ICNFP 2017, Kolymbari

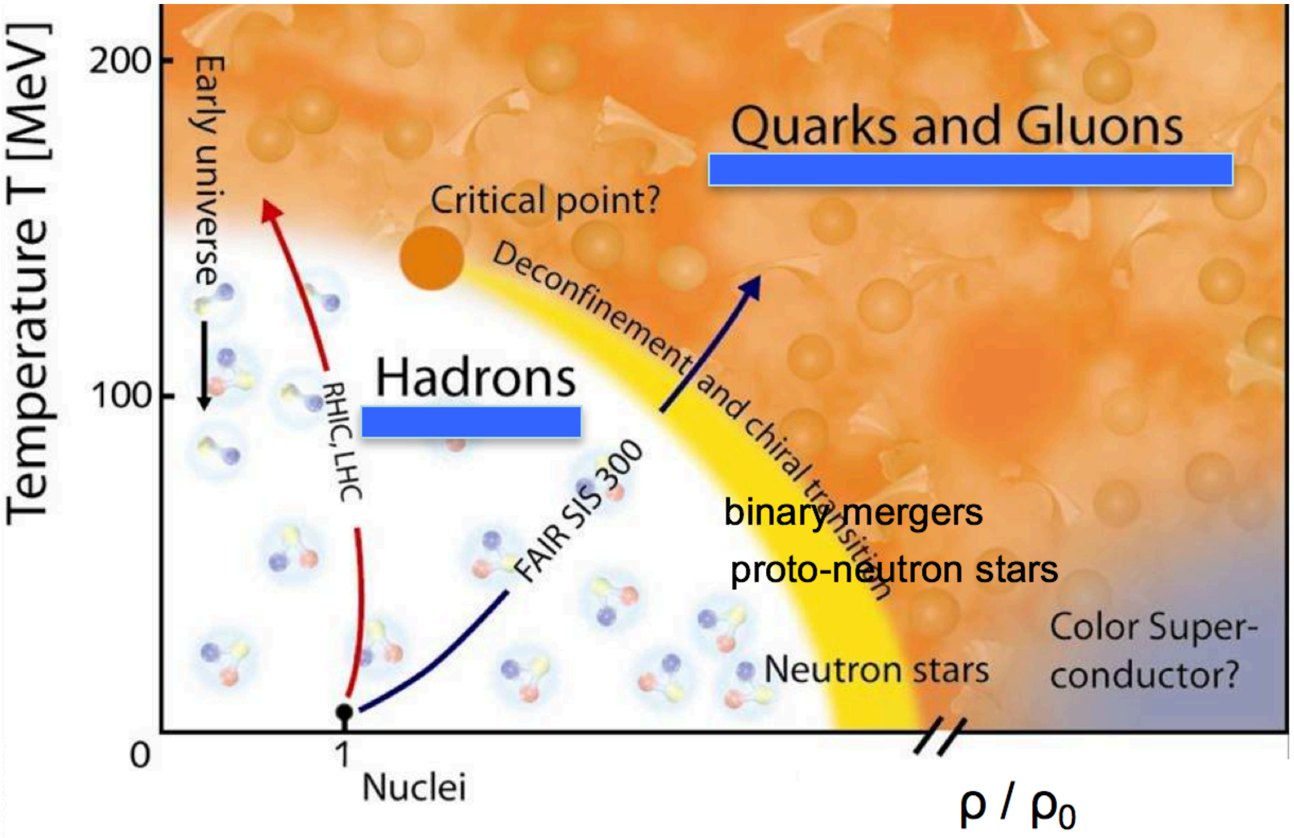
Exotic Matter in Neutron Stars

OUTLINE

- basics of neutron stars
- hyperons in the core
- quark matter in the star
- magnetic fields
- meson condensation

V. Dexheimer, R. Mallick, R. Nandi, R. Negreiros,
B. Franzon, R. Gomes, A. Mukherjee,, J. Steinheimer, SWS
FIAS ,Kent State, Rio de Janeiro, Porto Alegre, Bhopal , Mumbai

the usual phase diagram (sketch) of strong interactions



connect both worlds
in some reasonable way

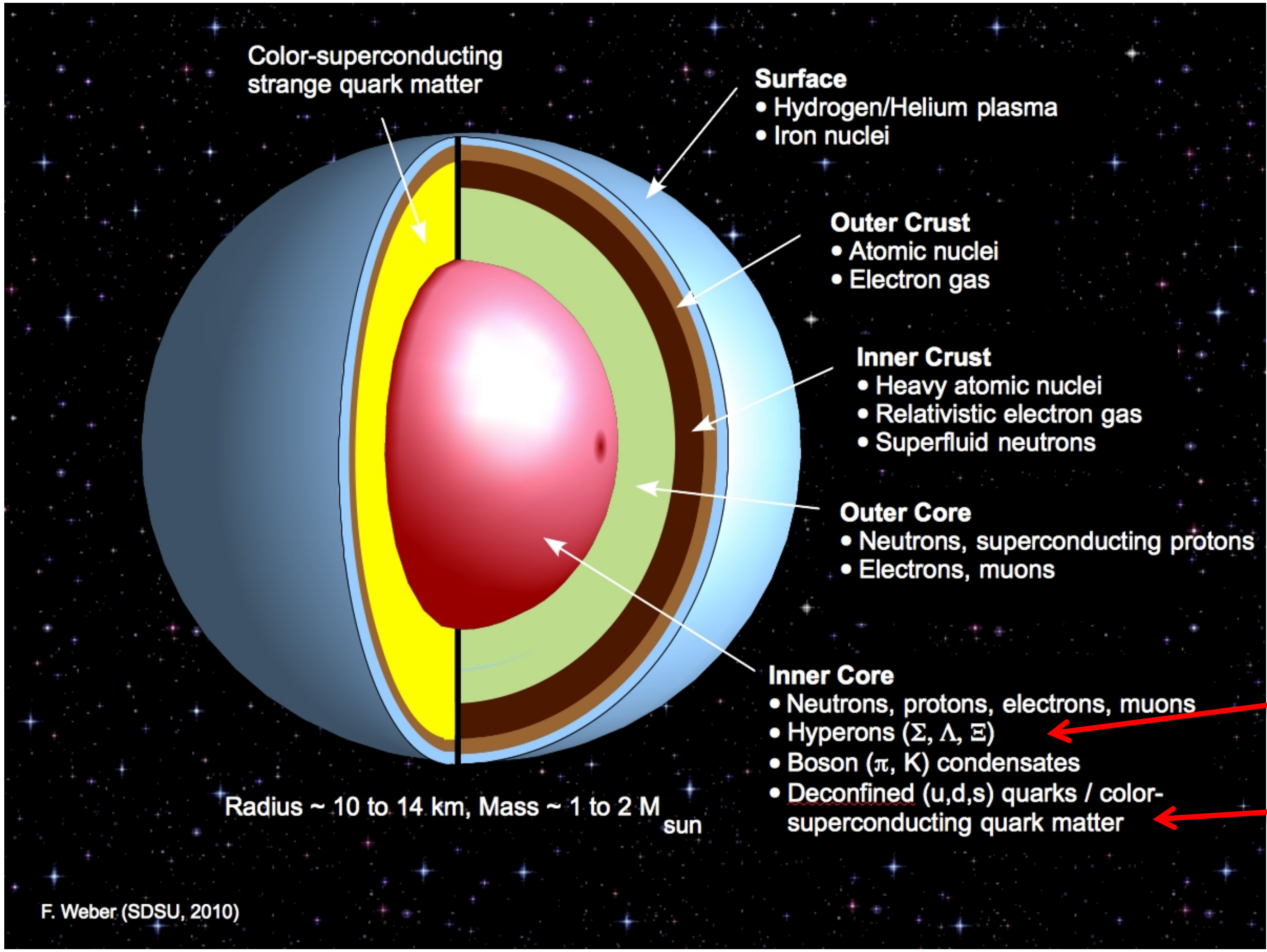
Practical model useful for heavy-ion simulations and compact star physics

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

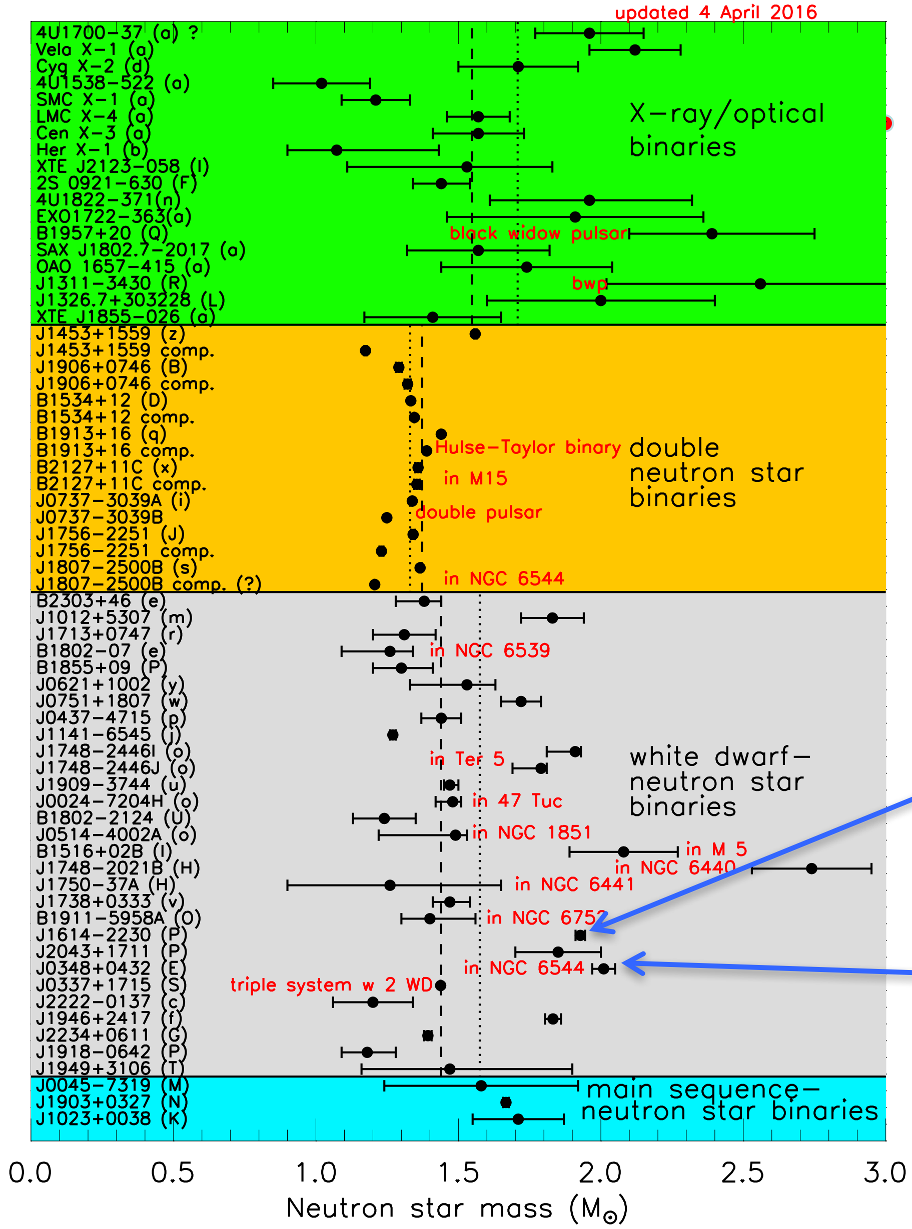
1 to 2 solar masses, radii around 10 - 15 km
maximum central densities 4 to 10 ρ_0

more than 2000 known neutron stars



hyper star

hybrid star



Lattimer, Ann. Rev. .Nucl. & Part. Sci., 62, 485 (2012)

Masses of Neutron Stars

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

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 masses, scalar attraction and vector repulsion

SU(3) interaction

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

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

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

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

plus explicit symmetry breaking

Nuclear Matter and Nuclei

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

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

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

$\varepsilon\ (A > 100) \sim 0.12\ \%$

+ correct binding energies of hypernuclei, reasonable charge radii

stellar crust/new fit in progress

SWS, Phys. Rev. C66, 064310

Neutron Stars with Hyperons

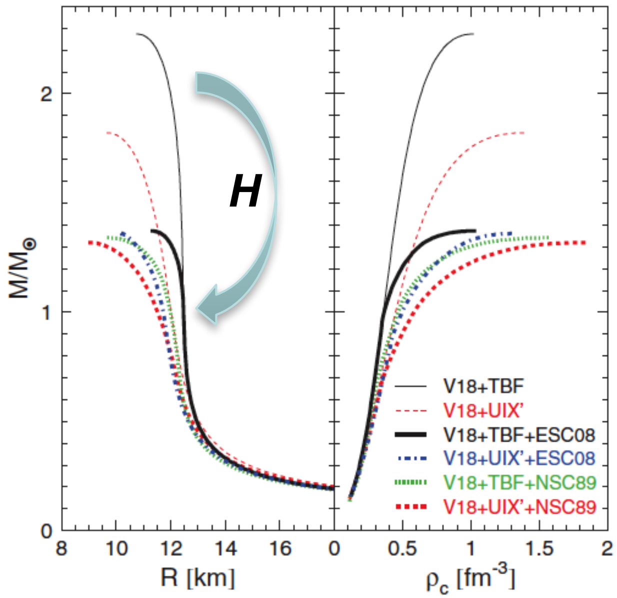
relatively easy to generate heavy stars with nucleonic EOS $M_{max} \sim 2.8\ M_{\odot}$ (NL3)

$\sim 2.2\ M_{\odot}$ (APR)

Causal limit beyond ρ_c - Rhoades, Ruffini (1974): $M_{max} < 3.2\ M_{\odot}$

additional degrees of freedom soften the equation of state reducing the maximum star mass

"hyperon puzzle"



Schulze, Rijken, PRC 84, 035801 (2011)

Nijmegen potential

hyper stars tend to have small mass

e.g.

Vidaña et. al., EPL 94 11002
Schulze et. al, PRC 84, 035801
…

most HN scattering data from the 60's !
no corresponding HH data

"Hyperon Puzzle"

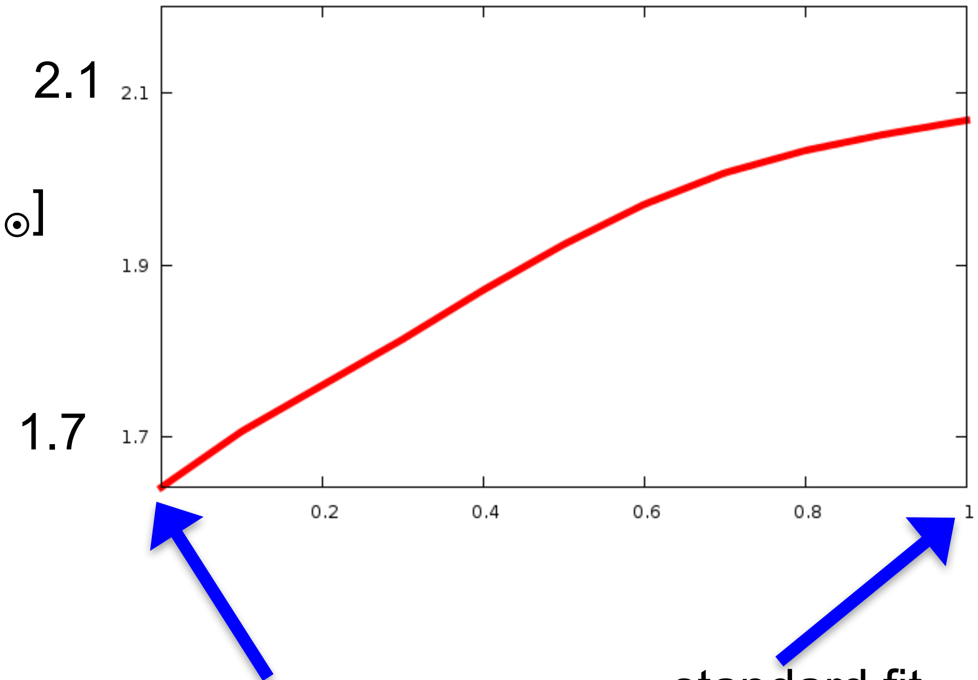
many hyperons soften EOS, reduce star masses significantly

hyperon-hyperon repulsion - impact of $s\bar{s}$ vector field Φ

strong nonlinear hyperon-nucleon interaction (Lonardoni et al, PRL 114 092301)

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

M_{max} $[M_\odot]$



no coupling

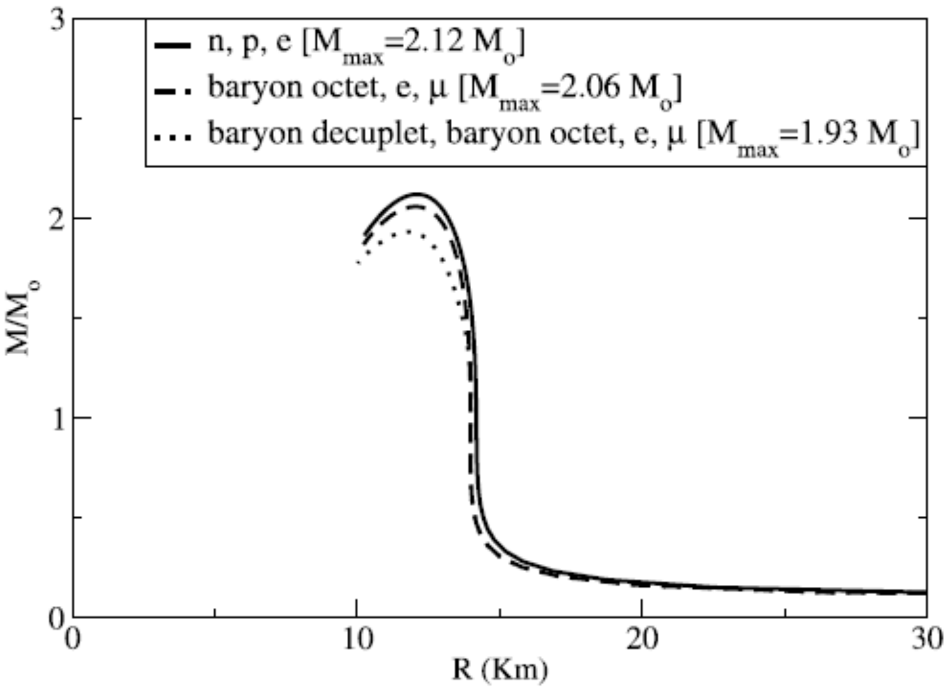
standard fit

$f_s = n_s / n_B$

hyper star with few hyperons

Dexheimer, SWS ApJ 683, 943 (2008)

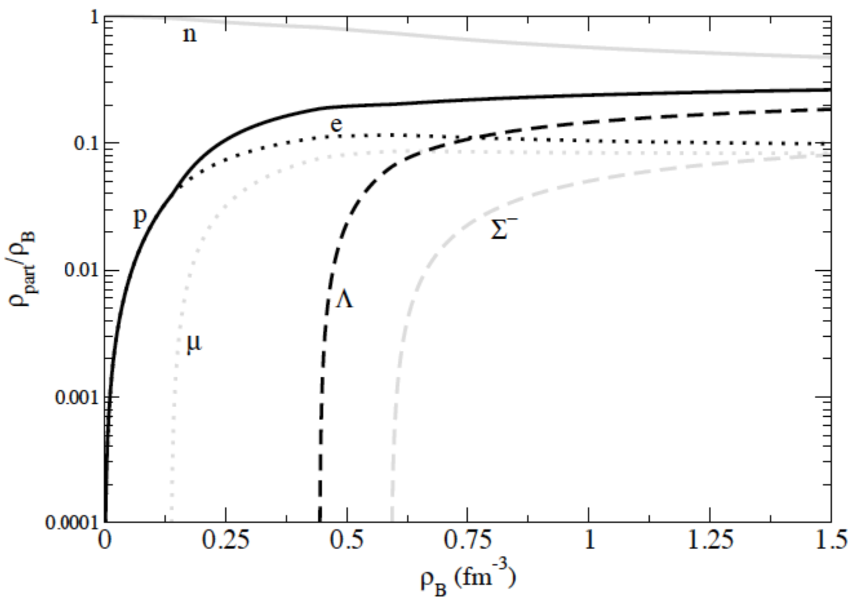
Neutron star masses including different sets of particles



Tolman-Oppenheimer-Volkov equations, static spherical star

changing masses with degrees of freedom

large star masses even with spin 3/2 resonances



normalized particle densities

Dexheimer, SWS ApJ 683, 943 (2008)

Δ baryons in compact stars?

Δ resonances
scalar couplings ➡ vacuum masses

vector couplings unclear

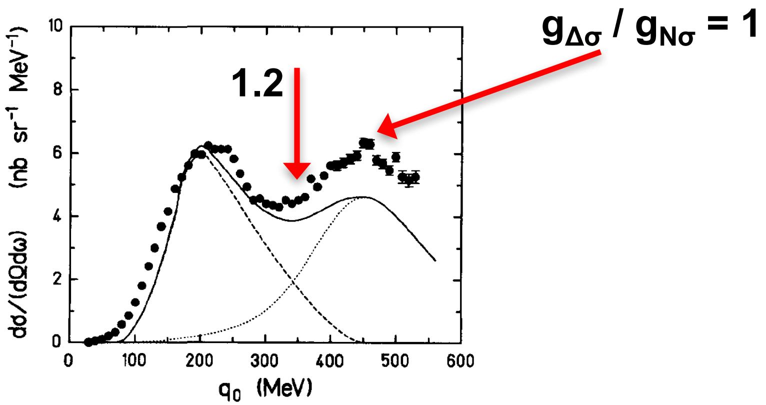
moderate changes $r_V = g_{\Delta\omega} / g_{n\omega}$

not far from SU(6)

constraints from πA scattering
photoabsorbtion

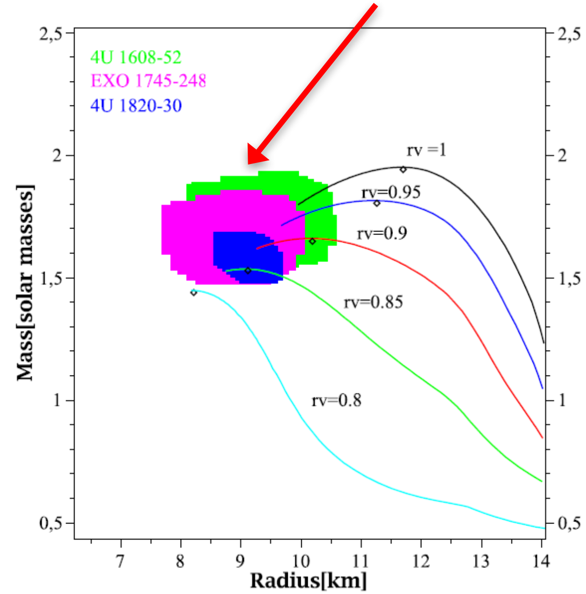
quasielastic eA scattering

E_e = 695 MeV ^{40}Ca



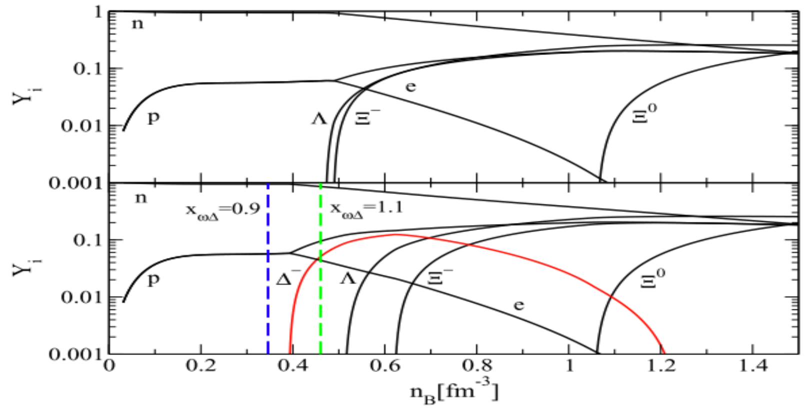
Wehrberger, Phys. Rep. 225, 273 (1993)

Özel et al, Phys.Rev.D82:101301,2010



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

$x_{\omega\Delta} = r_v$

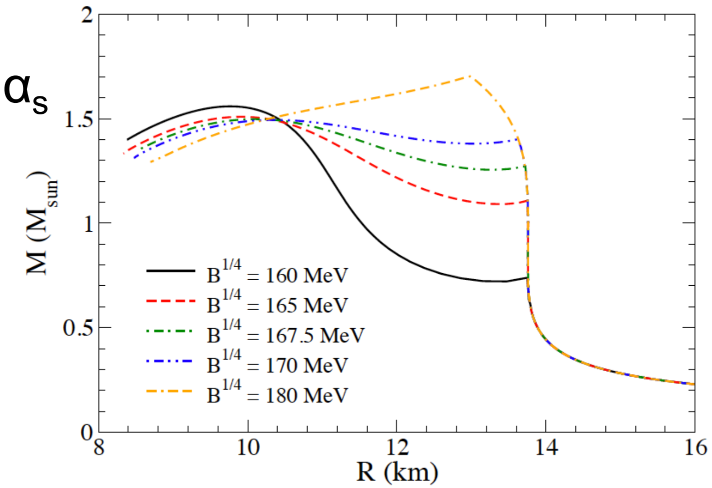


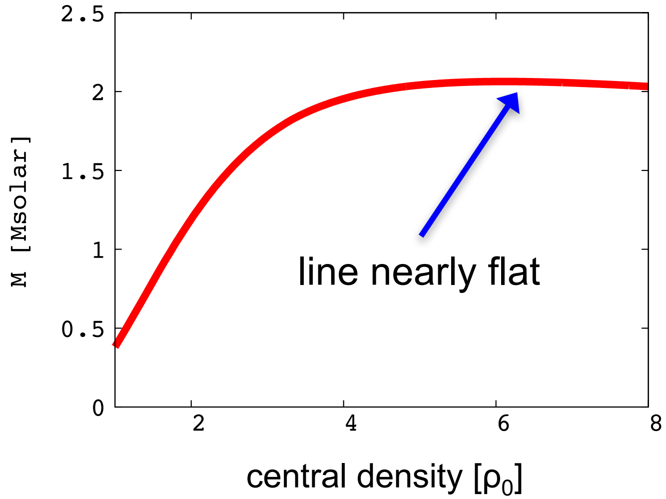
analysis in Drago et al astro-ph:1407.2843:
Onset of Δ population at 2 to 3 ρ_o

Quark star and ***Δ star*** families

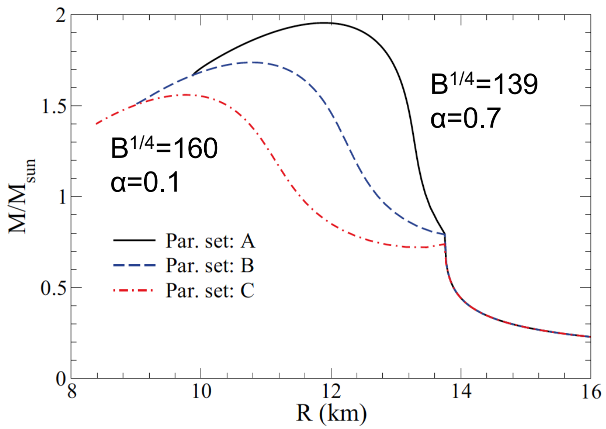
Hybrid Stars, Quark Interactions

no α_s



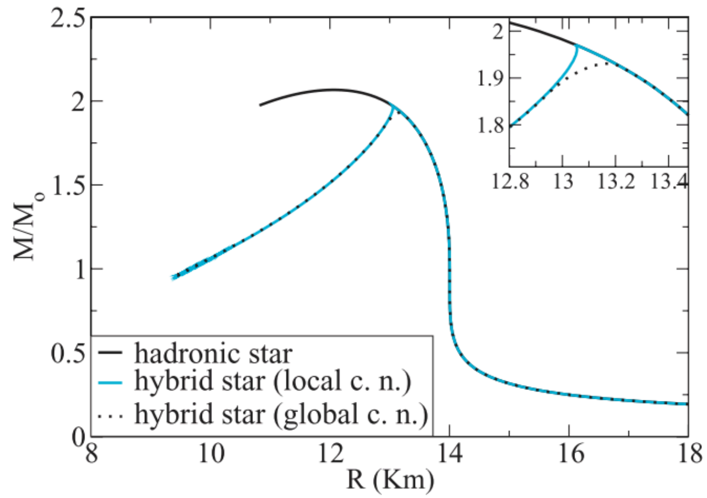


ingredients –
Standard baryonic EOS (G300)
plus MIT bag model + α_s corrections



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

unified hadron-quark model



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

hadrons, quarks, Polyakov loop and excluded volume

Include modified distribution functions for quarks/antiquarks

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

Φ confinement order parameter*

Following the parametrization used in PNJL calculations,
introduce Polyakov loop potential U(Φ ,T)

Ratti et al, EPJC49, 213

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

no reconfinement!

equation of state stays causal!

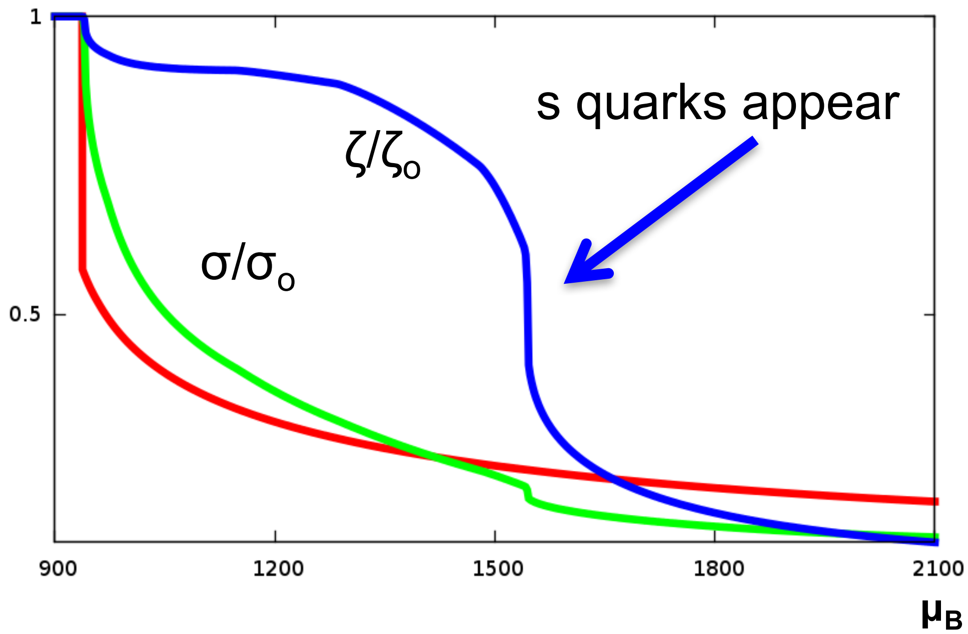
$V_q = 0$
$V_h = v$
$V_m = v / 8$

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

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

Steinheimer,SWS,Stöcker JPG 38, 035001

star matter in beta equilibrium in QH approach

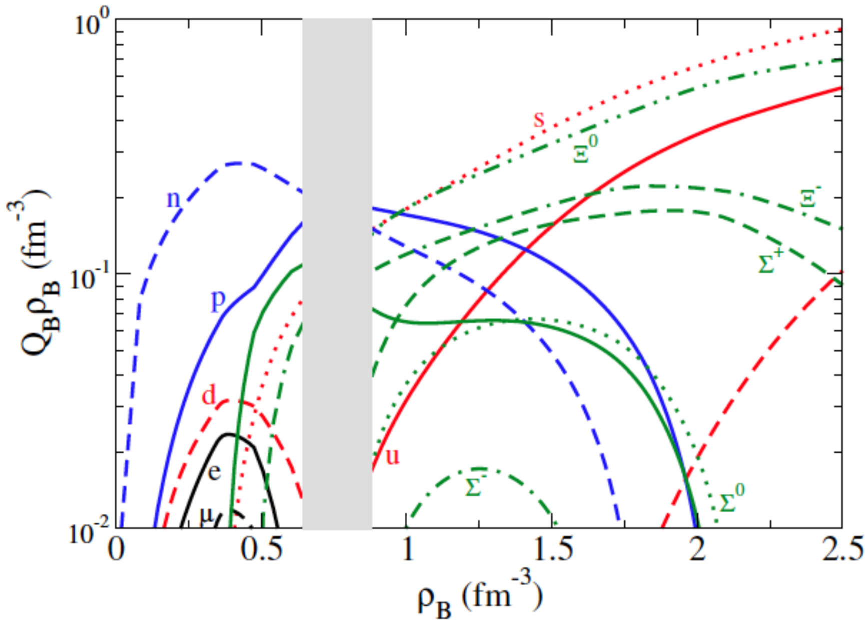


1st order phase transition
in star matter possible

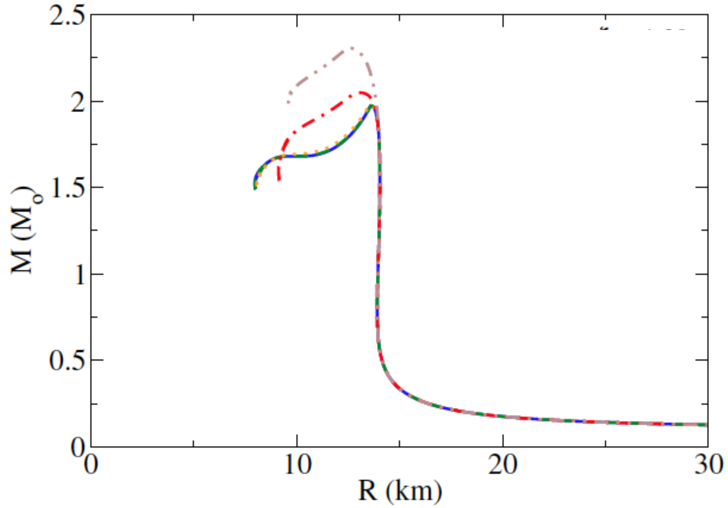
cross over in symmetric matter

f_s(core) jumps to ~ 1

particle cocktail



star masses M varying quark interactions



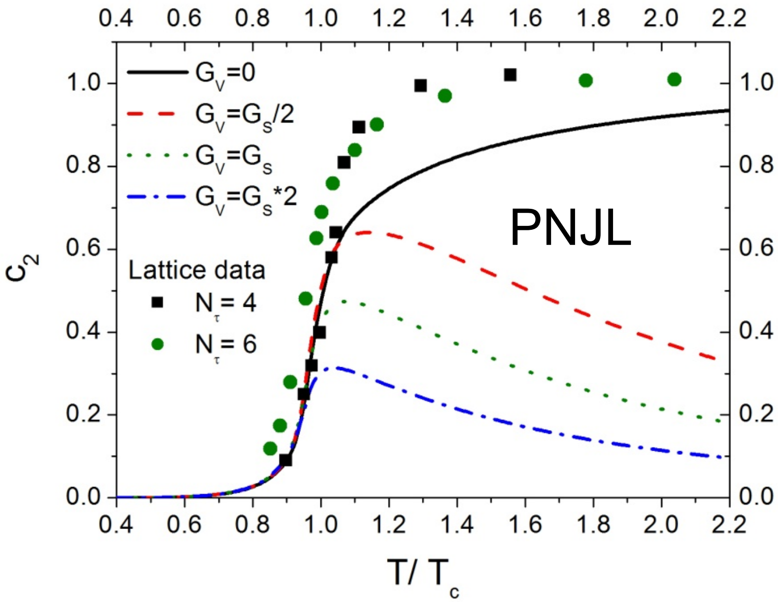
Mass ~ 2 – 2.3 $M_\odot$ Radius ~13 km

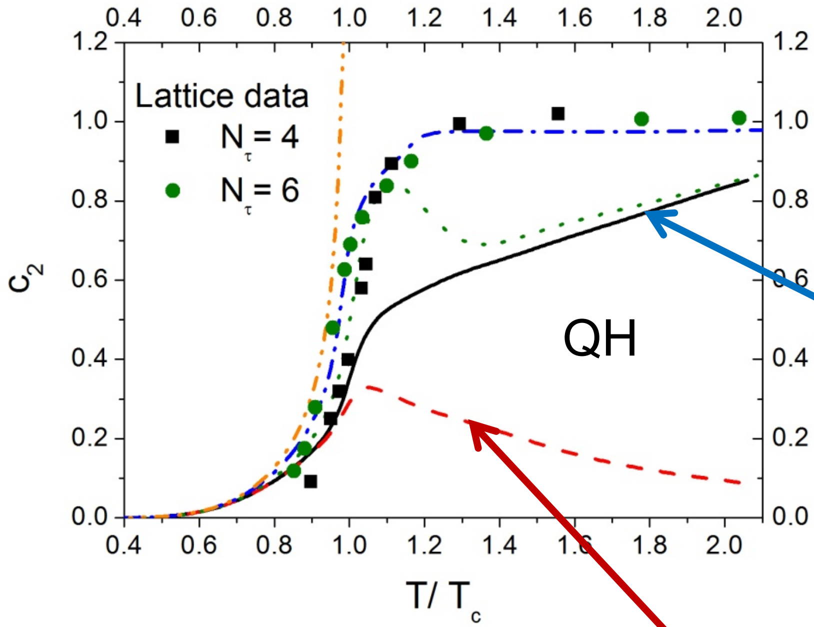
Dexheimer,Negreiros,SWS PRC91, 055808

Susceptibilitiy 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 !!





$g_{q\omega} = 0$

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

same behavior for strangeness susceptibilities

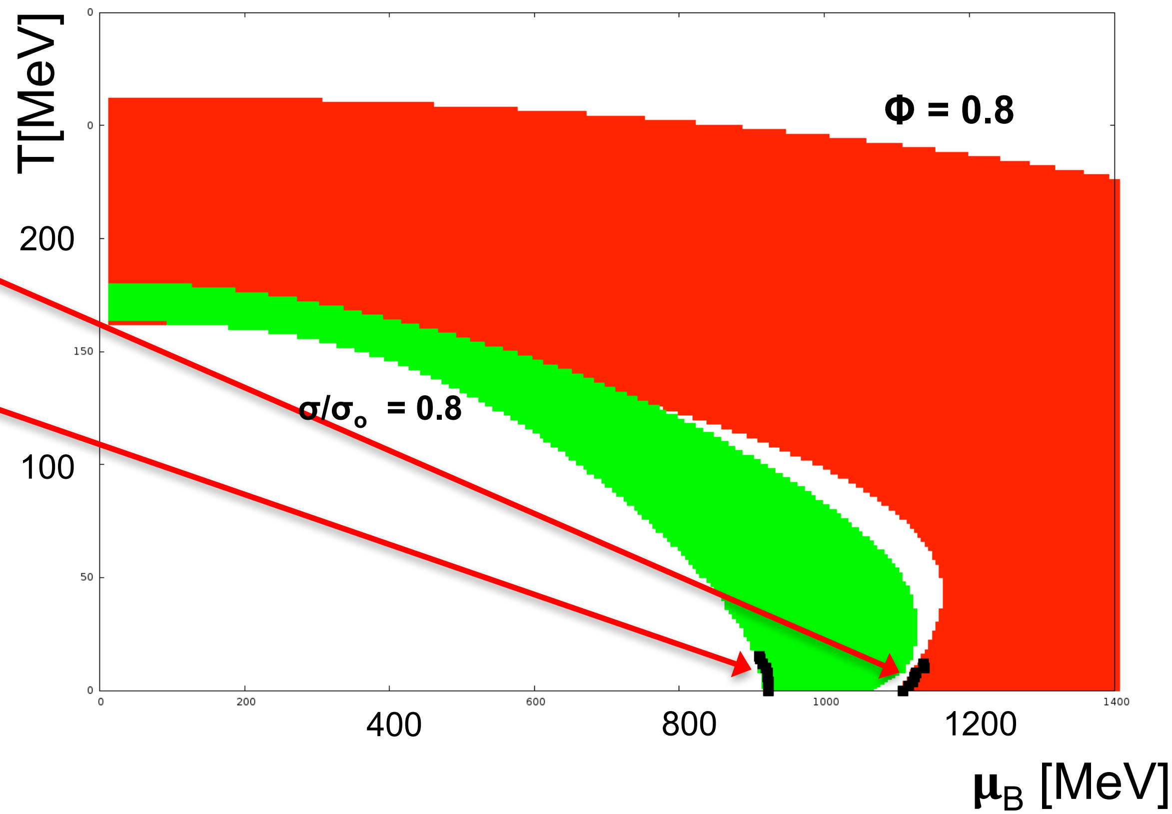
Steinheimer, SWS, PLB 696, 257
Rau et al, Phys.Lett.B733, 176

Excited quark-hadron matter in the parity-doublet approach

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

Chiral transition

Liquid-gas phase transition



compressibility *267 MeV* *(!)*
asymmetry energy *30 MeV*
slope parameter *57 MeV* *(!)*

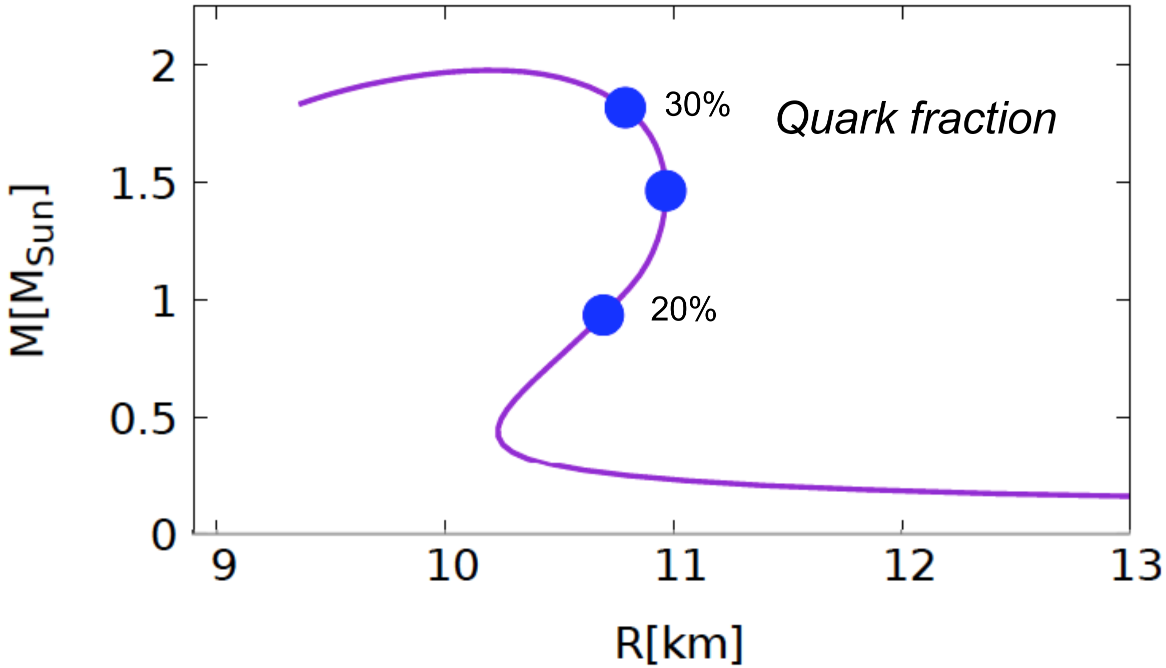
single particle energies

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

chirally invariant mass term

Mukherjee, SWS, Steinheimer, Dexheimer, arXiv: 1706.09191
Steinheimer, SWS, Stöcker, JPhysG 38, 035001
Y. Motohiro et al. PRC 92, 025201

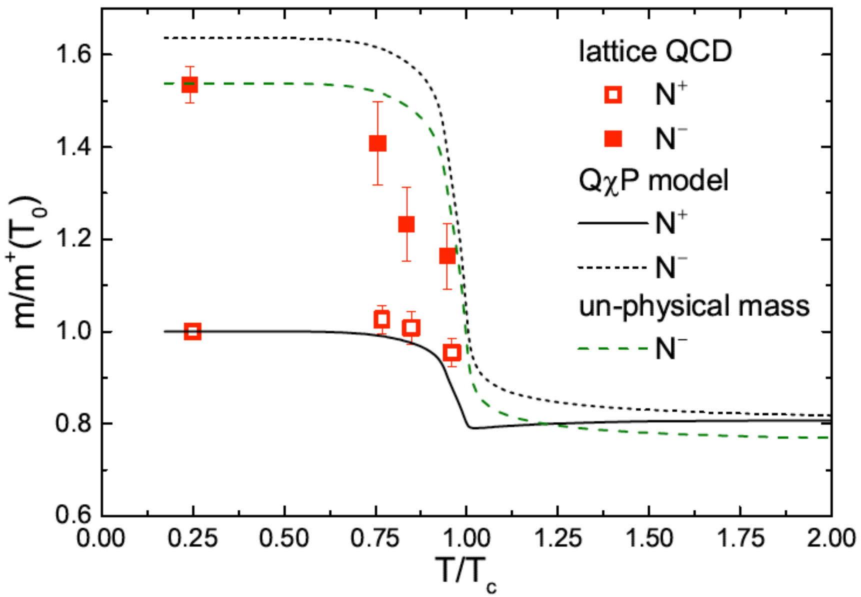
Mass radius diagram for hybrid star



A number of observations (LMXB binary systems) point to a small radius of 9 - 11 km of typical neutron star

e.g. Guillot et al. APJ 772, 7

negative parity state on the lattice and in the model



lattice data from Aarts et al, arXiv:1703.09246 [hep-lat]

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*

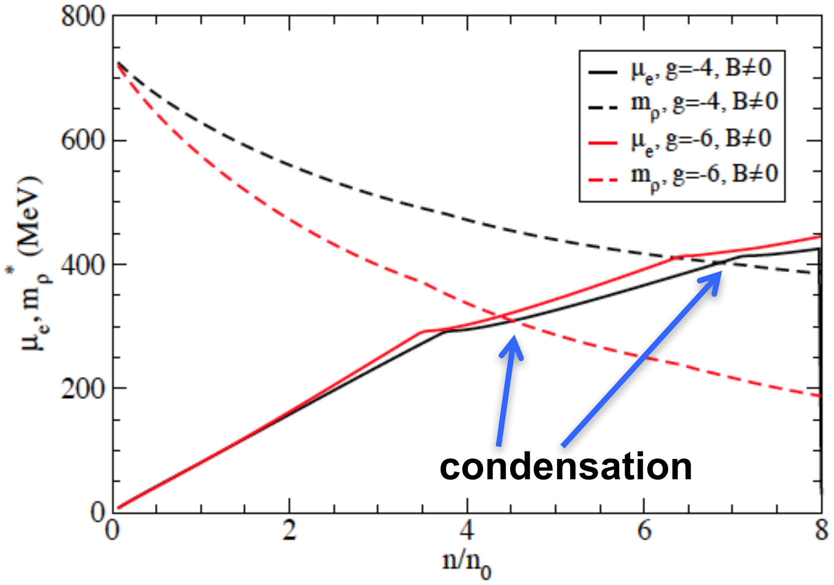
Advantage: high spin – strong interaction with magnetic field

Landau levels of the rho meson

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

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

charge chemical potential and effective rho mass as function of density



magnetars with surface fields up to 10^{15} G

Use standard hadronic model GM3 parameterization

B value: 7×10^{18} G

slight change of star masses
faster cooling

density dependence of rho mass ?

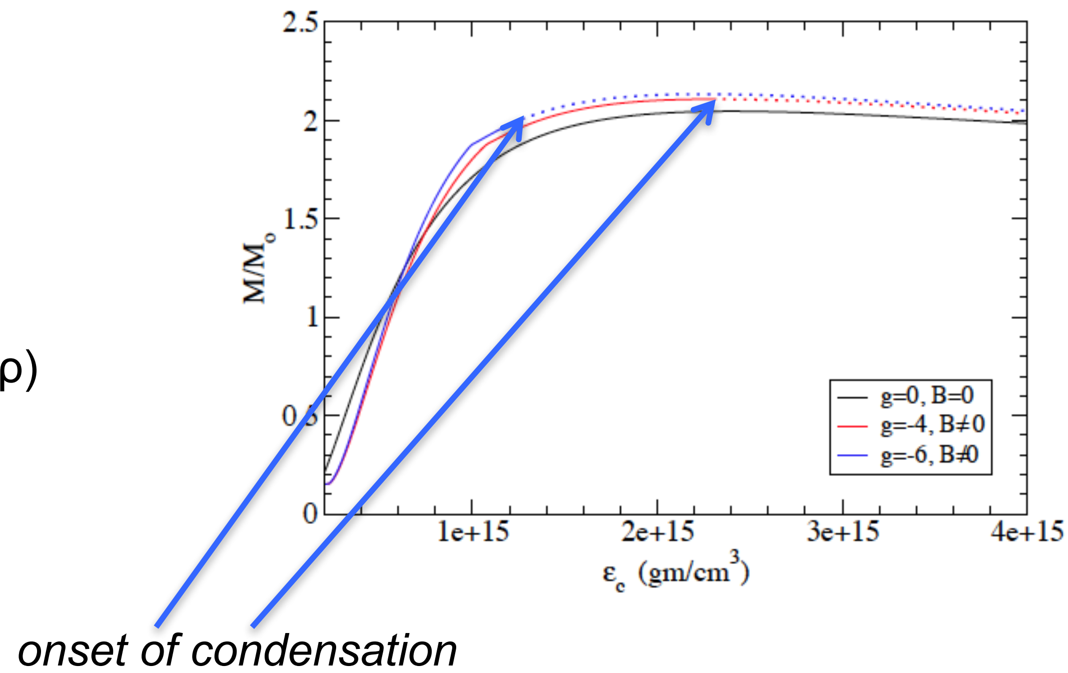
simple estimate $m_\rho^* = m_\rho - g\,\sigma$

readjust $g_{N\rho}$ to correct asymmetry energy a_{sym}

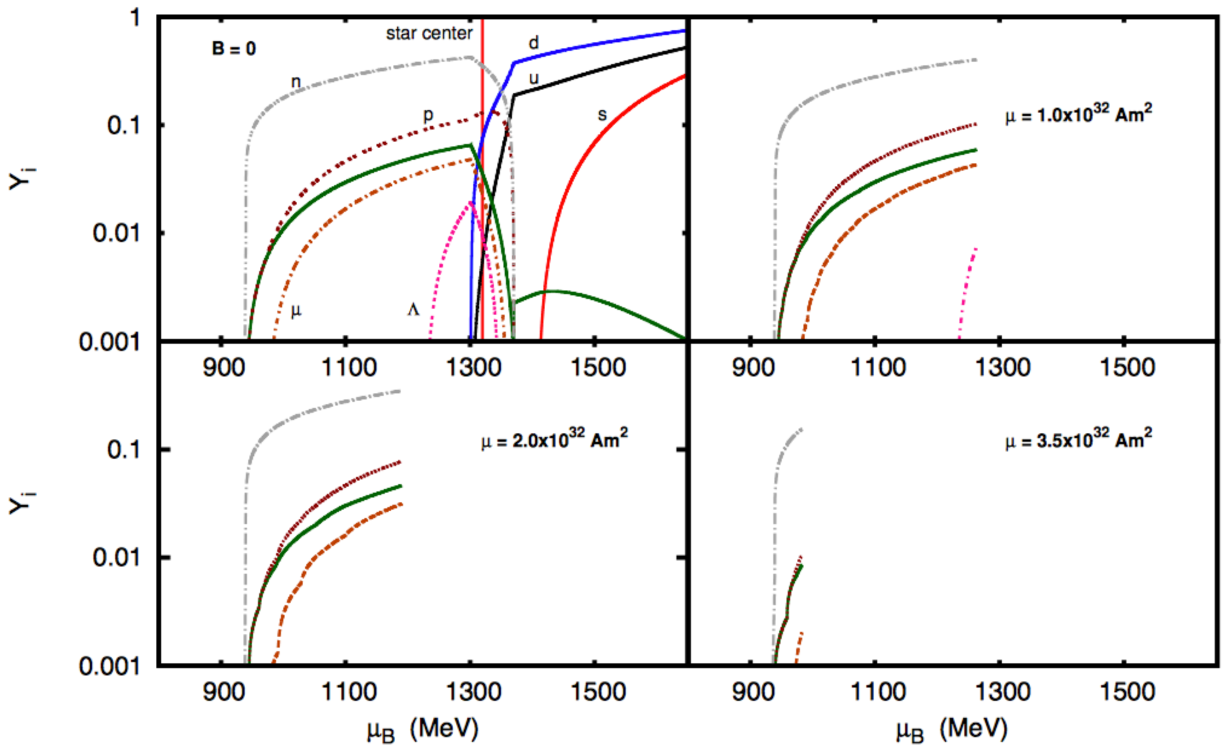
range of g limited by slope of $a_{sym}(\rho)$

Mallick, Dexheimer, SWS, Bhattacharyya, MNRAS (2015)

first: Voskresensky PLB 1997
Kolomeitsev, Voskresensky NPA 2005



effect of strong magnetic fields on hybrid star



$B_c = 5*10^{17}$ G

$B_c = 9.1*10^{17}$ G

$B_c = 8.8*10^{17}$ G

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

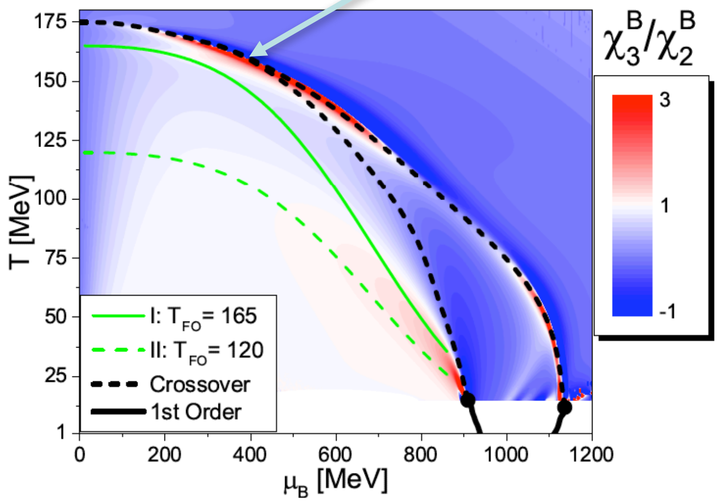
Conclusions, Outlook

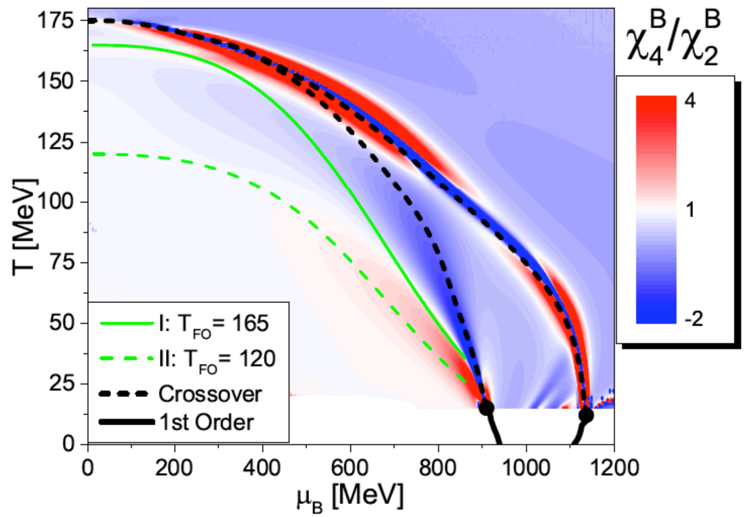
- coherent phenomenological model including reasonable asymptotic degrees of freedom
- heavy compact stars / hyper stars - little strangeness
- hybrid stars: stiff equation of state for quarks ? lattice susceptibilities
- large mixed phase in hybrid star
- rho meson condensate (just) possible
- magnetic fields remove quark core
- *comprehensive equation of state for a wide range of densities/temperatures (supernovae, mergers)*
- *consistent crust simulations*
- *couple hydro and kinetic equations for fields*

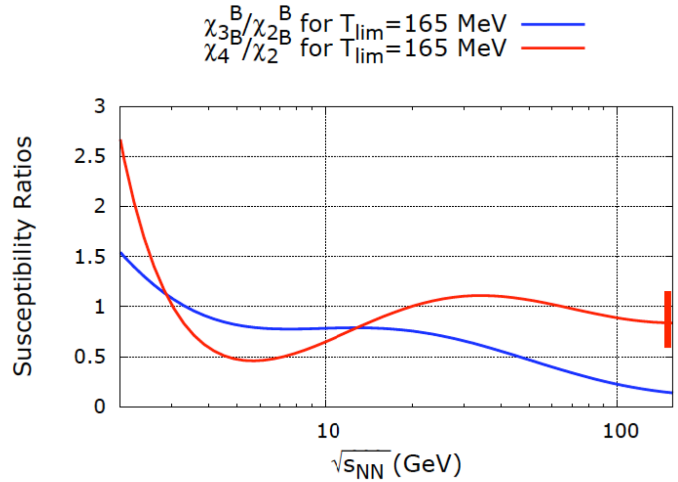
fluctuations in heavy-ion collisions

susceptibilities χ^B_n as marker of interesting phase structures

importance of liquid-gas transition





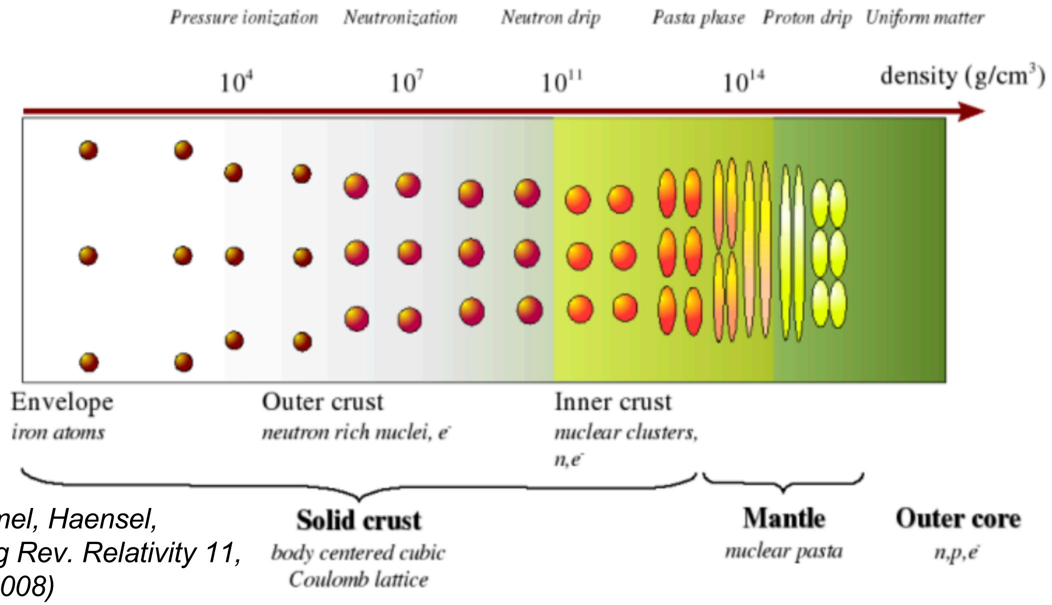


$\chi^B_n \sim n!\, c^B_n$

susceptibilities along freeze-out line
(temperatures rescaled)

Mukherjee, Steinheimer, SWS, PRC, arXiv:1611.10144

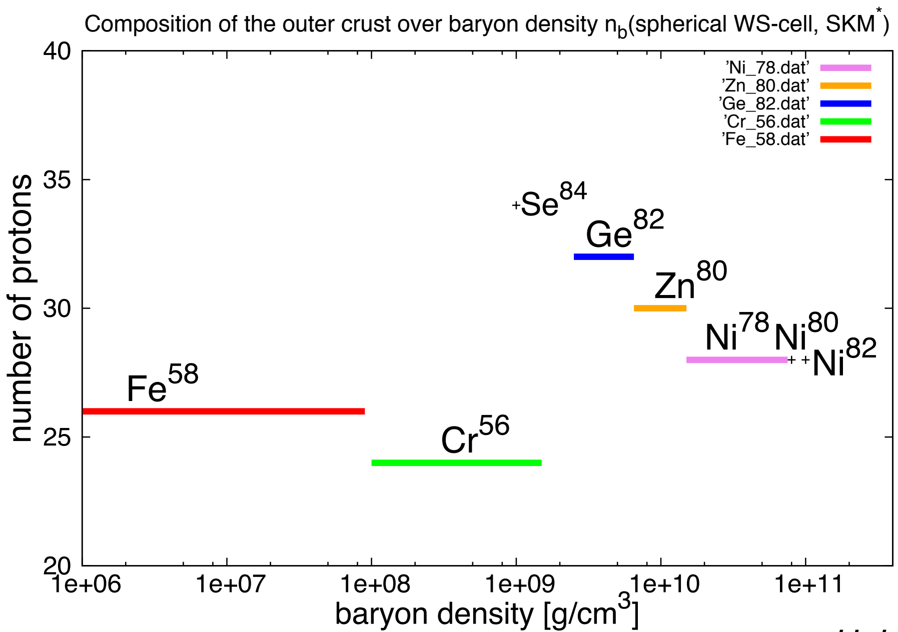
structure of the crust



Chamel, Haensel, Living Rev. Relativity 11, 10 (2008)

non-accreting crust (BPS)

	ρ [g/cm^3]
^{56}Fe	8.1×10^{6}
^{62}Ni	2.7×10^{8}
^{64}Ni	1.2×10^{9}
^{84}Se	8.1×10^{9}
^{82}Ge	2.2×10^{10}
^{80}Zn	4.9×10^{10}
^{78}Ni	1.6×10^{11}
^{76}Fe	1.8×10^{11}
^{124}Mo	1.9×10^{11}
^{122}Zr	2.7×10^{11}
^{120}Sr	3.7×10^{11}
^{118}Kr	4.3×10^{11}



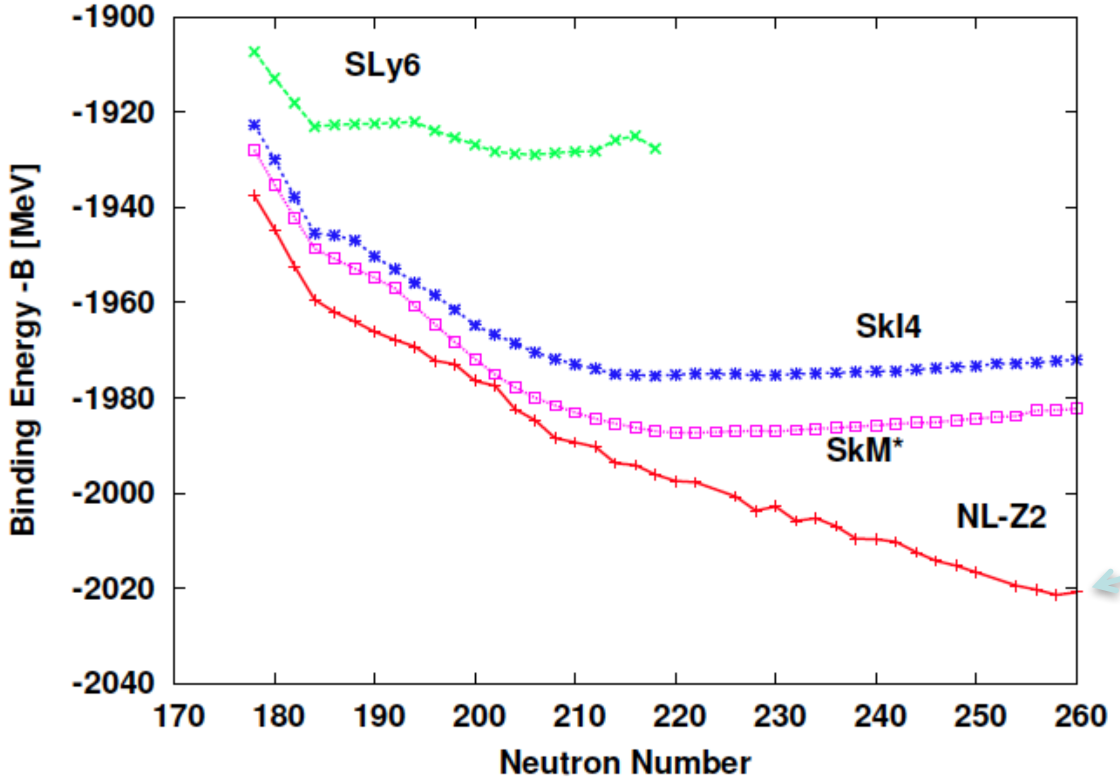
results can be very model-dependent

see e.g. Rüster et al, PRC **73**, 035804 (2006)

U. Heinzmann

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

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



more parameter sets behave similarly

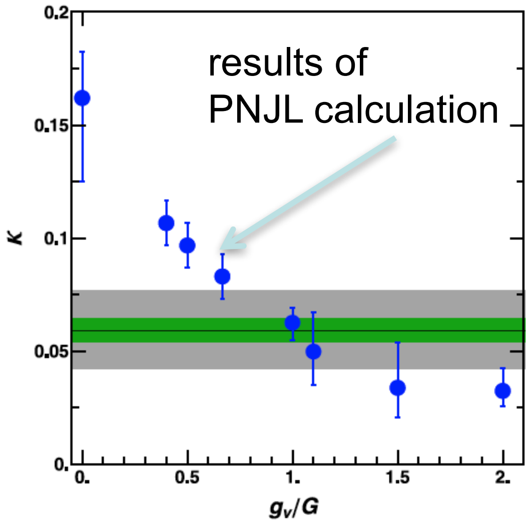
SWS,Gridnev,Tarasov,Tarasov,Geiner, IJMPE**21**, 1250047

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

phase transition line very flat, T_c changes slowly with μ

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

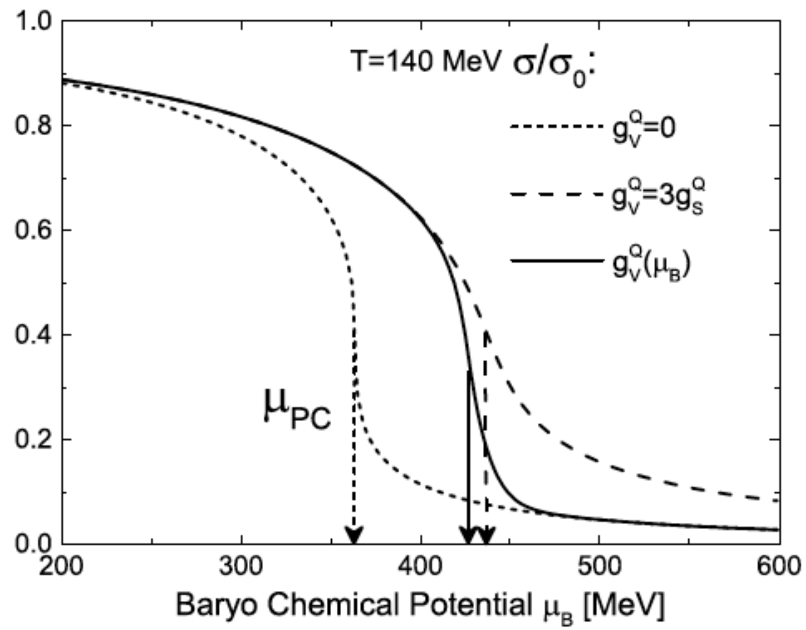
plot taken from
Bratovic et al, PLB 719, 131 (2013)



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

large quark vector repulsion?

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



turn on/off repulsion
of quarks and baryons

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

Steinheimer, SWS, PLB 736, 241