IWARA 2013, Rio de Janeiro

Exotic Matter in Compact Stars
Limits and Consequences

OUTLINE

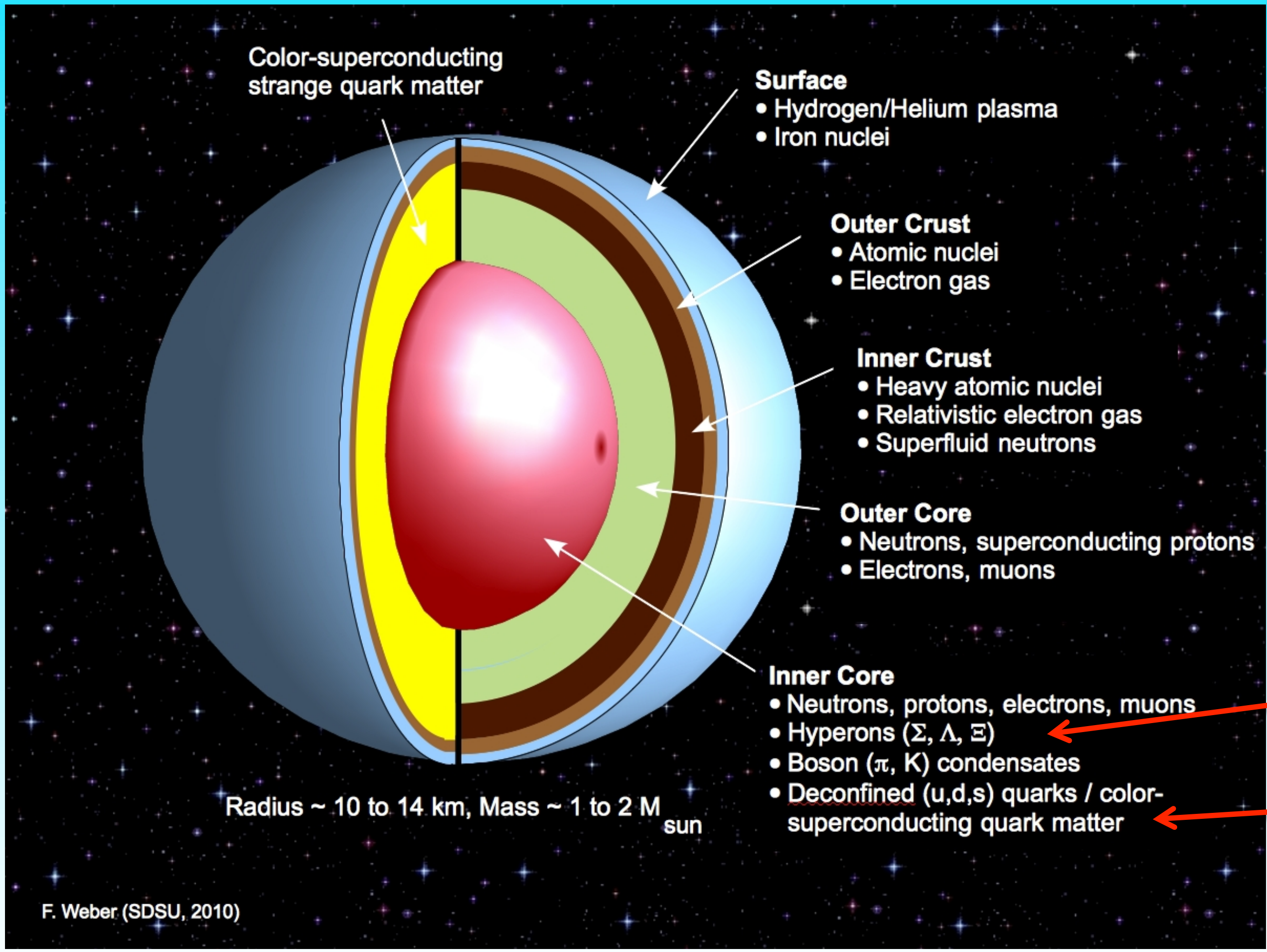
- observational constraints
- some remarks on nuclear structure
- hadrons and quarks
- susceptibilities
- adding magnetic fields
- to-do list

V. Dexheimer, B. Franzon, R. Mallick, R. Negreiros, T. Schürhoff, J. Steinheimer, 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

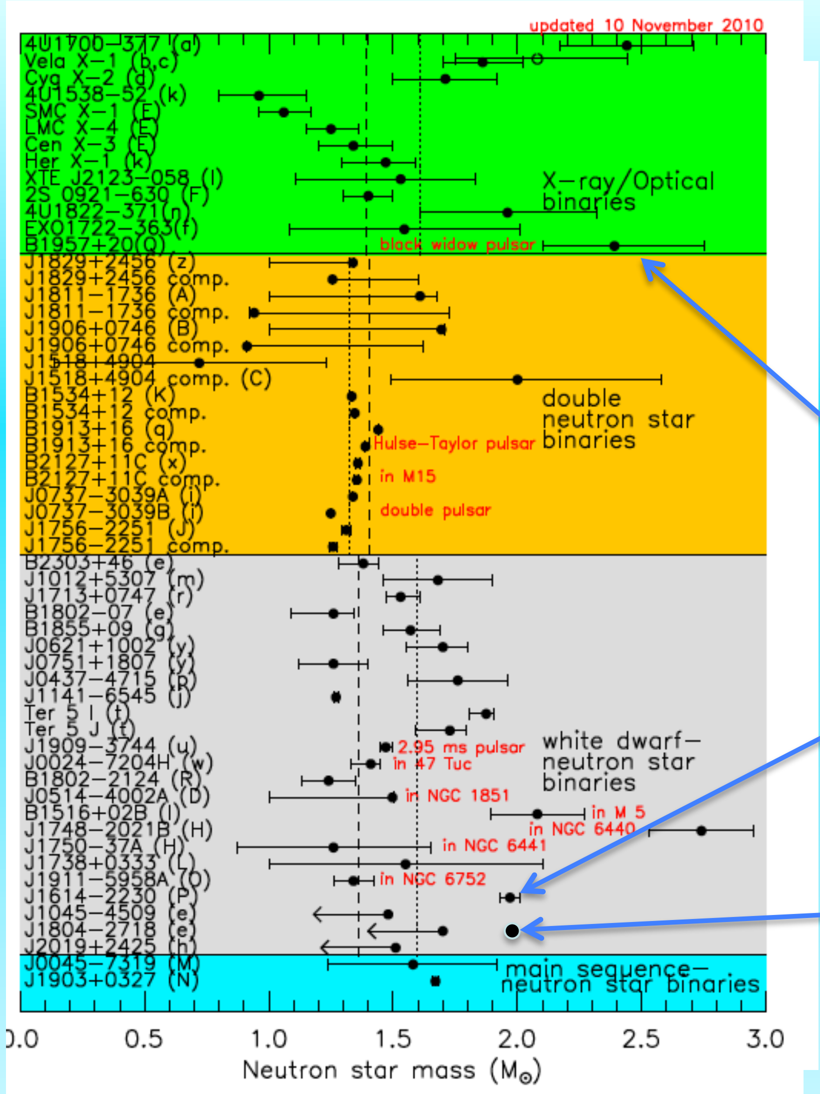
about 2000 known neutron stars



hyper star

hybrid star

Masses of Neutron Stars



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)

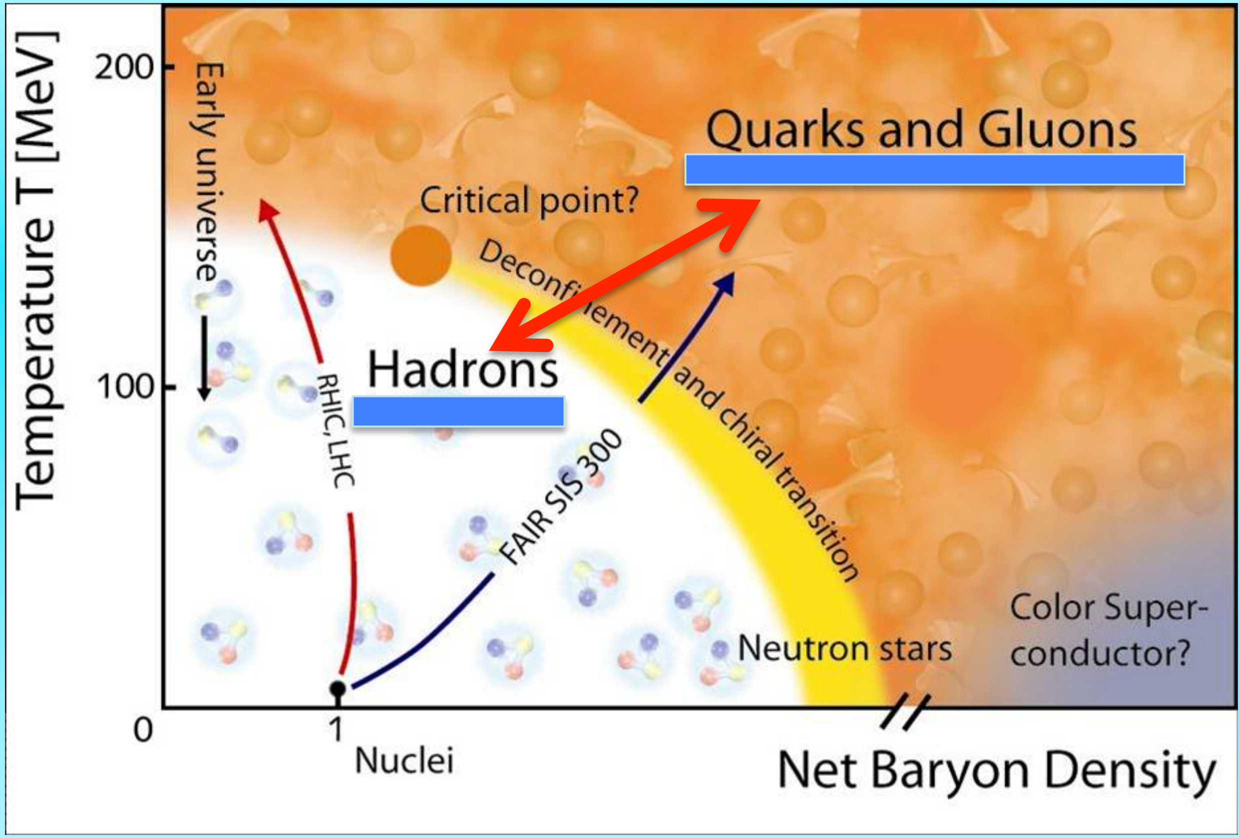
current benchmark for NS models
M = (1.97 +- .04) M_0
Demorest et al. Nature 467, 1081 (2010)

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

Lattimer, Prakash, astro-ph:1012.3208

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 based on non-linear realization of extended 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) $\langle\sigma\rangle = \sigma_0 \neq 0$ $\langle\zeta\rangle = \zeta_0 \neq 0$

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

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

fix scalar parameters to

baryon masses, decay constants, meson masses

New Fit - Nuclear Matter and Nuclei

binding energy E/A ~ -16.2 MeV saturation $(\rho_B)_0 \sim .16/fm^3$

compressibility **~ 235 MeV** asymmetry energy **~ 32.9 MeV**

slope L **~ 66.7 MeV**

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

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

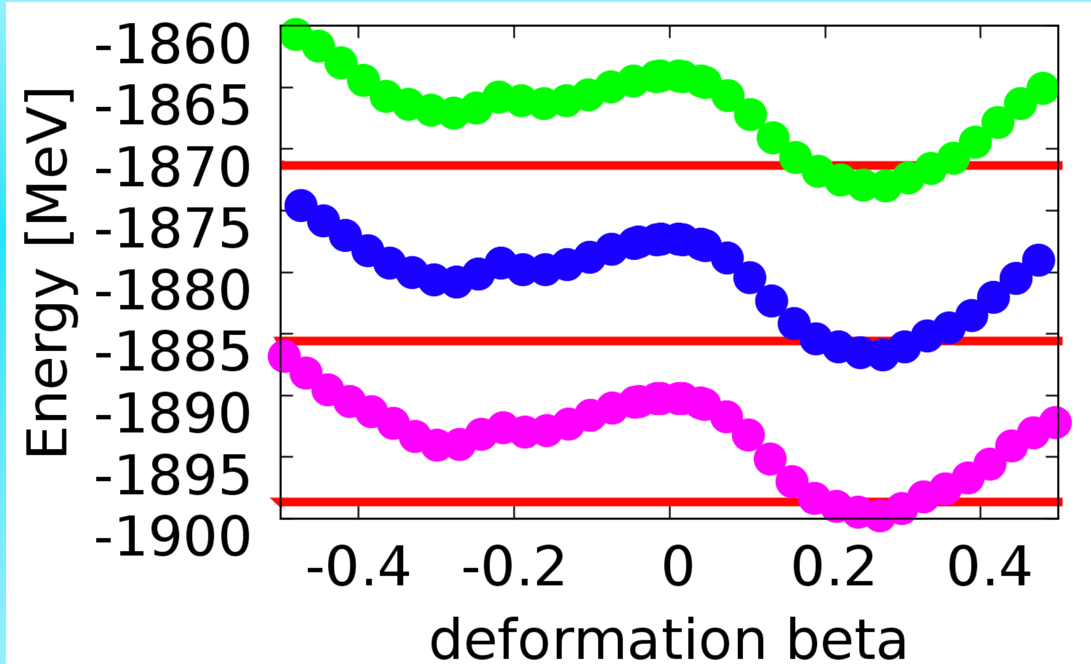
$\varepsilon\ (A > 100)$ ~ 0.12 % (NL3: 0.16 %)

relativistic nuclear structure models

\+ correct binding energies of hypernuclei

new fit for large star masses
by T. Schürhoff $\varepsilon \sim 0.28$, $\kappa < 300$ MeV, $M \sim 2\ M_\odot$

stellar crust calculations in progress deformation properties work out well



^{252}No

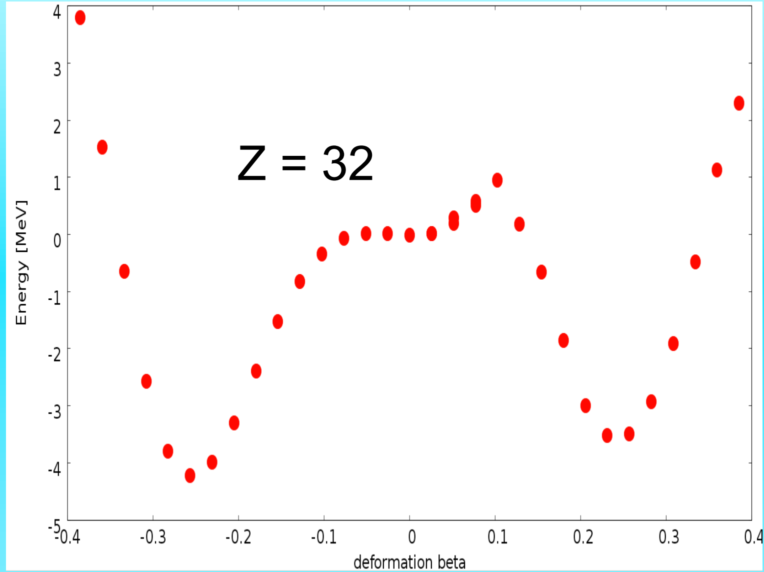
^{254}No

^{256}No

Nobelium (Z=102) isotopes experiment - $\beta_2 \sim 0.32 \pm 0.02$ (A=254)

0.31 ± 0.02 (A=252)

medium-heavy nucleus ^{68}Se

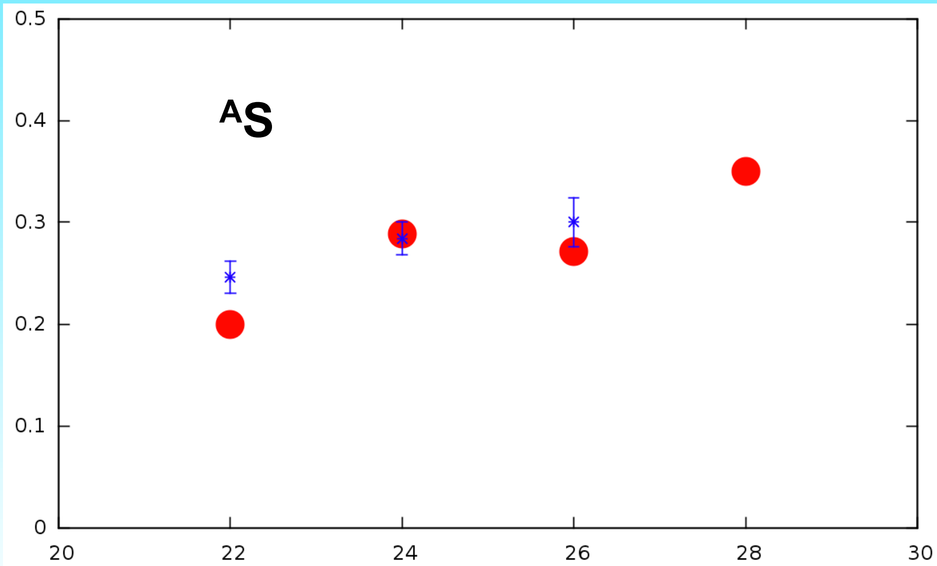


experiment - oblate groundstate
around $\beta_2 \sim -0.3$
+ strongly prolate excited band

Sulfur isotopes

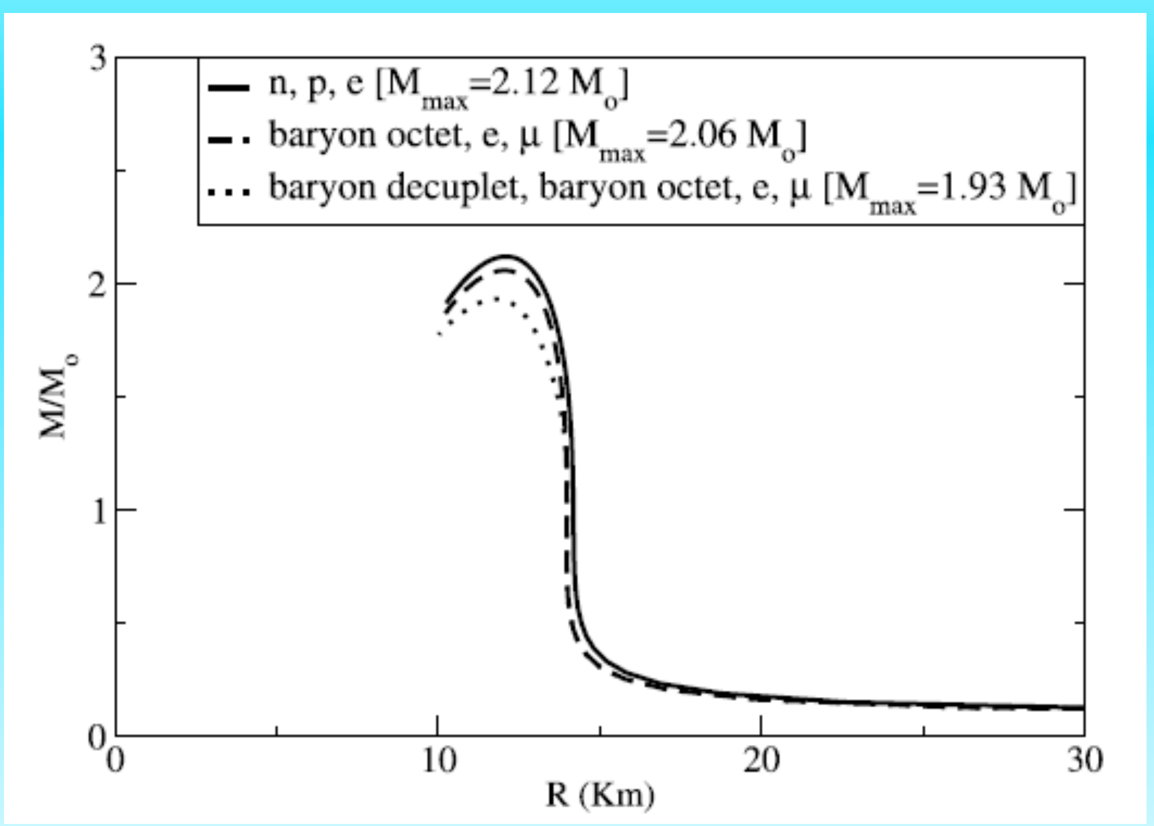
measured deformations
Compared to calculation

β_2



neutron number

Neutron star masses including different sets of particles



Tolman-Oppenheimer-Volkov equations, static spherical star

changing masses with degrees of freedom

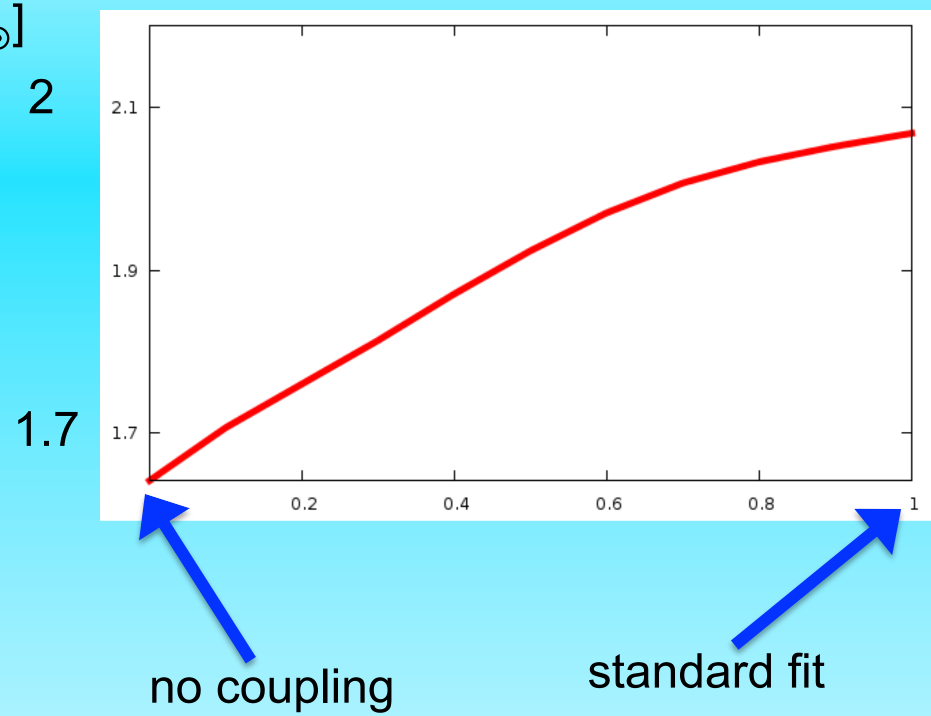
large star masses even with spin 3/2 resonances

Dexheimer, SWS ApJ 683, 943 (2008)

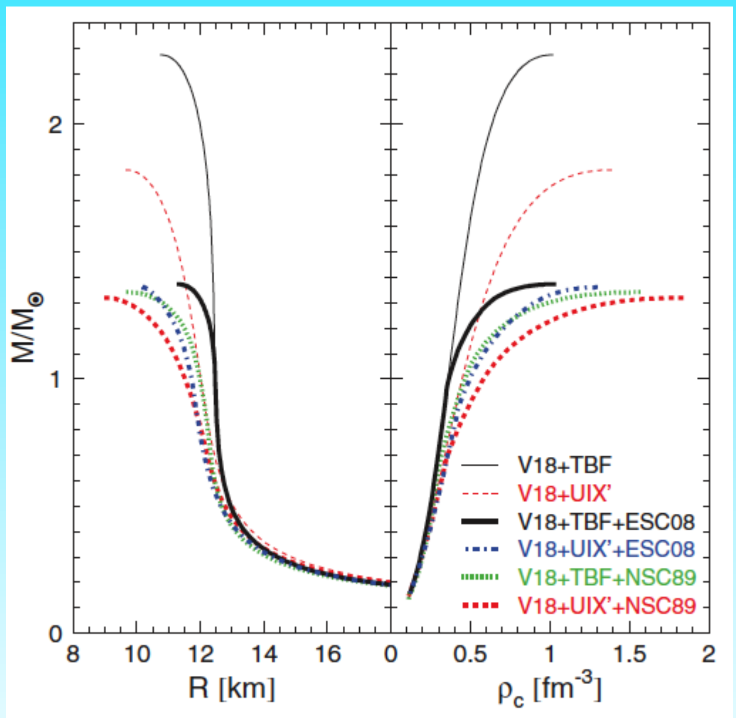
Impact of Φ field

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

M_{max} [$M_\odot$]



Nijmegen, no YY interaction



$f_s = n_s / n_B$

Schulze, Rijken, PRC 84, 035801 (2011)

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!

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

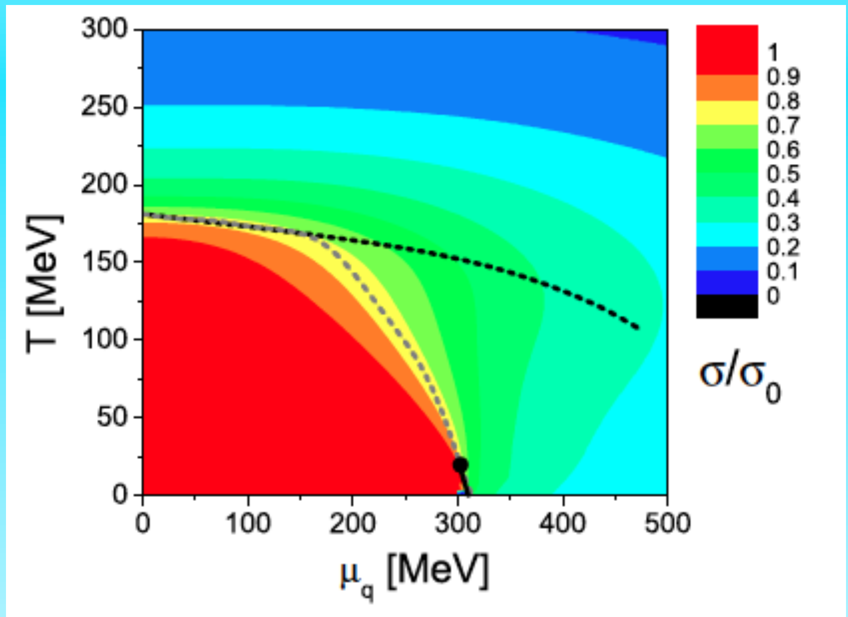
$\tilde{\mu}_i = \mu_i - v_i P$

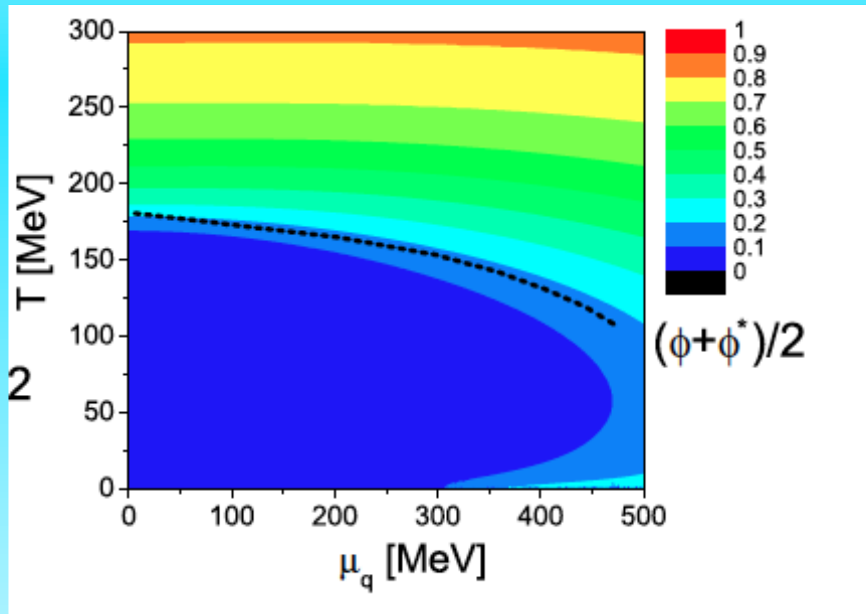
$e = \tilde{e} / (1 + \Sigma\, v_i \tilde{\rho}_i)$

equation of state stays causal!

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

Order parameters for chiral symmetry and confinement in μ and T





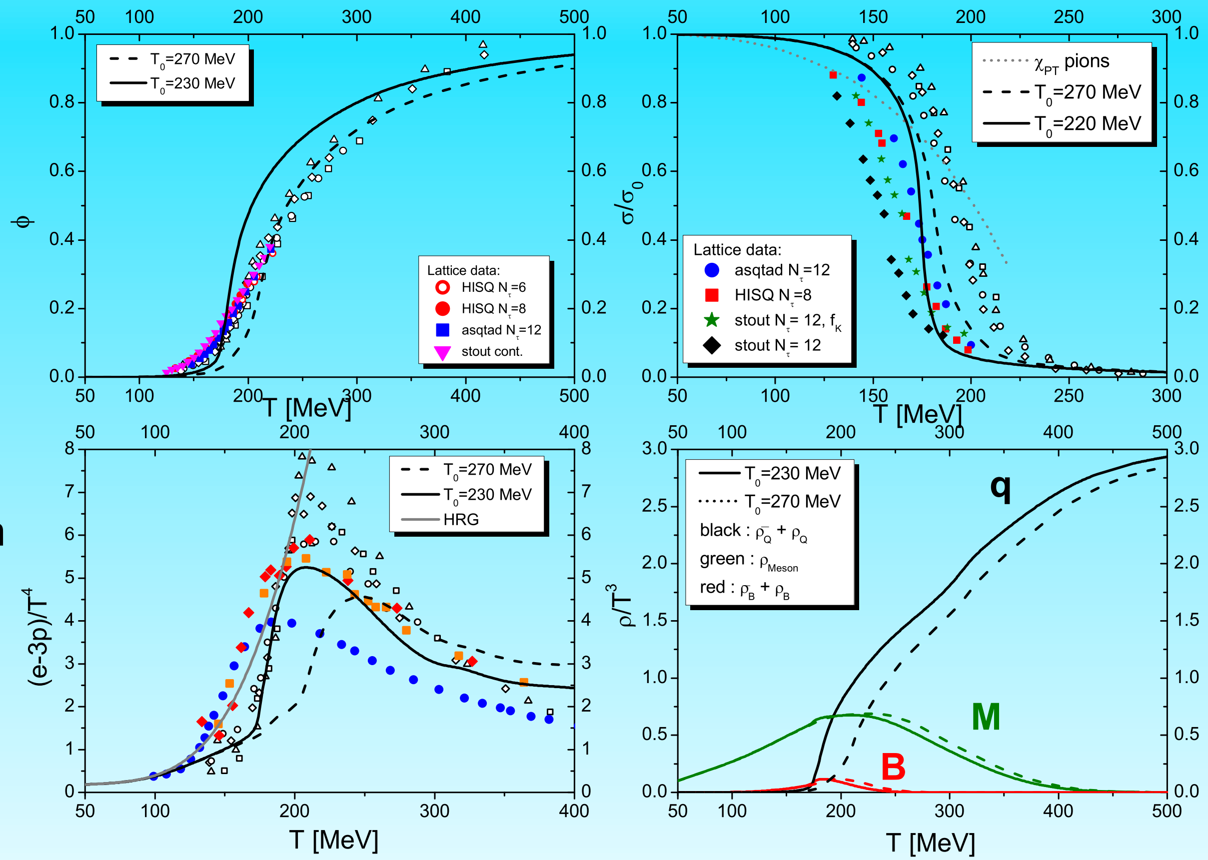
except for liquid-gas no first-order transition

results for hot matter at vanishing chemical potential

points are various lattice results

Polyakov loop

scalar condensate

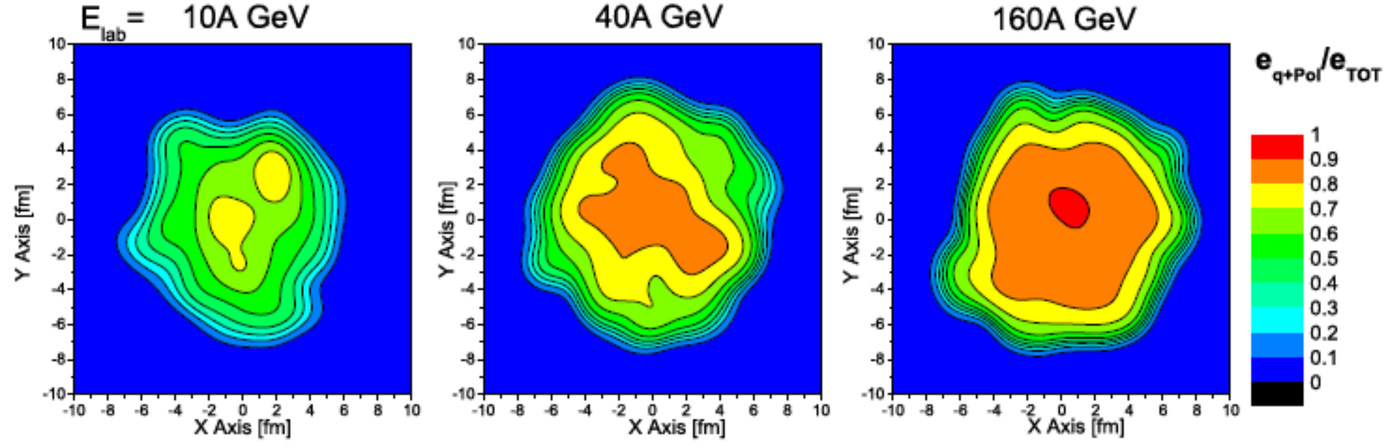


Interaction measure

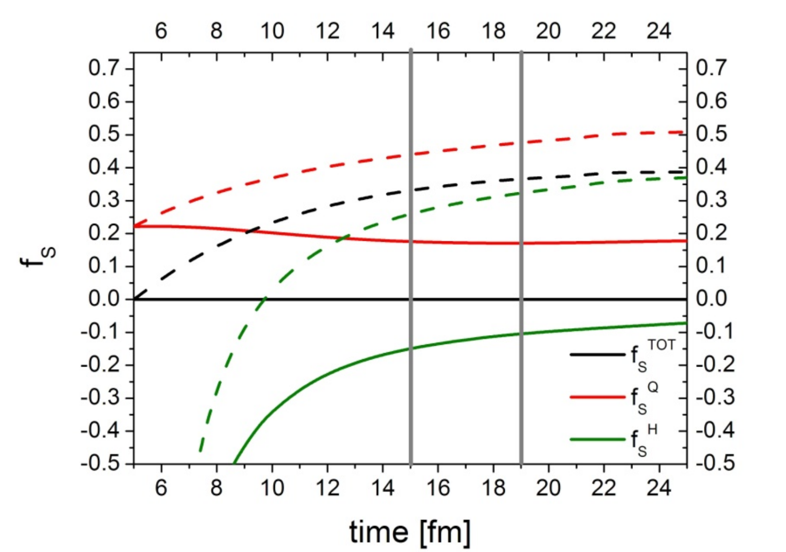
densities

part of UrQMD hybrid transport code

Initial transverse distributions of the deconfined fraction for central Au+Au collisions at different beam energies.



simple time evolution of f_s including π, K evaporation (E/A = 40 GeV)



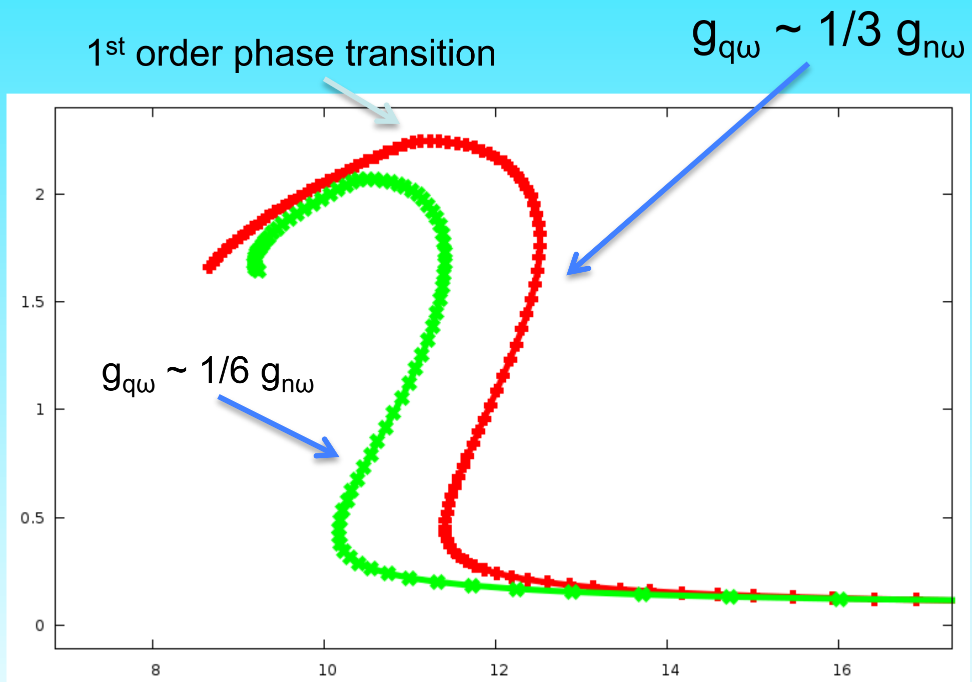
$$f_s = n_s / n_B$$

C. Greiner et al., PRD38, 2797 (1988)

Mass-radius relation and structure

Hybrid star within the QH model and realistic ground state + nuclei

different quark-vector couplings



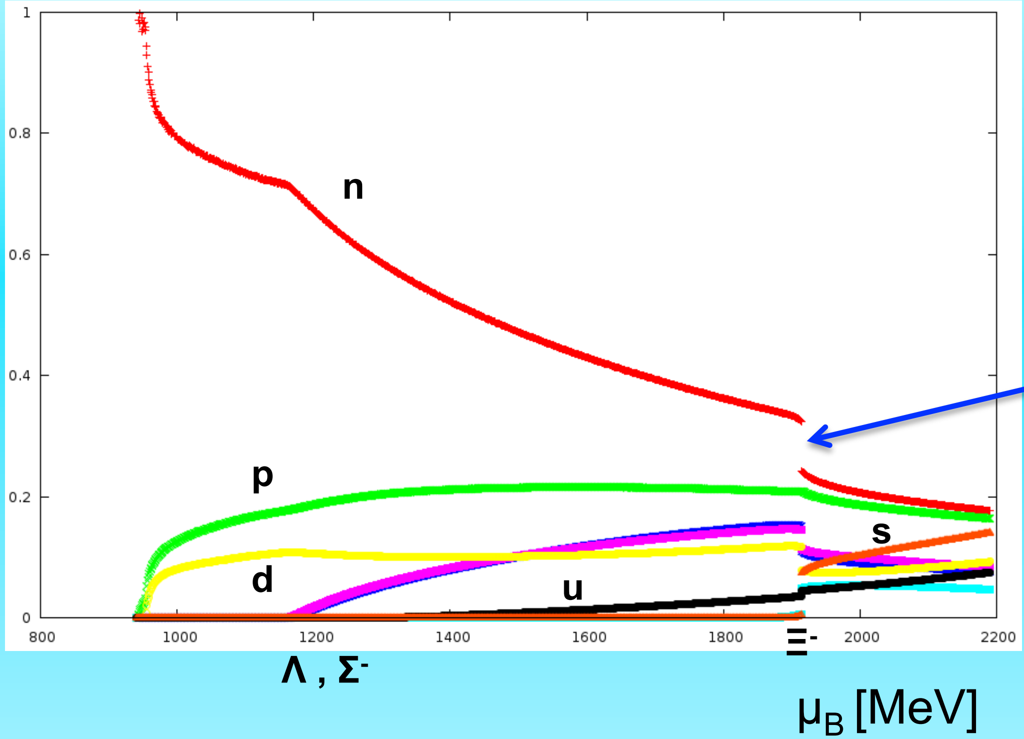
$M_{max} = 2.23\ M_\odot$

$R = 11.2$ km

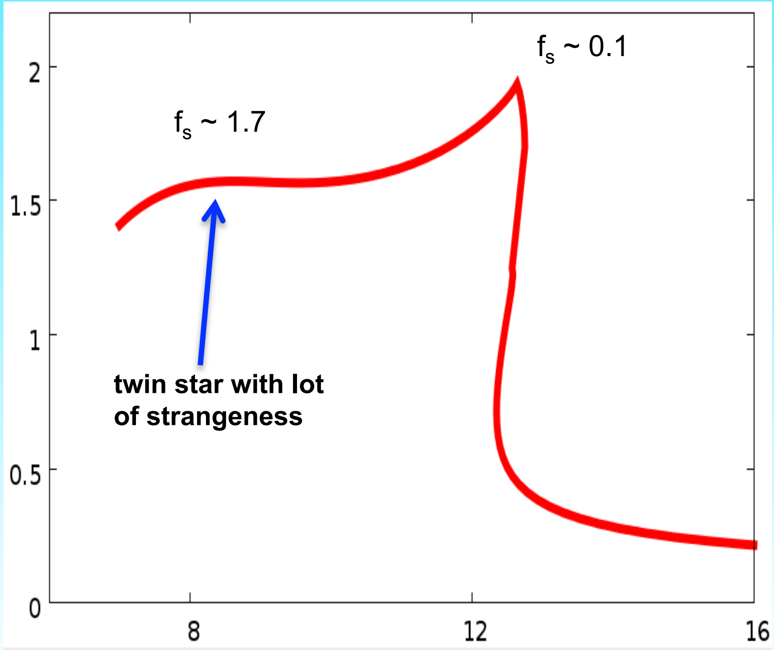
$\rho > 3\ \rho_o$:

$c_s^2 \sim -0.1 + \rho\ fm^3$

normalized particle numbers in hybrid star



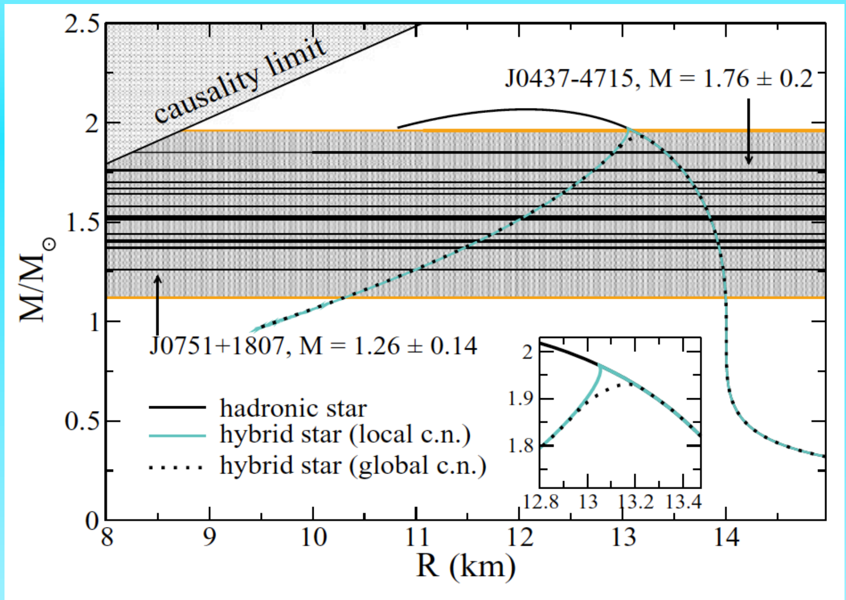
1st order phase transition due to strangeness



play around with parameters
second family of compact stars

Hybrid Stars

M-R diagram in QH model



Maxwell / Gibbs construction for
local / global charge neutrality

Large mixed region

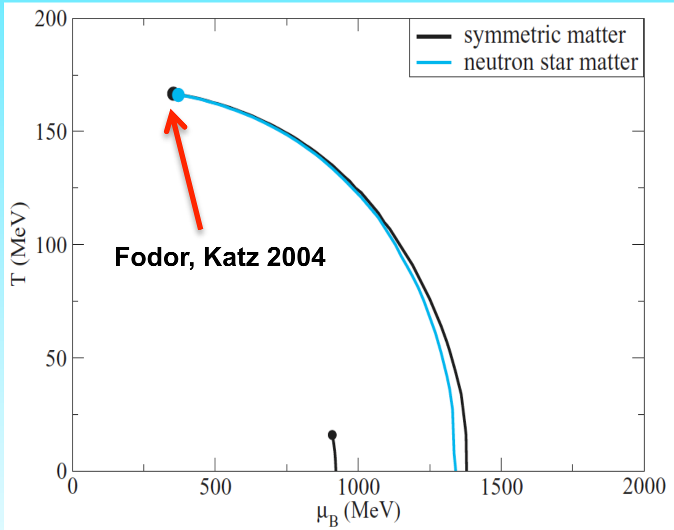
baryonic star with a 2km hybrid core

potential fitted to lattice data
generate critical end point

$U = -\frac{1}{2} a(T, \mu) \Phi\Phi^* + \ldots$

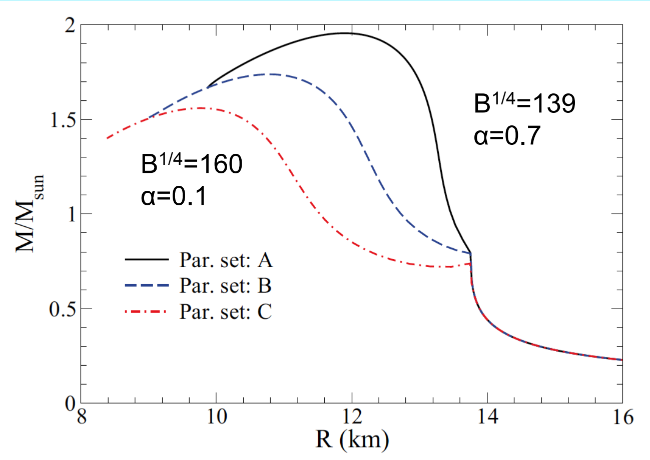
$a(T, \mu) = a_0 T^4 + a_1 \mu^4 + a_2 \mu^2 T^2$

(also Schäfer et al, PRD 76 074023)



Dexheimer, SWS, PRC 81 045201 (2010)
Negreiros, Dexheimer, SWS, PRC82 035803 (2010)

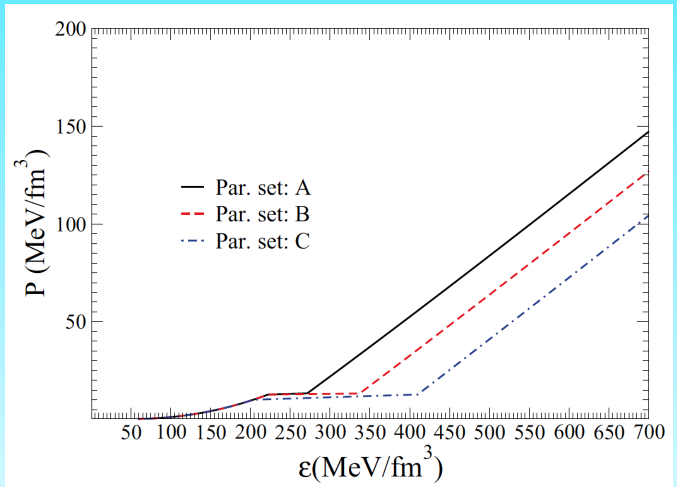
Hybrid Stars, Quark Interactions



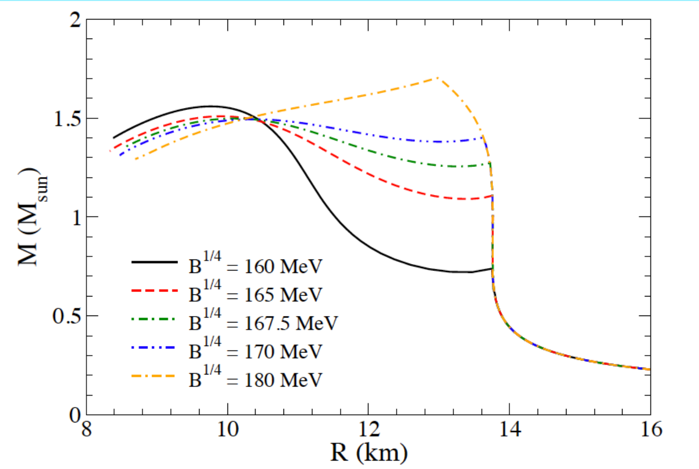
ingredients –
Standard baryonic EOS (G300)
plus MIT bag model + α_s corrections

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

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



no α_s



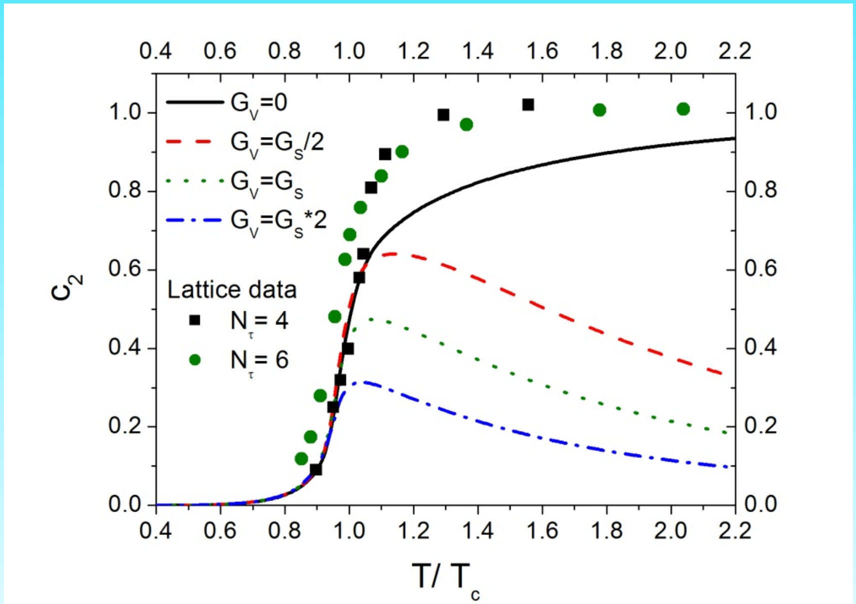
Negreiros, Dexheimer, SWS, PRC 035805 (2012)

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

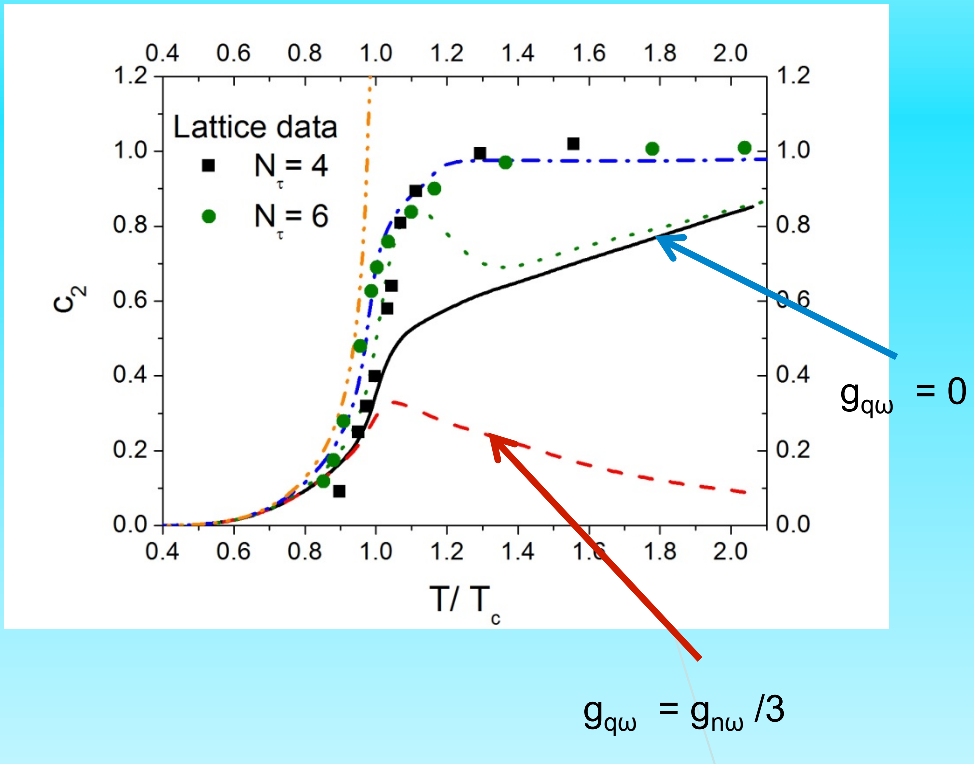
$$P(T,\mu) = P(T) + c_2(T)\,\mu^2\,T^2 + \dots$$

small quark vector repulsion !!

PNJL



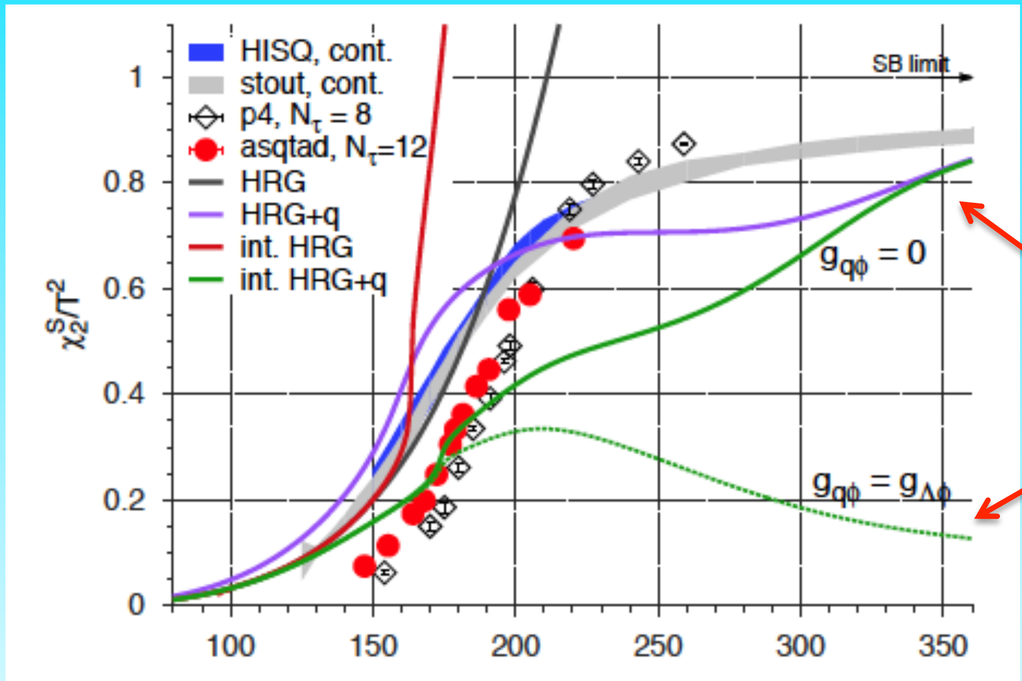
QH



Steinheimer, SWS, PLB 696, 257 (2011)

analogous behaviour of strange susceptibilitiy

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



off

strange quark repulsion

on

Rau, Steinheimer, Stöcker, SWS, arxiv:1308.4319

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:

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

anomalous magnetic moment

simple parameterization of the field

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

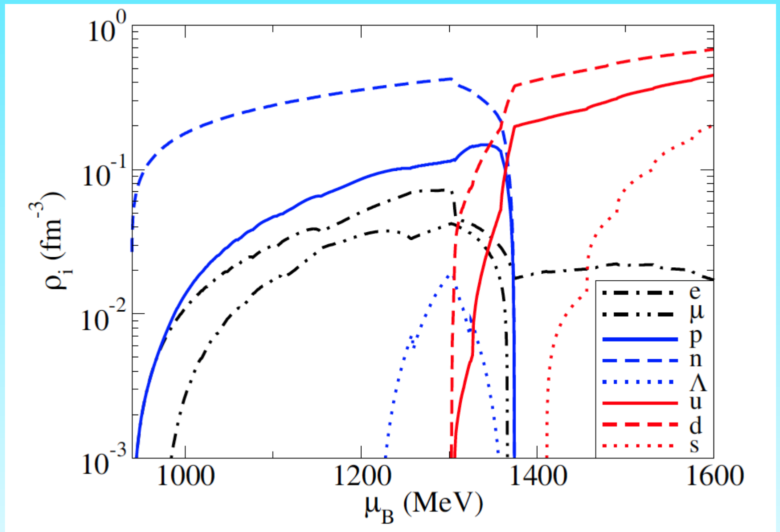
Dexheimer, Negreiros, SWS EPJA 2012

QH model with PT

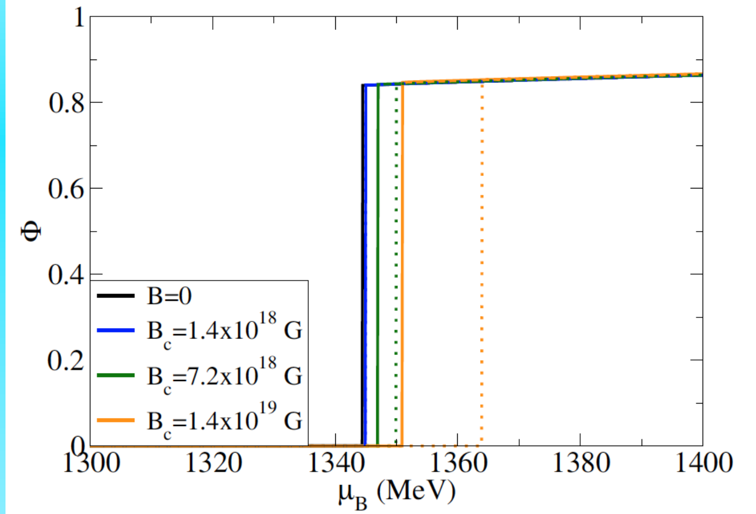
$e B_{cr} = m_e^2$, $B_{cr} = 4.4\ 10^{13}$ G

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

particle densities $B_c = 7.2{\times}10^{18}$ G



Polyakov loop and 1st order transition



PT gets shifted somewhat to higher μ

Dexheimer,Negreiros,SWS EPJA 2012

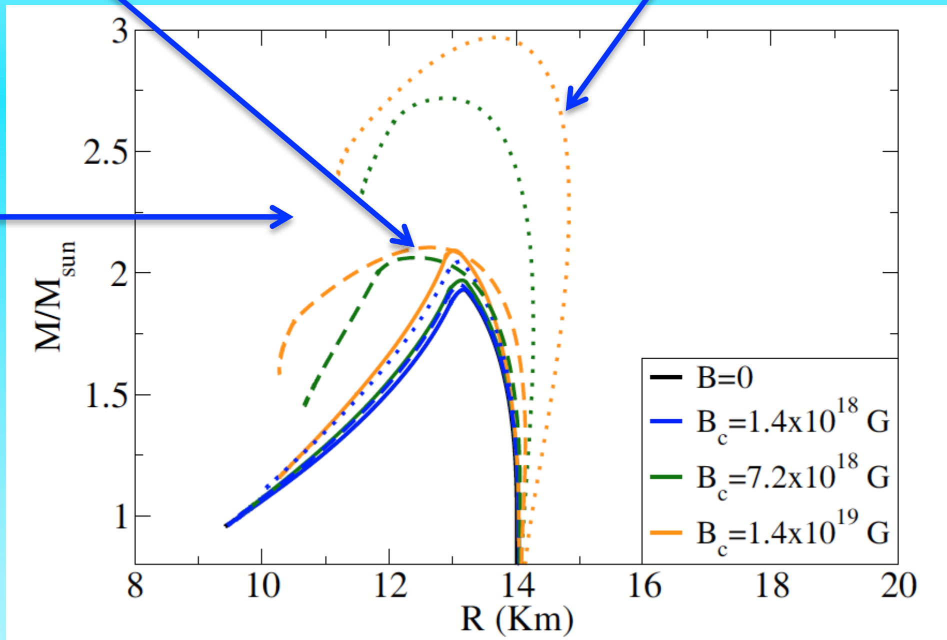
Impact on M(R) diagram for neutron/hybrid star

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

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

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

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

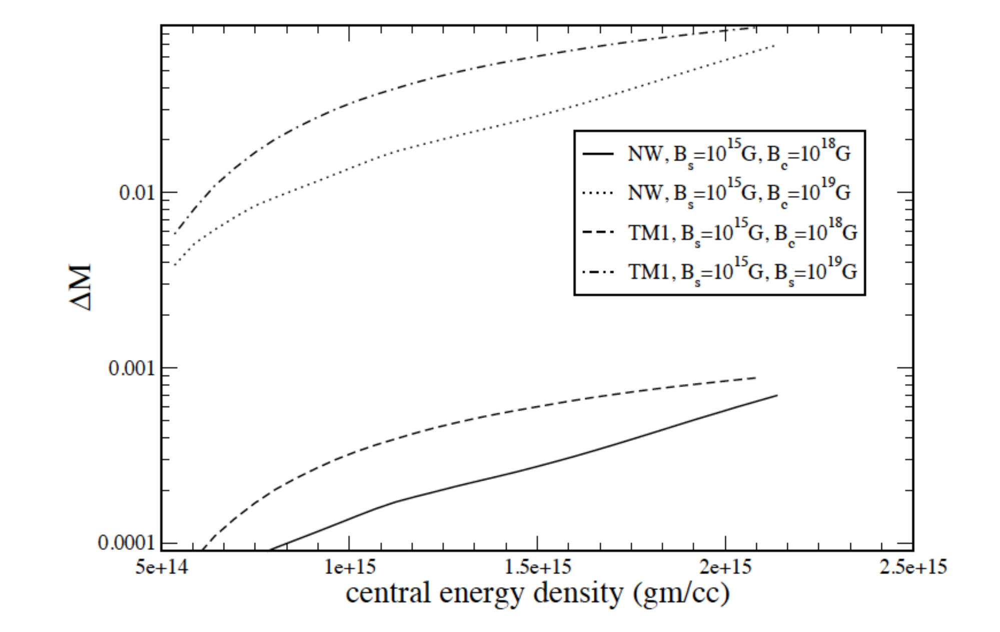
expand metric into multipoles

analogous to Hartle/rotation

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

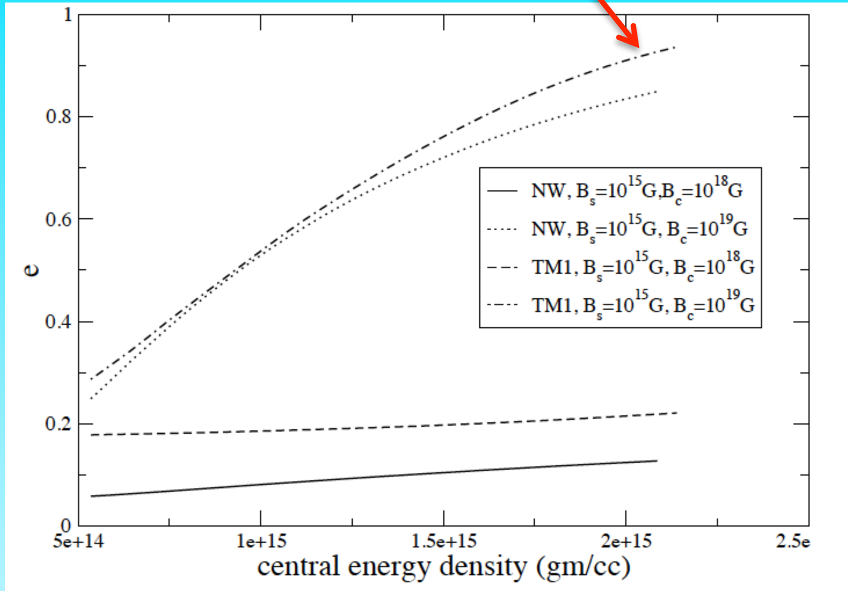
Hartle, APJ, 1967
Konno et al A&A, 1999

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



NW , TM1 hard / soft equation of state

Corrections to pressure ~ original value



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

Mallick, SWS arxiv:1307.5184

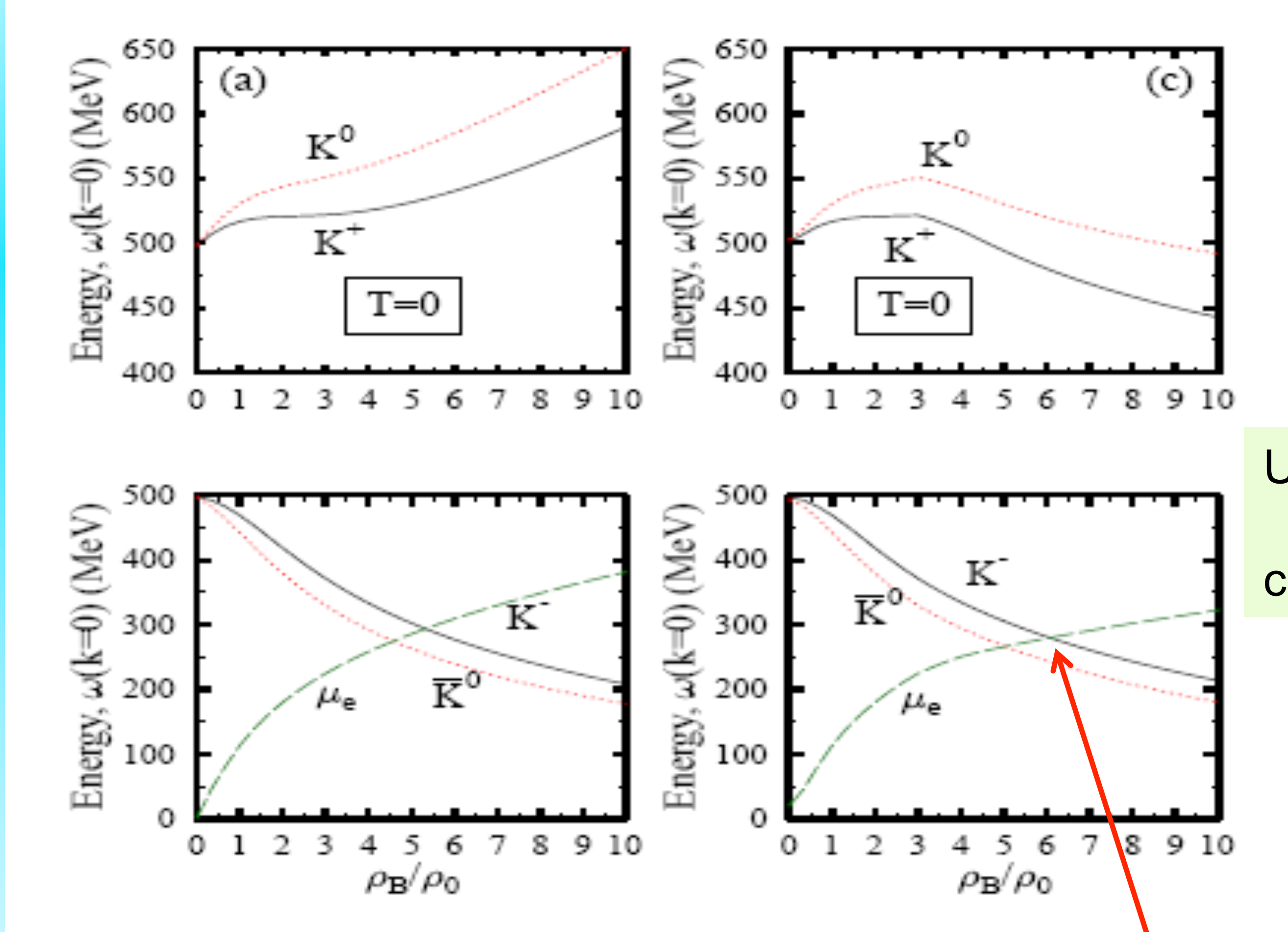
Conclusions, Outlook

- heavy hyper stars possible - not too hyper, though
- formulation of realistic quark-hadron model possible
- 2 solar mass hybrid star - again not very strange
- serious conflicts with lattice QCD
- simple treatment of deformation for high magnetic fields

- *comprehensive equation of state for a wide range of densities/ temperatures (supernovae, mergers)*

Many thanks to the organizers!

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



nucleons

nucleons + hyperons

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

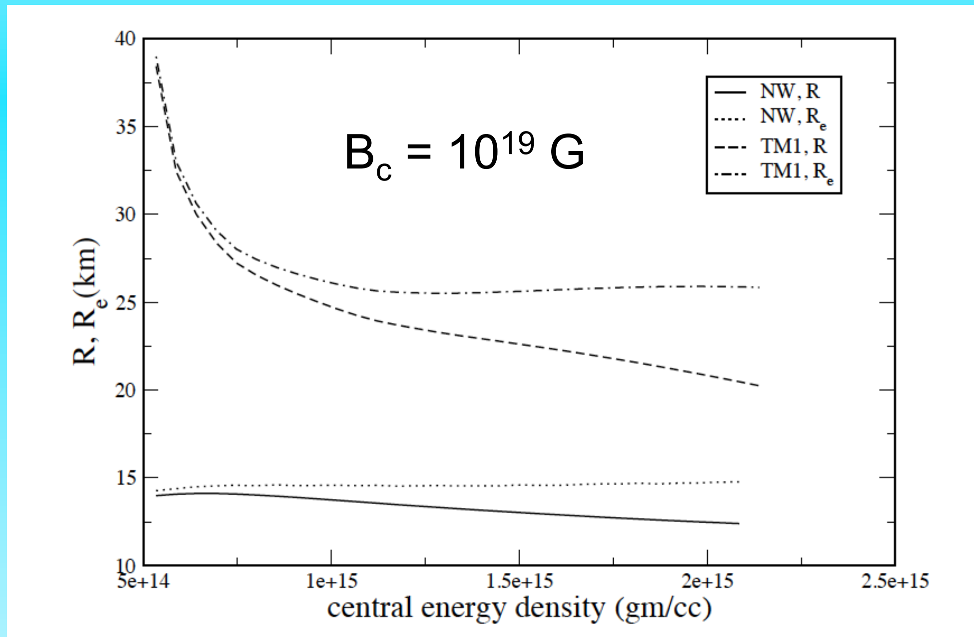
correct a_{KN} values

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

Hyperons shift ρ_c to higher values

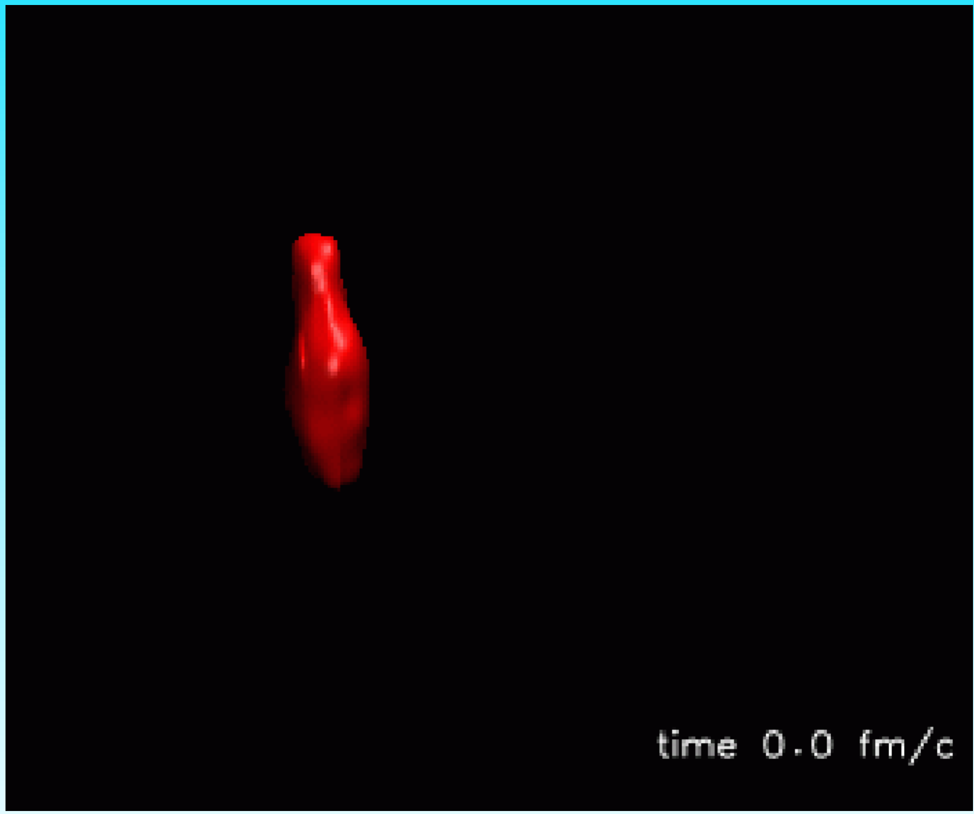
Mishra, Kumar, Sanyal, SWS, EPJA 41, 205

polar and equatorial radii



UrQMD/Hydro hybrid simulation of a Pb-Pb collision at 40 GeV/A

EOS part of the package



red regions show the areas dominated by quarks

Extension of the parity model to SU(3)

Baryon SU(3) multiplet + parity doublets

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

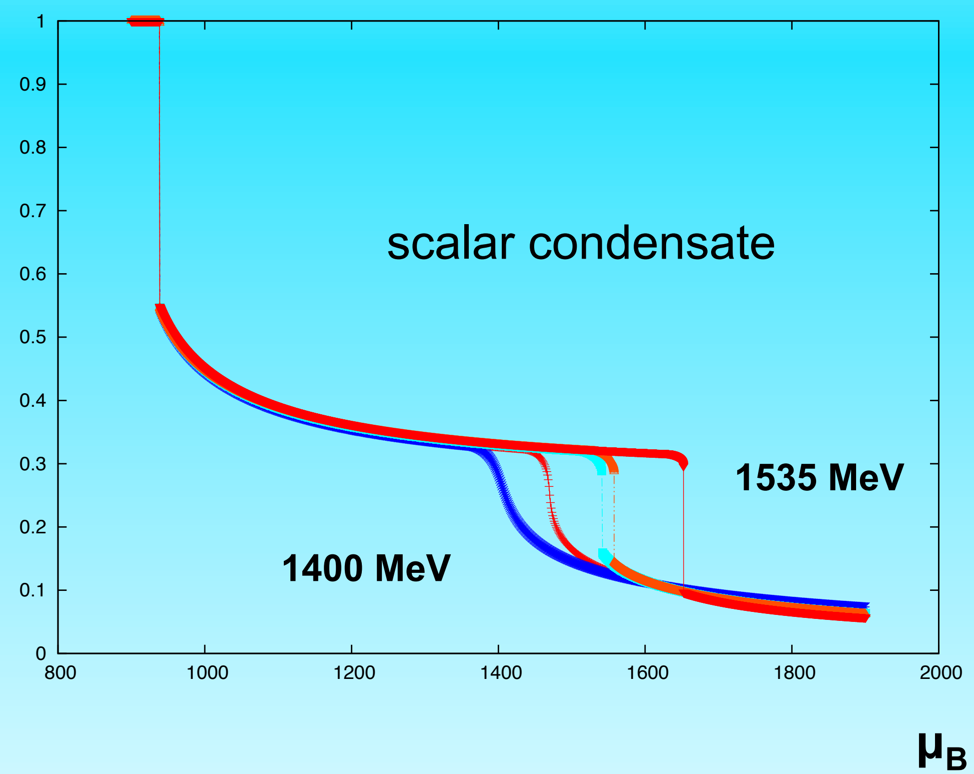
single particle energies $$E_{\pm} = \sqrt{(g_1\sigma + g_2\varsigma)^2 + m_0^2} \pm (g'_1\sigma + g'_2\varsigma)$$

simplify investigation – same mass shift for whole octet

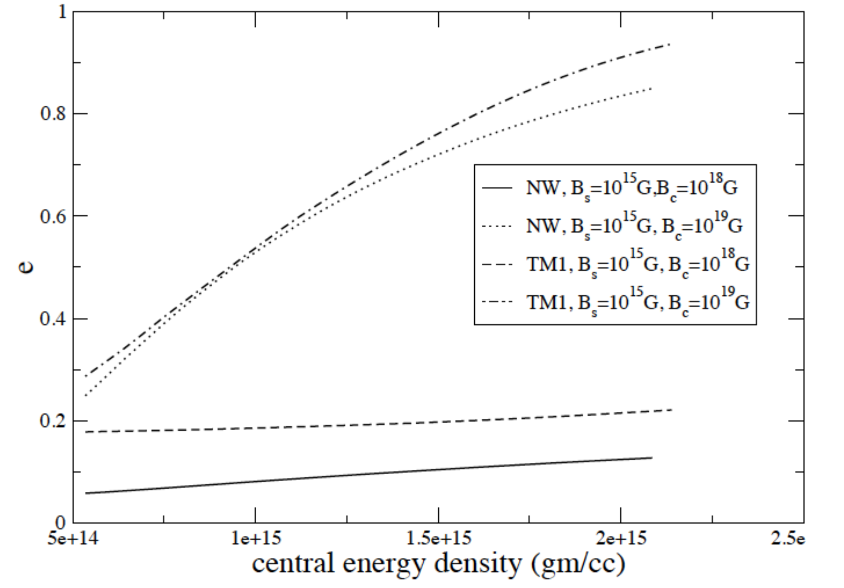
Candidates – Λ(1670), Σ(1750), Ξ (?) overall unclear

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

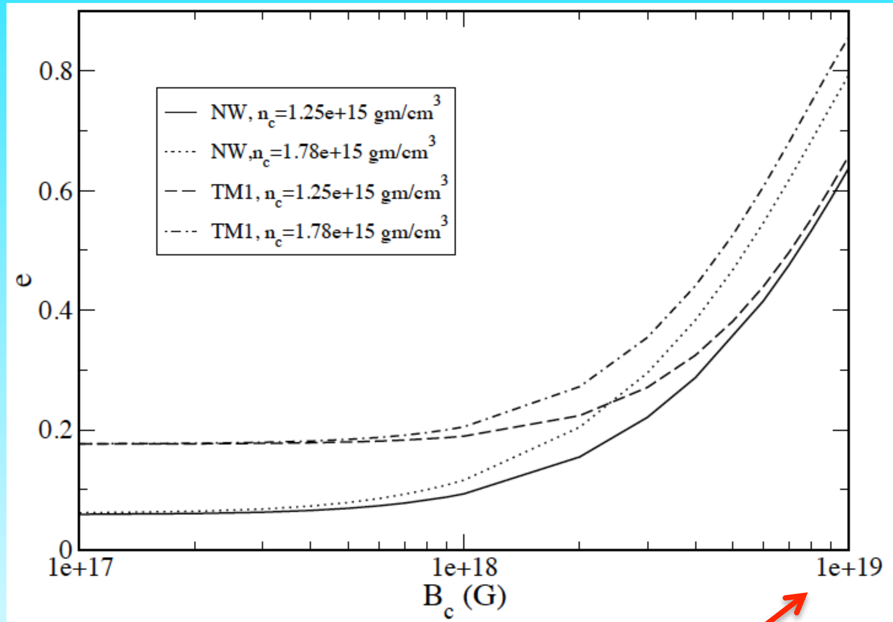
first study - Nemoto et al. PRD 57, 4124 (1998) scalar condensate for different masses m_{N^*}



First order transition for masses ≥ 1470 MeV, below crossover eccentricity = $(1 - R_p^2 / R_e^2)^{1/2}$



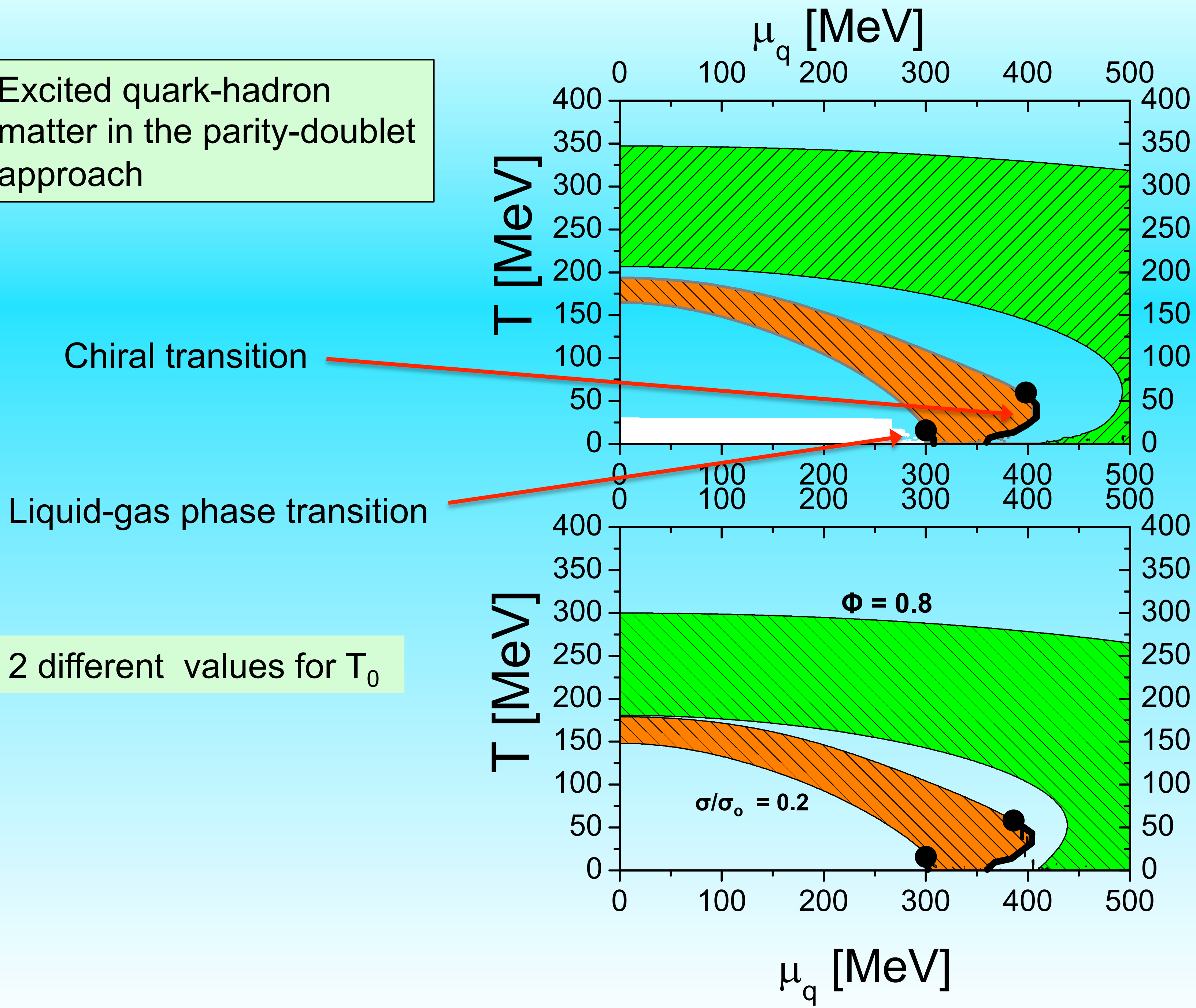
fixed central density,
varying the magnetic field



Mallick, SWS arxiv:1307.5184

Corrections to pressure ~ original value

Excited quark-hadron matter in the parity-doublet approach



2 different values for T_0