From Spins to Strings

Jacob M. Leedom

WISPs in String Cosmology

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w/Carl Beadle, Diego Blas, Itay Bloch, Jeff Dror,
Sebastian Ellis, Stefania Gori, & Nicholas Rodd

FZU

Introduction

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- WISPy States:
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  - Dark Photons
  - Gravitons

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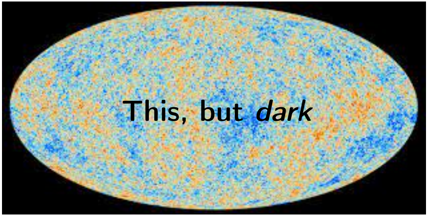
- As Cosmic Backgrounds:
  - Cosmic axion Background (CaB) - relic density of relativistic ultralight axions
  - hidden CMB (hCMB) - population of ultralight dark photons
  - Gravitational Wave Background (GWB)



[Cicoli,Goodsell,Jaeckel,Ringwald;'11]
[Cicoli,Goodsell,Ringwald;'12]
[Cicoli,Conlon,Quevedo;'12]
[Conlon,Marsh;'13]
[Cicoli,Piovano;'18]
[Cicoli,Hebecker,Jaeckel,Wittner;'22]
[Cicoli,Sinha,Deal;'22]
⋮

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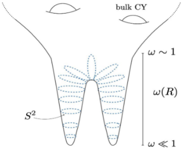
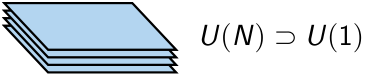
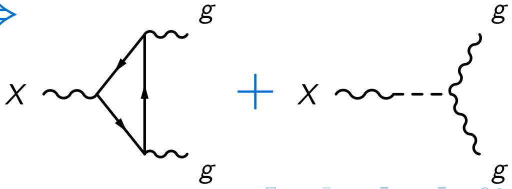
- WISP states are common predictions of string models: [Svrcek,Witten;'06] [Arvanitaki,Dimopoulos,Dubovsky, Kaloper,March-Russel;'09] [Cicoli,Goodsell,Ringwald;'12] [Cicoli,Guidetti,Righi,Westphal;'21]

$$a = \int_{\Sigma_p} C_p$$





$$\nabla\chi = \partial_\mu\chi - qA_\mu \quad \Longrightarrow$$



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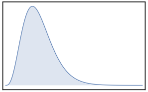

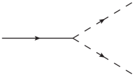

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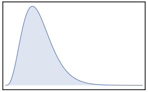
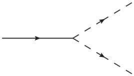
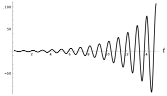
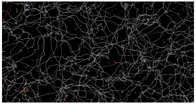
  - Topological Defects









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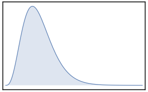
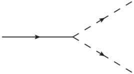
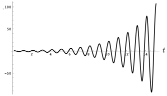

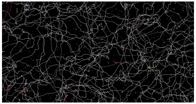

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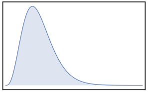

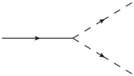

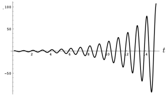

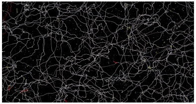

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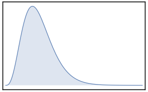
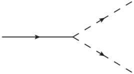
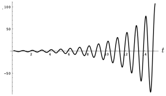
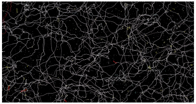

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How can we detect them?

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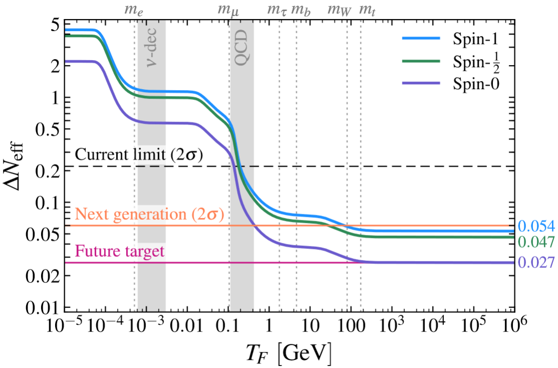

[Green et al;'19]

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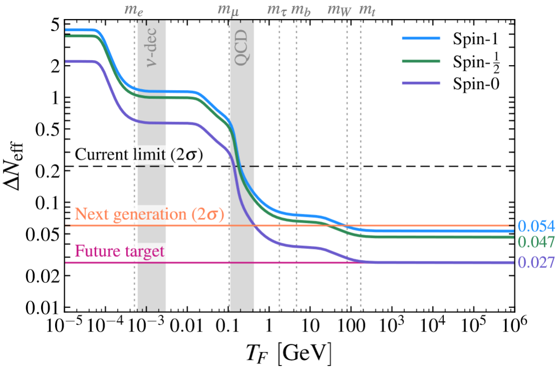

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- This would indicate **existence**
- How can we get some more fine-grained information?

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- Repurpose dark matter experiments to look for CWBs

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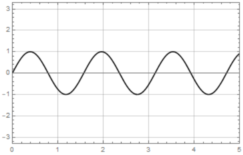

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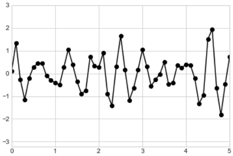

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WISPy Couplings to Standard Model

- Today we focus on **Spin** - Dirac Equation

  $\bullet \mathcal{L} \supset \bar{\Psi}(i\gamma^{\mu}\partial_{\mu} + q\gamma^{\mu}A_{\mu} - m)\Psi$

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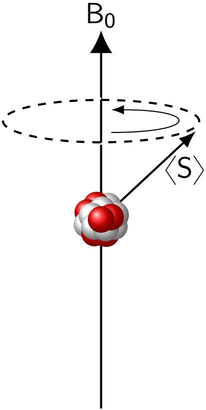
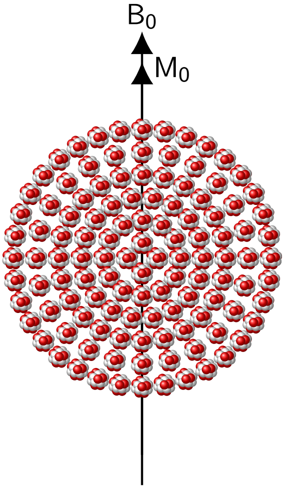
WISPs manifest as effective magnetic fields

Can be probed via spin-based experiments



- Larmor Frequency: $\omega_0 = \gamma B_0$

Basics of NMR



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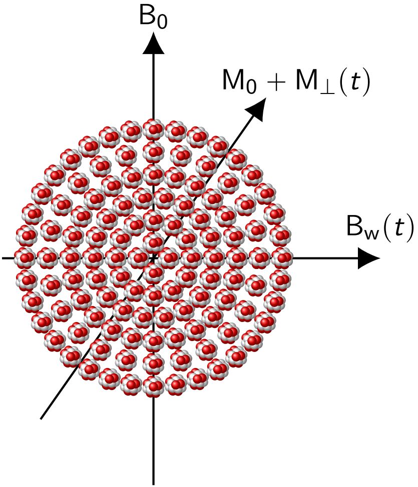
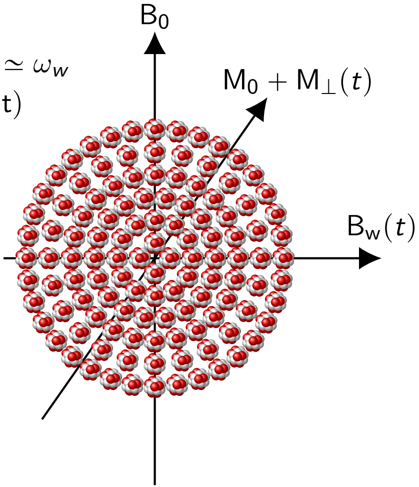


- On Resonance: $\omega_0 \simeq \omega_w$

  $M_\perp(t) \sim t\cos(\omega_w t)$



Nuclear Magnetic Resonance: Basics

- One can start from Schrödinger equation for spins to find magnetization....or use the Bloch Equations:

$$\frac{d\mathrm{M}}{dt} = \mathrm{M} \times \gamma \mathrm{B} - \frac{M_x \hat{\mathrm{x}} + M_y \hat{\mathrm{y}}}{T_2} - \frac{(M_z - M_0)\hat{\mathrm{z}}}{T_1}$$

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- Perturbative expansion and decouple the equations

$$\ddot{M}_x + \frac{2}{T_2}\dot{M}_x + \omega_0^2 M_x = \gamma\omega_0 M_0(\hat{x} \cdot \vec{B}_w) - \gamma M_0 \frac{d}{dt}(\hat{y} \cdot \vec{B}_w)$$

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$$M_x(t) = C_1 e^{-t/T_2}\cos(\omega_0 t) + C_2 e^{-t/T_2}\sin(\omega_0 t) + \int_0^t G(t-s)F(s)ds$$

- $G(t) = \frac{1}{\Omega}e^{-t/T_2}\sin[\Omega t]$
- $\Omega^2 = \omega_0^2 - T_2^{-2}$

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- $\Omega^2 = \omega_0^2 - T_2^{-2}$

- From here can get the power spectral density (PSD) of signal

$$P_k := \frac{\Delta t}{T}\langle \tilde{M}_k^2 \rangle \qquad \tilde{M}_k := \sum_{n=0}^{N-1} M(n\Delta t)e^{-2\pi ikn/N}$$

NMR Application: QCD Axion Dark Matter

- NMR used in **CASPEr** searches for QCD axion dark matter

[Graham,Rajendran,'13]
[Budker,Graham,Ledbetter, Rajendran,Sushkov,'13]
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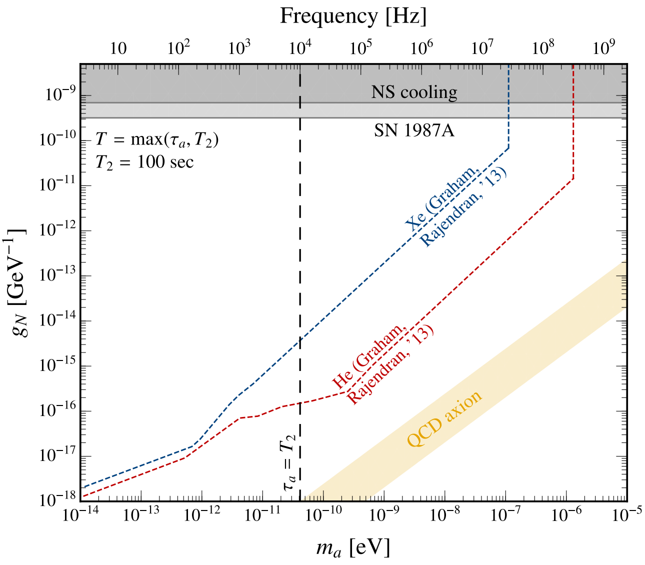
$$\nabla a(t) = \sqrt{\frac{2\rho_a}{N_a \bar{\omega}}} \sum_{i=1}^{N_a} \frac{\vec{k}_i}{\sqrt{\omega_i}} \sin[\omega_i t + \phi_i]$$

- $\omega_i \approx m_a(1 + v_i^2/2)$
- $\vec{k}_i \approx m_a \vec{v}_i$
- $\phi_i \in [0, 2\pi)$

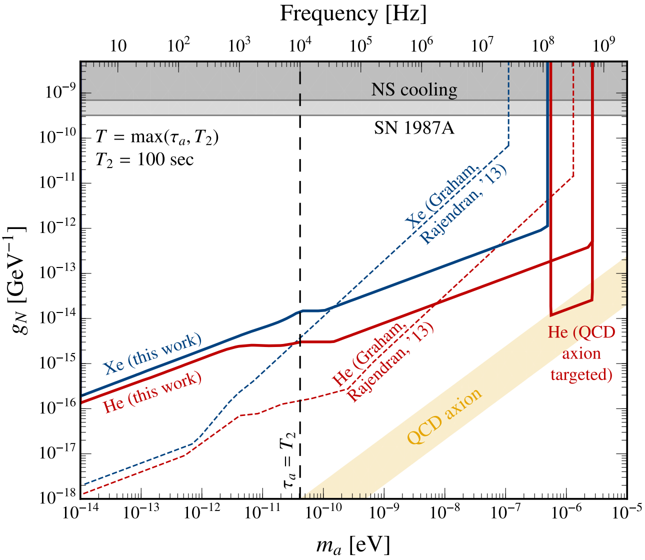
NMR Application: QCD Axion Dark Matter



$\mathcal{L} \supset g_N (\partial_\mu a) \bar{N} \gamma^\mu \gamma_5 N$

[Graham,Rajendran,'13]

NMR Application: QCD Axion Dark Matter



$$\mathcal{L} \supset g_N (\partial_\mu a) \bar{N} \gamma^\mu \gamma_5 N$$

[J. Dror, S. Gori, JML, N.Rodd]

NMR Application: CaB

- Assume CaB couples to nucleons: $\mathcal{L} \supset g_N^{(a)} (\partial_\mu a) \bar{N} \gamma^\mu \gamma^5 N$

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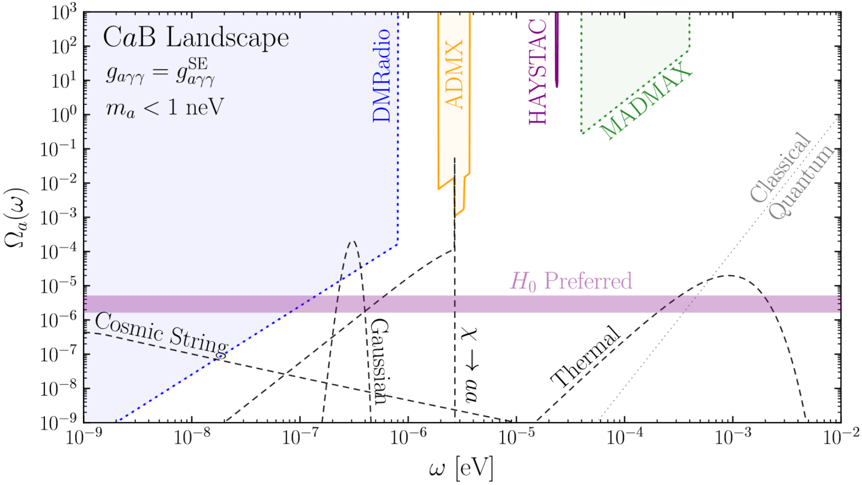
- Define

$$\Omega_a := \frac{1}{\rho_c} \frac{d\rho_a}{d \ln \omega}$$

- Assume CaB couples to photons: $\mathcal{L} \supset \frac{g_{ga\gamma\gamma}}{4} F_{\mu\nu}\widetilde{F}^{\mu\nu}$

[Dror,Murayama,Rodd, '21]



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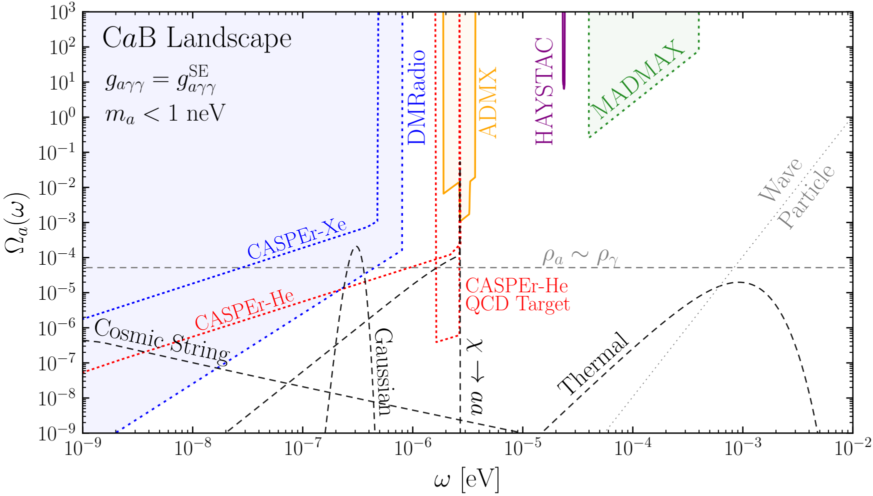

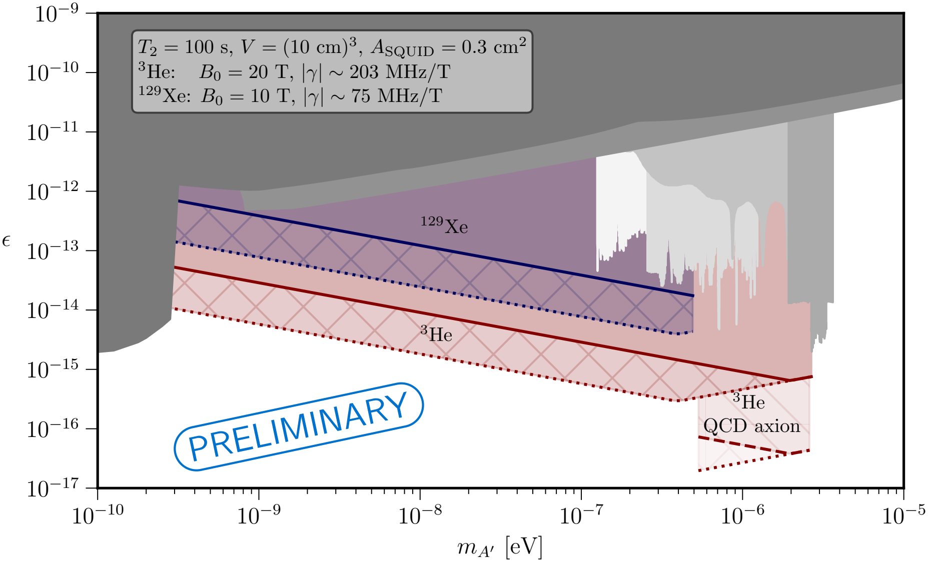
$T_2 = 100$ s, $V = (10\text{ cm})^3$, $A_{\text{SQUID}} = 0.3\text{ cm}^2$
^{3}He: $B_0 = 20$ T, $|\gamma| \sim 203$ MHz/T
^{129}Xe: $B_0 = 10$ T, $|\gamma| \sim 75$ MHz/T
^{129}Xe
^{3}He
^{3}He
QCD axion
PRELIMINARY
ϵ
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
$m_{A'}$ [eV]

NMR Application: Gravitational Waves

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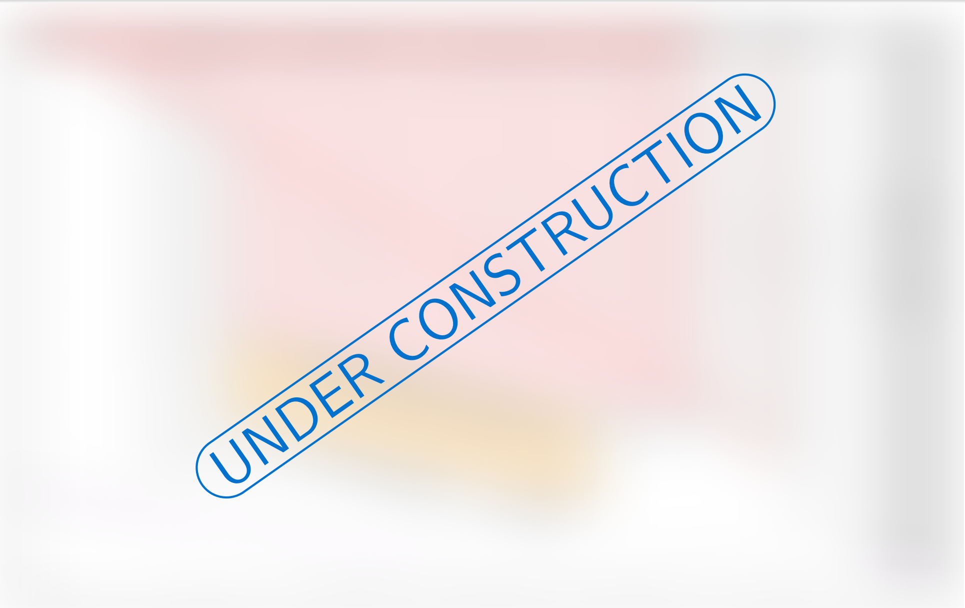

Conclusions

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From Nuclear Magnetic Resonance to CaBs hCMBs GWBs

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From *Spin* to *Strings*