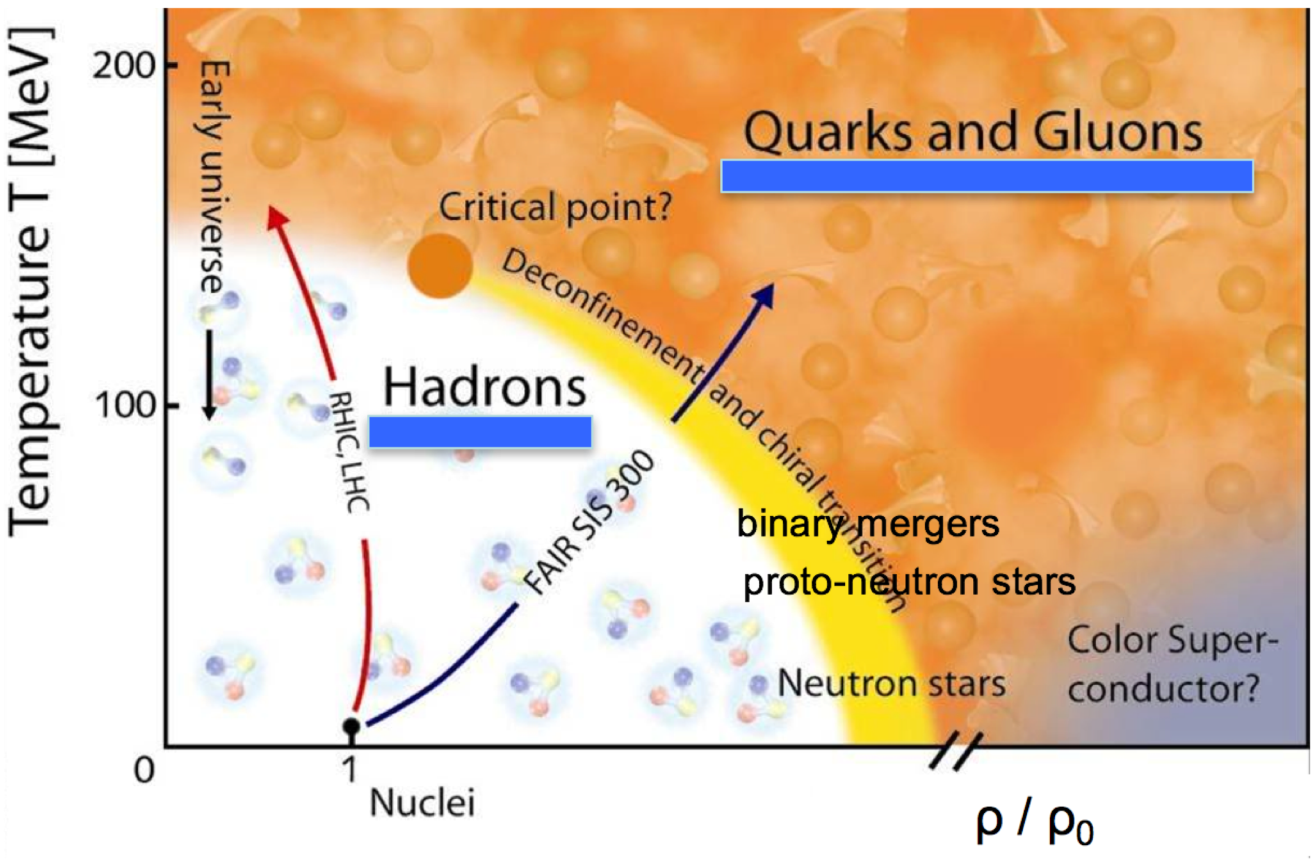
Modeling Hybrid Stars and Hot Matter

OUTLINE

- phenomenolgy of neutron stars
- nucleons in the core
- hyperons in the core
- quark matter in the star
- aspects for heavy-ion collisions
- lessons from the merger signal

V. Dexheimer, R. Gomes, R. Mallick, A. Motornenko,,
A. Mukherjee, R. Nandi, J. Steinheimer, SWS
FIAS ,Kent State, Rio de Janeiro, Bhopal , Mumbai

the usual phase diagram (sketch) of strong interactions



connect both worlds
in some reasonable way

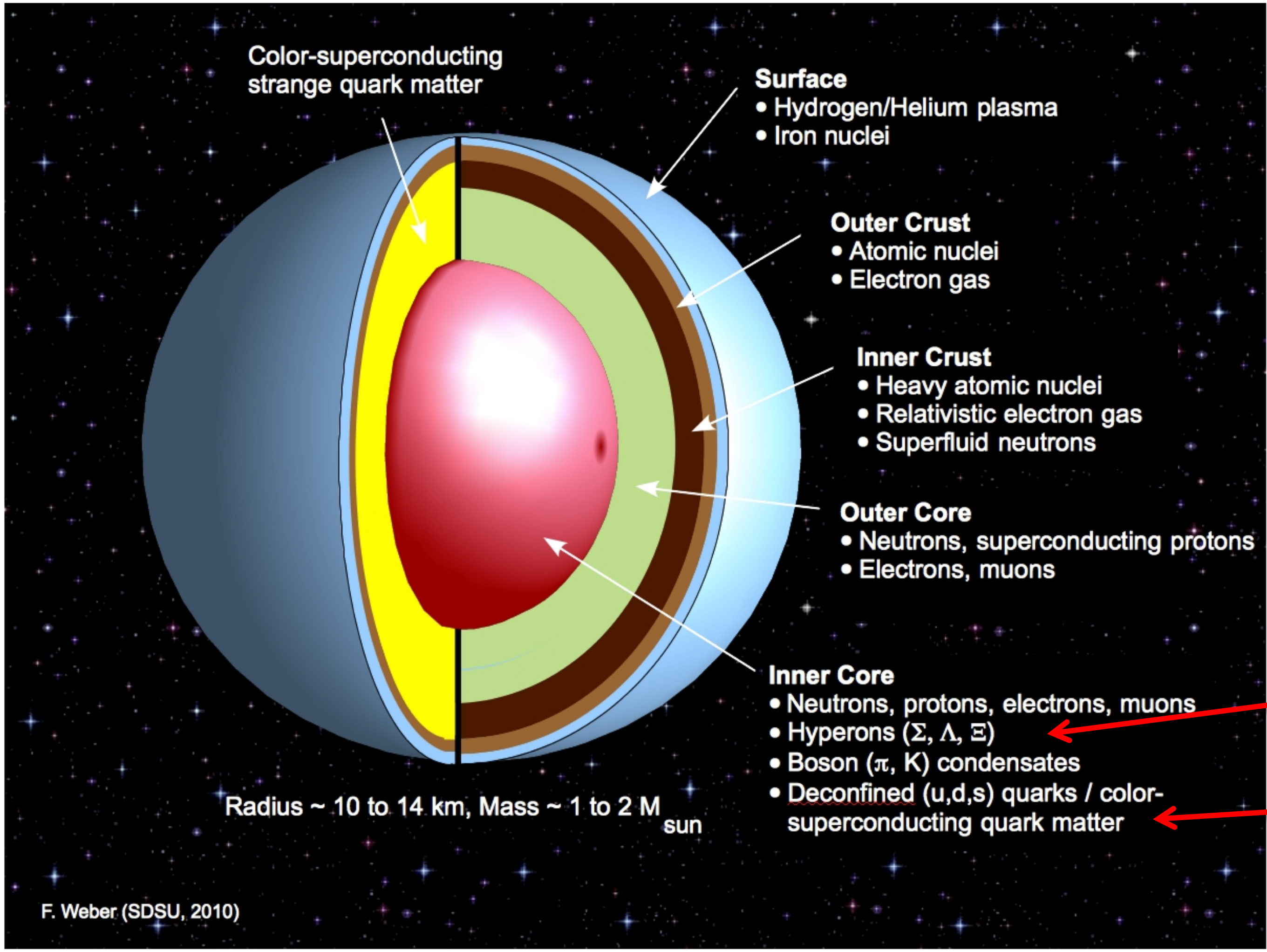
Practical model useful for heavy-ion simulations and compact star physics

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 2600 known neutron stars



hyper star

hybrid star

Neutron Star Masses

benchmark for NS models

2 solar masses

PSR J1614-2230 $M = (1.97 \pm .04)\, M_0$
Demorest et al. Nature 467, 1081 (2010)

PSR J0348+0432 $M = (2.01 \pm .04)\, M_0$
Antoniadis et al. Science 340, 448 (2013)

Neutron Star Radii

X-ray bursters, use luminosity, temperature information to extract radius

10.4 km < R < 12.9 km analysis of range of EOS, PRE XB, qLMXB *Steiner et al., APJL 765, L5*

9 km < R < 11 km PRE XB *Özel et al., PRD 82, 101301(R)*

R > 14 km PRE 4U 1724-307 *Suleimanov et al., APJ 742, 122*

7.6 km < R < 10.4 km single R, qLMXB *Guillot et al, APJ 772, 7*

10.4 km < R < 11.3 km bursts, qLMXB *Özel et al, arXiv:1505.05155*

tendency to small radii

CMF - 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

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

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

nuclear properties { error in energy $\varepsilon\,(A > 50) \sim 0.17\ \%$
$\varepsilon\,(A > 100) \sim 0.12\ \%$

+ correct binding energies of hypernuclei, reasonable charge radii

SWS, Phys. Rev. C66, 064310

constraints for the nucleonic part of the equation of state

- nuclear matter saturation density $\boldsymbol{\rho}_0 \approx 0.15 - 0.17\ \mathrm{fm}^{-3}$)
- binding energy per nucleon $E/N \approx 15 - 16$ MeV
- (in-)compressibility $\boldsymbol{\kappa} = 9\ (dP/d\boldsymbol{\rho})\ |_{\rho 0} \approx 190 - 270$ MeV
- (a-)symmetry energy $S = \frac{1}{2}\ \rho_0^2\ d^2(\varepsilon/\rho)\ /\ [d(\rho_p - \rho_n)]^2 \approx 25 - 35$ MeV
- slope parameter $L = 3\ \rho_0\ (dS\ /\ d\rho)(\rho_0) \approx 30 - 100$ MeV

sources for constraints – nuclear masses, GDR, Sn isotopes, ...

surveys:

*Dutra et al, Phys. Rev. C **85**, 035201 (2012)   (240 Skyrme parametrizations)*
*Dutra et al, Phys. Rev. C **90**, 055203 (2014)   (263 RMF models)*

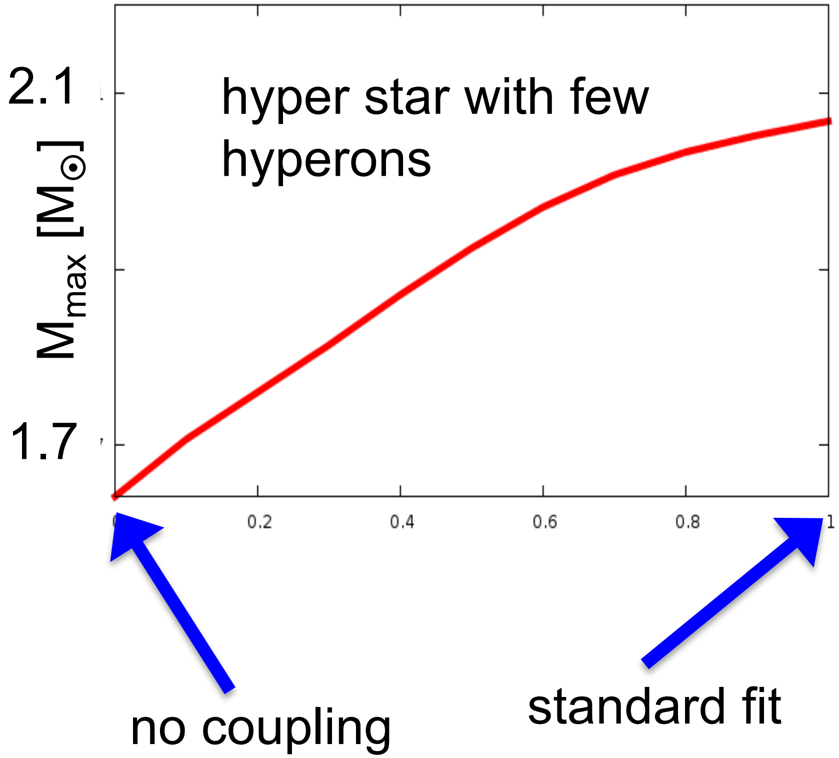
"Hyperon Puzzle"

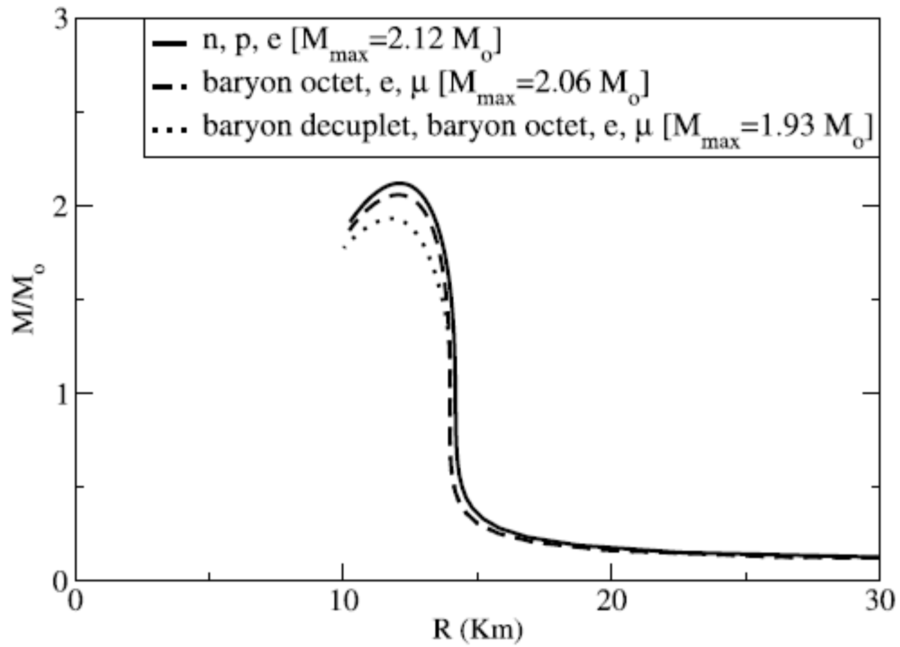
many hyperons soften EOS, reduce star masses significantly (far below 2 $M_\odot$)

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) = n_s / n_B varies between 0.1 and 1





Dexheimer, SWS ApJ 683, 943 (2008)

effect of vector self-interactions

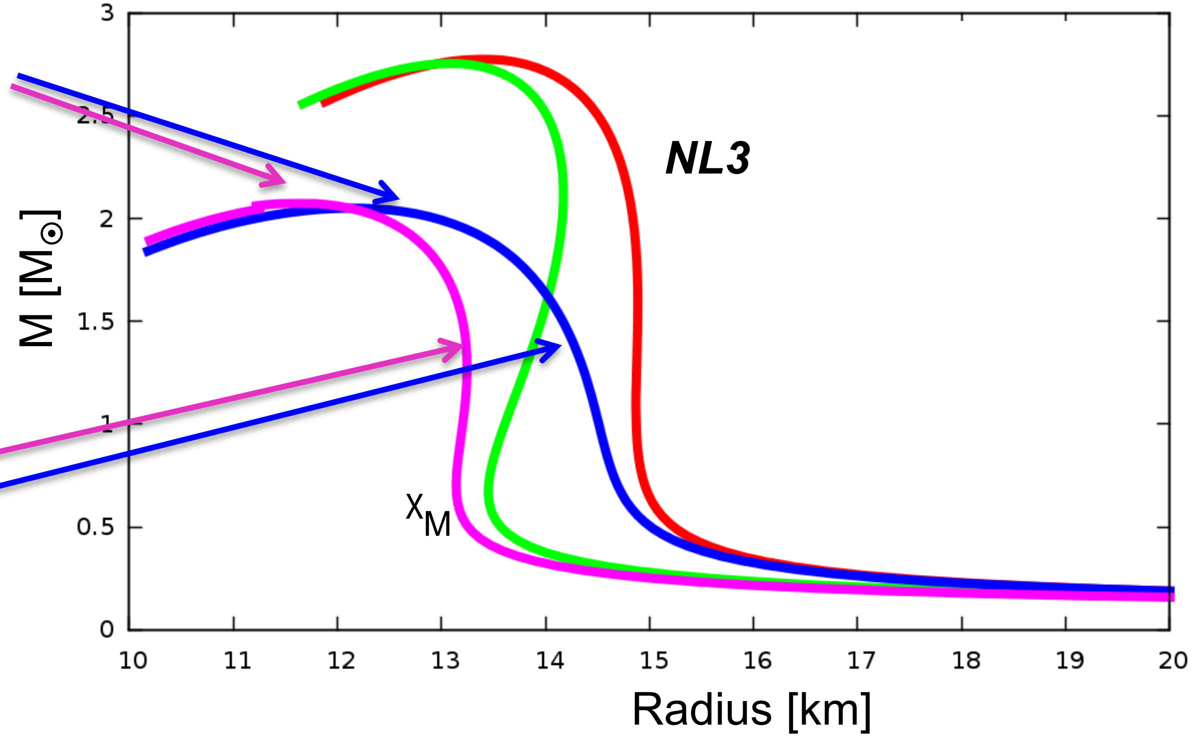
Dexheimer, Negreiros, SWS, PRC92, 012801(R)
Horowitz, Piekarewicz, PRC66, 055803
SWS, PLB 560, 164

non-linear isoscalar-isovector interactions like $V \sim \rho^2\omega^2$

→ non-trivial density dependence of isospin terms

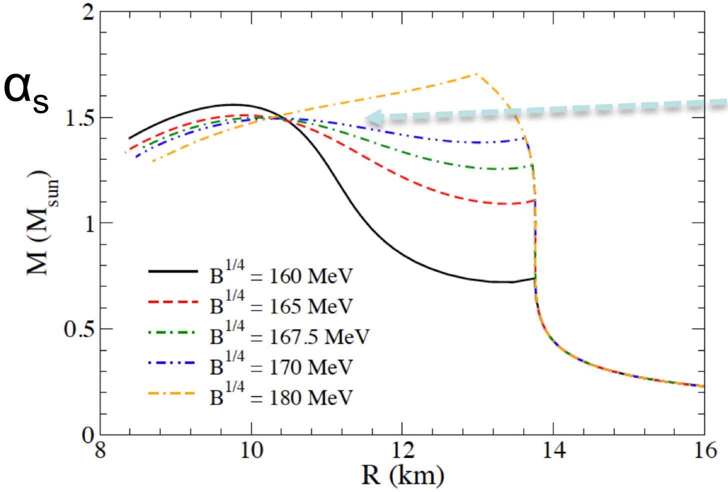
maximum mass unchanged

substantial reduction of radii



Hybrid Stars, Quark Interactions

no α_s



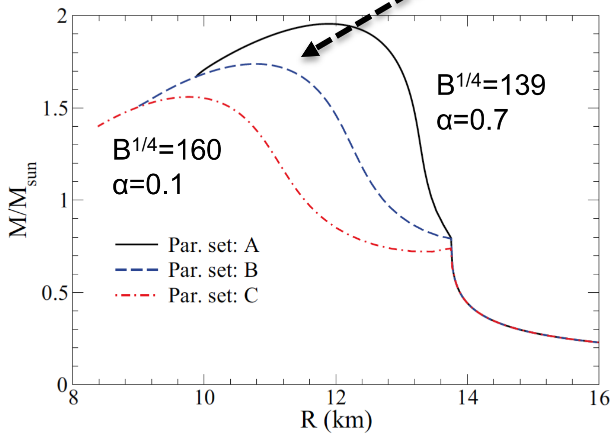
hybrid star with quark core
reduces maximum mass

requires strong repulsive forces

in contradiction with
lattice QCD susceptibilities

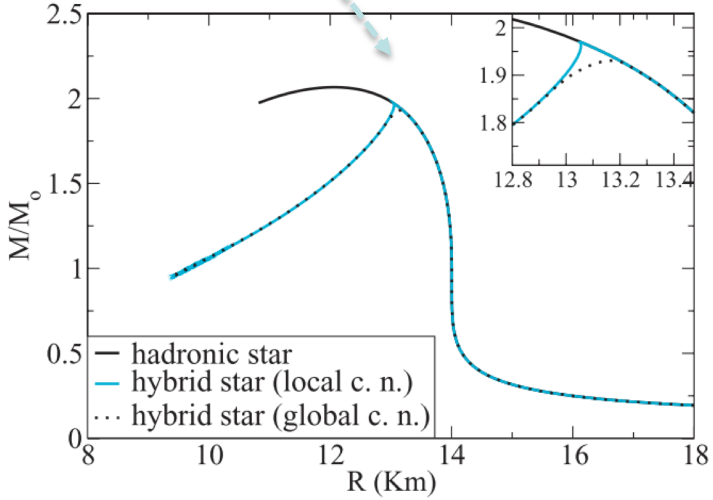
Steinheimer,SWS
PLB 696, 257 PLB 736,241

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*

Ratti et al, EPJC49, 213

plus Polyakov loop potential U(Φ ,T)

quarks couple to fields

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

- first-order, second-order, crossover transitions possible
- no reconfinement!
- equation of state stays causal

~

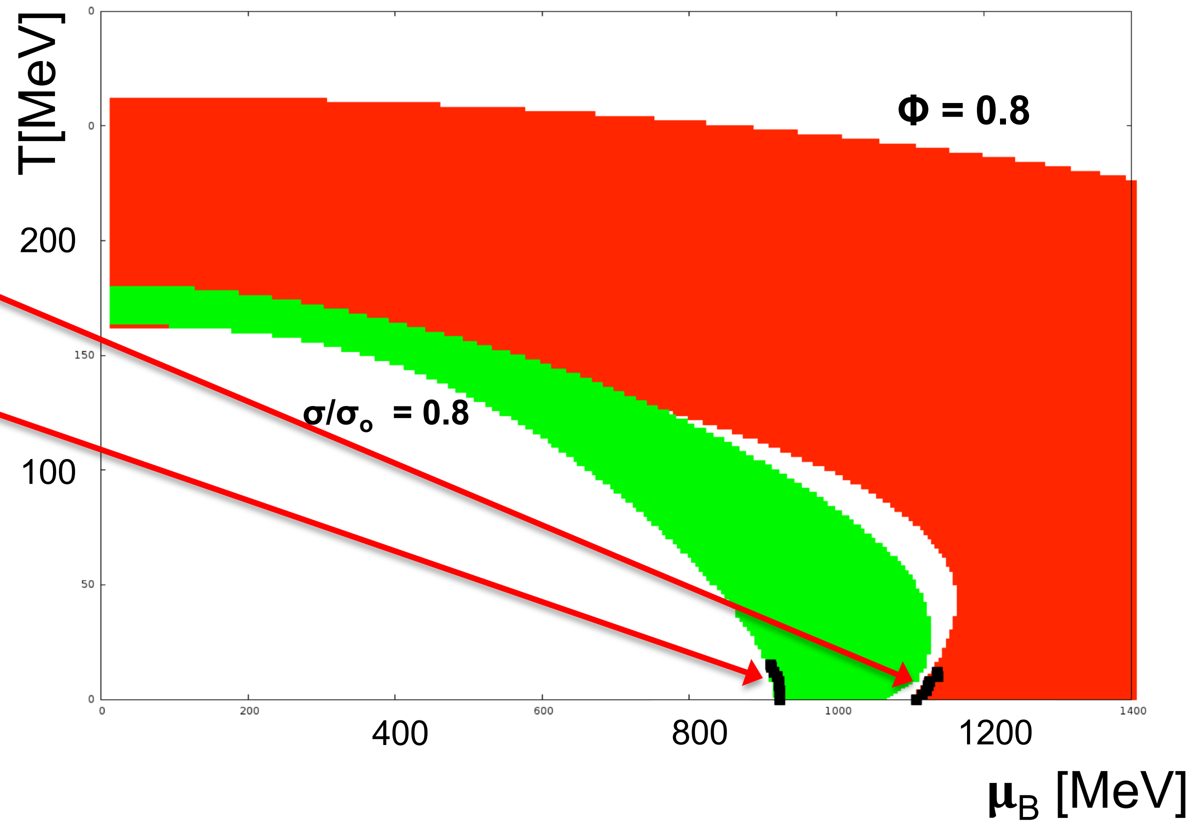
Steinheimer,SWS,Stöcker JPG 38, 035001

Excited quark-hadron matter in the parity-doublet approach

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

HQ transition

Liquid-gas phase transition



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

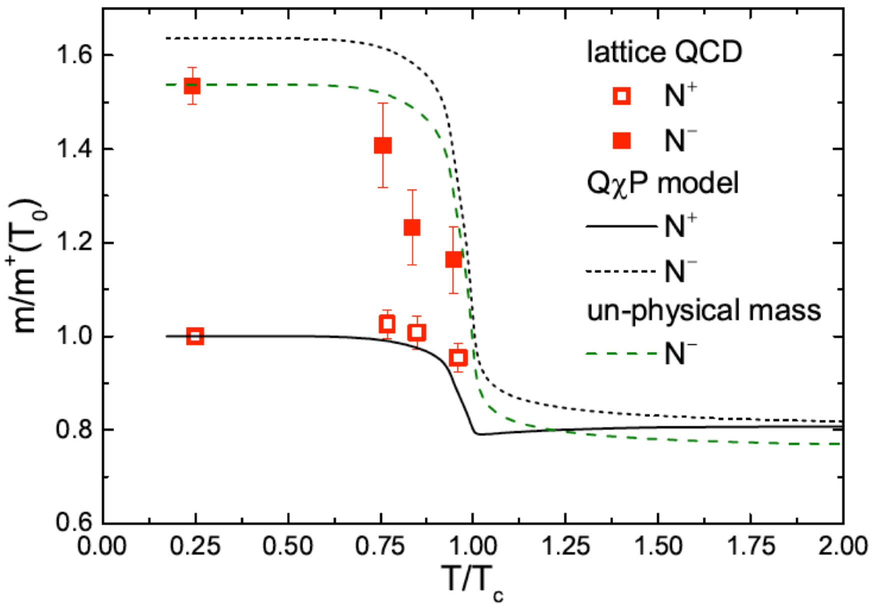
single particle energies

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

chirally invariant mass term

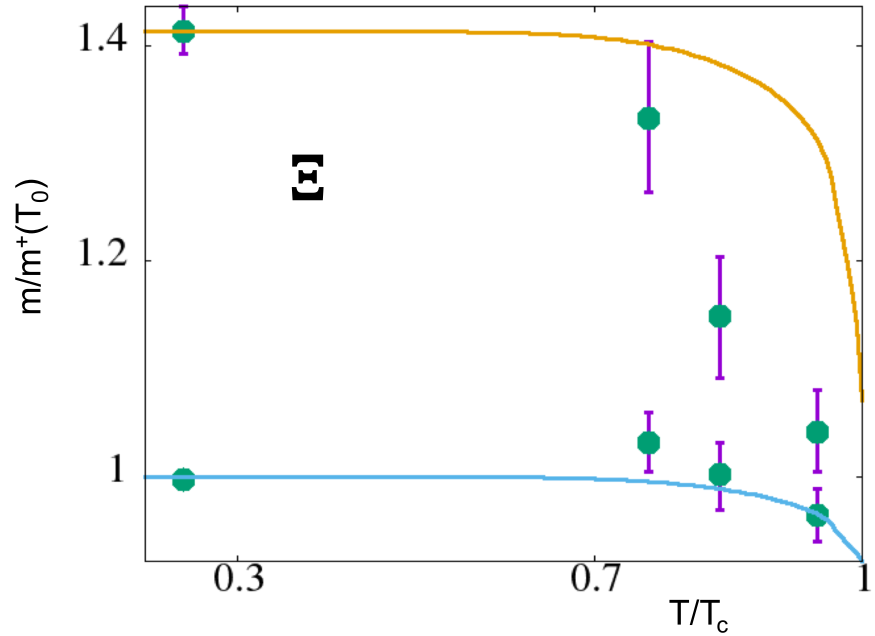
Mukherjee, SWS, Steinheimer, Dexheimer, A&A 608, A110
Steinheimer, SWS, Stöcker, JPhysG 38, 035001
Y. Motohiro et al. PRC 92, 025201

negative parity state on the lattice and in the model



lattice data from Aarts et al,
J. High Energ. Phys. (2017) 2017: 34
EPJ Conf. **175**, 07016 (2018)

similar results for hyperons



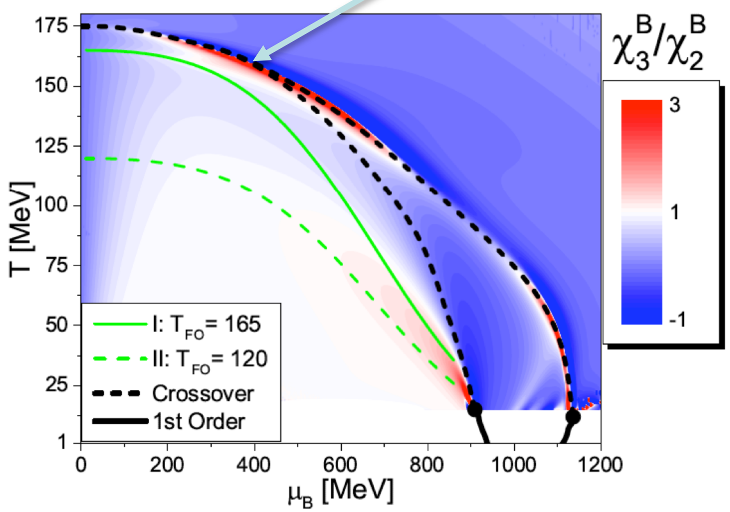
Conclusions from lattice susceptibilities

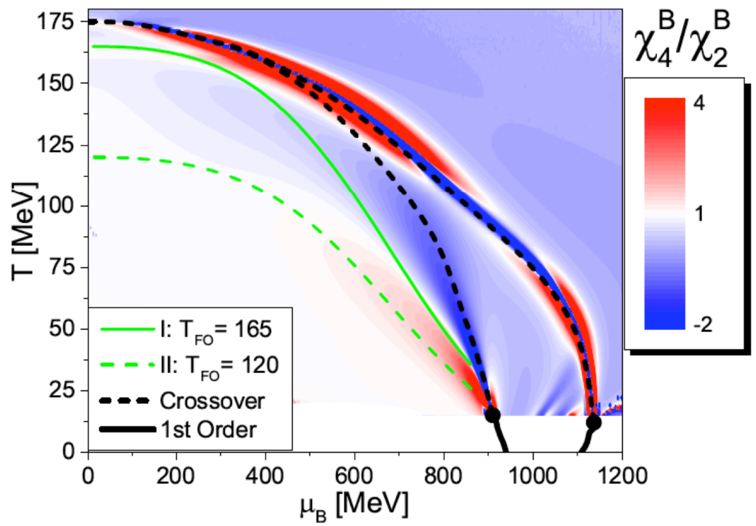
No quark repulsive interactions!

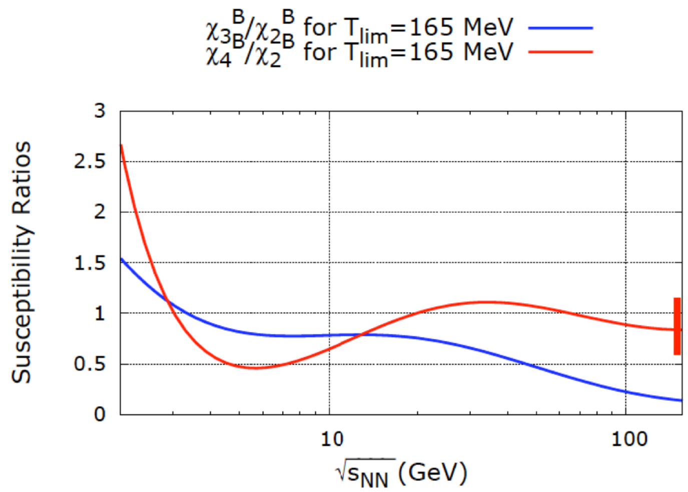
fluctuations in heavy-ion collisions

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 (2017)

gravitational wave signal GW170817

chirp mass $(m_1 m_2)^{3/5}/(m_1+m_2)^{1/5}$ ~ 1.188 $M_\odot$

Masses of 1.1 to 1.6 $M_\odot$. Total M ~2.74 $M_\odot$

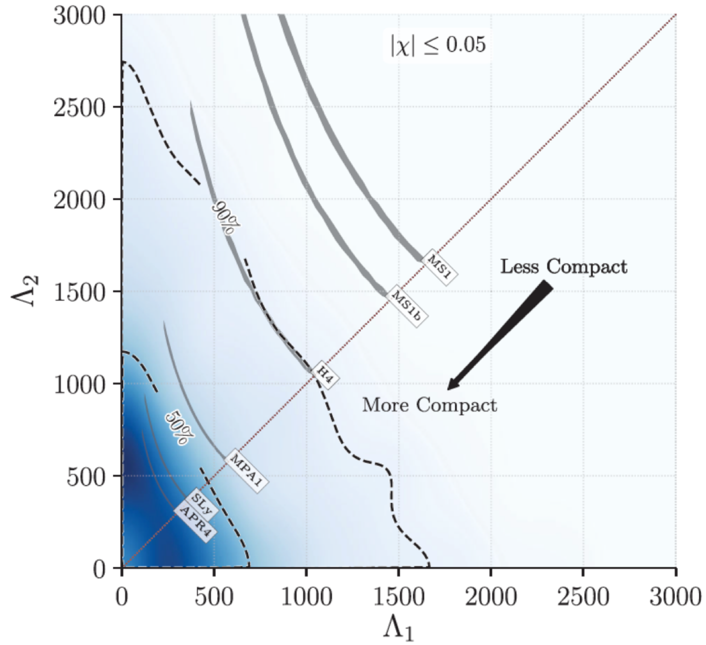
from Abbott etl al, PRL119, 161101 (2017)

NS merger , distance of ~ 40 Mpc

followed by GRB (GRB170817A) and optical/infrared signal (AT2017gfo)

EoS-dependent deformability $\Lambda \sim k_2 (R/M)^5$

$\Lambda(1.4\ M_\odot)$ < 800, 1400



hybrid stars with twins in agreement with **Λ** < 800

Paschalidis et al, arXiv:1712.00451

parametrized EoS with perturbative tail

11 km < R(1.4 $M_\odot$) < 13.4 km

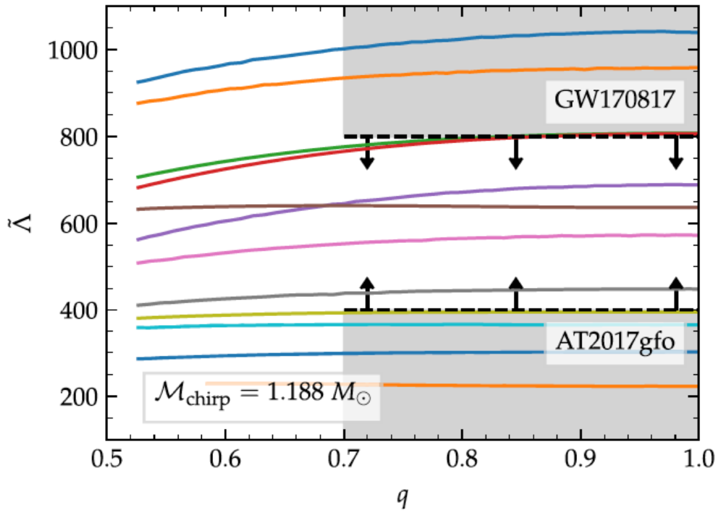
Annala et al, arXiv:171.02644

estimate for maximum static masses, lower Λ limit

idea: signal points to uniformly maximally rotating star at point of collapse

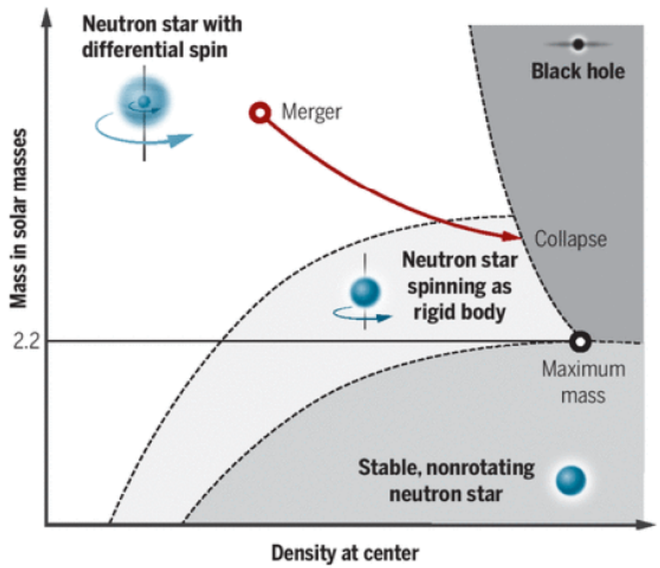
total mass known ➙ convert to baryon mass ➙ subtract ejecta mass
➙ estimate for max baryon number non-rotating ➙ convert back to TOV mass

Margalit, Metzger, APJ (2017): $M_{max} < 2.17\ M_\odot$
Shibata et al, PRD (2017): $M_{max} < 2.25\ M_\odot$
Rezzolla et al, APJ (2018): $M_{max} < 2.16\ M_\odot$
Ruiz et al, PRD (2018): $M_{max} < 2.28\ M_\odot$



range of Λ: 400 -800

Radice et al, APJL 852, L29 (2018)

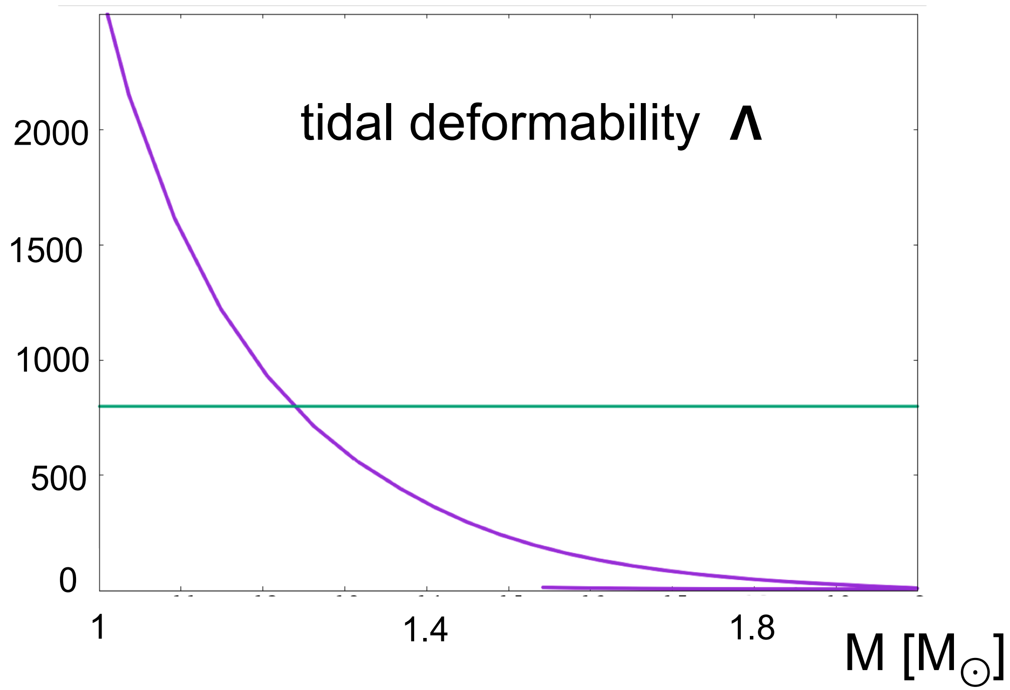


from Cho, Science 359, 724 (2018)

lower limit for deformation parameter
from electromagnetic signal / mass of disk

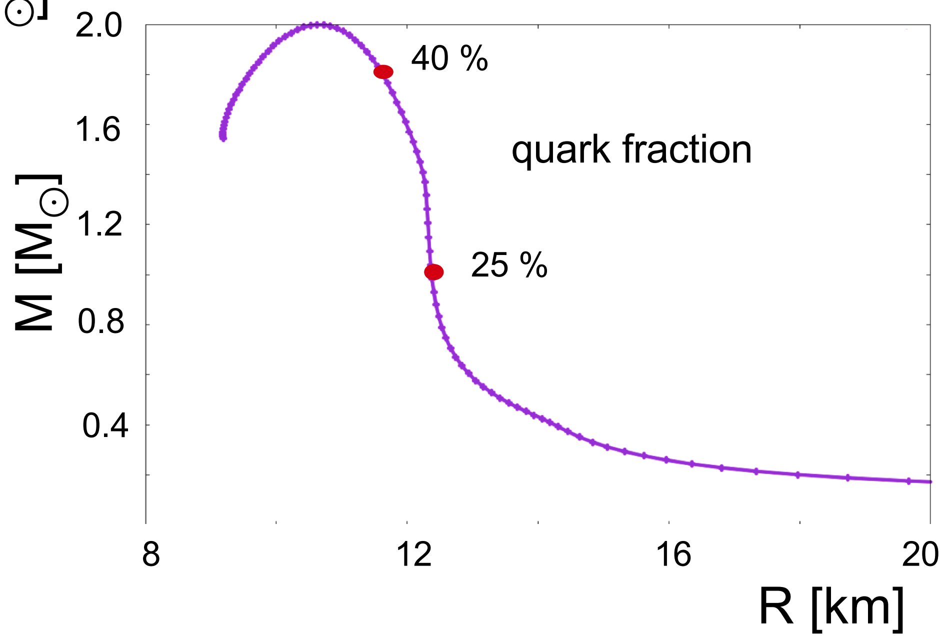
argument - low deformability, fast collapse into black hole, small mass of disk matter

Model results for star masses, radii, deformability



deformability Λ as function of mass

for GW170817 chirp mass
combined Λ between 430 and 450



CMF-Q model results in agreement with observation

merger calculations in progress

Conclusions

- heavy compact stars / hyper stars - little strangeness
- hybrid stars: stiff equation of state for quarks? lattice susceptibilities
- large mixed phase in hybrid star

- mergers evidence for smaller stellar radii and „small“ maximum masses
- substantial amount of ejected material in mergers, source of heavy nuclei

- rho meson condensate (just) possible
- magnetic fields remove quark core

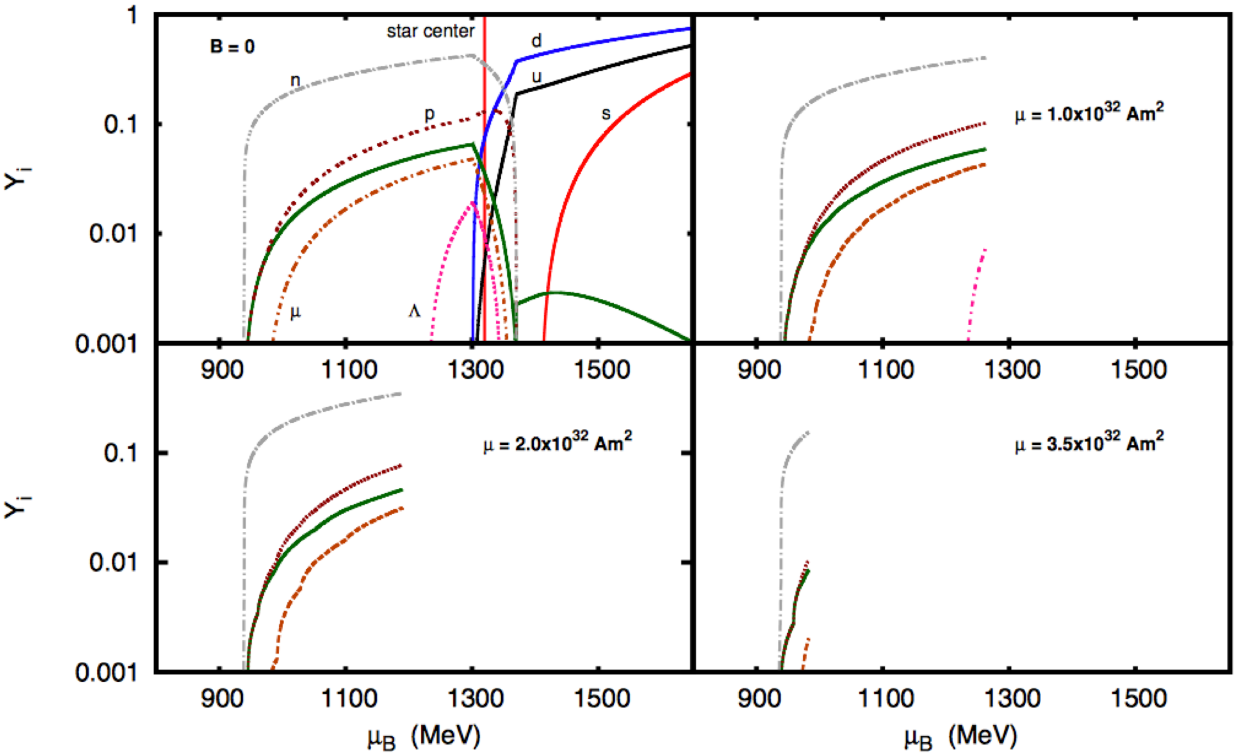
consequences for the equation of state

isospin-dependent nonlinearities
low slope parameter, affects drip line

exotic matter via extended mixed phase

hopefully more merger events, connecting astro and heavy-ion physics

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 is 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 bosons?

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*

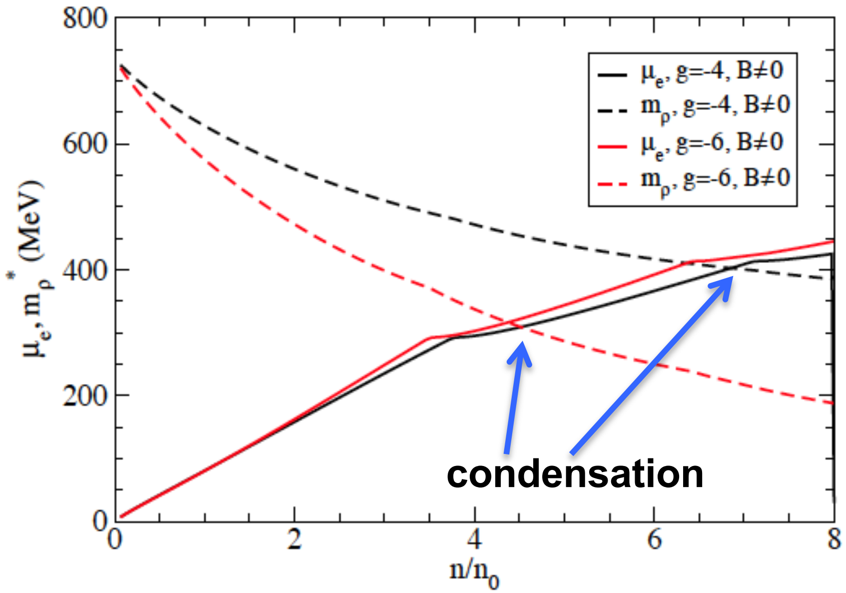
Advantage: high spin – strong interaction with magnetic field

Landau levels of the rho meson

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

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

charge chemical potential and effective rho mass as function of density



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 ?

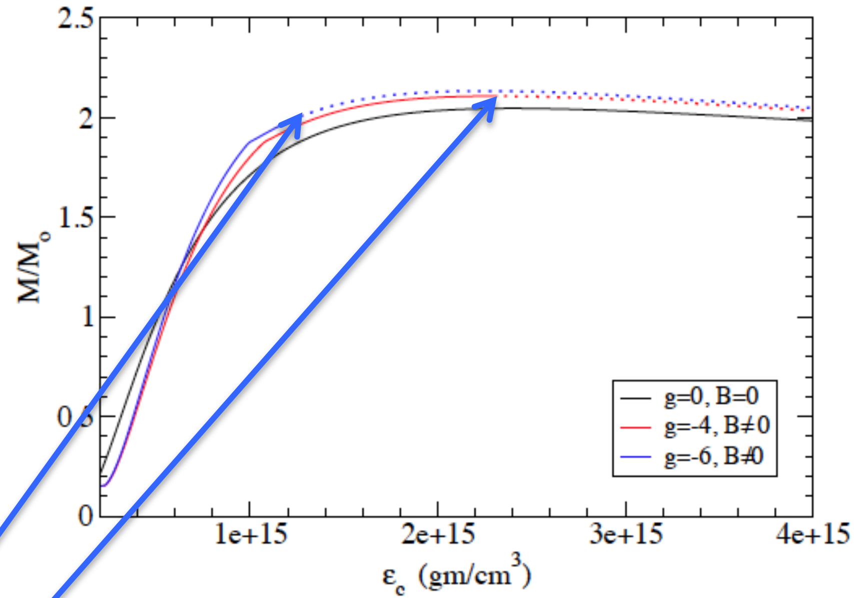
simple estimate $m_\rho^* = m_\rho - g\,\sigma$

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

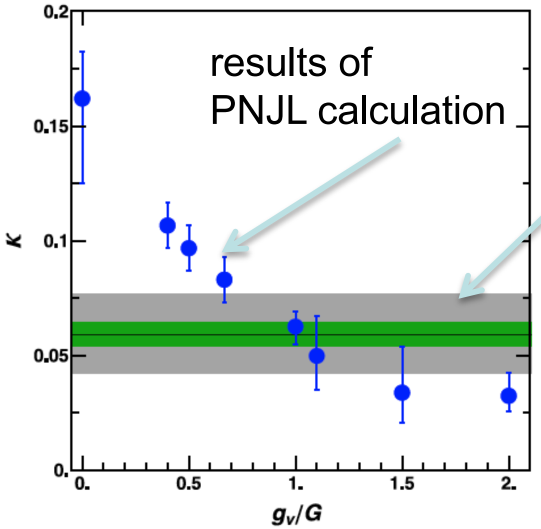


onset of condensation

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

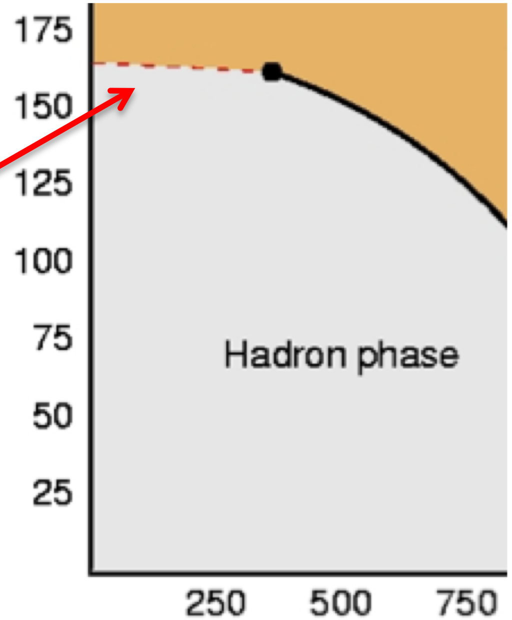
curvature $\kappa = -T_c \, dT_c(\mu)/d\mu^2|_{\mu=0}$

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



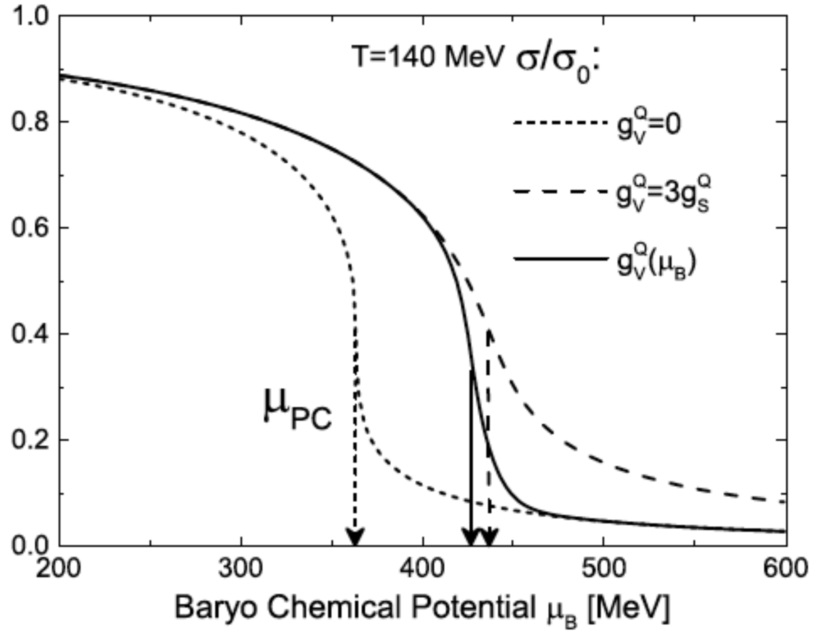
Lattice: Kacmarek et al
PRD 83, 014504 (2011)

large quark
vector repulsion?



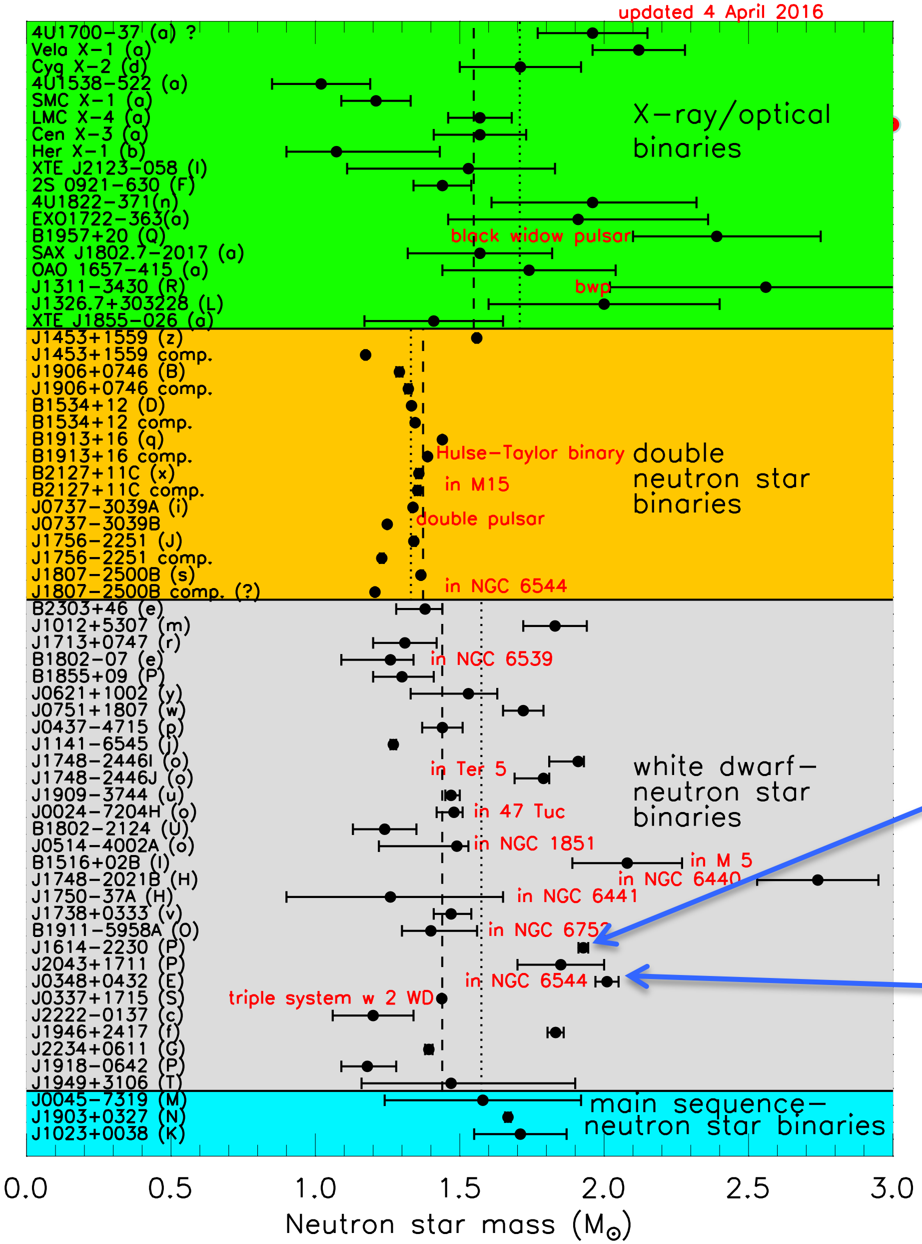
turn on/off repulsion
of quarks and baryons

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



Steinheimer,SWS,PLB 736,241

Masses of Neutron Stars



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

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

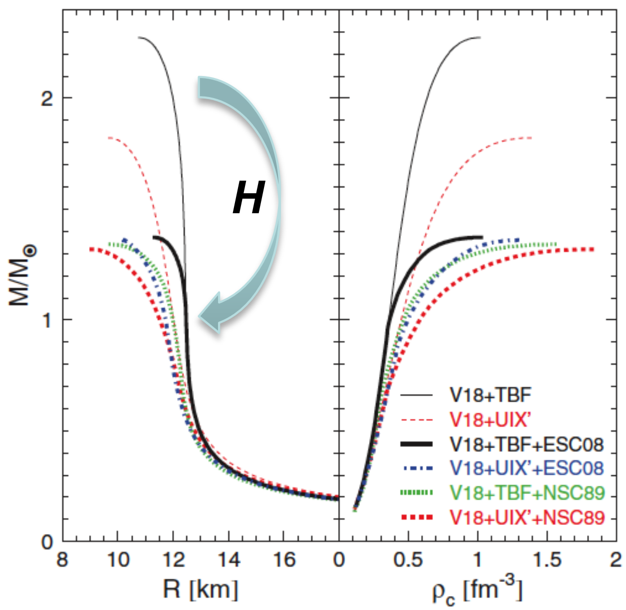
Neutron Stars with Hyperons

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

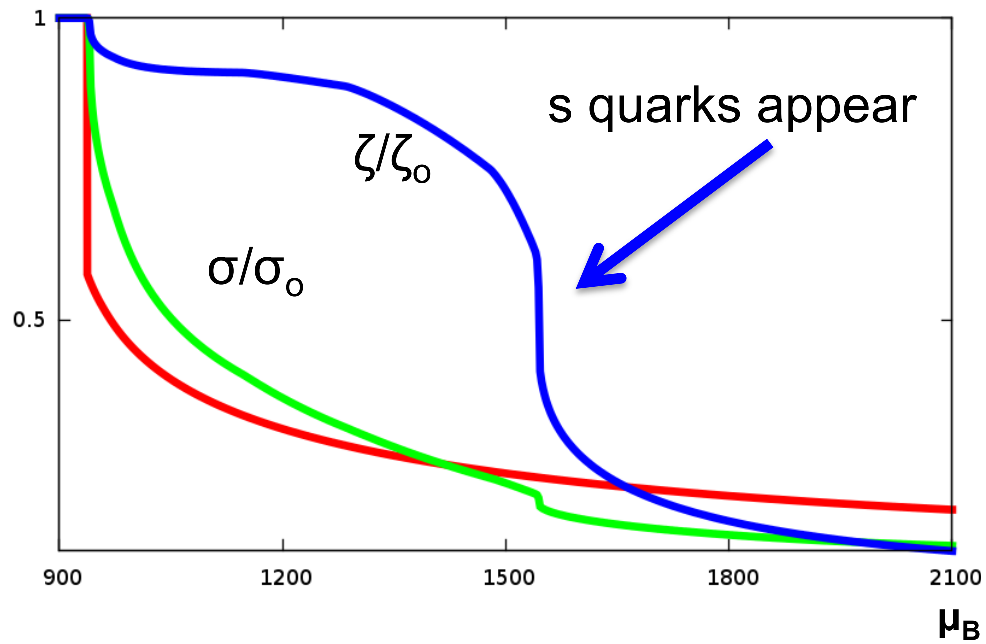
hyper stars tend to have small mass

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

star matter in beta equilibrium in QH approach

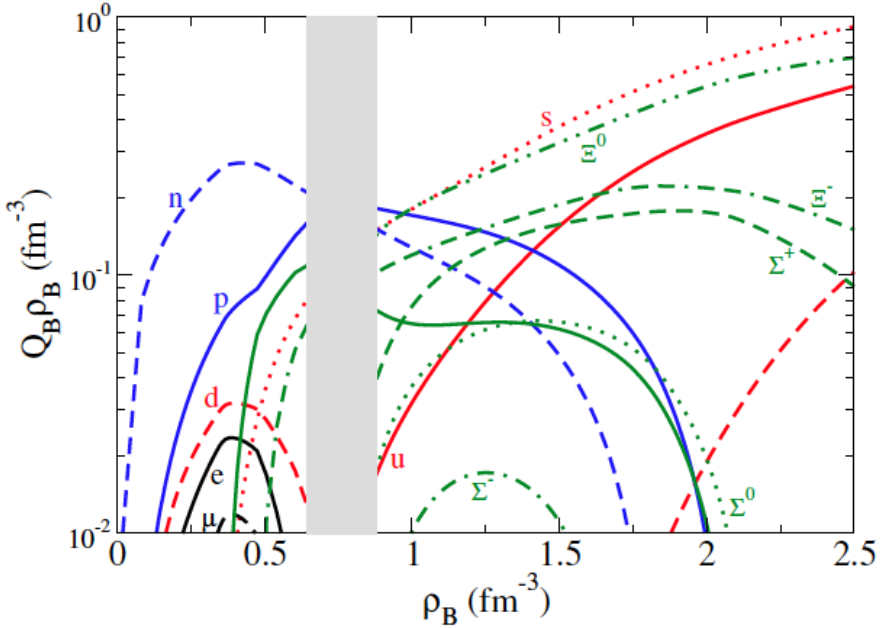


1st order phase transition
in star matter possible

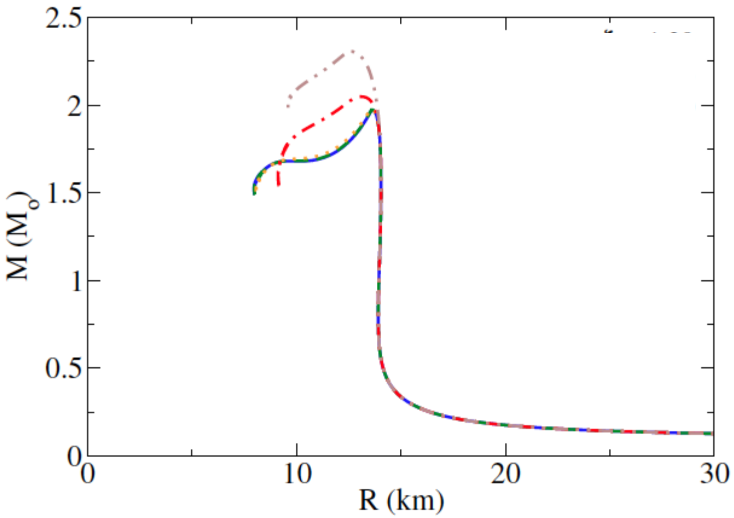
cross over in symmetric matter

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