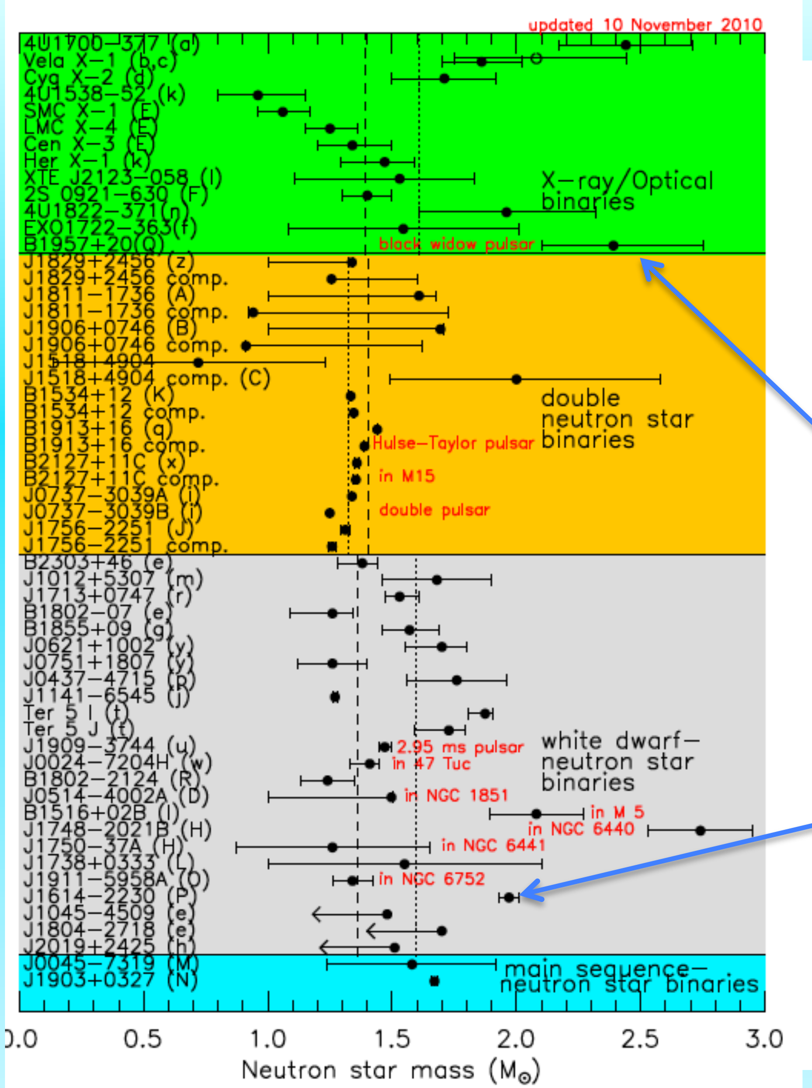
Modeling Hybrid Stars in Quark-Hadron Approaches

OUTLINE

- hadronic SU(3) model
- adding quarks
- alternative chiral formulation

V. Dexheimer, R. Negreiros, J. Steinheimer, T. Schürhoff, SWS
FIAS Frankfurt, Gettysburg/Kent State, LLBL, Fluminense

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)

well established
heavy neutron stars

hadronic model based on non-linear realization of chiral symmetry

degrees of freedom **SU(3) multiplets:**

baryons $(n, \Lambda, \Sigma, \Xi)$ scalars $(\sigma, \zeta, \delta^0)$ vectors (ω, ρ, φ) , pseudoscalars, glueball field χ

A) SU(3) interaction

$$\sim \mathrm{Tr}\, [\, \overline{B}, M\,]_{\pm}\, B \quad , \; (\, \mathrm{Tr}\, \overline{B}\, B\,)\, \mathrm{Tr}\, M$$

B) meson interactions

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

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

C) chiral symmetry $m_\pi = m_K = 0$

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

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

degrees of freedom

$$B = \begin{pmatrix} \Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & \Sigma^+ & p \\ \Sigma^- & -\Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & n \\ \Xi^- & \Xi^0 & -2\,\Lambda/\sqrt{6} \end{pmatrix}$$

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

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

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

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

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

+ term prop $(X - X_0)$, breaks SU(3)

Nuclear Matter and Nuclei

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

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

parameter fit to known nuclear binding energies and hadron masses

2d calculation of all measured (~ 800) even-even nuclei

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

relativistic nuclear structure models

error in energy ε (A > 50) ~ 0.21 % (NL3: 0.25 %)

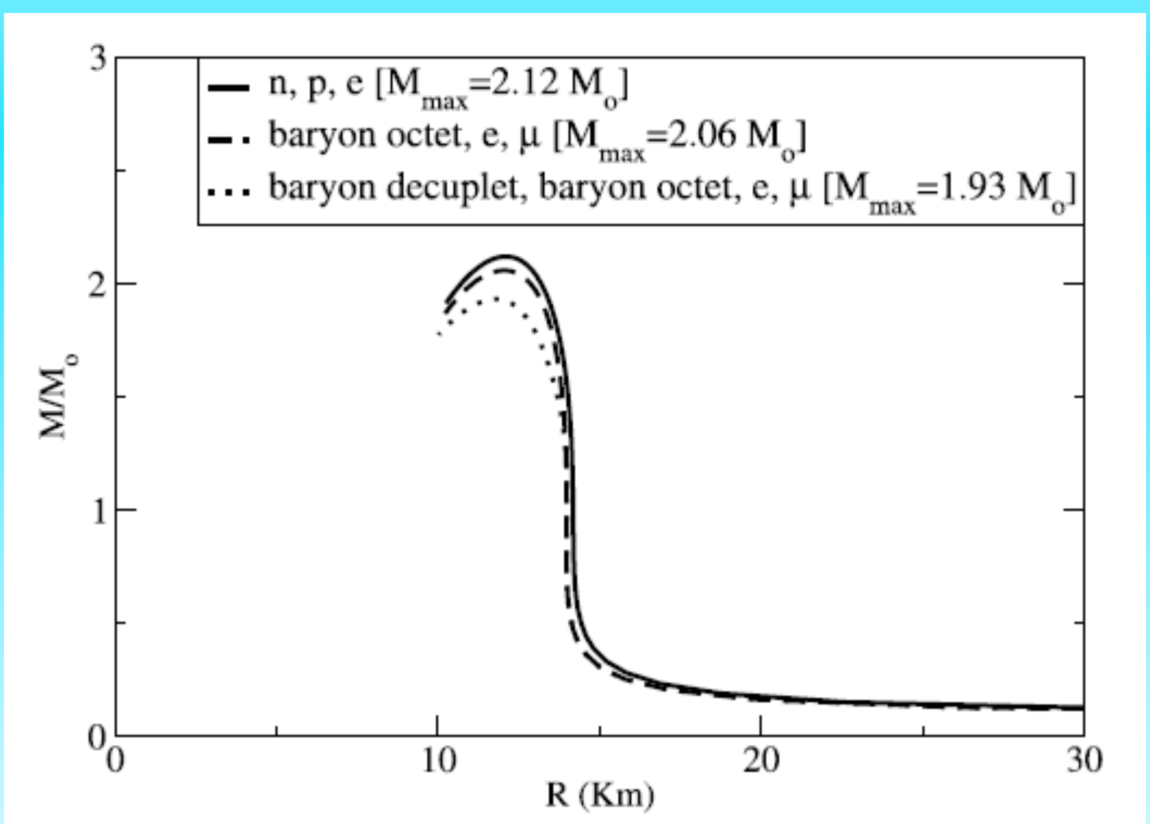
ε (A > 100) ~ 0.14 % (NL3: 0.16 %)

+ correct binding energies of hypernuclei

SWS, Phys. Rev. C66, 064310

new fit in the works by T. Schürhoff
currently ε ~0.28 , κ ~300 MeV, M ~2 $M_\odot$

Neutron star masses including different sets of particles



Tolman-Oppenheimer-Volkov equations, static spherical star

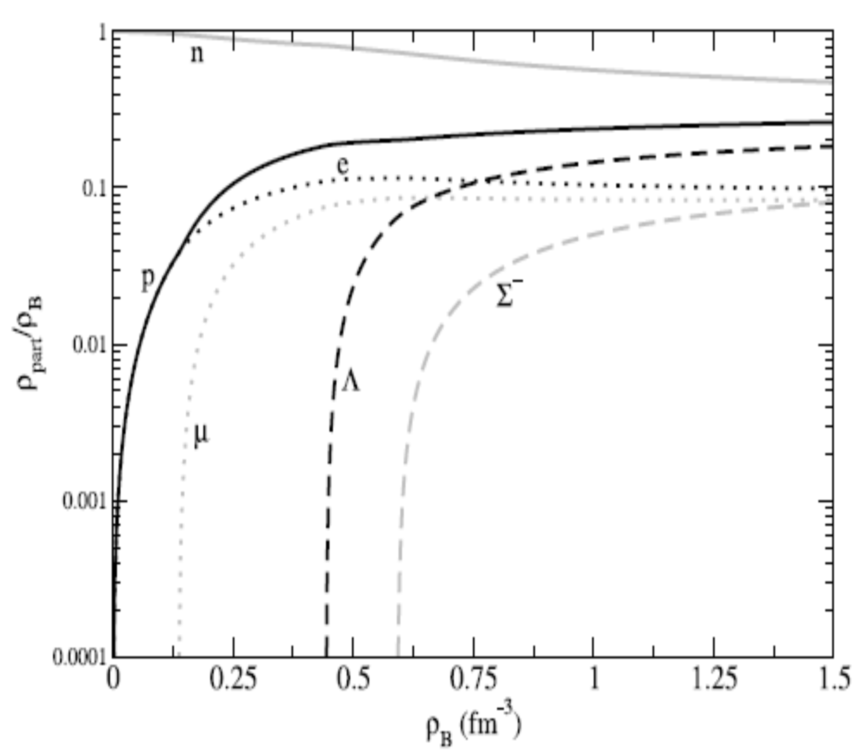
changing masses with degrees of freedom

large star masses even with spin 3/2 resonances

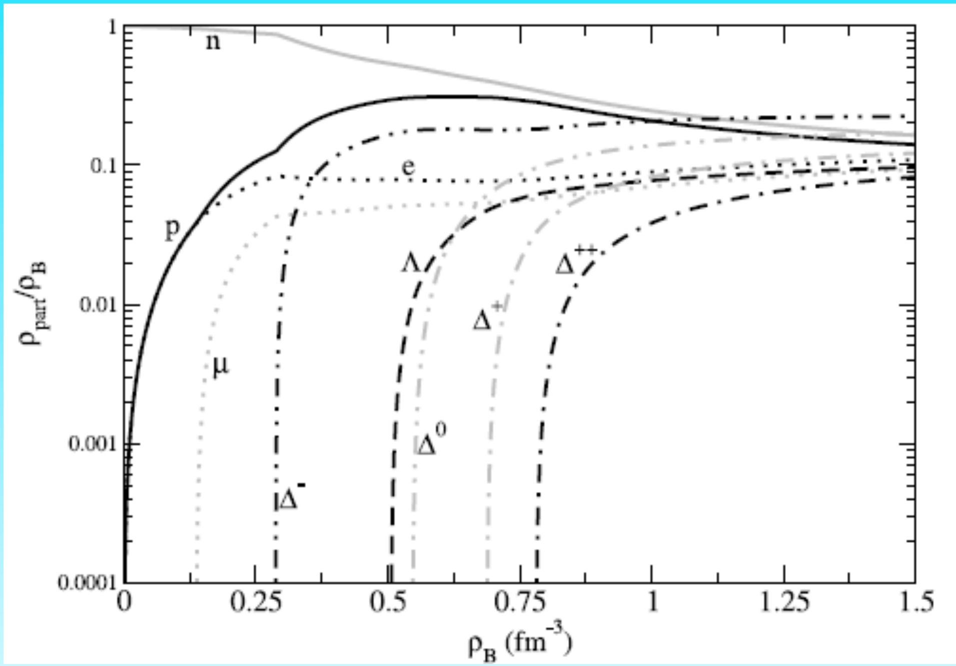
tuned parameters

Dexheimer, SWS ApJ 683, 943 (2008)

particle densities inside of the star



particle abundancies – no decuplet

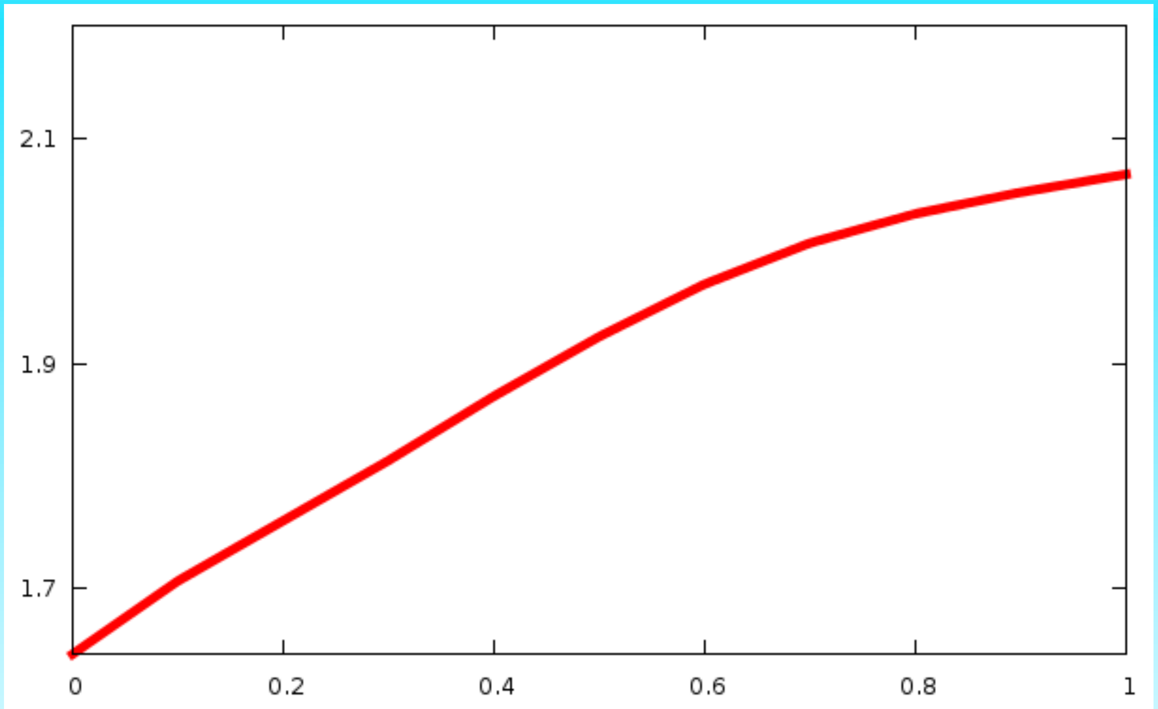


particle numbers as function of density
uncertainties from $g_{3/2}$ coupling

Impact of Φ field

rescale $g_{B\Phi}$ coupling parameters

M_{max} [$M_\odot$]

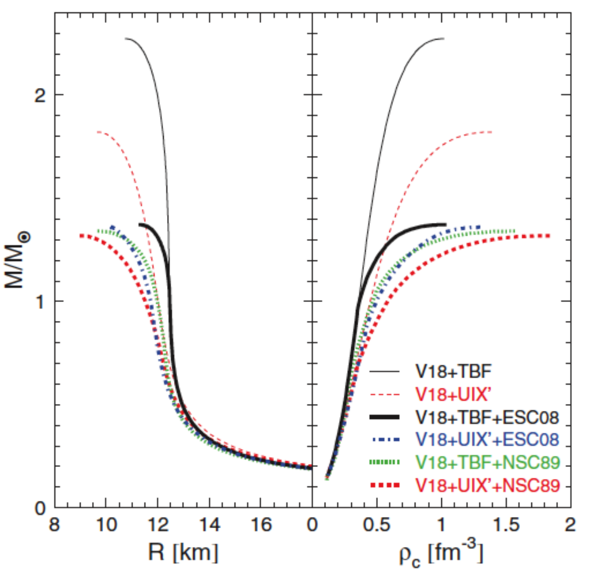


no coupling

standard fit

rather generic observation - no YY interaction ➔ very small star masses

Use Nijmegen potential
+ Argonne/Urbana / TBF



Schulze, Rijken, PRC 84, 035801 (2011)

Remark about SU(6) fllavor-spin symmetry

SU(3) three couplings for baryon-meson interaction, SU(6) one constant

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

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

$$[\bar{B}OBW]_F = Tr(\bar{B}OBW - \bar{B}OWB) \quad [\bar{B}OBW]_D = Tr(\bar{B}OBW + \bar{B}OWB) - 2/3\, Tr(\bar{B}OB)\, Tr(W)$$

usually only applied for vector meson interaction 2 M_S possible

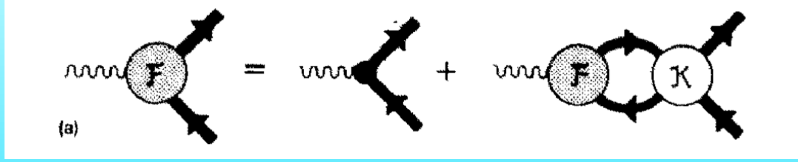
SU(6) $g_{N\omega} : g_{\Lambda\omega} : g_{\Xi\omega} = 3 : 2 : 1$ $g_{N\Phi} : g_{\Lambda\Phi} : g_{\Xi\Phi} = 0 : 1 : 2$

However – deviating from SU(6) deviation, keeping SU(3) leads to $g_{N\Phi} \neq 0$

$$g_{N\phi} = \sqrt{2}\, g_8 - 1/\sqrt{3}\, g_1 \qquad g_1/g_8\,(SU6) = \sqrt{6}$$

Experiments/Lattice show very small strangeness vector form factor

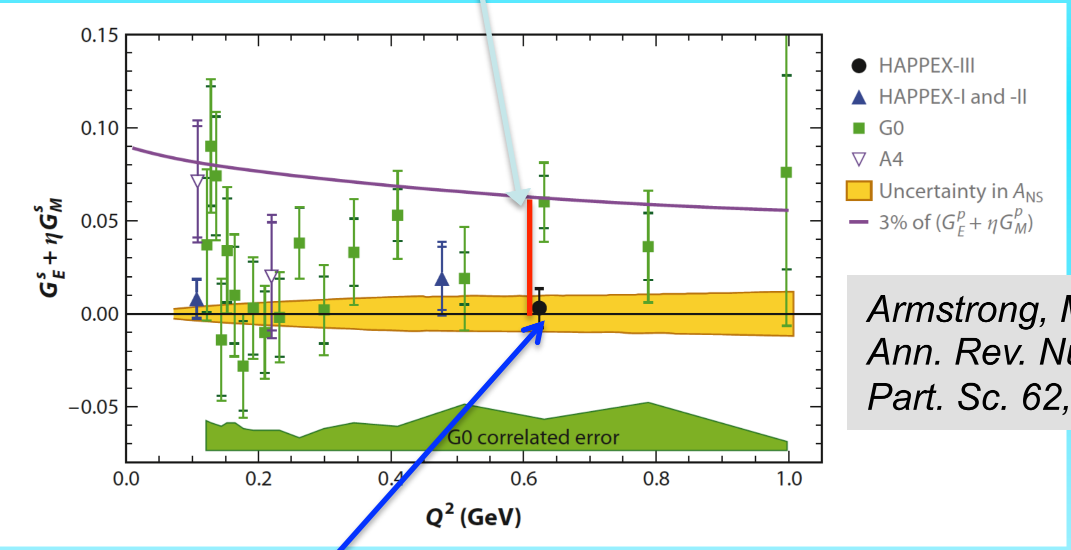
strange vector form factor of nucleon



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

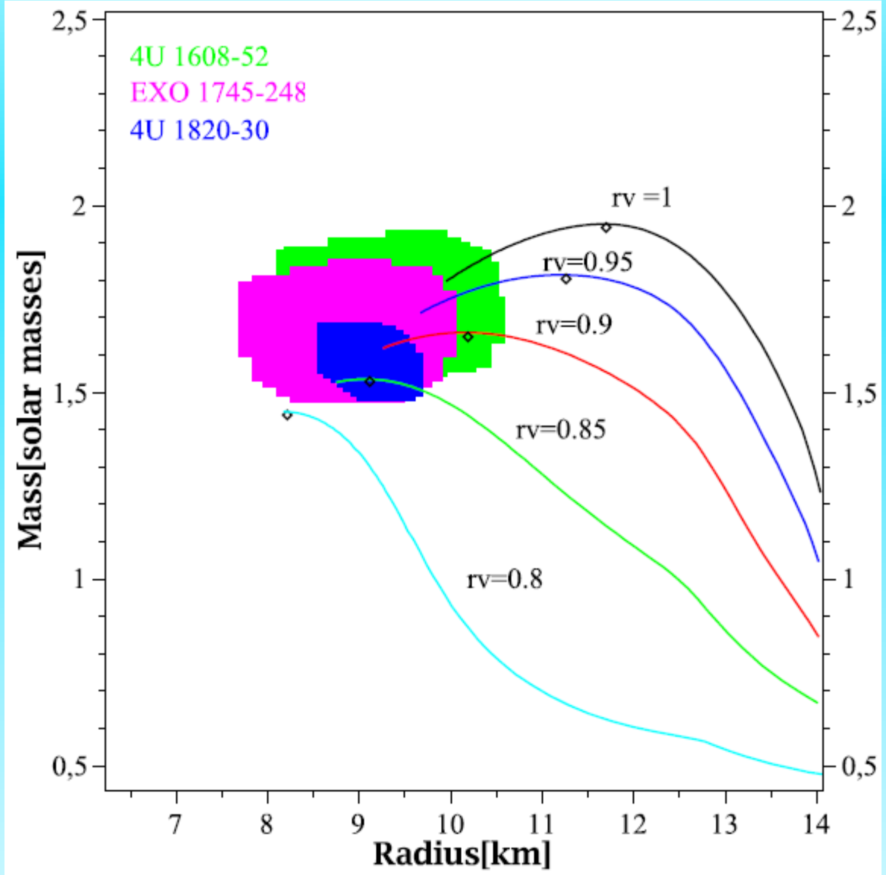
scalar couplings → vacuum masses

vector couplings unclear

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

not far from SU(6)

same from quasielastic eA scattering



Data from Özel et al, astro-ph:1002.3153

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

Schürhoff, SWS, Dexheimer, APJL 724 (2010) L74 connect hadronic and quark degrees of freedom

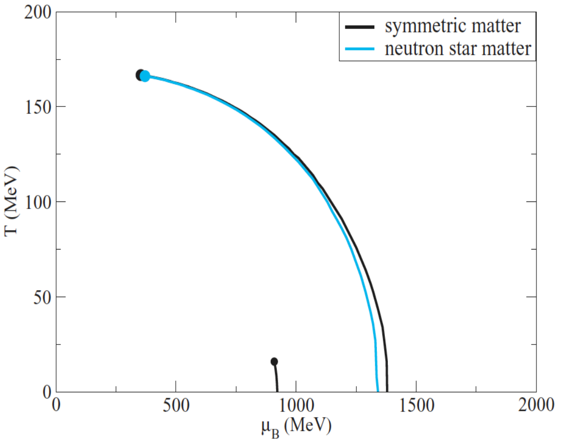
$$\Phi = \frac{1}{N_c}\mathrm{Tr}_c L$$

$$L(\vec{x}) = \mathcal{P}\exp\left[i\int_0^\beta d\tau A_4(\vec{x},\tau)\right]$$

order parameter of the phase transition

$\langle\Phi\rangle = 0$ confined phase

$\langle\Phi\rangle \neq 0$ deconfined phase



effective potential for Polyakov loop, fit to lattice data

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

$a(T) = a_0 T^4 + a_1 \mu^4 + a_2 \mu^2 T^2$

baryonic and quark mass shift $\delta m_B \sim f(\Phi)$ $\delta m_q \sim f(1-\Phi)$

quarks couple to mean fields via g^q_σ, g^q_ω

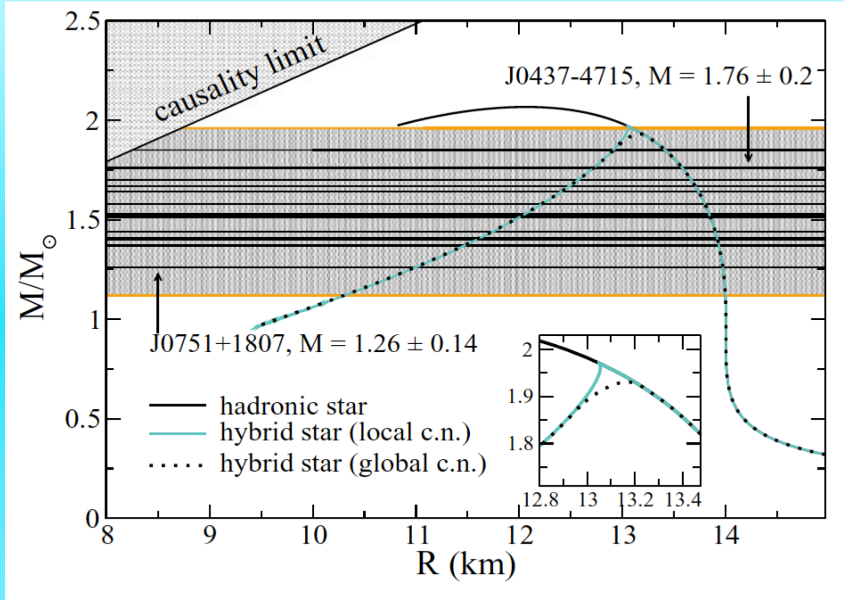
minimize grand canonical potential

V. Dexheimer, SWS, PRC 81 045201 (2010)

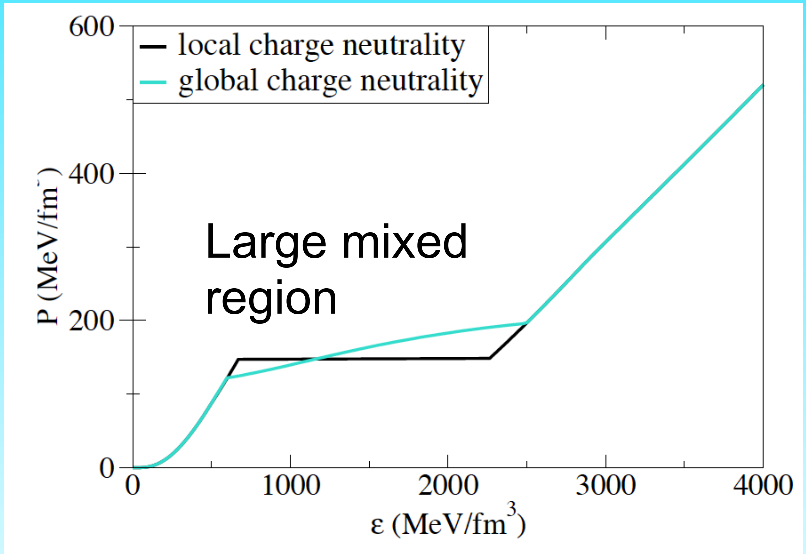
Ratti et al. PRD 73 014019 (2006)
Fukushima, PLB 591, 277 (2004)

M-R diagram in QH model

baryonic star with a 2km core of quarks



Maxwell / Gibbs construction for
local / global charge neutrality

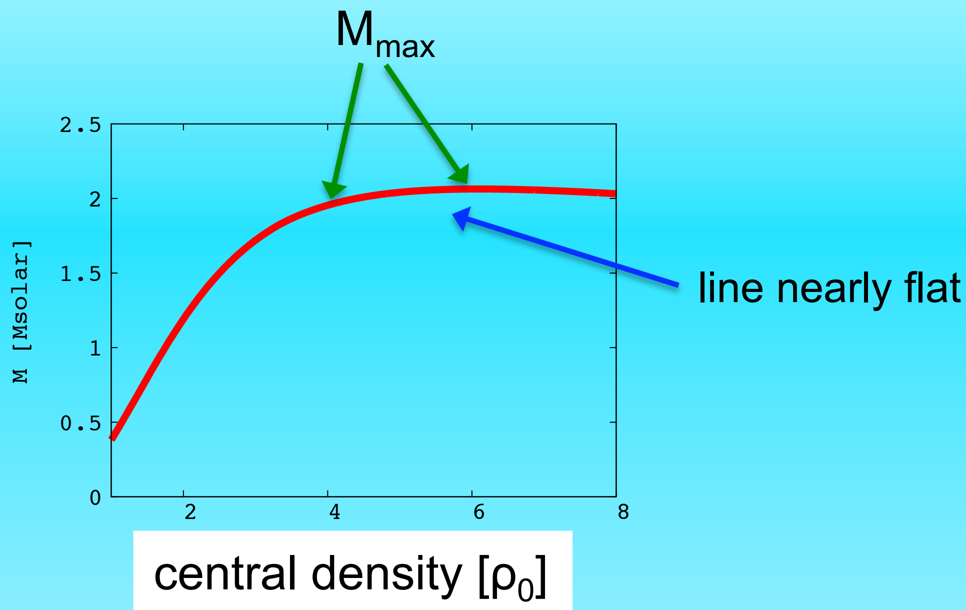


Large mixed region

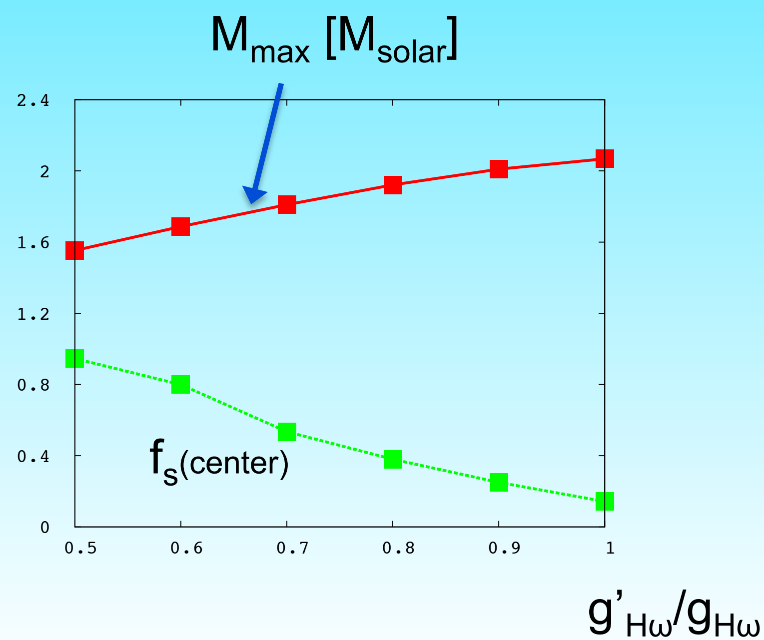
Negreiros, Dexheimer, SWS, PRC82 035803 (2010)

Dependence of M_{max} on quark core

SWS et al., arXiv:1112.1853 (2011)
SQM proceedings



strangeness content



rather slow decay of strange condensate

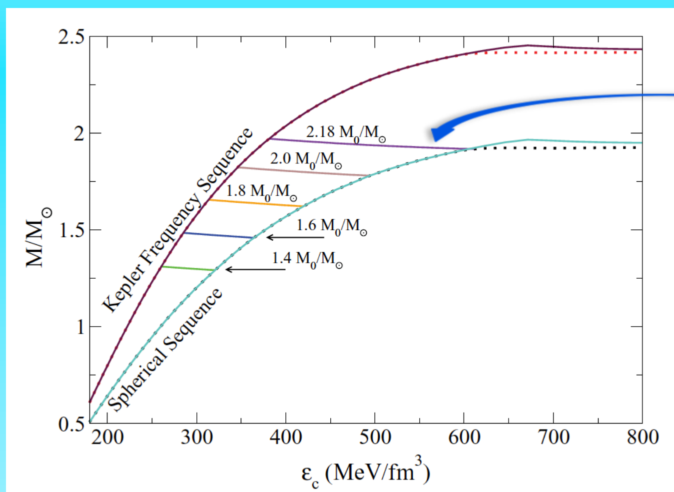
decrease (artificially)
vector potential for hyperons

preserve “canonical” values
$U_\Lambda \sim -29$ MeV, $U_\Xi \sim -19$ MeV, $U_\Sigma \gtrsim 0$ MeV

Effect of rotation

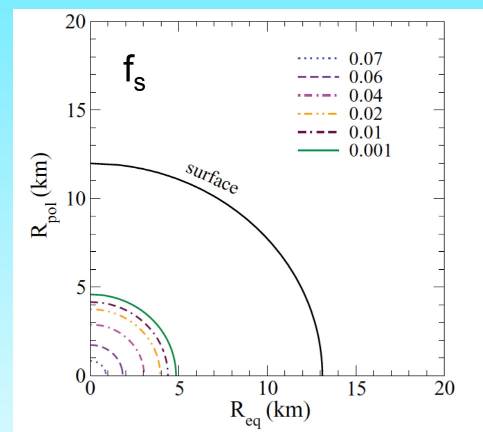
relatively small changes in M, M_{max}
substantial decrease in central density

PSR J1748-2446 Ω = 716 Hz



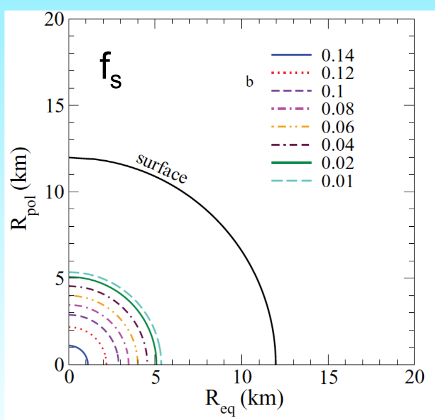
fixed baryon number (Ω_K~ 990 Hz)

Ω = 600 Hz



f_s doubled

Ω = 0



Negreiros, Dexheimer, SWS, PRC82 035803 (2010)

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!

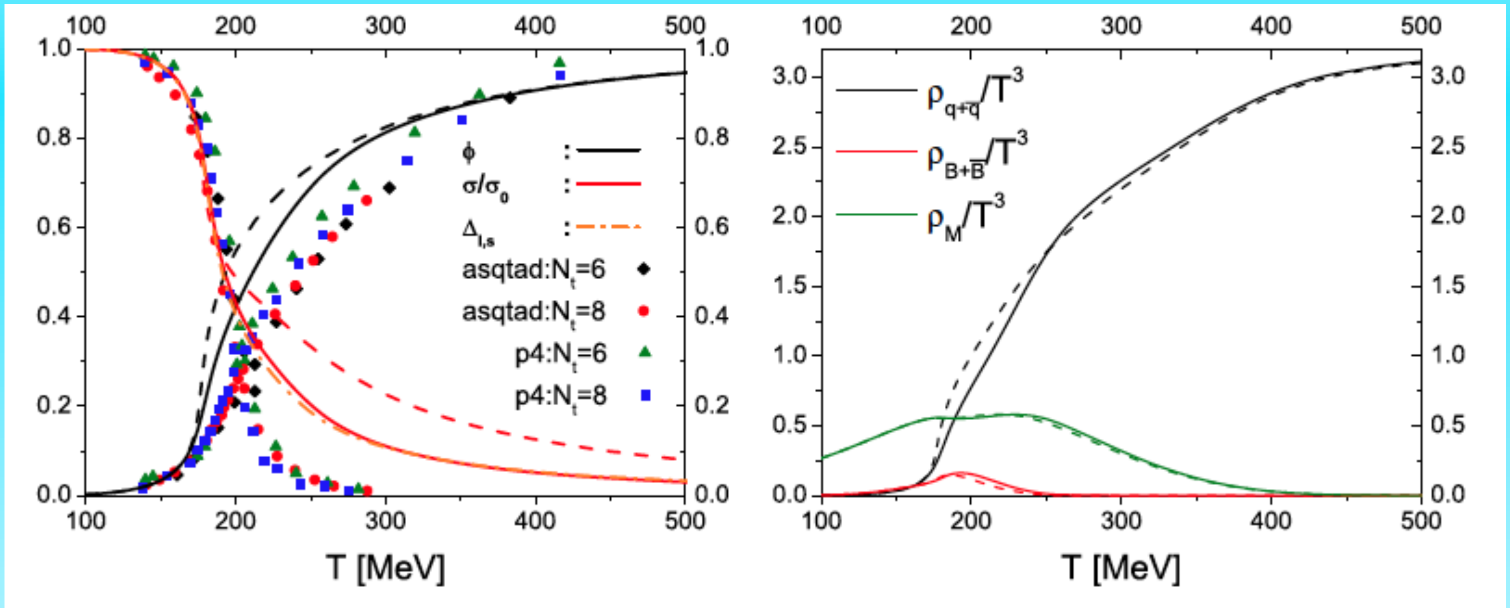
$V_q = 0$
$V_h = v$
$V_m = v / 8$

$$\tilde{\mu}_i = \mu_i - v_i P \qquad e = \tilde{e} / (1 + \Sigma v_i \tilde{\rho}_i)$$

equation of state stays causal!

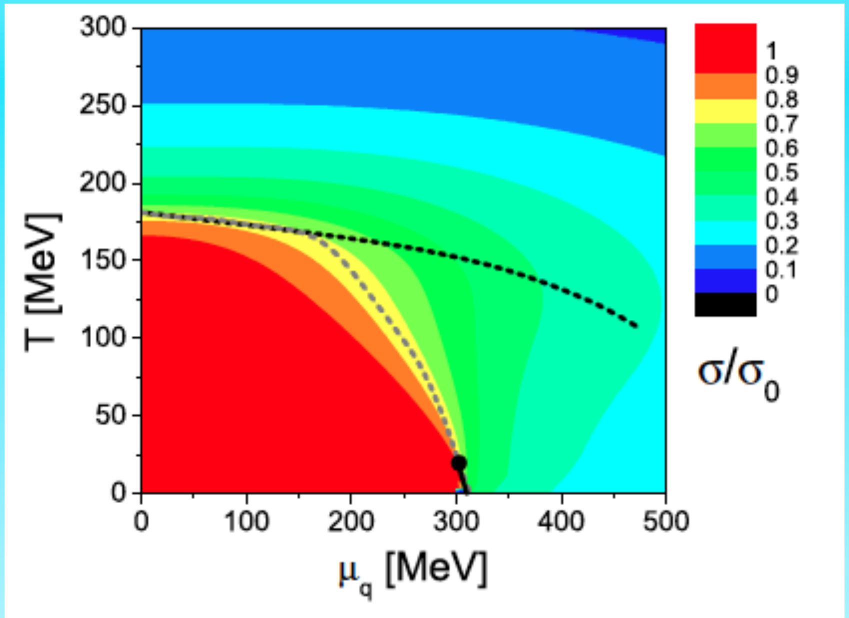
Steinheimer,SWS,Stöcker JPG 38, 035001 (2011)

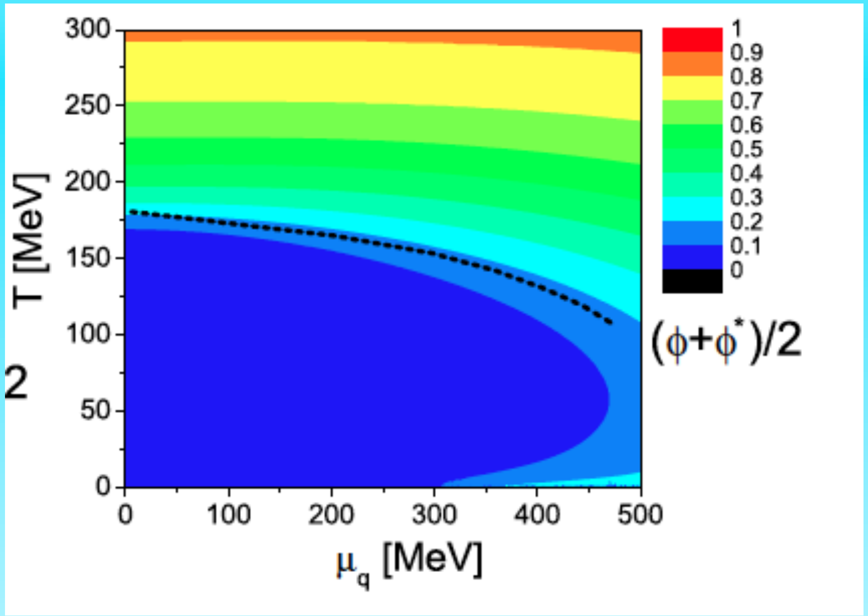
Results of the model at zero density



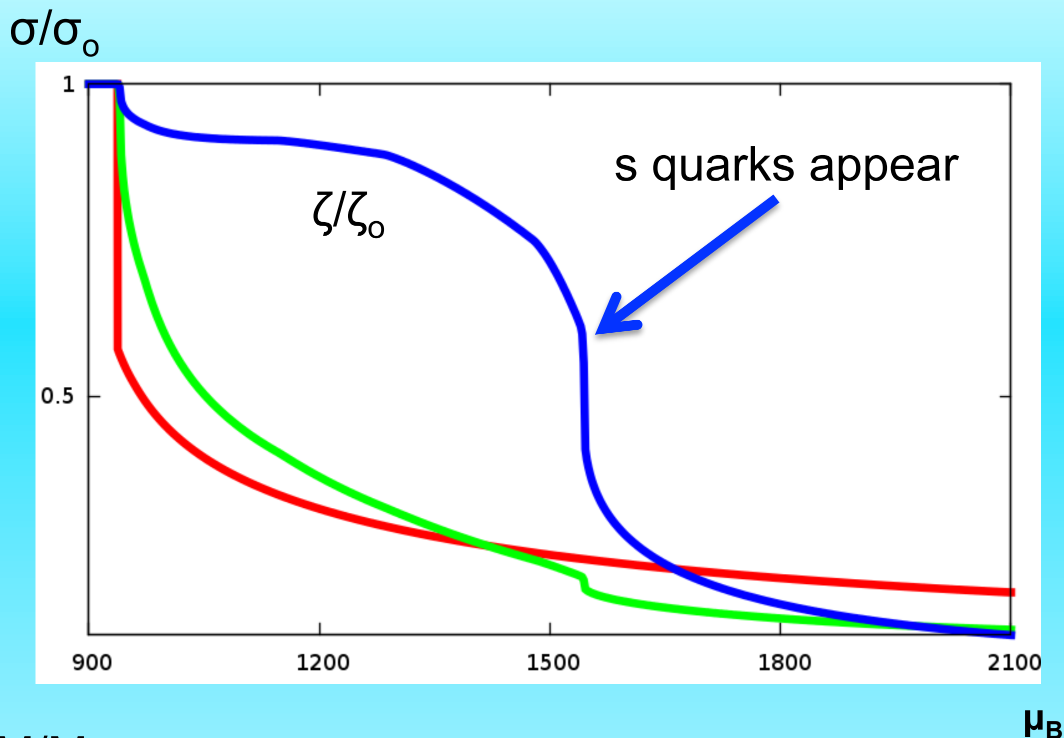
Reasonable agreement with lattice QCD
natural mixed phase of hadrons and quarks
no first-order transition

Order parameters for chiral symmetry and confinement in μ and T





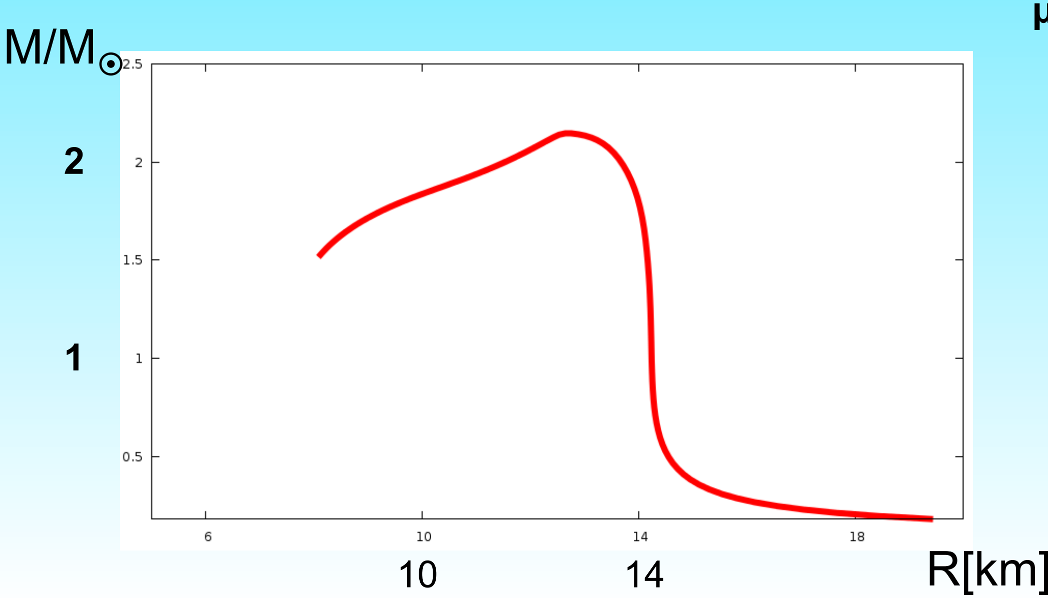
except for liquid-gas no first-order transition star matter in beta equilibrium



1st order phase transition
in star matter possible

cross over in symmetric matter

f_s(core) = 0.6 jumps to ~ 1



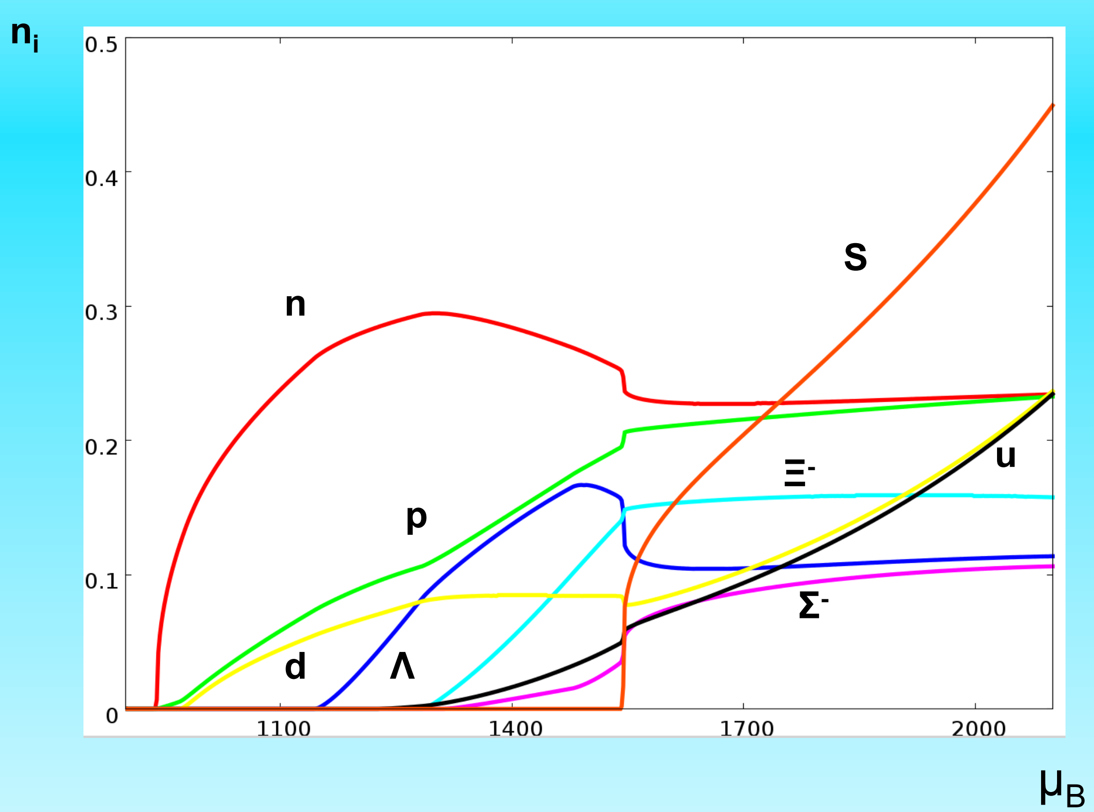
Star masses M(R)

Mass ~ 2.2 $M_\odot$ Radius ~13 km
depends on quark vector interaction

particle cocktail

κ = 305 MeV
E_{asym} = 34.5 MeV
L = 105 MeV

reasonable values for compressibility and asymmetry



large mixed phase (no Gibbs)

dense matter and stars in a parity doublet model

- treat N , N* as positive/negative parity doublet

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

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

standard σ model + vector mesons (ω, ρ)
diagonalize mass matrix ψ_1, ψ_2 to N N* with

$$M^*_{N\pm} = \sqrt{\left[\frac{(M_{N_+} + M_{N_-})^2}{4} - m_0^2\right]\frac{\sigma^2}{\sigma_0^2} + m_0^2} \pm \frac{M_{N_+} - M_{N_-}}{2}\frac{\sigma}{\sigma_0}$$

degenerate in the chiral limit

Dexheimer et al., PRC 77, 025803 (2008); EPJA 38, 105 (2008)
Zschiesche et al., PRC 75, 055202 (2007)
DeTar and Kunihiro,PRD 39, 2805 (1989)
Hatsuda and Prakash, PLB 224, 11 (1989)

scan of possible parameters

SU(2) constraint – reproduce basic n.m. saturation properties

$E/A - m_N = -16 \pm 0.5$ MeV $\rho_0 = 0.15 \pm 0.015$ fm^{-3}

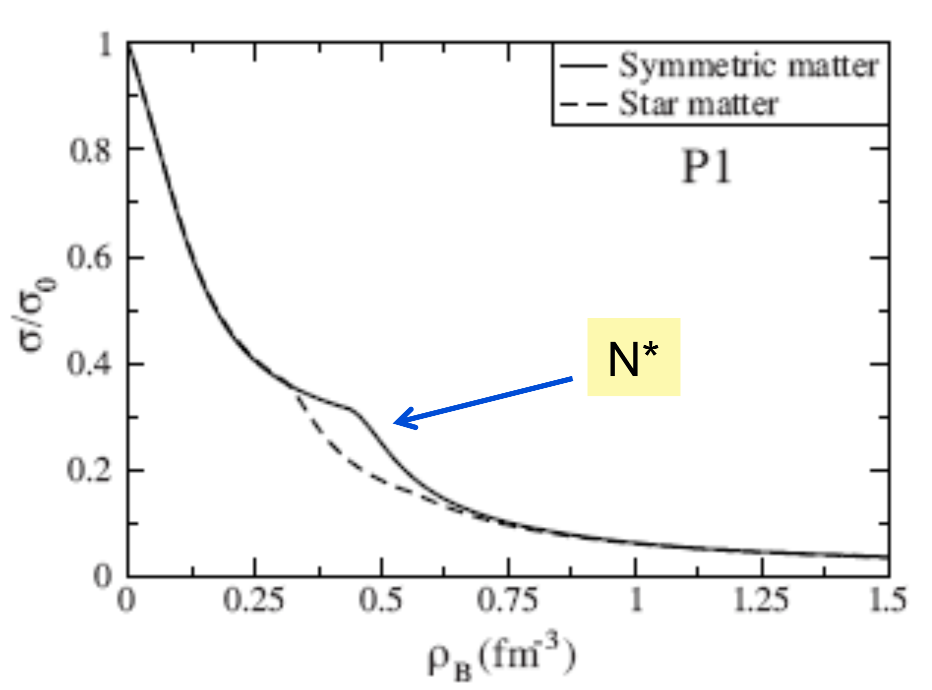
mass of the parity partner

possibility N*(1535) - *unclear*

keep mass as parameter

(m_σ g_ω m_{N^*} m_0)

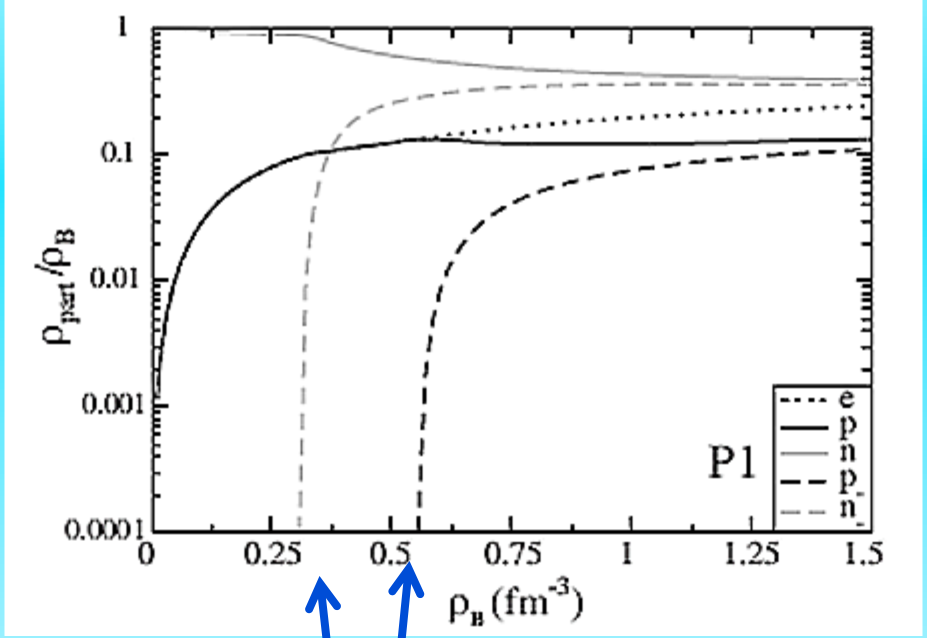
$m_{N^*} = 1200$ MeV



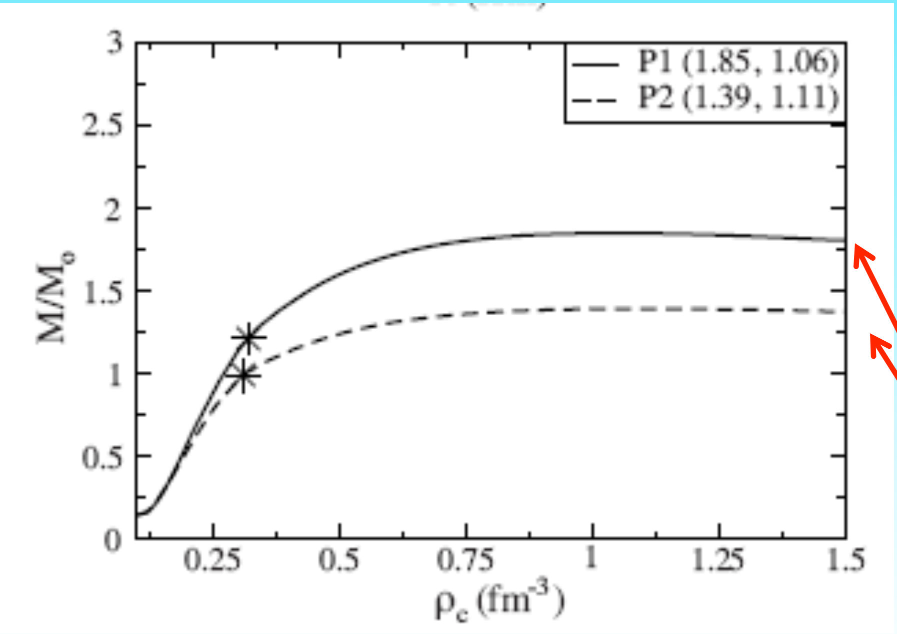
V. Dexheimer et al., PRC 77, 025803

Star Masses and Particles

m_{N^*} = 1200 MeV



parity partners



small vector self-interaction!

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

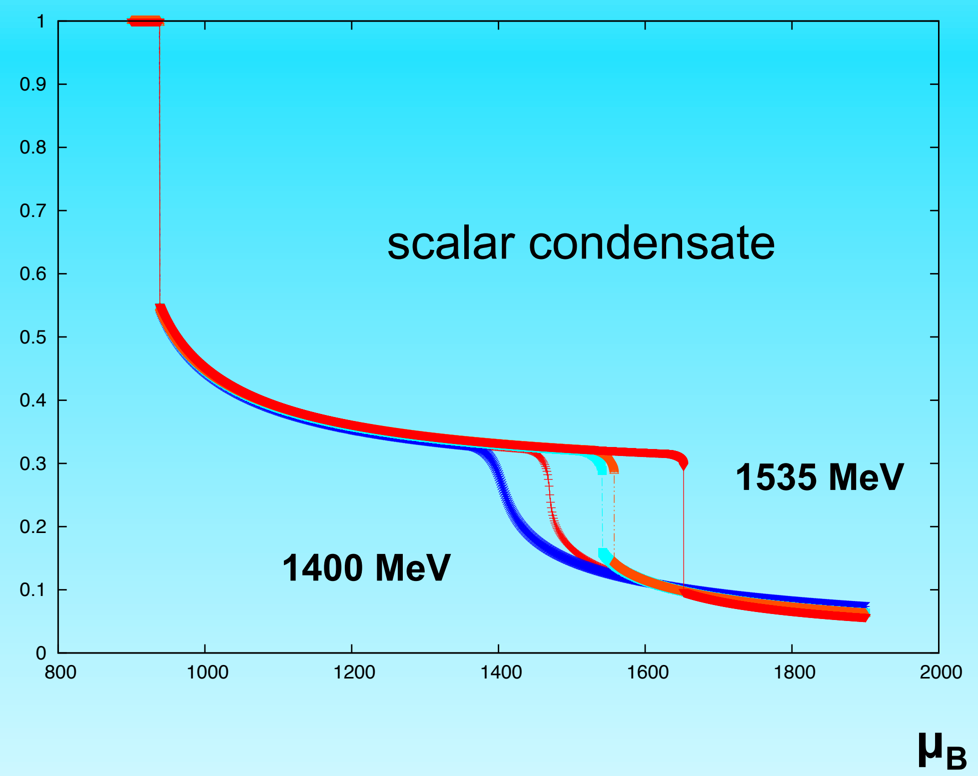
simplify investigation – same mass shift for whole octet

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

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

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

scalar condensate for different masses m_{N^*}

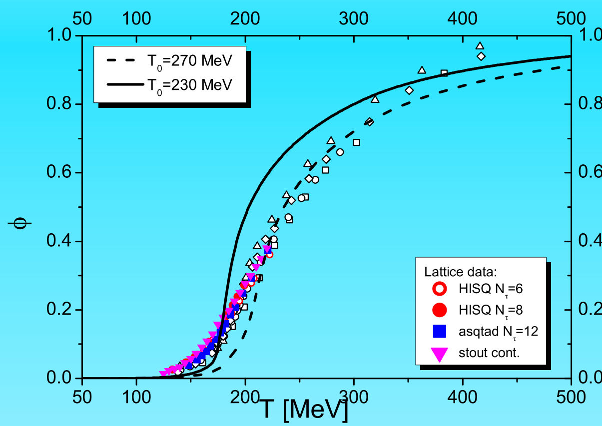


First order transition for masses ≥ 1470 MeV, below crossover

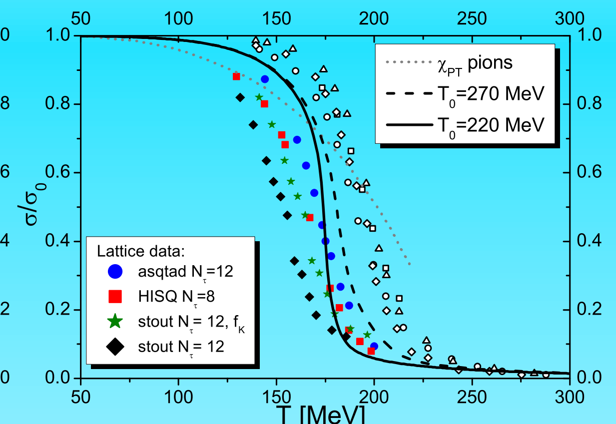
results for hot matter at vanishing chemical potential

points are various lattice results

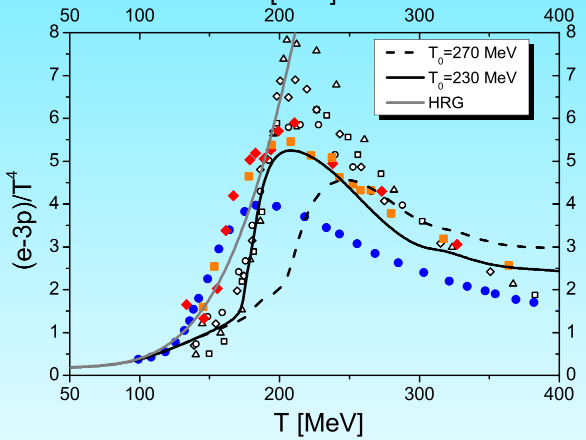
Polyakov loop



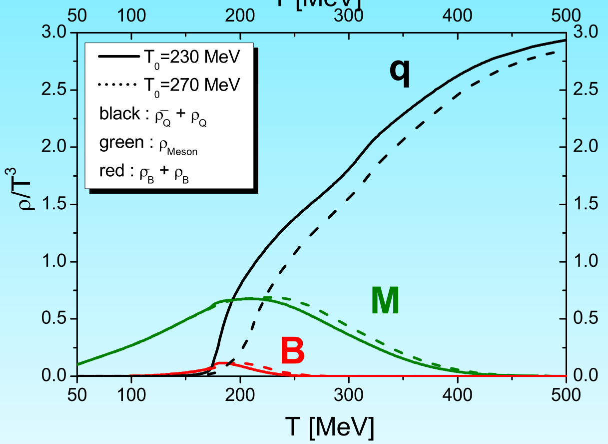
scalar condensate



Interaction measure



densities

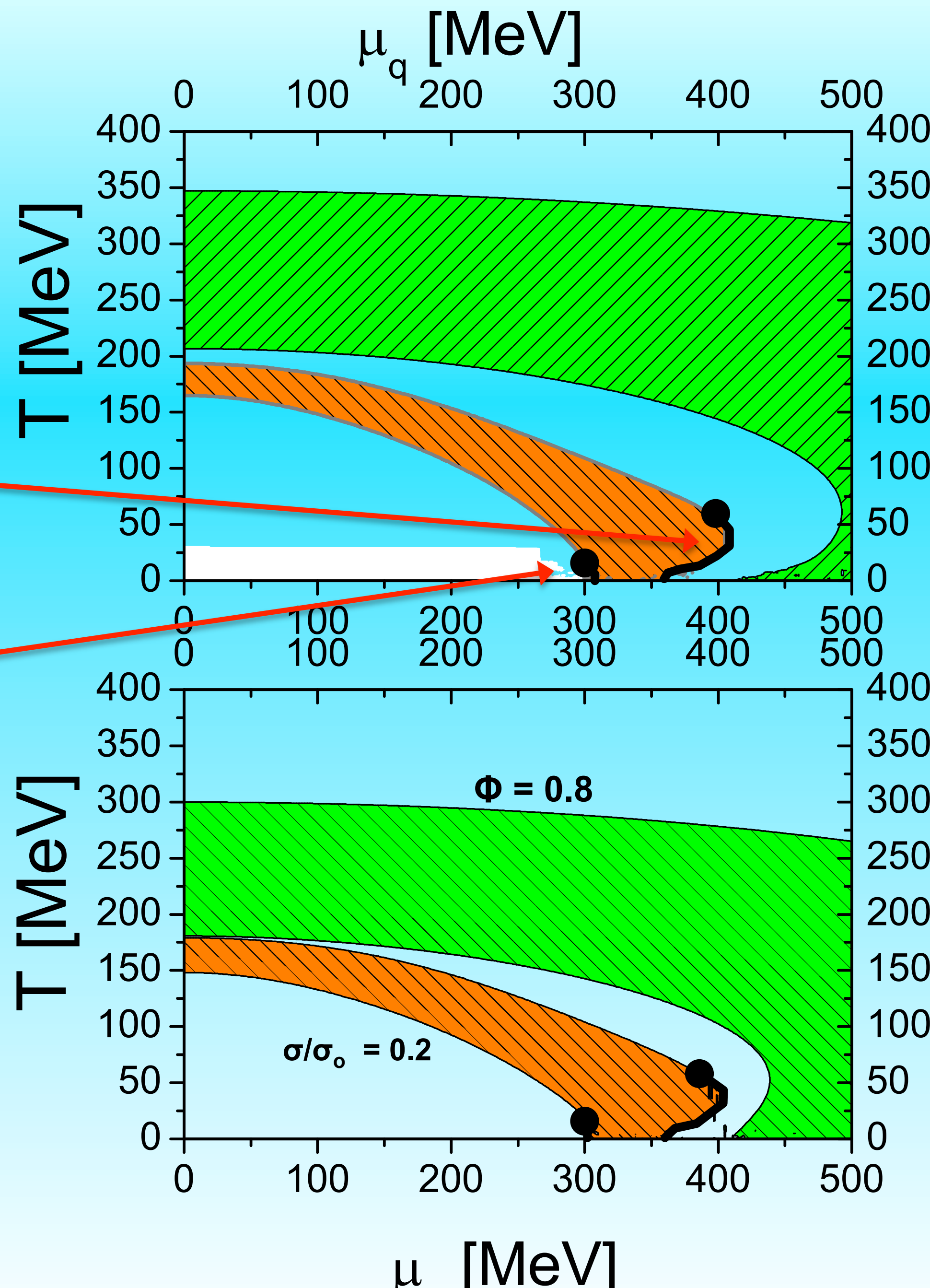


Excited quark-hadron matter in the parity-doublet approach

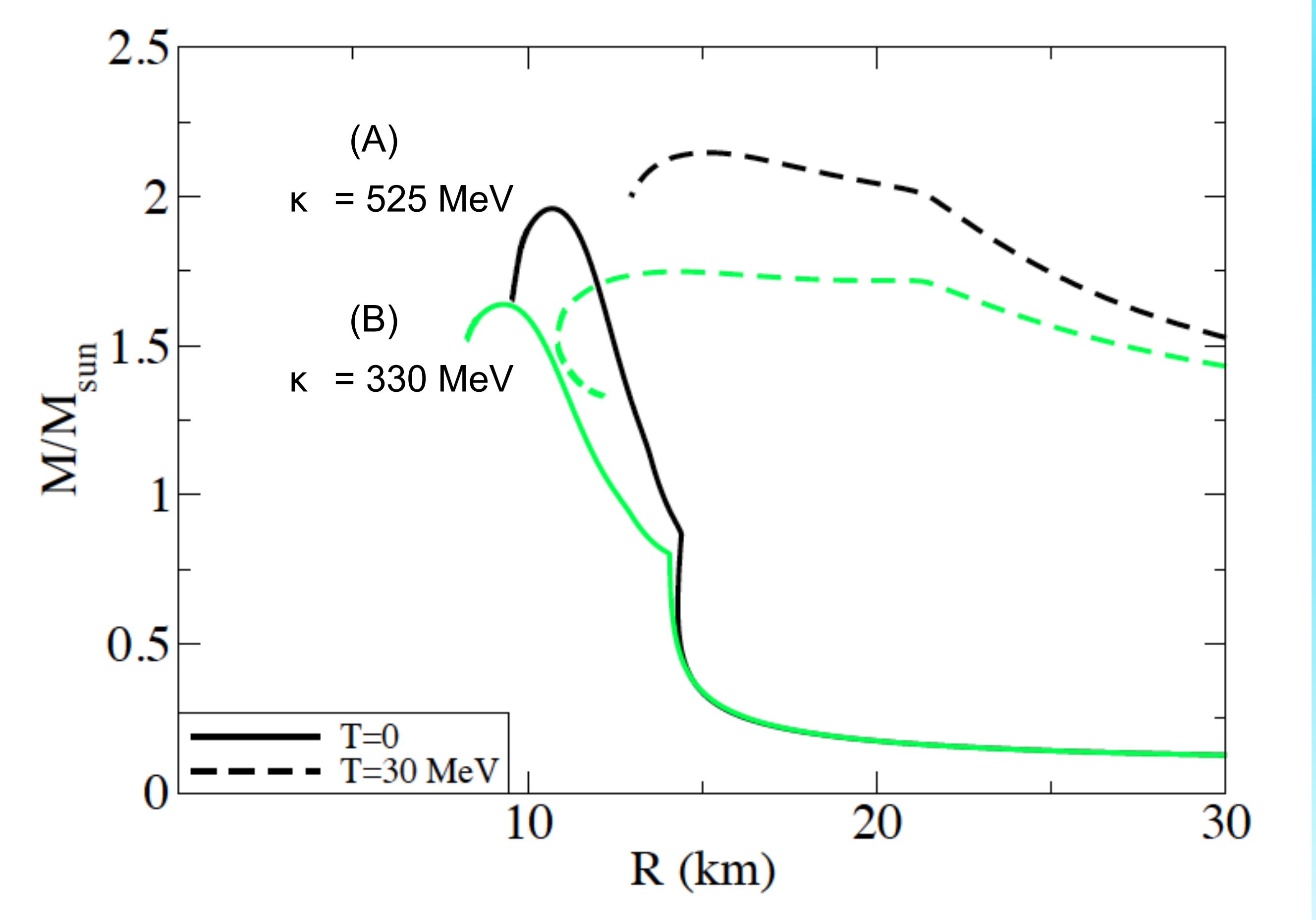
Chiral transition

Liquid-gas phase transition

2 different values for T_0

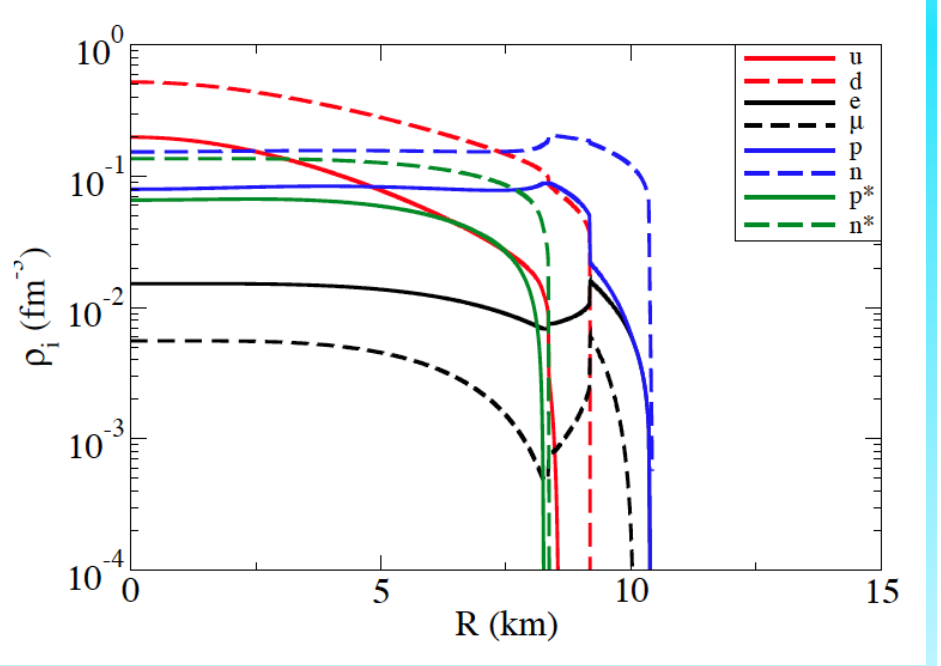


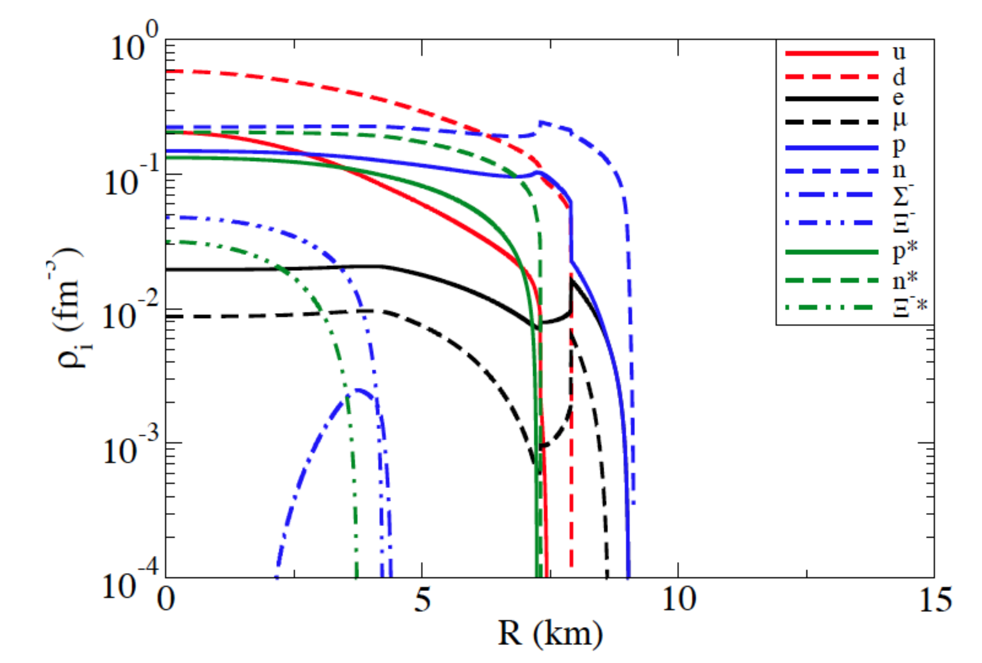
Neutron stars including quarks in the SU(3) parity doublet model



Improve on excluded volume treatment - not that trivial!

particle densities inside of the star for the parity doublet model





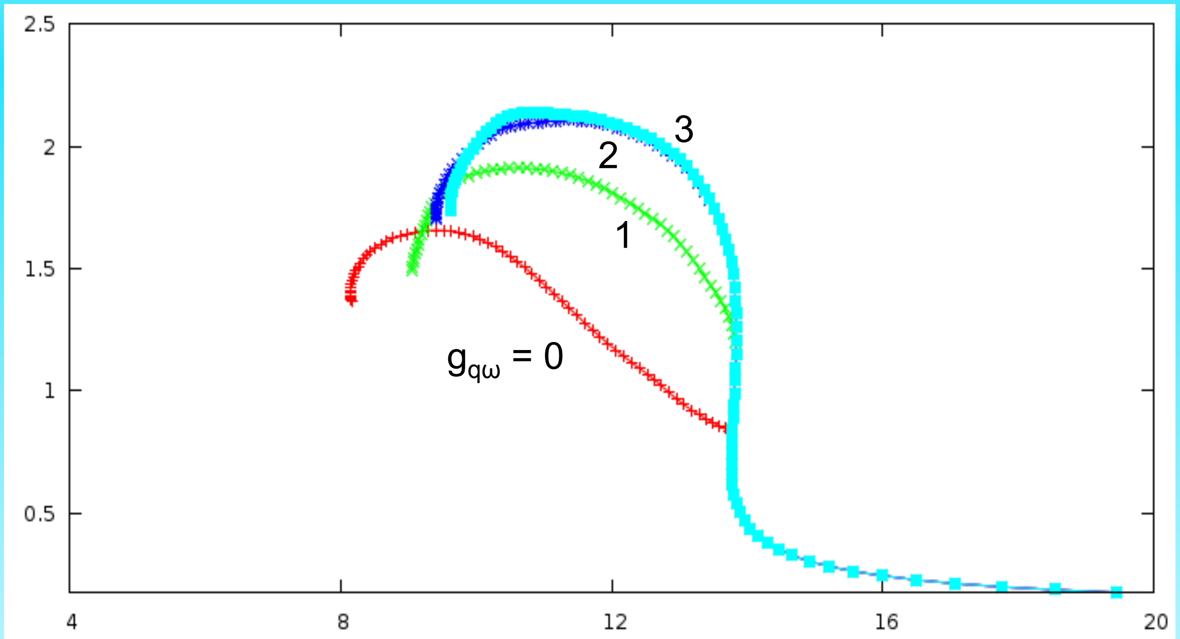
parameters (A)

(B)

Dexheimer,Steinheimer,Negreiros,SWS,
arXiv:1206.3086

Including vector interaction for quarks

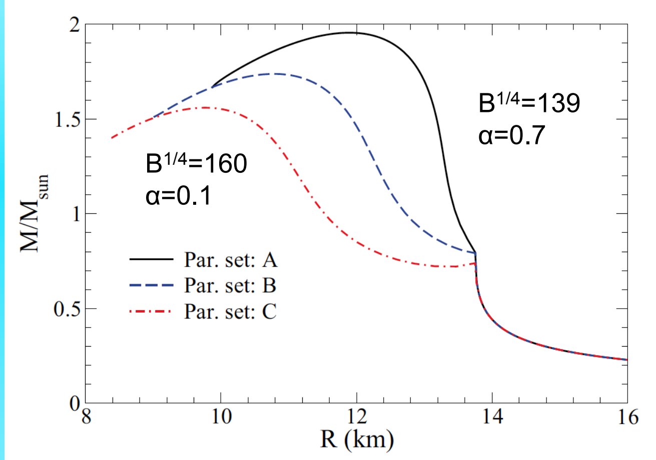
M [$M_\odot$]



R[km]

increase M / R, potential problems at μ = 0

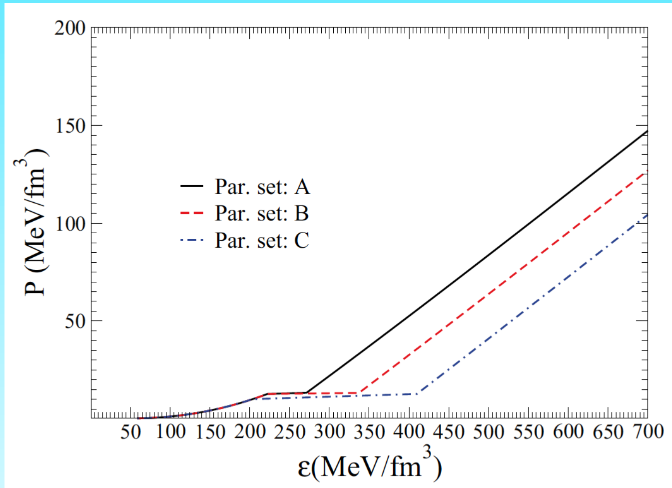
Hybrid Stars, Quark Interactions



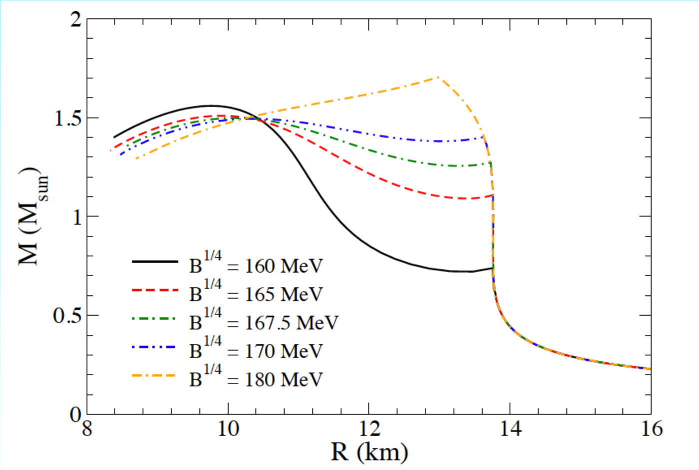
ingredients –
Standard baryonic EOS (G300)
plus MIT bag model + α_s corrections

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

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

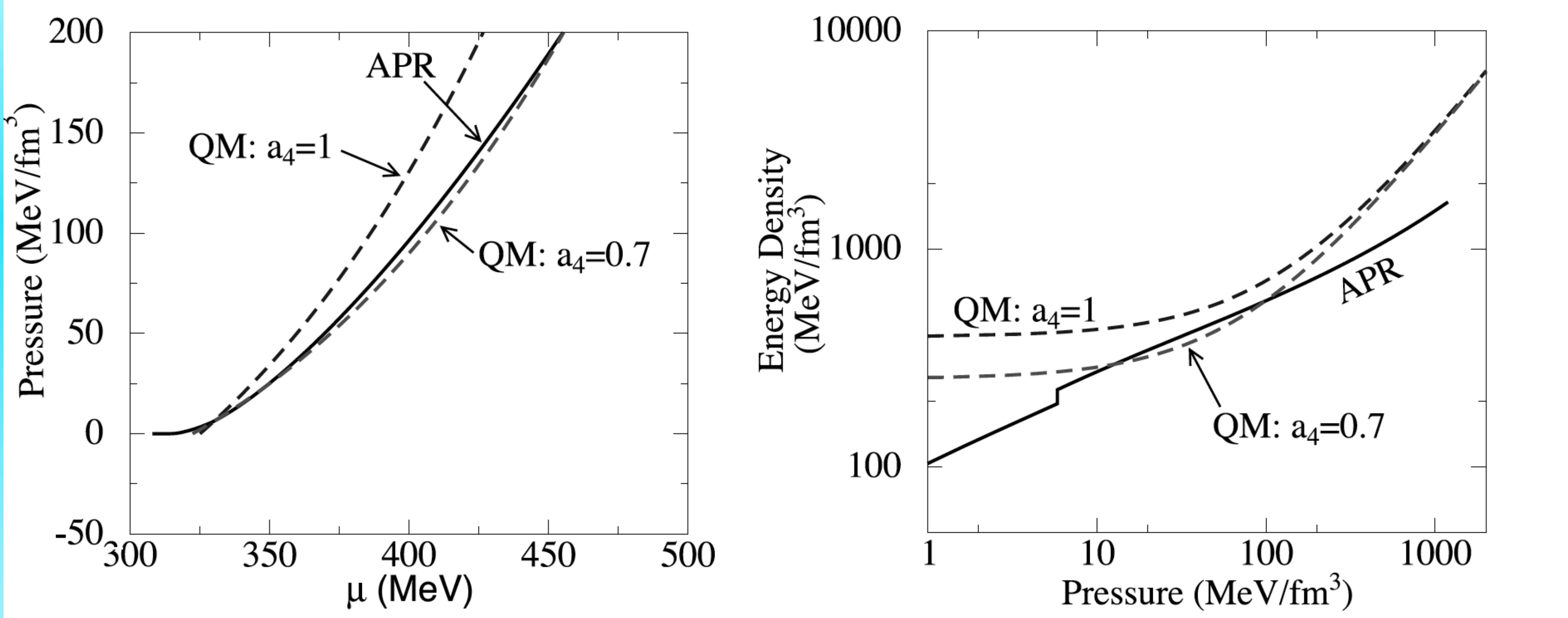


no α_s



Negreiros, Dexheimer, SWS, PRC 035805 (2012)

Quarks as Hadron Look-Alikes



$\Omega_q \sim c\, a_4\, \mu^4 + b\, a_2\, \mu^2 + B_{eff}$

$a_4 < 1$: perturbative QCD corrections

$a_2 \sim m_s^2 - 4\,\Delta^2$

$a_4 \sim 0.7$ Fraga et al. PRD63 121702 (2001)

$a_2 = (150\ \mathrm{MeV})^2$

Similar EOS ➔ similar M(R) diagram

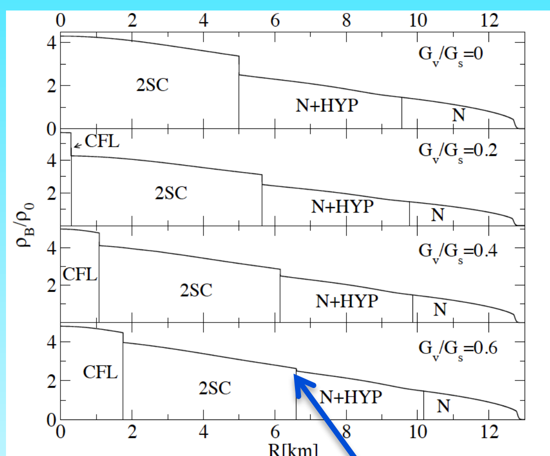
Hybrid star: $M_{max} \sim 2\, M_{solar}$

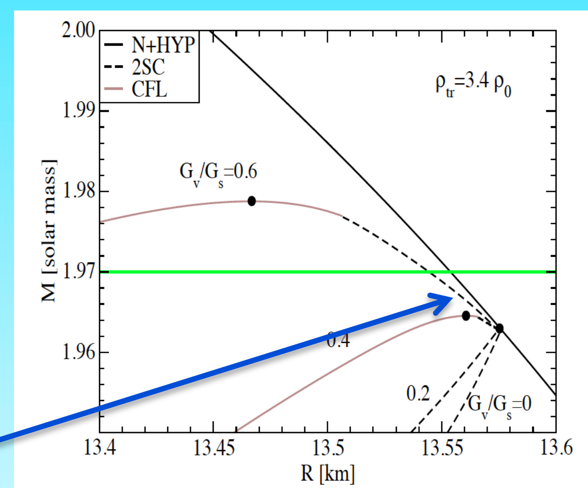
Alford, Braby, Paris, Reddy, APJ 629, 969 (2005)

nucleons plus hyperons
NJL with 2SC/CFL + vector repulsion

$M_{max} \sim 1.98\ M_{solar}$

Include various phases
heavy star





quark – hadron phases become similar
again “look-alikes”

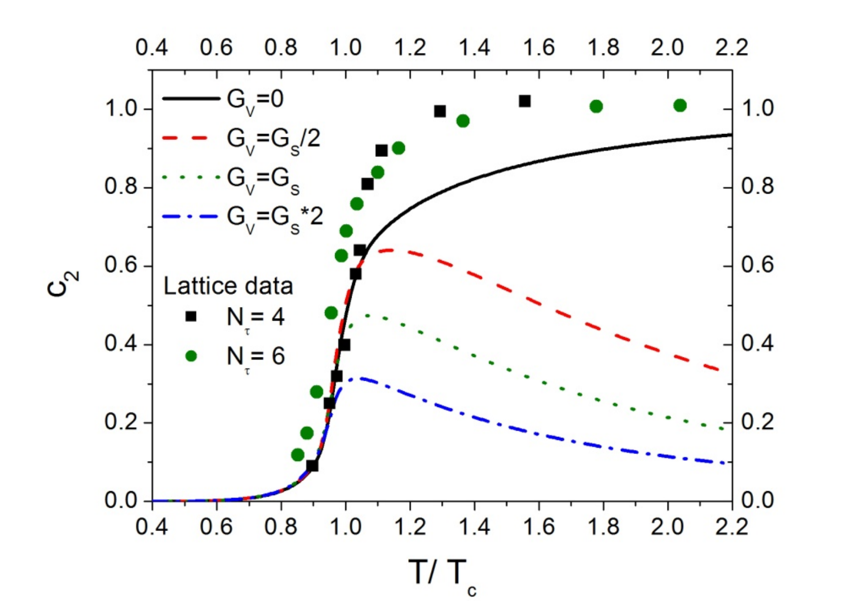
Bonanno, Sedrakian
A&A 539, A16 (2012)

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

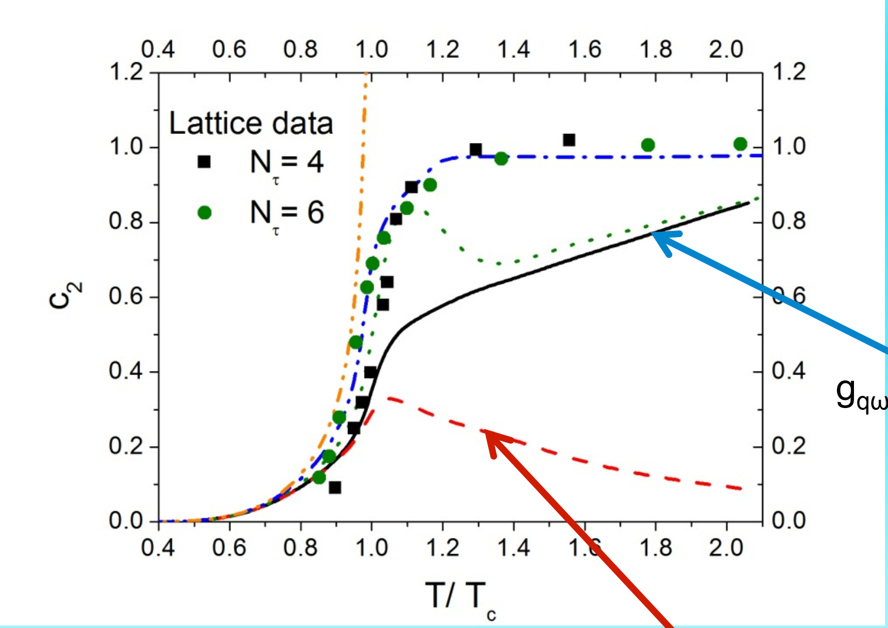
$$P(T,\mu) = P(T) + c_2(T)\,\mu^2\,T^2 + \ldots$$

small quark vector repulsion !!

PNJL



QH



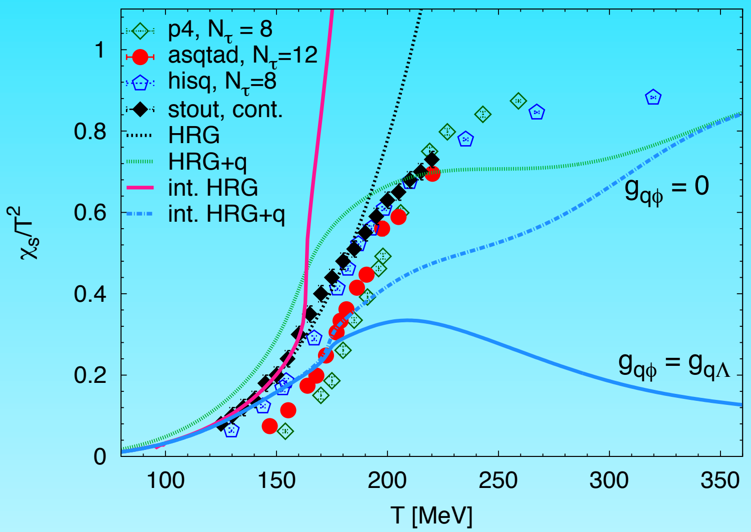
$g_{q\omega}$ = 0

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

Steinheimer, SWS, PLB 696, 257 (2011)

analogous behaviour of strange susceptibilitiy

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



off

strange quark repulsion

on

calc. by Philip Rau

Conclusions

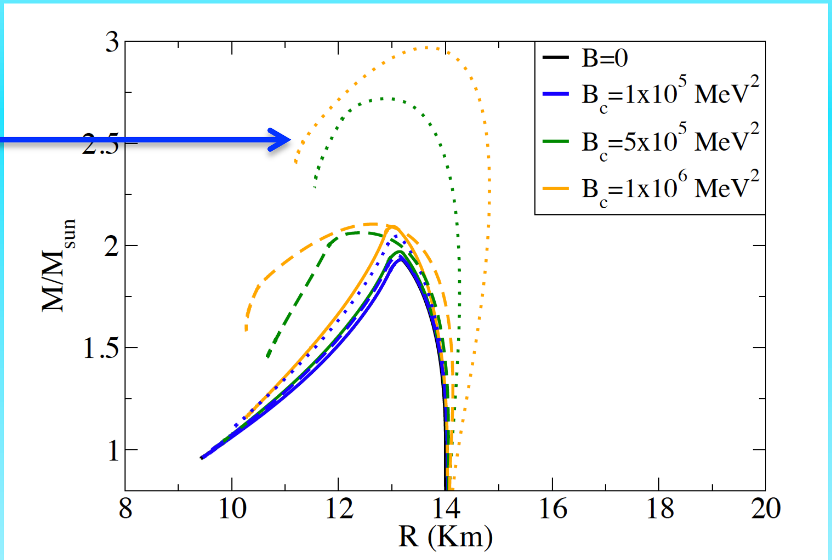
- 2 M_S does not preclude hyper-/hybrid stars
- SU(3) approach with dynamical baryon masses produces still reasonable star masses, need Φ
- Excluded volume effects interesting phase structure and heavy masses
- In general, similar results with parity doublet model
- Hybrid star approach tends to generate problems with small μ_B physics

Include magnetic fields

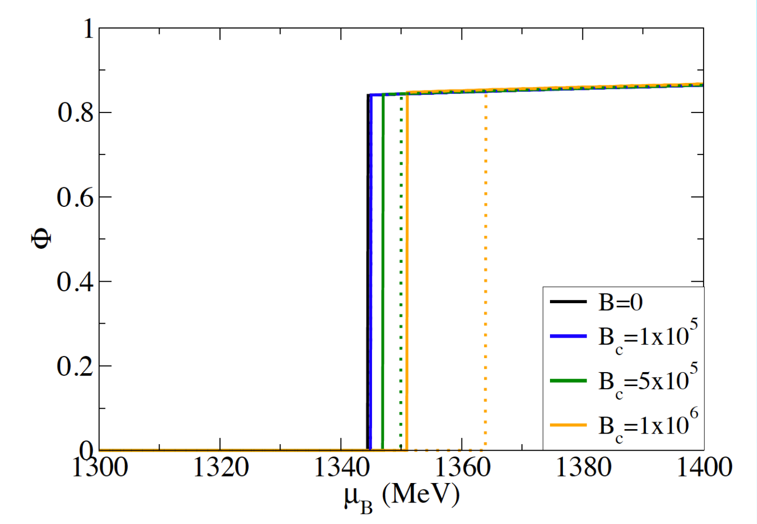
magnetars - up to 10^{15} Gauss surface field

$T^F_{\mu\nu} = \mathrm{diag}(\frac{1}{2}B^2, \frac{1}{2}B^2, \frac{1}{2}B^2, -\frac{1}{2}B^2)$

energy-momentum tensor not isotropic
consistent modeling of star needed



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



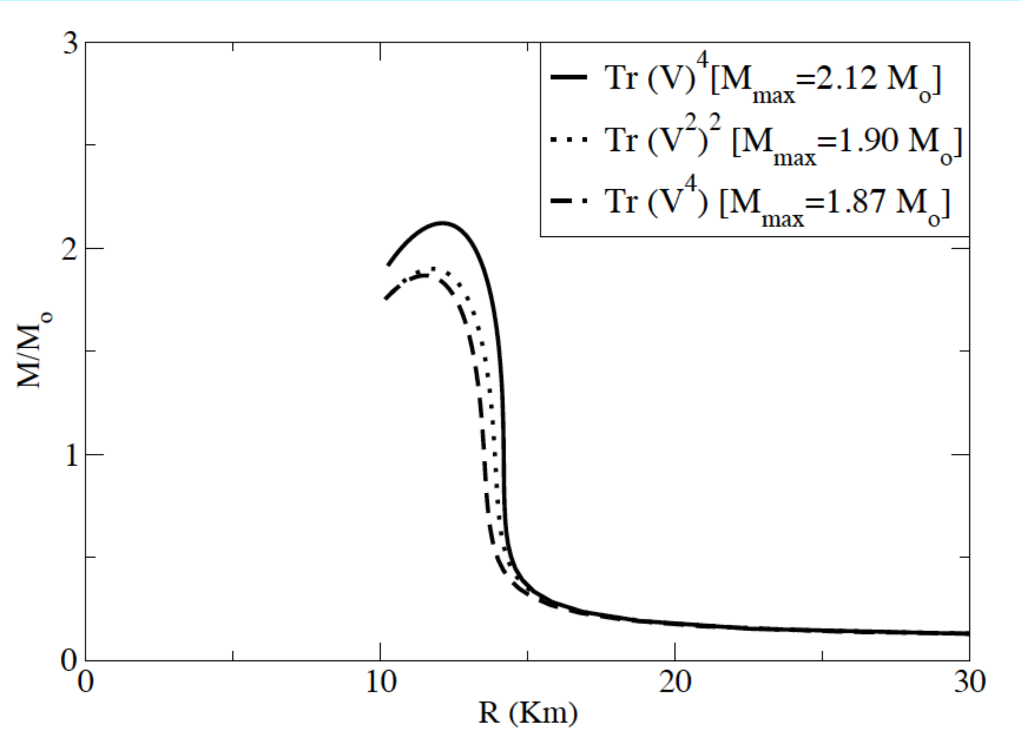
Small changes for B_c up to 10^{19} G

deconfinement transition
magnetic field stiffens hadronic EOS
moves transition to somewhat higher μ_B

Cooling behavior is slightly modified

Dexheimer, Negreiros, SWS, astro-ph:1108.4479

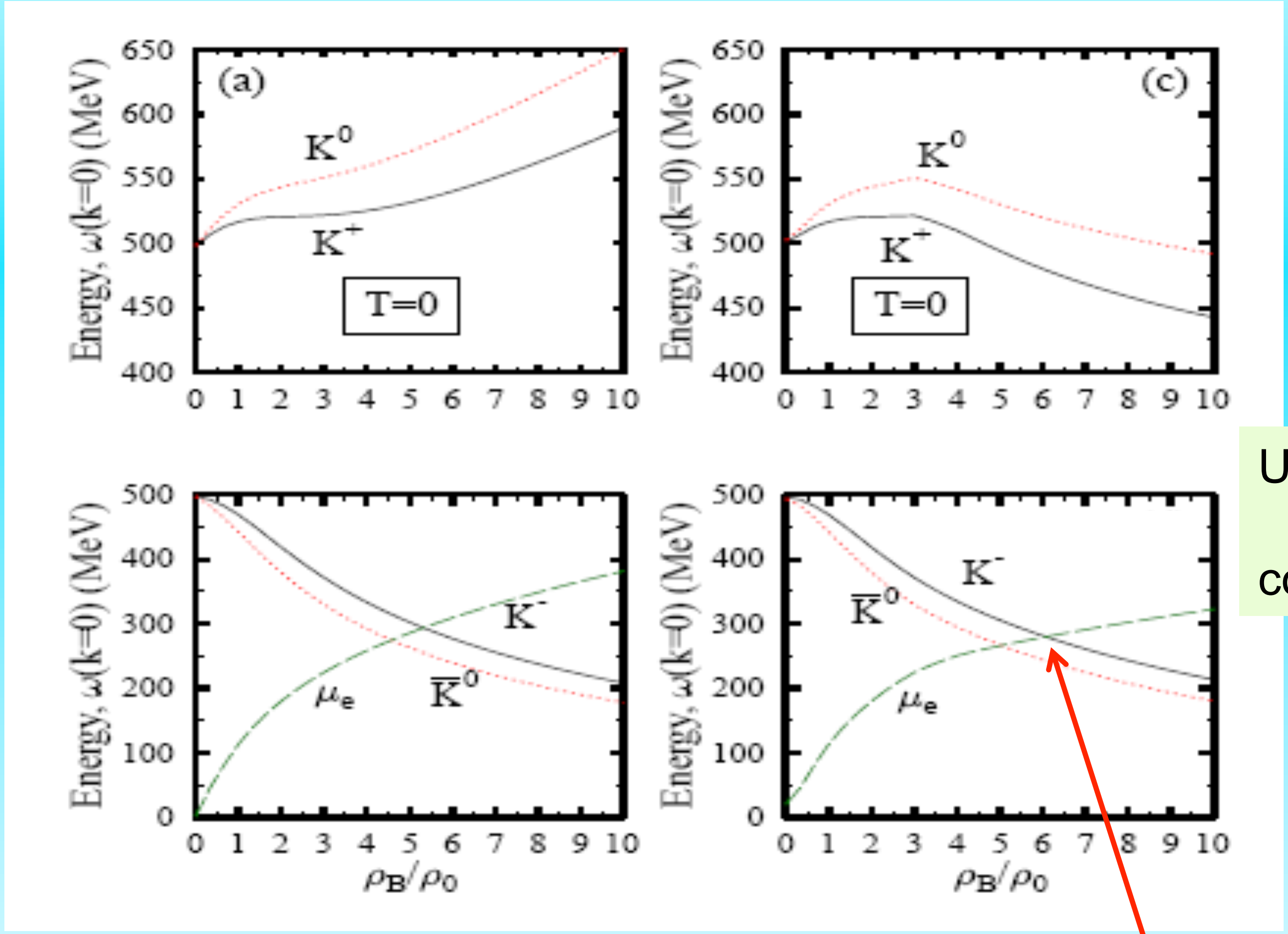
Different schemes for non-linear vector interactions



$$\mathrm{diag}(V_\mu) = \{ (\omega+\rho)/\sqrt{2} , (\omega-\rho)/\sqrt{2} , \phi \}$$

Dexheimer, SWS ApJ 683, 943 (2008)
SWS PLB 560 164 (2003)

kaon energies as function of density for neutron star at T = 0



nucleons

nucleons + hyperons

$U_{K^-}(\rho_0)$ ~ -50 MeV

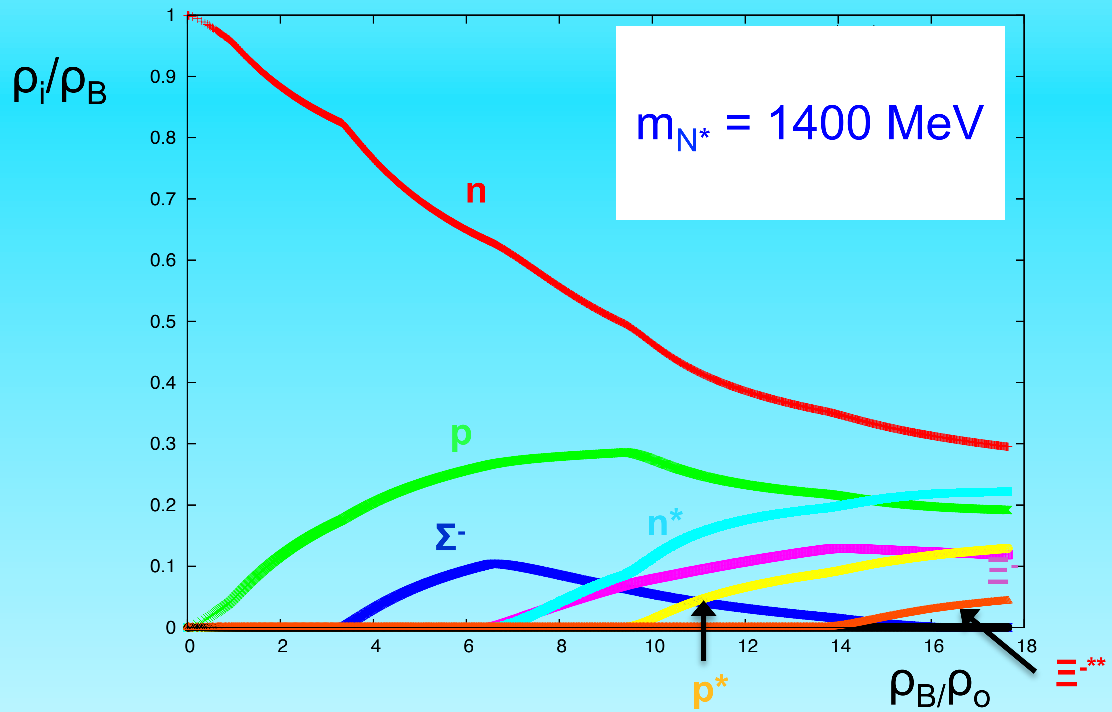
correct a_{KN} values

Kaon condensation sets in at around 5.5 ρ_0
no significant change of star properties

Hyperons shift ρ_c to higher values

Mishra, Kumar, Sanyal, SWS, EPJA 41, 205

Particle population in nuclear matter in beta equilibrium



particle mix not too exotic for reasonably large densities