Neutron Stars, Supernovae and the QCD Phase Transition

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HGSFP

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Outline

- Heavy-ion data and the maximum mass of neutron stars

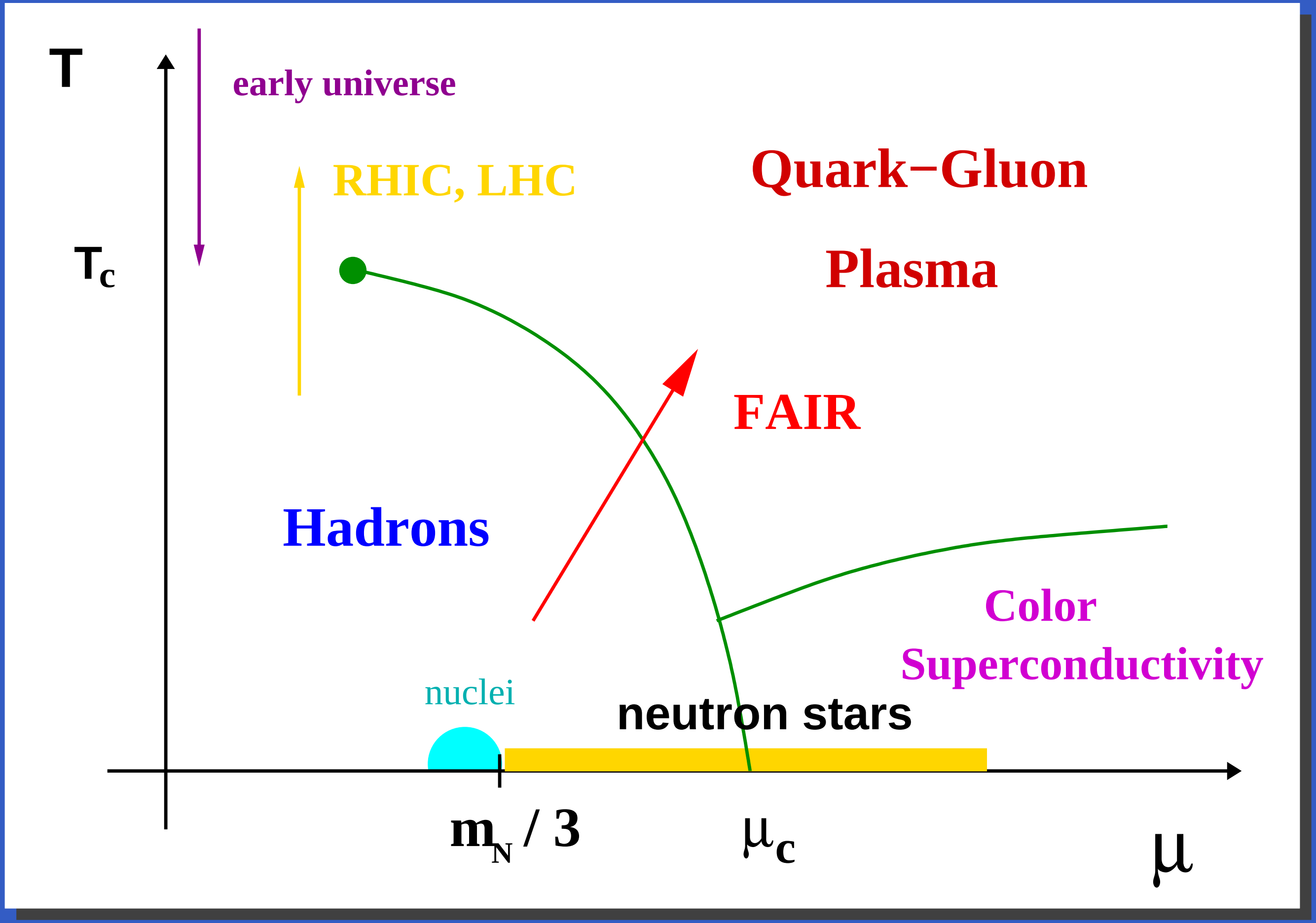
  (Irina Sagert, JSB, Christian Sturm, work in progress)
- Stability of color-flavor locked quark stars

  (Giuseppe Pagliara, JSB, 2008)
- New nuclear equation of state for core-collapse supernova simulations

  (Matthias Hempel, JSB, work in progress)
- Signals of the QCD phase transition in core-collapse supernovae

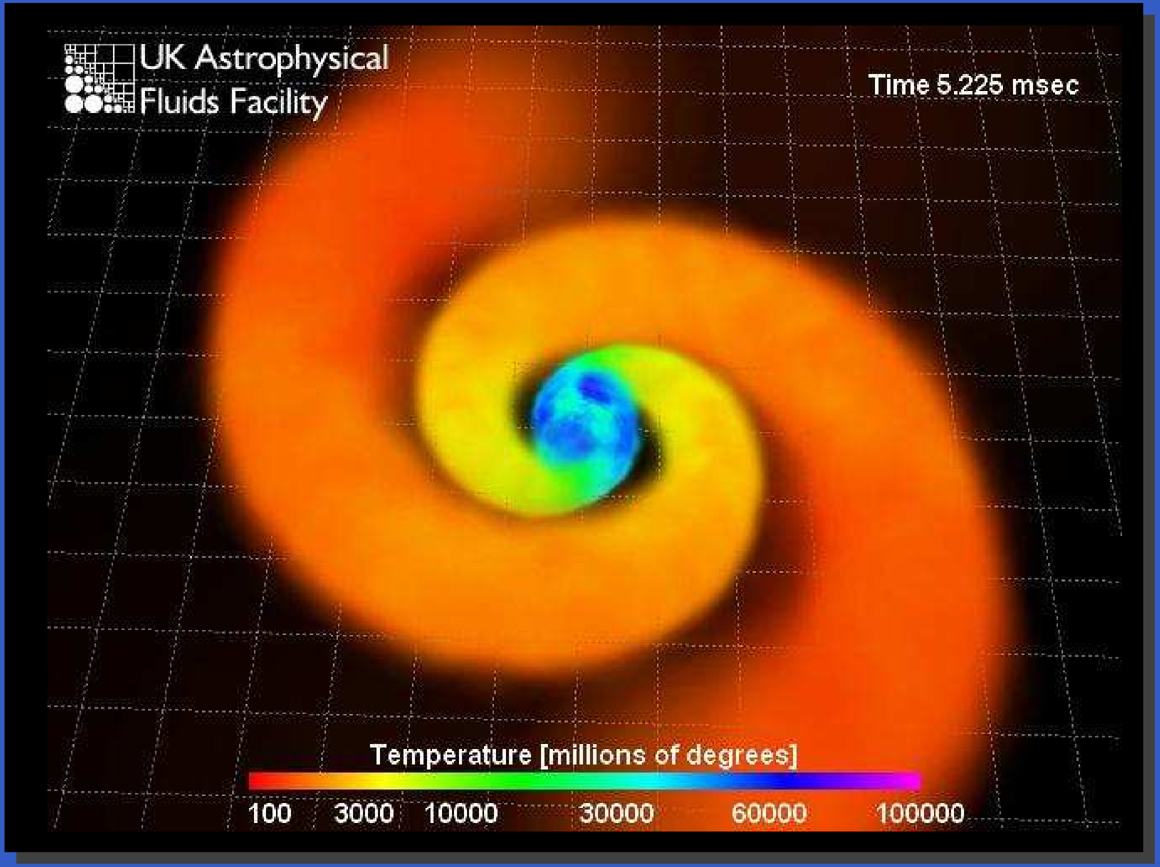
  (Sagert, Hempel, Pagliara, Hempel, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, arXive: 0809.4225)

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!

QCD Equation of State as Input in Astrophysics



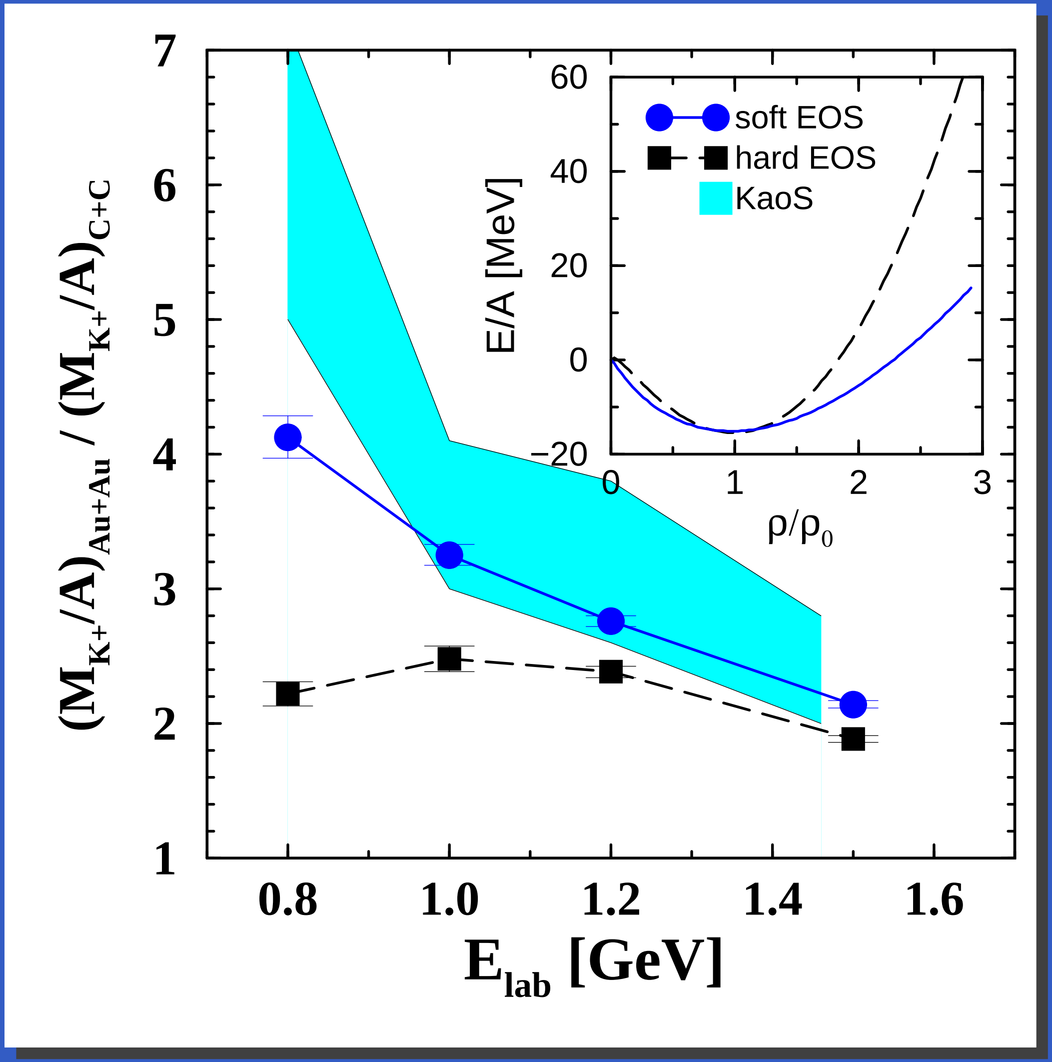
- supernovae simulations: $T = 1$–50 MeV, $n = 10^{-10}$–$2n_0$
- proto-neutron star: $T = 1$–50 MeV, $n = 10^{-3}$–$10n_0$
- global properties of neutron stars: $T = 0$, $n = 10^{-3}$–$10n_0$
- neutron star mergers: $T = 0$–175 MeV, $n = 10^{-10}$–$10n_0$

Constraint on the maximum mass of neutron stars from heavy-ion data

(Irina Sagert, JSB, Christian Sturm, 2009)

$\Longrightarrow$ talk by Christian Sturm on Friday

Kaon production in heavy-ion collisions

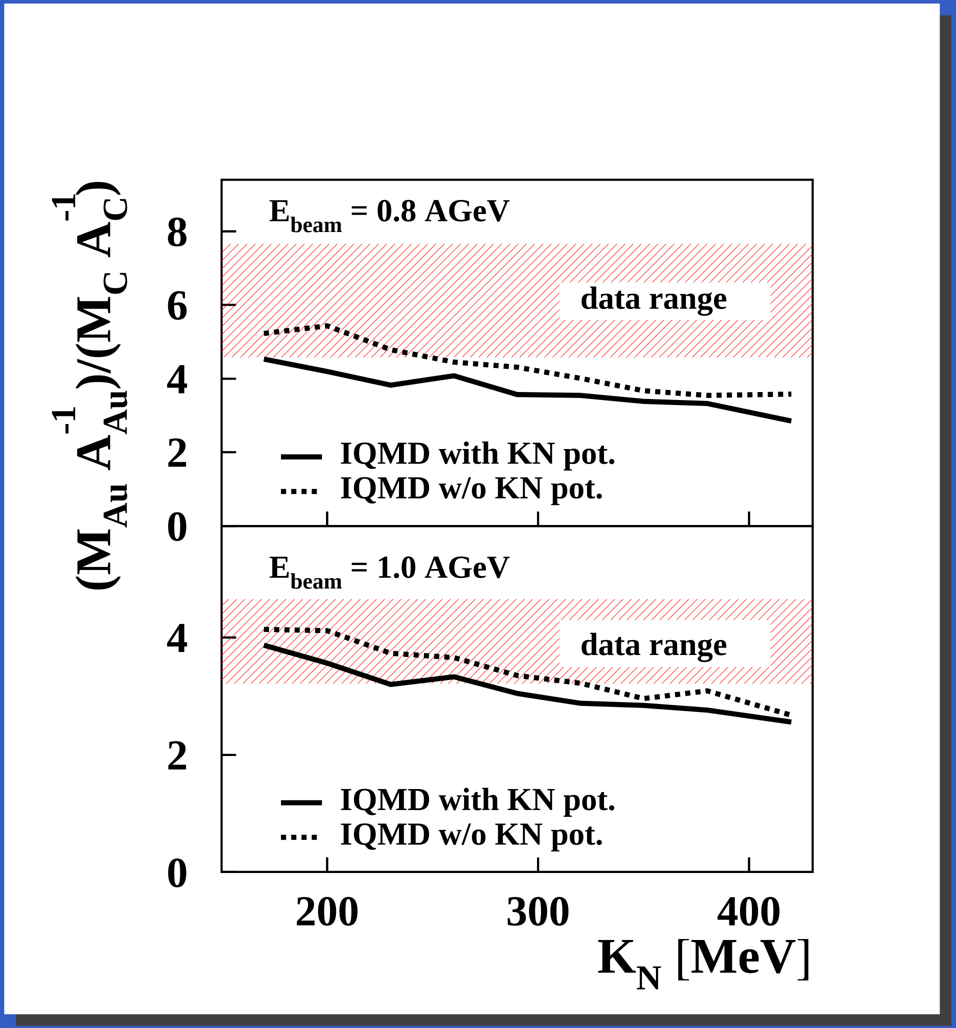


Sturm et al. (KaoS collaboration), PRL 2001

Fuchs, Faessler, Zabrodin, Zheng, PRL 2001

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

Confirmed 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 (Prakash et al. 1988):

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

with $u = n/n_0$; parameters A, B, σ 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).

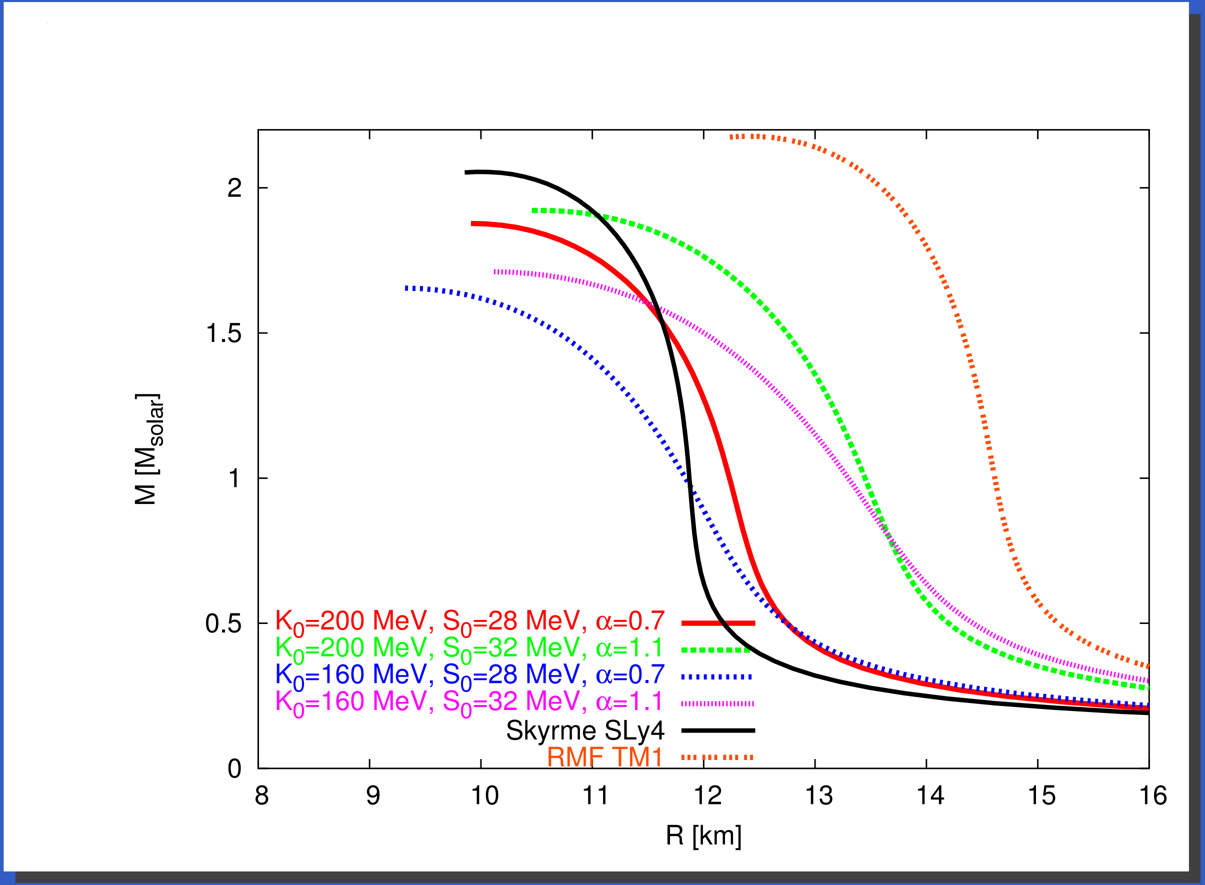
The pressure is determined by the thermodynamic relation

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

EoS used as input in transport model calculations.

Check: are low compressibilities ruled out by neutron star masses?

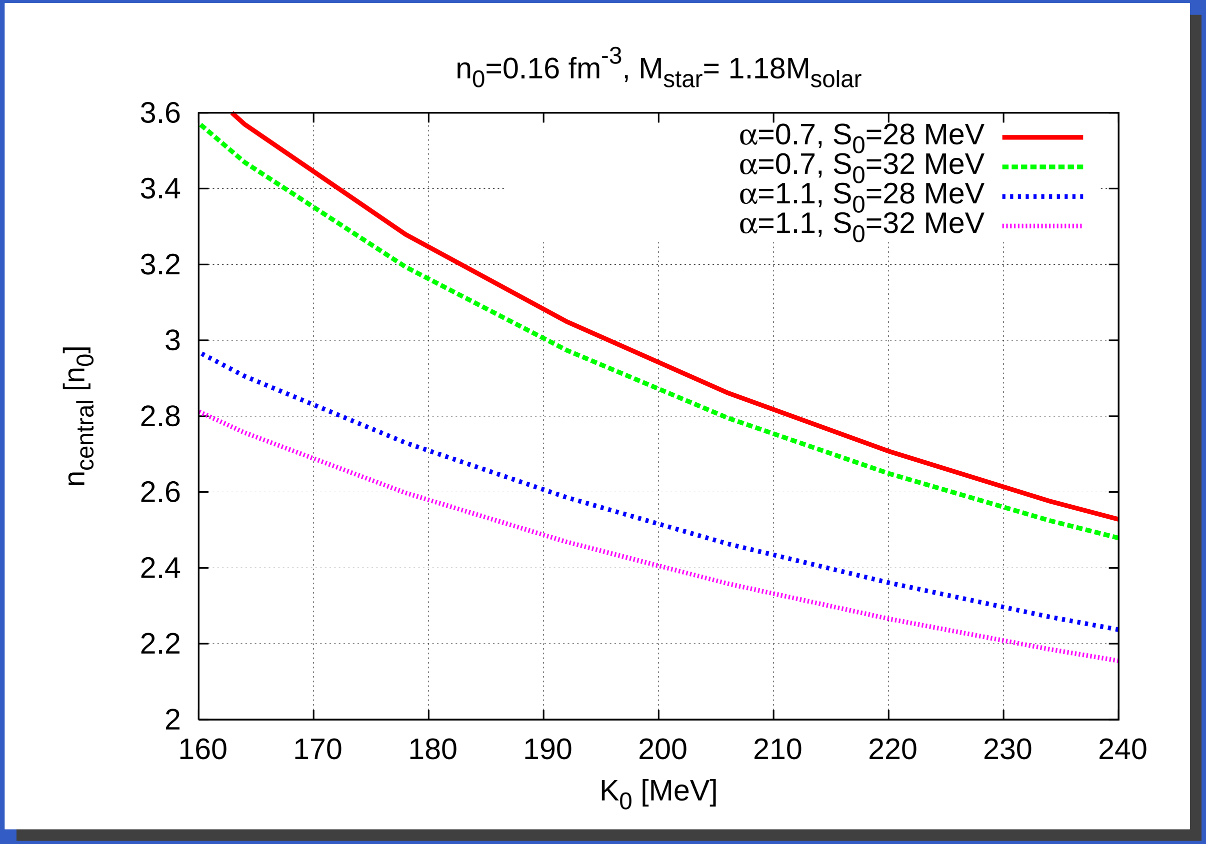
Maximum Masses of Neutron Stars



(Irina Sagert)

- Skyrme parameterization with density dependent asymmetry energy ($\sim n^{\alpha}$)
- asymmetry energy determines radii around $1M_{\odot}$, not maximum mass
- $\Longrightarrow$ a neutron star mass of $2M_{\odot}$ is compatible with a 'soft' equation of state
- but high central densities, typically seven to ten times saturation density

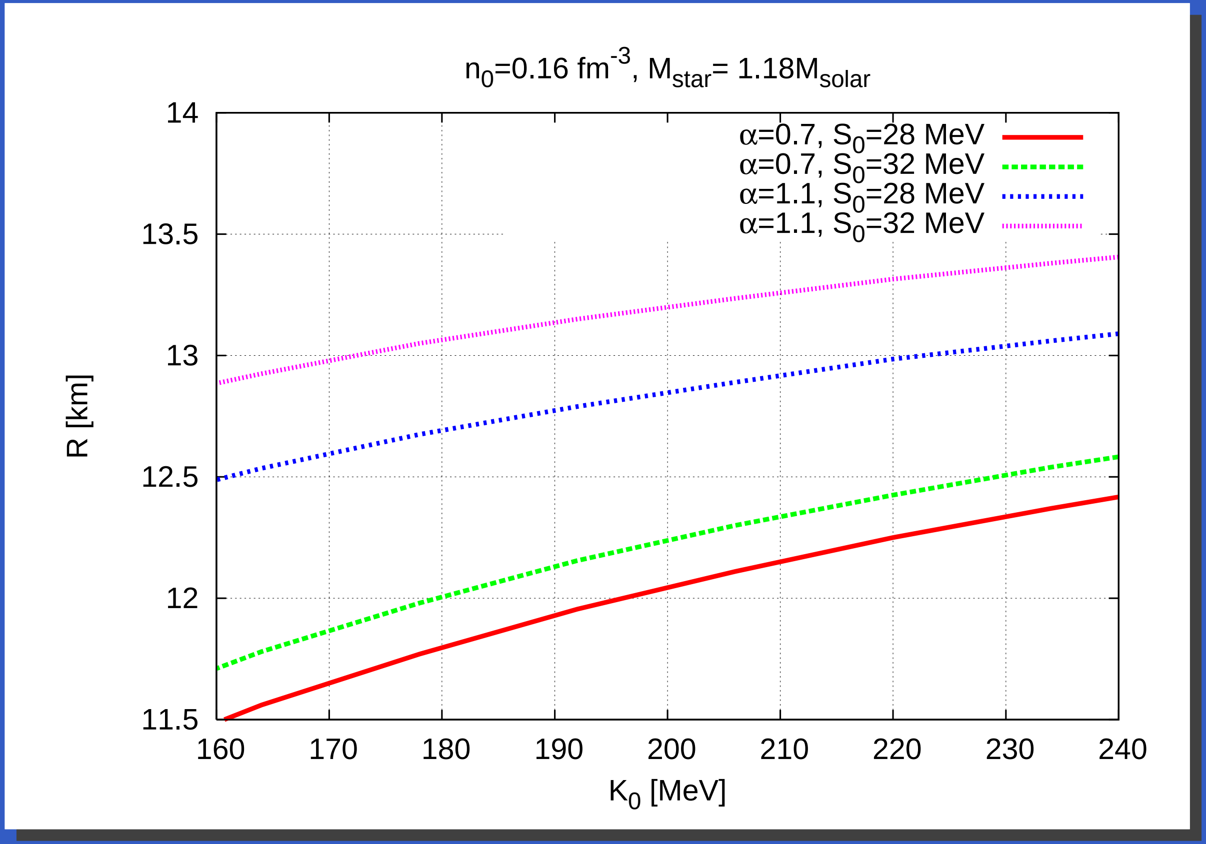
Low-Mass Neutron Star: the True Comparison!



(Irina Sagert)

- probes at maximum the EoS up to $n = (2.4 \div 3)n_0$ for $K \approx 200$ MeV!
- new particles (hyperons, kaon condensate) or phases quarks might start to be present but may not be dominating the EoS
- typically $n_{\max} \approx (2.5 \div 3)n_0$ for present heavy-ion experiments at GSI $\Longrightarrow$ direct comparison with heavy-ion data feasible!

Low-Mass Neutron Stars: Measure the Radius!

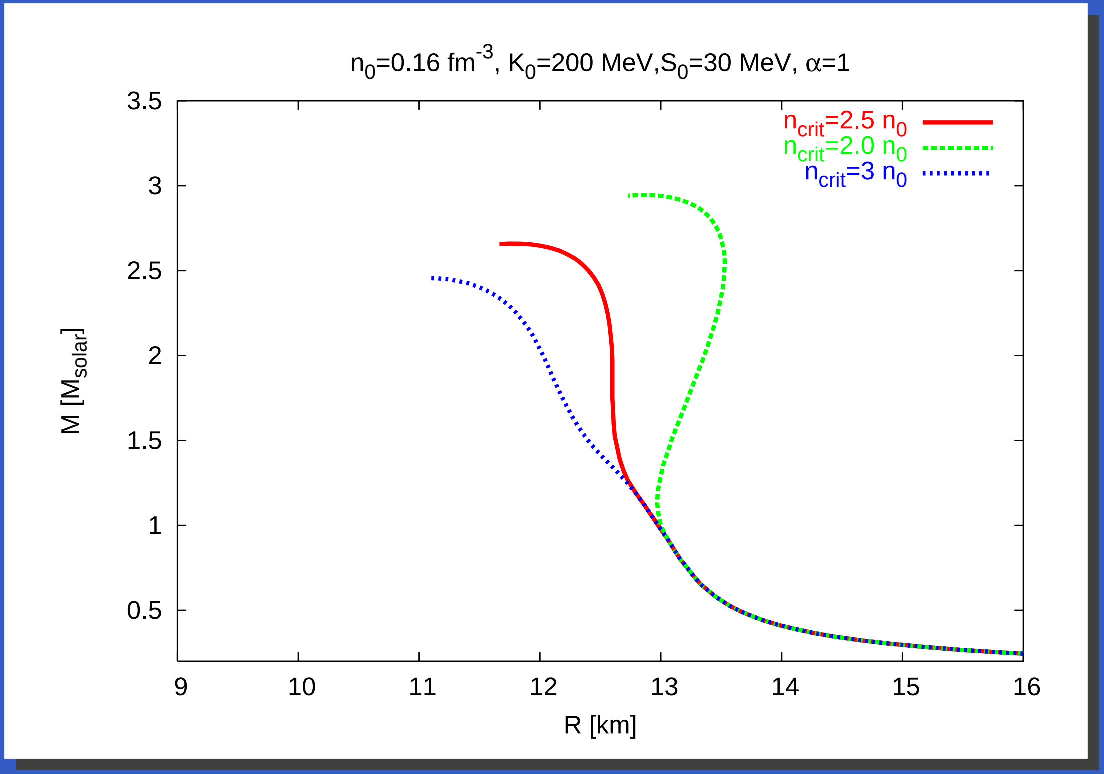


(Irina Sagert)

- radius of $1.18 M_\odot$ neutron star: sensitive to the asymmetry energy S_0 and its density dependence α!
- radius not that sensitive to the compression modulus K

(Lattimer and Prakash (2001), Carriere, Horowitz, Piekarewicz (2003), . . .)
see talks by Bao-An Li, William Lynch and Hermann Wolter

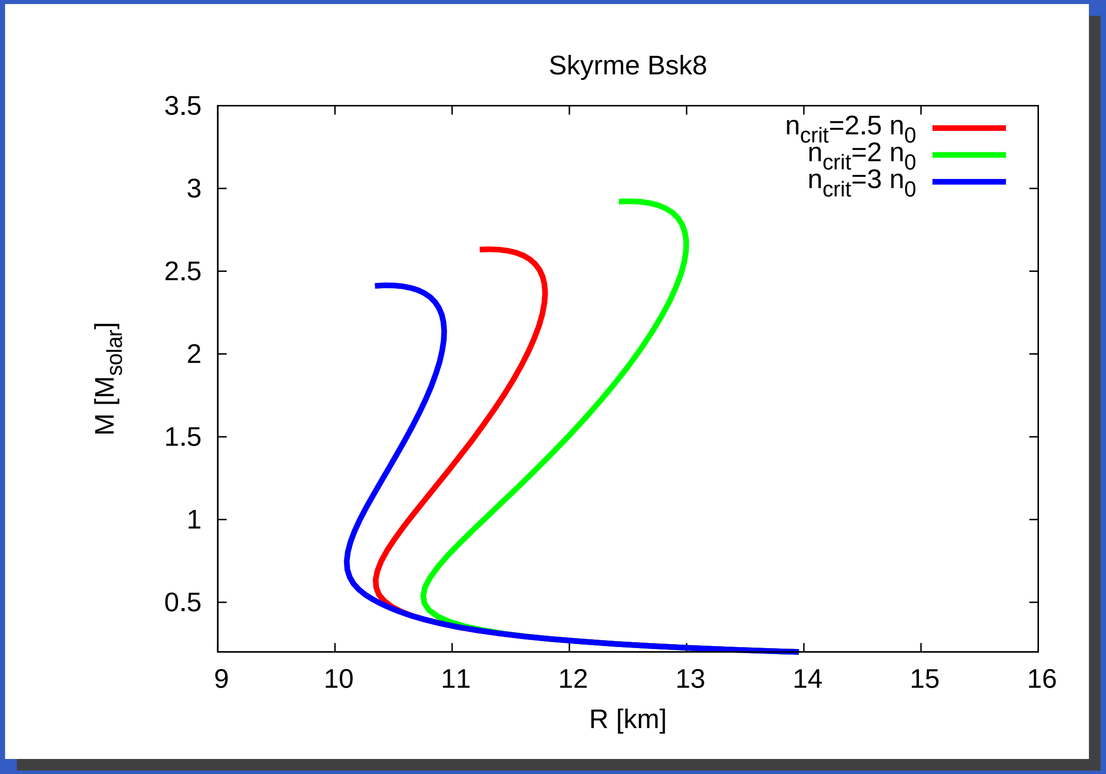
Maximum Masses of Neutron Stars – Causality



(Irina Sagert)

- Phenomenological parameter sets: fitted to properties of nuclear matter
- above a fiducial density (determined from the data analysis of the KaoS 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 $2.7 M_\odot$ from heavy-ion data!

Maximum Masses of Neutron Stars – Causality



(Irina Sagert)

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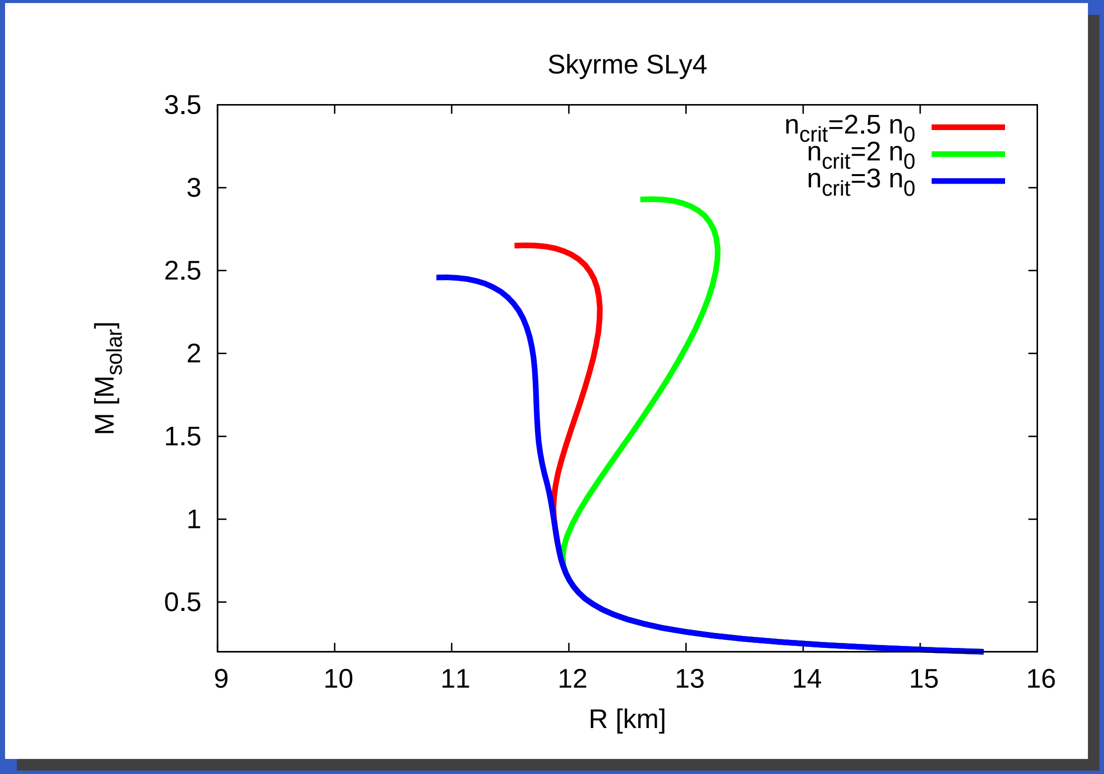

(Irina Sagert)

- Skyrme parameter set Sly4: fitted to properties of spherical nuclei
- above a fiducial density (determined from the data analysis of the KaoS 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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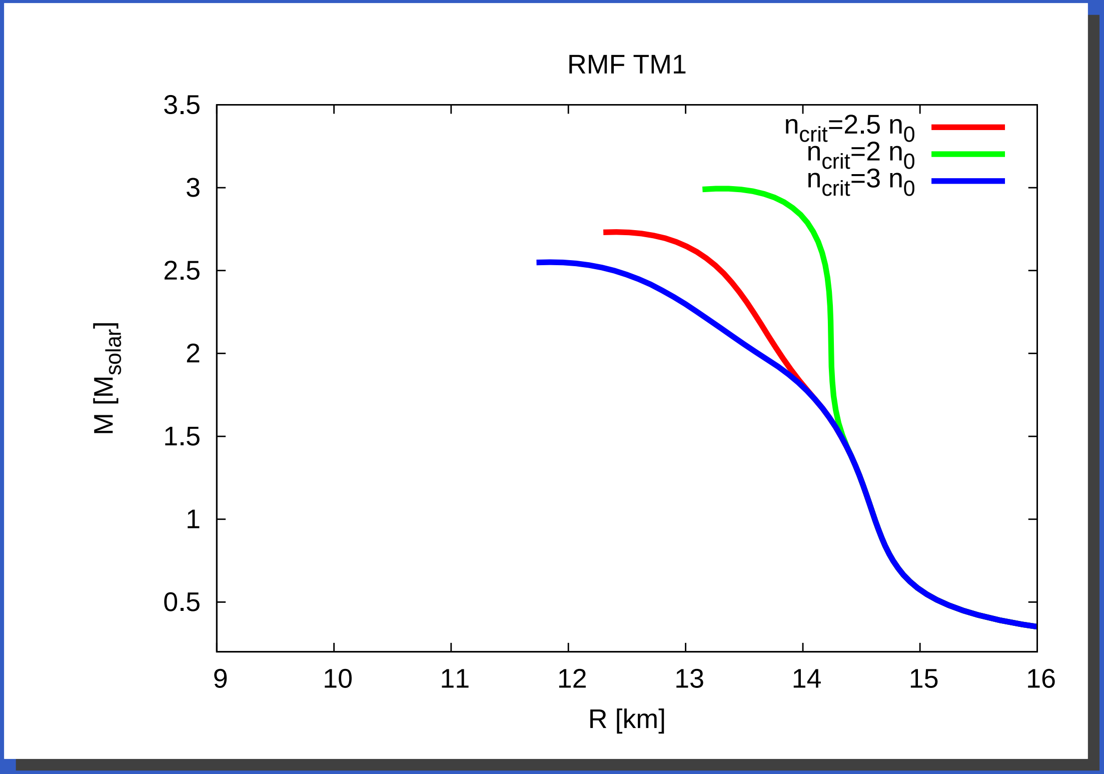
Maximum Masses of Neutron Stars – Causality



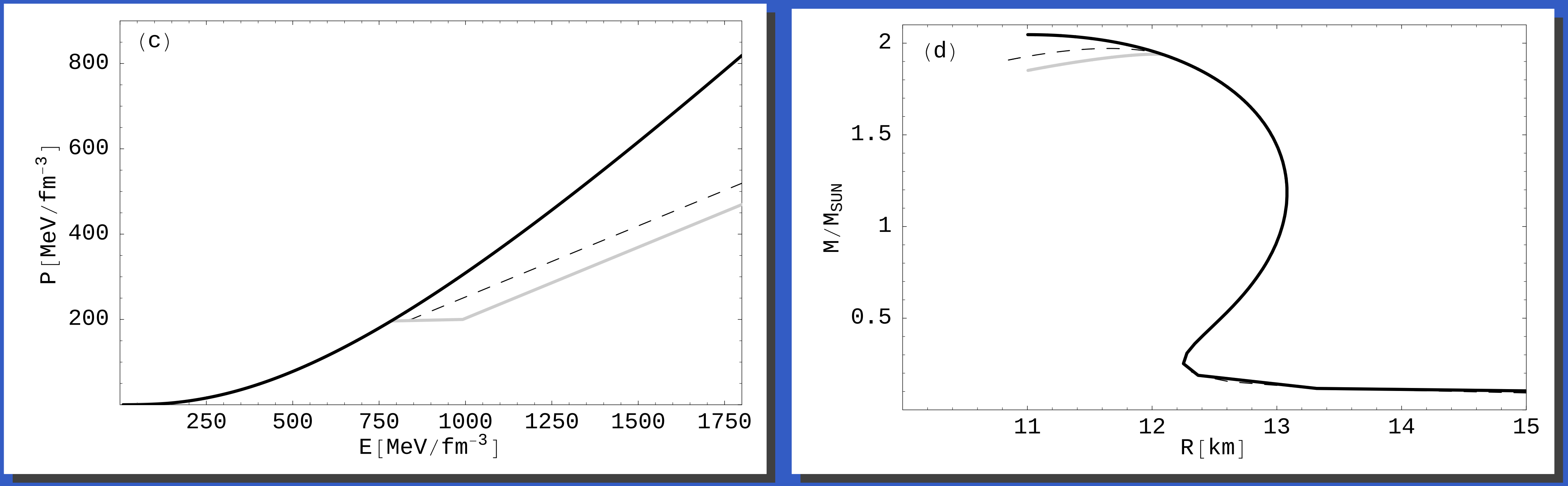
(Irina Sagert)

- RMF parameter set TM1: fitted to properties of spherical nuclei
- above a fiducial density (determined from the data analysis of the KaoS data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\rm max} = 4.2 M_\odot (\epsilon_0/\epsilon_f)^{1/2}$
- $\Longrightarrow$ new upper mass limit of about $2.8 M_\odot$ from heavy-ion data!

Stability of Color-Flavor-Locked Quark Cores in Hybrid Stars

(Giuseppe Pagliara and JSB, PRD77 (2008) 063004)

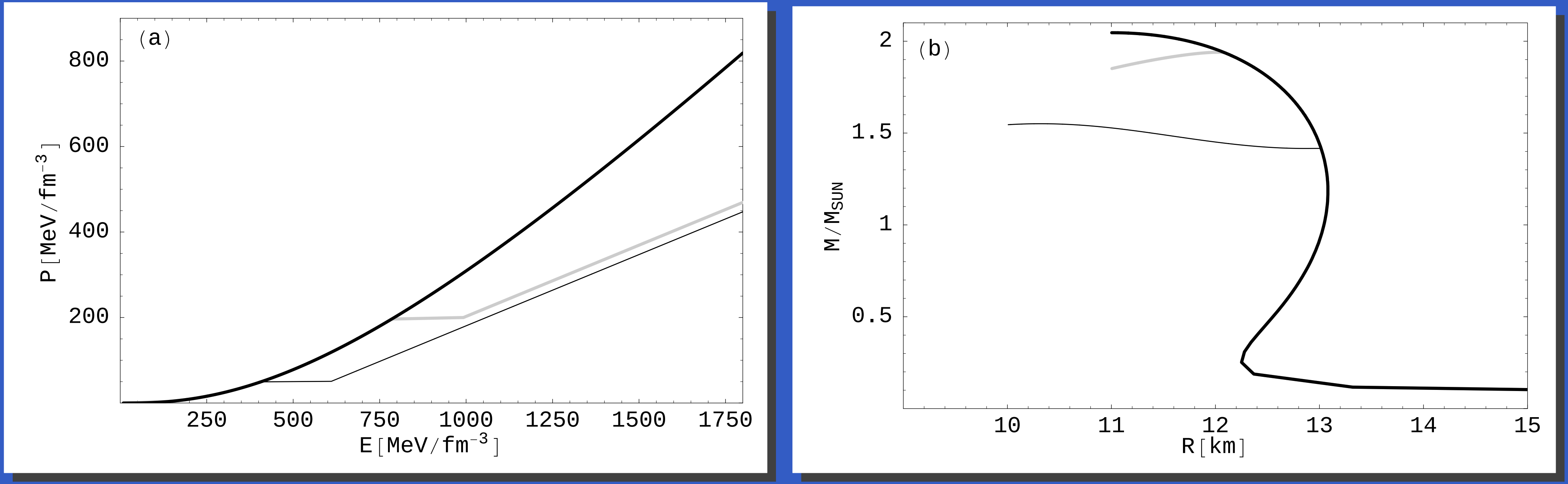
Phase Transition and Stability of Compact Stars



(Giuseppe Pagliara and JSB, 2008)

- 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, 2008)

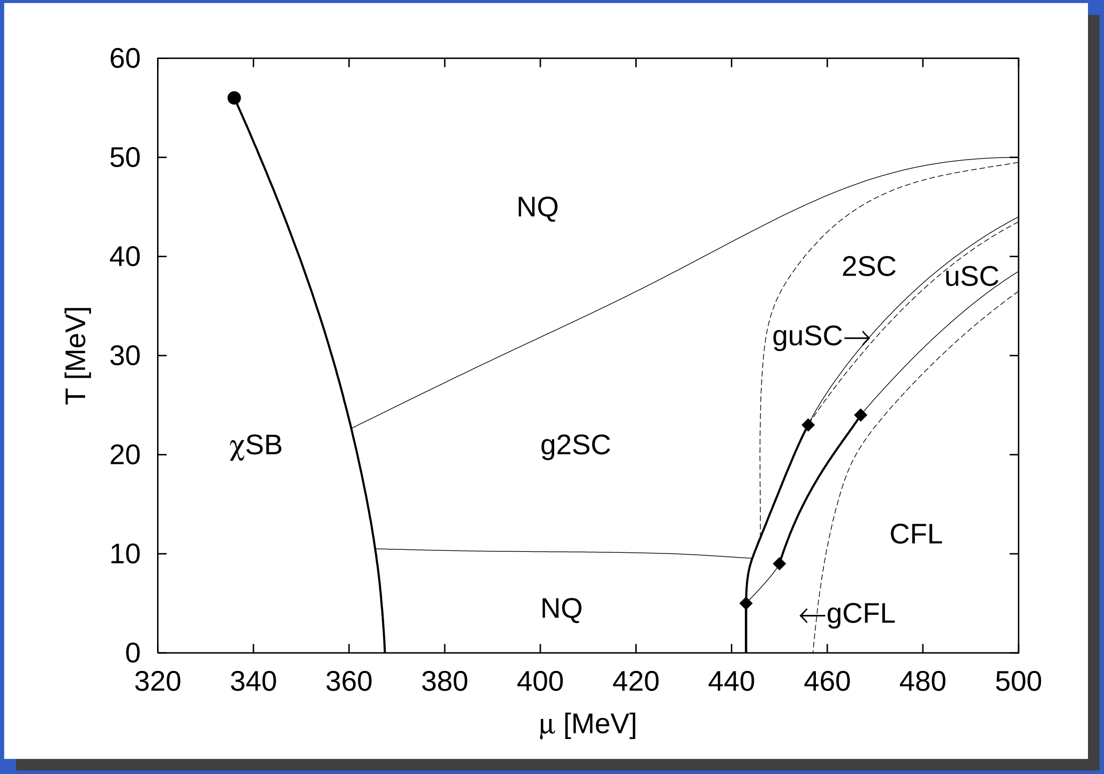
- change the critical energy density for the phase transition
- phase transition close to the maximum mass: unstable quark core
- onset of phase transition at moderate densities: stable quark core

Color-superconducting quark matter in the NJL model

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

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

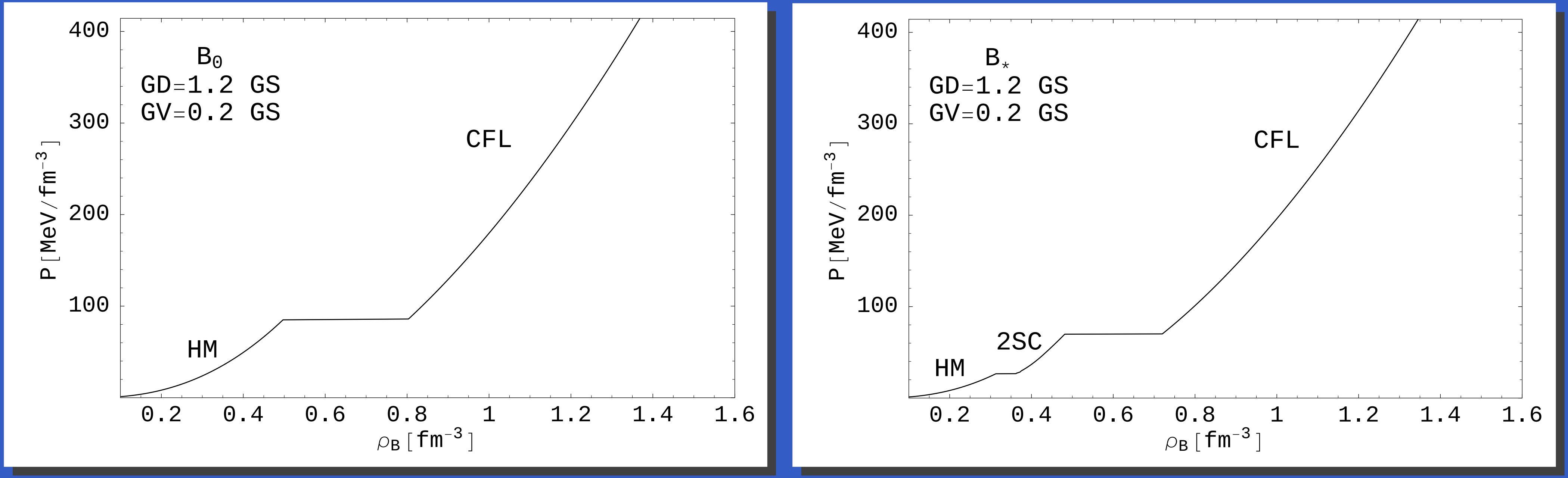
Phases in Quark Matter (Rüster et al. (2005))



- 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, . . .)

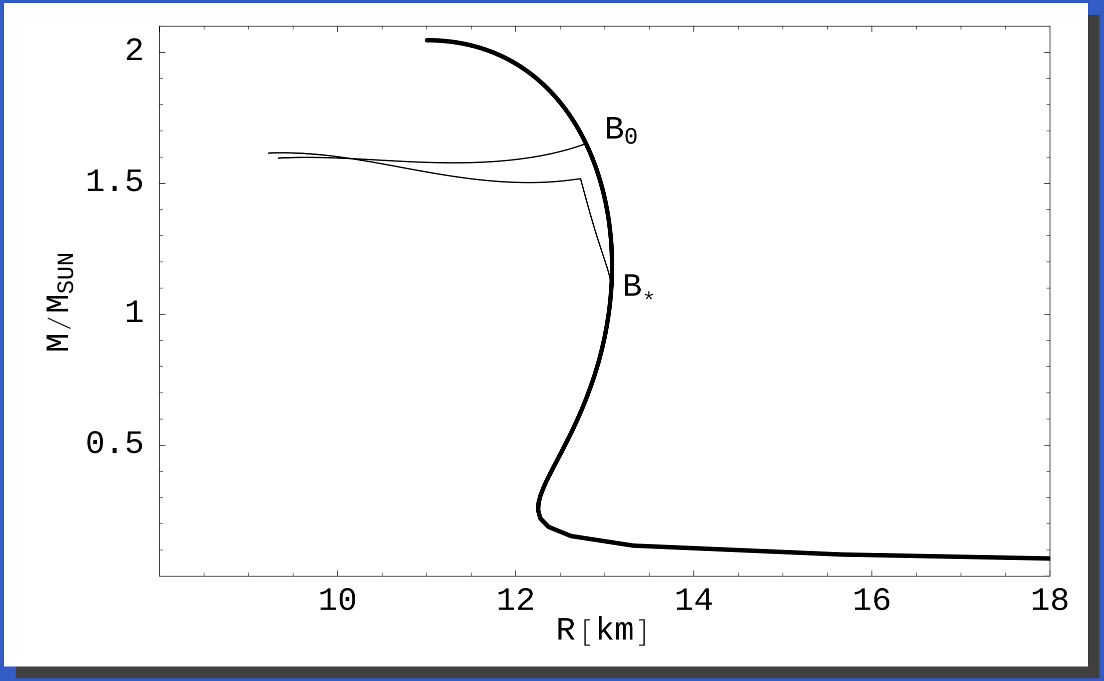
Hybrid Star Matter



(Giuseppe Pagliara and JSB, 2008)

- fix the pressure in vacuum (B_0) or at the chiral phase transition (B_*)
- first 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



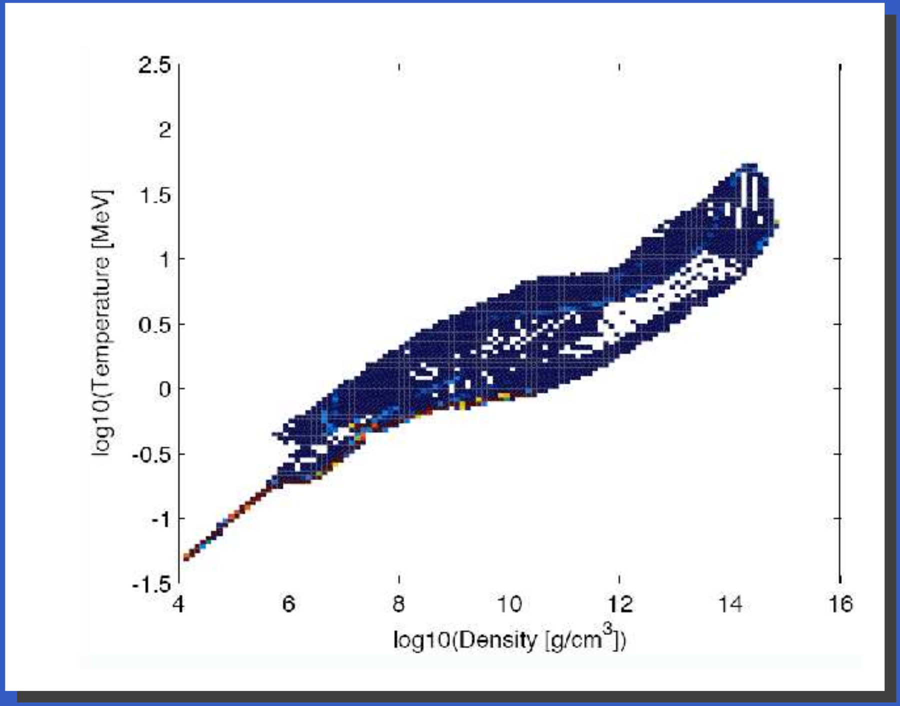
(Giuseppe Pagliara and JSB, 2008)

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

The Hot Nuclear Equation of State for Core-Collapse Supernovae

(Matthias Hempel and JSB, 2009)

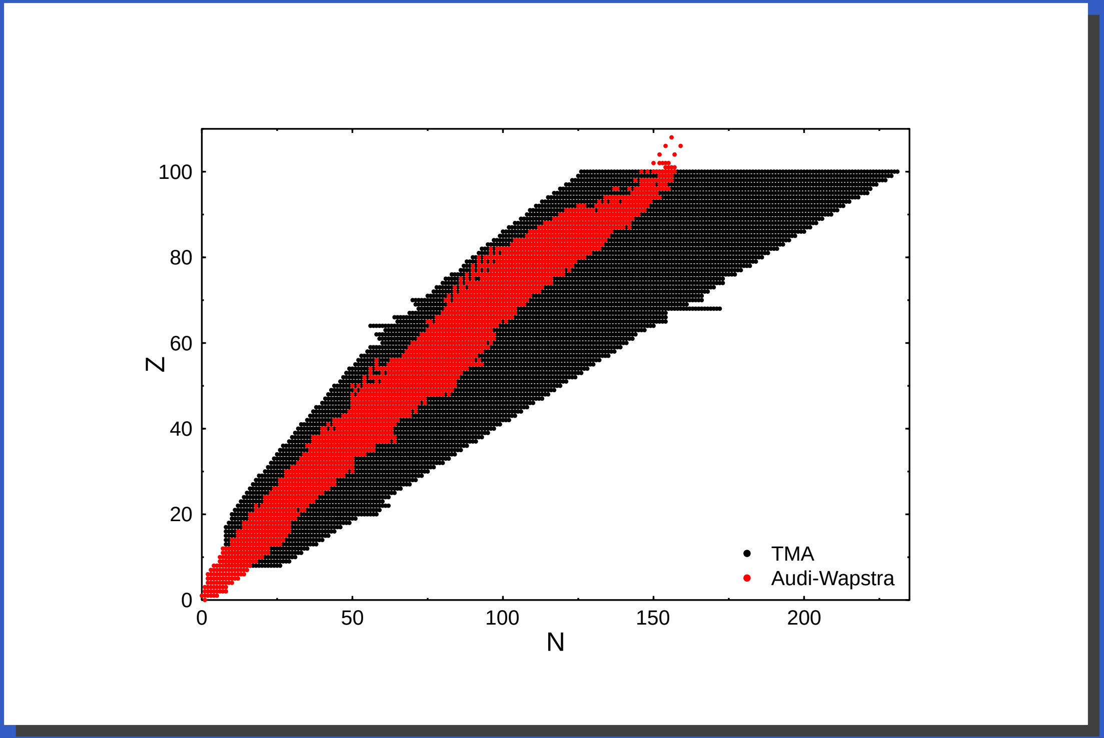
Supernova Matter



(M. Liebendörfer, T. Fischer, C. Fröhlich, F.-K. Thielemann, S. Whitehouse (2007))

- extremely broad range of densities and temperatures involved!
- conditions of core-collapse supernova matter at bounce: $\epsilon \sim (1 - 1.5)\epsilon_0$
- temperatures of $T \sim 20 - 30$ MeV, proton fraction of $Y_p \sim 0.2 - 0.3$
- other supernova EoS used so far: Lattimer-Swesty (Skyrme type force) and Shen et al. (relativistic mean field with local density approximation) with one representative heavy nucleus

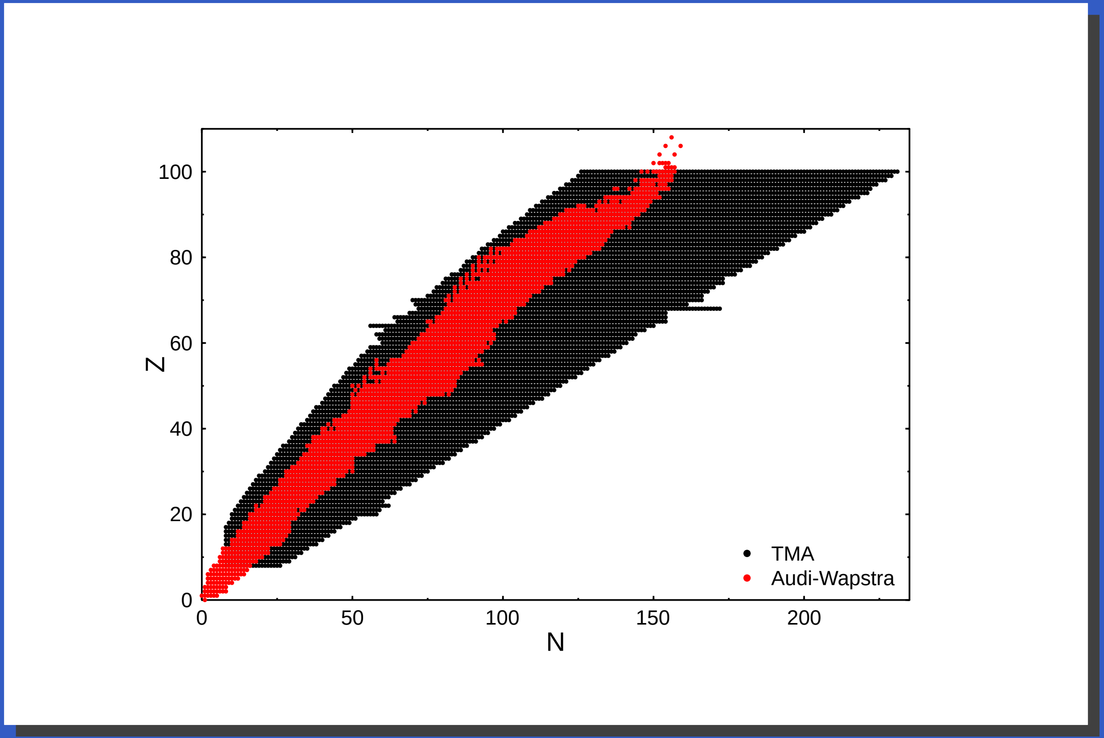
Hot Nuclear Equation of State



(Matthias Hempel)

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

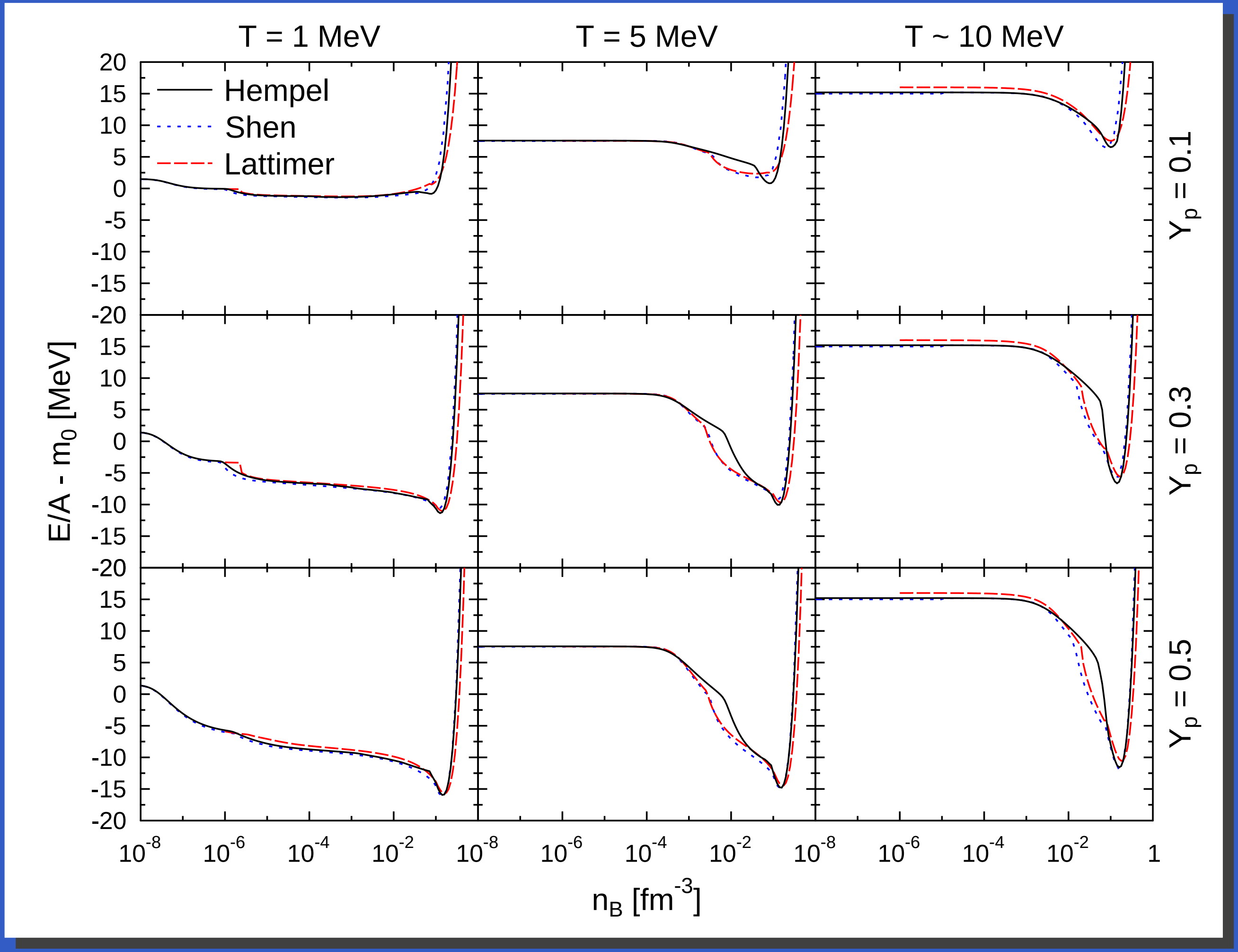
Hot Nuclear Equation of State



(Matthias Hempel)

- nuclear statistical equilibrium (NSE)
- effective degeneracy factor to take into account excited nuclear states
  $g_{AZ}(T) = g^0_{AZ} + \frac{c_1}{A^{5/3}} \int dE^* e^{-E^*/T} \exp(\sqrt{2a(A)E^*}$
  $a(A) = \frac{A}{8}(1 - c_2 A^{-1/3})$ MeV^{-1}, $c_1 = 0.2$ MeV^{-1}, $c_2 = 0.8$
- thermodynamic consistent treatment of excluded volumes, lattice energy and electron screening effects

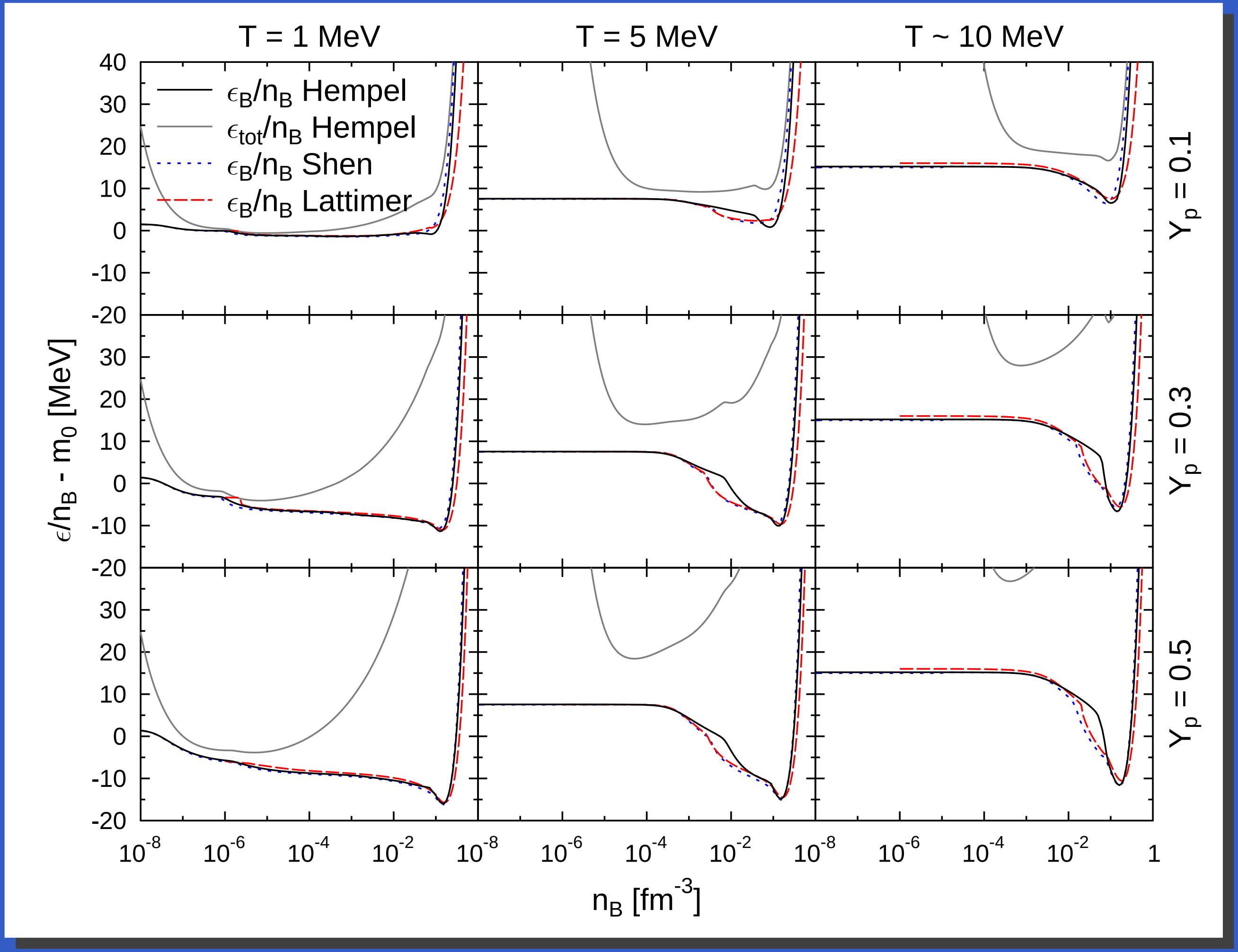
Supernova EoS in Comparison



(Matthias Hempel)

- supernova matter: no β-equilibrium for nucleons, fixed proton fraction Y_p
- comparison to Lattimer-Swesty EoS and Shen et al. EoS
- differences just below n_0 in particular for high T and large Y_p

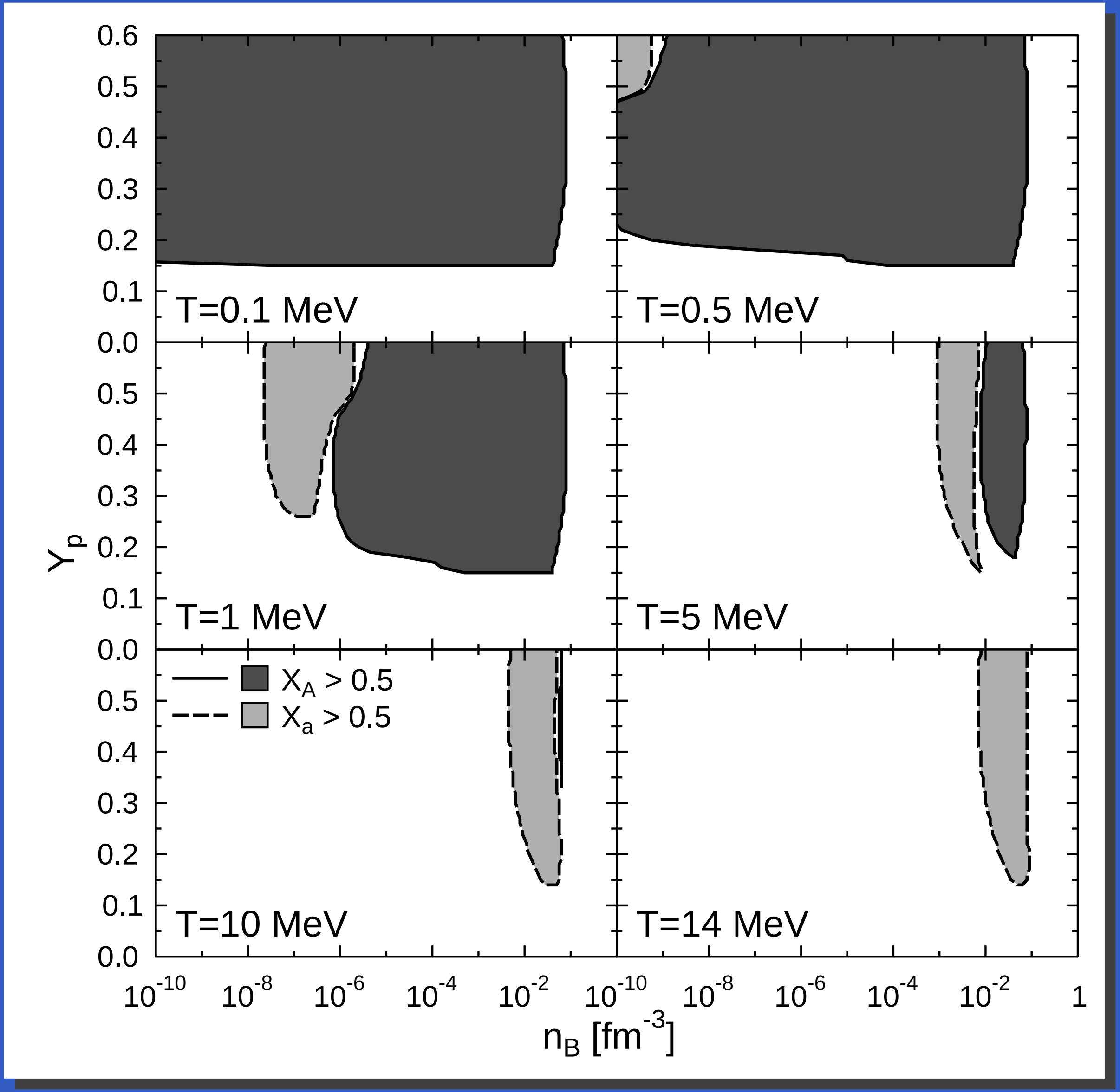
Supernova EoS in Comparison



(Matthias Hempel)

- supernova matter: no β-equilibrium for nucleons, fixed proton fraction Y_p
- comparison to Lattimer-Swesty EoS and Shen et al. EoS
- relative to the total energy density: differences relevant for small Y_p

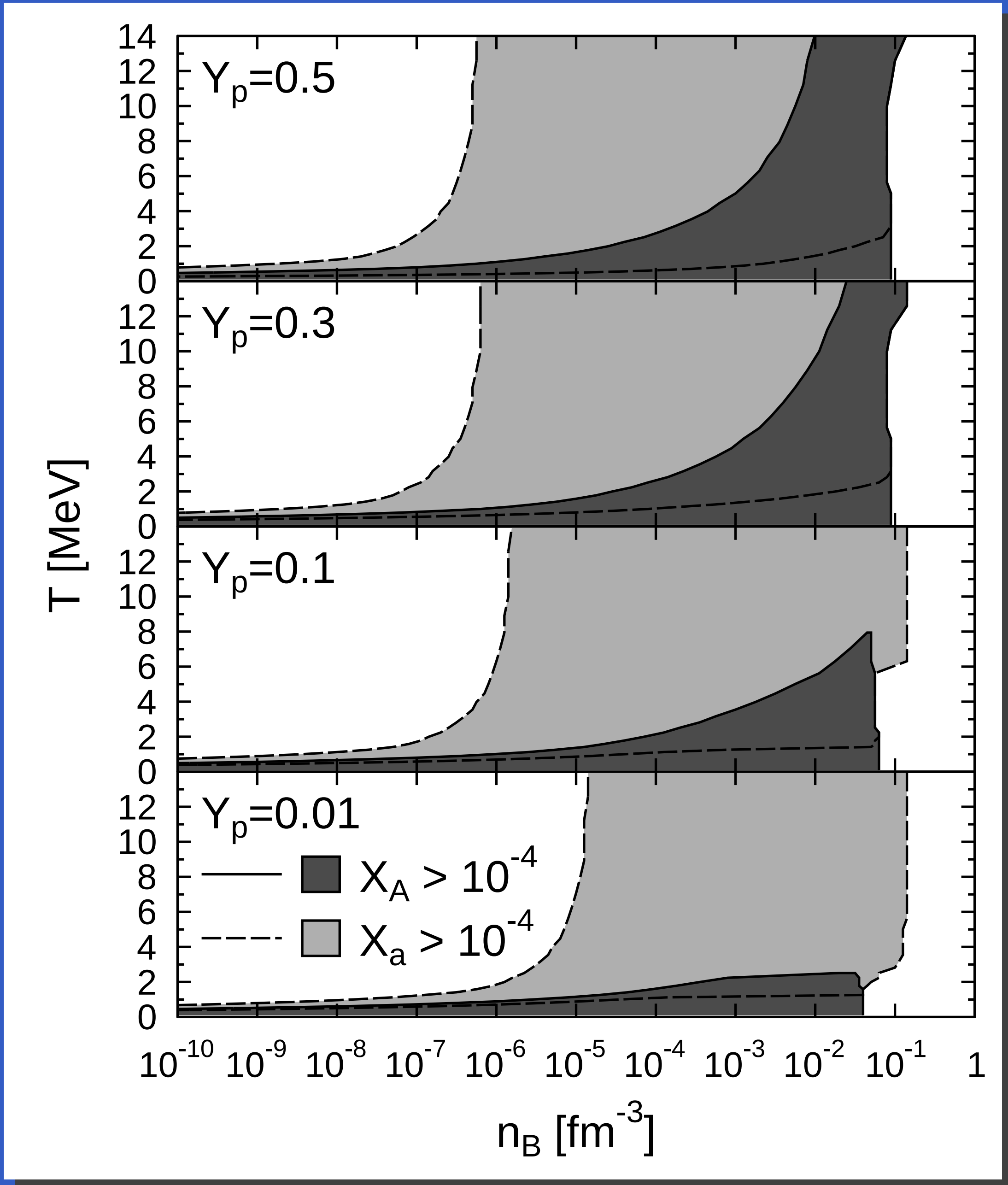
Composition of Supernova Matter (n-Y_p plane)



(Matthias Hempel)

- supernovae matter as a function of density and proton fraction Y_p
- heavy and light nuclei dominant contribution for $Y_p > 0.15$
- region shrinks towards n_0 for higher temperatures
- light nuclei more abundant at somehow lower densities

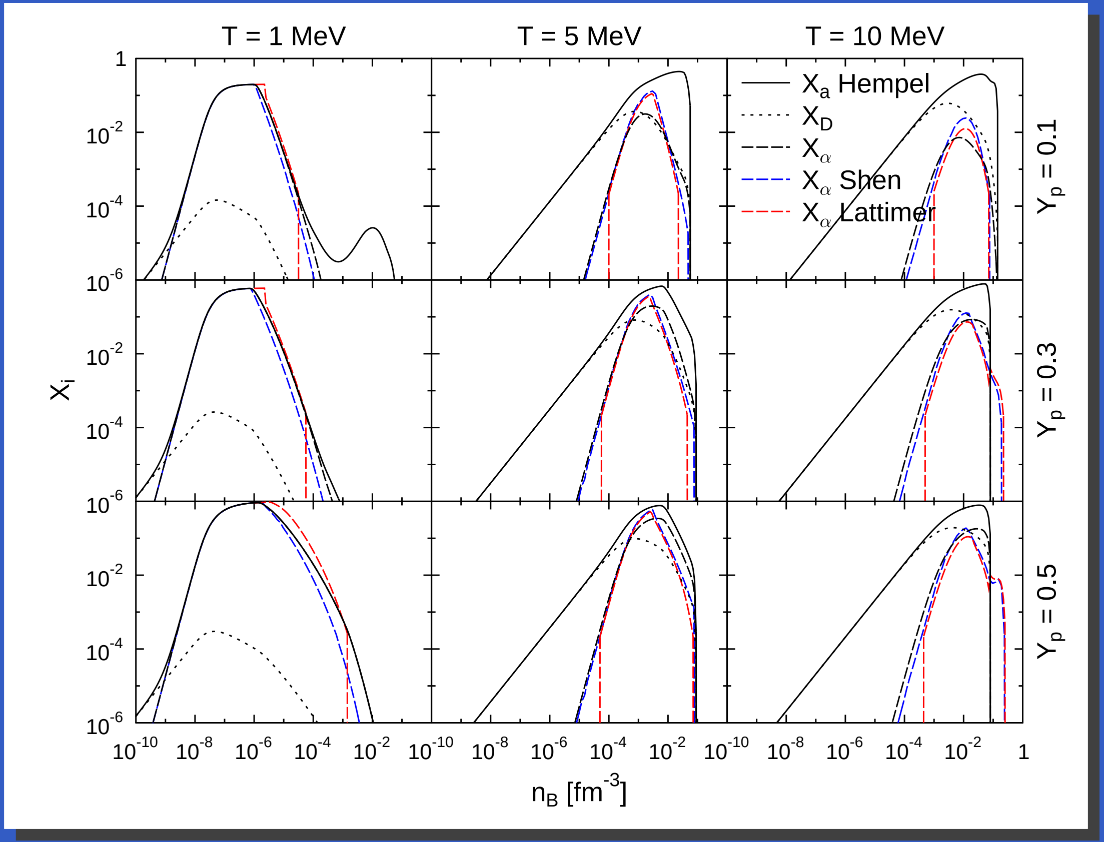
Composition of Supernova Matter (n-T plane)



(Matthias Hempel)

- supernovae matter as a function of density and temperature
- in particular light nuclei emerge at high temperatures
- heavy nuclei are suppressed for small Y_p, appear at lower temperatures and higher densities

Distribution of Light Nuclei



(Matthias Hempel)

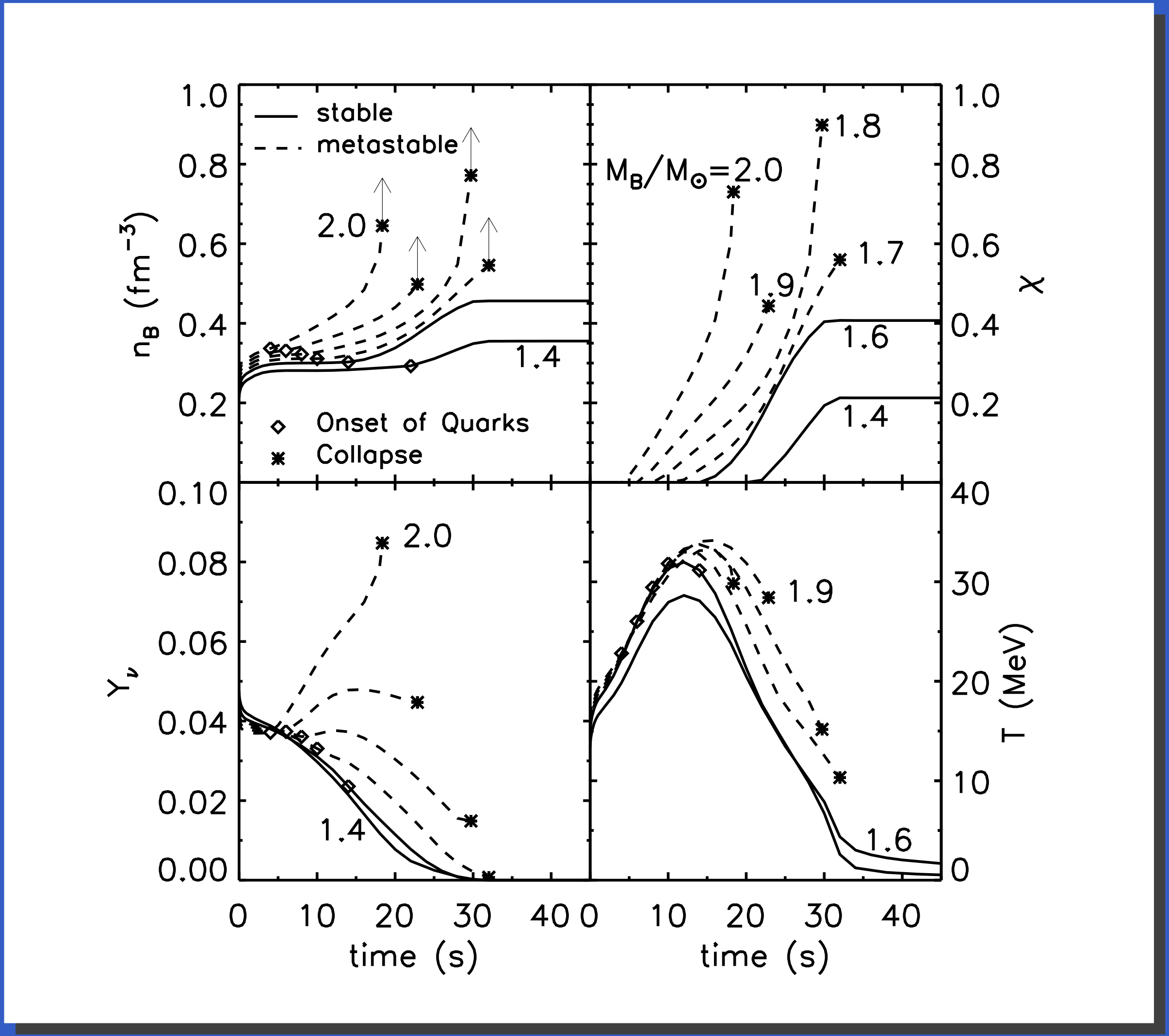
- fraction of light nuclei as a function of density
- deuterons are abundant for low densities and high temperatures
- differences of the helium fraction in comparison with other SN EoS
- impact of in-medium binding energies? (Roepke 2008)

Signals of the QCD phase transition in core-collapse supernovae

work done in collaboration with:

Irina Sagert, Matthias Hempel, Giuseppe Pagliara, Tobias Fischer, Anthony Mezzacappa, Friedel Thielemann, Matthias Liebendörfer

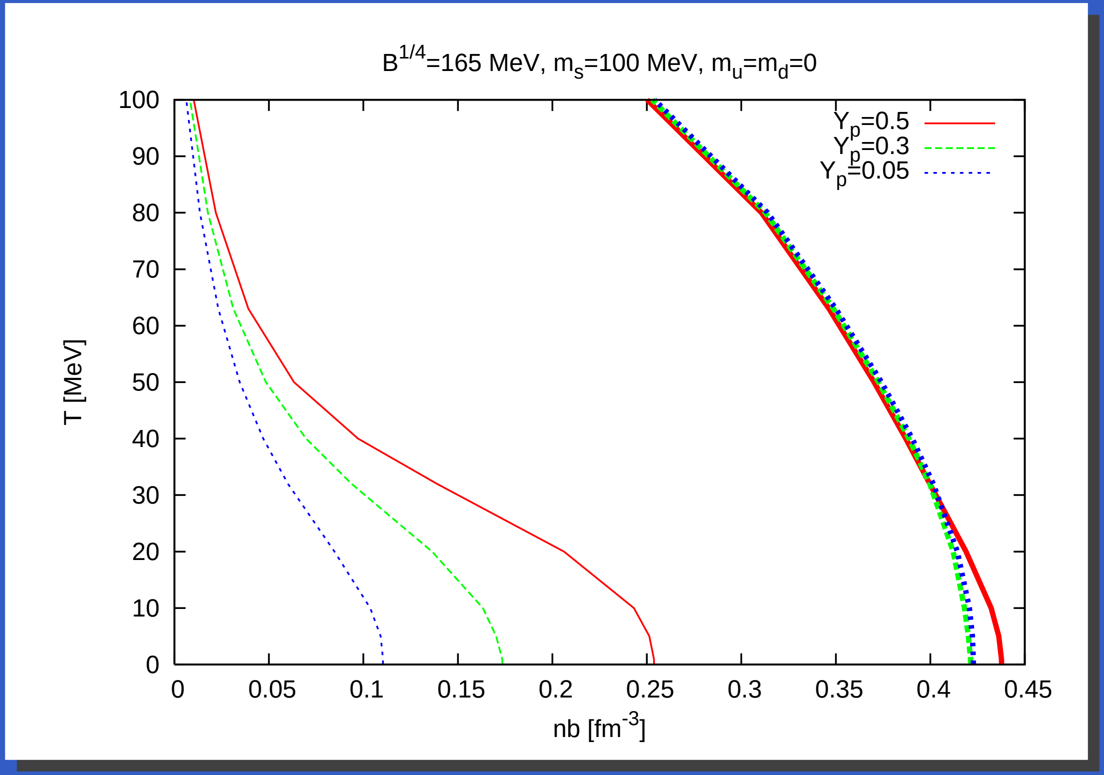
Proto-neutron star evolution with quarks



(J. Pons, A. Steiner, M. Prakash, J. Lattimer (2001))

- standard lore for the onset of the quark phase in core-collapse supernovae: during evolution of the proto-neutron star
- timescale for quark matter to appear (see volume fraction χ): typically $(5-20)$s (due to a large bag constant, $B^{1/4} > 180$ MeV!)
- supernova collapse timescale: milliseconds (with SASI 600 ms?)
- quark matter appears well after bounce?

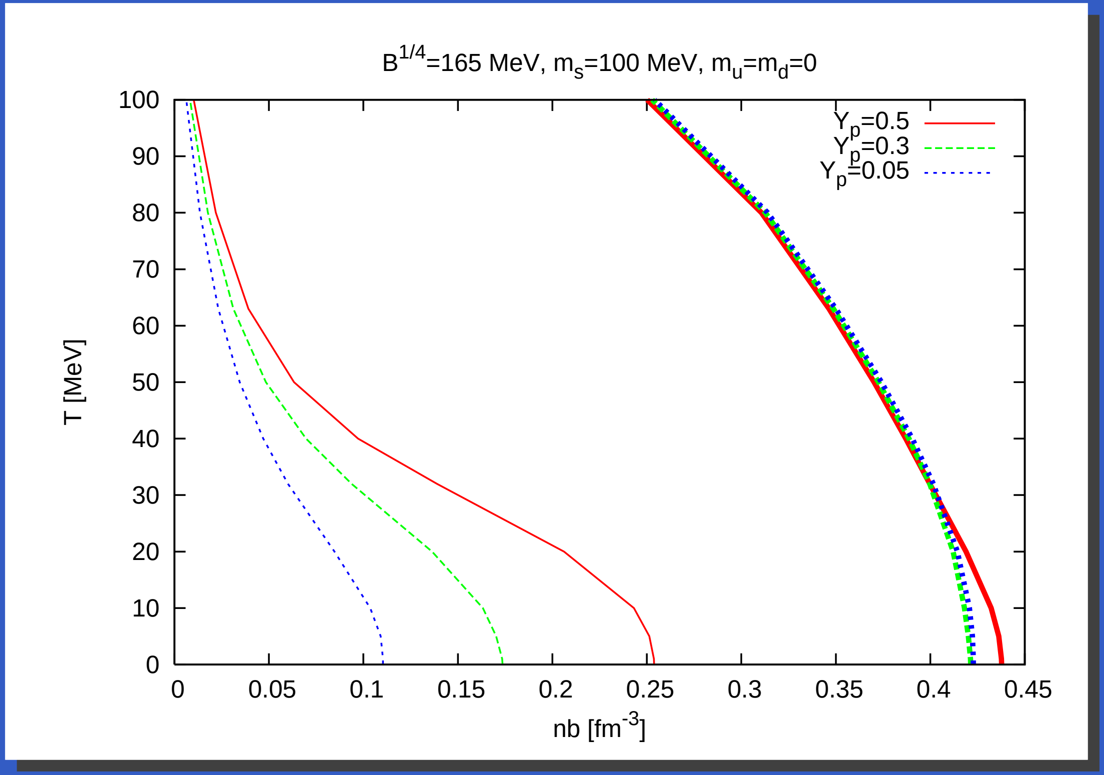
Phase Transition to Quark Matter for Astros



(Irina Sagert and Giuseppe Pagliara)

- quark matter appears at low density due to β-equilibrium for a bag constant of $B^{1/4} = 165$ MeV
- low critical density for low Y_p due to nuclear asymmetry energy
- quark matter favoured at finite temperature

Phase Transition to Quark Matter for Astros



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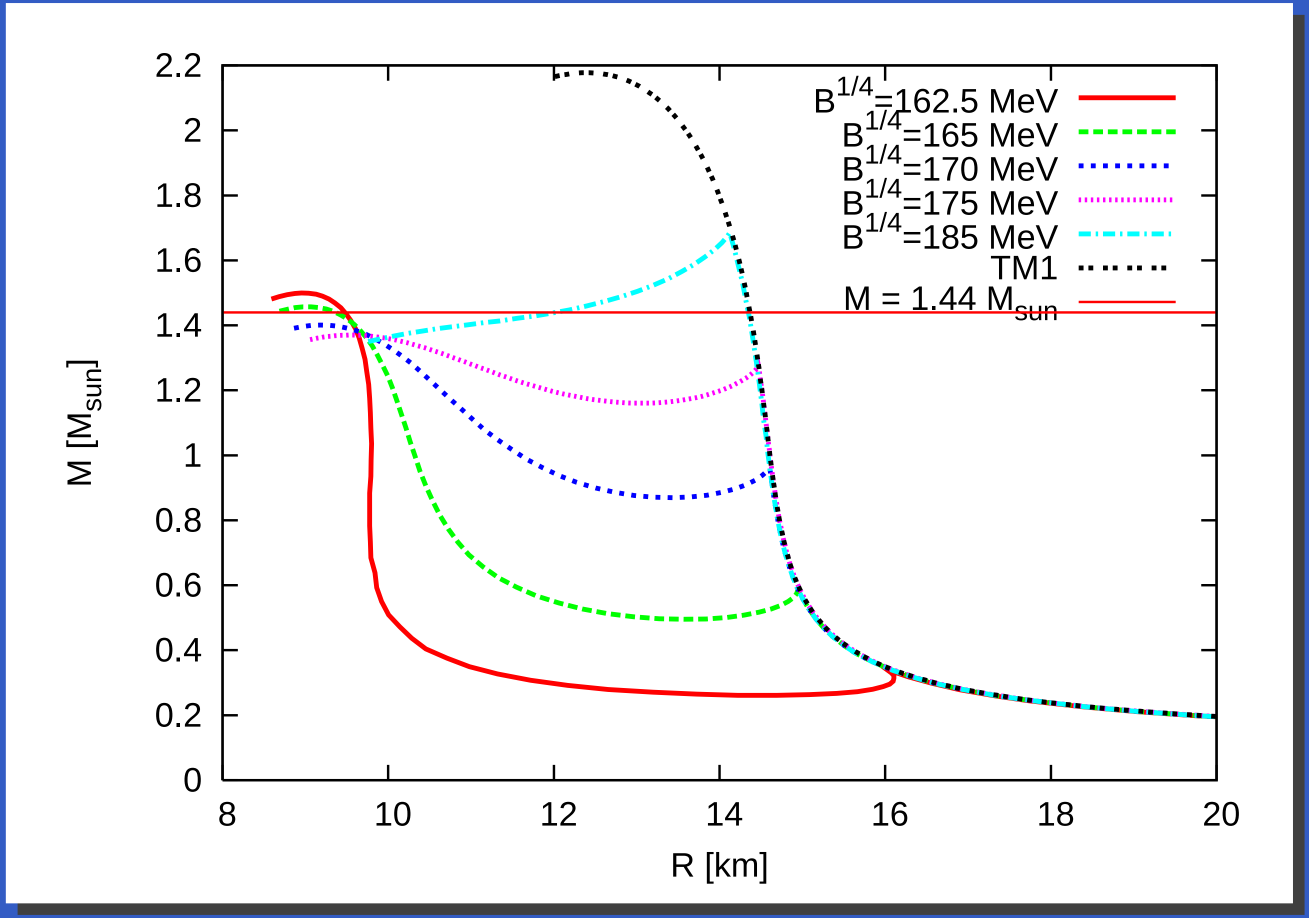
- quark matter appears at low density due to β-equilibrium for a bag constant of $B^{1/4} = 165$ MeV
- low critical density for low Y_p due to nuclear asymmetry energy
- quark matter favoured at finite temperature
- production of quark matter in supernovae at bounce possible!

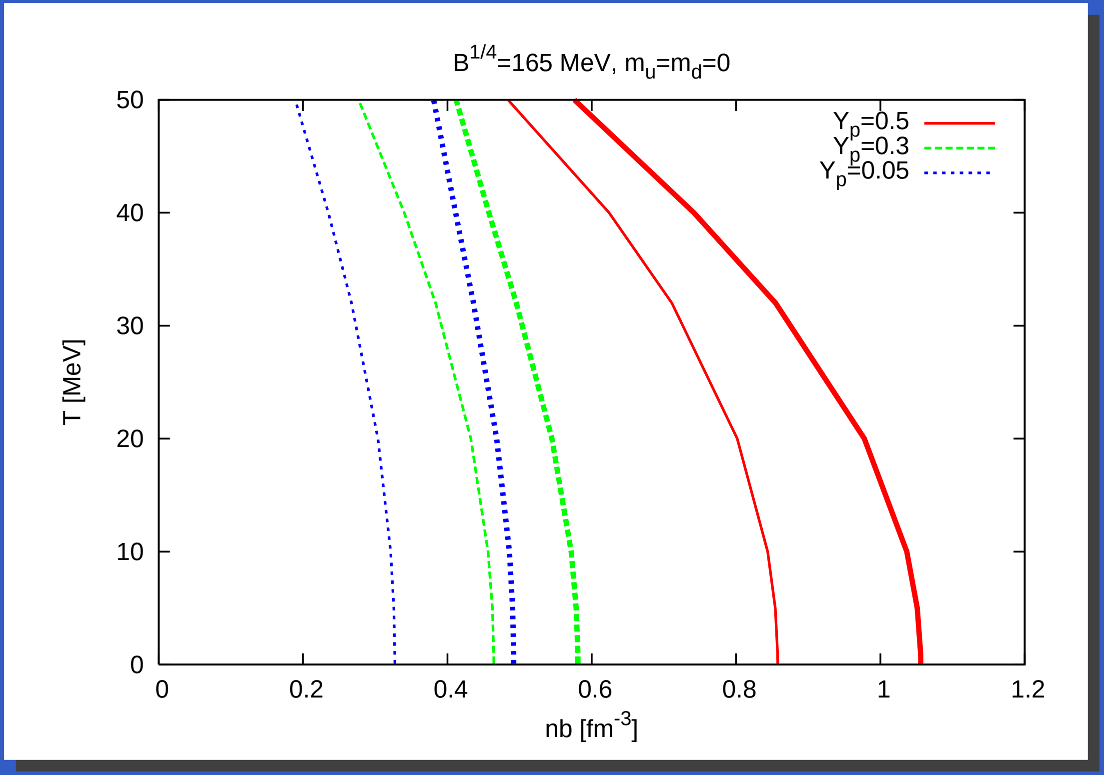
Check: Mass-Radius Diagram of Cold Neutron Stars



(Irina Sagert and Giuseppe Pagliara)

- presence of quark matter can change drastically the mass-radius diagram
- third family of solution for certain bag constants
- maximum mass: $1.56 M_{\odot}$ ($B^{1/4} = 162$ MeV), $1.5 M_{\odot}$ ($B^{1/4} = 165$ MeV)

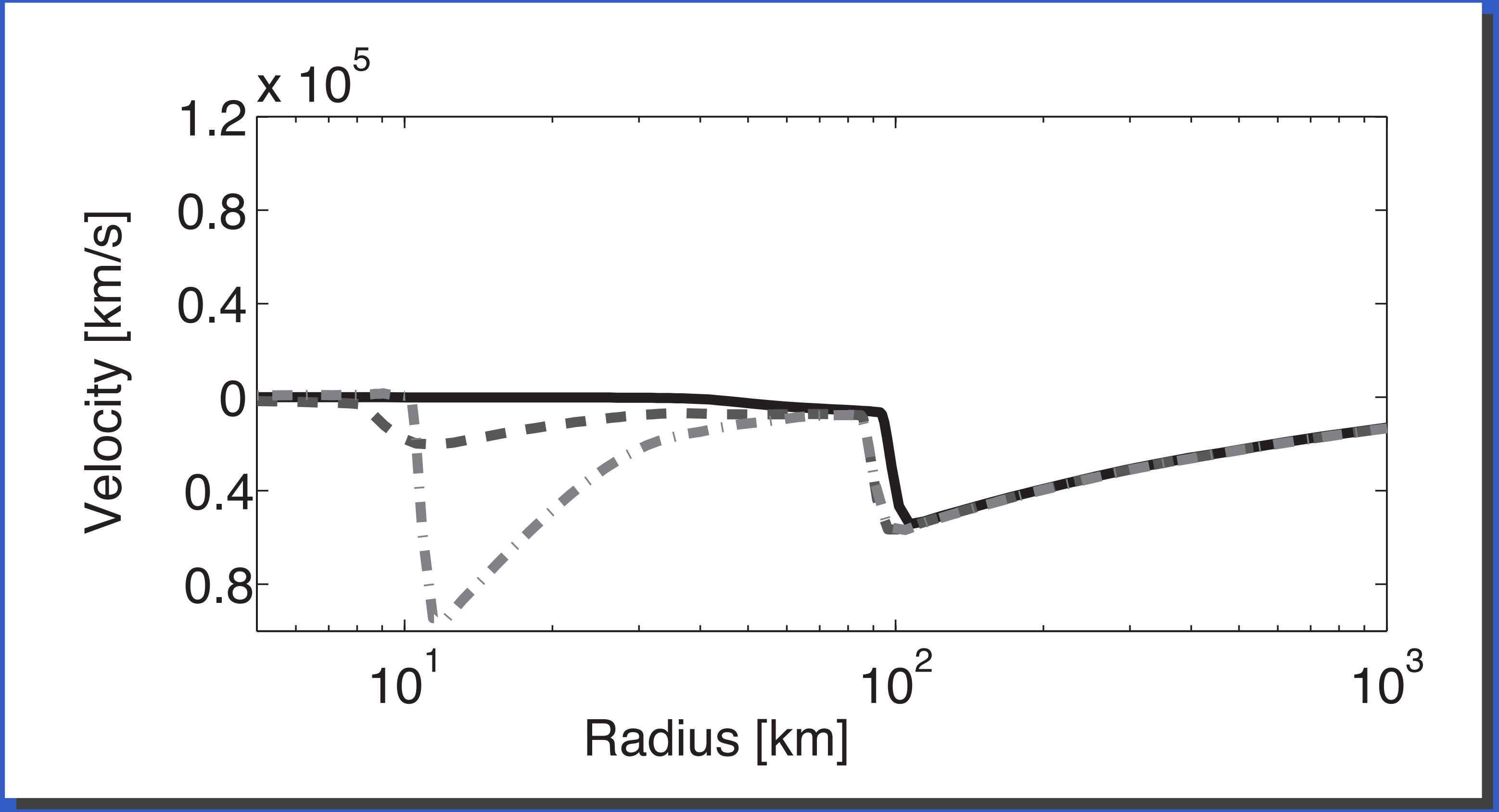
Check: Phase Transition for Heavy-Ion Collisions



(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
- no contradiction with heavy-ion data!

Implications for Supernovae – Explosion!



(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2008)

- velocity profile of a supernova for different times (around 250ms)
- formation of a core of pure quark matter produces a second shock wave

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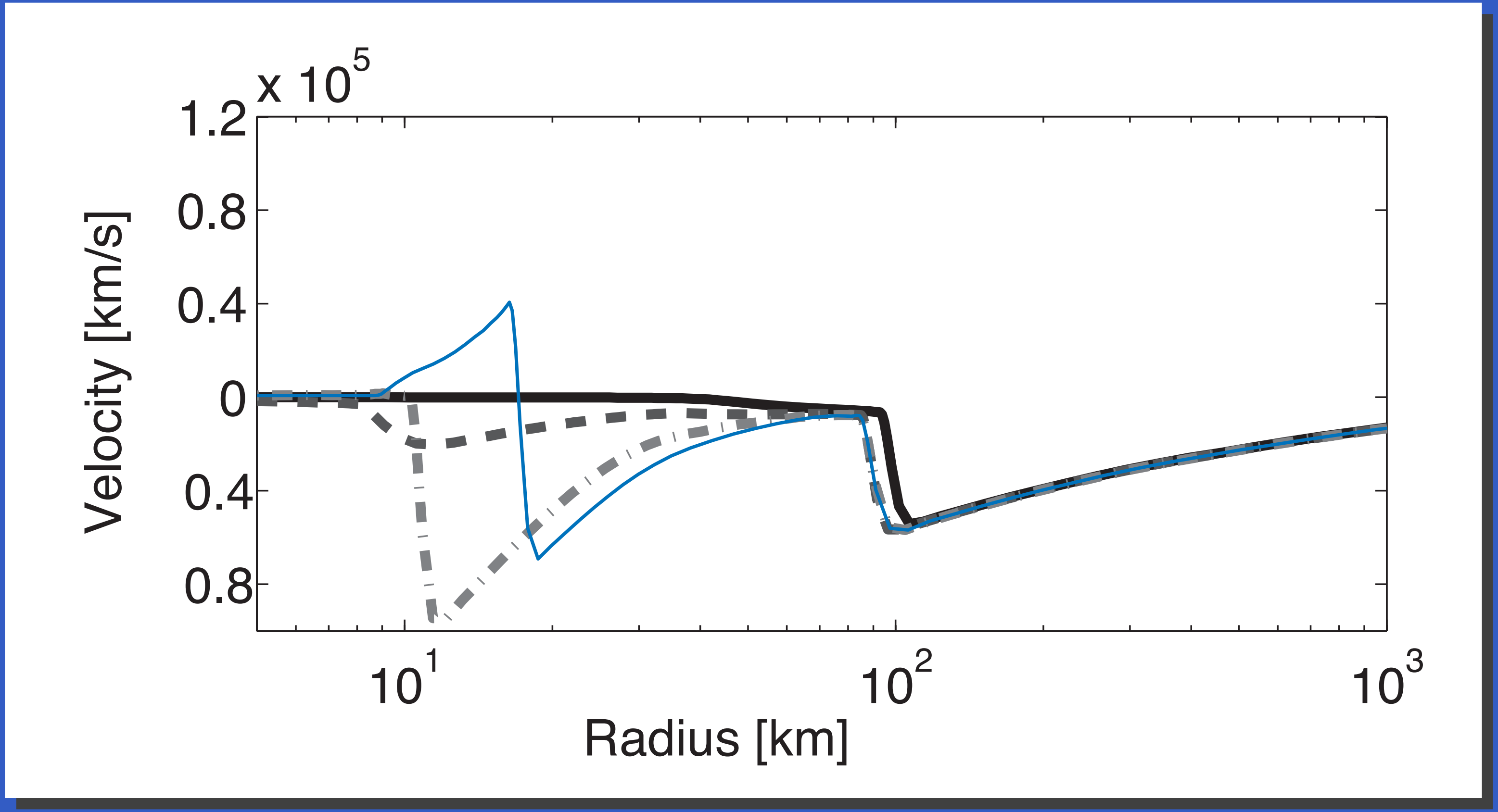

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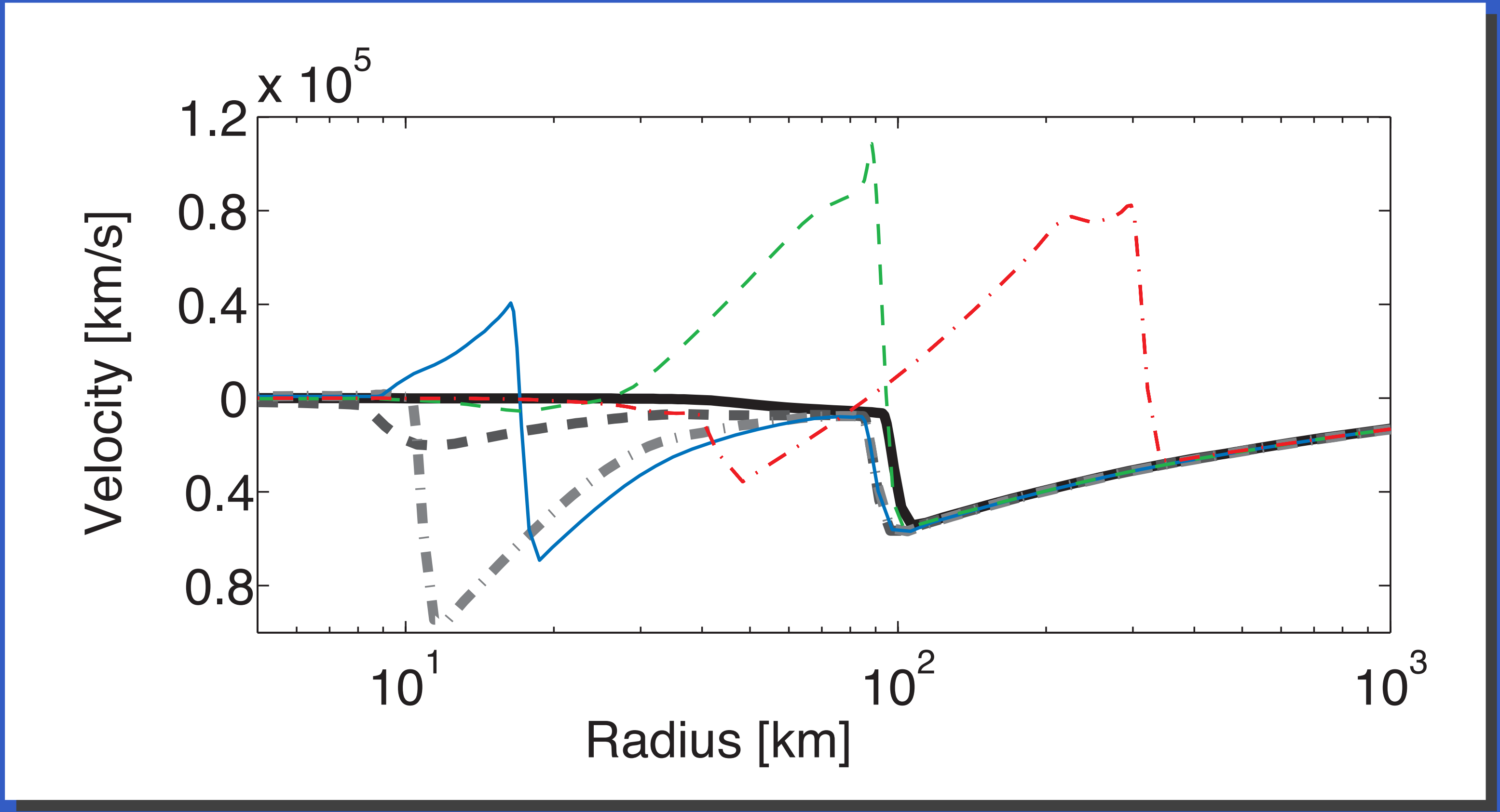
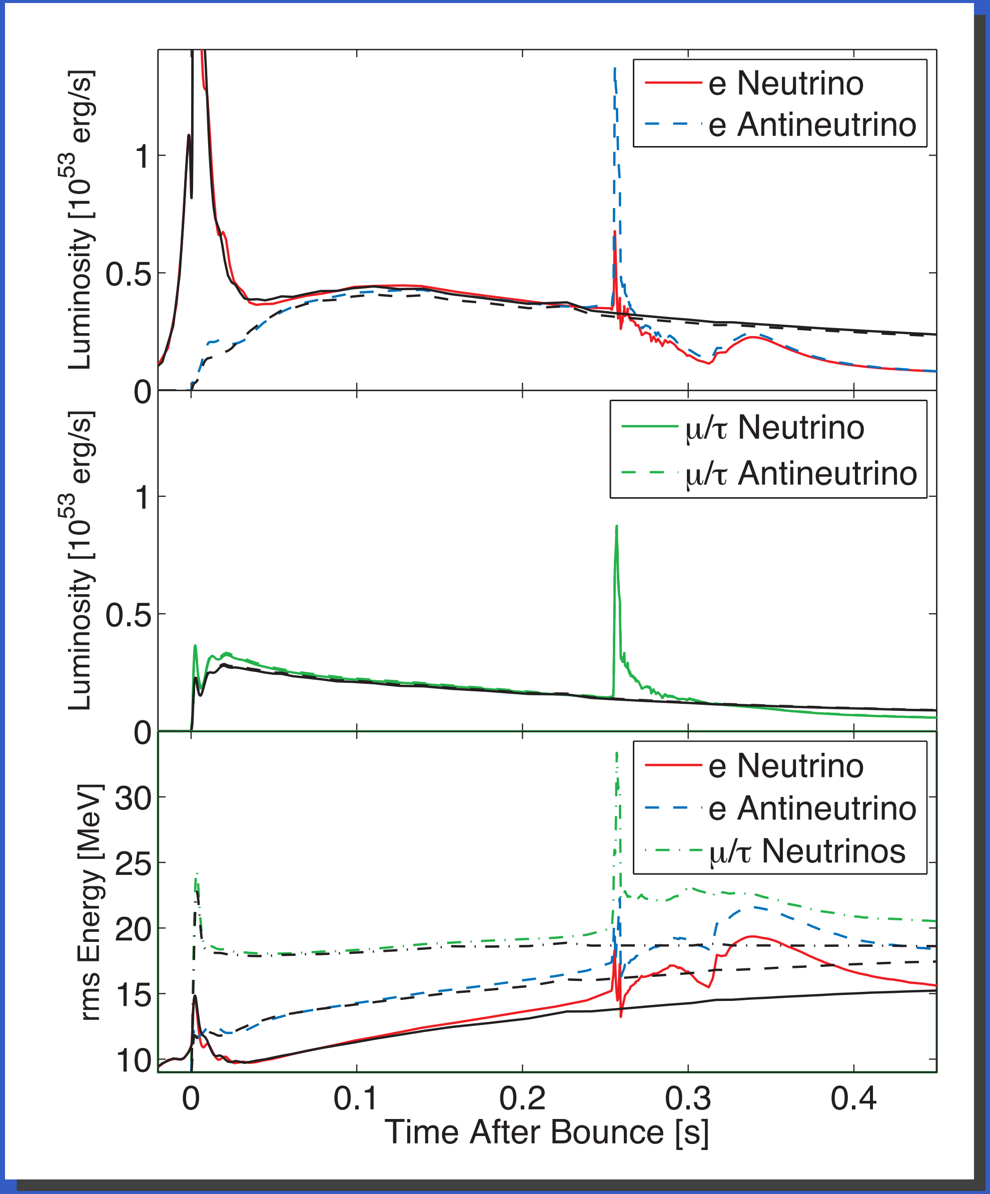


(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2008)

- velocity profile of a supernova for different times (around 250ms)
- formation of a core of pure quark matter produces a second shock wave
- leads to a successful explosion!

Implications for Supernova – Neutrino-Signal!



(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2008)

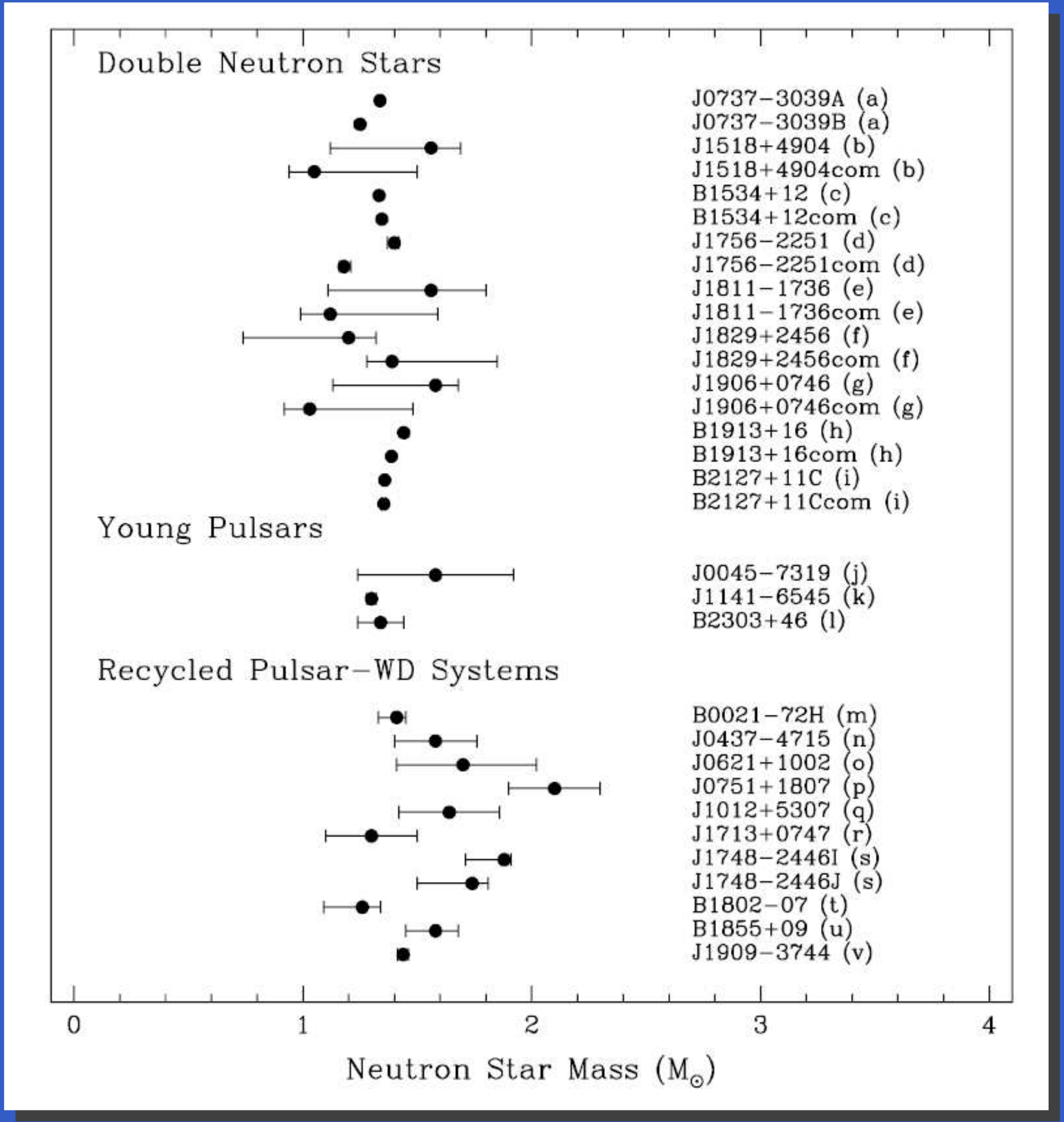
- temporal profile of the emitted neutrinos out of the supernova
- thick lines: without, thin lines: with a phase transition
- pronounced second peak of anti-neutrinos due to the formation of quark matter
- peak location and height determined by the critical density and strength of the QCD phase transition!!

Summary

- heavy ion data constrains the maximum mass of neutron stars to be less than $3M_\odot$
- color-flavour locked quark matter can exist in the core of neutron stars
- new improved EoS available for core-collapse supernova simulations
- quark matter can be formed in supernovae, even shortly after the first bounce
  - leads to a successful explosion (with enough explosion energy in the shock)
  - forms a second peak in the (anti-)neutrino signal
  - implications for gravitational wave signal?
  - and r-process nucleosynthesis?

Back-Up Slides

Masses of Pulsars (Stairs, 2006)

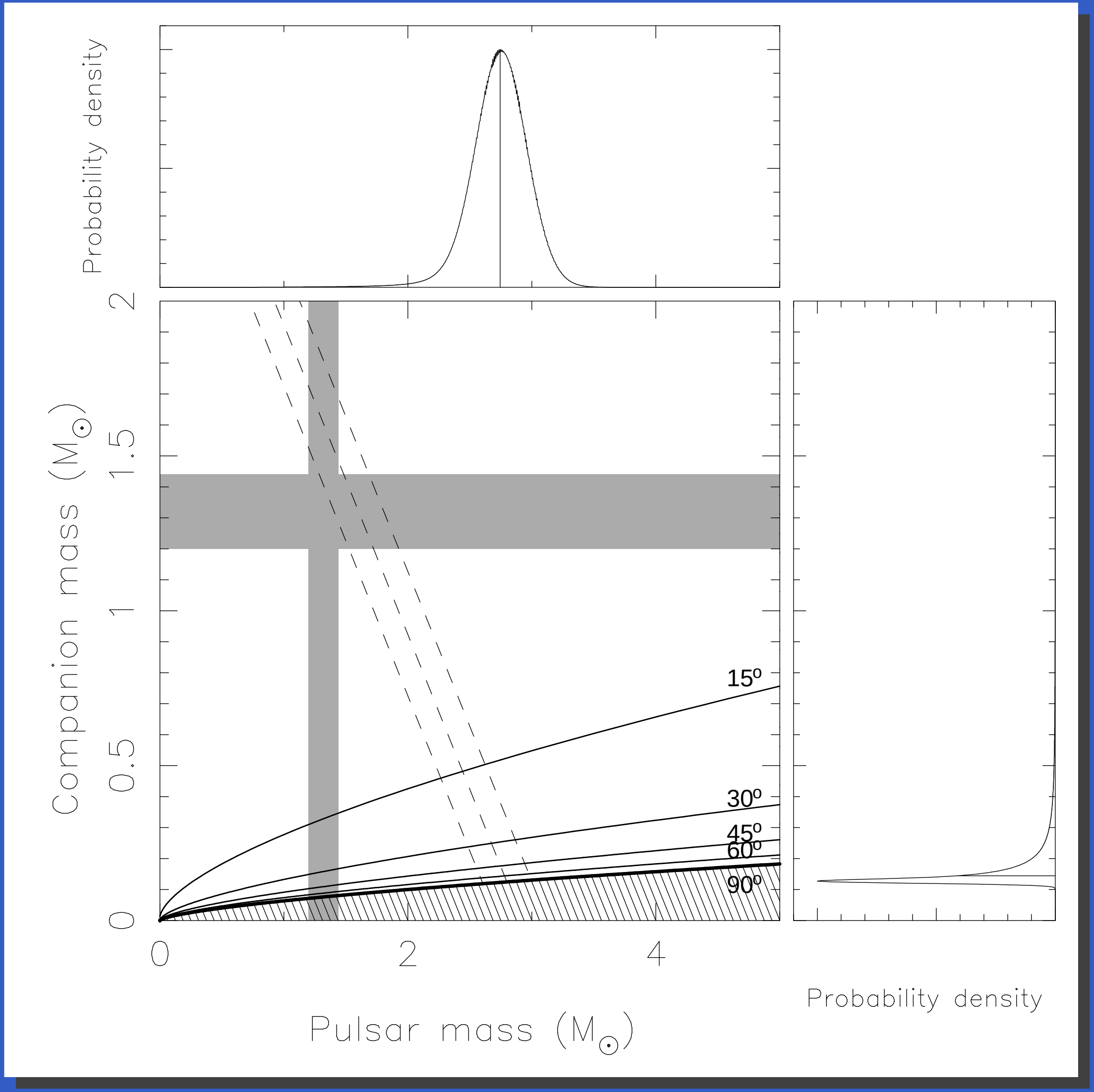


conservative neutron star mass limit of $1.44 M_\odot$

- more than 1700 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)
- mass of pulsar J0751+1807
  corrected from
  $M = 2.1 \pm 0.2 M_\odot$ to
  $M = 1.14 - 1.40 M_\odot$
  (Nice et al. 2008)

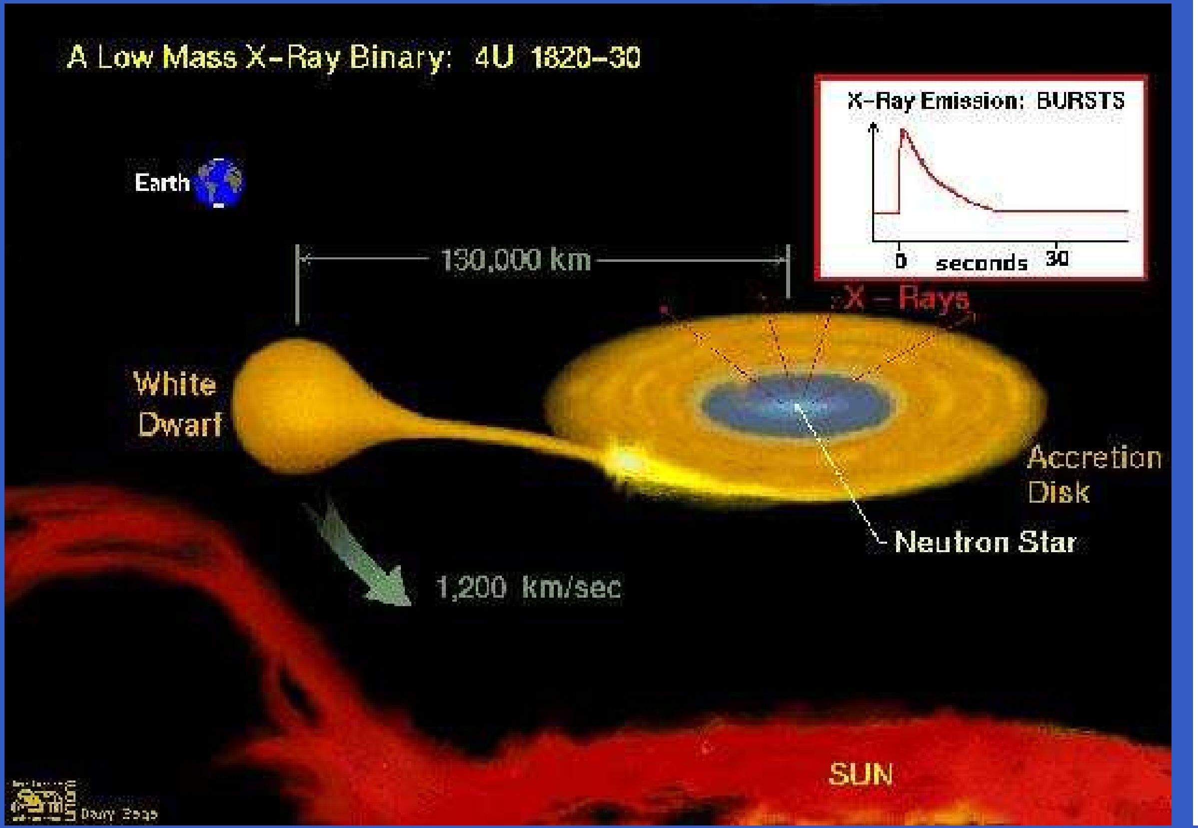
Supermassive Pulsar in Globular Cluster?

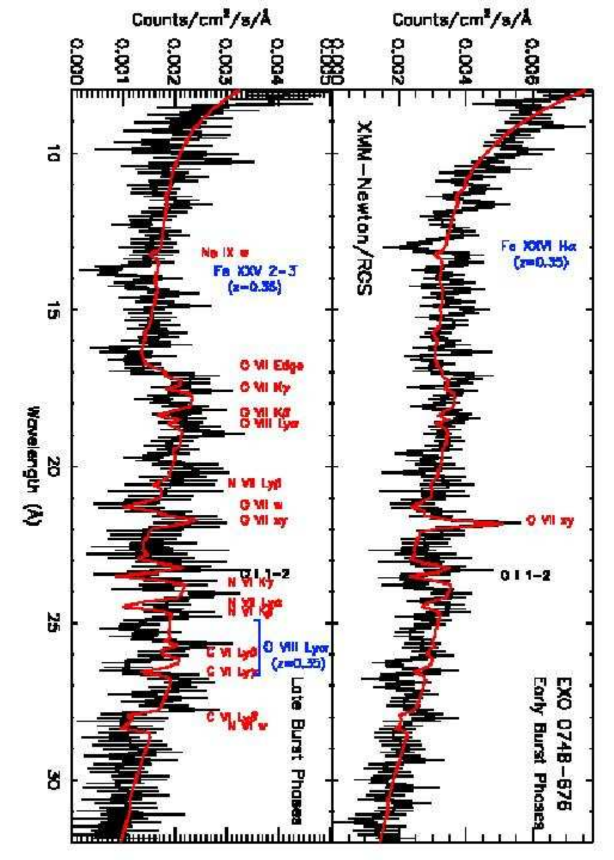
(Freire et al., arXiv:0711.0925v2 (2007))



- 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!

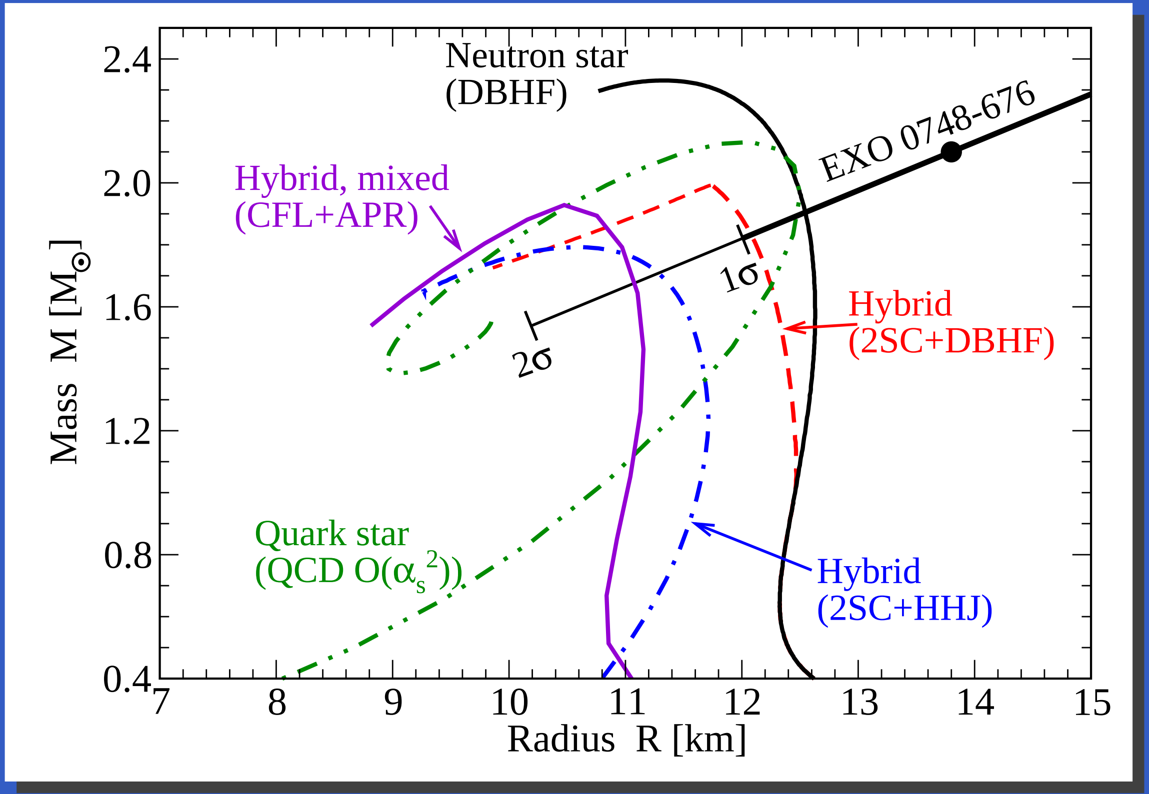
X-Ray burster





- binary systems of a neutron star with an ordinary star
- accreting material on the neutron star ignites nuclear burning
- red shifted spectral lines measured!
  ($z = 0.35 \rightarrow M/M_\odot = 1.5$ (R/10 km)) (Cottam, Paerels, Mendez (2002))
- Cottam et al. (2008): not confirmed with burst data from 2003

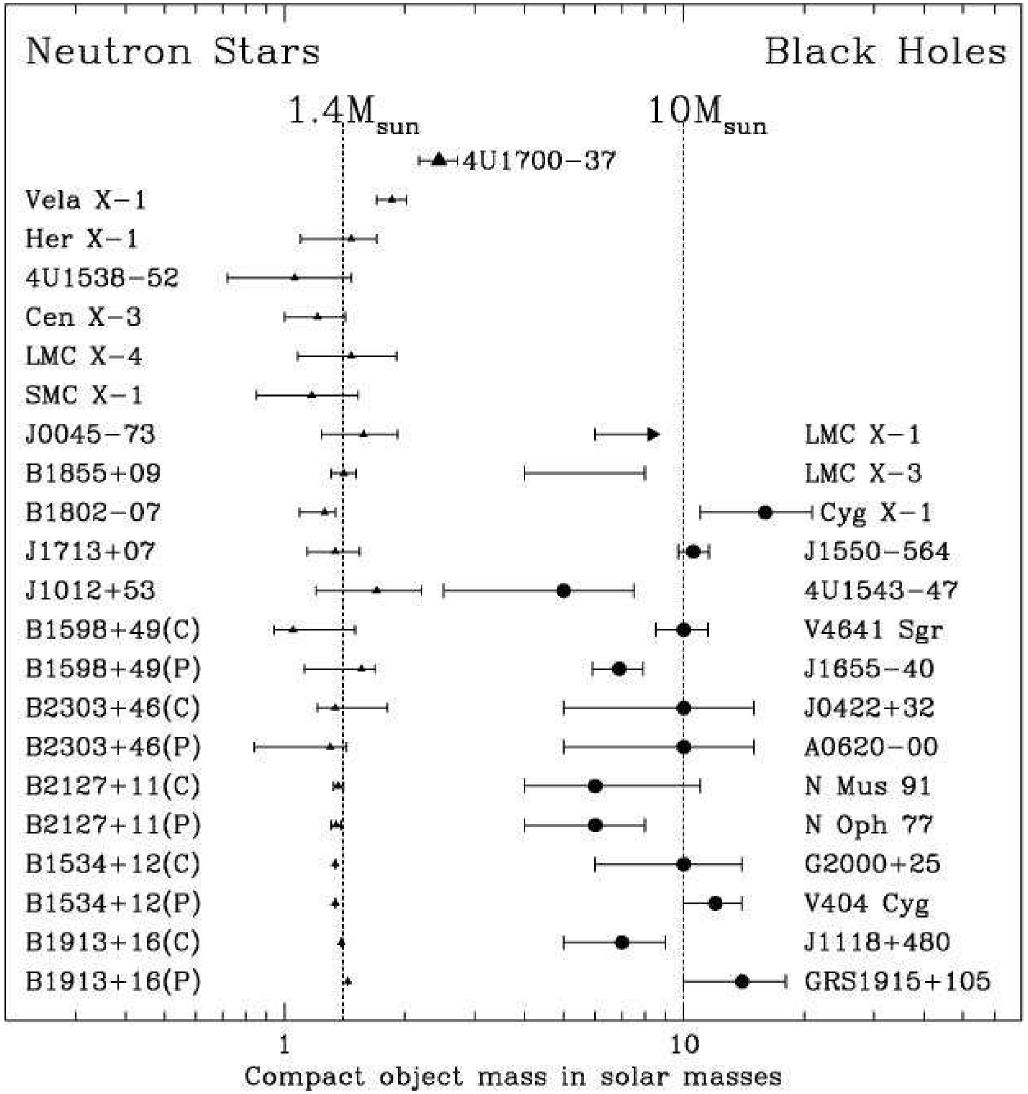
X-Ray burster EXO 0748–676: the EoS is hard!



- 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!

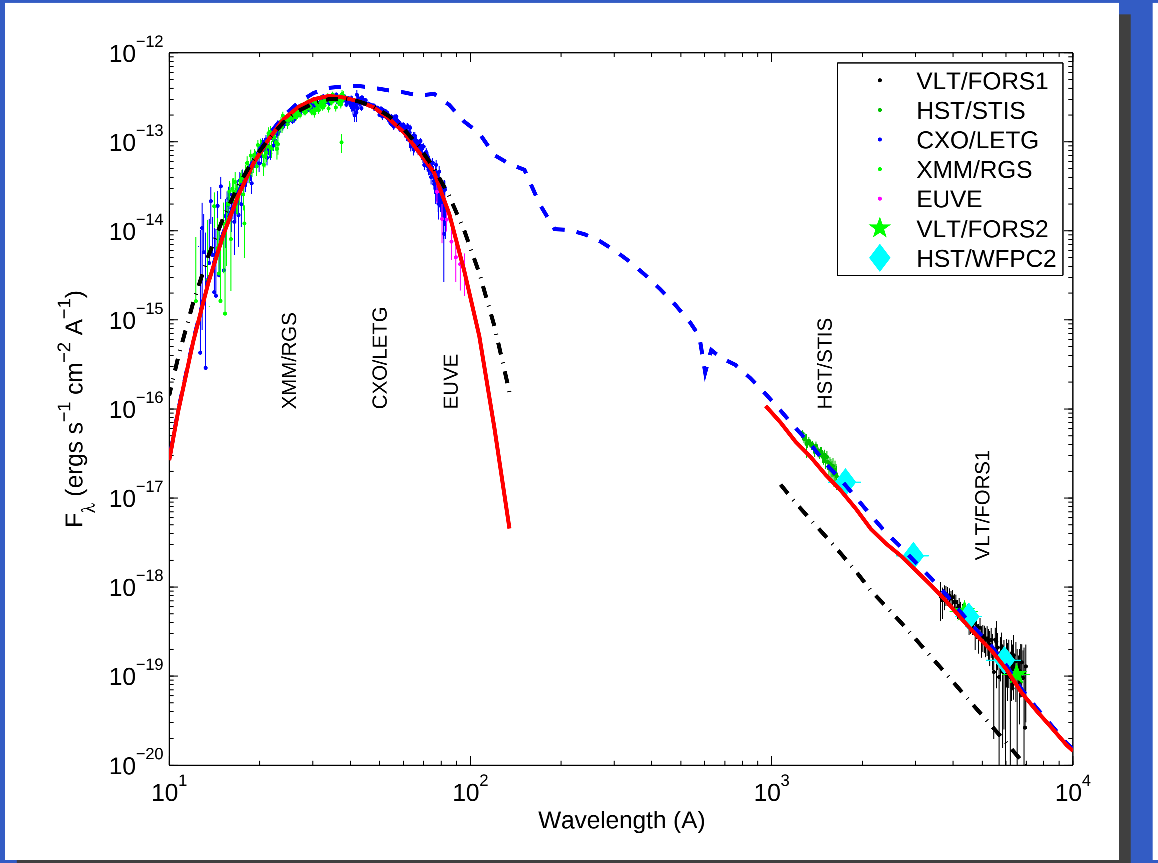
$\Longrightarrow$ the nuclear equation of state (EoS) would be hard

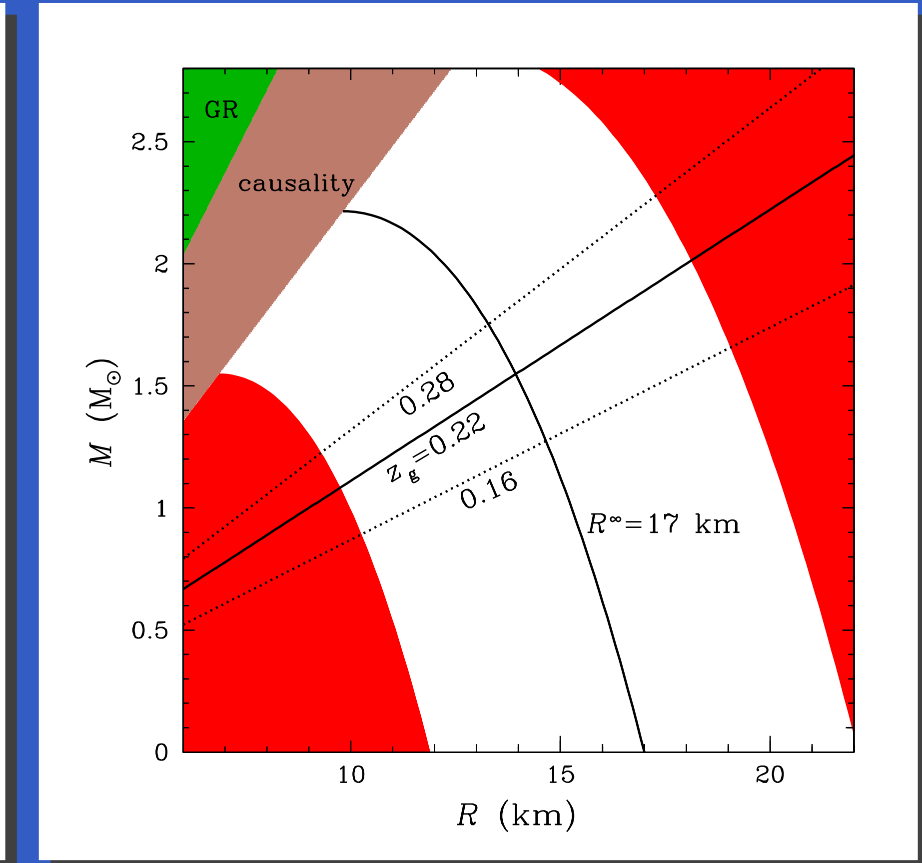
Massive Compact Objects In X-ray Binaries? (Clark et al. 2002)



- 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!

RXJ 1856: Neutron Star or Quark Star? (Trümper et al. (2003), Ho et al. (200

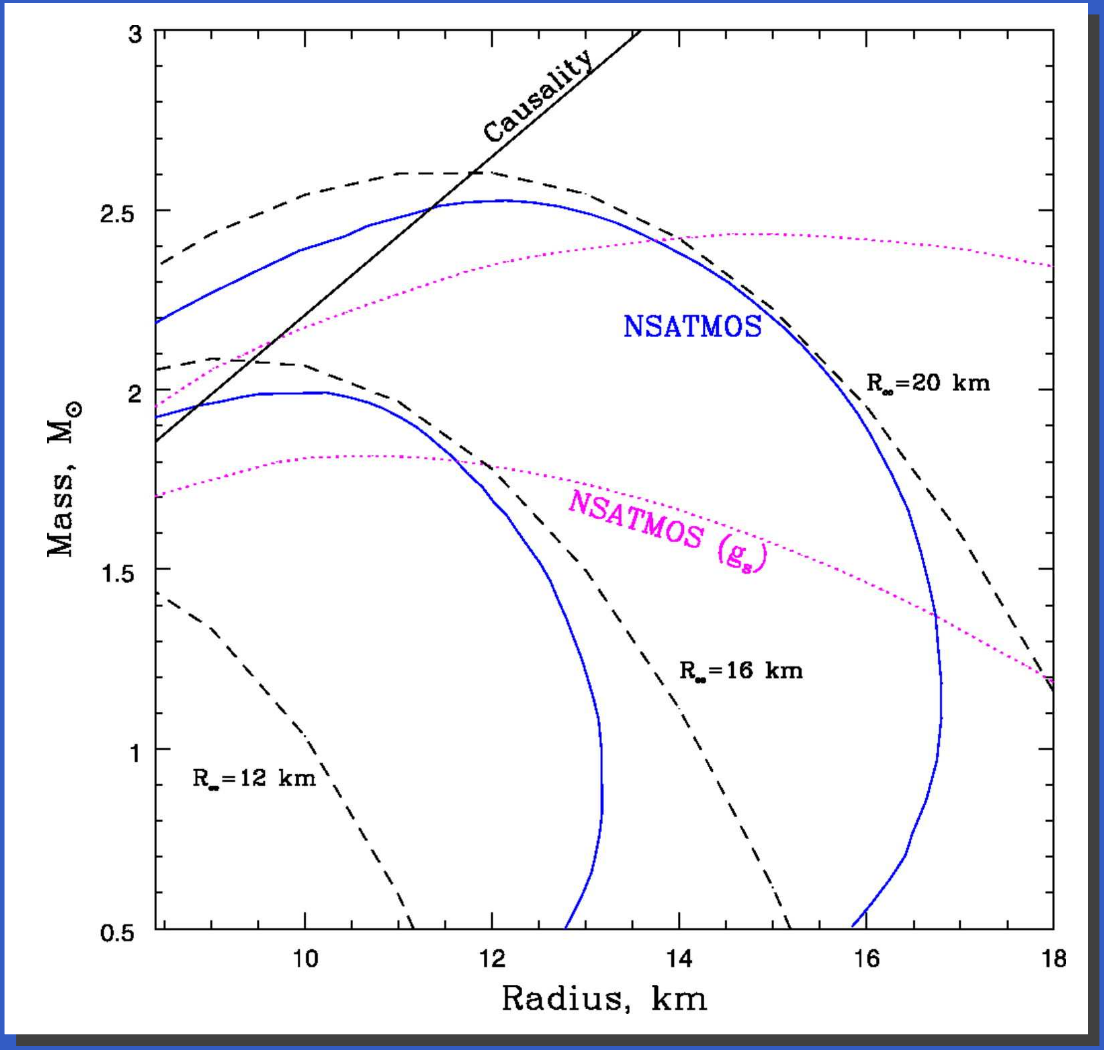




- two-component blackbody: small soft temperature, so as not to spoil the x-ray
- this implies a rather LARGE radius so that the optical flux is right!
- lower limit for radiation radius: $R_\infty = R/\sqrt{1-2GM/R} = 17$ km (d/140 pc)
- redshift $z_g \approx 0.22$: $R \approx 14$ km and $M \approx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

Spectral Model for Neutron Star X7

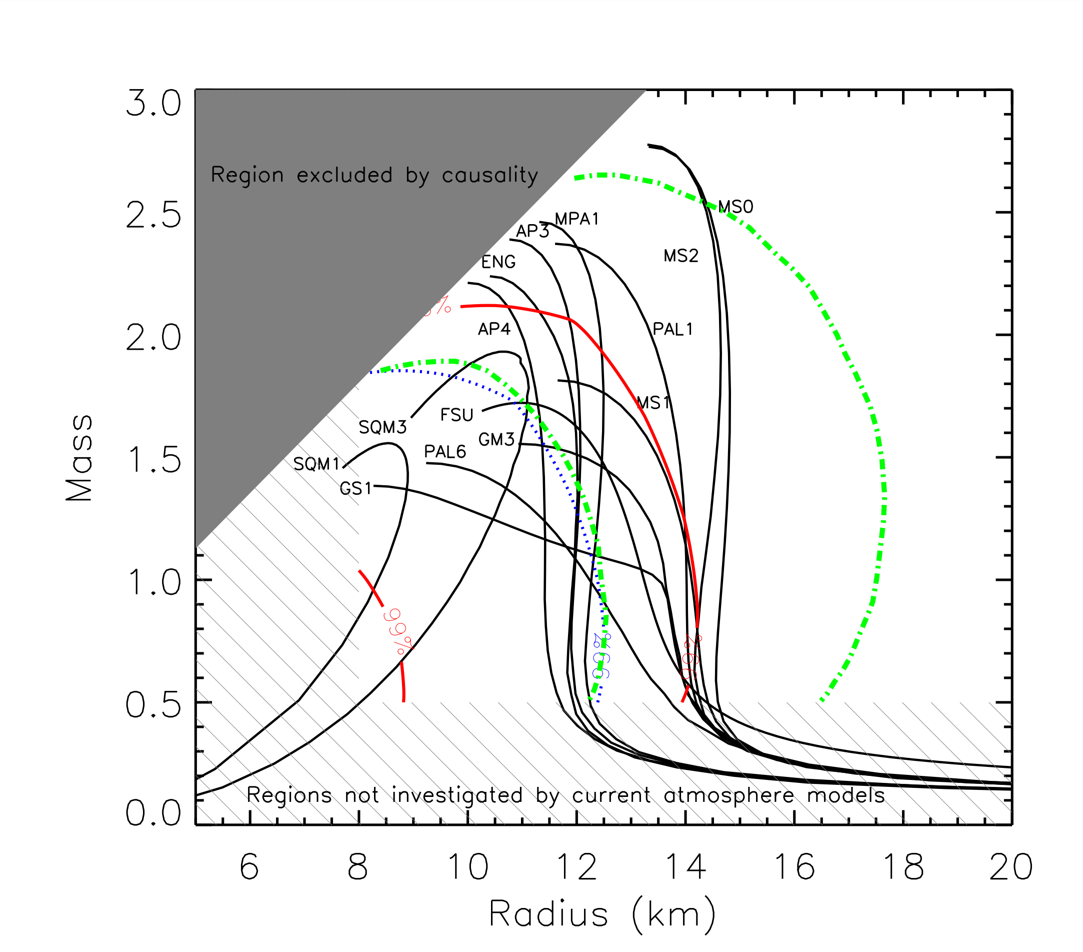
(Heinke, Rybicki, Narayan, Grindlay (2006)



- 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!

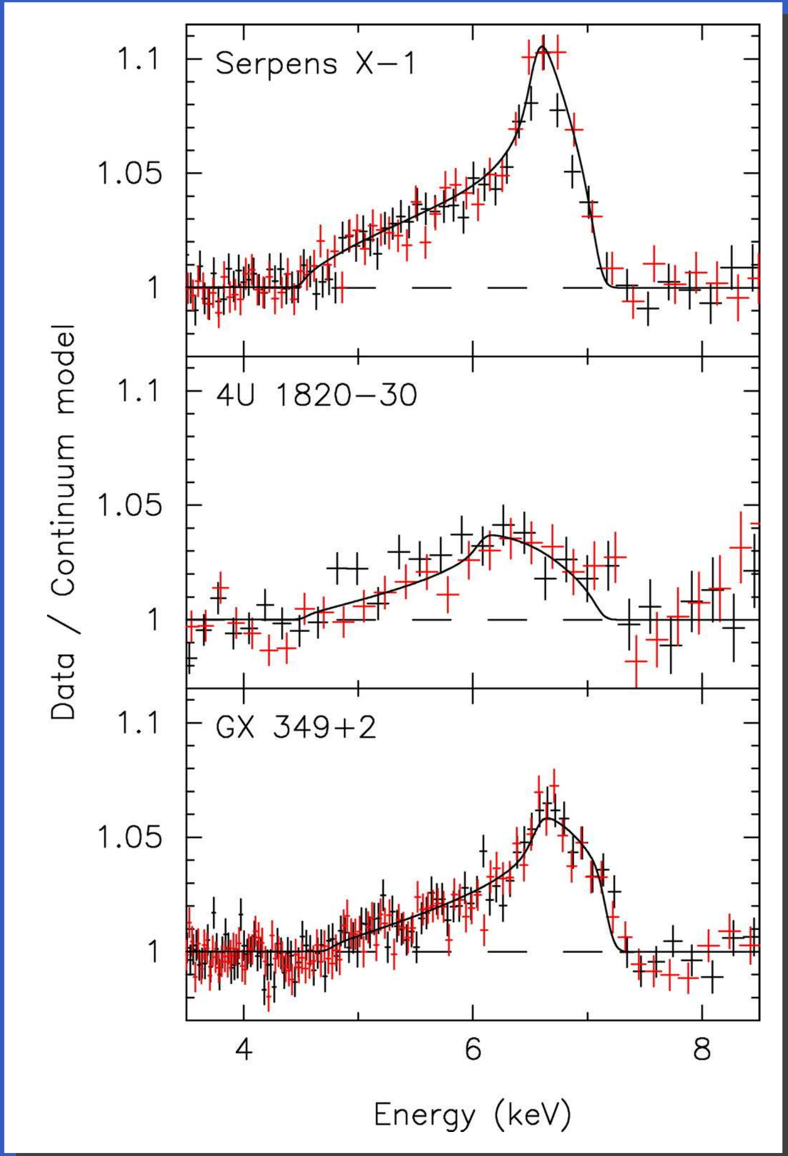
Spectral Modelling of Neutron Stars in Globular Clusters

(Webb and Barret (2007))

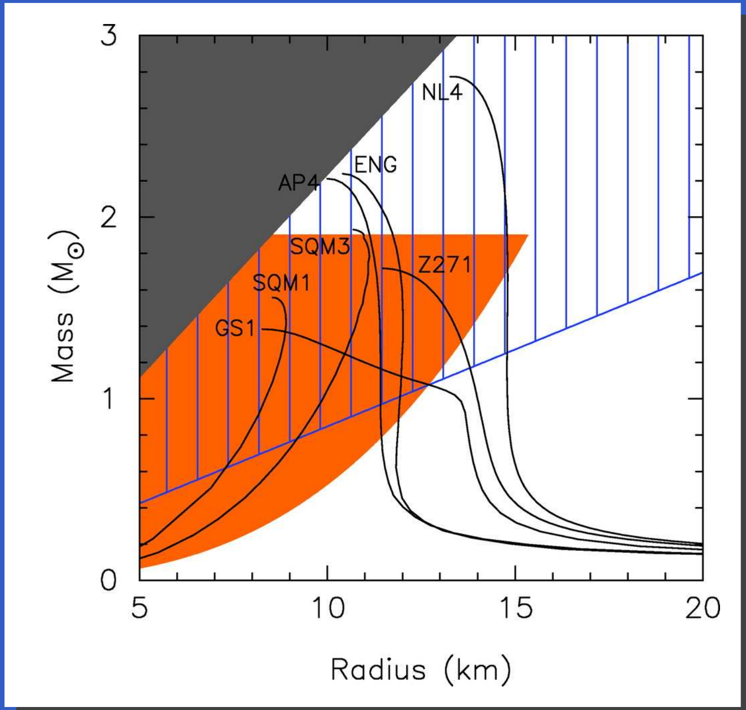


- spectral modelling of neutron stars in M13 (dotted blue line) and ω Cen (solid red line) and X7 in 47 Tuc (dash-dotted green line) all 99% c.l.
- mass-radius curve has to pass through all three regions: data from M13 demands a small mass

Broadened Iron Lines from LMXBs

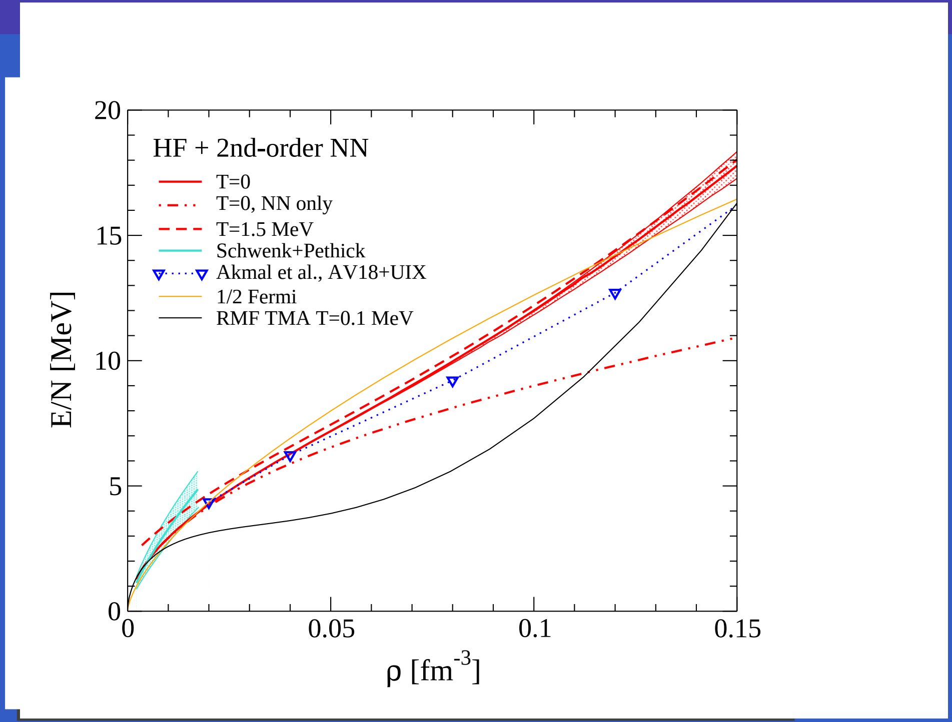


(Cackett et al. (2008)



- broadened 6.4keV iron line measured for LMXBs (as seen in AGNs) measured with Suzaku (and XMM Newton)
- inner radius of the accretion disk at $R_{in} = (7 - 8)GM$ $(14.5 - 16.5$ km for $M = 1.4M_\odot)$
- neutron star radius must be smaller

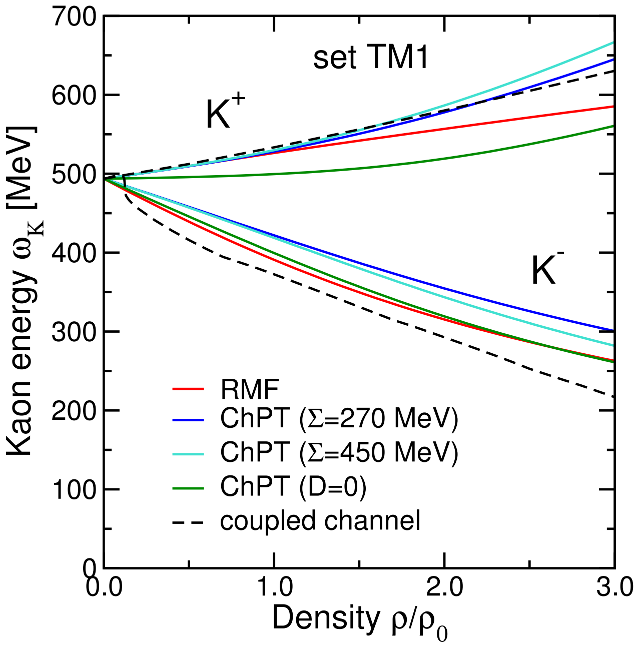
Pure Neutron Matter



(Matthias Hempel)

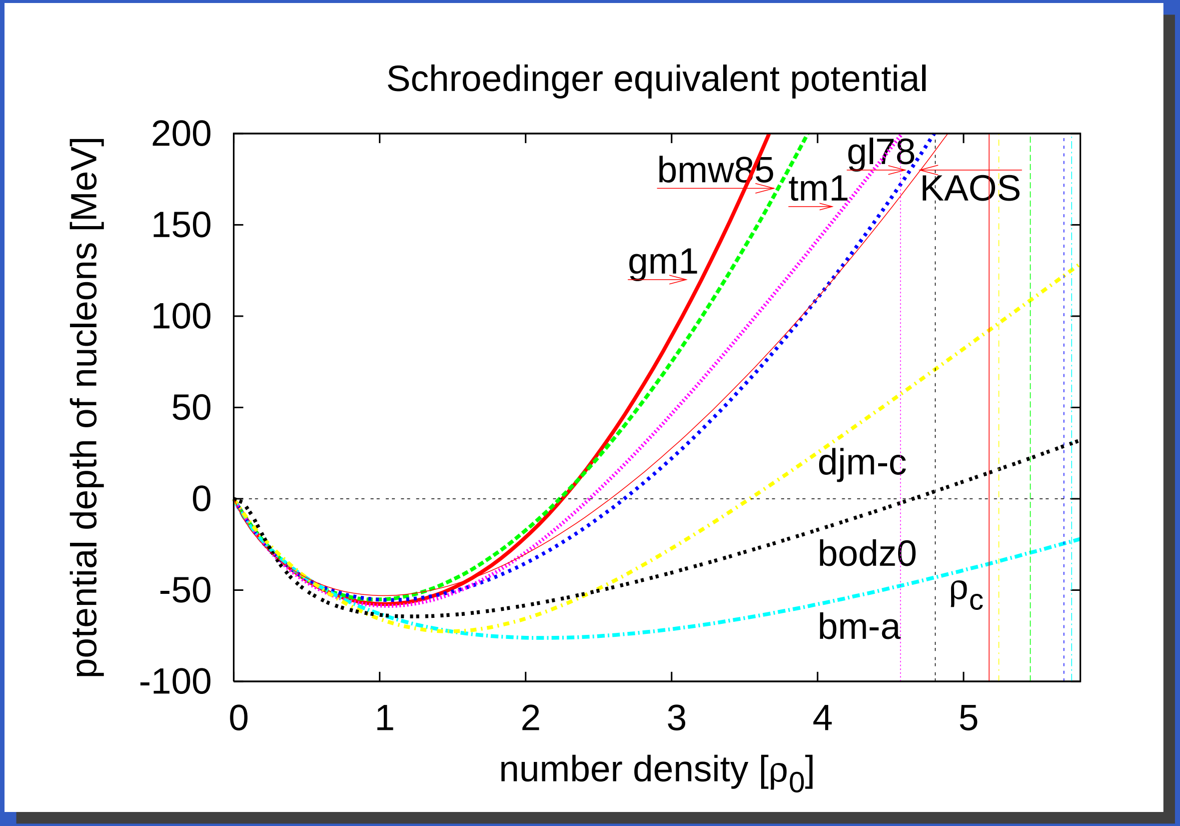
- pure neutron matter: comparison with ab-initio calculations
- calculations with V_{lowk} potential (Tolos, Friman, Schwenk, 2007), virial theorem and Argonne potential kompatible
- relativistic mean-field calculation with parameter set TM1 significantly below the other curves
- completely different density dependence of the asymmetry energy even below saturation density!

Kaons probe the dense nuclear medium (JSB, Bondorf, Mishustin, 1997)



- for kaons (K^+): in-medium energy <u>increases</u> with density (low-density theorem)
- for antikaons (K^-): in-medium energy <u>decreases</u> with density (Weinberg-Tomozawa term)
- kaon production serves as a measure of the baryon density reached (in heavy-ion collisions)!

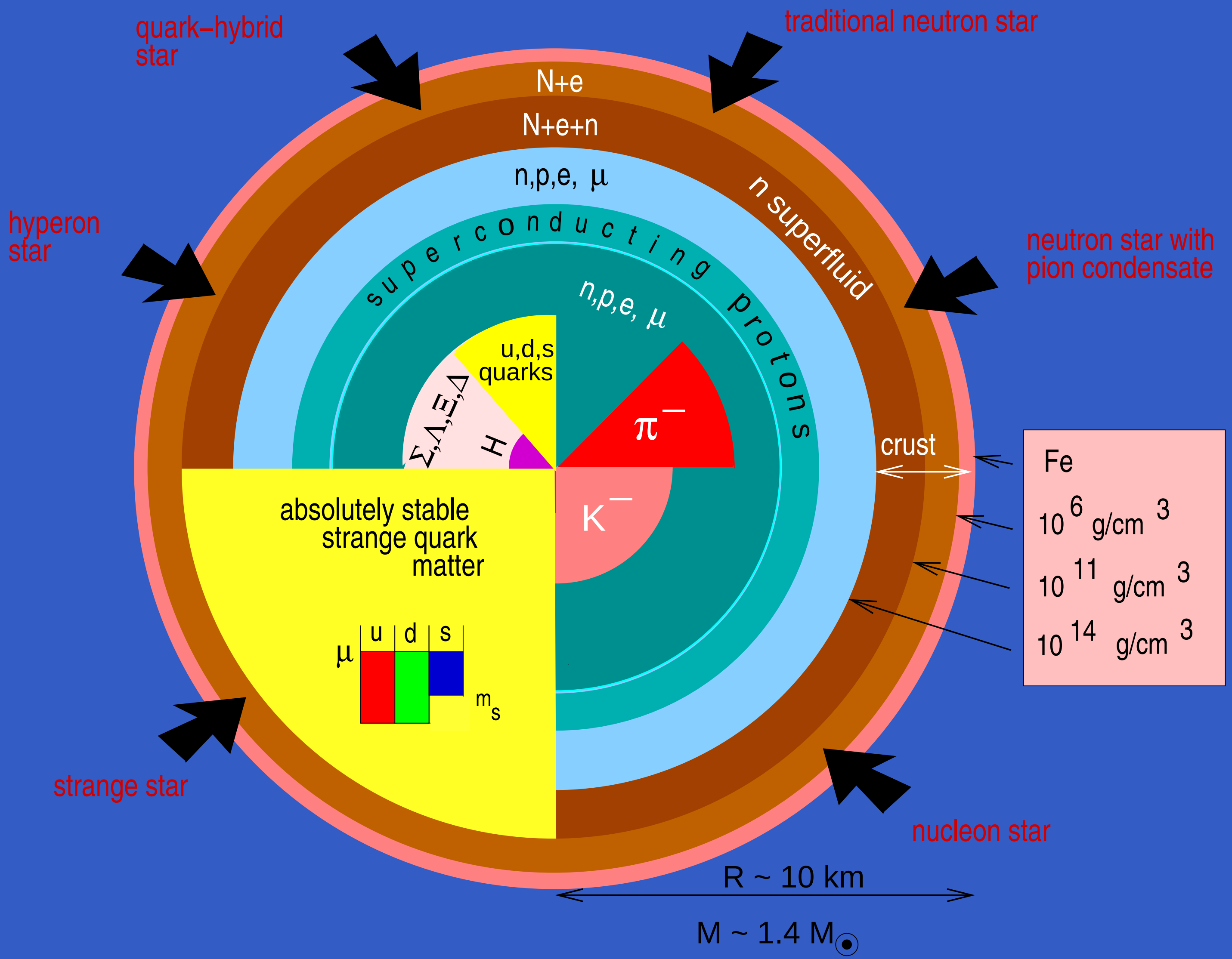
The EoS using Relativistic Mean–Field Models



(Mirjam Wietoska, 2006)

- essential input to transport models: non-relativistic Schrödinger equivalent potential (SEV), kaon production data: $K = 200$ MeV (line labelled KaoS)
- compare to: RMF model (gl78, bmw85, gm1), with vector selfinteractions (bodz0) fit to nuclei (tm1) or to many-body approaches (djm-c, bm-a)
- maximum density in neutron stars: around only $5n_0$

Structure of a Neutron Star — the Core (Fridolin Weber)



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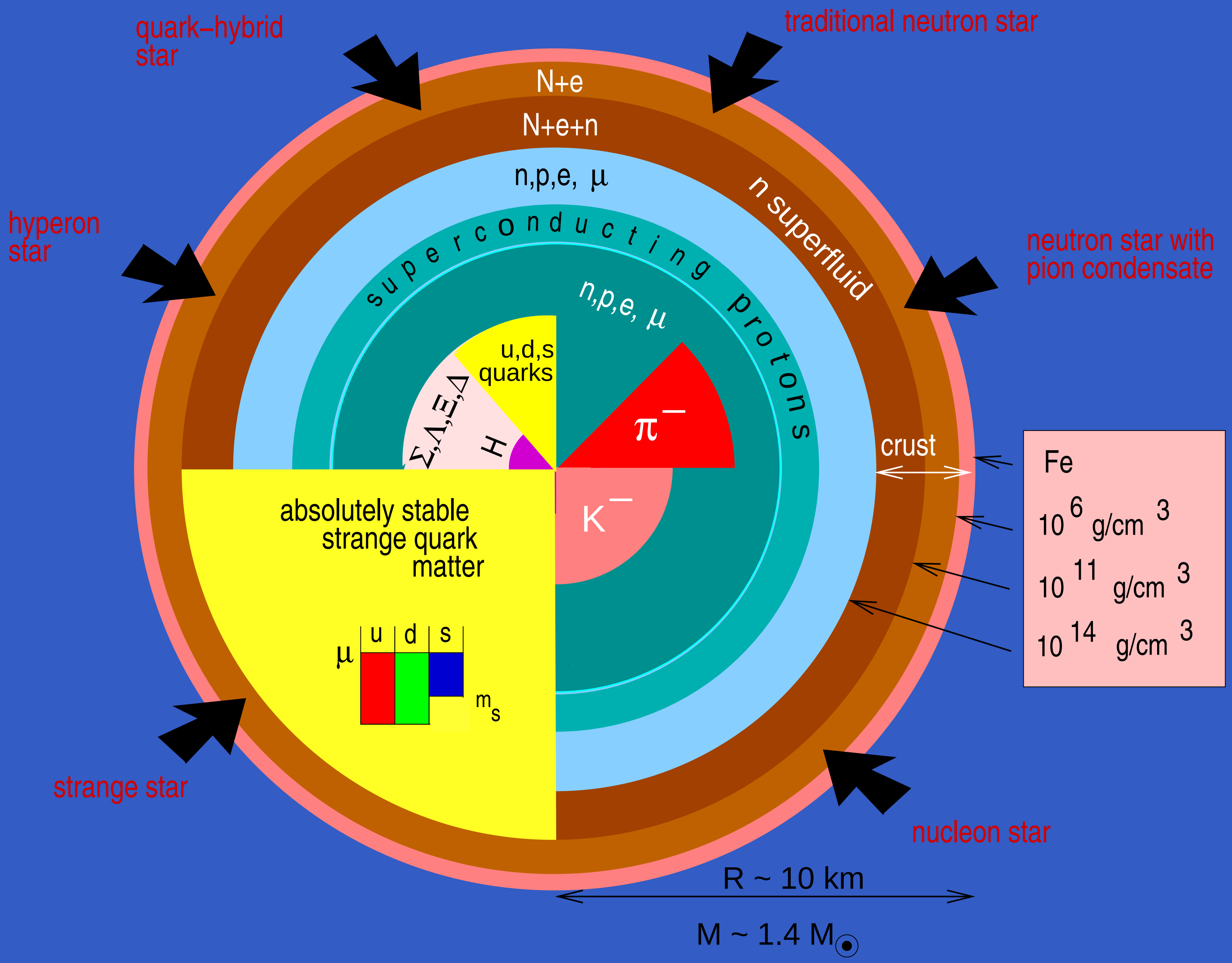
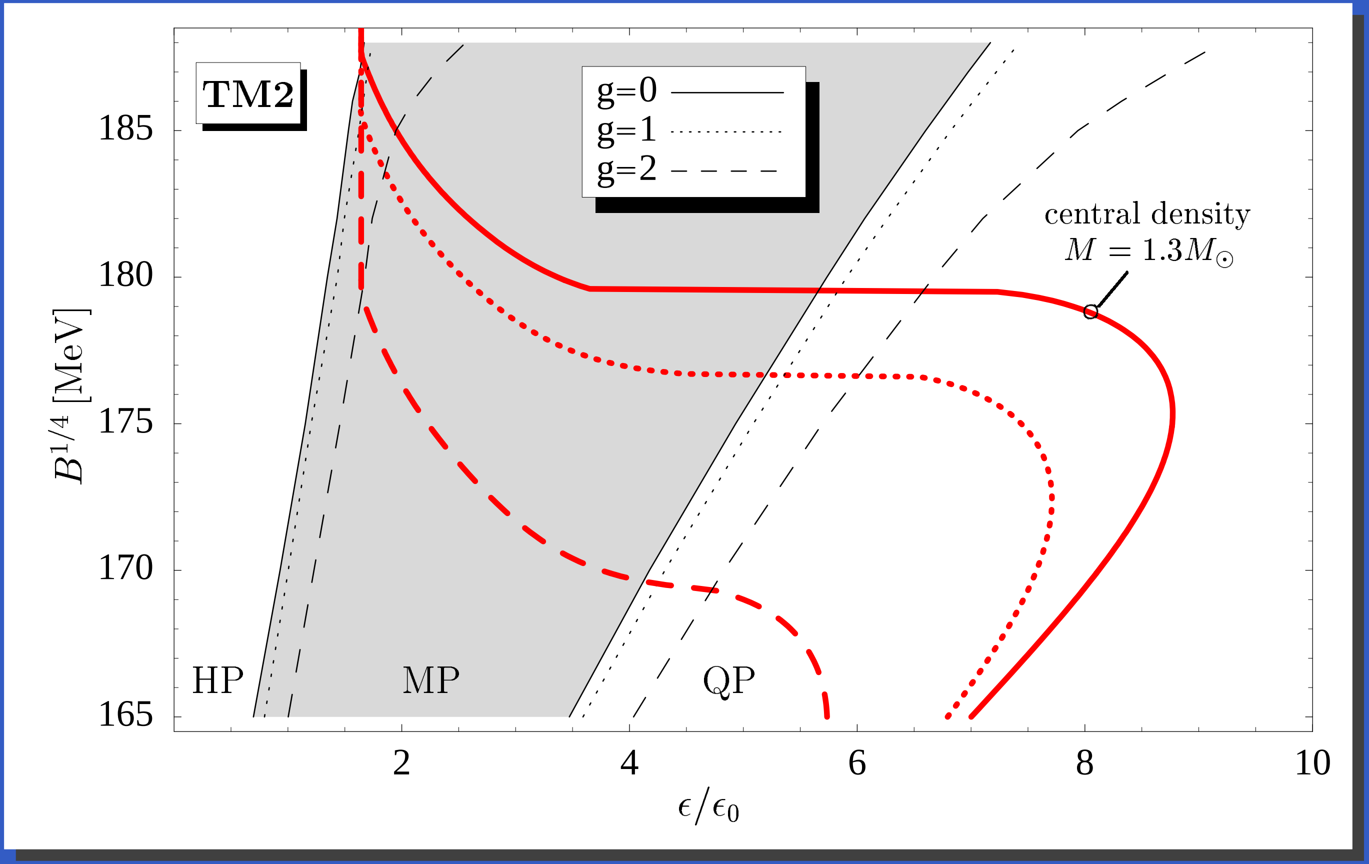


We have no idea what is going on inside a neutron star!

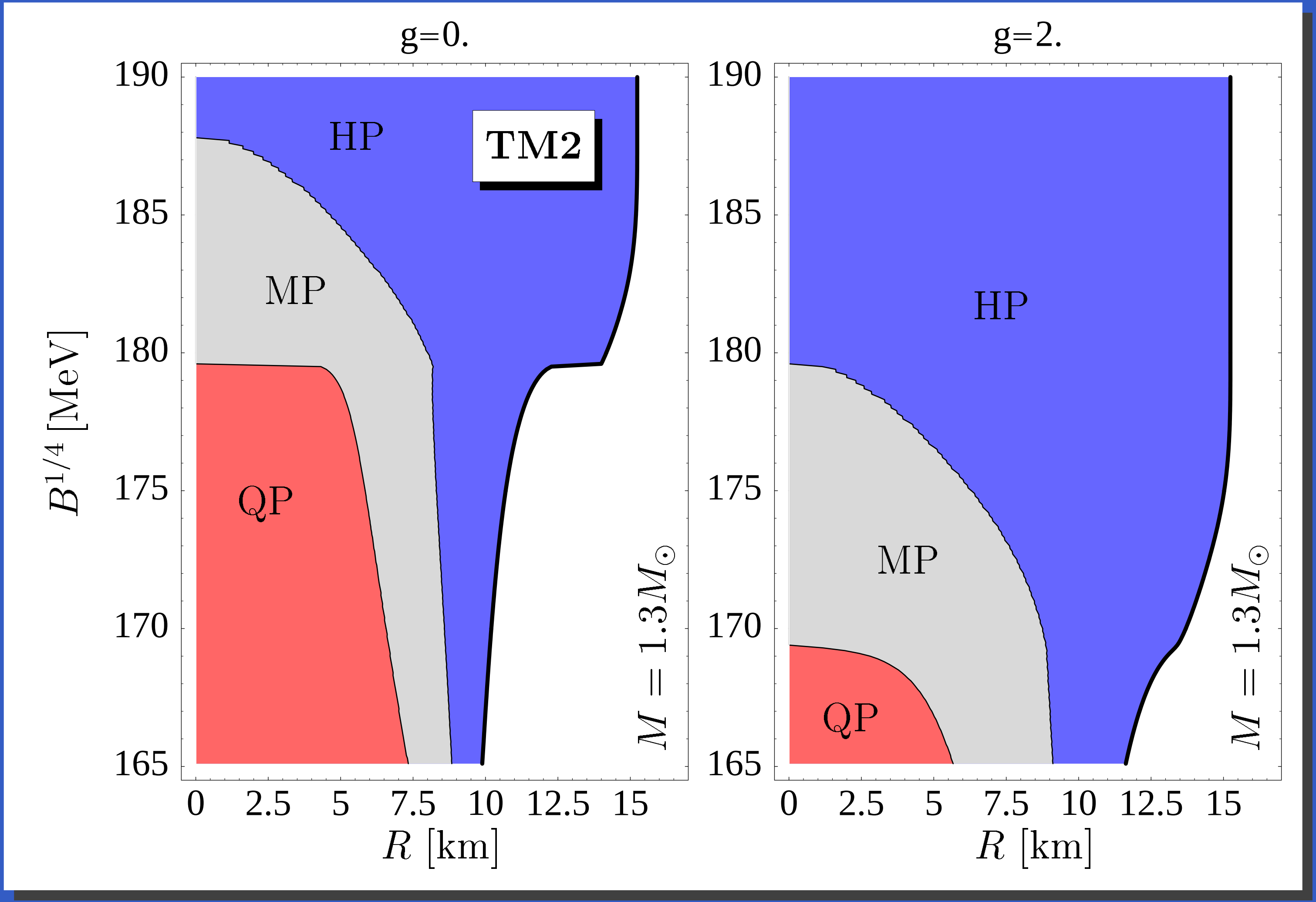
Quark Matter in Cold Neutron Stars



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

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

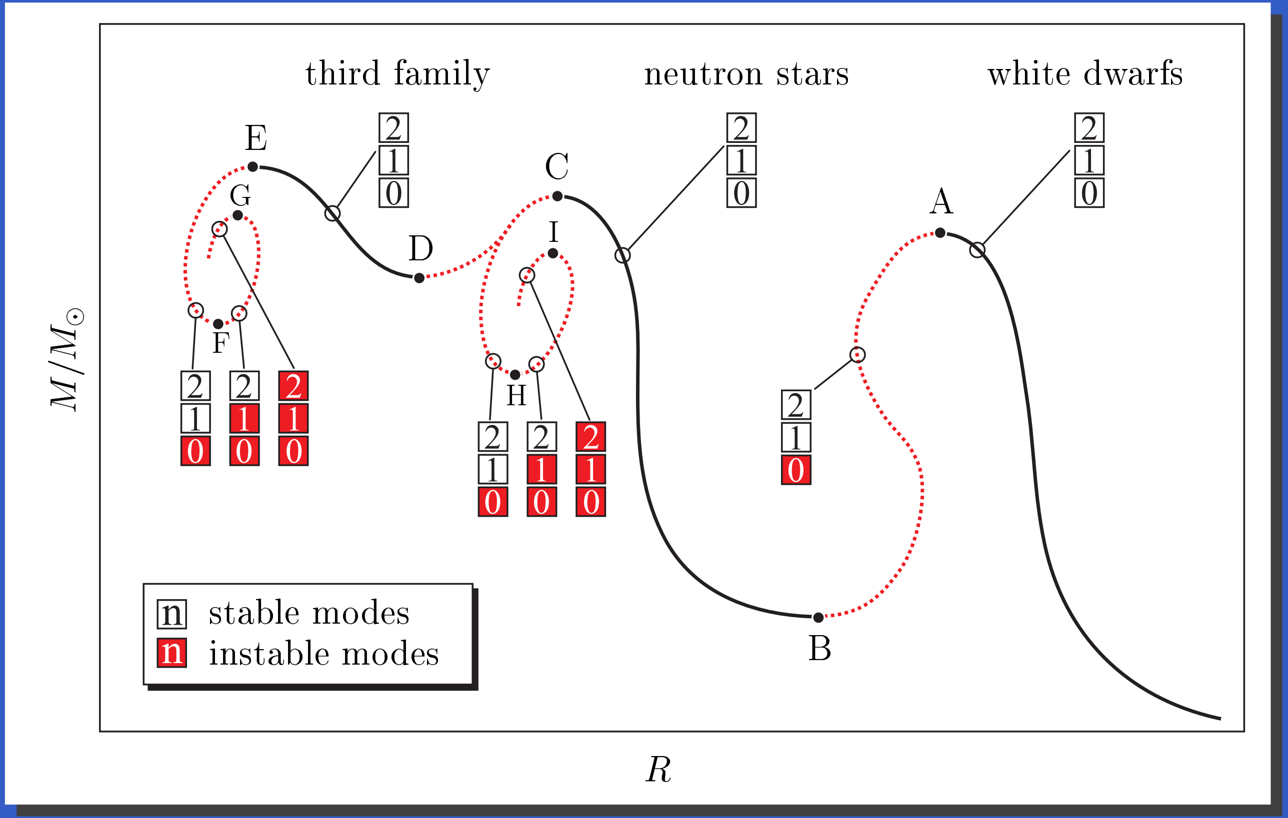
Hybrid Stars (Schertler et al. (2000))



- 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!)

Third Family of Compact Stars

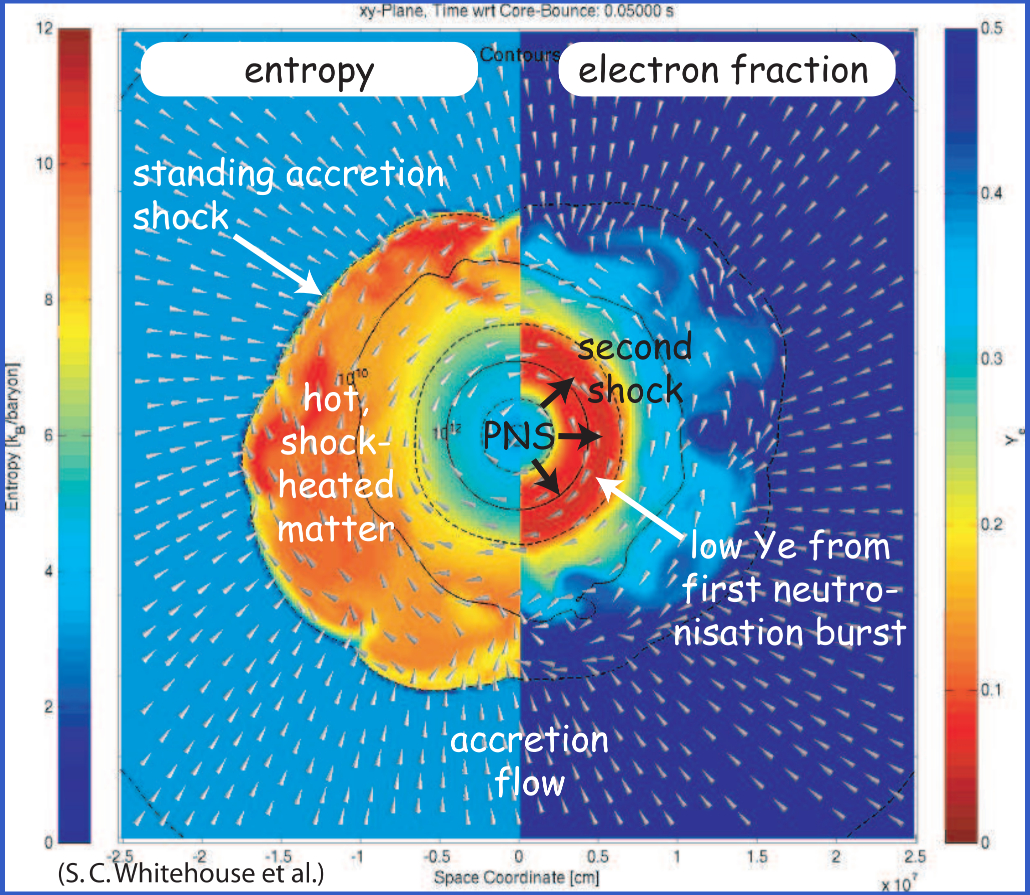
Gerlach (1968), Kämpfer (1981), Haensel and Proszynski (1982), Glendenning and Kettner (2000), . . .



(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 first order phase transition!

Supernova Explosions

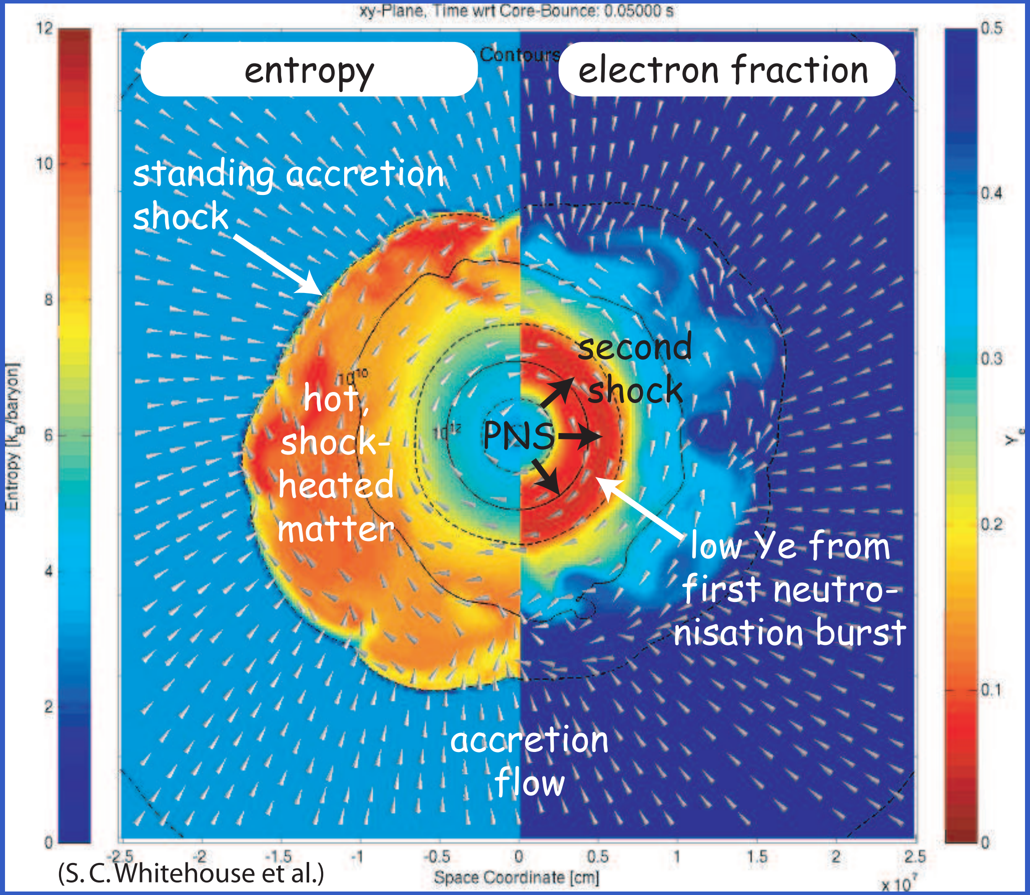


(S.C.Whitehouse et al.)

- 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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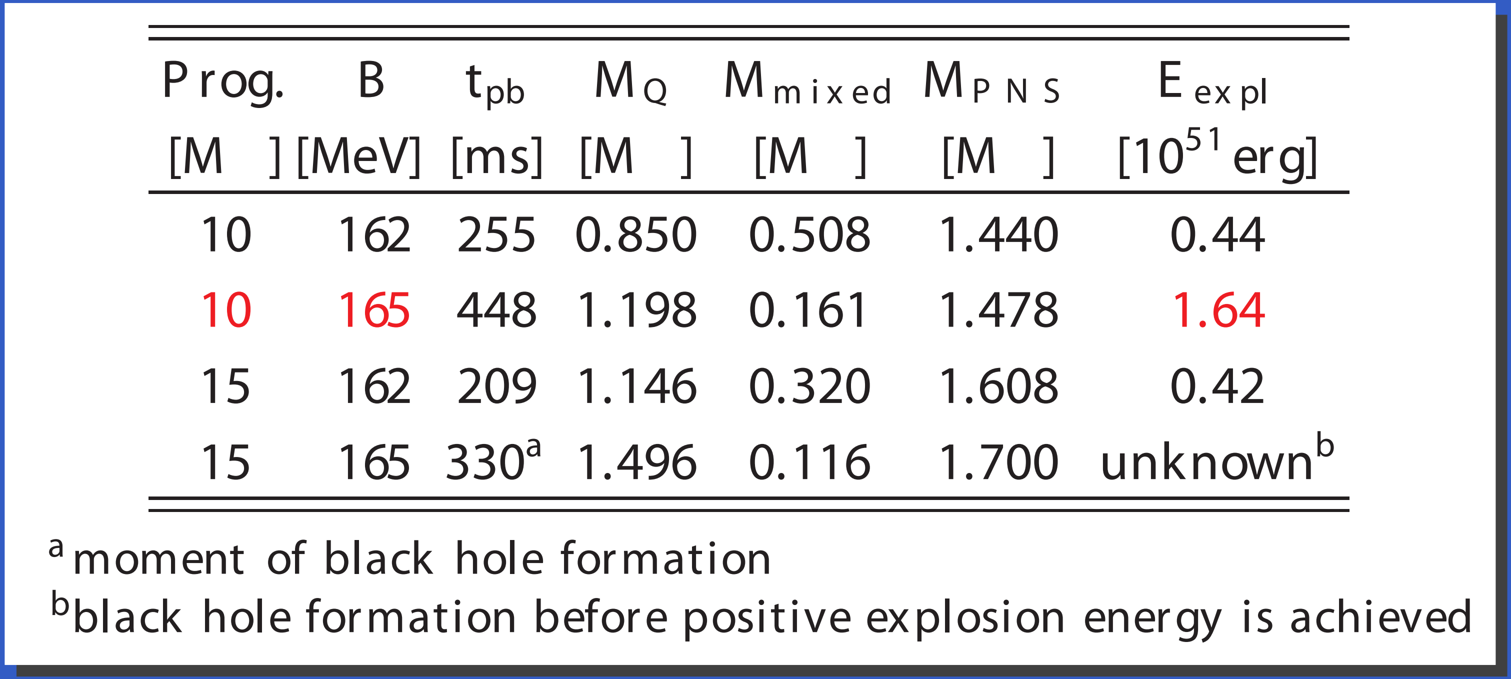
SASI: standing accretion shock instability, the models *do* explode after 600ms! (Marek and Janka, arXiv:0708.3372)

Successful Supernova Explosion – Parameter dependence



Prog. [M]	B [MeV]	t_{pb} [ms]	M_Q [M]	M_{mixed} [M]	M_{PNS} [M]	E_{expl} [10^{51} erg]
10	162	255	0.850	0.508	1.440	0.44
10	165	448	1.198	0.161	1.478	1.64
15	162	209	1.146	0.320	1.608	0.42
15	165	330[a]	1.496	0.116	1.700	unknown[b]

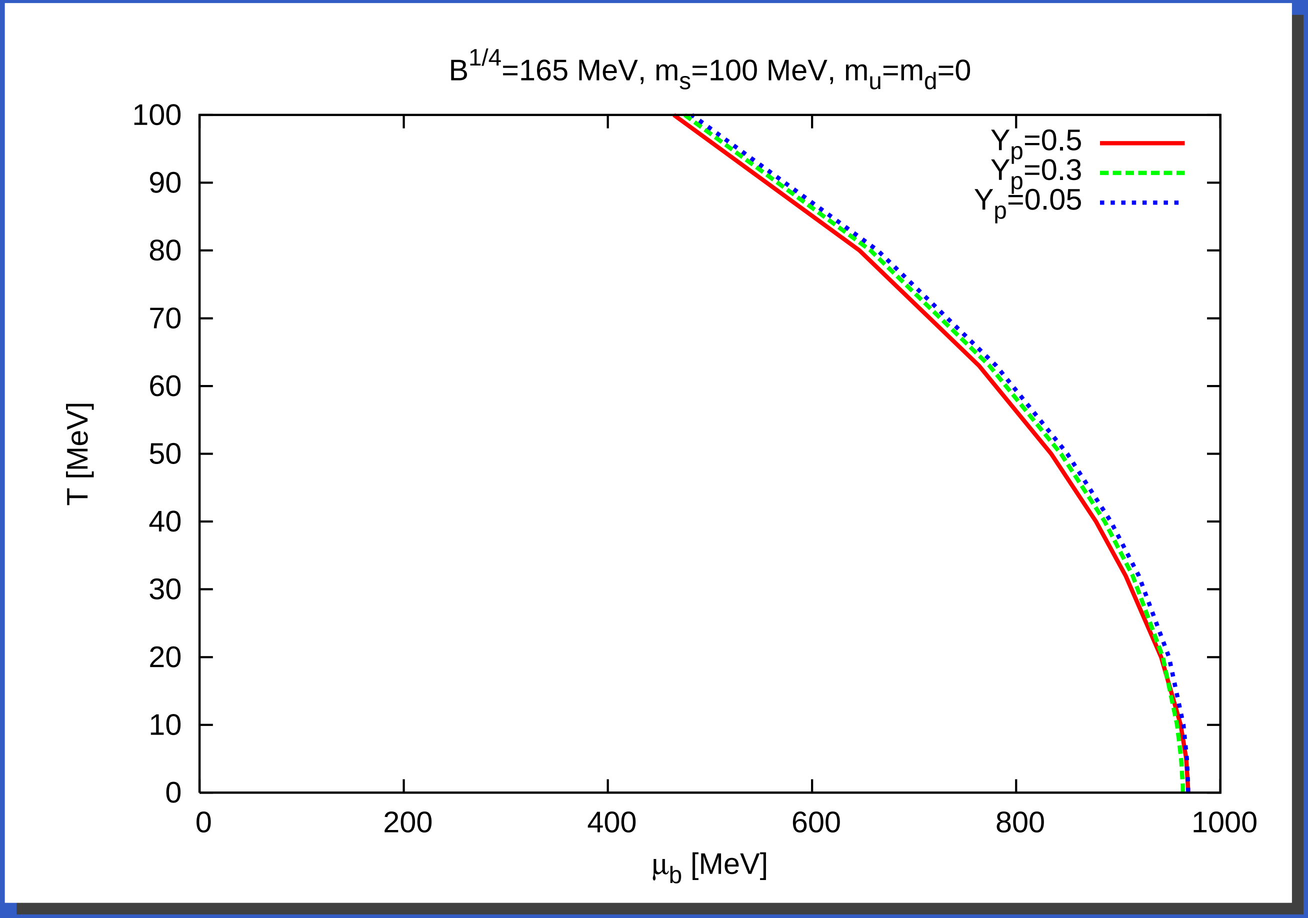
[a] moment of black hole formation

[b] black hole formation before positive explosion energy is achieved

(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2008)

- supernova simulation runs for different parameters
- appearance of the quark core at $t_{\rm pb} = 200$ to 500 ms
- results ($t_{\rm pb}$, baryonic mass and explosion energy) are significantly sensitive to the location of the QCD phase transition (bag constant)
- heavier progenitor masses can lead to the formation of a black hole

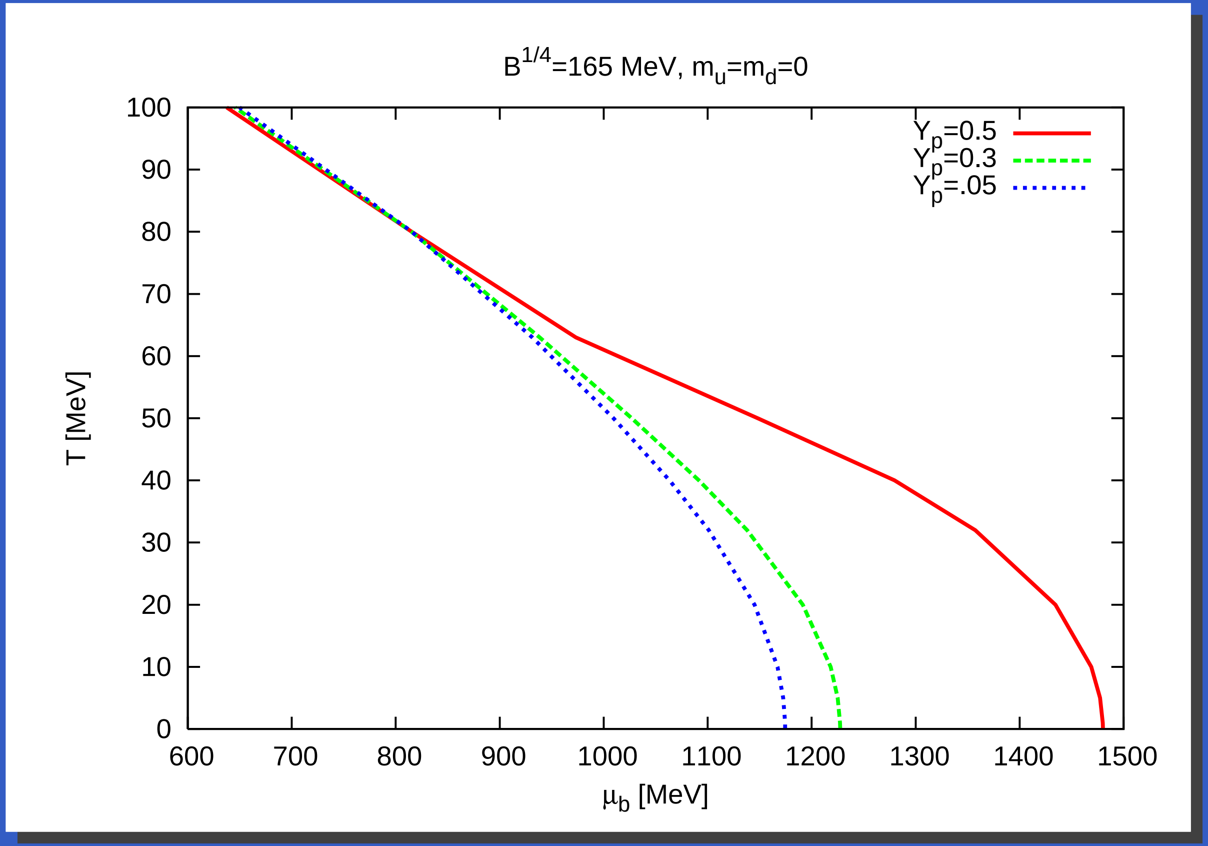
Phase Transition Line to Quark Matter for Astros



(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

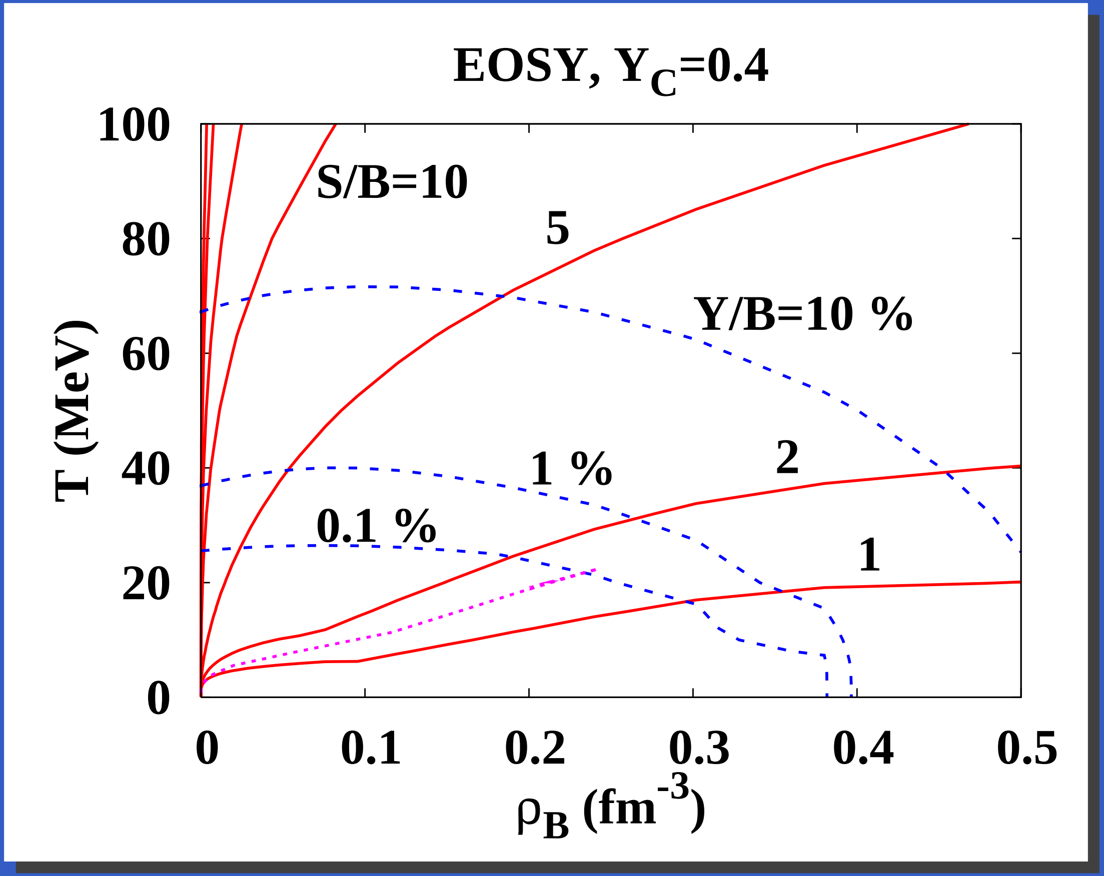
Phase Transition Line to Quark Matter for HICs



(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

Strangeness in Supernova Matter: Hyperons



C. Ishizuka, A. Ohnishi, K. Tsubakihara, K. Sumiyoshi, S. Yamada (arXiv:0802.2318)

- supernova matter for $Y_c = 0.4$ with constant entropy/baryon ratio S/B
- hyperon fraction at bounce $T \sim 20$ MeV: about 0.1%
- thermally produced strangeness, hyperons are in β-equilibrium!