CONFXI 2014, St. Petersburg

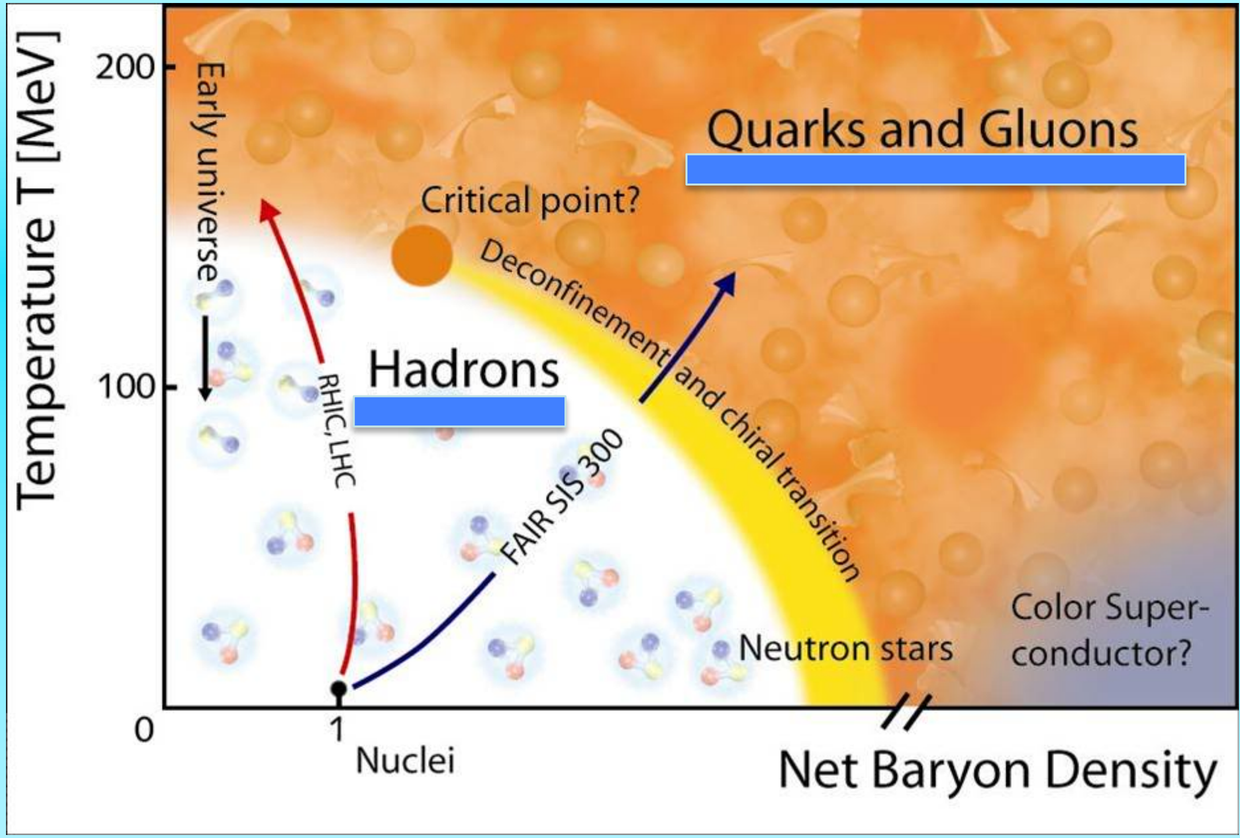
Models of Quark-Hadron Matter and Compact Stars

OUTLINE

- hadronic SU(3) model
- adding quarks
- some results for μ = 0 and heavy-ions
- dense matter, compact stars
- conclusions, to-do list

V. Dexheimer, R. Negreiros, P. Rau, J. Steinheimer, SWS
FIAS Frankfurt, Kent State, Fluminense,

the usual phase diagram (sketch) of strong interactions



connect both worlds
in some reasonable way

Practical model useful for heavy-ion simulations and compact star physics

correct asymptotic degrees of freedom
reasonable description on a quantitative level for high T down to nuclei
possibility of studying first-order as well as cross-over transitions

hadronic SU(3) approach based on non-linear realization of σω model

Lowest multiplets

$B = \{ p , n , \Lambda , \Sigma^{\pm/0} , X^{-/0} \}$ baryons

$\mathrm{diag}(V) = \{ (\omega + \rho) / \sqrt{2} , (\omega - \rho) / \sqrt{2} , \phi \}$ vector mesons

$\mathrm{diag}(X) = \{ (\sigma + \delta) / \sqrt{2} , (\sigma - \delta) / \sqrt{2} , \varsigma \}$ scalar mesons

Mean fields generate scalar attaction and vector repulsion

Scalar self interaction $L_0 = - \frac{1}{2} k_0 I_2 + k_1 (I_2)^2 + k_2 I_4 + 2 k_3 I_3 + L_{ESB}$

invariants $I_1 = \mathrm{Tr}(X)$ $I_2 = \mathrm{Tr}(X)^2$ $I_3 = \det(X)$

+ dilaton field $L_\chi = -k_4 \chi^4 - \frac{1}{4} \chi^4 \ln(\chi^4/\chi_0^4) + \delta/3 \chi^4 \ln(I_3/\langle X \rangle)$

hadronic SU(3) approach ... continued

SU(3) interaction

$$L_{BW} = - \sqrt{2}\, g_8^W \left(\alpha_W [\overline{B}OBW]_F + (1 - \alpha_W) [\overline{B}OBW]_D \right)$$

$$- g_1^W / \sqrt{3}\, \mathrm{Tr}(\overline{B}OB)\, \mathrm{Tr}(W)$$

V(M) $\quad <\sigma> = \sigma_0 \neq 0 \quad <\zeta> = \zeta_0 \neq 0$

$$\sigma \sim <\bar{u}u + \bar{d}d> \qquad \zeta \sim <\bar{s}s> \qquad \delta^0 \sim <\bar{u}u - \bar{d}d>$$

explicit breaking $\sim \mathrm{Tr}[\, c\, \sigma\,] \quad (\sim m_q \bar{q} q)$

fix scalar parameters to

baryon masses, decay constants, meson masses

Nuclear Matter and Nuclei

binding energy E/A ~ -15.2 MeV saturation $(\rho_B)_0 \sim .16/fm^3$

compressibility **~ 223 MeV** asymmetry energy **~ 31.9 MeV**

parameter fit to known nuclear binding energies and hadron masses

1d to 3d code 2d calculation of all measured (~ 800) even-even nuclei

good charge radii δr_{ch} ~ 0.5 % (+ LS splittings)

error in energy ε (A > 50) ~ 0.17 % (NL3: 0.25 %)

ε (A > 100) ~ 0.12 % (NL3: 0.16 %)

relativistic nuclear structure models

+ correct binding energies of hypernuclei

new fit in the works by T. Schürhoff

currently $\varepsilon \sim 0.3$, $\kappa < 300$ MeV, M ~2 $M_\odot$

stellar crust calculations in progress

SWS, Phys. Rev. C66, 064310

hadrons, quarks, Polyakov loop and excluded volume

Include modified distribution functions for quarks/antiquarks

$$\Omega_q = -T \sum_{j \in Q} \frac{\gamma_i}{(2\pi)^3} \int d^3k \ln\left(1 + \Phi \exp\frac{E_i^* - \mu_i}{T}\right)^*$$

Φ confinement order parameter*

Following the parametrization used in PNJL calculations

$$U = -\tfrac{1}{2} a(T)\, \Phi\Phi^* + b(T) \ln[1 - 6\, \Phi\Phi^* + 4\, (\Phi\Phi^*)^3 - 3\, (\Phi\Phi^*)^2]$$

$$a(T) = a_0 T^4 + a_1\, T_0 T^3 + a_2\, T_0^2 T^2 \quad , \quad b(T) = b_3\, T_0^3\, T$$

The switch between the degrees of freedom is triggered by excluded volume corrections

thermodynamically consistent - *no reconfinement!*

$V_q = 0$
$V_h = v$
$V_m = v / 8$

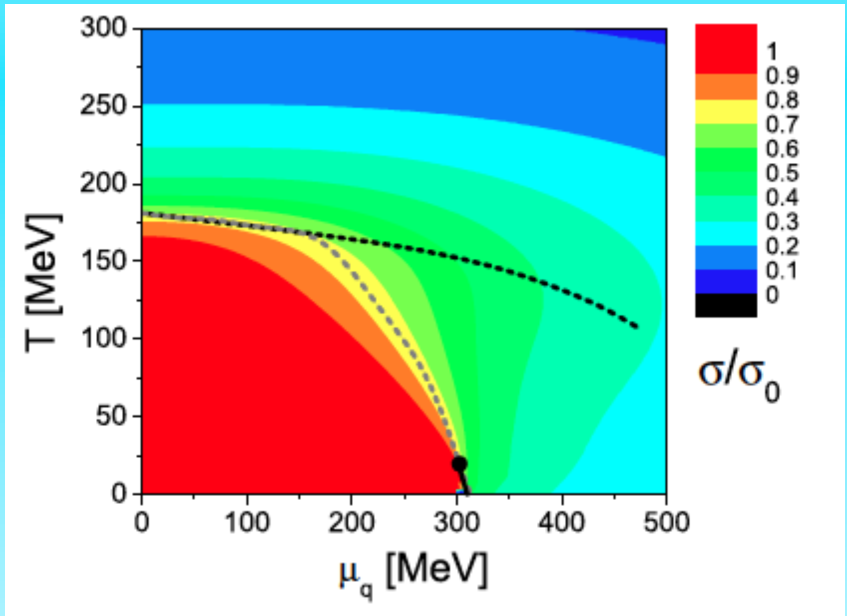
$\tilde{\mu}_i = \mu_i - v_i P$

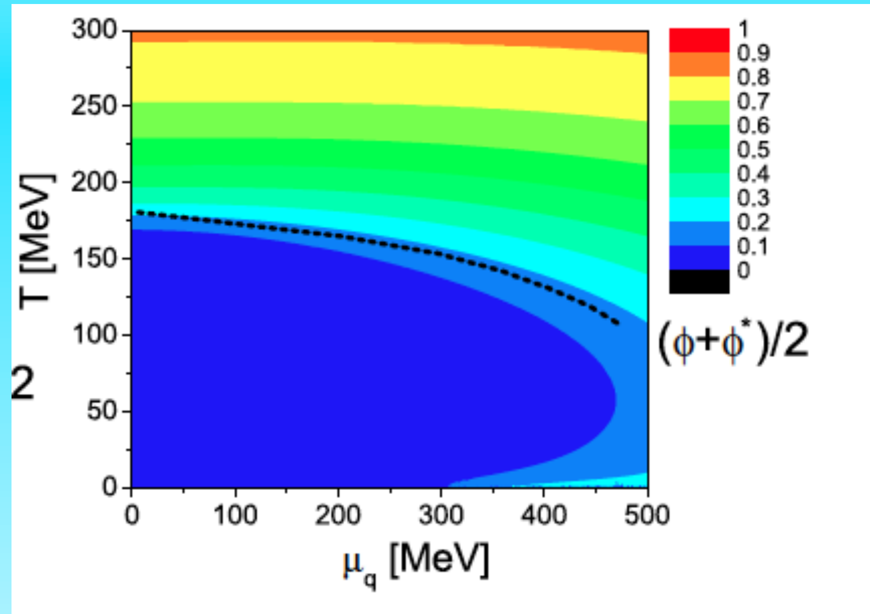
$e = \tilde{e} / (1 + \Sigma\, v_i\, \tilde{\rho}_i)$

equation of state stays causal!

Steinheimer,SWS,Stöcker JPG 38, 035001 (2011)

Order parameters for chiral symmetry and confinement in μ and T





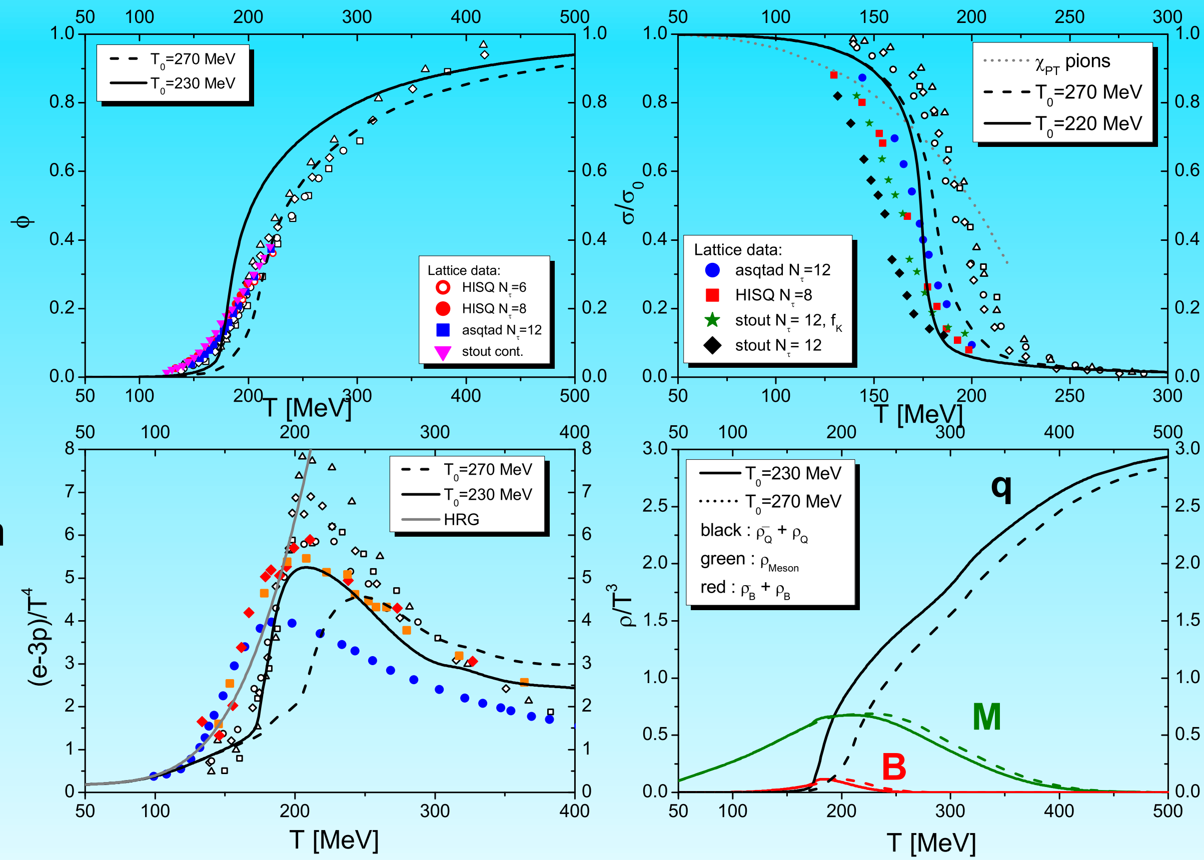
except for liquid-gas no first-order transition

results for hot matter at vanishing chemical potential

points are various lattice results

Polyakov loop

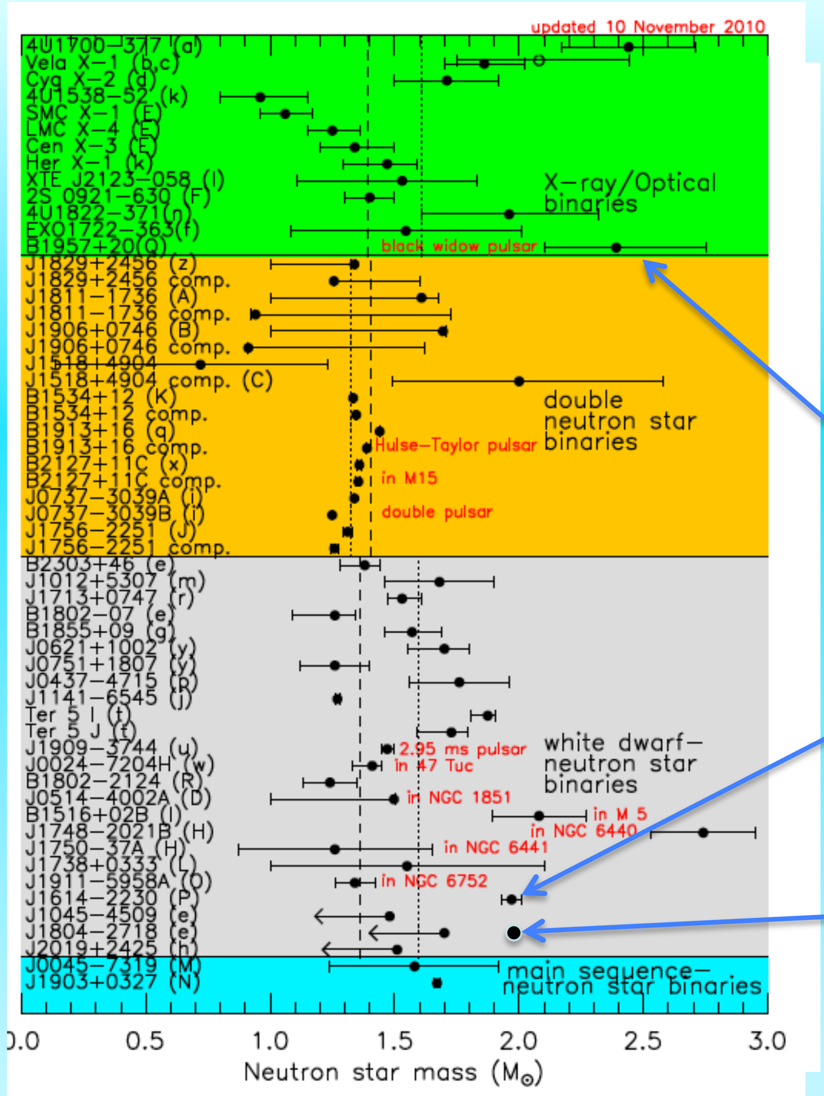
scalar condensate



Interaction measure

densities

Masses of Neutron Stars



Lattimer, Prakash, astro-ph:1012.3208

Masses of radio pulsars

Kiziltan, Kottas, Thorsett, astro-ph:1011.4291

no signature for mass cut off

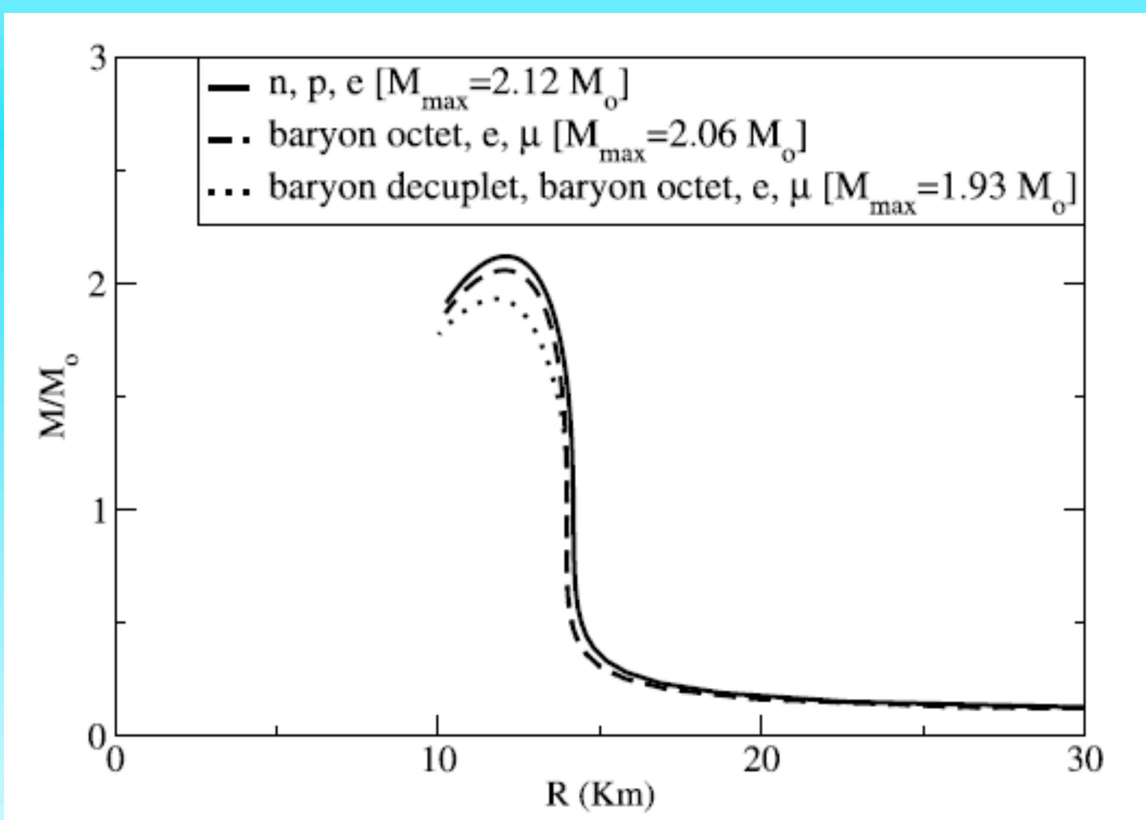
M = (2.4 +- 0.12) M_s ?
van Kerkwijk et al., ApJ 728, 95 (2011)

current benchmark for NS models
M = (1.97 +- .04) M_0
Demorest et al. Nature 467, 1081 (2010)

new observation PSR J0348+0432
M = (2.01 +- .04) M_0
Antoniadis et al. Science 340, 448 (2013)

well established - heavy neutron stars

Neutron star masses including different sets of particles



Tolman-Oppenheimer-Volkov equations, static spherical star

changing masses with degrees of freedom

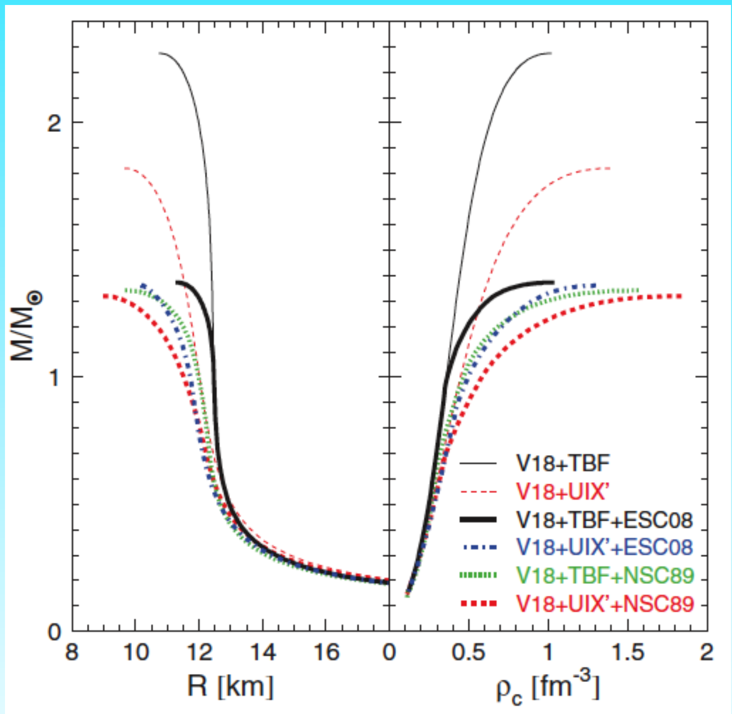
large star masses even with spin 3/2 resonances

Dexheimer, SWS ApJ 683, 943 (2008)

Impact of Φ field

rescale $g_{B\Phi}$ coupling parameters , f_s(core) varies between 0.1 and 1

Nijmegen, no YY interaction

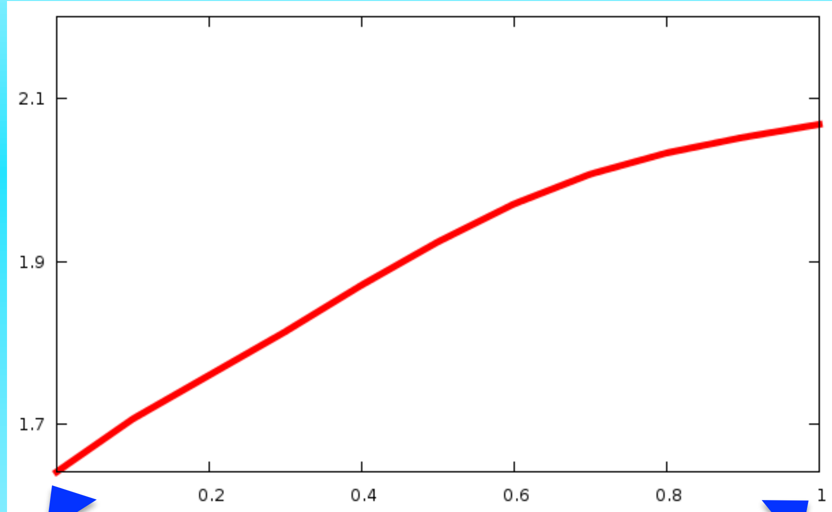


Schulze, Rijken, PRC 84, 035801 (2011)

M_{max} [$M_\odot$]

2

1.7

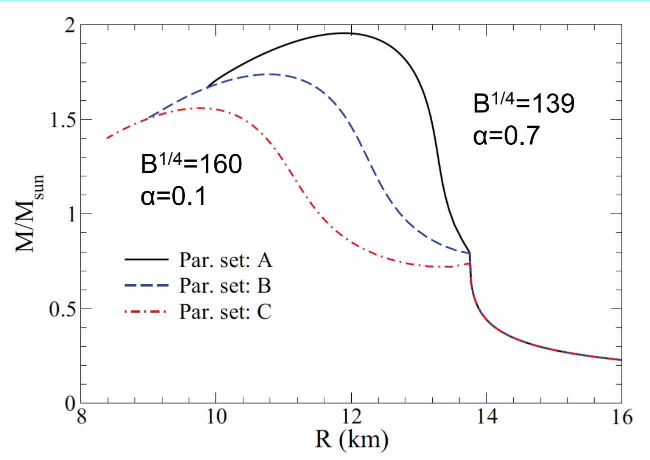


no coupling

standard fit SU(6)

$f_s = n_s / n_B$

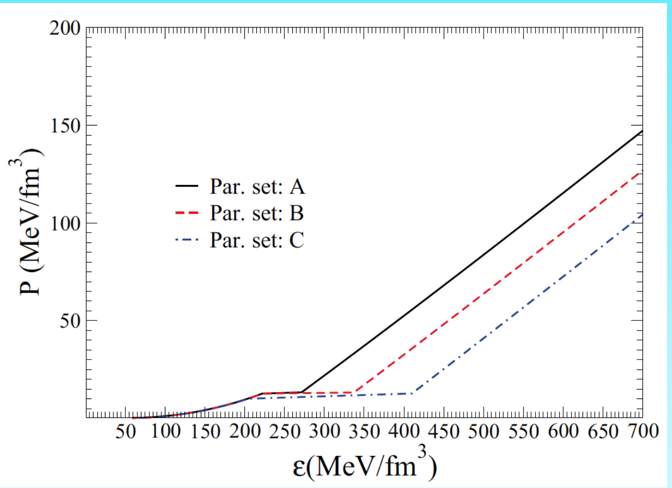
Hybrid Stars, Quark Interactions



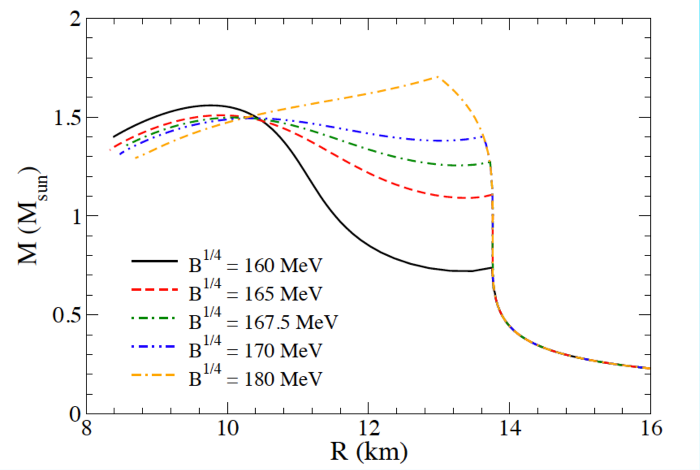
ingredients –
Standard baryonic EOS (G300)
plus MIT bag model + α_s corrections

Fast cooling in the quark core
need gaps in the quark phase

baryons alone M_{max} ~1.8 M_{solar}

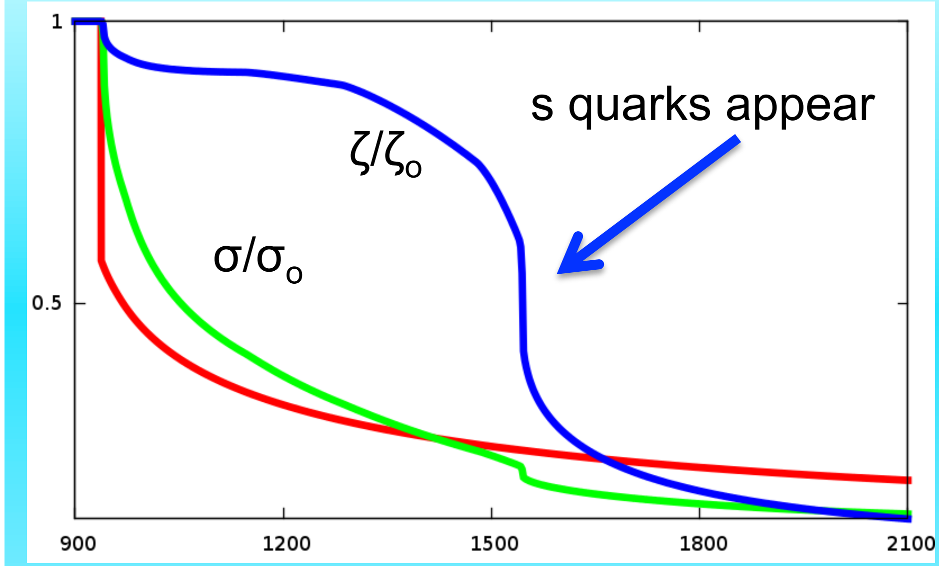


no α_s



Negreiros, Dexheimer, SWS, PRC 035805 (2012)

star matter in beta equilibrium in QH approach

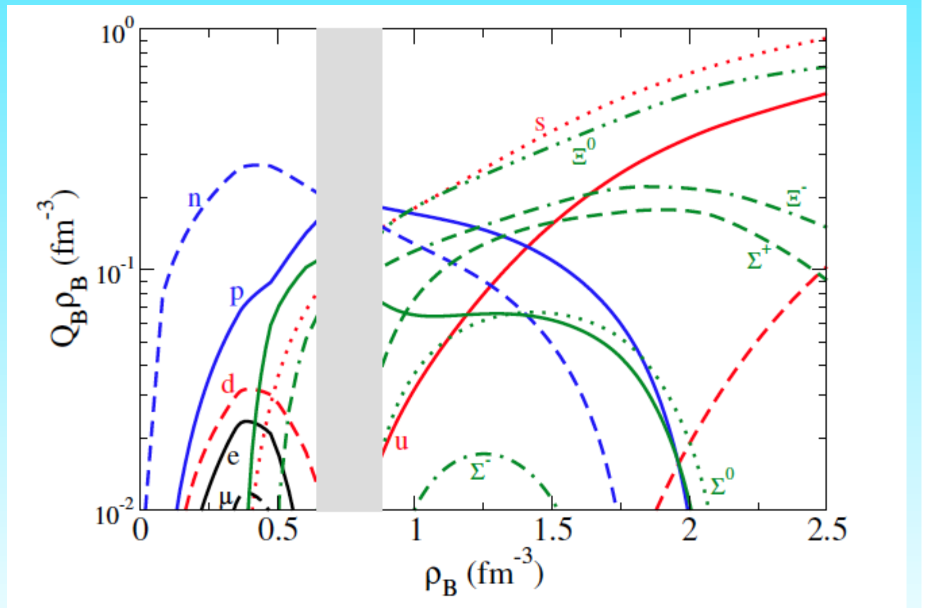


1^{st} order phase transition
in star matter possible

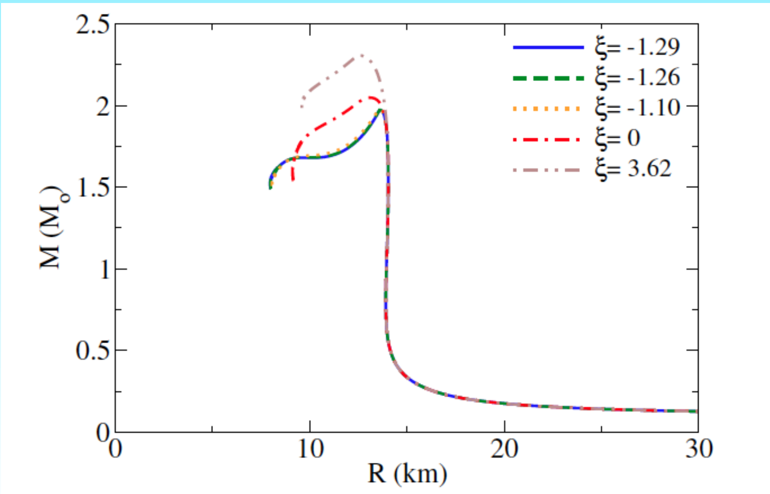
cross over in symmetric matter

f_s(core) jumps to ~ 1

particle cocktail



star masses $M_\odot$ varying quark interactions



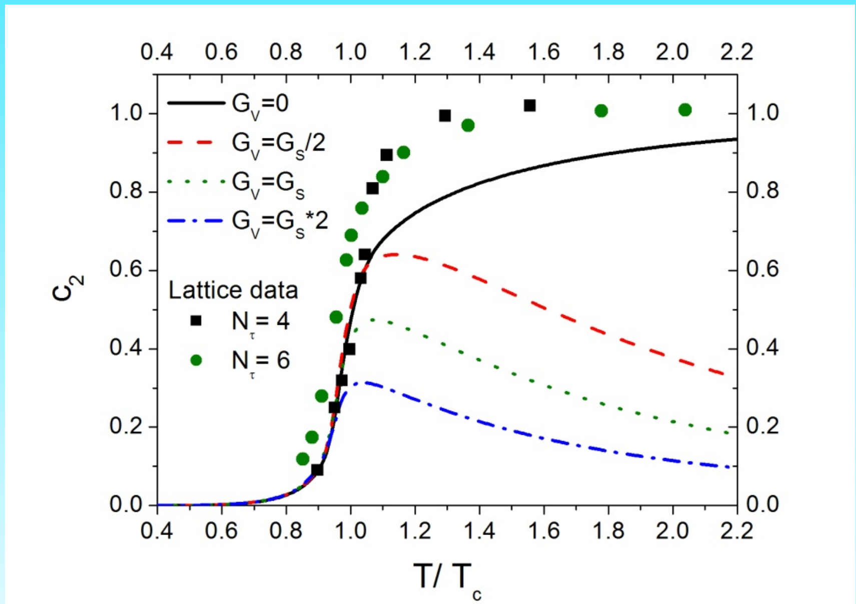
Mass ~ 2 – 2.3 $M_\odot$ Radius ~13 km

Susceptibilitiy c_2 in PNJL and QH model for different quark vector interactions

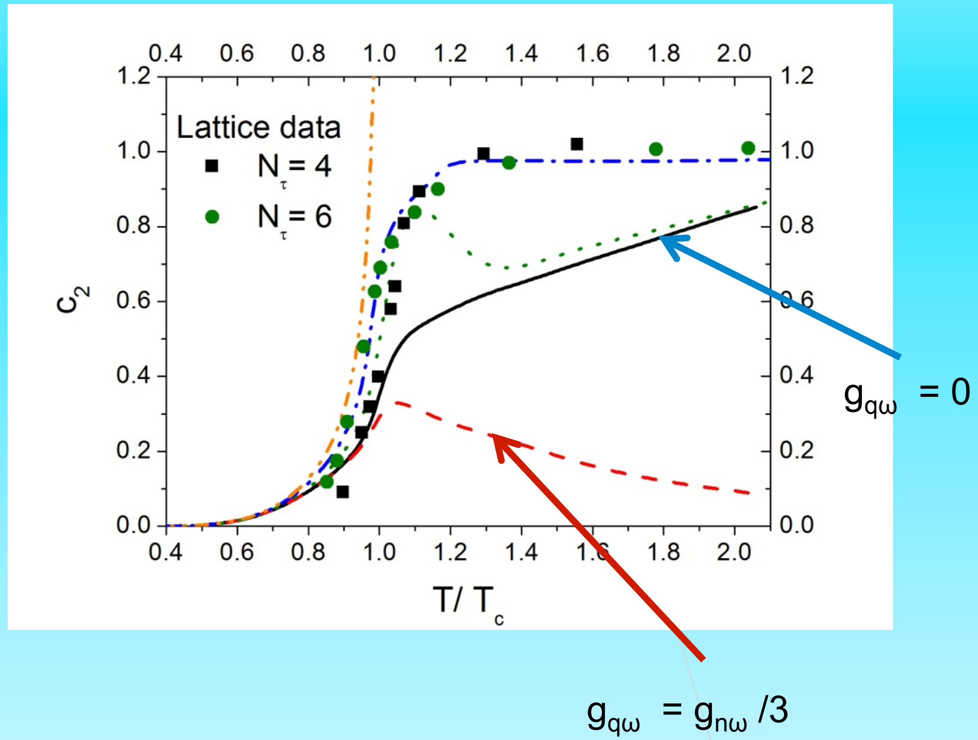
$$P(T,\mu) = P(T) + c_2(T)\,\mu^2\,T^2 + \ldots$$

small quark vector repulsion !!

PNJL



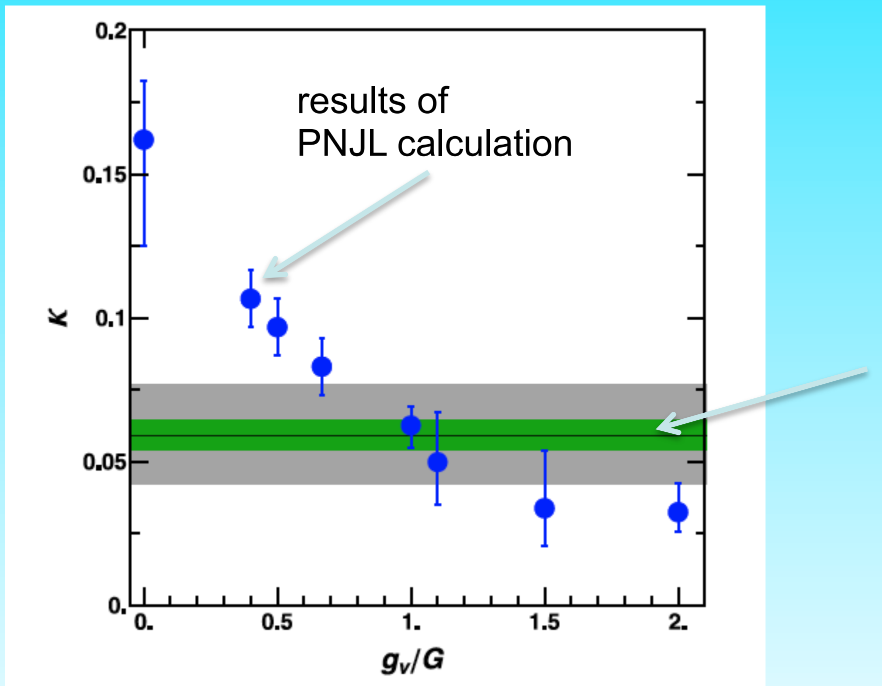
QH



Steinheimer, SWS, PLB 696, 257 (2011)

signs of vector repulsion in $T_c(\mu)$ behavior

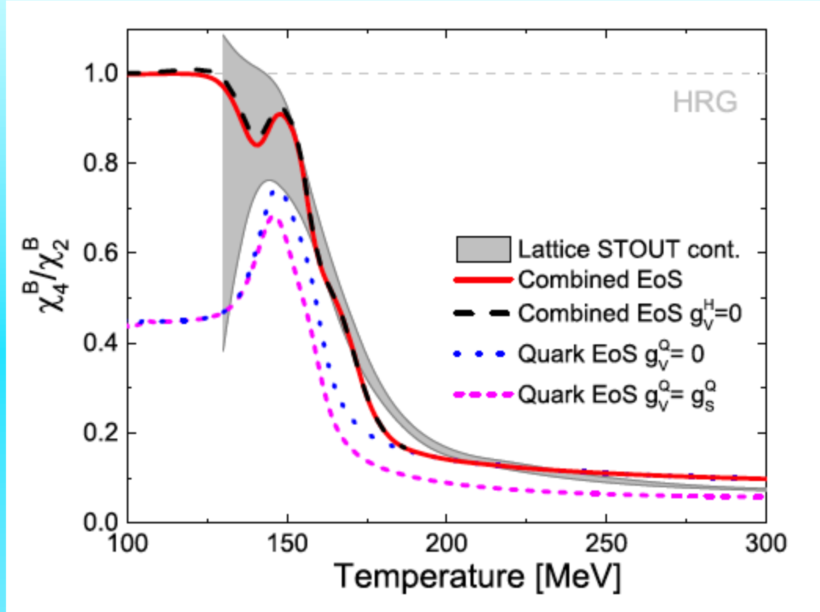
curvature of transition line $\kappa = -T_c \, dT_c(\mu)/d\mu^2|_{\mu=0}$



Plot taken from
Bratovic, Hatusda, Weise, PLB 719, 131 (2013)

large quark vector repulsion?

T_c rather difficult to determine

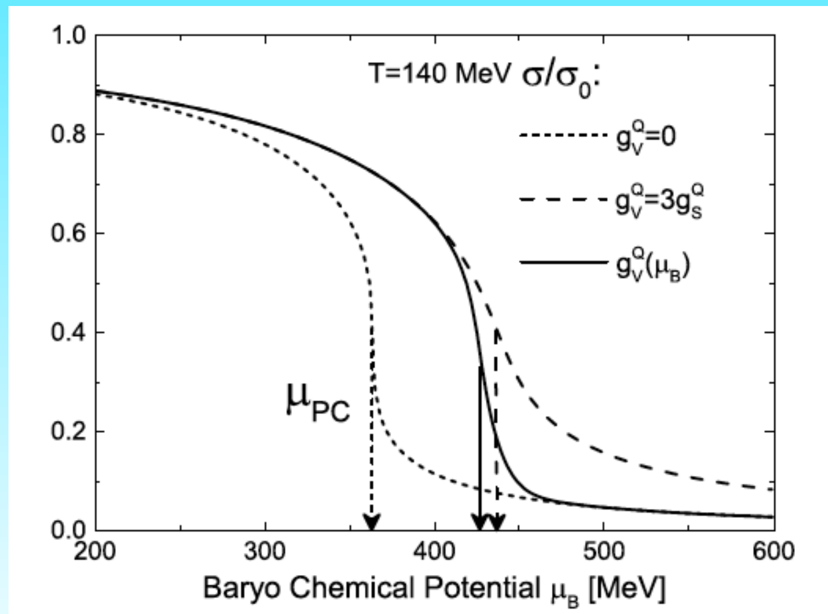


ratio of susceptibilities

turn on/off repulsion
or quarks and baryons

$$g_V^Q(\mu_B) = g_V^Q(\mu_B = 0)\cdot(1+\exp(\mu_B-\mu_B^{PC})/\delta_\mu)^{-1}$$

scalar field as function of μ
for fixed T = 140 MeV



only quarks here

Conclusion:

quark interaction should be small
in the hadron sector either heavy baryons
and/or repulsion (liquid-gas, nuclei)

Condensation of charged higher spin particles?

Heavy-ion collisions can generate very large B fields

W boson condensation at LHC? *Ambjørn, Olesen,PLB257, 201 (1991)*

however, see SWS, Müller, A. Schramm, PLB 277, 512 (1992)

ρ mesons? Simple estimate requires B ~ 10^{20} G

SWS, Müller, A. Schramm MPLA 7, 9773 (1992)

heavy-ion collisions – bind away the whole mass of the particle

*Chernodub, Phys. Rev. Lett. **106**, 142003* *Hidaka, Yamamoto PRD87, 094502*

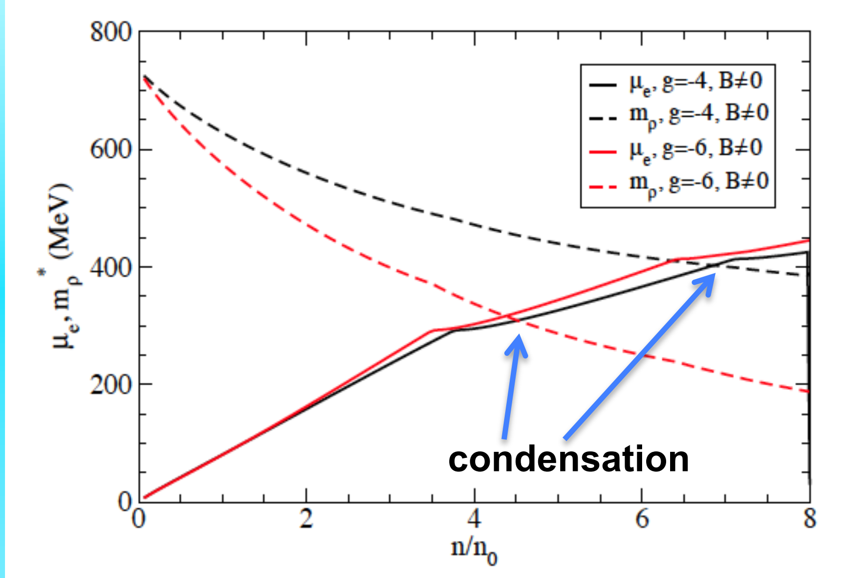
Advantage: high spin – strong interaction with magnetic field

Landau levels of the rho meson

$$E^2_{n,Sz} = p^2 + m^2 + (2n - 2S_z + 1)\, e B$$

$$m_{\rho^-}^{2\;*} = m_{\rho^-}^2 - eB.$$

charge chemical potential and effective rho mass as function of density



Use standard hadronic model

GM3 parameterization

B value: 7×10^{18} G

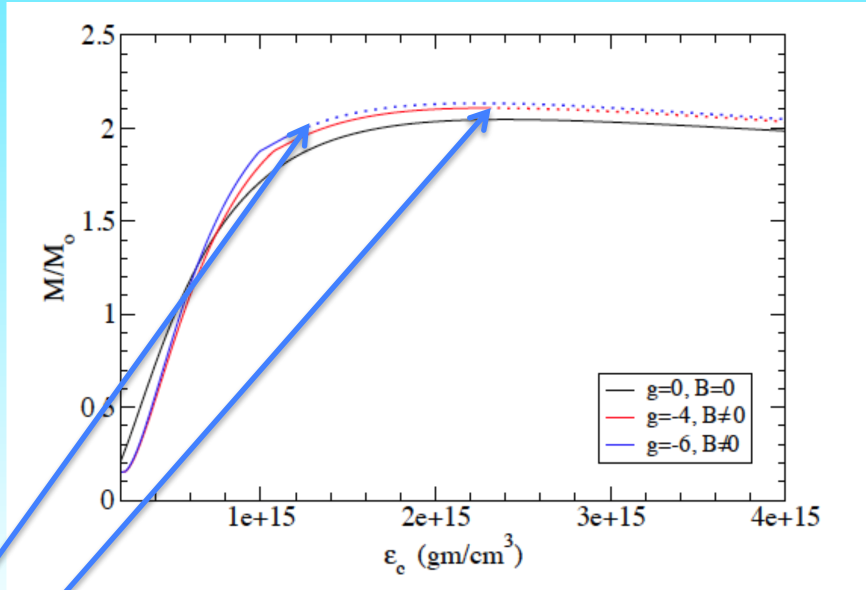
slight change of star masses
faster cooling

density dependence of rho mass ?

simple estimate $m_\rho^* = m_\rho - g\,\sigma$

readjust coupling to correct
asymmetry energy (32.5 MeV)

range of g limited by L, …



onset of condensation

Conclusions, Outlook

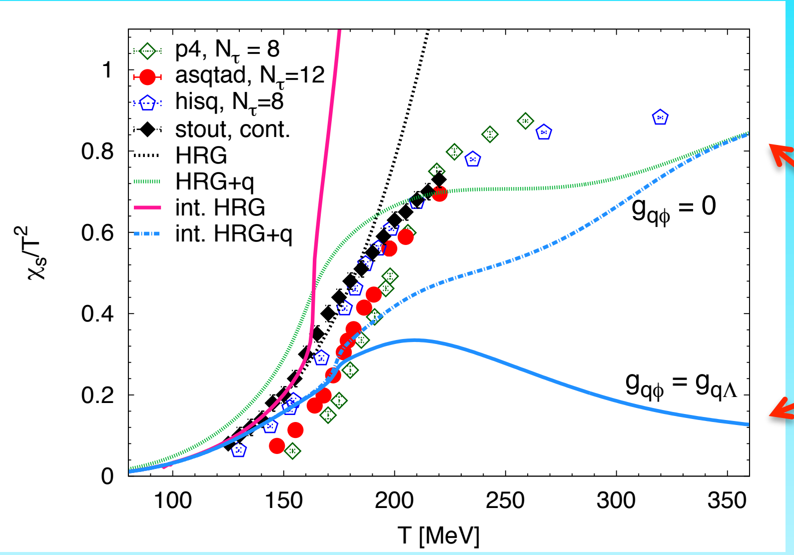
- coherent phenomenological model including correct asymptotic degrees of freedom
- useful input for heavy-ion simulation (extracting interesting signals of PT hard work)
- heavy compact stars / hyper stars - little strangeness
- hybrid stars: stiff equation of state for quarks
- what about lattice susceptibilities?
- possibility of rho meson condensates in compact stars

- *comprehensive equation of state for a wide range of densities/temperatures (supernovae, mergers)*
- *couple hydro and kinetic equations for fields*

Many thanks to the organizers!

analogous behaviour of strange susceptibilitiy

$$X_s \quad = \quad d^2(P) / (d\ \mu_S)^2 \,|_{\mu B, \mu S = 0}$$



off

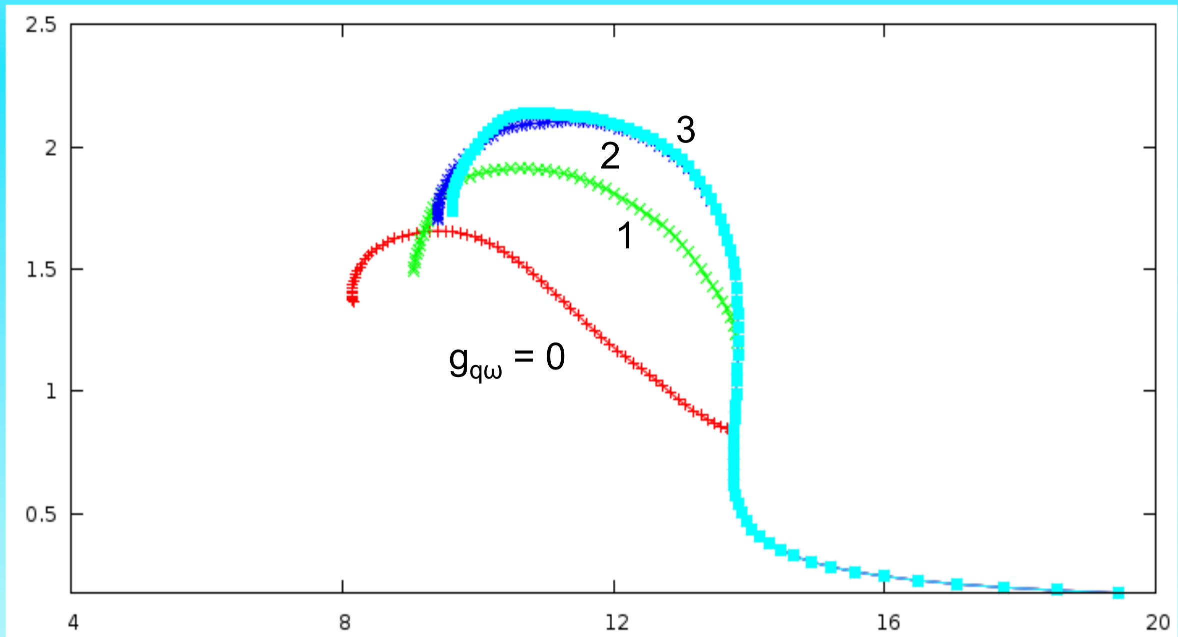
strange quark repulsion

on

calc. by Philip Rau

Including vector interaction for quarks

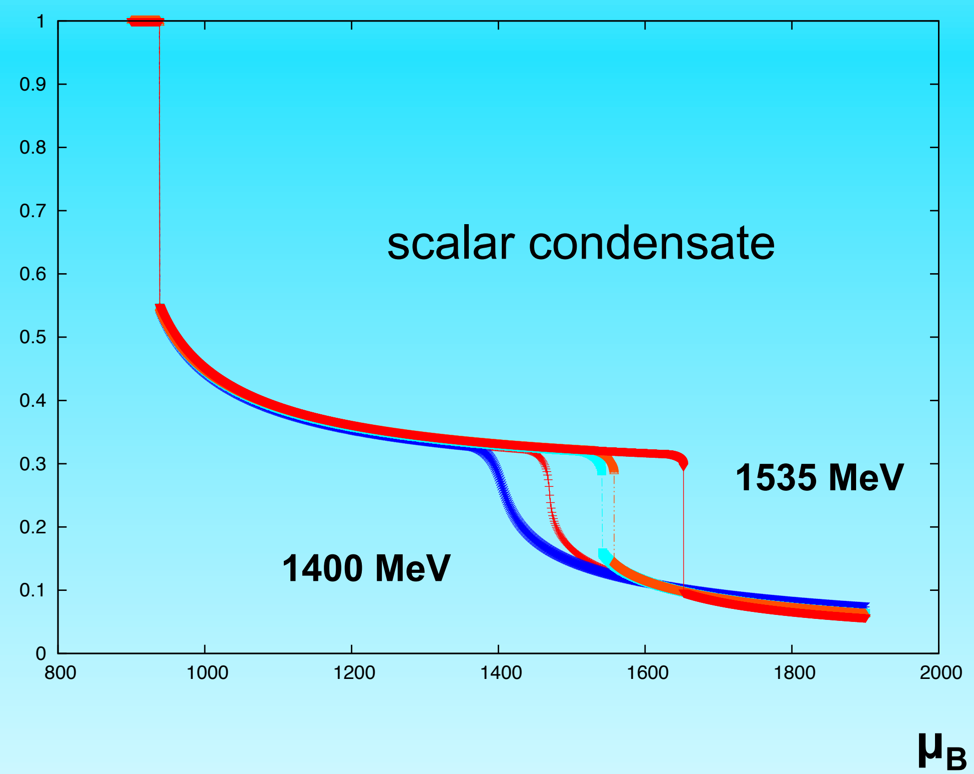
M [M⊙]



R[km]

increase M / R, potential problems at μ = 0

scalar condensate for different masses m_{N^*}



First order transition for masses ≥ 1470 MeV, below crossover

Extension of the parity model to SU(3)

Baryon SU(3) multiplet + parity doublets

Similar approach, SU(3)-invariant potential for scalar fields

single particle energies $$E_{\pm} = \sqrt{\left(g_1\sigma + g_2\varsigma\right)^2 + m_0^2} \pm \left(g'_1\sigma + g'_2\varsigma\right)$$

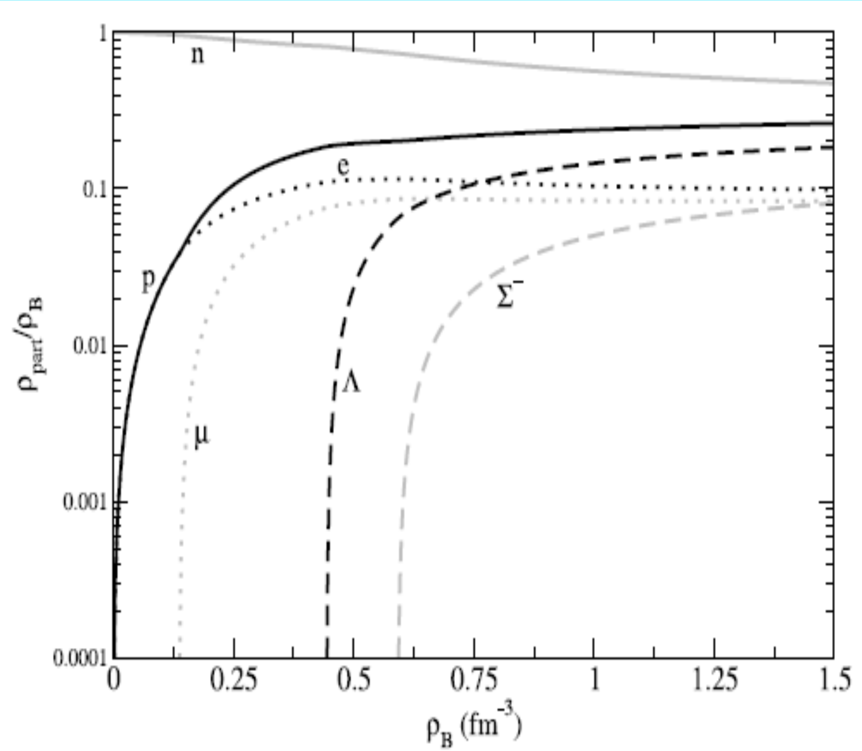
simplify investigation – same mass shift for whole octet

Candidates – Λ(1670), Σ(1750), Ξ (?) overall unclear

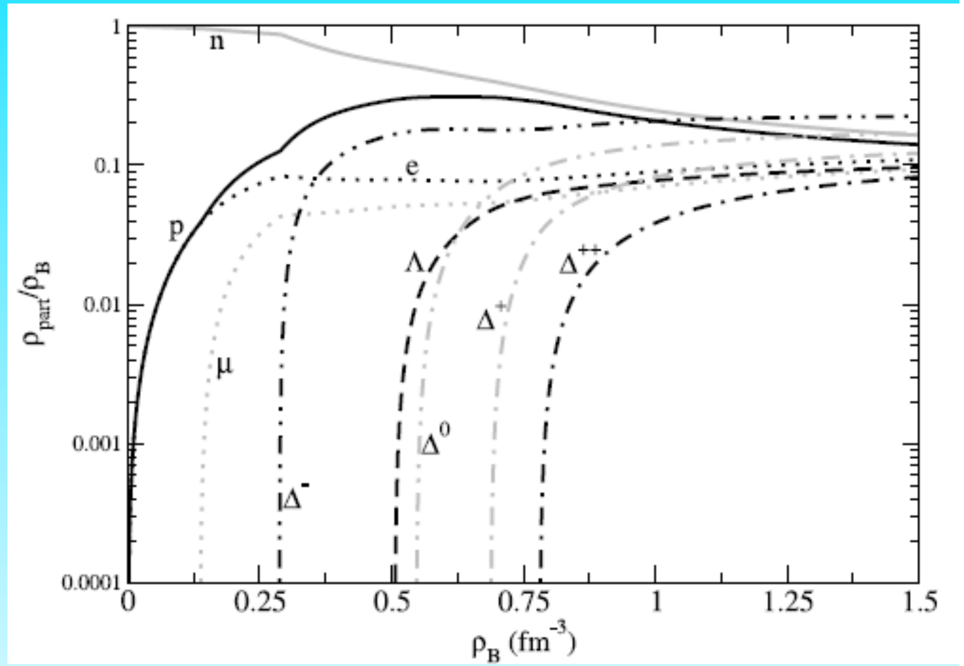
Steinheimer, SWS, Stöcker, *JPhysG 38, 035001 (2011)*

first study - Nemoto et al. PRD 57, 4124 (1998)

particle densities inside of the star

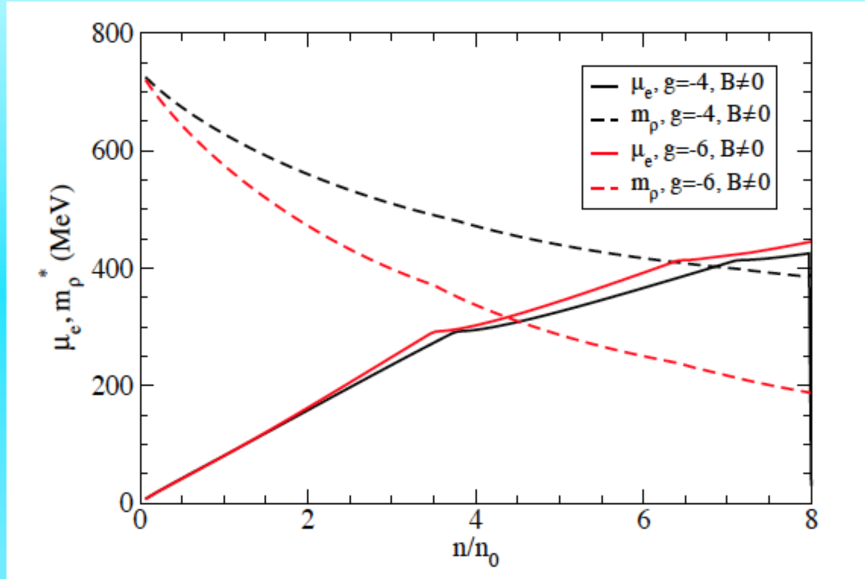


particle abundancies – no decuplet



particle numbers as function of density
uncertainties from $g_{3/2}$ coupling

charge chemical potential and effective rho mass as function of density



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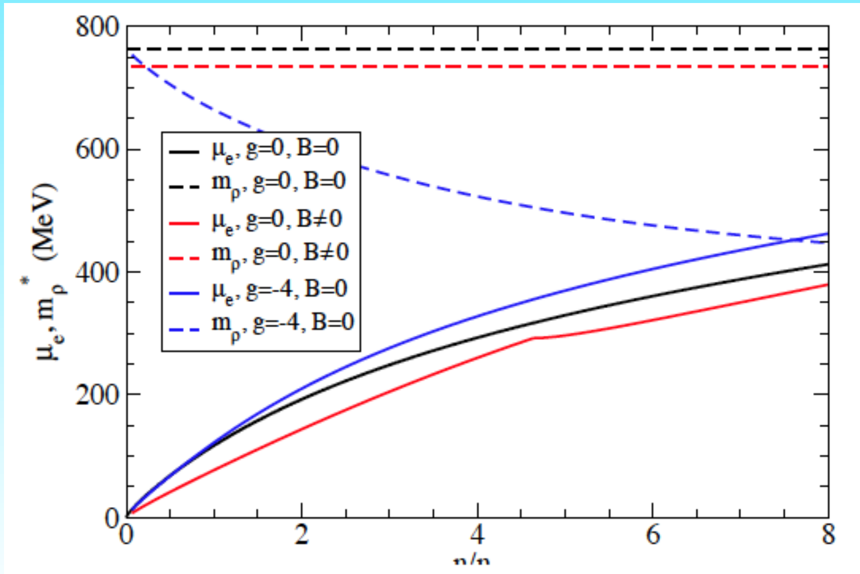
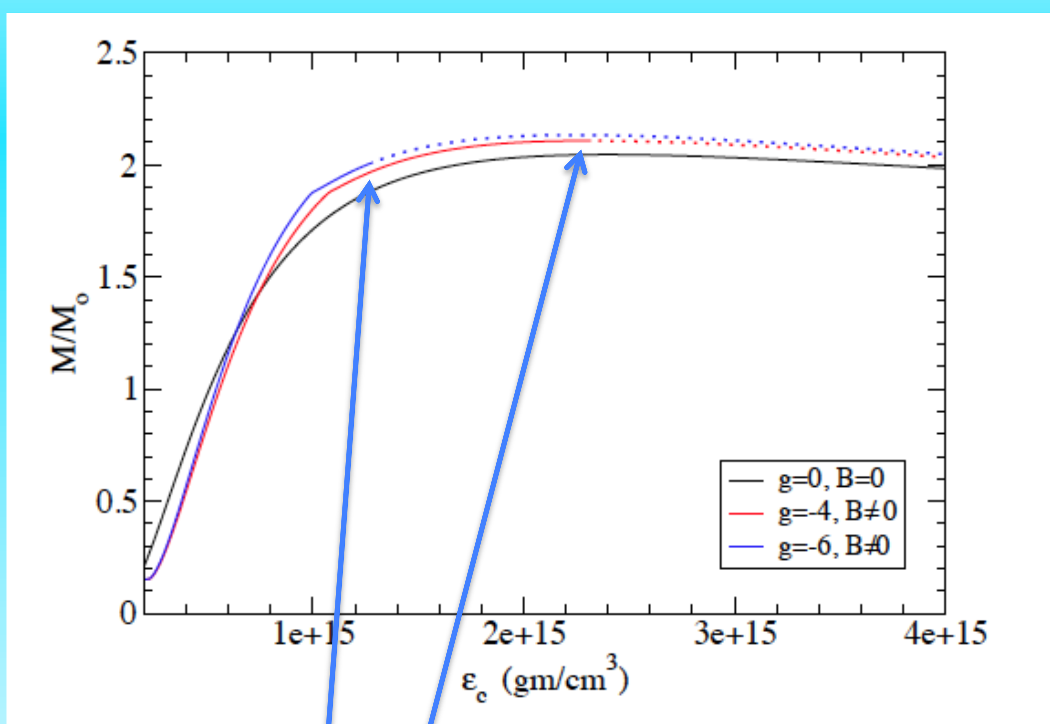


Neutron star masses as function of central energy density



onset of condensation

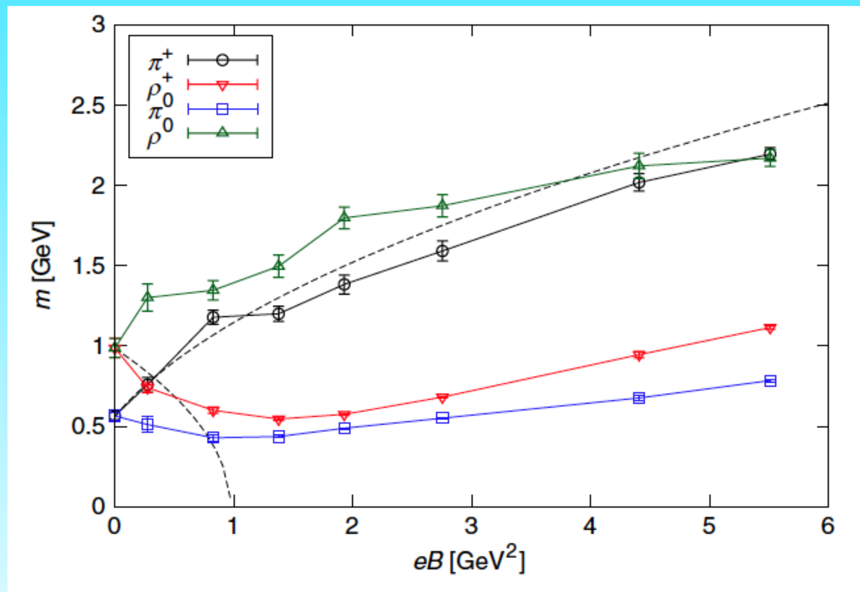
slight change of star masses, faster cooling

Different in compact stars

Advantages - long time scales (beta equilibrium)
large size
potentially large magnetic fields

quenched lattice calculations from

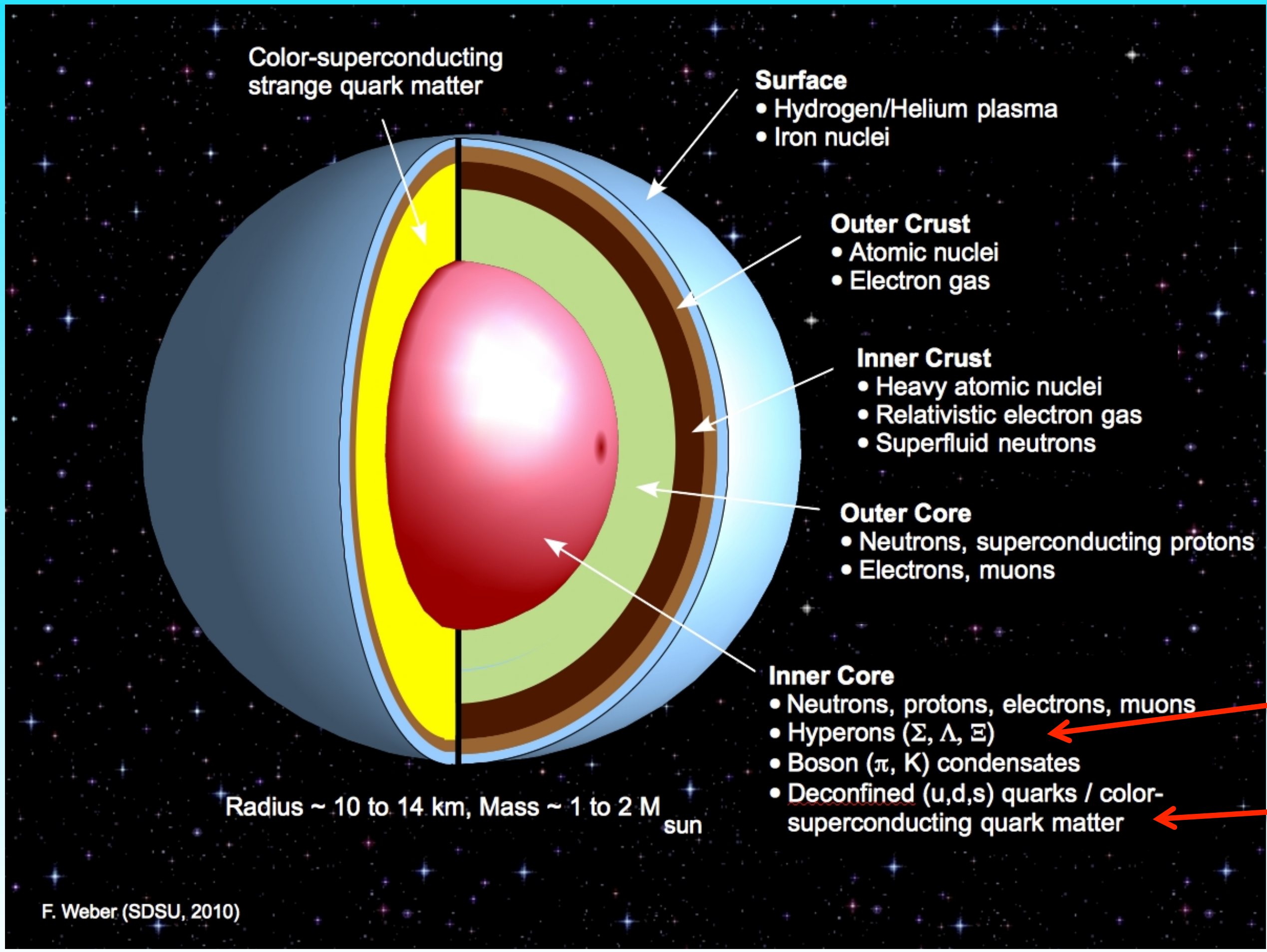
Hidaka, Yamamoto PRD87, 094502



neutron stars are remnants of Type II supernovae

1 to 2 solar masses, radii around 10 - 15 km
maximum central densities 4 to 10 ρ_0

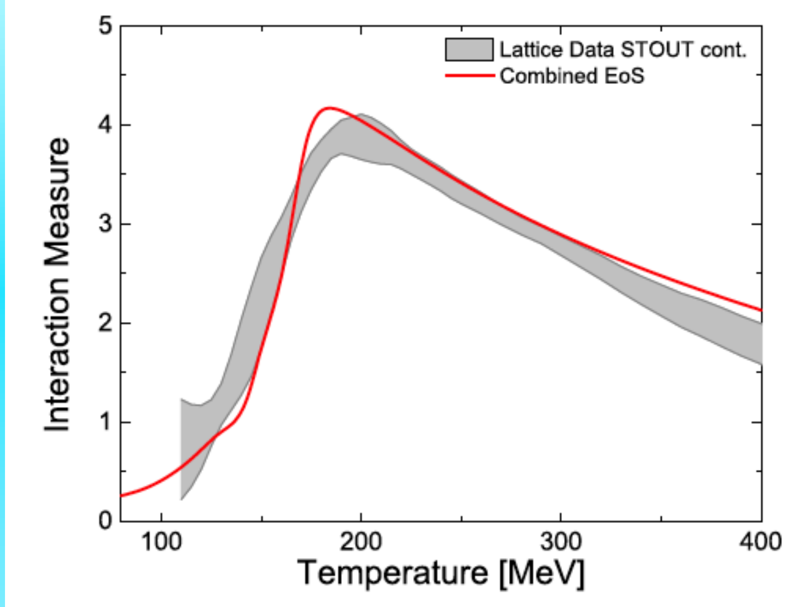
about 2000 known neutron stars



hyper star

hybrid star

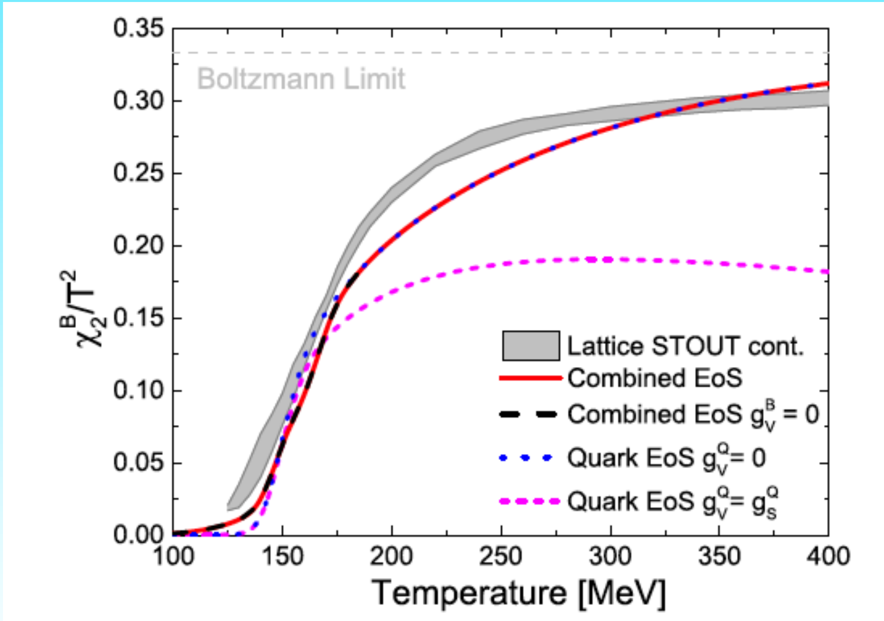
after fine-tuning parameters



"interaction measure" $(e - 3p)/T^4$

Lattice (STOUT) and model

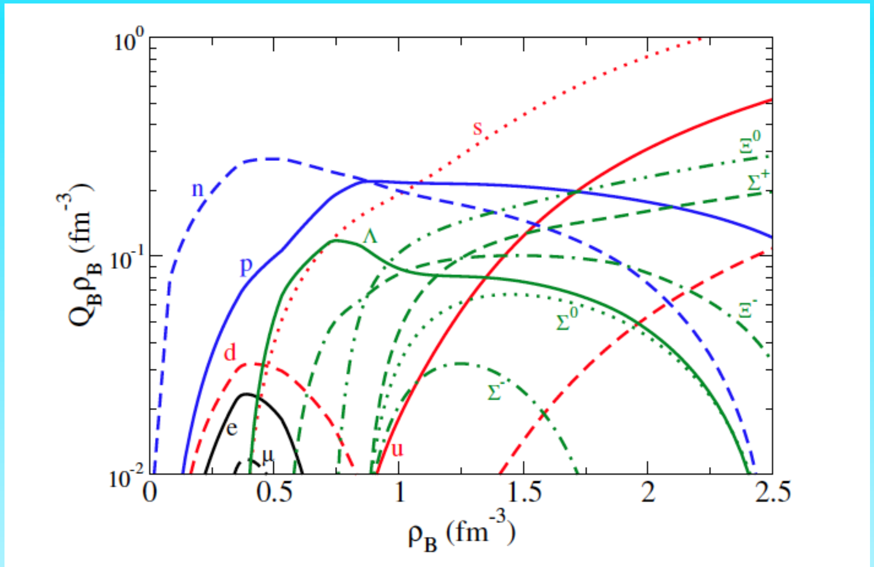
X_2 for different vector couplings

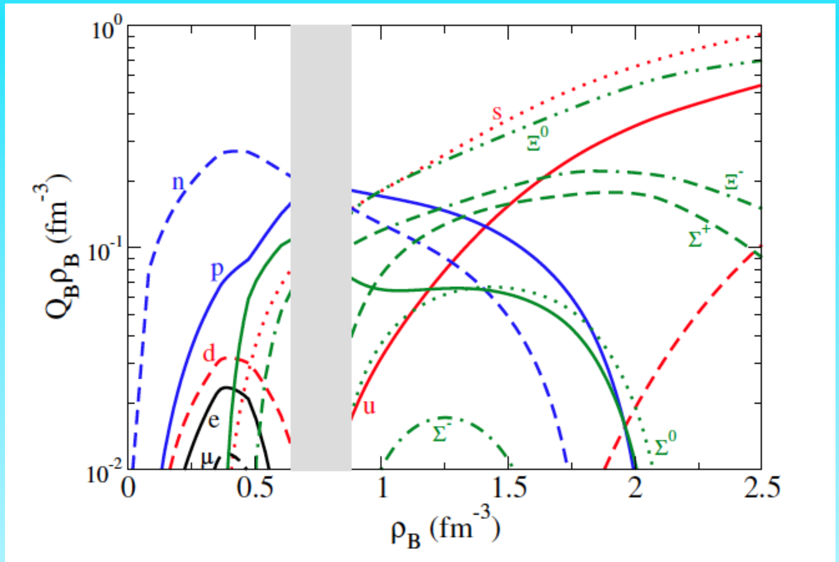


susceptibilities χ_n, c_n

$$\frac{\chi_n^B}{T^2} = n! c_n^B(T) = \frac{\partial^n (p(T, \mu_B)/T^4)}{\partial(\mu_B/T)^n}$$

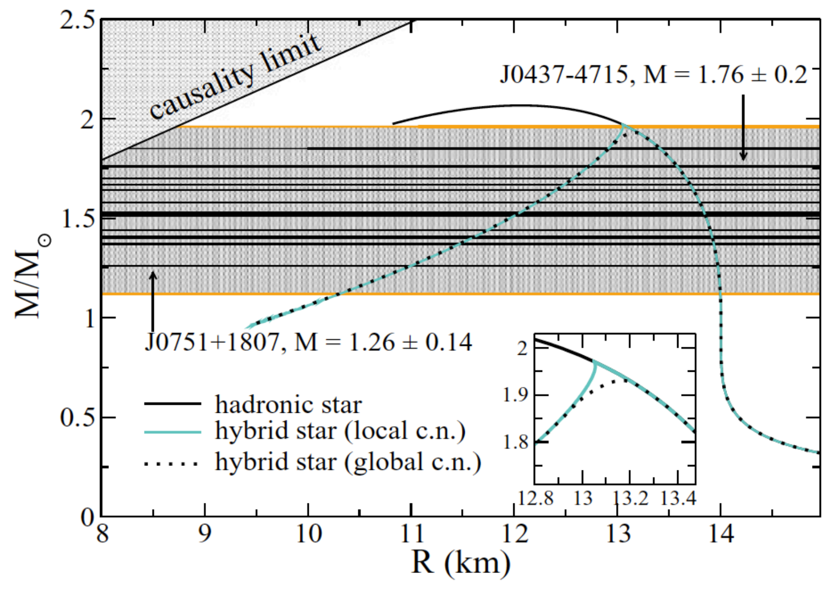
particle “cocktail” as function of density





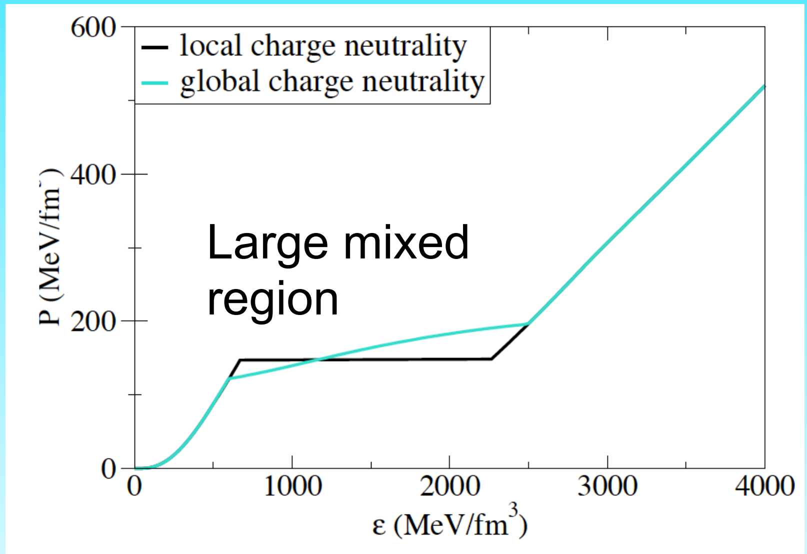
with first-order transition

Hybrid Stars



M-R diagram in QH model

baryonic star with a 2km core of quarks



Maxwell / Gibbs construction for
local / global charge neutrality

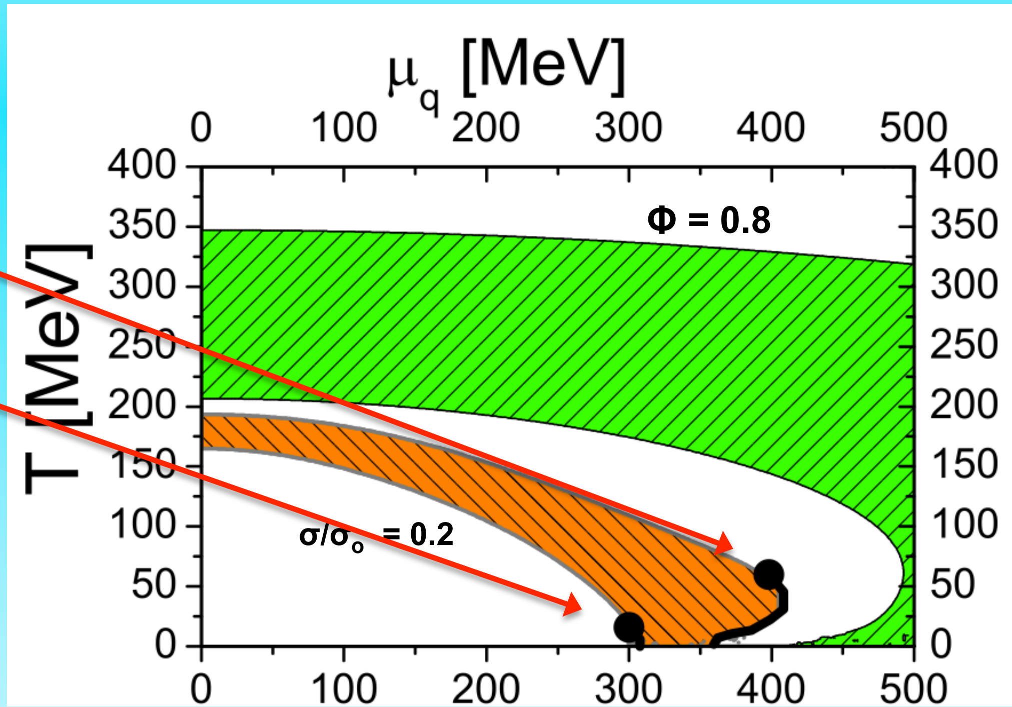
Negreiros, Dexheimer, SWS, PRC82 035803 (2010)

Excited quark-hadron matter in the parity-doublet approach

Chiral transition

Liquid-gas phase transition

2 different values for T_0



single particle energies

$$E_{\pm} = \sqrt{\left(g_1\sigma + g_2\varsigma\right)^2 + m_0^2} \pm \left(g'_1\sigma + g'_2\varsigma\right)$$

Steinheimer, SWS, Stöcker, JPhysG 38, 035001