The boundaries on the mass of Sexaquark as a candidate for dark matter

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What is a Sexaquark?

- S: Q=0, B = 2, s= −2
- Three diquarks in spin-color-flavor-singlet state
- $m_{\Lambda\Lambda} = 2231$ MeV
- The lowest channel for Λ decay:

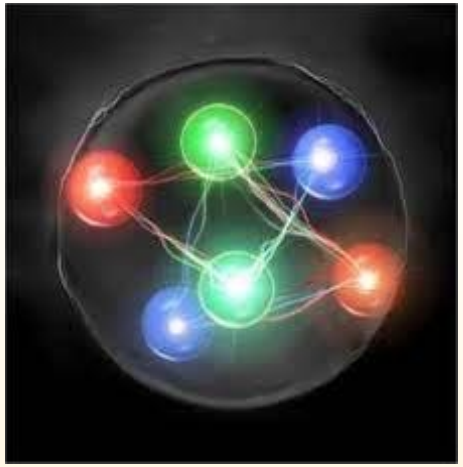
$\Lambda \rightarrow p + e + \bar{\nu}$

$m_{\Lambda} + m_p + m_e$= 1115.5+938+0.5= 2054 MeV

$2\,(m_p + m_e) \quad = 2(938 + 0.5) \quad$ =1877 MeV

if 2054 MeV $< m_s <$ 2231 MeV: S decays

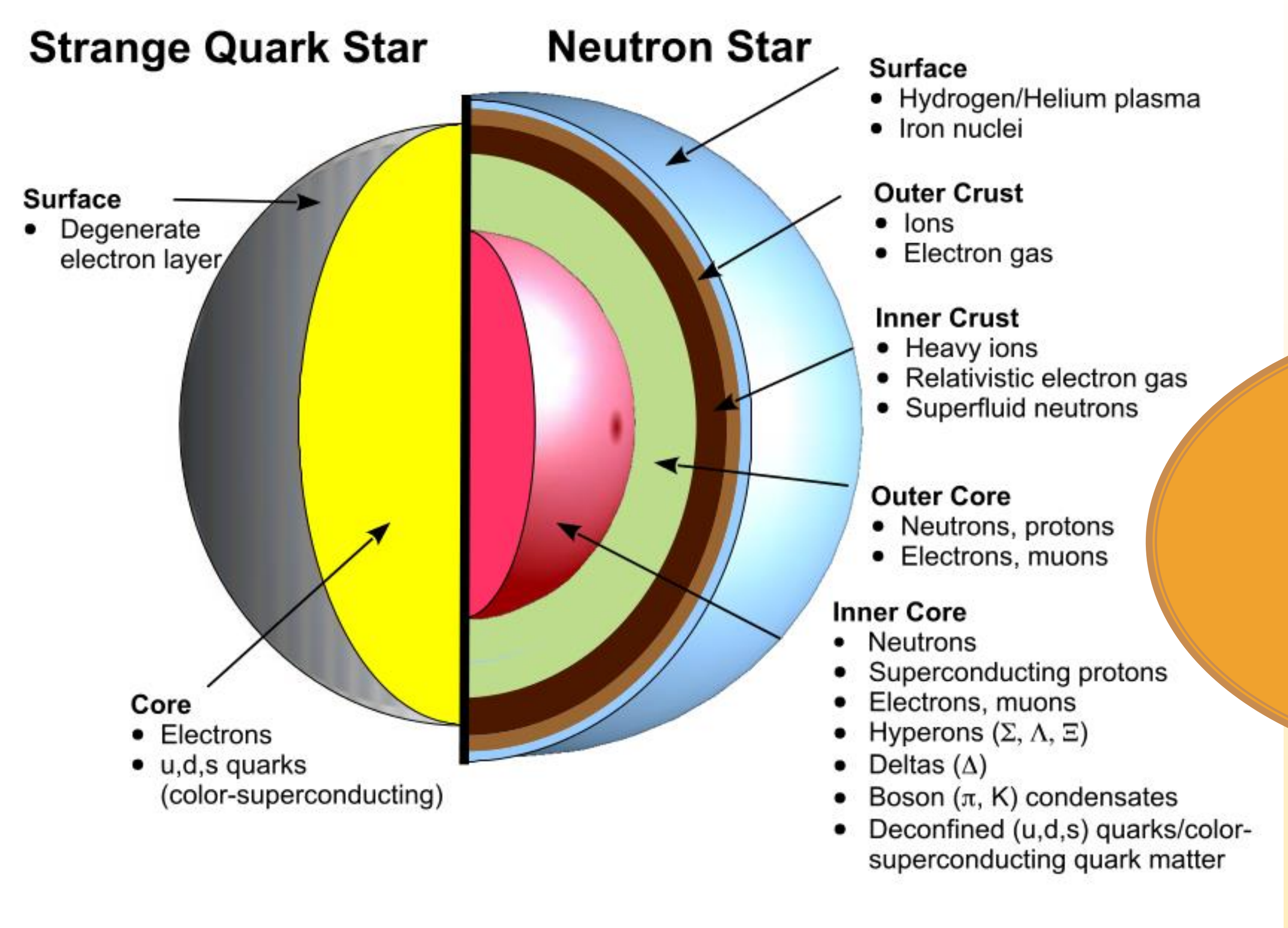
- If $m_s \leq (m_{\Lambda} + m_p + m_e) = 2054$ MeV, S decays with a lifetime more than the age of the universe
- If $m_s \leq 2(m_p + m_e) = 1877$ MeV : S is absolutely stable



uuddss

G. R. Farrar, (2022), arXiv:2201.01334 [hep-ph]
G. R. Farrar, (2018), arXiv:1805.03723 [hep-ph]

What are the consequences for Neutron Stars?



Also probably dibaryons like $d^*(2380)$ or $S(m_S < 2054)$ As compact, bosonic multiquark state

The high density of the inner core of neutron star, makes it a suitable environment for forming Sexaquark.

A RELATIVISTIC DENSITY FUNCTIONAL APPROACH TO HYPERNUCLEAR MATTER WITH SEXAQUARK (DD2Y-T+S)

$\Omega = \Omega(\{\mu_i\})$ & $\mu_i = B_i\mu_b + Q_i\mu_q + S_i\mu_s + L_i\mu_l$

$$n_B = \sum_i B_i n_i^{(v)} = n_p^{(v)} + n_n^{(v)} + n_\Lambda^{(v)} + n_{\Sigma^+}^{(v)} + n_{\Sigma^0}^{(v)} + n_{\Sigma^-}^{(v)} + n_{\Xi^0}^{(v)} + n_{\Xi^-}^{(v)} + 2n_S^{(v)}$$

- All constituent particles are considered as quasiparticles in the medium with effective mass and effective chemical potentials.

$m_i^* = m_i - S_i$, $\mu_i^* = \mu_i - V_i$

S. Typel and H. H. Wolter, Nucl. Phys. A **656**, 331 (1999)

S_i : *Scalar potential* $\quad S_i = \Gamma_{i\sigma}\sigma \quad \Gamma_{im} = g_{im}\Gamma_m(n_{cpl})$

V_i : *Vector potential* $\quad V_i = \Gamma_{i\omega}\omega + \Gamma_{i\rho}\rho + \Gamma_{i\phi}\phi + B_i V^{(r)} + W_i^{(r)}$

- The substructure of S and its interactions are not known yet. So it has been considered as an ideal bosonic gas with the mass as the only parameter.

- A constant mass of S violates the stability of NS.

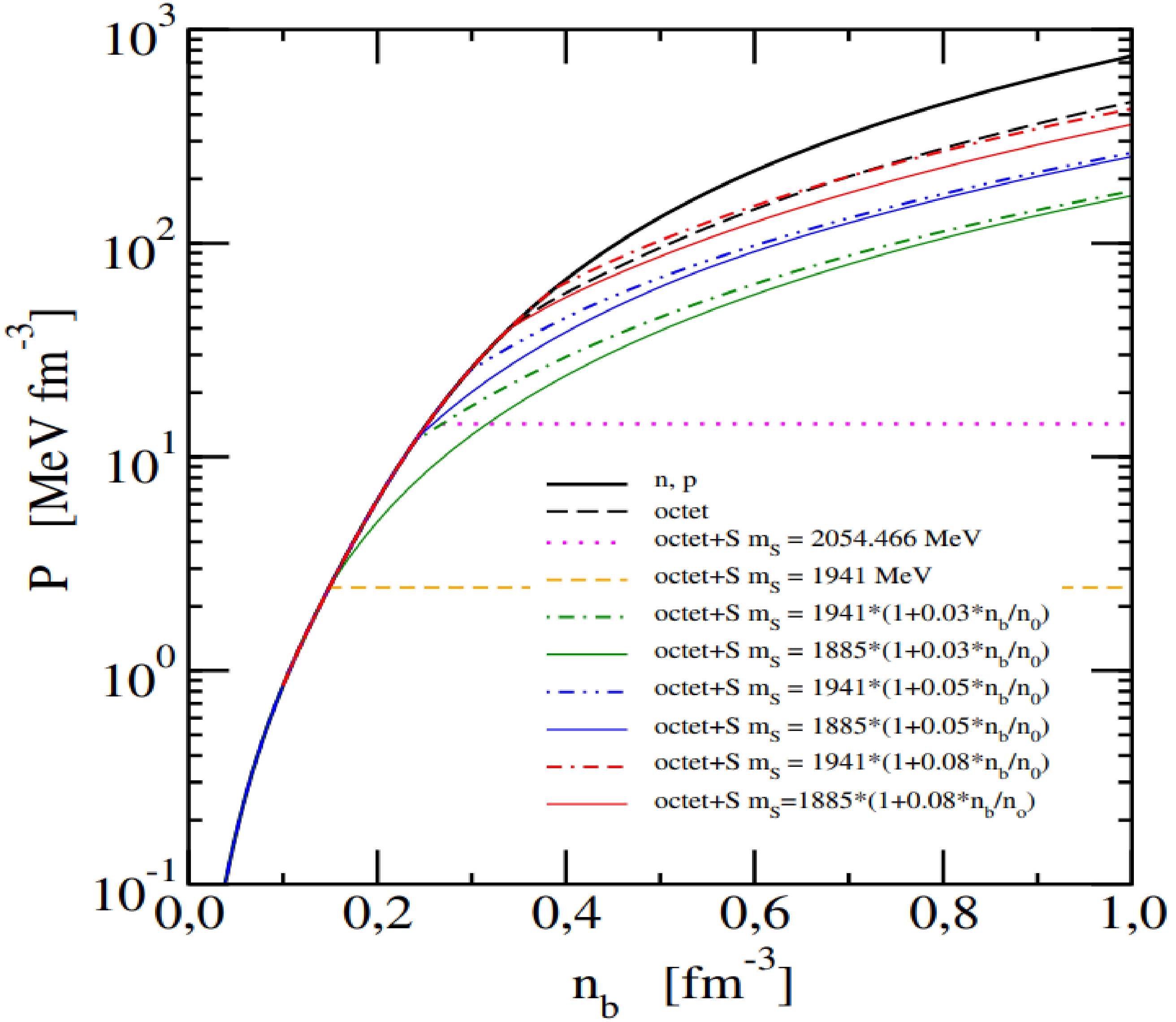
- A linear mass shift has been assumed instead of a meson-coupling interaction as all medium effects.

$$S_S = -\Delta m_S \quad V_S = W_S^{(r)} \quad \Delta m_S = m_S \left(1 + x_S \frac{n_B}{n_0}\right)$$

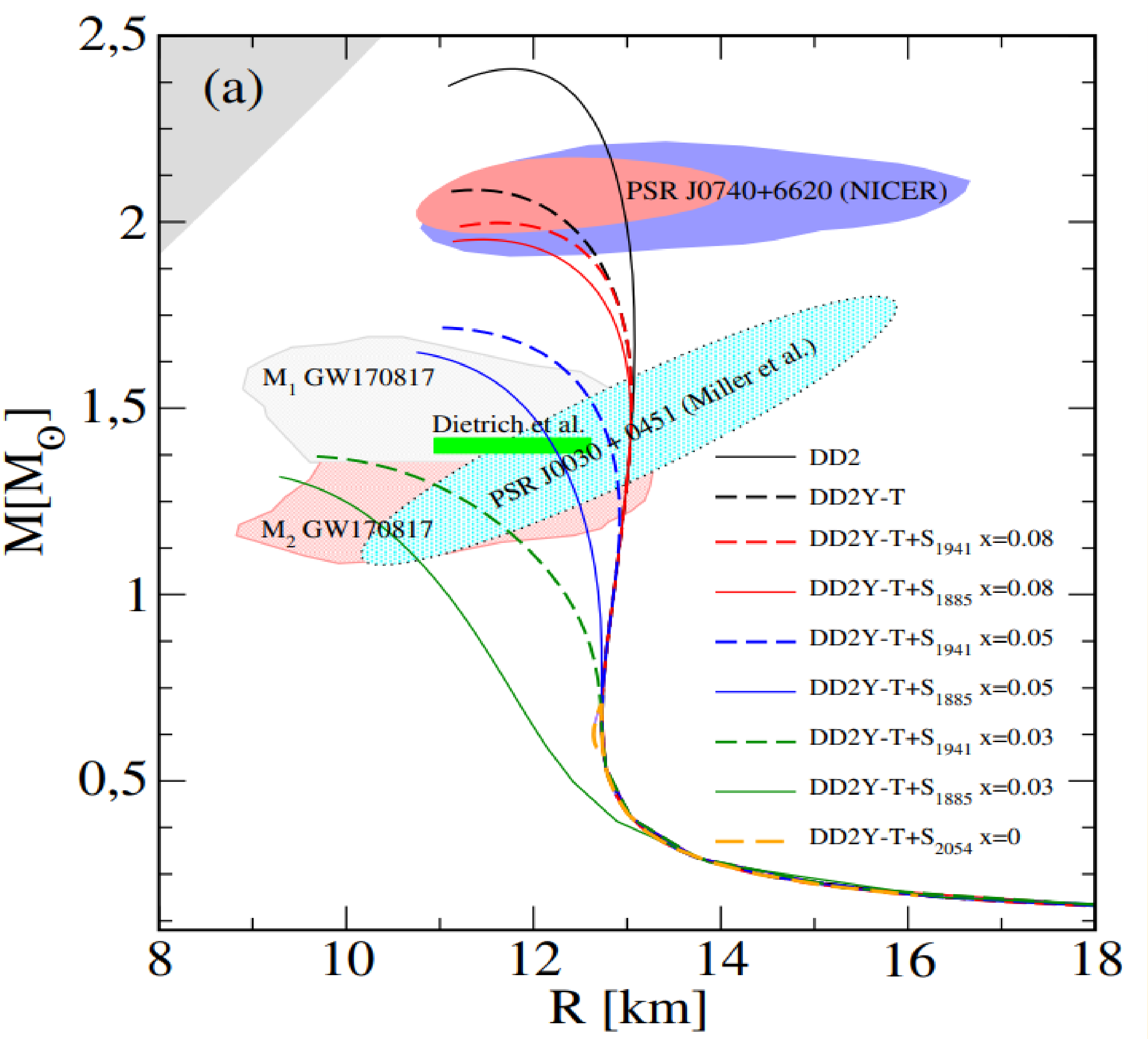
- This assumption results in an increase of the S onset density as well as the condensation density so that there is still an increase of the pressure at higher densities.

$$P = -\Omega.\ f = \varepsilon = \Omega + \sum_i \mu_i n_i^{(v)}$$

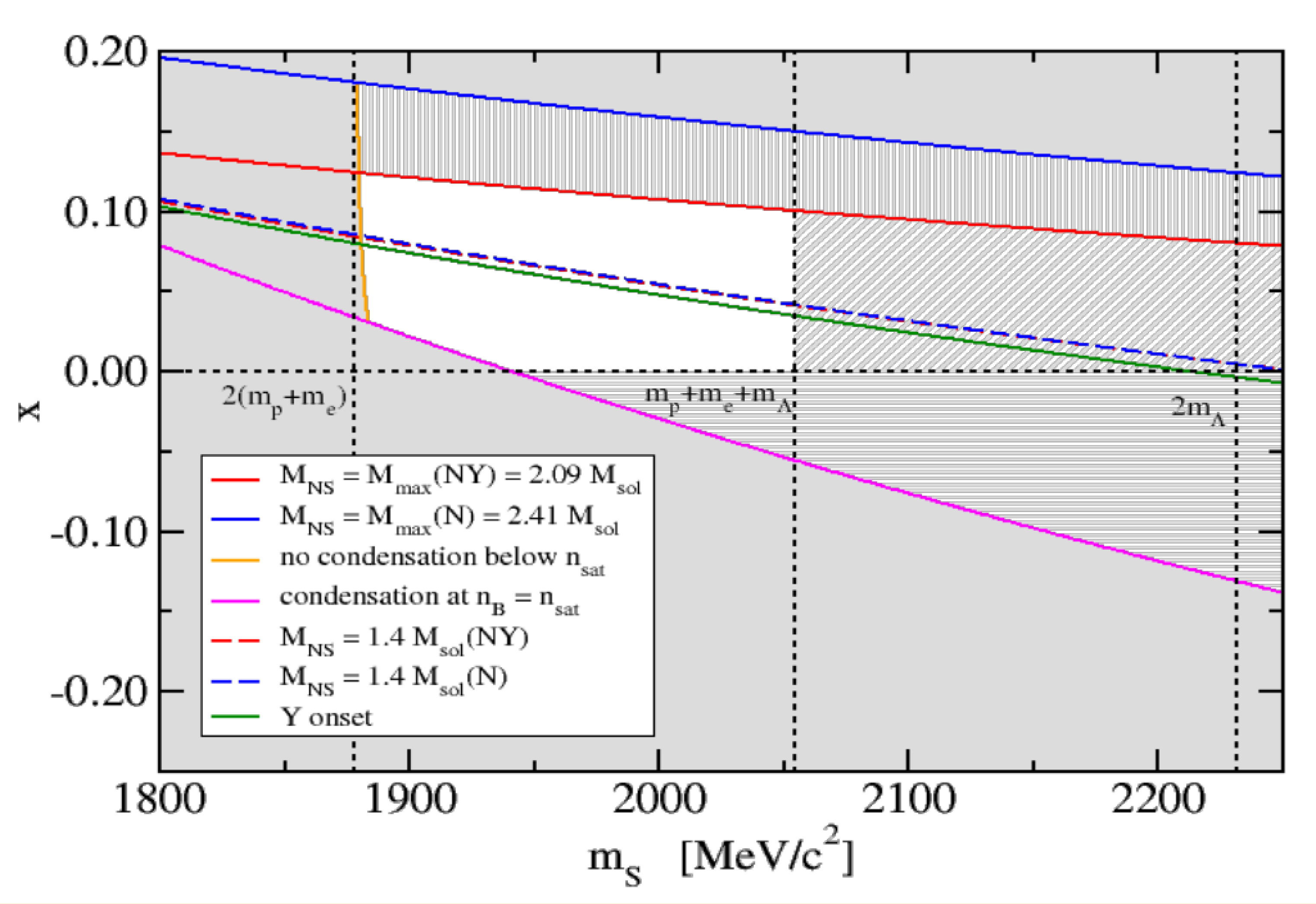
EoS for hadronic matter



Mass-Radius curves from TOV equations for pure hadronic EoS and the sexaquark dilemma



Constraints on the mass and the slope of mass shift for the Sexaquark



Phase Transition from Hadronic matter to deconfined Quark matter

M. Sh, D. Blaschke, S. Typel, G. R. Farrar and D. E. Alvarez-Castillo, Phys. Rev. D (105) (2022)

Quark matter EoS
The simple parameterization of CSS with 3 free parameters: A, c_s, B

$$P(\mu) = A\left(\frac{\mu}{\mu_x}\right)^{1+\beta} - B$$

$$c_s^2 = \frac{dP}{d\varepsilon}$$

$$n = \frac{dP}{d\mu}\ , \quad \varepsilon = -P + \mu n$$

$$\beta = \frac{1}{c_s^2}, \qquad \mu_x = 1\,GeV$$

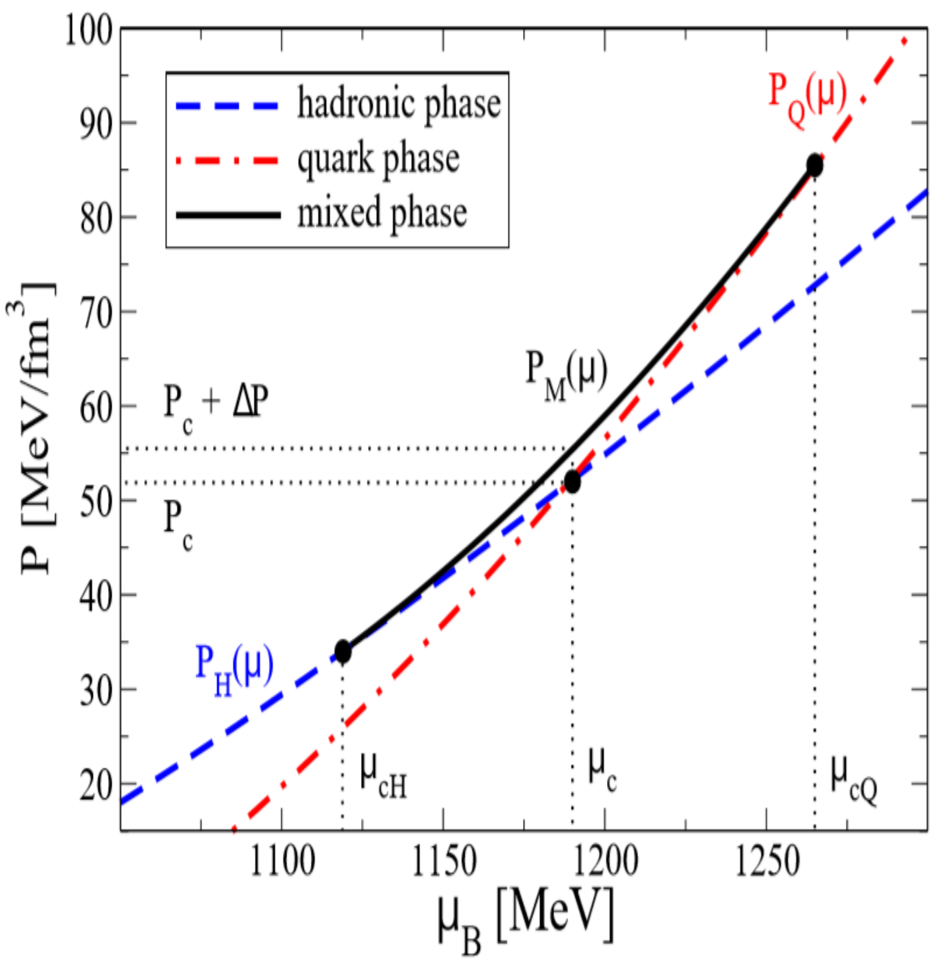
B can be either constant or **μ**-dependent: $B = B_0 + B_{eff}$

J. L. Zdunik and P. Haensel, Astron. Astrophys. 551, A61 (2013)

- The favorable parameters of nlNJL have been obtained from Bayesian analysis
- nlNJL EoS has been mapped to CSS parameterization.
- For the phase transition, both the Maxwell construction (MC) and replacement interpolation construction (RIC) are used.

M. Sh., et al., Phys. Rev. D (107) (2023)

Replacement Interpolation construction (RIC)
A Mixed Phase Approach



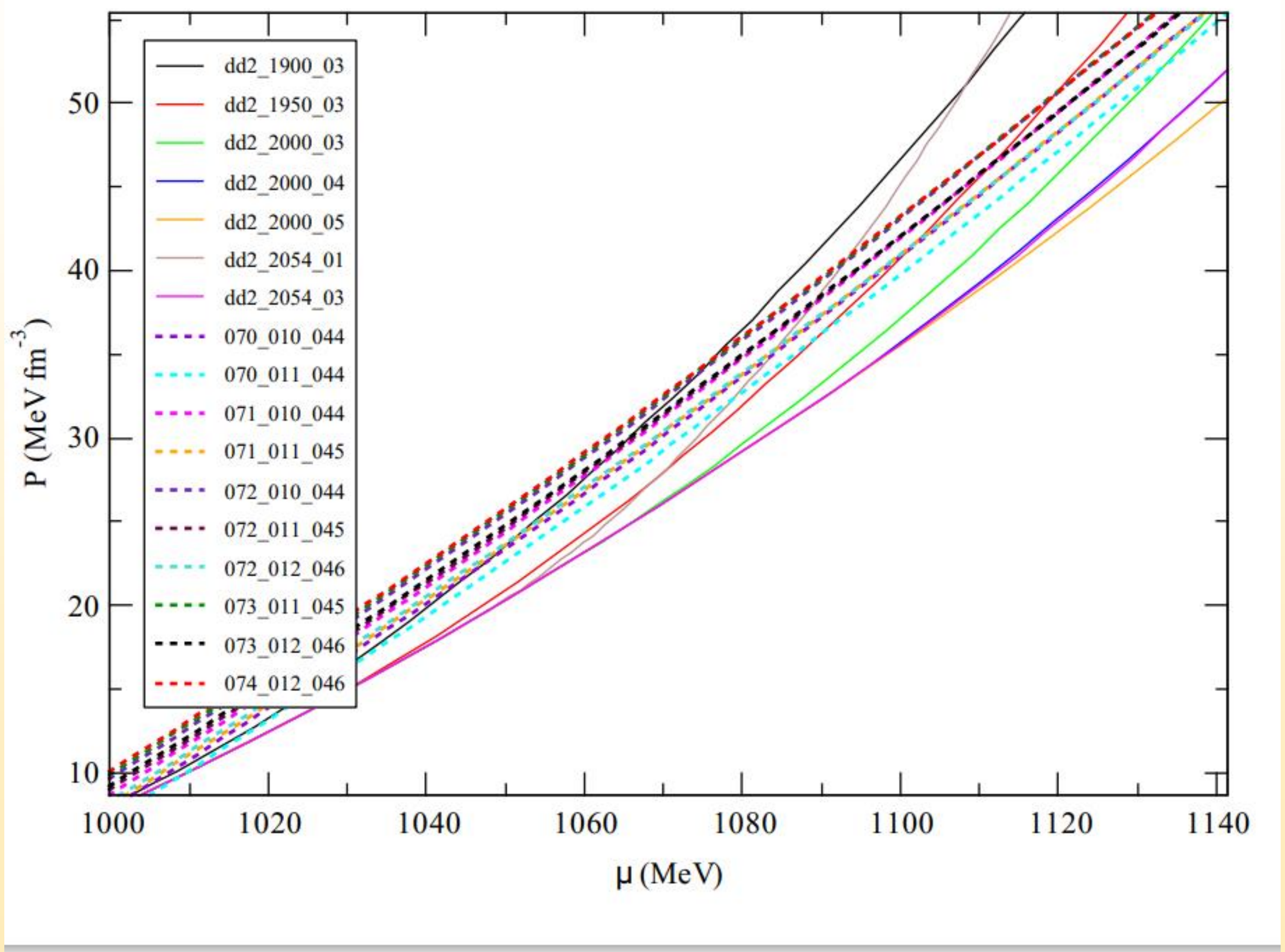
$$P_M(\mu) = a(\mu - \mu_c)^2 + b(\mu - \mu_c) + P_c + \Delta P.$$

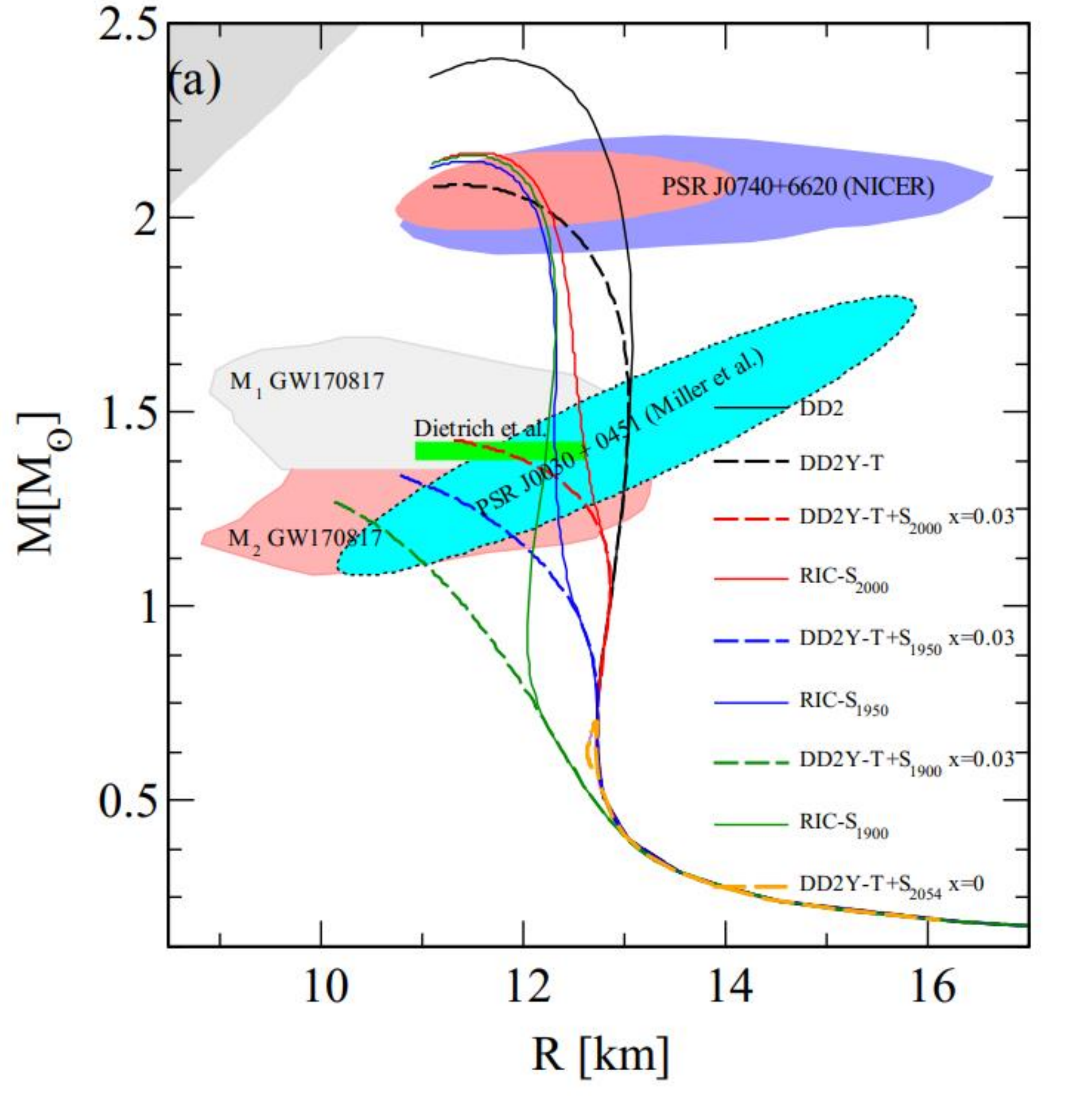
$$P_M(\mu_c) = P_c + \Delta P = P_M.$$

$$P_M(\mu_{cH}) = P_H(\mu_{cH}) = P_H,$$
$$P_M(\mu_{cQ}) = P_Q(\mu_{cQ}) = P_Q,$$

$$n_M(\mu_{cH}) = n_H(\mu_{cH}),$$
$$n_M(\mu_{cQ}) = n_Q(\mu_{cQ}).$$

RIC for the reconfinement region with a negative value of $-\Delta P$



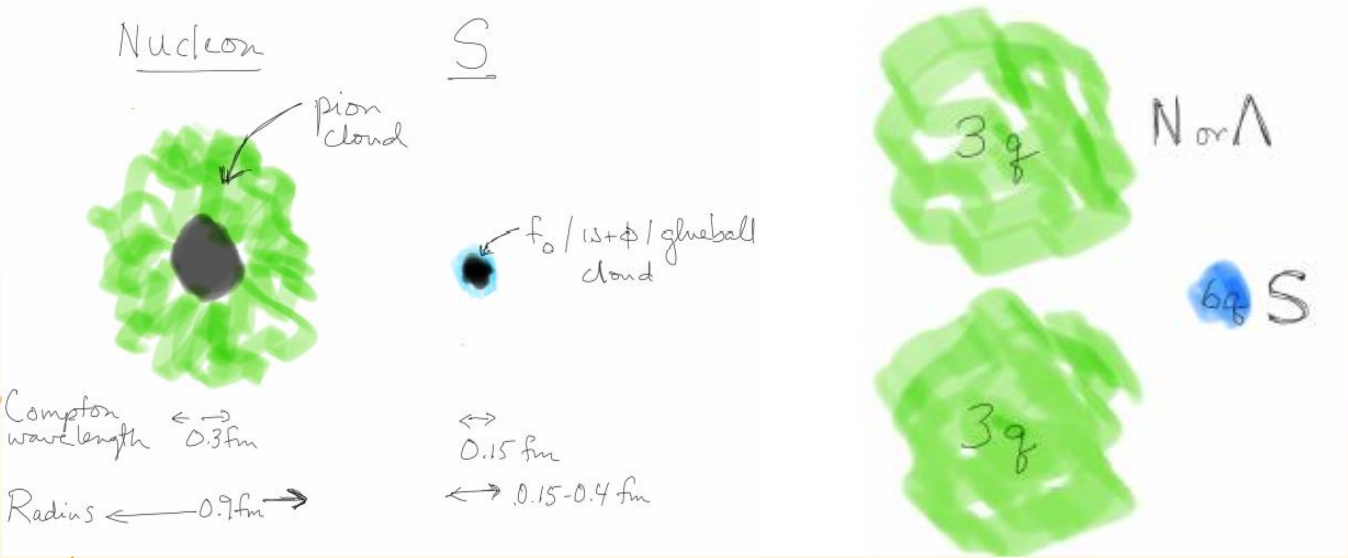

(a)
PSR J0740+6620 (NICER)
M1 GW170817
M2 GW170817
Dietrich et al.
PSR J0030 + 0451 (Miller et al.)
DD2
DD2Y-T
DD2Y-T+S2000 x=0.03
RIC-S2000
DD2Y-T+S1950 x=0.03
RIC-S1950
DD2Y-T+S1900 x=0.03
RIC-S1900
DD2Y-T+S2054 x=0
M[M⊙]
R [km]
2.5
2
1.5
1
0.5
10
12
14
16

- Sexaquark as a dark matter candidate can appear in the core of NS using RIC.
- $1885\ MeV < m_S < 2000\ MeV$.
- The results are model dependent.

- The Hadronic model can be still improved.

Thank you 😊

Size of a Sexaquark



❖ If S is a ΛΛ molecule:
$r_S \approx$ 2 fm like deuteron

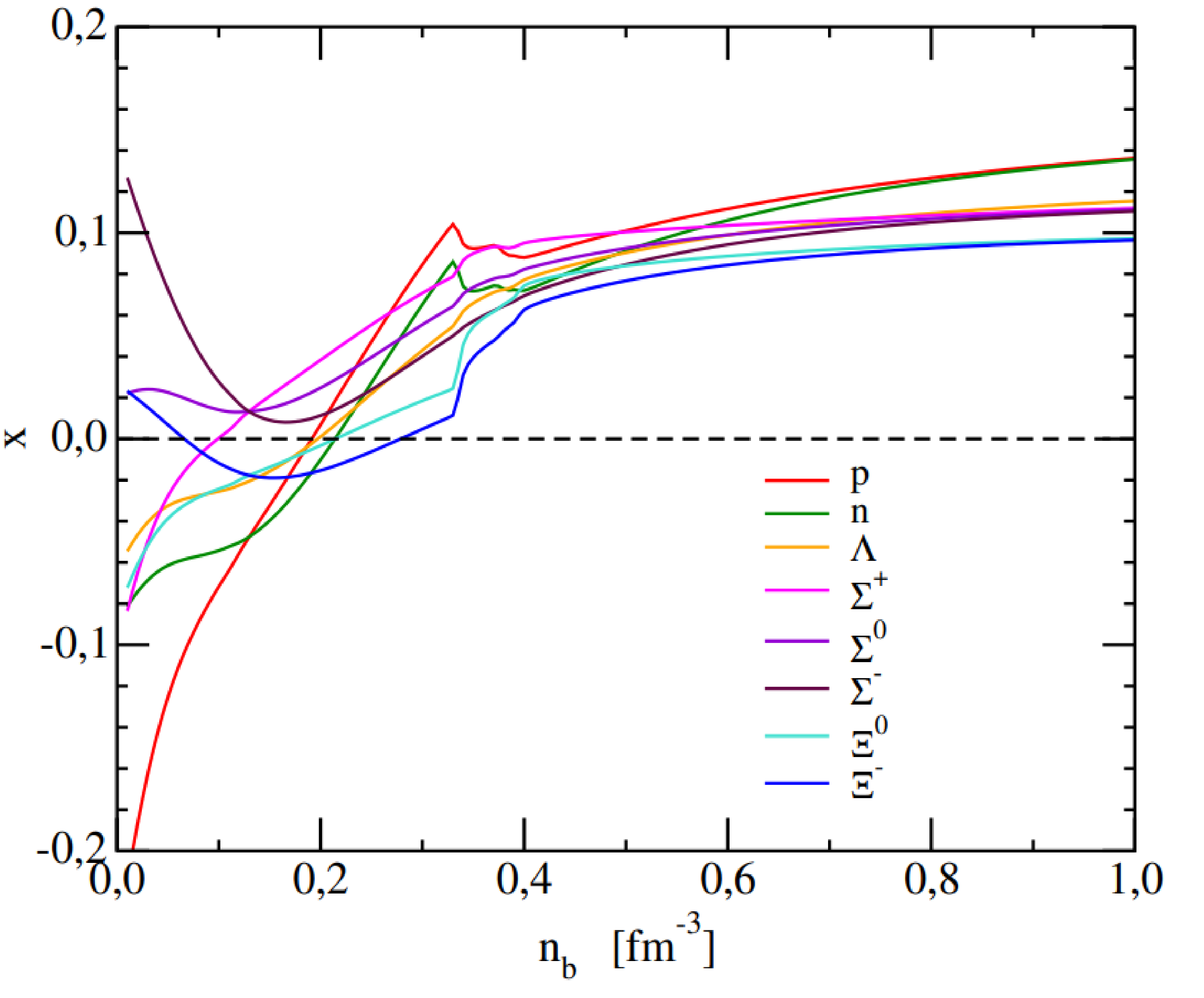
❖ If S is a bound state of 3 diquark:
$r_S \approx$ 0.5 fm

- If S is a Molecule state, ΛΛ, since Λ is a color neutral particle, two Λs can be bound only by exchange color neutral particles like mesons
- If S is a complex system of 3 colored diquark, these objects should interact via color force which is much stronger than meson exchange force at short distances.
- G. Farrar suggests hyperfine attraction between uuddss quarks in S which is the strongest interaction in singlet configuration.
- The binding is maximal in sexaquark channel and S should be more compact than normal hadrons

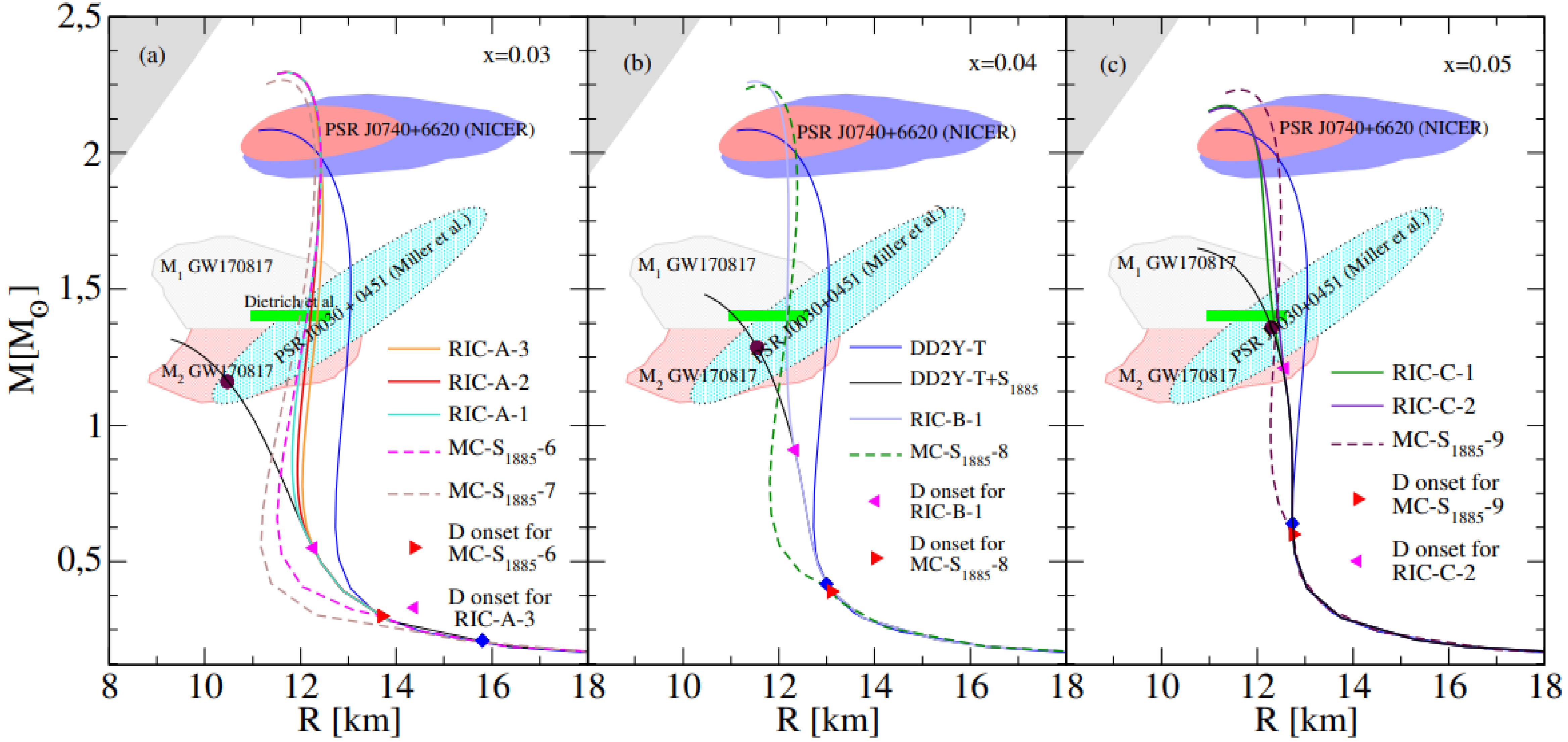
The effective slope of mass shift for all octet baryons within DD2Y-T considering the effective potential and effective mass

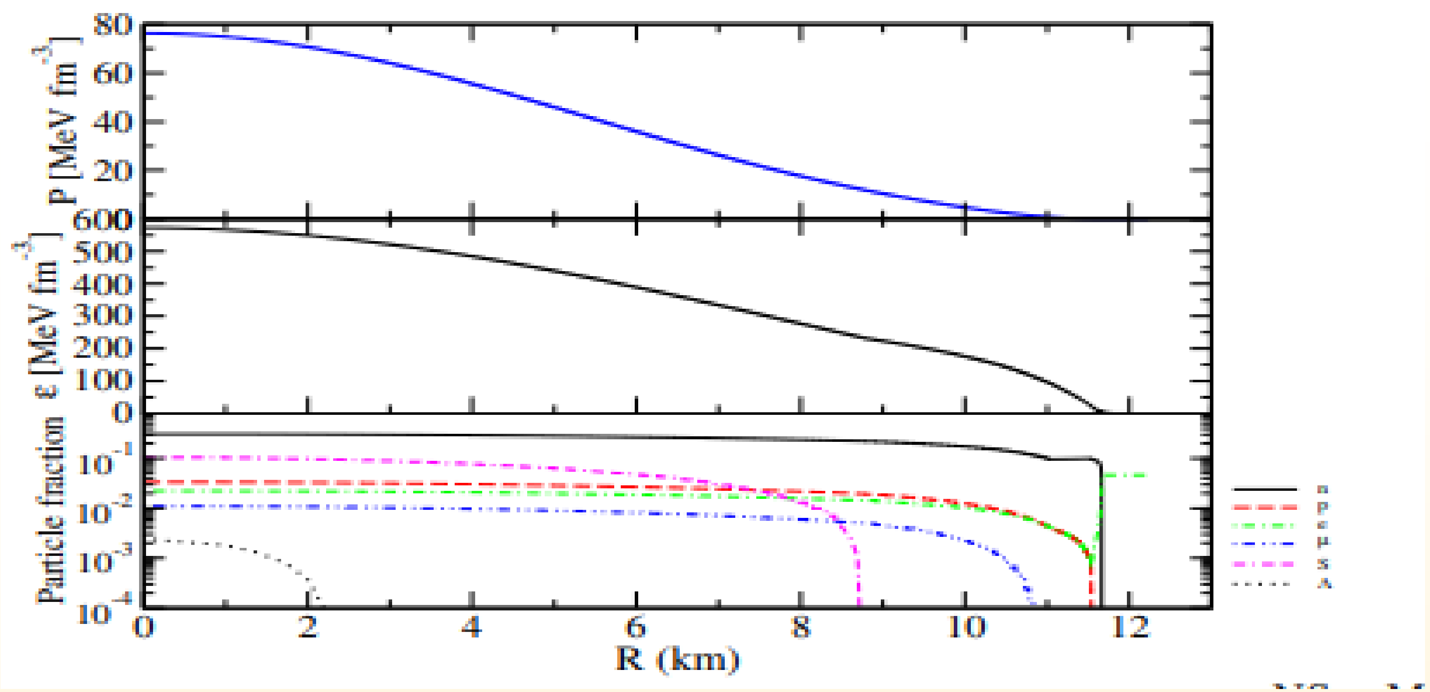
$$x_i = \frac{n_0}{m_i} \frac{dU_i}{n_B}$$

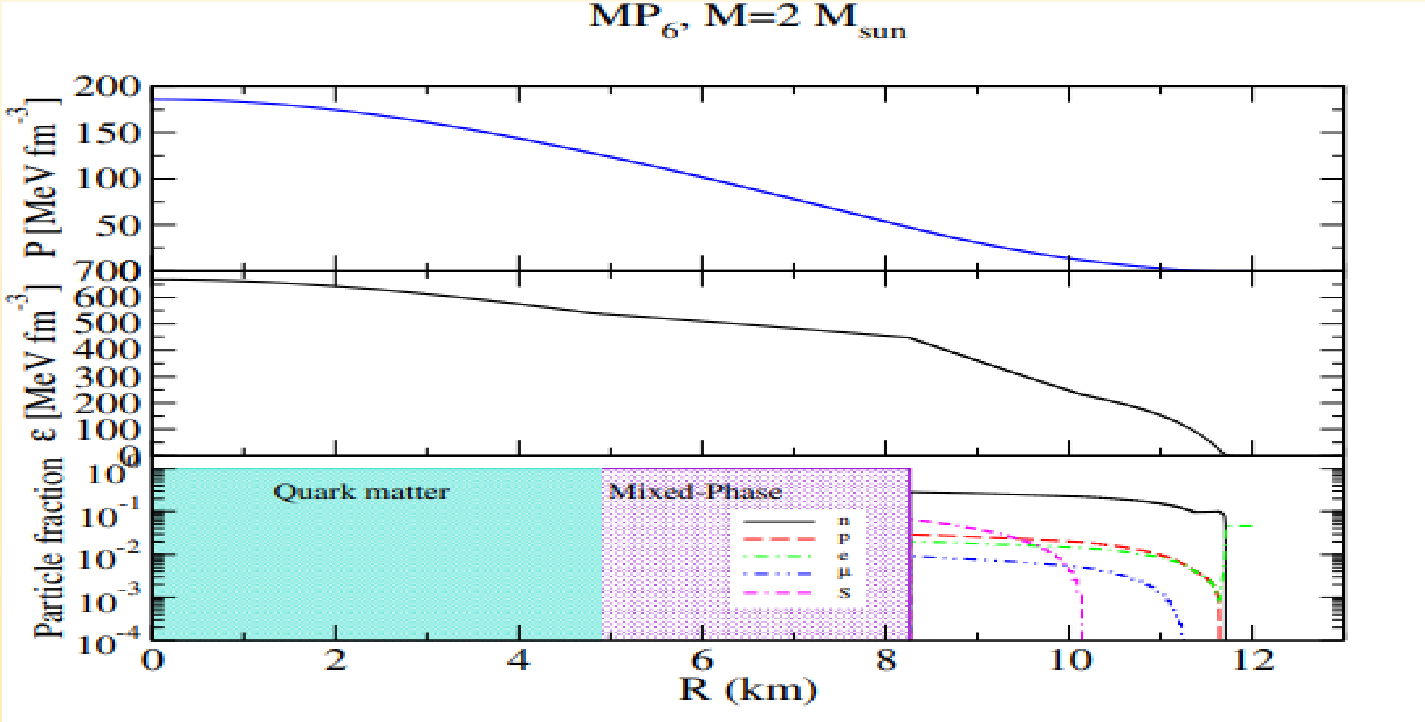
The values of x which have been used as the slope of the mass shift of S, are in agreement with the value of x for other octet baryons at the range of density where we expect S onset.



M. Sh, D. Blaschke, S. Typel, G. R. Farrar and D. E. Alvarez-Castillo, Phys. Rev. D (105) (2022)




P [MeV fm^{-3}]
ε [MeV fm^{-3}]
Particle fraction
R (km)
n
p
e
μ
S
Λ


MP$_6$, M=2 M$_{sun}$
P [MeV fm^{-3}]
ε [MeV fm^{-3}]
Particle fraction
Quark matter
Mixed-Phase
n
p
e
μ
S
R (km)