Uniformly rotating compact stars with a dark matter halo

David Álvarez Castillo

Institute of Nuclear Physics PAS
Cracow, Poland

Dark Matter and Stars: Multi-Messenger Probes of Dark Matter and Modified Gravity
Universidade de Lisboa, Portugal
May the 4th, 2023

CREDO
THE QUEST FOR THE UNEXPECTED

PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

comp
star

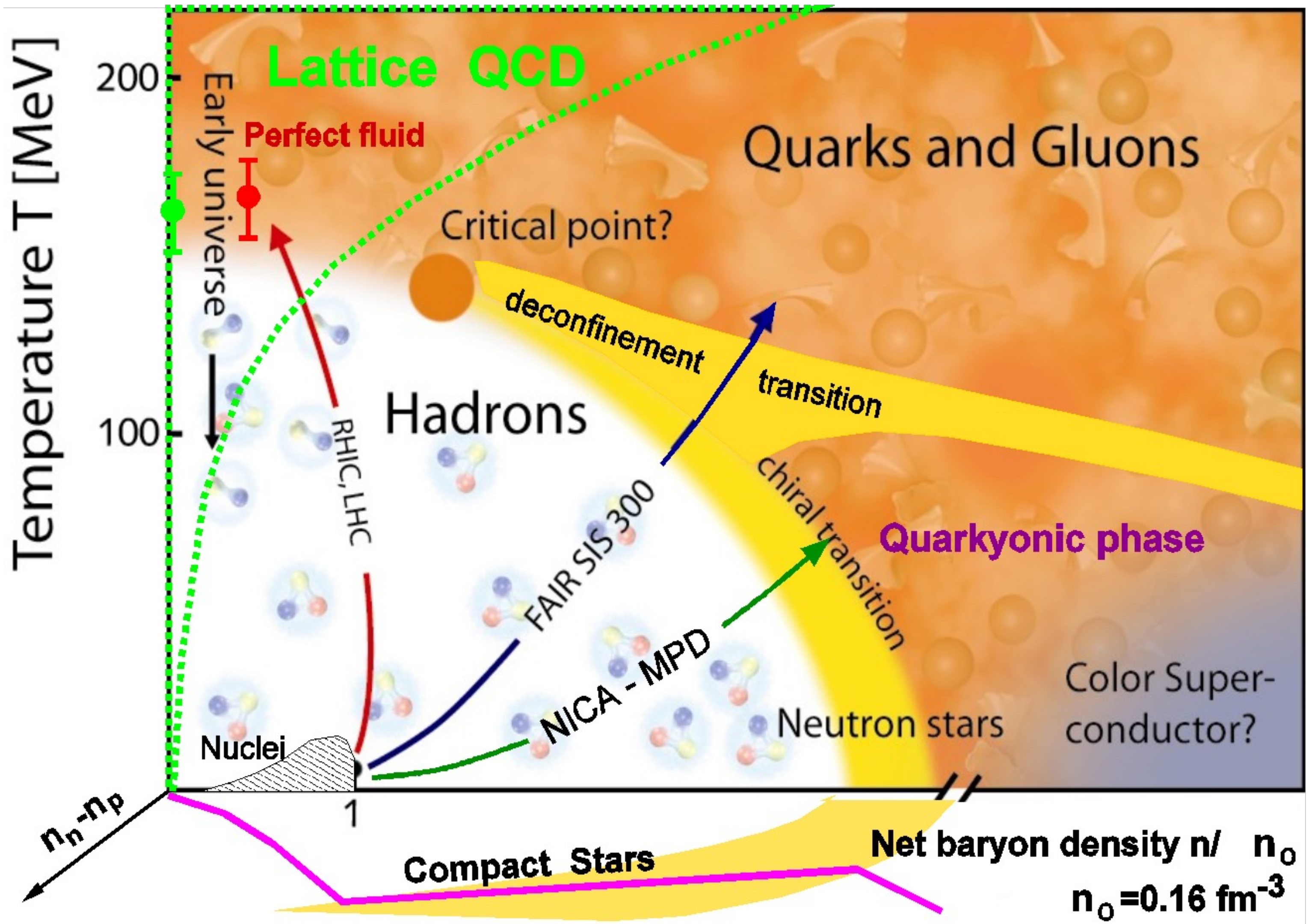
Outline

- 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

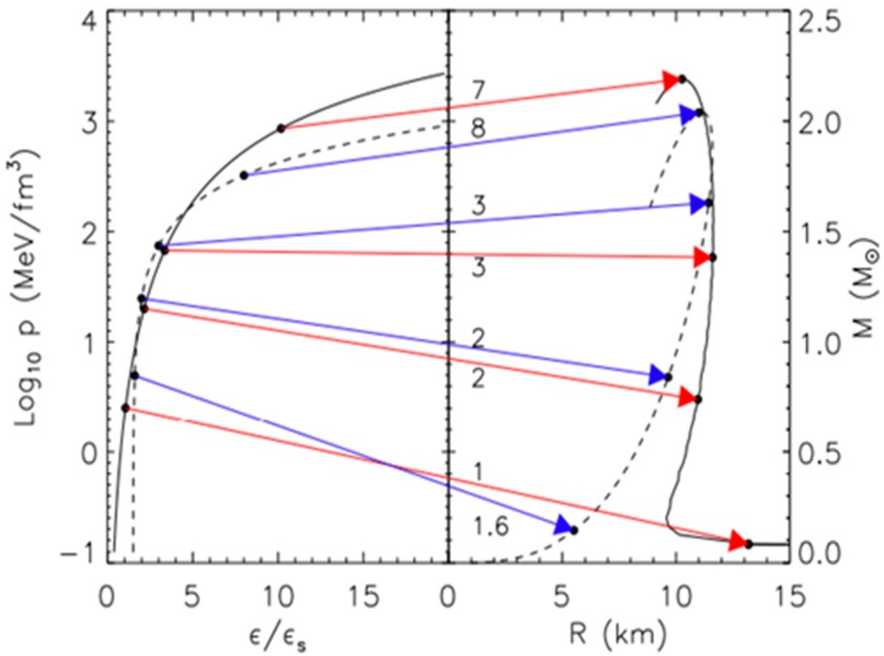
- New channels of multi-messenger observations like gravitational radiation from merger events of binary systems of compact stars or radio and X-ray signals from isolated pulsars allow to study their most basic structural properties like mass, radius, compactness, cooling rates and compressibility of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

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)

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

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon \qquad p(\varepsilon)$$

Journal of High Energy Astrophysics 13–14 (2017) 10–16

Contents lists available at ScienceDirect

Journal of High Energy Astrophysics

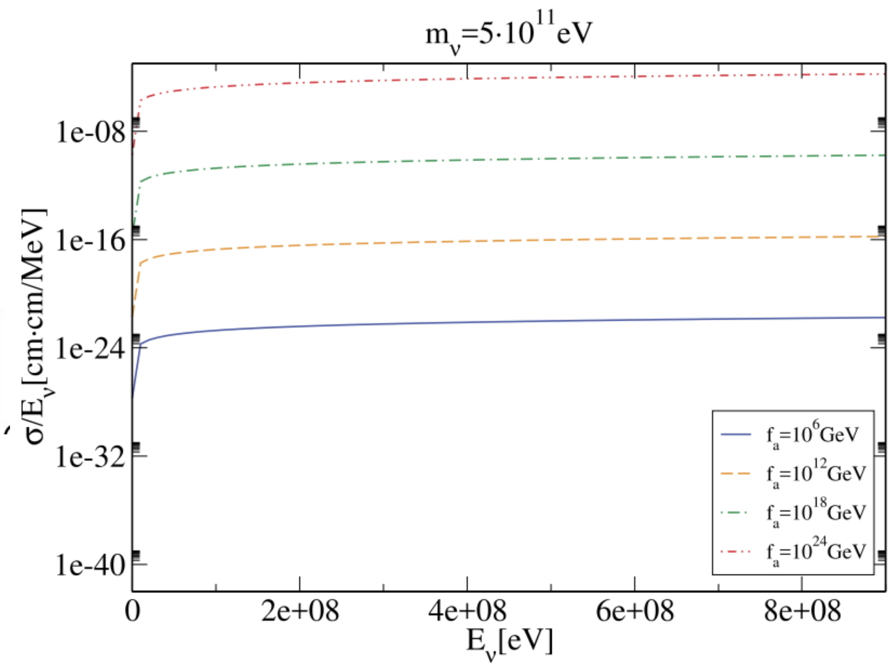
www.elsevier.com/locate/jheap

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

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

$$\sigma_\nu^{flip}(\beta) = \left(\frac{j\mu mc}{4\hbar}\right)\left(\frac{(1-d)^2}{\pi^2 d}\right)^2 \frac{4E^2}{(E+mc^2)^2}\left[1.09416 + Ln\left(\frac{2(E^2-m^2c^4)}{q^2_{\min}}\right)\left(Ln\left(\frac{2(E^2-m^2c^4)}{q^2_{\min}}\right)-0.613706\right)\right],$$

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

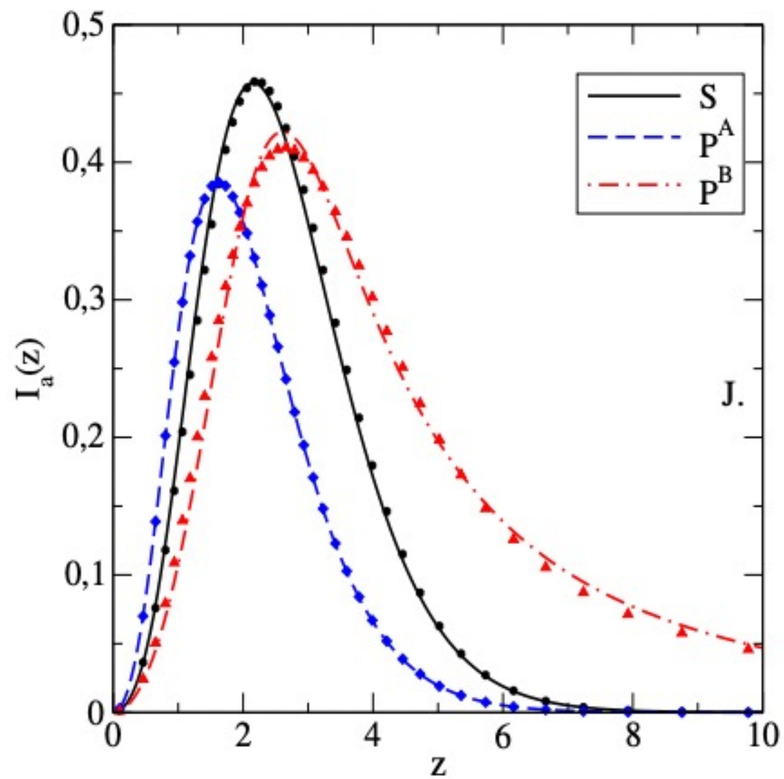


Effects of NS Axion Cooling

Axion emissivity for S-wave condensate

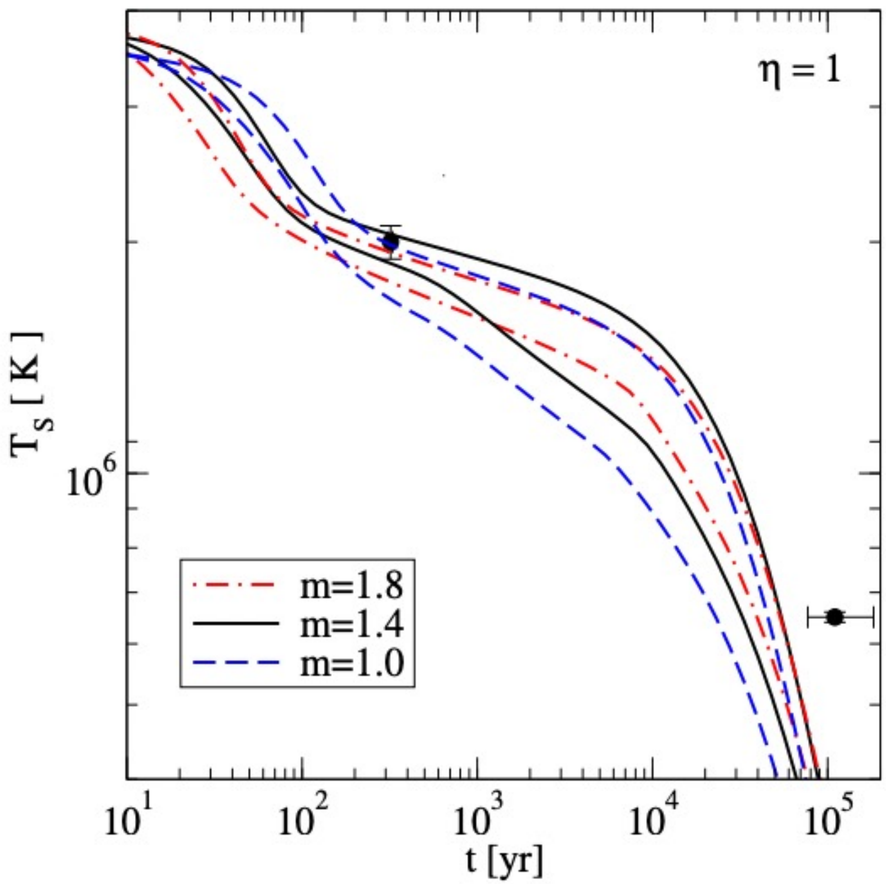
$$\epsilon^S_{aN} = \frac{2C_N^2}{3\pi} f_a^{-2}\, \nu_N(0)\, v_{FN}^2\, T^5\, I^S_{aN},$$

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



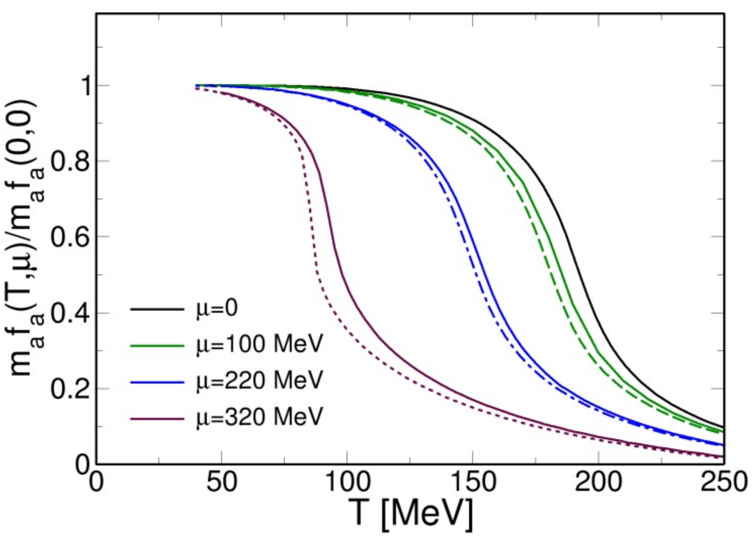
CAS A data, A. Sedrakian, Phys. Rev. D 93, 065044 (2016)

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



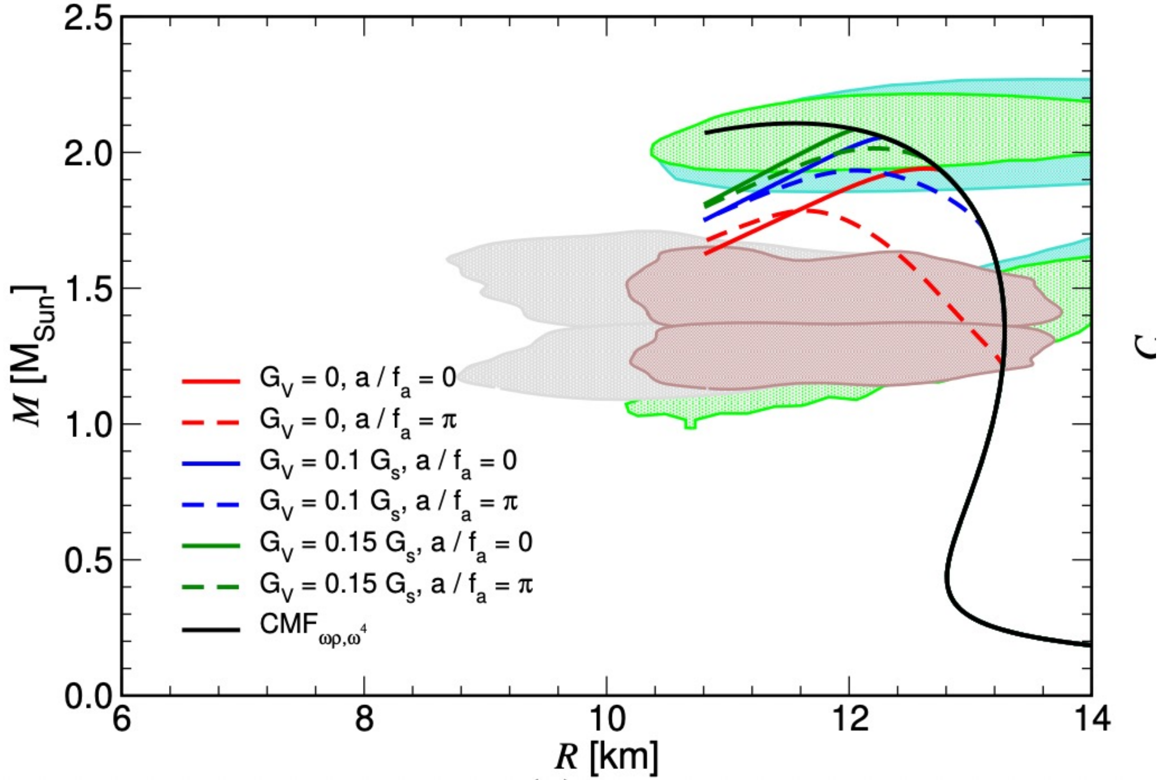
$$\mathcal{L} = \bar{q}\left(i\partial\!\!\!/ + \hat{\mu}\gamma_0 - m_0\right) q + \bar{e}\left(i\partial\!\!\!/ + \mu_e\gamma_0\right) e + \mathcal{L}_{\text{int}}$$

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

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 $\mu_e = 0$.

Bonan Zhang, David Alvarez C., Ana G. Grunfeld, Marco Ruggieri
arXiv:2304.10240

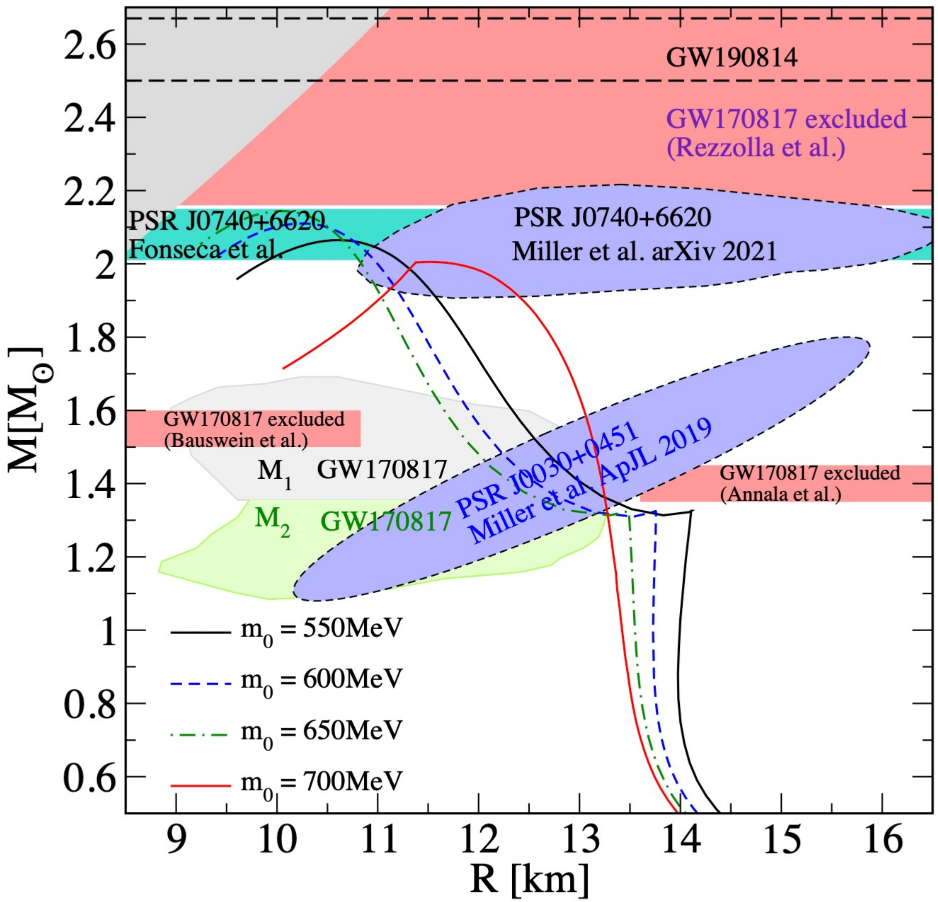
Axion effects in the stability of Hybrid Stars



$$\mathcal{L} = \bar{\psi}\left(i\gamma^\mu\partial_\mu - m_0\right)\psi$$
$$+ G_s \sum_{b=0}^{8}\left[\left(\bar{\psi}\lambda^b\psi\right)^2 + \left(\bar{\psi}i\gamma_5\lambda^b\psi\right)^2\right] - G_V\left(\bar{\psi}\gamma^\mu\psi\right)^2$$
$$- K\left\{e^{i\frac{a}{f_a}}\det\left[\bar{\psi}\left(1+\gamma^5\right)\psi\right] + e^{-i\frac{a}{f_a}}\det\left[\bar{\psi}\left(1-\gamma^5\right)\psi\right]\right\}$$

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

Compact Star Twins with a Dark Matter Core

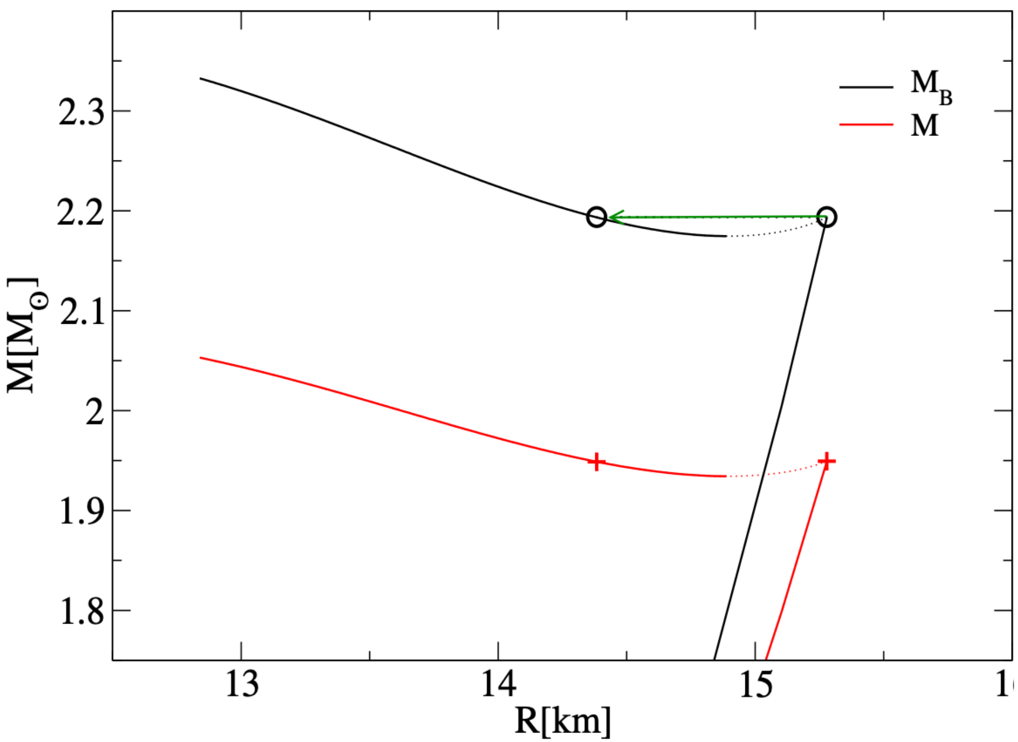


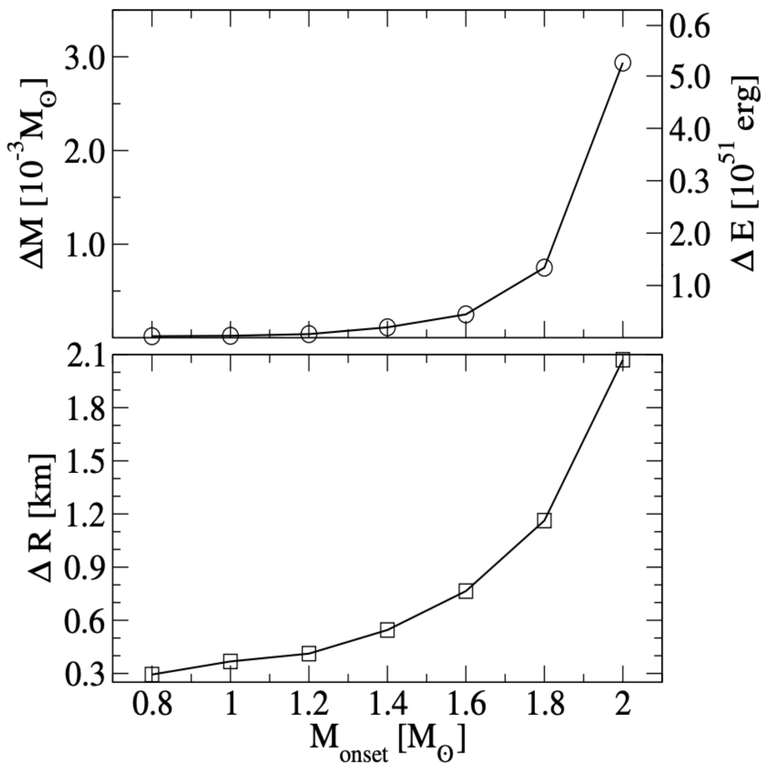
Parity Double Model, featuring chiral partners N± without quark deconfinement.

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

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

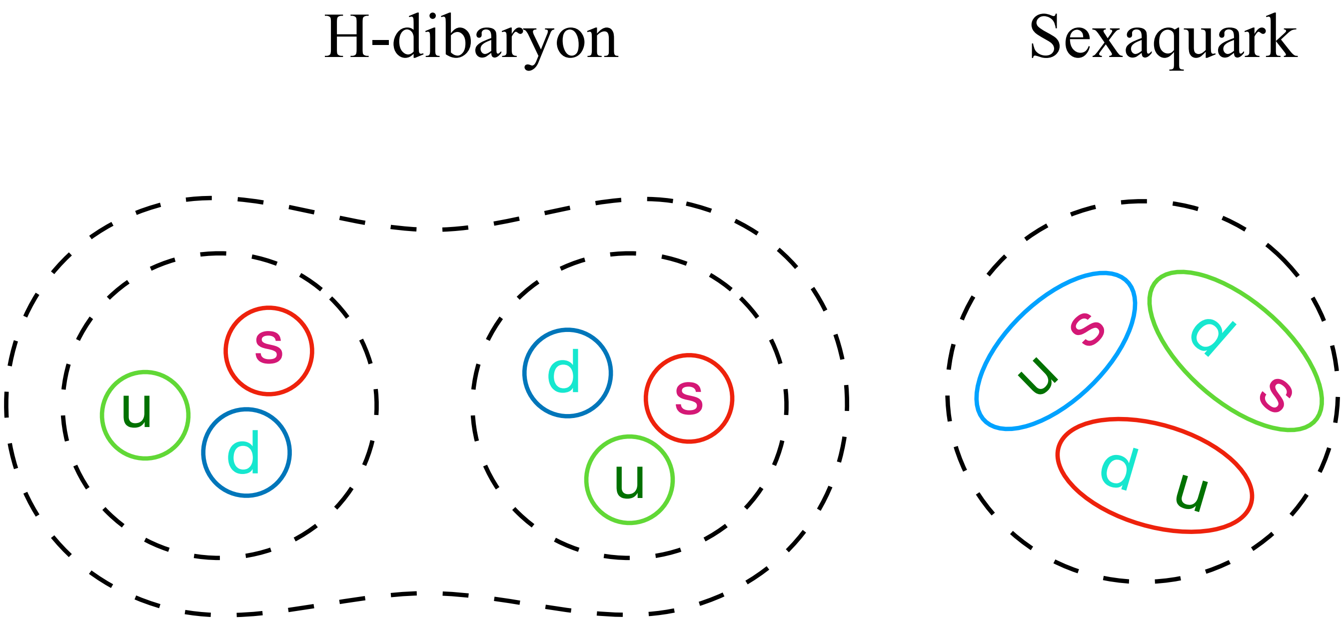
Mass Twins – Energy Released





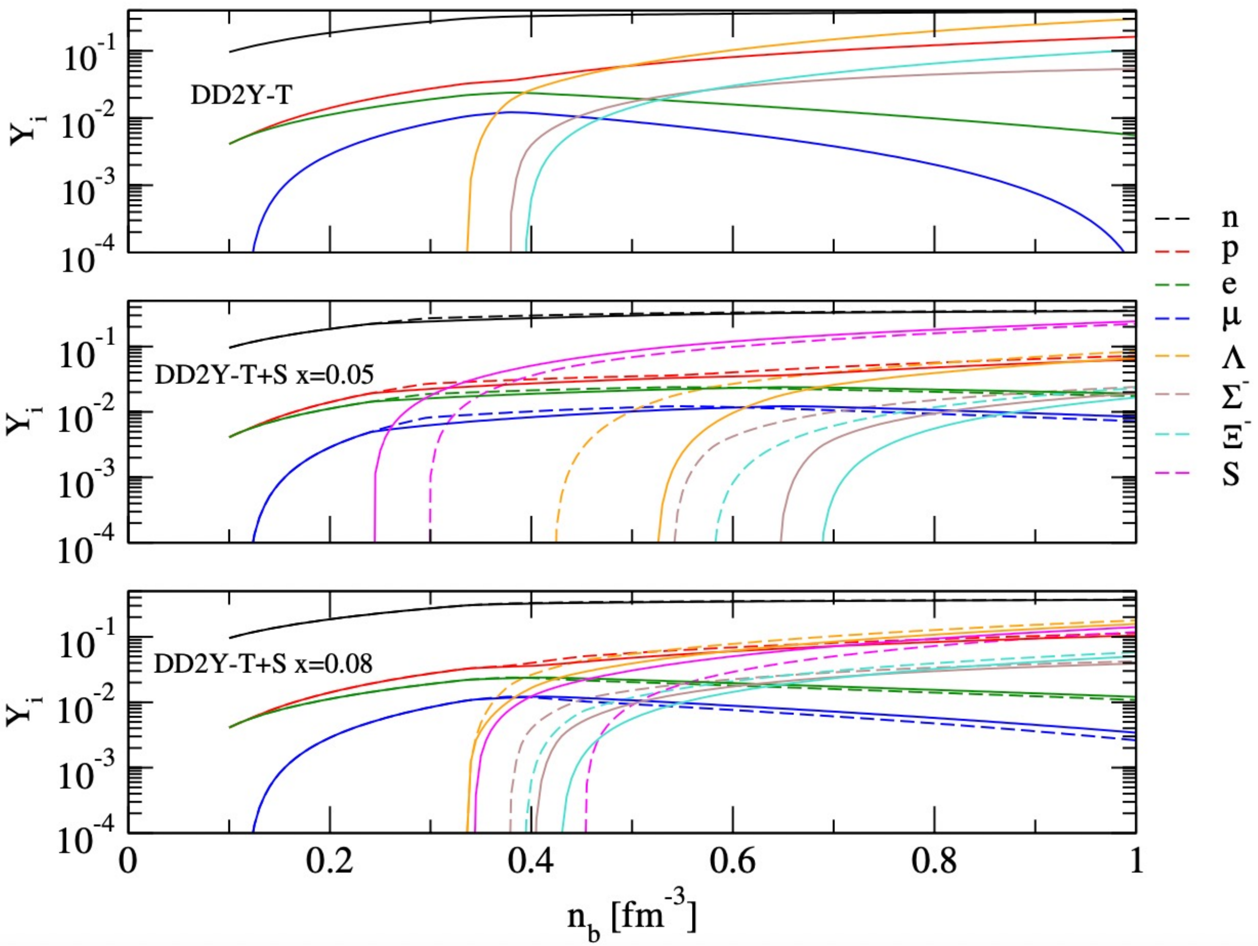
DD2MEV-CSS EoS, D. A-C, Astronomischen Nachrichten (2021) 1–6, arXiv: 2011.11145

Sexaquarks in NS



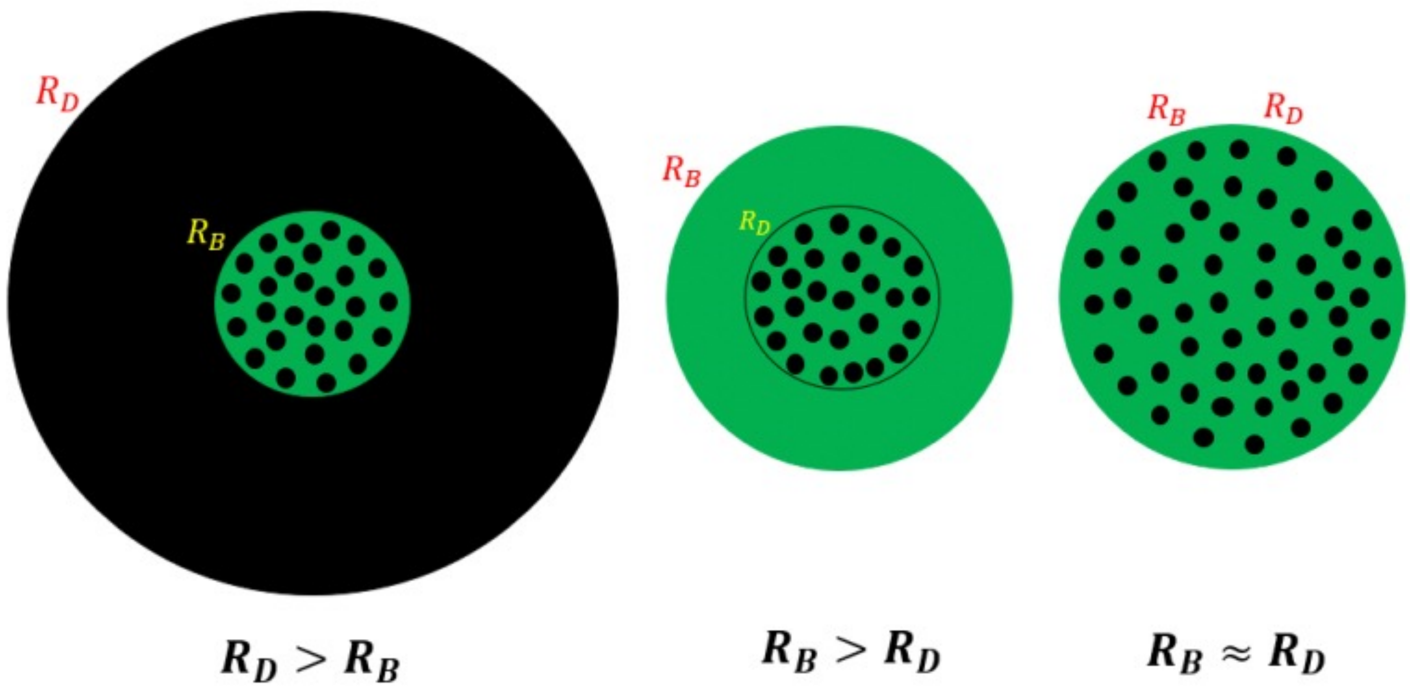
M. Shahrbaf, D. Blaschke, S. Typel, G. R. Farrar, and D. A-C
Phys. Rev. D 105, 103005, (2022)

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



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

Bosonic Dark Matter in NS

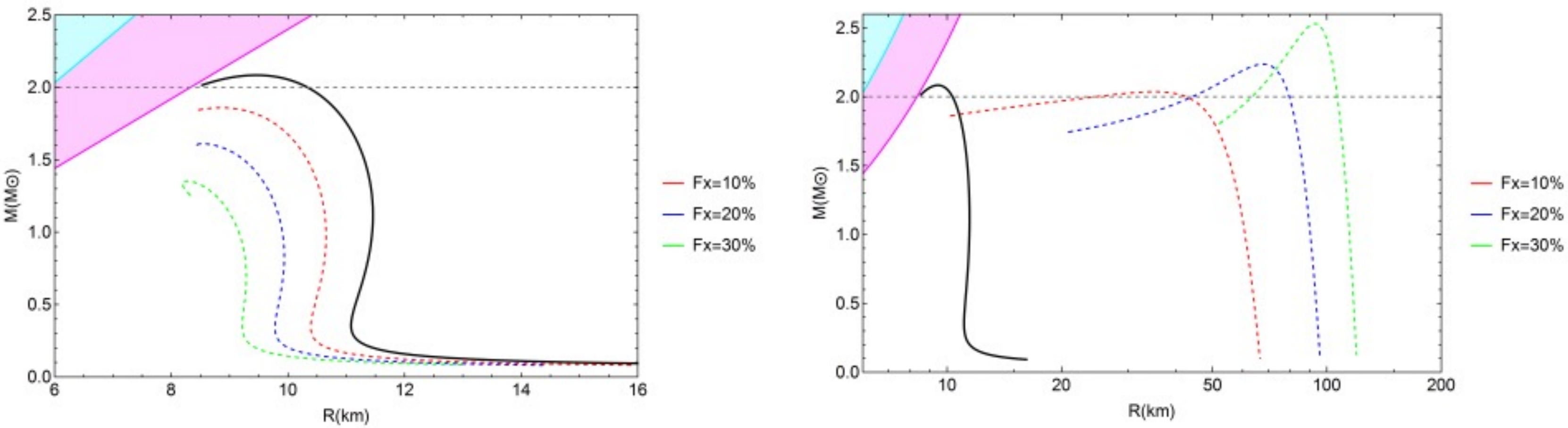


Fig. 7. Mass-Radius profiles for DM admixed NSs for $m_\chi = 400$ MeV (left) which corresponds to a DM core formation and $m_\chi = 100$ MeV (right) that represents an extended DM halo formation around a NS. Coupling constant is fixed to $\lambda = \pi$ and different F_χ are considered as labeled.

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

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

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

Bosonic Dark Matter in NS

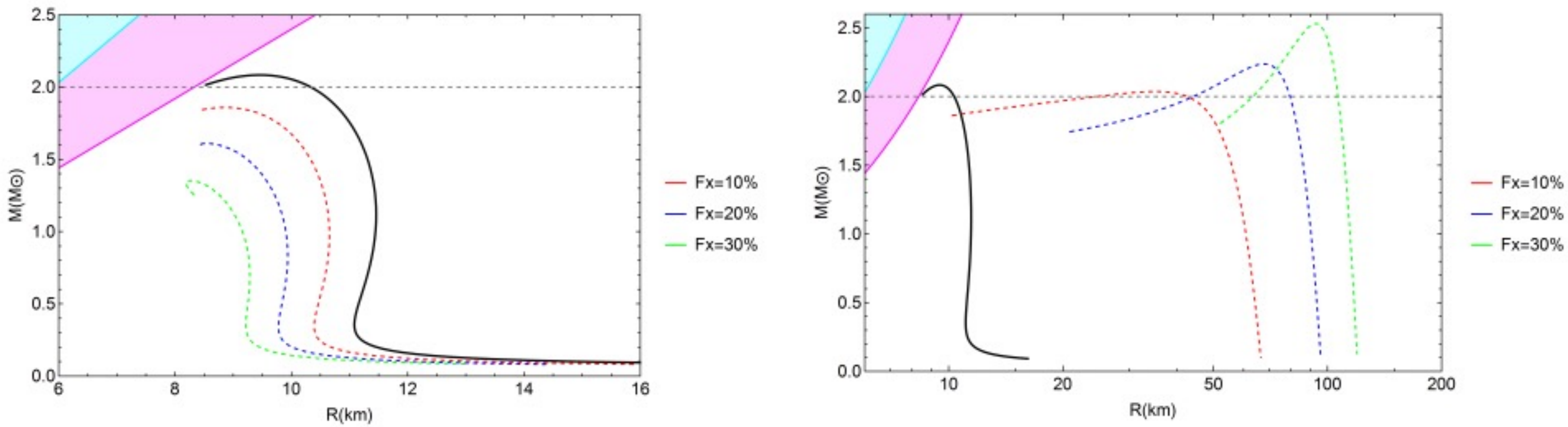
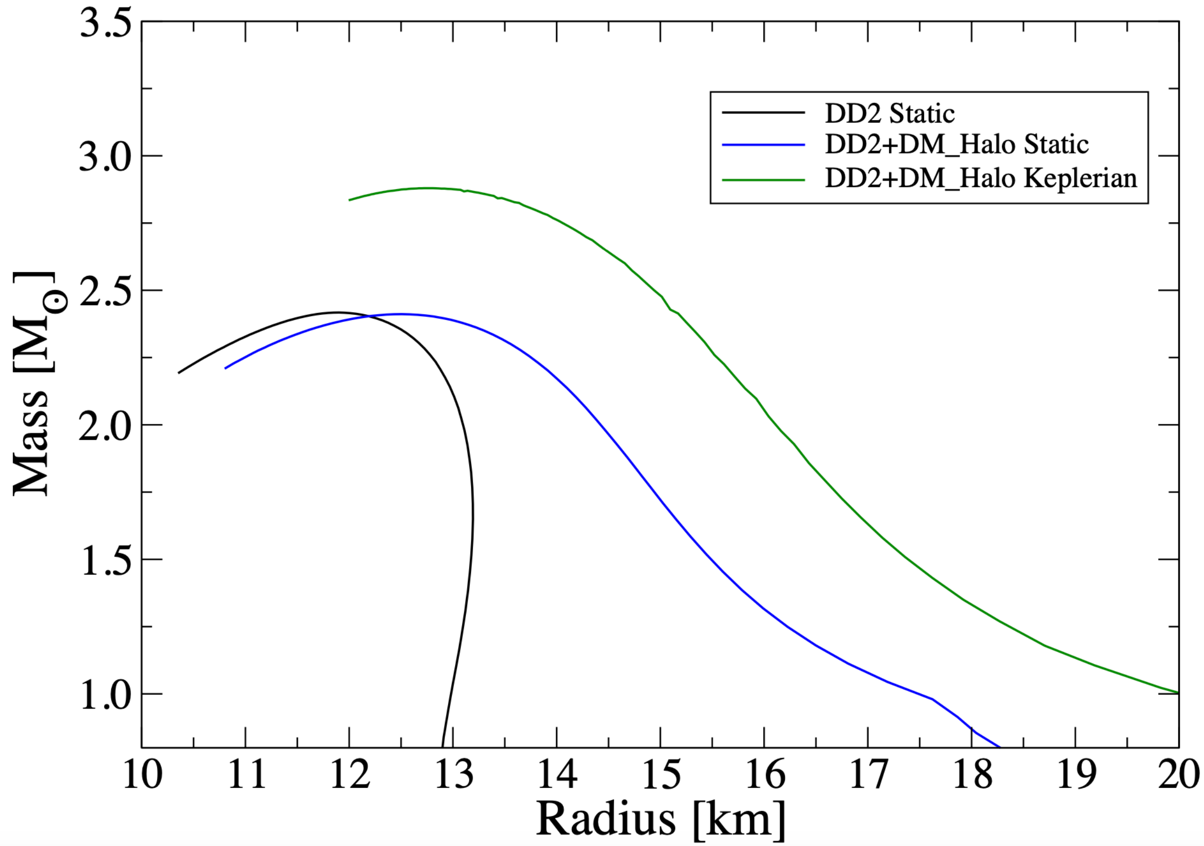


Fig. 7. Mass-Radius profiles for DM admixed NSs for $m_\chi = 400$ MeV (left) which corresponds to a DM core formation and $m_\chi = 100$ MeV (right) that represents an extended DM halo formation around a NS. Coupling constant is fixed to $\lambda = \pi$ and different F_χ are considered as labeled.

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

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

Uniformly rotating compact stars with a dark matter halo

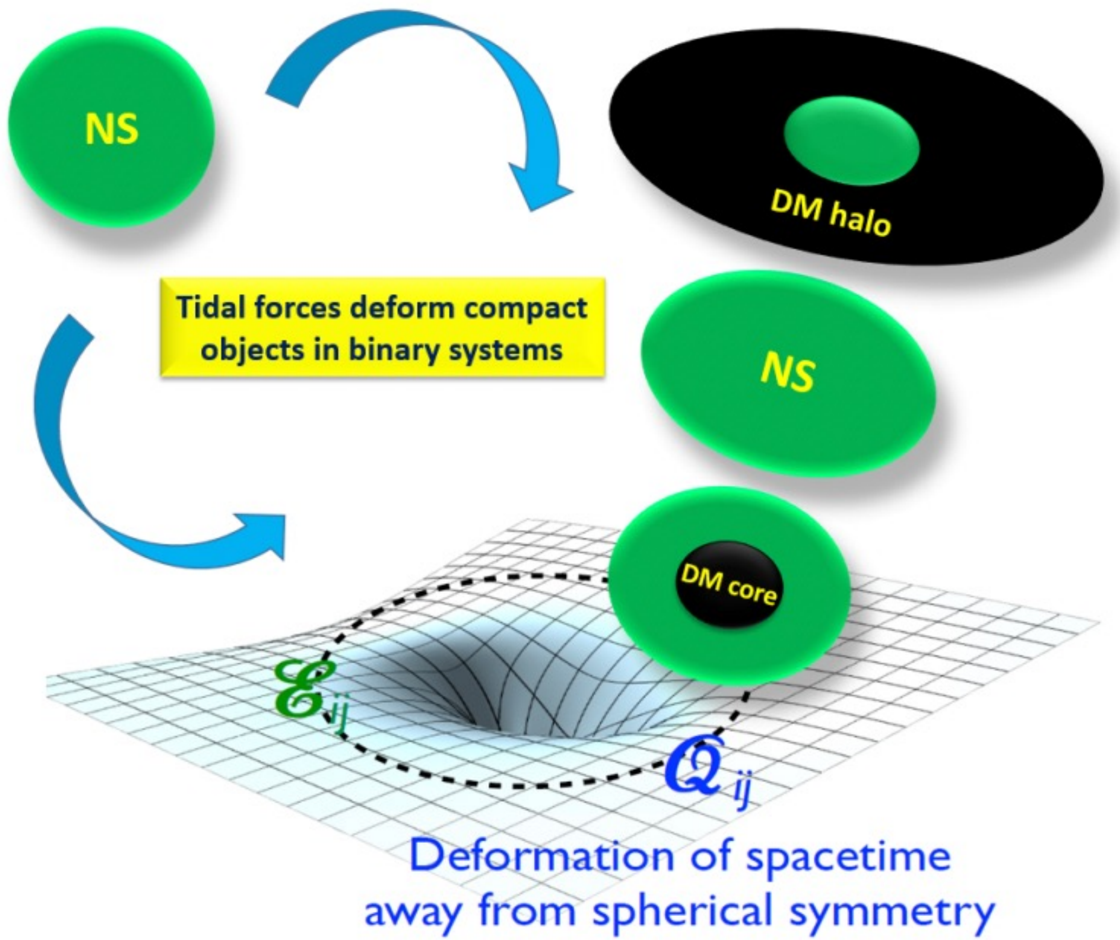


Properties of the edge of the halo:

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}

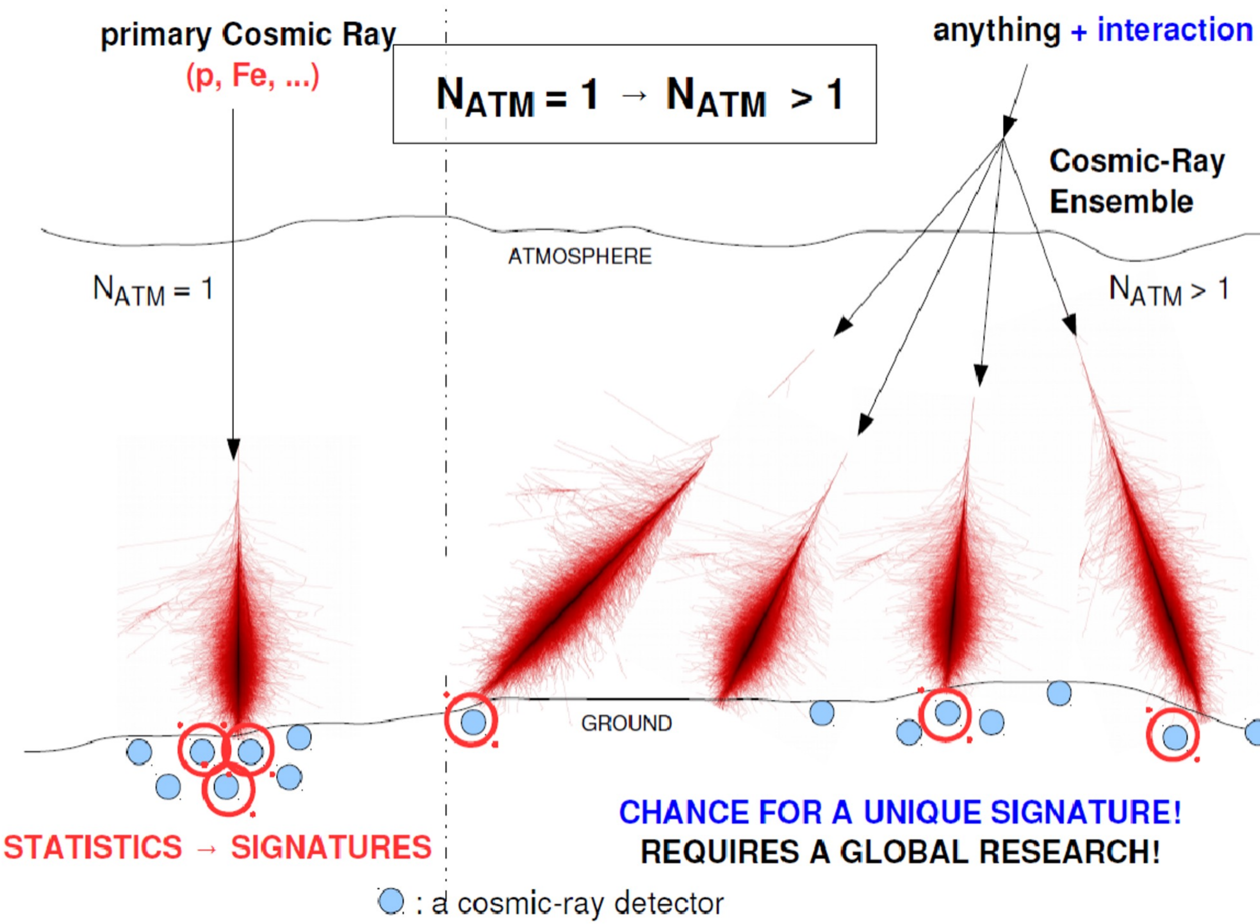
*Derived using rotating CS code following the Ω^2 approximation based on J. B. Hartle by Victor Danchev

Bosonic Dark Matter in NS



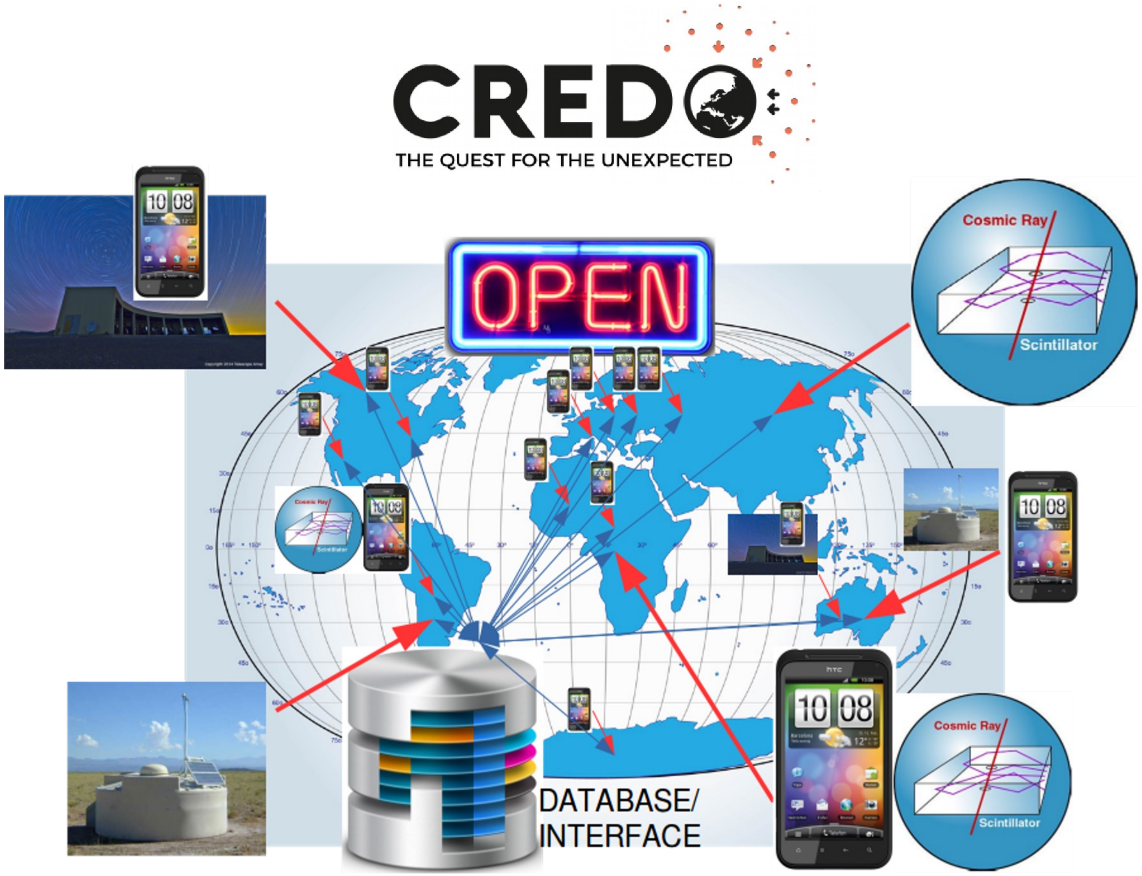
D. R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, arXiv:2112.14231

Novel science: cosmic ray large scale correlations



CREDO
THE QUEST FOR THE UNEXPECTED

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.