The Structure of Neutron Stars

Jürgen Schaffner-Bielich

Institute for Theoretical Physics and
Heidelberg Graduate School for Fundamental Physics

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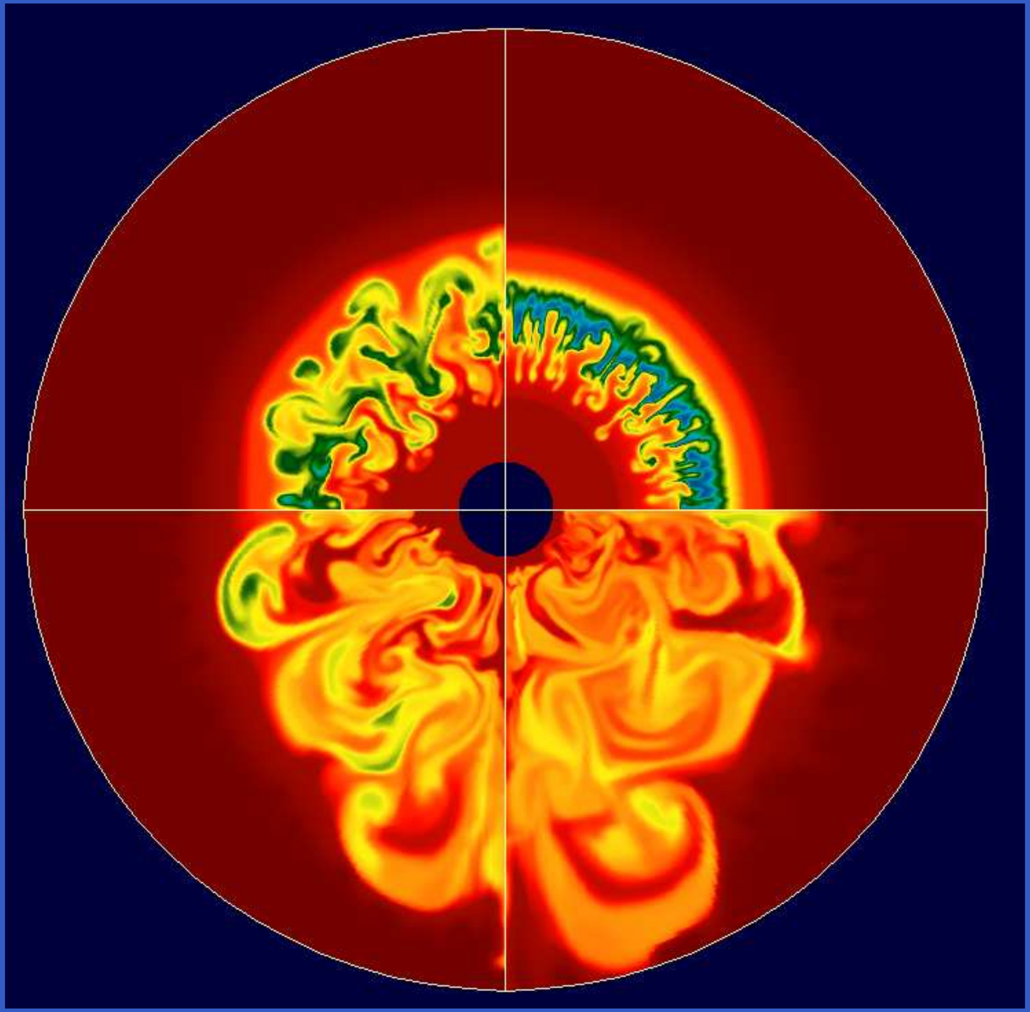
Introduction

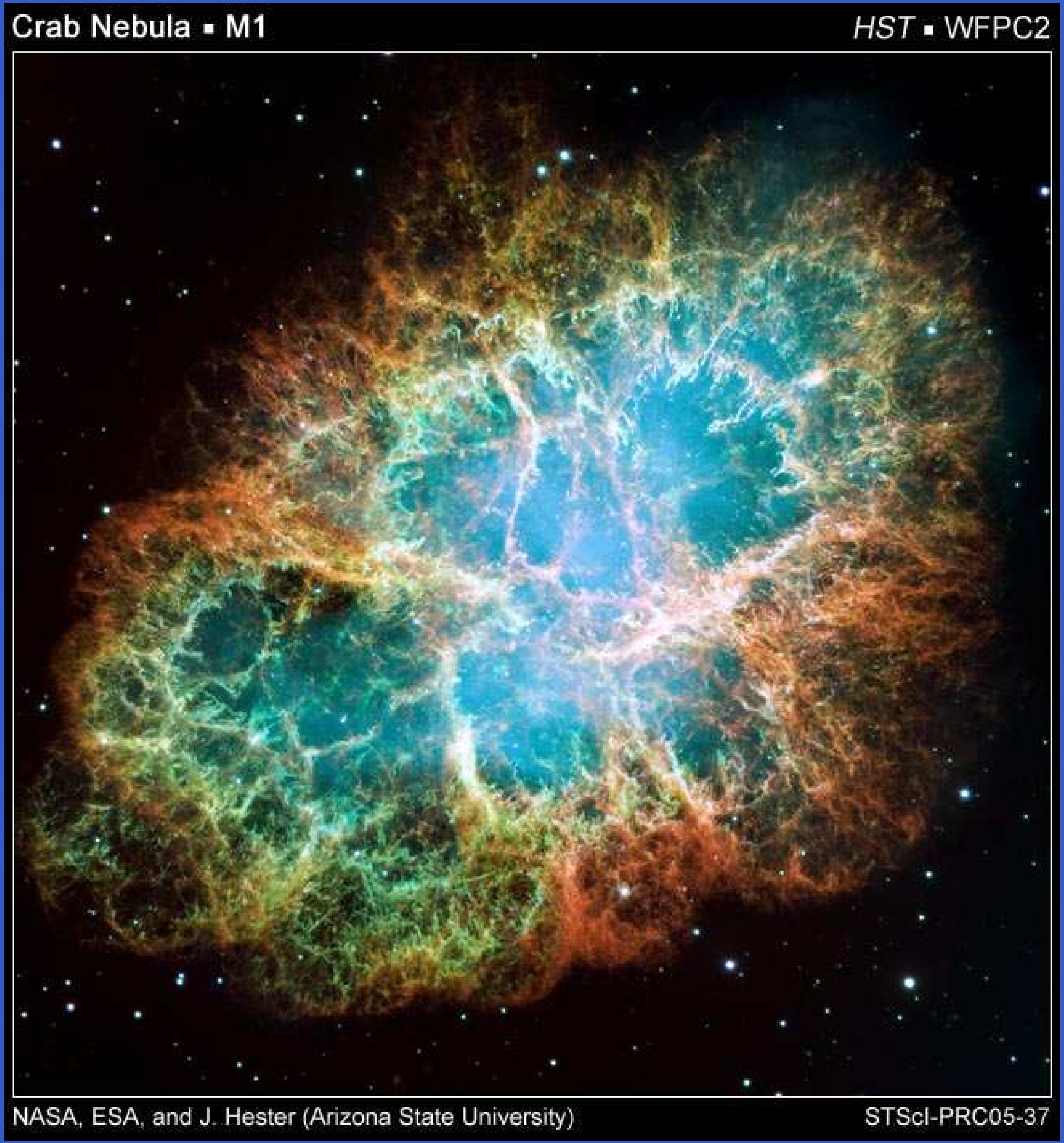
Supernova Explosions

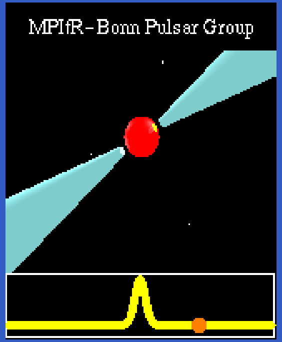


- stars with a mass of more than 8 solar masses end in a (core collapse) supernova (type II)
- Supernova of AD 1054 was visible for three weeks during daytime (crab nebula)!
- supernovae are several thousand times brighter than a whole galaxy!
- last supernova explosion for the last 400 years in our local group: SN1987A
- most prominent candidate in the universe for producing the heavy elements (r-process)

Animation of a supernova explosion (Chandra, NASA)

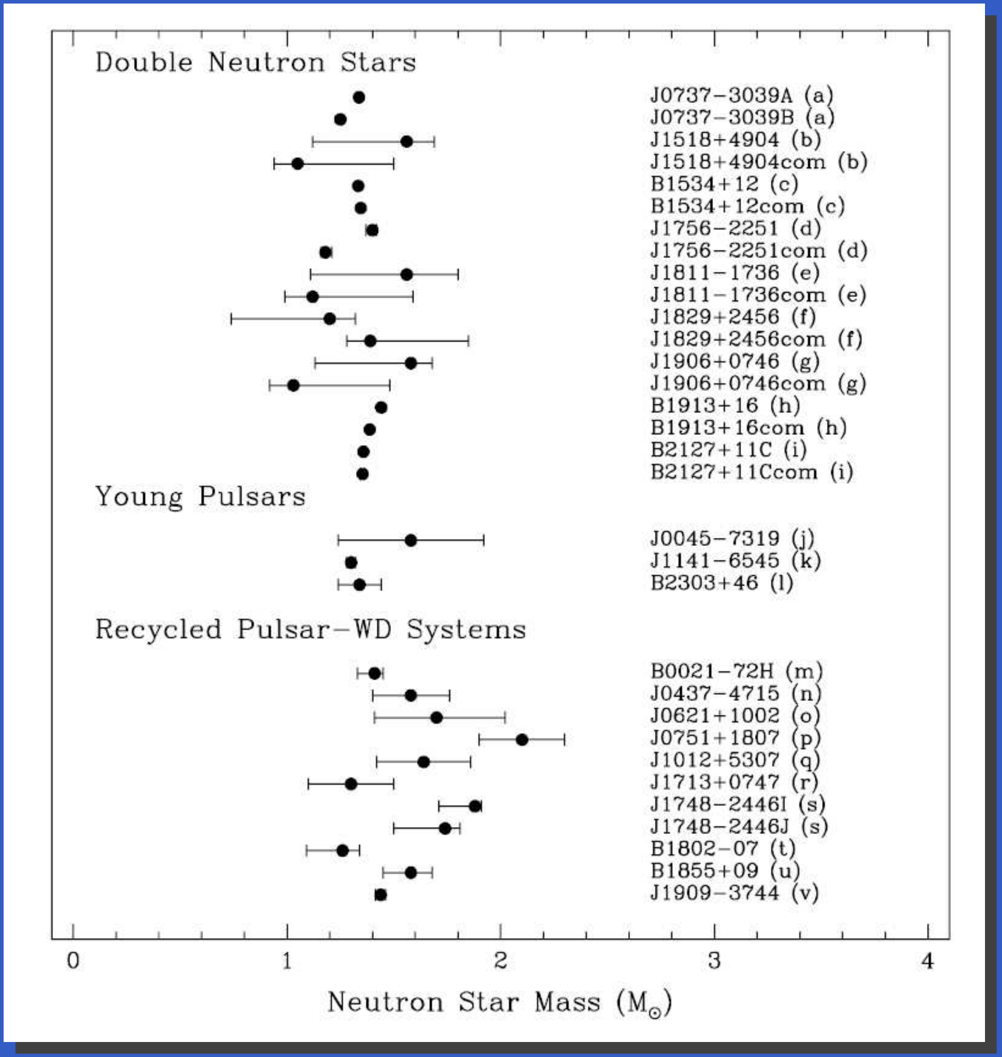
Neutron Stars





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

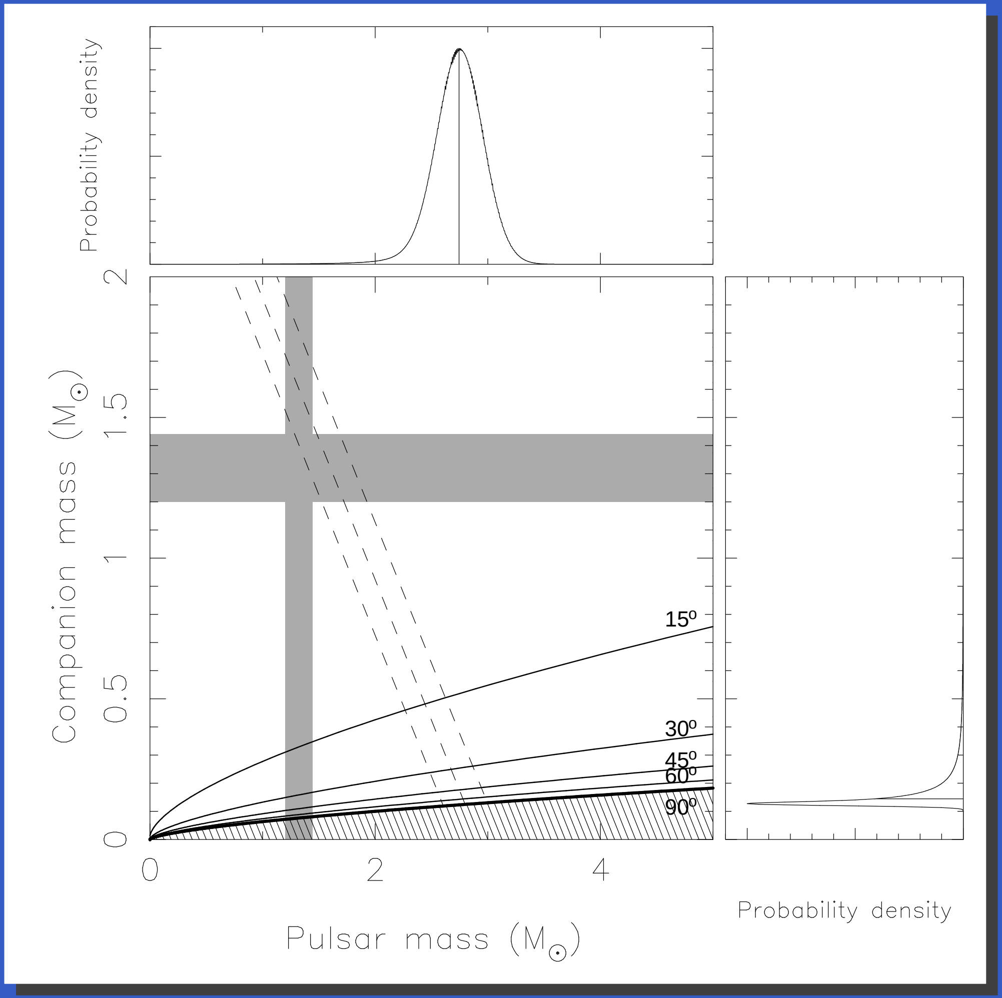
Masses of Pulsars (Stairs, 2006)



- 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)
- PSR J0751+1807 corrected from $M = 2.1 \pm 0.2 M_\odot$ to $M = 1.14 - 1.40 M_\odot$ (Nice et al. 2008)

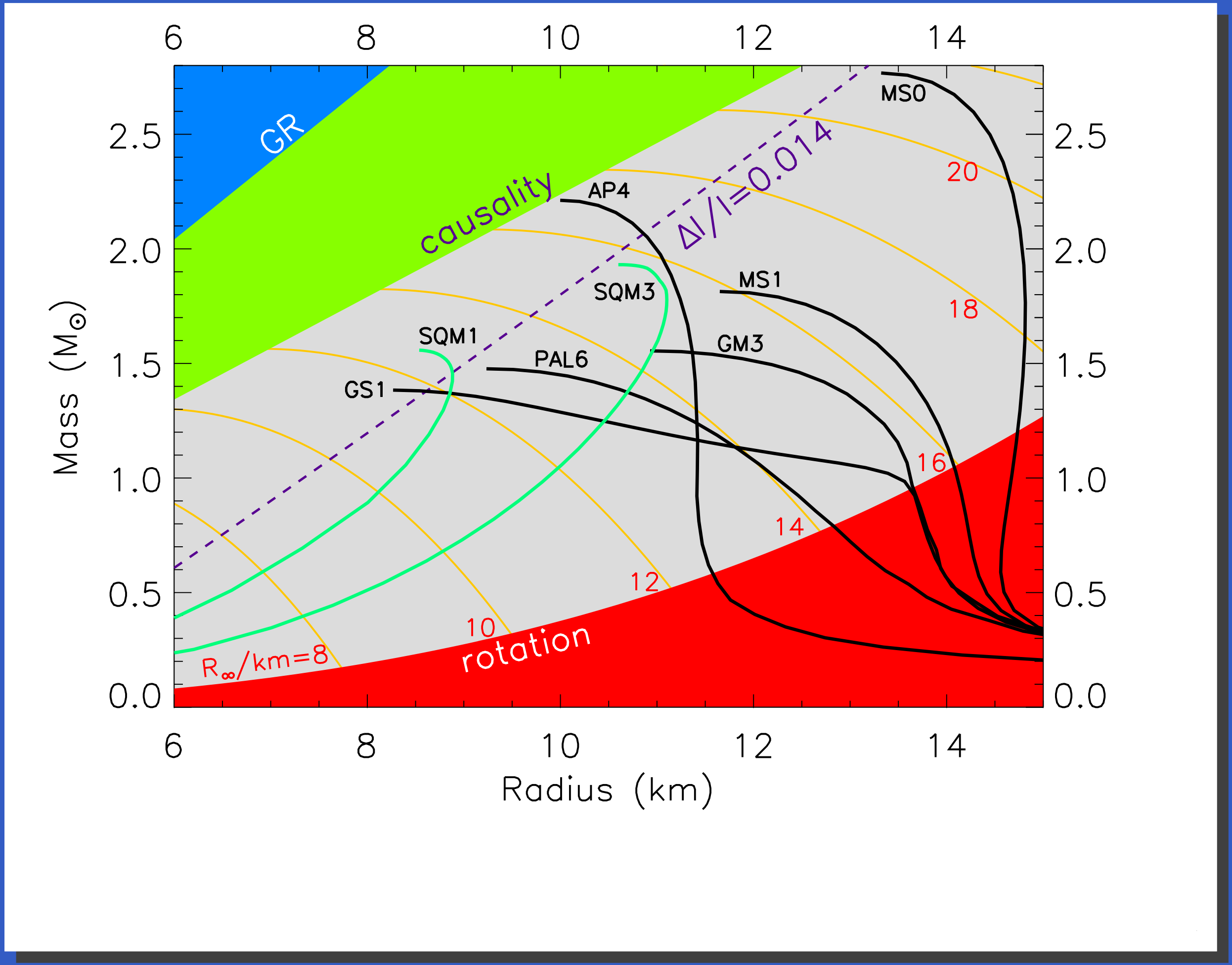
Supermassive Pulsar in Globular Cluster?

(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 $M \sim 1.4 M_\odot$ possible for $i = 4 - 5$ degrees
- measurement of a second GR effect needed to draw a firm conclusions! Beware! not a real measurement!
- mass would be at variance with heavy-ion data (Sagert et al. in preparation)

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



- spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4 M_\odot$
- observed giant glitch from Vela pulsar: moment of inertia changes by 1.4%
- Schwarzschild limit (GR): $R > 2GM = R_s$
- causality limit for EoS: $R > 3GM$

How To Measure Masses AND Radii of Compact Stars

- mass from binary systems (pulsar with a companion star)
- radius and mass from thermal emission, for a blackbody:

$$F_\infty = \frac{L_\infty}{4\pi d^2} = \sigma_{\rm SB} T^4_{\rm eff,\infty} \left(\frac{R_\infty}{d}\right)^2$$

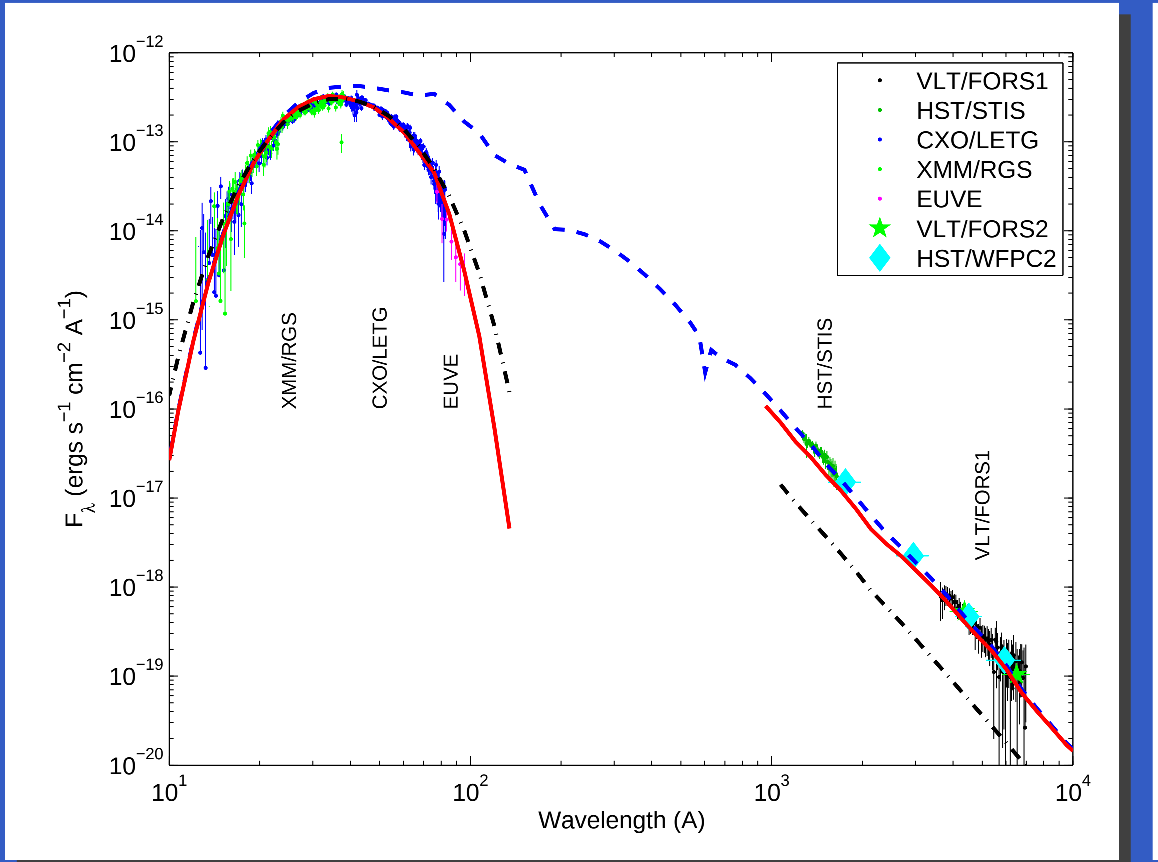
with $T_{\rm eff,\infty} = T_{\rm eff}/(1+z)$ and $R_\infty = R/(1+z)$

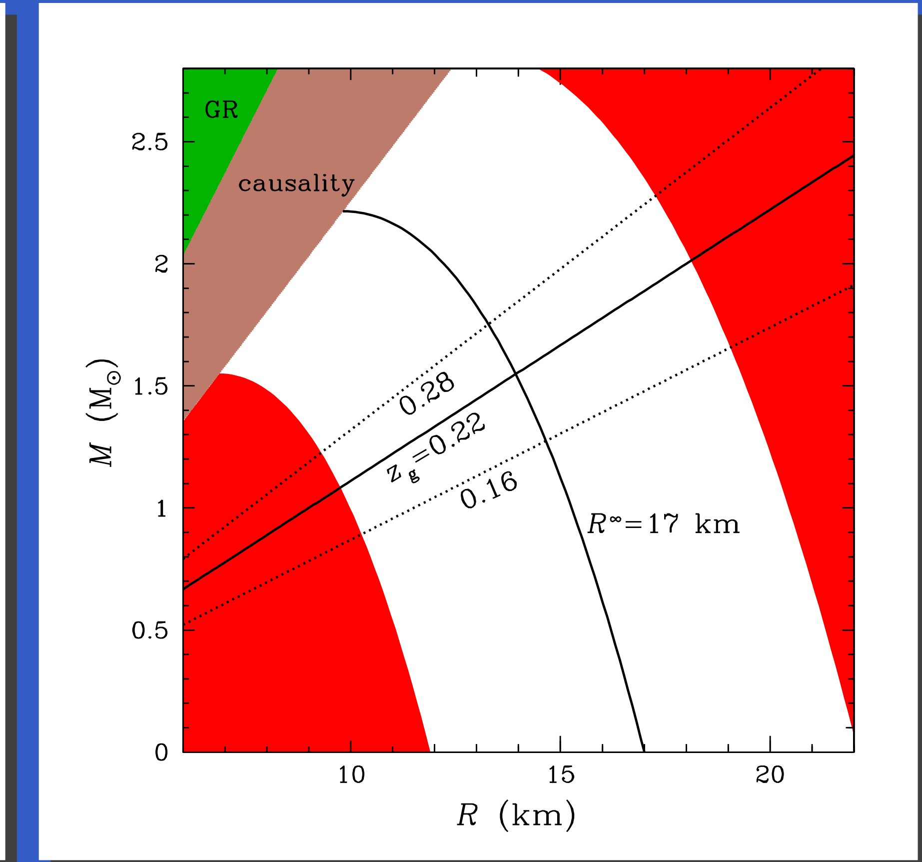
- redshift:

$$1 + z = \left(1 - \frac{2GM}{R}\right)^{-1/2}$$

- need to know distance and effective temperature to get R_∞
- radius measured depends on true mass and radius of the star
- additional constraint from redshift measurement from e.g. redshifted spectral lines fixes mass and radius uniquely

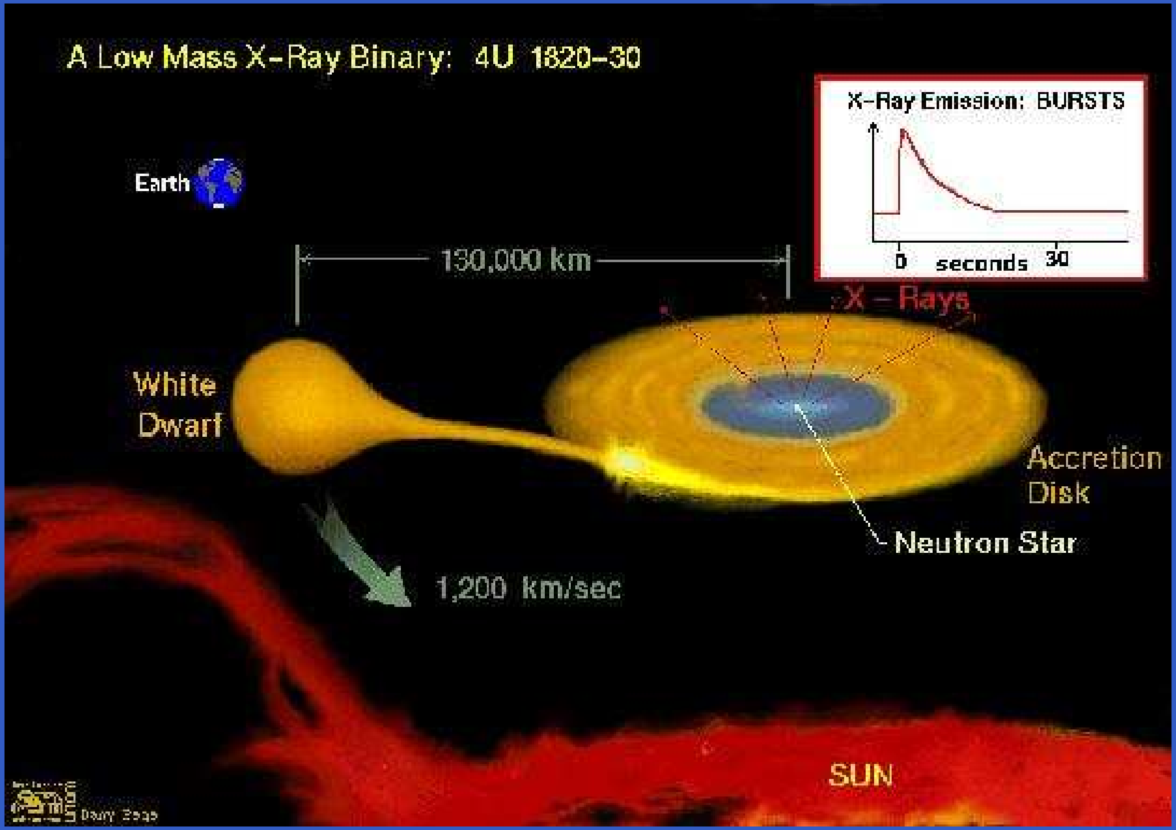
RXJ 1856: Neutron Star or Quark Star? (Trümper et al. (2003), Ho et al. (20

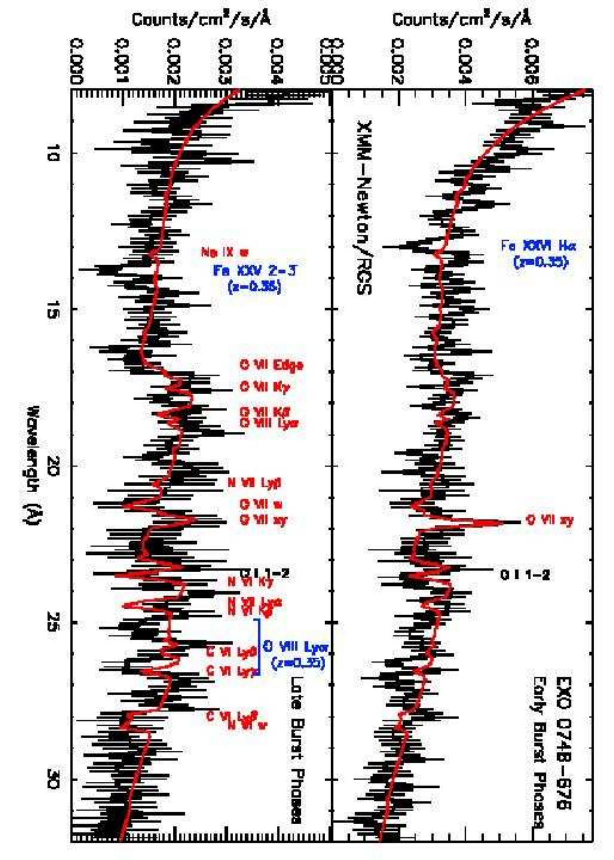




- two-component blackbody: small soft temperature, so as not to spoil the x-ray
- this implies a rather LARGE radius so that the optical flux is right!
- lower limit for radiation radius: $R_\infty = R/\sqrt{1-2GM/R} = 17$ km (d/140 pc)
- redshift $z_g \approx 0.22$: $R \approx 14$ km and $M \approx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

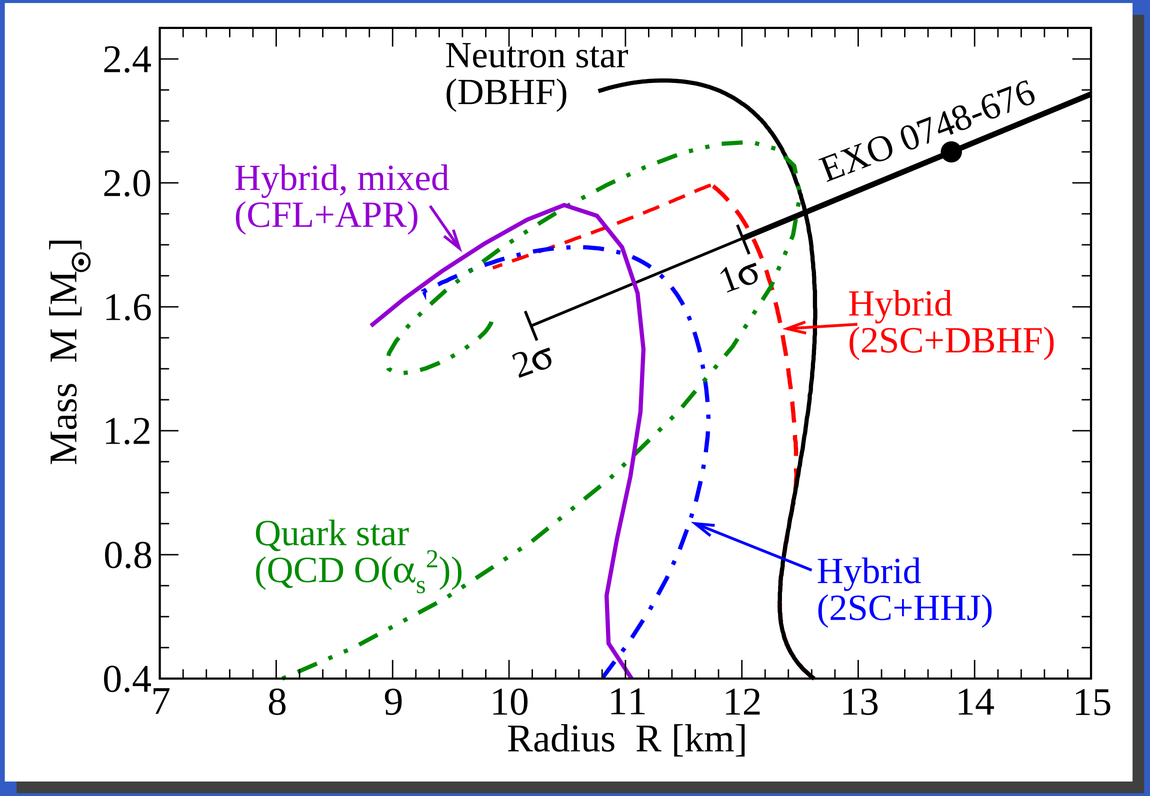
X-Ray burster





- binary systems of a neutron star with an ordinary star
- accreting material on the neutron star ignites nuclear burning
- explosion on the surface of the neutron star: x-ray burst
- red shifted spectral lines measured!
  ($z = 0.35 \rightarrow M/M_\odot = 1.5$ (R/10 km)) (Cottam, Paerels, Mendez (2002))

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

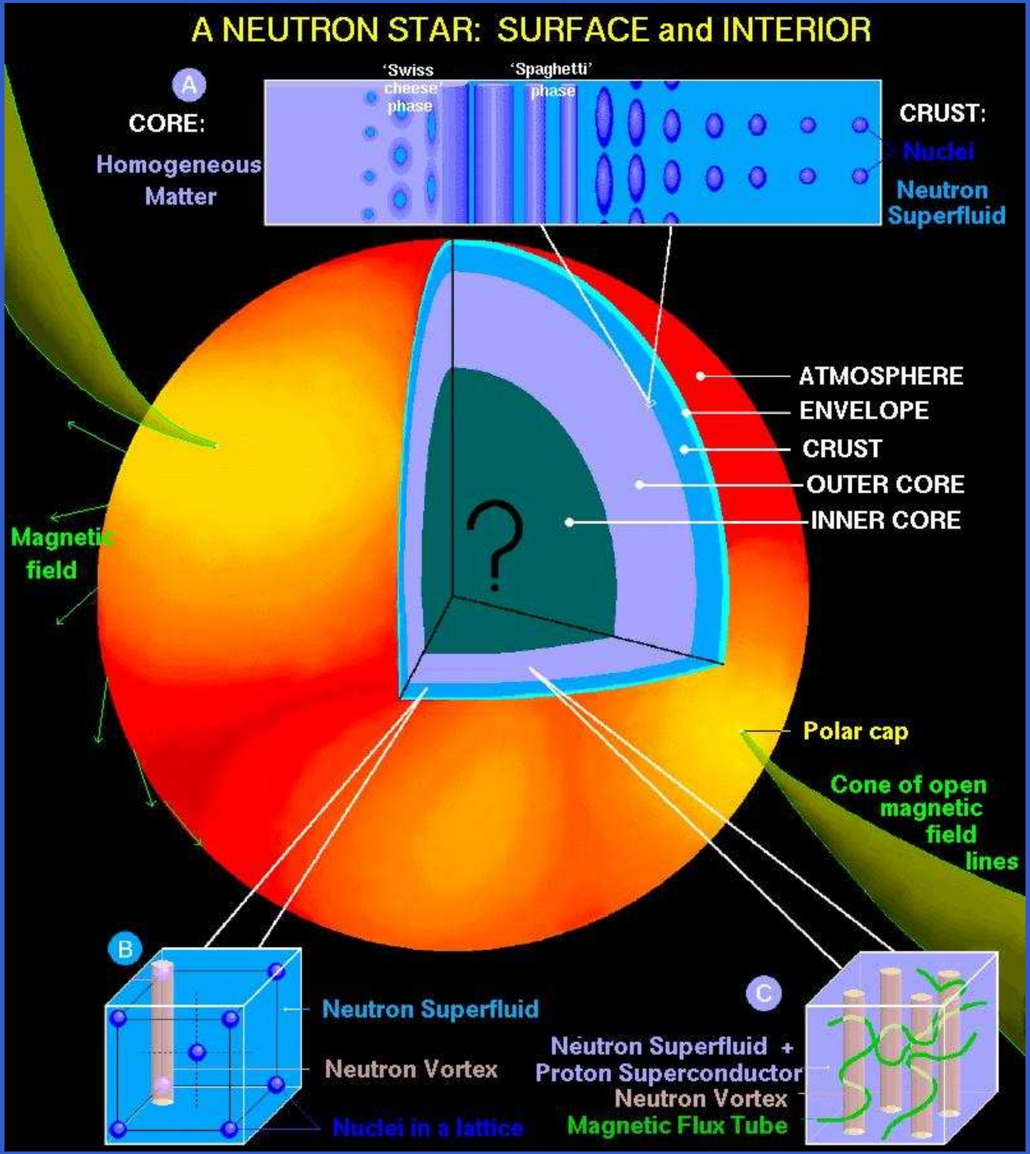


- analysis of Özel (Nature 2006): $M \geq 2.10 \pm 0.28 M_\odot$ and $R \geq 13.8 \pm 1.8$ km, claims: 'unconfined quarks do not exist at the center of neutron stars'!
- reply by Alford, Blaschke, Drago, Klähn, Pagliara, JSB (Nature 445, E7 (2007)): limits rule out soft equations of state, not quark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

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

Modelling the Neutron Star

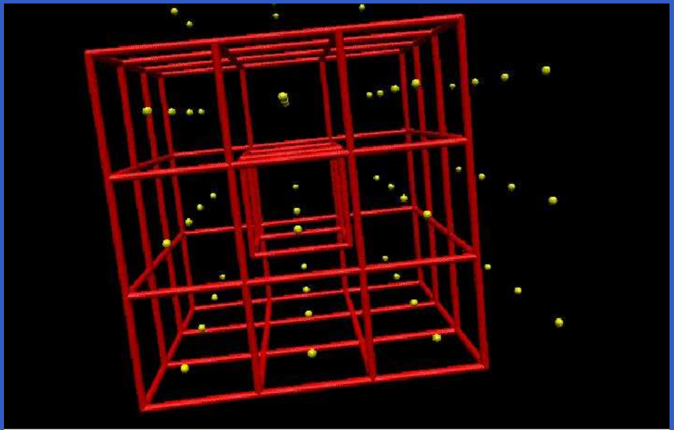
Structure of Neutron Stars — the Crust (Dany Page)



- $n \leq 10^4$ 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^-)

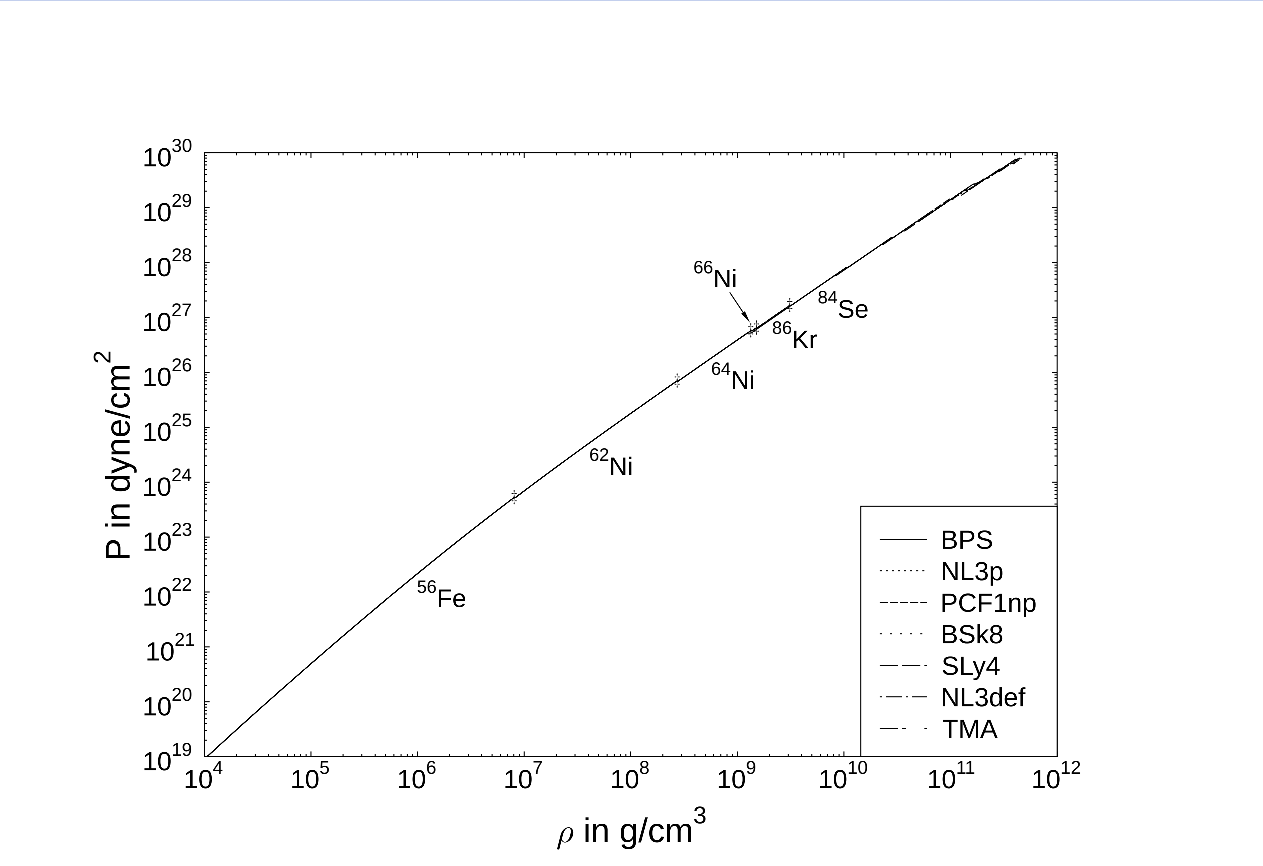
Composition of the crust of a neutron star

lattice of nuclei surrounded by free electrons



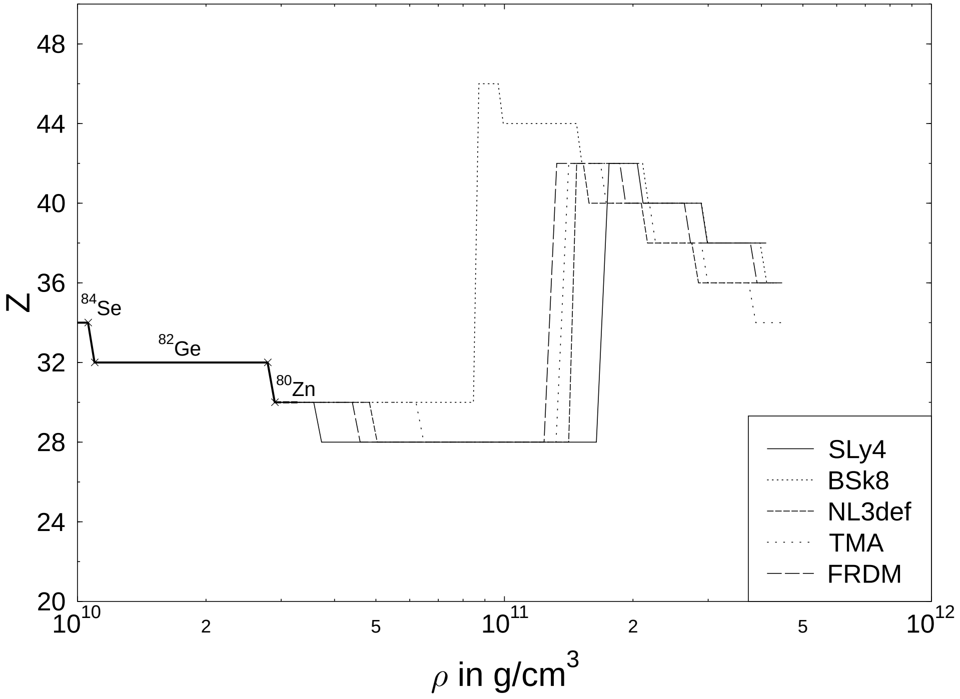
- Wigner–Seitz–cell, lattice structure is bcc
- minimize $E = E_{\mathrm{nuclei}} + E_{\mathrm{lattice}} + E_{\mathrm{electrons}}$
- loop over all particle stable nuclei (up to 14.000)
- use atomic mass evaluation of 2003 by Audi, Wapstra, and Thibault
- extrapolate to the drip–line with various models
- $\Longrightarrow$ sequence of nuclei ${}^{A}Z$ as a function of density

Sequence to the Dripline (Hempel, Rüster, JSB 2005)



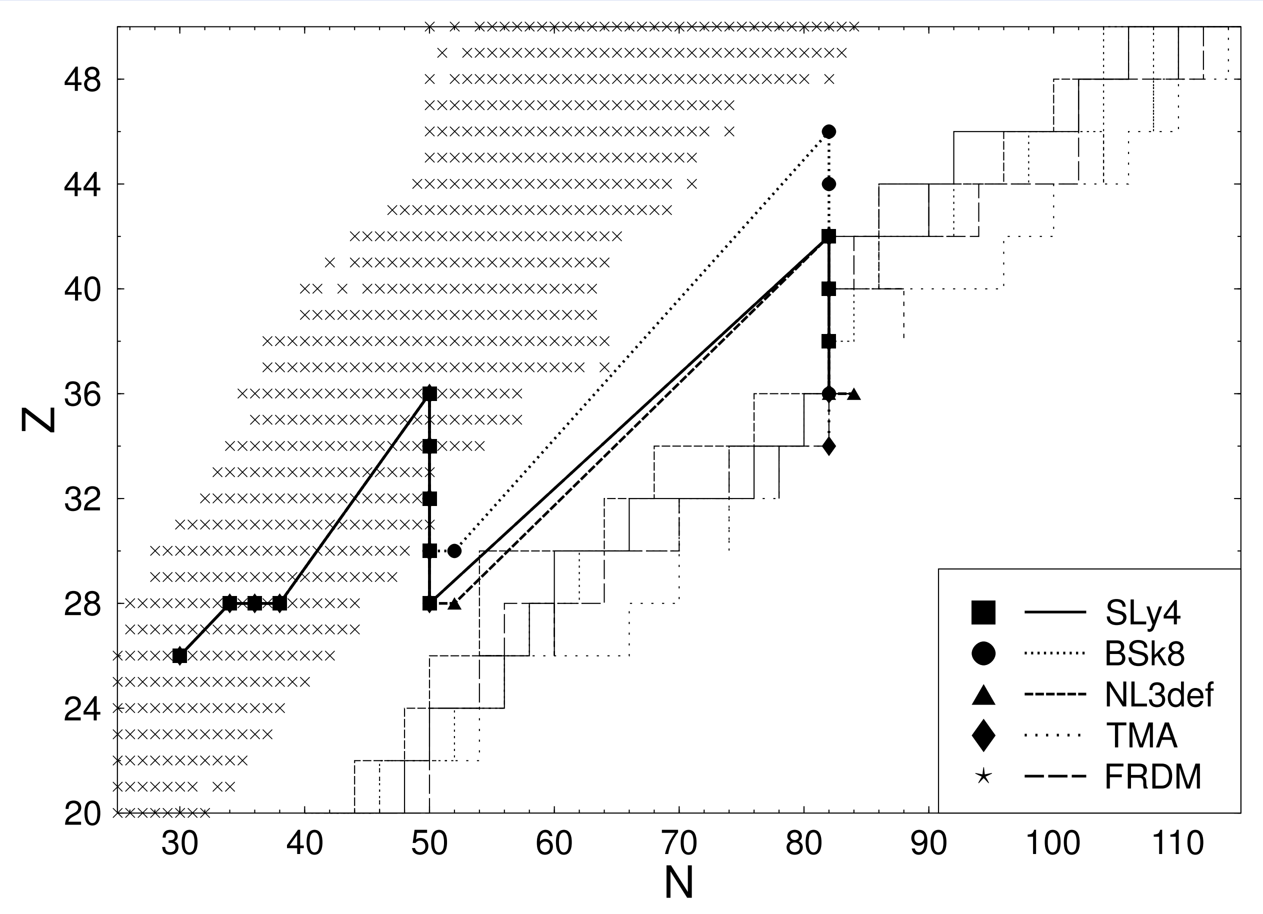
- outer crust starts with iron (^{56}Fe) up to $\rho \approx 10^7$ g/cm^3
- continues along nickel isotopes ($Z = 28$), then Kr, Se ($N = 50$)
- initial sequence at low densities independent of parameter set (data)!
- equation of state (nearly) independent of parameter set!

Sequence to the Dripline II (Hempel, Rüster, JSB 2005)



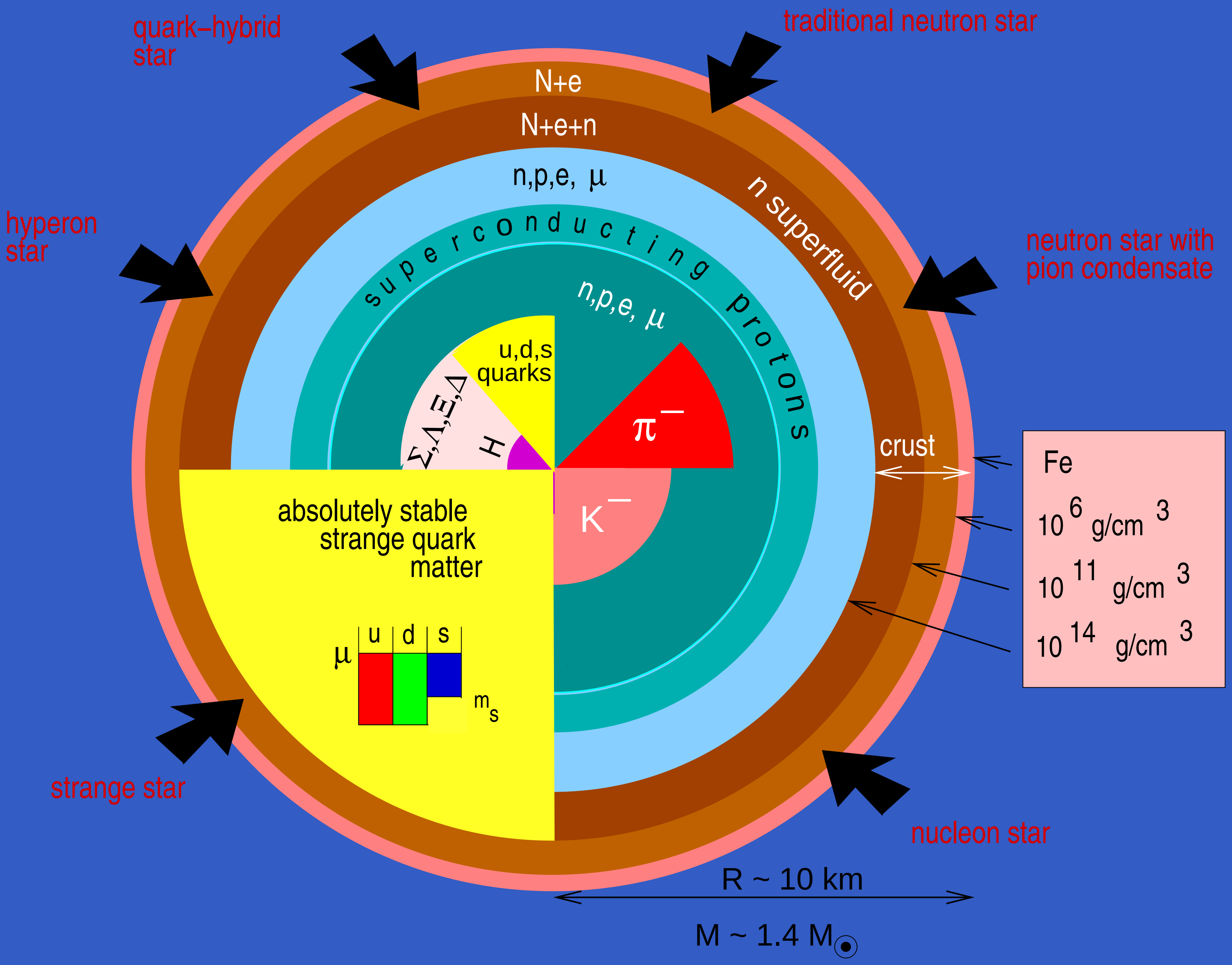
- selection of state-of-the-art mass tables (deformed calculations)
- initial sequence of nuclei: Se, Ge, Zn (data)
- overall narrow range in Z
- neutron drip around $5 \cdot 10^{11}$ g/cm^3

Nuclei in the crust (Hempel, Rüster, JSB 2005)



- sequence of nuclei: along $N = 50$ then along $N = 82$ with $Z = 46 - 34$
- common endpoint around $N = 82$ and $Z = 36$ (!)
- common location of the dripline at N$= 82$ (!)
- updates classic work of Baym, Pethick, Sutherland from 1971!

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



Neutron Star Matter for a Free Gas

(Ambartsumyan and Saakyan, 1960)

Hadron	p,n	Σ^-	Λ	others
appears at:	$\ll n_0$	$4n_0$	$8n_0$	$> 20n_0$

but the corresponding equation of state results in a maximum mass of only

$$M_{\rm max} \approx 0.7 M_\odot < 1.44 M_\odot$$

(Oppenheimer and Volkoff, 1939)

$\Longrightarrow$ effects from strong interactions are essential to describe neutron stars!

Baryon–Baryon Interactions

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

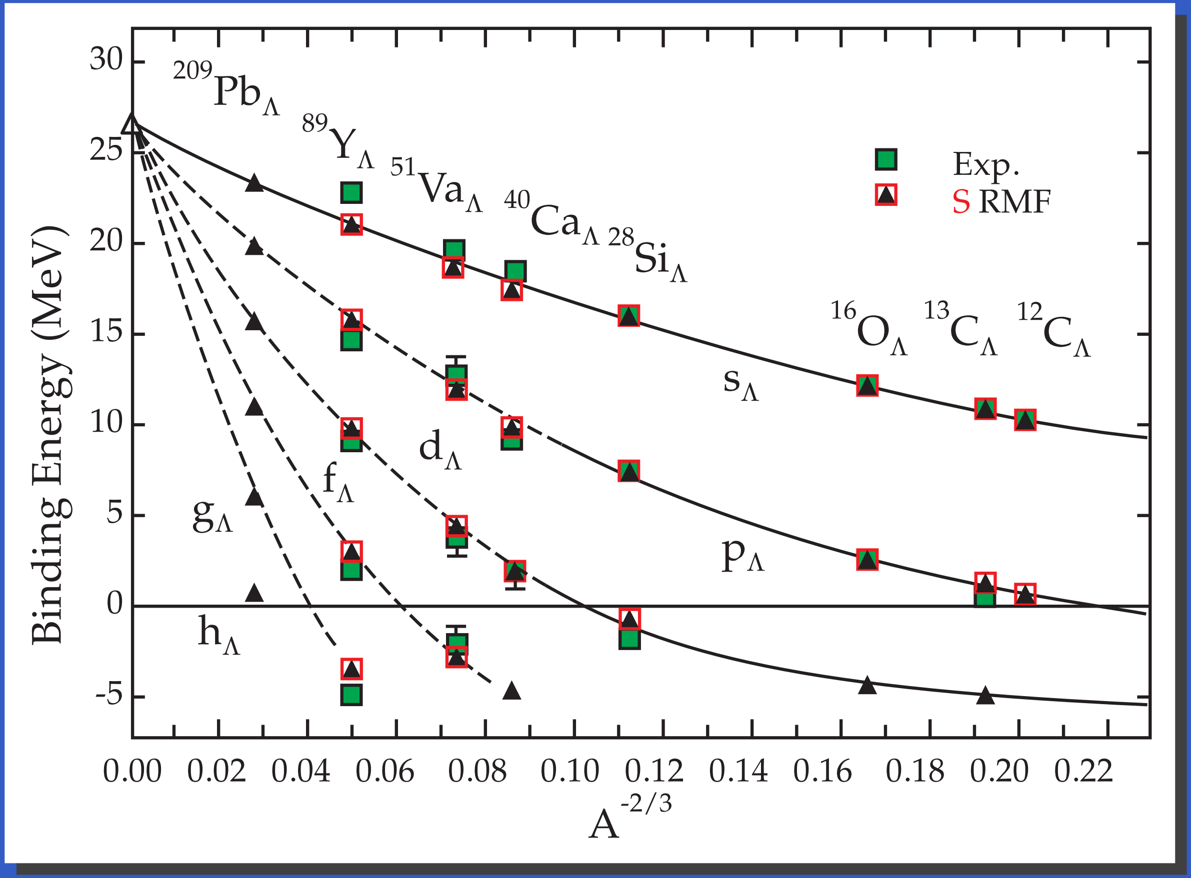
NΣ: ${}^4_\Sigma$He hypernucleus bound by isospin forces
Σ^- atoms: potential is repulsive

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 $\rightarrow$ 5 $\Lambda\Lambda$ hypernuclear measurements
more attractive than NΛ?

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

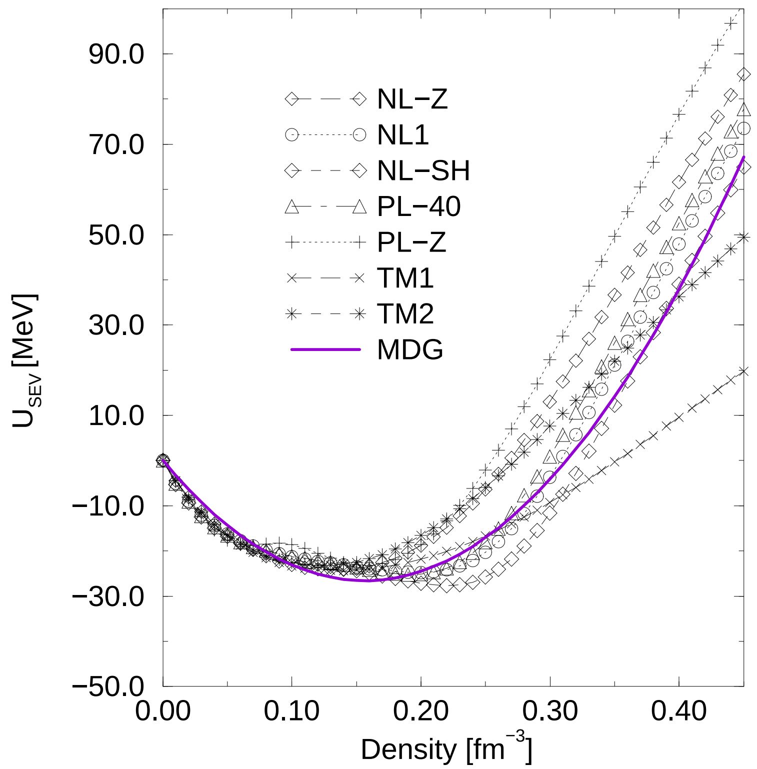
Λ Single–Particle Energies



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

- measured in (π^+, K^+) reactions
- spin–orbit splitting smaller than experimental resolution
- fit to single particle energies: $U_\Lambda = -27$ MeV for $A \to \infty$

Λ potential in nuclear matter (JSB, Bondorf, Mishustin 1997)



- hyperon potential in various (relativistic) parameterizations
- hyperon potential becomes repulsive above $2n_0$
- compatible with hypernuclear data, three-body interactions for hyperons (MDG: Millener, Dover, Gal 1988)

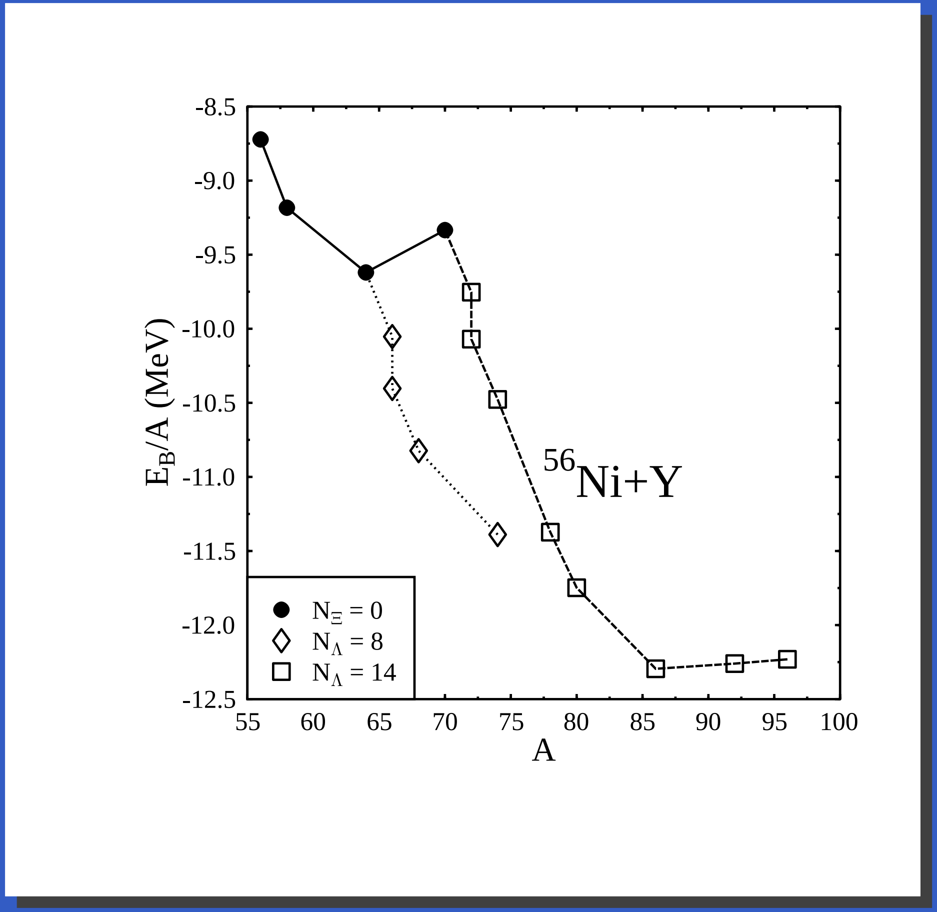
$\Lambda\Lambda$ Hypernuclei

two Λs bound in a nucleus, produced by Ξ^- capture

1963 Danysz et al.:	${}^{10}_{\Lambda\Lambda}\mathrm{Be}\longrightarrow{}^{9}_{\Lambda}\mathrm{Be}+\mathrm{p}+\pi^-$
1966 Prowse:	${}^{6}_{\Lambda\Lambda}\mathrm{He}\longrightarrow{}^{5}_{\Lambda}\mathrm{He}+\mathrm{p}+\pi^-$
1991 Aoki et al.:	${}^{13}_{\Lambda\Lambda}\mathrm{B}\longrightarrow{}^{13}_{\Lambda}\mathrm{C}+\pi^-$
2001 E373 (KEK):	${}^{6}_{\Lambda\Lambda}\mathrm{He}\longrightarrow{}^{5}_{\Lambda}\mathrm{He}+\mathrm{p}+\pi^-$
2001 E906 (BNL):	${}^{4}_{\Lambda\Lambda}\mathrm{H}\longrightarrow{}^{4}_{\Lambda}\mathrm{He}+\pi^-$ (≈ 400 events!)

- $\Lambda\Lambda$ interaction is attractive
- no strong decay to the H-dibaryon seen
  $\Lambda+\Lambda\rightarrow H \leadsto m_H > 2m_\Lambda - B_{\Lambda\Lambda} \sim 2220$ MeV

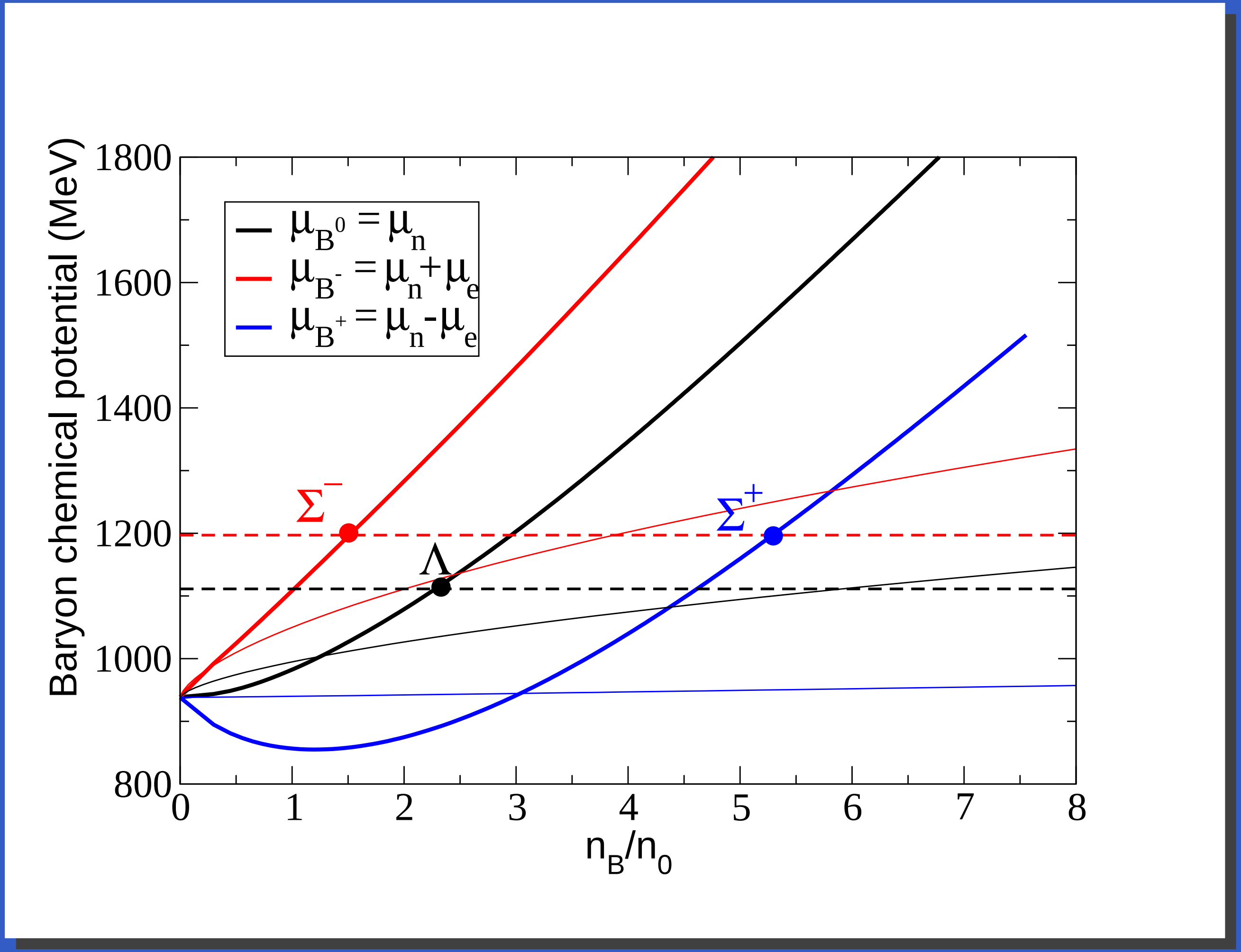
Systems of Nucleons and Hyperons



(JS, Dover, Gal, Greiner, Stöcker (1993))

- Pauli–blocking of the reactions: $\Lambda + \Lambda \leftrightarrow \Xi + N$, $Q \approx -25$ MeV
- Σs are not stable: $\Sigma + N \rightarrow \Lambda + N$, $Q \approx -80$ MeV
- nuclear binding energy with Λs and Ξs increases to $E/A = -12$ MeV!

At which density do new particles appear? (Page and Reddy (2006))



- hyperons appear, when its in-medium energy equals its chemical potential:

$$\mu(Y) = \omega(Y) = m_Y + U_Y(n)$$

- thin lines: no potential, thick lines: with mean-field potential

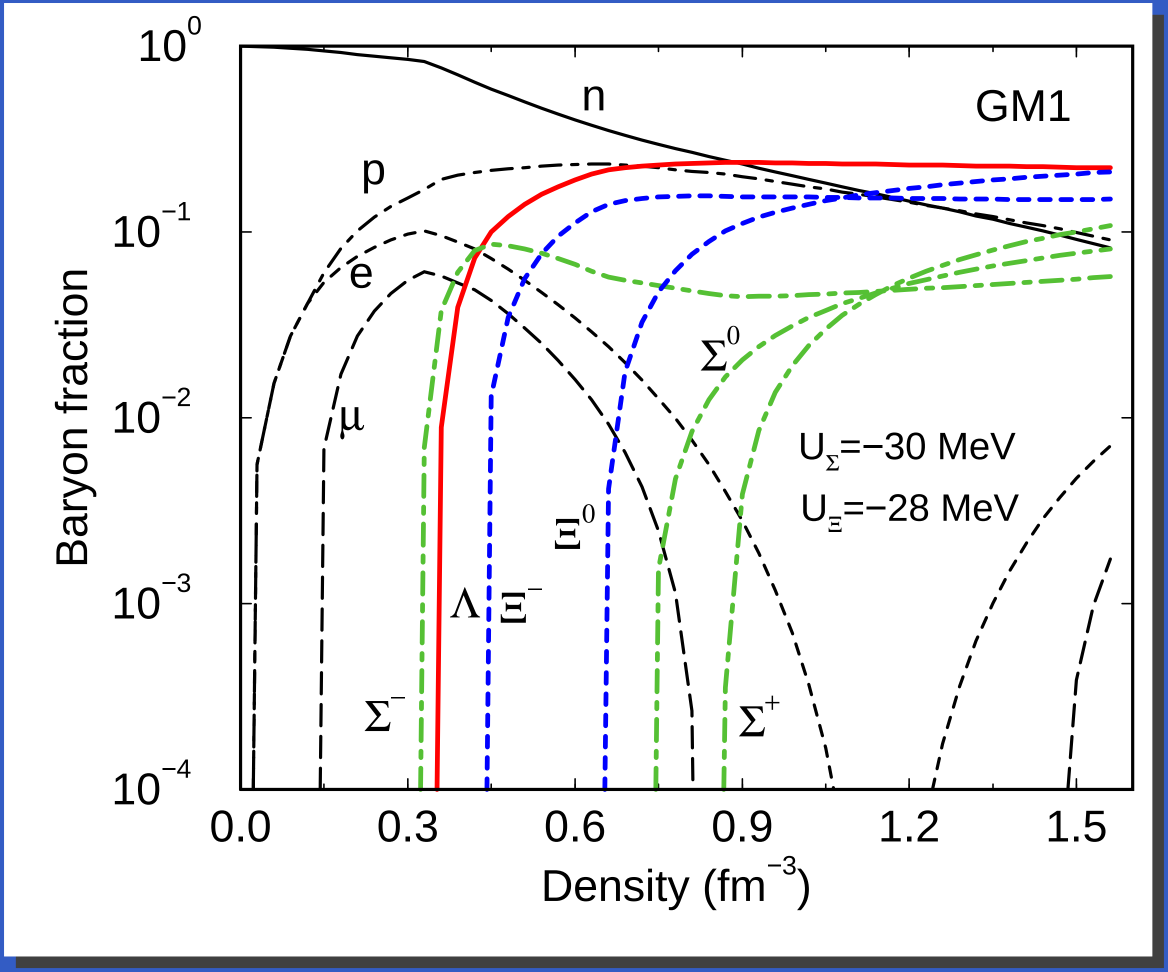
Neutron Star Matter and Hyperons

Hyperons appear at $n \approx 2n_0$!

- nonrelativistic potential model (Balberg and Gal, 1997)
- quark-meson coupling model (Pal et al., 1999)
- relativistic mean–field models (Glendenning, 1985; Knorren, Prakash, Ellis, 1995; JS and Mishustin, 1996)
- relativistic Hartree–Fock (Huber, Weber, Weigel, Schaab, 1998)
- Brueckner–Hartree–Fock (Baldo, Burgio, Schulze, 2000; Vidana et al., 2000)
- chiral effective Lagrangian's (Hanauske et al., 2000)
- density-dependent hadron field theory (Hofmann, Keil, Lenske, 2001)
- RG approach alias V_{lowk} (Djapo, Schäfer, Wambach, 2008)

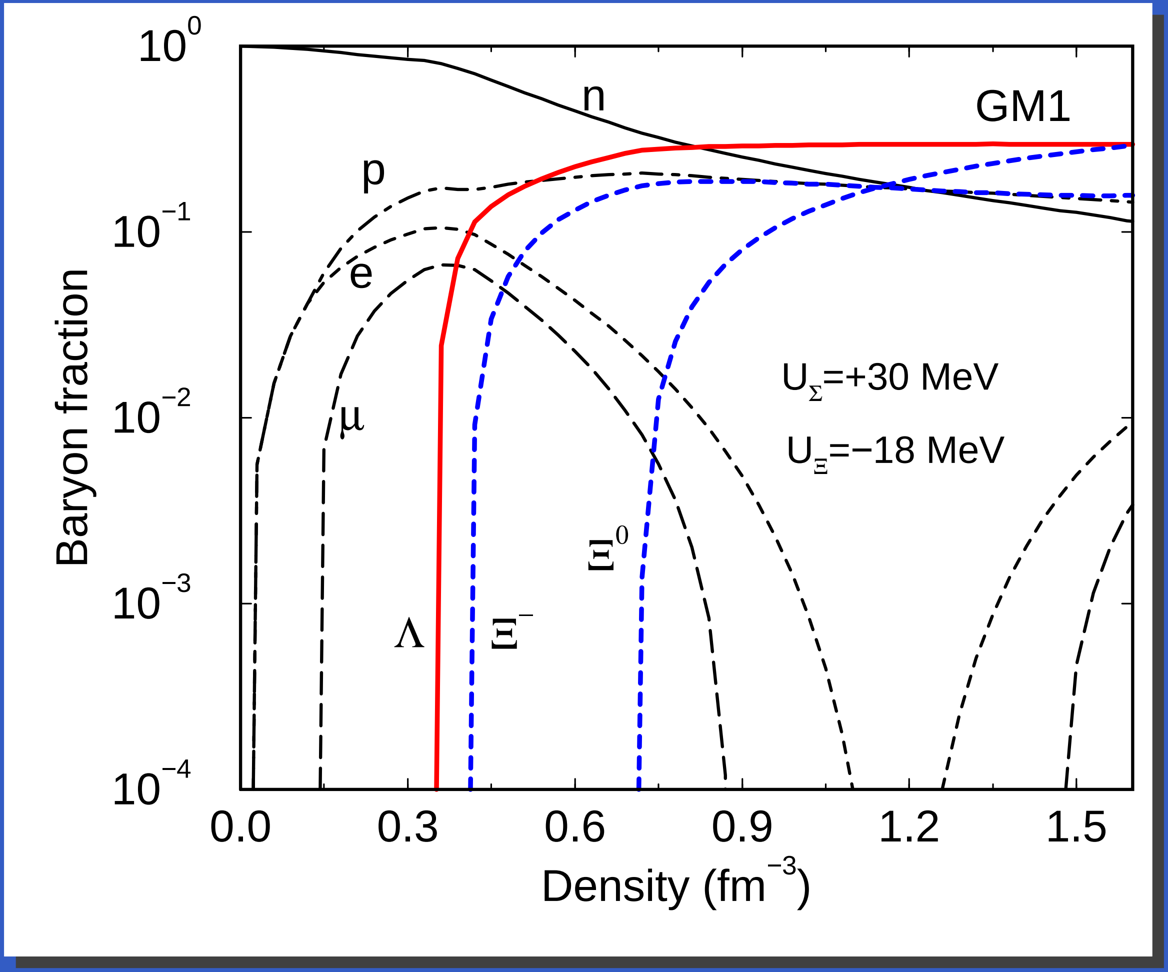
$\Rightarrow$ neutron stars are strange !!!

Composition of Neutron Star Matter



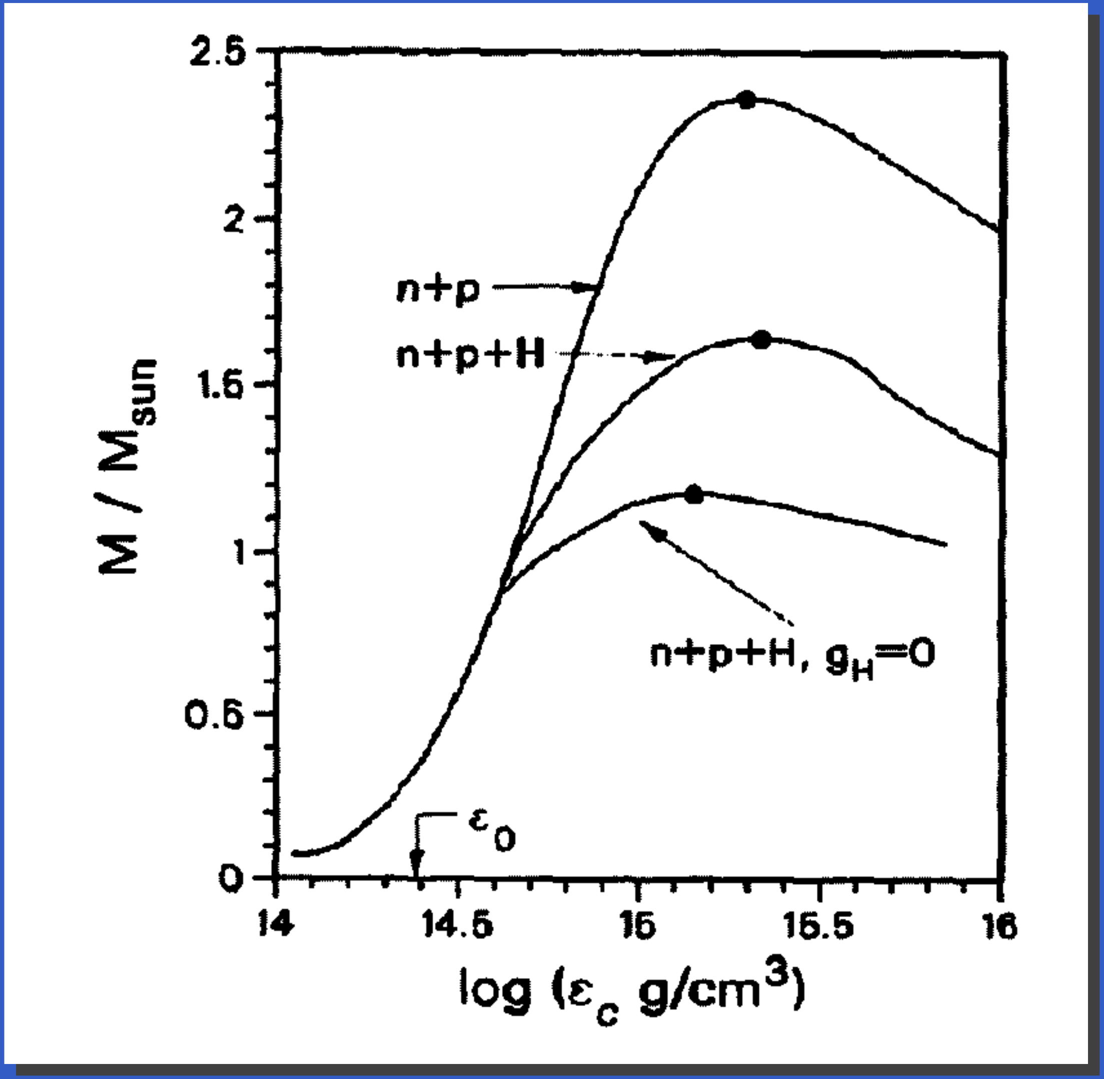
- attractive potential for Σs and Ξs
- Σ^- appear shortly before Λs around $n = 2n_0$
- Λs present in matter at $n = 2.5n_0$, Ξ^- before $n = 3n_0$

Composition of Neutron Star Matter



- Λs are present close to $n = 2n_0$
- repulsive potential for Σs: Σ hyperons do not appear at all!
- population is highly sensitive to the in-medium potential!

Impact of hyperons on the maximum mass of neutron stars



(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: $M < 1.4 M_\odot$!

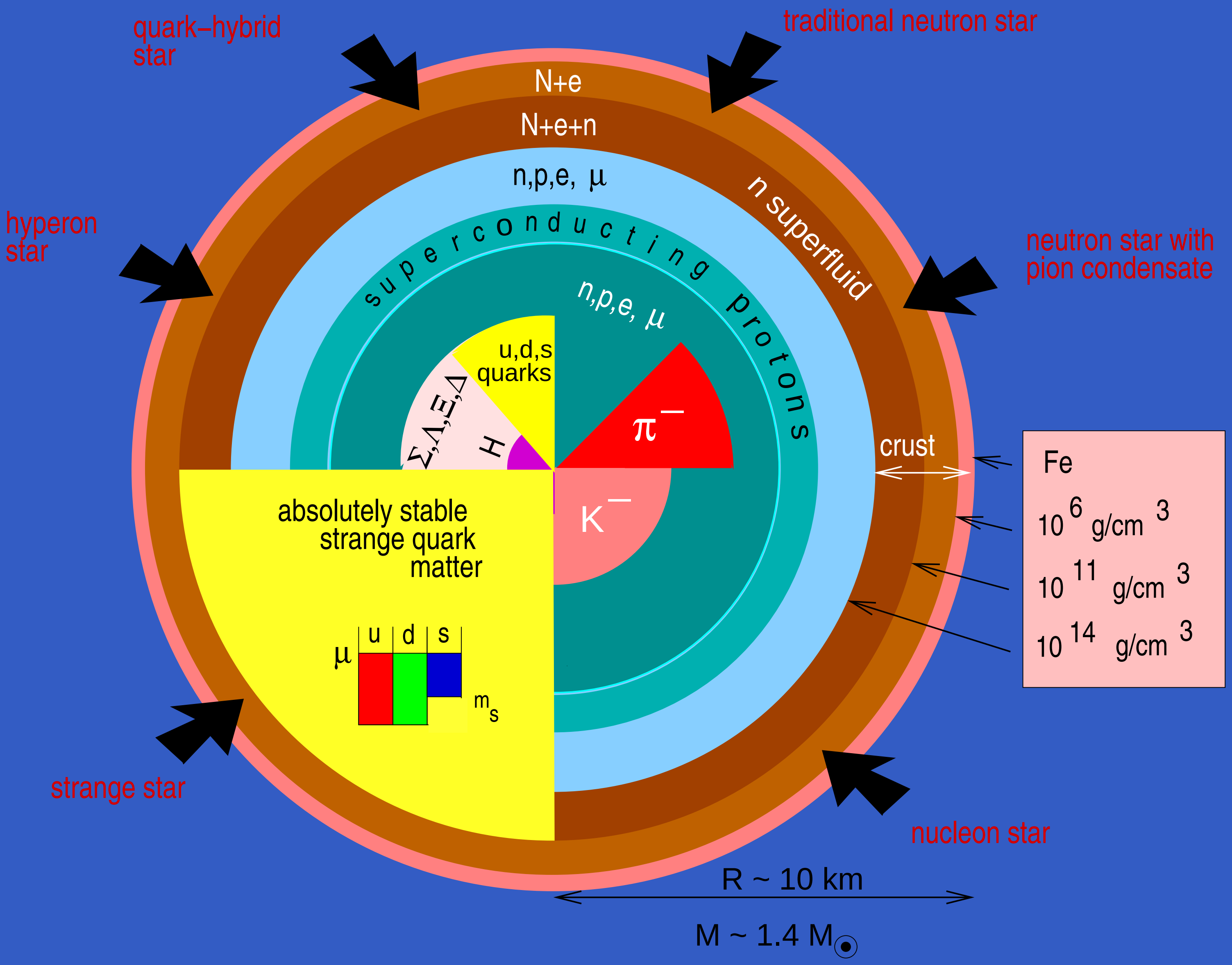
Modern many-body approaches to neutron stars

beyond mean-field . . .

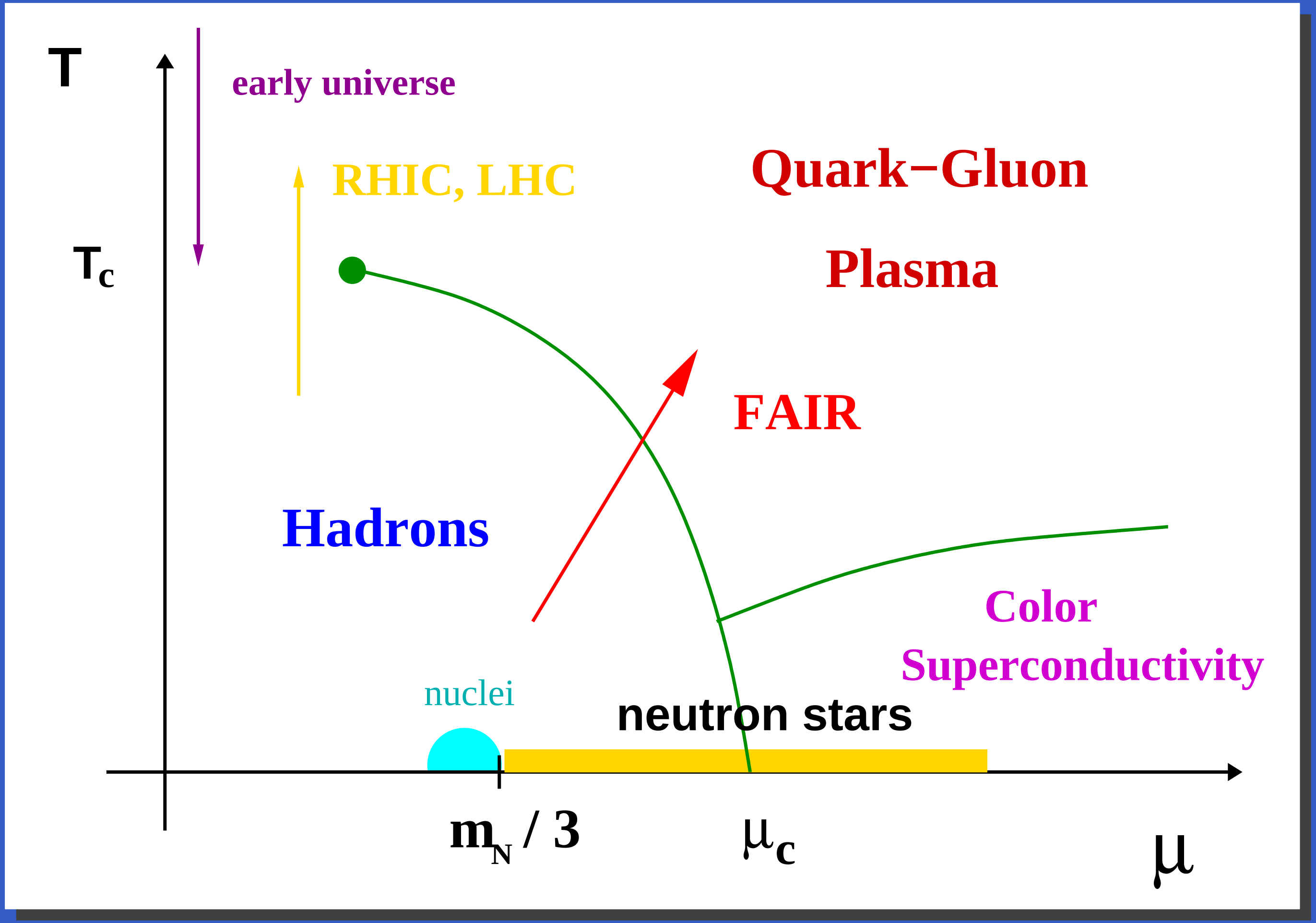
- Relativistic Hartree-Fock (Huber et al. 1998): $M_{\max} = 1.3 - 1.6 M_\odot$ depending on hyperon coupling strength
- Brueckner-Hartree-Fock: using Nijmegen soft-core YN potential
- Vidana et al. (2000): $M_{\max} = 1.47 M_\odot$ (NN and YN interactions), $M_{\max} = 1.34 M_\odot$ (NN, NY, YY interactions)
- Baldo et al. (2000): $M_{\max} = 1.26 M_\odot$ including three-body forces
- Djapo, Schäfer, Wambach (2008): $M_{\max} = 0.8$–$1.3 M_\odot$ (RG approach)
- too soft EoS, too low masses!
- three-body force for hyperons? momentum dependence? typically $p = 300 - 600$ MeV

Quark Matter in Neutron Stars

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

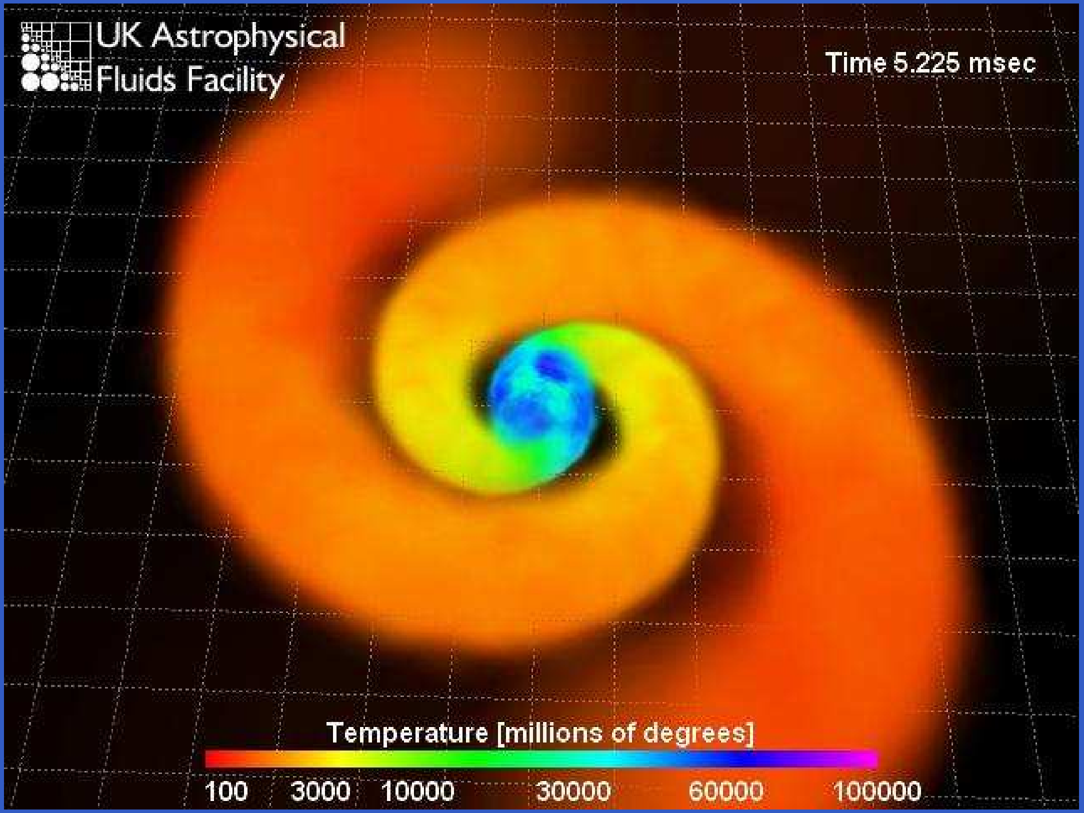


Phase Transitions in Quantum Chromodynamics QCD



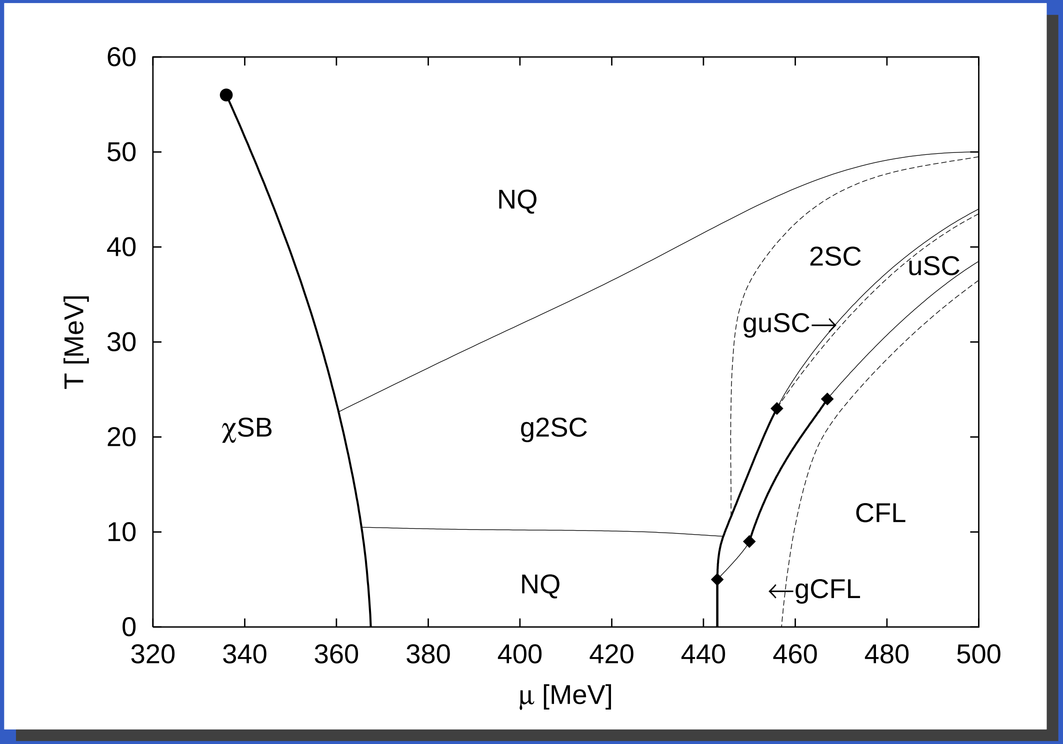
- Early universe at zero density and high temperature
- neutron star matter at small temperature and high density
- first order phase transition at high density (not deconfinement)!
- probed by heavy-ion collisions at GSI, Darmstadt (FAIR!)

Nuclear EoS in Astrophysics



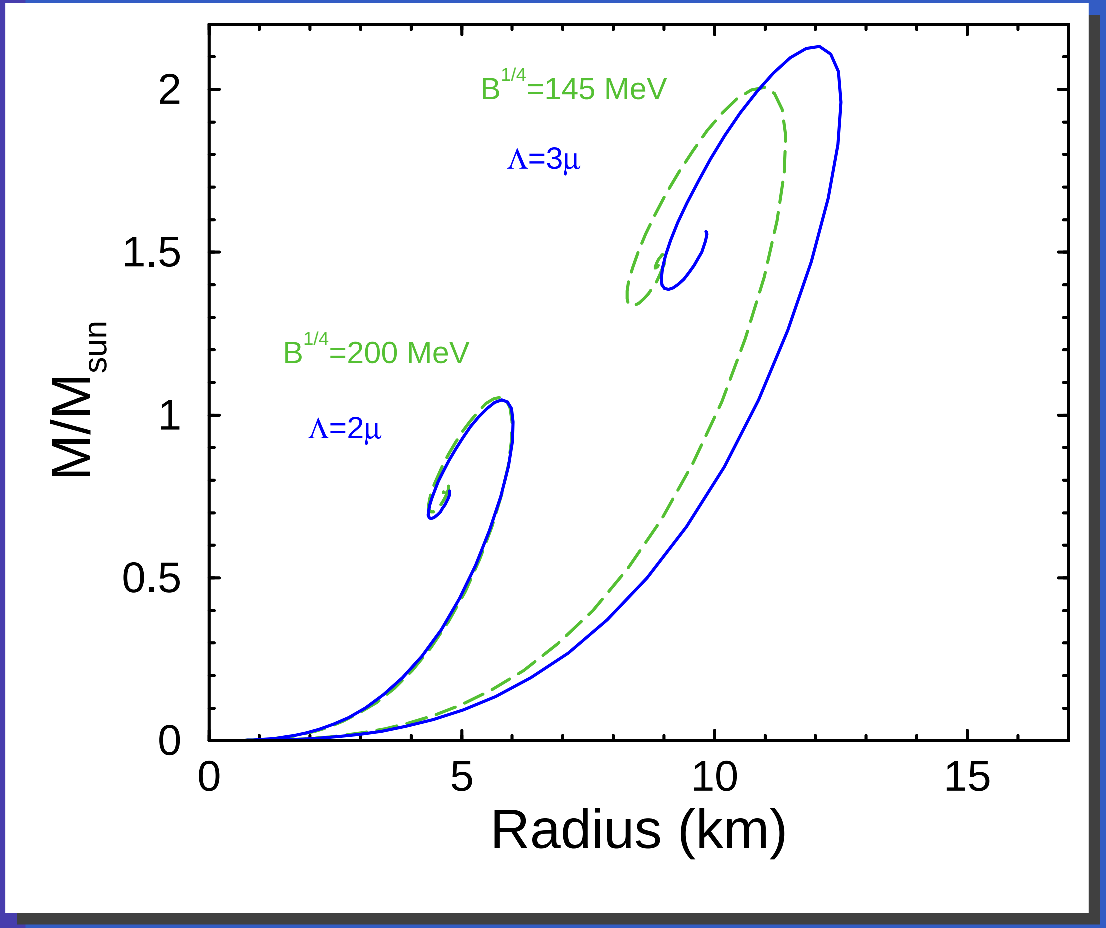
- supernovae simulations: $T = 1$–50 MeV, $n = 10^{-10}$–$2n_0$
- proto-neutron star: $T = 1$–50 MeV, $n = 10^{-3}$–$10n_0$
- global properties of neutron stars: $T = 0$, $n = 10^{-3}$–$10n_0$
- neutron star mergers: $T = 0$–100 MeV, $n = 10^{-10}$–$10n_0$

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, . . .)

Mass-radius and maximum density of pure quark stars



- green curves: MIT bag model
- blue curves: perturbative QCD calculations (Fraga, JSB, Pisarski 2001)

- case $\Lambda = 2\mu$: $M_{\rm max} = 1.05\, M_\odot$, $R_{\rm max} = 5.8$ km, $n_{\rm max} = 15\, n_0$
- case $\Lambda = 3\mu$: $M_{\rm max} = 2.14\, M_\odot$, $R_{\rm max} = 12$ km, $n_{\rm max} = 5.1\, n_0$
- other nonperturbative approaches: Schwinger–Dyson model (Blaschke et al.), massive quasiparticles (Peshier, Kämpfer, Soff), NJL model (Hanauske et al.), HDL (Andersen and Strickland), . . .

A Simple Model of Dense QCD

- star made of a gas of u, d and s quarks
- interaction taken into account perturbatively up to α_s^2 ; $\alpha_s = g^2/4\pi$
- α_s runs according to the renormalization group equation ($u = \ln(\bar{\Lambda}^2/\Lambda^2_{\overline{\text{MS}}})$):

$$\alpha_s(\bar{\Lambda}) = \frac{4\pi}{\beta_0 u}\left[1 - \frac{2\beta_1}{\beta_0^2}\frac{\ln(u)}{u} + \frac{4\beta_1^2}{\beta_0^4 u^2}\left(\left(\ln(u) - \frac{1}{2}\right)^2 + \frac{\beta_2\beta_0}{8\beta_1^2} - \frac{5}{4}\right)\right]$$

- Particle Data Group: $\alpha_s(2\text{ GeV}) = 0.3089 \longrightarrow \Lambda_{\overline{\text{MS}}} = 365$ MeV for $N_f = 3$
- No bag constant is introduced!
- star temperature $\ll$ typical chemical potentials $\longrightarrow$ zero temperature
- $m_s = 100$ MeV $\ll \mu_{\text{min}} = m_N/3 \longrightarrow$ three flavor massless quarks
- charge neutrality and β equilibrium: $\mu_s = \mu_d = \mu_u \equiv \mu$

Equation of State in pQCD

The thermodynamic potential (Freedman and McLerran (1978))

$$\Omega(\mu) = -\frac{N_f\mu^4}{4\pi^2}\left\{1 - 2\left(\frac{\alpha_s}{\pi}\right)\right.$$

$$\left. - \left[G + N_f \ln\frac{\alpha_s}{\pi} + \left(11 - \frac{2}{3}N_f\right)\ln\frac{\bar{\Lambda}}{\mu}\right]\left(\frac{\alpha_s}{\pi}\right)^2\right\}$$

G is scheme dependent and in $\overline{\mathrm{MS}}$ scheme:

$G = G_0 - 0.536N_f + N_f \ln N_f$, $G_0 = 10.73 \pm 0.13$

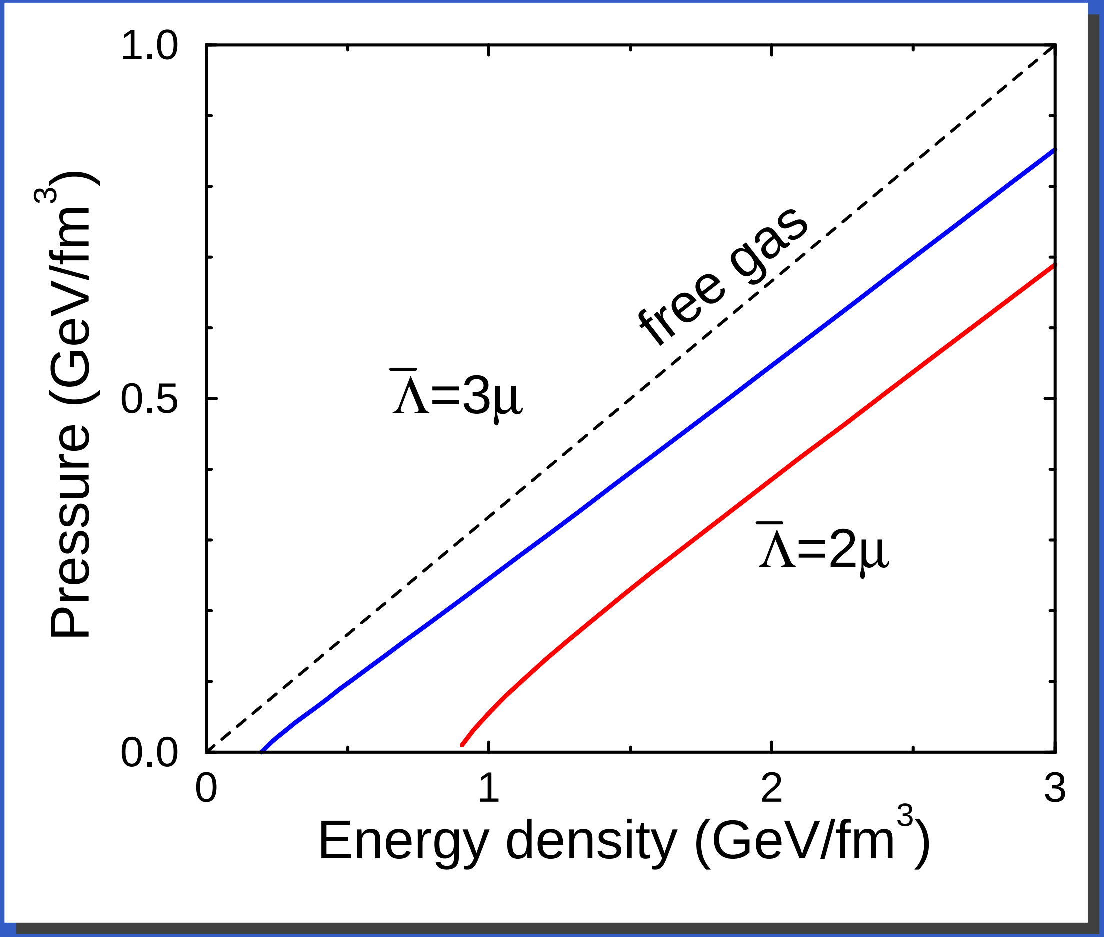
From $\Omega(\mu)$ we have

pressure: $p(\mu) = -\Omega(\mu)$

number density: $n(\mu) = (\partial p/\partial\mu)$

energy density: $\epsilon = -p + \mu n$

Equation of State in pQCD



Nearly linear behavior of the pressure with the energy density

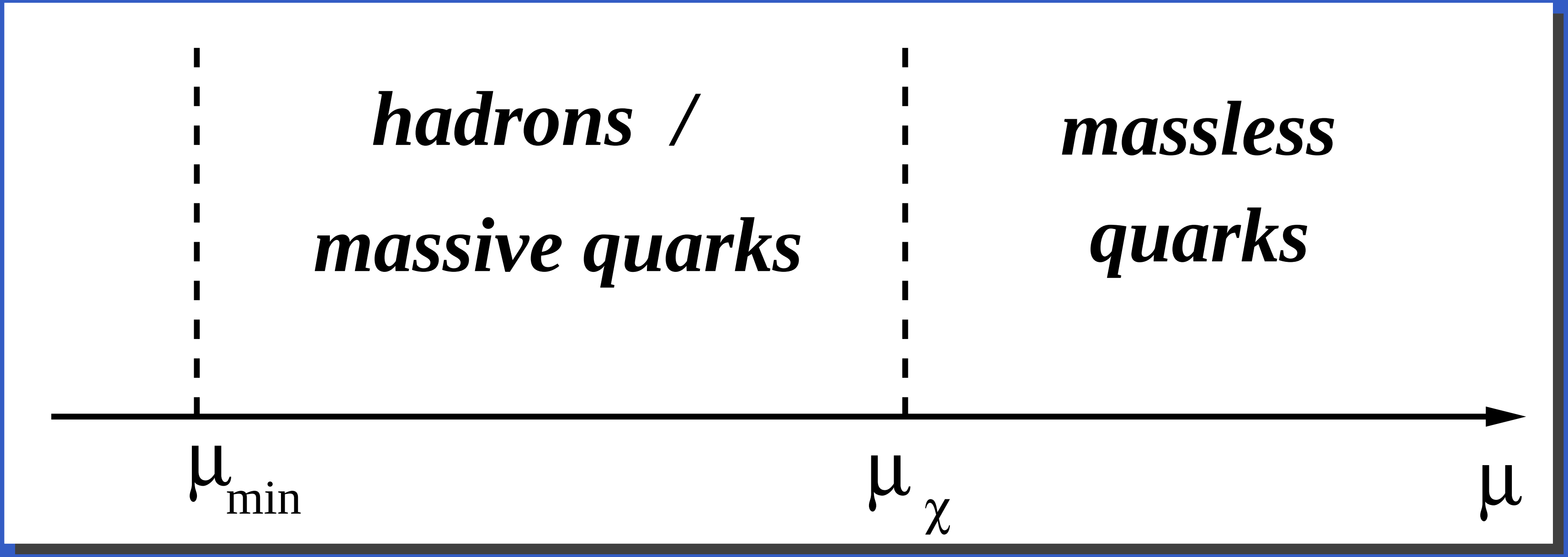
⇒ approximation with an effective nonideal bag model:

$\Omega(\mu) = -\frac{N_f}{4\pi^2}\, a_{\text{eff}}\, \mu^4 + B_{\text{eff}}$

case 2: $B_{\text{eff}}^{1/4} = 199$ MeV, $a_{\text{eff}} = 0.628$ (≤ 4%)

case 3: $B_{\text{eff}}^{1/4} = 140$ MeV, $a_{\text{eff}} = 0.626$ (≤ 2%)

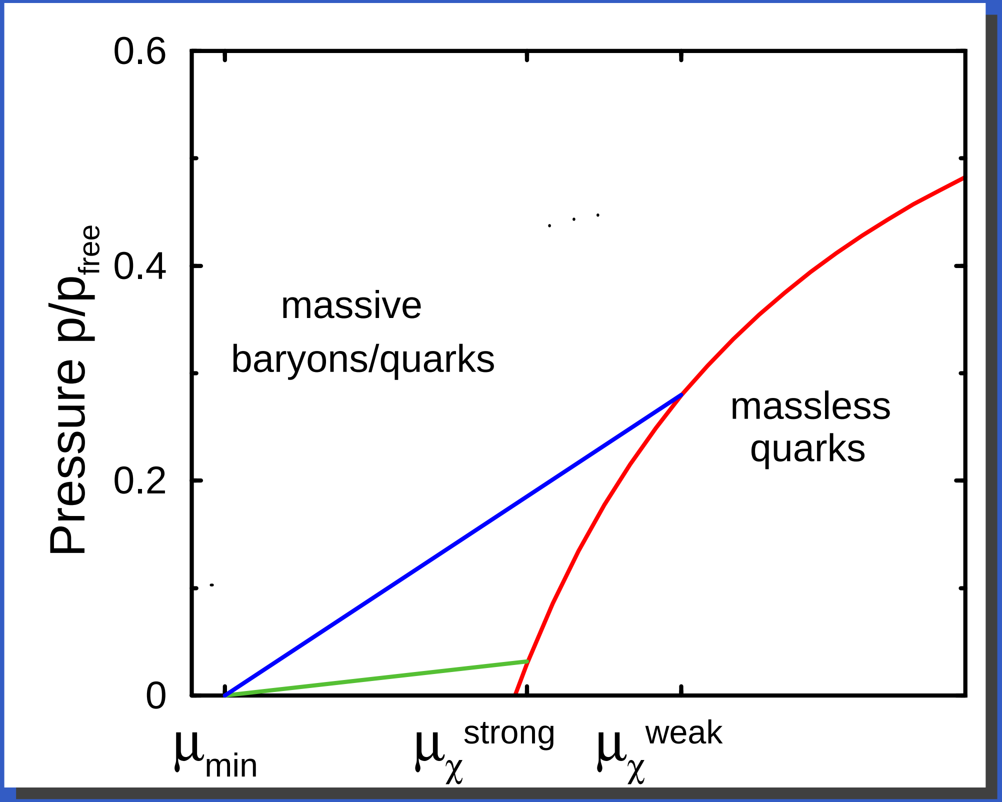
A Model For Cold And Dense QCD



Two possibilities for a first-order chiral phase transition:

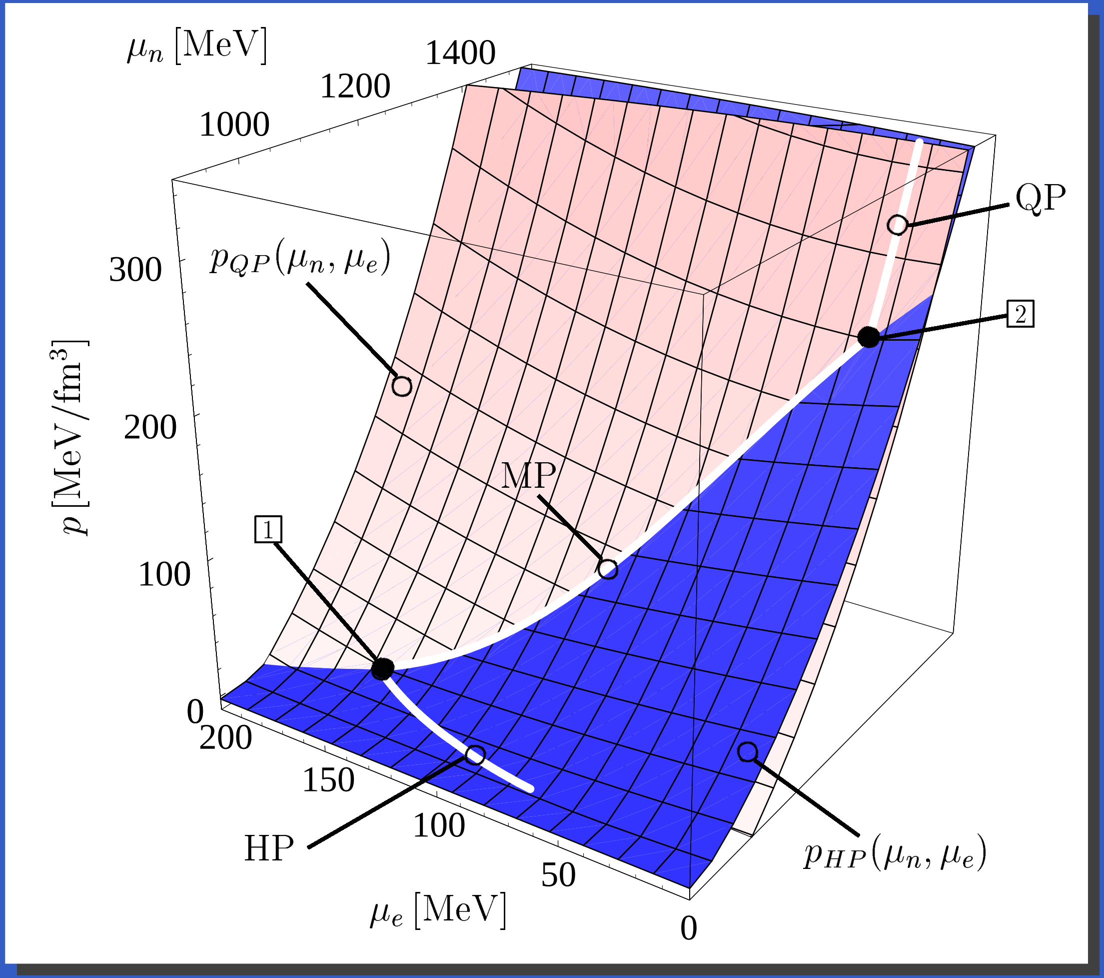
- A weakly first-order chiral transition (or no true phase transition),
  $\Longrightarrow$ one type of compact star (neutron star)
- A strongly first-order chiral transition
  $\Longrightarrow$ two types of compact stars:
  a new stable solution with smaller masses and radii

Matching the two phases: two possible scenarios



- Weak: phase transition is weakly first order or a crossover $\longrightarrow$ pressure in massive phase rises strongly
- Strong: transition is strongly first order $\longrightarrow$ pressure rises slowly with μ
- asymmetric matter up to $\sim 2n_0$: suggest a slow rise with density!

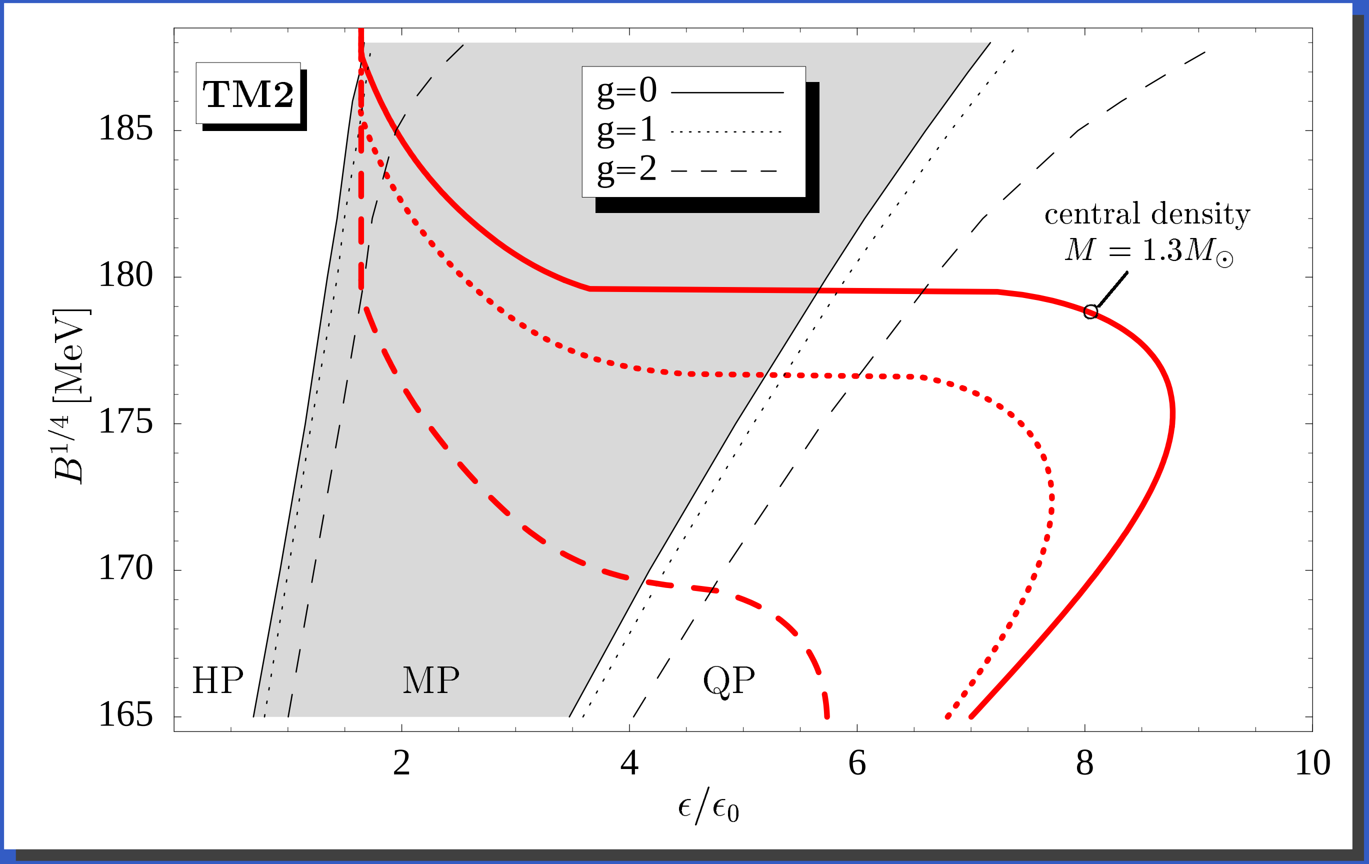
Gibbs Phase Construction (Glendenning (1992))



(Schertler et al. (2000))

- two conserved charges in β-equilibrium: baryon number and charge!
- Gibbs criterion for phase equilibrium: equal pressure for equal chemical potentials $P_I(\mu_B, \mu_e) = P_I I(\mu_B, \mu_e)$
- globally charge neutral matter: mixed phase with charged bubbles forms!

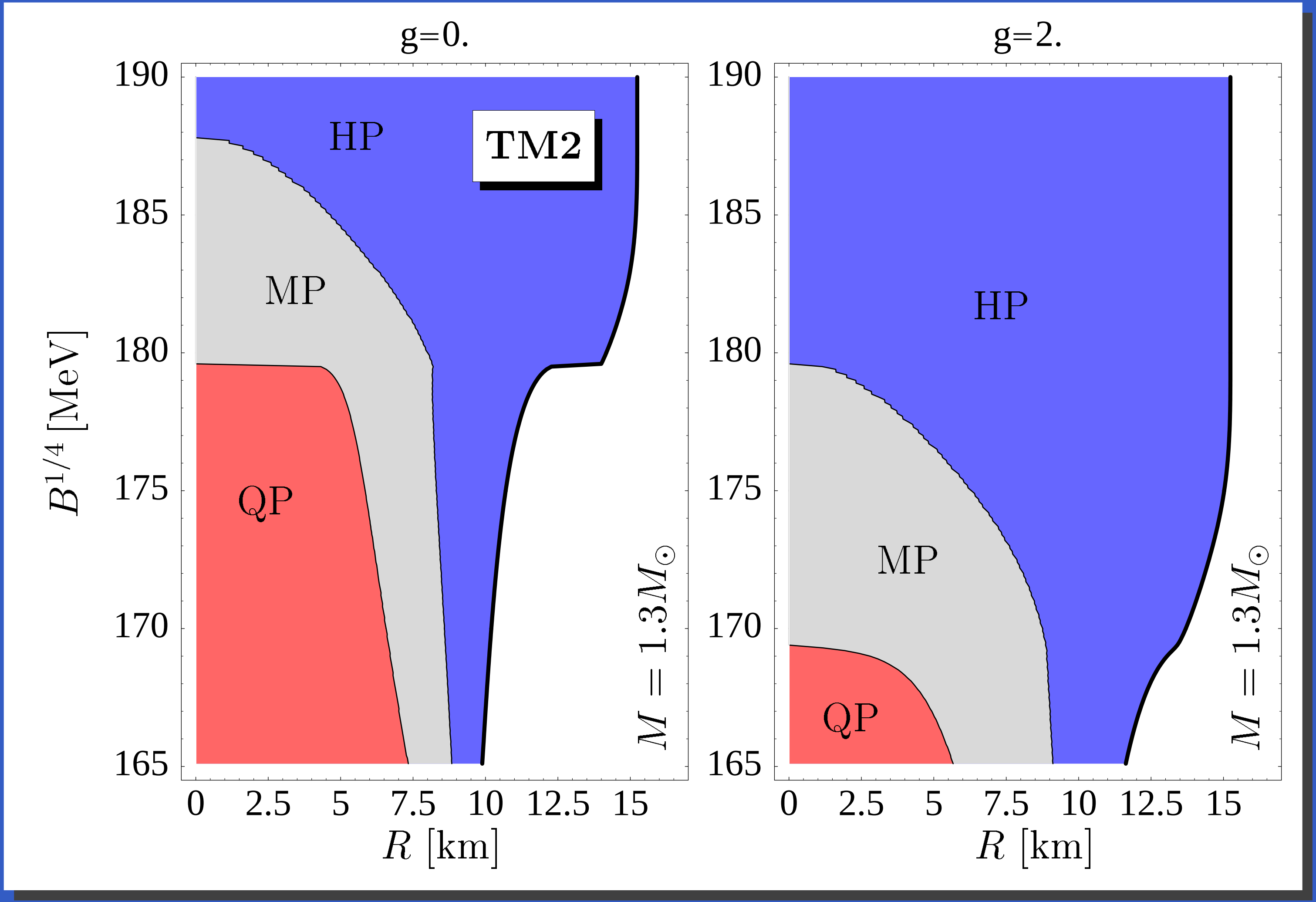
Quark Matter in Cold Neutron Stars



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

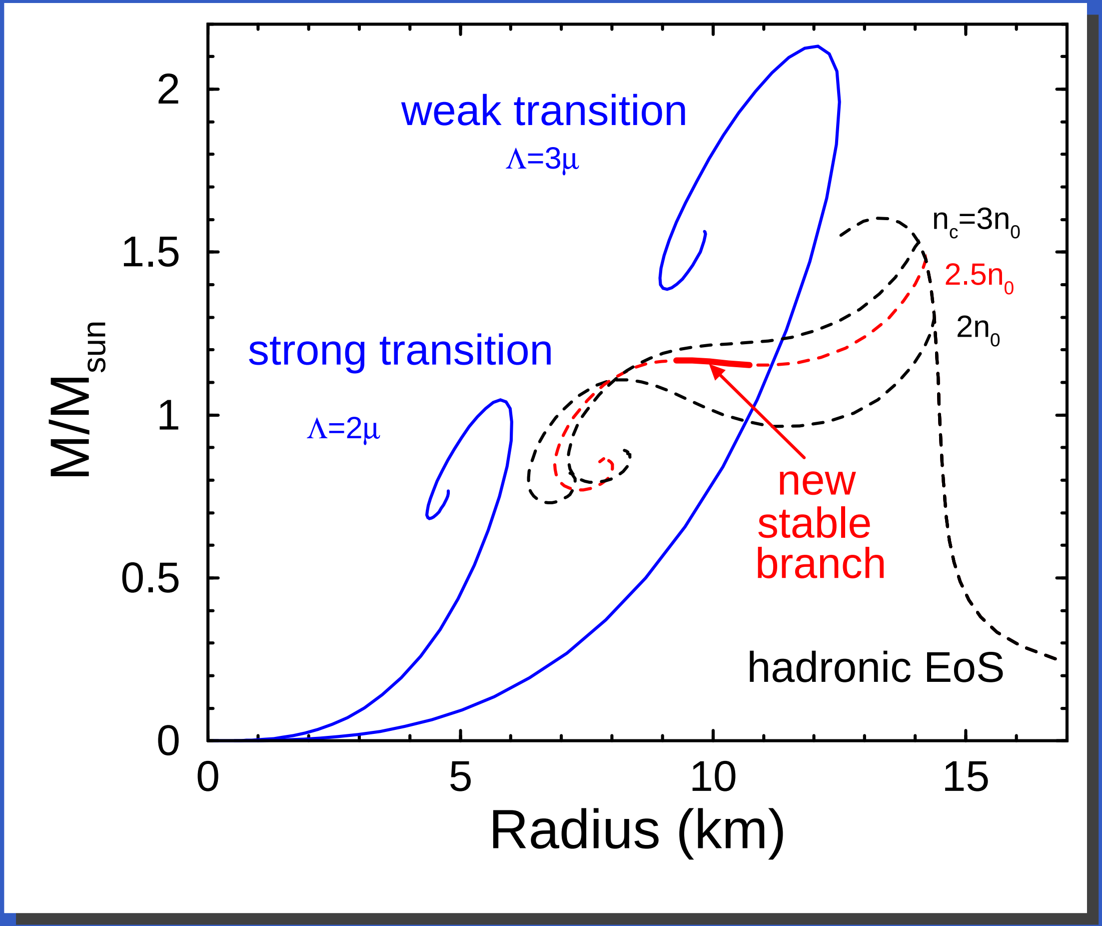
- phase transition to quark matter in the MIT bag model
- onset of mixed phase appears between $(1-2)n_0$ even for large values of the bag constant
- sufficiently high densities reached in the core for a $1.3M_\odot$ neutron star to have quark matter

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!)

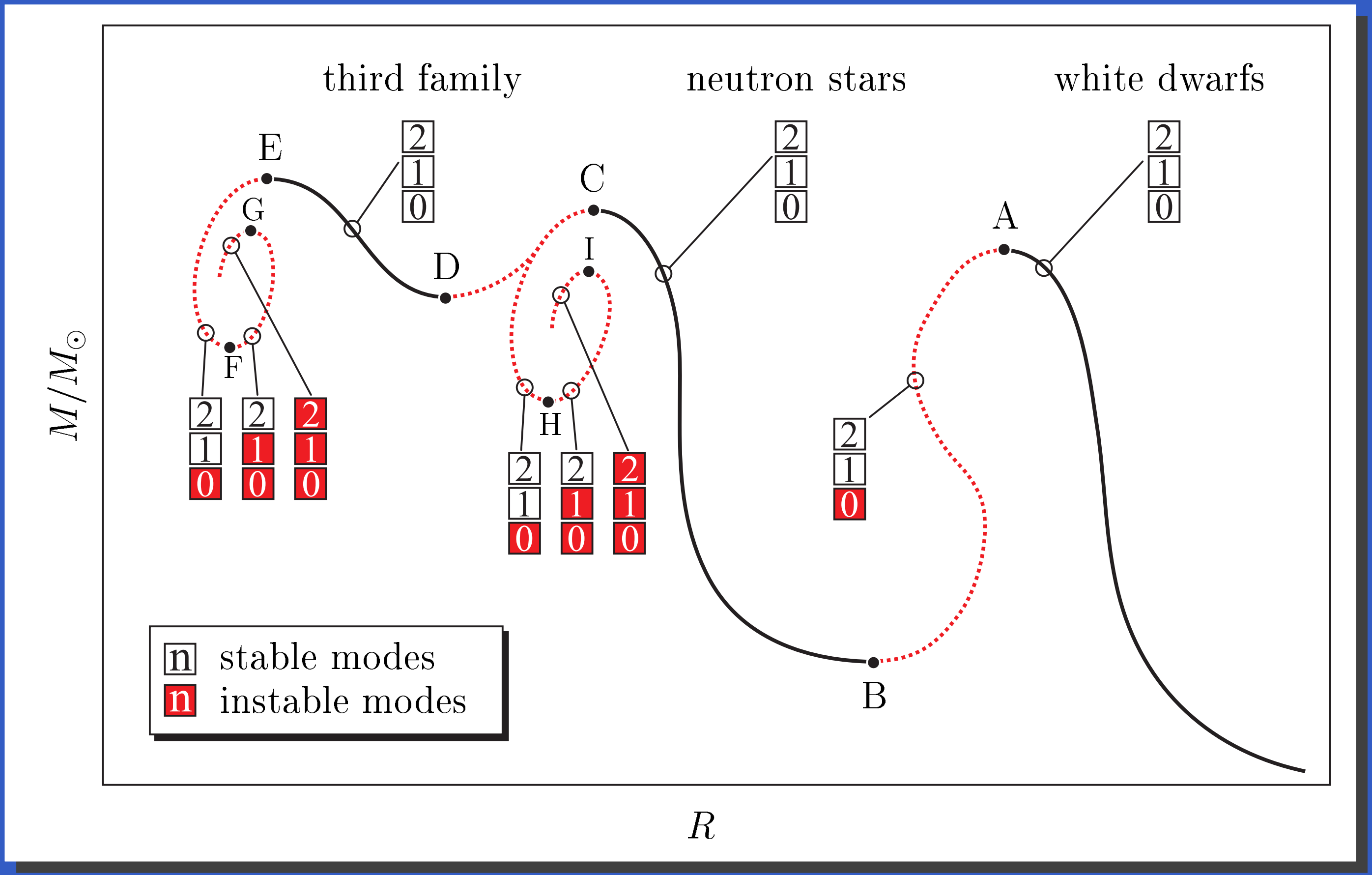
Quark star twins? (Fraga, JSB, Pisarski (2001))



- 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

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!

Signals for a Third Family/Phase Transition?

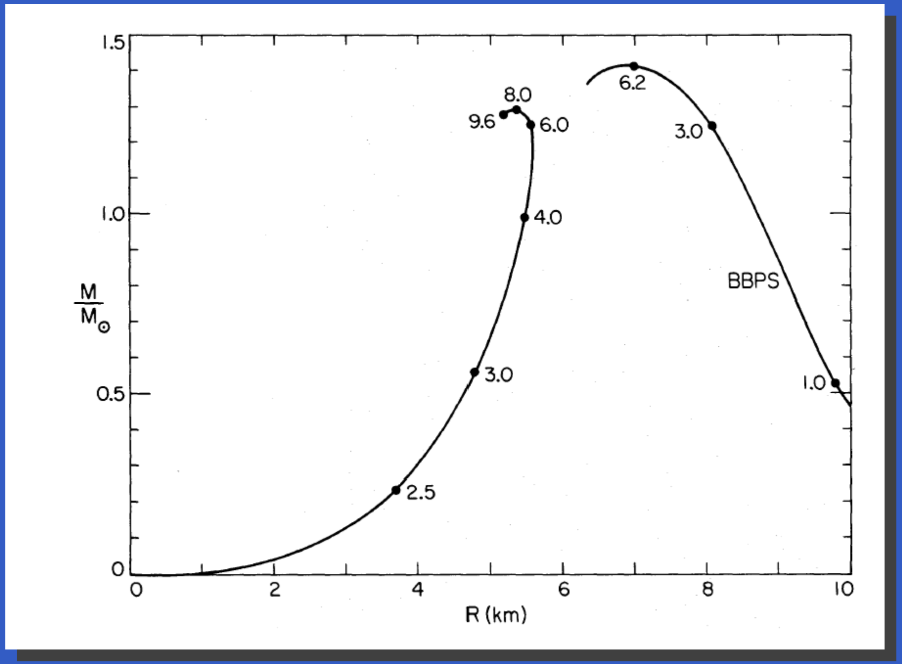
- mass-radius relation: rising twins (Schertler et al., 2000)
- spontaneous spin-up of pulsars (Glendenning, Pei, Weber, 1997)
- delayed collapse of a proto-neutron star to a black hole (Thorsson, Prakash, Lattimer, 1994)
- bimodal distribution of pulsar kick velocities (Bombaci and Popov, 2004)
- collapse 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?

Difference between quark stars, hybrid stars, etc?

- hybrid stars: neutron stars mixed with quark matter in the core
- quark star twins: special hybrid stars with a pure quark matter core
- strange stars or selfbound stars: consists of stable quark matter only, purely hypothetical!!!

Hypothetical Selfbound Star versus Ordinary Neutron Star

(Hartle, Sawyer, Scalapino (1975!))



<u>selfbound stars:</u>

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

<u>neutron stars:</u>

- 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

Signals for Strange Stars?

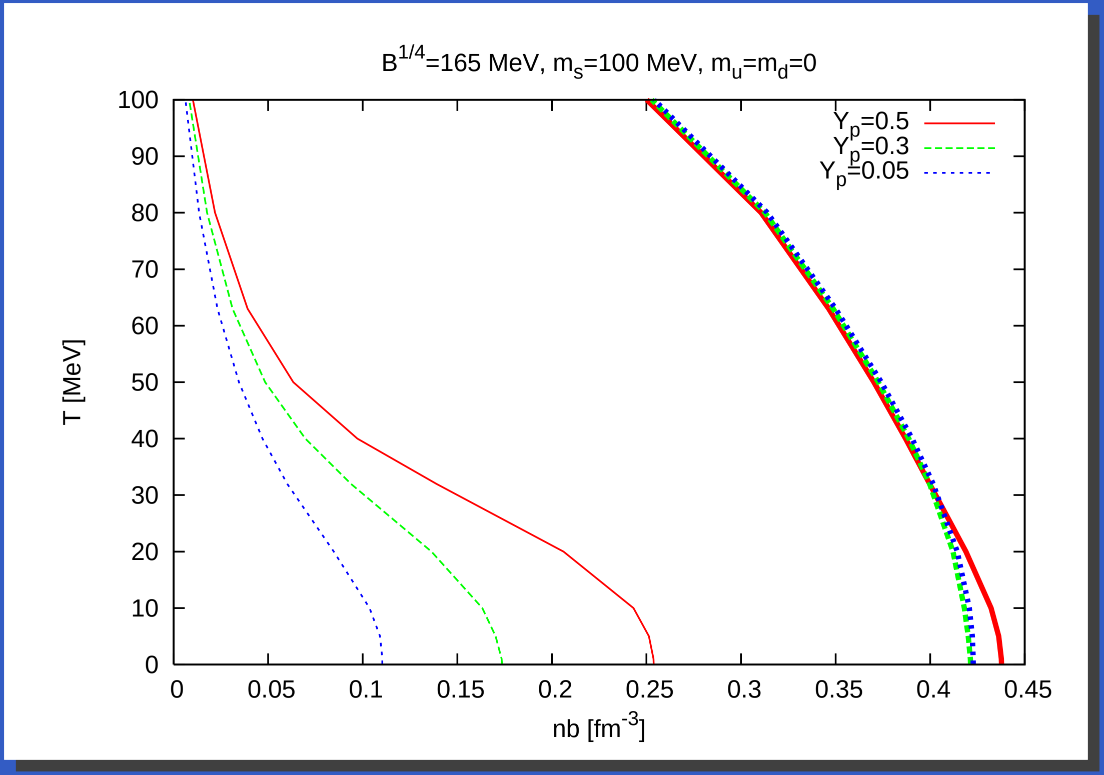
similar masses and radii, cooling, surface (crust), . . . but look for

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

Summary

- equation of state (EoS) determines the maximum mass and its radius
- in-medium potentials of hadrons determine the population
- new hadronic degrees of freedoms normally soften the EoS!
- but quark matter can also stiffen the EoS!
- strong chiral phase transition leads to a third family of compact stars
- implications for mass-radius relation, cooling, neutrino emission, gravitational waves emission
- and for supernovae!

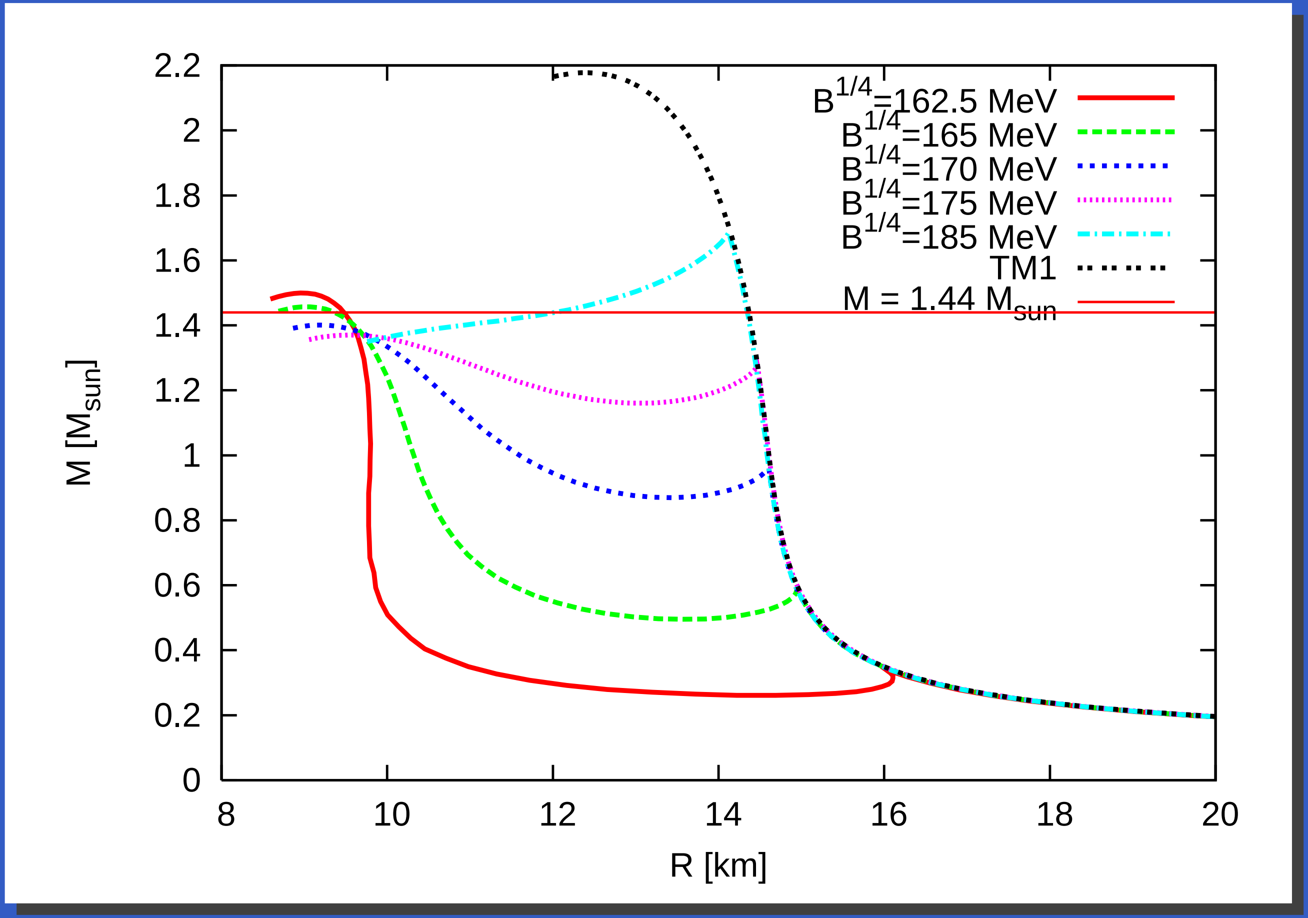
Phase Transition to Quark Matter for Astros



(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 favored in hot matter due to the QCD phase diagram
- production of quark matter in supernovae at bounce possible!

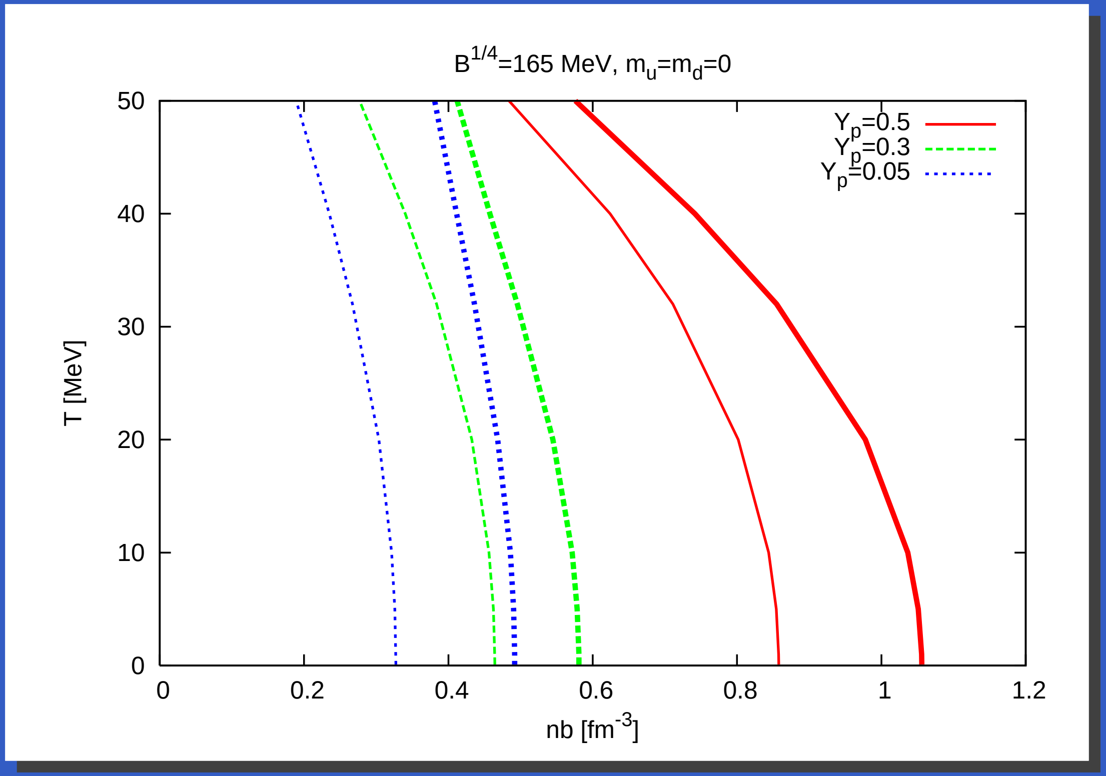
Check: Mass-Radius Diagram of Cold Neutron Stars



(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)

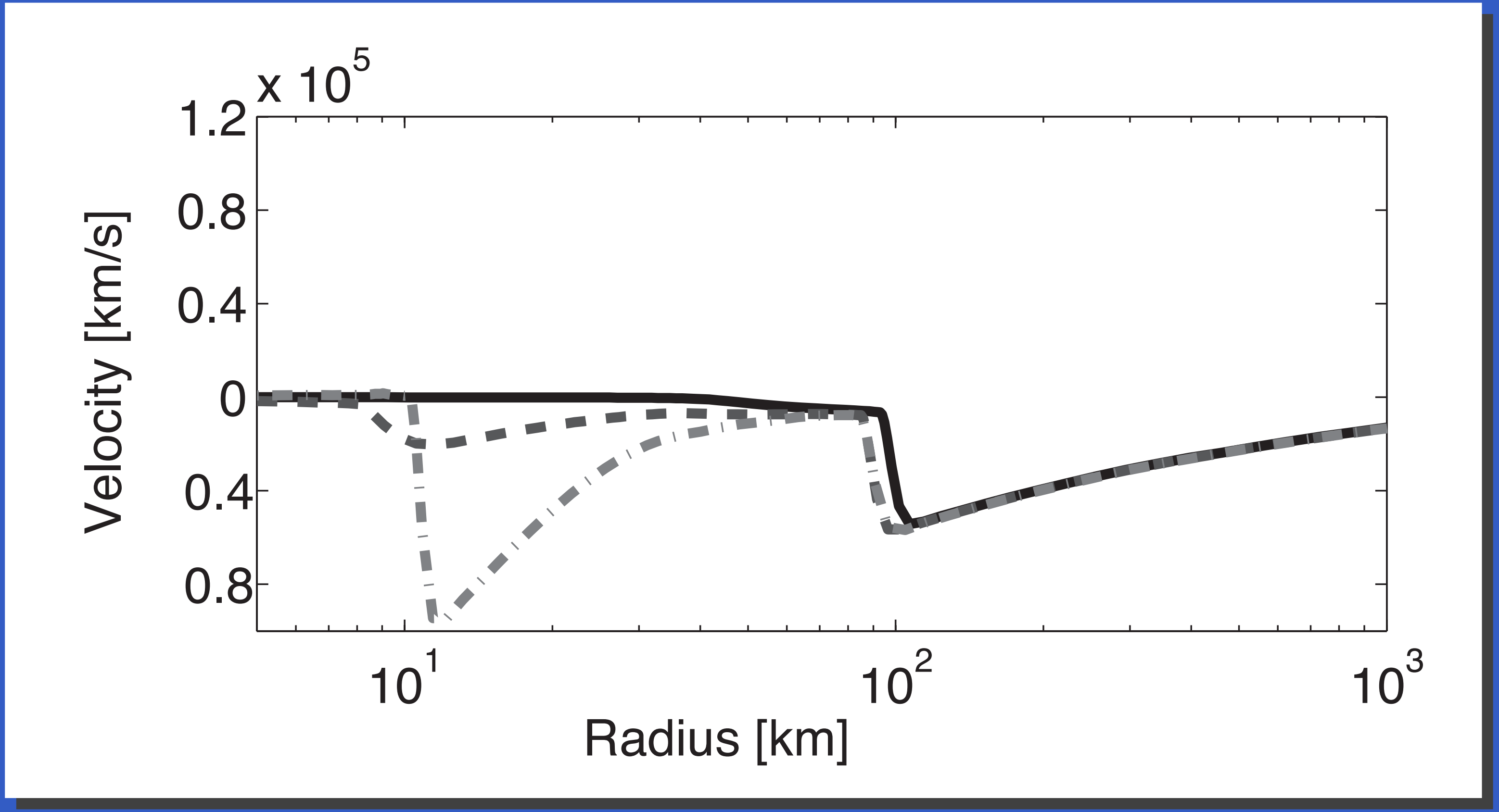
Check: Phase Transition for Heavy-Ion Collisions



(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!

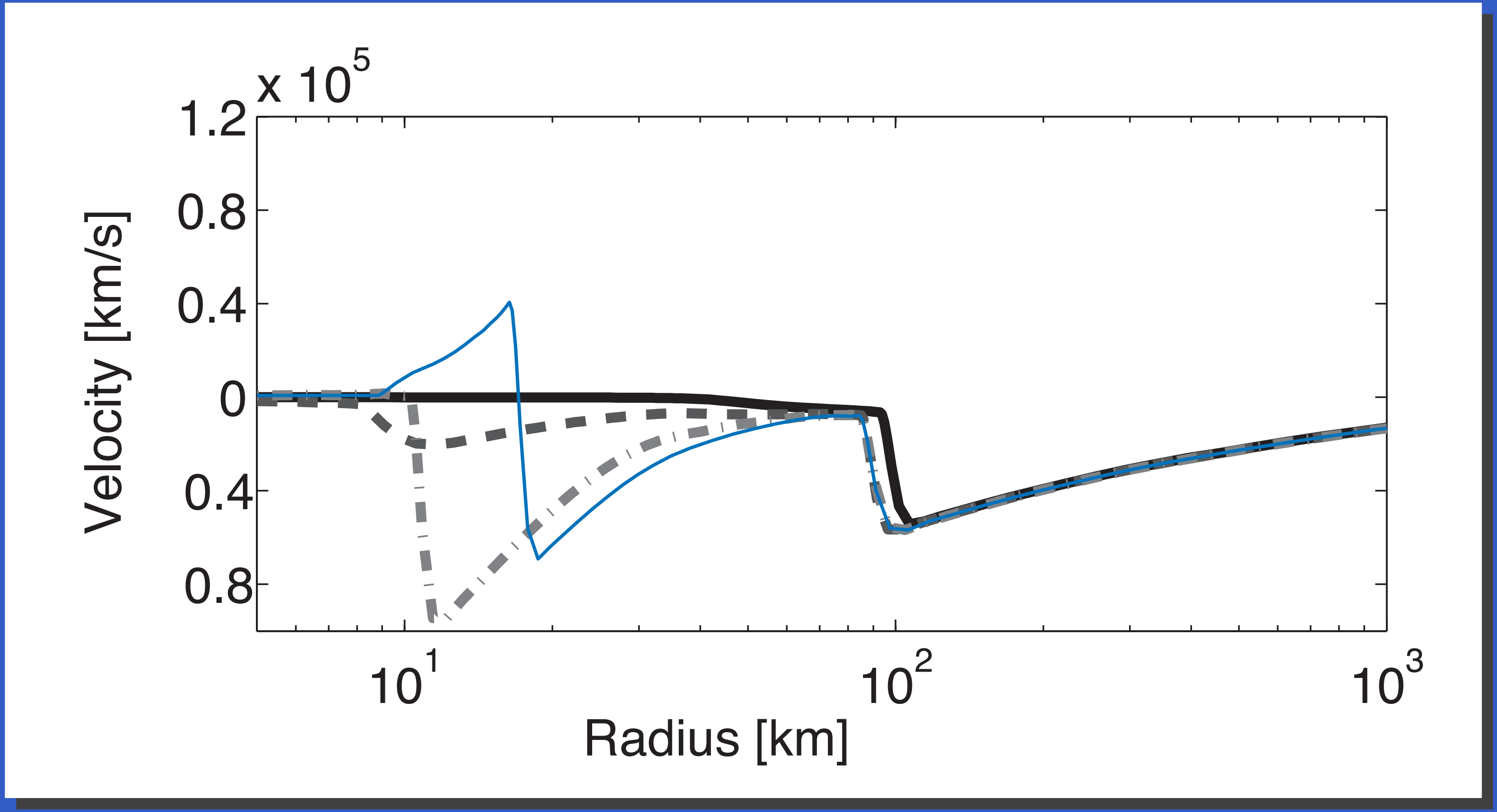
Implications for Supernovae – Explosion!



(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

Implications for Supernovae – Explosion!



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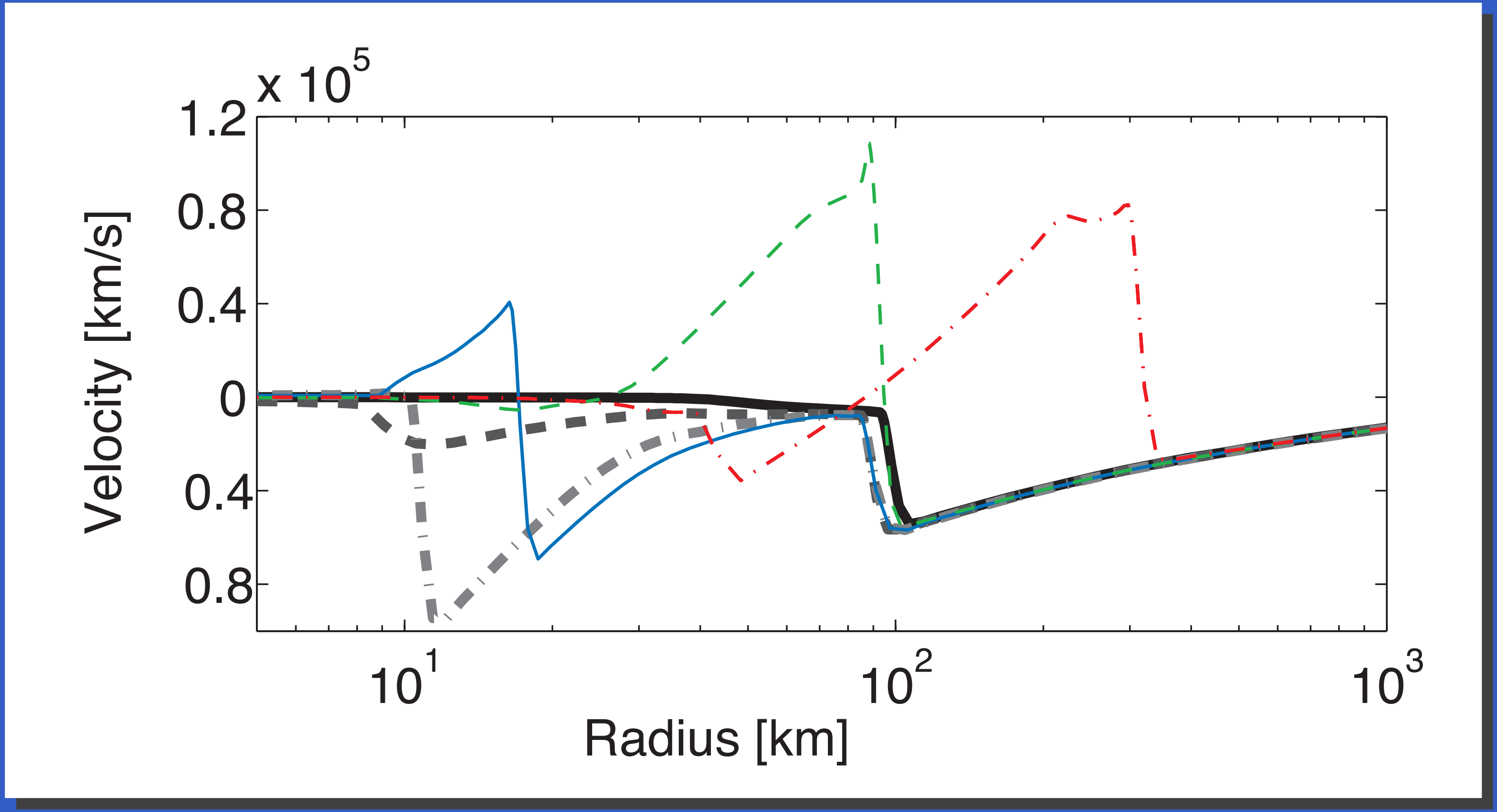
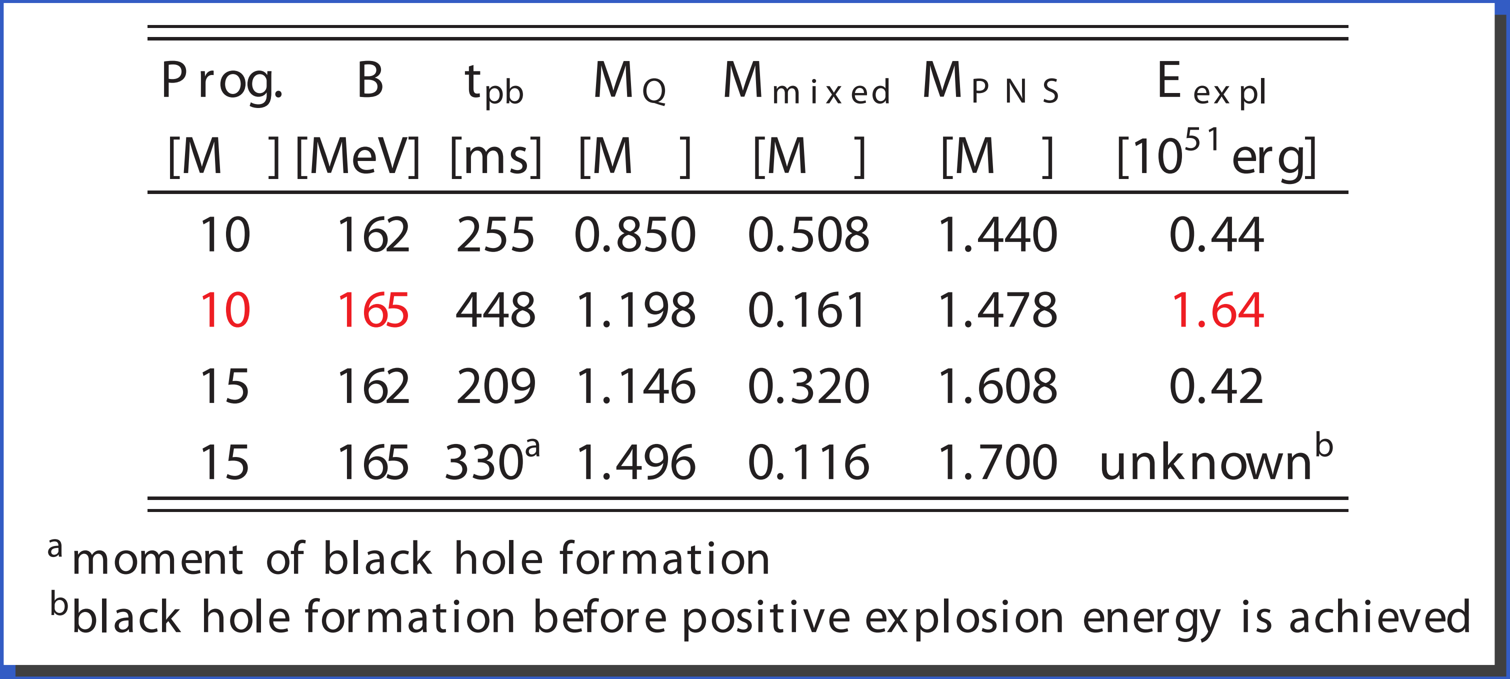


(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2008)

- 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!

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]

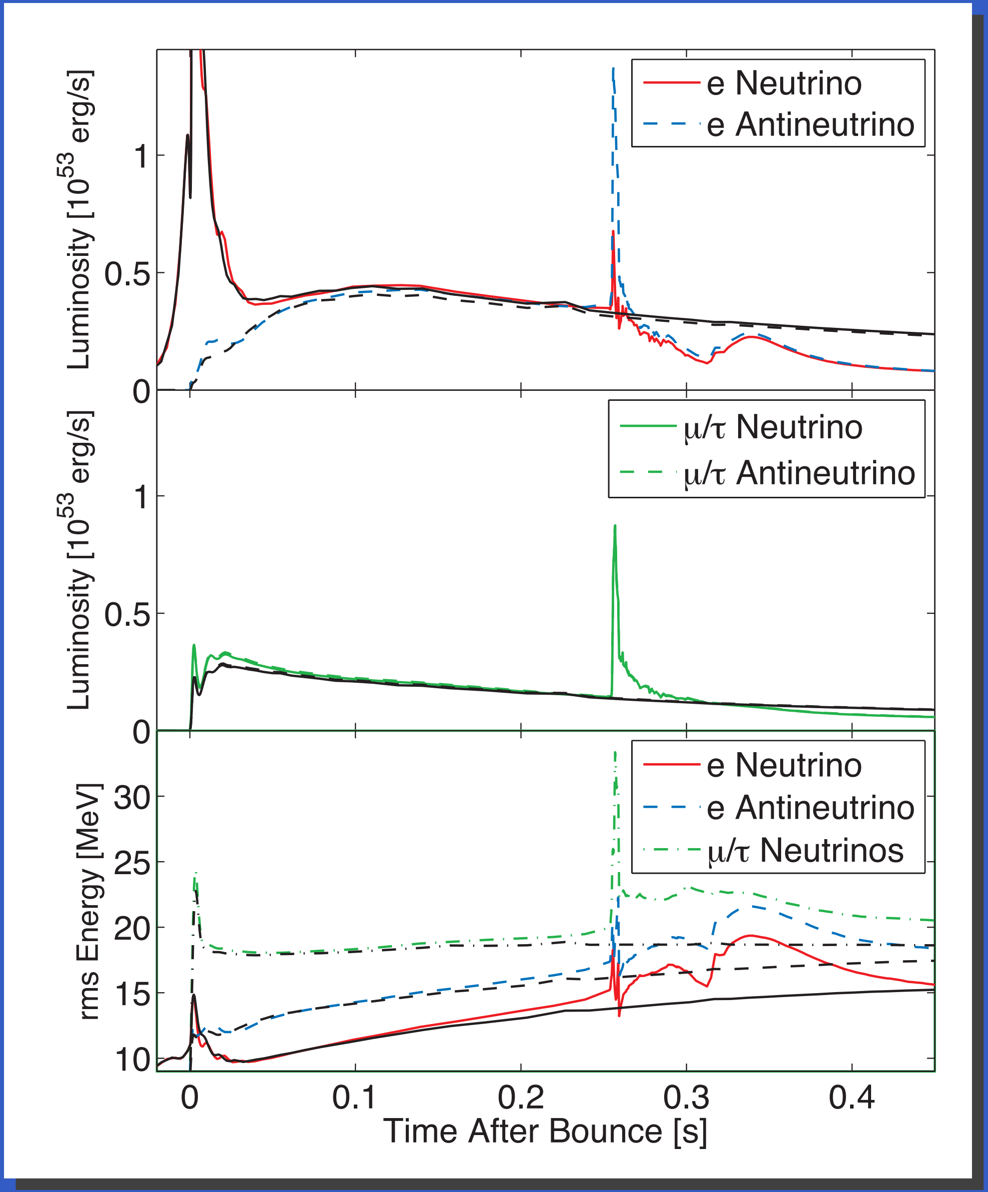
[a] moment of black hole formation

[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

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!!

Thanks to:

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- Dr. Giuseppe Pagliara
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- Dr. Basil Sa’d
  (r-mode instability, gravitational wave emission, csc phases)
- Dipl.-Phys. Till Boeckel
  (QCD phase transition in the early universe)
- Dipl.-Phys. Matthias Hempel
  (low density SN EoS, NSE) (03/09)
- Dipl.-Phys. Irina Sagert
  (EoS from heavy ions, SN EoS, proto-neutron stars)
- Rainer Stiele
  (interacting dark matter in the early universe) (03/09)