ANALYZING FERMIONIC DARK MATTER SCENARIOS WITH THE HESS J1731-347 COMPACT OBJECT

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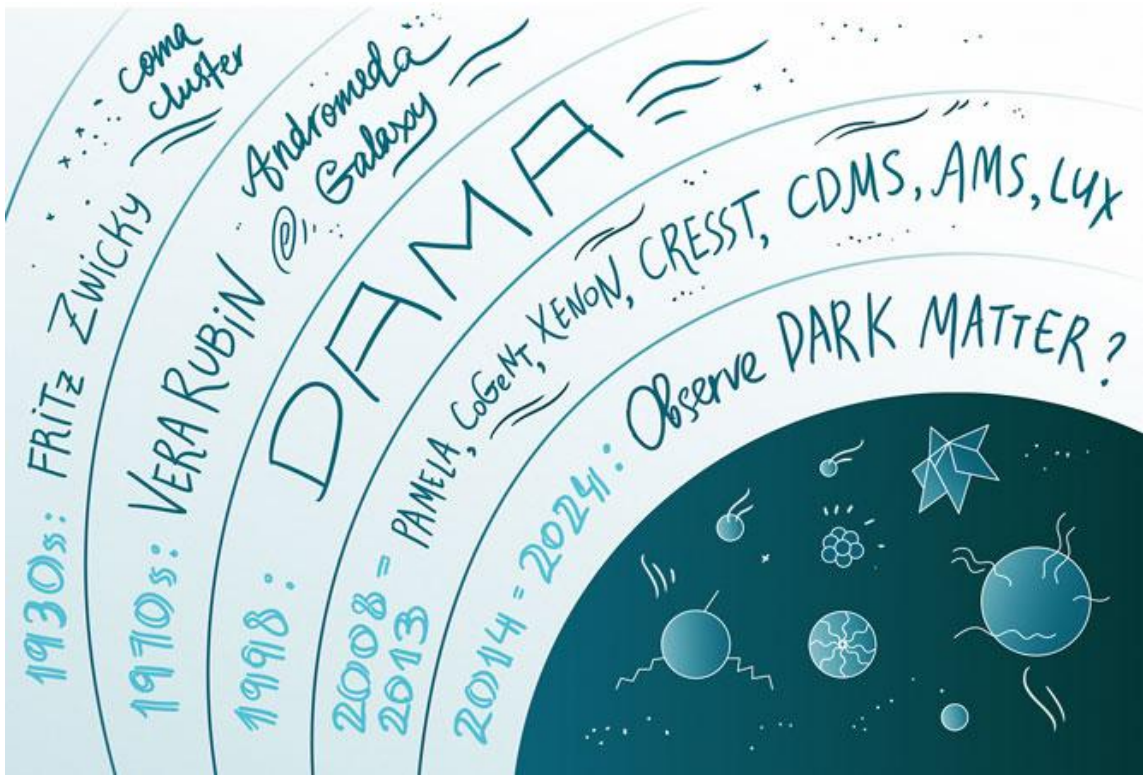
2nd Workshop on modern equations of state and spectroscopy in neutron-star matter

MOTIVATION

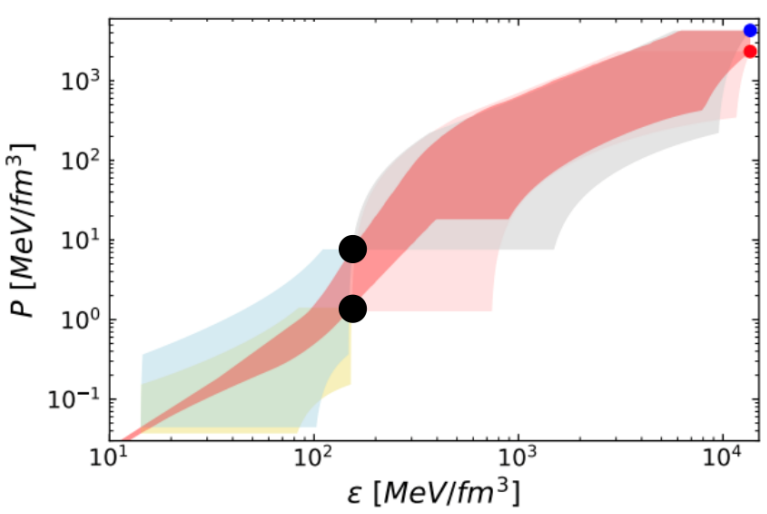


[Symmetry magazine]

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

See talk by Eva Lope Oter on Wednesday!

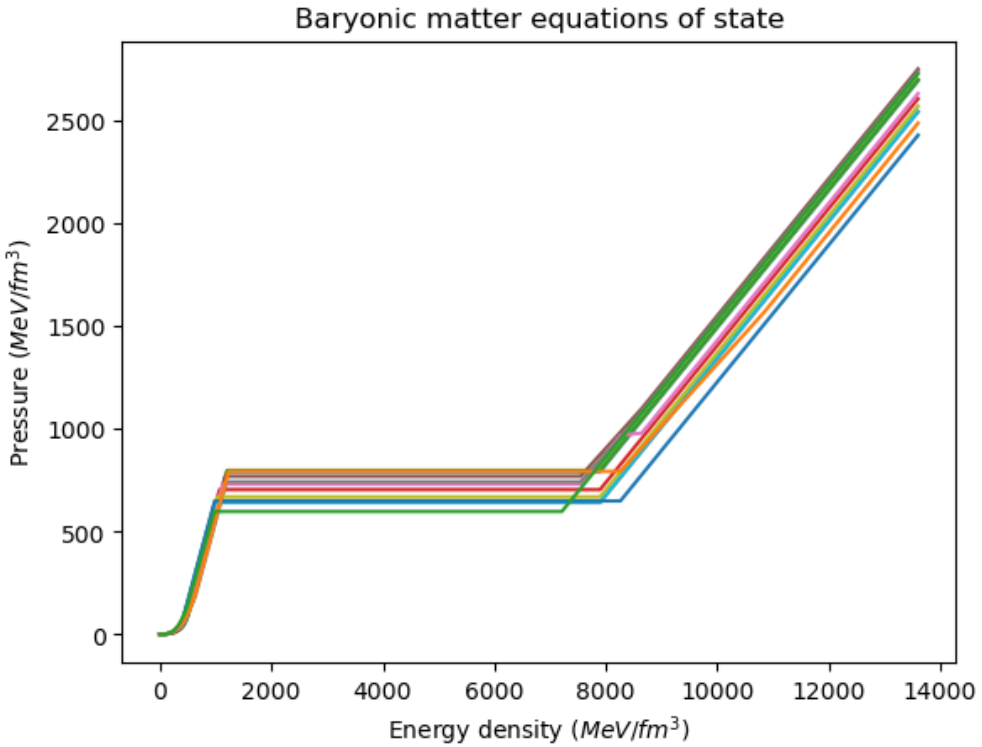
High density regime

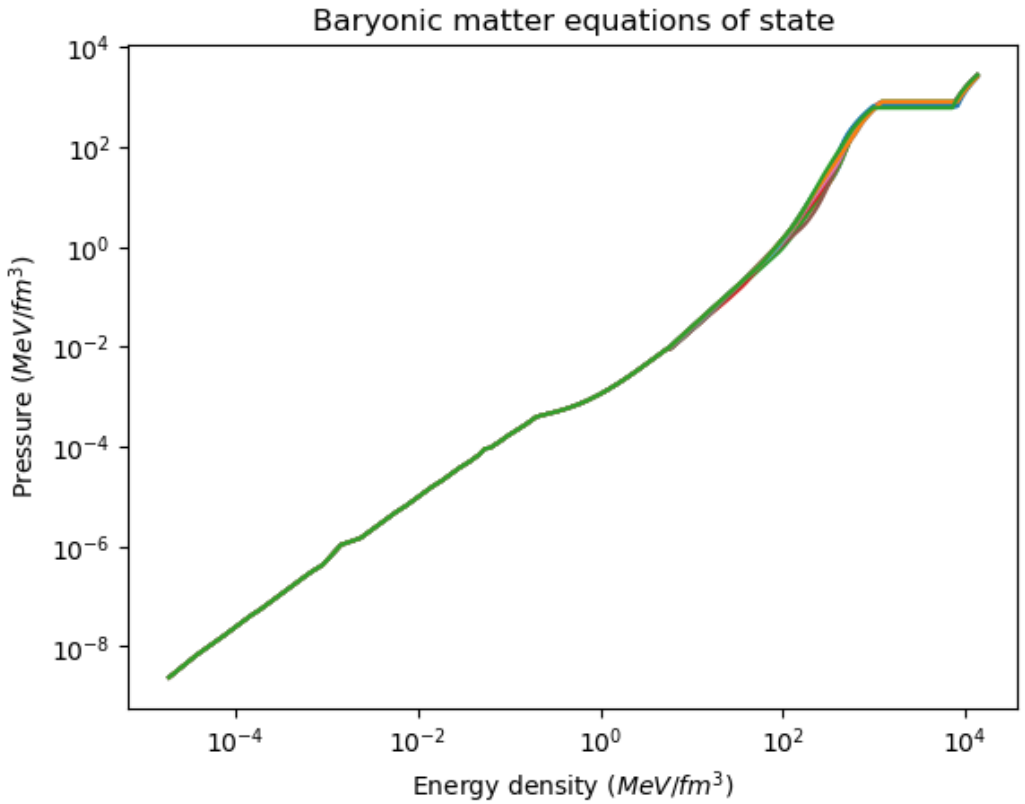
- $n > n_s$
- Perturbative Quantum Chromodynamics
- Limit to (P,ε,μ) at matching point → constraints on EoS

Crust

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

NUCLEAR EQUATION OF STATE





DARK MATTER EQUATION OF STATE

Free Fermi gas

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

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

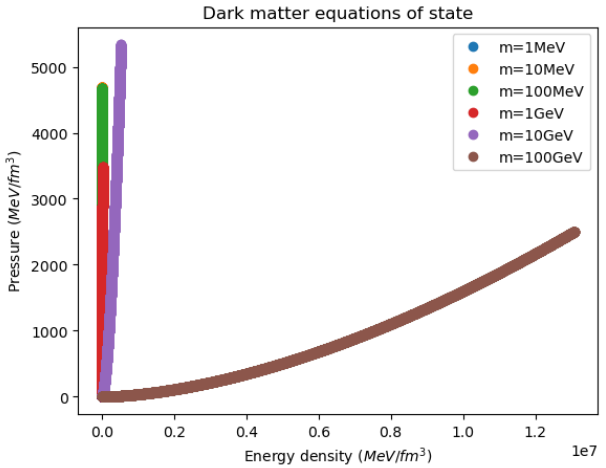
$$P = \frac{1}{6\pi^2}\int_0^{k_F}\frac{k^4}{\sqrt{k^2+m_f^2}}$$

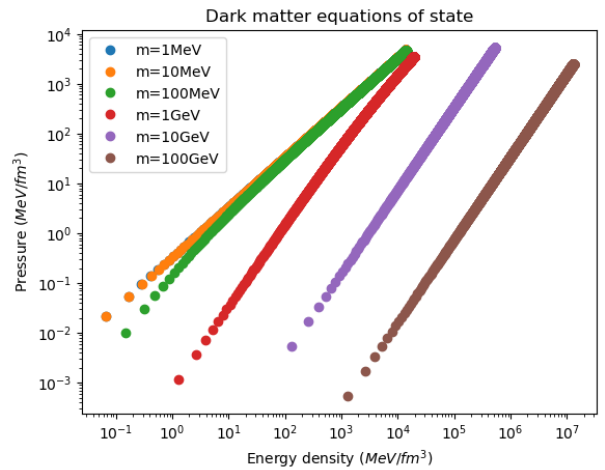
$$= \frac{1}{24\pi^2}\left[k_F\sqrt{k_F^2+m_f^2}(2k_F^2-3m_f^2) + 3m_f^4\ln\left(\frac{k_F+\sqrt{k^2+m_f^2}}{m_f}\right)\right]$$

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

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

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

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

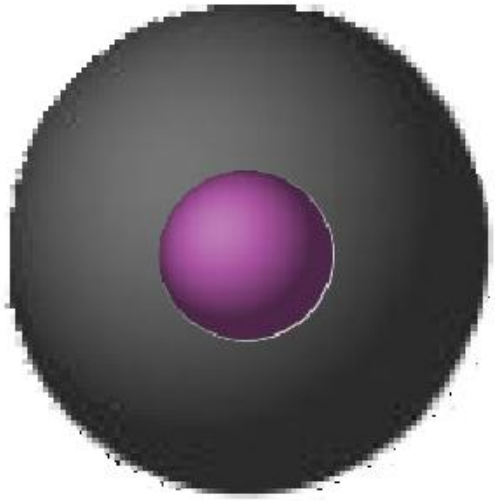
13 nuclear EoS + 6 dark matter EoS

4th order Runge-Kutta method

2 FLUID FORMALISM FOR TOLMAN-OPPENHEIMER-VOLKOFF EQUATIONS

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

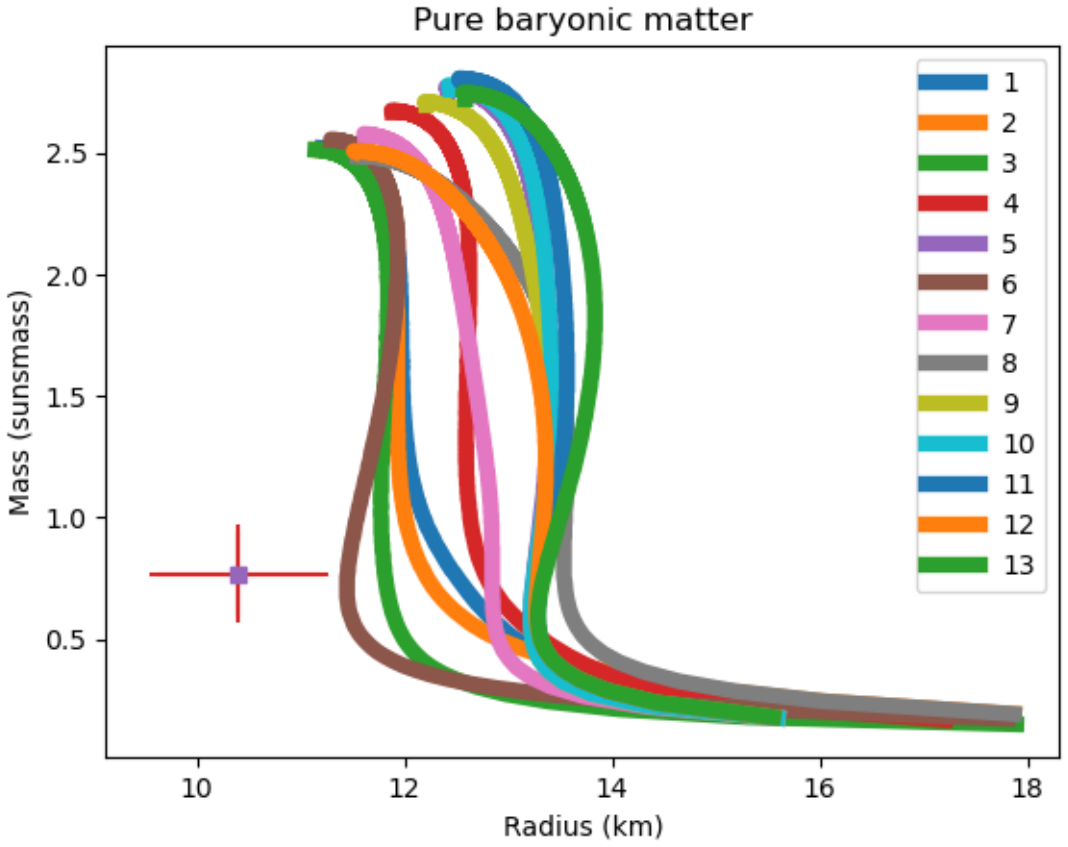
$$M(R) = M_{BM}(R_{BM}) + M_{DM}(R_{DM})$$



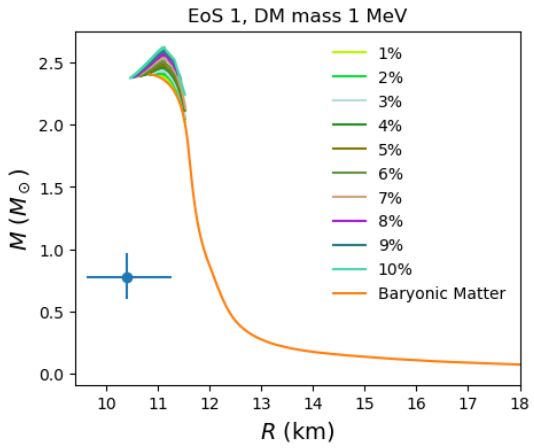
Dark matter halo around NS

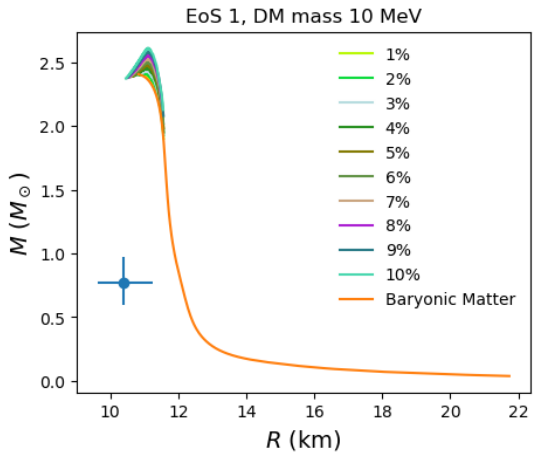
Dark matter core inside NS

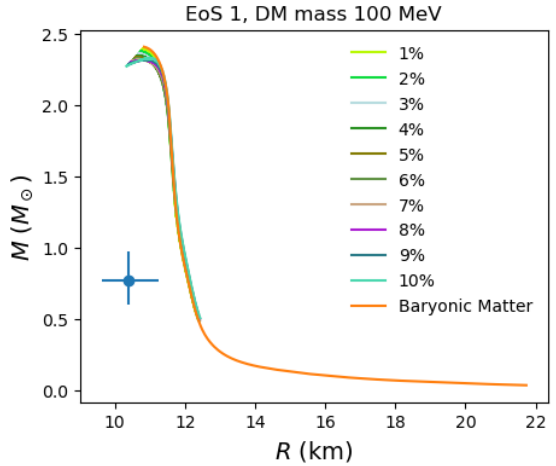
RESULTS: PURE NEUTRON STAR

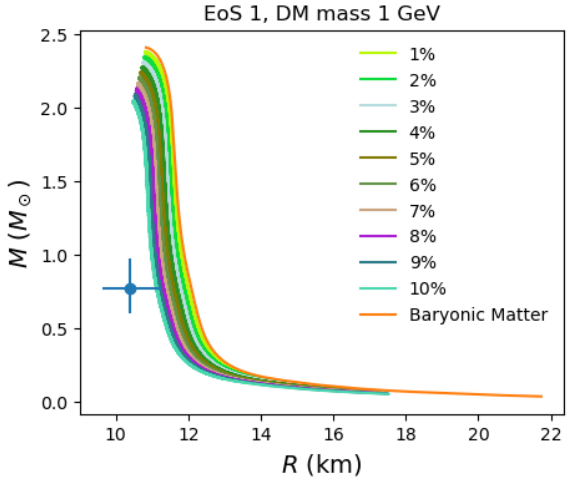


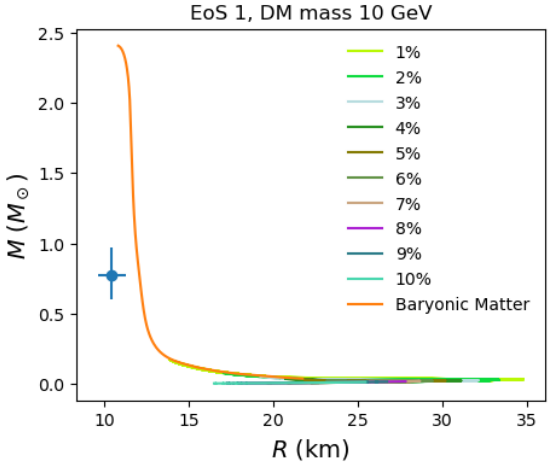
RESULTS: ADMIXTURE FOR DIFFERENT DM PARTICLE MASSES



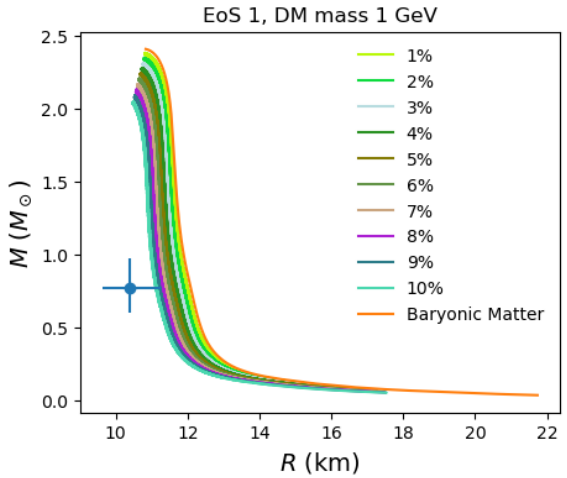


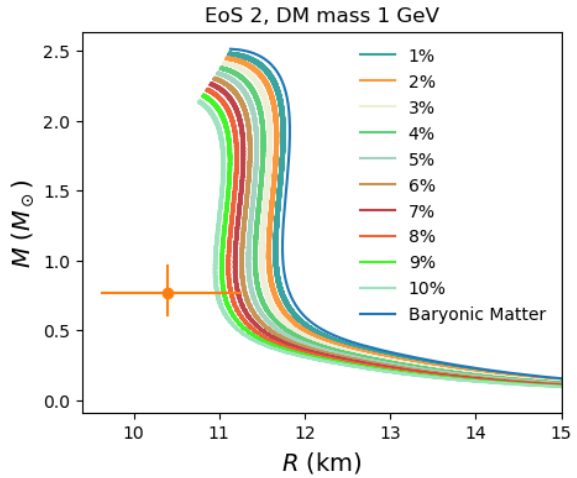


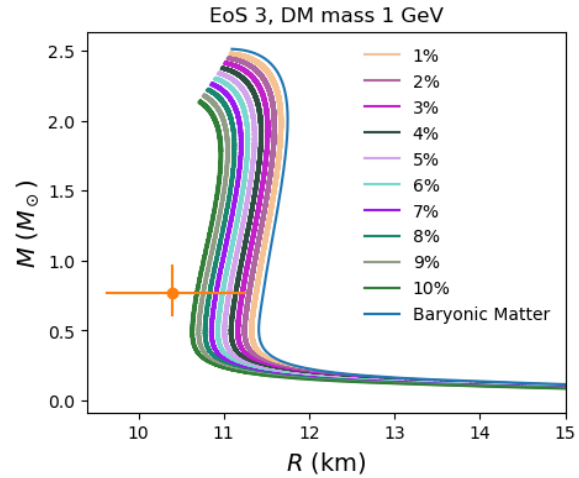


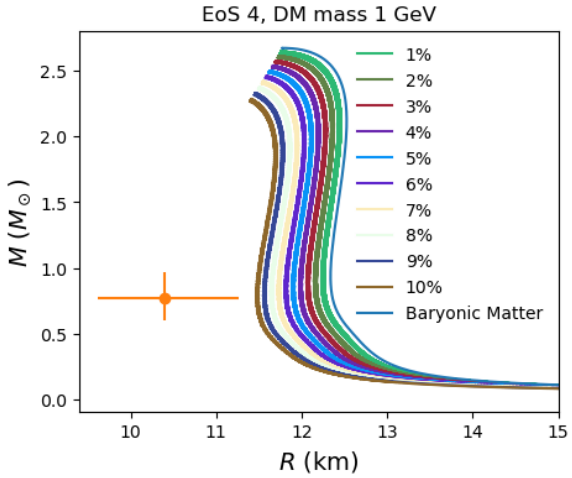


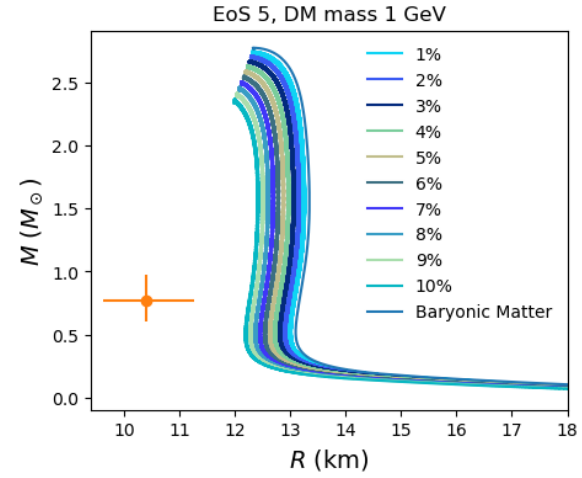
RESULTS: ADMIXTURE $m_{DM} = 1GeV$

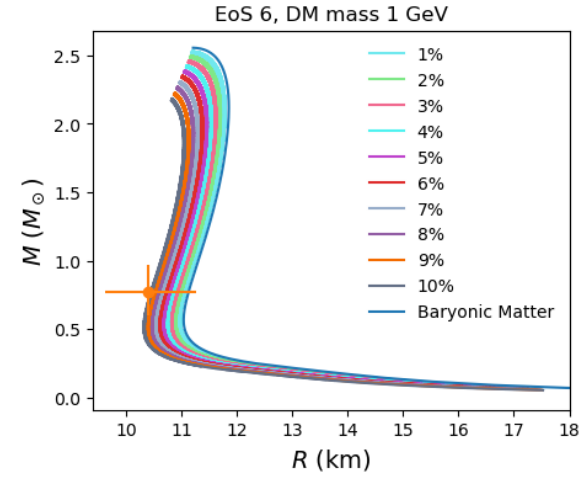












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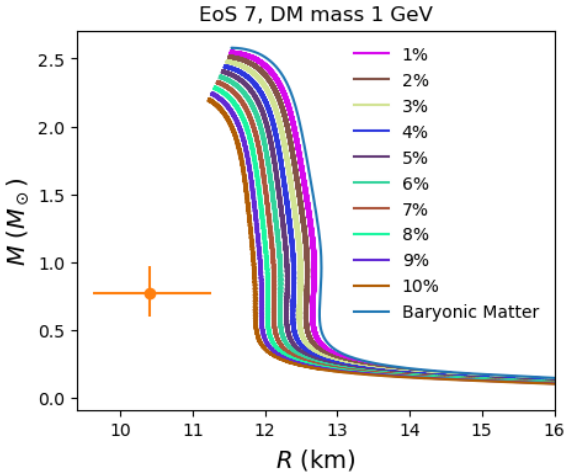
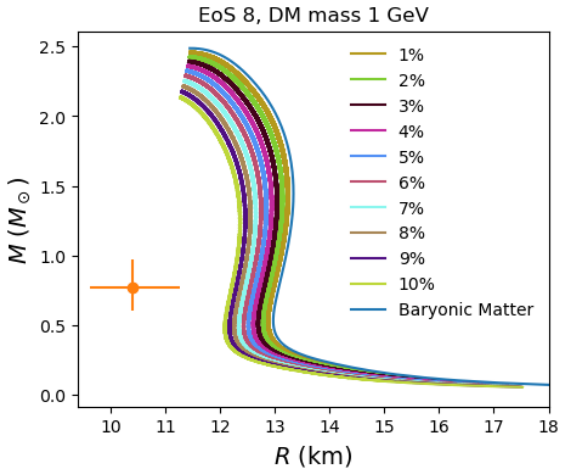
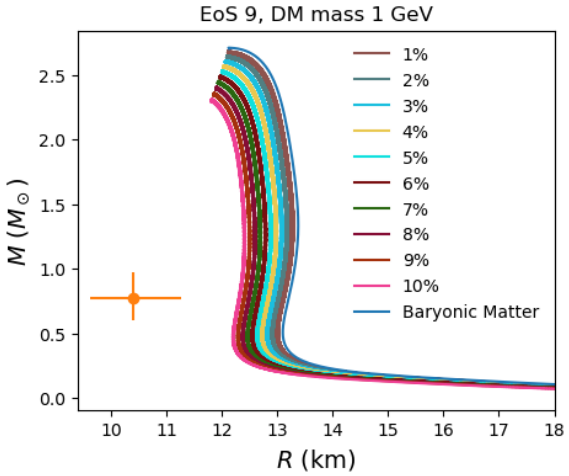
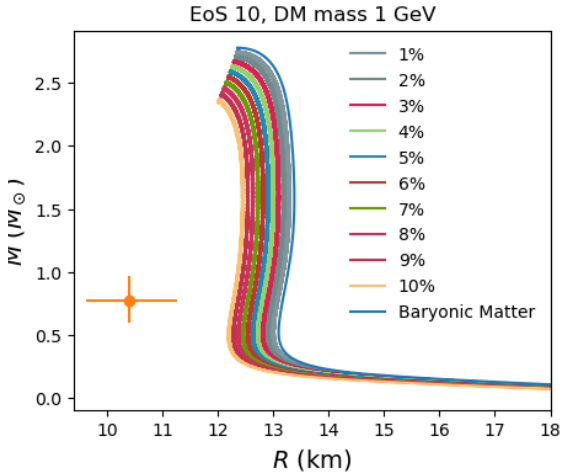
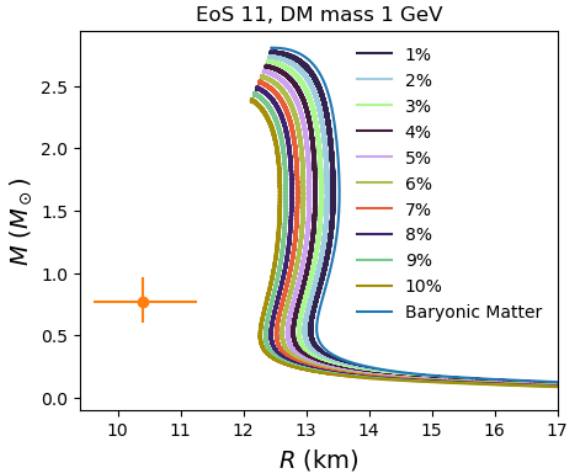
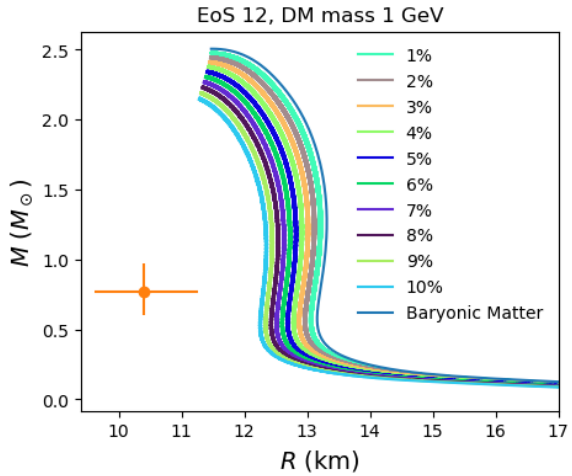


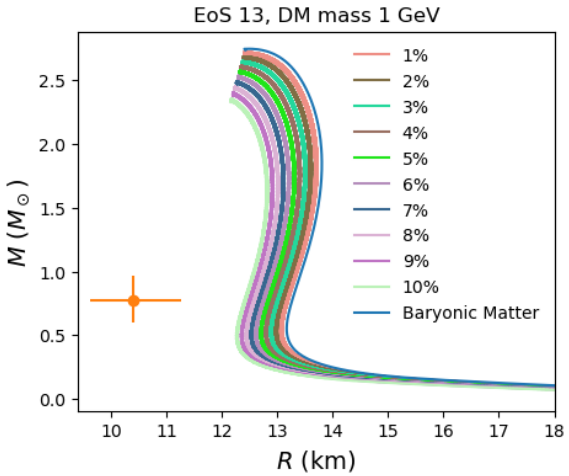












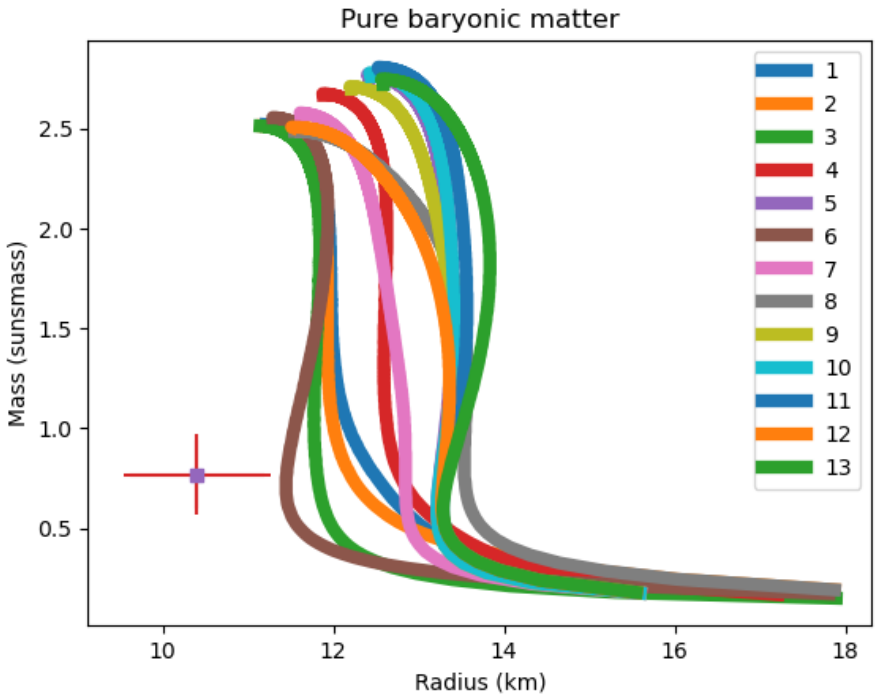
COMPATIBILITY ANALYSIS WITH HESS J1731-347

Confidence level 1σ

Nuclear Equation of State	Necessary DM fraction
EoS6	0%
EoS3	>3%
EoS4	>4%
EoS2	>7%
EoS1 , EoS5, EoS6, EoS7, EoS8, EoS9, EoS10, EoS11, EoS12, EoS13	>10%

$$M_{HESS} = 0.77^{+0.2}_{-0.17}\ M_{\odot} \qquad R_{HESS} = 10.4^{+0.86}_{-0.78}\ km$$

$$\chi^2 = \left(\frac{R_{interpol} - R_{HESS}}{\Delta R_{HESS}}\right)^2 \qquad 1\ DF$$



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

$$\rho_{\rm bound} = \rho_{\rm DM}\frac{4\pi}{3}\left(\frac{3\phi}{\pi\bar{v}^2}\right)^{3/2}$$

$$M_{\rm tot} \sim 2\times 10^{-13} M_\odot \left(\frac{\rho_{\rm DM}}{100\,{\rm GeV/cm^3}}\right)\left(\frac{10\,{\rm km/s}}{\bar{v}}\right)^3 \qquad \boxed{10^{-13} M_\odot}$$

- Capture during star lifetime

$$F_{\rm max} = \left(\frac{8\pi}{3}\right)^{1/2} n R_*^2 \bar{v}\left(1+\frac{3v_{\rm esc}^2}{2\bar{v}^2}\right) \simeq \sqrt{6\pi} n R_*^2 v_{\rm esc}^2/\bar{v} = \sqrt{6\pi} n \frac{R_* R_g}{\bar{v}} c^2 \qquad \boxed{10^{-14} M_\odot}$$

$$mF \sim 2.5\times 10^{26}\,{\rm GeV/s}\left(\frac{\rho_{\rm DM}}{0.5\,{\rm GeV/cm^3}}\right)\left(\frac{220\,{\rm km/s}}{\bar{v}}\right) f \qquad \boxed{10^{-15} M_\odot}$$

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

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 → decrease of mass and radius
- For mDM<1GeV: DM forms a halo around the NS →increases the mass

HESS as a DANS

- Huge density of DM in its Galaxy/slow DM particles
- DM in HESS 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
- Gravitational waves [Private communication with Milton Ruiz, U. Valencia]

END

THANK YOU!