CMB Distortions From an Axion-Dark Photon-Photon Interaction

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Probing Axion Dark Matter

Dark Sector

Dark Matter: Axion ϕ

$10^{-22}\text{eV} < m_{\text{a}} < 10^{-13}\text{eV}$

Dark Photon A_D^{μ}

$m_{\text{D}} < 10^{-7}\ \text{eV}$

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Dark Photon A_D^μ

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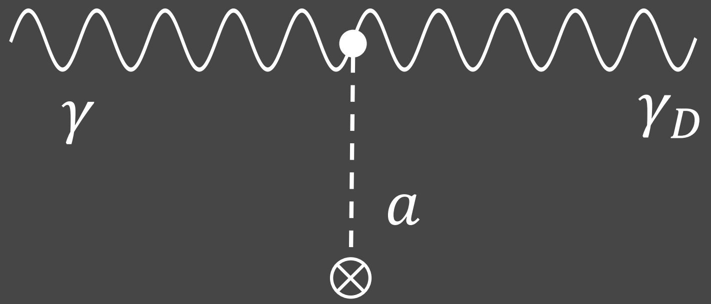
$m_\text{D} < 10^{-7}$ eV

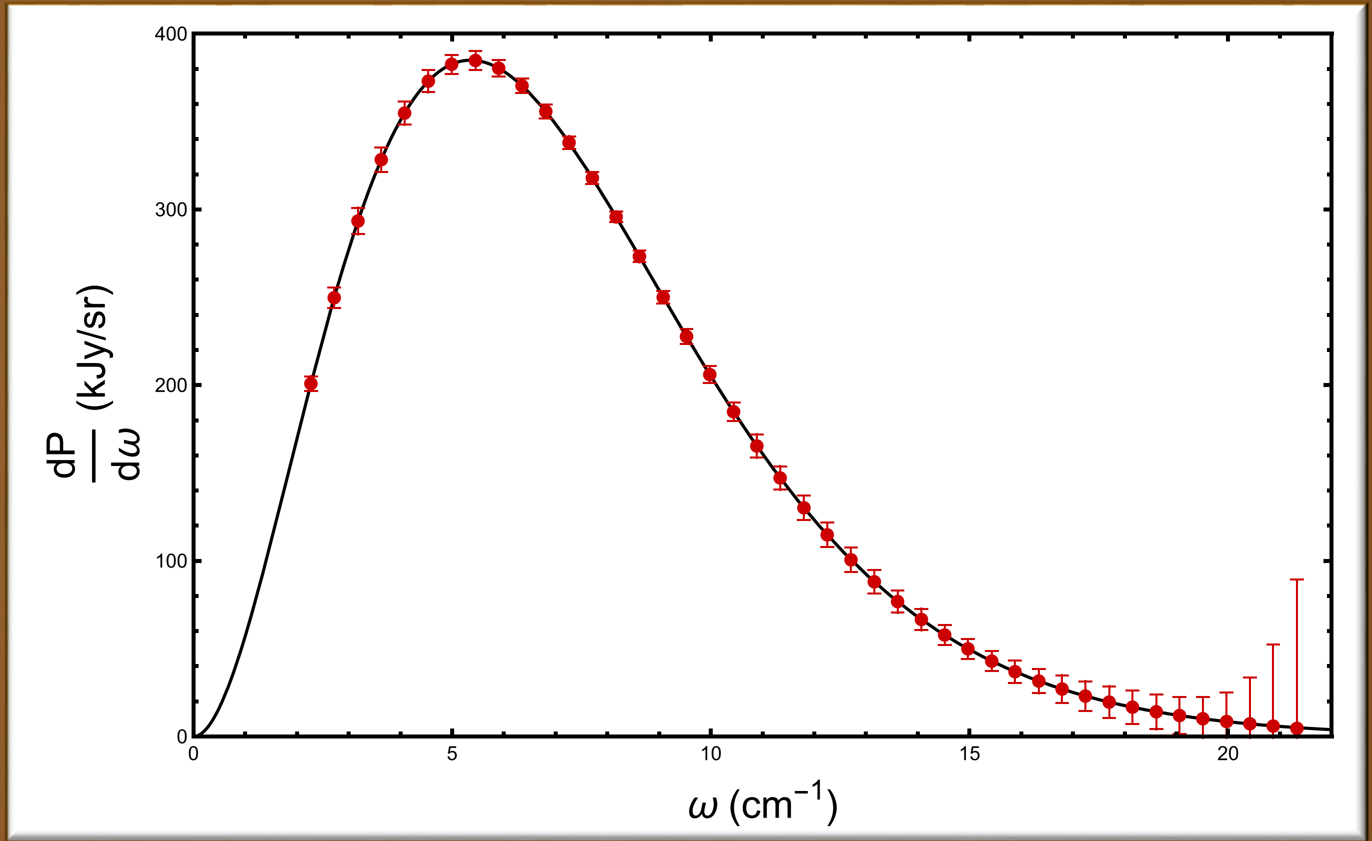
Lowest order coupling:

$\mathcal{L} \supset \frac{\phi}{2f_a}\tilde{F}^D_{\mu\nu}F^{\mu\nu}$ where $\tilde{F}^D_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}$



Cosmic Microwave Background (CMB)

FIRAS: CMB Monopole Spectrum



Fixsen et al. 1996, Astrophysical Journal, 473, 576

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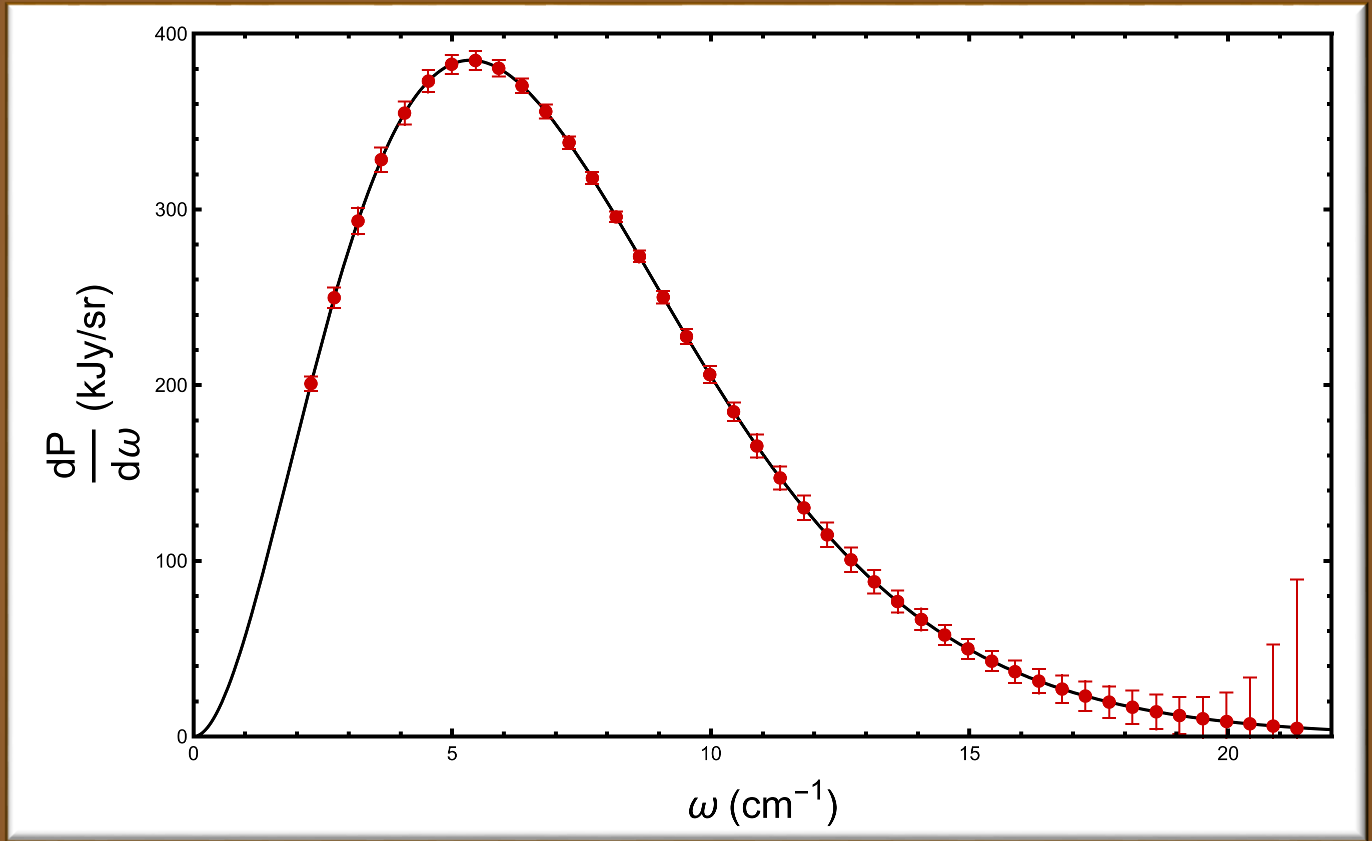
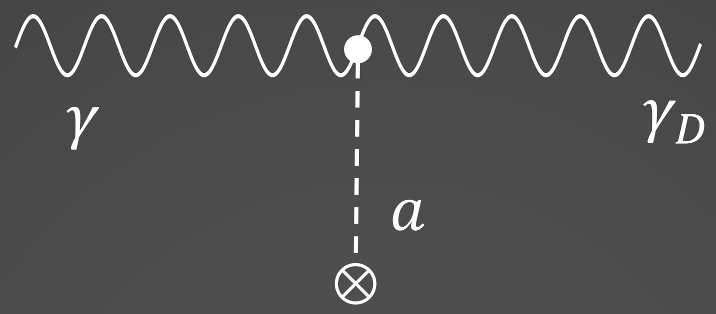


*Error bars are increased by a factor of 300

- Power spectrum matches perfect blackbody to 10^{-4} – 10^{-5} precission
- Any effect that would cause a deviation is highly constrained

Fixsen et al. 1996, Astrophysical Journal, 473, 576

CMB Distortion



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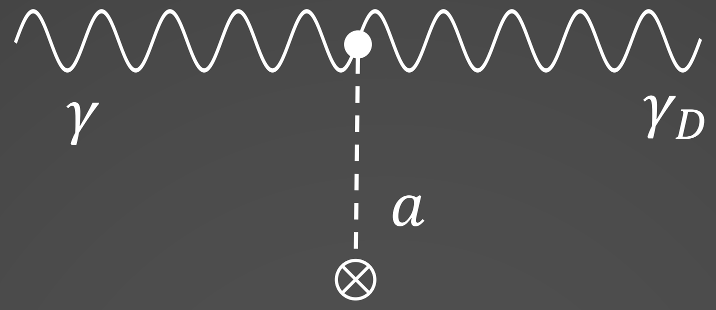

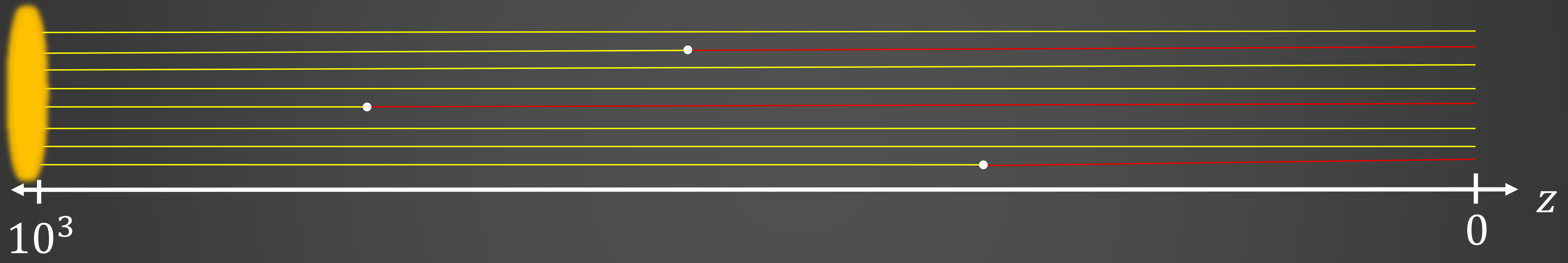

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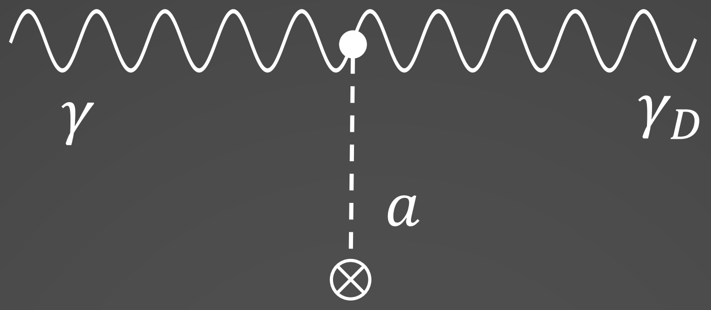

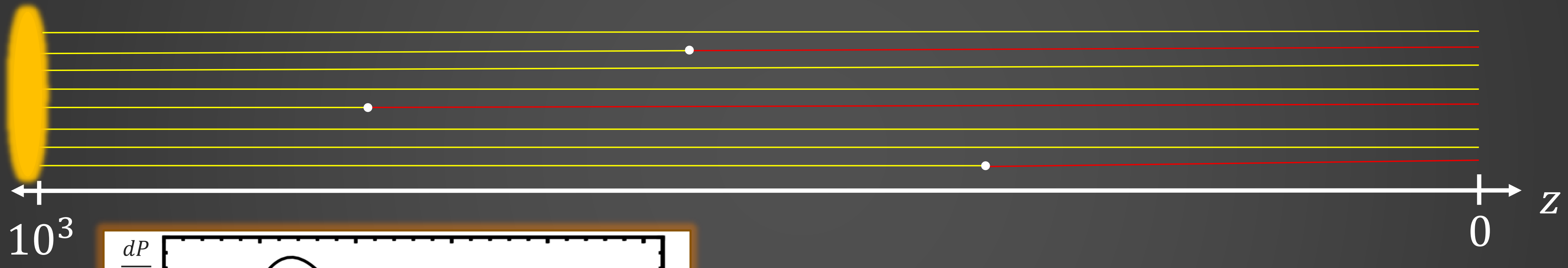

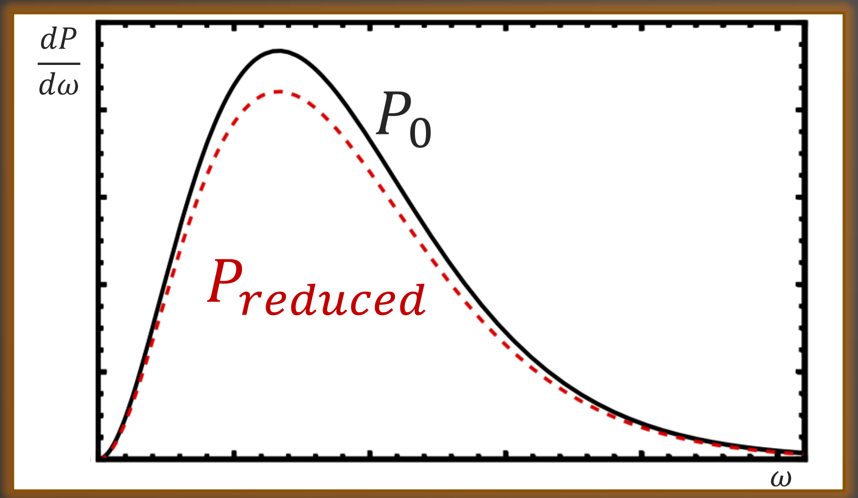

$$P_{reduced}(\omega) = P_0(\omega)(1 - \epsilon(\omega))$$

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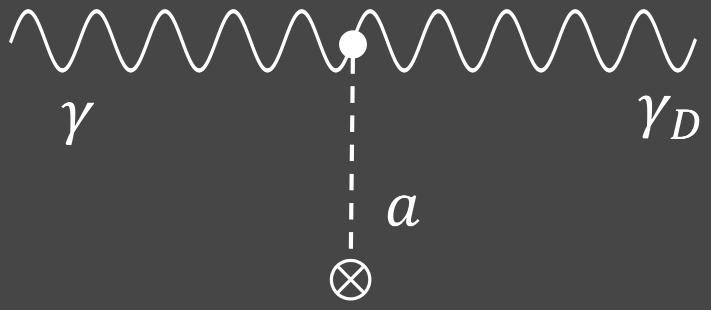

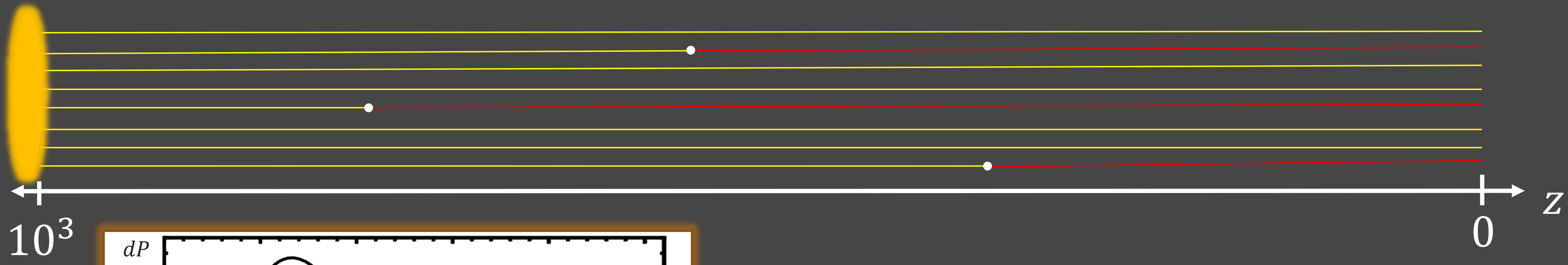

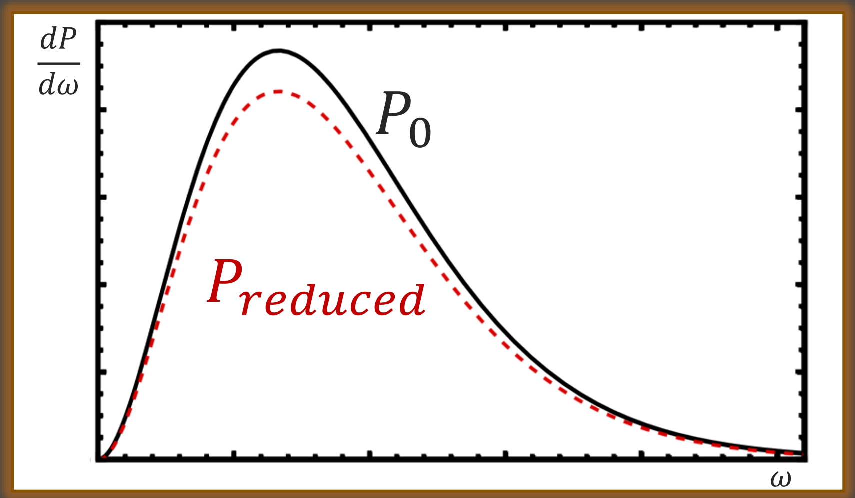

$$P_{reduced}(\omega) = P_0(\omega)(1 - \epsilon(\omega))$$

$\epsilon(\omega)$ is the proportion of photons lost in each mode ω

$$\epsilon(\omega) = \frac{n_D(\omega)}{n_\gamma(\omega)} = \frac{\overline{\left|\tilde{A}_D(\omega)\right|^2}}{\overline{\left|\tilde{A}(\omega)\right|^2}}$$

Equations of Motion

FRLW Expanding Universe: $ds^2 = dt^2 - a^2(t)d\boldsymbol{x}^2 = a^2(\eta)(d\eta^2 - d\boldsymbol{x}^2)$

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Changes in A and ϕ are second order in $\frac{1}{f_a}$

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Changes in A and ϕ are second order in $\frac{1}{f_a}$

Treat the photon and axion as static backgrounds

Solve for A_D using Greens functions

$$\epsilon(|\boldsymbol{k}|) = \frac{\overline{|\tilde{A}_D(|\boldsymbol{k}|)|^2}}{\overline{|\tilde{A}(|\boldsymbol{k}|)|^2}} = \frac{1}{4f_a^2}\left|\int_{t_0}^{t} dt\, e^{i\int_{t_0}^{t'} d\tilde{t}\left(\omega_D(\tilde{t})-\omega_\gamma(\tilde{t})\right)}\partial_t\phi(t')\right|^2$$

Limits of the distortion

$$\epsilon(|\boldsymbol{k}|) = \frac{1}{4f_a^2}\left|\int_{t_0}^{t} dt'\, \underbrace{e^{i\int_{t_0}^{t'} d\tilde{t}\left(\omega_D(\tilde{t})-\omega_\gamma(\tilde{t})\right)}}_{\omega_D-\omega_\gamma}\,\underbrace{\partial_t\phi(t')}_{m_a}\right|^2$$

Oscillates at: $\omega_D - \omega_\gamma$ m_a

Axion is nonrelativistic:

$$\phi(x) = \frac{\phi_0}{a^{3/2}(t)}\cos(m_a t + \beta)$$

Photon and Dark Photon are relativistic:

$$\omega_D - \omega_\gamma \approx \frac{a(t)}{2|\boldsymbol{k}|}\left(m_D^2 - m_\gamma^2(t)\right)$$

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Limit 1: $m_a \gg \left|\omega_D - \omega_\gamma\right|$:

Exponential is constant

$$\epsilon(|\boldsymbol{k}|) = \frac{\phi_0^2}{8f_a^2 a_*^3} = \frac{\rho_{DM}}{4\, f_a^2 m_a^2 a_*^3}$$

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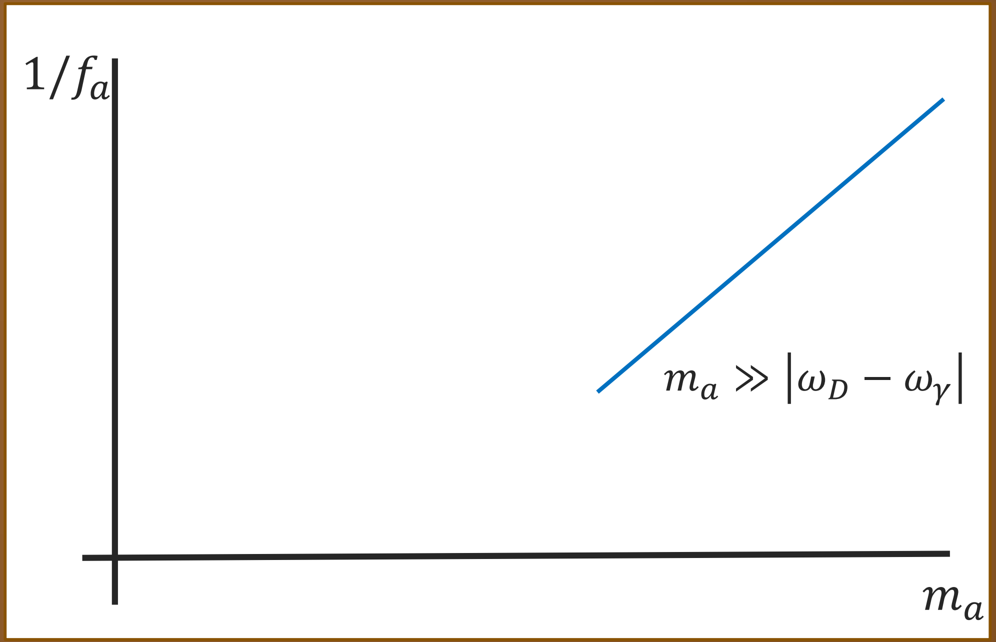

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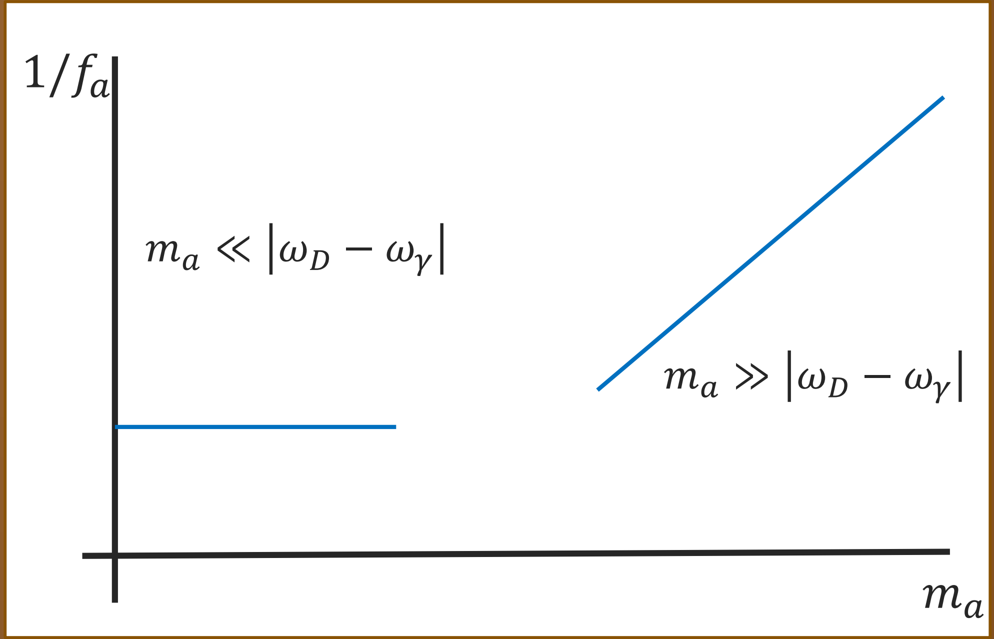
The bound on $\frac{1}{f_a}$ in independent of m_a



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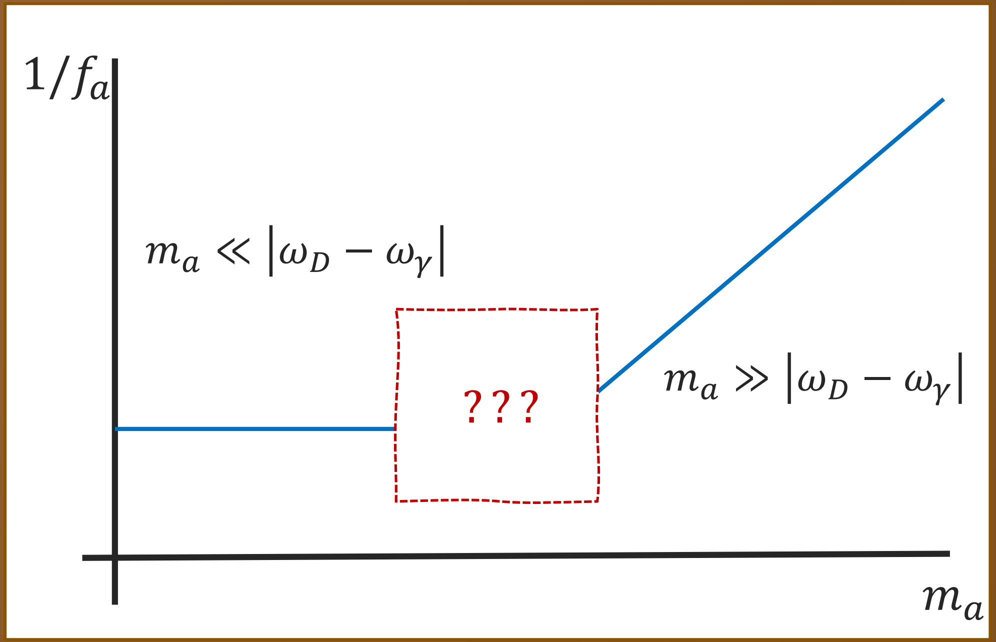

Limits of the distortion: Resonance

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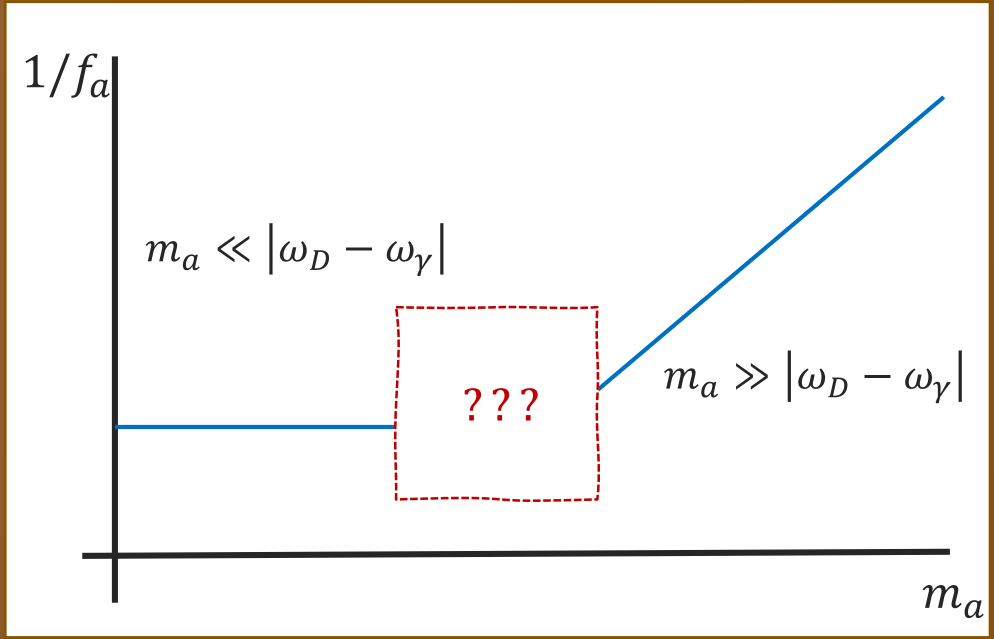
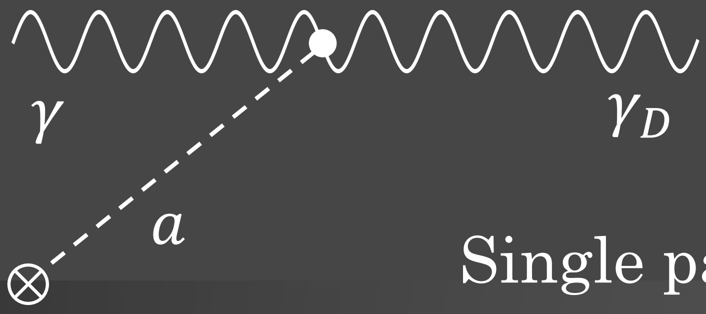
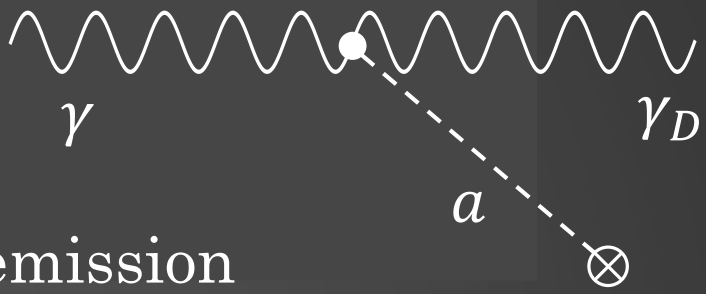


Limits of the distortion: Resonance

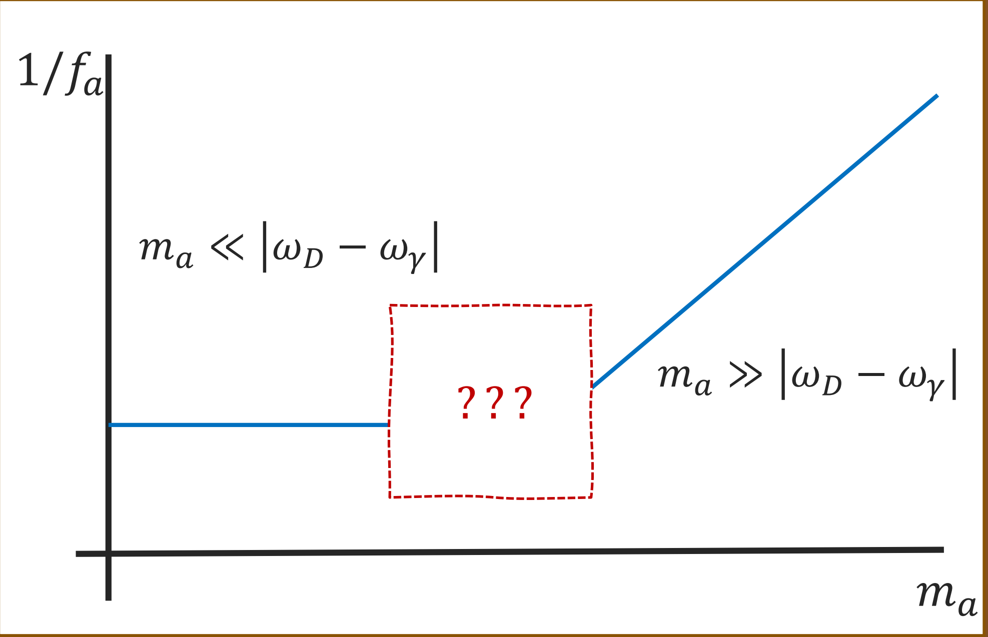
$$|\omega_D - \omega_\gamma| \approx m_a$$





Single particle absorption/emission

Driven SHO Analogy: Axion drives conversion at the resonant frequency



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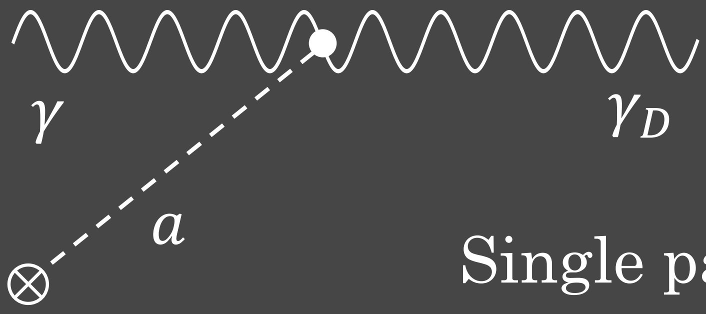

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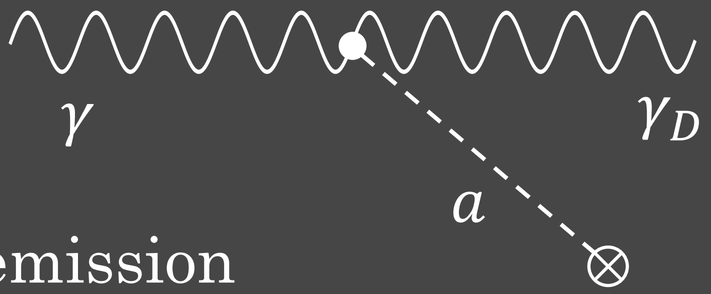
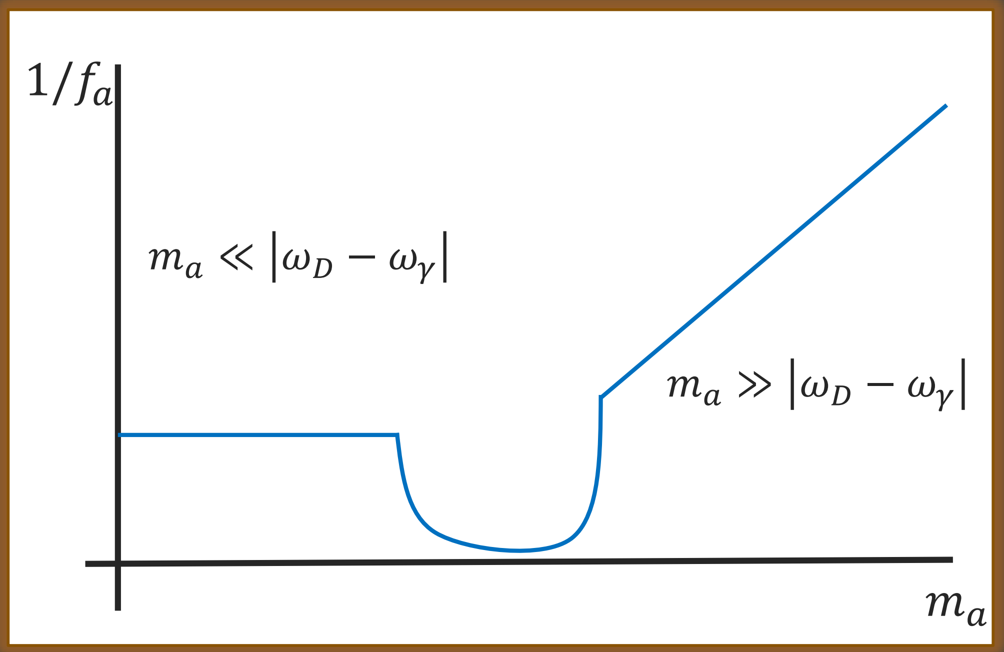


Driven SHO Analogy: Axion drives conversion at the resonant frequency

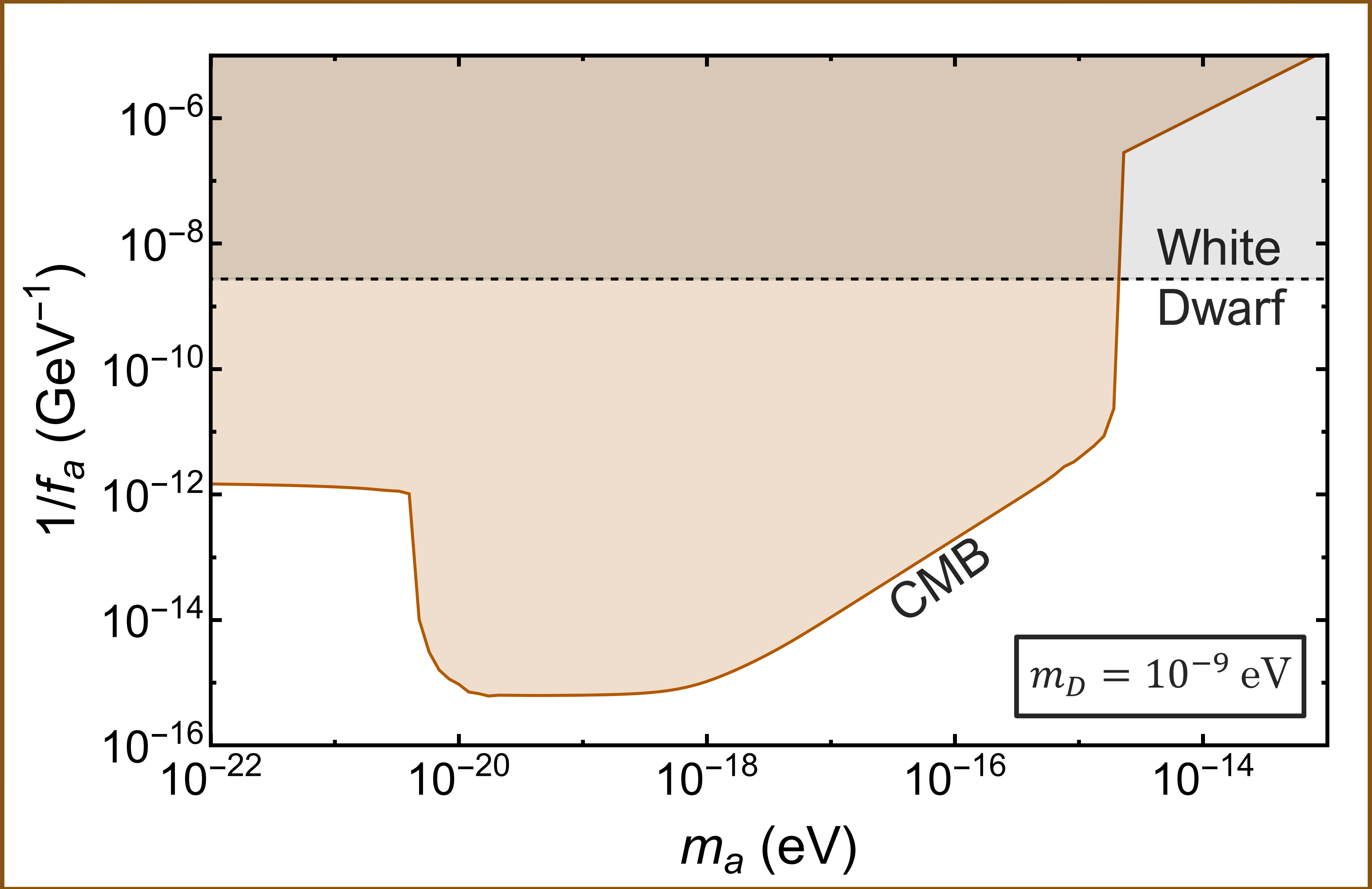
$$\epsilon_{res}(|\boldsymbol{k}|) \sim \frac{\rho_{DM}}{f_a^2 H |\omega_D - \omega_\gamma|} = \frac{\rho_{DM}}{f_a^2 H m_a}$$

$$\frac{\epsilon_{res}(|\boldsymbol{k}|)}{\epsilon_{non-res}(|\boldsymbol{k}|)} = \frac{m_a}{H} \gtrsim \frac{10^{-19} eV}{10^{-29} eV} = 10^{10}$$

Resonance can enhance conversation to dark photons by factors $\gtrsim$ 10^{10}!



Bounds on Coupling



White Dwarf Bound: A. Hook, G. Marques-Tavares and C. Ristow, JHEP 06, 167 (2021)

Conclusion

- Interactions that couple photons to dark matter (axion) and another dark sector particle (dark photon) can be highly constrained by CMB monopole spectrum
- Careful treatment of the various effects (expanding universe, plasma) is necessary and can improve naïve bounds by several orders of magnitude

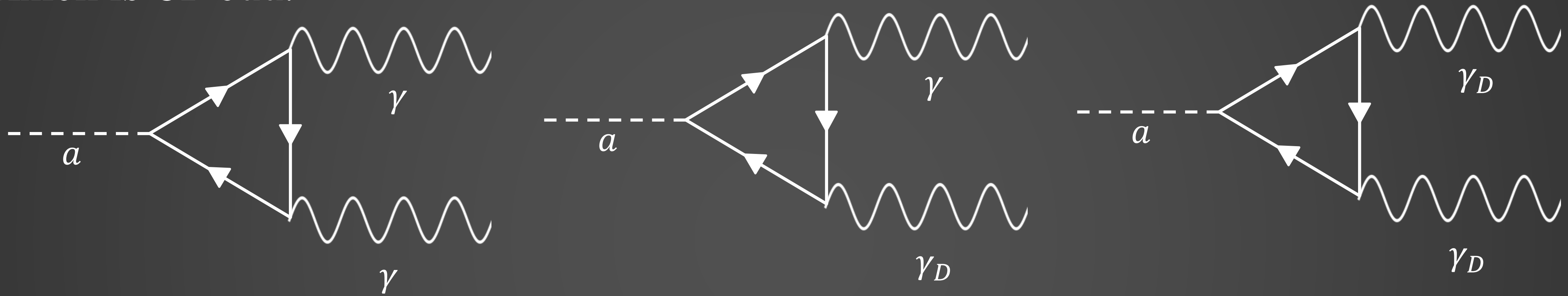
Thanks

- Anson Hook and Gustavo Marques-Tavares
- University of Maryland, MCFP, NSF
- PHENO 2022 and the University of Pittsburgh

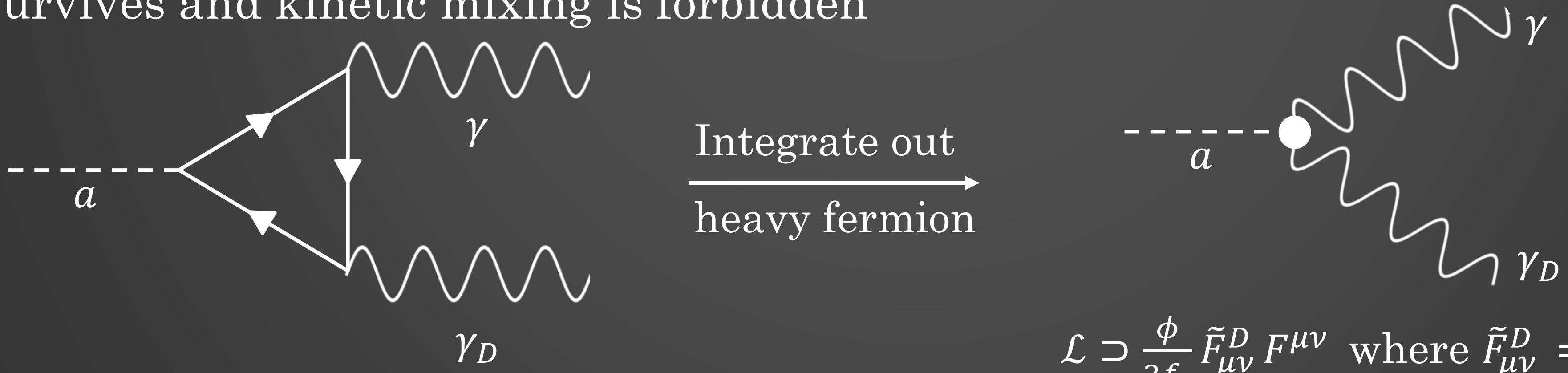
Backup Slides

Coupling

- Start with Axion (ϕ), Photon (A), Dark Photon (A_D), and heavy Fermion (ψ)
- Axion is CP odd:



- Axion is odd under C_D (Dark Charge Conjugation) → only middle diagram survives and kinetic mixing is forbidden



$$\mathcal{L} \supset \frac{\phi}{2f_a} \tilde{F}^D_{\mu\nu} F^{\mu\nu} \text{ where } \tilde{F}^D_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}$$

Kunio Kaneta, Hye-Sung Lee, and Seokhoon Yun *Phys.Rev.Lett.* 118 (2017) 10, 101802

Plasma Effects

Plasma effects change photon dispersion and polarization and give rise to a potential longitudinal polarization (plasmon)

Plasma effects are characterized by scale, $\omega_p \sim \sqrt{\frac{n_e}{m_e}}$

Plasma frequency is largest at recombination: $\omega_p \lesssim 10^{-10}$ eV

Photon momenta is smallest at the present day: $\omega_\gamma \gtrsim 10^{-4}$ eV

We are always working in the limit $\omega_\gamma \gg \omega_p$. In this limit:

- Longitudinal polarizations (plasmons) are forbidden from propagating
- Polarization renormalizations reduce to 1
- The effective dispersion is

$$\omega_\gamma^2 - |\boldsymbol{k}|^2 = m_\gamma^2 \quad \text{where} \quad \omega_p^2 = m_\gamma^2$$

E. Braaten and D. Segel, Phys. Rev. D 48 (1993) 1478–1491

Frequency dependence of distortions

How do the distortions depend on photon momentum $|\mathbf{k}|$?

$\boldsymbol{m_a \gg |\omega_D - \omega_\gamma|}$: $\epsilon(|\boldsymbol{k}|) = \frac{\rho_{DM}}{4\, f_a^2 m_a^2 a_*^3}$ ⟶ $\epsilon(|\boldsymbol{k}|)$ is independent of $|\boldsymbol{k}|$

$\boldsymbol{m_a \ll |\omega_D - \omega_\gamma|}$: $\epsilon(|\boldsymbol{k}|) = \frac{\rho_{DM}}{4\, f_a^2 a_*^3 (\omega_D - \omega_\gamma)^2}$ ⟶ $\omega_D - \omega_\gamma \sim \frac{\Delta m^2}{|\boldsymbol{k}|}$ ⟶ $\epsilon(|\boldsymbol{k}|) \sim |\boldsymbol{k}|^2$

Resonant Region: $\epsilon(|\boldsymbol{k}|) = \frac{\rho_{DM}}{8\, f_a^2 a_{res}^3\, H m_a}$

$|\mathbf{k}|$ dependence is found by determining where resonance happened

$$m_a = \Delta\omega(a_{res}) = \frac{a_{res}}{|\boldsymbol{k}|}\Delta m^2 \longrightarrow a_{res} = \frac{|\boldsymbol{k}| m_a}{\Delta m^2}$$

Matter Domination: $H \sim a^{-3/2}$

$$\epsilon_{res}(|\boldsymbol{k}|) \sim a_{res}^{-3/2} \sim |\boldsymbol{k}|^{-3/2}$$

Green's Functions

- Fourier Transform in space,
- Solve the free equations for $\eta > \eta'$
- Derive Boundary matching conditions from E.o.M.
- Do boundary matching between the two regions

$$G_{\mu\nu}(x,x') = \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} \sum_{\lambda=1,2,L} \frac{\epsilon_\mu^\lambda(\boldsymbol{k},\eta)\epsilon^{*\lambda}_{\nu}(\boldsymbol{k},\eta')}{\sqrt{\omega_D(\eta)\omega_D(\eta')}} e^{-i(\int_{\eta'}^{\eta} \int d\tilde{\eta}\omega_D(\tilde{\eta}) - \boldsymbol{k}\cdot(\boldsymbol{x}-\boldsymbol{x}'))} + h.c.$$

Compare with flat space Greens Function:

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