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# How neutron star mergers and astrophysical observations could constrain dark matter properties

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# Neutron stars: introduction

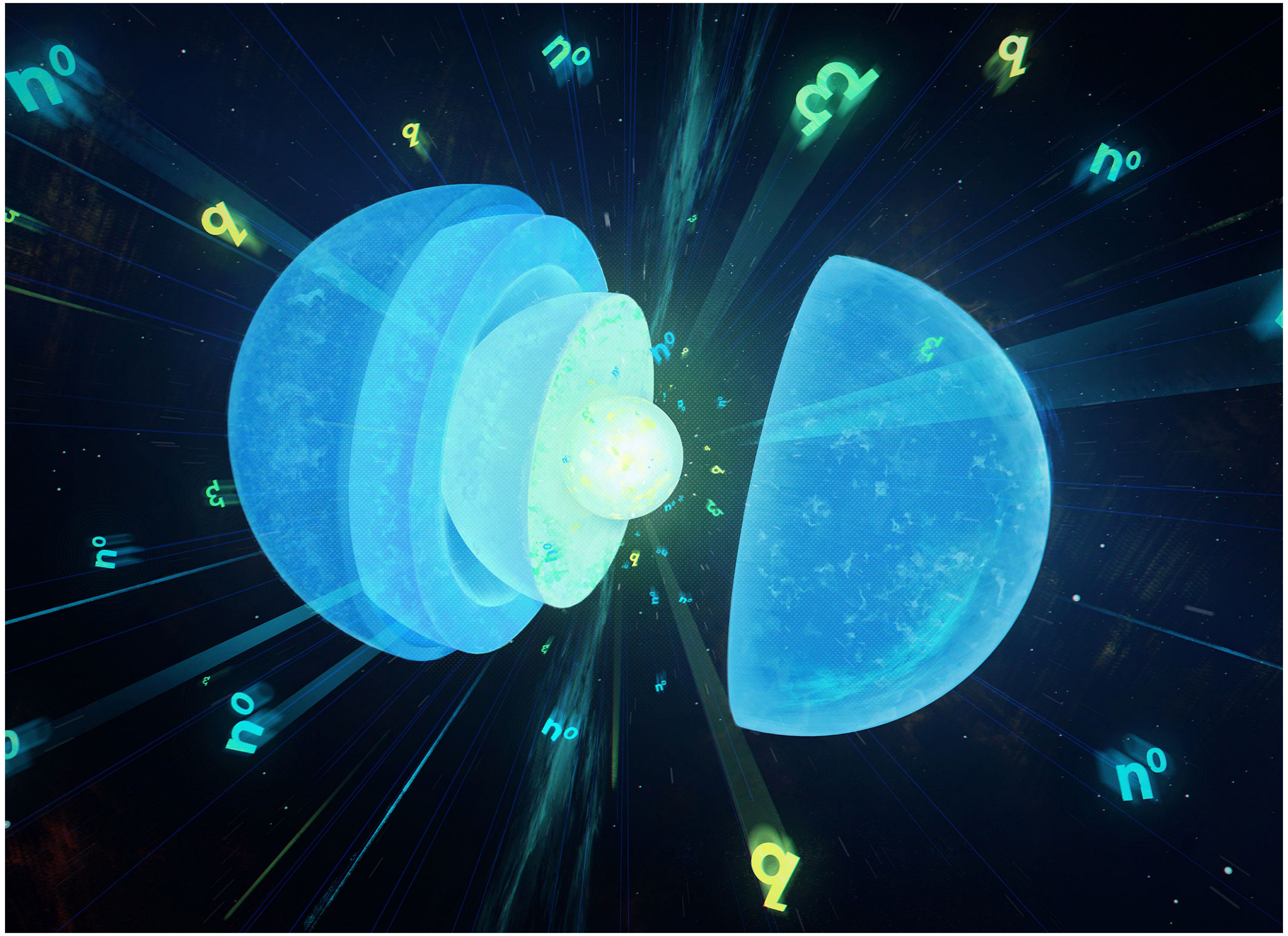
- Highly asymmetric matter

$$\delta = \frac{n_n - n_p}{n_n + n_p} > 0;$$

- Dense environment $n_b \simeq 5 - 10\ n_{sat}$ ;
- Neutron Stars (NS) are cold objects

$$T_{CO} \to 0 \text{ MeV};$$

- During mergers, $T \simeq 100$ MeV;
- High compactness;



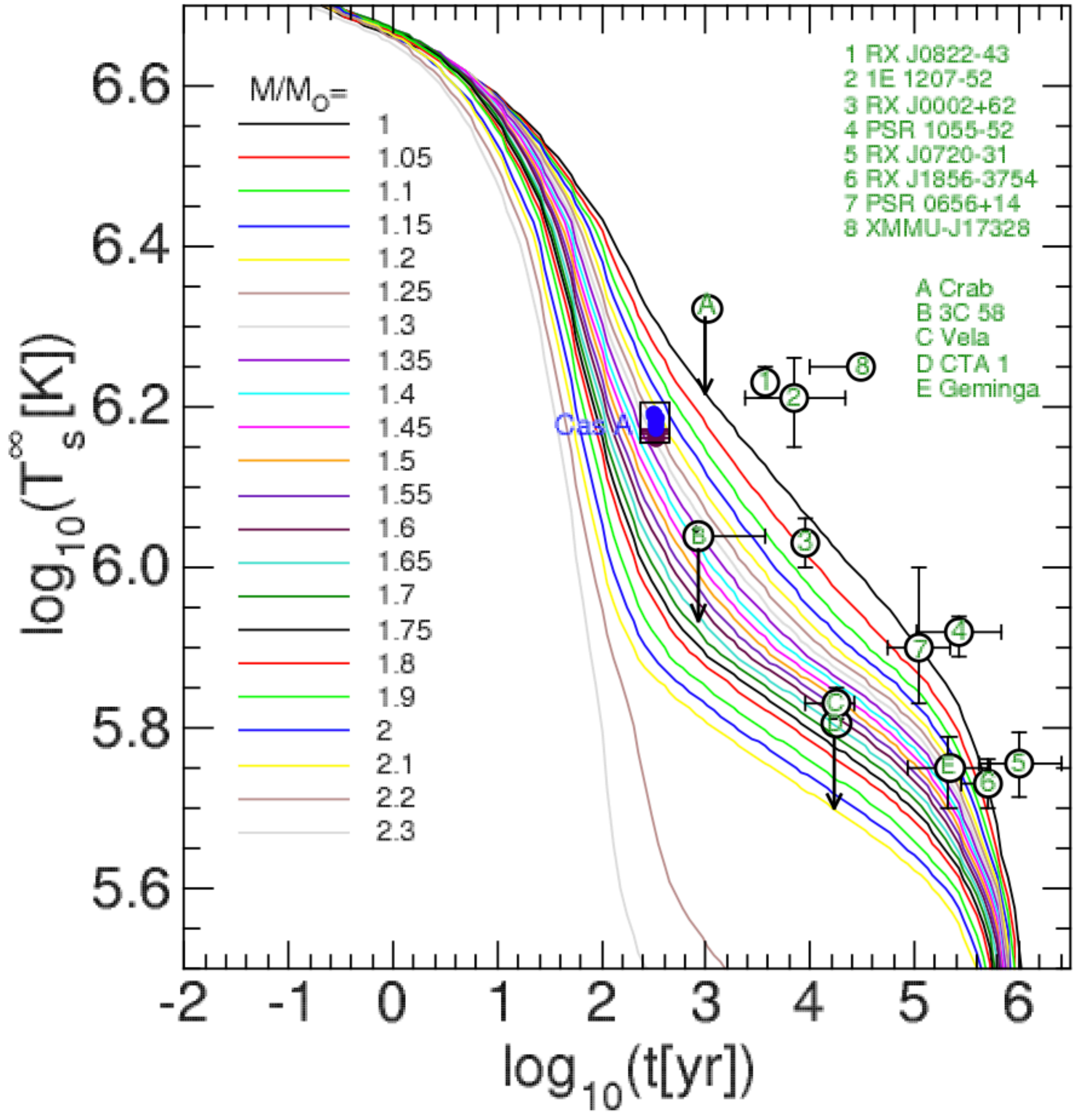
Credits: Maciej Rebisz for Quanta Magazine

# Dark Matter admixed Neutron Stars

- Due to the high compactness, NS may be able to capture Dark Matter (DM);

**SYMMETRIC DM**

- Same amount of particles and anti-particles;
- Annihilation;
- New heating source ⟶ thermal evolution;



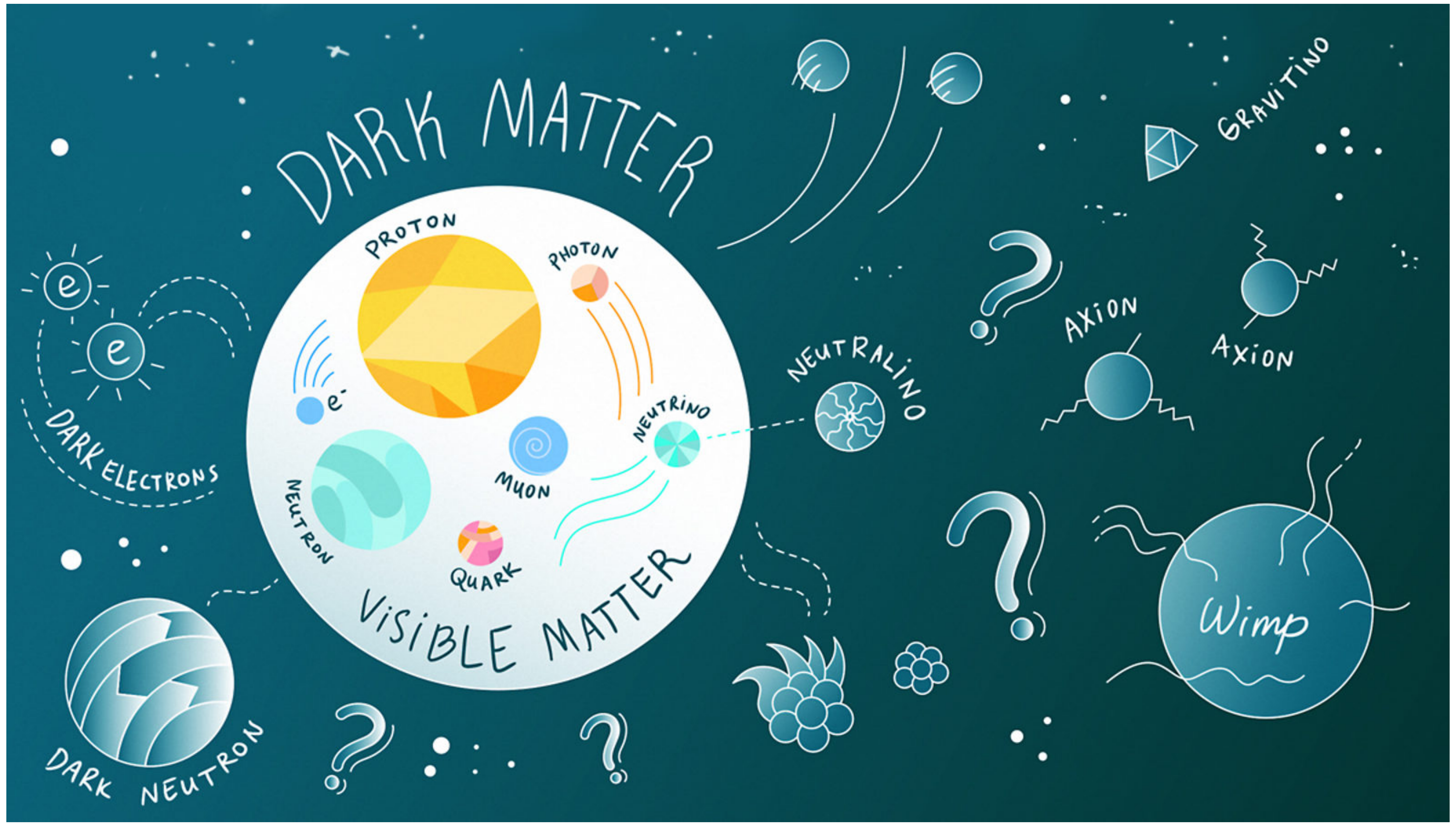

Example of cooling curves for NS described by an EoS with hyperons.
[Grigorian et al., Nuclear Physics A, **980**, (2018)]

Kouvaris, Adv. High Energy Phys., **856**-196 (2013)

# Dark Matter admixed Neutron Stars

## ASYMMETRIC DM

- Fermionic DM models;
- Fermi degenerate pressure given by Pauli exclusion principle;
- Effects on astrophysical NS properties (e.g. masses and radii)
- Possible collapse to a Black Hole (BH) when:




$$\frac{GNm^2}{r} > k_F = \left(\frac{3\pi^2 N}{V}\right)^{1/3} \longrightarrow N \gtrsim \alpha \left(\frac{M_{pl}}{m}\right)^3$$

After choosing a baryonic EoS we can study the effects of DM on NS;

being $M_{\rm pl}$ the planck mass, $\alpha$ a constant and $m$ the particle's mass;

Kouvaris, Adv. High Energy Phys., **856**-196 (2013)

# Induced-surface-tension Equation of State (EoS)

- The grand canonical <u>phenomenological</u> EoS with $n, p, e^-$ has the following form:

Symmetric matter HEP-constraints — Asymmetric matter Astrophysics-constraints

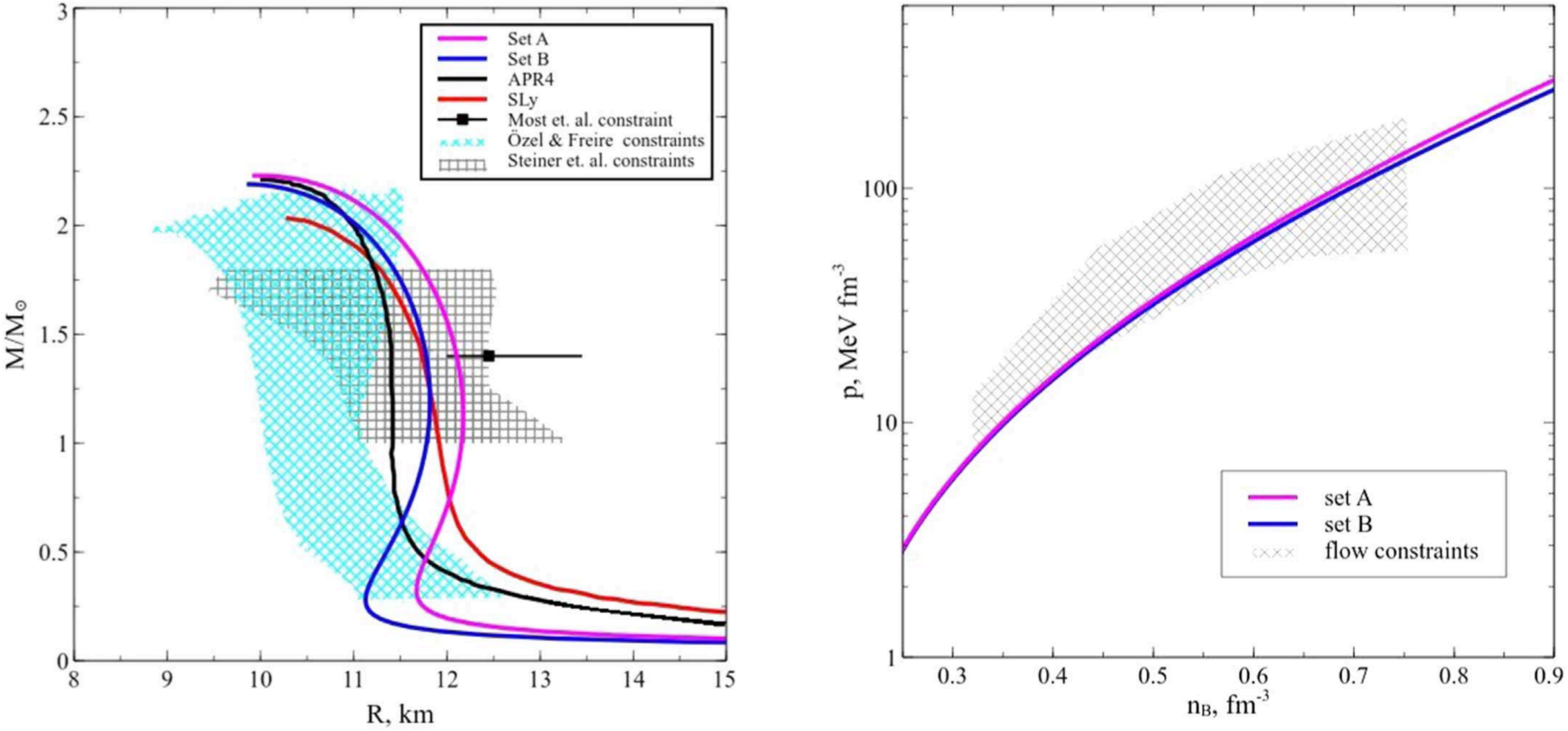
$$\begin{cases} p = \sum_i p_{id}(T, \mu_i - pV_i - \sigma S_i + U_{at} \pm U_{sym}) + p_{id}(\mu_e) - p_{at} + p_{sym} \\ \sigma = \sum_i p_{id}(T, \mu_i - pV_i - \alpha\sigma S_i + U_0)R_i \end{cases}$$

- Hard-core sphere repulsion;
- Highly asymmetric matter and its interactions;

| | |
|---|---|
| $\sigma$ | Induced surface tension parameter |
| $V_i$ | Excluded volume |
| $S_i$ | Surface |
| $R_i$ | Hard core radius of the particle |
| $p_{id}$ | Ideal pressure for QM |
| $U_0 = 162.87$ MeV | Model parameter |
| $\alpha = 1.245$ | Model parameter |
| $A_{sym}$=138.30 MeV $\cdot$ fm$^3$ | Model parameter |
| $B_{sym}$=16.0 fm$^3$ | Model parameter |
| $C_d^2 = 146.30$ MeV $\cdot$ fm$^{3\kappa}$ | Model parameter |
| $\kappa = 0.25$ | Model parameter |
| $L_0 = 93.19$ MeV | Symmetry energy slope |
| $K_0 = 201.02$ MeV | Incompressibility parameter |

Sagun et al., <u>arXiv:2002.12209</u> (2020)
Ivanytskyi et al., PRC **97**, 064905 (2018)
Reed at al., Phys. Rev. Lett. **126**, 172503 (2021)

# Induced-surface-tension Equation of State (EoS)




MR diagram and EoS of the IST EoS with two different sets of the model parameters.
[Sagun et al., ApJ 871:157 (2019)]

We can now add the Dark Matter inside the NS

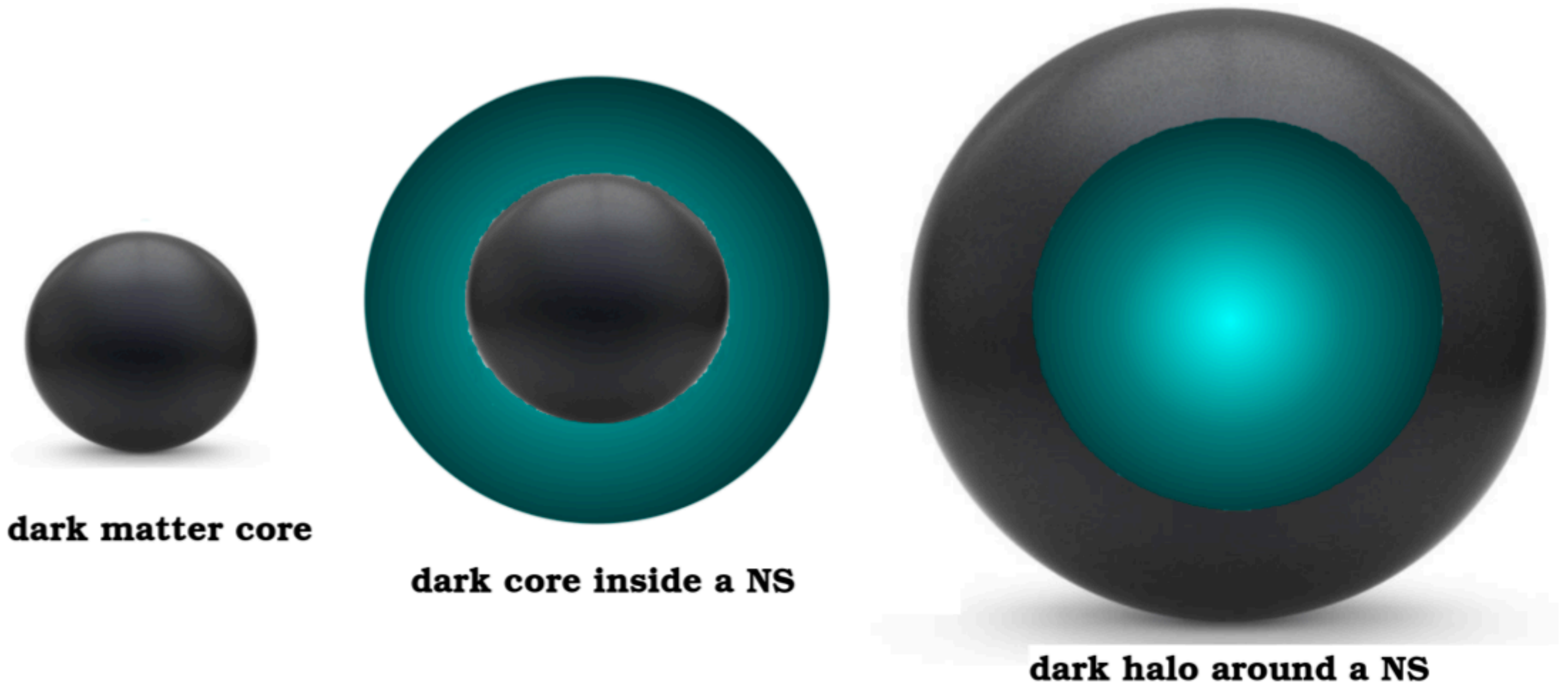
# Fermionic Dark Matter

- Relativistic Fermi gas of non-interacting particles with spin one-half;

- Baryonic matter and DM weakly interact:

$$\sigma_\chi \sim 10^{-45}\ \mathrm{cm}^2 \ll \sigma_N \sim 10^{-24}\ \mathrm{cm}^2$$

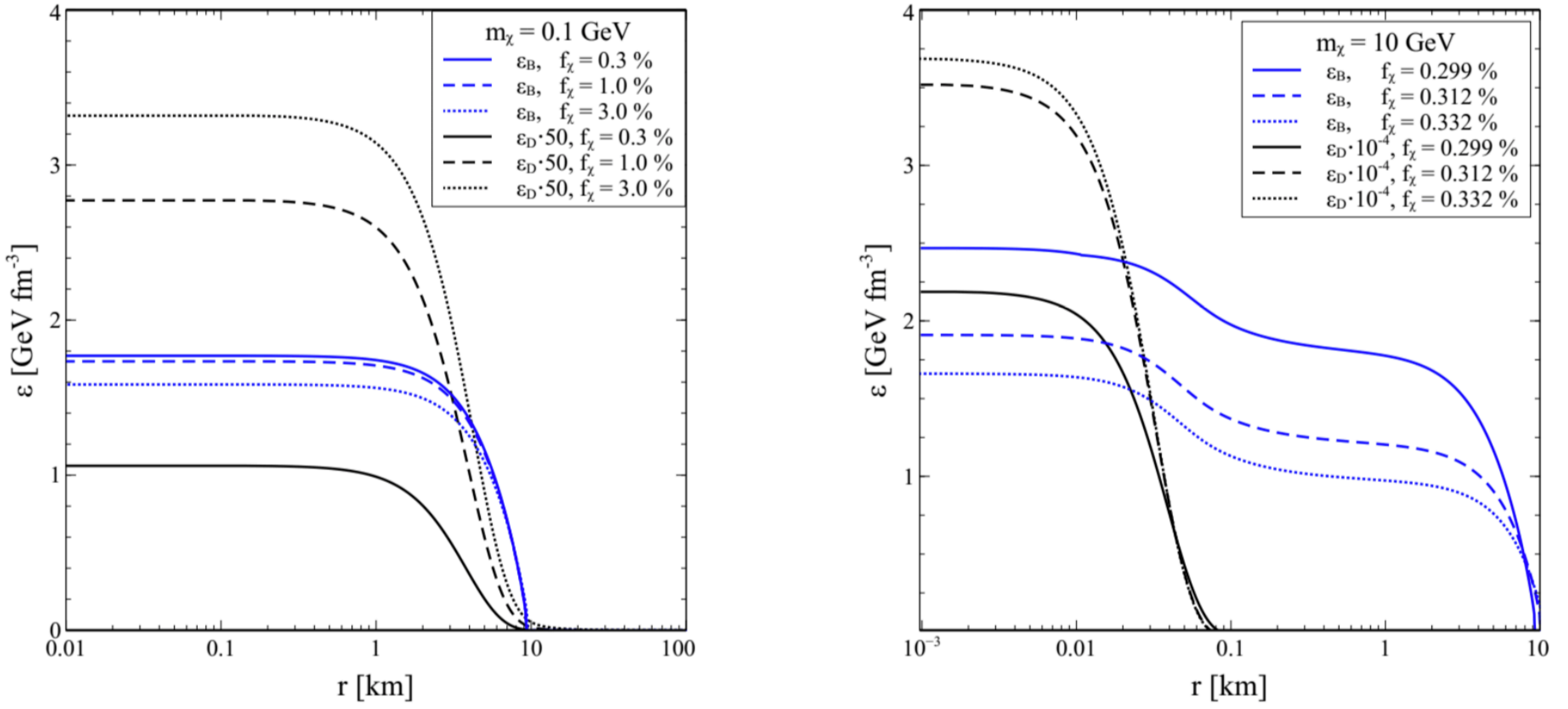
- We consider here just the gravitational interaction between the two of them;




$$\frac{dp_i}{dr} = -\frac{m\rho_i}{r^2}\left(1+\frac{4\pi r^3}{m}\right)\left(1+\frac{p_i}{\rho_i}\right)\left(1-\frac{2Gm}{r}\right)^{-1}$$

DM affects the baryonic energy density profiles, radius and mass;

# Internal structure of the star

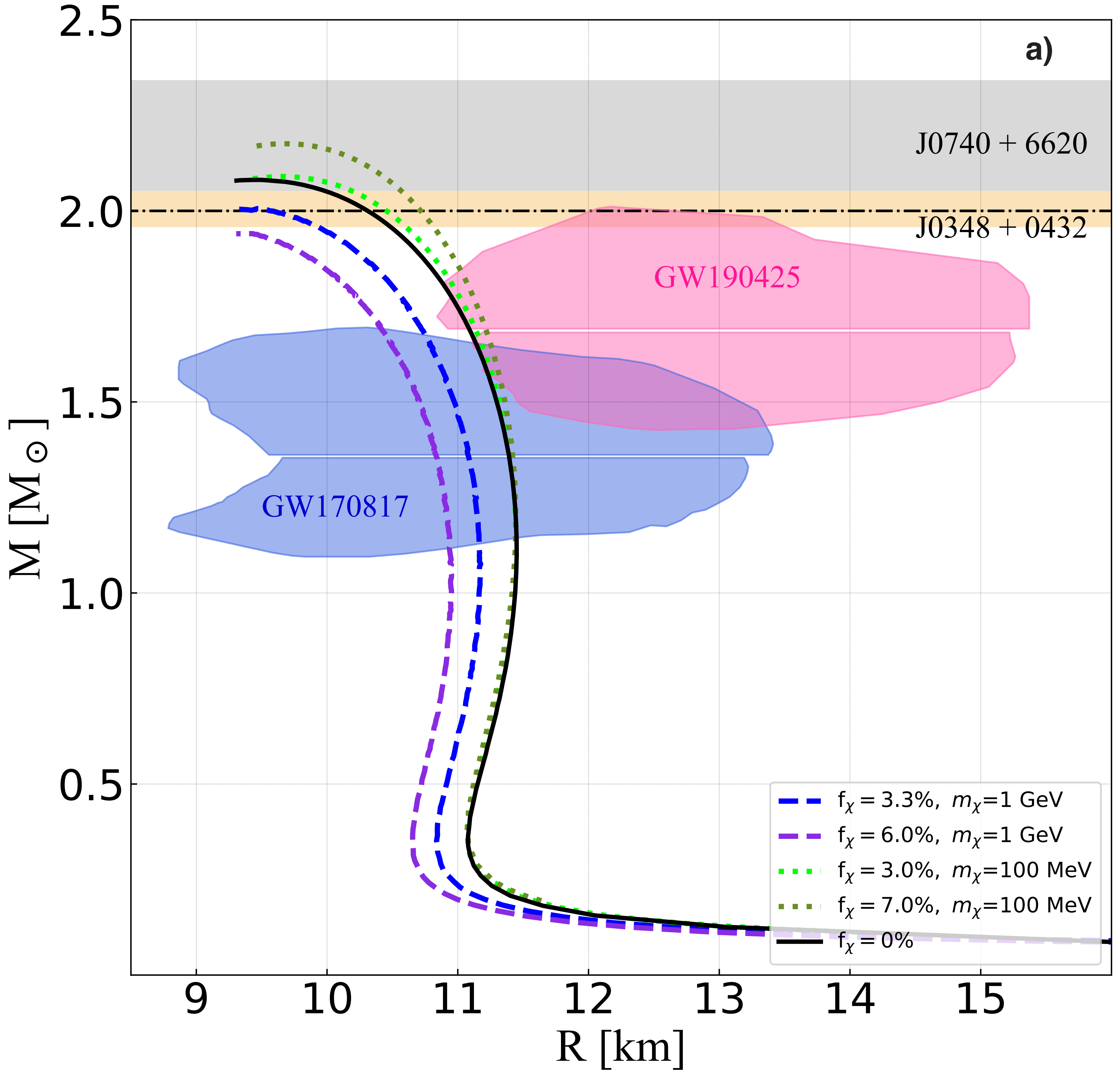



Energy density profiles in DM halo (L) and core (R) configurations.
[Ivanytskyi, PR D, **102**, (2020)]

- Large values of the DM radius is related to the presence of a diluted DM halo which embeds the NS;

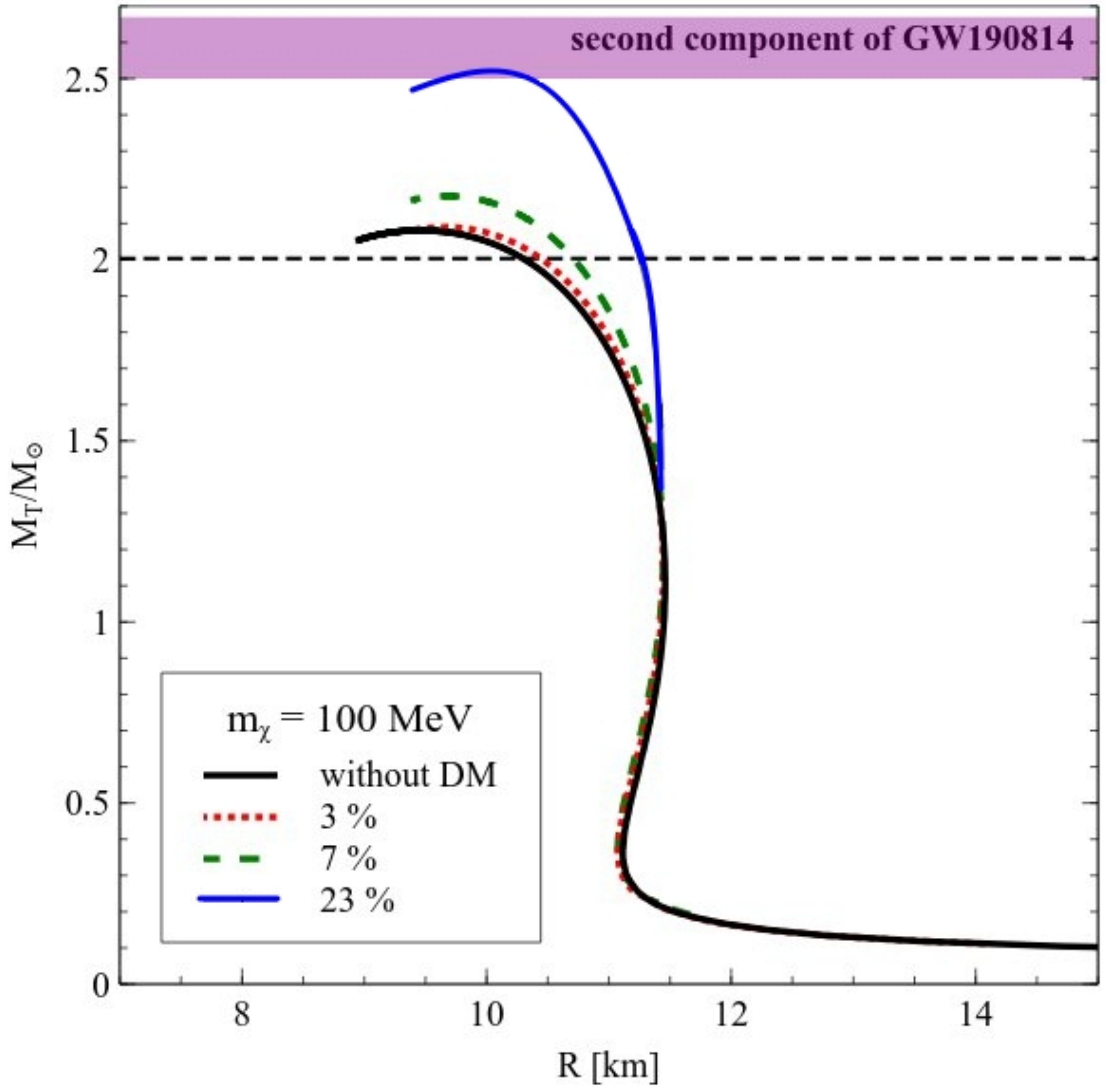
# Mass-Radius curves

- DM-Cores lead to a decrease of the maximum gravitational mass;
- On the other hand, halo configurations produce a relative increase;
- Halo-configurations have high masses which could explain the compact object of GW190814;




Mass-Radius diagram for fermionic DM-admixed NS.
[Sagun, *Giangrandi* et al., PoS PANIC2021 (2022)]

# GW190814 secondary component as a DM admixed NS




Sagun et al., (*in prep 2022*)

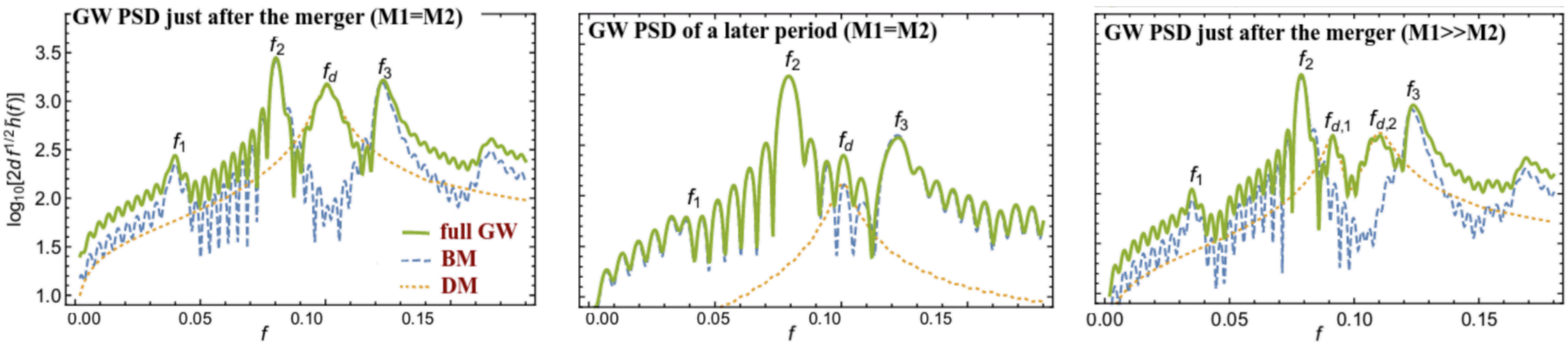
- Secondary component of GW190814 could be explained by the DM extended halo formation around a NS with the DM fraction

$$f_\chi \sim 23\,\% \text{ for } m_\chi = 100 \text{ MeV}$$

- DM can also affect GW waveform and tidal deformability;

# Gravitational waves constraints

- The DM cores may produce a supplementary peak(s) in the characteristic GW spectrum of NS mergers;
- New future constraints coming new detections and numerical relativity simulations;
- From the wave form, we can obtain the tidal deformability parameter;




Gravitational waves frequency peaks in symmetric and strongly asymmetric systems with DM.
[Ellis et al. PLB, **781**, 607 (2018). M. Bezares et al., PRD, **100** 044049 (2019)]

# Tidal disruption: a new constraint

- Tidal deformability parameter:

$$\Lambda_i = \frac{2}{3} k_2 \left( \frac{R_i}{GM_i} \right)^5$$

- Love's number:

$$k_2 = k_2(\beta, R_{\rm NS})$$

- Mass extracted from the gravitational wave;

$$\begin{cases} \Lambda(1.4\ \mathrm{M}_\odot) \leq 800 \\ R(1.4\ \mathrm{M}_\odot) \leq 11.8^{+2.7}_{-3.3}\ \mathrm{km} \end{cases}$$

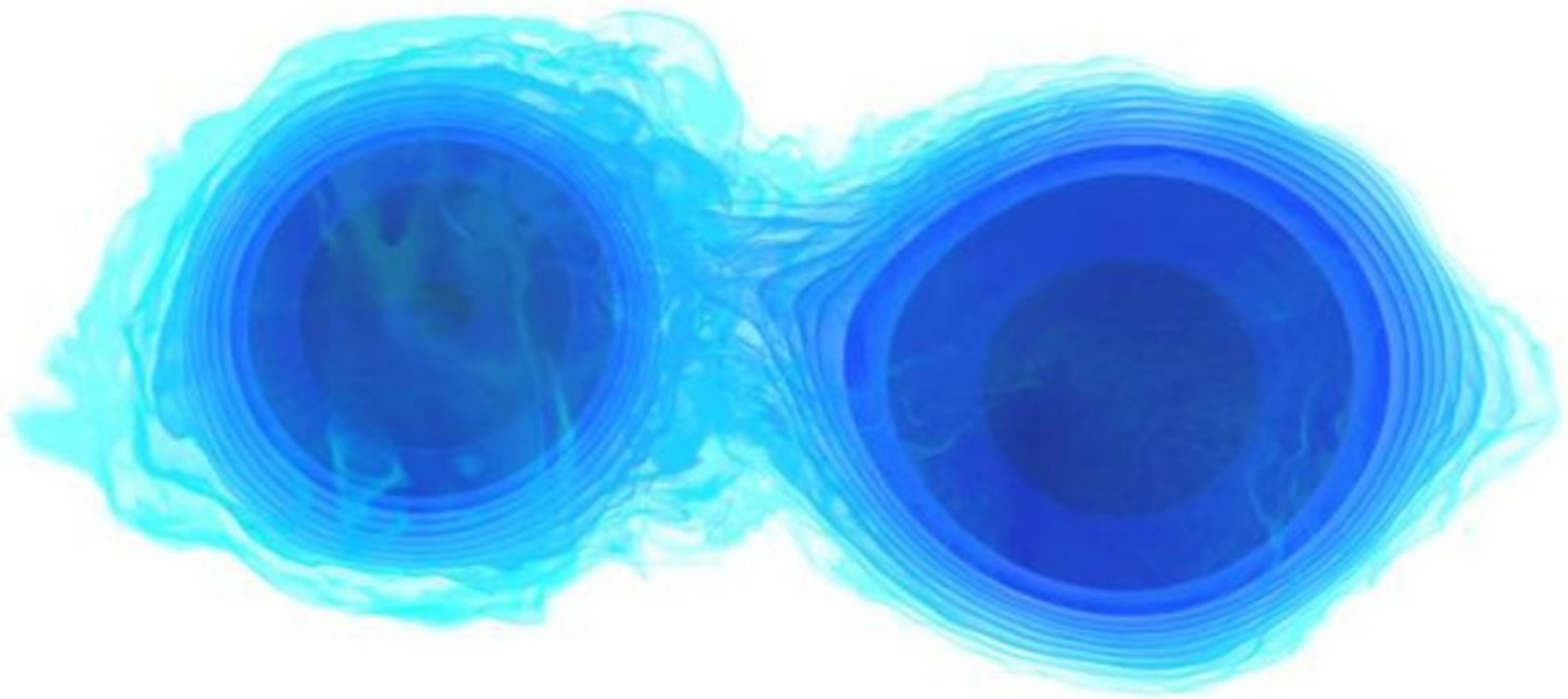
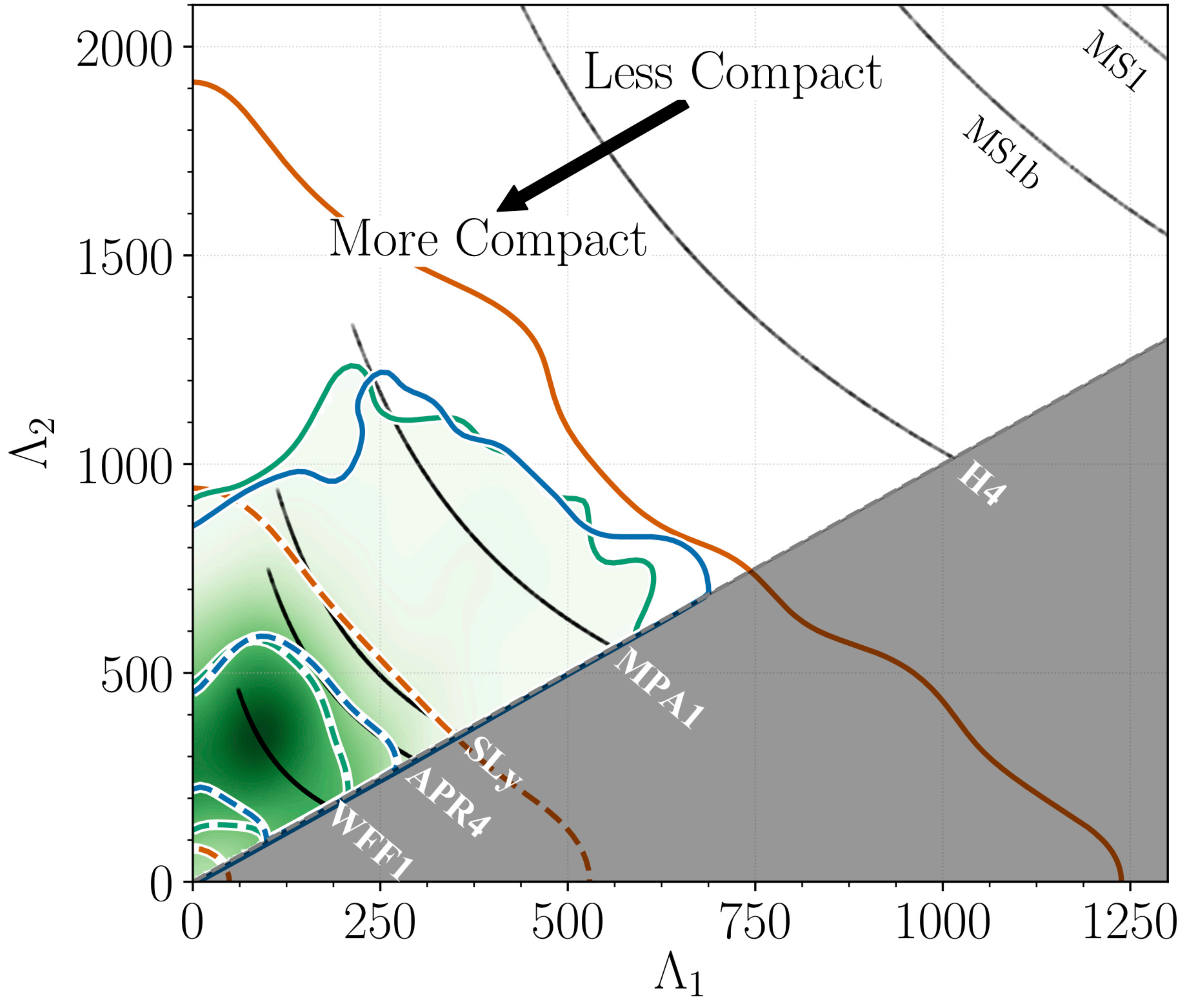


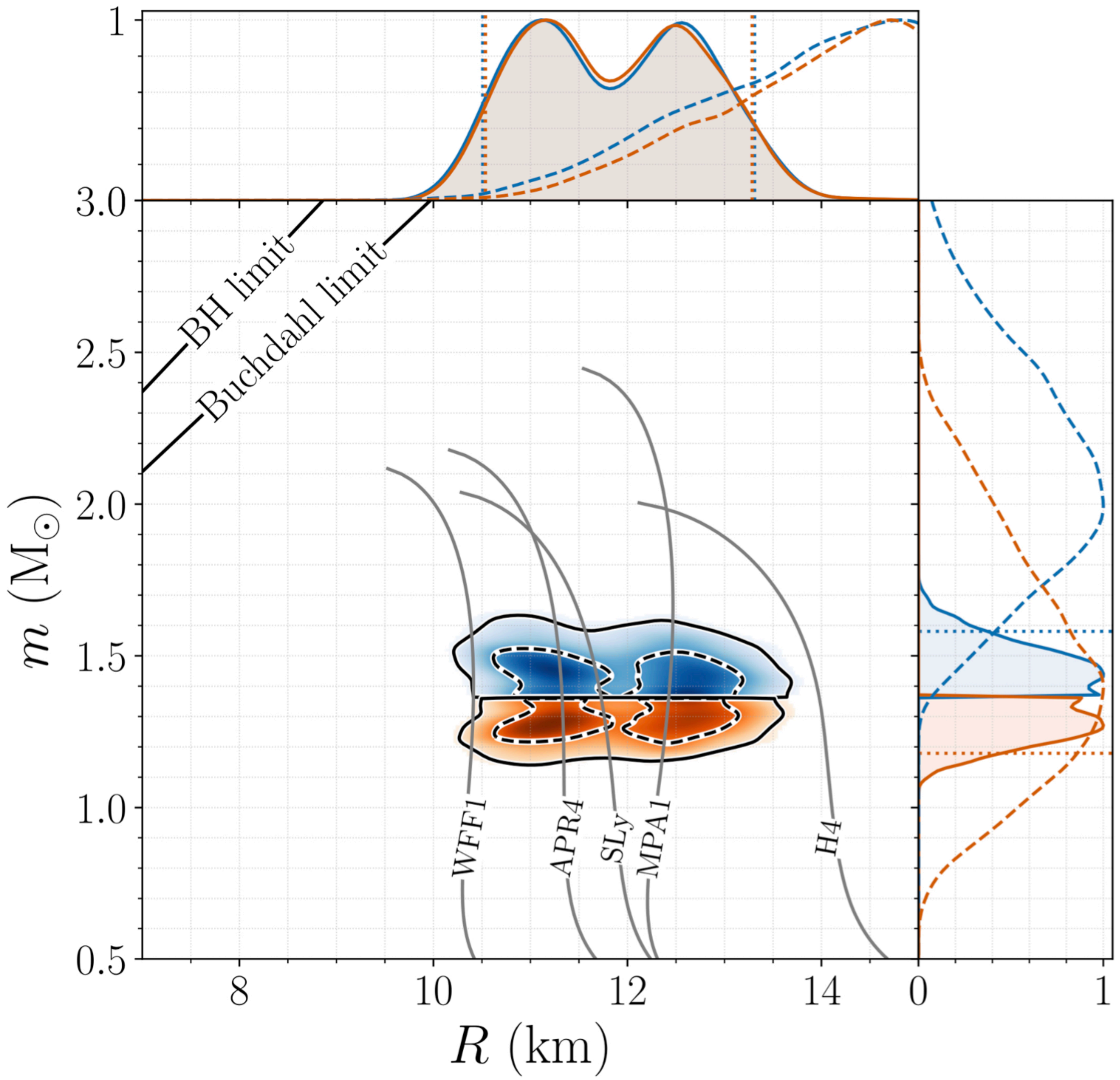
Image by NASA Goddard Space Flight Center

LIGO-Virgo Collab. PRL **121**, 161101 (2018)

# An insight on the NS interior

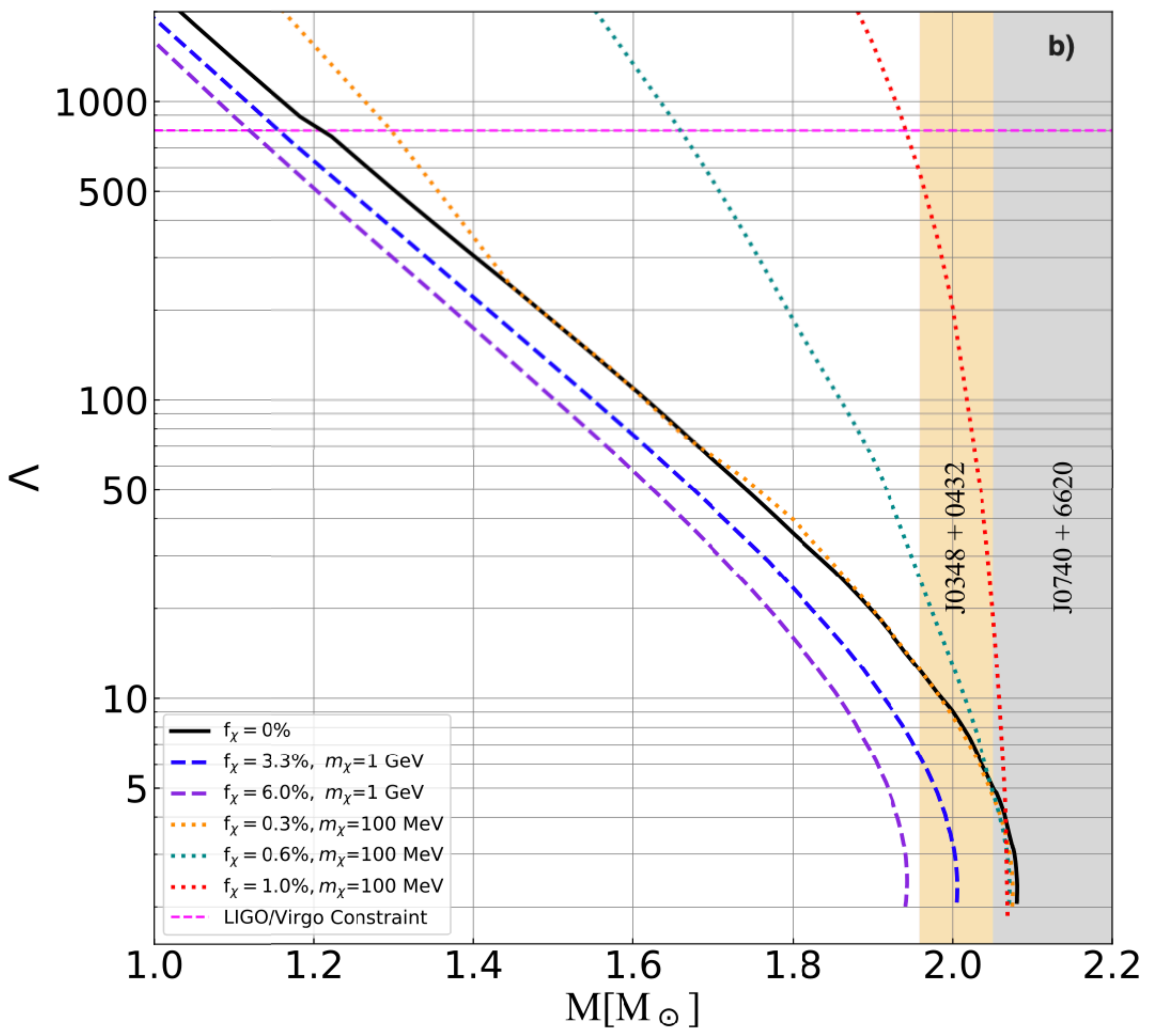



Constraint on the tidal deformability parameter obtained from GW170817.
[LIGO-Virgo Collaboration Phys. Rev. X **9**, 011001 (2019)]




Constraints on mass-radius relation and EoSs from GW170817
[LIGO-Virgo Collaboration, Phys. Rev. Lett. **121**, 161101 (2018)]

# Tidal deformabilities of DM-admixed NS




Tidal deformability parameter for DM-admixed NS.
[Sagun, *Giangrandi* et al., PoS PANIC2021 (2022)]

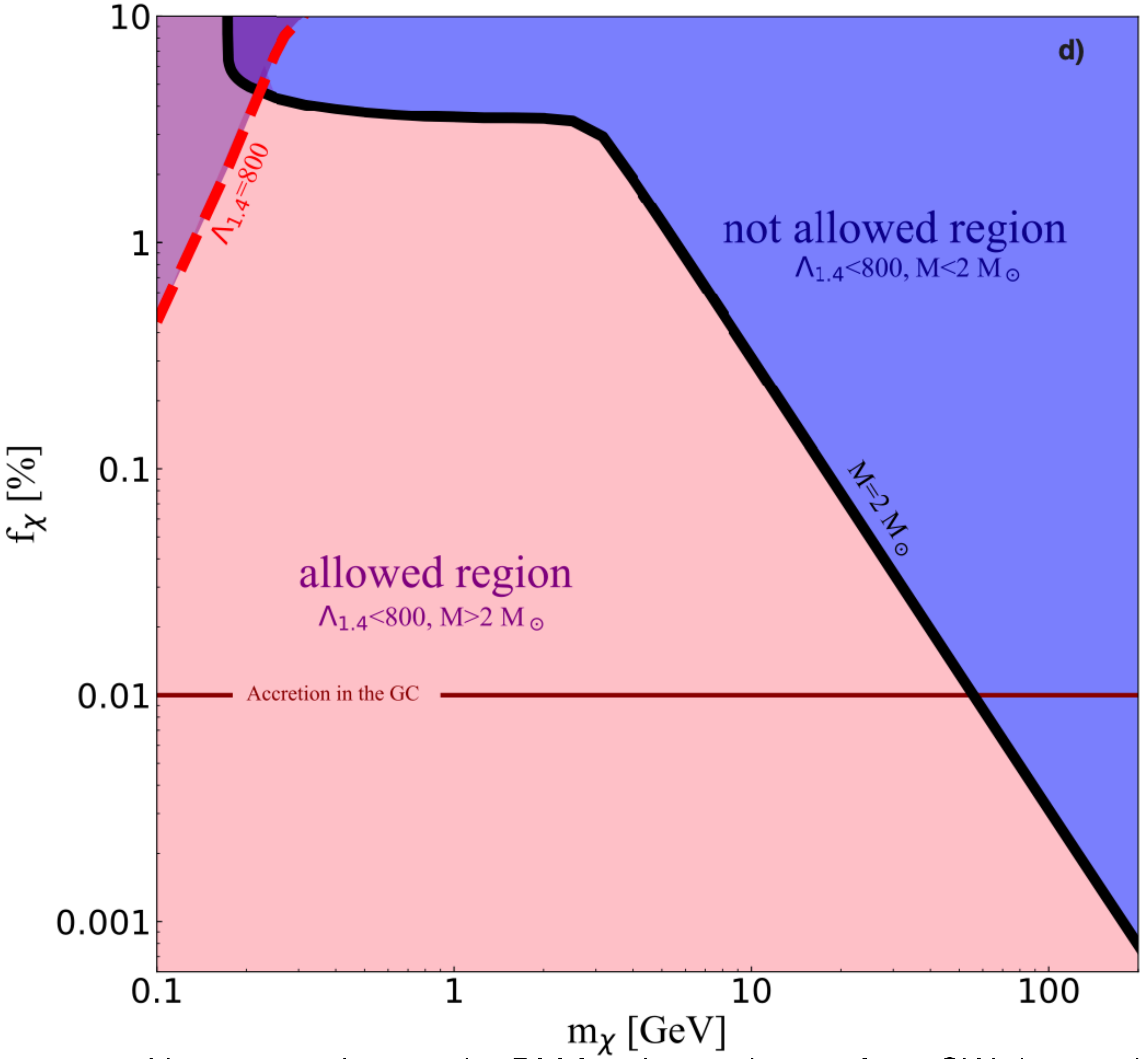
- Recalling the definition of $\Lambda$:

$$\Lambda = \frac{2}{3} k_2 \left( \frac{R_{\text{outermost}}}{G M_{\text{tot}}} \right)^5$$

- Considering halo-configurations, the outermost radius can be extremely large $R_{\text{outermost}} \simeq 10^2$ km;

- We can use all of this to constrain DM mass and fraction inside NS;

# New Dark Matter constraints




New constraints on the DM fraction and mass from GW data and Astrophysical observations.
[Sagun, *Giangrandi* et al., PoS PANIC2021 (2022)]

# Wrap up

- DM can be accumulated in the core of a NS ⇒ significant decrease of the maximum mass and radius of a star.
- DM halo ⇒ increase of the maximum mass and the outermost radius.
- The secondary component of the GW190814 binary merger might be a DM admixed NS;
- NSs in different regions of the Galaxy may contain different amount of DM

↓

different modifications of M, R, Λ, waveform, etc.

# Obrigado!