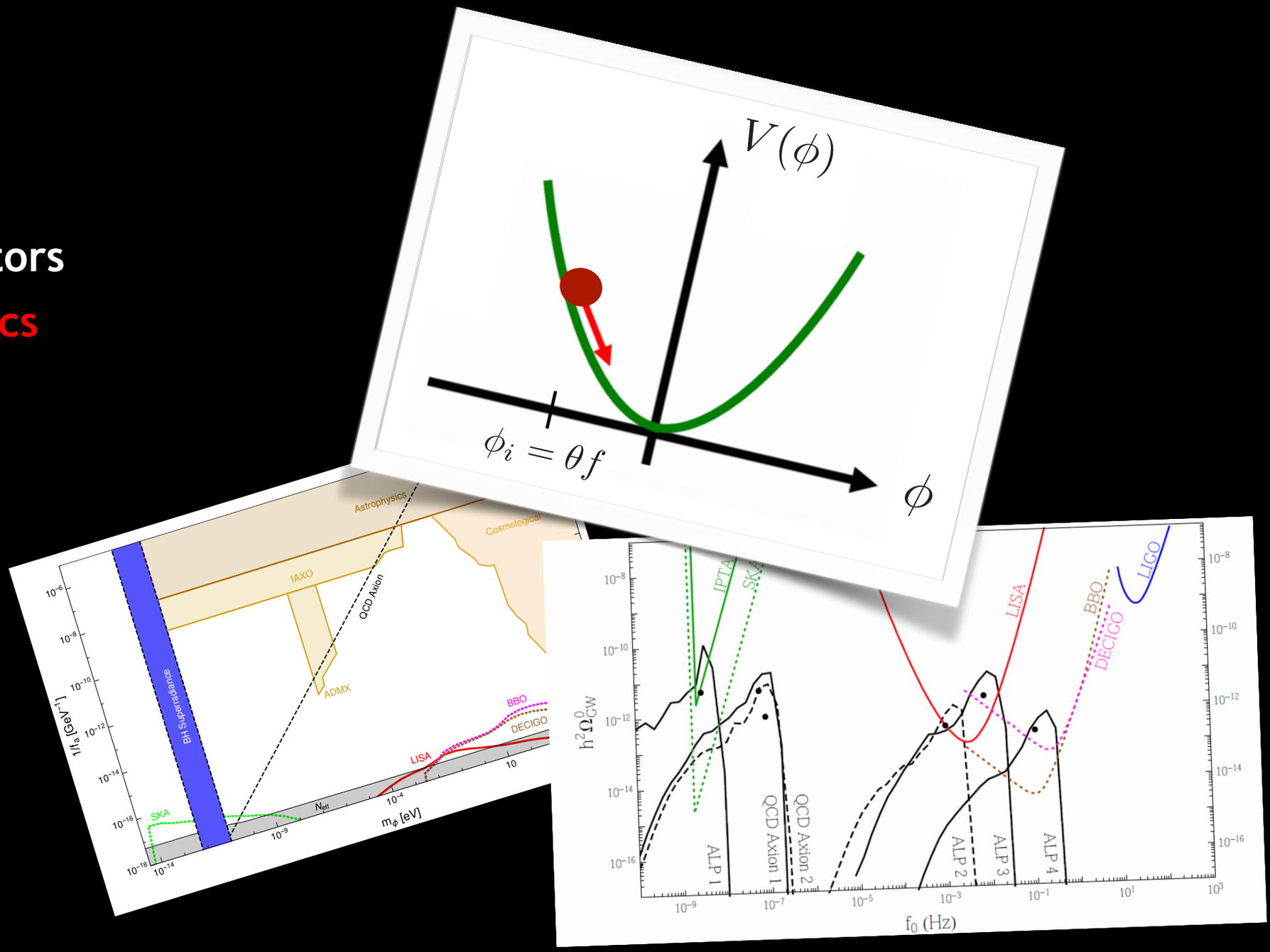
Gravitational wave probes of axion like particles

A Rainbow of Dark Sectors

Aspen Center for Physics

March 22, 2021

Pedro Schwaller
(JGU Mainz)



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

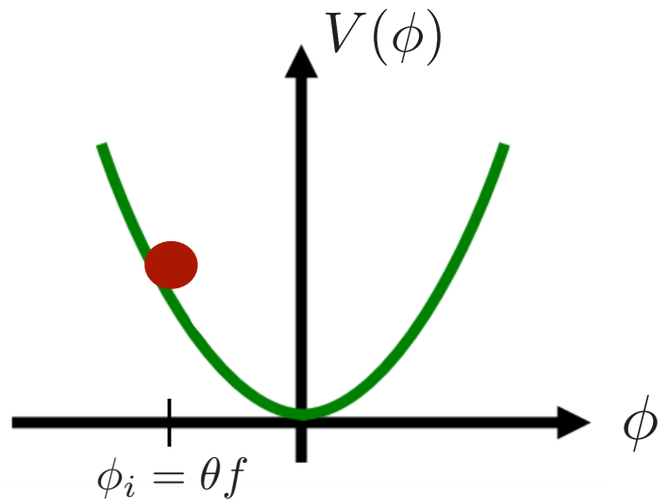
- Superradiance
  - Probes presence of very light scalars due to BH spin-down
- GWs from phase transitions
  - Probes possible UV completions of ALP models
- Here: GWs sourced by axion dynamics after inflation
  - In models where ALP couples to dark photon

ALP dynamics

- Equation of motion

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

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

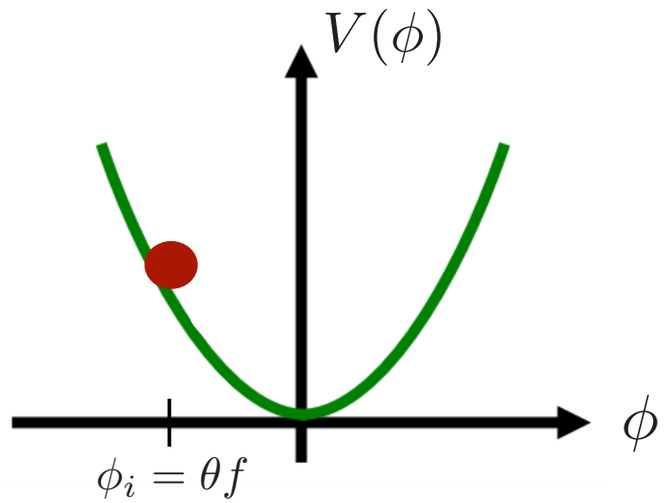


ALP dynamics

- Equation of motion

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

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



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

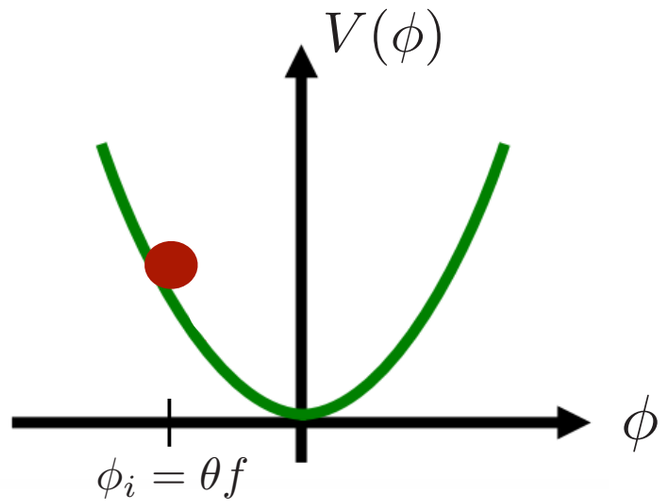
- Redshifts like non-relativistic matter (a^{-3})
  - Candidate for “non-particle” DM

ALP dynamics - with dark photon

- Equation of motion

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

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



- 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

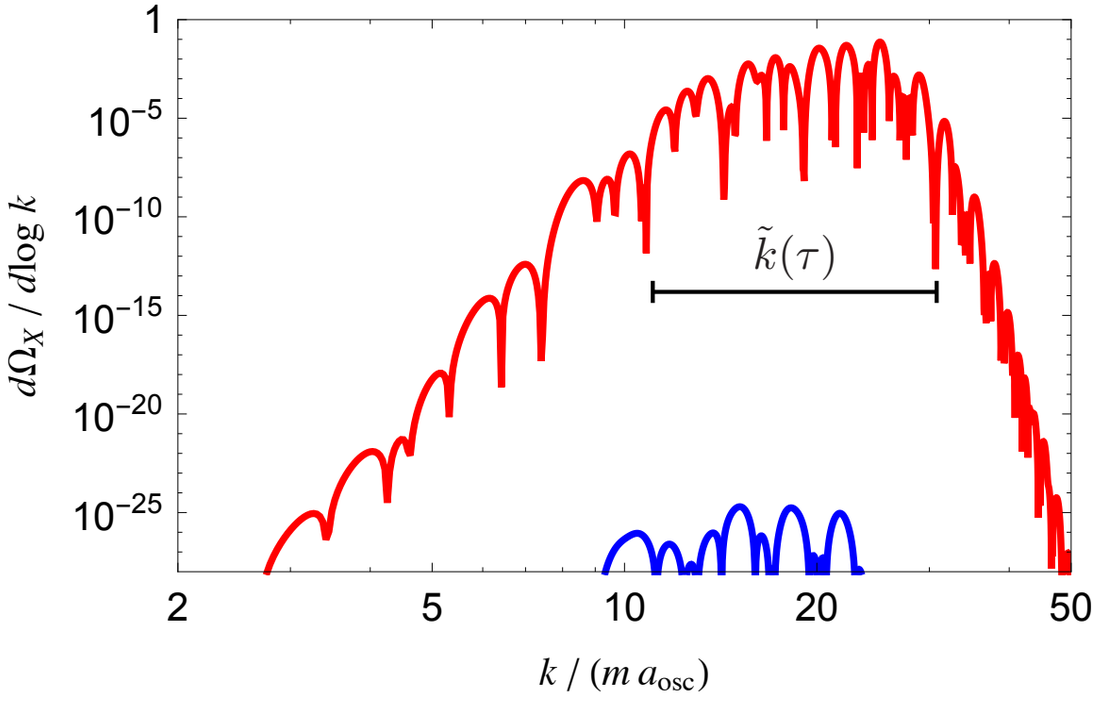
$$X''_{\pm} + \omega_{\pm}(\tau) X_{\pm} = 0 \qquad \text{with} \quad \omega_{\pm} = k^2 \mp k\frac{\alpha}{f}\phi'$$

- Exponential growth of a range of dark photon modes

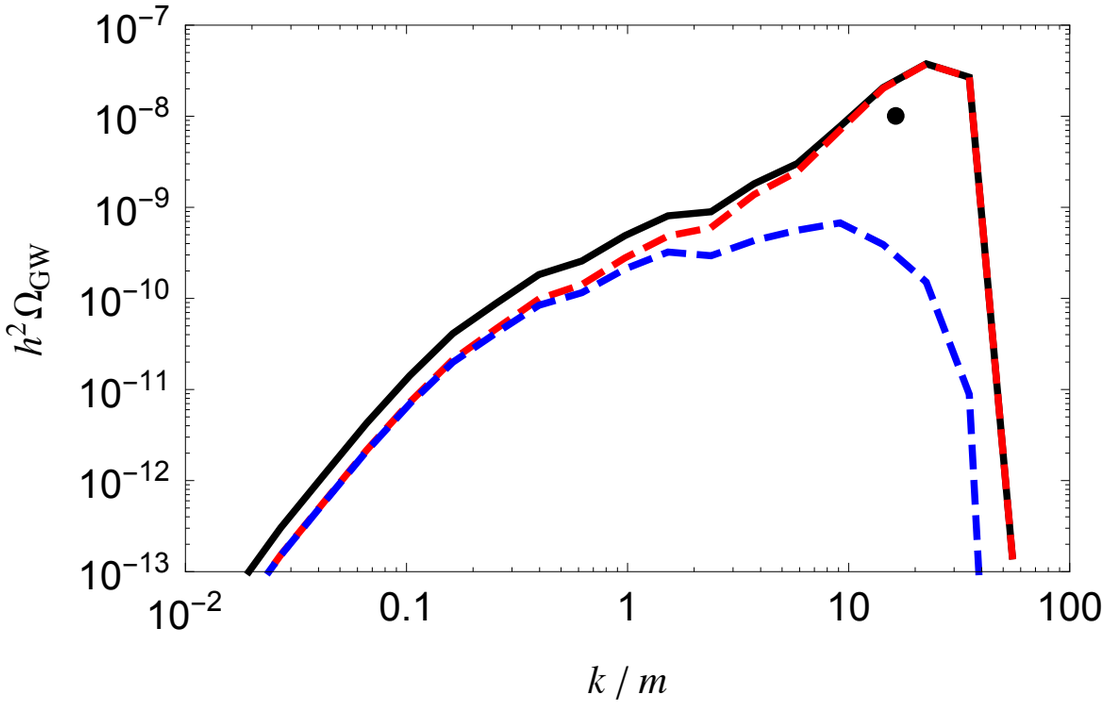
$$X(\tau) \propto e^{|\omega|\tau} \quad \text{for} \quad k \sim \frac{\alpha\phi'}{2f}$$

From dark photons to GWs

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

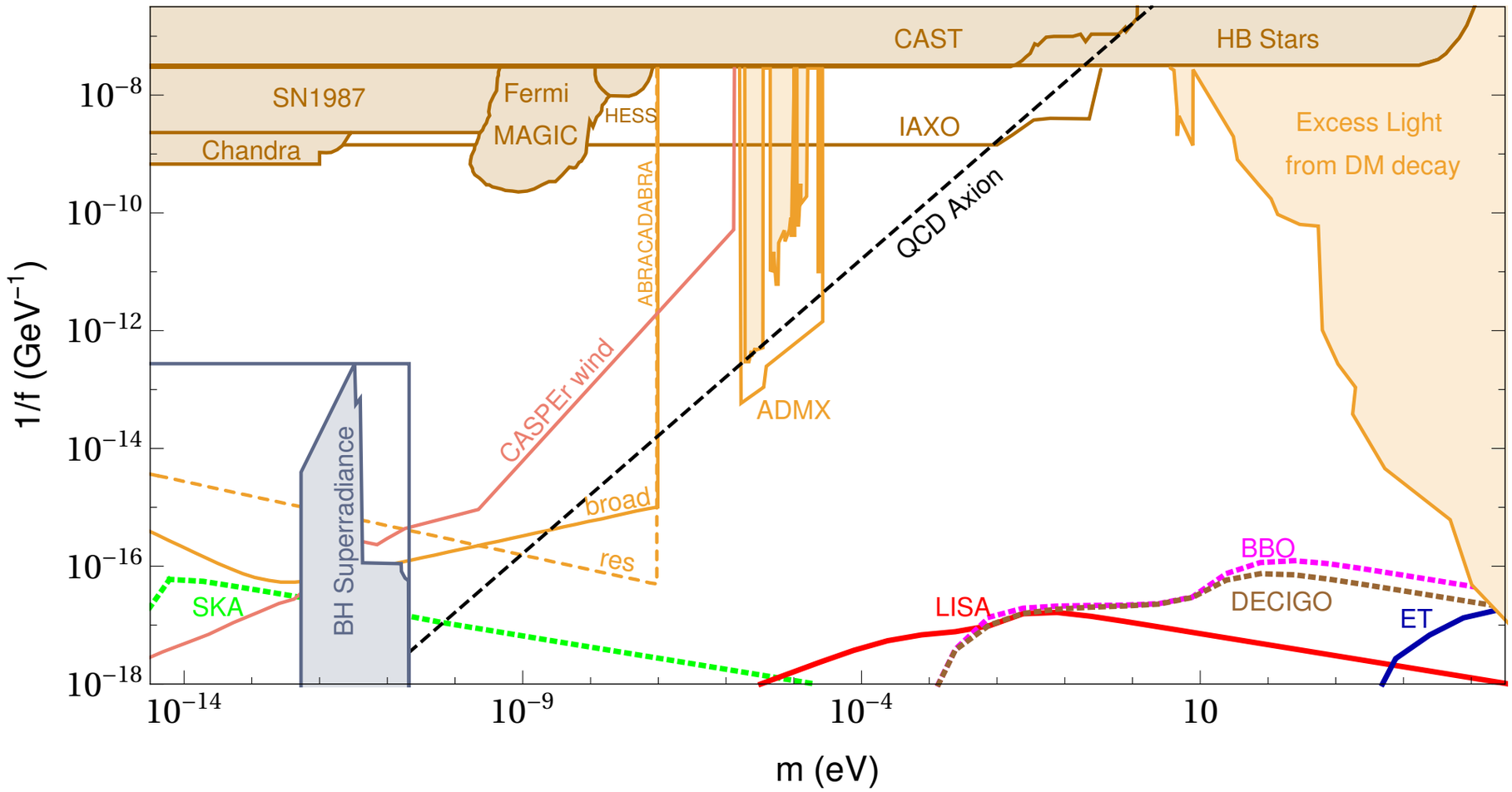


Dark photon spectrum



GW spectrum

GW probes of audible ALPs



- Mainly sensitive to high scale ALPs, since

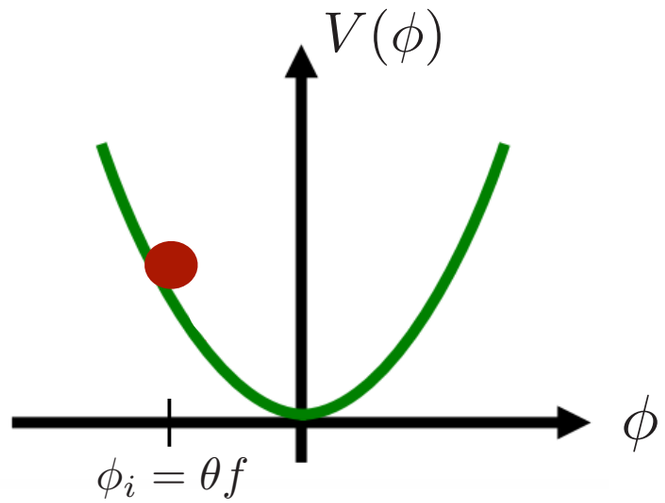
$$f_0 \approx m \left(\frac{T_0}{T_*}\right) (\alpha\theta)^{2/3} = \sqrt{\frac{m}{M_P}}\, T_0\, (\alpha\theta)^{2/3}\,, \qquad \Omega^0_{\rm GW} \approx \Omega^0_\gamma \left(\frac{f}{M_P}\right)^4 \left(\frac{\theta^2}{\alpha}\right)^{\frac{4}{3}}$$

ALP dynamics - once more

- Equation of motion

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

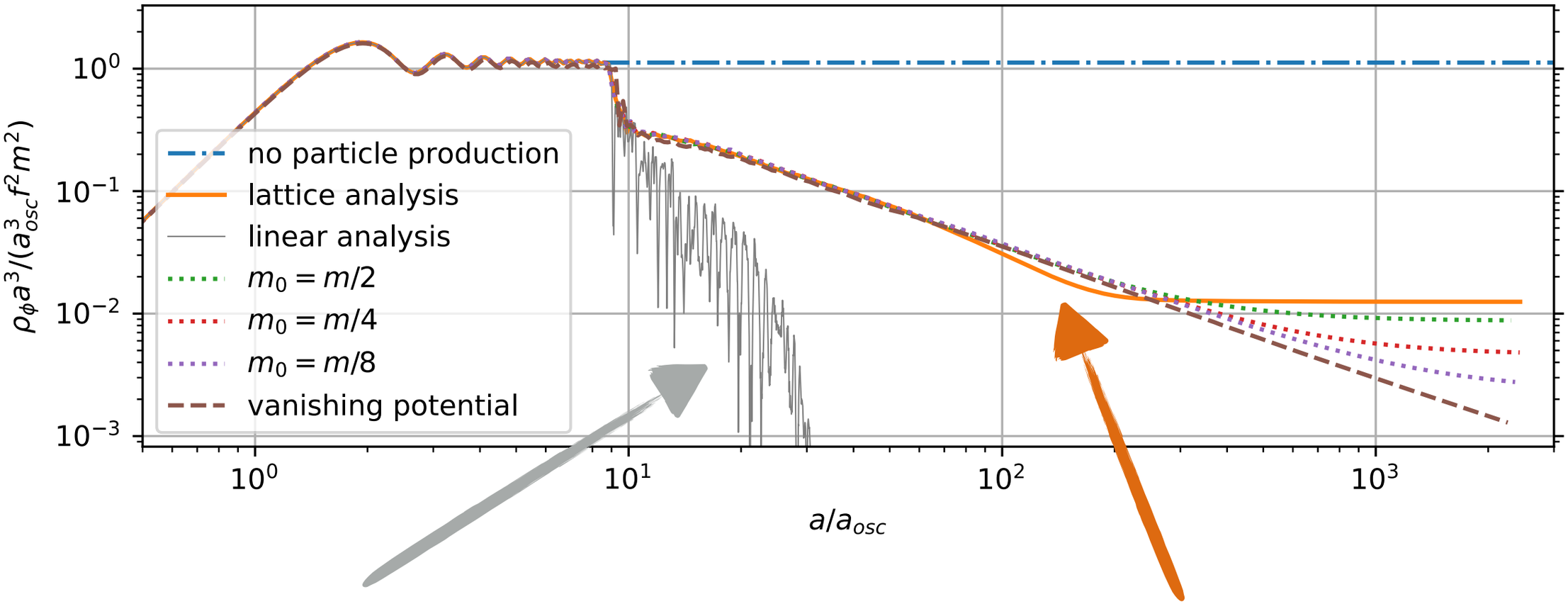
$$-\nabla^2\phi - \frac{\alpha}{fa^2}\mathbf{X}' \cdot (\nabla \times \mathbf{X}) = 0$$



- 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

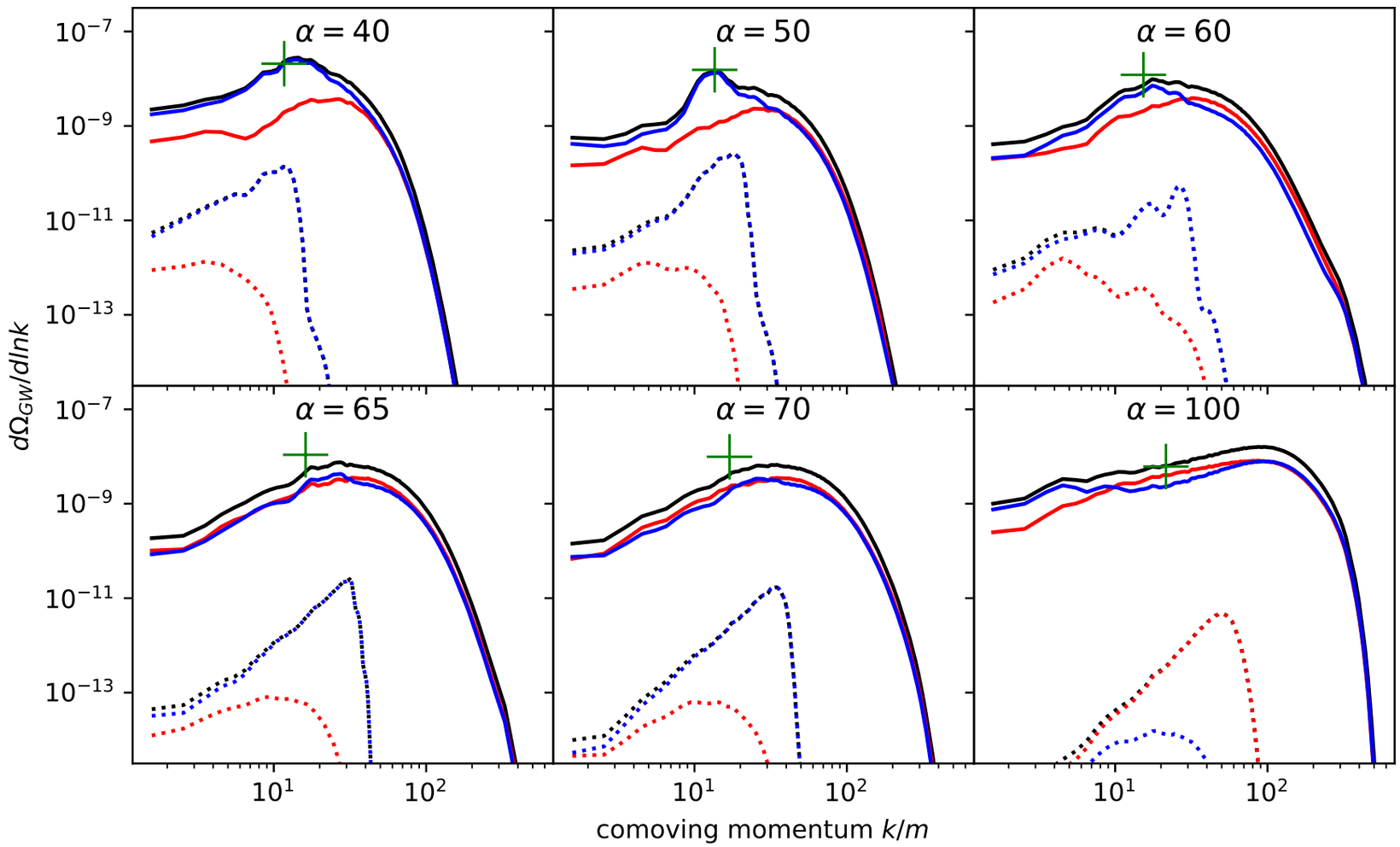


without back-scattering

Lattice result

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

Corrections to GW signal

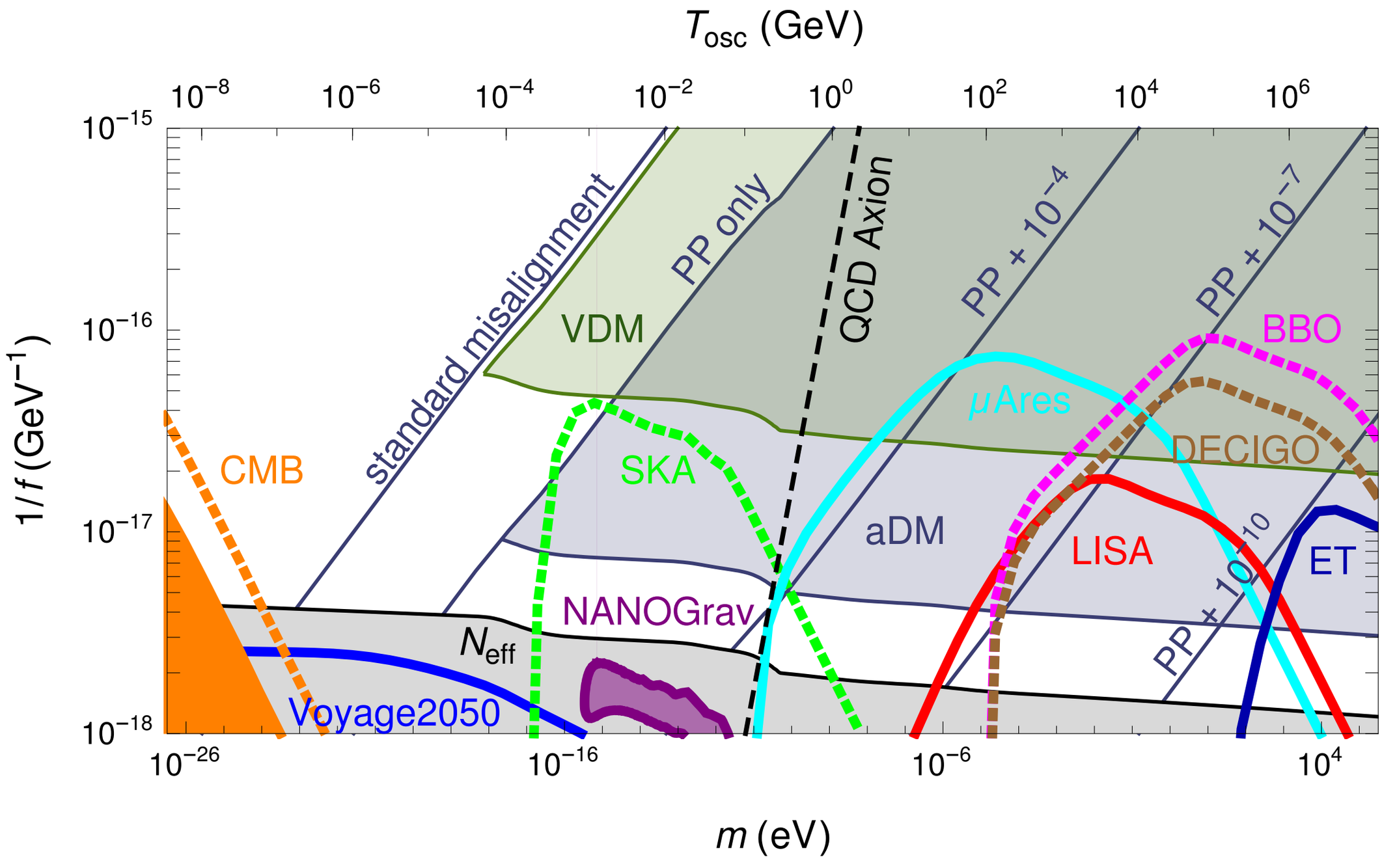


- Qualitative features unchanged, but polarisation is washed out at large couplings

From 2012.11584 with W. Ratzinger, B. Stefanek

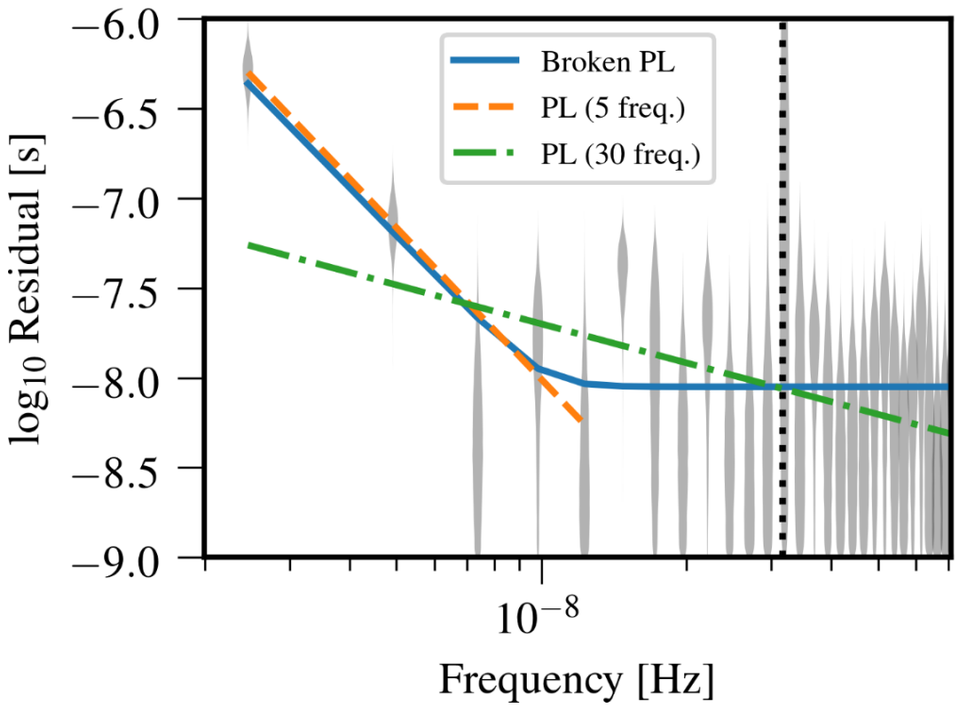
see also 2010.10990 by (Kitajima, Soda, Urakawa)

Detectable region - update

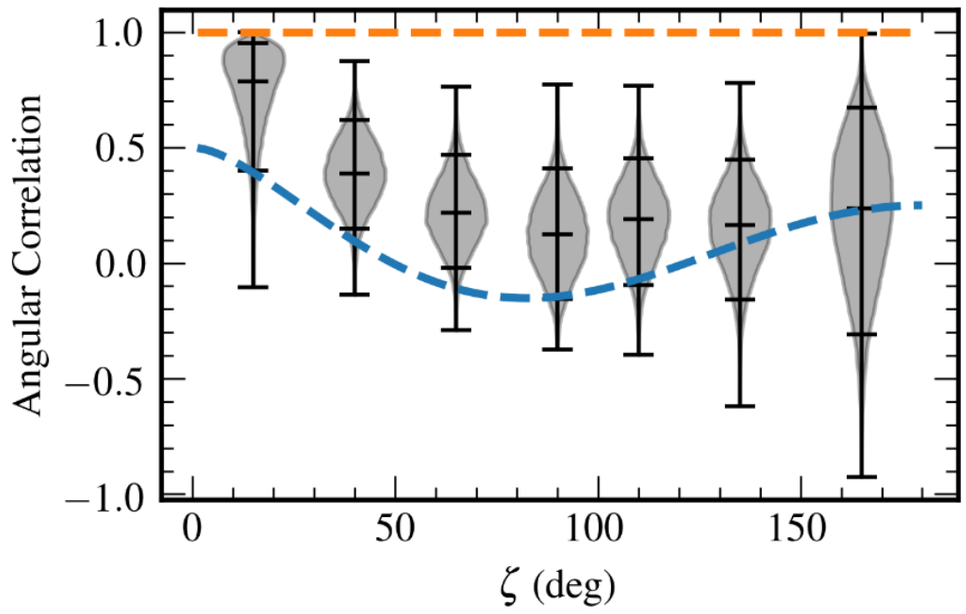


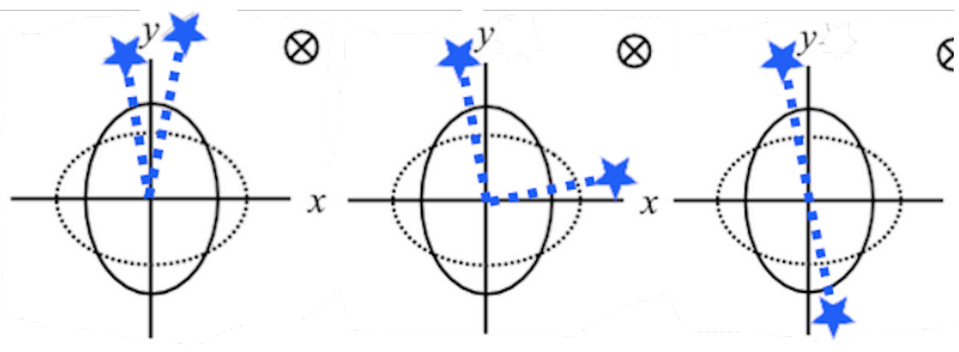
NANOGrav saw something!

Significant Strain at low frequencies



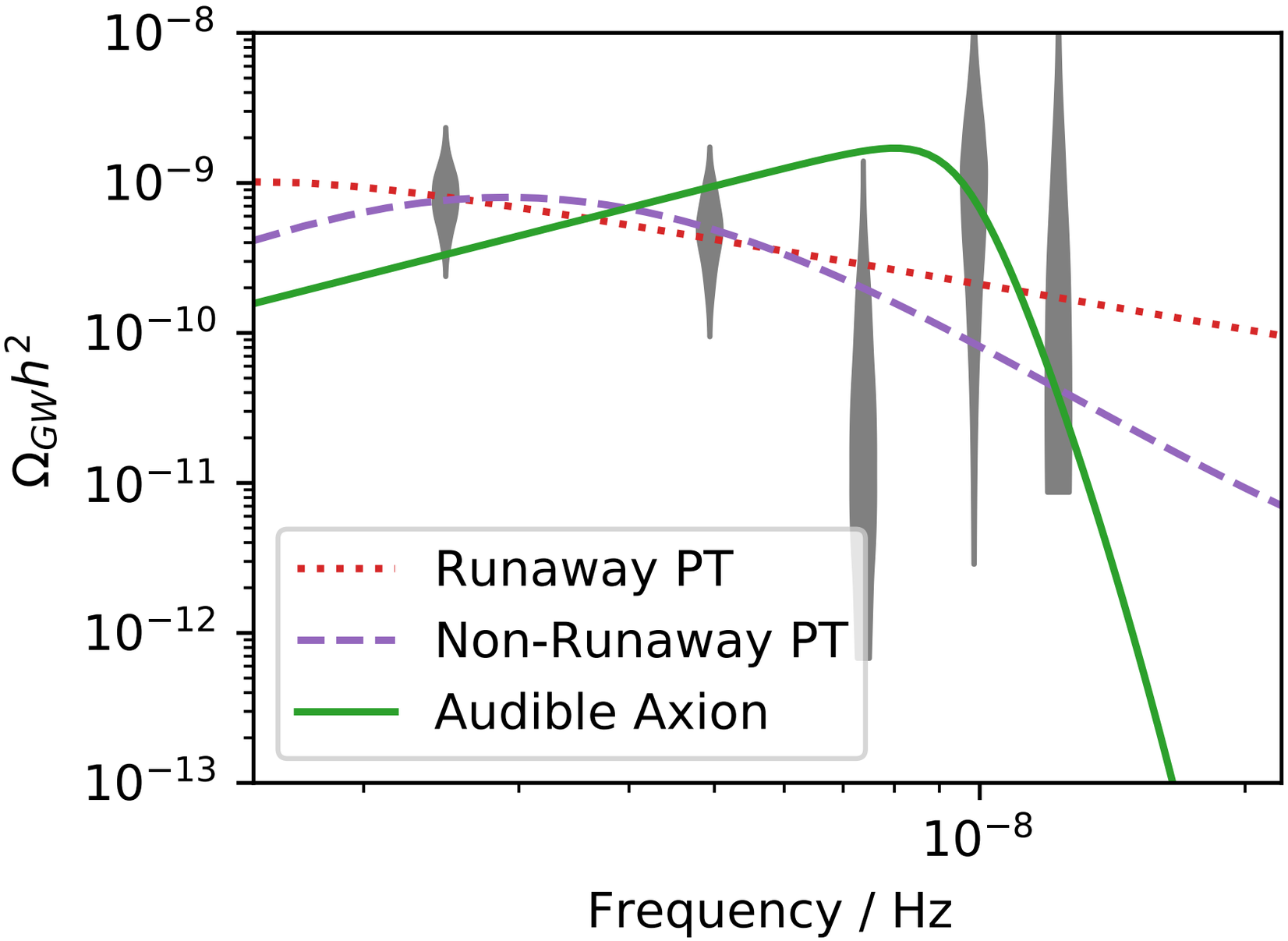
No 4σ evidence for Quadrupole





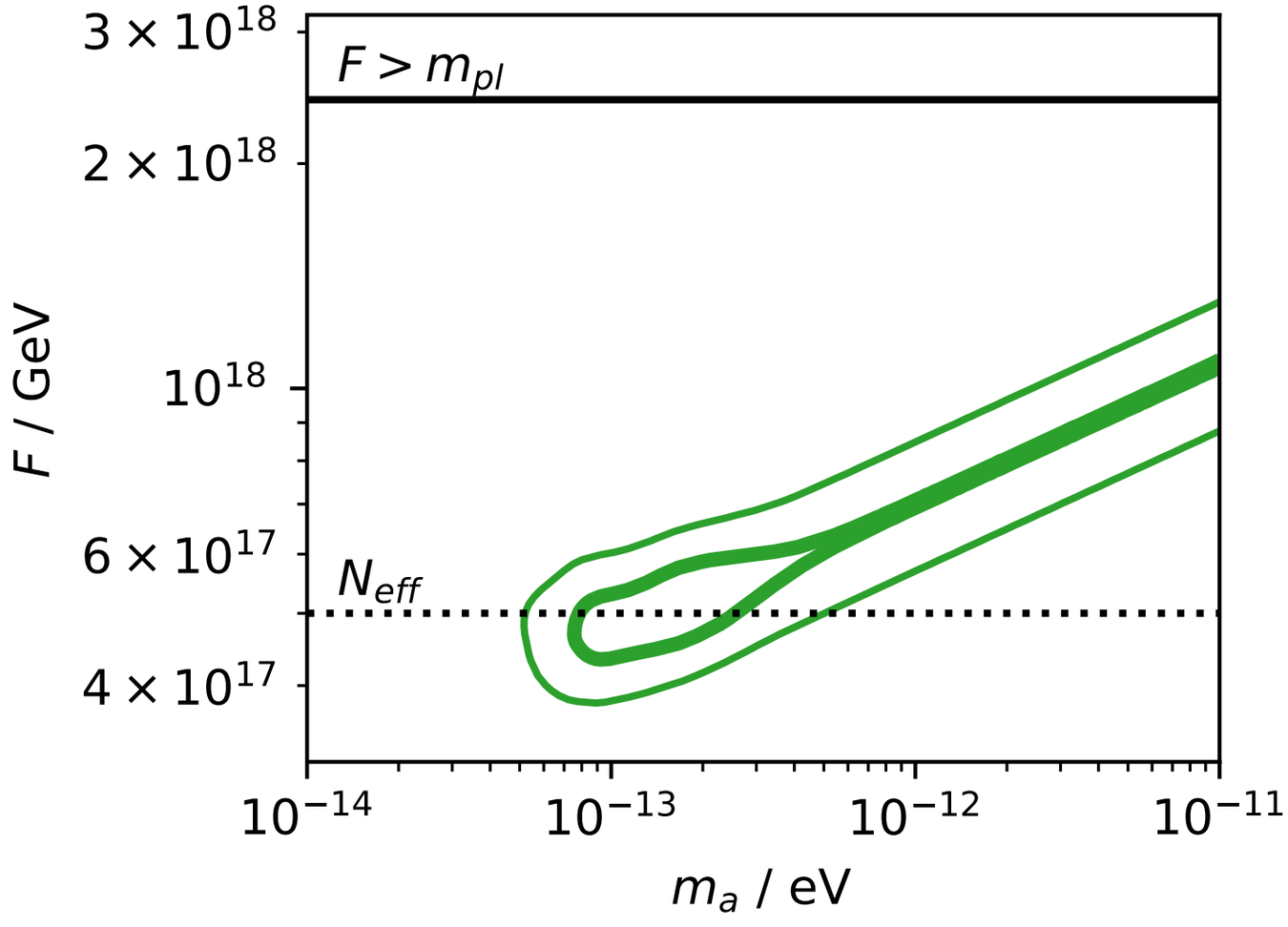
from NANOGrav colaboration: 2009.04496

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

Summary

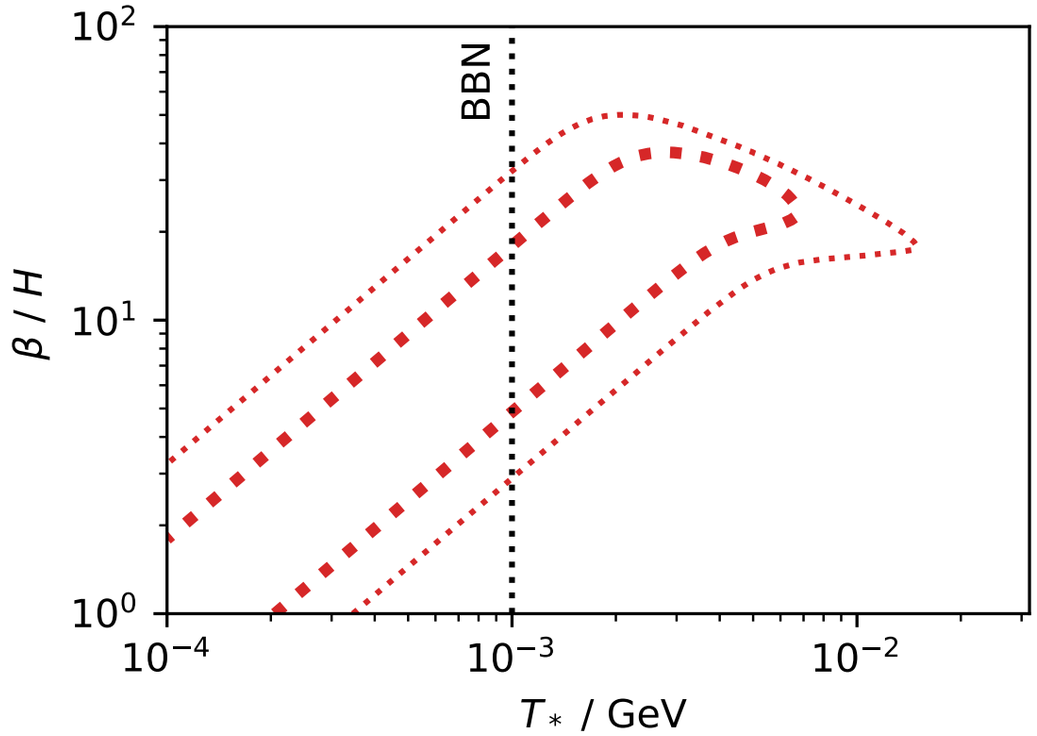
- Gravitational waves offer unique window into the early universe

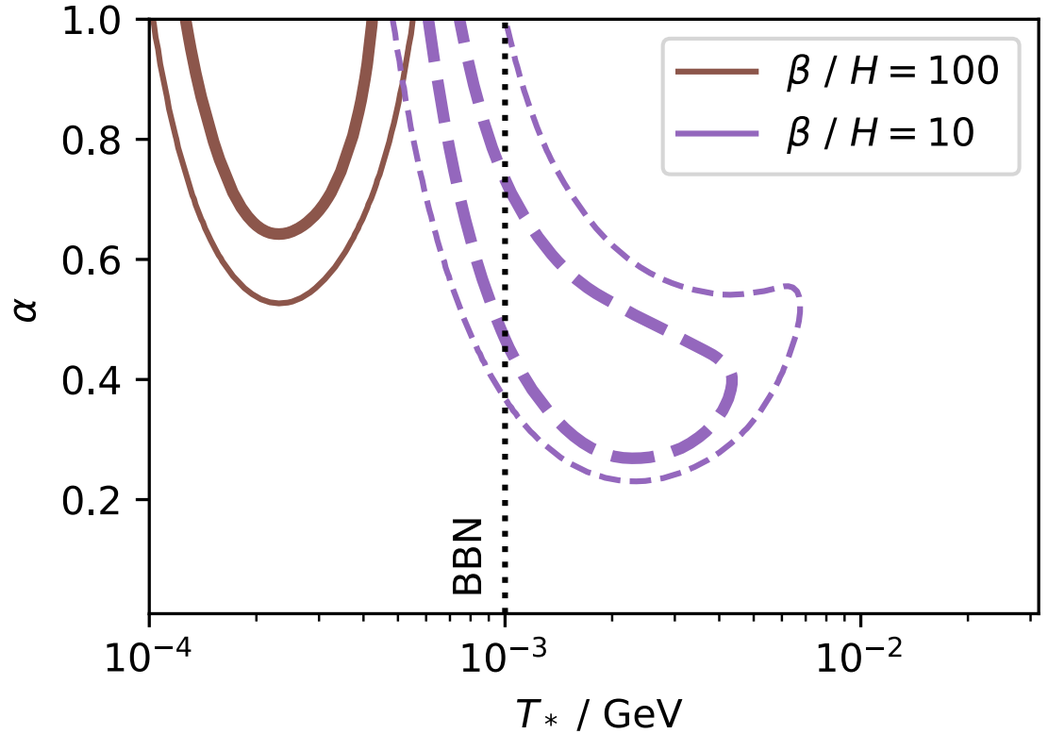
- New way to probe axions/ALPs

- 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!

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