~~Audible Axions~~, ~~the Sound of Saxions~~, and Reverb from Relaxions

– GWs from ALP dark-photon systems –

[Axions: Machado, Ratzinger, Schwaller, Stefanek – 1811.01950, 1912.01007
(Lattice: " " " – 2012.11584)]

Kin. Misalignment: EM, Ratzinger, Schmitt, Schwaller – 2111.12730

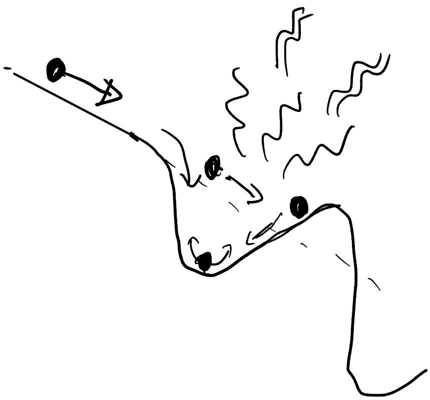
Relaxion: Banerjee, EM, Perez, Ratzinger, Schwaller – 2105.12135

Gravitational Wave Echo from Relaxion Trapping

- Relaxion + dark photon: $\mathcal{L} \supset -V(H,\phi) - \frac{r_x}{4}\frac{\phi}{f_\phi} X_{\mu\nu}\tilde{X}^{\mu\nu}$

$$V(H,\phi) = \underbrace{(\Lambda^2 - g\Lambda\phi)}_{\mu^2(\phi)}|H|^2 - \overset{c\sim 1}{c}\, g\Lambda^3\phi - \Lambda_{br}^4 \frac{|H|^2}{v_H^2}\cos\frac{\phi}{f_\phi}$$

$\langle H\rangle \sim v_H \Rightarrow g\Lambda^3 \sim \Lambda_{br}^4/f_\phi$



- EoM:

$$\ddot{\phi} + 3H\dot{\phi} - \frac{\Lambda_{br}^4}{f_\phi} + \frac{r_x}{f_\phi}\frac{\langle \tilde{X}_{\mu\nu}X^{\mu\nu}\rangle}{4a^4} = 0$$

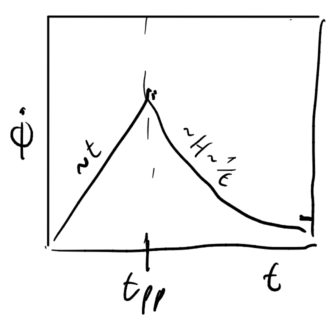
$$X''_\lambda(\tau,k) + \underbrace{\left(k^2 - \lambda k \frac{r_x\phi'(\tau)}{f_\phi}\right)}_{\omega^2(k)} X_\lambda(\tau,k) = 0$$

- tachyonic modes: $k < r_x\Theta'$
- largest growth: $\tilde{k} = \frac{r_x\Theta'}{2}$, $\tilde{\omega} = \tilde{k}$

- initially: $\langle X\tilde{X}\rangle \sim 0 \Rightarrow \dot{\phi} \sim t$
- particle production: $\langle X\tilde{X}\rangle \sim \Lambda_{br}^4$

WKB: $\langle X\tilde{X}\rangle \sim e^{r_x\Theta'/aH}$

$$\Rightarrow \Theta' = \frac{\xi}{r_x} aH, \quad \xi \sim \mathcal{O}(10\text{-}100)$$



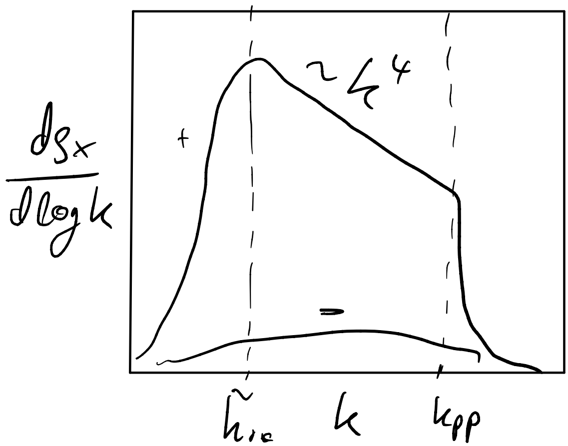
• DP spectrum: $X_+(\tau,k) = \begin{cases} A_k \cos(k\tau - \xi), & \tilde{k}(\tau) < k < k_{pp} \\ 0 & \text{otherwise} \end{cases}$

$$\Delta\rho_X \sim \frac{k^4}{a^4}|A_k|^2 \Delta k \sim \frac{\tilde{a}_k^4}{a^4}\Delta V \sim \frac{\tilde{a}_k^4}{a^4}\Lambda_{br}^4 \Delta\Theta$$

$$\sim \frac{\tilde{a}_k^4}{a^4}\Lambda_{br}^4 \frac{\xi}{r_X}\frac{\Delta\tilde{\tau}}{\tilde{\tau}} \sim \frac{\tilde{a}_k^4}{a^4}\Lambda_{br}^4 \frac{\xi}{r_X}\frac{\Delta k}{k}, \quad \tilde{a}_k \sim \frac{1}{k}$$

$$\Rightarrow A_k \sim \Lambda_{br}^2 \sqrt{\frac{\xi}{r_X}}\, k^{-9/2}$$

$$\Rightarrow \frac{d\rho_X}{d\log k} \sim k^{-4}$$



• GW spectrum:

$$(\partial_\tau^2 + k^2)\, a(\tau)\, h_{ij}(\tau,\vec{k}) = \frac{2a(\tau)}{M_{pl}^2}\Pi_{ij}(\tau,\vec{k})$$

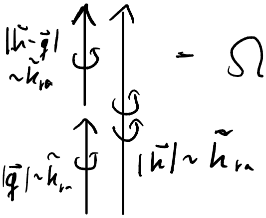
$$\Pi_{ij}(\tau,k) = -\frac{\Lambda_{ij}^{kl}}{a^2}\int\frac{d^3q}{(2\pi)^3}\left[E_k(\vec{q},\tau)\,E_l(\vec{k}-\vec{q},\tau) + (E\to B)\right]$$

$$\rho_{GW} = \frac{M_{pl}^2}{4a^2}\langle h'_{ij} h'^{ij}\rangle = \int d\log k\, \frac{M_{pl}^2 k^3}{8\pi^2 a^2} P_h(k,\tau)$$

• production at τ_{ra}:

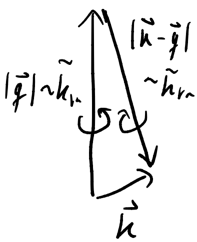
peak:

- $f_p \sim \dfrac{\tilde{k}_{ra}}{a_0} \sim \dfrac{a_{ra}}{a_0}\xi H_{ra} \sim 1\,\mu\text{Hz}\left(\dfrac{\xi}{25}\right)\left(\dfrac{T_{ra}}{1\,\text{GeV}}\right)$

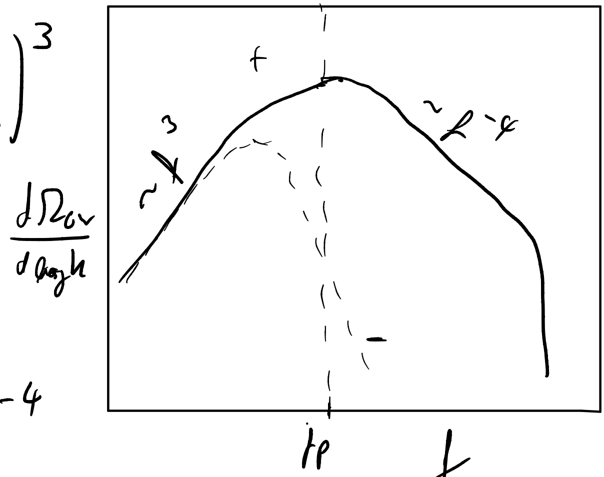


- $\Omega_p \sim \left(\dfrac{a_{ra}}{a_0}\right)^4 \dfrac{\left(\rho_\phi^{ra}/\tilde{k}_{ra}\right)^2}{M_{pl}^2\,\rho_c} \sim 10^{-10}\left(\dfrac{25}{\xi}\right)^2\left(\dfrac{m_\phi f_\phi}{T_{ra}^2}\right)^4$

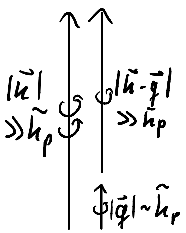
IR: $f \ll f_p$



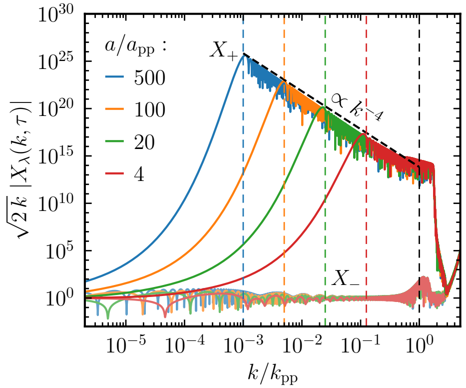
- $\Omega_{IR} \sim \Omega_p\,\xi^2\left(\dfrac{f}{f_p}\right)^3$
- unpolarized



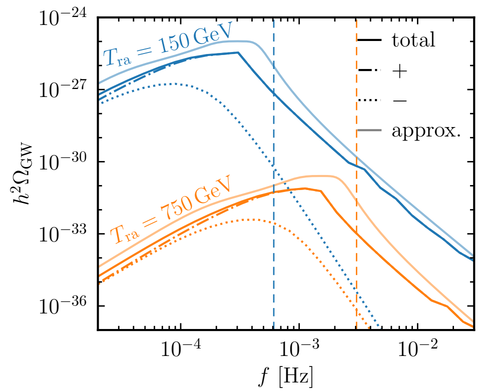
UV: $f \gg f_p$



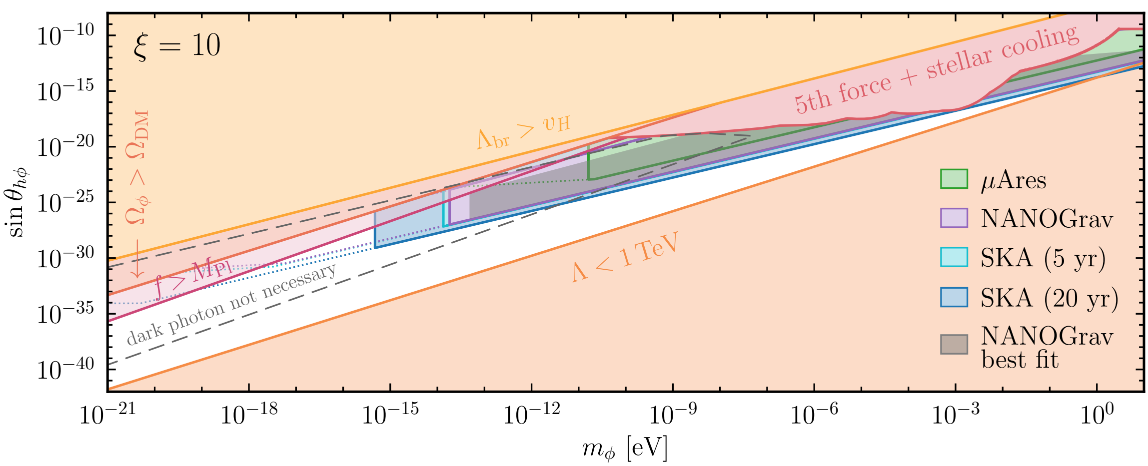
- $\Omega_{UV} \sim \Omega_p\left(\dfrac{f}{f_p}\right)^{-4}$
- polarized



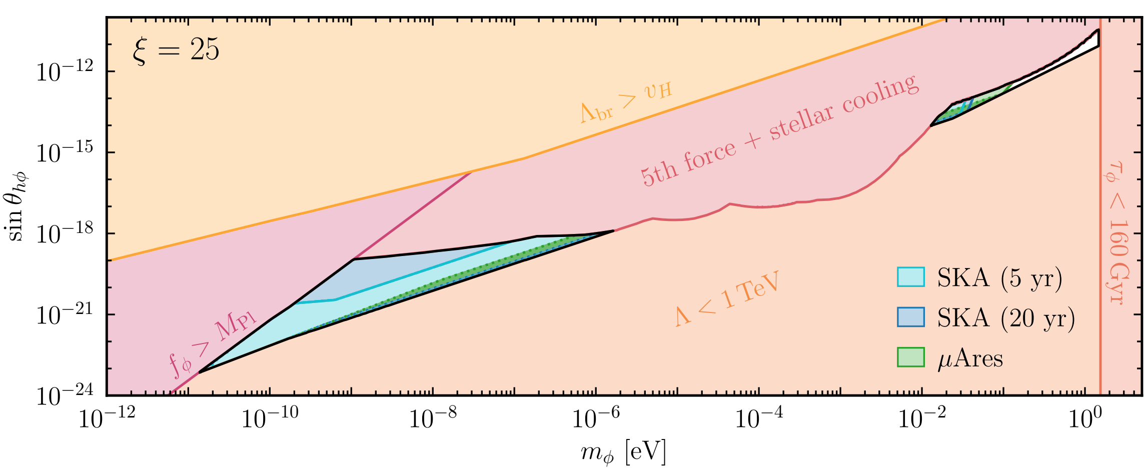
$a/a_{\rm pp}$:
500
100
20
4
X_+
X_-
$\propto k^{-4}$
$\sqrt{2k}\,|X_\lambda(k,\tau)|$
$k/k_{\rm pp}$



$T_{\rm ra} = 150$ GeV
$T_{\rm ra} = 750$ GeV
total
+
−
approx.
$h^2\Omega_{\rm GW}$
f [Hz]



$\xi = 10$
$\Lambda_{\rm br} > v_H$
5th force + stellar cooling
$\longleftarrow \Omega_\phi > \Omega_{\rm DM}$
$f > M_{\rm Pl}$
dark photon not necessary
$\Lambda < 1$ TeV
μAres
NANOGrav
SKA (5 yr)
SKA (20 yr)
NANOGrav best fit
$\sin\theta_{h\phi}$
m_ϕ [eV]



$\xi = 25$
$\Lambda_{\rm br} > v_H$
5th force + stellar cooling
$f_\phi > M_{\rm Pl}$
$\Lambda < 1$ TeV
$\tau_\phi < 160$ Gyr
SKA (5 yr)
SKA (20 yr)
μAres
$\sin\theta_{h\phi}$
m_ϕ [eV]