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

Joshua Foster
University of Michigan

August 10, 2017

17xx.xxxxx J.F., N. Rodd, B. Safdi
Dark Matter Substructure Scenarios

**SHM**

**SGR**

**Subhalos/Streams**

**Dark Disk**

- [Image of SHM distribution](#)
- [Image of SGR distribution](#)
- [Image of subhalos and streams](#)
- [Image of dark disk simulations](#)
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

\[ \lambda(f) \equiv \langle S_{\Phi\Phi}(f) \rangle = A \frac{\pi f(v)}{m_{a} v} \bigg|_{v=\sqrt{2(2\pi f - m_{a})/m_{a}}} + S_{\Phi0}. \]

- \( A \propto g_{\bar{a}\gamma\gamma}^2. \)
**Some Signal Examples**

**SHM**

- $v_{th} = 20 \text{ km/s}$
- $v_{obs} = 232 \text{ km/s}$

**SGR**

- $v_{th} = 220 \text{ km/s}$
- $v_{obs} = 232 \text{ km/s}$
- $f_{str} = .05$

**Ultracold**

- $v_{th} = 1 \text{ km/s}$
- $v_{obs} = 232 \text{ km/s}$
- $f_{str} = .01$

**Dark Disk**

- $v_{th} = 50 \text{ km/s}$
- $v_{obs} = 50 \text{ km/s}$
- $f_{str} = .1$
THE ANALYSIS FRAMEWORK

▶ Given a model $\mathcal{M}$ and model parameters $\theta$, 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 $TS$.

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

- For general boosted halo

$$TS \sim -g^4 \frac{T \pi}{2ma \text{PSD}_{\text{back}}^2} \int dv f(v)^2 \frac{v}{v}$$

$$\sim -g^4 \frac{T \pi}{2ma \text{PSD}_{\text{back}}^2} \frac{\text{erf} \left( \frac{\sqrt{2}v_{\text{obs}}}{v_0} \right)}{\sqrt{2\pi v_0 v_{\text{obs}}}}$$

- 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

\[
f_{\text{SHM}}(v, t) = \frac{v}{\sqrt{\pi v_0 v_{\text{obs}}(t)}} e^{-(v+v_{\text{obs}}(t))^2/v_0^2} \left(e^{4vv_{\text{obs}}(t)/v_0^2} - 1\right).
\]

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

\[
p(S_{\Phi \Phi} | M, \theta) = \prod_i \prod_k \frac{1}{\lambda_k(i, \theta)} e^{-S_{\Phi \Phi}^i / \lambda_k(i, \theta)}.
\]

- 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**

- $v_{\text{Stream}} = 4.84 + 1.23 - 1.01$
- $v_{\text{Stream}} \odot v_{\text{Stream}} = \ldots$
- $\alpha_{\text{Stream}} = 0.84 + 0.04 - 0.04$
- $\bar{t}_{\text{Stream}} = 87.78 + 1.96 - 2.13$
- $\text{frac}_{\text{Stream}} = 0.02 + 0.00 - 0.00$
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.