Signatures of dark-matter sub-structure in axion direct detection experiments

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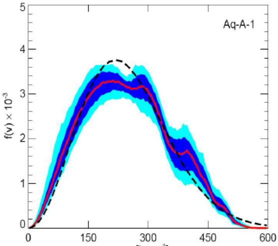
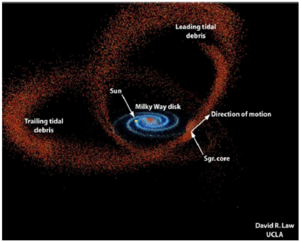
DARK MATTER SUBSTRUCTURE SCENARIOS

SHM

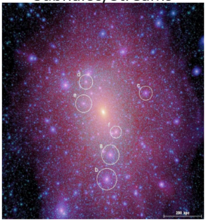


0809.0898

SGR

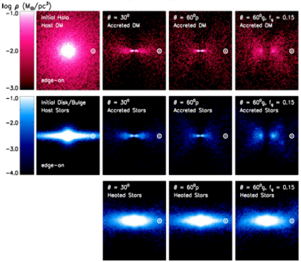


Subhalos/Streams



Vogelsberger

Dark Disk



0906.5348

THE AXION SIGNAL

- Measuring a signal proportional to local axion field:

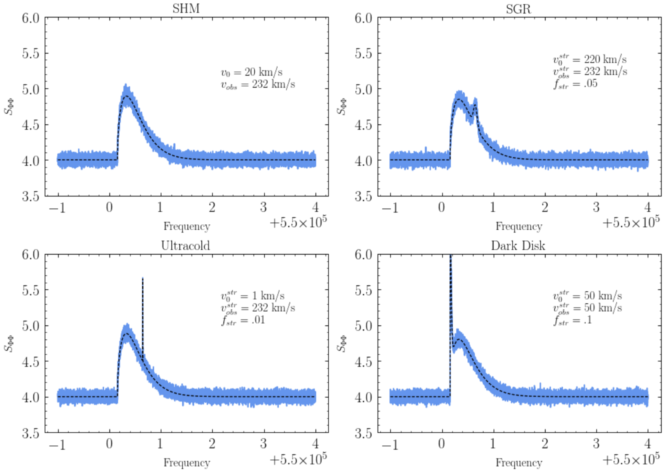
$$\Phi_{\text{Squid}} \sim \sum_{i}^{N_a} \cos\left[m_a\left(1+\frac{v_i^2}{2}\right)+\phi_i\right].$$

- v_i drawn from speed distribution $f(v)$
- For the analysis, use the Power Spectral Density $S_{\Phi\Phi}(f)$ following exponential distribution with

$$\lambda(f) \equiv \langle S_{\Phi\Phi}(f)\rangle = A\,\frac{\pi f(v)}{m_a v}\Bigg|_{v=\sqrt{2(2\pi f - m_a)/m_a}} + S_{\Phi 0}.$$

- $A \propto g_{a\gamma\gamma}^2$.

Some Signal Examples



THE ANALYSIS FRAMEWORK

- Given a model $\mathcal{M}$ and model parameters θ, compute the likelihood of observed $S_{\Phi\Phi}$

$$p(S_{\Phi\Phi}|\mathcal{M},\theta) = \prod_k \frac{1}{\lambda_k(\theta)} e^{-S_{\Phi\Phi}(k)/\lambda_k(\theta)}.$$

- Compute test statistic TS to compare the goodness of fit of models $\mathcal{M}_{\text{signal}}$ and $\mathcal{M}_{\text{null}}$

$$TS(S_{\Phi\Phi}|\mathcal{M}_{\text{null}},\mathcal{M}_{\text{signal}},\theta) = 2\log\frac{p(S_{\Phi\Phi}|\mathcal{M}_{\text{signal}},\theta)}{p(S_{\Phi\Phi}|\mathcal{M}_{\text{null}})}.$$

THE ASIMOV ANALYSIS

- With Asimov analysis, given a model, can compute the expected *TS*.

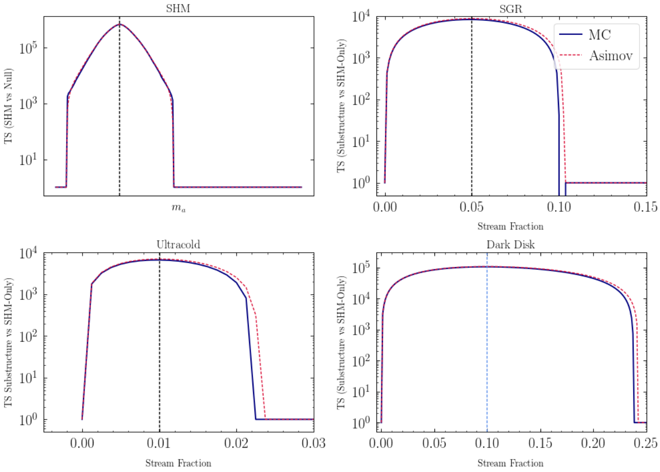
$$TS_{\max}^{\text{Asimov}} = 2 \times \sum \left[-\lambda_k(\theta) \left(\frac{1}{\lambda_k(\theta)} - \frac{1}{\lambda_k^{\text{null}}} \right) - \; log \left(\frac{\lambda_k(\theta)}{\lambda_k^{\text{null}}} \right) \right]$$

- For general boosted halo

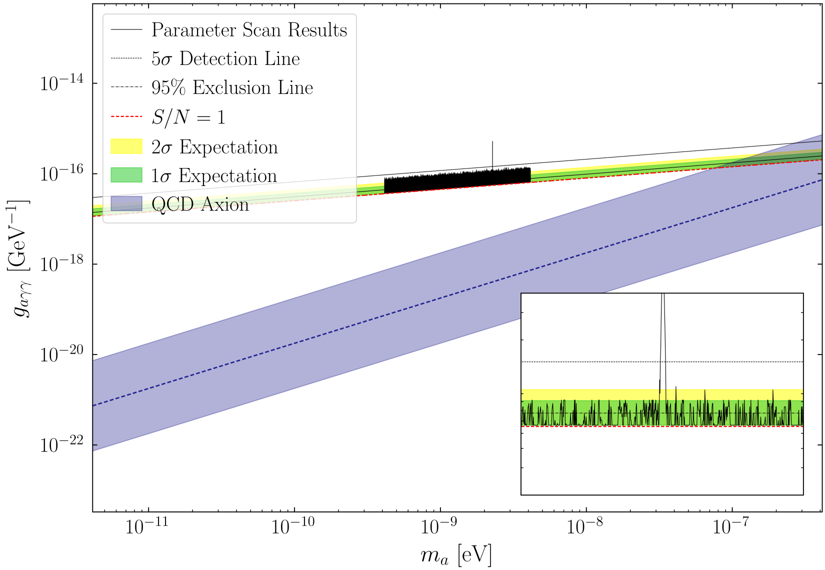
$$TS \sim -g^4 \frac{T\pi}{2m_a \text{PSD}_{\text{back}}^2} \int dv \frac{f(v)^2}{v}$$
$$\sim -g^4 \frac{T\pi}{2m_a \text{PSD}_{\text{back}}^2} \frac{\text{erf}\left(\frac{\sqrt{2}v_{\text{obs}}}{v_0}\right)}{\sqrt{2\pi} v_0 v_{\text{obs}}}$$

- Determines the expected significance → constraint/detection sensitivity

Monte Carlo and Asimov TS



AN MC EXAMPLE FOR AN SHM CONSTRAINT



PARAMETER ESTIMATION

- After a detection, extend the set of parameters we fit in with our log-likelihood scan.
- Can also estimate the error on parameter estimation by Asimov analysis
- Significantly improved sensitivity from resonant mode

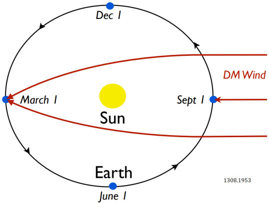
ANNUAL MODULATION

- Earth's motion about the sun causes the speed distribution to evolve over time

$$f_{\rm SHM}(v,t) = \frac{v}{\sqrt{\pi}v_0 v_{\rm obs}(t)} e^{-(v+v_{\rm obs}(t))^2/v_0^2}(e^{4vv_{\rm obs}(t)/v_0^2} - 1).$$

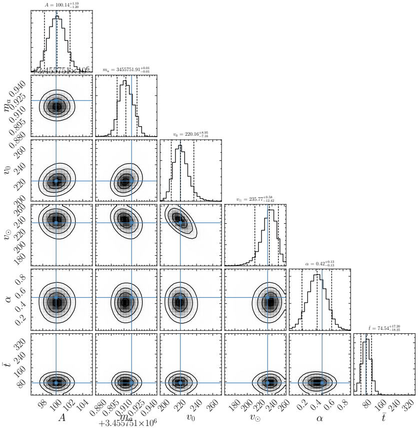
- Collect i "days" of PSD data, compute TS from the joint likelihood

$$p(S_{\Phi\Phi}|\mathcal{M},\theta) = \prod_i \prod_k \frac{1}{\lambda_k(i,\theta)} e^{-S^i_{\Phi\Phi}(k)/\lambda_k(i,\theta)}.$$



- Also consider gravitational focusing

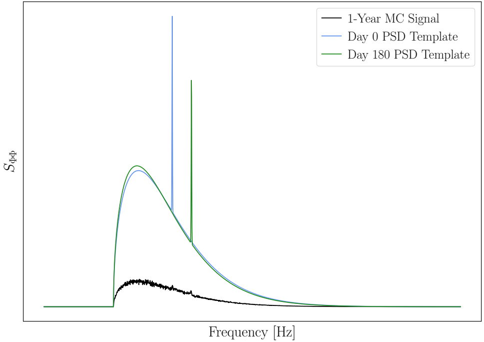
BULK HALO ANNUAL MODULATION



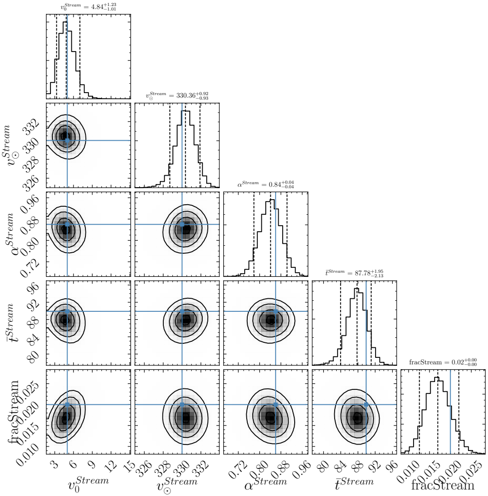
- $\alpha = \sqrt{(\hat{v}_\odot \cdot e_1)^2 + (\hat{v}_\odot \cdot e_2)^2}$
- $\bar{t} = \arctan\left(\frac{\hat{v}_\odot \cdot e_2}{\hat{v}_\odot \cdot e_1}\right)$

SUBSTRUCTURE ANNUAL MODULATION

- Need to look for modulation to detect coherent features in velocity distribution



STREAM ANNUAL MODULATION



CONCLUSION

- Now understand basic sensitivities of ABRACADABRA to axion DM scenarios.
- Tested, functioning analysis framework for axion detection.
- Ongoing work towards more complex analyses of ABRACADABRA data and its astrophysical relevance.