Audible Axions - from NANOGrav to the lattice

Gravitational Wave Probes of
Physics Beyond Standard Model

Warsaw University / Online

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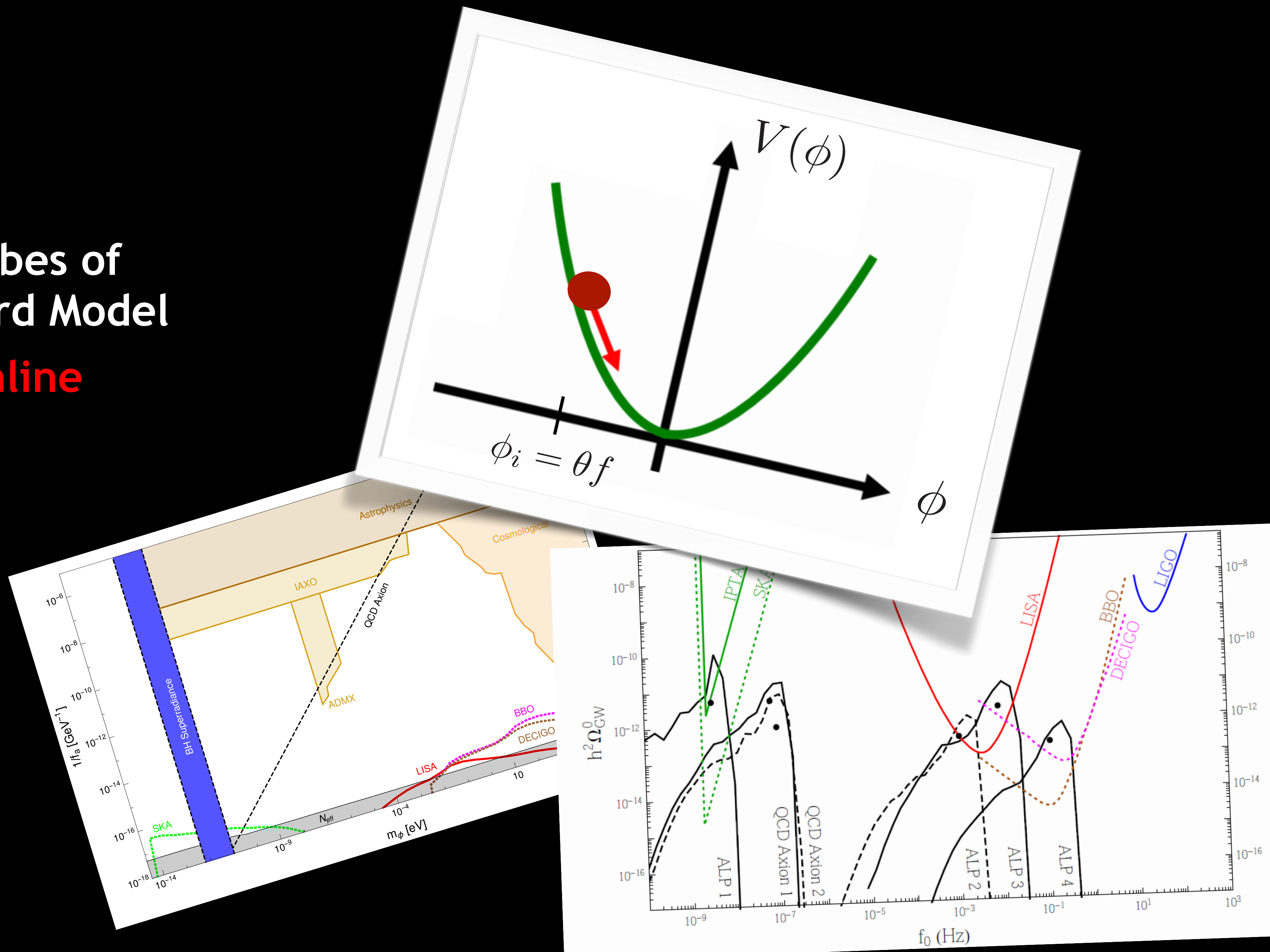


Overview

- ALPs in the early universe
- GW production from ALPs coupled to dark photons
- New numerical results
- Fit to NANOGrav GW signal

Based on work with
Camila Machado
Wolfram Ratzinger
Ben Stefanek

1811.01950
1912.01107
2009.11875
2012.11584

ALPs and the early Universe

- ALP: Pseudoscalar with shift symmetric potential (discrete or continuous)

$$\mathscr{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{\alpha}{4f}\phi X_{\mu\nu}\tilde{X}^{\mu\nu} + \ldots$$

- Motivation:
  - DM candidate via misalignment mechanism
  - Often appear in UV theories

- $m_\phi \sim 10^{-16}\ \mathrm{eV} - 1\ \mathrm{eV}$

  $f \sim 10^{12}\ \mathrm{GeV} - 10^{18}\ \mathrm{GeV}$

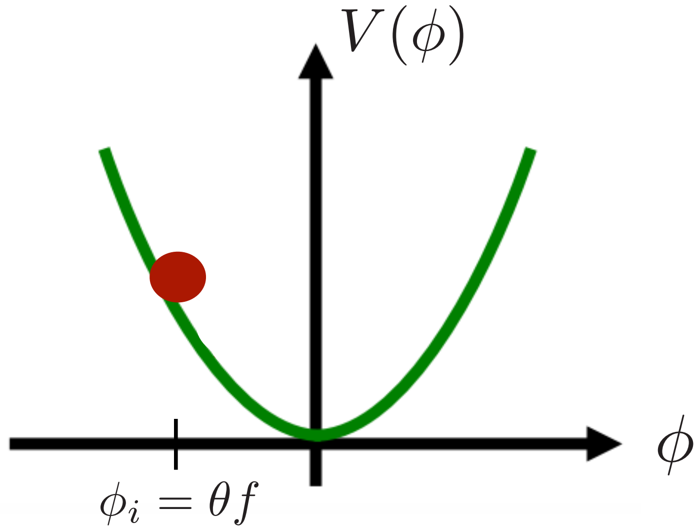
ALPs and GWs

- Superradiance
    - Probes presence of very light scalars due to BH spin-down
- GWs from phase transitions
    - Probes possible UV completions of ALP models
- Here: GWs sourced by axion dynamics after inflation
    - In models where ALP couples to dark photon

ALP dynamics

- Equation of motion

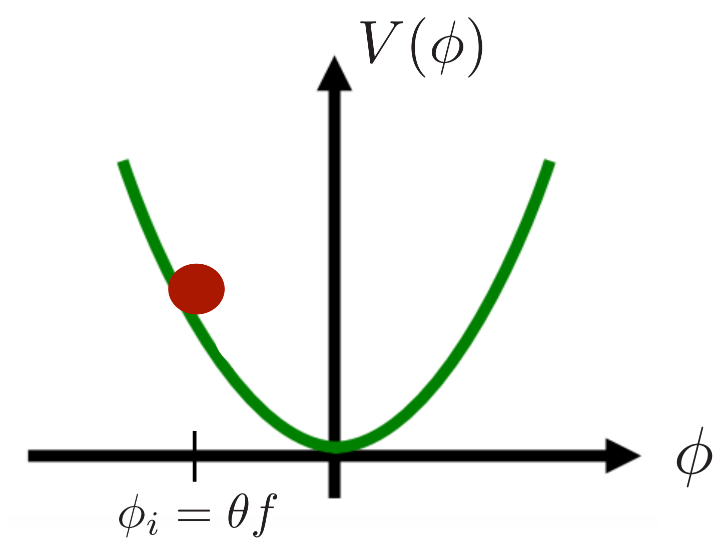
$$\phi'' + 2aH\phi' + a^2V'(\phi) - \nabla^2\phi - \frac{\alpha}{fa^2}\mathbf{X}' \cdot (\nabla \times \mathbf{X}) = 0$$



ALP dynamics

- Equation of motion

$$\phi'' + 2aH\phi' + a^2V'(\phi) \cancel{- \nabla^2\phi - \frac{\alpha}{fa^2}\mathbf{X}'\cdot(\nabla\times\mathbf{X})} = 0$$



- ALP starts rolling when $H \sim m_\phi$

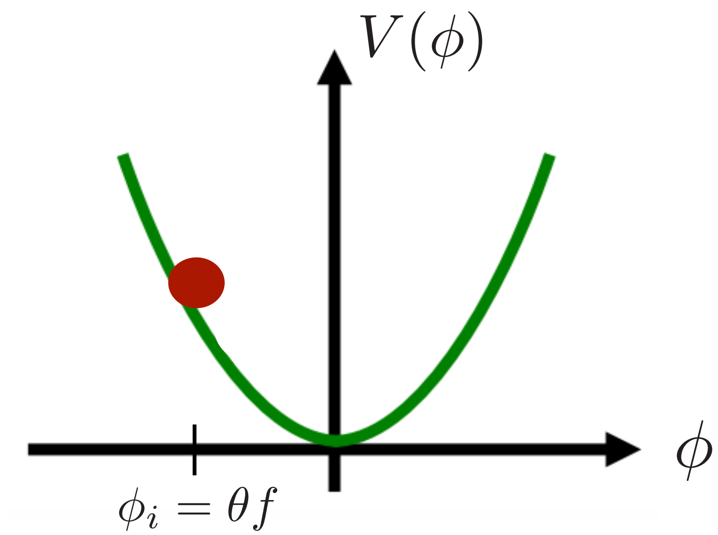
- Redshifts like non-relativistic matter (a^{-3})
    - Candidate for “non-particle” DM

ALP dynamics - with dark photon

- Equation of motion

$$\phi'' + 2aH\phi' + a^2V'(\phi)$$

$$\cancel{-\nabla^2\phi} - \frac{\alpha}{fa^2}\mathbf{X}'\cdot(\nabla\times\mathbf{X}) = 0$$



- ALP starts rolling when $H \sim m_\phi$

- ALP is damped due to exponential production of dark photons
    - Reduced relic abundance

Agrawal, Marques-Tavares, Xue, 2018

What about the dark photon?

- Equation of motion (in momentum space)

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

- The rolling ALP induces a tachyonic instability

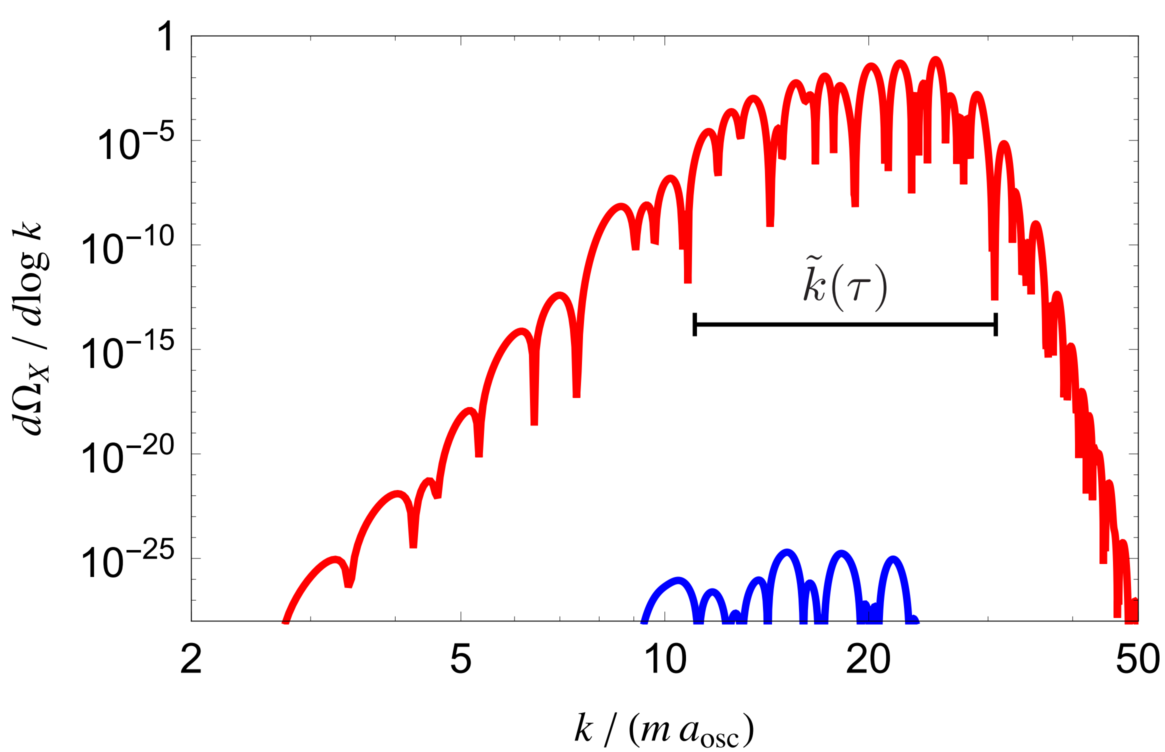
$$X''_{\pm} + \omega_{\pm}(\tau)X_{\pm} = 0 \qquad \text{with} \quad \omega_{\pm} = k^2 \mp k\frac{\alpha}{f}\phi'$$

- Exponential growth of a range of dark photon modes

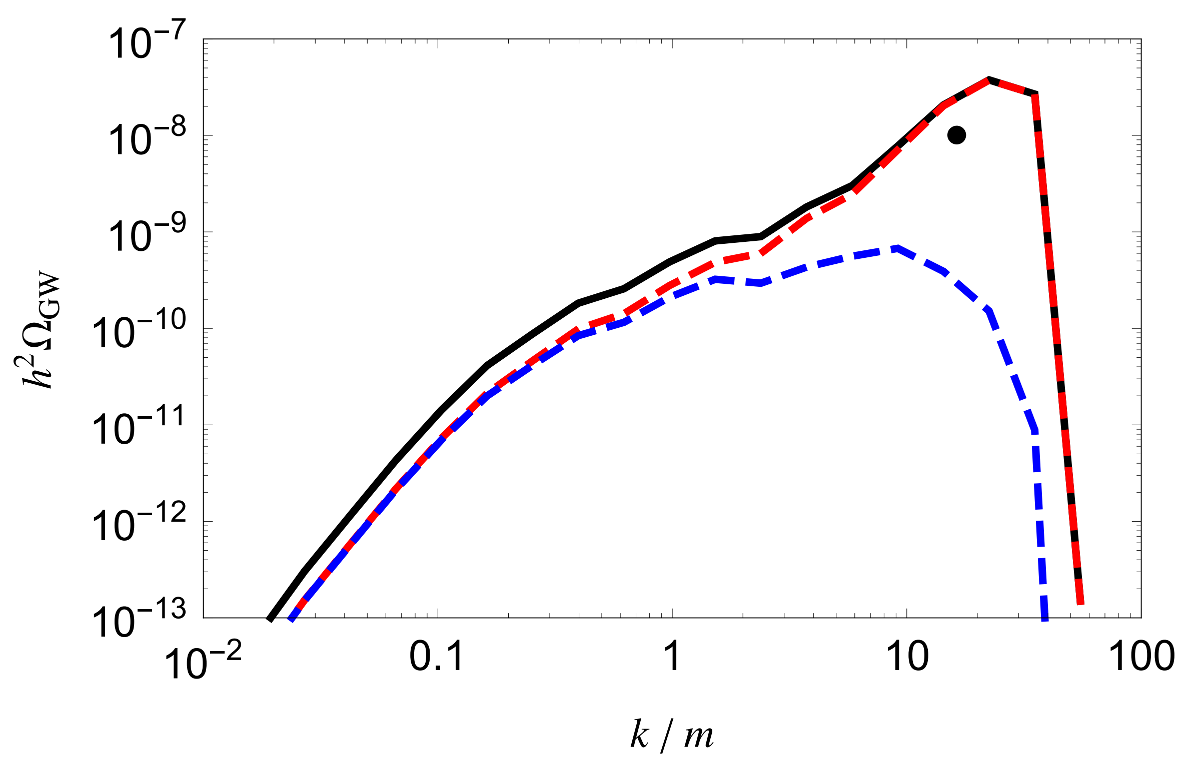
$$X(\tau) \propto e^{|\omega|\tau} \quad \text{for} \quad k \sim \frac{\alpha\phi'}{2f}$$

From dark photons to GWs

- The exponential growth amplifies quantum fluctuations in the dark photon fields which source a chiral gravitational wave background



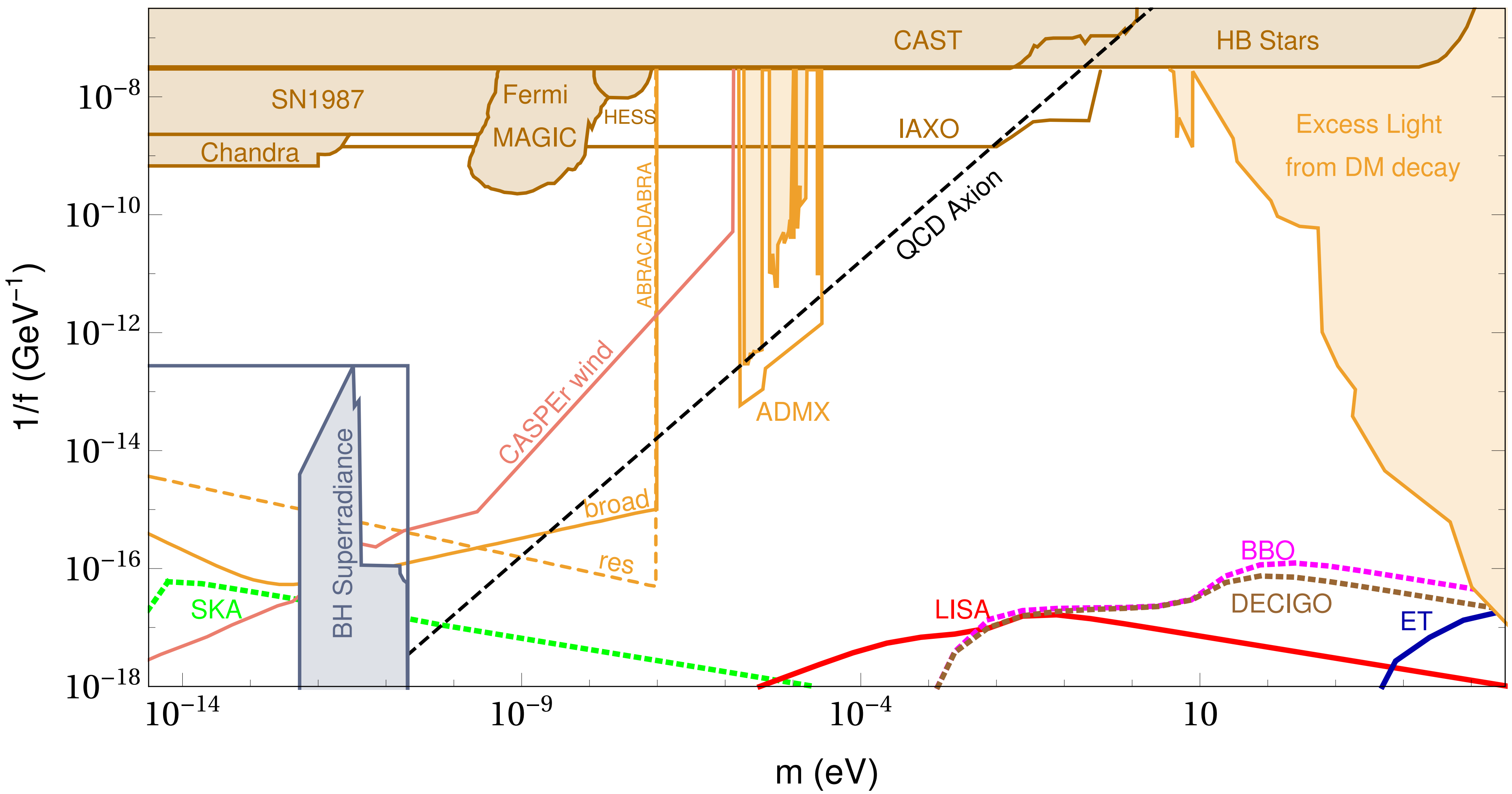
Dark photon spectrum



GW spectrum

Machado, Ratzinger, Stefanek, PS, 1811.01950

GW probes of audible ALPs



- Mainly sensitive to high scale ALPs, since

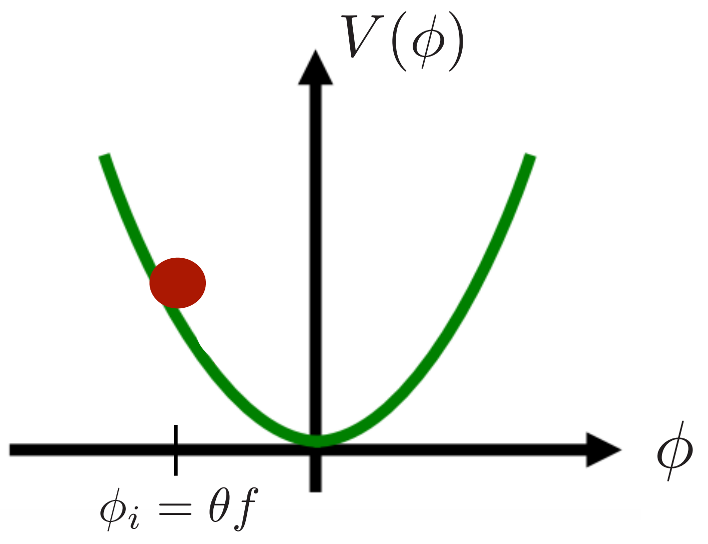
$$f_0 \approx m \left(\frac{T_0}{T_*}\right) (\alpha\theta)^{2/3} = \sqrt{\frac{m}{M_P}}\, T_0\, (\alpha\theta)^{2/3}, \qquad \Omega^0_{\rm GW} \approx \Omega^0_\gamma \left(\frac{f}{M_P}\right)^4 \left(\frac{\theta^2}{\alpha}\right)^{\frac{4}{3}}$$

Machado, Ratzinger, Stefanek, PS, 1912.01107

ALP dynamics - once more

- Equation of motion

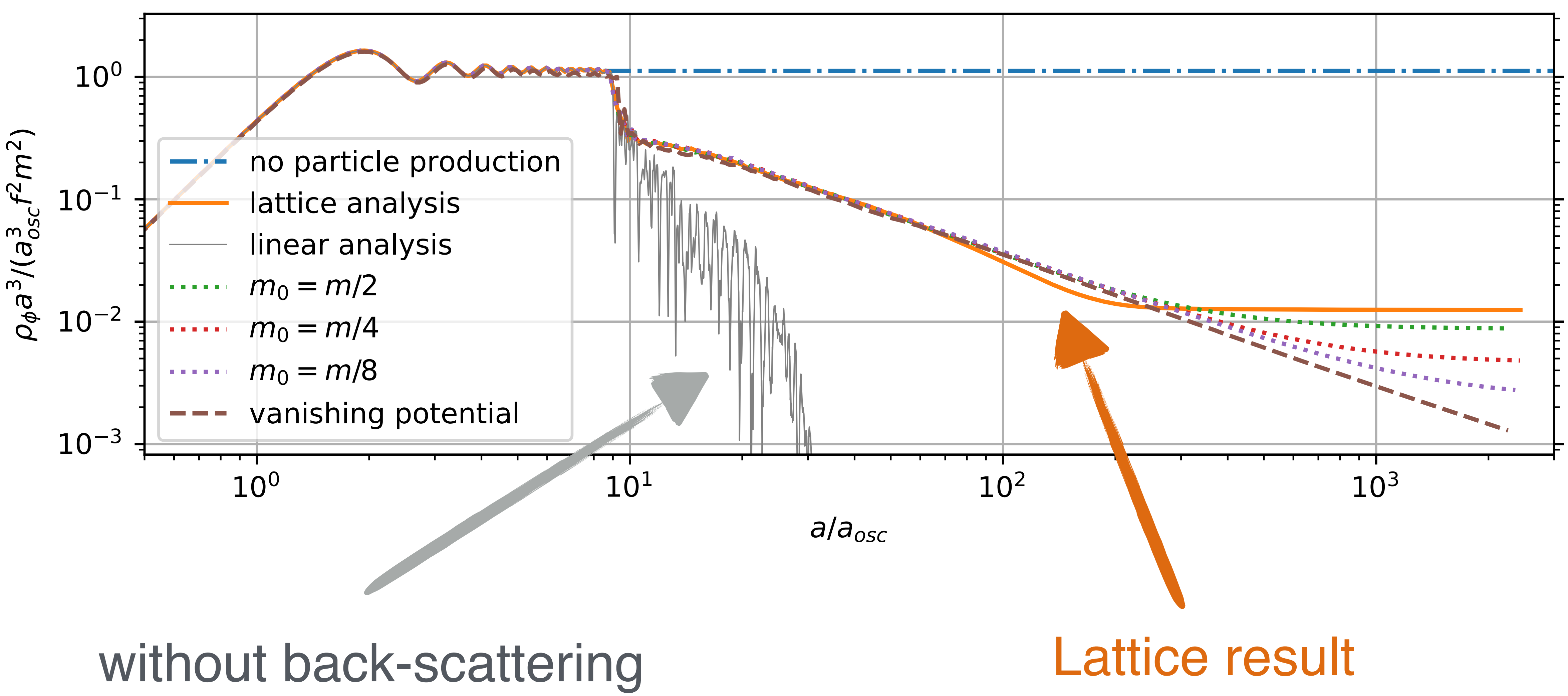
$$\phi'' + 2aH\phi' + a^2V'(\phi) - \nabla^2\phi - \frac{\alpha}{fa^2}\mathbf{X}'\cdot(\nabla\times\mathbf{X}) = 0$$



- Once a significant population of dark photons is produced, the back-scattering into ALP fluctuations becomes non-negligible

- Requires fully numerical treatment on the lattice

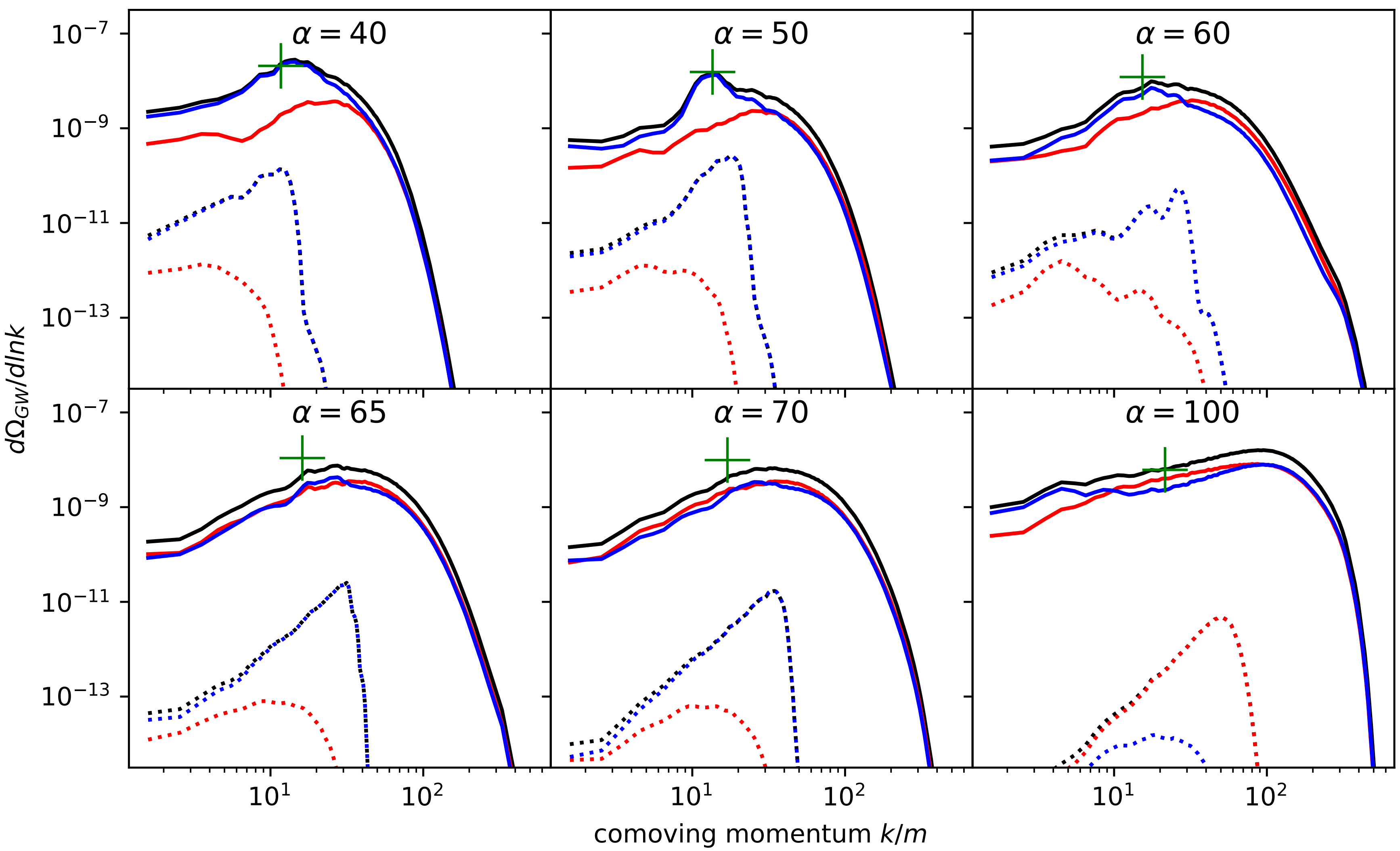
Important to get correct relic abundance prediction



From 2012.11584 with W. Ratzinger, B. Stefanek

See also Kitajima, Sekiguchi, Takahashi, 2018
Agrawal, Kitajima, Reece et al, 2020

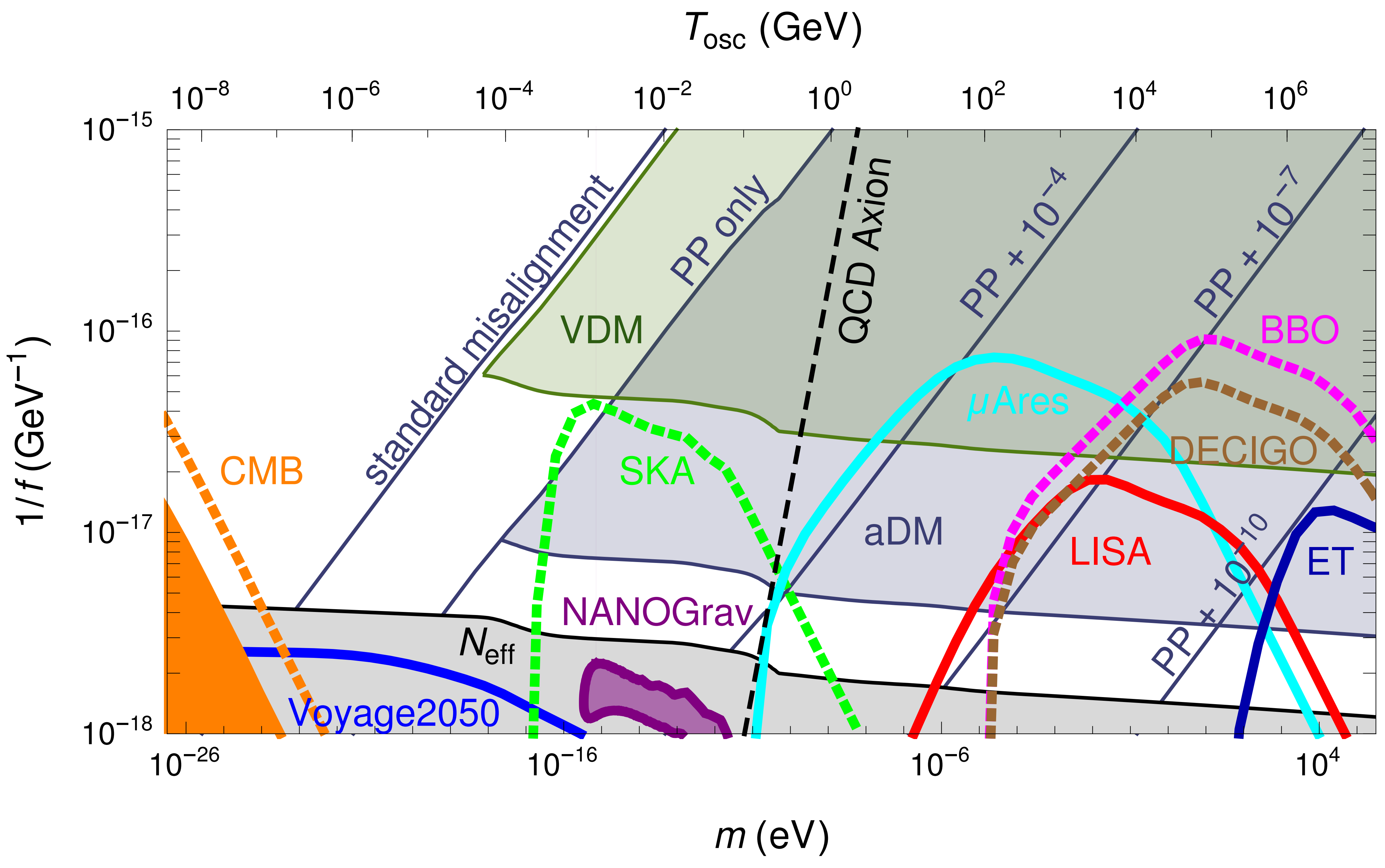
Corrections to GW signal



- Qualitative features unchanged, but polarisation is washed out at large couplings

From 2012.11584 with W. Ratzinger, B. Stefanek
see also 2010.10990 by (Kitajima, Soda, Urakawa)

Detectable region - update

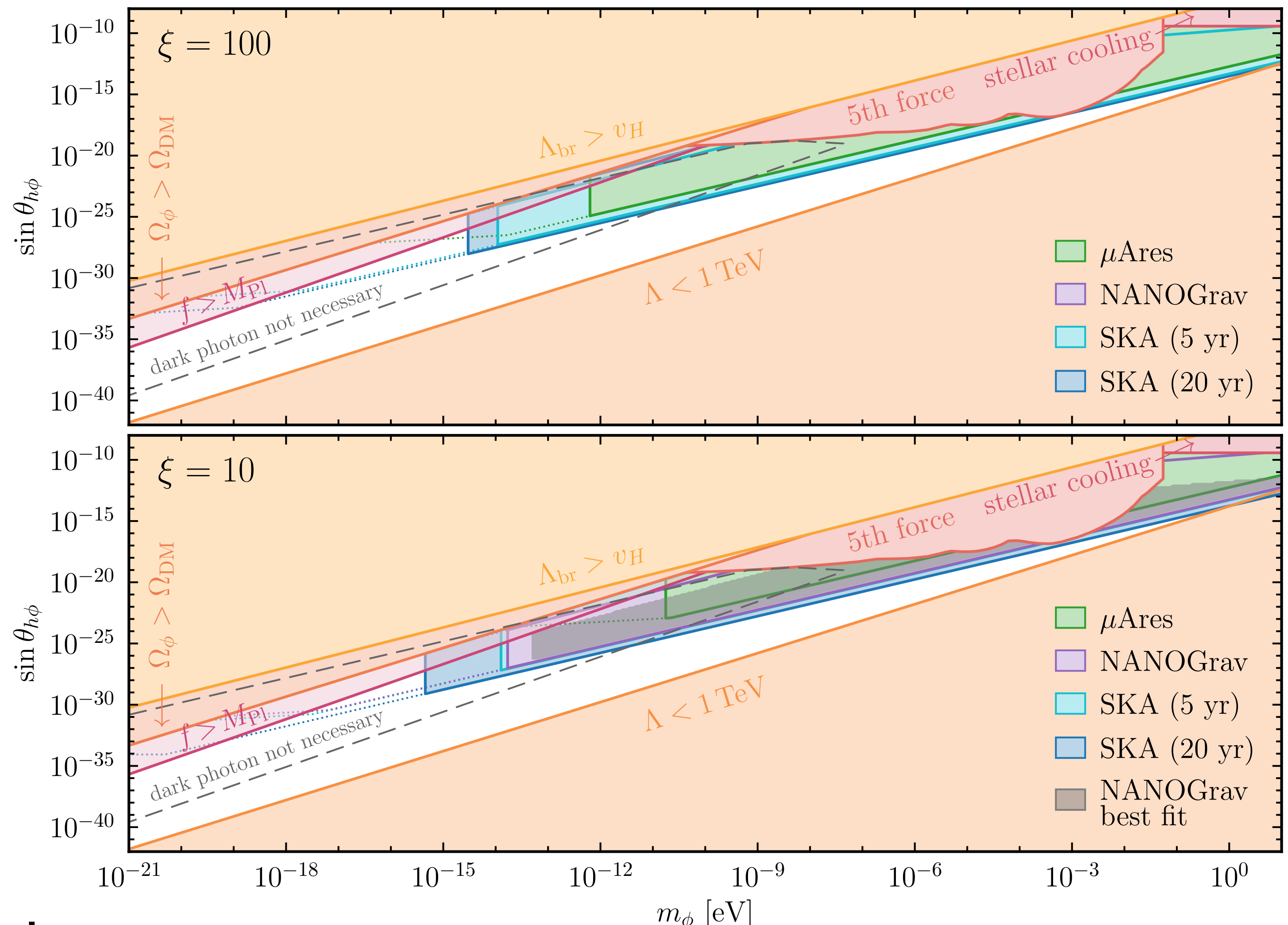


Audible relaxion

- Audible relaxion

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

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



- Dark photon friction essential for trapping relaxion after reheating

- → Potentially observable GW signal

Banerjee, Madge, Perez, Ratzinger, PS, 2105.12135

GWs from kinetic misalignment

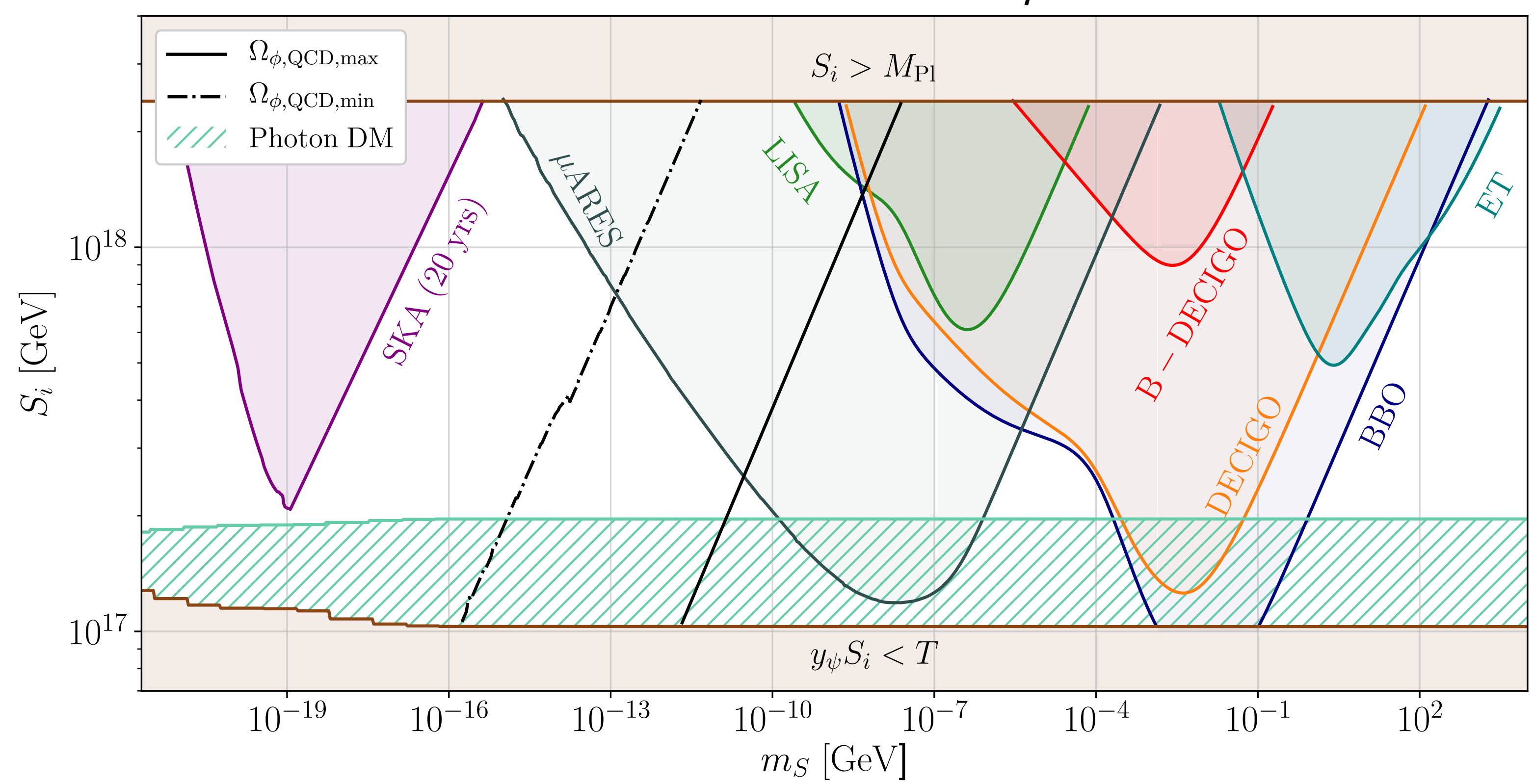
- Consider the case of large initial $\dot{\phi}$

- Detectable signal also for smaller decay constants

- Fix ALP mass to fit DM relic abundance

- Also consistent with Axiogenesis!

$f_\phi = 5 \times 10^{13}$ GeV



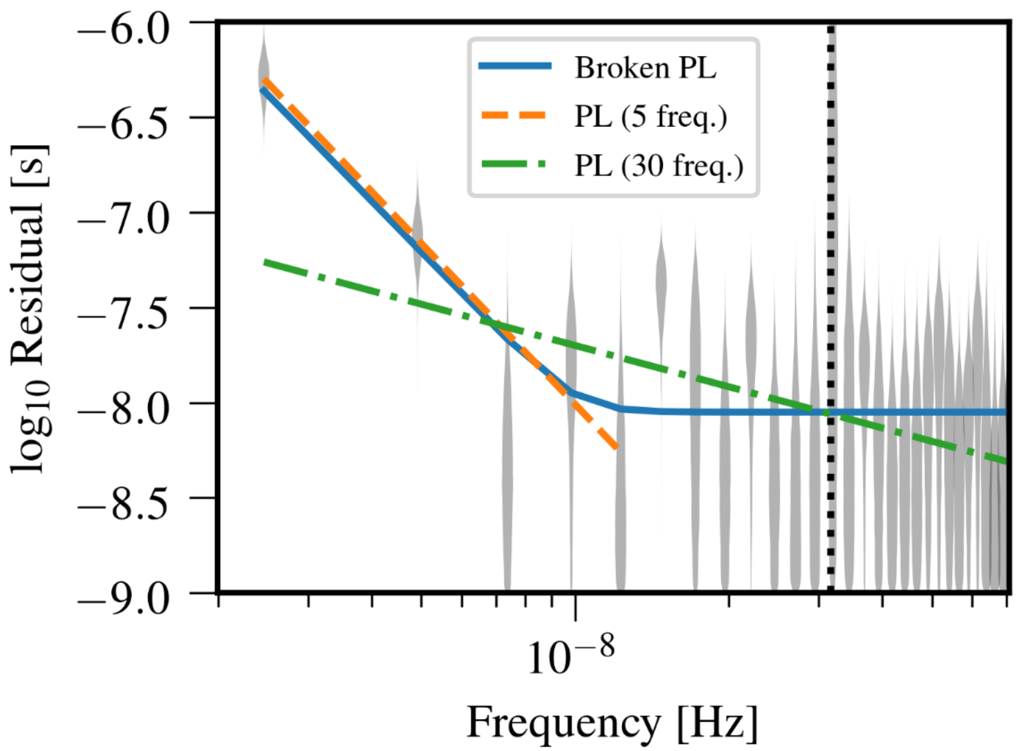
From Madge, Ratzinger, Schmitt, PS, (in preparation)

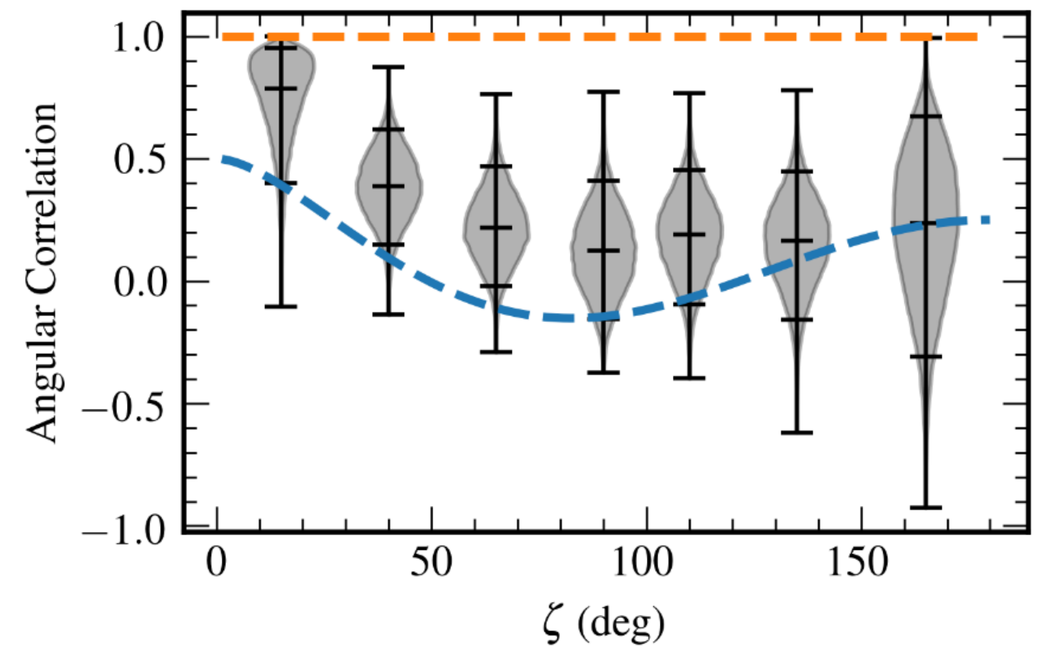
See also Co, Harigaya, Pierce, 2104.02077

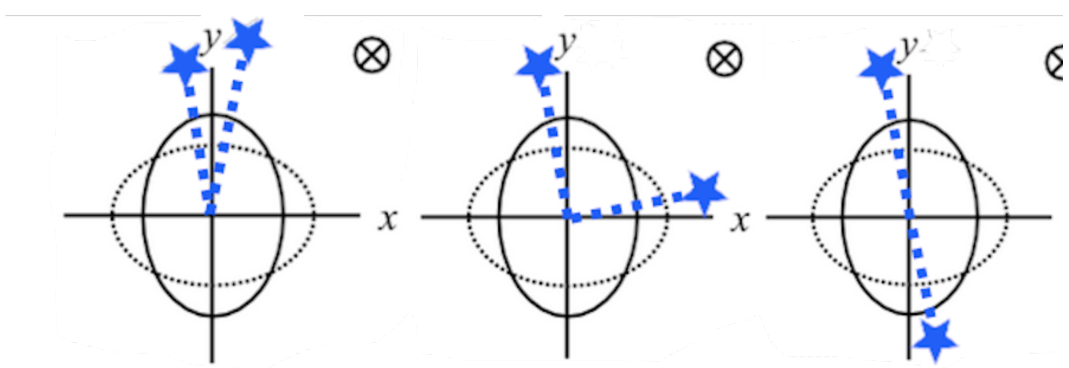
NANOGrav saw something!

No 4σ evidence for Quadrupole

Significant Strain at low frequencies

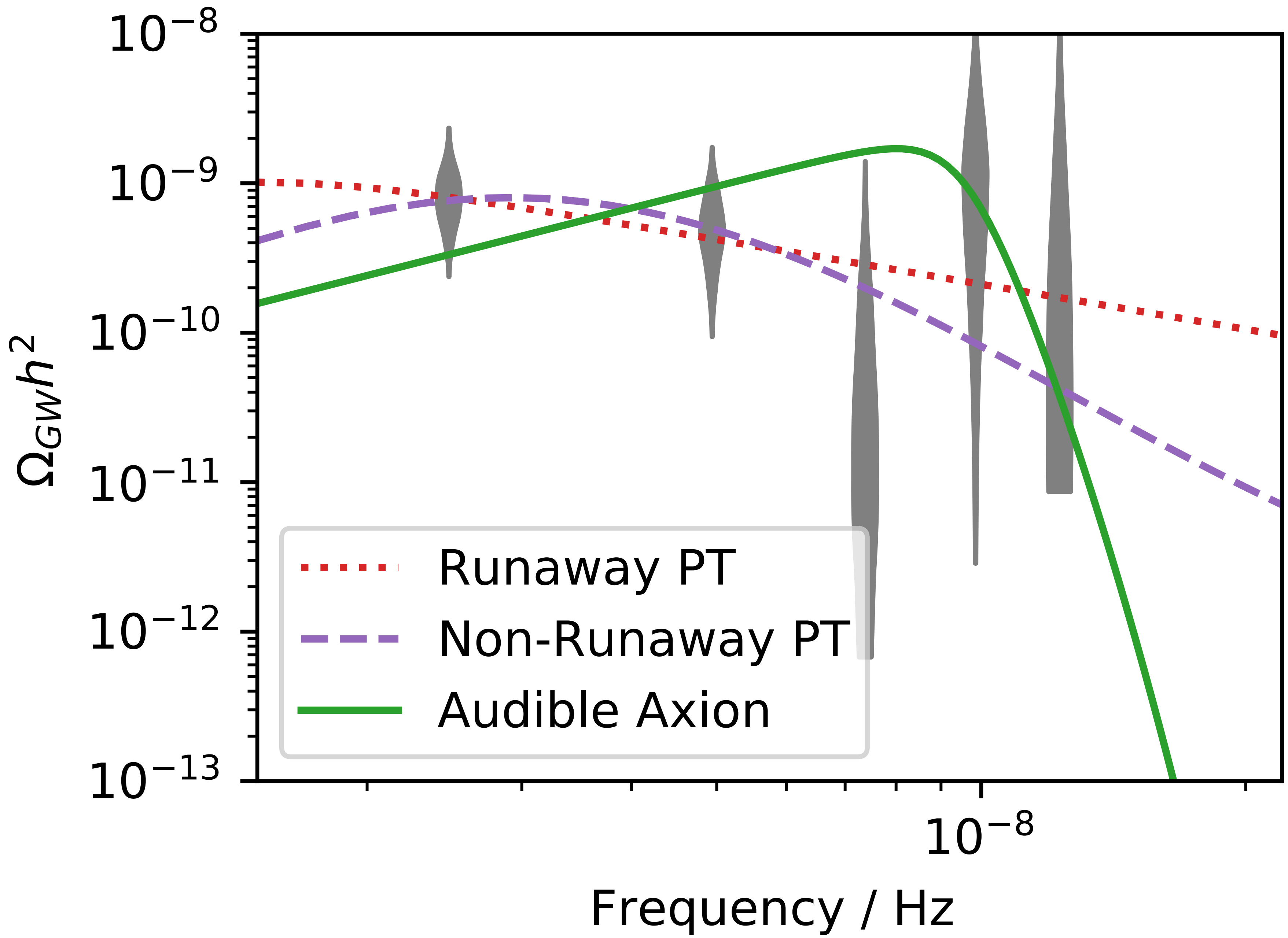






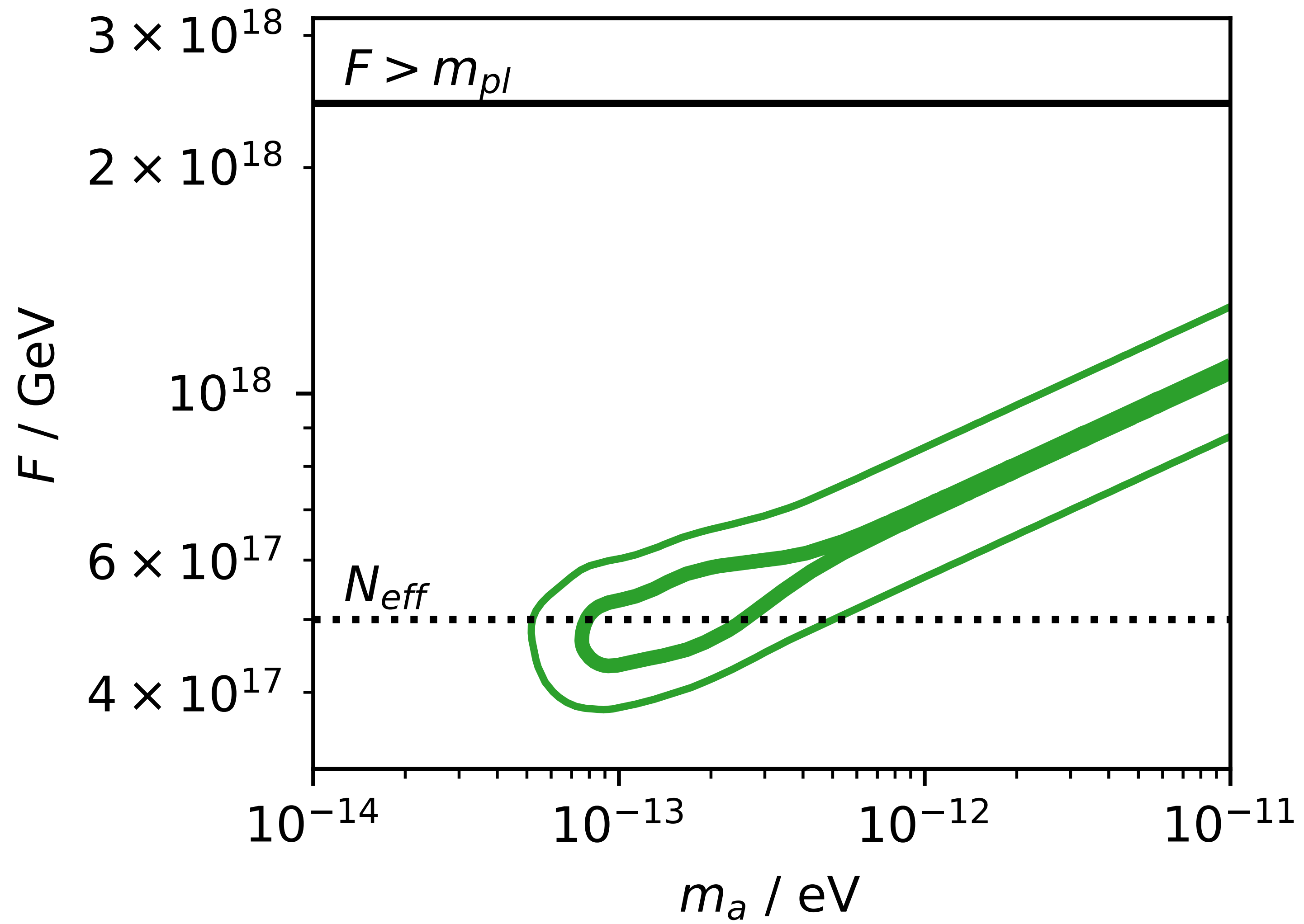
from NANOGrav colaboration: 2009.04496

Fit with broken power law signals



Wolfram Ratzinger & PS, 2009.11875

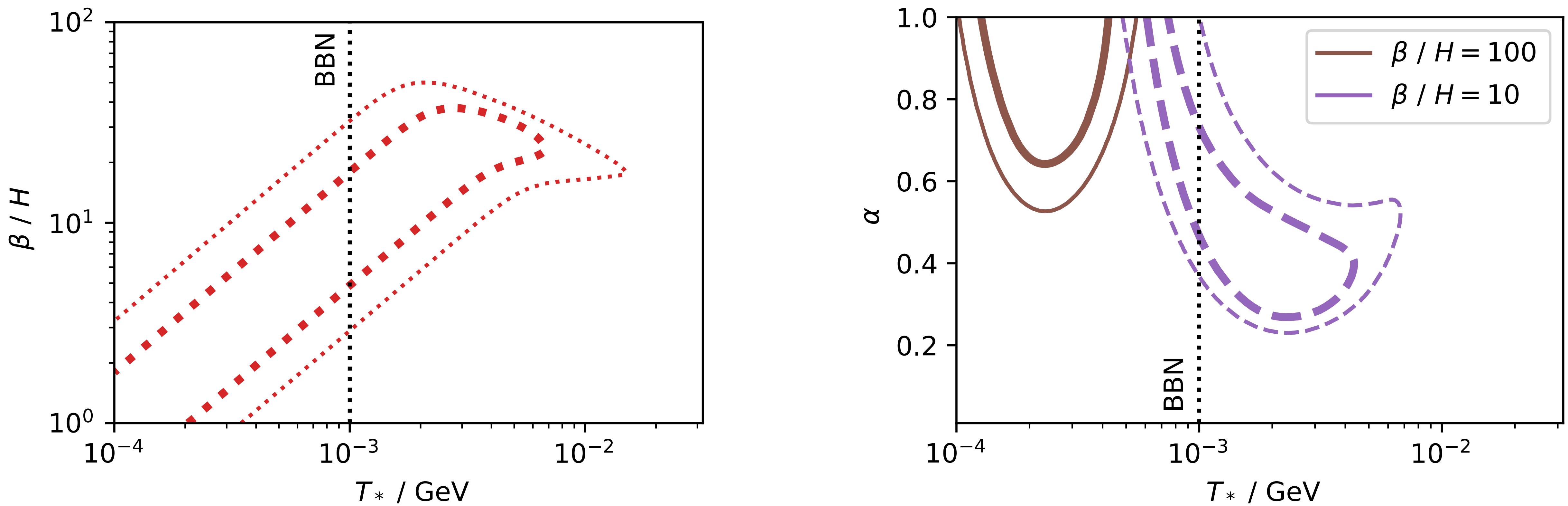
Example: Audible Axion



- Parameter reconstruction already possible
- Non-trivial constraints from cosmology (N_{eff})

Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition



- Generic PT parameterisation, best fit with PT at temperatures in few MeV range

- Also here, challenging to build model that does not break cosmology (BBN and/or N_{eff})

Wolfram Ratzinger & PS, 2009.11875

Summary

- Gravitational waves offer unique window into the early universe
- New way to probe axions/ALPs
- Tachyonic particle production frequently used in model building (inflation, relaxion, reheating)
    - We now have precise numerical simulations
- NANOGrav might have seen a glimpse from a dark sector
    - Waiting for future data - exciting!