Constraints on the Parameter Space of Dark Matter Admixed Neutron Stars

CSQCQ 2024

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October 9, 2024

Framework to Model Dark Matter Inside Neutron Stars

Nuclear Matter

- Skyrme or Gogny Models (Non-relativistic) (single-particle interaction; neutron-neutron; proton-proton)
- Piecewise Polytropic EOS (GR-Astrophysicists)
- Quantum Chromodynamics (QCD)
- Effective Field Theory; Bruckner-Hartree-Fock
- Relativistic Mean-Field Formalism

Dark Matter

- Bosonic Dark Matter EoS (PRD 107, 103051, 2023; Nathan Rutherford, Geert Raaijmakers, Chanda Prescod-Weinstein, and Anna Watts)
- Fermionic Dark Matter EoS
- Asymmetric Dark Matter EoS (PRD 92, 063526, 2015; Chris Kouvaris and Niklas Gronlund Nielsen)
- Neutrons decay into Dark Matter EoS (PRL 120, 191801, 2018; Bartosz Fornal and Benjamin Grinstein)

Relativistic Mean-Field (RMF) Lagrangian for NM

$$\mathscr{L}_{NM} = \sum_{i=p,n} \bar{\psi}_i \left\{ \gamma_\nu (i\partial^\nu - g_\omega \omega^\nu - \frac{1}{2} g_\rho \vec{\tau}_i \cdot \vec{\rho}^{\,\nu}) - (M - g_\sigma \sigma - g_\delta \vec{\tau}_i \cdot \vec{\delta}) \right\} \psi_i$$

$$-\frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{2} \partial^\nu \sigma \, \partial_\nu \sigma + \frac{1}{2} m_\omega^2 \omega^\nu \omega_\nu - \frac{1}{4} F^{\alpha\beta} F_{\alpha\beta} + \frac{1}{2} m_\rho^2 \rho^\nu \cdot \rho_\nu - \frac{1}{4} \overrightarrow{R}^{\alpha\beta} \cdot \overrightarrow{R}_{\alpha\beta}$$

$$-\frac{1}{2} m_\delta^2 \vec{\delta}^2 + \frac{1}{2} \partial^\nu \vec{\delta} \, \partial_\nu \vec{\delta} - g_\sigma \frac{m_\sigma^2}{M} \left(\frac{\kappa_3}{3!} + \frac{\kappa_4}{4!} \frac{g_\sigma}{M} \sigma \right) \sigma^3 + \frac{1}{2} \frac{g_\sigma \sigma}{M} \left(\eta_1 + \frac{\eta_2}{2} \frac{g_\sigma \sigma}{M} \right) m_\omega^2 \omega^\nu \omega_\nu$$

$$+\frac{\zeta_0}{4!} g_\omega^2 (\omega^\nu \omega_\nu)^2 + \frac{1}{2} \eta_\rho \frac{m_\rho^2}{M} g_\sigma \sigma \, (\vec{\rho}^{\,\nu} \cdot \vec{\rho}_\nu) - \Lambda_\omega g_\omega^2 g_\rho^2 (\omega^\nu \omega_\nu)(\vec{\rho}^{\,\nu} \cdot \vec{\rho}_\nu) + \sum_{j=e^-,\mu} \bar{\phi}_j (i\gamma_\nu \partial^\nu - m_j) \phi_j$$

Beta Equilibrium and Charge Neutrality

$$\mu_n = \mu_p + \mu_{e^-}$$

$$\mu_\mu = \mu_{e^-}$$

$$n_p = n_{e^-} + n_\mu$$

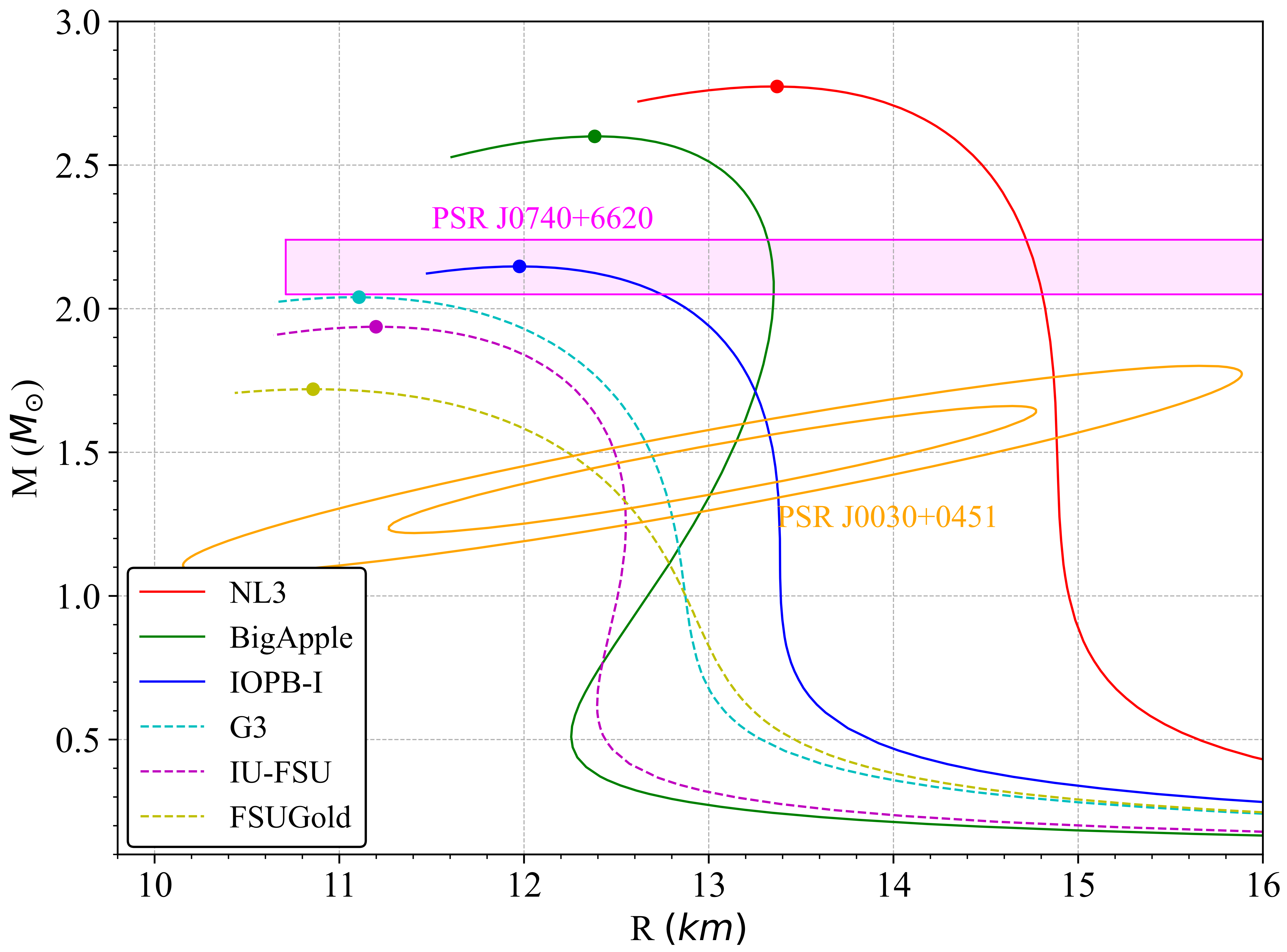

Figure 1. NS mass and radius relations constructed with several EOSs without any effects of DM. The mark on each line denotes the stellar model with the maximum mass. For reference, two astronomical constraints are also shown, i.e., the mass of the massive NS, i.e., $M = 2.08^{+0.07}_{-0.07} M_\odot$ (68.3 % credibility), and mass and radius region constrained from NICER observation for PSR J0030+0451.

Dark Matter Lagrangian

Weekly Interacting Massive Particles (WIMPs) (Fermionic)

$$\mathscr{L}_{DM} = \bar{\chi}\left[i\gamma^{\mu}\partial_{\mu} - M_{\chi} + yh\right]\chi + \frac{1}{2}\partial_{\mu}h\,\partial^{\mu}h - \frac{1}{2}M_h^2\,h^2 + \frac{fM}{v}\,\bar{\psi}\,h\,\psi$$

$\chi \rightarrow$ Neutralino wave function (Dark Matter Candidate)

$M_{\chi} \rightarrow$ Mass of dark matter candidate

$h \rightarrow$ Higgs field

$y \rightarrow$ Neutralino-Higgs Coupling = 0.07 (theoretical defined range 0.001 - 0.1)

$v \rightarrow$ Higgs vacuum expectation value (246 GeV)

$f \rightarrow$ Parameter for Higgs-Nucleon Coupling (0.3)

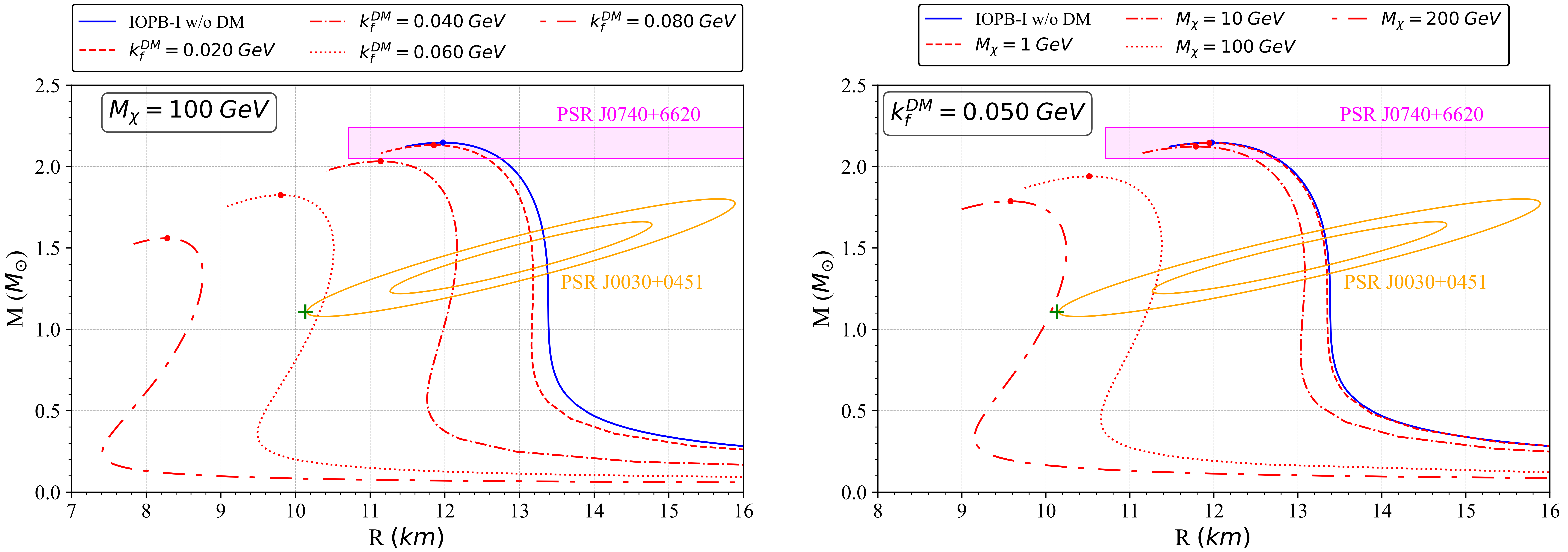

Figure 2. The mass and radius of DM admixed NS models for various DM parameters, adopting the IOPB-I parameter set. As in Fig. 1, the mass of PSR J0740+6620 and the constraints on the NS mass and radius for PSR J0030+0451 obtained from the NICER observations are shown. The plus denotes the NS model with $M = 1.108\, M_\odot$ and $R = 10.13$ km, which corresponds to the leftmost boundary in the 95 % credibility for PSR J0030+0451.

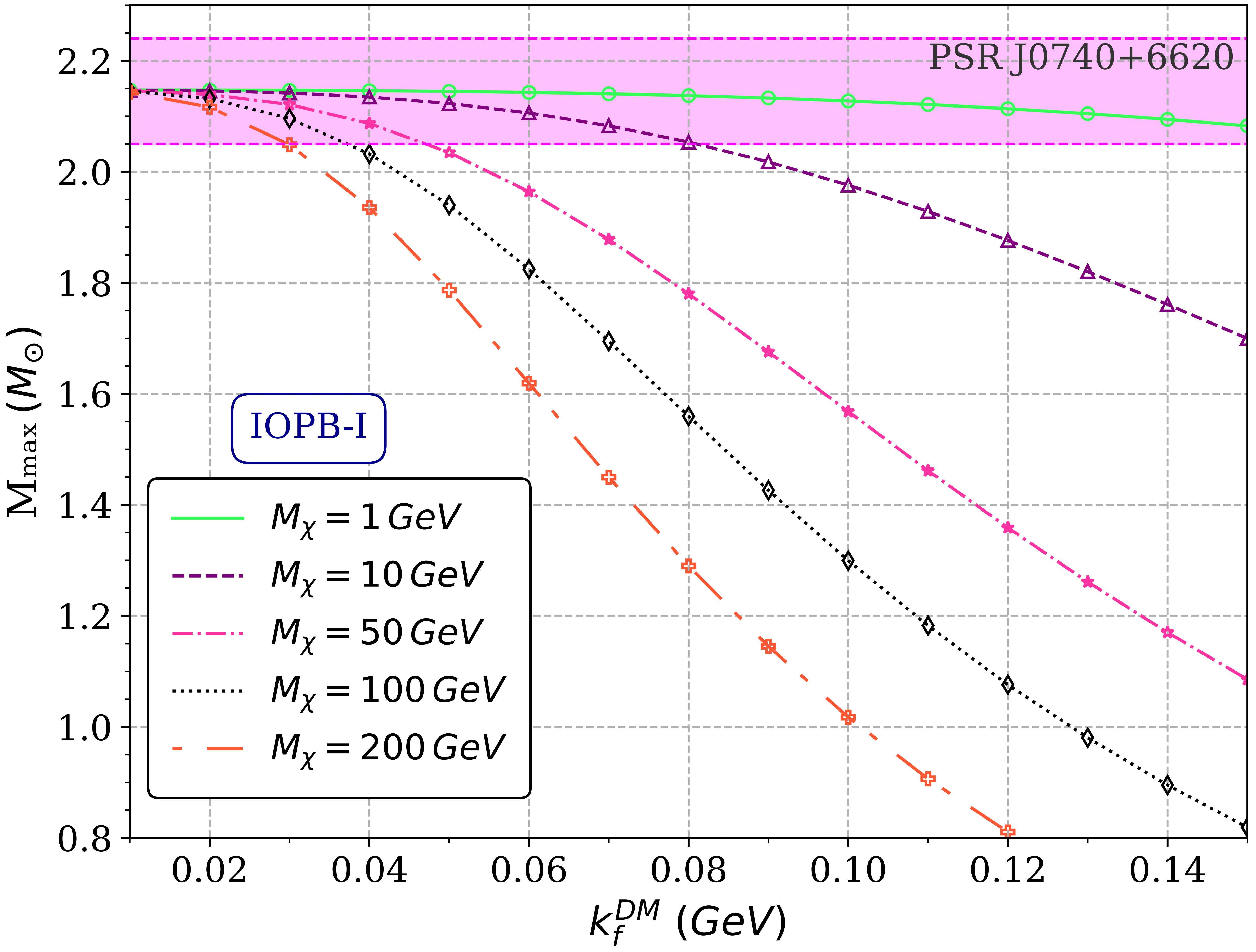

Figure 3. Dependence of the maximum mass of NSs on the DM parameters, M_χ and $k_f^{\rm DM}$, using the IOPB-I parameter set. For reference, the mass of PSR J0740+6620 is also shown.

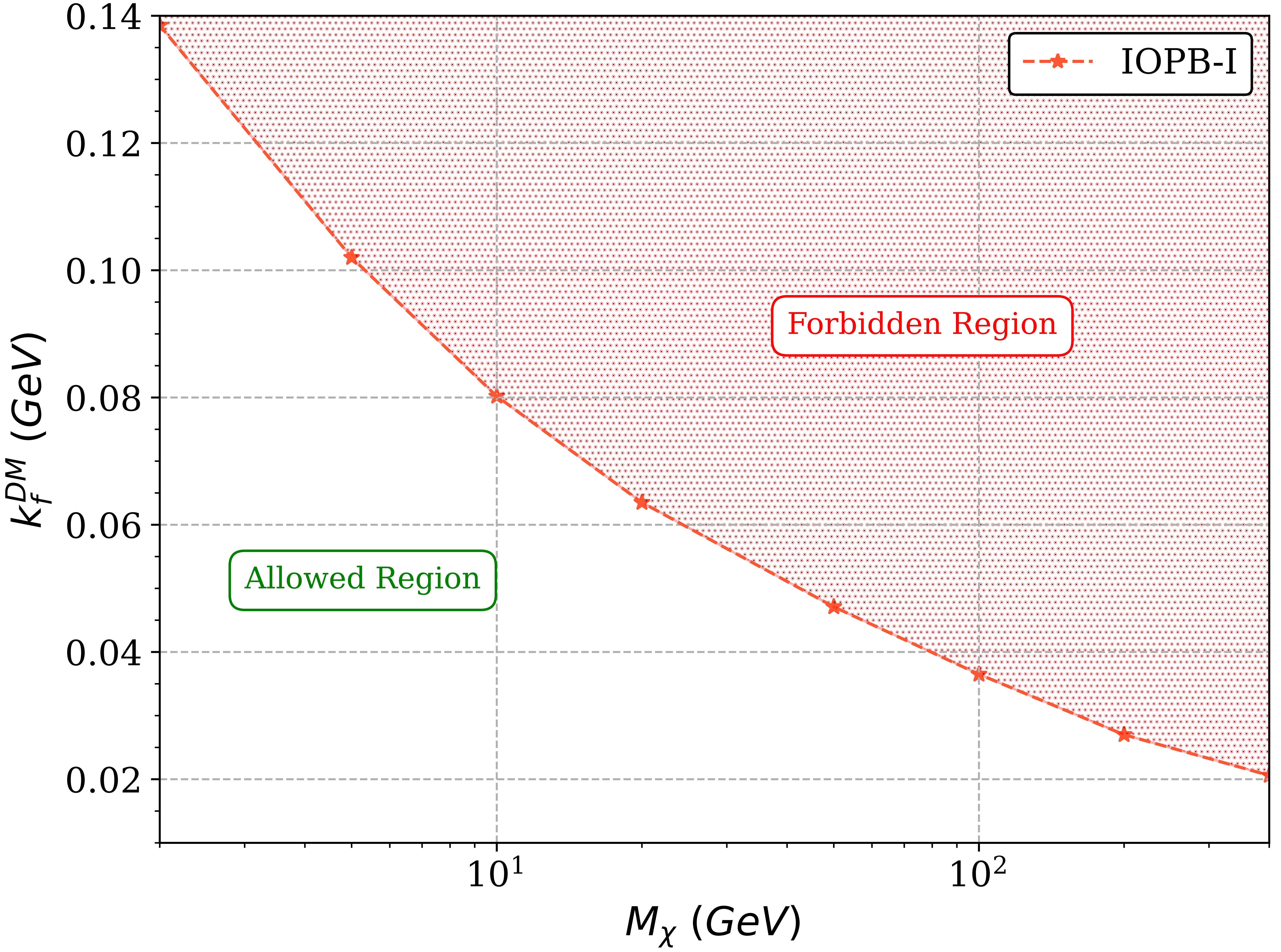

Figure 4. Allowed parameter space in the $(M_\chi, k_f^{\rm DM})$ -plane obtained from mass limits of PSR J0740+6620 data shown in left side figure, using the IOPB-I parameter set.

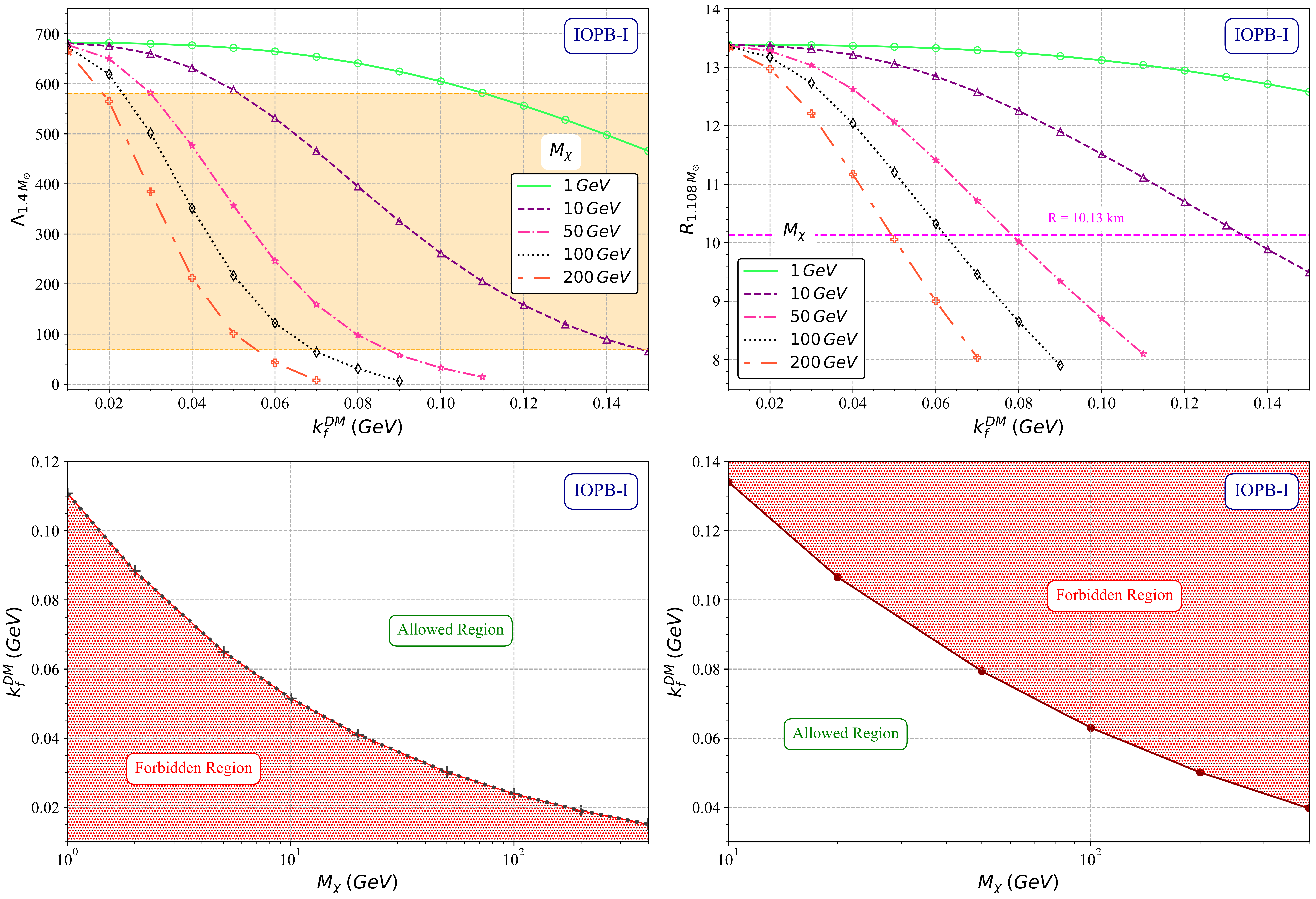

Figure 5

- The left-top and right-top panels are respectively the dependence of the dimensionless tidal deformability for the 1.4 solar mass NS model, and the NS radius for 1.108 solar mass with various DM parameters, adopting the IOPB-I parameter set.
- The shaded region in the left-top panel denotes the constraint obtained from the GW170817, while the horizontal dashed line in the right-top panel denotes the minimum radius for 1.108 solar mass NS constrained from the NICER for PSR J0030+0451.
- Considering these constraints, the value of dimensionless tidal deformability of 1.4 solar mass star should be at least less than 580, which corresponds to the upper boundary of the shaded region in the left-top panel and radius for 1.108 solar mass star should be larger than 10.13 km, which give us the allowed region in the (mass-momentum) parameter space as shown in the left-bottom and right-bottom panels.

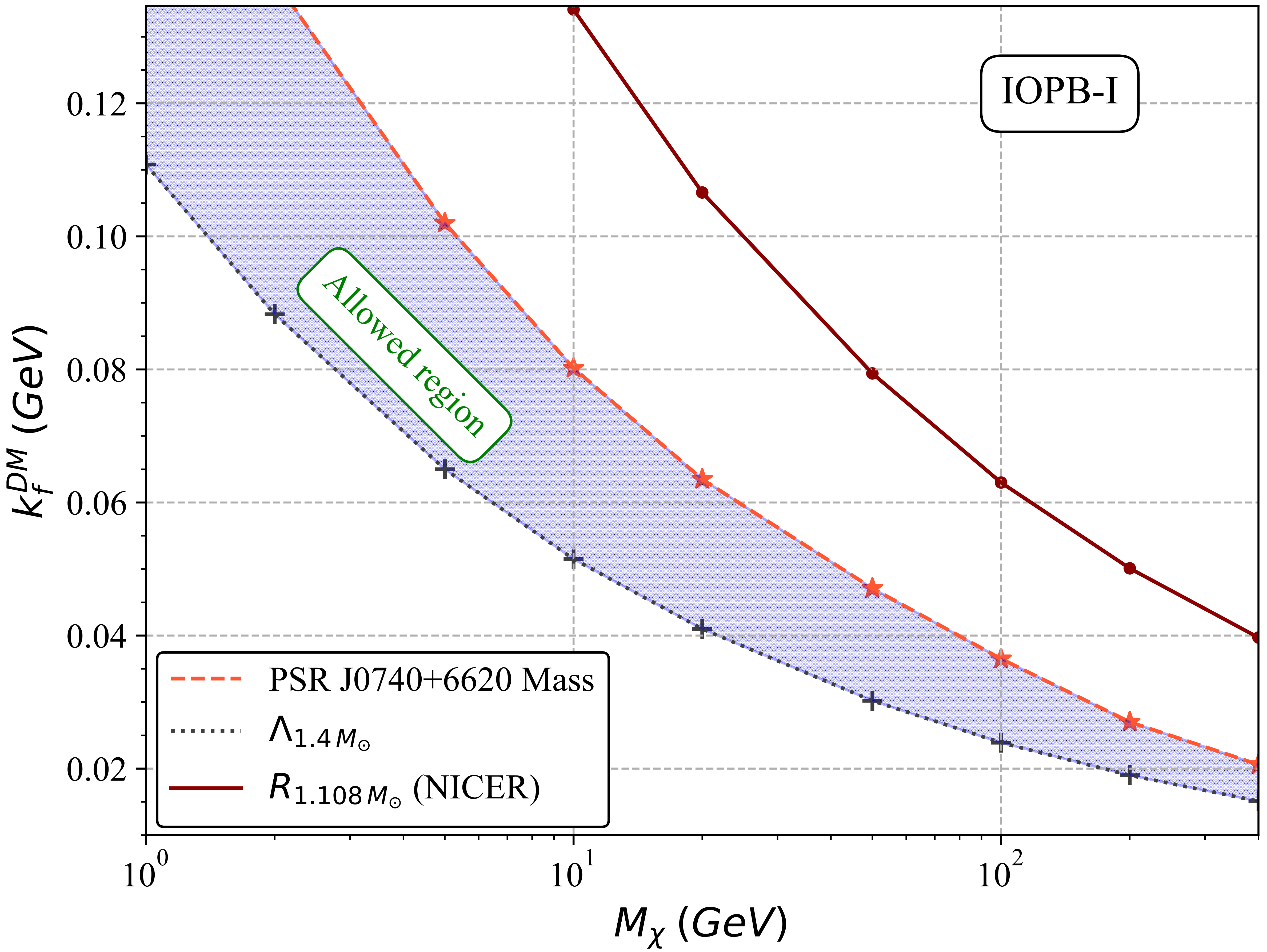

Figure 6. The allowed region in the (M_χ , $k_f^{\rm DM}$) parameter space, obtained from the mass of PSR J0740+6620, the dimensionless tidal deformability constrained from GW170817, and the NS mass and radius constraint obtained from NICER observation for PSR J0030+0451, adopting the IOPB-I parameter set, derived from the overlapped space among the three allowed regions shown in Fig. 4 and the left-bottom and right-bottom panels in Fig. 5.

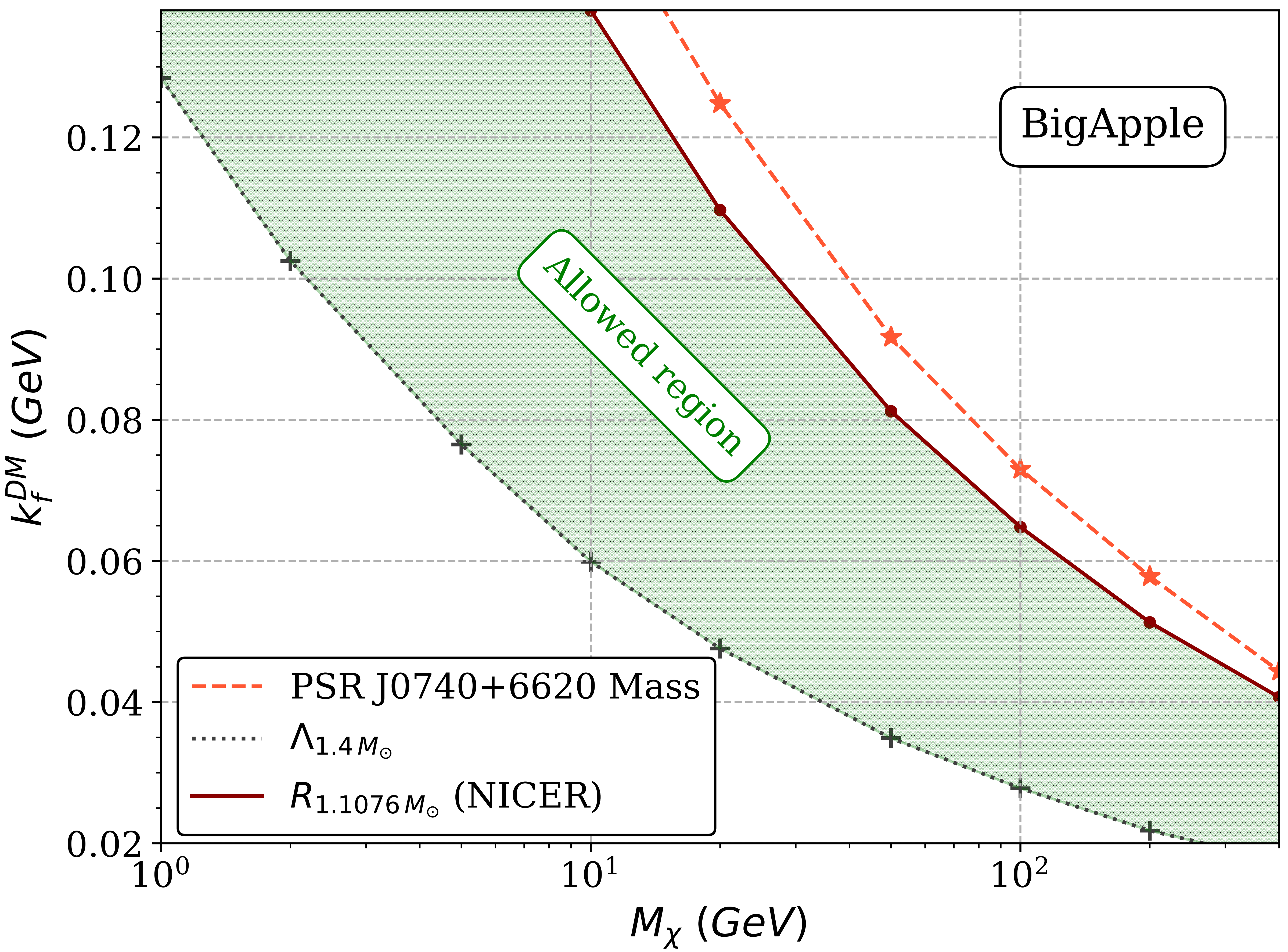

Figure 7. Same as Fig. 6, but for the BigApple parameter set. We note that the right boundary in Fig. 6 for the IOPB-I parameter set is given by the constraint on the mass of PSR J0740+6620, while those for the NL3 and BigApple parameter sets are given by the constraint from the NICER observation for PSR J0030+0451.

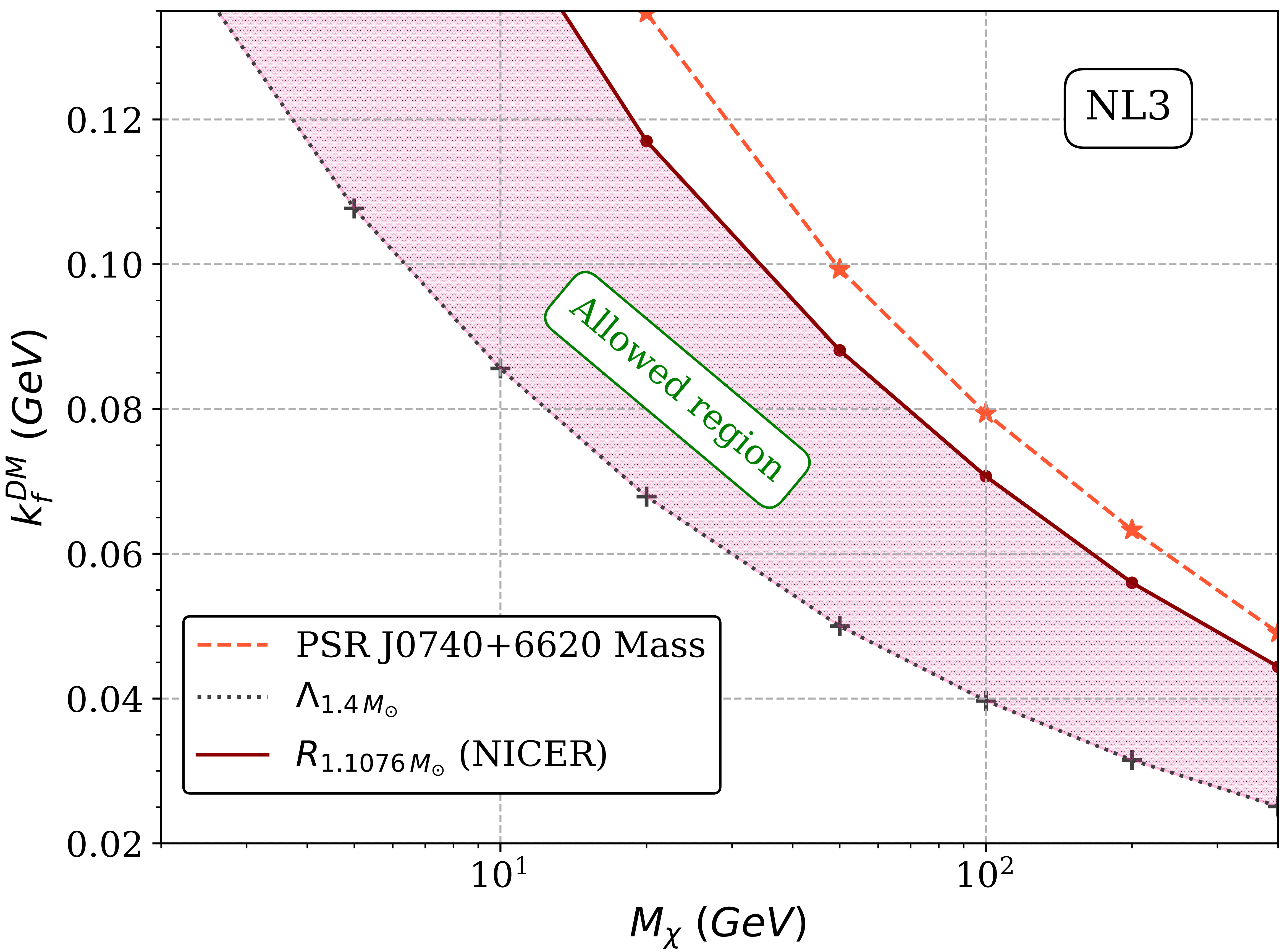

Figure 8. Same as Fig. 6 and Fig. 7, but for the NL3 parameter set. We note that the right boundary in Fig. 6 for the IOPB-I parameter set is given by the constraint on the mass of PSR J0740+6620, while those for the NL3 and BigApple parameter sets are given by the constraint from the NICER observation for PSR J0030+0451.

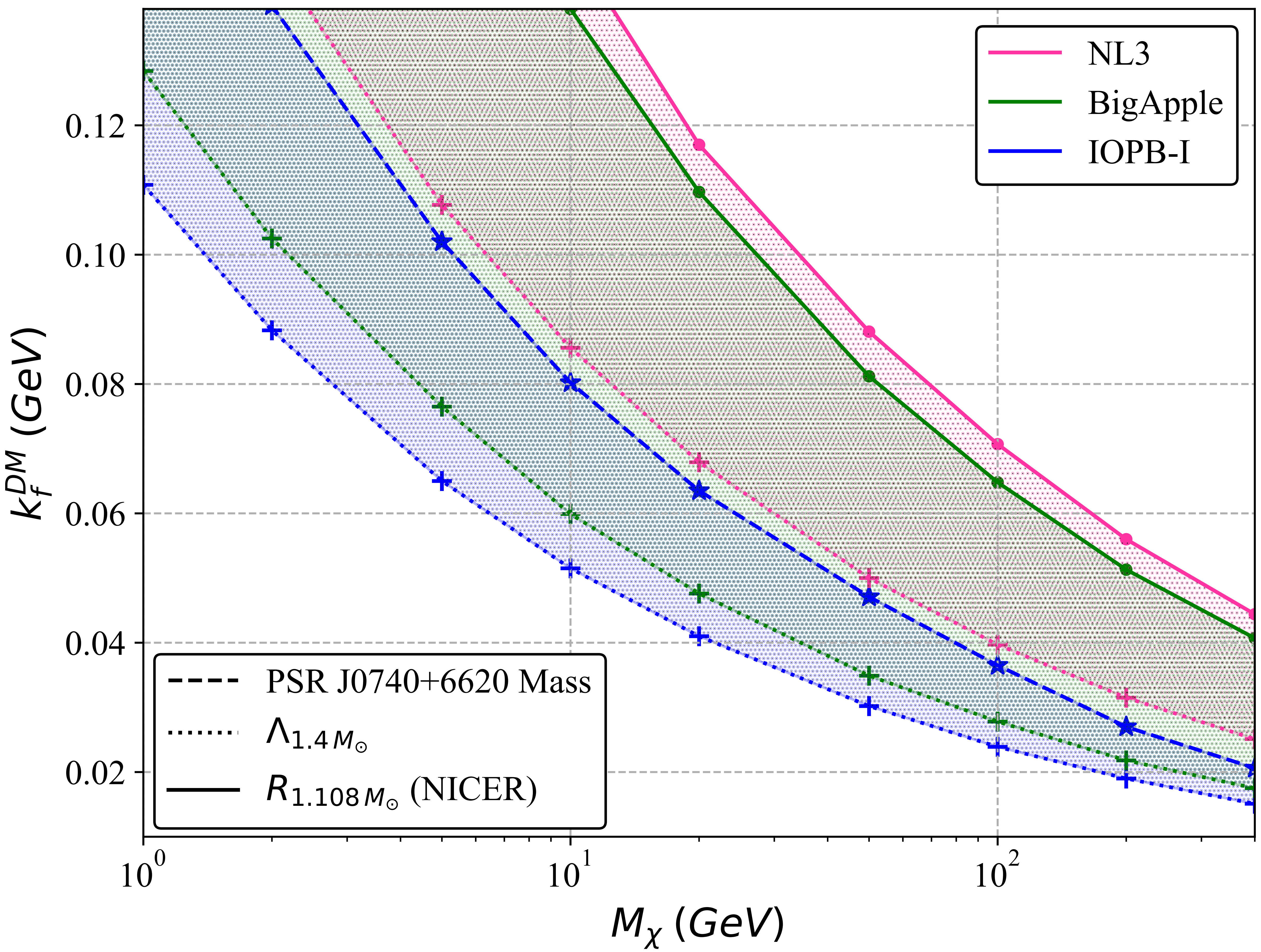

Figure 9. Comparing the allowed regions for the NL3, BigApple, and IOPB-I parameter sets. Considering that the NL3 parameter set is already excluded from the terrestrial experiments, the allowed region may become more severe. Or, we may say that the overlap region between the allowed regions with the BigApple and IOPB-I parameter sets is the parameter space, which is allowed from the astronomical observations independently of the EOSs.

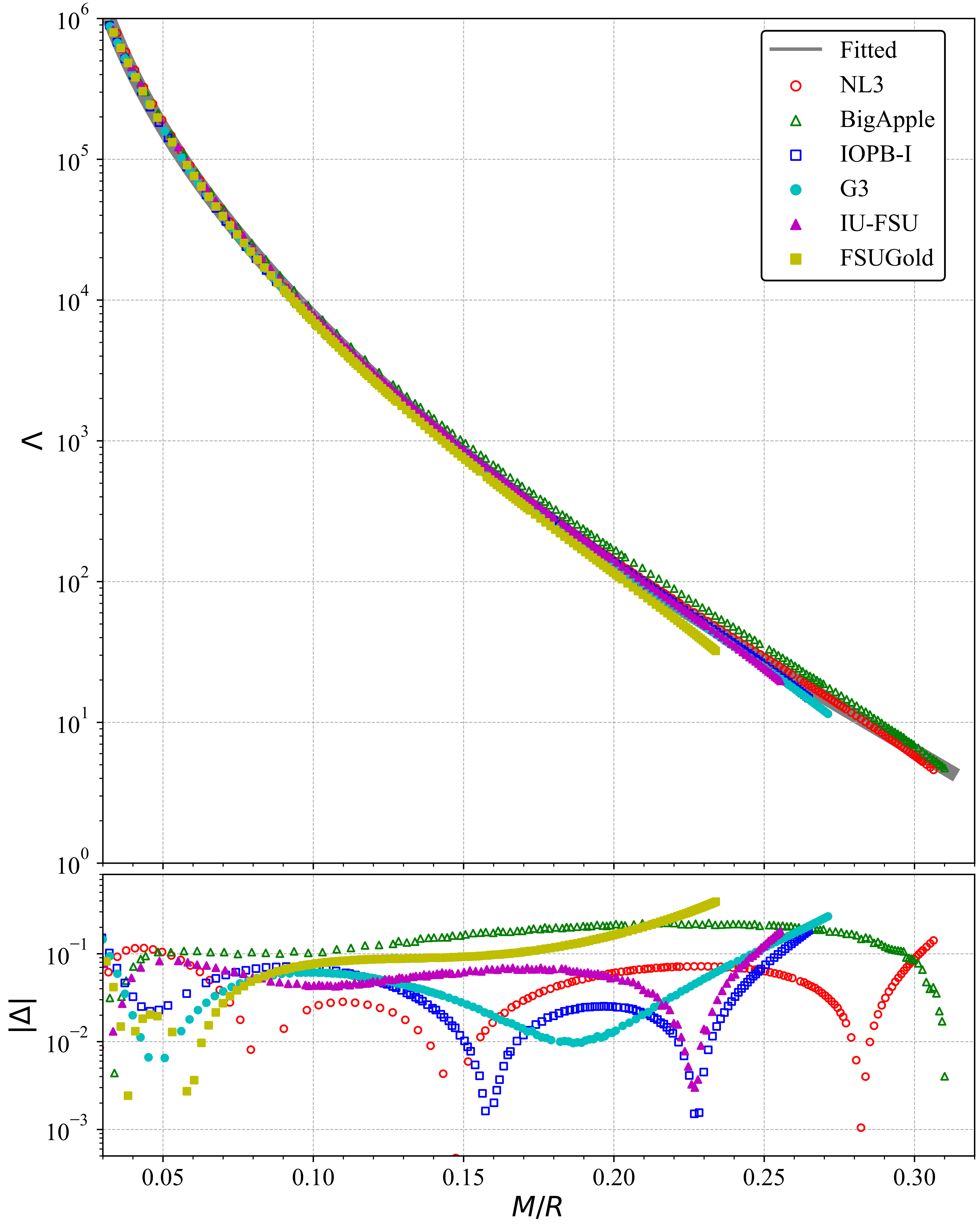

Figure 10.

- Mathematically, dimensionless tidal deformability is expressed as

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

- In the top panel, the dimensionless tidal deformability, is shown as a function of the stellar compactness, M/R, for various EOS models in the absence of DM. The thick-solid line denotes the fitting line given by,

$$\log_{10} \Lambda = \frac{0.1641}{X} + 5.7791 - 5.3095X + 1.9191X^2 - 0.4275X^3$$

where X is scaled as $[X \equiv (M/R)/0.2]$. The bottom panel of the figure displays the absolute values of the relative errors for each RMF parameter set with respect to the empirical fitting formula.

- This error analysis evaluates the consistency and reliability of the empirical relationship across different theoretical models. The small and consistent error margins underscore the robustness of the fitted relationship, suggesting its potential applicability as a universal tool for predicting NS properties across a broad spectrum of scenarios

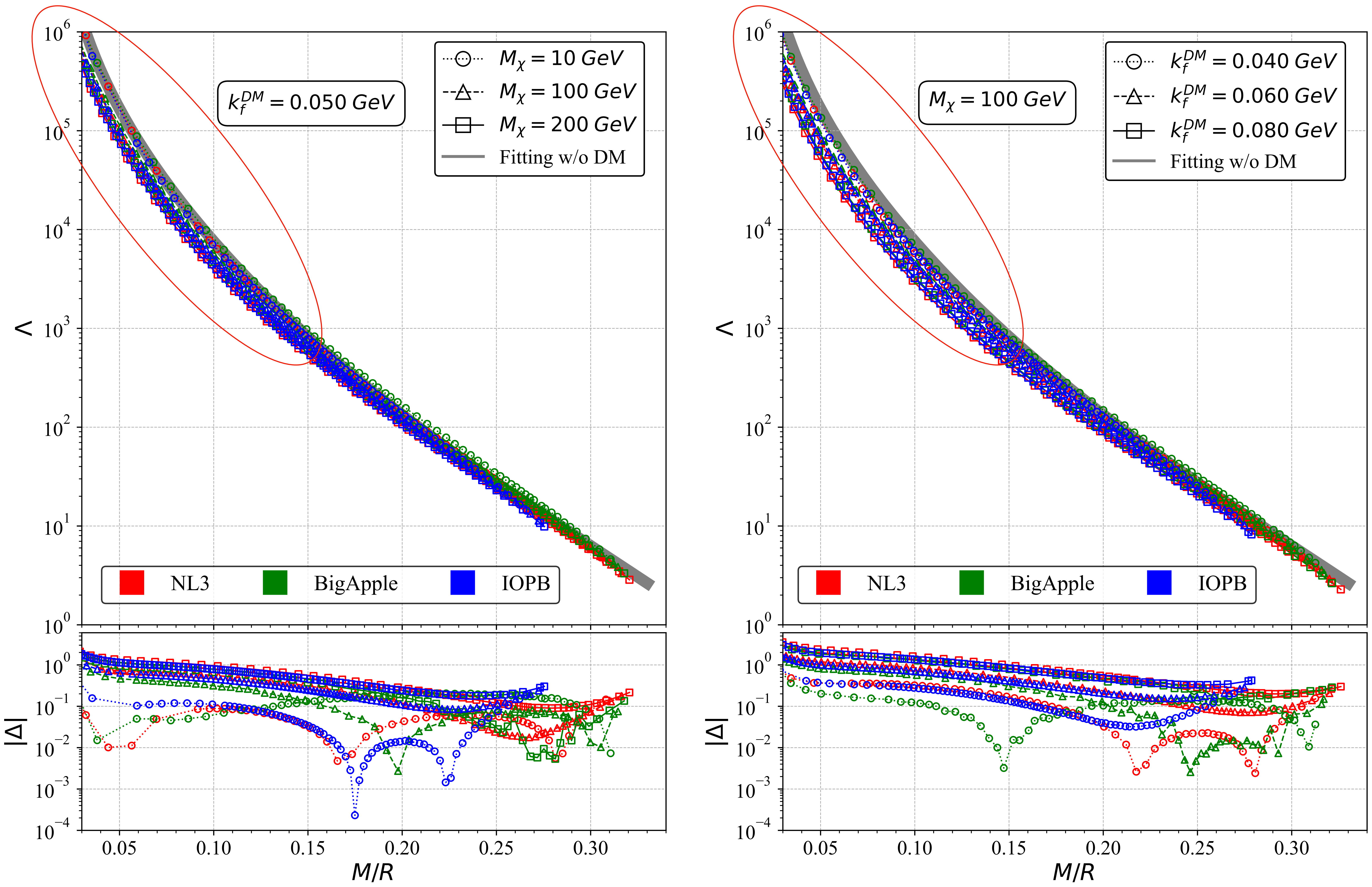

Figure 11. The values of Λ for the DM admixed NSs constructed with various EOSs are shown as a function of M/R. The left panel corresponds to the results by varying M_χ with the fixed value of $k_f^{\rm DM} = 0.05$ GeV, while the right panel is by varying DM fermi momentum with the fixed value of $M_\chi = 100$ GeV. In both panels, the universal relation obtained in the NS models without DM given by fitting equation is shown with the thick-solid line. In the bottom panels, the absolute value of the relative deviation from the solid line is shown.

Concluding Remarks:

- We derived constraints on DM Fermi momentum and mass using observational data from PSR J0740+6620, GW170817, and NICER measurements of PSR J0030+0451.

- Our analysis revealed that the maximum mass constraint from PSR J0740+6620 imposes the most stringent limits on DM parameters, particularly for softer EOS models. The tidal deformability constraint from GW170817 and the radius constraint from NICER significantly restrict the DM parameter space, particularly for stiffer EOS models.

- The intersection of constraints from different observational sources and theoretical models has allowed us to delineate a robust set of permissible DM parameters, highlighting the importance of integrating multi-modal scientific observations to delineate the properties of DM within NSs.

- Moreover, this study challenges the assumption of universality in the presence of DM, showing that DM parameters could lead to deviations from the established empirical relationship, particularly for less compact NSs. This suggests a need to refine theoretical models to better account for DM effects, enhancing the predictive power and accuracy of NS models used in multimessenger astronomy.

References

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Thank You for Your Attention