Bosonic Dark matter in Neutron stars and Gravitational waves

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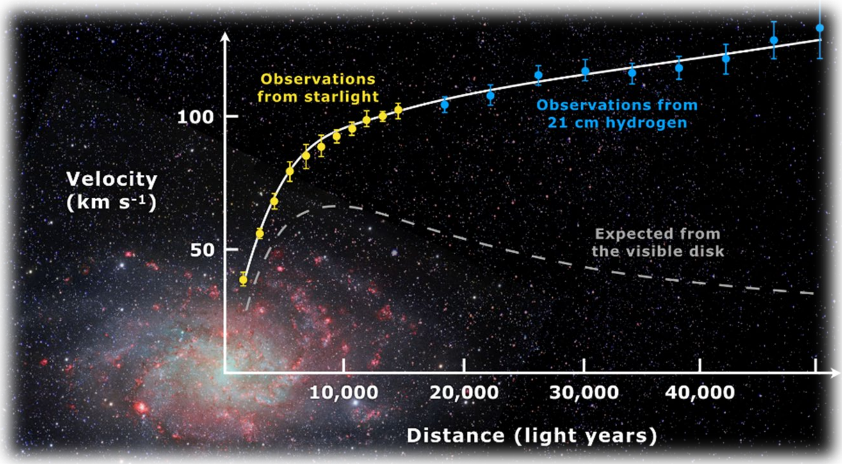
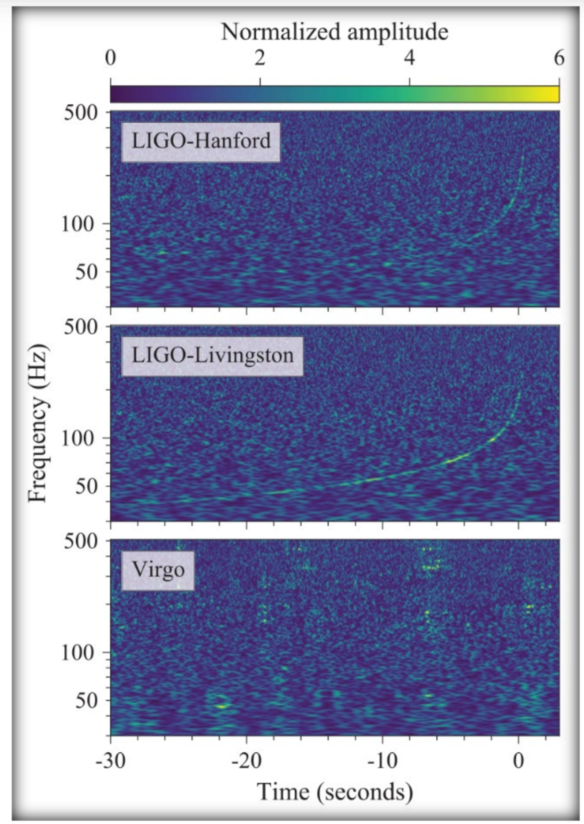
دانشگاه صنعتی اصفهان

MG16 5-10 JULY 2021
SIXTEENTH MARCEL GROSSMANN MEETING

Perspective:





GW 170817

Dark matter accumulation by a neutron star:

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

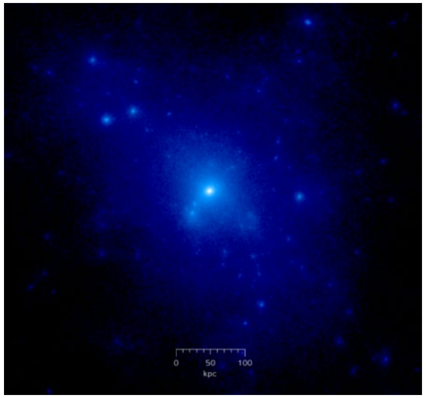
Different scenarios that DM can exist in a NS

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

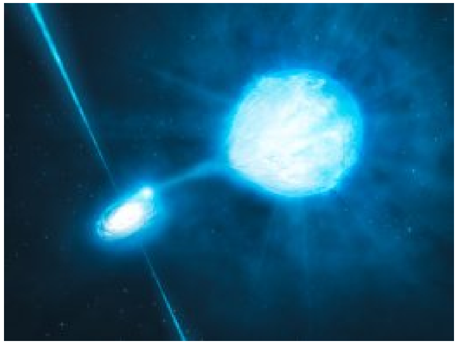
O. Ivanytskyi, V. Sagun, I. Lopes. Phys. Rev. D 102, 063028 (2020)

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

A. Del Popolo, et al. Universe 6 (2020) 12, 222
X. Y. Li, et al. JCAP10(2012)031
F. Sandin & P. Ciarcelluti. Astropart.Phys.32:278-284,2009
Deliyergiyev, et.al. Phys. Rev. D 99, 063015 (2019)
Ang Li, et al. astropartphys.2012.07.006



Dark star as an accretion center of baryonic matter



John Ellis, et al. Phys. Rev. D 97, 123007 (2018)
Qian-Fei Xiang,, et al. Physical Review C 89, 025803 (2014)
I.Goldman, et al. Phys.Lett.B 725 (2013) 200-207
P. Ciarcelluti & F. Sandin. Phys.Lett. B695:19-21,2011
F. Sandin & P. Ciarcelluti. Astropart.Phys.32:278-284,2009

DM production in the NS matter

John Ellis, et al. Phys. Rev. D 97, 123007 (2018)
A. Nelson, S. Reddy, D. Zhou, JCAP07(2019)012

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

I. Goldman, et al. Phys.Lett.B 725 (2013) 200-207
Moira I. Gresham, et al. Phys. Rev. D 99, 083008 (2019)
P. Ciarcelluti & F. Sandin. Phys.Lett. B695:19-21,2011
F. Sandin & P. Ciarcelluti. Astropart.Phys.32:278-284,2009

Dark matter admixed Neutron star

Asymmetric DM

Mass - Radius profile
Tidal deformability

Self-annihilating DM

Luminosity and the effective temperature

Chris Kouvaris, Phys.Rev.D77:023006,2008
M.A. Perez-Garcıa and J. Silk, Phys. Lett. B 711, 6 (2012).

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)

Two-fluid DM admixed NS

DM and BM interact only through gravitational force

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. Tidal deformability constraint from the NS-NS merger (GW170817)

V.Sagun, I.Lopes, O.Ivanytskyi, *Astrophys.J.* 871 (2019) 2, 157
V.Sagun, I.Lopes, O.Ivanytskyi, *Nucl.Phys.A* 982 (2019) 883-886

Dark matter EoS

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. M. Colpi, S. Shapiro, and I. Wasserman, Phys. Rev. Lett. 57, 2485 (1986).
III. Free parameters of the DM model: boson mass (m_D), coupling constant (λ)
IV. Dark star

Andrea Maselli, et al. Phys. Rev. D 96, 023005 (2017)
Joshua Eby, et al. JHEP 02 (2016) 028
Pau Amaro-Seoane, et al. *JCAP* 11 (2010) 002

Tolman-Oppenheimer-Volkof equation

BM and DM fluids interact only gravitationally

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

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

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

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

DM and BM EoSs ⟷ **Two-fluid TOV equation**

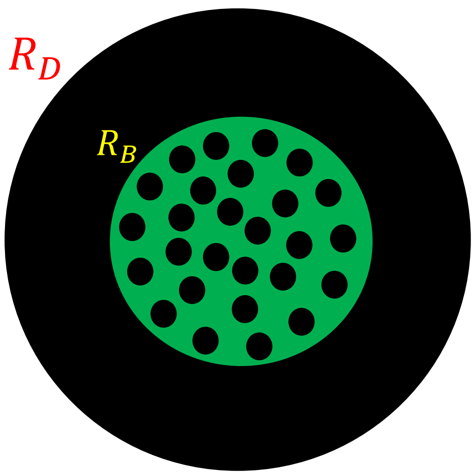
Two central BM and DM pressures: $p_{B_c}(r \simeq 0)\,;\ p_{D_c}(r \simeq 0)$

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

$p_B \leq 0$

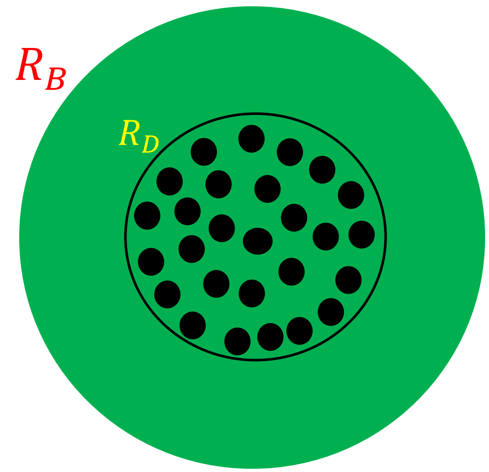
$p_D \leq 0$

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



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

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



Radius : R_D

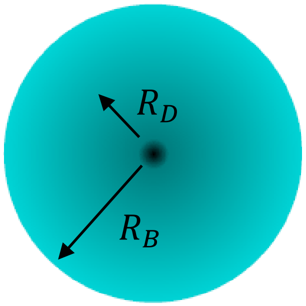
DM halo

R_B is the visible radius

Radius : R_B

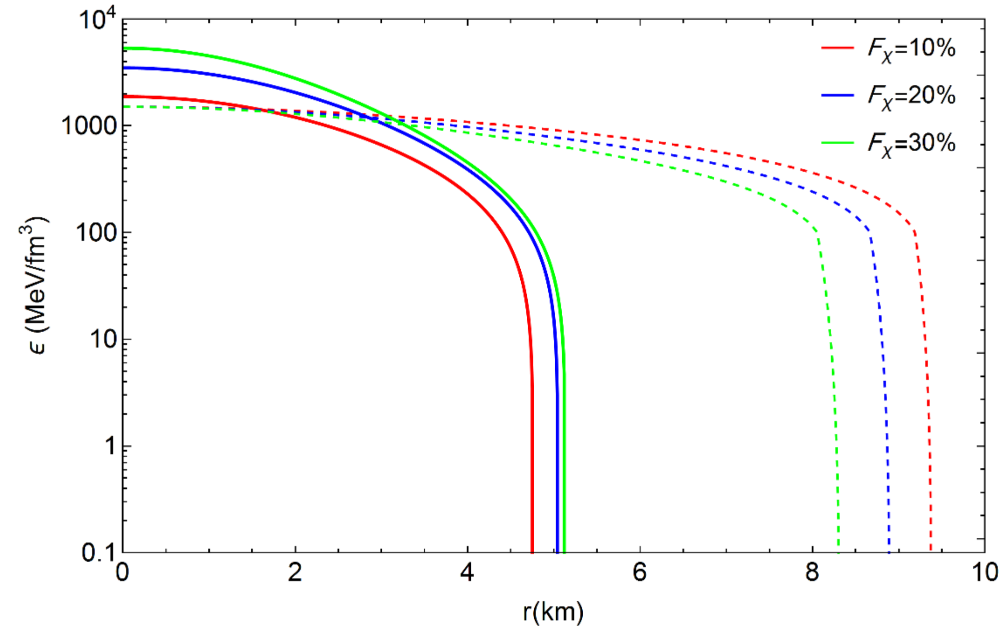
DM core

p_{B_c} ; p_{D_c} correspond to the considered F_χ

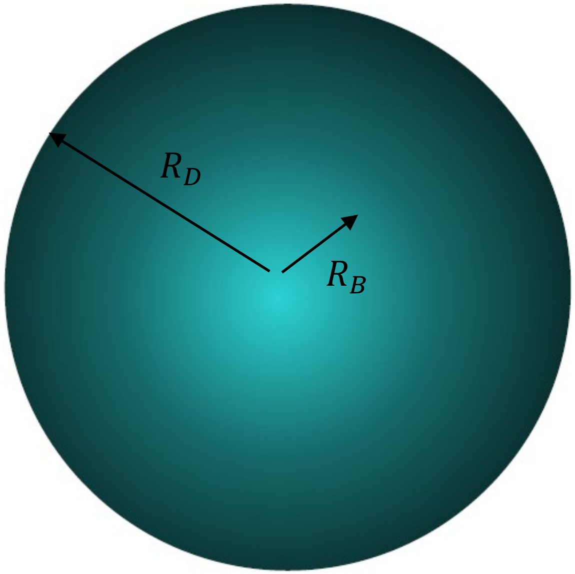


DM core

$m_D = 400$ MeV
$\lambda = \pi$

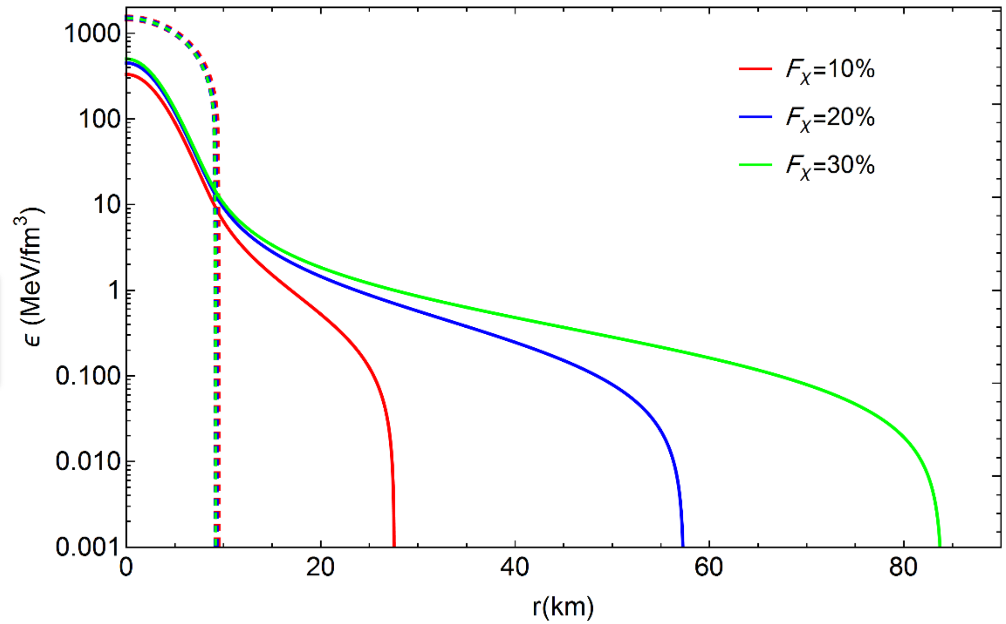


Solid lines : **DM fluid** Dashed lines: **BM fluid**



DM halo

$m_D = 100$ MeV
$\lambda = \pi$



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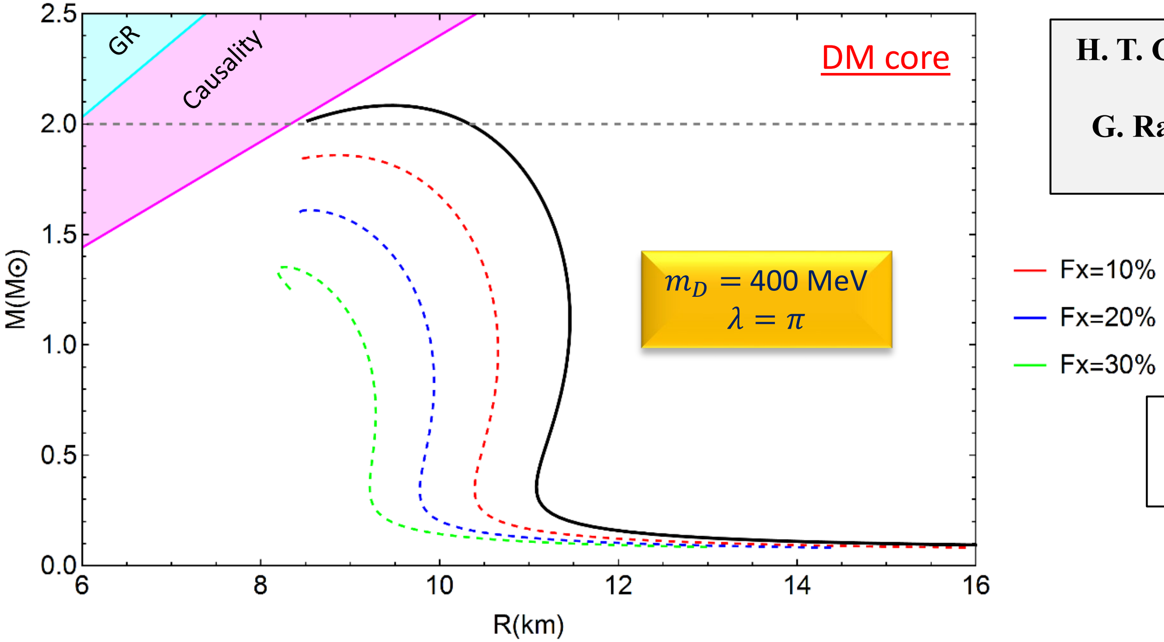
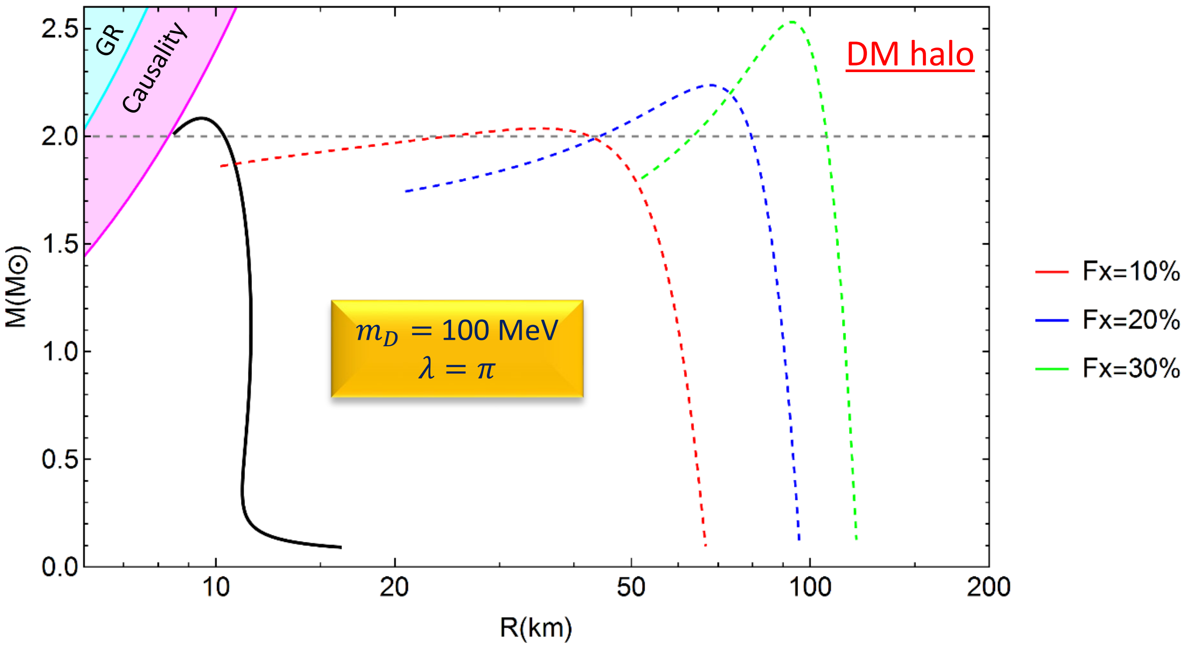




D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, In preparation (July 2021)

H. T. Cromartie, et al. *Nature Astron.* 4 (2019) 1, 72-76 **(PSR J0740+6620)**
G. Raaijmakers, et al. arXiv:2105.06981v2 **[NICER] (PSR J0740+6620)**

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

Only BM (without DM) **Black solid line**
Maximum mass: 2.08 M⊙ Radius: 9.4 km

DM core

↓

Decrease in maximum mass and radius

DM halo

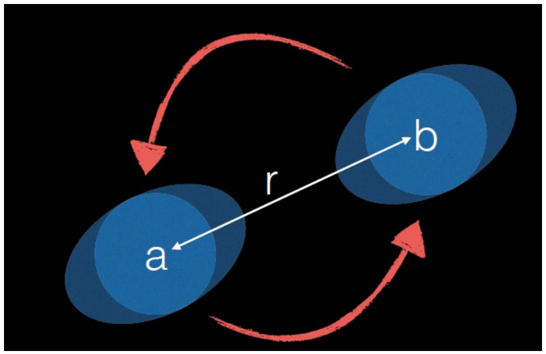
↓

Increase in maximum mass and radius

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)



Tidal forces deform NSs in binary systems

Tanja Hinderer
"Tidal Love Numbers of Neutron Stars"
Astrophys.J. 677 (2008) 1216-1220
Tanja Hinderer, et al.
Phys.Rev.D81:123016,2010
Sergey Postnikov, et al.
Phys.Rev.D 82 (2010) 024016

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

Induced quadrupole moment (Q_{ij})
Tidal deformability (λ_t)
External tidal field (ε_{ij})

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

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

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

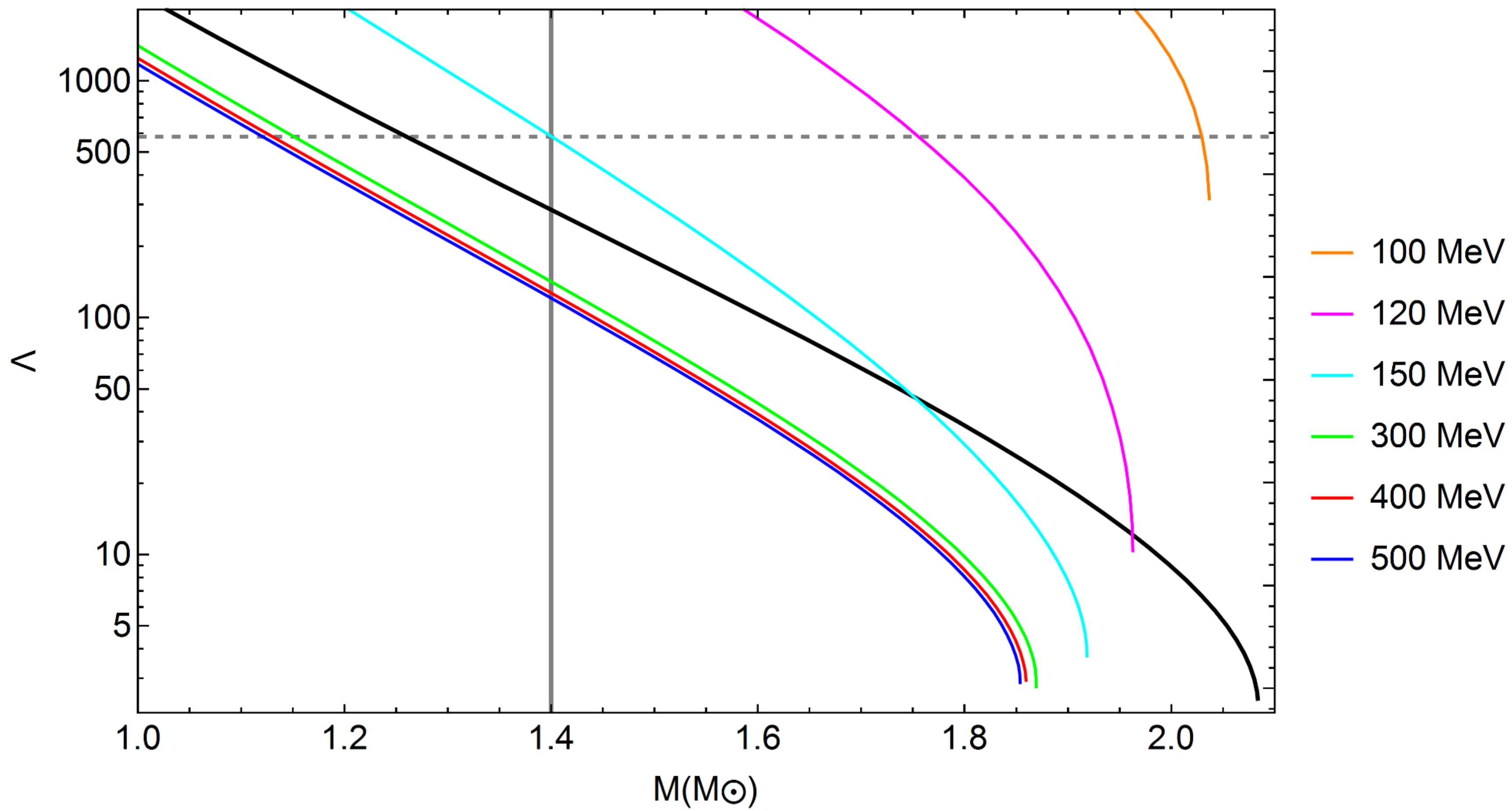
Dimensionless tidal deformability GW170817, $\Lambda \leq 580$ for $M = 1.4 M_\odot$

Effect of changing the boson's mass for $\lambda = \pi$ and $F_\chi = 10\%$

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

Black solid line: Only BM (without DM)

DM halo to DM core transform ⟹ Decrease in tidal deformability



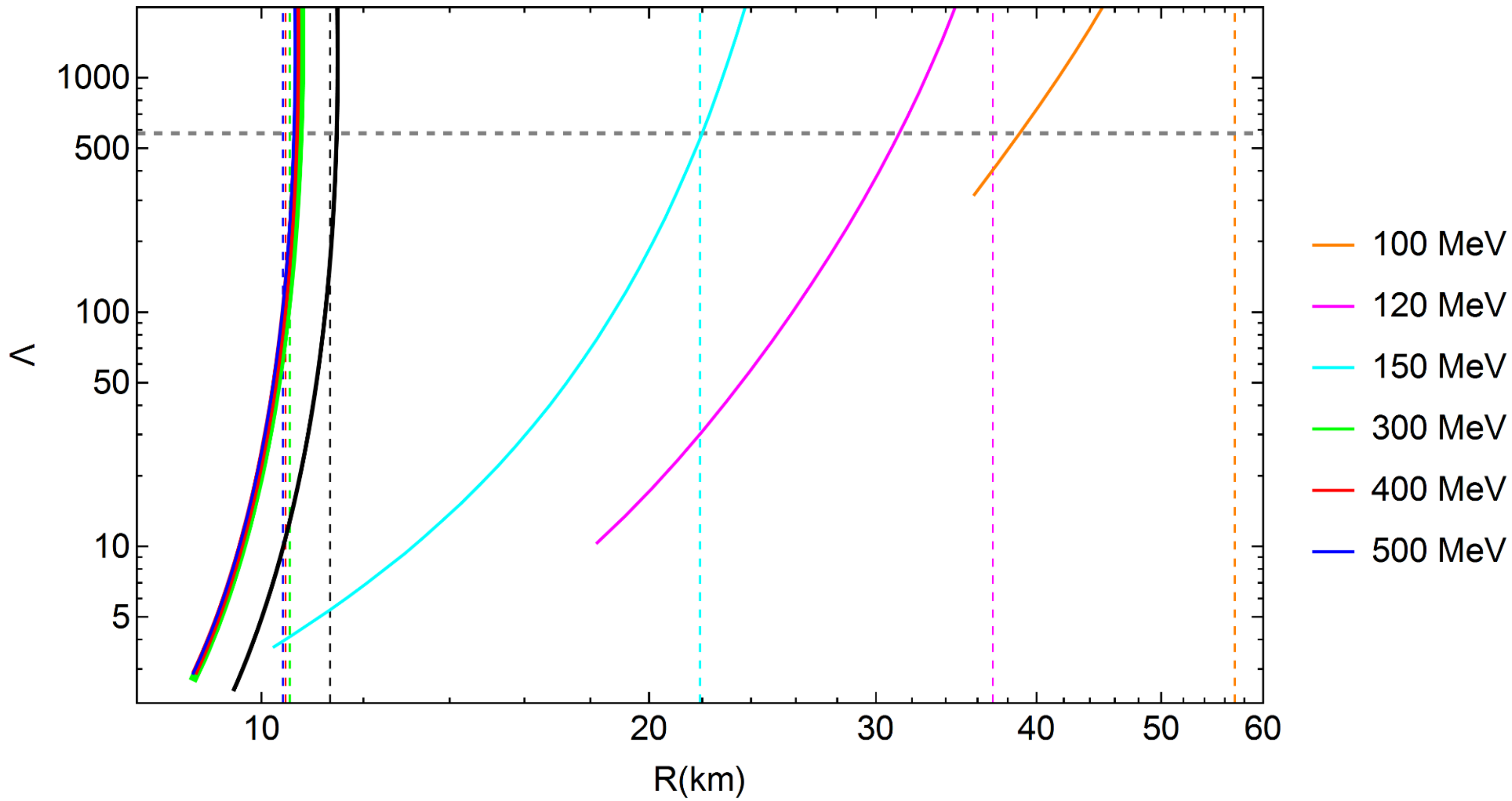
D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, In preparation (July 2021)

Tidal deformability crucially depends on radius

Colored vertical dashed lines: $R_{M_{1.4}}$

$\lambda = \pi \;, F_\chi = 10\%$

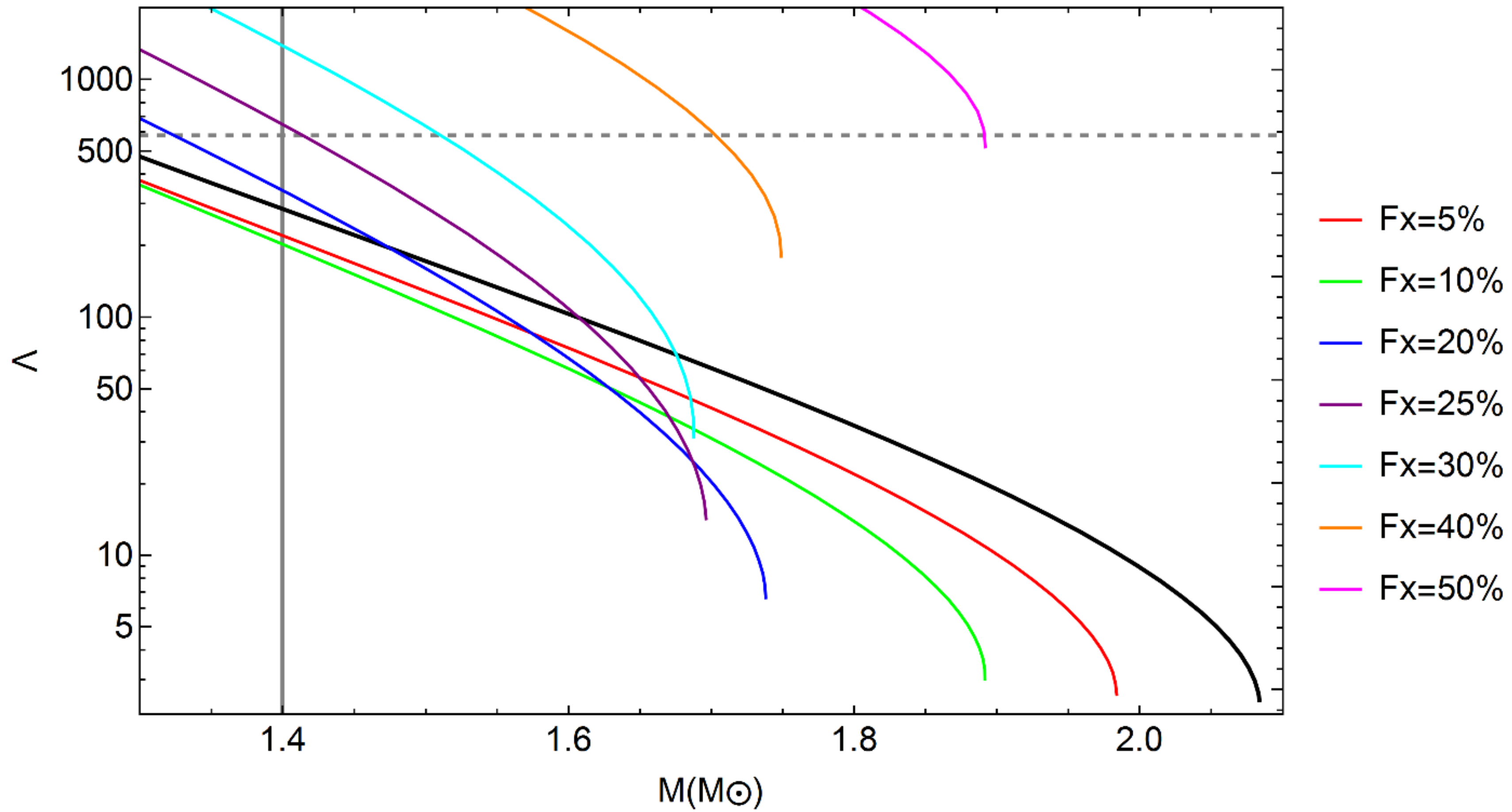
Radius is the outermost radius of star, for DM halo R_D and for DM core R_B



D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, In preparation (July 2021)

Effect of changing the DM fraction F_χ for $m_D = 200$ MeV and $\lambda = \pi$

Higher values of $F_\chi \Rightarrow$ tidal deformability grows

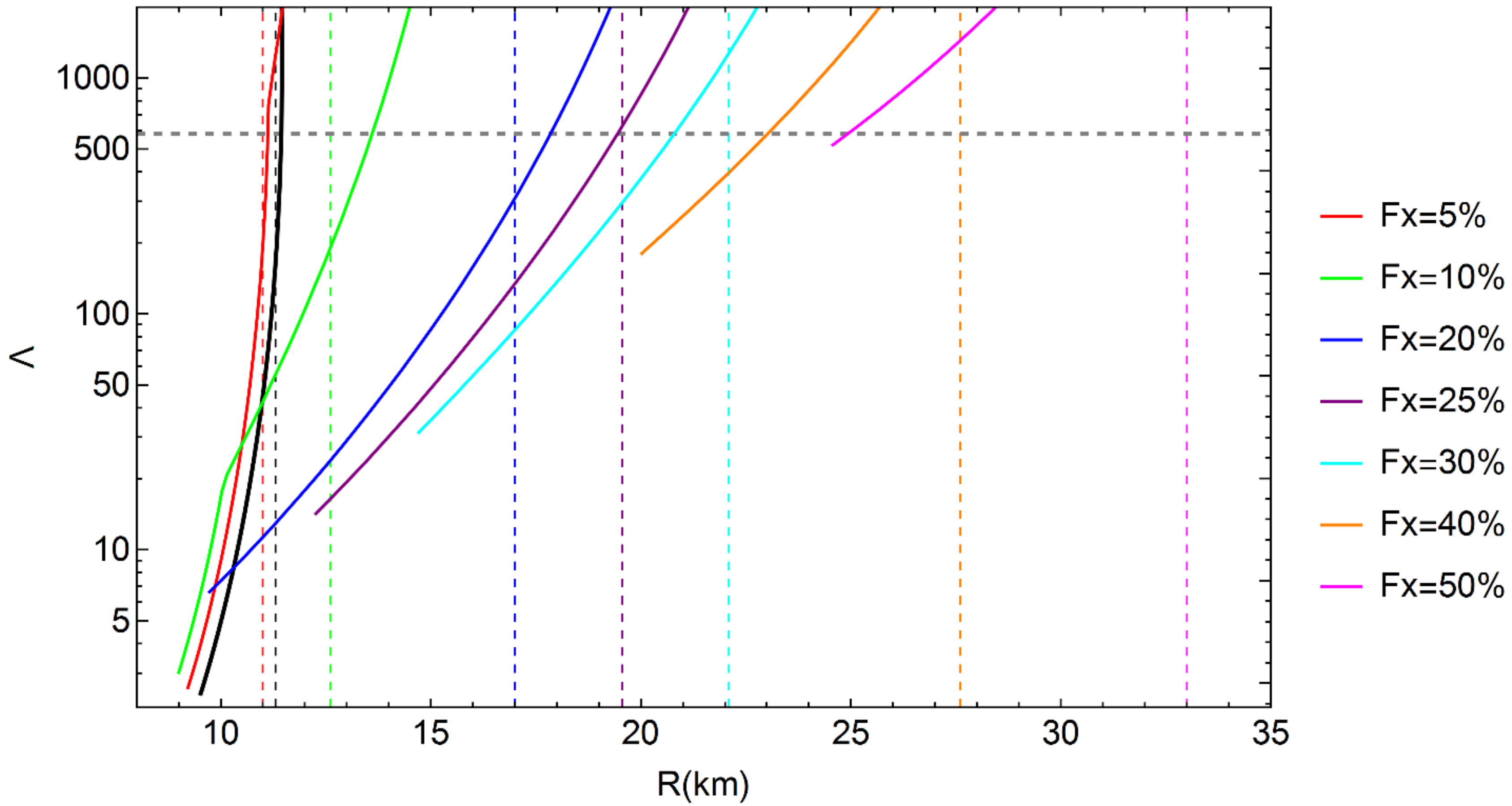


D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, In preparation (July 2021)

DM halo – DM core formation by changing DM fraction

$m_D = 200$ MeV , $\lambda = \pi$

DM halo increases tidal deformability, however, DM core decrease Λ



D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, In preparation (July 2021)

Self-interacting complex scalar field as the DM candidate in a DM admixed NS

DM core and DM halo formation considering λ , m_D and F_χ

Mass-Radius profile of DM admixed NS

DM core decreases the mass and radius of the object, however, DM halo increases them.

Tidal deformability as a new observational constraint

DM core decreases Λ, however, DM halo increases it.

$2M\odot$ observational limit on maximum mass

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

Constraining the parameter space of the DM model

D.R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, In preparation (July 2021)

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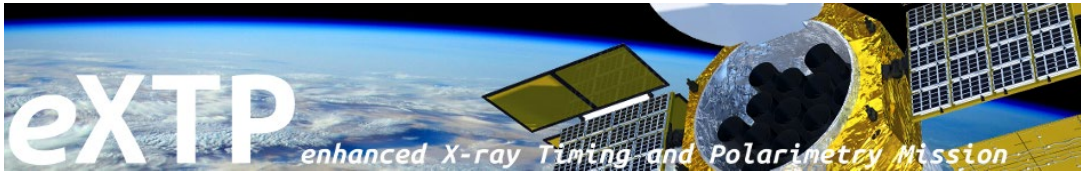
SKA SQUARE KILOMETRE ARRAY



MeerKAT

Radius as an important constraint

STROBE-X

Strange objects GW190814

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