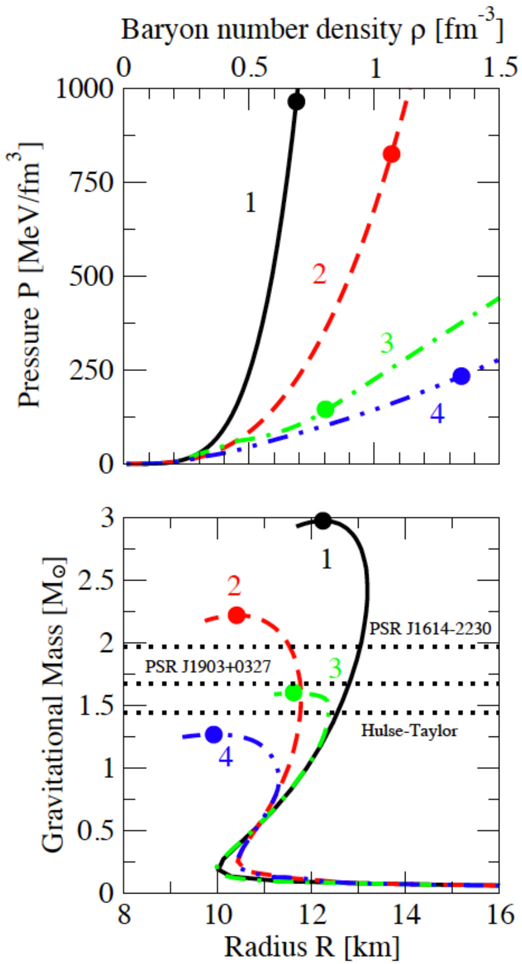
Some results on hyperons in neutron stars and the parity-doublet model

relatively easy to generate heavy stars with nucleonic EOS M_{max} ~ 2.8 $M_\odot$ (NL3)
~ 2.2 $M_\odot$ (APR)

Causal limit beyond ρ_c - $\varepsilon \sim p + \text{const}$



Rhoades, Ruffini (1974): $M_{max} < 3.2\ M_\odot$

Example of Brückner-HF calculation

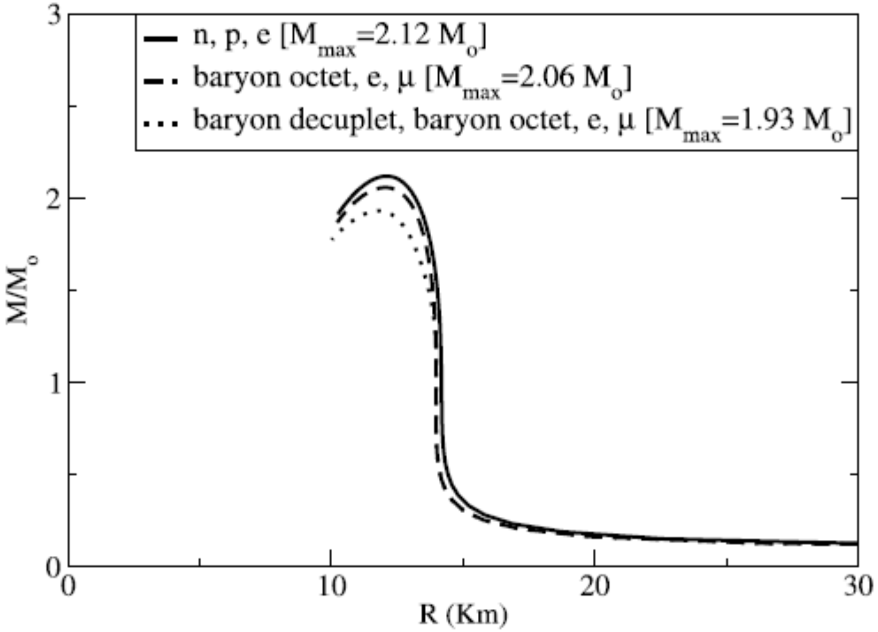
Includes 3-body forces

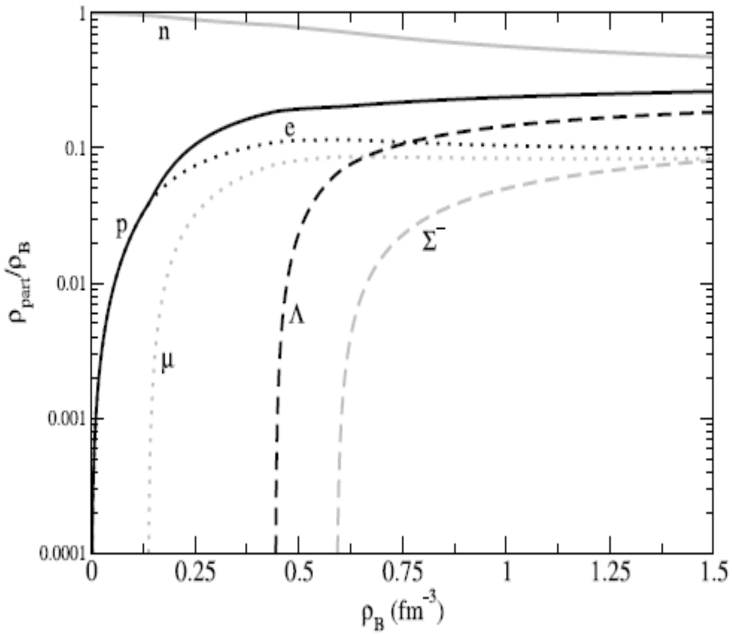
hyperons can reduce maximum mass significantly

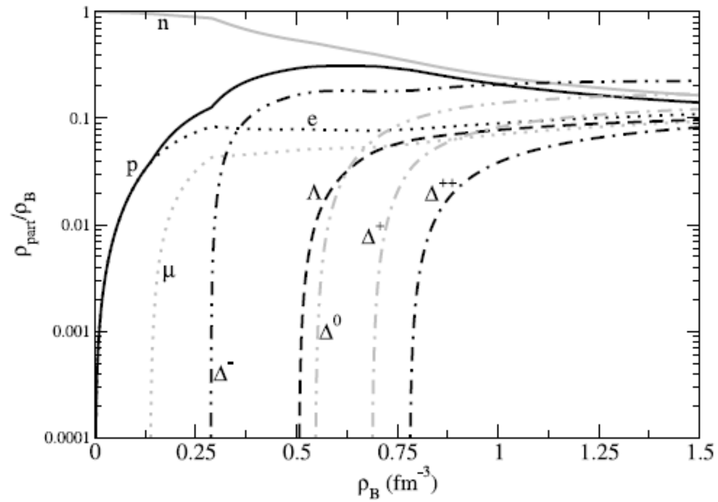
Tolman-Oppenheimer-Volkov equations
static spherical star - input $\varepsilon(p)$

Vidaña et. al., EPL 94 11002

Neutron star masses including different sets of particles







very good agreement with nuclear binding energies
refit of parameters to nuclear data – T. Schürhoff

changing masses with degrees of freedom

Dexheimer, SWS ApJ 683, 943 (2008)

hadronic model based on non-linear realization of chiral symmetry

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

baryons (n,Λ, Σ, Ξ) scalars (σ, ζ, δ^0) vectors (ω, ρ, φ) , pseudoscalars, glueball field χ

A) SU(3) interaction

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

B) meson interactions

$\sigma \sim <\bar{u}\,u + \bar{d}\,d> \qquad \zeta \sim <\bar{s}\,s> \qquad \delta^0 \sim <\bar{u}\,u - \bar{d}\,d>$

$\sim V(M) \qquad <\sigma> = \sigma_0 \neq 0 \qquad <\zeta> = \zeta_0 \neq 0$

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

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

→ light pseudoscalars, breaking of SU(3)

Nuclear Matter and Nuclei

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

compressibility ~ 221 MeV asymmetry energy ~ 32.6 MeV

parameter fit to known nuclear binding energies and hadron masses

new improved fit χ_{M^*} 2d calculation of all even-even nuclei

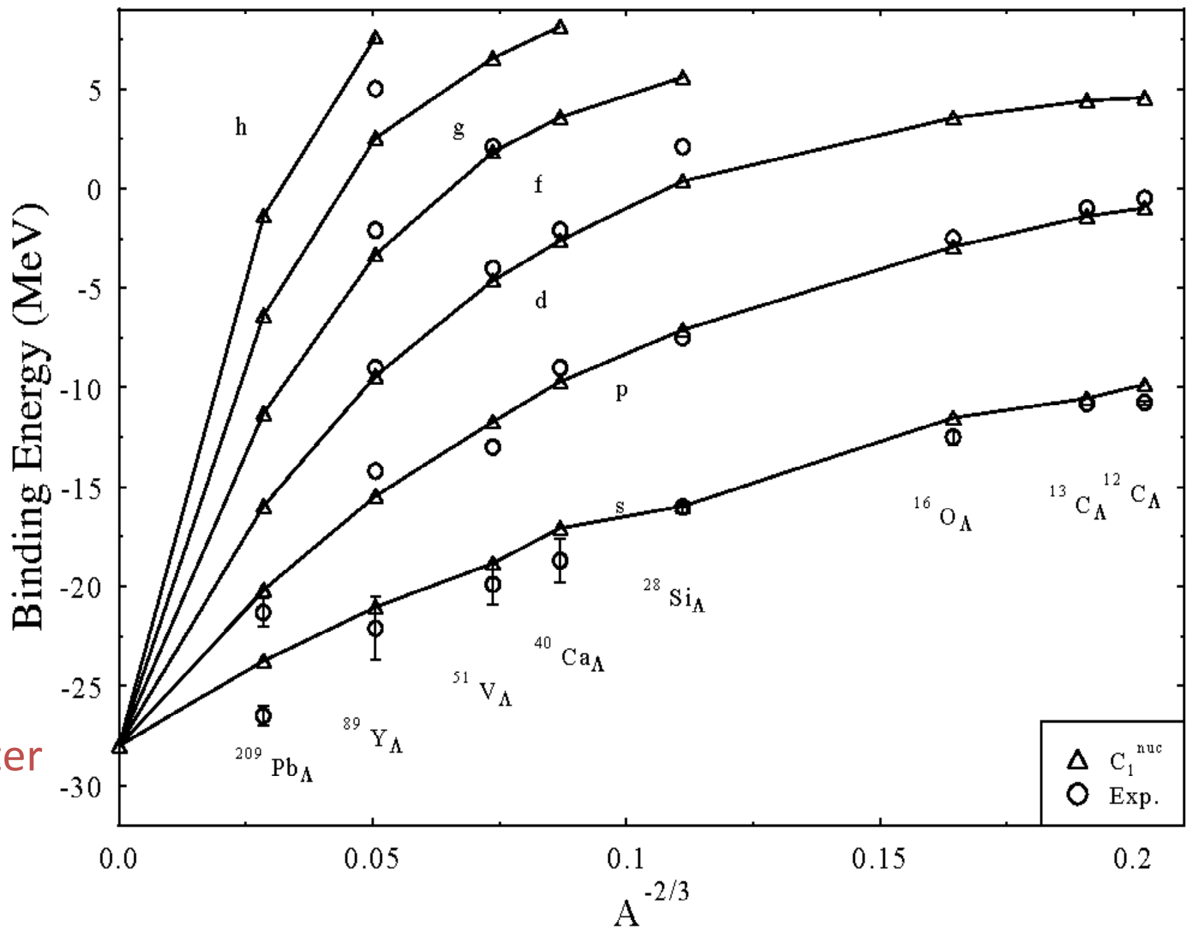
relativistic nuclear structure models

error in energy ε (A > 50) ~ 0.17 % (χ_M :0.21%, NL3: 0.25 %)
ε (A > 100) ~ 0.12 % (χ_M :0.14%, NL3: 0.16 %)

+ correct binding energies of hypernuclei

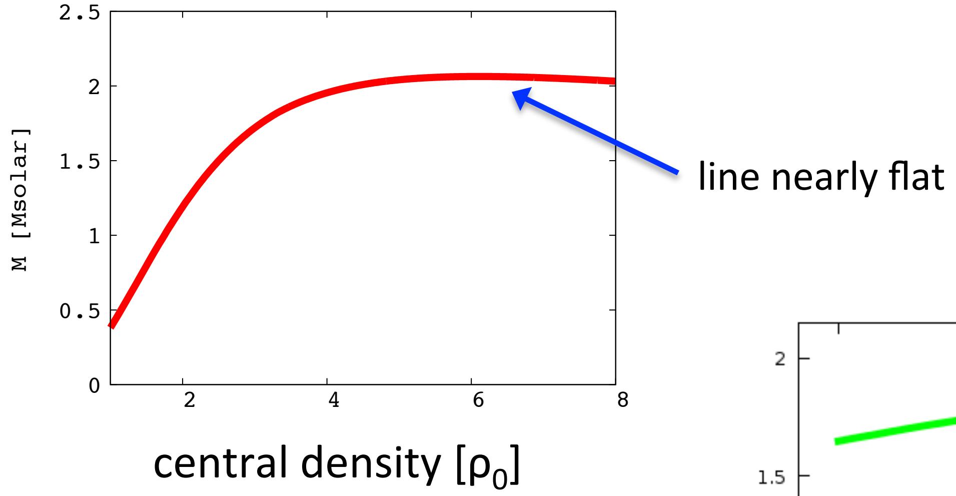
SWS, Phys. Rev. C66, 064310
+ in preparation

Λ (uds) single-particle energies



Nuclear matter

Dependence of M_{max} on quark core

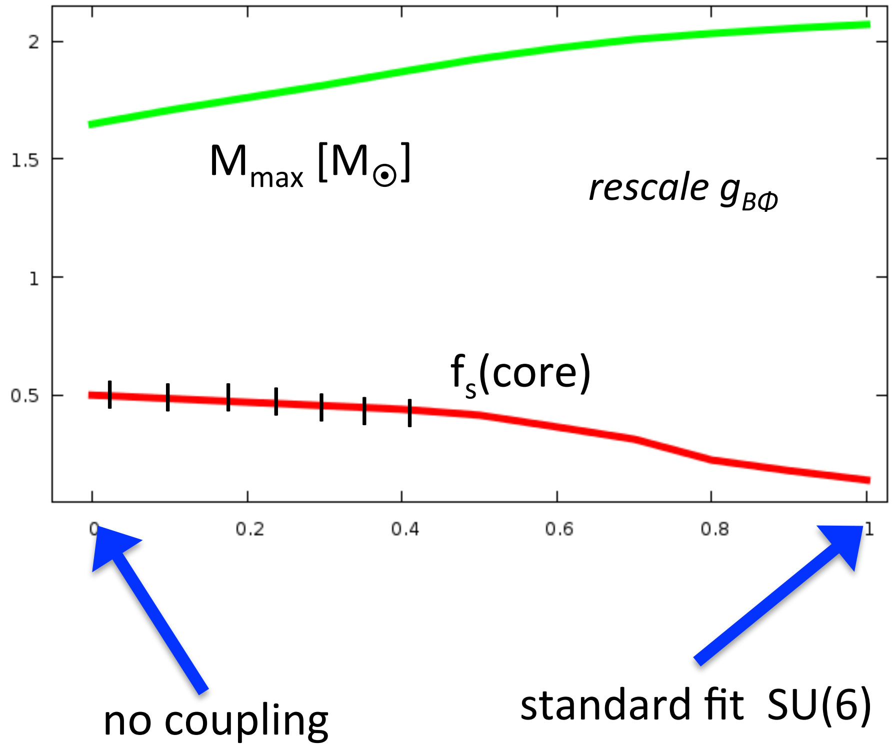


rather slow decay of strange condensate

decrease (artificially)
vector potential for hyperons

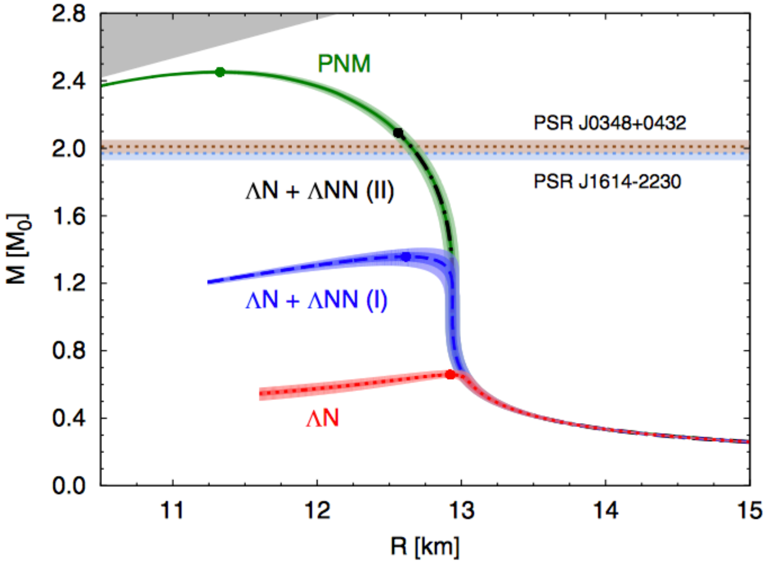
preserve “canonical” values
$U_\Lambda \sim -29$ MeV, $U_\Xi \sim -19$ MeV, $U_\Sigma > 0$ MeV

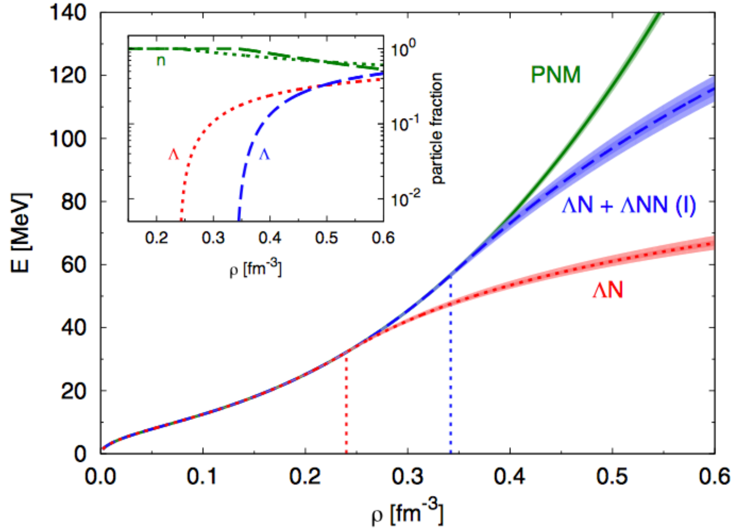
Impact of Φ field



Quantum Monte Carlo based on Argonne Potential

playing around with 3B forces



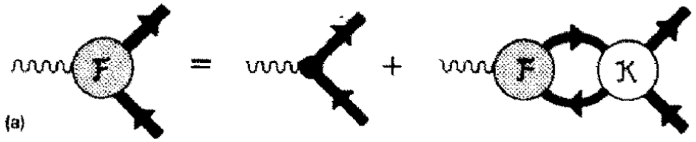


Lonardoni et al, PRL 114, 092301 (2015)

strong Lambda NN force – no hyperons in star below 2 M_{solar}

favored by Lambda separation energies of medium-light nuclei

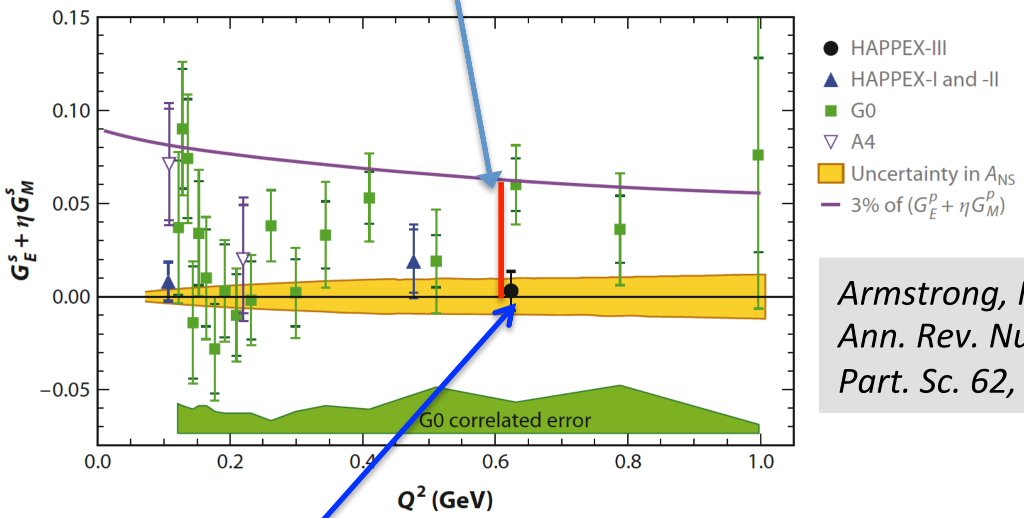
Strong coupling of N to Φ? - strange vector form factor of nucleon



band of possible values from calculation

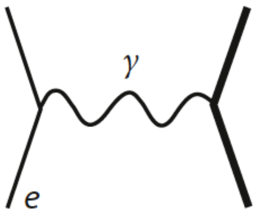
SWS, MPLA 10 1201 (1995)

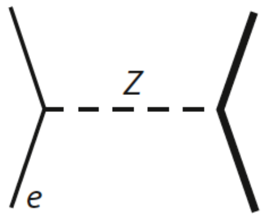
Summary of PV polarized eA scattering experiments



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)

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

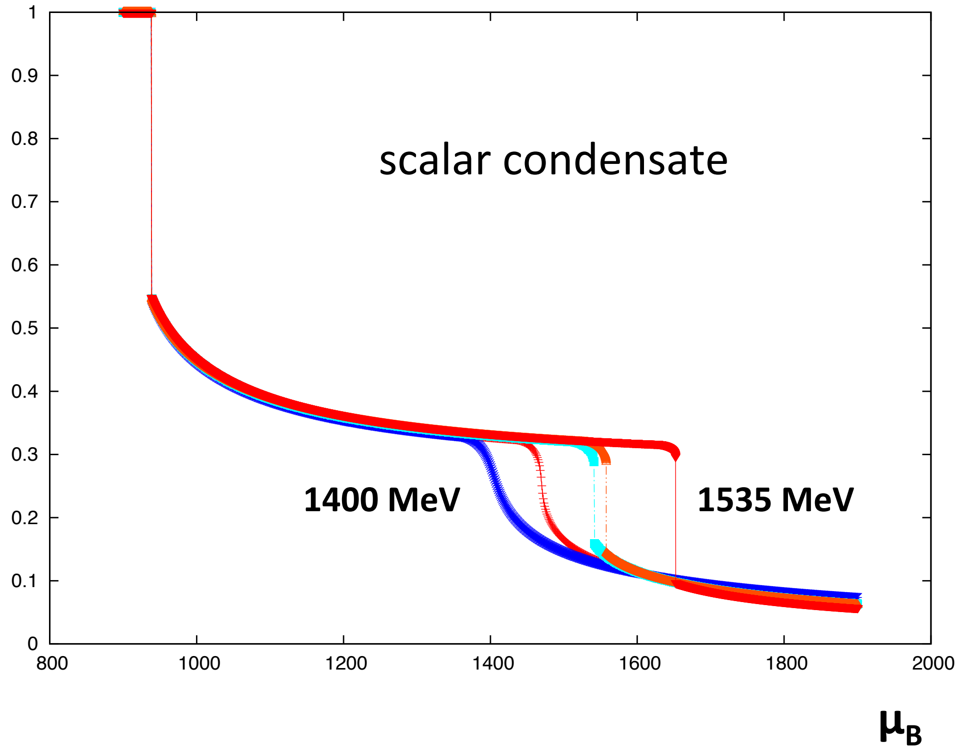
simplify investigation – same mass shift for whole octet

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

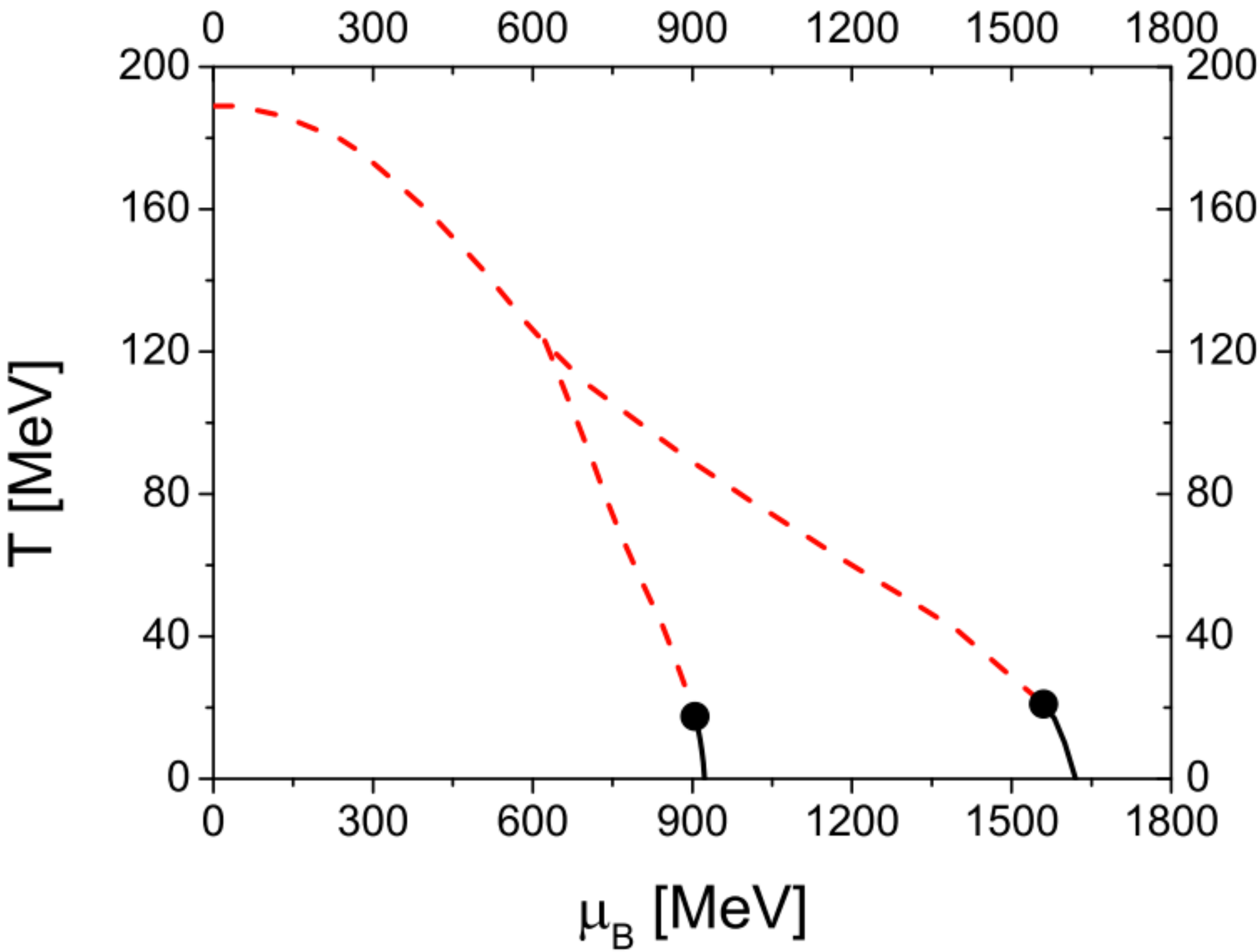
Steinheimer, SWS, Stöcker, PRC 84, 045208
Dexheimer, Steinheimer, Negreiros, SWS, PRC 87, 015804

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

Quark condensate for different masses m_{N*}

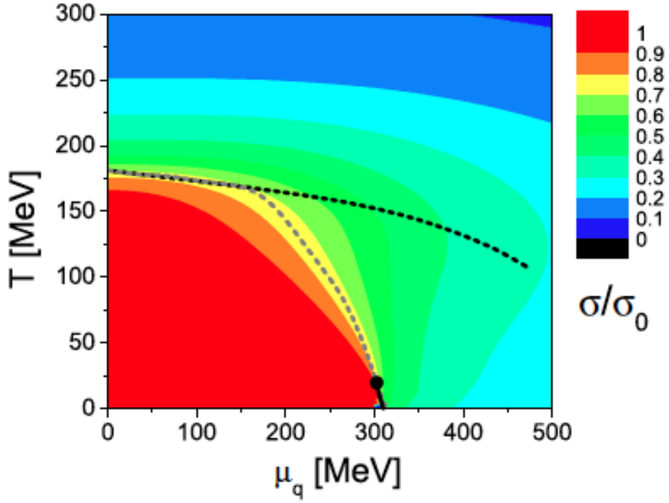


First order transition for masses ≥ 1470 MeV, below crossover



0
300
600
900
1200
1500
1800
200
160
120
80
40
0
T [MeV]
μB [MeV]

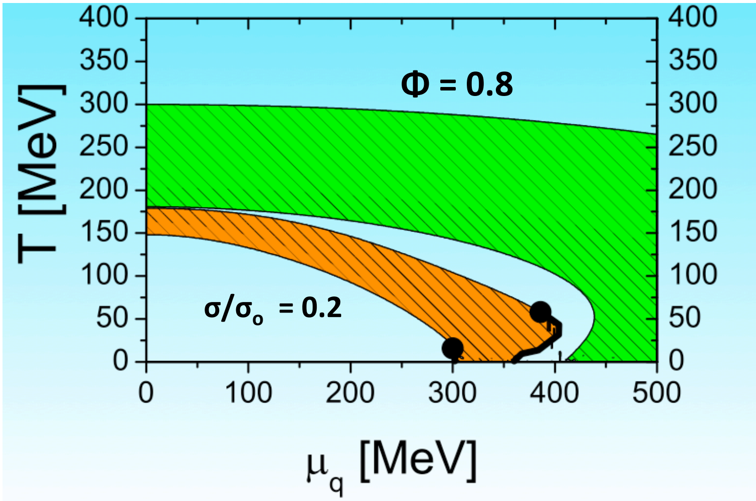
Order parameters for chiral symmetry and confinement in μ and T



except for liquid-gas no first-order transition

results for isospin symmetric matter

Excited quark-hadron matter in the parity-doublet approach

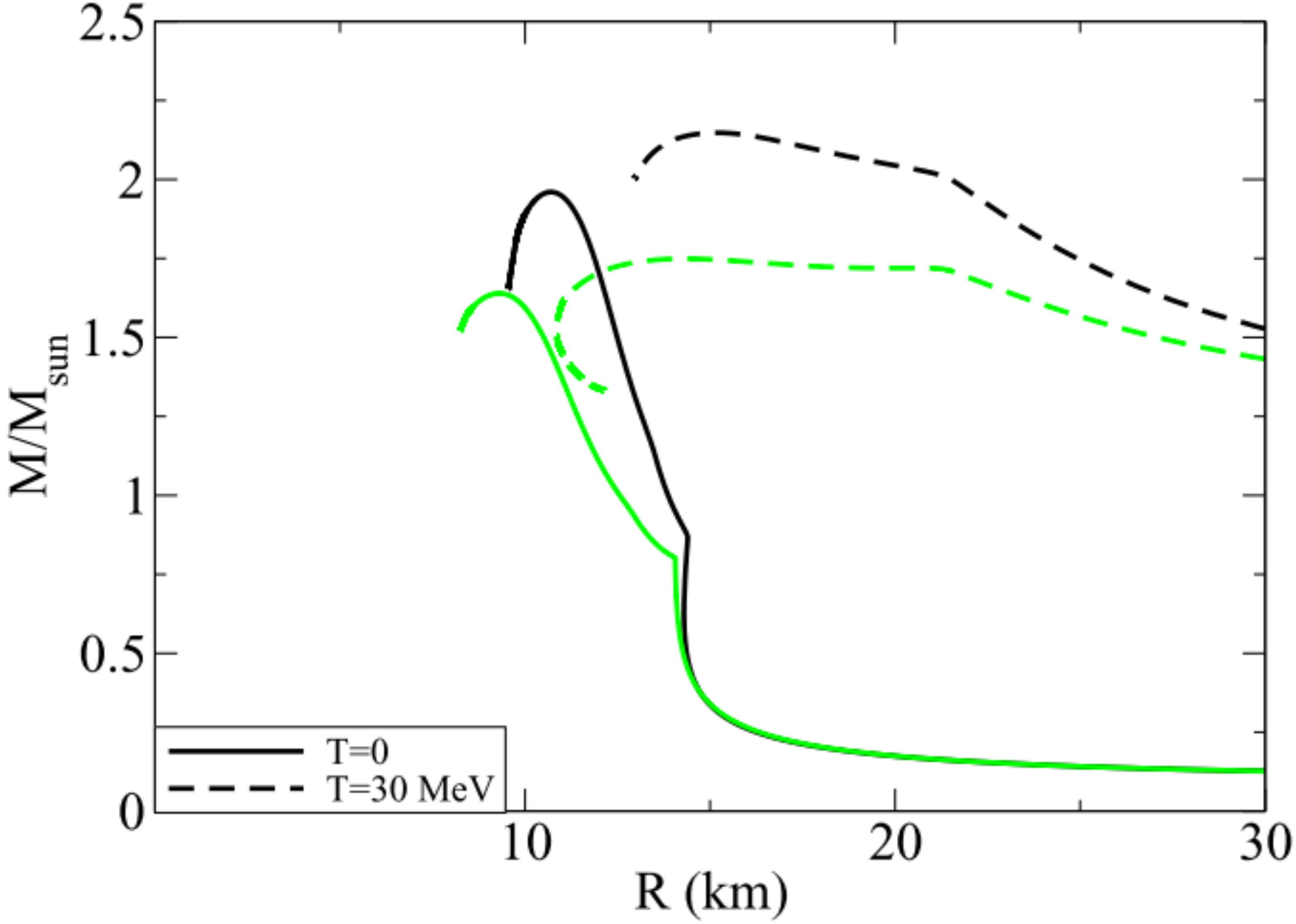


First-order phase transition
with low-T critical end point
due to chiral parity partners

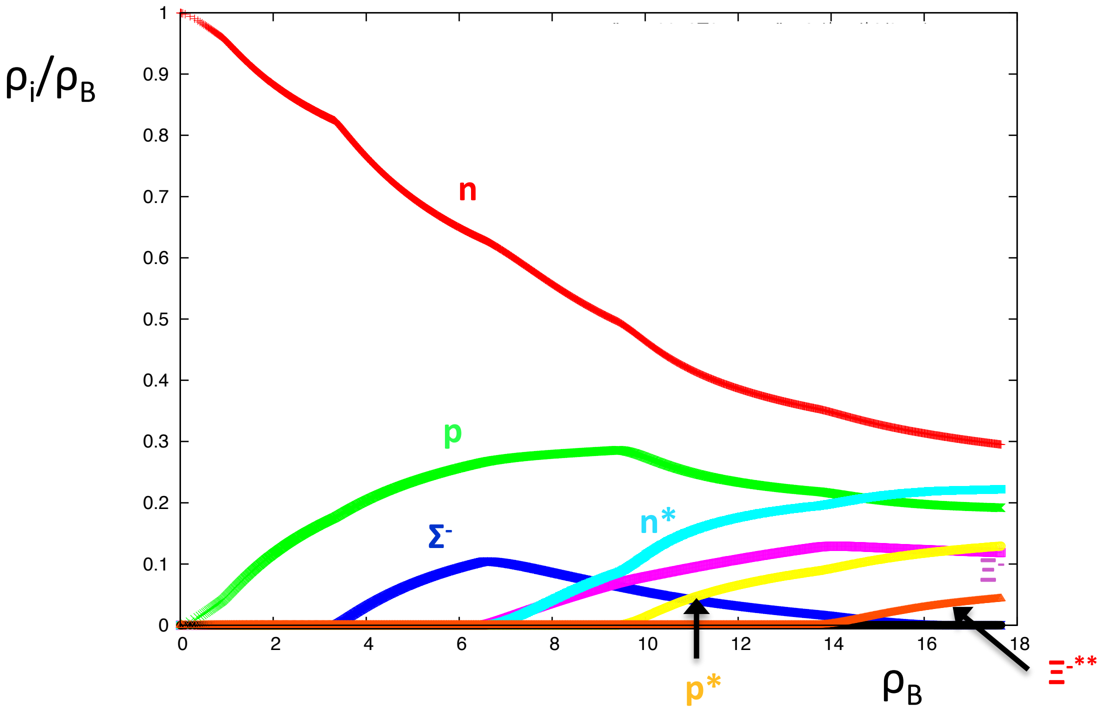
$$E_{\pm} = \sqrt{\left(g_1\sigma + g_2\varsigma\right)^2 + m_0^2} \pm \left(g'_1\sigma + g'_2\varsigma\right)$$

Steinheimer, SWS, Stöcker, PRC 84, 045208
Dexheimer, Steinheimer, Negreiros, SWS, PRC 87, 015804

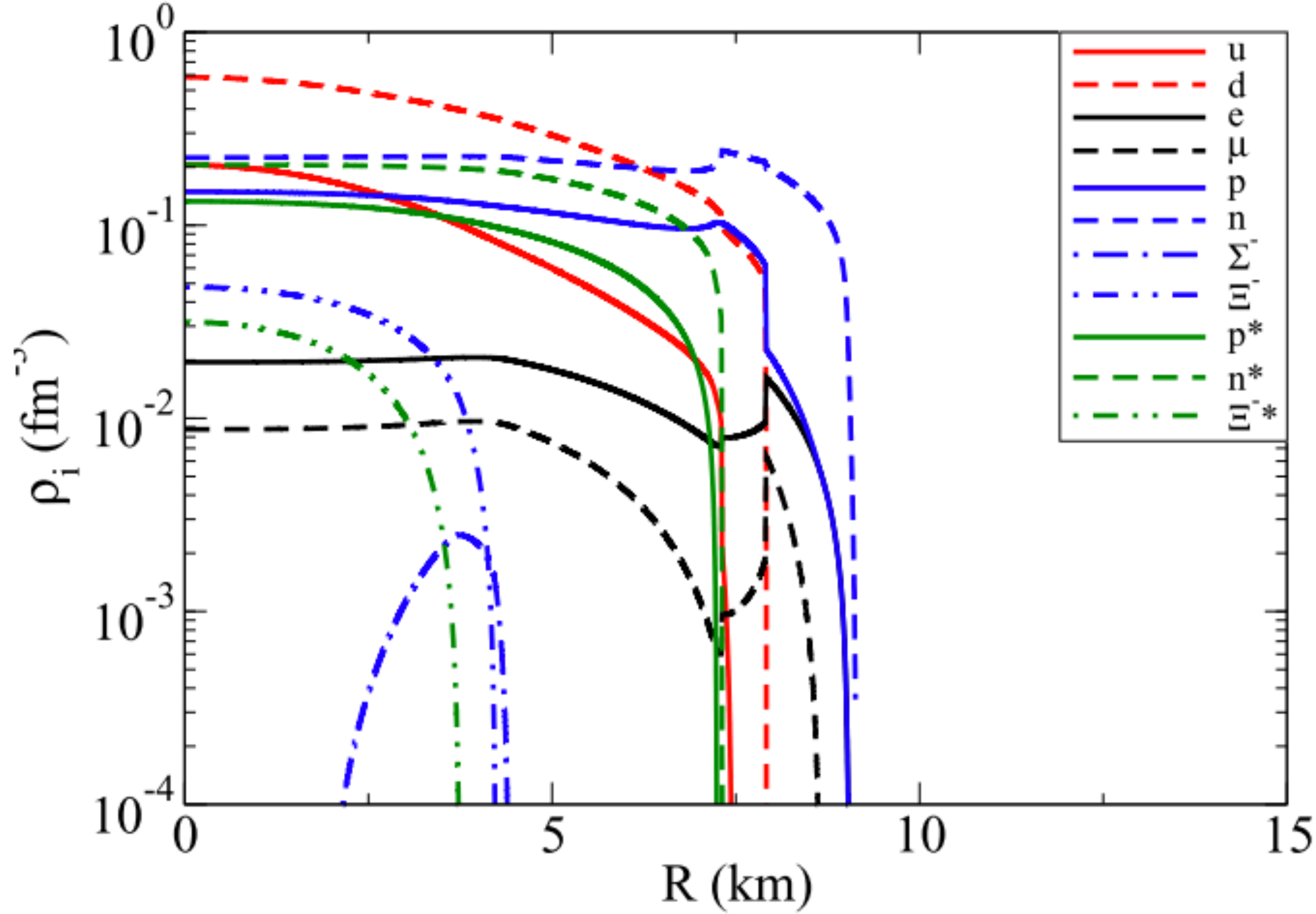
Neutron stars in parity-doublet approach



Particle population in nuclear matter in beta equilibrium with m_{N*} = 1400 MeV



particle mix not too exotic for reasonably large densities



u
d
e
μ
p
n
Σ⁻
Ξ⁻
p*
n*
Ξ⁻*
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
ρ_i (fm^{-3})
0
5
10
15
R (km)

some remarks on SU(6)

Classification / mass formulae with constituent quark models

assume flavor and spin independence

SU(6) symmetry $u_{\uparrow\downarrow}$, $d_{\uparrow\downarrow}$, $s_{\uparrow\downarrow}$

Baryonic states $[6] \times [6] \times [6] = [56]_S + \ldots$

Rearrange to $SU(3) \times SU(2)$: $[56] = [10]^{3/2} + [8]^{1/2}$

- decuplet degenerate with the octet

Mass formulae : degenerate + hypercharge + spin

(e.g. bag model - color-magnetic hyperfine splitting)

general linear SU(3)-invariant baryon-meson interaction

$$\mathcal{L}_{\mathrm{BW}} = -\sqrt{2} g_8^W (\alpha_W [\bar{B}\mathcal{O}BW]_F + (1-\alpha_W)[\bar{B}\mathcal{O}BW]_D)$$

$$- g_1^W \frac{1}{\sqrt{3}} \operatorname{Tr}(\bar{B}\mathcal{O}B) \operatorname{Tr} W,$$

$$[\bar{B}\mathcal{O}BW]_F := \operatorname{Tr}(\bar{B}\mathcal{O}WB - \bar{B}\mathcal{O}BW)$$
$$[\bar{B}\mathcal{O}BW]_D := \operatorname{Tr}(\bar{B}\mathcal{O}WB + \bar{B}\mathcal{O}BW) - \tfrac{2}{3} \operatorname{Tr}(\bar{B}\mathcal{O}B) \operatorname{Tr} W$$

three coupling parameters g_8, g_1, α

Vector mesons ($O = \gamma^\mu$, $W = V_\mu$)

$g_{N\omega} = 1/3\ (1 - 4\alpha)\ g_8 - \sqrt{(2/3)}\ g_1$

$g_{\Lambda\omega} = 2/3\ (1 - \alpha)\ g_8 - \sqrt{(2/3)}\ g_1$

$g_{\Sigma\omega} = 2/3\ (-1 + \alpha)\ g_8 - \sqrt{(2/3)}\ g_1$

$g_{\Xi\omega} = 1/3\ (1 + 2\alpha)\ g_8 - \sqrt{(2/3)}\ g_1$

$g_{N\varphi} = \sqrt{2}\ 1/3\ (-1 + 4\alpha)\ g_8 - 1/\sqrt{3}\ g_1$

$g_{\Lambda\varphi} = \sqrt{2}\ 2/3\ (-1 + \alpha)\ g_8 - 1/\sqrt{3}\ g_1$

$g_{\Sigma\varphi} = \sqrt{2}\ 2/3\ (1 - \alpha)\ g_8 - 1/\sqrt{3}\ g_1$

$g_{\Xi\varphi} = \sqrt{2}\ 1/3\ (-1 - 2\alpha)\ g_8 - 1/\sqrt{3}\ g_1$

Isovector:

$g_{p\rho} = -\, g_8$ $\quad g_{\Lambda\rho} = 0$ $\quad g_{\Sigma^+\rho} = -2\,\alpha\, g_8$ $\quad g_{\Xi^0\rho} = (1 - 2\,\alpha)\, g_8$

universality: $\quad \alpha = 1$

$g_{N\omega} = -\, g_8 - \sqrt{(2/3)}\, g_1$ $\quad g_{N\varphi} = \sqrt{2}\, g_8 - 1/\sqrt{3}\, g_1$

$g_{\Lambda\omega} = \quad - \sqrt{(2/3)}\, g_1$ $\quad g_{\Lambda\varphi} = \quad - 1/\sqrt{3}\, g_1$

$g_{\Sigma\omega} = \quad - \sqrt{(2/3)}\, g_1$ $\quad g_{\Sigma\varphi} = \quad - 1/\sqrt{3}\, g_1$

$g_{\Xi\omega} = \quad g_8 - \sqrt{(2/3)}\, g_1$ $\quad g_{\Xi\varphi} = -\sqrt{2}\, g_8 - 1/\sqrt{3}\, g_1$

SU(6) limit: $\quad \alpha = 1$ $\quad g_1/g_8 = \sqrt{6}$

$g_{N\omega} = -3\, g_8$ $\quad g_{N\varphi} = 0$

$g_{\Lambda\omega} = -2\, g_8$ $\quad g_{\Lambda\varphi} = -\sqrt{2}\, g_8$

$g_{\Sigma\omega} = -2\, g_8$ $\quad g_{\Sigma\varphi} = -\sqrt{2}\, g_8$

$g_{\Xi\omega} = -1\, g_8$ $\quad g_{\Xi\varphi} = -2\sqrt{2}\, g_8$

simple quark counting

Nijmegen ESC08 values :

Rijken et al., PTP Suppl. 185, 14 (2010)

D-type coupling = 0 but octet to singlet contribution not the SU(6) value

g_8/g_1 ~ 5.13 compared to 2.45

but – more complicated

adding pomeron/odderon (singlet, short-range)

experimental sources

K + p ➔ H + π, H scattering
from the 60s
plus Σ^+p scattering data at KEK

Summary – HN sparse data, HH nothing
hyper stars possible, but with few hyperons (repulsion)
more hyperons -> escape to hyper stars
probably most important ΞΞ interaction