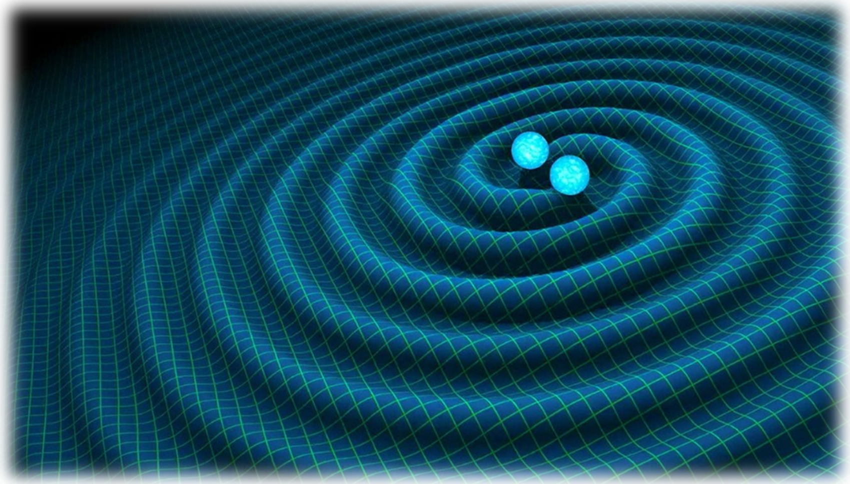
Shedding new light on Bosonic Dark Matter with X-ray and Gravitational-Wave observations of Neutron Stars



Davood Rafiei Karkevandi

ICRANet-Isfahan, Isfahan University of Technology, Iran

Main reference :

S. Shakeri, **D.R. K**, **Bosonic Dark Matter in Light of the NICER Precise Mass-Radius Measurements**
arXiv:2210.17308v2 (Submitted to PRD)

The new version will be appeared on arXiv in the following month

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Isfahan University of Technology, Iran
ICRANet-Isfahan, Iran

Other key references :

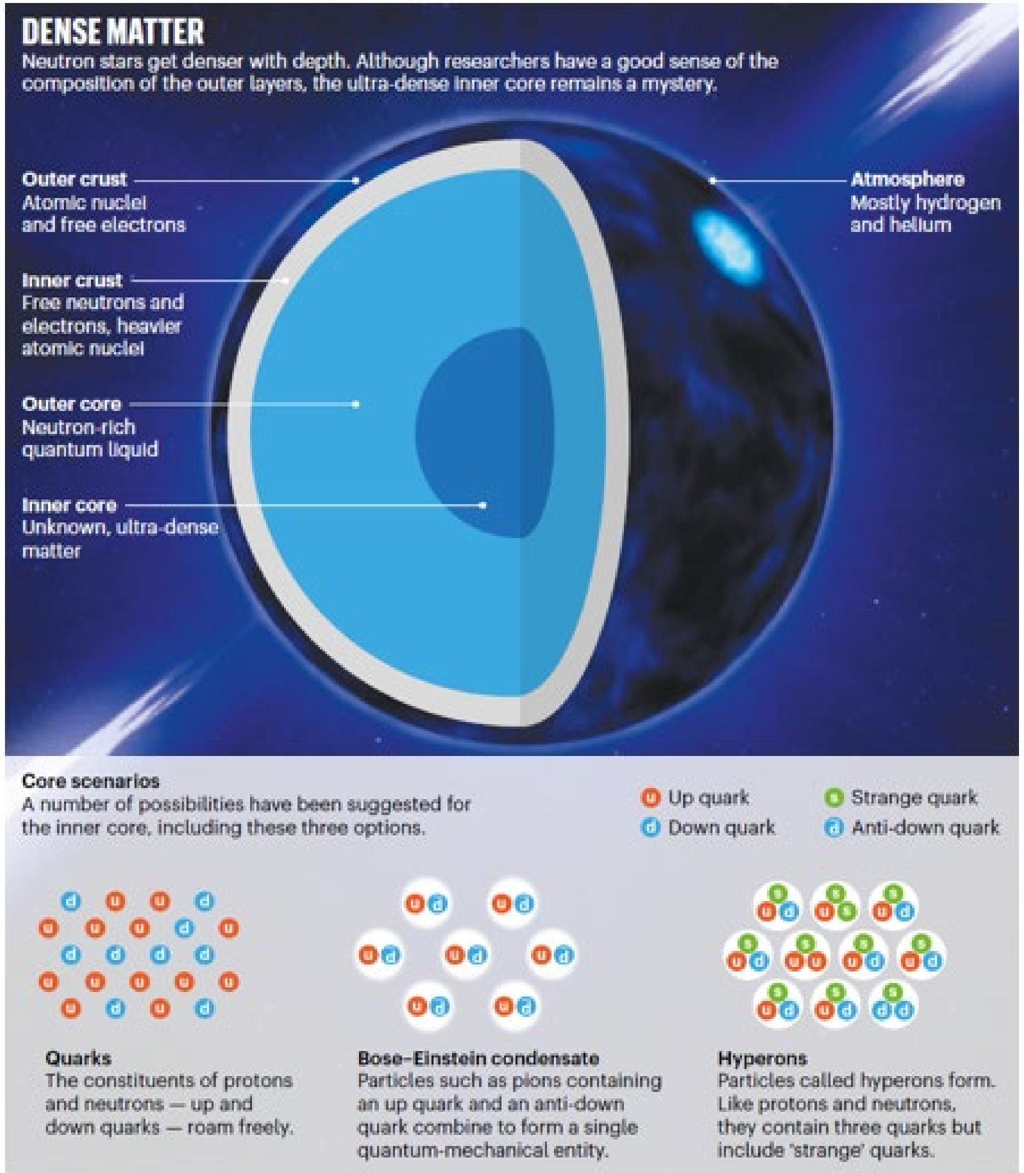
D.R. K, S. Shakeri, V. Sagun, O. Ivanytskyi, **Phys. Rev. D 105, 023001 (2022),** [arXiv:2109.03801v2]

D.R. K, S. Shakeri, V. Sagun, O. Ivanytskyi, **Sixteenth Marcel Grossmann Meeting**, MG16 Proceedings, [arXiv:2112.14231]

Violetta Sagun
University of Coimbra, Portugal

Oleksii Ivanytskyi
University of Wroclaw, Poland

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.

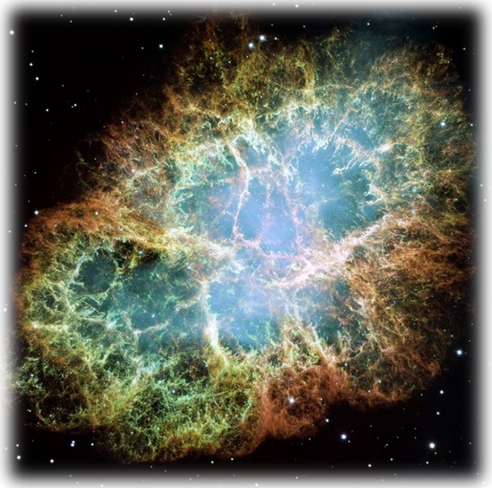
Bose–Einstein condensate

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

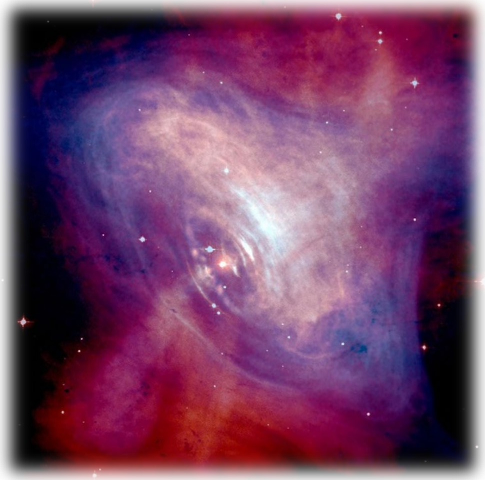
Hyperons

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

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



Crab Pulsar



Mass: 1.4 – 2 solar mass $(M\odot)$

Radius: 11 – 13 km

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

Tolman-Oppenheimer-Volkof (TOV) equations

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

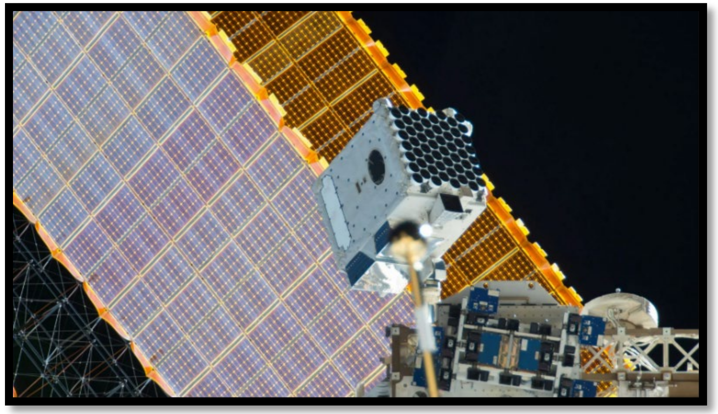
R. C. Tolman, Phys. Rev. 55, 364 (1939).

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

X-ray and Gravitational-Wave (GW) observations of neutron stars

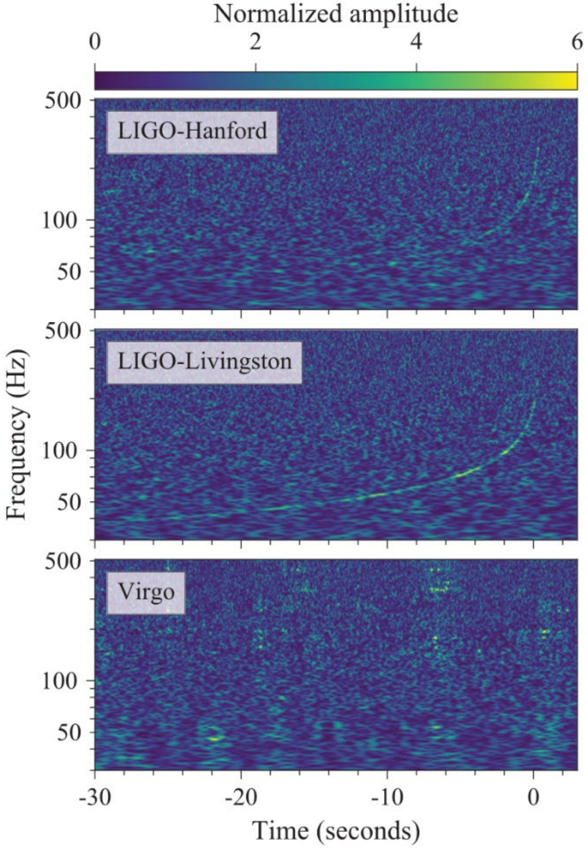
X-ray pulse profile of hot spots on neutron stars surface

Neutron star Interior Composition ExploreR (NICER)

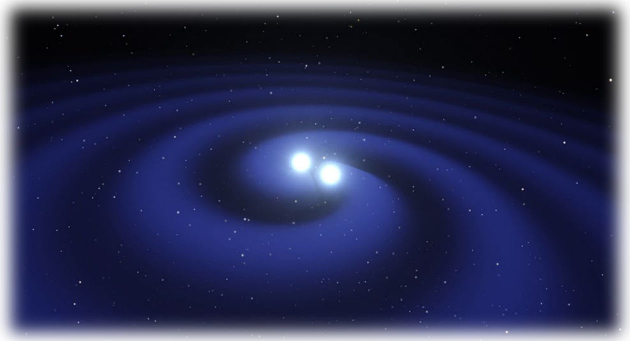


Measuring Mass and Radius

Gravitational waves of neutron stars merger

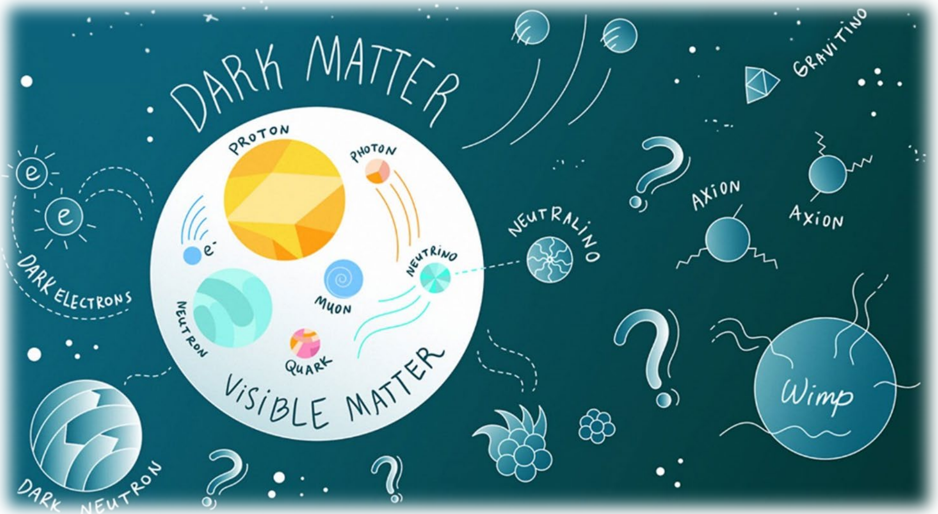


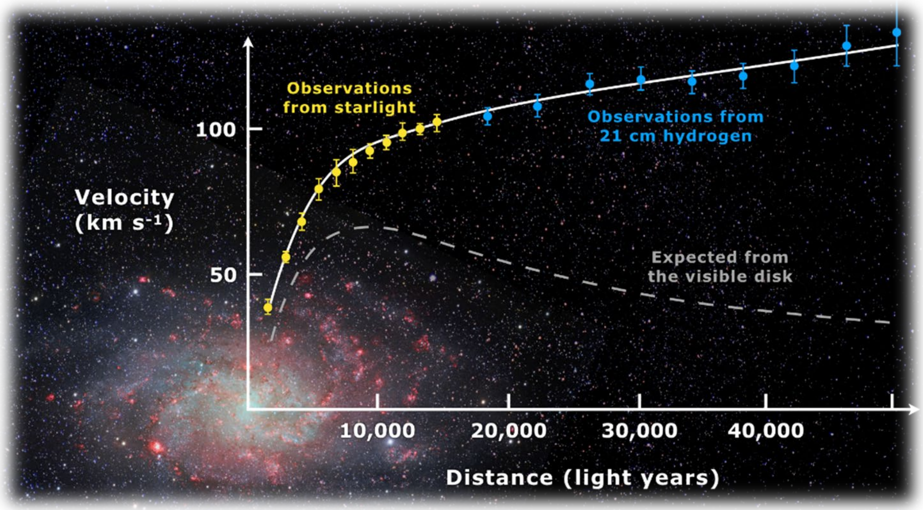
GW 170817



LIGO & Virgo GW detectors

Measuring Tidal deformability





Gravitationally stable astrophysical objects composed of dark matter

Fermionic or Bosonic dark matter even with self-interaction

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**

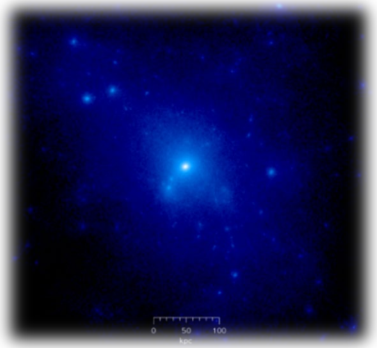
Dark matter admixed
neutron star/white dwarf

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**
S.-C. Leung, et al. **PRD 87, 123506 (2013)**
C.J. Horowitz**, PRD 102 (2020) 8, 083031**

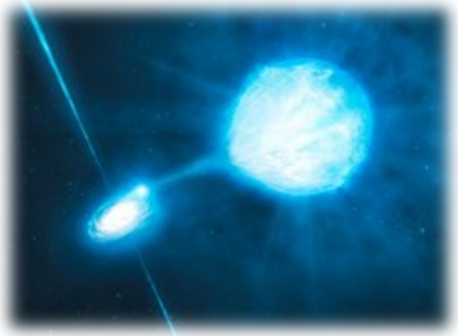
Dark matter (DM) admixed neutron star (NS)

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)

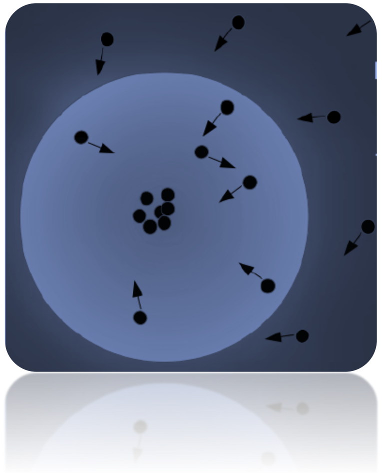


Dark star as an accretion center of baryonic matter

DM production in the NS matter or supernova explosions

Neutron decay anomaly

Accretion of DM into a NS



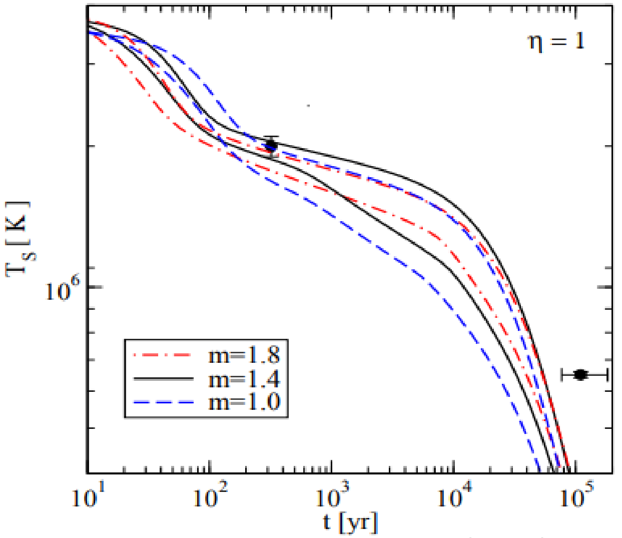
DM capture by NS in a binary system including Dark star or Dark star – NS merger

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***

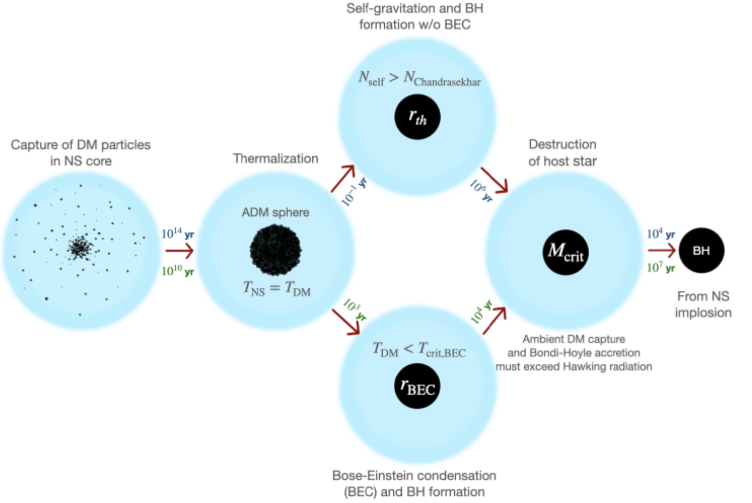
Ang Li, et al. ***astropartphys.2012.07.006***
S. Shirke, S. Ghosh, D. Chatterjee, L. Sagunski, J. Schaffner-Bielich, ***arXiv:2305.05664***
W. Husain, T. F. Motta, A.W. Thomas, ***JCAP 10 (2022) 028***

Cooling and Heating of NSs



Armen Sedrakian, ***PRD. 93 (2016) 6, 065044 PRD. 99, 043011 (2019)***
M. A. Pérez-García, H. Grigorian, et al. **Physics Letters B 827(2022)136937**

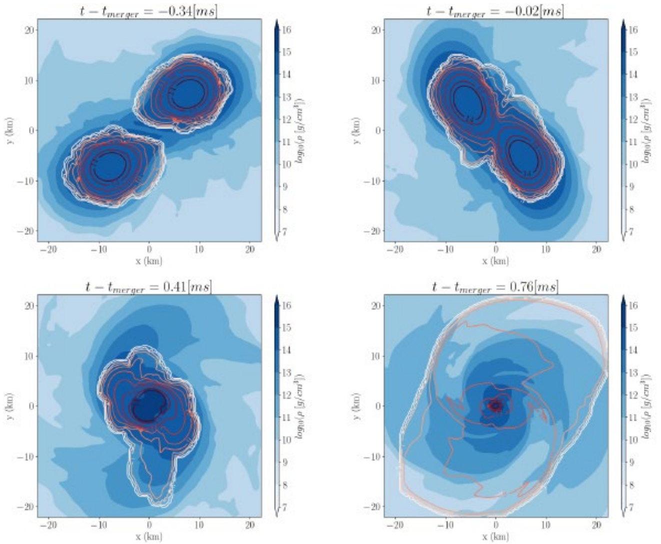
Black hole formation inside NSs



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

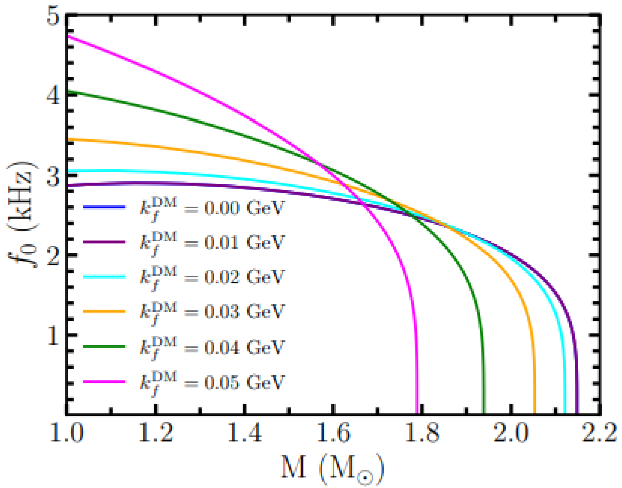
N. F. Bell, A. Melatos, K. Petraki, ***Phys.Rev.D 87 (2013) 12, 123507***

Numerical simulation of compact objects



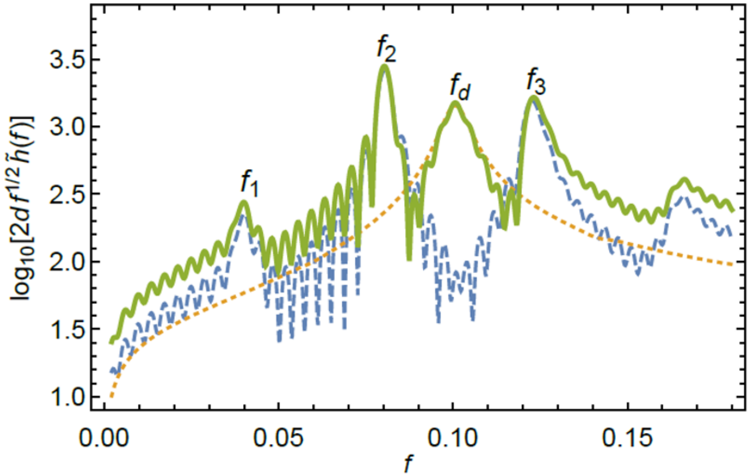
M. Emma, F. Schianchi , F. Pannarale , V. Sagun , T. Dietrich, ***Particles 5 (2022) 3, 273-286***
Andreas Bauswein, et al. ***Phys.Rev.D 107 (2023) 8, 083002***

Radial oscillation



Pinku Routray et al. ***Phys. Rev. D 107, 103039 (2023)***
S. Shirke, S. Ghosh, D. Chatterjee, L. Sagunski, J. Schaffner-Bielich, ***arXiv:2305.05664***

Gravitational waves signals



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

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**, ***arXiv:2210.17308v2***

Modeling of a DM admixed NS

Asymmetric DM

Mass, Radius and Tidal deformability

Single fluid DM admixed NS

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

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

Arpan Das, et al. ***Phys. Rev. D 99, 043016 (2019)***

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

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

Ask Mahboubhe, Prof. Blaschke

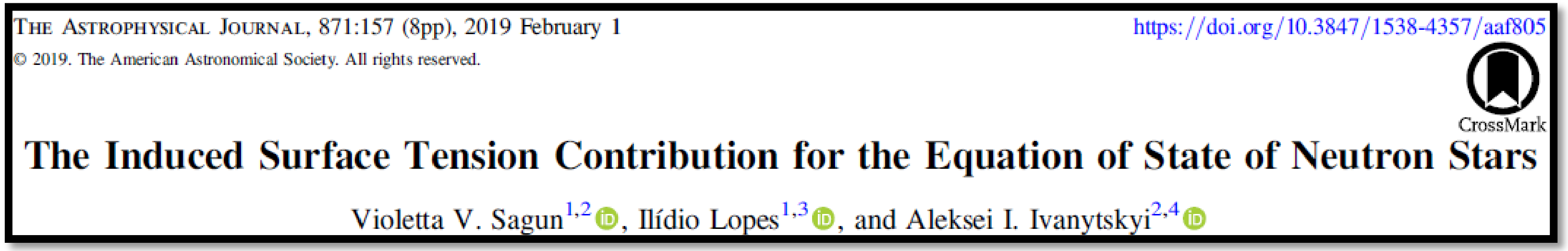
Two-fluid DM admixed NS

DM and BM interact only through gravitational force

EoS for BM and EoS for DM

Our considered model

Baryonic matter and dark matter equation of states



The Astrophysical Journal, 871:157 (8pp), 2019 February 1 https://doi.org/10.3847/1538-4357/aaf805

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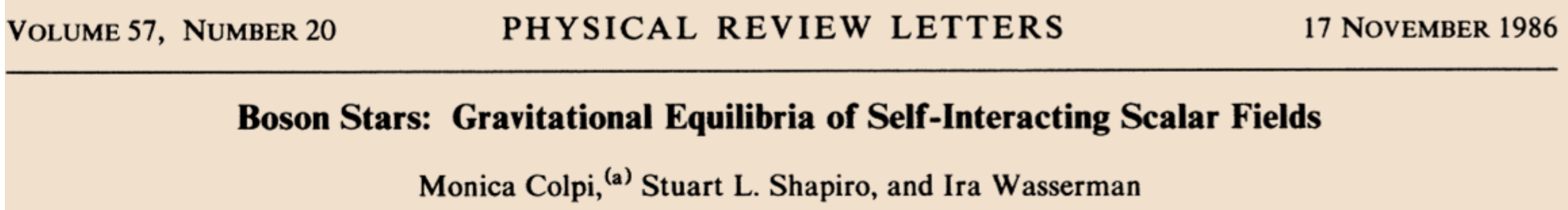
CrossMark

The Induced Surface Tension Contribution for the Equation of State of Neutron Stars

Violetta V. Sagun[1,2], Ilídio Lopes[1,3], and Aleksei I. Ivanytskyi[2,4]

BM: IST EoS, beta stable matter (n,p,e)

I. Nuclear matter ground state properties
II. Proton flow data
III. Heavy-ion collisions data
IV. Astrophysical observations



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 BS

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

Free parameters of the DM model

boson mass (m_χ), coupling constant (λ)

Strong coupling regime (Prefect fluid approximation)

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

m_χ sub-GeV bosonic DM particles (∝ 100 MeV)
Dimensionless coupling constant λ in order of 1

D.R. Karkevandi**, S. Shakeri, et al., **Phys. Rev. D 105, 023001 (2022)

Mean-field approximation

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***.

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

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

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

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

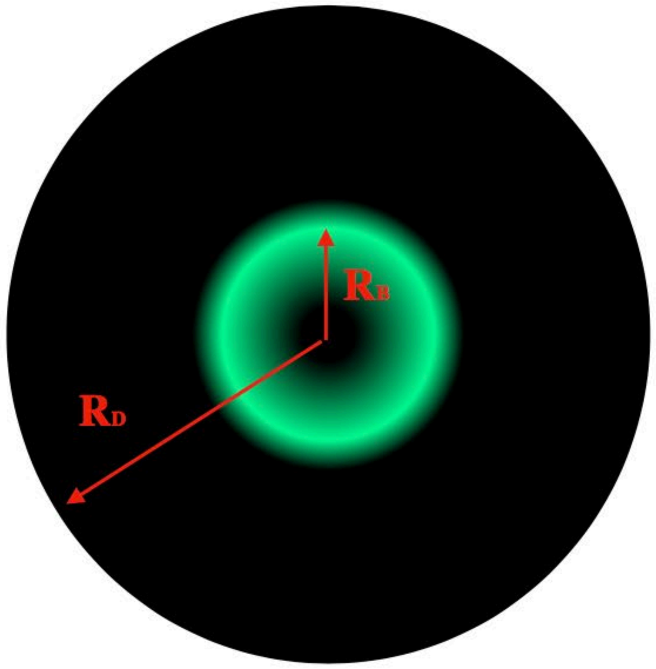
DM and BM EoSs

Two central BM and DM pressures: $p_{B_c}(r \simeq 0)$; $p_{D_c}(r \simeq 0)$

The pressure of which of the fluids gets zero first ???

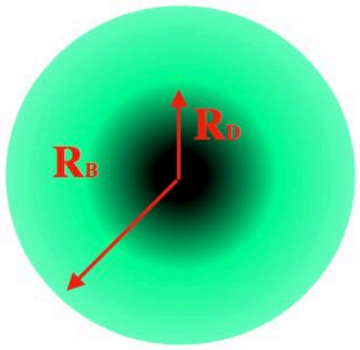
Three Possible DM distributions within NSs

DM halo



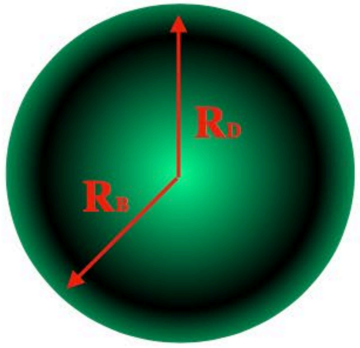
$$R_D > R_B$$

DM Core



$$R_B > R_D$$

DM distributed in entire NS



$$R_B \approx R_D$$

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

Green : BM
Black : DM

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

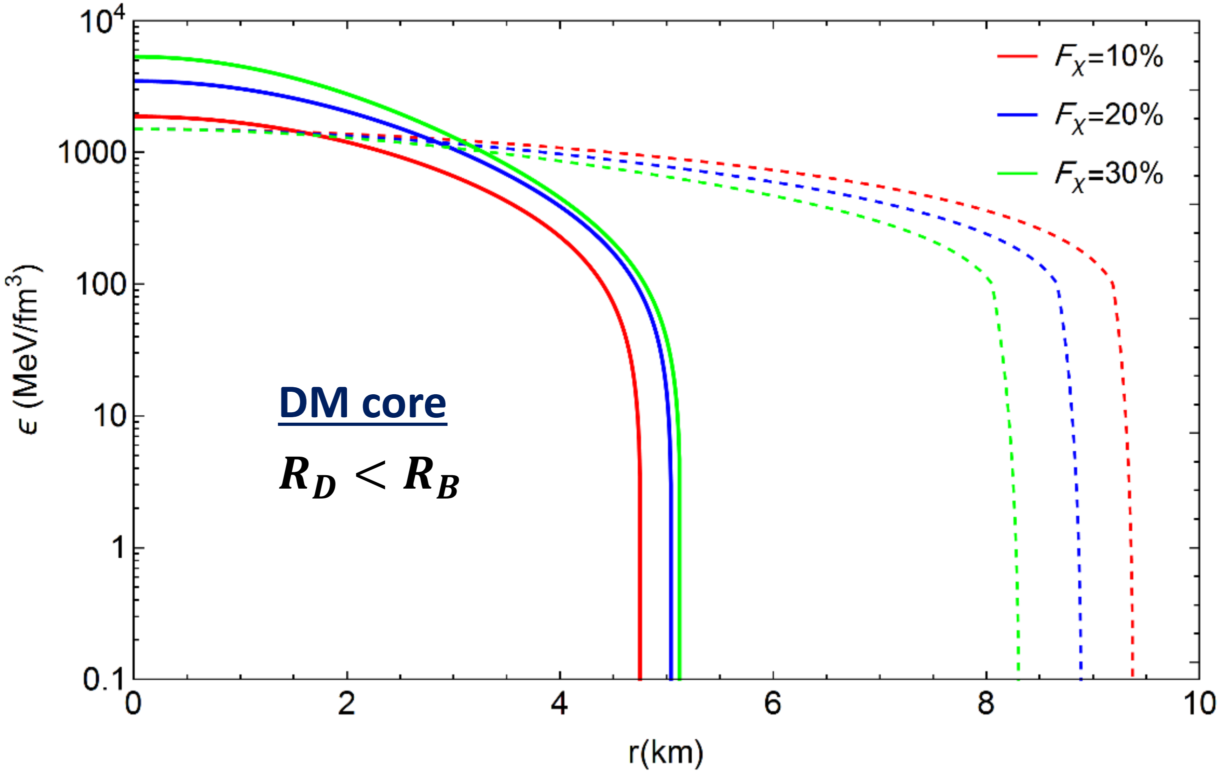
$F_\chi = \frac{M_D(R_D)}{M_T}$, DM Fraction

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]

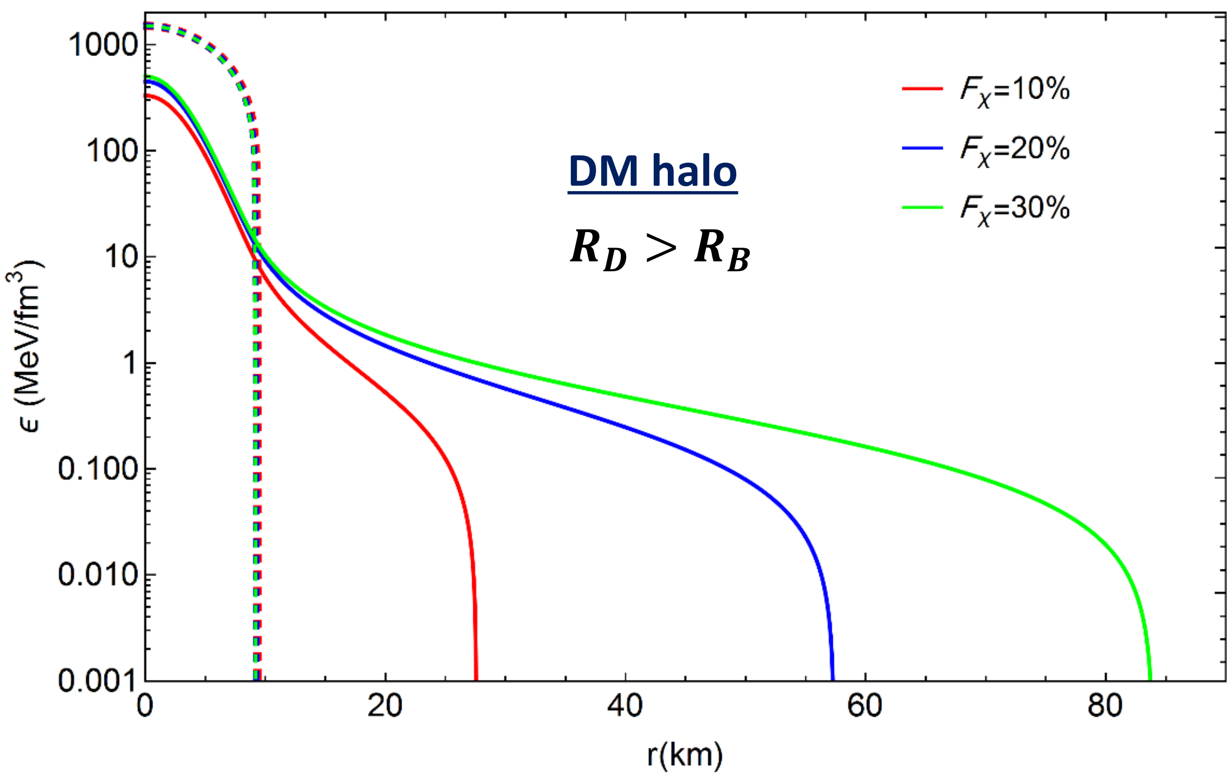
Two-fluid TOV → Energy density profile of a DM admixed NS

Solid lines : DM fluid (R_D) **Dashed lines**: BM fluid (R_B)



m_χ = 400 MeV
$\lambda = \pi$

Heavy DM particles reside as a dense core inside NSs



m_χ = 100 MeV
$\lambda = \pi$

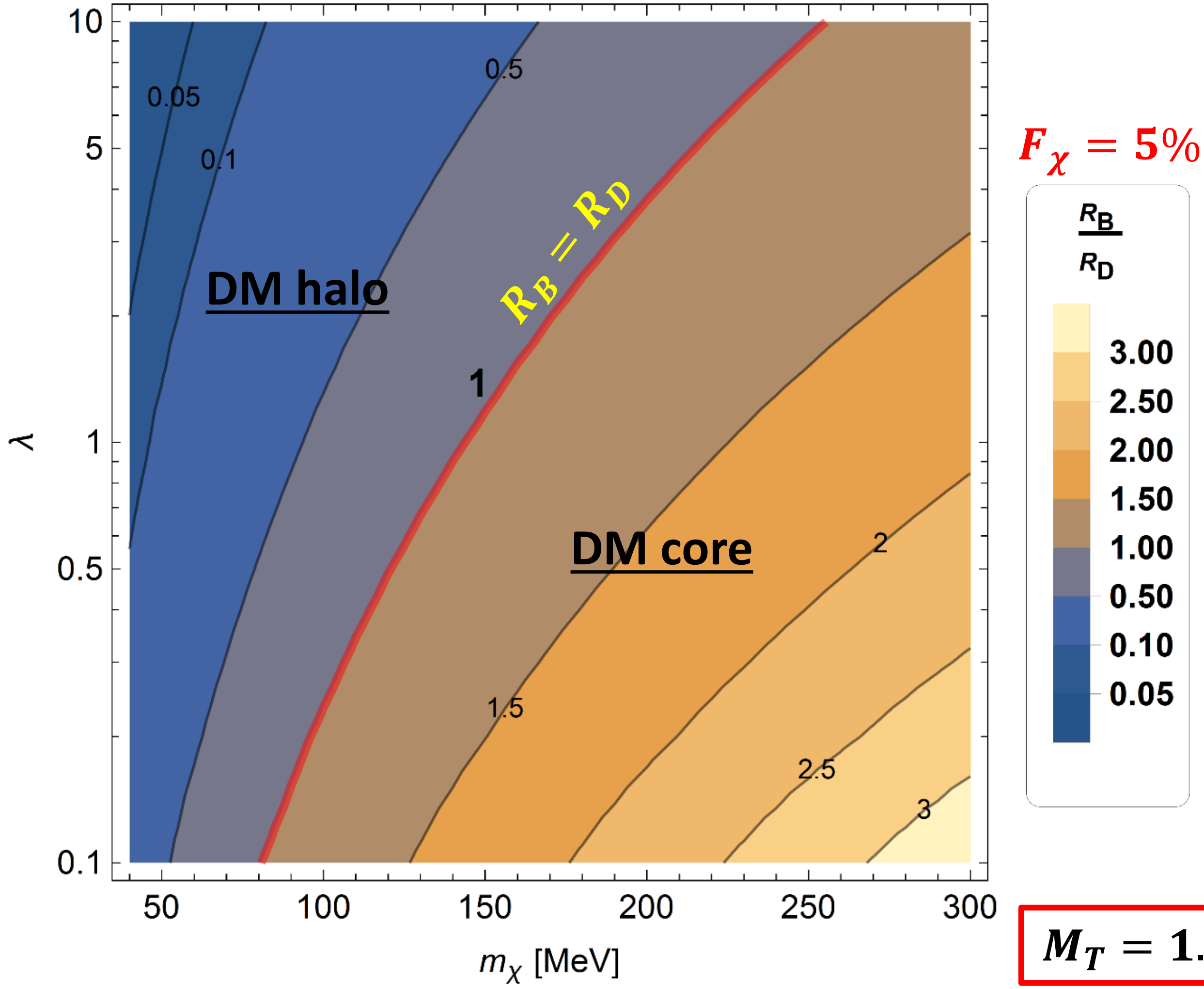
Light DM particles form an extended halo around NSs

DM core and DM halo formation in the mixed compact object

A transition can be seen from DM core to DM halo formation

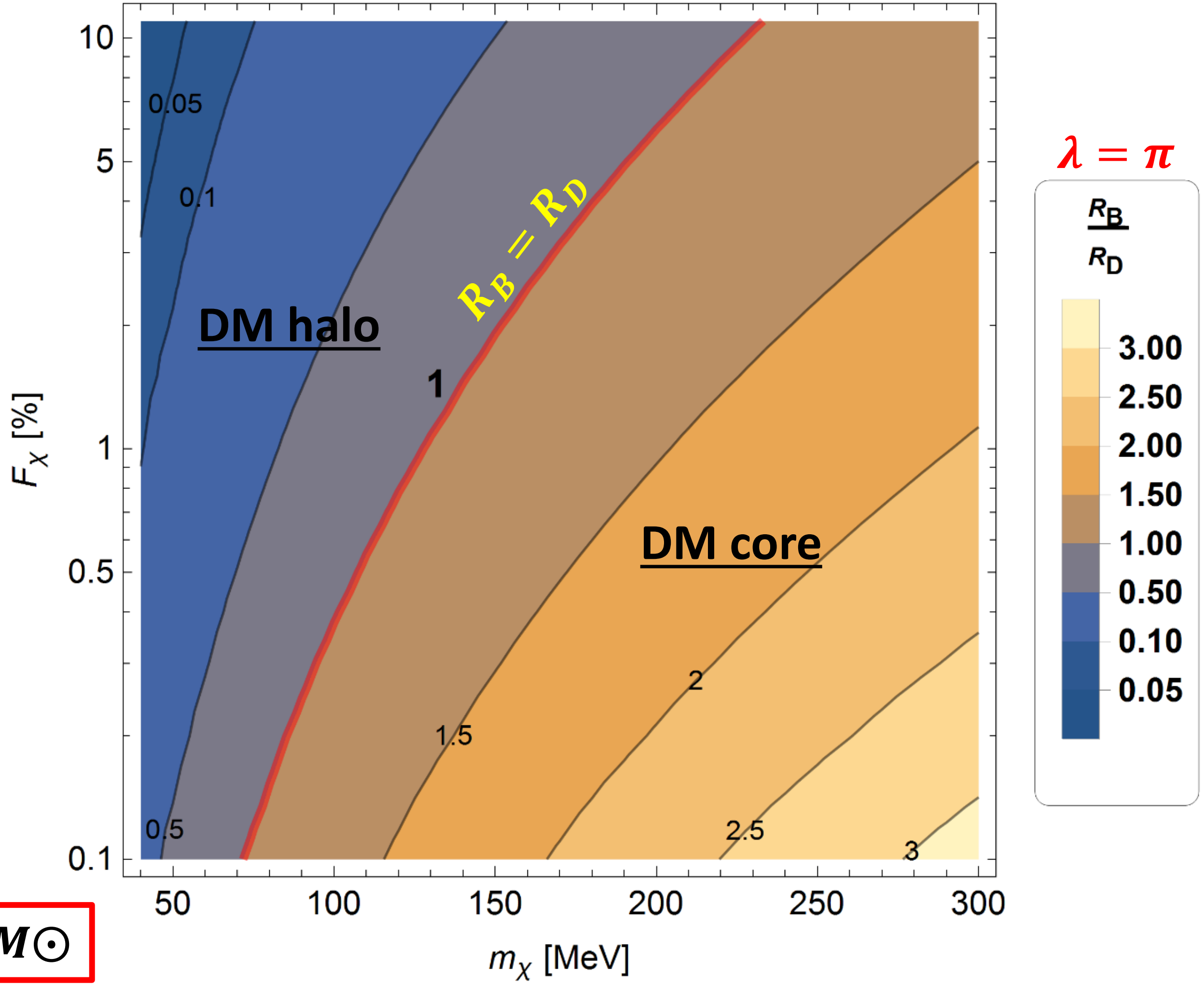
D.R. K, et al. ***Phys. Rev. D 105, 023001 (2022)***

$\lambda - m_\chi$ parameter space



$F_\chi = 5\%$

$F_\chi - m_\chi$ parameter space



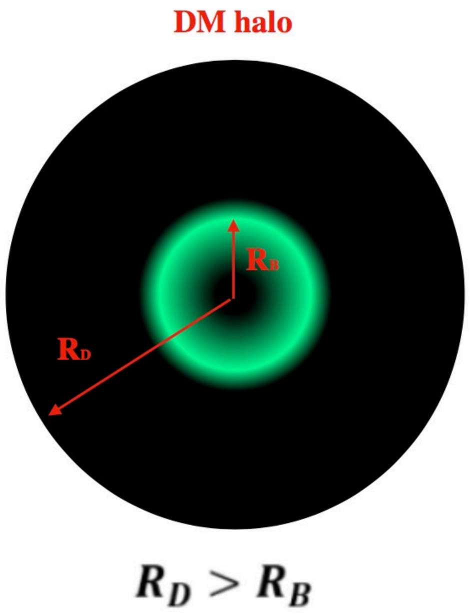
$\lambda = \pi$

$M_T = 1.4 M_\odot$

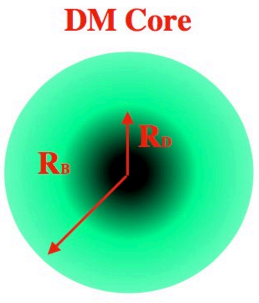
S. Shakeri, **D.R. K**, ***arXiv:2210.17308v2***

Mass-Radius profile of DM admixed NSs

<u>Outermost</u> radius of DM admixed NSs are considered



$R_D > R_B$



$R_B > R_D$

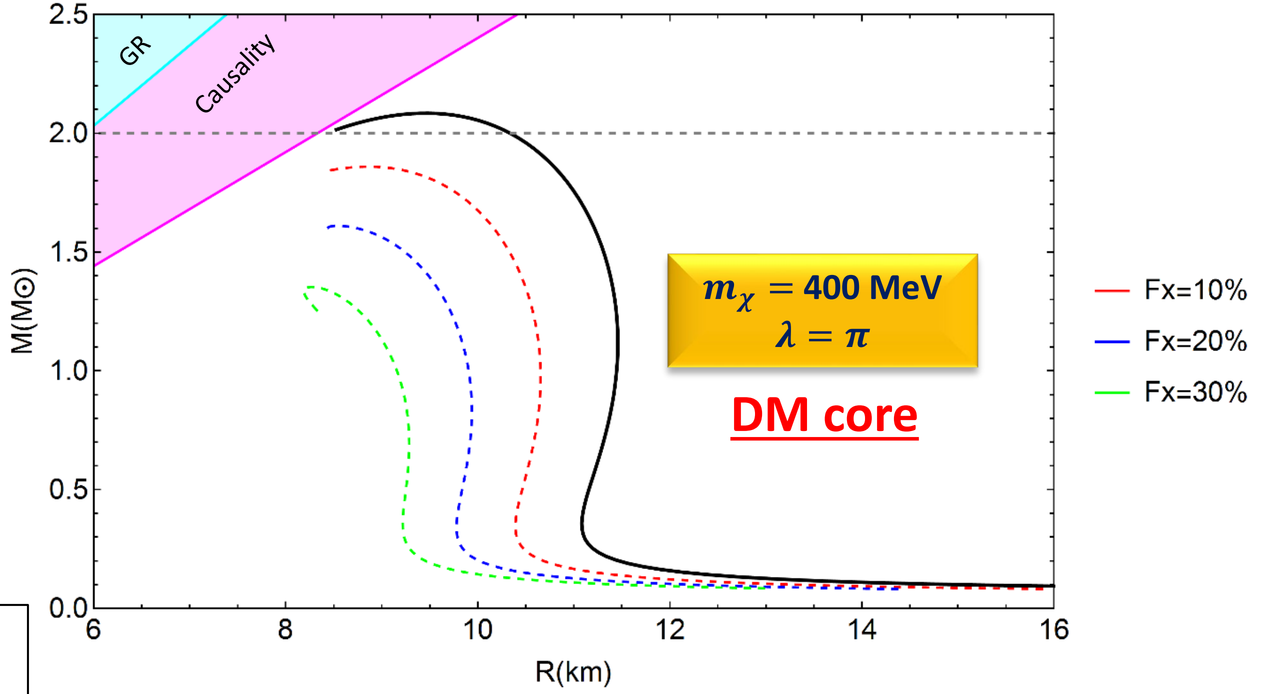
Black solid line

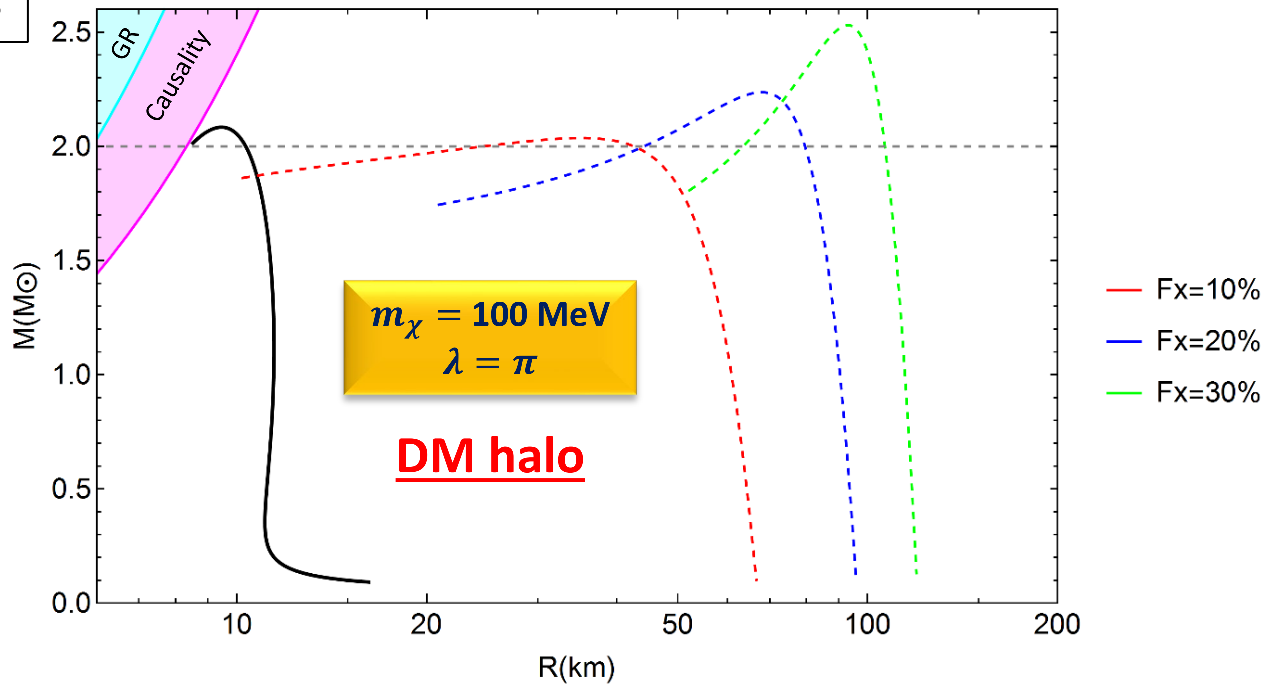
<u>Only BM (without DM)</u>

Maximum mass: 2.08 M⊙

<u>DM core</u> → **<u>Decrease</u>** **in maximum mass and radius**

<u>DM halo</u> → **<u>Increase</u>** **in maximum mass and radius**



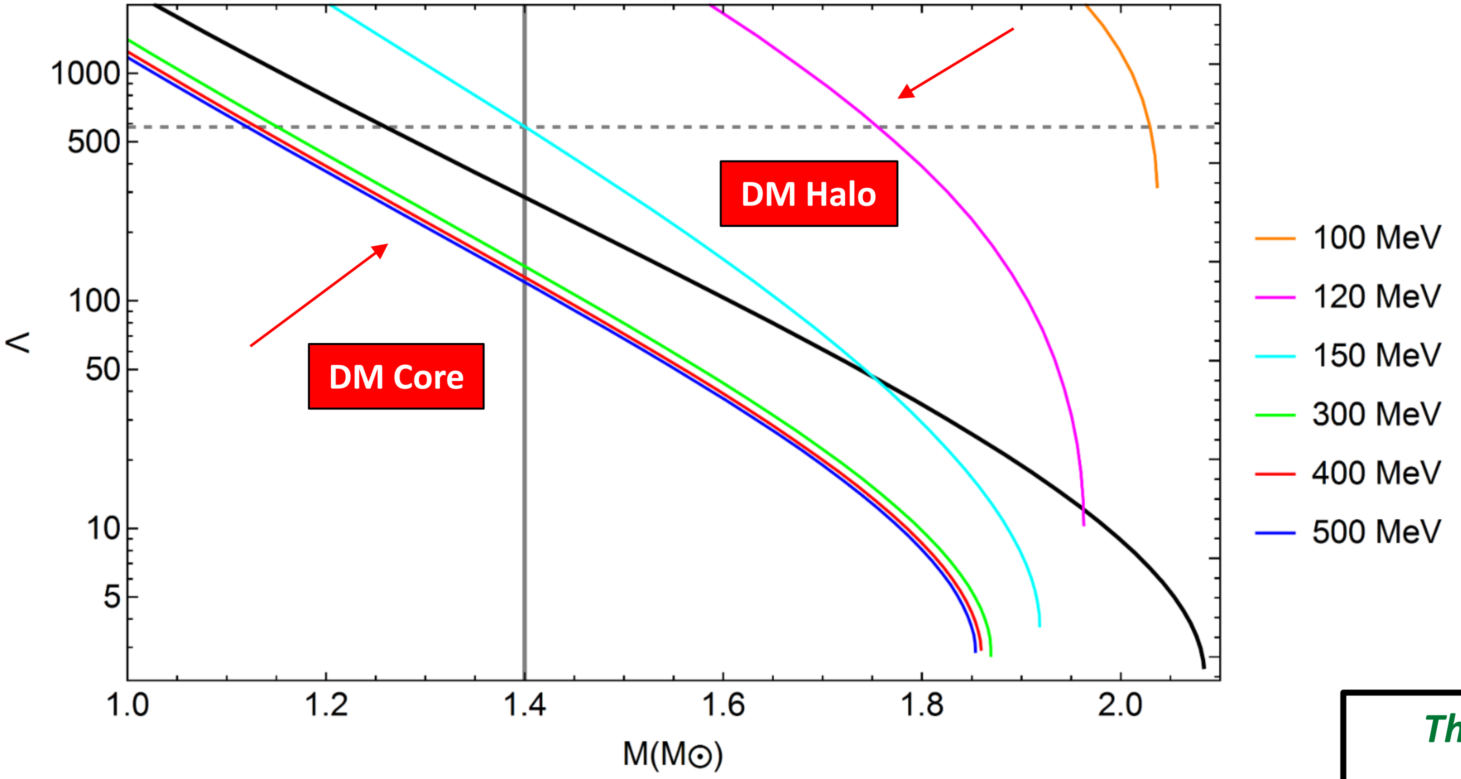


Tidal deformability of DM admixed NSs

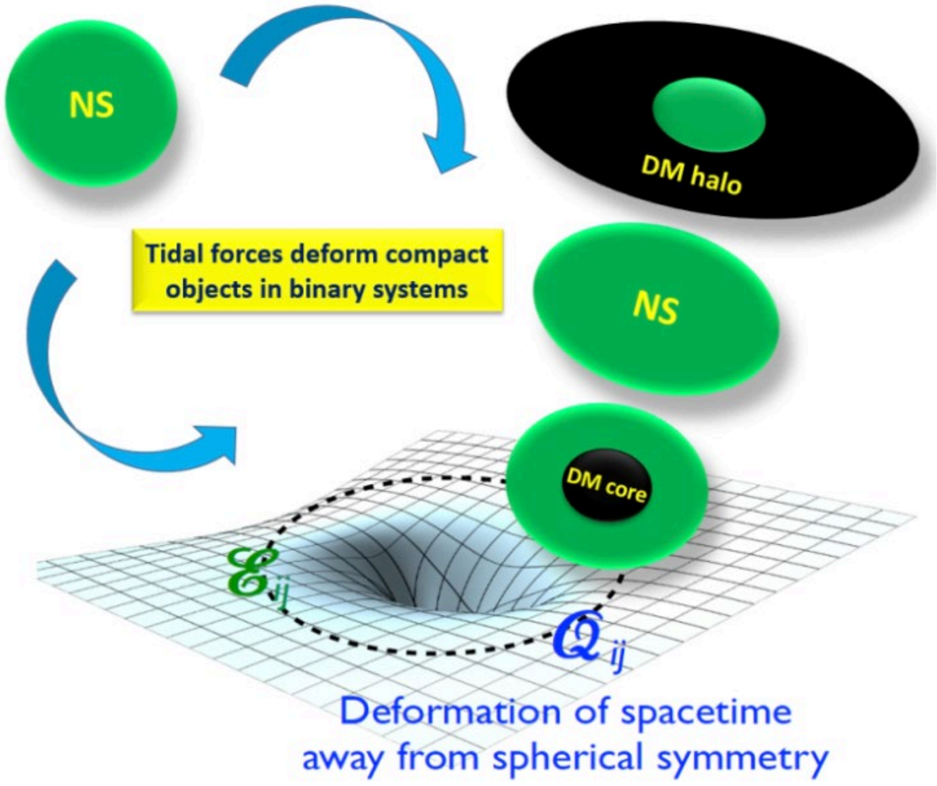
Black solid line: Only BM (without DM)

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

Gray solid line : $M = 1.4M_\odot$ Gray dashed line: $\Lambda = 580$



$\lambda = \pi$ and $F_\chi = 10\%$



Tidal forces deform compact objects in binary systems

Deformation of spacetime away from spherical symmetry

The effect of tidal deformability on the deformation of DM admixed NSs in comparison to the pure baryonic NS

DM core $\Longrightarrow$ Decreases tidal deformability

DM halo $\Longrightarrow$ Increases tidal deformability

Heavy bosonic particles → **DM core formation inside NSs** → **Decrease in maximum mass and radius**

Light bosonic particles → **DM halo formation around NSs** → **Increase in tidal deformability**

Considering multi-messenger constraints from GW and X-ray observations

$M_{max} \geq 2M\odot$

M. C. Miller, *et al.* **2021 *ApJL* 918 L28**
T. E. Riley, *et al.* **2021 *ApJL* 918 L27**

$R_{1.4M\odot} \geq 11\ km$

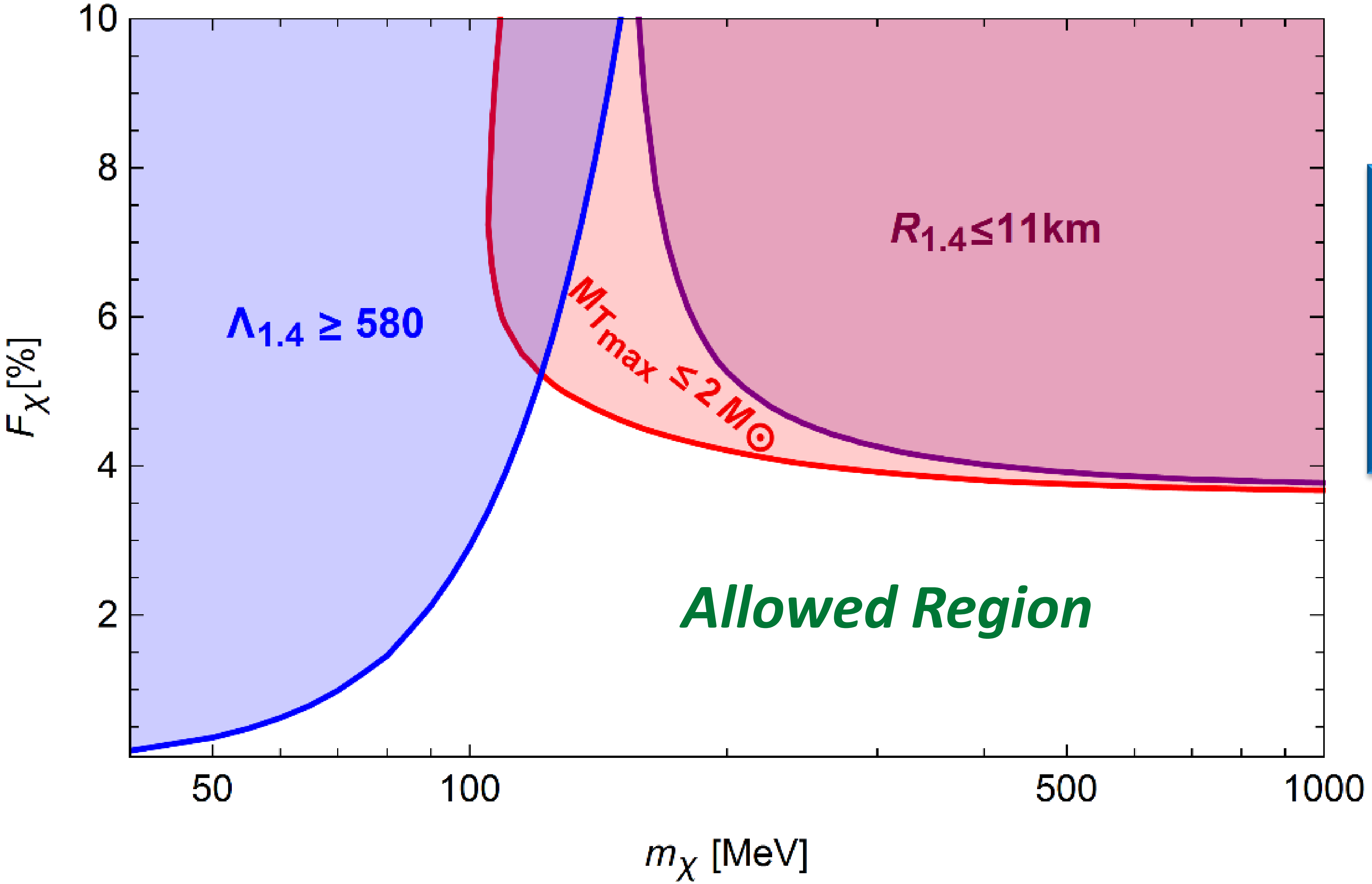
S. Huth et al. ***Nature 606 (2022) 276-280.***
Tim Dietrich, et al. ***Science 370 (2020) 652.***

$\Lambda_{1.4} \leq 580$

LIGO Scientific and Virgo Collaborations
***Phys.Rev.Lett.* 121 (2018) 16**

investigating the possible DM fraction (F_{χ}) inside DM admixed NSs and probing the bosonic DM model parameters (m_{χ},λ)

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

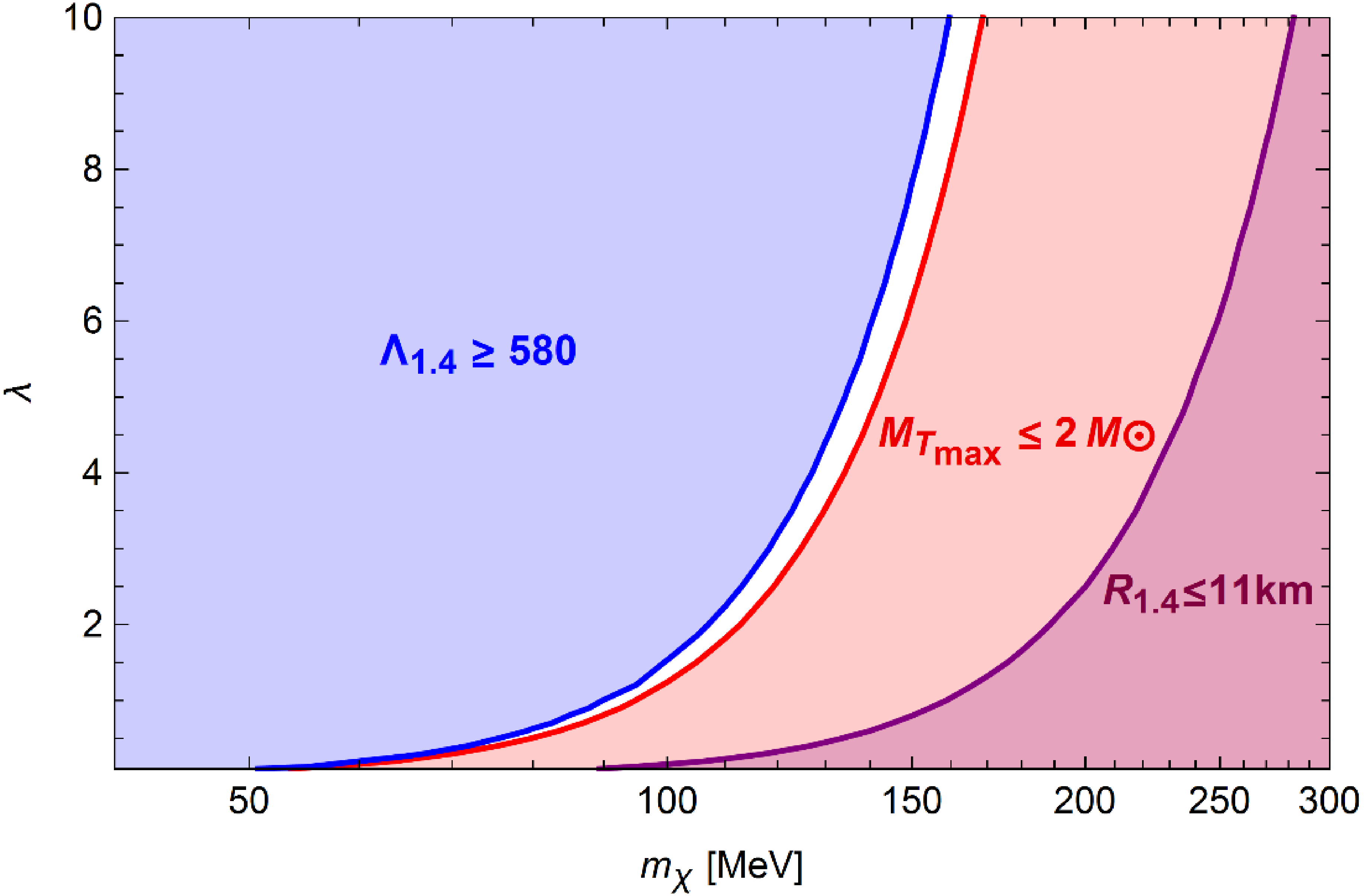


Low DM fractions in NSs $F_\chi \leq 5\%$, are favorable for sub-GeV bosonic particles in strong coupling regime.

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

S. Shakeri, D.R. K, ***arXiv:2210.17308v2***

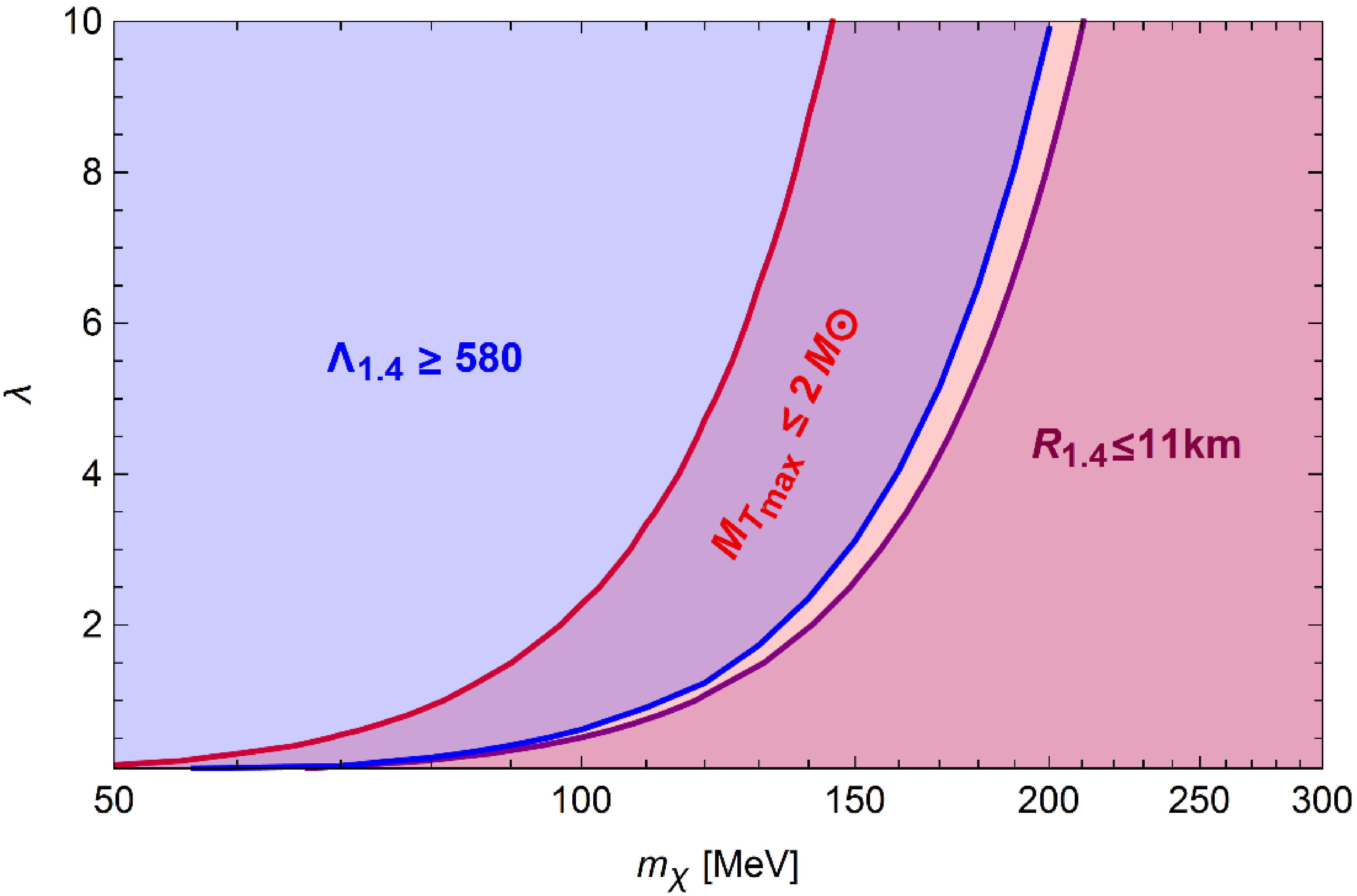
Scan over the $\lambda - m_\chi$ parameter space of DM admixed NSs for $F_\chi = 5\%$



It is seen that the $\lambda - m_\chi$ parameter space of bosonic DM is significantly limited by the astrophysical constraints of NSs.

S. Shakeri, **D.R. K**, ***arXiv:2210.17308v2***

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

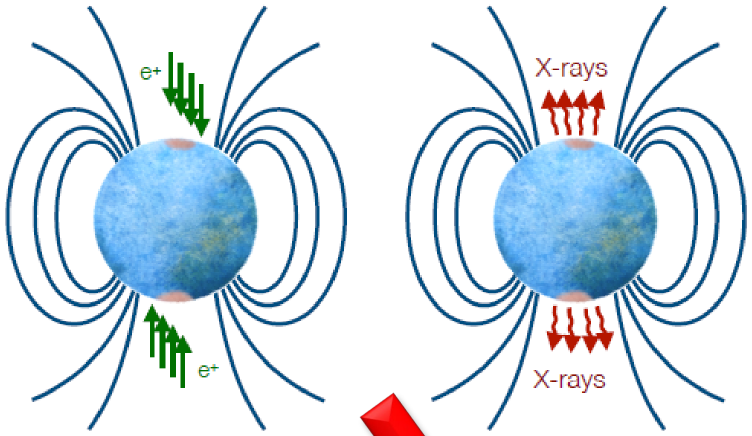


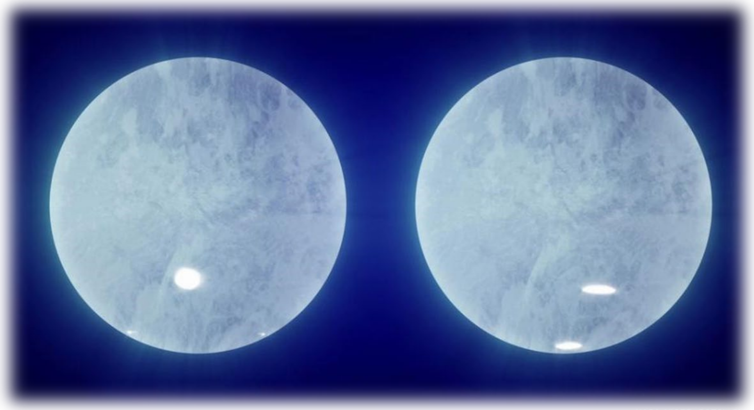
For $F_\chi \gtrsim 5\%$ the Sub-GeV bosonic particles in strong self-coupling regime are not consistent with $M_{T_{max}}$, $R_{1.4}$ and $\Lambda_{1.4}$ constraints.

S. Shakeri, **D.R. K**, ***arXiv:2210.17308v2***

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

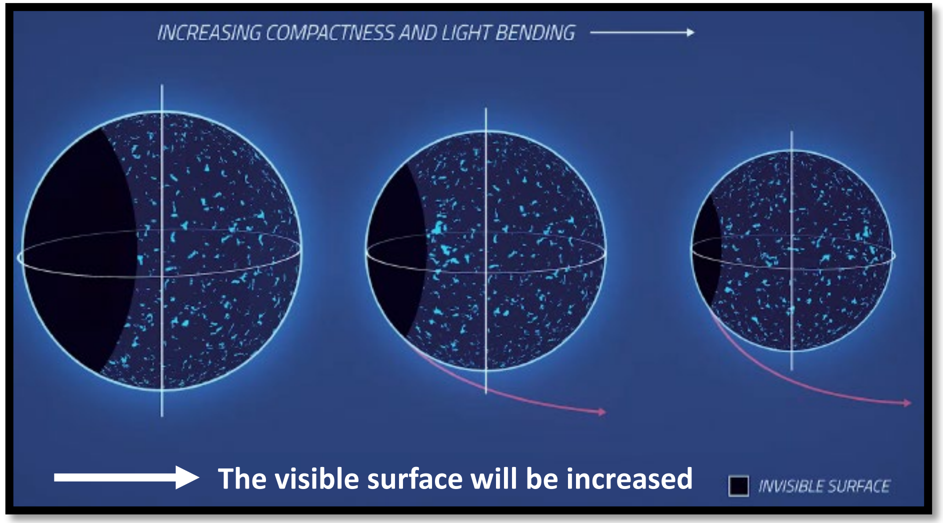
X-ray hot spots on NSs surface





PSR J0030+0451, NASA's Neutron star Interior Composition ExploreR (NICER)

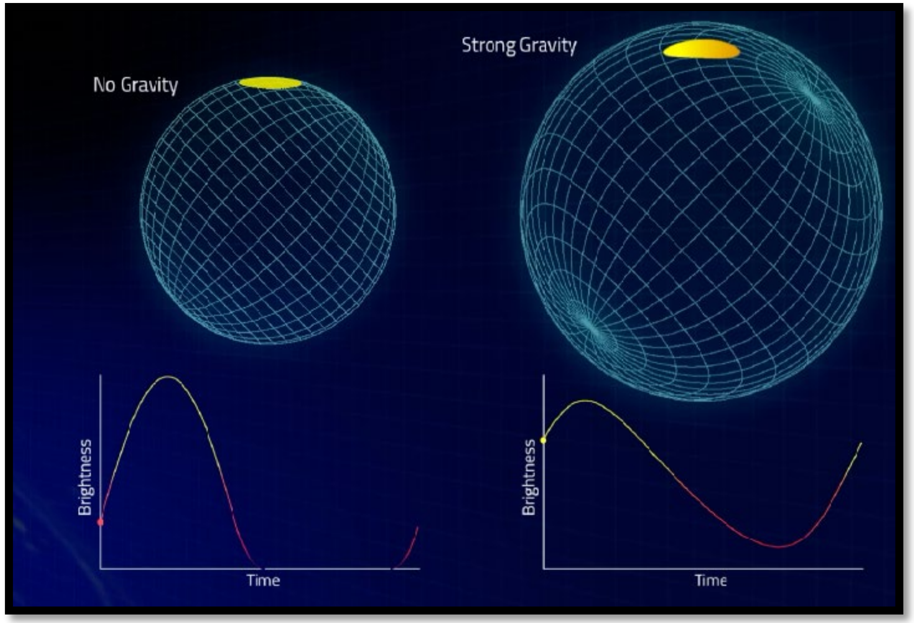
The effect of compactness on the visible surface



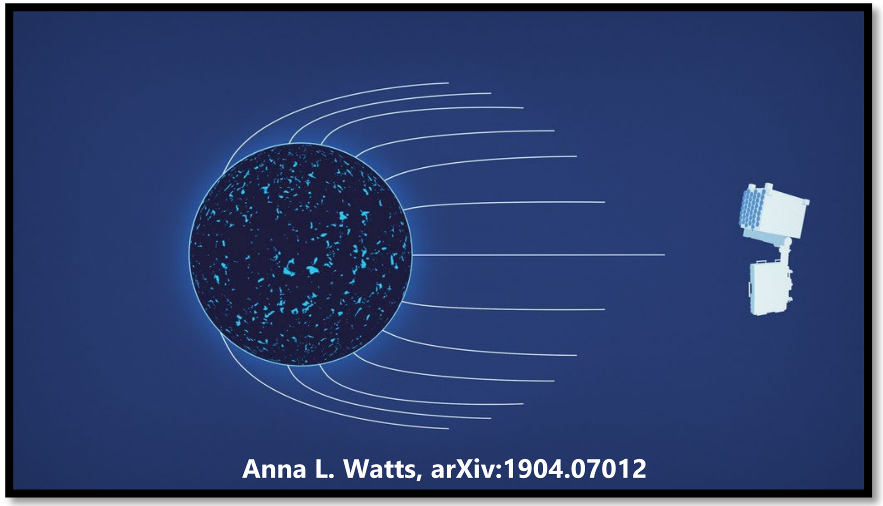
Credit: NASA's Goddard Space Flight Center Conceptual Image Lab

Gravitational light bending due to the curved space-time in the vicinity of NSs surface.

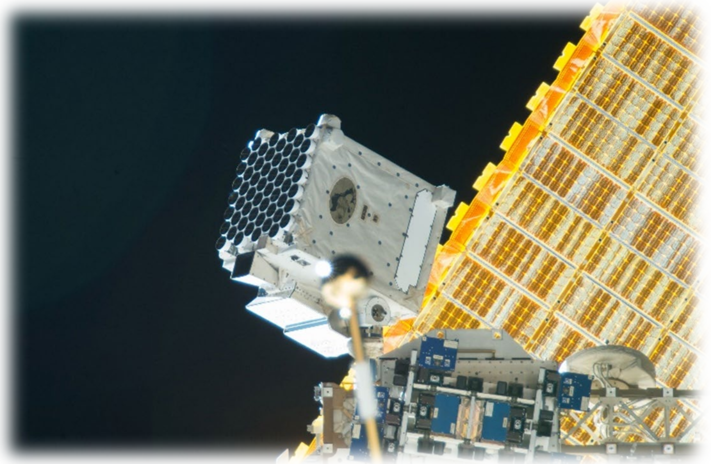
The impact of Gravity on the X-ray pulse profile



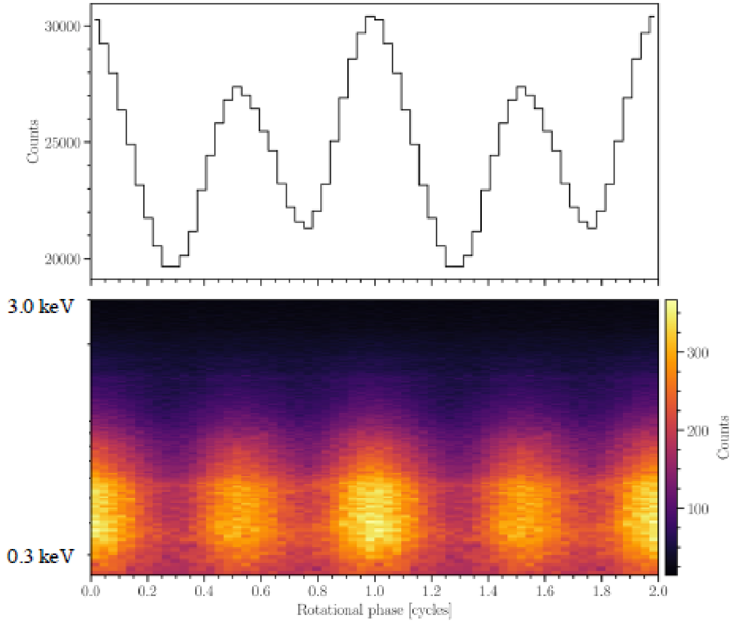
Neutron star Interior Composition ExploreR (NICER)



Anna L. Watts, arXiv:1904.07012

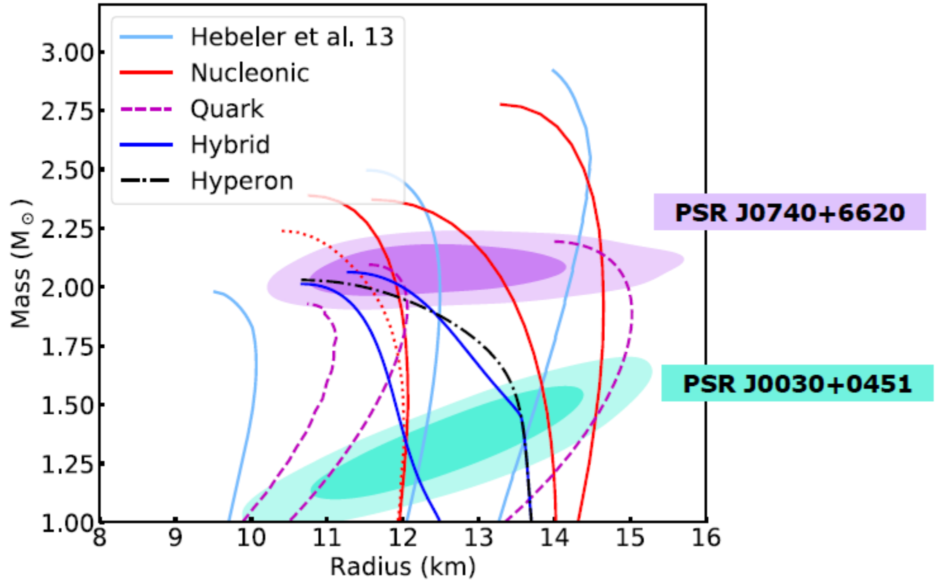


PSR J0030+0451 light curve (pulse profile)

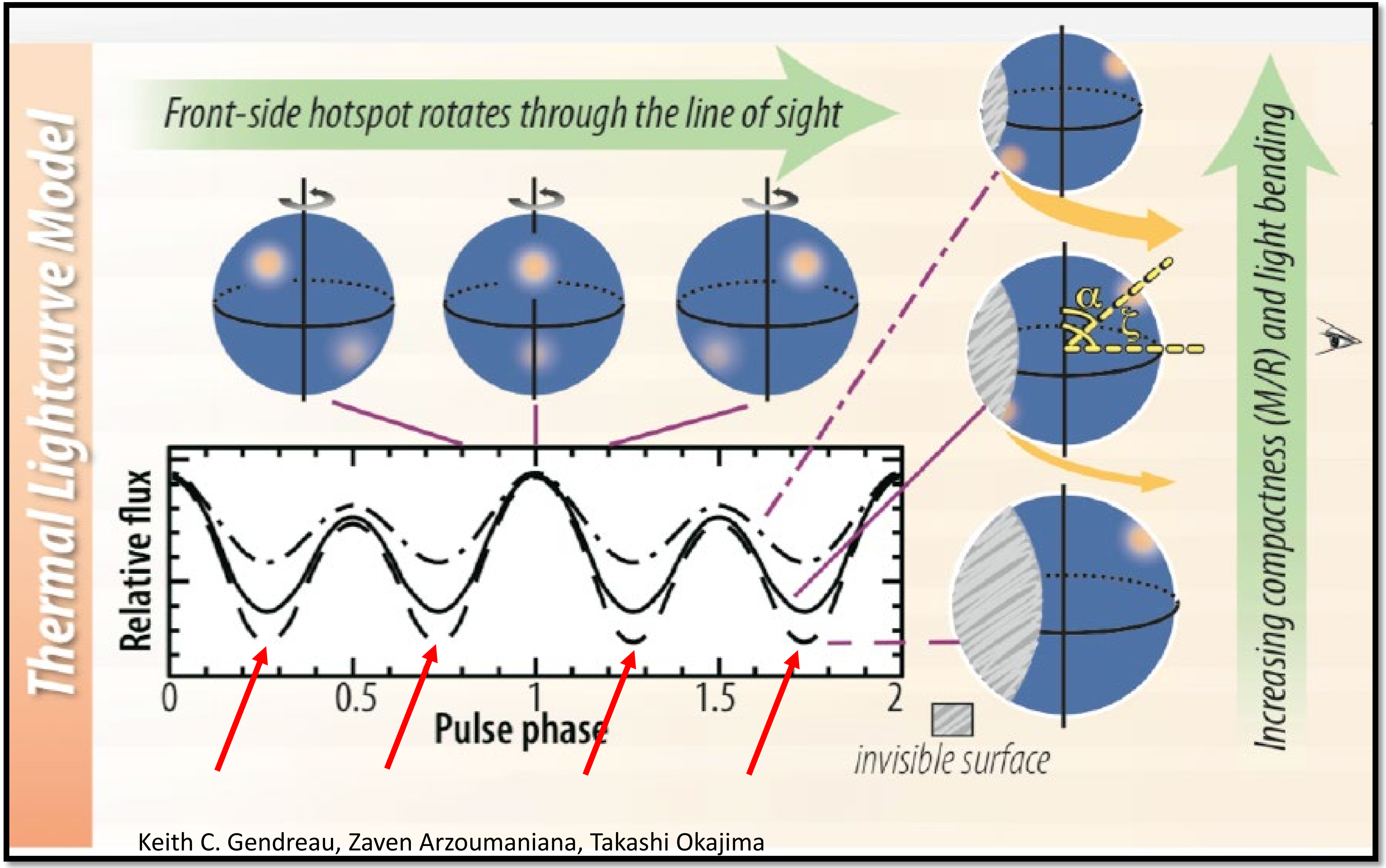


By coupling such lightcurve models to a sampler, one can use Bayesian inference to derive posterior probability distributions for mass and radius, or the EOS parameters, directly from pulse profile data.

M. C. Miller *et al* 2021 *ApJL* 918 L28
T. E. Riley *et al* 2021 *ApJL* 918 L27



The effect of compactness on the pulse profile of neutron stars



Keith C. Gendreau, Zaven Arzoumaniana, Takashi Okajima

As the photons propagate through the curved space-time of the star, information about mass and radius is encoded into the shape of the waveform (pulse profile) via special and general relativistic effects.

The effect of compactness on the pulse profile of DM admixed NSs with DM halo

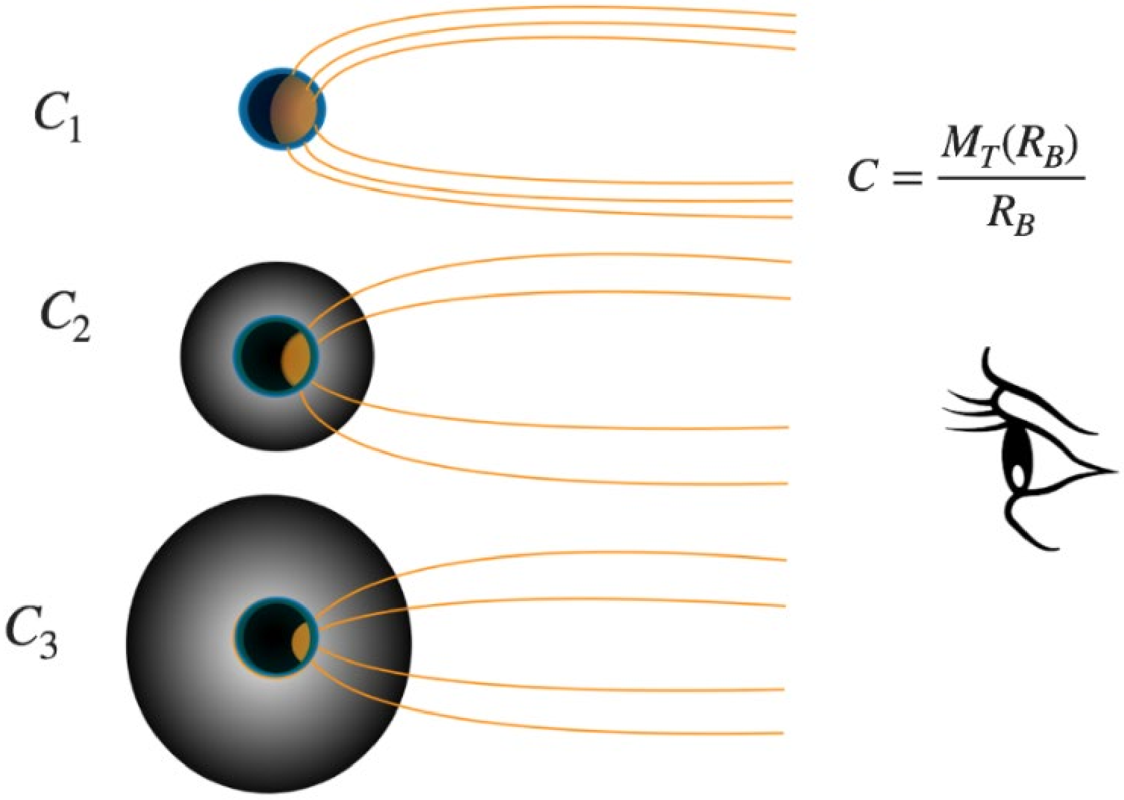
DM halo around NSs changes the compactness of the object

DM halo alters the geometry outside the visible surface of the star

The light propagation will be affected due to the halo of DM

Investigating the impacts of DM halo on the X-ray pulse profile of DM admixed NSs

Visible surface is increasing with the compactness

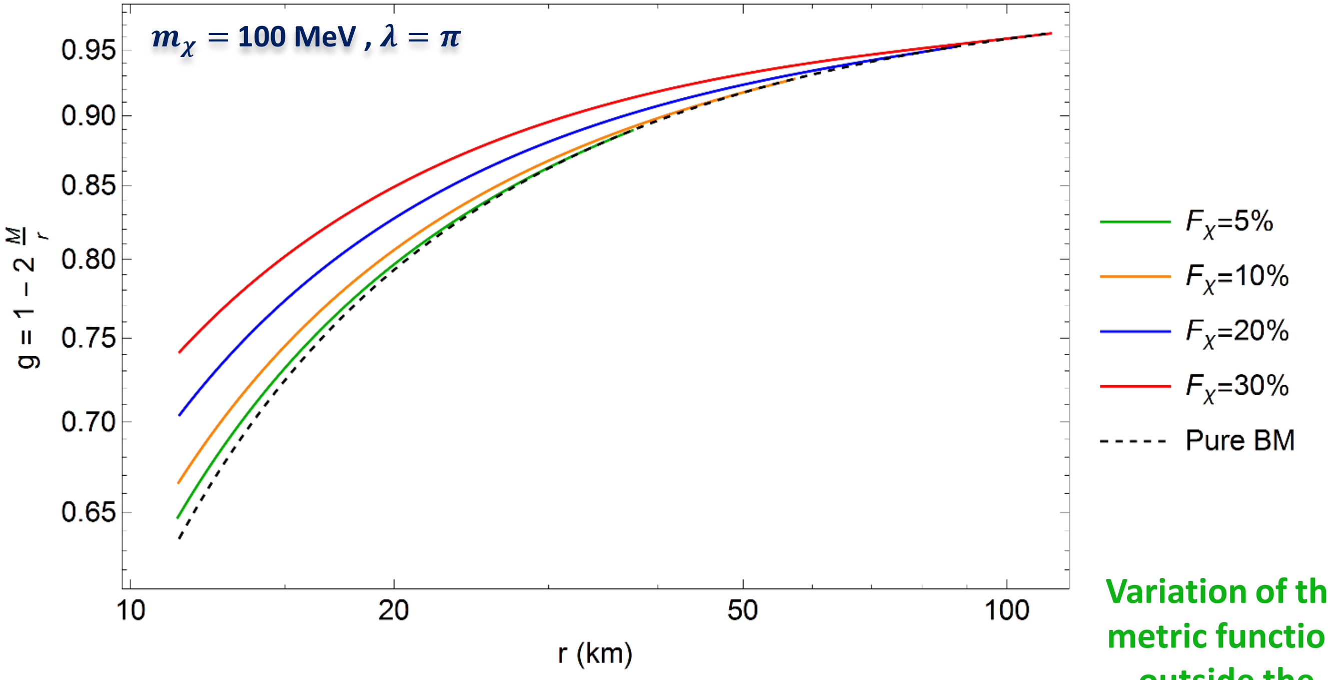


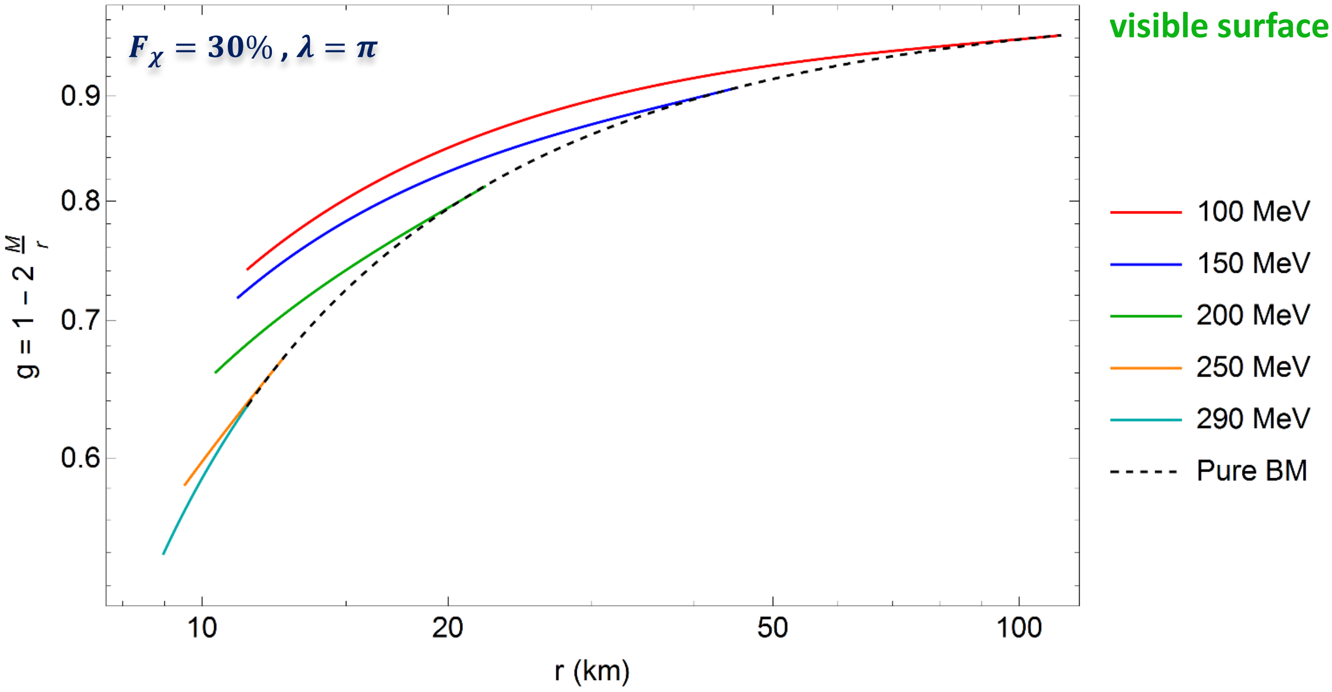
$$C = \frac{M_T(R_B)}{R_B}$$

$C_1 > C_2 > C3$

$M_T = 1.4 M_\odot$ **For all cases**

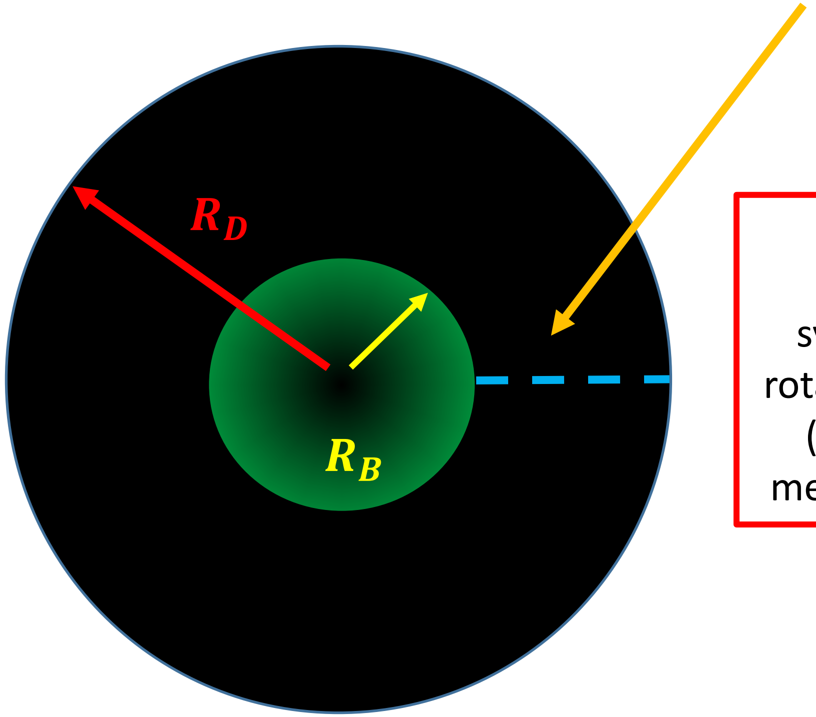
We need to determine the metric function $g(r)$ outside the surface of NS by taking into account the DM halo contribution





Variation of the metric function outside the visible surface.

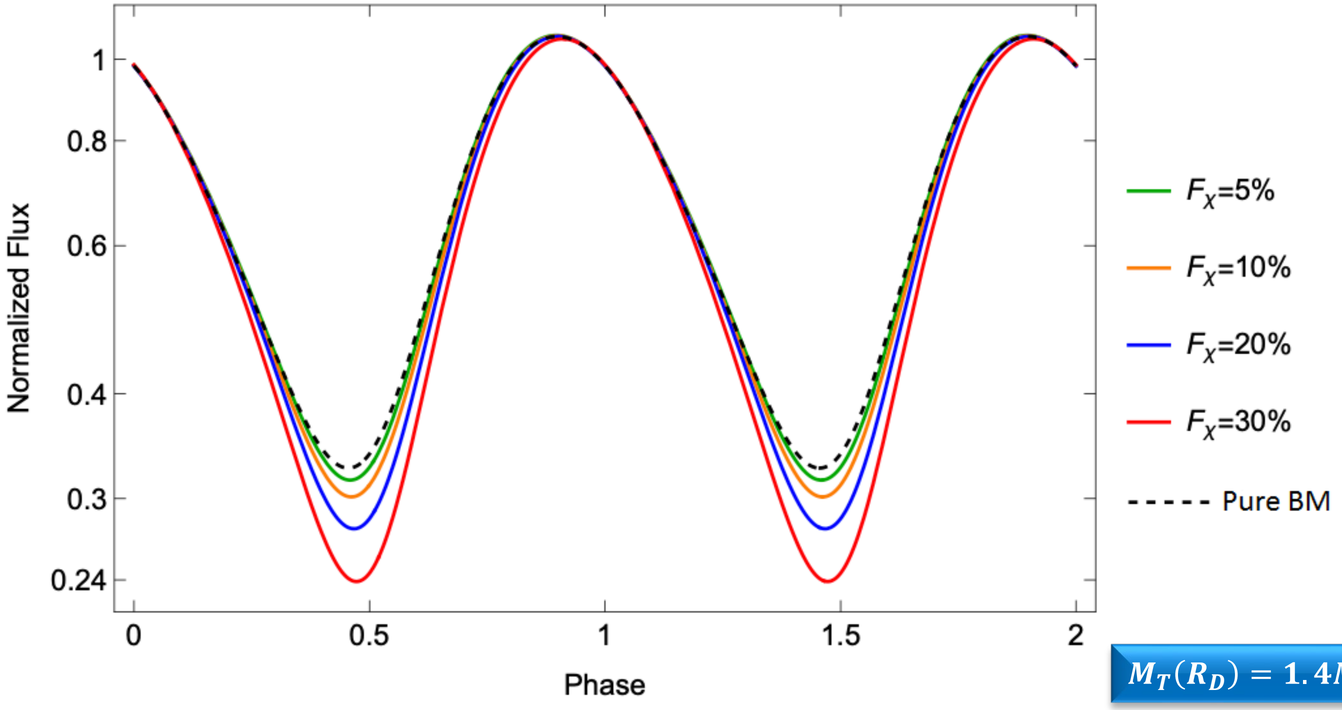
$$g(r) = f(r)^{-1} = 1 - 2M(r)/r$$



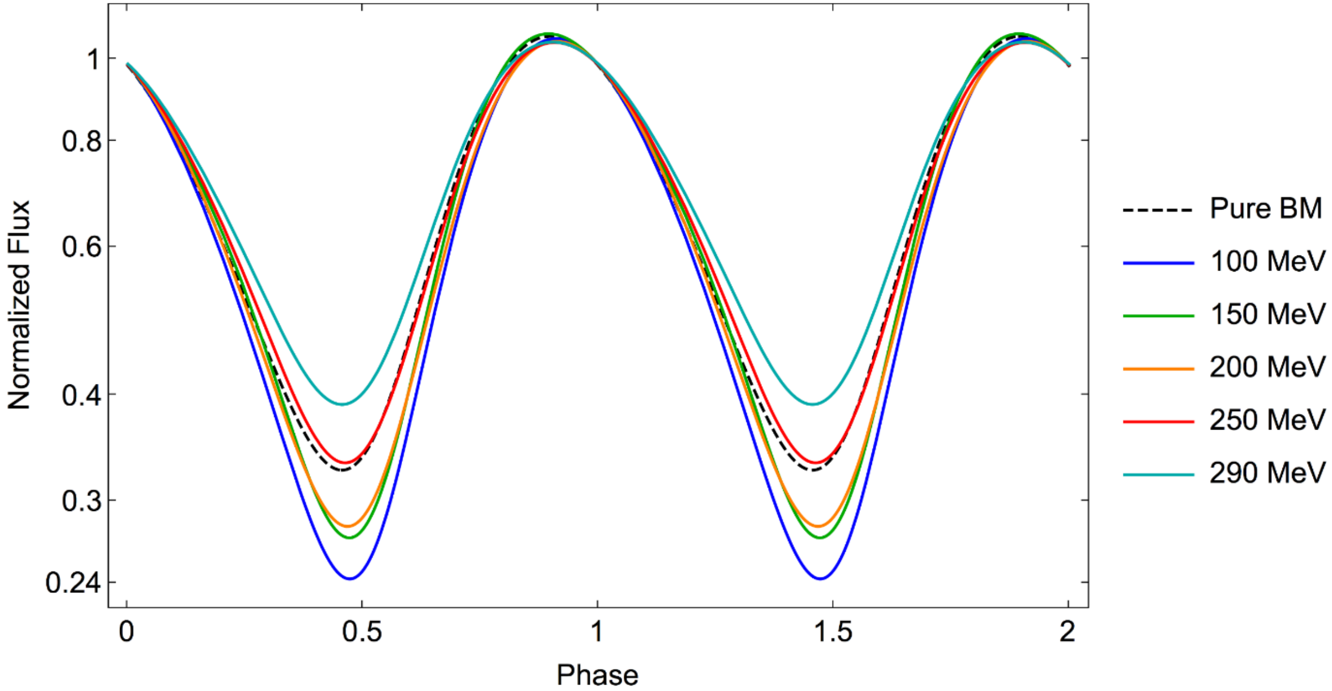
We assume a spherically symmetric non-rotating space-time (Schwarzschild metric) outside R_B

$M_T(R_D) = 1.4M_\odot$ for all of the cases, thus for an observer outside the DM halo, the mixed objects are similar to a star with total mass $1.4M_\odot$.

S. Shakeri, **D.R. K**, ***arXiv:2210.17308v2***



$M_T(R_D) = 1.4M_\odot$



The pulse profile of DM admixed NSs

The fall and grow of the flux as a function of the rotational phase is due to changing the position of the spot compare to a distant observer, **the minimum flux corresponds to the far-side position**.

The **depth of the minimums** crucially depends on the **compactness,** *the* ***less compact object*** *gives* ***more deeper minimum***.

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

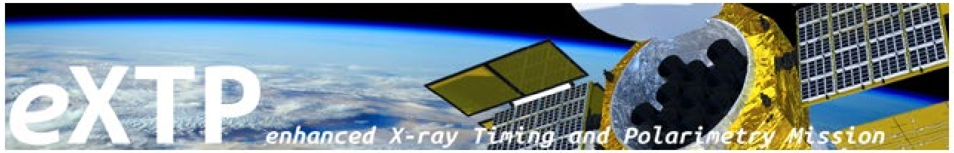
Our results show that the **DM admixed NSs** could be considered **as a novel possibility** in the **Pulse Profile modeling** and **numerical simulation codes** to interpret X-ray observations of compact objects during the **(Bayesian) analysis** of NICER, STROBE-X and eXTP telescopes.

S. Shakeri, **D.R. K**, ***arXiv:2210.17308v2***

KAGRA

ET EINSTEIN TELESCOPE

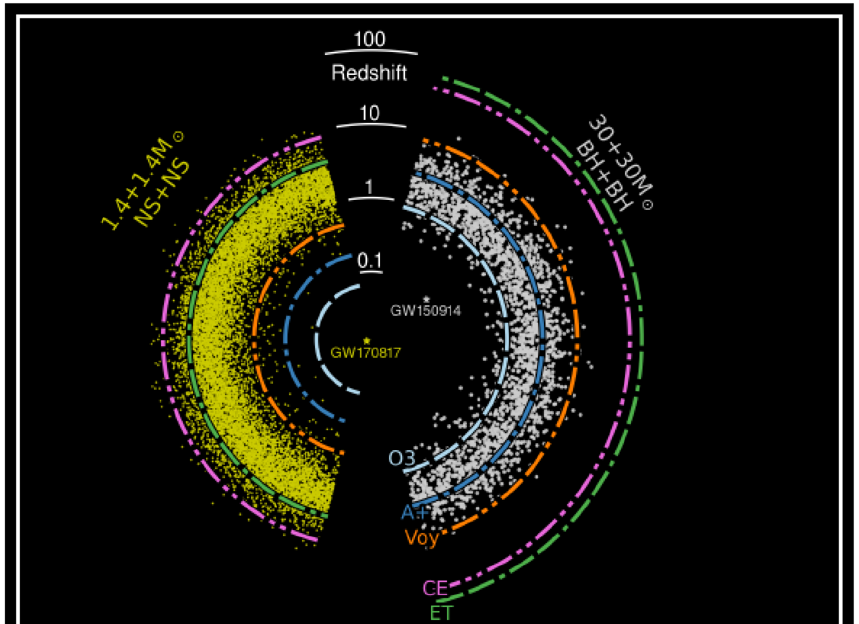
MeerKAT



LISA CONSORTIUM

COSMIC EXPLORER

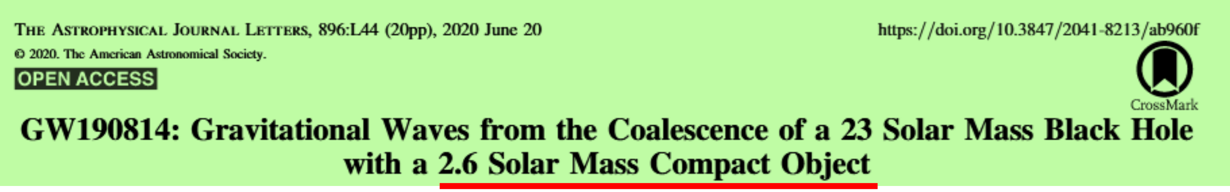
H.E.S.S.



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

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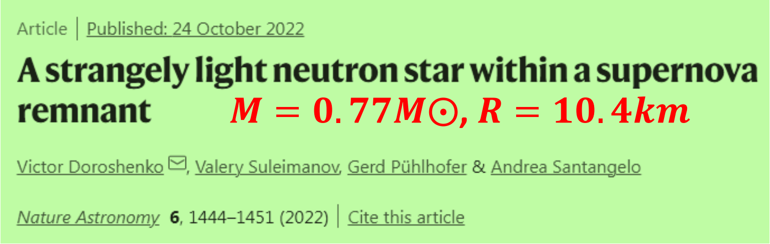
GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object



Article | Published: 24 October 2022

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

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)
arXiv:2306.12326
arXiv:2307.12748

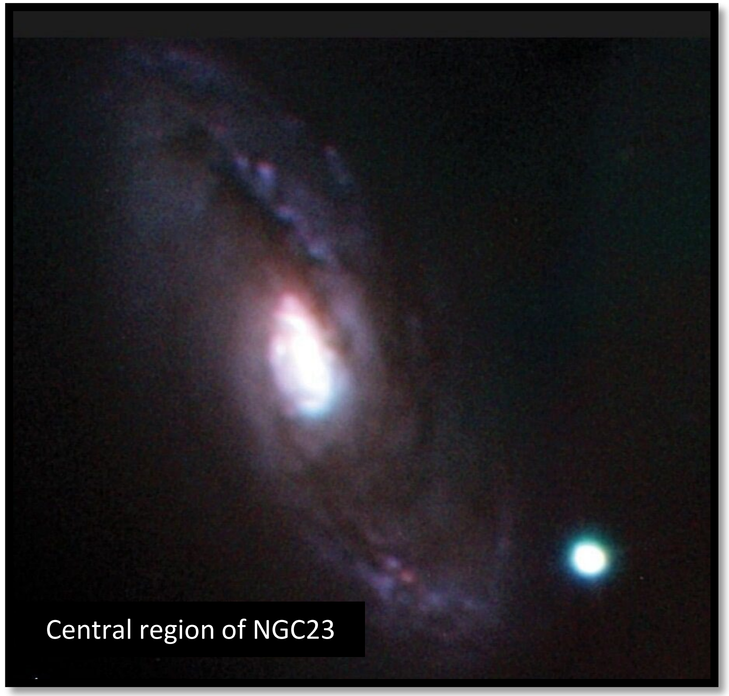
Optical observations of Neutron Stars

Iranian National Observatory (INO)

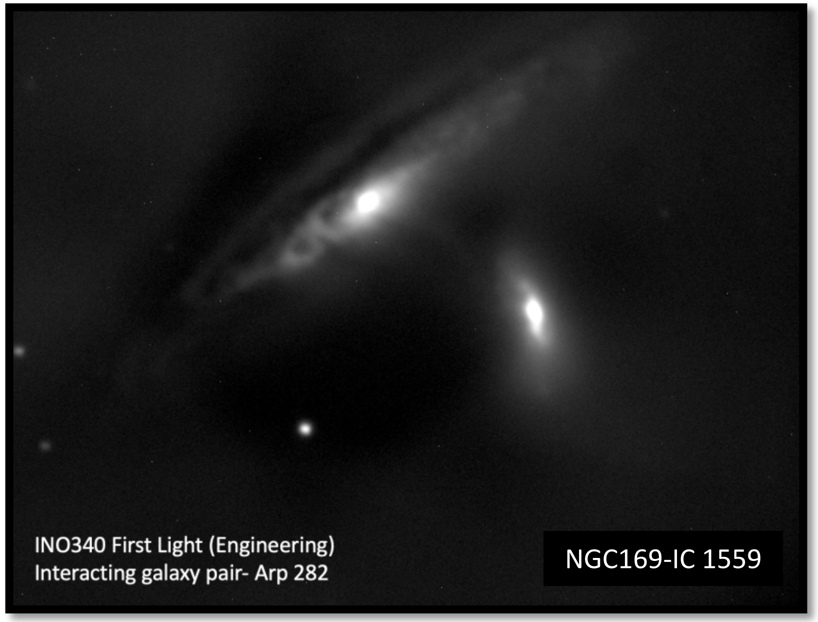
3.4 meter optical telescope

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

Thank you very much for your attention and also for organizing this outstanding conference