Role of Strangeness in Neutron Stars

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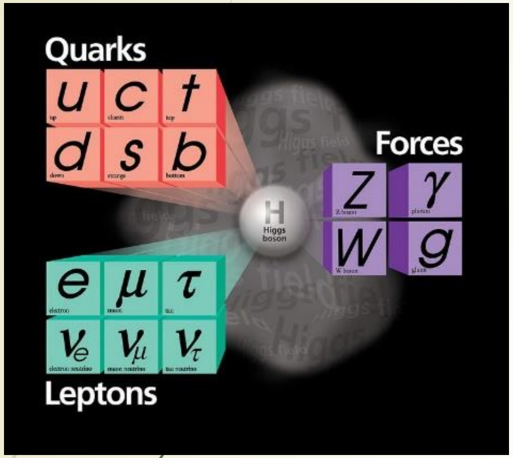
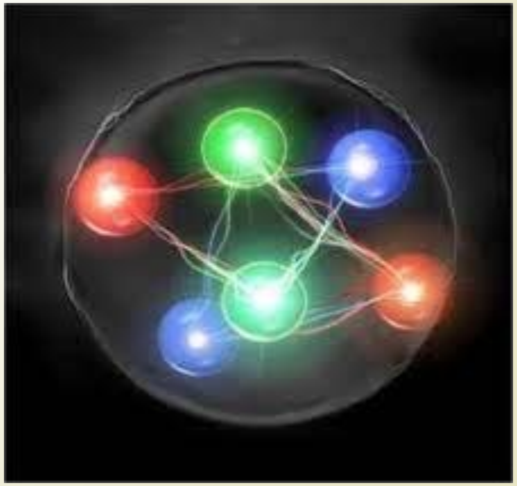
Different form of Strange Matter in NS



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

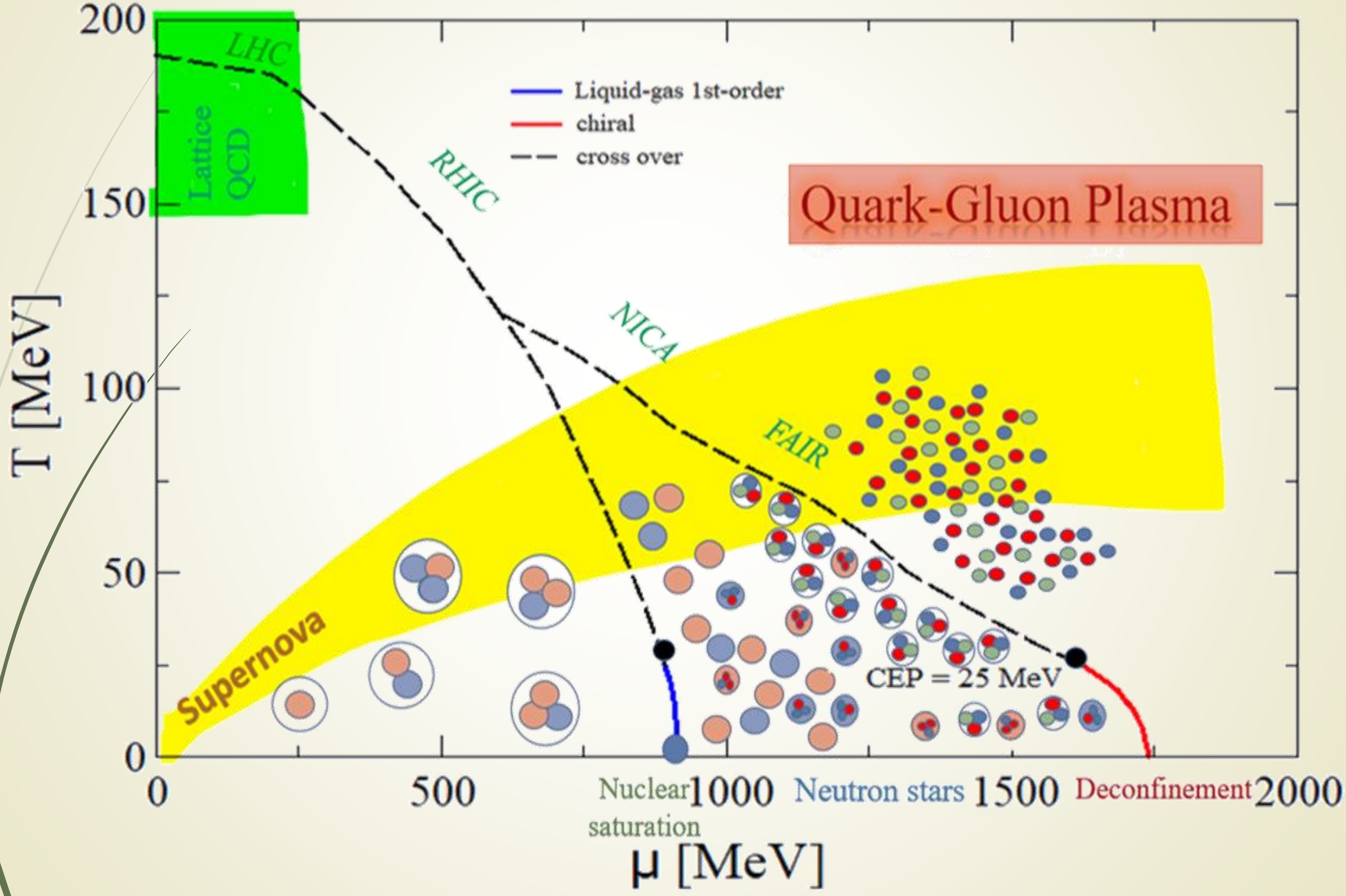


Appearance of Strange Hadronic and Quark Degrees of Freedom in Astrophysics

- Softening of the Equation of State (EoS)
- Hyperon puzzle which is still an open question.
- Affecting both the density and temperature profiles inside NS [1]
- Reducing neutrino opacity and generating higher luminosities in supernovae
- Resulting in a successful supernova explosion in 3D simulations [2]
- Changing the frequency and amplitude of Gravitational Wave (GW) before and after merger [3]
- Generating in large amounts in hot neutron star mergers [4,5] resulting in a faster collapse of hypermassive stars into black holes [6]
- Shifting the position of deconfinement onset

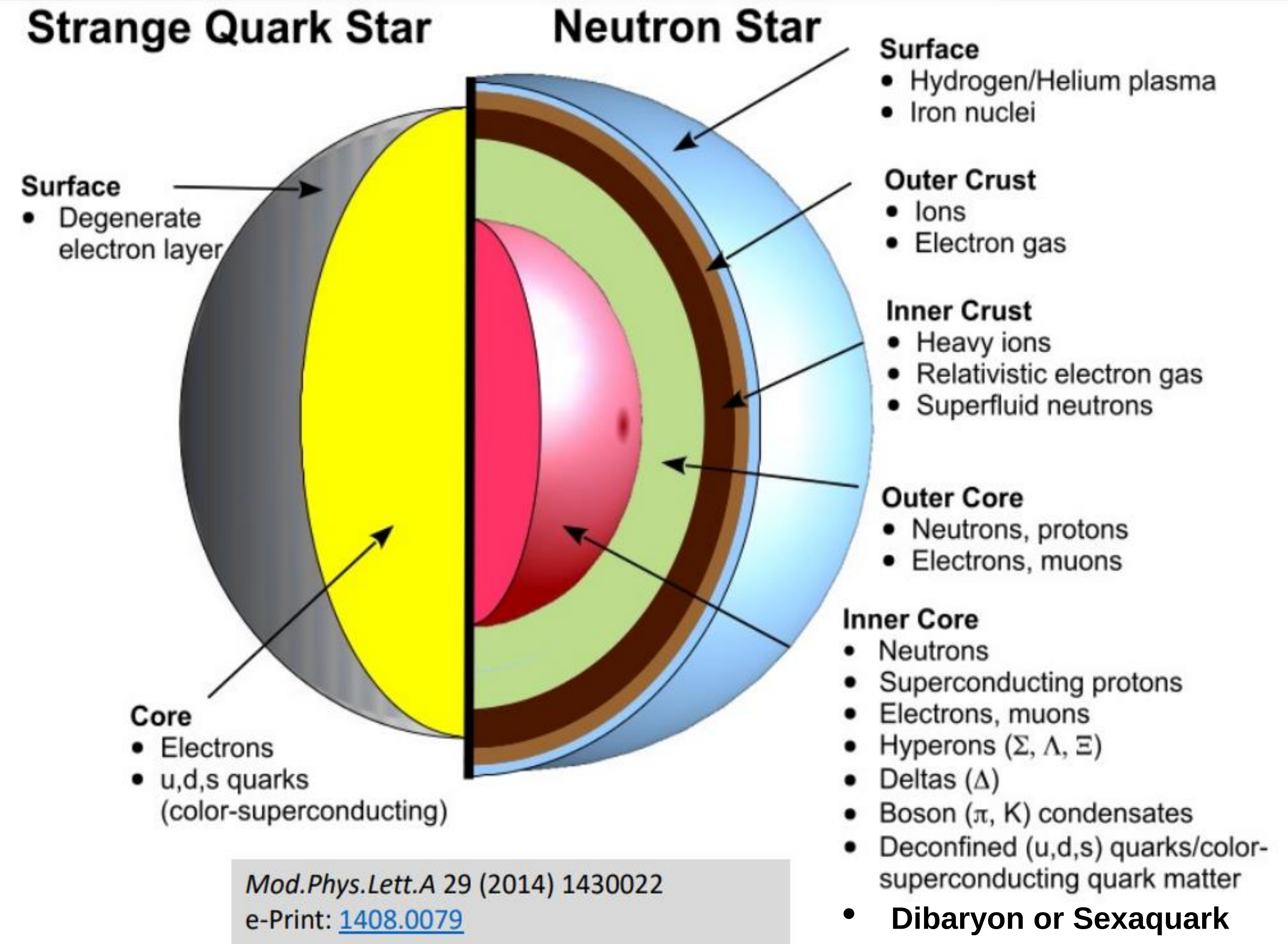
[1] P. Char et al., The Astrophysical Journal 809, 116 (2015)
[2] T. Melson, et al., The Astrophysical Journal 808, L42 (2015)
[3] Y. Sekiguchi,et al., Phys. Rev. Lett. 107, 211101 (2011)
[4, 5] E.R.Most,et al.,Phys. Rev. Lett. 122, 061101 (2019), E.R.Most et al., Eur. Phys. J. A56, 59 (2020)
[6] A. Perego, S. Bernuzzi, D. Radice, Eur. Phys. J. A 55, 124 (2019)

QCD Phase Diagram



M. Sh, [arXiv:2303.03030 [nucl-th]]

Role of Compact Stars



Strange Quark Star

Surface
- Degenerate electron layer

Core
- Electrons
- u,d,s quarks (color-superconducting)

Neutron Star

Surface
- Hydrogen/Helium plasma
- Iron nuclei

Outer Crust
- Ions
- Electron gas

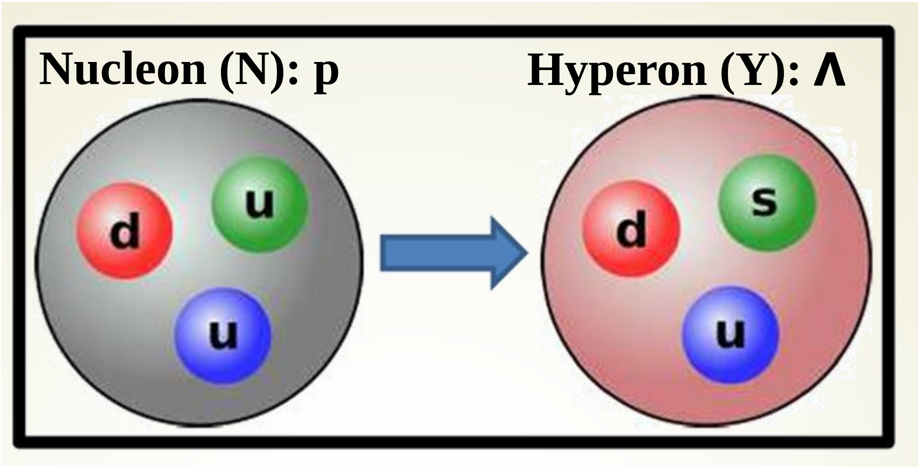
Inner Crust
- Heavy ions
- Relativistic electron gas
- Superfluid neutrons

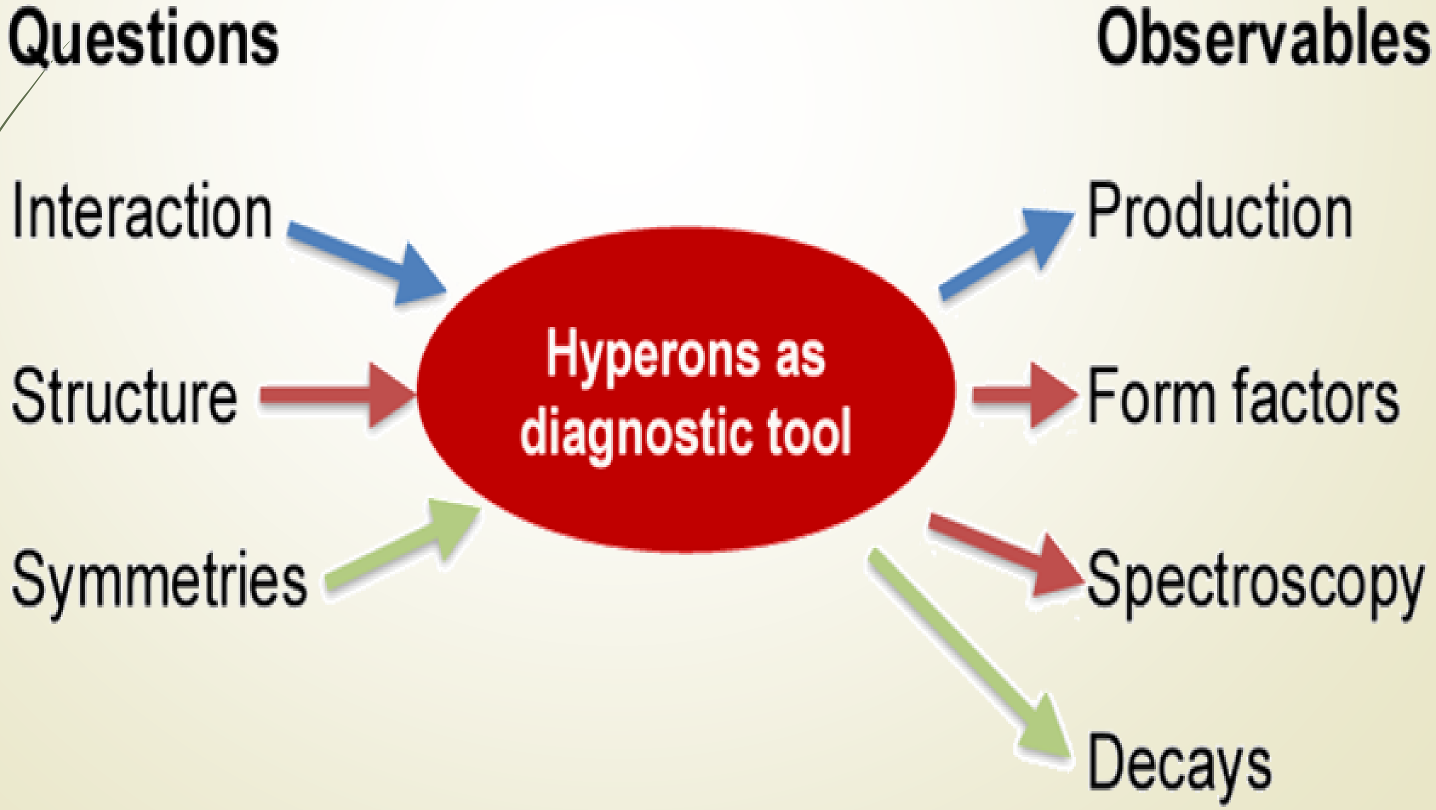
Outer Core
- Neutrons, protons
- Electrons, muons

Inner Core
- Neutrons
- Superconducting protons
- Electrons, muons
- Hyperons (Σ, Λ, Ξ)
- Deltas (Δ)
- Boson (π, K) condensates
- Deconfined (u,d,s) quarks/color-superconducting quark matter
- **Dibaryon or Sexaquark**

Mod.Phys.Lett.A 29 (2014) 1430022
e-Print: 1408.0079

Hyperons as a Laboratory for Strong Interaction and Baryon Structure





Questions

Observables

Interaction

Structure

Symmetries

Hyperons as diagnostic tool

Production

Form factors

Spectroscopy

Decays

Equation of State (EoS) of Hypernuclear Matter

Hypernuclei

Well constraint EoS

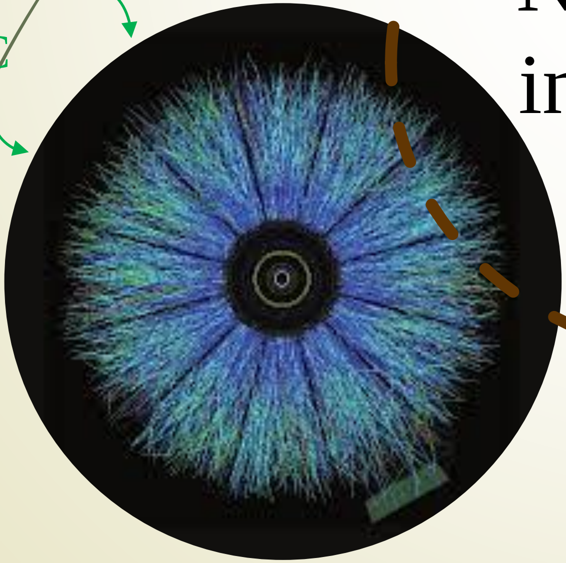
Neutron Stars
(NS)

NY and YY
interactions

HypHI

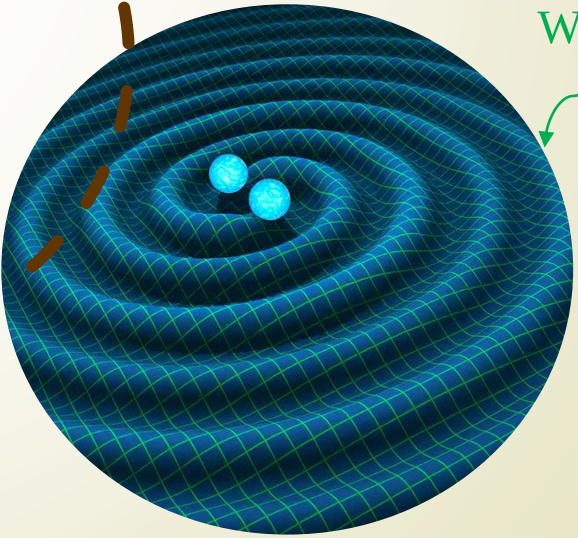
HADES

J-PARC



NSs and their Merger

Gravitational
Waves



LOCV:Lowest Order Constrained Variational method

$$E=\langle H\rangle=\frac{1}{N}\frac{\langle\Psi|H|\Psi\rangle}{\langle\Psi|\Psi\rangle}=E_1+E_{MB}\cong E_1+E_2\,;$$

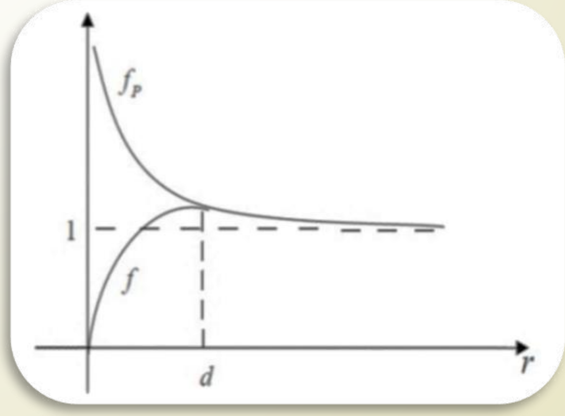
$$\Psi(1\ldots A)=F(1\ldots A)\Phi(1\ldots A);\qquad F=S\prod_{i>j}f(ij)$$

$$E_2=\frac{1}{2N}\sum_{ij}\left\langle ij\left|\frac{\hbar^2}{m}\left[f(12),\left[\nabla_{12}^2,f(12)\right]\right]+f(12)V(12)f(12)\right|ij-ji\right\rangle$$

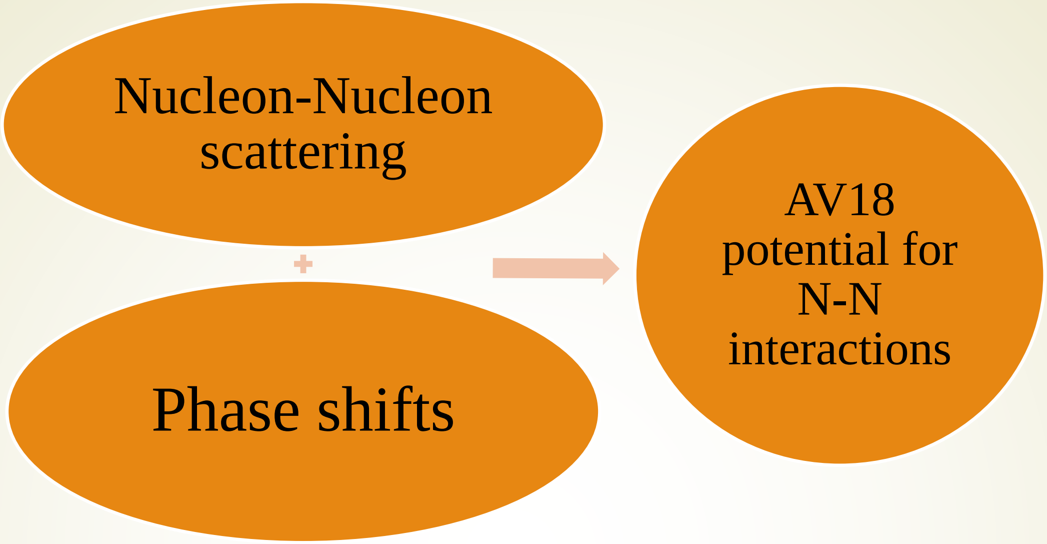
$$\Big|ij\Big\rangle=\Big|k_1,{}^1\!/_2\,,m_{\sigma_1},\frac{1}{2},m_{\tau_1},S_1,k_2,{}^1\!/_2\,,m_{\sigma_2},\frac{1}{2},m_{\tau_2},S_2\Big\rangle$$

$$\langle\Psi\,|\Psi\,\rangle=1-\sum_{ij}\langle ij|F_p^2-F^2|ij-ji\rangle$$

$$\chi=\frac{1}{N}\sum_{ij}\langle ij|F_p^2-F^2|ij-ji\rangle=0$$



Nucleon-Nucleon interactions



Nucleon-Nucleon scattering

+

Phase shifts

AV18 potential for N-N interactions

$$O_{ij}^{p=1,6} = (1, \boldsymbol{\sigma}_i . \boldsymbol{\sigma}_j, S_{ij}) \otimes (1, \boldsymbol{\tau}_i . \boldsymbol{\tau}_j),$$

$$O_{ij}^{p=7,8} = \boldsymbol{L}.\boldsymbol{S} \otimes (1, \boldsymbol{\tau}_i . \boldsymbol{\tau}_j),$$

$$O_{ij}^{p=9,14} = (L^2, L^2 \boldsymbol{\sigma}_i . \boldsymbol{\sigma}_j, (\boldsymbol{L}.\boldsymbol{S})^2) \otimes (1, \boldsymbol{\tau}_i . \boldsymbol{\tau}_j)$$

$$O_{ij}^{p=15,18} = T_{ij}, (\boldsymbol{\sigma}_i . \boldsymbol{\sigma}_j) T_{ij}\ , S_{ij} T_{ij}, (\tau_{zi} + \tau_{zj}).$$

R. B. Wiringa, V. G. J. Stoks, R. Schiavilla, Phys. Rev. C 51, 38 (1995)

Nucleon-Hyperon and Hyperon-Hyperon interactions

Splitting energy and binding energy in hypernuclei

Spin-parity dependent potentials: Nijmegen and the models based on it

$^{4}_{\Lambda}H\ and\ ^{7}_{\Lambda}Li$ hypernuclei

$$V^{(\mathrm{C})}_{\Lambda N}(r) = \sum_{\alpha} \sum_{i=1}^{3} v_i^{(\alpha)} \exp\left[-(r/\beta_i)^2\right],$$

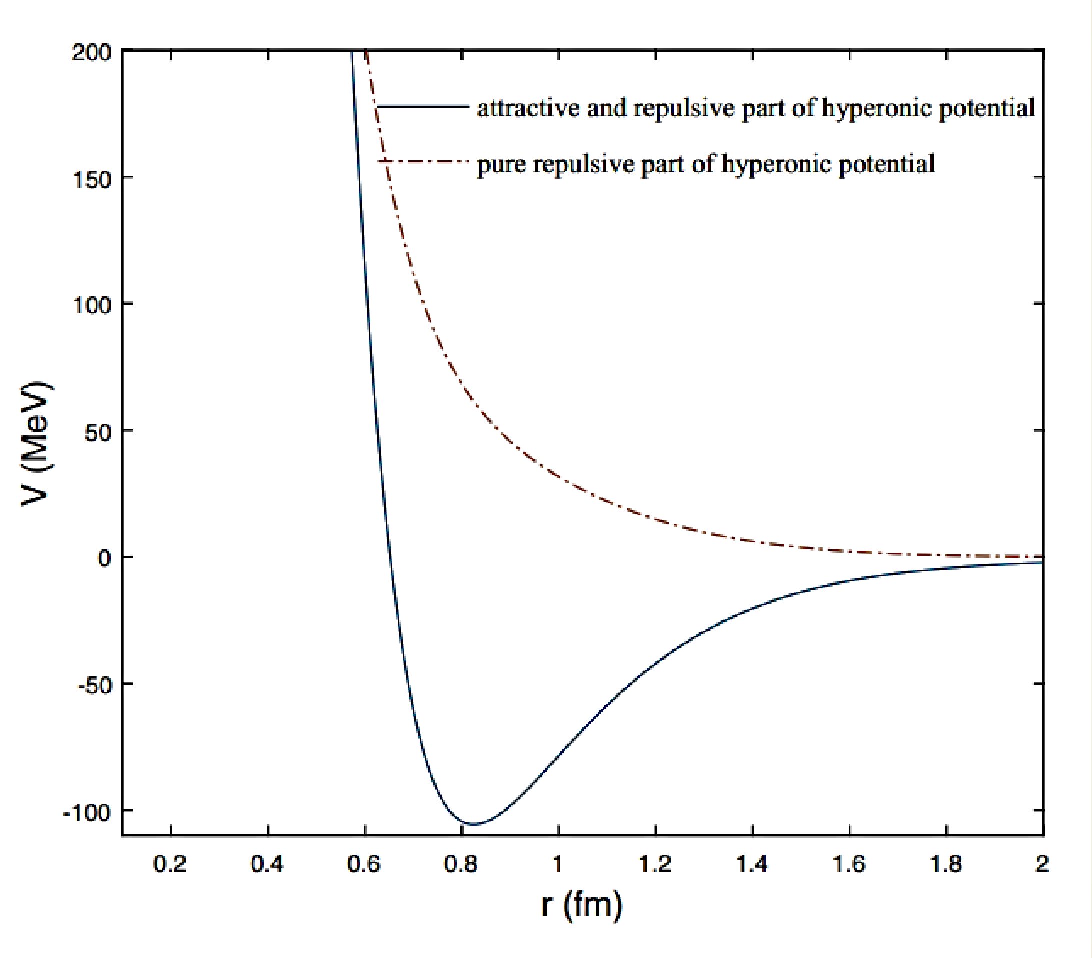
$^{6}_{\Lambda\Lambda}He\ and\ ^{10}_{\Lambda\Lambda}Be$ hypernuclei

$$V_{ij}^{\Lambda\Lambda,\mathrm{even}} = \sum_{k=1}^{3} \left(v_k^{\mathrm{even}} + v_k^{\sigma,\mathrm{even}} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j\right) e^{-\beta_k^{\mathrm{even}} r_{ij}^2}.$$

$$V_{ij}^{\Lambda\Lambda,\mathrm{odd}} = \sum_{k=1}^{3} \left(v_k^{\mathrm{odd}} + v_k^{\sigma,\mathrm{odd}} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j\right) e^{-\beta_k^{\mathrm{odd}} r_{ij}^2}.$$

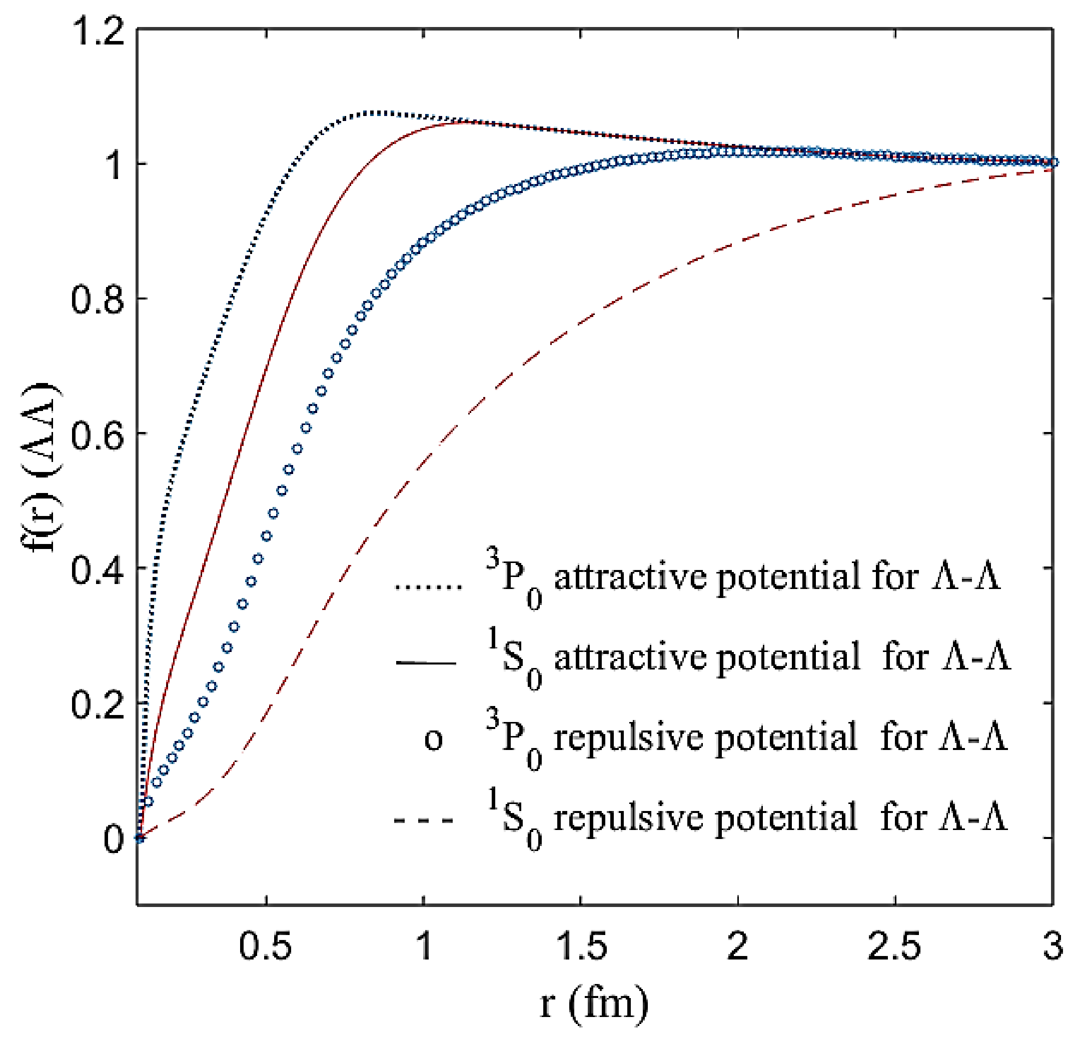
H. Togashi, E.Hiyama, Y. Yamamoto, M. Takano, Phys. Rev. C 93, 035808 (2016)

The Behavior of Phenomenological Hyperonic Potential

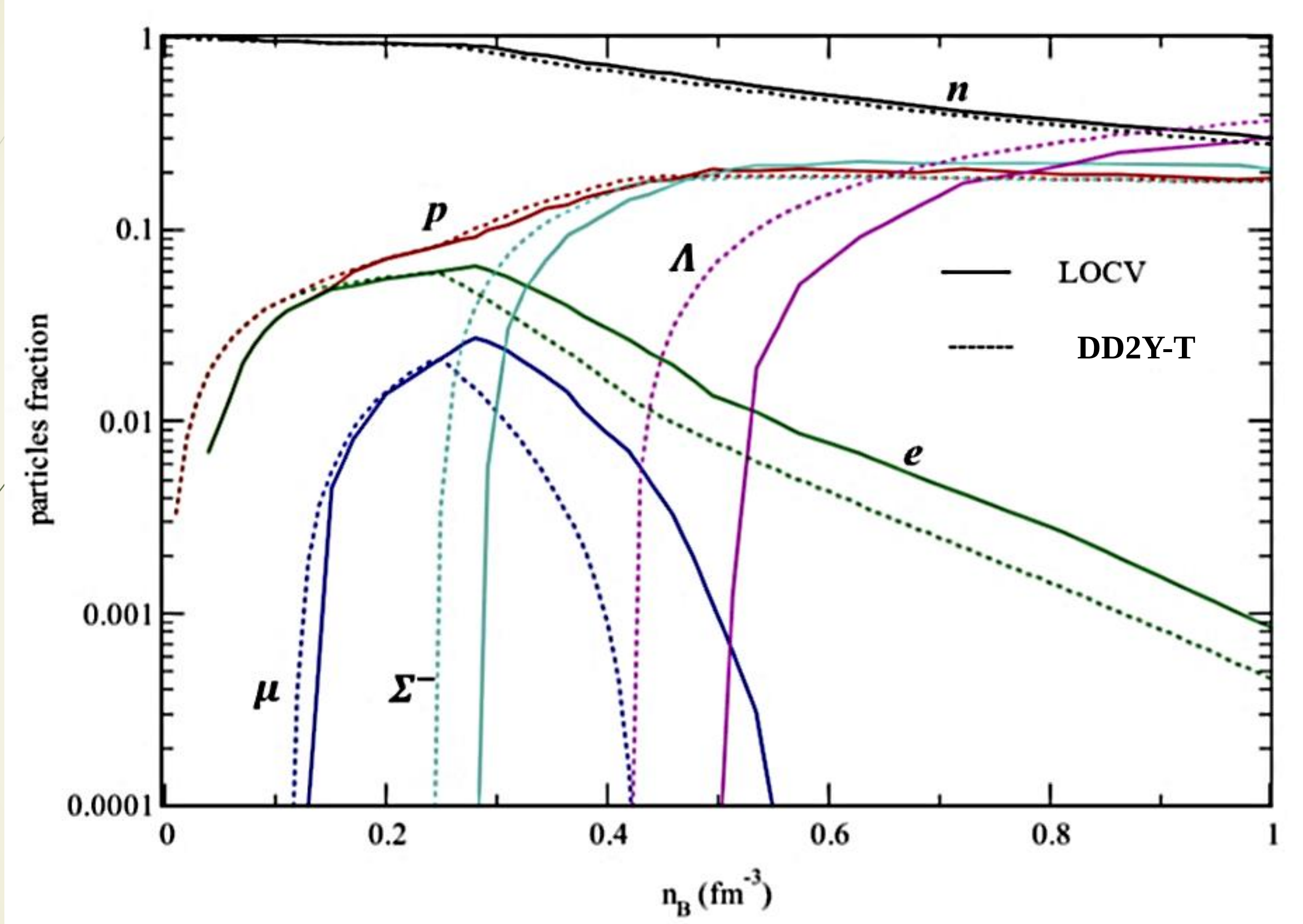


The potentials have a repulsive and attractive part based on LS (orbital and spin angular momentum) channels.

Correlation Functions (CFs) for different types of hyperonic potentials in two arbitrary channels



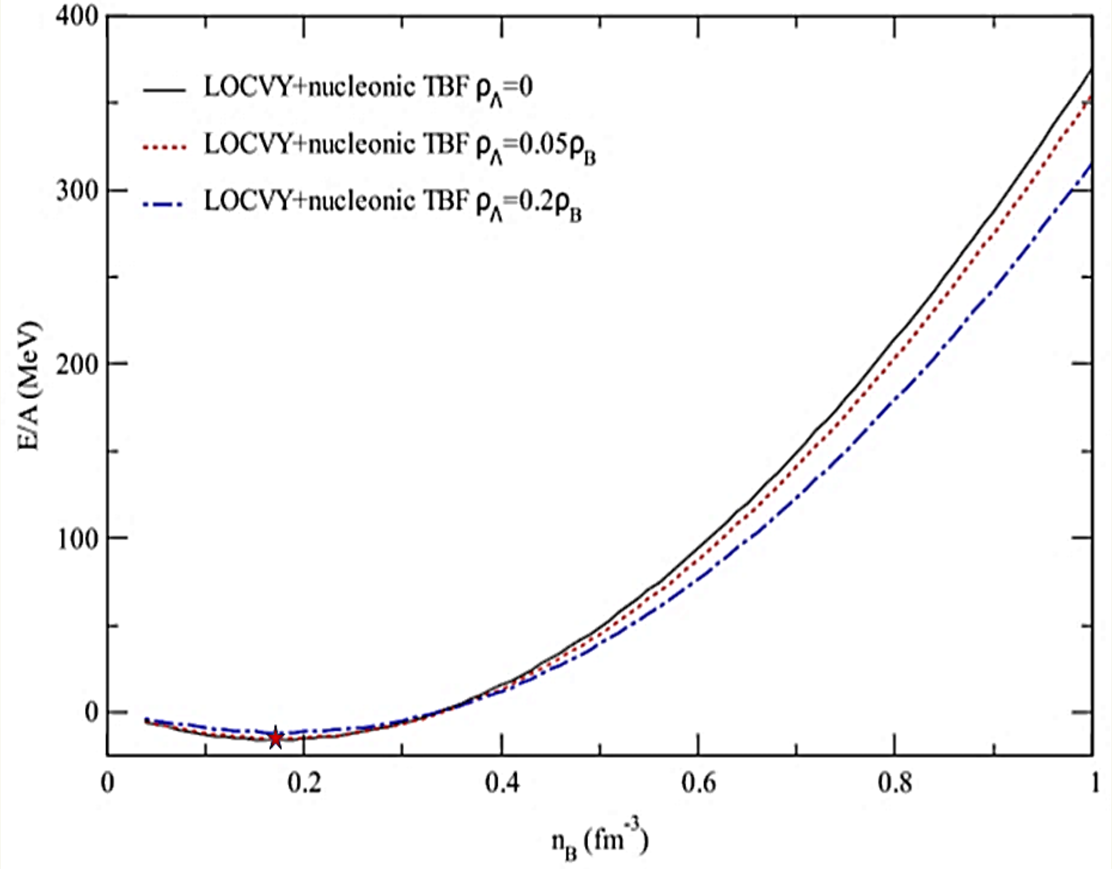
Particle fraction as a function of baryon density



Since the exact values of the hyperonic potentials are not very well known yet, the hyperonic couplings in RMF approaches could be tuned in such a way to have the same behavior as realistic potential based methods.

EoS of Hypernuclear Matter within LOCV method

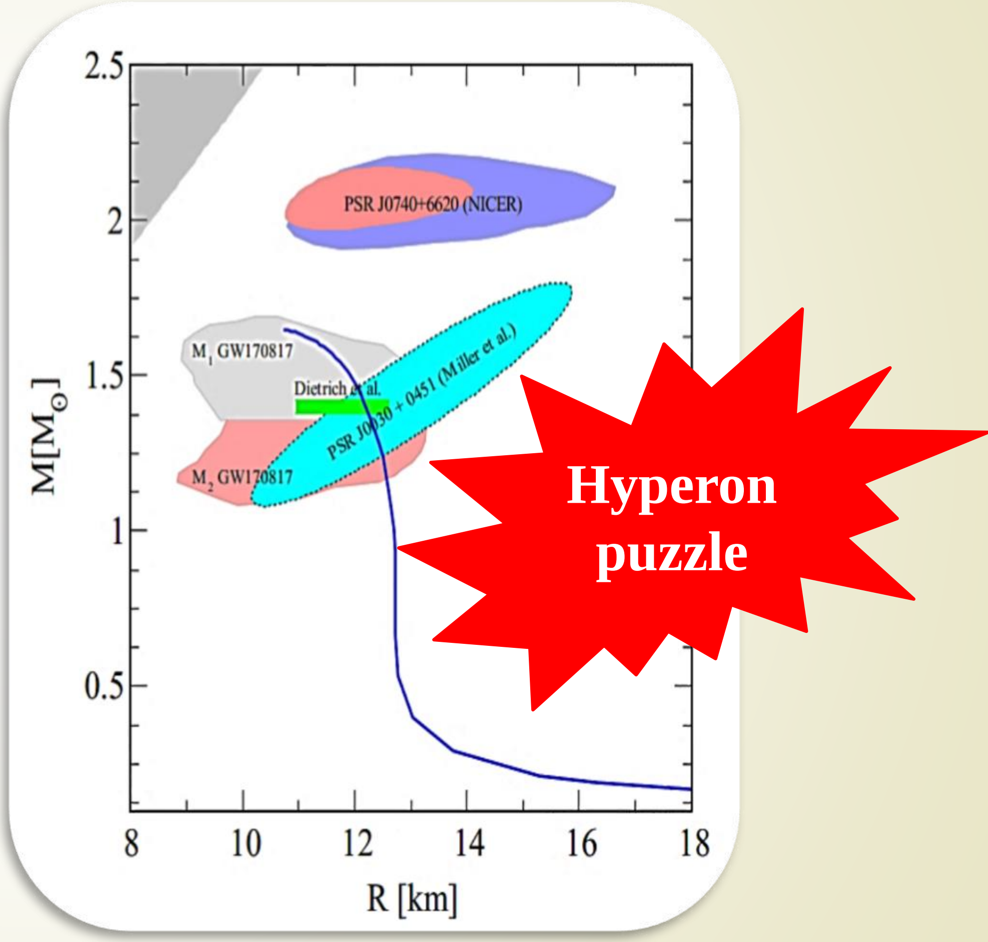
The EoS gets soft by including Hyperon!



	LOCV	**Experiment**
$\rho_0(fm^{-3})$	**0.1748**	**0.16 ± 0.01**
E/A (MeV)	**-15.58**	**-16 ± 1**

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

TOV Equations and Mass-Radius Relation



Hyperon puzzle

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

In some RMF models, the NY and YY couplings are adjusted in such a way that there is no hyperon puzzle. Indeed, vector mesons generate repulsion at short distances

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)

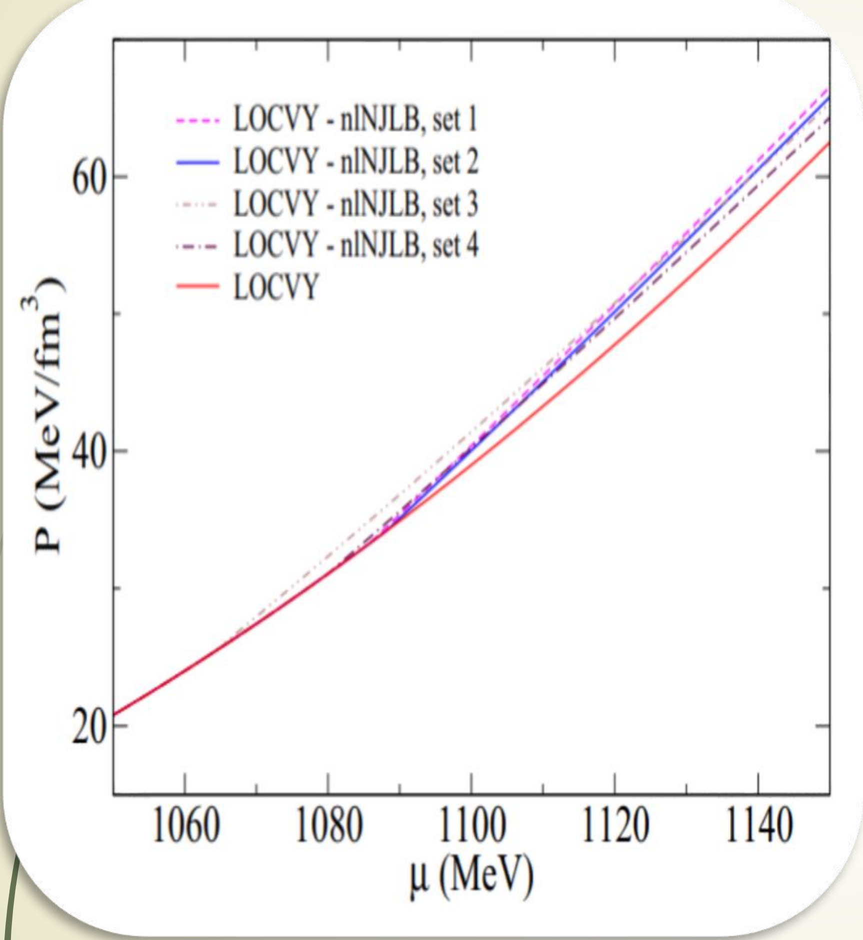
- **Constructing a phase transition from hypernuclear matter to deconfined quark matter**

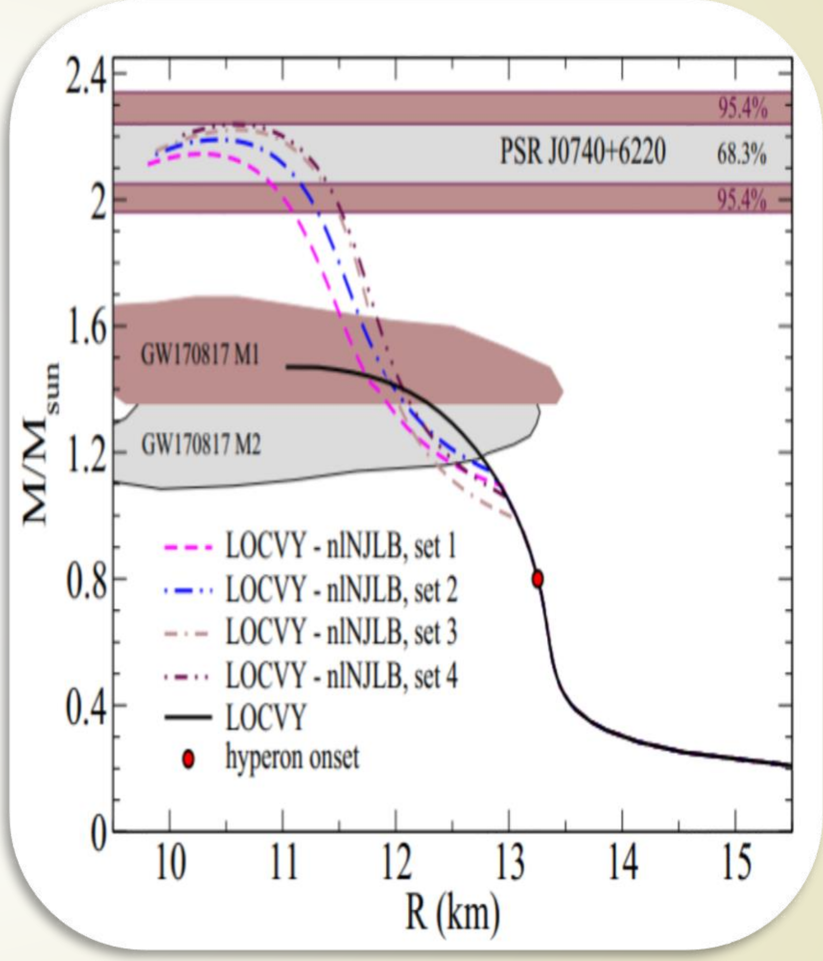
M. Shahrbaf, D. Blaschke, A. G. Grunfeld and H. R. Moshfegh, Phys. Rev. C, no.2, 025807 (2020)

- Using the modified gravity

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

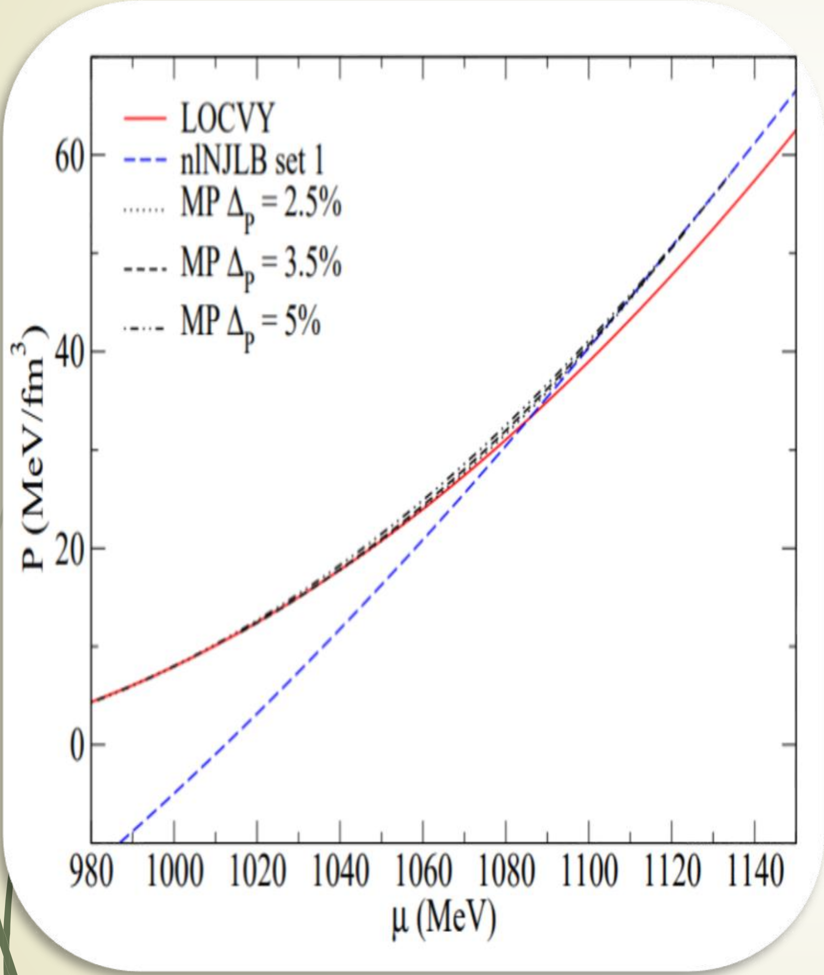
Phase transition from hypernuclear matter to deconfined quark matter within a Maxwell construction

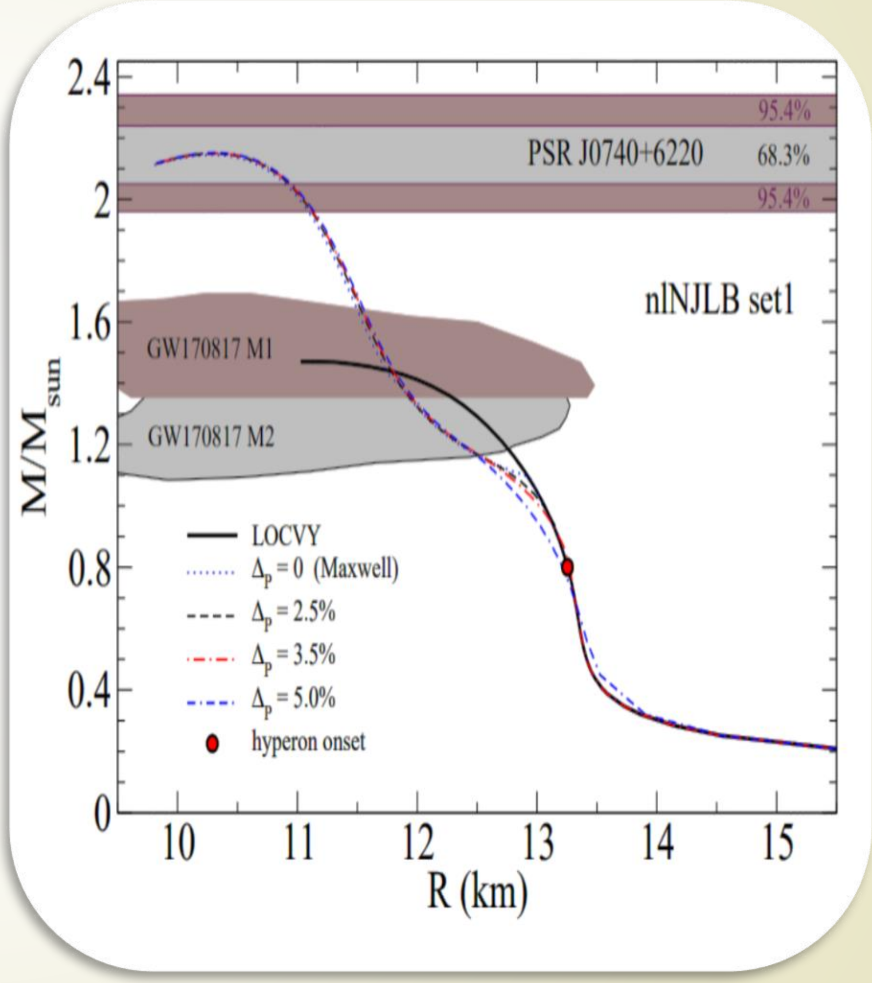




M. Sh, D. Blaschke, A. G. Grunfeld, H. R. Moshfegh, Phys. Rev. C 101 (2020)

Phase transition from hypernuclear matter to deconfined quark matter within a cross-over construction





M. Sh, D. Blaschke and S. Khanmohamadi,J. Phys. G 47 (2020)

Changing the direction from Variational method to RMF approaches

at which the old hyperon puzzle is already solved

A Relativistic Density Functional Approach to Hypernuclear Matter with SEXAQUARK (DD2Y-T)

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

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

❖ 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* $\qquad S_i = \Gamma_{i\sigma}\sigma \qquad \Gamma_{im} = g_{im}\Gamma_m(n_{cpl})$

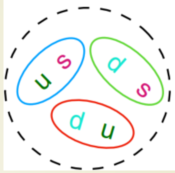
V_i : *Vector potential* $\qquad V_i = \Gamma_{i\omega}\omega + \Gamma_{i\rho}\rho + \Gamma_{i\phi}\phi + B_i V^{(r)} + W_i^{(r)}$

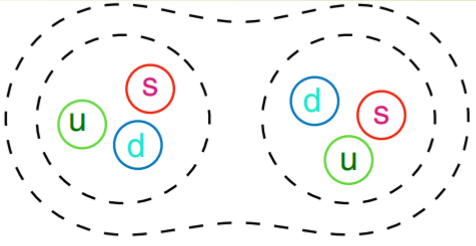
❖ The potentials for all octet baryons are the meson coupling interactions.

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

What is a Sexaquark?

uuddss





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

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

$$m_{\Lambda} + m_{p} + m_{e} = 1115.5+938+0.5 = 2054 \text{ MeV}$$

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

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

- 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!!

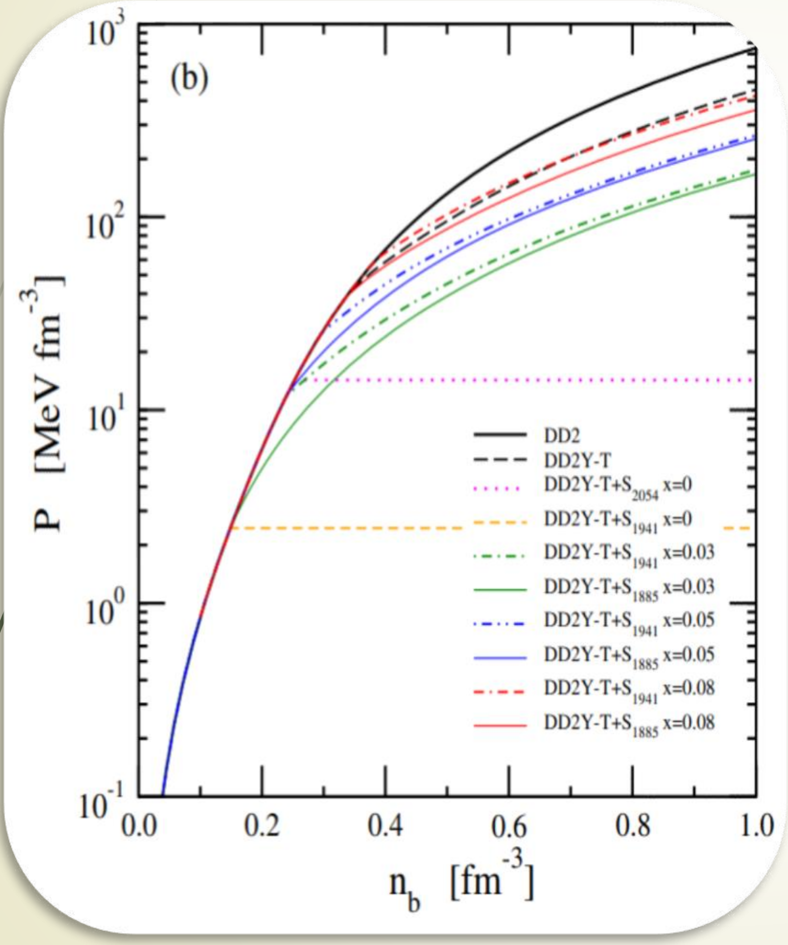
- Therefore, a linear mass shift has been assumed instead of a meson-coupling interaction as all medium effects.

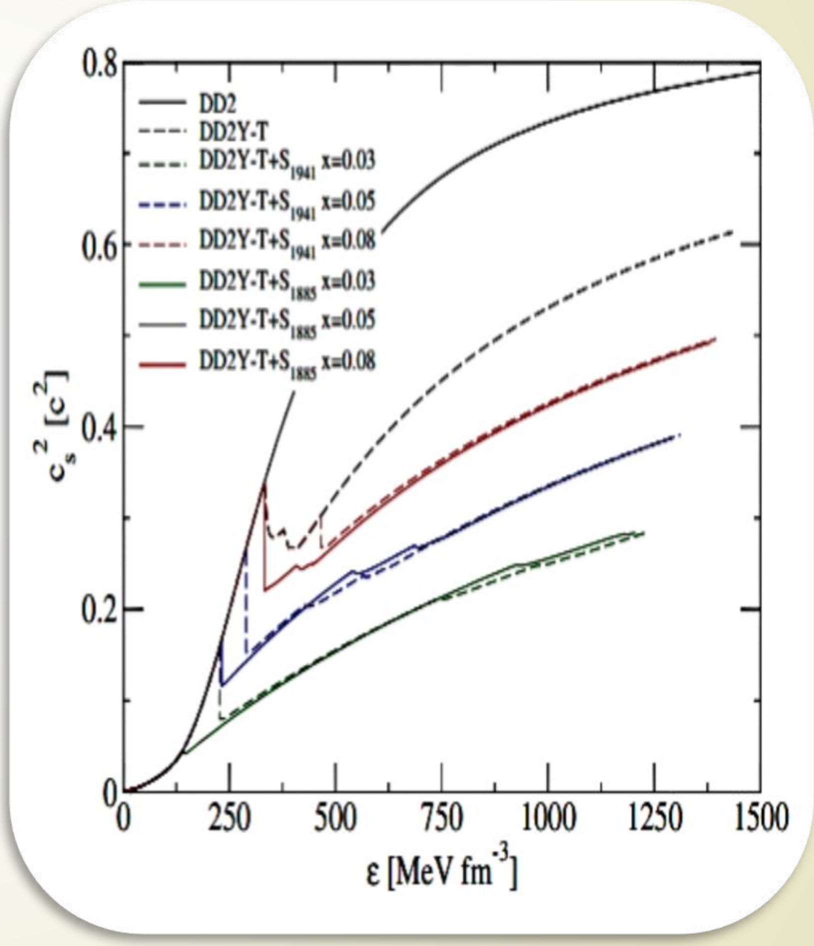
$$S_S = -\Delta m_S \quad V_S = W_S^{(r)} \quad \Delta m_S = m_S \left(1 + x_S \frac{n_B}{n_0}\right)$$

- 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.

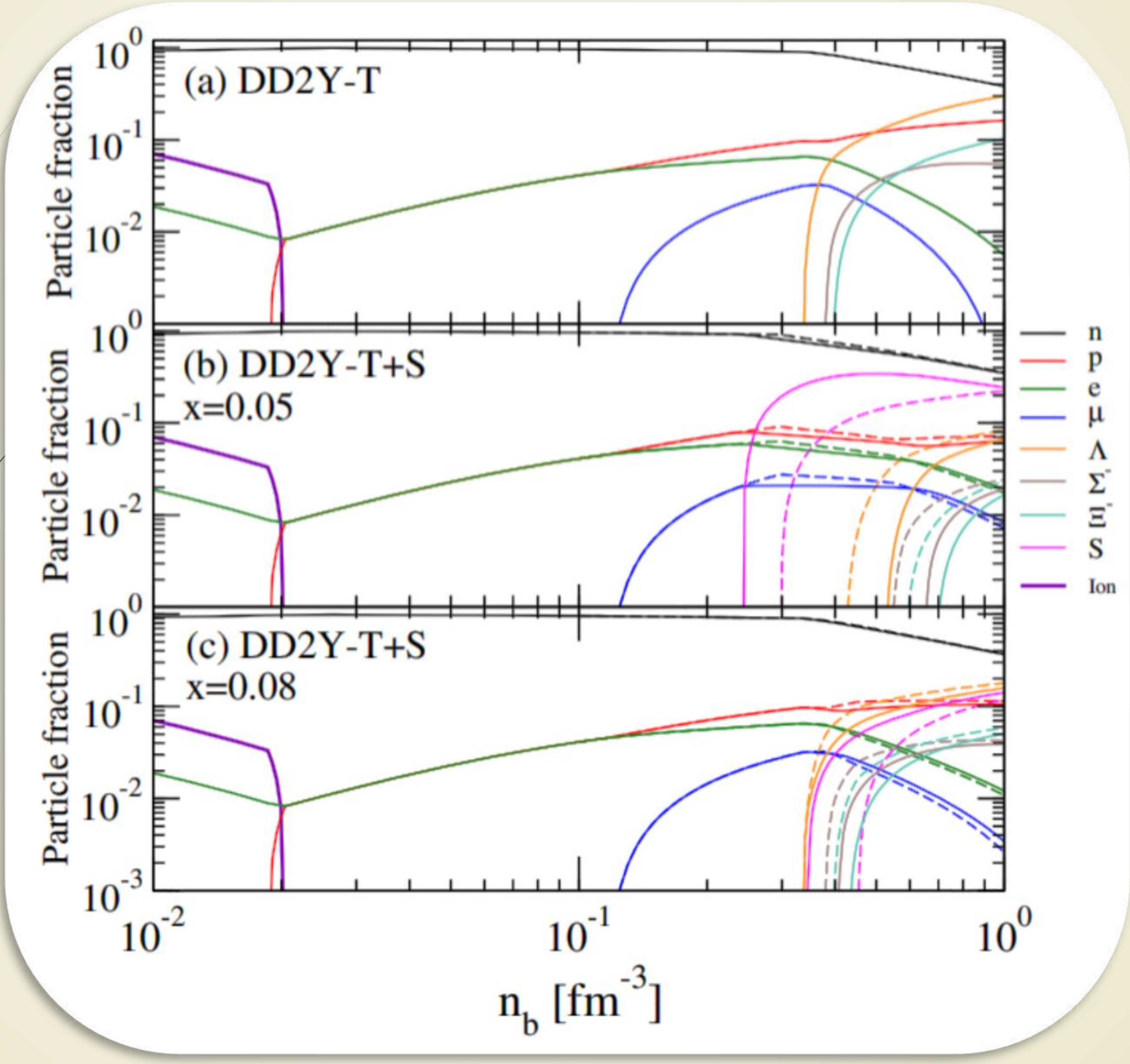
$$P = -\Omega . \; f = \varepsilon = \Omega + \sum_i \mu_i n_i^{(v)}$$

Softening of the EoS by including S in addition to hyperons

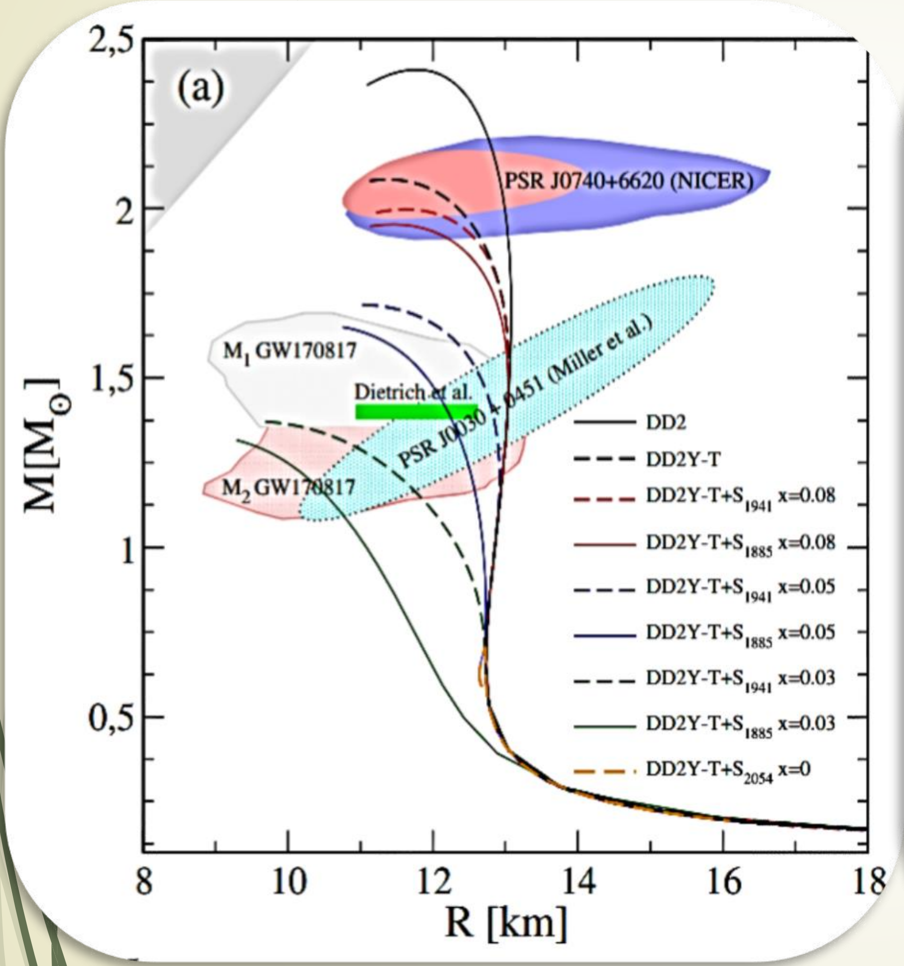


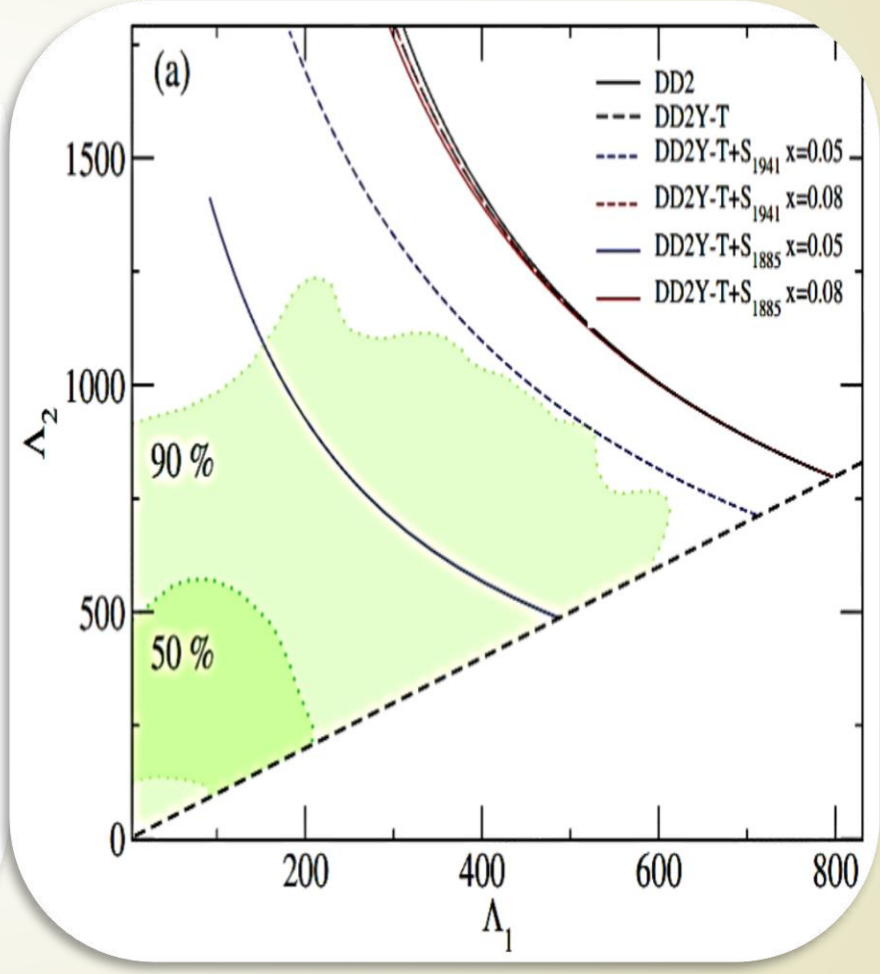


Sexaquark formation postpones hyperon onset



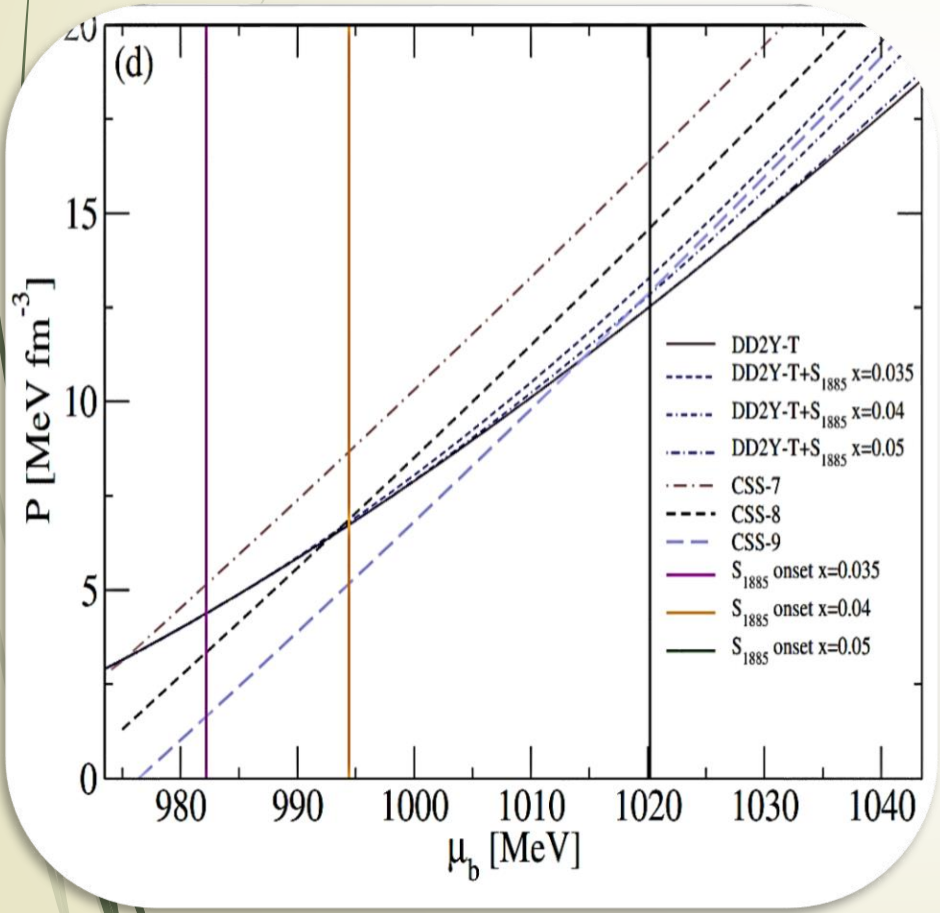
Mass-Radius and Tidal deformability of the modeled NSs

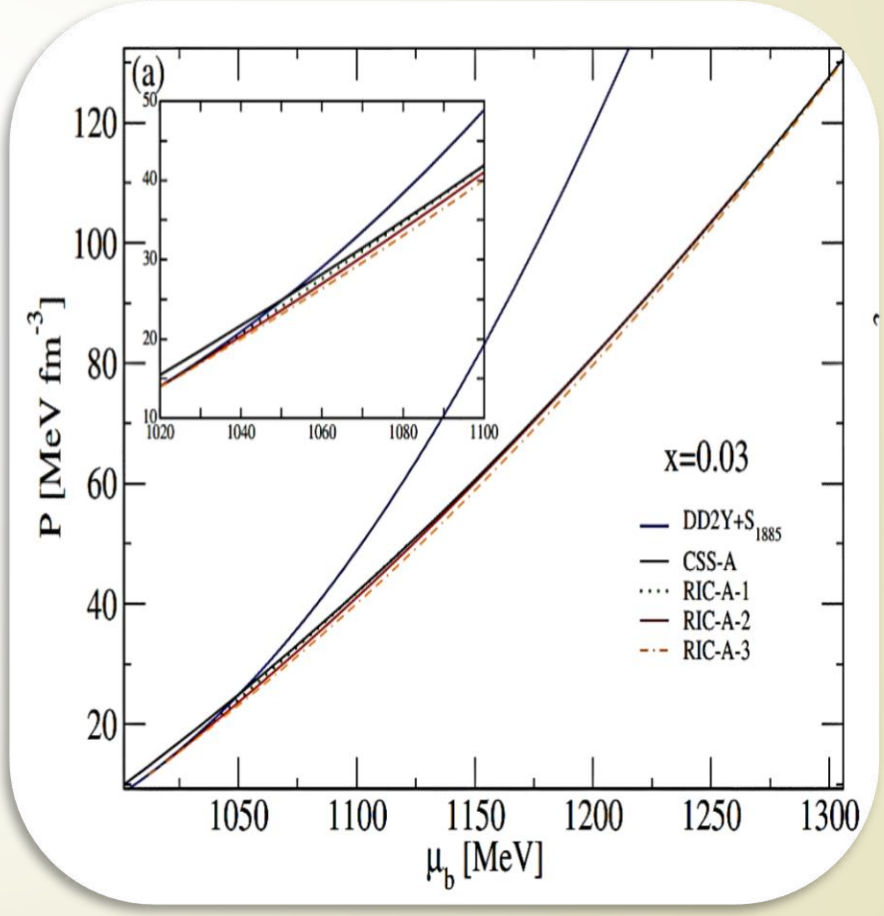




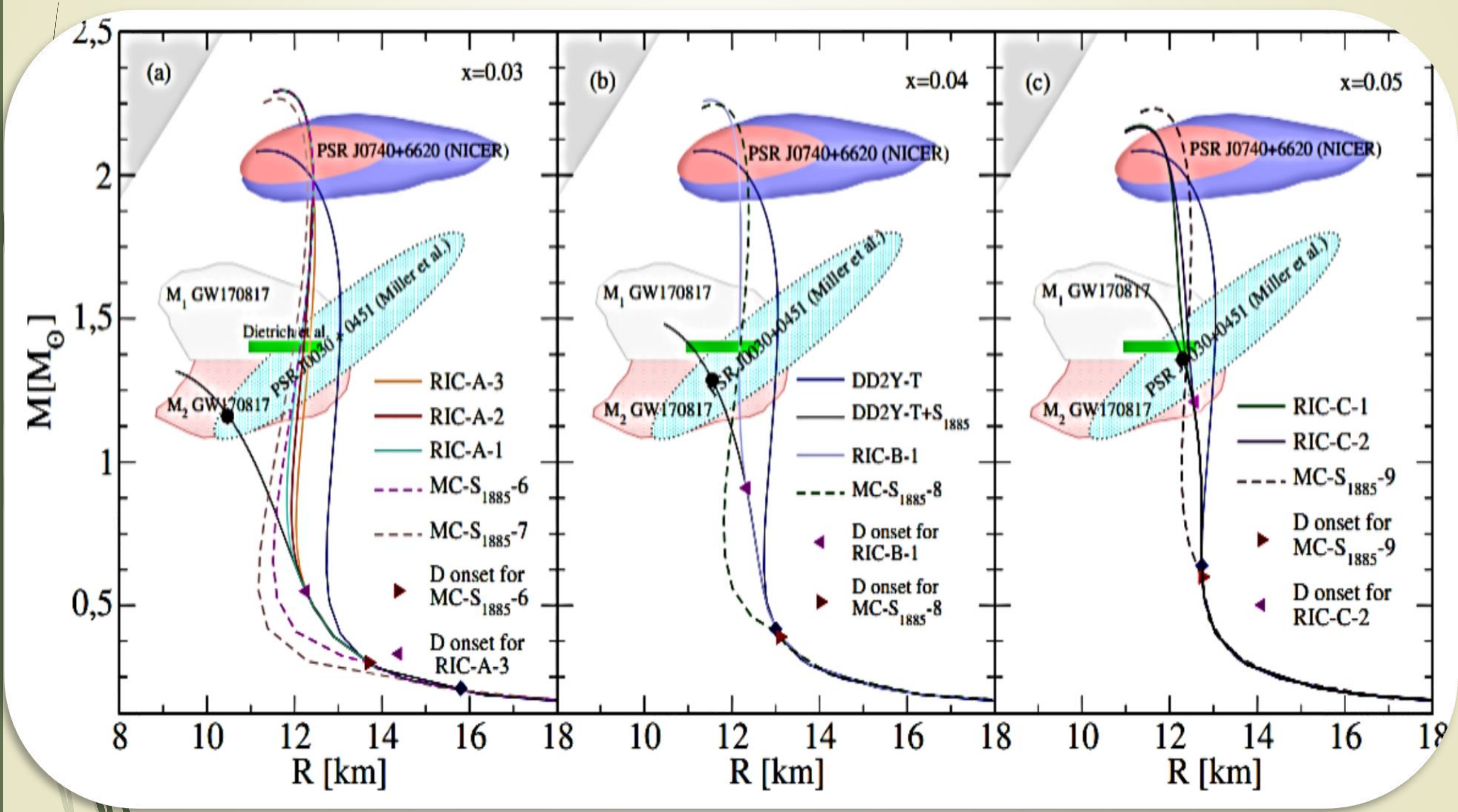
Phase transition to deconfined QM in CFL phase

The quark matter EoS is softer in CFL phase by including strangeness and the position of phase transition shifts to lower densities



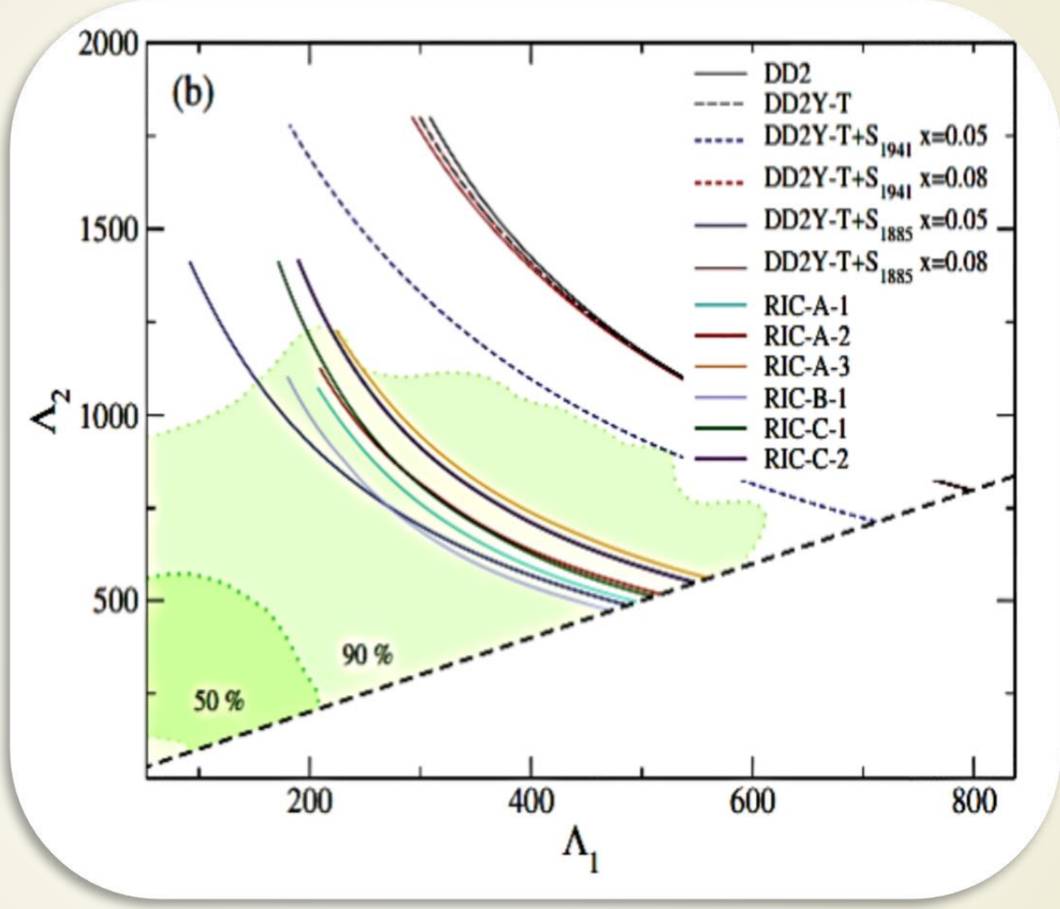


In Maxwell construction, neither hyperons nor sexaquark appear before transition to deconfined phase



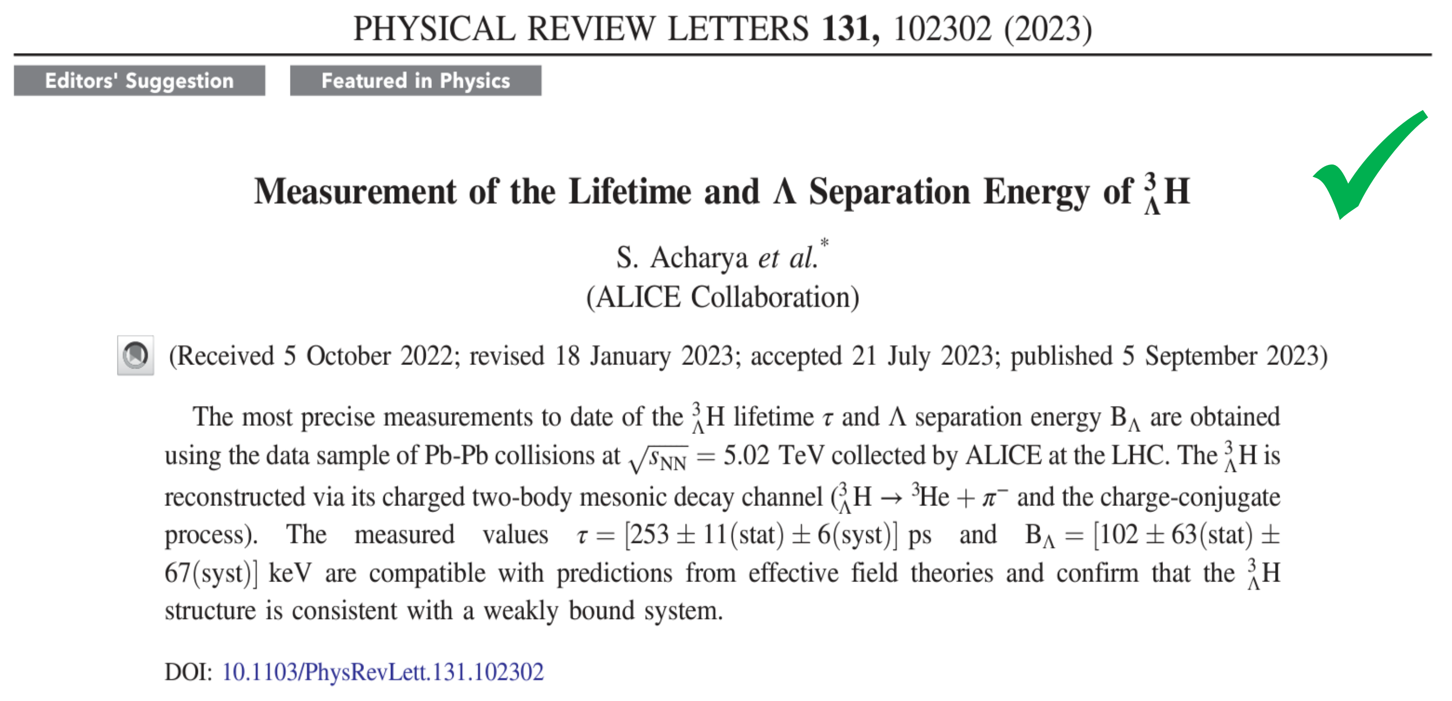
M. Sh, D.Blaschke, et al., Phys. Rev. D 105 (2022)
M. Sh, J. Phys. Conf. Ser. 2536 (2023)

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



All observational constraints are fulfilled for $m_S = 1885$ MeV
But eventually the cooling of NS could potentially give an observable signature of Sexaquark formation as a candidate of dark matter in CS.

Research about hypernuclei, hyperon interactions, and hyperon puzzle is still broadly continuing …



PHYSICAL REVIEW LETTERS **131,** 102302 (2023)

Measurement of the Lifetime and Λ Separation Energy of ${}^{3}_{\Lambda}\mathrm{H}$ ✓

S. Acharya *et al.*[*]
(ALICE Collaboration)

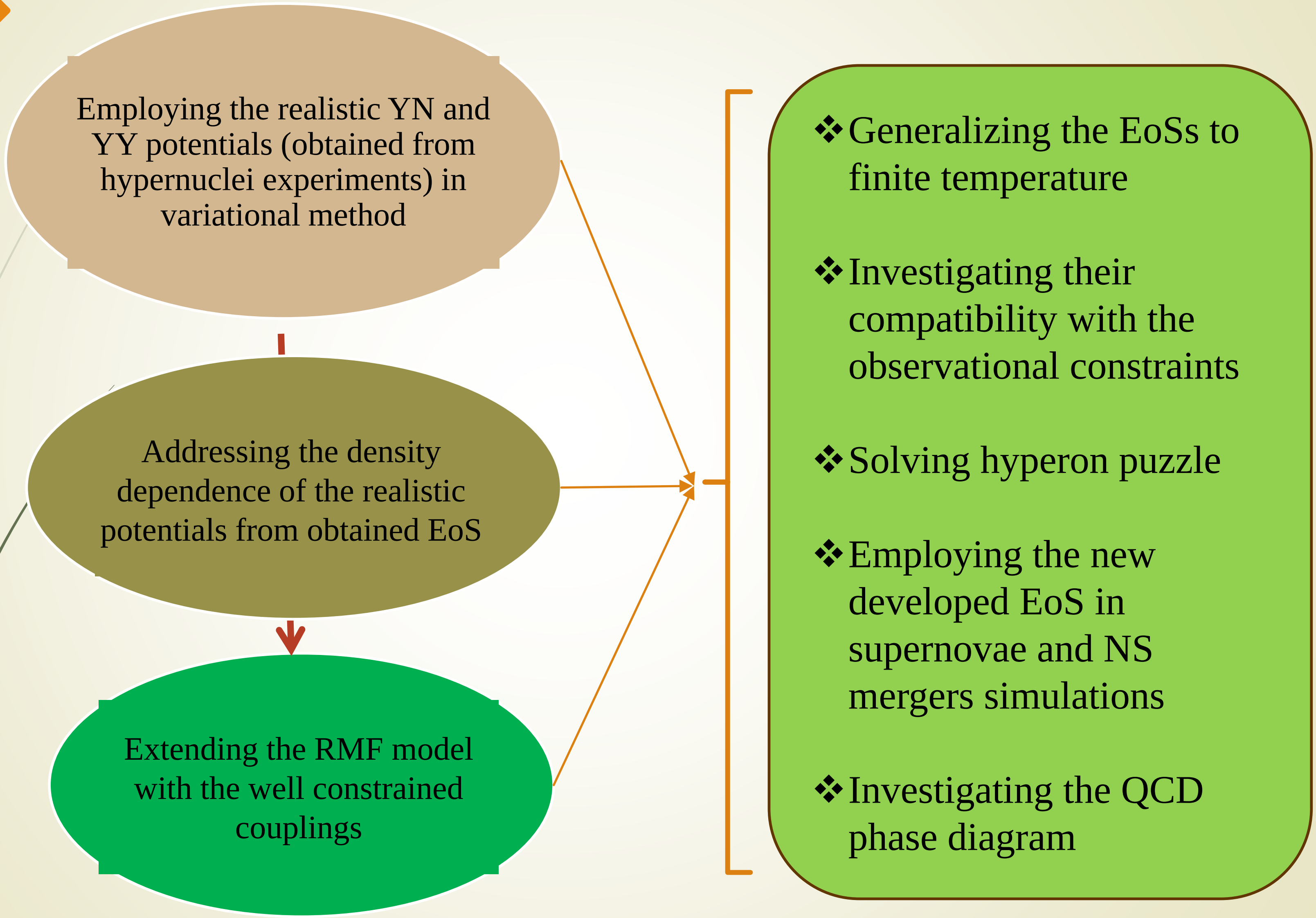
(Received 5 October 2022; revised 18 January 2023; accepted 21 July 2023; published 5 September 2023)

The most precise measurements to date of the ${}^{3}_{\Lambda}\mathrm{H}$ lifetime τ and Λ separation energy B_{Λ} are obtained using the data sample of Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV collected by ALICE at the LHC. The ${}^{3}_{\Lambda}\mathrm{H}$ is reconstructed via its charged two-body mesonic decay channel (${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$ and the charge-conjugate process). The measured values $\tau = [253 \pm 11(\mathrm{stat}) \pm 6(\mathrm{syst})]$ ps and $\mathrm{B}_{\Lambda} = [102 \pm 63(\mathrm{stat}) \pm 67(\mathrm{syst})]$ keV are compatible with predictions from effective field theories and confirm that the ${}^{3}_{\Lambda}\mathrm{H}$ structure is consistent with a weakly bound system.

DOI: 10.1103/PhysRevLett.131.102302

Hypertriton’s lifetime has been found to be close to that of a free lambda hyperon, so it’s a loosely bound particle. This precise determination of the lambda hyperon’s binding energy could help explaining the existence of neutron stars with masses beyond the expected range.

Outlook of my Sonatina Grant



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

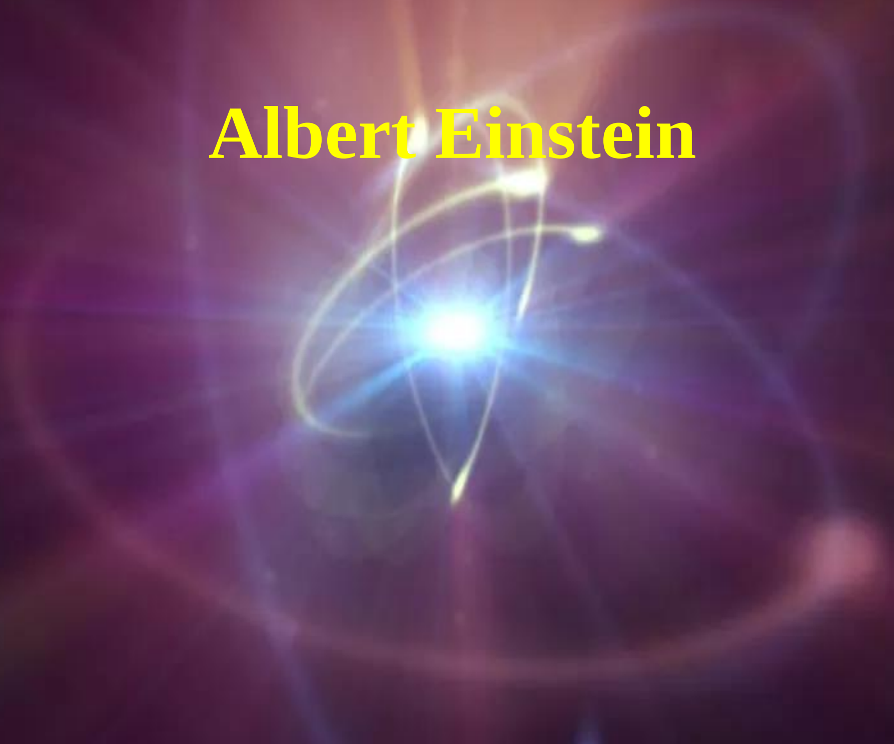
Addressing the density dependence of the realistic potentials from obtained EoS

Extending the RMF model with the well constrained couplings

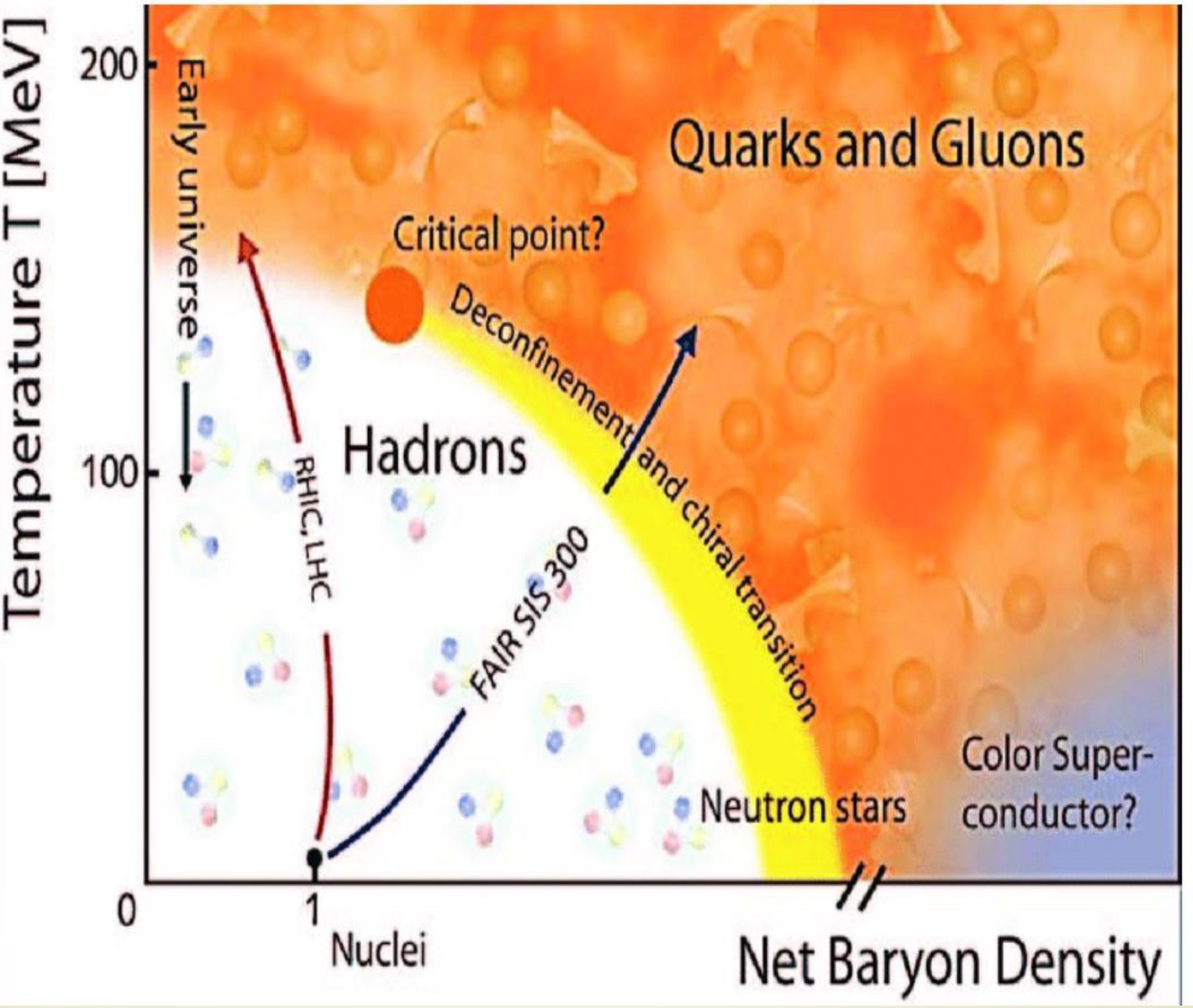
- Generalizing the EoSs to finite temperature
- Investigating their compatibility with the observational constraints
- Solving hyperon puzzle
- Employing the new developed EoS in supernovae and NS mergers simulations
- Investigating the QCD phase diagram

“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


Temperature T [MeV]
200
100
0
1
Nuclei
Net Baryon Density
Early universe
RHIC, LHC
FAIR SIS 300
Hadrons
Critical point?
Quarks and Gluons
Deconfinement and chiral transition
Neutron stars
Color Super-conductor?

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.