GRAVITATIONAL WAVE PROBES OF AXION-LIKE PARTICLES

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Gravitational wave probes of new physics

Focus on primordial GWs

Overview of sources

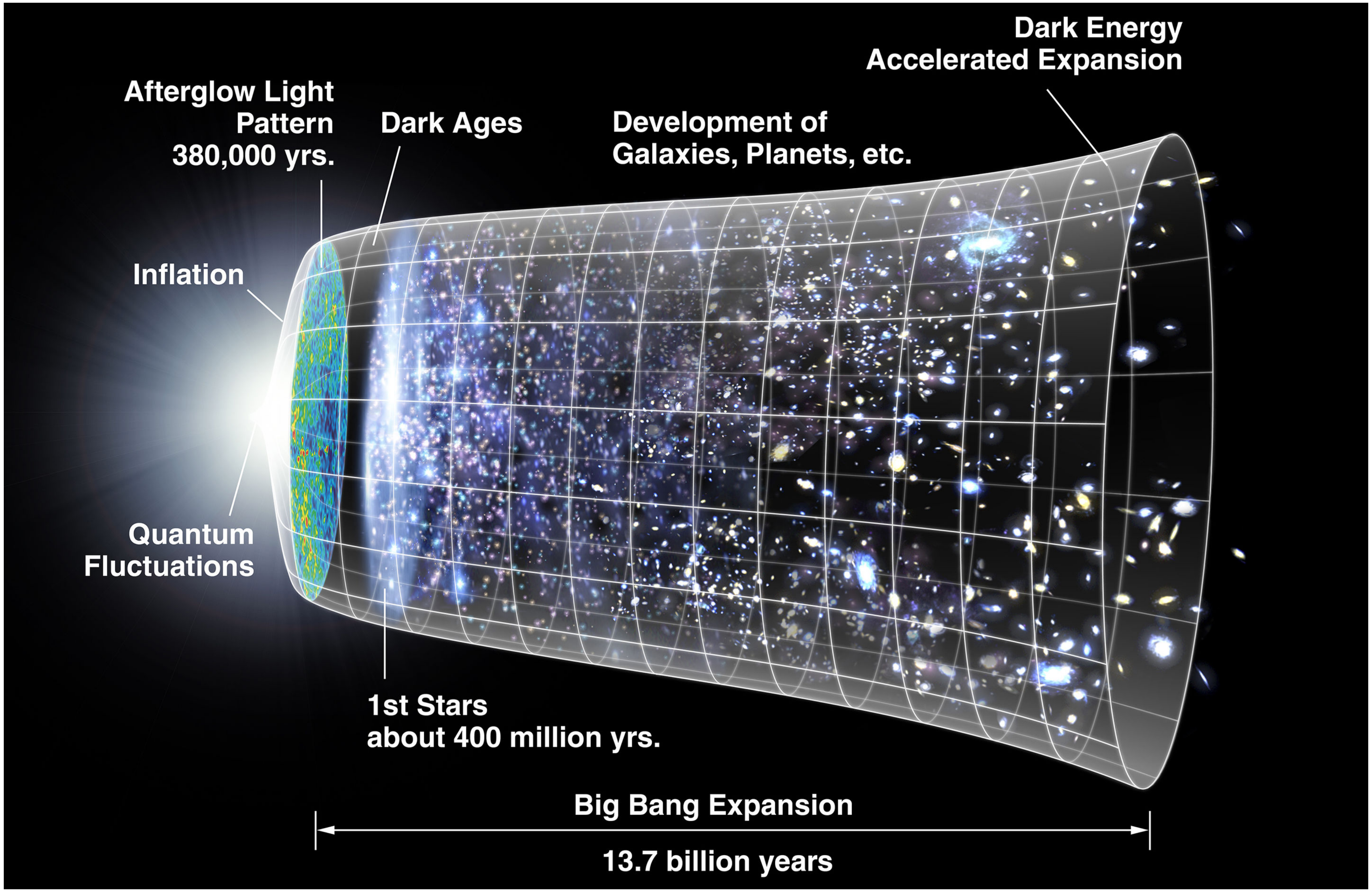
GWs from axion dynamics

- Audible axions
- Lattice results
- Model variations

NANOGrav GW evidence

Spectral distortions as probe of early Universe dynamics

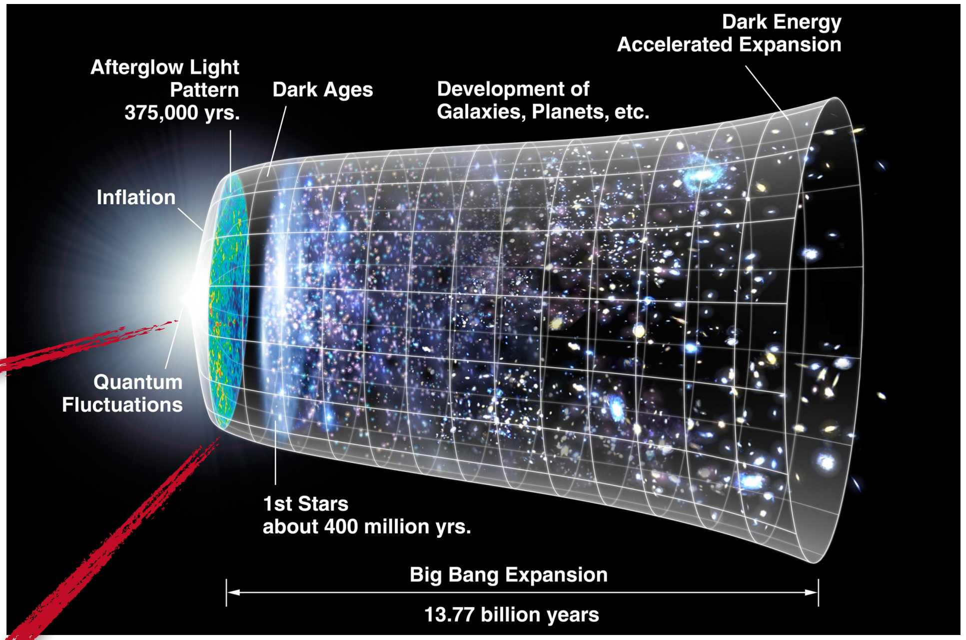
Thermal History

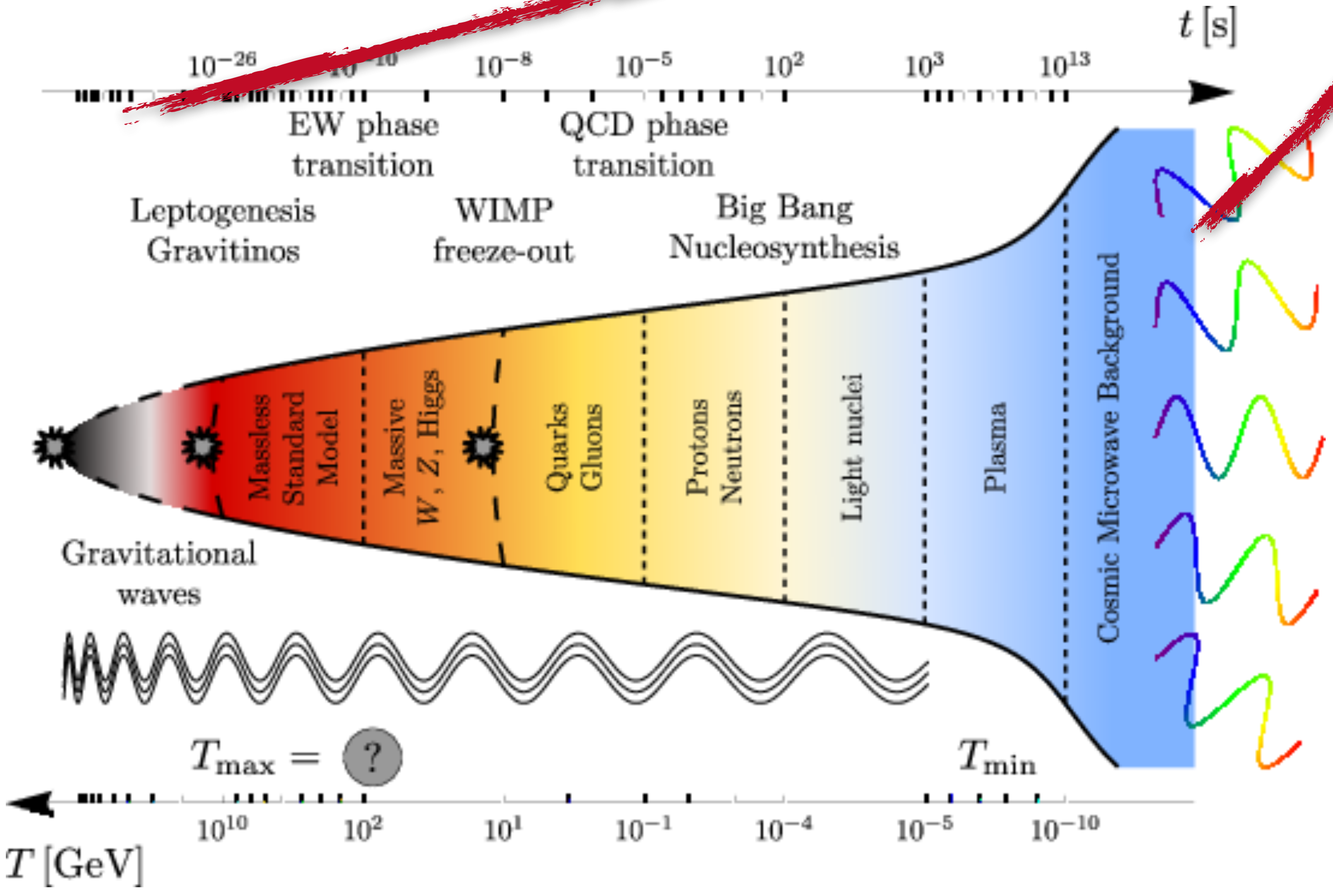


Gravitational Waves?

Zoom into interesting region

New window into early universe





e.g.

Electroweak symmetry breaking

Baryogenesis

Dark matter production

GWs & early Universe

CMB encodes information about the state of the universe at the time of its emission

- Densities of matter, radiation, dark matter
- Fluctuations, Hubble rate, …

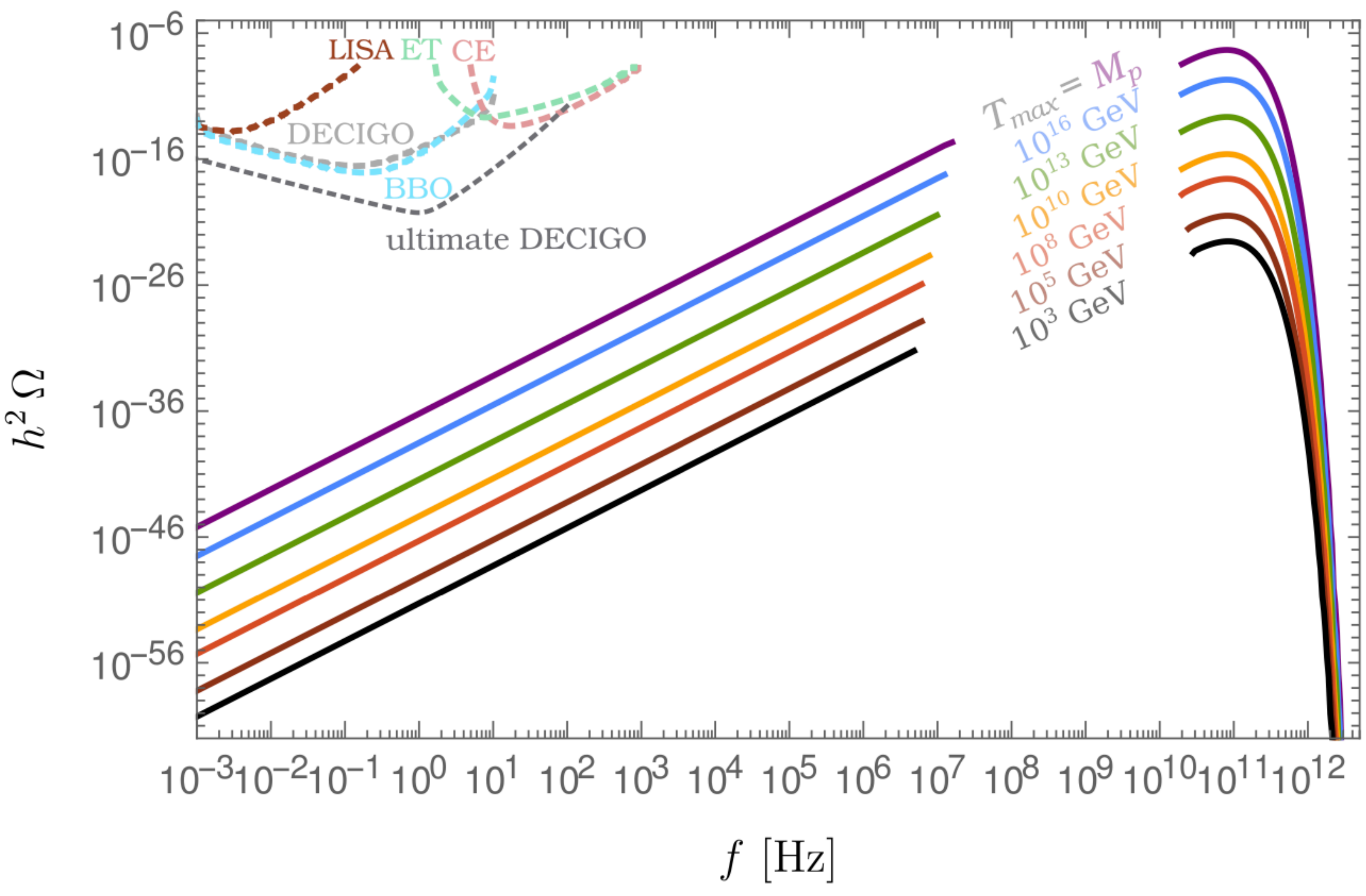
GWs could do the same

- For earlier times
- For different periods!
- Need a strong source (CMB photons are just there!)

Standard model

The hot early Universe sources GWs!

- Classical picture: thermal fluctuations source tensor fluctuations
- Quantum picture: gluon + gluon -> graviton

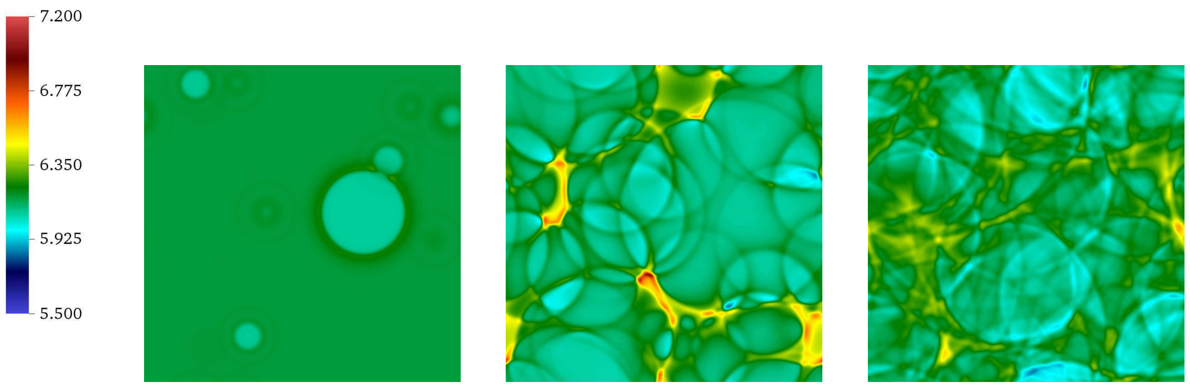


From Ringwald, Schütte-Engel, Tamarit, 2020

Original computations:
Ghiglieri, Laine, 2015
Ghiglieri, Jackson, Laine, Zhu, 2020

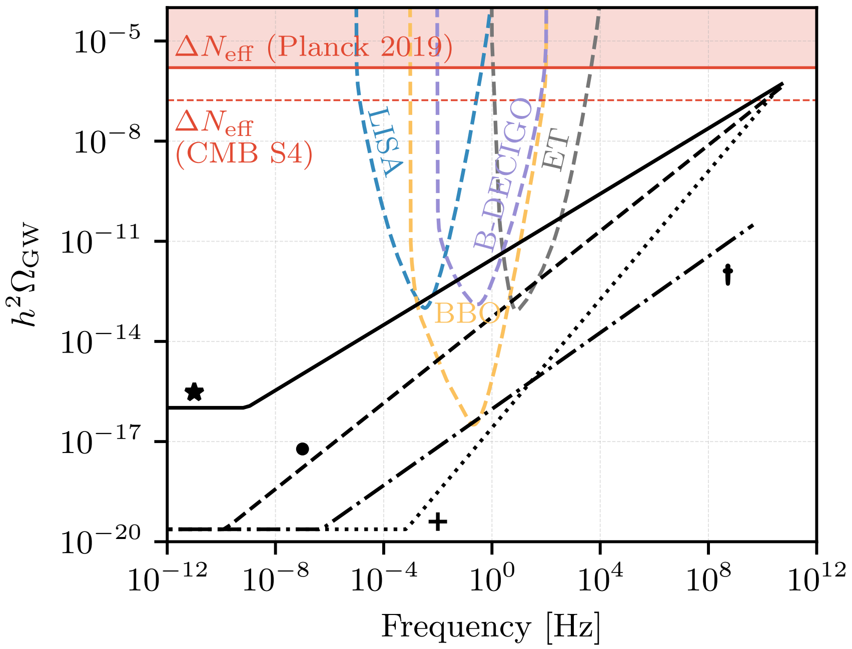
Primordial sources of GWs

First order phase transitions (symmetry breaking)

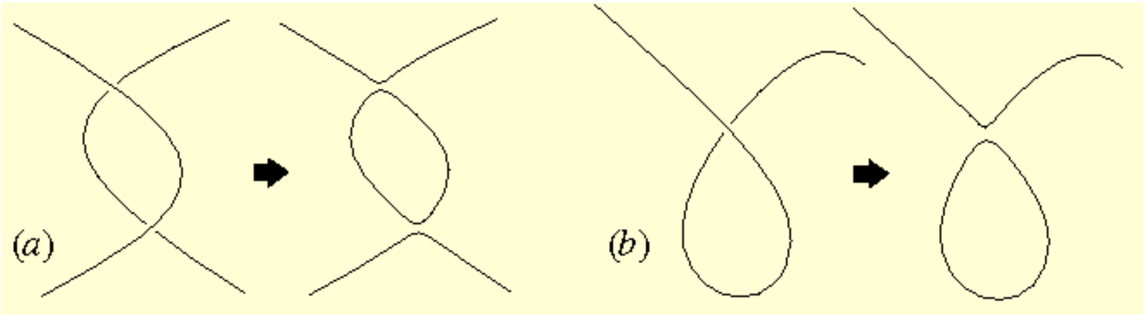


from Hindmarsh et al

Inflation/Reheating



Cosmic strings



Axions/ALPs!

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Peccei Quinn Phase transition ✔

Axion Strings ✔

Axion dynamics ➡ rest of this talk!

Axions/ALPs!

Peccei Quinn Phase transition ✔

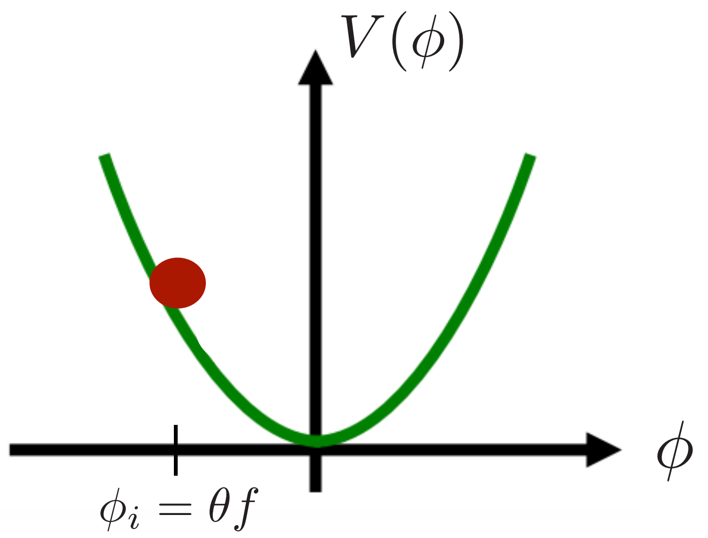
Axion Strings ✔

Axion dynamics ➡ rest of this talk!

- Note: After inflation/reheating. ALP is not the inflaton!

Axion misalignment and DM

Axion EOM



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

Starts rolling when $H \sim m_\phi$

Redshifts with a^{-3}, i.e. like non-relativistic matter

Candidate for non-particle dark matter

Relic abundance

Energy density $$\rho_\phi = \frac{1}{2} m_\phi^2 \theta^2 f^2$$

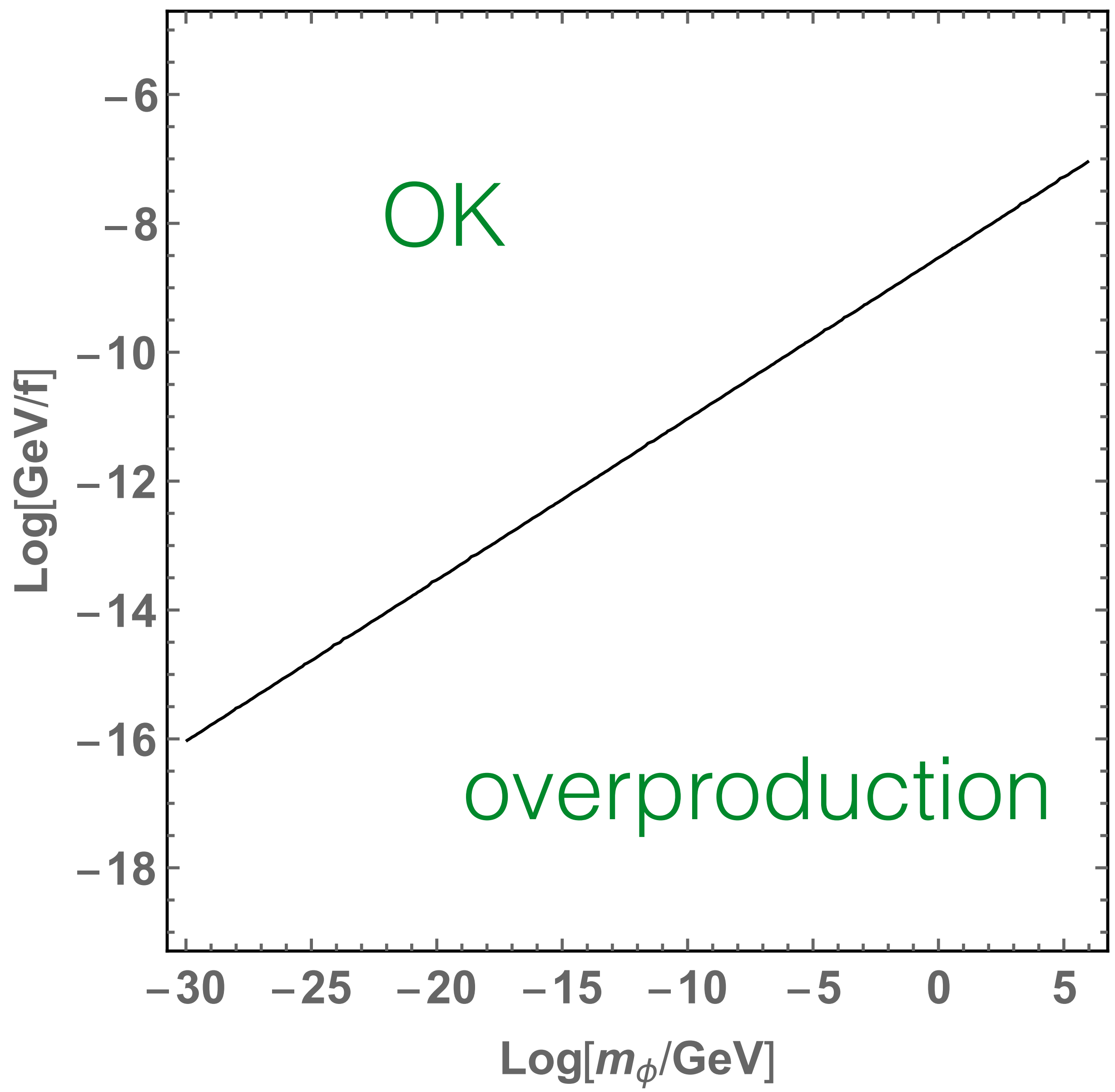
Hubble $$m_\phi \sim H_{\rm osc} \sim \frac{T_{\rm osc}^2}{M_P}$$

Energy fraction $$\frac{\rho_\phi}{\rho_{\rm rad}} \sim \frac{m_\phi^2 \theta^2 f^2}{T_{\rm osc}^4} \sim \frac{\theta^2 f^2}{M_P^2}$$

Increases due to redshift $$\frac{a_{\rm osc}}{a_{\rm eq}} \sim \frac{\sqrt{m_\phi M_P}}{\rm eV}$$

Relic abundance II (ALP)

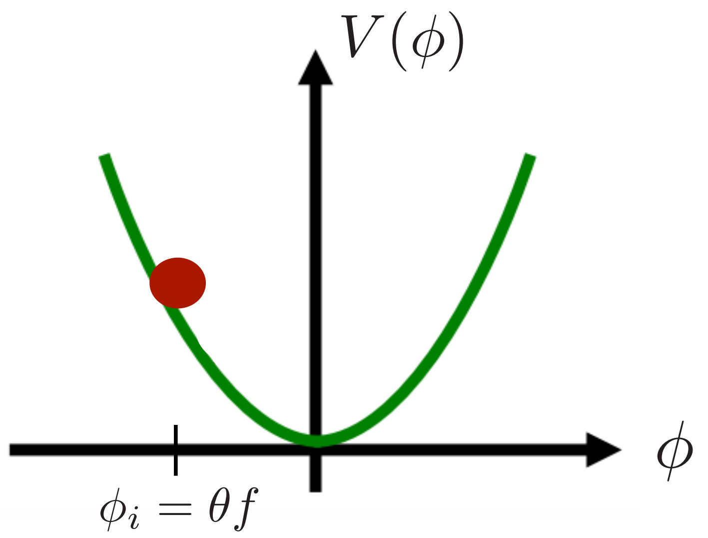
$$\Omega_{\text{today}} \sim \theta^2 f^2 \frac{m_\phi^{1/2}}{M_P^{3/2}\text{eV}} \qquad \Omega_{\text{observed}} \approx 0.12$$



ALP coupled to dark photon X

Equation of motion

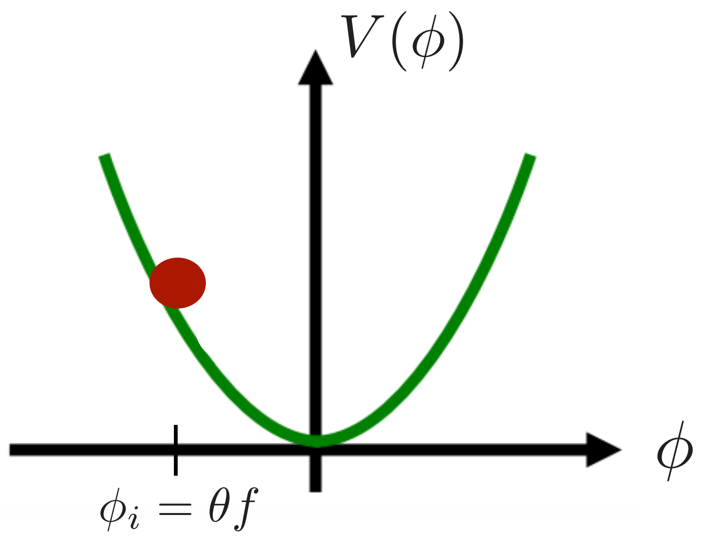
$$\phi'' + 2aH\phi' + a^2V'(\phi)$$
$$-\nabla^2\phi - \frac{\alpha}{fa^2}\mathbf{X}'\cdot(\nabla\times\mathbf{X}) = 0$$



ALP dynamics

Equation of motion

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

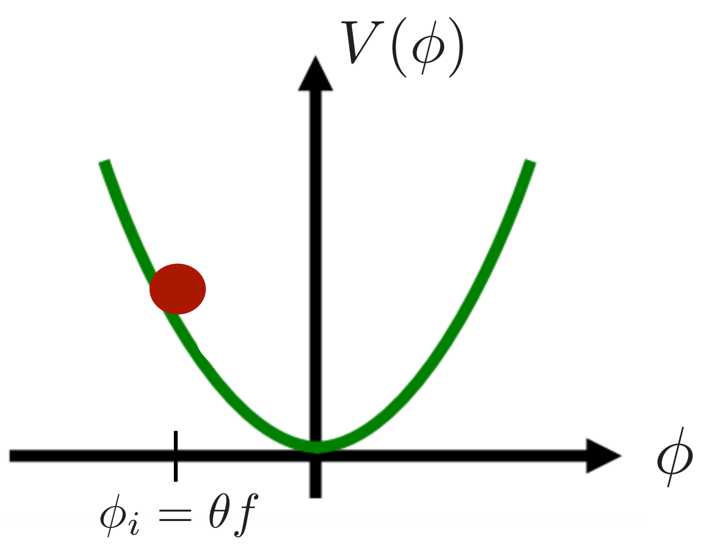


Ordinary misalignment

ALP dynamics - with dark photon

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 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

How does this work?

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

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

Exponential growth of a range of dark photon modes

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

(Note: Ordinary ALP decay is inefficient)

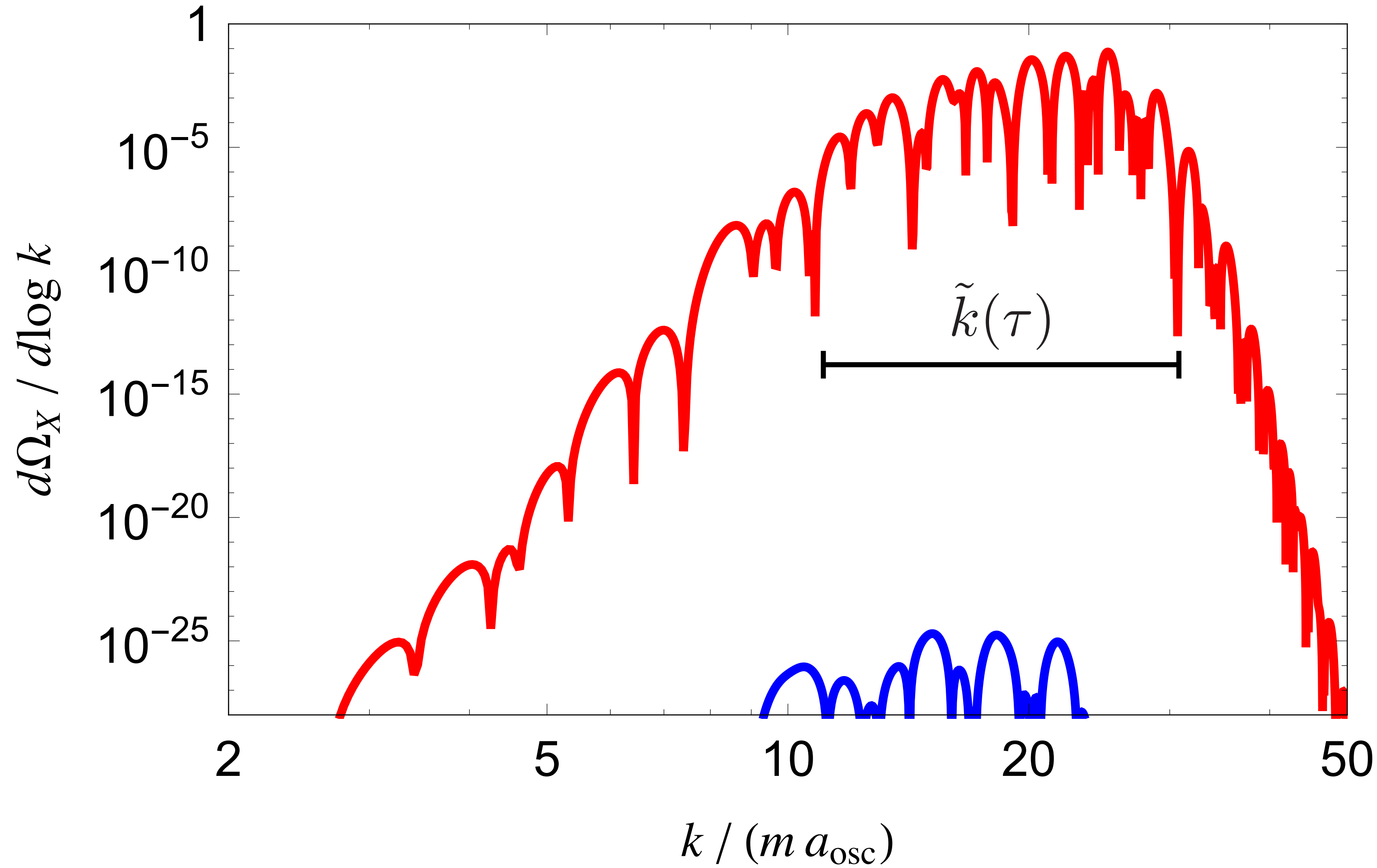
Dark photon spectrum

Initial condition violates parity (field rolls to the left or to the right)

One dark photon helicity dominates

A certain range of modes undergoes

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



GW production

These rapidly growing modes amplify quantum fluctuations of the dark photon into a time-varying, anisotropic classical energy distribution which sources gravitational waves

Gravity Waves

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

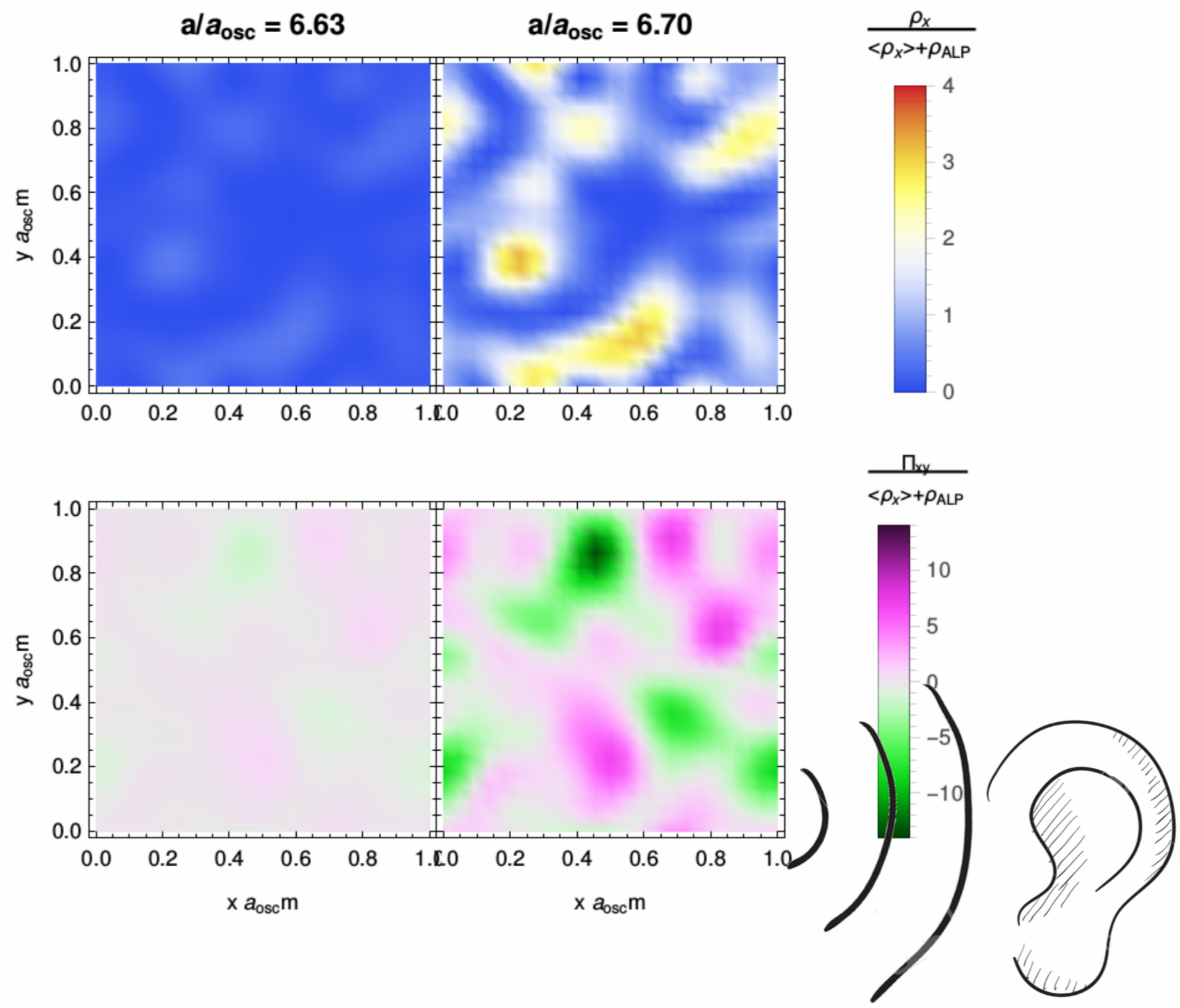
Anisotropic stress

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

GW production II

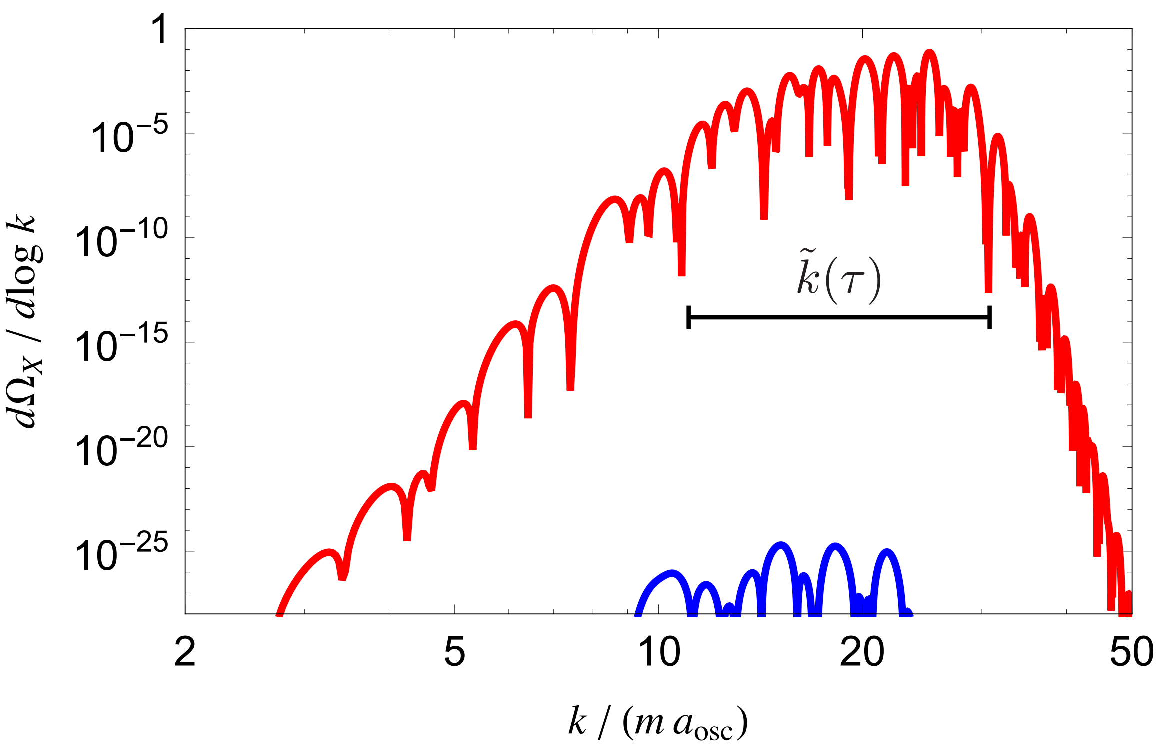
Energy Density of Dark Photon

Anisotropic Stress

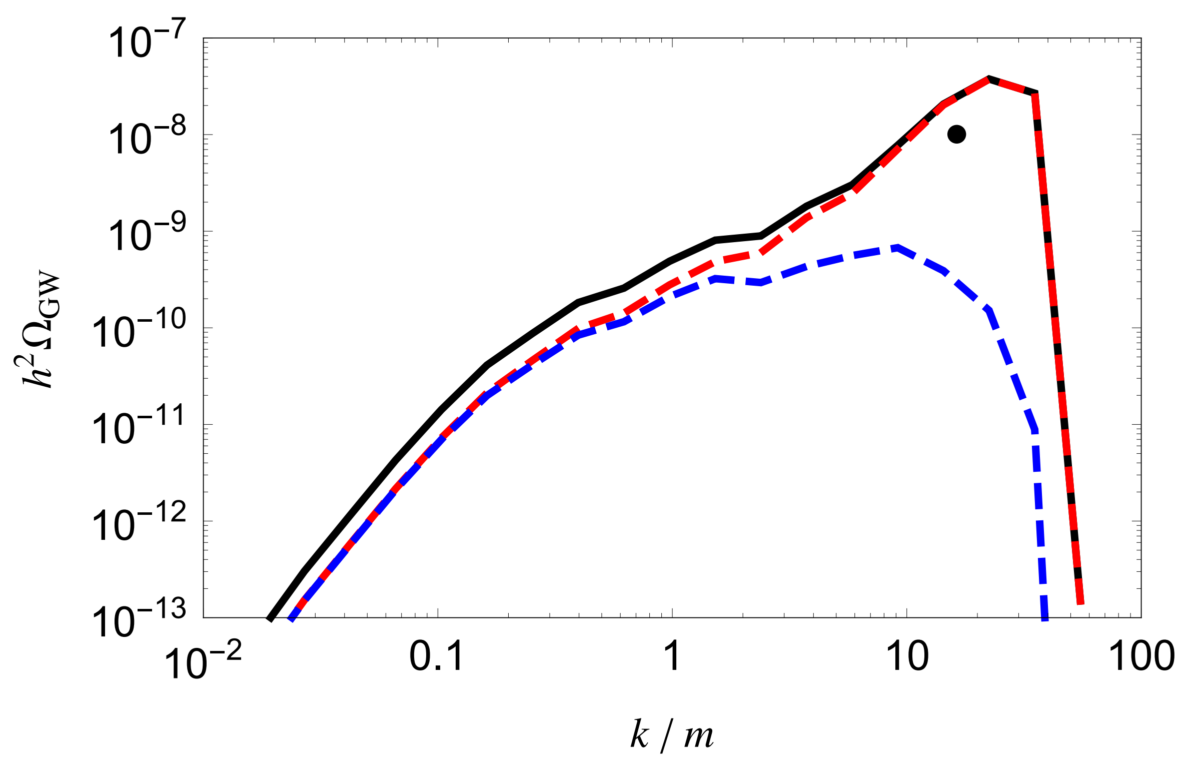


From dark photons to GWs

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



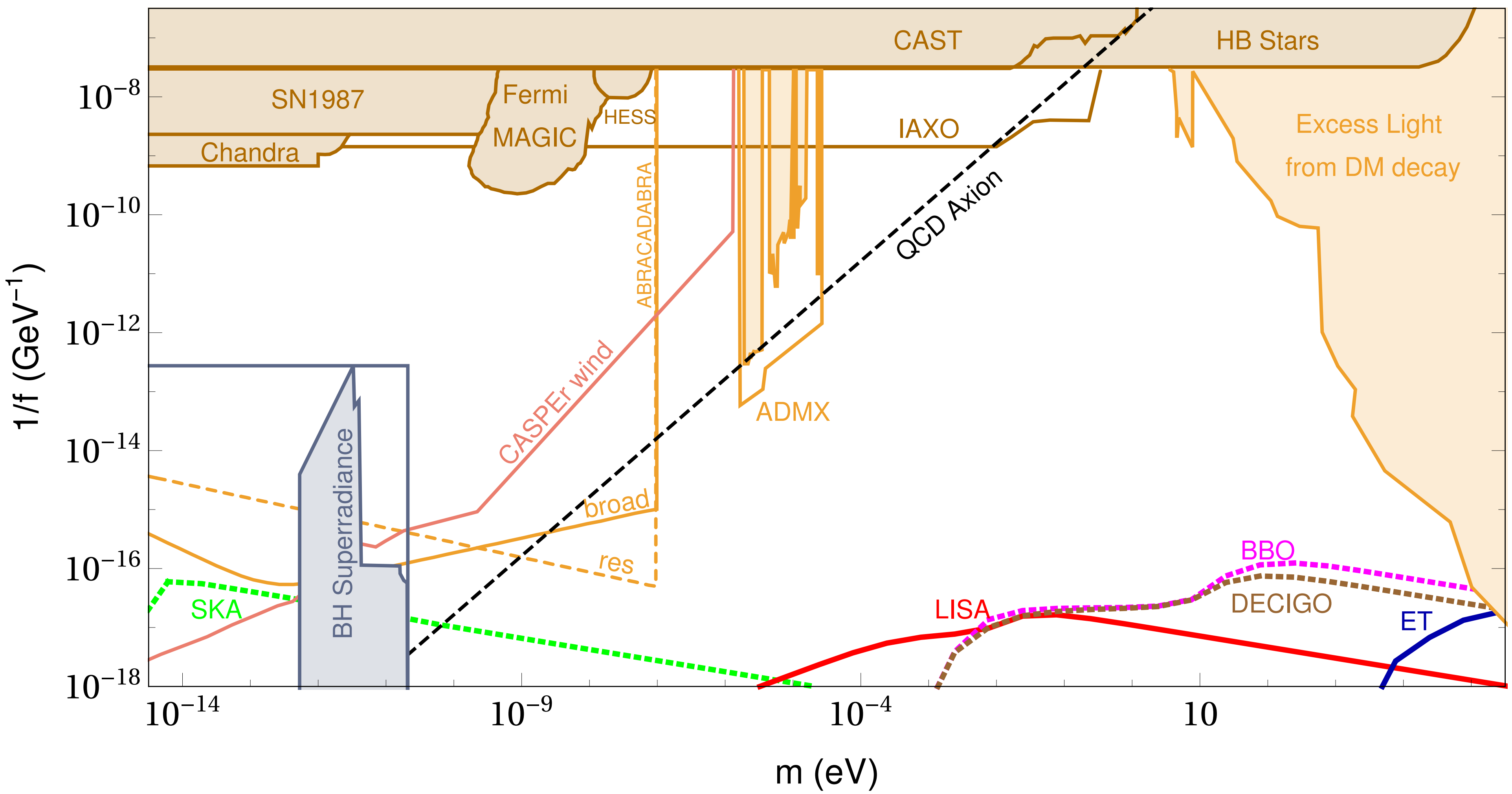
Dark photon spectrum



GW spectrum

Machado, Ratzinger, Stefanek, PS, 1811.01950

GW probes of audible ALPs



Mainly sensitive to high scale ALPs, since

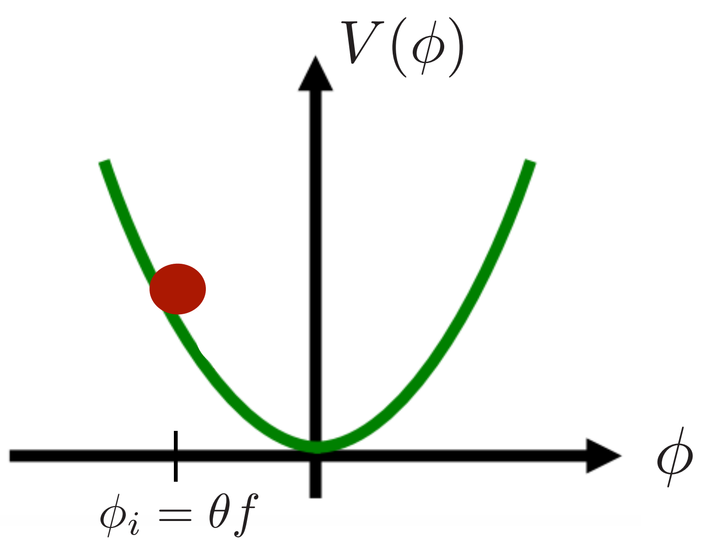
$$f_0 \approx m \left(\frac{T_0}{T_*}\right) (\alpha\theta)^{2/3} = \sqrt{\frac{m}{M_P}}\, T_0\, (\alpha\theta)^{2/3}\,, \qquad \Omega^0_{\rm GW} \approx \Omega^0_\gamma \left(\frac{f}{M_P}\right)^4 \left(\frac{\theta^2}{\alpha}\right)^{\frac{4}{3}}$$

Machado, Ratzinger, Stefanek, PS, 1912.01107

ALP dynamics - once more

Equation of motion

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

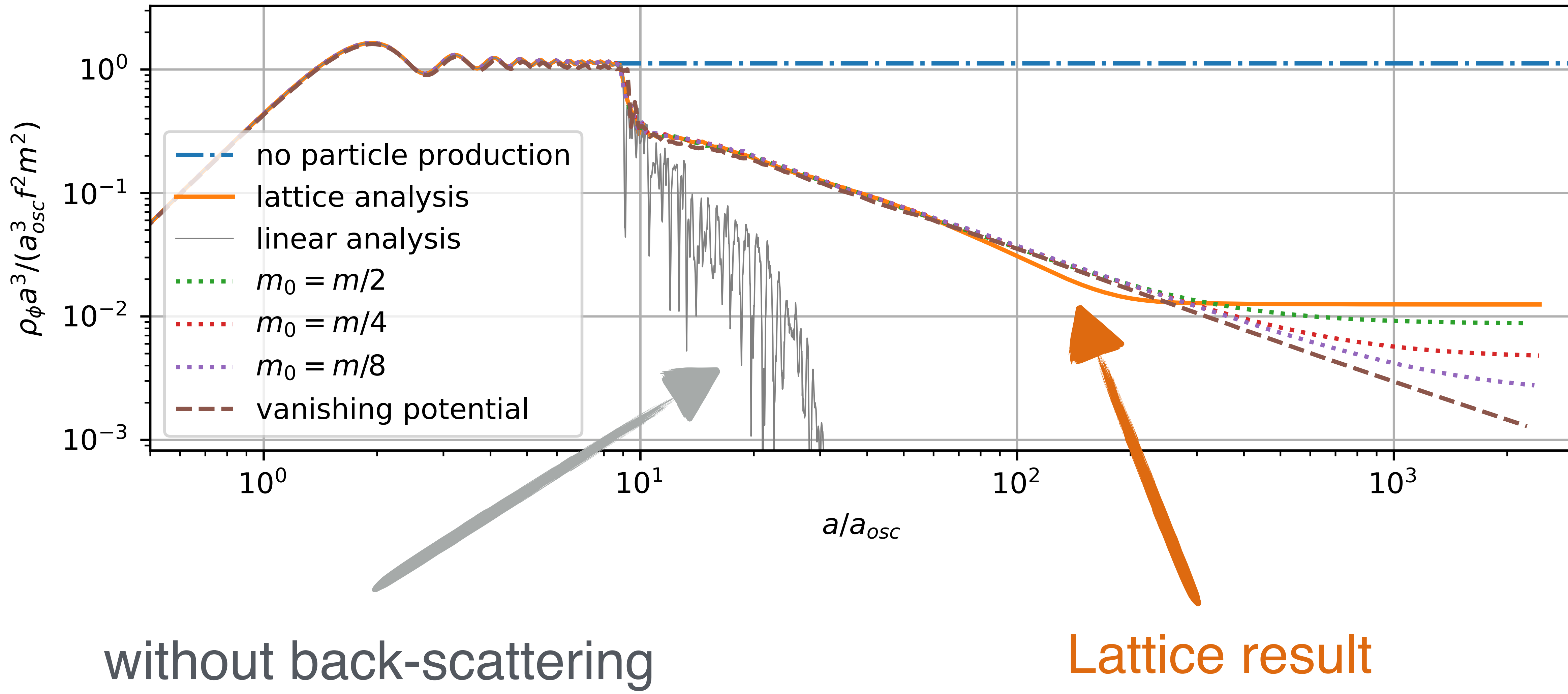


Once a significant population of dark photons is produced, the back-scattering into ALP fluctuations becomes non-negligible

Requires fully numerical treatment on the lattice

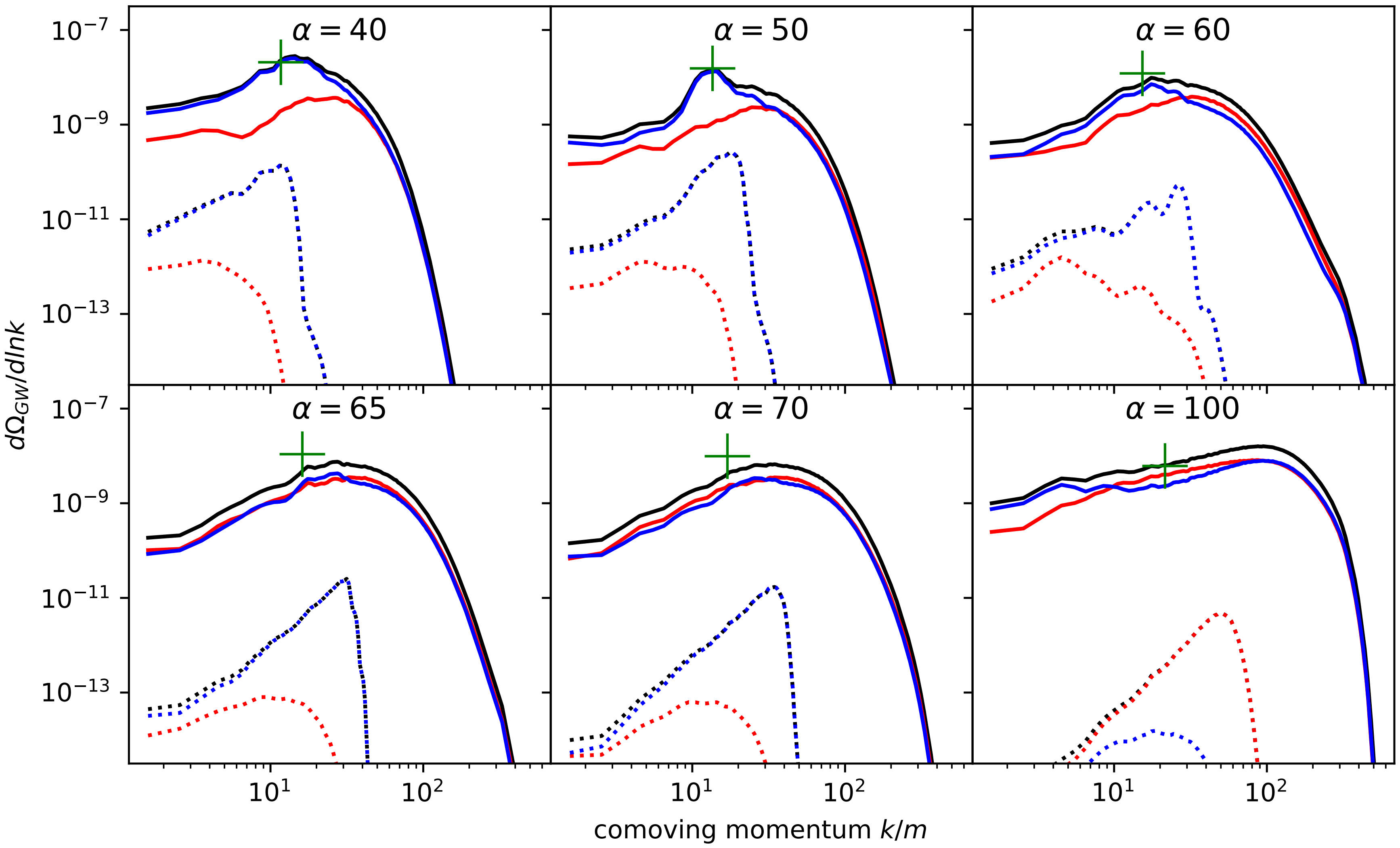
Important to get correct relic abundance prediction

From 2012.11584 with W. Ratzinger, B. Stefanek



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

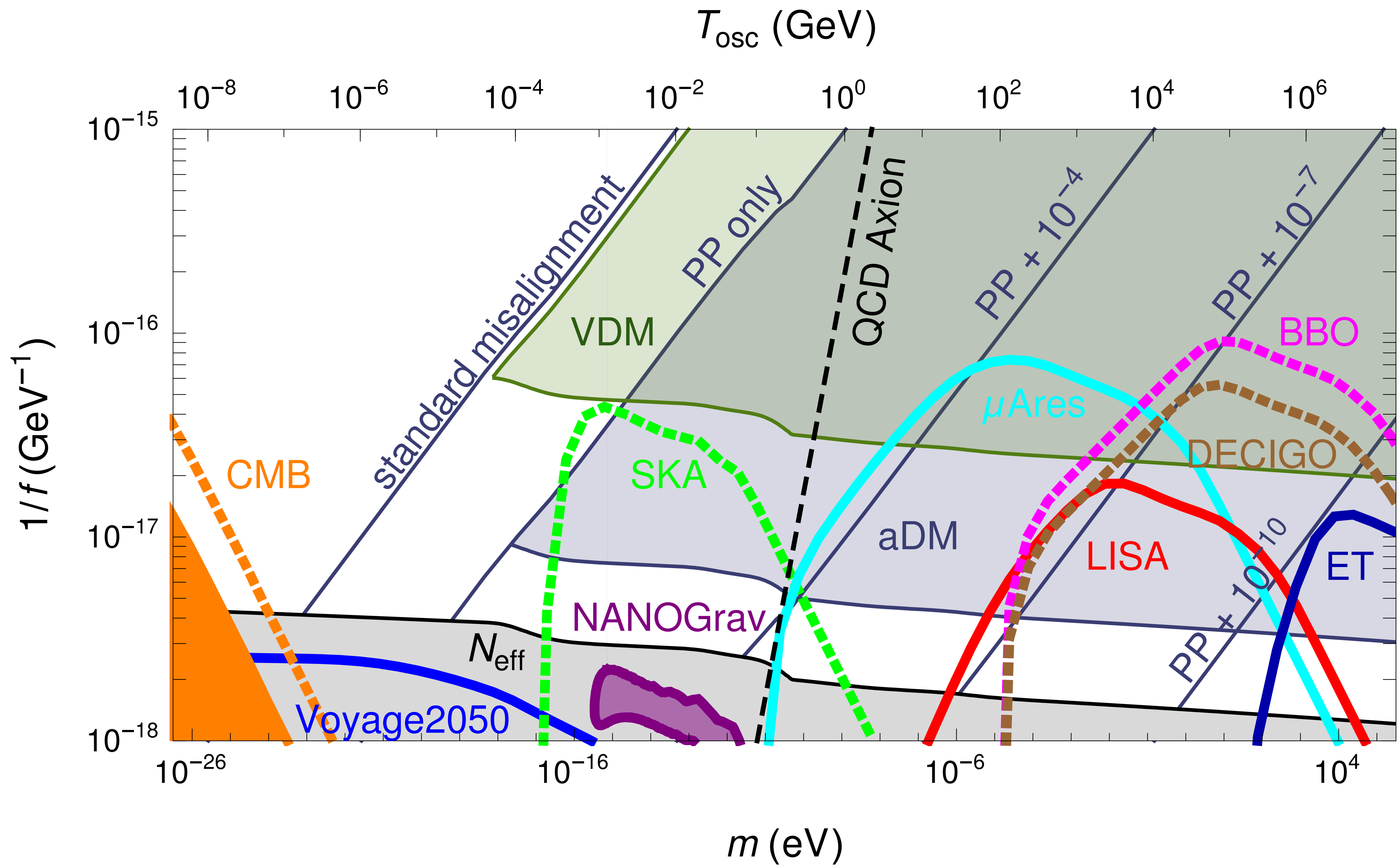
Corrections to GW signal



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



From 2012.11584 with W. Ratzinger, B. Stefanek

Situation?

Good:

- GWs
- More ALP DM parameter space

Room for improvement:

- Large coupling $\alpha \gtrsim 20$ required
- ALP DM abundance still a problem
- GWs only for large f

Possible solutions

Delay onset of ALP oscillations

- Observable GWs with smaller f
- Realised e.g. in relaxion models with reheating

Use ALP kinetic energy instead of potential energy

- Again can lower f
- Now also works with smaller (perturbative) couplings
- Realised in kinetic misalignment scenarios

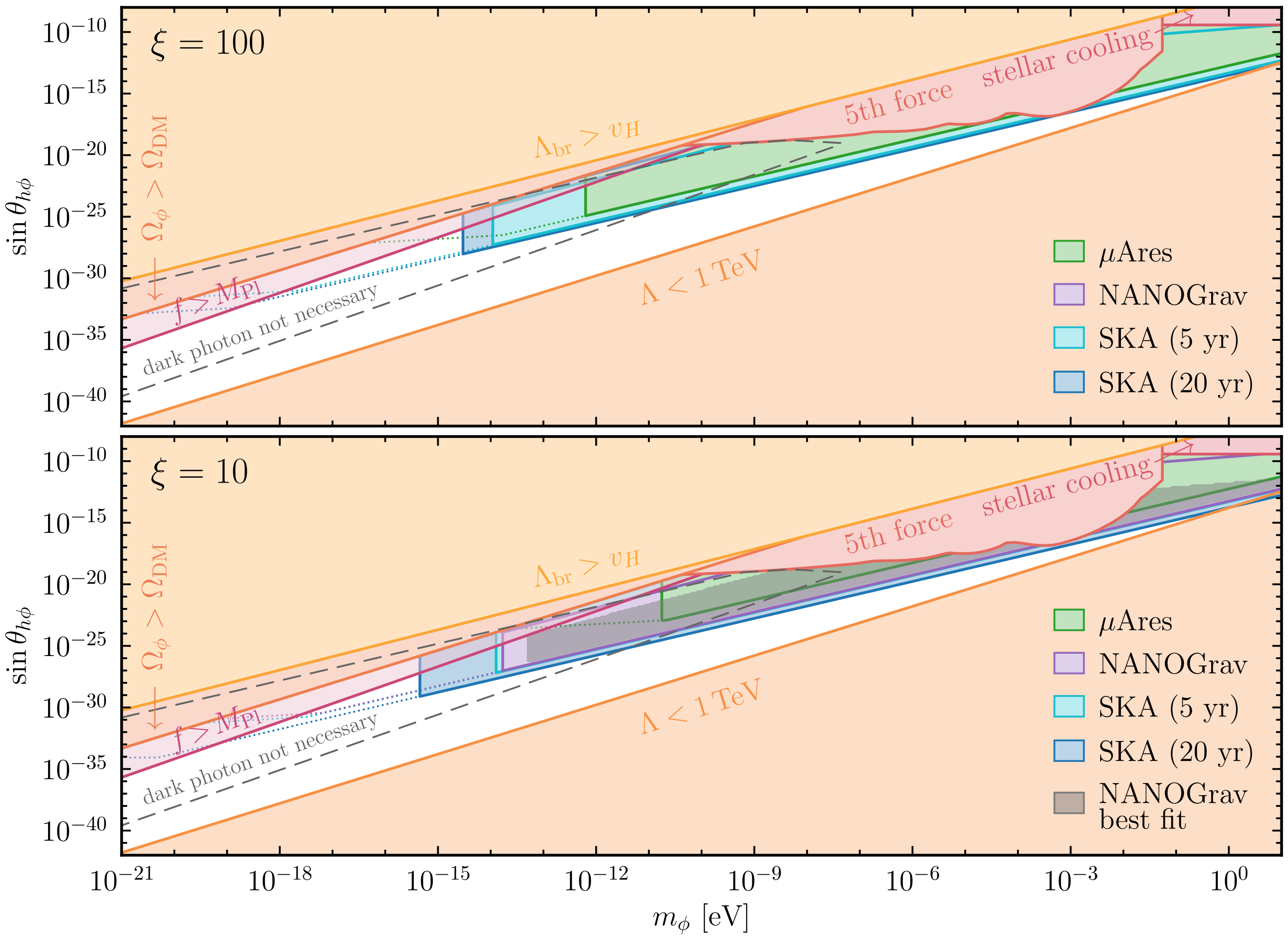
Audible relaxion

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

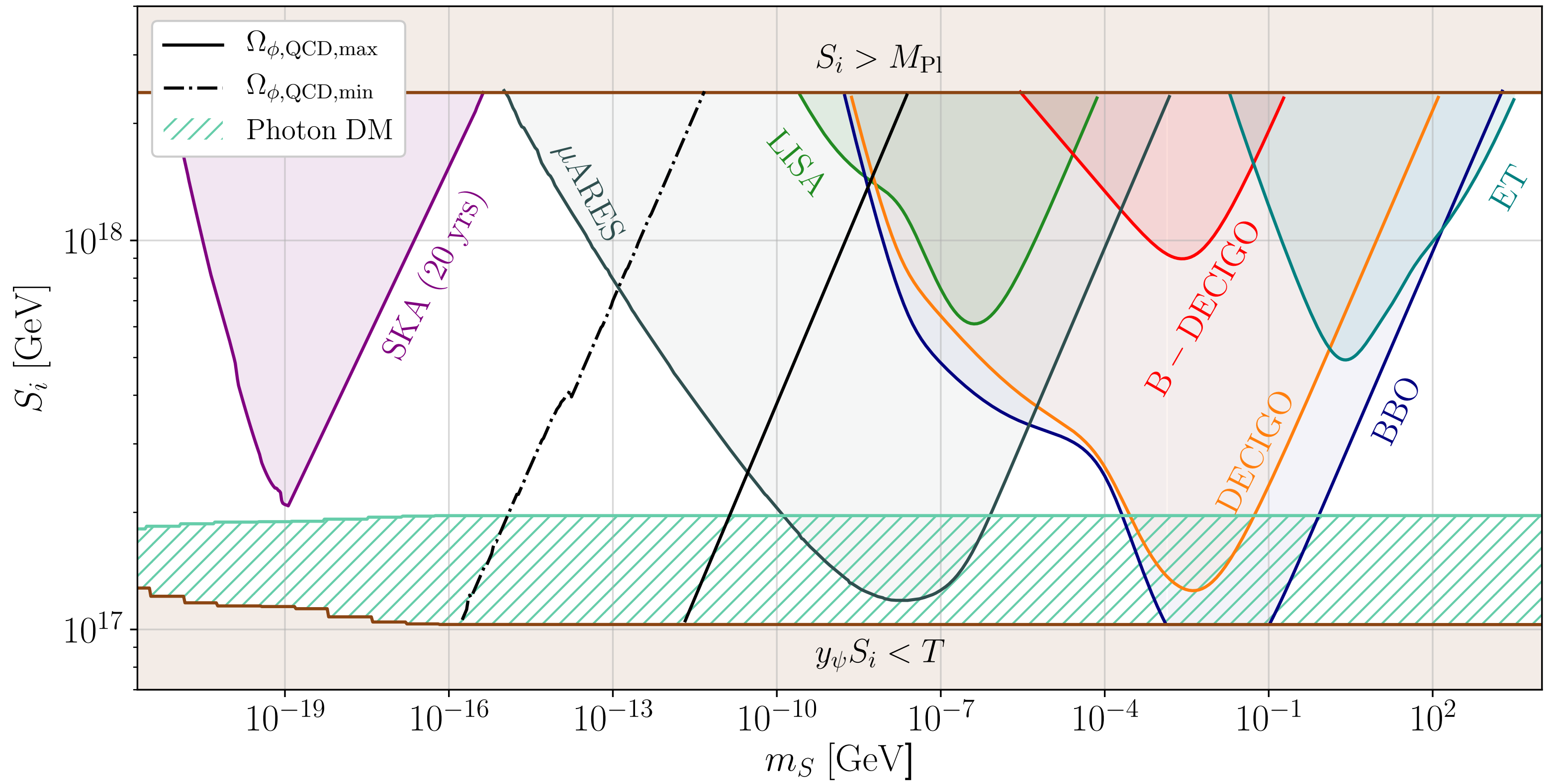
GWs from kinetic misalignment

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!



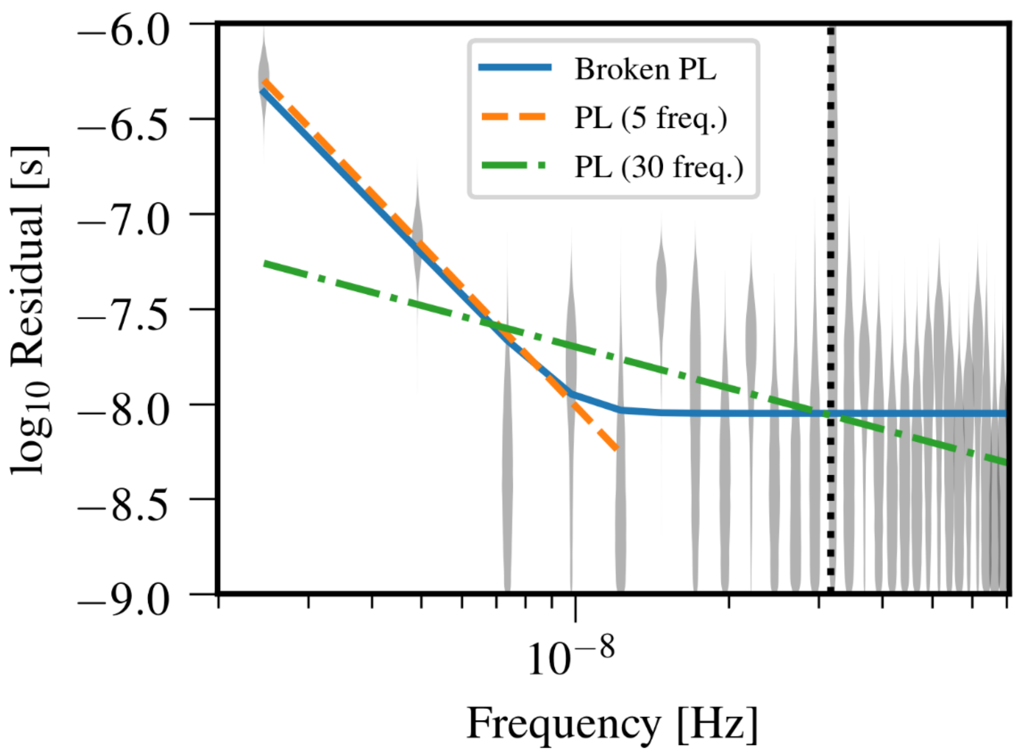
From Madge, Ratzinger, Schmitt, PS, 2111.12730

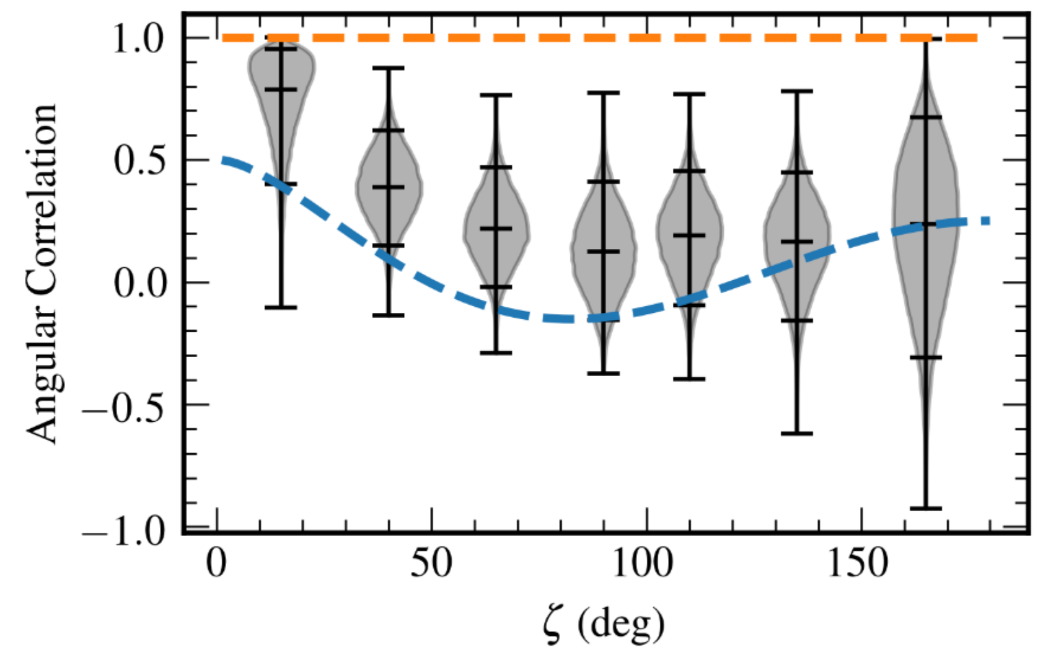
See also Co, Harigaya, Pierce, 2104.02077

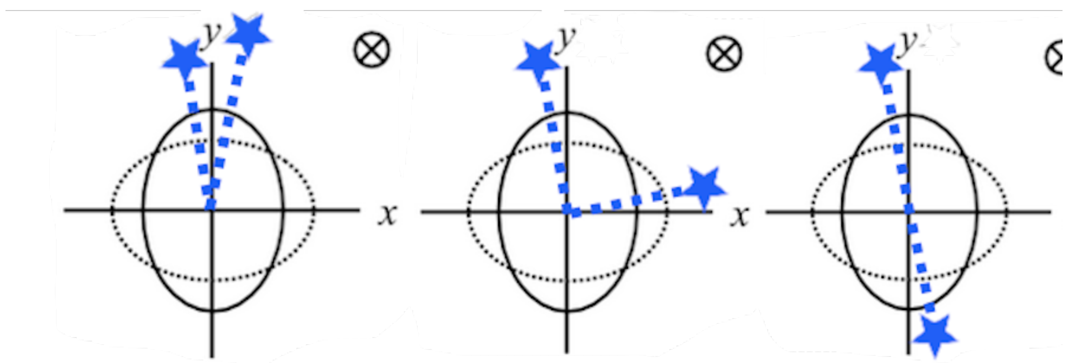
NANOGrav saw something!

No 4σ evidence for Quadrupole

Significant Strain at low frequencies

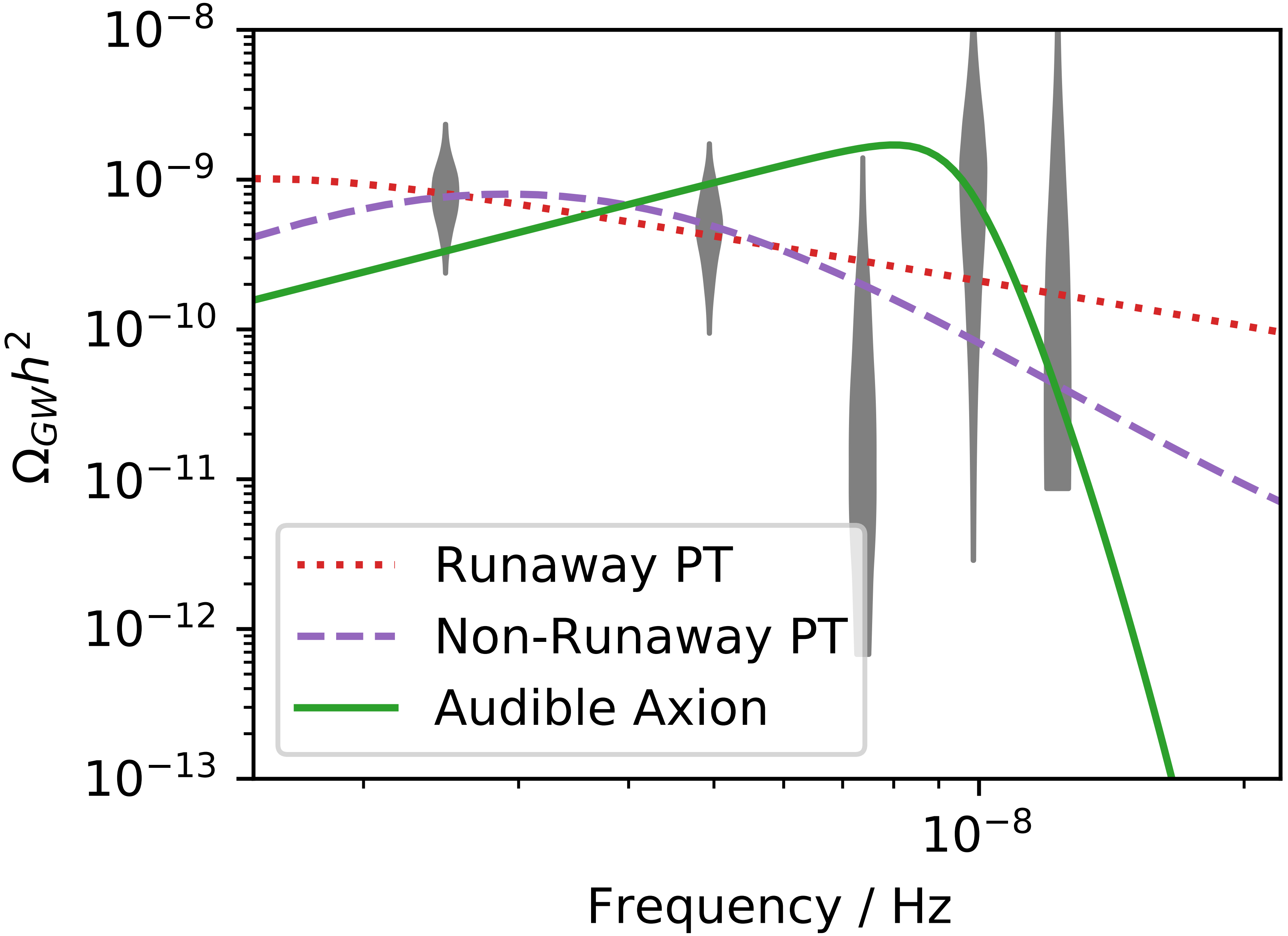






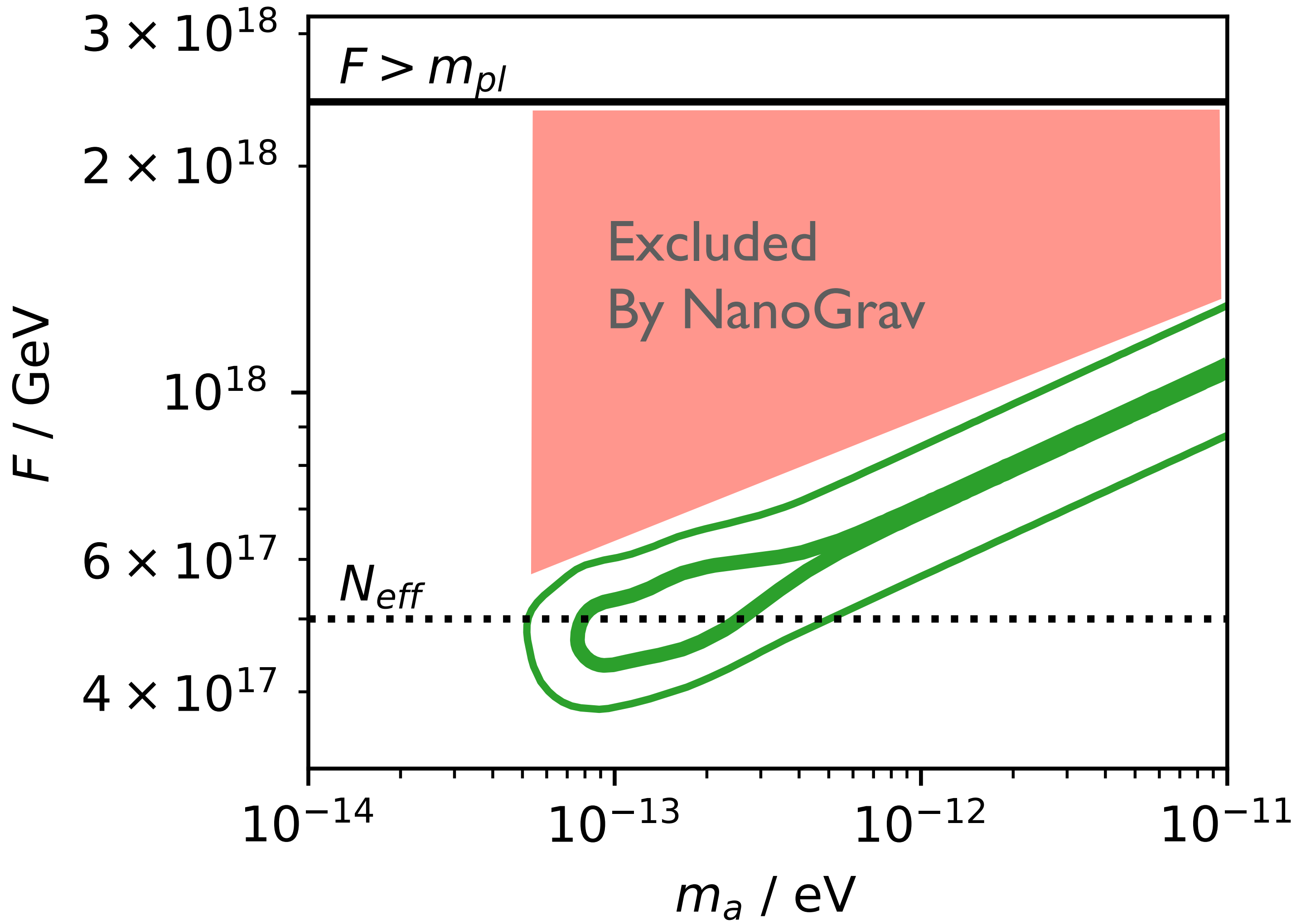
From NANOGrav collaboration, 2009.04496
Now also consistent signals in PPTA, EPTA and IPTA - still not fully conclusive though

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

Another probe of early Universe dynamics:

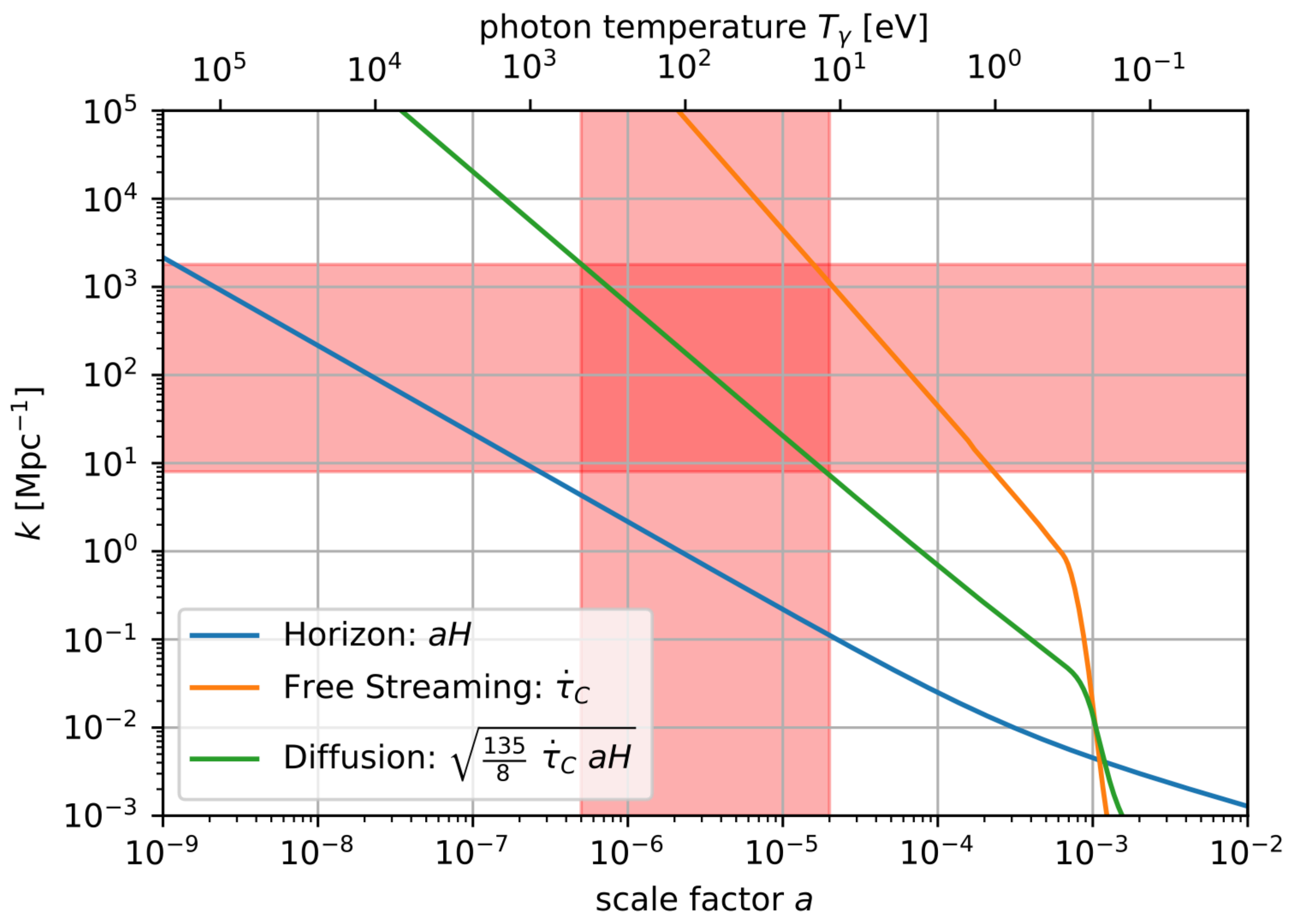
CMB spectral distortions

Spectral distortions?

Around $10^4 \lesssim z \lesssim 10^6$, photon number is frozen

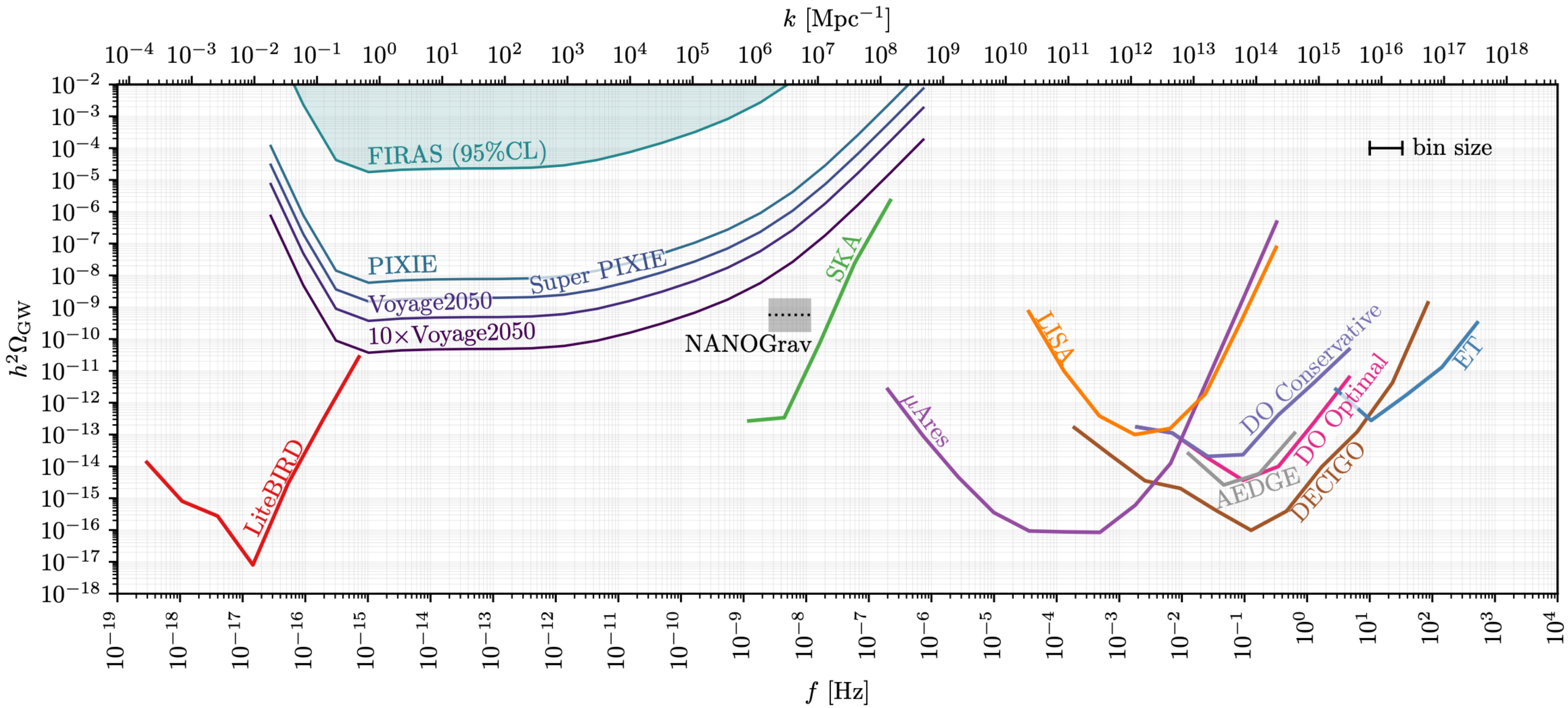
Any energy added to the photons leads to a so called μ distortion

Energy source we consider here: Gravitational damping of dark sector fluctuations



Ramberg, Ratzinger & PS, 2209.14313

Spectral distortions as probes of low scale GWs

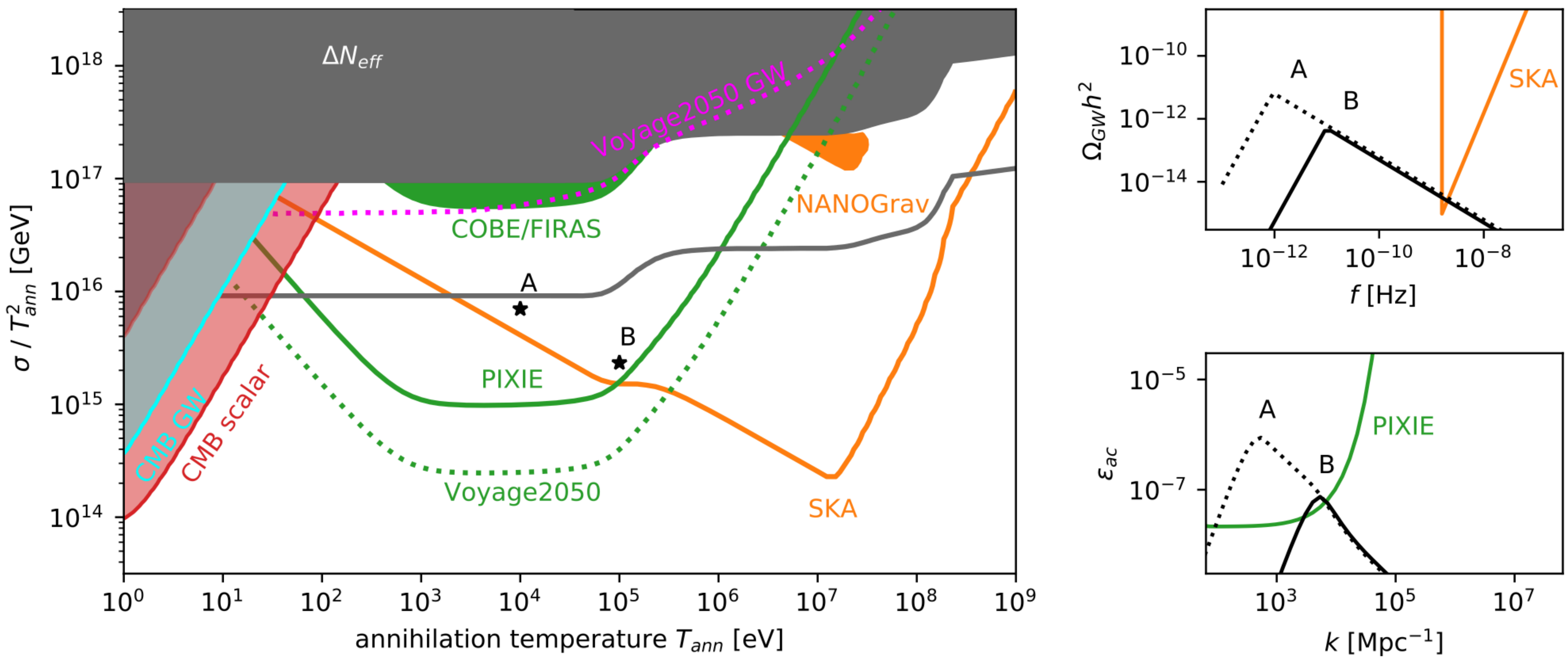


From Kite, Ravenni, Patil, Chluba, MNRAS 2021

Tensor fluctuations (GWs) also source μ distortions

- But difficult to test. Better to directly go for the scalar fluctuations (that also source the GWs)

Example source I: Annihilating domain walls



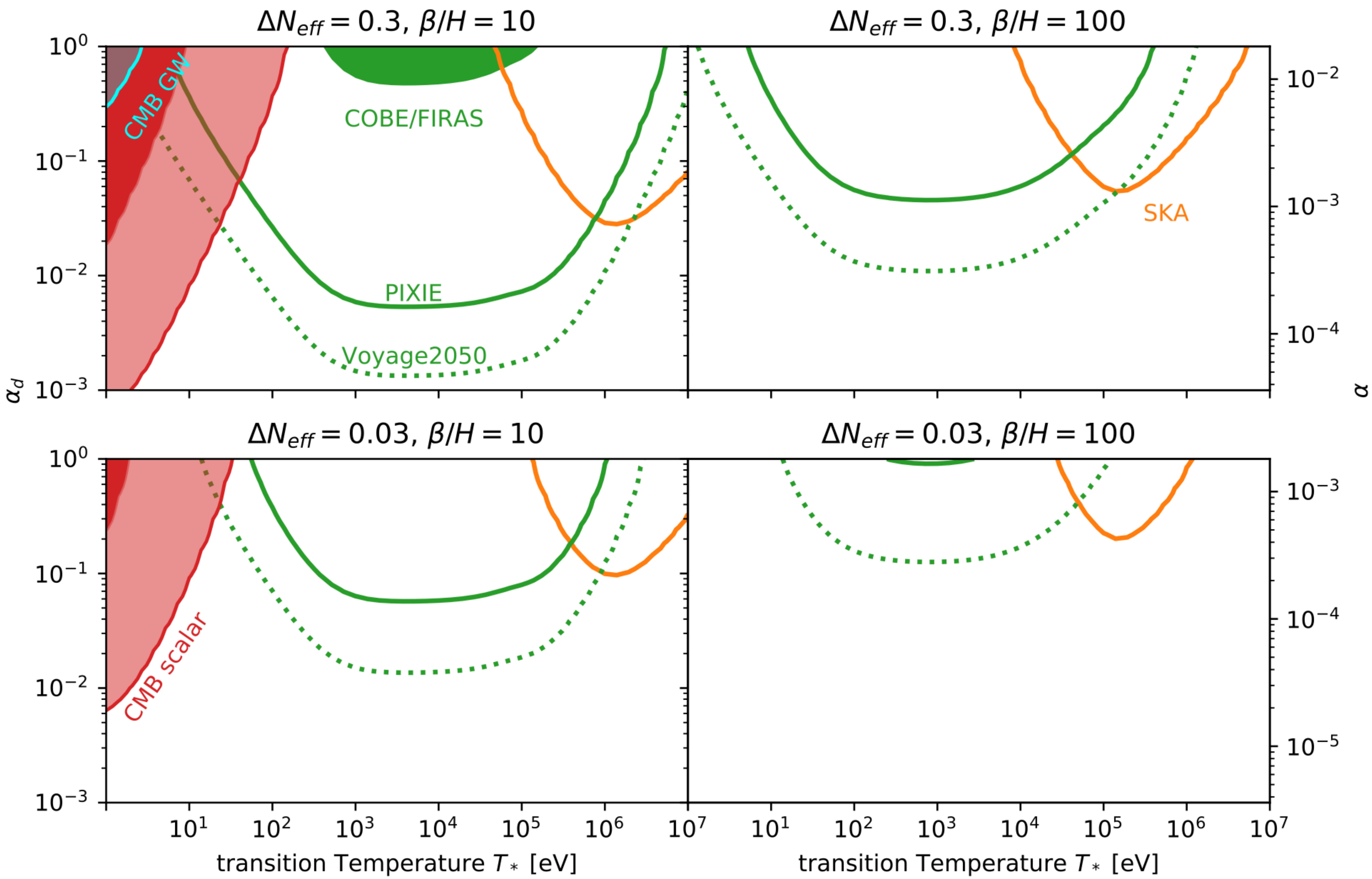
Already probes allowed parameter space

Complementary to GW probes, can break degeneracy

- Multi-messenger cosmology

Ramberg, Ratzinger & PS, 2209.14313

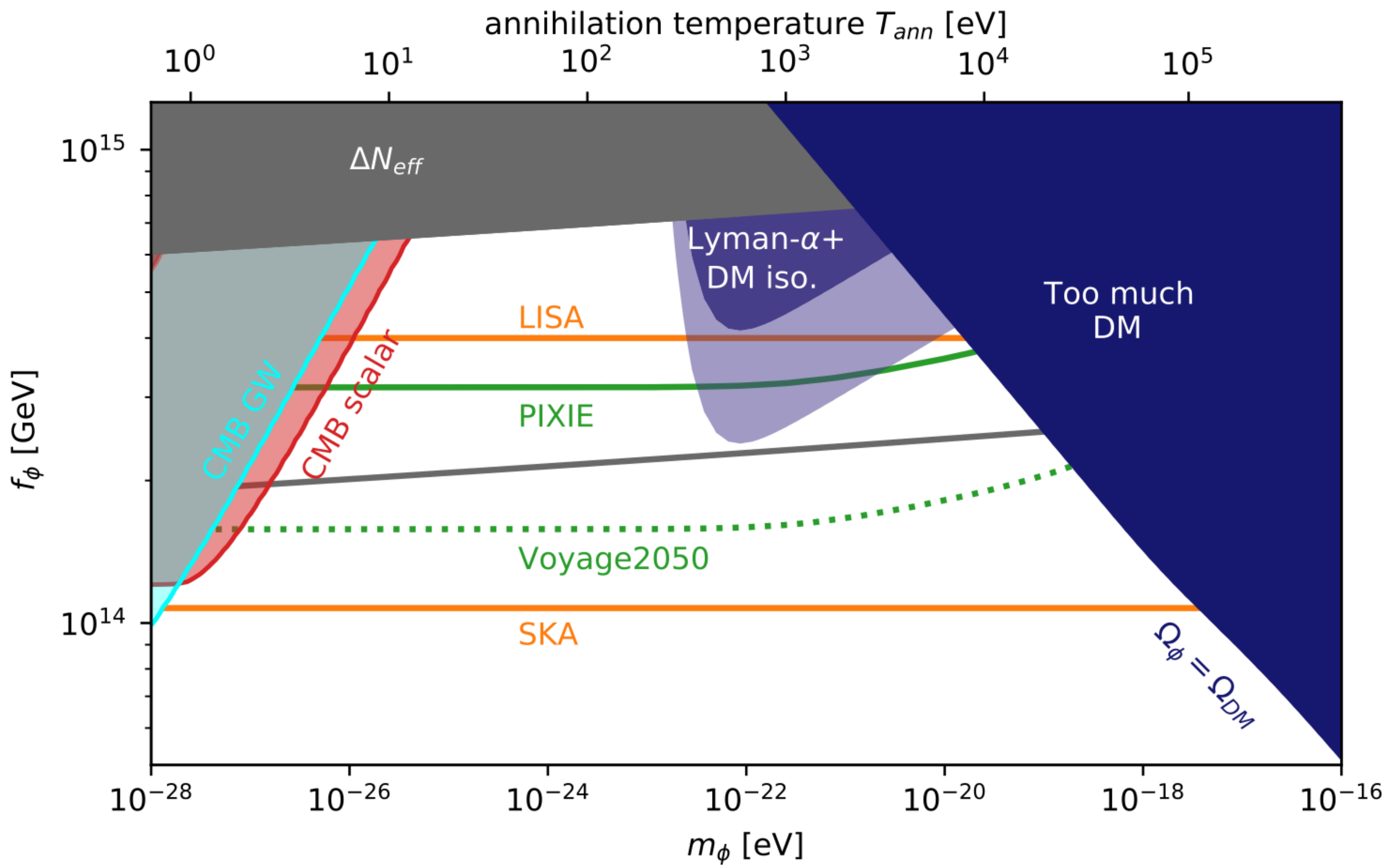
Example source II: Dark sector phase transition



Note: Ω_d fixed to satisfy N_{eff} constraints

Ramberg, Ratzinger & PS, 2209.14313

Source III: (global) cosmic strings



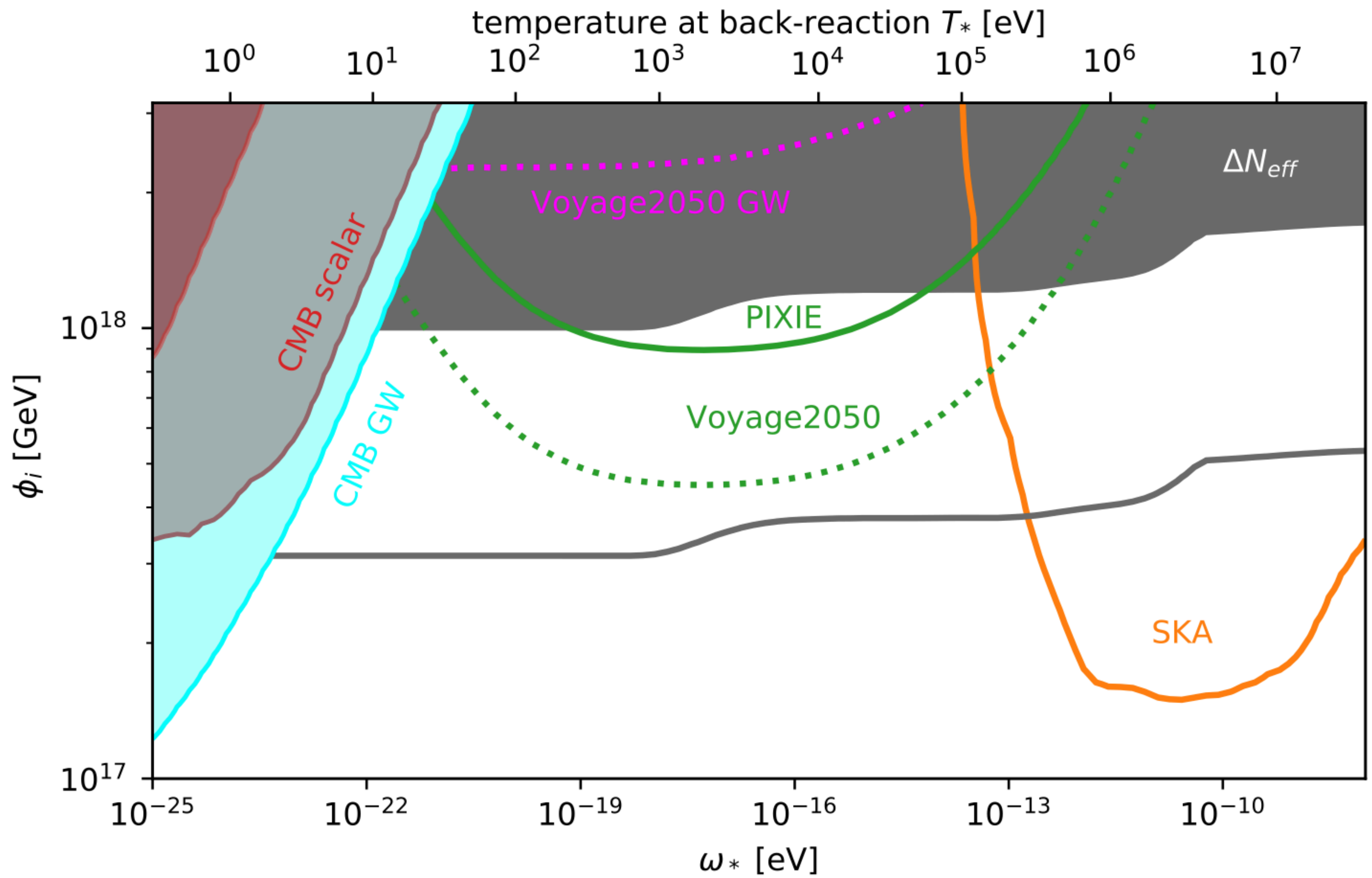
Note: Local strings mainly radiate from small loops and are thus NOT an efficient source of spectral distortions

Example source IV: Audible axions…

Not yet…

Results for scalar toy model

Constraints not as strong since fluctuations are not horizon size



Expect better sensitivity for axion fragmentation

Ramberg, Ratzinger & PS, 2209.14313

Summary

GWs are cool

New way to probe axions/ALPs

Tachyonic particle production frequently used in model building

- We now have precise numerical simulations

NANOGrav might have seen a glimpse from a dark sector

- Waiting for future data - exciting!

CMB spectral distortions are also cool!

Team:

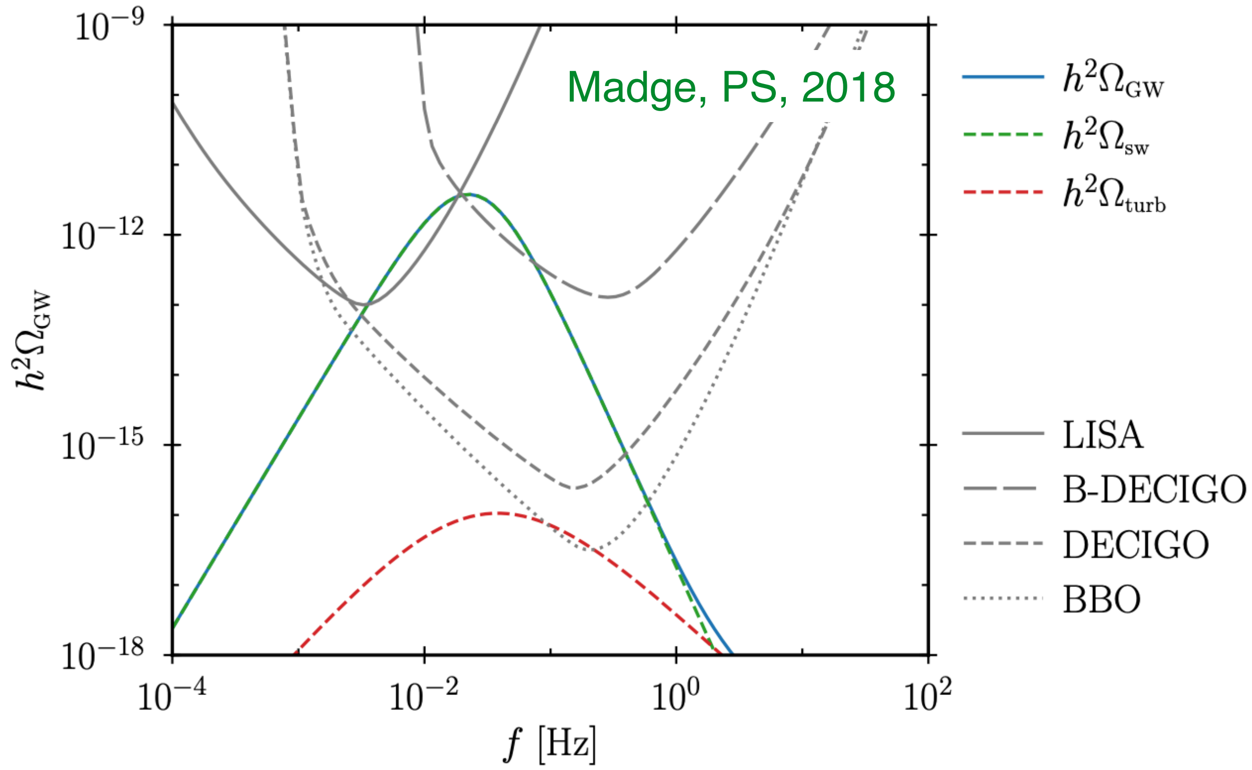
Wolfram Ratzinger
Ben Stefanek
Camila Machado

Daniel Schmitt
Nicklas Ramberg
Enrico Morgante

Signal shape and frequency is characteristic for the source. Examples:

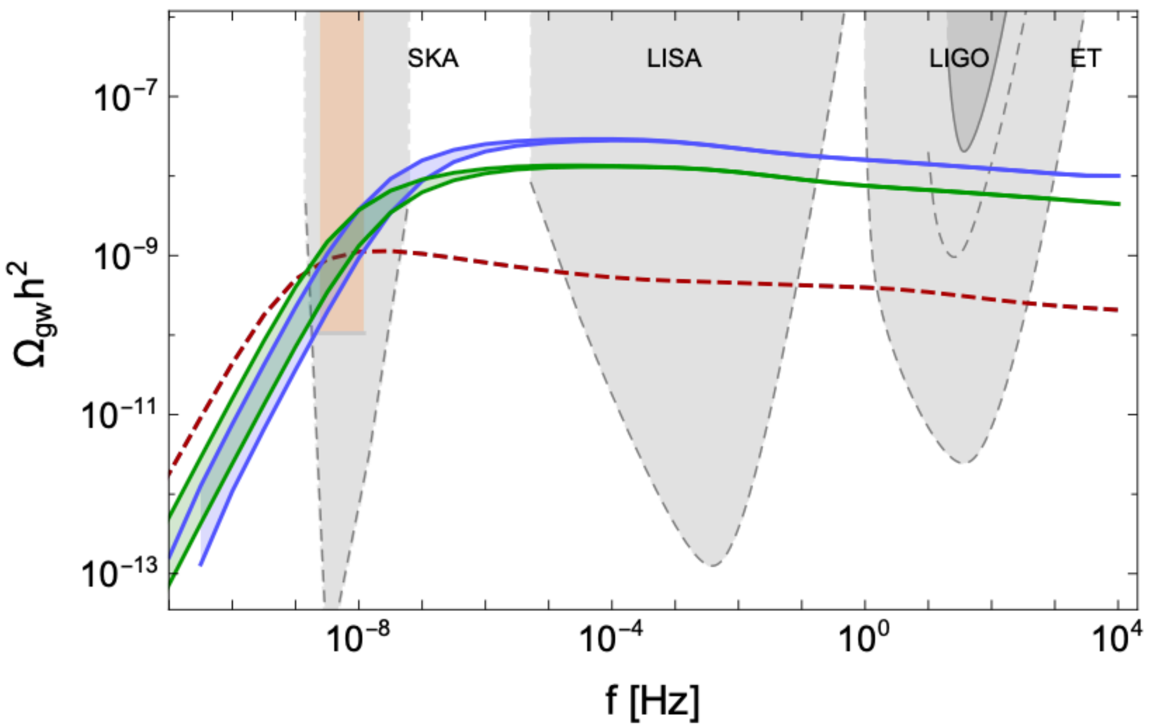
Phase transition

- Peak position depends on critical temperature



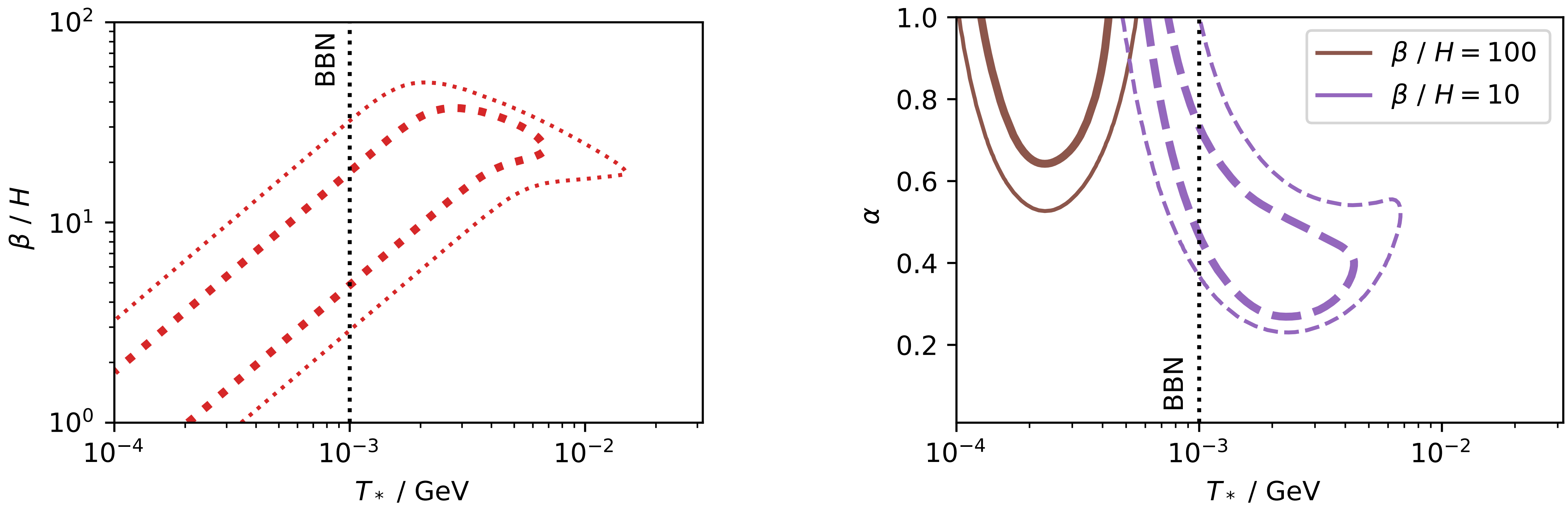
Cosmic strings

- Flatter spectrum



Buchmuller, Domcke, Schmitz, 2021

Fit with Phase Transition

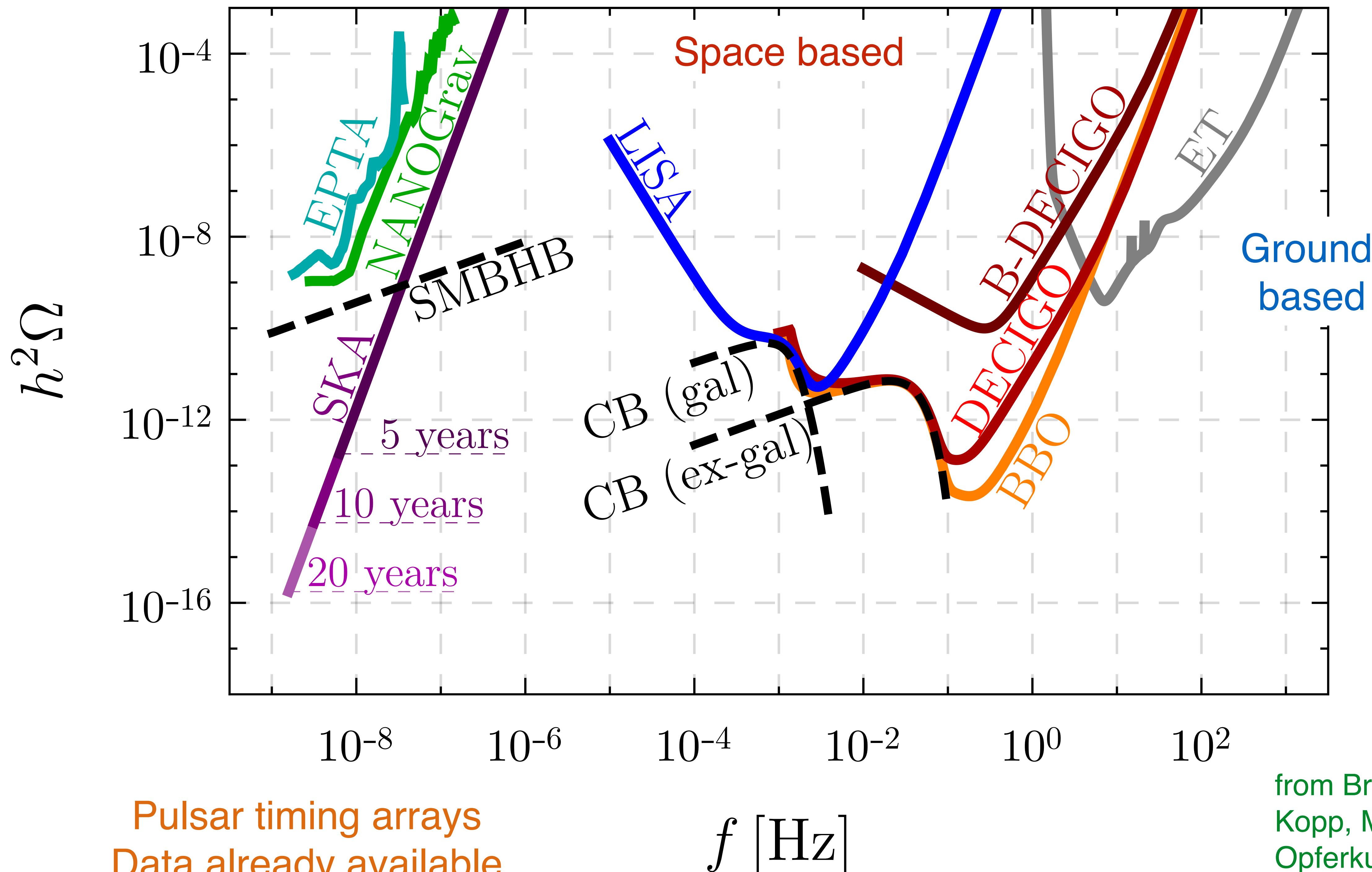


Generic PT parameterisation, best fit with PT at temperatures in few MeV range

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

Wolfram Ratzinger & PS, 2009.11875

Frequency ranges



Pulsar timing arrays
Data already available

from Breitbach, Kopp, Madge, Opferkuch, PS 1811.11175

GW signal shape

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