Is there Quark Matter in (Low-Mass) Pulsars?

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International Conference on Ultra-Relativistic Nucleus Nucleus Collisions

Quark Matter 2008, Jaipur, India, February 4-10, 2008

H-QM Helmholtz Research School Quark Matter Studies

Is there Quark Matter in (Low-Mass) Pulsars?

work done by:

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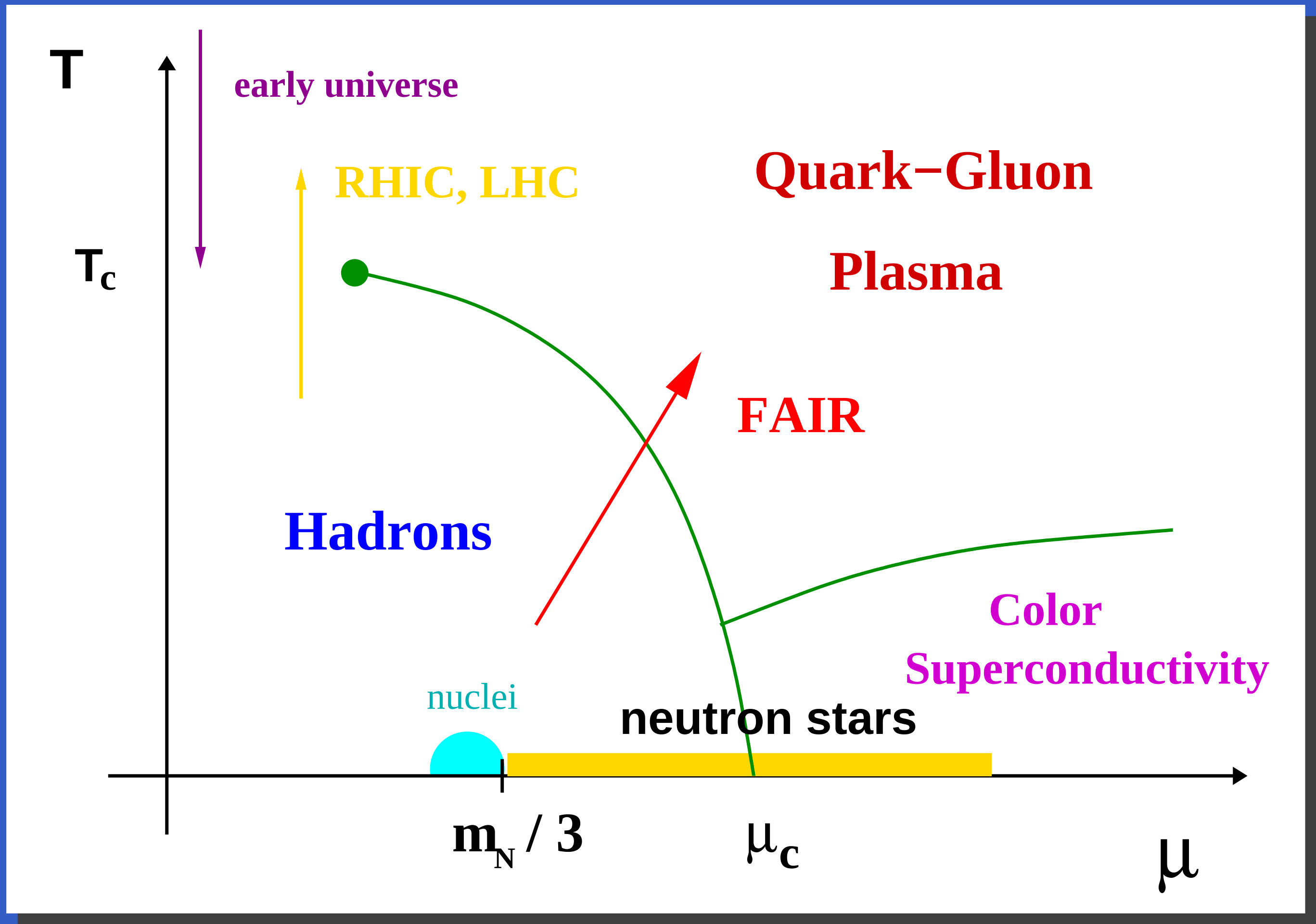
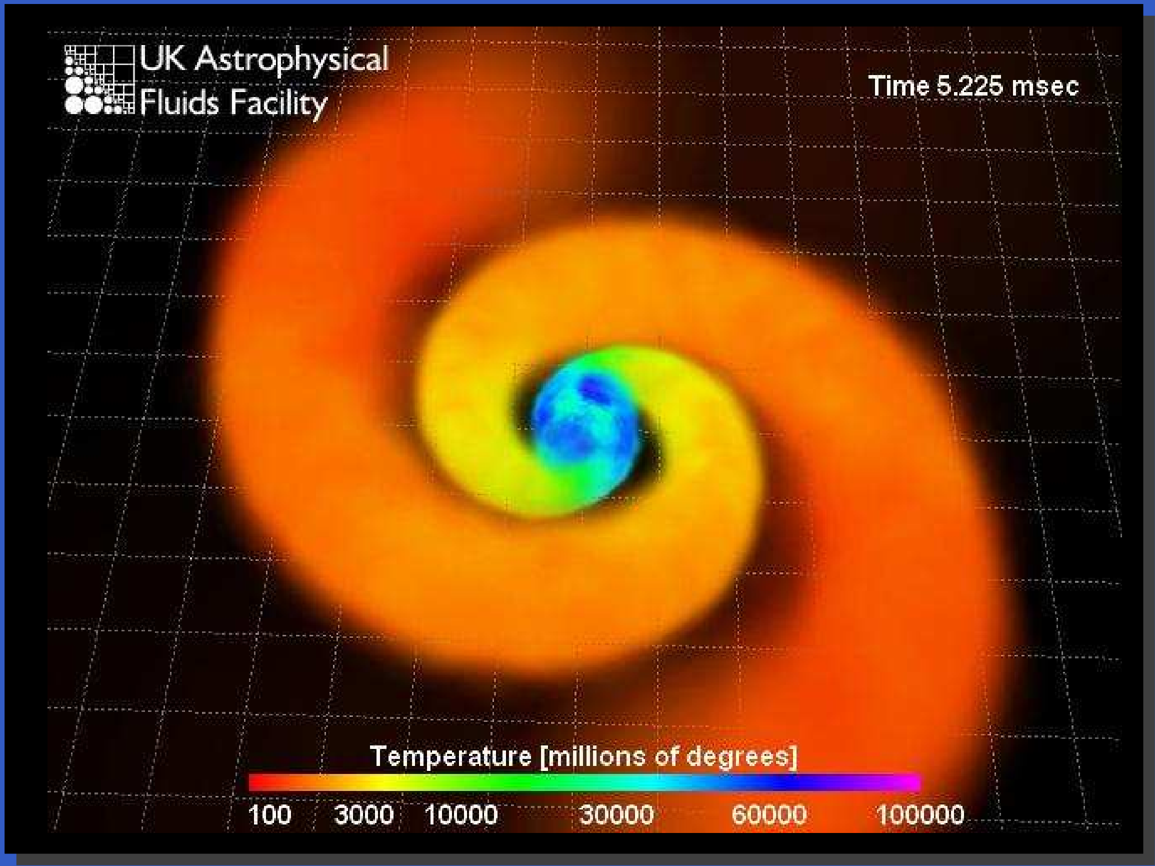
Phase Transitions in QCD



- early universe at small baryon 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 with CBM@FAIR!

Nuclear Equation of State as Input in Astrophysics

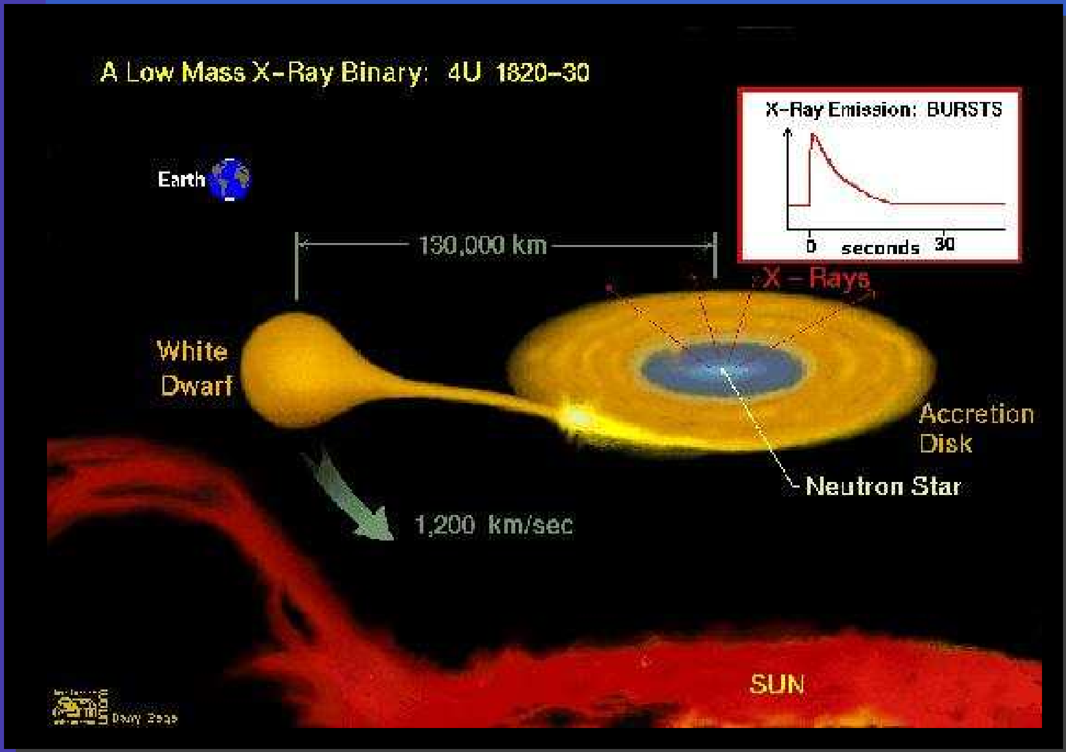


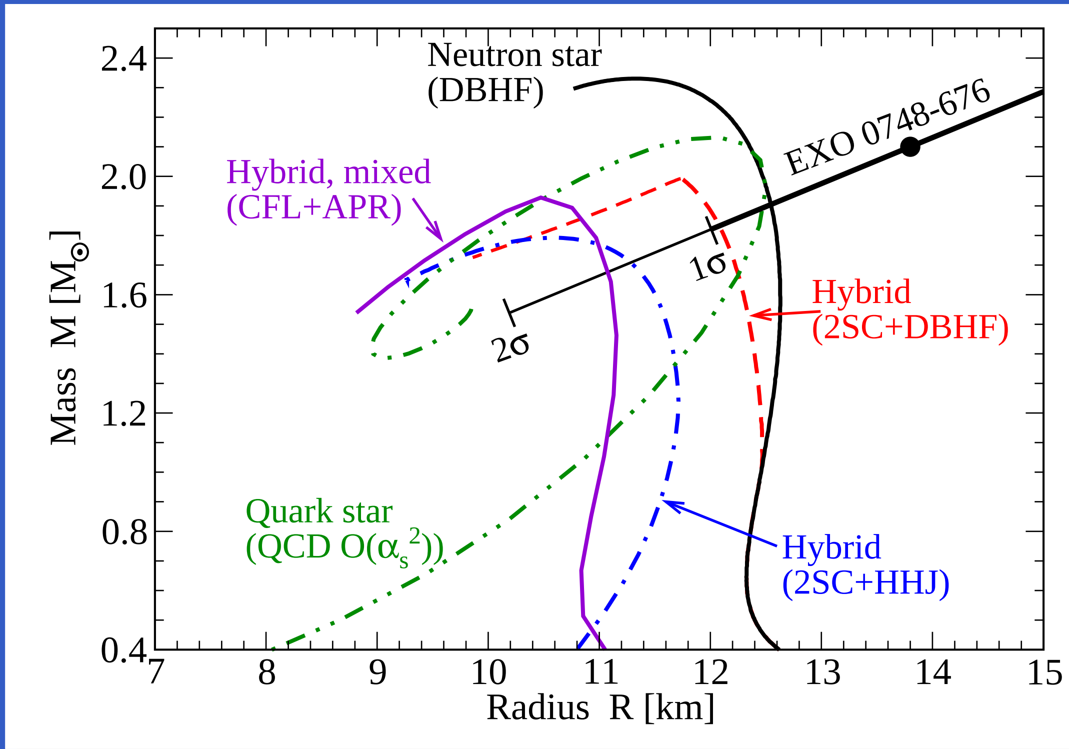
- supernovae simulations: $T = 1$–50 MeV, $n = 10^{-10}$–$2n_0$
- proto-neutron star: $T = 1$–50 MeV, $n = 10^{-3}$–$10n_0$
- global properties of neutron stars: $T = 0$, $n = 10^{-3}$–$10n_0$
- neutron star mergers: $T = 0$–175 MeV, $n = 10^{-10}$–$10n_0$

Coming of age! Some suggestive signals:

- ’exotic’ mass-radius relation of compact stars
- rapidly rotating pulsars due to r-mode *stability* window
- enhanced cooling of neutron stars
- gamma-ray bursts by transition to strange quark matter (GRBs without a supernova, late x-ray emission, long quiescent times)
- gravitational wave signals of phase transitions
  - binary neutron star collisions
  - collapse of neutron star to a hybrid star
  - r-mode spin-down of hybrid stars
- core-collapse supernovae?

X-Ray burster EXO 0748–676: Quarks are alive and kicking!

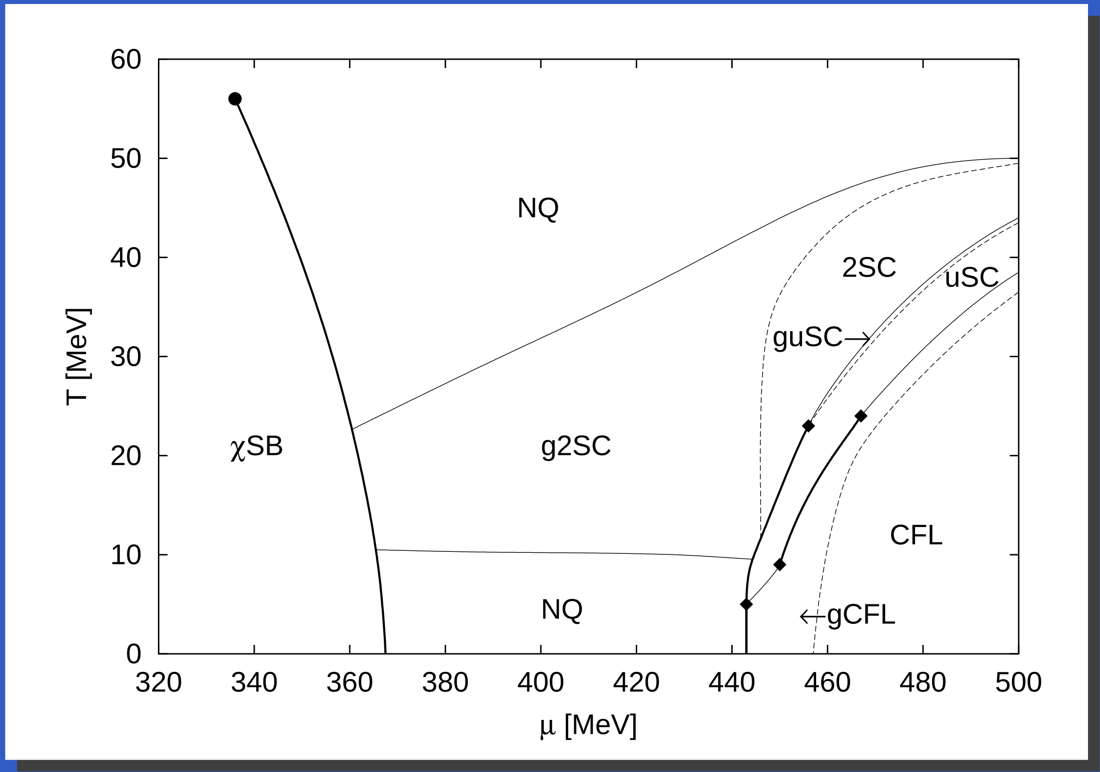




- redshifted spectral lines measured (Cottam, Paerels, Mendez (2002))
- analysis of Özel (Nature 2006): $M \geq 2.10 \pm 0.28 M_{\odot}$ and $R \geq 13.8 \pm 1.8$ km, claims: 'unconfi ned quarks do not exist at the center of neutron stars'!
- reply by Alford, Blaschke, Drago, Klähn, Pagliara, JSB (Nature 445, E7 (2007)): limits would rule out soft equations of state, not quark stars or hybrid stars!

The EoS for Quark Matter

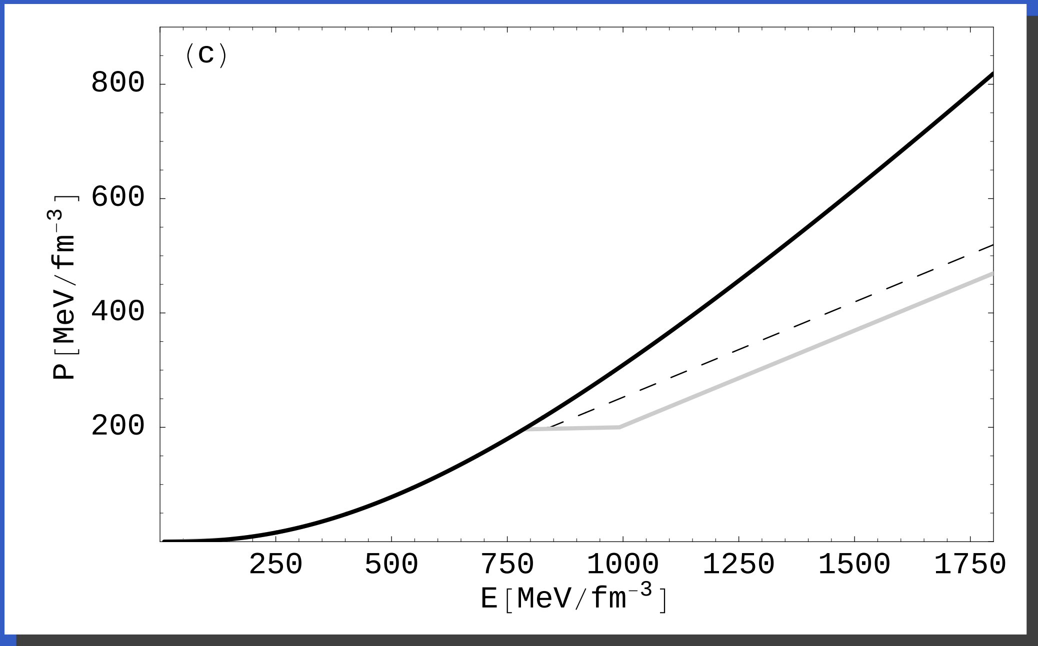
Phases in Quark Matter (Rüster et al. (2005))

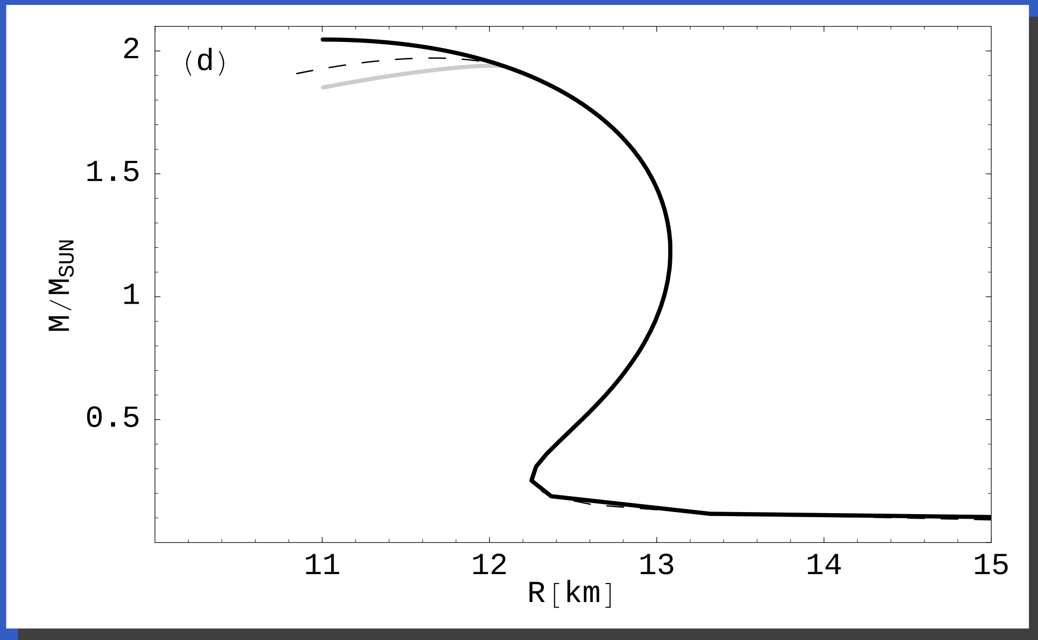


- fi rst order phase transition based on symmetry arguments!
- phases of color superconducting quark matter in β equilibrium: normal (unpaired) quark matter (NQ), two-flavor color superconducting phase (2SC), gapless 2SC phase, color-flavor locked phase (CFL), gapless CFL phase, metallic CFL phase

(Alford, Rajagopal, Wilczek, Reddy, Buballa, Blaschke, Shovkovy, Drago, Rüster, Rischke, Aguilera, Banik, Bandyopadhyay, Pagliara, . . .)

Phase Transition and Stability of Compact Stars

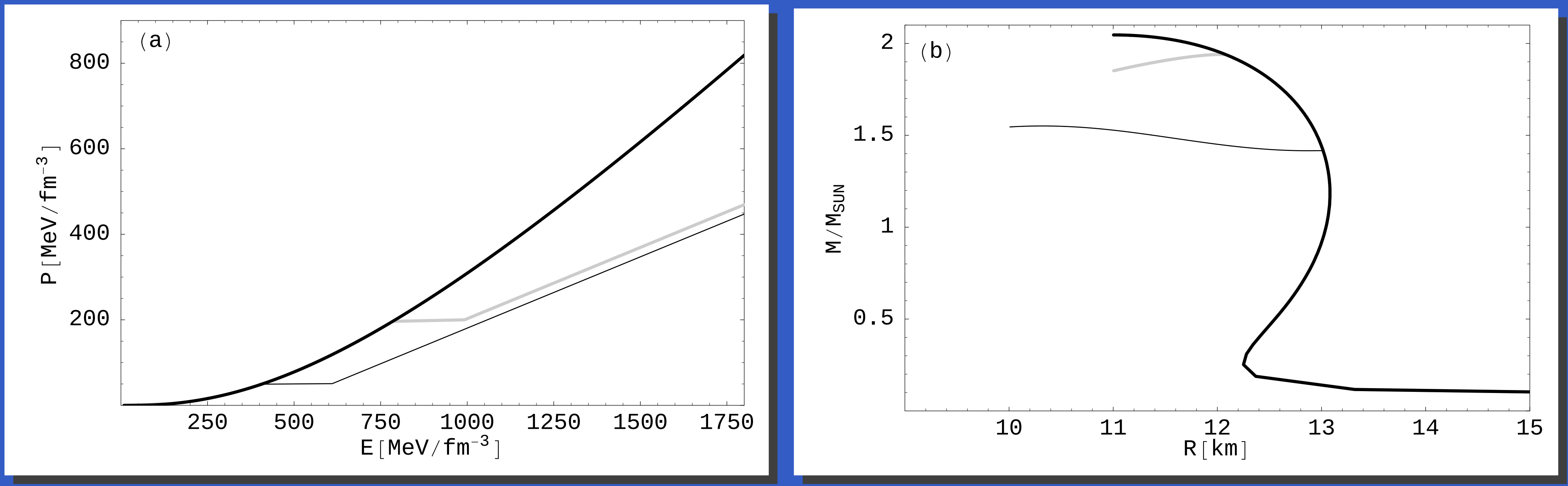




(Giuseppe Pagliara and JSB, arXiv:0711.1119)

- use toy model EoS for quark matter: $p = a \cdot \epsilon$ with constant $a = 1/3$ and a given energy density jump
- use RMF model (here set GM3) for the low-density nuclear EoS
- phase transition close to the maximum: always unstable solutions for the quark core

Phase Transition and Stability of Compact Stars II



(Giuseppe Pagliara and JSB, arXiv:0711.1119)

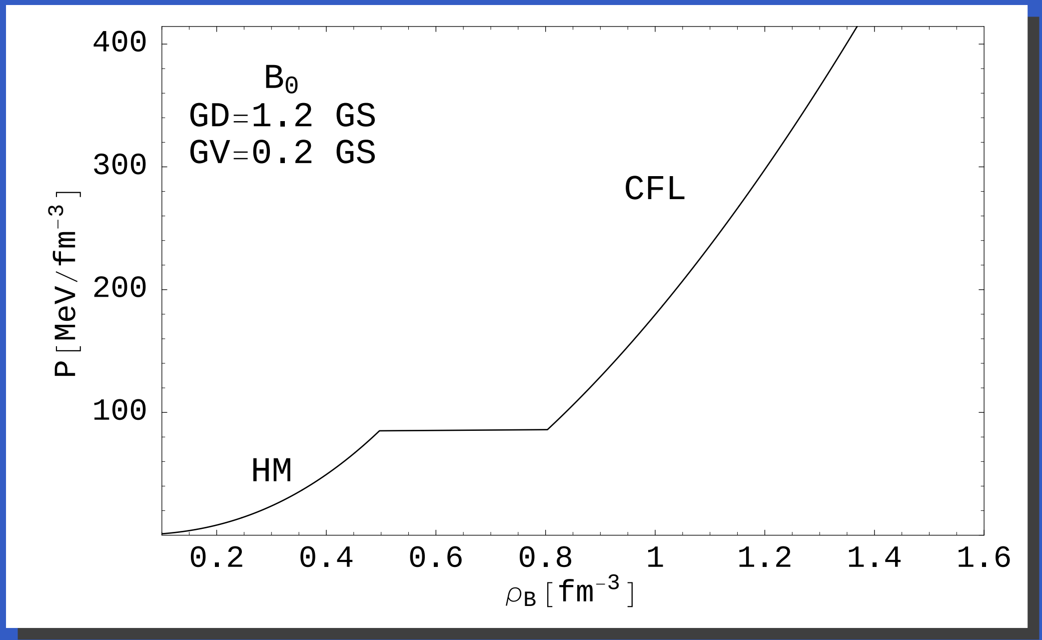
- change the critical energy density for the phase transition
- phase transition close to the maximum mass: unstable quark core
- onset of phase transition at moderate densities: stable quark core

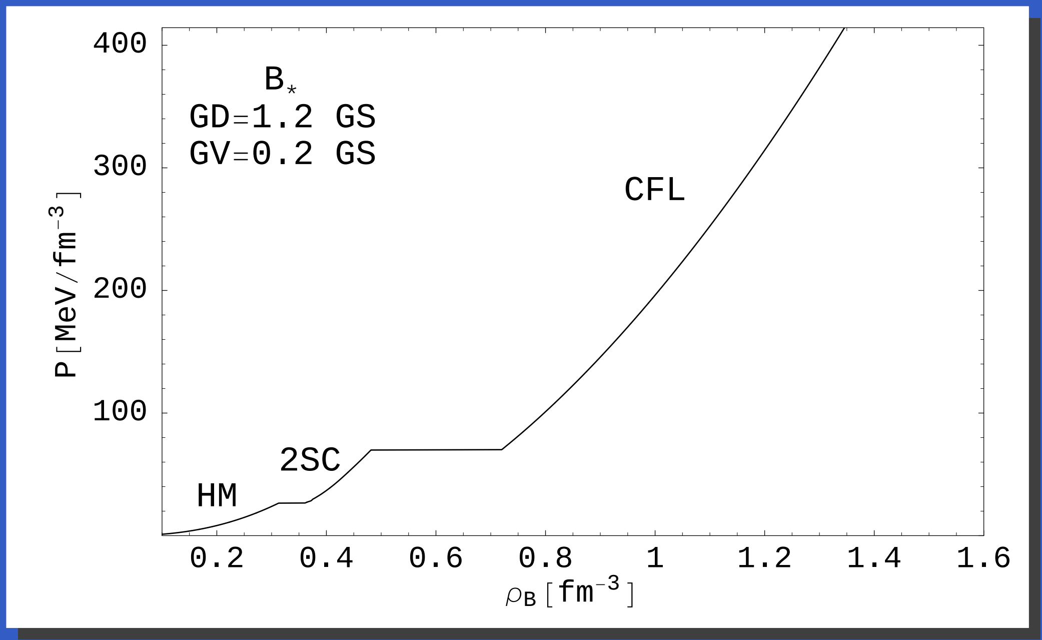
Color-superconducting quark matter in the NJL model

$$p = \frac{1}{2\pi^2}\sum_{i=1}^{18}\int_0^\Lambda \mathrm{d}k\, k^2|\epsilon_i| + 4K\sigma_u\sigma_d\sigma_s - \frac{1}{4G_D}\sum_{c=1}^{3}|\Delta_c|^2$$
$$-2G_S\sum_{\alpha=1}^{3}\sigma_\alpha^2 + \frac{1}{4G_V}\omega_0^2 + p_e$$

- use Nambu–Jona-Lasinio model for describing quark matter
- describes both dynamical quark masses (quark condensates σ) and the color-superconducting gaps Δ
- so far 'best' model in the fi eld (Rüster et al. (2005))
- parameters: cutoff, scalar and vector coupling constants G_S, G_V, diquark coupling G_D, 't Hooft term coupling K
- fi xed to hadron masses, pion decay constant, free: G_D and G_V

Hybrid Star Matter

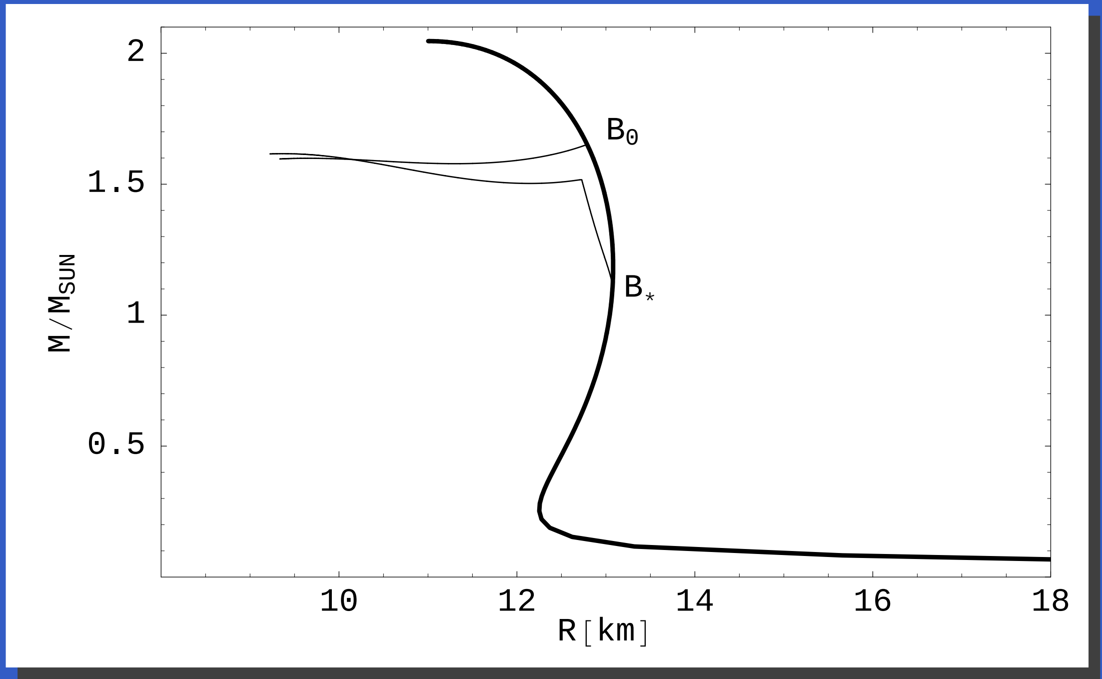




(Giuseppe Pagliara and JSB, arXiv:0711.1119)

- fi x the pressure in vacuum (B_0) or at the chiral phase transition (B_*)
- fi rst case: phase transition to CFL quark matter (left plot)
- second case: two phase transition to 2SC then to CFL phase (right plot)

Hybrid Star Mass-Radius Diagram

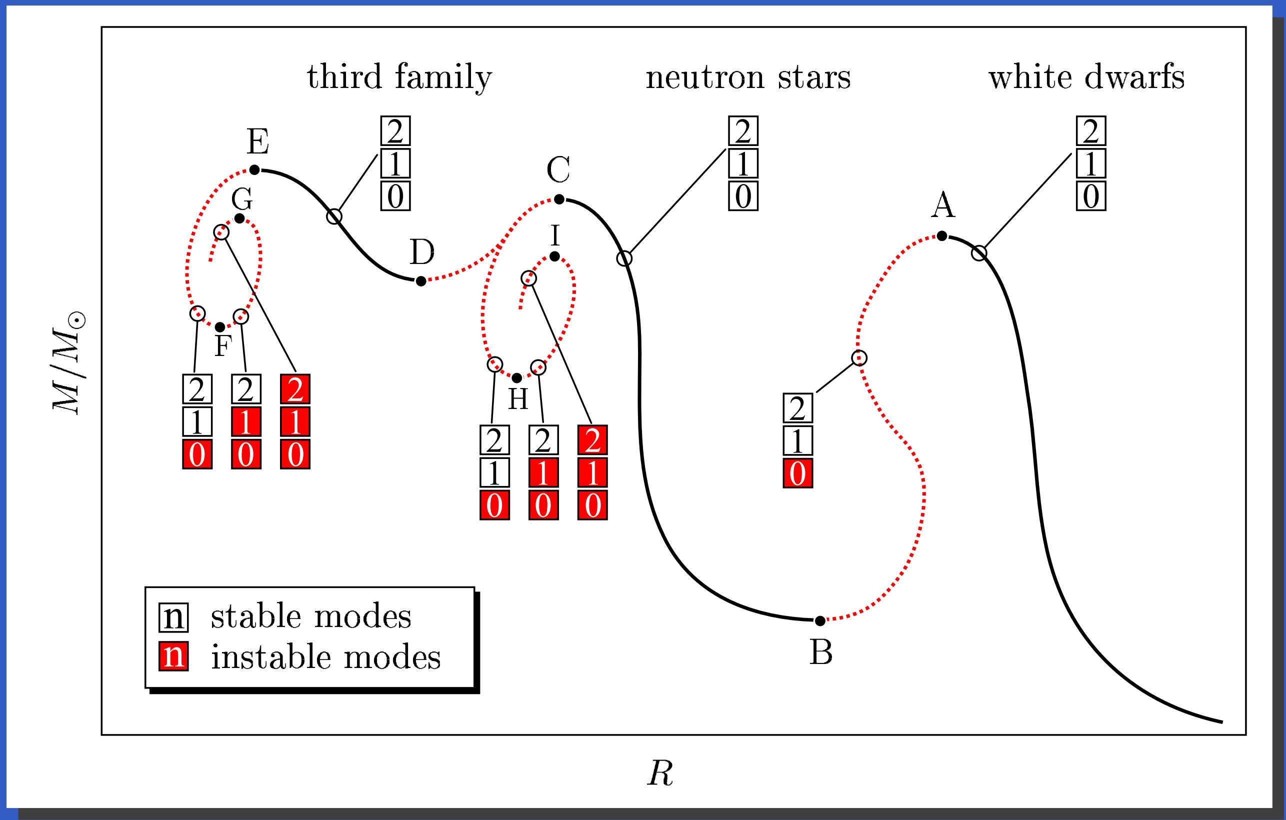


(Giuseppe Pagliara and JSB, arXiv:0711.1119)

- phase transition directly to CFL phase: unstable fi rst then stable branch
- two phase transitions: two kinks in curve, also two stable solutions
- new stable solution possible $\longrightarrow$ third family of compact stars!
- two phase transitions can be present in compact star matter: implications for supernovae?

Third Family of Compact Stars

Gerlach (1968), Kämpfer (1981), Haensel and Proszynski (1982), Glendenning and Kettner (2000), . . .



(Schertler, Greiner, JSB, Thoma (2000))

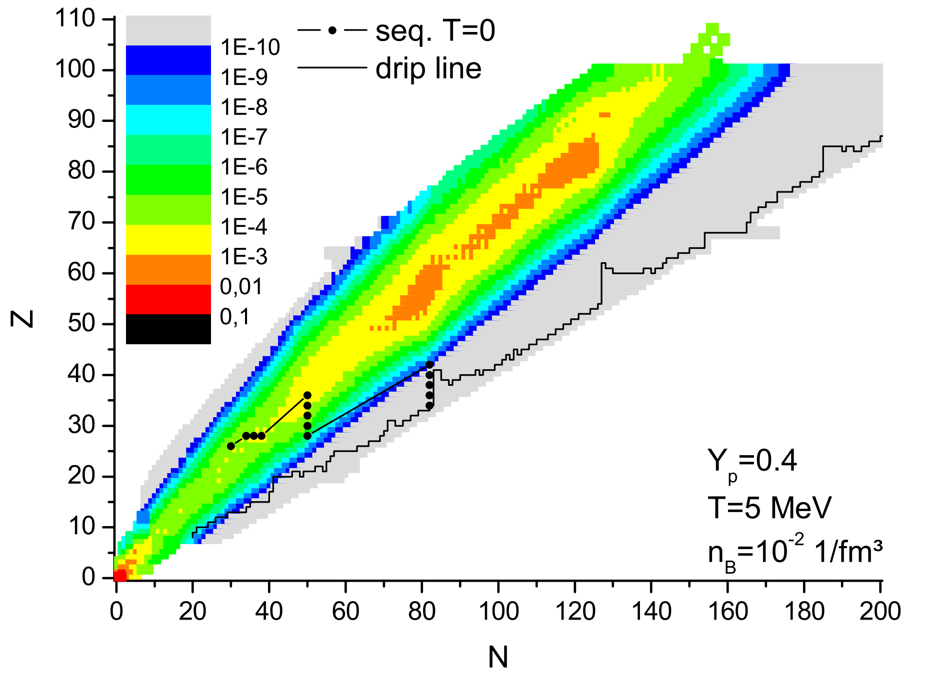
- third solution to the TOV equations besides white dwarfs and neutron stars, solution is stable!
- generates stars more compact than neutron stars
- possible for any fi rst order phase transition!

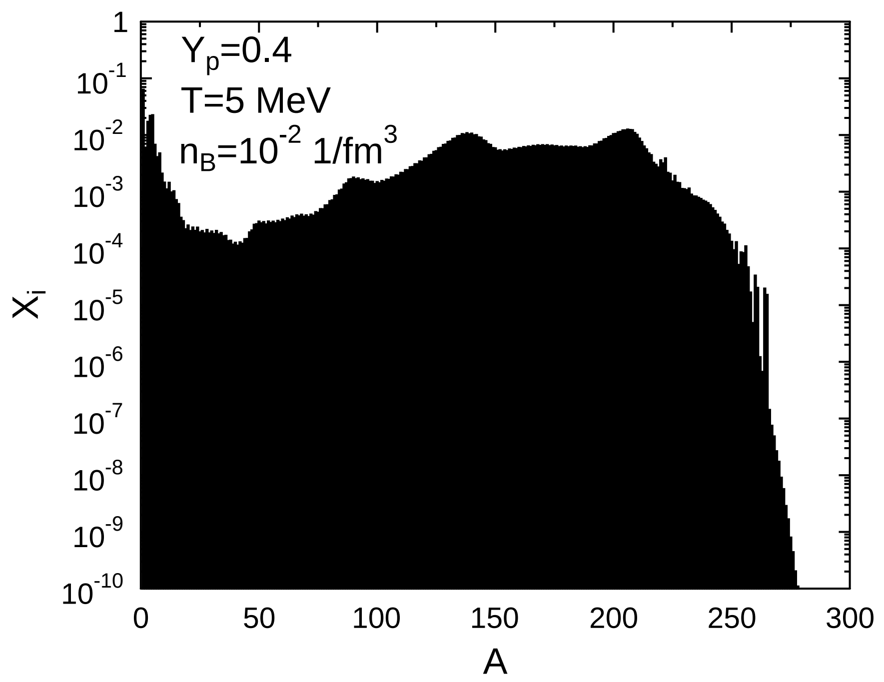
Signals for a Third Family/Phase Transition?

- mass-radius relation: rising twins (Schertler et al., 2000)
- spontaneous spin-up of pulsars (Glendenning, Pei, Weber, 1997)
- collapse of a neutron star to the third family? (gravitational waves, γ-rays, neutrinos)
- r-mode instabilities: millisecond pulsars, gravitational wave burst (Drago, Pagliara, Berezhiani, 2006), . . .
- gamma-ray bursts with late x-ray emission, long quiescent times (Drago and Pagliara, 2007), . . .
- secondary shock wave in supernova explosions?
- gravitational waves from colliding neutron stars?

The hot EoS for Supernovae

Composition of Supernova Matter (Low Densities)

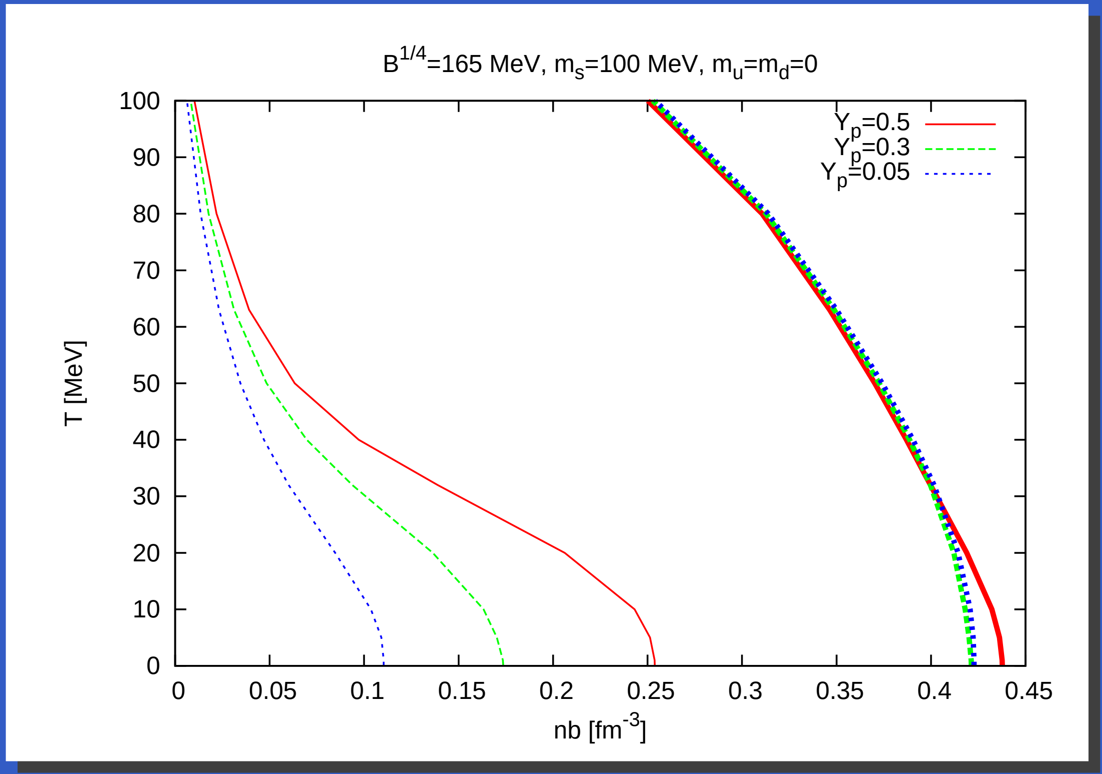




(Matthias Hempel)

- need thermodynamic consistent low-density EoS
- gas of nucleons, nuclei and electrons (plus Coulomb-lattice)
- here: supernovae matter for a proton fraction $Y_p = 0.4$ and $T = 5$ MeV
- broad distribution, many exotic nuclei $\Longrightarrow$ relation to FAIR physics!

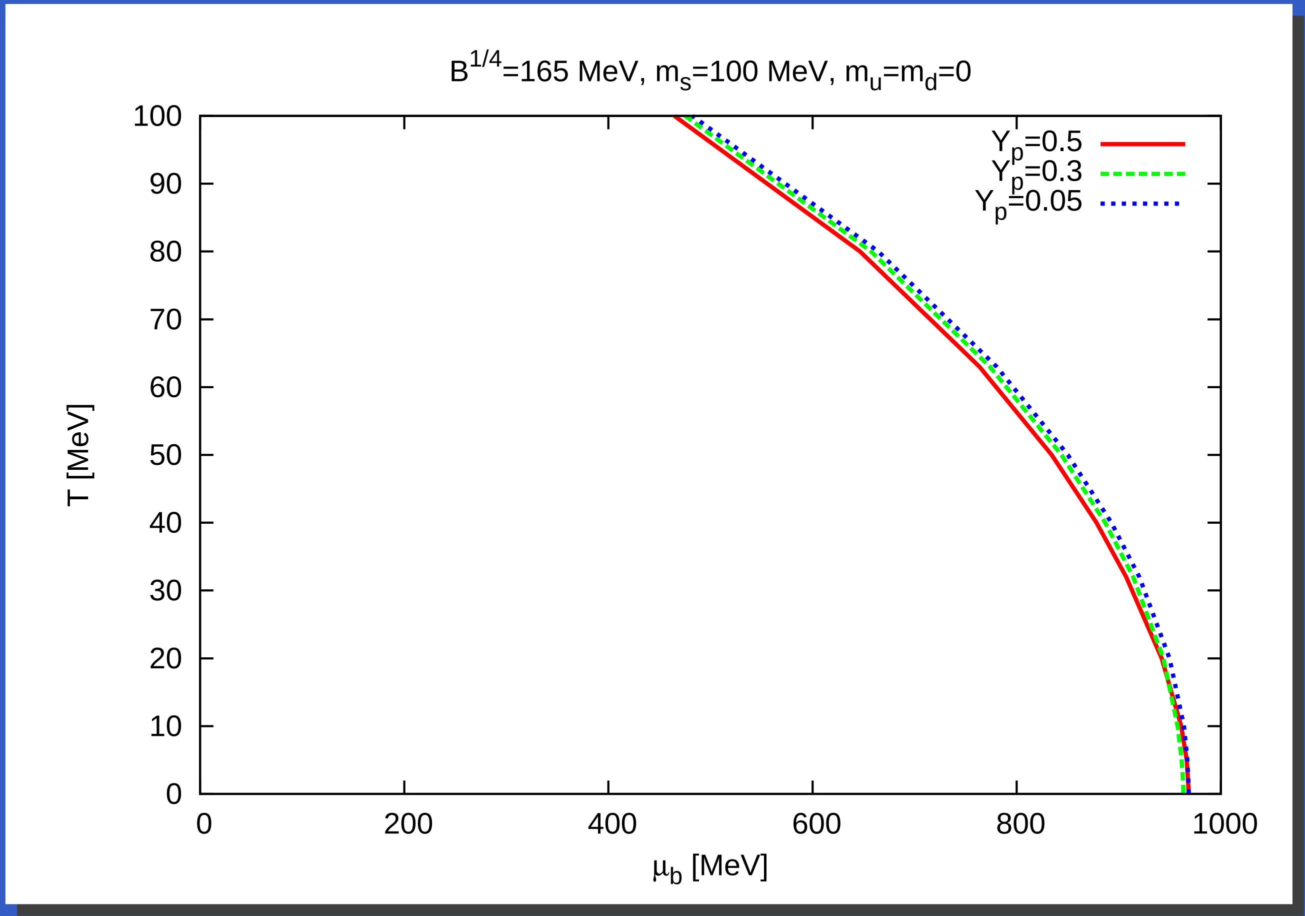
Phase Transition to Quark Matter for Astros



(Irina Sagert and Giuseppe Pagliara)

- start of the mixed phase at quite low densities due to β-equilibrium, strange quark matter is more stable than nucleon matter (using RMF model TMA)
- even lower critical densities for isospin-asymmetric matter (low proton fraction Y_p) due to asymmetry energy for nucleons
- quark matter favoured in hot matter due to the QCD phase diagram
- production of quark matter in supernovae at bounce possible!

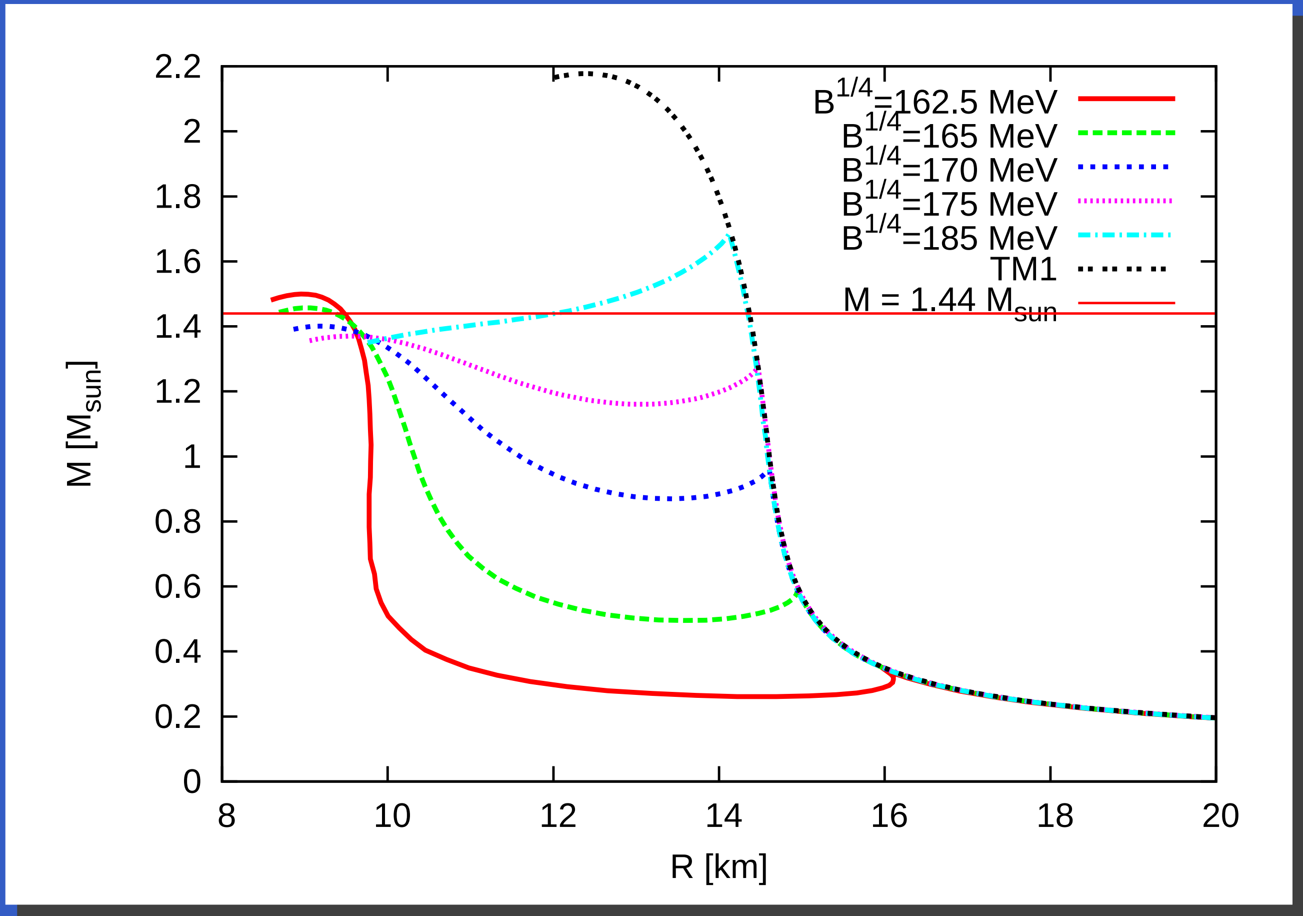
Phase Transition Line to Quark Matter for Astros



(Irina Sagert and Giuseppe Pagliara)

- plot of the phase transition line of temperature versus chemical potential
- phase transition nearly independent on the proton fraction Y_p
- phase transition line bends towards low chemical potentials for large T

Impact on Mass-Radius Diagram of Cold Neutron Stars



(Irina Sagert and Giuseppe Pagliara)

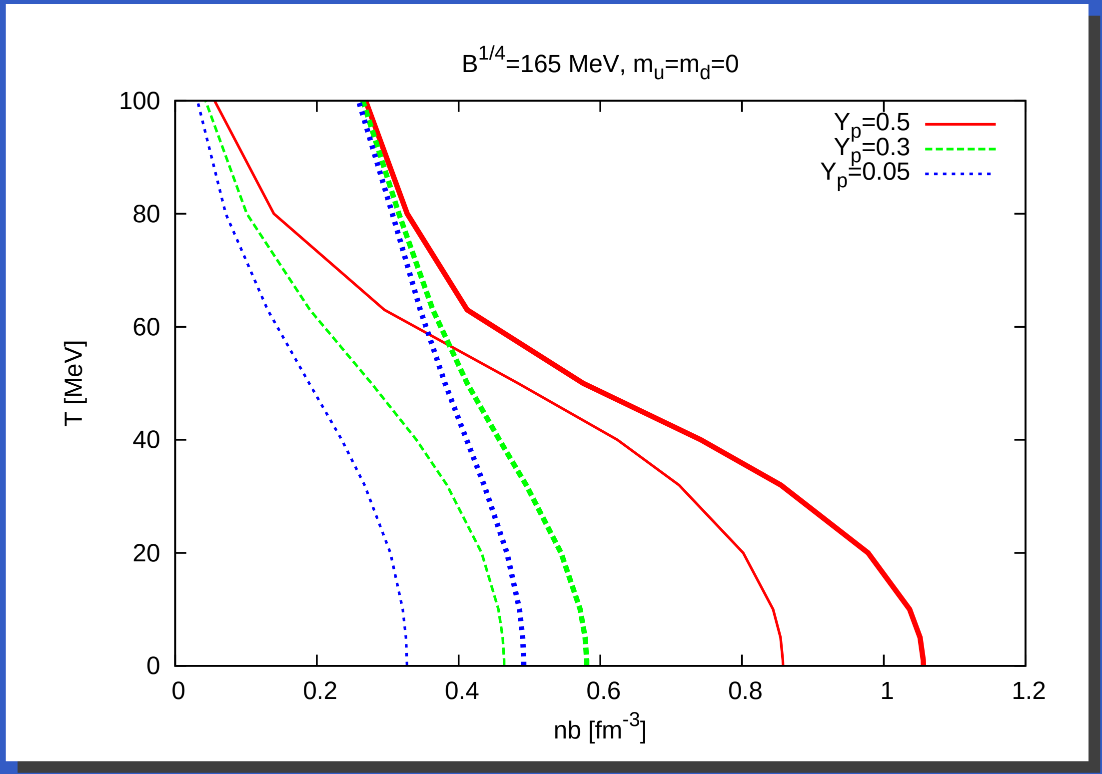
- presence of quark matter can change drastically the mass-radius diagram
- third family of solution for certain bag constants
- unique feature: small radii for moderate neutron star masses!

Summary

- the phase transition to quark matter leads to a rich variety of astrophysical signals involving compact stars and supernovae
- do not look for supermassive neutron stars!
  - supermassive neutron stars well above $2.3M_\odot$: hard to achieve with *any* realistic modern EoS
  - maximum mass around $2M_\odot$: can be normal nuclear matter or a hybrid star with quark matter
  - maximum mass of $1.5M_\odot$ (well below $2M_\odot$): must involve exotic matter, hyperons or quarks!
- look for light pulsars and measure the radius!
- quark matter likely to be formed in core collapse supernovae!
- opportunities for a cross-check between heavy-ion physics and relativistic astrophysics!

Back-Up Slides

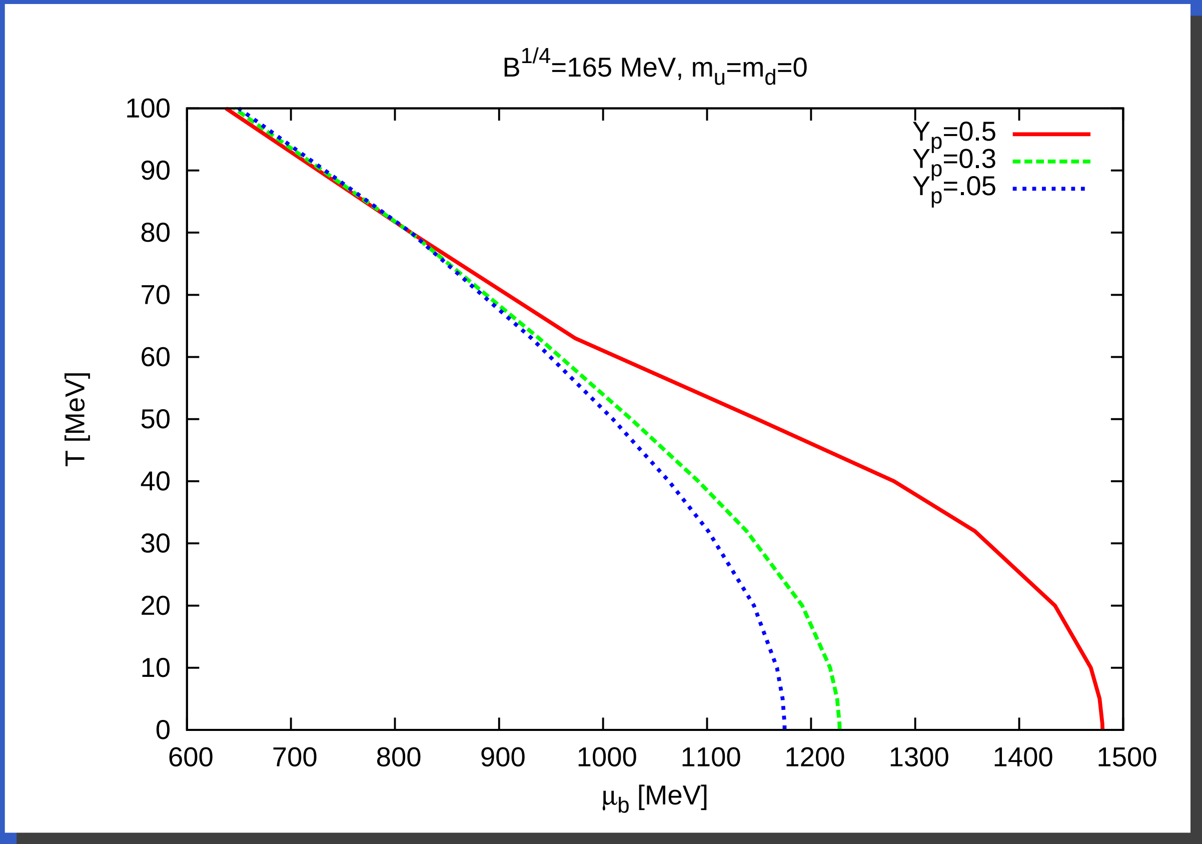
Phase Transition Density to Quark Matter for HICs



(Irina Sagert and Giuseppe Pagliara)

- no β-equilibrium (just up-/down-quark matter)
- large critical densities in particular for isospin-symmetric matter (proton fraction $Y_p = 0.5$)
- production of ud-quark matter unfavoured for HICs at small T and high density

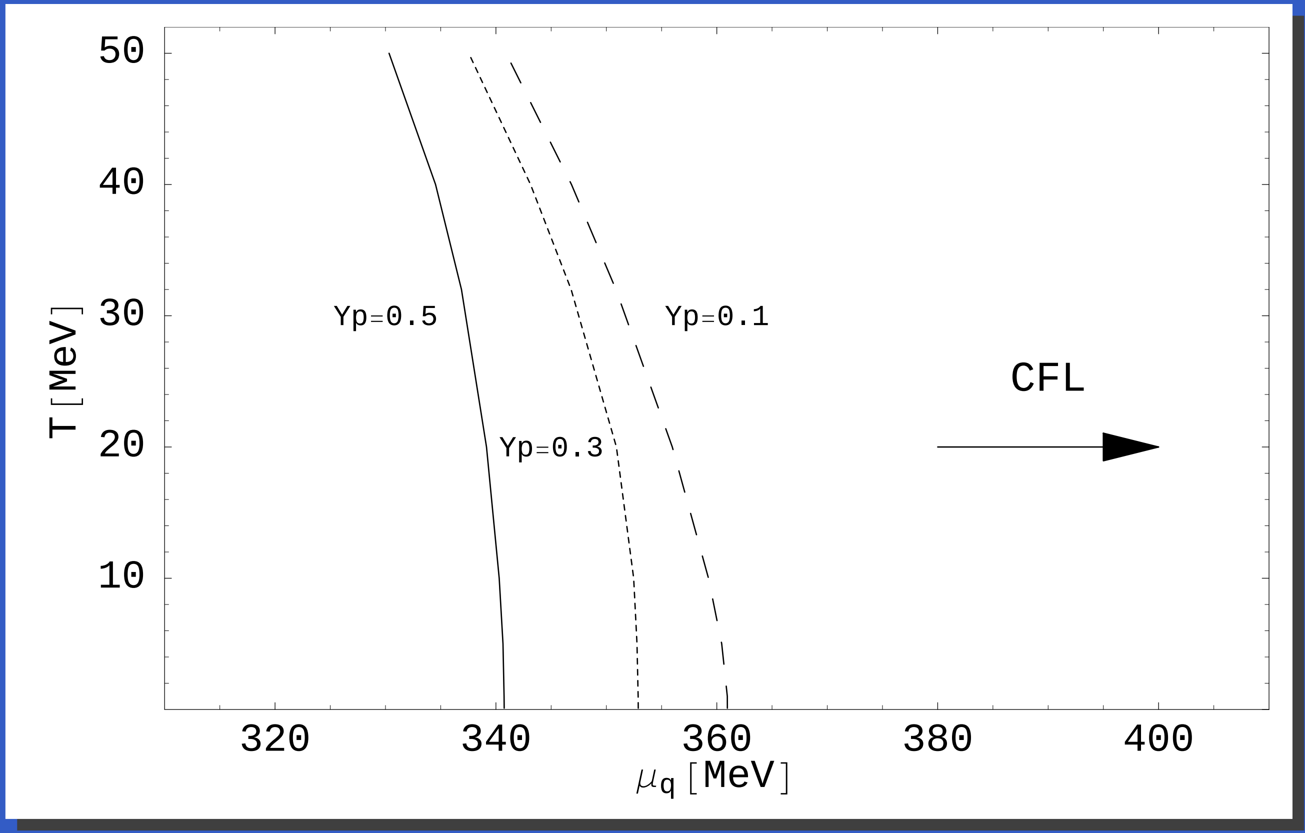
Phase Transition Line to Quark Matter for HICs



(Irina Sagert and Giuseppe Pagliara)

- phase transition line for ud-quark matter
- phase transition is at larger chemical potentials for ud-quark matter
- 'quasi-consistent' picture for freeze-out parameters at low energies:
  SIS: $\mu_{f.o.} = 700 - 800$ MeV, $T_{f.o.} = 50 - 70$ MeV
  AGS: $\mu_{f.o.} \sim 500$ MeV, $T_{f.o.} \sim 120$ MeV

Phase Transition Line to CSC Quark Matter

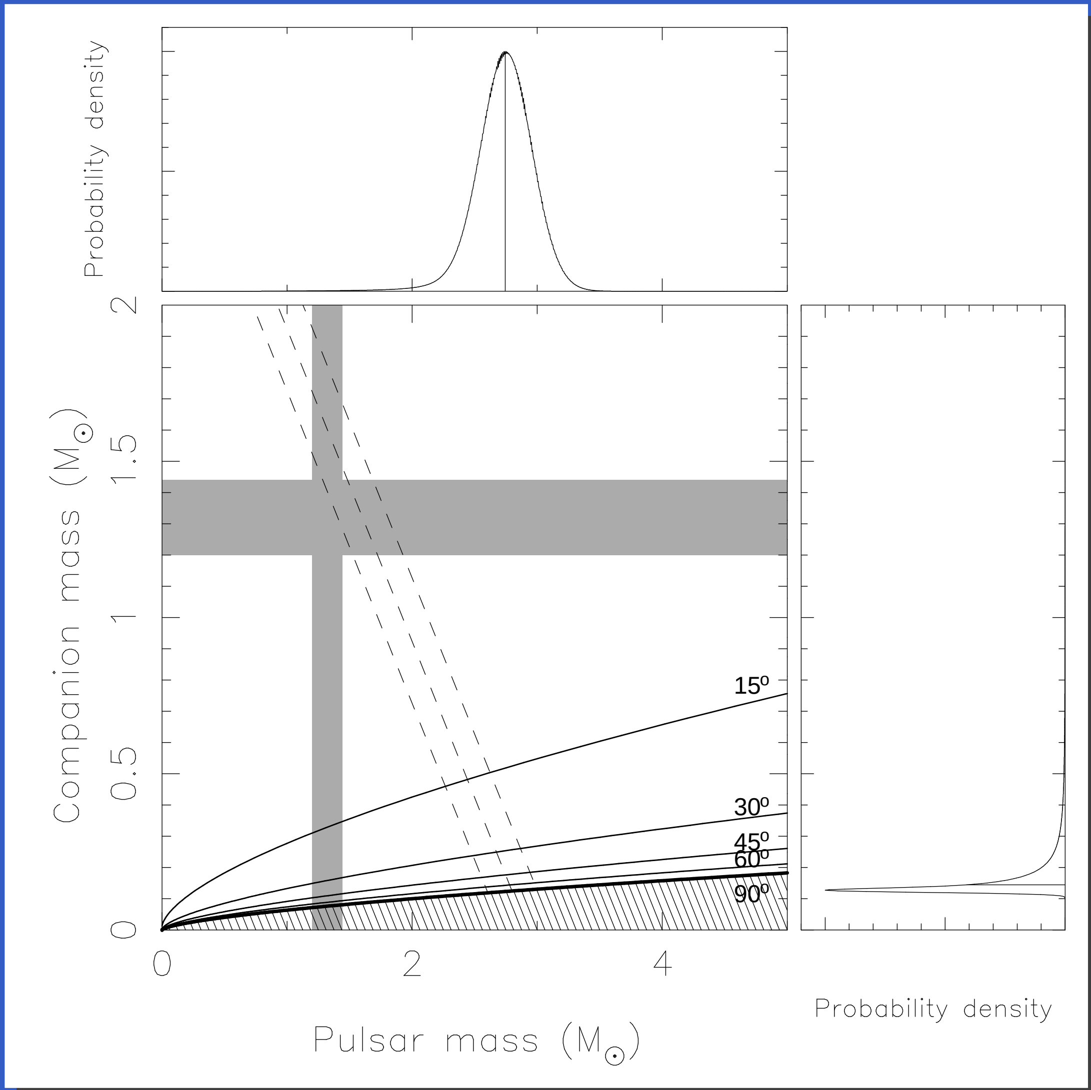


(Giuseppe Pagliara)

- plot of the *chiral* phase transition line within the NJL model
- phase transition is at small chemical potentials, in particular for $Y_p = 0.5$
- 2SC phase likes symmetric matter, as only u- and d-quarks pair (CFL phase is at higher densities)

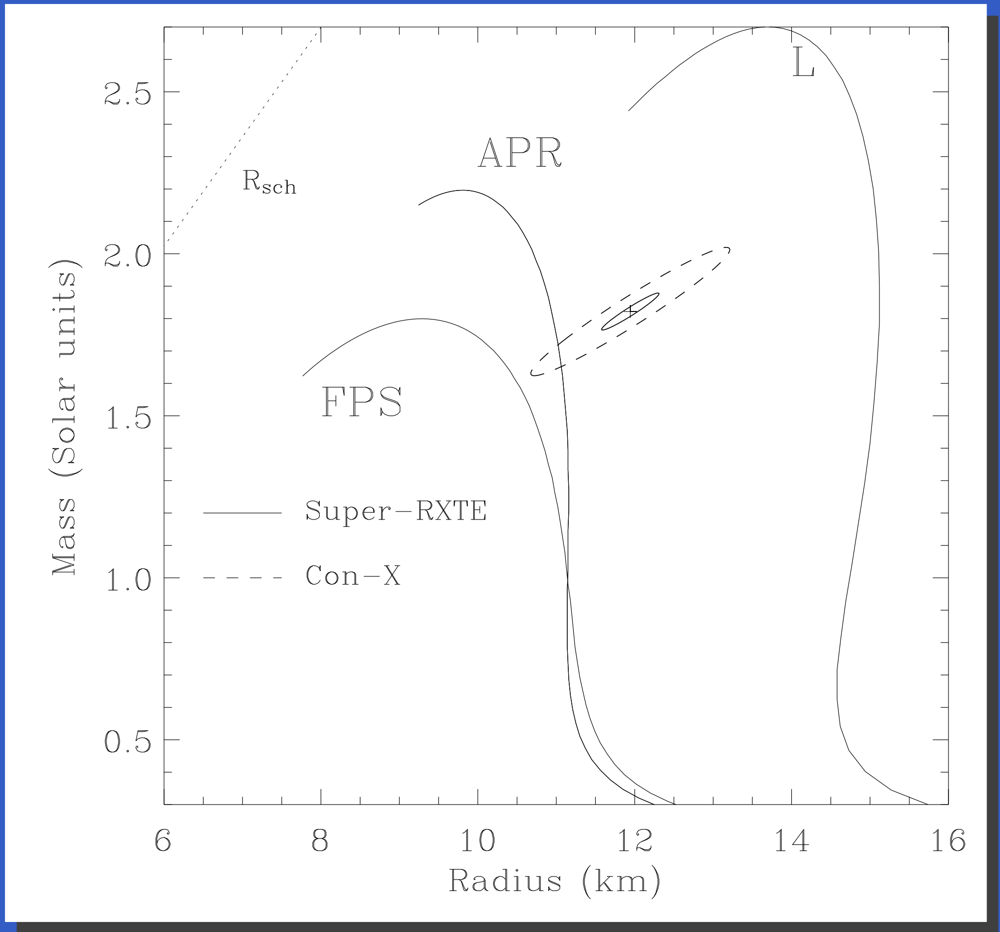
Supermassive Pulsar in Globular Cluster?

(Freire et al., arXiv:0711.0925v2 (2007))



- measurement of periastron advance of the pulsar PSR J1748-2021B
- inclination angle i of orbital plane unknown
- statistical analysis (for angle i): $M = 2.74 \pm 0.21 M_\odot$ (1σ) and $M > 2.0 M_\odot$ (99% c.l.)
- two neutron stars with $M \sim 1.4 M_\odot$ 'unlikely' but possible for $i = 4 - 5$ degrees
- measurement of a second GR effect needed to draw a firm conclusions!

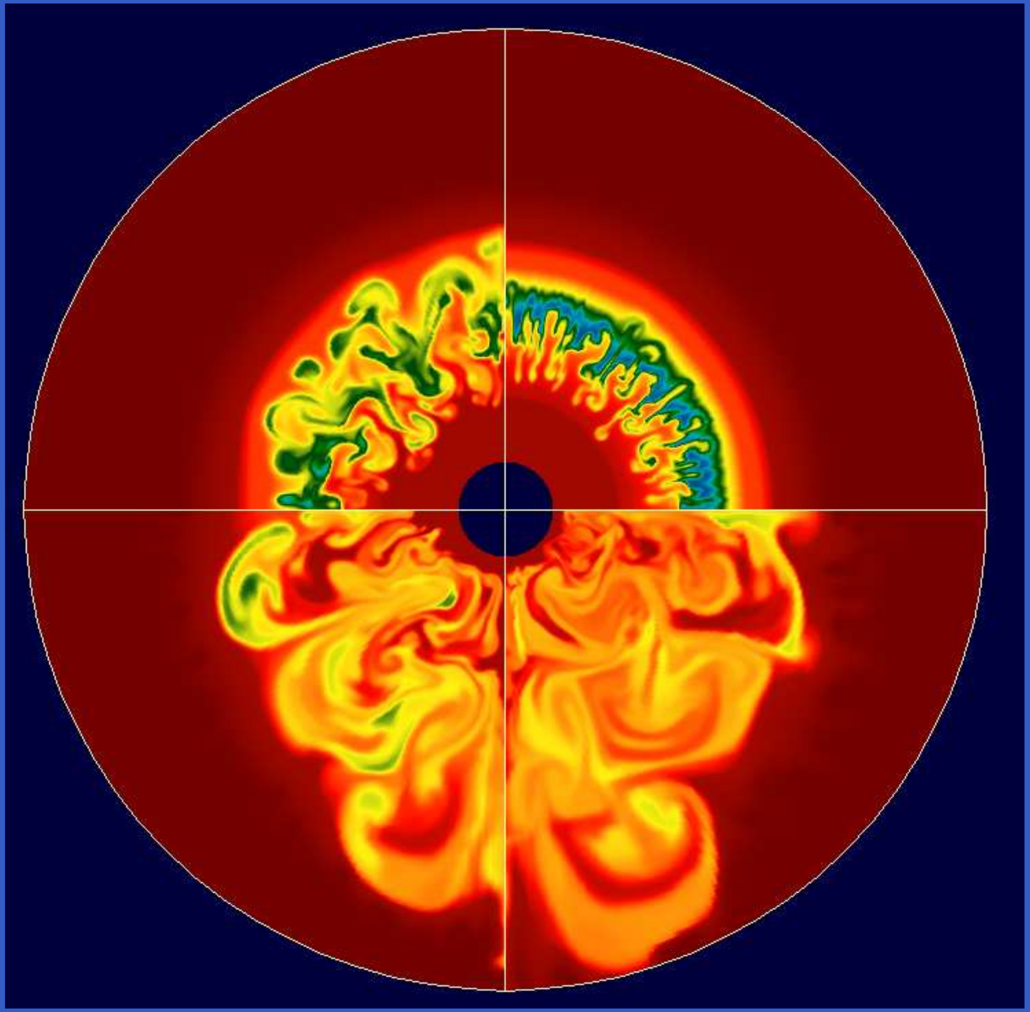
Probes Using X–Ray Bursts



(Strohmayer (2004))

- X-ray bursts from accreting neutron stars originating from the surface
- spectral profi le is modifi ed from space-time warpage
- → gives a model independent mass and radius!
- Constellation-X will determine the mass-radius ratio to within 5% ! (Bhattacharyya et al. 2004)

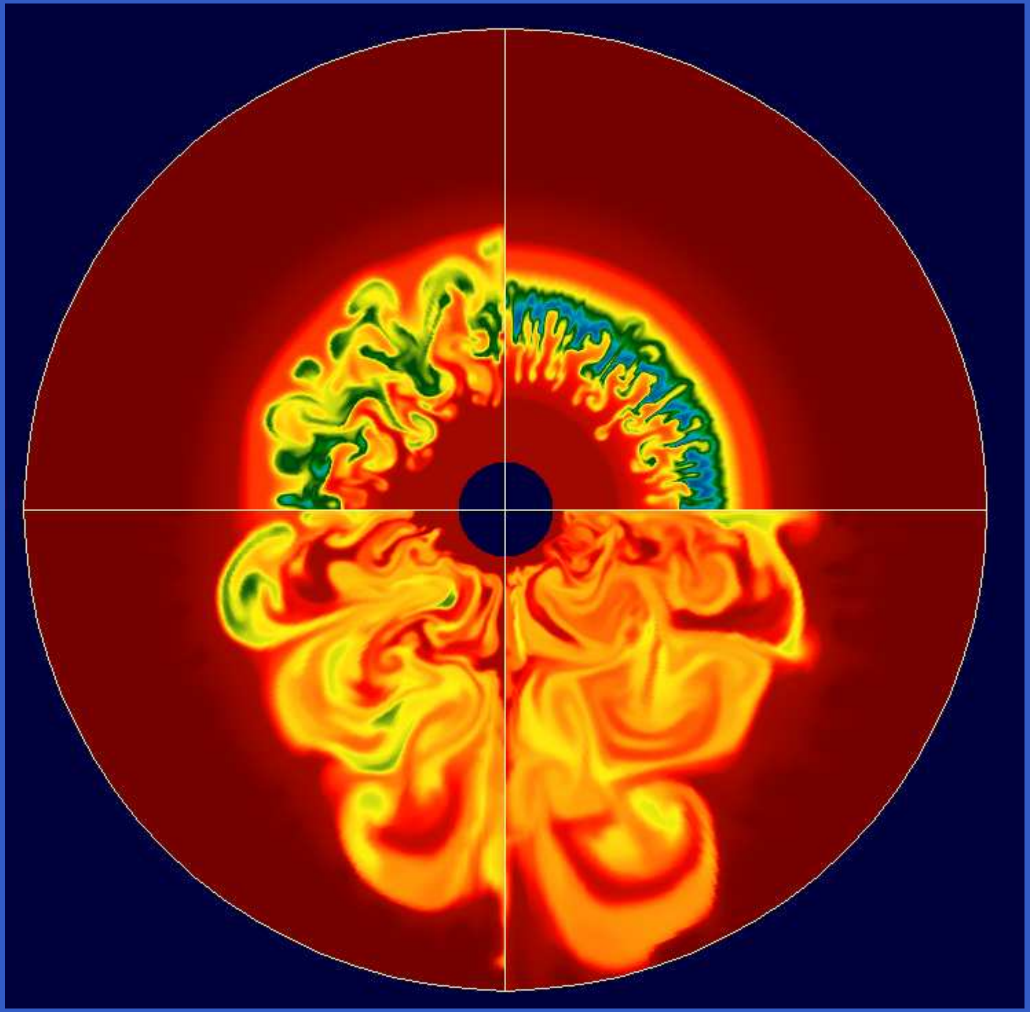
Supernova Explosions



- stars with a mass of more than 8 solar masses end in a (core collapse) supernova (type II)
- new generation of simulation codes: 3D, Boltzmann neutrino transport
- Improved Models of Stellar Core Collapse and Still no Explosions: What is Missing? (Buras, Rampp, Janka, Kifonidis, PRL 2004)

'. . . the models do not explode. This suggests missing physics, possibly with respect to the nuclear equation of state . . . ' !

Supernova Explosions



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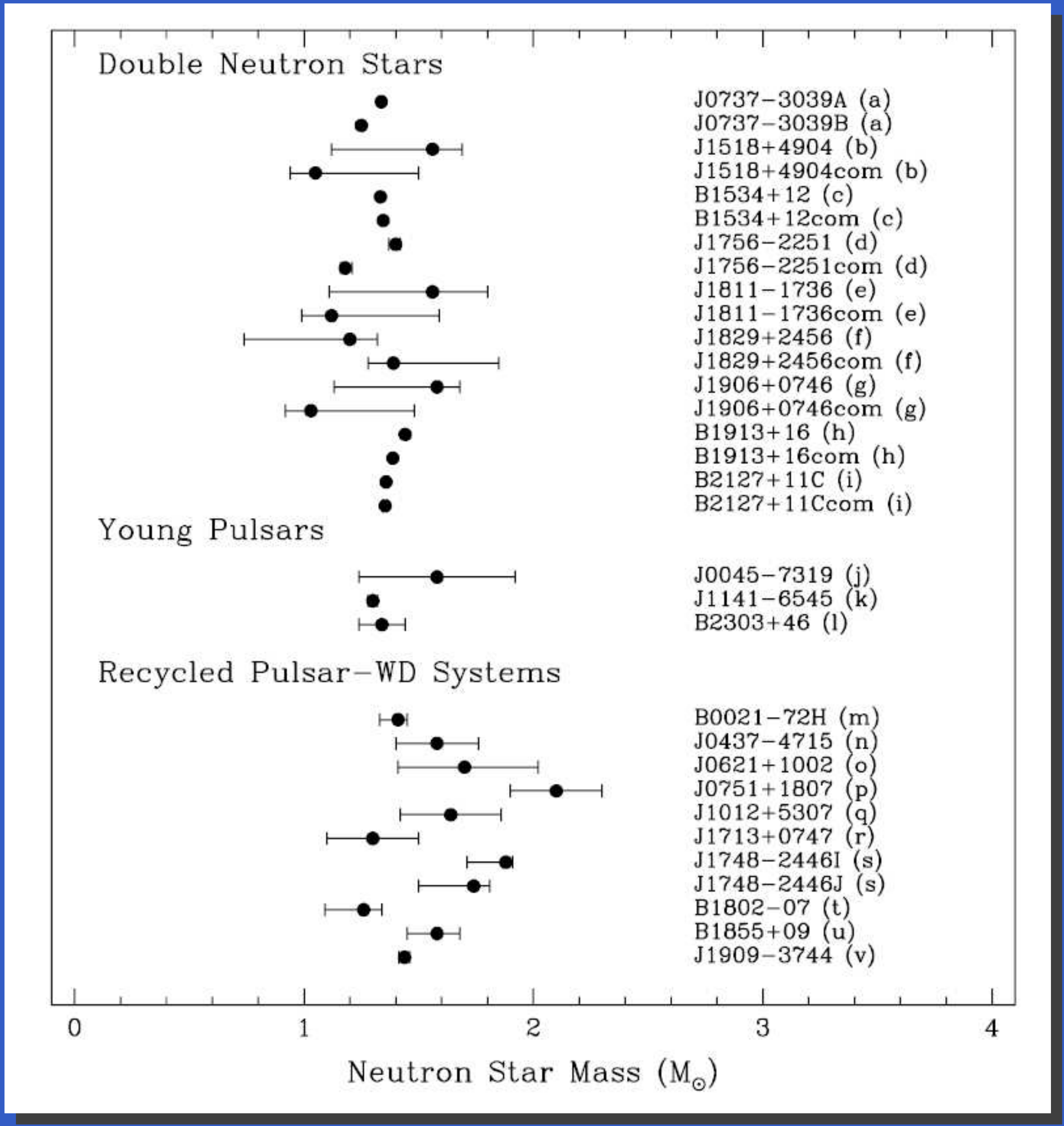
SASI: standing accretion shock instability, the models *do* explode!

(Janka, GSI Theory Seminar, July 11, 2007)

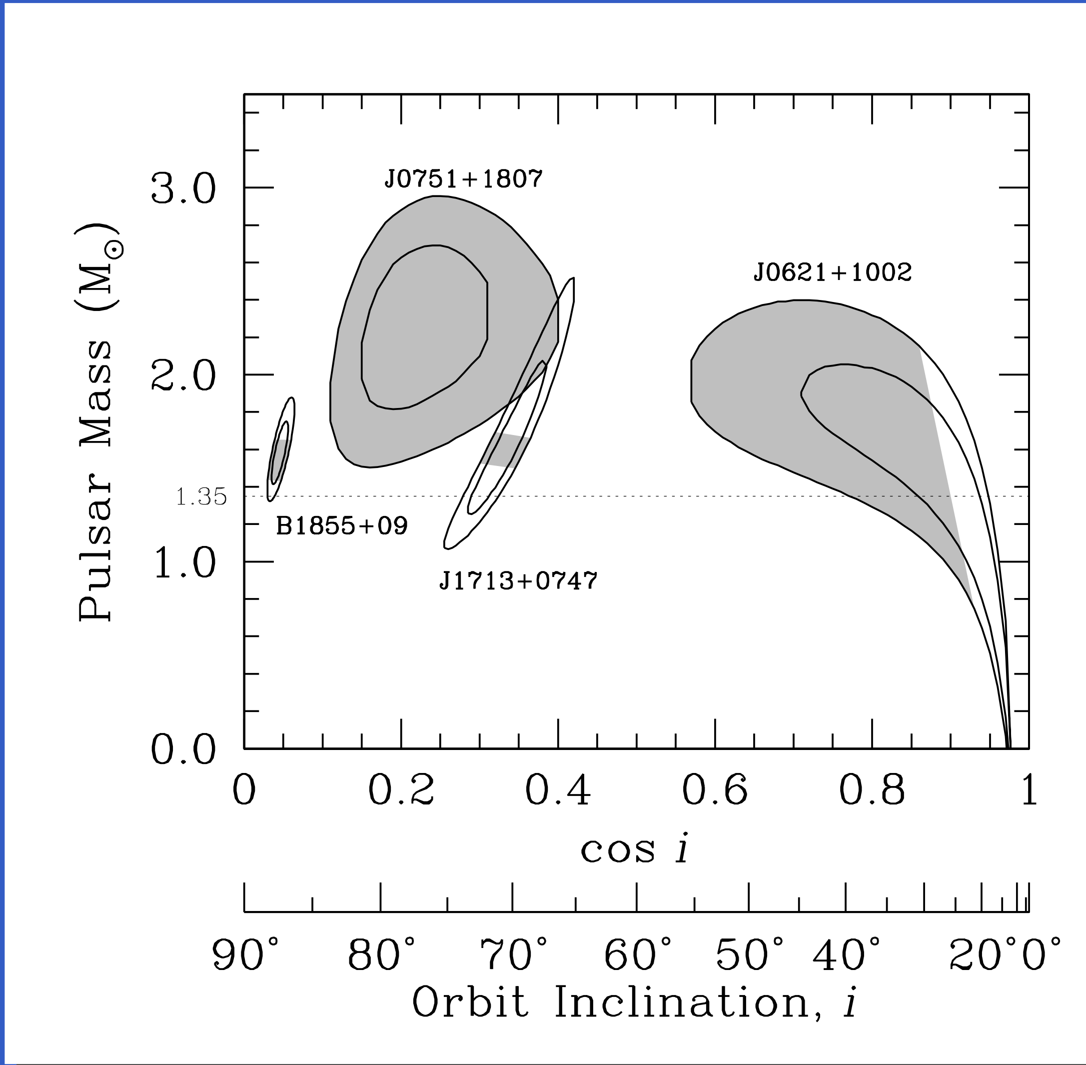
Masses of Pulsars (Stairs, 2006)



- more than 1600 pulsars known
- best determined mass: $M = (1.4414 \pm 0.0002) M_\odot$ for the Hulse-Taylor pulsar (Weisberg and Taylor, 2004)
- smallest known mass: $M = (1.18 \pm 0.02) M_\odot$ for pulsar J1756-2251 (Faulkner et al., 2005)

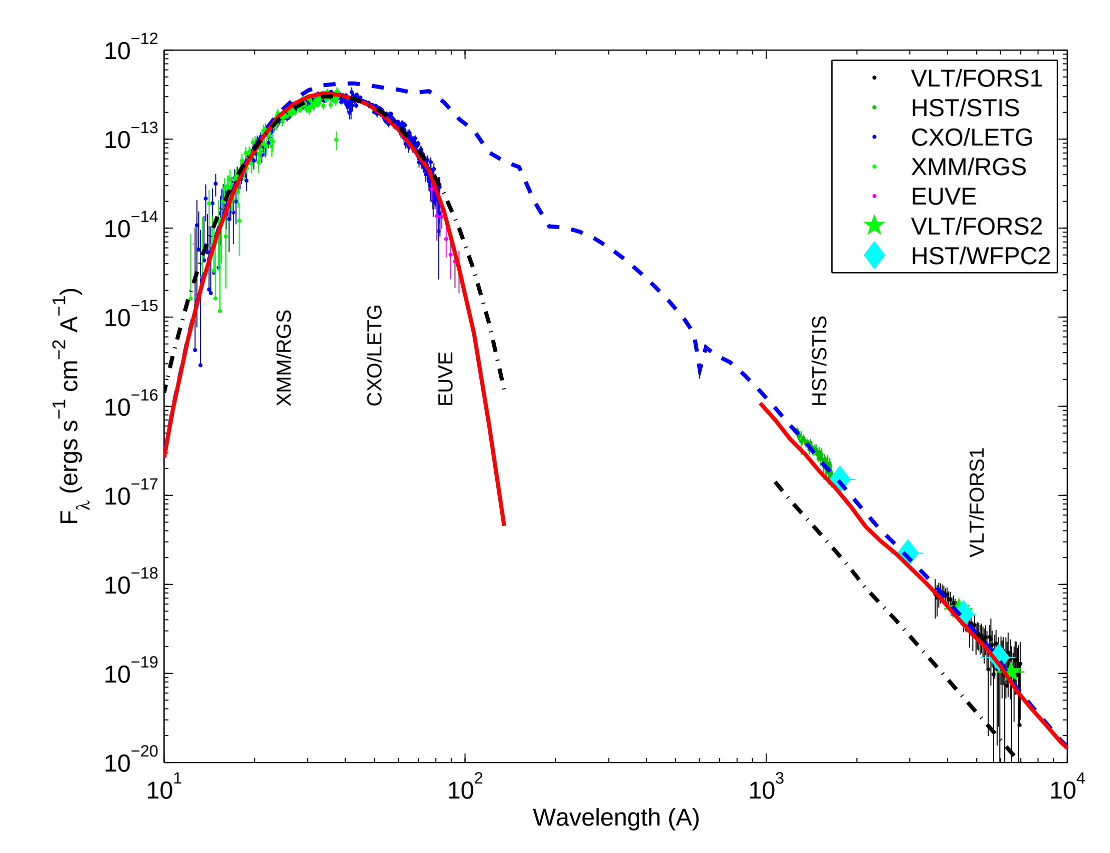
Massive Neutron Stars in Pulsar–White Dwarf Systems?

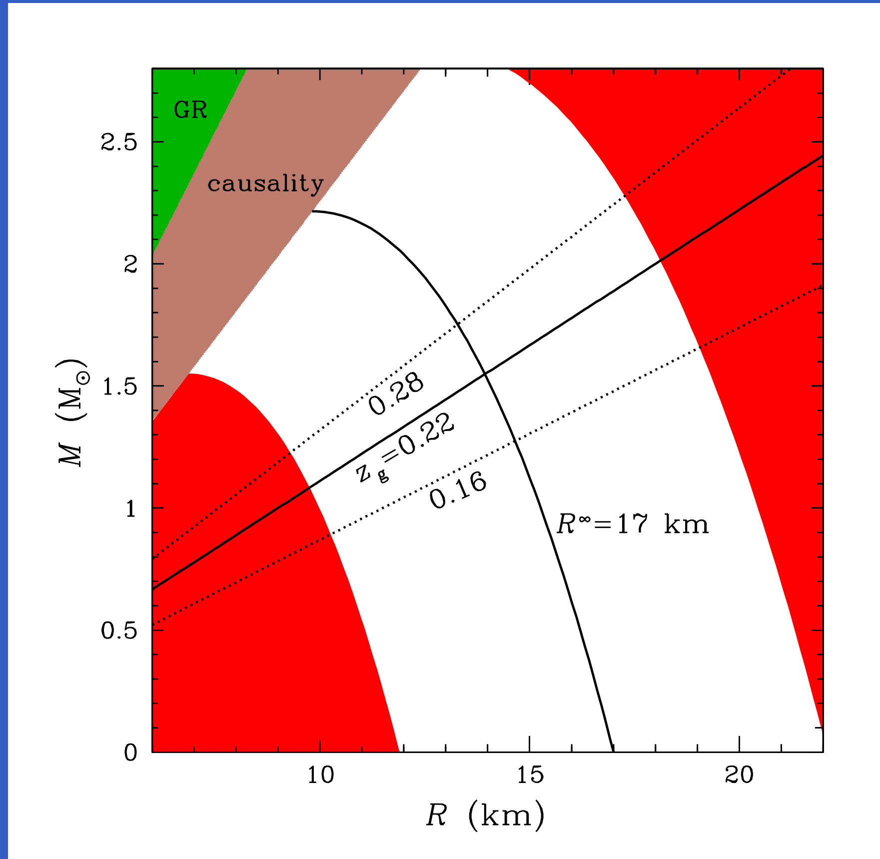
(Nice, Splaver, Stairs (2003))



- shaded area: from theoretical limits for white–dwarf companion
- Nice et al. (2005): $M = 2.1 \pm 0.2 M_\odot$ (1σ) and $M = 1.6 - 2.5 M_\odot$ (2σ)!!!
- David Nice and Ingrid Stairs, private communication (2007): $M = 1.14 - 1.40 M_\odot$!!!

RXJ 1856: Neutron Star or Quark Star? (Trümper et al. (2003), Ho et al. (20

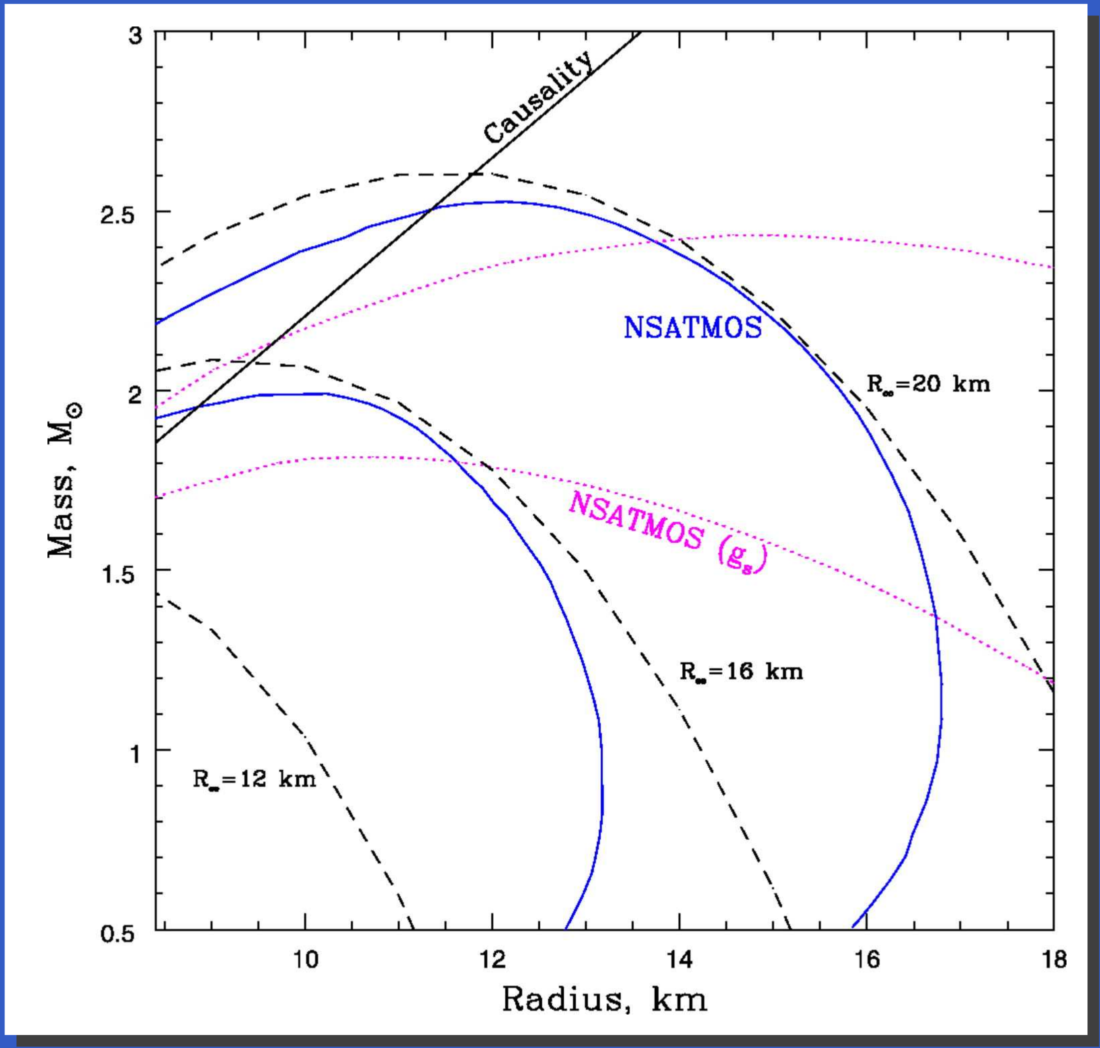




- two-component blackbody: small soft temperature, so as not to spoil the x-ray
- this implies a rather LARGE radius so that the optical flux is right!
- lower limit for radiation radius: $R_\infty = R/\sqrt{1 - 2GM/R} = 17$ km (d/140 pc)
- redshift $z_g \approx 0.22$: $R \approx 14$ km and $M \approx 1.55 M_\odot$
- largest uncertainty in distance d

Spectral Model for Neutron Star X7

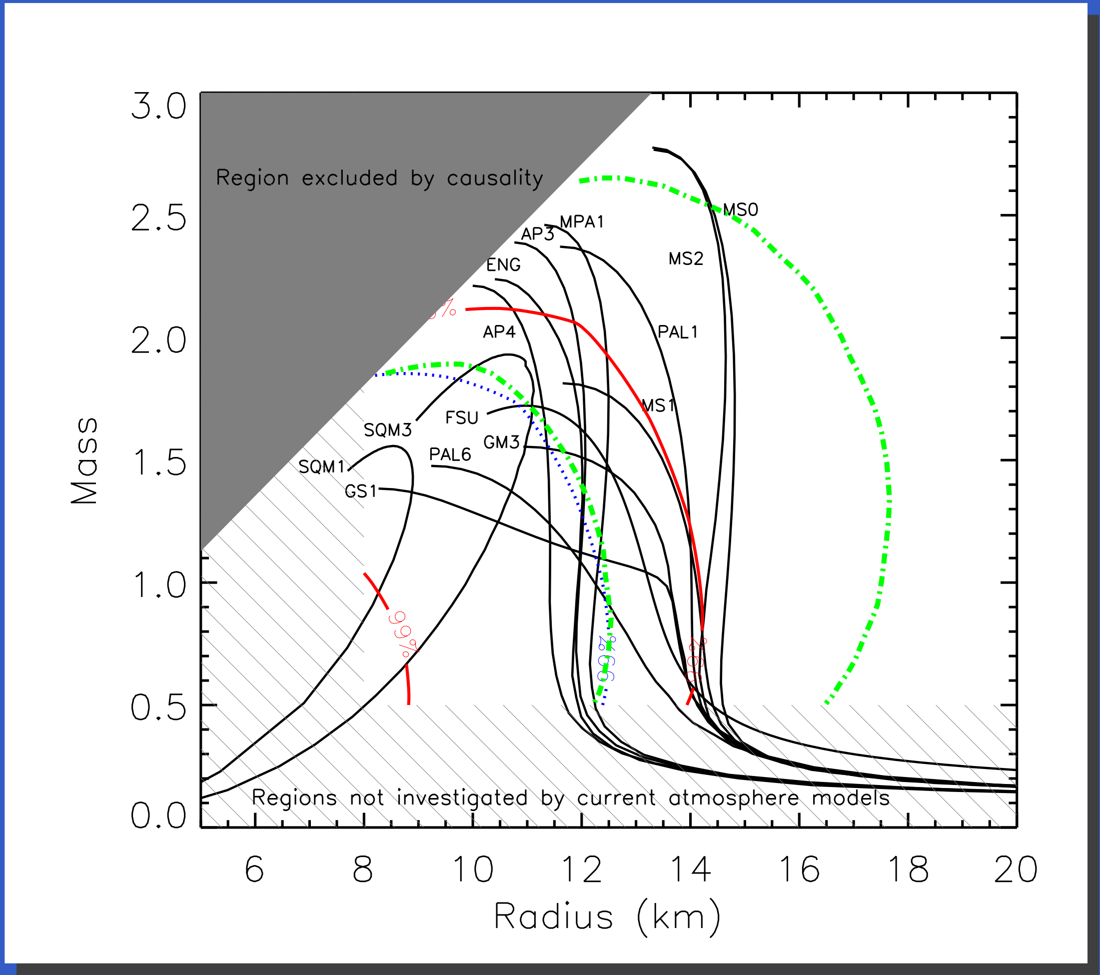
(Heinke, Rybicki, Narayan, Grindlay (2006))



- improved hydrogen atmosphere: adjusted surface gravity g_s (solid blue lines, 90% c.l.) vs. fixed g_s (pink dotted lines)
- for fixed radius of 10km: $M = 2.20^{+0.03}_{-0.16} M_\odot$ (90% c.l.)
  for fixed mass of $1.4 M_\odot$: $R = 14.5^{+1.8}_{-1.6}$ km (90% c.l.)
- nearly no constraint on the mass for $R \approx 14$ km!
- any mass from $0.5 M_\odot$ to $2.3 M_\odot$ allowed!

Spectral Modelling of Neutron Stars in Globular Clusters

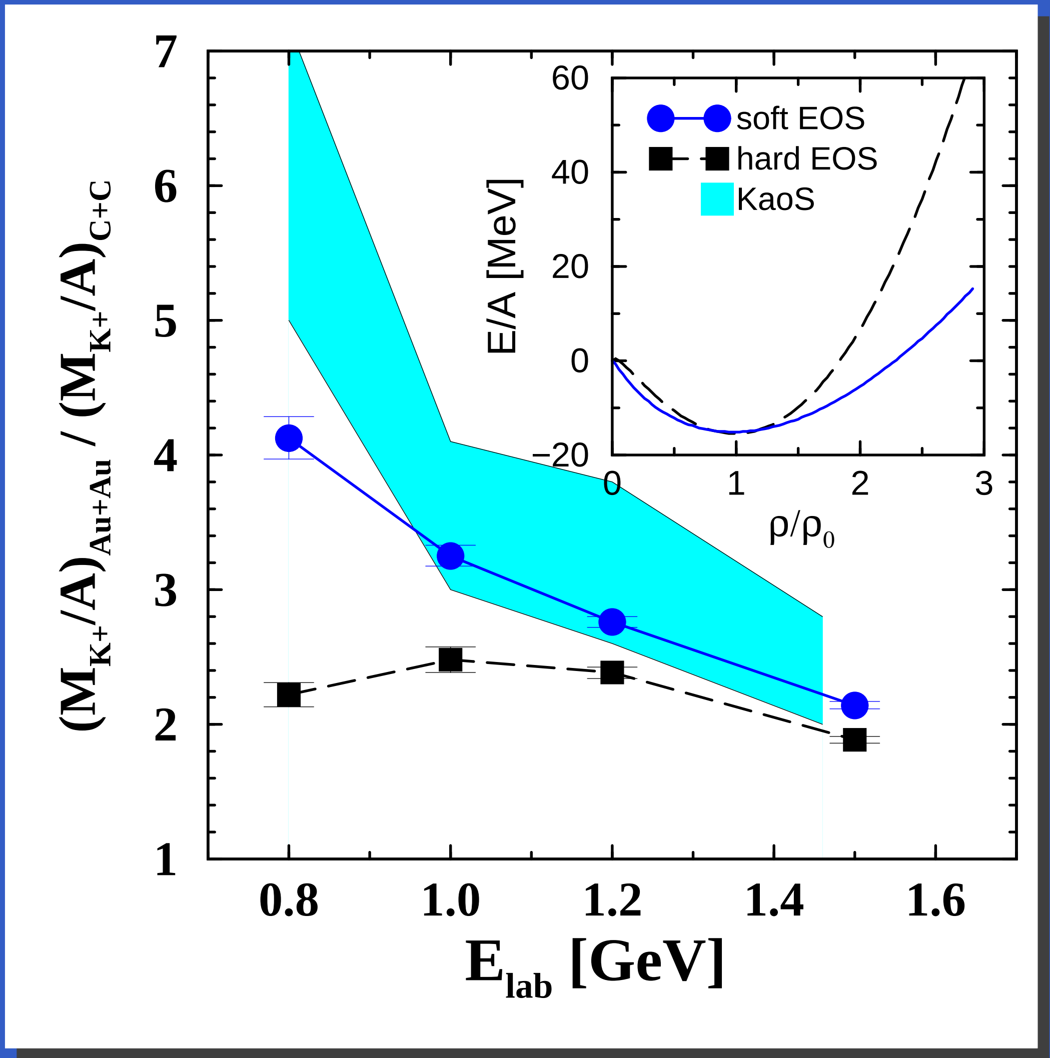
(Webb and Barret (2007)



- spectral modelling of neutron stars in M13 (dotted blue line) and ω Cen (solid red line) and X7 in 47 Tuc (dash-dotted green line) all 99% c.l.
- mass-radius curve has to pass through all three regions: data from M13 demands a small mass

The EoS from Heavy-Ion Data versus Astro Data

Kaon production in heavy-ion collisions

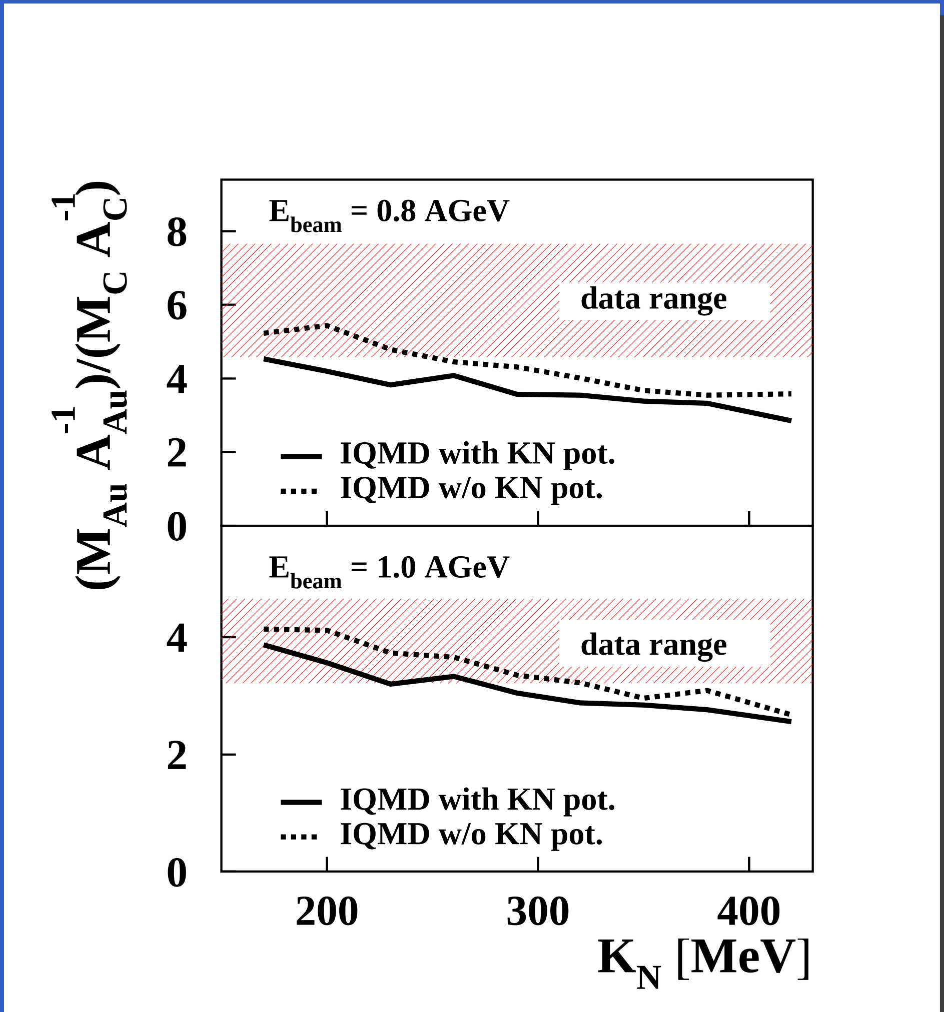


Sturm et al. (KaoS collaboration), PRL 2001

Fuchs, Faessler, Zabrodin, Zheng, PRL 2001

- Kaons produced by associated production: NN→ NΛK, NN→NNK$\overline{\mathrm{K}}$
- in-medium processes (rescattering): πN $\rightarrow$ ΛK, $\pi\Lambda$ $\rightarrow$ N$\overline{\mathrm{K}}$
- nuclear matter is compressed up to $3n_0$!
- long mean-free path of kaons: kaons can escape high density matter

Confi rmed KaoS data analysis: the nuclear EoS is soft!



The KAOS Collaboration

- kaon production (K^+) in heavy-ion collisions at subthreshold energies
- double ratio: multiplicity per mass number for C+C collisions and Au+Au collisions at 0.8 AGeV and 1.0 AGeV (rather insensitive to input parameters)
- only calculations with a compression modulus of $K_N \approx 200$ MeV can describe the data (Hartnack, Oeschler, Aichelin, PRL 2006; KaoS collaboration, 2007)

$\Longrightarrow$ the nuclear equation of state is SOFT!

Probing the EoS: Empirical Nucleon-Nucleon Interaction

Ansatz for the energy per particle:

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

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, α varies between 0.7 and 1.1 (B.-A. Li et al. 2007).

The pressure is determined by the thermodynamic relation

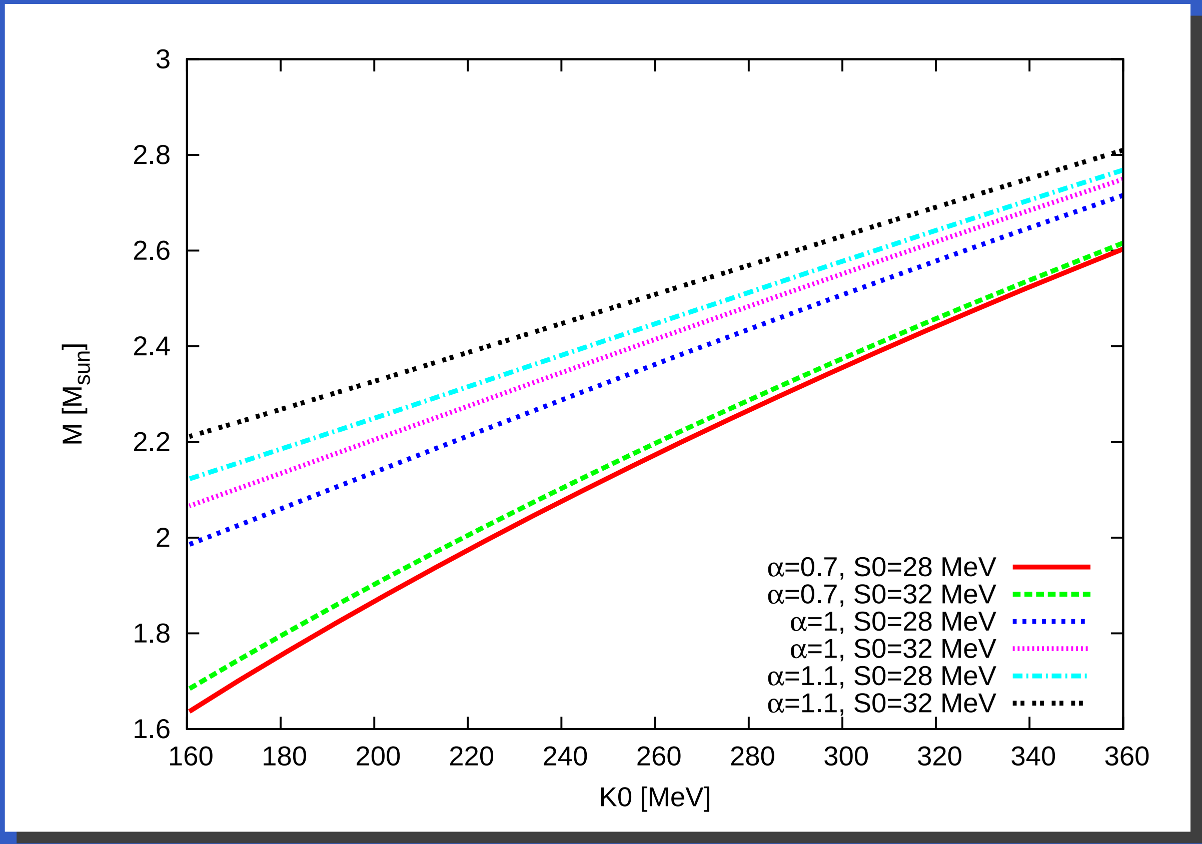
$$P = n^2 \frac{d}{dn} \left(\frac{\epsilon}{n} \right)$$

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 masses?

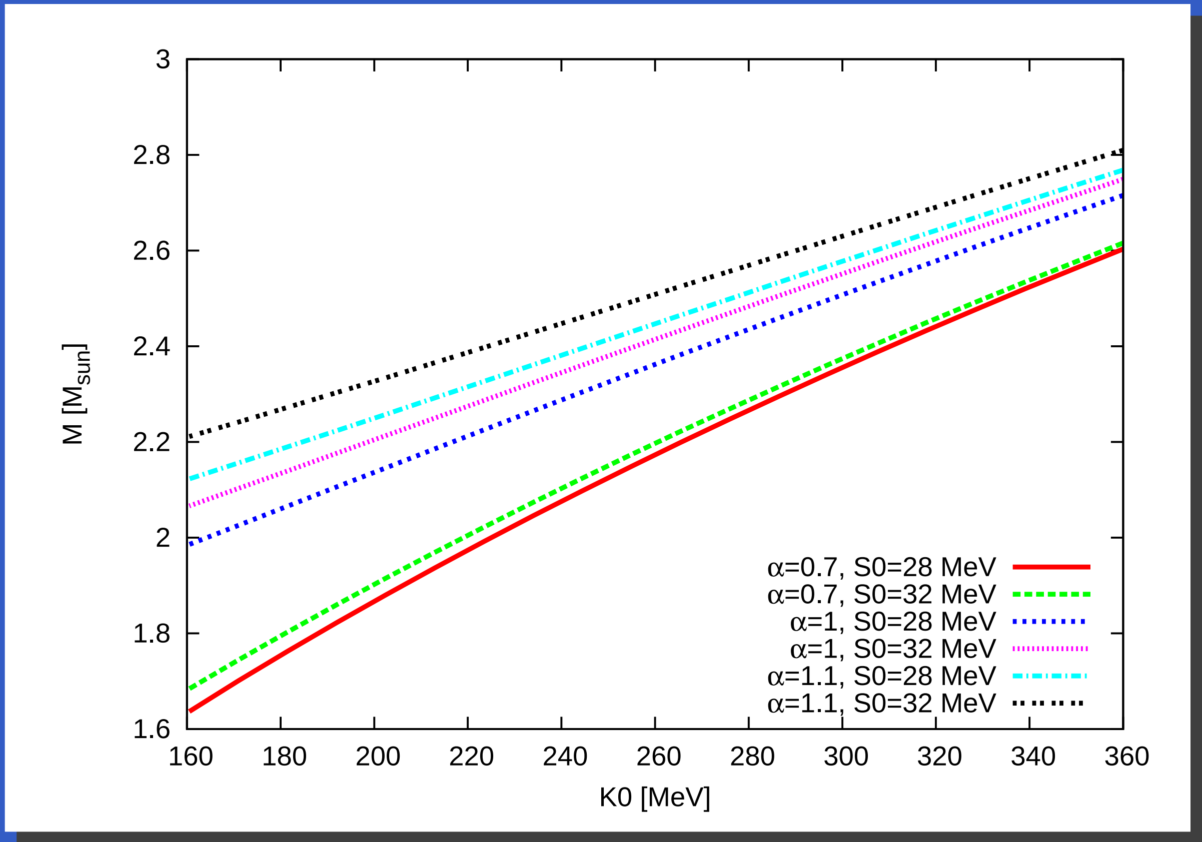
Empirical Nucleon-Nucleon Interaction: Maximum Masses



(Irina Sagert)

- small variation of the maximum mass with the compression modulus K and the asymmetry energy for normal density dependence $\alpha = 1.0, 1.1$
- strong dependence on the compression modulus K for $\alpha = 0.7$
- maximum mass $M \geq 1.6 M_\odot$ for $K_0 > 160$ MeV!
- maximum mass $M \geq 2 M_\odot$ for $K_0 > 160$ MeV and $\alpha = 1.0, 1.1$!

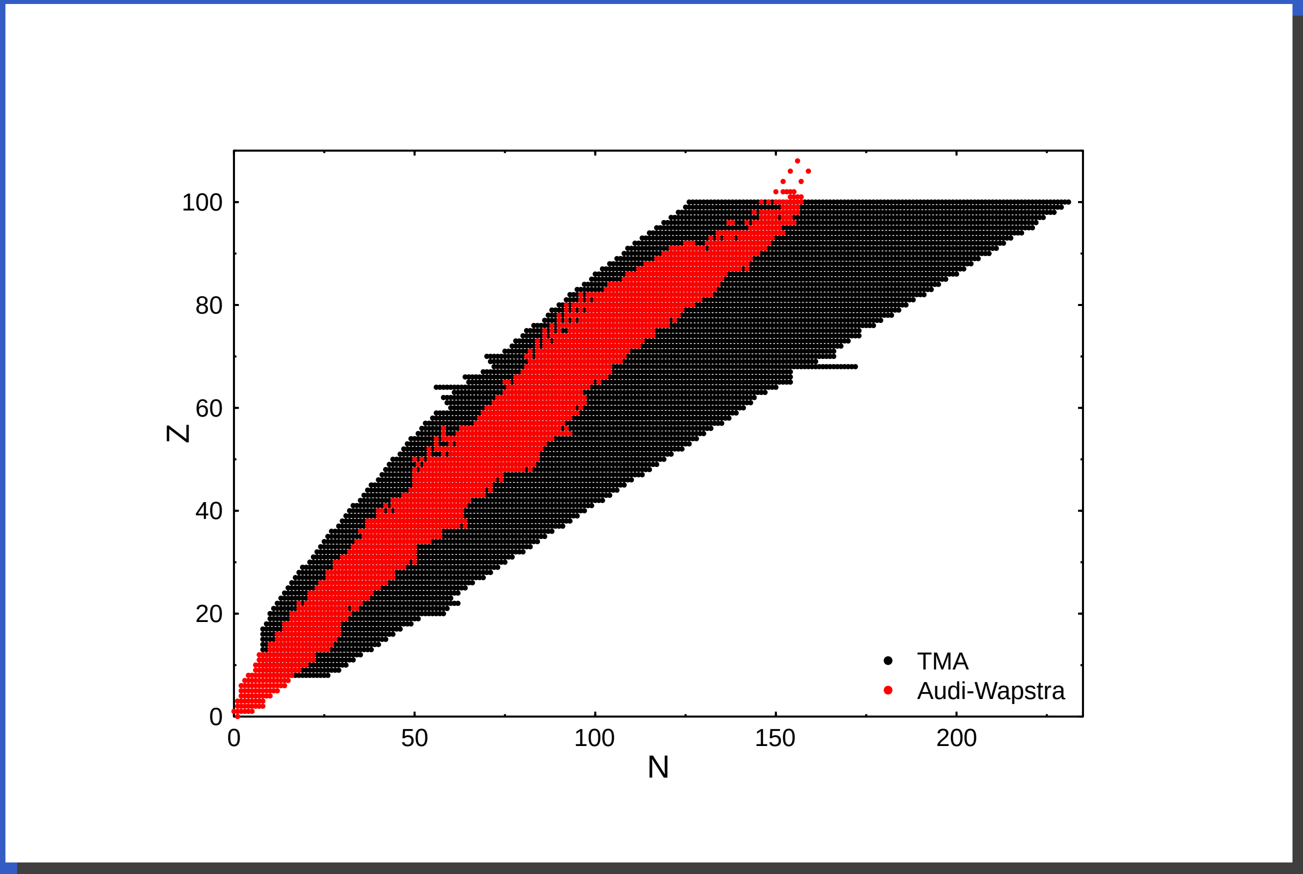
Empirical Nucleon-Nucleon Interaction II



(Irina Sagert)

- slight dependence on asymmetry energy S_0, up to $\Delta M = \pm 0.1 M_\odot$ for low K
- maximum central density $n_c = (7 \div 8) n_0$ for $\alpha = 1.0, 1.1$ and $10 n_0$ for $\alpha = 0.7$
- EoS causal up to $K_0 = 340$ MeV ($M = 2.6 M_\odot$) for $\alpha = 1.0, 1.1$, and up to $K = 280$ MeV for $\alpha = 0.7$
- $\Longrightarrow$ A $2M_\odot$ pulsar mass is compatible with a 'soft' EoS!

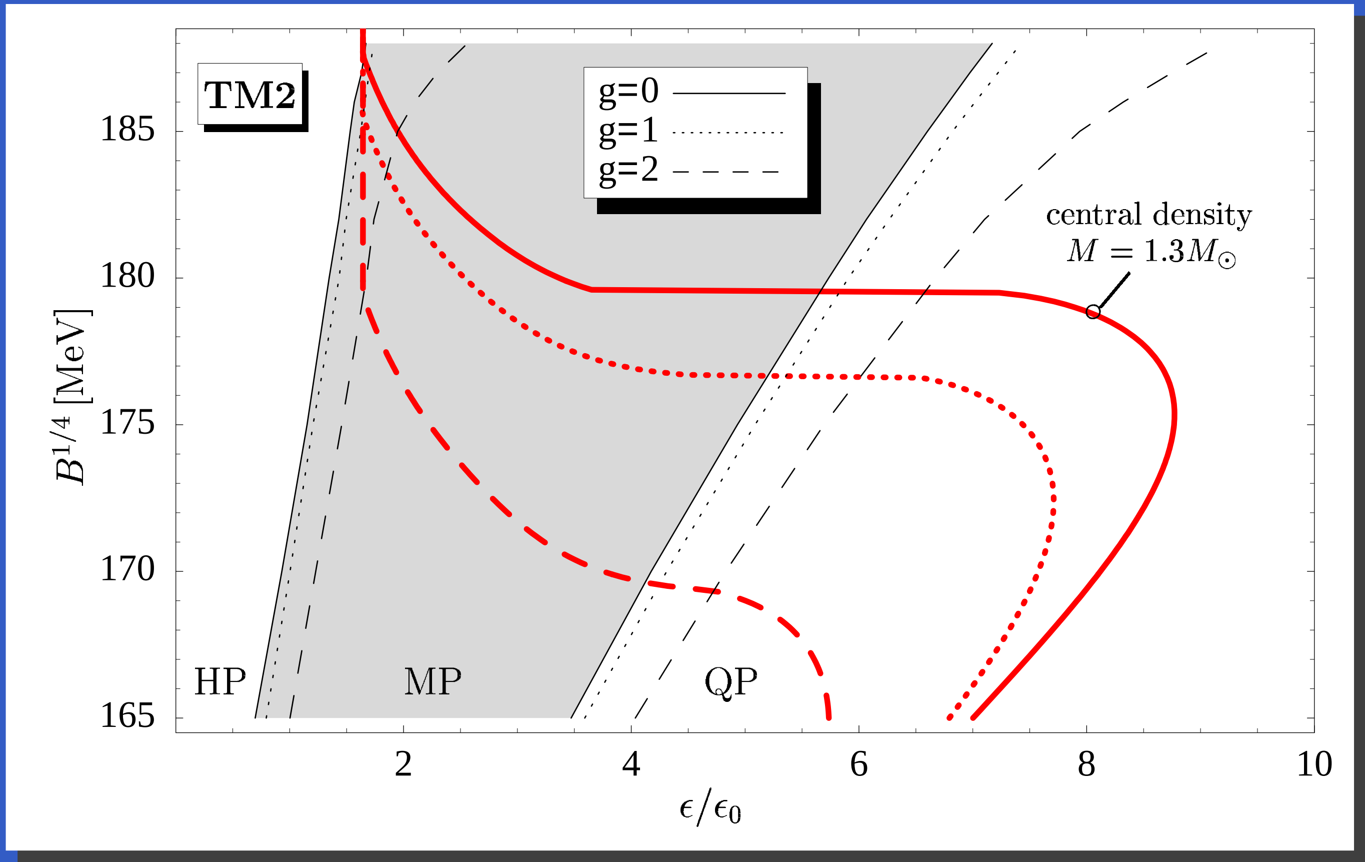
Hot Nuclear Equation of State



(Matthias Hempel)

- taken into account nucleons, electrons and all nuclei
- input: 2003 update of nuclear mass data
- state-of-the-art (relativistic) nuclear model for unknown nuclear masses
- Coulomb, shell-effects, pairing, axial deformations included!

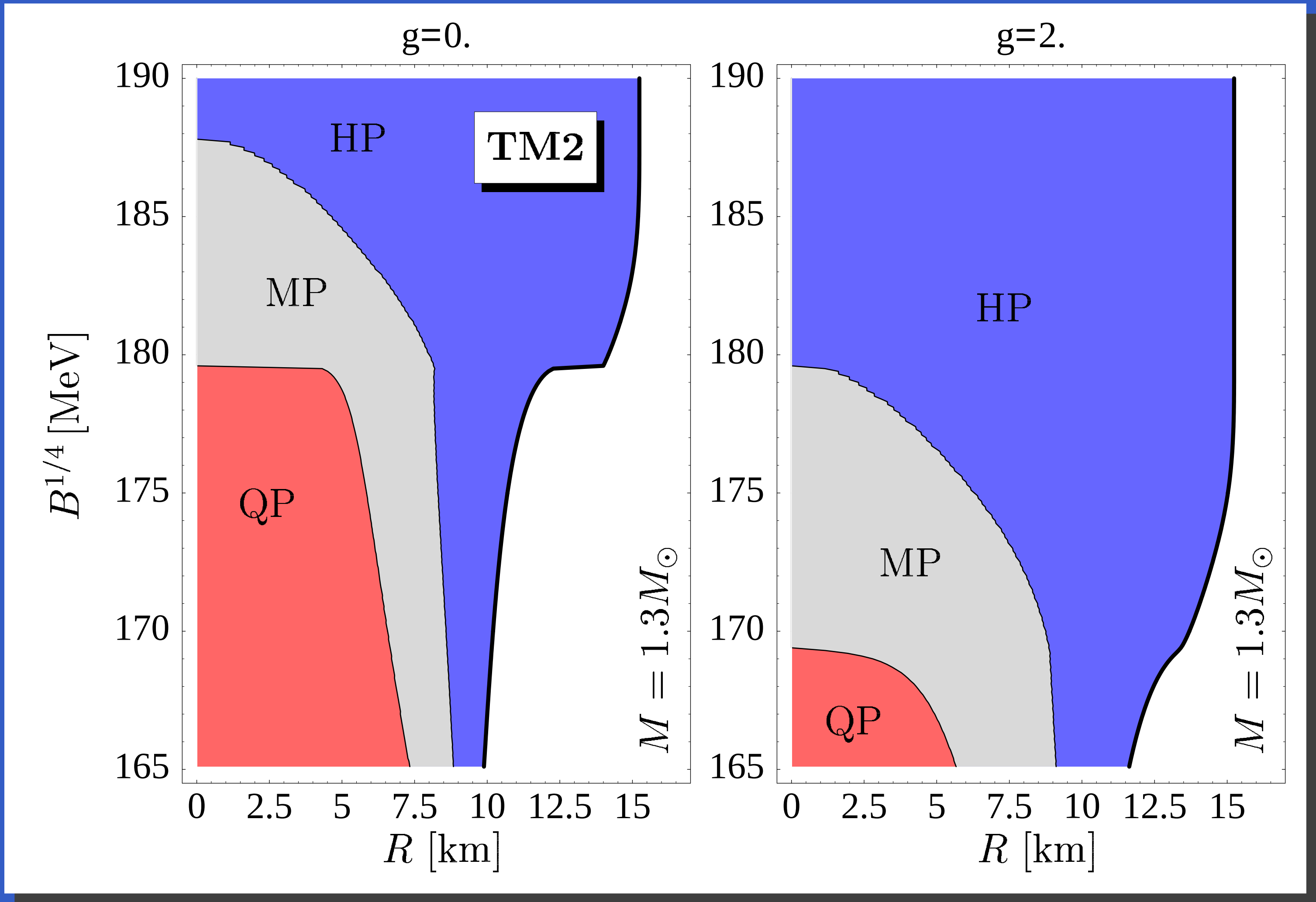
Quark Matter in Cold Neutron Stars



(Schertler, C. Greiner, JSB, Thoma (2000))

- phase transition to quark matter in the MIT bag model
- onset of mixed phase appears between $(1-2)n_0$ even for large values of the bag constant
- suffi ciently high densities reached in the core for a $1.3M_\odot$ neutron star to have quark matter

Hybrid Stars (Schertler et al. (2000))



- hybrid star: consists of hadronic and quark matter
- three phases possible: hadronic, mixed phase and pure quark phase
- composition depends crucially on the parameters as the bag constant B (and on the mass!)