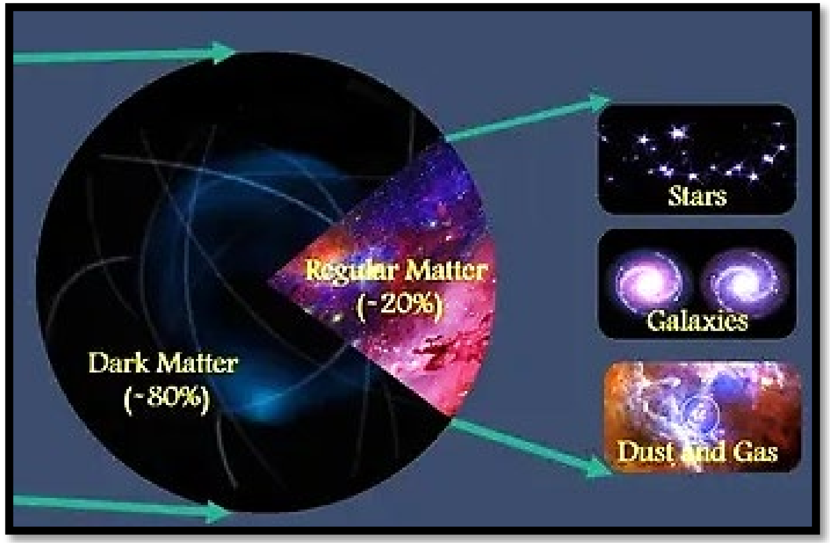
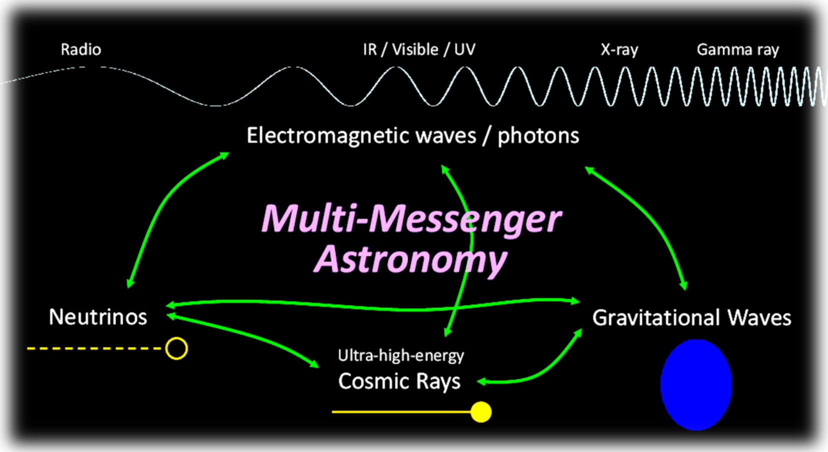
Inclusion of bosonic dark matter in neutron star to satisfy the observable features induced by nuclear matter models





Davood Rafiei Karkevandi

ICRANet-Isfahan, Isfahan University of Technology, Iran

The 60th Karpacz Winter School on Theoretical Physics and WE-Heraeus Physics School
16-25 May 2024

D.R. K, S. Shakeri, V. Sagun, O. Ivanytskyi,
Bosonic dark matter in neutron stars and its effect on gravitational wave signal
Phys. Rev. D 105, 023001 (2022), [arXiv:2109.03801v2]

S. Shakeri, D.R. K,
Bosonic Dark Matter in Light of the NICER Precise Mass-Radius Measurements
Phys. Rev. D 109, 043029 (2024), [arXiv:2210.17308v2]

D.R. K, M. Shahrbaf, S. Shakeri, S. Typel
Exploring the distribution and impact of bosonic dark matter in neutron stars
Particles 7 (2024) 1, 201-213, [arXiv:2402.18696]

M. Shahrbaf, D.R. K, S. Typel
Constraints on the mass of a bosonic dark matter candidate within the DD2Y-T model
arXiv:2402.18686

D.R. K, S. Shakeri, V. Sagun, O. Ivanytskyi,
Tidal deformability as a probe of dark matter in neutron stars
MG16 Proceedings, (**World Scientific pp. 3713-3731 (2023)**), [arXiv:2112.14231]


Soroush Shakeri
Isfahan University of Technology
ICRANet-Isfahan, Iran

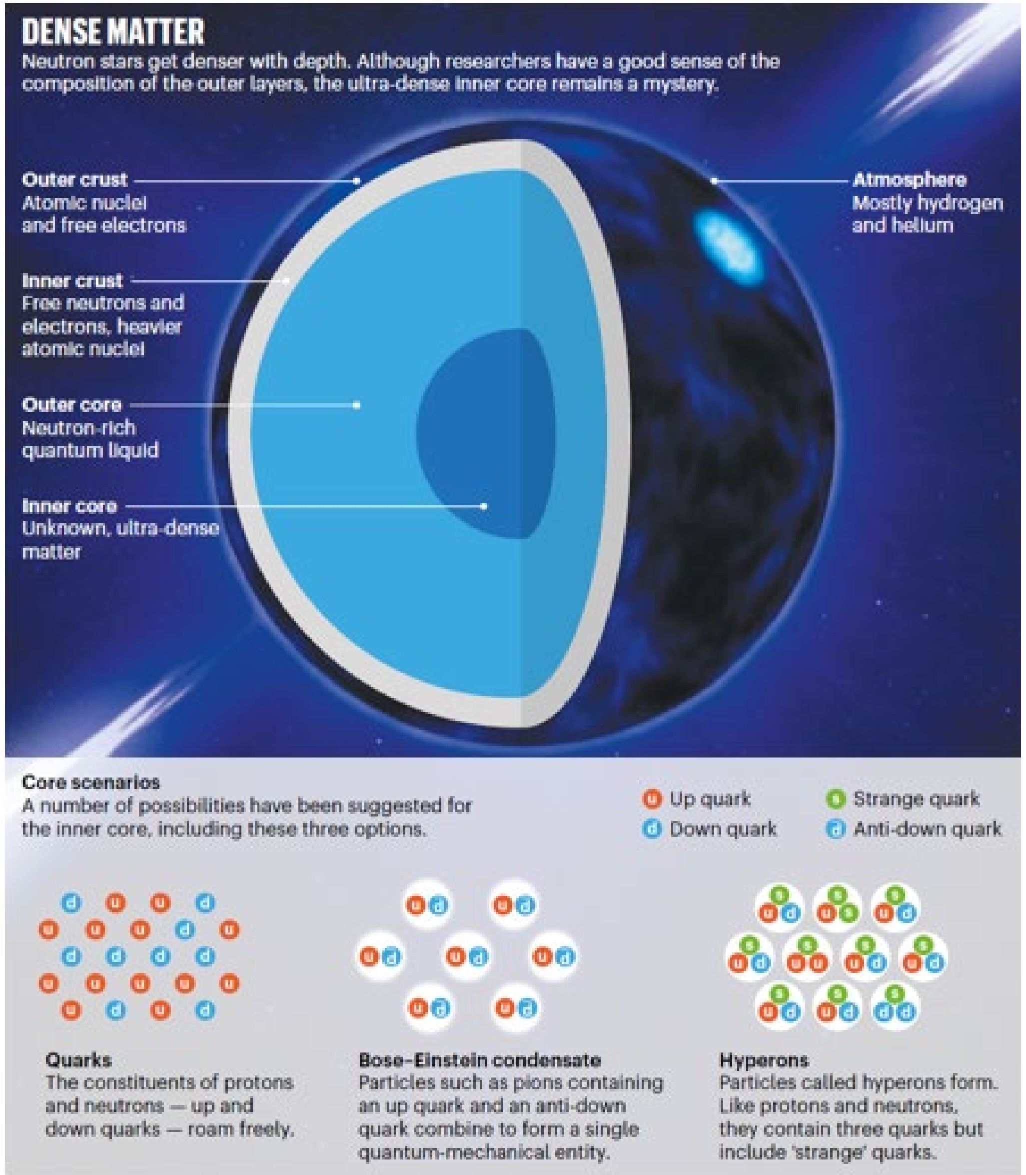

Violetta Sagun
University of Coimbra, Portugal


Oleksii Ivanytskyi
University of Wroclaw, Poland


Mahboubeh Shahrbaf
University of Wroclaw, Poland


Stefan Typel
Darmstadt University and GSI institute, Germany

Neutron stars as a natural laboratory for high density matter



DENSE MATTER

Neutron stars get denser with depth. Although researchers have a good sense of the composition of the outer layers, the ultra-dense inner core remains a mystery.

Core scenarios

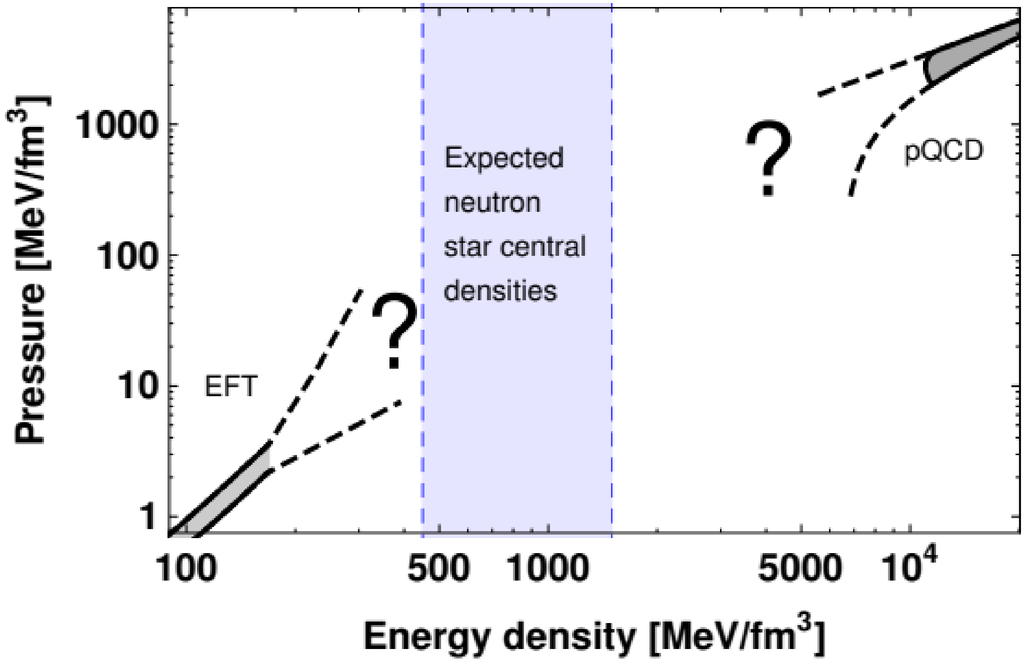
A number of possibilities have been suggested for the inner core, including these three options.

Quarks
The constituents of protons and neutrons — up and down quarks — roam freely.

Bose–Einstein condensate
Particles such as pions containing an up quark and an anti-down quark combine to form a single quantum-mechanical entity.

Hyperons
Particles called hyperons form. Like protons and neutrons, they contain three quarks but include 'strange' quarks.

A. Mann, Nature (London) 579, 20 (2020)



Matti Järvinen, Eur. Phys. J. C (2022) 82:282

$$\frac{dP(r)}{dr} = -\frac{GM(r)\varepsilon(r)}{c^2 r^2}\left[1+\frac{P(r)}{\varepsilon(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)c^2}\right]\left[1-\frac{2GM(r)}{c^2 r}\right]^{-1}$$

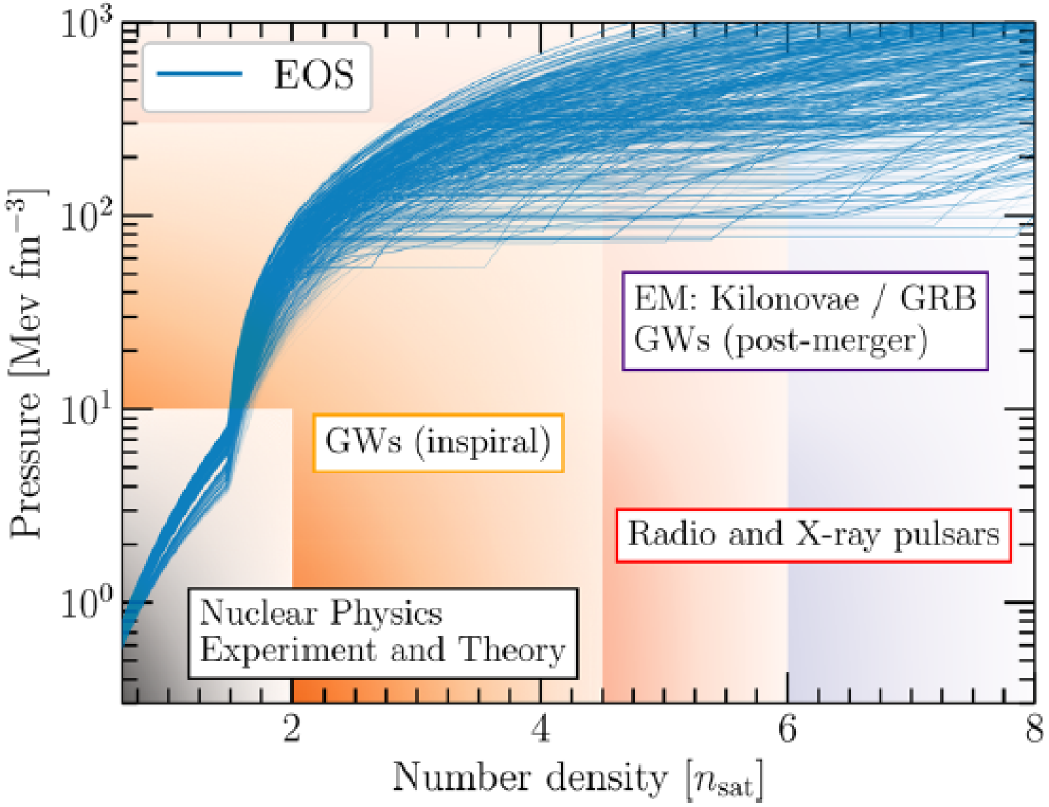
$$\frac{dM(r)}{dr} = \frac{4\pi r^2 \varepsilon(r)}{c^2}$$

Tolman-Oppenheimer-Volkof (TOV) equations

R. C. Tolman, Phys. Rev. 55, 364 (1939).

J. R. Oppenheimer and G. M. Volko, Phys. Rev. 55,374 (1939).

Multi-messenger observations of neutron stars



Peter T. H. Pang, et al. , Nature Commun. 14 (2023) 1, 8352

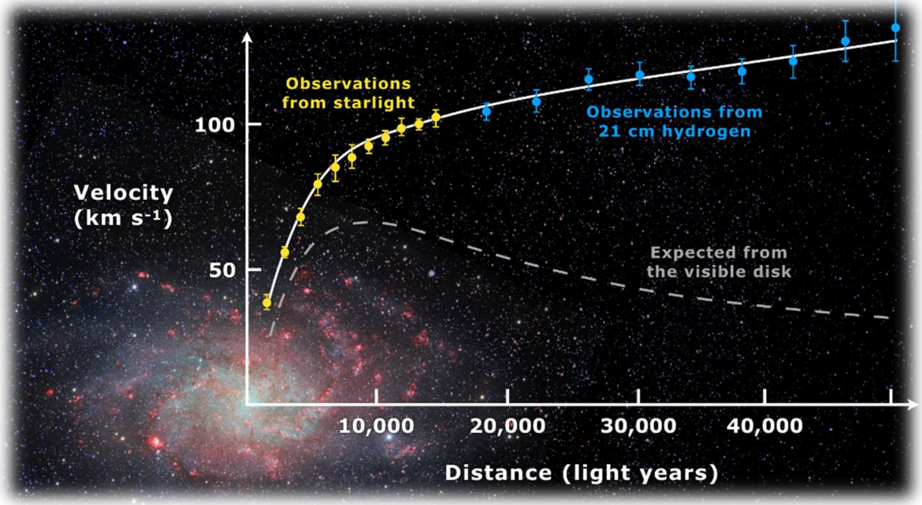
Radio telescopes

Optical telescopes

X-ray telescopes

Gravitational-Wave detectors

Observable features of neutron stars such as mass, radius and tidal deformability



Gravitationally stable astrophysical objects composed of dark matter

Fermionic or Bosonic dark matter

Dark Star
Boson or Fermion star

Andrea Maselli, et al. **PRD 96, 023005 (2017)**
Joshua Eby, et al. **JHEP 02 (2016) 028**
G. Narain, J. Schaffner-Bielich, et al. **PRD 74, 063003 (2006)**
Chris Kouvaris, et al. **PRD 92 (2015) 6, 063526**
P.A.Seoane, J.Barranco, A.Bernal, L. Rezzolla, **JCAP 11 (2010) 002**
S. L. Liebling, C. Palenzuela, **Living Rev.Rel. 26 (2023) 1**
Luca Visinelli, **Int.J.Mod.Phys.D 30 (2021) 15, 2130006**

Dark matter admixed neutron star

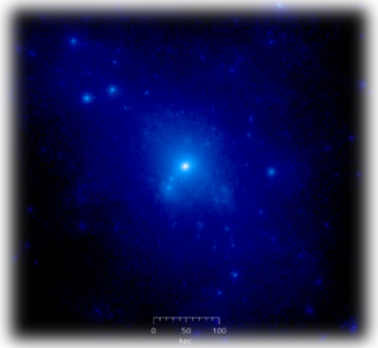
E. Giangrandi, V. Sugun, O. Ivanytskyi, C. Providência, T. Dietrich
Astrophys.J. 953 (2023) 1, 115
H.M Liu, J.B. Wei, Z.H. Li, G.F. Burgio, H.-J. Schulze, **Phys.Dark Univ. 42 (2023) 101338**
Harish Chandra Das, et al. **Mon.Not.Roy.Astron.Soc. 495 (2020) 4893-4903**
A. Nelson, S. Reddy, D. Zhou, **JCAP07(2019)012**
John Ellis, et al. **PRD 97, 123007 (2018)**
Y.Dengler, J. Schaffner-Bielich, L. Tolos, **PRD 105 (2022) 4, 043013**

Dark matter (DM) admixed neutron star (NS)

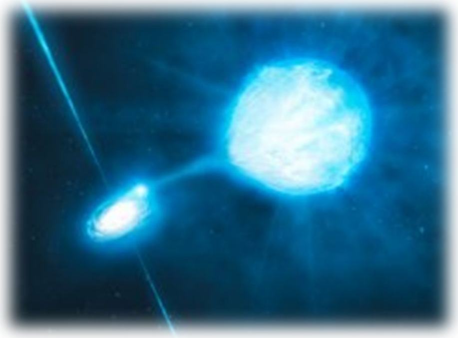
Ask Oleksii

Accumulation of DM
by a star or a NS
during its life time

A) Progenitor B) Main sequence (MS) star, C) Supernova explosion & formation of a proto-NS D) Equilibrated NS



NS exists in a dense halo or
region of DM
or passes through it
(Near the center of galaxy)

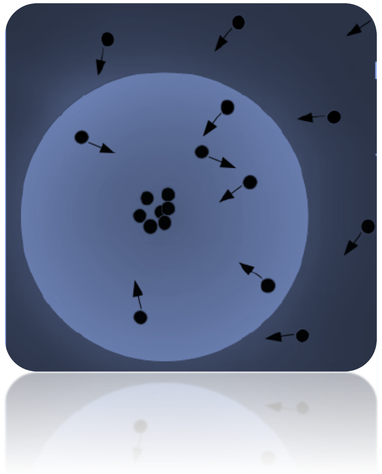


Dark star as an accretion
center of baryonic matter

DM production in the NS matter
or supernova explosions

Neutron decay anomaly

Accretion of
DM into a NS



DM capture by NS in a binary system
including Dark star or Dark star – NS merger

A. Nelson, S. Reddy, D. Zhou, **JCAP07(2019)012**

John Ellis, et al. **PRD 97, 123007 (2018)**

A. Del Popolo, et al. **Universe 6 (2020) 12, 222**

D.R. Karkevandi*, S. Shakeri, V. Sagun, O. Ivanytskyi,* **PRD 105, 023001 (2022)**

O. Ivanytskyi, V. Sagun, I. Lopes. **PRD 102, 063028 (2020)**

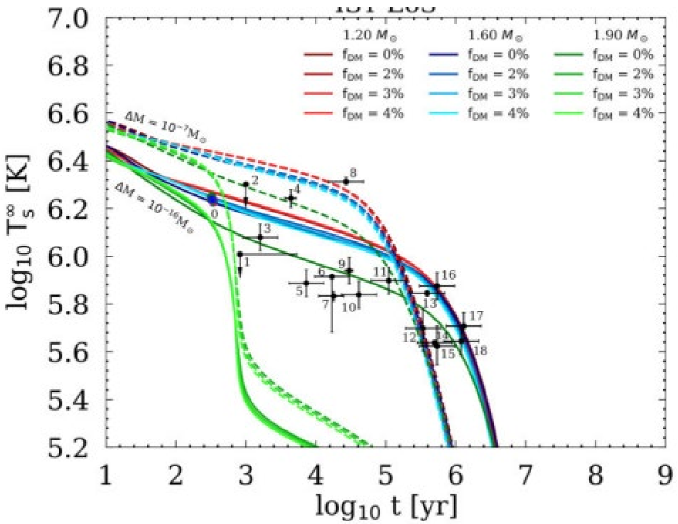
Raul Ciancarella, et al. **Phys.Dark Univ. 32 (2021) 100796**

P. Ciarcelluti & F. Sandin. **Phys.Lett. B695:19-21,2011**

S. Shirke, S. Ghosh, D. Chatterjee, L. Sagunski, J. Schaffner-Bielich, **JCAP 12 (2023) 008**

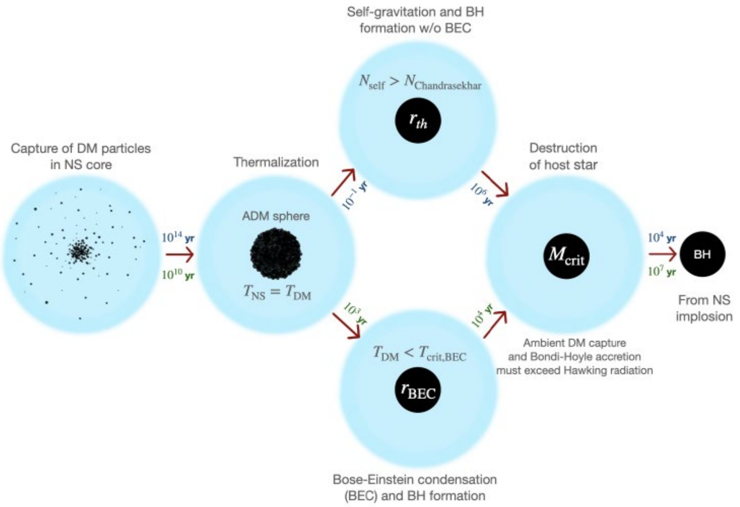
M. Deliyergiyev, A. Del Popolo, M. Le Delliou, **Mon.Not.Roy.Astron.Soc. 527 (2023) 3**

Cooling and Heating of NSs



Ávila, E. Giangrandi, V. sagun, O. Ivanytskyi,
C. Providência, ***Mon.Not.Roy.Astron.Soc. 528 (2024) 4***
Armen Sedrakian, ***Phys.Rev.D 93 (2016) 6, 065044***
Chris Kouvaris, ***Phys.Rev.D 77 (2008) 023006***

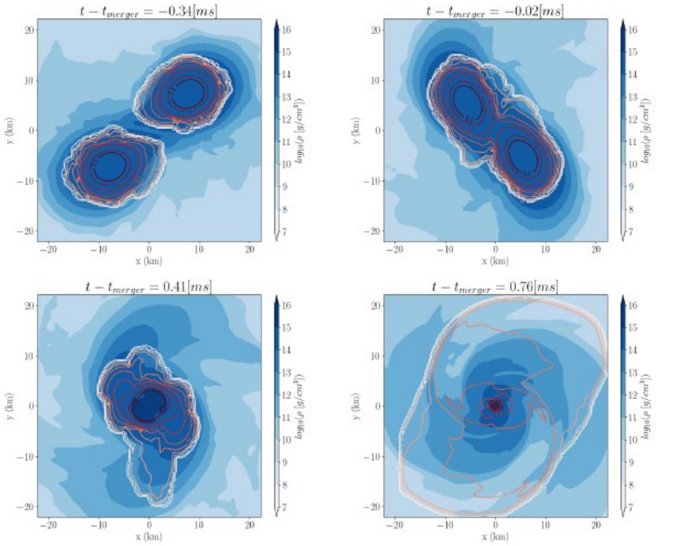
Black hole formation inside NSs



D. Singh, A. Gupta , E. Berti , S. Reddy , B. S. Sathyaprakash,
Phys.Rev.D 107 (2023) 8, 083037

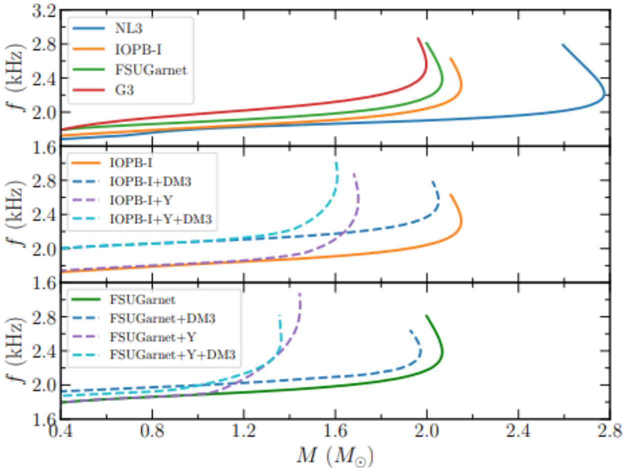
N. F. Bell, A. Melatos, K. Petraki, ***Phys.Rev.D 87 (2013) 12, 123507***

Numerical simulation of compact objects



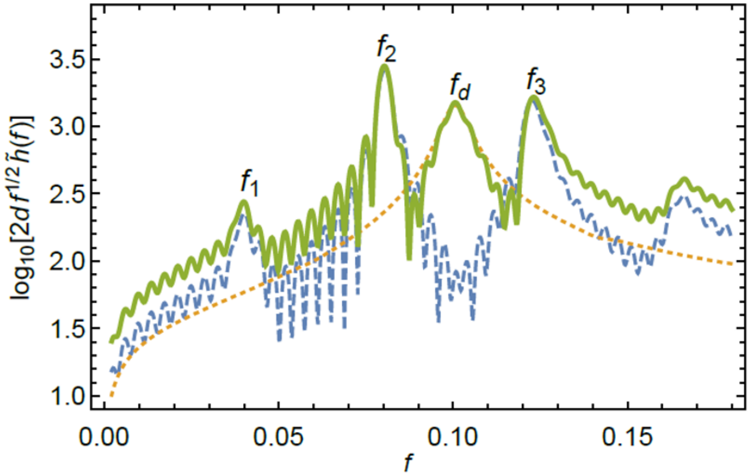
M. Emma, F. Schianchi , F. Pannarale , V. Sagun ,
T. Dietrich, ***Particles 5 (2022) 3, 273-286***
Andreas Bauswein, et al. ***Phys.Rev.D 107 (2023) 8, 083002***
H. R. Rüter, V. Sagun, W. Tichy, T. Dietrich, ***PRD 108, 124080***

Different modes oscillation



Harish Chandra Das, et al. ***Phys.Rev.D 104 (2021) 12, 123006***
S. Shirke, S. Ghosh, D. Chatterjee, L. Sagunski, J. Schaffner-Bielich,
JCAP 12 (2023) 008

Gravitational waves signals



John Ellis, et al. ***Phys.Lett.B 781 (2018) 607-610***
Harish Chandra Das, et al. ***Mon.Not.Roy.Astron.Soc. 57 4053 (2021)***

Mass-Radius profile , Tidal deformability and moment of inertia

Pulse profile modeling

Z. Miao, Y. Zhu, Ang Li, F. Huang, ***Ap.J. 936 (2022) 1, 69***
S. Shakeri, ***D.R. K,*** ***Phys. Rev. D 109, 043029 (2024)***

Modeling of a DM admixed NS

Asymmetric DM

Single fluid DM admixed NS

An equation of state (EoS) by considering DM-Baryonic matter (BM) interaction

M. Shahrbaf, D. Blaschke, S. Typel, et al. ***Phys. Rev. D 105, 103005 (2022)***

Harish Chandra Das, ***arXiv:2305.02065***

G. Panotopoulos and I. Lopes, ***Phys.Rev.D 96 (2017) 8, 083004***

D. E. *Alvarez-Castillo, M. Marczenko,* ***Phys.Polon.Supp. 15 (2022) 3, 28***

Direct impacts on nuclear models

Ask Harish, Mahboubeh

See Mahboubeh's poster

Two-fluid DM admixed NS

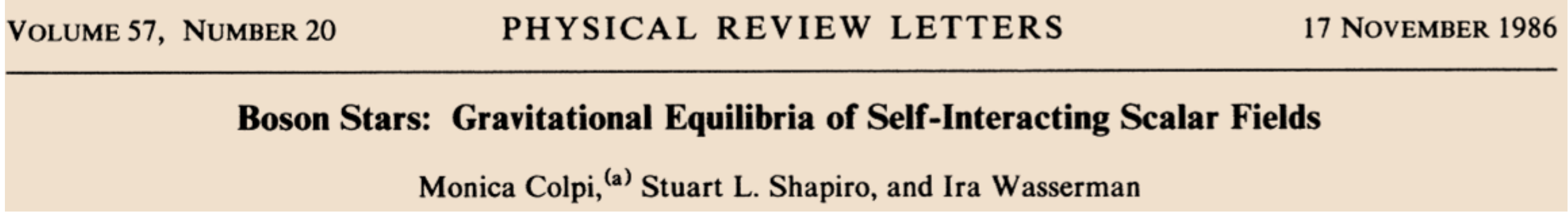
DM and BM interact only through gravitational force

EoS for BM and EoS for DM

Our considered model

Impacts on the observable features resulting from nuclear models

DM and Baryonic matter EoSs for *two-fluid* DM admixed NSs



VOLUME 57, NUMBER 20 PHYSICAL REVIEW LETTERS 17 NOVEMBER 1986

Boson Stars: Gravitational Equilibria of Self-Interacting Scalar Fields

Monica Colpi,(a) Stuart L. Shapiro, and Ira Wasserman

DM: Self-interacting complex scalar field

Bosonic DM with **repulsive** self-interaction

$V(\phi) = \frac{1}{4}\lambda|\phi|^4$ Leads to stellar mass Boson star

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi^*\partial^\mu\phi - \frac{m_\chi^2}{2}\phi^*\phi - \frac{\lambda}{4}(\phi^*\phi)^2.$$

Free parameters of the DM model

boson mass (m_χ), coupling constant (λ)

Strong coupling regime (Prefect fluid approximation)

In locally flat space-time by mean-field approximation

D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, ***PRD 105, 023001 (2022)***

$$P = \frac{m_\chi^4}{9\lambda}\left(\sqrt{1 + \frac{3\lambda}{m_\chi^4}\rho} - 1\right)^2.$$

DD2, a widely used and well-known nuclear matter equation of state (EoS)

Stiff EoS for which the tidal deformability *is not consistent* with the observational constraints

S. Typel and H.H. Wolter, ***Nucl.Phys.A 656 (1999) 331-364***
S. Typel, ***Phys.Rev.C 71 (2005) 064301***

Two-fluid DM admixed NS

BM and DM fluids interact only gravitationally

↕

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi (T^{\mu\nu}_{DM} + T^{\mu\nu}_{BM})$$

Energy-momentum tensors are conserved separately

Two-fluid Tolman-Oppenheimer-Volkof equation

F. Sandin & P. Ciarcelluti. ***Astropart.Phys.32:278-284,2009****.*
P. Ciarcelluti & F. Sandin. ***Phys.Lett. B695:19-21,2011****.*

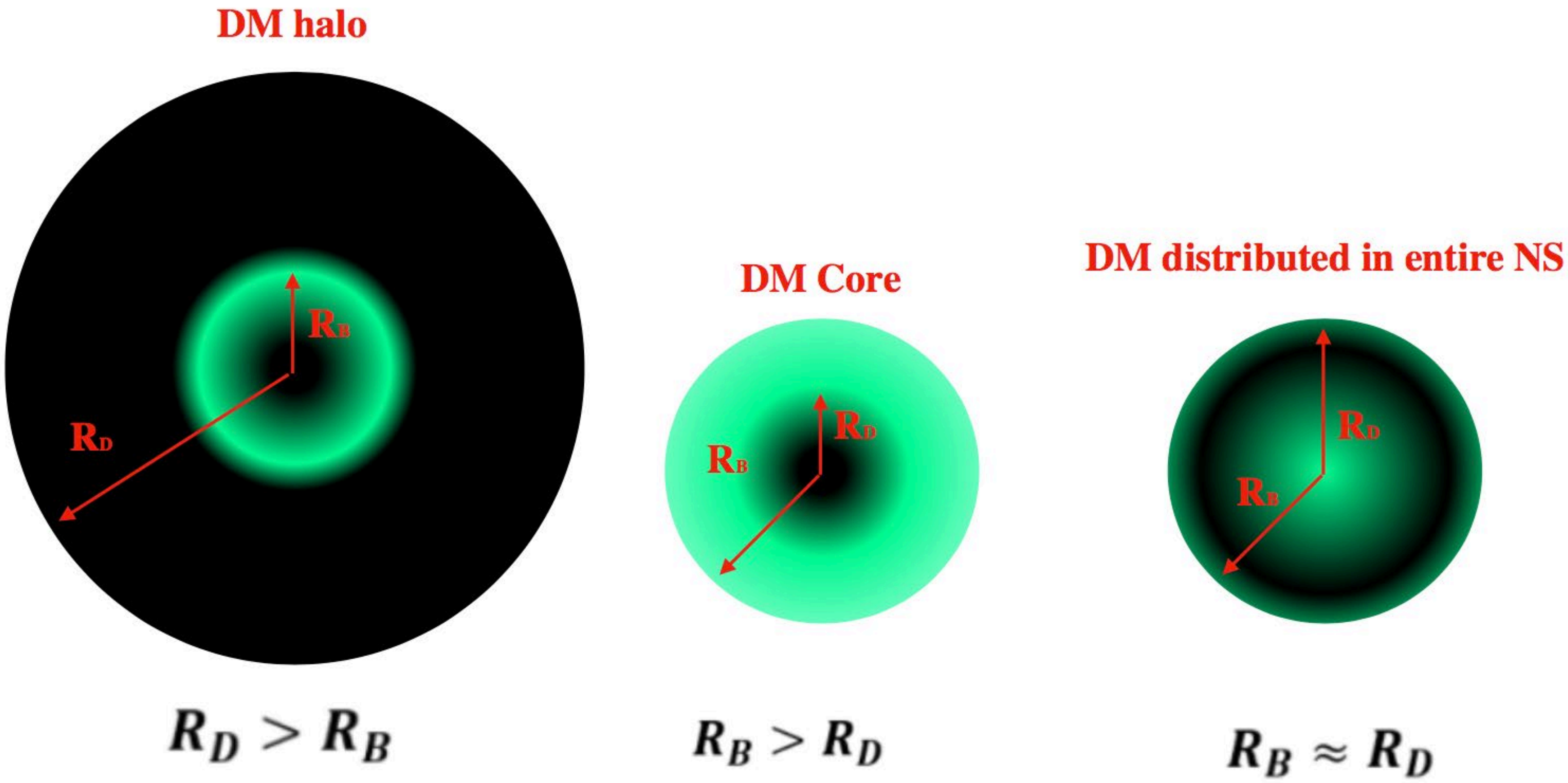
$$\frac{dp_B}{dr} = -\left(p_B + \varepsilon_B\right) \frac{m + 4\pi r^3 p}{r\,(r - 2m)}$$

$$\frac{dp_D}{dr} = -\left(p_D + \varepsilon_D\right) \frac{m + 4\pi r^3 p}{r\,(r - 2m)}$$

$$m(r) = \underbrace{\int_0^r 4\pi r^2 \varepsilon_B}_{m_B(r)} + \underbrace{\int_0^r 4\pi r^2 \varepsilon_D}_{m_D(r)}$$

$$p(r) = p_B(r) + p_D(r)$$

Three Possible DM distributions within NSs



$R_D > R_B$

$R_B > R_D$

$R_B \approx R_D$

Core of a DM admixed NS is composed of both of the fluids

Green : BM
Black : DM

$M_T = M_B(R_B) + M_D(R_D)$

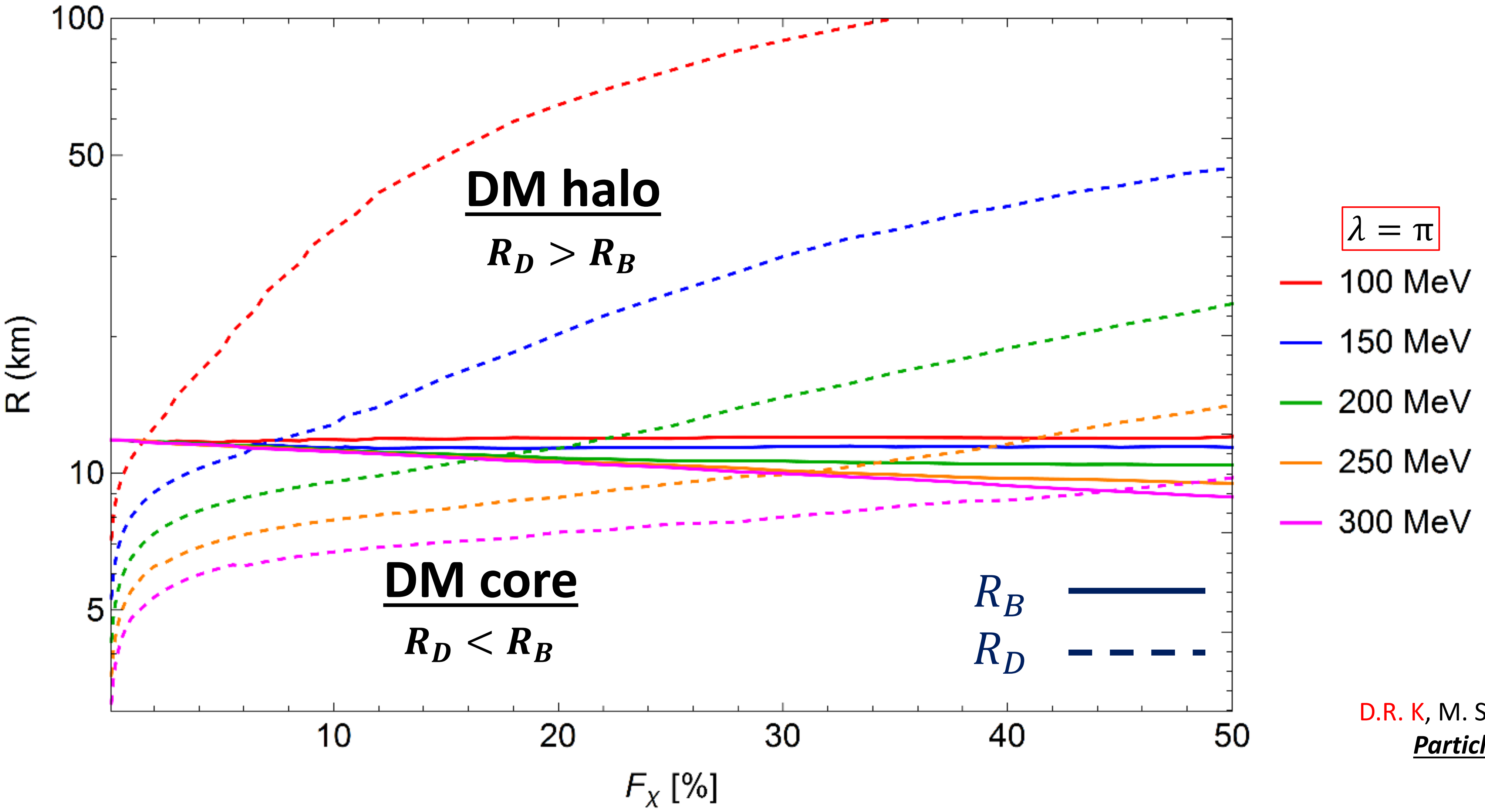
$F_\chi = \frac{M_D(R_D)}{M_T}$, DM Fraction

R_B is the visible radius

D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, The Proceedings of Sixteenth Marcel Grossmann Meeting (MG16), [arXiv:2112.14231]

Variation of BM radius (*solid lines*) and DM radius (*dashed lines*) in DM admixed NSs

By increasing the DM fraction, a *transition* can be seen from DM core to DM halo formation

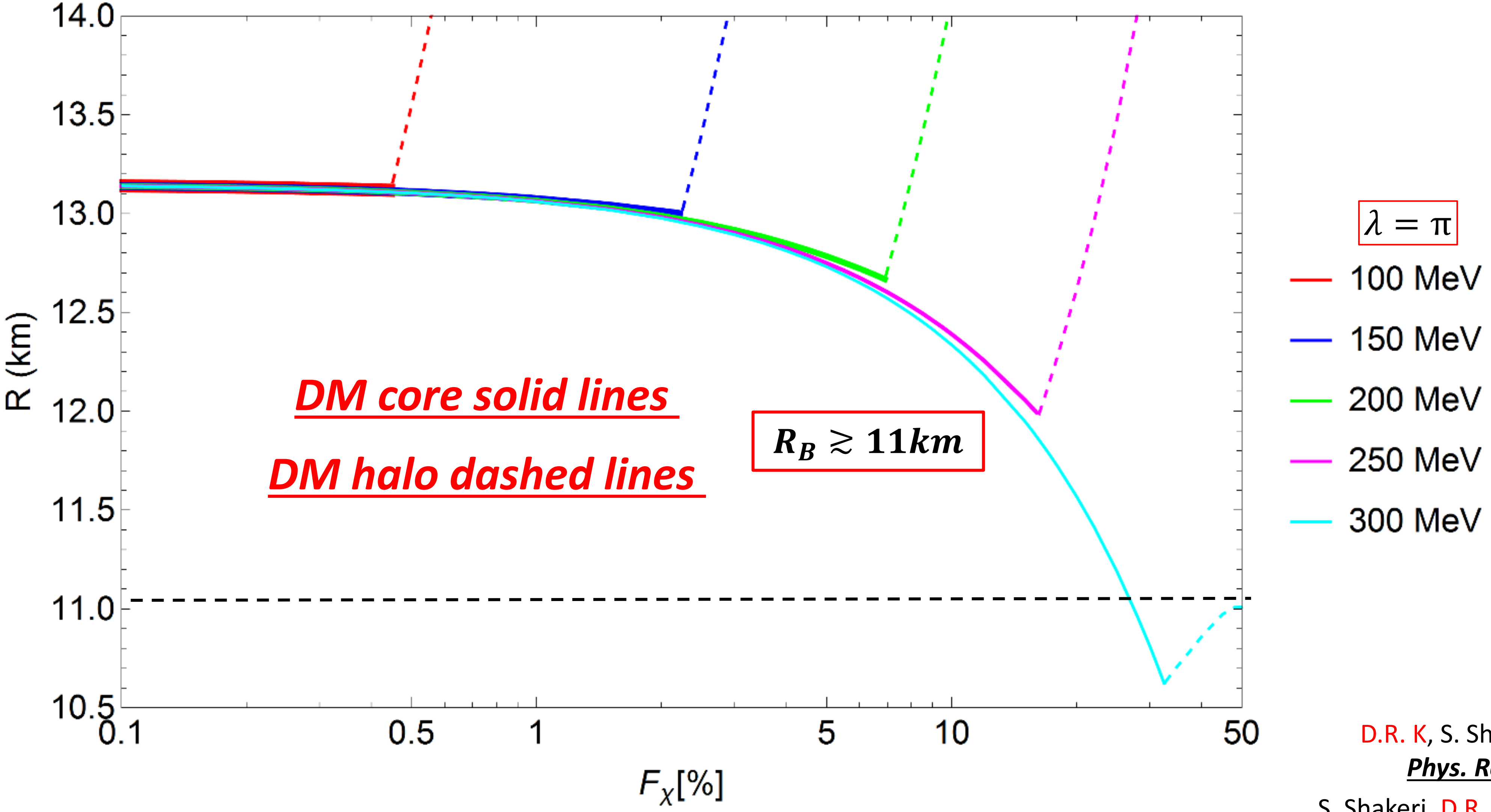


Even in low DM fractions a ***DM halo*** *can be formed for light bosons. However, Heavy bosons lead mainly to* ***DM core*** *formation.*

D.R. K, M. Shahrbaf, S. Shakeri, S.Typel, ***Particles 7 (2024) 1, 201-213***

Variation of *outermost radius* of DM admixed NSs

DM core: R_B (BM radius) is the outermost radius **DM halo**: R_D (DM radius) is the outermost radius



DM core solid lines

DM halo dashed lines

$R_B \gtrsim 11km$

DM core formation, solid lines, *decreases* the outermost radius.

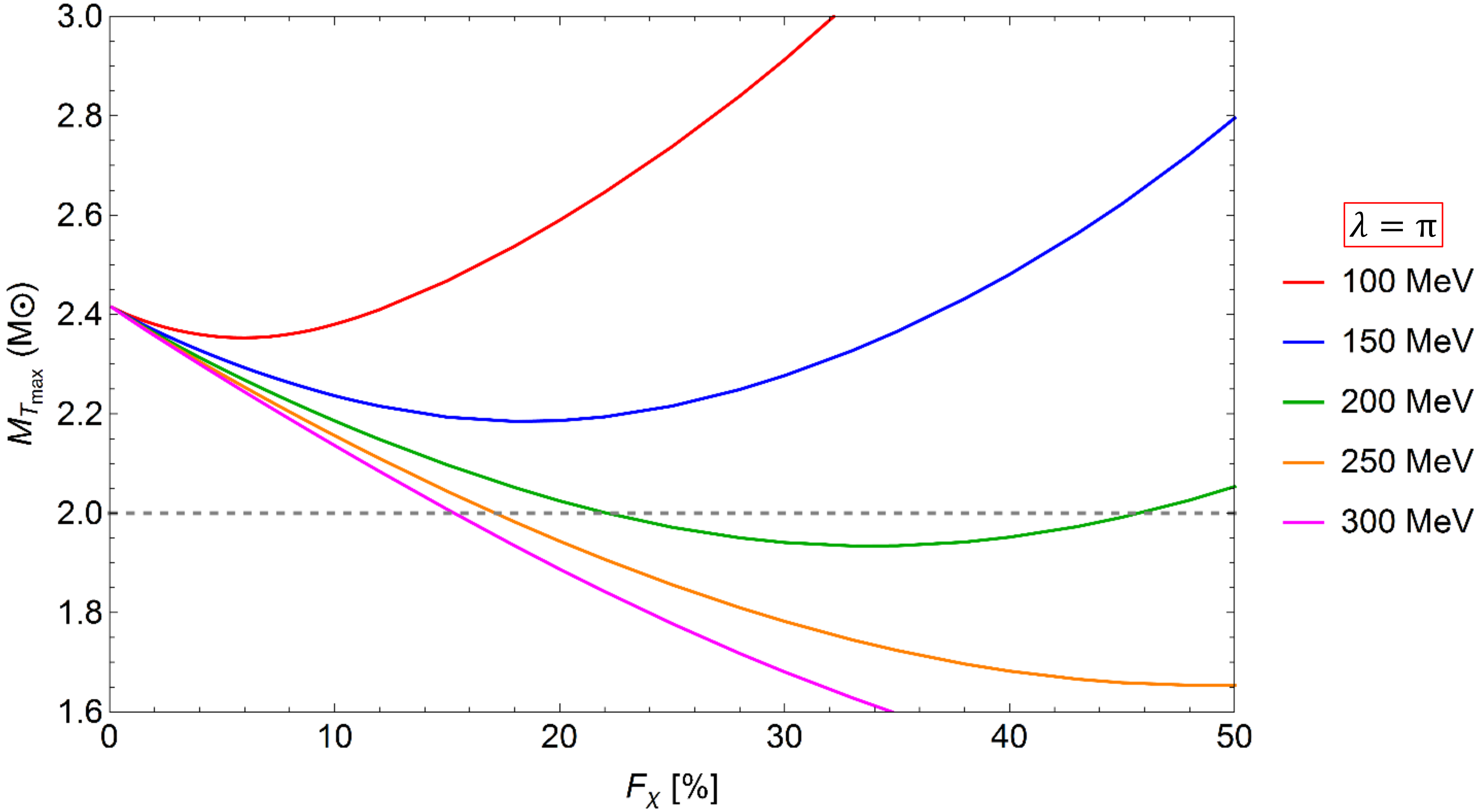
DM halo formation, dashed lines, *increases* the outermost radius.

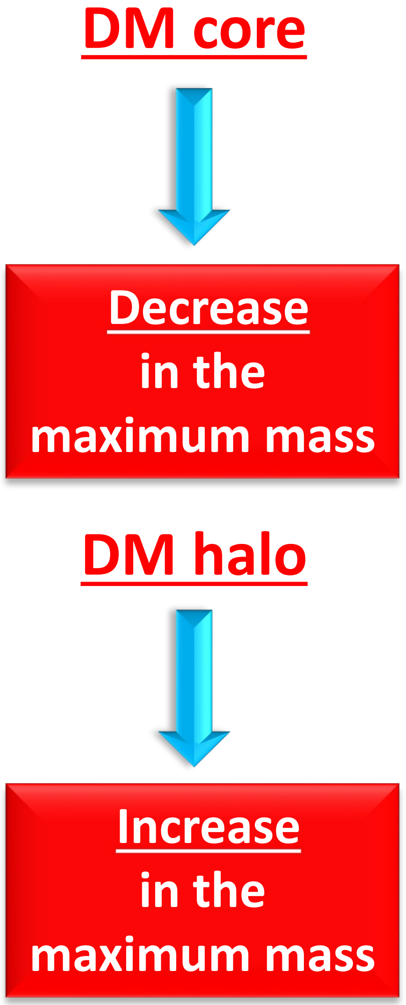
D.R. K, S. Shakeri, V. Sagun, O. Ivanytskyi, ***Phys. Rev. D 105, 023001 (2022)***

S. Shakeri, D.R. K, ***Phys. Rev. D 109, 043029 (2024)***

Variation of the ***total maximum mass*** of DM admixed NSs

For **light bosons** the maximum mass constraint is satisfied for the whole range of DM fractions while for **heavy bosons** the $2M\odot$ limit will be violated for some DM fractions.





DM core

Decrease in the maximum mass

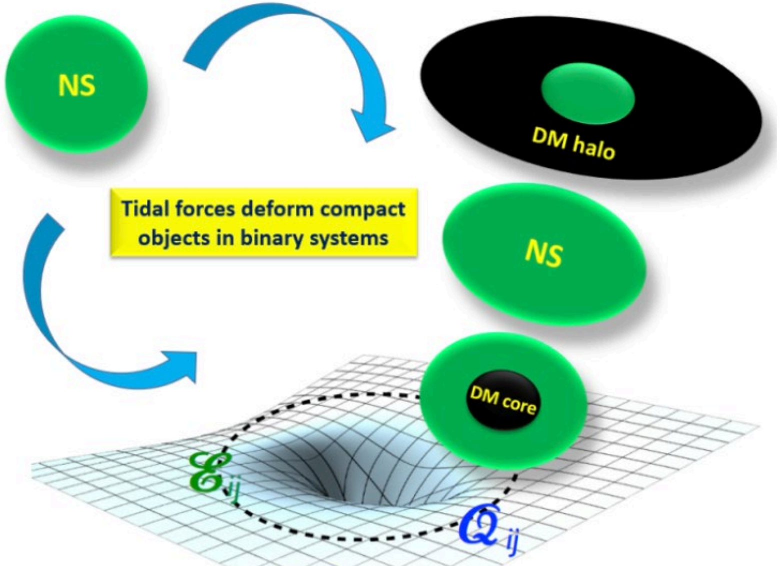
DM halo

Increase in the maximum mass

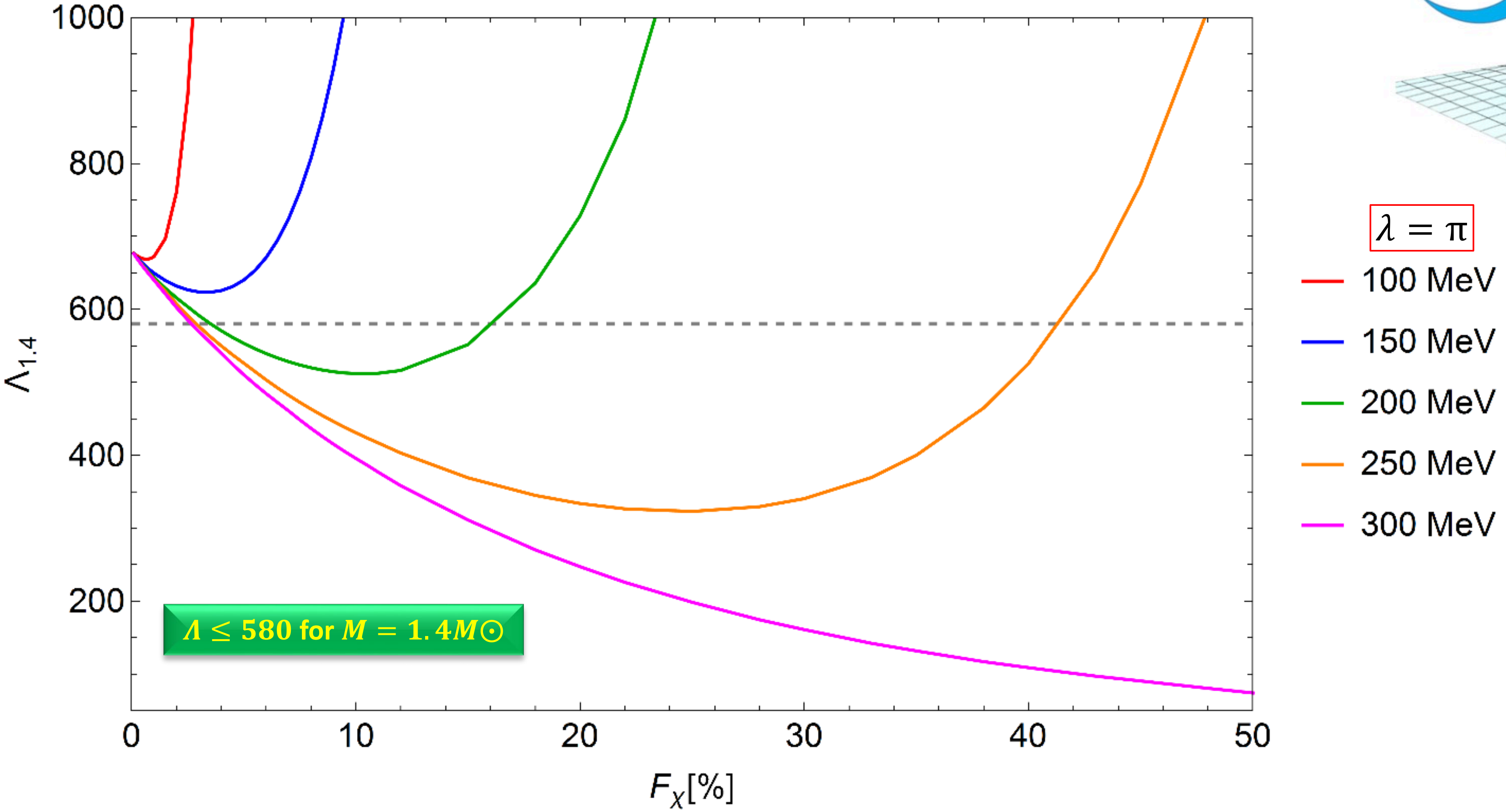
D.R. K, M. Shahrbaf, S. Shakeri, S. Typel, ***Particles 7 (2024) 1, 201-213***

Variation of the *tidal deformability* of DM admixed NSs

Heavy bosons mainly reside as a core inside NS,
while light bosons form a large halo around the NS.



Deformation of spacetime
away from spherical symmetry



$\Lambda \leq 580$ for $M = 1.4M_\odot$

$$\Lambda = \frac{\lambda_t}{M^5} = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5$$

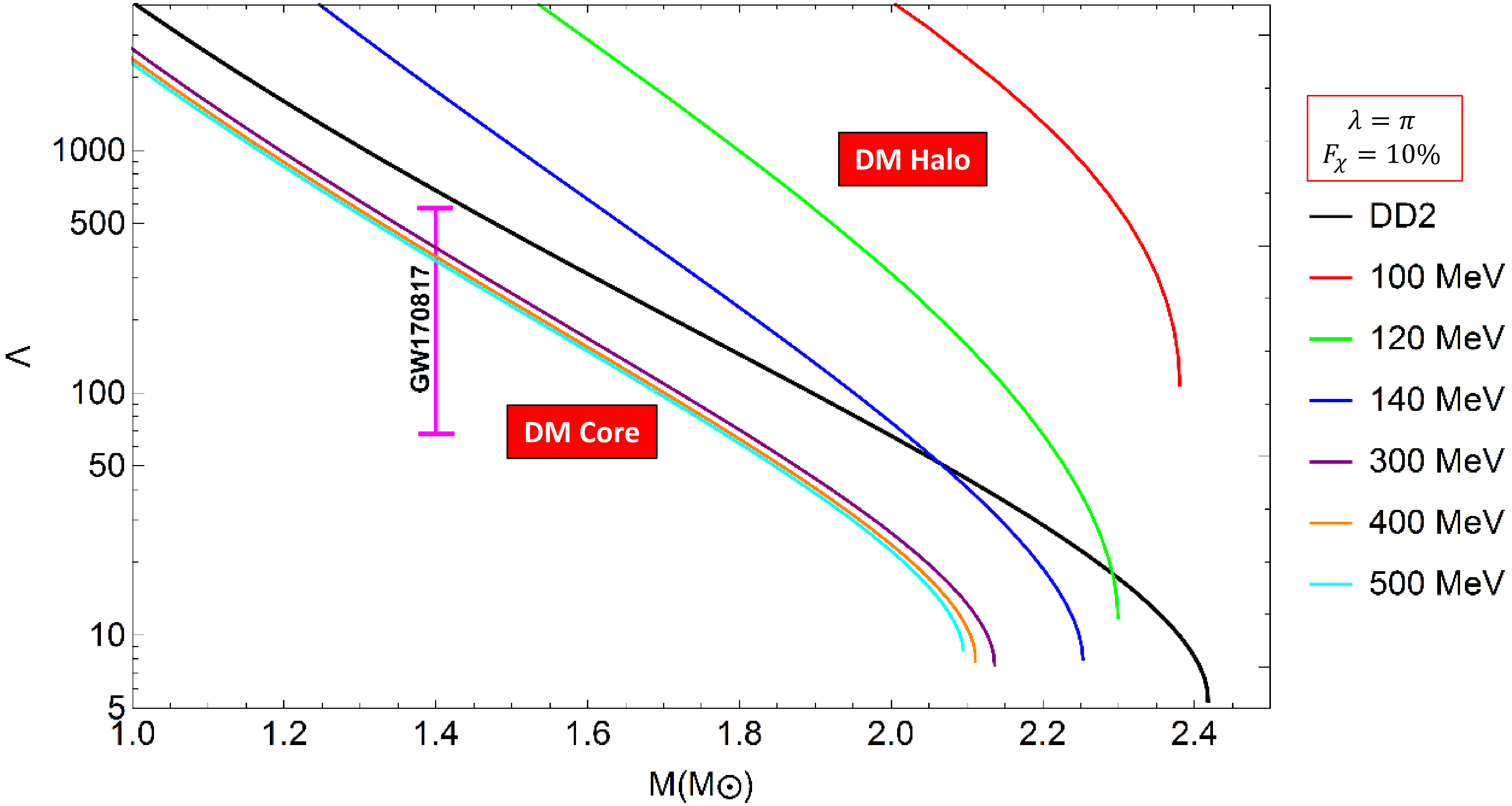
DM core decreases tidal deformability

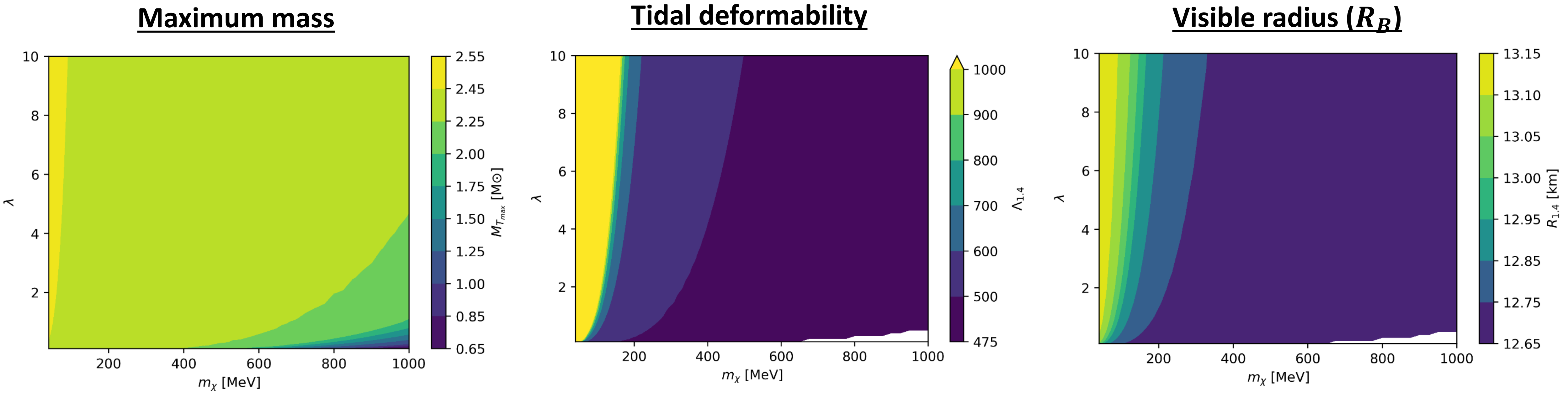
DM halo increases tidal deformability

D.R. K, M. Shahrbaf, S. Shakeri, S. Typel,
Particles 7 (2024) 1, 201-213

Tidal deformability of DD2 EoS will be modified due to the presence of bosonic DM in the core of NSs.

Black solid lines corresponds to DD2 EoS without DM



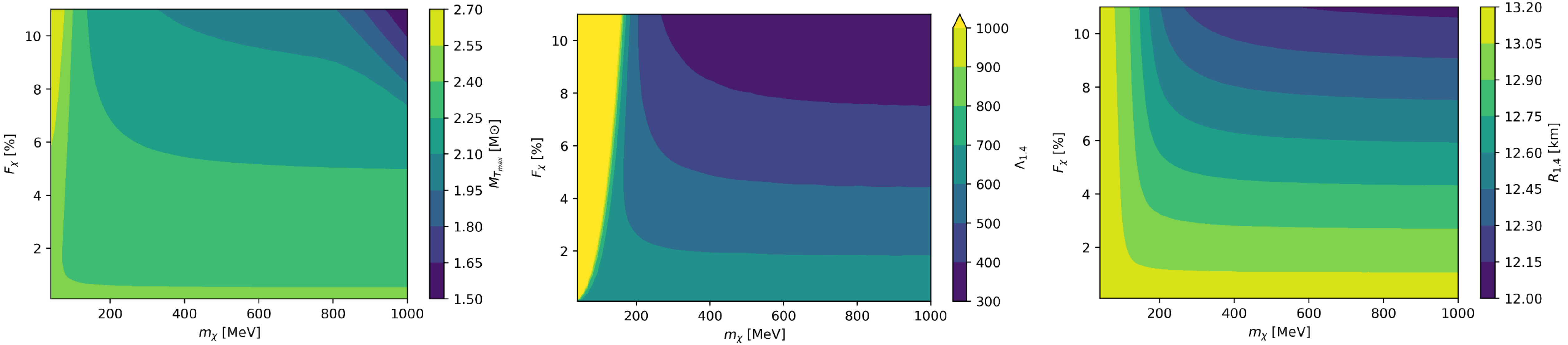


Maximum mass

Tidal deformability

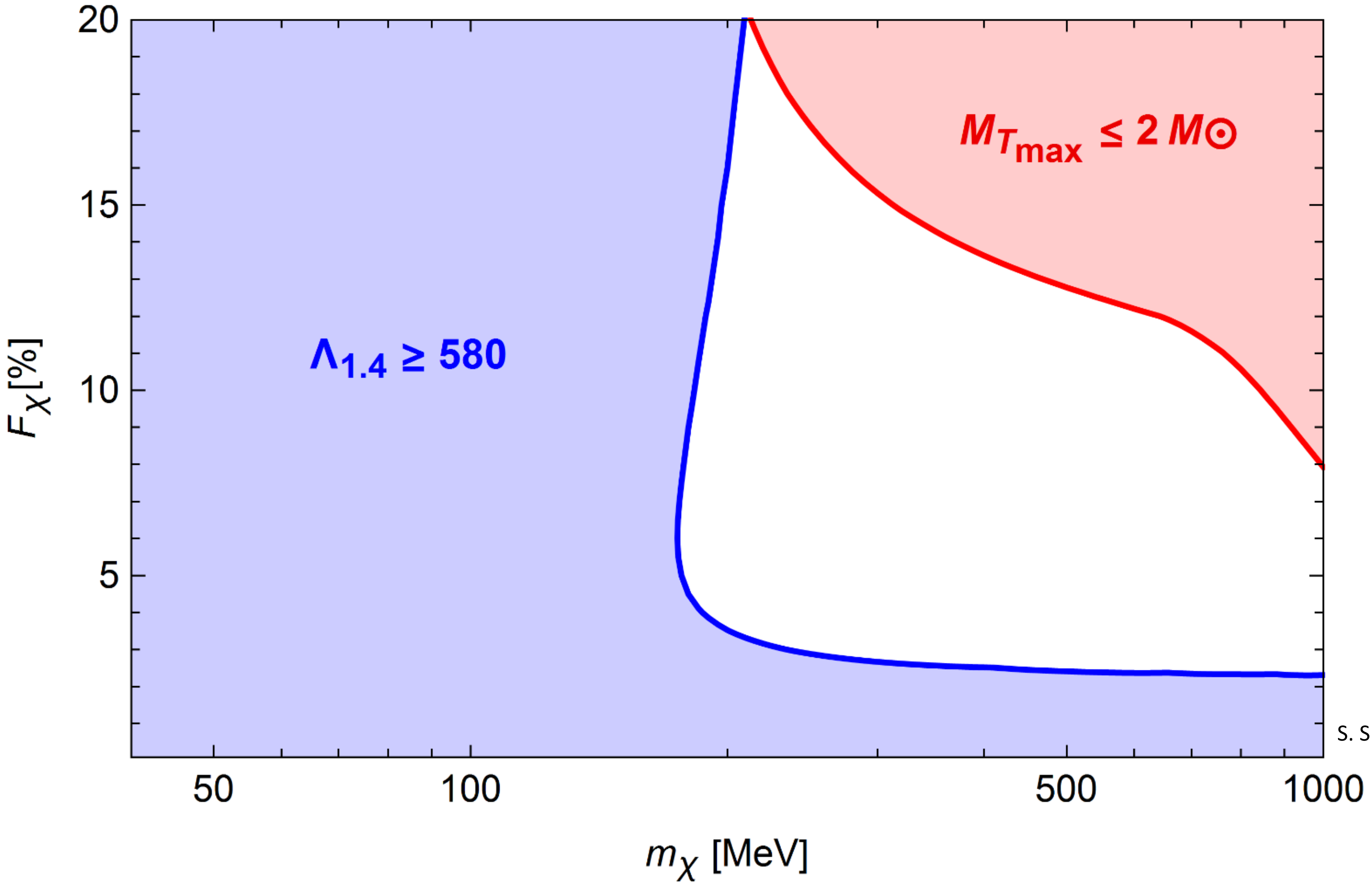
Visible radius (R_B)

Scan over the parameter space of the bosonic DM model, **Top**: $\lambda - m_\chi$ and **Bottom:** $F_\chi - m_\chi$



S. Shakeri, D.R. K, ***Phys. Rev. D 109, 043029 (2024)***

Scan over the $F_\chi - m_\chi$ parameter space of DM admixed NSs for $\lambda = \pi$

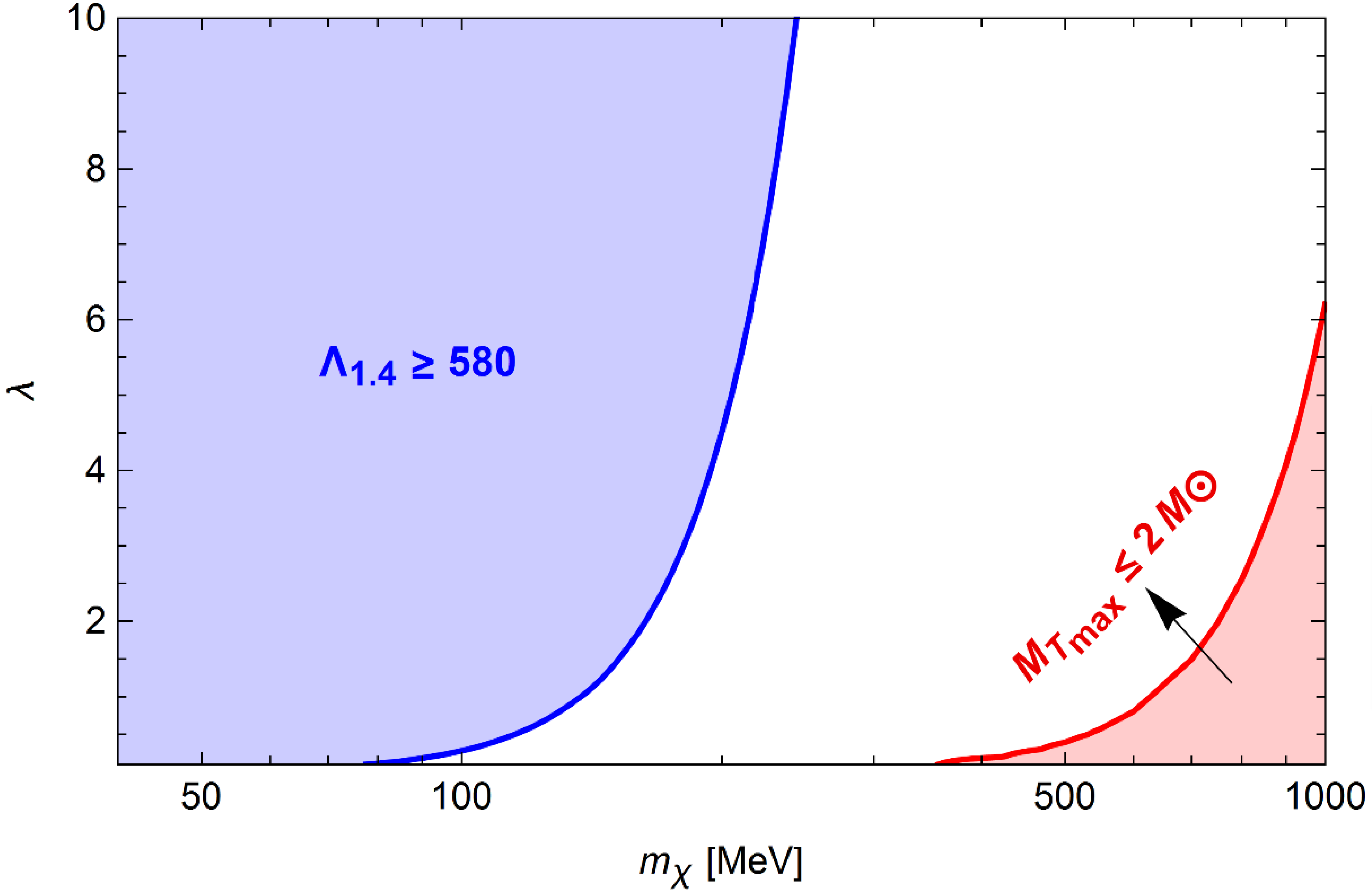


DM fraction is limited between 2% and 20% for which all the considered observable features are satisfied.

S. Shakeri, D.R. K, ***Phys. Rev. D 109, 043029 (2024)***

Scan over the $\lambda - m_\chi$ parameter space for $F_\chi = 10\%$

Light bosonic DM particles $(m_\chi \lesssim 200\ MeV)$ are excluded by tidal deformability parameter for the whole range of λ.



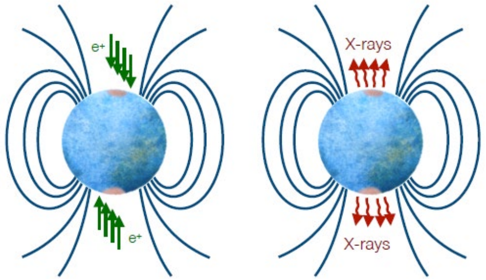
For heavy bosons $(m_\chi \gtrsim 500\ MeV)$ and low coupling constants, the maximum mass is not consistent with observational constraint.

The allowed region shows where all the given observable properties of the NS, induced from DD2 EoS, is in agreement with the astrophysical bounds.

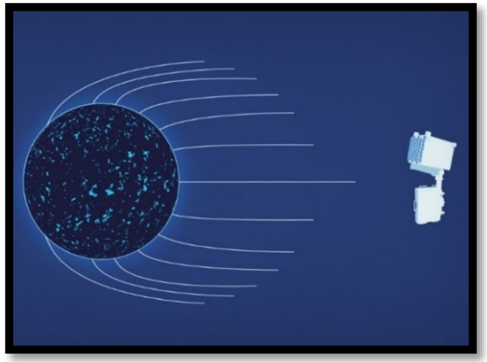
S. Shakeri, D.R. K, ***Phys. Rev. D 109, 043029 (2024)***

Pulse profile modeling as a novel probe for DM halo formation around NSs

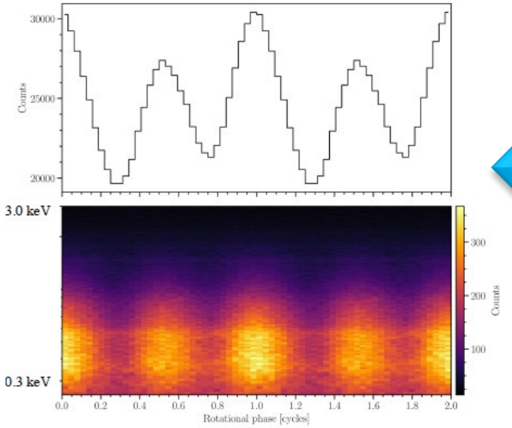
X-ray hot spots



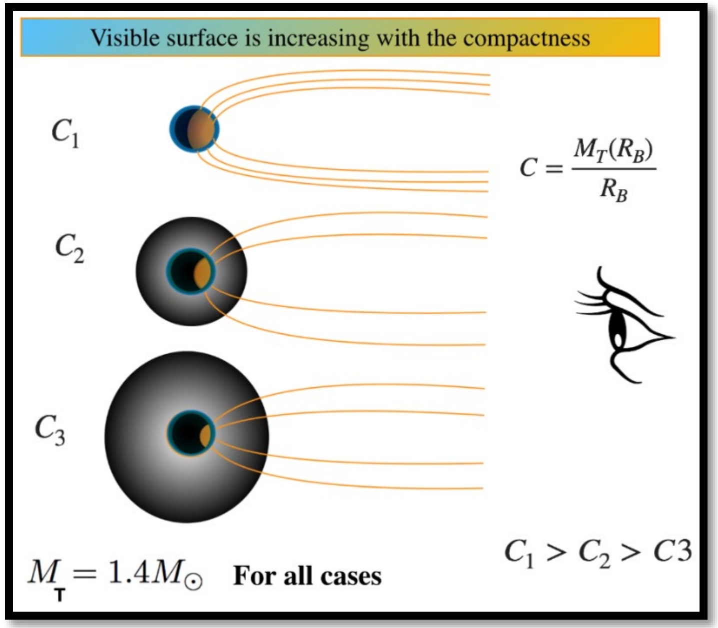
NICER and light bending due to the curved of space time



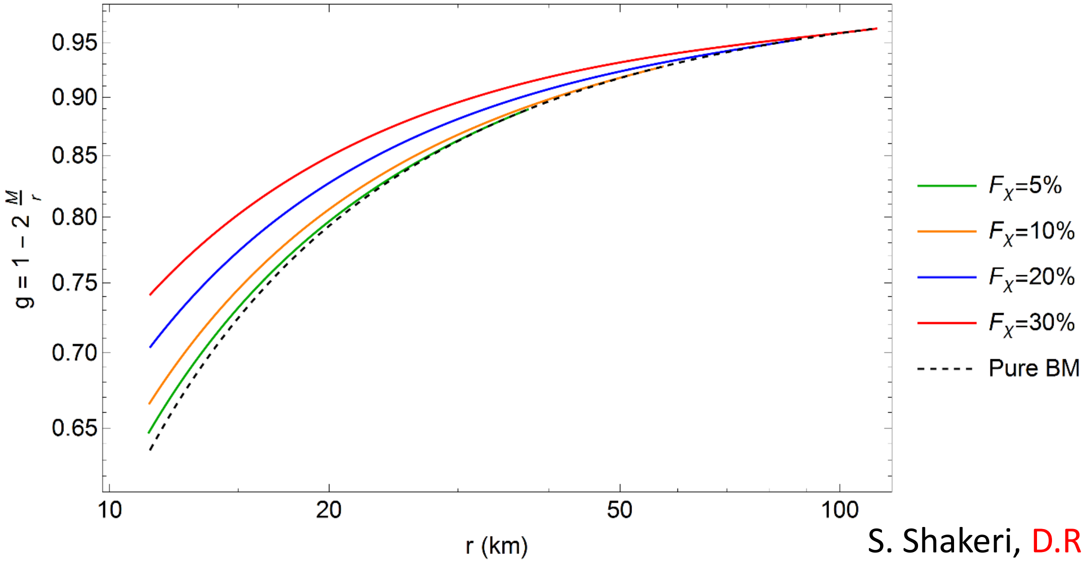
X-ray Pulse profile



DM halo

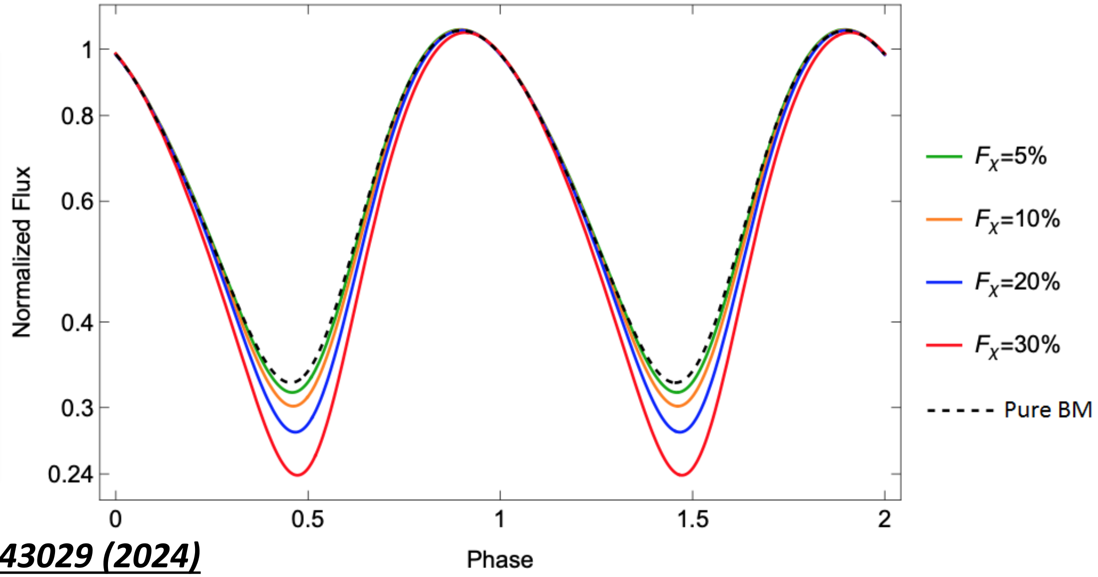


Variation of metric function due to the DM halo



The deviation of the minimums of the fluxes compare to the pure NS is a remarkable signature of the DM halo.

X-ray pulse profile in the presence of DM halo

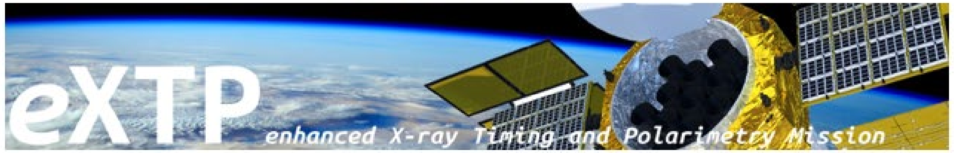


S. Shakeri, D.R. K, ***Phys. Rev. D 109, 043029 (2024)***

KAGRA

ET EINSTEIN TELESCOPE

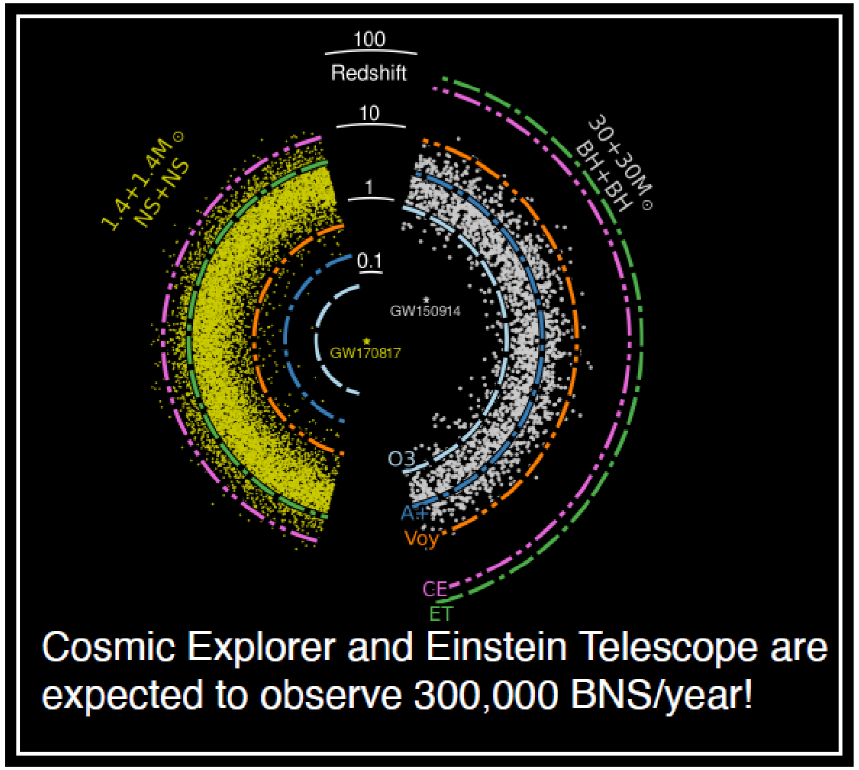
MeerKAT



LISA CONSORTIUM

COSMIC EXPLORER

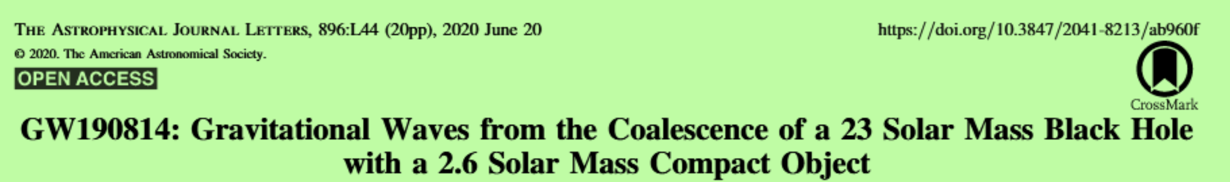
H.E.S.S.



Cosmic Explorer and Einstein Telescope are expected to observe 300,000 BNS/year!

arXiv:2109.09882

Exotic measurements

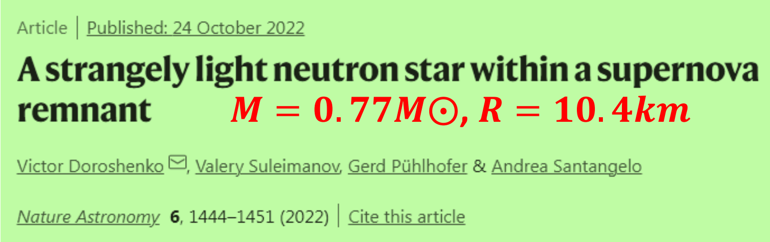


The Astrophysical Journal Letters, 896:L44 (20pp), 2020 June 20 https://doi.org/10.3847/2041-8213/ab960f

© 2020. The American Astronomical Society.

OPEN ACCESS

GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object



Article | Published: 24 October 2022

A strangely light neutron star within a supernova remnant $M = 0.77M_\odot, R = 10.4km$

Victor Doroshenko, Valery Suleimanov, Gerd Pühlhofer & Andrea Santangelo

Nature Astronomy 6, 1444–1451 (2022) | Cite this article

PRD. 105, 063005
APJ. 922 (2021) 242
PRD. 104, 063028 (2021)
Astrophys. J. 958, 49 (2023)
arXiv:2307.12748

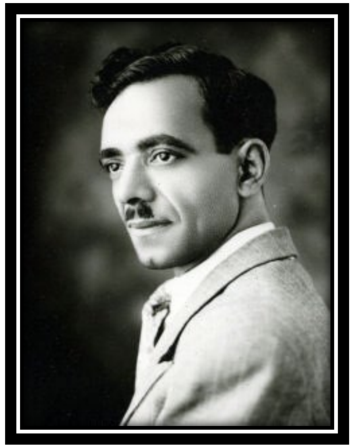
Isfahan miasto Polskich dzieci

Isfahan - the City of Polish Children

1942-1945

2590 Polish children mainly below 9

Khajoo bridge, Isfahan-Iran



The Photographer

Abolqasem Jala

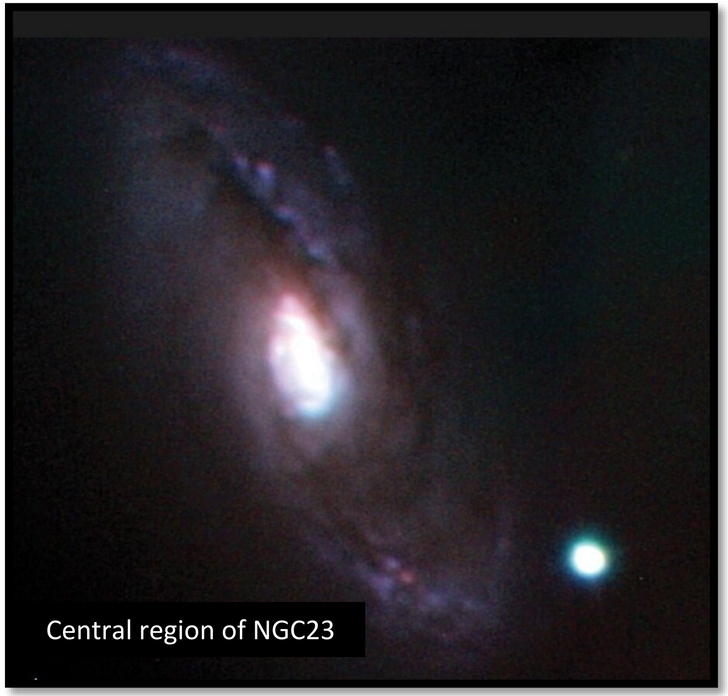
Optical observations of black-widow pulsars

Iranian National Observatory (INO)

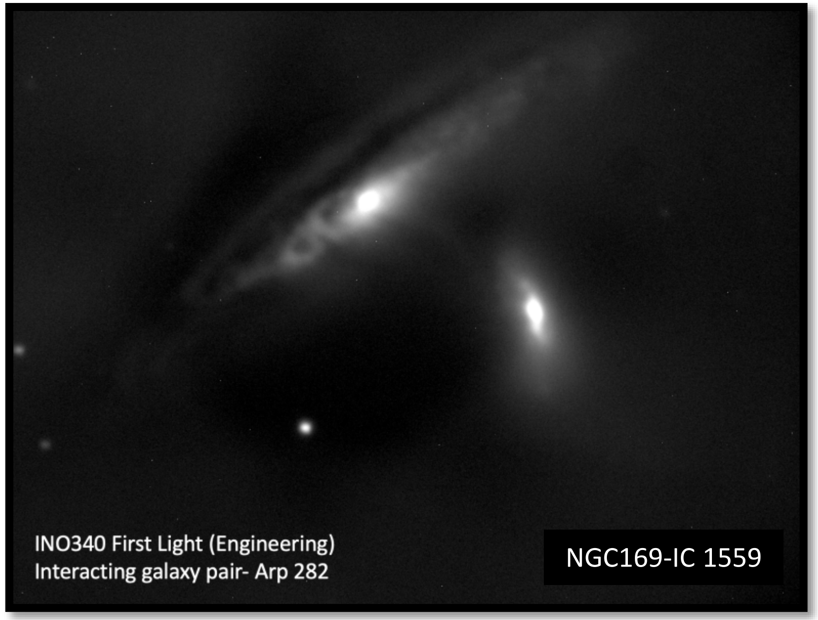
3.4 meter optical telescope

3600m above the sea level

Iranian National Observatory (INO), the largest home-grown scientific facility project, has recorded the first light image of its 3.4m optical telescope on October 2022.



Central region of NGC23



INO340 First Light (Engineering)
Interacting galaxy pair- Arp 282

NGC169-IC 1559

‘The door is open’: Iranian astronomers seek collaborations for their new, world-class telescope.

Science
AAAS

Seventeenth Marcel Grossmann Meeting

7–12 Jul 2024
The 'Gabriele d'Annunzio' University, ICRANet and Aurum
Europe/Rome timezone

Bosonic dark matter and/in neutron stars

DM5

Chairpersons: Soroush Shakeri and Davood Rafiei Karkevandi

Among different Dark Matter (DM) candidates the scalar or pseudoscalar bosons are of great interest from various aspects in astrophysics and cosmology. Generally, bosonic DM could form gravitationally stable configurations or be substantially accumulated in compact objects such as Neutron Stars (NSs) through different scenarios. In this regard, the advent of multi-messenger observations via gravitational and electromagnetic waves provide a unique opportunity to probe the existence of dense astrophysical objects made entirely or fractionally by bosonic DM.

In this section, we will focus on both theoretical and observational aspects of boson stars, fermion-boson stars, DM admixed NSs and other exotic type of compact stars. Recently, the GW detections by LIGO-Virgo-KAGRA and X-ray observations by NICER telescopes have opened a new window towards understanding the structure of compact objects and may shed light on the nature of DM through exploring exotic results.