Audible axions with a booster

References: 2111.12730 w. Eric Madge, Wolfram Ratzinger, Daniel Schmitt

previous work: 1811.01950, 1912.01007, 2012.11584, 2009.11875

w. Camila Machado, Wolfram Ratzinger, Ben Stefanek

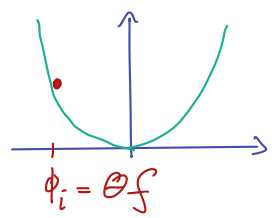
see also: 1708.05008, 1810.07188 (P. Agrawal et al)

1910.02080, 1910.14152, 2104.02077 (R. Co et al, kinetic misalignment)

- Axion misalignment

ALP light pseudoscalar ϕ with potential $U(\phi) \to \frac{d^2U}{d\phi^2} = m_\phi^2$

$$\phi'' + 2aH\phi' + a^2 m_\phi^2 \phi = 0$$



rad. dom: $H \sim T^2/M_{pl}$

PQ before inflation

Oscillations start when $H \sim m_\phi$

↳ redshifts as a^{-3} → scalar field DM.

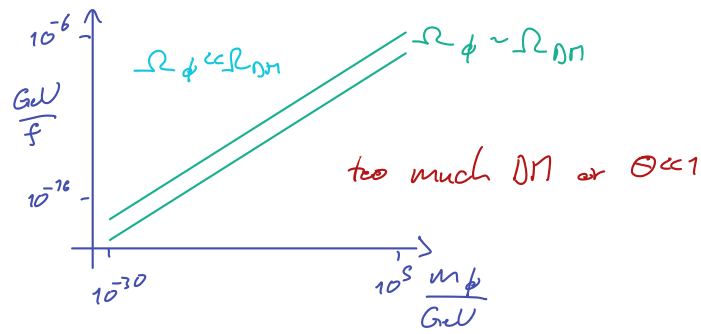
ALP relic abundance

at t_{osc}: $H \approx \frac{T_{osc}^2}{M_{pl}} = m_\phi$

$$\Omega_{\phi,osc} = \frac{\rho_\phi}{\rho_{rad}} \approx \frac{m_\phi^2 \theta^2 f^2}{T_{osc}^4} \approx \frac{\theta^2 f^2}{M_{pl}^2}$$

At matter-radiation equality : $\frac{a_{osc}}{a_{eq}} \sim \frac{\sqrt{m_\phi M_{pl}}}{eV}$

$$\Rightarrow \Omega_{\phi,\text{today}} \sim \theta^2 f^2 \frac{m_\phi^{1/2}}{M_{pl}^{3/2}\, eV}$$



• Add a dark photon $\quad \frac{\alpha}{4f}\phi X_{\mu\nu}\tilde{X}^{\mu\nu}$

$$\phi'' + 2aH\phi' + a^2\frac{dV(\phi)}{d\phi} - \frac{\alpha}{fa^2}\underbrace{\vec{X}'\cdot(\nabla\times\vec{X})}_{\propto\, \vec{E}_D\times\vec{B}_D} = 0$$

extra friction damps ALP

$$X_\pm''(\tau,\vec{k}) + \left(k^2 \pm k\frac{\alpha}{f}\phi'(\tau)\right)X_\pm(\tau,\vec{k}) = 0$$

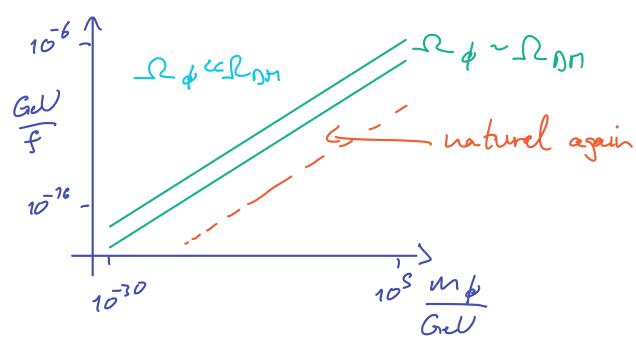
Dark photon mode fn in momentum space

↳ frequency $\quad \omega_\pm^2 = k^2 \mp k\frac{\alpha}{f}\phi'$

Occupation number grows exponentially

$$X(\tau) \propto e^{|\omega|\tau} \quad \text{for} \quad k \sim \frac{\alpha\phi'}{2f}$$

⇒ Very efficient damping of ALP abundance



Some more details: $\phi' \sim \theta f\, a m$

- Growth time $|\omega|^{-1}$ must be smaller than oscillation period: $|\omega|^{-1} \lesssim \frac{1}{am}$

$$\Rightarrow \quad \frac{2f}{\alpha \theta f a m} \lesssim \frac{1}{am} \quad \Leftrightarrow \quad 2 \lesssim \alpha\theta \quad \text{initially}$$

Actually $\alpha\theta \gtrsim 20$ for complete (90%+) energy transfer.

- Polarisation Only one helicity of dark photons produced

- Gravitational wave production

Amplified vacuum fluctuations for scales $\tilde{k} \sim \frac{\alpha\theta\, a m}{2}$

↳ Source of GWs with $k \sim 2\tilde{k} \sim (\alpha\theta)^{2/3}\, m\, a_{osc}$

GW amplitude $\Omega^*_{GW} \sim \Omega_s^2 \left(\frac{a_k^2 H_k^2}{k_{peak}}\right)^2$

$$\sim c_{eff}^2\, \Omega_\phi^2 \left(\frac{\theta^2}{\alpha}\right)^{4/3} \sim c_{eff} \left(\frac{f}{M_{pl}}\right)^4 \left(\frac{\theta^2}{\alpha}\right)^{4/3}$$

Peak frequency today $f_0^{peak} \sim 6 \cdot 10^{-4}\,\text{Hz} \left(\frac{\alpha\theta}{66}\right)^{2/3} \left(\frac{m}{10\,\text{meV}}\right)^{1/2}$

Notes:
- detectable in LISA, PTAs etc for $f \gtrsim 10^{17}$
- strongly chiral
- Relic abundance ↯
- N_{eff} ⇝ $f \lesssim 10^{18}$.
- Backscattering

Can use: - lower f

- remove the DM problem

- have a smaller coupling?

• Kinetic misalignment / spinning axion

Basic idea: $\rho_{\phi,pot} \sim \theta^2 m^2 f^2 \rightsquigarrow \rho_{\phi,kin}$

Now $\rho_{\phi,kin} \propto a^{-6}$ (kination) $\rightarrow$ tachyonic window either open initially or not at all

$\rightsquigarrow$ Need some insight into source of $\rho_{\phi,kin}$

(Toy) model: $P = S \exp(i\theta)$ $\phi = \theta S$, S = saxion

(Co et al) $V(P)$ s.th. $\langle S \rangle = f_\phi$ + PQ breaking at high scale.

$\hookrightarrow$ Will now depend on S_i(initial), m_S.

Dynamics:

$S \gg f_\phi \rightsquigarrow P$ = radiation $\dot{\phi} \propto a^{-2}$, $\rho_\phi \propto a^{-4}$ $S \propto \frac{1}{a}$

$S = f_\phi$ ϕ enters kination $\dot{\phi}^2 \propto a^{-3}$, $\rho_\phi \propto a^{-6}$

$\rho_\phi \leq 2 m_\phi^2 f_\phi^2 \rightsquigarrow$ trapped in minimum, CDM phase

- Tachyon / GW production

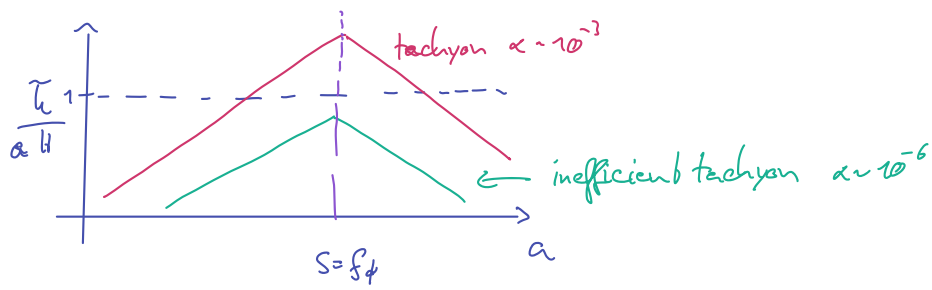
$$\omega_\pm^2 = k^2 \mp k \frac{\alpha}{S} \phi'$$

↑ Since $S > f_\phi$ initially

Growth rate? $\tilde{k}/a \gtrsim H$ ← only scale since ϕ massless

$S > f_\phi$: $\frac{\tilde{k}}{a} = \frac{\alpha}{2S(\tau)} |\dot{\phi}(\tau)| \propto a^{-1}$ → drops slower than $H \sim a^{-2}$.

$S = f_\phi$: $\frac{\tilde{k}}{a} = \frac{\alpha}{2f_\phi} |\dot{\phi}(\tau)| \propto a^{-3}$ → drops faster than $H \sim a^{-2}$.



Rest same as before

$$f_0^{peak} \sim \sqrt{\frac{m_s}{f_\phi} \frac{S_i}{M_{pl}}}$$

$$\Omega_{GW,0} \sim \left(\frac{\Sigma S_i}{M_{pl}}\right)^4$$

→ independent of f_ϕ, m_ϕ

↳ relic density ok.

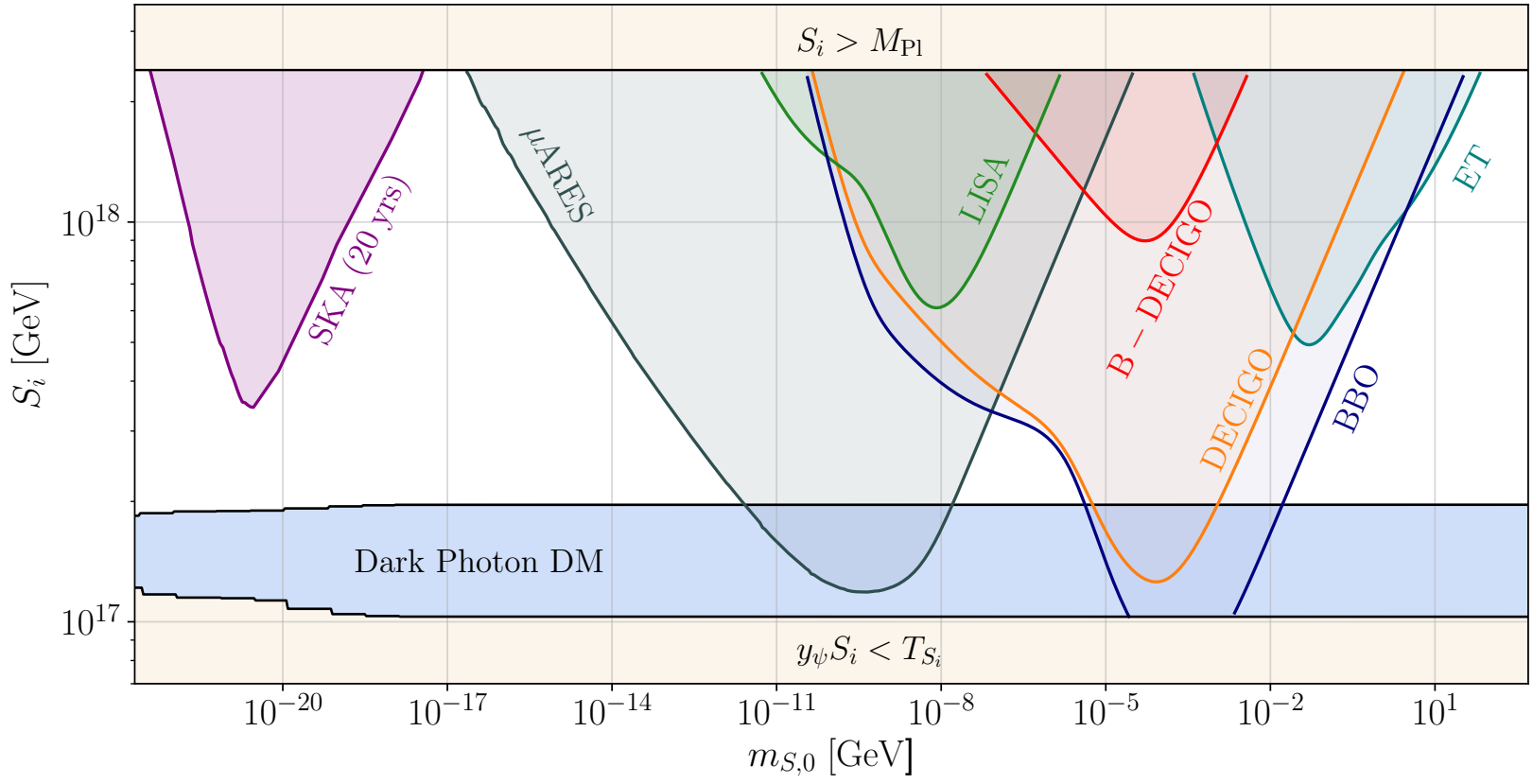
small α.

Mega ? Dark photon fluctuations (or backscattered ALPs)

unsuppressed ⇝ pBH ?

ALP clusters / stars

Also axiogenesis, DM, model building


$S_i > M_{\rm Pl}$
SKA (20 yrs)
μARES
LISA
B – DECIGO
DECIGO
BBO
ET
Dark Photon DM
$y_\psi S_i < T_{S_i}$
10^{18}
10^{17}
S_i [GeV]
10^{-20}
10^{-17}
10^{-14}
10^{-11}
10^{-8}
10^{-5}
10^{-2}
10^{1}
$m_{S,0}$ [GeV]