

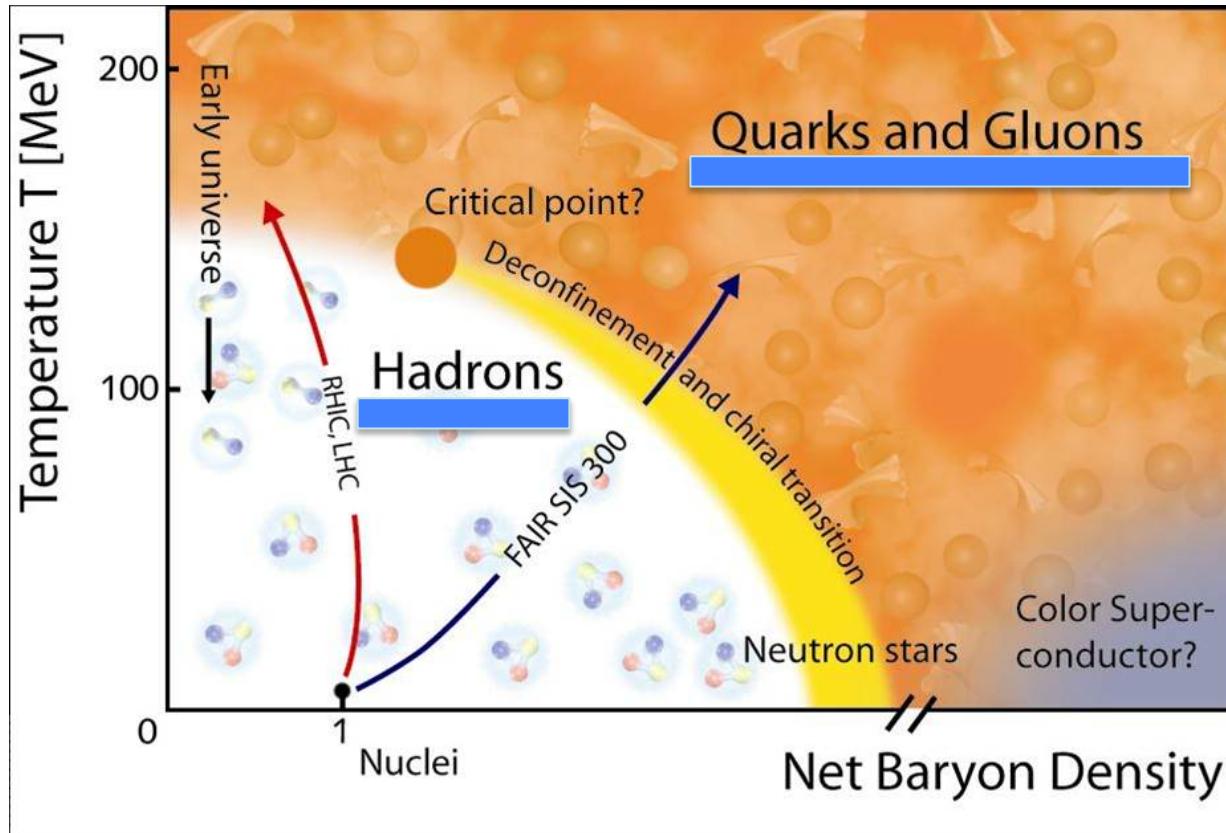
Models of Hyper and Hybrid Stars

OUTLINE

- hadronic model
- adding quarks
- phase diagram, constraints
- magnetic fields, meson condensation
- conclusions

*V. Dexheimer, R. Mallick, R. Negreiros,
B. Franzon, R. Gomes, J. Steinheimer, SWS
FIAS, Kent State, Fluminense, Porto Alegre, Bhopal*

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

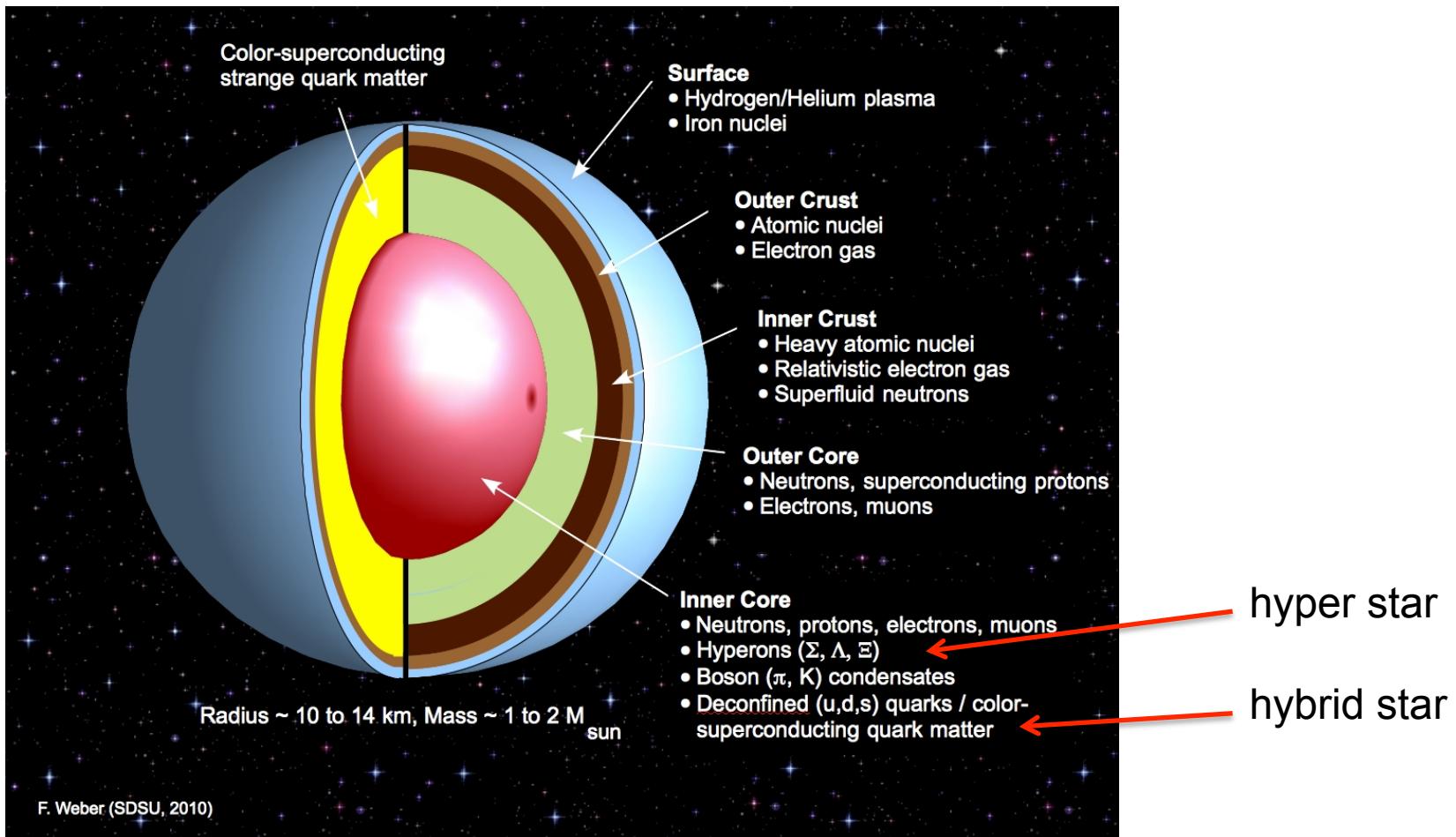
reasonable description on a quantitative level for high T down to nuclei

possibility of studying first-order as well as cross-over transitions

neutron stars are remnants of Type II supernovae

1 to 2 solar masses, radii around 10 - 15 km
maximum central densities $4 \text{ to } 10 \rho_0$

about 2000 known neutron stars



hadronic SU(3) approach based on non-linear realization of $\sigma\omega$ model

Lowest multiplets

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

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

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

Mean fields generate scalar attraction and vector repulsion

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

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

$$+ \text{dilaton field } L_X = -k_4 X^4 - \frac{1}{4} X^4 \ln (X^4/X_0^4) + \delta/3 X^4 \ln (I_3/\langle X \rangle)$$

hadronic SU(3) approach ... continued

SU(3) interaction

$$L_{BW} = -\sqrt{2} g_8^W (\alpha_w [\bar{B}OBW]_F + (1 - \alpha_w) [\bar{B}OBW]_D) - g_1^W / \sqrt{3} \text{Tr}(\bar{B}OB) \text{Tr}(W)$$

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

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

plus explicit breaking

fix scalar parameters to

baryon masses, decay constants, meson masses

Nuclear Matter and Nuclei

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

compressibility $\sim 223 \text{ MeV}$ asymmetry energy $\sim 31.9 \text{ MeV}$

parameter fit to known nuclear binding energies and hadron masses

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

reasonable charge radii $\delta r_{ch} \sim 0.5 \%$

error in energy $\varepsilon (A > 50) \sim 0.17 \%$ (NL3: 0.25 %)

$\varepsilon (A > 100) \sim 0.12 \%$ (NL3: 0.16 %)

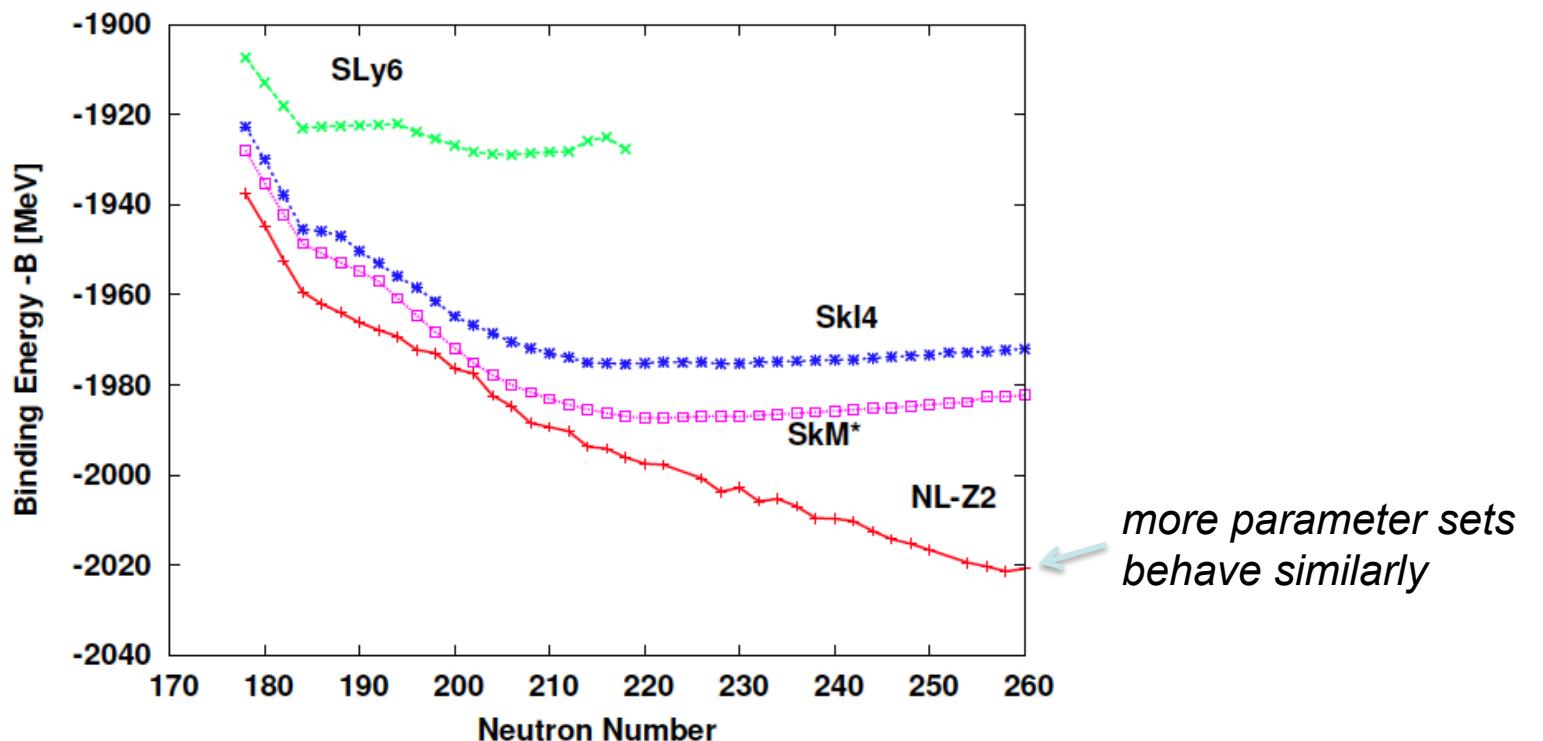
+ correct binding energies of hypernuclei

relativistic nuclear
structure models

stellar crust/new fit calculations in progress

extreme example - total binding energy $-B$ (MeV) for Uranium Isotopes

side remark - drip line for heavy nuclei highly uncertain (far beyond crust conditions)

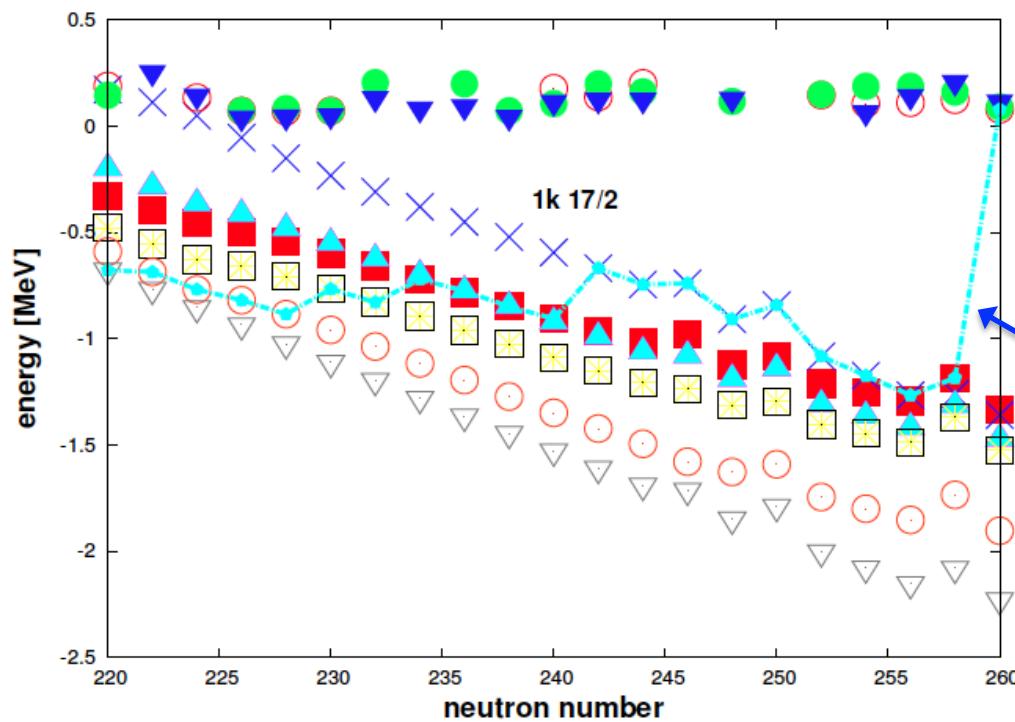


Model	N(1d)	N(2d)	B _{2d} [MeV]
NL-Z2	258	258	2021.34
SkM*	246	220	1987.39
SkI4	258	218	1975.41
SLy6	184	206	1928.92
χ_M	184	184	1957.56
χ_M^*		224	1965.7

different Skyrme,
RMF, CMF models

drip line nuclei 1d, 2d

new shell generates magic number at N = 258

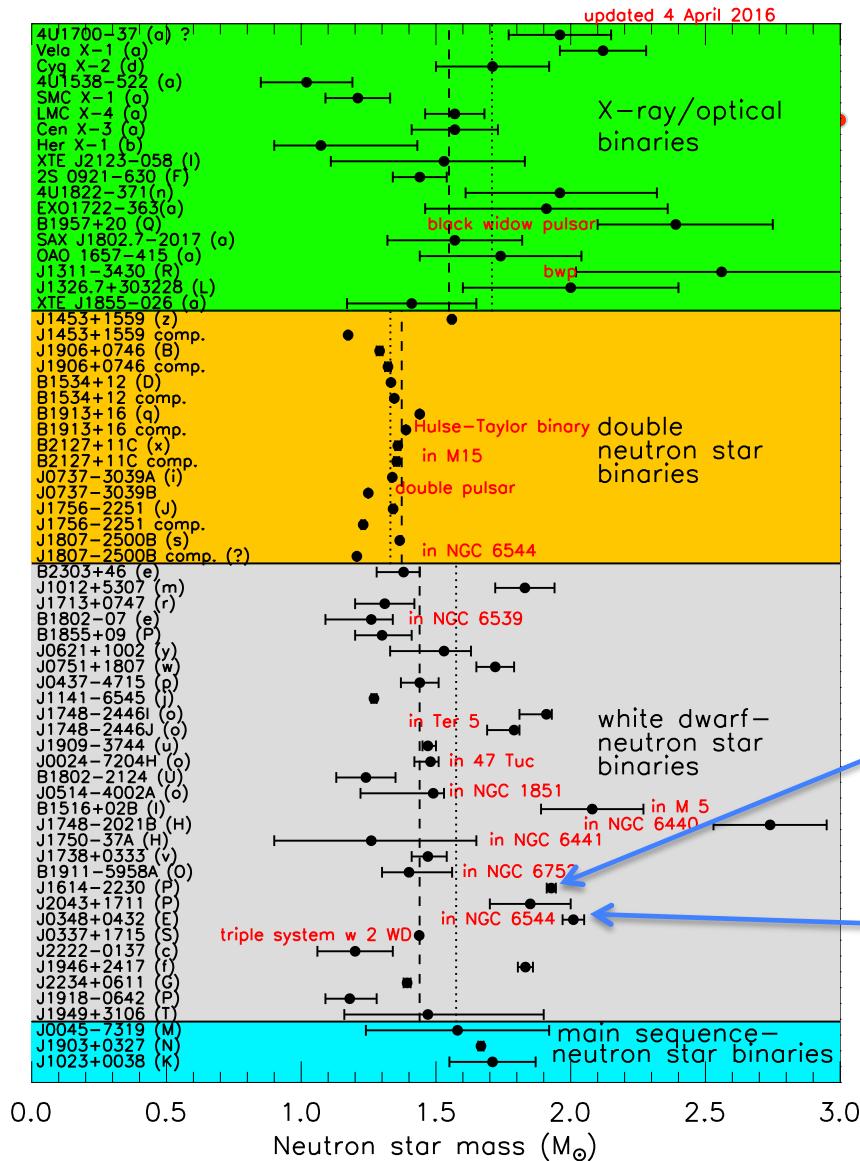


Uranium Isotopes

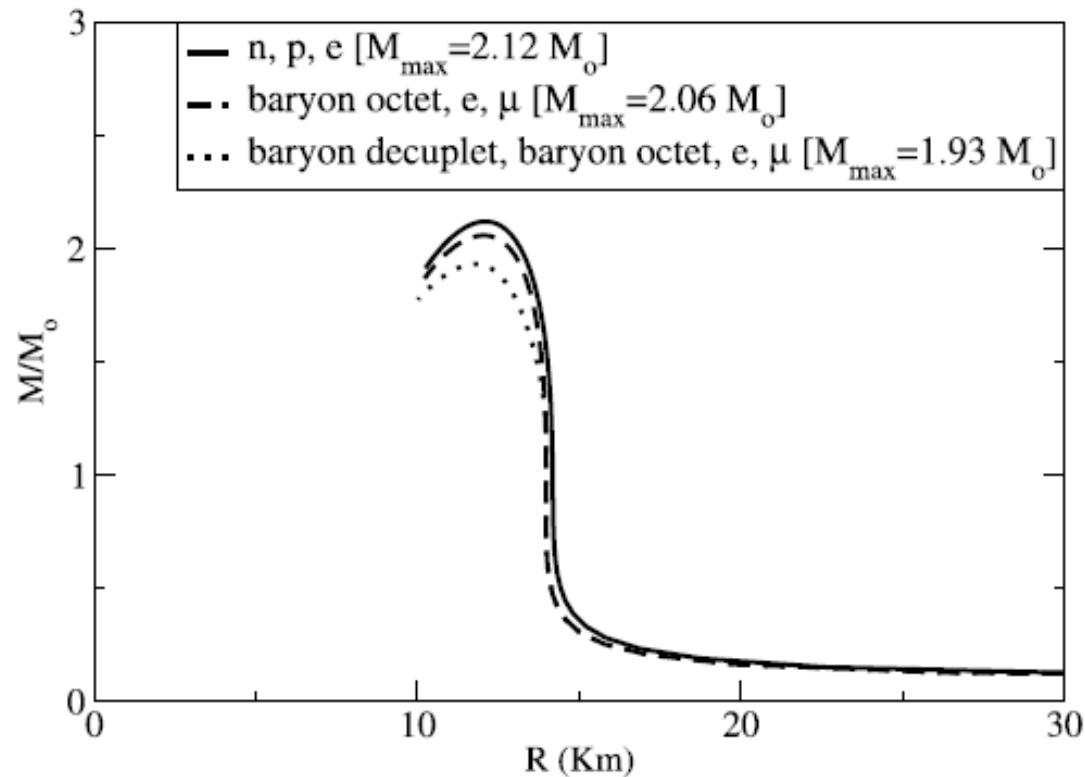
Example: NL-Z2 RMF

Fermi energy

*drip line uncertainty
of more than 70 neutrons!*



Neutron star masses including different sets of particles



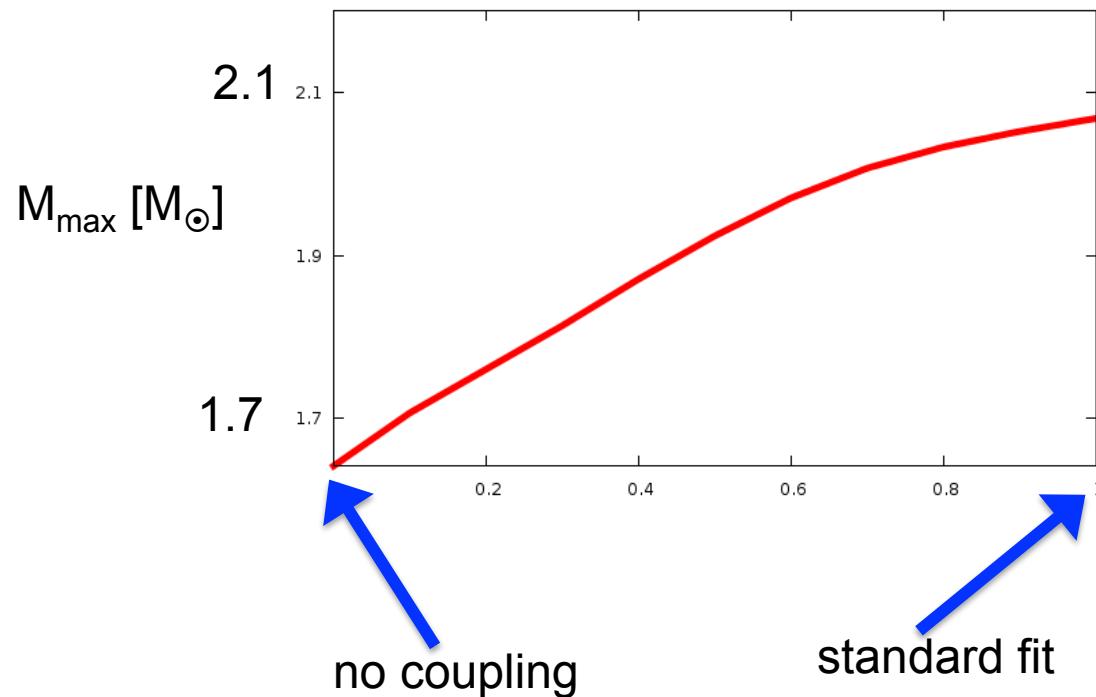
Tolman-Oppenheimer-Volkov
equations, static spherical star

changing masses with degrees
of freedom

large star masses even with
spin 3/2 resonances

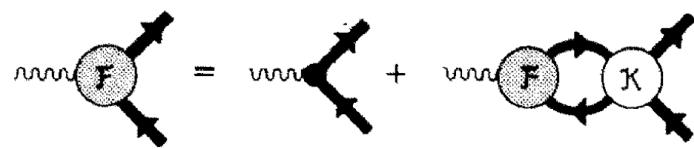
Impact of Φ field

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



$$f_s = n_s / n_B$$

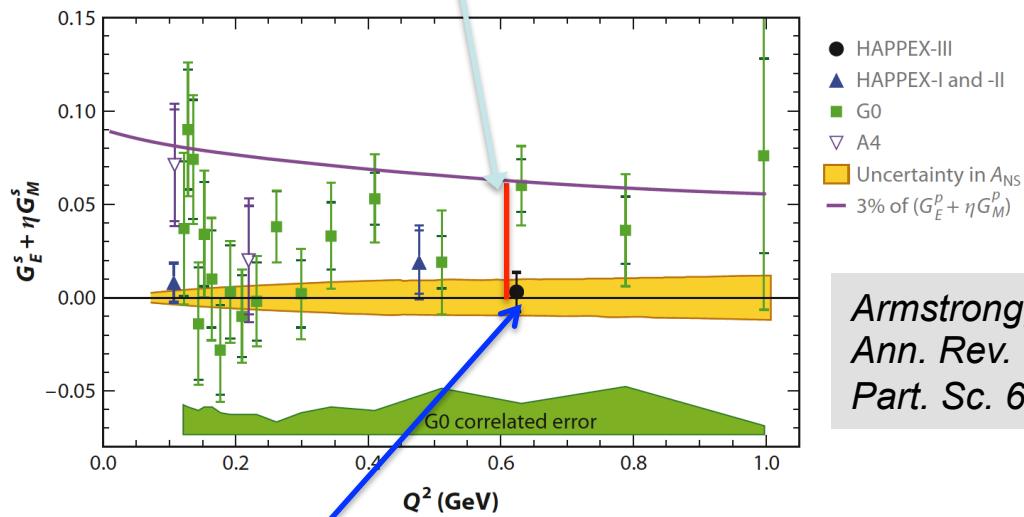
no coupling of N to Φ - strange vector form factor of nucleon



band of possible values from calculation

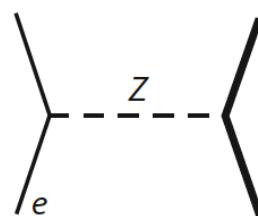
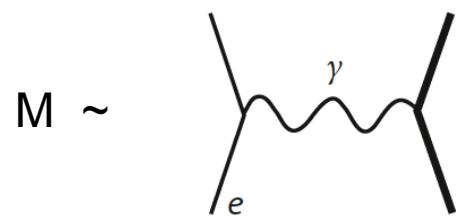
SWS, MPLA 10 1201 (1995)

PV polarized
eA scattering experiments



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

most recent experiment - strangeness contribution consistent with 0



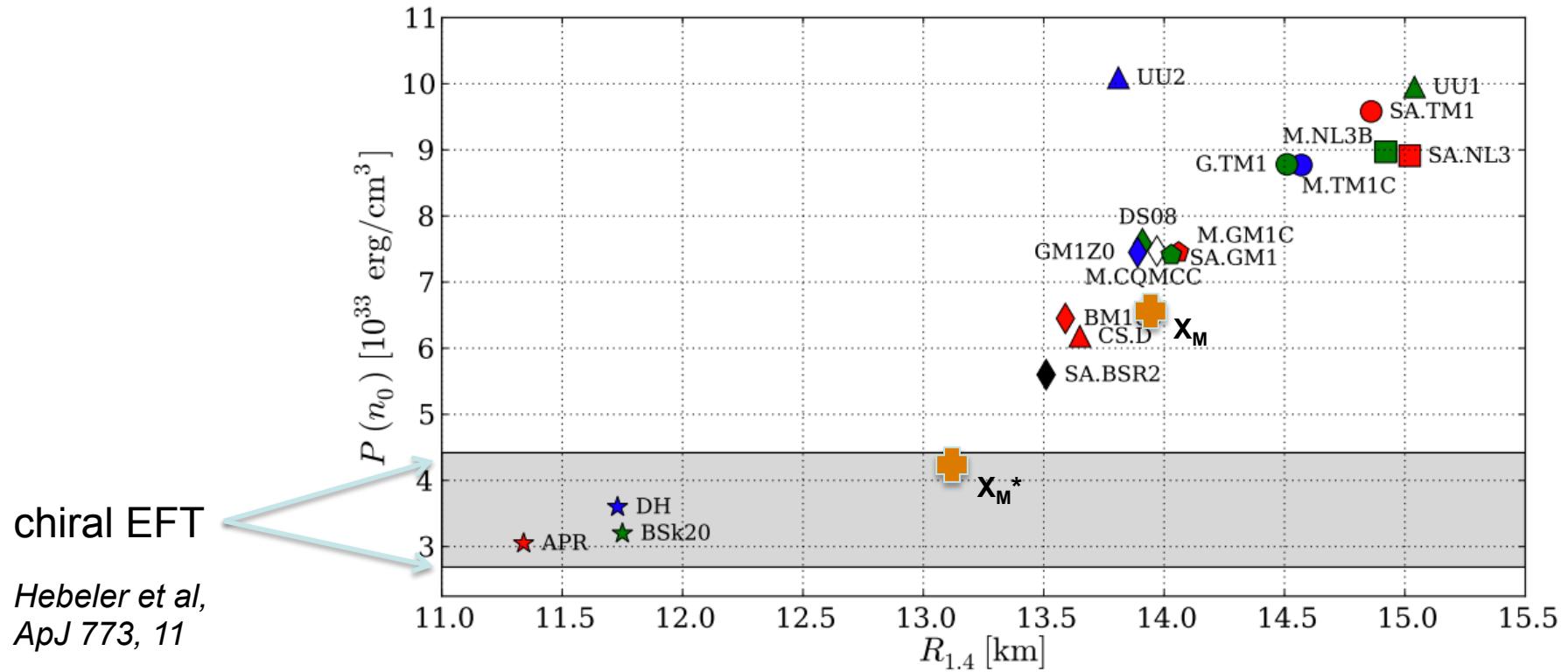
interference term $\sigma_{PV} \sim M_\gamma M_Z^*$

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

χ QCD collaboration small values for μ_s and r_s ,

PRD80 094503 (2009)

pressure of star matter at ρ_0



“working” hyper star models fail at smaller densities?

→ not necessarily

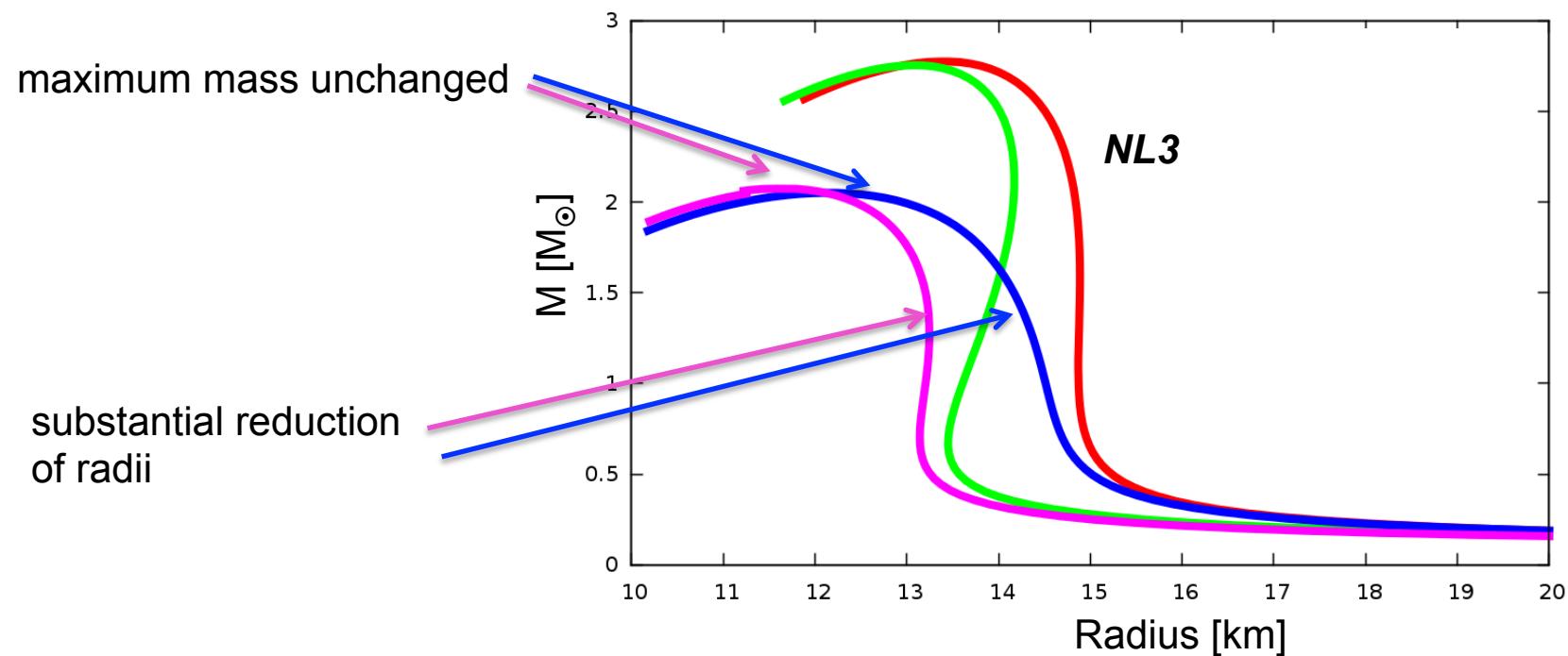
Fortin et al., A&A 576, A68 (2015)

modifying vector self-interactions

Dexheimer, Negreiros, SWS, PRC92, 012801(R)
Horowitz, Piekarewicz, PRC66, 055803
SWS, PLB 560, 164

non-linear isoscalar-isovector interactions

→ non-trivial density dependence of isospin terms



Δ baryons in compact stars?

Δ resonances
scalar couplings \rightarrow vacuum masses

vector couplings unclear

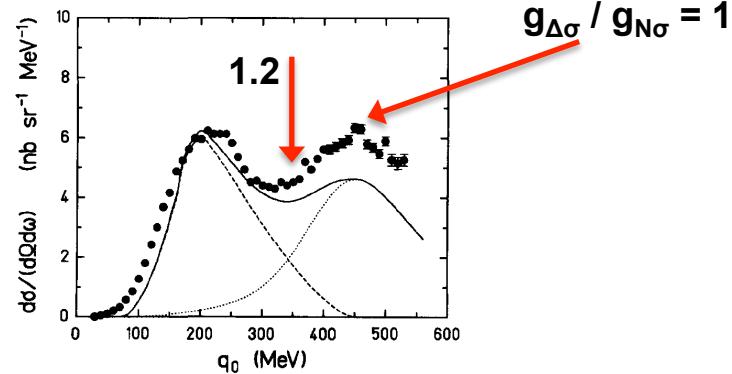
moderate changes $r_V = g_{\Delta\omega} / g_{n\omega}$

not far from SU(6)

constraints from πA scattering
photoabsorption

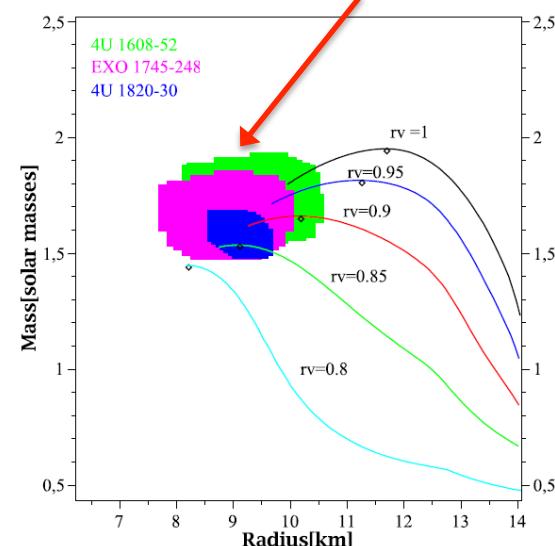
quasielastic eA scattering

$E_e = 695 \text{ MeV}$ ^{40}Ca

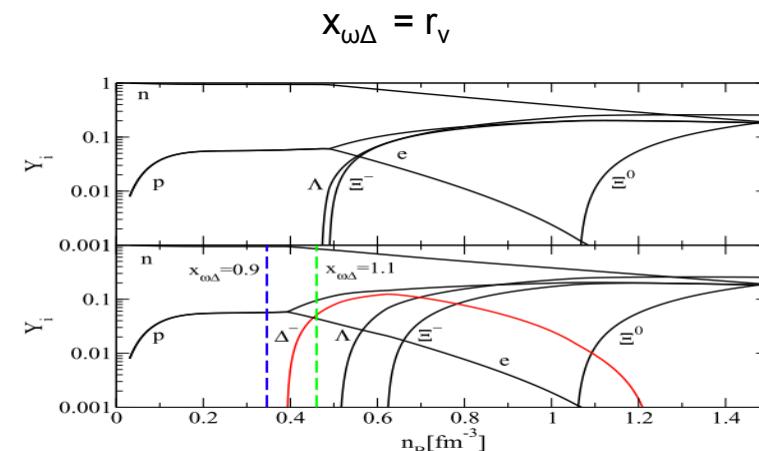


Wehrberger, Phys. Rep. 225, 273 (1993)

Özel et al, Phys.Rev.D82:101301,2010



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



new analysis in Drago et al astro-ph:1407.2843:
Onset of Δ population at 2 to 3 ρ_0

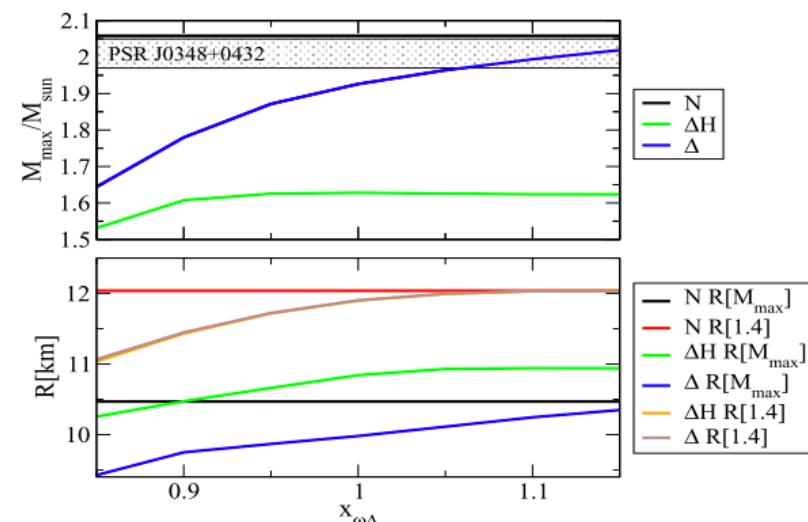
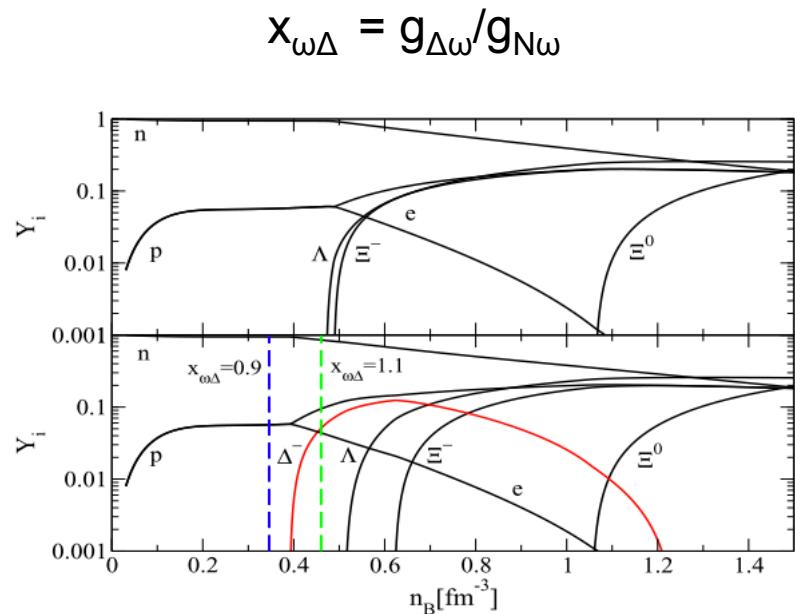
Quark star and Δ star families

Drago et al., arXiv:1407.2843

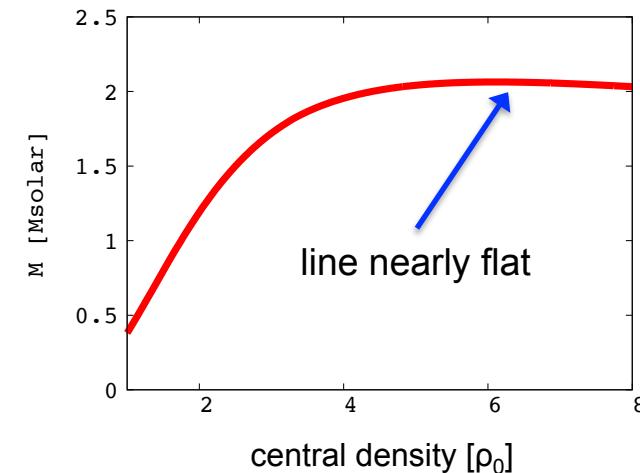
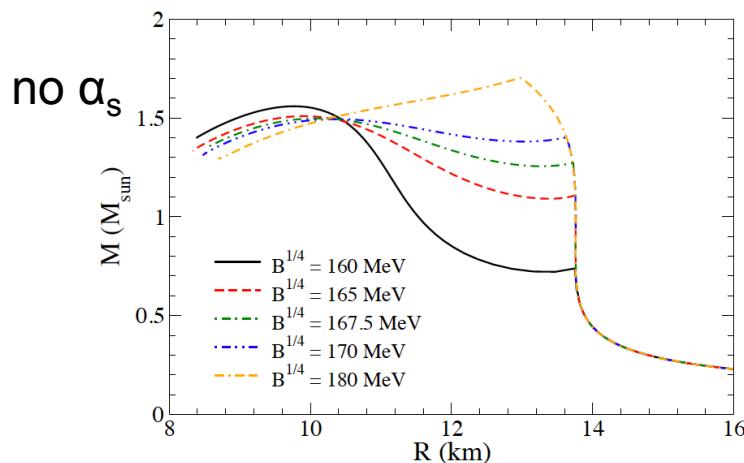
The Δ – it should be there!

Information from pion / electron nucleus scattering and photo absorption point to similar coupling strengths of meson-nucleon and meson- Δ

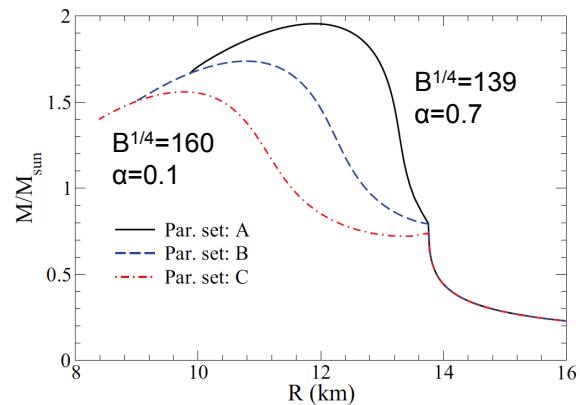
small values for L point to early onset of Δ population in stars



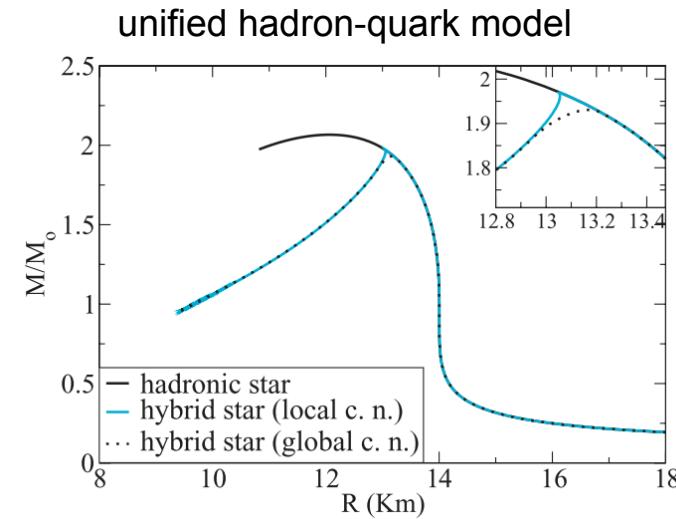
Hybrid Stars, Quark Interactions



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



baryons alone $M_{\text{max}} \sim 1.8 M_{\text{solar}}$



*Negreiros, Dexheimer, SWS, PRC85 035805
Dexheimer, SWS, PRC81 045201*

hadrons, quarks, Polyakov loop and excluded volume

Include modified distribution functions for quarks/antiquarks

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

Φ confinement order parameter*

Following the parametrization used in PNJL calculations

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

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

Ratti et al, EPJC49, 213

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

thermodynamically consistent -

no reconfinement!

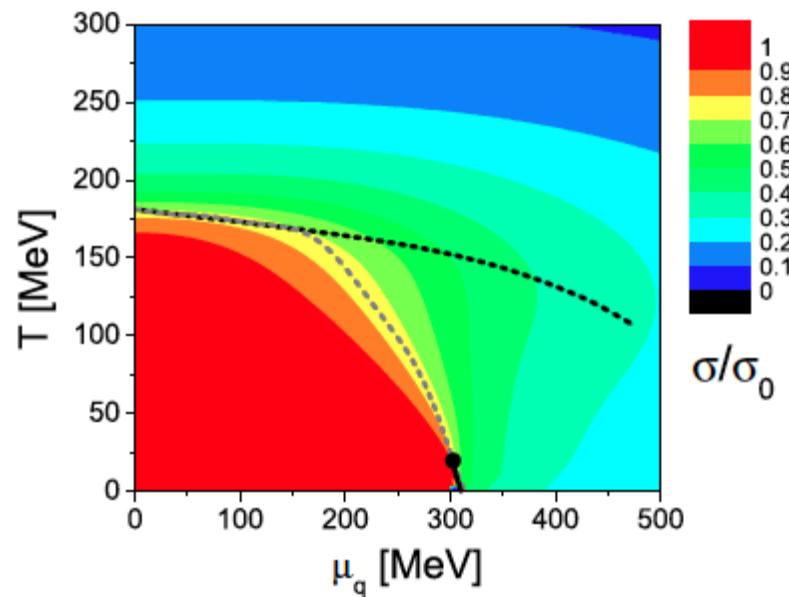
$$\begin{array}{lll} V_q & = 0 \\ V_h & = v \\ V_m & = v/8 \end{array}$$

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

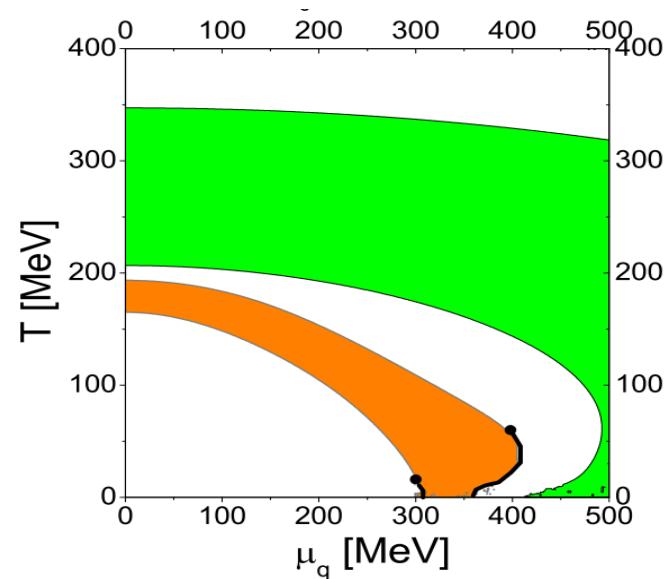
$$e = \tilde{e} / (1 + \sum v_i \tilde{\rho}_i)$$

equation of state stays causal!

Order parameters for chiral symmetry and confinement in μ and T

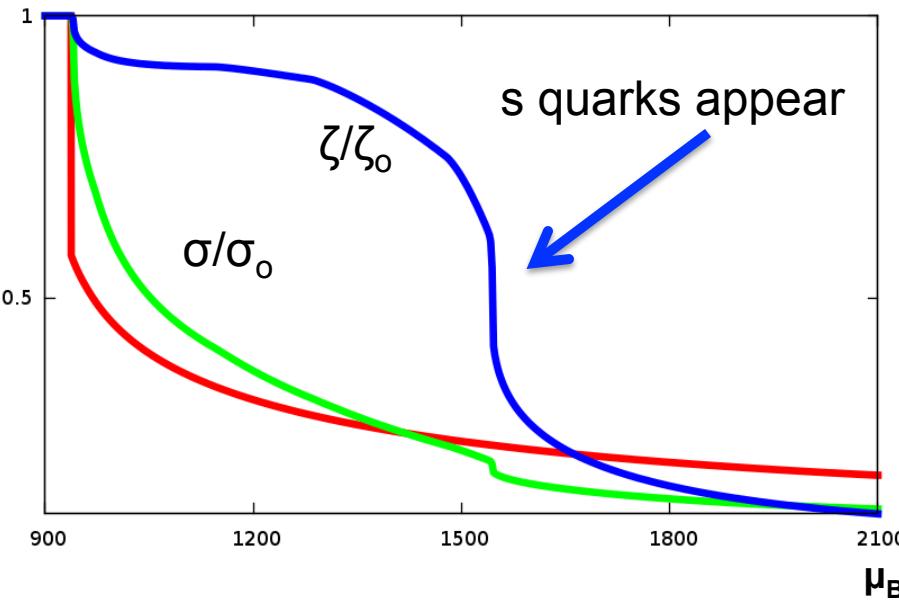


except for liquid-gas no first-order transition

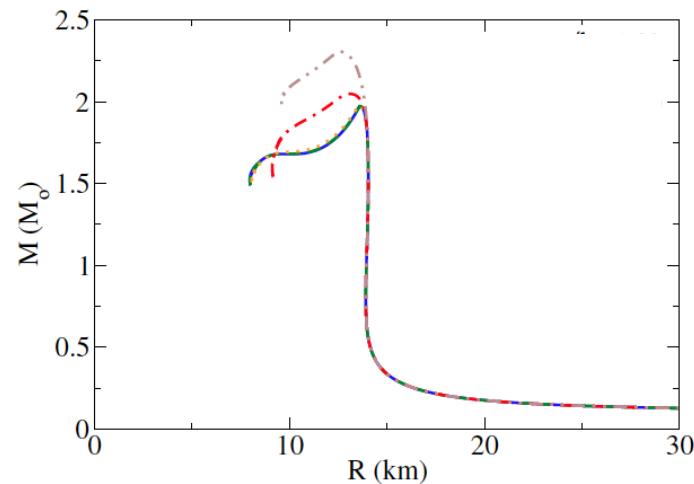


$SU(3)$ parity-doublet model

star matter in beta equilibrium in QH approach



star masses M varying quark interactions

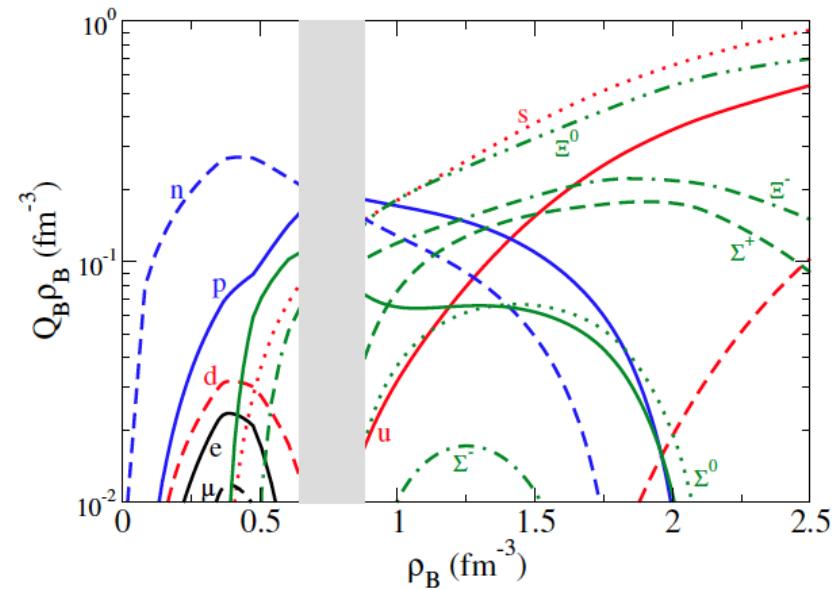


1st order phase transition
in star matter possible

cross over in symmetric matter

$f_s(\text{core})$ jumps to ~ 1

particle cocktail

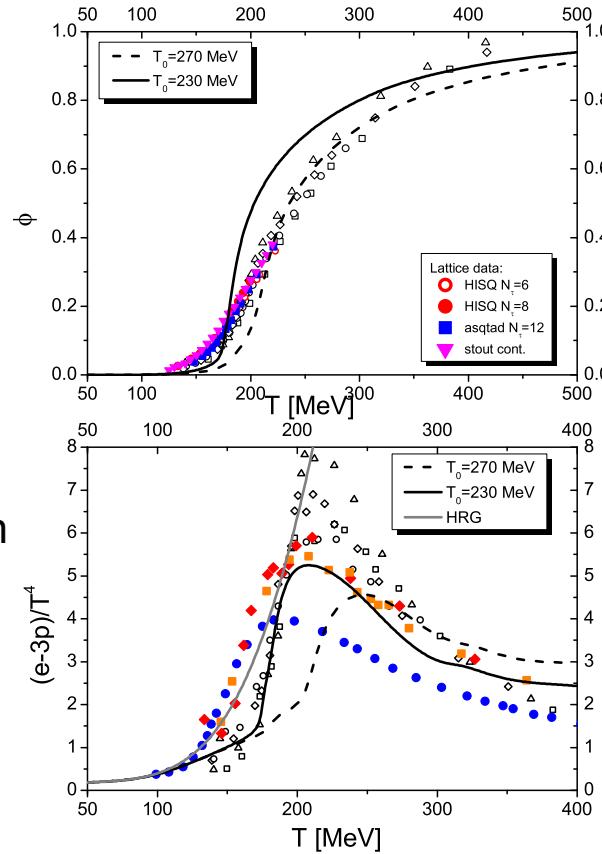


Mass $\sim 2 - 2.3 M_\odot$ Radius ~ 13 km

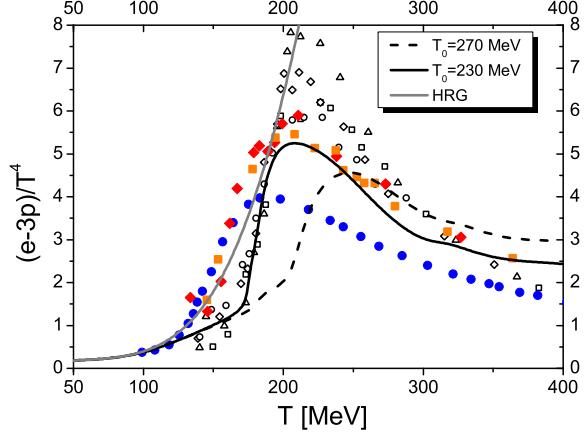
results for hot matter at vanishing chemical potential

points are various lattice results

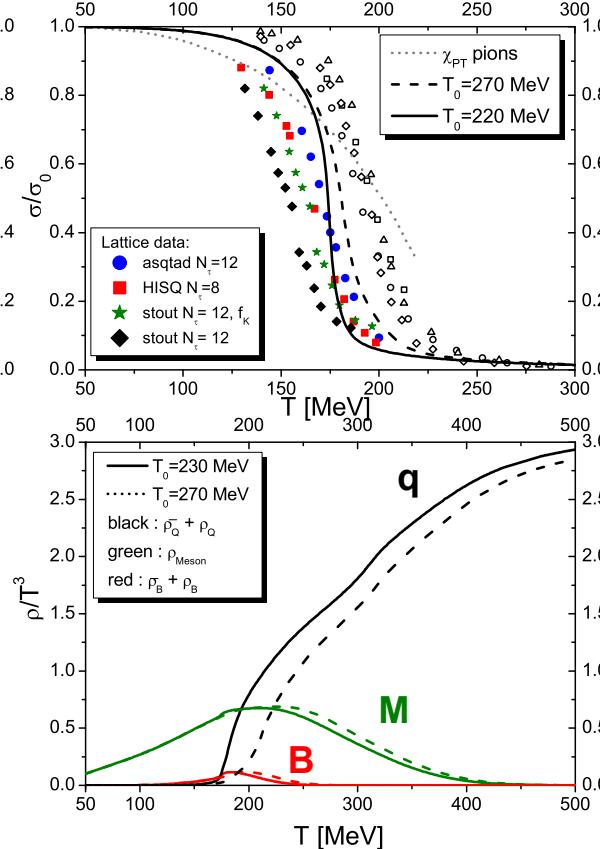
Polyakov
loop



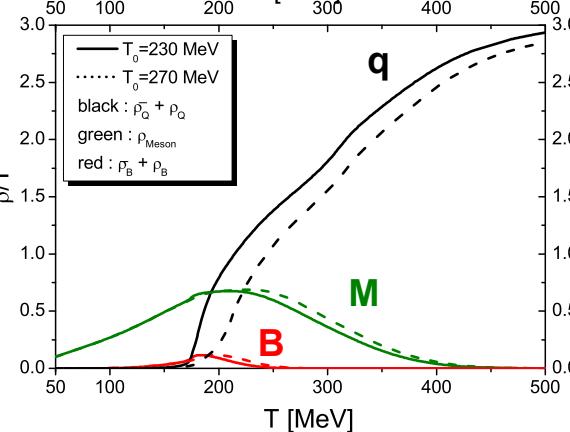
Interaction
measure



scalar
condensate



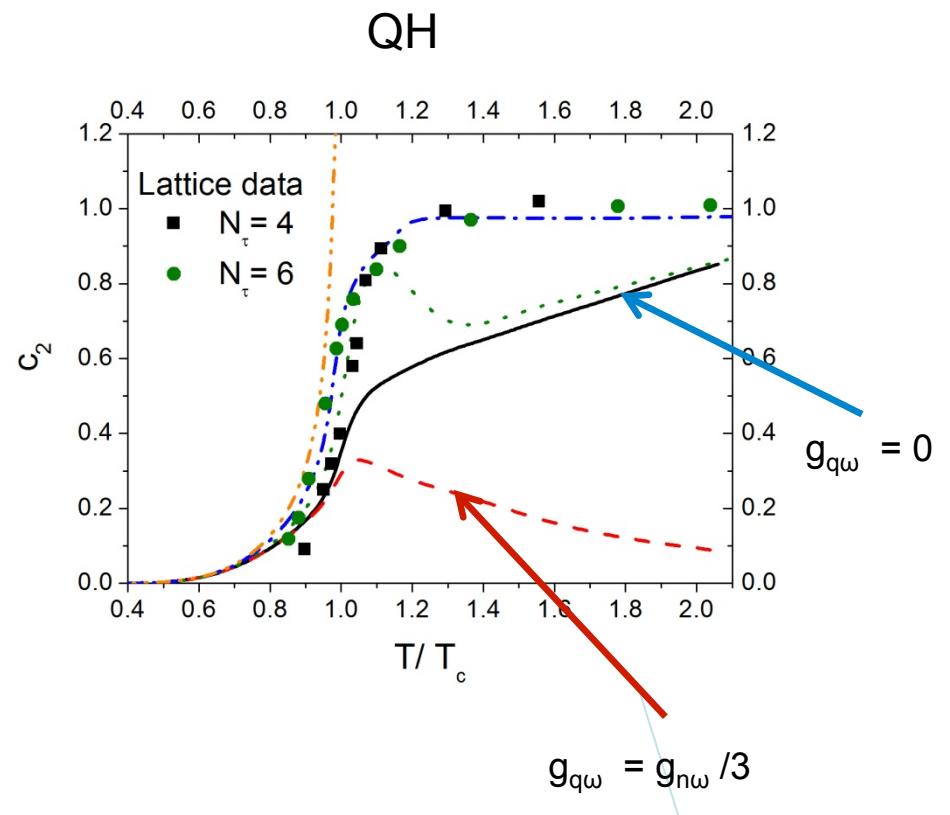
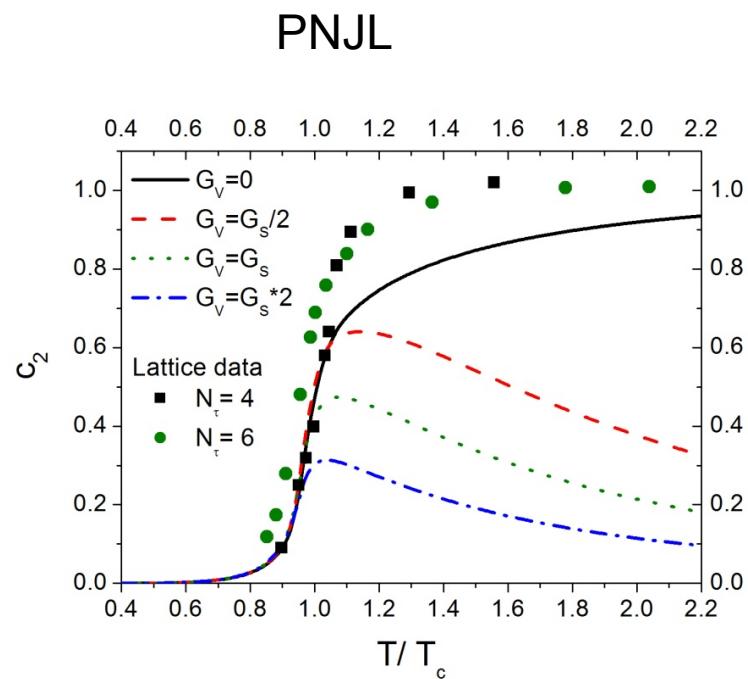
densities



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

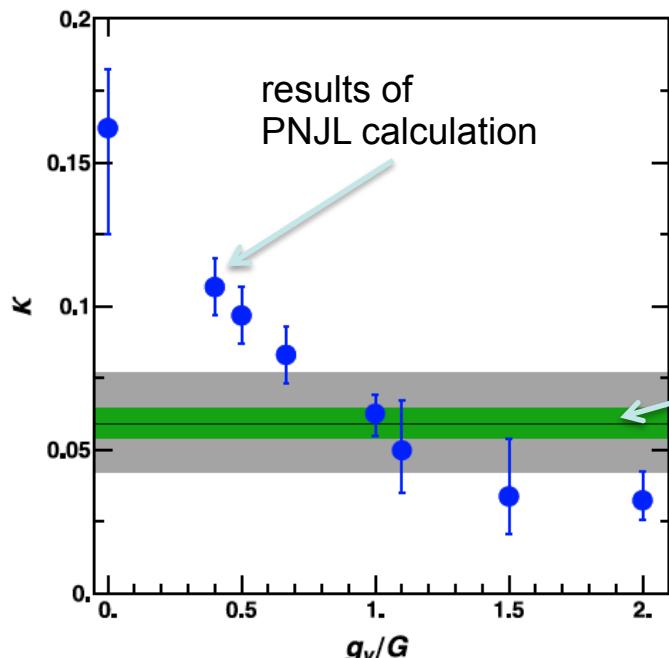
$$P(T, \mu) = P(T) + c_2(T) \mu^2 T^2 + \dots$$

small quark vector repulsion !!



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

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



Plot taken from
Bratovic et al, PLB 719, 131 (2013)

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

large quark vector repulsion?

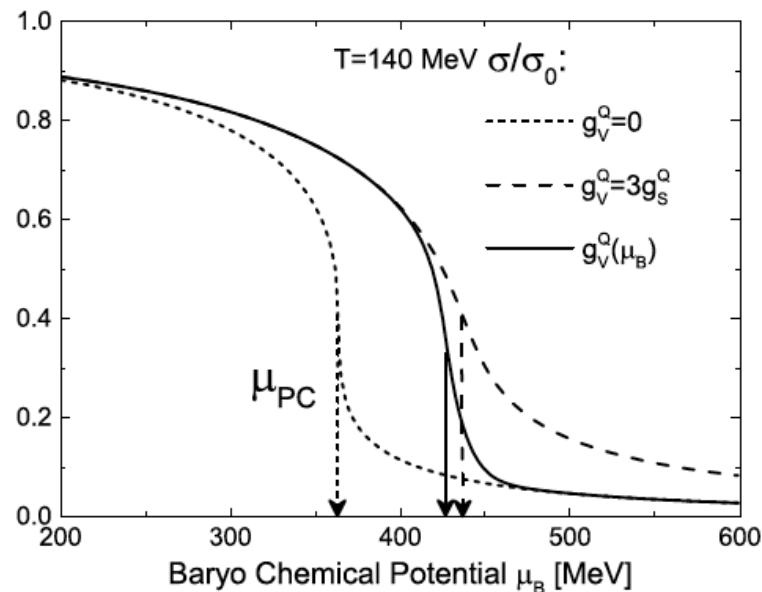
T_c rather difficult to determine

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

ratio of susceptibilities

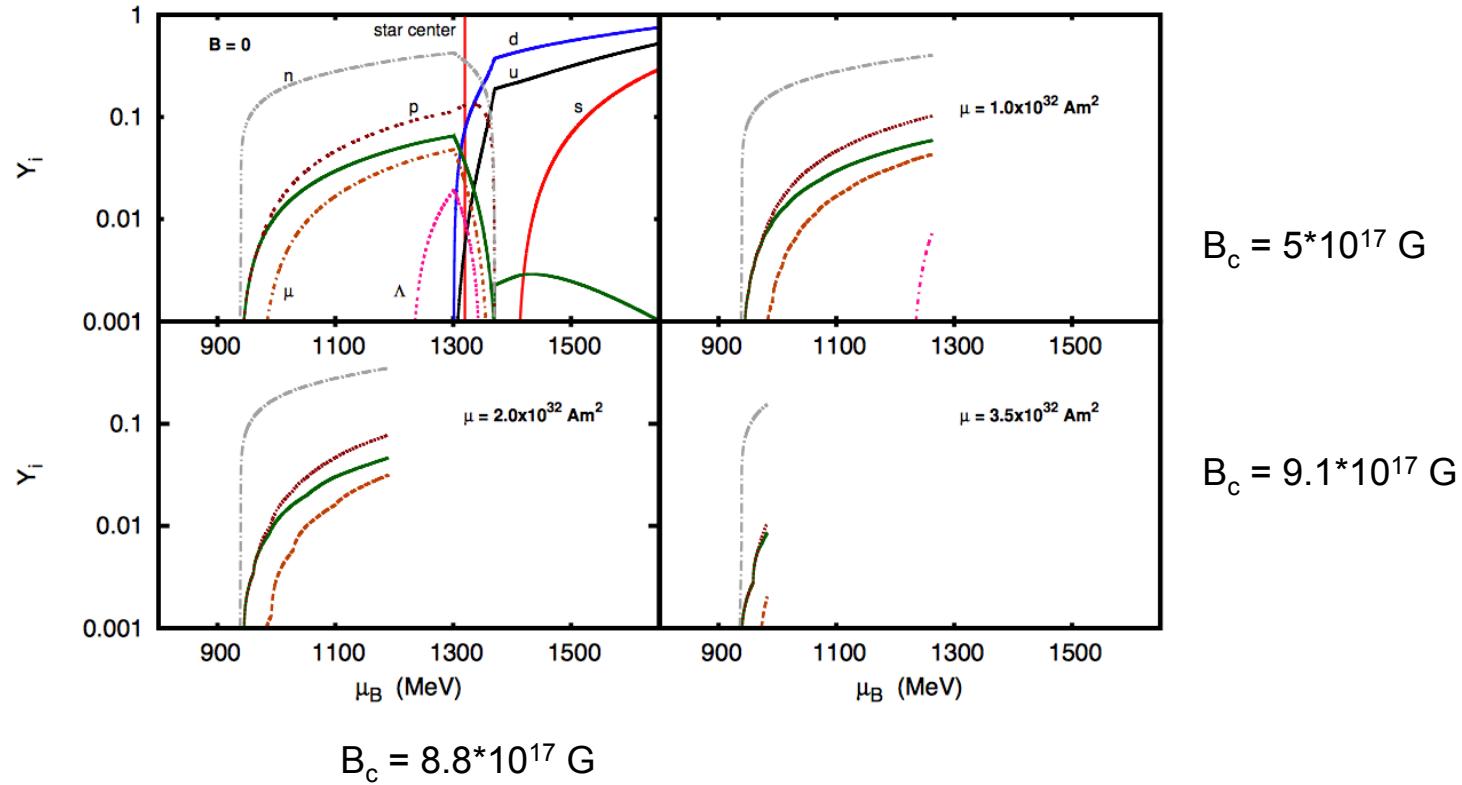
$$g_V^Q(\mu_B) = g_V^Q(\mu_B = 0) \cdot (1 + \exp(\mu_B - \mu_B^{PC})/\delta_\mu)^{-1}$$

turn on/off repulsion
or quarks and baryons



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

effect of strong magnetic fields on hybrid star



equation of state not strongly affected by B fields,
but the population is!

possible backbending/spin-up for slow rotation

Franzon, Dexheimer, SWS, MNRAS 2016
 Franzon, Gomes, SWS, MNRAS 2016

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 $B \sim 10^{20}$ 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

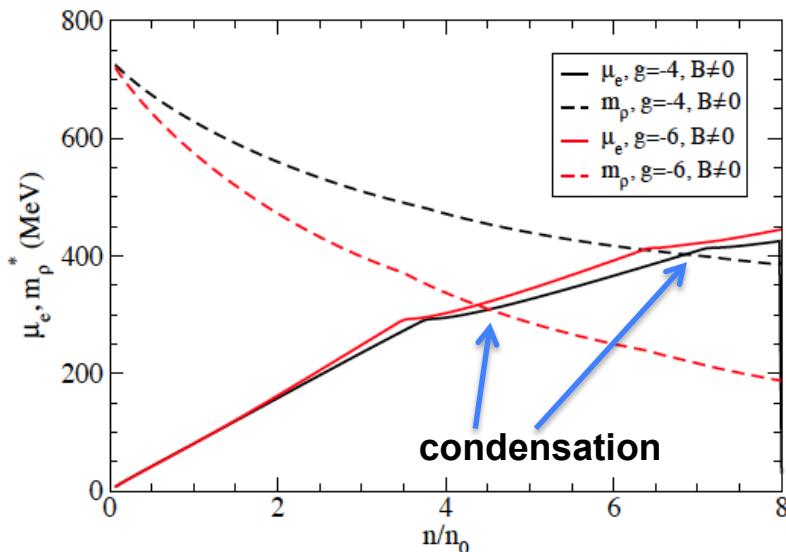
Advantage: high spin – strong interaction with magnetic field

Landau levels of the rho meson

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

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

charge chemical potential and effective rho mass as function of density



Use standard hadronic model

GM3 parameterization

B value: 7×10^{18} G

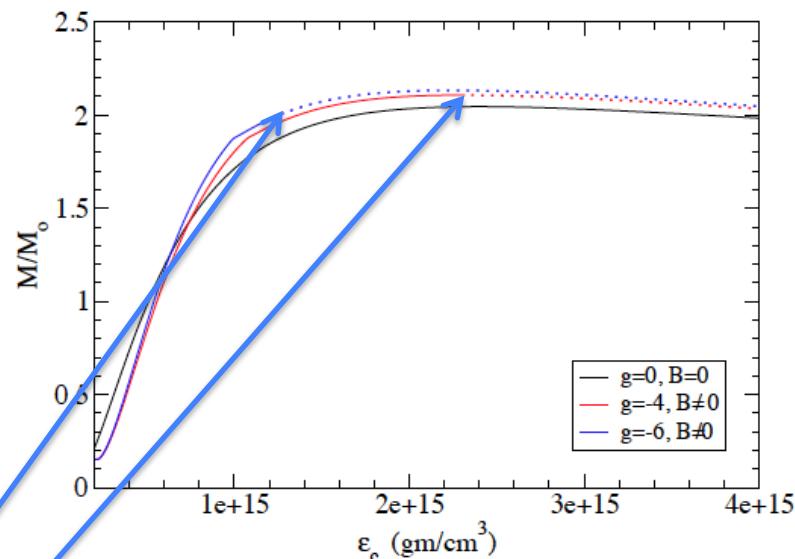
slight change of star masses
faster cooling

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, \dots

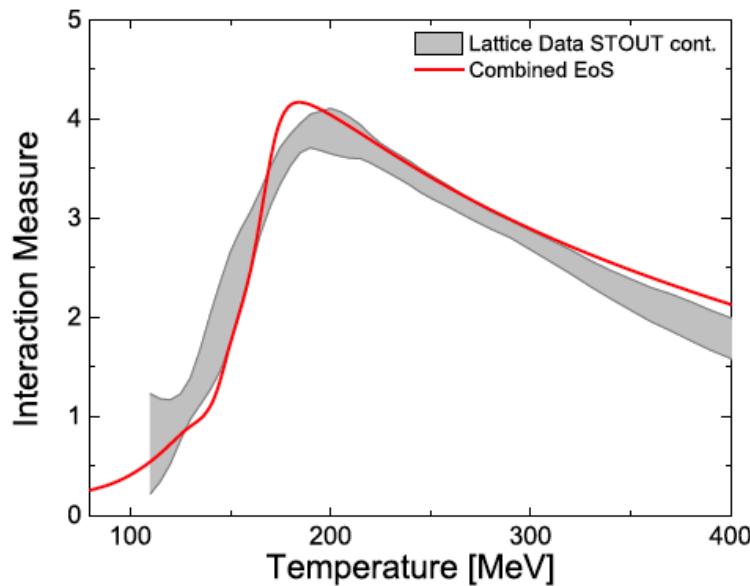


onset of condensation

Conclusions, Outlook

- coherent phenomenological model including reasonable asymptotic degrees of freedom
- 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)*
- *crust simulations*
- *couple hydro and kinetic equations for fields*

after fine-tuning parameters



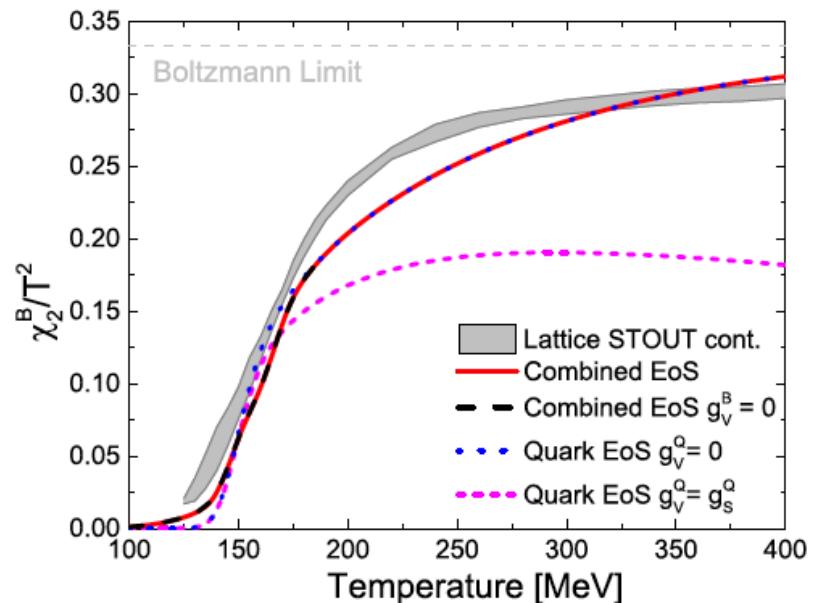
susceptibilities χ_n , c_n

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

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

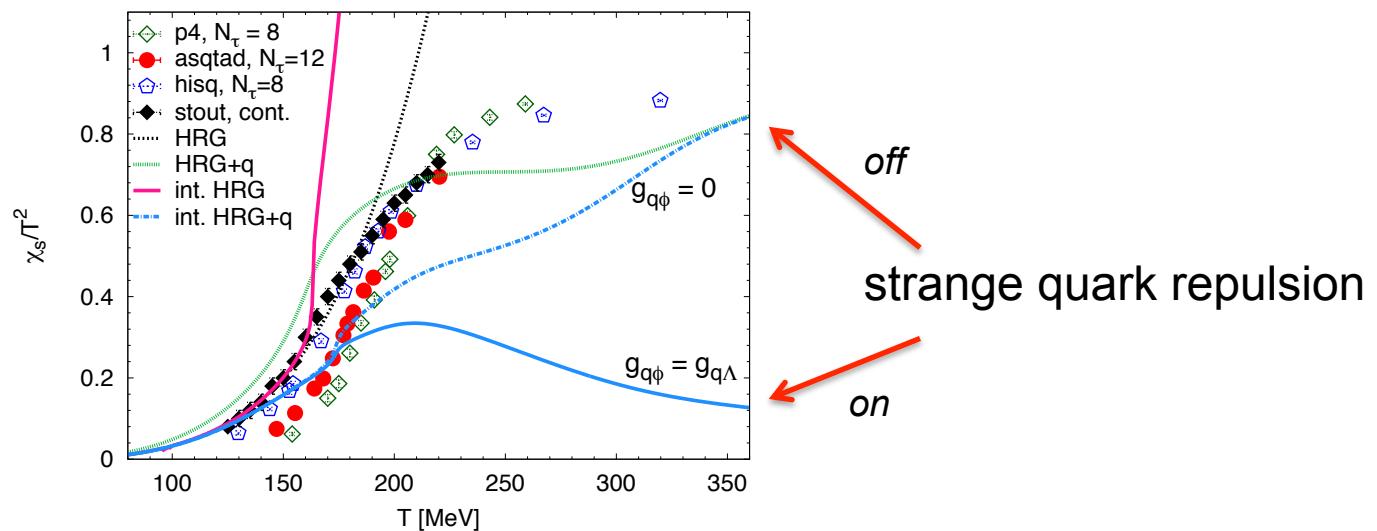
Lattice (STOUT) and model

χ_2 for different vector couplings



analogous behaviour of strange susceptibility

$$X_s = d^2(P) / (d \mu_s)^2 |_{\mu_B, \mu_S = 0}$$



calc. by Philip Rau