Strangeness in Neutron Stars

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GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

EMMI

HIC for FAIR Helmholtz International Center

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

Outline

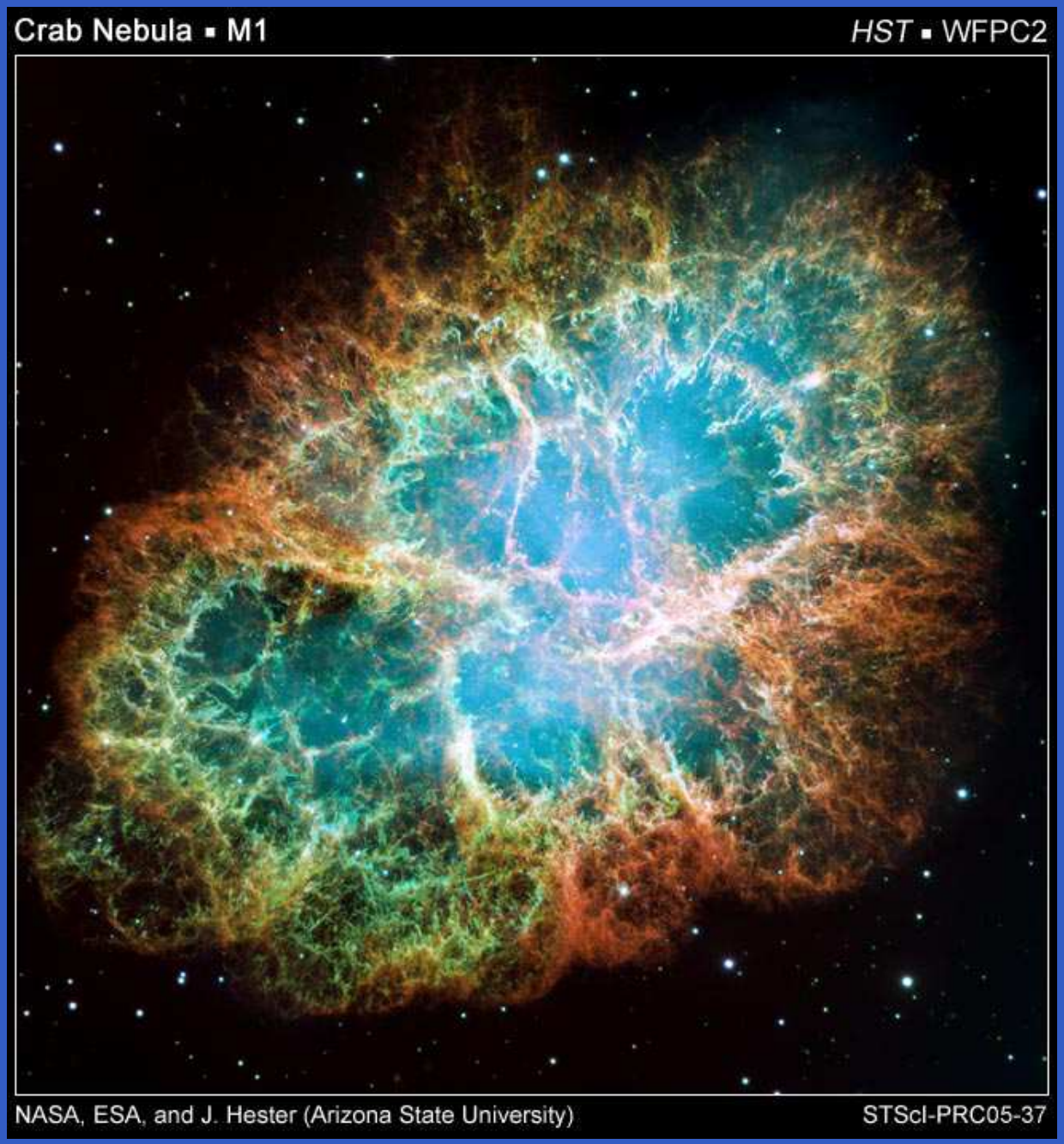
- Introduction
- Hyperons in Neutron Stars: incompatible with massive pulsars?
  - Maximum neutron star masses with hyperons
  - The hyperon puzzle
- Strange Matter in Compact Stars: The QCD Equation of State
  - Low- and high-density limit: neutron matter and QCD
  - Constraints from pulsar mass measurements
  - Implications for EoS and mass-radius relation
- Summary

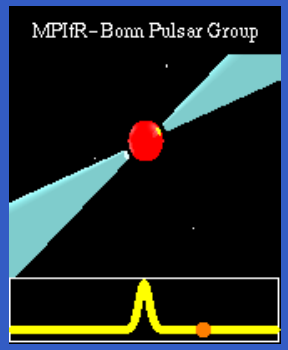
Work done in collaboration with:

- Aleksi Kurkela (CERN)
- Aleksi Vuorinen (Helsinki)
- Eduardo Fraga (Rio de Janeiro)
- Simon Weissenborn (Heidelberg)
- Debarati Chatterjee (Paris)
- Giuseppe Pagliara (Ferrara)
- Matthias Hempel (Basel)
- Irina Sagert (Urbana Champaign)
- Andreas Zacchi (Frankfurt)

Introduction

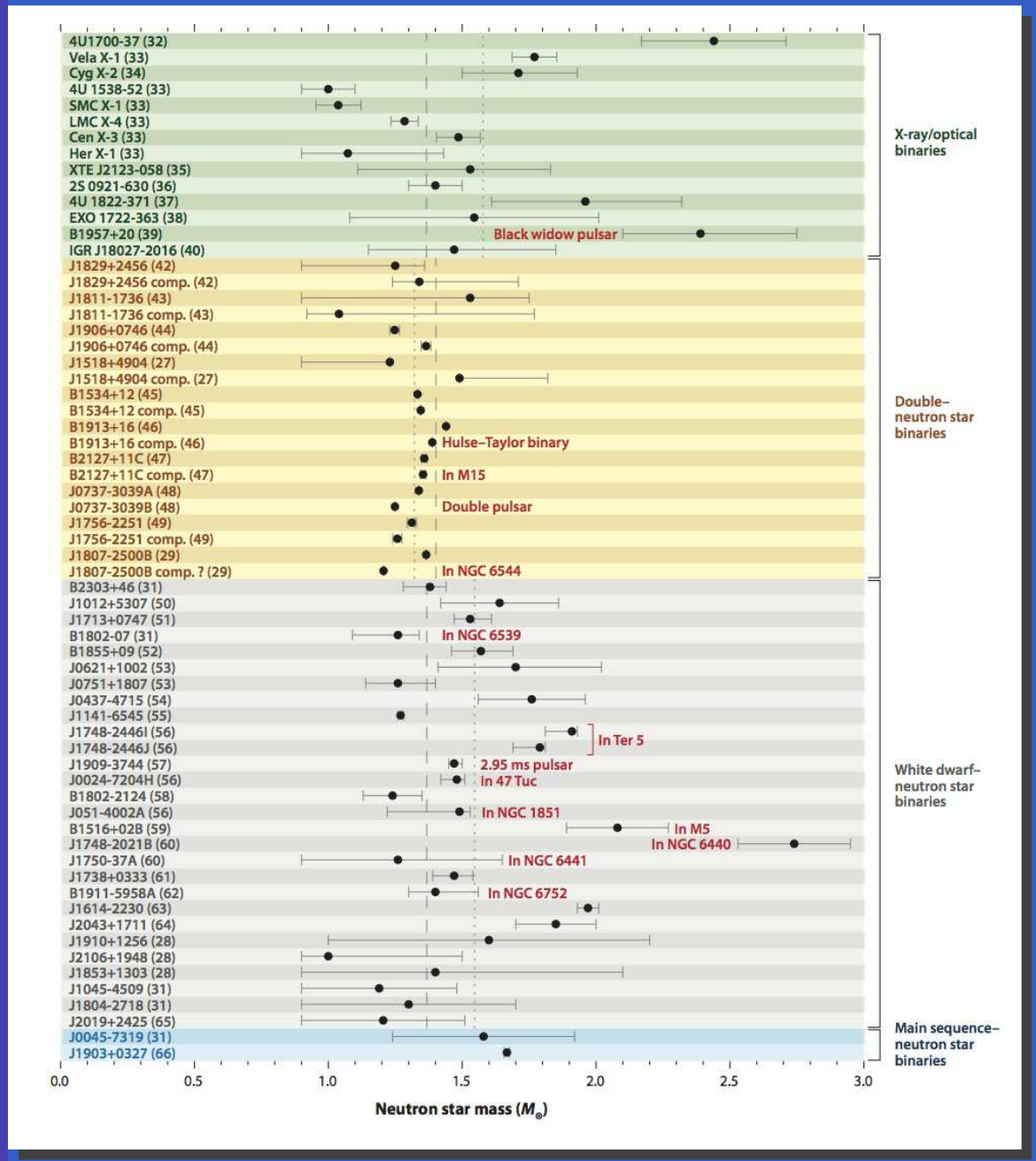
Neutron Stars





- produced in core collapse supernova explosions
- compact, massive objects: radius $\approx$ 10 km, mass $1 - 2M_\odot$
- extreme densities, several times nuclear density: $n \gg n_0 = 2.5 \cdot 10^{14}$ g/cm^3
- in the middle of the crab nebula: a pulsar, a rotating neutron star!

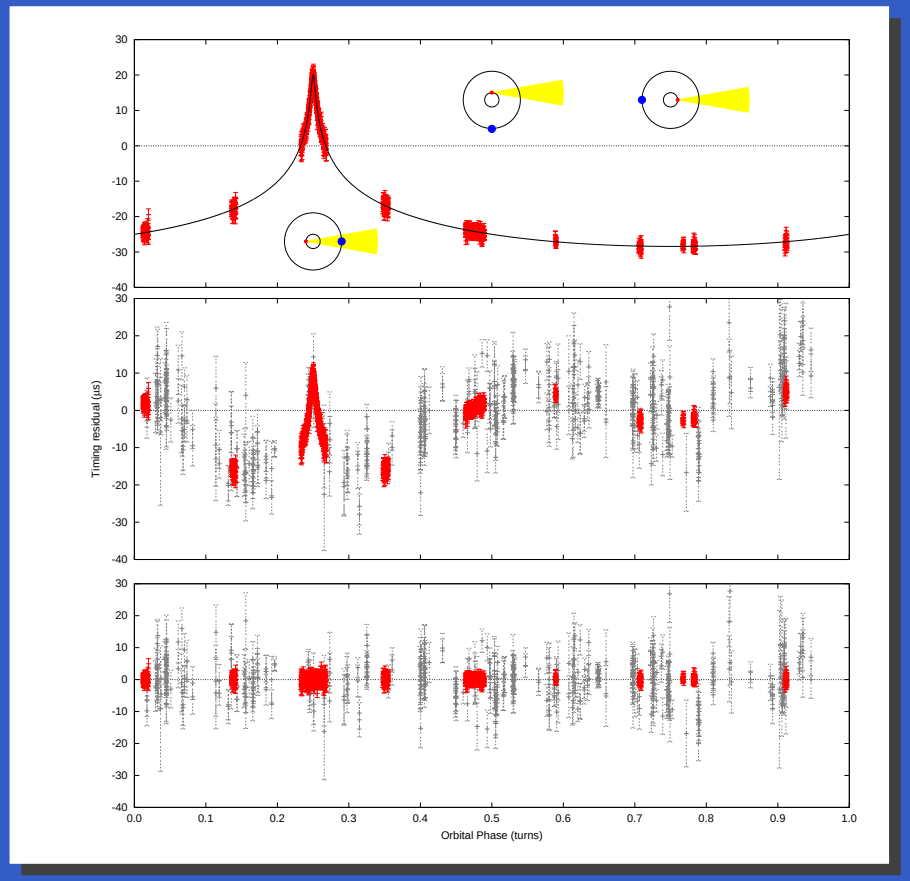
Masses of Pulsars

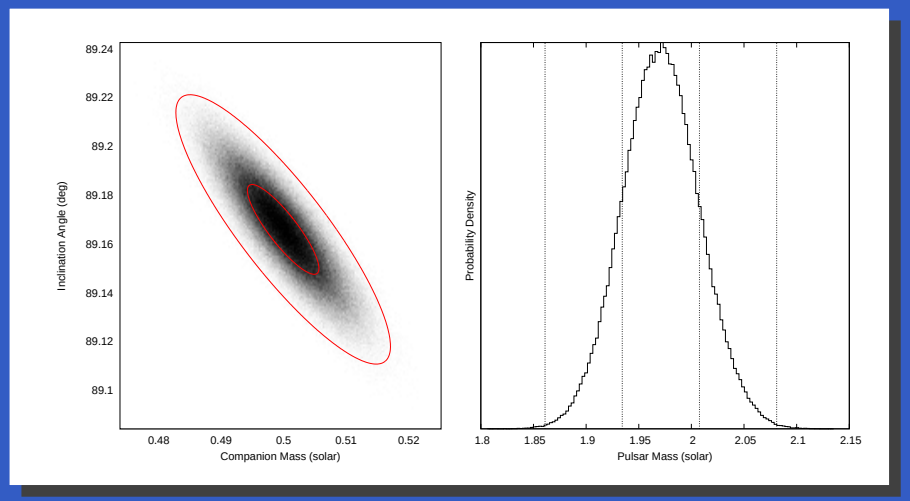


(Lattimer 2012)

- more than 2000 pulsars known with 140 binary pulsars
- best determined mass: $M = 1.4414 \pm 0.0002 M_\odot$ Hulse-Taylor pulsar
- PSR 1748-2021B: $M = 2.74 \pm 0.21 M_\odot$ (stat. analysis in inclination) (Freire et al. 2007)
- black-widow pulsar PSR B1957+20: $M = 2.40 \pm 0.12 M_\odot$ (pulsar consumes its star) (van Kerkwijk et al. 2010)
- black widow pulsar PSR J1311-3430: $M > 2.1 M_\odot$ (Romani et al. 2012)

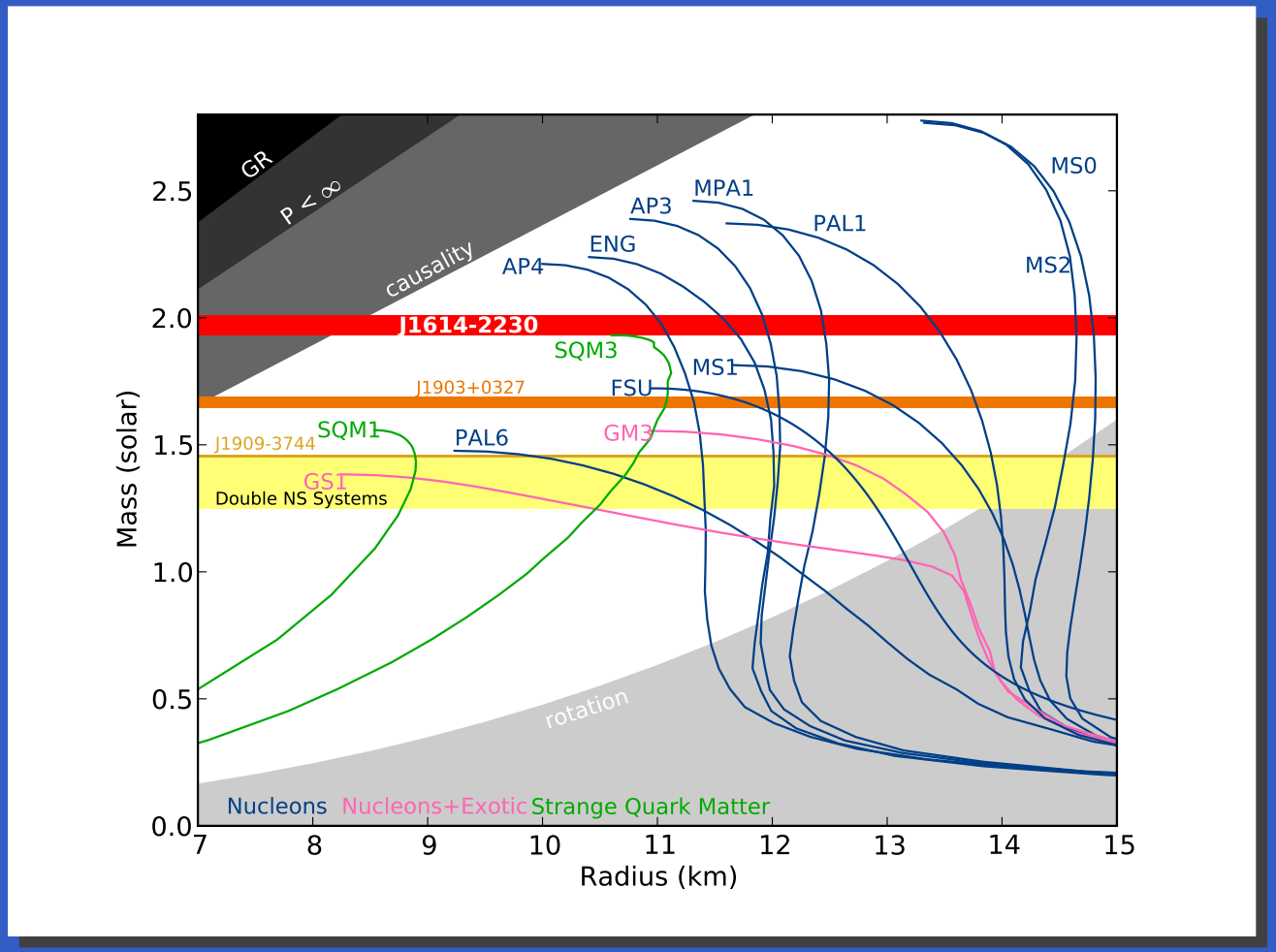
Mass measurement of pulsar PSR J1614-2230 (Demorest et al. 2010)





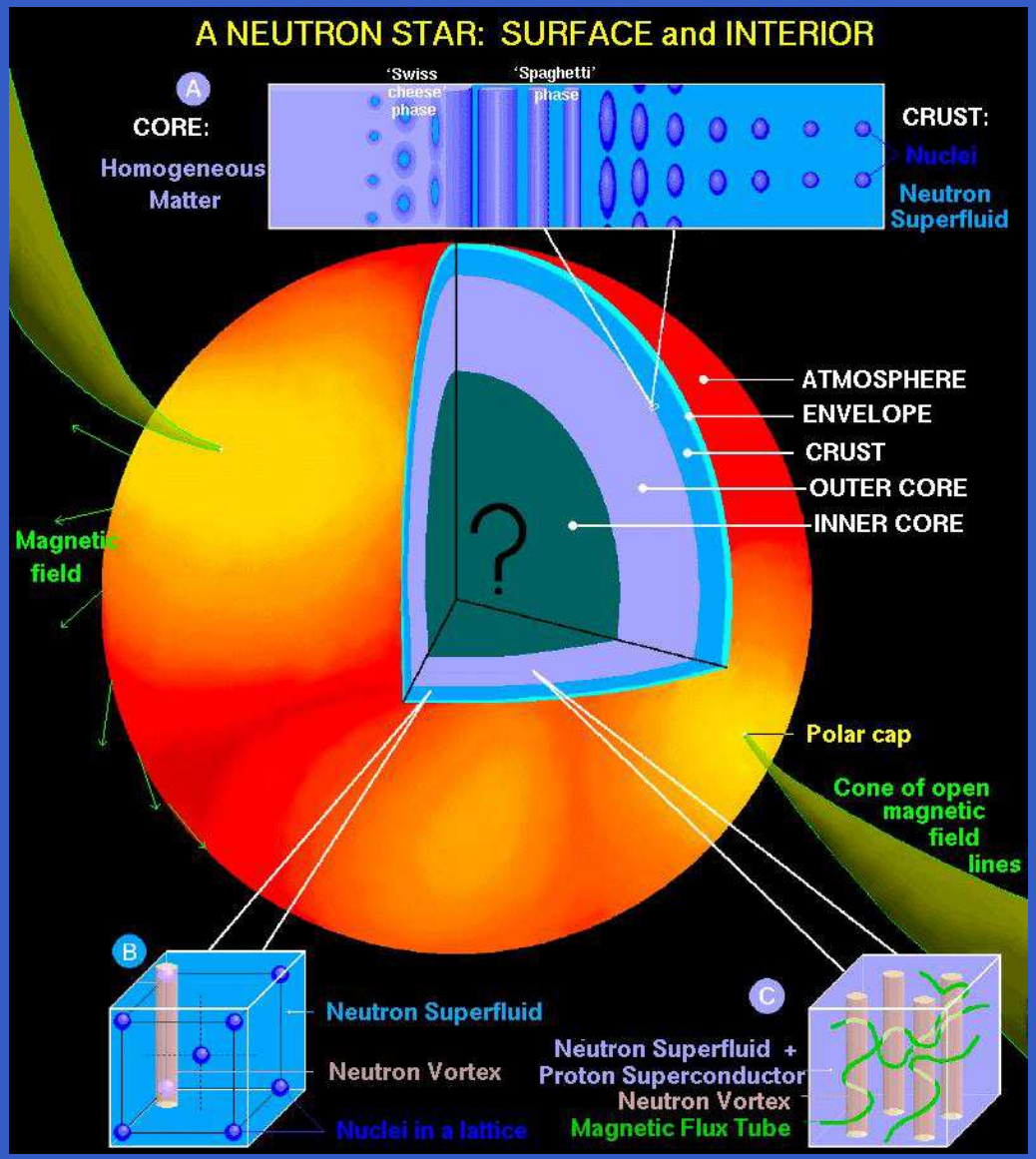
- extremely strong signal for Shapiro delay
- Shapiro delay parameters r and s alone give $M = (1.97 \pm 0.04) M_\odot$ – very high mass!
- high pulsar masses confirmed with PSR J0348+0342: $M = (2.01 \pm 0.04) M_\odot$ (Antoniadis et al. 2013)
- considerable constraints on neutron star matter properties!

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



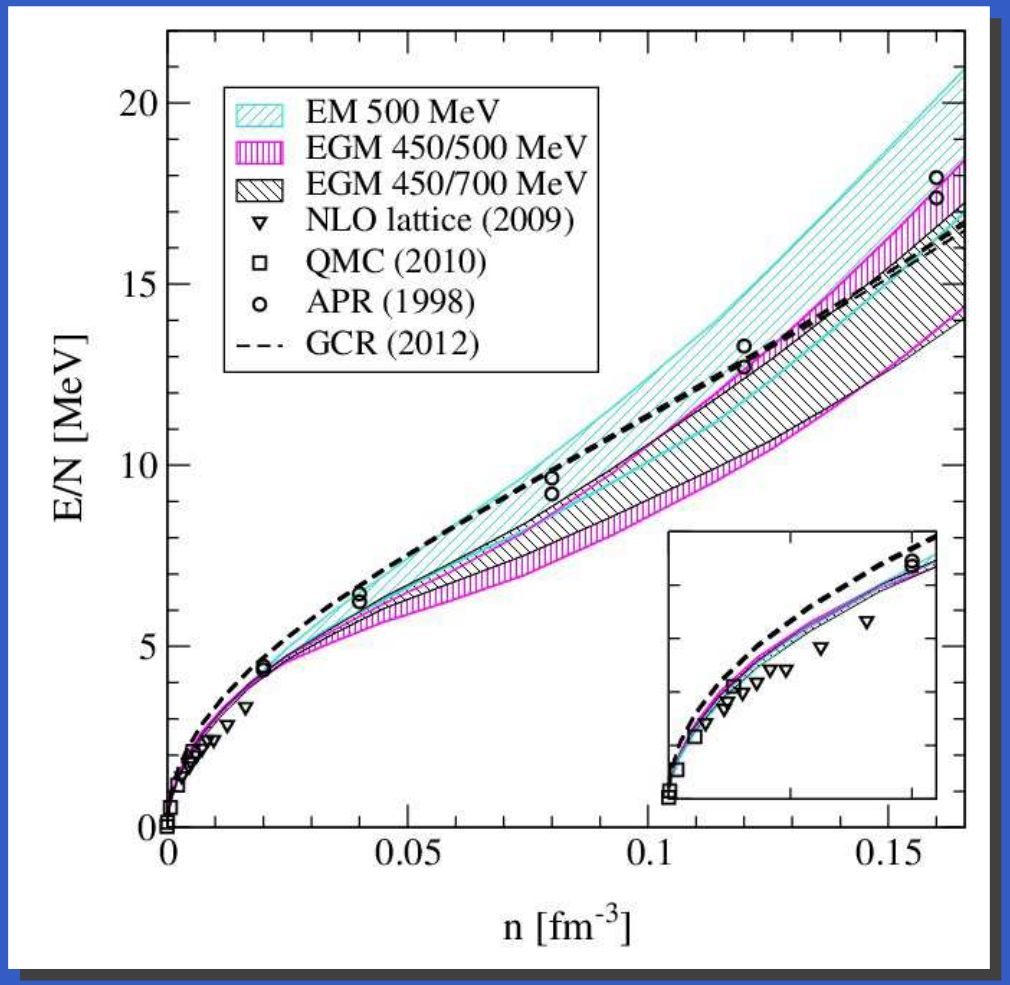
- spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4 M_\odot$
- Schwarzschild limit (GR): $R > 2GM = R_s$
- causality limit for EoS: $R > 3GM$
- mass limit from PSR J1614-2230 (red band): $M = (1.97 \pm 0.04) M_\odot$

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^-)

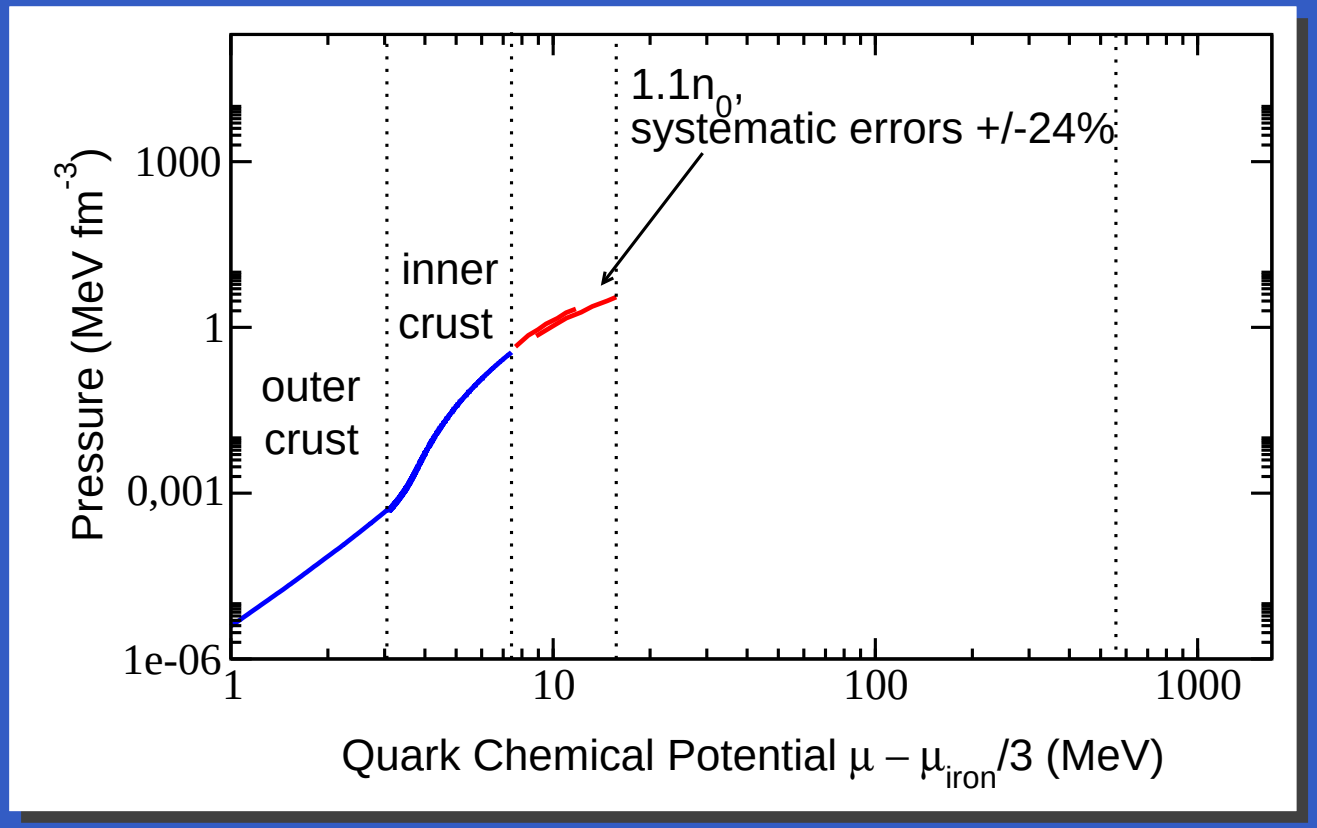
Pure Neutron Matter: State of the Art



(Tews, Krüger, Hebeler, Schwenk 2012)

- chiral effective field theory including N^{3}LO terms with 3N and 4N forces
- comparison to Quantum Monte Carlo Simulations QMC and GCR
- band of uncertainty for the neutron equation of state up to saturation density

The EoS for the neutron star crust and neutron matter



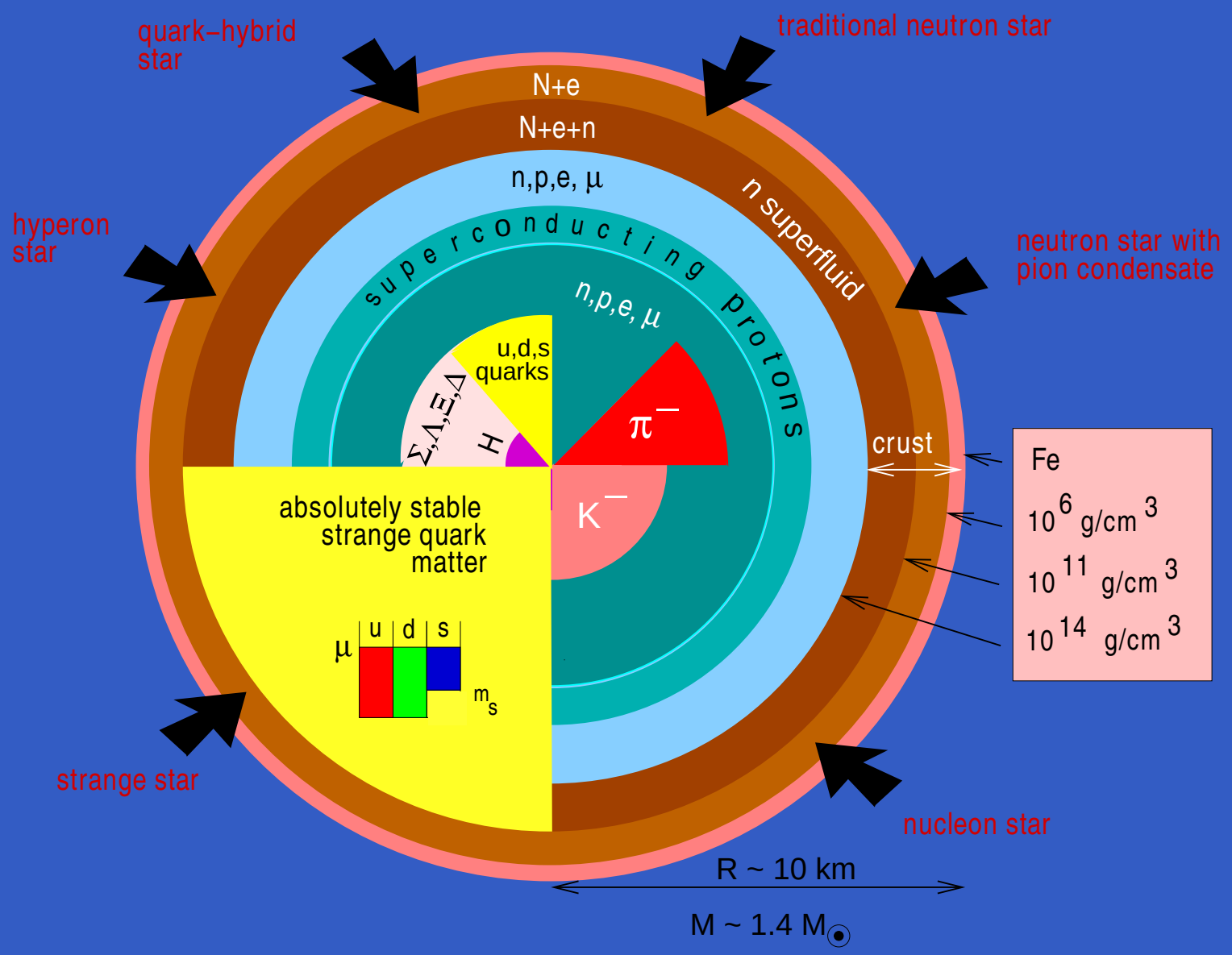
(Kurkela et al. (2014))

- EoS for pure neutron matter very well determined recently

  (Gandolfi, Carlson, Reddy 2012; Tews, Krüger, Hebeler, Schwenk 2012; Sammarruca, Chen, Coraggio, Itaco, Machleidt 2012; Holt, Kaiser, Weise 2011; Hebeler, Schwenk 2010)

- up to and slightly above saturation density ($\epsilon_0 = 2.5 \cdot 10^{14}$ g/cm^3)

Structure of a Neutron Star (Fridolin Weber)



Hyperons in Neutron Stars

Experimental Status of Hypernuclear Systems

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

NΣ: ${}^4_\Sigma$He hypernucleus bound by isospin forces
Σ^- atoms: potential is repulsive

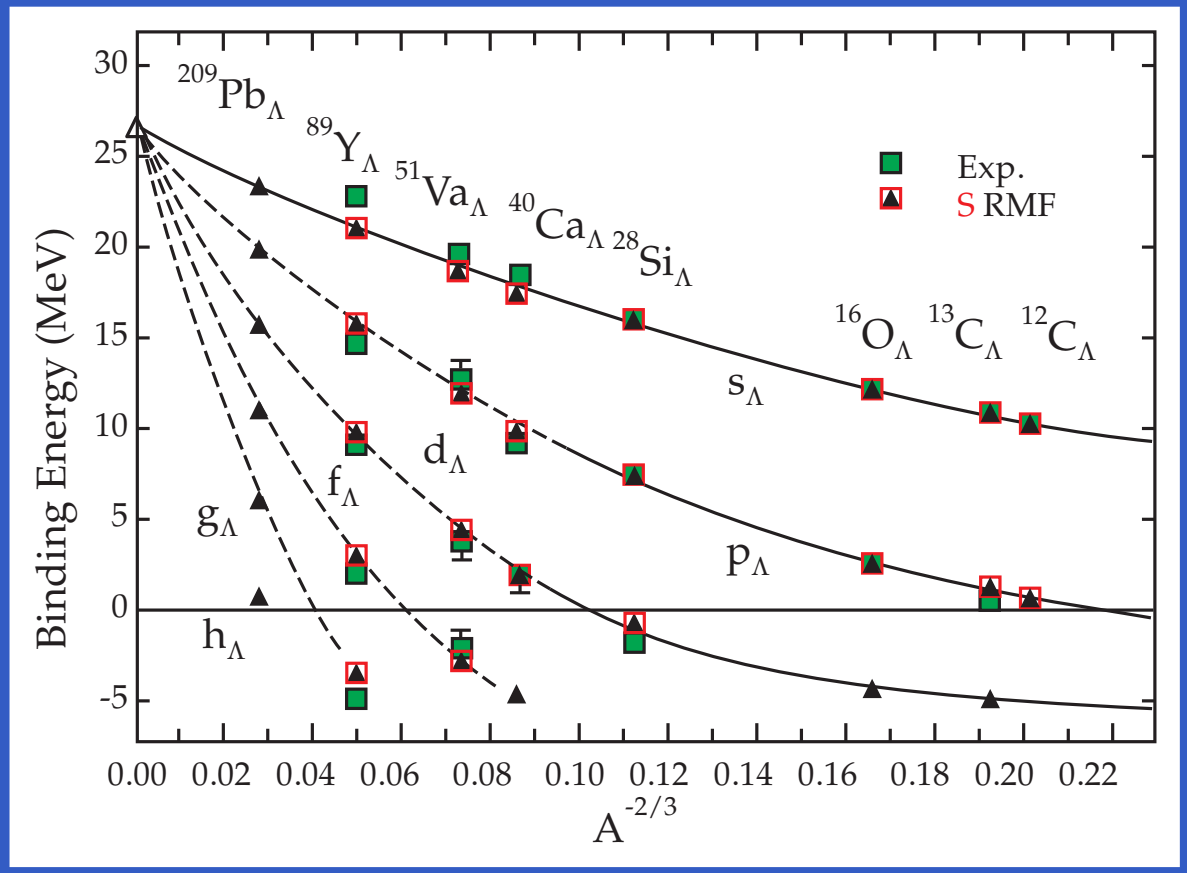
NΞ: attractive $\rightarrow$ 7 Ξ hypernuclear events
$U_\Xi = -28$ MeV at $n = n_0$
quasi-free production of Ξ: $U_\Xi = -18$ MeV

$\Lambda\Lambda$: attractive $\rightarrow$ 3 $\Lambda\Lambda$ hypernuclei measured

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

hypernuclear programs: JLab, J-PARC, PANDA, Alice@LHC, PANDA, HYPHI, CBM@FAIR: access to strange dibaryons, multi-hypernuclei!

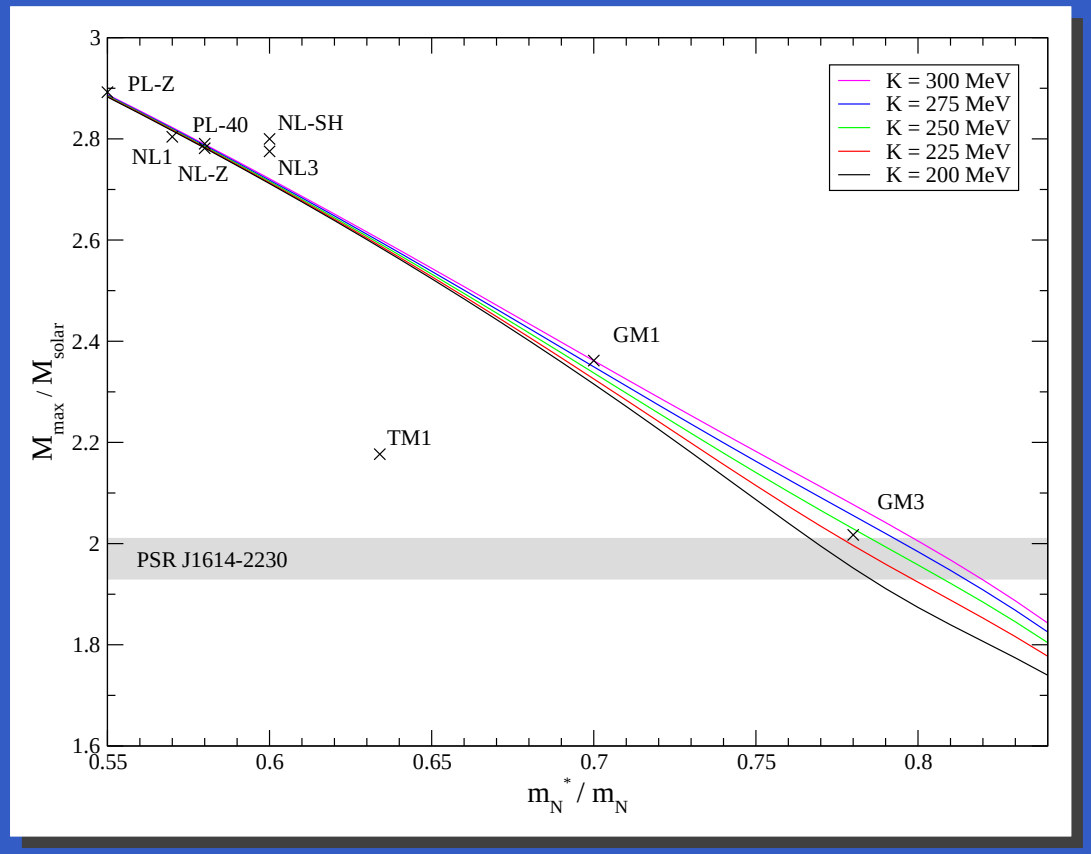
Λ Single–Particle Energies



(Rufa, JS, Maruhn, Stöcker, Greiner, Reinhard (1990))

- measured in (π^+, K^+) reactions
- fit to single particle energies: $U_\Lambda = -27$ MeV for $A \to \infty$
- note: only for the Λ (besides nuclei) do we *know* its in-medium properties!
- need to be considered for neutron star matter due to weak equilibrium!

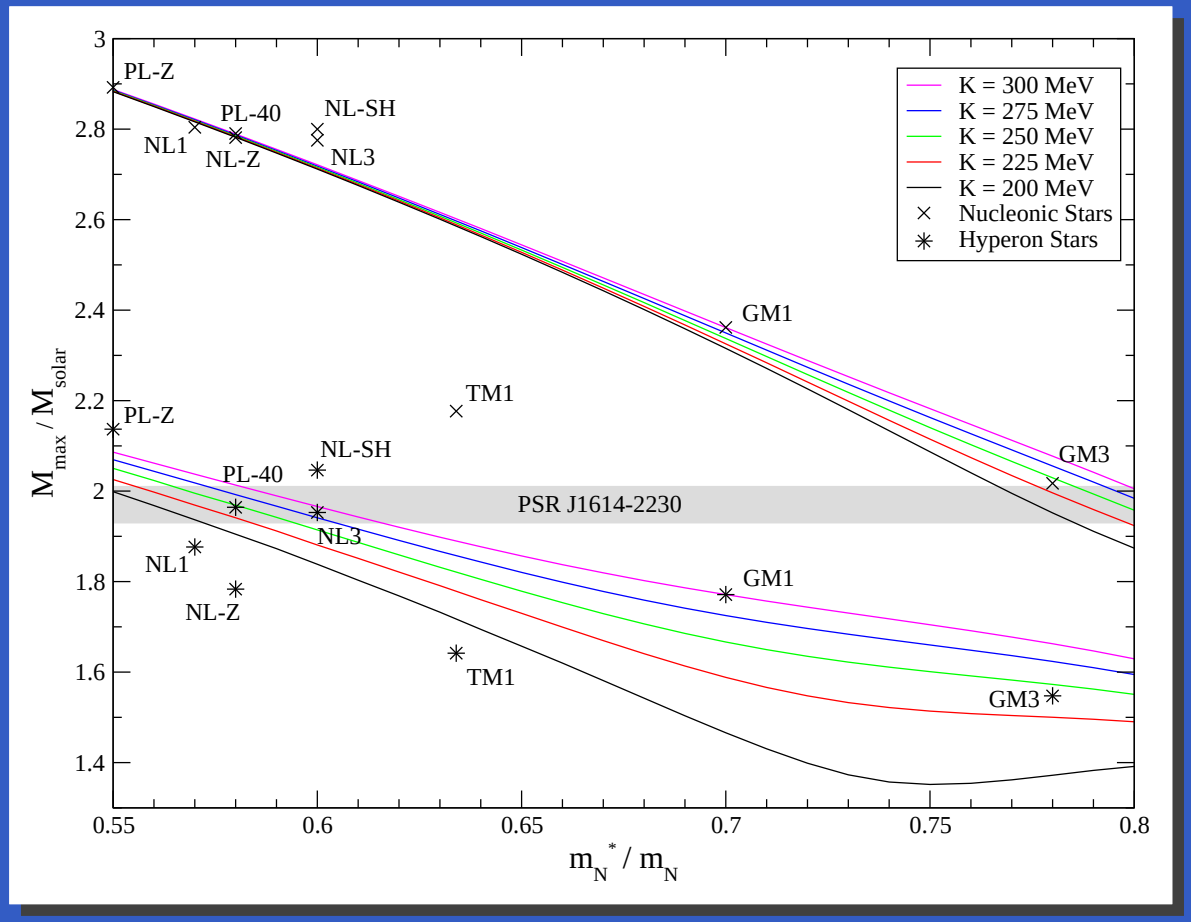
Maximum mass with nucleons only (mean field models)



(Weissenborn, Chatterjee, JSB 2011)

- maximum mass for different effective masses m^*/m and compressibility K
- change in maximum mass for different compressibilities: at most $0.1 M_\odot$
- change in maximum mass for different m^*/m: up to $1 M_\odot$!
- values of $M > 2 M_\odot$ possible for reasonable values of m^*/m

Maximum mass with hyperons (mean field models)

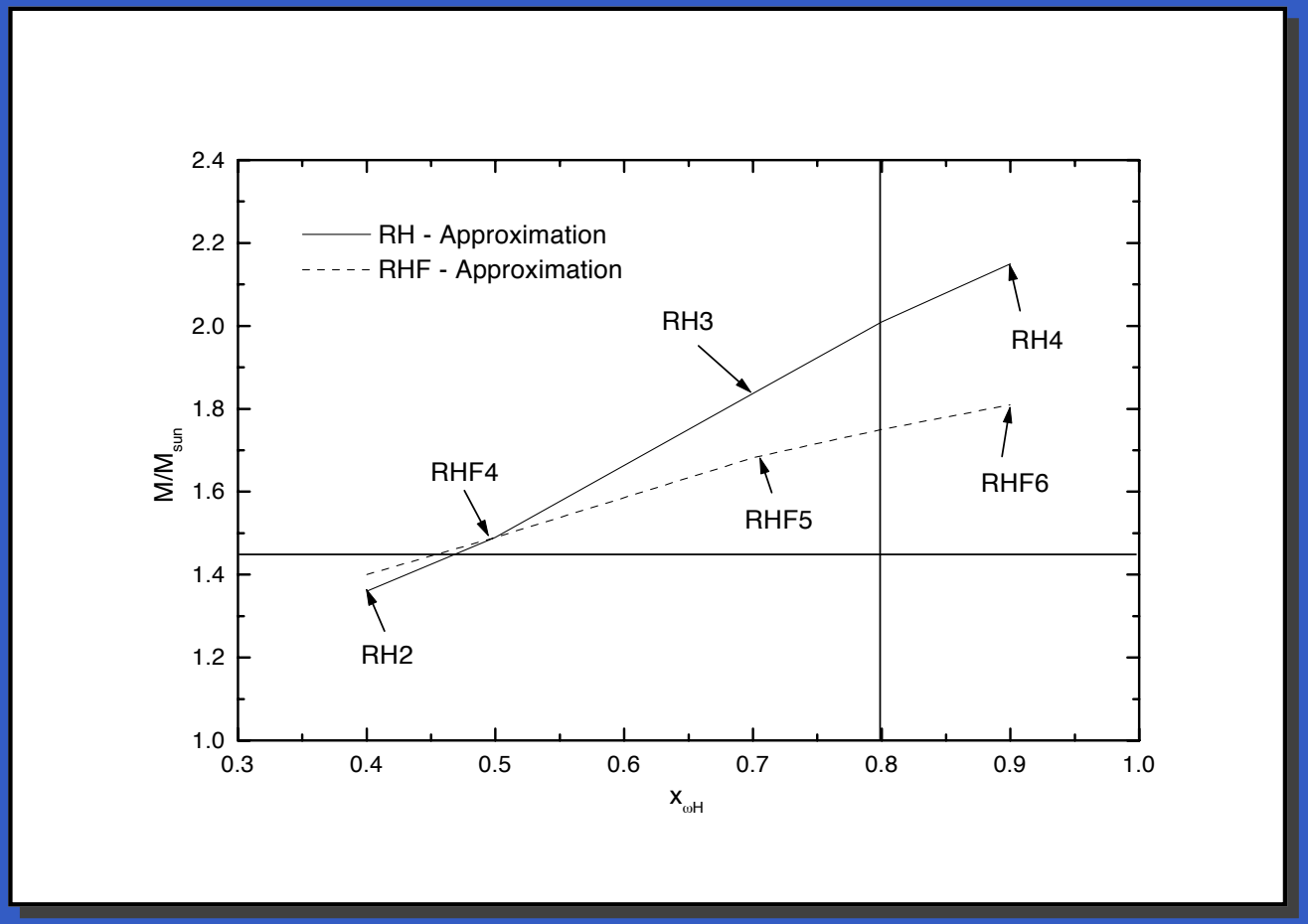


(Weissenborn, Chatterjee, JSB 2011)

- maximum mass for different effective masses of RMF parameter sets
- stars: parameter sets with standard SU(6) baryon couplings (no ϕ meson)
- values of $M > 2M_\odot$ possible with hyperons for stiff nuclear EoS

Maximum neutron star masses with hyperons

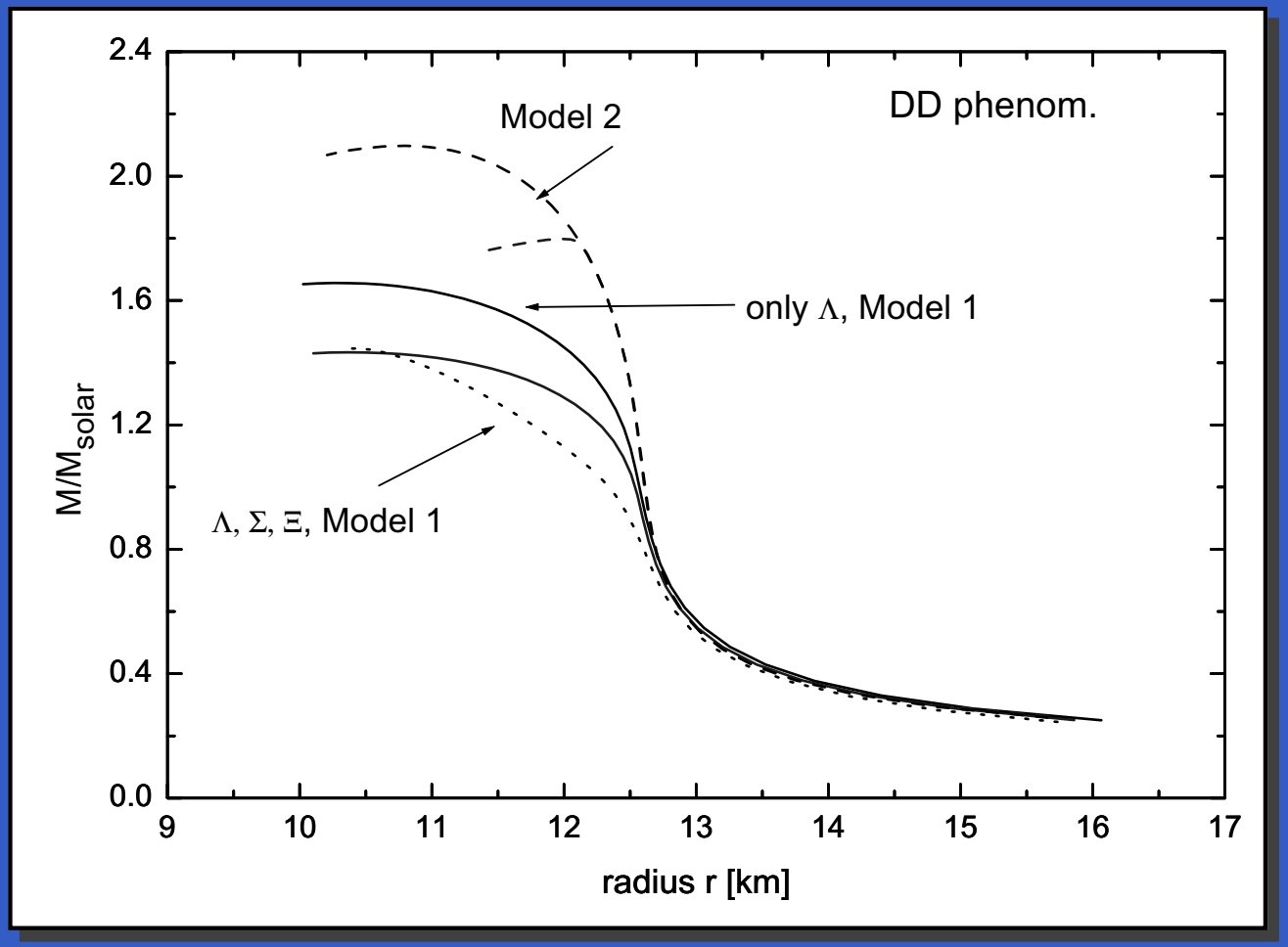
Maximum mass with hyperons (Relativistic Hartree)



(Huber, Weigel, Weber 1999)

- maximum mass in relativistic Hartree (RH) and relativistic Hartree-Fock (RHF)
- maximum mass increases with vector coupling strength
- relativistic Hartree model can reach $2M_\odot$

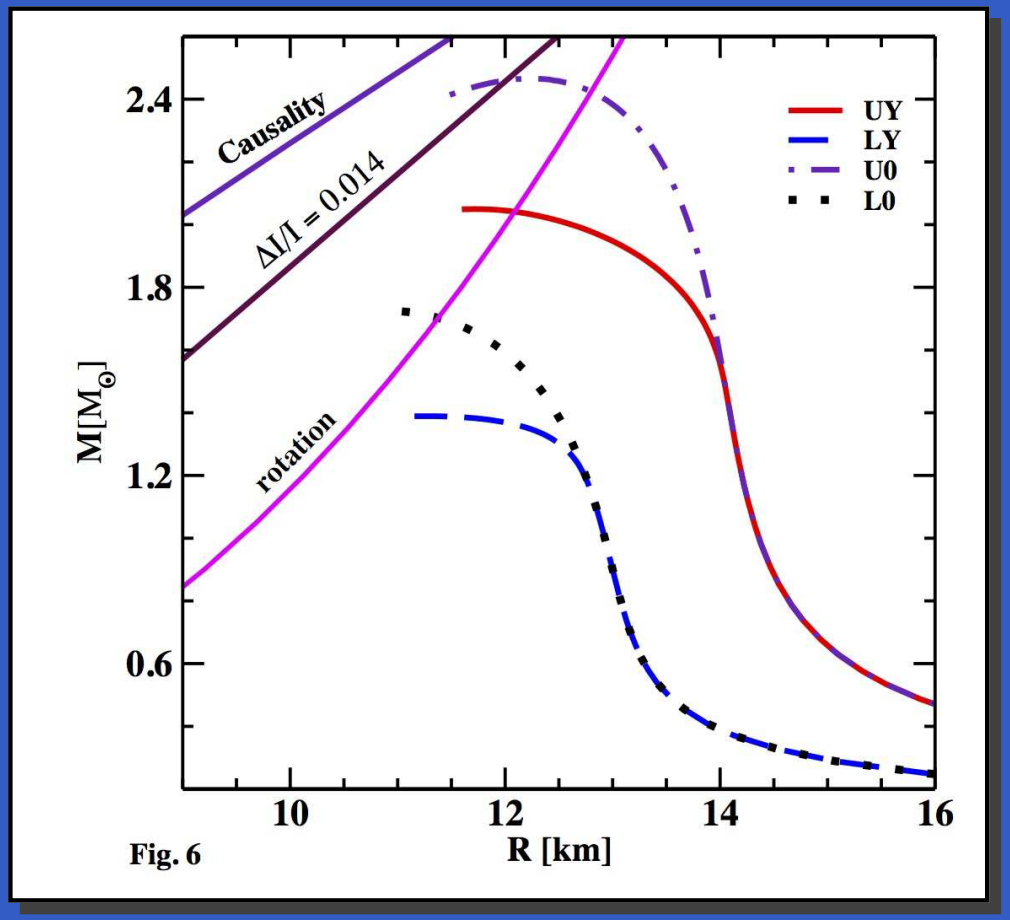
Maximum mass in Density Dependent Hadron Field Theory



(Hofmann, Keil, Lenske 2001)

- maximum mass in Density Dependent Hadron Field Theory
- model 2: vertex function for hyperons depends on hyperon density
- upper curve: SU(6) symmetry for vector coupling strength

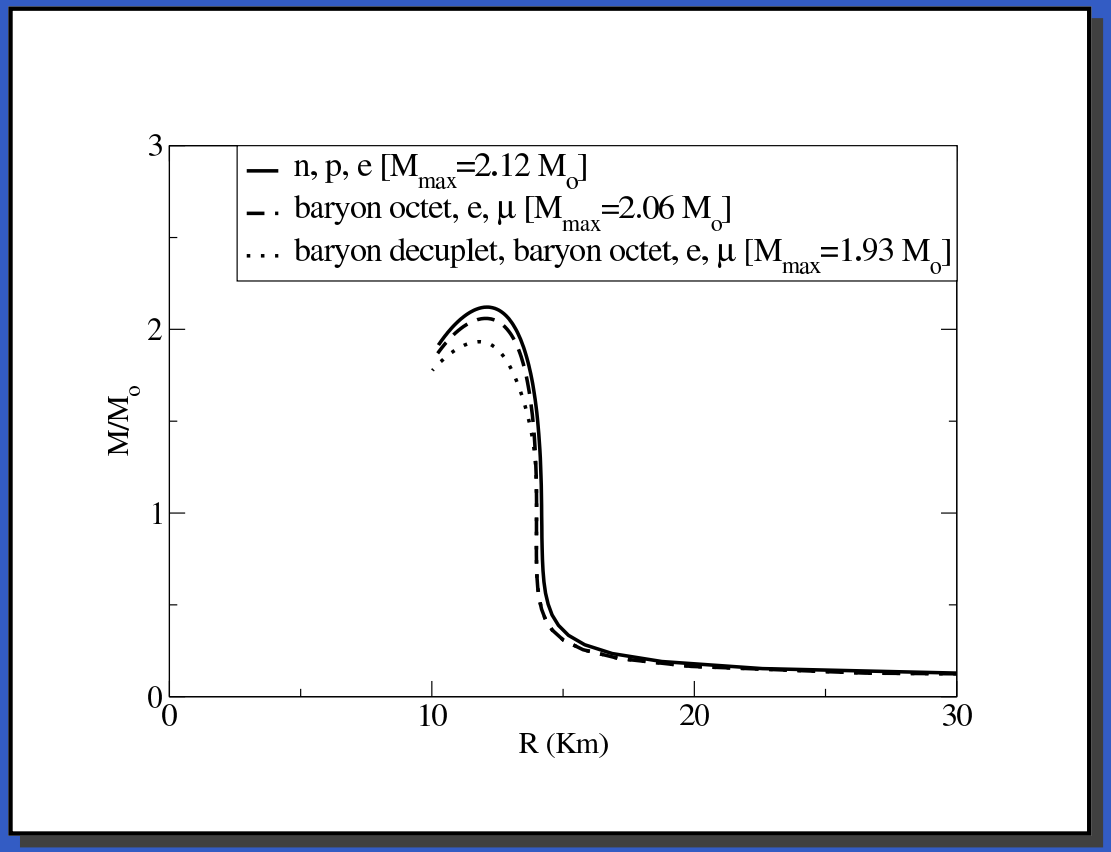
Maximum mass in Extended RMF model



(Dhiman, Kumar, Agrawal 2007)

- maximum mass in extended relativistic field theoretical model
- fitted to properties of nuclei and hypernuclei
- L0, U0: without hyperons; LY, UY: with hyperons
  (with different neutron skin thicknesses for ^{208}Pb)

Maximum mass in a chiral SU(3) model



(Dexheimer and Schramm 2008)

- maximum mass in a hadronic chiral SU(3) model
- describes properties of nuclei and hypernuclei
- interaction (repulsion!) with full SU(3) flavour symmetry
- inclusion of full baryon octet gives $M = 2.06 M_\odot$

The hyperon puzzle

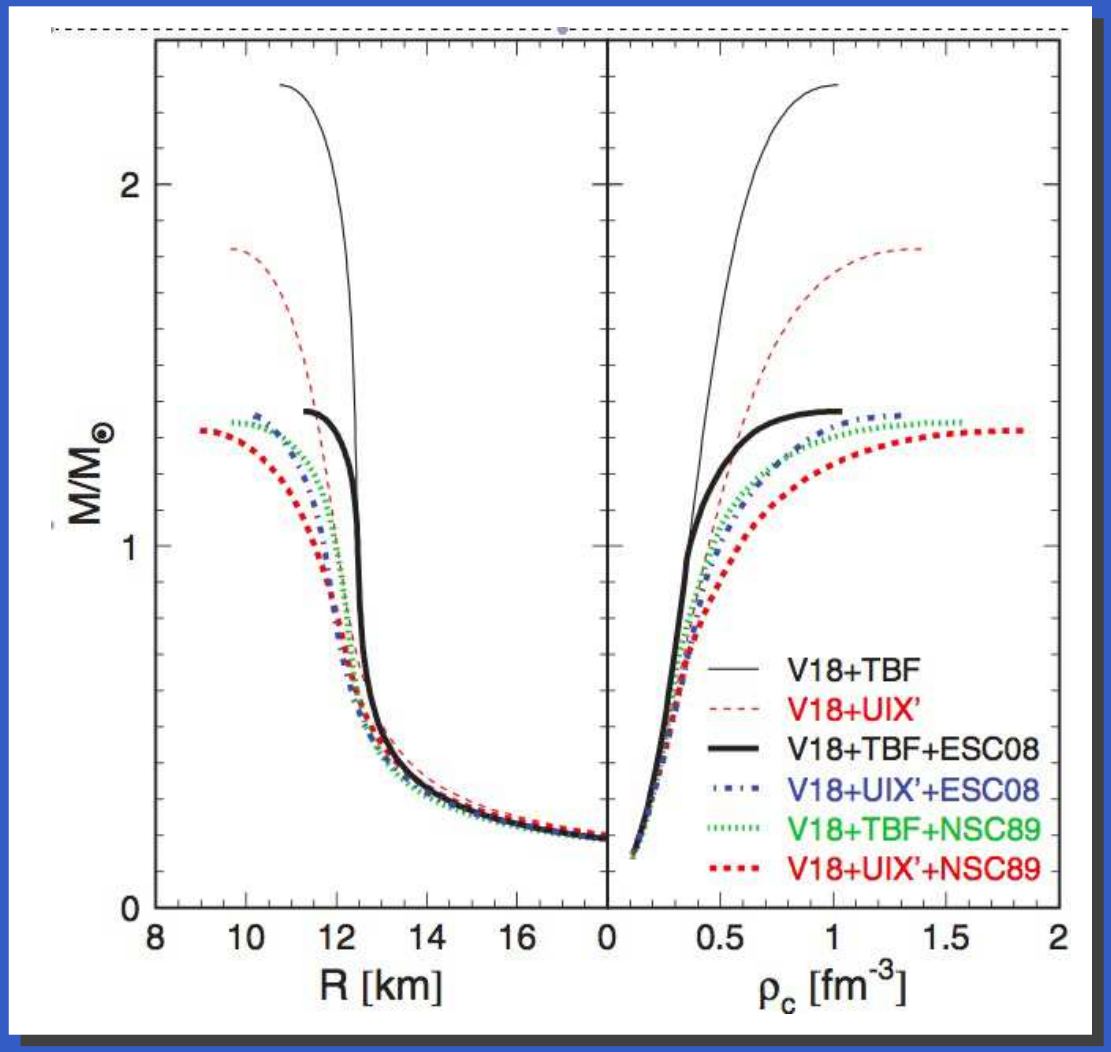
Maximum mass with hyperons in ab-initio approaches

modern many-body calculations based on two-body potentials (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): $M_{\rm max} < 1.4 M_\odot$ ($V_{\rm low-k}$)
- Schulze and Rijken (2011): $M_{\rm max} < 1.4 M_\odot$ (ESC08)
- EoS too soft with hyperons, too low masses!

$\Longrightarrow$ The Hyperon Puzzle!!!

Maximum masses of neutron stars with hyperons (ab-initio)



(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

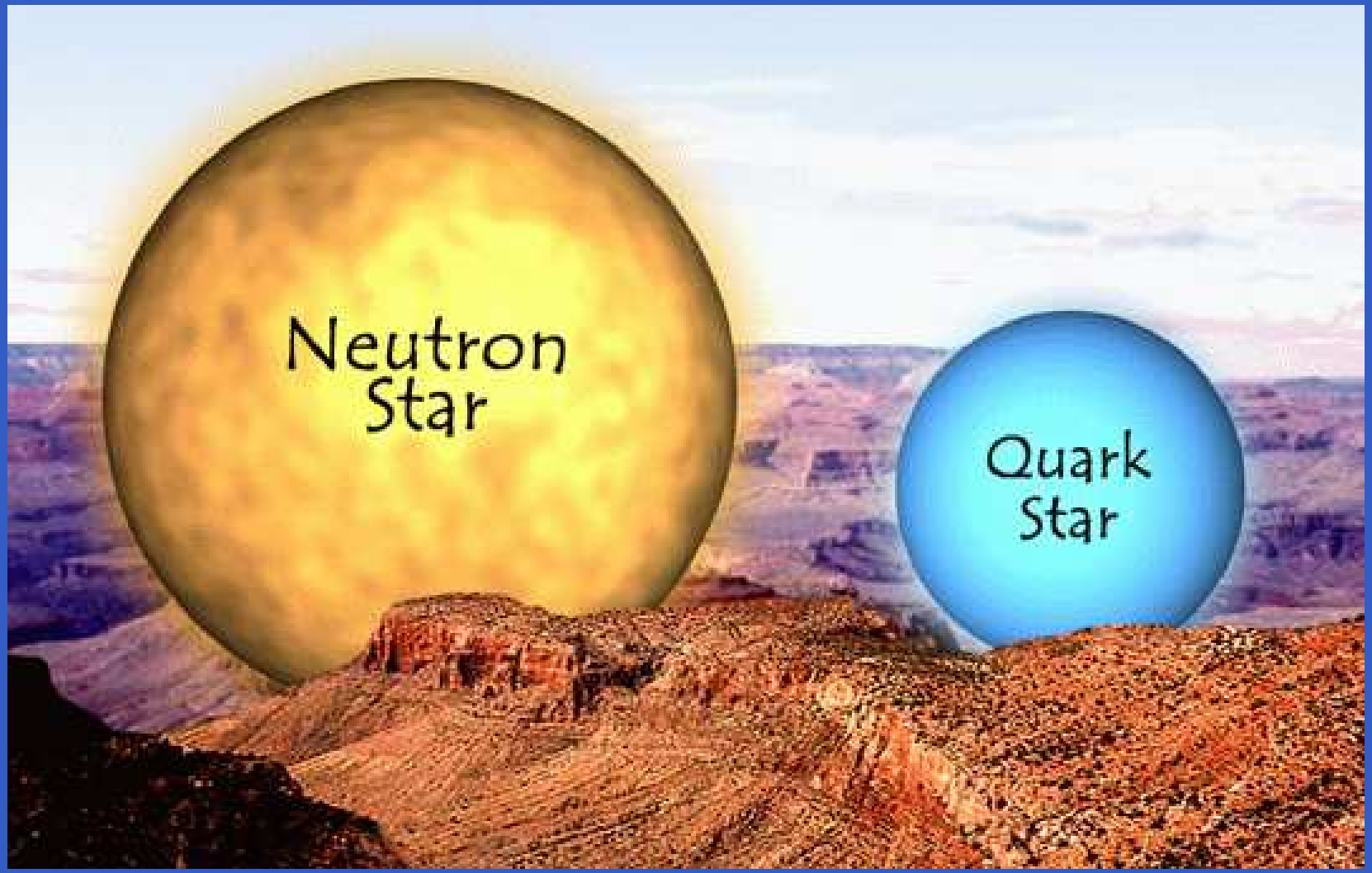
$\Longrightarrow$ models based on two- and three-body baryon potentials fail!

The hyperon puzzle: new vistas?

- many models with hyperons fail to describe a $2M_\odot$ pulsar mass
- closing the eyes and ignoring hyperons is NOT an option!
- breakdown of baryon-based models around $2n_0$?
- matter not describable with standard baryonic models appears at high densities?
- the hyperon puzzle $\Longrightarrow$
  signaling the onset of a new phase?

Strange Matter in Compact Stars

A Quark Star? (NASA press release 2002)

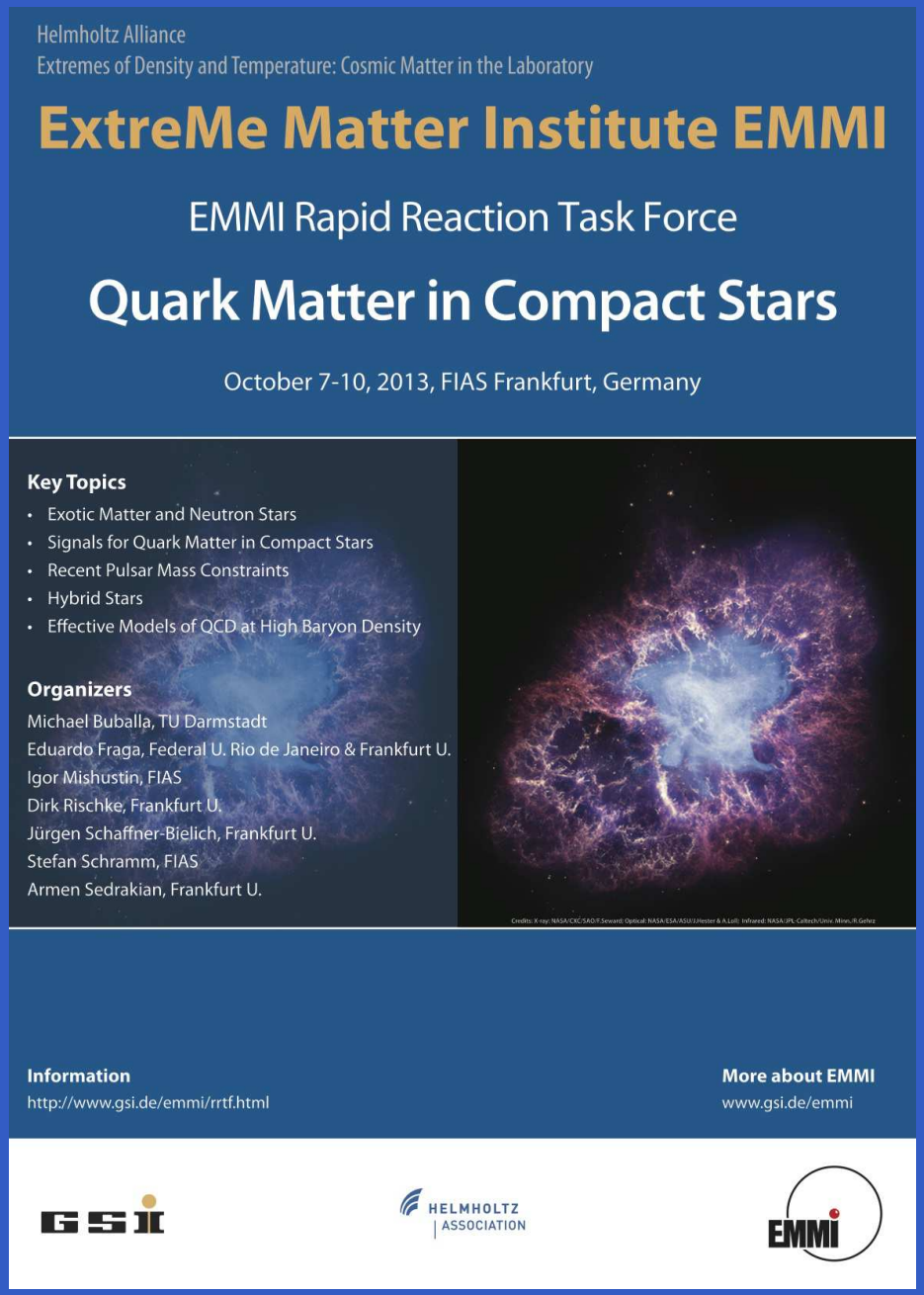


NASA news release 02-082:

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

— a quark star?

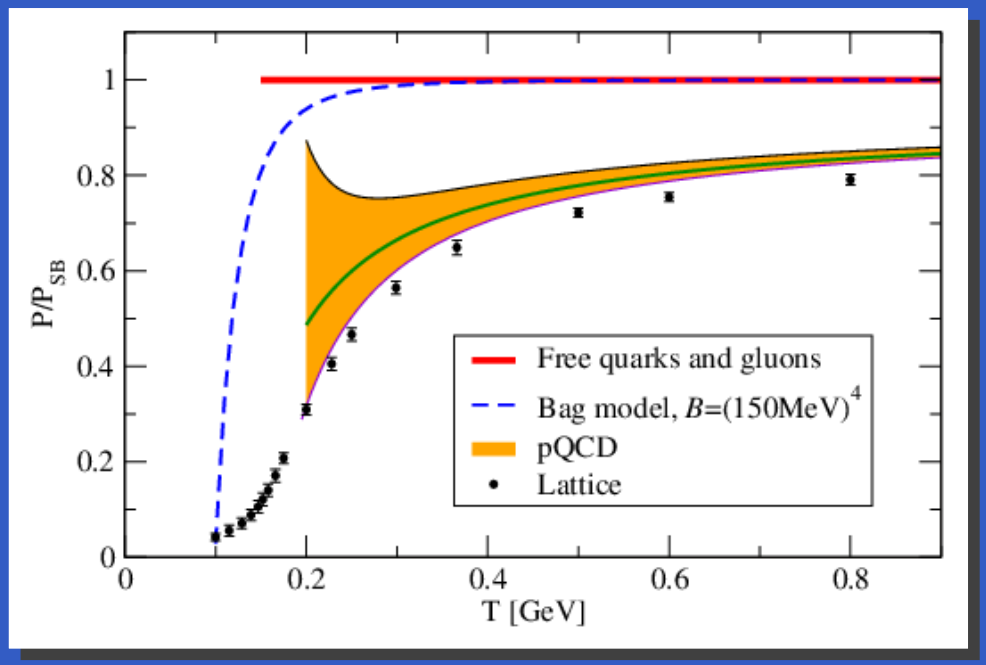
Task Force Meeting on Quark Matter in Compact Stars

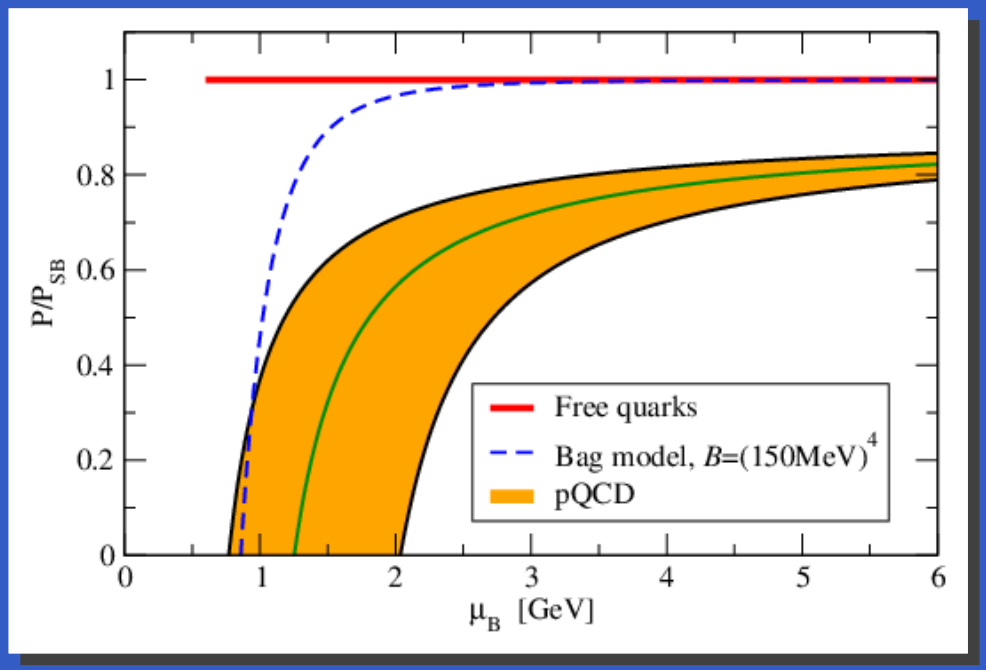


EMMI Rapid Reaction Task Force Meeting on 'Quark Matter in Compact Stars', FIAS, October 6-10, 2013

(report: Buballa, Dexheimer, Drago, Fraga, Haensel, Mishustin, Pagliara, JSB, Schramm, Sedrakian, Weber, arXiv:1402.6911)

High-Density Side: perturbative QCD

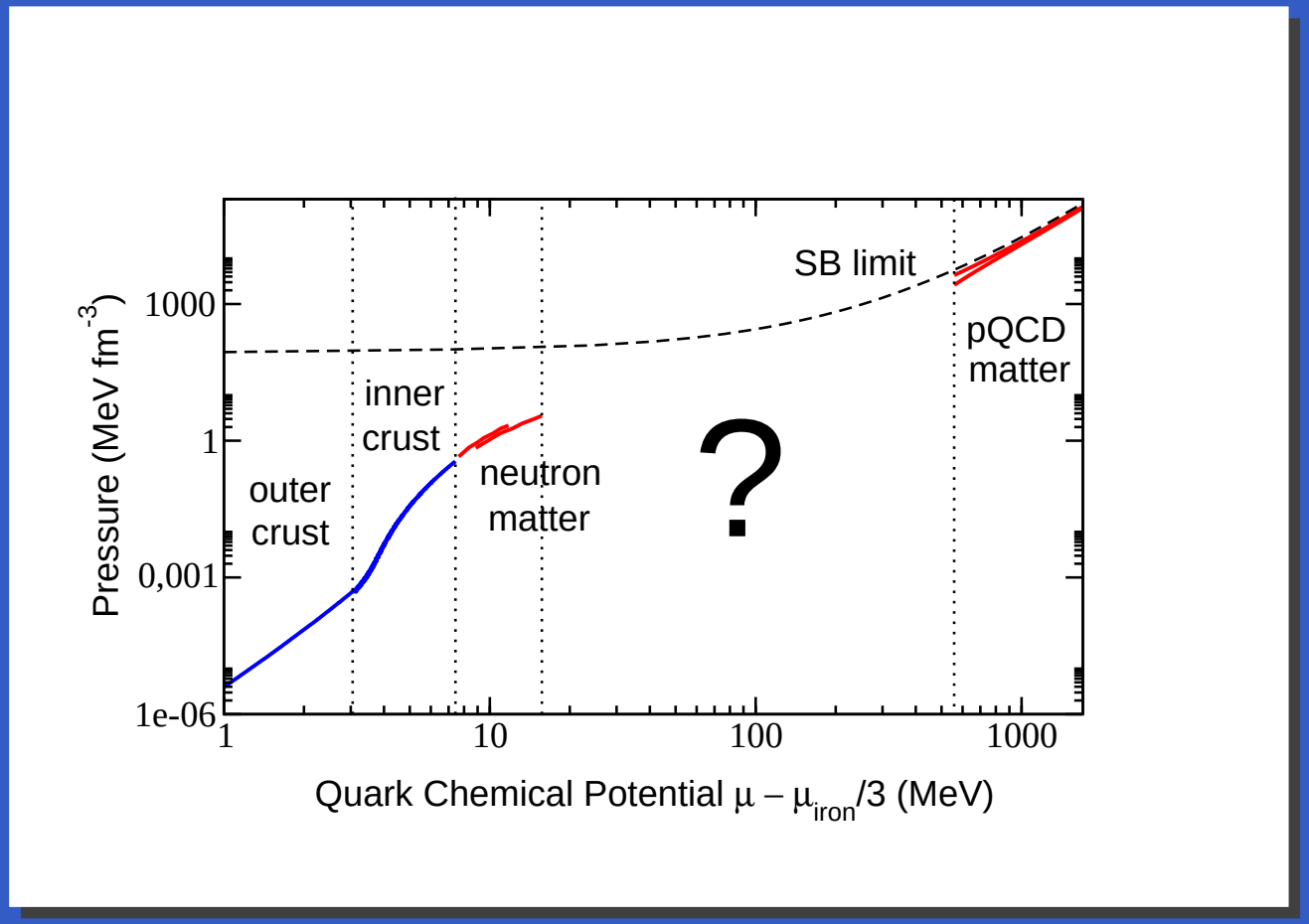




(Fraga, Kurkela, Vuorinen, 2013)

- asymptotic freedom of strong interactions (QCD): weakly interacting at large scales (temperature and/or chemical potential)
- perturbative calculations up to $\mathcal{O}(\alpha_s^2)$:
  follows lattice data at nonzero temperature
- band of uncertainty for the pQCD equation of state at nonzero μ
  (from choice of renormalization scale)

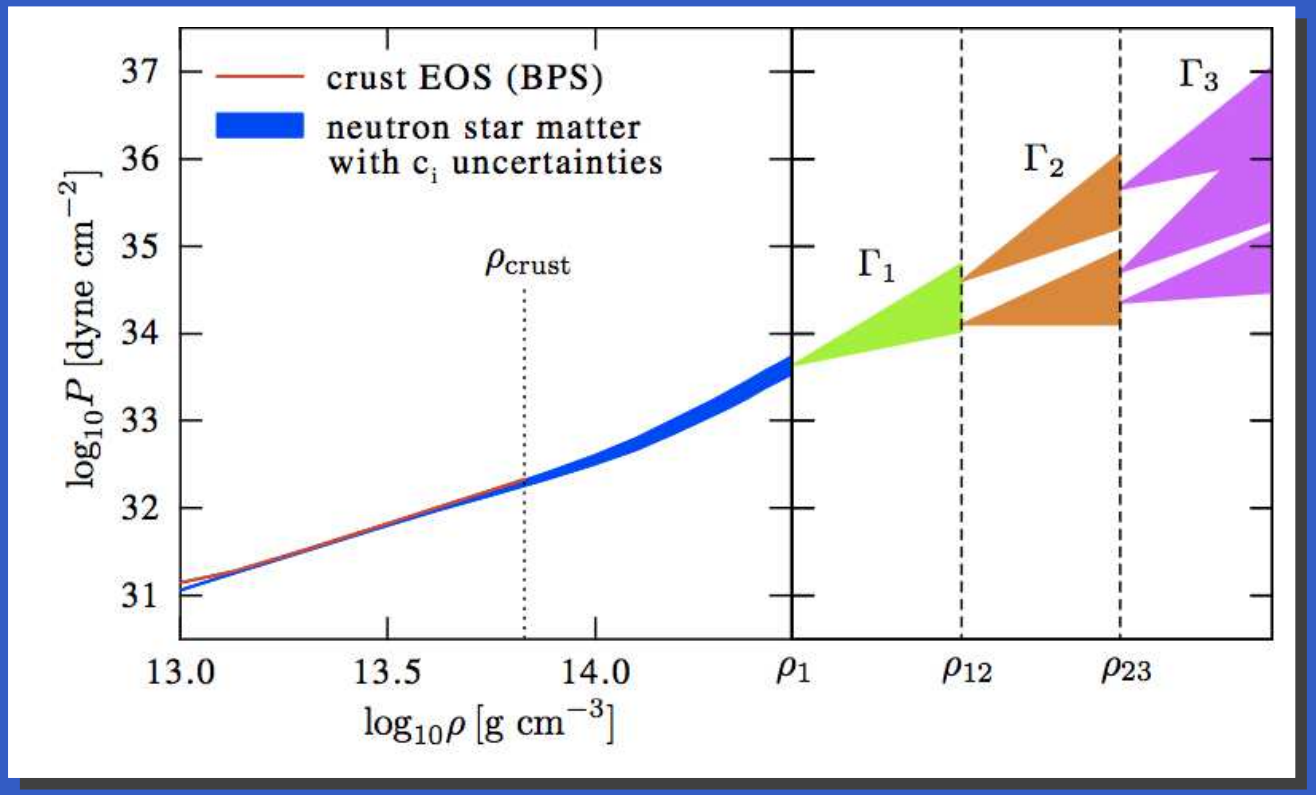
What we know about the EoS for neutron star matter



(Kurkela, Fraga, JSB, Vuorinen (2014))

- pressure versus the quark chemical potential (above the one of ^{56}Fe)
- low-density regime: outer crust (lattice of nuclei), inner crust (lattice of nuclei in a neutron fluid), neutron matter
- high-density regime: pQCD, close to Stefan-Boltzmann limit

Extrapolate EoS from neutron matter with polytropes

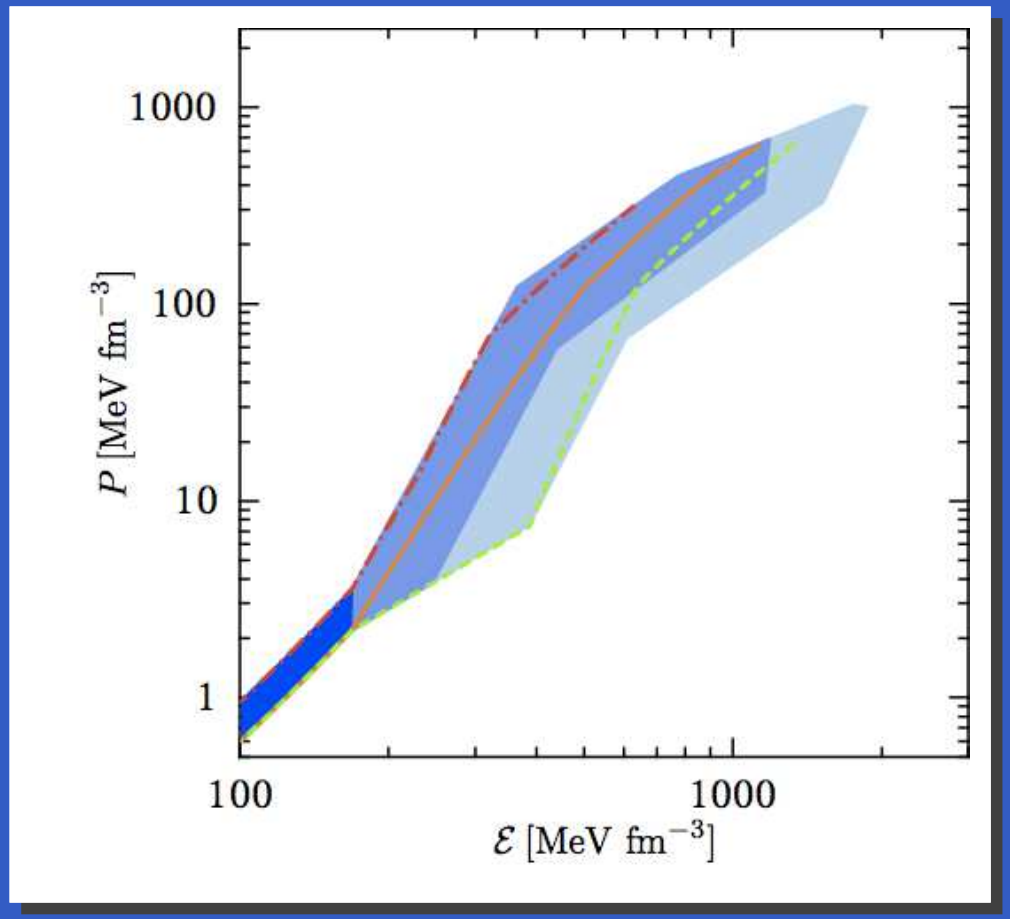


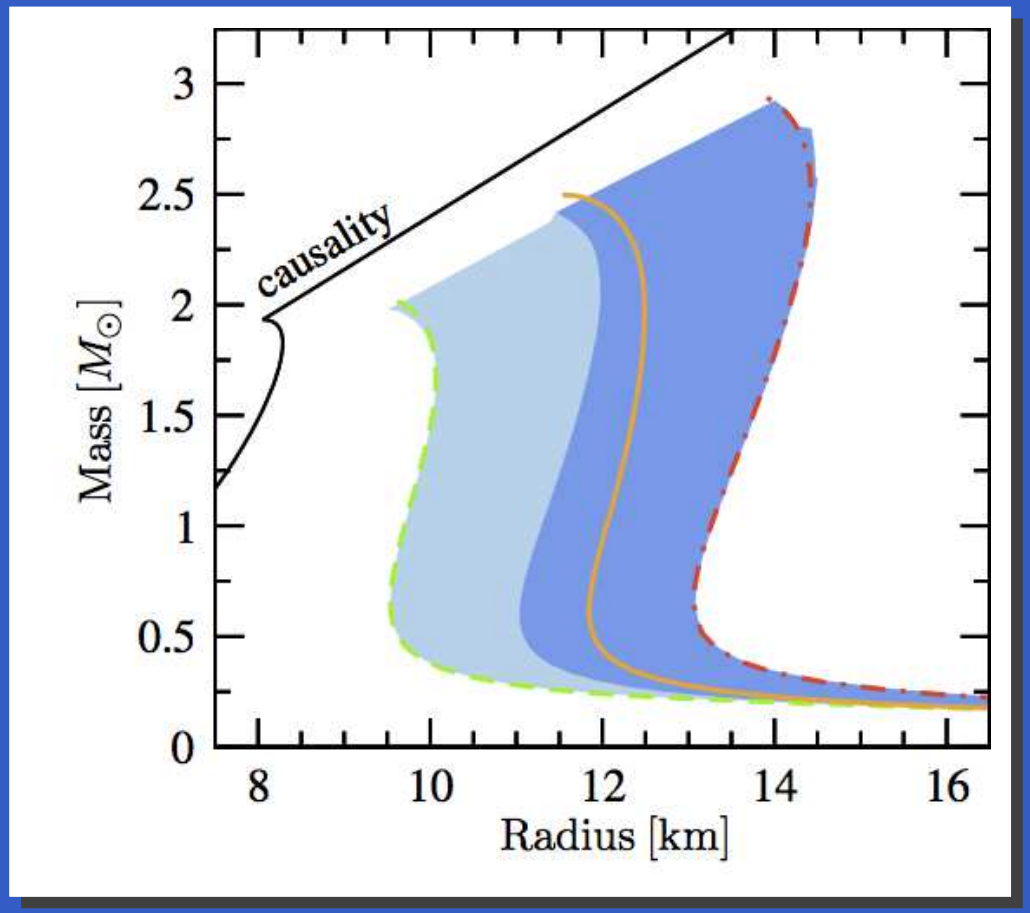
(Hebeler, Lattimer, Pethick, Schwenk 2013)

- low-densities: crust EoS (BPS plus Negele and Vautherin)
- neutron matter EoS from ChEFT with uncertainties up to $1.1 n_0$
- extrapolate by using three piecewise polytropes
- parametrizes an extensive set of high-density neutron star EoSs

(Read, Lackey, Owen, Friedman 2009)

Extrapolated EoS and Mass-Radius Relation

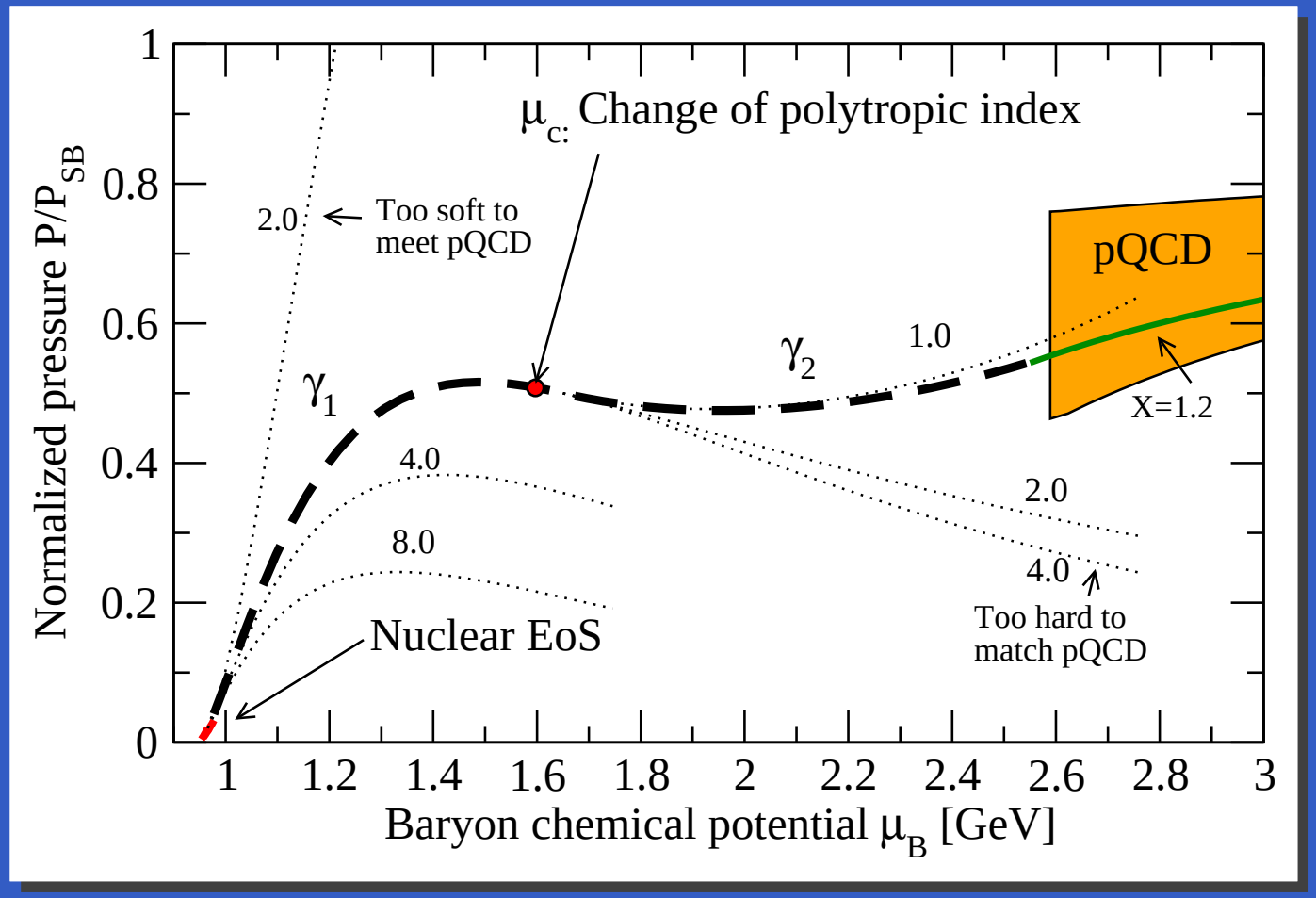




(Hebeler, Lattimer, Pethick, Schwenk 2013)

- neutron matter EoS (dark blue) extrapolated by piecewise polytropes
- light blue region: $M > 1.97 M_\odot$, blue region: $M > 2.4 M_\odot$
- range of radii: 9.7-13.9km for $1.4 M_\odot$ and 9.3-14.4km for $1.97 M_\odot$

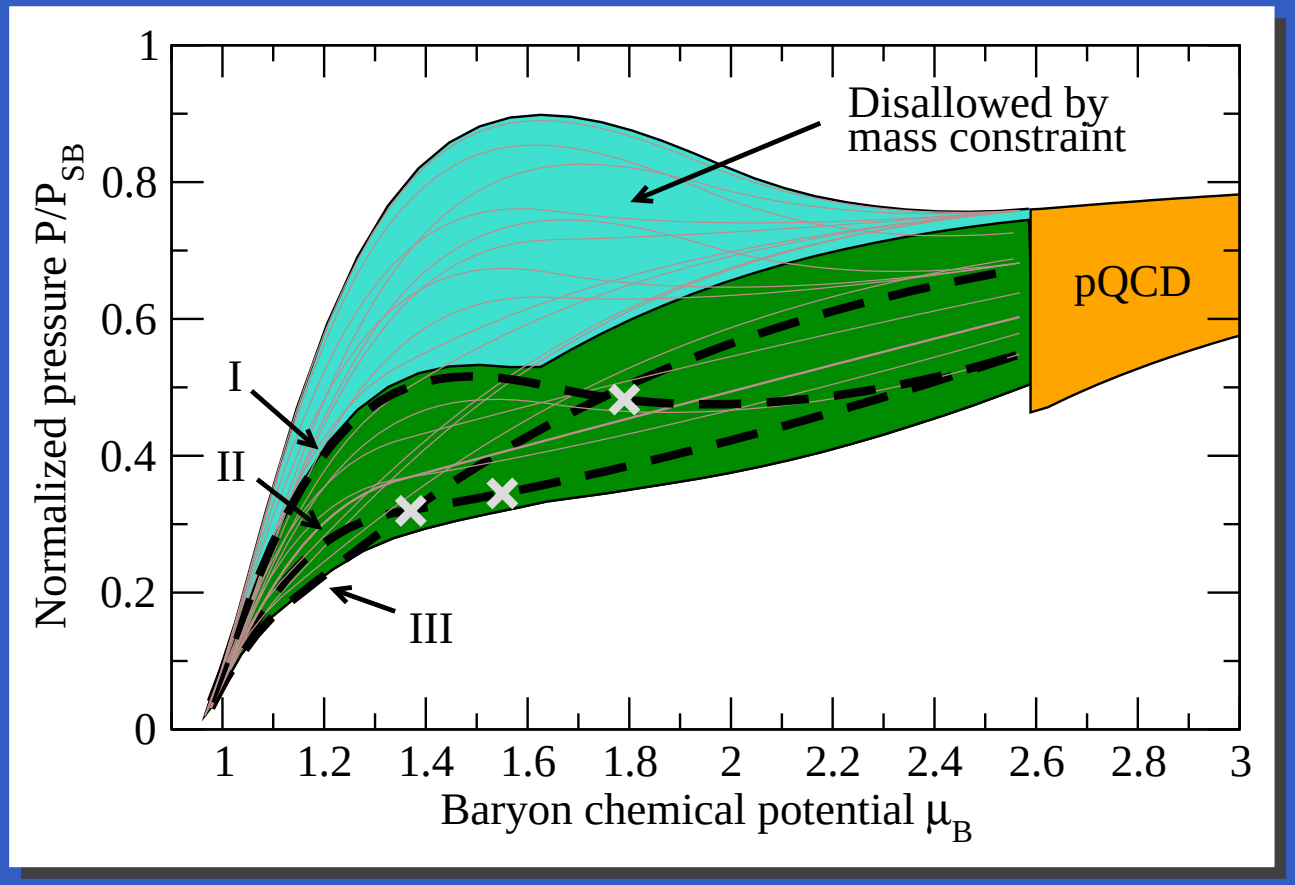
Interpolated Equation of State: Matching to pQCD!



(Kurkela, Fraga, JSB, Vuorinen (2014))

- use two matched polytropes to interpolate
- demand causality and smooth matching
- matching to pQCD limit rules out certain EoS

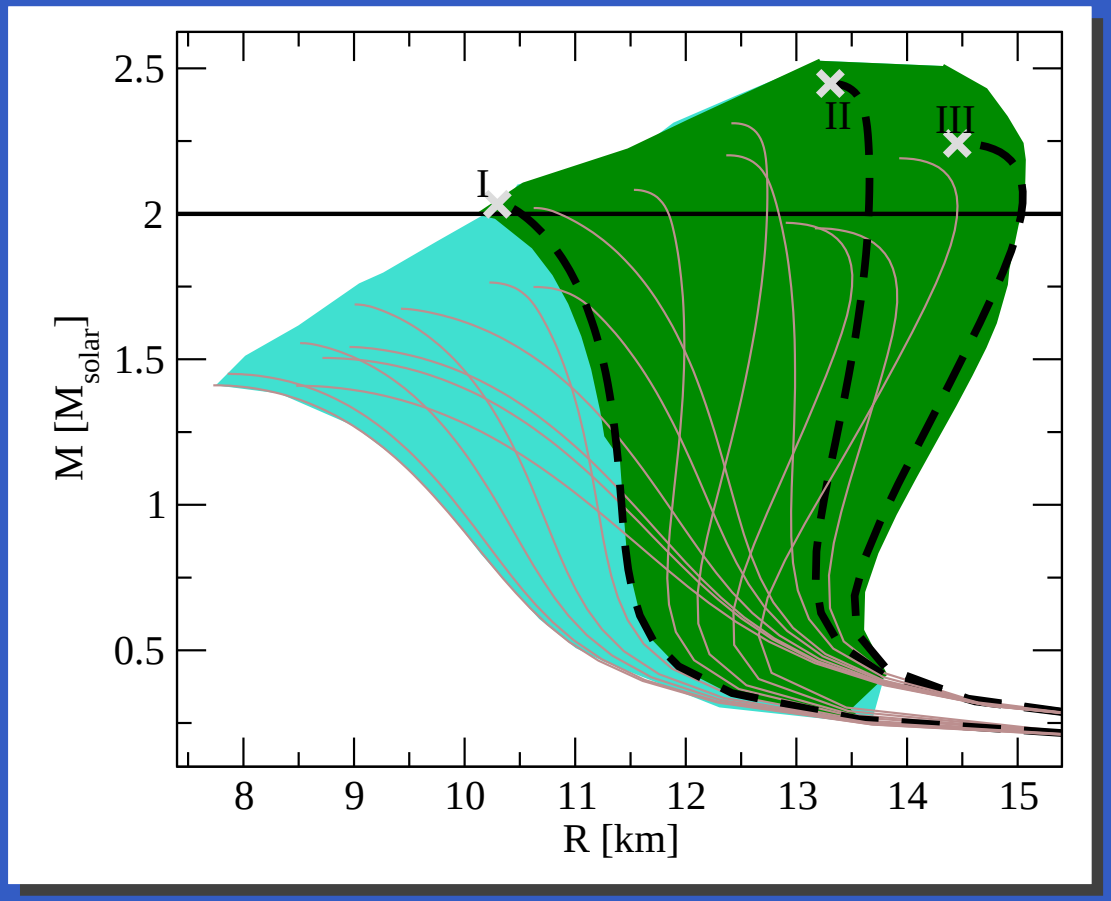
Interpolated Equation of State: pulsar mass constraint



(Kurkela, Fraga, JSB, Vuorinen (2014))

- use two matched polytropes to interpolate
- demand causality and smooth matching
- cyan region: maximum mass less than $2M_\odot$
- green region: fulfills all constraints (labels I,II,III: representative EoS)

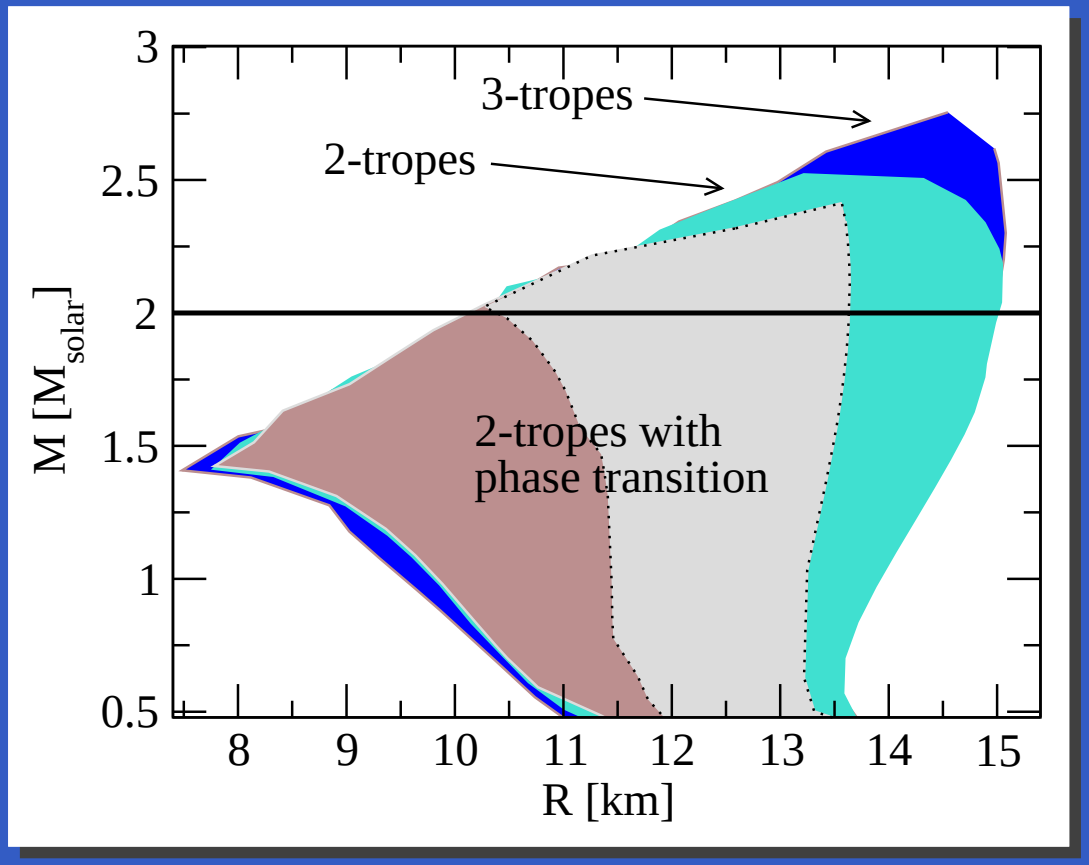
Interpolated Mass-Radius Relation



(Kurkela, Fraga, JSB, Vuorinen (2014))

- corresponding band of the interpolated EoS in mass-radius plot
- cyan band: excluded by $2M_\odot$ mass constraint
- green band: masses of up to $2.5M_\odot$ possible
- typical radii: 11-14.5km for $1.4M_\odot$ and 10-15 km for $2M_\odot$

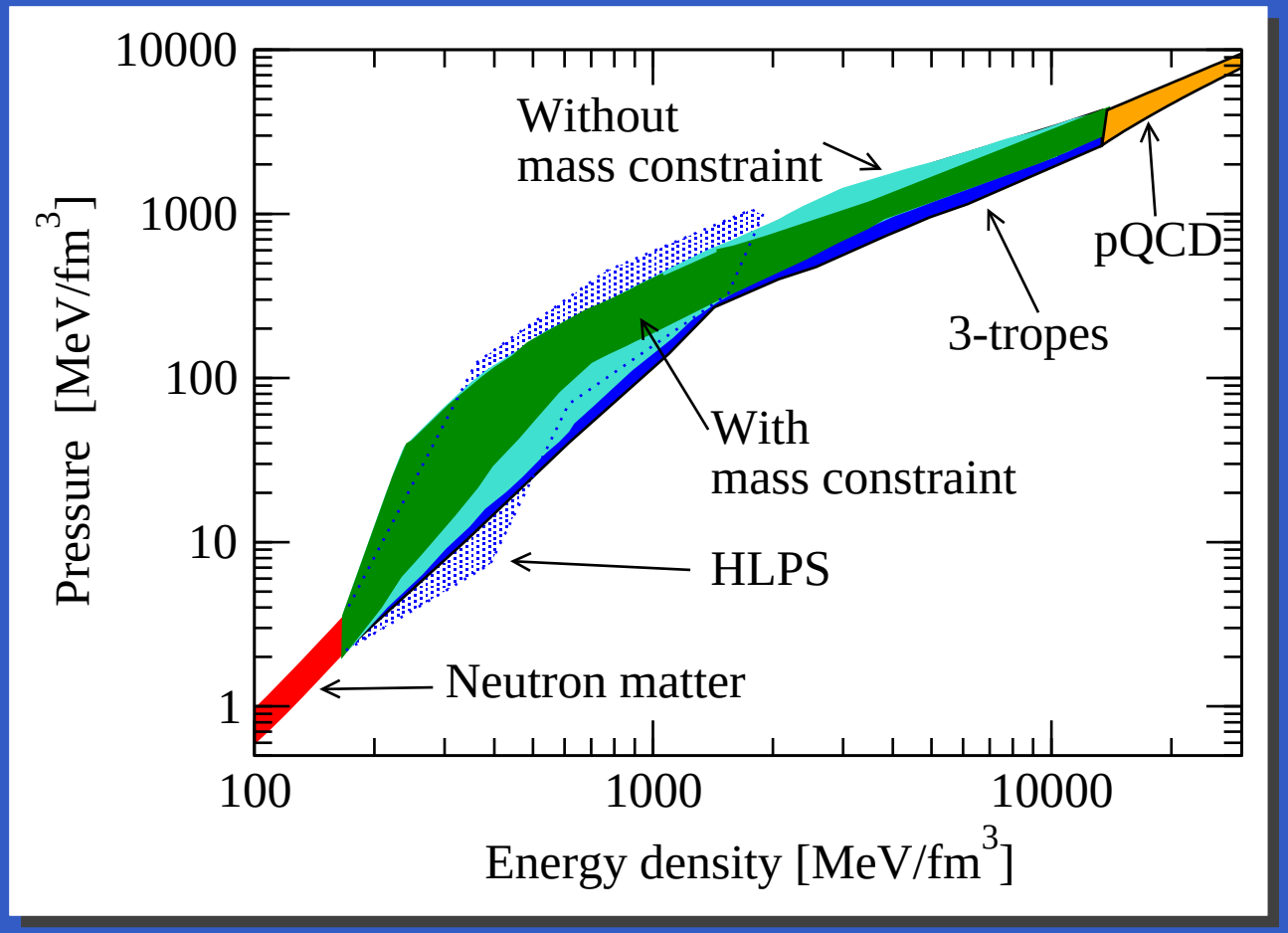
Mass-Radius Relation with phase transition



(Kurkela, Fraga, JSB, Vuorinen (2014))

- possible band of mass-radius relation shrinks with a phase transition
- allowed radii: 11.5-13.5km for $1.4M_\odot$ and 10-13.5km for $2M_\odot$
- with three polytropes: maximum masses of up to $2.75M_\odot$
- note: effects of phase transition not fully explored here

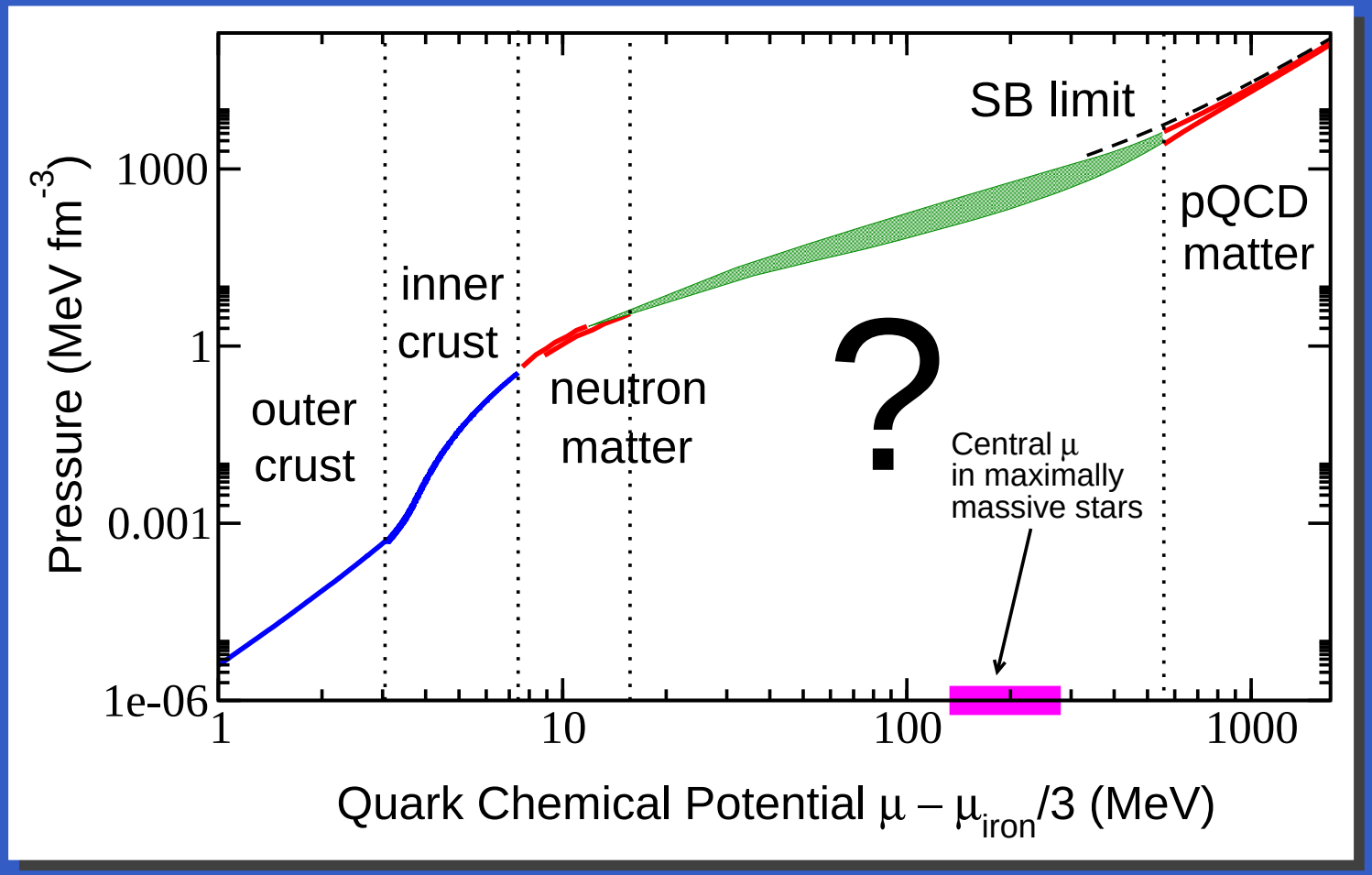
QCD Equation of State



(Kurkela, Fraga, JSB, Vuorinen (2014))

- green band: allowed band for the EoS with mass constraint
- comparison to analysis of Hebeler, Lattimer, Pethick, Schwenk 2013 (HLPS): case without pQCD constraint (extrapolated case)

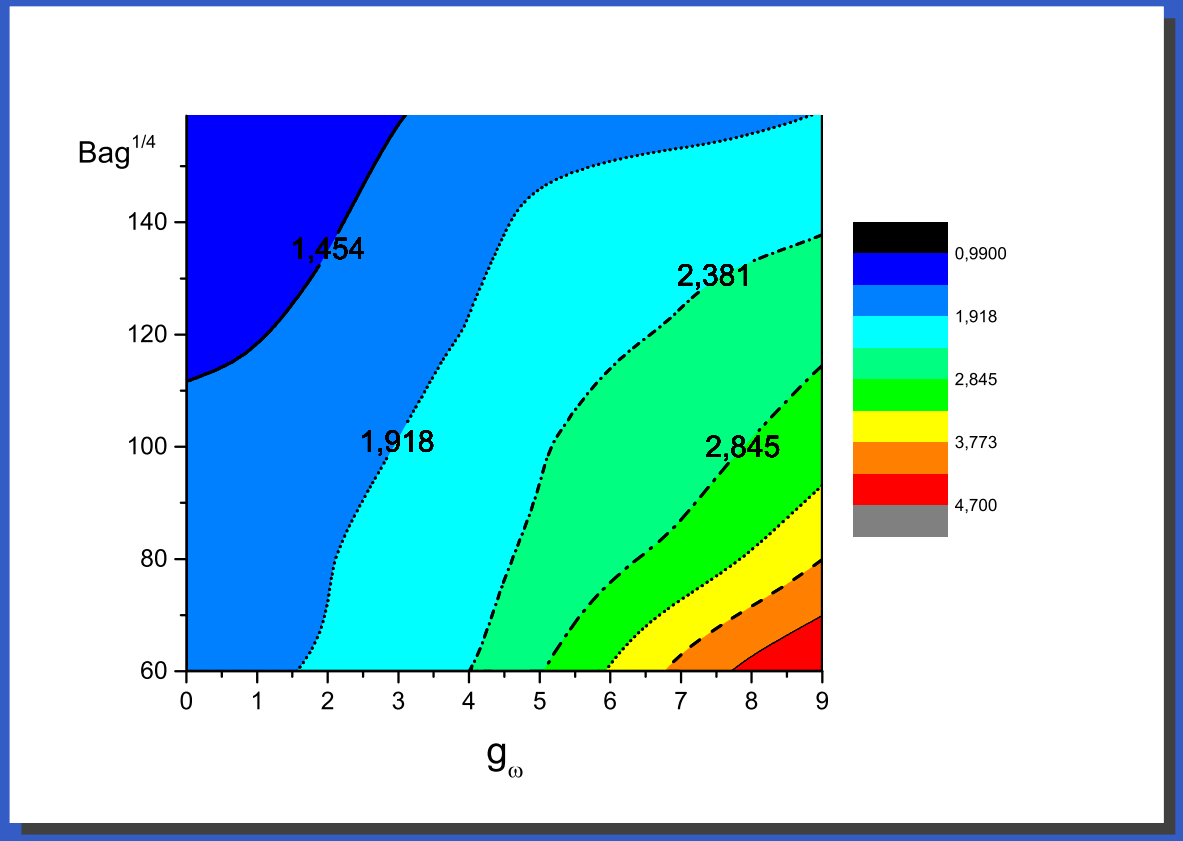
QCD Matter in Compact Stars



(Kurkela, Fraga, JSB, Vuorinen (2014))

- green band: interpolated region compatible with pulsar mass constraint
- only pretty narrow region allowed for the EoS!
- note: we do not know what the matter within the green band is made of!

Outlook: Improved Models for Cold Quark Matter



(Zacchi and JSB, in preparation)

- need models beyond the simple MIT bag model
- one approach: the Quark-Meson model as an effective model of QCD
- repulsive vector meson interaction needed to get massive neutron stars

Summary:

- Hyperons in Neutron Stars
  - many baryon-based models with hyperons do not reach $2M_\odot$ (however some do reach $2M_\odot$)
  - does NOT rule out hyperons in neutron stars
  - ignoring hyperons by hand can NOT rescue the model used!
  - hyperon puzzle:
    breakdown of baryonic models at high densities?
    onset of a new phase not based on baryon d.o.f.?
- QCD matter in compact stars
  - interpolating QCD EoS at low- and high-densities possible
  - constraints on allowed mass-radius relations
  - composition of high-density neutron star cores: unknown!
  - further input needed from relativistic heavy-ion experiments!