Pulsars as a Probe for the Nuclear and Quark Matter Equation of State

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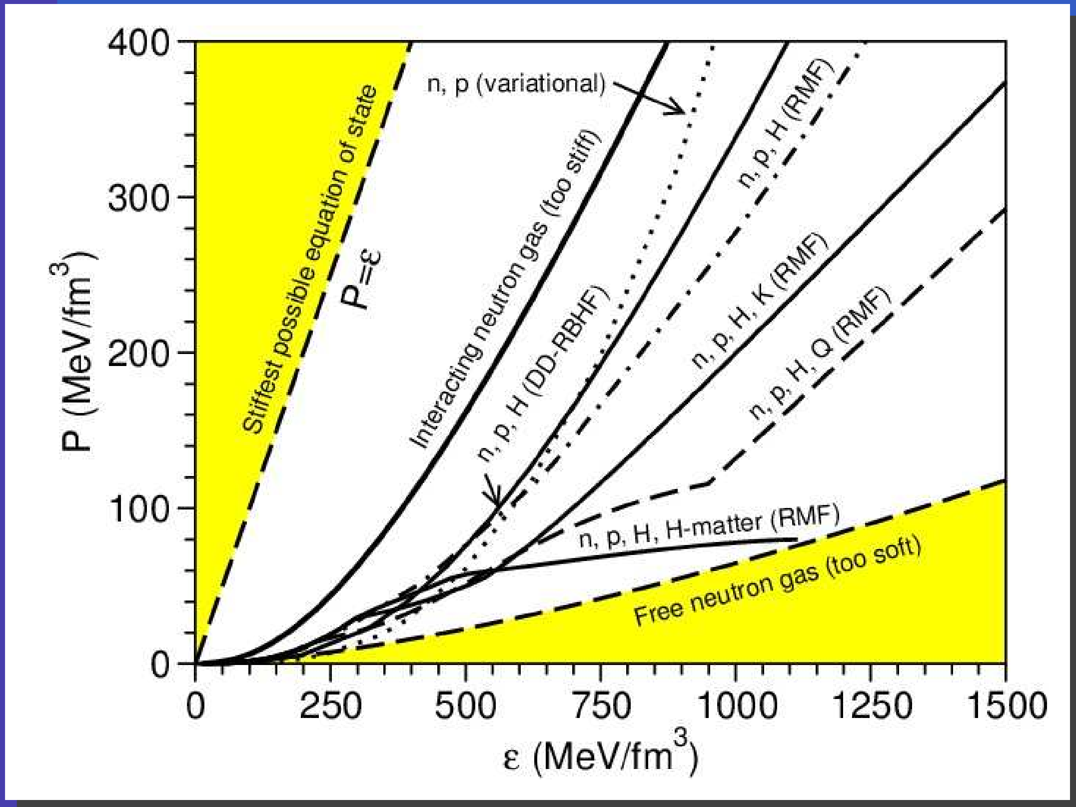
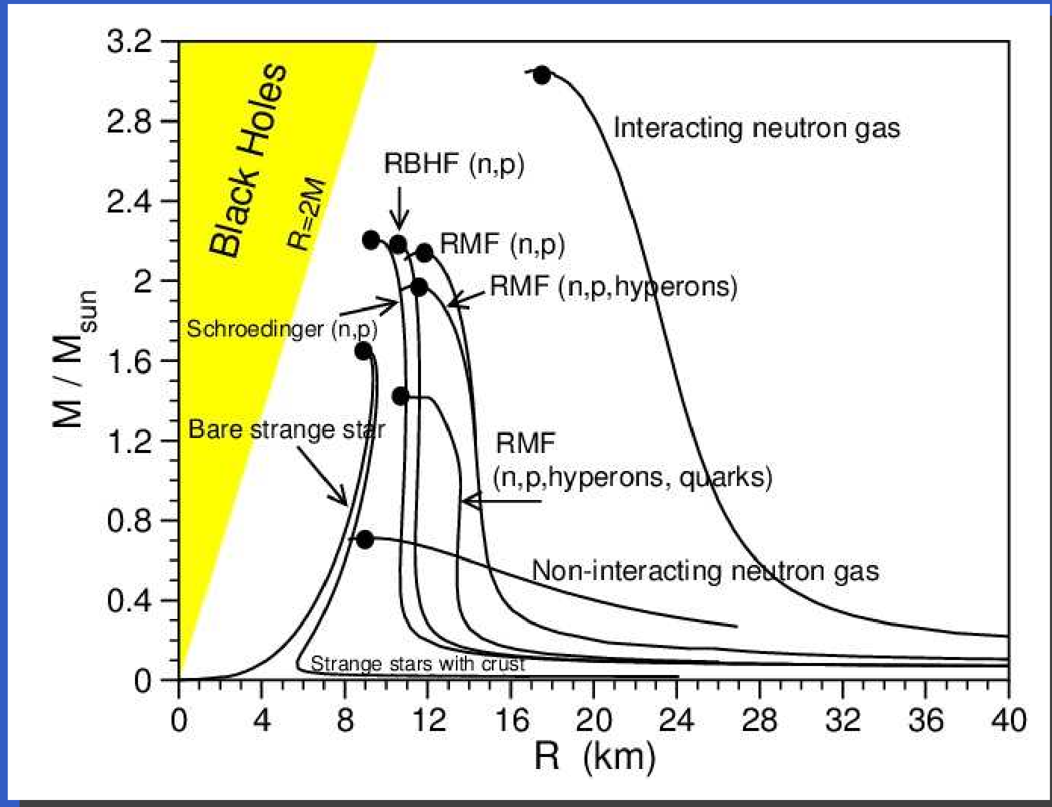
Simon Weissenborn, Irina Sagert, Giuseppe Pagliara, Matthias Hempel, JSB:

Quark matter in massive neutron stars,

e-Print: arXiv:1102.2869 [astro-ph.HE], ApJL in press

EoS and mass-radius relation of compact stars

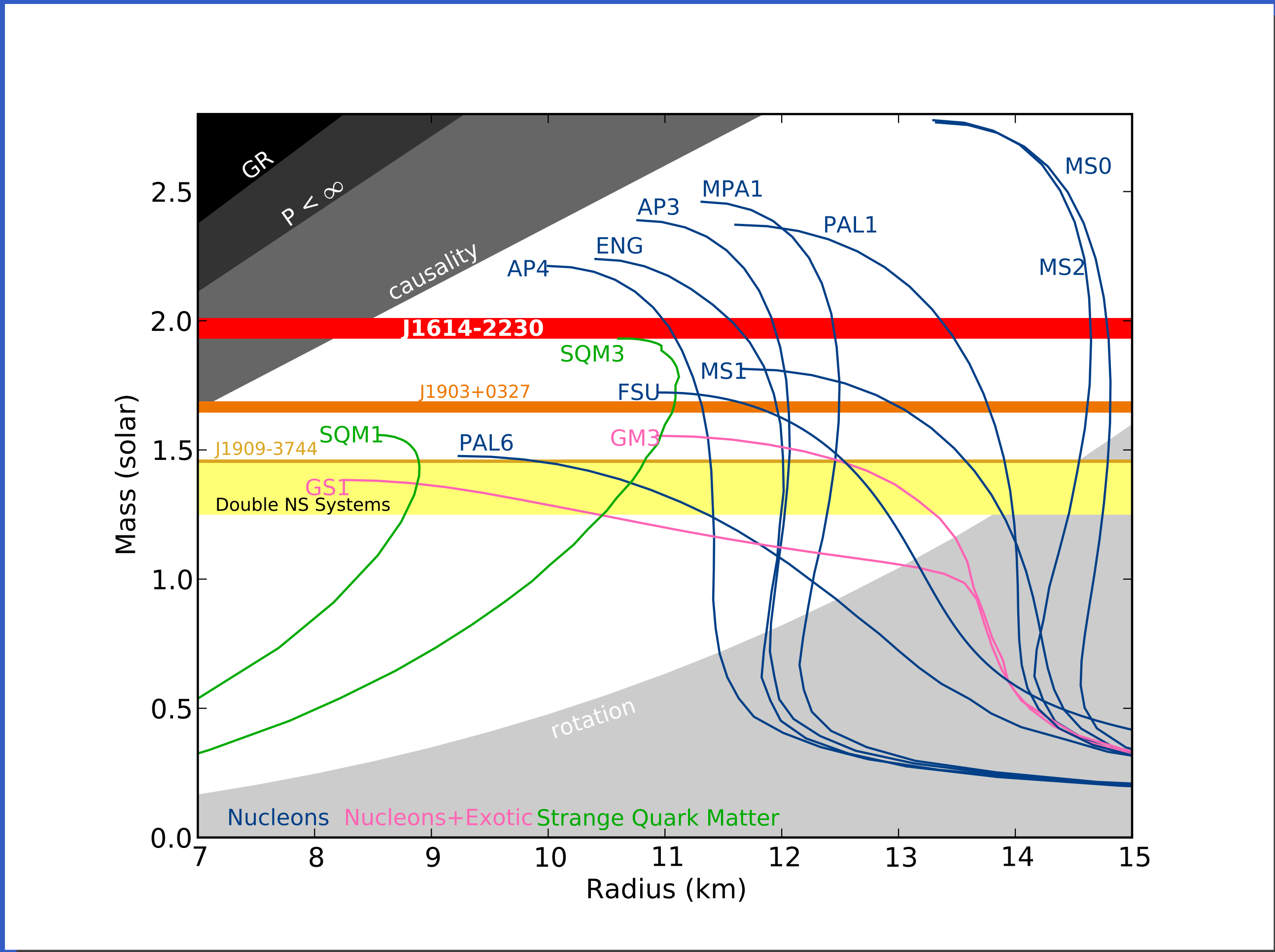




(Weber, Negreiros, Rosenfield, Steijner 2006)

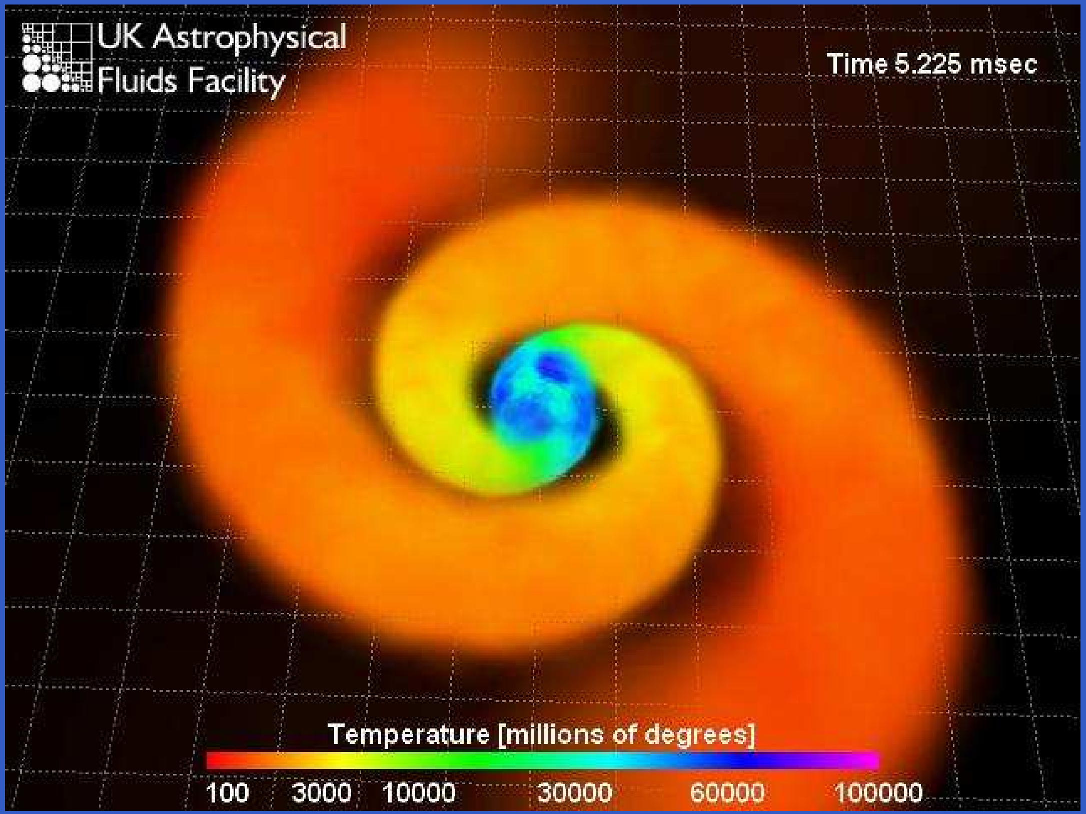
- many, many different equation of state EoS . . .
- result in various different mass-radius relation for compact stars
- Tolman-Oppenheimer-Volkoff (TOV) equation: one-to-one relation between EoS and mass-radius relation

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



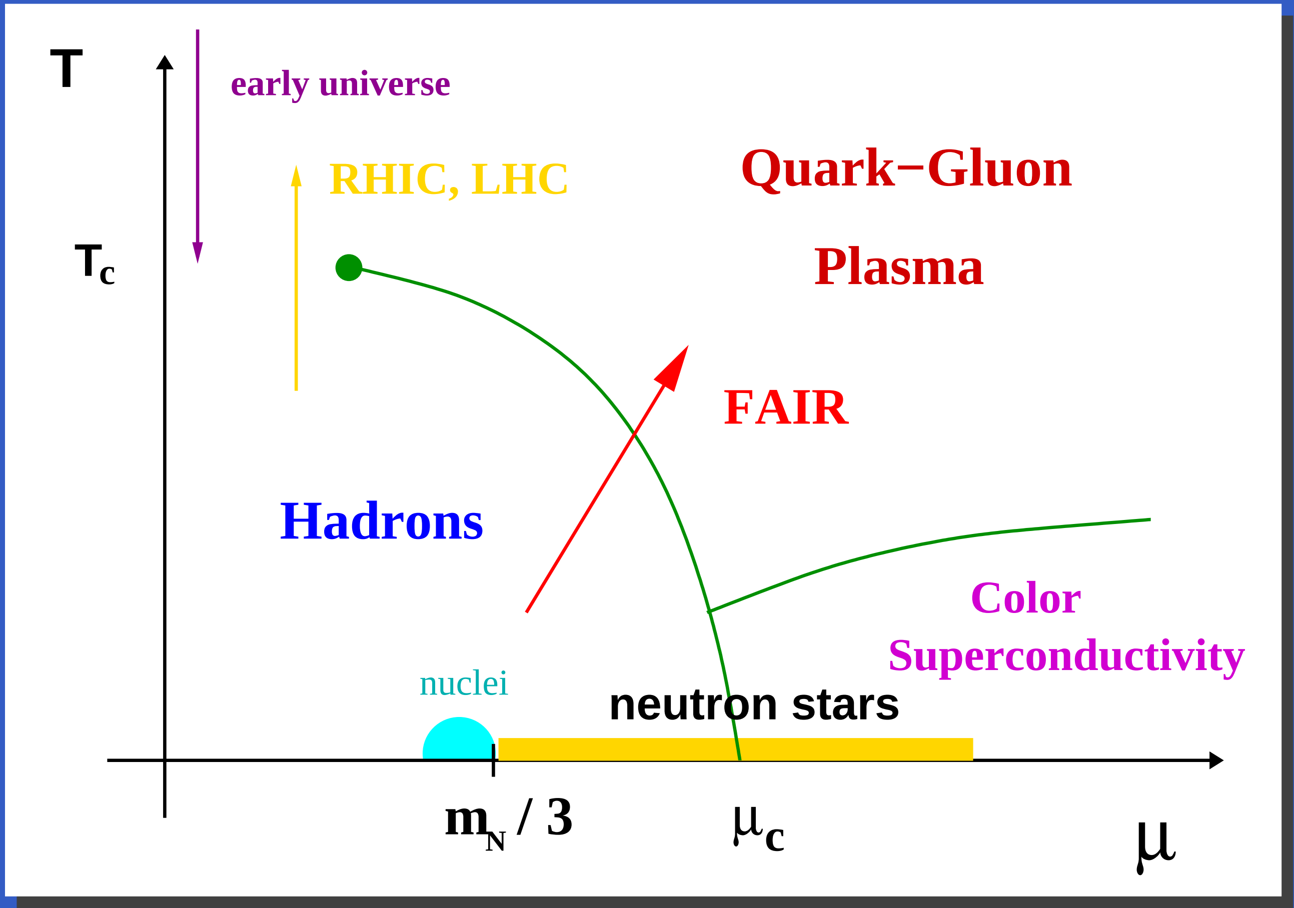
- spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4 M_\odot$
- Schwarzschild limit (GR): $R > 2GM = R_s$
- causality limit for EoS: $R > 3GM$
- mass limit from PSR J1614-2230 (red band): $M = (1.97 \pm 0.04) M_\odot$

Nuclear Equation of State as Input in Astrophysics



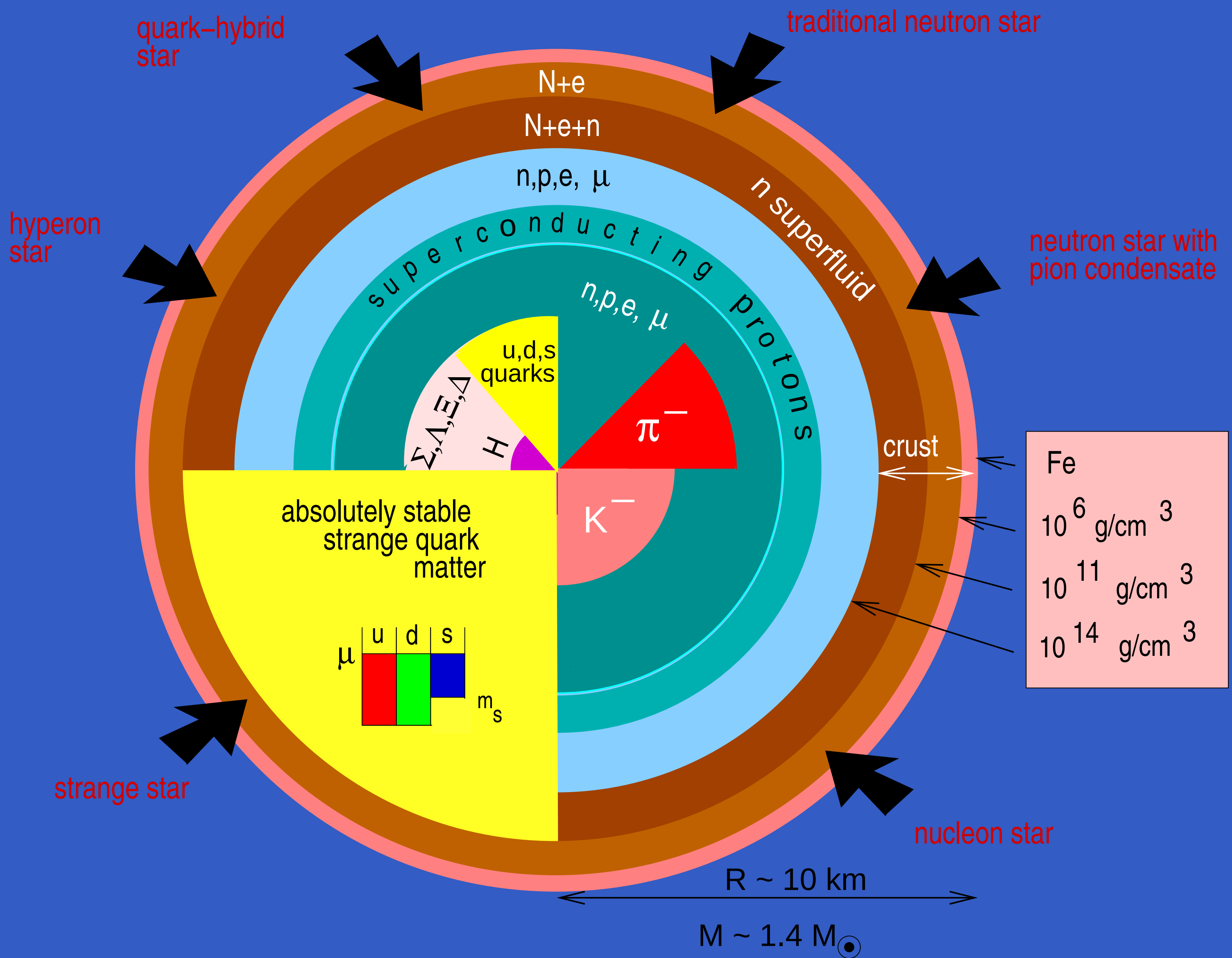
- supernovae simulations: $T = 1$–50 MeV, $n = 10^{-10}$–$2n_0$
- proto-neutron star: $T = 1$–50 MeV, $n = 10^{-3}$–$10n_0$
- global properties of neutron stars: $T = 0$, $n = 10^{-3}$–$10n_0$
- neutron star mergers: $T = 0$–100 MeV, $n = 10^{-10}$–$10n_0$

Phase Diagram of Quantum Chromodynamics QCD

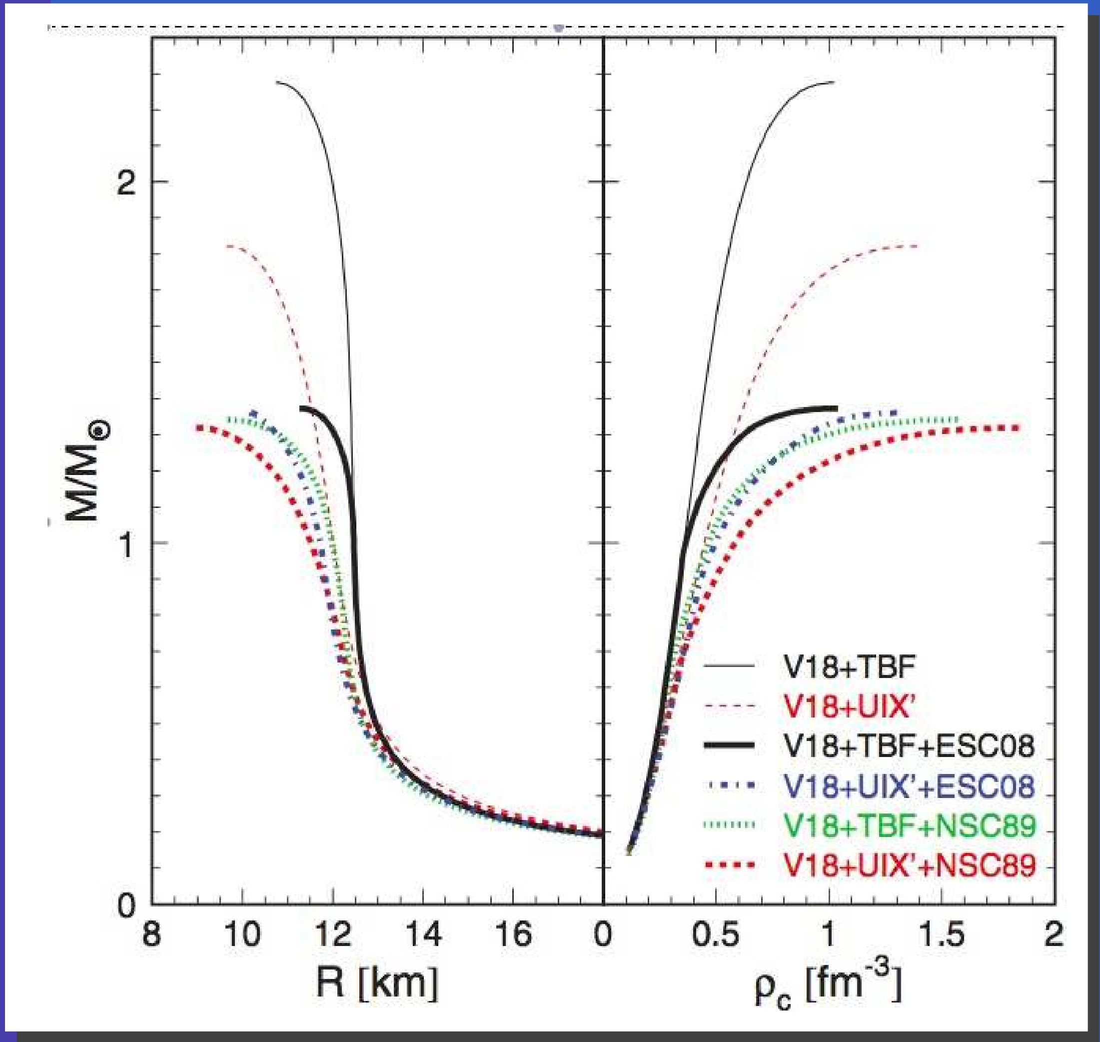


- Early universe at zero density and high temperature
- neutron star matter at small temperature and high density
- first order phase transition at high density (not deconfinement!)
- probed by heavy-ion collisions at GSI, Darmstadt (FAIR)

Structure of a Neutron Star (Fridolin Weber)



Maximum masses of neutron stars with hyperons

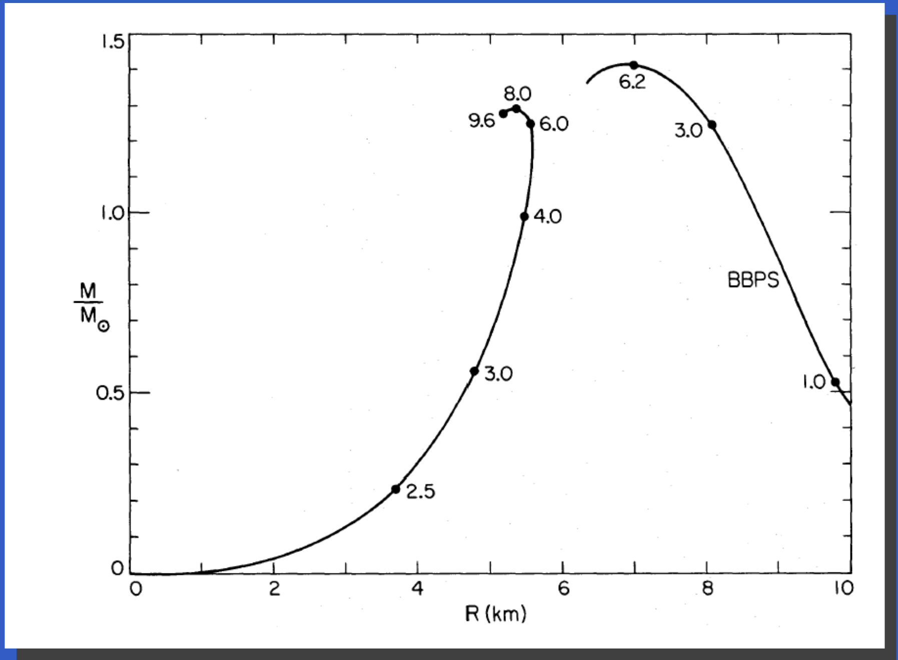


(Schulze and Rijken 2011)

- Brueckner-Hartree-Fock calculation with most recent soft core Nijmegen potential ESC08
- includes repulsive three-body forces (TBF, UIX')
- overall findings: $M < 1.4 M_\odot$ when hyperons are included
- higher masses possible within RMF model and SU(3) symmetry (Weissenborn, Chatterjee, JSB, in preparation)
- other possible solution: a stiff quark matter core

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

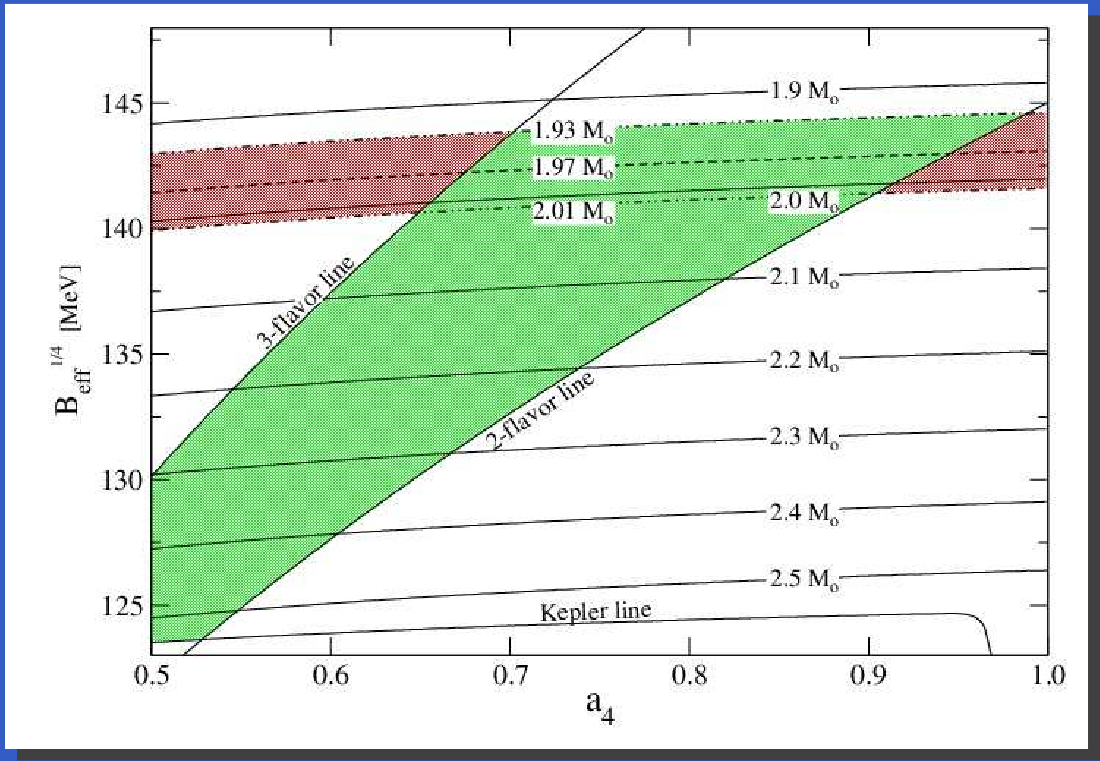
Quark Star Masses: Unpaired Case

Use free gas of quarks with a term from interactions and from a vacuum energy:

$$\Omega_{QM} = \sum_{i=u,d,s,e} \Omega_i + \frac{3\mu^4}{4\pi^2}(1 - a_4) + B_{\mathit{eff}}$$

- Effective model with an expansion in the chemical potential μ
- Two parameters: effective bag constant B_{eff} and interaction parameter a_4
- 2-flavour constraint: nuclei do not collapse to (u,d) quark matter!
- 3-flavour constraint: strange (u,d,s) quark matter shall be more stable than nuclear matter, so that selfbound quark stars dubbed strange stars can exist

Quark Star Masses: Unpaired Case



(Weissenborn, Sagert, Pagliara, Hempel, JSB 2011)

- Kepler line: mass shedding limit for 716 Hz (highest observed pulsar frequency)
- green region: allowed parameter space from maximum pulsar mass
- corrections from interactions are needed ($a_4 < 1$) to be compatible with observations!

Quark Star Masses: effects of quark pairing

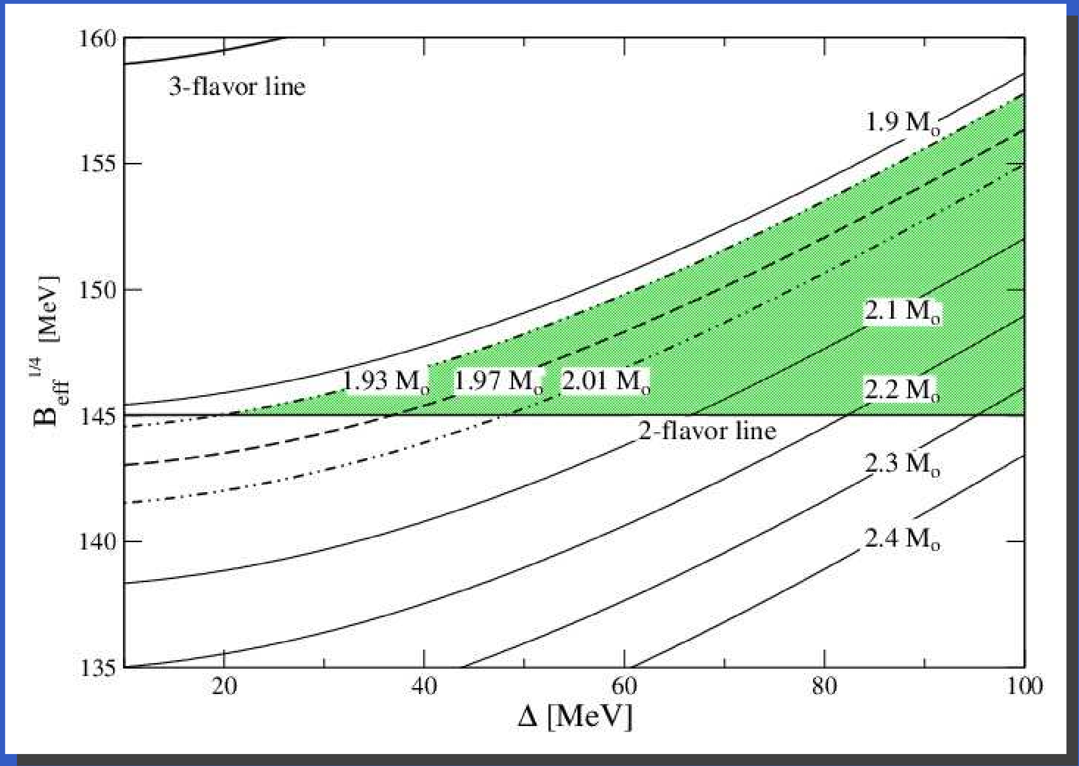
Add to a free gas of quarks terms from interaction, from pairing and from an vacuum energy:

$$\Omega_{CFL} = \frac{6}{\pi^2}\int_0^{\nu} dp\, p^2(p-\mu) + \frac{3}{\pi^2}\int_0^{\nu} dp\, p^2(\sqrt{p^2+m_s^2}-\mu) + (1-a_4)\frac{3\mu^4}{4\pi^2} - \frac{3\Delta^2\mu^2}{\pi^2} + B_{eff}$$

where $\nu = 2\mu - \sqrt{\mu^2 - m_s^2/3}$.

- Δ: gap energy of the color-superconducting phase (normally $\Delta \leq 100$ MeV)
- fix strange quark mass to $m_s = 100$ MeV
- set for simplicity $a_4 = 0$

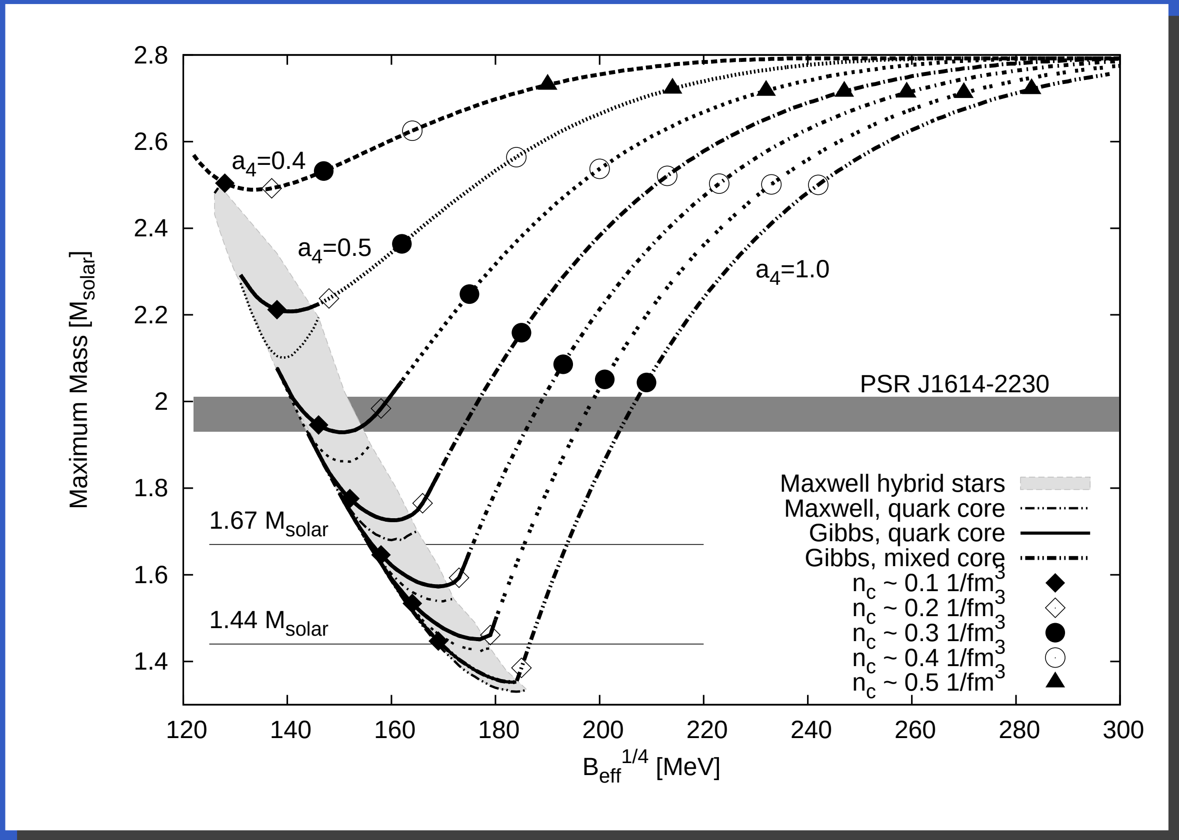
Quark Star Masses: effects of quark pairing



(Weissenborn, Sagert, Pagliara, Hempel, JSB 2011)

- two constraints on quark matter: 2-flavour and 3-flavour line
- green region: allowed parameter space from maximum pulsar mass
- a gap of at least $\Delta = 20$ MeV is needed to be compatible with observations
- pulsar masses above $1.9 M_\odot$ start to constrain QCD parameters!
- additional interactions needed for pulsar masses well above $2.3 M_\odot$

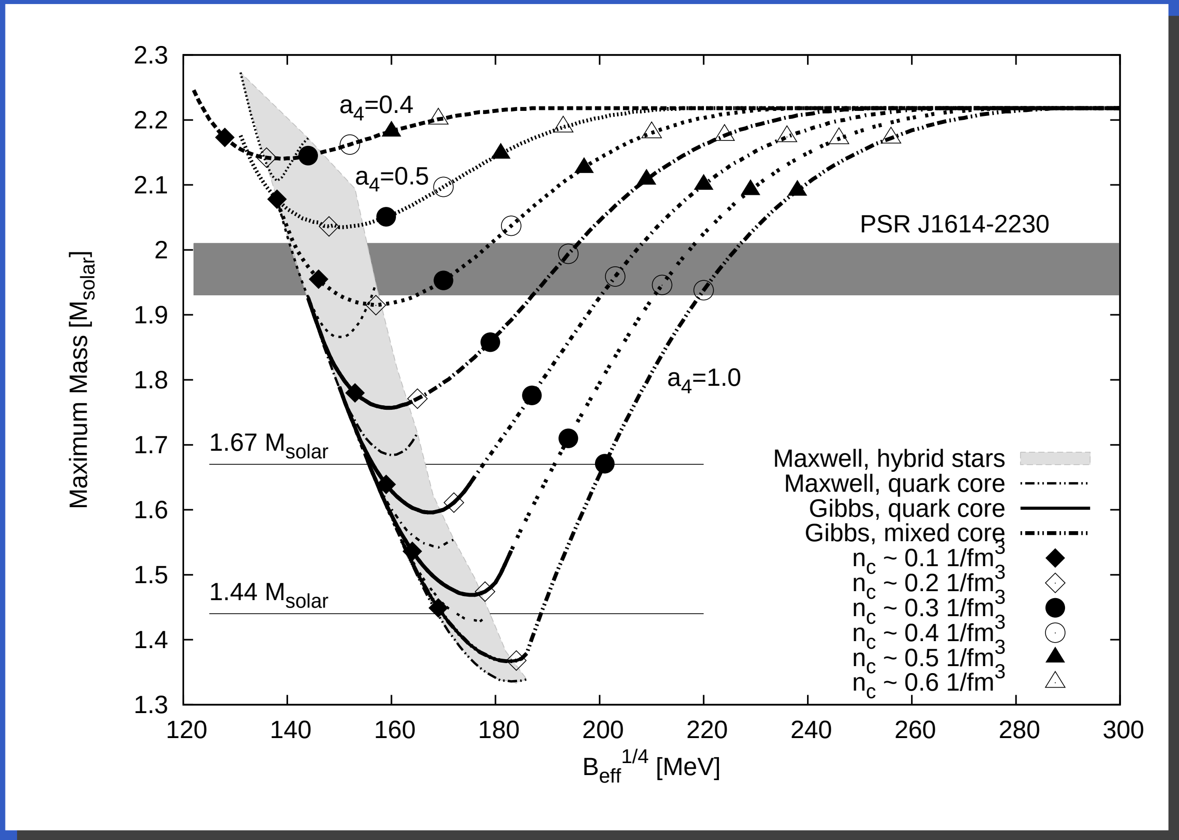
Hybrid Stars with a stiff nuclear EoS



(Weissenborn, Sagert, Pagliara, Hempel, JSB 2011)

- nuclear phase: relativistic mean field model with parameter set NL3 (fitted to properties of nuclei)
- match with Gibbs (lines) or Maxwell construction (shaded area)
- solid lines: pure quark matter cores, dashed lines: mixed phase cores

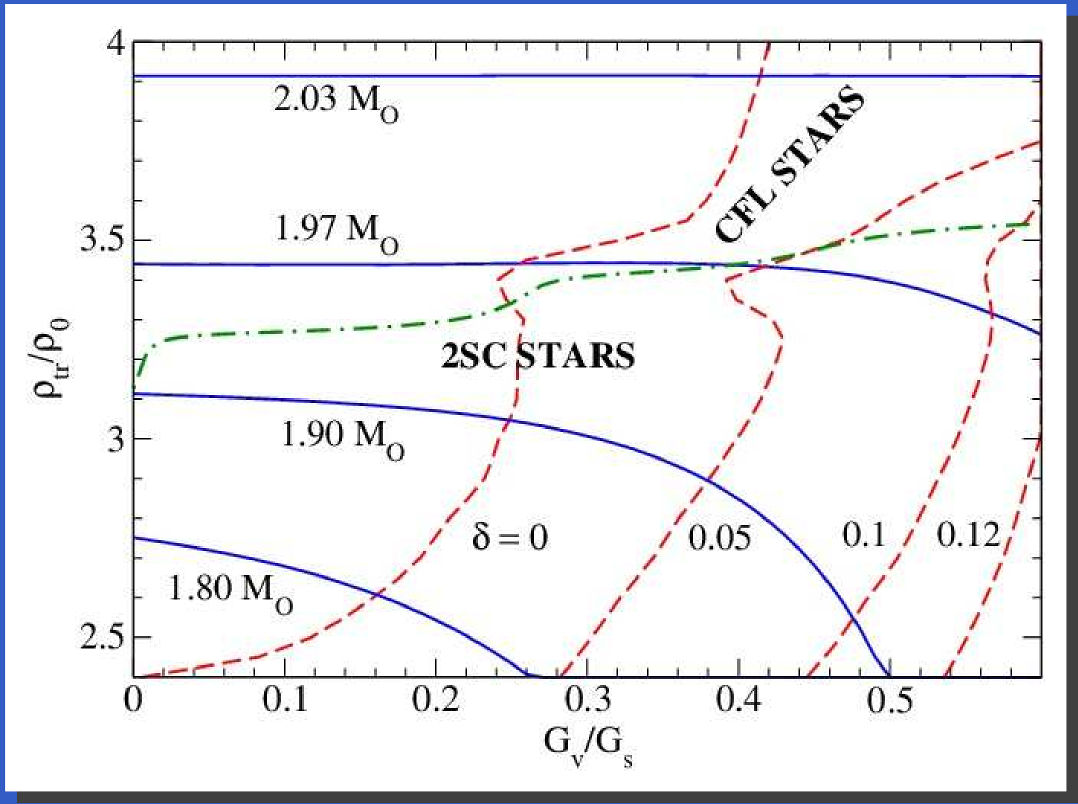
Hybrid Stars with a soft nuclear EoS



(Weissenborn, Sagert, Pagliara, Hempel, JSB 2011)

- nuclear phase: relativistic mean field model with parameter set TM1 (fitted to properties of nuclei)
- match with Gibbs (lines) or Maxwell construction (shaded area)
- solid lines: pure quark matter cores, dashed lines: mixed phase cores
- no pure quark cores compatible with data for a soft nuclear EoS

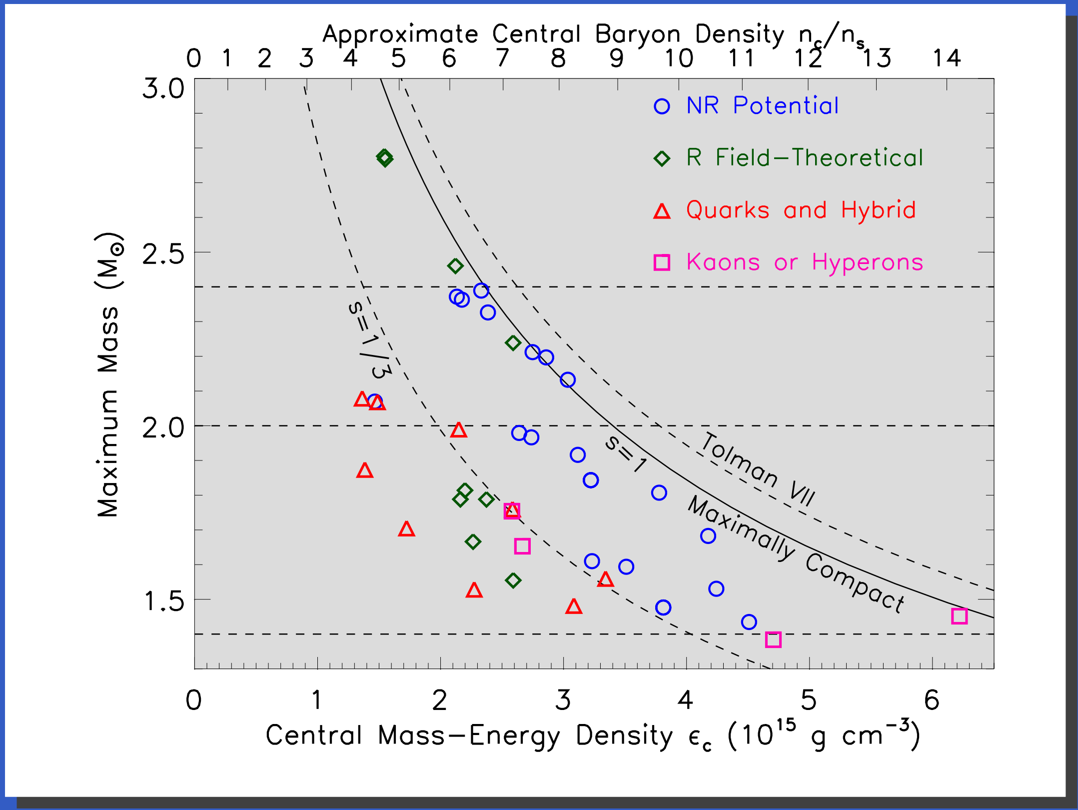
Hybrid Stars with a NJL model



(Bonanno and Sedrakian 2011)

- uses Nambu-Jona-Lasinio model for quark matter
- matches to nuclear EoS with hyperons (RMF with set NL3)
- 2SC quark matter below green line
- $\delta = R_{\rm CFL}/R$: amount of CFL quark matter

Maximum central density of a compact stars

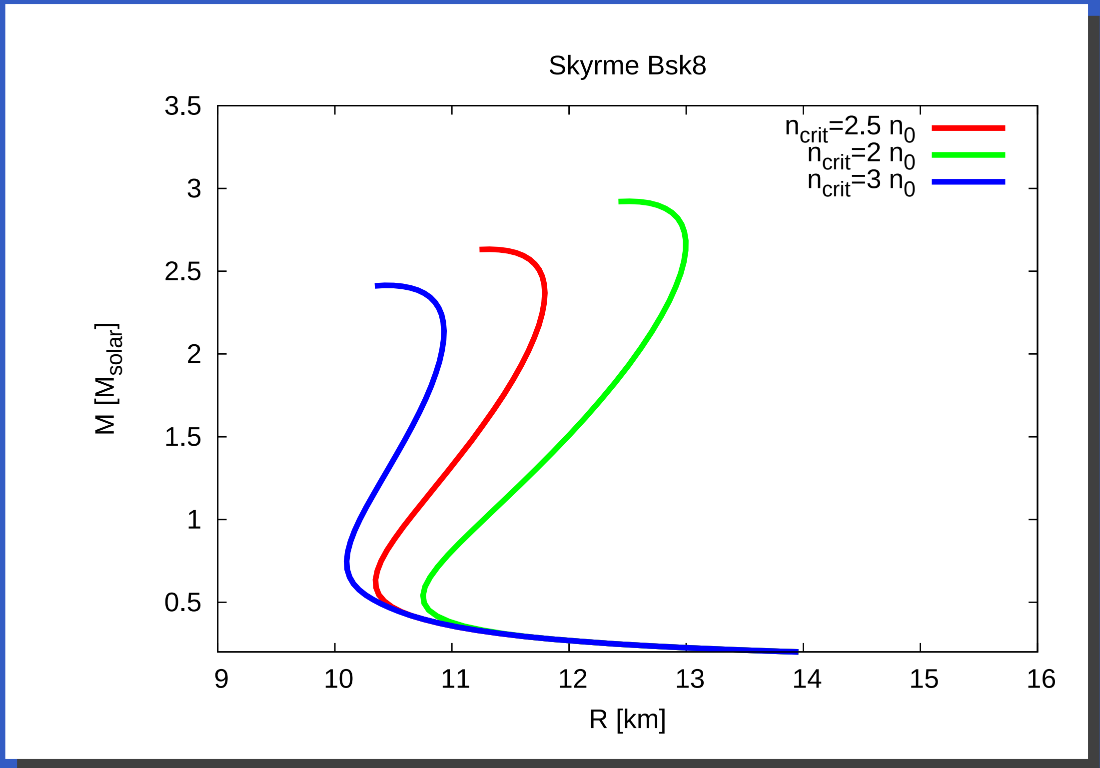


(Lattimer and Prakash 2011)

- maximally compact EoS: $p = s(\epsilon - \epsilon_c)$ with $s = 1$
- stiffest possible EoS (Zeldovich 1961)
- gives upper limit on compact star mass: $M_{\max} = 4.2 M_\odot (\epsilon_{\text{sat.}}/\epsilon_f)^{1/2}$

(Rhoades and Ruffini 1974, Hartle 1978, Kalogera and Baym 1996, Akmal, Pandharipande, Ravenhall 1998)

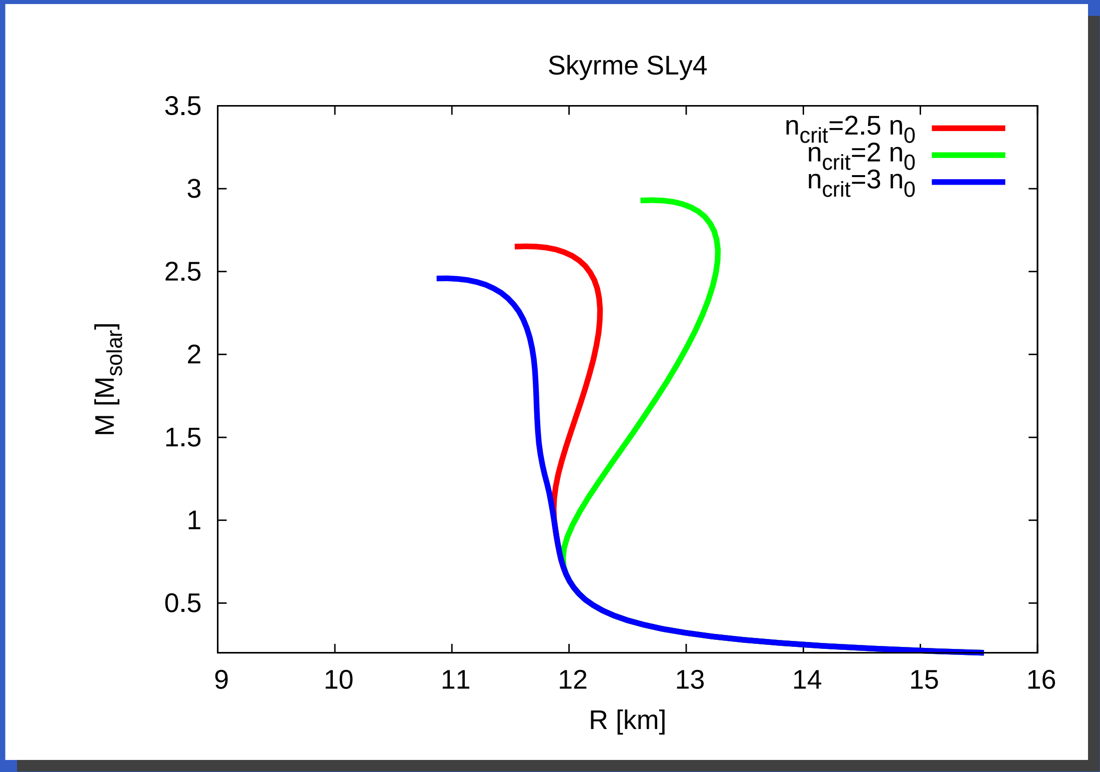
Maximum Masses of Neutron Stars – Causality



(Sagert, Sturm, Chatterjee, Tolos, JSB in preparation)

- Skyrme parameter set BSK8: fitted to masses of all known nuclei
- above a fiducial density (determined from the analysis of the KaoS heavy-ion 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!

Maximum Masses of Neutron Stars – Causality



(Sagert, Sturm, Chatterjee, Tolos, JSB in preparation)

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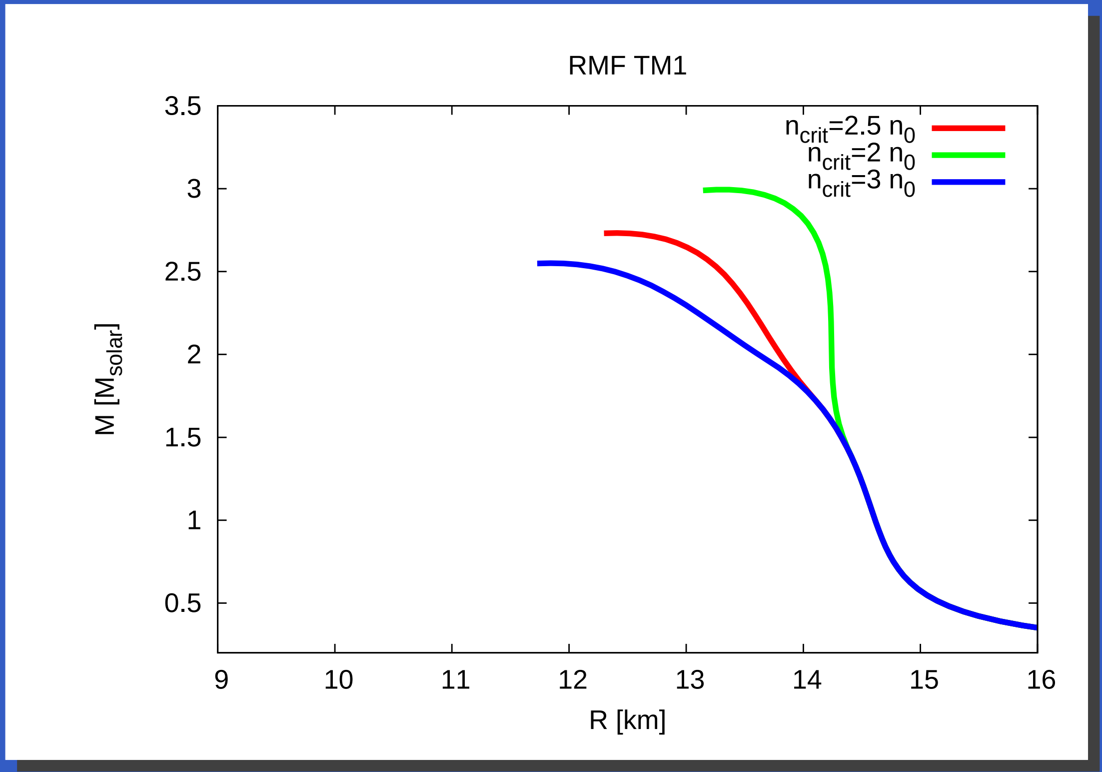
Maximum Masses of Neutron Stars – Causality



(Sagert, Sturm, Chatterjee, Tolos, JSB in preparation)

- RMF parameter set TM1: fitted to properties of spherical nuclei
- above a fiducial density (determined from the analysis of the KaoS heavy-ion 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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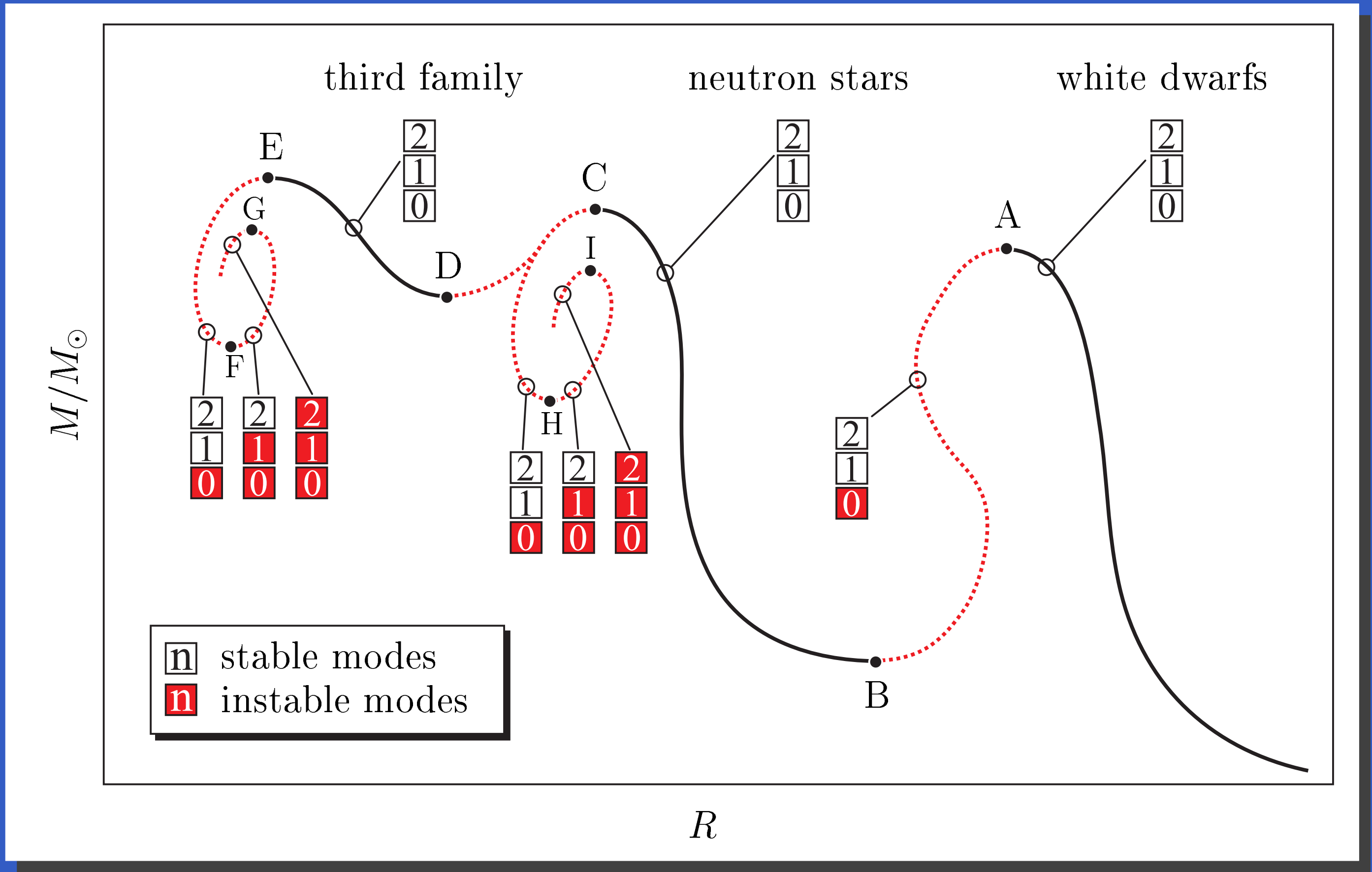
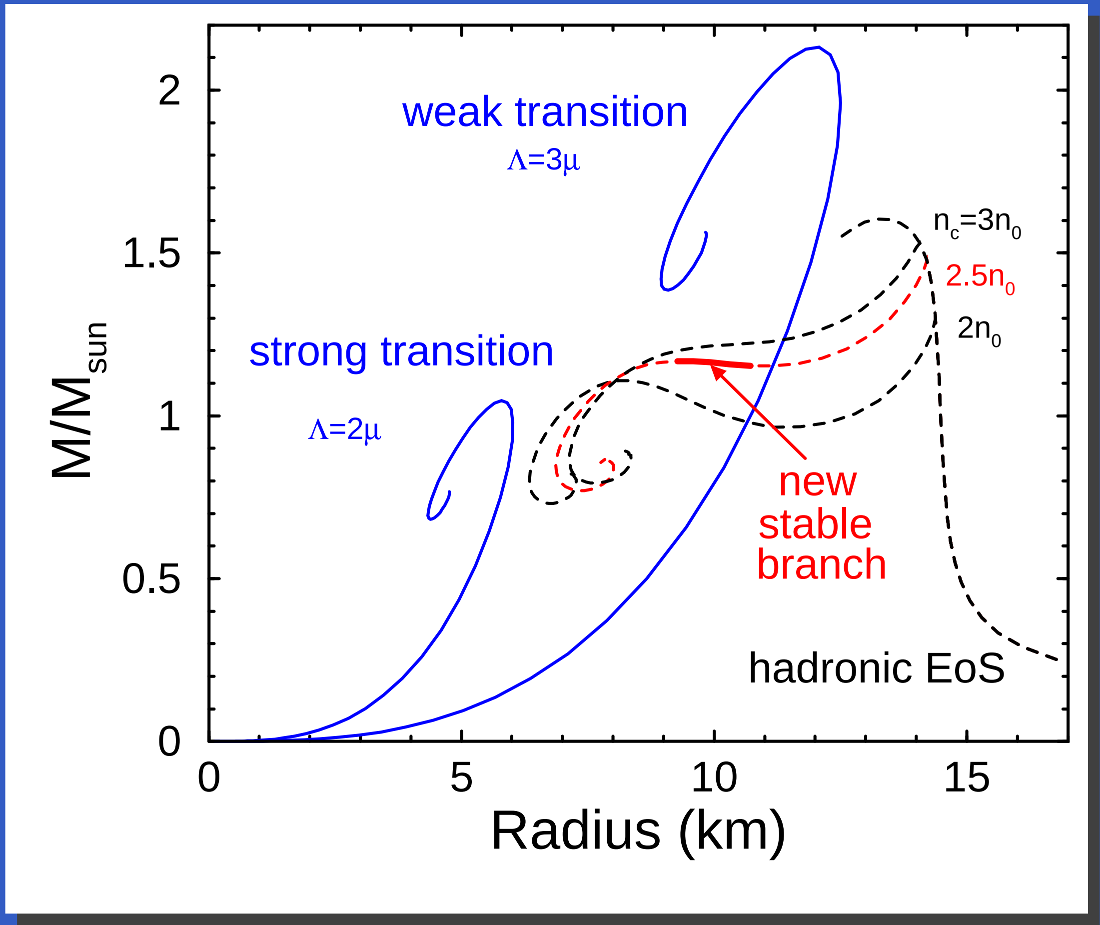
Third Family of Compact Stars (Gerlach 1968)

(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!

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

Summary

- equation of state (EoS) determines the maximum mass and its radius
- new hadronic degrees of freedoms normally soften the EoS
- but quark matter can also stiffen the EoS
- strong QCD phase transition leads to a third family of compact stars
- pulsar mass measurements can severely constrain models of QCD
- unique opportunity to test QCD at extreme conditions

Onset of Hyperons in Neutron Star Matter

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

- relativistic mean–field models

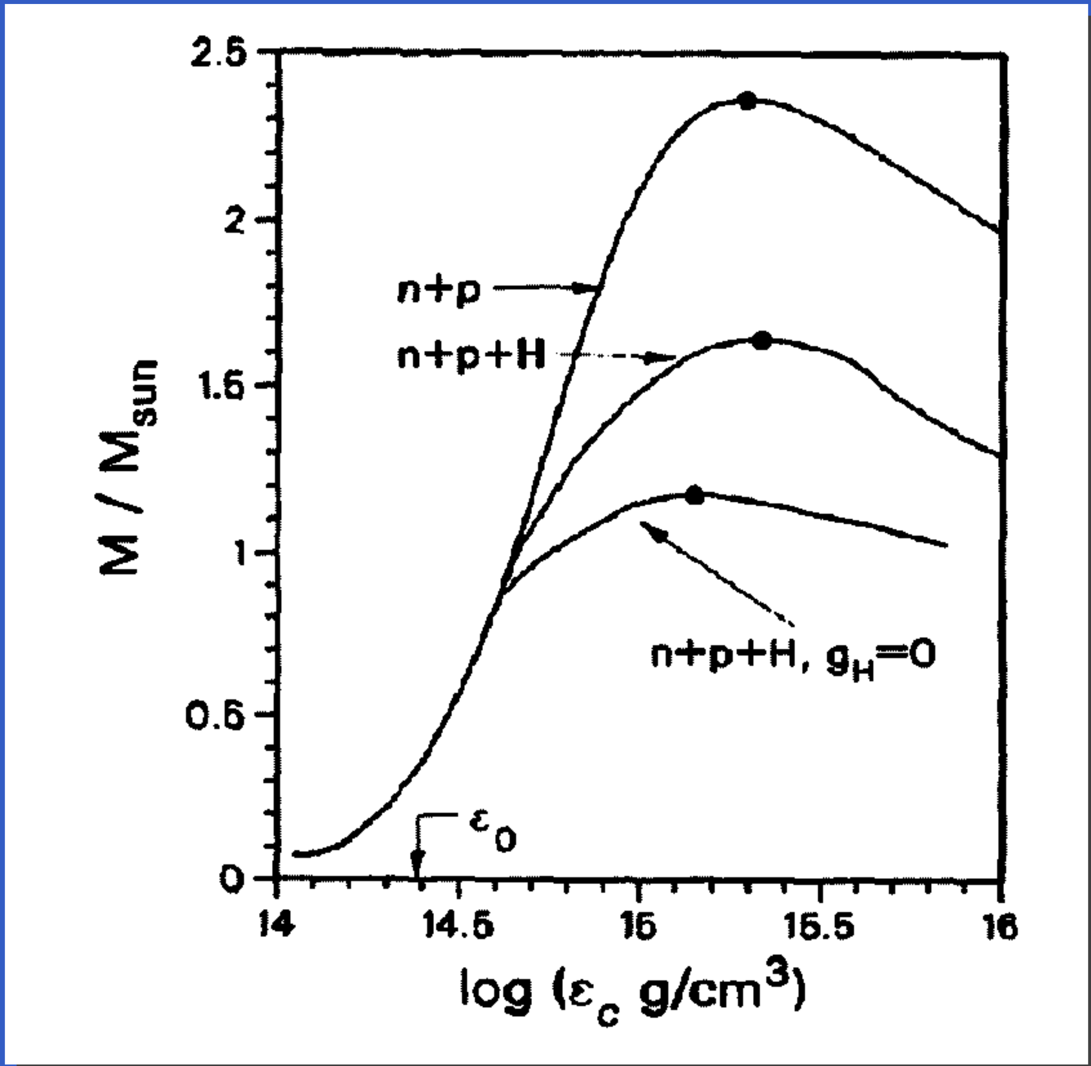
  (Glendenning 1985; Knorren, Prakash, Ellis 1996; JS and Mishustin 1996)
- nonrelativistic potential model (Balberg and Gal 1997)
- quark-meson coupling model (Pal et al. 1999)
- relativistic Hartree–Fock (Huber, Weber, Weigel, Schaab 1998)
- Brueckner–Hartree–Fock

  (Baldo, Burgio, Schulze 1998, 2000; Vidana et al. 2000; Schulze, Polls, Ramos, Vidana 2006)
- chiral effective Lagrangian using SU(3) symmetry

  (Hanauske et al. 2000; Schramm and Zschiesche 2003; Dexheimer and Schramm 2008)
- density-dependent hadron field theory (Hofmann, Keil, Lenske 2001)
- G-matrix calculation (Nishizaki, Takatsuka, Yamamoto 2002)
- RG approach with $V_{\text{low k}}$ (Djapo, Schäfer, Wambach 2008)

$\Rightarrow$ neutron stars are giant hypernuclei !!!

Impact of hyperons on the maximum mass



(Glendenning and Moszkowski 1991)

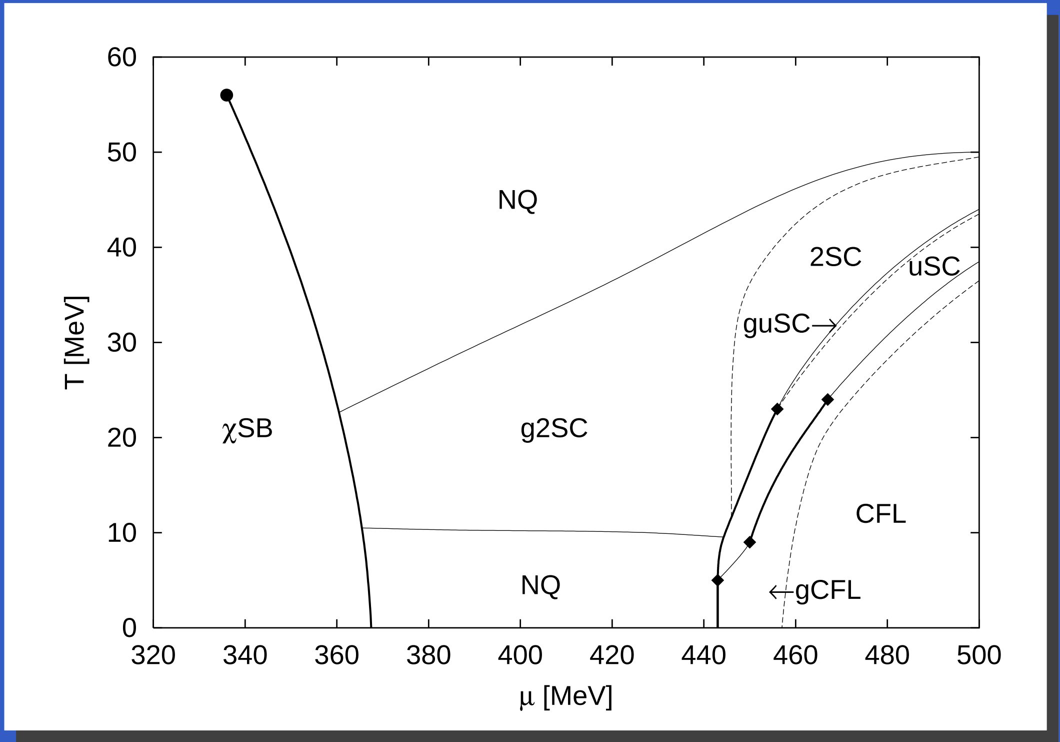
- neutron star with nucleons and leptons only: $M \approx 2.3 M_\odot$
- substantial decrease of the maximum mass due to hyperons!
- maximum mass for “giant hypernuclei”: $M \approx 1.7 M_\odot$
- noninteracting hyperons result in a too low mass: $M < 1.4 M_\odot$!

Maximum mass and modern many-body approaches

modern many-body calculations
(using Nijmegen soft-core YN potential)

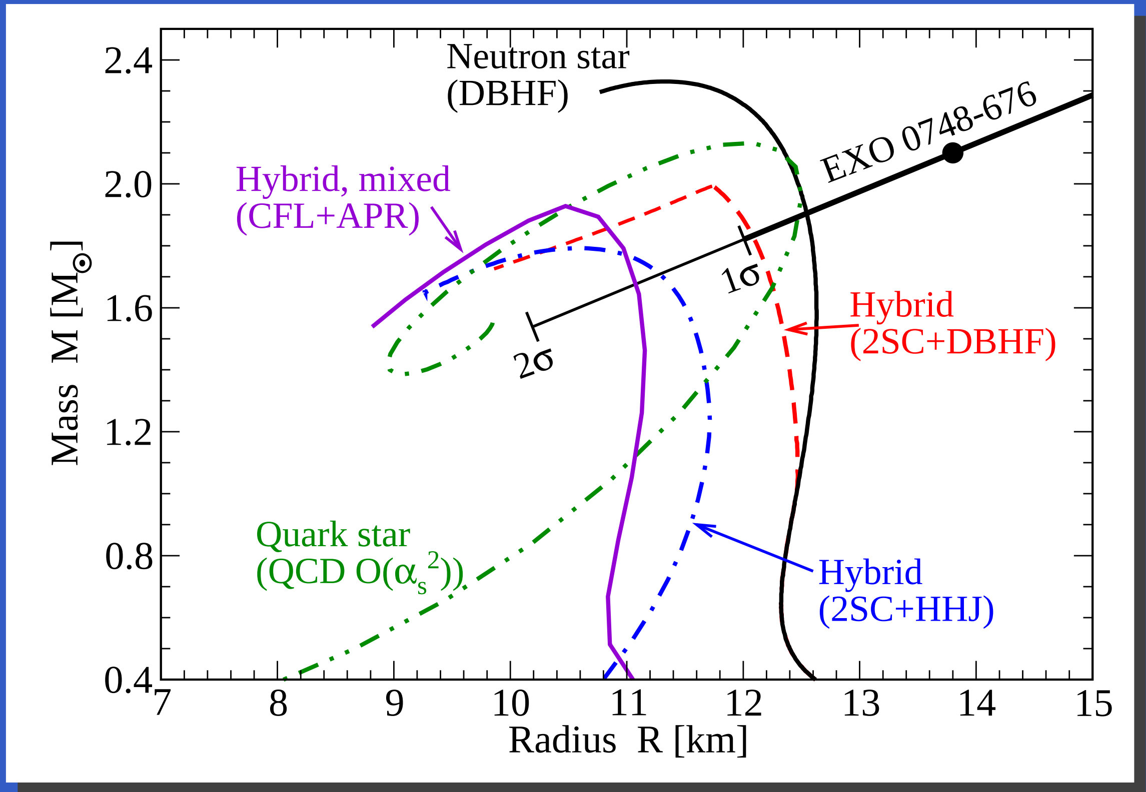
- Vidana et al. (2000): $M_{\rm max} = 1.47 M_\odot$ (NN and YN interactions), $M_{\rm max} = 1.34 M_\odot$ (NN, NY, YY interactions)
- Baldo et al. (2000): $M_{\rm max} = 1.26 M_\odot$ (including three-body nucleon interaction)
- Schulze et al. (2006): $M_{\rm max} < 1.4 M_\odot$
- Djapo et al. (2008): $M_{\rm max} < 1.4 M_\odot$
- Schulze and Rijken (2011): $M_{\rm max} < 1.4 M_\odot$ (ESC08)
- too soft EoS, too low masses!
- resolution: make EoS stiffer by the presence of quark matter!?!

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, . . .)

X-Ray burster EXO 0748–676 and Quark Matter



- 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 $M = 2.1 M_\odot$

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?

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!)
- . . .