Constraining Bosonic Asymmetric Dark Matter With Neutron Star Mass-Radius Measurements

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Based on Rutherford et al. (2023)
arXiv: 2208.03282

Uncertainties In The Neutron Star Equation Of State (EoS)

- Neutron stars may contain exotic states of matter, e.g., deconfined quarks or hyperons.
- The effects of the hypothetical components are captured by the equation of state.
- The EoS can be deduced from measurable properties, e.g., the mass and radius.

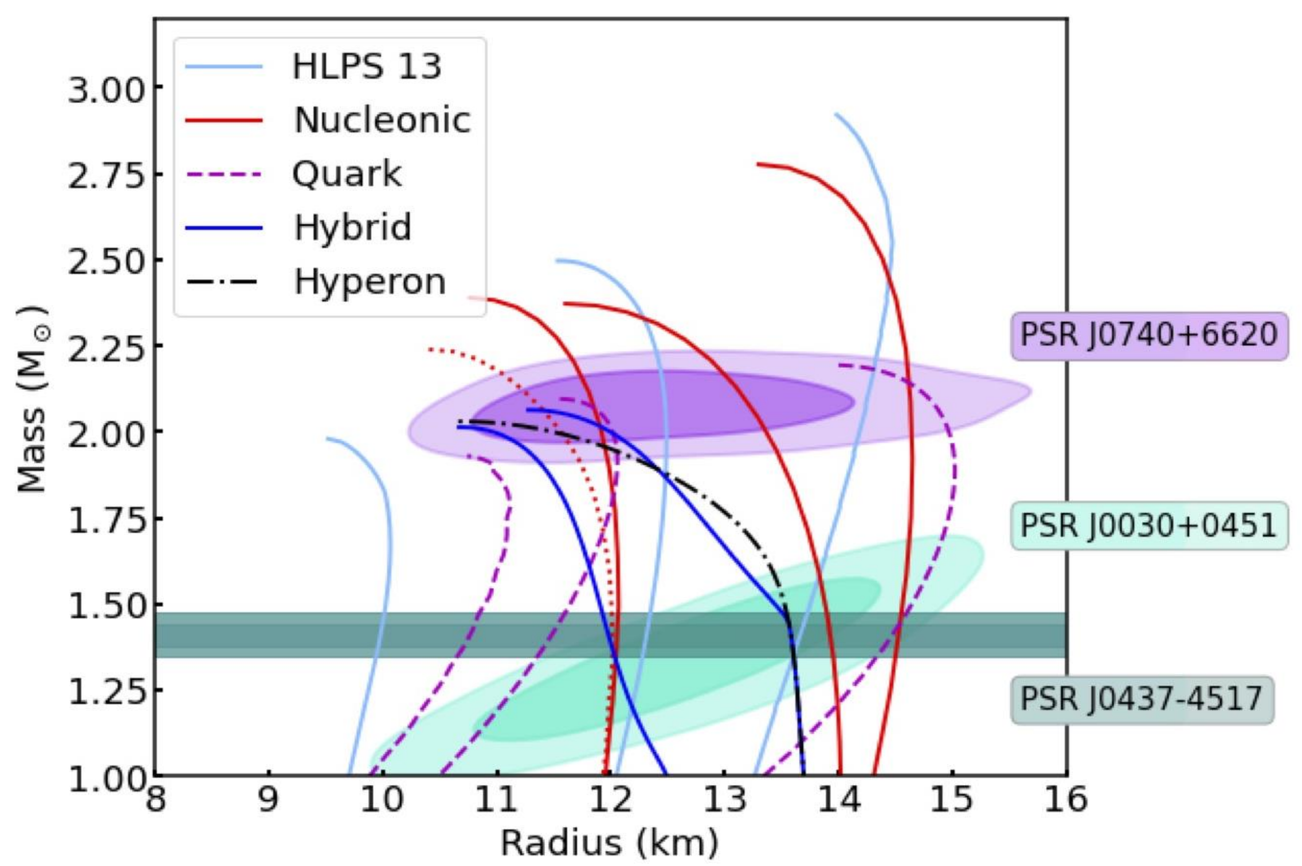

Figure made by Anna Watts

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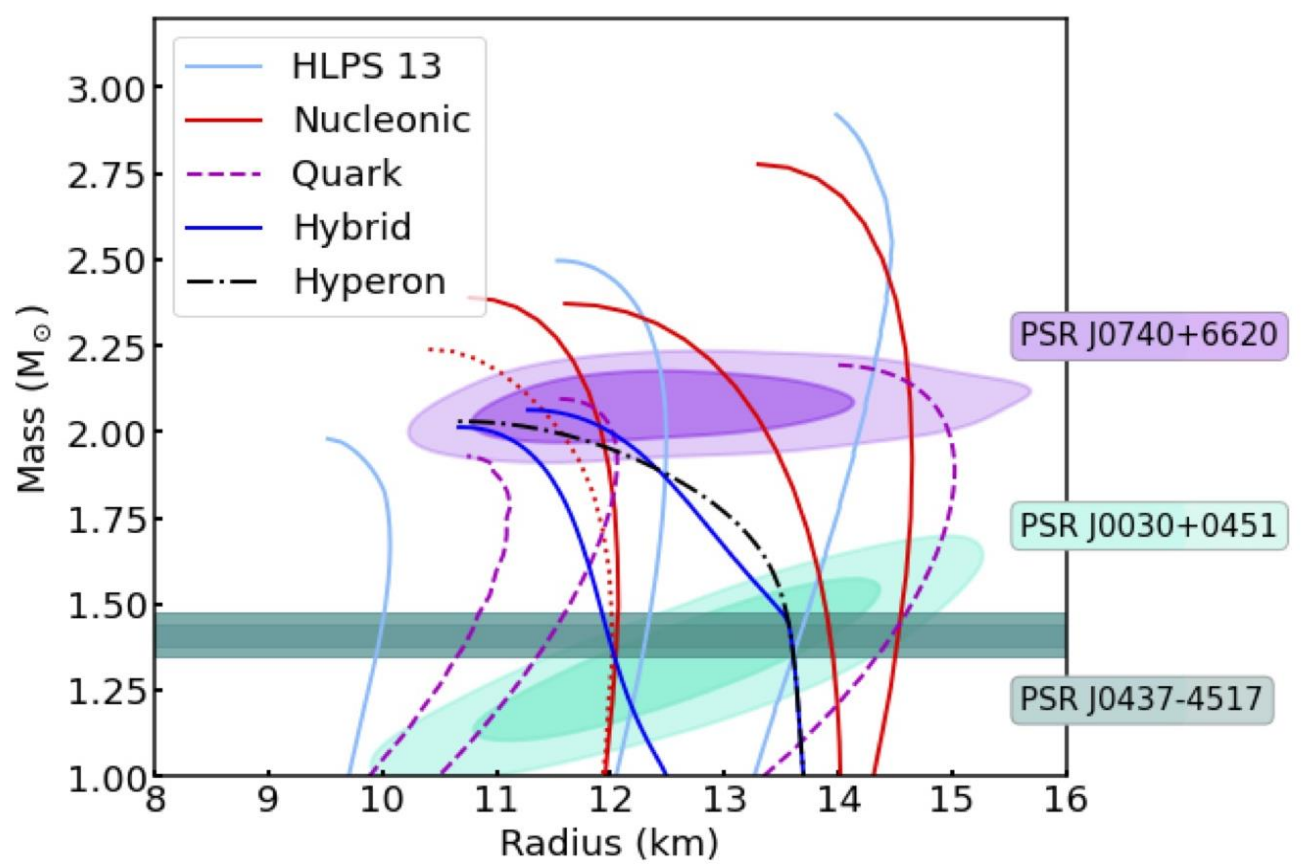

Neutron stars are an excellent hunting ground for dark matter!

Figure made by Anna Watts

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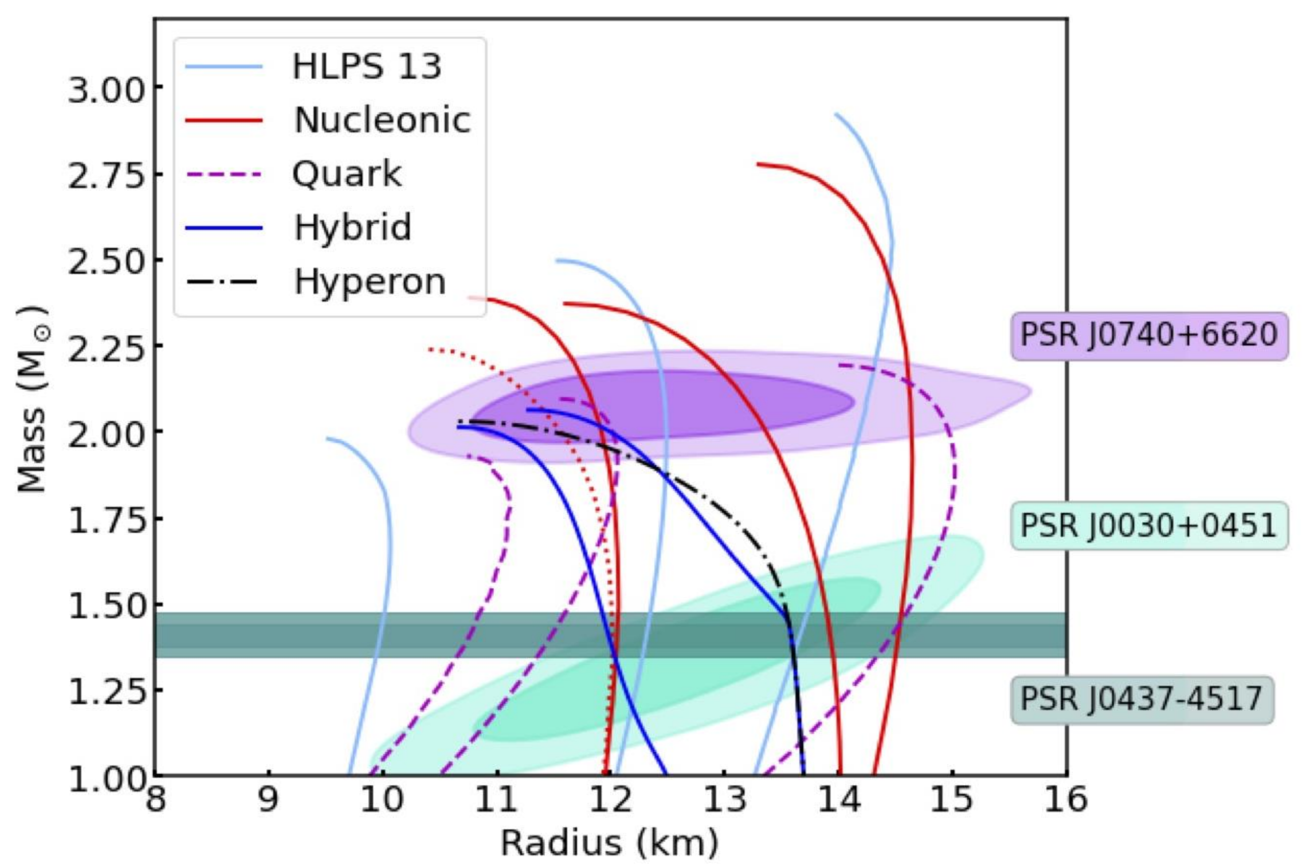


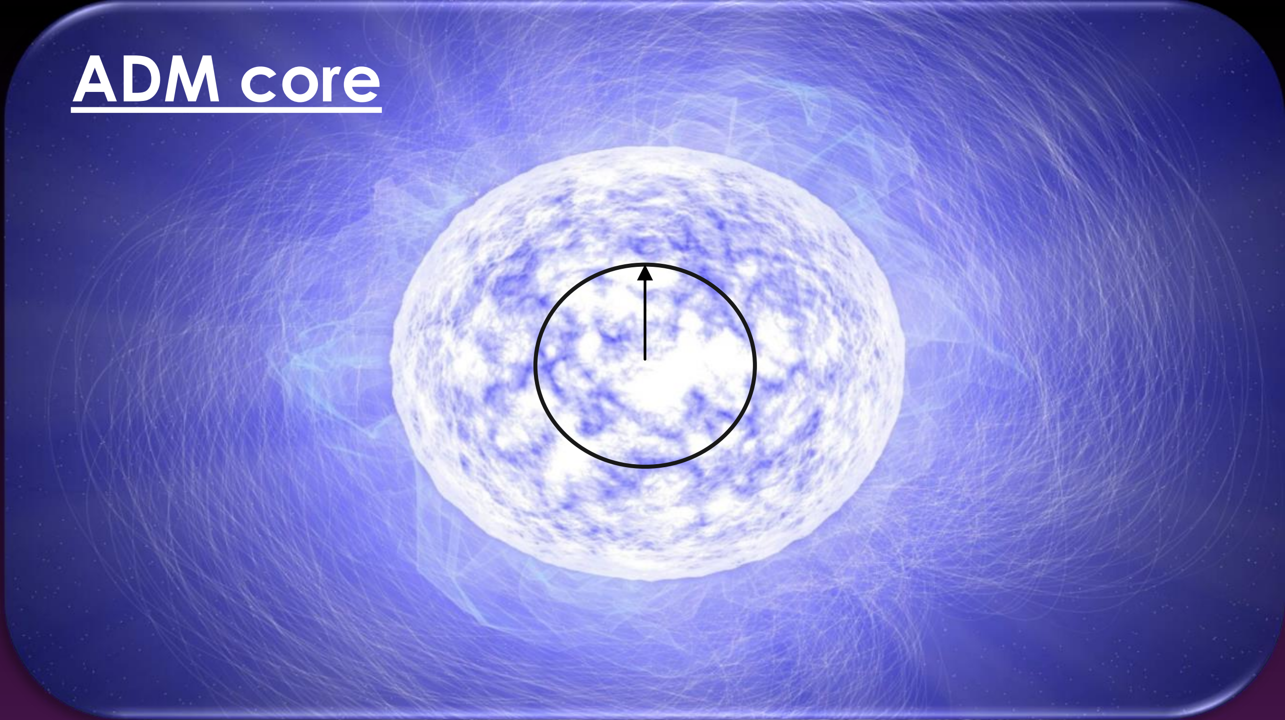
Neutron stars are an excellent hunting ground for dark matter!

For the new mass-radius measurement of PSR J0437-4517 check out Choudhury et al. 2024 and Rutherford et al. 2024 (both in review at APJ Letters!)

Figure made by Anna Watts

Asymmetric Dark Matter (ADM) In Neutron Stars

- ADM can accumulate in two spatial regimes: the neutron star core and in the exterior spacetime.
- ADM cores reduce the gravitational mass, radius, and tidal deformability.
- ADM halos increase the gravitational mass and tidal deformability.



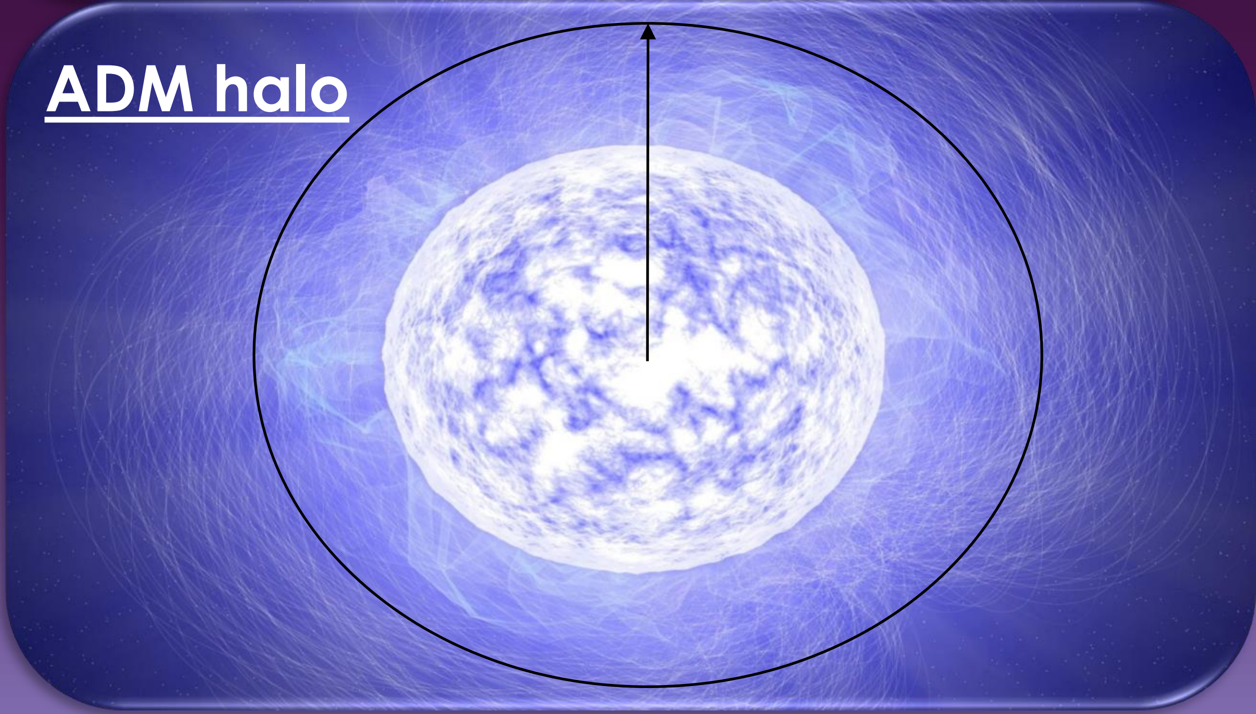


Image of the neutron star taken from:
https://newatlas.com/physics/neutron-stars-dark-matter-axion/

The *Bosonic* ADM Model

- Modeled after the Nelson et al. model[1].

- Describes MeV-GeV mass-scale bosonic ADM particles with repulsive self-interactions mediated by an eV-MeV mass-scale vector gauge boson.

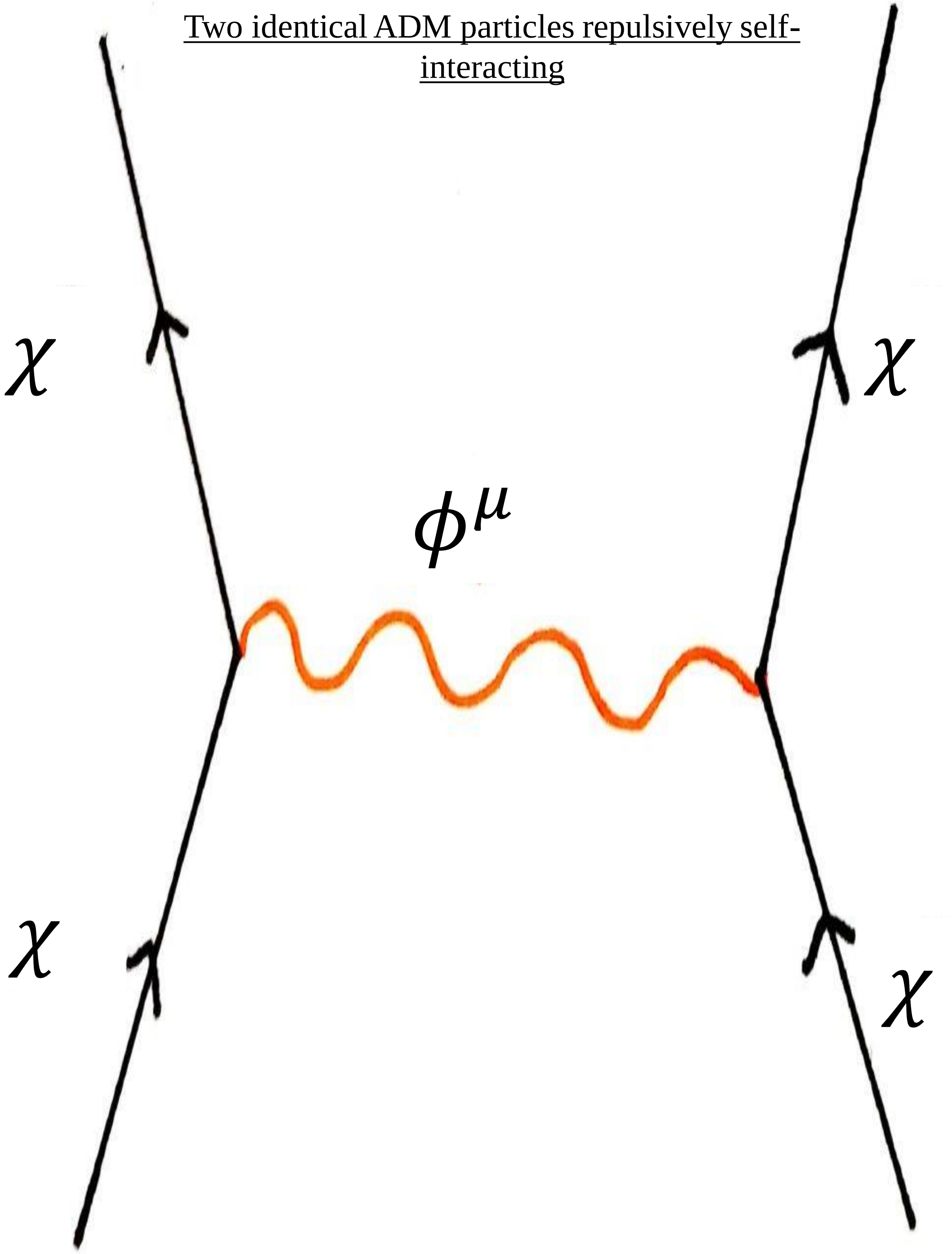
- The defining parameters of this model are:

  1) The *bosonic* ADM particle mass (m_χ)

  2) The effective self-repulsion strength $\left(\frac{g_\chi}{m_\phi}\right)$

  3) The fraction of ADM mass inside the neutron star (F_χ)

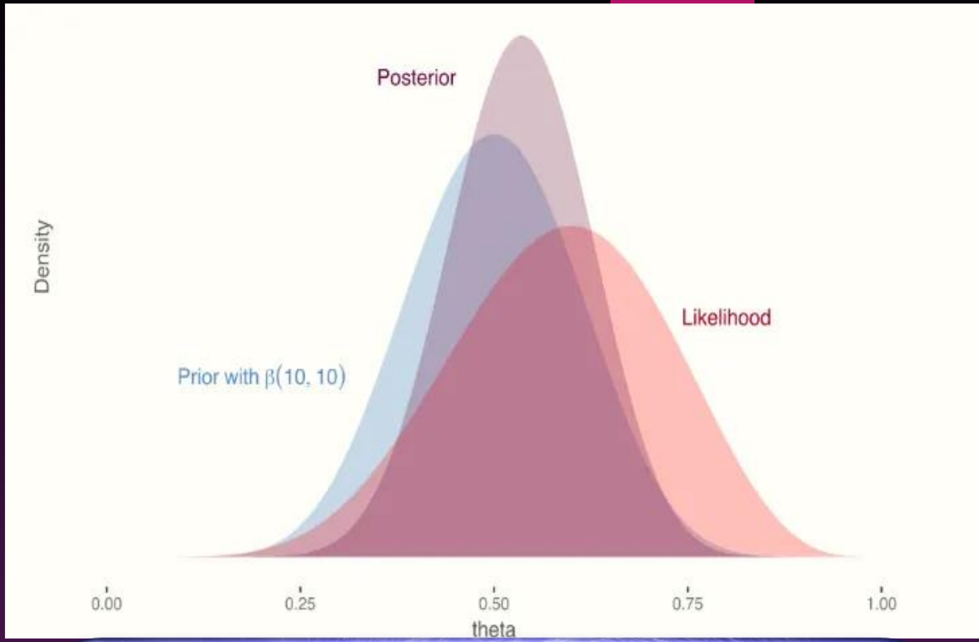
Two identical ADM particles repulsively self-interacting

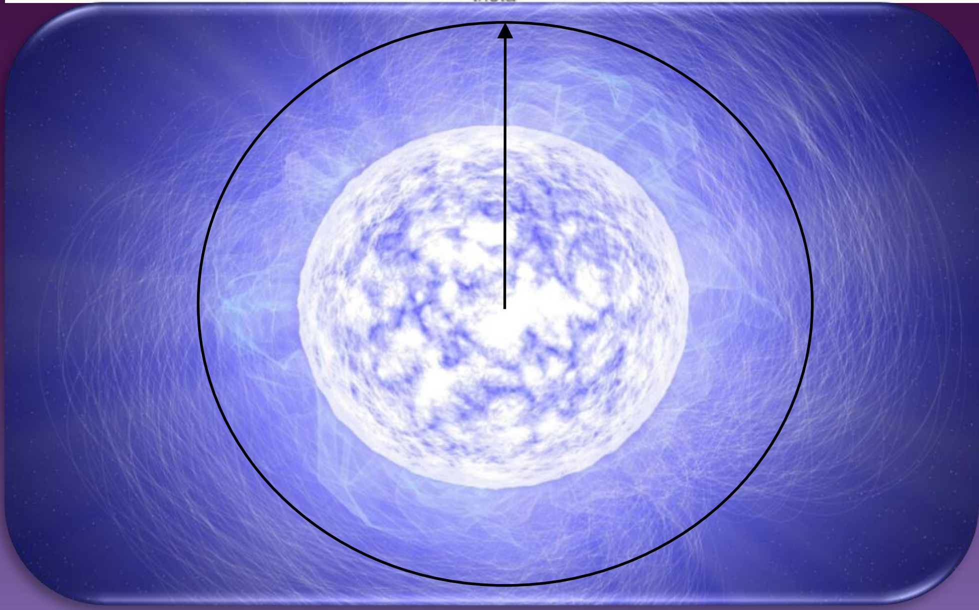


1. Nelson et al. (2018) arXiv: 1803.0366

Using Bayesian Inference To Study Bosonic ADM In Neutron Stars

- We perform a Bayesian analysis where we:
  - Vary the baryonic matter and ADM EoS
  - Vary the ADM EoS, but fix the baryonic matter EoS
- For both cases, we consider synthetic mass and radius measurements and not allow for ADM halos since:
  - ADM halos modify the exterior spacetime
  - ADM could modify the universal relations that are used to model the oblateness

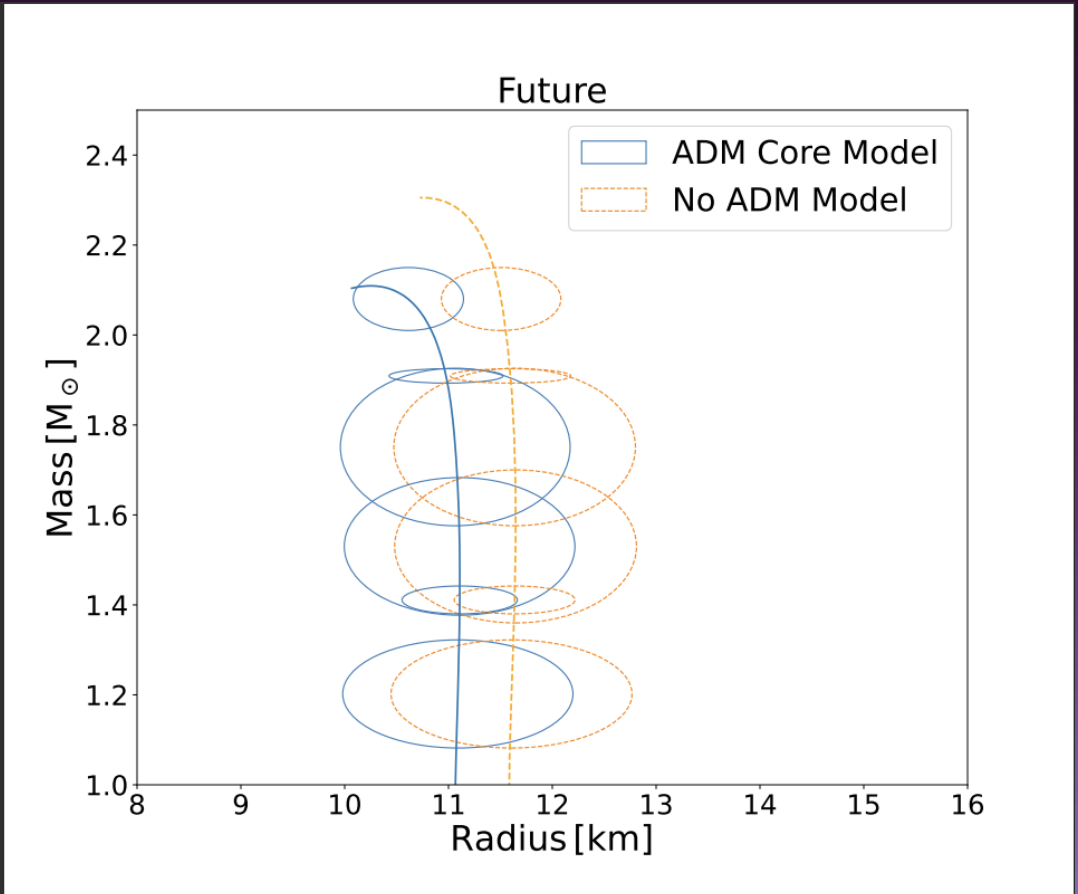


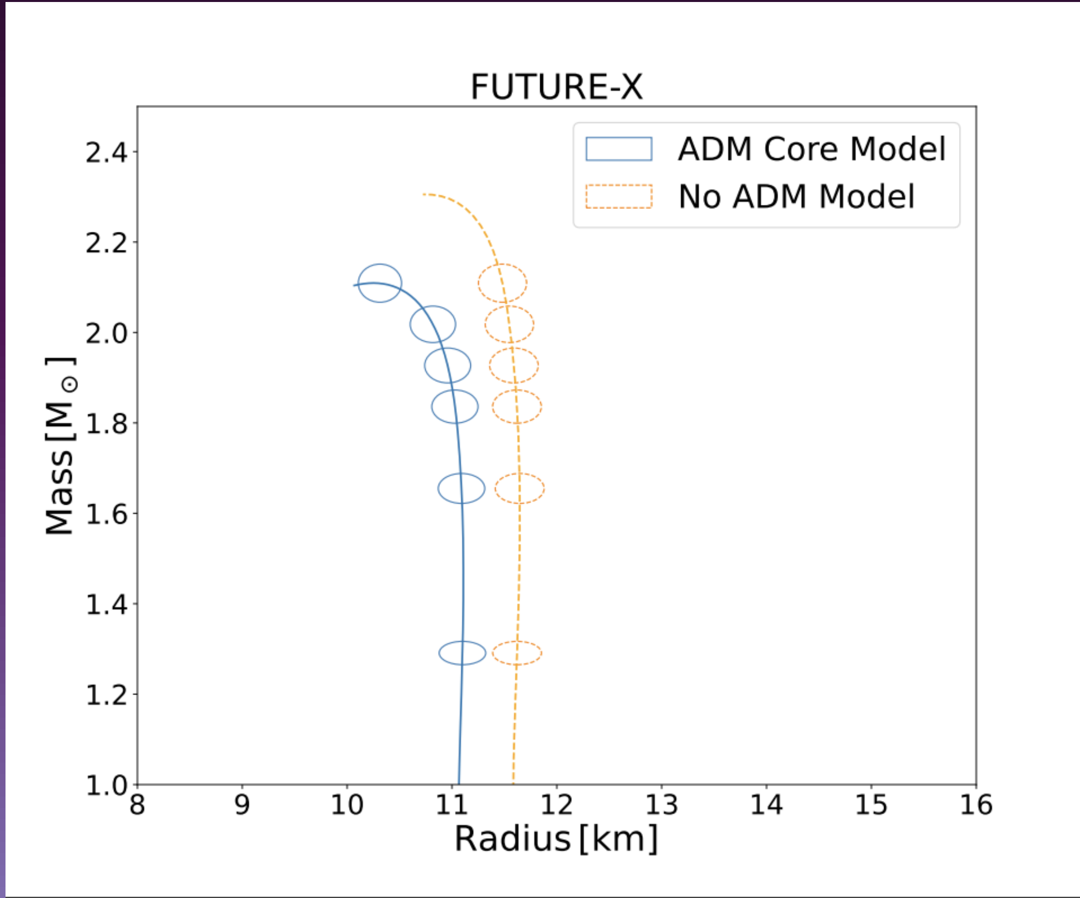


(Adapted from "Statistical Rethinking — Bayesian Analysis in R" by Marc Jacobs)

Source Selection

- Radius of the sources calculated using two ground-truth models:
  - "ADM Core Model": Baryonic neutron star with ADM core defined by [$m_\chi = 15$ GeV, $\frac{g_\chi}{m_\phi/\mathrm{MeV}} = 0.1$, $F_\chi = 7\,\%$]
  - "No ADM Model": Identical to *"ADM Core Model", except we set* $F_\chi = 0\,\%$.



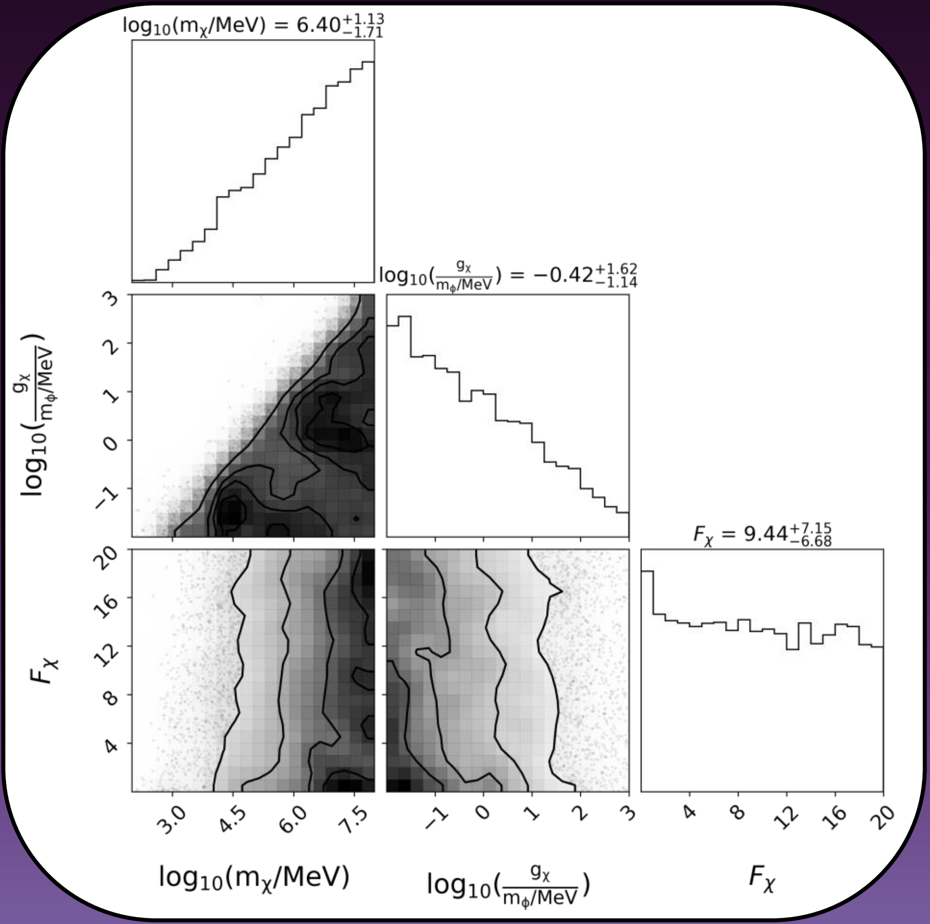


The ADM Priors

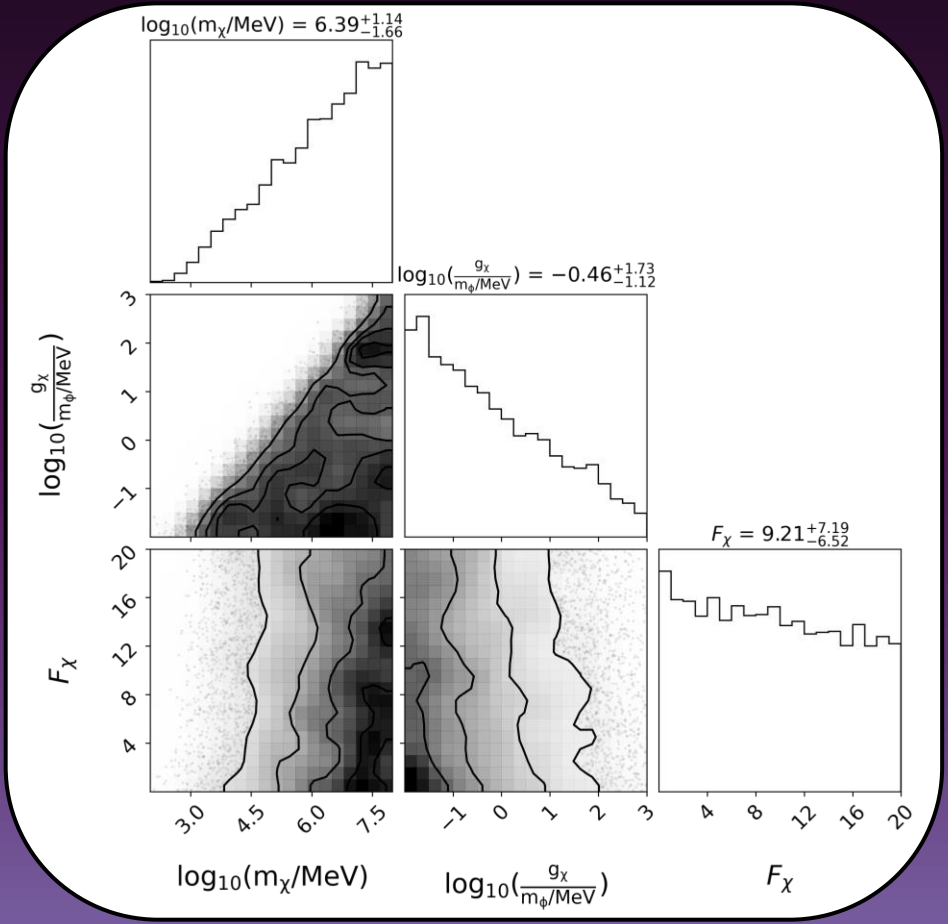
- $m_\chi \in [10^{-2}, 10^{8}]$ MeV [1,2]
- $\frac{g_\chi}{m_\phi/\mathrm{MeV}} \in [10^{-2}, 10^{3}]$ [3]
- $F_\chi \in [0,20]\%$ [4]

We sample uniformly in all three intervals and then eliminate any halo configurations.

Future



Future-X



1: Kourvaris & Tinyakov (2011), 2: Bramante et al. (2013), 3: Nelson et al. (2018), 4: Karkevandi et al. (2022)

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Halo Configurations

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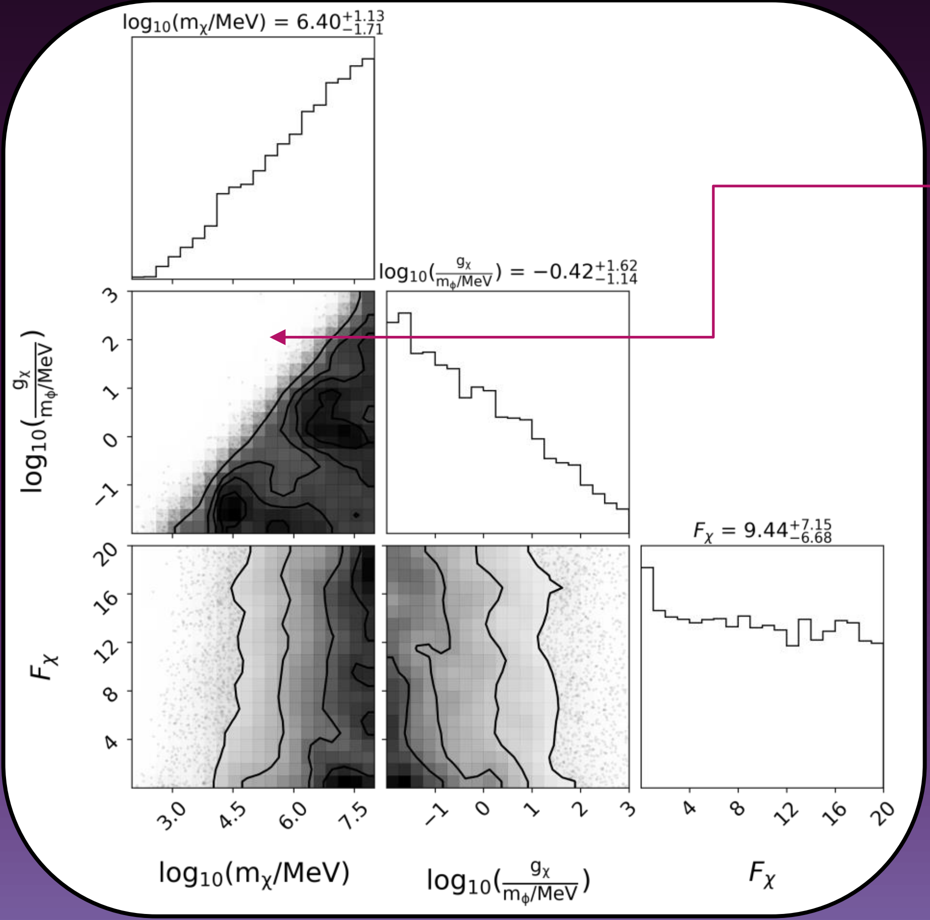

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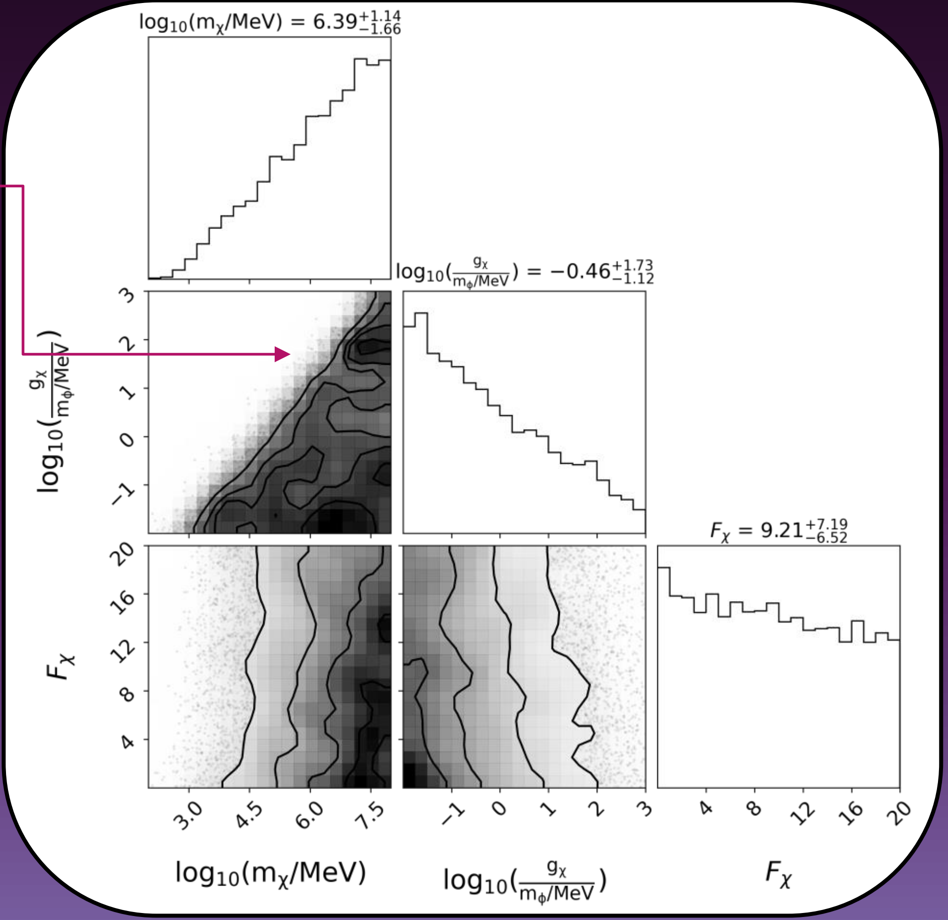

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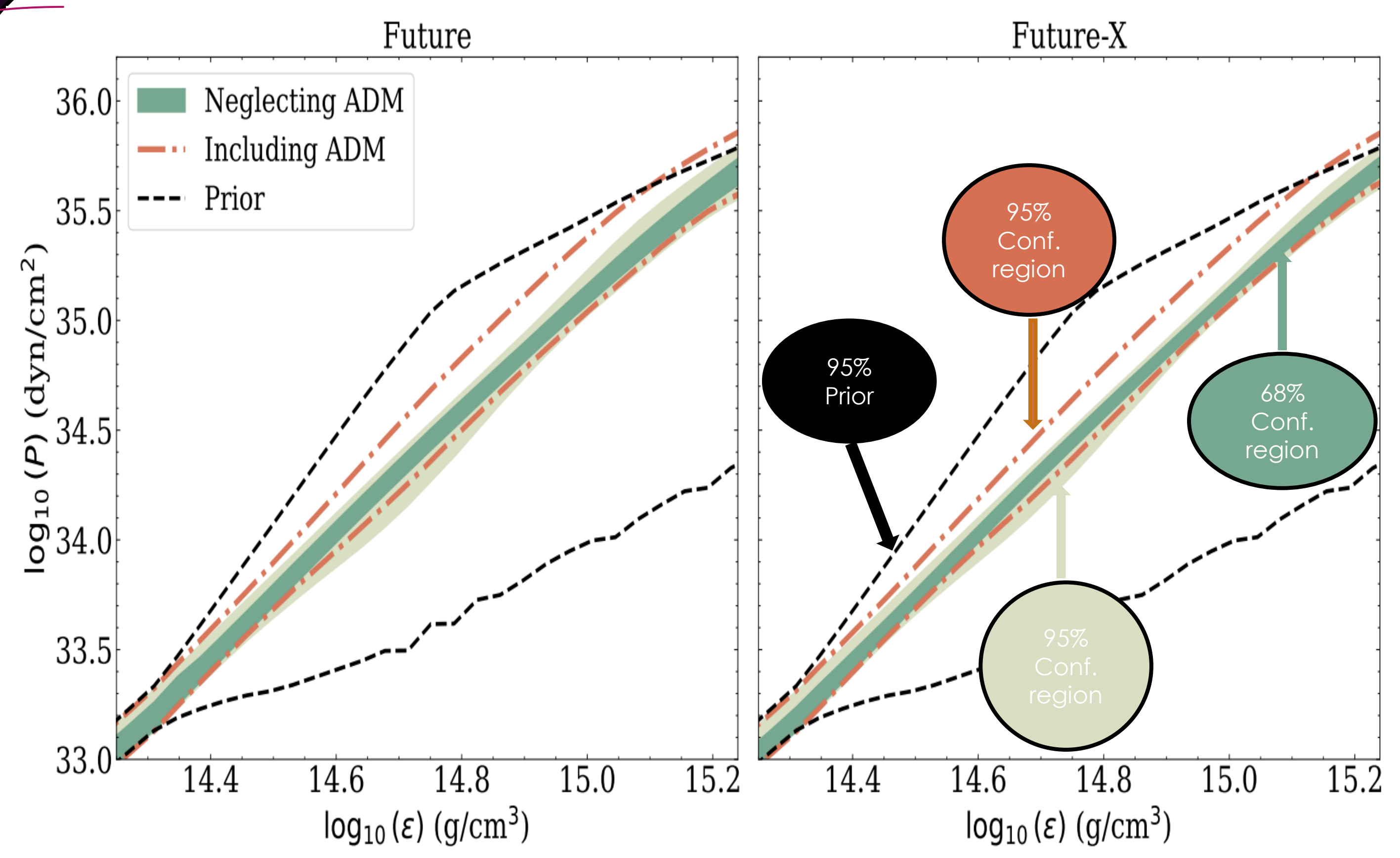
Future/ *Future-X*: Varying Baryonic EoS

- The 'Including ADM' band is noticeably wider than the 'Neglecting ADM' band.
- A stiffer baryonic EoS $\Longrightarrow$ posterior constraints from all NICER and STROBE-X sources can be relaxed if ADM is considered.
- *Future-X* can more tightly constrain the neutron star EoS than *Future*.

ADM Core Model



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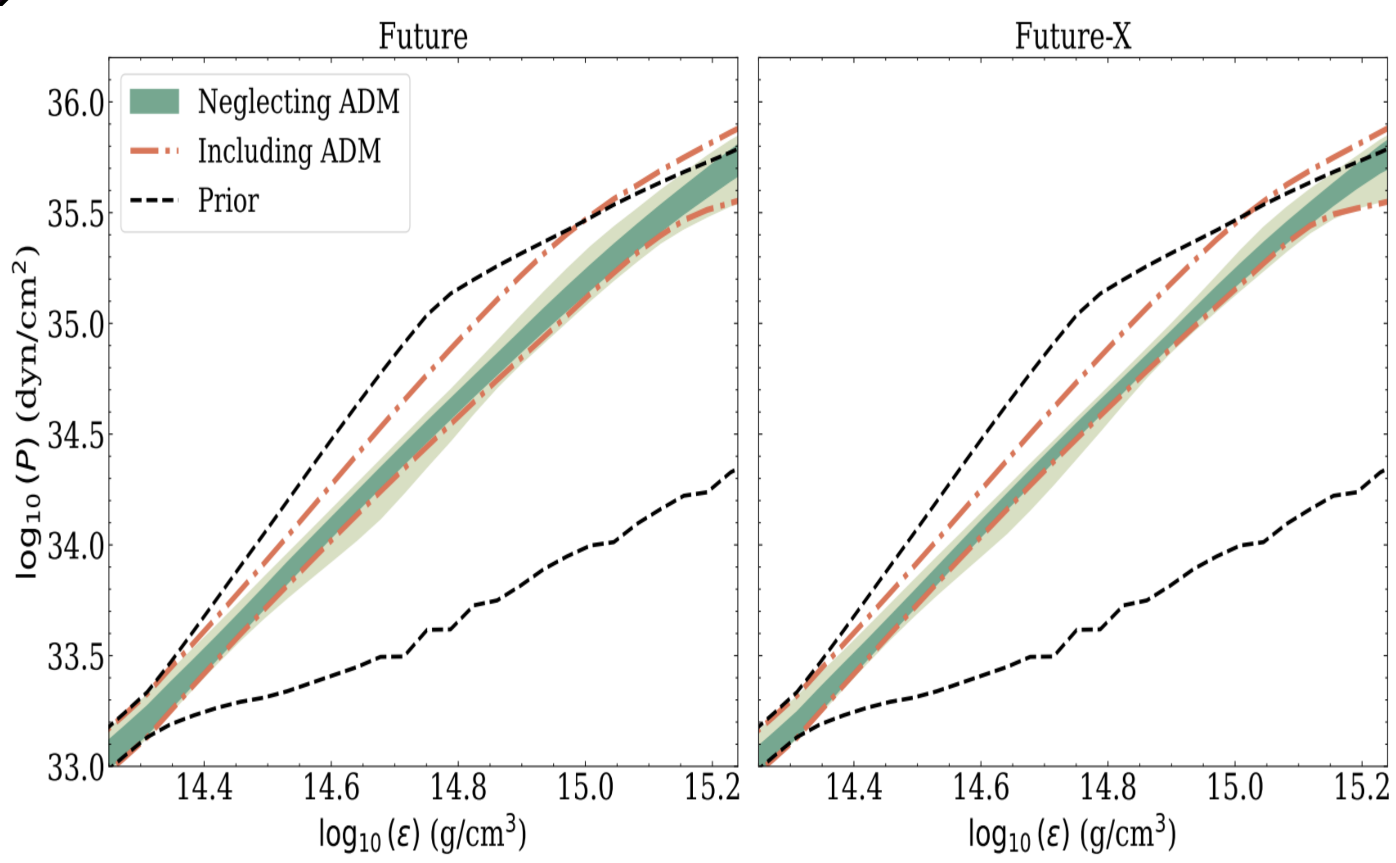

Future/ *Future-X*: Fixed Baryonic EoS

- The ratio of $\log_{10}\left(\frac{g_\chi}{m_\phi/\mathrm{MeV}}\right)$ and $\log_{10}(m_\chi/\mathrm{MeV})$ is constrained to a stripe.
- The stripe widens for "No ADM" model.
- g_χ / m_ϕ and m_χ are individually unconstrained.
- Gaussian-like shape of the 1-D F_χ posteriors $\Longrightarrow$ tight constraints on F_χ can be imposed.
- *Future-X* will be able to provide tighter constraints on F_χ than *Future*.

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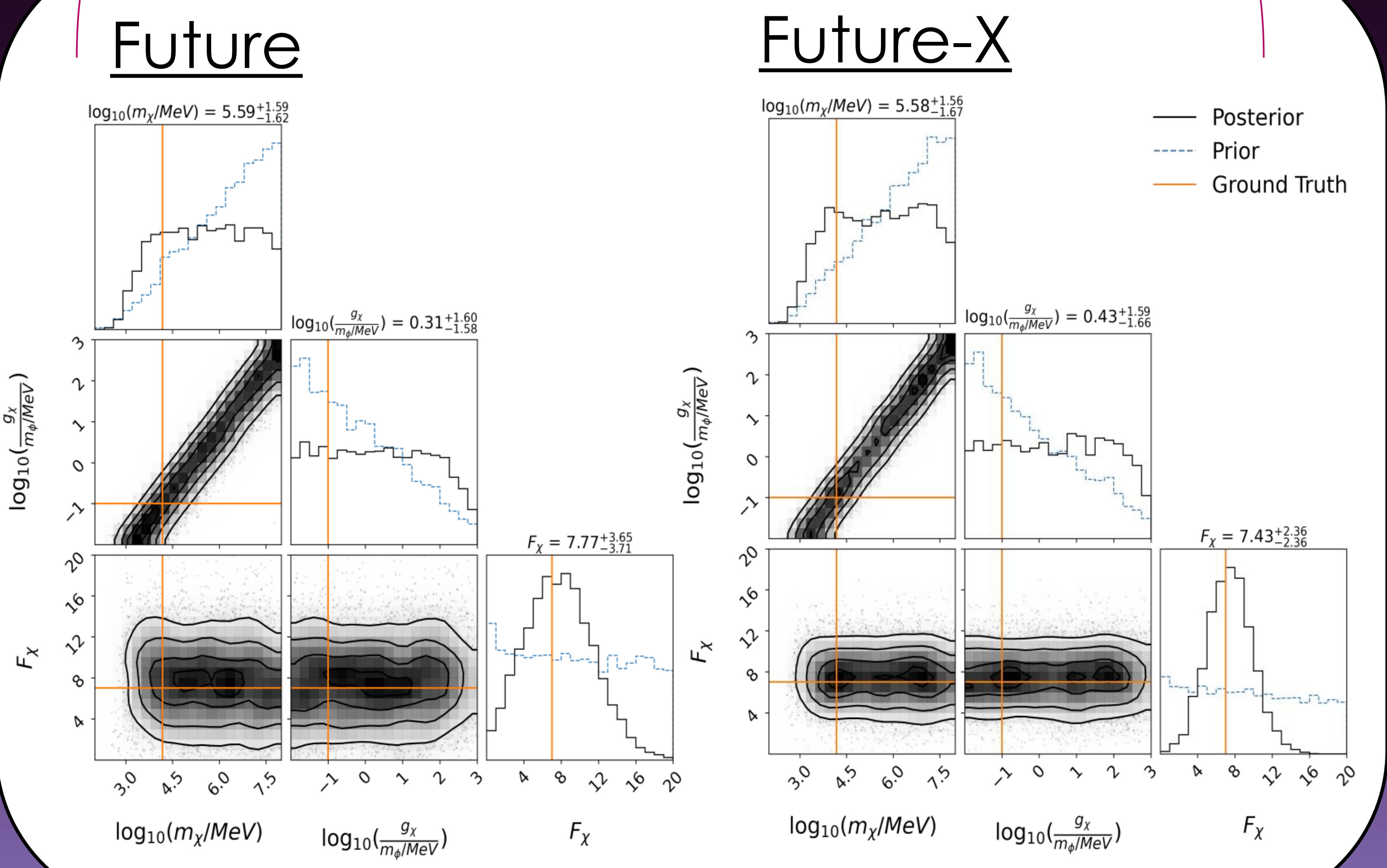

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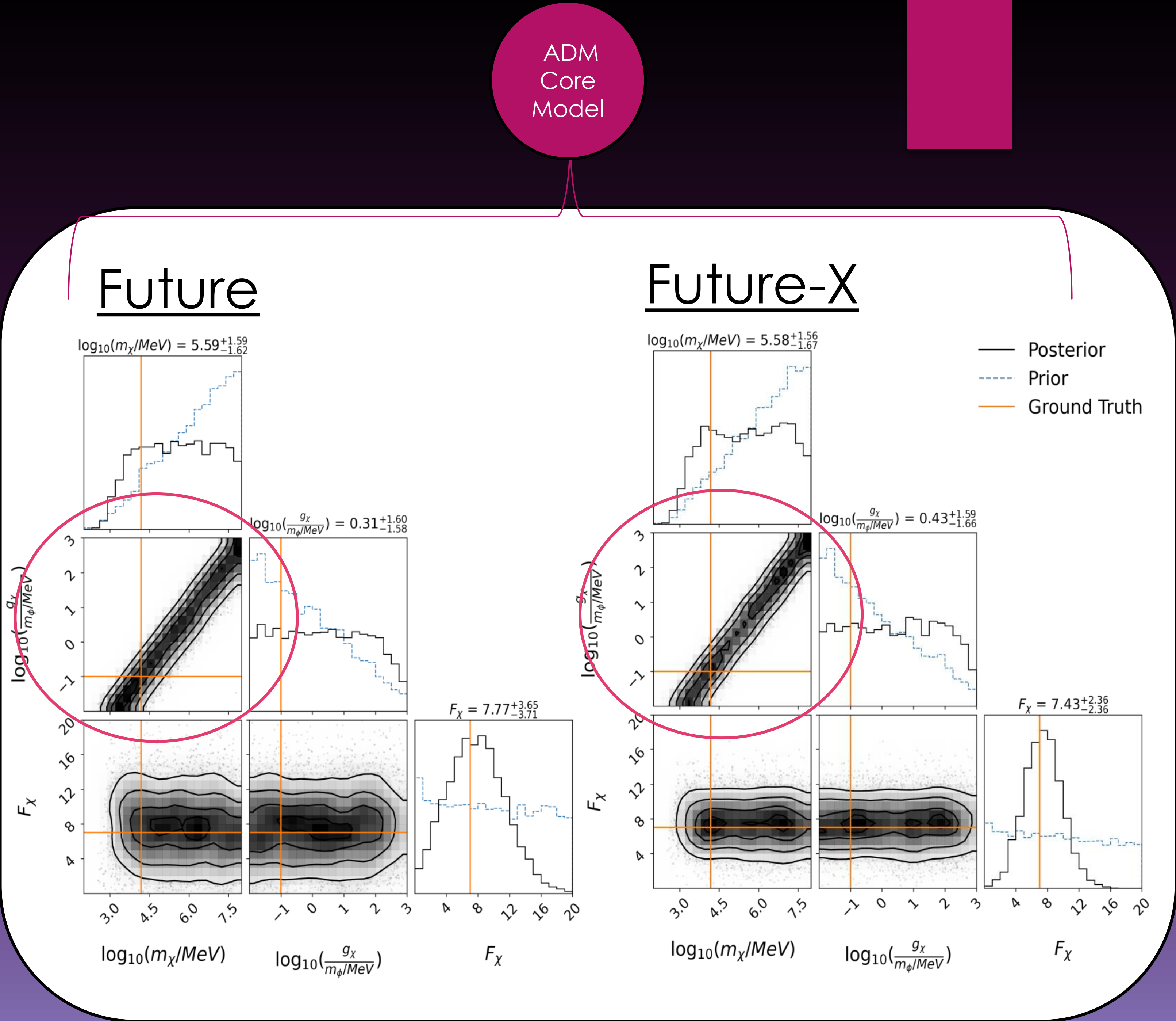

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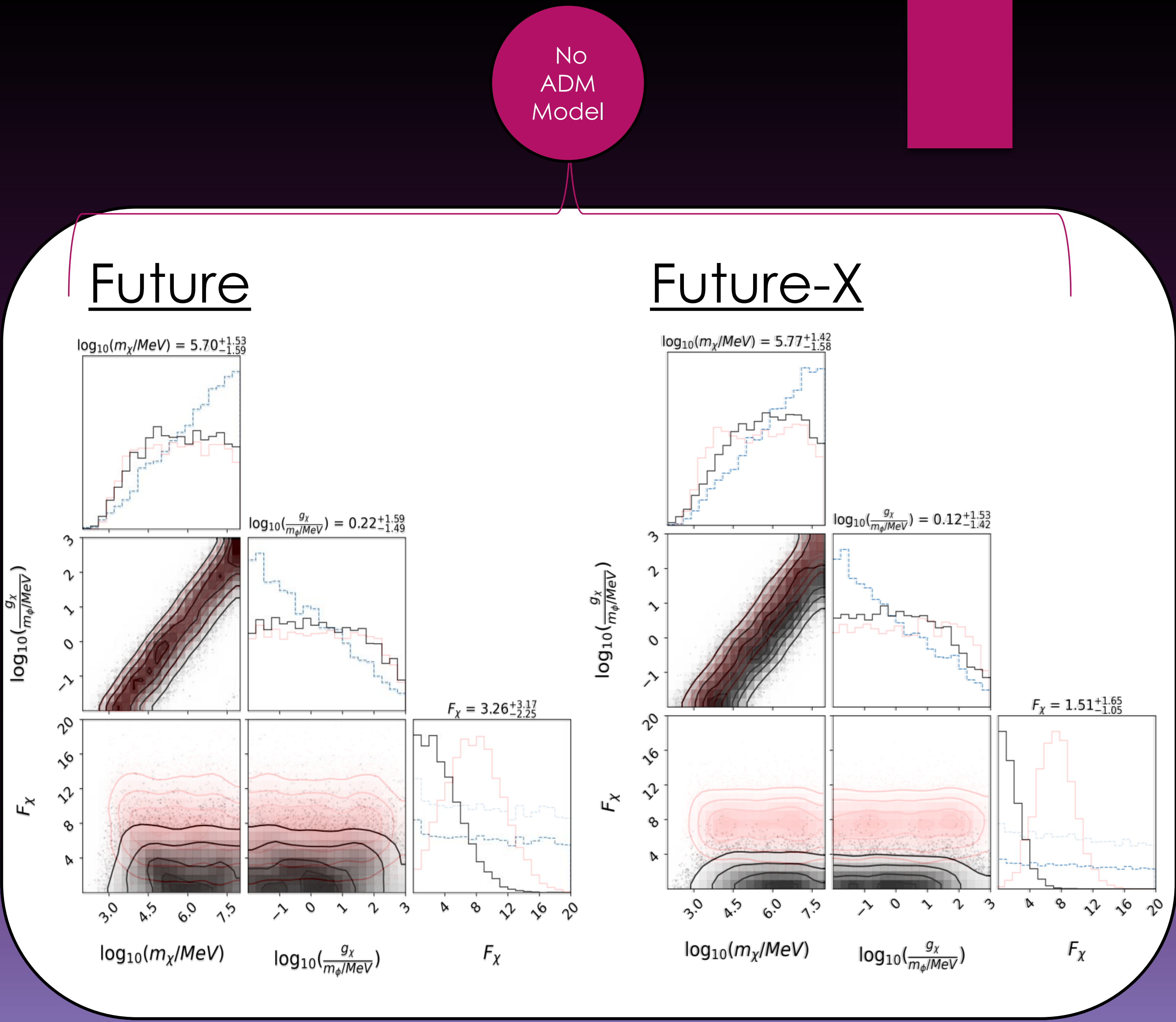
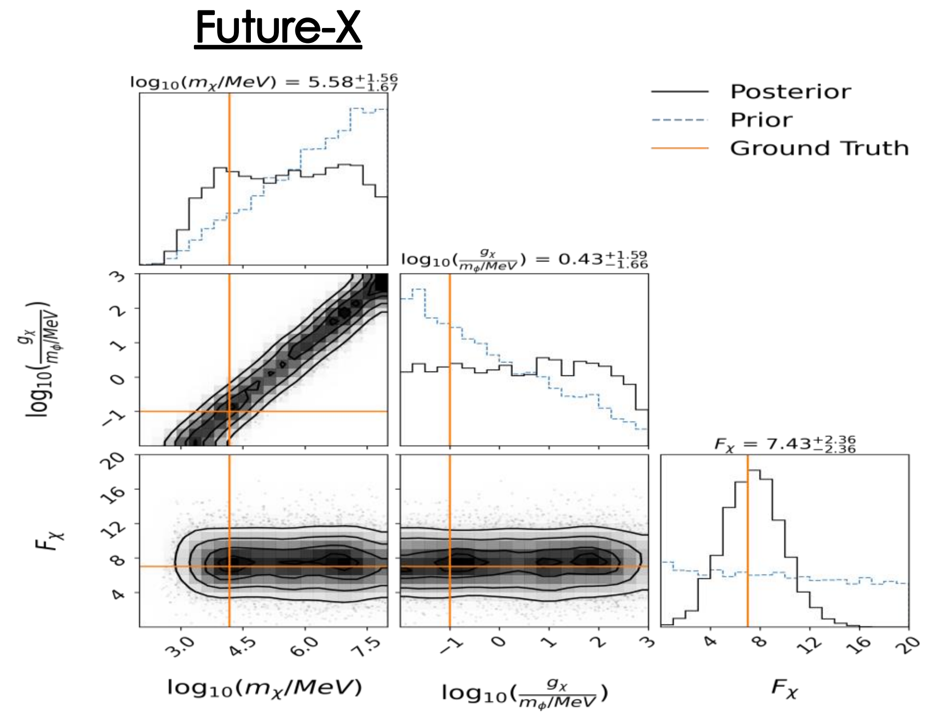
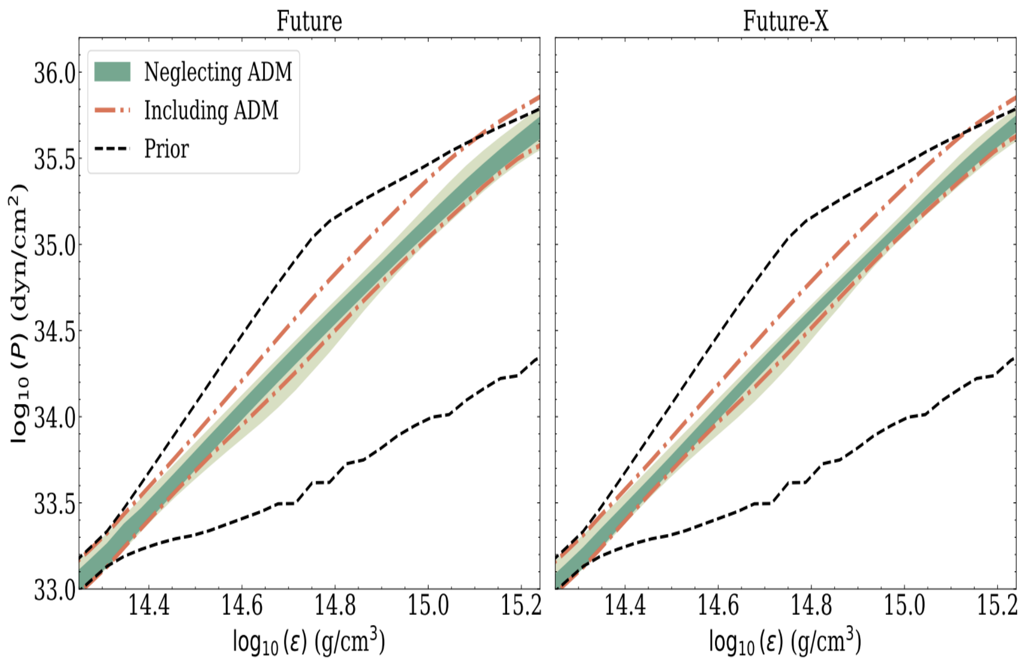


Takeaways

- The current uncertainties of the baryonic EoS are being underestimated because the possibility of ADM cores is not currently being accounted for.
- If the baryonic EoS is constrained independent of ADM, i.e., fixed, the ratio of $\log_{10}\left(\frac{g_\chi}{m_\phi/\mathrm{MeV}}\right)$ and $\log_{10}(m_\chi/\mathrm{MeV})$, and F_χ can be tightly constrained.
- We have shown the value in performing full inference runs on the ADM parameter space, rather than drawing conclusions only from the effects of ADM on the mass-radius relation.





Thank you!

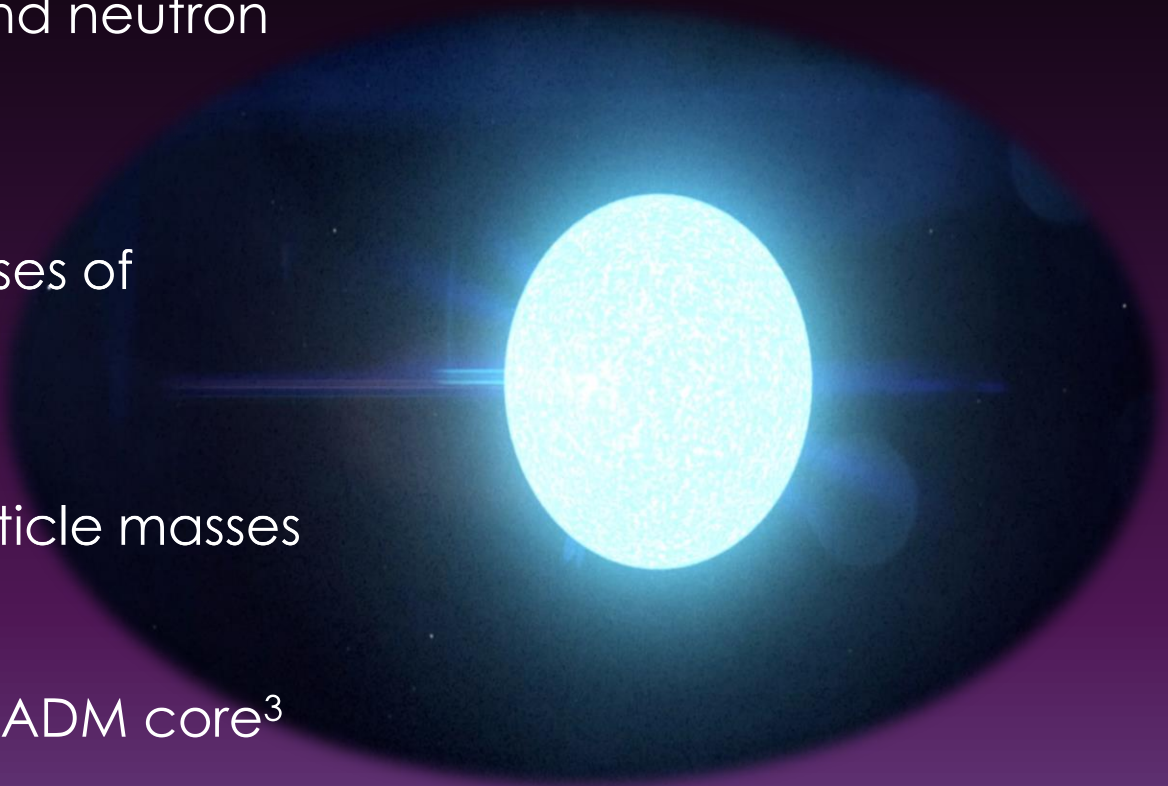
Extra Slides

Accumulation methods of ADM in neutron stars

- One possibility: neutron bremsstrahlung of ADM[1] and neutron conversion to scalar ADM[2]

- Both processes combined can produce ADM masses of $0.07\ \mathrm{M_{Ns}}$.

- To achieve high ADM fractions for higher ADM particle masses other possibilities must be considered:
  - Accretion of baryonic matter onto a pre-existing ADM core[3]
  - A neutron star passed through a local ADM over-density[3]
  - Absorption of an ADM star by baryonic matter[2]



1. Nelson et al. (2018) arXiv: 1803.03266
2. Ellis et al. (2018) arXiv: 1804.01418
3. Karkevandi et al. (2022) arXiv: 2109.03801

Future/ Future-X: Varying Baryonic EoS (extra slide)

- The PDF contours widen along the $\log_{10}\left(\frac{g_\chi}{m_\phi\ \mathrm{MeV}^{-1}}/(\mathrm{m}_\chi/\mathrm{MeV})\right)$ axis for low F_χ.

- If the actual F_χ in neutron stars is sufficiently large, the ratio of g_χ/m_ϕ and m_χ can be well constrained.

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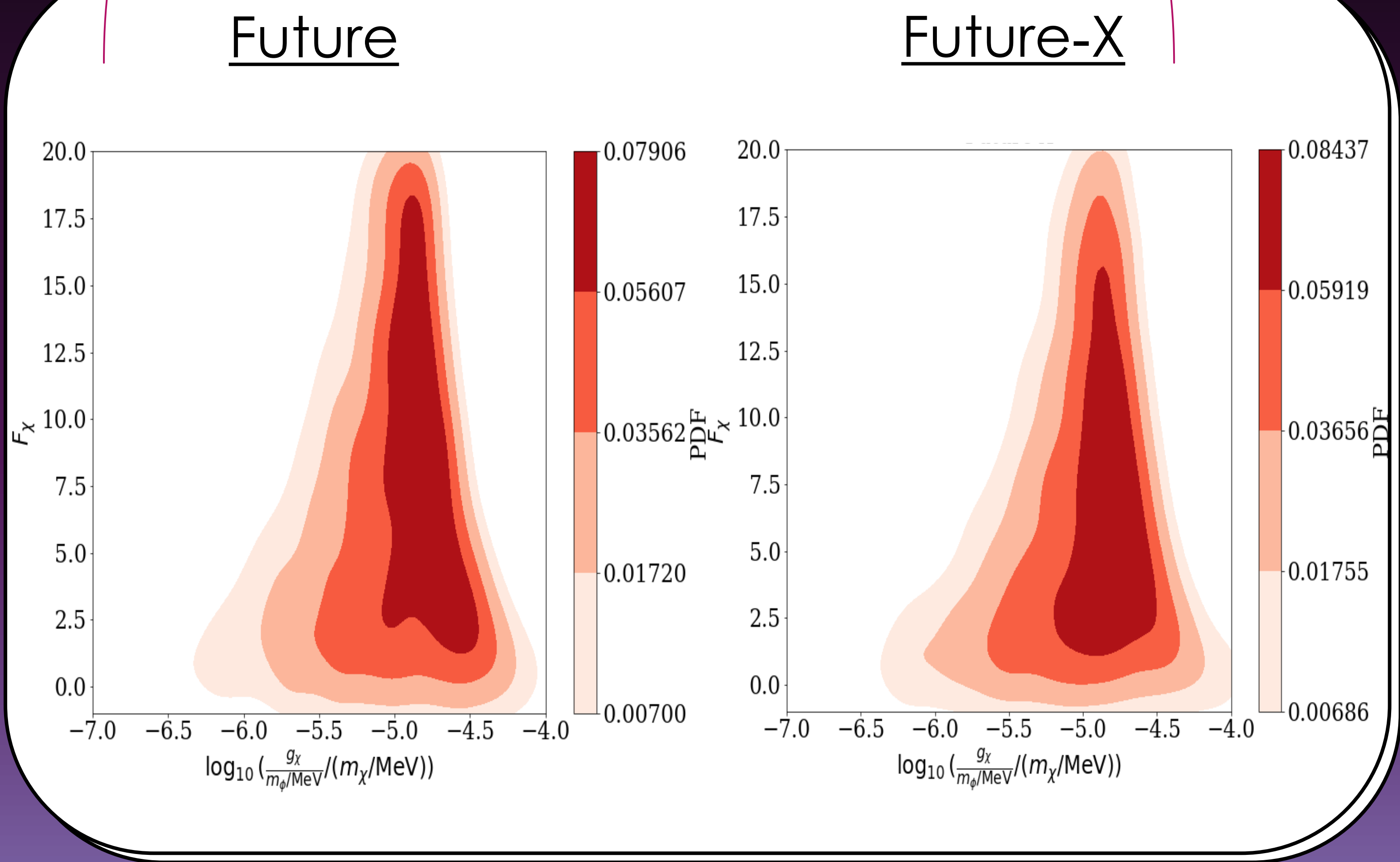

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No ADM Model