Dark Matter Substructure and Axion Astronomy

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Axions as the Dark Matter

- QCD axion introduced as a solution to the strong CP problem

\[ \mathcal{L}_{\text{QCD}} \supset \left( \bar{\theta} - \frac{a}{f_a} \right) \frac{g^2}{32\pi^2} \text{Tr} G_{\mu\nu} \tilde{G}^{\mu\nu} \]

- Axion-like particles motivated by UV theories
- Viable DM candidate, rich phenomenology
- Generic photon coupling

\[ \mathcal{L}_{\text{EM}} \supset g a_{\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \]
A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus

• Ampere’s law modified by axions

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} - g_{a\gamma\gamma} \left( \mathbf{E} \times \nabla a - \mathbf{B} \frac{\partial a}{\partial t} \right)$$

• Time-varying axions induces magnetic flux

• Broadband and Resonant readout modes

• Protoype built – data and analysis soon
Axion Signal at Direct Detectors

• Experiments measure axion field up to some scaling

\[ \Phi(t) = \sqrt{A} \sum_{i}^{N_{a}} \cos \left[ m_{a} \left( 1 + \frac{v_{i}^{2}}{2} \right) t + \phi_{i} \right] \]

• Calculable power spectral density
  • exponential distribution at each frequency

\[ \langle S_{\phi \phi}(f) \rangle = A \frac{\pi f(v)}{m_{a} v} + S_{\phi 0} \]
Likelihood Analysis Framework

- Compute the likelihood of observed data assuming model and parameters

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

\[ \lambda_k(\theta) = \langle S_{\Phi\Phi}(f | M, \theta) \rangle \]

- Test Statistic (TS) as a goodness-of-fit test

\[ TS = 2 \log \frac{p(S_{\Phi\Phi} | M_{\text{signal}}, \hat{\theta})}{p(S_{\Phi\Phi} | M_{\text{null}}, \hat{\theta})} \]
Signal Analysis Example

Injected Signal Recovery

- 5σ Detection
- 95% Upper Limit
- 1/2σ containment
- Monte Carlo Data

$g_{\eta\gamma} \times 10^{17}$ [1/GeV]

$(\omega - m_{a}^{\text{inj}}) \times 10^{14}$ [eV]

Axion Mass

$m_{a}^{\text{inj}} = 10^{-8}$ eV
Annual Modulation

• Lab velocity varies over the year
  • ± 30 km/s
• Gravitational focusing by sun
• Apparent time-dependent speed distribution
DM Substructure

• Local substructure contributes to local speed distribution
• Small dispersion
• Significant annual modulation
Time-Dependent Data Analysis
Signal Analysis Example
Signal Analysis Example

SHM Signal Verification

Stream Reconstruction
Current Status

• Working, well-tested analysis framework

• ABRACADABRA results soon

• How can we help you?
Backup Slides
Substructure-Enhanced Sensitivity

The graph shows the collection time reduction factor as a function of the fraction of local Dark Matter in the stream. Three different cases are illustrated:

- $v_0^\text{str} = 10 \text{ km/s}$ (blue line)
- $v_0^\text{str} = 1 \text{ km/s}$ (green line)
- $v_0^\text{str} = 0.1 \text{ km/s}$ (red line)

The y-axis represents the collection time reduction factor on a logarithmic scale, while the x-axis represents the fraction of local Dark Matter in the stream.