Audible Axions

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Based on:

1811.01950 1912.01007

lattice results soon to come

Axion Cosmology: Misalignment Mechanism

Axion Evolution in Expanding Universe

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0 \qquad (\phi \text{ homogeneous})$$

Pinned by Hubble Friction

$H > m$

ϕ displaced from minimum

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$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0 \qquad (\phi \text{ homogeneous})$$

Pinned by Hubble Friction

$H > m$

ϕ displaced from minimum

Oscillating

$H < m$

Hubble Friction $\rightarrow$ Redshift

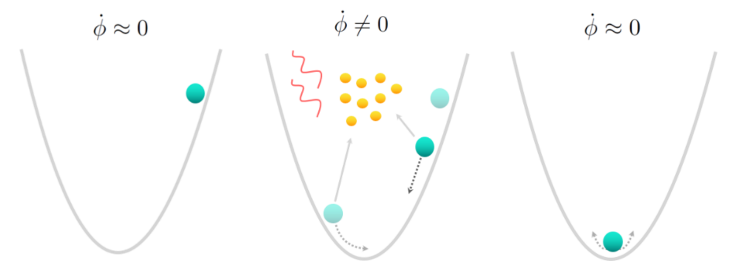
$\Rightarrow$ Cold Dark Matter

Additional Ingredient: Dark Photon

Dark Photon X + Coupling

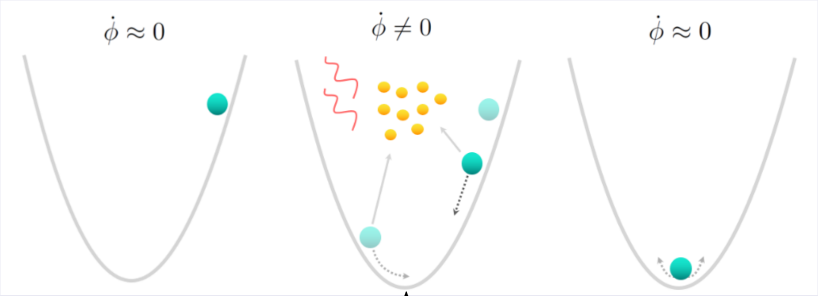
$$\mathcal{L} \supset -\frac{\alpha}{4f}\phi X_{\mu\nu}\widetilde{X}^{\mu\nu}$$

Dark Photon Production



Motivation

-Deplete Axion Abundance — Agrawal et al '17, Kitajima et al '17
-Produce Vector DM — Agrawal et al '18



Dispersion of X:

$\Uparrow$

$$\omega_\pm^2(t,k) = k^2 \mp \frac{\alpha}{f}\dot\phi(t)\,k < 0 \quad \text{for} \quad \begin{cases} \text{one helicity} \\ \mathbf{0} < \boldsymbol{k} < \alpha|\phi'|/f \end{cases}$$

~~Propagation~~ $\Rightarrow$ Exponential Growth $\propto \exp(|\omega_\pm|t)$

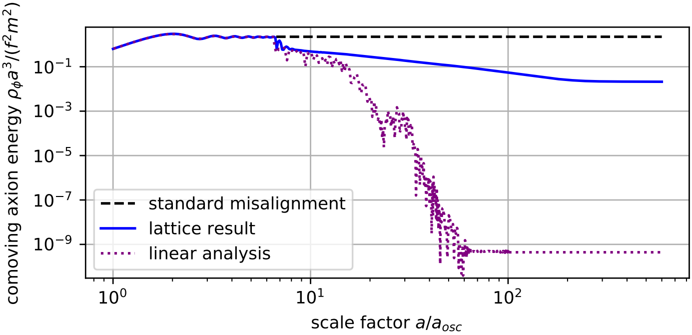
Lattice Results I: Less Axion Suppression

Old: Solve for DP mode functions, treat Axion as homogeneous

New: Solve E.O.M for discretized space-time

-include all the symmetries from the continuum

-includes full back-reaction onto axion Figueroa et al '17



Axion inhomogenities prohibit late time suppression! Agrawal et al '17

Gravitational Waves

Before Particle Production

Quantum Fluctuations in Dark Photon Field:

$$v(\tau, k) = 1/\sqrt{2\omega}\ \exp(i\omega\tau)$$

Energy in Axion
→homogeneous, isotropic

→

During Particle Production

Fluctuations grow exponentially:

$$v \propto \exp(|\omega|\tau)$$

Energy in Dark Photon
→inhomogeneous, anisotropic

⇒ Particle Production leads to time-varying, anisotropic energy density that acts as source of Gravitational Waves:

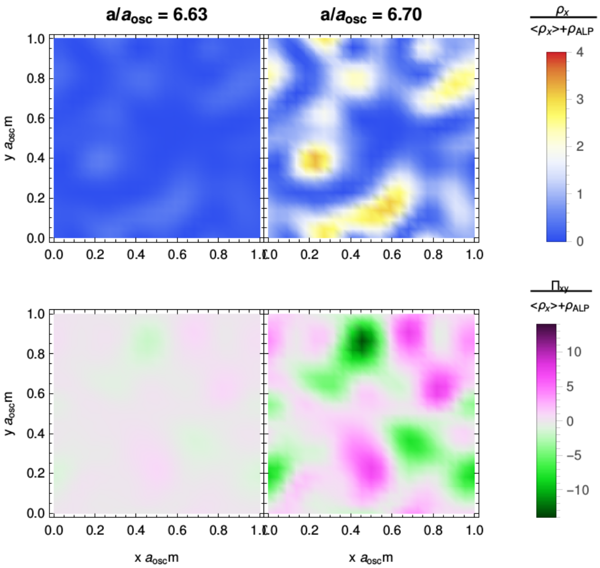
Gravitational Wave → $h''_{ij}(\tau, k) + k^2 h_{ij}(\tau, k) = \frac{2}{m_{\rm pl}^2}\Pi_{ij}(\tau, k)$ ⇜ Anisotropic Stress

$$\Pi_{ij}(\tau, k) = -\frac{\Lambda_{ij,kl}}{a^2}\int \frac{d^3q}{(2\pi)^3}\left[E_k(\tau, q)E_l(\tau, k-q) + B_k(\tau, q)B_l(\tau, k-q)\right]$$

Growth of Fluctuations

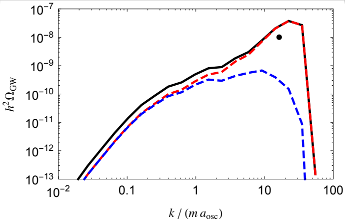
Energy Density of Dark Photon

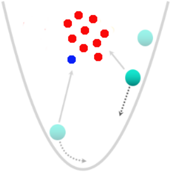
Anisotropic Stress



Lattice Results II: GW spectrum

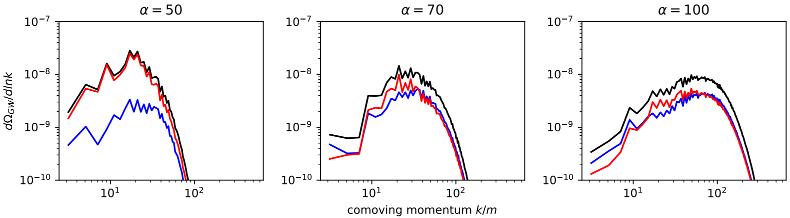
Old, linear analysis:



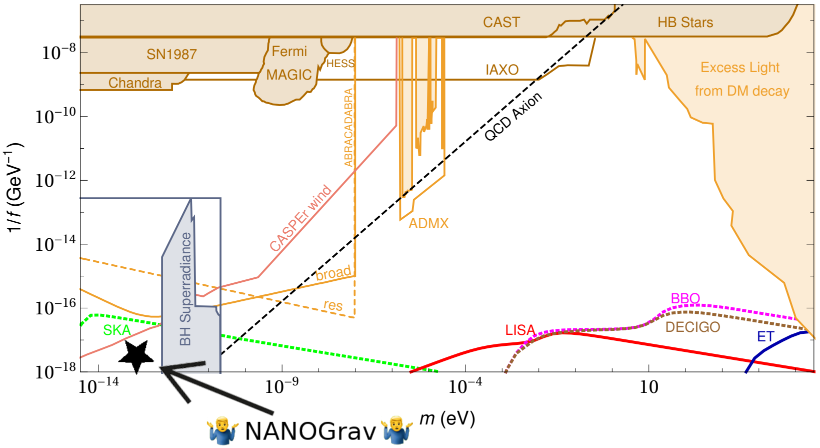


New, lattice result:

Subdominant Helicity from Re-Scatterings $\Rightarrow$ Less Polarization



Axion Discovery Potential



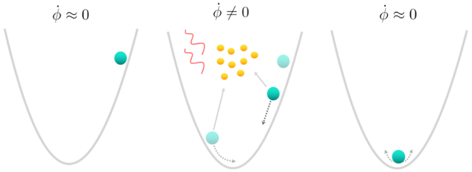
↑ Decay Constant f

Source Strength $\Omega_\phi \approx \left(\frac{f}{m_{pl}}\right)^2$

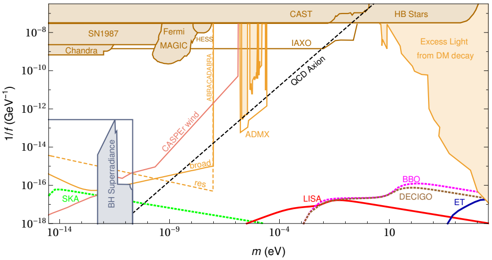
↑ Axion Mass m

Mass ⇔ Frequency ⇔ Detector

Model: Axion + Dark Photon + Coupling $\frac{\alpha}{4f}\phi X_{\mu\nu}\widetilde{X}^{\mu\nu}$

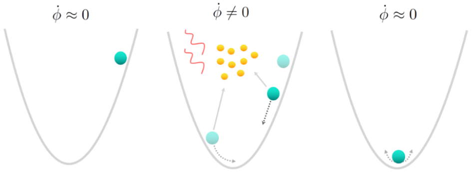


Produces:
-Dark Photons
-Anisotropies/GWs



Potential for
Axion Discovery

Model: Axion + Dark Photon + Coupling $\frac{\alpha}{4f}\phi X_{\mu\nu}\widetilde{X}^{\mu\nu}$



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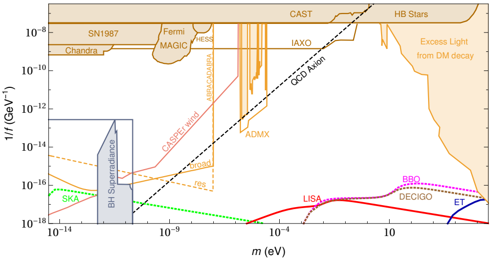


Potential for
Axion Discovery

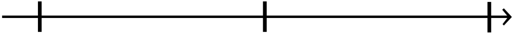
Thanks!

Backup

Axion Cosmology: Misalignment Mechanism

End of Inflation

- ϕ homogeneous



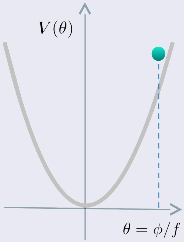
$T \sim f$

Spon. Symmetry Breaking
(Peccei-Quin Symmetry)

- Light Degree of Freedom: Axion ϕ

$T \sim \Lambda$

Small Exp. Breaking (QCD Confines)



- Potential generated: $V(\phi) \sim \Lambda^4 (1 - \cos(\Theta + \phi/f))$
- Displacement from Minimum: $\phi = \Theta f$, $\Theta \sim 1$

Tachyonic Band

$$\omega_\pm^2(\tau,k) = k^2 \mp \frac{\alpha}{f}\phi'(\tau)\, k$$

$$\phi' \sim \phi_{osc} m \;\cdot\; a\left(\frac{a_{osc}}{a}\right)^{3/2} \;\cdot\; \cos(am\,\tau)$$

$\hookrightarrow$Produced Helicity changes

Efficient Tachyonic Growth:

Axion Oscillation Period $am <$ Growth Rate $|\omega_\pm|$

$$\omega_\pm^2 < 0 \quad \rightarrow \quad \omega_\pm^2 < -(am)^2$$

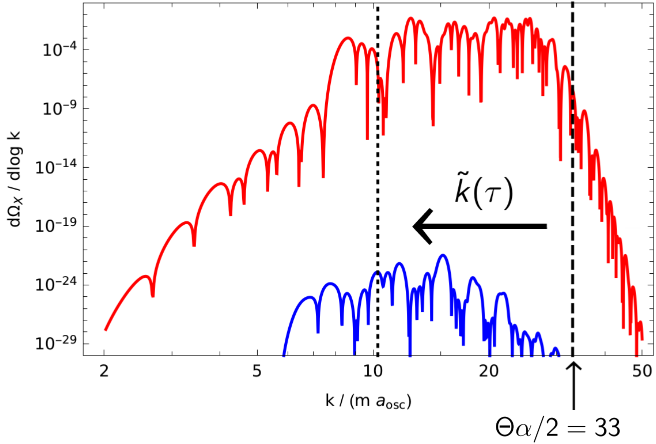
Tachyonic Band closes: $a/a_{osc} = (\theta\alpha/2)^{2/3}$

Fastest growing Mode - Peak in Photon Spectrum

$$\tilde{k}(\tau) = \frac{\alpha}{2f}\phi'(\tau) \approx \frac{\theta\alpha}{2} m\left(\frac{a_{osc}}{a}\right)^{3/2} a$$

Dark Photon Spectrum

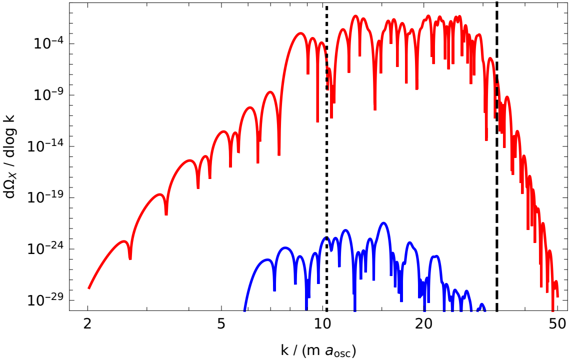
Fastest growing Mode: $\tilde{k}(\tau) = \frac{\alpha}{2f}\phi'(\tau)$

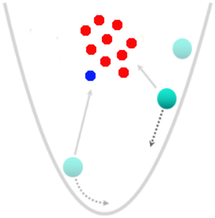


$\Theta = 1.2\ , \quad \alpha = 55$

Polarization of the Spectrum

$$\omega_\pm^2(\tau, k) = k^2 \mp \frac{\alpha}{f}\phi'(\tau)\, k \qquad v_\pm \propto \exp(|\omega_\pm|\tau)$$





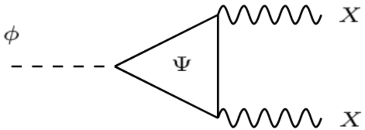
Parity Violation

$$\langle\phi\rangle \neq 0 \quad \longrightarrow \quad \text{Polarized Spectrum}$$

Axion - Dark Photon coupling

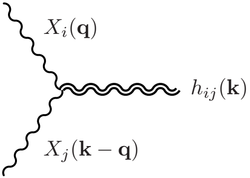
Starting from shift-symmetric coupling to ferminons that carry dark charge e_d, using P.I. and fermion EoM:

$$\frac{1}{2}\,\frac{\partial^\mu \phi}{f}\,\overline{\Psi}\gamma_\mu\gamma_5\Psi = -\frac{m_\Psi}{f}\,\phi\,\overline{\Psi}i\gamma_5\Psi + \frac{N_\Psi e_d^2}{16\pi^2}\frac{\phi}{f}X_{\mu\nu}\widetilde{X}^{\mu\nu}$$



$\Rightarrow$ Easiest way to get $\alpha > 1$, is large number of fermions N_Ψ

Features of the GW Spectrum



Peak Momentum/Frequency

$$k_{\text{peak}} \sim \sqrt{2}\tilde{k} \leftarrow \text{Dark Photon Peak}$$
$$\sim m\,(\theta\alpha)^{2/3}$$

↪Axion Mass m determines Peak Frequency

Peak Amplitude

$$\frac{d\,\Omega_{\rm GW}}{d\log k}(k_{peak}) \approx \Omega_X^2 \left(\frac{H}{k_{peak}}\right)^2 \approx \left(\frac{f}{m_{\rm pl}}\right)^4 \left(\frac{\theta^2}{\alpha}\right)^{4/3}$$

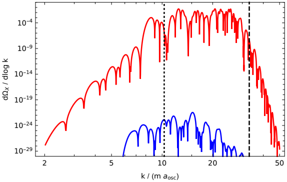
$\Omega_X \approx \Omega_\phi \approx \left(\frac{\Theta f}{m_{\rm pl}}\right)^2$

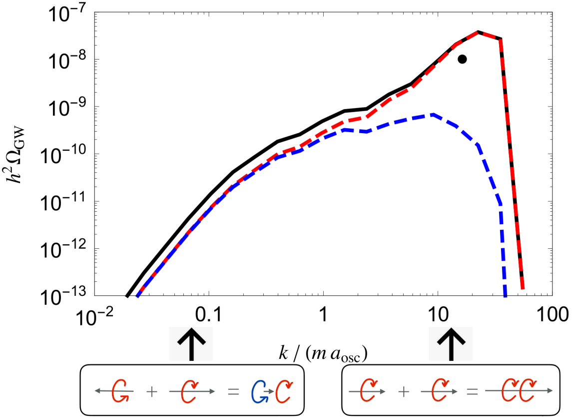
↪ f determines Peak Amplitude

↪ $f \gtrsim 10^{17}$ GeV for Detectable Signal

Features of the GW Spectrum: Chirality

Polarization of dark Photon Spectrum causes the Peak of the GW Spectrum to be polarized as well





GW Redshift

Frequency

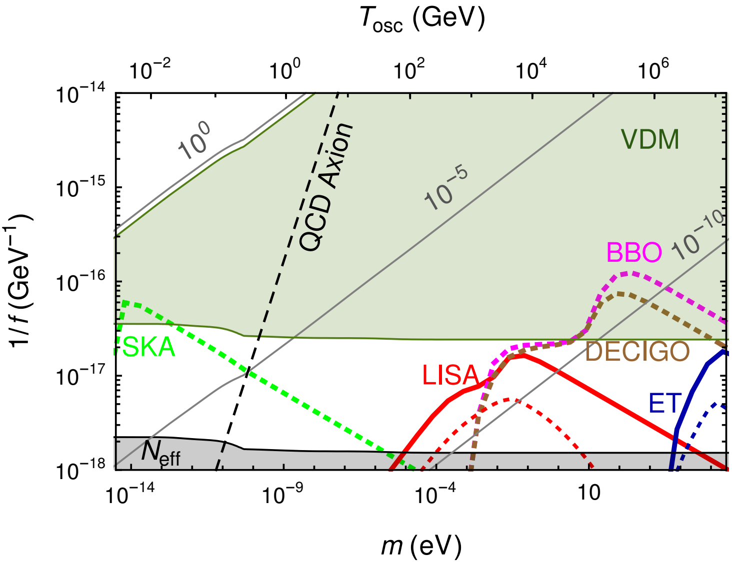
$$f_0 = \frac{k}{a_0} = \left(\frac{g_{s,\mathrm{eq}}}{g_{s,\mathrm{osc}}}\right)^{\frac{1}{3}} \left(\frac{T_0}{T_{\mathrm{osc}}}\right) \frac{k}{a_{\mathrm{osc}}}$$

For the peak:

$$\begin{aligned} f_0^{\mathrm{peak}} &\approx (\theta\alpha)^{\frac{2}{3}}\ T_0 \left(\frac{g_{s,\mathrm{eq}}}{g_{s,*}}\right)^{\frac{1}{3}} \left(\frac{m}{m_{\mathrm{pl}}}\right)^{\frac{1}{2}} \\ &\approx 6 \times 10^{-4}\ \mathrm{Hz} \left(\frac{\alpha\theta}{66}\right)^{\frac{2}{3}} \left(\frac{m}{10\,\mathrm{meV}}\right)^{\frac{1}{2}} . \end{aligned}$$

Amplitude

$$\begin{aligned} \Omega^0_{\mathrm{GW}} &= \Omega^*_{\mathrm{GW}} \left(\frac{g_{s,\mathrm{eq}}}{g_{s,*}}\right)^{\frac{4}{3}} \left(\frac{g_{\rho,*}}{g^{\gamma}_{\rho,0}}\right) \Omega^0_{\gamma} \\ &\approx 1.67 \times 10^{-4}\, g_{\rho,*}^{-1/3}\, \Omega^*_{\mathrm{GW}} . \end{aligned}$$



T_{osc} (GeV)
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
$1/f$ (GeV^{-1})
10^{0}
QCD Axion
10^{-5}
VDM
BBO
10^{-10}
SKA
DECIGO
LISA
ET
N_{eff}
10^{-14}
10^{-9}
10^{-4}
10
m (eV)