Stability and gravitational collapse of dark matter admixed neutron stars

E. Giangrandi
V. Sagun
O. Ivanytskyi
C. Providência
T. Dietrich

Universidade de Coimbra
Universität Potsdam
FCT Fundação para a Ciência e a Tecnologia
CFisUC

Neutron Stars environment

- Highly asymmetric matter

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

Typical nuclear density

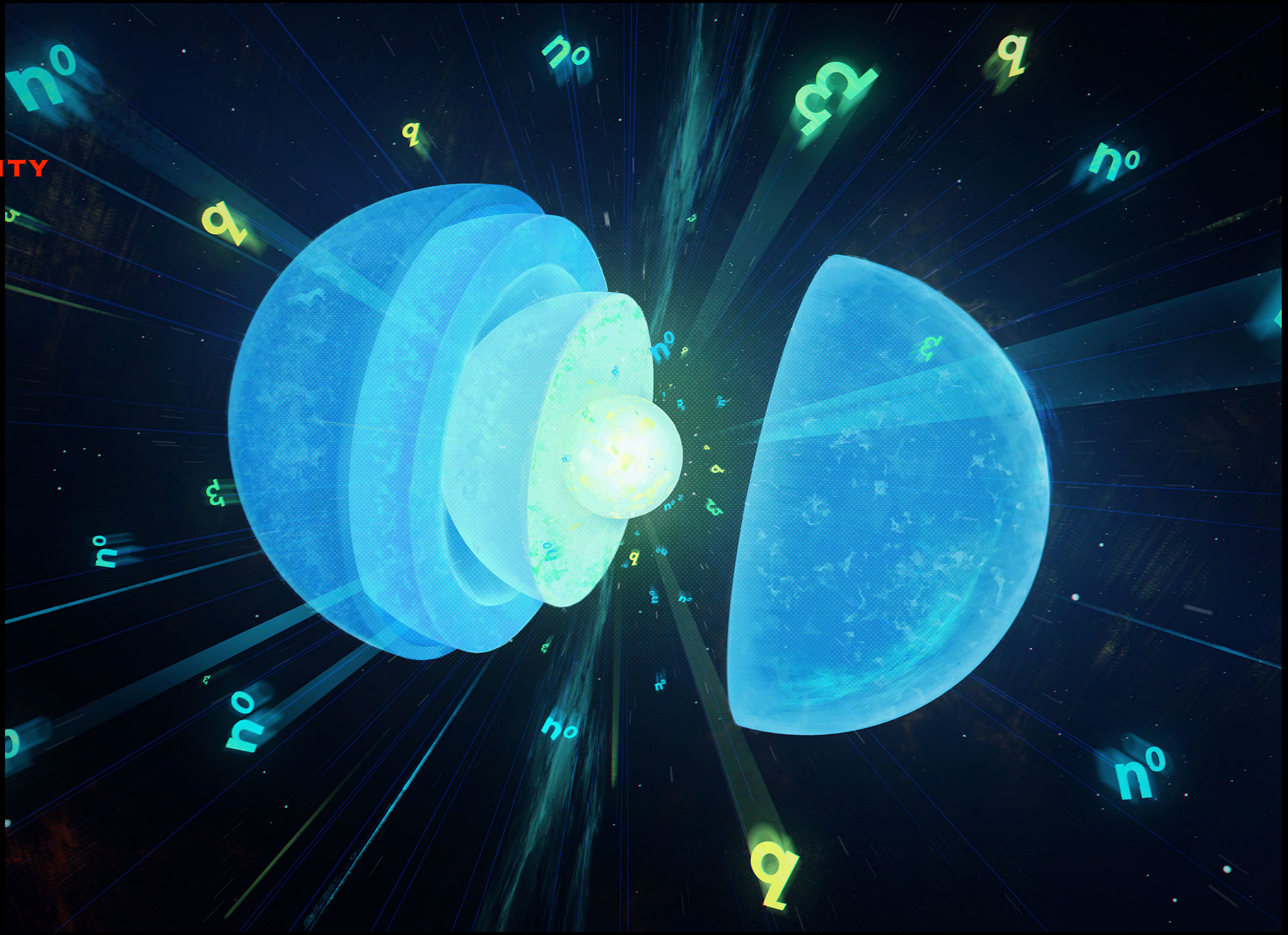
- Dense environment $n_b \simeq 5 - 10\, n_{sat}$

- Neutron Stars (NS) are cold objects

$$T_{CO} \rightarrow 0 \text{ MeV}$$

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

- High compactness $\begin{cases} M \sim 1.4\, M_\odot \\ R \sim 12.5 \text{ km} \end{cases}$



Credits: Maciej Rebisz for Quanta Magazine

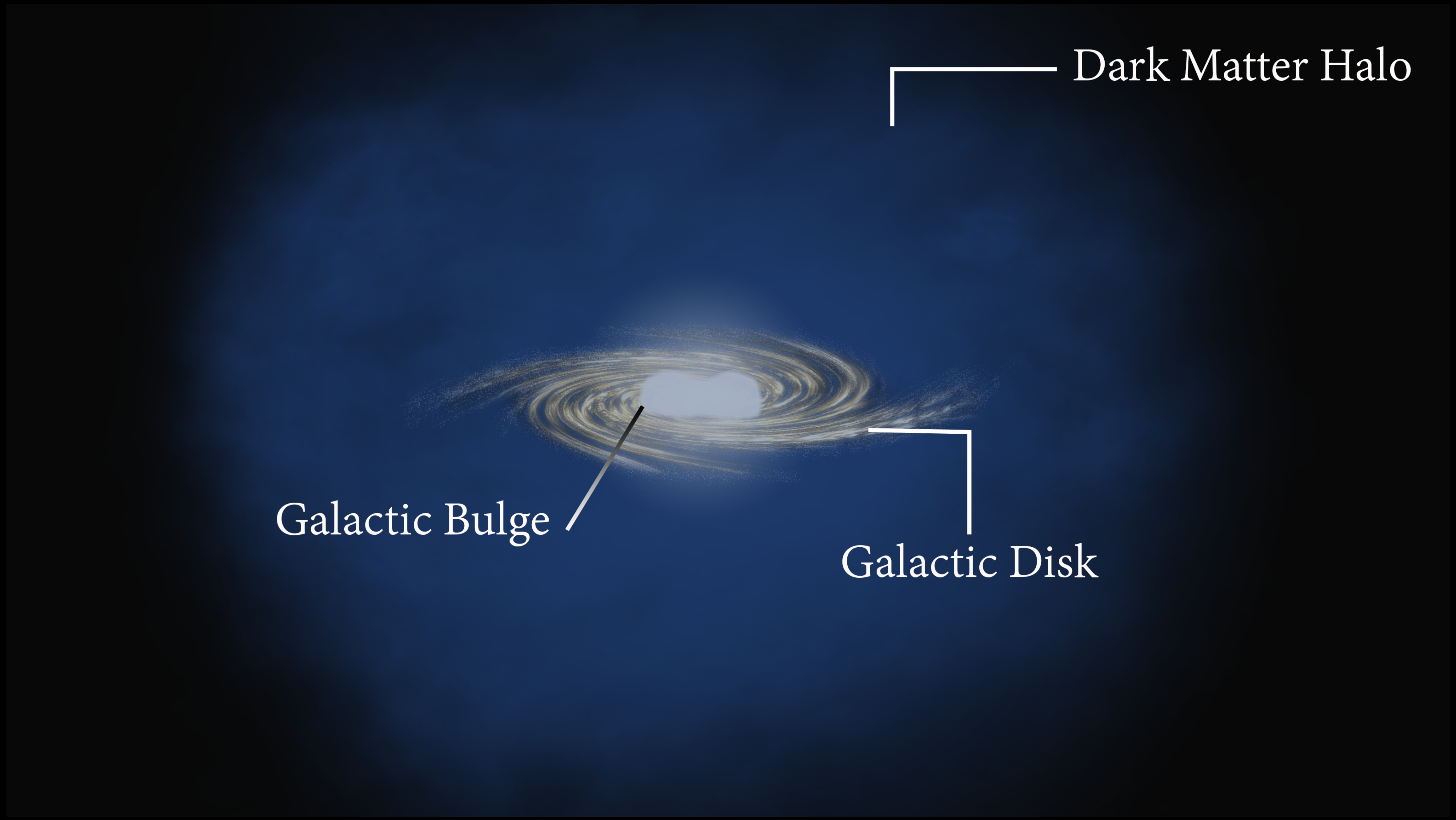
Dark Matter admixed Neutron Stars

- Due to their huge compactness, NS may be able to accumulate a sizeable amount of Dark Matter (DM);

Equilibrated NS stage
Main Sequence Stars

$$M_{\rm acc} \sim 10^{-14} \left(\frac{\rho_\chi}{0.3 \frac{GeV}{cm^3}} \right) \left(\frac{\sigma_{\chi n}}{10^{-45} \mathrm{cm}^2} \right) \left(\frac{t}{\mathrm{Gyr}} \right) M_\odot$$

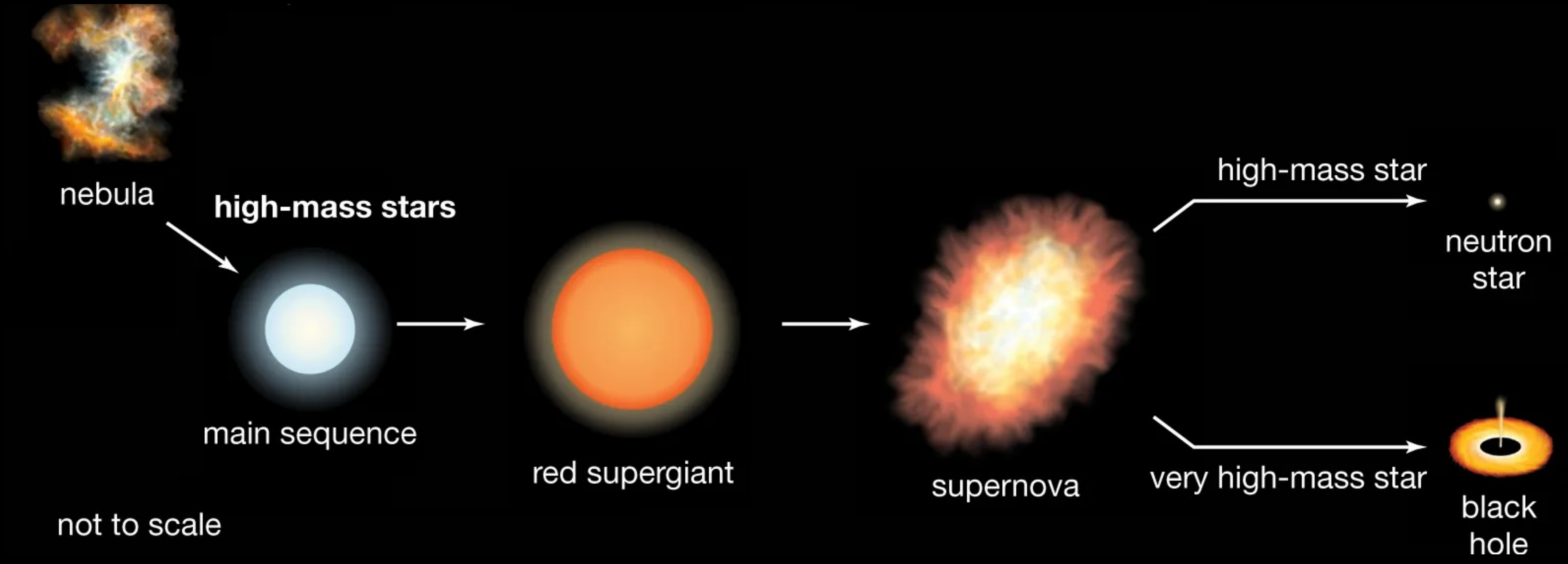
Kouvaris 2008
Kouvaris&Tinyakov, 2010



DM galactic halo embedding NSs environments;

DM accumulation regimes

- Proto-cloud - mixture of Baryonic Matter (BM) and Dark Matter (DM);
- Supernovae - creation of DM; → Never taken into account!
- DM Clumps;



Credits: E.Britannica

DM and NS configurations

Dark matter and baryon components do not expel each other but overlap due to absence of non-gravitational interaction

How can we obtain astrophysical properties of DM-admixed NSs?

TOV Equation - 2 fluids approach

$$\begin{cases} \frac{dP_B}{dr} = -\frac{Gm}{r^2}\left(\rho_B + P_B\right)\left(1 + \frac{4\pi r^3 P}{m}\right)\left(1 - \frac{2Gm}{r}\right)^{-1} \\ \frac{dP_\chi}{dr} = -\frac{Gm}{r^2}\left(\rho_\chi + P_\chi\right)\left(1 + \frac{4\pi r^3 P}{m}\right)\left(1 - \frac{2Gm}{r}\right)^{-1} \end{cases}$$

Total pressure $$P(r) = P_B(r) + P_\chi(r)$$

Gravitational Mass $$m(r) = m_B(r) + m_D(r)$$

$$m_i(r) = 4\pi \int_0^r \rho_i(r') r'^2 dr'$$

Total gravitational mass $$M_{\text{tot}} = M_B(R_B) + M_D(R_D)$$

DM fraction $$f_\chi = \frac{M_D}{M_{\text{tot}}}$$

The Bullet Cluster provides constraints on the cross section $\sigma_{\chi n}$

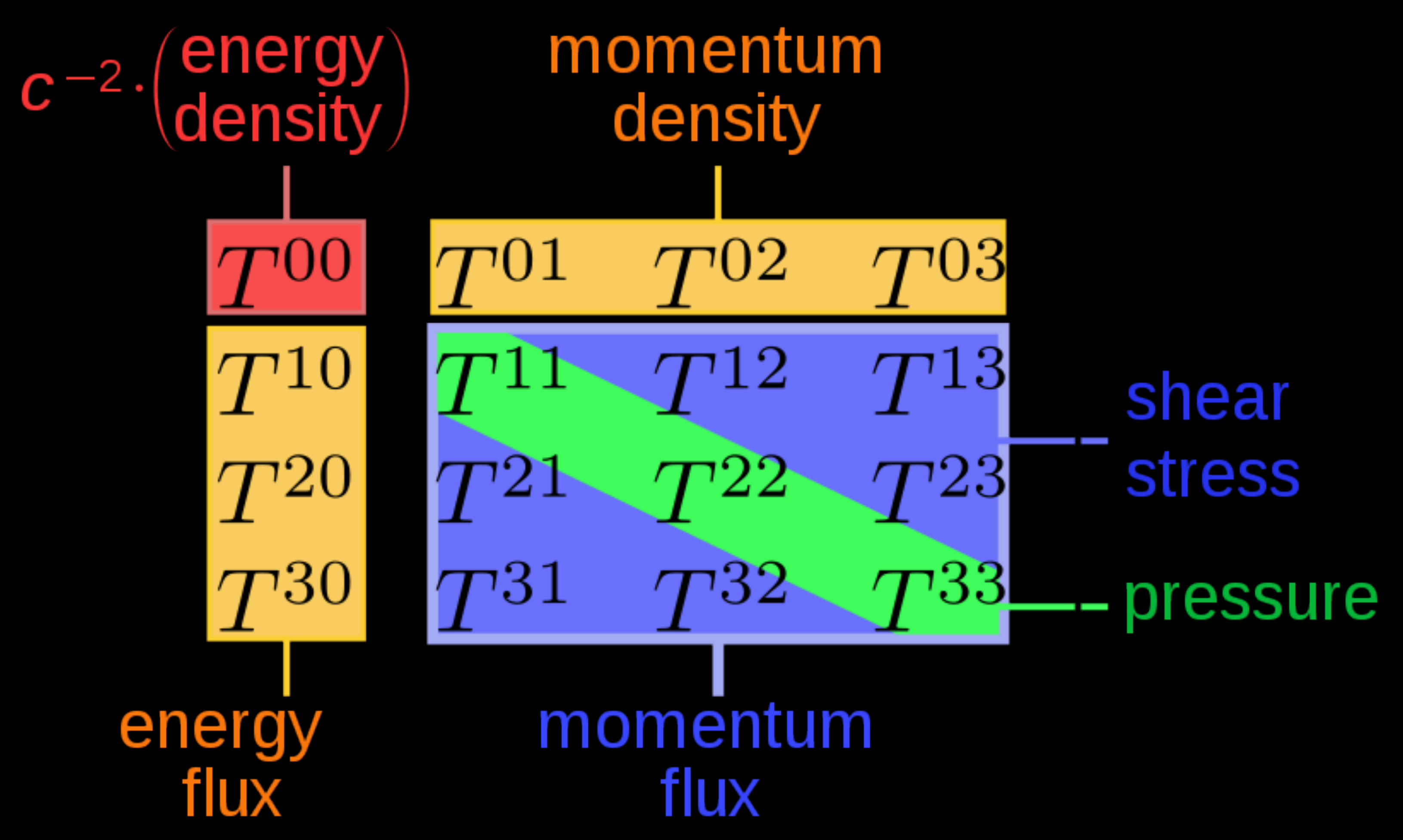
Robertson et al., 2016

↓

BM and DM are coupled just through gravity

↓

Energy-momentum tensors are conserved separately



DM-admixed NSs

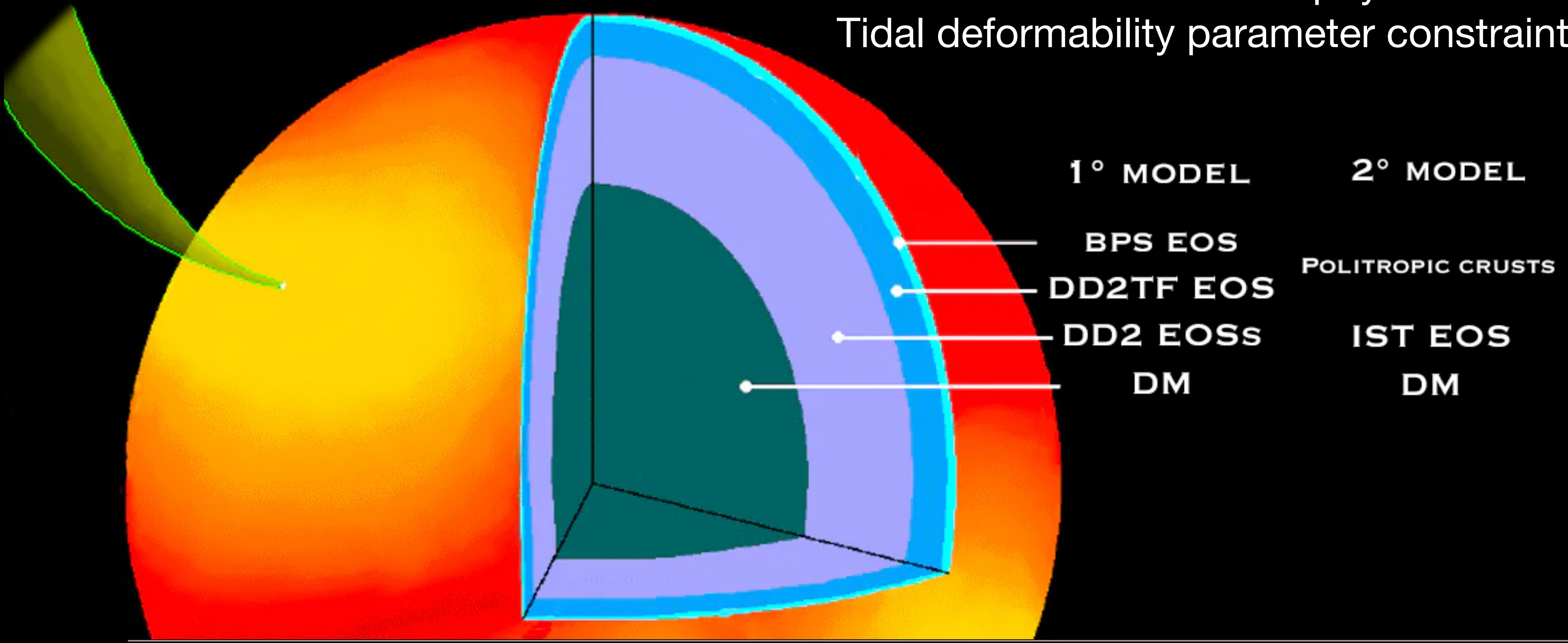
Dark Matter EoS — Self-interacting bosonic DM

Baryonic Matter EoS

- Induced Surface Tension (IST) EoS
- DD2 EoS+DD2TF Inner crust+BPS Crust
- DD2 with Hyperons+DD2TF Inner crust+BPS Crust

consistent with:

Nuclear ground matter state properties
Proton flow data
Heavy-Ion collisions data
Astrophysical observations
Tidal deformability parameter constraints from GW170817 - *IST EoS*



GIANGRANDI ET AL., 2022

SAGUN ET AL., 2014
SAGUN ET AL., 2019
TYPEL ET AL., 2010
TYPEL&WOLTER, 1999

BAYM ET AL., 1971

KHAN, 2009
DUTRA ET AL., 2012
ZHANG ET AL., 2013

DANIELEWICZ ET AL., 2002

ANDRONIC ET AL., 2006
BUGAEV ET AL., 2018

ANTONIADIS ET AL., 2013
FONSECA ET AL., 2021
ROMANI ET AL., 2021
ROMANI ET AL., 2022MILLER ET AL., 2019
RILEY ET AL., 2019
MILLER ET AL., 2021
RILEY ET AL., 2021ABBOTT ET AL., 2017
ABBOTT ET AL., 2019
NAGHDI, 2014

Self-interacting Bosonic DM

Lagrangian of the model

$$\mathcal{L} = (D_\mu \chi)^* D^\mu \chi - m_\chi^2 \chi^* \chi - \frac{\Omega_{\mu\nu}\Omega^{\mu\nu}}{4} + \frac{m_\omega^2 \omega_\mu \omega^\mu}{2}$$

BOSONIC MATTER — INTERACTIONS → ω MESON

$$D^\mu = \partial^\mu - ig\omega^\mu$$ Covariant derivative

$$\Omega_{\mu\nu} \equiv \partial_\mu \omega_\nu - \partial_\nu \omega_\mu$$ Inside the kinetic term

$$m_\chi$$ DM particle mass

$$m_I \equiv \frac{m_\omega}{g}$$ Interaction strength

$m_I \gg 1$ weaker interaction

$m_I \ll 1$ stronger interaction

Mean field approximation

GIANGRANDI ET AL., 2022

Self-interacting Bosonic DM

Pressure and energy density can be written as:

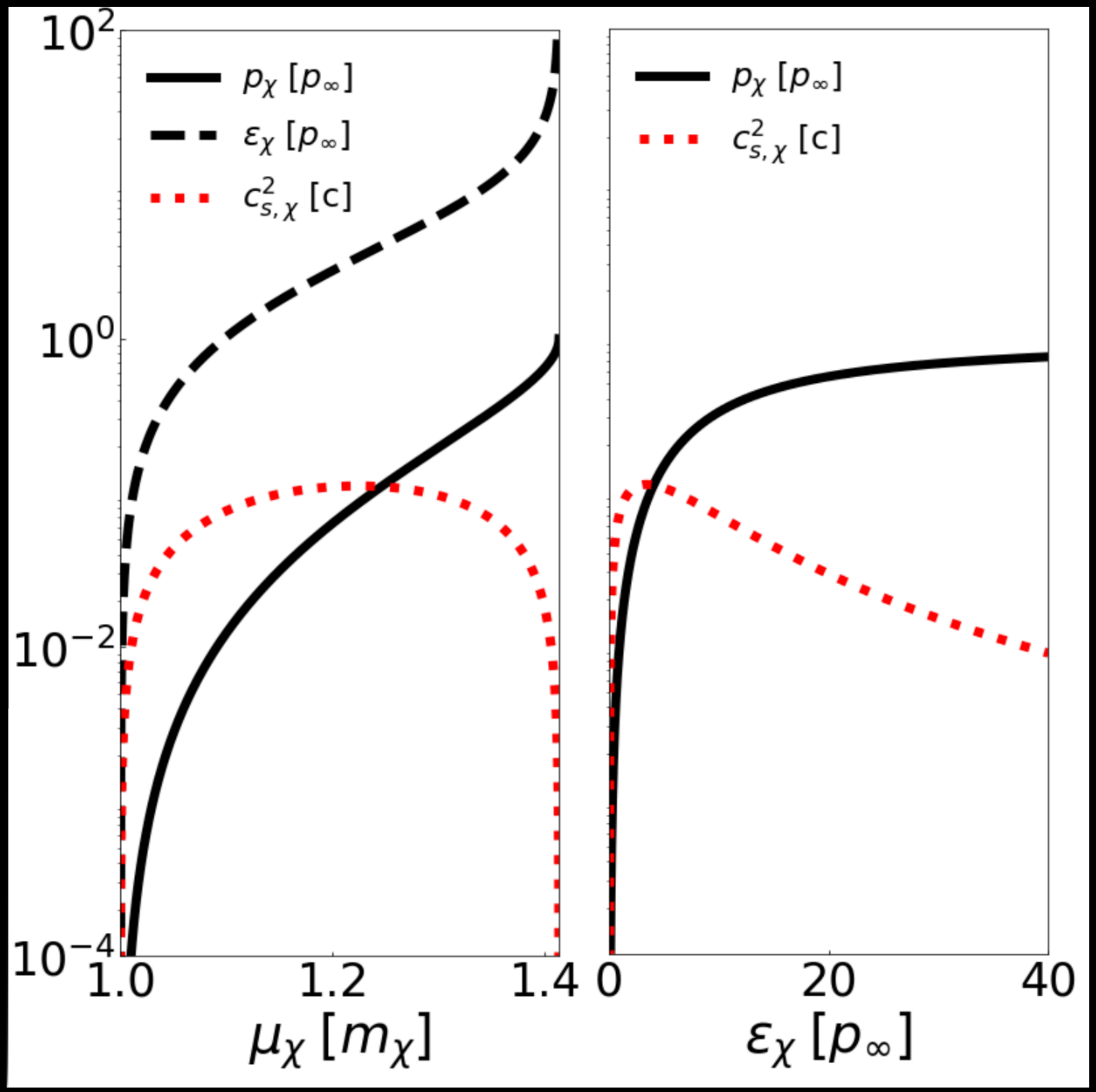
$$\begin{cases} p_\chi = \frac{m_I^2}{4}\left(m_\chi^2 - \mu_\chi\sqrt{2m_\chi^2 - \mu_\chi^2}\right) \\ \varepsilon_\chi = \frac{m_I^2}{4}\left(\frac{\mu_\chi^3}{\sqrt{2m_\chi^2 - \mu_\chi^2}} - m_\chi^2\right) \end{cases}$$

Chemical potential is restricted in the range

$$\mu_\chi \in [m_\chi, \sqrt{2}m_\chi]$$

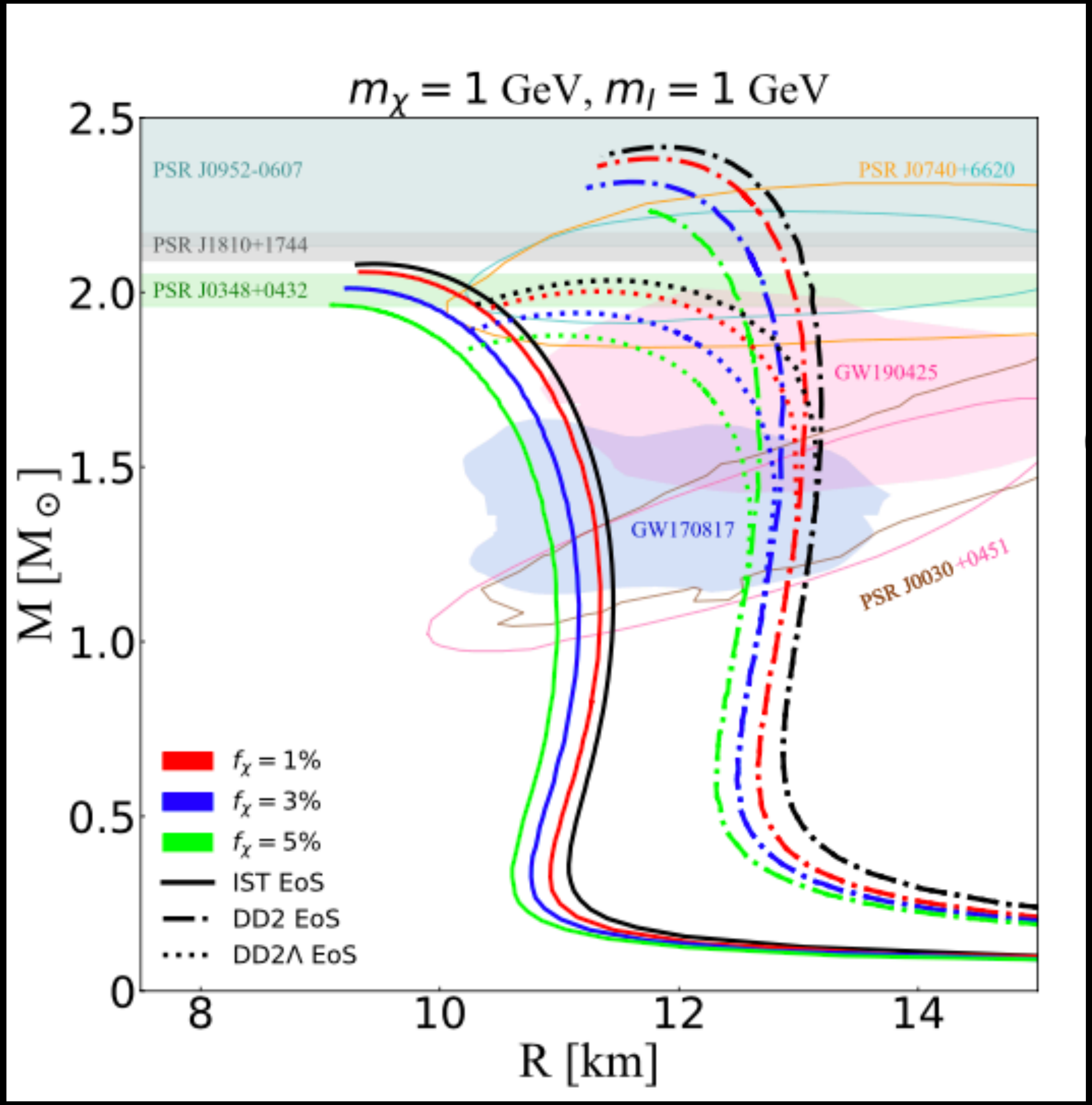
Maximum pressure limit at

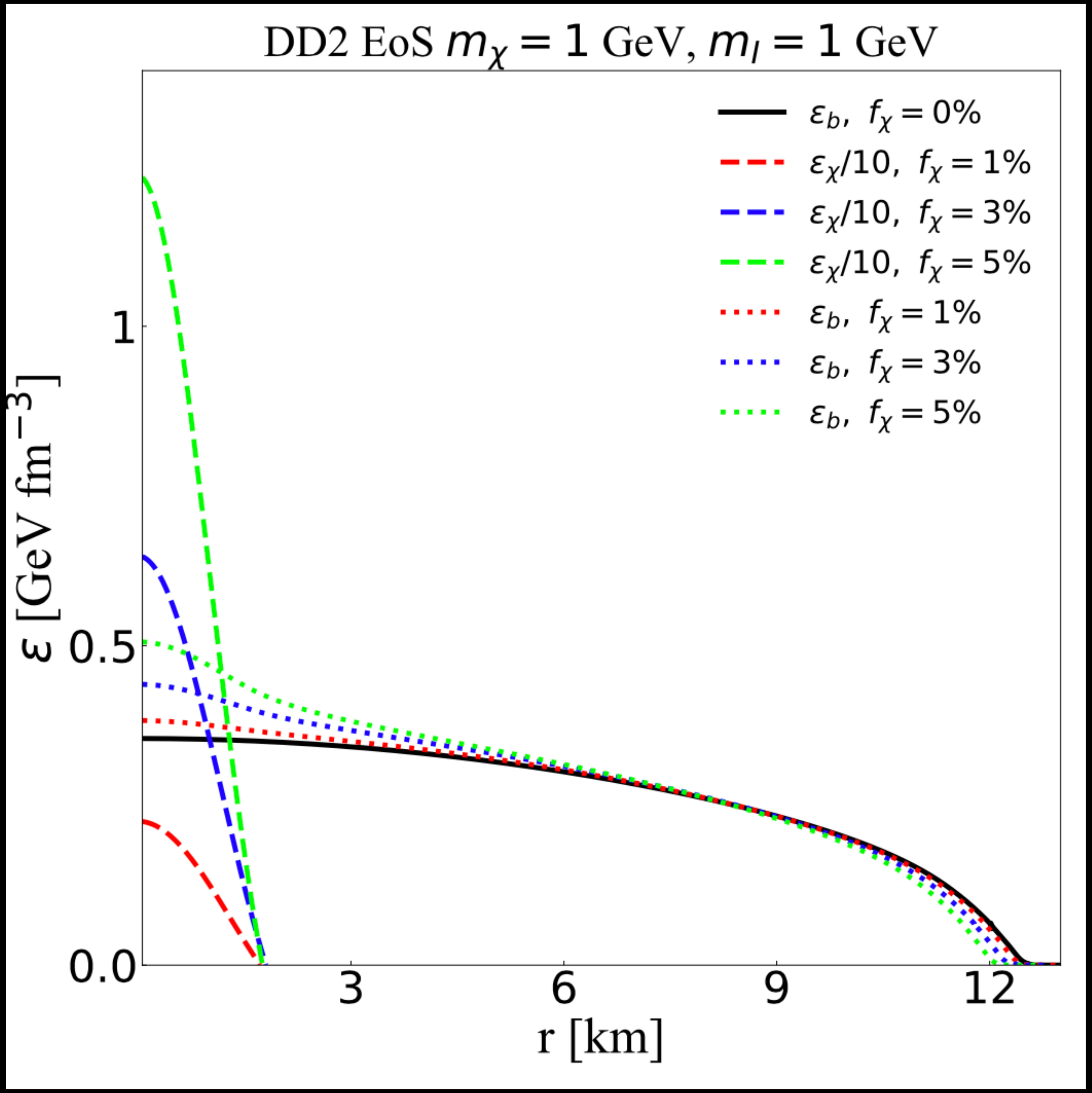
$$p_\infty \equiv p_\chi(\varepsilon_\chi \to +\infty) = \frac{m_I^2 m_\chi^2}{4}$$



Giangrandi et al., 2022

DM Core configuration





GIANGRANDI ET AL., 2022

Tidal deformability parameter

$$\Lambda = \frac{2}{3} k_2 \left(\frac{cR_{\text{out}}}{GM_{\text{tot}}} \right)^5$$

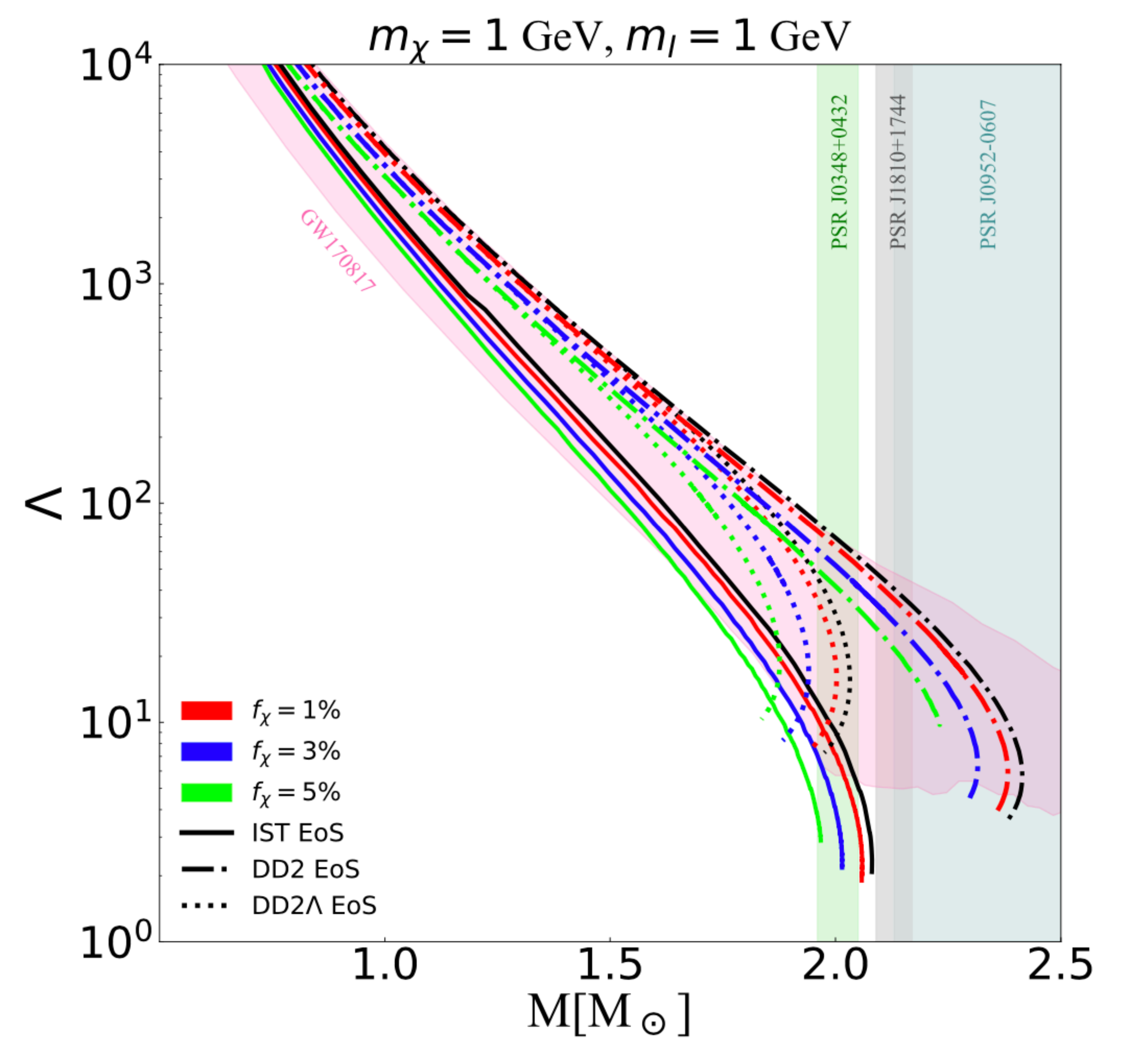
$$\Lambda_{1.4\,M_\odot} < 800$$

ABBOTT ET AL., 2018

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

LIGO-VIRGO COLLAB. PRL. 121, 161101 (2018)

Effective speed of sound approach for the 2 fluids system;



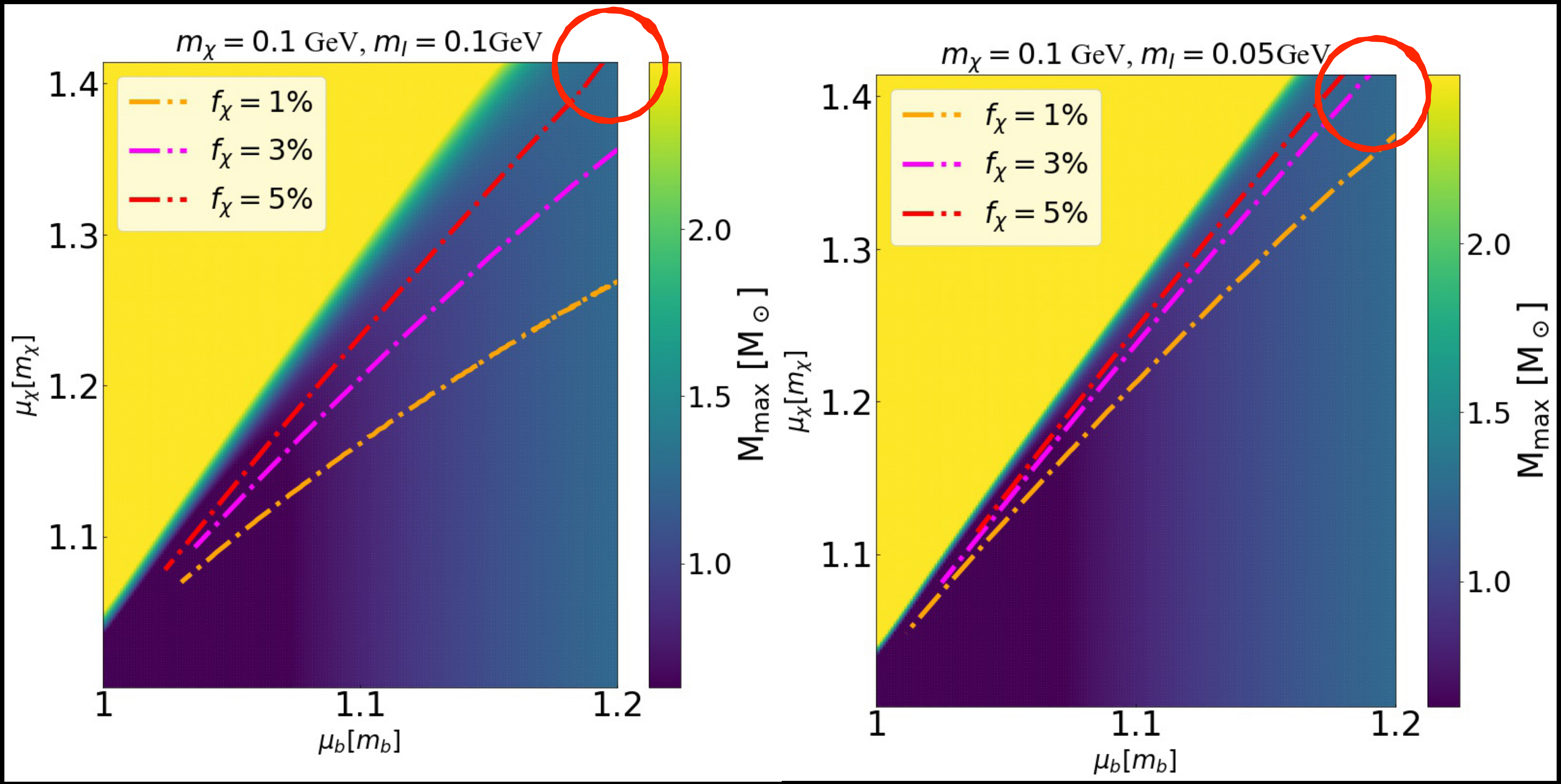
Tidal deformabilities of DM-admixed NSs.

GIANGRANDI ET AL., 2022

Parameter scan for BH collapse

When $\varepsilon_\chi\left(\mu_\chi \to \sqrt{2}m_\chi\right) \to +\infty$, we have that the pressure assumes a constant value $p_\infty \equiv p_\chi(\varepsilon_\chi \to +\infty) = \dfrac{m_I^2 m_\chi^2}{4}$

→ DM becomes gravitationally unstable → Collapse to a **Black Hole**



GIANGRANDI ET AL., 2022

Smoking guns of the DM presence in NSs

1) Measuring mass, radius and moment of inertia of NSs with few-% accuracy

Radio telescopes: MeerKAT, SKA, ngVLA plan to increase pulsar timing and discover Galactic centre pulsars
Space telescopes: NICER, ATHENA, eXTP, STROBE-X are expected to measure mass and radius of NSs with high accuracy

DM core	Mass and radius reduction of NSs towards the Galaxy centre
DM halo	Mass increase of NSs toward the Galaxy centre

2) Performing numerical simulations of binary neutron star mergers and kilonova ejecta for DM-admixed NS for different DM candidates, particle mass, interaction strength and fractions

! supplementary peak in the characteristic GW spectrum of NS mergers; exotic waveforms; modification of the kilonova ejecta; post-merger regimes: the next generation of GW detectors, i.e., the Cosmic Explorer and Einstein Telescope.

Large statistic on NS-NS, NS-BH mergers by LIGO/Virgo/KAGRA and Einstein Telescope would be very helpful

- Supplementary peak in the GW spectrum
- Exotic waveforms
- Modification of the kilonova ejecta

High precision required, thus the Einstein Telescope

3) Detecting objects that go in contradiction with our understanding

4) High/Low surface temperature of NSs towards the Galaxy Centre due to symmetric DM

5) Modification of the pulsar pulse profile or light bending as a consequence of a DM Halo

DARK MATTER AND STARS

Multi-Messenger Probes of Dark Matter and Modified Gravity

Center for Astrophysics and Gravitation (CENTRA)
Instituto Superior Técnico (IST) - University of Lisbon, Portugal

3 - 5 May 2023

CONFERENCE TOPICS

- Dark matter in compact stars (neutron stars, white dwarfs, exotic stars)
- Multi-messenger and gravitational wave probes of dark matter
- Models of dark matter
- Cosmology
- Modified gravity

Conclusions

1. DM can be accumulated in the core of NS, leading to a decrease of the maximum mass and radius of the star;
2. DM halo leads to an increase of the maximum mass and outermost radius;

Changing the position of the NS in the Galaxy leads to a different DM accretion rate, hence DM fraction

↓

Different changes of mass, radius, tidal deformability, surface temperature etc

3. Effects of DM could mimic the properties of strongly interacting matter

Thanks for your attention!

Grazie per l'ascolto!

Obrigado para vossa atenção!

Vielen Dank für Ihre Aufmerksamkeit.

Don't ask me how to pronounce this, please

Dark matter - Models

PARTICLE - ANTIPARTICLE ASYMMETRIC

It may accumulate inside a NS

FERMIONIC

Pauli blocking may prevent them from a collapse

BOSONIC

@ T=0, it could form a Bose Einstein Condensate

↓

Gravitational instability

↓

Collapse to a BH

Models of asymmetric DM should allow old NSs to exist

KOUVARIS 2013

PARTICLE - ANTIPARTICLE SYMMETRIC

DM particles can self-annihilate

Electromagnetic emission in X-ray and γ -ray

Neutrino

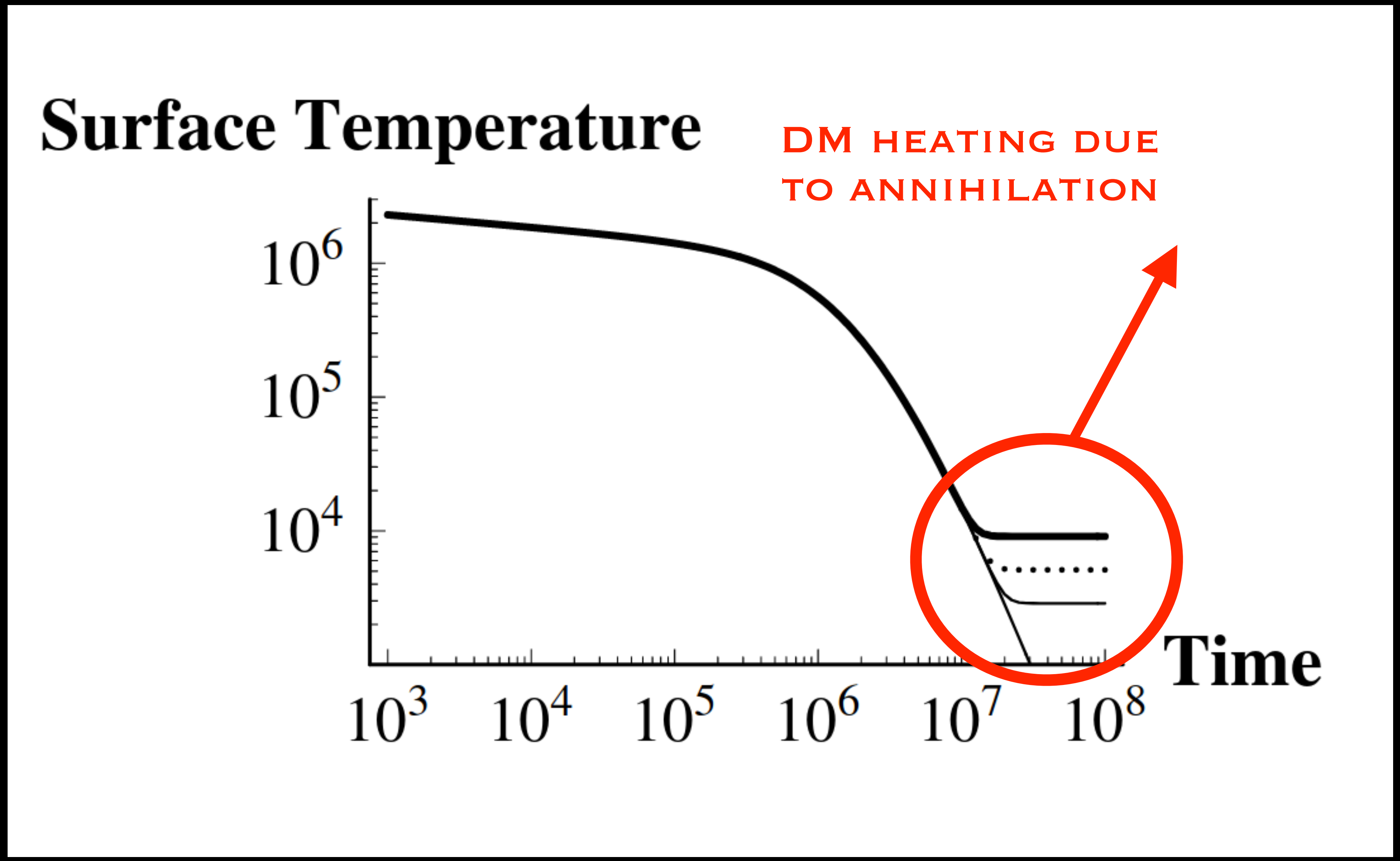
KOUVARIS 2008

Late-time heating
Higher surface temperature in old NSs

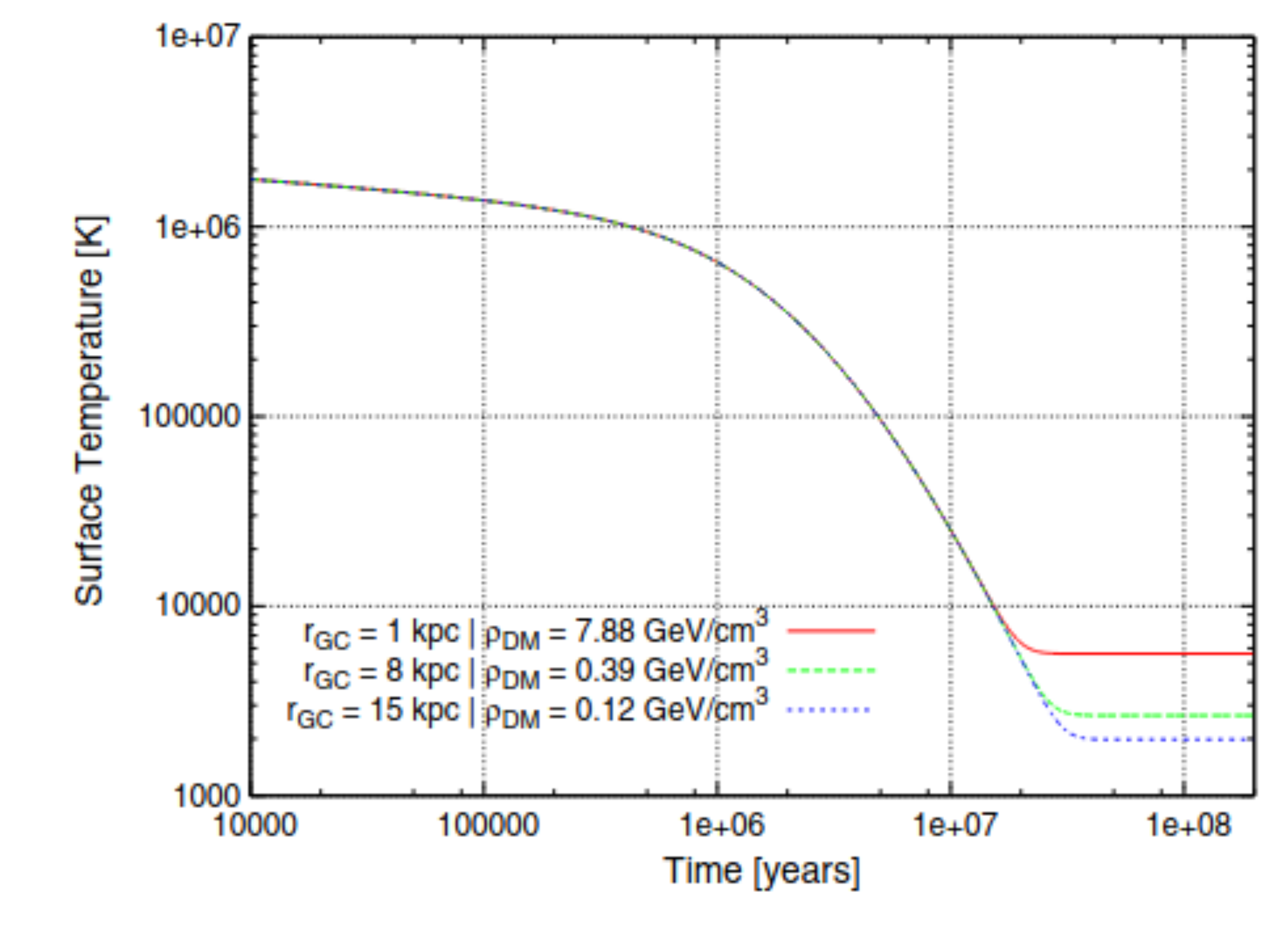
DE LAVALLAZ ET AL., 2010
HAMAGUCHI ET AL., 2019

How can we model the EoS for a DM-admixed NS?

Equation for thermal balance



Kouvaris 2008
Kouvaris&Tinyakov, 2010
Hamaguchi et al., 2019

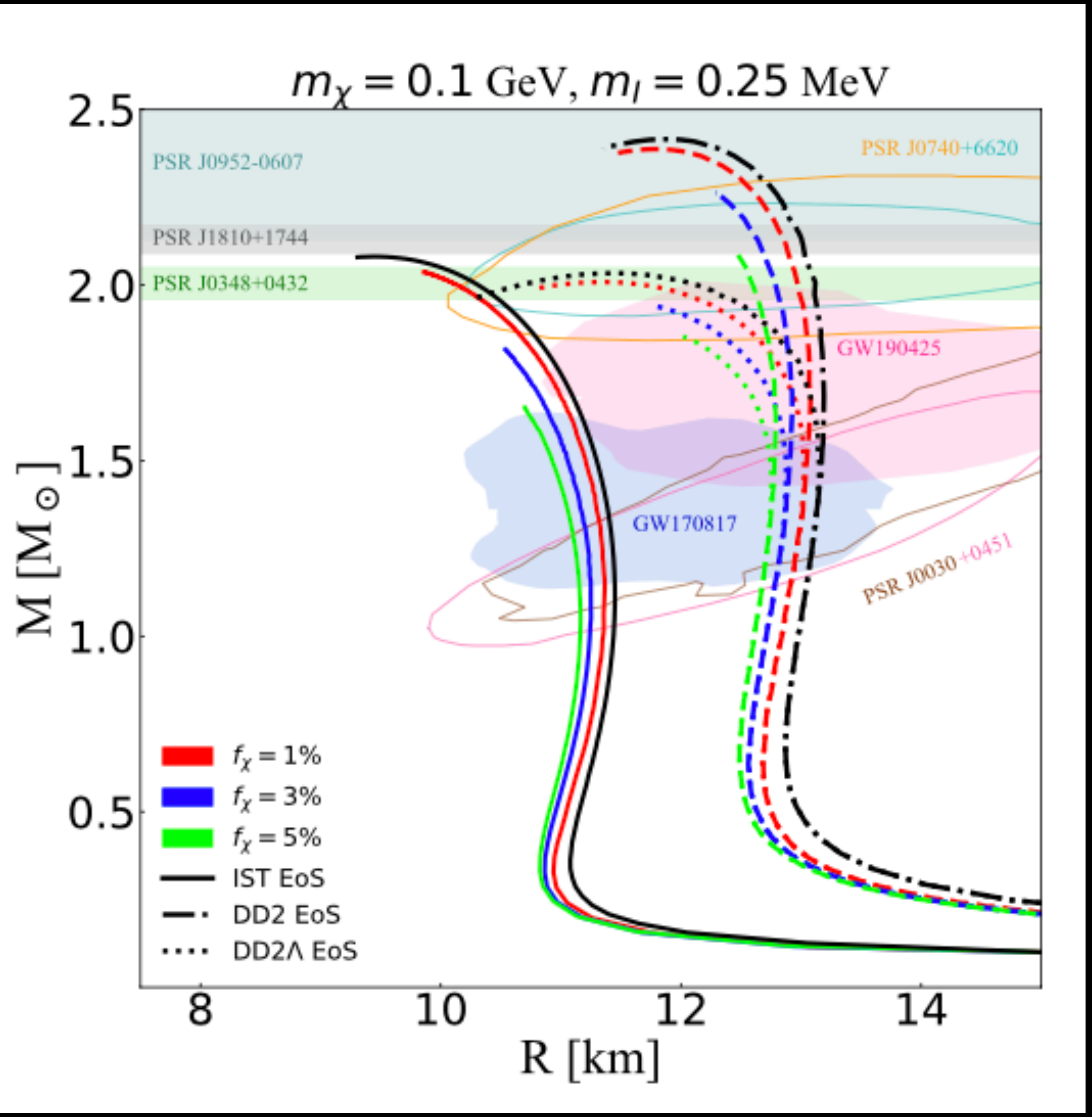


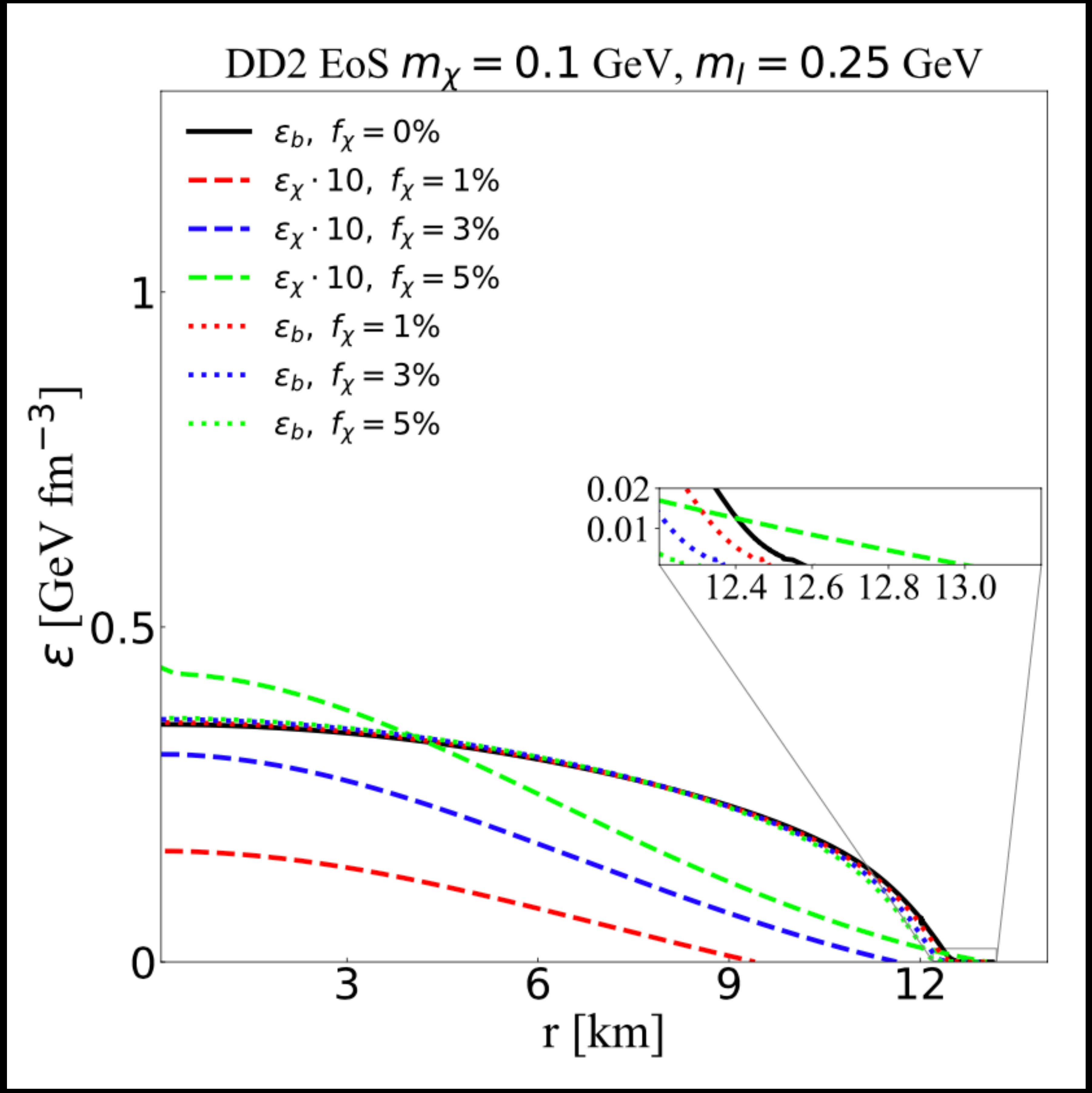
Evolution of the surface temperatures of a 1.44 $M_\odot$ neutron star situated at various galactic radii. In the present case, $m_\chi = 10$ GeV, $\sigma_0 = 1.5 \times 10^{-41}$ cm^2 and $(r_{-2}, \alpha) = (16$ kpc$, 0.19)$.

Lavallaz & Fairbairn, 2010

The closer to the Galactic centre, the greater the DM amount, hence the heating

DM Halo configuration





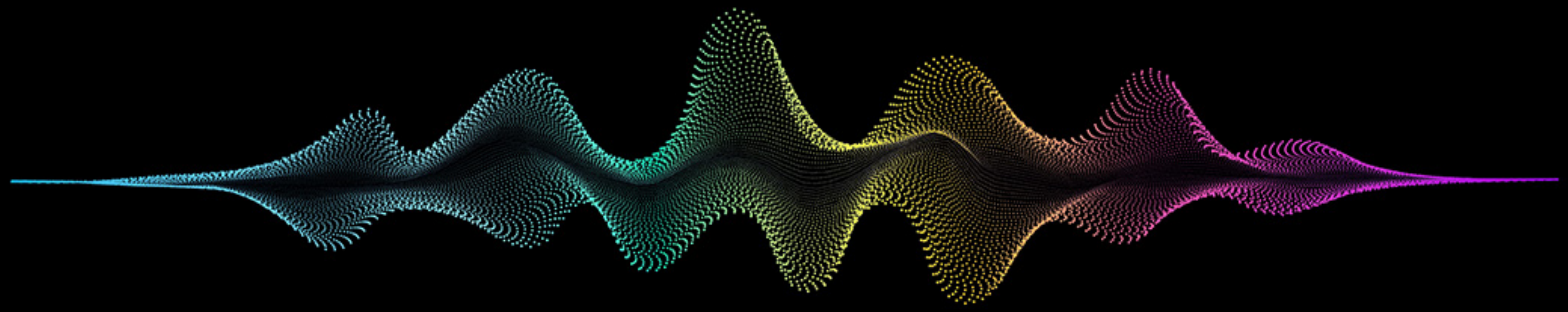
Large values of the DM radius relate to the existence of diluted and extended DM haloes around a central baryonic core of NS

Giangrandi et al., 2022

What about the tidal deformability and the speed of sound?

Effective speed of sound approach

BM and DM chemical potentials scale proportionally



$$\mu_{\chi,c} = \xi \mu_{b,c}$$

We can rewrite the speed of sound squared as follows

$$c_{s,tot}^2 = \frac{dp_{tot}}{d\varepsilon_{tot}} = \frac{\frac{\partial p_B}{\partial \mu_B} + \frac{\partial p_\chi}{\partial \mu_\chi}\frac{d\mu_\chi}{d\mu_B}}{\frac{\partial \varepsilon_B}{\partial \mu_B} + \frac{\partial \varepsilon_\chi}{\partial \mu_\chi}\frac{d\mu_\chi}{d\mu_B}} = \frac{\frac{\partial \varepsilon_B}{\partial \mu_B}c_{s,B}^2 + \frac{\partial \varepsilon_\chi}{\partial \mu_\chi}\frac{d\mu_\chi}{d\mu_B}c_{s,\chi}^2}{\frac{\partial \varepsilon_B}{\partial \mu_B} + \frac{\partial \varepsilon_\chi}{\partial \mu_\chi}\frac{d\mu_\chi}{d\mu_B}}$$

$\longrightarrow$

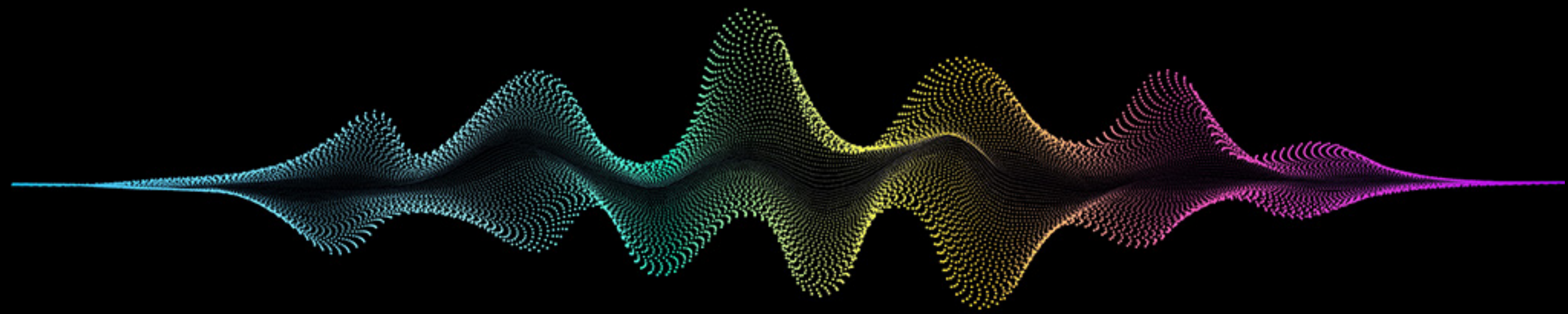
$$c_{s,\mathrm{eff}}^2 = \eta c_{\mathrm{s,B}}^2 + (1-\eta)c_{s,\chi}^2$$

By construction, we have

$$\eta \in [0,1]$$

Let's define a new parameter

$$\eta \equiv \frac{\partial \varepsilon_B}{\partial \mu_B}\left[\frac{\partial \varepsilon_B}{\partial \mu_B} + \frac{\partial \varepsilon_\chi}{\partial \mu_\chi}\frac{d\mu_\chi}{d\mu_B}\right]^{-1} = \frac{\partial n_B}{\partial \mu_B}\left[\frac{\partial n_B}{\partial \mu_B} + \xi^2\frac{\partial n_\chi}{\partial \mu_\chi}\right]^{-1}$$



Giangrandi et al., 2022