Signals of the QCD Phase Transition in Compact Stars

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HGSFP

EMMI

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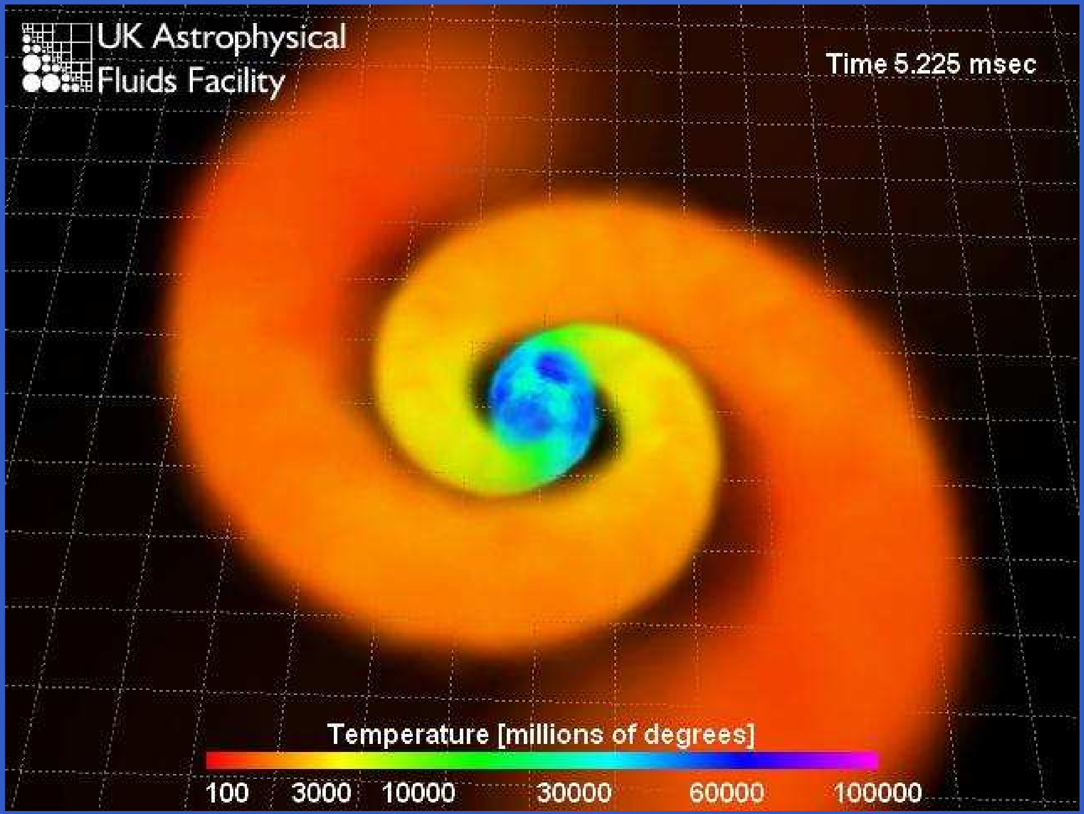
Outline

- Introduction: Nuclear Equation of State and Supernovae
- Constraints on Quark Matter from Pulsar Masses
- QCD Phase Transition and Supernovae
- Summary

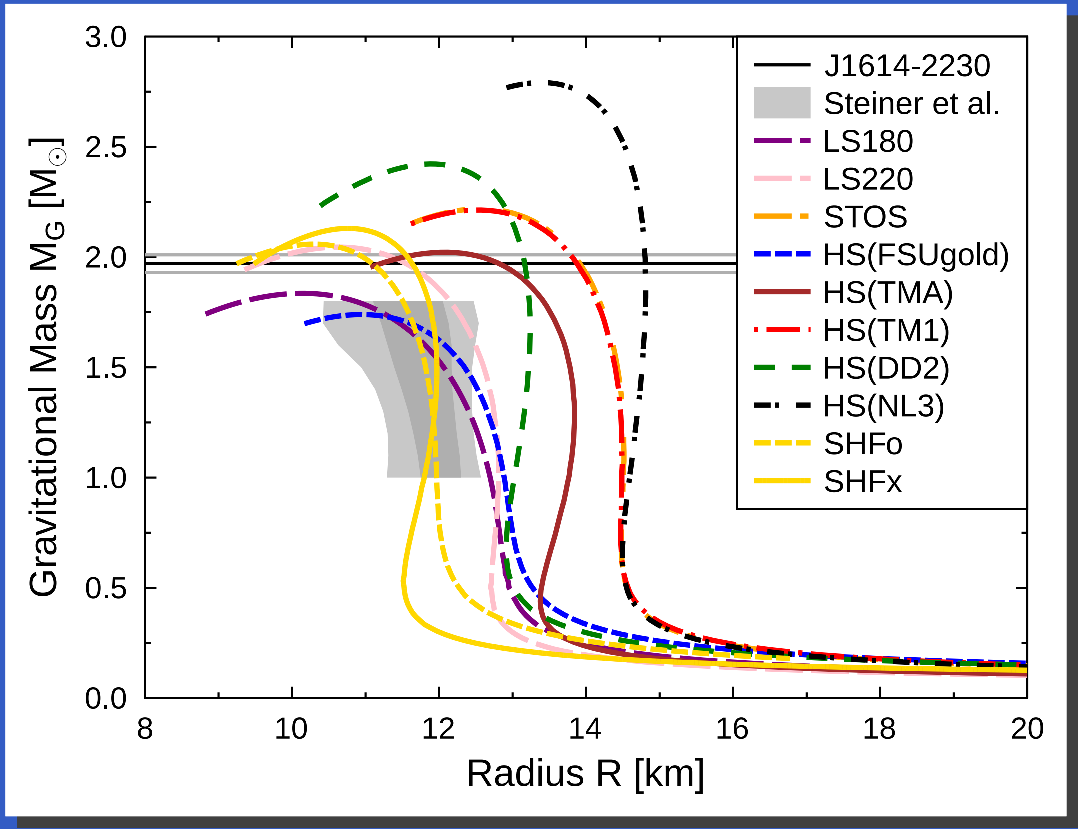
Introduction: Nuclear Equation of State and Supernovae

Nuclear Equation of State as Input in Astrophysics



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

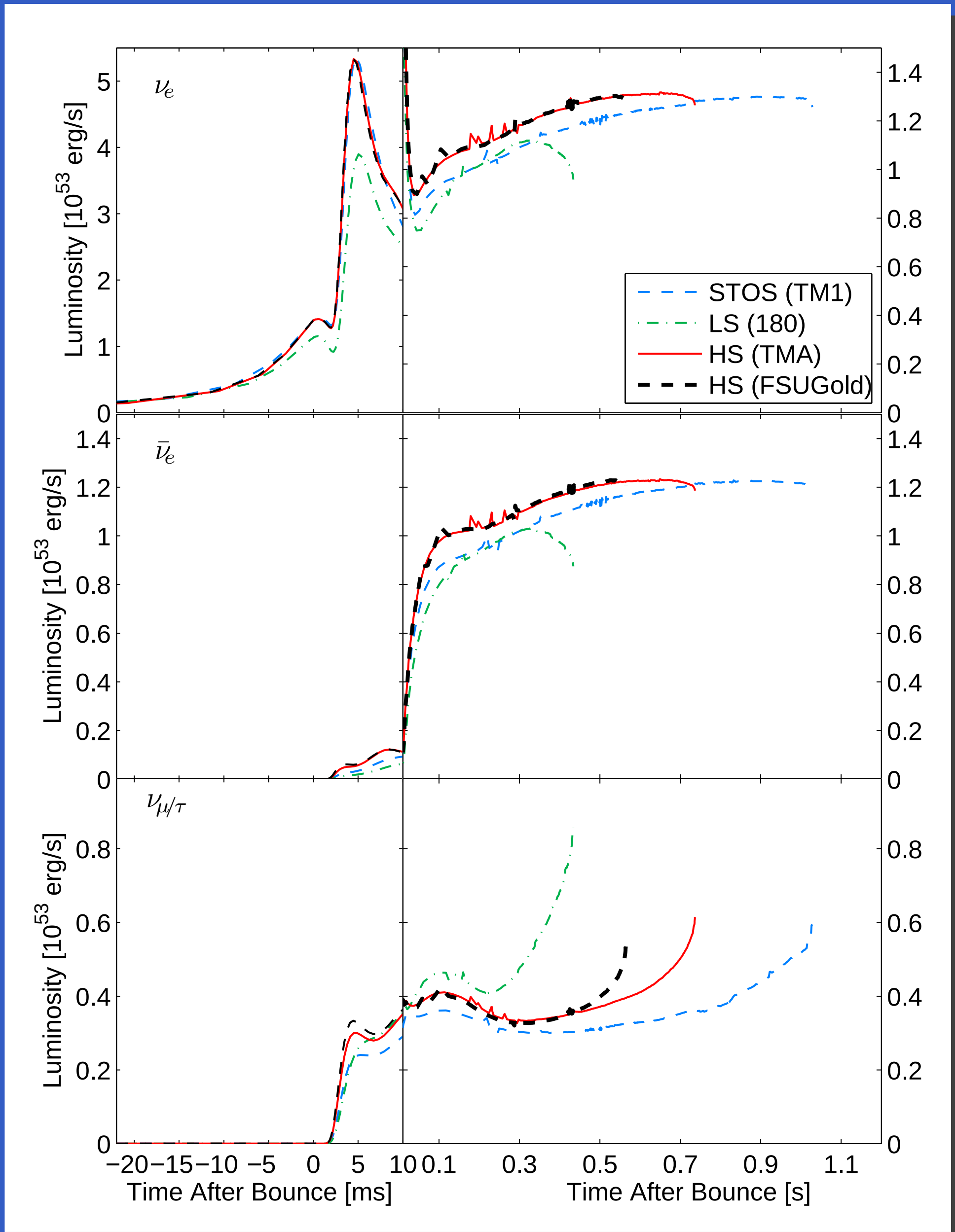
New Equations of State for Supernovae



(Hempel, Fischer, JSB, Liebendörfer 2012, Steiner, Hempel, Fischer 2012)

- new equation of state for supernova simulations available
- check with new pulsar mass limit
- based on models for describing nuclear properties (nucleons only)
- improvement in NSE (Hempel and JSB 2010)

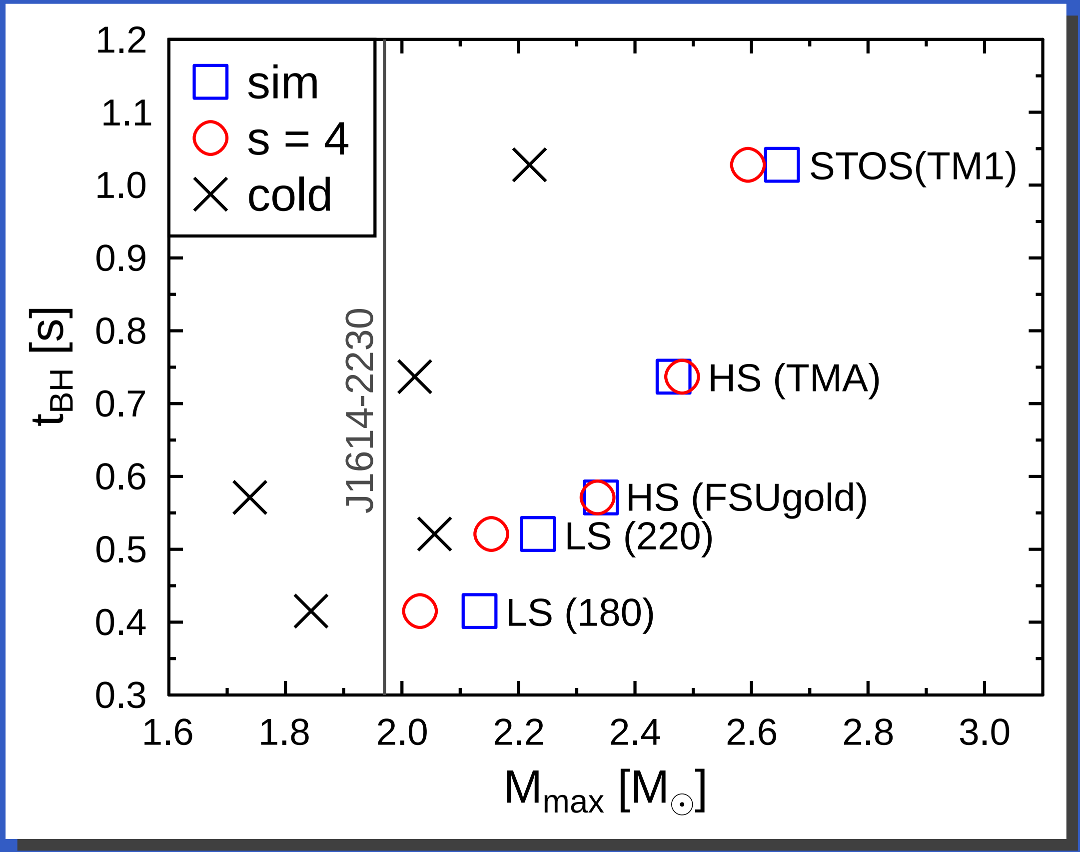
Neutrino Luminosities for a 40 $M_\odot$ Progenitor



(Hempel, Fischer, JSB, Liebendörfer 2012)

- neutrino luminosities for a 40 $M_\odot$ progenitor star
- collapse to a black hole within 1s
- collapse time depends on equation of state
- differences in particular in ν_μ and ν_τ spectra

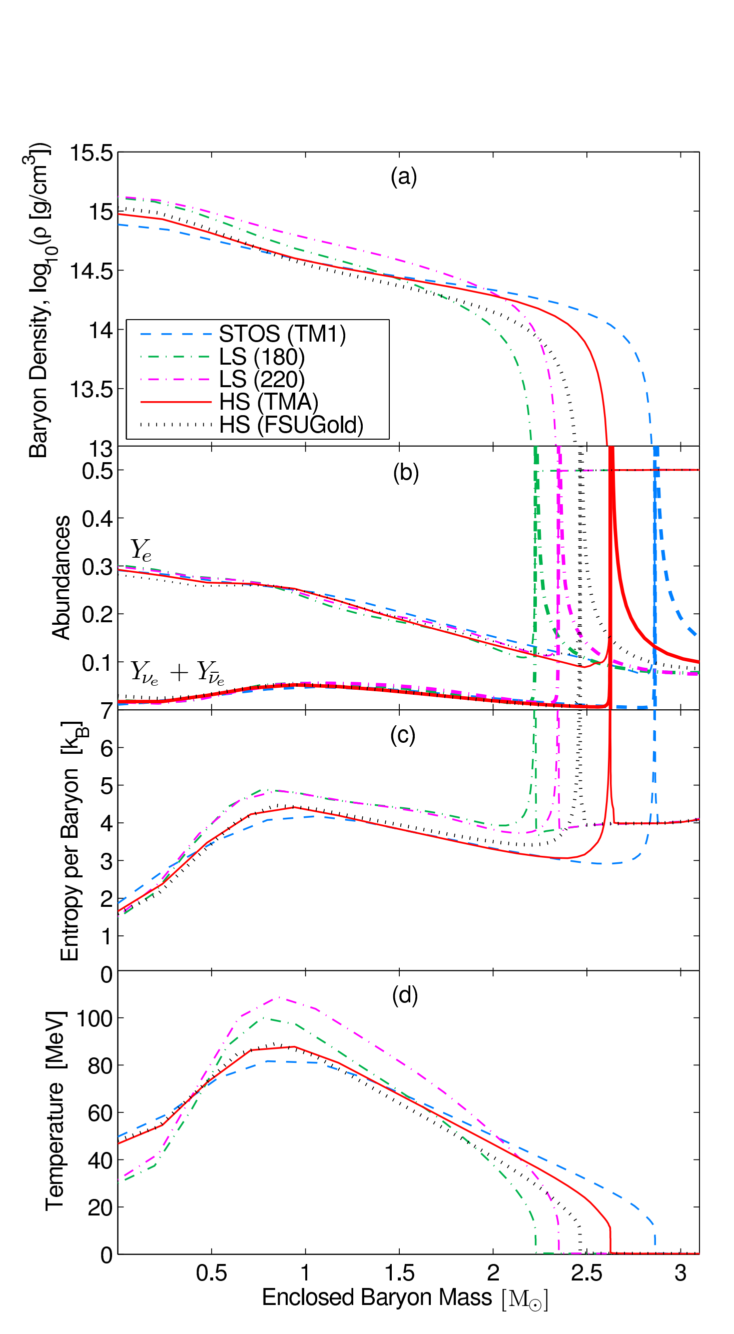
Correlation between maximum mass and collapse time



(Hempel, Fischer, JSB, Liebendörfer 2012)

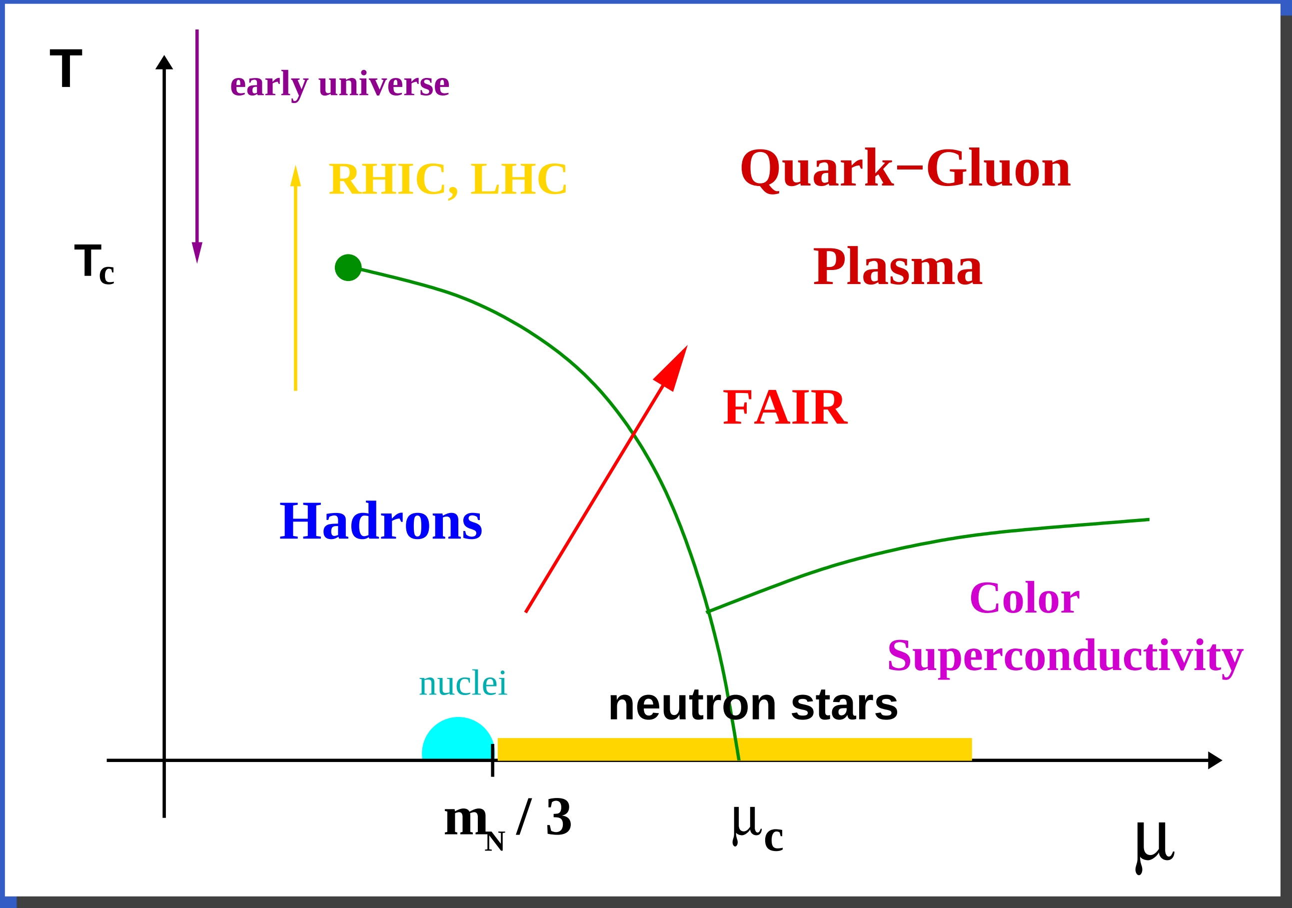
- relation between collapse timescale to a black hole and compact star masses
- cases for cold case (crosses), for constant entropy per baryon $S/A = 4$ (circles), and from simulation (boxes) for different EoS
- constant $S/A = 4$ describes maximum mass achieved in simulations quite well

Profiles just before collapse (Hempel, Fischer, JSB, Liebendörfer 2012)



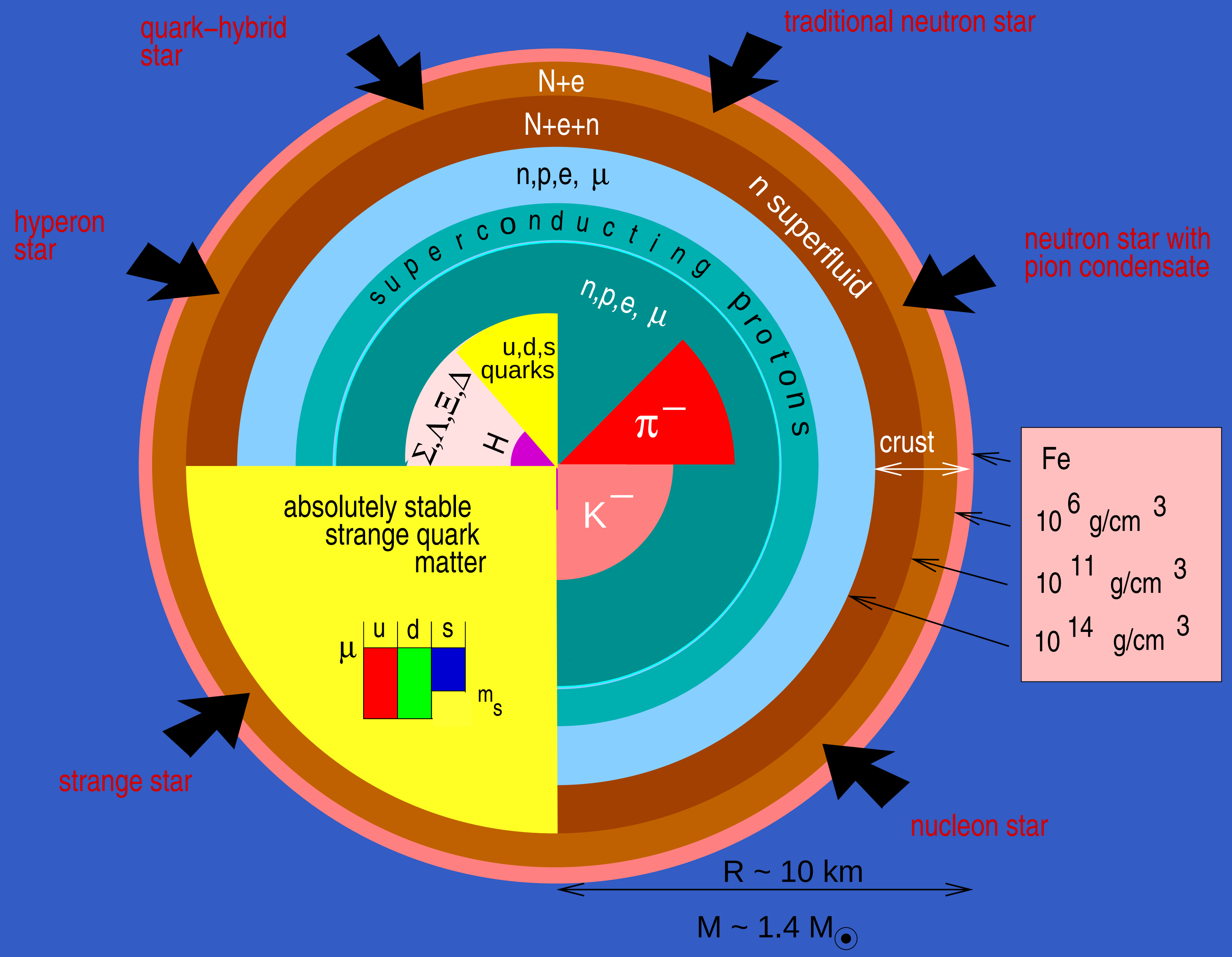
- radial profiles of density, abundances, entropy, temperature
- situation just before collapse to a black hole
- rather constant entropy per baryon of $S/A = 4$
- extremely high densities and temperatures (about 100 MeV!)

Phase Diagram of Quantum Chromodynamics QCD

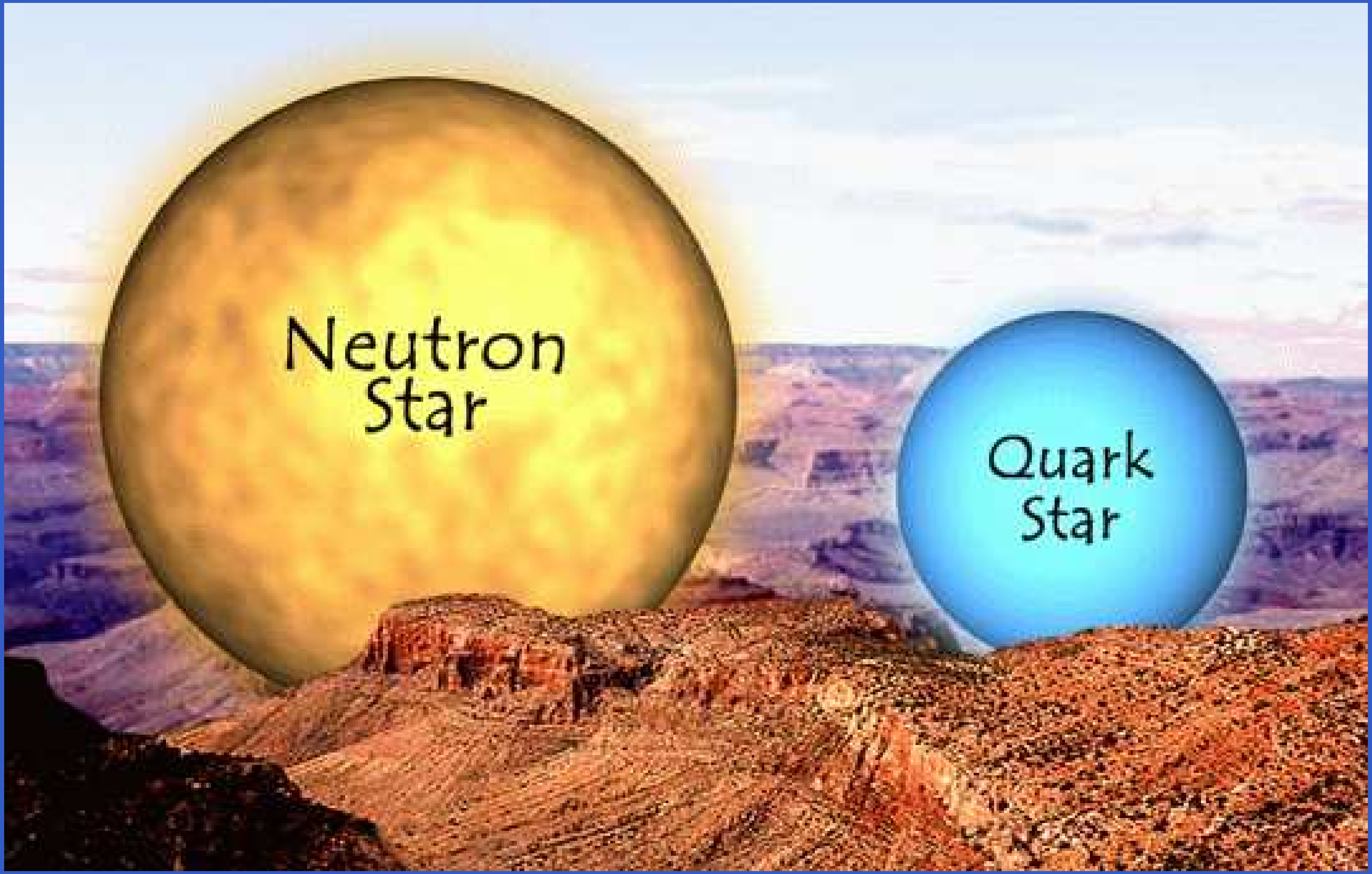


- Early universe at zero density and high temperature
- neutron star matter at small temperature and high density
- first order phase transition at high density (not deconfinement!)
- probed by heavy-ion collisions at GSI, Darmstadt (FAIR)

Structure of a Neutron Star (Fridolin Weber)



A Quark Star? (NASA press release 2002)

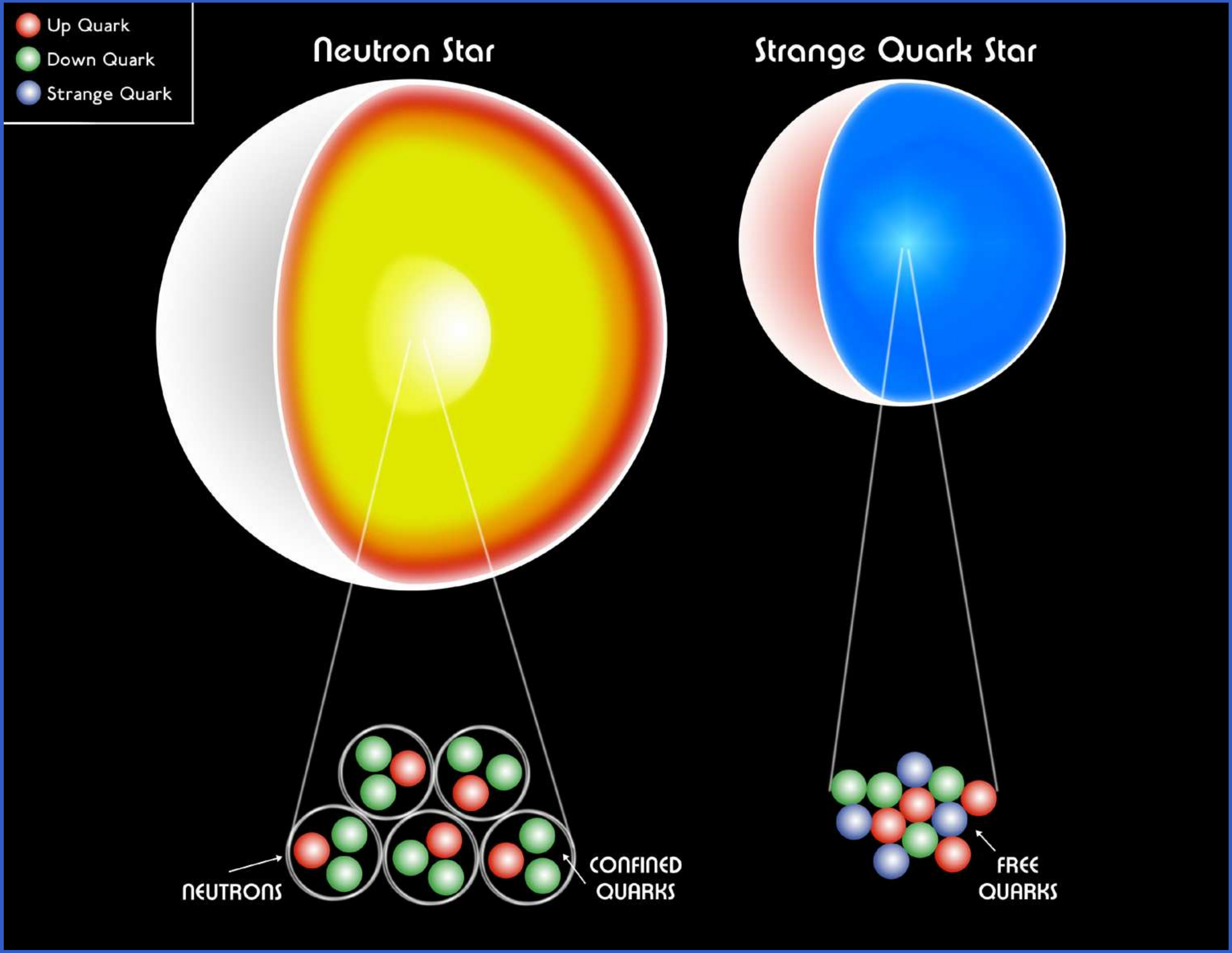


NASA news release 02-082:

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

— a quark star?

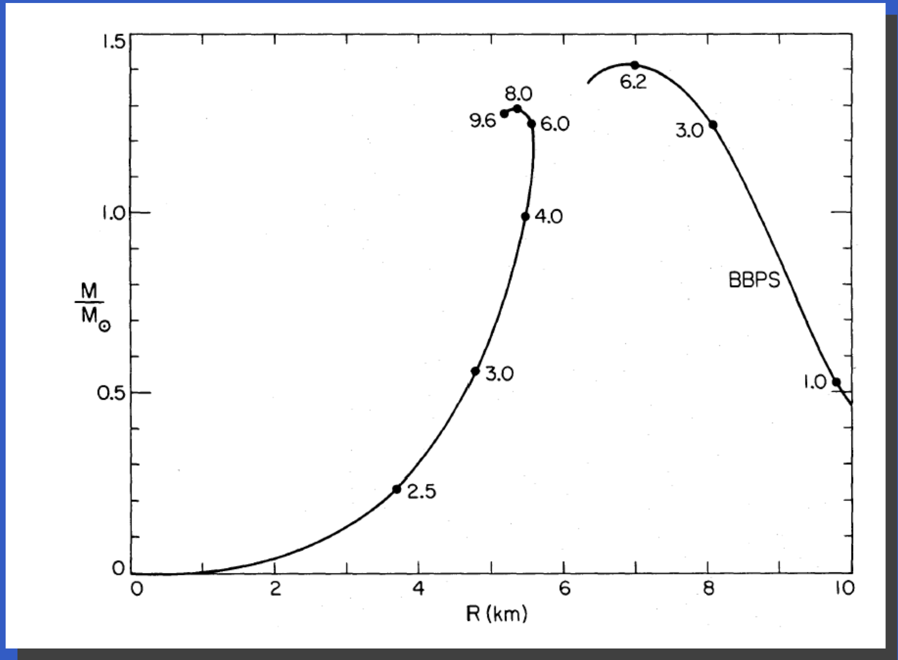
Neutron Star versus Strange Quark Star



(Chandra X-Ray Center, 2002)

Selfbound Star versus Ordinary Neutron Star

(Hartle, Sawyer, Scalapino (1975!))



<u>selfbound stars:</u>

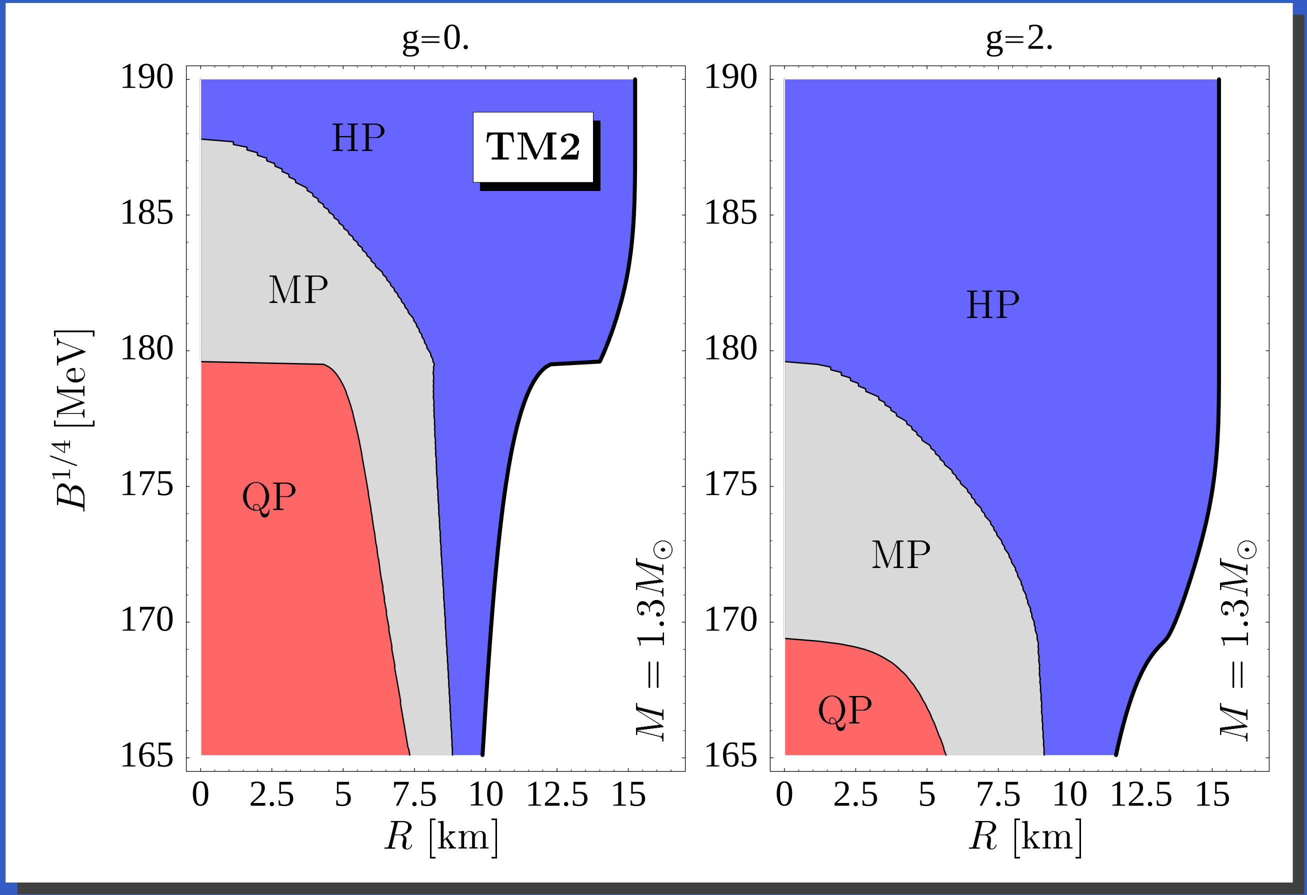
- vanishing pressure at a finite energy density
- mass-radius relation starts at the origin (ignoring a possible crust)
- arbitrarily small masses and radii possible

<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

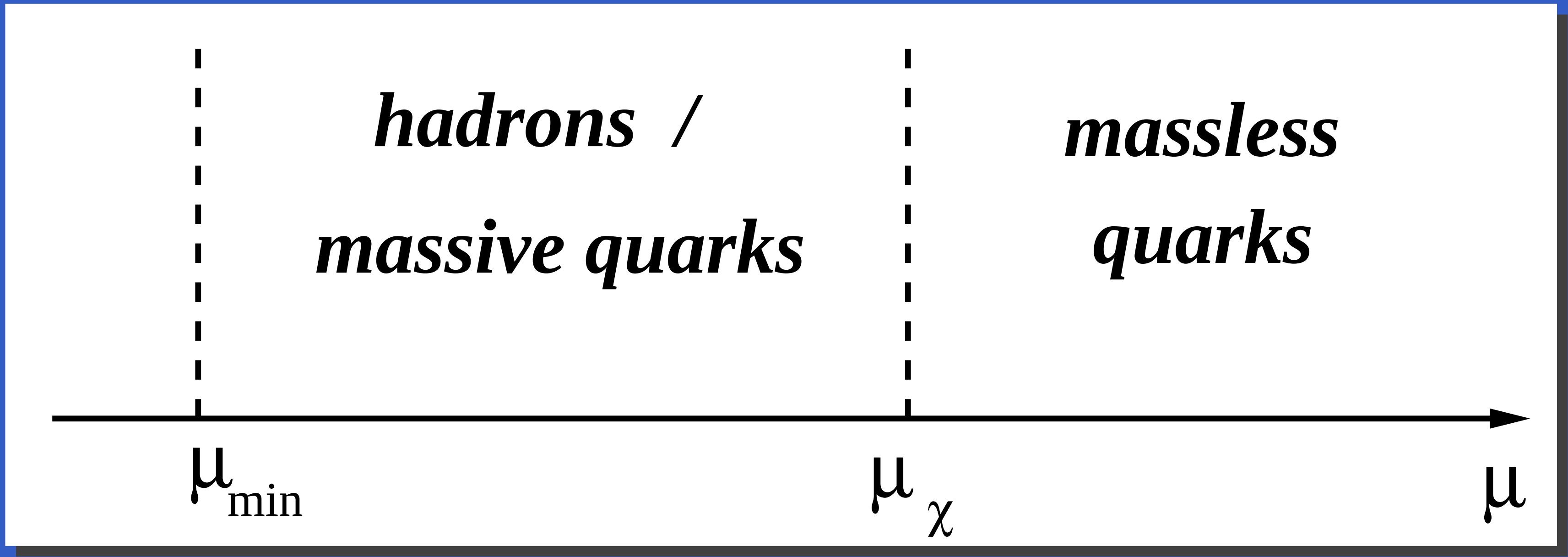
Hybrid Stars in the effective mass bag model

(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)

Matching to low density EoS

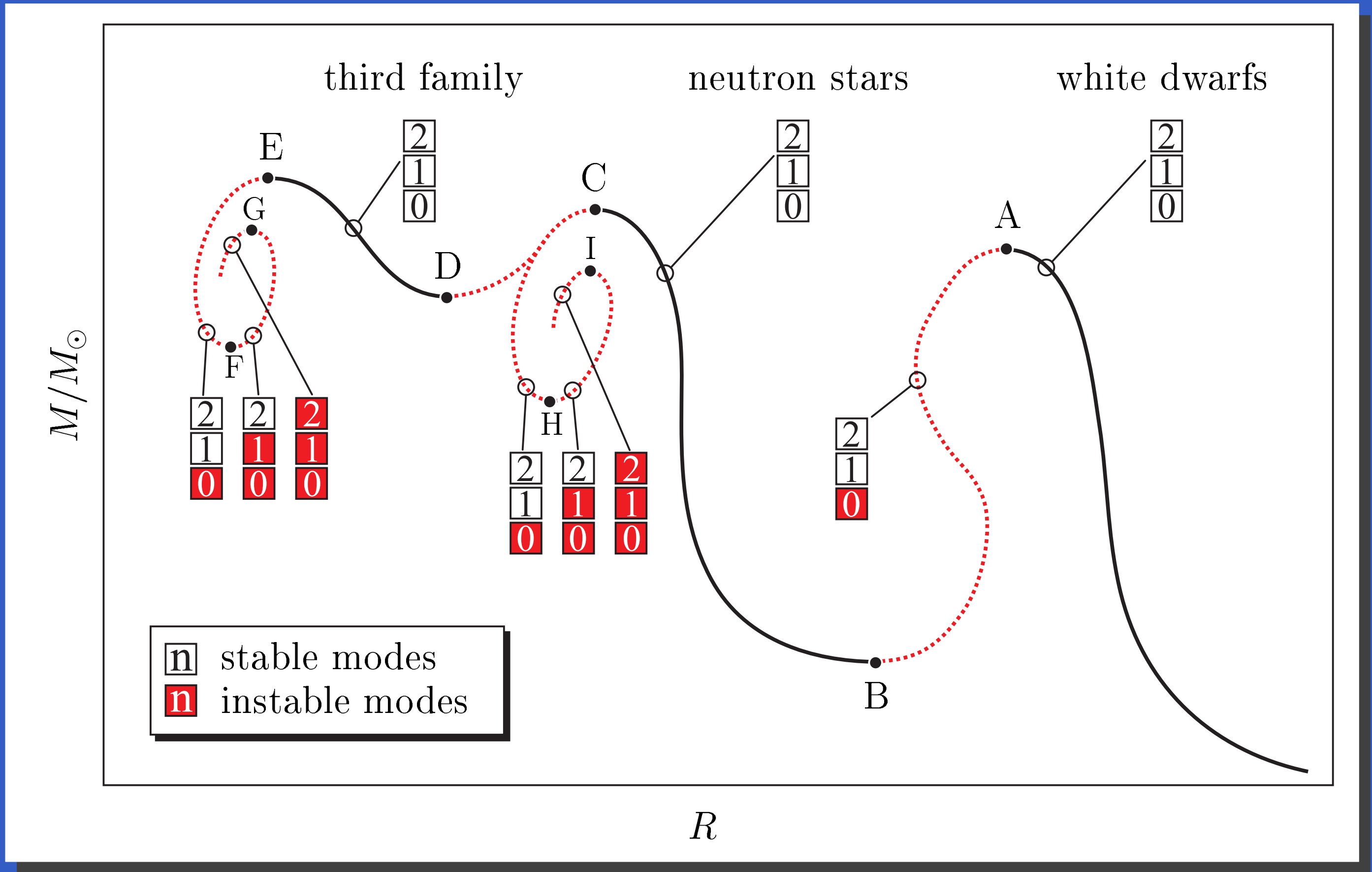


Two possibilities for a first-order chiral phase transition:

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

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 Quark Matter/Phase Transition?

- delayed collapse of a proto-neutron star to a black hole (Thorsson, Prakash, Lattimer, 1994)
- spontaneous spin-up of pulsars (Glendenning, Pei, Weber, 1997)
- mass-radius relation: rising twins (Schertler et al., 2000)
- rapidly rotating pulsars due to r-mode *stability* window
- enhanced cooling of neutron stars
- collapse of a neutron star to the third family? (gravitational waves, γ-rays, neutrinos)
- gravitational wave signals of phase transitions from neutron star mergers?
- secondary shock wave in supernova explosions (Sagert, Fischer et al. 2009)

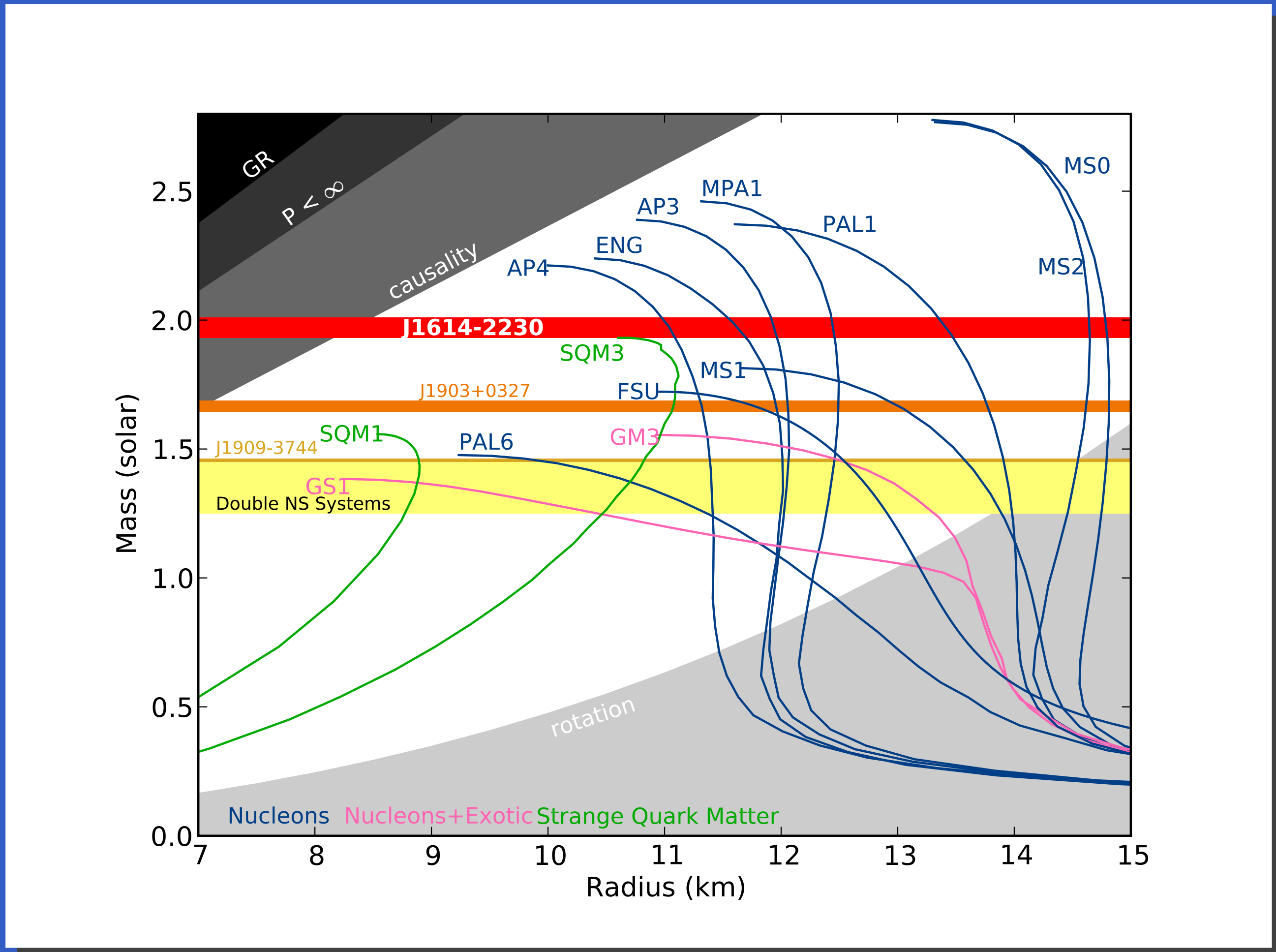
Signals for Strange Stars?

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)
- quark novae with modified r-process nucleosynthesis (Jaikumar, Meyer, Otsuki, Ouyed 2007)
- gamma-ray bursts by conversion to strange quark matter (GRBs without a supernova, late x-ray emission, long quiescent times)
- . . .

Constraints on quark matter from pulsar masses

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): $M = (1.97 \pm 0.04) M_\odot$

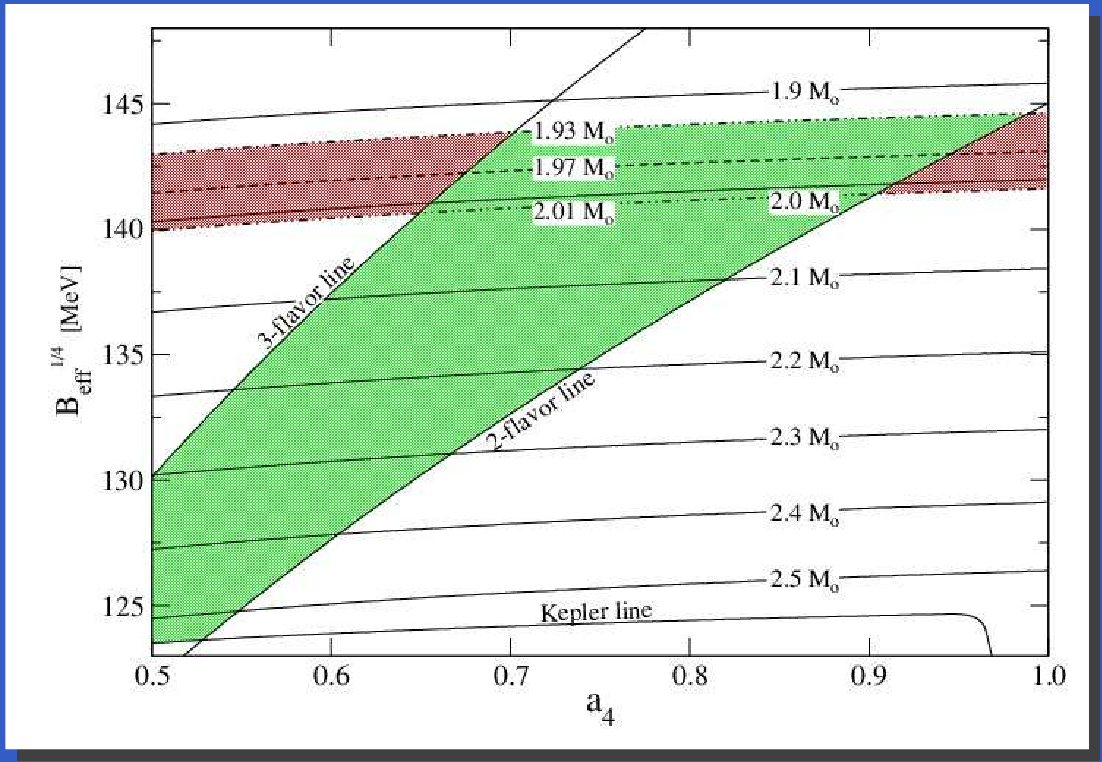
Quark Star Masses: Unpaired Case

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

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

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

Quark Star Masses: Unpaired Case



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

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

Quark Star Masses: effects of quark pairing

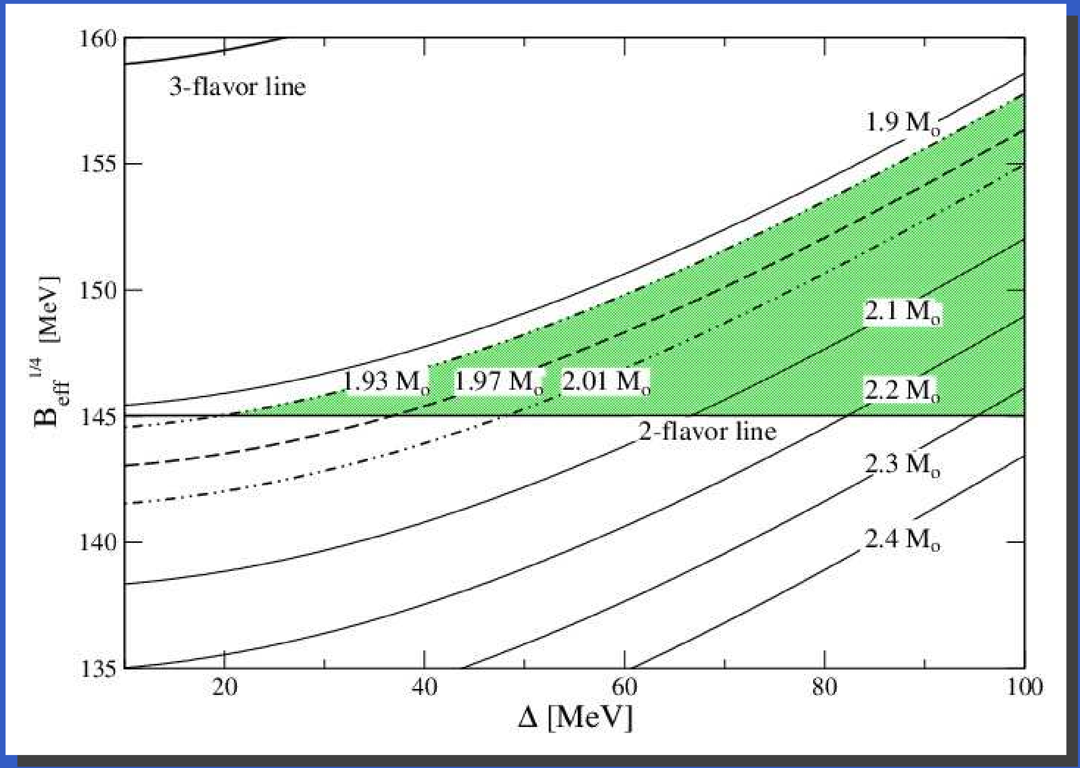
Add to a free gas of quarks terms from interaction, from pairing and from an vacuum energy:

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

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

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

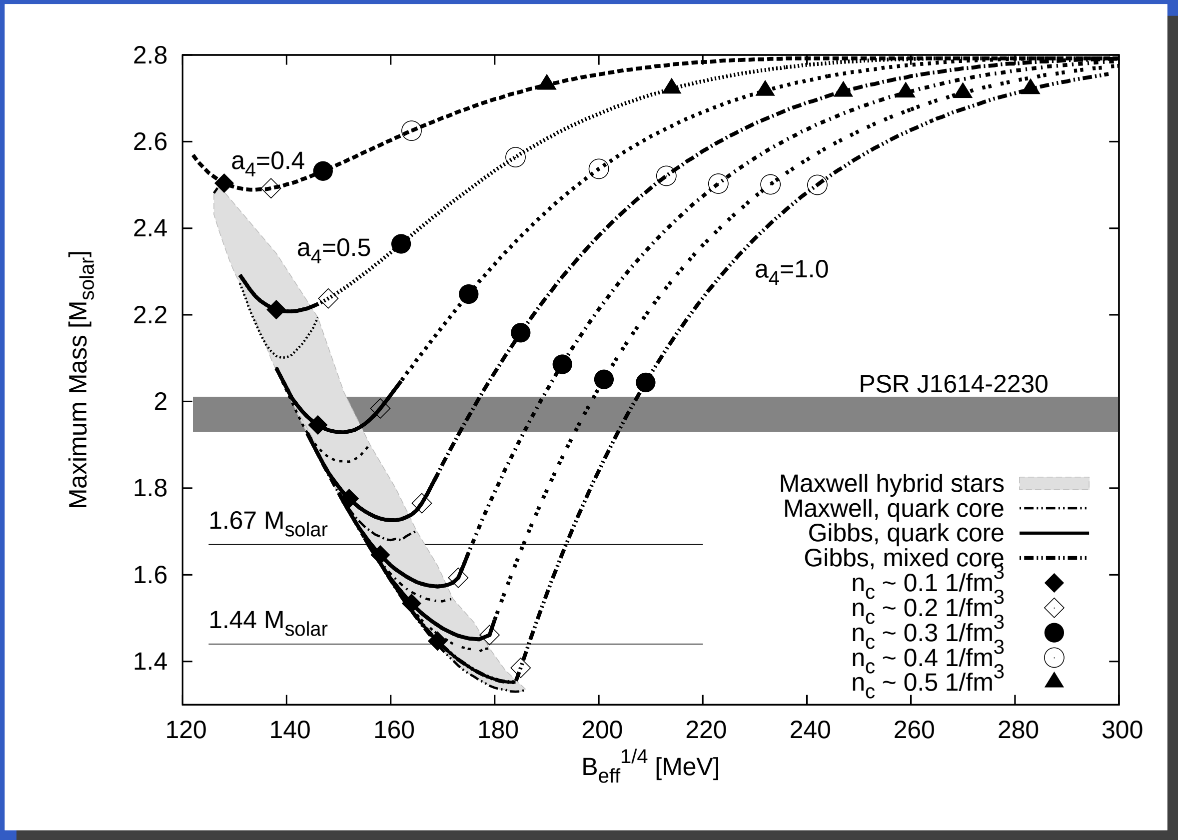
Quark Star Masses: effects of quark pairing



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

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

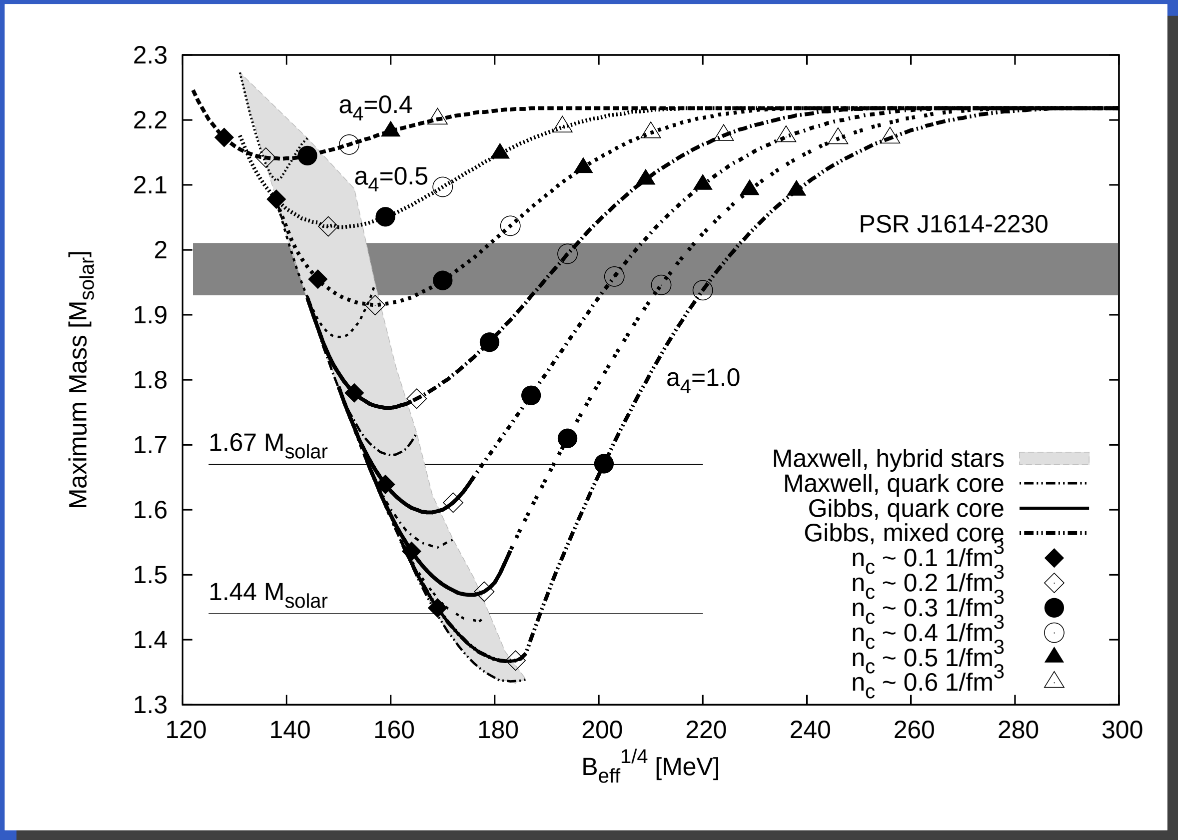
Hybrid Stars with a stiff nuclear EoS



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

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

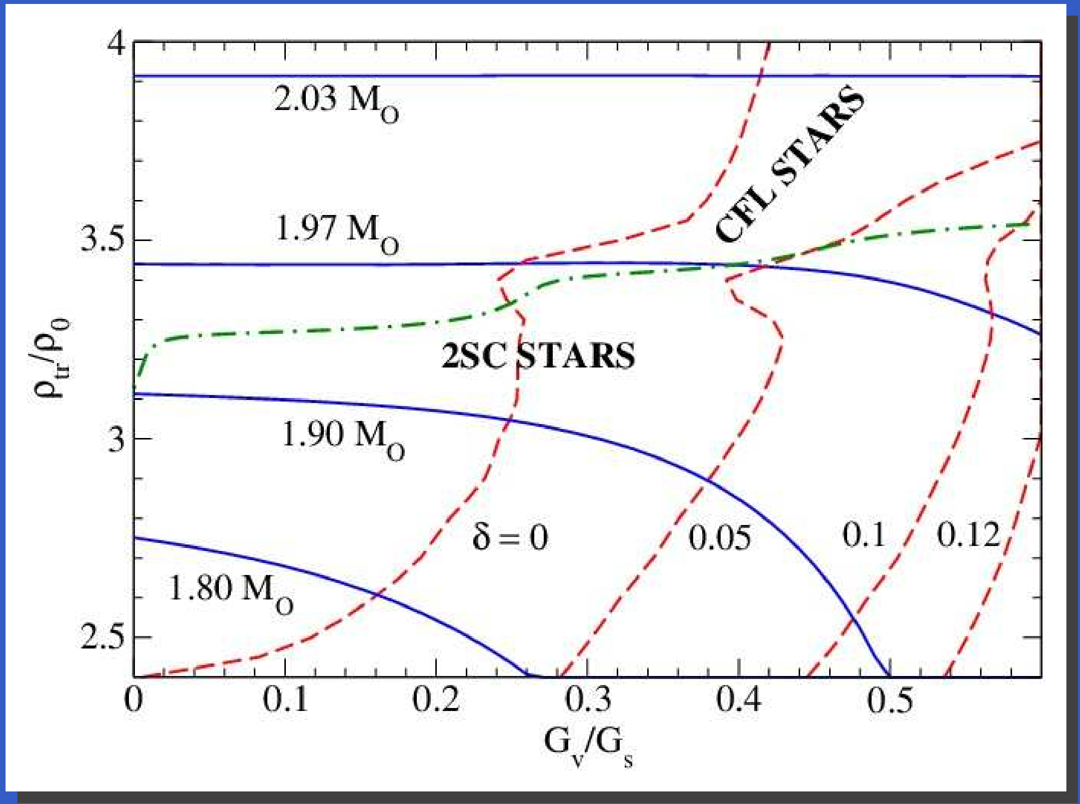
Hybrid Stars with a soft nuclear EoS



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

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

Hybrid Stars with a NJL model



(Bonanno and Sedrakian 2011)

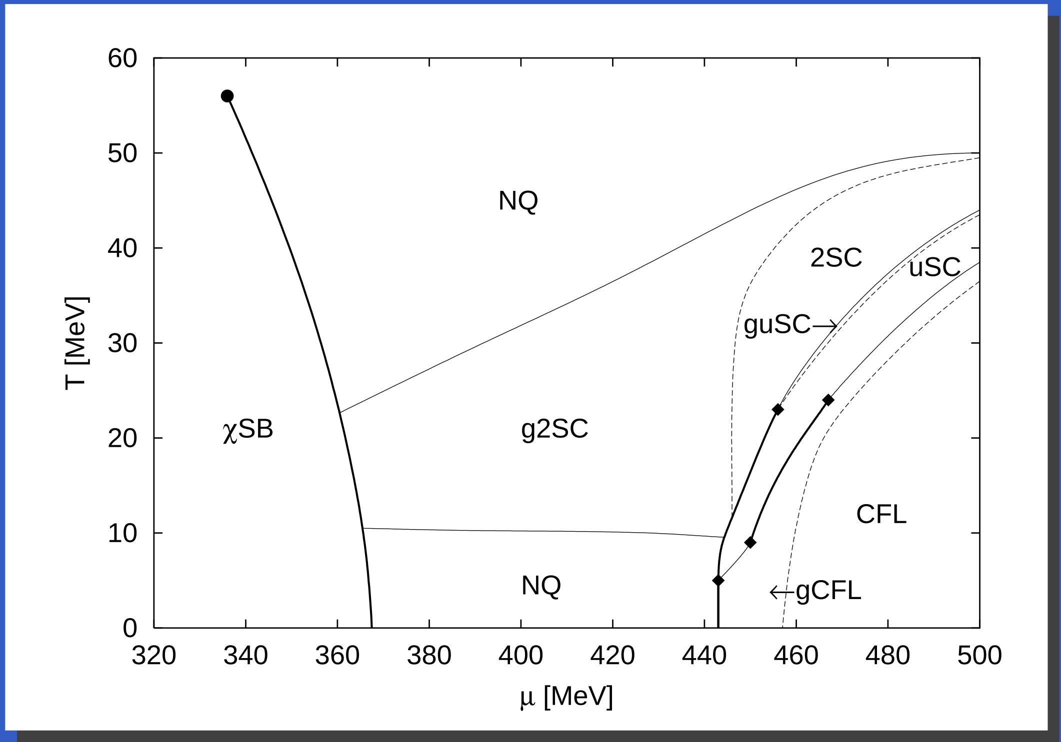
- uses Nambu-Jona-Lasinio model for quark matter
- matches to nuclear EoS with hyperons (RMF with set NL3)
- 2SC quark matter below green line
- $\delta = R_{\rm CFL}/R$: amount of CFL quark matter

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 (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

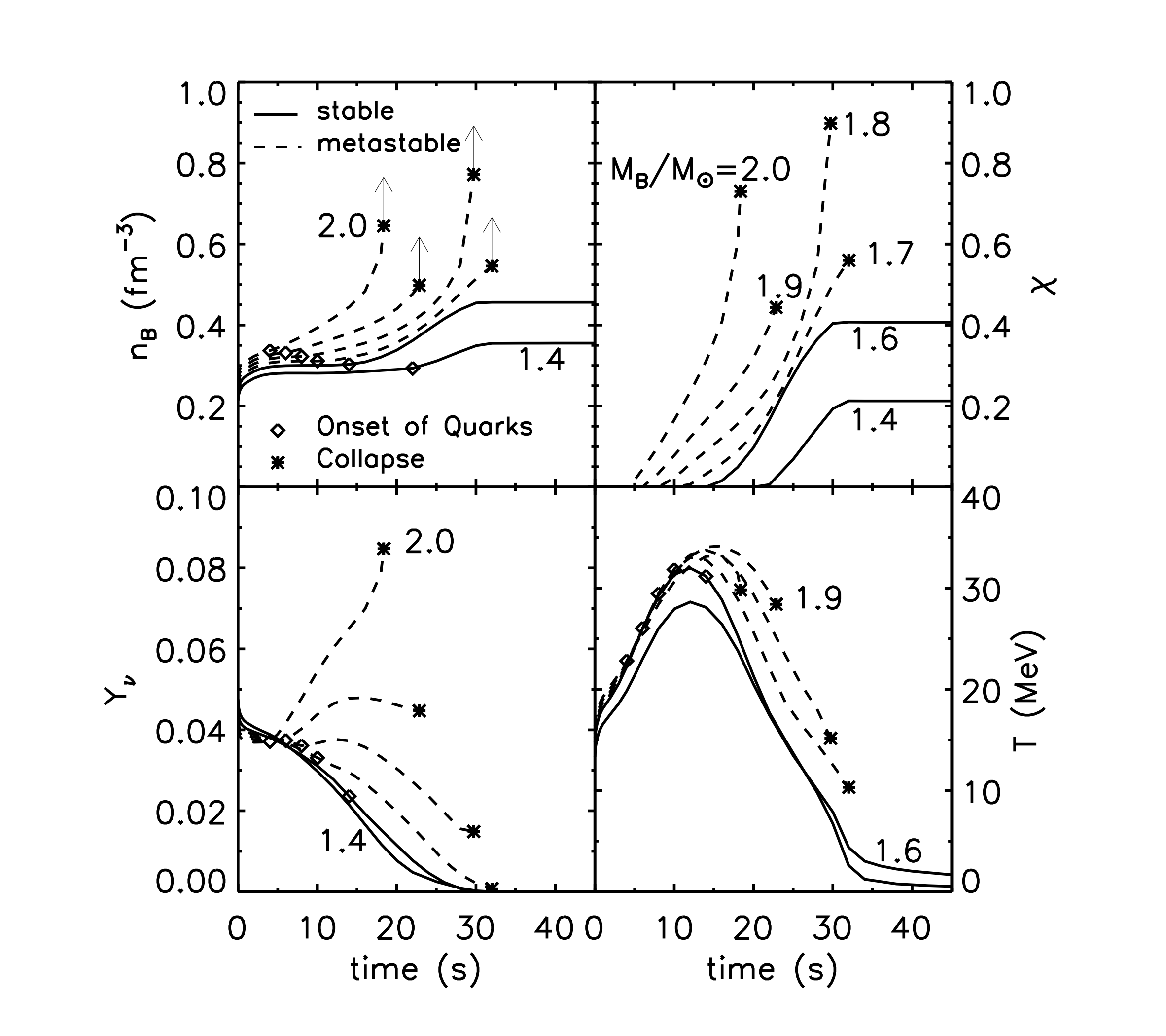
  (Alford, Rajagopal, Wilczek, Reddy, Buballa, Blaschke, Shovkovy, Drago, Rüster, Rischke, Aguilera, Banik, Bandyopadhyay, Pagliara, . . .)

QCD Phase Transition and Supernovae

Historical Notes:

- De Rujula 1987: May a supernova bang twice? (two neutrino peaks from SN1987A delayed by 5 hours)
- Hatsuda 1987: formation of a strange star within 1s!
- Gentile et al. 1993: hydro simulation with a phase transition (second shock wave, but no neutrinos included)
- Drago and Tambini 1999: prompt bounce by strange quark matter formation
- Nakazato, Sumiyoshi, Yamada 2008: SN simulation for $100 M_\odot$ with phase transition (no second shock wave)

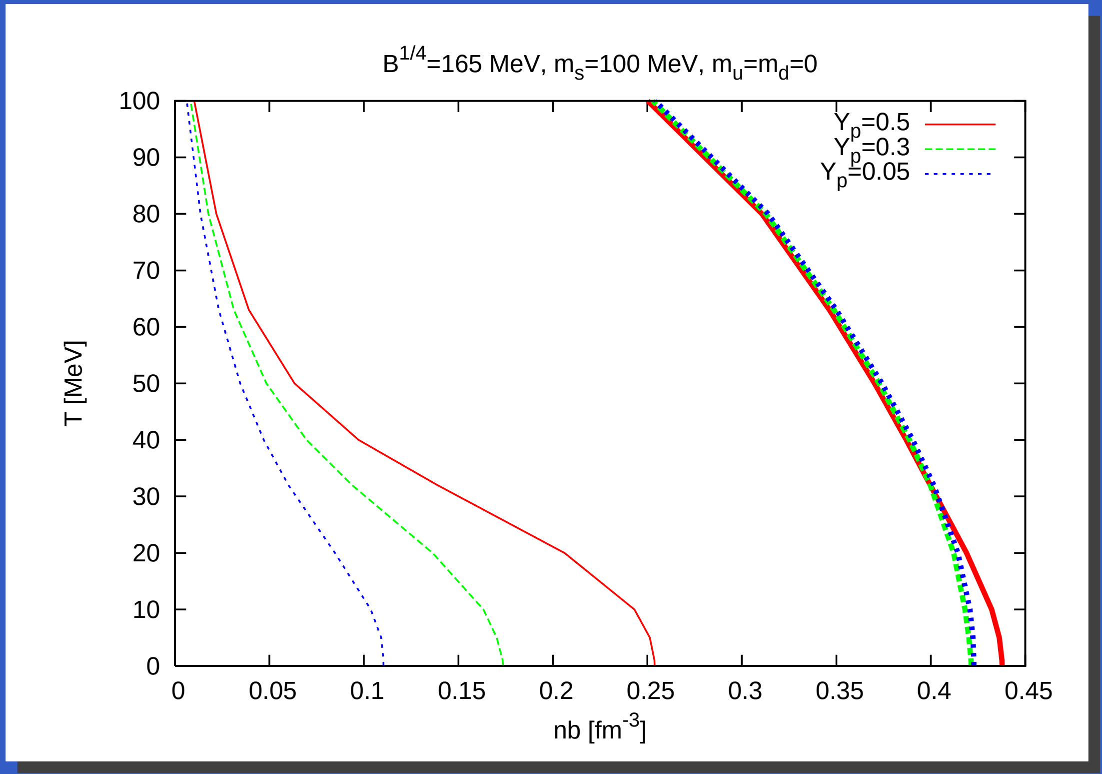
Proto-neutron star evolution with quarks



(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?

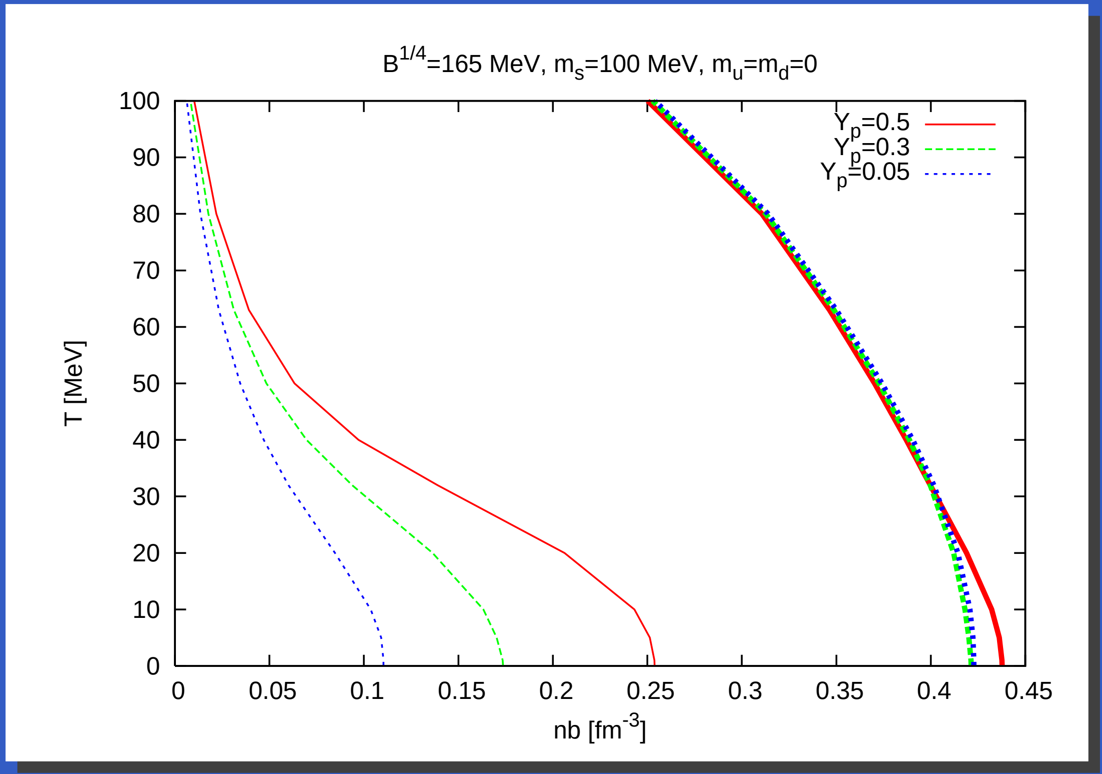
Phase Transition to Quark Matter for Astros



(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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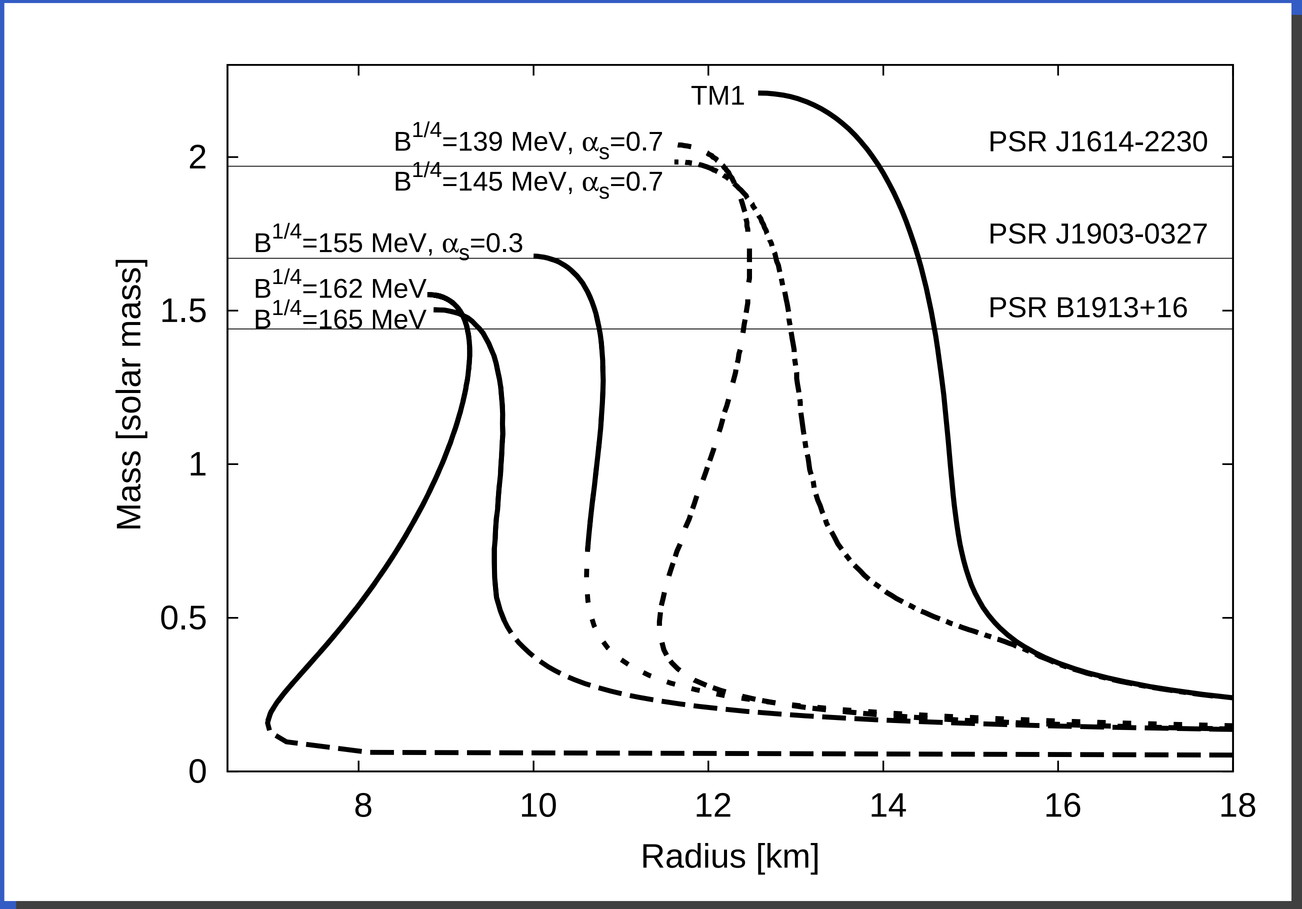
- low critical density for low Y_p due to nuclear asymmetry energy
- quark matter favoured at finite temperature
- production of quark matter in supernovae at bounce possible!

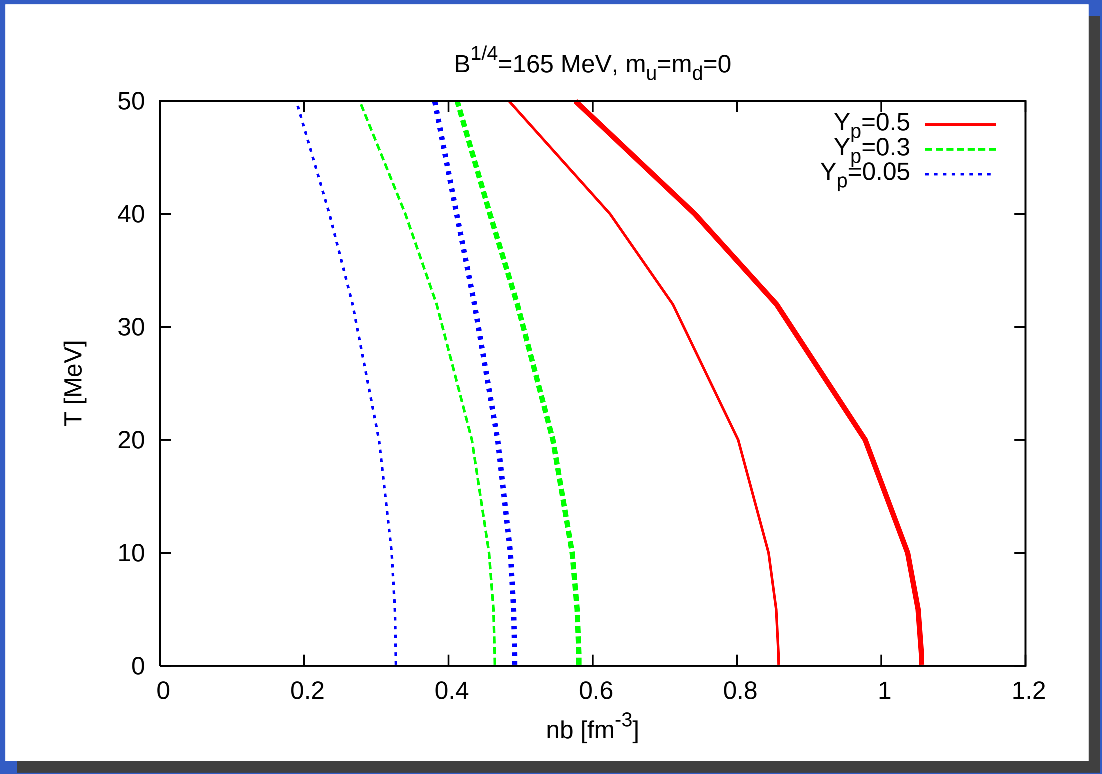
Check: Mass-Radius Diagram of Cold Neutron Stars



(Sagert, Fischer, Hempel, Pagliara, JSB, Thielemann, Liebendörfer 2011)

- presence of quark matter can change drastically the mass-radius diagram
- maximum mass: $1.56 M_\odot$ ($B^{1/4} = 162$ MeV), $1.5 M_\odot$ ($B^{1/4} = 165$ MeV)
  $\rightarrow$ too low! need α_s corrections!

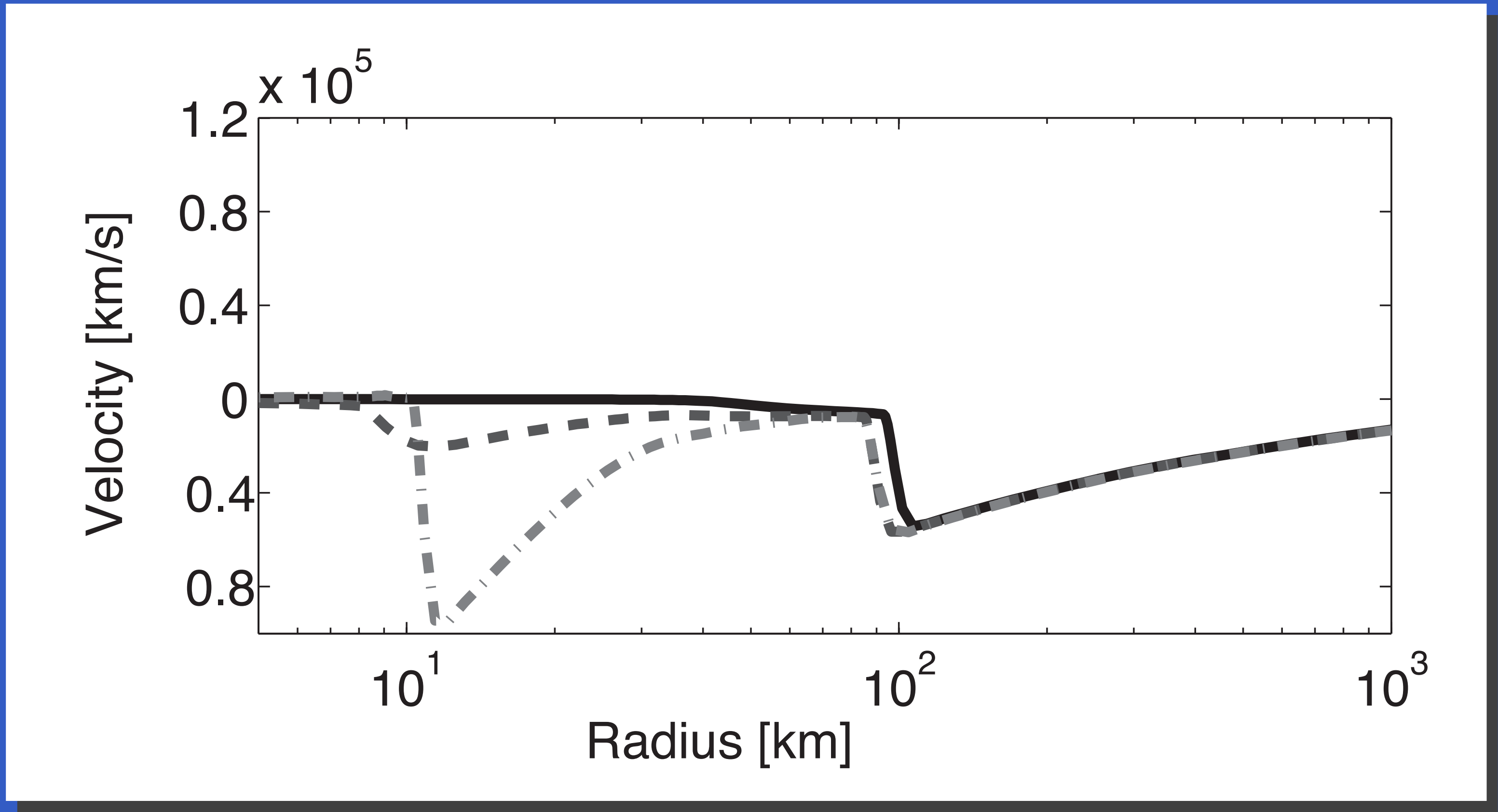
Check: Phase Transition for Heavy-Ion Collisions



(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, 2009)

- 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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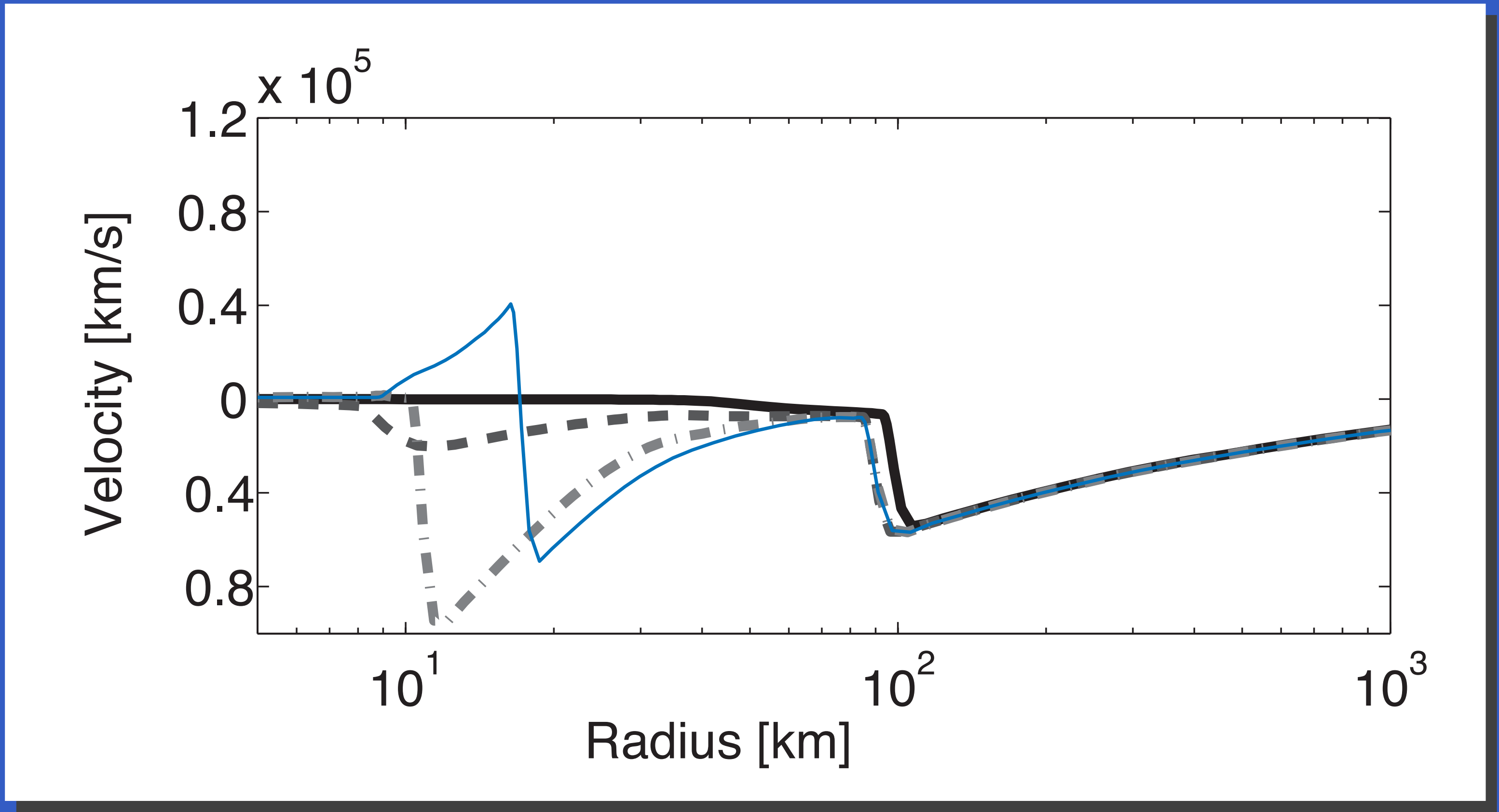

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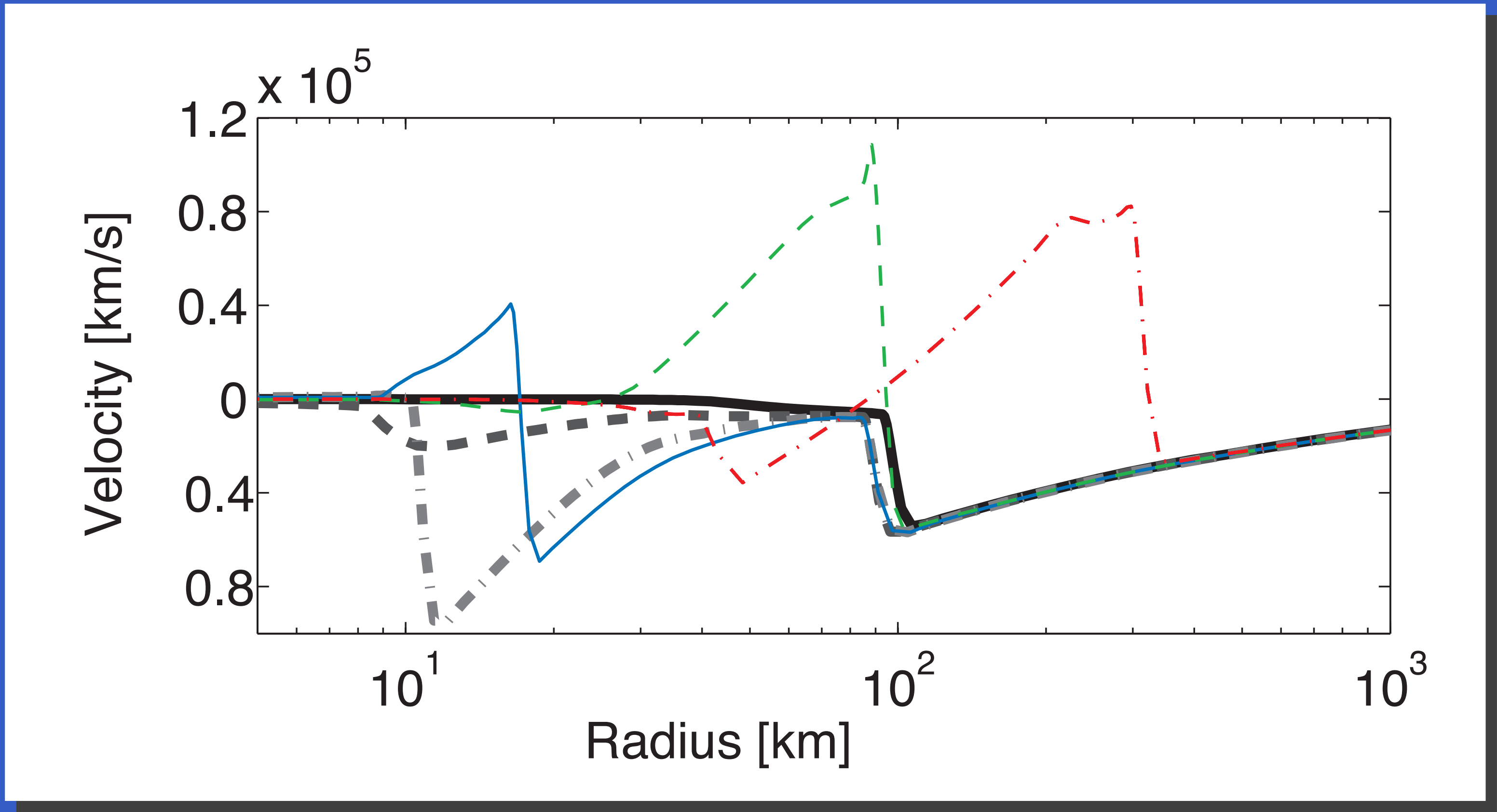
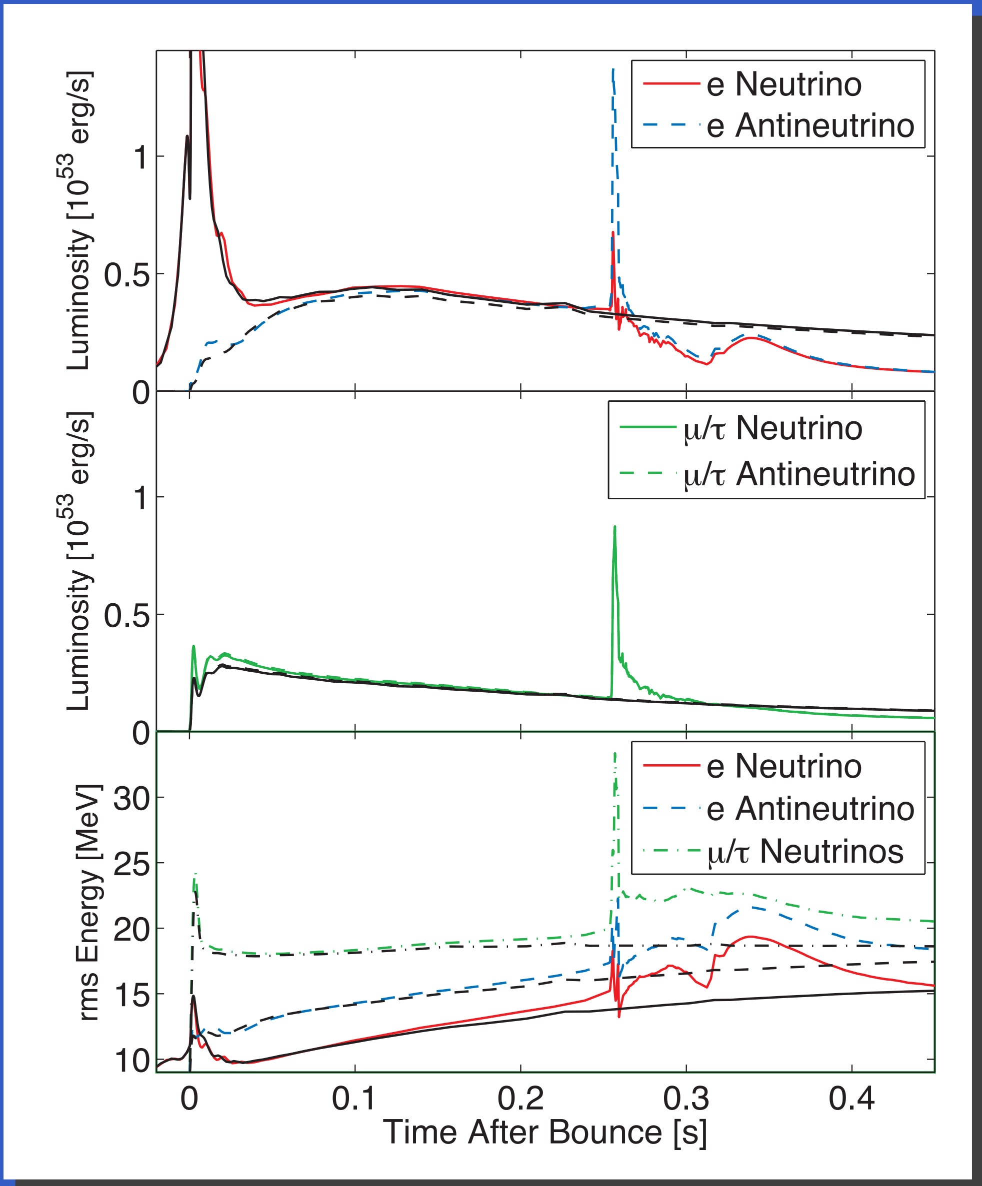


(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2009)

- 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 an delayed explosion

Implications for Supernova – Neutrino-Signal!



(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2009)

- 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

Supernova Explosion – Parameter dependence

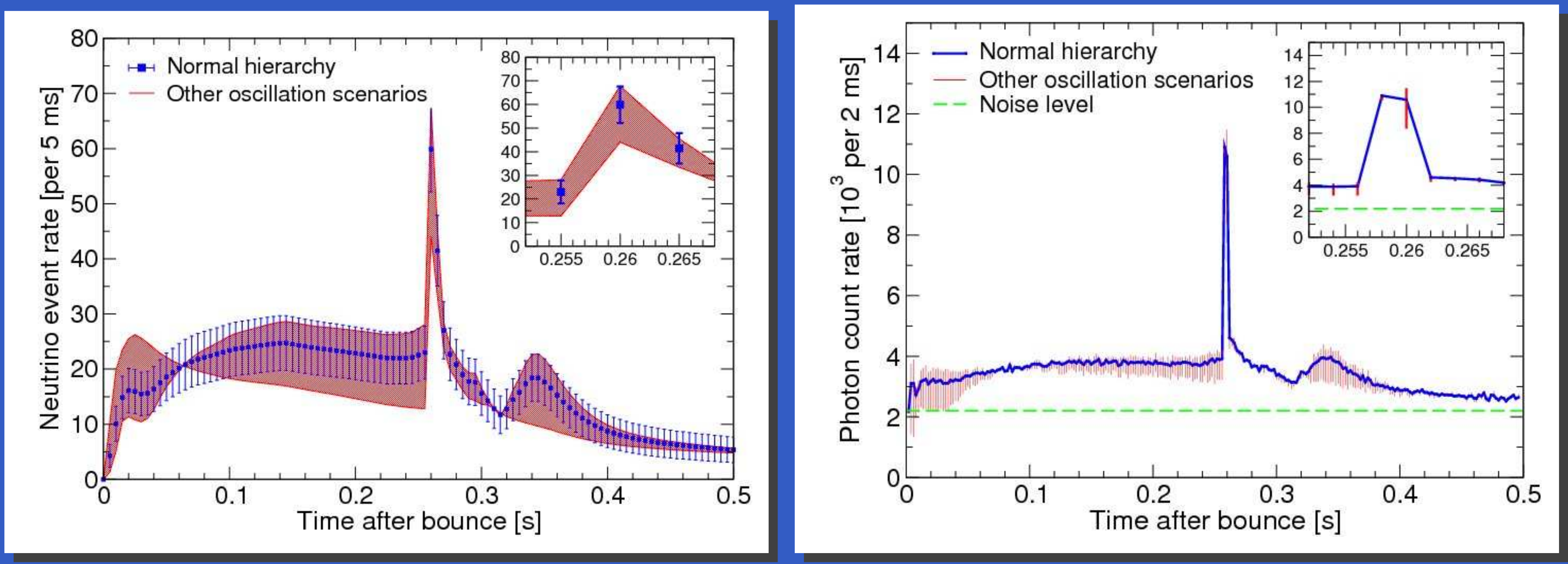
Prog. [M]	B [MeV]	t_{pb} [ms]	M_Q [M]	M_{mixed} [M]	M_{PNS} [M]	E_{expl} [10^{51} erg]
10	162	255	0.850	0.508	1.440	0.44
10	165	448	1.198	0.161	1.478	1.64
15	162	209	1.146	0.320	1.608	0.42
15	165	330[a]	1.496	0.116	1.700	unknown[b]

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

(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2009)

- 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)
- problem: so far explosion only for cases with too low a maximum mass!

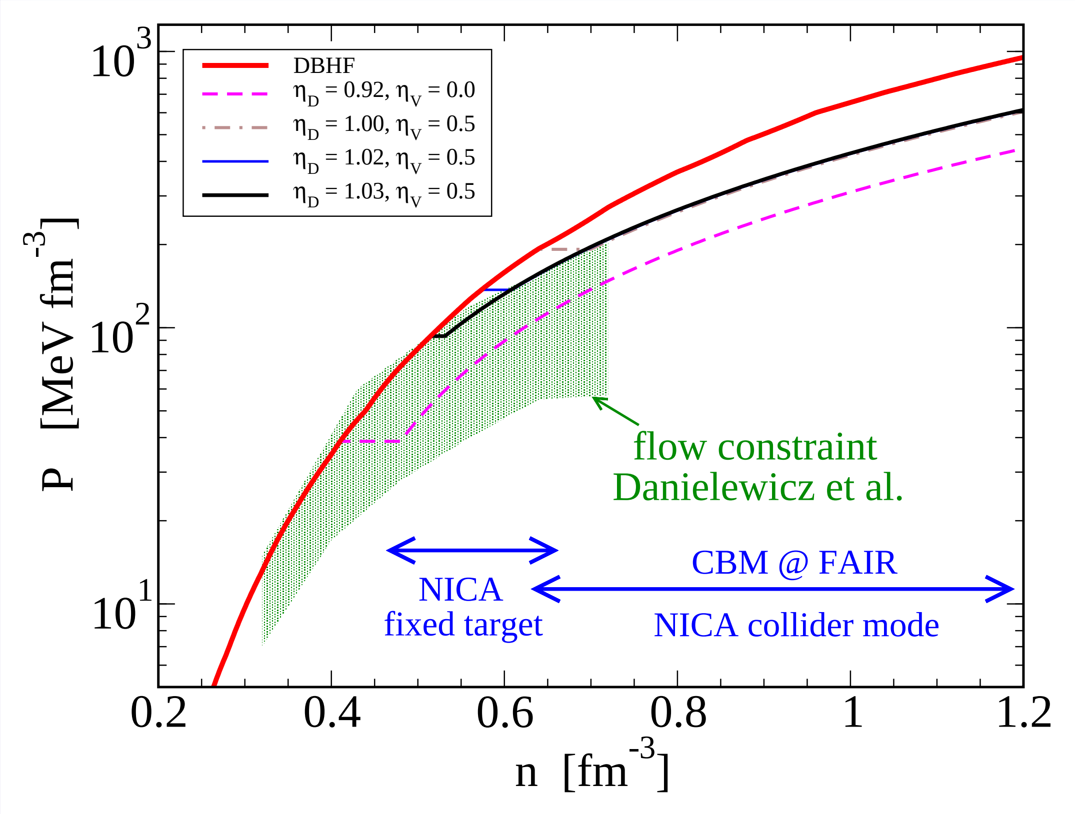
Detection with Neutrino Detectors

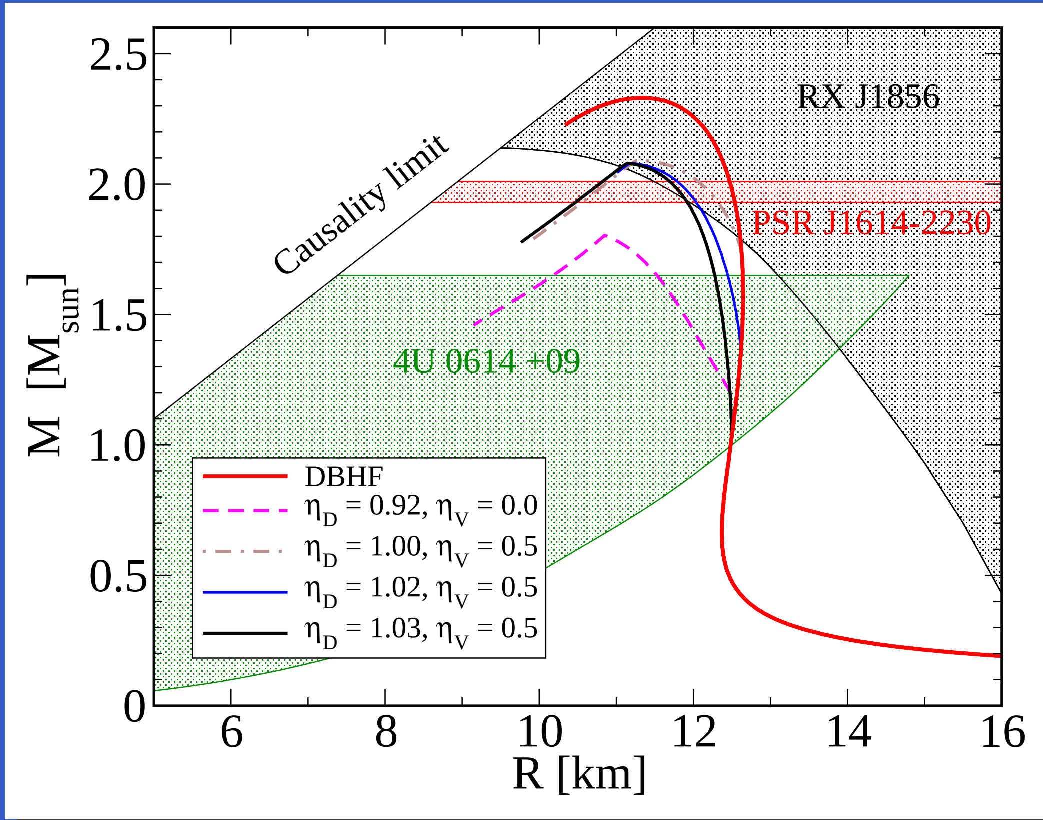


(Dasgupta, Fischer, Horiuchi, Liebendörfer, Mirizzi, Sagert, JSB, arXiv:0912.2568)

- detection of neutrinos from a SN with SuperK (left) and IceCube (right)
- mostly sensitive to antineutrinos by inverse β decay reactions ($\bar{\nu}_e P \to n e^+$)
- take spectrum from supernova simulation, SN at distance of 10 kpc
- highly sensitive to second burst from QCD phase transition!

The Future: CBM@FAIR and NICA





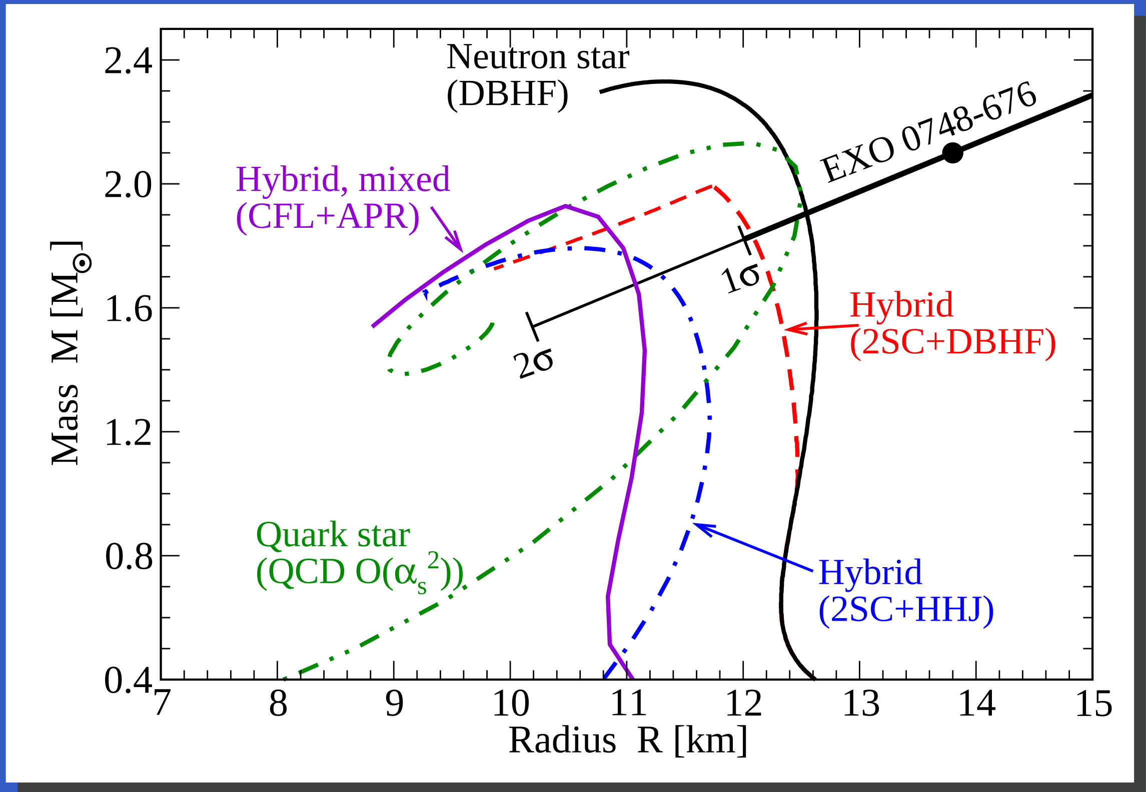
(Klähn, Blaschke, Weber 2011)

- left: equation of state and flow constraints,
  right: compatible mass-radius relations and astrophysical constraints
- higher baryon densities achieved at higher bombarding energy
- probing densities beyond $2 - 3n_0$

Summary

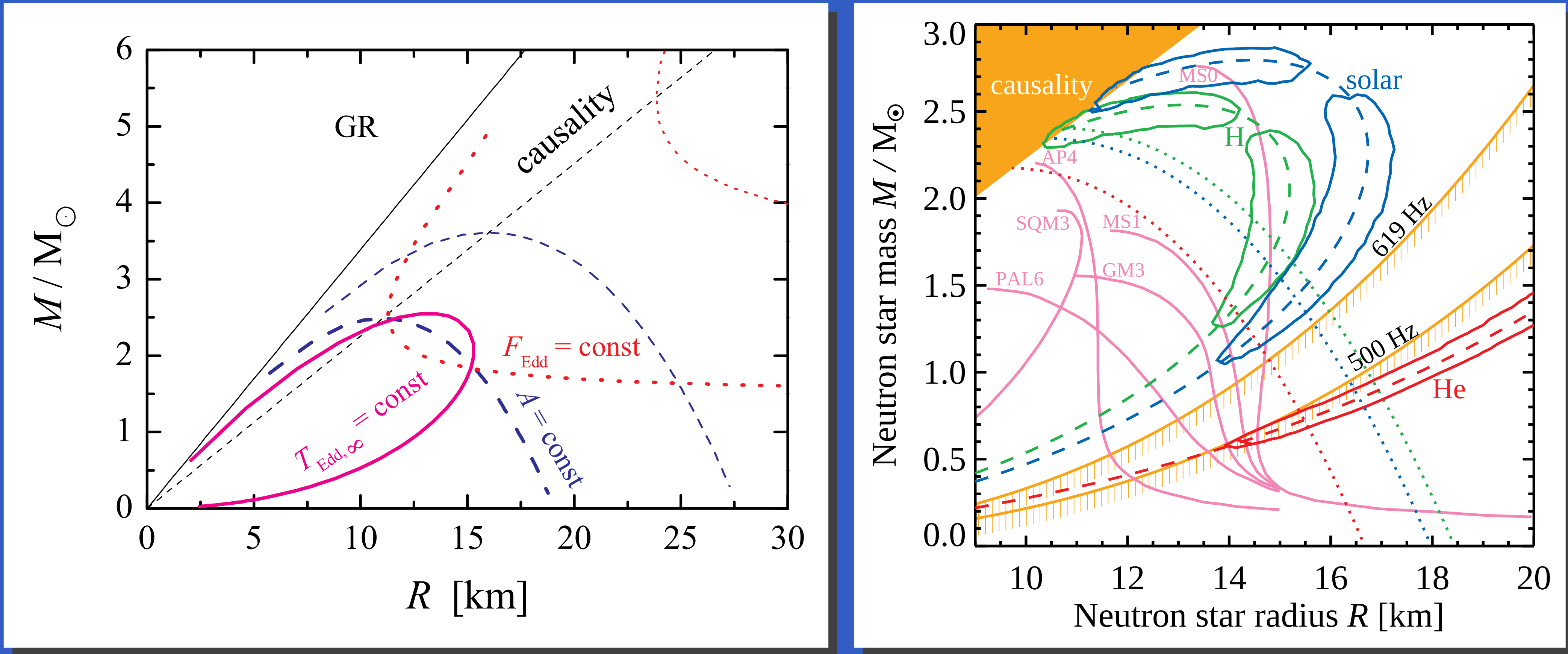
- QCD phase transition can occur in the core of neutron stars
  $\Longrightarrow$ new family of compact stars possible, explosive phenomena
- transition can be present during a supernova, shortly after the first bounce
  $\Longrightarrow$ second shock forms, visible in a a second peak in the (anti-)neutrino signal, gravitational waves (?), r-process nucleosynthesis (?) ...
- to stimulate your fancies: color superconducting phase change transport properties – implications for SN neutrino spectra?

X-Ray burster EXO 0748–676 and Quark Matter



- analysis of Özel (Nature 2006): $M \geq 2.10 \pm 0.28 M_\odot$ and $R \geq 13.8 \pm 1.8$ km, claims: 'unconfined quarks do not exist at the center of neutron stars'!
- reply by Alford, Blaschke, Drago, Klähn, Pagliara, JSB (Nature 445, E7 (2007)): limits rule out soft equations of state, not quark stars or hybrid stars!
- multiwavelength analysis of Pearson et al. (2006): data more consistent with $M = 1.35 M_\odot$ than with $M = 2.1 M_\odot$

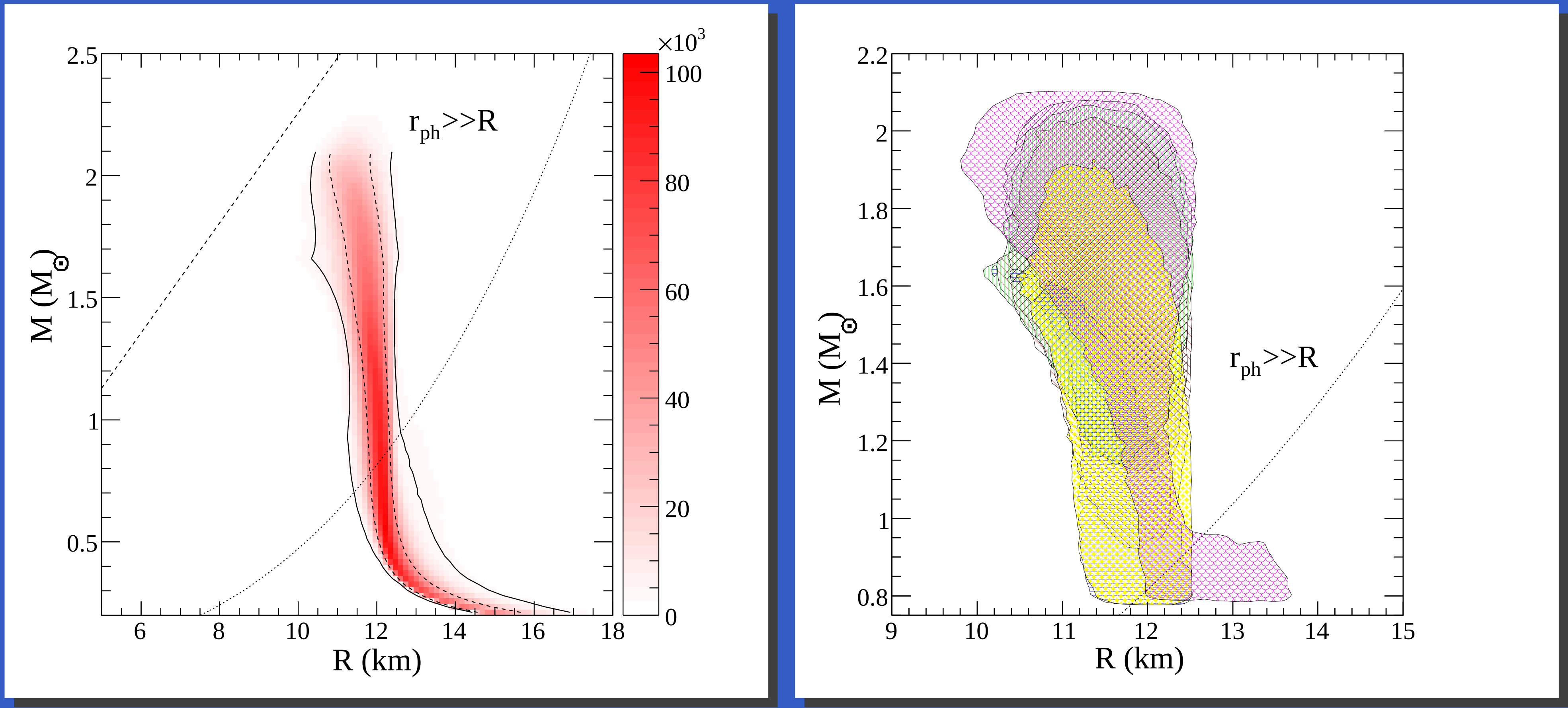
Fits to X-Ray Burster Spectra



(Suleimanov, Poutanen, Revnivtsev, Werner 2011)

- x-ray burster with photospheric radius expansion
- assume (color-corrected) black-body emission and Eddington flux at ’touch-down’ (Ozel 2006): simple model fit fails above a certain distance!
- large correction from model atmosphere composition

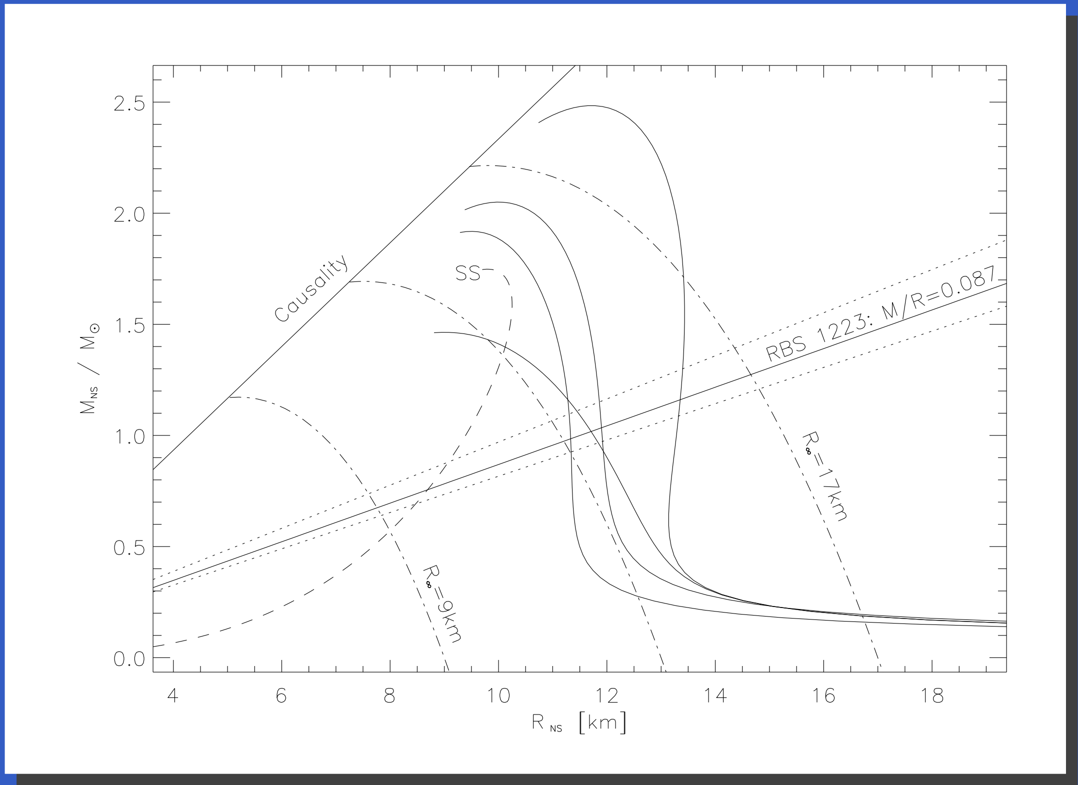
Mass-Radius Constraints from X-Ray Burster and Binaries



(Steiner, Lattimer, Brown 2011)

- fit to three x-ray burster data with photospheric radius expansion and three quiescent x-ray binaries (from previous analysis)
- relax constraint at 'touch-down' to be on the surface ($r_{ph} \gg R$)
- strong constraint on radius relation (left: combined fit, right: separate fits)

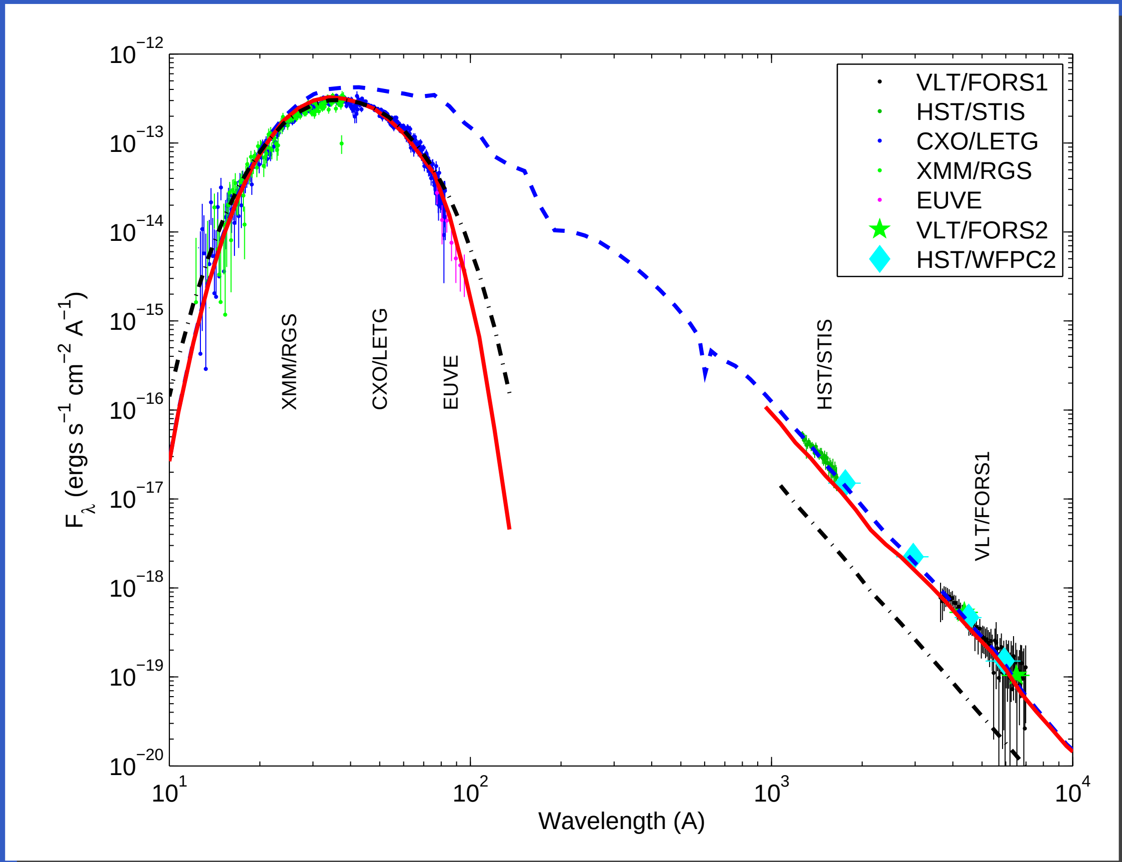
Mass-Radius Constraints from Isolated Neutron Stars

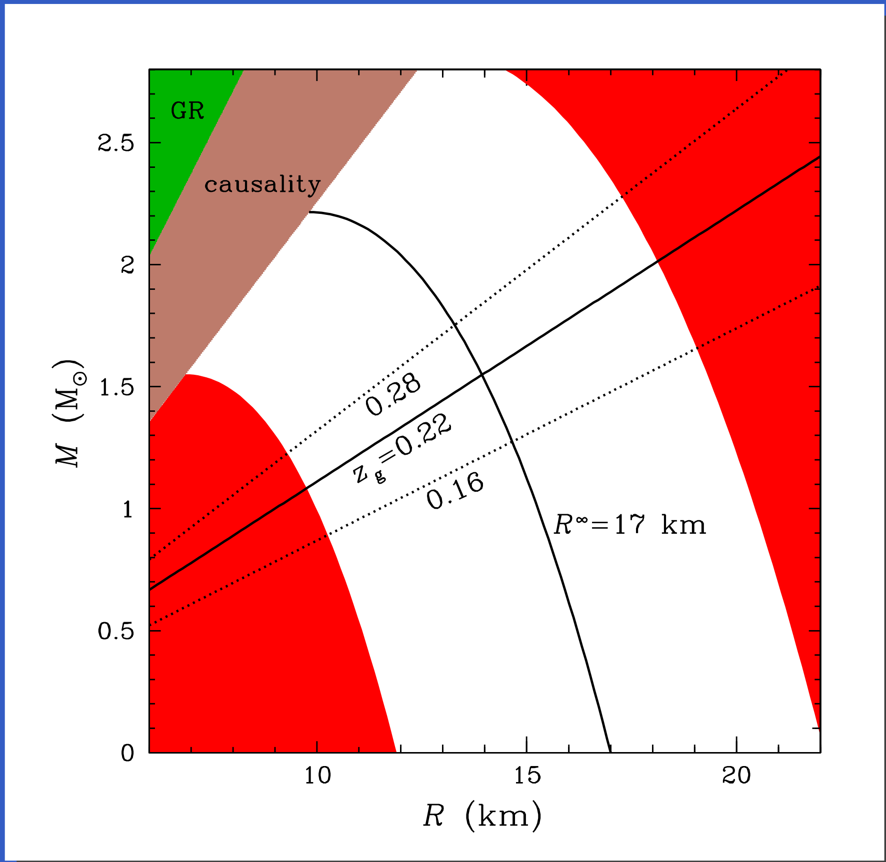


(Hambaryan, Suleimanov, Schwope, Neuhäuser, Werner, Potekhin 2011)

- isolated neutron star, pulses in x-rays
- phase space resolved x-ray spectroscopy
- fit to geometry of hot spot etc. including redshift z
- resulting compactness: $(M/M_\odot)/(R/\mathrm{km}) = 0.087 \pm 0.004$
- indication for a stiff equation of state

RXJ 1856: Neutron Star or Quark Star? (Trümper et al. (2003), Ho et al. (2007))

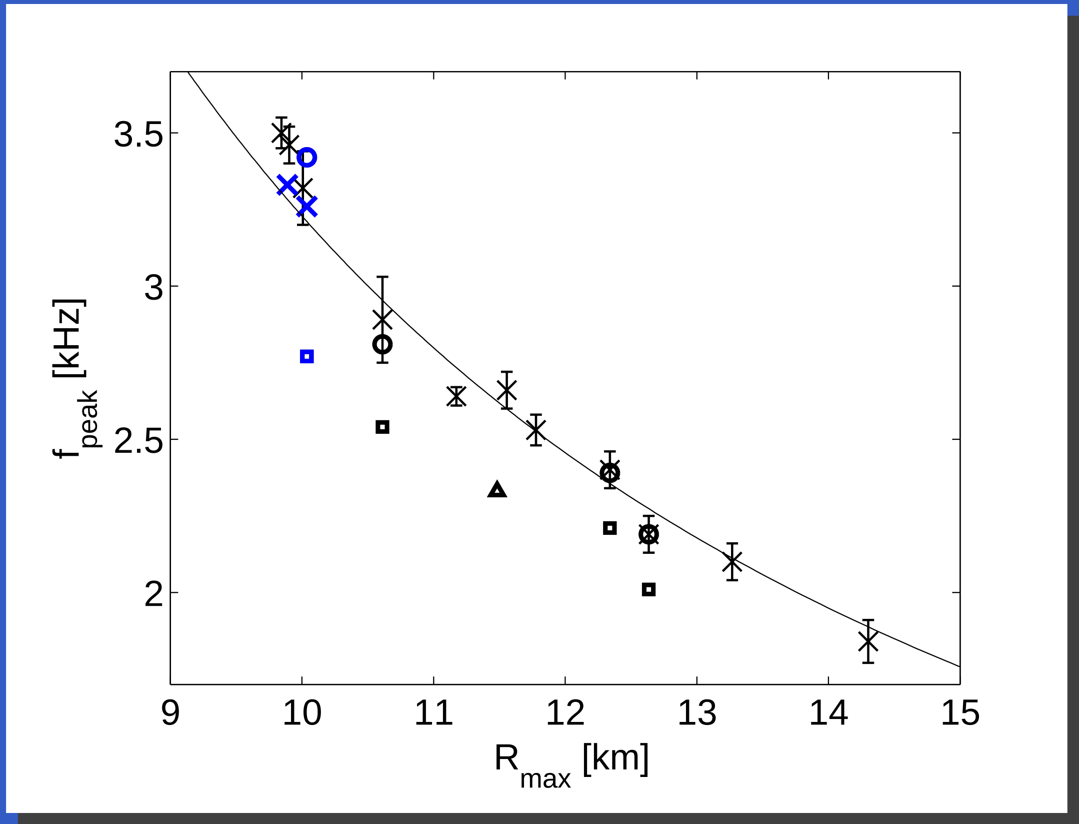




- two-component blackbody: small soft temperature, so as not to spoil the x-ray
- this implies a rather LARGE radius so that the optical flux is right!
- lower limit for radiation radius: $R_\infty = R/\sqrt{1-2GM/R} = 17$ km (d/140 pc)
- from parallax measurement: distance $d = 123(+11, -15)pc$

(Walter, Eisenbeiss, Lattimer, Kim, Hambaryan, Neuhaeuser 2011)

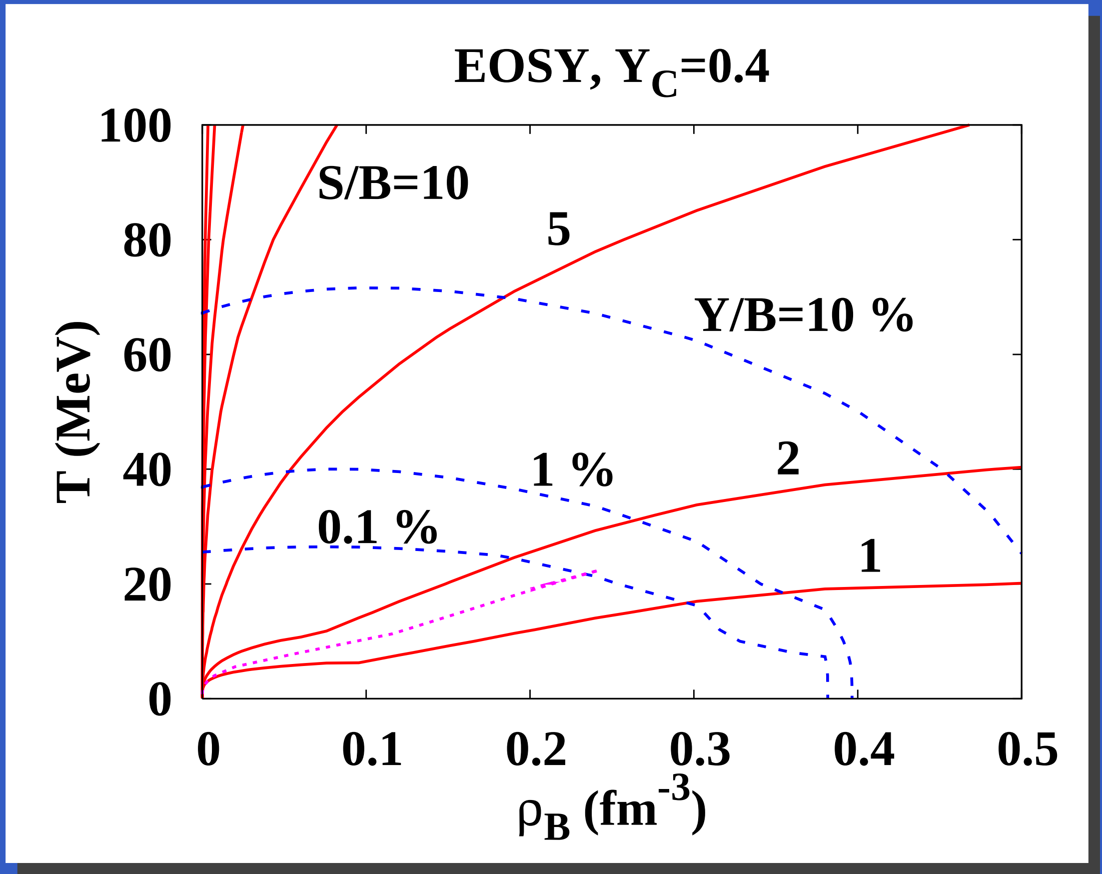
Neutron Star Radii from Neutron Star Mergers



(Bauswein and Janka, 2012)

- neutron star merger simulation with 3D smoothed particle hydro code using conformal flatness approximation
- strong correlation with peak frequency in gravitational waves and neutron star radius rather insensitive to masses of neutron stars
- measurable with advanced LIGO in a few years

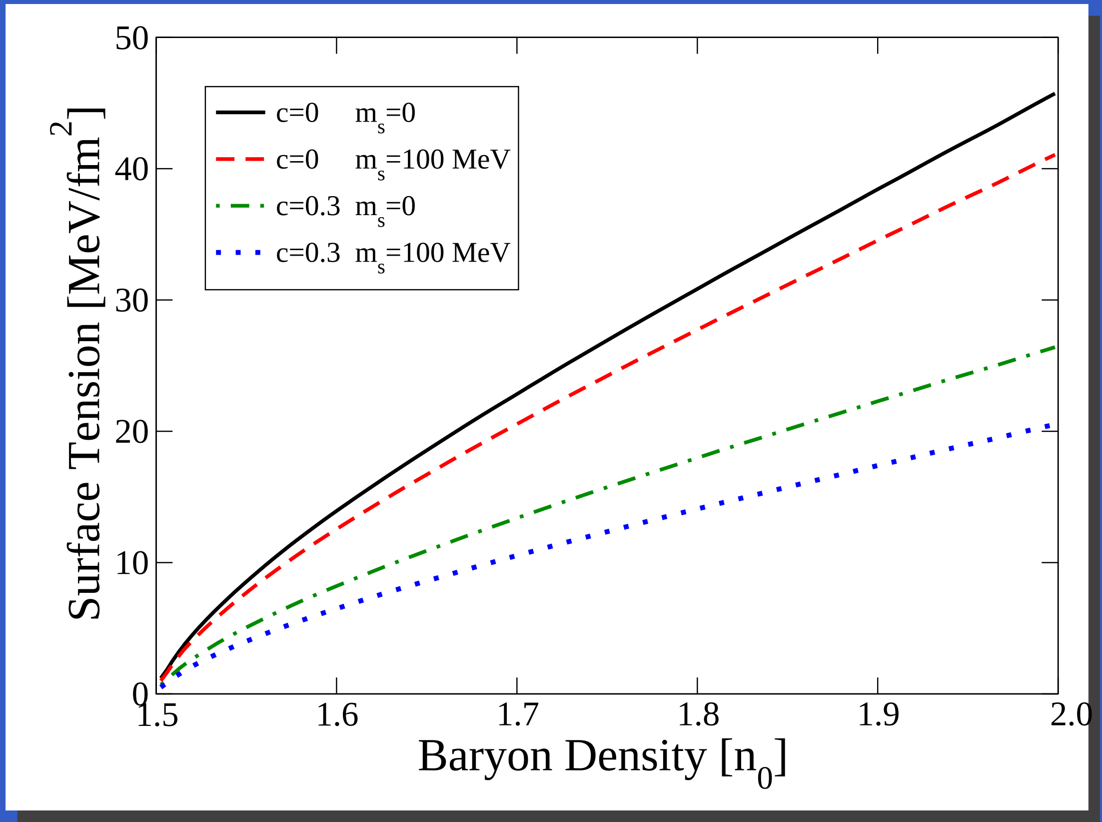
Strangeness in Supernova Matter: Hyperons



C. Ishizuka, A. Ohnishi, K. Tsubakihara, K. Sumiyoshi, S. Yamada (2008)

- 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!

Nucleation Timescales for strange quark matter

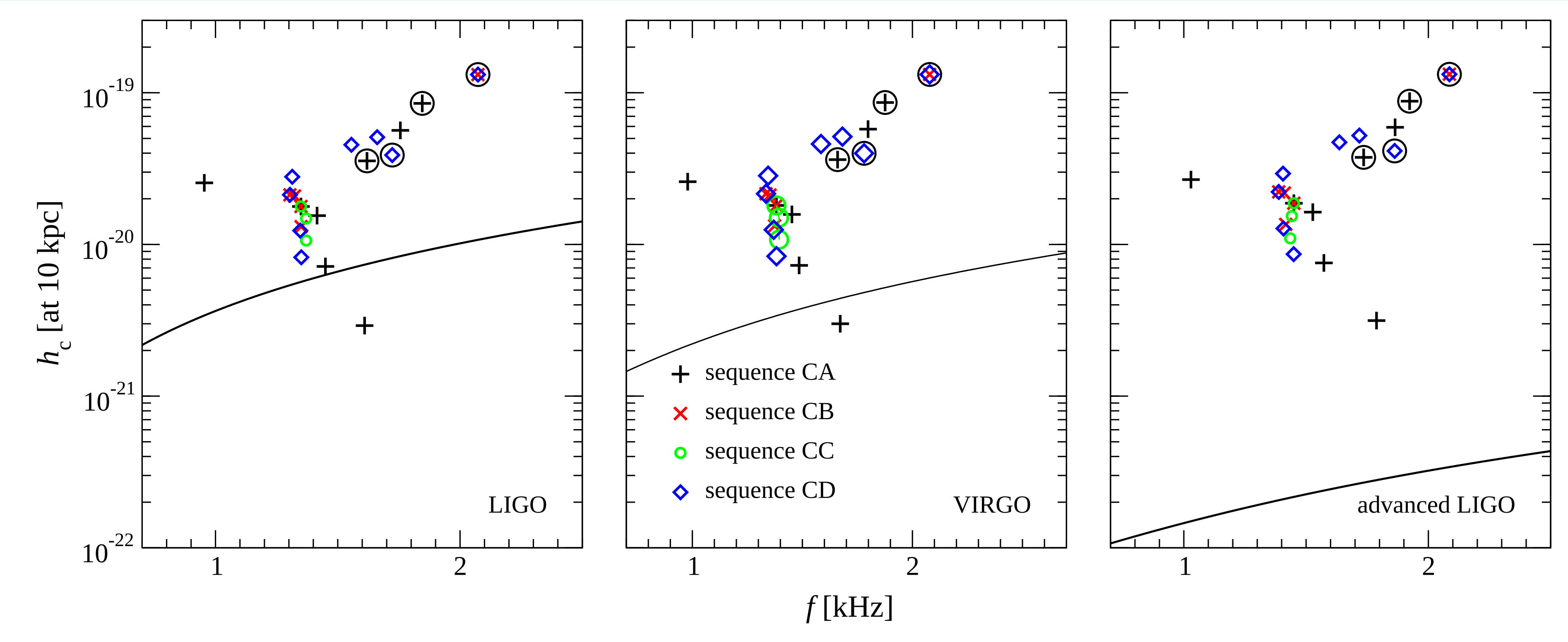


(B. W. Mintz, E. Fraga, G. Pagliara, JSB, arXiv:0910.3927)

- nucleation of strange quark matter via fluctuations in strangeness
- timescales for different surface tensions and densities (quark EoS used: $p = (1-c)\mu_i^4/(4\pi^2)$)
- bubble nucleation within 1 km^3 within 100 ms for $\sigma < 20$ MeV fm^{-2}

Gravitational Wave Amplitudes

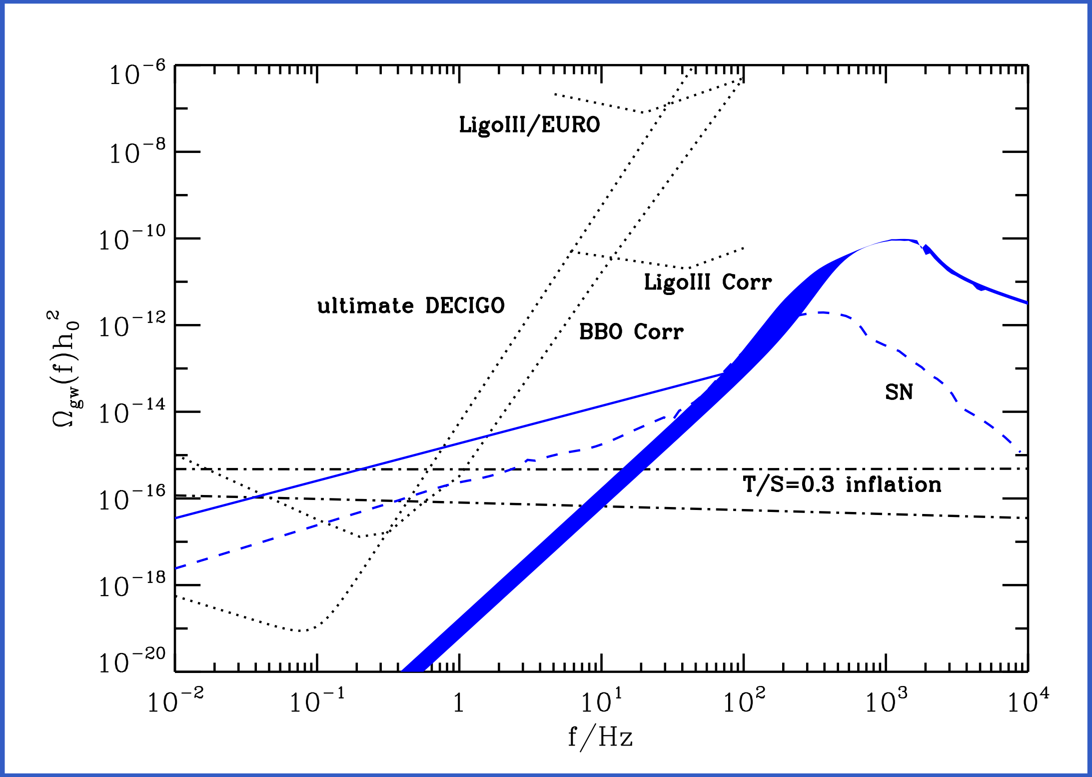
(Abdikamalov, Dimmelmeier, Rezzolla, Miller 2008)



- amplitude of gravitational wave signal from collapsing neutron stars at 10kpc
- above sensitivity of present (LIGO, VIRGO) and well above future (Advanced LIGO) detector
- events in Virgo cluster (20 Mpc) needs probably third generation detectors

Gravitational Wave Background from Phase Transitions

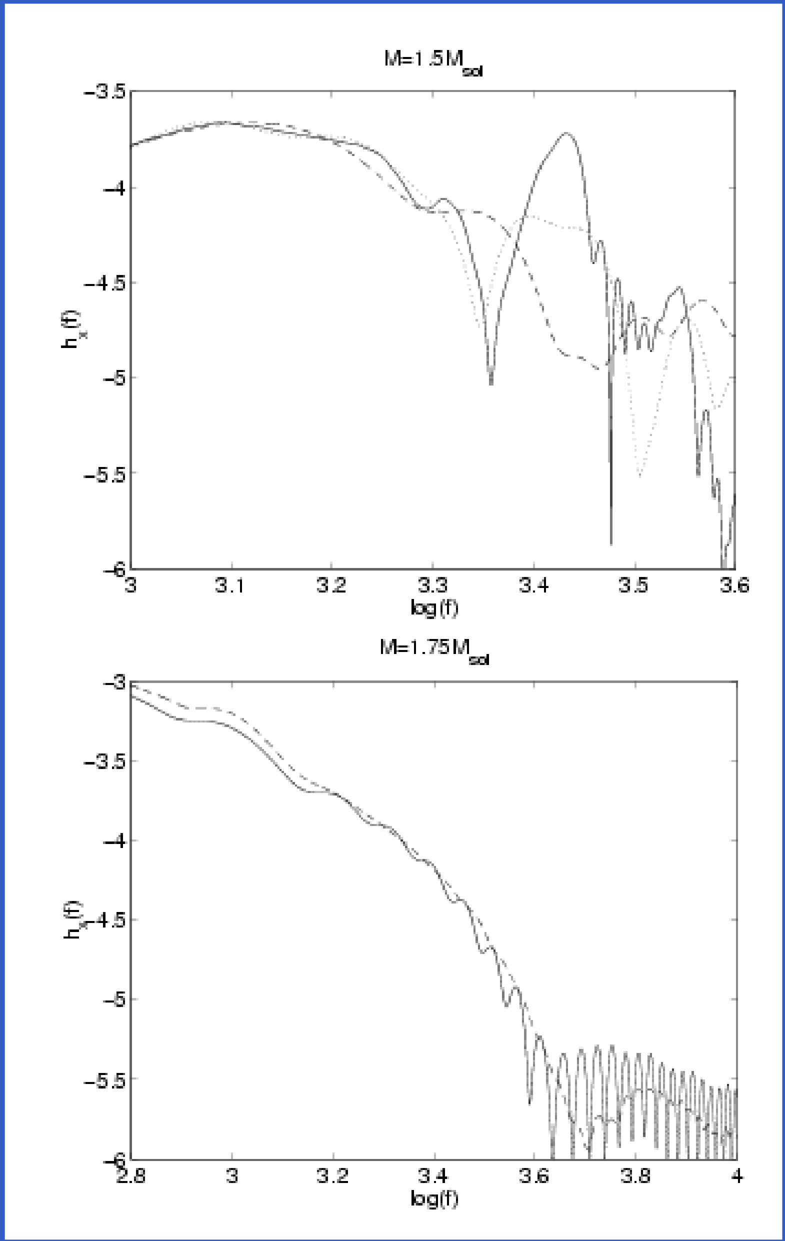
(Sigl 2007)



- Phase transitions in neutron stars generate gravitional waves (blue band, for anisotropic neutrino emission: solid blue line)
- background of such gravitational waves detectable with future space detectors!
- signal larger than the one for conventional type II Supernovae (dashed line) and from inflation (dash-dotted lines)

Gravitational wave signals from hybrid stars

(Oechslin, Uryū, Pogosyan, Thielemann 2004)



- Fourier spectra of gravitational waves
- increasing initial mass from top to bottom
- solid line: neutron star, dashed line: hybrid star
- different spectra for hybrid stars!