Axion Comagnetometry

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Princeton University
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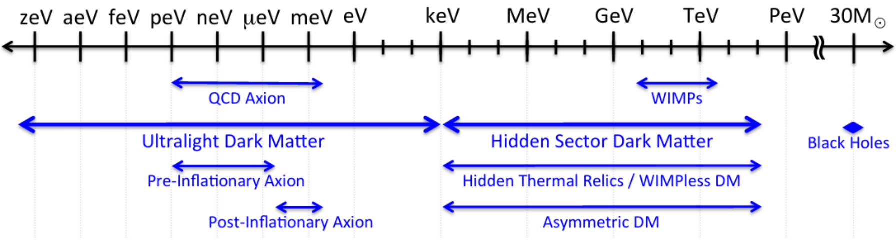
work(s) in progress
with J. Lee, M. Lisanti, M. Romalis, and W. Terrano

PRINCETON UNIVERSITY

Ultralight Dark Matter



US Cosmic Visions (1707.04591)

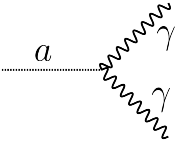
- The range of possible masses for dark matter is huge!
  - If a fermion: $m \gtrsim 10^2$ eV Tremaine, Gunn (1979)
  - If a boson: $m \gtrsim 10^{-22} - 10^{-20}$ eV Hu, Barkana, Gruzinov (astro-ph/0003365)
- As $m \to$ "ultralight", the dark matter can be treated as a classical field

$$\frac{\rho_{\rm DM}}{m_a}\left(\frac{2\pi}{m_a}\right)^3 \gg 1 \quad \Longrightarrow \quad m_a \ll {\rm eV}$$

Ultralight Axions

- Theoretically motivated:
  - any (pseudo-) Nambu-Goldstone boson of a global symmetry
  - QCD axion: $m_a \sim \frac{m_\pi f_\pi}{f_a} \gtrsim 10^{-12}$ eV

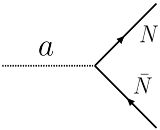
    Peccei, Quinn (1977); Dine, Fischler, Srednicki (1981); ...
  - generic in string theory Svrček, Witten (hep-th/0605206); Arvanitaki+ (0905.4720)
- Pseudoscalar couplings:



$$\mathcal{L}_{\text{eff}} \supset \frac{1}{4} g_{a\gamma\gamma} a F \tilde{F} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

- classical E&M techniques

  Sikivie (1983)

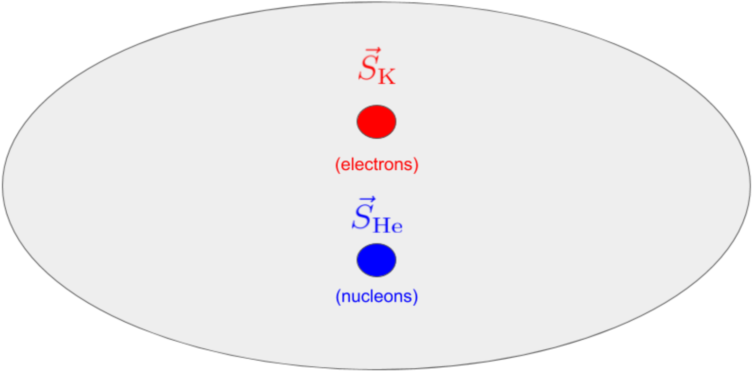


$$\mathcal{L}_{\text{eff}} \supset g_{aNN} \partial_\mu a \bar{N} \gamma^5 \gamma^\mu N$$
$$\supset g_{aNN} \vec{\nabla} a \cdot \vec{S}_N$$

- NMR and AMO techniques

Moody, Wilczek (1984); Graham, Rajendran (1306.6088)

Axion Direct Detection Example: Comagnetometers



Kornack, Romalis (2002); Kornack (PhD Thesis); Vasilakis (PhD Thesis); Bloch+ (1907.03767)

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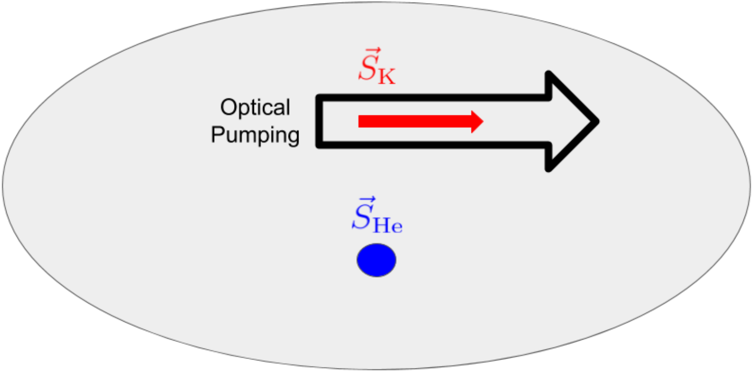

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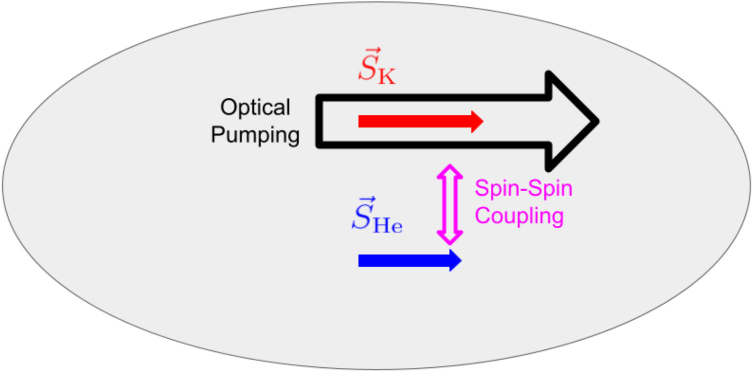

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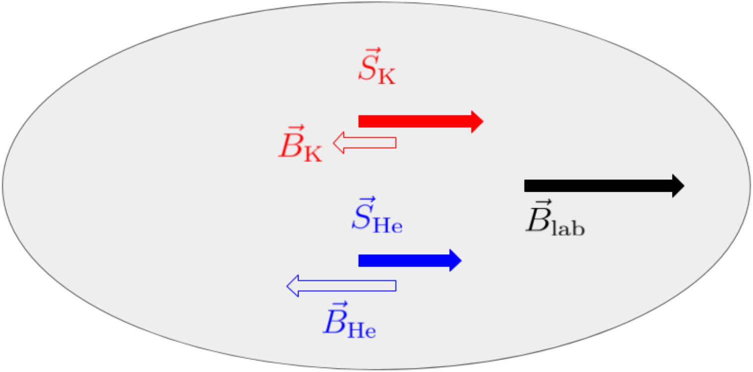

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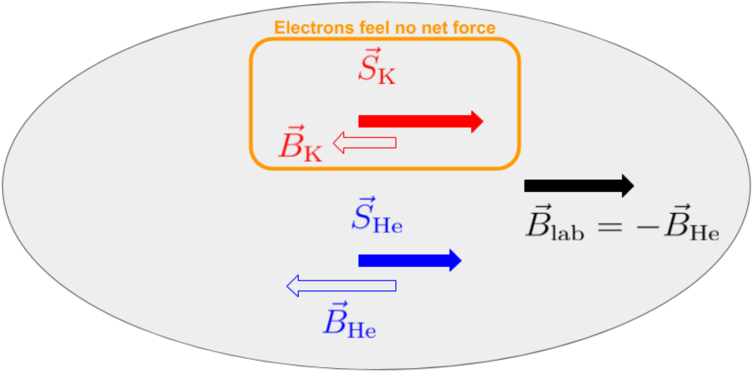

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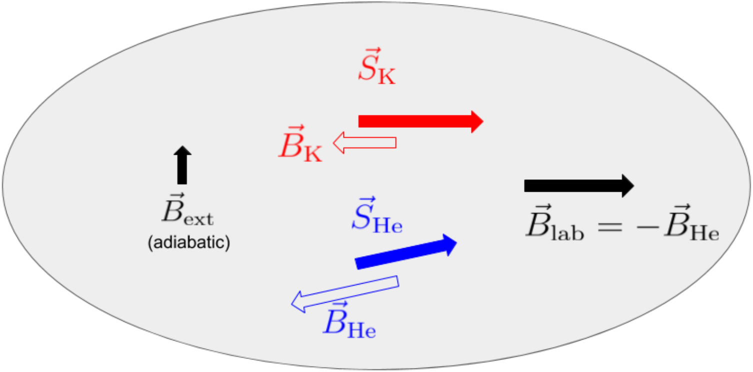

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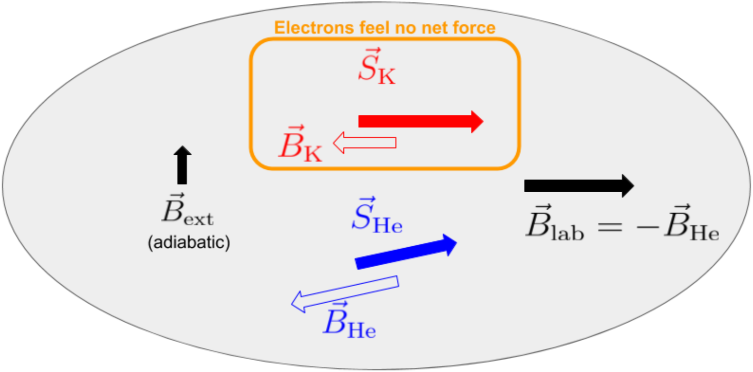

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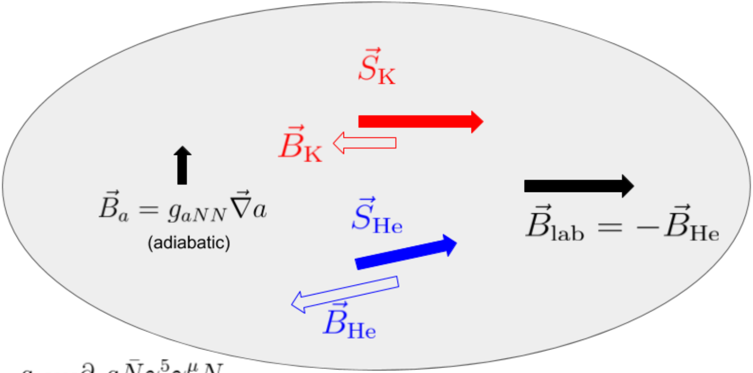

$$\mathcal{L} \supset -g_{aNN}\partial_\mu a\bar{N}\gamma^5\gamma^\mu N$$

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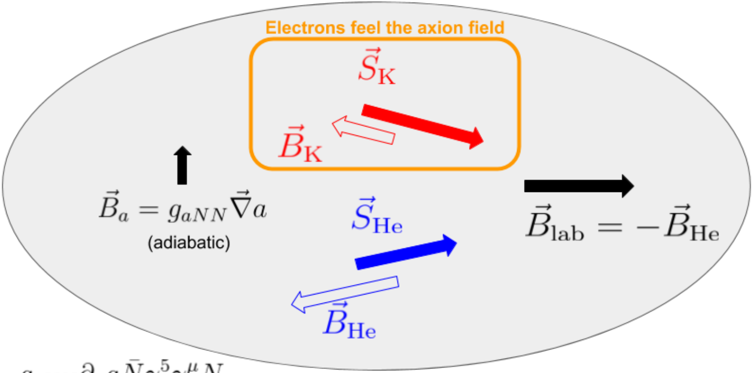

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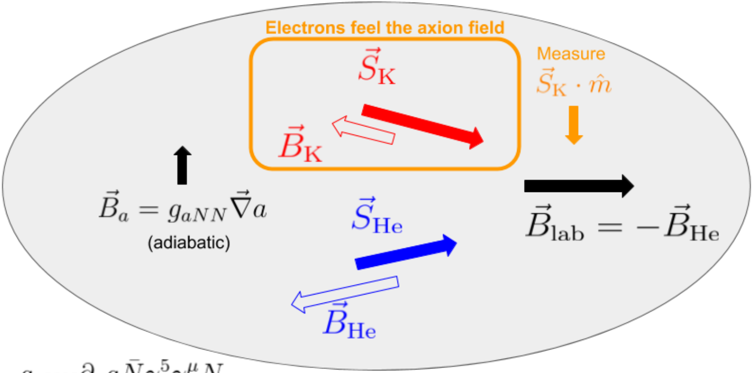
$$\text{Observable} \propto g_{\text{aNN}} \vec{\nabla} a \cdot \hat{m}$$



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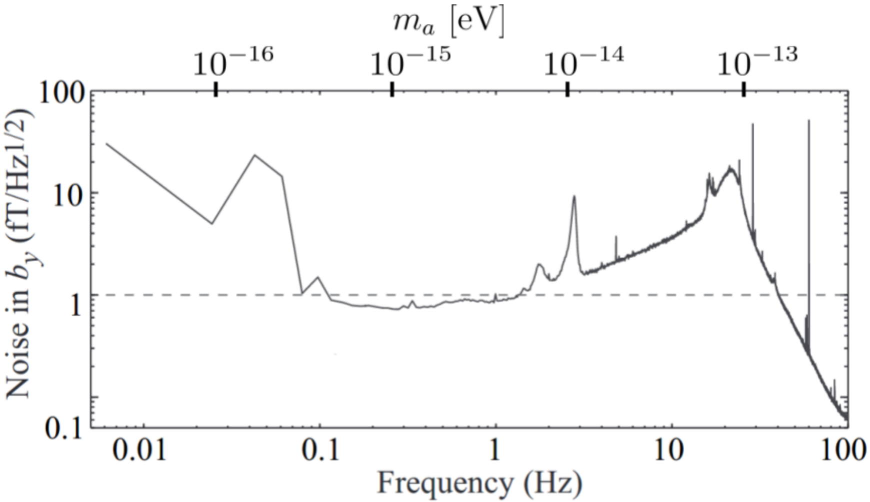
Kornack, Romalis (2002); Kornack (PhD Thesis); Vasilakis (PhD Thesis); Bloch+ (1907.03767)

The Princeton Comagnetometer (c. 2008)

~ 40 days of data $\implies$ $\sim 10^{-18}$ T sensitivity ($g_{\mathrm{aNN}} \sim 10^{-10}\ \mathrm{GeV}^{-1}$)



Vasilakis+ (0809.4700); Vasilakis (PhD Thesis); Bloch+ (1907.03767)

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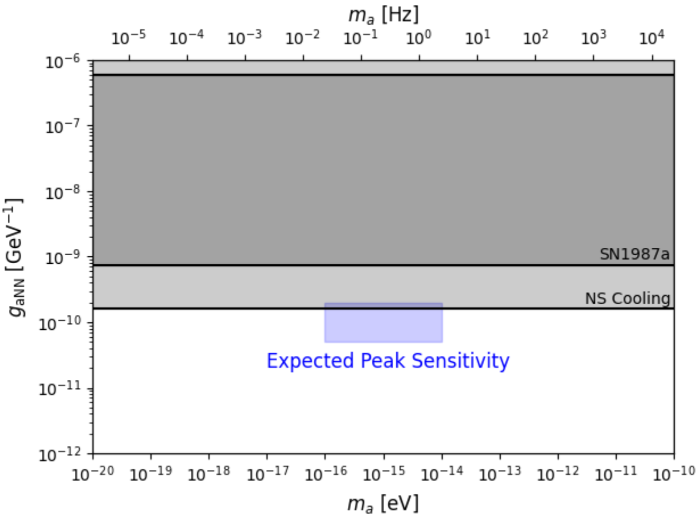


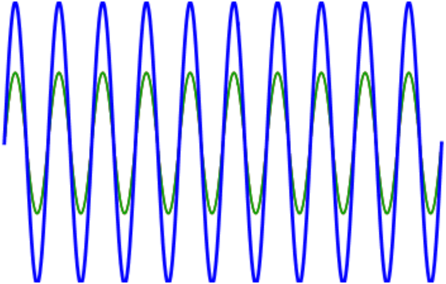
Vasilakis+ (0809.4700); Vasilakis (PhD Thesis); Bloch+ (1907.03767)

The Classical Axion Field

- For a single mode with velocity v:

$$a_v(t) \sim \cos\left(m_a t + \frac{1}{2} m_a v^2 t\right)$$

- Total field is the superposition of all modes

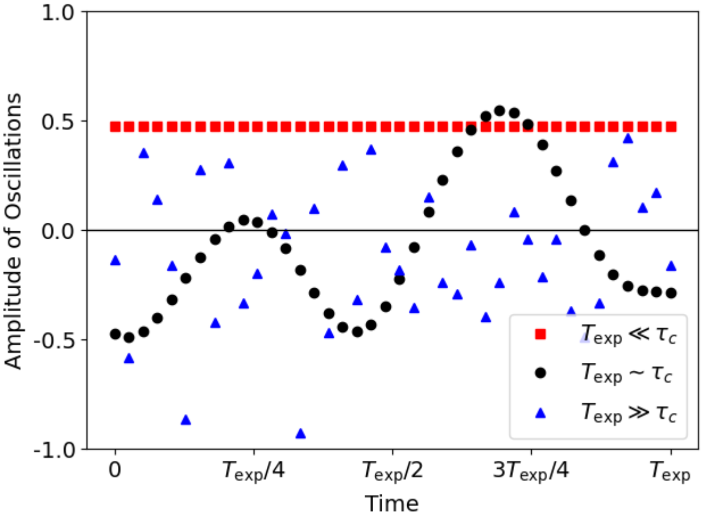


- random amplitude fluctuations on the coherence timescale

$$\tau_c \sim \frac{1}{m_a \sigma^2} \sim 1 \text{ day } \left(\frac{m_a}{10^{-14} \text{ eV}}\right)^{-1} \left(\frac{\sigma}{220 \text{ km/s}}\right)^{-2}$$

  - σ: velocity dispersion

The Coherence Timescale



Effects of Stochasticity

- For timescales $T_{\rm exp} \ll \tau_c$:

$$a(t) \sim \sum_v \cos\left(m_a t + \frac{1}{2} m_a v^2 t\right) \quad \Longrightarrow \quad a(t) \sim \sum_v \cos\left(m_a t + \phi_v\right)$$

  - random phase for each mode: $\phi_v \in [0, 2\pi]$

- Reduce sums over random variables using Central Limit Theorem

$$\begin{aligned} a(t) &\sim \cos(m_a t)\left[\sum_v \cos\phi_v\right] - \sin(m_a t)\left[\sum_v \sin\phi_v\right] \\ &\sim \frac{1}{\sqrt{2}} X \cos(m_a t) - \frac{1}{\sqrt{2}} Y \sin(m_a t) \end{aligned}$$

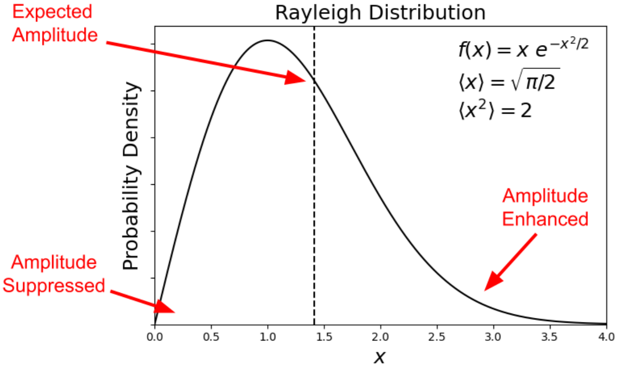
  - X,Y: standard normal random variables

Derevianko (1605.09717); Foster+ (1711.10489)

- Change of variables:

$$a(t) \sim \frac{1}{\sqrt{2}} \alpha \cos(m_a t + \phi)$$

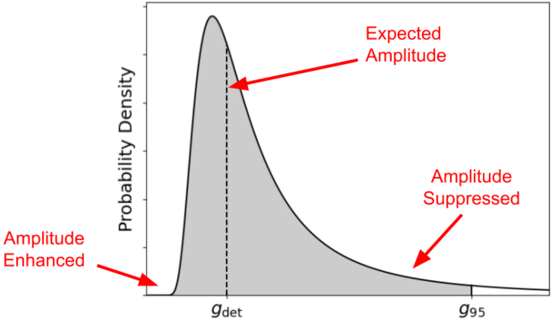
  - $\alpha = \sqrt{X^2 + Y^2}$: Rayleigh-distributed amplitude
  - $\phi = \arctan(Y/X)$: uniform random phase



Experimental Implications

- Consider an experiment sensitive to $ga(t)$
- What values of g are excluded at 95% confidence?
  - g_{det}: deterministic limit

$$\frac{\alpha g}{\sqrt{2}} \sim g_{\text{det}} \quad \Rightarrow \quad g \sim \frac{g_{\text{det}}\sqrt{2}}{\alpha}$$



Null sensitivity is significantly weaker than expected!

Centers+ (1905.13650)

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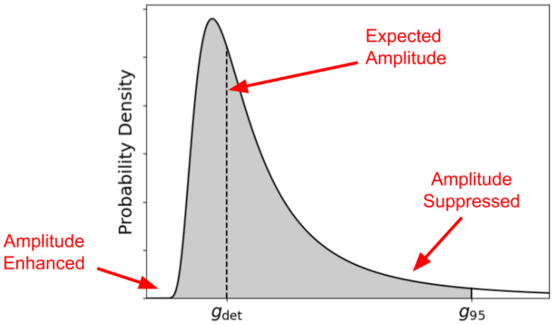


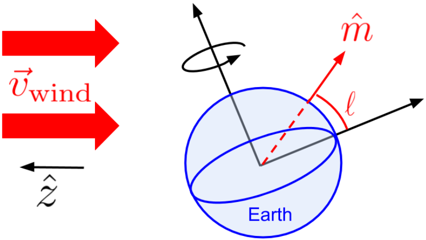
What about $\vec{\nabla} a(t)$?

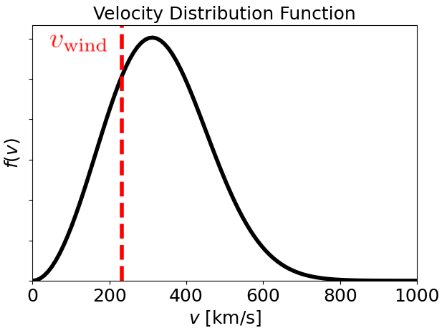
1D Construction of the Local Axion Field Gradient

- Gradient should be: $\vec{\nabla}a(t) = a(t)\ m_a\vec{v}$

$$\implies \quad \vec{\nabla}a(t) = \sqrt{\rho_{\rm DM}}\alpha\cos(m_a t + \phi)\vec{v}$$

- Assume all axions have the same velocity $\vec{v}$ (drawn from distribution)

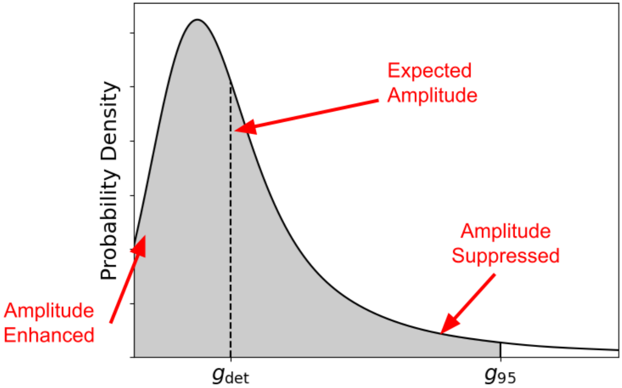




Experimental Implications

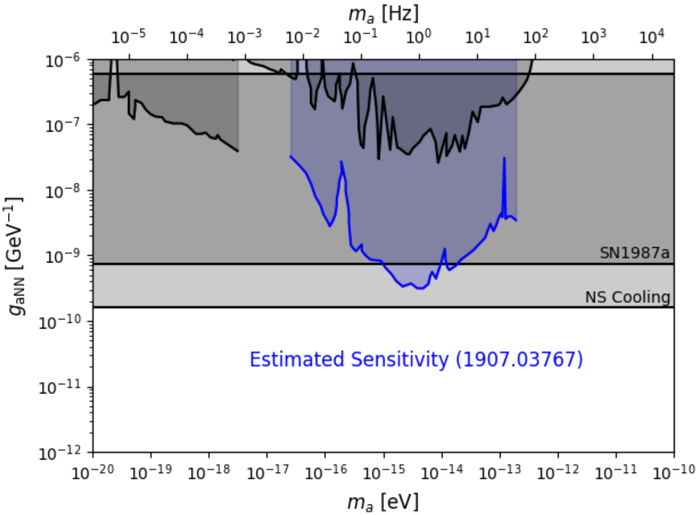
- Consider an experiment sensitive to $g\vec{\nabla}a(t)\cdot\hat{m}$
- What values of g are excluded at 95% confidence?
  - 1D Solution:

$$\alpha v g/\sqrt{2} \sim g_{\rm det} v_{\rm wind} \quad \Rightarrow \quad g \sim g_{\rm det} v_{\rm wind}\sqrt{2}/\alpha v$$



Effectively same result as experiment coupled to $ga(t)$

Experimental Sensitivity



Bloch+ (1907.03767)

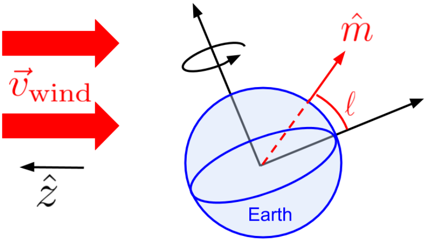
Full Constrution of the Local Axion Field Gradient

For timescales $T_{\text{exp}} \ll \tau_c$

- Full Solution:

$$\begin{aligned}\vec{\nabla}a(t)\cdot\hat{m} &= \sqrt{\rho_{\text{DM}}(\sigma^2+v_{\text{wind}}^2)}\ \alpha_z\cos(m_a t+\phi_z)\hat{z}\cdot\hat{m}\\ &\quad+\sqrt{\rho_{\text{DM}}\sigma^2}\ \alpha_x\cos(m_a t+\phi_x)\hat{x}\cdot\hat{m}\\ &\quad+\sqrt{\rho_{\text{DM}}\sigma^2}\ \alpha_y\cos(m_a t+\phi_y)\hat{y}\cdot\hat{m}\end{aligned}$$

  - α_i: 3 independent Rayleigh-distributed amplitudes
  - ϕ_i: 3 independent random phases



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$$\begin{aligned}\vec{\nabla} a(t) \cdot \hat{m} \quad = \quad & \sqrt{\rho_{\text{DM}}(\sigma^2 + v_{\text{wind}}^2)}\ \alpha_z \cos(m_a t + \phi_z)\hat{z} \cdot \hat{m} \\ & + \sqrt{\rho_{\text{DM}}\sigma^2}\ \alpha_x \cos(m_a t + \phi_x)\hat{x} \cdot \hat{m} \\ & + \sqrt{\rho_{\text{DM}}\sigma^2}\ \alpha_y \cos(m_a t + \phi_y)\hat{y} \cdot \hat{m}\end{aligned}$$

- 1D Solution:

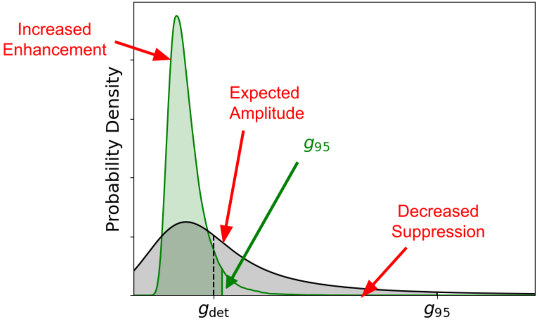
$$\vec{\nabla} a(t) \cdot \hat{m} = \sqrt{\rho_{\text{DM}}}\alpha \cos(m_a t + \phi)\vec{v} \cdot \hat{m}$$

- Agree only in the limit $\sigma \ll v_{\text{wind}}$ (NOT a good approximation)

Experimental Implications

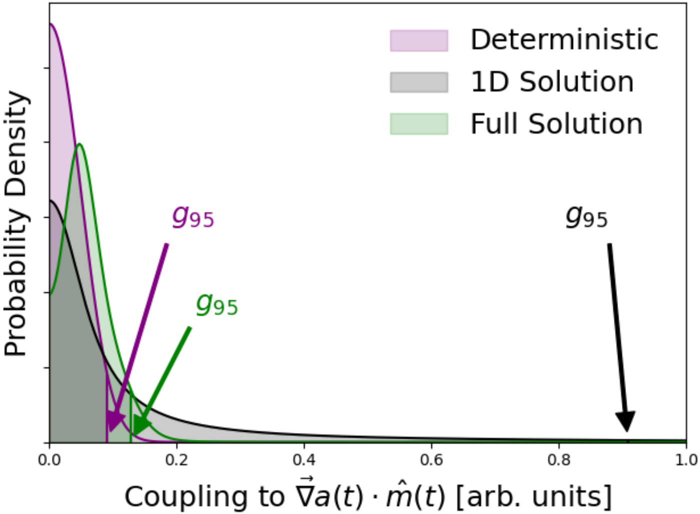
- Consider an experiment sensitive to $g\vec{\nabla}a(t)\cdot\hat{m}$
- What values of g are excluded at 95% confidence?
  - Full Solution:

$$\sqrt{{\alpha_x}^2+{\alpha_y}^2+{\alpha_z}^2}\,\frac{g}{\sqrt{2}}\sim g_{\rm det} \quad\Rightarrow\quad g\sim\frac{g_{\rm det}\sqrt{2}}{\sqrt{{\alpha_x}^2+{\alpha_y}^2+{\alpha_z}^2}}$$



Null sensitivity is significantly stronger than 1D estimate!

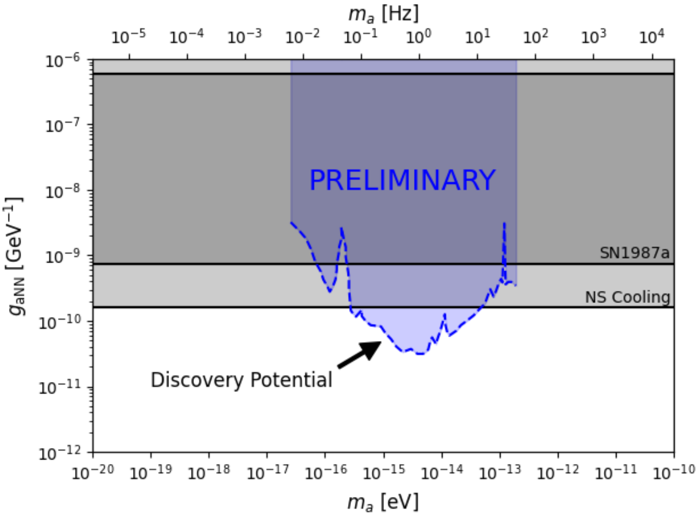
Null Sensitivity on Mock Data



Stochastic effects do NOT lead to significant loss in sensitivity!

contrary to Centers+ (1905.13650)

Experimental Sensitivity



Theory: Moschella, et al. (to appear)

Data Analysis: Lee, et al. (to appear)

Conclusions

- Comagnetometers can be powerful probes of ultralight dark matter
- Understanding the stochastic behavior of ultralight fields is necessary to correctly interpret experimental results
- Experiments sensitive to $\vec{\nabla}a(t)$ do NOT lose sensitivity if $T_{\mathrm{exp}} \ll \tau_c$, contrary to previous claims
- We expect to probe entirely new parameter space with upcoming re-analysis of comagnetometer data

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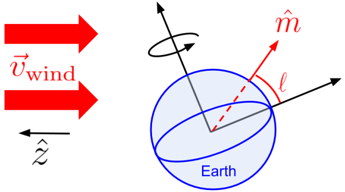
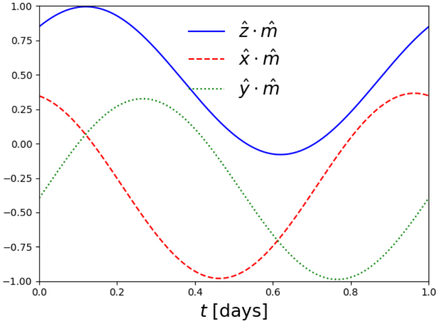
Backup

Daily Modulation

Experimental Observable $\propto \vec{\nabla} a(t) \cdot \hat{m}$



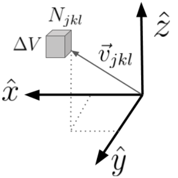


Full Construction of the Local Axion Field Gradient

- For a single mode with velocity $\vec{v}_i$,

$$\vec{\nabla} a_i(t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a\sqrt{N}} \cos\left[m_a t + \frac{1}{2} m_a v_i^2 t + \phi_i\right] \ (m_a \vec{v}_i)$$

  - N: total number of modes
  - ϕ_i: random initial phase for each mode



- Discretize velocities with with N_{jkl} modes per bin
- The (vector) contribution from each bin is:

$$\vec{\nabla} a_{jkl}(t) = \frac{\sqrt{2\rho_{\rm DM}}}{\sqrt{N_{jkl}}} \sum_{i\in\Omega_{jkl}} \sqrt{f(\vec{v}_{jkl})\Delta V} \cos\left[m_a t + \frac{1}{2} m_a v_{jkl}^2 t + \phi_i\right] \ \vec{v}_{jkl}$$

  - $f(\vec{v}_{jkl})$: velocity distribution

c.f. Foster+ (arXiv:1711.10489)

Full Construction of the Local Axion Field Gradient

- Using the Central Limit Theorem,

$$\vec{\nabla} a_{jkl}(t) = \sqrt{\rho_{\mathrm{DM}} f(\vec{v}_{jkl}) \Delta V} \alpha_{jkl} \cos\left[m_a t + \frac{1}{2} m_a v_{jkl}^2 t + \phi_{jkl}\right] \vec{v}_{jkl}$$

- The total axion field is then $\vec{\nabla} a(t) = \sum_{jkl} \vec{\nabla} a_{jkl}(t)$
- Reparametrize

$$\vec{\nabla} a(t) \cdot \hat{m}(t) = \sqrt{\rho_{\mathrm{DM}}} \sum_{i=x,y,z} \left[A_i(t) \cos(m_a t) + B_i(t) \sin(m_a t)\right] \hat{e}_i \cdot \hat{m}(t)$$

  - Each A_i and B_i contains a $\sum_{jkl} F(\vec{v}_{jkl}, \alpha_{jkl}, \phi_{jkl})$
  - Central Limit Theorem $\implies$ all $A_i(t)$ and $B_i(t)$ are Gaussian

Full Construction of the Local Axion Field Gradient

A_i and B_i are uncorrelated on short timescales $\tau \ll \tau_c$