Searching for dark matter through observations of compact stars and detections of cosmic rays
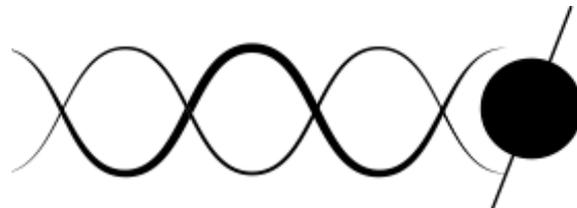
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July 27 2023

Outline

- A brief introduction to the physics of compact stars.

- Selected dark matter scenarios: axions and other bosons in compact stars, neutron star collapse into a third family.

- Discussion of uniformly rotating compact stars with a dark matter halo.

Motivation

- New channels of multi-messenger observations like gravitational radiation from merger events of binary systems of compact stars or radio and X-ray signals from isolated pulsars allow to study their most basic structural properties like mass, radius, compactness, cooling rates and compressibility of their matter.

- Nuclear measurement and experiments have narrowed the Equation of State (EoS) uncertainty in the lowest to intermediate density range.

- Violent, transient energetic emissions are associated not only with the strong magnetic fields and extreme gravity in the proximity of NS but with explosive, evolutionary stages often triggered by mass accretion from companion stars. Therefore, we expect that the presence of dark matter will leave an imprint in the many kinds of future detectable signals.
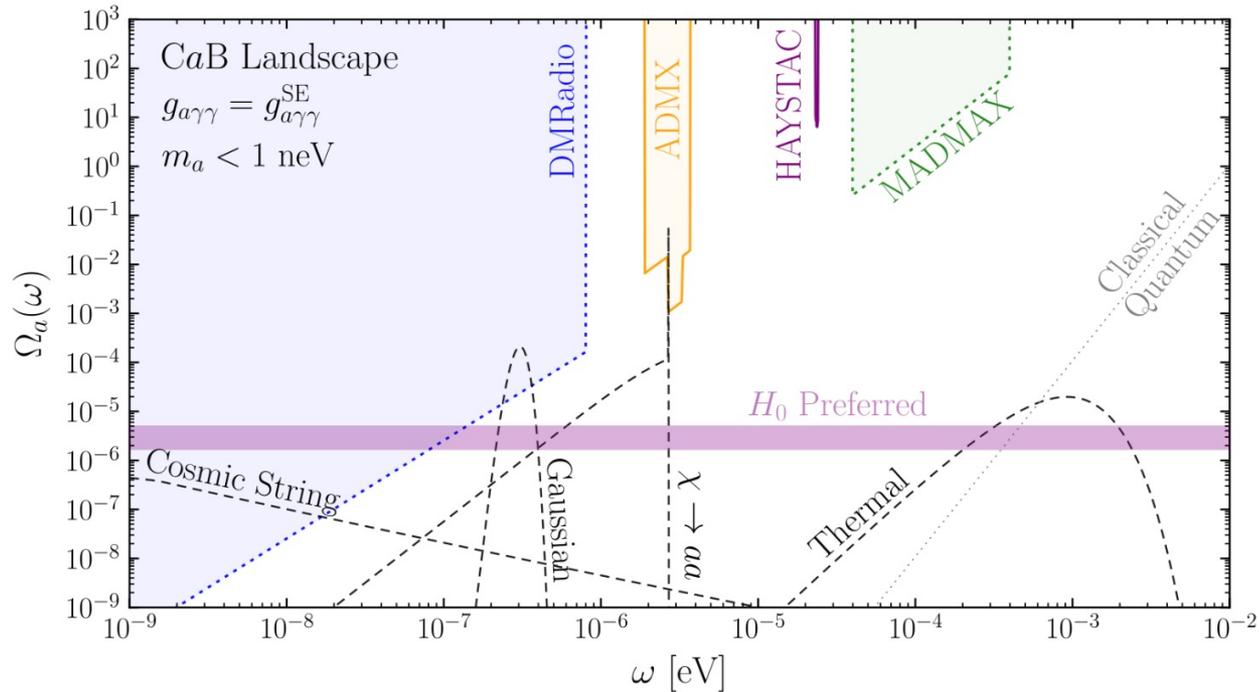
The Axion

Figure 3: Energy density diagram for allowed energy of the cosmic Axion background together with state-of-the-art physical and cosmological constraints. The axion is a particle candidate for dark matter that moreover provides a solution to the strong CP problem. Therefore it is of high relevance to consider its interaction in compact star interiors or in the proximity of pulsars and magnetars. For details on this diagram, see [12].

[12] J. A. Dror, H. Murayama, N. L. Rodd Phys. Rev. D 103, 115004 (2021)
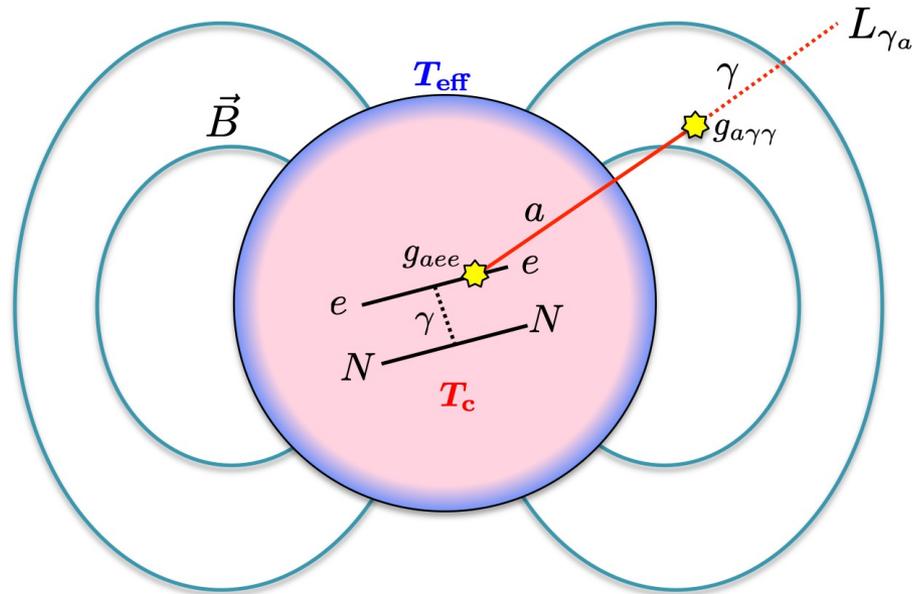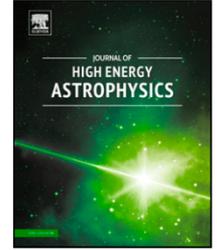
The Axion

Figure 4: Eschematic dynamics of the conversion of an axion into a photon as it interacts with a white dwarf magnetic field. The core temperature T_c is higher than the surface temperature T_{eff}, see [1] for details.
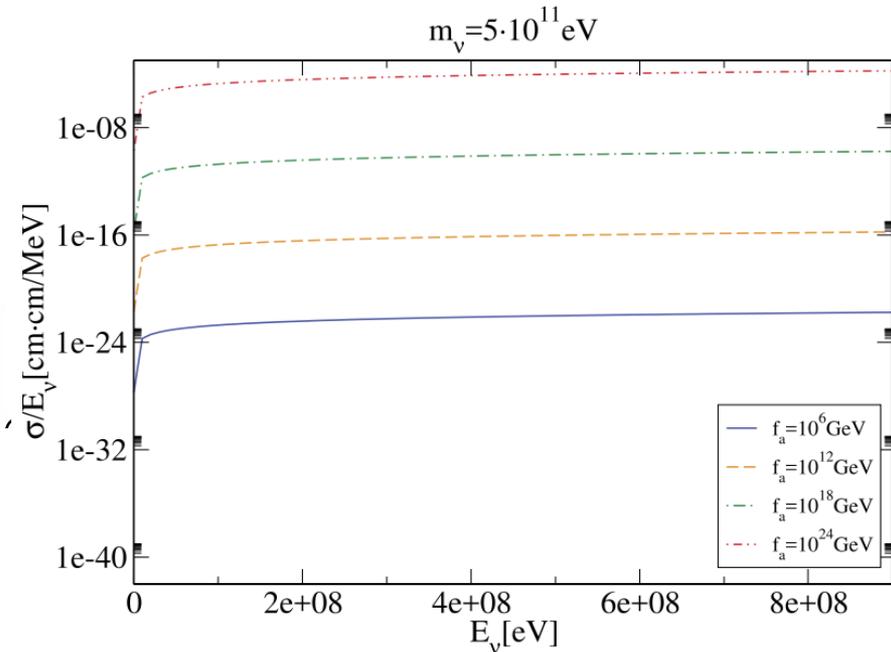
ELSEVIER

Dark matter candidates, helicity effects and new affine gravity with torsion
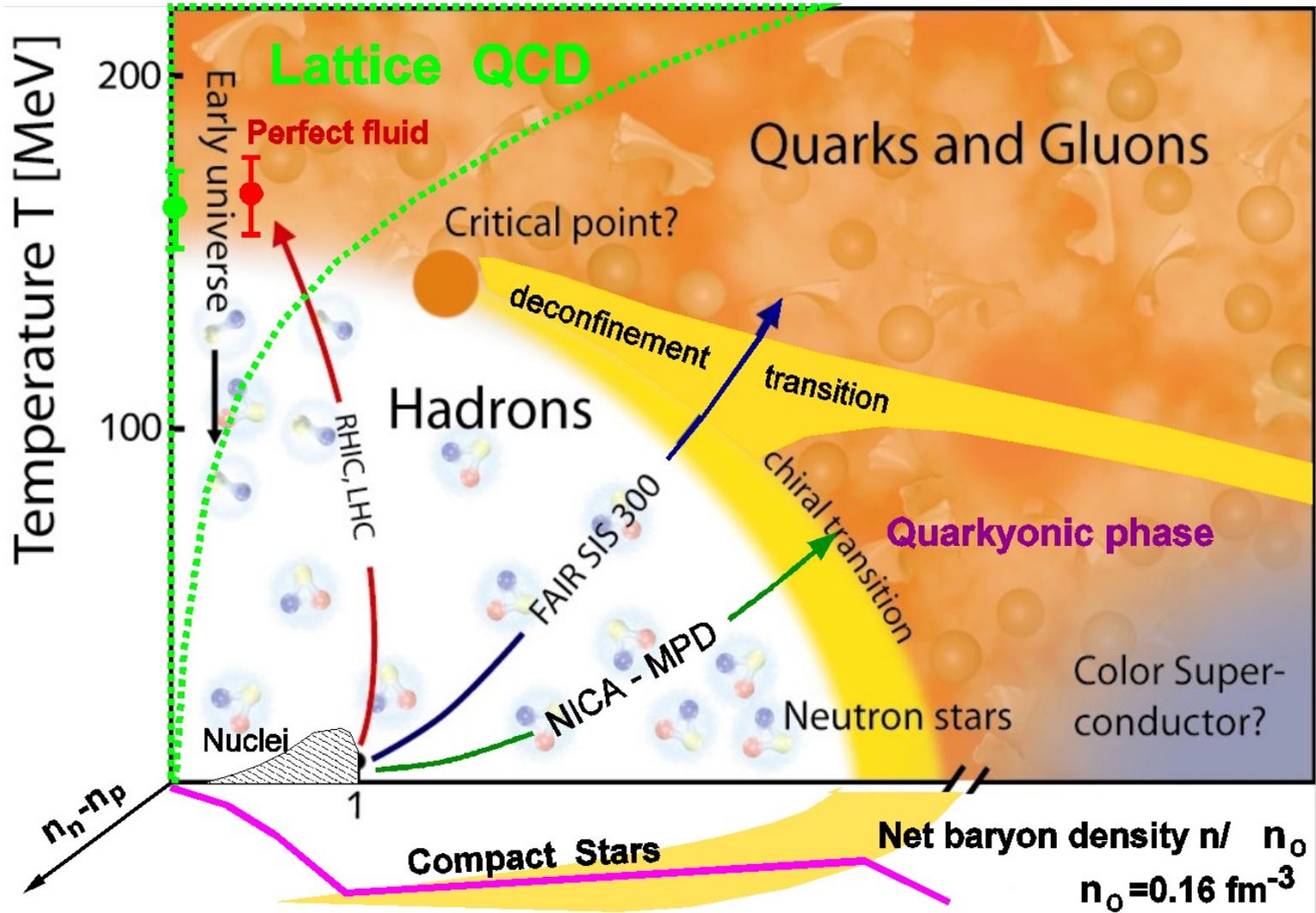
CrossMark

David Alvarez-Castillo [a], Diego Julio Cirilo-Lombardo [a,b,*], Jilberto Zamora-Saa [c]

$$
\sigma_\nu^{flip}(\beta)
$$

$$
= \left(\frac{j\mu mc}{4\hbar}\right)\left(\frac{(1-d)^2}{\pi^2 d}\right)^2 \frac{4E^2}{(E+mc^2)^2}\left[1.09416\right.
$$

$$
\left. + Ln\left(\frac{2(E^2-m^2c^4)}{q_{min}^2}\right)\left(Ln\left(\frac{2(E^2-m^2c^4)}{q_{min}^2}\right) - 0.613706\right)\right],
$$

$$
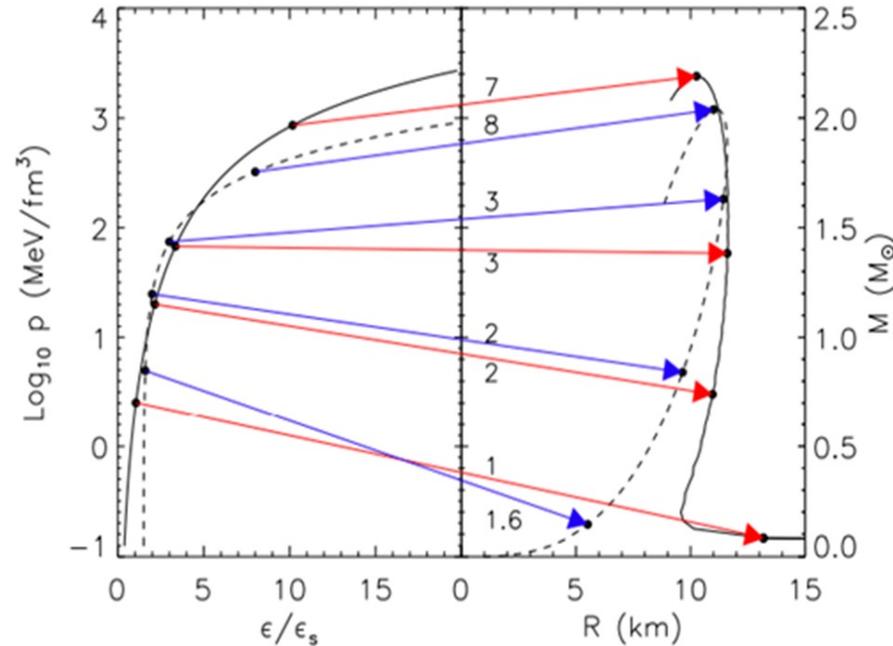L_{int} \approx j^{\frac{1}{2}}\,\overline{\psi}_f\,\frac{1-d}{d}\gamma^\alpha \gamma_5 h_\alpha \psi_f,
$$

Critical Endpoint in QCD

Compact Star Sequences
(M-R ⇔ EoS)

James Lattimer,
Annu. Rev. Nucl. Part. Sci. 62,
485 (2012), arXiv:1305.3510

- TOV Equations

- Equation of State (EoS)

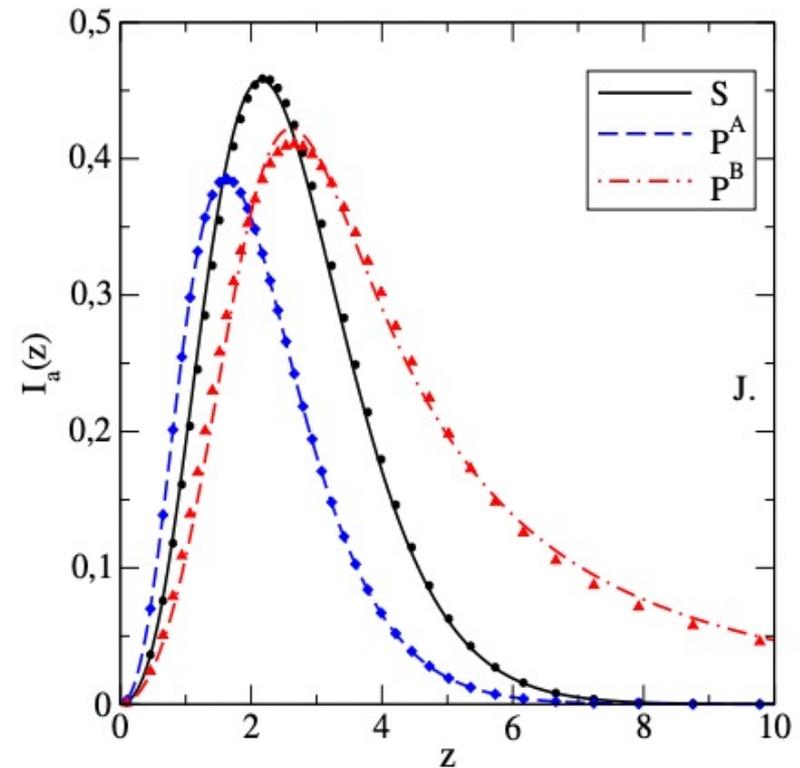$$\frac{dp}{dr} = -\frac{(\varepsilon + p/c^2)G(m + 4\pi r^3 p/c^2)}{r^2(1 - 2Gm/rc^2)}$$

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon \qquad p(\varepsilon)$$
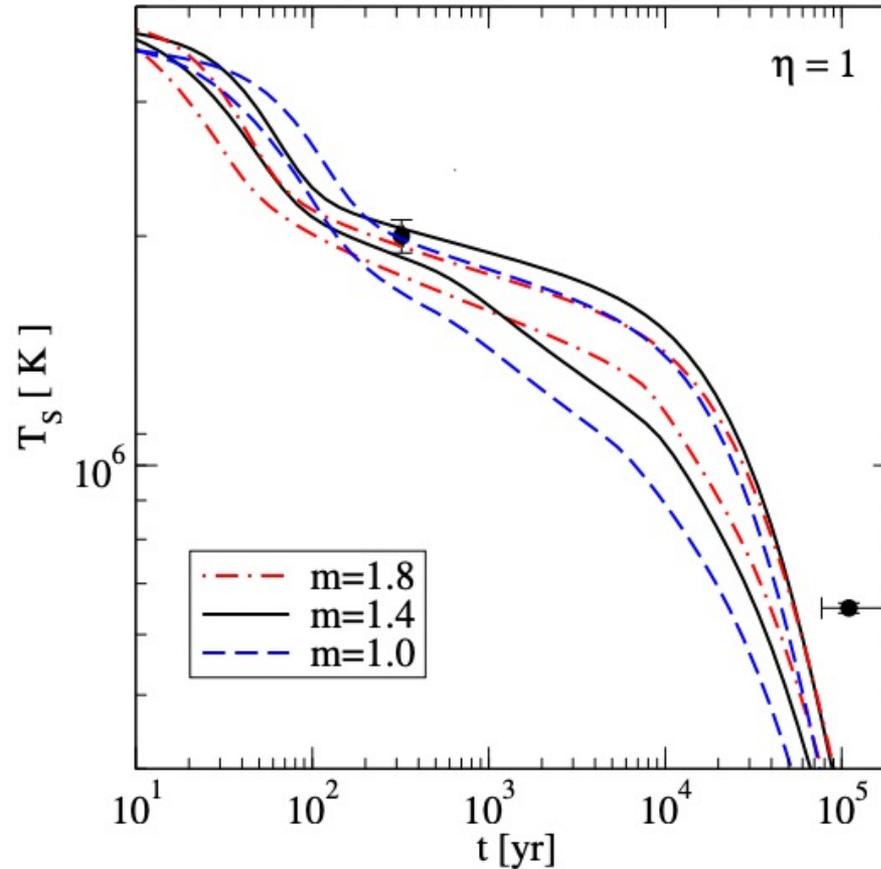
Effects of NS Axion Cooling

Axion emissivity for S-wave condensate

$$\epsilon_{aN}^S = \frac{2C_N^2}{3\pi} f_a^{-2} \, \nu_N(0) \, v_{FN}^2 \, T^5 \, I_{aN}^S,$$

$$I_{aN}^S = z_N^5 \int_1^\infty dy \, \frac{y^3}{\sqrt{y^2 - 1}} f_F \, (z_N y)^2 .$$

CAS A data, A. Sedrakian, Phys. Rev. D 93, 065044 (2016)

Effects of NS Axion Cooling

CAS A data, A. Sedrakian, Phys. Rev. D 93, 065044 (2016)

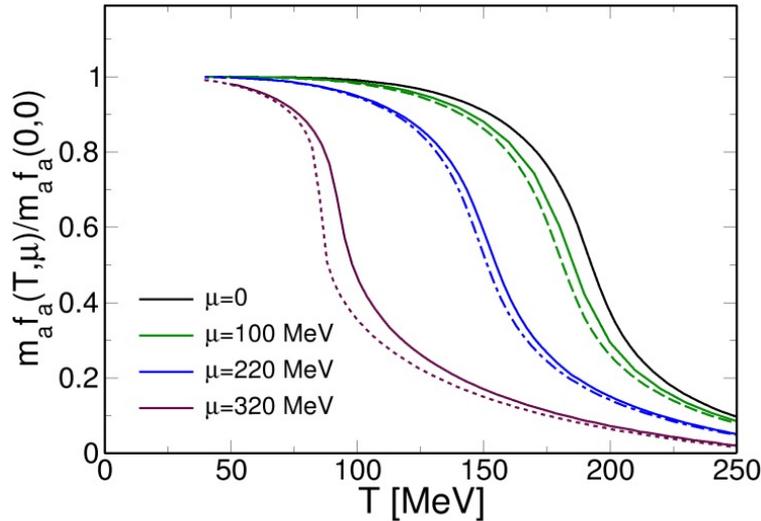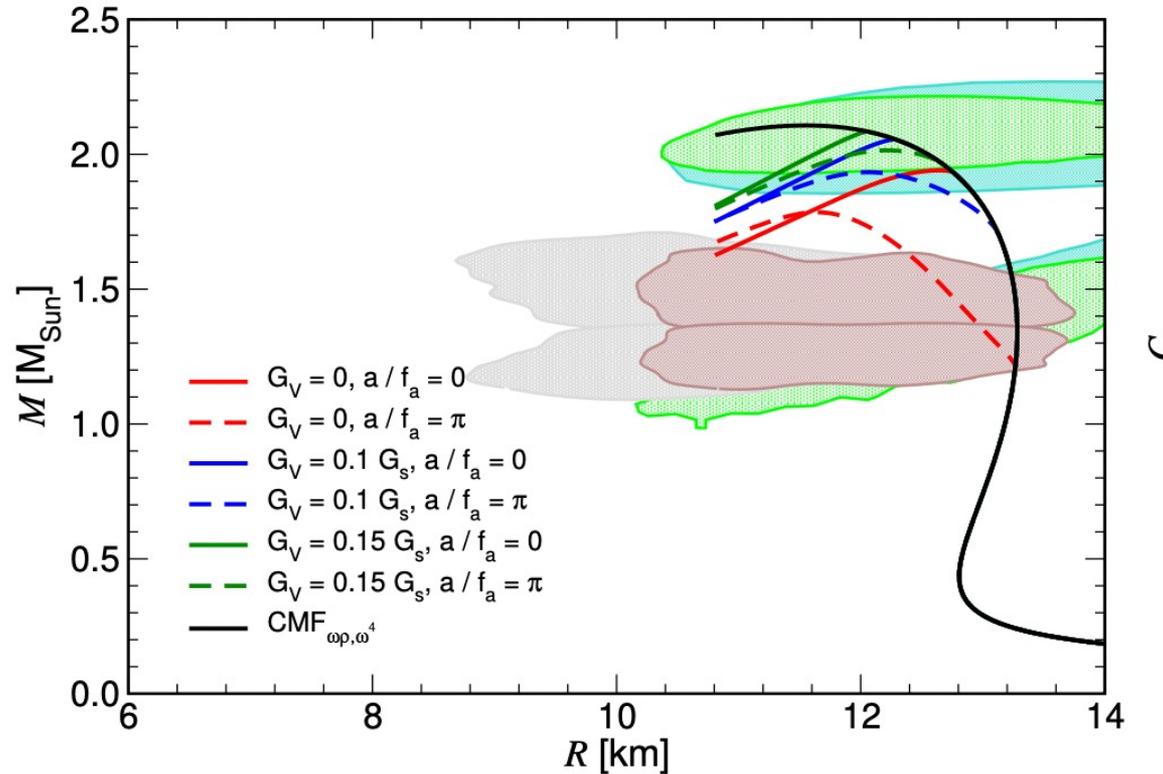# Exploring the axion potential and axion walls in dense quark matter

FIG. 2. $m_a f_a$ versus T for several values of μ. Solid lines correspond to the calculations with electrical neutrality while dashed lines denote the results for $\mu_e = 0$.

$$\mathcal{L} = \bar{q}\left(i\slashed{\partial} + \hat{\mu}\gamma_0 - m_0\right)q + \bar{e}\left(i\slashed{\partial} + \mu_e\gamma_0\right)e + \mathcal{L}_{\text{int}}$$

$$\mathcal{L}_{\text{int}} = G_1\left[(\bar{q}\tau_a q)(\bar{q}\tau_a q) + (\bar{q}\tau_a i\gamma_5 q)(\bar{q}\tau_a i\gamma_5 q)\right]$$
$$+ 8G_2\left[e^{i\frac{a}{f_a}}\det(\bar{q}_R q_L) + e^{-i\frac{a}{f_a}}\det(\bar{q}_L q_R)\right]$$

Bonan Zhang, David Alvarez C., Ana G. Grunfeld, Marco Ruggieri

Axion effects in the stability of Hybrid Stars

$$\mathcal{L} = \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m_0\right)\psi$$

$$+ G_s \sum_{b=0}^{8}\left[\left(\bar{\psi}\lambda^b\psi\right)^2 + \left(\bar{\psi}i\gamma_5\lambda^b\psi\right)^2\right] - G_V\left(\bar{\psi}\gamma^{\mu}\psi\right)^2$$

$$- K\left\{e^{i\frac{a}{f_a}}\det\left[\bar{\psi}\left(1+\gamma^5\right)\psi\right] + e^{-i\frac{a}{f_a}}\det\left[\bar{\psi}\left(1-\gamma^5\right)\psi\right]\right\}$$

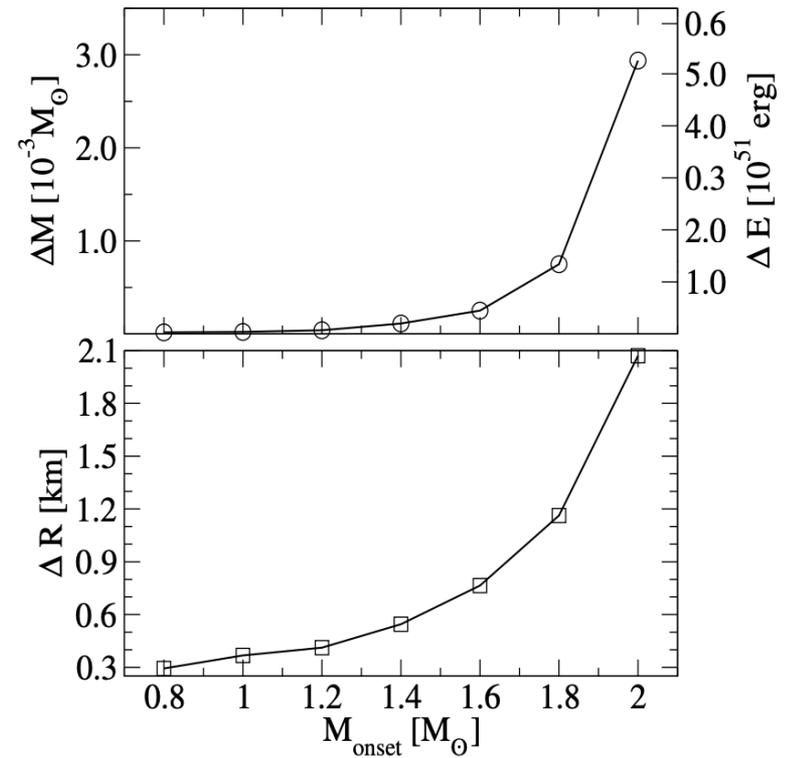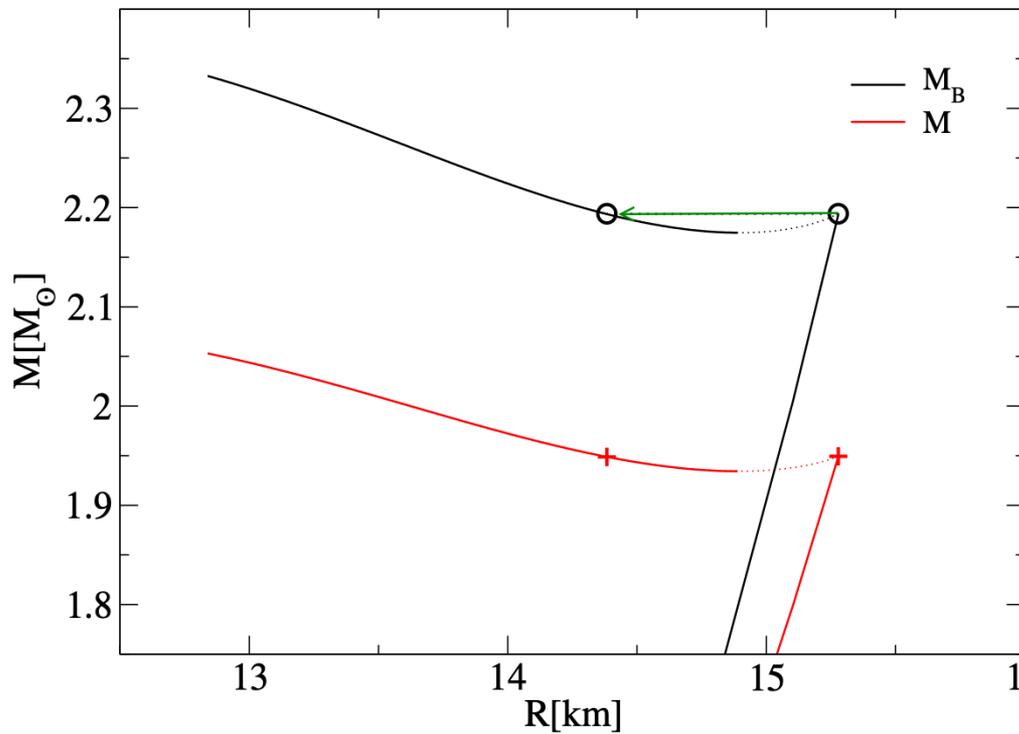Axion effects in the stability of hybrid stars - Bruno S. Lopes et al. – arXiv: 2206.01631

Compact Star Twins with a Dark Matter Core

Parity Double Model, featuring chiral partners N± without quark deconfinement.

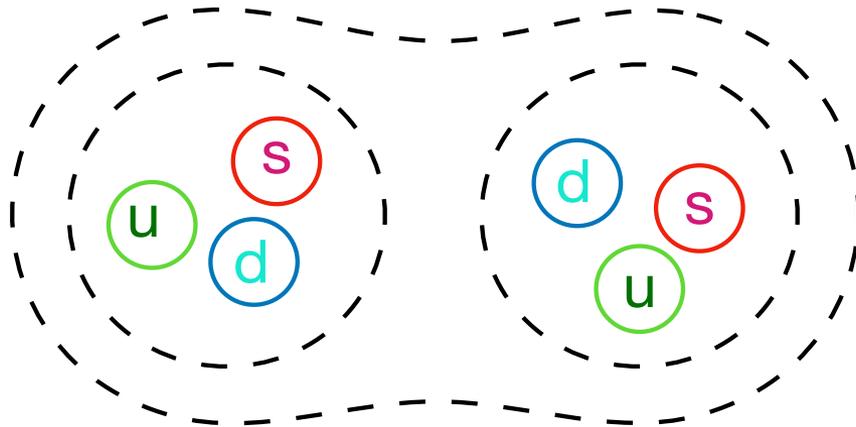$$m_{\pm} = \frac{1}{2}\left(\sqrt{(g_1+g_2)^2\sigma^2 + 4m_0^2} \mp (g_1-g_2)\sigma\right)$$

David Alvarez-Castillo and Michał Marczenko.
Acta Phys. Pol. B Proc. Suppl. 15, 3-A28 (2022)

Mass Twins – Energy Released

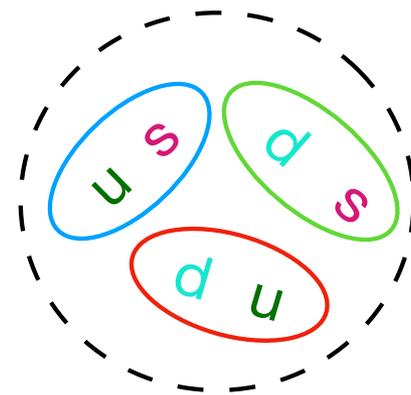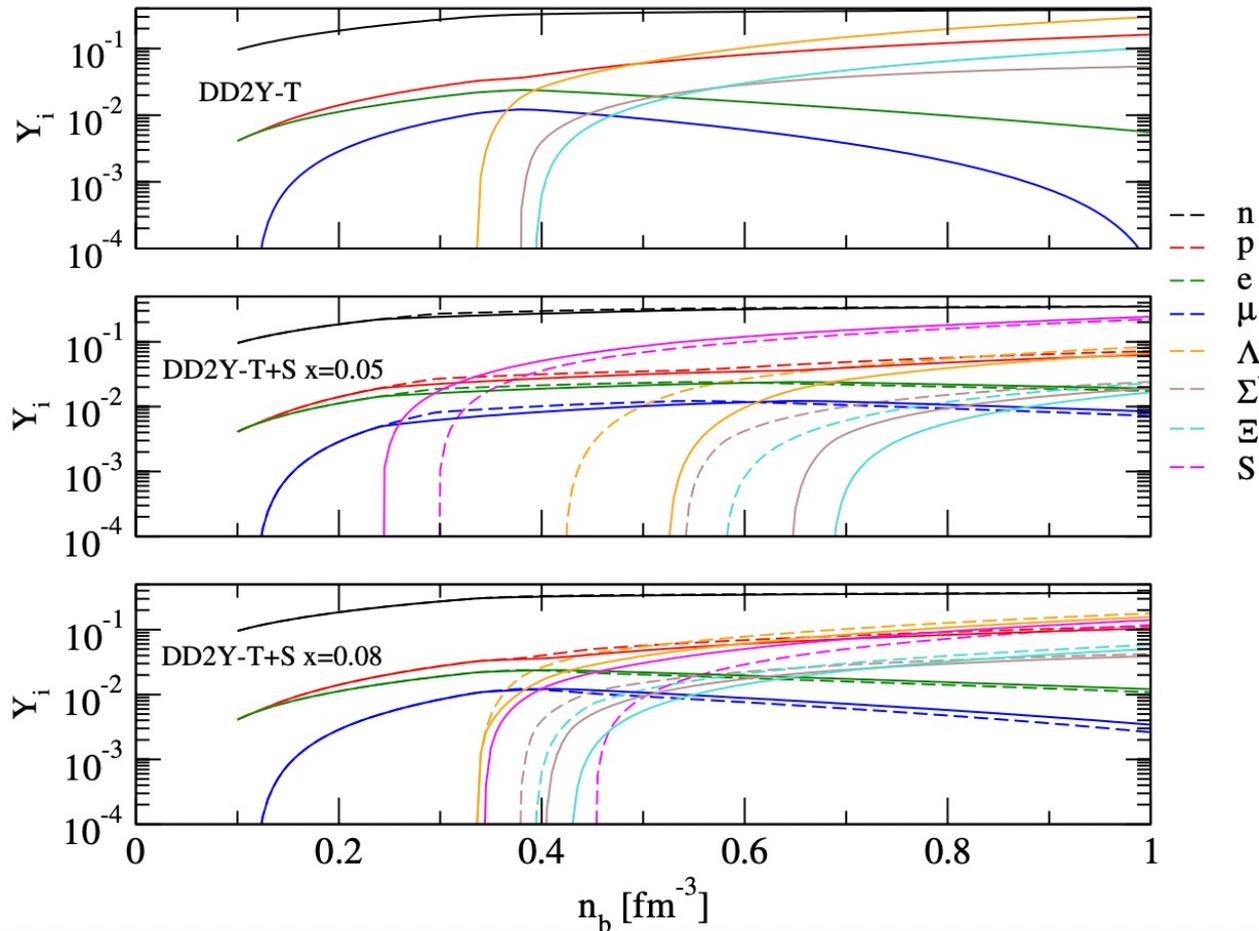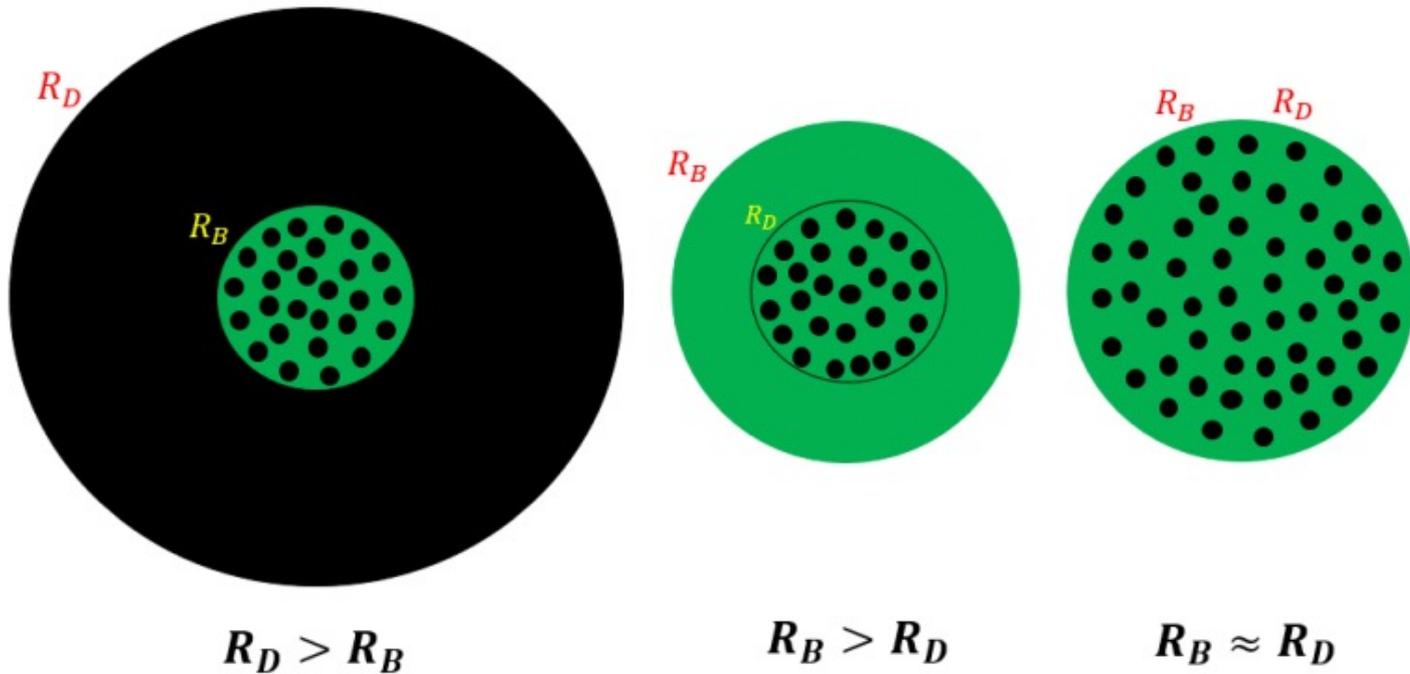# Sexaquarks in NS

Sexaquarks in NS

M. Shahrbaf, D. Blaschke, S. Typel, G. R. Farrar, and D. A-C
Phys. Rev. D 105, 103005, (2022)

Bosonic Dark Matter in NS

$$R_D > R_B \qquad R_B > R_D \qquad R_B \approx R_D$$

D. R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, arXiv:2112.14231
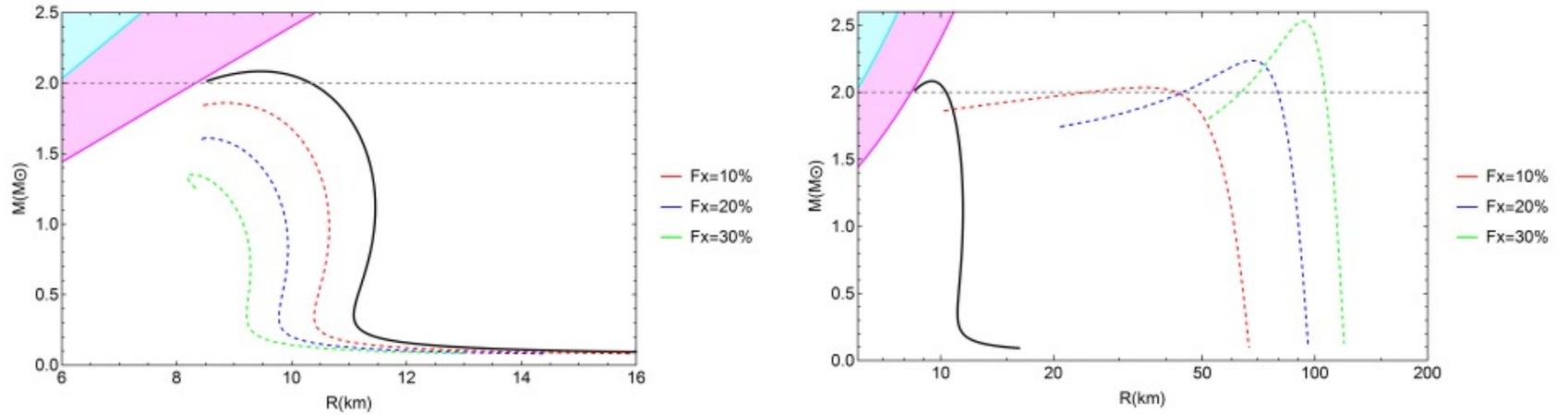
Bosonic Dark Matter in NS

Fig. 7. Mass-Radius profiles for DM admixed NSs for $m_\chi = 400$ MeV (left) which corresponds to a DM core formation and $m_\chi = 100$ MeV (right) that represents an extended DM halo formation around a NS. Coupling constant is fixed to $\lambda = \pi$ and different F_χ are considered as labeled.

$$\frac{dp_{\mathrm{B}}}{dr} = -(p_{\mathrm{B}} + \epsilon_{\mathrm{B}}) \frac{M + 4\pi r^3 p}{r(r - 2M)},$$

$$\frac{dp_{\mathrm{D}}}{dr} = -(p_{\mathrm{D}} + \epsilon_{\mathrm{D}}) \frac{M + 4\pi r^3 p}{r(r - 2M)},$$

O. Ivanytskyi, V. Sagun, and I. Lopes - Phys. Rev. D 102, 063028 (2020)
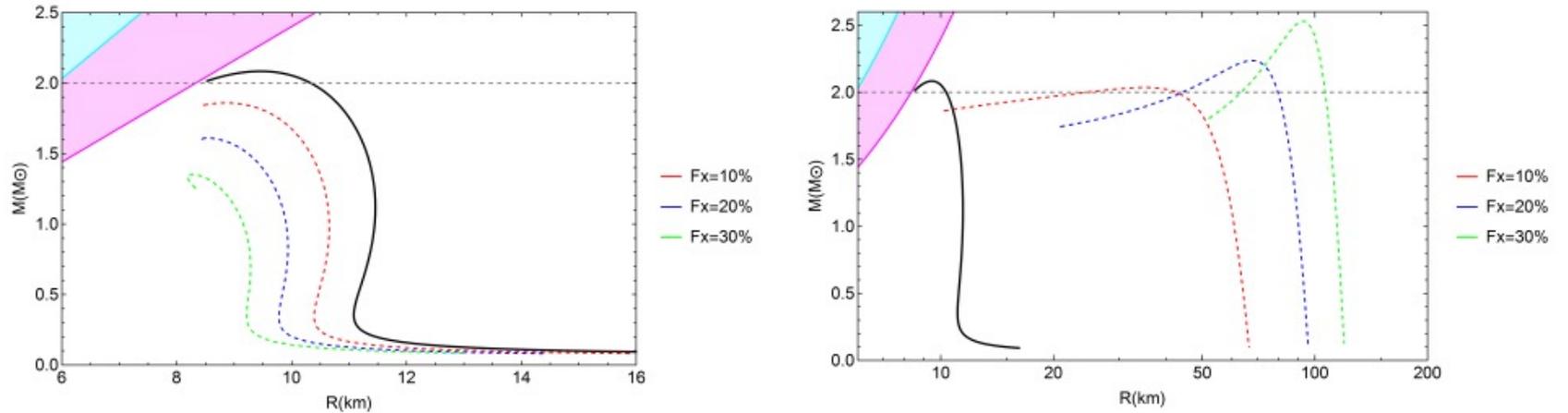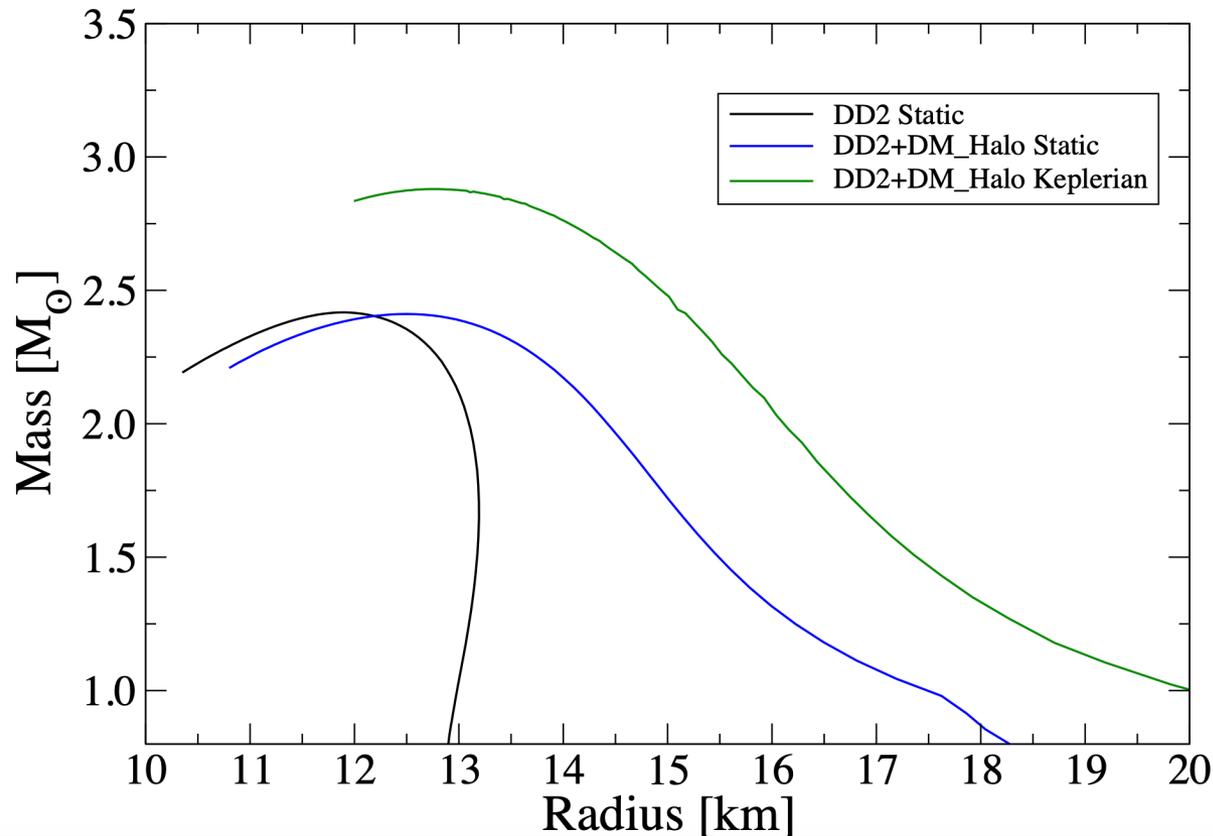
Bosonic Dark Matter in NS

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$$\frac{d\ln\mu_B}{dr} = \frac{d\ln\mu_\chi}{dr} = -\frac{M_{\rm tot} + 4\pi r^3 p_{\rm tot}}{r^2(1 - 2M_{\rm tot}/r)}$$

O. Ivanytskyi, V. Sagun, and I. Lopes - Phys. Rev. D 102, 063028 (2020)

Uniformly rotating compact stars with a dark matter halo

Properties of the edge of the halo:

ε [MeV/fm^3] = 3.8*10^{-6}, p [MeV/fm^3] = 3.16*10^{-10}, μ [MeV] = 716, n [1/fm^3] = 5.3*10^{-9}

*Derived using rotating CS code following the Ω^2 approximation based on J. B. Hartle by Victor Danchev

Bosonic Dark Matter in NS

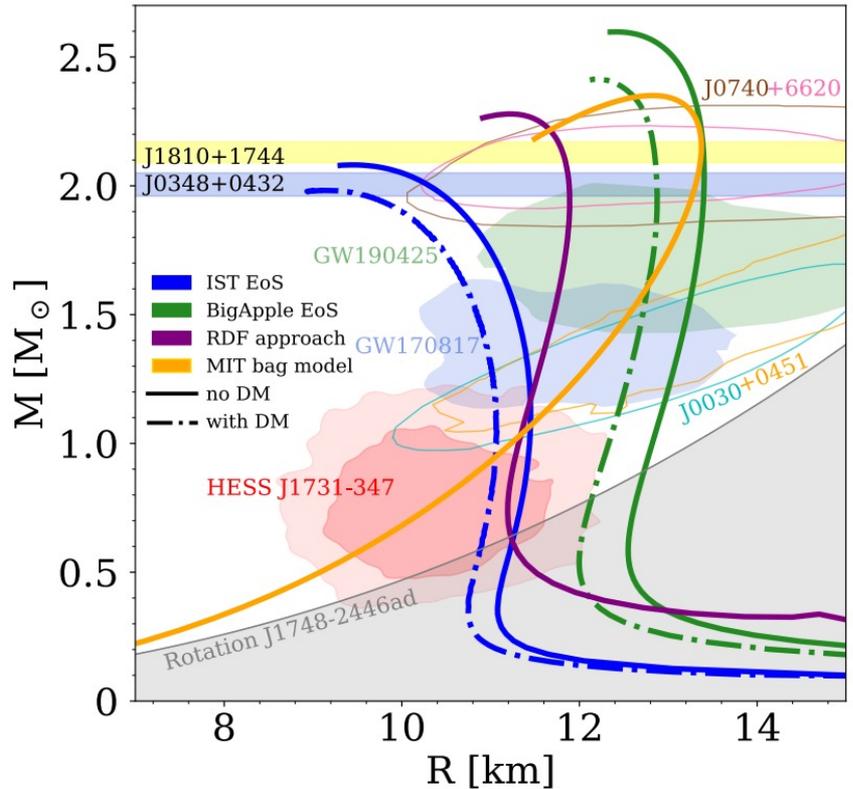D. R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, arXiv:2112.14231

HESS J1731-347

Relativistic mean field model for ultra-compact low mass neutron star of HESS J1731-347
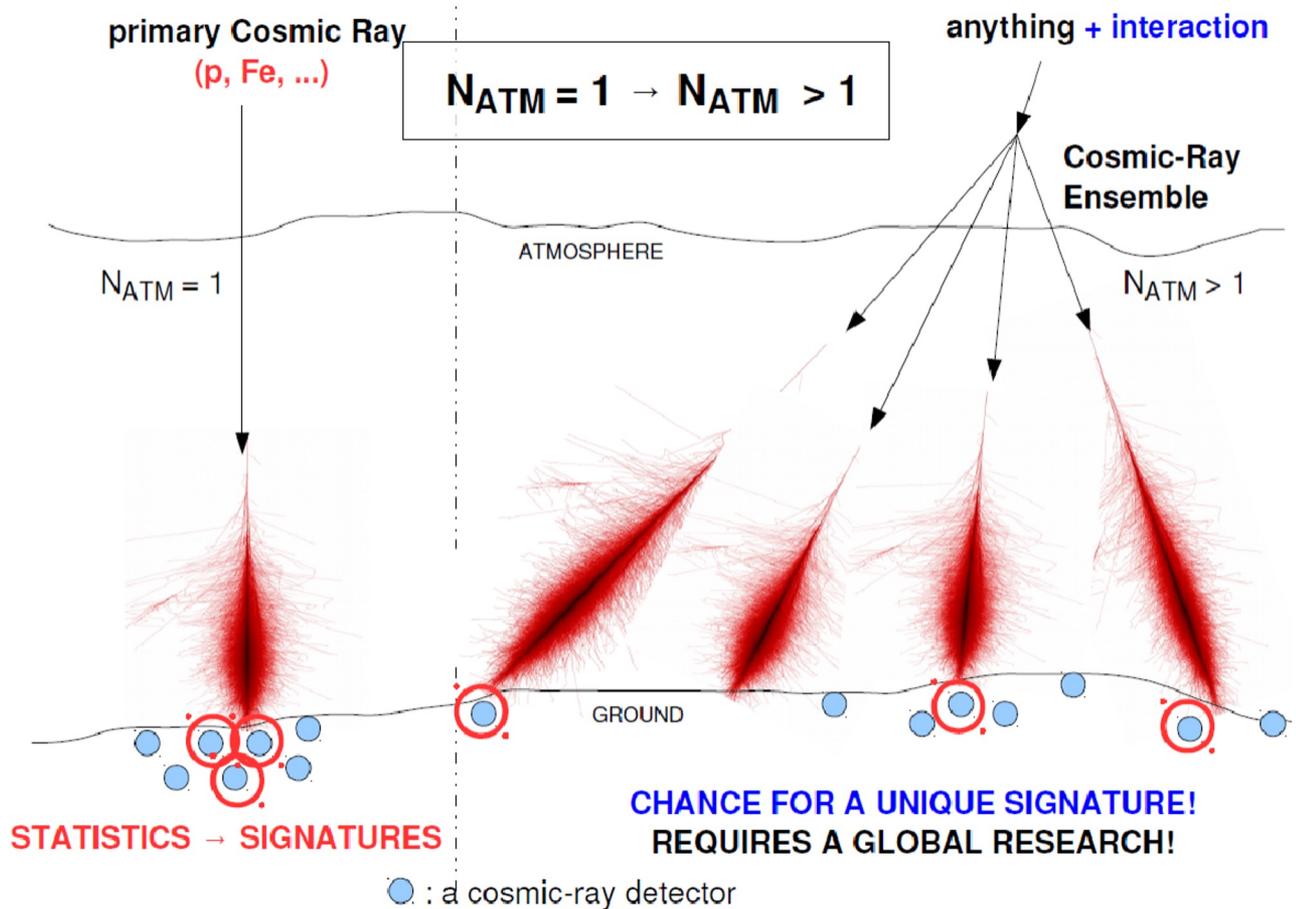Kubis et al. arXiv:2307.02979

What is the nature of the HESS J1731-347 compact object?
Sagun et al. arXiv:2306.12326

Novel science: cosmic ray large scale correlations

Novel Global Solutions

Outlook

- Multi-messenger astronomy and collider experiments will continue probing the properties of dense matter.

- As we advance on the quest for clarification of the neutron star internal content, we will be able to reveal or discard the existence of dark matter in the corresponding stellar interiors and environments.

- Bayesian Analysis and Machine Learning methods are useful for estimation of unknown physical parameters, specially for simultaneously studying the various physical processes involving dark matter.

- Studies of halo effects in different scenarios like tidal deformabilities from neutron star mergers or cooling rates of compact stars.

- Probing the universal L-Love-Q relations taking into account dark matter.

- Studying Finite temperature effects.