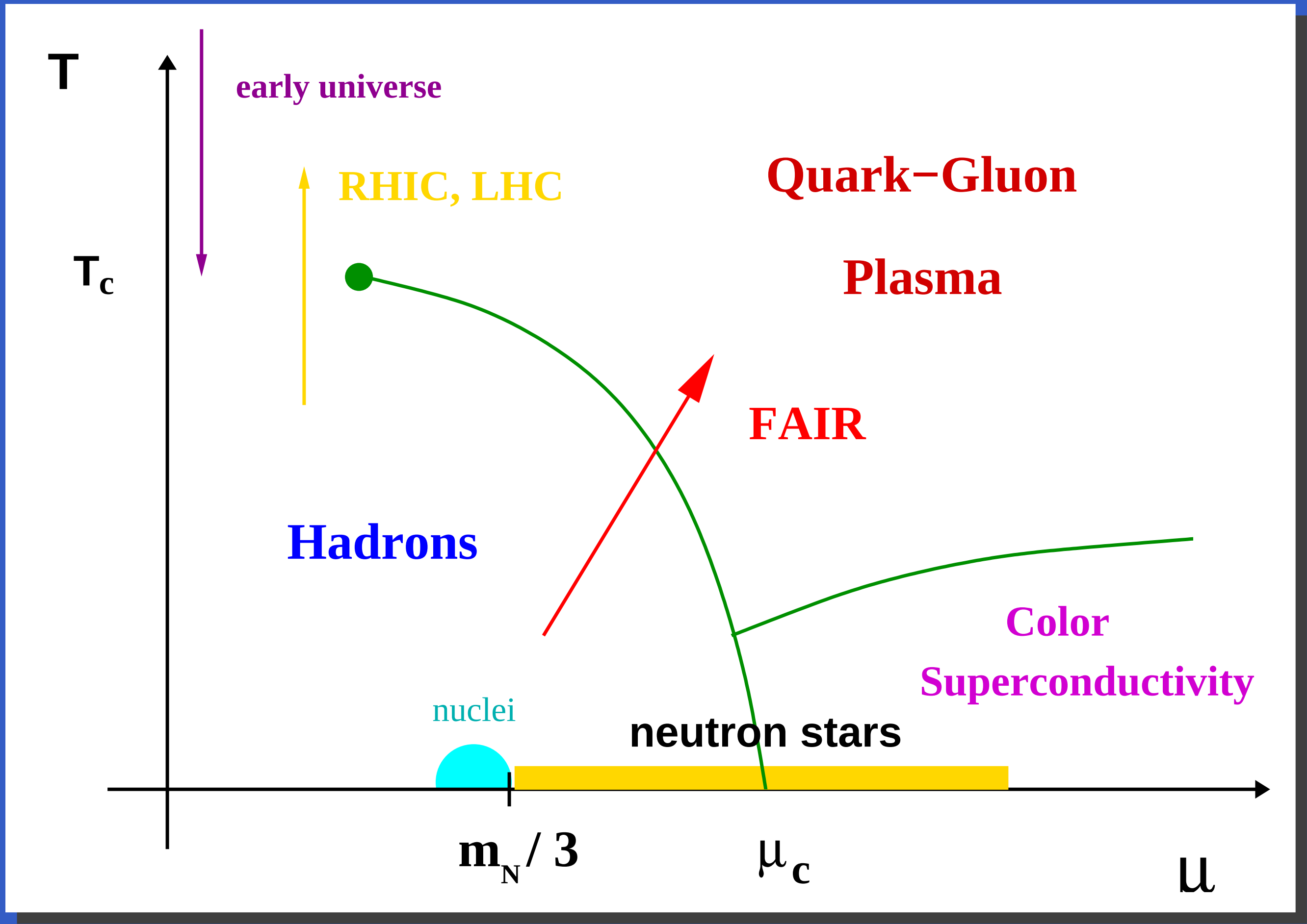
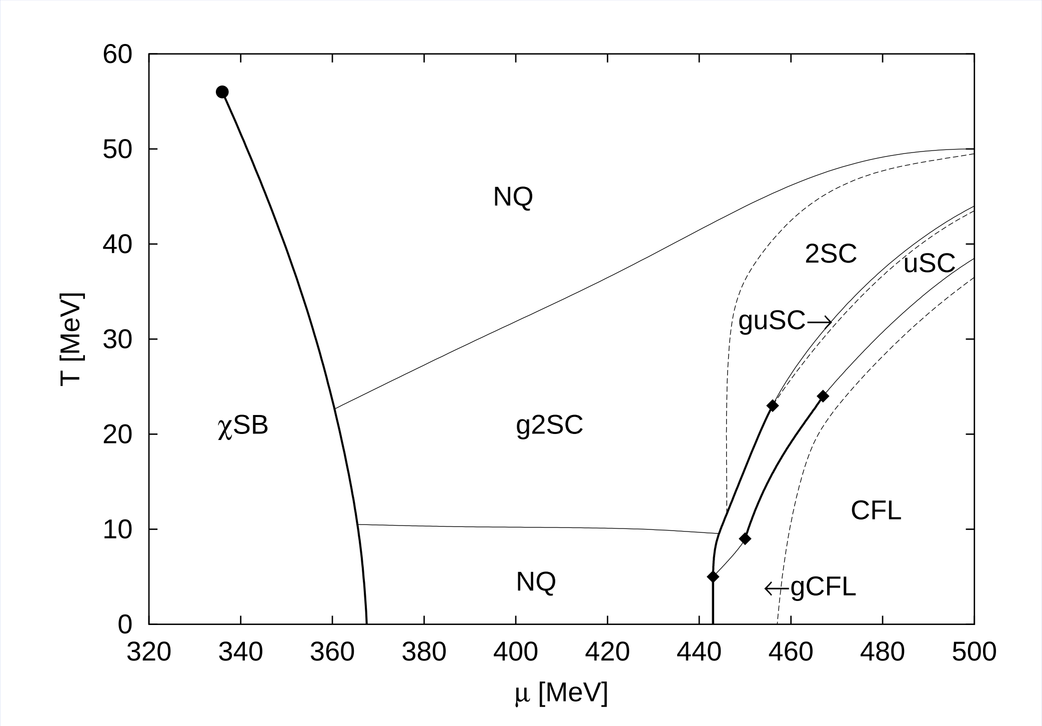
there is more to it . . .

Phase Transitions in Quantum Chromodynamics QCD



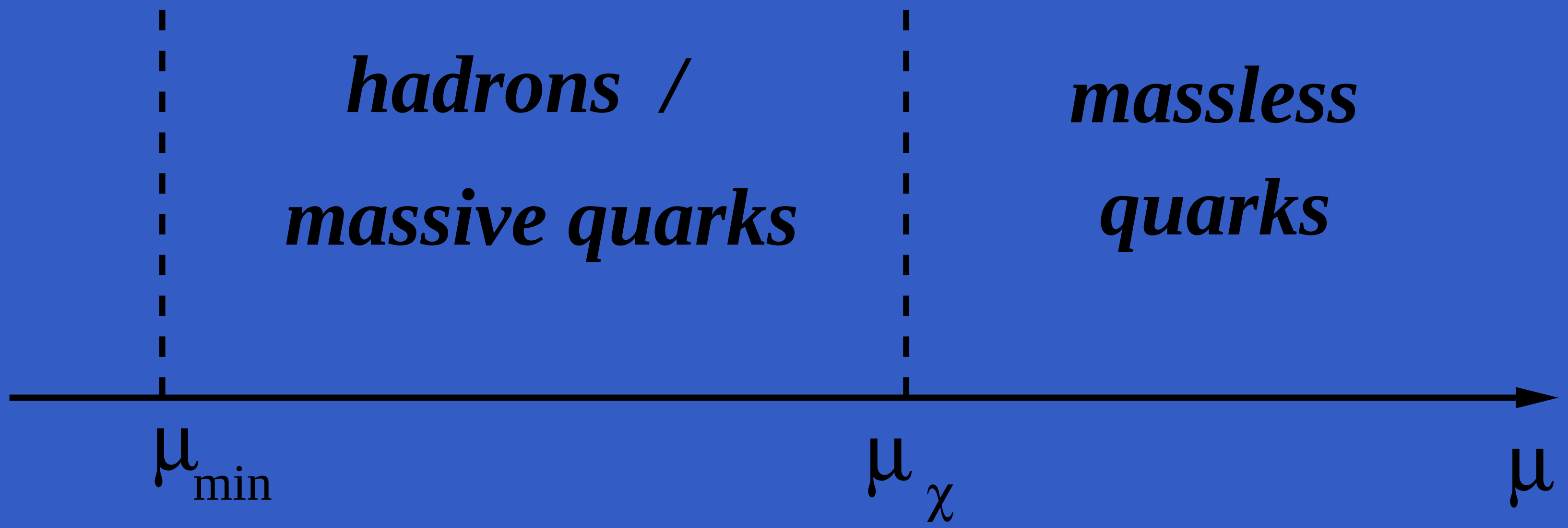
- Early universe at zero density and high temperature
- neutron star matter at small temperature and high density
- first order phase transition at high density (not deconfinement)!
- probed by heavy-ion collisions at GSI, Darmstadt (FAIR!)

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, . . .)

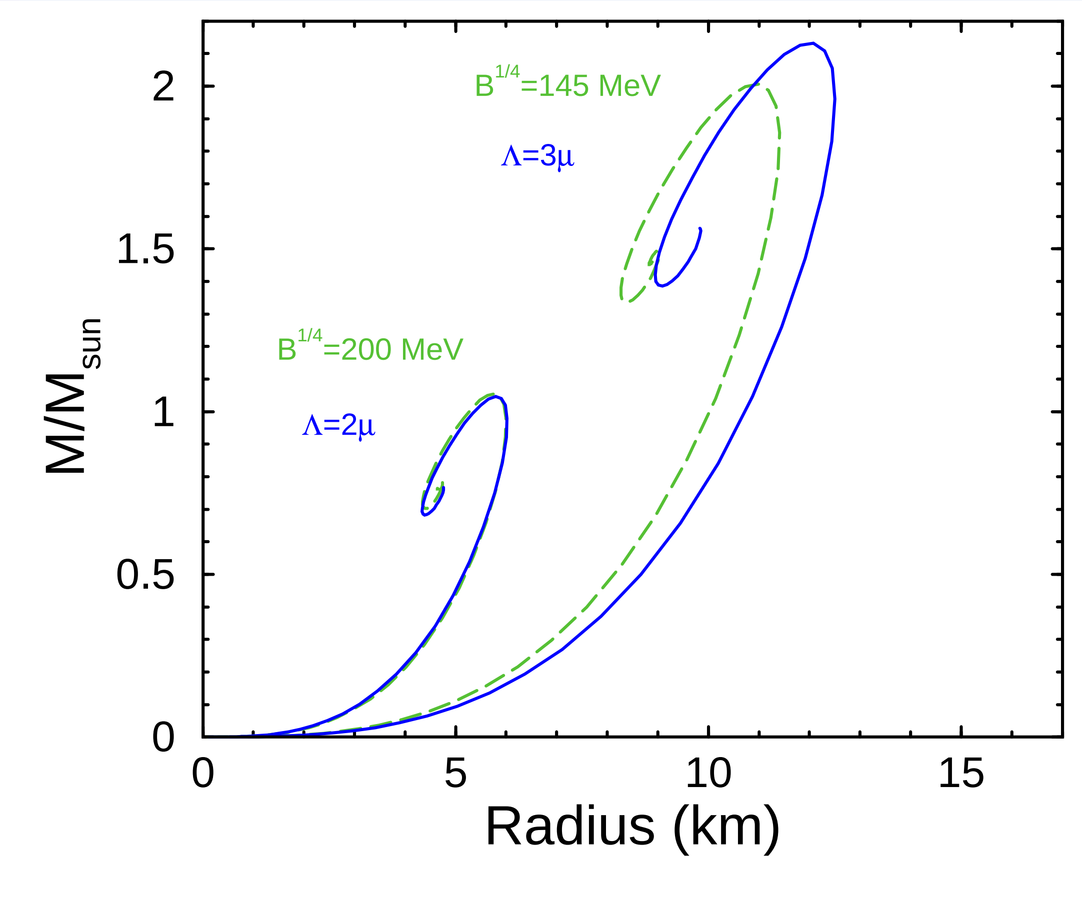
A Model For Cold And Dense QCD



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

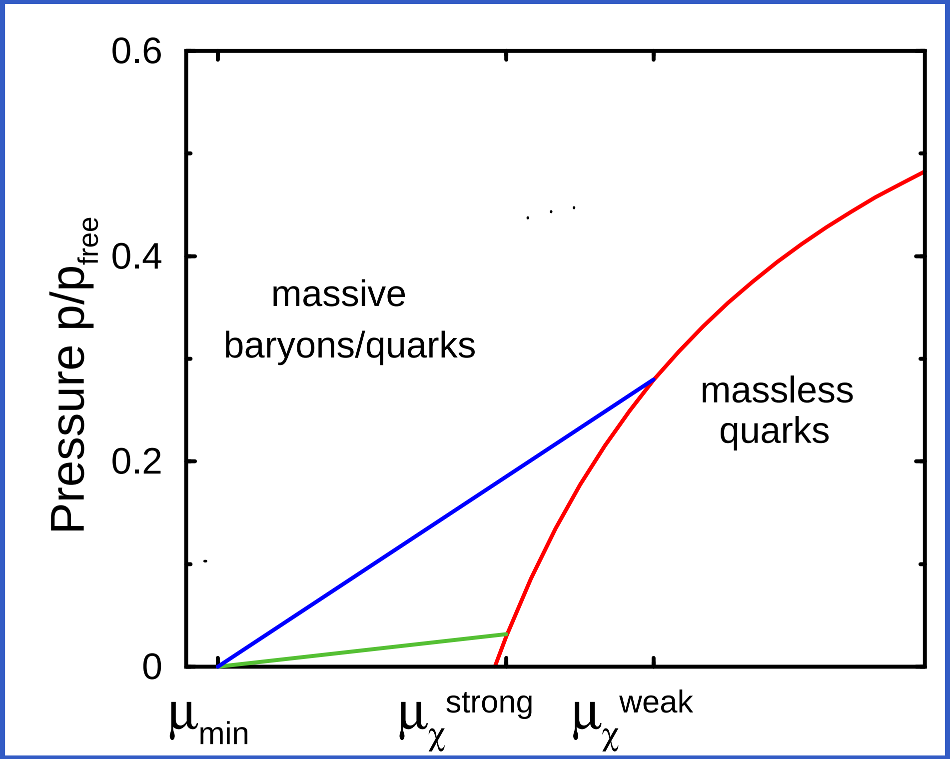
Mass-radius and maximum density of pure quark stars



- 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, $n_{\max} = 5.1\, n_0$
- other nonperturbative approaches: Schwinger–Dyson model (Blaschke et al.), massive quasiparticles (Peshier, Kämpfer, Soff), NJL model (Hanauske et al.), HDL (Andersen and Strickland), . . .

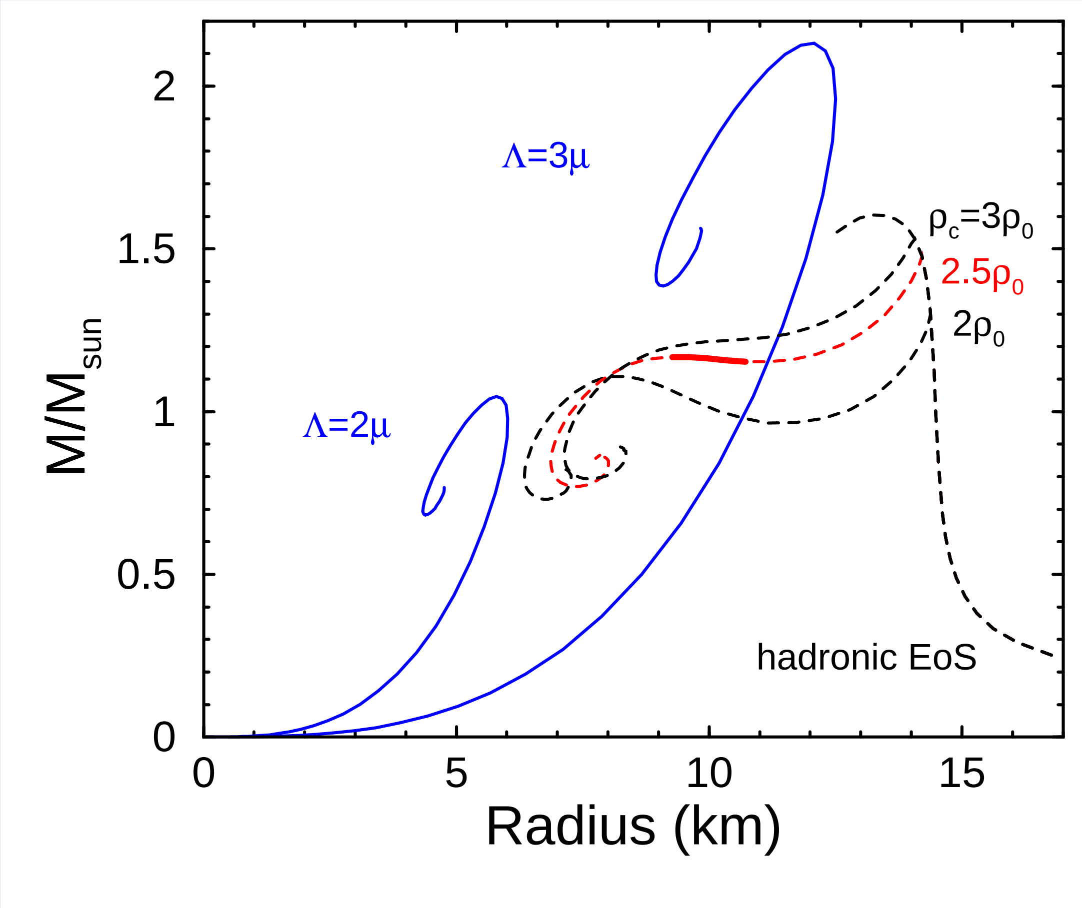
Matching the two phases: two possible scenarios



- 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? (Fraga, JSB, Pisarski (2001))

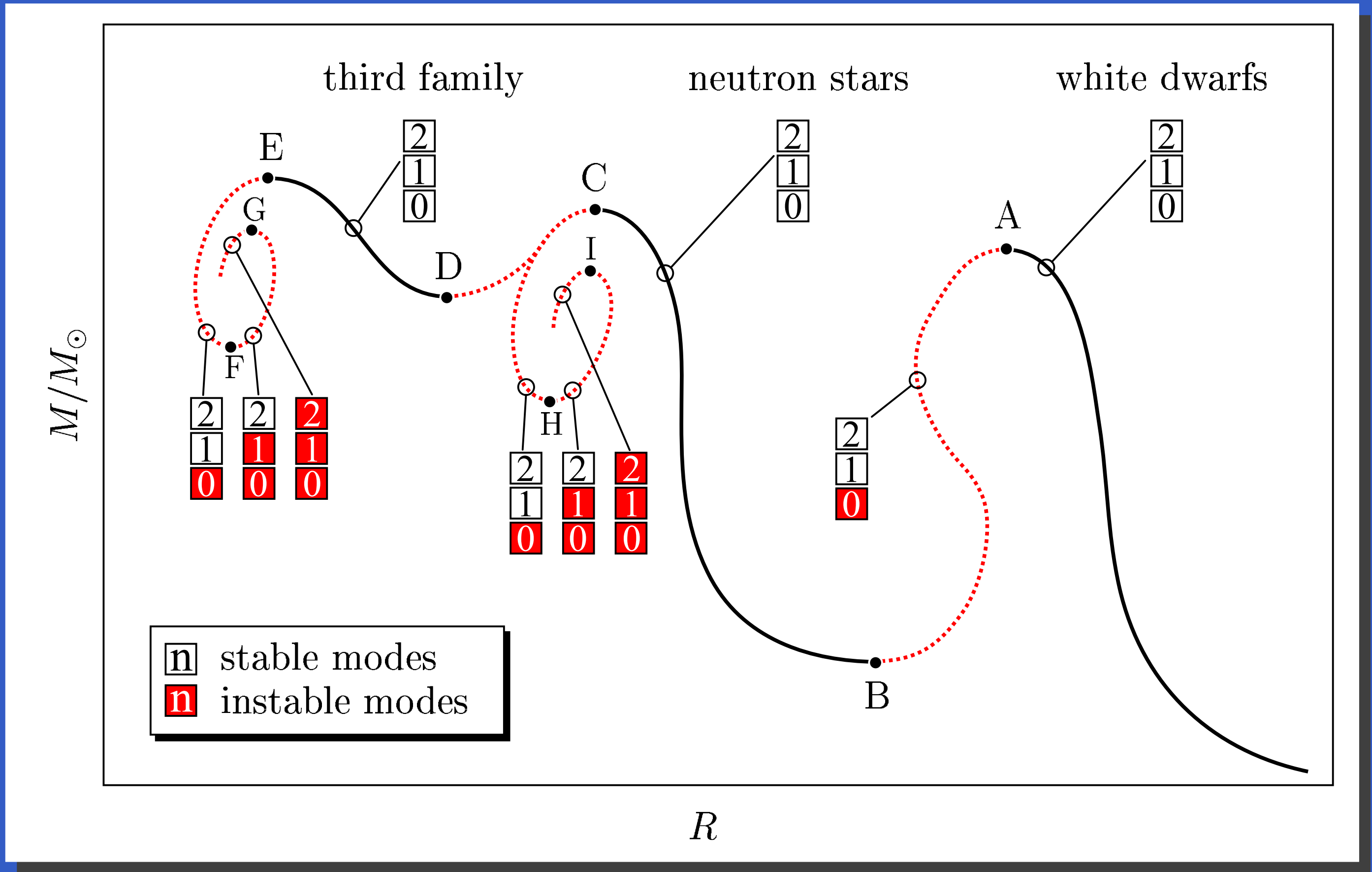


blue curves: pQCD calculation

- 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

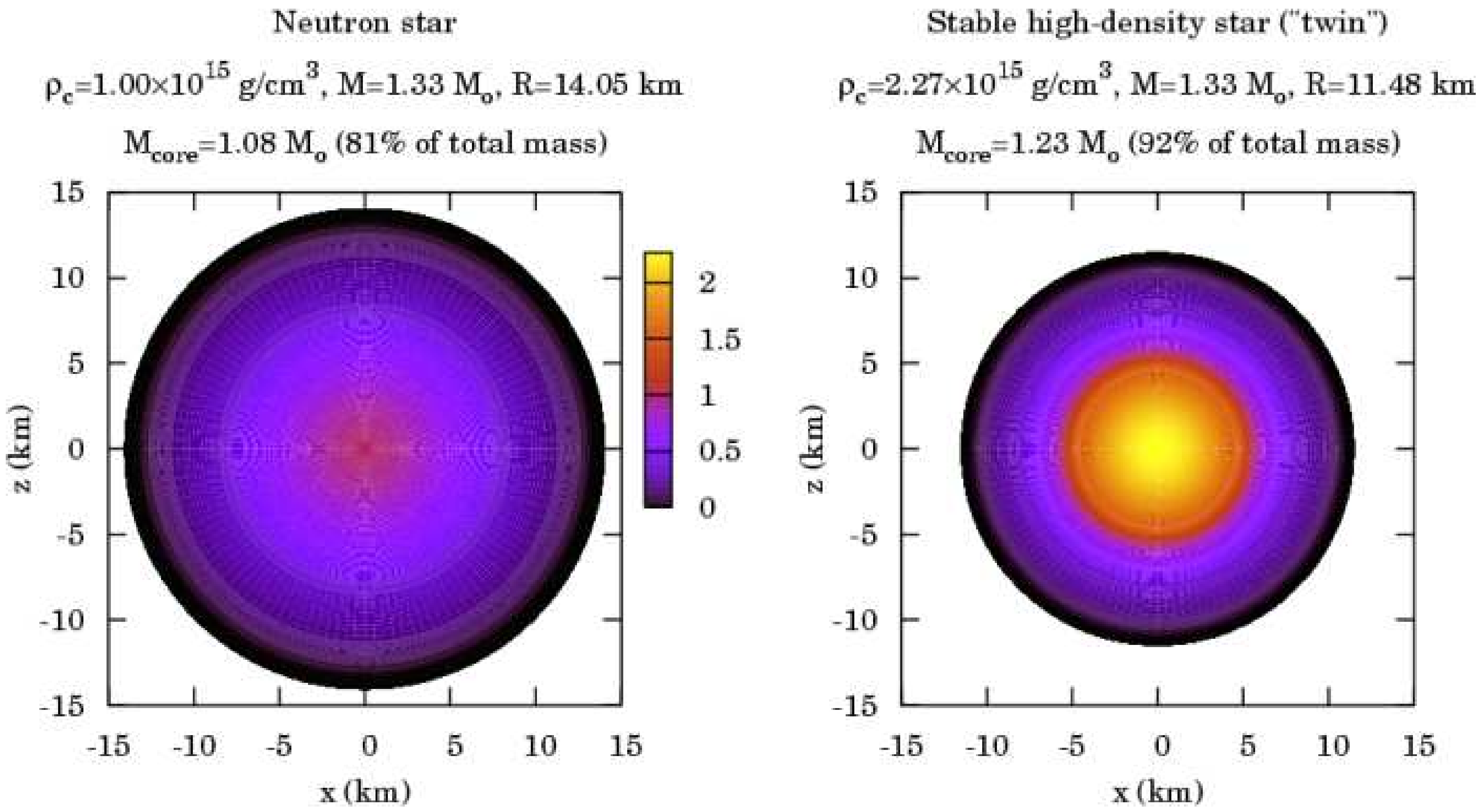
Third Family of Compact Stars (Gerlach 1968)

(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 neutron star twins (Papasotiriou 2006)



The Third Family: Quark Stars, Hyperon Stars . . .

- MIT bag model (Glendenning and Kettner, 2000)
- massive quasi-particles of quarks (Schertler, C. Greiner, JSB, Thoma, 2000)
- interacting quarks in pQCD (Fraga, JSB, Pisarski, 2001)
- Kaon condensate (Banik and Bandyopadhyay, 2001)
- Hyperon Matter (JSB, Hanauske, Stöcker, W. Greiner, 2002)
- MIT bag model (Mishustin, Hanauske, Bhattacharyya, Satarov, Stöcker, W. Greiner, 2003)
- color-superconducting quarks (Banik and Bandyopadhyay, 2003)
- MIT bag and rotation (Bhattacharyya, Ghosh, Hanauske, Raha, 2004)
- Kaon condensate, quarks and rotation (Banik, Hanauske, Bandyopadhyay, W. Greiner, 2004)

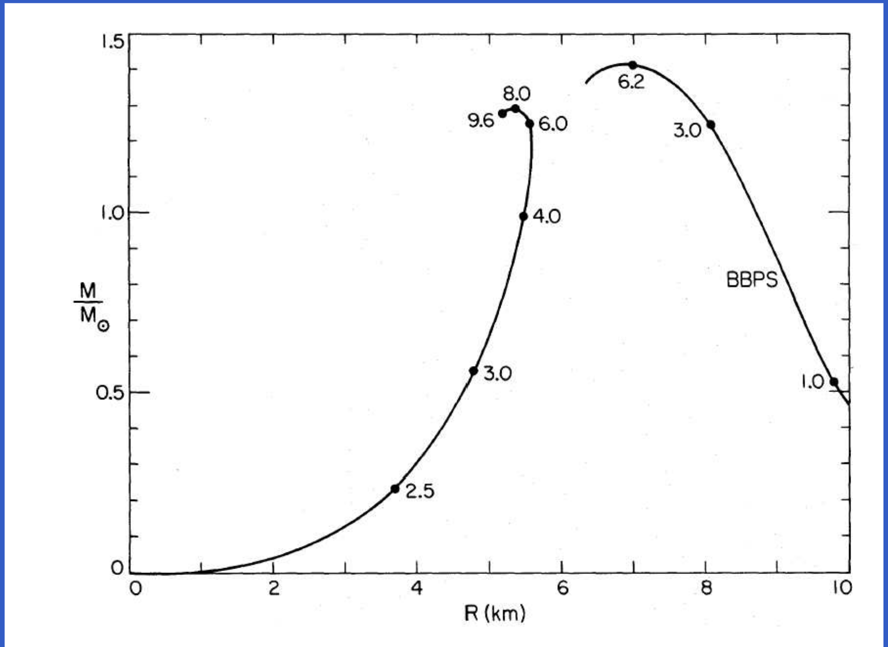
Signals for a Third Family/Phase Transition?

- 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)
- 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?
- high pulsar kick velocities? (see Poster by Irina Sagert)

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, hypothetical!!!

Hypothetical Selfbound Star versus Ordinary Neutron Star



selfbound stars:

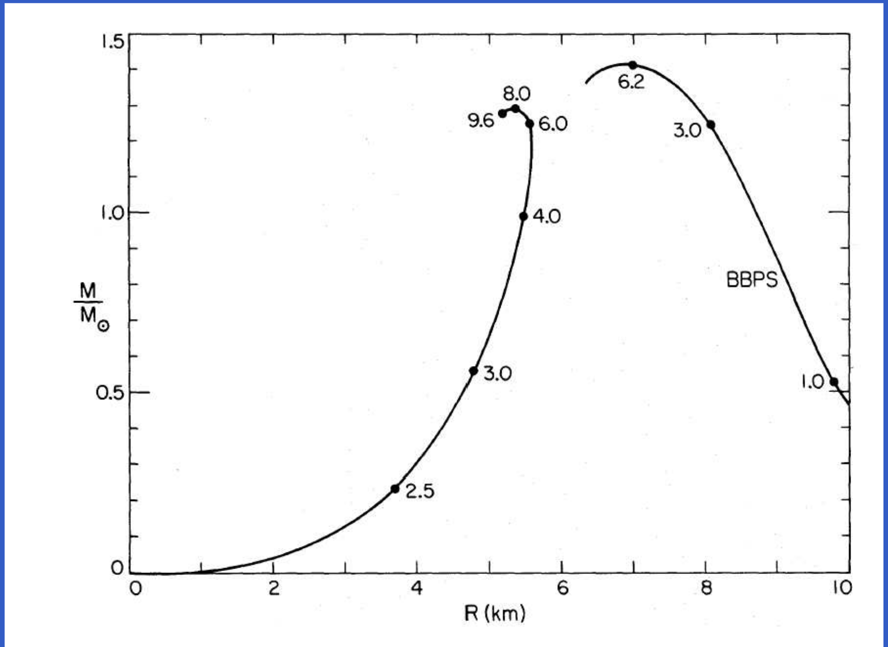
- vanishing pressure at a finite energy density
- mass-radius relation starts at the origin (ignoring a possible crust)
- arbitrarily small masses and radii possible

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

Hypothetical Selfbound Star versus Ordinary Neutron Star

(Hartle, Sawyer, Scalapino (1975!))



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Signals for Strange Stars?

similar masses and radii, cooling, surface (crust), . . . but look for

- extremely small mass, small radius stars (includes strangelets!)
- strange dwarfs: small and light white dwarfs with a strange star core (Glendenning, Kettner, Weber, 1995)
- super-Eddington luminosity from bare, hot strange stars (Page and Usov, 2002)
- conversion of neutron stars to strange stars (explosive events!)
- . . .

Summary

- first order phase transition to exotic matter in dense QCD likely!
- $\longrightarrow$ generates a new, stable solution for compact stars! (besides white dwarfs and neutron stars)
- not constraint by mass-radius data yet!
- impacts on supernovae, proto-neutron star evolution, neutron star properties, pulsars, . . .
- look for two different classes of pulsars !!!

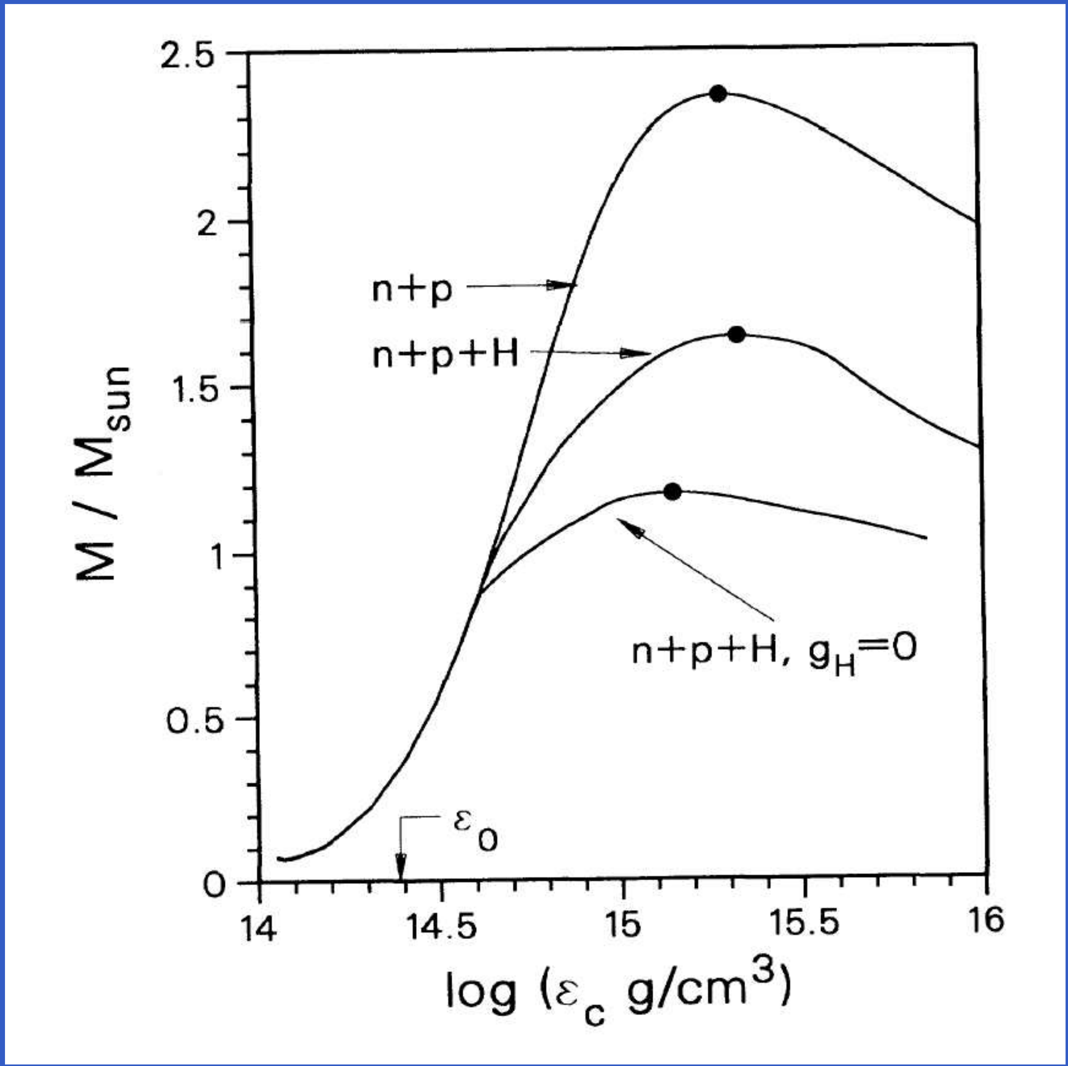
Neutron Star Matter and Hyperons

Hyperons appear at $n \approx 2n_0$!
(based on hypernuclear data!)

- 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)
- density-dependent hadron field theory (Hofmann, Keil, Lenske, 2001)

$\Rightarrow$ neutron stars are strange !!!

Impact of hyperons on the maximum mass of neutron stars

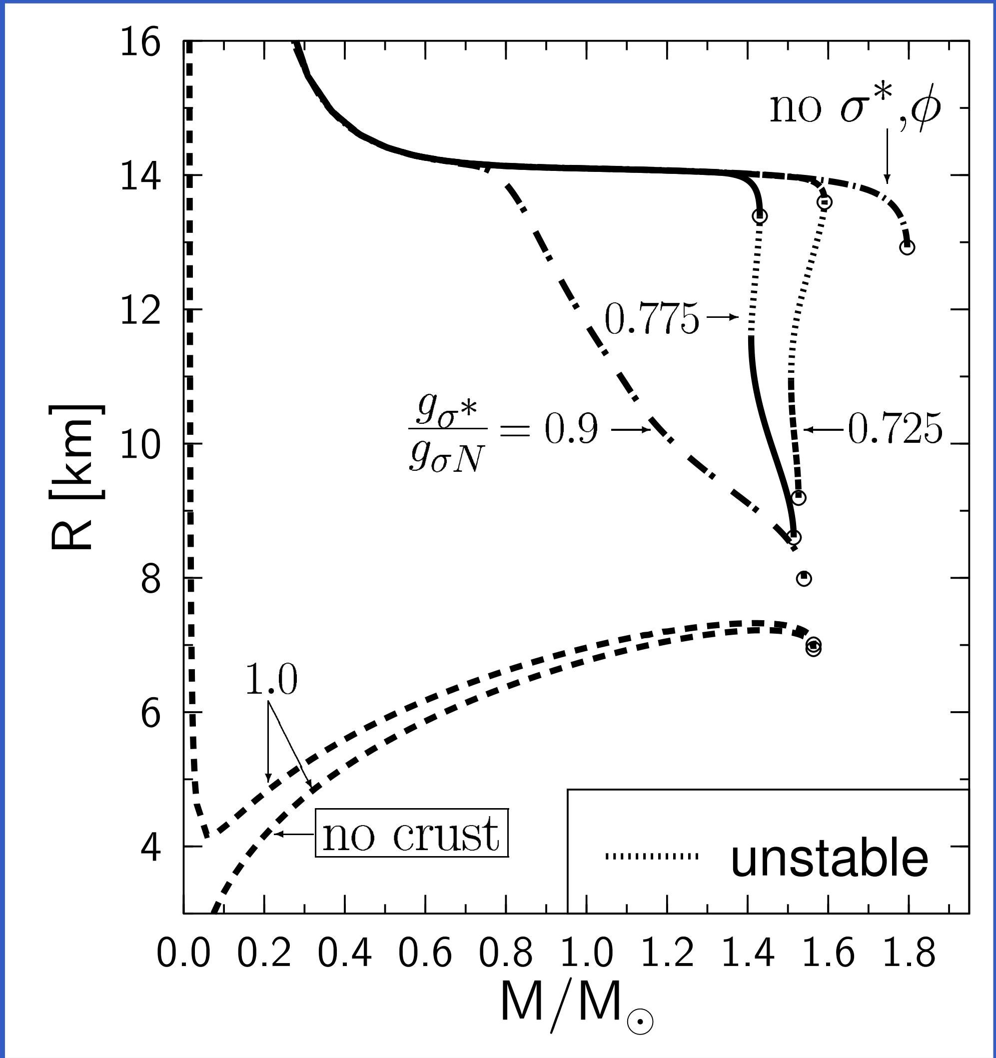


(Glendenning and Moszkowski 1991)
(uses consistently constraints from hypernuclear data)

- 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: $M < 1.4 M_\odot$!

Ultracompact Neutron Stars with Hyperons — Hyperon Stars

(Heintzmann, Hillebrandt, El Eid, Hilf 1974(!): Hyperon Stars within Pandharipande's EoS with hyperons)



- 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

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