Gravitational Wave Probes of Axion-like Particles

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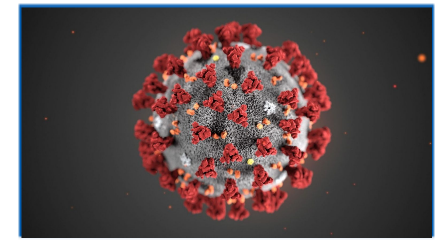
Talk based on:

Machado, Ratzinger, Schwaller, BAS: 1811.01950
Machado, Ratzinger, Schwaller, BAS: 1912.01007

Probing Axions in the Early Universe



What do know about cosmological history?

- Lots of evidence for inflation at an energy scale of at most the GUT scale.
- Need a thermal plasma for BBN at temperatures of order MeV.

What happens in between?

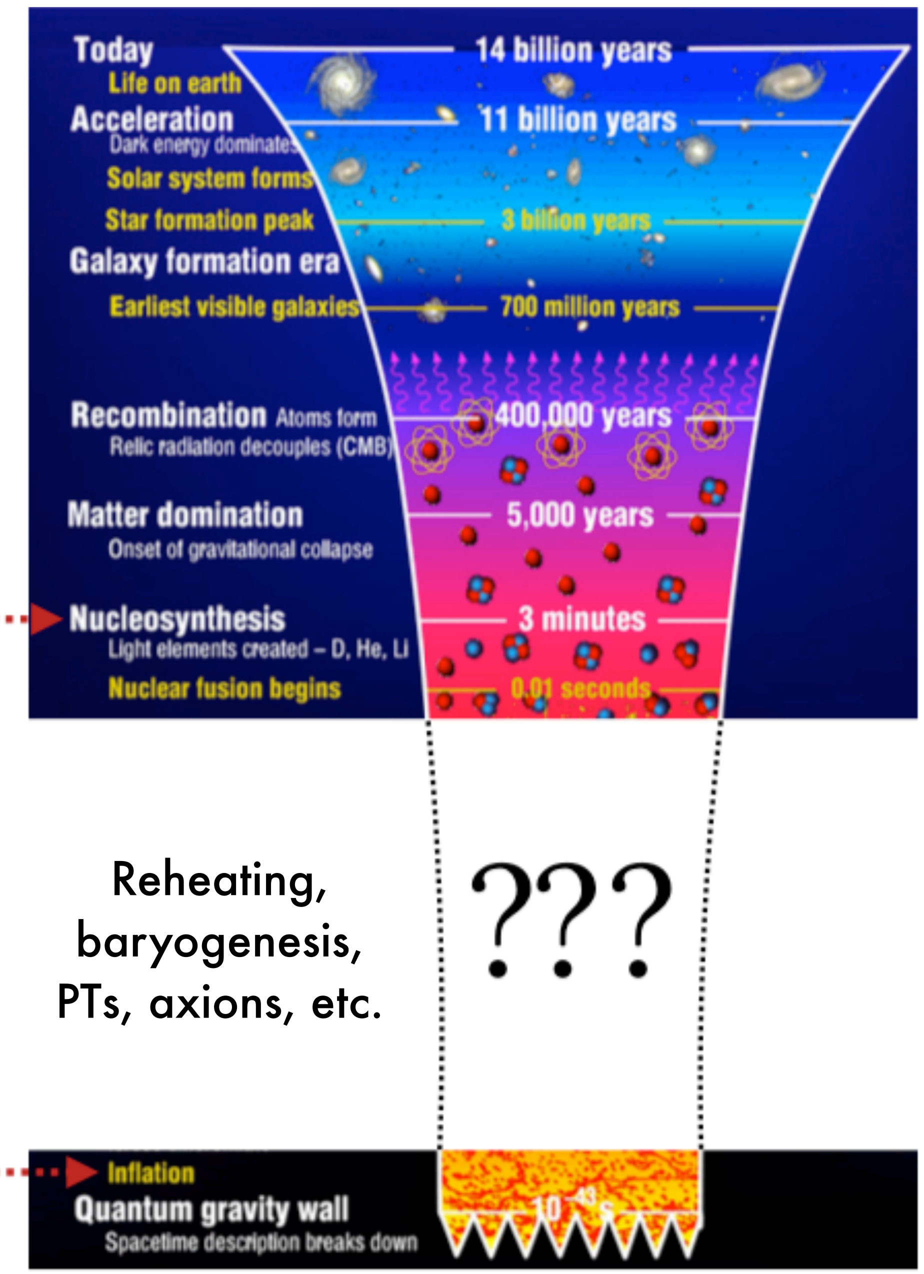
- Can axions/ALPs leave a signature in this era?
- Need a messenger which carries information from the early universe.

$T \sim 10^{-3}$ GeV

$$E_{\rm inf} = V_{\rm inf}^{1/4} \sim \sqrt{H_* M_P}$$

Energy scale separation potentially $E \sim \mathcal{O}(10^{19})$

$H_* \lesssim 10^{14}$ GeV



[http://www.ctc.cam.ac.uk]

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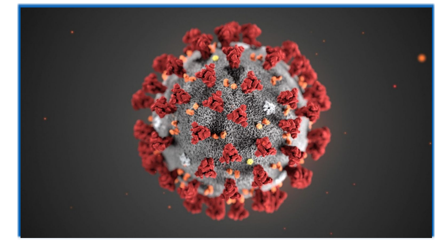

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- Lots of evidence for inflation at an energy scale of at most the GUT scale.
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Can we probe with GW?

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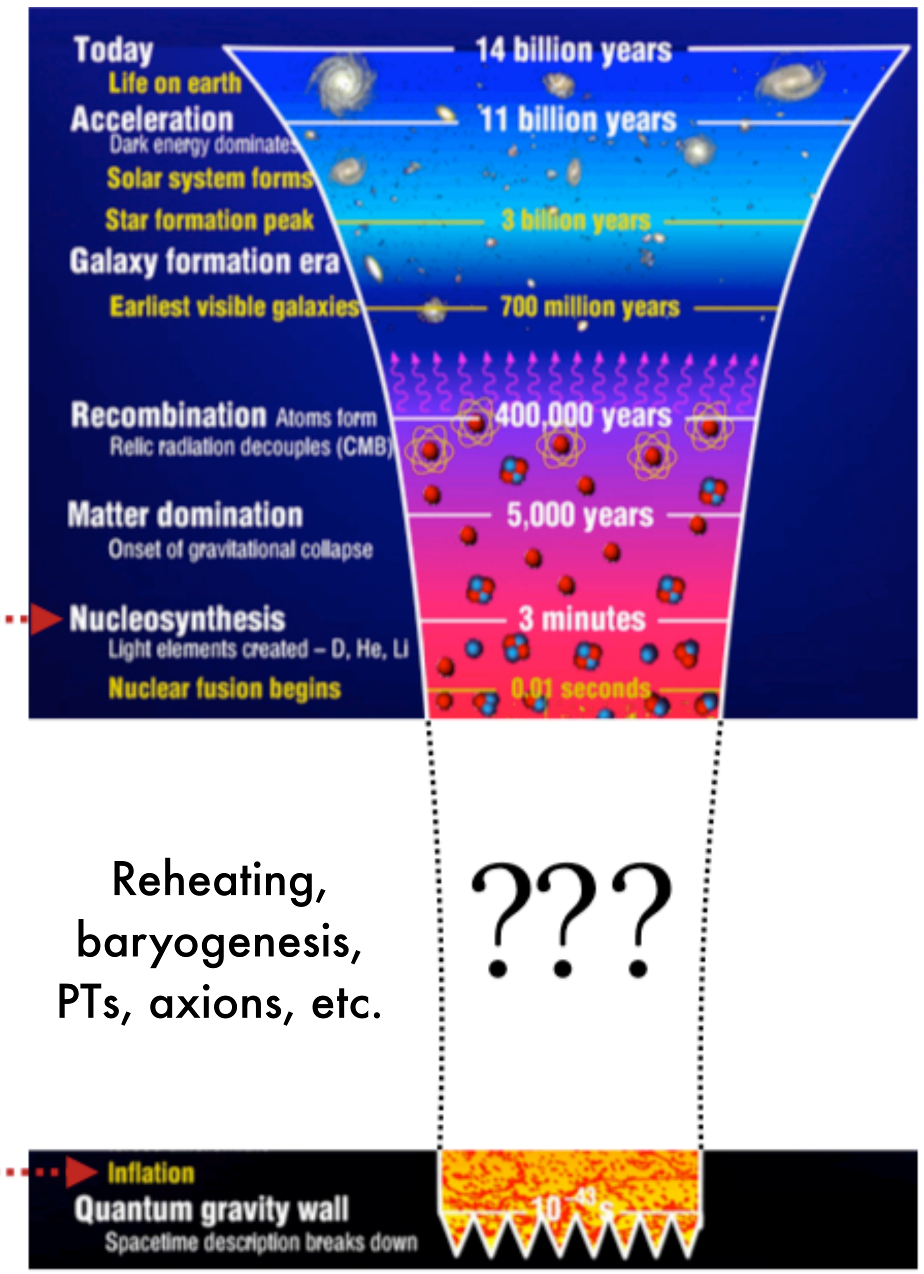

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Dark Axions in the Early Universe

Axions which have a mass heavier than H_{BBN} will begin to oscillate in the early universe.

$$T_{\mathrm{osc}} \sim \sqrt{m M_P}\ , \qquad\qquad m > H_{\mathrm{BBN}} \approx 10^{-16}\ \mathrm{eV}$$

One possibility is that these axions couple to hidden gauge groups rather than to the SM (or couple only very weakly to the SM)

- Axion becomes invisible- evades constraints based on coupling to photons, etc.
- Can still be probed via gravitational effects, e.g. superradiance, but these mainly focus on very light axions.
- Other gravitational probes for heavier ALPs?

Gravitational Waves from Dark Axions

Focus on a simple toy model with an ALP coupled to a dark photon of a hidden U(1):

$$\phi X_{\mu\nu} \widetilde{X}^{\mu\nu}$$

Dark photon can be non-perturbatively produced when the ALP has non-trivial dynamics.

- GW from the same process as preheating, axion inflation, etc.
- Aforementioned cases occur during or at the end of inflation, fixing the mass scale.
- But ALPs can also have non-trivial dynamics after inflation which result in GW production.

The Audible Axion Model

- We consider the following effective field theory consisting of an axion-like particle (ALP) ϕ and a dark photon X_μ

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi) - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\alpha}{4f}\phi X_{\mu\nu}\widetilde{X}^{\mu\nu}\right]$$

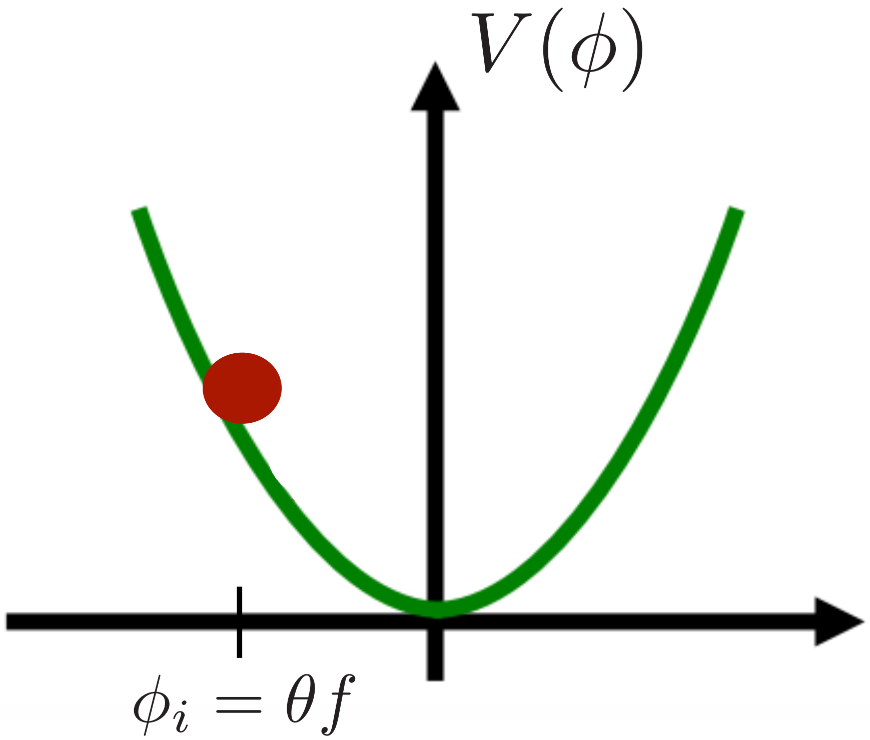
- We assume some explicit breaking of the global symmetry at the scale $\Lambda = \sqrt{mf}$, which generates a mass for the ALP

$$V(\phi) = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$$

Initial Conditions: Vacuum Misalignment

- Since the ALP has no reason to be near the minimum of the potential when it is generated, we generically expect initial conditions of the form

$$\phi_i = \theta f\,, \qquad \phi_i' \approx 0\,, \qquad \theta \sim \mathcal{O}(1)$$



Model Parameters

- In principle, the model has 5 parameters

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{1}{2} \partial_\mu \phi \, \partial^\mu \phi - V(\phi) - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\alpha}{4f} \phi X_{\mu\nu} \widetilde{X}^{\mu\nu} \right]$$

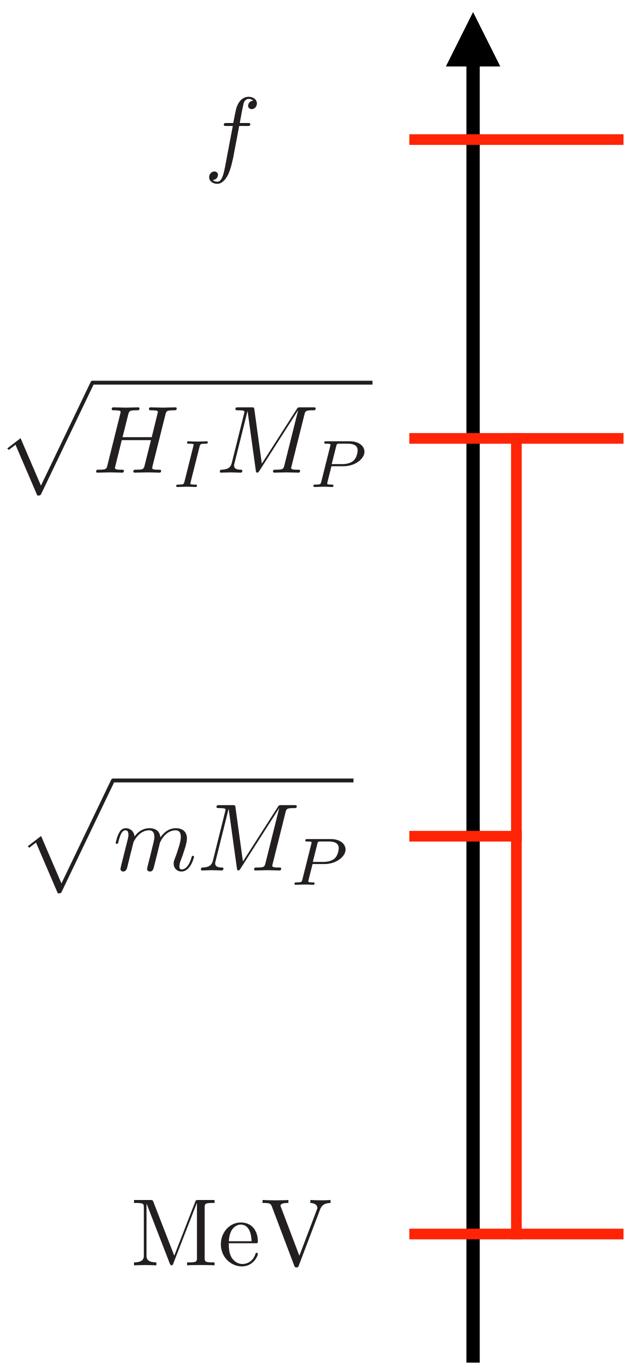
$$V(\phi) = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f} \right) \right] , \qquad \phi_i \, , \qquad \phi_i'$$

- But effectively 3 if we apply misalignment arguments

$$\phi_i = \theta f \, , \qquad \phi_i' \approx 0 \, , \qquad \theta \sim \mathcal{O}(1)$$

$$\boxed{m \, , \quad f \, , \quad \alpha}$$

Cosmological History



Global symmetry spontaneously broken

Inflation

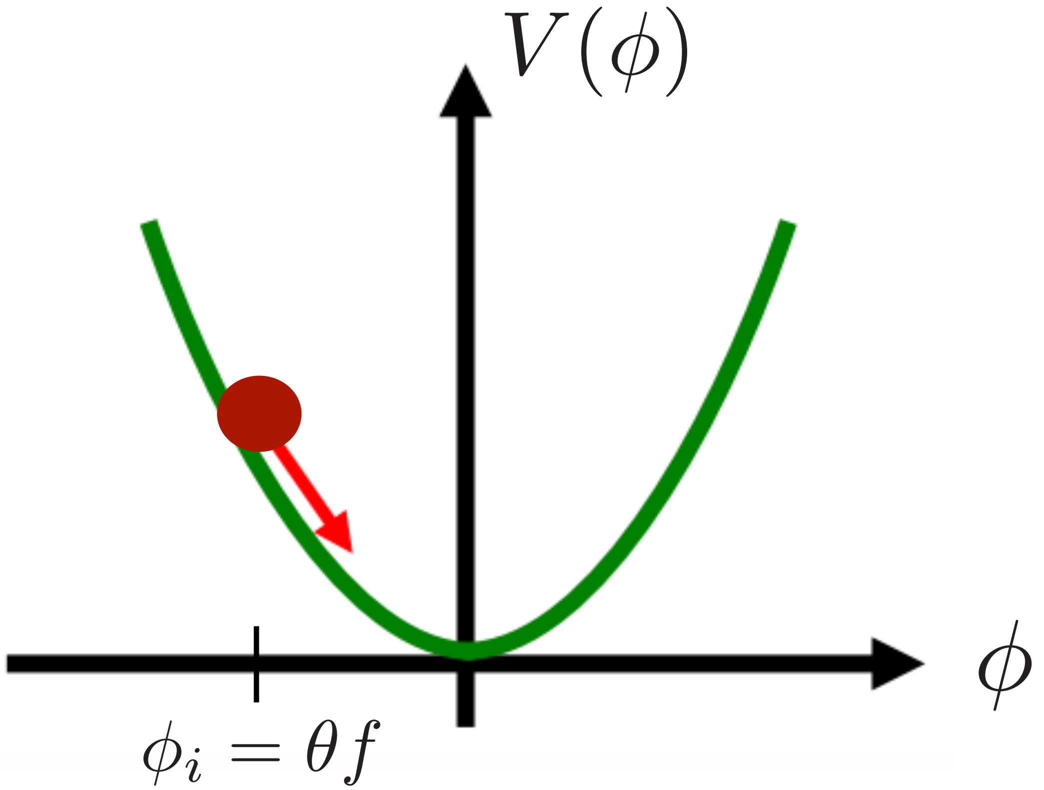
ALP begins to oscillate, transfers energy to dark photons. GW produced.

Big Bang Nucleosynthesis

Initial Dynamics

- The ALP begins to oscillate when the Hubble rate drops below the ALP mass

$$H_{\rm osc} \sim m\,, \qquad T_{\rm osc} = \sqrt{m M_P}$$



$$\rho_\phi^{\rm osc} \sim \frac{1}{2} m^2 \phi_i^2$$

$$\Omega_\phi^{\rm osc} = \frac{\rho_\phi^{\rm osc}}{\rho_{\rm tot}^{\rm osc}} \approx \frac{m^2\theta^2 f^2/2}{3M_P^2 H_{\rm osc}^2} \approx \left(\frac{\theta f}{M_P}\right)^2$$

Initial ALP and Dark Photon Energy Density

- We assume the dynamics occur when the universe is radiation dominated and take the ALP energy density to be a subdominant fraction

$$\Omega_\phi^{\rm osc} \approx \left(\frac{\theta f}{M_P}\right)^2 < 1$$

- But to source GW with a large amplitude, should be not be too small. We will require:

$$f \lesssim M_P$$

- For simplicity, we assume the no initial abundance for the dark photon. However, it can be sourced as the ALP rolls.

$$\Omega_X^{\rm osc} = 0$$

Dark Photon Production

Dark E and B, sink for ALP

- We assume that the ALP begins oscillating in a post-inflationary radiation-dominated FRW universe ($\Omega_\phi < \Omega_{\rm rad}$), in which the ALP obeys:

$$\phi'' + 2aH\phi' + a^2\frac{\partial V}{\partial \phi} = \frac{\alpha}{f}a^2\vec{E}\cdot\vec{B}\,,$$

and the dark photon obeys a wave equation sourced by ϕ'

$$\left(\frac{\partial^2}{\partial\tau^2} - \nabla^2\right)\vec{X} = \alpha\frac{\phi'}{f}\vec{\nabla}\times\vec{X}\,, \qquad \vec{\nabla}\cdot\vec{X} = 0\,.$$

Source for dark photons (while ALP rolls)

Dark Photon Production: Quantum Picture

circular pols. $(\mathbf{k} \times \varepsilon_\pm = \mp i k \varepsilon_\pm)$

We quantize the dark photon field as

$$\hat{X}^i(\mathbf{x},\tau) = \sum_{\lambda=\pm} \int \frac{d^3k}{(2\pi)^3} v_\lambda(k,\tau)\, \varepsilon^i_\lambda(\mathbf{k})\, \hat{a}_\lambda(\mathbf{k})\, e^{i\mathbf{k}\cdot\mathbf{x}} + \text{h.c.}$$

which leads to the following equation for the dark photon mode functions

$$v''_\pm + \omega^2_\pm(\tau) v_\pm = 0\,, \qquad \omega^2_\pm(\tau) = k^2 \mp k \frac{\alpha}{f}\phi'$$

As the ALP rolls, there exist momenta for which $\omega^2_\pm$ is negative. The corresponding modes are tachyonic and grow exponentially:

$$v_\pm(k,\tau) \sim e^{|\omega_\pm|\tau}$$

Dark Photon Spectrum and Parity Violation

Because the initial sign of ϕ' determines which helicity becomes tachyonic first, the system violates parity and one helicity experiences exponentially more production than the other.

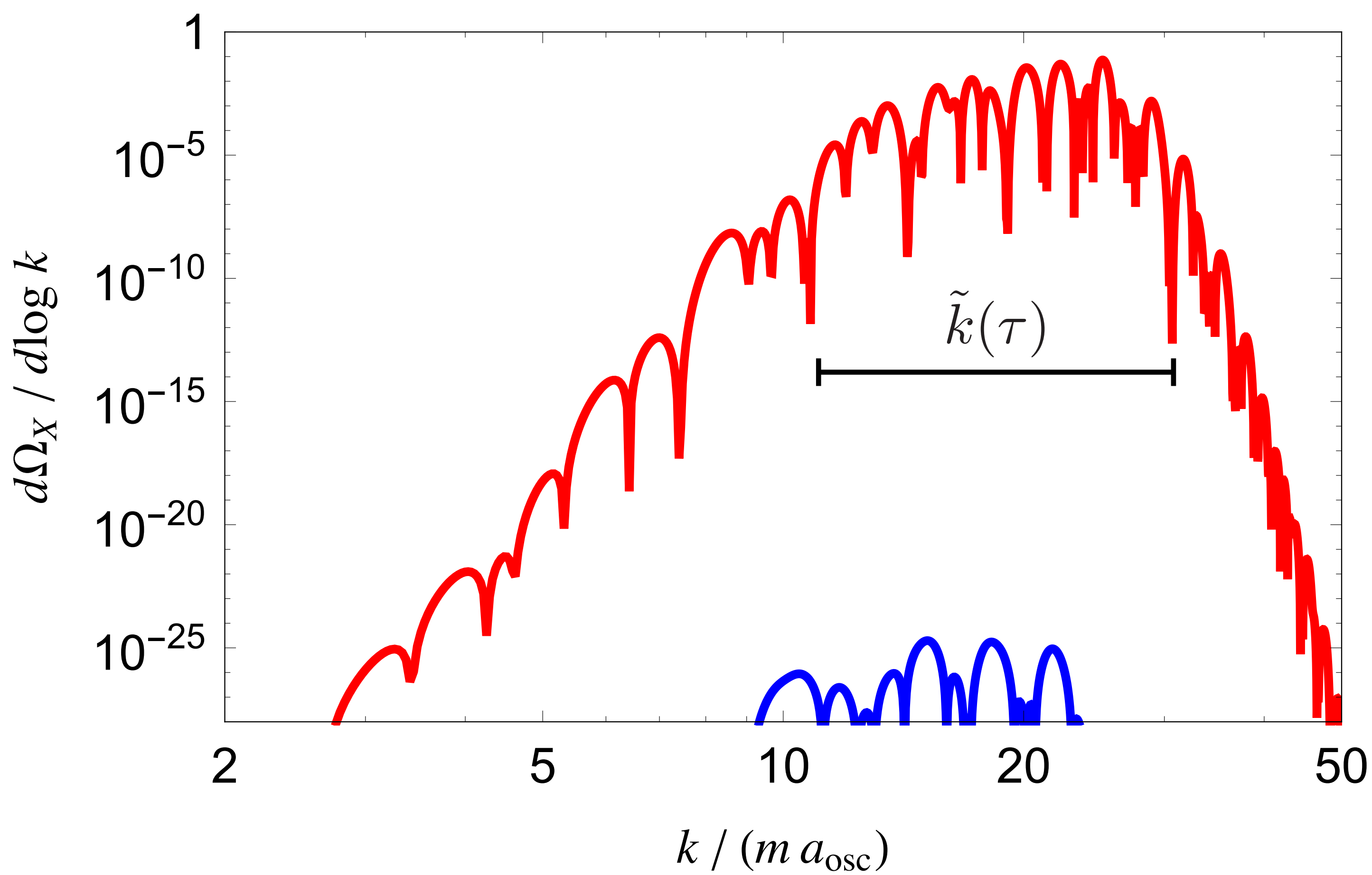
$$\omega_{+}^{2}(\tau) = k^2 - k\frac{\alpha}{f}\phi'$$

Tachyonic modes:

$$0 < k < \frac{\alpha\phi'}{f}\,, \qquad \frac{k}{m} \lesssim \alpha\theta$$

Most tachyonic mode:

$$\tilde{k} = \frac{\alpha\phi'}{2f} \lesssim \frac{\alpha\theta}{2}m$$



Stochastic Gravitational Waves

Dark photon modes in the range $0 < k < \theta \alpha m$ which were initially in vacuum grow exponentially when the axion begins to oscillate

$$v_\pm(k, \tau \ll \tau_{\rm osc}) = \frac{1}{\sqrt{2k}} e^{-ik\tau} \xrightarrow[\omega_\pm^2 < 0]{} v_\pm(k,\tau) \sim e^{|\omega_\pm|\tau}$$

These exponentially growing modes become highly occupied. Quantum fluctuations amplified into a rapidly time-varying, anisotropic classical energy distribution, sourcing GW.

Gravity Waves

$$h''_{ij}(\mathbf{k},\tau) + k^2 h_{ij}(\mathbf{k},\tau) = \frac{2}{M_P^2} \Pi_{ij}(\mathbf{k},\tau) \,,$$

Anisotropic stress

$$\hat{\Pi}_{ij}(\mathbf{k},\tau) = \frac{\Lambda_{ij}^{kl}}{a^2} \int \frac{d^3 q}{(2\pi)^3} \left[\hat{E}_k(\mathbf{q},\tau) \hat{E}_l(\mathbf{k}-\mathbf{q},\tau) + \hat{B}_k(\mathbf{q},\tau) \hat{B}_l(\mathbf{k}-\mathbf{q},\tau) \right] .$$

Gravitational Waves: More Detail

Anisotropic stress comes from exponentially growing dark photon modes:

$$\hat{\Pi}_{ij}(\mathbf{k},\tau) = \frac{\Lambda_{ij}^{kl}}{a^2}\int \frac{d^3q}{(2\pi)^3}\left[\hat{E}_k(\mathbf{q},\tau)\hat{E}_l(\mathbf{k}-\mathbf{q},\tau) + \hat{B}_k(\mathbf{q},\tau)\hat{B}_l(\mathbf{k}-\mathbf{q},\tau)\right].$$

$$\hat{E}_i(\mathbf{q},\tau) = v'_\lambda(q,\tau)\,\varepsilon_i^\lambda(\mathbf{q})\,\hat{a}_\lambda(\mathbf{q})$$

$$\hat{B}_i(\mathbf{q},\tau) = \lambda\, q\, v_\lambda(q,\tau)\,\varepsilon_i^\lambda(\mathbf{q})\,\hat{a}_\lambda(\mathbf{q})$$

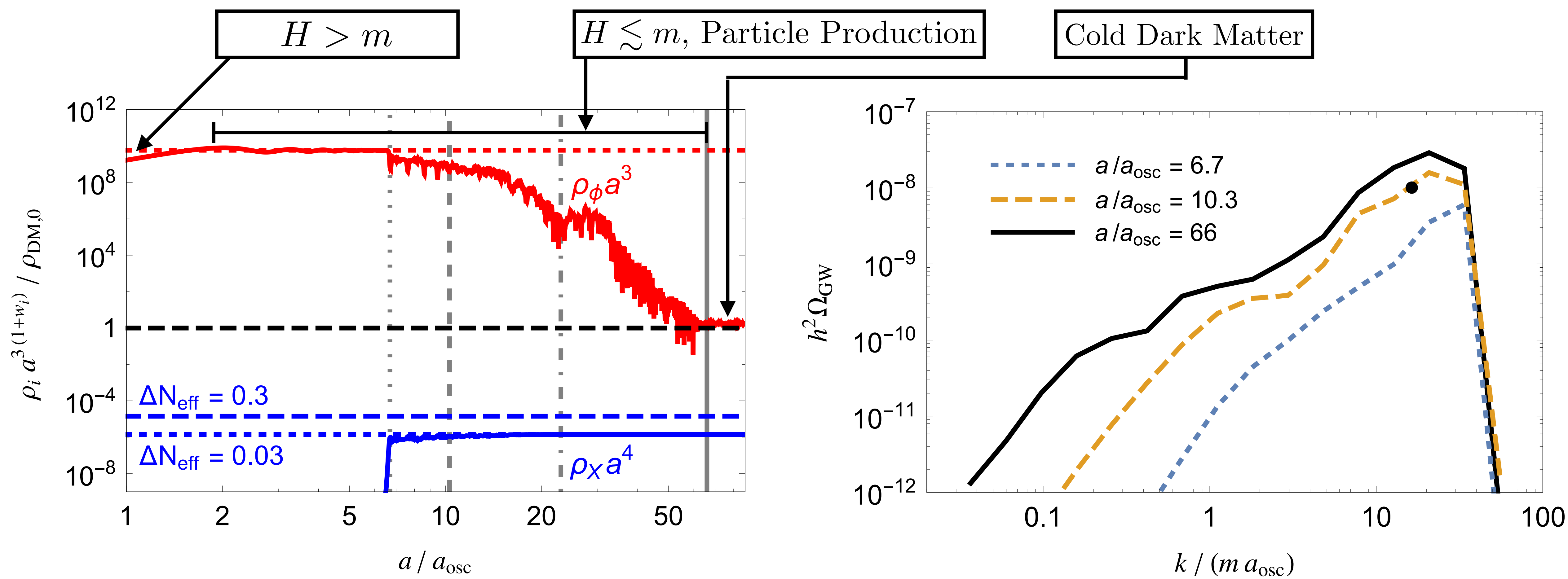
$$v_\pm(k,\tau) \sim e^{|\omega_\pm|\tau}$$

We compute the GW spectrum as follows:

$$\frac{d\rho_{\rm GW}}{d\log k} = \frac{k^3}{4\pi^2 a^4 M_P^2}\int_{\tau_{\rm osc}}^{\tau} d\tau' d\tau'' a(\tau')a(\tau'')\cos\left[k(\tau'-\tau'')\right]\Pi^2(\mathbf{k},\tau',\tau'')$$

$$\langle 0|\hat{\Pi}_{ij}(\mathbf{k},\tau)\hat{\Pi}^*_{ij}(\mathbf{k}',\tau')|0\rangle = (2\pi)^3\Pi^2(\mathbf{k},\tau,\tau')\delta(\mathbf{k}-\mathbf{k}')$$

Numerical Results: Linear Analysis



<u>Comoving Energy Densities</u>

[P. Agrawal, G. Marques-Tavares, W. Xue: arXiv:1708.05008]

<u>GW Spectrum</u>

[Machado, Ratzinger, Schwaller, BAS: 1811.01950]

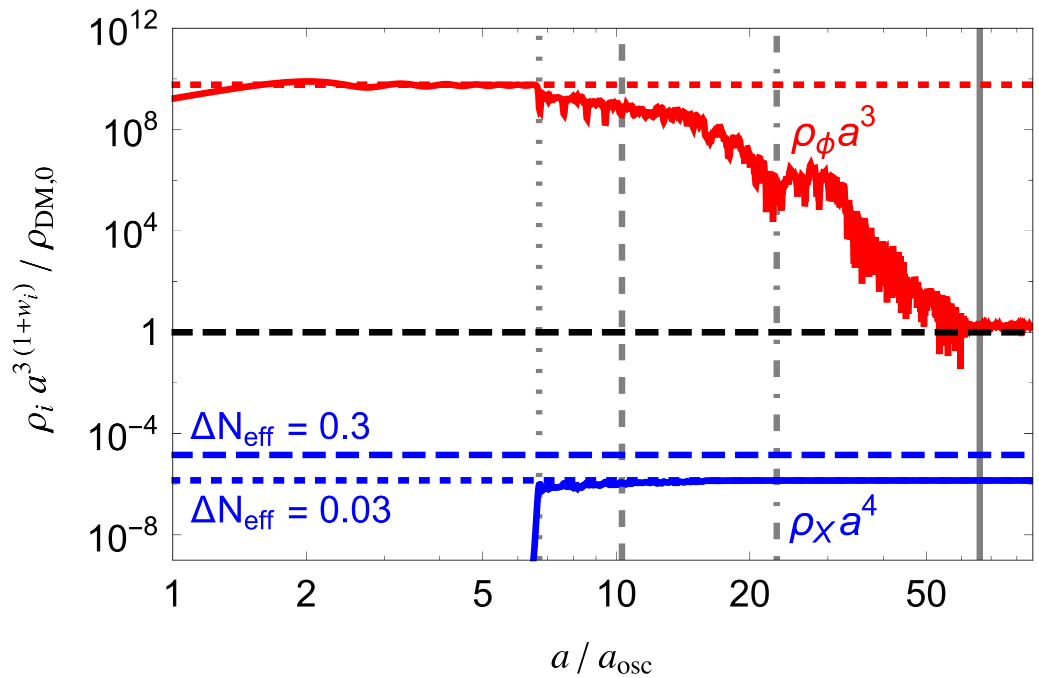
Benchmark Point: $m = 10^{-2}\,\mathrm{eV}\,, \quad f = 10^{17}\,\mathrm{GeV}\,, \quad \alpha = 55\,, \quad \theta = 1.2$

Tachyonic Instability

Because the helicity which experiences tachyonic growth switches every half period, only the modes which have growth timescales less than the conformal oscillation time will grow efficiently

$$\omega^2 = k^2 - k\frac{\alpha}{f}\phi' < -(am)^2$$

$$k_\pm \approx \tilde{k}\left[1 \pm \sqrt{1 - \left(\frac{2}{\alpha\theta}\right)^2 \left(\frac{a}{a_{\rm osc}}\right)^3}\right]$$



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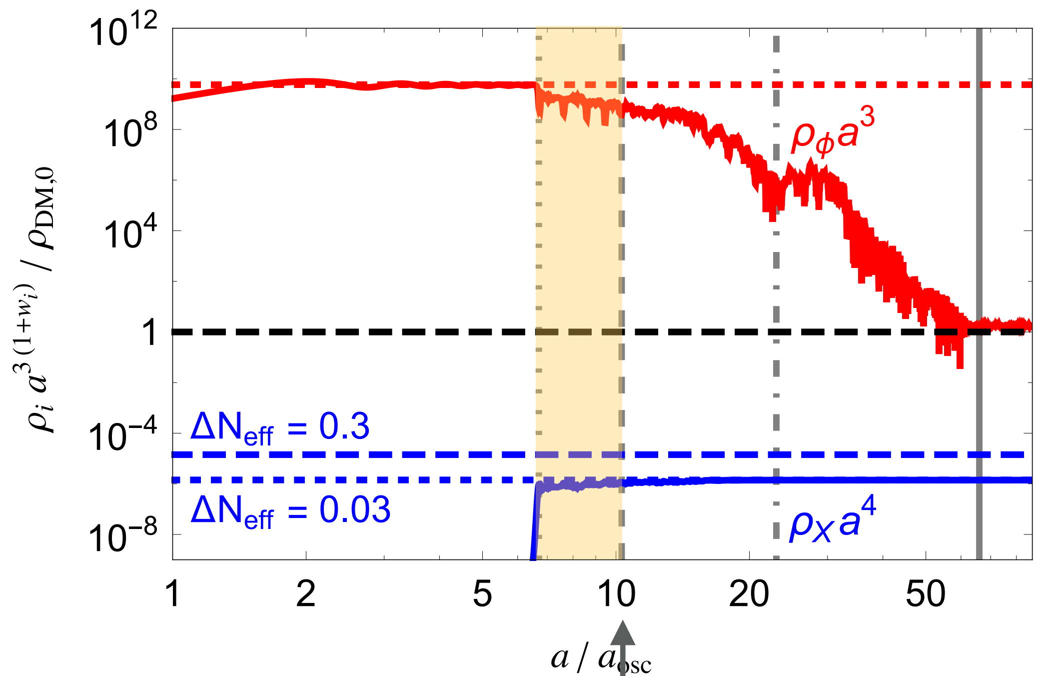
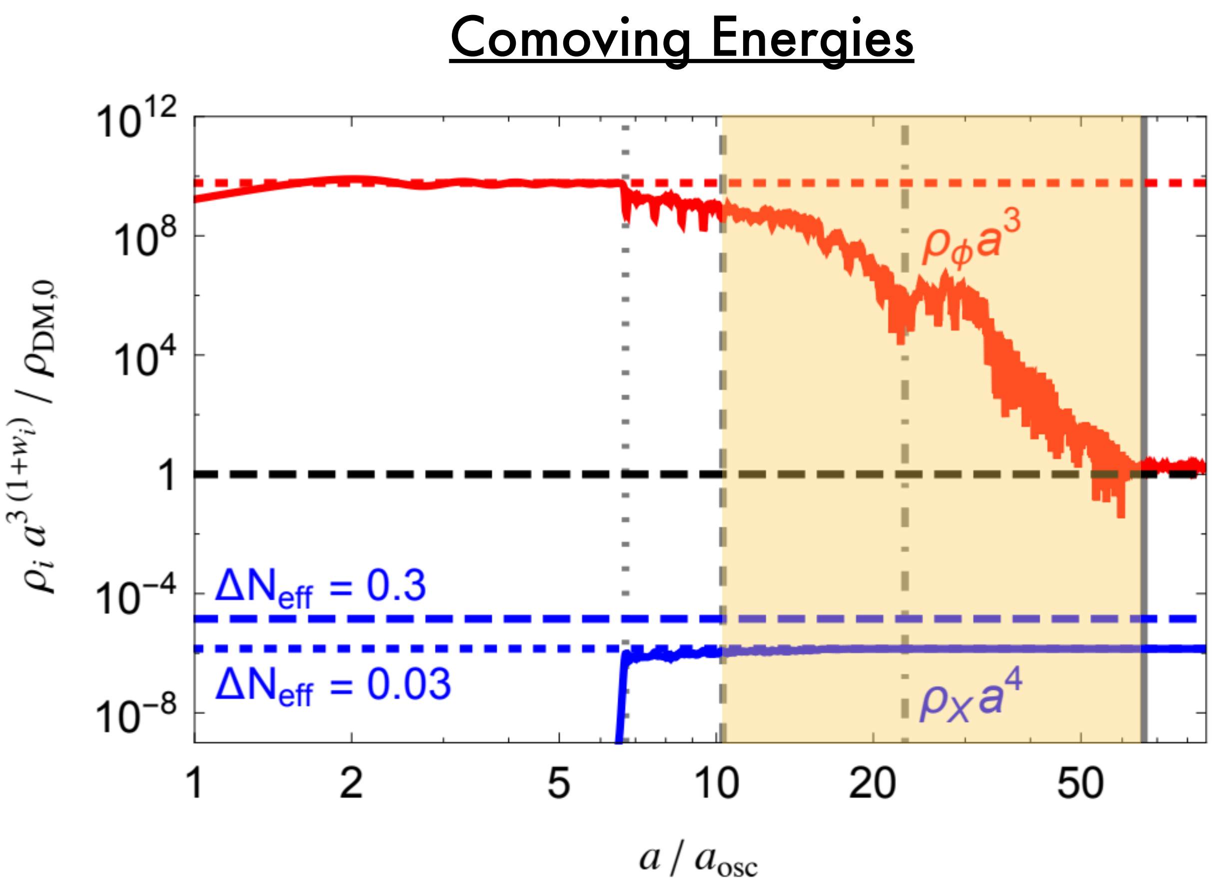


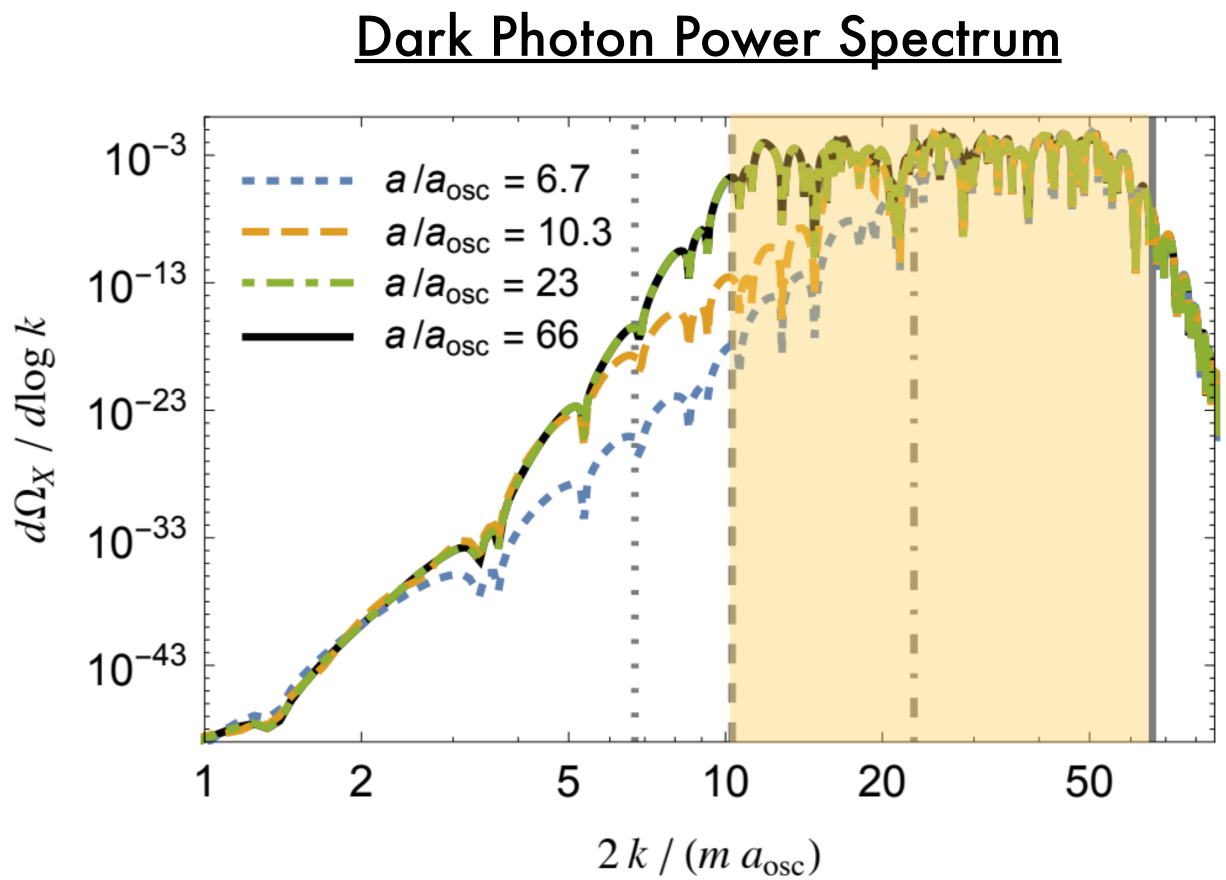
Tachyonic band is $k_- < k < k_+$ and closes when

$$a/a_{\rm osc} = (\alpha\theta/2)^{2/3} \approx 10 \qquad \tilde{k} = a_{\rm osc} m(\alpha\theta/2)^{2/3} \approx 10m$$

Will use this to estimate the time of GW emission.

Parametric Resonance





Modes → Mathieu Equation

$$\frac{d^2 v_\pm(k,z)}{dz^2} + \left[A_k \pm 2qF(z)\right] v_\pm(k,z) = 0$$

$$A_k = 4\left(\frac{k}{am}\right)^2 = n^2$$

Narrow Resonance Bands

For small amplitude

$$k = ma/2 \quad (n = 1)$$

$$a_f / a_{osc} \approx \alpha\theta \approx 66$$

GW Spectrum: NDA

The energy in GW is limited by the energy in the axion field

$$\Omega_\phi^{\rm osc} = \frac{\rho_\phi^{\rm osc}}{\rho_{\rm tot}^{\rm osc}} \approx \frac{m^2\theta^2 f^2/2}{3M_P^2 H_{\rm osc}^2} \approx \left(\frac{\theta f}{M_P}\right)^2 .$$

Rough estimate for the peak of the GW spectrum

$$k_{\rm peak} \approx \tilde{k}(\tau_*)\,, \qquad \Omega_{\rm GW}(k_{\rm peak}) = \Omega_\phi^2 \left(\frac{a_* H_*}{k_{\rm peak}}\right)^2 .$$

Estimating at the time of emission leads to

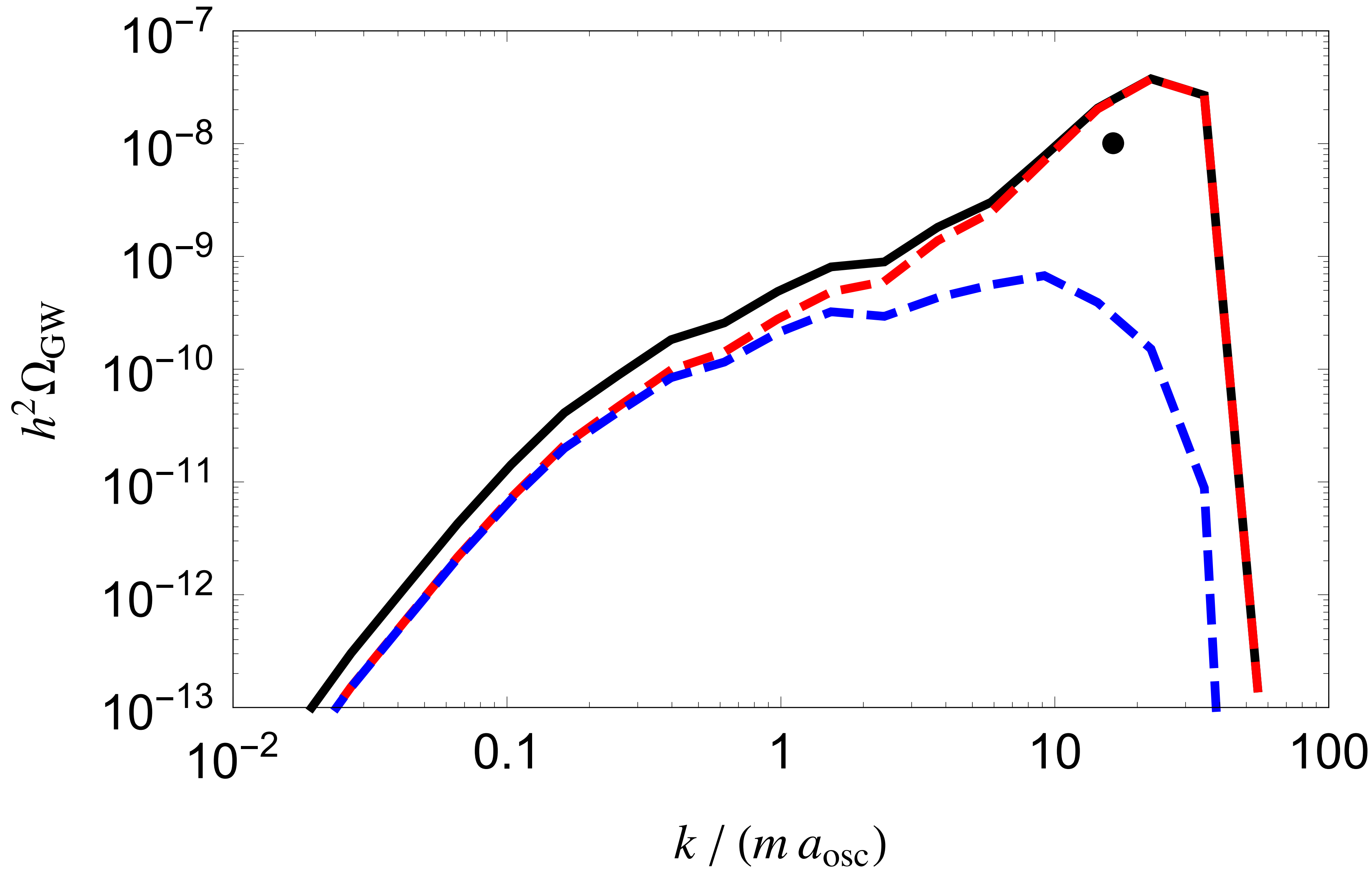
$$k_{\rm peak} \approx (\alpha\theta)^{2/3}\, m\,, \qquad \Omega_{\rm GW}(k_{\rm peak}) \approx \left(\frac{f}{M_P}\right)^4 \left(\frac{\theta^2}{\alpha}\right)^{\frac{4}{3}} .$$

ALP mass sets peak frequency

Large decay constant required

GW Spectrum: Numerical Result

Scaling Estimate: $k_{\rm peak} \approx (\alpha\theta)^{2/3}\, m\,, \qquad \Omega_{\rm GW}(k_{\rm peak}) \approx \left(\frac{f}{M_P}\right)^4 \left(\frac{\theta^2}{\alpha}\right)^{\frac{4}{3}}\,.$



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[Machado, Ratzinger, Schwaller, BAS: 1811.01950]

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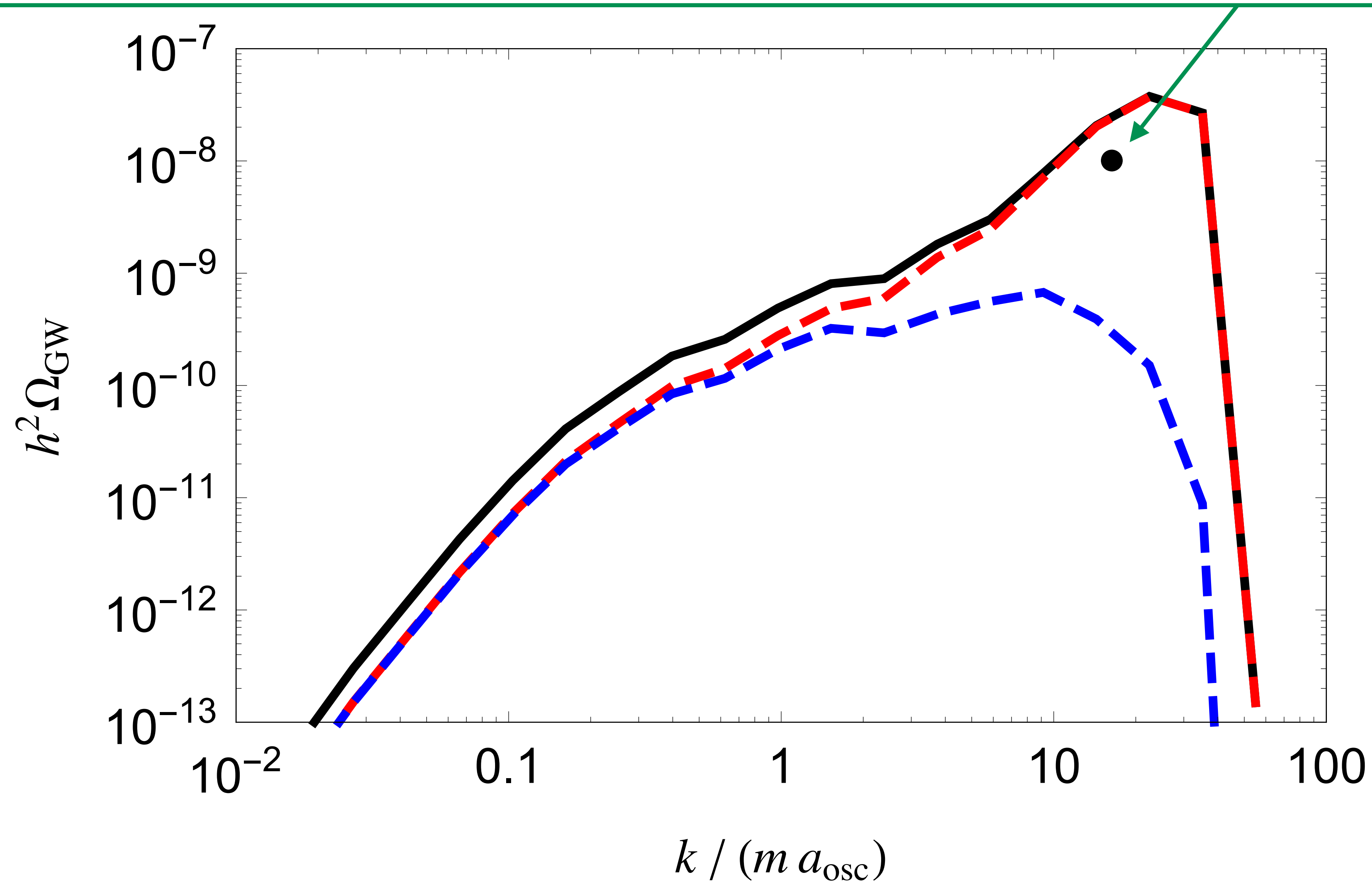

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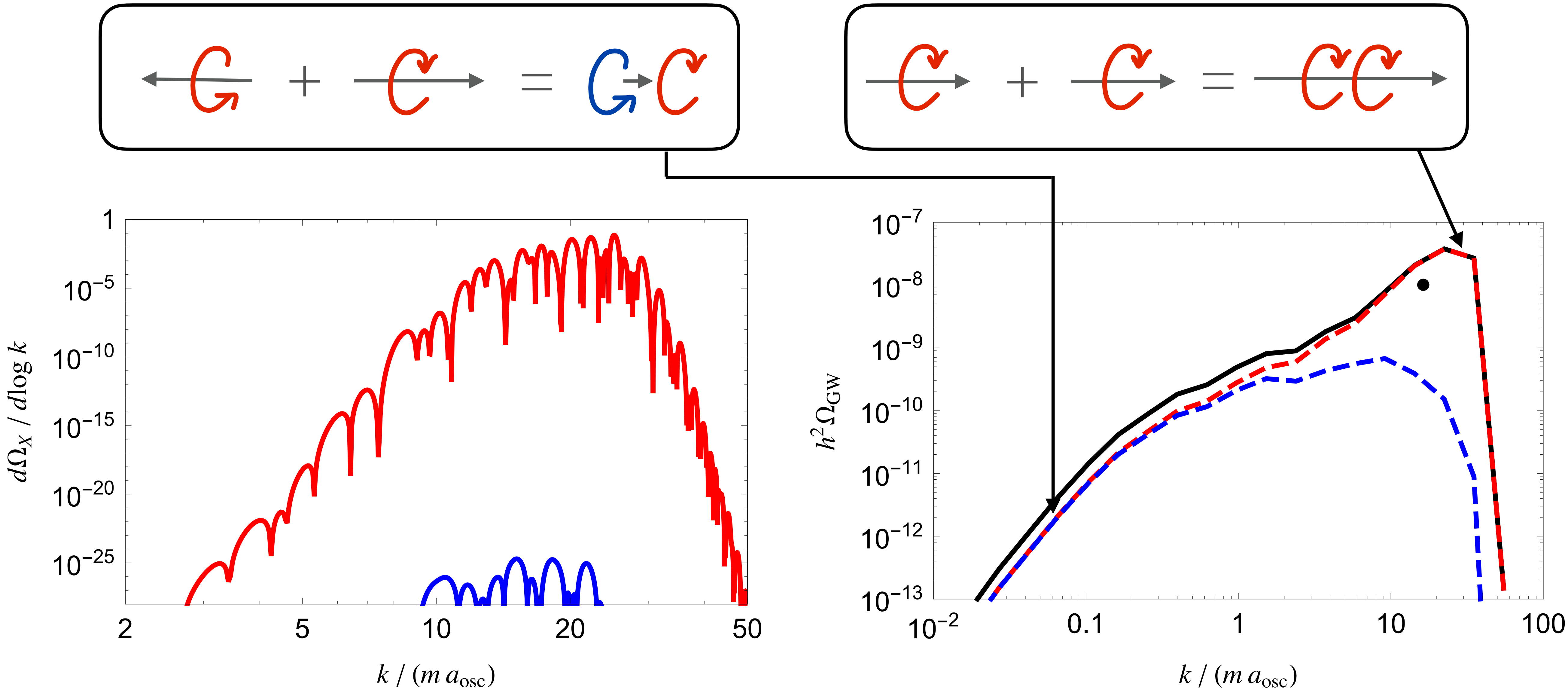
GW Spectrum: Chirality

The produced GW spectrum is highly polarized because the GWs inherit the parity violation in the dark photon population.



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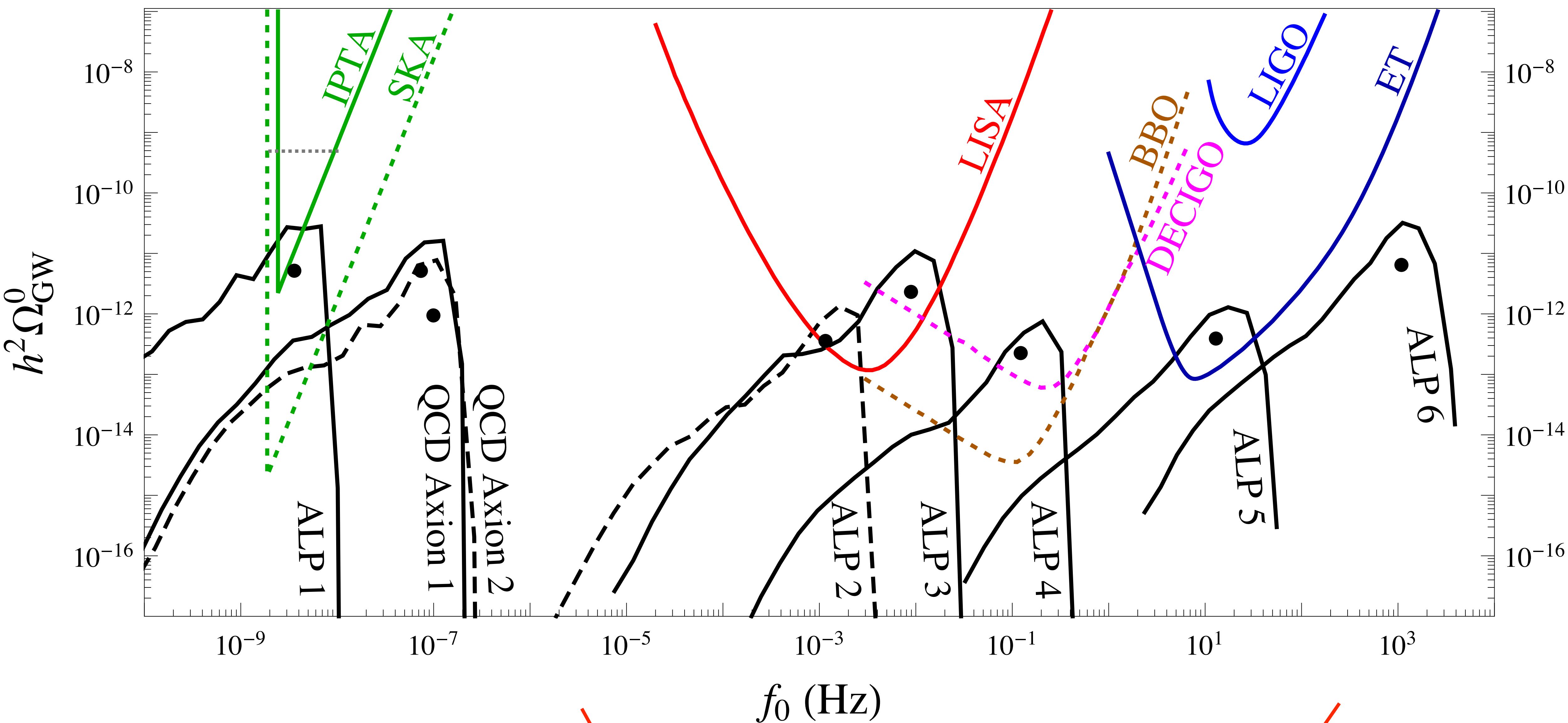
Probing ALPs with Gravitational Waves



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

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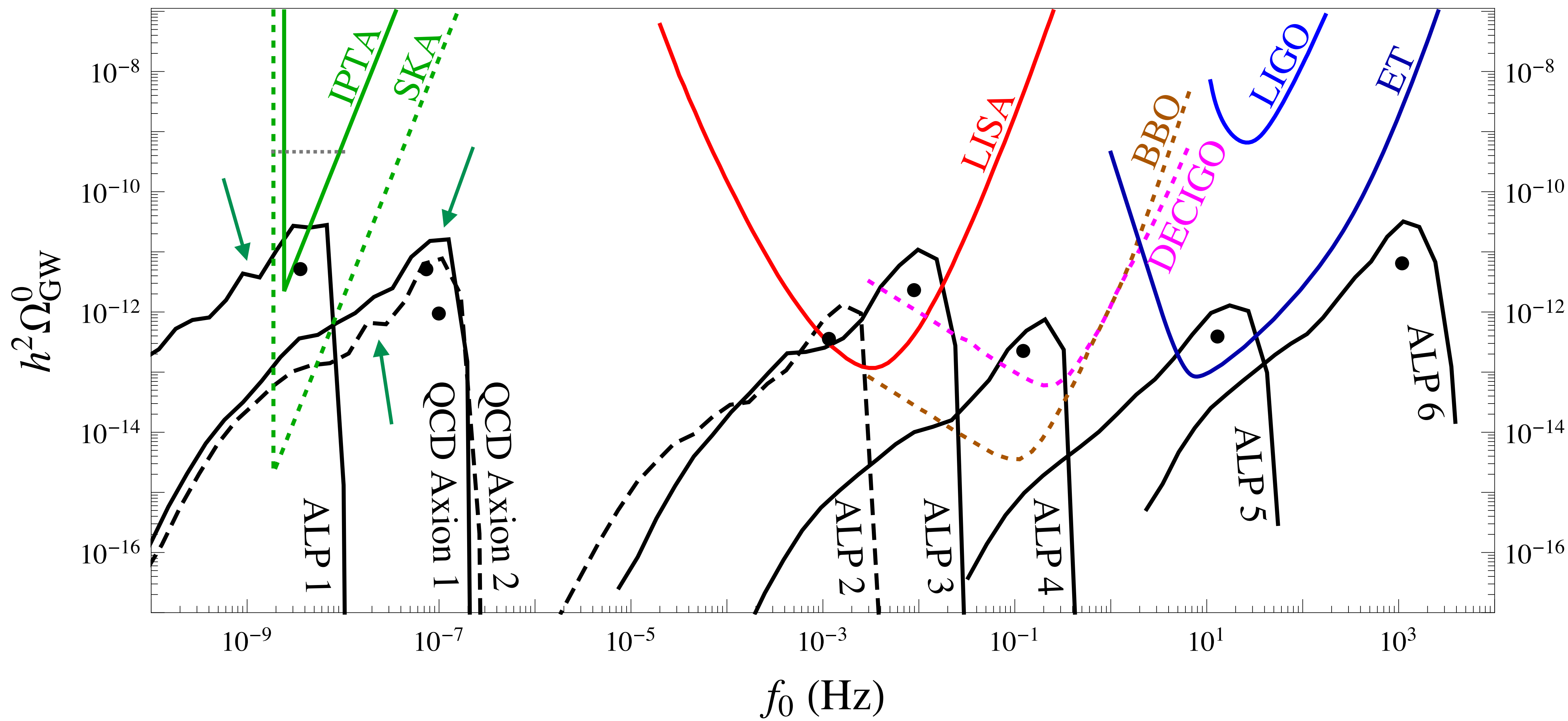


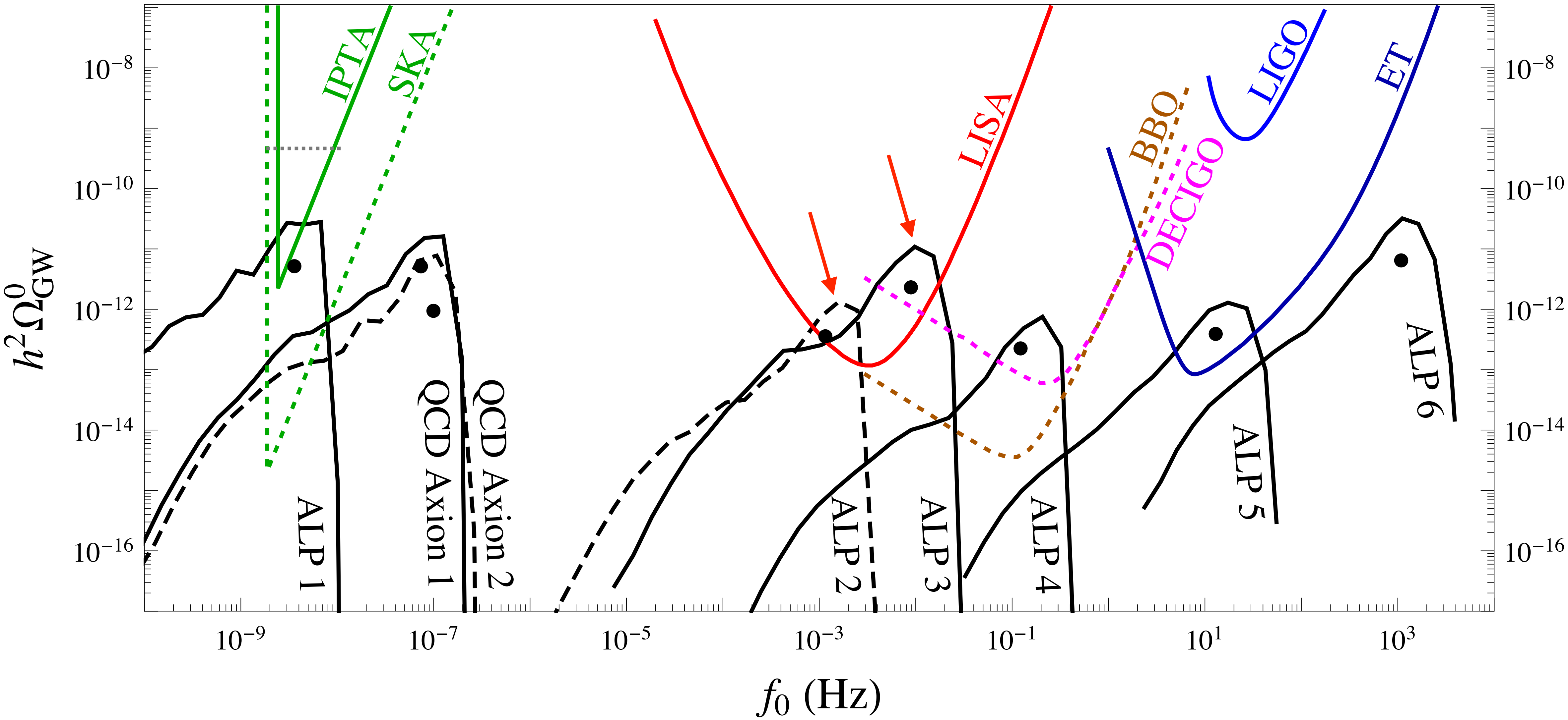
GW Spectrum	m (eV)	f (GeV)	θ	α	$\rho^0_\phi/\rho^0_{\rm DM}$	$\Delta N_{\rm eff}$
ALP 1	5.6×10^{-14}	2.0×10^{17}	1.0	75	0.011	0.24
QCD Axion 1	3.0×10^{-11}	2.0×10^{17}	1.0	73	1.1	0.18
QCD Axion 2	6.1×10^{-11}	1.0×10^{17}	1.3	55	1.9	0.075
ALP 2	1.0×10^{-2}	1.0×10^{17}	1.2	55	1.7	0.030
ALP 3	5.0×10^{-1}	2.0×10^{17}	1.0	75	0.85	0.069
ALP 4	1.0×10^{2}	1.0×10^{17}	1.1	65	0.020	0.018
ALP 5	1.0×10^{6}	1.0×10^{17}	1.3	60	0.29	0.020
ALP 6	1.0×10^{10}	2.0×10^{17}	1.2	50	*	*

<u>ALPs Detectable by Pulsar Timing Arrays:</u>

$m \sim 10^{-13}$ - 10^{-10} eV

$f \gtrsim 10^{17}$ GeV

[Machado, Ratzinger, Schwaller, BAS: 1811.01950]



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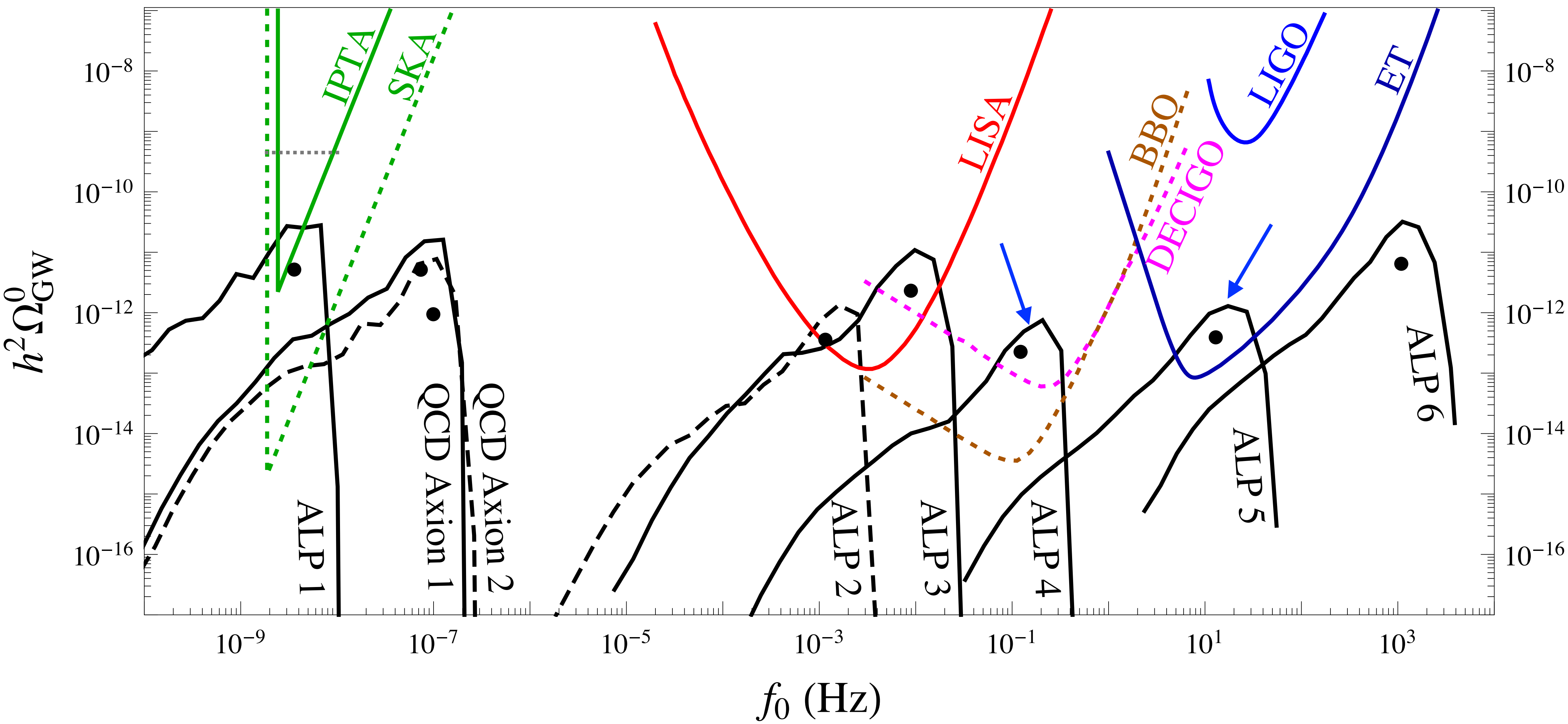
ALPs Detectable by LISA:

$m \sim 0.01 - 1$ eV

$f \gtrsim 10^{17}$ GeV

[Machado, Ratzinger, Schwaller, BAS: 1811.01950]



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Future High Frequency Detectors:

$m \sim 10^2\text{-}10^6$ eV

$f \gtrsim 10^{17}$ GeV

[Machado, Ratzinger, Schwaller, BAS: 1811.01950]

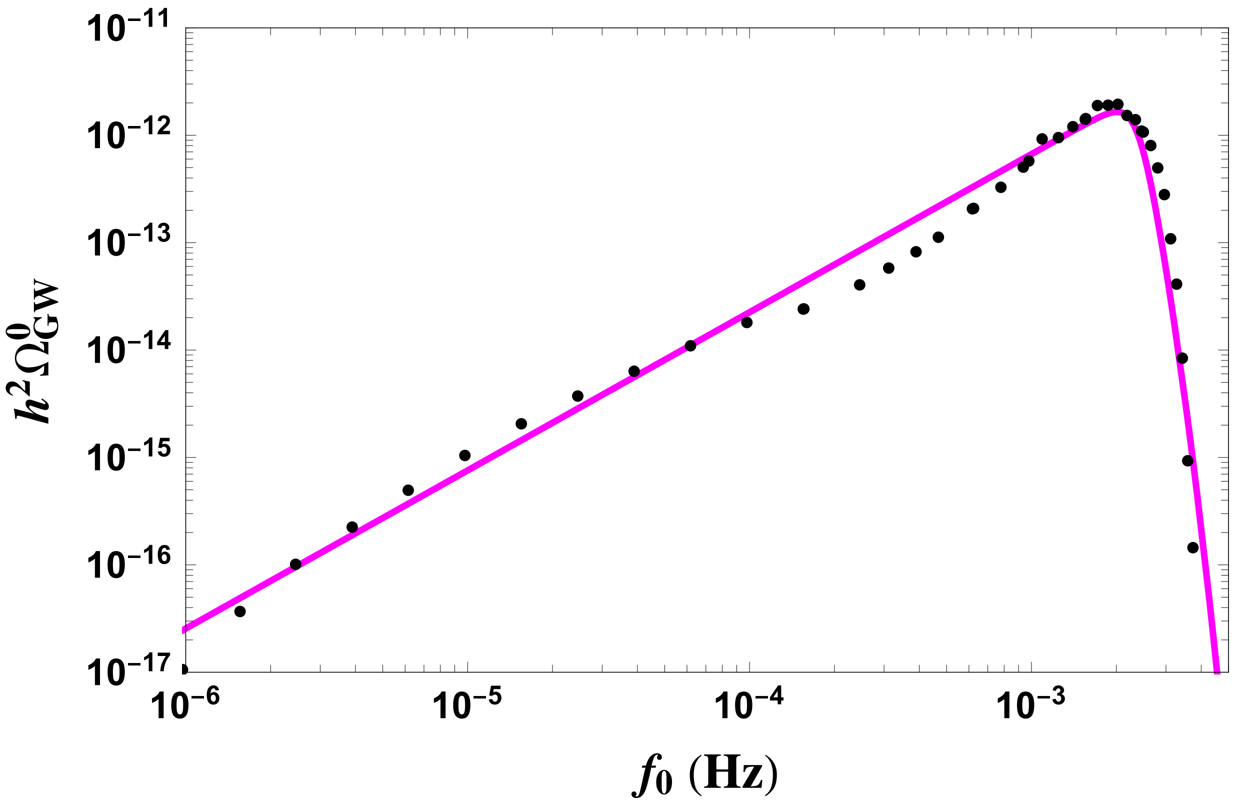
GW Spectrum: Fit Template

Scaling Relations: $f_{\text{peak}} \approx (\alpha\theta)^{2/3} m\,, \qquad \Omega_{\text{GW}}(f_{\text{peak}}) \approx \left(\frac{f}{M_P}\right)^4 \left(\frac{\theta^2}{\alpha}\right)^{\frac{4}{3}}$

Fit Template

$$\tilde{\Omega}_{\text{GW}}(\tilde{f}) = \frac{\mathcal{A}_s \left(\tilde{f}/f_s\right)^p}{1 + \left(\tilde{f}/f_s\right)^p \exp\left[\gamma(\tilde{f}/f_s - 1)\right]}$$

	$\mathcal{A}_s$	f_s	γ	p
Total spectrum (black)	6.3	2.0	12.9	1.5

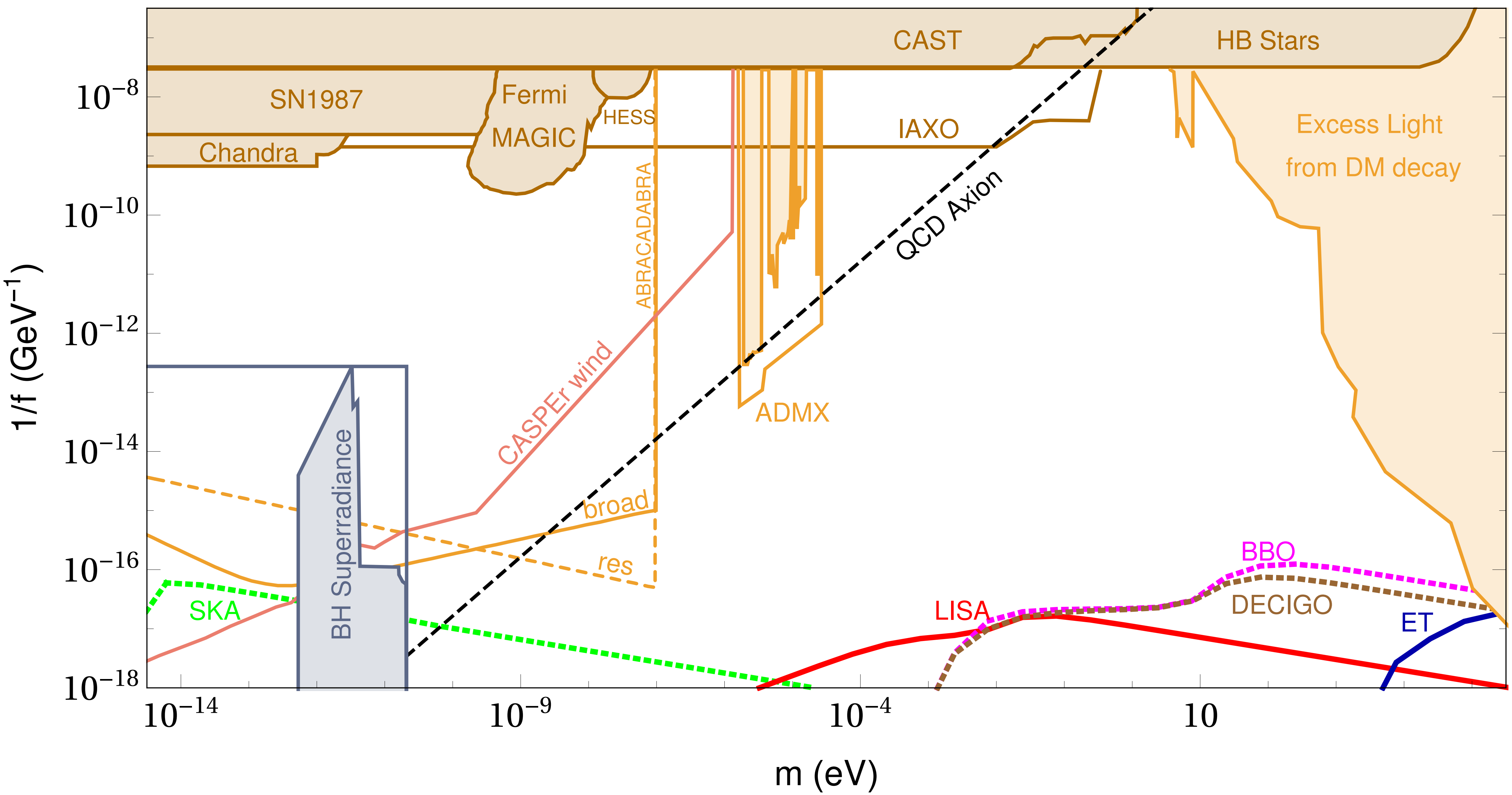


- Can use the template to go directly from a set of underlying model parameters $\{\alpha, m, f\}$ to the GW spectrum without running a time-consuming numerical simulation.

[Machado, Ratzinger, Schwaller, BAS: 1912.01007]

Probing ALPs with Gravitational Waves

Because larger decay constants correspond to larger GW amplitude, gravitational wave detectors can probe these models from the "bottom up"!



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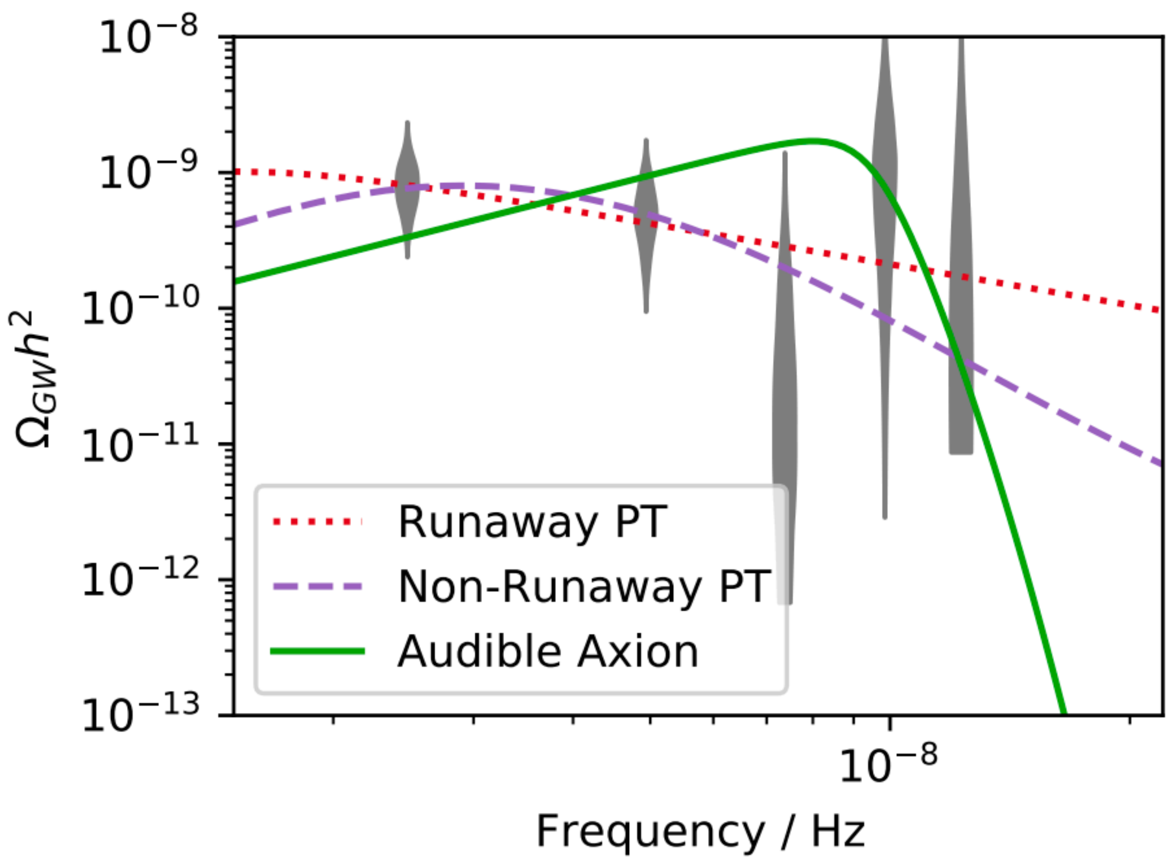
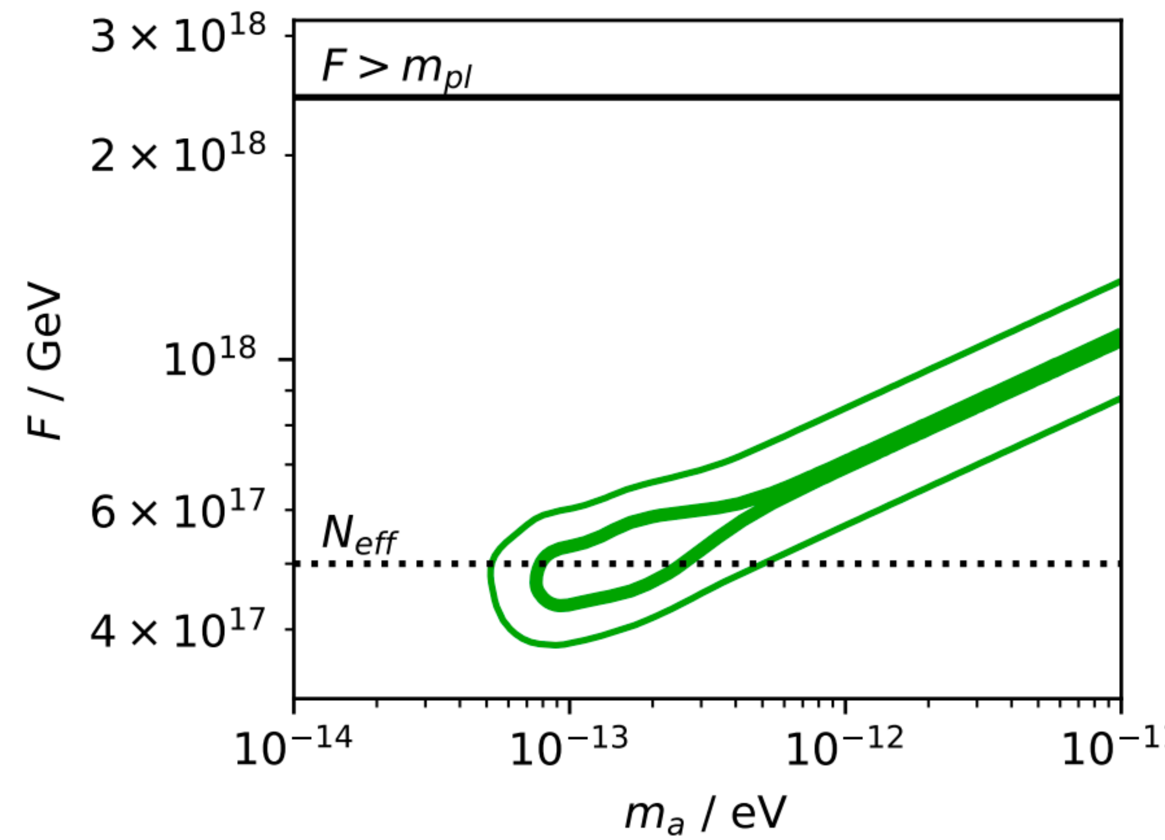
Did NANOGrav hear an ALP?

Here's what we would need:



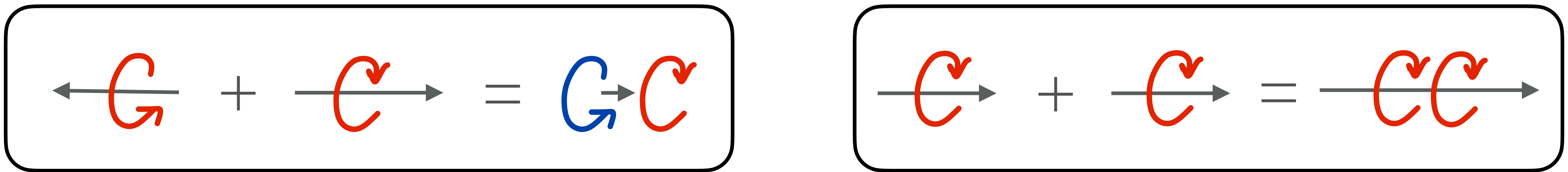


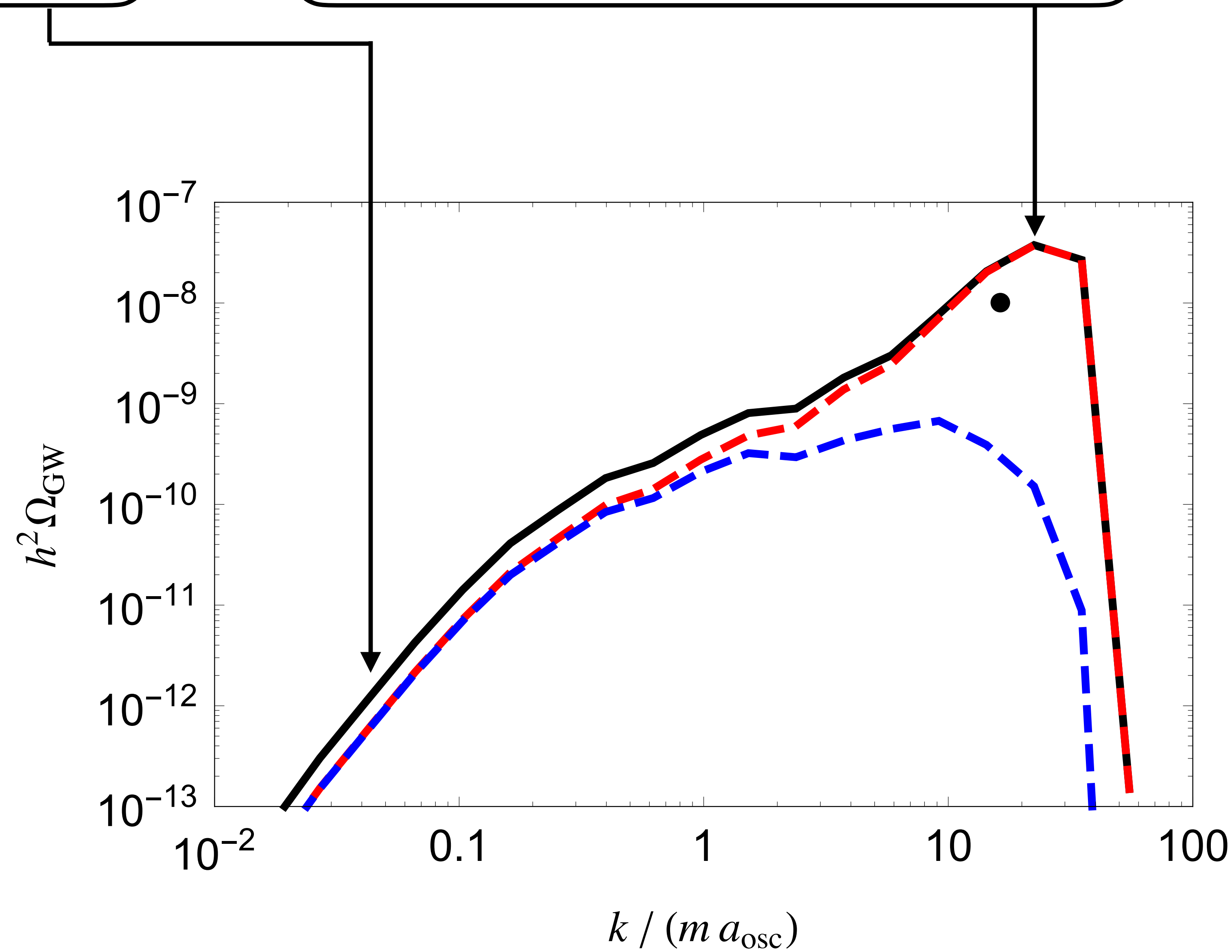
Best fit point: $m \sim 2 \times 10^{-13}$ eV, $f \sim 5 \times 10^{17}$ GeV

*BFP close to N_{eff} bound, requires a 10^{-5} suppression of the relic abundance.

[Ratzinger, Schwaller: 2009.11875]

Probing Polarization?



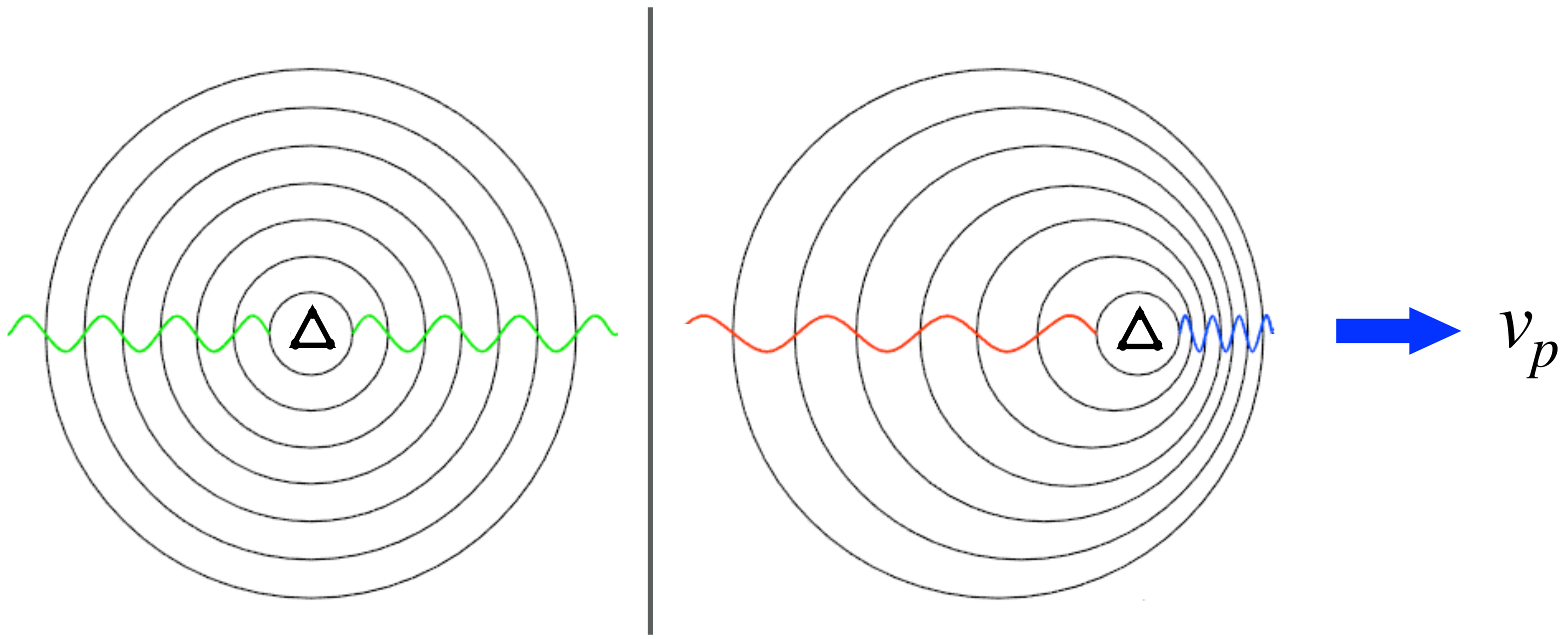


- Can we detect? Main problem is that we are dealing with planar detectors (LISA, ET, etc).
- Planar detectors cannot measure the polarization of an isotropic SGWB.
- Need to break planarity or isotropy.

[N. Seto, A. Taruya: 0707.0535
N. Seto, A. Taruya: 0801.4185
T. Smith, R. Caldwell: 1609.05901]

Probing Polarization: Breaking Isotropy

Relative motion of our solar system w.r.t the cosmic reference frame induces dipolar anisotropy in the SWGB (similar to CMB dipole)



Allows for directional information on the wave. Detector dipole response function changes sign under a chirality flip!

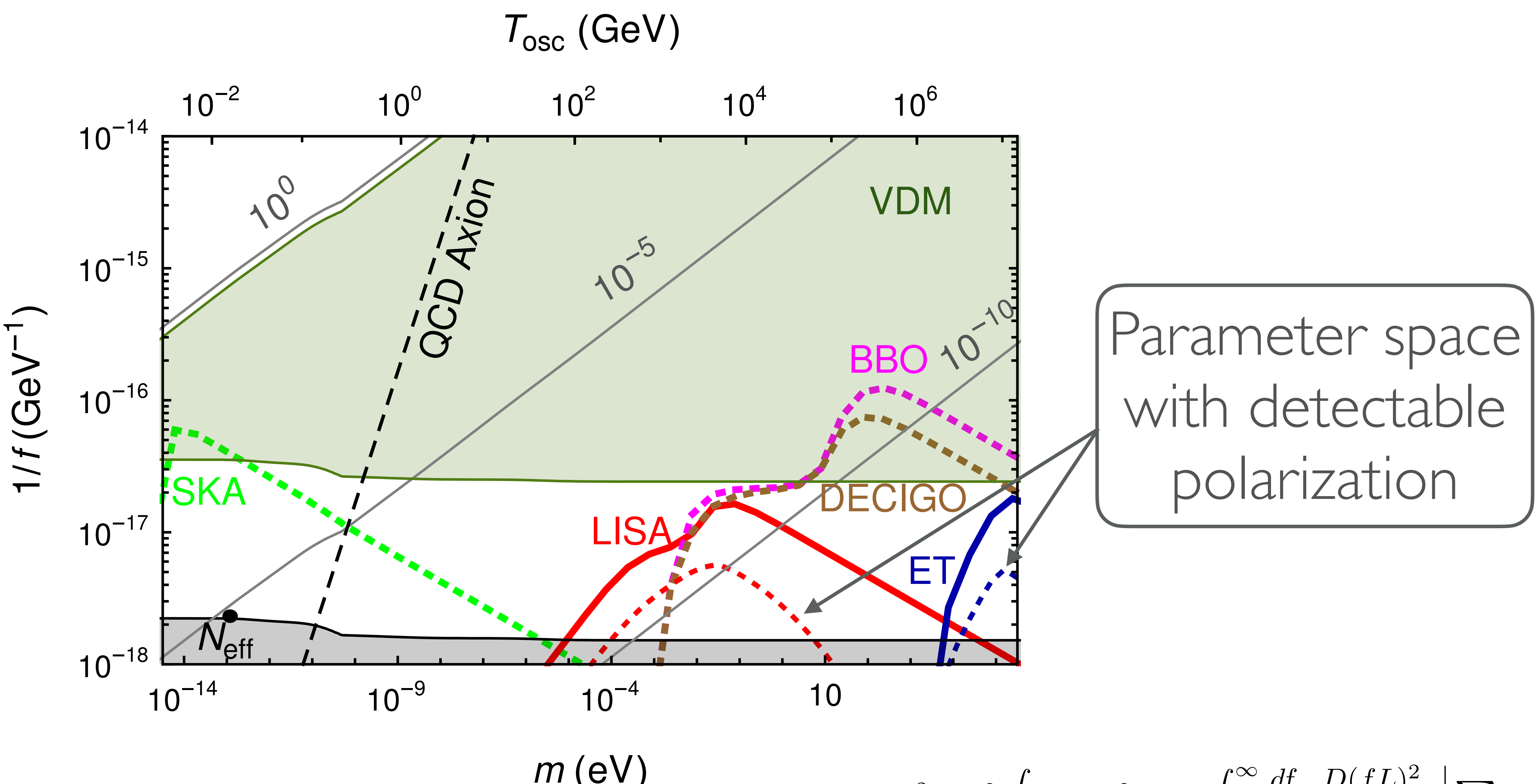
But, effect is suppressed by the small peculiar velocity $O(10^{-3})$ since it must vanish in the $v_p \to 0$ limit.

[N. Seto: astro-ph/0609504, astro-ph/0609633]

[V.Domcke, J.Garcia-Bellido, M.Peloso, M.Pieroni, A.Ricciardone, L.Sorbo and G.Tasinato: 1910.08052]

Polarization and Model Cosmology

- For large decay constants, polarization detectable in LISA or ET.



$$\mathrm{SNR}^2 \propto v^2 \int dT \cos^2\alpha(T) \int_0^\infty \frac{df}{f^4} \frac{D(fL)^2}{(fP_n(f))^2} \left| \sum_\lambda \lambda\, \Omega^\lambda_{\rm GW}(f) \right|^2$$

- Dipole response functions from:

[V.Domcke, J.Garcia-Bellido, M.Peloso, M.Pieroni, A.Ricciardone, L.Sorbo and G.Tasinato: 1910.08052]

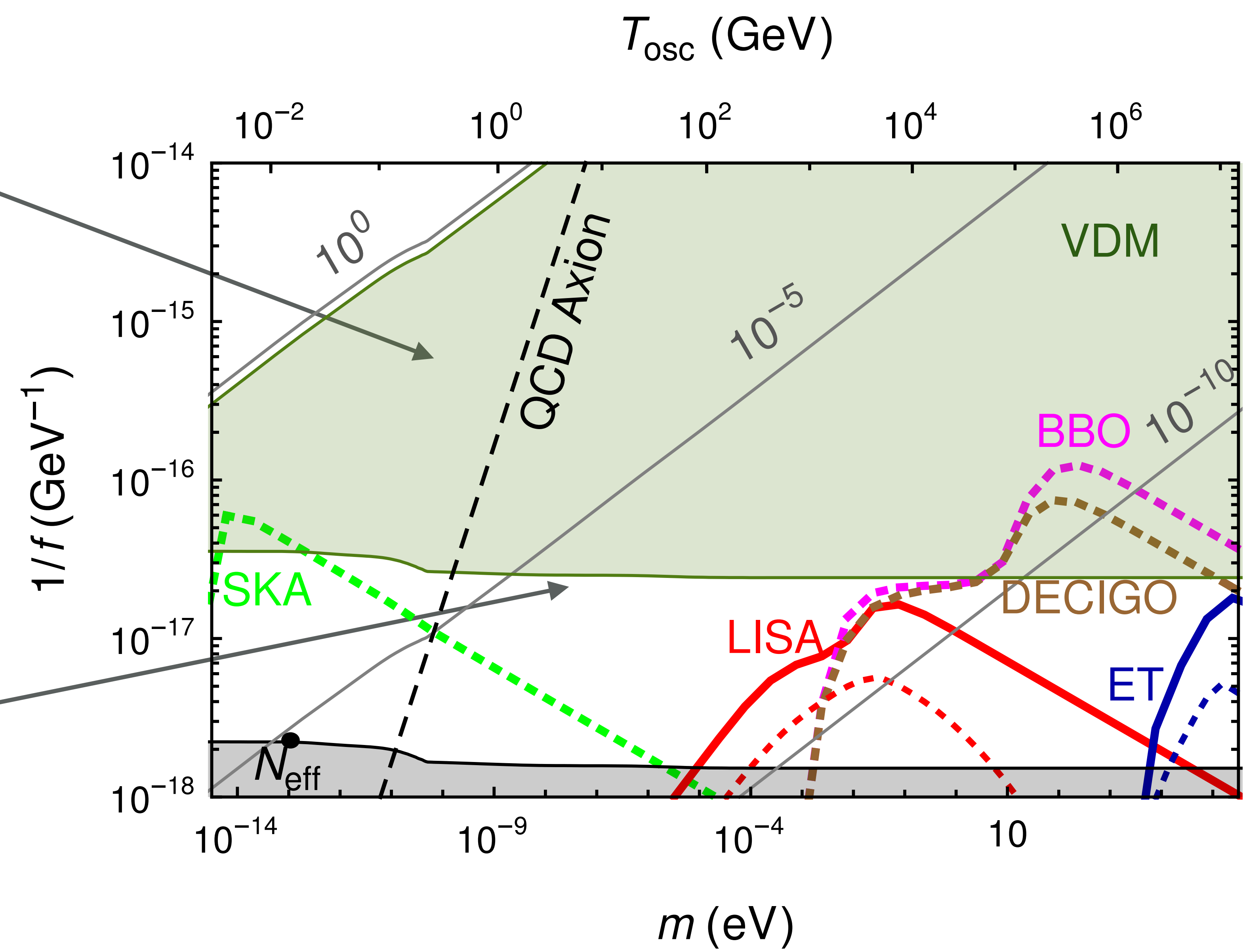
[Machado, Ratzinger, Schwaller, BAS: 1912.01007]

Polarization and Model Cosmology

- Dark photons can contribute to DM or relativistic DOFs.

$$\frac{\Omega_{\rm VDM}}{\Omega_{\rm CDM}} = 1$$

Warm VDM



- Viable mechanism to produce VDM.

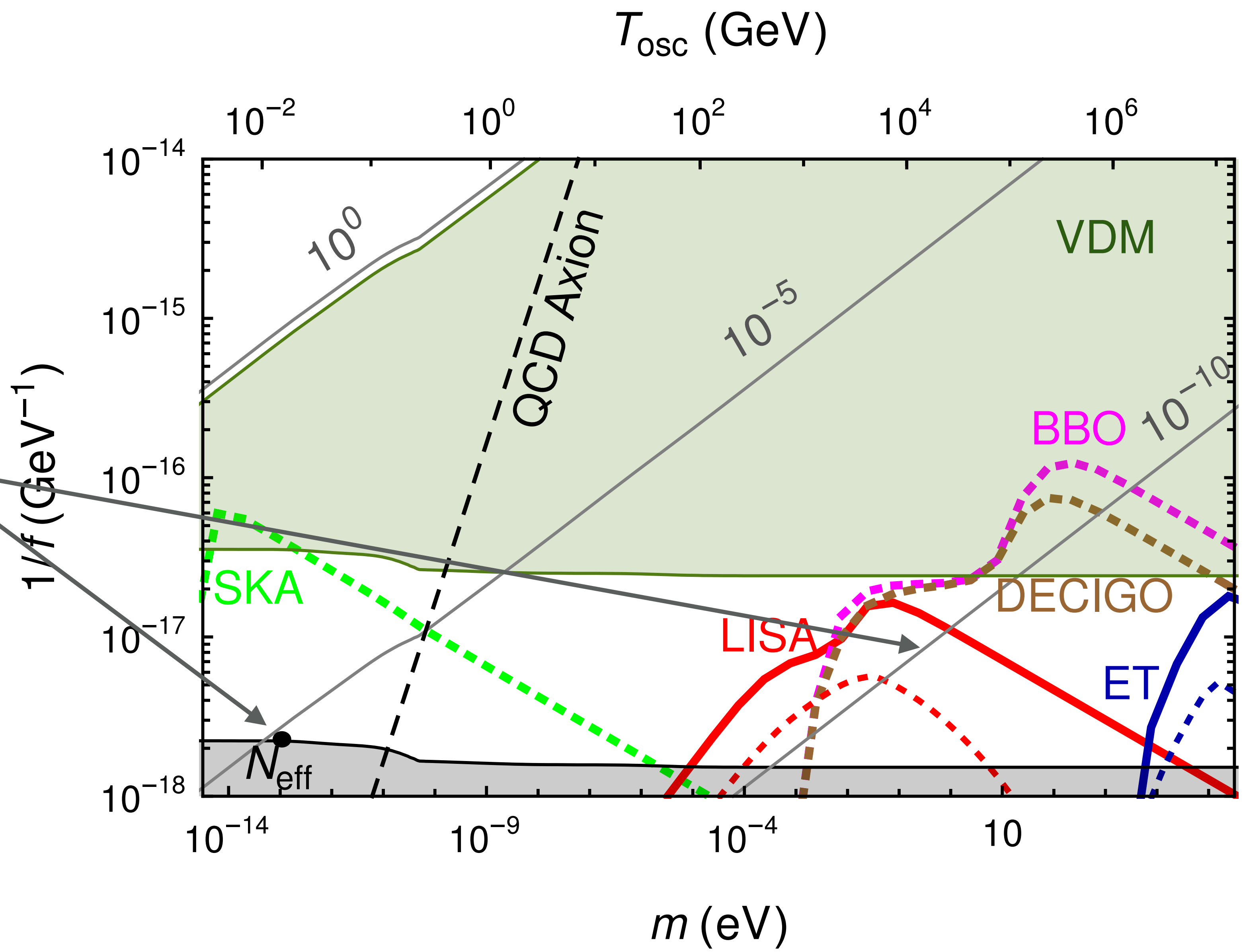
[1810.07188, 1810.07208, 1810.07196, 1810.07195]

[Machado, Ratzinger, Schwaller, BAS: 1912.01007]

Polarization and Model Cosmology

- In general, a large suppression of the relic abundance is needed.

Required suppression of relic abundance



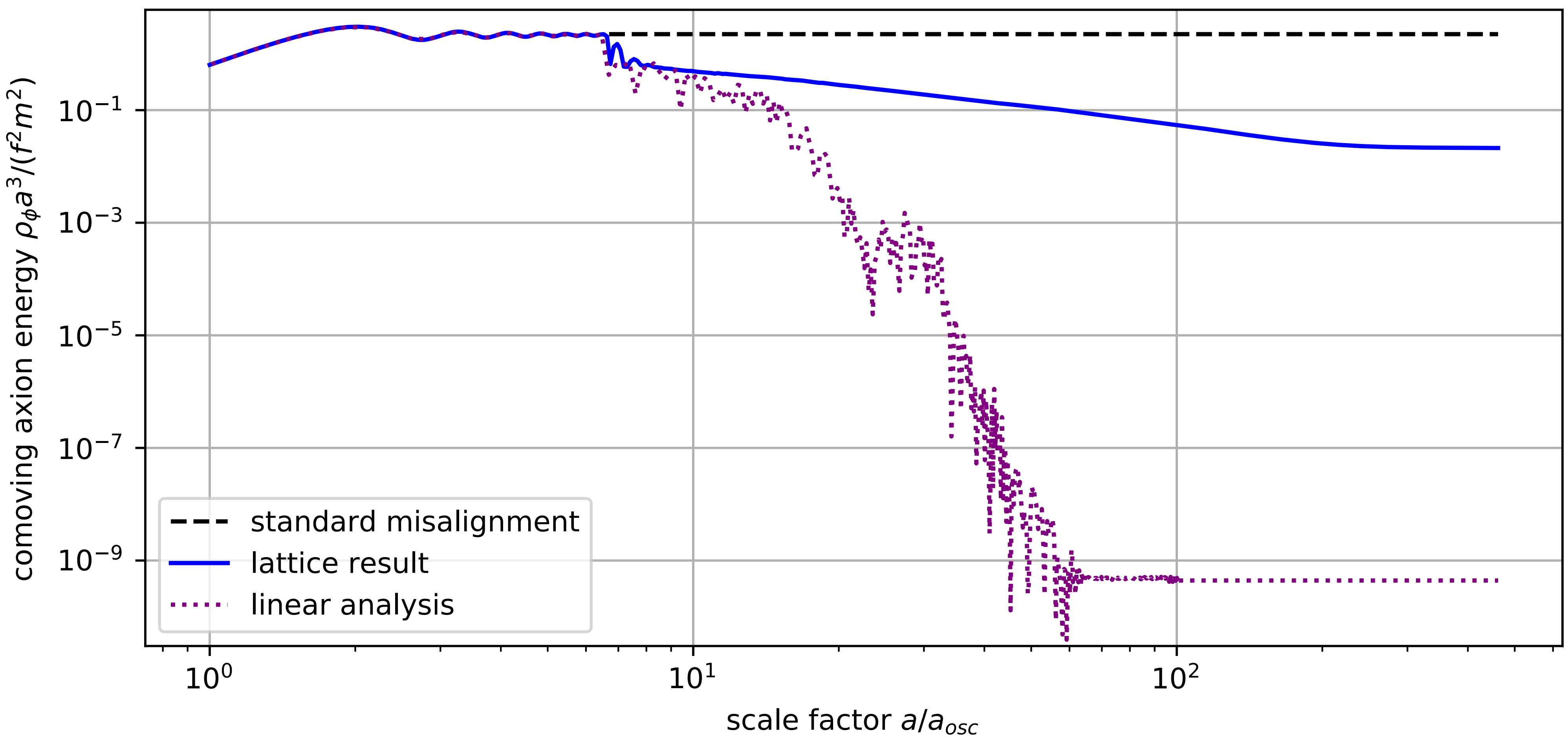
- Due to non-linearity, question must be answered on the lattice.

[Machado, Ratzinger, Schwaller, BAS: 1912.01007]

PRELIMINARY

Lattice Results: Relic Abundance

- Dark photon backscattering induces inhomogeneities in the axion field- destroys the coherently oscillating condensate.



- Lose parametric resonance, so can only suppress by $10^{-2} - 10^{-3}$

Lattice Specs : $128^3, \;\; L = \mathcal{O}(m^{-1})$

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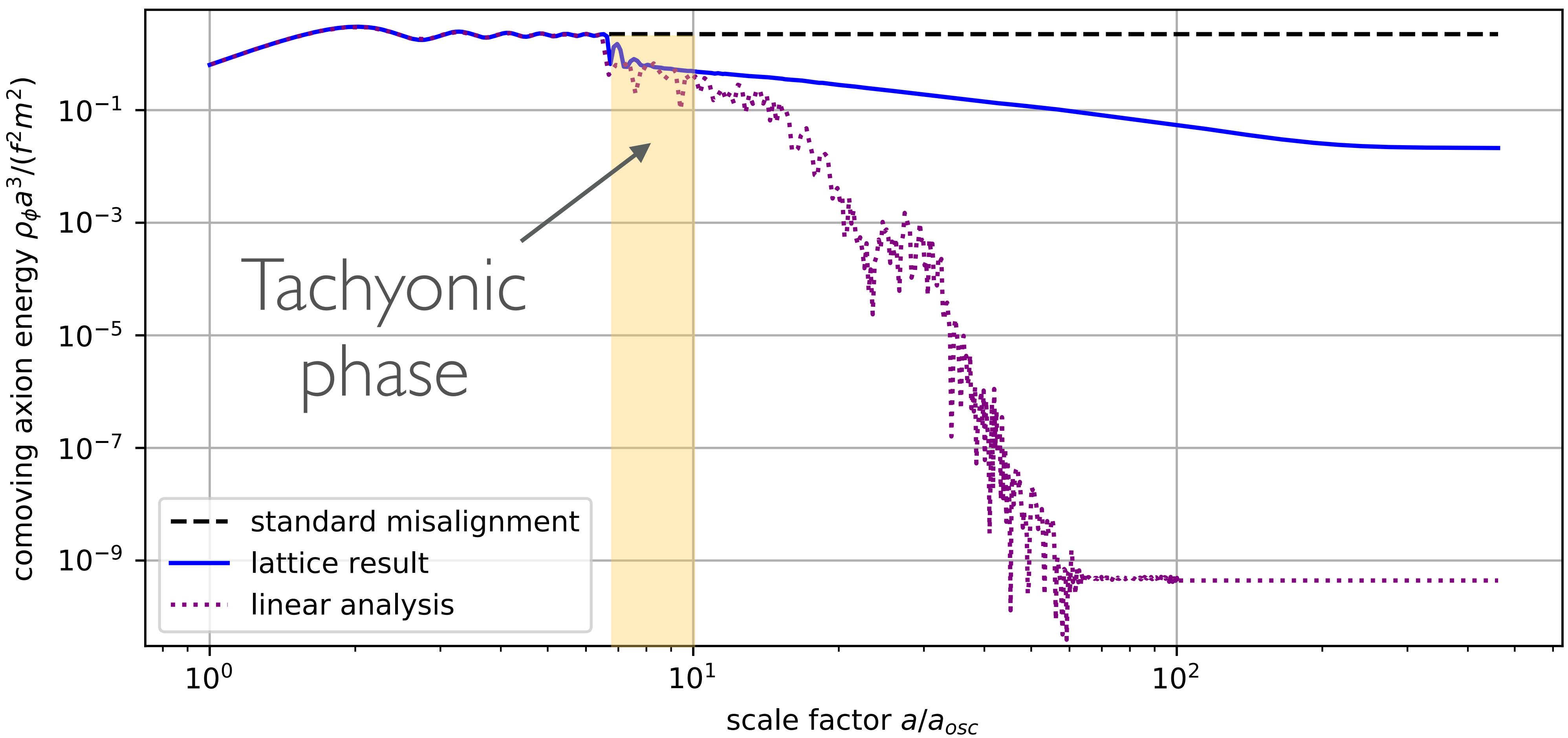

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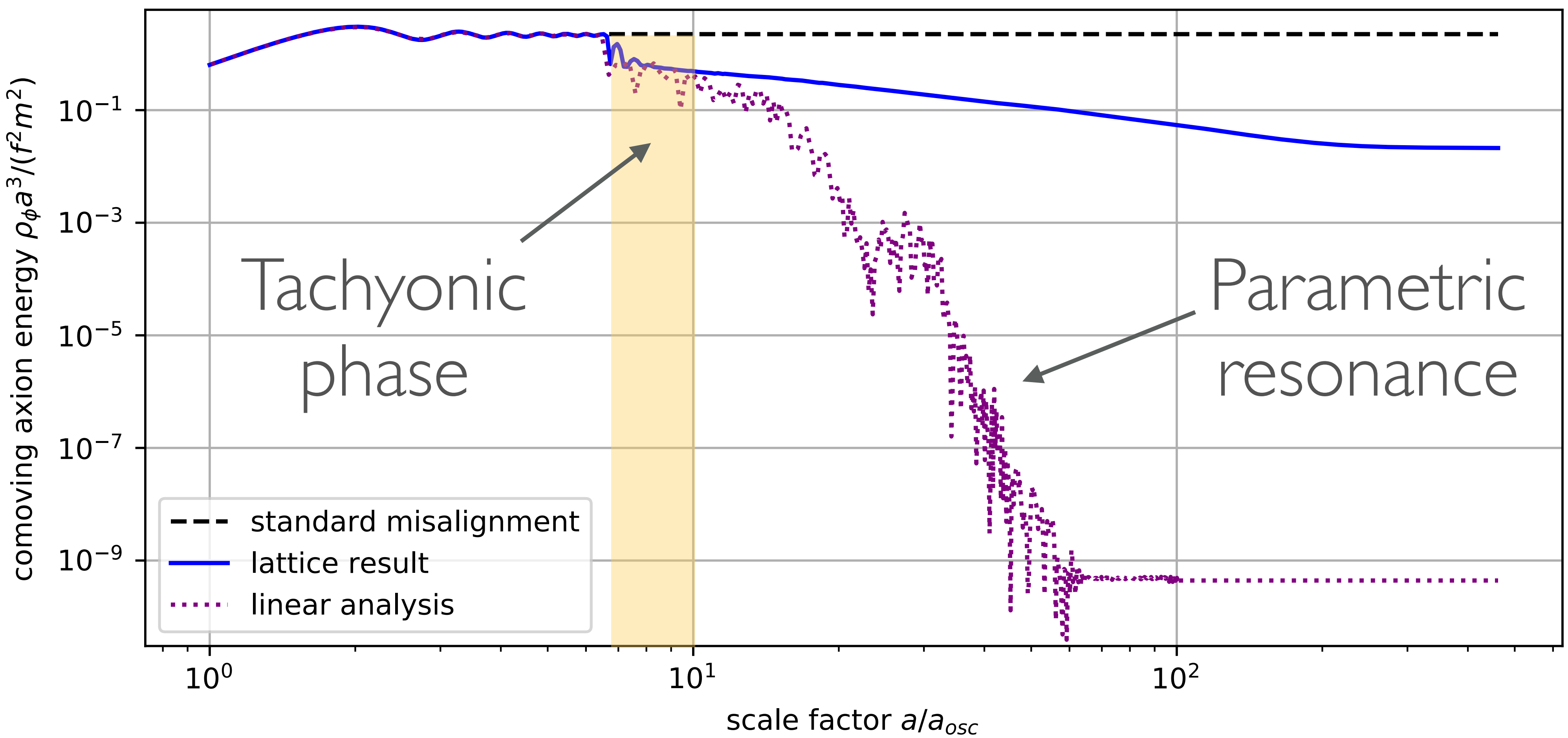

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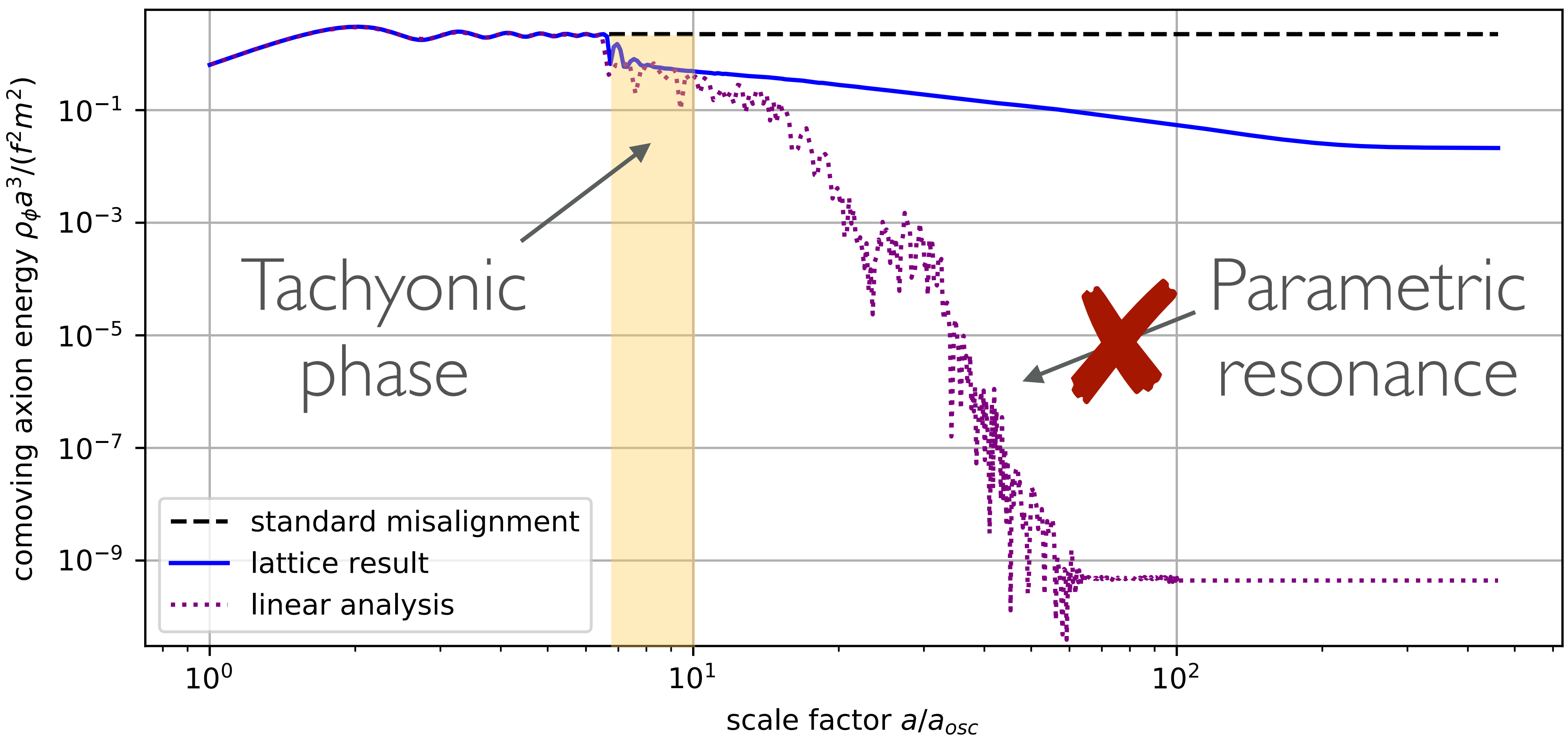

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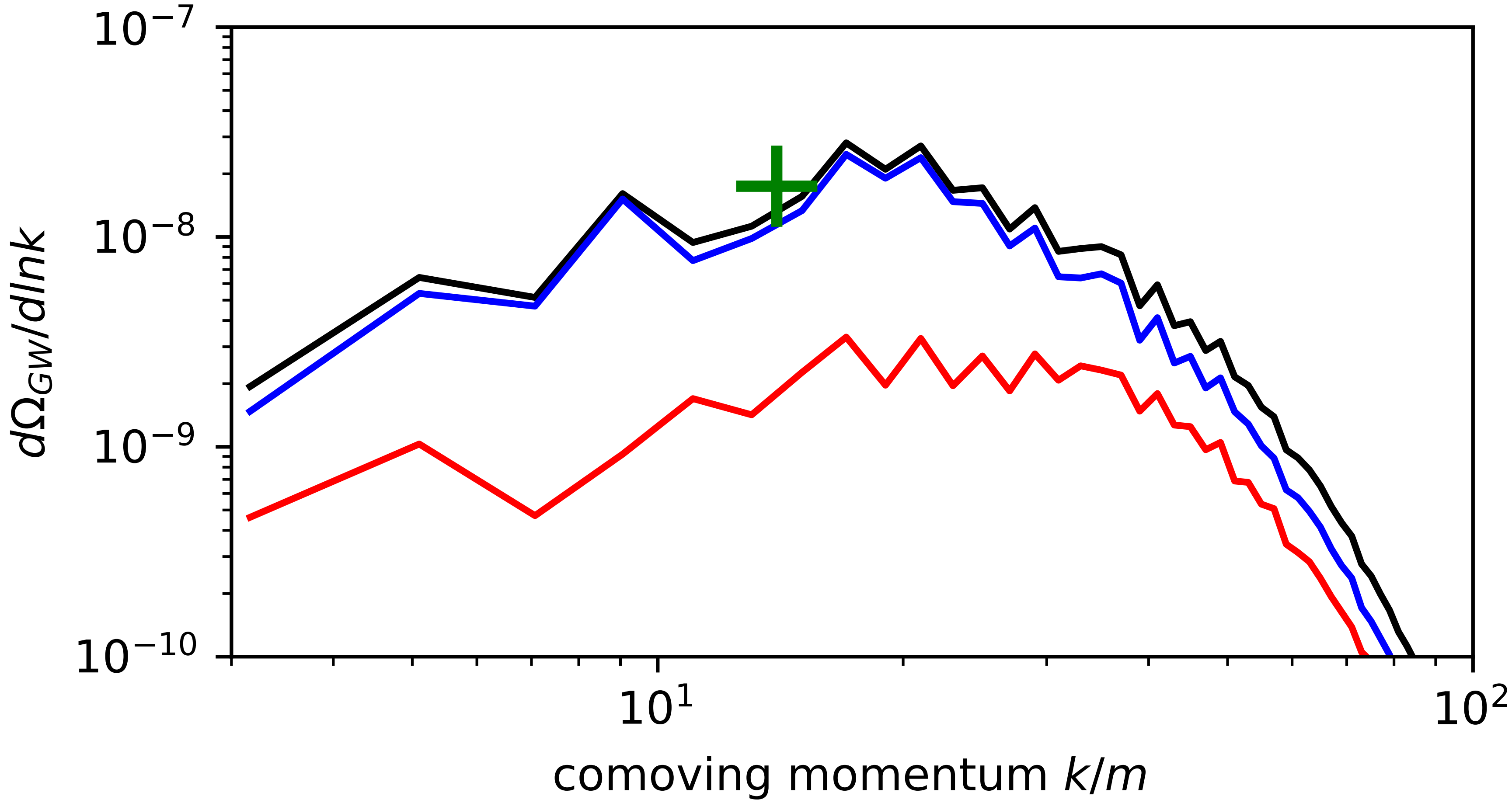
PRELIMINARY

Lattice Results: GW Spectrum

- GW signal survives, as it is produced mainly during the tachyonic phase. Scalar contribution to the stress-energy tensor now included.



- Overall, still peaks close to NDA expectation, but broader shape that extends to higher momenta due to $2 \to 1$ processes.

Lattice Specs : 128^3, $L = \mathcal{O}(m^{-1})$

Ongoing Work: Lattice and Cosmology

Will continue to study the model on the lattice. Preliminary results suggest only SKA is available, so new ideas are needed to open up the parameter space compatible with cosmology.

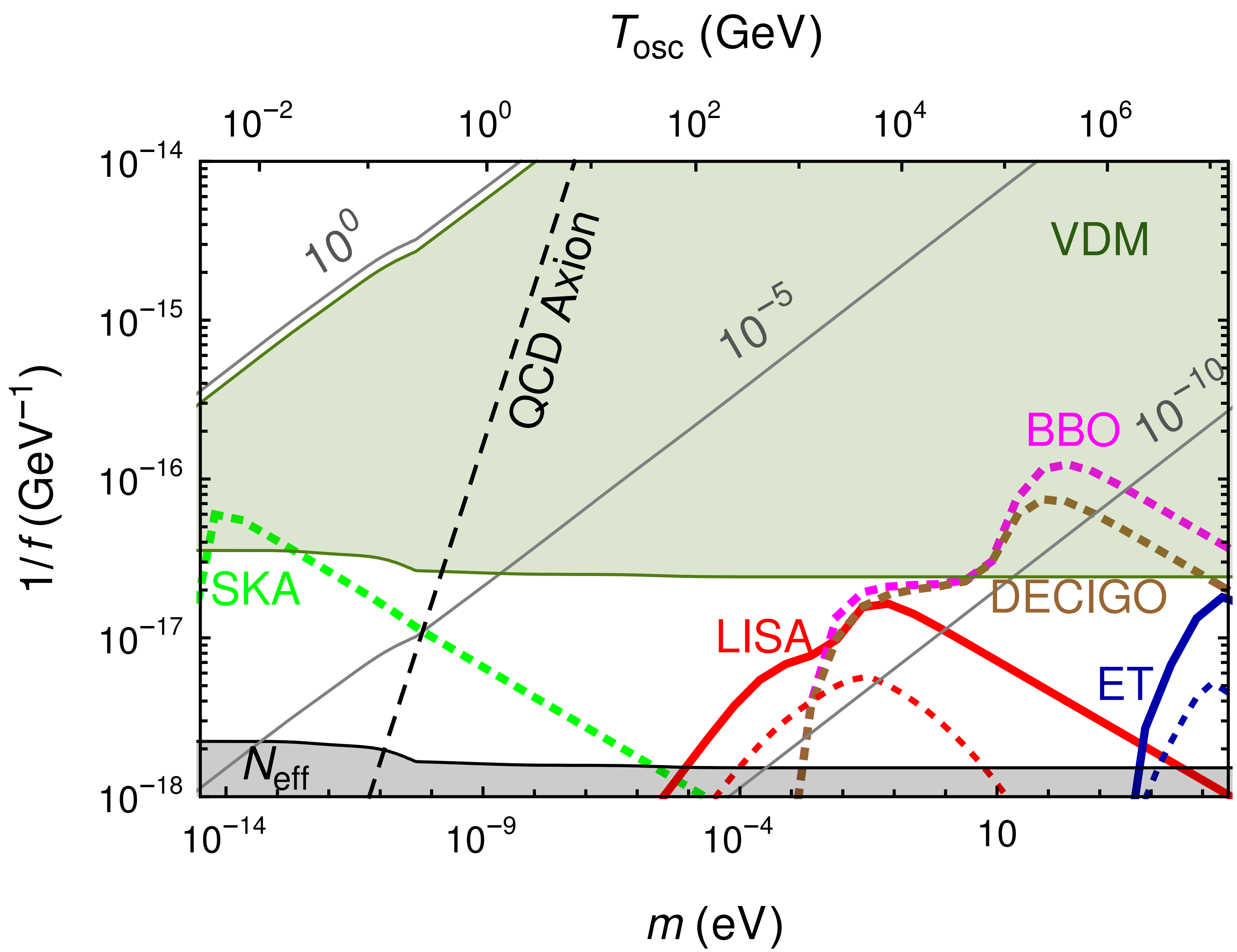
- Monodromy? (lower axion mass at the bottom of potential)

→ Tune 2 cosine terms

- Shut off ϕ potential

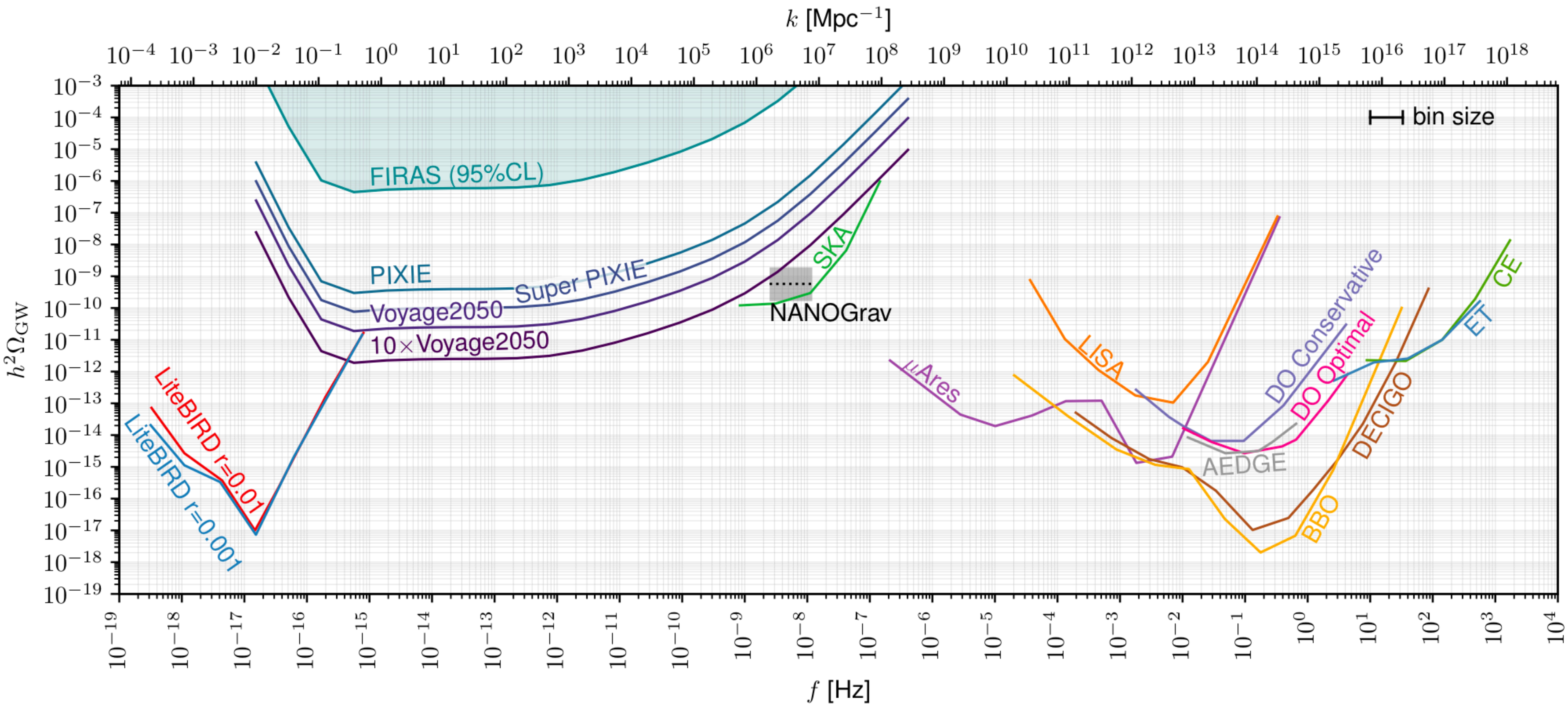
→ Requires inverse PT?

- Lower mass probes?



Lower Mass Probes via Spectral Distortions

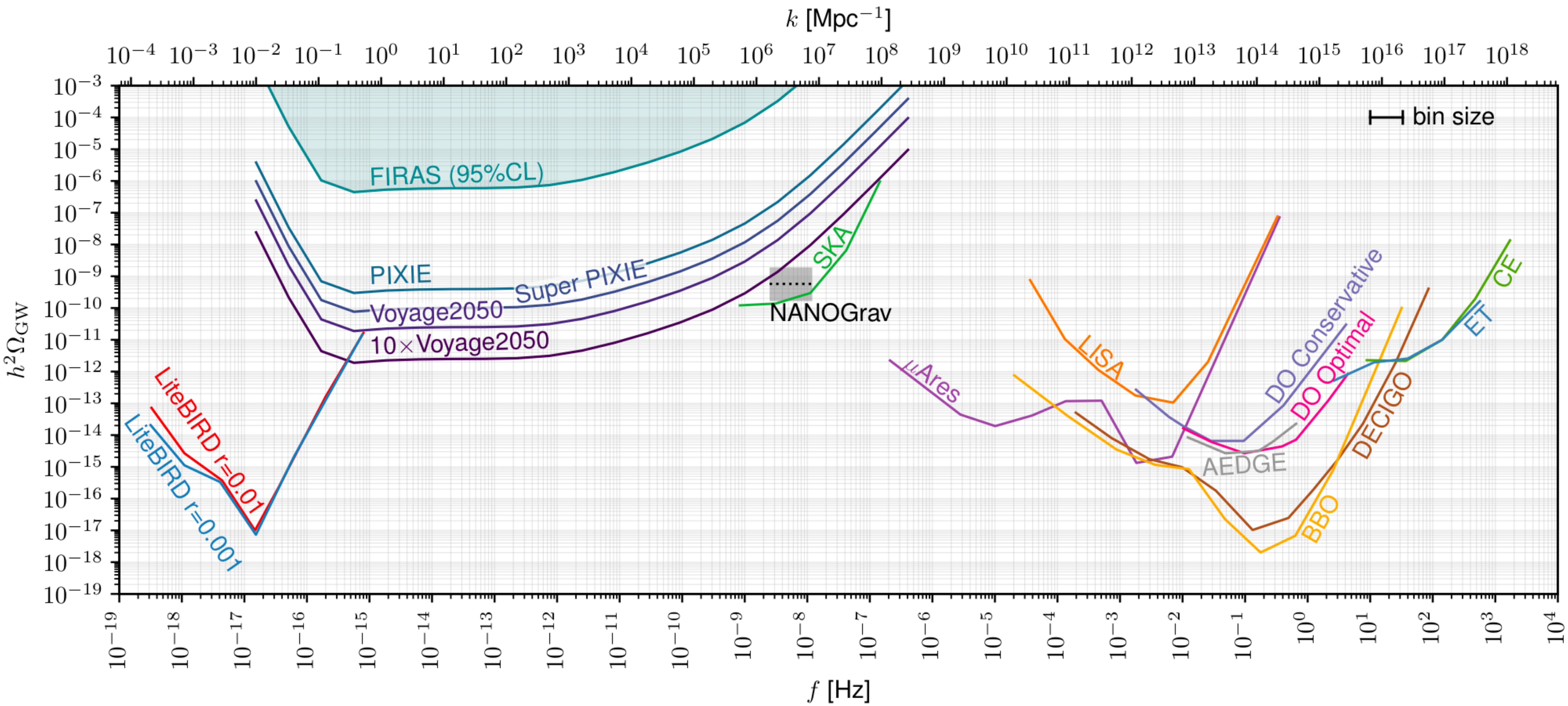
Spectral distortions of the CMB can be used to probe GWs at frequencies much lower than pulsar timing arrays.



[Kite, Ravenni, Patil, Chluba: 2010.00040]

Lower Mass Probes via Spectral Distortions

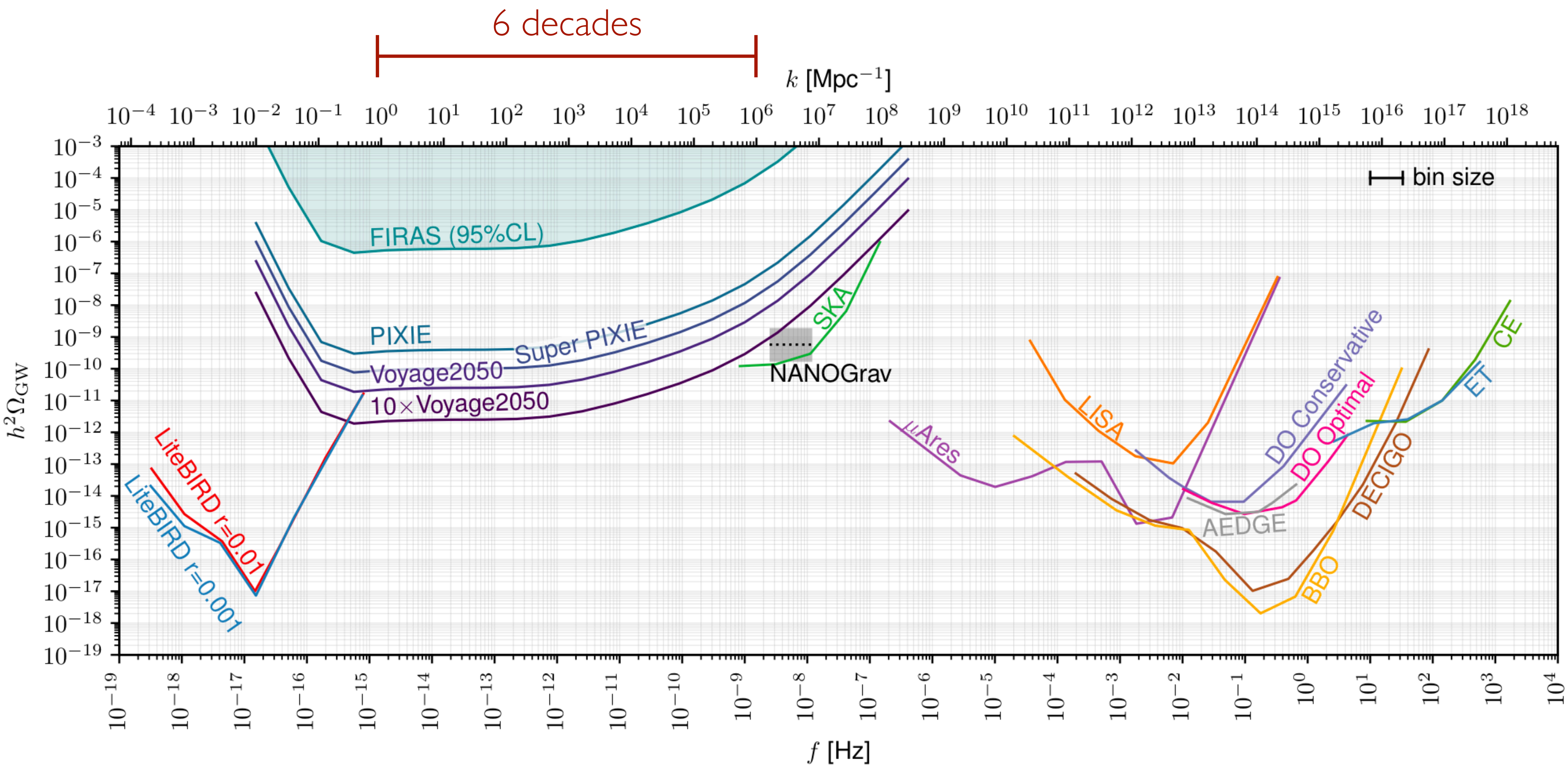
Tensors source perturbations in photon fluid- mainly dissipated by free streaming effects.



[Kite, Ravenni, Patil, Chluba: 2010.00040]

Lower Mass Probes via Spectral Distortions

CMB can be distorted over a wide range of scales where there is no other probe.



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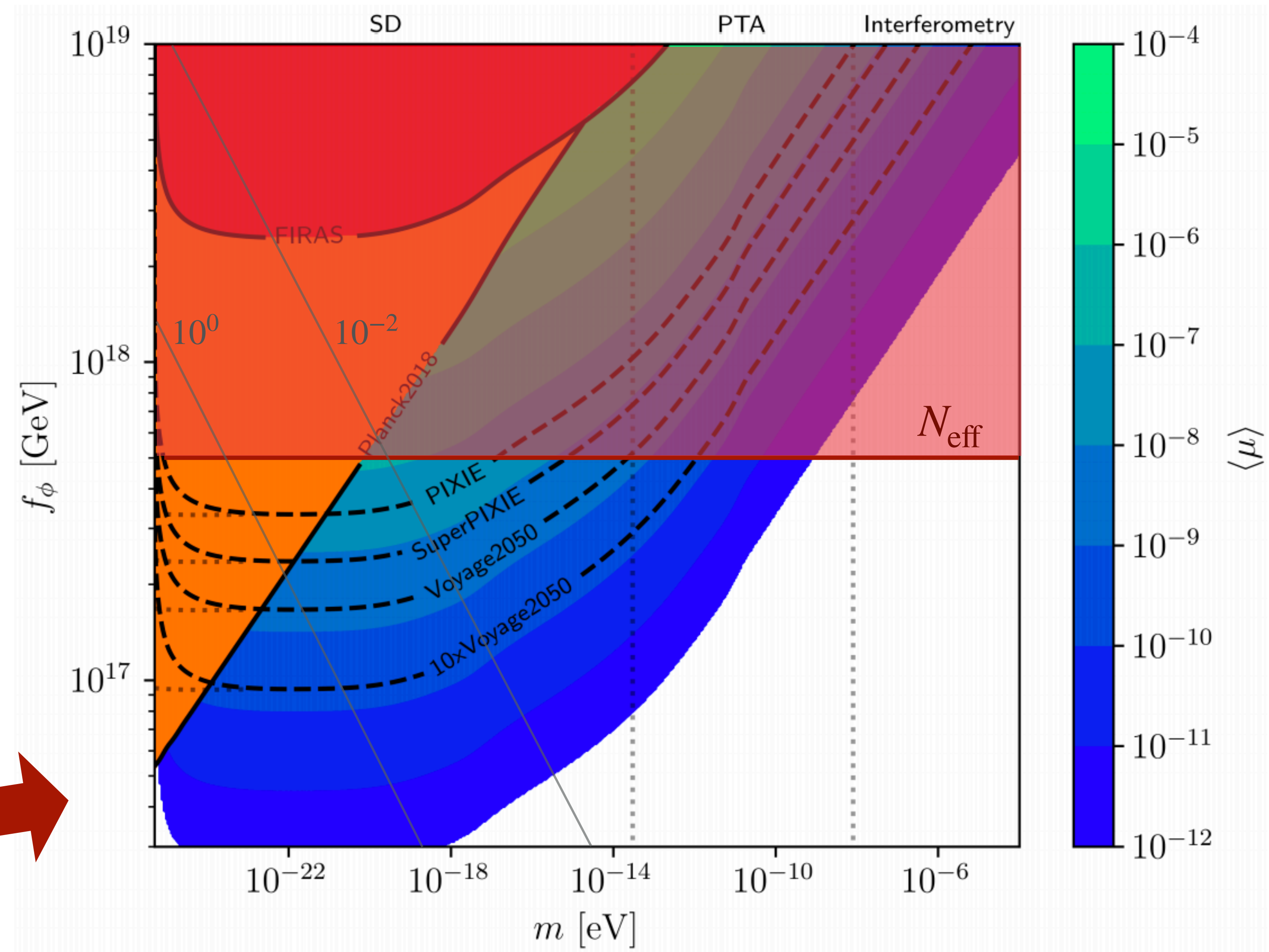
- Analysis done specifically for our model, using our fit template.



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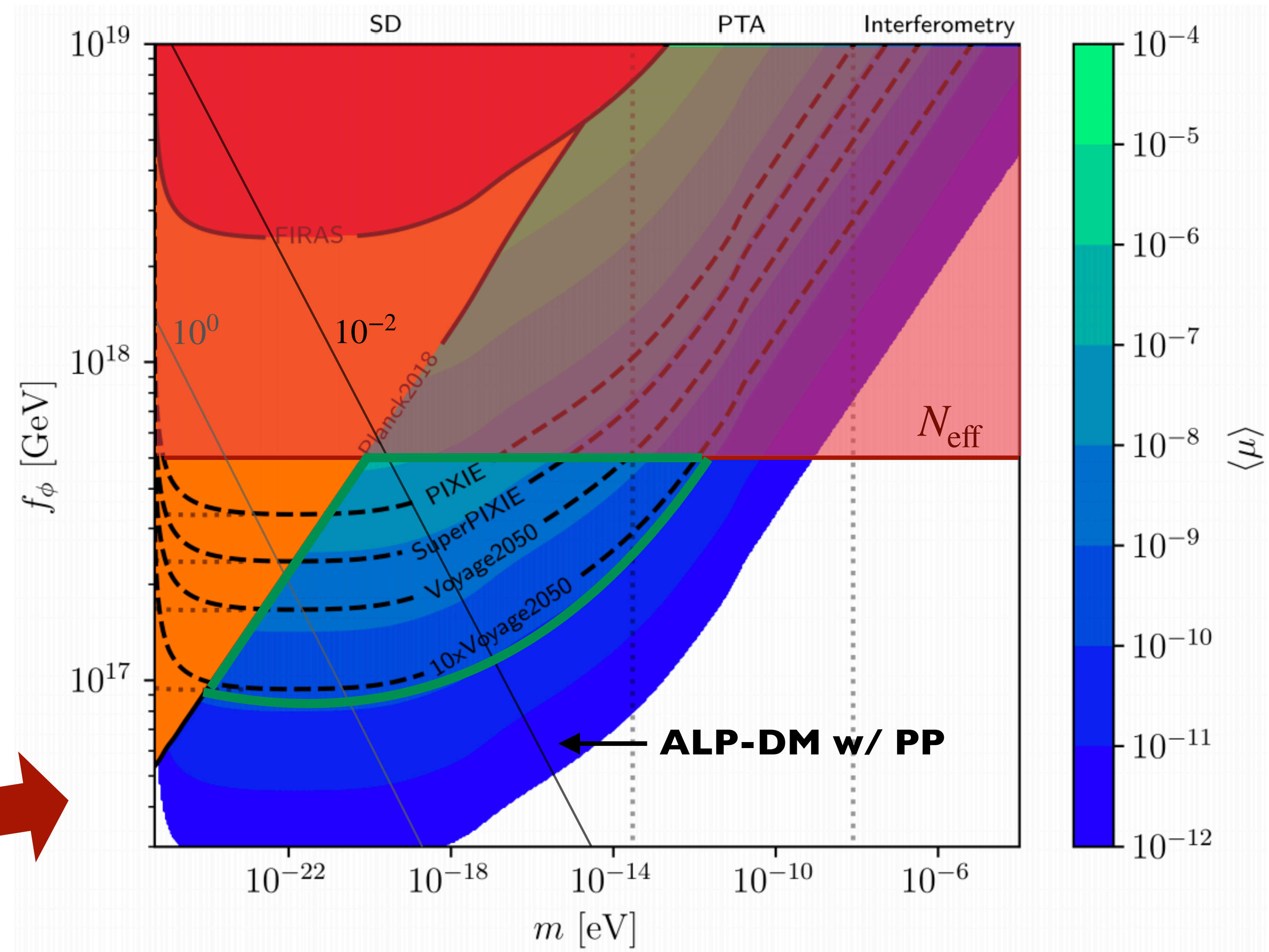

[Kite, Ravenni, Patil, Chluba: 2010.00040]

Conclusions

- Axions that begin to oscillate in the early universe may emit a SGWB if they are coupled to a light dark photon.
- Axion GW signal is peaked near the mass and detectable by future GW experiments for large decay constants.
- Signal is highly polarized due to underlying parity violation in the system. Can be probed by planar detectors using the kinematically induced dipolar anisotropy.
- As most of the viable GW parameter space is for low masses $m \lesssim 10^{-14}\ \mathrm{eV}$, spectral distortions could be the best probe of the model. New ideas needed make the larger mass region compatible with cosmology.