Probing bosonic dark matter in the light of multi-messenger constraints of neutron stars

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INT PROGRAM INT-22-2B

Dark Matter in Compact Objects, Stars, and in Low Energy Experiments

August 1, 2022 - September 2, 2022

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ICRANet-Isfahan, Iran

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University of Coimbra, Portugal

Oleksii Ivanytskyi
University of Wroclaw, Poland

Key References

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

D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, **Sixteenth Marcel Grossmann Meeting**, MG16 Proceedings, 08 July 2021, **[arXiv:2112.14231]**

D.R. Karkevandi, S. Shakeri, **PHAROS Conference**, Poster Presentation, La Sapienza University, May 2022

D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, Presented in **17th Italian-Korean Symposium for Relativistic Astrophysics** - 05 August, 2021

V. Sagun, O. Ivanytskyi, I. Lopes, D.R. Karkevandi, S. Shakeri, Presented in **The Modern Physics of Compact Stars and Relativistic Gravity**, Yerevan, Armenia, 29 September 2021

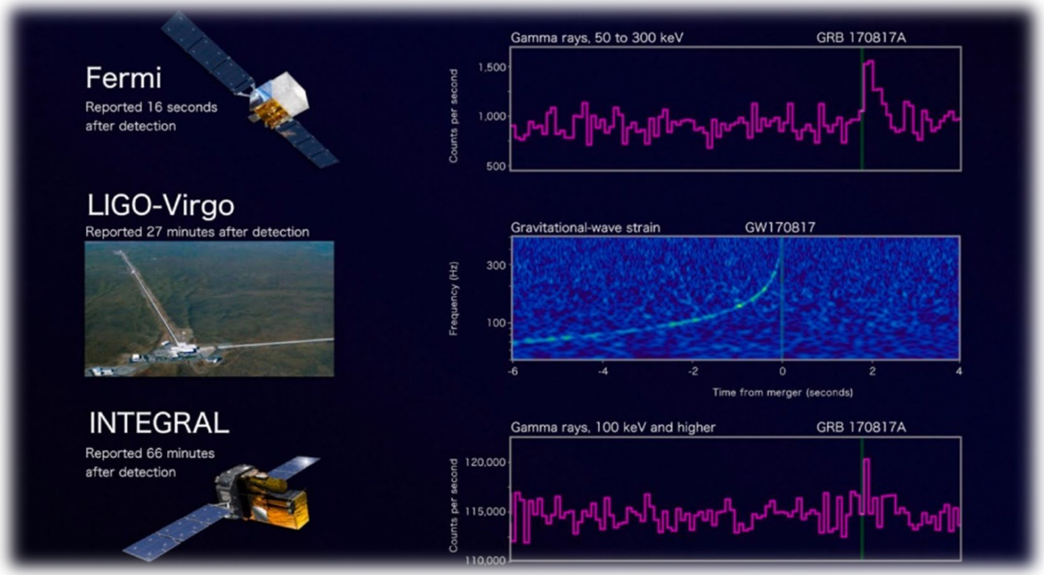
V. Sagun, O. Ivanytskyi, D. R. Karkevandi, S. Shakeri, E. Giangrandi, I. Lopes, K. A. Bugaev, **The Gravitational Wave Physics and Astronomy Workshop**, Poster Presentation, Hannover, Germany , December 2021

GW170817 a multi-messenger event

Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

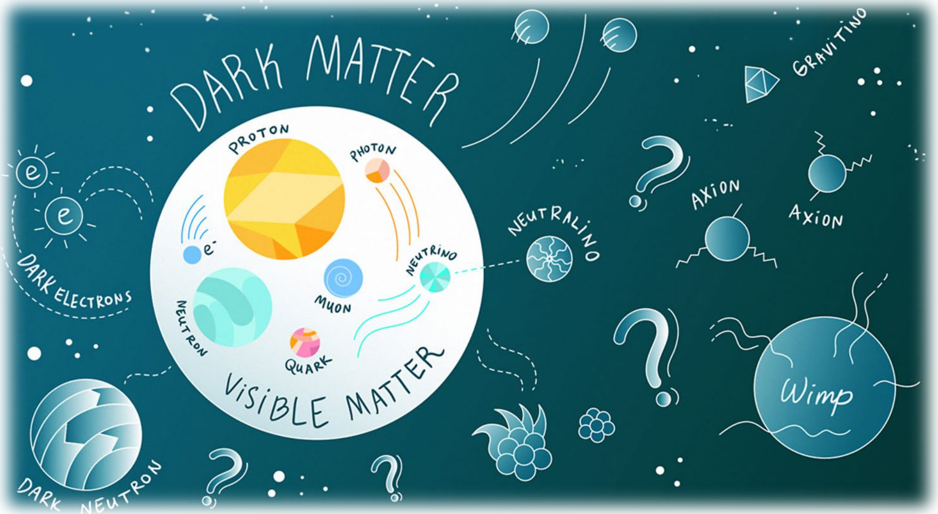
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

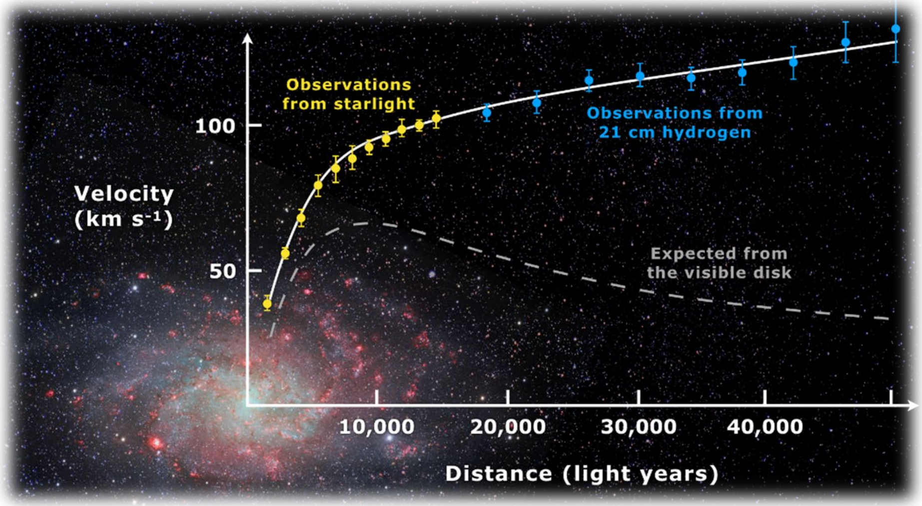


Multi-messenger constraints for Neutron stars

Tidal Deformability	Maximum Mass	Radius
Gravitational waves	Radio waves & X-rays	X-rays
$\Lambda_{1.4M\odot} \leq 580$	$M_{max} \simeq 2M\odot$	$R_{1.4M\odot} \simeq 12\ km$

Gravitationally stable astrophysical objects made of Dark matter





See Prof. Horowitz talk, August 10

Dark Star
Dark boson or fermion star

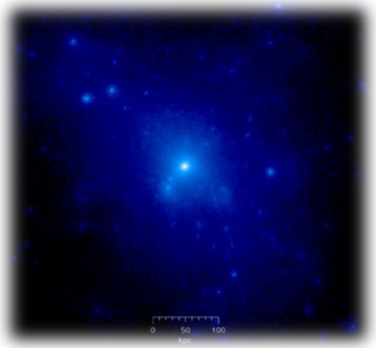
Andrea Maselli, et al. **PRD 96, 023005 (2017)**
Joshua Eby, et al. **JHEP 02 (2016) 028**
G. Narain, **J. Schaffner-Bielich**, et al. **PRD 74, 063003 (2006)**
Chris Kouvaris, et al. **PRD 92 (2015) 6, 063526**
P.A.Seoane, J.Barranco, A.Bernal, L. Rezzolla, **JCAP 11 (2010) 002**

Dark matter admixed neutron star/white dwarf

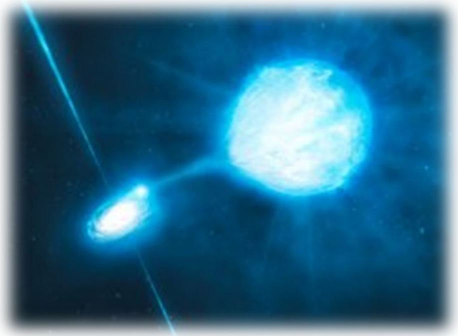
A. Nelson**, S. Reddy**, D. Zhou, **JCAP07(2019)012**
John Ellis, et al**. PRD 97, 123007 (2018)**
Y.Dengler**, J. Schaffner-Bielich**, L. Tolos, **PRD 105 (2022) 4, 043013**
S.-C. Leung, et al. **PRD 87, 123506 (2013)**
C.J. Horowitz, PRD 102 (2020) 8, 083031

Dark matter admixed neutron star

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**



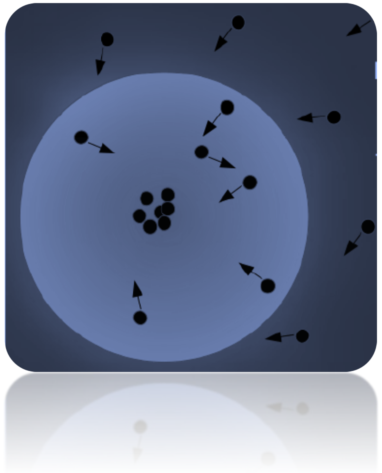
NS exists in a dense halo or region of DM or passes through it



Dark star as an accretion center of baryonic matter

DM production in the NS matter

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)***

F. Sandin & P. Ciarcelluti. ***Astropart.Phys.32:278-284,2009***

Dark Stars Powered by Self-Interacting Dark Matter
Y. Wu, S. Baum, K. Freese, L. Visinelli and H.B. Yu
arXiv:2205.10904

Modeling of a dark matter admixed neutron star

Asymmetric DM

Mass - Radius profile
Tidal deformability

Single fluid DM admixed NS

Equation of state by considering DM-Baryonic matter interaction

G. Panotopoulos and I. Lopes, **Phys.Rev.D 96 (2017) 8, 083004**
Abdul Quddus, et al. ***J.Phys.G* 47 (2020) 9, 095202**
Arpan Das, et al. **Phys. Rev. D 99, 043016 (2019)**

Axion effects in the stability of hybrid stars
B.S Lopes, R.L.S. Farias, V. Dexheimer, A. Bandyopadhyay, R. Ramos
arXiv:2206.01631

See Ricardo Sonego Farias talk, August 10

Self-annihilating DM

Luminosity and the effective temperature

Chris Kouvaris, **Phys.Rev.D. 77:023006,2008**
M.A. Perez-Garcıa and J. Silk, **Phys. Lett. B 711, 6 (2012)**

Two-fluid DM admixed NS

DM and BM interact only through gravitational force

Our considered model

EoS for BM and EoS for DM

Baryonic matter EoS

EoS with induced surface tension (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

V. Sagun and I.Lopes 2017 ApJ 850 75
V.Sagun, I.Lopes, O.Ivanytskyi, ApJ 871 157

Dark matter EoS

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

Self-interacting complex scalar field : Bosonic DM with self-interaction

I. Boson star EoS , repulsive self-interaction, $V(\phi) = \frac{1}{4}\lambda|\phi|^4$
II. Free parameters of the DM model: boson mass (m_χ), coupling constant (λ)
III. Sub-GeV DM and λ in strong coupling regime (<u>Prefect fluid approximation</u>)

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.
R. C. Tolman, Phys. Rev. 55, 364 (1939).
J. R. Oppenheimer and G. M. Volko, Phys. Rev. 55,374 (1939).

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

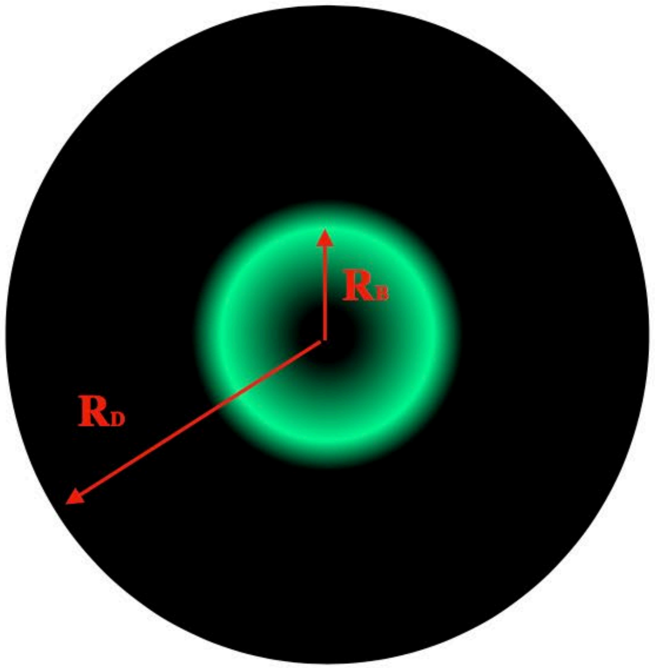
$$\frac{dp_D}{dr} = -(p_D + \varepsilon_D)\frac{m + 4\pi r^3 p}{r(r-2m)}$$

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

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

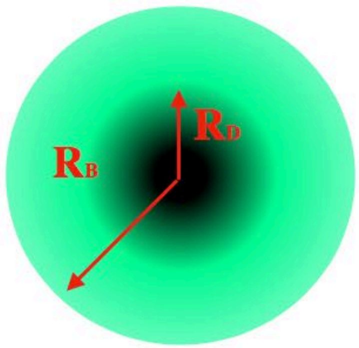
DM distribution through NSs

DM halo



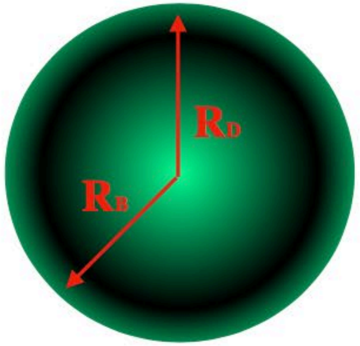
$R_D > R_B$

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

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

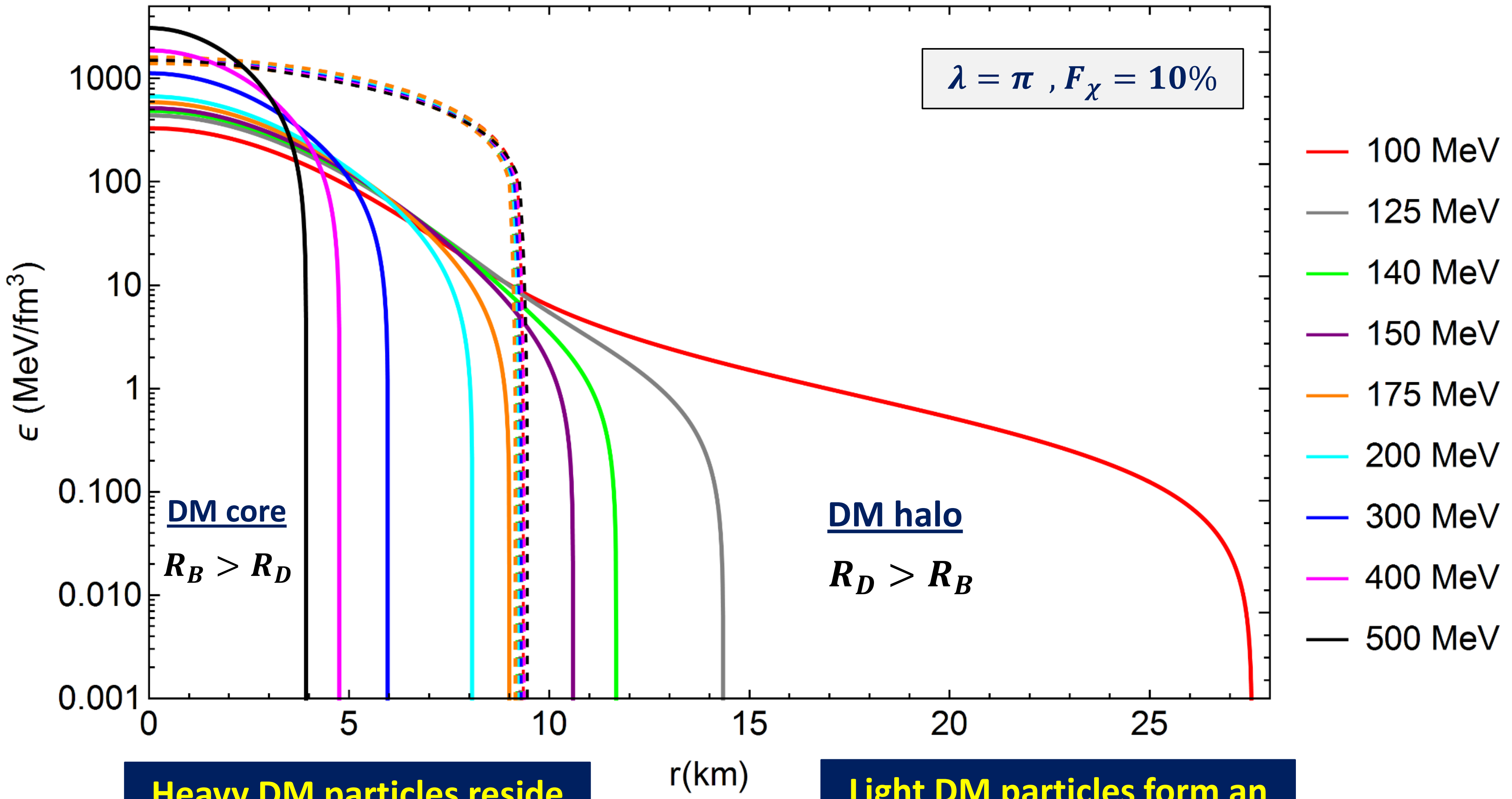
$F_\chi = \frac{M_D(R_D)}{M_T}$, DM Fraction

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]

Energy density profile through a DM admixed NS

Solid lines : **DM fluid** Dashed lines: **BM fluid**



Heavy DM particles reside as a dense core inside NSs

Light DM particles form an extended halo around NSs

Radio waves of pulsars

$M_{max} \simeq 2M_{\odot}$

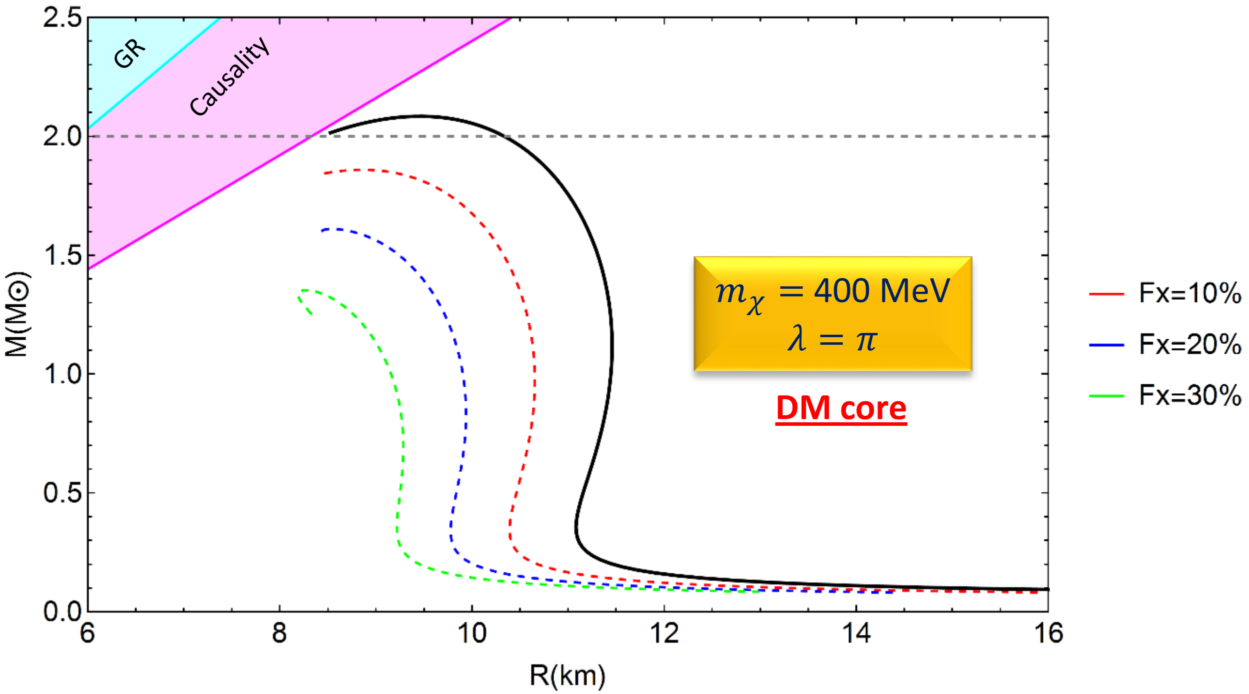
Mass-Radius profile of DM admixed NSs

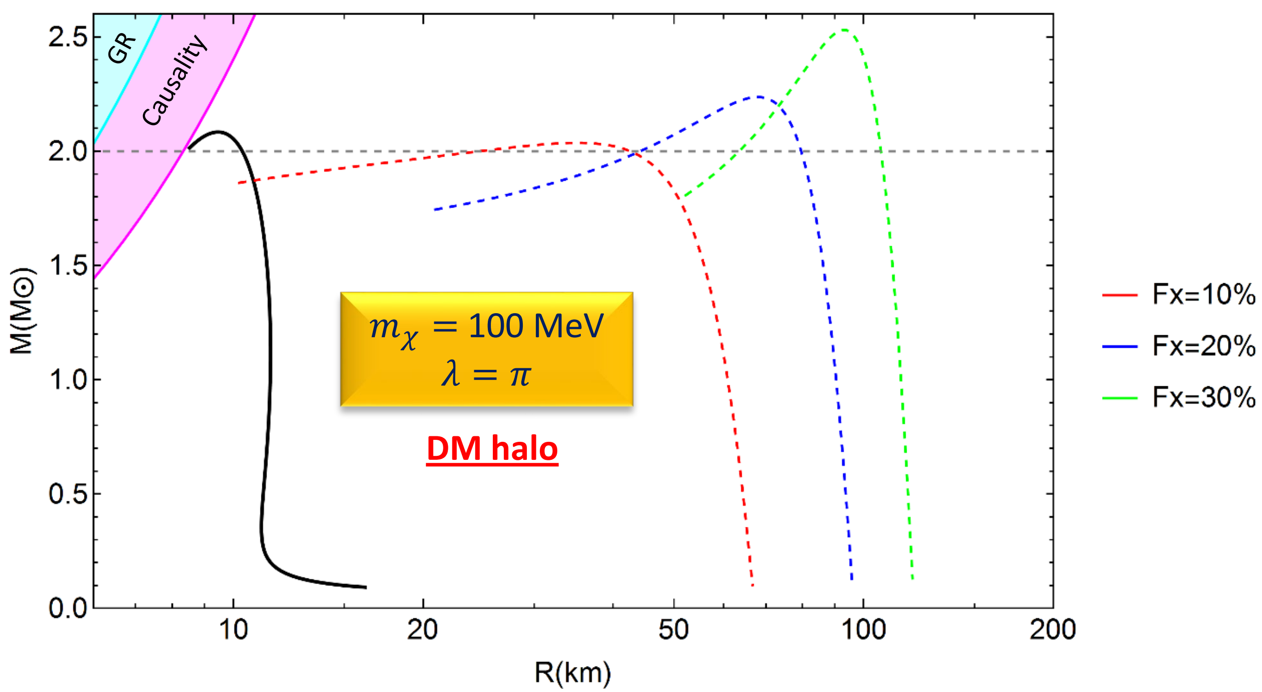
Outermost radius of the DM admixed NSs are considered

nature astronomy LETTERS
https://doi.org/10.1038/s41550-019-0880-2

Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar

A Massive Pulsar in a Compact Relativistic Binary
John Antoniadis *et al.*
Science **340**, (2013);
DOI: 10.1126/science.1233232





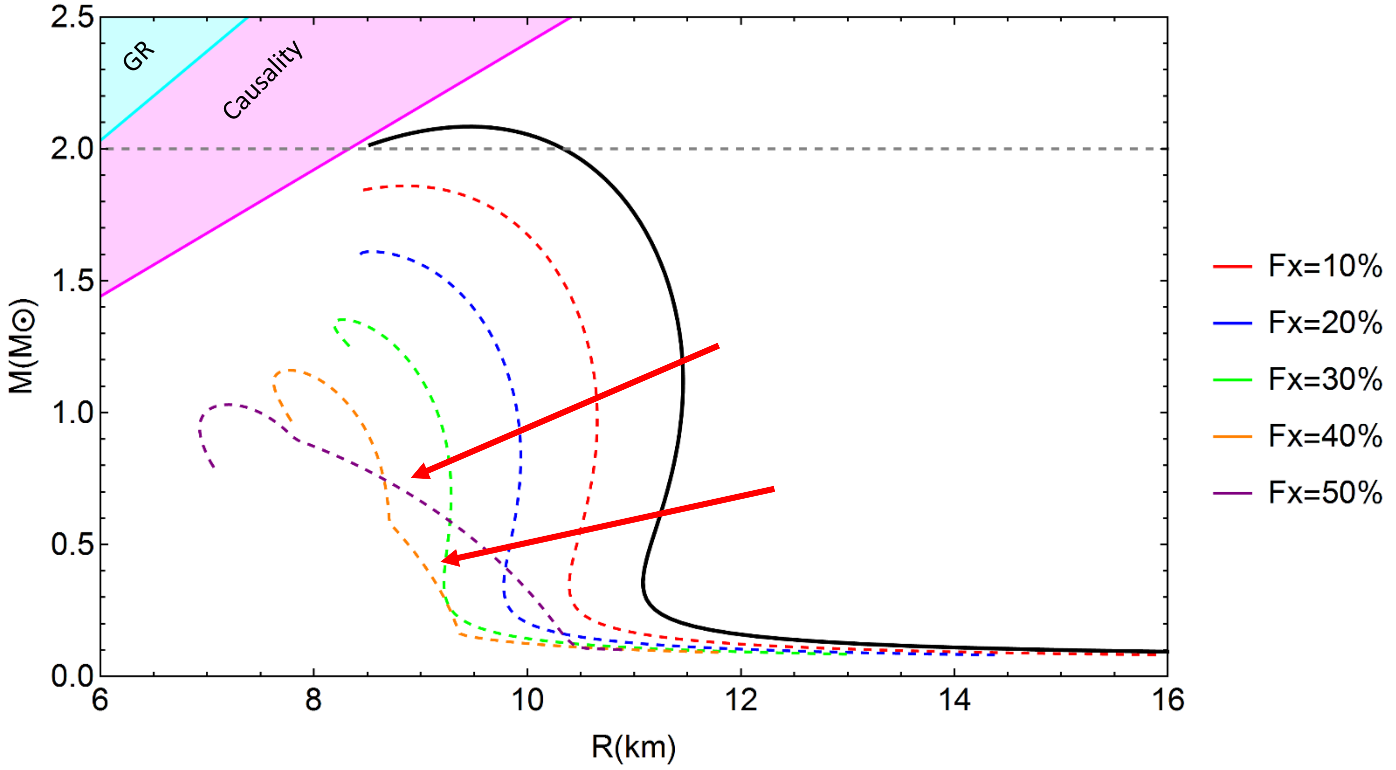
Decrease in maximum mass and radius

Only BM (without DM)
Black solid line
Maximum mass: 2.08 M☉

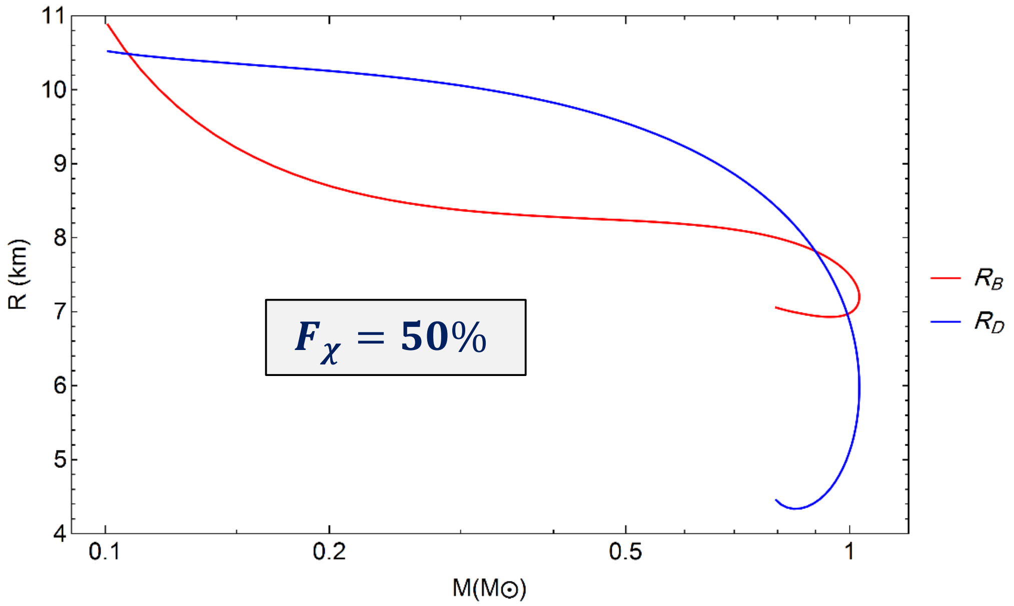
Increase in maximum mass and radius

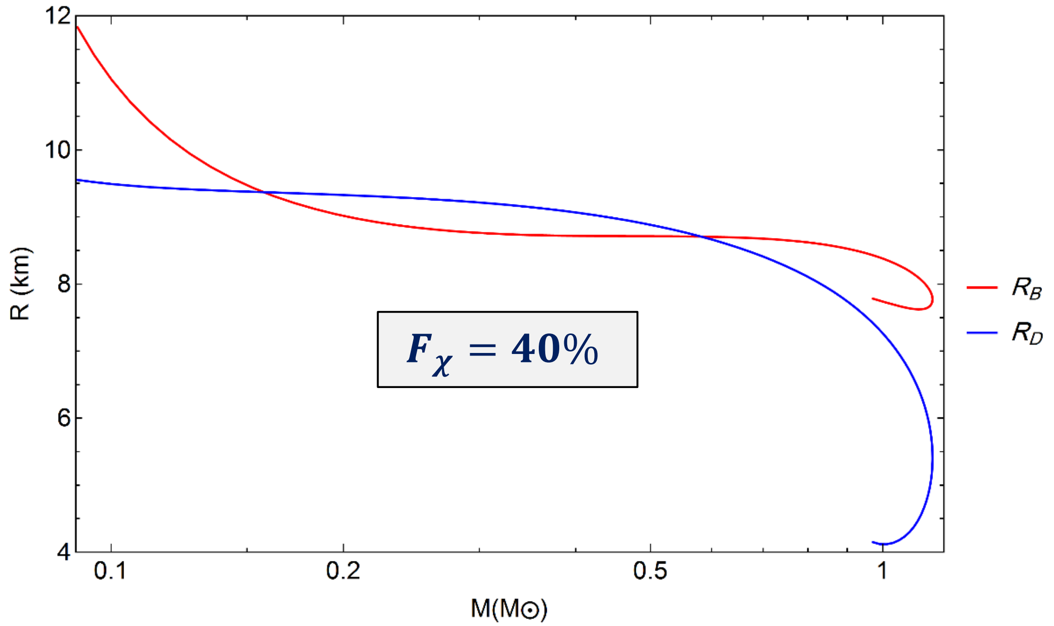
D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, Phys. Rev. D 105, 023001 (2022)

DM core-halo transition

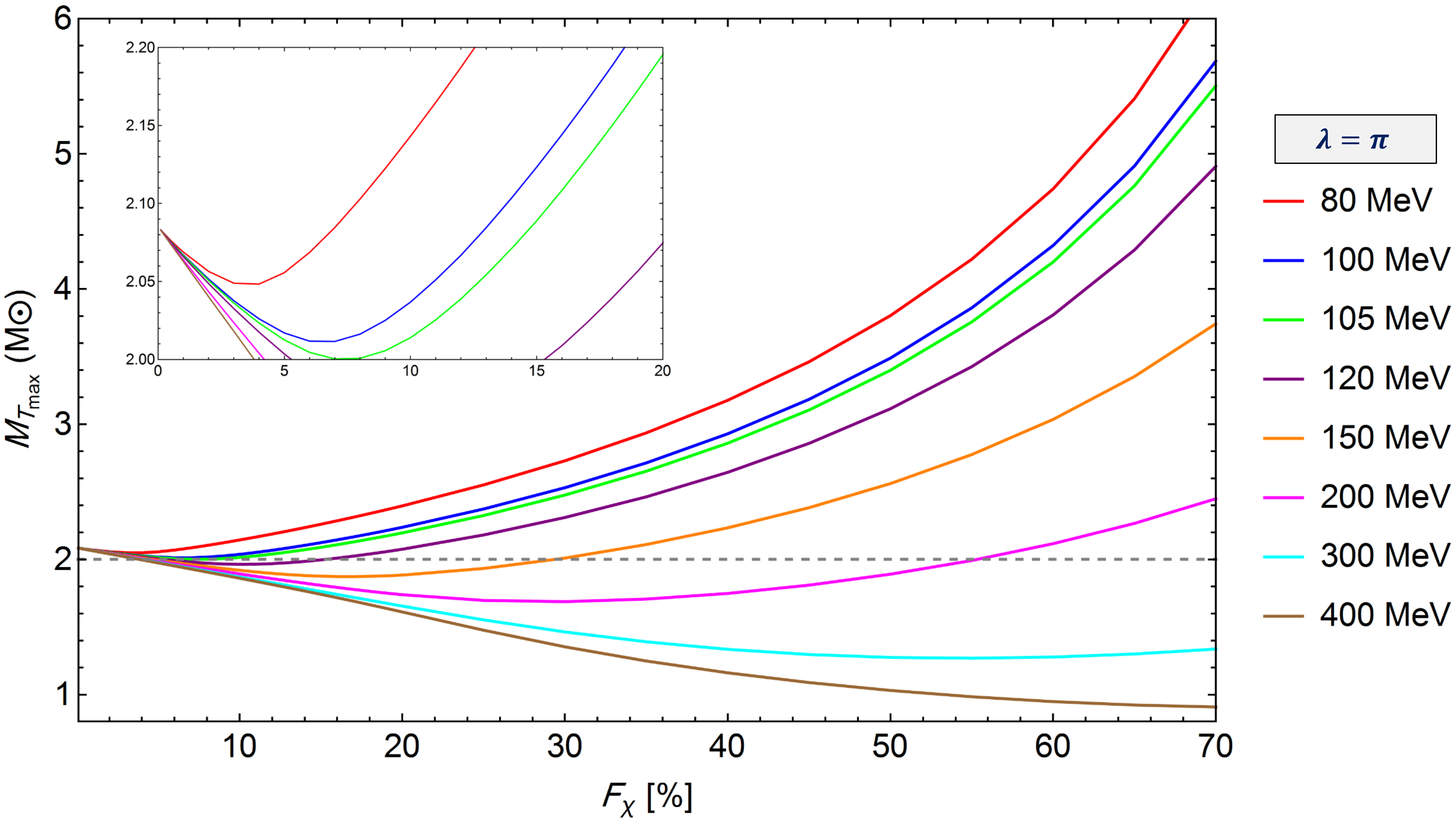


$m_{\chi} = 400$ MeV
$\lambda = \pi$

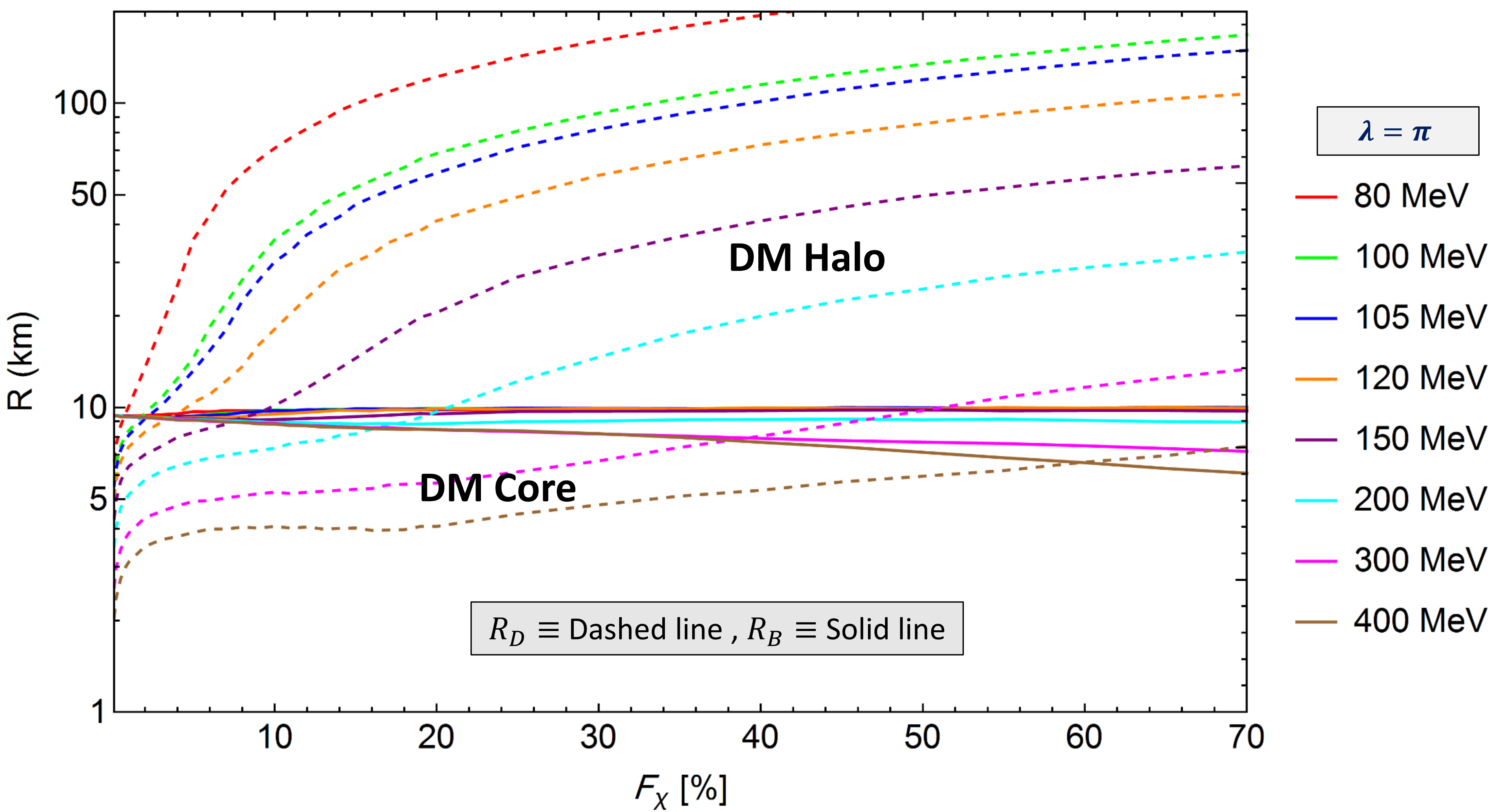




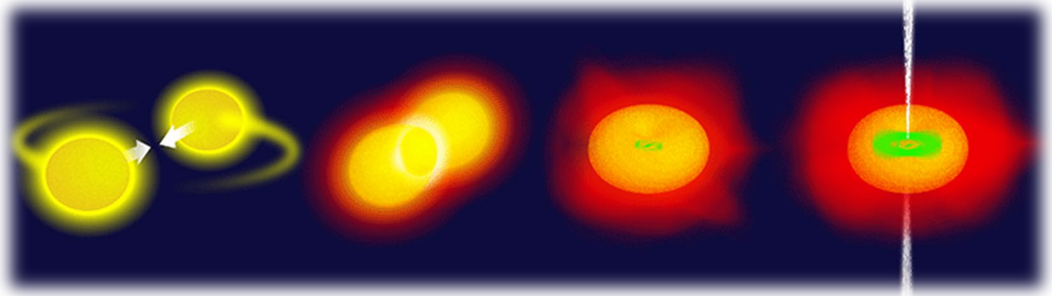
Probing the effects of DM fraction on the maximum mass of DM admixed NSs



DM core to DM halo transition with respect to DM fraction

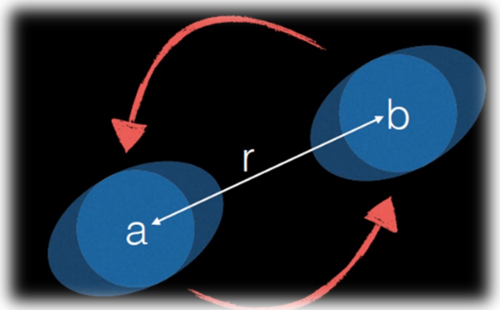


Tanja Hinderer
"Tidal Love Numbers of Neutron Stars"
Astrophys.J. 677 (2008) 1216-1220
Tanja Hinderer, et al.
Phys.Rev.D81:123016,2010



Gravitational-Wave

NS binary mergers, GW170817



Tidal forces deform NSs in binary systems

$$Q_{ij} = \lambda_t \varepsilon_{ij}$$

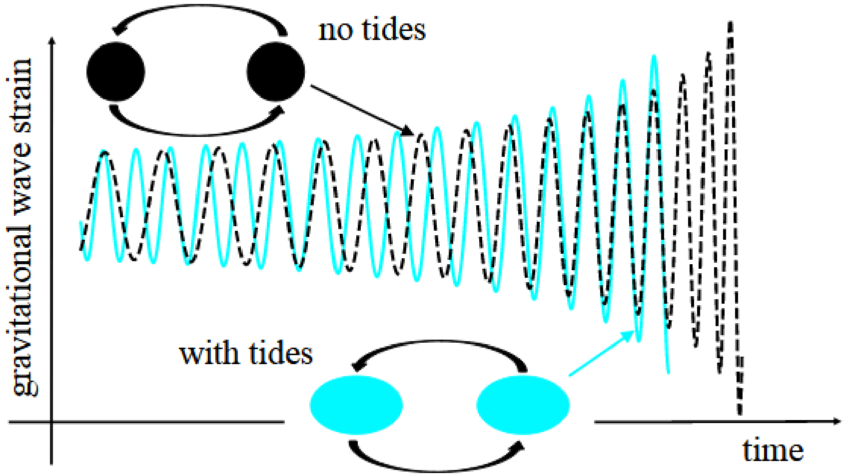
Induced quadrupole moment

Tidal deformability

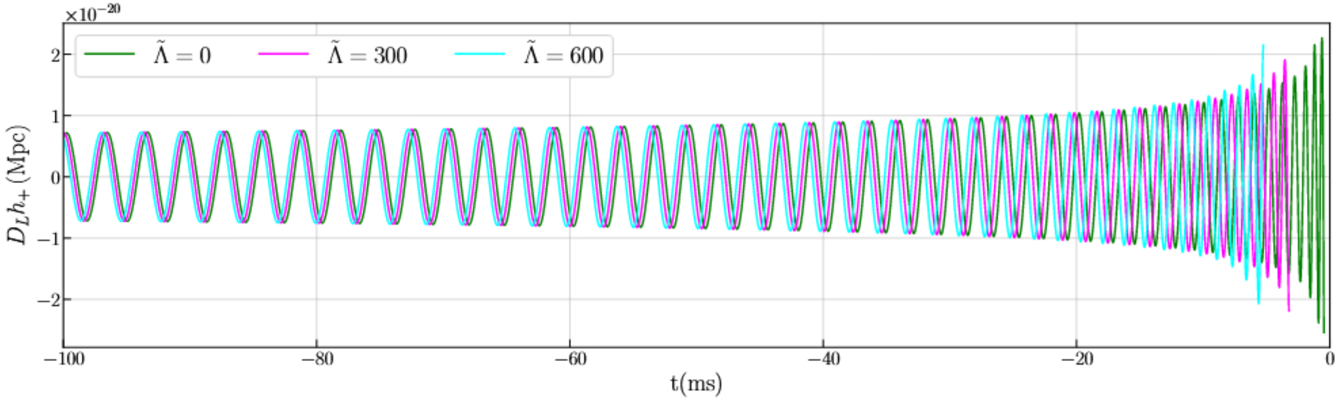
External tidal field

$$\lambda_t = \frac{2}{3} k_2 R^5$$

k_2: Dimensionless tidal love number
R: radius of star
k_2 will be calculated by TOV equation, so it is related to the NS matter and the EoS



Nicolas Yunes et al. Nature Rev.Phys. 4 (2022) 4, 237-246



Katerina Chatziioannou, Gen.Rel.Grav. 52 (2020) 11, 109

Dimensionless tidal deformability : $\Lambda = \frac{\lambda_t}{M^5} = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5$
R and M are the mass and radius of star

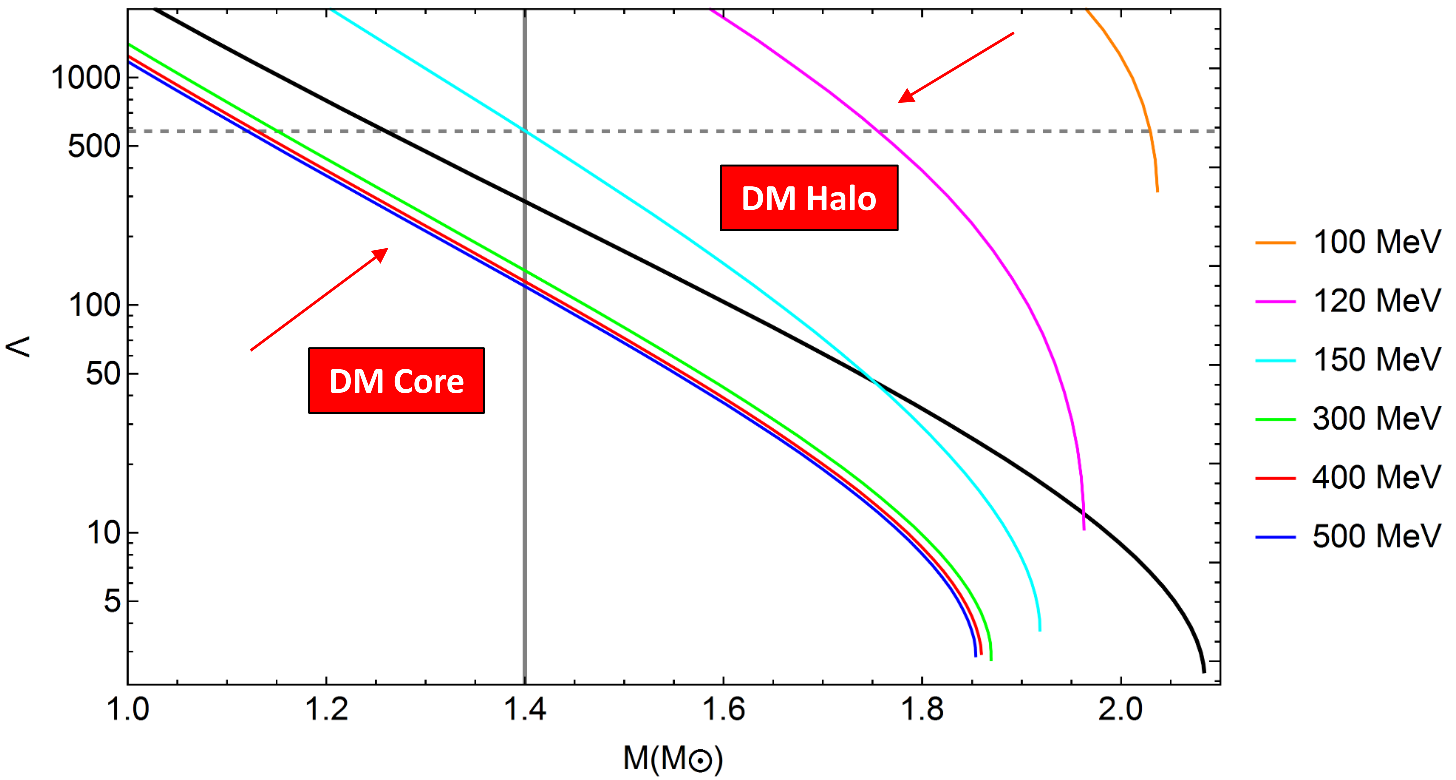
Dimensionless tidal deformability GW170817, $\Lambda \leq 580$ for $M = 1.4 M_\odot$

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

Tidal deformability of DM admixed NSs

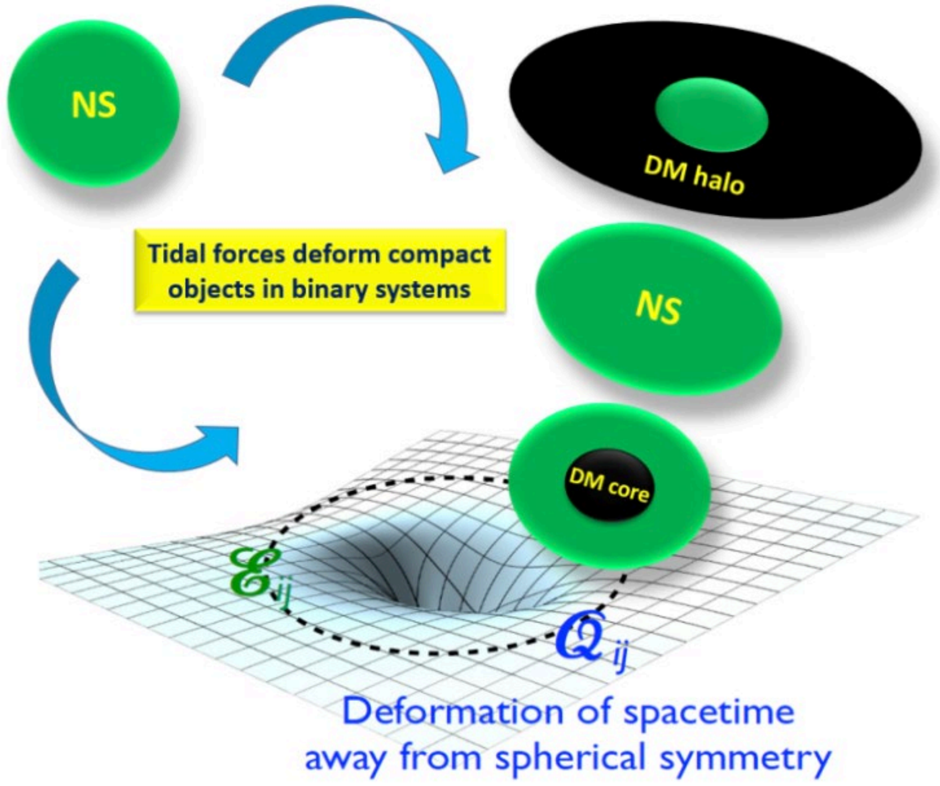
Black solid line: Only BM (without DM)

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



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

DM core ⟹ Decreases tidal deformability
DM halo ⟹ Increases tidal deformability



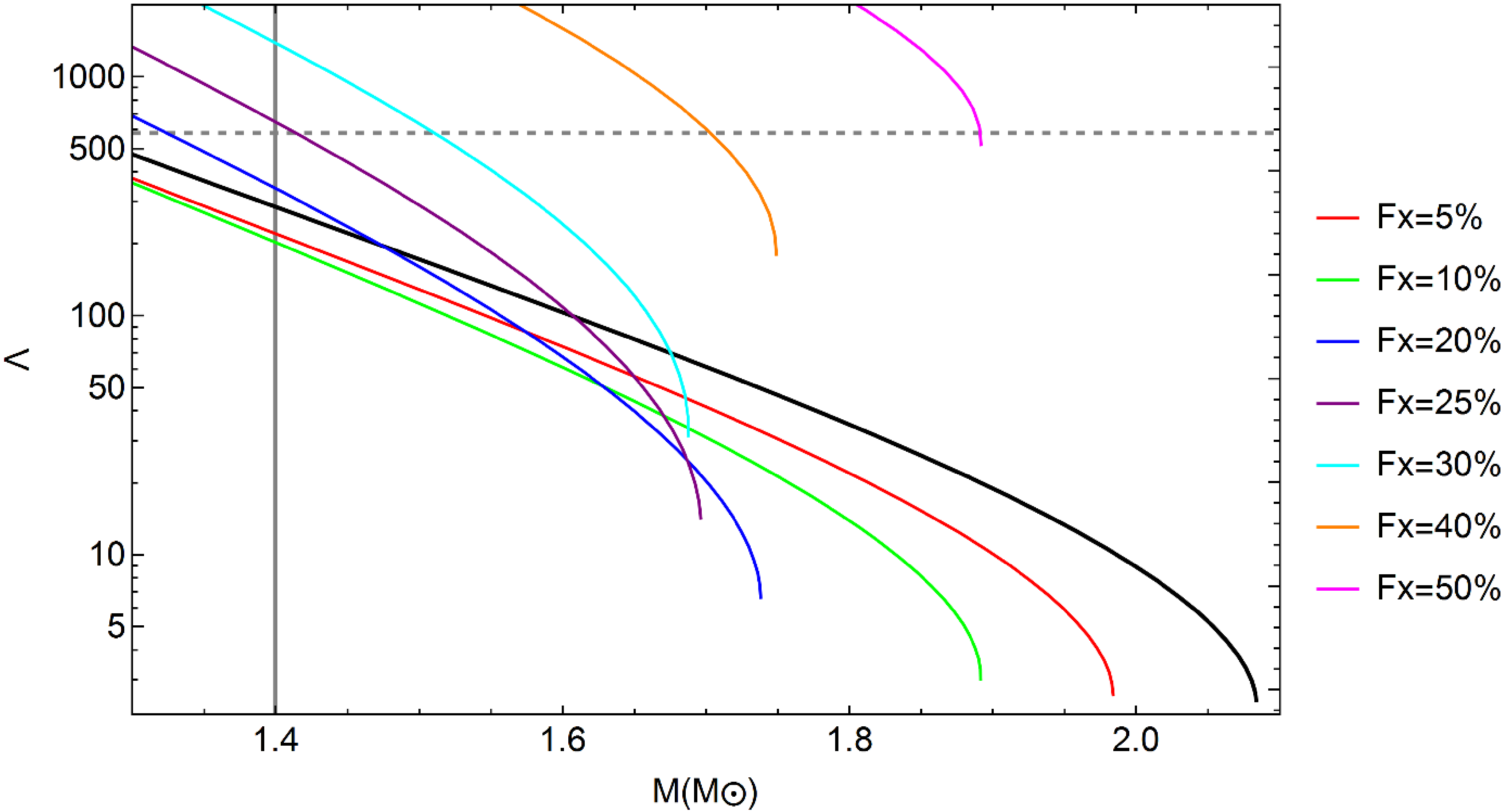
The effect of tidal deformability on the deformation of DM admixed NSs in comparison to the pure baryonic NS

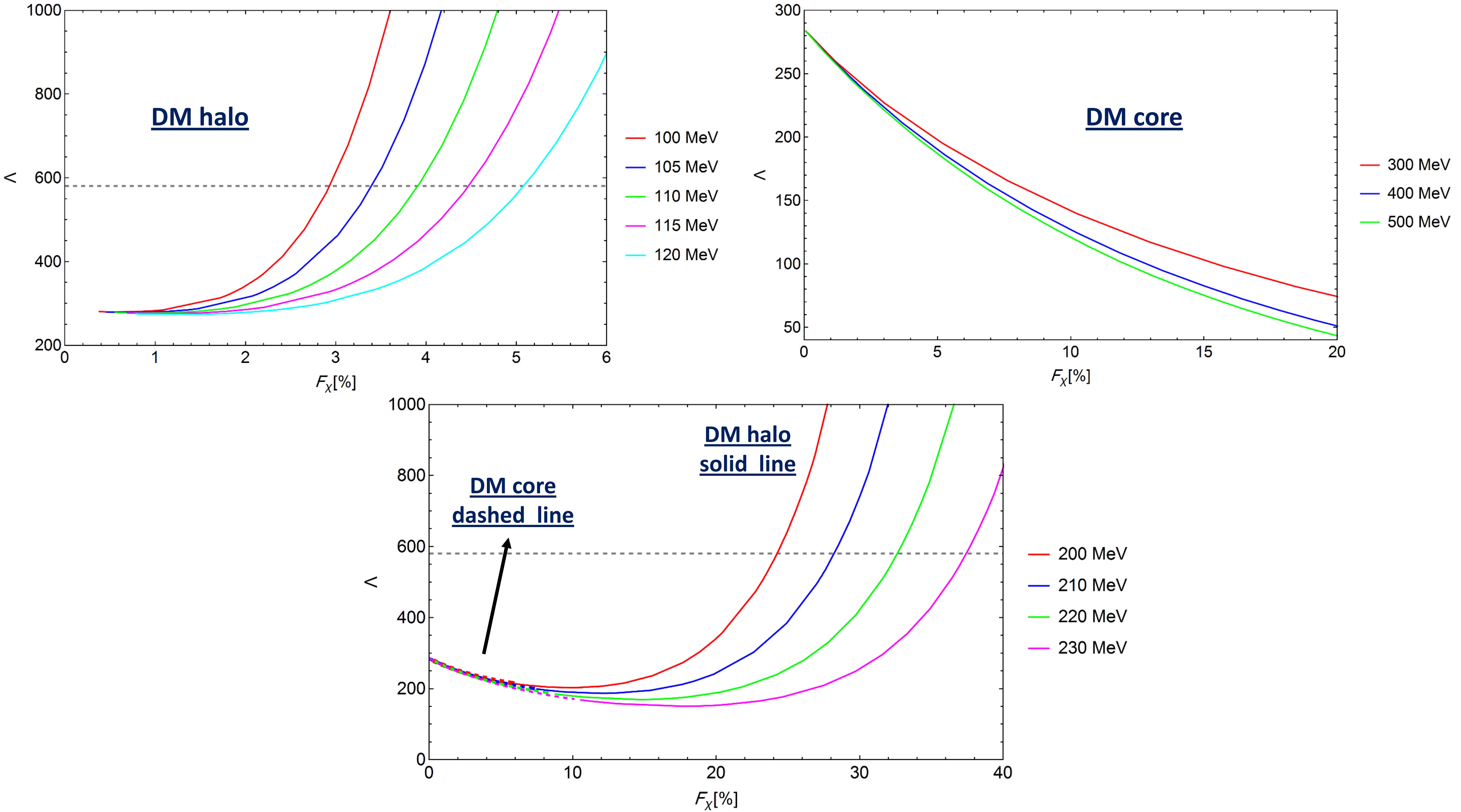
D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, Phys. Rev. D 105, 023001 (2022)

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

Effect of changing the DM fraction for $m_\chi = 200$ MeV and $\lambda = \pi$

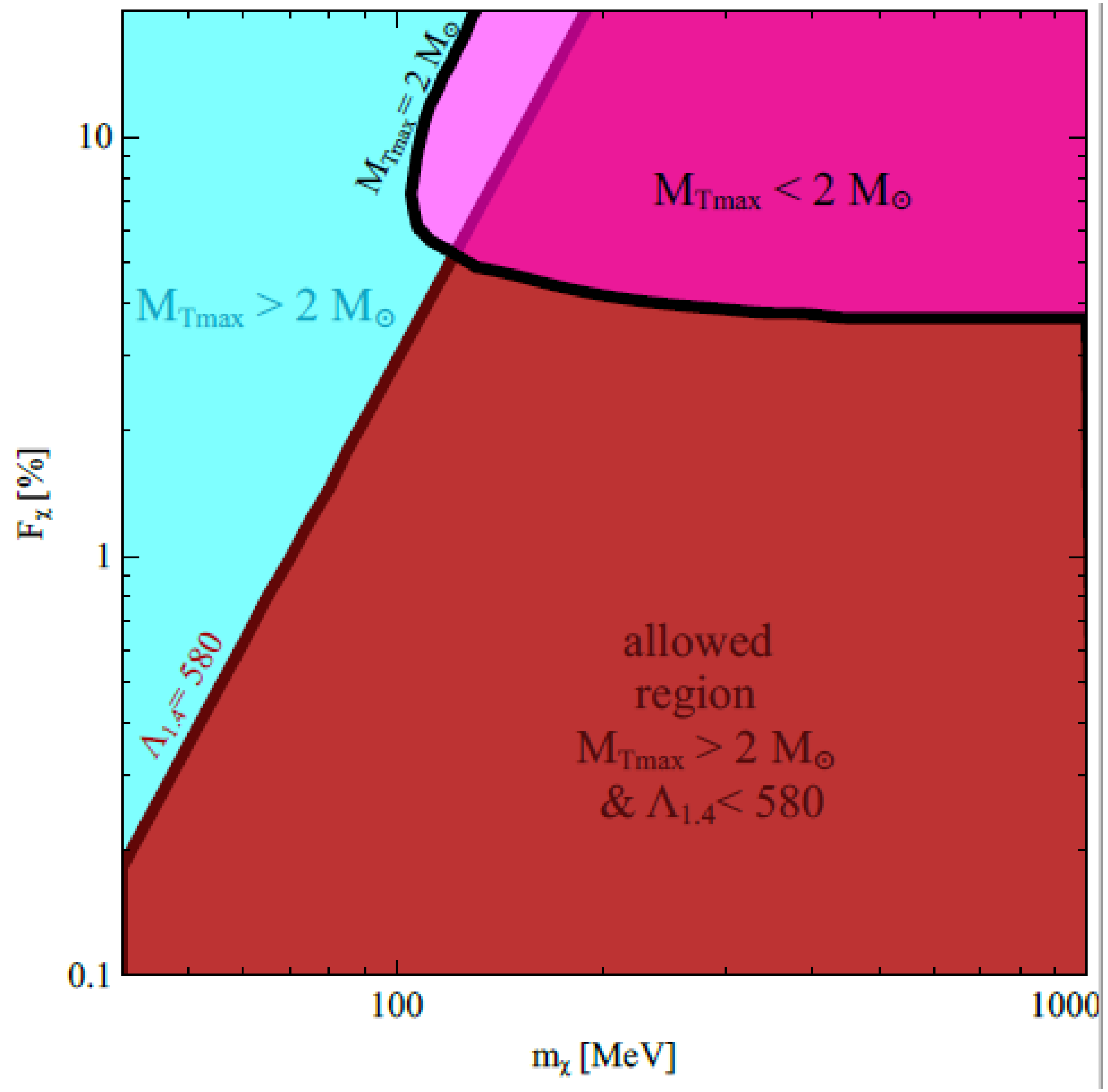
Higher values of $F_\chi \Rightarrow$ tidal deformability grows due to the DM halo formation





DM halo
100 MeV
105 MeV
110 MeV
115 MeV
120 MeV
Λ
F_χ[%]
DM core
300 MeV
400 MeV
500 MeV
Λ
F_χ[%]
DM halo
solid line
DM core
dashed line
200 MeV
210 MeV
220 MeV
230 MeV
Λ
F_χ[%]

Joint Multi-messenger constraints for DM admixed NSs and the self-interacting Bosonic DM model



GW170817 , $\Lambda \leq 580$ for $M = 1.4M\odot$

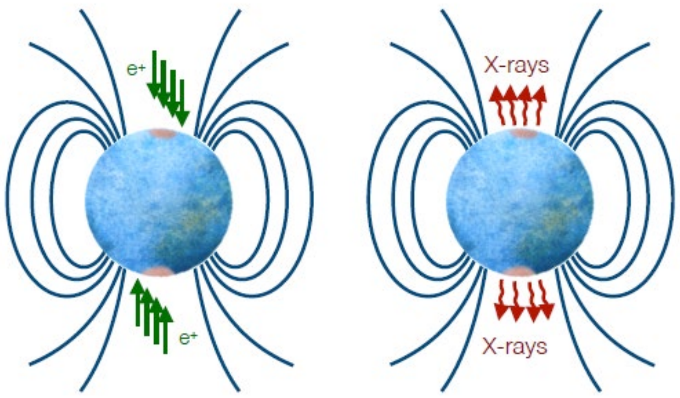
$2M\odot$ observational limit on maximum mass

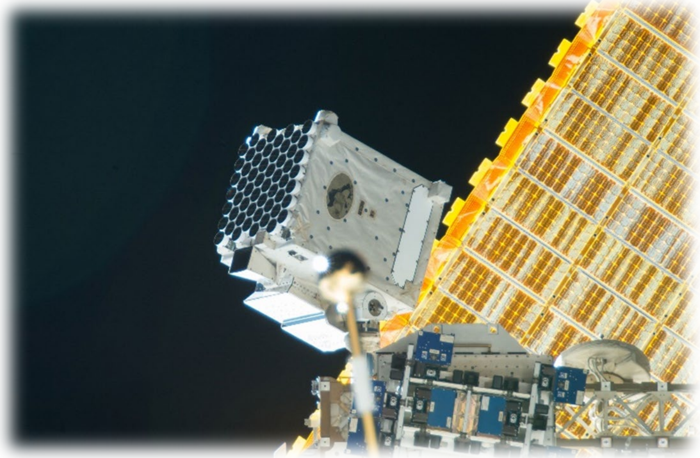
DM core decreases the maximum mass and tidal deformability, while DM halo increases them

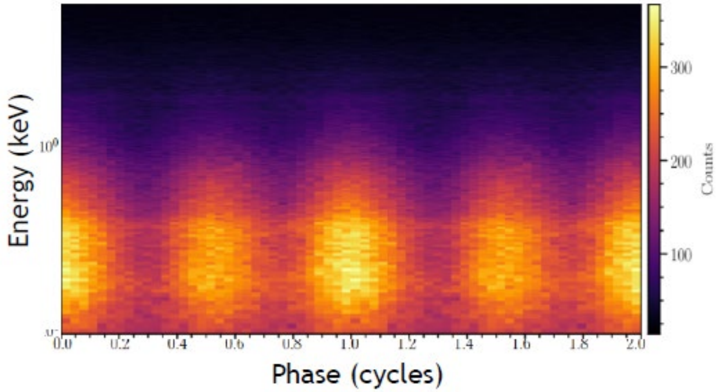
The multi-messenger constraints from Gravitational-Wave of binary NSs merger and the radio or X-ray observations of Pulsars favor sub-GeV bosonic DM particles with low fractions **below 5%** in strong coupling regime.

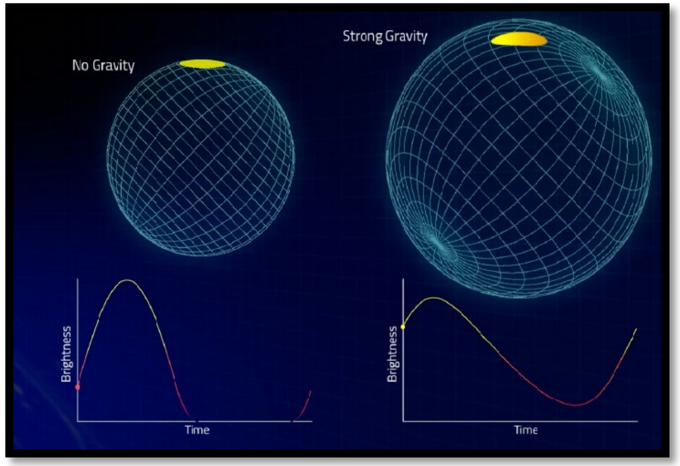
D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi,
Phys. Rev. D 105, 023001 (2022)

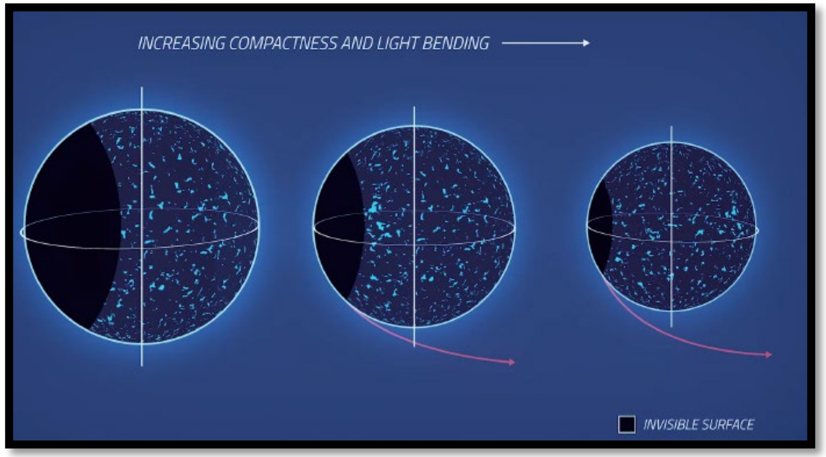
Neutron star Interior Composition ExploreR (NICER)

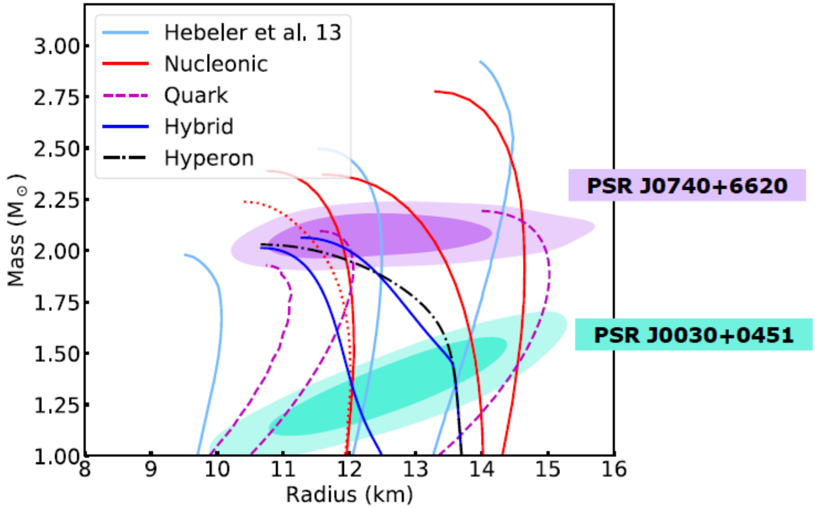












PSR J0030+0451

M ≈ 1.4 M⊙
R =12.45 ± 0.65 km

Mass and for the first time precise radius measurements for NSs

PSR J0740+6620

M = 2.08 M⊙
R = 12.35 ± 0.75 km

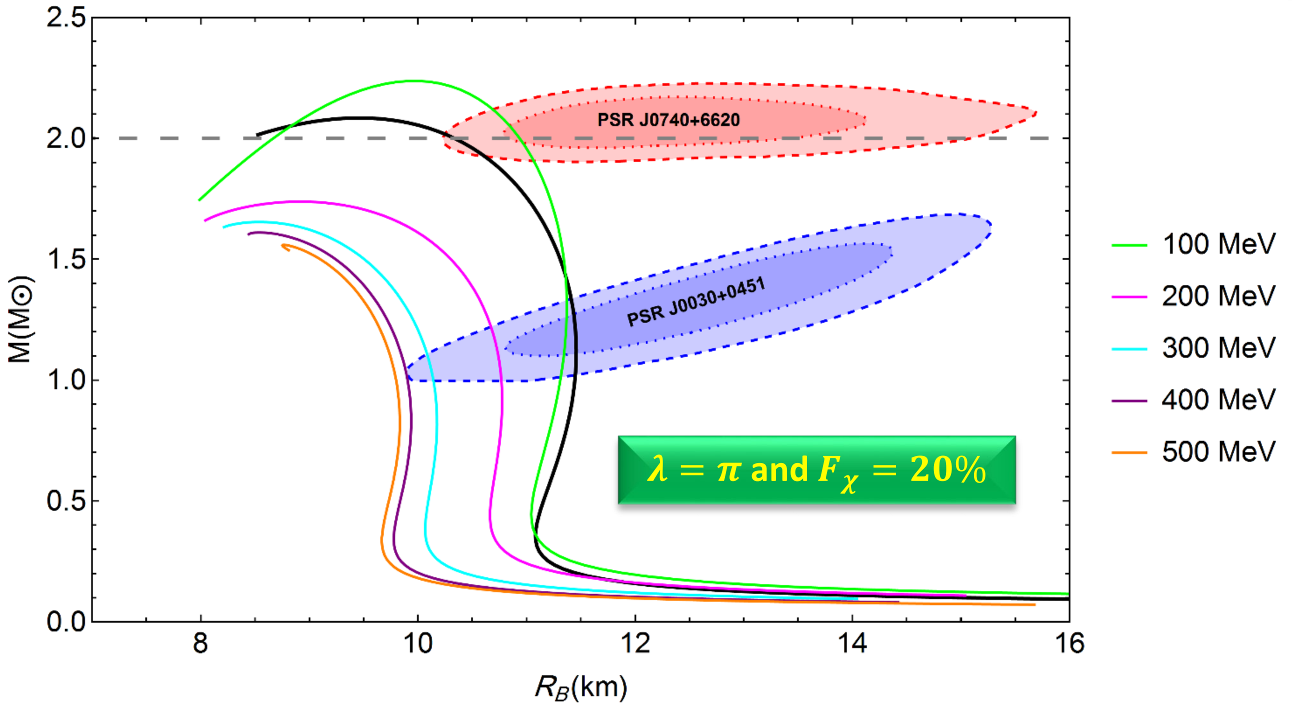
T. E. Riley *et al* 2019 *ApJL* **887** L21

T. E. Riley *et al* 2021 *ApJL* **918** L27

M. C. Miller *et al* 2019 *ApJL* **887** L24

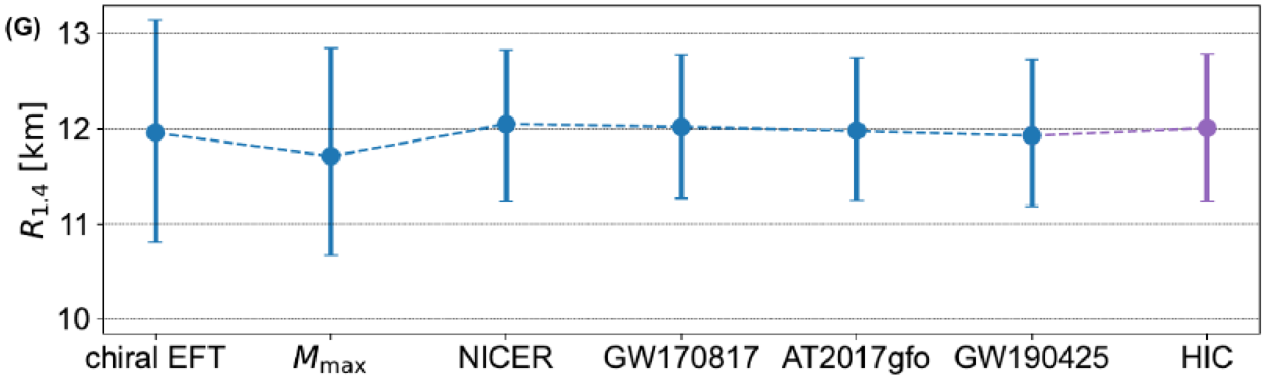
M. C. Miller *et al* 2021 *ApJL* **918** L28

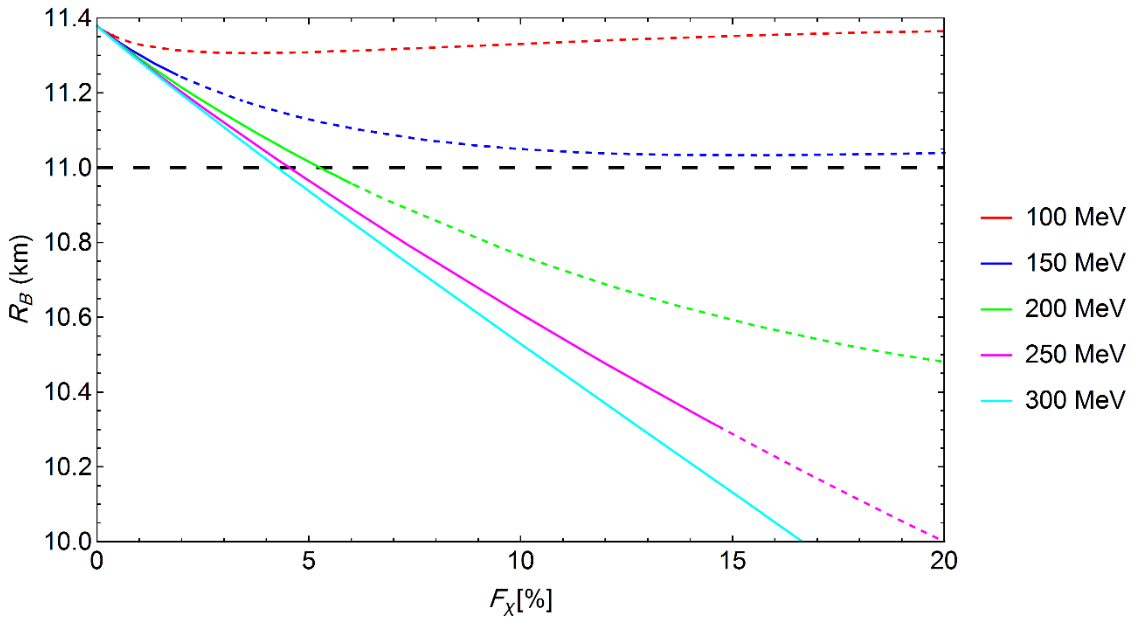
NICER and Radius constraint for visible radius of DM admixed NSs



Considering the latest **NICER** allowed parameter spaces for mass-radius profile of DM admixed NSs

D.R. Karkevandi, et al.
will be appeared on arXiv soon





Multi-messenger constraints for radius of NSs

Dietrich et al., **Science** 370, 1450–1453 (2020)
Huth et al., **Nature** 606 (2022) 276-280

$$R_B\ (M_T = 1.4 M_\odot) > 11\ km$$

Constraining bosonic asymmetric dark matter with neutron star mass-radius measurements

Nathan Rutherford,[1,*] Geert Raaijmakers,[2,†] Chanda Prescod-Weinstein,[1,‡] and Anna Watts[3,§]
[1] Department of Physics and Astronomy, University of New Hampshire, Durham, New Hampshire 03824
[2] GRAPPA, Anton Pannekoek Institute for Astronomy and Institute of High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
[3] Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1090GE Amsterdam, the Netherlands

Neutron stars can capture asymmetric dark matter (ADM), which affects the neutron star's measurable properties and makes compact objects prime targets to search for ADM. In this work, we use Bayesian inference to explore potential neutron star mass-radius measurements, from current and future X-ray telescopes, to constrain the bosonic ADM parameters for the case where bosonic ADM has accumulated in the neutron star interior. We find that the high bosonic ADM particle mass (m_χ) and low effective self-interaction strength (g_χ/m_ϕ) regime is disfavored due to the observationally and theoretically motivated constraint that neutron stars must have at least a mass of 1 $M_\odot$. However, within the remaining parameter space, m_χ and g_χ/m_ϕ are individually unconstrained. On the other hand, the ADM mass-fraction, i.e., the fraction of ADM mass inside the neutron star, can be constrained by such neutron star measurements. The inclusion of bosonic ADM in neutron star cores also relaxes the constraints on the baryonic equation of state space and suggests that ADM should be taken into account when interpreting constraints from mass-radius measurements.

I. INTRODUCTION

Neutron stars have been of great interest to astronomers because of the rich phenomena they produce, allowing us to probe, for example, strong gravity, cosmology, and heavy element enrichment. For instance, neutron stars can be a source of continuous gravitational waves, which can provide insight into their interiors. Signals from their mergers can also be used in determining the Hubble constant [1, 2]. Neutron stars have additionally been of great interest to nuclear physicists because the microphysical behavior of ultradense neutron-rich matter is poorly understood. Neutron stars may contain exotic states of matter, such as hyperons or deconfined quarks [3–5]. The effects of the hypothetical components that comprise neutron star interiors are pa-

the tidal deformabilities and the total masses of the stars have been shown to increase [7–11]. Thus, if dark matter is present in neutron stars, it must be accounted for in estimates of the measurable properties of neutron stars [6–19]. There have been efforts to constrain the dark matter particle mass, self-interaction strength, and mass-fraction using neutron star and gravitational wave (GW) measurements [9, 12, 14, 17, 20], and these rely on assumptions about the EoS. These efforts include placing mass-fraction constraints on sub-GeV bosonic dark matter particles [9], demonstrating that a stiffer baryonic matter EoS with dark matter can evade constraints that the baryonic matter EoS alone cannot achieve [14, 17], and calculating Bayesian parameter estimations of the dark matter parameter space [12, 20].

To quantify the effects of dark matter on neutron stars,

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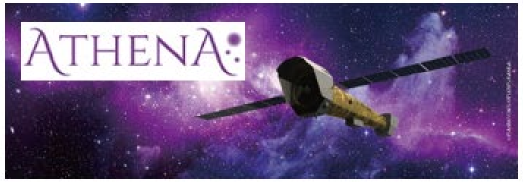

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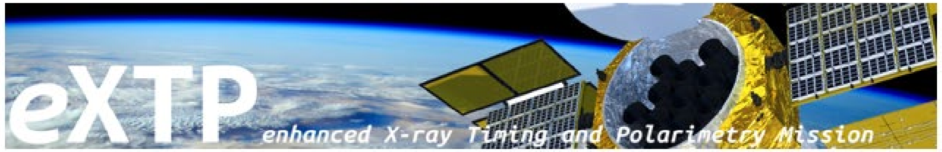

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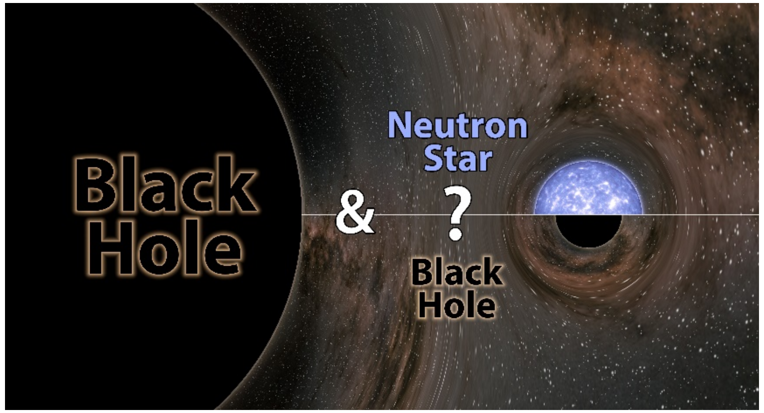

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GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object

Could be explained by DM admixed NSs model

D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, The Proceedings (MG16)


Thanks a lot for your attention
Naghsh-e Jahan Square Isfahan-Iran