Equation of State for Heavy-Ion and Compact Star Physics

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HGSFP

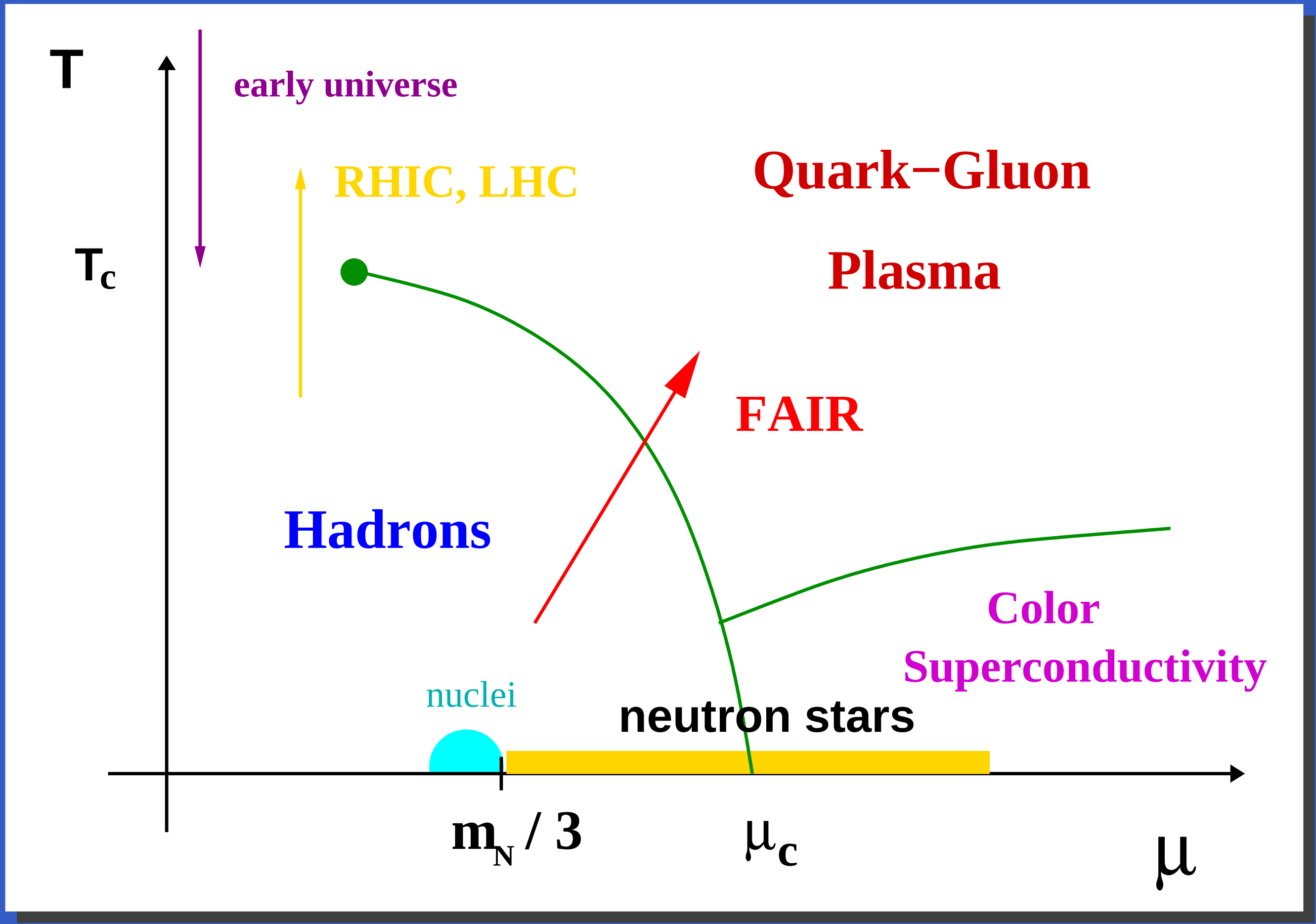
EMMI

World Class University Heavy-Ion Meeting

Asian Pacific Center for Theoretical Physics (APCTP)

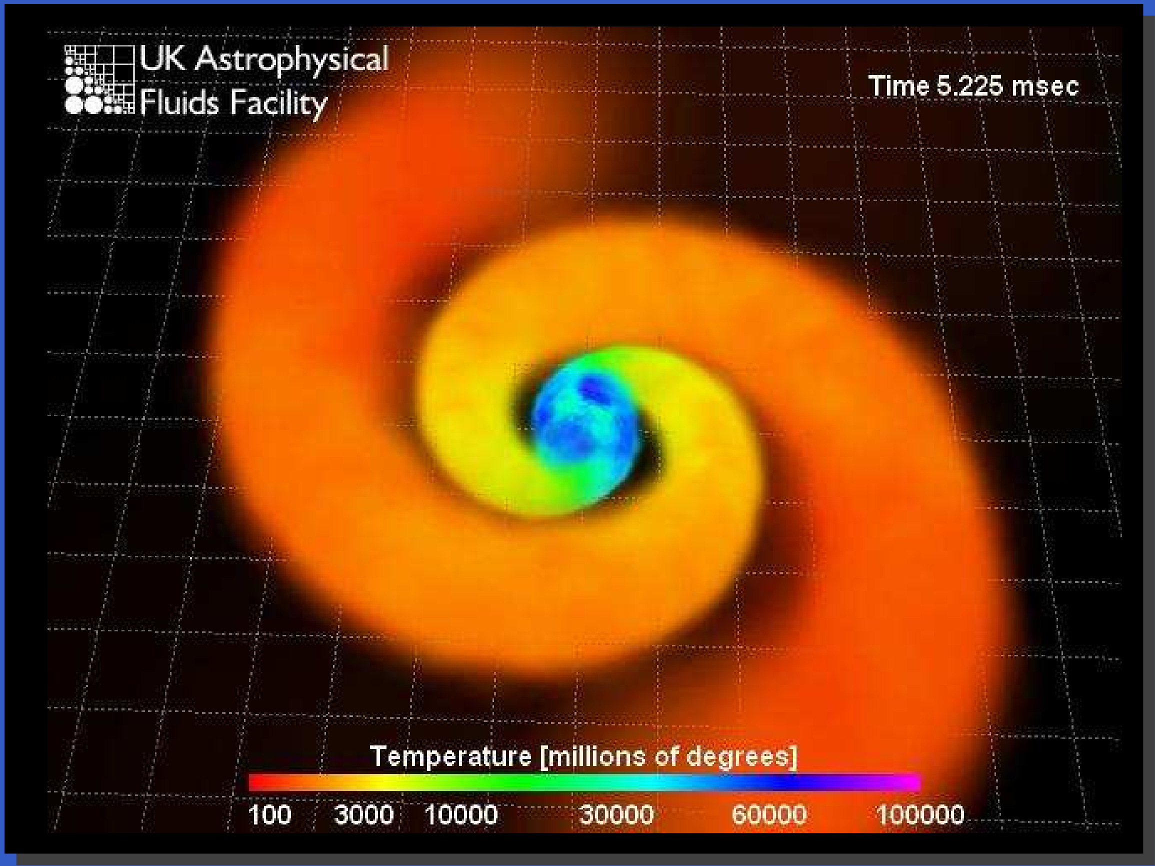
Pohang, South Korea, May 29, 2010

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!

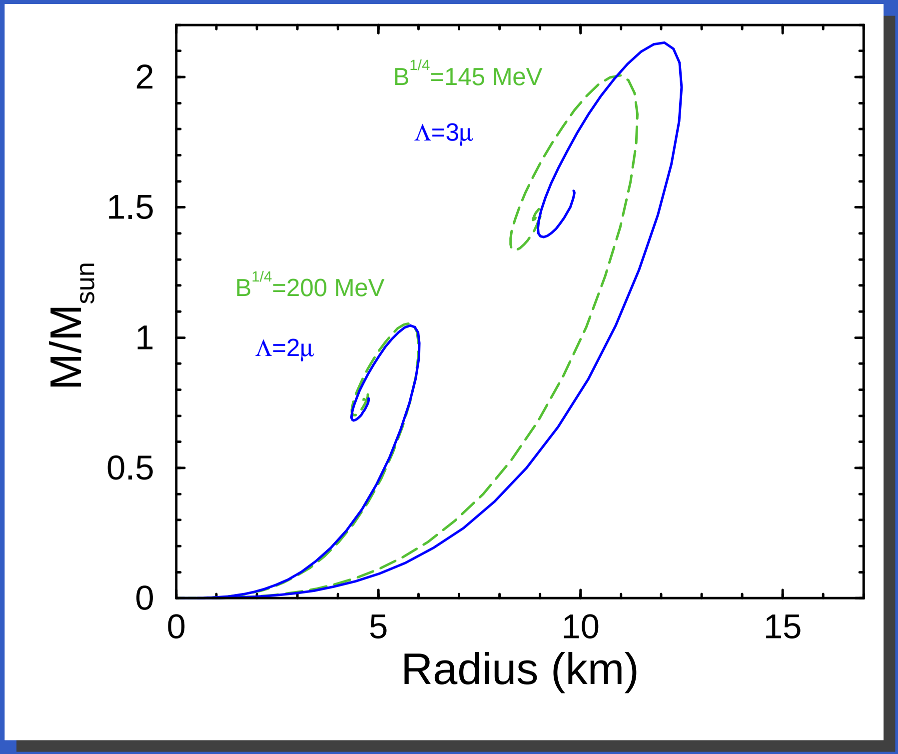
QCD Equation of State as Input in Astrophysics



- 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, $n = 10^{-10}$–$10n_0$

QCD Phase Transition in Neutron Stars

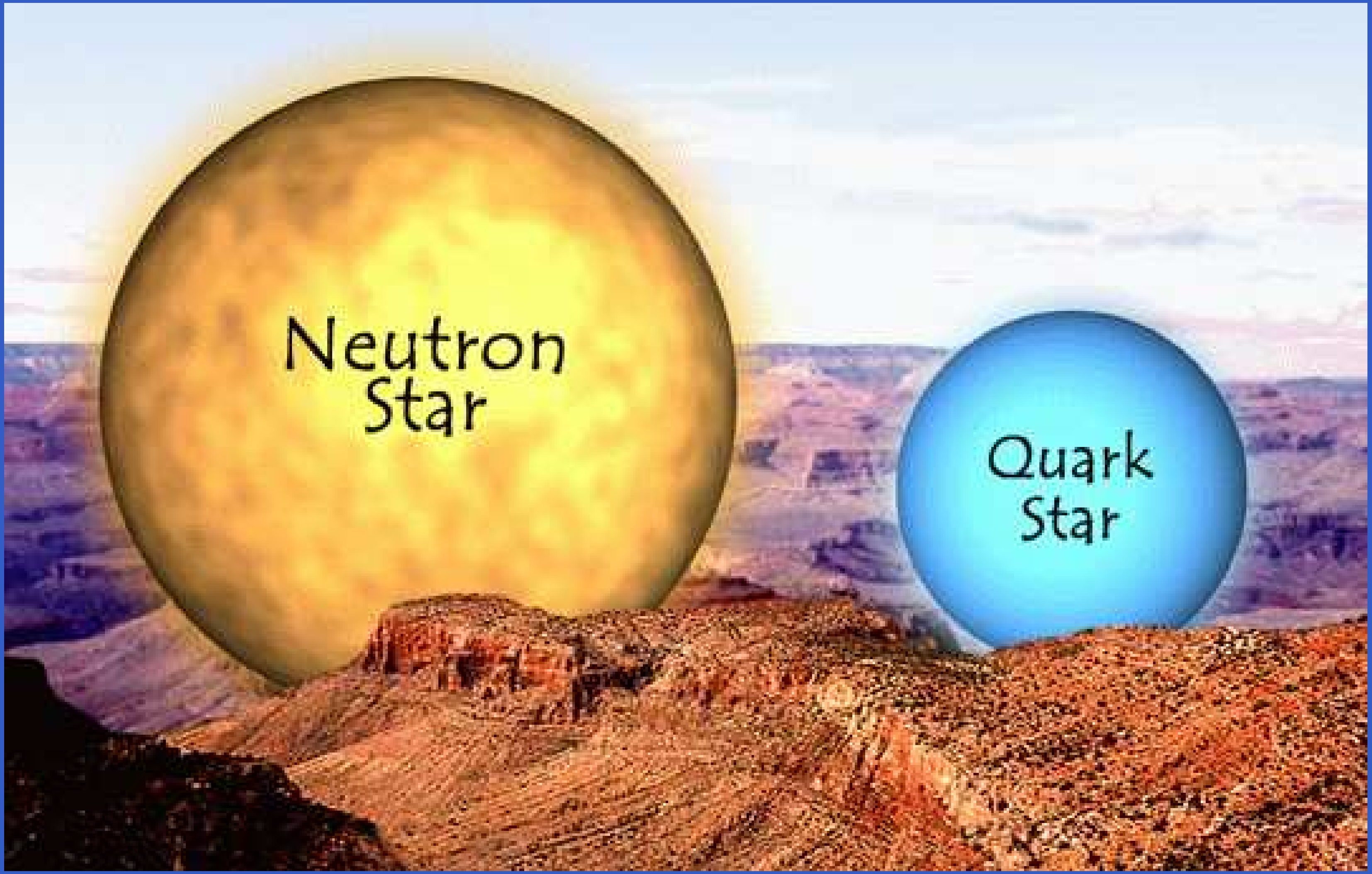
Pure quark(yonic) stars



- green curves: MIT bag model (Witten 1984, Haensel, Zdunik, Schaeffer 1986, Alcock, Farhi, Olinto 1986, see also Baym and Chin 1976)
- blue curves: perturbative QCD calculations to $\mathcal{O}(\alpha_s^2)$ (Freedman and McLerran 1978, Fraga, JSB, Pisarski 2001)

- case $\Lambda = 2\mu$: $M_{\max} = 1.05\, M_\odot$, $R_{\max} = 5.8$ km, $n_{\max} = 15\, n_0$
- case $\Lambda = 3\mu$: $M_{\max} = 2.14\, M_\odot$, $R_{\max} = 12$ km, $n_{\max} = 5.1\, n_0$
- other nonperturbative approaches: Schwinger–Dyson model (Blaschke et al.), massive quasiparticles (Peshier, Kämpfer, Soff), NJL model (Hanauske et al.), HDL (Andersen and Strickland), . . .
- note: pure quark stars can be very similar to ordinary neutron stars!

A Quark Star? (NASA press release 2002)

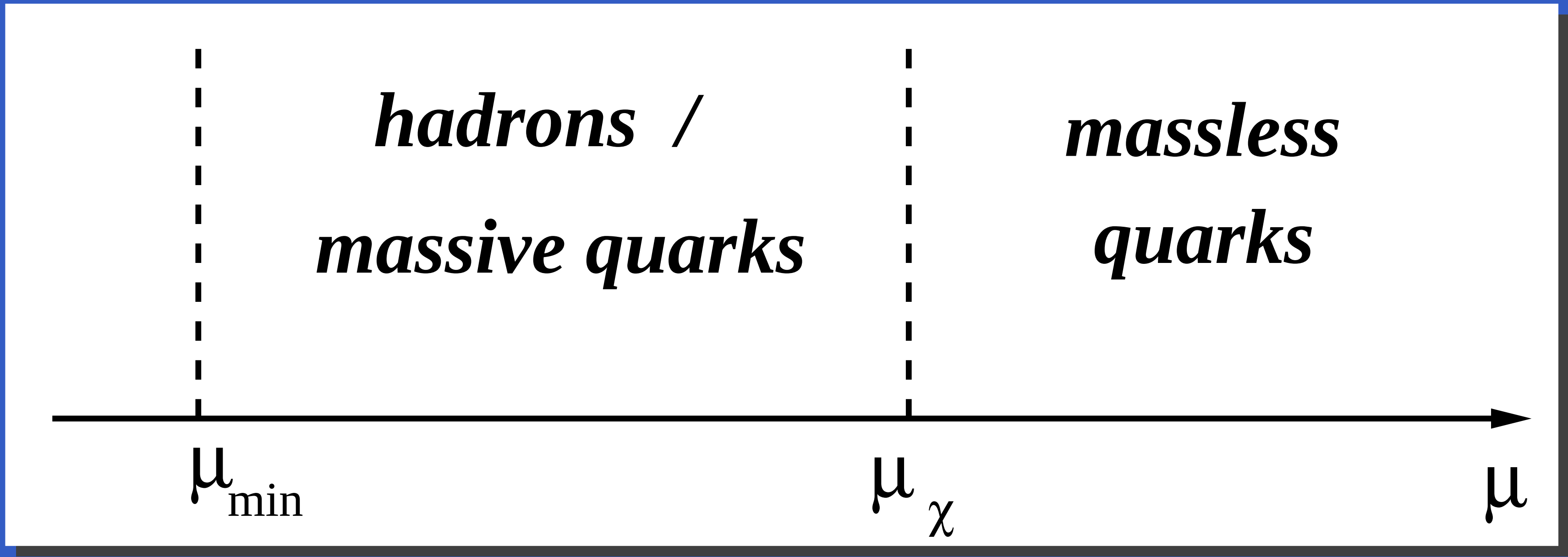


NASA news release 02-082:

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

— a quark star?

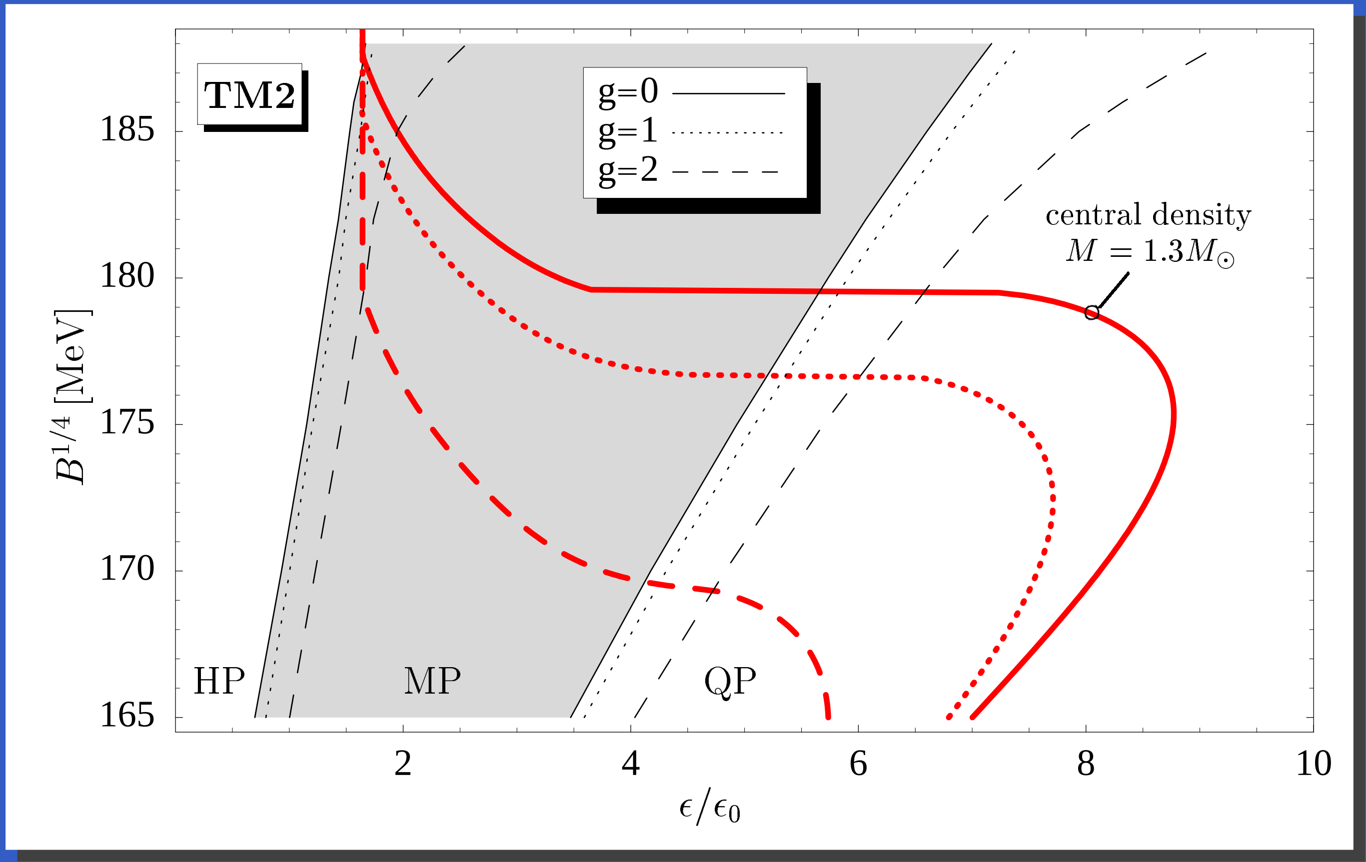
Matching to low density EoS



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

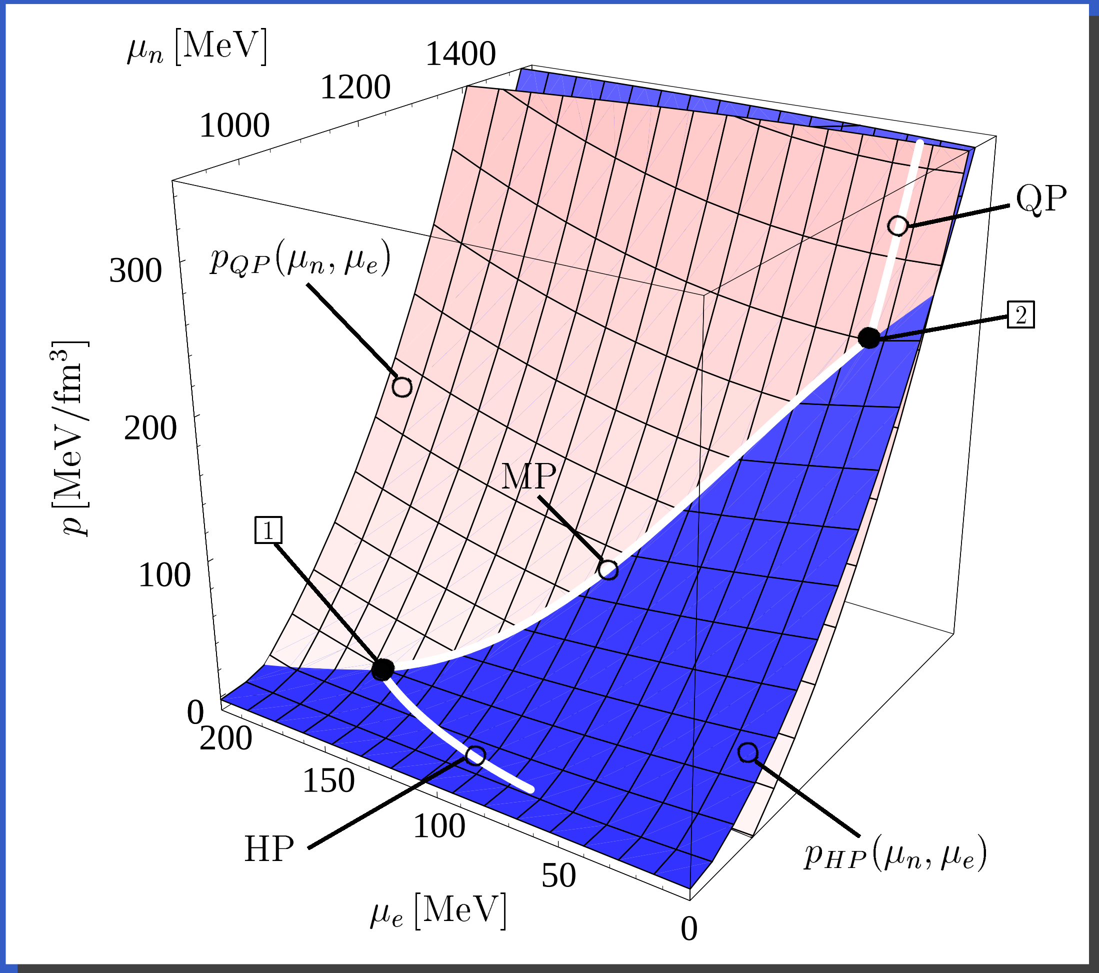
Quark Matter in Cold Neutron Stars



(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

Gibbs Phase Construction (Glendenning (1992))

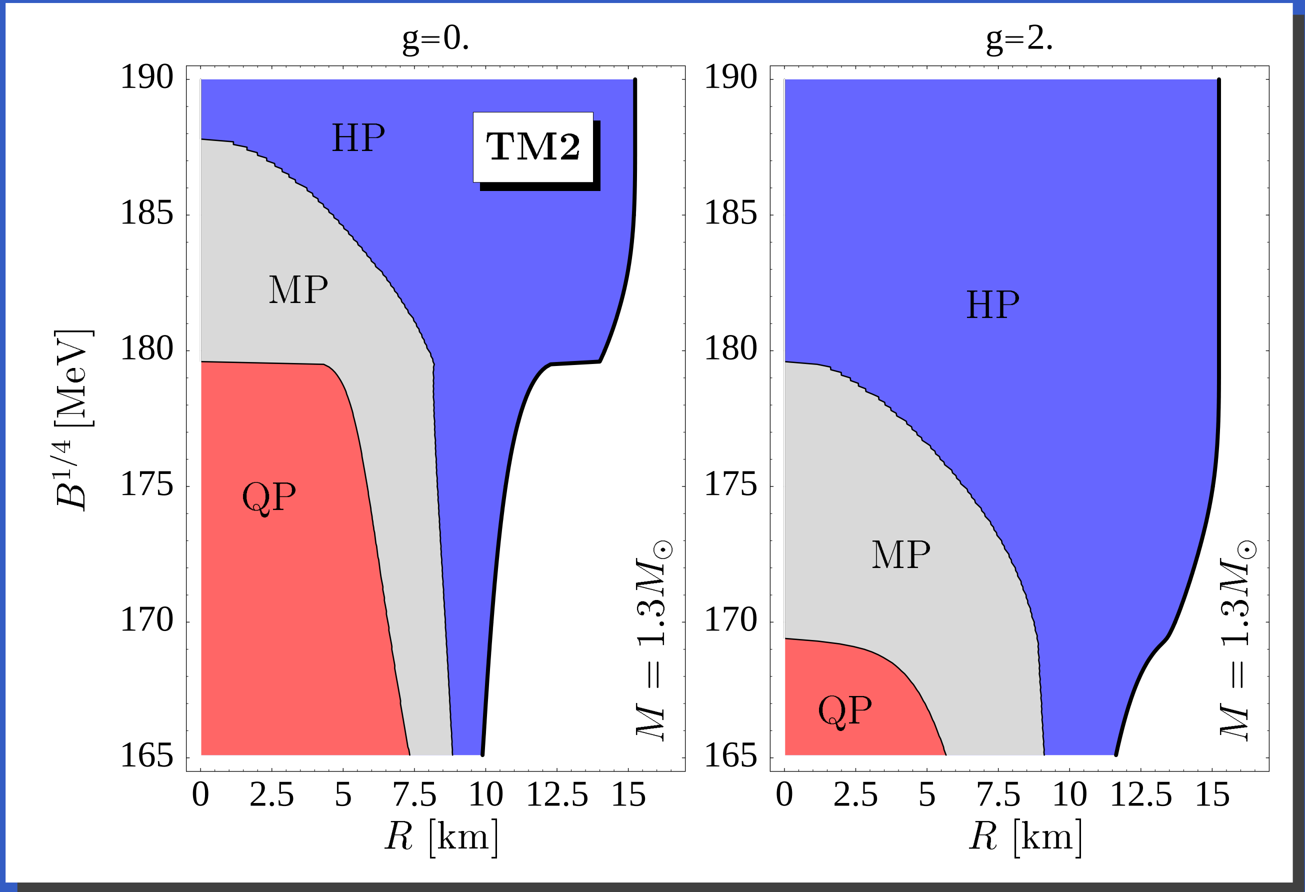


(Schertler et al. (2000))

- two conserved charges in β-equilibrium: baryon number and charge!
- Gibbs criterium 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!

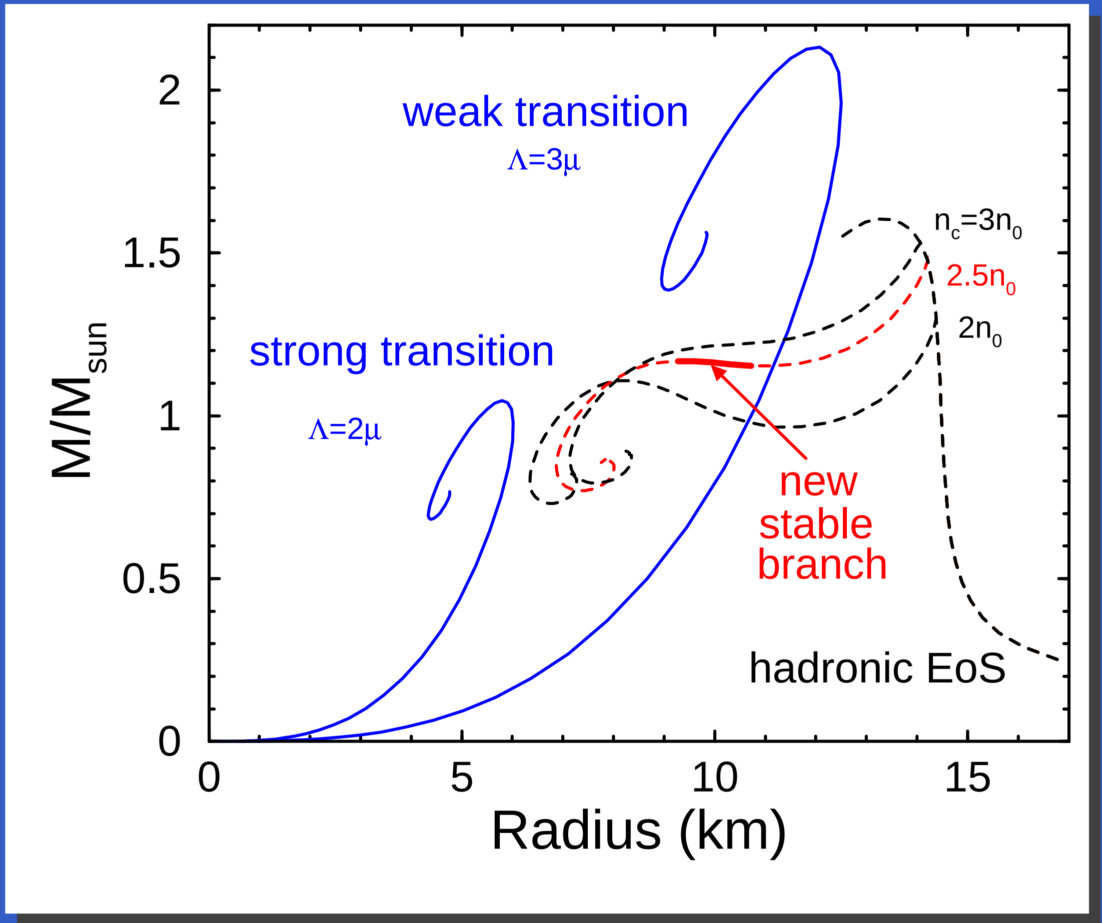
Hybrid Stars in the effective mass bag model

(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!)

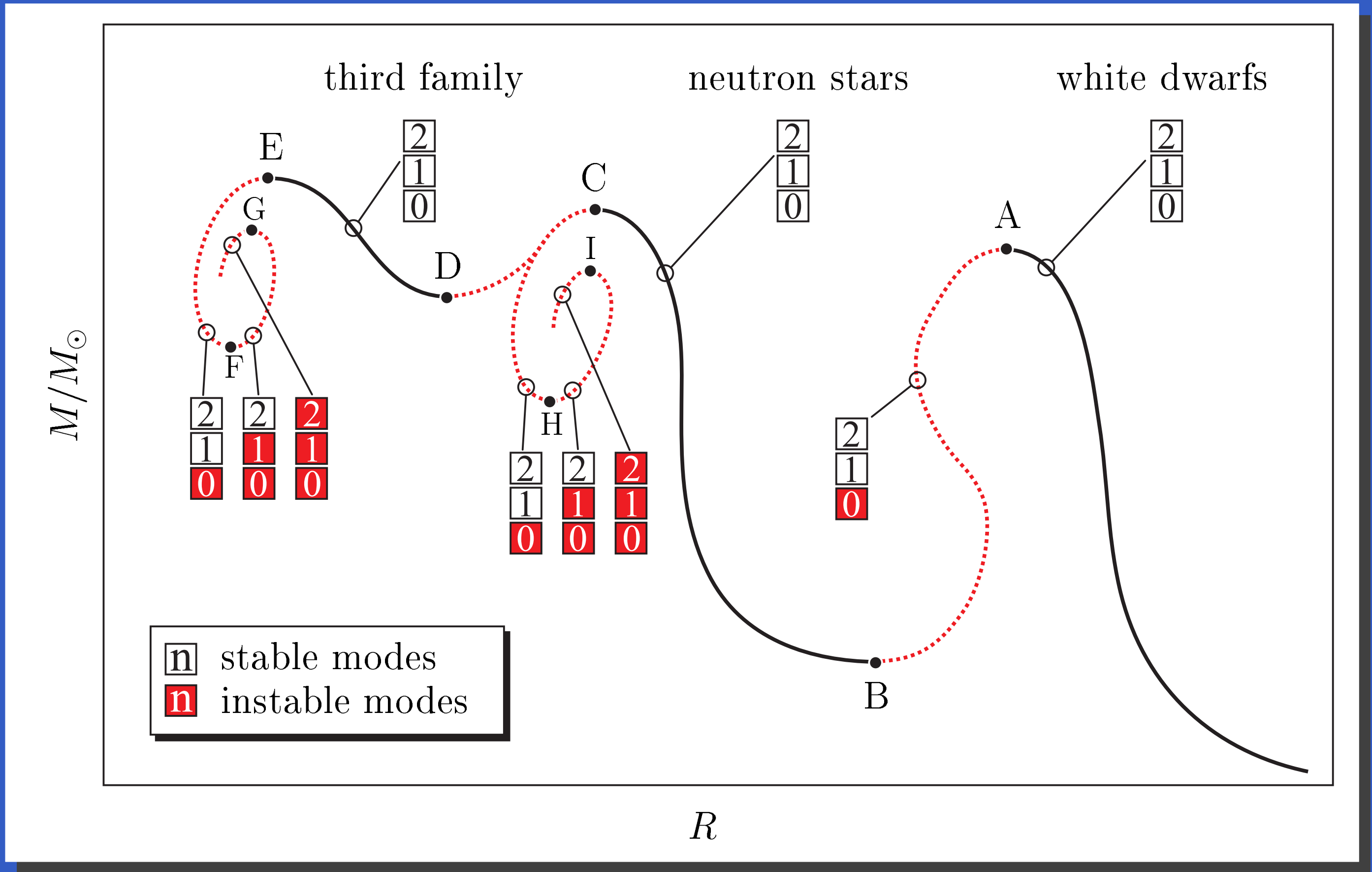
Quark star twins? (Fraga, JSB, Pisarski 2001)



- 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)



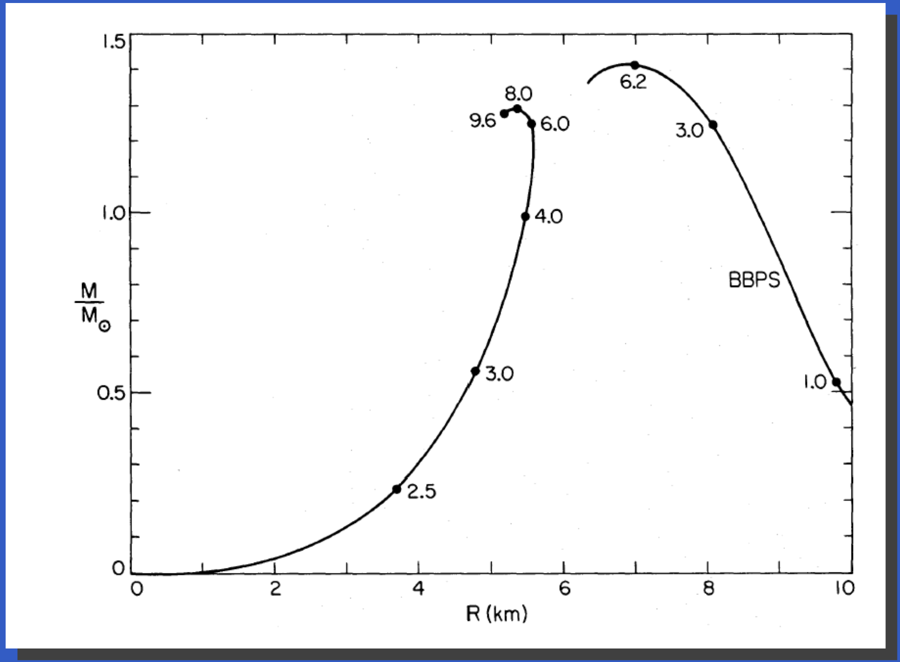
- third solution to the TOV equations besides white dwarfs and neutron stars, solution is stable!
- generates stars more compact than neutron stars
- possible for any first order phase transition!

Signals for a Third Family/Phase Transition?

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

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!)
- . . .

Signals of the QCD phase transition in core-collapse supernovae

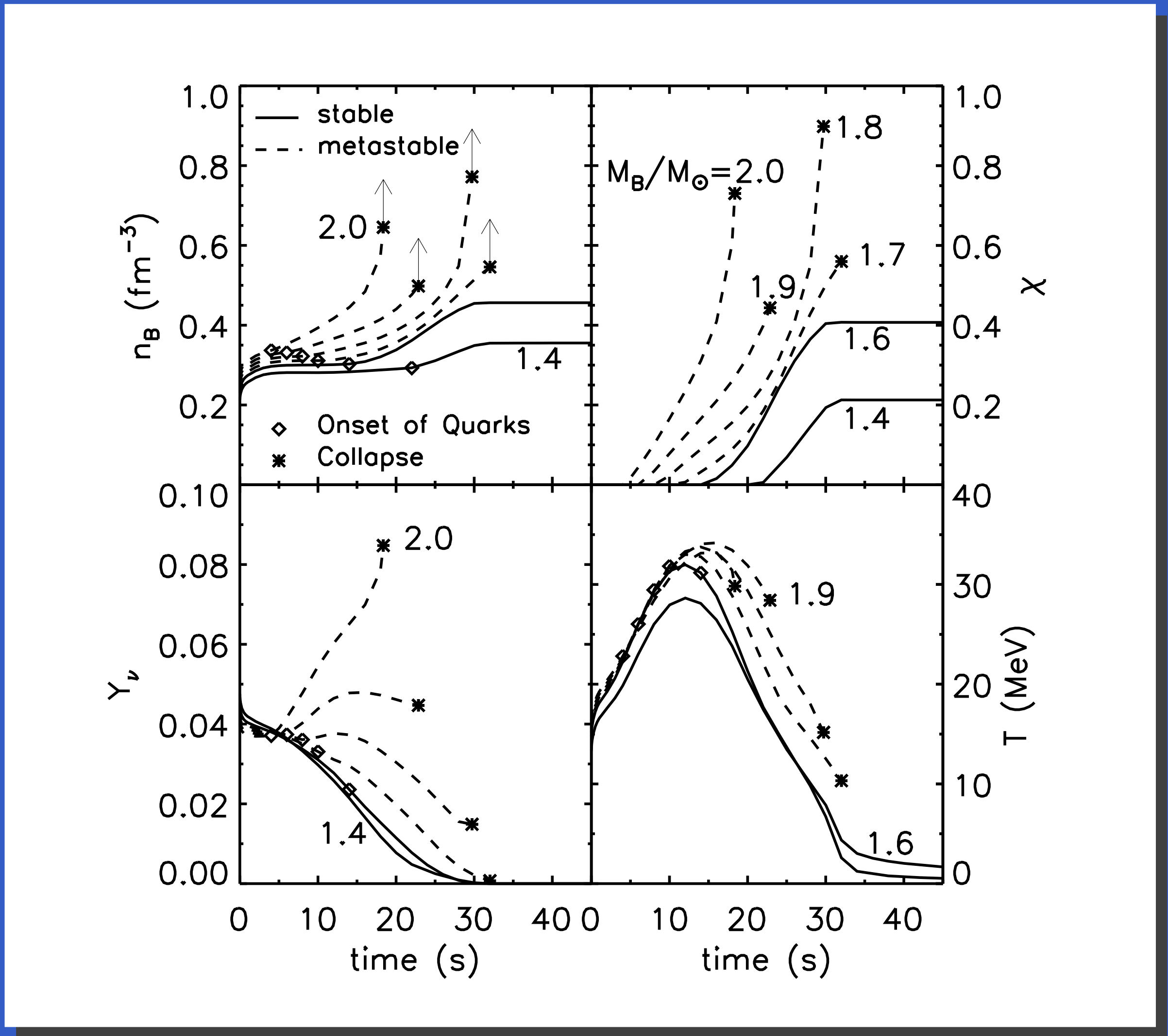
Irina Sagert, Matthias Hempel, Giuseppe Pagliara, Tobias Fischer,
Anthony Mezzacappa, Friedel Thielemann, Matthias Liebendörfer

PRL 102, 081101 (2009)

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 not 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)

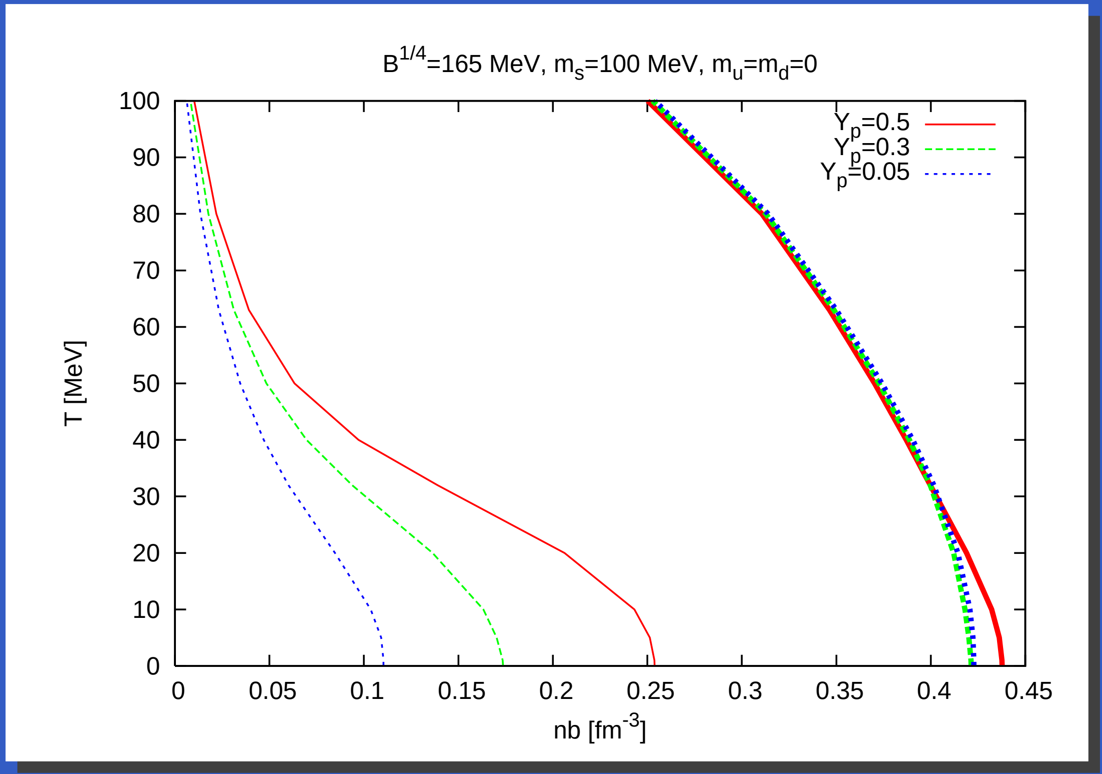
Proto-neutron star evolution with quarks



(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

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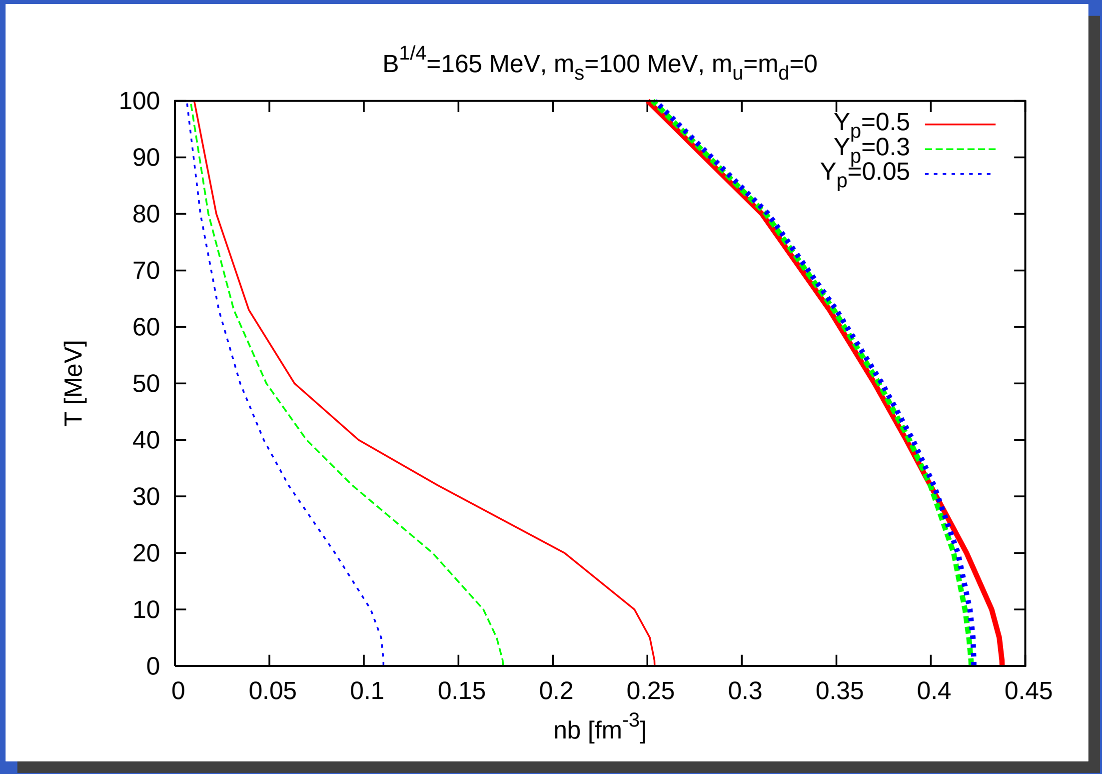

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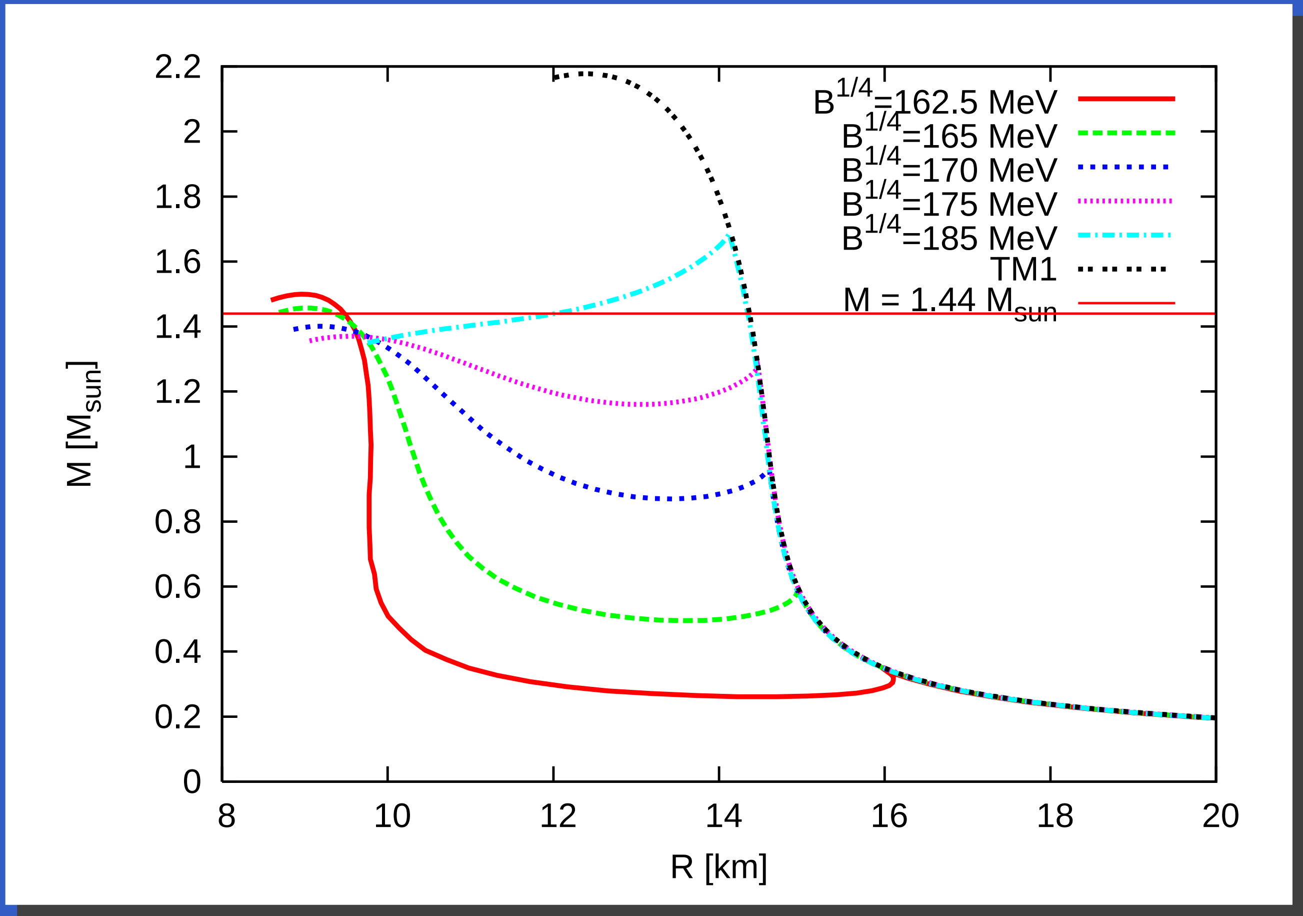
- quark matter appears at low density due to β-equilibrium for a bag constant of $B^{1/4} = 165$ MeV
- low critical density for low Y_p due to nuclear asymmetry energy
- quark matter favoured at finite temperature
- production of quark matter in supernovae at bounce possible!

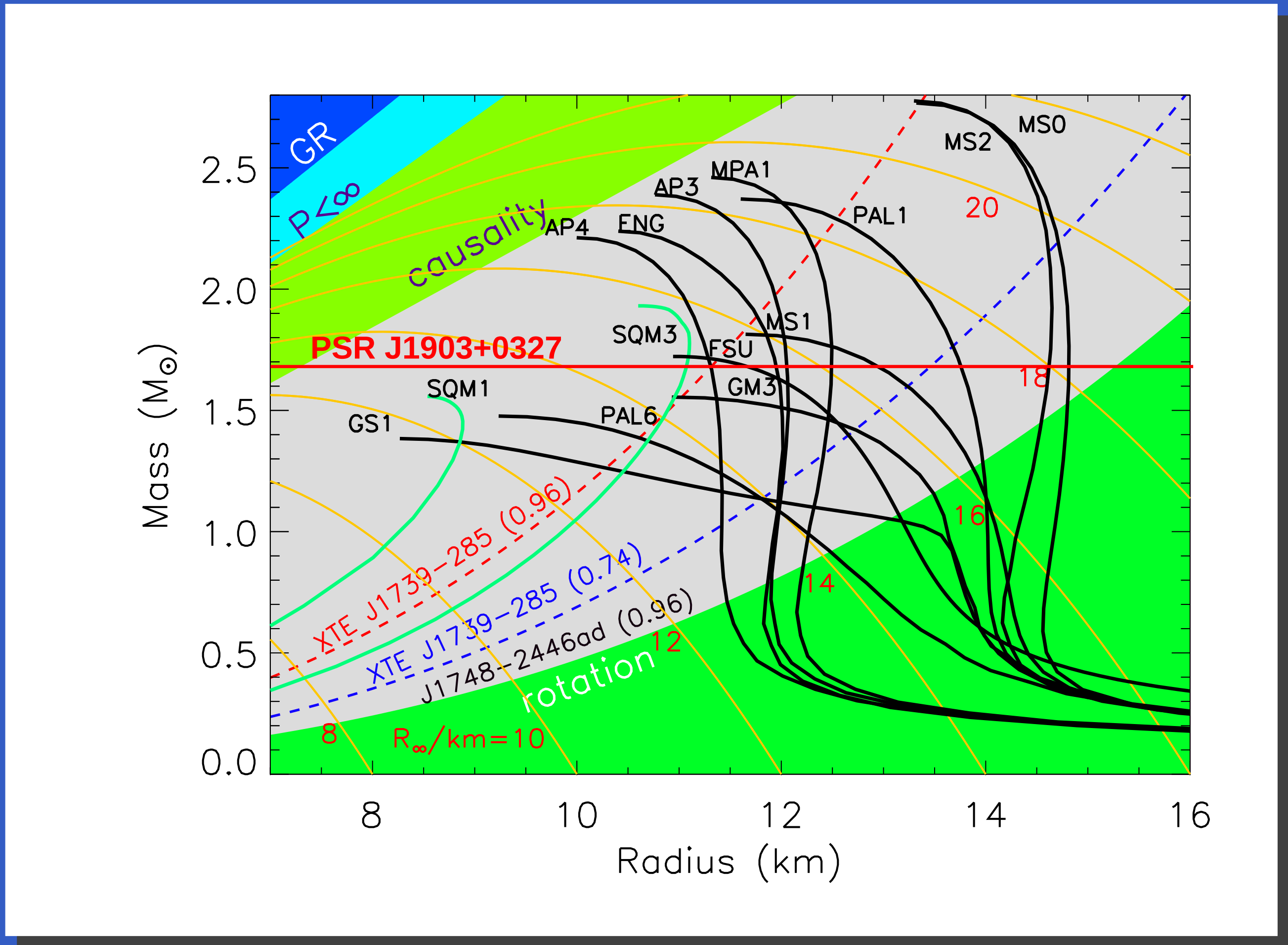
Check: Mass-Radius Diagram of Cold Neutron Stars



(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: $1.56M_\odot$ ($B^{1/4} = 162$ MeV), $1.5M_\odot$ ($B^{1/4} = 165$ MeV)

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 1903+0327 (Freire et al. 2009): $M = (1.67 \pm 0.01) M_\odot$

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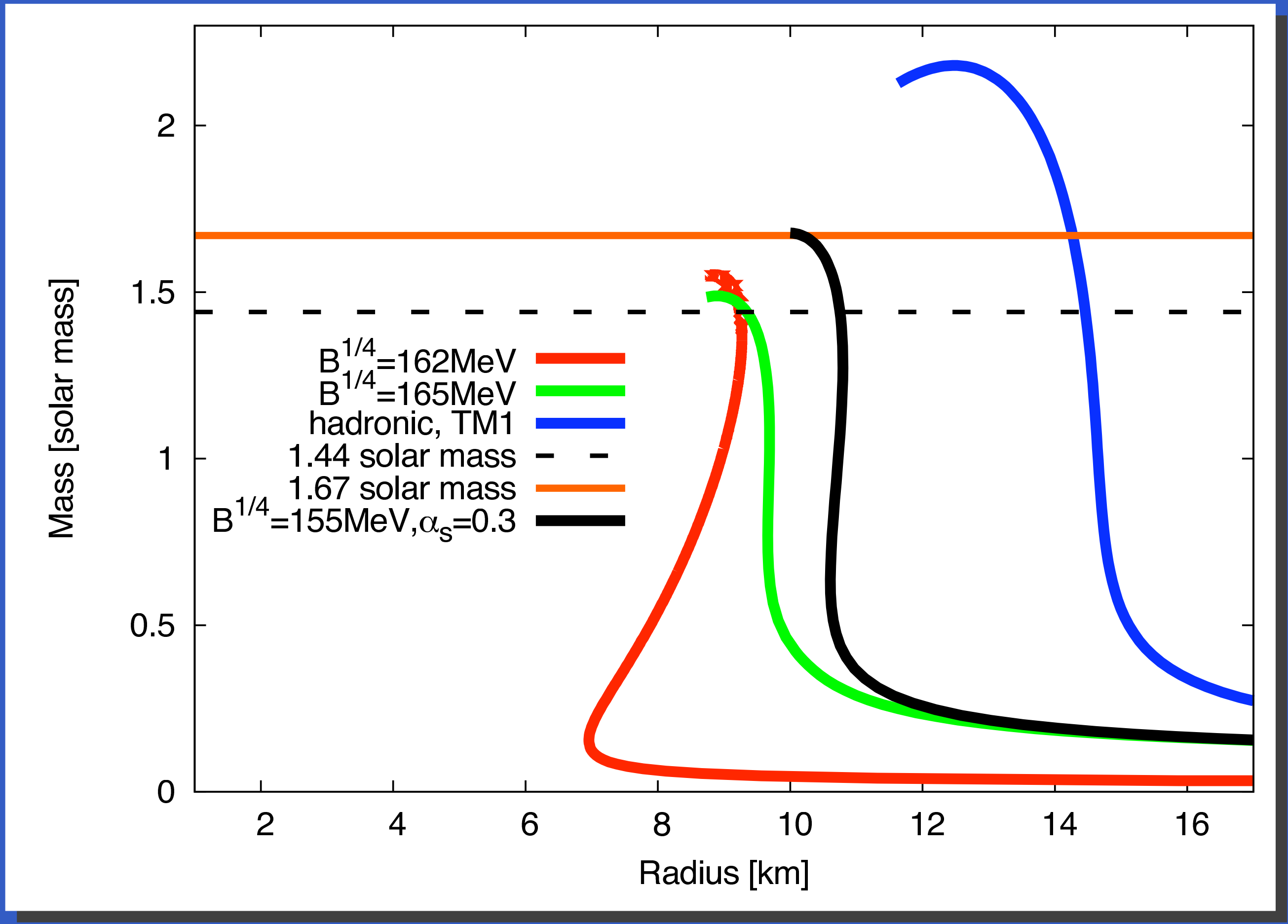
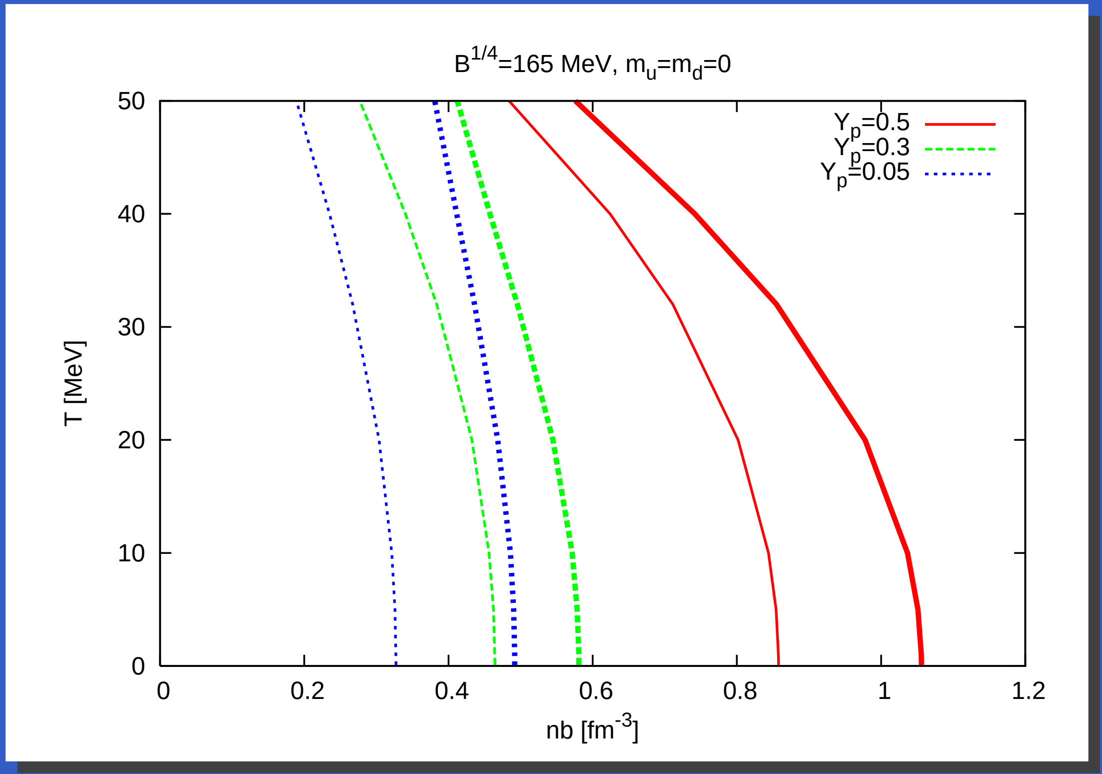


(Irina Sagert and Giuseppe Pagliara)

- take into account corrections from one-gluon exchange ($\alpha_s = 0.3$)
- possible to reduce the bag constant to $B^{1/4} = 155$ MeV
- increase of the maximum mass to $M = 1.67 M_\odot$

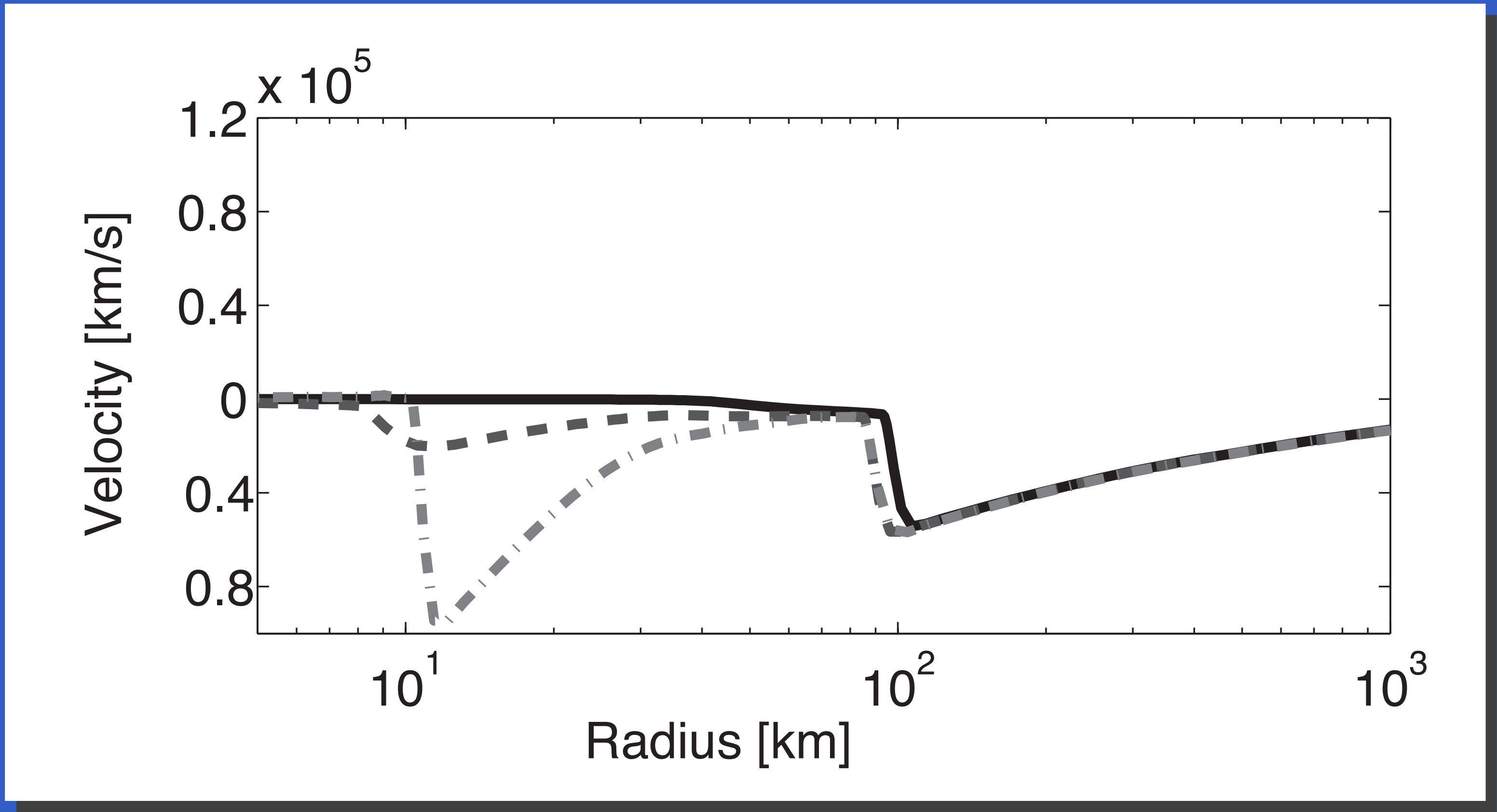
Check: Phase Transition for Heavy-Ion Collisions



(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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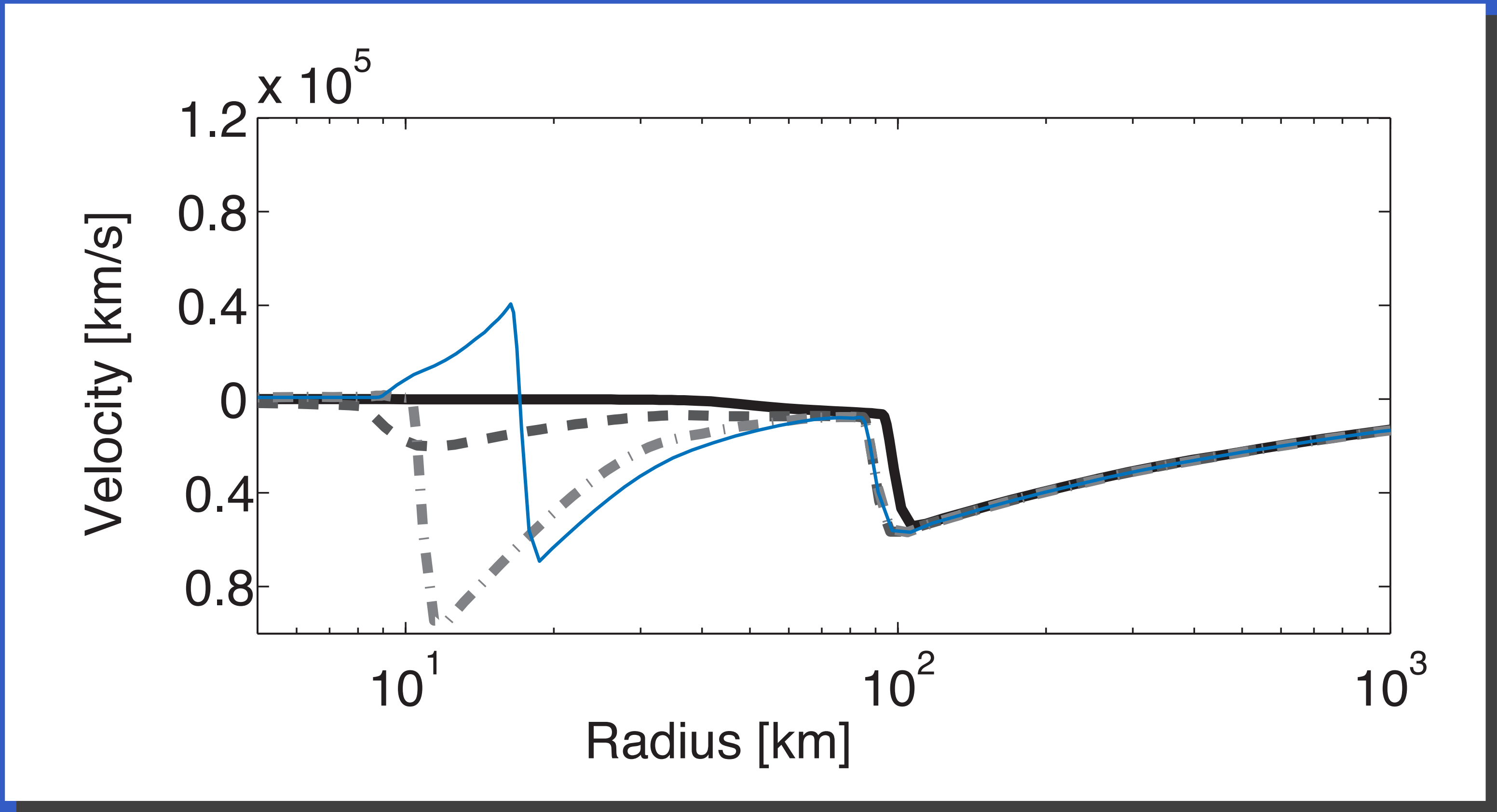

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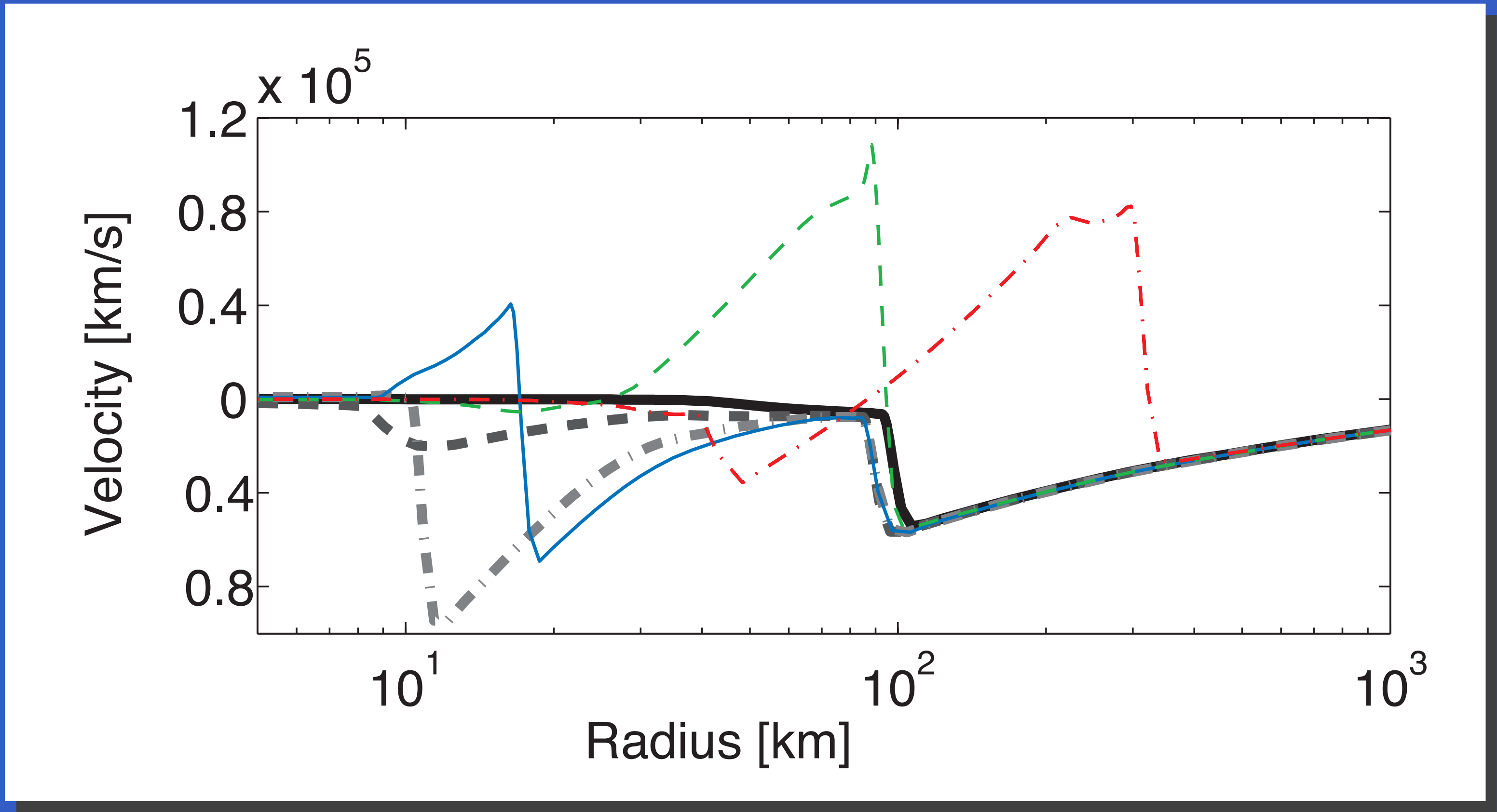
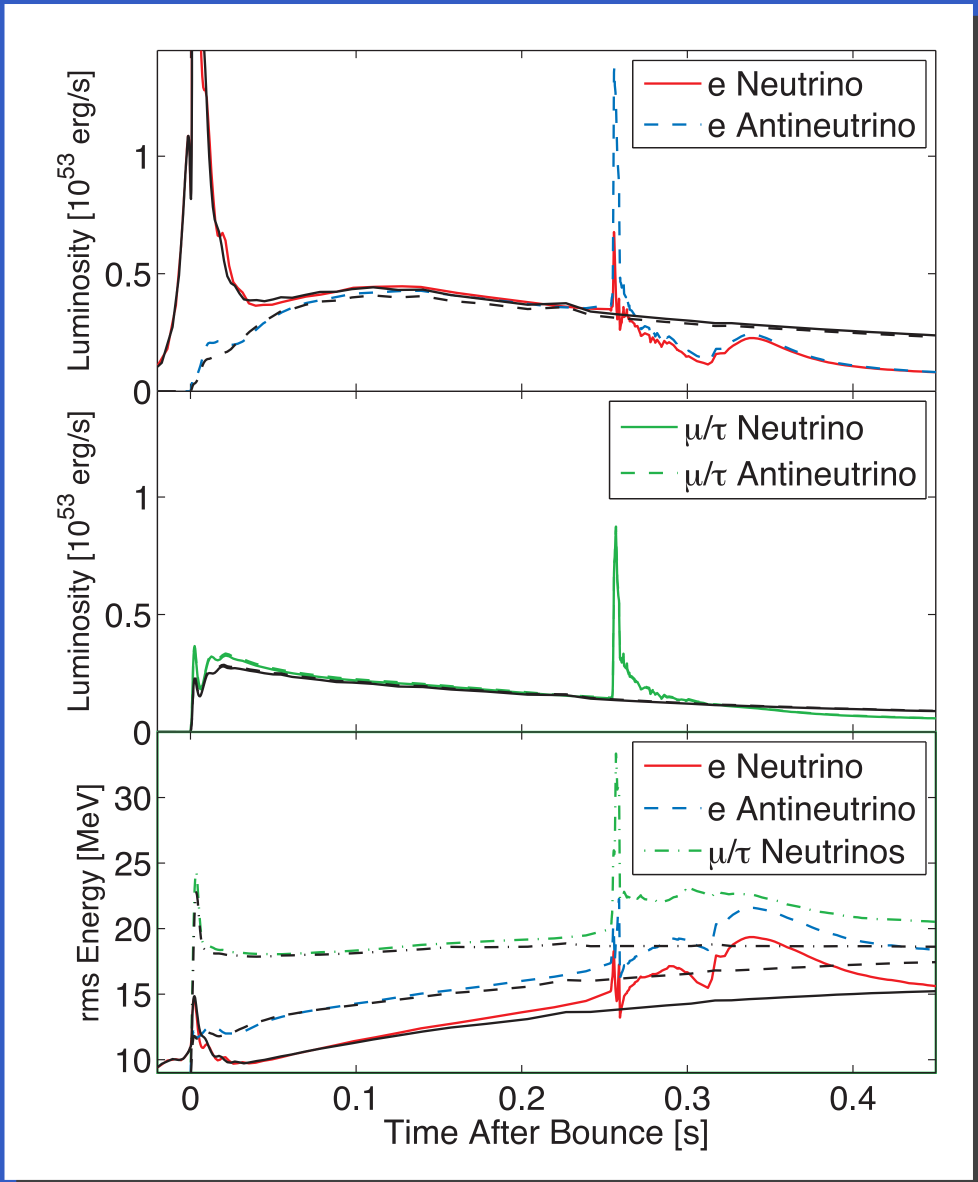


(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2009)

- 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 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

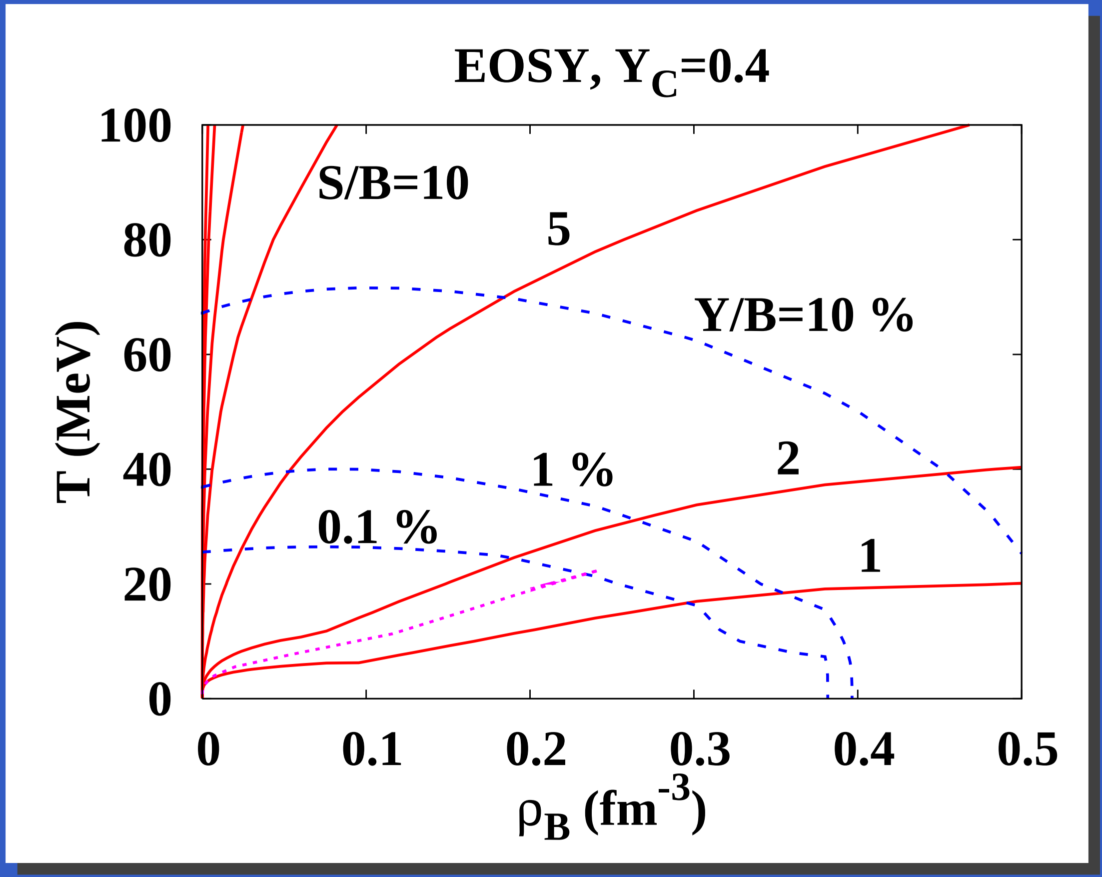
Prog. [M]	B [MeV]	t_{pb} [ms]	M_Q [M]	M_{mixed} [M]	M_{PNS} [M]	E_{expl} [10^{51} erg]
10	162	255	0.850	0.508	1.440	0.44
10	165	448	1.198	0.161	1.478	1.64
15	162	209	1.146	0.320	1.608	0.42
15	165	330[a]	1.496	0.116	1.700	unknown[b]

[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)
- heavier progenitor masses can lead to the formation of a black hole

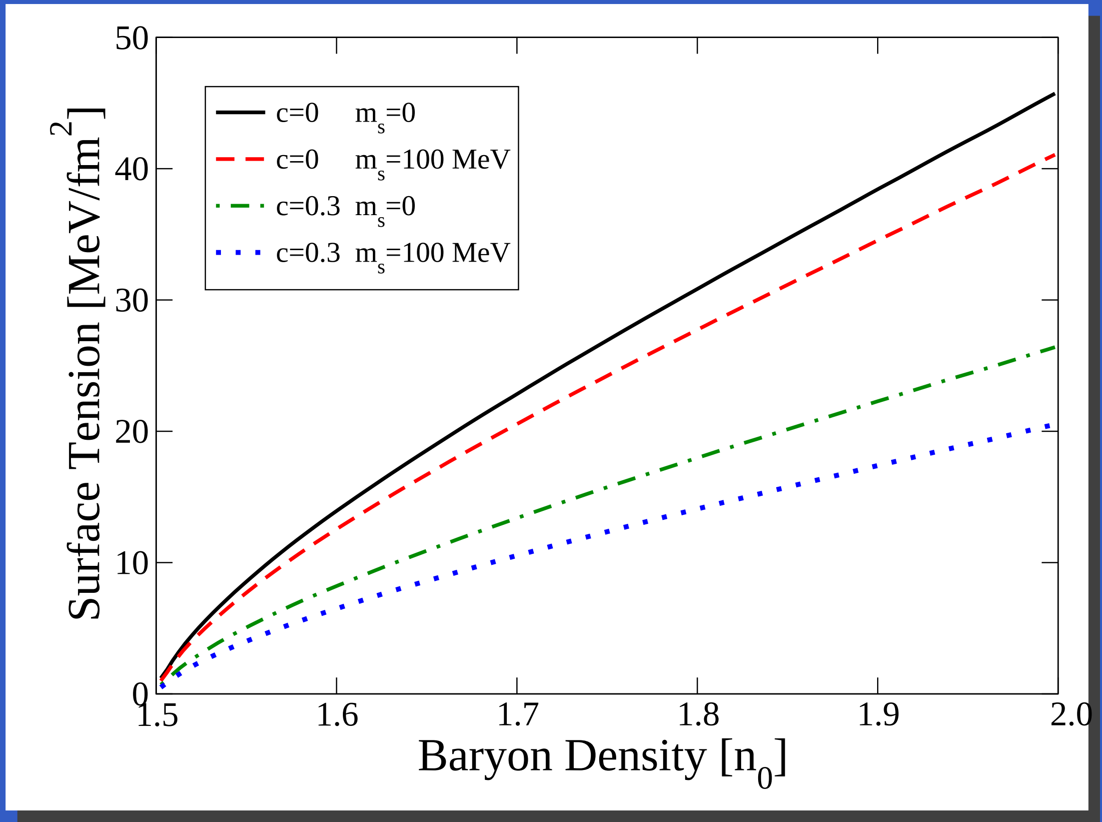
Strangeness in Supernova Matter: Hyperons



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!

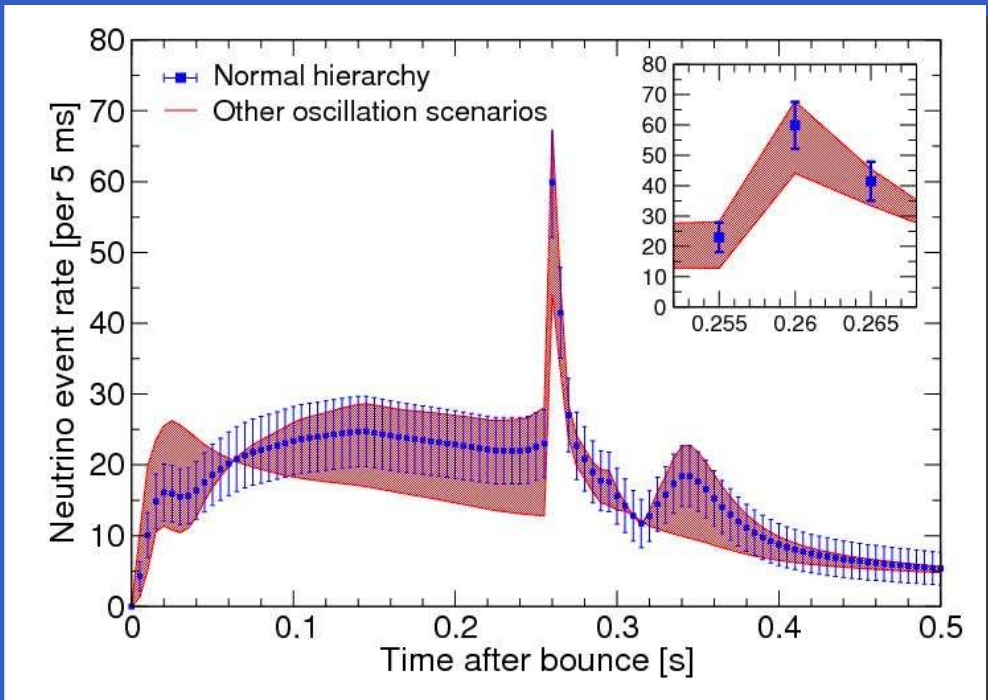
Nucleation Timescales for strange quark matter

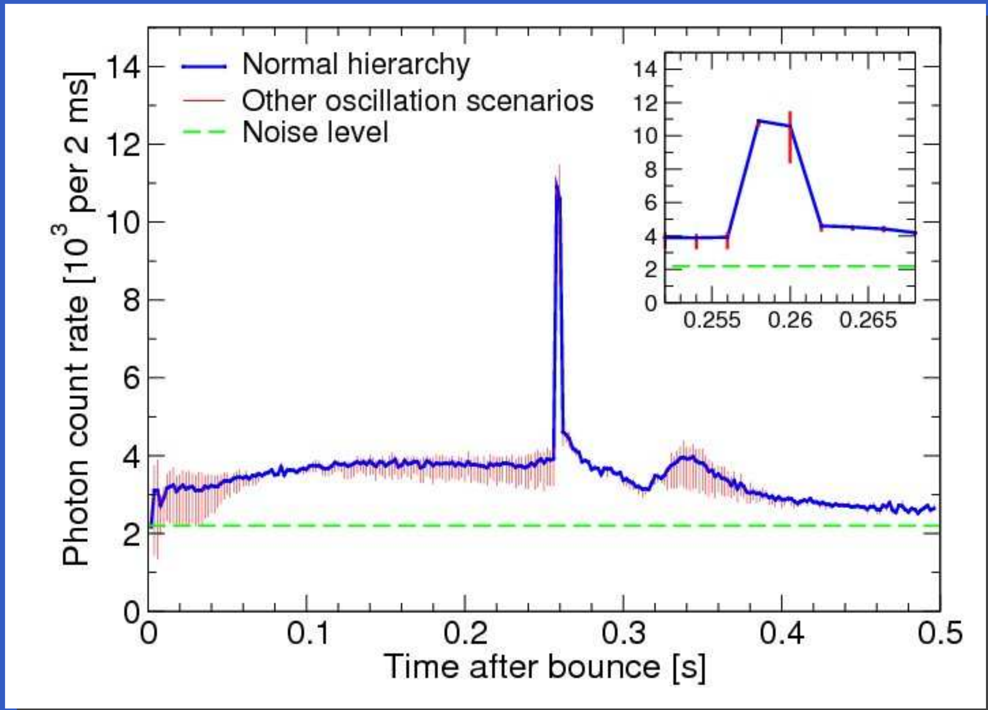


(B. W. Mintz, E. Fraga, G. Pagliara, JSB, arXiv:0910.3927)

- 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}

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!

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 (?) . . .