Cosmological profile likelihood constraints on dark matter scattering with protons

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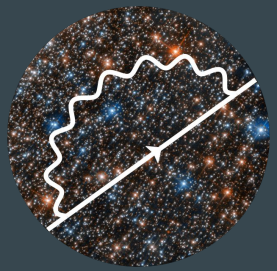
Collaborators: Tanvi Karwal, José Bernal, Kimberly Boddy



Texas TACOS 2024

The University of Texas at Austin
Department of Astronomy
College of Natural Sciences

Searching for hints of dark matter

Lambda Cold Dark Matter (ΛCDM)

- Cold, collisionless fluid
- Only interacts gravitationally

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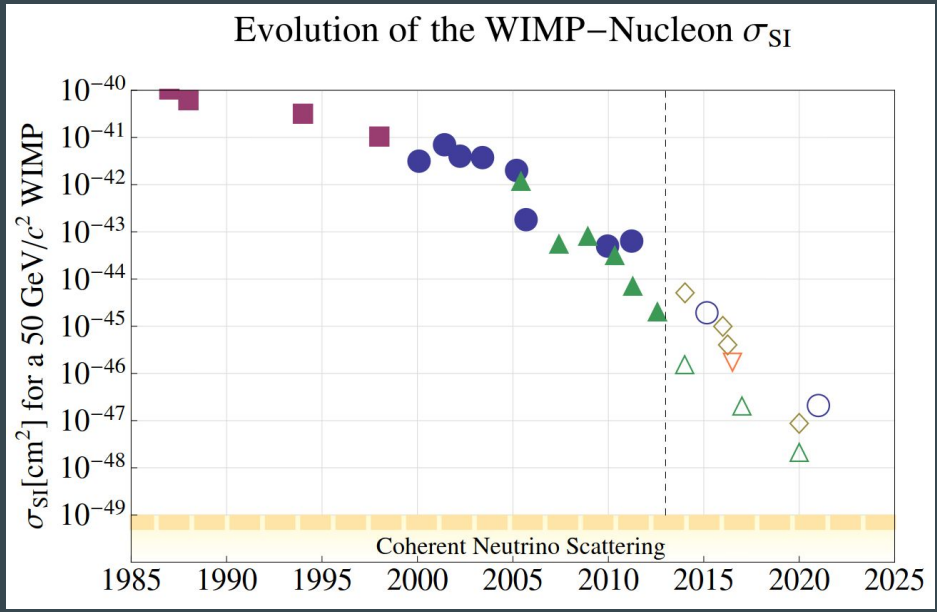

Snowmass CF1 Summary

Searching for hints of dark matter

Lambda Cold Dark Matter (ΛCDM)

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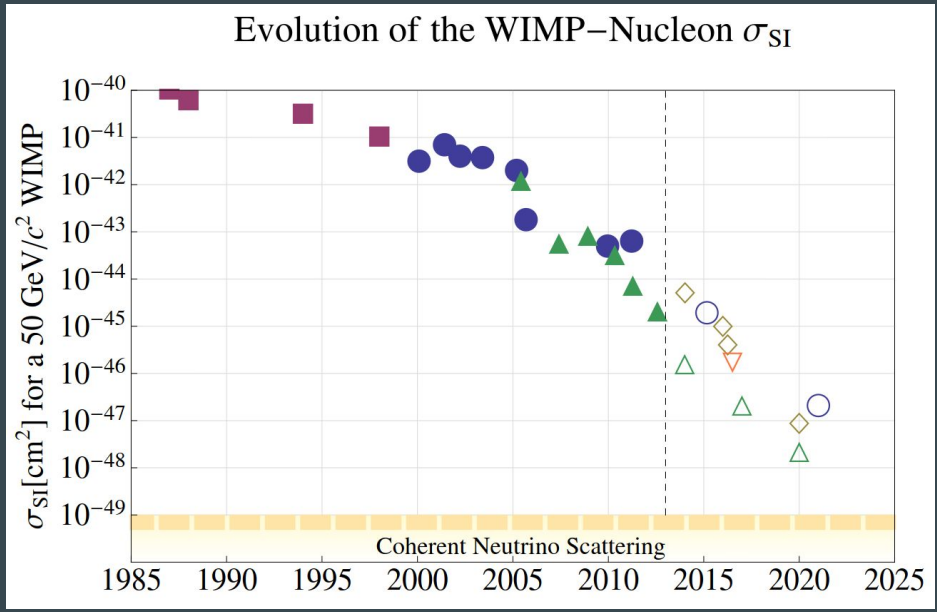
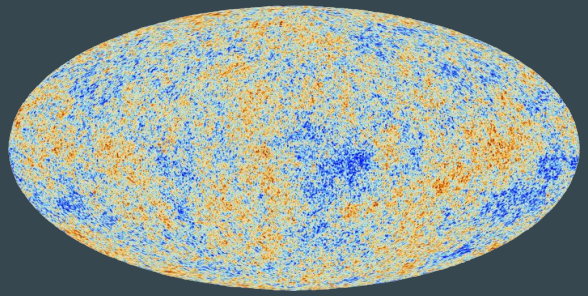
Expand Search:

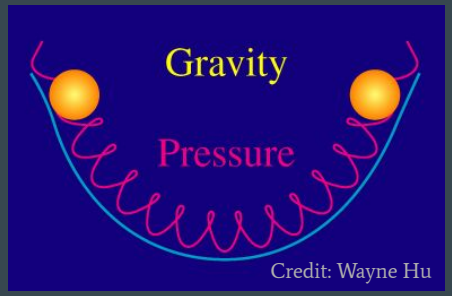
- Non-gravitational interactions
- Cosmological observations can probe a larger range of masses and interaction strengths



Snowmass CF1 Summary

Dark matter-baryon interactions





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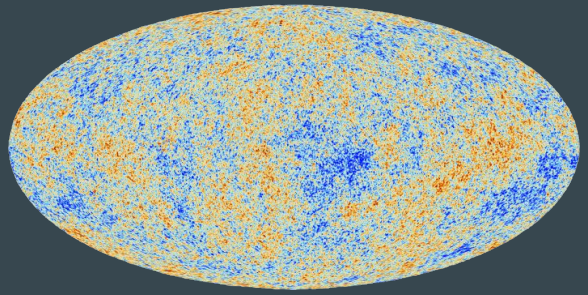

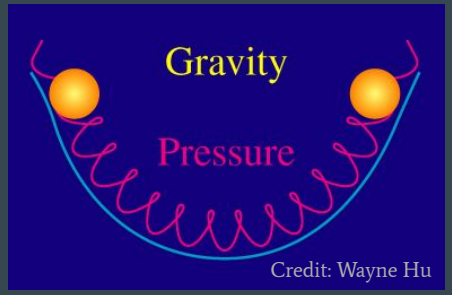

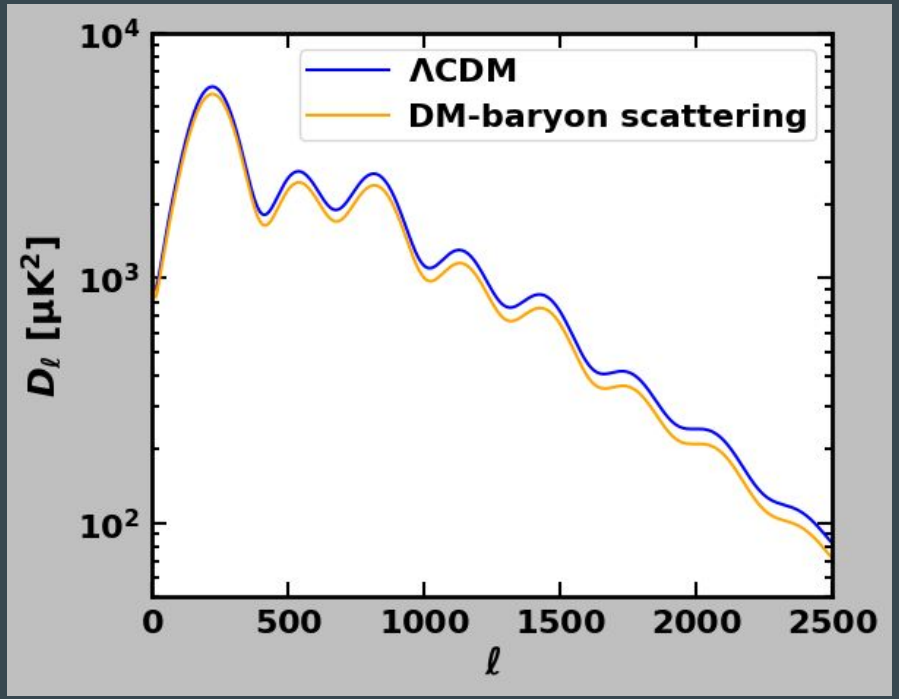

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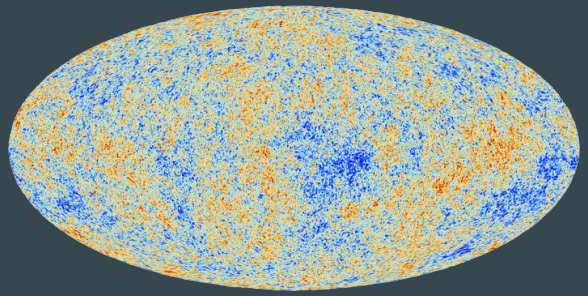
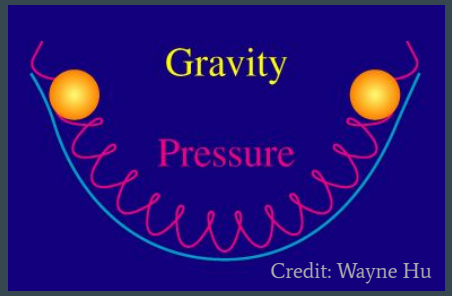
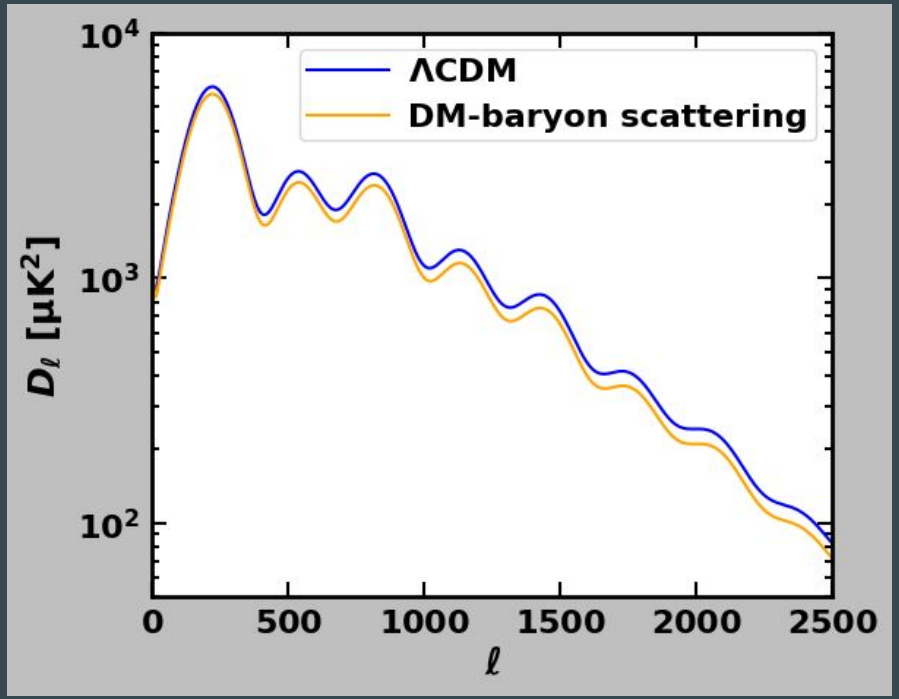




- Dampen CMB anisotropies
- Suppress the matter power spectrum on small scales



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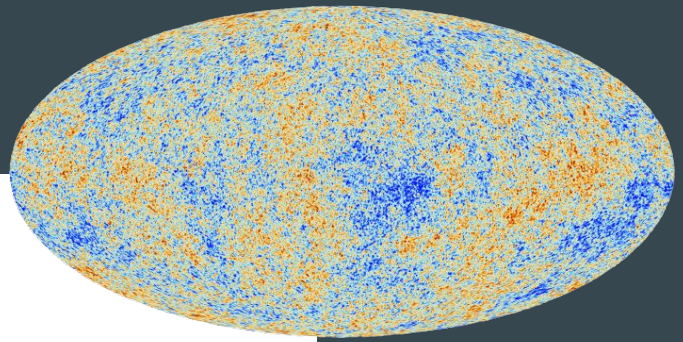

$$\dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2}, \quad \dot{\delta}_b = -\theta_b - \frac{\dot{h}}{2}$$

$$\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi(\theta_b - \theta_\chi)$$

$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_b^2 k^2 \delta_b + R_\gamma(\theta_\gamma - \theta_b) + \frac{\rho_\chi}{\rho_b} R_\chi(\theta_\chi - \theta_b)$$

$$R_{\chi p}^{(\mathrm{SI/SD})} = \mathcal{N}_0 a \rho_b (1 - Y_{\mathrm{He}}) \frac{\sigma_p^{(\mathrm{SI/SD})}}{m_\chi + m_p} \left(\frac{T_b}{m_p} + \frac{T_\chi}{m_\chi} \right)^{\frac{1}{2}}$$

$$\sigma_p^{(\mathrm{SI})} = \frac{\mu_{\chi p}^2}{m_v^4 \pi} \left[c_p^{(\mathrm{SI})} \right]^2$$

$$\dot{T}_\chi = -2\frac{\dot{a}}{a} T_\chi + 2R'_\chi (T_b - T_\chi)$$

$$R'^{(\mathrm{SI})}_\chi \equiv (\mu_{\chi p}/m_p) R^{(\mathrm{SI})}_{\chi p} + (\mu_{\chi \mathrm{He}}/m_{\mathrm{He}}) R^{(\mathrm{SI})}_{\chi \mathrm{He}}$$

Gluscevic & Boddy 2018

CMB constraints on dark matter scattering with protons

- Spin-independent
- Velocity-independent ($n = 0$)
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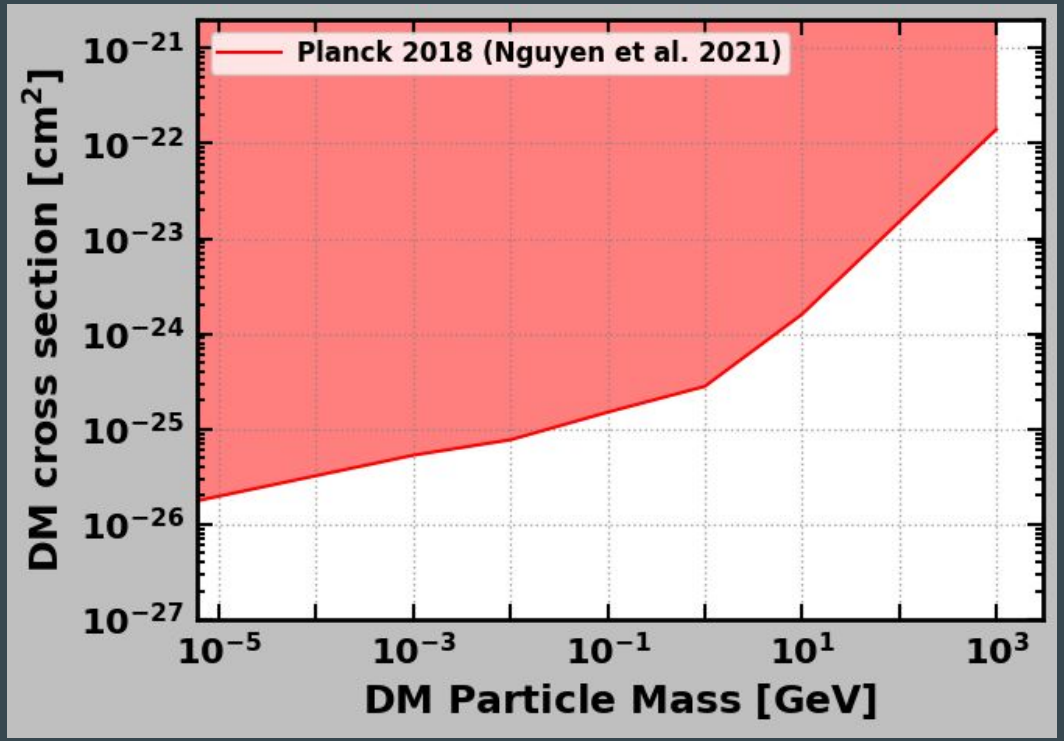

Bayesian statistics and prior volume effects

posterior distribution of model parameters given the data

$$\mathcal{P}(\boldsymbol{\theta}|d) \propto \underbrace{\Pi(\boldsymbol{\theta})}\underbrace{\mathcal{L}(d|\boldsymbol{\theta})}$$

prior probability distribution

data likelihood given model parameters

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Beyond ΛCDM model constraints may be influenced by prior volume effects

Bayesian vs. Frequentist statistics

Bayesian

- Posterior

posterior →

$$\mathcal{P}(\boldsymbol{\theta}|d) \propto \underbrace{\Pi(\boldsymbol{\theta})}_{\text{prior}}\underbrace{\mathcal{L}(d|\boldsymbol{\theta})}_{\text{likelihood}}$$

Frequentist

- Likelihood

profile likelihood →

$$\mathcal{L}(\theta_i) = \max \mathcal{L}(\boldsymbol{\theta}|\theta_i = \theta_i')$$

traces and maximizes likelihood
at each point in parameter space

Prior volume effects for Early Dark Energy

Cosmological parameterization:

- ϕ_i - initial value of the scalar field
- z_c - redshift when EDE density peaks
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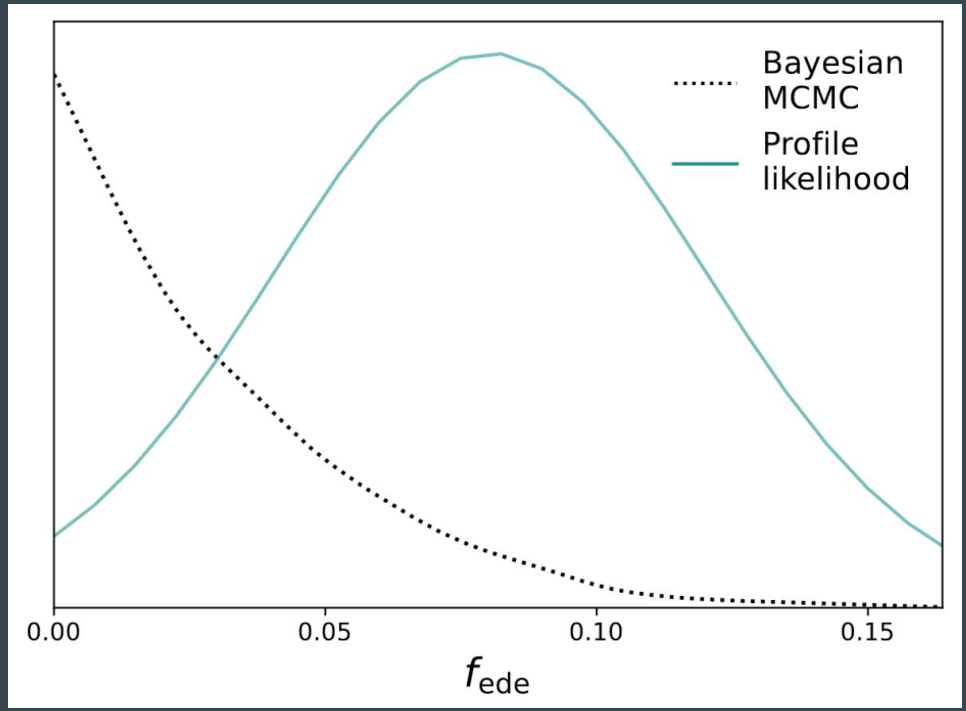
Bayesian posterior vs. likelihood profile:



Karwal et al. 2024

Procoli

- Python package for cosmological profile likelihoods
  - Modified version of CLASS (Gluscevic & Boddy 2018)
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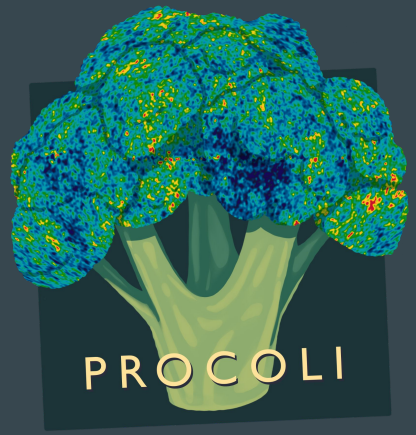

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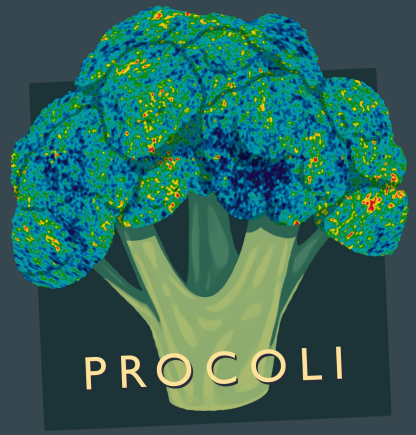

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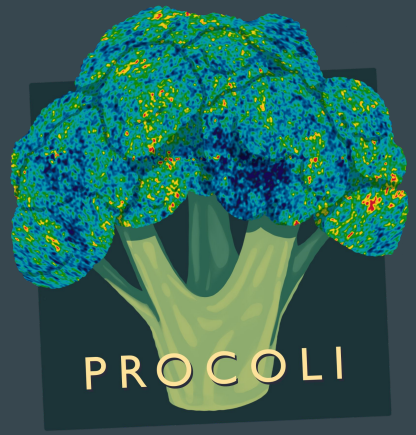

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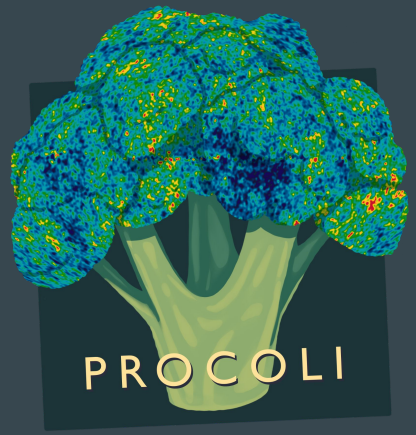

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$$m_\chi = 10 \text{ keV} - 1 \text{ TeV}$$

$$\sigma_\chi = 10^{-27} - 10^{-21} \text{ cm}^2$$

$$f_\chi = 1, 0.1, 0.01$$

Profile likelihoods of the cross section

- No preference for interactions
- Obtain upper limits

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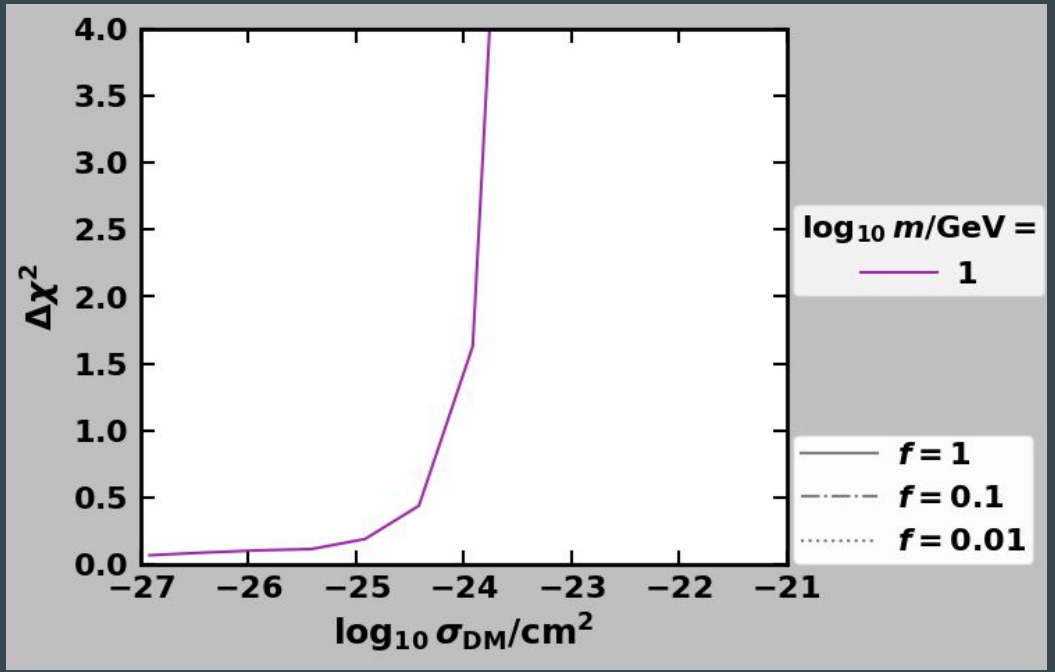

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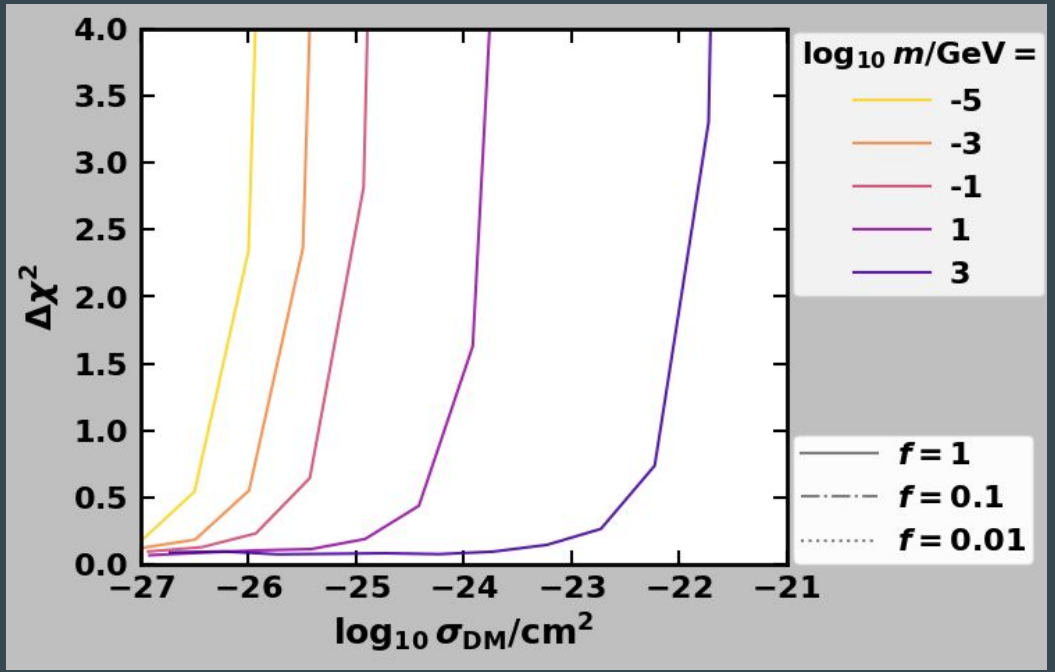

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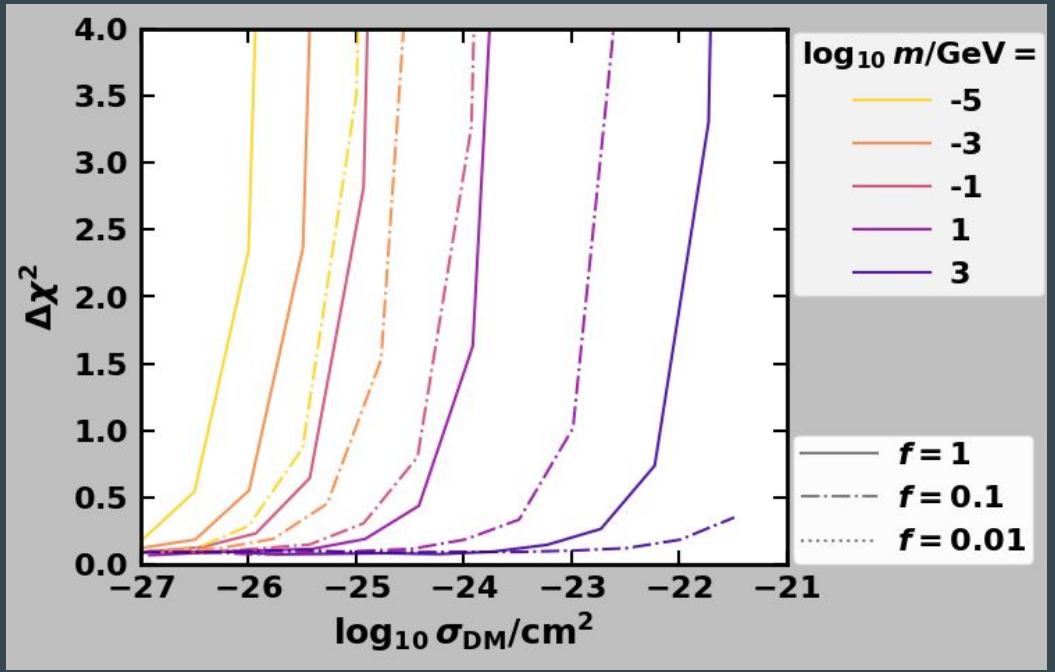

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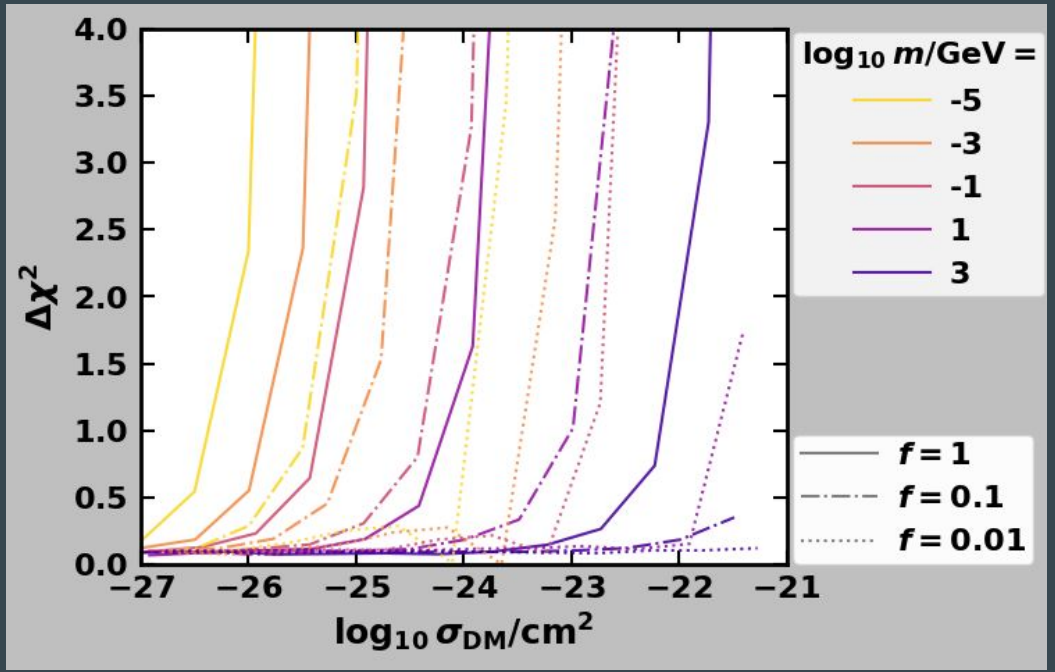
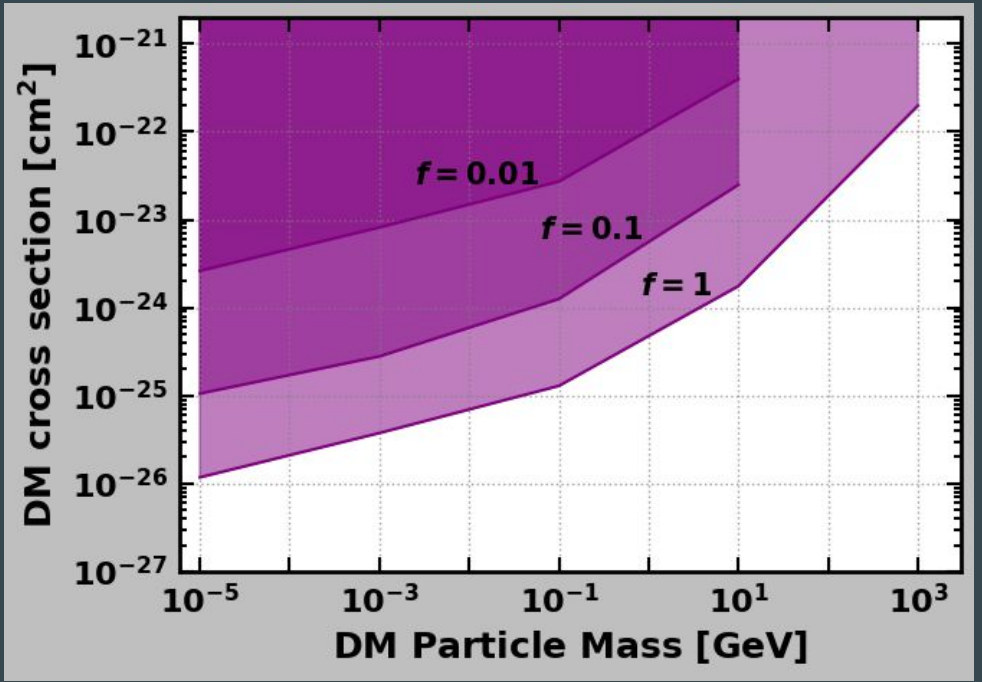


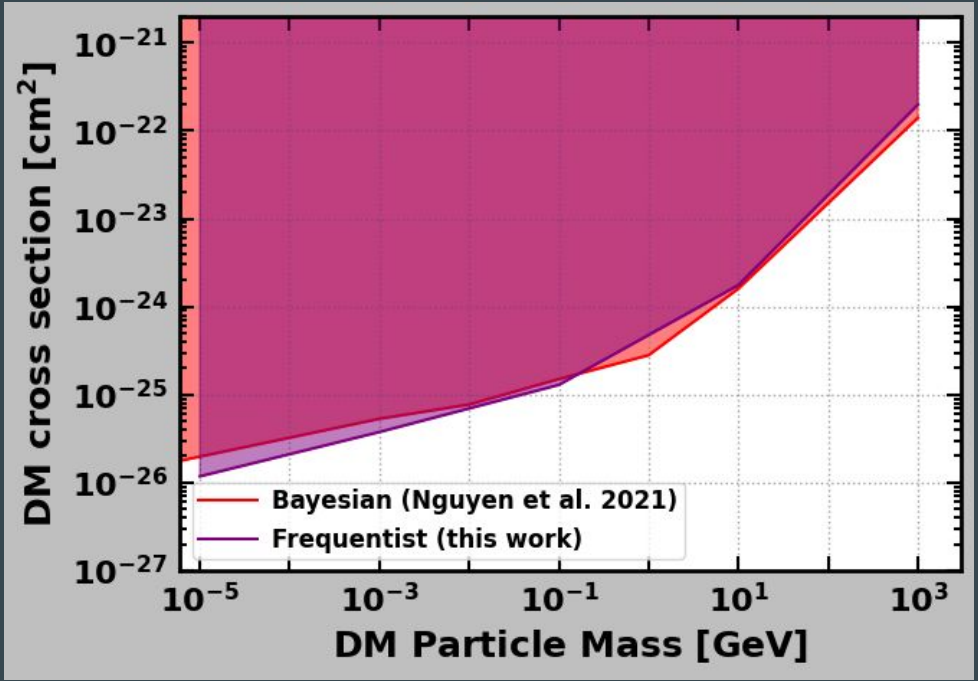
Excluded regions of parameter space

- Smaller fractions allow for larger cross sections
- These limits extend to arbitrarily large cross sections (direct detection limits have a detection ceiling)



Comparison to Bayesian result

- Frequentist limits agree with the Bayesian constraints
- This confirms that the results are not strongly affected by the choice of priors



Conclusions

- We used profile likelihoods to test dark matter scattering with protons
- We find no evidence of interactions
- Our upper limits are consistent with the Bayesian constraints
- The constraints on this model are not strongly affected by the choice of priors

Future work

- Next, I will consider velocity-dependent models

Velocity-dependent DM scattering with protons

Nguyen et al. 2021

(arXiv: 2107.12380)