Role of Strangeness in Neutron Stars

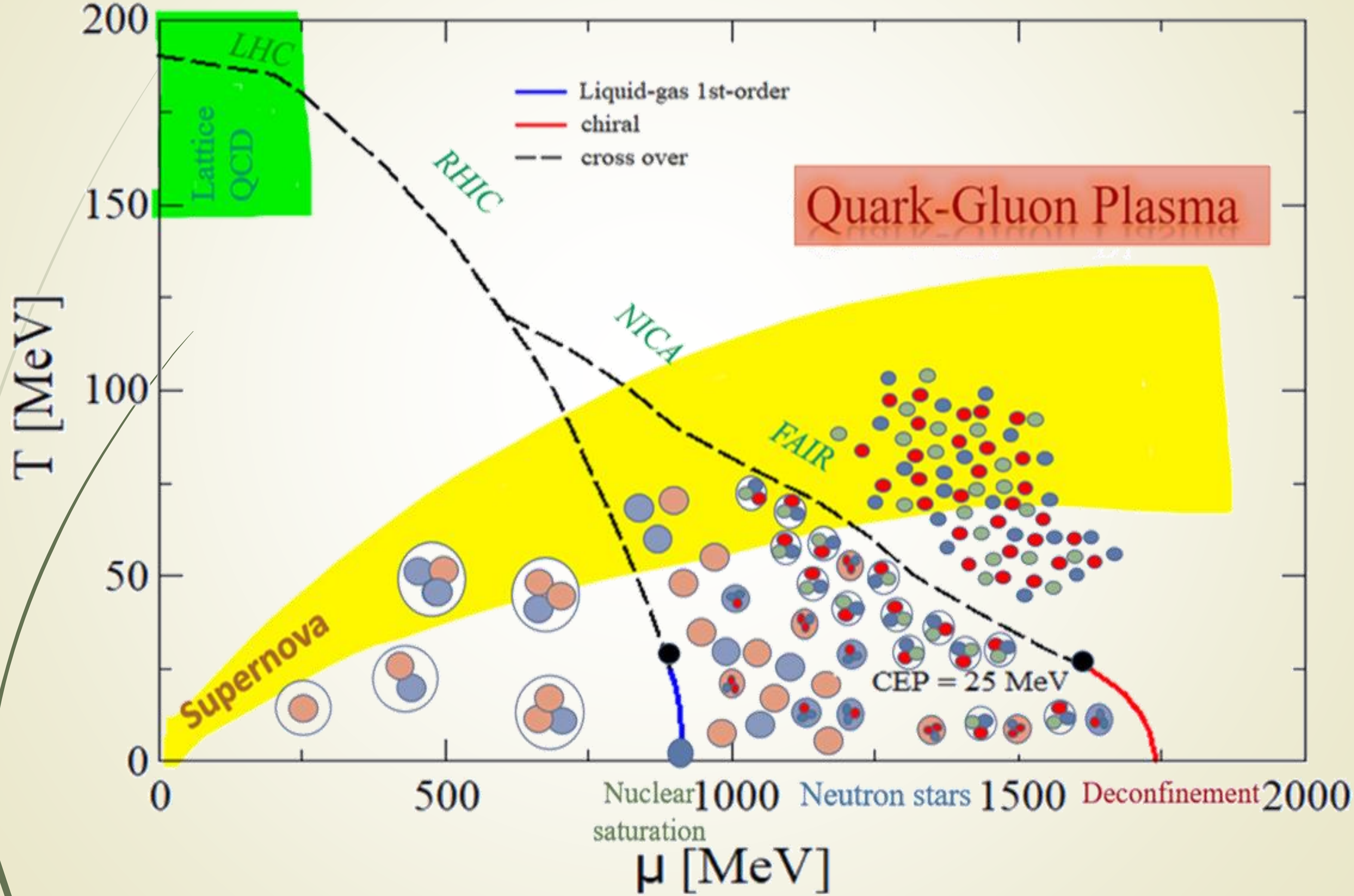
Mahboubeh Shahrbaf

Various Faces of QCD

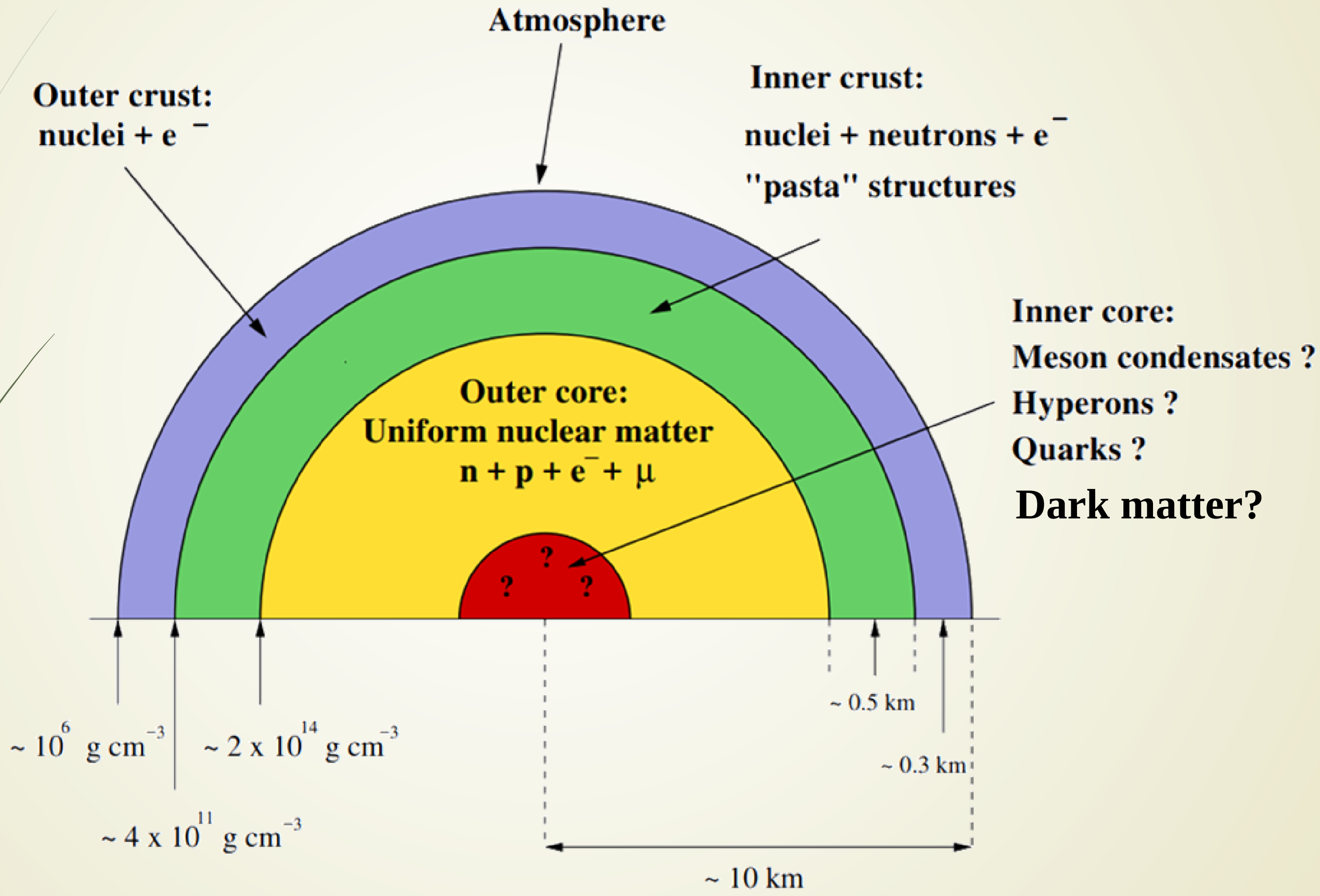
26-28 April
Wrocław-Poland

Uniwersytet Wrocławski

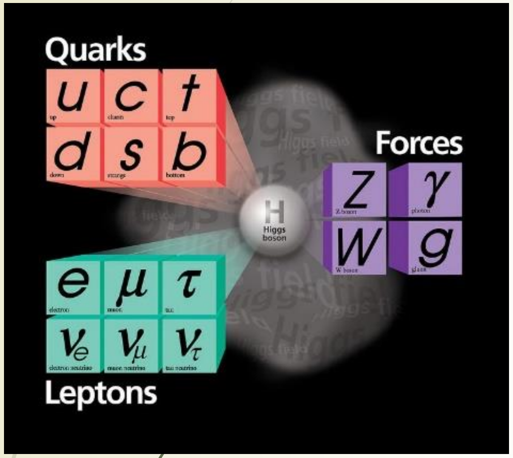
QCD Phase Diagram



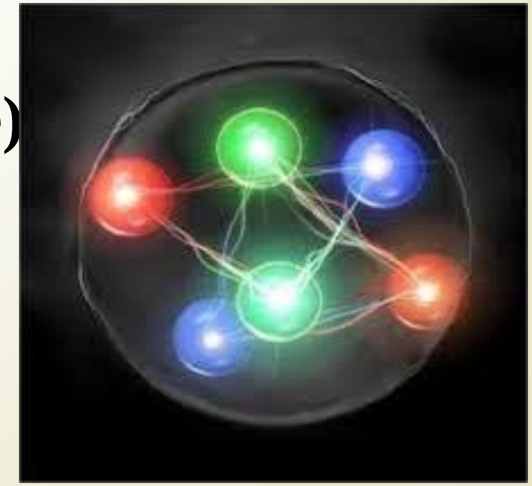
Role of Compact Stars



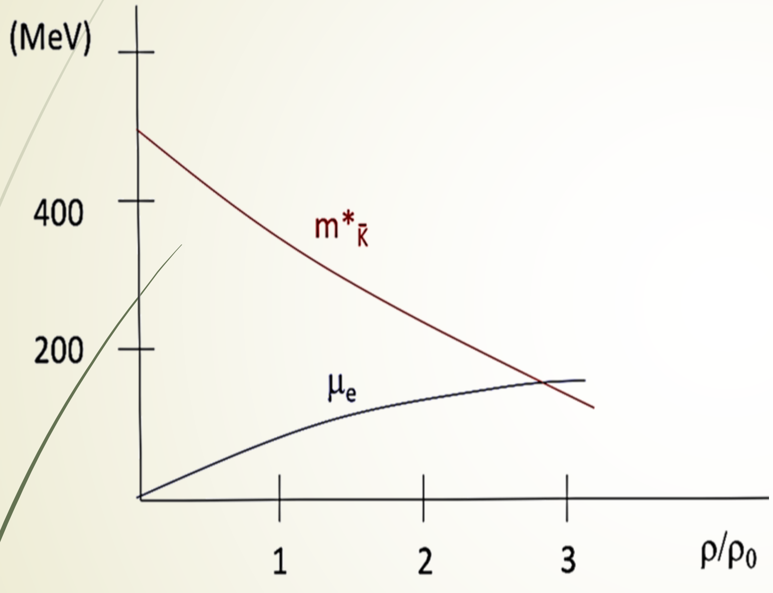
Different form of Strange Matter in NS

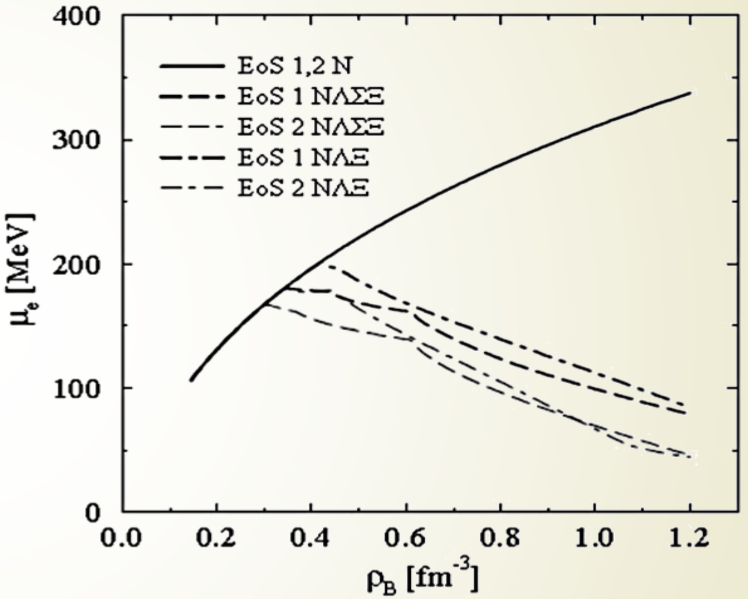


- ❑**Hyperons**
- ❑**Strange quark matter**
- ❑**Multi-quark states (Sexaquark (uuddss) Dark Matter candidate)**
- ❑ Kaon condensation



Kaon Condensation?!





$$n \rightarrow p\, e^- \, \bar{\nu}_e$$

$$n \leftrightarrow p + \bar{K}$$

The Effects of Appearance of Strange Hadronic and Quark Degrees of Freedom in Neutron Stars

- Changing the frequency and amplitude of Gravitational Wave (GW) before and after merger [1]

- Softening of the Equation of State (EoS)
    - Hyperon puzzle which is still an open question.
    - Shifting the position of deconfinement onset

- Affecting both the density and temperature profiles inside NS
    - New branches for direct Urca processes
    - Superfluidity of Hyperons

- Postponing Kaon Condensation to higher densities

[1] Y. Sekiguchi,et al., Phys. Rev. Lett. 107, 211101 (2011)

Equation of State (EoS) of Hypernuclear Matter

Experiments
Nuclear Physics

Well constraint EoS

Observations
Neutron Stars

1. Saturation density
2. Binding energy
3. Incompressibility
4. Symmetry energy coefficients

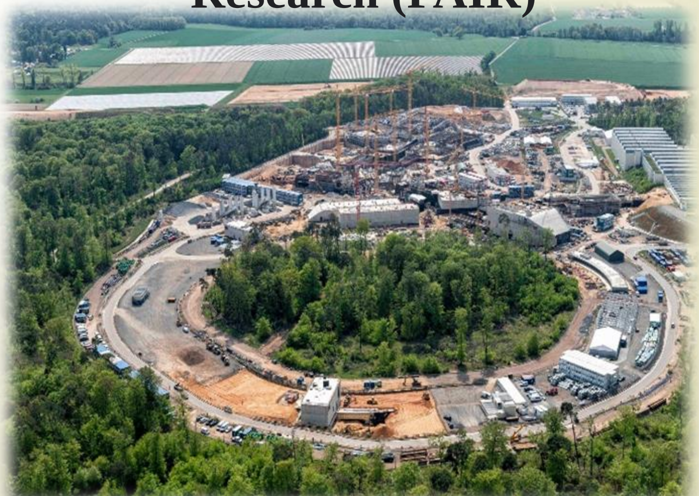
At saturation point

1. Maximum mass of NS
2. Radius of NS
3. Tidal deformability
4. Cooling

Various detectors probing GWs from compact objects and experimental facilities for investigating hypernuclei

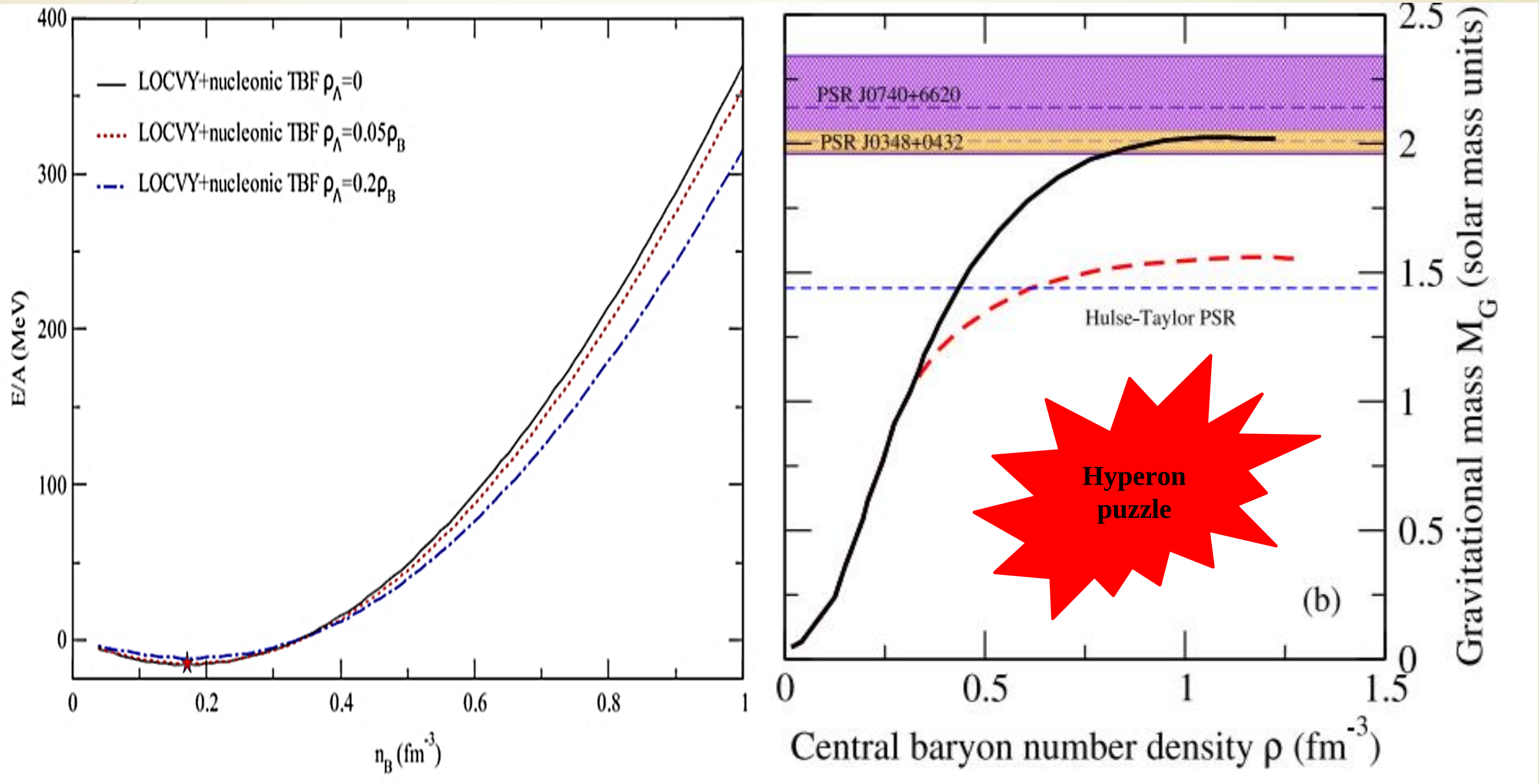
Japan Proton Accelerator Research Complex (J-PARC)

Facility for Antiproton and Ion Research (FAIR)



EoS of Hypernuclear Matter within LOCV method

The EoS gets soft by including Hyperon!



M. Sh and H. R. Moshfegh, Annals Phys.402 (2019)

M. Sh, H. R. Moshfegh and M. Modarres, Phys. Rev. C 100 (2019)

Solutions for solving hyperon puzzles

- ➢Using a relativistic model in which the meson couplings are adjusted for producing the necessary stiffness

V. B. Thapa, M. Sinha, J. J. Li, and A. Sedrakian, Phys. Rev. D **103**, 063004 (2021)

H. Grigorian, D. N. Voskresensky, and K. A. Maslov, Nucl. Phys. A **980**, 105 (2018)

- ➢Modifying the hyperonic interactions and including the hyperonic 3BF

E. Friedman, A. Gal, PLB 837, 137669 (2023)

Y. Yamamoto, T. Furumoto, N. Yasutake and T. A. Rijken, Eur. Phys. J. A **52**, no.2, 19 (2016)

I. Vidana, D. Logoteta, C. Providencia, A. Polls, I. Bombaci, EPL 94, no.1, 11002 (2011)

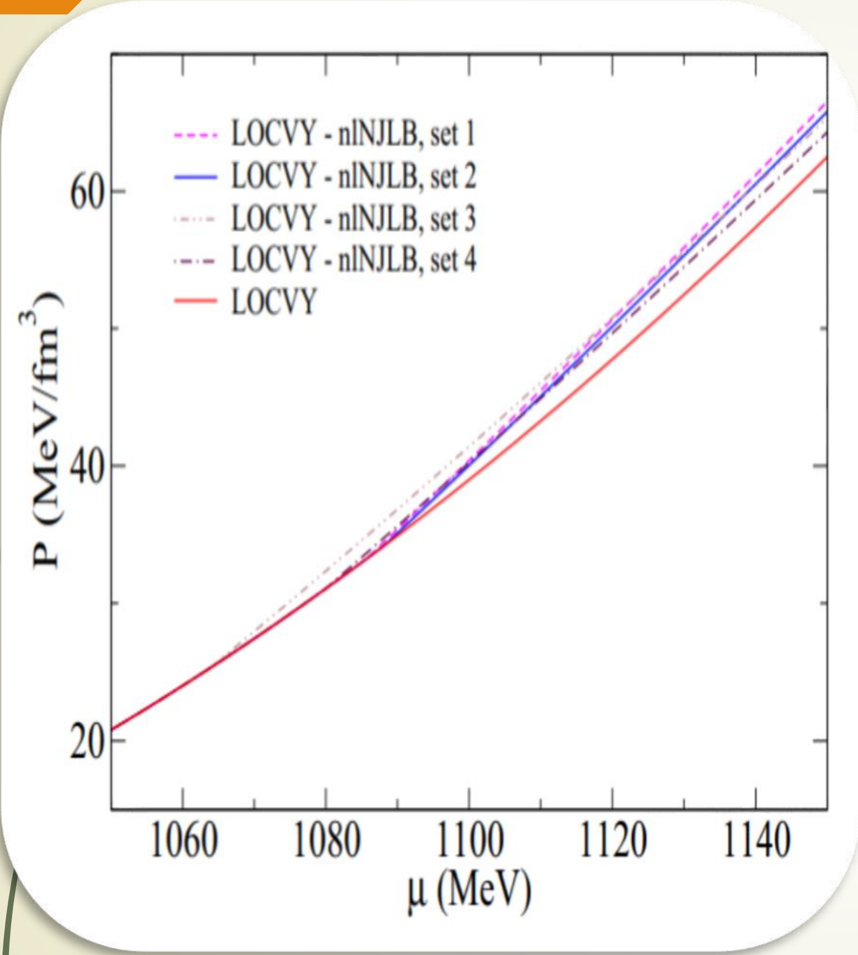
- ➢Constructing a phase transition from hypernuclear matter to deconfined quark matter

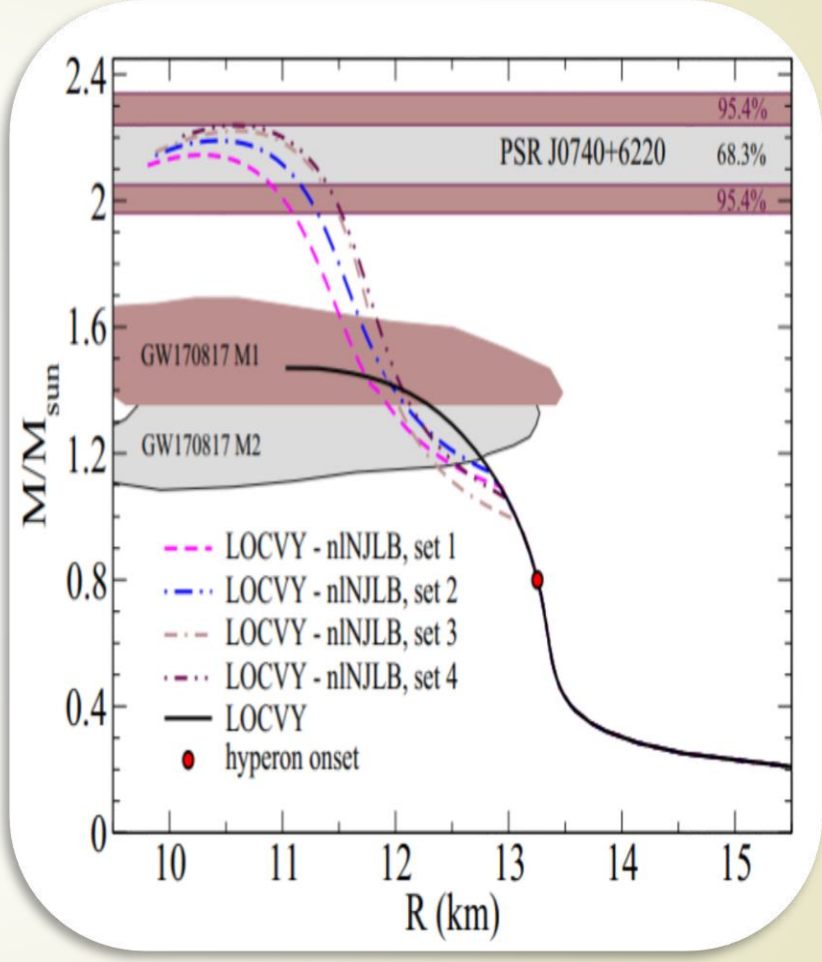
M. Shahrbaf, D. Blaschke, A. G. Grunfeld and H. R. Moshfegh, Phys. Rev. C, no.2, 025807 (2020)

- ➢Using the modified gravity

A. V. Astashenok, S. Capozziello, S. D. Odintsov, Phys. Rev. D 89, no. 10, 103509 (2014)

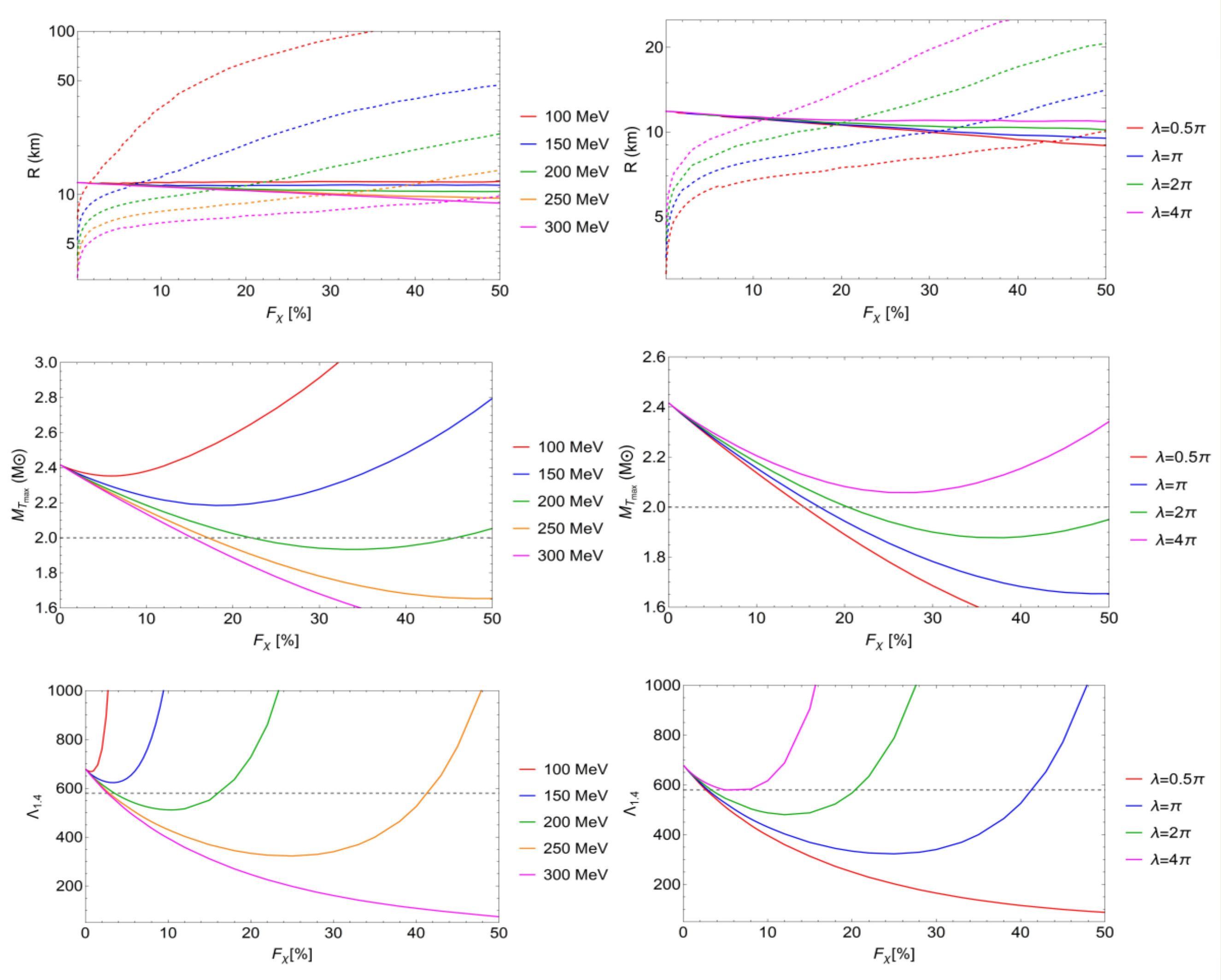
Phase transition from hypernuclear matter to deconfined quark matter within a Maxwell construction





M. Sh, D. Blaschke, A. G. Grunfeld, H. R. Moshfegh, Phys. Rev. C 101 (2020)
M. Sh, D. Blaschke and S. Khanmohamadi,J. Phys. G 47 (2020)

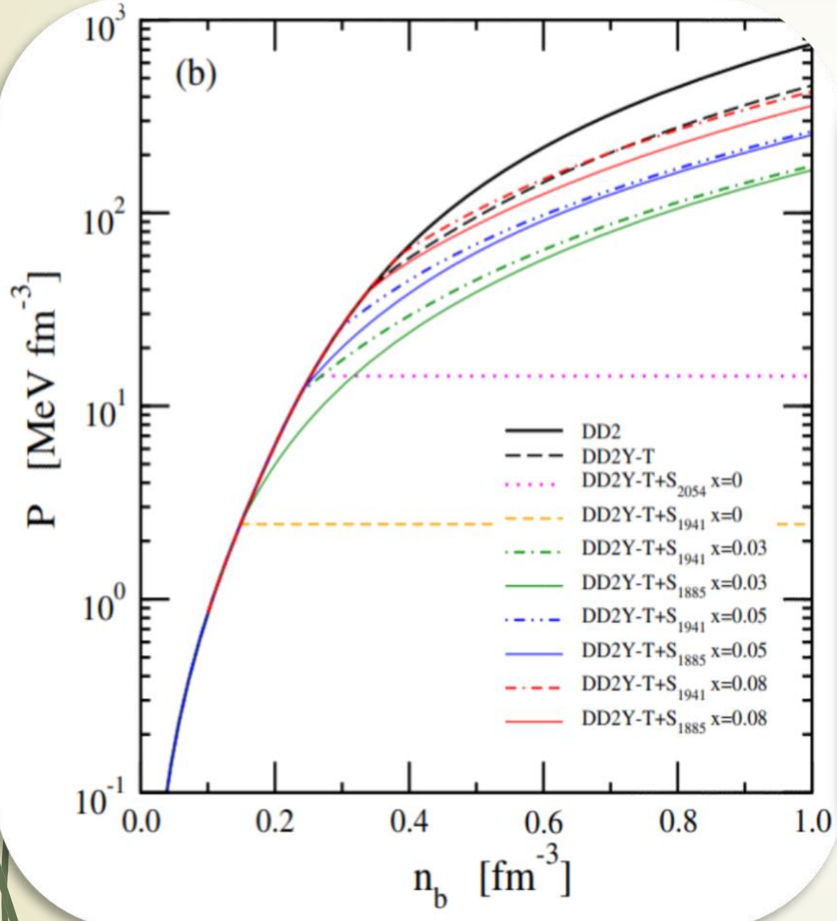
Dark Matter admixed Neutron Stars

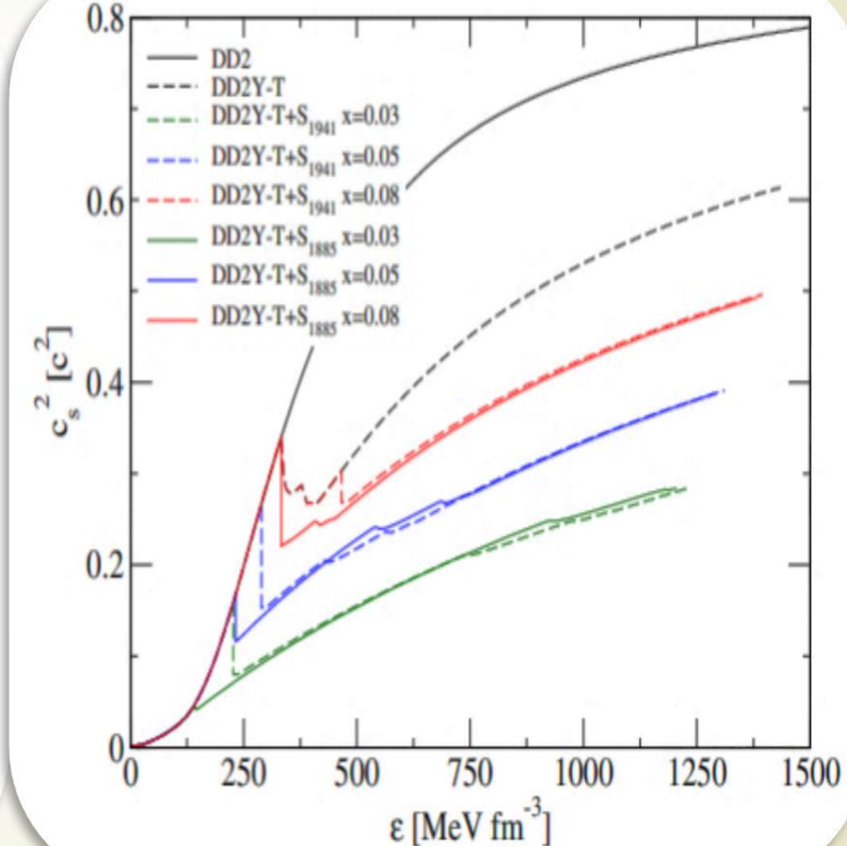


For m>200 MeV, 4%<F<20%, and λ<2π in DM parameter space, all observational constraints are satisfied.

D.R.Karkevandi, **M.Sh**, S.Shakeri and S.Typel, Particles 7, no.1, (2024)

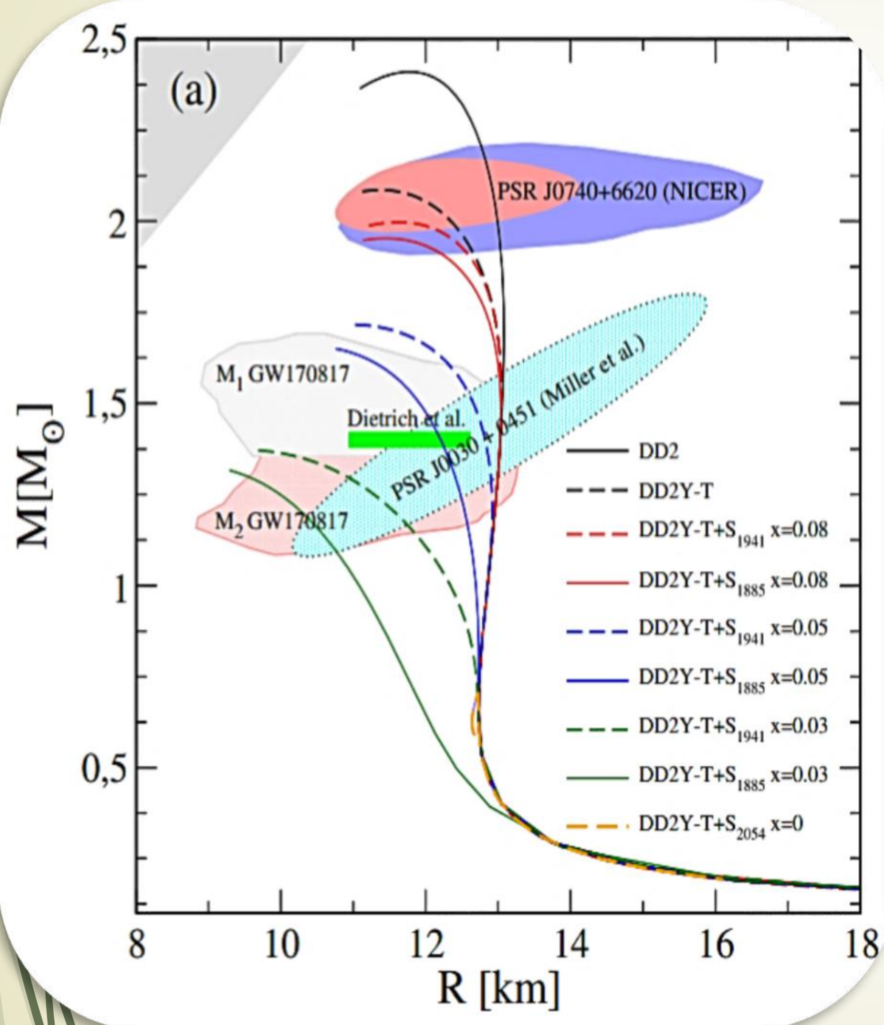
Softening of the EoS by including Sexaquark as a candidate for dark matter in addition to hyperons

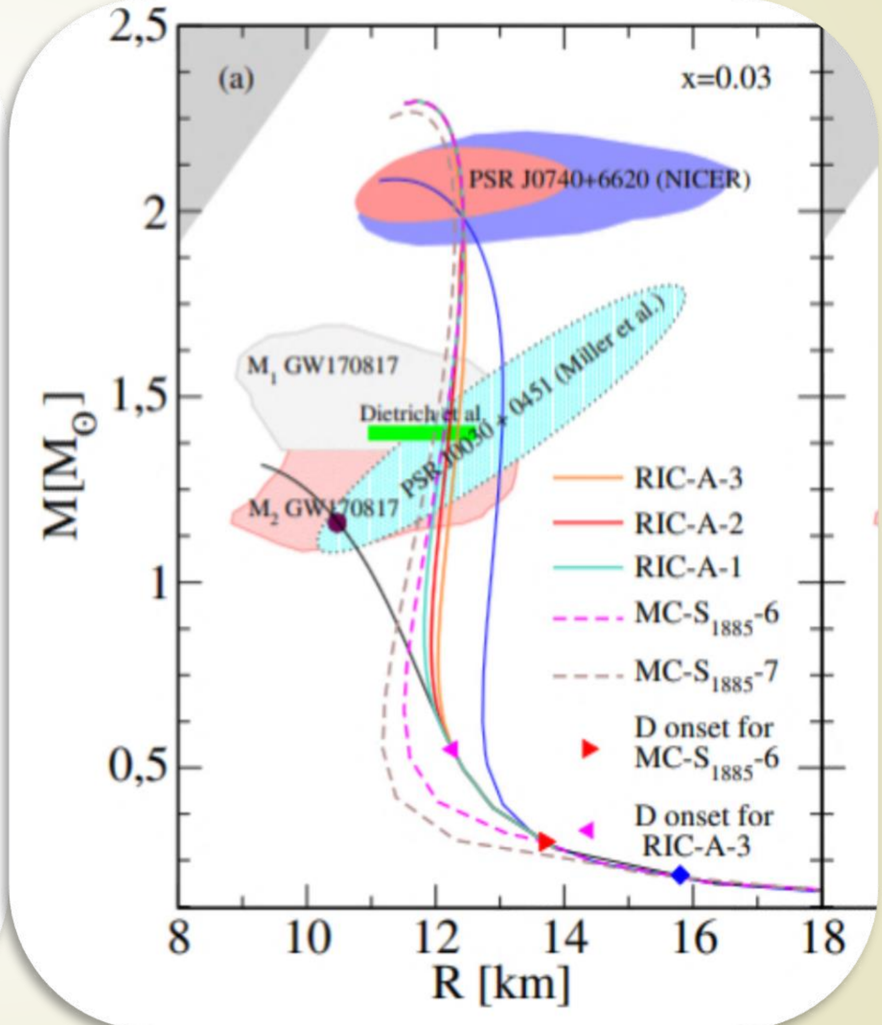




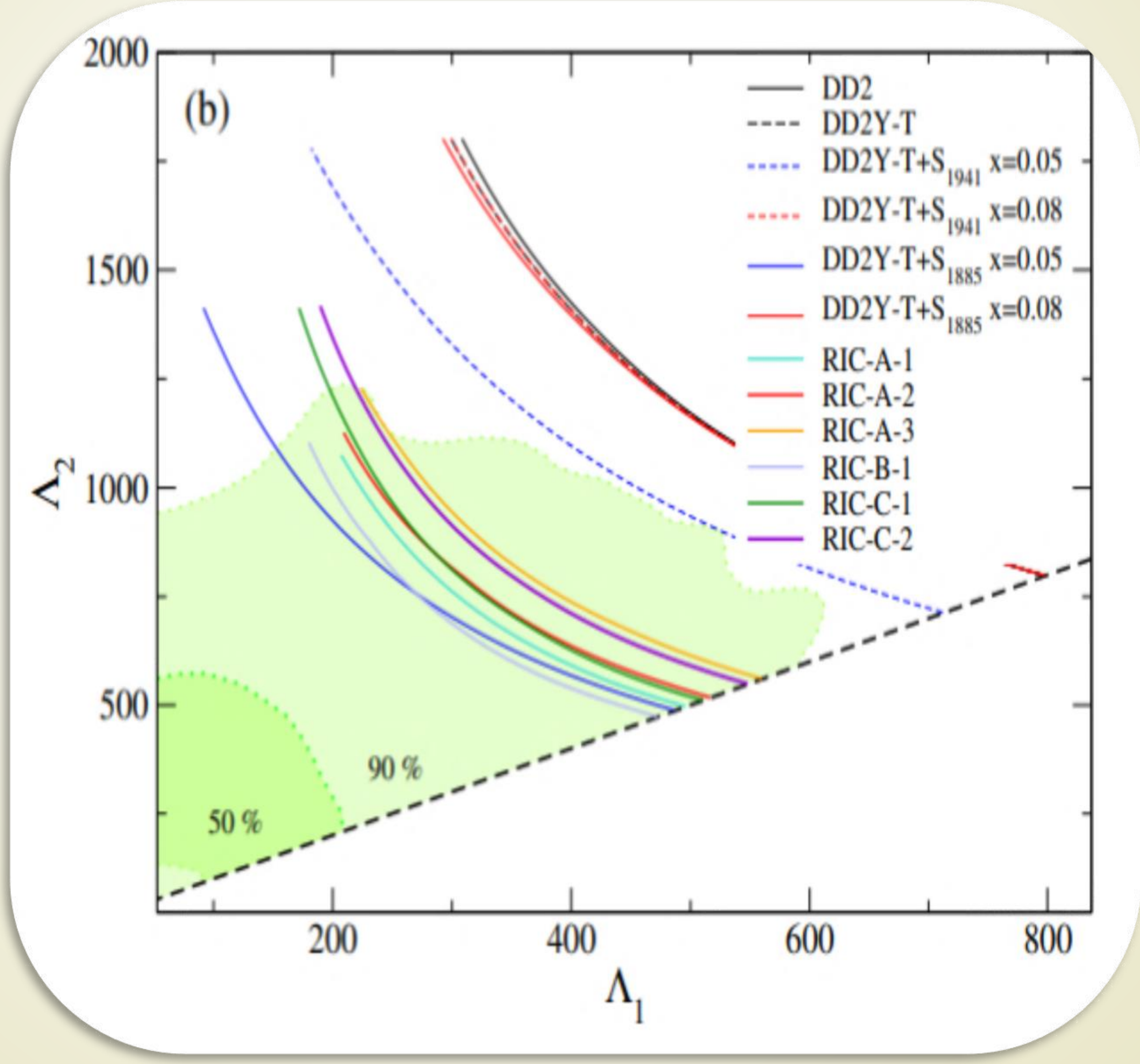
M. Sh, D.Blaschke, et al., Phys. Rev. D 105 (2022)

Mass-Radius of the modeled NSs

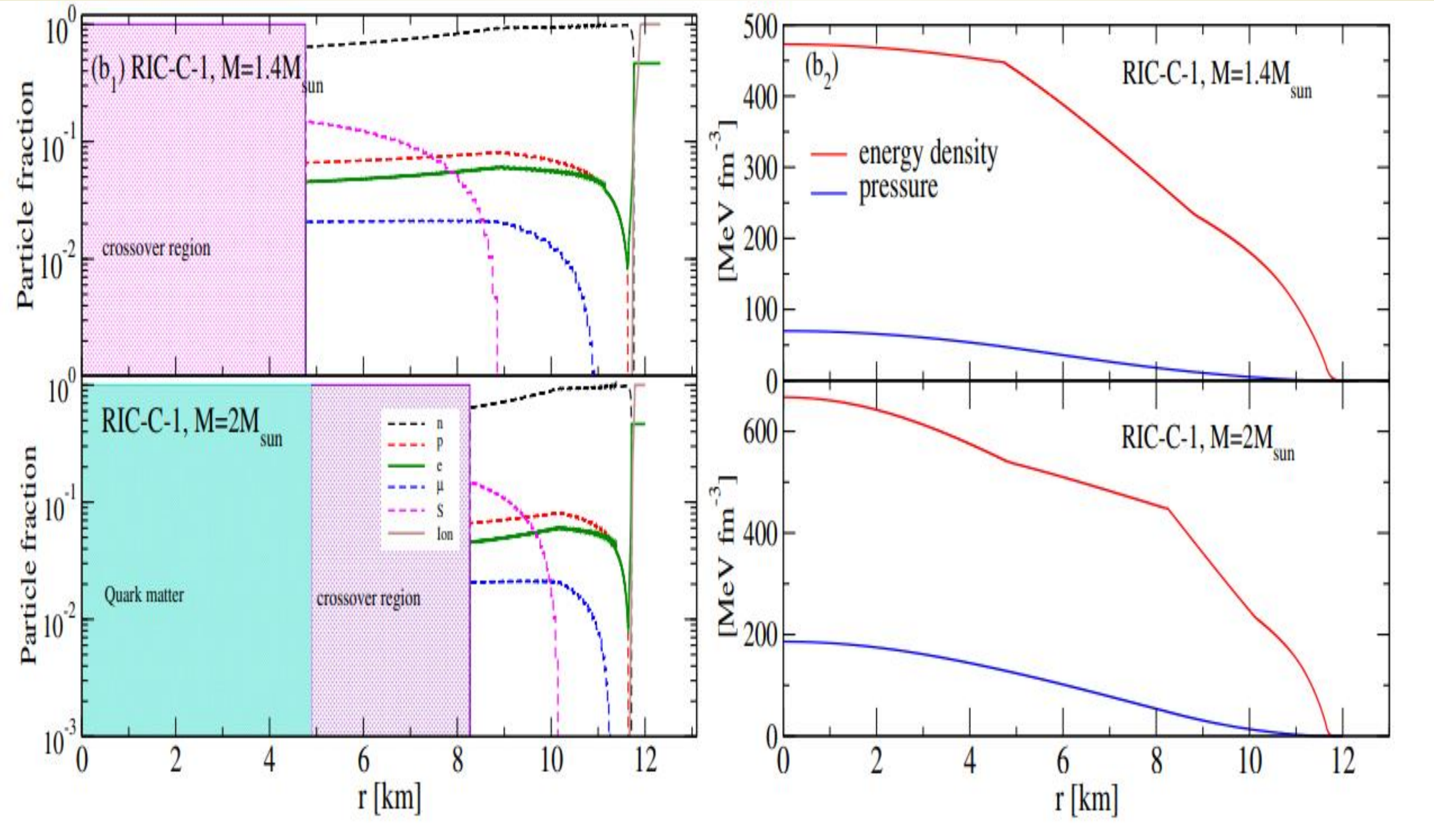




Tidal deformability for hybrid stars with ordinary nuclear matter, hyperons, sexaquark and quark matter core



Profile of the Star including hyperon and dark matter and deconfined quark matter



Neutron Stars with a core of deconfined QM sorrounded by hypernuclear matter including strange DM particle with m=1885 MeV, x= 0.03 and F≤20% agree all observational constraints.

NARODOWE CENTRUM NAUKI

Sonatina 7 grant

Hypernuclear Matter from
the Phenomenology of Neutron Stars
and Hypernuclei

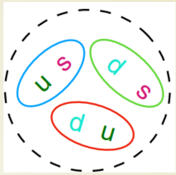
"A theory is something nobody believes, except the person who made it.
An experiment is something everybody believes, except the person who made it."

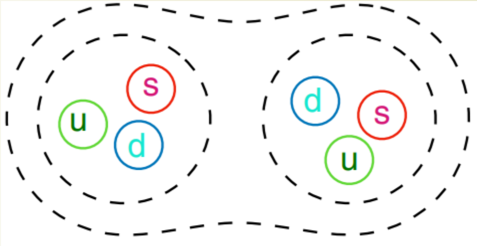
Albert Einstein

Thank you

What is a Sexaquark?

uuddss





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

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

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

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

if $2054\ \text{MeV} < m_s < 2231\ \text{MeV}$: S decays

- If $m_s \leq \left(m_{\Lambda} + m_p + m_e\right) = 2054$ MeV,

S decays with a lifetime more than the age of the universe

- If $m_s \leq 2\left(m_p + m_e\right) = 1877$ MeV : S is absolutely stable

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

Including Sexaquark (S) in DD2Y-T model

- 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 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!!

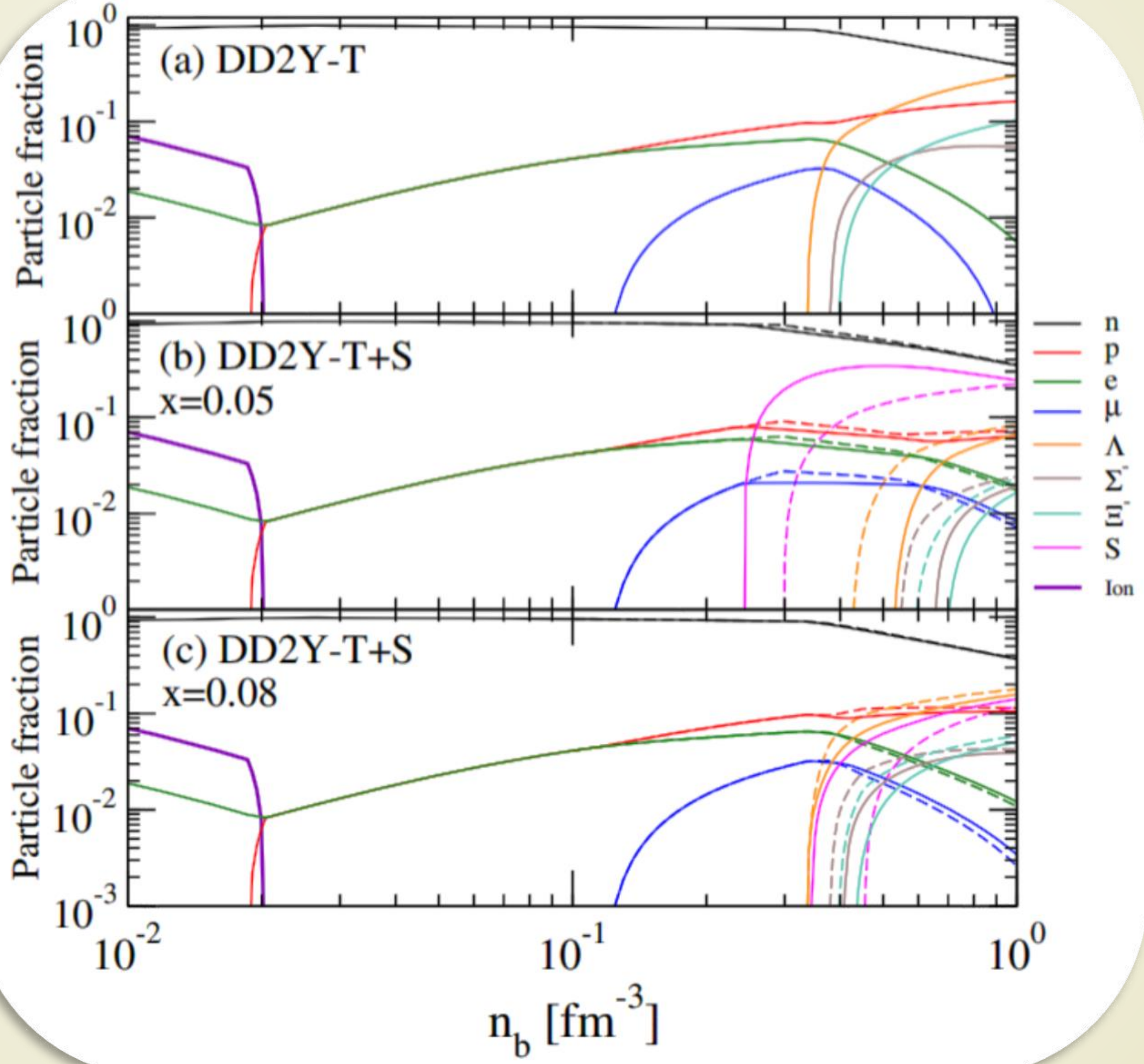
- Therefore, a linear mass shift has been assumed instead of a meson-coupling interaction as all medium effects.

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

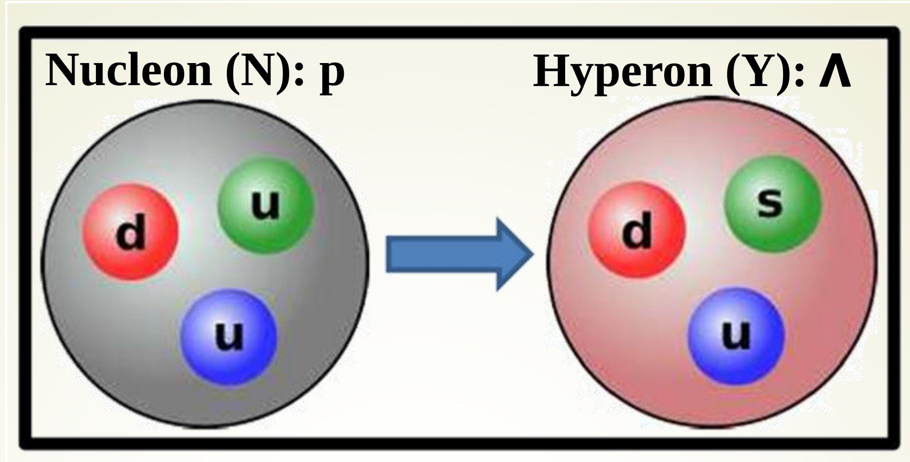
- This assumption results in an increase of the S onset density as well as the condensation so that there is still an increase of the pressure at higher densities.

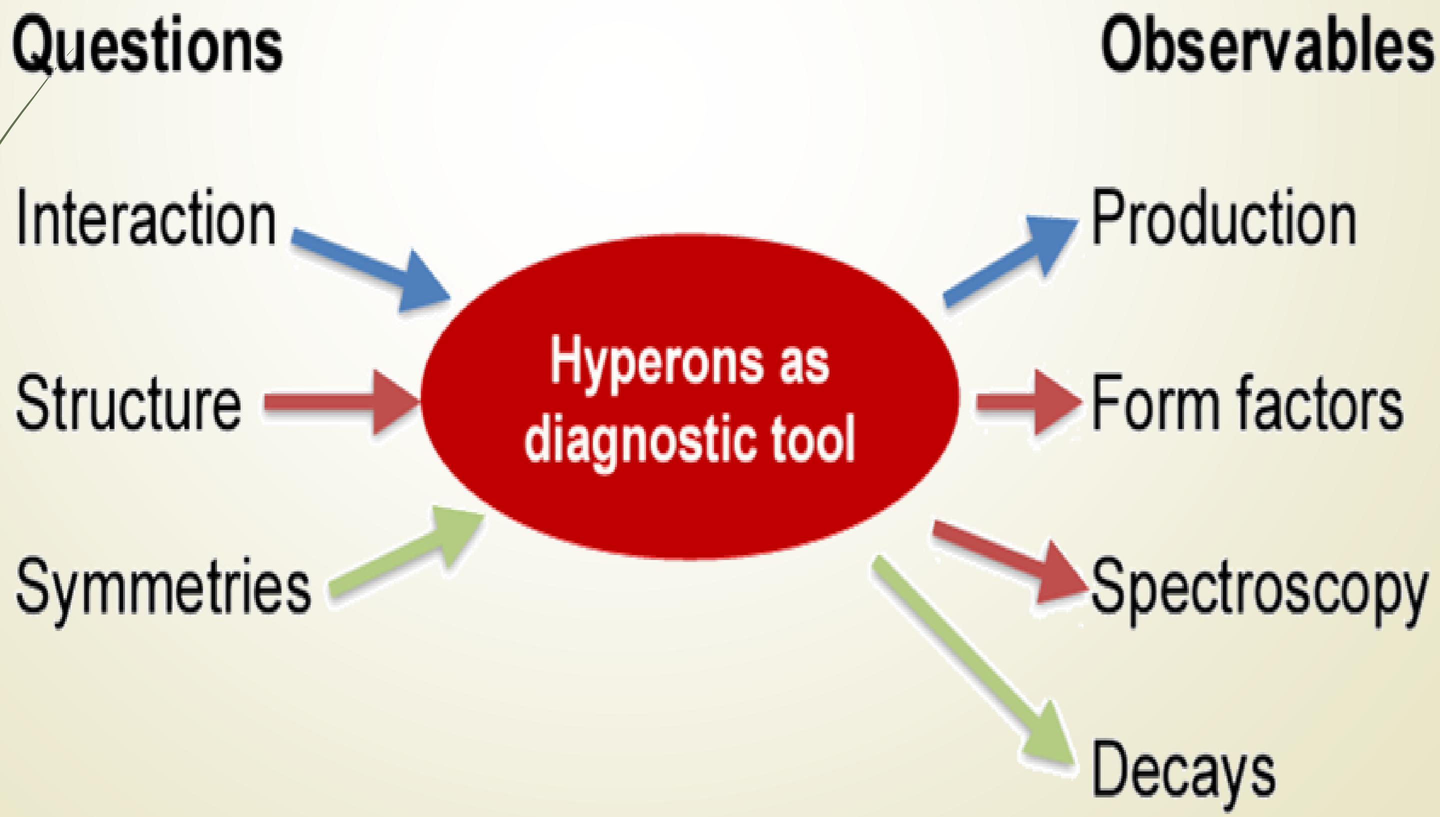
$$P = -\Omega, \; f = \varepsilon = \Omega + \sum_i \mu_i n_i^{(v)}$$

Sexaquark formation postpones hyperon onset



Hyperons as a Laboratory for Strong Interaction and Baryon Structure





Employing the realistic YN and YY potentials (obtained from hypernuclei experiments) in variational method

Addressing the density dependence of the realistic potentials from obtained EoS

Extending Chiral model to SU(3) with the well constrained couplings

- Generalizing the EoSs to finite temperature
- Investigating their compatibility with the observational constraints
- Solving hyperon puzzle
- Employing the new developed EoS in supernovae and NS mergers simulations
- Investigating the QCD phase diagram