Audible Axions

Wolfram Ratzinger

Based on:

1811.01950 2012.11584

with Camila Machado, Pedro Schwaller and Ben Stefanek

July 28, 2021 Cambridge

Gravitational Waves and ALPs

- Supperradiance
  - Probes presence of very light scalars due to BH spin-down
- GWs from phase transitions
  - Probes possible UV completions of ALP models
  - See Rachel Houtz talk
- This talk: GWs from axion dynamics after inflation
  - Axion coupling to dark photon causes instability

Overview

- Axion coupled to Dark Photon
  - Introduction to dynamics
  - Source of GWs
  - Numerics: Lattice Analysis
- Realisations in Model Building
  - Relaxion
  - Kinetic Misalignment

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

$H < m$

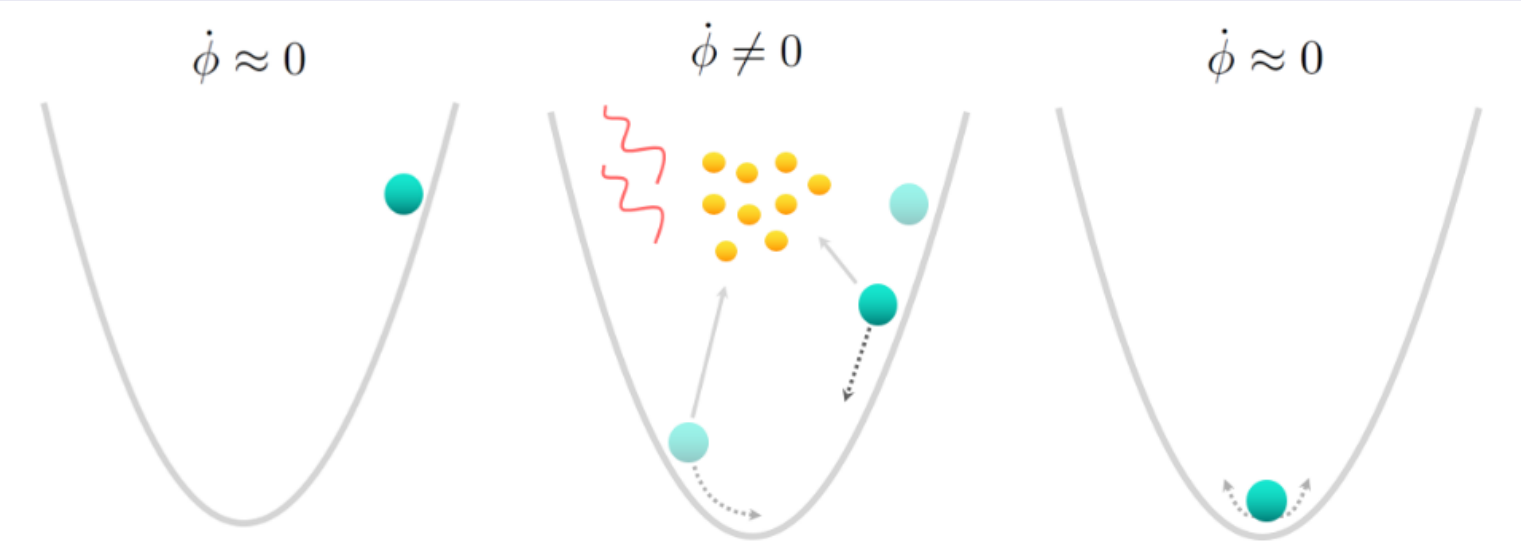
Hubble Friction $\rightarrow$ Redshift
$\Rightarrow$ Cold Dark Matter

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

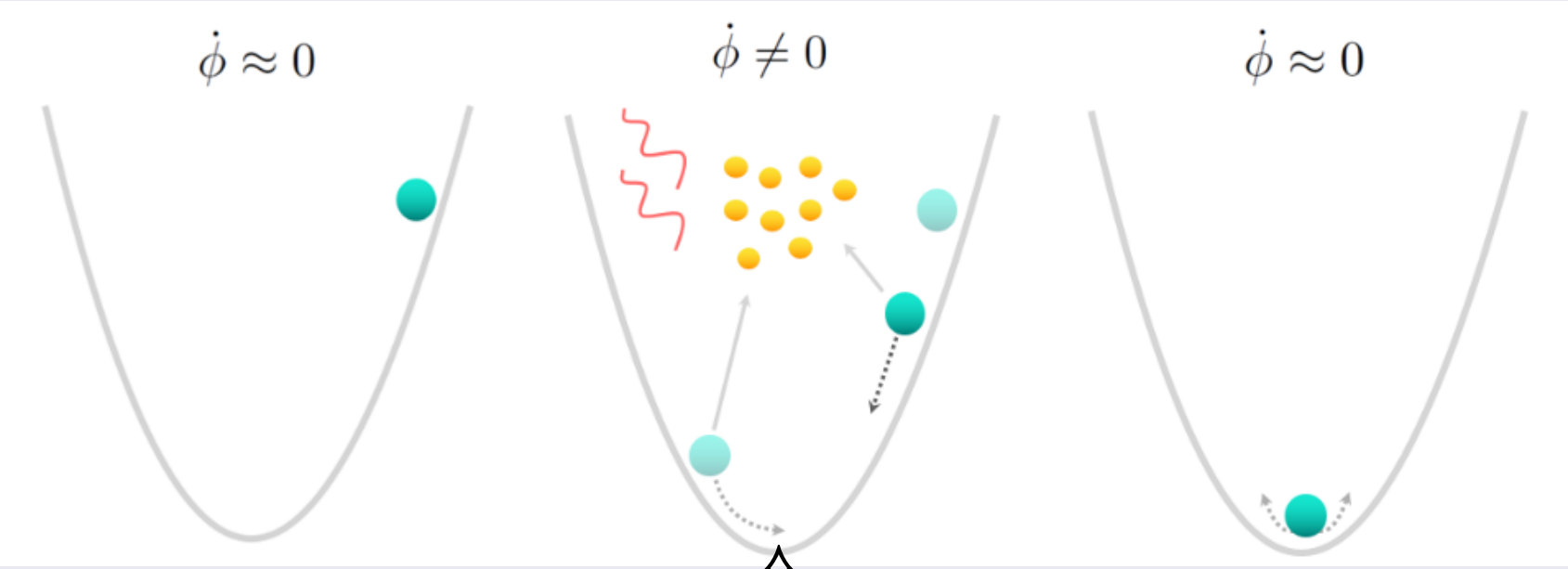


Motivation

-Deplete Axion Abundance — Agrawal et al '17, Kitajima et al '17

-Produce Vector DM — Agrawal et al '18

Production of Dark Photon



Dispersion of X: $\Uparrow$

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

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

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
$\rightarrow$homogeneous, isotropic

$\rightarrow$

During Particle Production

Fluctuations grow exponentially:

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

Energy in Dark Photon
$\rightarrow$inhomogeneous, anisotropic

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

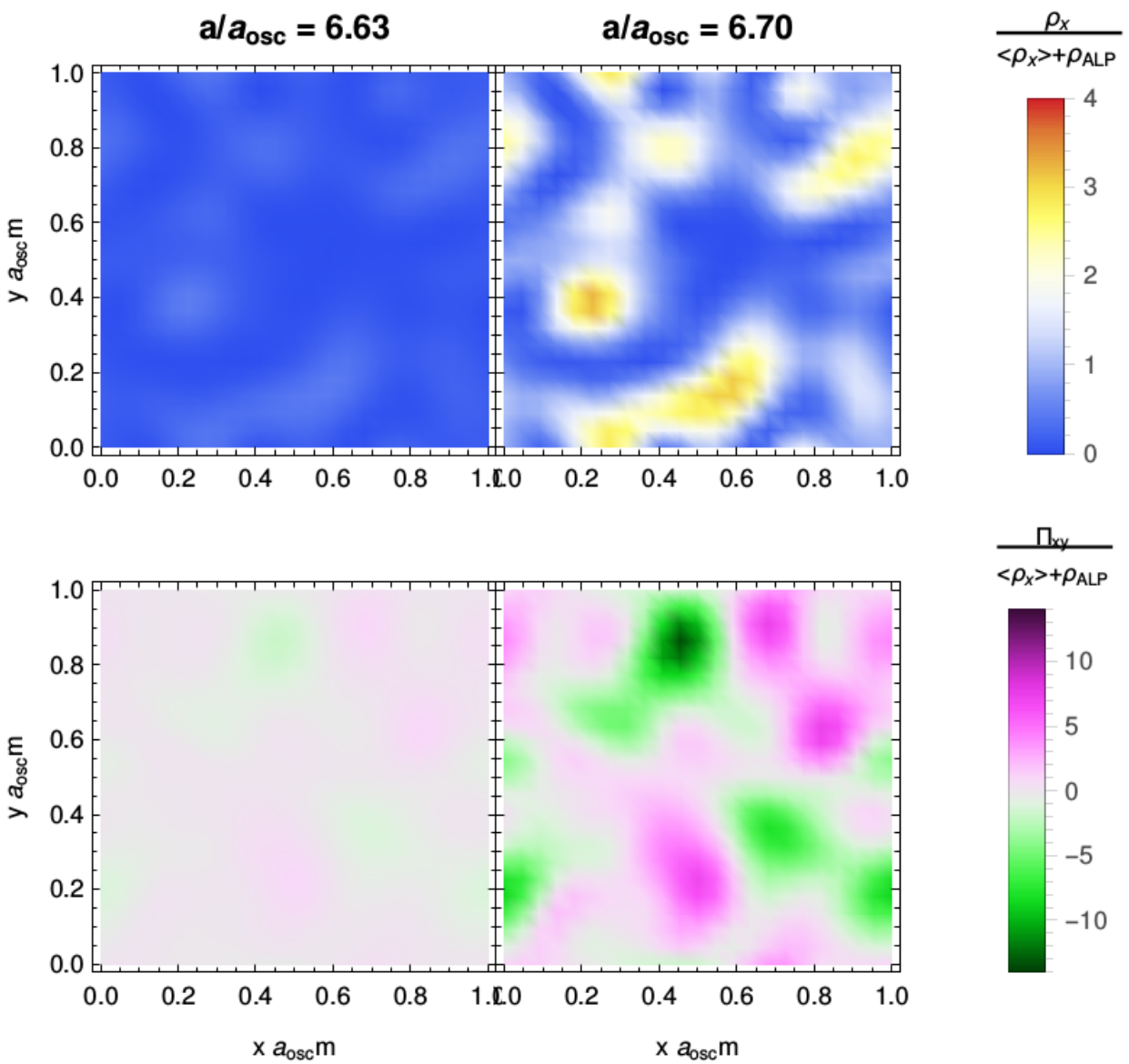
Gravitational Wave $\rightarrow h''_{ij}(\tau, k) + k^2 h_{ij}(\tau, k) = \frac{2}{m_{\rm pl}^2}\Pi_{ij}(\tau, k)$ Anisotropic Stress

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

Growth of Fluctuations

Energy Density of Dark Photon

Anisotropic Stress

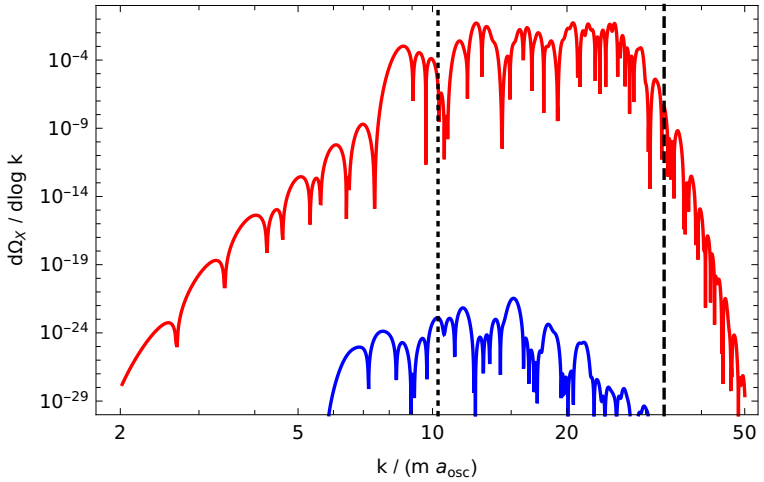


Gravitational Waves: Results

Rolling Axion

↓

Polarized dark photon spectrum



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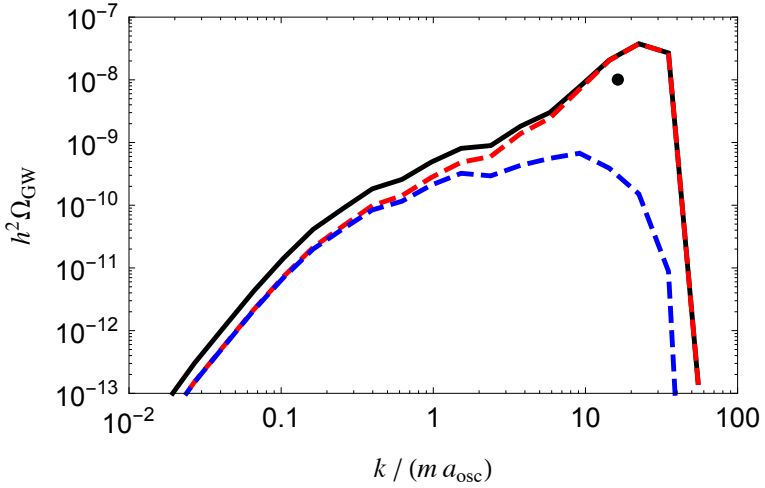
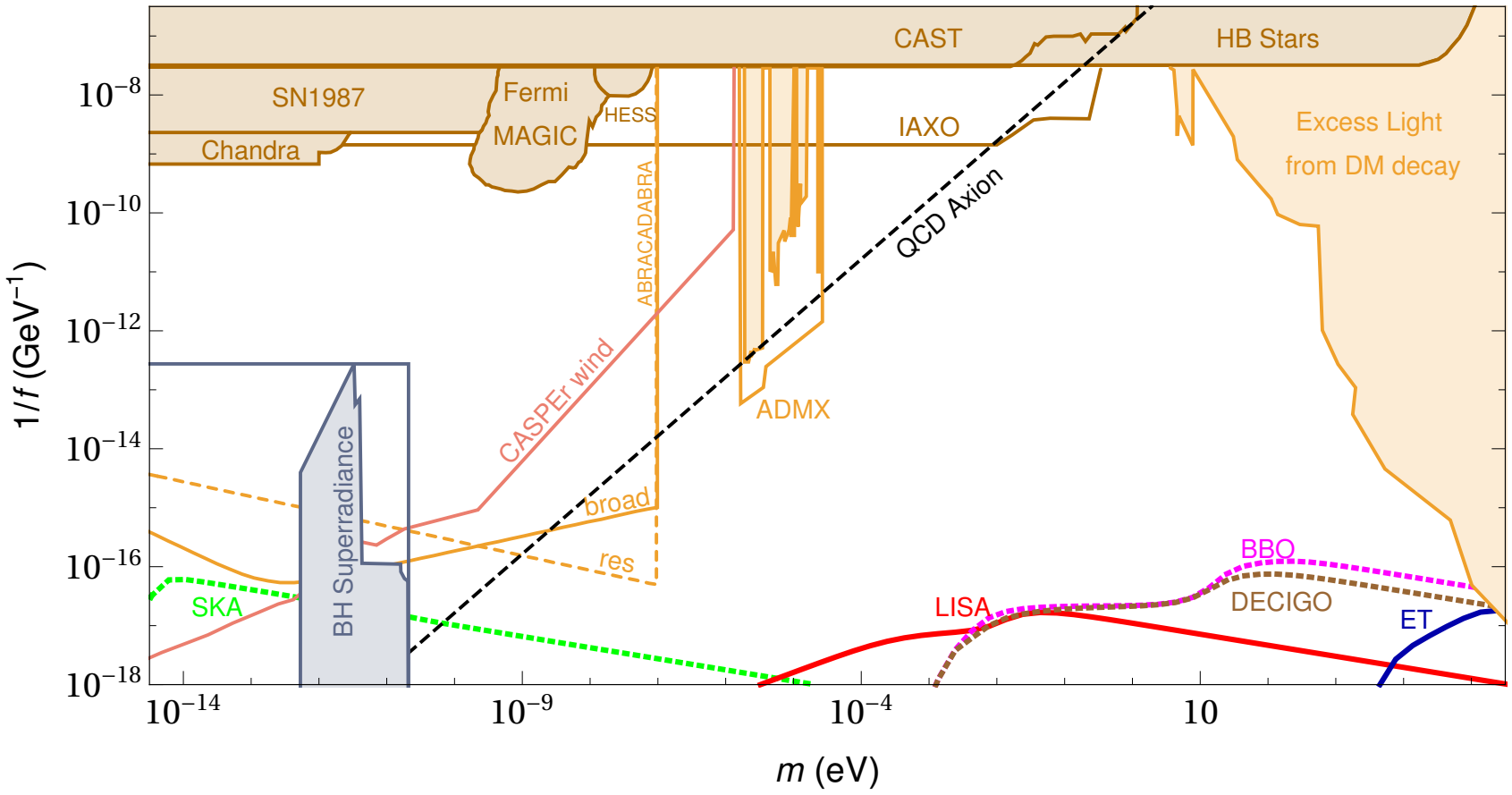
Polarized GWs



Axion Discovery Potential



↑ Decay Constant f

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

↑ Axion Mass m

Mass ⇔ Frequency ⇔ Detector

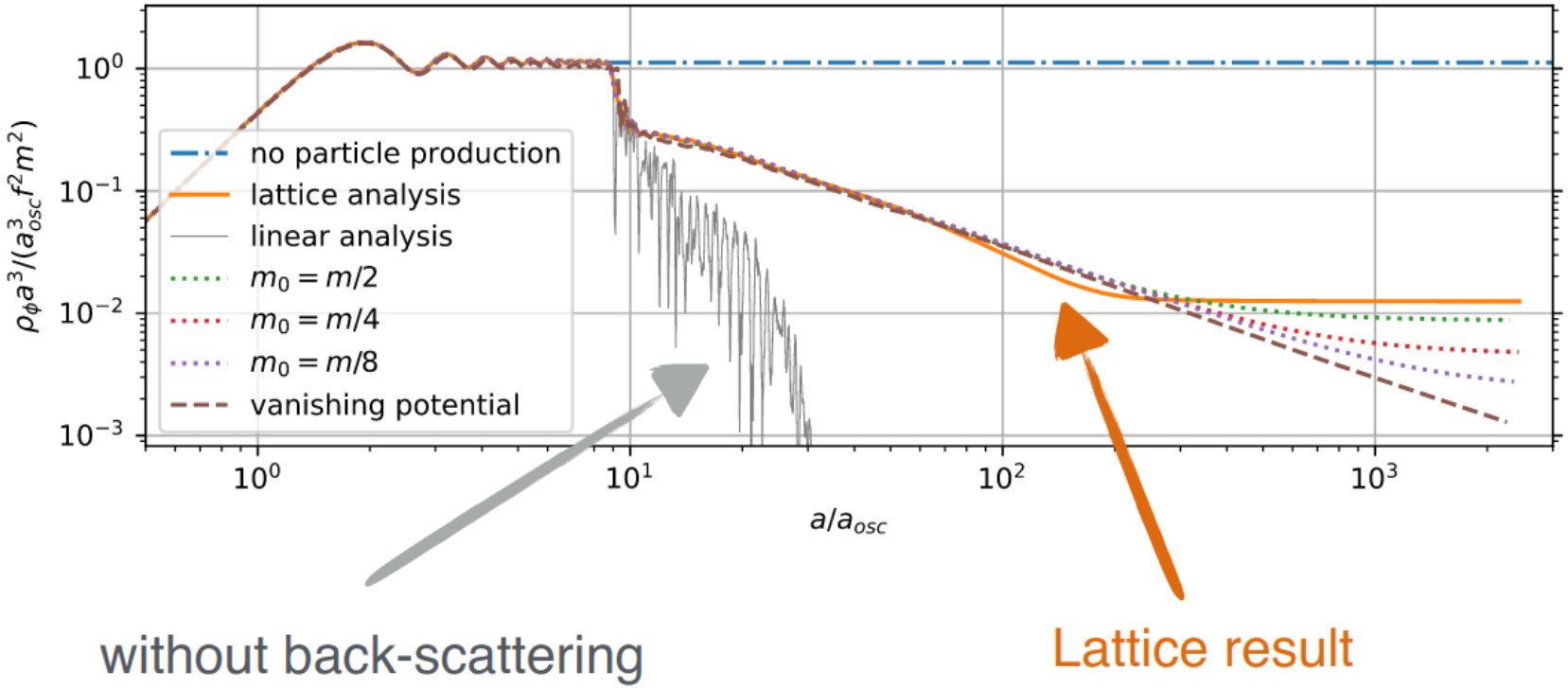
Lattice Results I: Less Axion Suppression

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

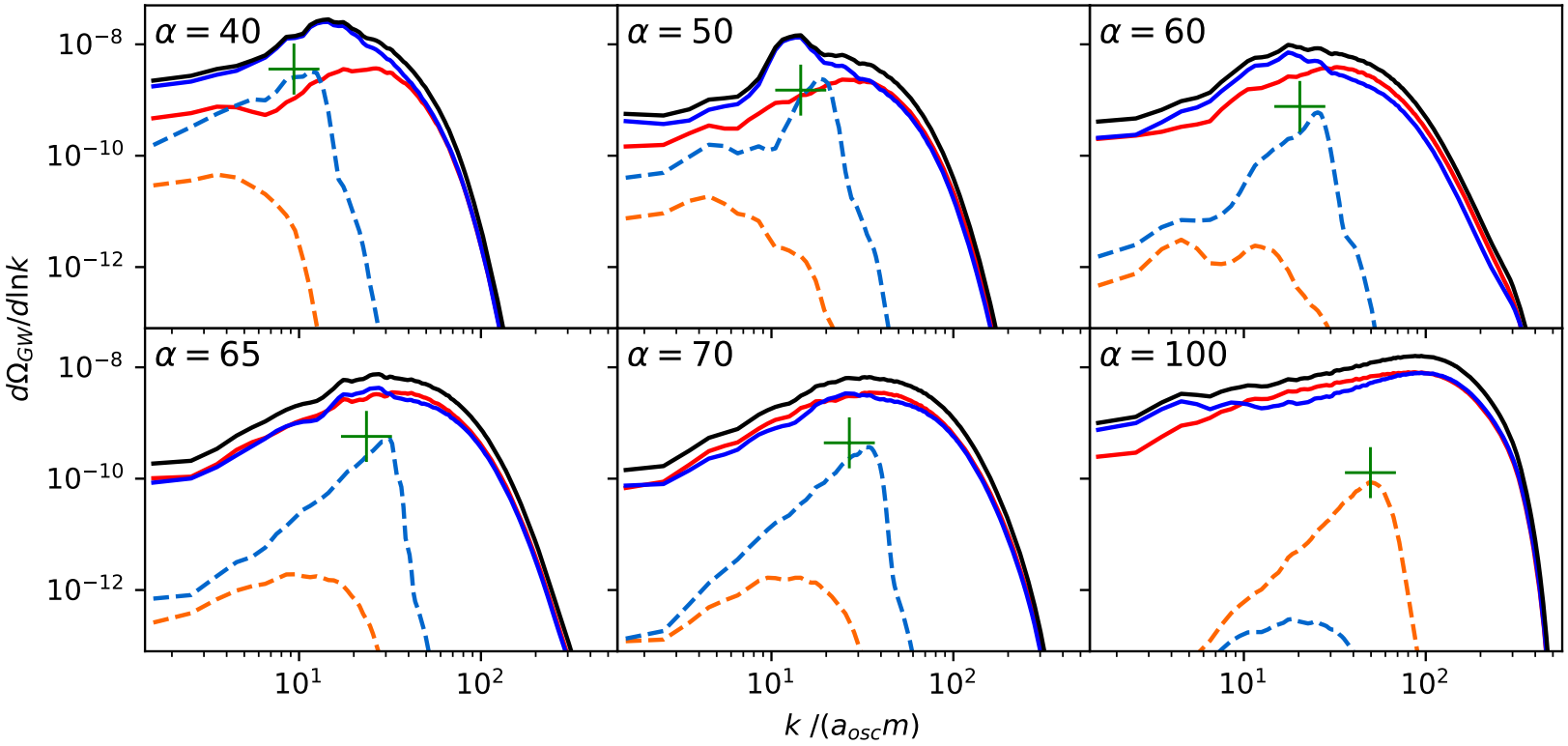
-includes full back-reaction onto axion Figueroa et al '17



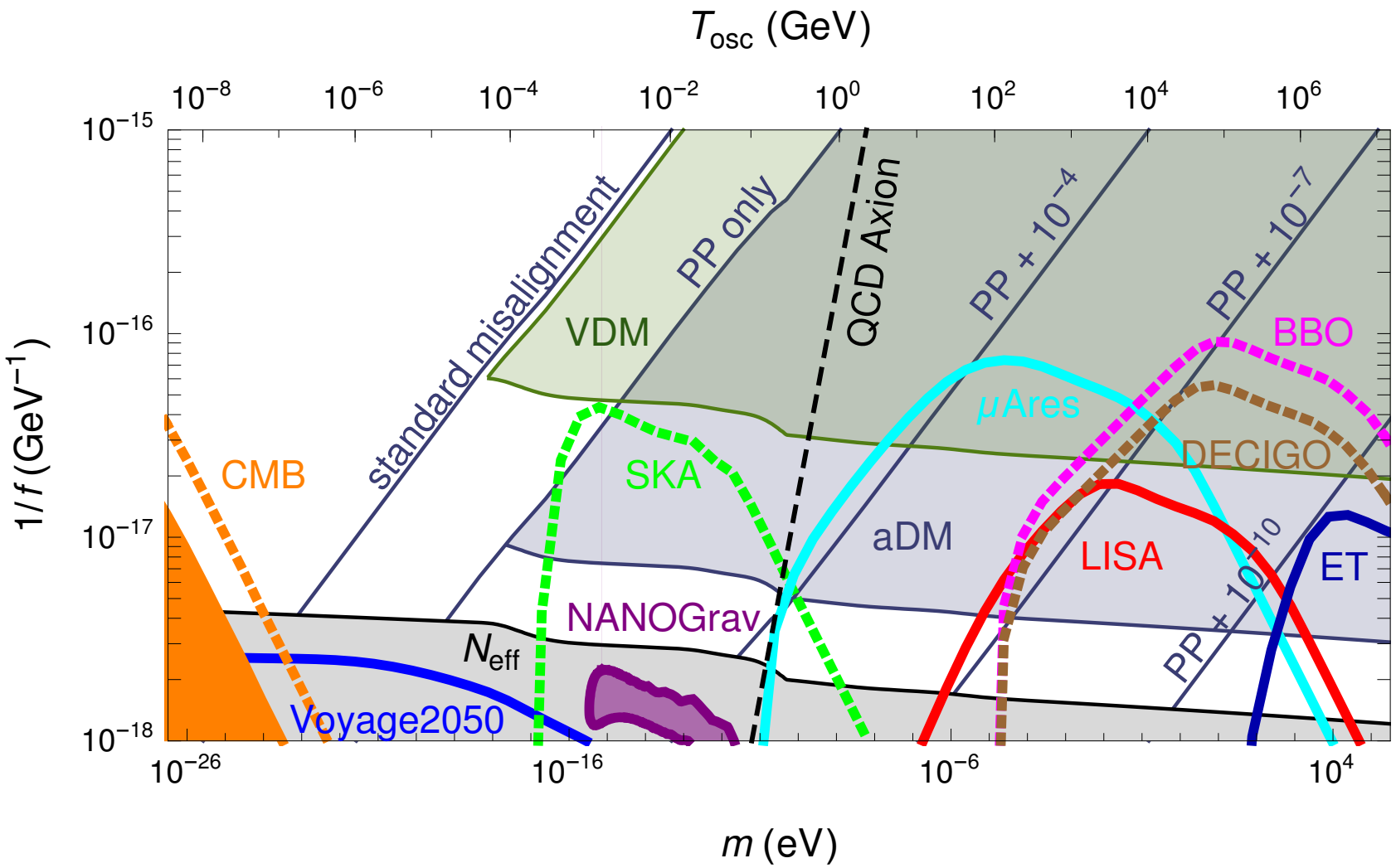
Axion inhomogenities prohibit late time suppression! Agrawal et al '17

Lattice Results II: Less/ $\alpha + \theta$-dependent Polarization

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

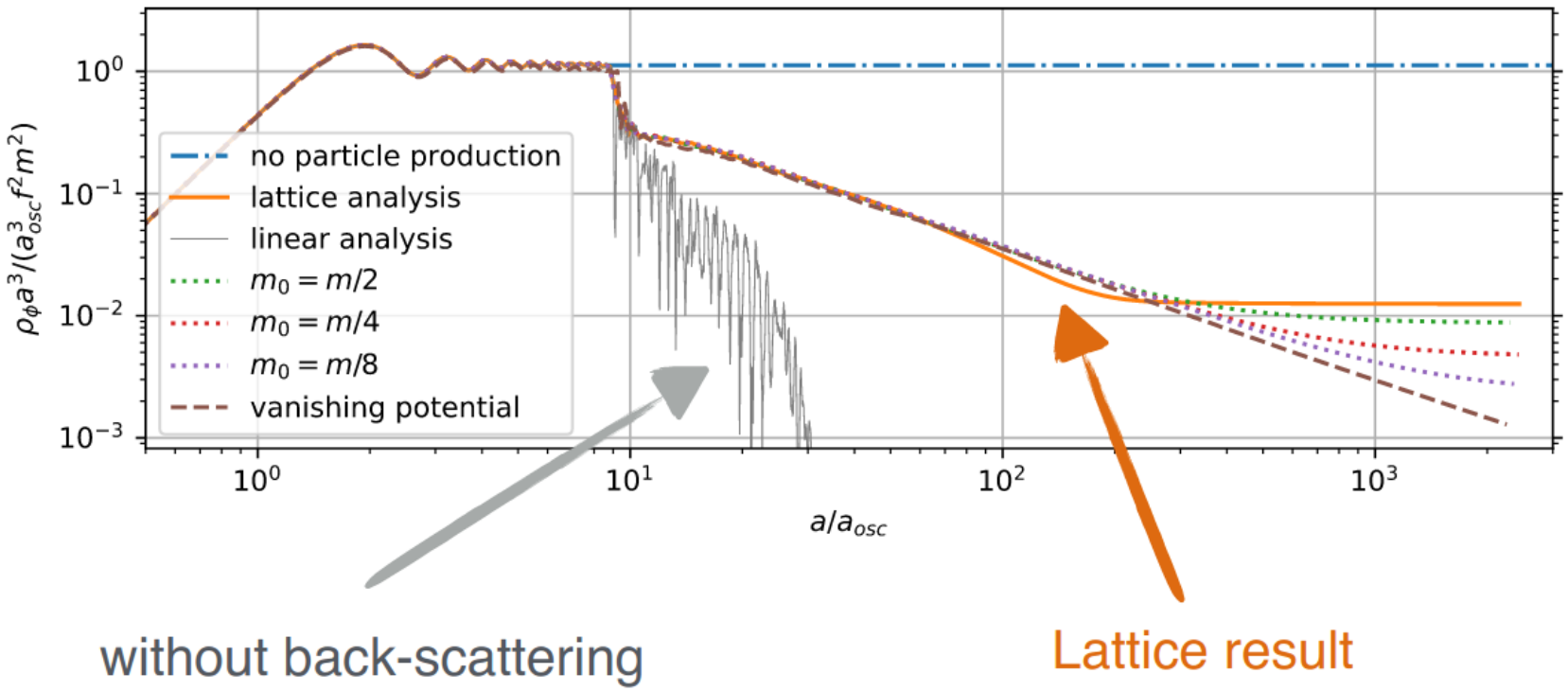


Detectable Region - Update



Most detectable parameters need extra axion suppression!

Achieving more Axion Suppression



- Time varying potential/mass
- Other source of $\dot{\phi}$ than potential

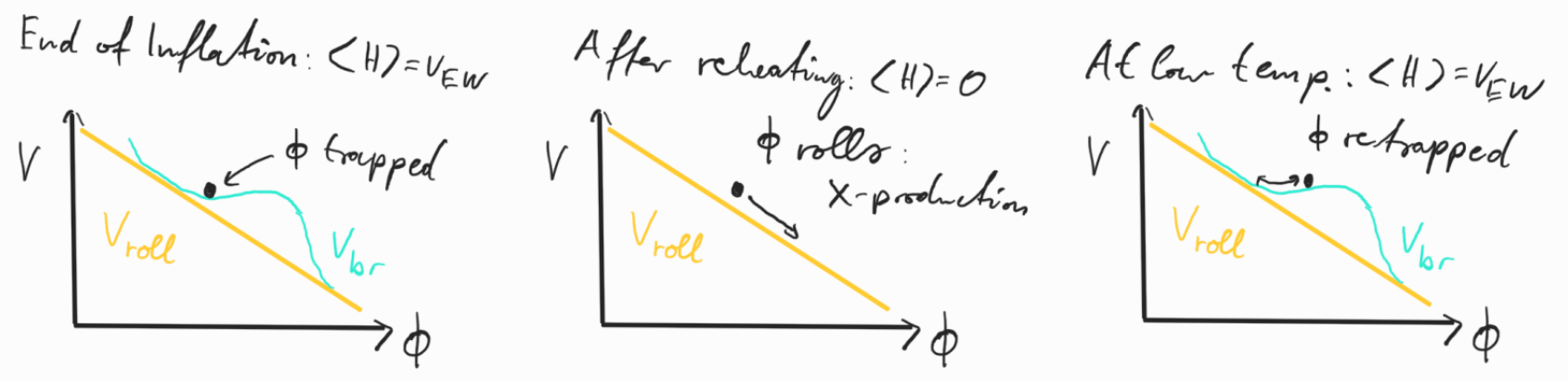
Audible Relaxion

Setup:

$$-\mathcal{L} \supset V(H,\phi) + \frac{\alpha}{4}\frac{\phi}{f} X_{\mu\nu}\widetilde{X}^{\mu\nu}$$

$$V(H,\phi) = V_{\text{roll}}(\phi) + \mu_H^2(\phi)|H|^2 + \lambda|H|^4 + V_{\text{br}}(H,\phi)$$

Evolution:



Results:

- Dark photon friction essential for retrapping
- Potentially observable GW signal

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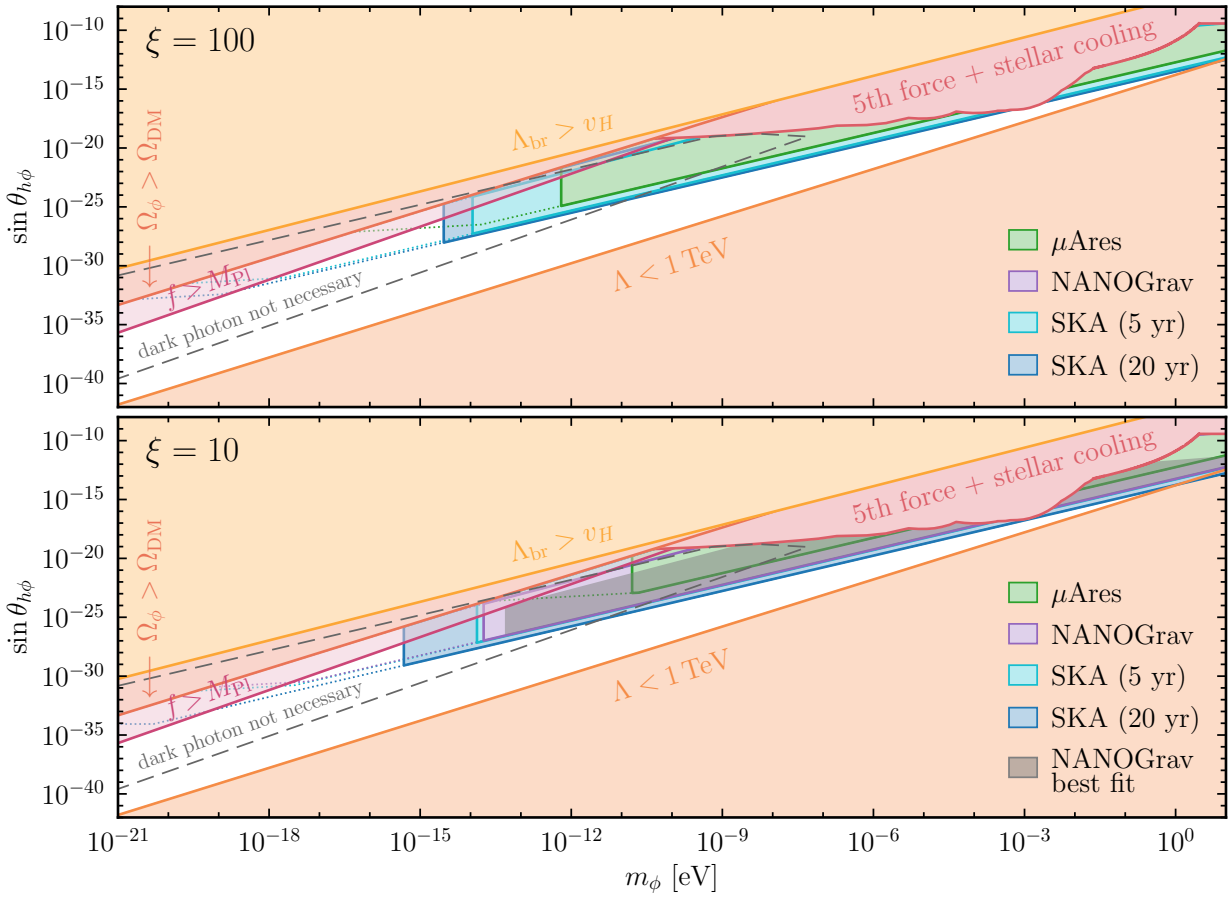


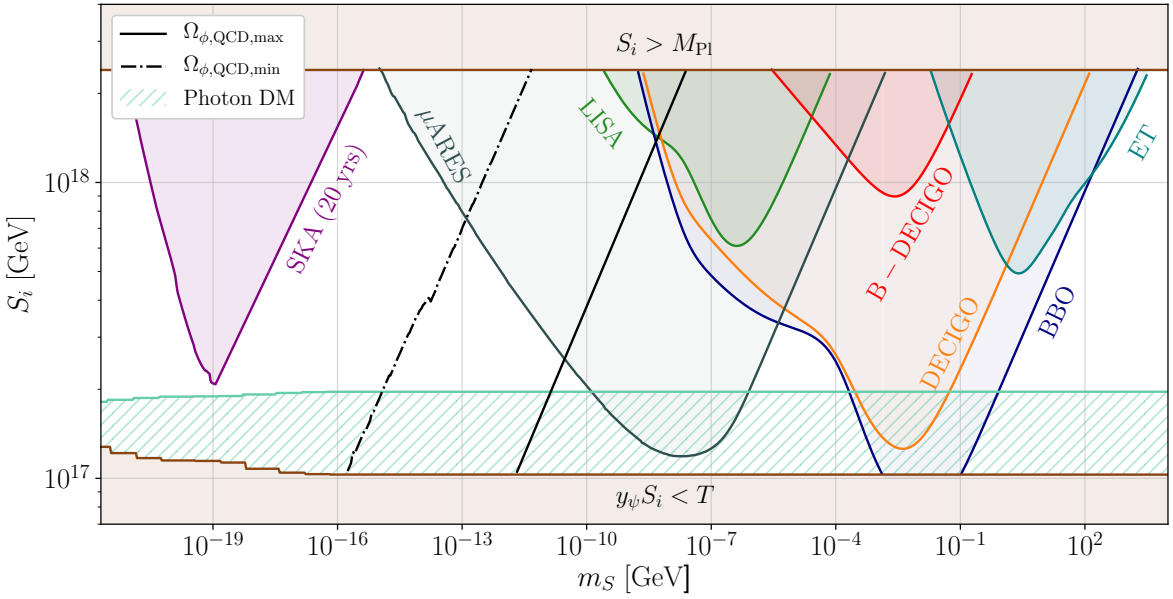
Banerjee, Madge, Perez, WR, Schwaller '21

Kinetic Misalignment

Consider the case of large initial $\dot{\phi}$ (Affleck–Dine):

- Detectable signal for smaller decay constants f / smaller couplings α
- Fix ALP mass to fit DM abundance
- Consistent with Axiogenesis

With $f = 5 \times 10^{13}$GeV and $\alpha = 10^{-2}$:



From Madge, WR, Schmitt, Schwaller (in preperation)

See also Co, Hall, Harigaya '20 and Co, Harigaya, Pierce '21

Conclusion

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

- Tachyonic production of Dark Photon

-Tachyonic particle production frequently used in model building: Inflation, Reheating, Relaxion, Axion Suppression, Vector DM

- We now have percise numerical simulations

-GWs offer new way to probe axions/ALPs

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Thanks!

Backup

Axion Cosmology: Misalignment Mechanism

End of Inflation

- ϕ homogeneous

Time

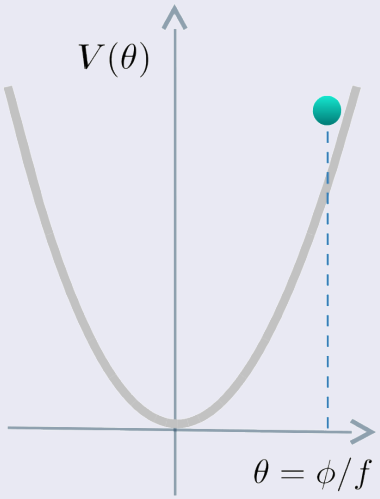
$T \sim f$

Spon. Symmetry Breaking
(Peccei-Quin Symmetry)

- Light Degree of Freedom: Axion ϕ

$T \sim \Lambda$

Small Exp. Breaking (QCD Confines)



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

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 $|\omega_\pm|$

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

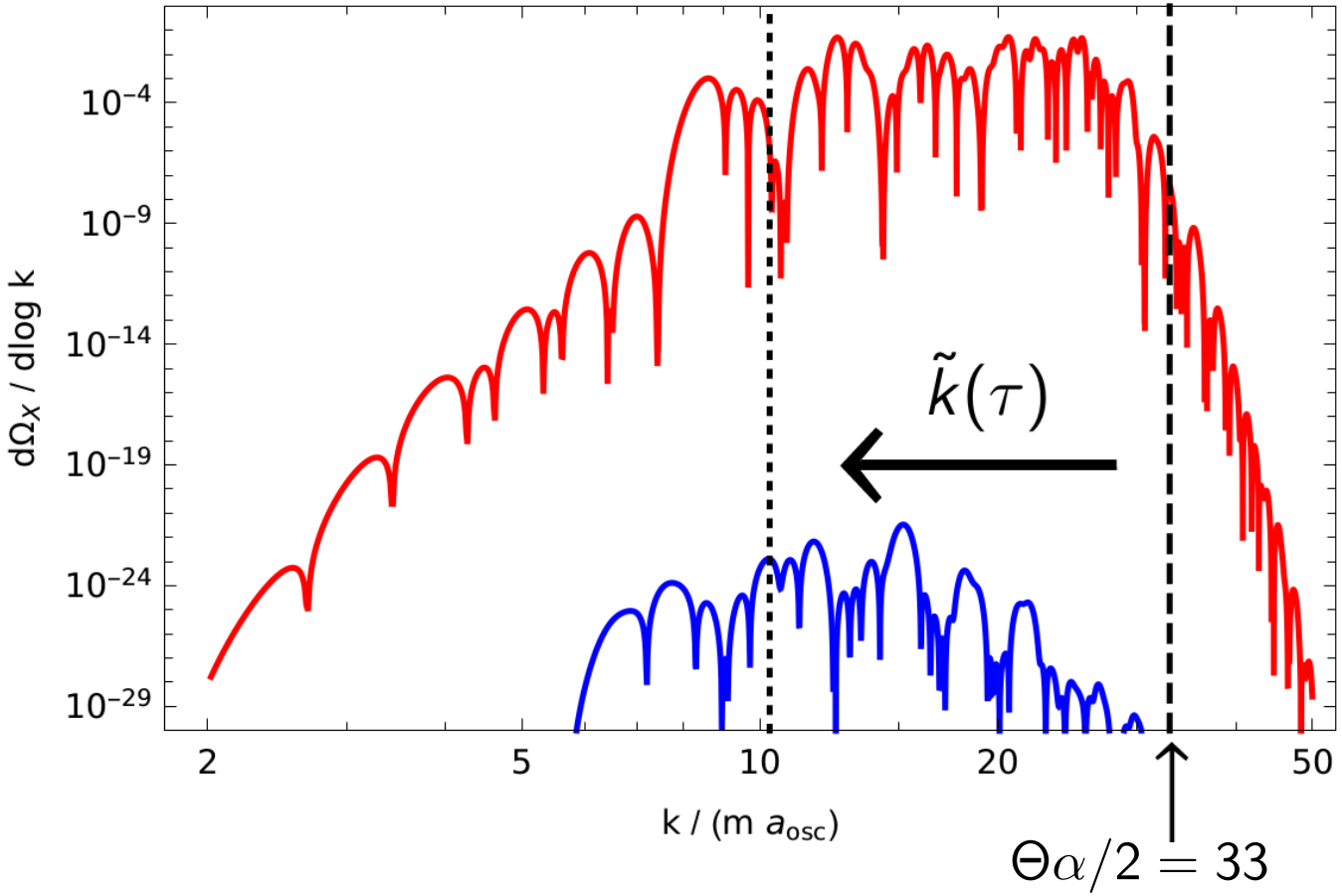
Tachyonic Band closes: $a/a_{osc} = (\theta\alpha/2)^{2/3}$

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

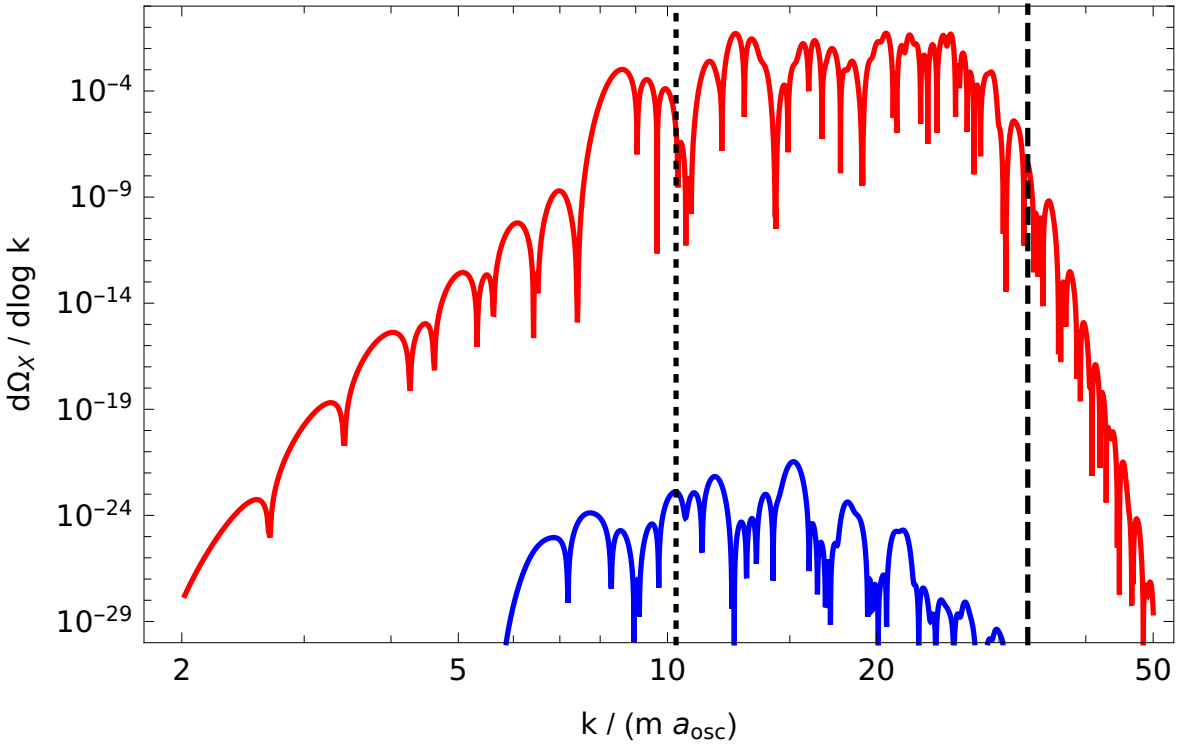
Fastest growing Mode: $\tilde{k}(\tau) = \frac{\alpha}{2f}\phi'(\tau)$

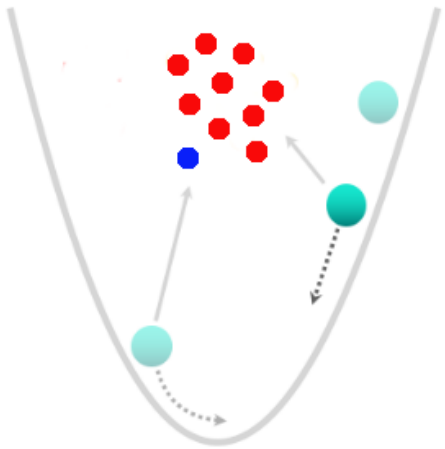


$\Theta = 1.2\ , \quad \alpha = 55$

Polarization of the Spectrum

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





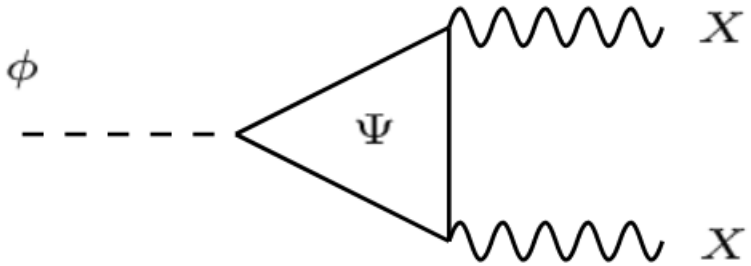
Parity Violation

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

Axion - Dark Photon coupling

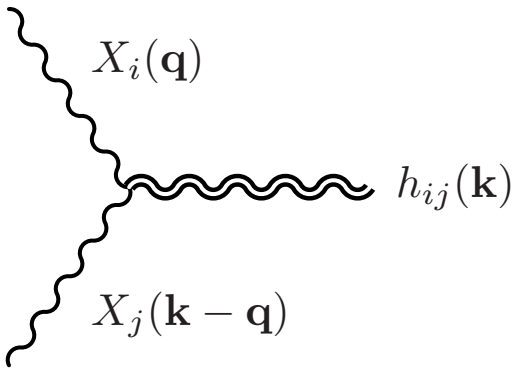
Starting from shift-symmetric coupling to ferminons that carry dark charge e_d, using P.I. and fermion EoM:

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



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

Features of the GW Spectrum



Peak Momentum/Frequency

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

$\hookrightarrow$Axion Mass m determines Peak Frequency

Peak Amplitude

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

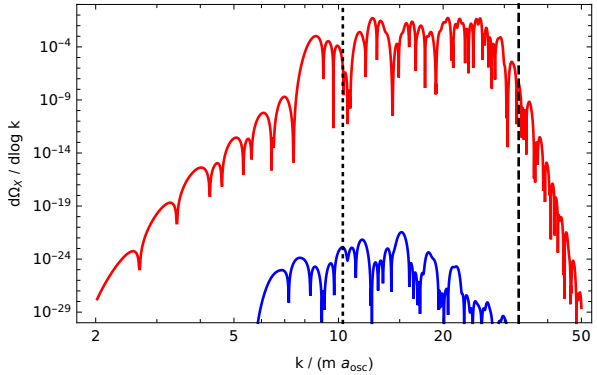
$\Omega_X \approx \Omega_\phi \approx \left(\frac{\Theta f}{m_{\rm pl}}\right)^2$

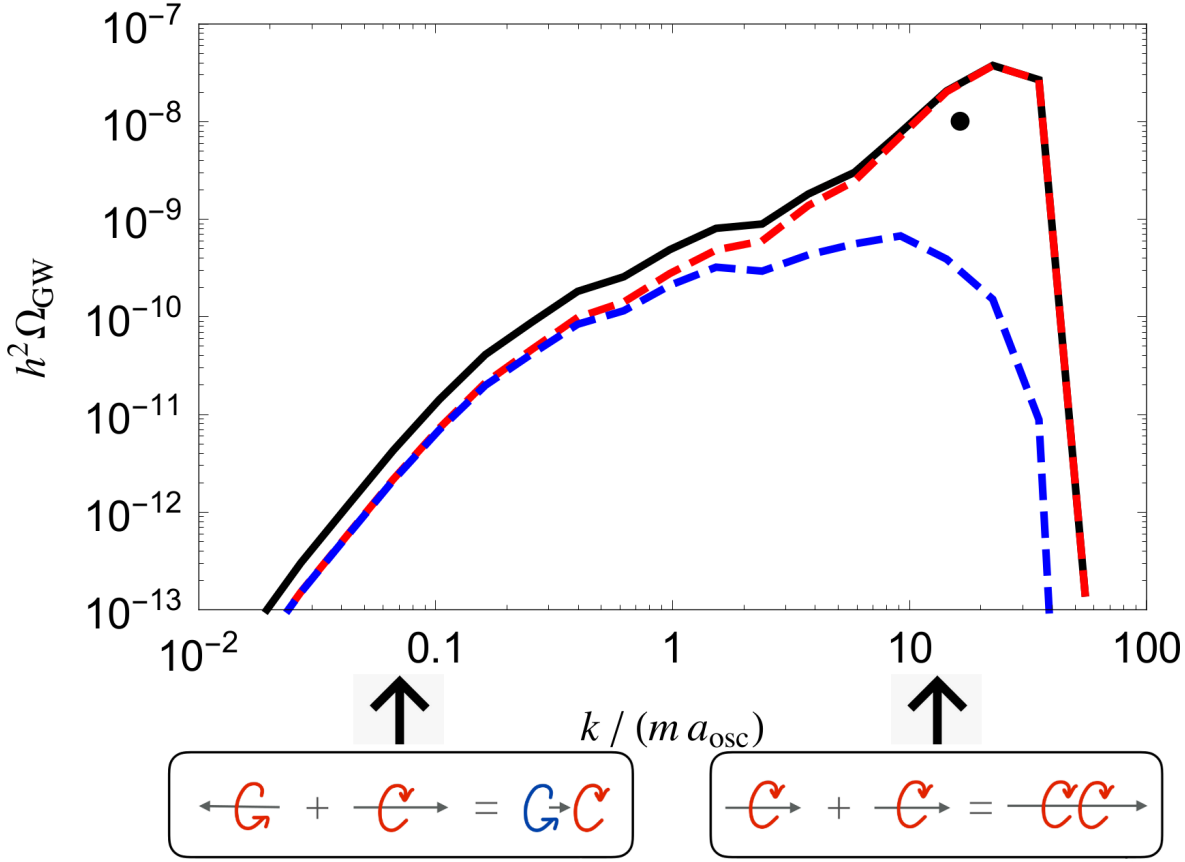
$\hookrightarrow$ f determines Peak Amplitude

$\hookrightarrow$ $f \gtrsim 10^{17}$ 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:

$$f_0^{\mathrm{peak}} \approx (\theta\alpha)^{\frac{2}{3}}\, T_0 \left(\frac{g_{s,\mathrm{eq}}}{g_{s,*}}\right)^{\frac{1}{3}} \left(\frac{m}{m_{\mathrm{pl}}}\right)^{\frac{1}{2}}$$

$$\approx 6 \times 10^{-4}\ \mathrm{Hz} \left(\frac{\alpha\theta}{66}\right)^{\frac{2}{3}} \left(\frac{m}{10\,\mathrm{meV}}\right)^{\frac{1}{2}} .$$

Amplitude

$$\Omega_{\mathrm{GW}}^0 = \Omega_{\mathrm{GW}}^* \left(\frac{g_{s,\mathrm{eq}}}{g_{s,*}}\right)^{\frac{4}{3}} \left(\frac{g_{\rho,*}}{g_{\rho,0}^{\gamma}}\right) \Omega_\gamma^0$$

$$\approx 1.67 \times 10^{-4}\, g_{\rho,*}^{-1/3}\, \Omega_{\mathrm{GW}}^* .$$