Constraining the mass of sexaquark from neutron star observables

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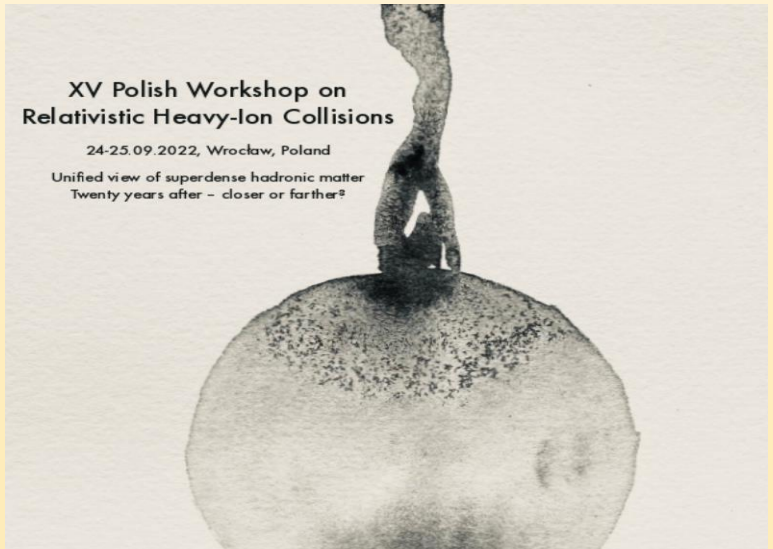
M. Shahrbaf, D. Blaschke, S. Typel, G. R. Farrar and D. E. Alvarez-Castillo, Phys. Rev. D 105, no.10, 103005 (2022)

D. Blaschke, O. Ivanytskyi and M. Shahrbaf, [arXiv:2202.05061 [nucl-th]]



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What is a Sexaquark?

- S is a neutral boson
- This exotic particle is proposed to be consist of 3 scalar diquarks (ud, us, ds)
- Baryon number = 2, Strangeness= −2
- In spin-color-flavor-singlet state
- **S≡ Λ Λ** $m_{\Lambda\Lambda} = 2231$ MeV
- The lowest channel for Λ decay:

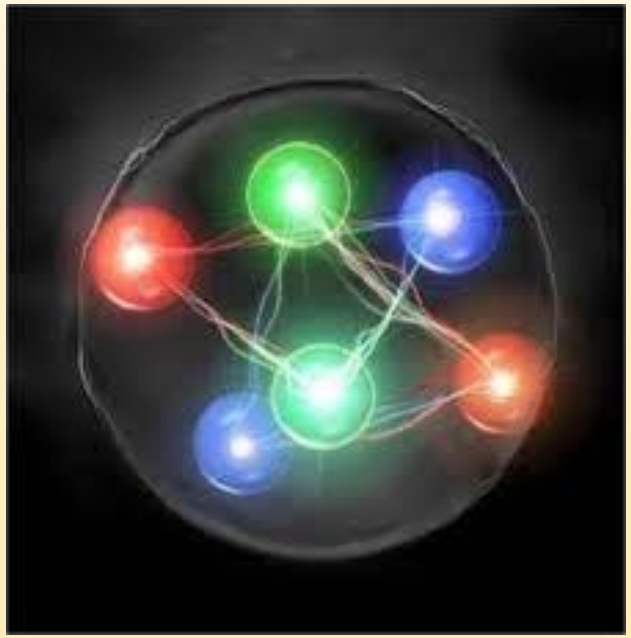
$\mathbf{\Lambda} \rightarrow \mathrm{p} + \mathrm{e} + \bar{\nu}$

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

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

if $2054\ \mathrm{MeV} < m_s < 2231\ \mathrm{MeV}$ it decays

uuddss



G. R. Farrar, 1805.03723 (2018)
F. Buccella, PoS CORFU2019, 024 (2020)

S is a good candidate for dark matter

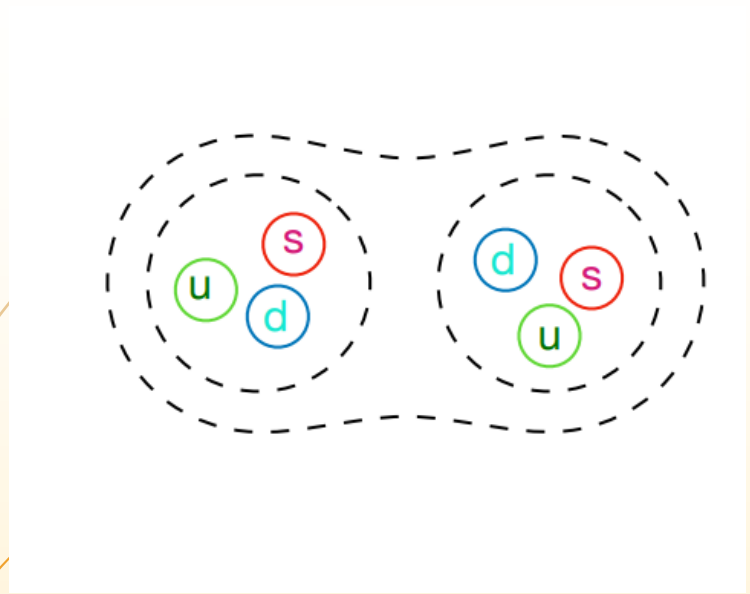
- If $m_s \leq (m_\Lambda + m_p + m_e) = 2054$ MeV: it will decay with a lifetime more than the age of the universe
- If $m_s \leq 2(m_p + m_e) = 1877$ MeV : S is an absolutely stable particle

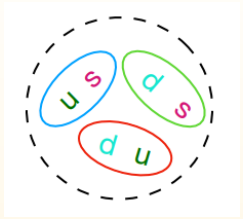
- Franco Buccella has calculated the mass of S from chromomagnetic interaction: m_s = 1883 MeV F. Buccella, PoS CORFU2019, 024 (2020)

- Ω_{SDM}/Ω_b has been found in a good agreement with the measured ratio $\Omega_{DM}/\Omega_b = 5.3 \pm 0.1$
- Therefore, S has been considered as a good candidate for dark matter for the first time by Glennys Farrar G. R. Farrar, (2022), arXiv:2201.01334 [hep-ph]

We consider: 1885 MeV < m_s < 2054 MeV

Size of a Sexaquark



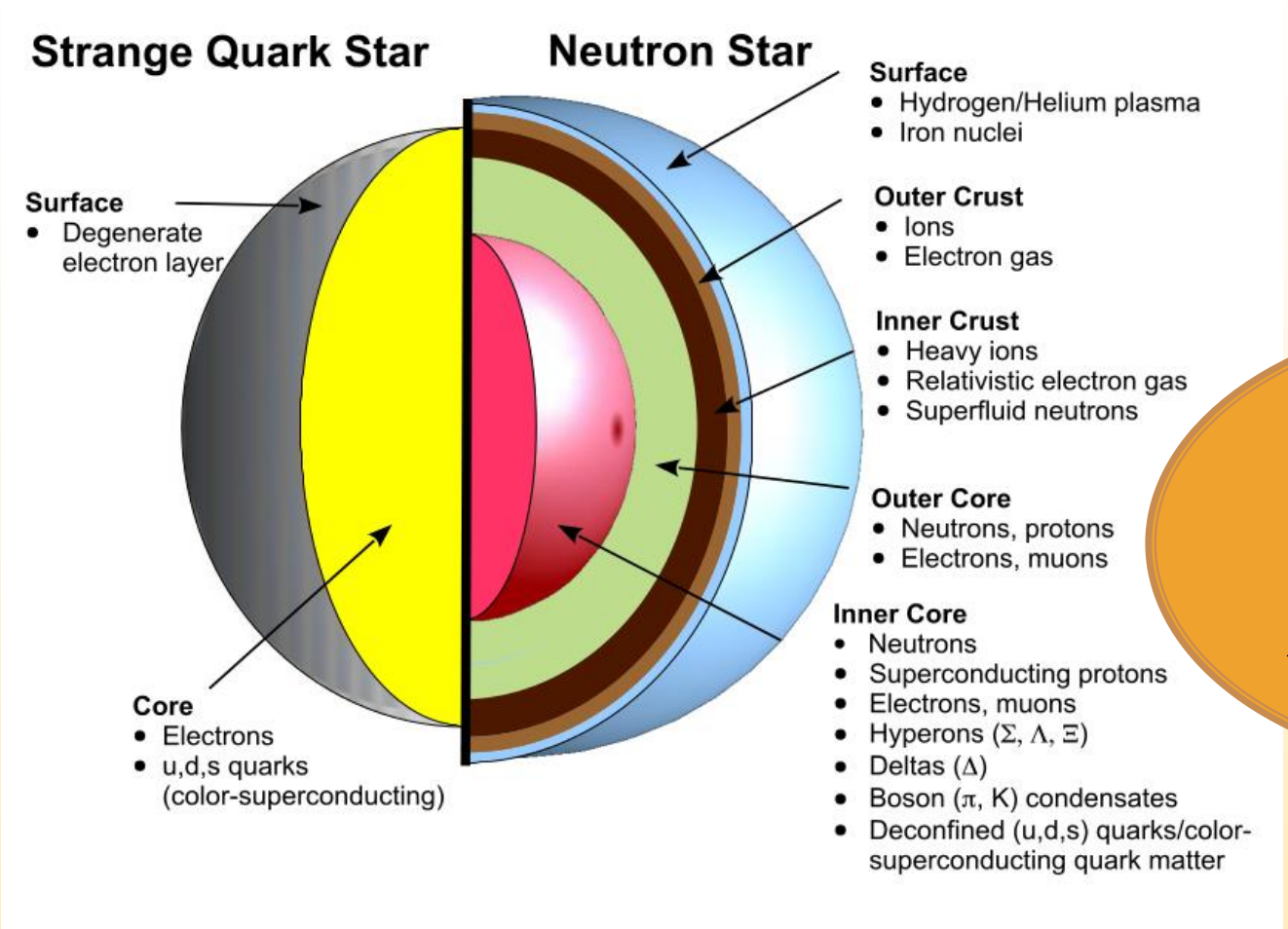


❖ If S is a ΛΛ molecule:
$r_S \approx 2$ fm like deuteron

❖ 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.
- The binding is maximal in sexaquark channel and S should be more compact than normal hadrons

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)

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

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

❖ All constituent particles with vacuum rest masses are considered as quasiparticles in the medium with effective mass and effective chemical potentials.

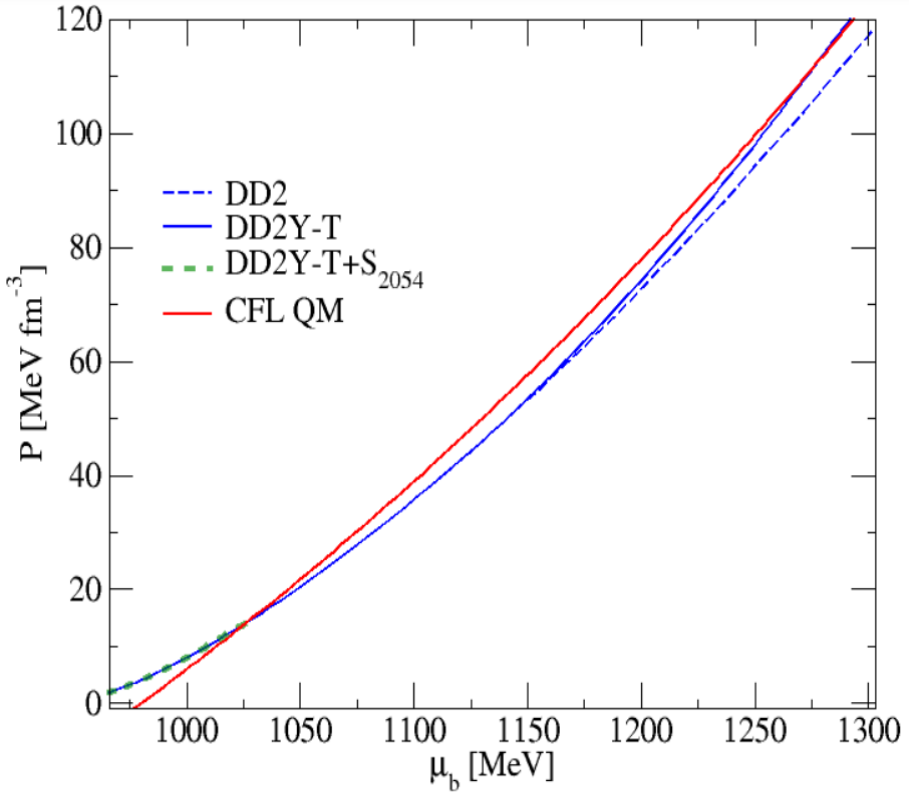
$m_i^* = m_i - S_i$, $\mu_i^* = \mu_i - V_i$ S. Typel and H. H. Wolter, Nucl. Phys. A **656**, 331 (1999)

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

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 density dependence of the couplings is adjusted to describe properties of atomic nuclei.

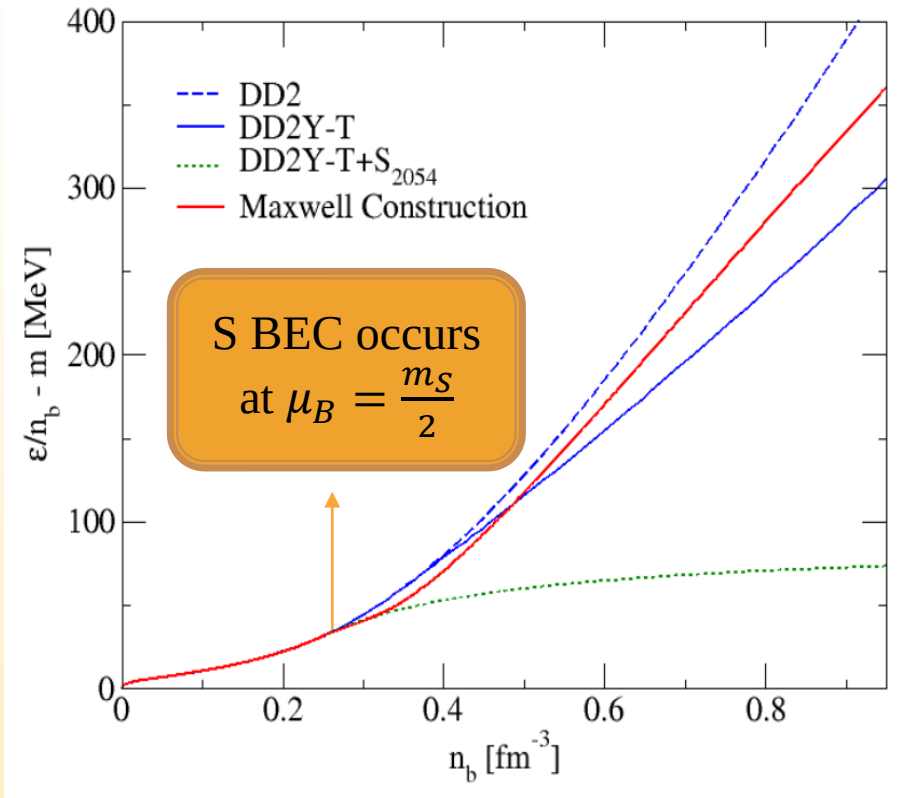
The constant mass of S and the Bose-Einstein condensation (BEC)



$$\Omega_{QM} = -3/4\pi^2 a_4 \mu^4 + 3/4\pi^2 a_2 \mu^2 + B_{\text{eff}}$$

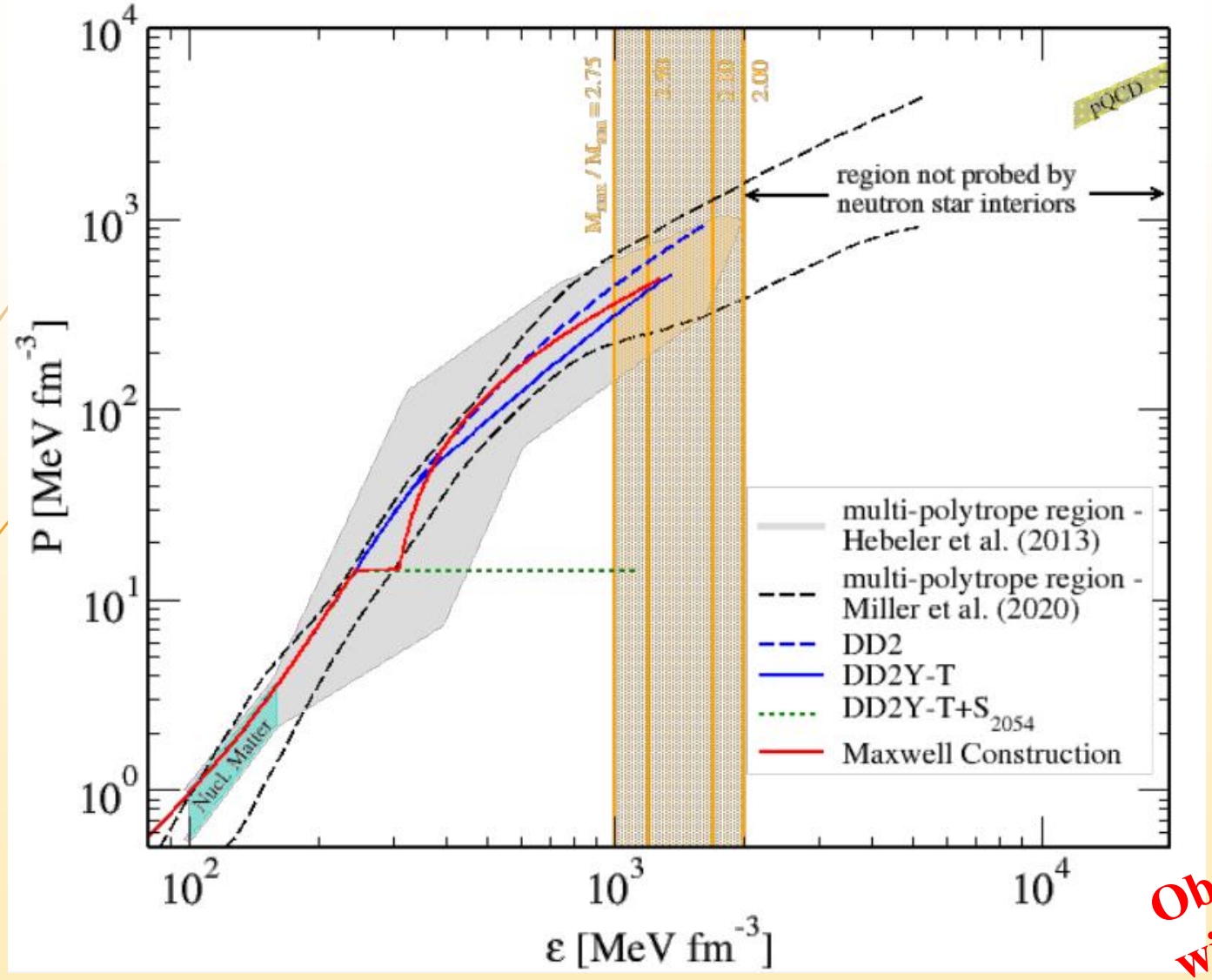
Alford, M., Braby, M., Paris, M. W., and Reddy, S. (2005)

Antić, S., Shahrbaf, M., Blaschke, D., and Grunfeld, A. G. (2021)



$$n_S^{onset} = 0.25\ fm^{-3}$$

Early quark deconfinement in compact stars is triggered by the BEC of a light sexaquark with a mass $m_S = 2054$ MeV

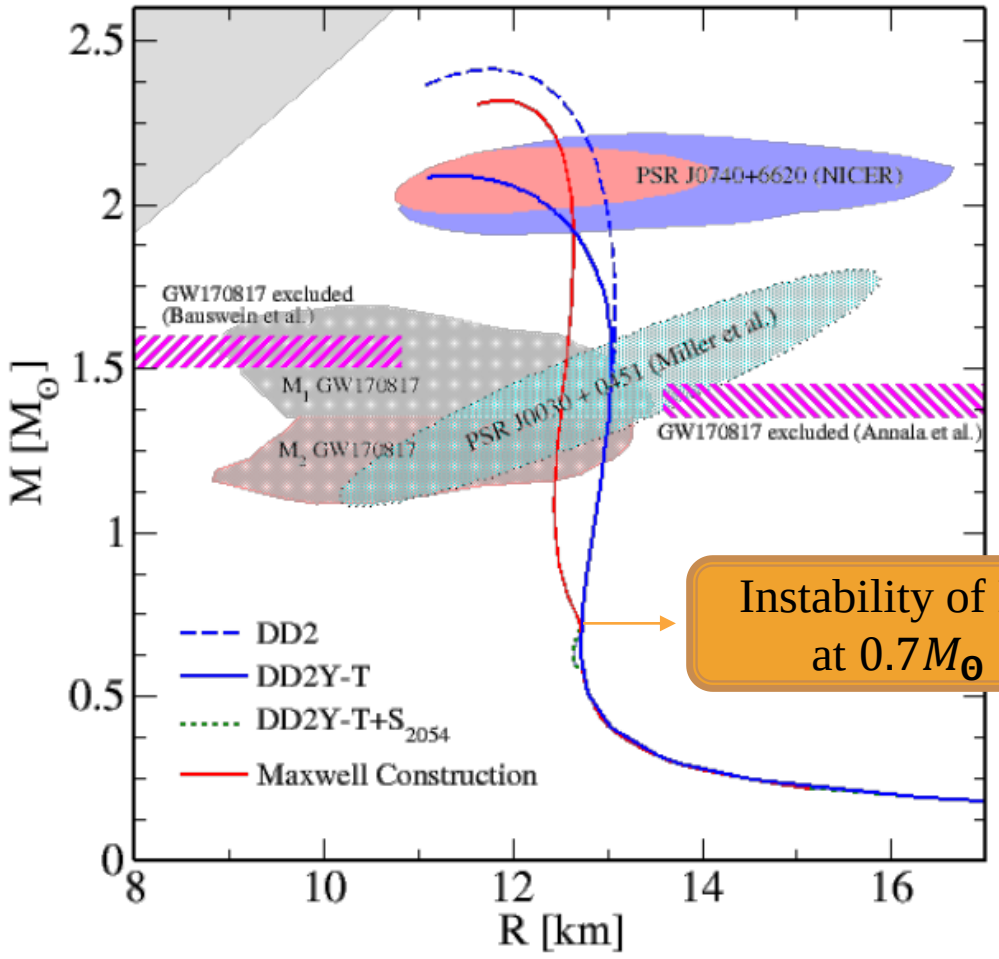


A constant mass of S results in a constant pressure after BEC. From TOV equations, a phase without pressure gradient cannot be realized in compact stars. The threshold mass is then the maximum mass!!

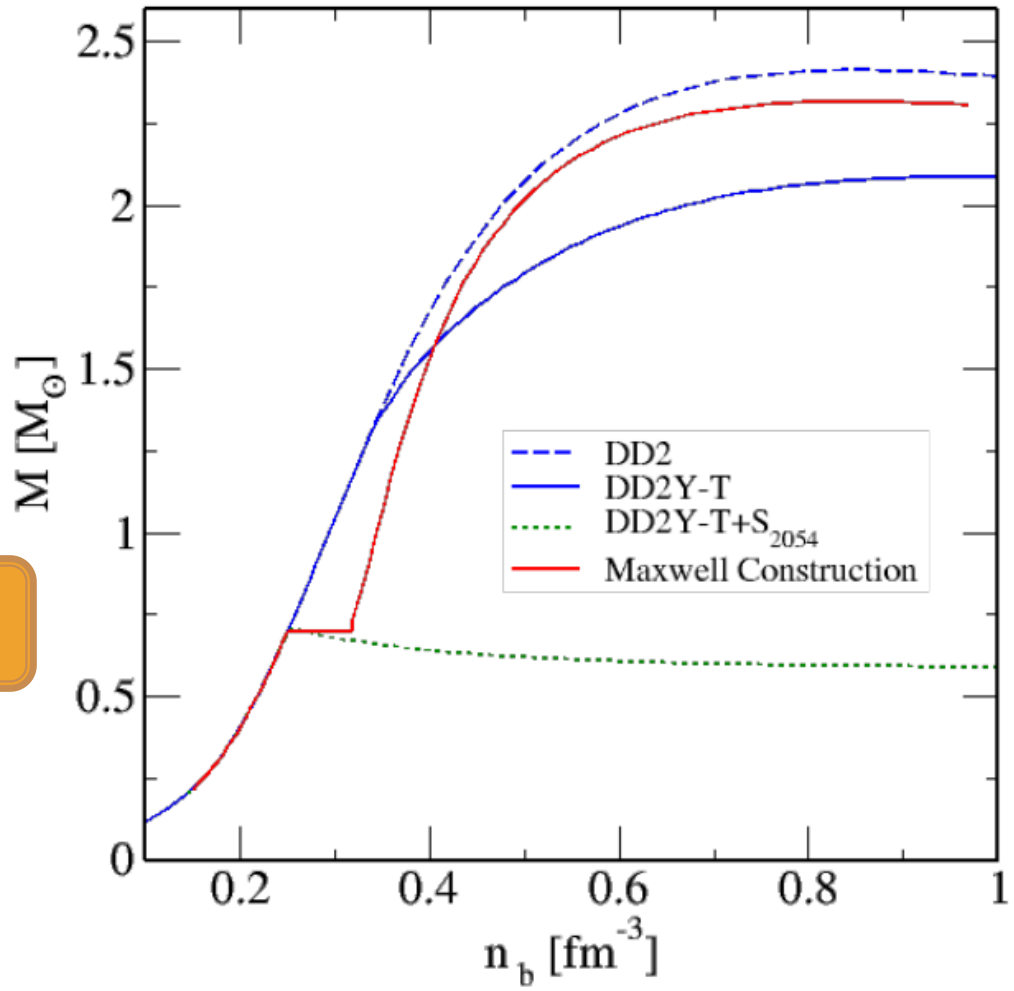
$$M_{max} = 0.7\ M_{\odot}$$

Obvious contradiction with the observational constraints from the pulsars!!!

All observational constraints regarding the maximum mass and the radius are fulfilled for the hybrid stars with early deconfinement.



Instability of NS at $0.7M_{\odot}$



What if the sexaquark interacts with the superdense medium???

Back to DD2Y-T+S model with a density-dependent mass of S

- 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 linear mass shift has been assumed instead of a meson-coupling interaction.

$$S_S = -\Delta m_S \qquad V_S = W_S^{(r)} \qquad \Delta m_S = m_S x_S \frac{n_b}{n_0},$$

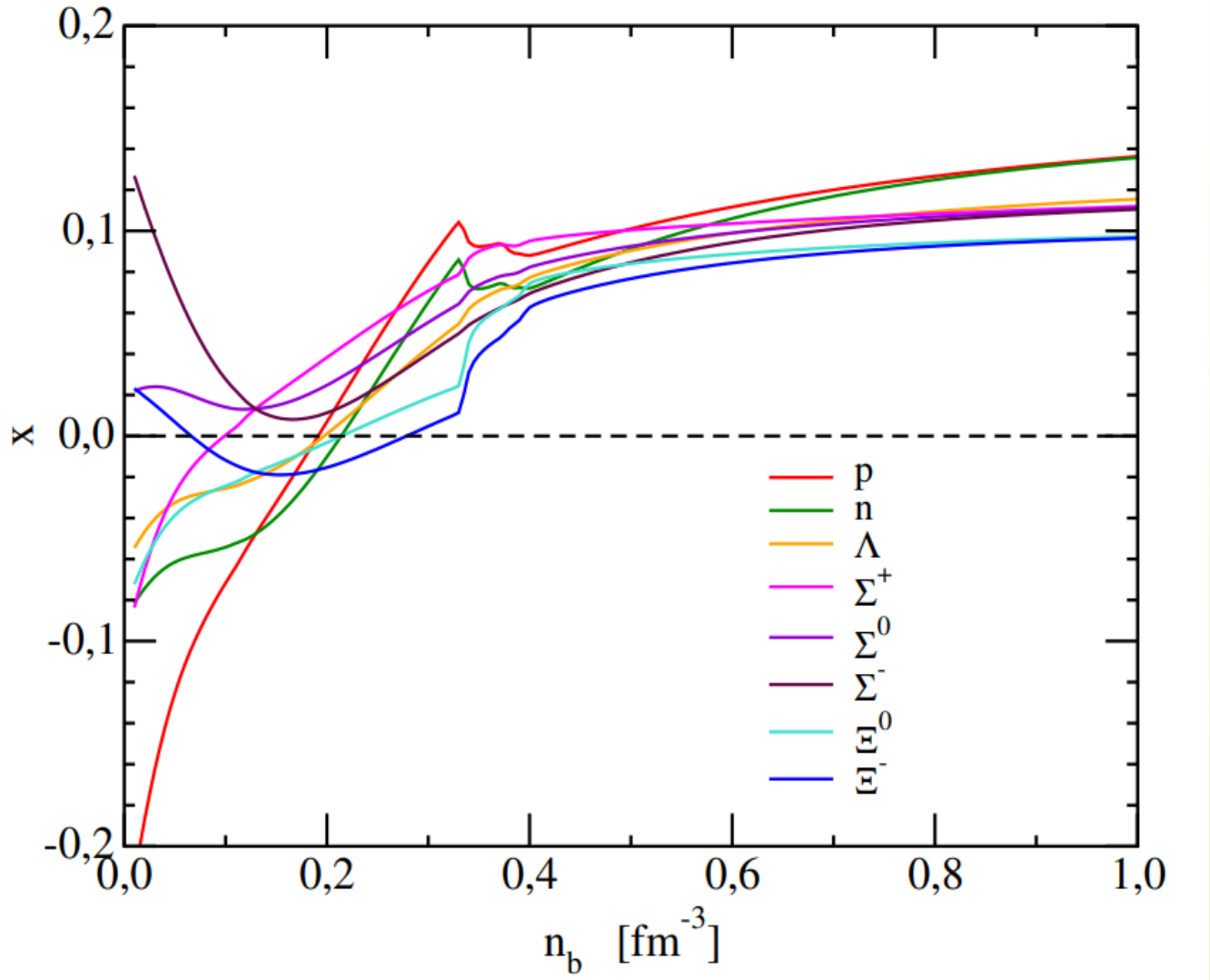
- This assumption results in an increase of the S onset density as well as the condensation so that there is still an increase of the pressure at higher densities.

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

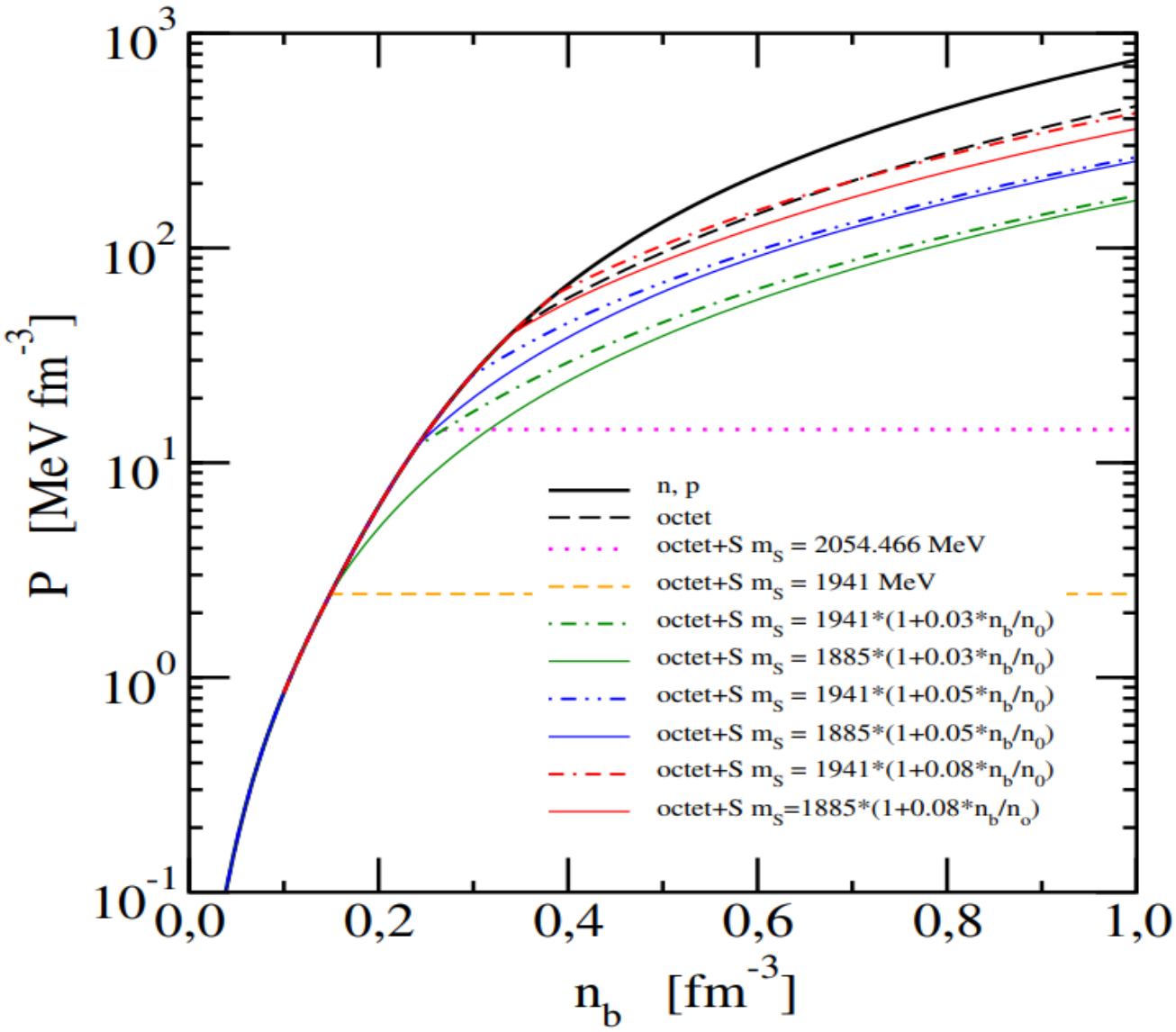
The effective slope of mass shift for all octet baryons within DD2Y-T considering the effective potential and effective mass

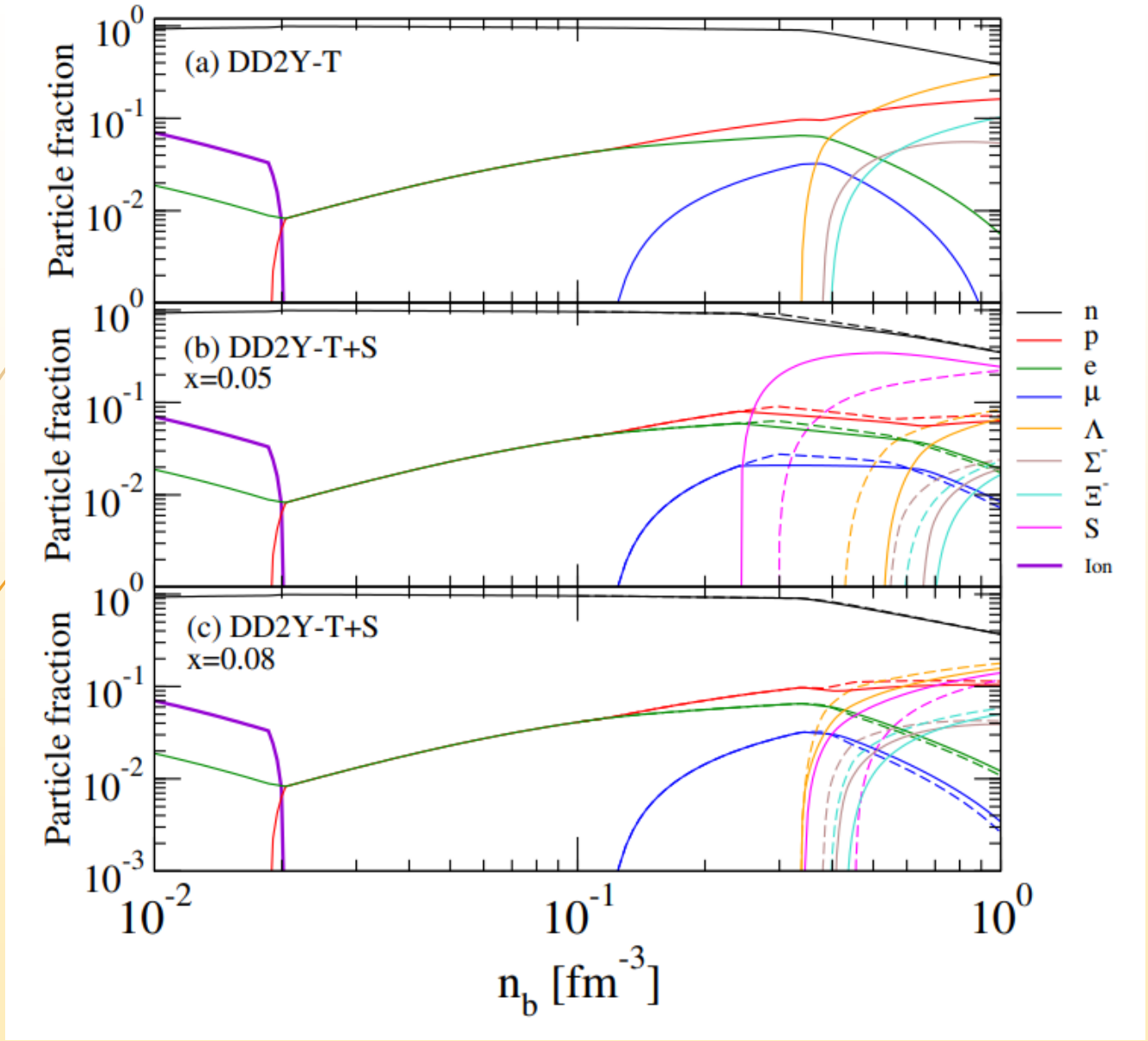
$$x_i = \frac{n_0}{m_i}\frac{dU_i}{dn_b}$$

The values of x, the slope of the mass shift of S, are selected to be in agreement with the value of x for other octet baryons at the range of density where we expect the S onset.



EoS for hadronic matter

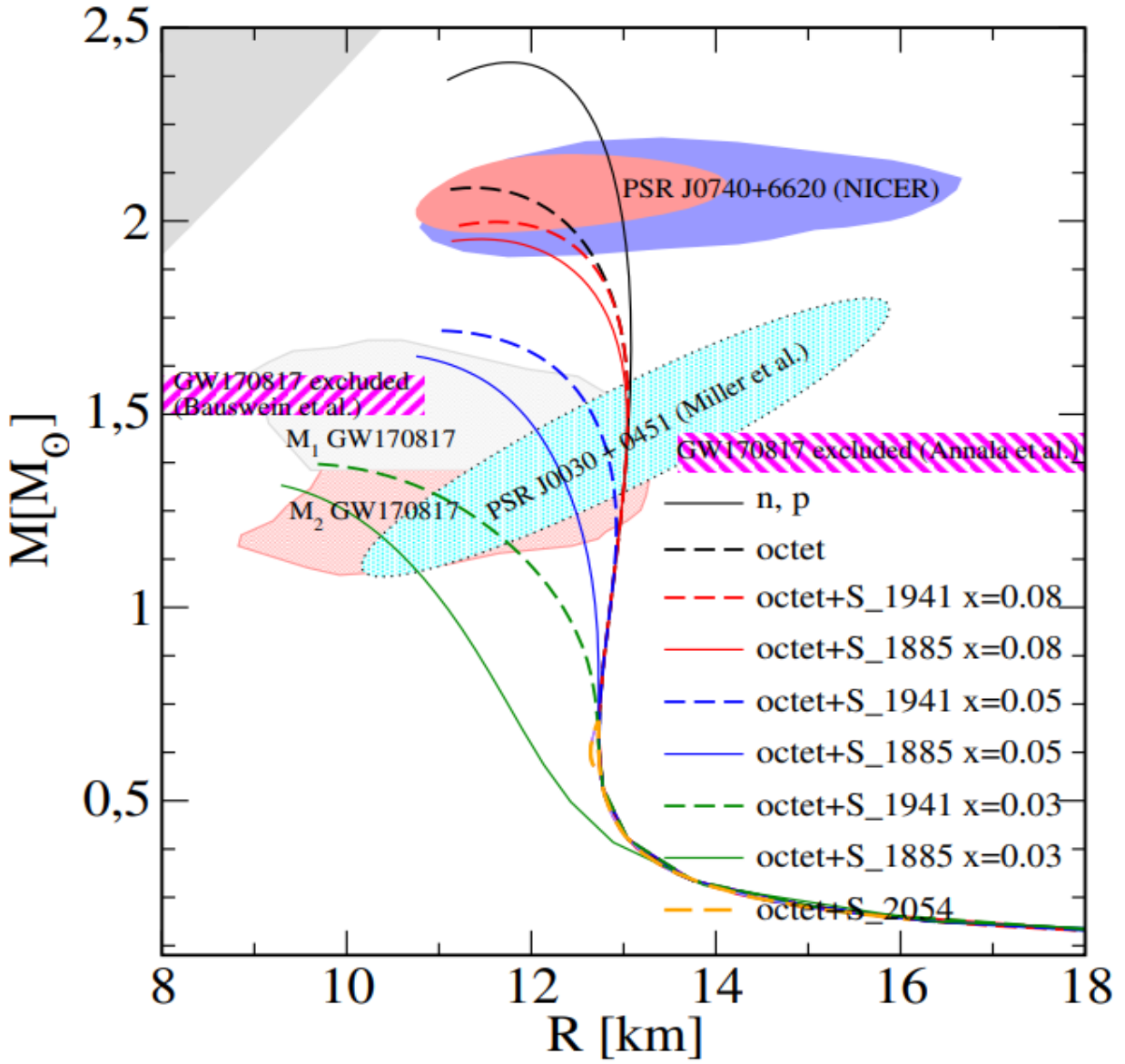




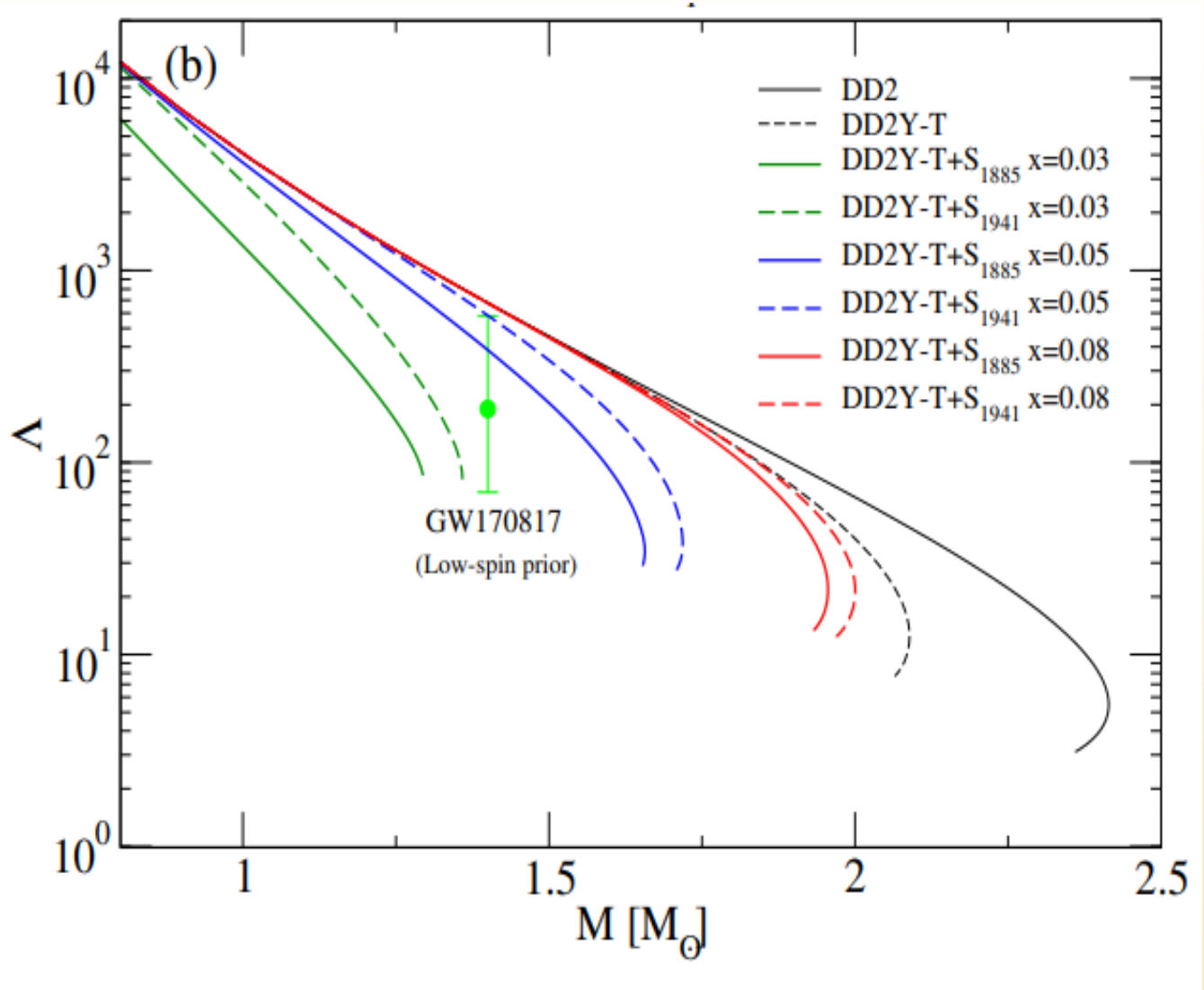
Particles fraction For DD2Y and DD2Y_S for two different values of x

The solid lines correspond to $m_S = 1885$ MeV While the dashed lines show the results for $m_S = 1941$ MeV

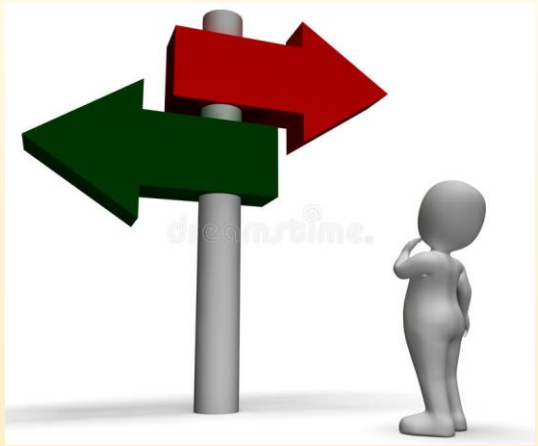
Mass-Radius curves from TOV equations for pure hadronic EoS



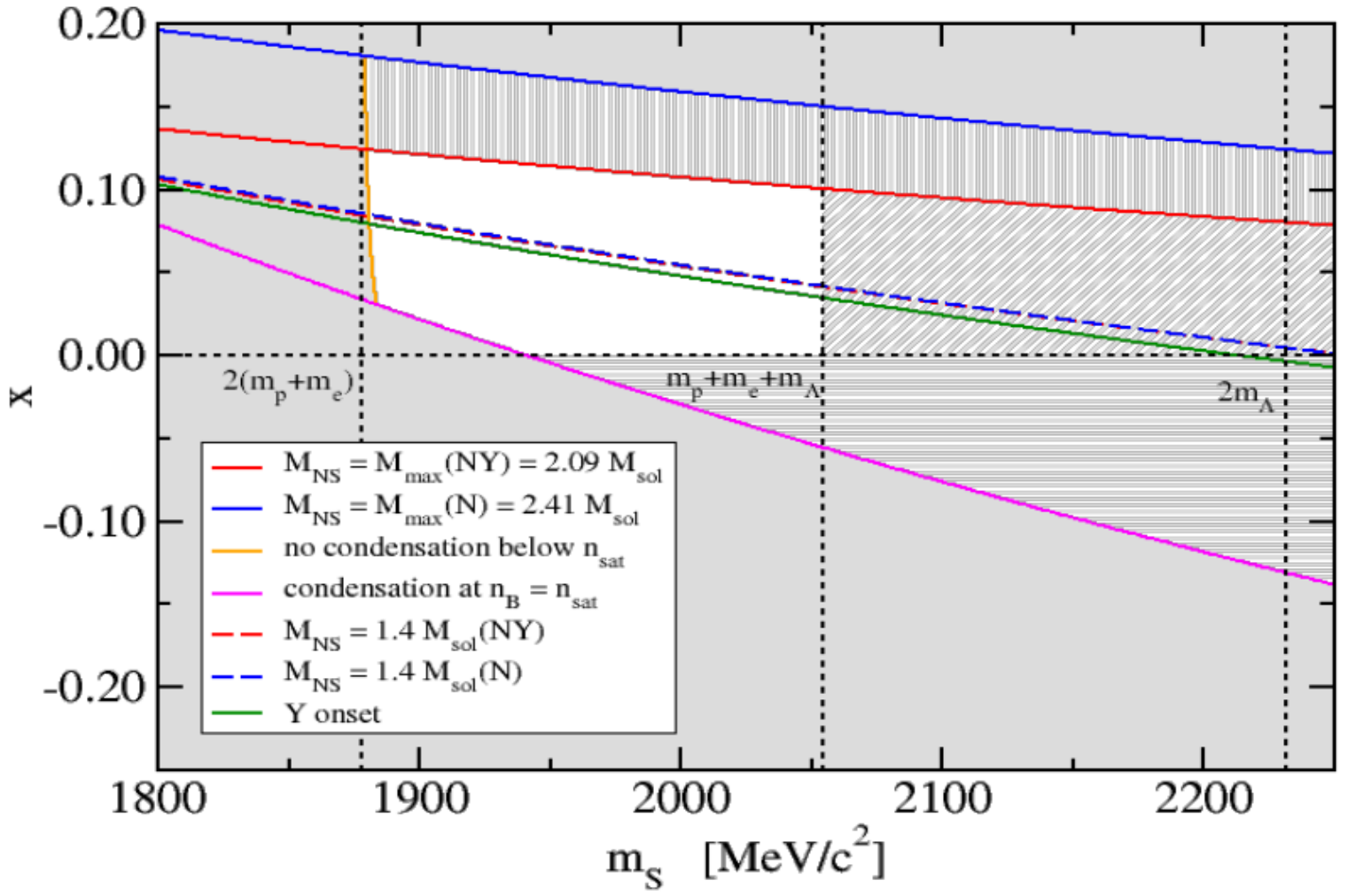
Tidal deformability

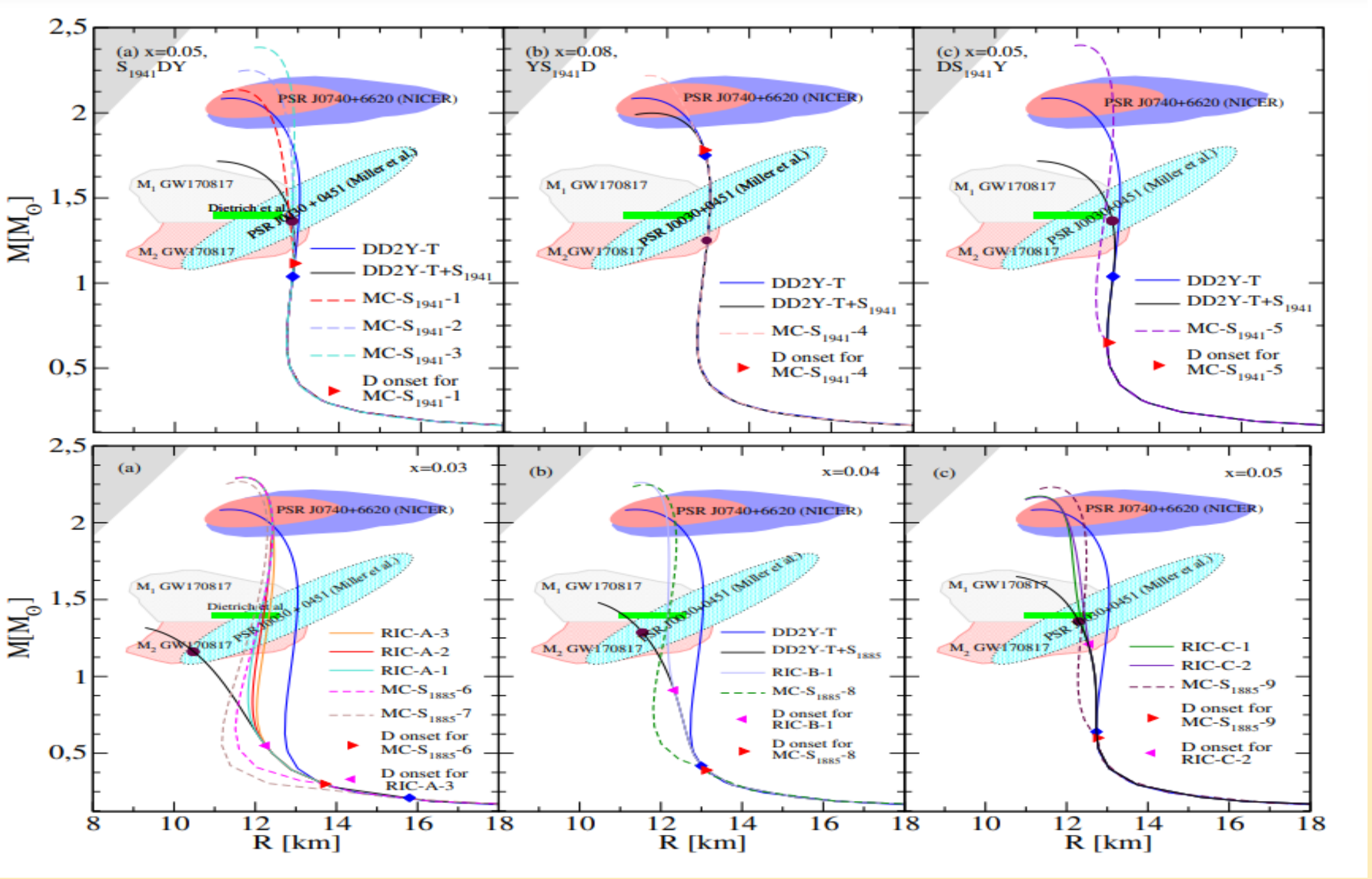


Sexaquark dilemma!



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




(a) x=0.05, S1941DY
(b) x=0.08, YS1941D
(c) x=0.05, DS1941Y
PSR J0740+6620 (NICER)
M1 GW170817
M2 GW170817
Dietrich et al.
PSR J0030+0451 (Miller et al.)
DD2Y-T
DD2Y-T+S1941
MC-S1941-1
MC-S1941-2
MC-S1941-3
MC-S1941-4
MC-S1941-5
D onset for MC-S1941-1
D onset for MC-S1941-4
D onset for MC-S1941-5
(a) x=0.03
(b) x=0.04
(c) x=0.05
DD2Y-T+S1885
RIC-A-3
RIC-A-2
RIC-A-1
MC-S1885-6
MC-S1885-7
RIC-B-1
MC-S1885-8
RIC-C-1
RIC-C-2
MC-S1885-9
D onset for MC-S1885-6
D onset for RIC-A-3
D onset for RIC-B-1
D onset for MC-S1885-8
D onset for MC-S1885-9
D onset for RIC-C-2
M[M⊙]
R [km]

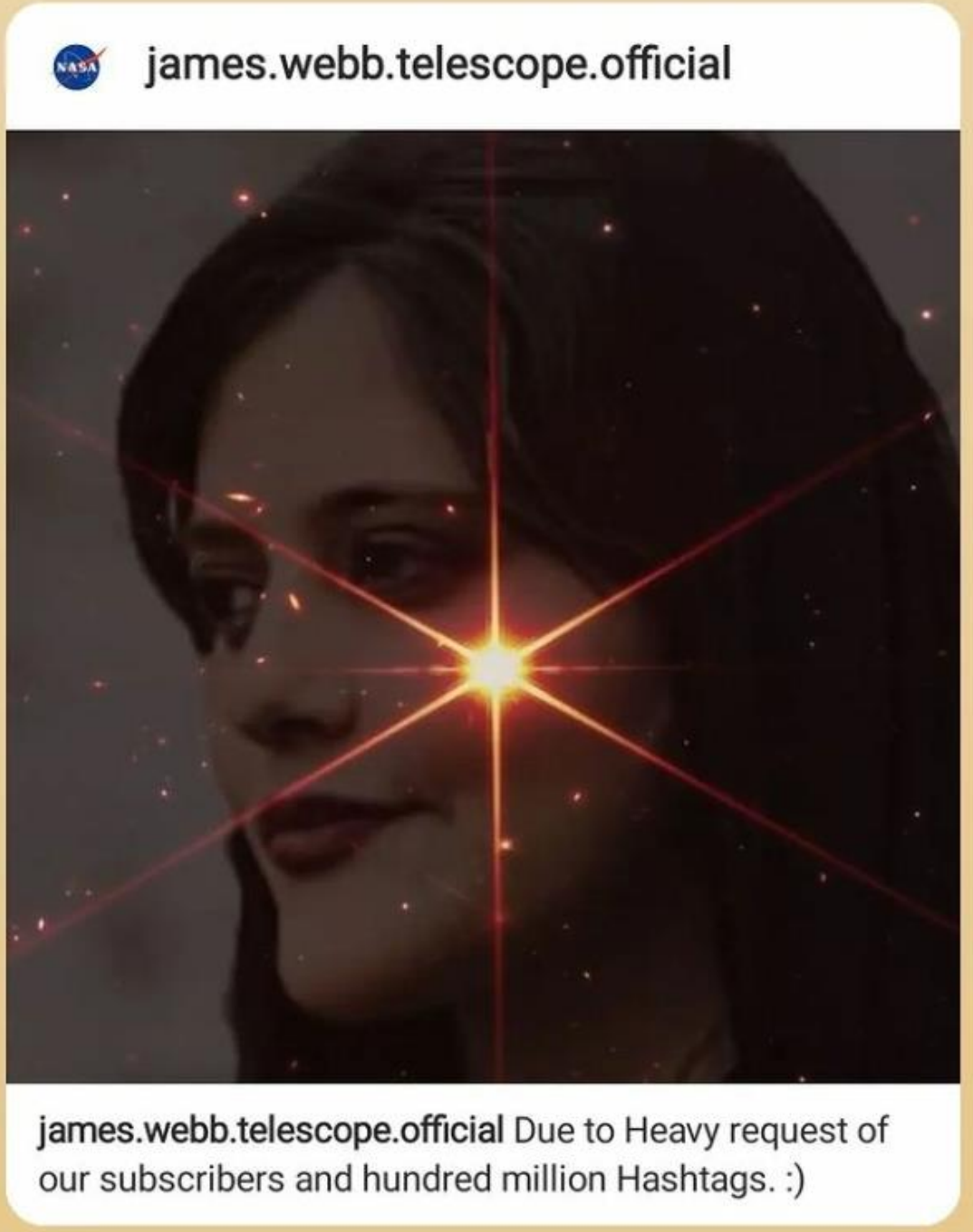
Outlook

Define couplings for S

Taking in to account the substructure of S

Modify the mass shift and find a pure hadronic solution

???...



زن، زندگی، آزادی
ژن، ژیان، ئازادی
Woman, life, liberty