The Structure and Signals of Neutron Stars, from Birth to Death, Florence 2014

Compact stars and general constraints on exotic phases

OUTLINE

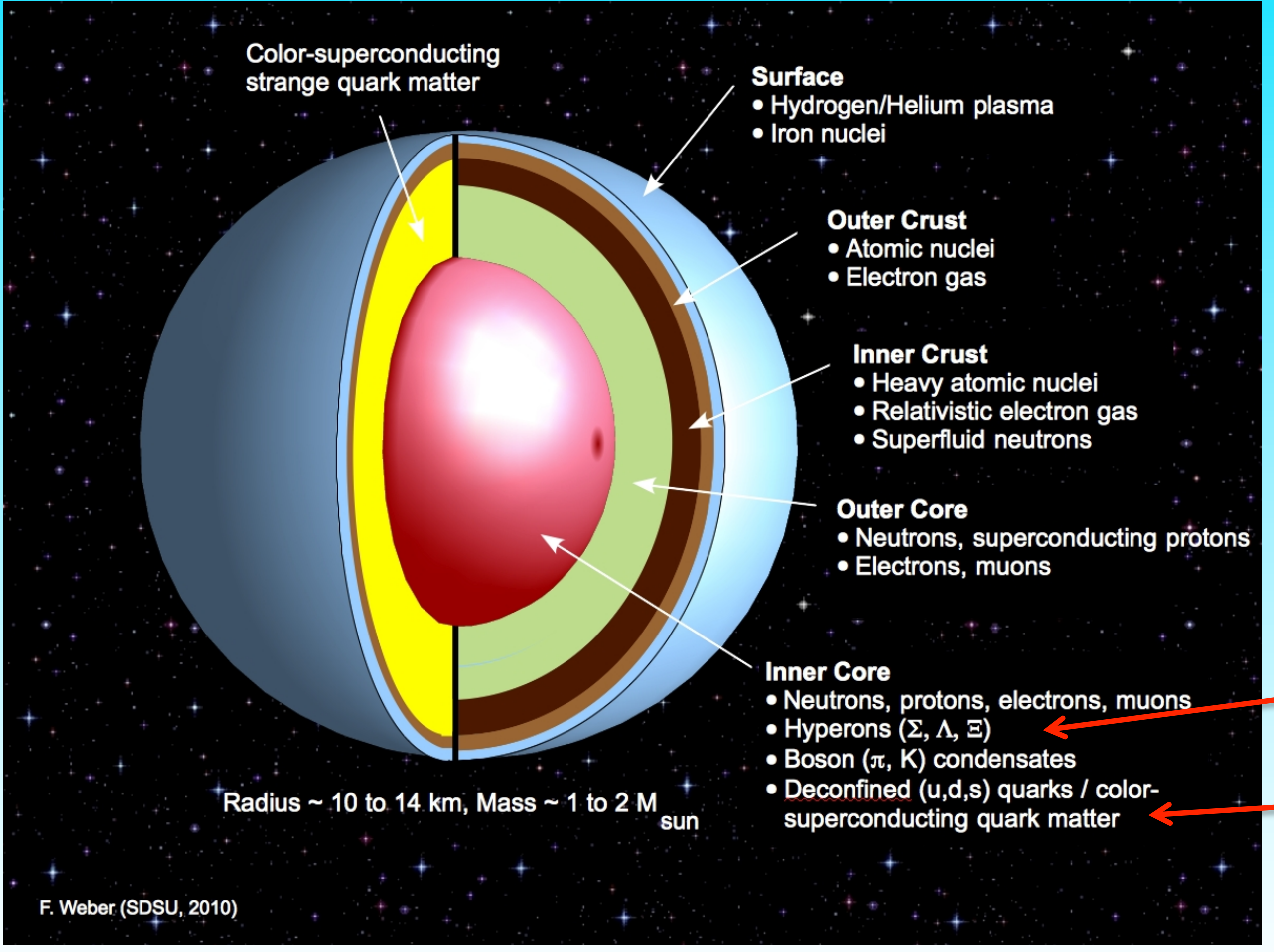
- observational situation
- compact stars – nucleons + hyperons
- additional degrees of freedom
- adding quarks
- comparison to various lattice results
- magnetic fields

V. Dexheimer, B. Franzon, R. Mallick, R. Negreiros, T. Schürhoff, SWS
FIAS Frankfurt, Kent State, Fluminense

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

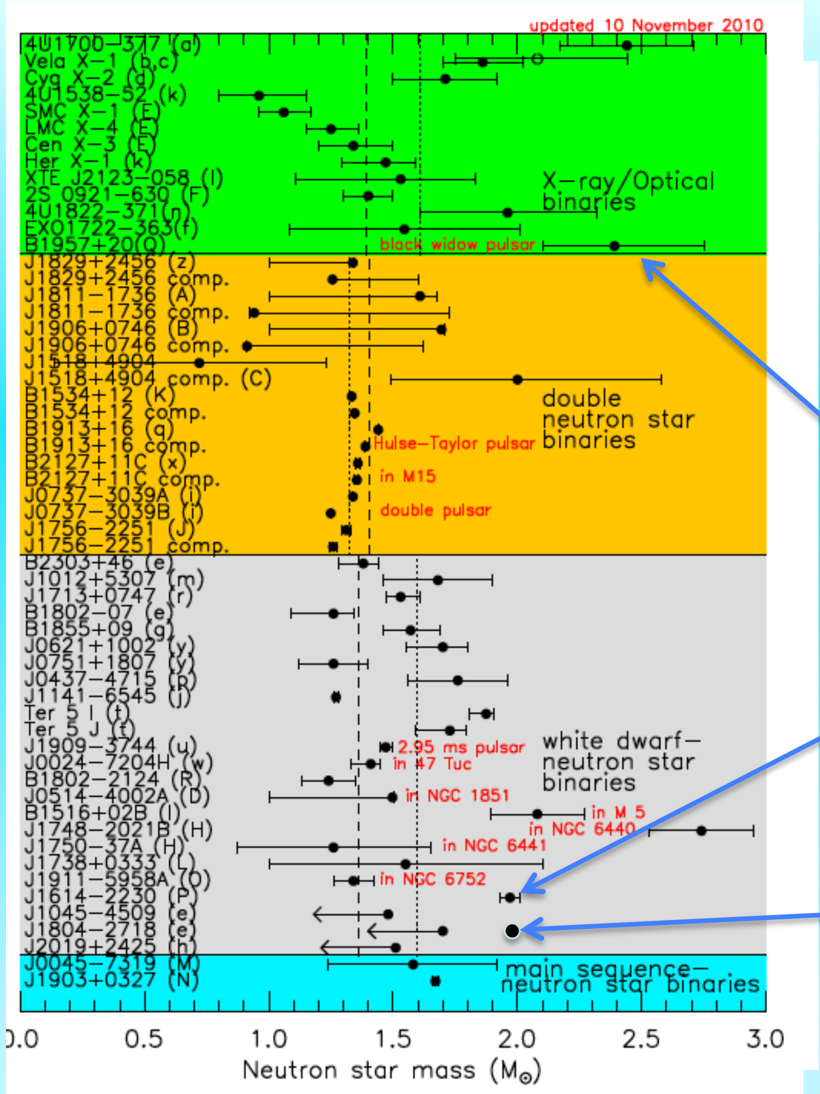
about 2000 known neutron stars



hyper star

hybrid star

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

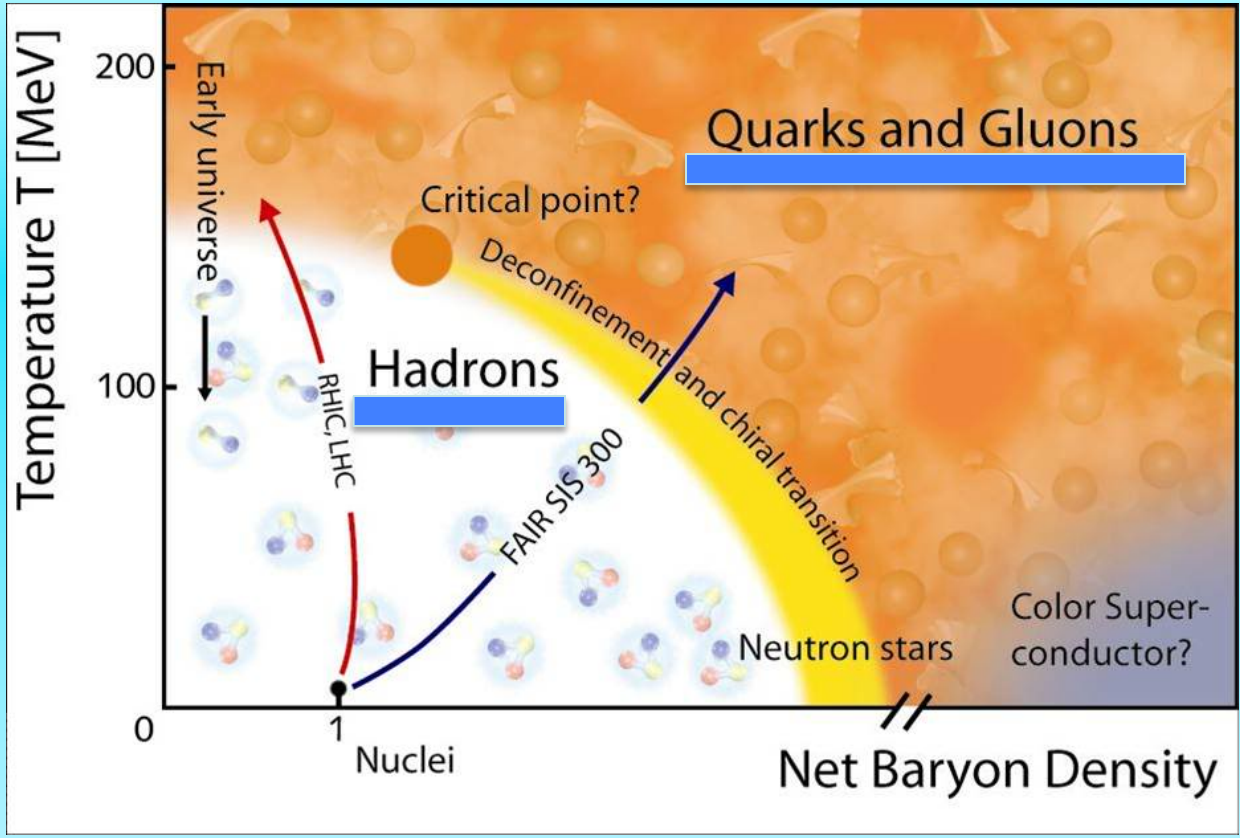
M = (2.4 +- 0.12) M_s ?
van Kerkwijk et al., ApJ 728, 95 (2011)

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

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

$B = \{ p , n , \Lambda , \Sigma^{\pm/0} , X^{-/0} \}$ 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 $I_1 = \mathrm{Tr}(X)$ $I_2 = \mathrm{Tr}(X)^2$ $I_3 = \det(X)$

V(M) $\langle\sigma\rangle = \sigma_0 \neq 0$ $\langle\zeta\rangle = \zeta_0 \neq 0$

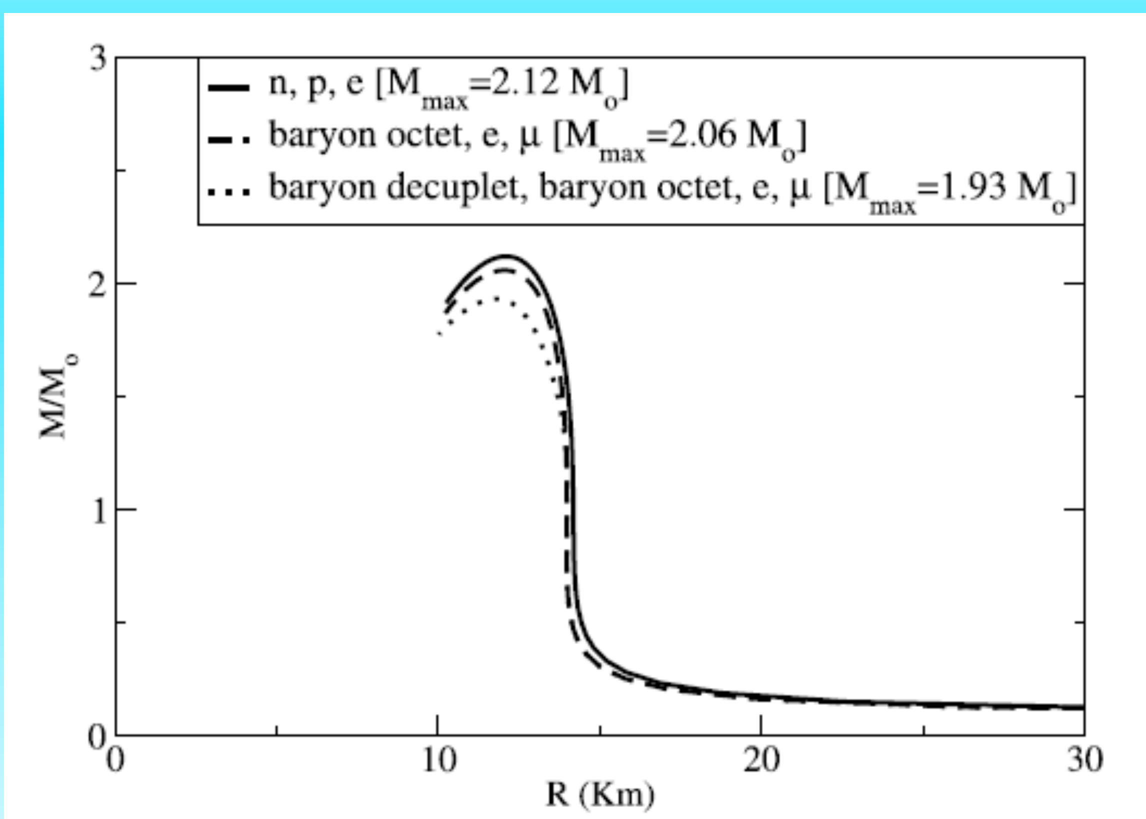
$\sigma \sim \langle \bar{u} u + \bar{d} d \rangle$ $\zeta \sim \langle \bar{s} s \rangle$ $\delta^0 \sim \langle \bar{u} u - \bar{d} d \rangle$

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

fix scalar parameters to baryon masses, decay constants, meson masses

fit for large star masses T. Schürhoff $\varepsilon \sim 0.28$, $\kappa \sim 275$ MeV, $M \sim 2 M_\odot$

Neutron star masses including different sets of particles



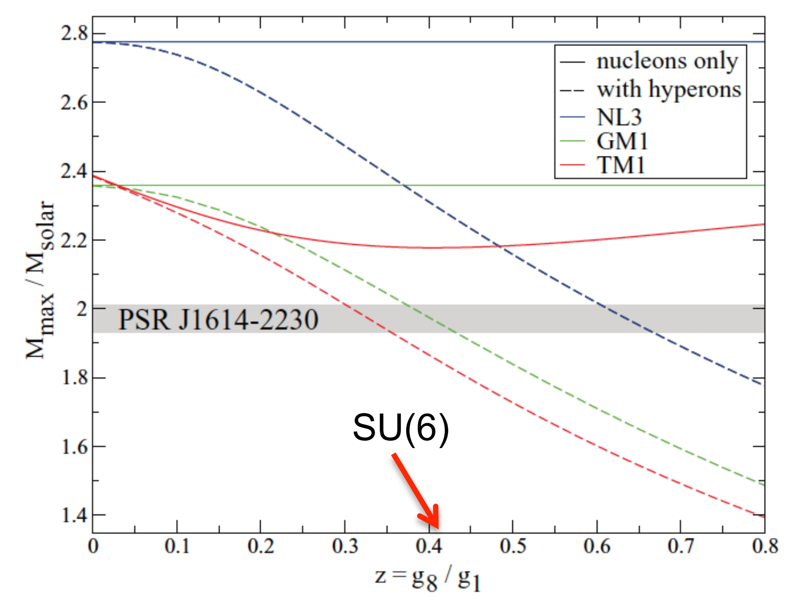
Tolman-Oppenheimer-Volkov equations, static spherical star

changing masses with degrees of freedom

large star masses even with spin 3/2 resonances

Dexheimer, SWS ApJ 683, 943 (2008)

systematically “playing around” with vector couplings away from SU(6)



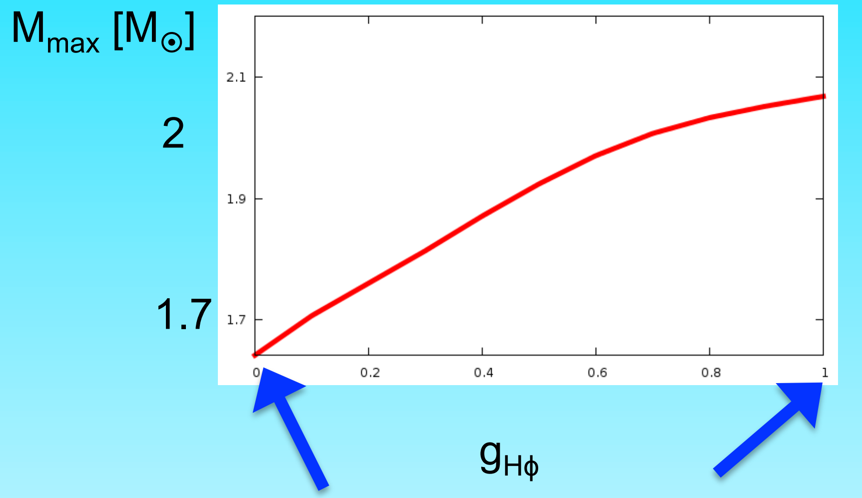
$$\frac{M_{\max}}{M_\odot} = \frac{M_{\max}(f_s = 0)}{M_\odot} - c\left(\frac{f_s}{0.1}\right)$$

with c ~ 0.6

however, SU(6) limit: $g_{N\phi} = 0$

SU(3): $g_{N\phi} = \sqrt{2}\ 1/3\ (-1 + 4\ \alpha)\ g_8 - 1/\sqrt{3}\ g_1$

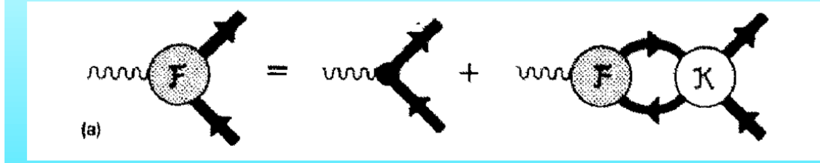
f_s(core) varies between 0.1 and 1



➔ not a whole lot of strangeness

Weissenborn, Chatterjee, Schaffner-Bielich, PRC85,065802 (2012)

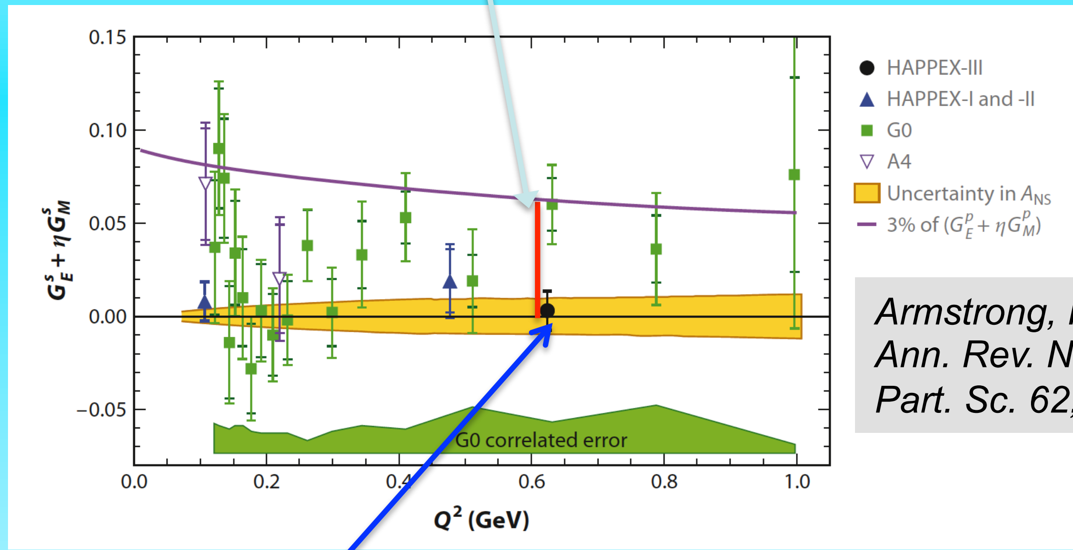
Strong coupling of N to Φ? - strange vector form factor of nucleon



band of possible values from calculation

SWS, MPLA 10 1201 (1995)

Summary of PV polarized eA scattering experiments



Armstrong, McKeown, Ann. Rev. Nucl. & Part. Sc. 62, 337 (2012)

most recent experiment - strangeness contribution consistent with 0

M ~ 

interference term $\sigma_{PV} \sim M_\gamma M^*_Z$

asymmetry $A \sim G_F Q^2 / \alpha \sim 10^{-5}$

χQCD collaboration small values for μ_s and r_s ,

PRD80 094503 (2009)

playing around with the Δ baryon

Δ resonances
scalar couplings → vacuum masses

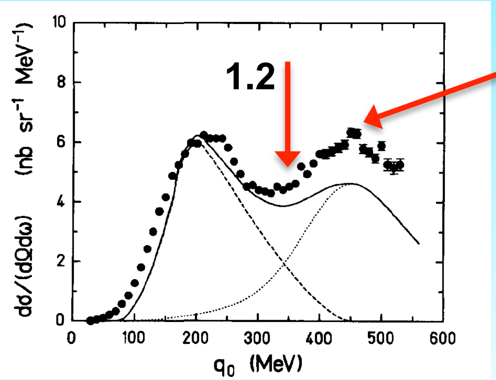
vector couplings unclear

moderate changes $r_V = g_{\Delta\omega} / g_{n\omega}$

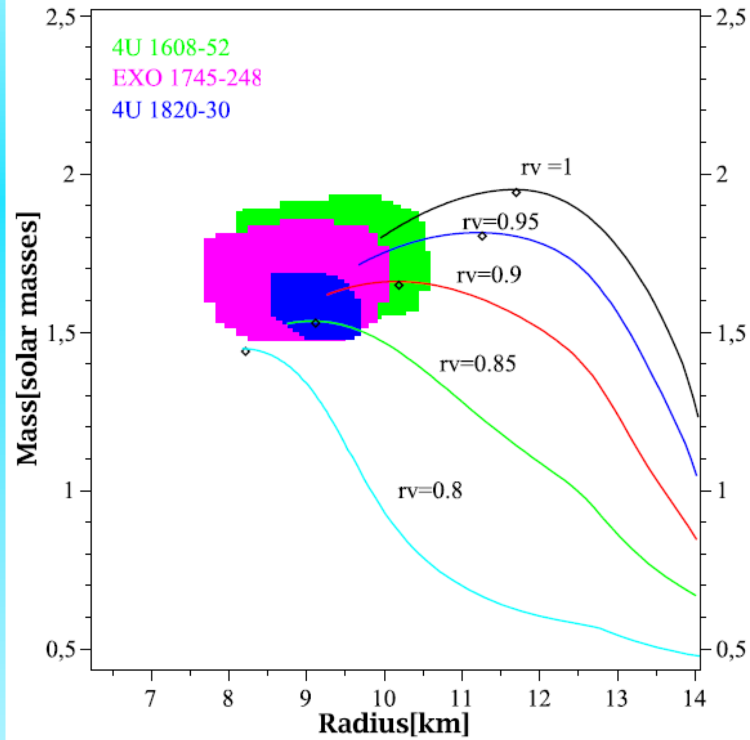
not far from SU(6)

same from quasielastic eA scattering

E = 695 MeV ^{40}Ca



Wehrberger, Phys. Rep. 225, 273 (1993)

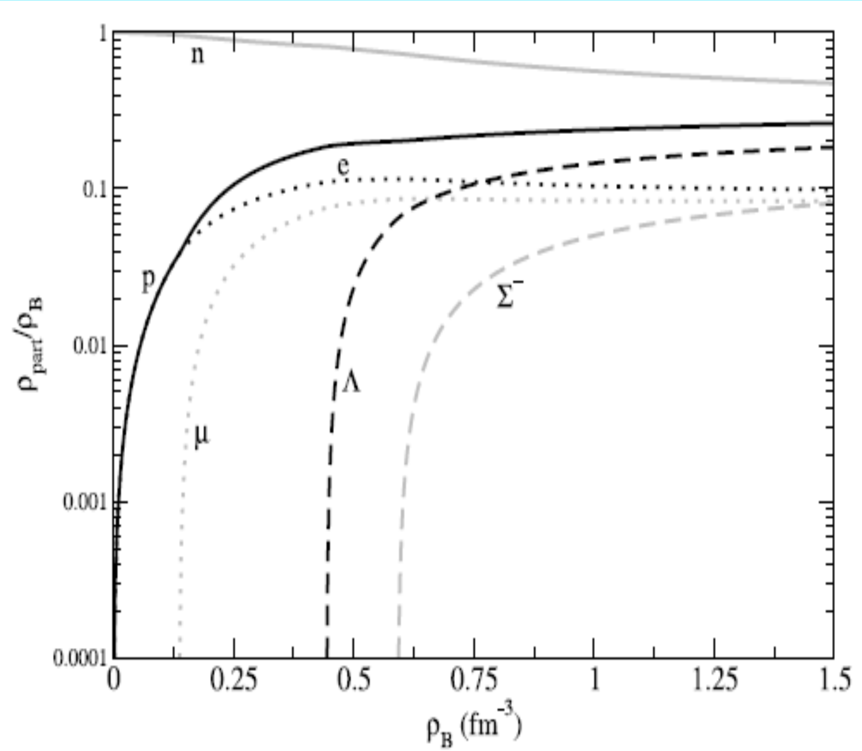


Schürhoff, SWS, Dexheimer, APJL 724 (2010) L74

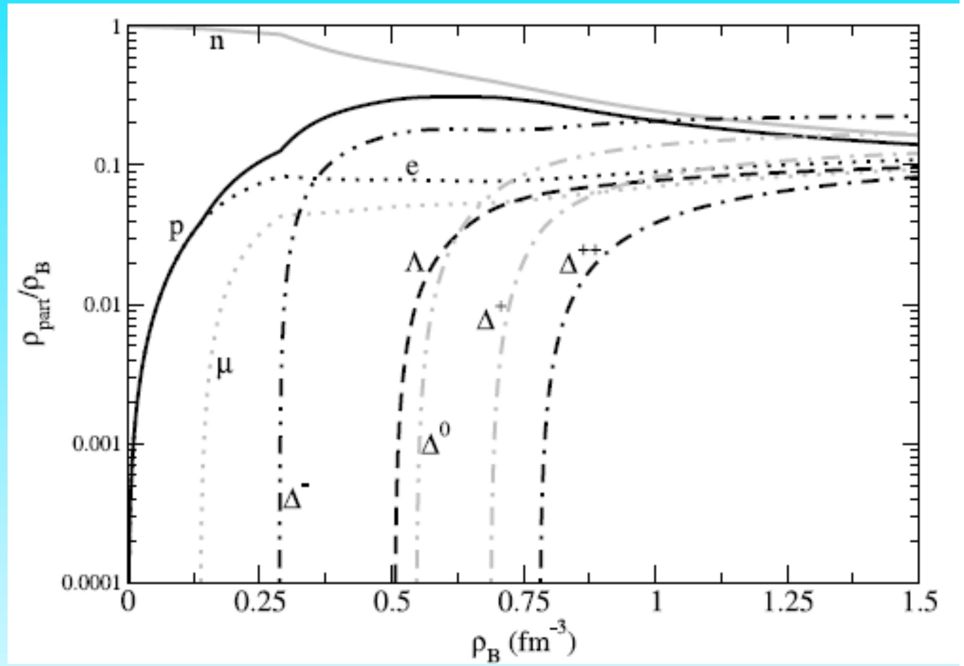
Data from Özel et al, astro-ph:1002.3153

see however, Steiner et al, astro-ph:1005.0811

particle densities inside of the star



particle abundancies – no decuplet

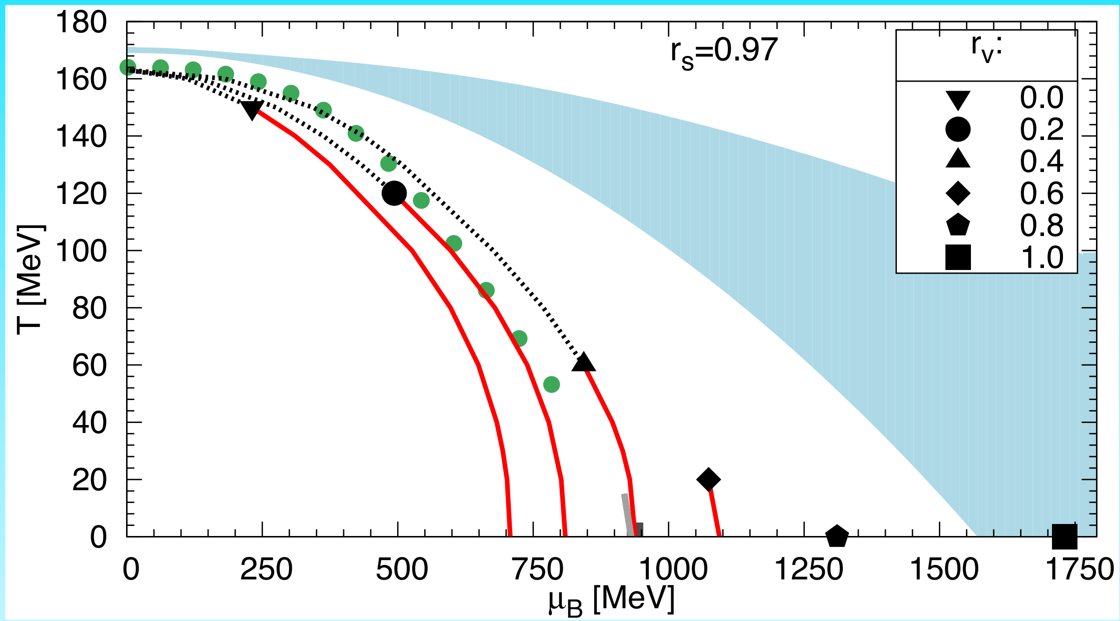


particle numbers as function of density
uncertainties from $g_{3/2}$ coupling

Adding resonances up to 2.6 GeV

In principle - many (!!) parameters

rescale lowest-multiplet coupling strengths



Advantage: EOS has same degrees of freedom as hybrid code
Usually mismatch - d.o.f. hydro and cascade parts

Rau, Steinheimer, SWS, Stöcker, *PRC 2012*

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!

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

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

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

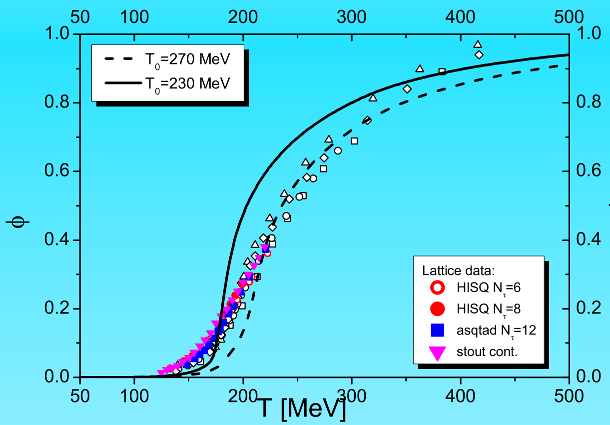
equation of state stays causal!

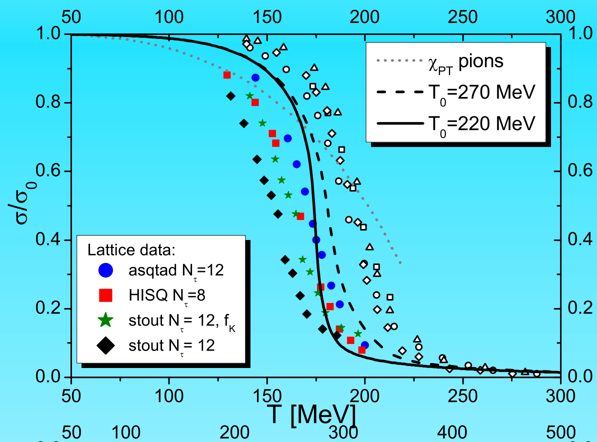
Steinheimer,SWS,Stöcker JPG 38, 035001 (2011)

results for hot matter at vanishing chemical potential

points are various lattice results

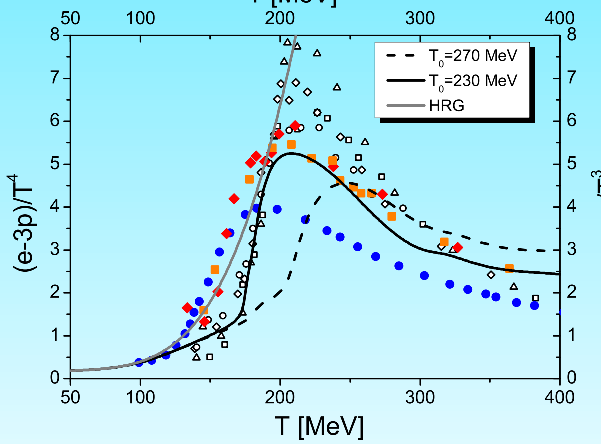
Polyakov loop

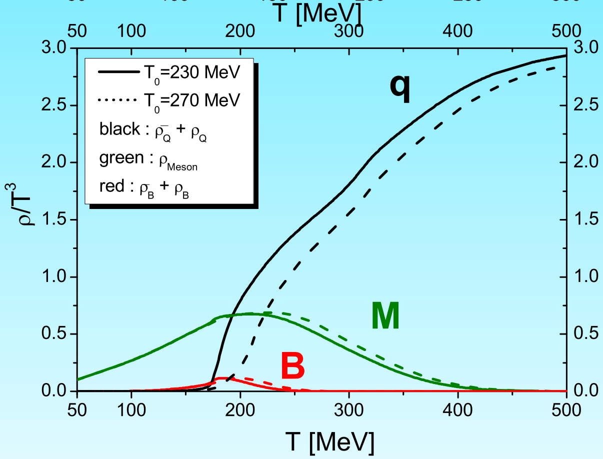




scalar condensate

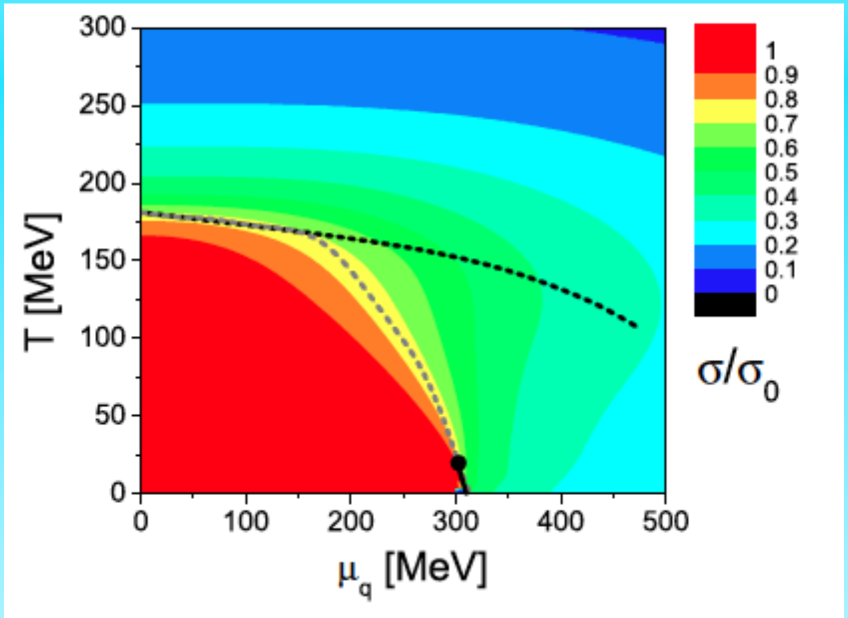
Interaction measure

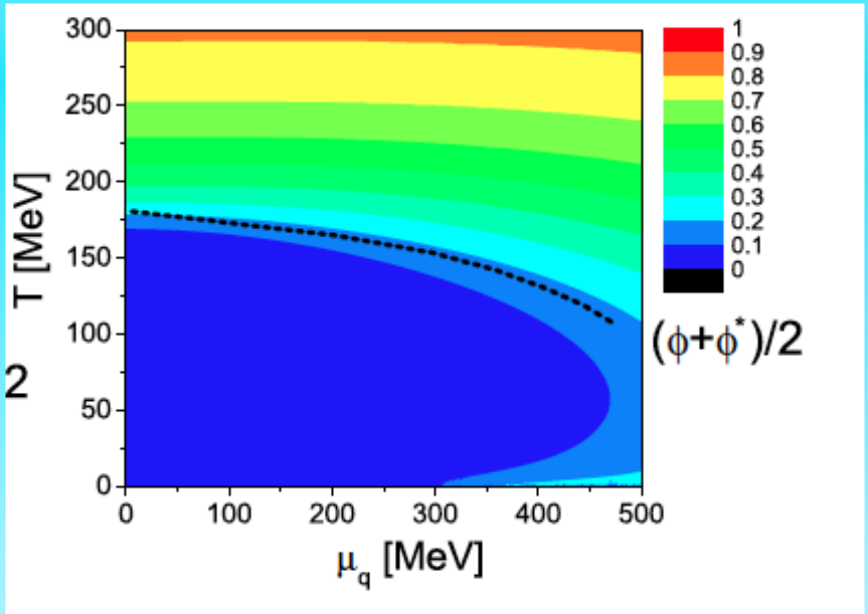




densities

Order parameters for chiral symmetry and confinement in μ and T





except for liquid-gas no first-order transition

dense matter and stars in a parity doublet model

- treat B , B* as positive/negative parity doublet s

transformation:

$$\psi_{1R} \longrightarrow R\psi_{1R}, \quad \psi_{1L} \longrightarrow L\psi_{1L},$$
$$\psi_{2R} \longrightarrow L\psi_{2R}, \quad \psi_{2L} \longrightarrow R\psi_{2L}.$$

chirally invariant mass term

$$m_0(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2) = m_0(\bar{\psi}_{2L}\psi_{1R} - \bar{\psi}_{2R}\psi_{1L} - \bar{\psi}_{1L}\psi_{2R} + \bar{\psi}_{1R}\psi_{2L})$$

Candidates – N(1535), Λ(1670), Σ(1750), Ξ (?) overall unclear

single particle energies

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

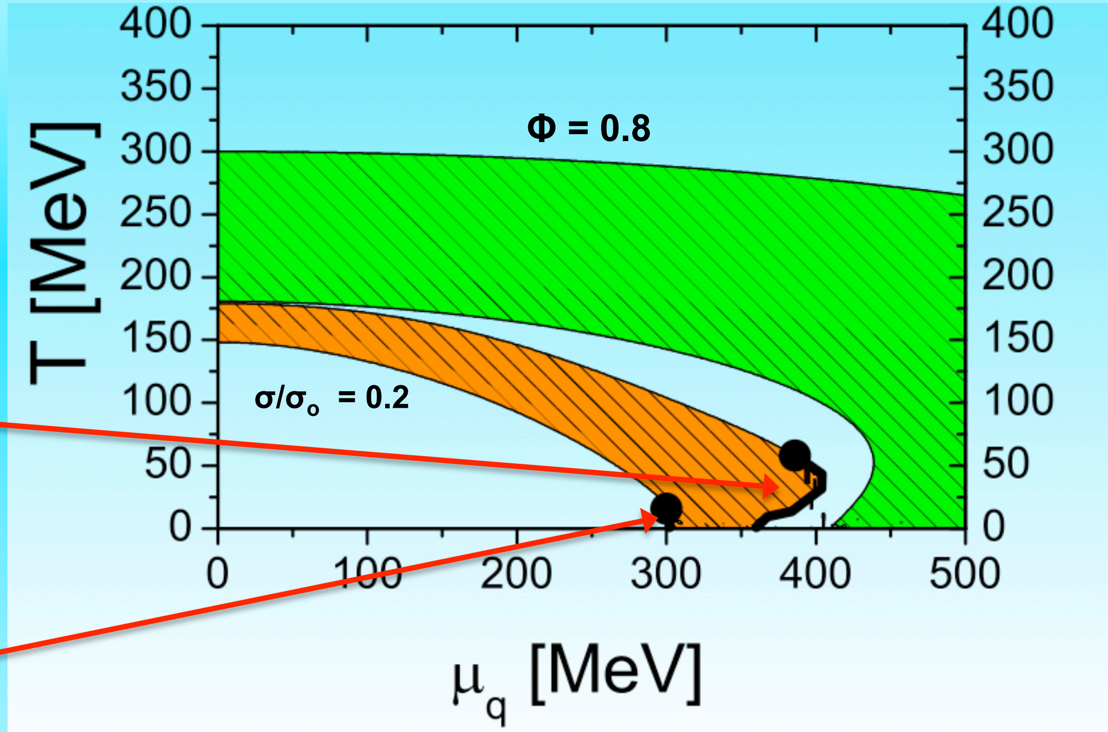
degenerate in the chiral limit

Steinheimer, SWS, Stöcker, PRC 84, 045208
Dexheimer, Steinheimer, Negreiros, SWS, PRC 87, 015804

Excited quark-hadron matter in the parity-doublet approach

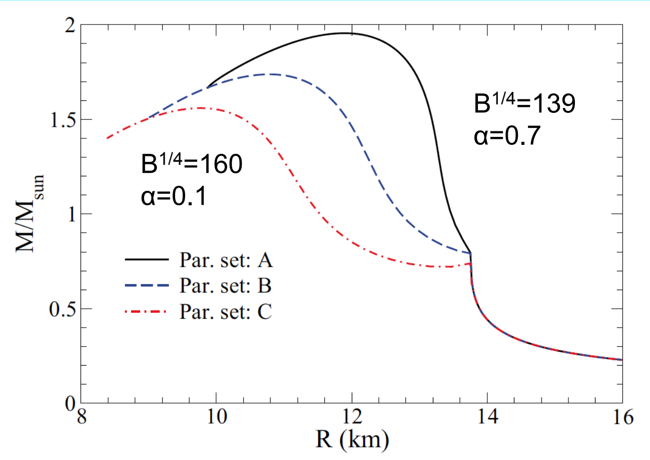
Chiral transition

Liquid-gas phase transition



First-order phase transition with low-T critical end point due to chiral parity partners

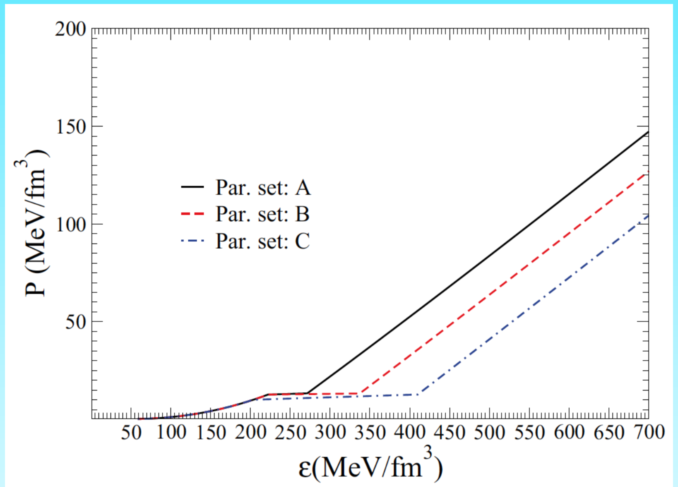
Hybrid Stars, Quark Interactions



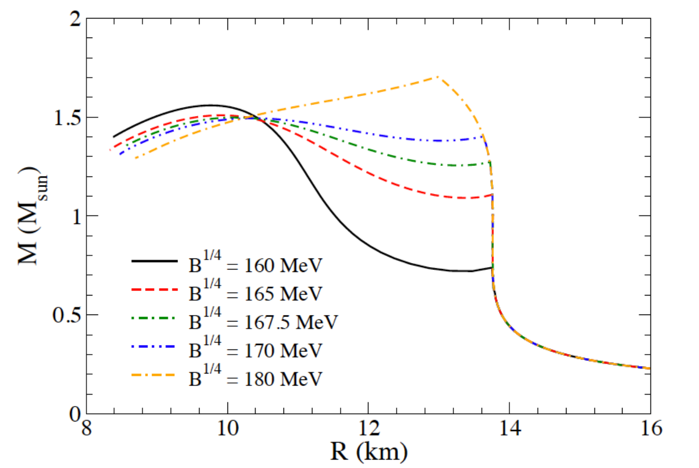
ingredients –
Standard baryonic EOS (G300)
plus MIT bag model + α_s corrections

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

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

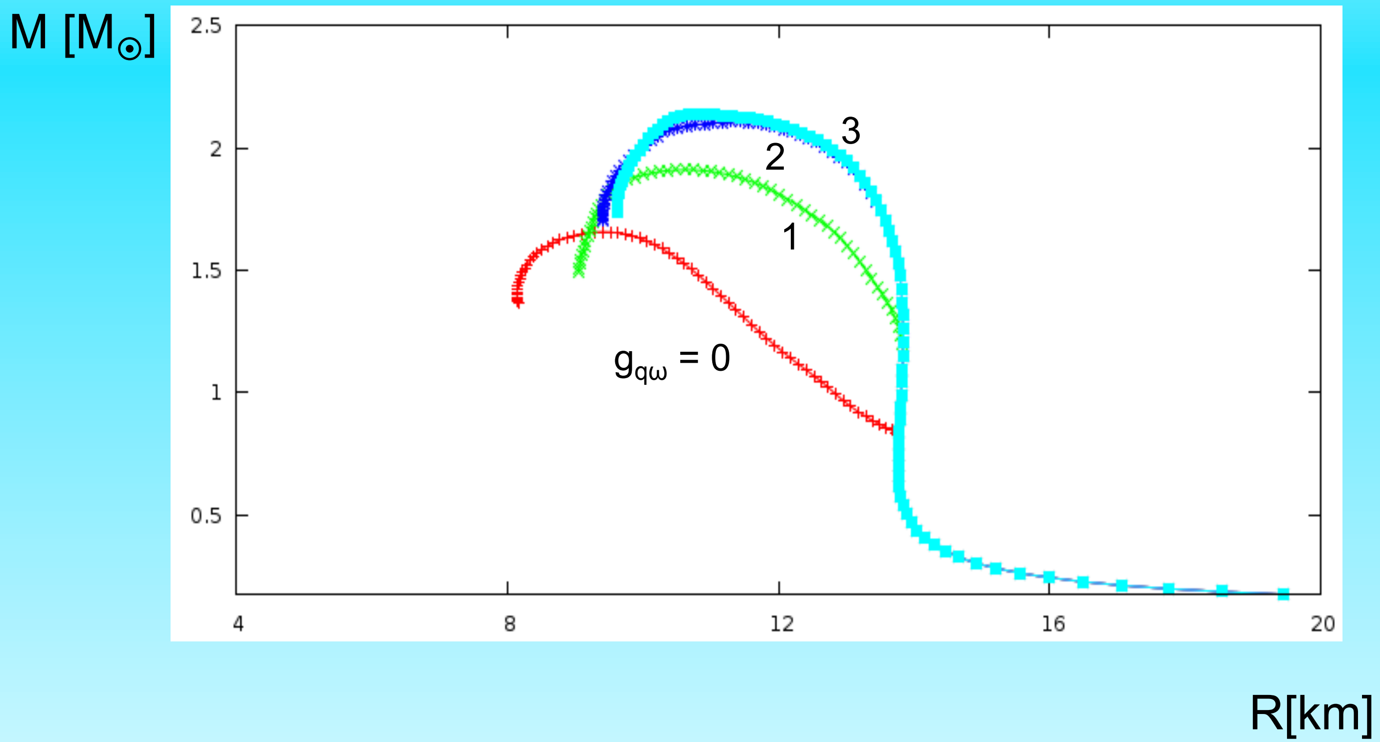


no α_s



Negreiros, Dexheimer, SWS, PRC 035805 (2012)

Including vector interaction for quarks

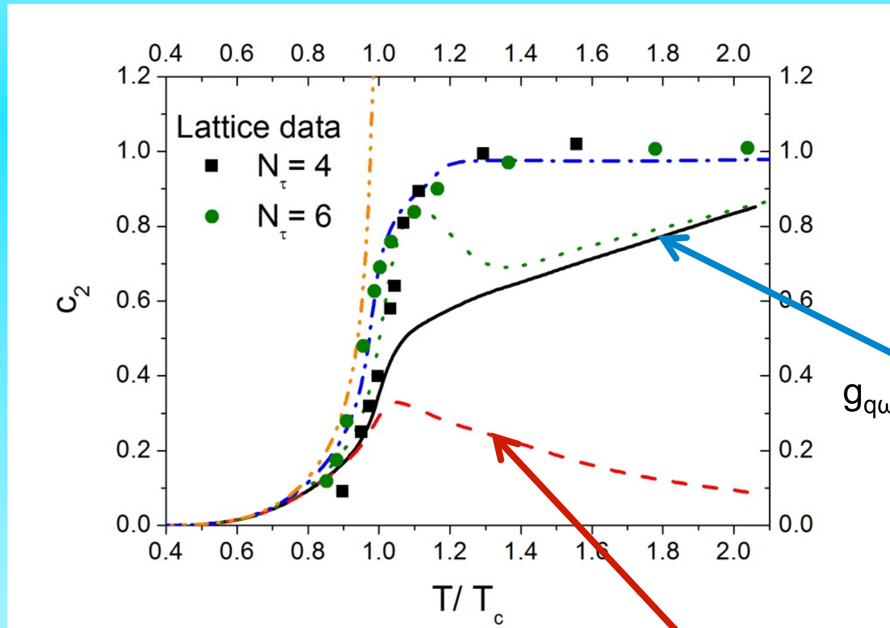


increase M / R, potential problems at μ = 0

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

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

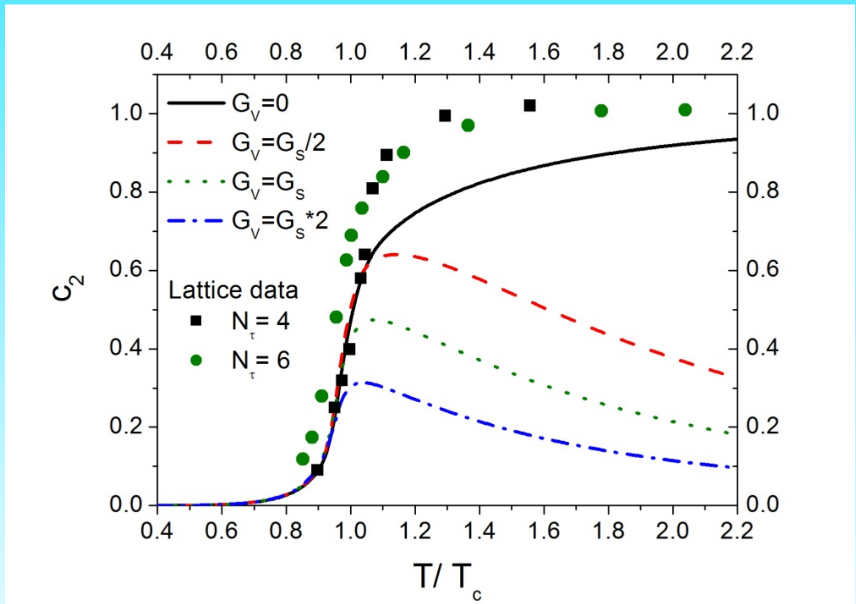
QH



$g_{q\omega} = 0$

small quark vector repulsion !!

PNJL

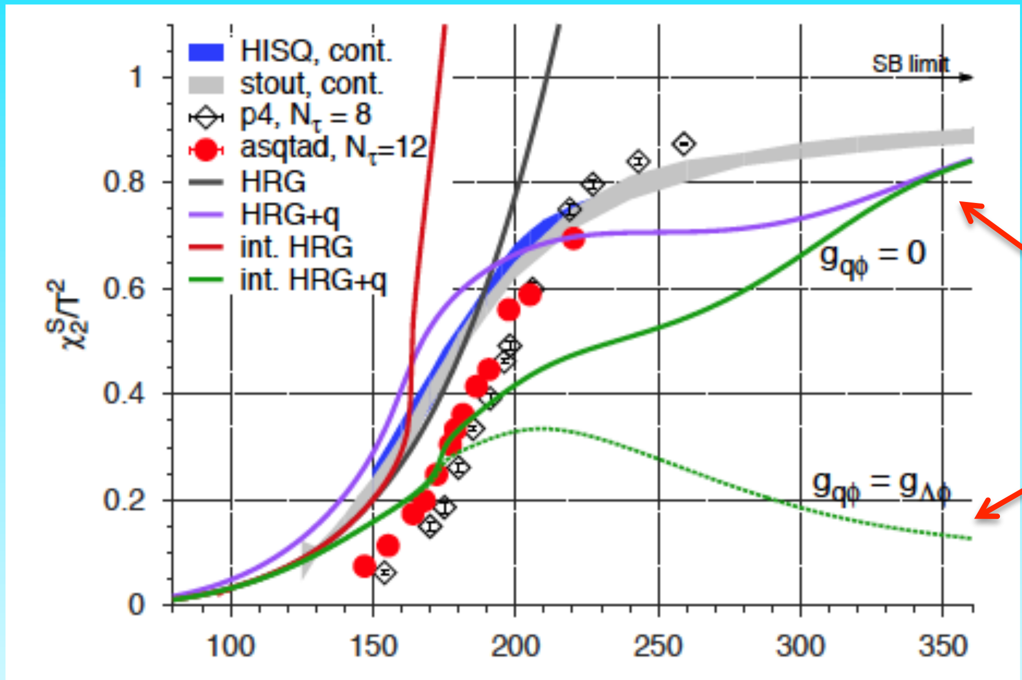


$g_{q\omega} = g_{n\omega}/3$

Steinheimer, SWS, PLB 696, 257 (2011)

analogous behaviour of strange susceptibility

$$X_s = T^2 d^2(P/T^4) / (d \mu_S)^2 |_{\mu B, \mu S = 0}$$



off

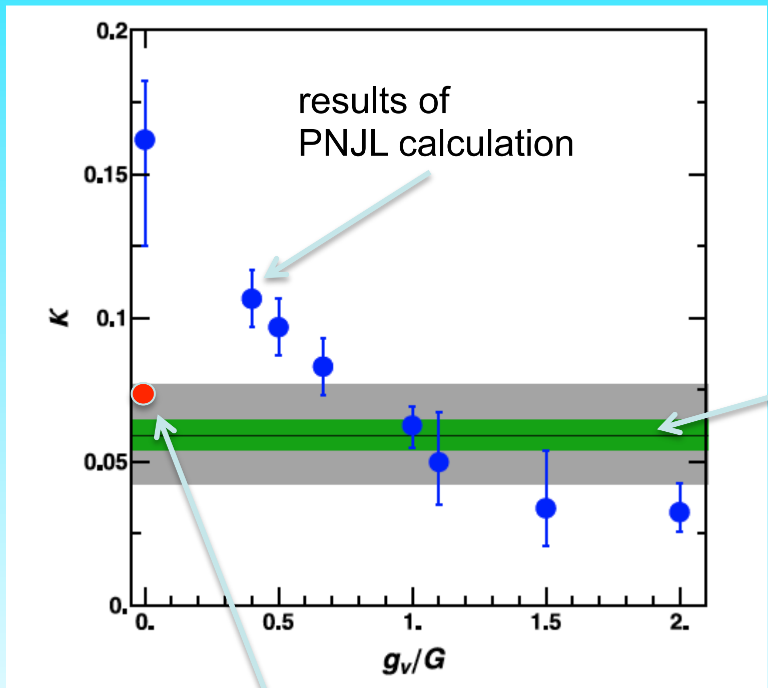
strange quark repulsion

on

Rau,Steinheimer,Stöcker,SWS, arxiv:1308.4319

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

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



this calculation

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

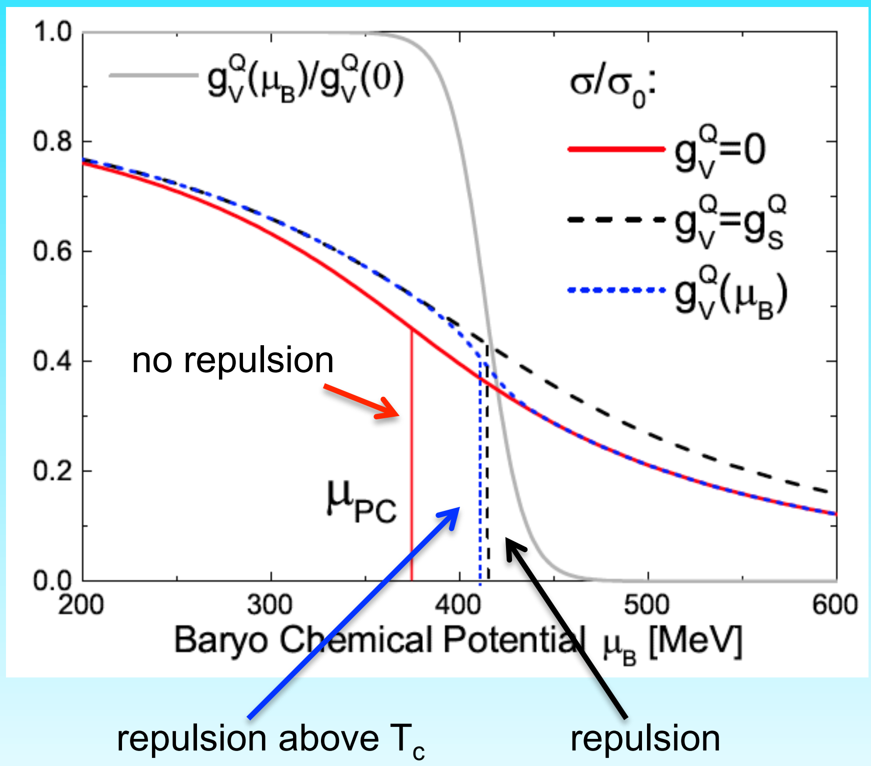
Lattice results Kacmarek et al
PRD 83, 014504 (2011)

large quark vector repulsion?

What is the source for the shift in T_c ?

Simple exercise – switch off vector coupling above T_c

scalar condensate as function of T



Conclusion: transition temperature governed by low-T behaviour

T = 140 MeV

Steinheimer,SWS, arxiv:1401.4051

Include magnetic field effects

observed surface fields up to ~ 10^{15} G - magnetars

might be significantly larger in the interior of the star

Landau levels:

$$E^*_{i\nu s} = \sqrt{k^2_{z_i} + \left(\sqrt{m_i^{*2} + 2\nu|q_i|B^*} - s_i\kappa_i B^*\right)^2}$$

anomalous magnetic moment

simple parameterization of the field

$$B^*(\mu_B) = B_{surf} + B_c\left[1 - e^{b\frac{(\mu_B - 938)^a}{938}}\right]$$

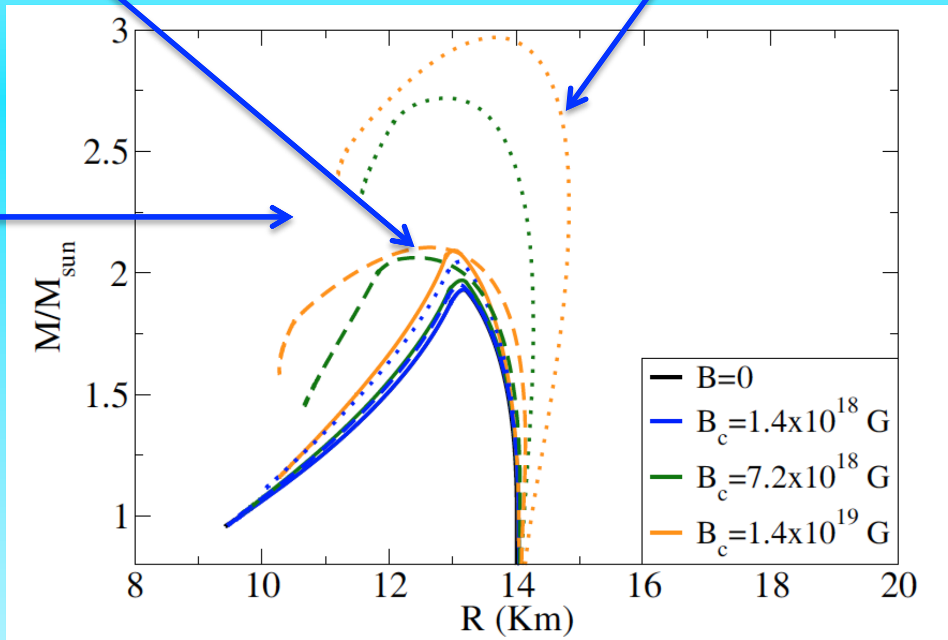
Impact on M(R) diagram for neutron/hybrid star

$T^F_{\mu\nu}$ = diag(B^2, B^2, B^2, $-B^2$) / ($8\pi^2$)

energy-momentum tensor not isotropic
consistent modeling of star needed

add average pressure

add isotropic pressure



2d calculations:
Bocquet et al. A&A 301, 757 (1995)
Cardall et al. APJ 554, 322 (2001)

for “interesting” field strengths field energy dominates changes in the EOS

include deformation in approximate fashion

include effect of magnetic field in GR

$$\epsilon = \epsilon_m + \frac{B^2}{8\pi}$$
$$P_\perp = P_m + \frac{B^2}{8\pi}$$
$$P_\parallel = P_m - \frac{B^2}{8\pi}.$$

assume a dipole field

$$P = P_m + \frac{B^2}{8\pi}(1 - 2cos^2\theta)$$

$$P = P_m + [p_0 + p_2 P_2(cos\theta)].$$

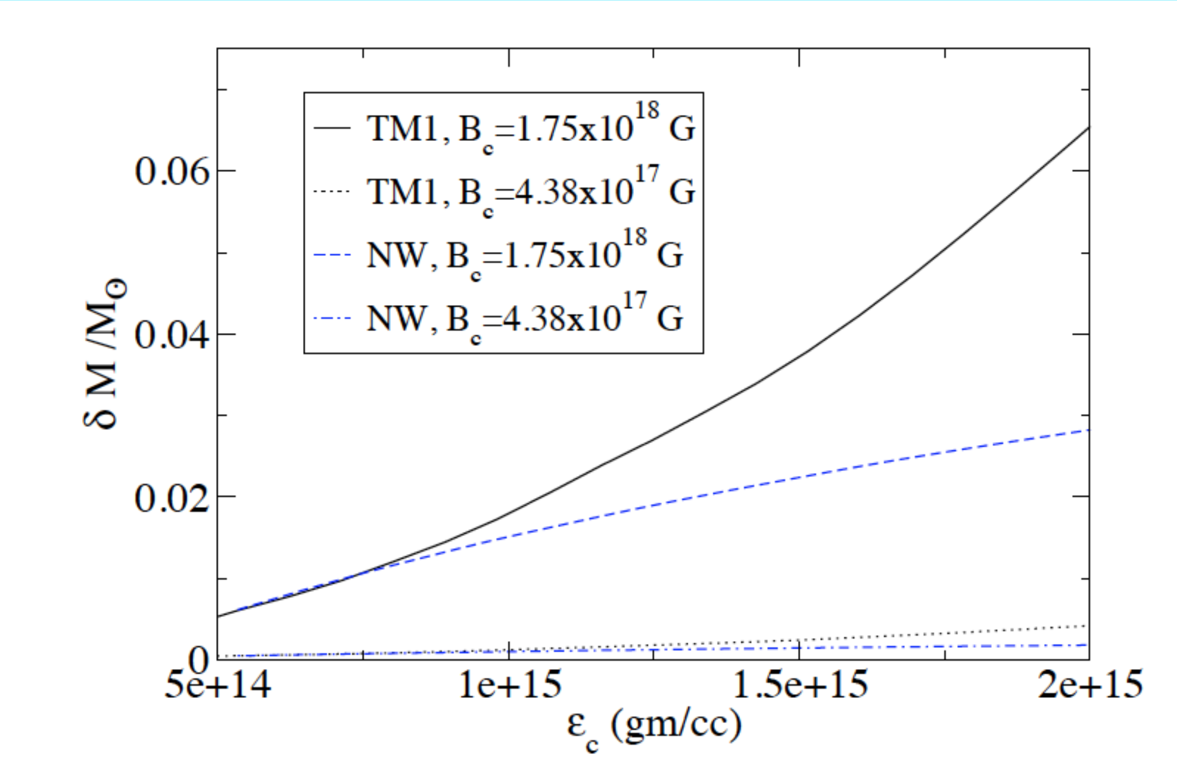
expand metric into multipoles

analogous to Hartle/rotation

$$\begin{aligned} ds^2 &= -e^{\nu(r)}[1 + 2(h_0(r) + h_2(r)P_2(cos\theta))]dt^2 \\ &+ e^{\lambda(r)}[1 + \frac{e^{\lambda(r)}}{r}(m_0(r) + m_2(r)P_2(cos\theta))]dr^2 \\ &+ r^2[1 + 2k_2(r)P_2(cos\theta)](d\theta^2 + sin^2\theta d\phi^2), \end{aligned}$$

Hartle, APJ, 1967

Mass shift for different values of central energy density and magnetic field

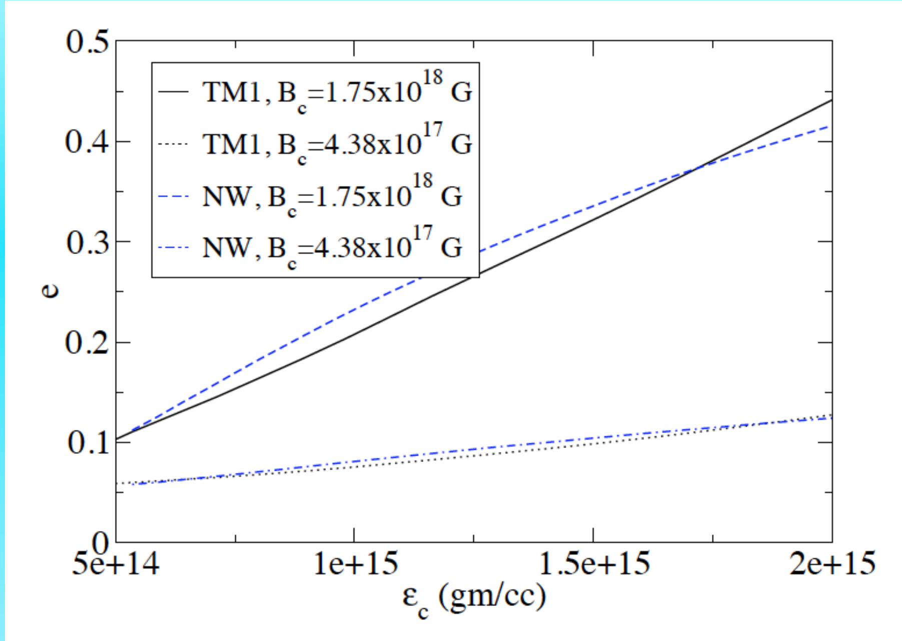


NW , TM1 hard / soft equation of state

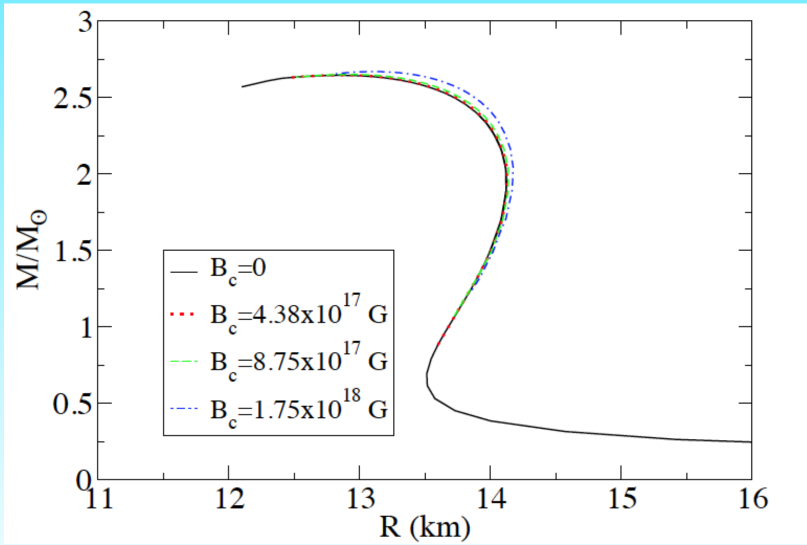
assume a profile of the magnetic field

$$B(n_b) = B_s + B_0 \left\{ 1 - e^{-\alpha \left(\frac{n_b}{n_0} \right)^\gamma} \right\}$$

eccentricity = $(1 - R_p^2 / R_e^2)^{1/2}$



M(R) change due to B field

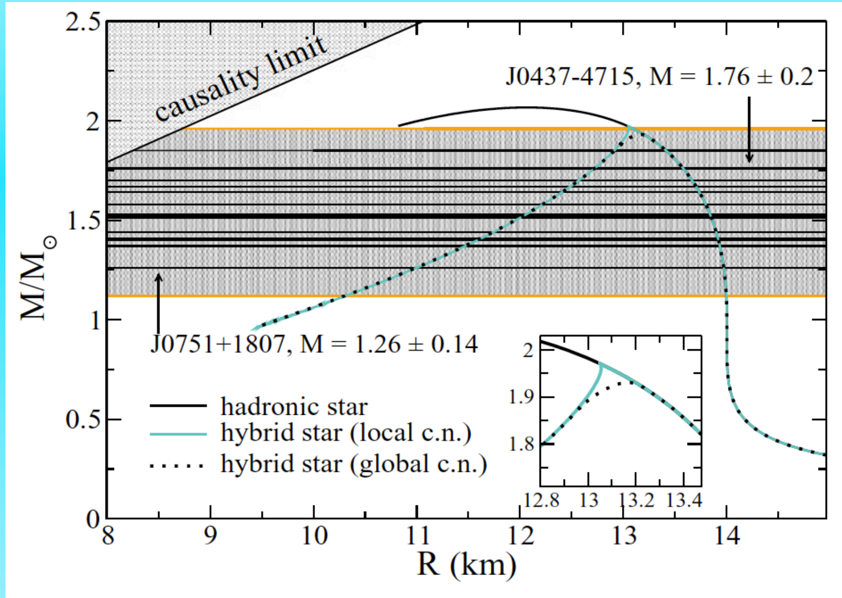


Conclusions, Outlook

- observations lead to significant modeling constraints
- hadronic and quark-hadron approaches
- SU(3) schemes – no vector strangeness in nuclei
- limits on couplings of higher resonances
- phase structure with critical endpoint?
- constraints from lattice QCD results

Many thanks to the organizers!

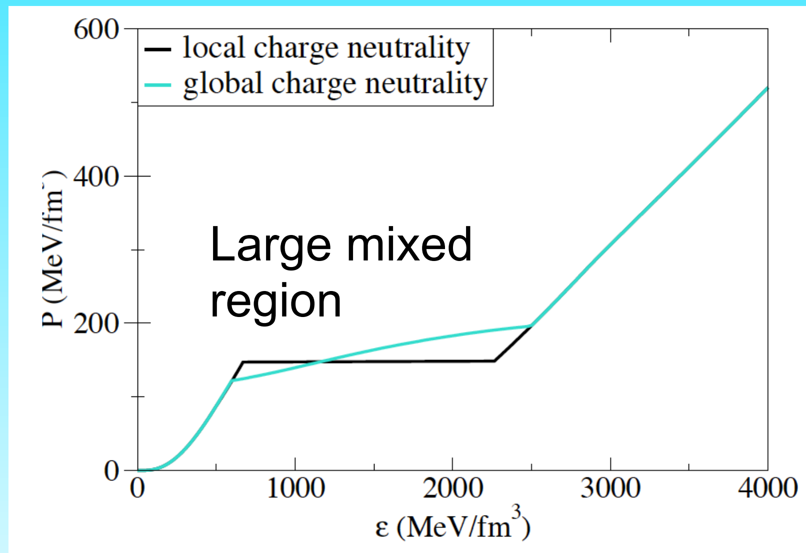
Hybrid Stars



M-R diagram in QH model

baryonic star with a 2km core of quarks

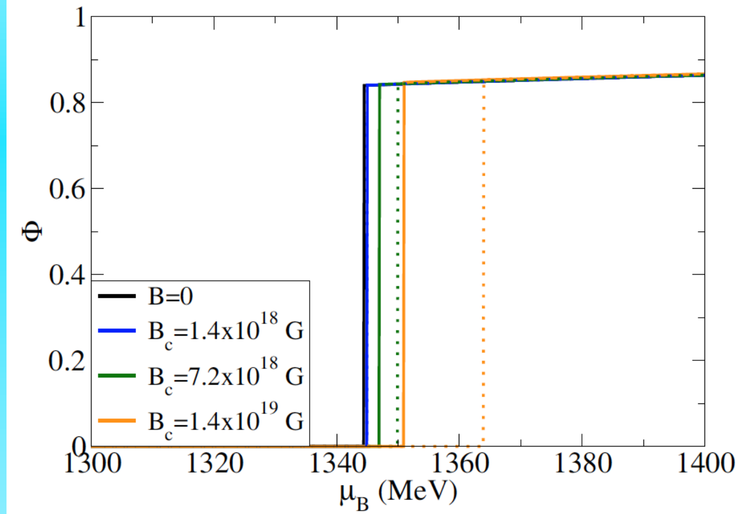
Maxwell / Gibbs construction for
local / global charge neutrality



Negreiros, Dexheimer, SWS, PRC82 035803 (2010)

QH model with PT

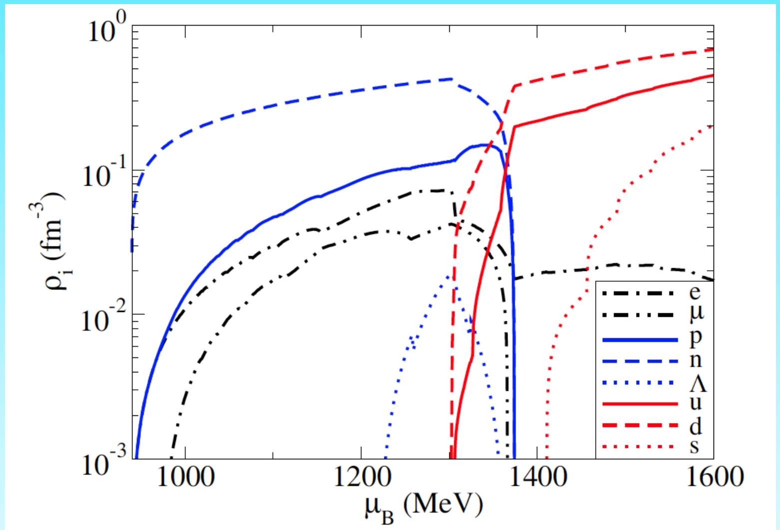
Polyakov loop and 1st order transition



$e B_{cr} = m_e^2$, $B_{cr} = 4.4\ 10^{13}$ G

$(1.5\ 10^{20}$ G)

particle densities $B_c = 7.2\times10^{18}$ G



PT gets shifted somewhat to higher μ

Dexheimer,Negreiros,SWS EPJA 2012