ANALYZING FERMIONIC DARK MATTER SCENARIOS WITH ANOMALOUS COMPACT OBJECT

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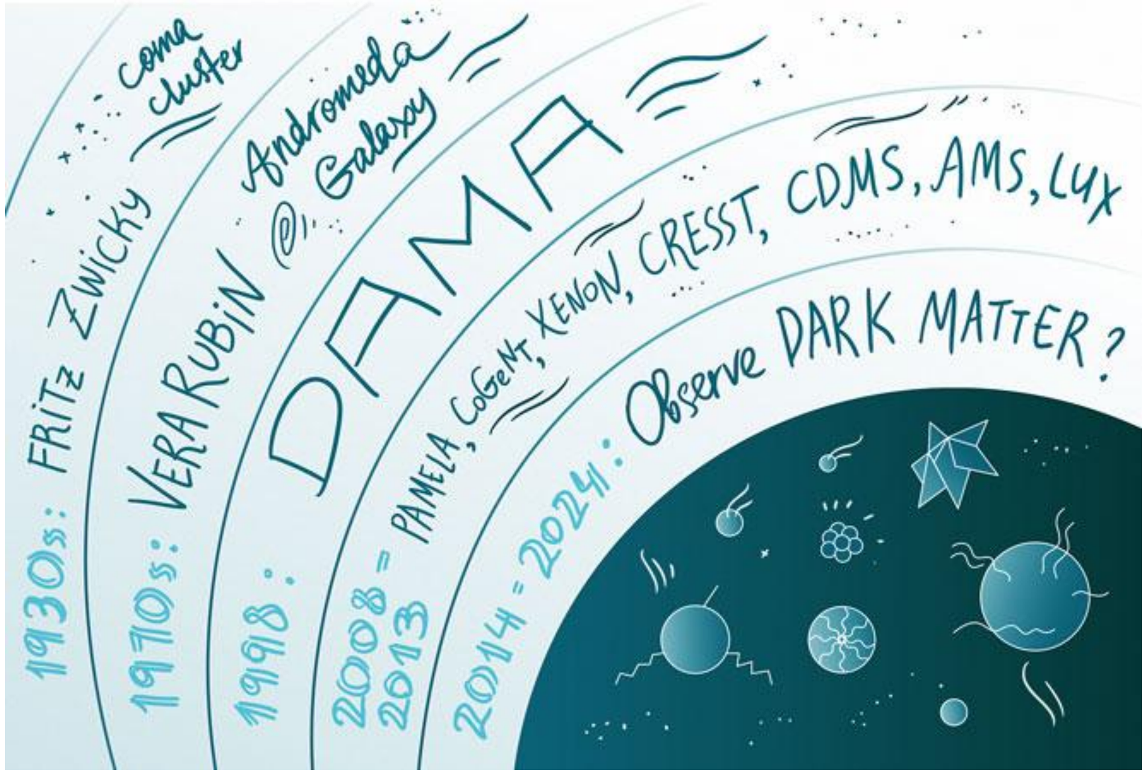
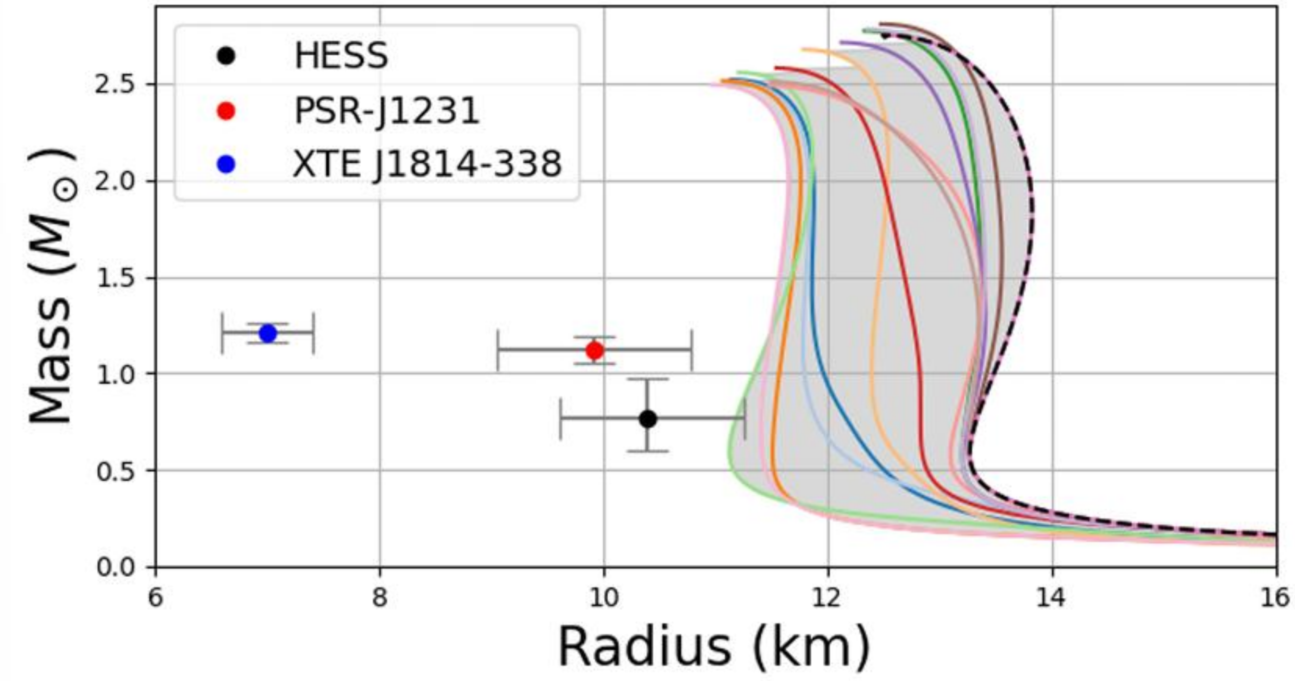
MOTIVATION



[Symmetry magazine]

ANOMALOUS COMPACT OBJECTS



PSR J1231-1411 ($R = 9.91^{+0.86}_{-0.86}$ km, $M = 1.12^{+0.07}_{-0.07}$ $M_\odot$)

[L. Qi, S. Zheng, J. Zhang, 2025]

XTE J1814-338 ($R = 7.0^{+0.4}_{-0.4}$ km, $M = 1.21^{+0.05}_{-0.05}$ $M_\odot$)

[Y. Kini, et al, 2024]

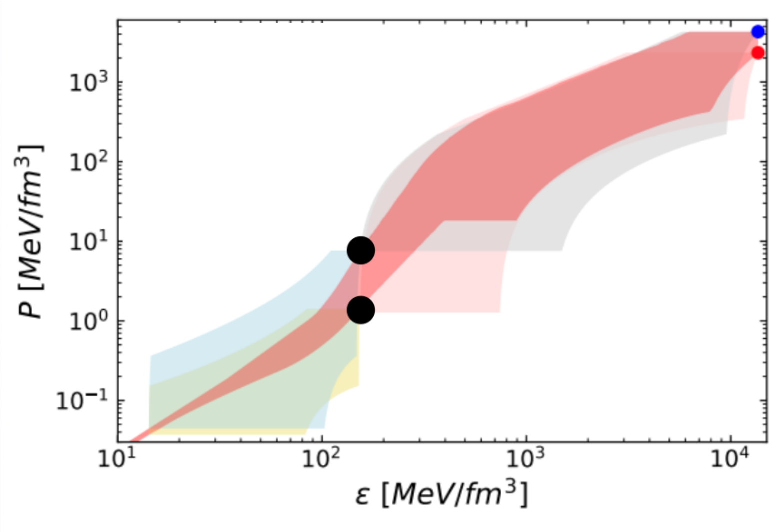
HESS J1731-347 ($R = 10.4^{+0.86}_{-0.78}$ km, $M = 0.77^{+0.20}_{-0.17}$ $M_\odot$)

[V Doroshenko, V. Suleimanov, G. Pühlhofer, A. Santangelo, 2022]

NUCLEAR EQUATION OF STATE [J.M Alarcón, E. Lope-Oter, J.A Oller 2024]

Low density regime

- $n \leq 0.1 n_s$
- E/N result different from the one of EFT calculations



Medium density regime

- Thermodynamic consistency

$$c_s^{-2} = \frac{\mu}{n}\frac{\partial n(\mu)}{\partial \mu} \geq 1 \, .$$

- Casualty $c_s^2 = \frac{\partial P(\varepsilon)}{\partial \varepsilon} \, , \quad 0 \leq c_s^2 \leq 1$
- Stability
- CREX II and PREX symmetry energy
- Astrophysical measurements of known NS

See talk by Eva Lope Oter on Wednesday!

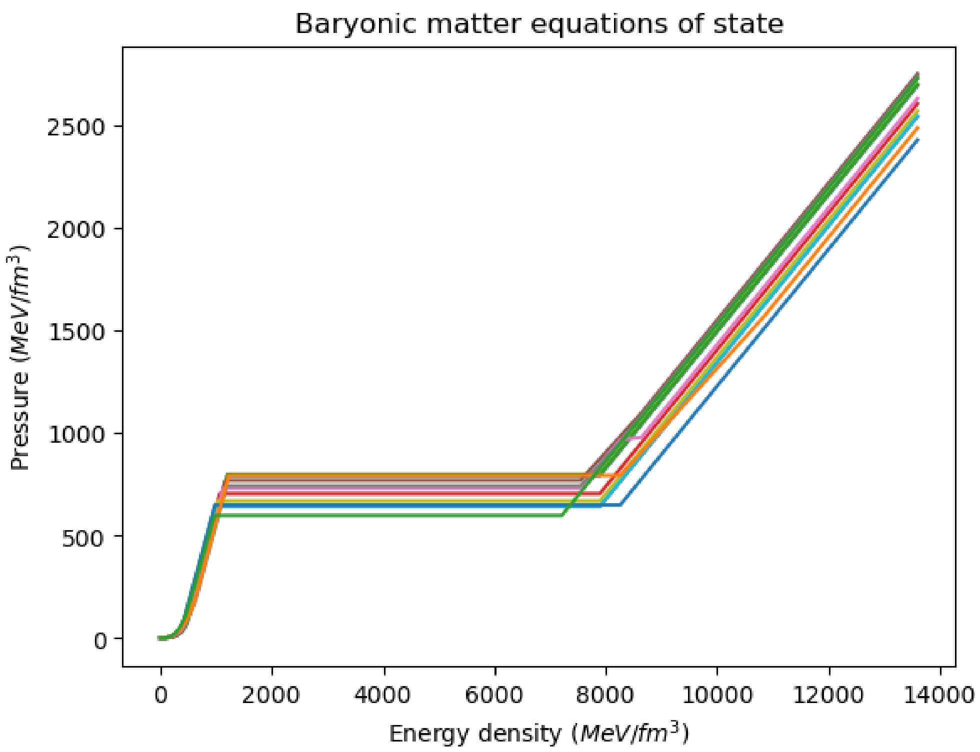
High density regime

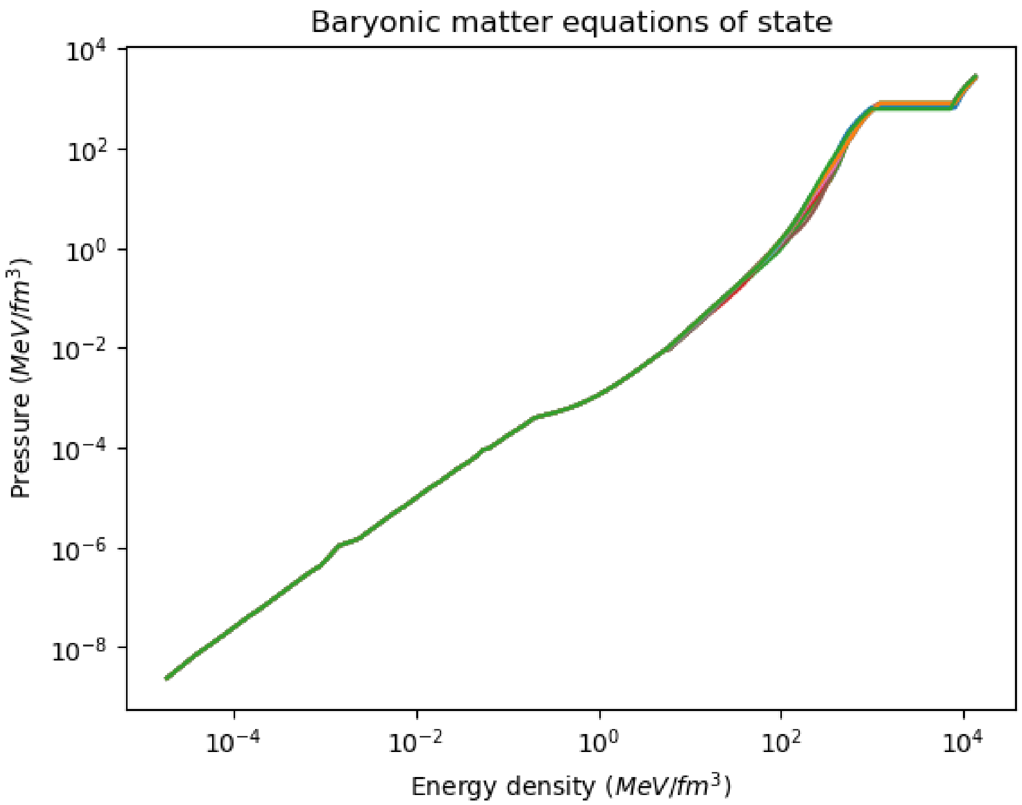
- $n > n_s$
- Perturbative Quantum Chromodynamics
- Limit to (P, ε, μ) at matching point → constraints on EoS

Crust

- SLy4
- Matching at $5 \times 10^{-3}\ fm^{-3}$

NUCLEAR EQUATION OF STATE





DARK MATTER EQUATION OF STATE

Free Fermi gas

$$\epsilon = \frac{1}{2\pi^2}\int_0^{k_F} k^2\sqrt{k^2+m_f^2}dk$$

$$= \frac{1}{8\pi^2}\left[k_F\sqrt{k_F^2+m_f^2}(2k_F^2+m_f^2) - m_f^4 \ln\left(\frac{k_F+\sqrt{k_F^2+m_f^2}}{m_f}\right)\right]$$

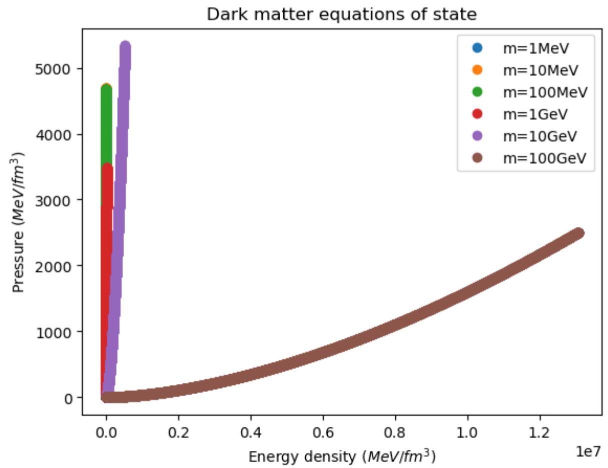
$$P = \frac{1}{6\pi^2}\int_0^{k_F} \frac{k^4}{\sqrt{k^2+m_f^2}}$$

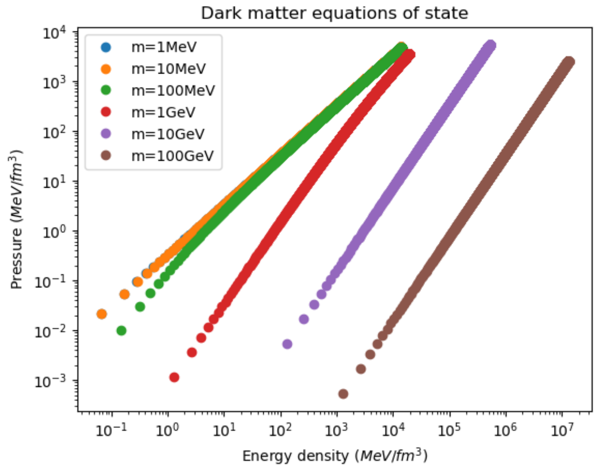
$$= \frac{1}{24\pi^2}\left[k_F\sqrt{k_F^2+m_f^2}(2k_F^2-3m_f^2) + 3m_f^4 \ln\left(\frac{k_F+\sqrt{k_F^2+m_f^2}}{m_f}\right)\right]$$

$$n = \frac{k_F^3}{3\pi^2}$$

Masses:

- 1MeV
- 10MeV
- 100MeV
- 1GeV
- 10GeV
- 100GeV





2 FLUID FORMALISM FOR TOLMAN-OPPENHEIMER-VOLKOFF EQUATIONS

TOV equations

$$\frac{dP_1}{dr} = -(P_1 + \varepsilon_1)\frac{4\pi r^3(P_1 + P_2) + m(r)}{r(r - 2m(r))}$$

$$\frac{dP_2}{dr} = -(P_2 + \varepsilon_2)\frac{4\pi r^3(P_1 + P_2) + m(r)}{r(r - 2m(r))}$$

$$\frac{dm_i(r)}{dr} = 4\pi(\varepsilon_i(r))r^2$$

$$m(r) = m_1(r) + m_2(r)$$

Initial conditions

$$M_{DM}(0) = M_{BM}(0) = 0$$

$$P_{DM}, P_{BM} \in (757.5 \cdot 10^{-5}, 757.5) MeV/fm^3$$

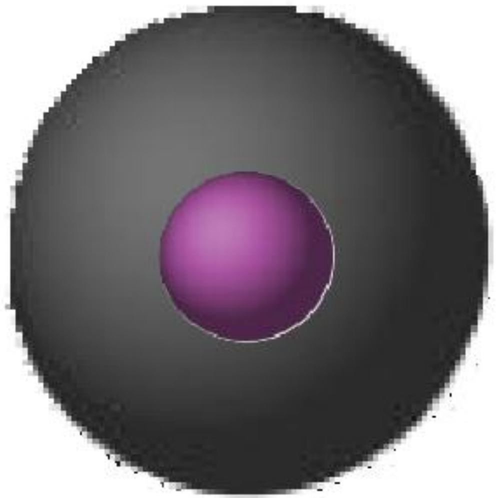
13 nuclear EoS x 6 dark matter EoS

4th order Runge-Kutta method

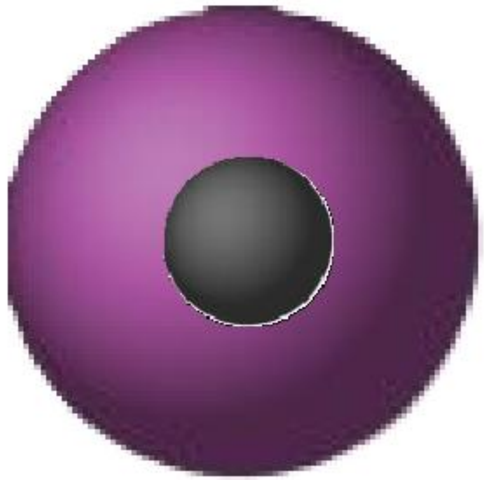
2 FLUID FORMALISM FOR TOLMAN-OPPENHEIMER-VOLKOFF EQUATIONS

$$P_{BM}(R_{BM}), P_{DM}(R_{DM}) \simeq 0$$

$$M(R) = M_{BM}(R_{BM}) + M_{DM}(R_{DM})$$



Dark matter halo around NS



Dark matter core inside NS

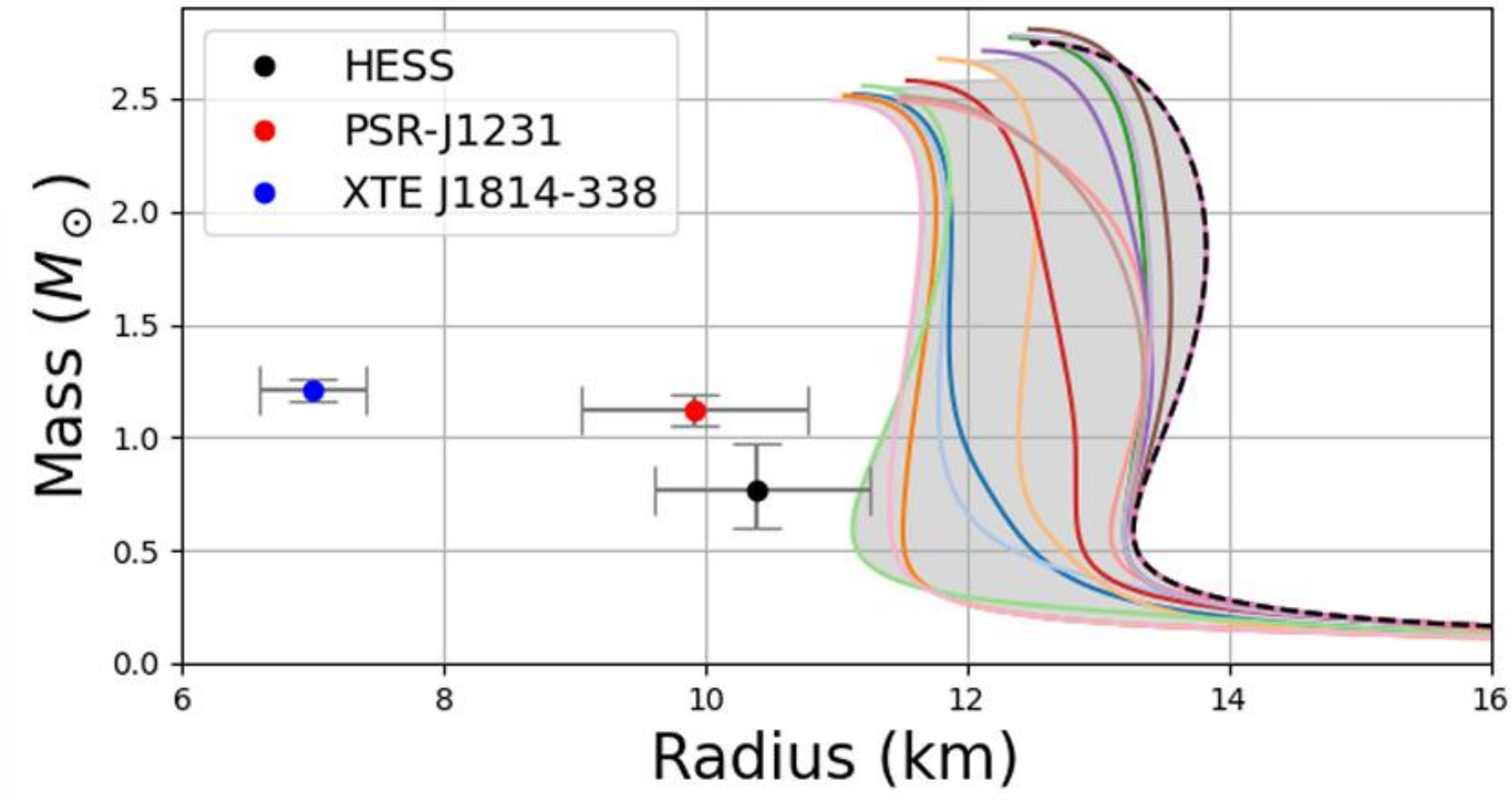
STABILITY ANALYSIS

$$\begin{pmatrix} \delta N_{BM} \\ \delta N_{DM} \end{pmatrix} = \begin{pmatrix} \partial N_{BM}/\partial \varepsilon^c_{BM} & \partial N_{BM}/\partial \varepsilon^c_{DM} \\ \partial N_{DM}/\partial \varepsilon^c_{BM} & \partial N_{DM}/\partial \varepsilon^c_{DM} \end{pmatrix} \begin{pmatrix} \delta \varepsilon^c_{BM} \\ \delta \varepsilon^c_{DM} \end{pmatrix} = 0$$

$$\begin{pmatrix} \delta N_A \\ \delta N_B \end{pmatrix} = \begin{pmatrix} \kappa_A & 0 \\ 0 & \kappa_B \end{pmatrix} \begin{pmatrix} \delta \varepsilon_c^A \\ \delta \varepsilon_c^B \end{pmatrix}$$

- Stable: k_A, k_B ∈ ℝ; k_A, k_B > 0
- Unstable: Im(K_A), Im(k_B) ≠ 0, k_A, k_B <0

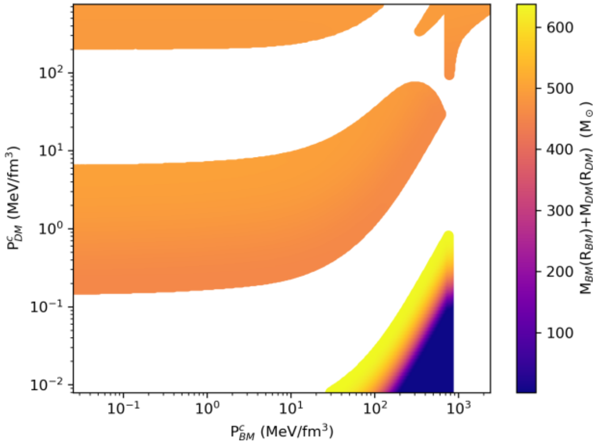
RESULTS: PURE NEUTRON STAR



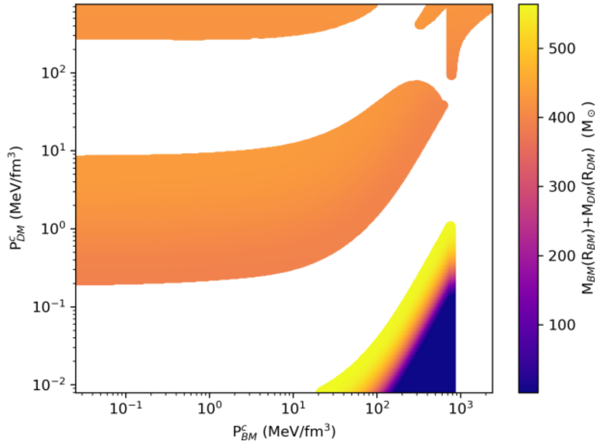
One of our EoS is already compatible with HESS!

STABILITY ANALYSIS: EOS1, DIFFERENT DARK MATTER MASS

$m_{DM} = 1\ MeV$



$m_{DM} = 10\ MeV$



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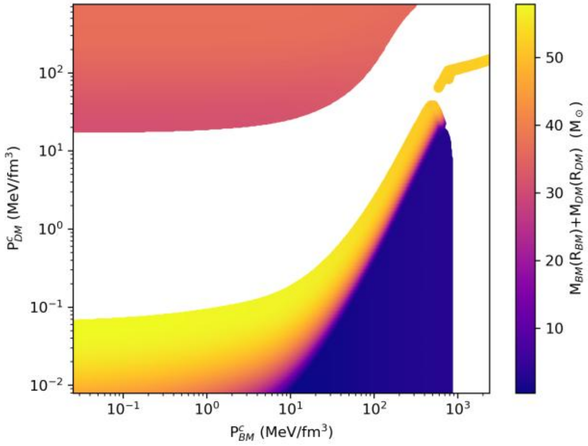
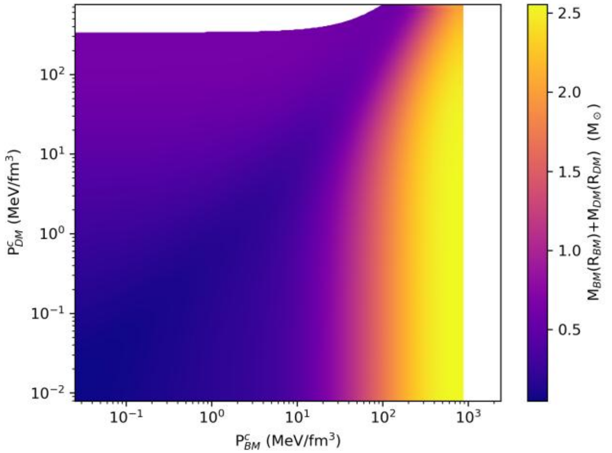
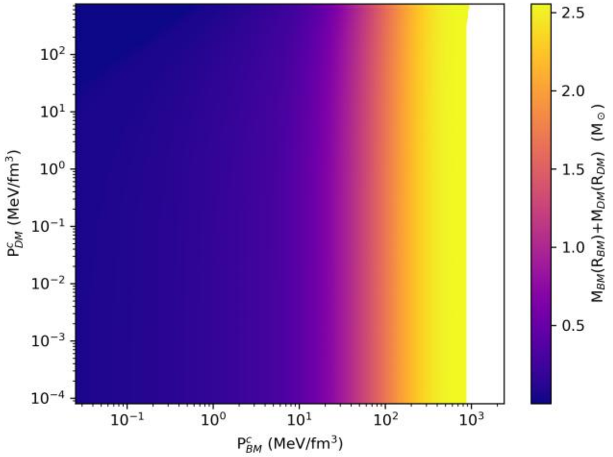


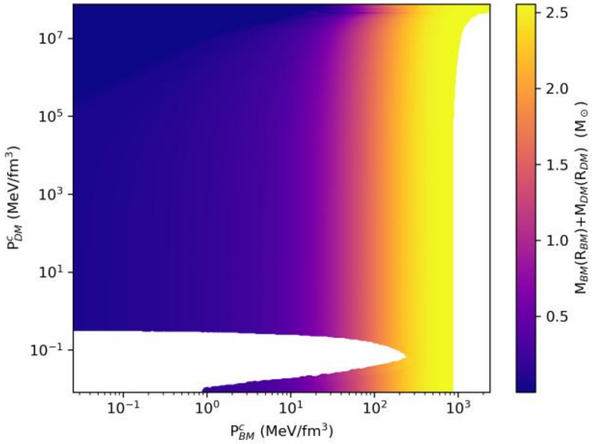
$m_{DM} = 1$ GeV



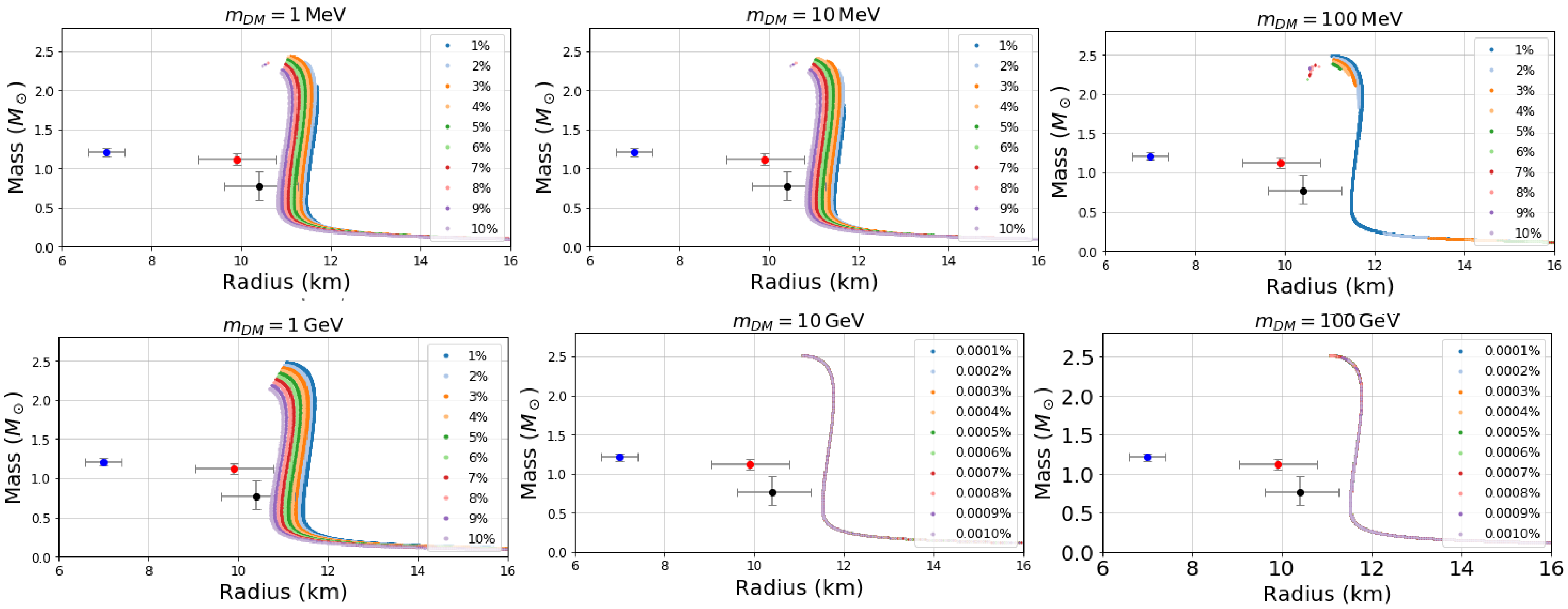
$m_{DM} = 10$ GeV



$m_{DM} = 100$ GeV

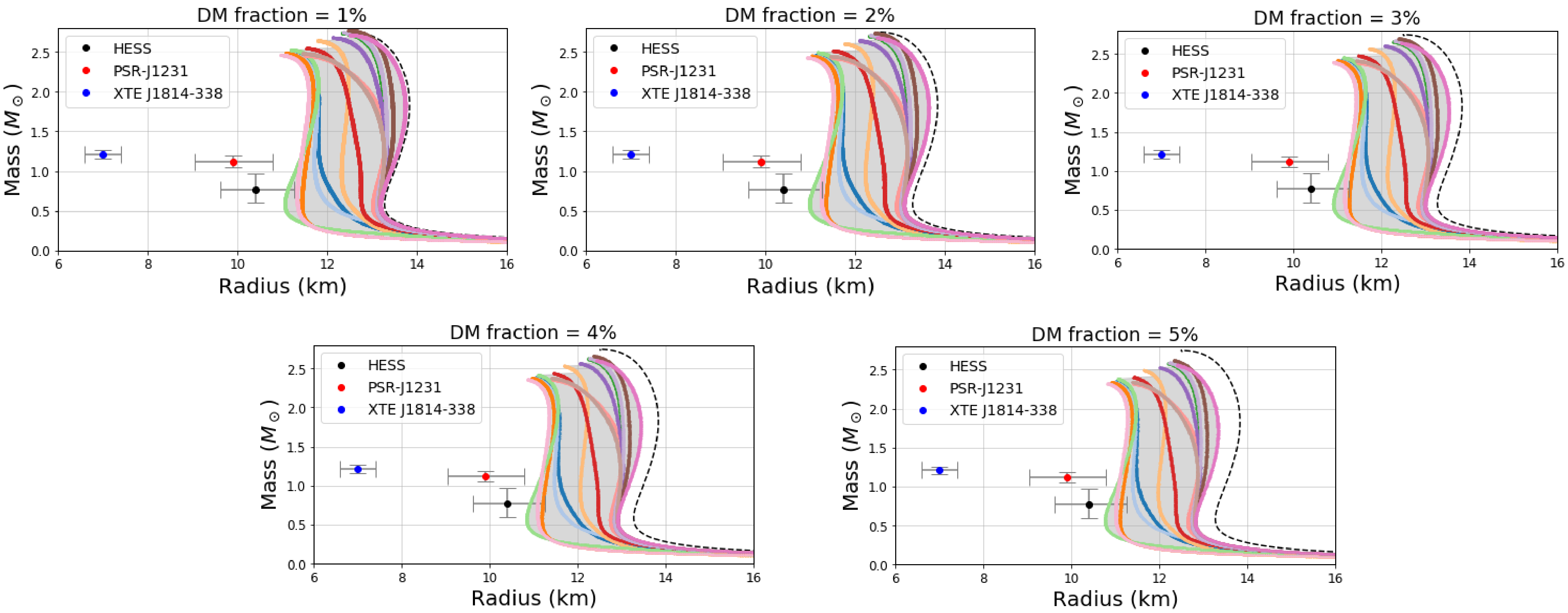


RESULTS: ADMIXTURE FOR DIFFERENT DM PARTICLE MASSES

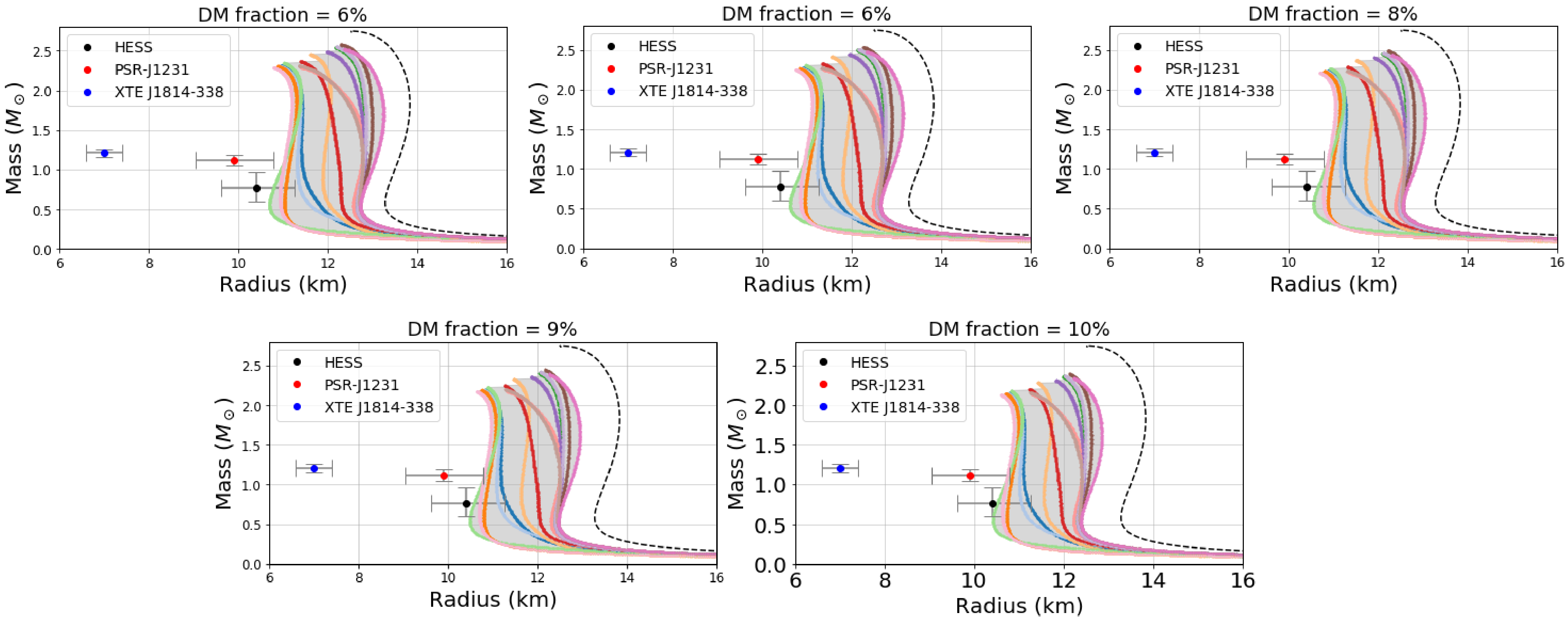


$$M(R) = M_{BM}(R_{BM}) + M_{DM}(R_{DM})$$

RESULTS: ADMIXTURE $m_{DM} = 1GeV$



RESULTS: ADMIXTURE $m_{DM} = 1GeV$



X^2 ANALYSIS WITH COMPACT OBJECTS: 1GEV

DM %	HESS J1731-347	PSR-J1231	XTE J1814-338
1 %	0.69	2.74	122.44
2 %	0.57	2.52	117.64
3 %	0.44	2.30	114.24
4 %	0.36	2.04	110.47
5 %	0.27	1.81	106.47
6 %	0.19	1.58	102.73
7 %	0.13	1.37	99.02
8 %	0.08	1.19	95.31
9 %	0.04	1.04	91.43
10 %	0.02	0.89	88.16

- We do not need dark matter to explain HESS
- We need >9% DM content to explain PSR
- We cannot explain XTE even with DM

DARK MATTER CAPTURE

Is it possible to have such fractions of DM in the star?

Most likely no [P. Tinyakov, M. Pshirkov, S. Popov. 2021]

- Capture at star formation: might not stay in NS after supernova explosion
- Capture during star lifetime $10^{-23} M_\odot$

$$mF \sim 2.5 \times 10^{26}\,\mathrm{GeV/s}\left(\frac{\rho_{\mathrm{DM}}}{0.5\,\mathrm{GeV/cm^3}}\right)\left(\frac{220\,\mathrm{km/s}}{\bar{v}}\right) f$$

$$f = \sigma/\sigma_{\mathrm{cr}} \quad \text{if } \sigma < \sigma_{\mathrm{cr}},$$
$$f = 1 \quad \text{otherwise.}$$

$10^{-5} M_\odot$:

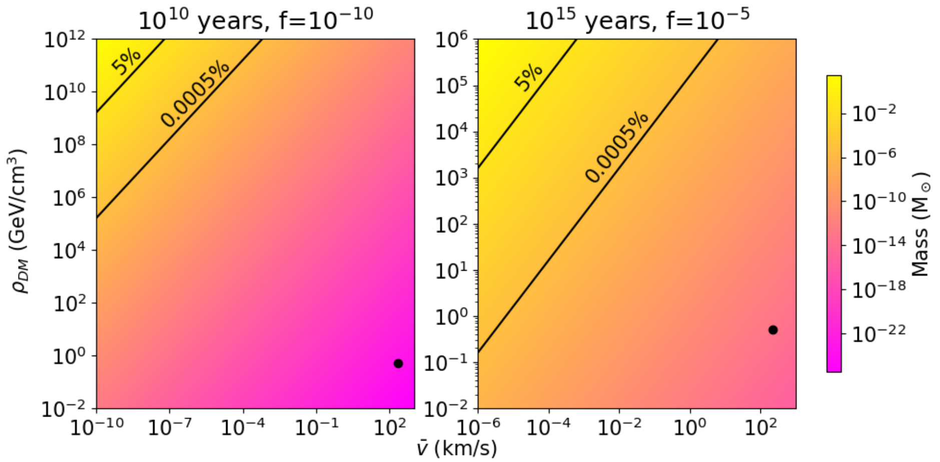
$$10^{10}\ \text{years},\ f = 10^{-10}: \quad \left(\frac{\rho_{DM}}{\bar{v}}\right) = 10^{17}\left(\frac{\rho_{DM}}{\bar{v}}\right)\Big|_{\text{average}}$$

$$10^{15}\ \text{years},\ f = 10^{-5}: \quad \left(\frac{\rho_{DM}}{\bar{v}}\right) = 10^{6}\left(\frac{\rho_{DM}}{\bar{v}}\right)\Big|_{\text{average}}$$

How to maximize the capture

- Strong DM-nucleon interaction
- Unusually slow DM particles
- Unusually high DM densities
- DM self-interactions

  [T. Güver, A.E. Erkoca, M. Hall Reno, I. Sarcevic, 2014]



DISCUSSION

On DANSs

- For mDM⩾1GeV: DM accumulates in the core of the NS.
- 1 GeV doesnt compromise the stability of the star
- For mDM<1GeV: DM forms a halo around the NS

COs as a DANS

- Huge density of DM in its Galaxy/slow DM particles
- DM in COs it’s not a free Fermi gas
- Pure neutron matter (EoS1) → constraints on nuclear equation of state

Future searches for DM

- X-Ray pulse profiles [Z. Miao, Y. Zhu, A. Li, F. Huang, 2022]
- Tidal deformabilities and gravitational waves

END

THANK YOU!