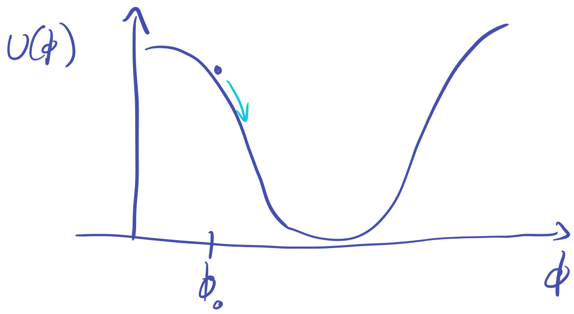
GW's from axion dynamics

What is an axion? For all practical purposes, a very light scalar field ϕ.

Useful: Compact field range (+ shift symmetry), i.e. $\phi + 2\pi \underset{\uparrow \text{ PQ scale}}{f} = \phi$.

If m_ϕ is sufficiently small, then any initial value is equally likely, i.e.

$$\phi_0 = \Theta f \quad \text{with} \quad \Theta \in [-\pi, \pi]$$



Axion EOM: $$\phi'' + 2aH\phi' + a^2 \underbrace{\frac{\partial U}{\partial \phi}}_{\approx\, m_\phi^2 \phi} = 0$$

Note: $\phi' = \frac{d\phi}{d\tau}$ with τ conformal time, i.e. $d\tau = a\,dt$

a is the scale factor, H the Hubble rate.

Rolling prevented by friction if $H \gg m_\phi$.

↳ Starts when $m_\phi \sim H$.

Radiation domination : $H \sim \frac{T^2}{M_{pl}}$ ← Temperature

← Planck scale ~ 10^{18} GeV

ϕ starts oscillating in Potential at

$$m_\phi \approx \frac{T_{osc}^2}{M_{pl}} \iff T_{osc} \approx \sqrt{M_{pl}\, m_\phi}$$

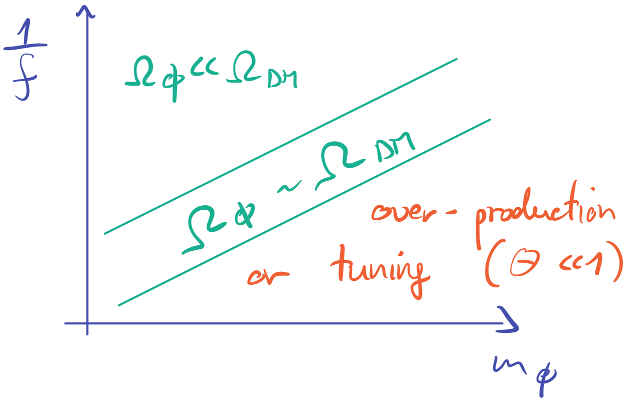
We can compute the energy density that is in "axions" at T_{osc}

$$\Omega_\phi^{osc} = \frac{\rho_\phi^{osc}}{\rho_{radiation}^{osc}} \sim \frac{m_\phi^2\, \phi_0^2}{T_{osc}^4} \sim \frac{\theta^2 f^2}{M_{pl}^2}$$

It redshifts like matter : $\rho_\phi = \left(\frac{a_{osc}}{a}\right)^3 \rho_\phi^{osc}$

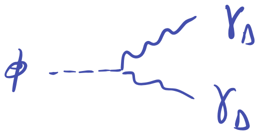
↳ DM candidate. Non-thermal, also <u>non-particle</u>

Parameter space :



Idea to avoid tuning : Add more friction, e.g. from particle production

add $\frac{\phi}{f} X_{\mu\nu} \tilde{X}^{\mu\nu}$ ⟷



"dark photon"

Normal decays not efficient. However this specific coupling adds a "tachyonic instability" for the dark photon

$$u_\pm''(k) + \underbrace{\left(k^2 \mp k\,\frac{\phi'}{f}\right)}_{\text{harmonic oscillator with } \omega_\pm^2 = k^2 \mp k\frac{\phi'}{f}} u_\pm(k) = 0$$

occupation number of momentum mode "k"

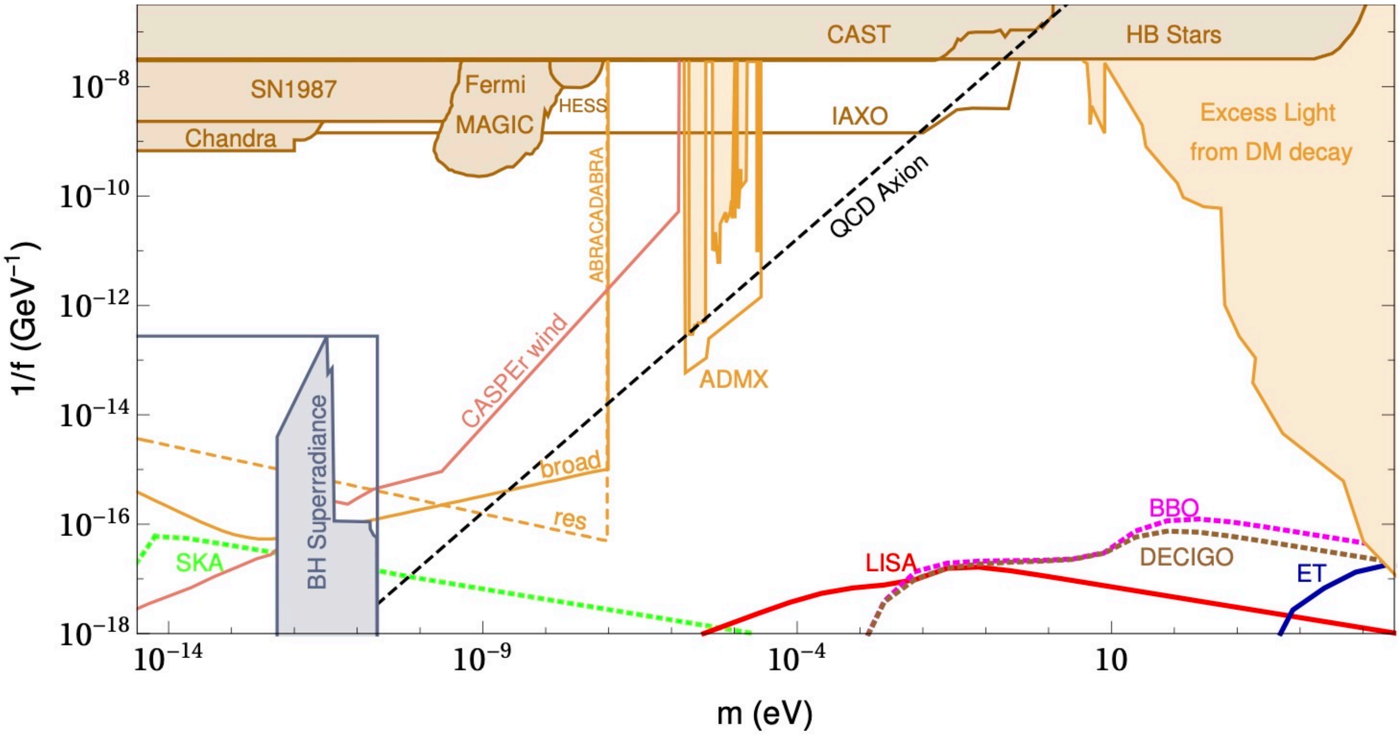
=> Imaginary frequencies for some momenta, while ϕ' is non-zero

$$e^{i\omega t} \longrightarrow e^{\pm|\omega_\pm| t}$$

exponential growth

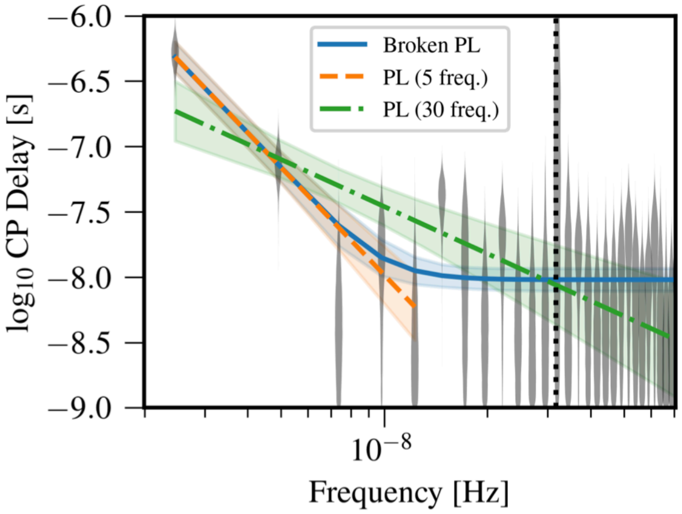
↳ Quantum fluctuations become macroscopic
  ↳ Large anisotropies
    ↳ GW production

GW spectrum can be computed directly from dark photon spectrum, e.g. 1811.01950 ; 2012.11584 "Audible Axion"



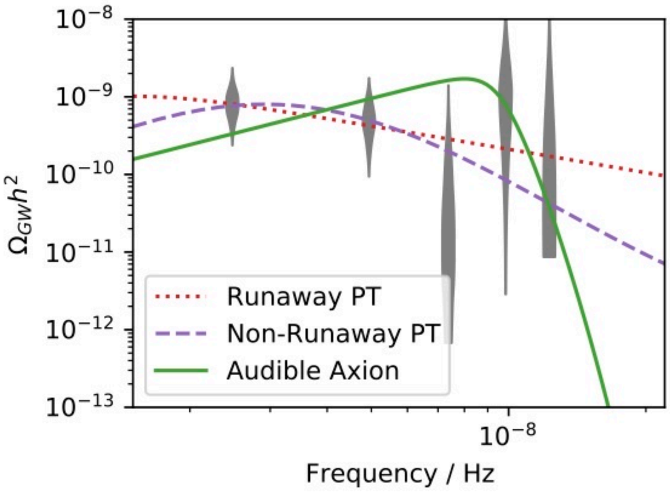
NANOGrav

2009.06607



Fit with BSM

2009.11875



Black hole superradiance

Ref: Brito, Cardoso, Pani ; 1501.06570

Light particles can form bound states with black holes, similar to Hydrogen atoms.
Through the "Penrose" process, particles can extract energy from spinning black holes, thereby reducing the BH spin.

If the Compton wavelength of the particle $\lambda \sim \frac{\hbar}{mc}$ $\left(= \frac{1}{m}\right)$ is similar to the Schwarzschild radius, this superradiant instability is very efficient at spinning down black holes.

		r_s		m_ϕ
stellar BH	↔	30 km	↔	10^{-12} eV
SMBH	↔	10^{8} km	↔	10^{-17} eV

LIGO could more firmly establish the existence of BHs with large spin. Strong bounds on existence of very light bosons.
(only apply for case of very weak interactions.)