Dark Matter Searches Through Multi-Messenger Observations of Compact Stars

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RAGTIME 2022
24th Relativistic Astrophysics Group Meeting
October 12, 2022

PHAROS
THE MULTI-MESSENGER
PHYSICS AND ASTROPHYSICS
OF NEUTRON STARS

comp
star

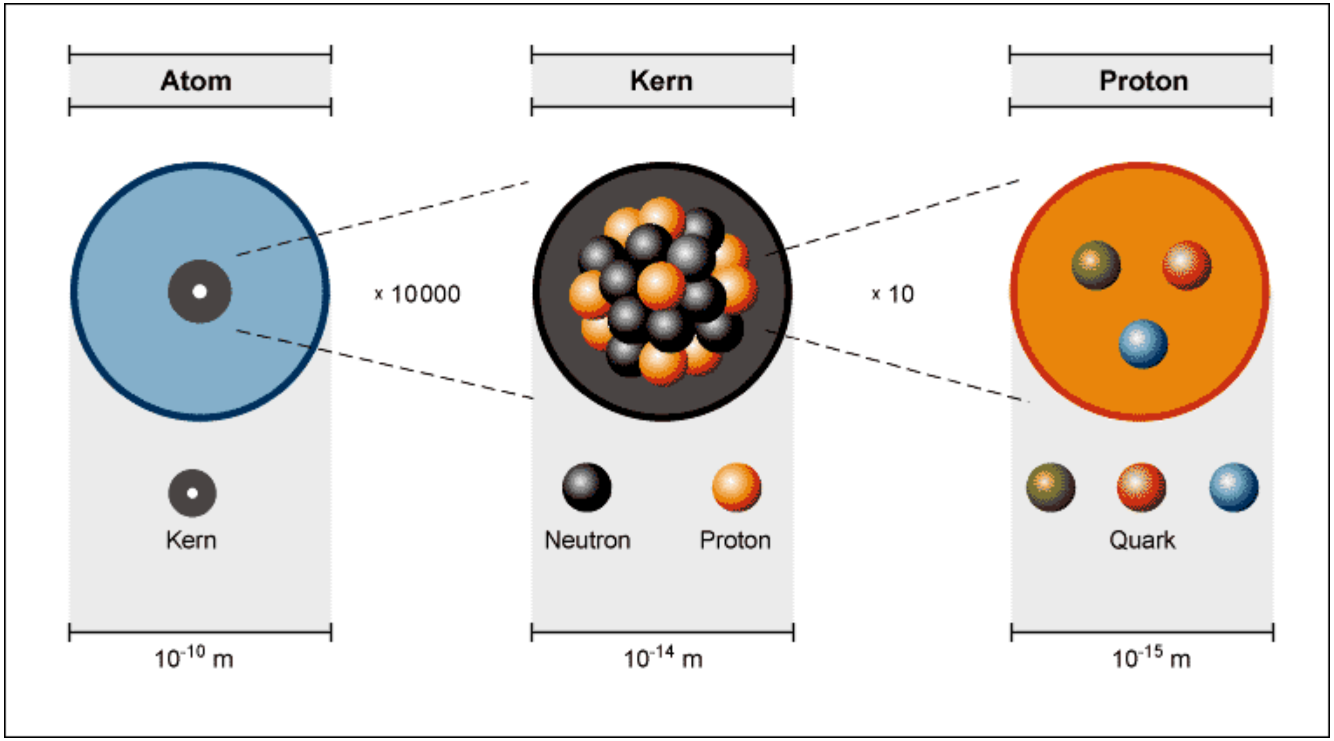
Outline

- A brief introduction to the physics of compact stars.

- Selected scenarios: cooling of compact stars by axions, neutron star collapse into a third family of hybrid stars, neutron star combustion into strange star, mergers of neutron stars, primordial black holes, sexaquarks in compact stars.

- Multi-messenger astronomy measurements that could probe dark matter in compact stars.

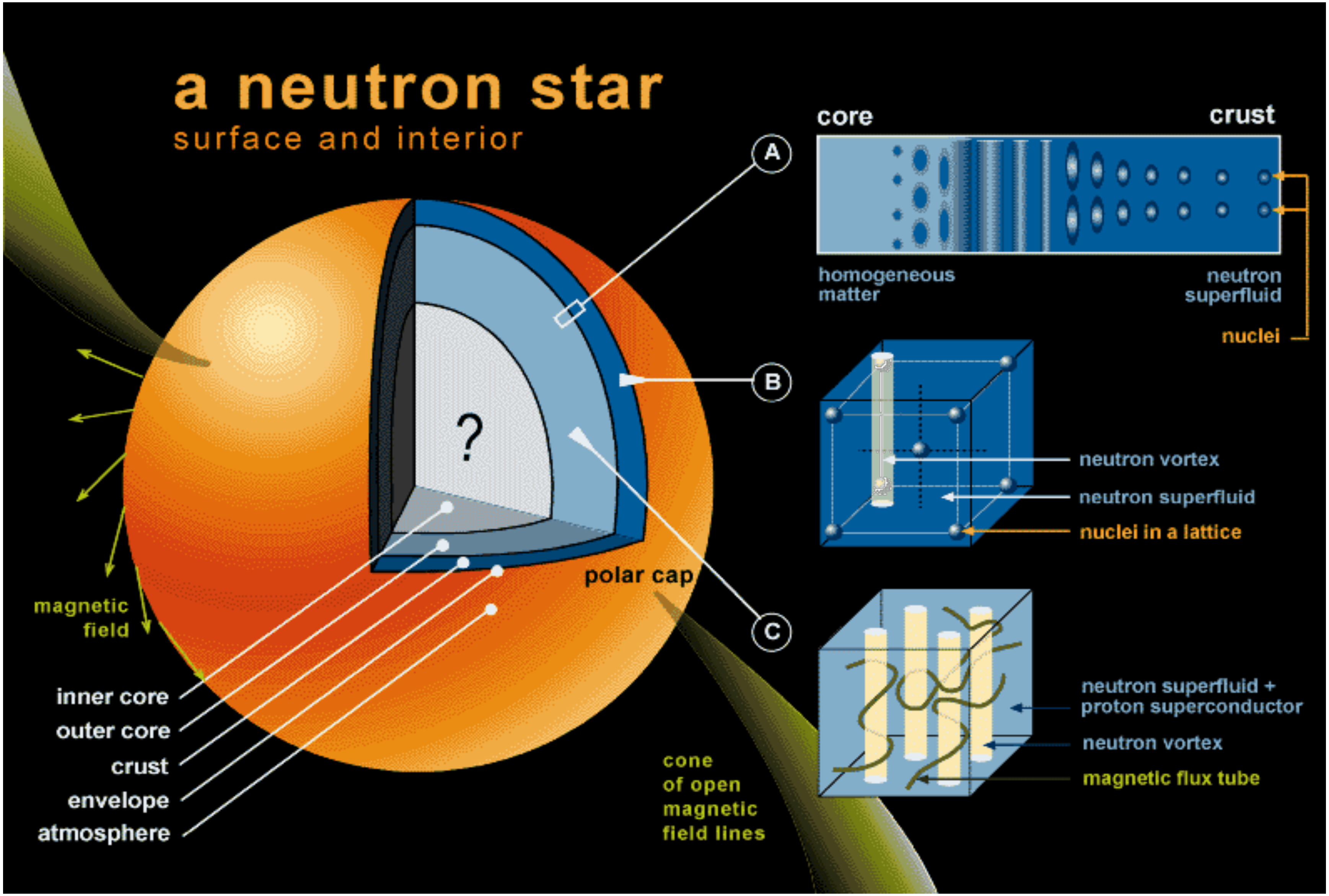
Superdense objects – what is inside?



Nucleus, A nucleons: R_A=1.2 10^{-13} cm $A^{1/3}$; ρ_0=A1.67 10^{-24} g/(4π/3 $R_A{}^3$)= 2.3 10^{14} g/cm^3

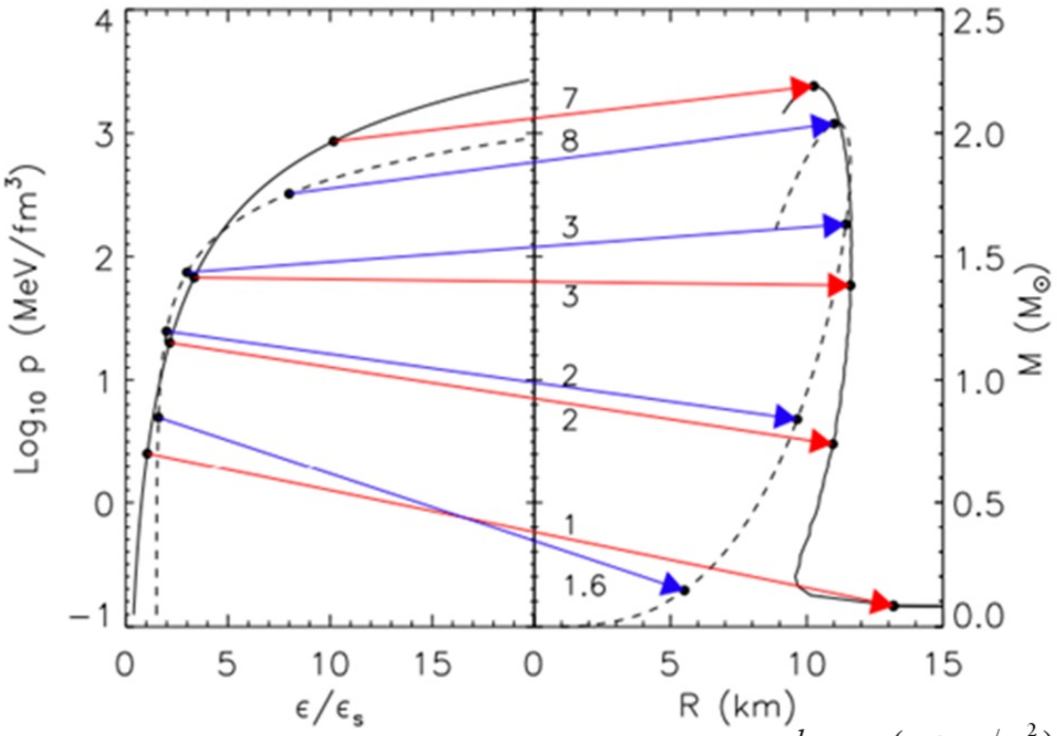
Neutron star: R= 10 km; ρ= 2 Mo/(4π/3 R^3) = 4 10^{33} g/(4 10^{18} cm^3)= 10^{15} g/cm^3 = 4 ρ_0

Superdense objects – what is inside?



Compact Star Sequences

(M-R ⇔ EoS)



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

- TOV Equations

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

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

- Equation of State (EoS)

$$p(\varepsilon)$$

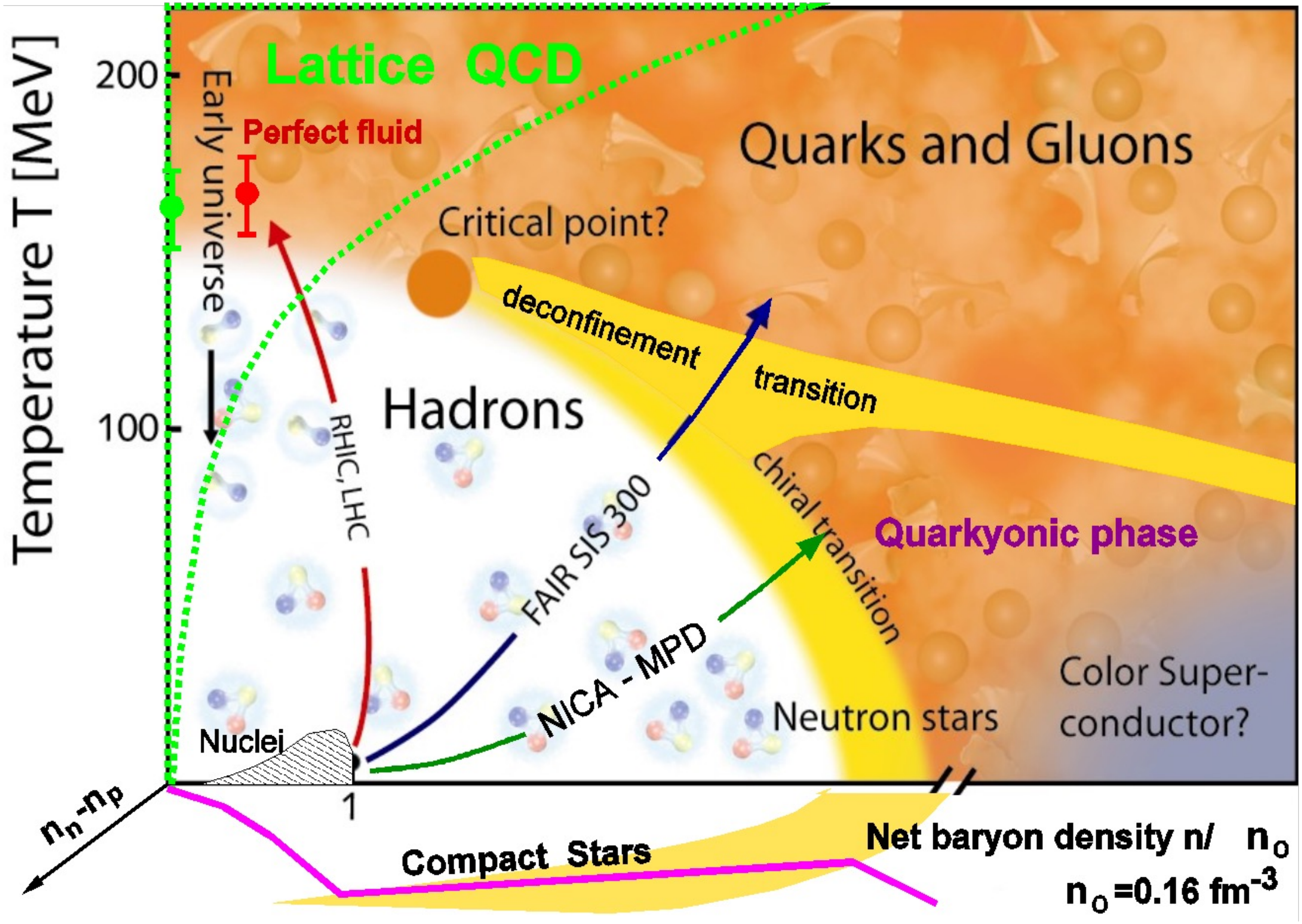
Motivation

- 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 expected signals to be detected.

Critical Endpoint in QCD



Massive Neutron Stars

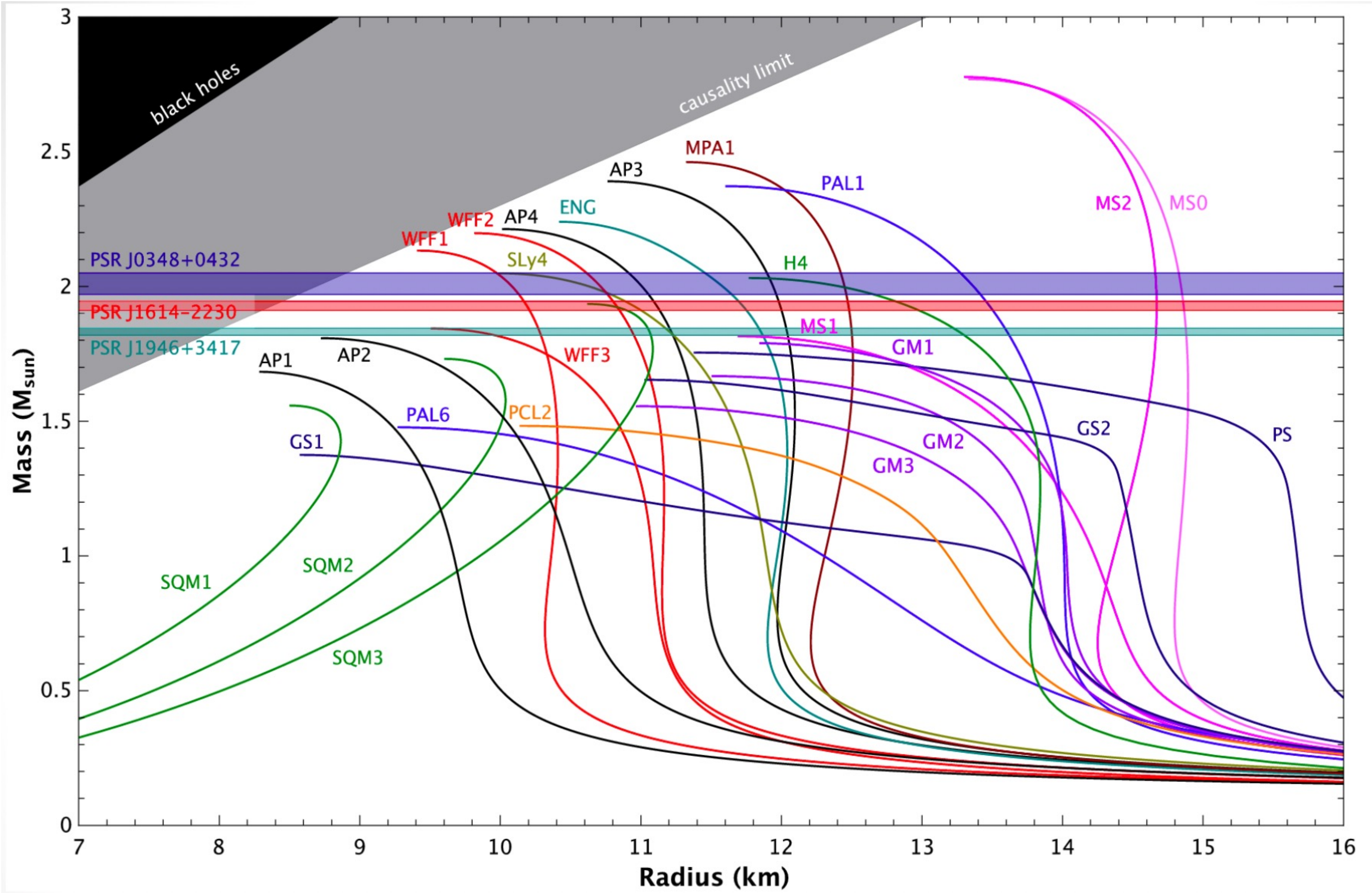


Figure created by Norbert Wex. EoS tabulated in Lattimer & Prakash (2001) and provided by the authors.

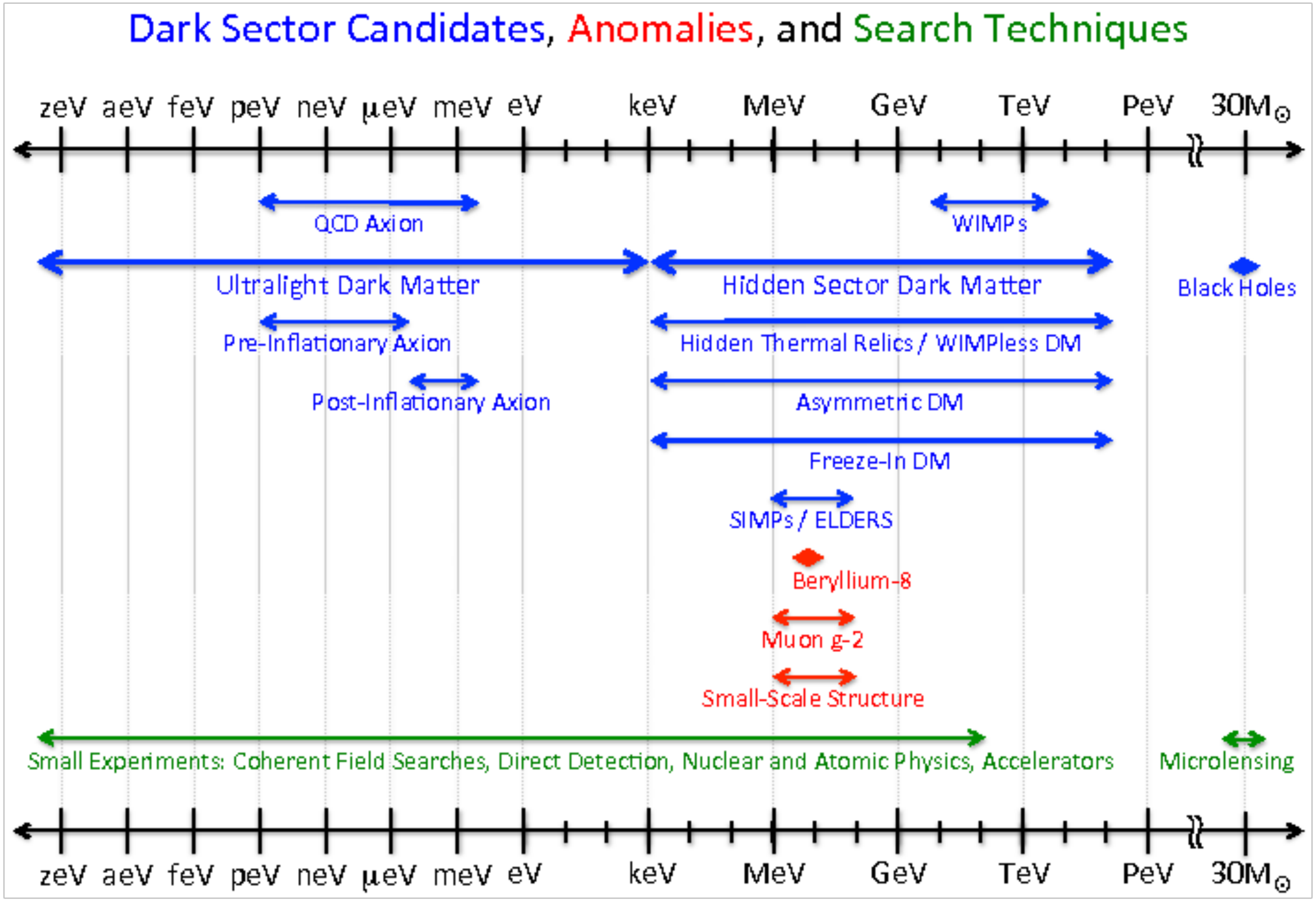
PSR J0952-0607

The latest most massive neutron star 2.35±0.17 Solar Masses.
This pulsar rotates at a frequency of 707 Hz (1.41 ms period), making it the second-fastest-spinning pulsar known, and the fastest-spinning pulsar that is located in the Milky Way.

PSR J0952−0607 - The Fastest and Heaviest Known Galactic Neutron Star
Roger W. Romani et al. Astrophys.J.Lett. 934 2, L18 (2022)

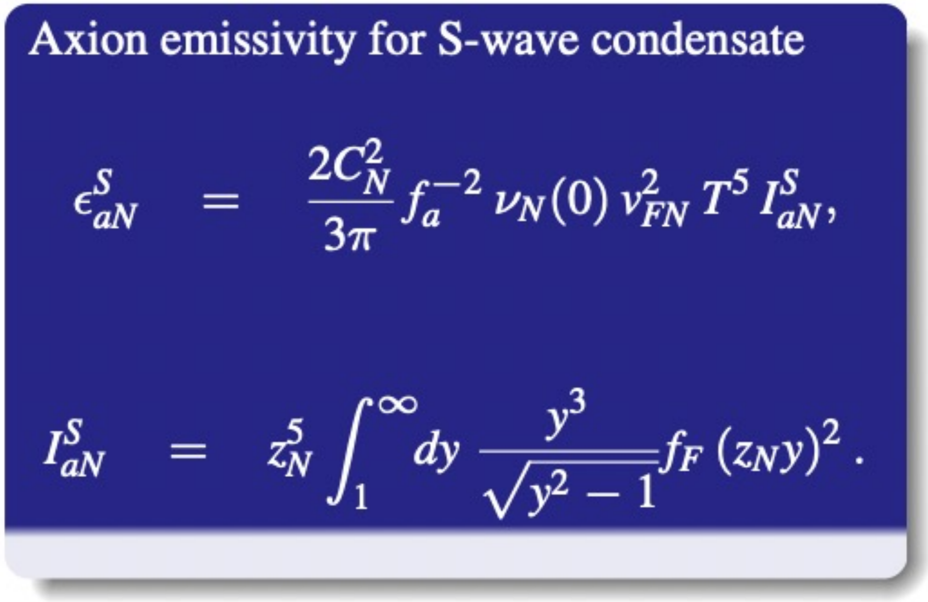
Dark Matter in Compact Stars?

Dark Matter Candidates and Searches



US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report - Battaglieri, Marco et al.
arXiv:1707.04591FERMILAB-CONF-17-282-AE-PPD-T

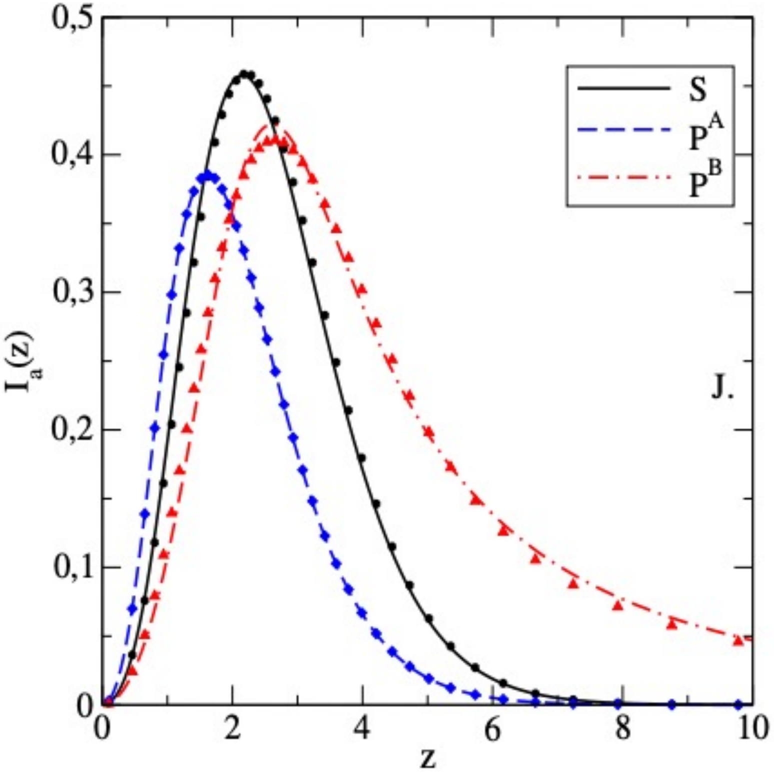
Effects of NS Axion Cooling



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)

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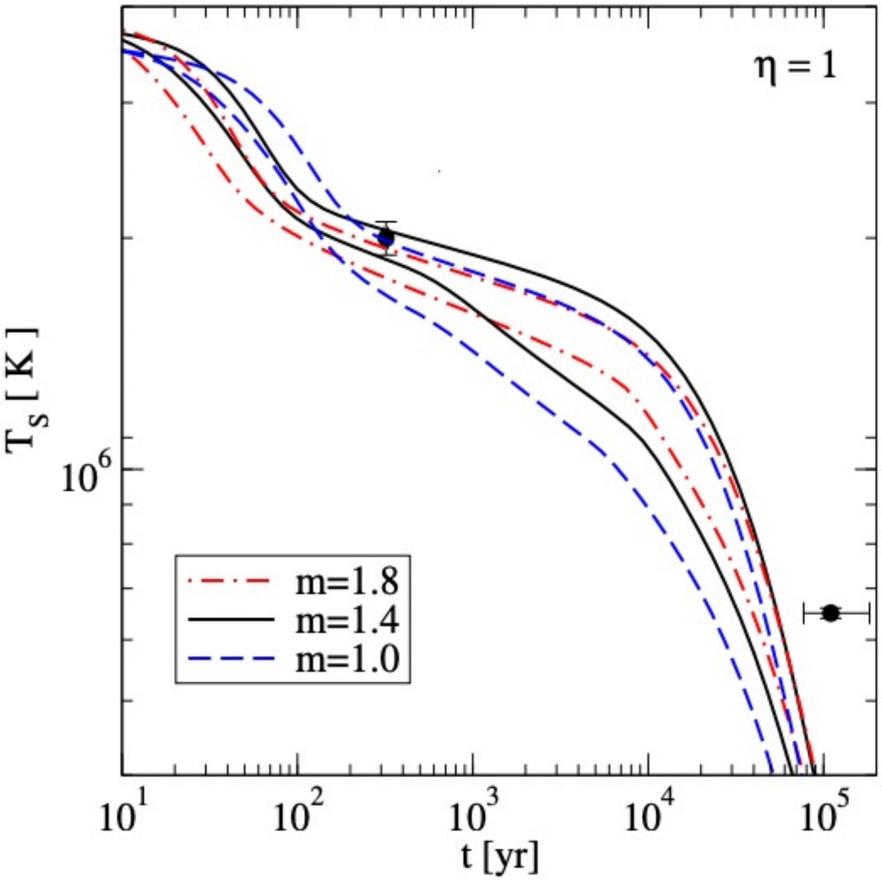


CAS A data, A. Sedrakian, Phys. Rev. D 93, 065044 (2016)

The axion potential in quark matter

M. Ruggieri[1], *D. E. A.* Castillo[2], *A. G.* Grunfeld[3], and *Bonan* Zhang[1]

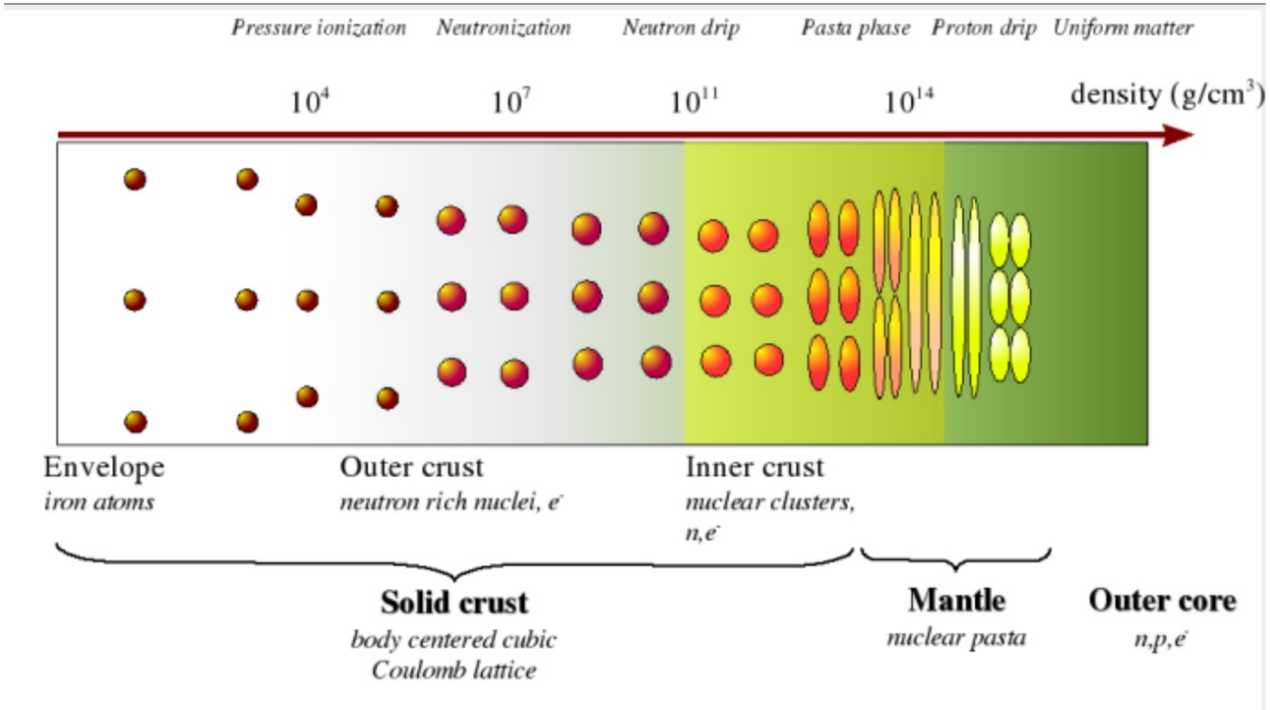
[1]School of Nuclear Science and Technology, Lanzhou University, 222 South Tianshui Road, Lanzhou 730000, China

[2]Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, 31-342 Cracow, Poland

[3]CONICET, Godoy Cruz 2290, C1425FQB Ciudad Autonoma de Buenos Aires, Argentina *and* Departamento de Física, Comisión Nacional de Energía Atómica, Av. Libertador 8250, C1429 BNP, Ciudad Aut ónoma de Buenos Aires, Argentina

Abstract. We study the QCD axion potential in hot and dense quark matter, within an NJL-like model that includes the coupling of the axion to quarks. Firstly we compute the effect of the chiral QCD crossover on the axion mass and self-coupling. Then, we compute the axion potential and study the domain walls. We find that the energy barrier between two adjacent vacuum states decreases in the chirally restored phase: this results in a lower surface tension of the walls. Finally we comment on the possibility of abundant production of walls in hot and dense quark matter.

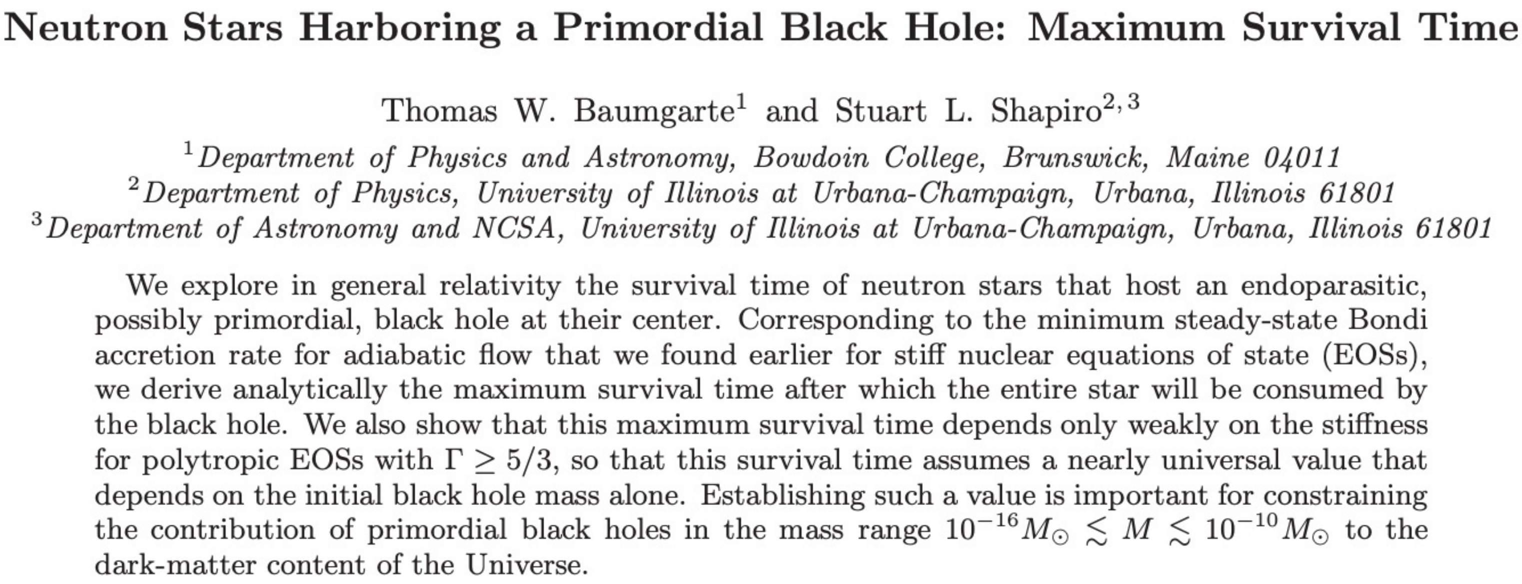
Dark Matter scattering in the NS crust: phonons



$$\mathcal{L}_{\mathcal{I}} = \sum_{N=n,p} g_{s,N}\chi\overline{\chi}N\overline{N} + g_{v,N}\chi\gamma^{\mu}\overline{\chi}N\gamma_{\mu}\overline{N},$$

Cermeño, PG & Silk, PHYSICAL REVIEW D 94, 023509 (2016),
PHYSICAL REVIEW D 94, 063001 (2016)

Primordial Black holes

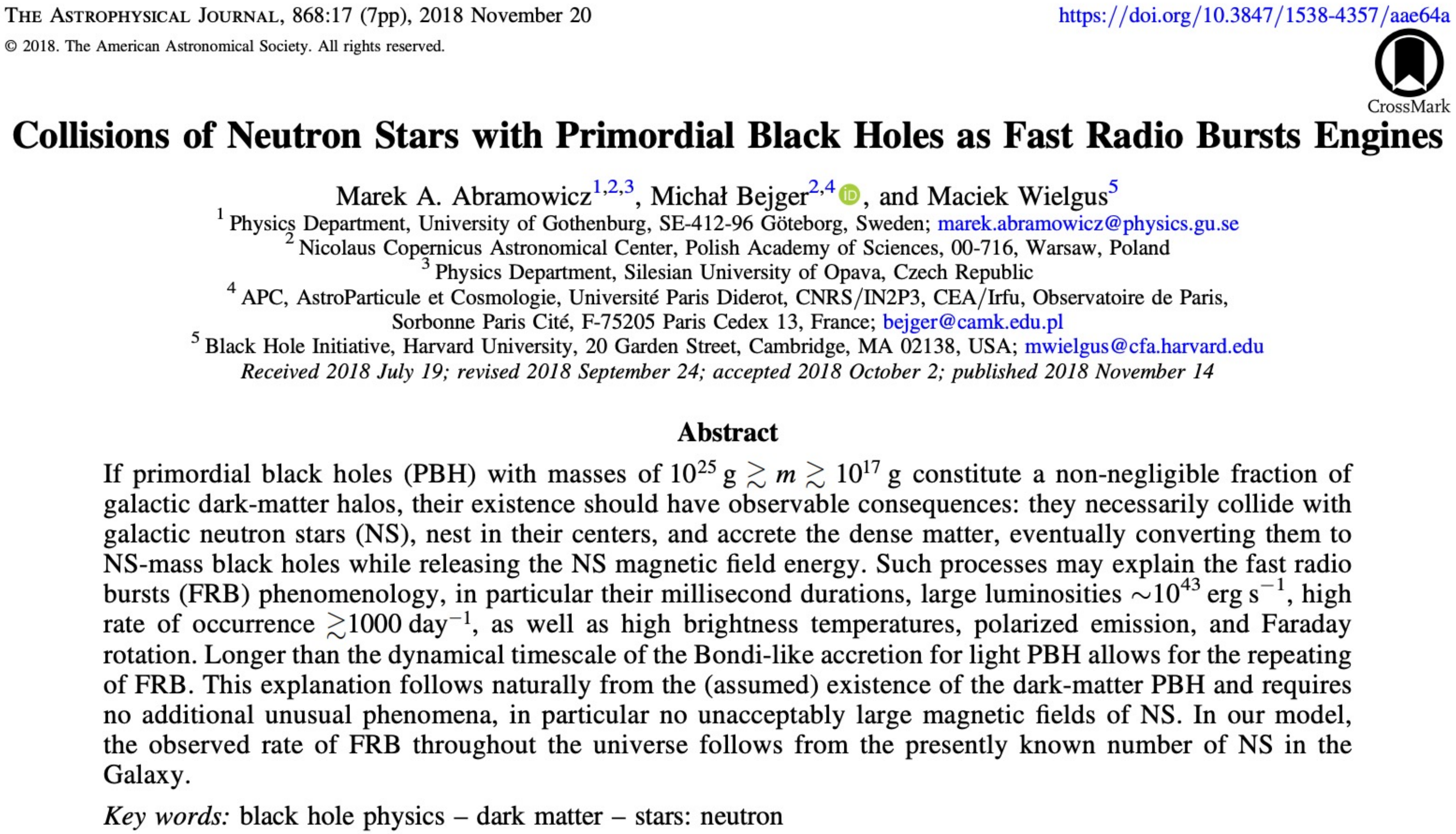


Neutron Stars Harboring a Primordial Black Hole: Maximum Survival Time

Thomas W. Baumgarte[1] and Stuart L. Shapiro[2,3]
[1] *Department of Physics and Astronomy, Bowdoin College, Brunswick, Maine 04011*
[2] *Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801*
[3] *Department of Astronomy and NCSA, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801*

We explore in general relativity the survival time of neutron stars that host an endoparasitic, possibly primordial, black hole at their center. Corresponding to the minimum steady-state Bondi accretion rate for adiabatic flow that we found earlier for stiff nuclear equations of state (EOSs), we derive analytically the maximum survival time after which the entire star will be consumed by the black hole. We also show that this maximum survival time depends only weakly on the stiffness for polytropic EOSs with $\Gamma \geq 5/3$, so that this survival time assumes a nearly universal value that depends on the initial black hole mass alone. Establishing such a value is important for constraining the contribution of primordial black holes in the mass range $10^{-16} M_{\odot} \lesssim M \lesssim 10^{-10} M_{\odot}$ to the dark-matter content of the Universe.

Primordial Black holes



The Astrophysical Journal, 868:17 (7pp), 2018 November 20 https://doi.org/10.3847/1538-4357/aae64a

Collisions of Neutron Stars with Primordial Black Holes as Fast Radio Bursts Engines

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[1] Physics Department, University of Gothenburg, SE-412-96 Göteborg, Sweden; marek.abramowicz@physics.gu.se
[2] Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland
[3] Physics Department, Silesian University of Opava, Czech Republic
[4] APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris,
Sorbonne Paris Cité, F-75205 Paris Cedex 13, France; bejger@camk.edu.pl
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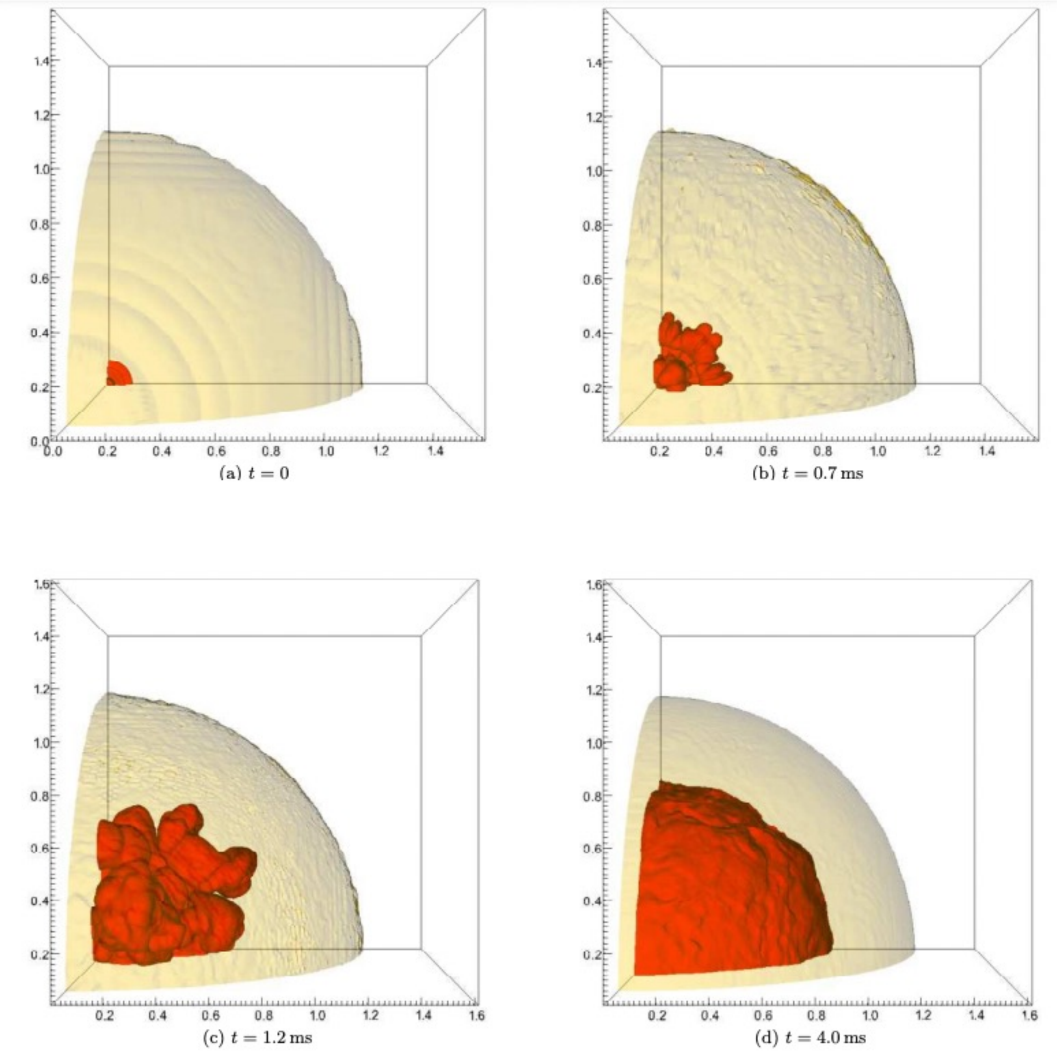
Received 2018 July 19; revised 2018 September 24; accepted 2018 October 2; published 2018 November 14

Abstract

If primordial black holes (PBH) with masses of $10^{25}\,\mathrm{g} \gtrsim m \gtrsim 10^{17}\,\mathrm{g}$ constitute a non-negligible fraction of galactic dark-matter halos, their existence should have observable consequences: they necessarily collide with galactic neutron stars (NS), nest in their centers, and accrete the dense matter, eventually converting them to NS-mass black holes while releasing the NS magnetic field energy. Such processes may explain the fast radio bursts (FRB) phenomenology, in particular their millisecond durations, large luminosities $\sim 10^{43}\,\mathrm{erg\,s^{-1}}$, high rate of occurrence $\gtrsim 1000\,\mathrm{day^{-1}}$, as well as high brightness temperatures, polarized emission, and Faraday rotation. Longer than the dynamical timescale of the Bondi-like accretion for light PBH allows for the repeating of FRB. This explanation follows naturally from the (assumed) existence of the dark-matter PBH and requires no additional unusual phenomena, in particular no unacceptably large magnetic fields of NS. In our model, the observed rate of FRB throughout the universe follows from the presently known number of NS in the Galaxy.

Key words: black hole physics – dark matter – stars: neutron

Combustion of a NS into a Strange Quark Star



(a) $t = 0$

(b) $t = 0.7\,\mathrm{ms}$

(c) $t = 1.2\,\mathrm{ms}$

(d) $t = 4.0\,\mathrm{ms}$

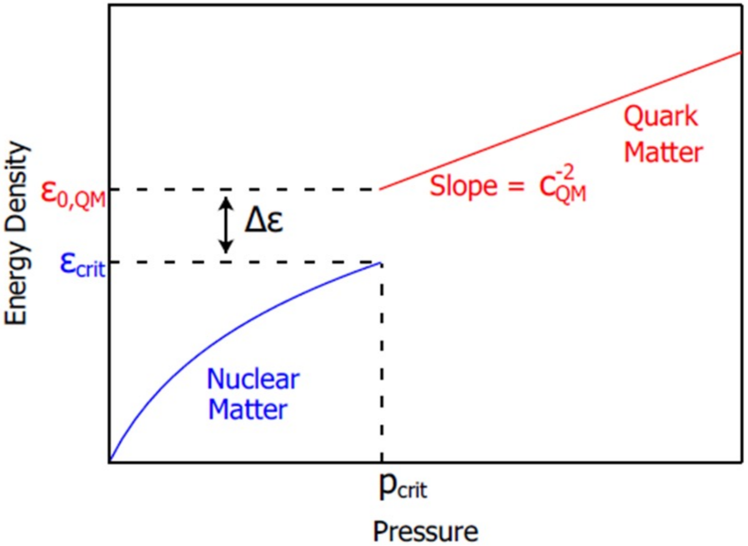
G. Pagliara, M. Herzog, F. K. Roepke, Phys. Rev. D 87, 103007 (2013)

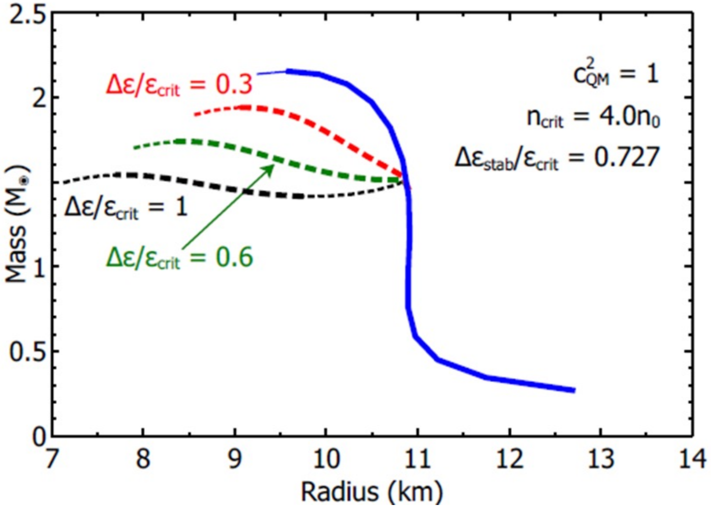
Compact Star Mass Twins and the AHP scheme

- First order PT can lead to a stable branch of hybrid stars with quark matter cores which, depending on the size of the "latent heat" (jump in energy density), can even be disconnected from the hadronic one by an unstable branch → "**third family of CS**".

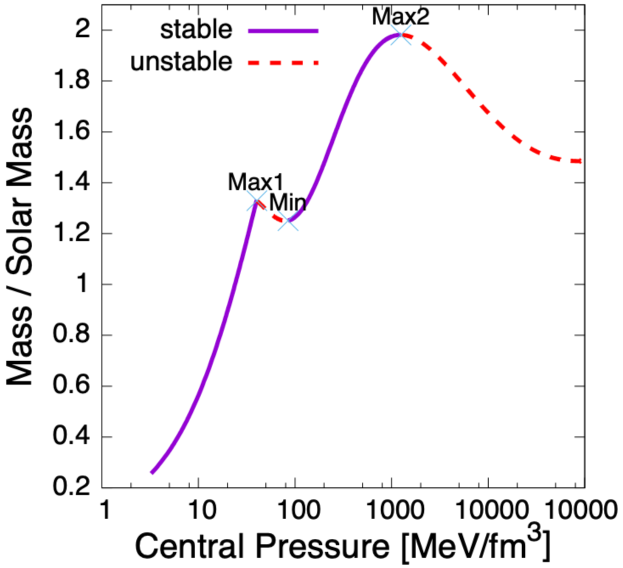
- Measuring two **disconnected populations** of compact stars in the M-R diagram would represent **the detection of a first order phase transition** in compact star matter and thus the indirect proof for the existence of a **critical endpoint (CEP) in the QCD phase diagram**!

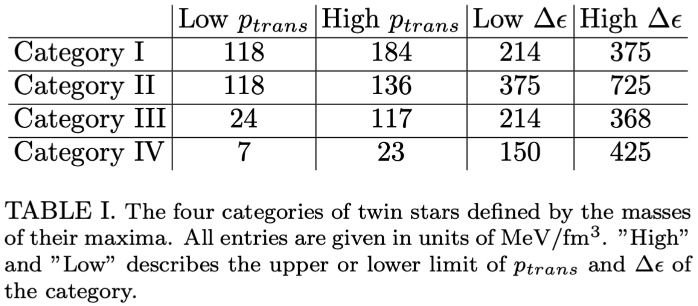
Alford, Han, Prakash,
Phys. Rev. D 88, 083013 (2013)
arxiv:1302.4732





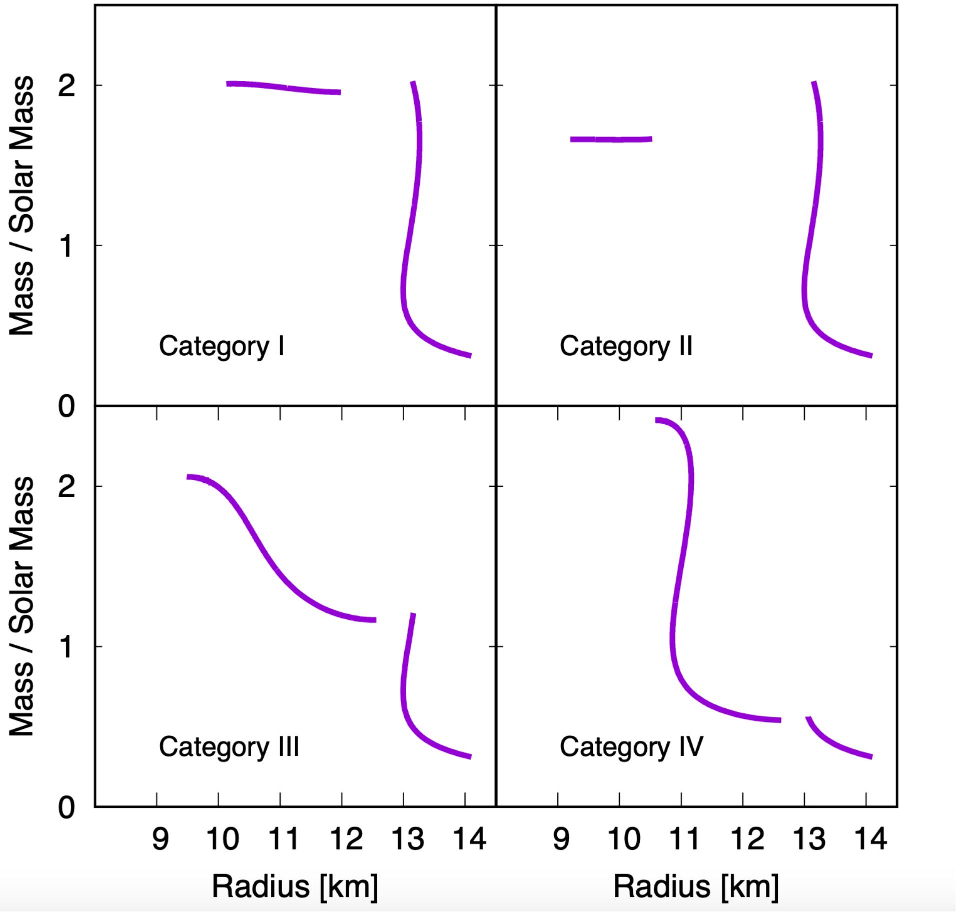
Twin Mass Stars Compact Stars





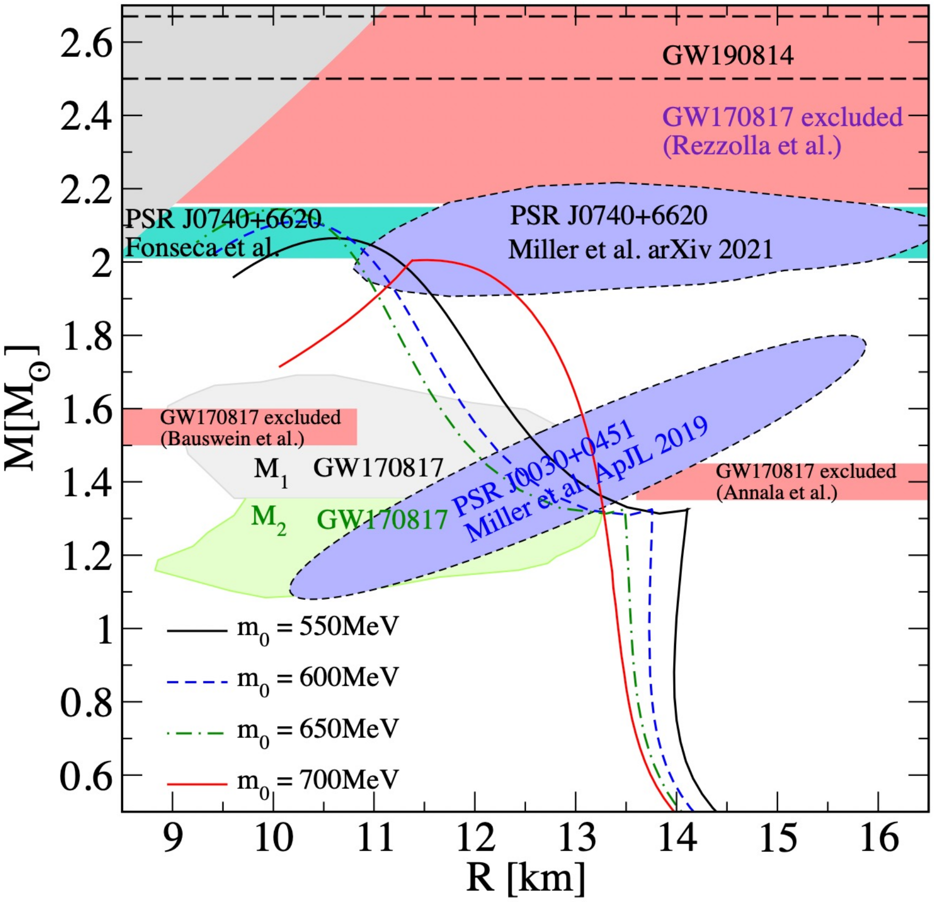
	Low p_{trans}	High p_{trans}	Low $\Delta\epsilon$	High $\Delta\epsilon$
Category I	118	184	214	375
Category II	118	136	375	725
Category III	24	117	214	368
Category IV	7	23	150	425

TABLE I. The four categories of twin stars defined by the masses of their maxima. All entries are given in units of MeV/fm^3. ”High” and ”Low” describe the upper or lower limit of p_{trans} and $\Delta\epsilon$ of the category.



Christian, J., Zacchi, A. & Schaffner-Bielich, J.
Eur. Phys. J. A **54,** 28 (2018).

Compact Star Twins with a Dark Matter Core

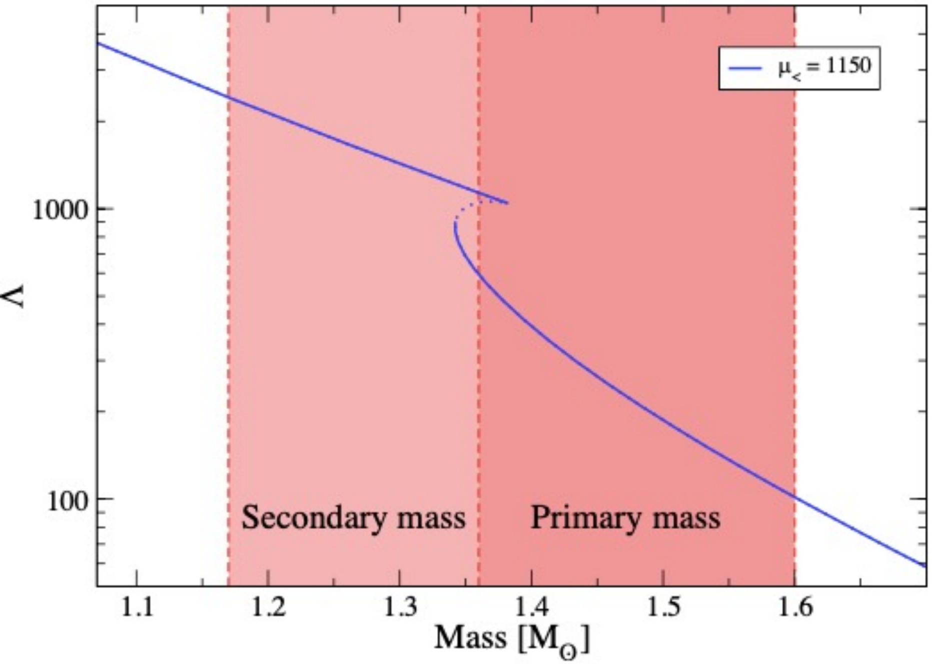


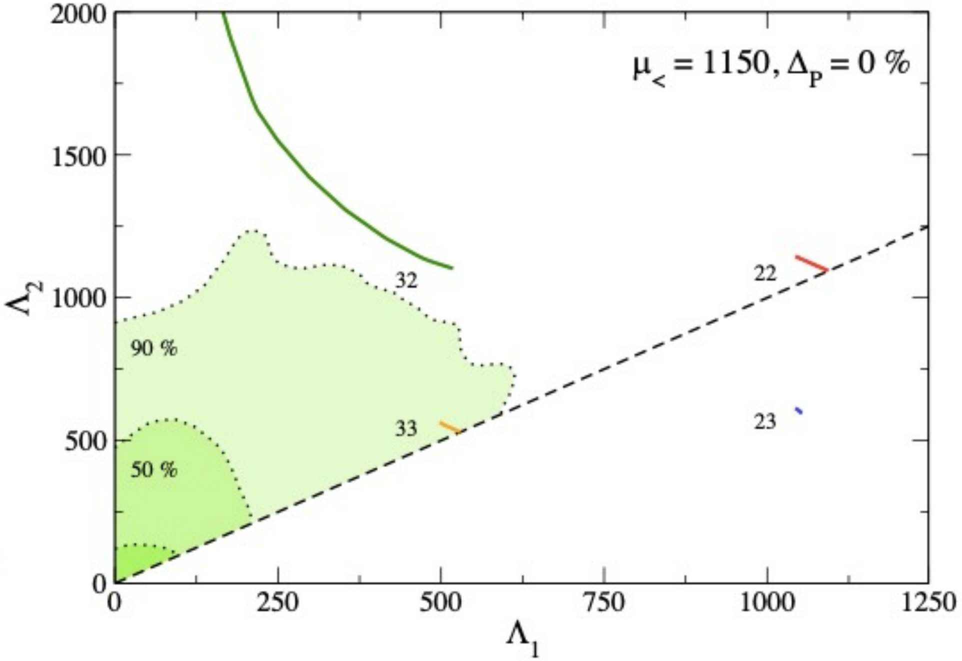
Parity Double Model, featuring chiral partners N± without quark deconfinement.

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

David Alvarez-Castillo and Michał Marczenko.
To appear in Acta Physical Polonica B (2022)

Was GW170817 a canonical neutron star merger?





A. Ayriyan, D. Alvarez-Castillo, D. Blaschke and H. Grigorian,
Universe 6, 81 (2020)

D. Alvarez-Castillo, D. Blaschke, G. Grunfeld, V. Pagura
Phys. Rev. D 99, 063010 (2019) - arXiv: 1805.04105

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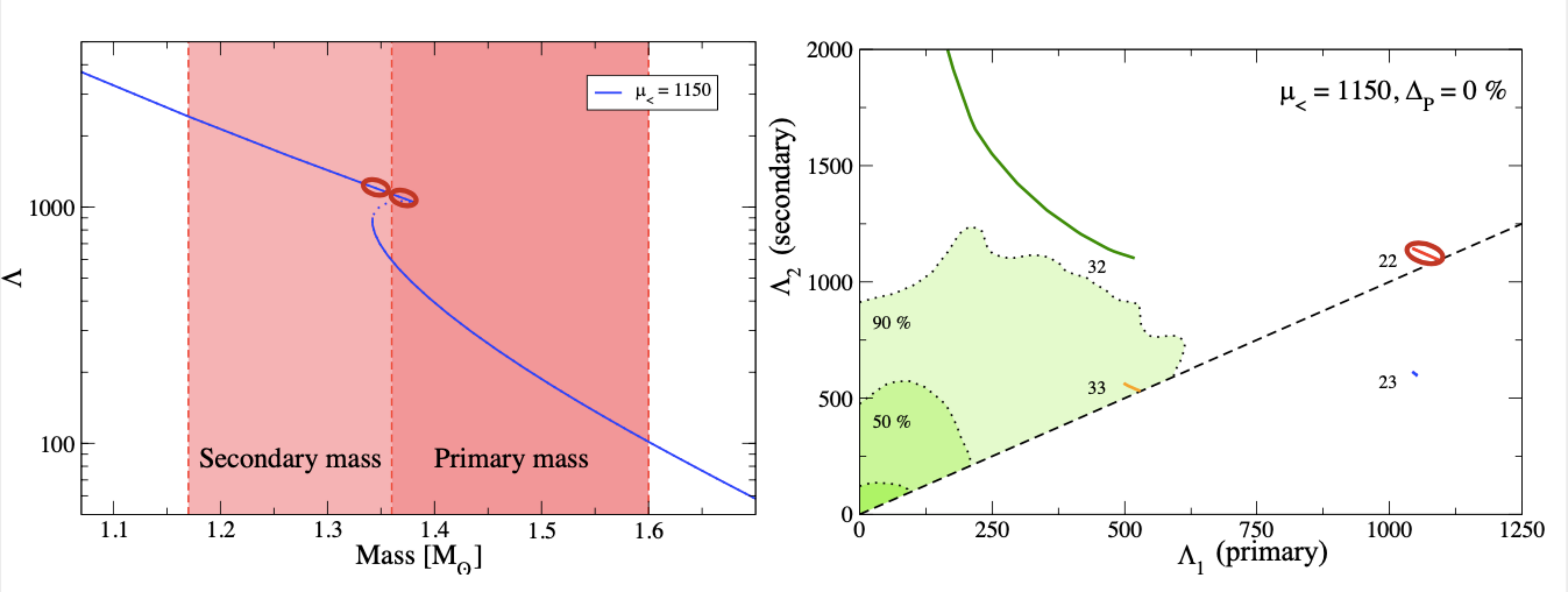

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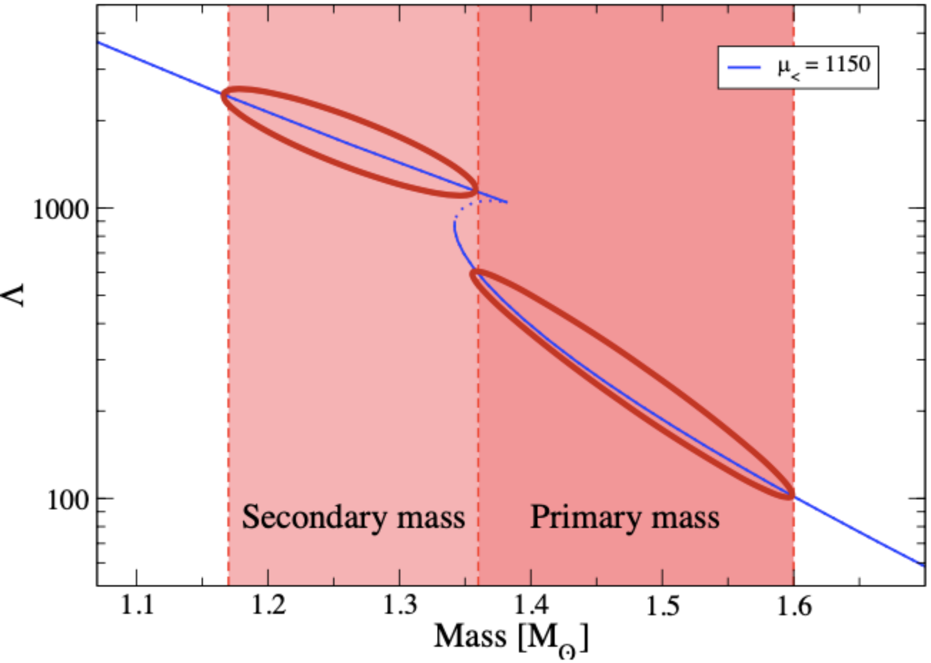

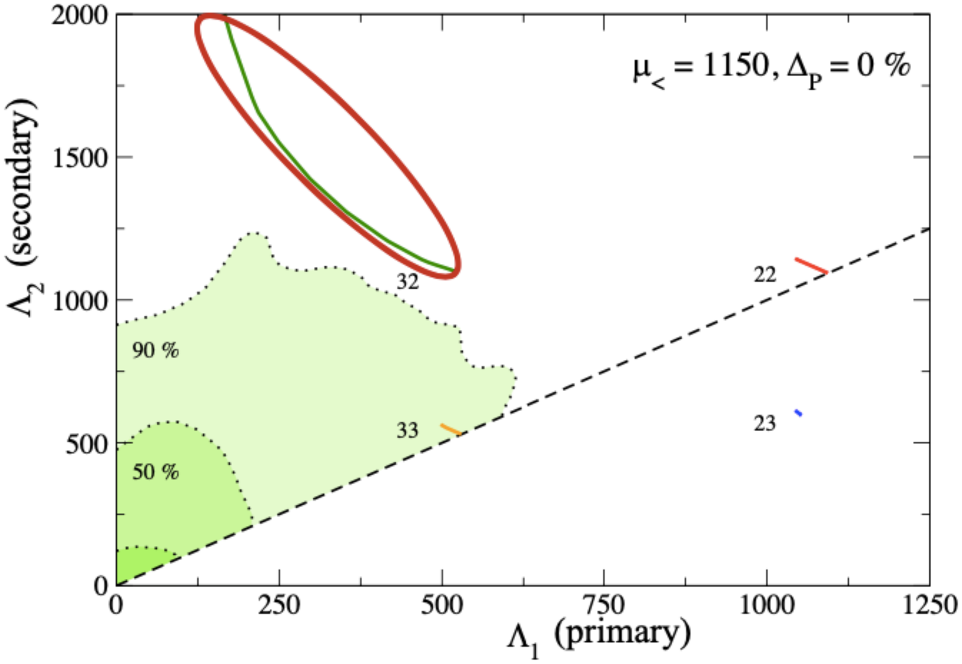

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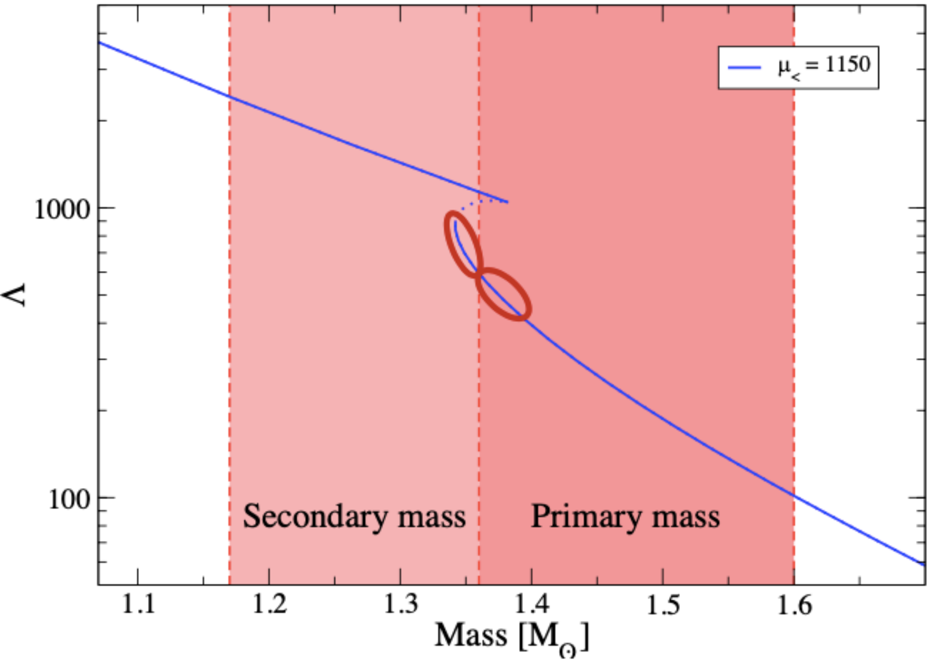

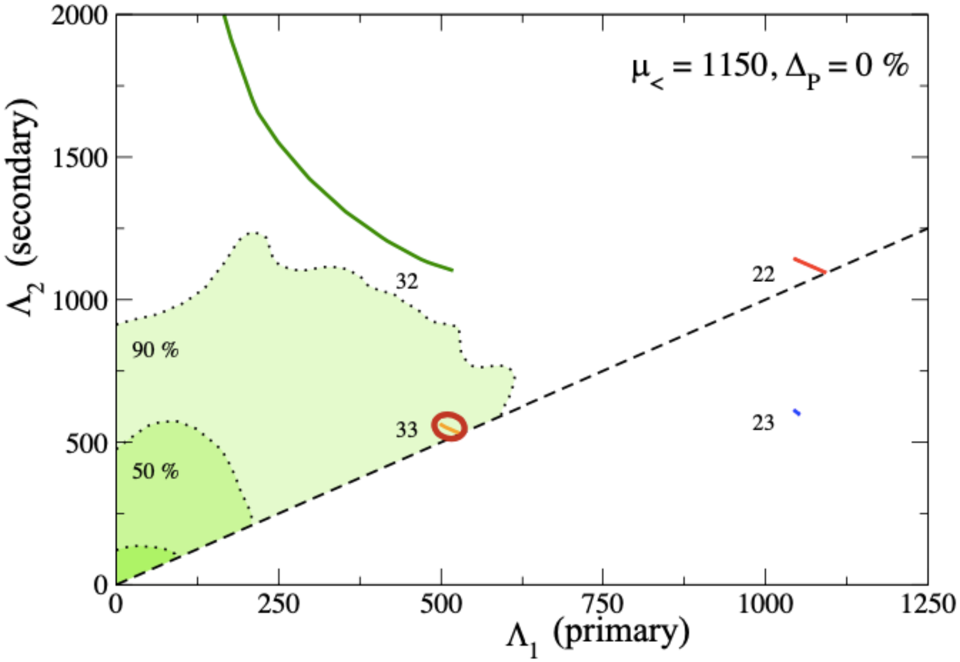

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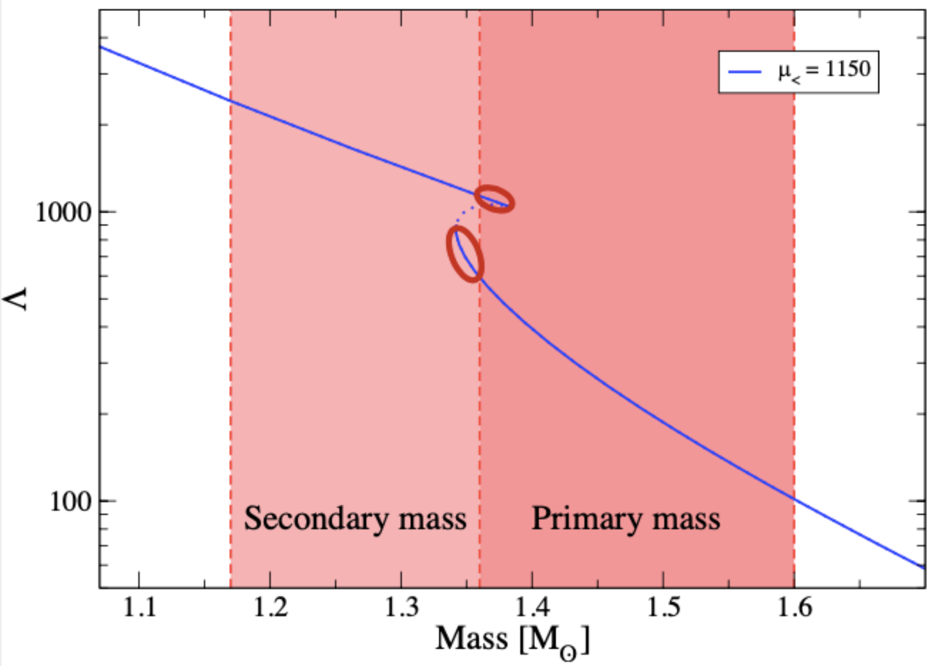

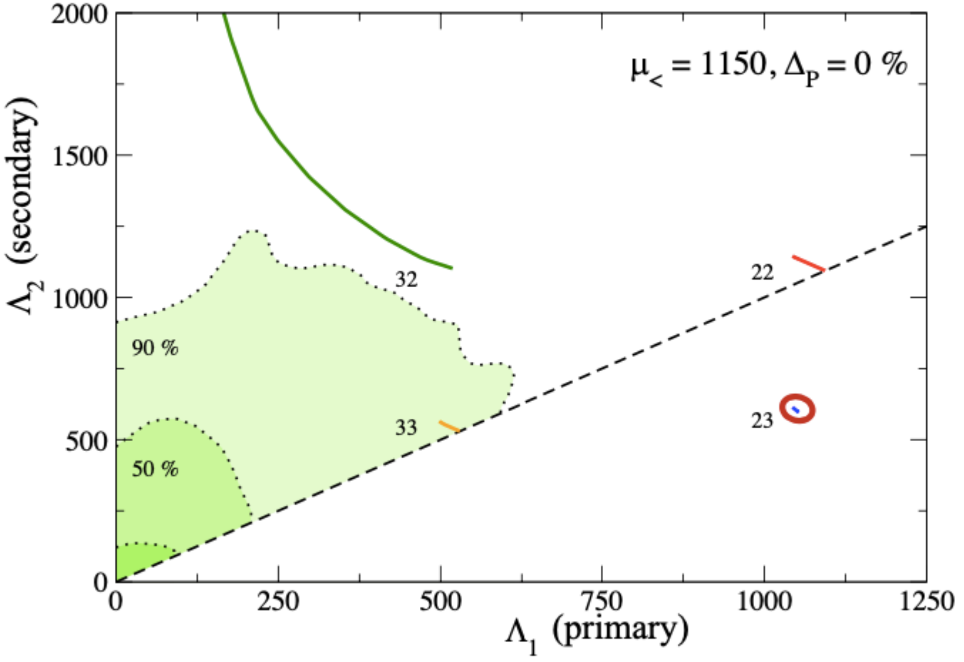

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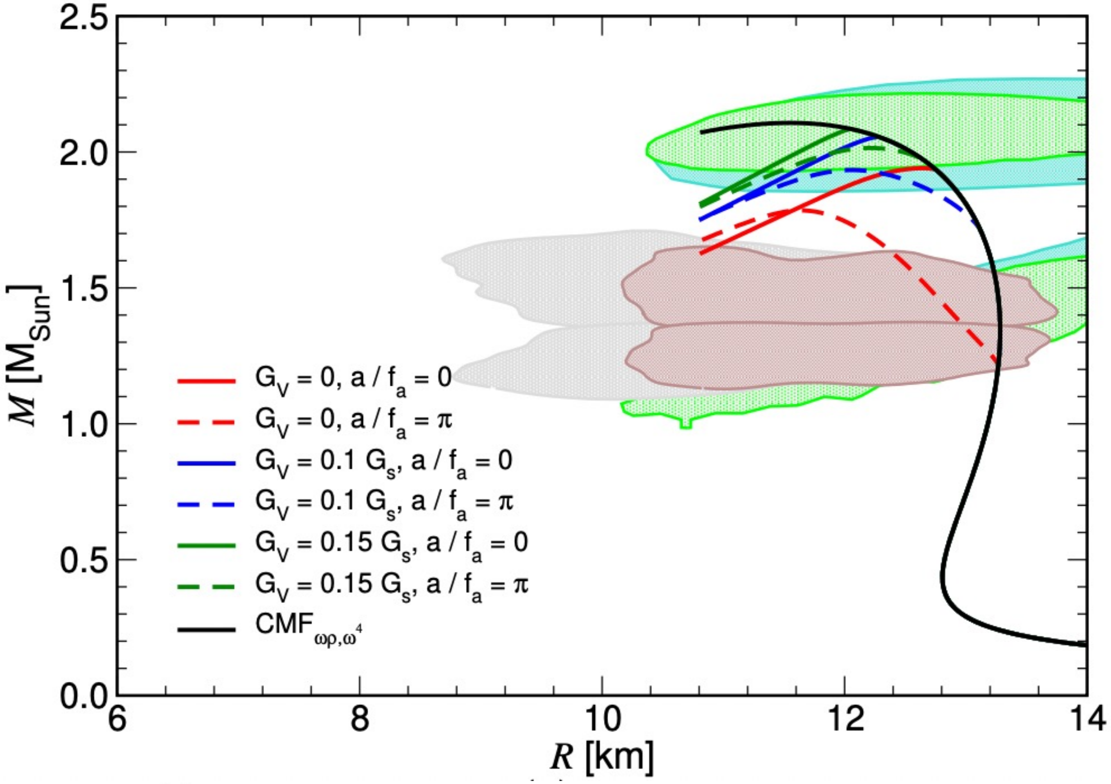
Phys. Rev. D 99, 063010 (2019) - arXiv: 1805.04105

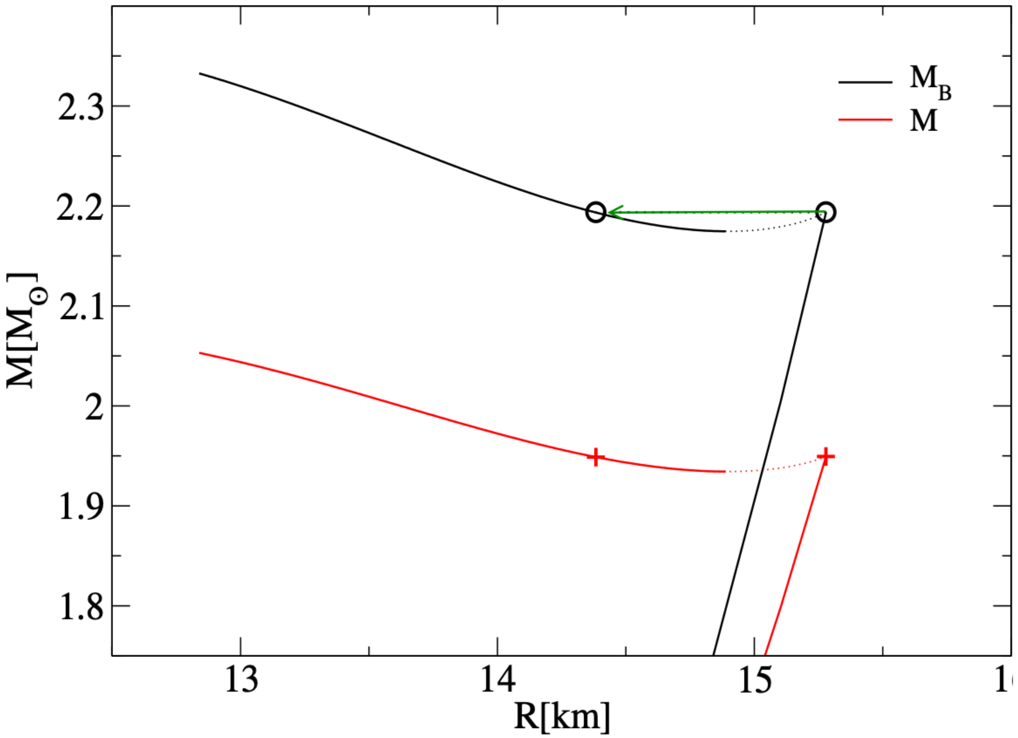
Axion effects in the stability of Hybrid Stars

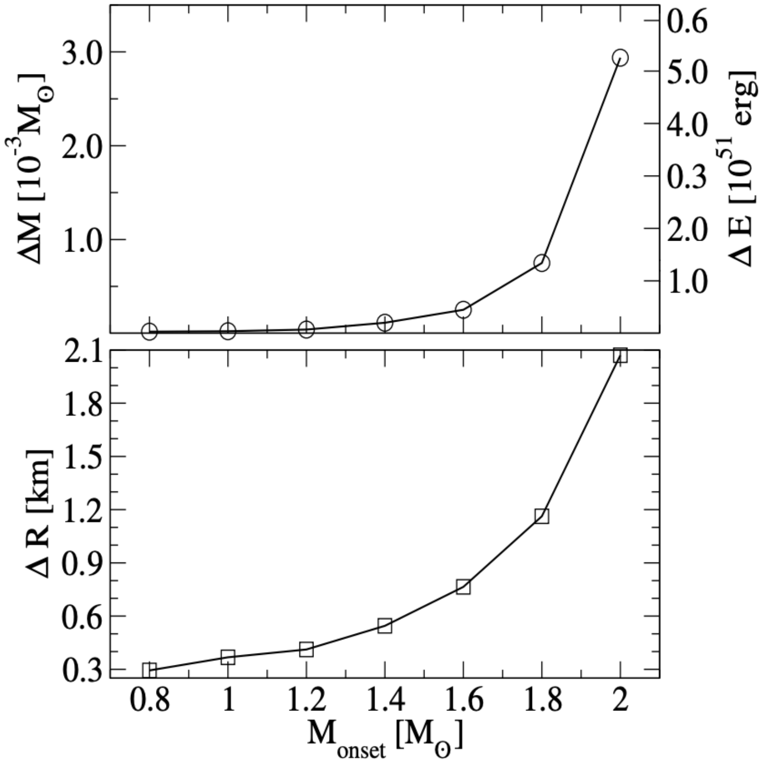


$$\begin{aligned}\mathcal{L} &= \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m_0\right)\psi \\ &+ G_s \sum_{b=0}^{8}\left[\left(\bar{\psi}\lambda^b\psi\right)^2 + \left(\bar{\psi}i\gamma_5\lambda^b\psi\right)^2\right] - G_V\left(\bar{\psi}\gamma^{\mu}\psi\right)^2 \\ &- K\left\{e^{i\frac{a}{f_a}}\det\left[\bar{\psi}\left(1+\gamma^5\right)\psi\right]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

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

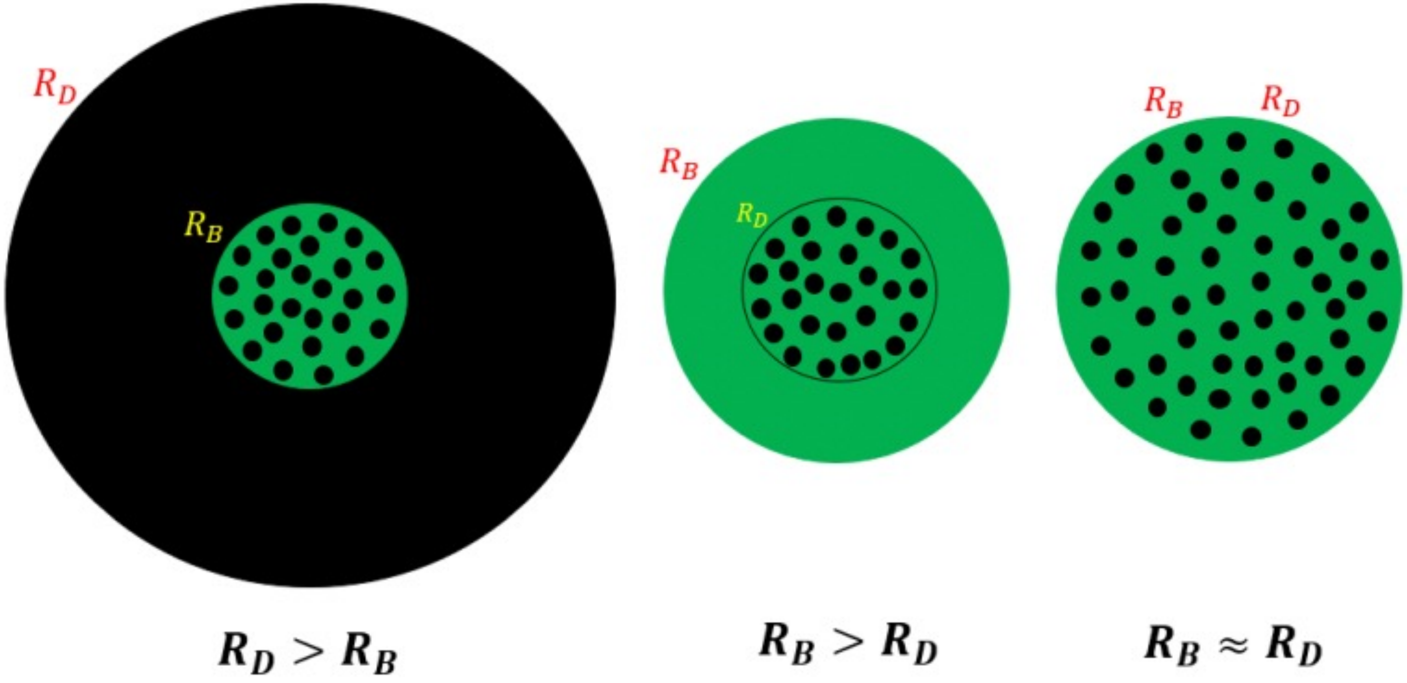
Mass Twins – Energy Released





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

Bosonic Dark Matter in NS



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

Bosonic Dark Matter in NS

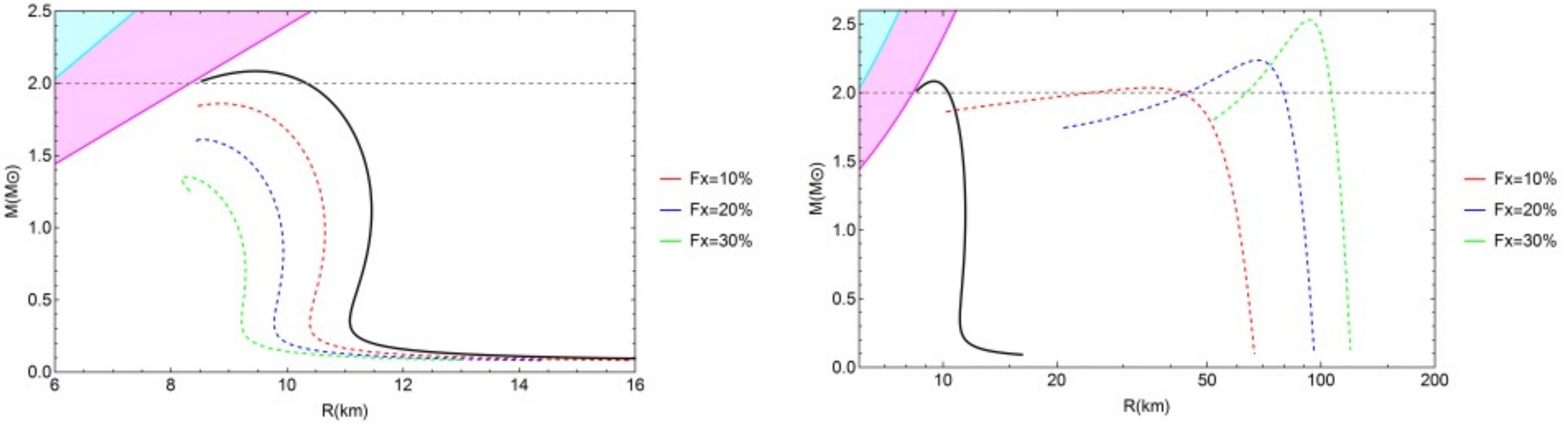


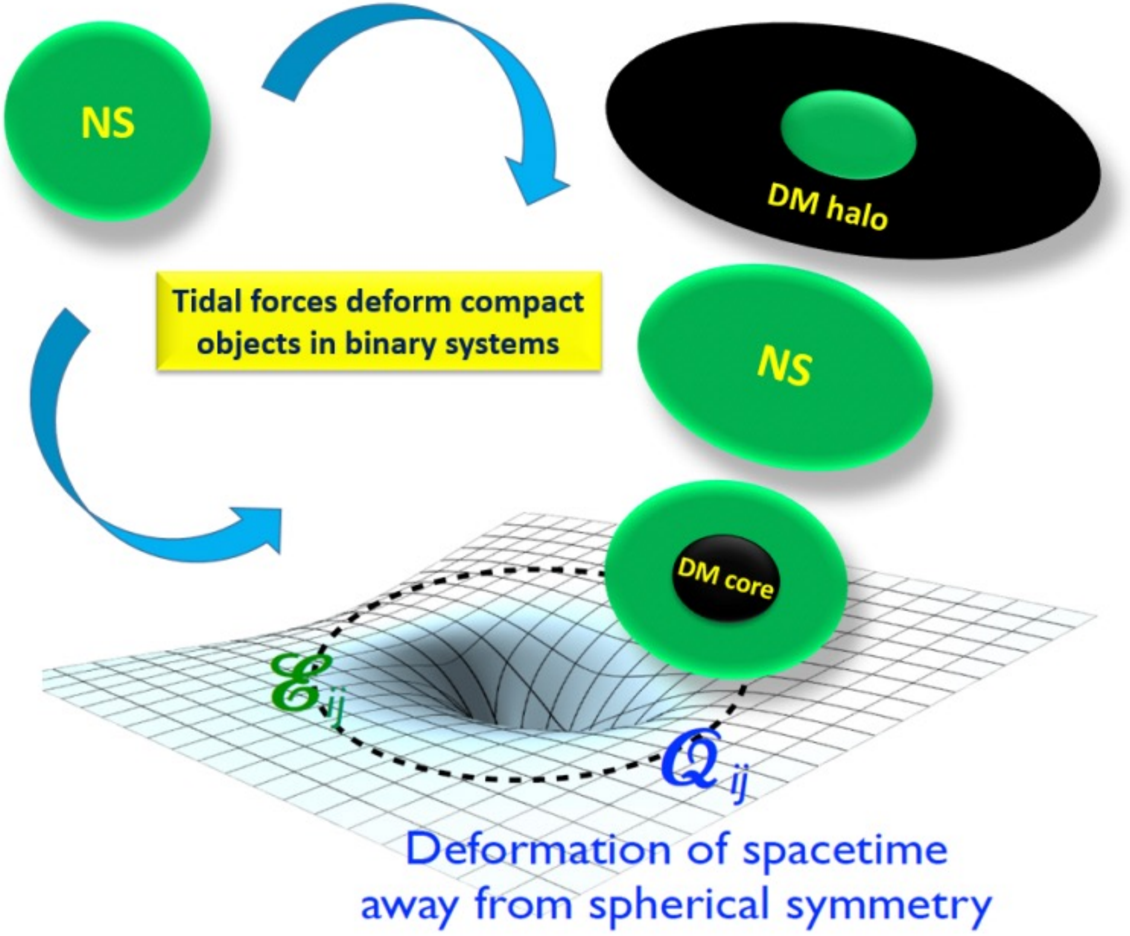
Fig. 7. Mass-Radius profiles for DM admixed NSs for $m_\chi = 400$ MeV (left) which corresponds to a DM core formation and $m_\chi = 100$ MeV (right) that represents an extended DM halo formation around a NS. Coupling constant is fixed to $\lambda = \pi$ and different F_χ are considered as labeled.

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

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

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

Bosonic Dark Matter in NS



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Bosonic Dark Matter in NS

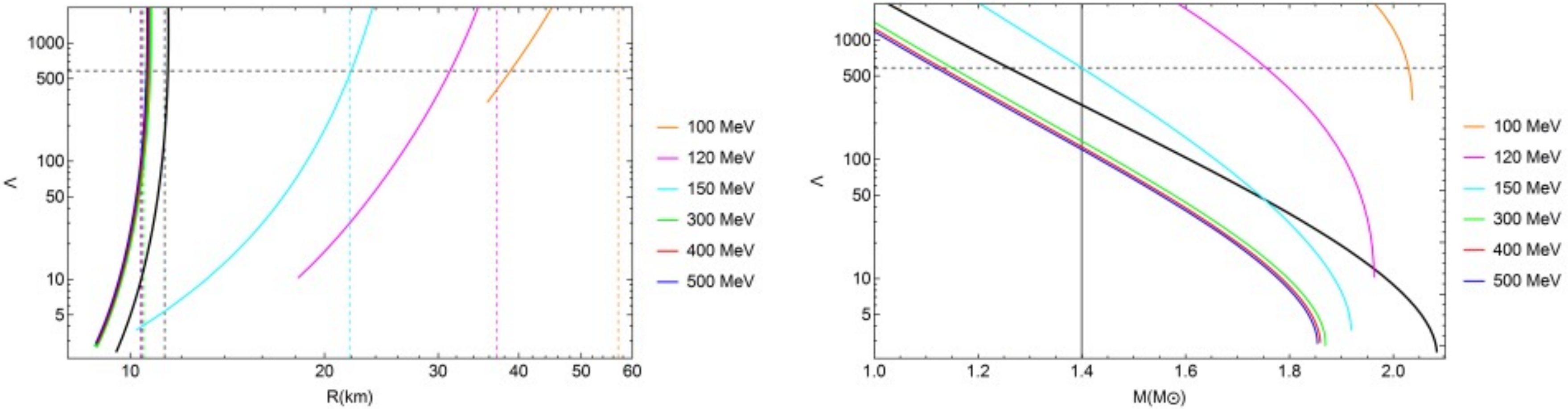
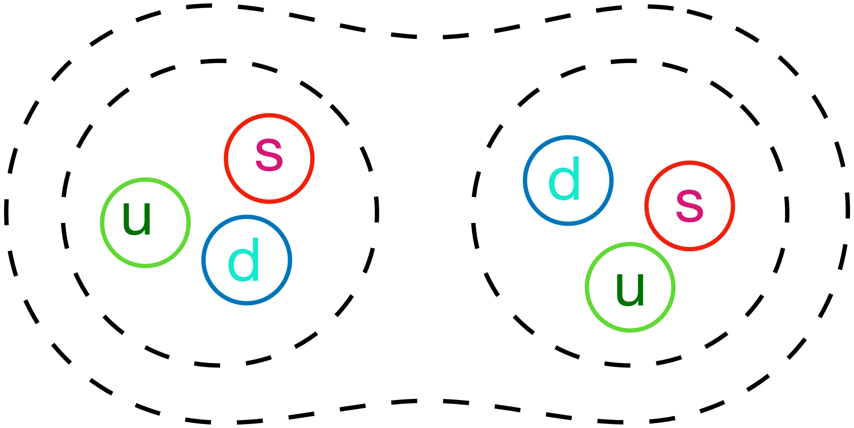


Fig. 8. Tidal deformability (Λ) as a function of total mass (right) and outermost radius (left) for stable sequences of DM admixed NSs. Various boson masses are considered, $m_\chi = 100, 120, 150$ MeV correspond to a DM halo formation while for $m_\chi = 300, 400, 500$ MeV a DM core is formed inside NS. Coupling constant and DM fraction are fixed at π and 10%, respectively.

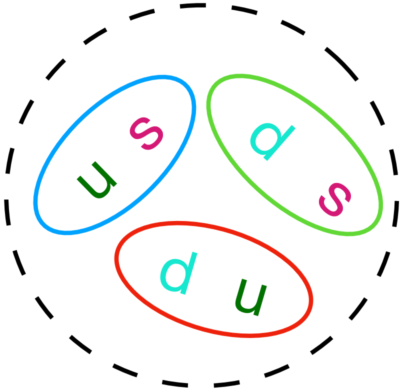
D. R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, arXiv:2112.14231

Sexaquarks in NS

H-dibaryon



Sexaquark



M. Shahrbaf, D. Blaschke, S. Typel, G. R. Farrar, D. E. Alvarez-Castillo.
Phys. Rev. D 105, 103005 (2022).

Sexaquarks in NS

- An S with mass below 2054 MeV is either absolutely stable or has a lifetime greater than the age of the Universe. Two separate baryons with the same quark content as the *S* have a mass $\geq 2m_\Lambda = 2231.36$ MeV. Thus for the *S* to be effectively stable, its quarks must be more deeply bound by at least 176.9 MeV.

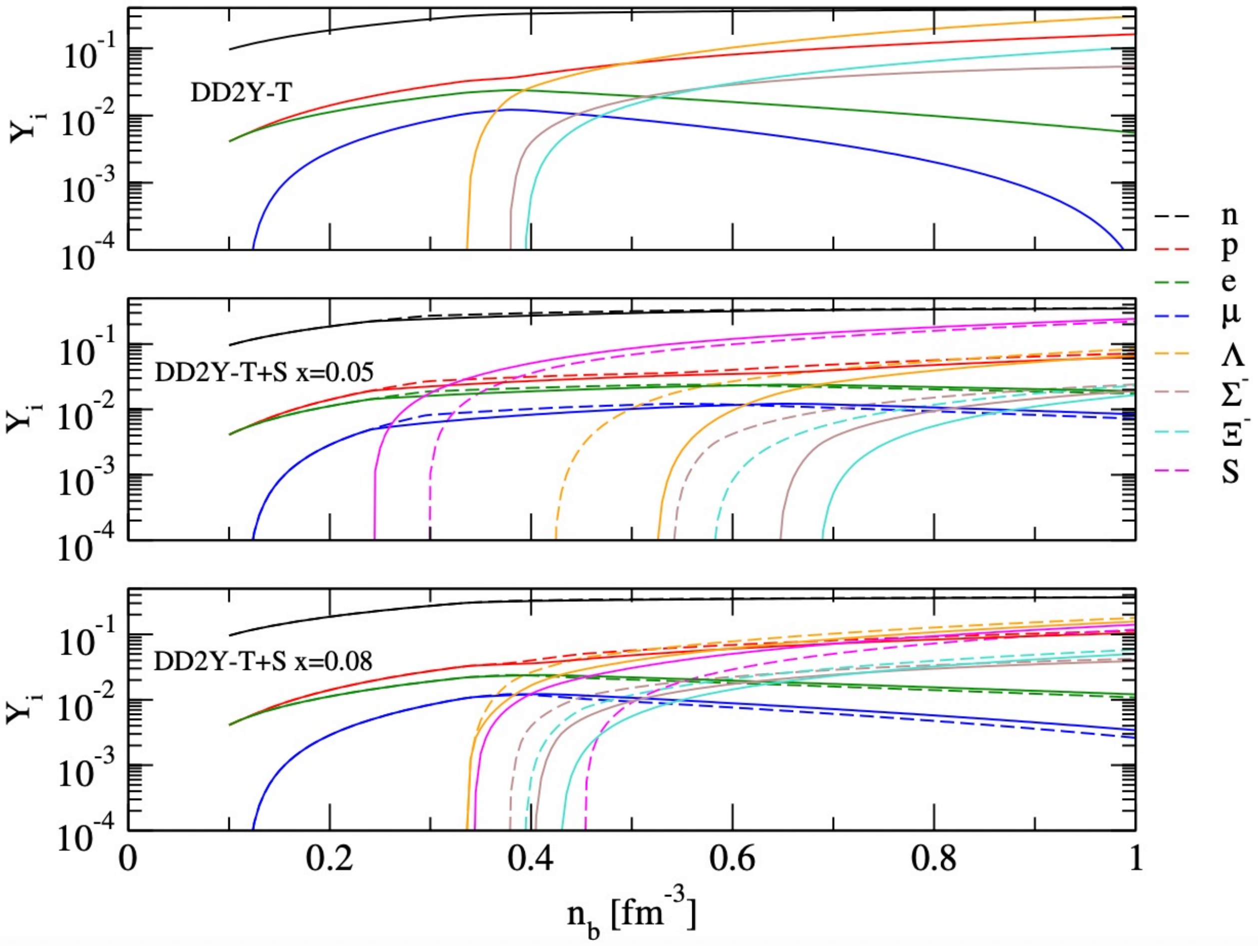
- The observed dark matter to baryon ratio is $\Omega_{DM} / \Omega_B = 5.3 \pm 0.1$. An abundance of *S* dark matter (SDM) in agreement with this observation has been obtained within a statistical model on the basis of the assumptions for the quark masses and an effective temperature $T_{eff} = 156$ MeV of the transition from the quark-gluon plasma to the hadronic phase when $m_S = 1860$ MeV.

- *S* might be a deeply bound state with low enough mass to be stable so that it can not decay on the weak interaction timescale and is therefore a dark matter (DM) candidate.

- The fact that the light S cannot decay and that it is electrically neutral explains why it has so far evaded detection in laboratory experiments. For an overview and detection strategies, see arXiv:2201.01334.

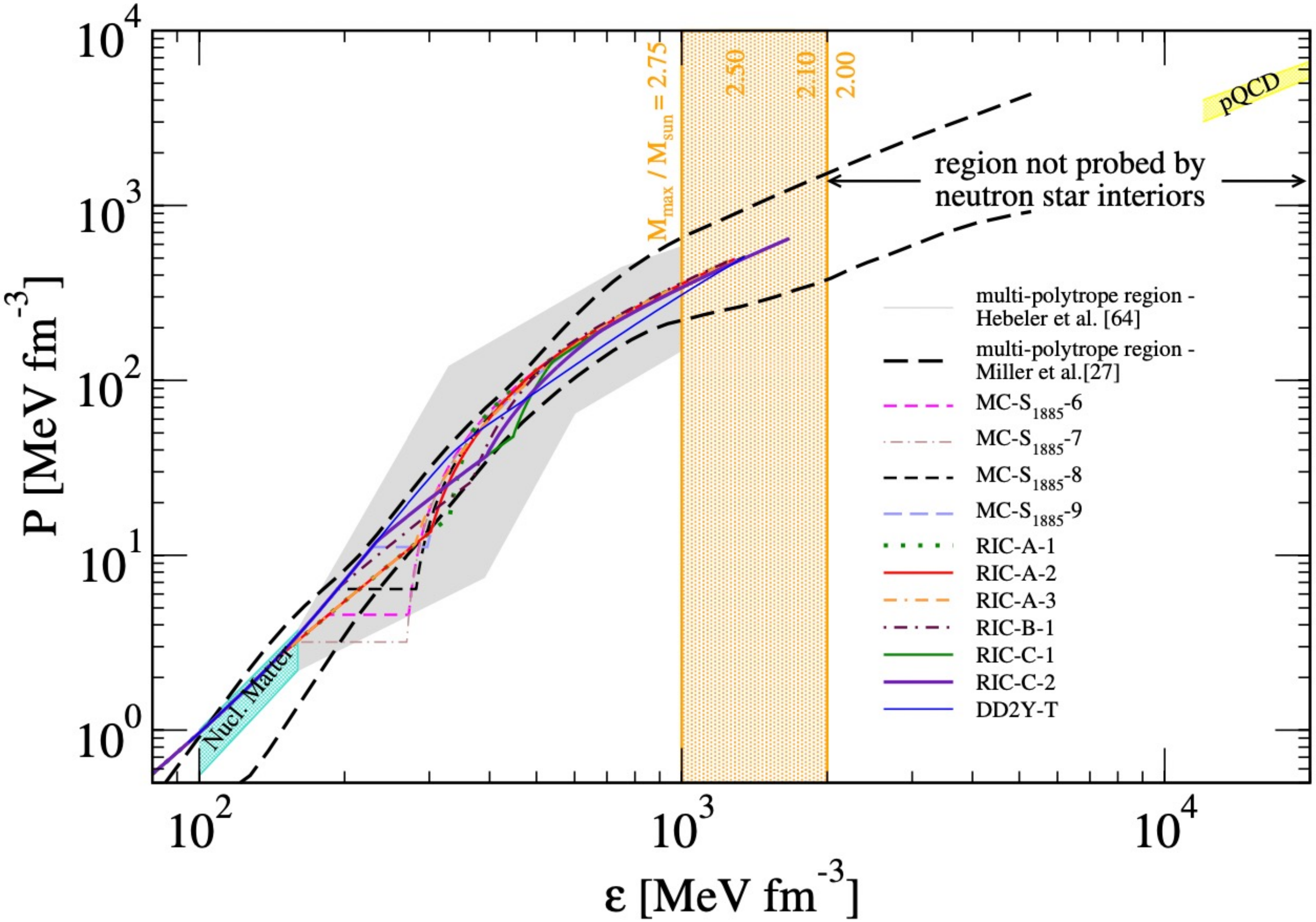
M. Shahrbaf, D. Blaschke, S. Typel, G. R. Farrar, and D. A-C
Phys. Rev. D 105, 103005, (2022)

Sexaquarks in NS

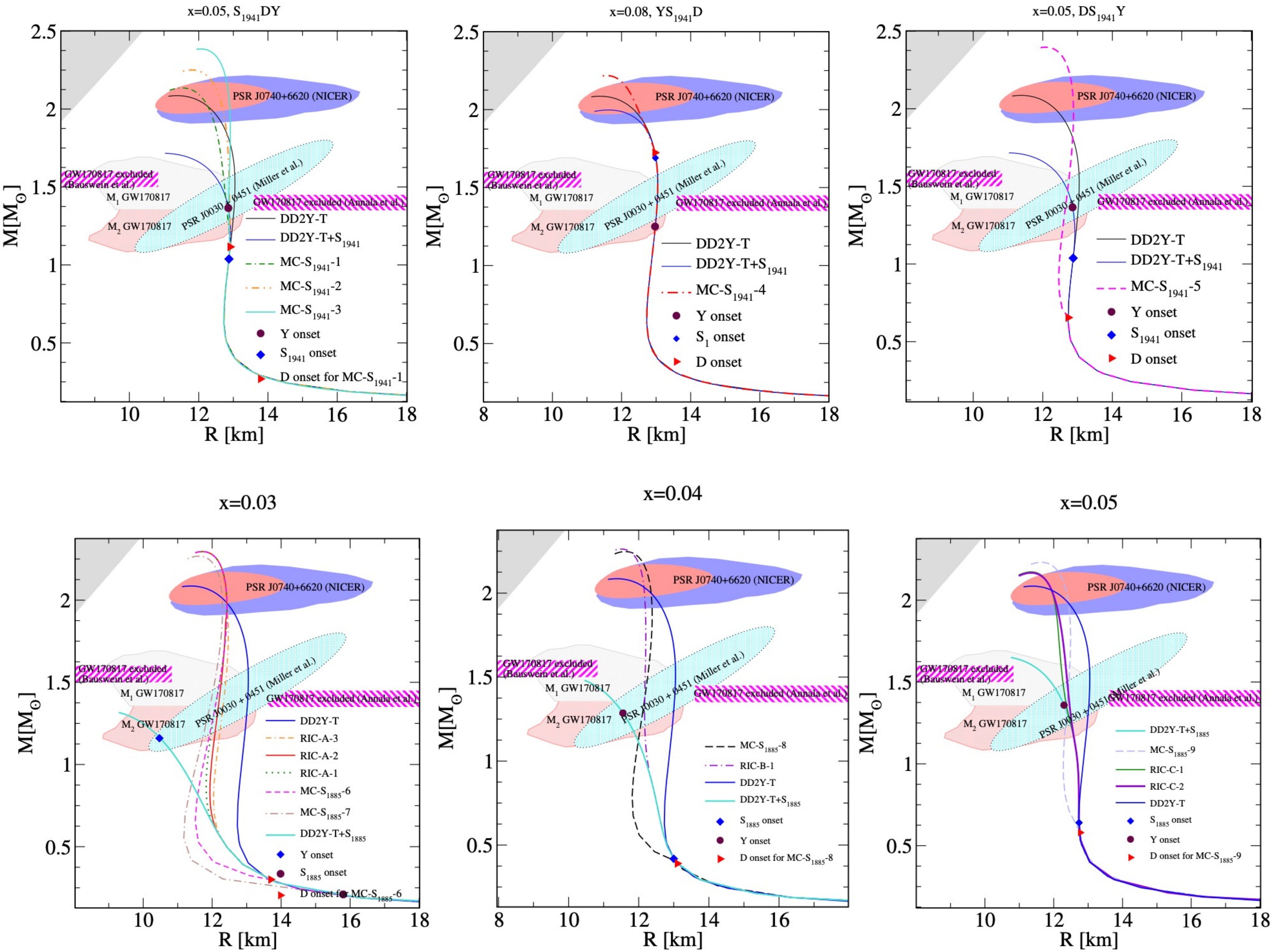


M. Shahrbaf, D. Blaschke, S. Typel, G. R. Farrar, and D. A-C
Phys. Rev. D 105, 103005, (2022)

Sexaquarks in NS



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

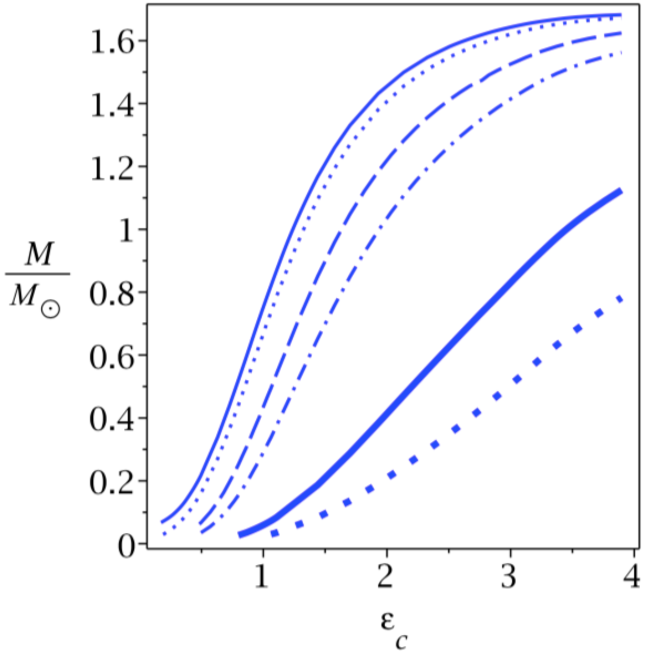

x=0.05, S_1941DY
x=0.08, YS_1941D
x=0.05, DS_1941Y
x=0.03
x=0.04
x=0.05
M[M_⊙]
R [km]
PSR J0740+6620 (NICER)
PSR J0030 + 0451 (Miller et al.)
GW170817 excluded (Bauswein et al.)
GW170817 excluded (Annala et al.)
M_1 GW170817
M_2 GW170817
DD2Y-T
DD2Y-T+S_1941
MC-S_1941-1
MC-S_1941-2
MC-S_1941-3
Y onset
S_1941 onset
D onset for MC-S_1941-1
MC-S_1941-4
S_1 onset
D onset
MC-S_1941-5
RIC-A-3
RIC-A-2
RIC-A-1
MC-S_1885-6
MC-S_1885-7
DD2Y-T+S_1885
S_1885 onset
D onset for MC-S_1885-6
MC-S_1885-8
RIC-B-1
D onset for MC-S_1885-8
MC-S_1885-9
RIC-C-1
RIC-C-2
D onset for MC-S_1885-9
0.5
1
1.5
2
2.5
8
10
12
14
16
18

Beyond Dark Matter

TOV with Λ

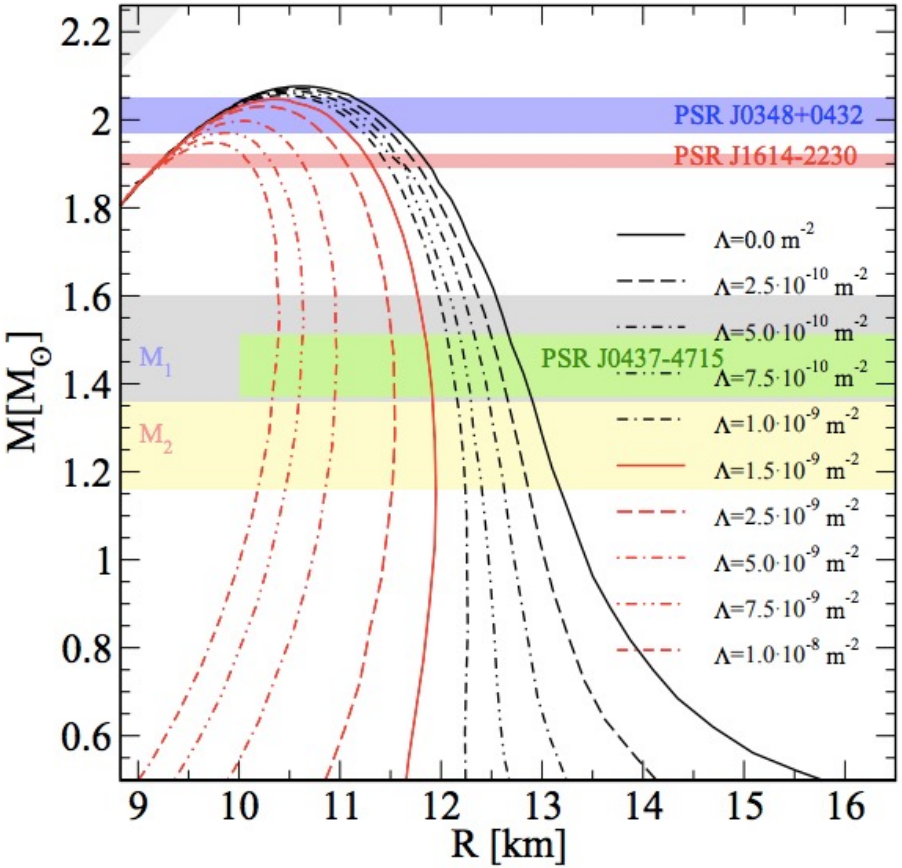
$$\frac{dp}{dr} = \frac{3c^2Gm + r^3(\Lambda c^4 + 12\pi Gp)}{c^2r[6Gm - c^2r(\Lambda r^2 + 3)]}(c^2\epsilon + p)$$

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



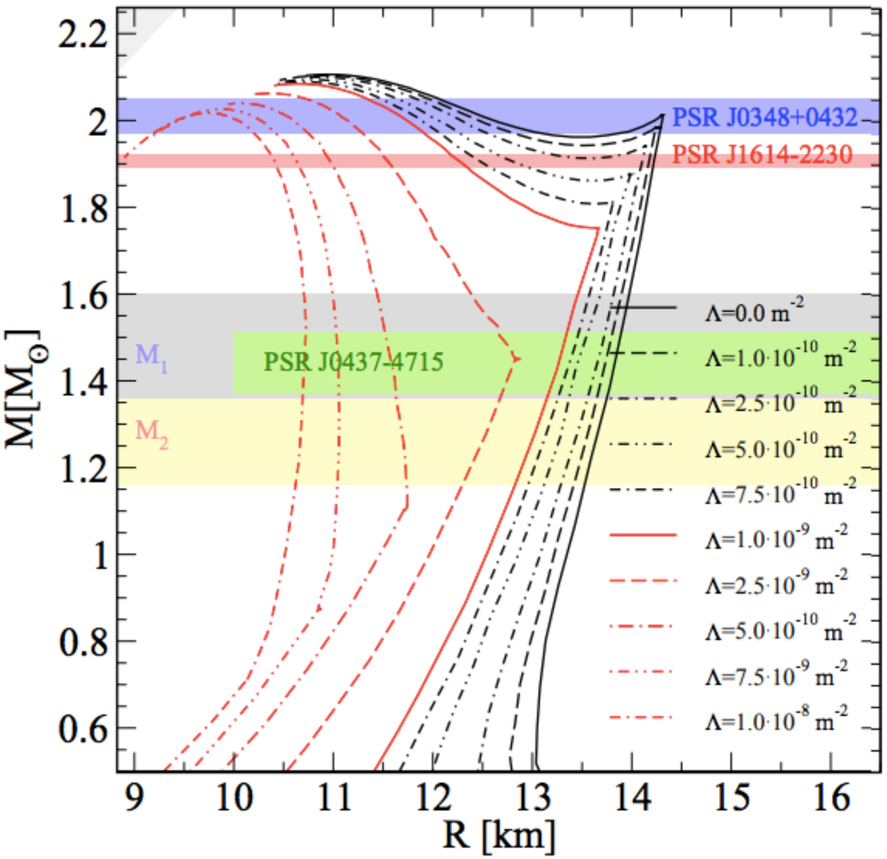
G.H. Bordbar, S.H. Hendi1 and B. Eslam Panah
Eur. Phys. J. Plus (2016) 131: 315

TOV with Λ
(DD2F hadronic EoS)



Noshad Khosravi Largani and D. A-C, EPJ Web Conf. Volume 201, 2019.
arXiv:1806.01698

TOV with Λ
(HMTs hadron-quark EoS)



Noshad Khosravi Largani and D. A-C, EPJ Web Conf. Volume 201, 2019.
arXiv:1806.01698

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.

KAGRA

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MeerKAT