FUN WITH PTA INTERPRETATIONS

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Cluster of Excellence PRISMA+

Fundamental physics and GW detectors

Pollica
September 13, 2024

New era in fundamental (particle) physics

Standard model is valid to high energies

No clear hint where new physics is

New era in fundamental (particle) physics

At the same time:

SM is incomplete, does not explain dark matter, baryon asymmetry, inflation, …

All linked to very early Universe dynamics

New era in fundamental (particle) physics

At the same time:

SM is incomplete, does not explain dark matter, baryon asymmetry, inflation, …

All linked to very early Universe dynamics

Gravitational waves are messengers from this era

- great opportunity

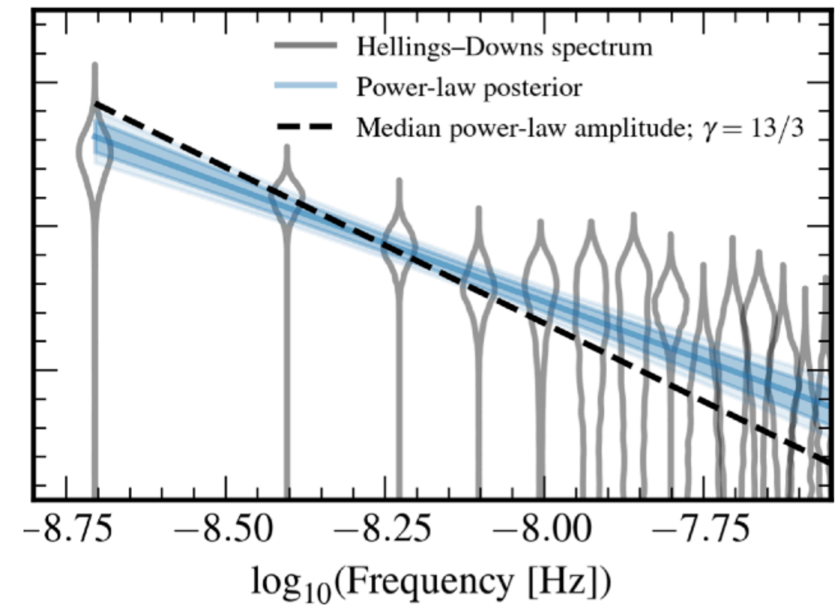
PTA: First observation of stochastic GW background

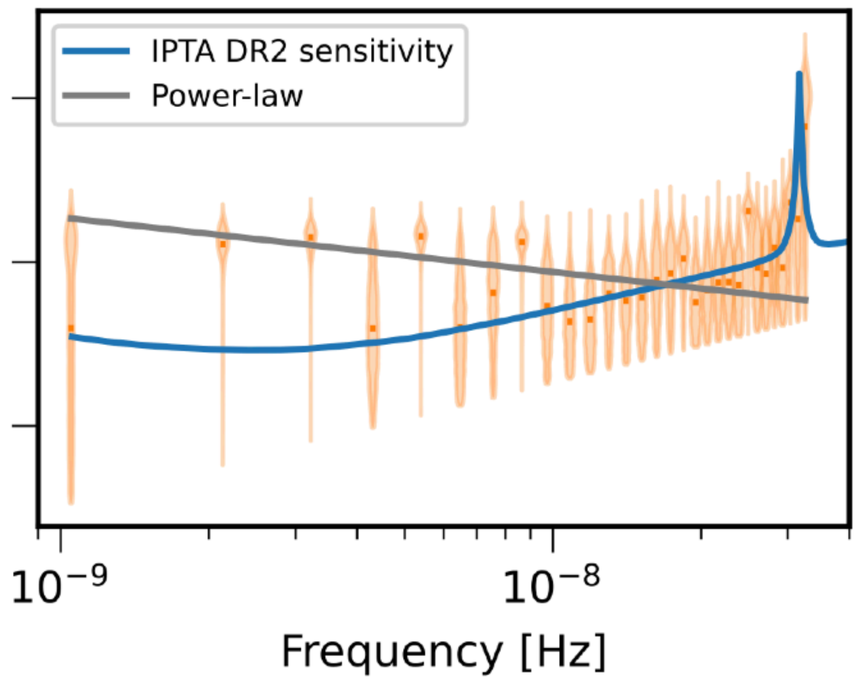
Could be of primordial origin, though a large astrophysical contribution (SMBHB) is likely

In any case:

Testing ground for model building, parameter reconstruction, …

- what can we learn from GW data
- how else can we probe and distinguish models





Outline

Audible axions: GWs from rolling axions & PTA

GWs from domain walls

- spectral distortions as complementary probe of GW sources

PTA GWs from supermassive pBH

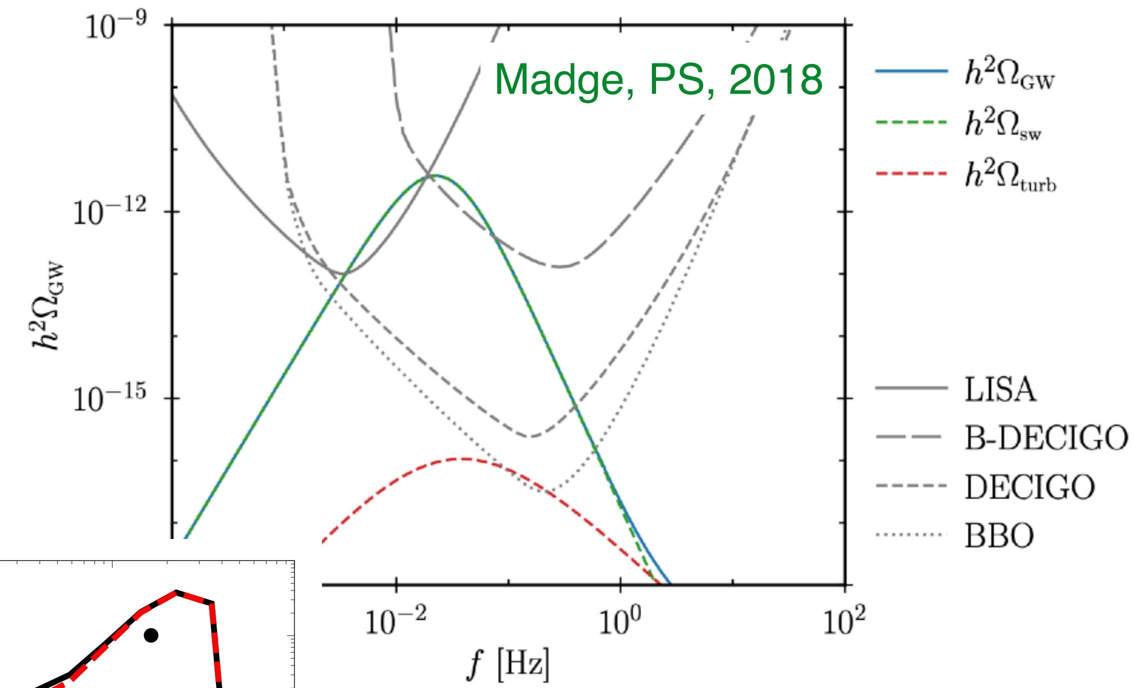
Not today:

- Ultra-high frequency GWs
- Supercooled PTs
- Strongly coupled PTs from holography

GW sources and their signal shapes

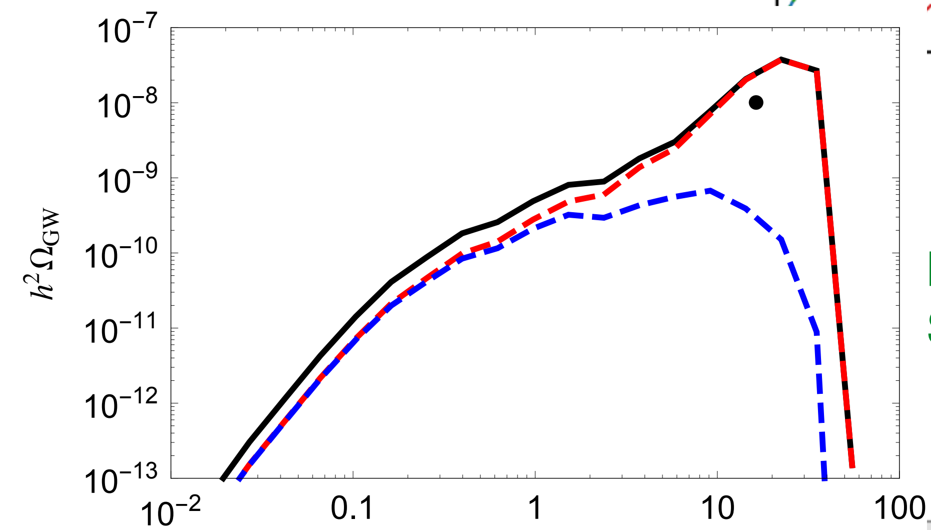
Phase transition

- Peak position depends on critical temperature



Audible axions:

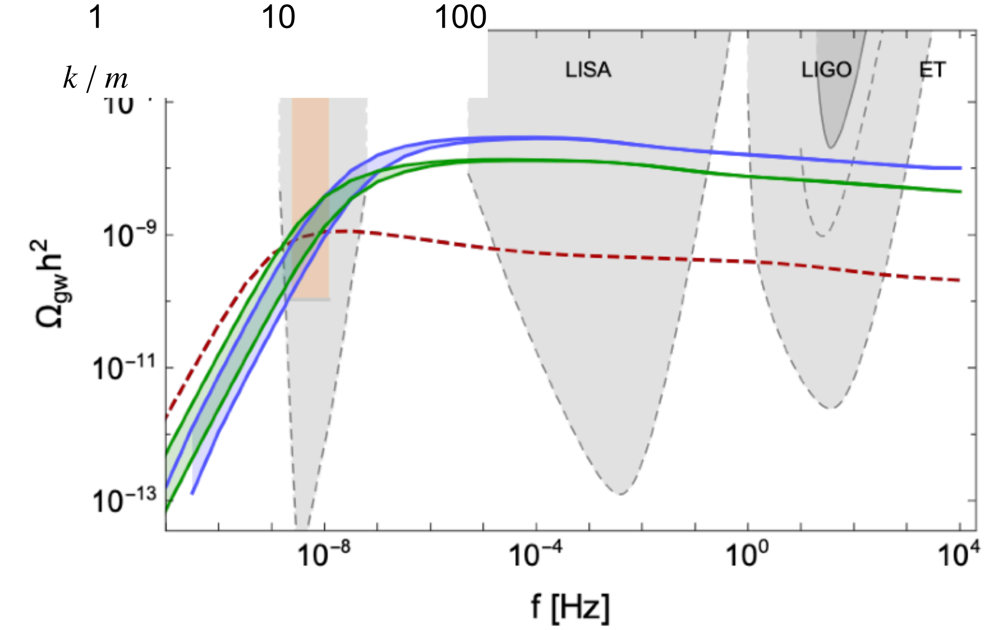
- Peaked but chiral



Machado, Ratzinger, Stefanek, PS, 2018/19

Cosmic strings

- Flatter spectrum



Buchmuller, Domcke, Schmitz, 2021

Audible Axions

Axion/ALP with dark photon

Take an axion ϕ

Dark photon X

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

In radiation domination,
i.e. after inflation!

Axion/ALP with dark photon

Take an axion ϕ

Dark photon X

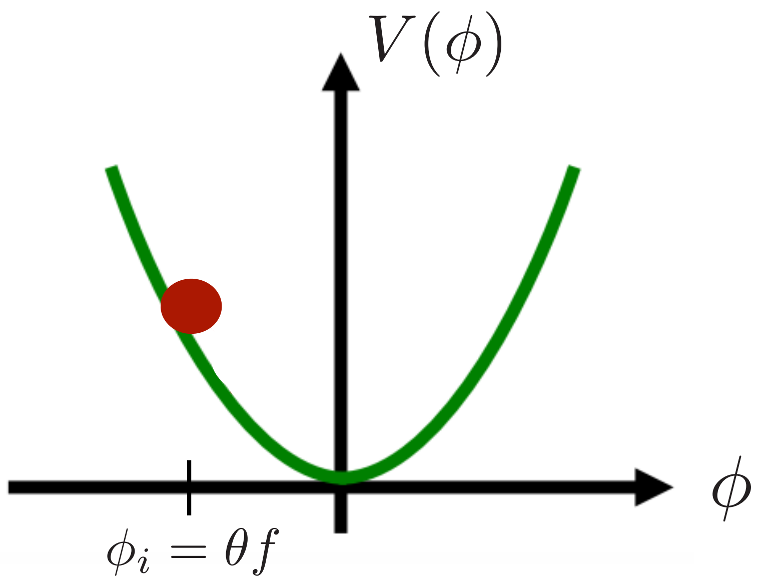
$$\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{1}{2} \partial_\mu \phi \, \partial^\mu \phi - V(\phi) - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\alpha}{4f} \phi X_{\mu\nu} \widetilde{X}^{\mu\nu} \right]$$

In radiation domination, i.e. after inflation!

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

Initial ϕ_i, starts rolling when

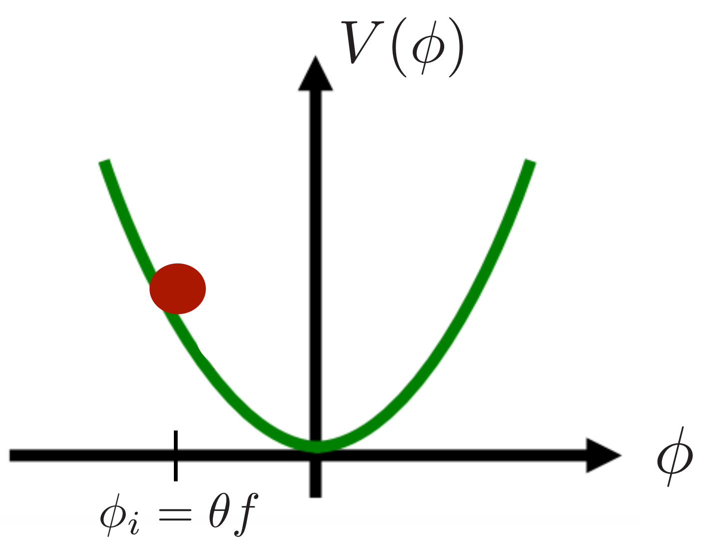
$$H \sim m_\phi$$



ALP dynamics - with dark photon

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 $H \sim m_\phi$

ALP is damped due to exponential production of dark photons

- Reduced relic abundance - enlarge natural DM parameter space
- Or production of vector DM

Agrawal, Marques-Tavares, Xue, 2018
And others…

See Marcos talk yesterday

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

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

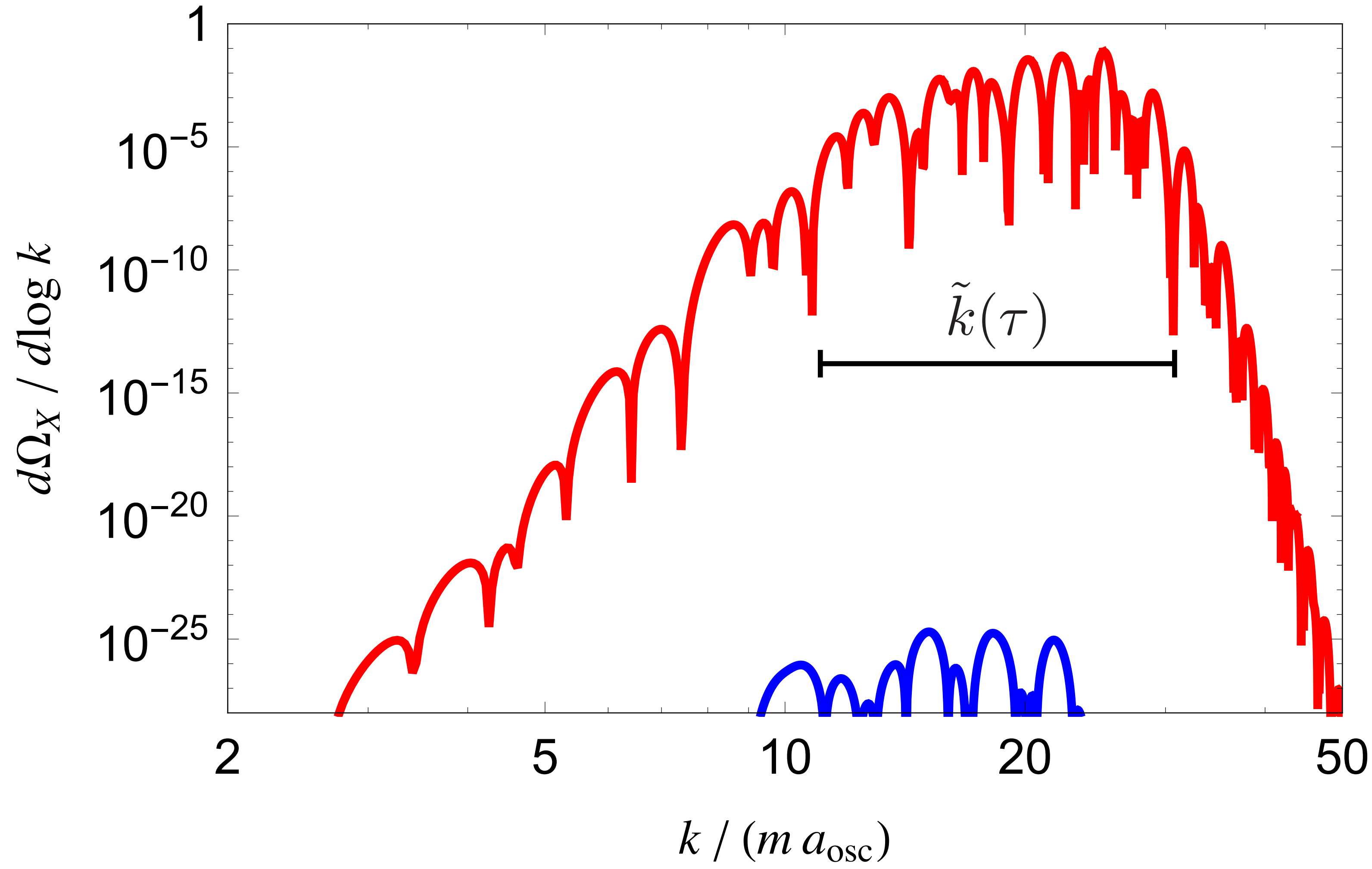
Dark photon spectrum

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

One dark photon helicity dominates

A certain range of modes undergoes growth

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

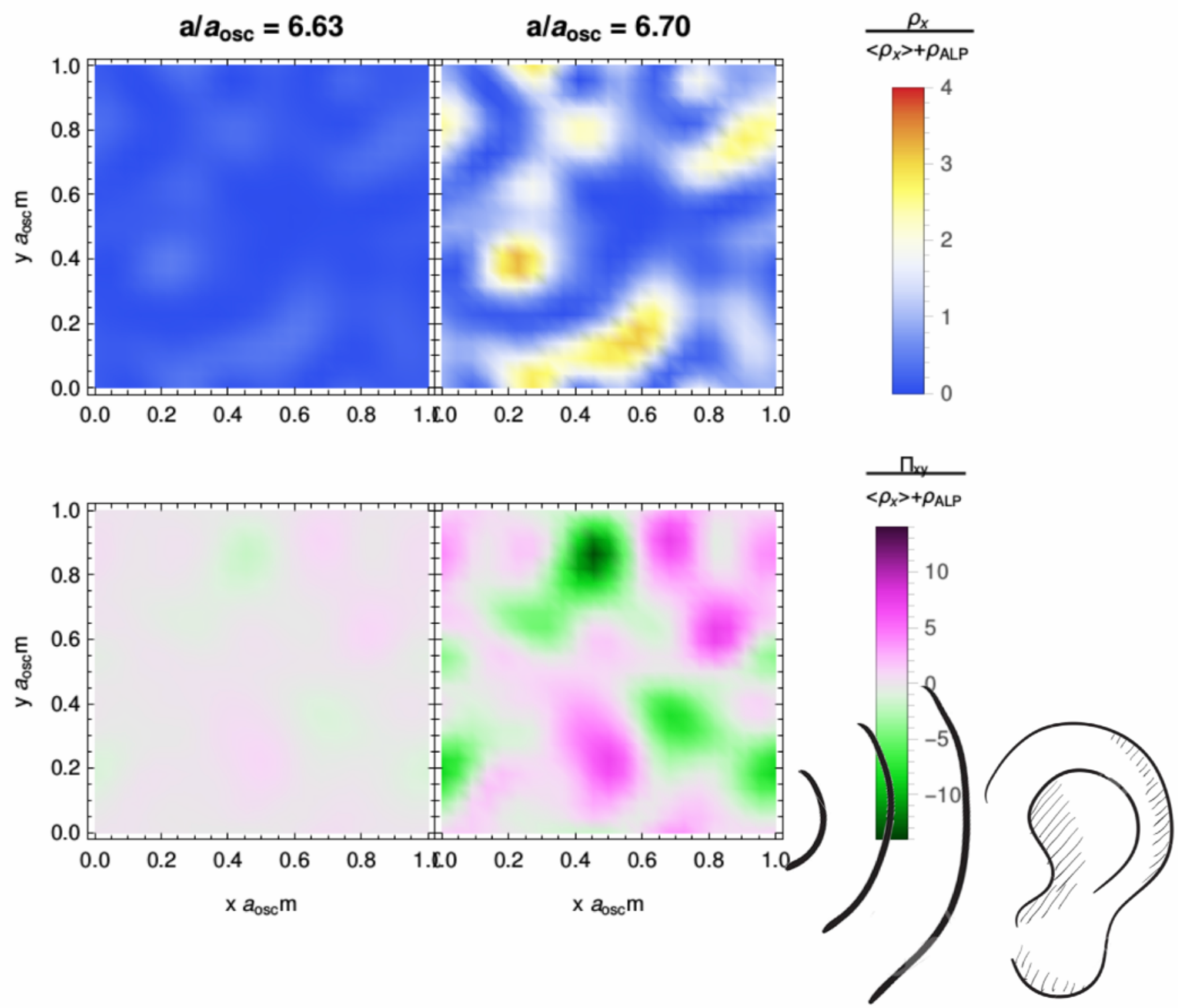


Machado, Ratzinger, Stefanek, PS, 1811.01950

GW production

Energy Density of Dark Photon

Anisotropic Stress



Gravity Waves →

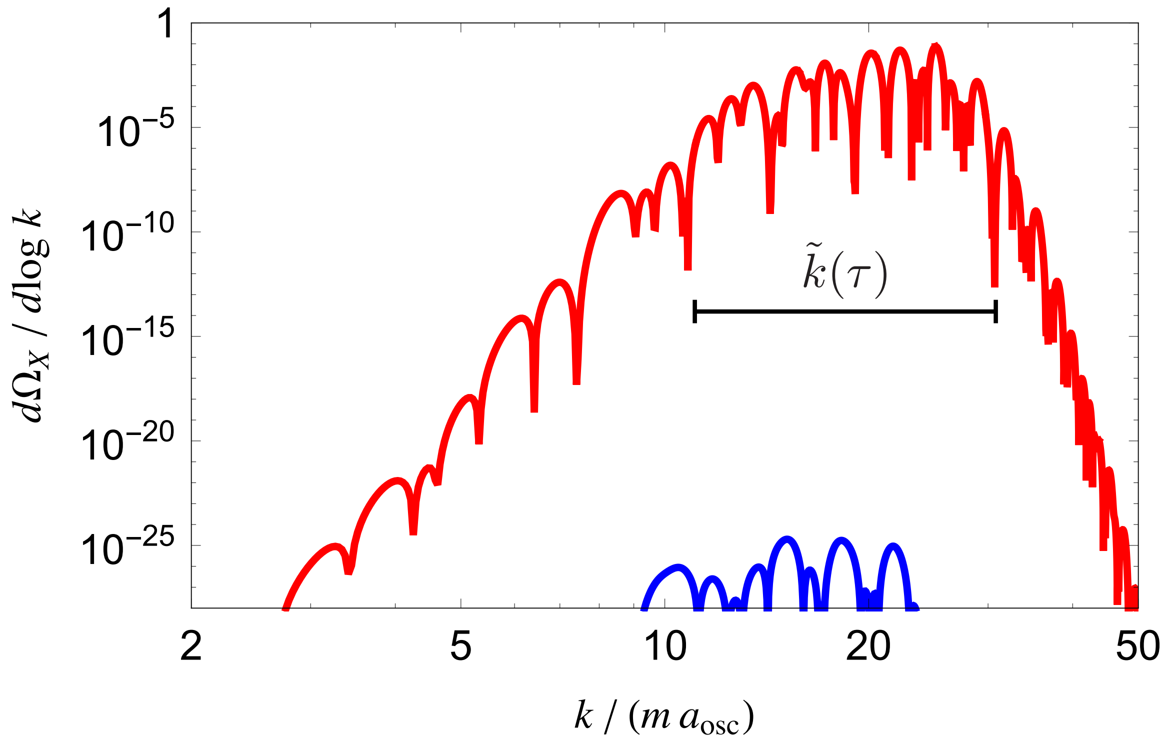
$$h''_{ij}(\mathbf{k},\tau) + k^2 h_{ij}(\mathbf{k},\tau) = \frac{2}{M_P^2}\Pi_{ij}(\mathbf{k},\tau)\,,$$

Anisotropic stress

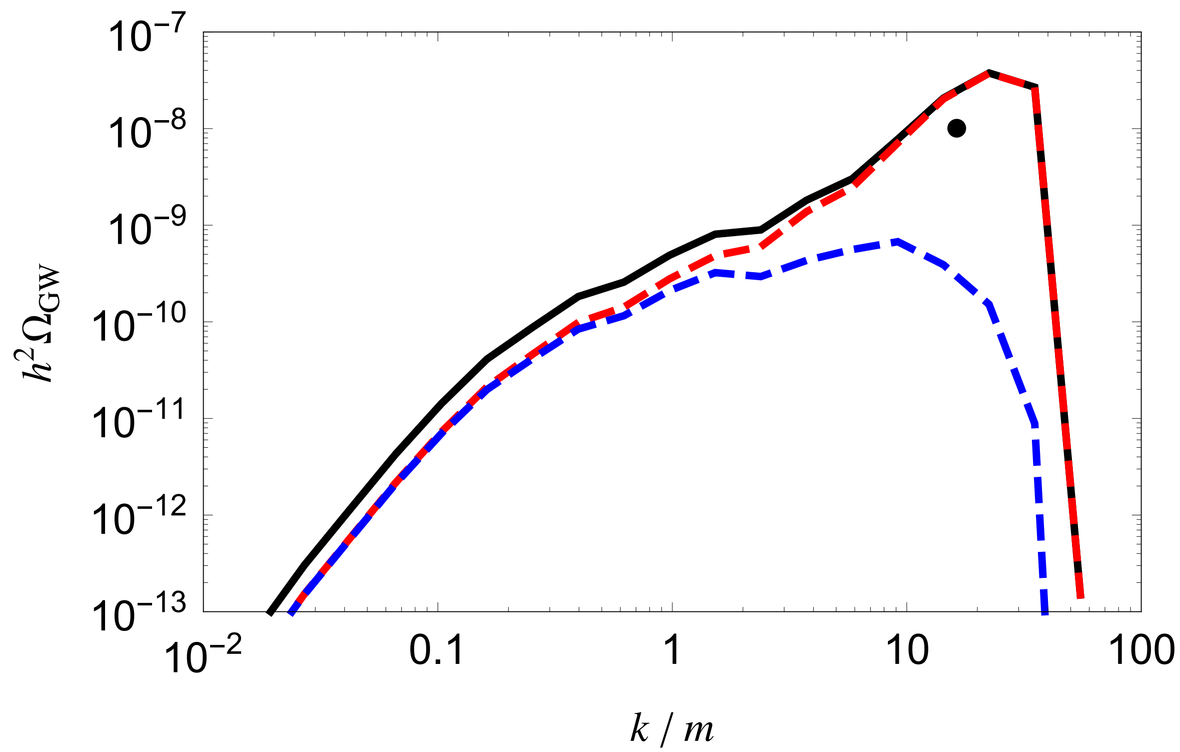
$$\hat{\Pi}_{ij}(\mathbf{k},\tau) = \frac{\Lambda_{ij}^{kl}}{a^2}\int\frac{d^3q}{(2\pi)^3}\left[\hat{E}_k(\mathbf{q},\tau)\hat{E}_l(\mathbf{k}-\mathbf{q},\tau) + \hat{B}_k(\mathbf{q},\tau)\hat{B}_l(\mathbf{k}-\mathbf{q},\tau)\right].$$

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

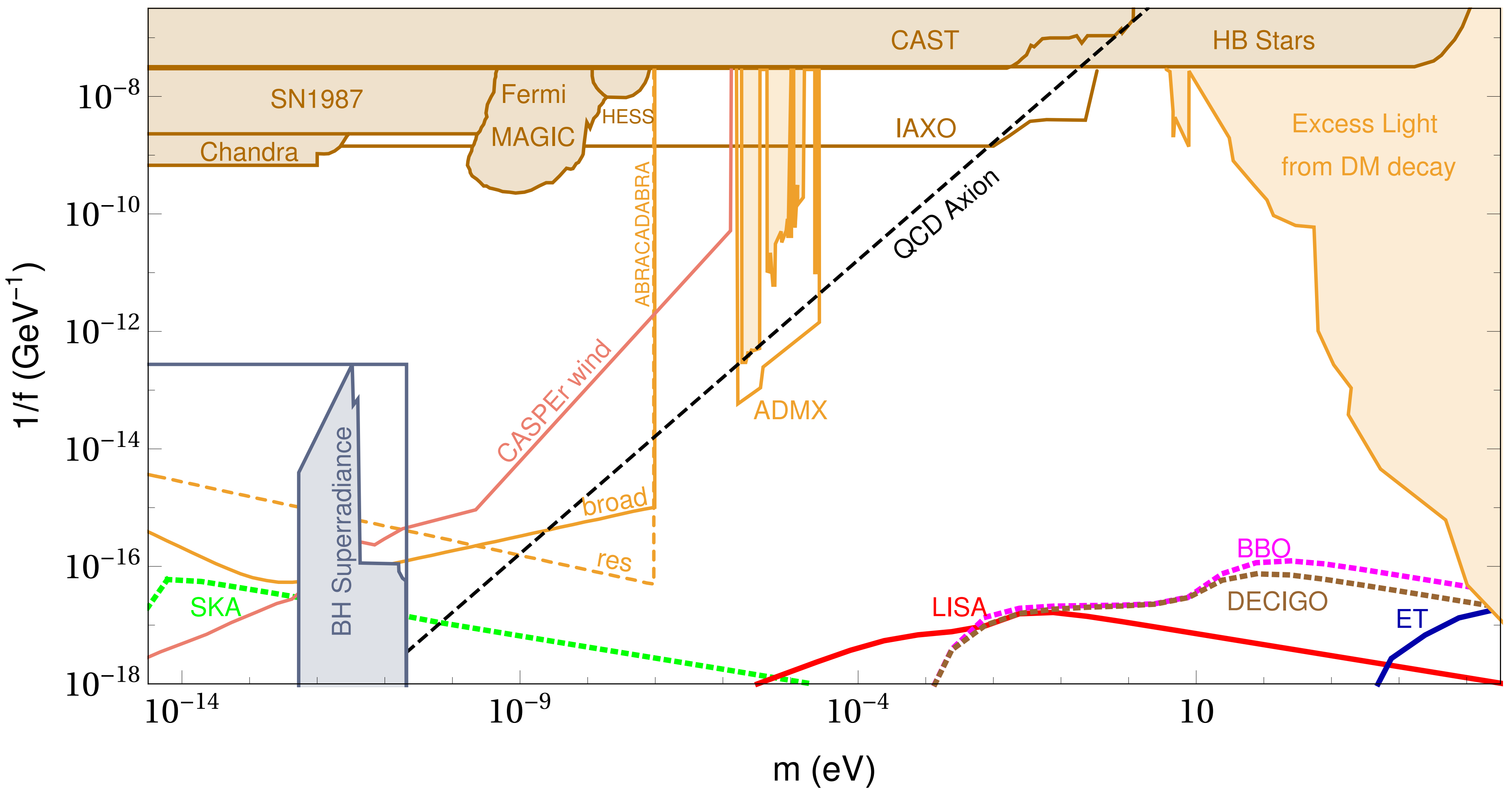


GW spectrum

Machado, Ratzinger, Stefanek, PS, 1811.01950

GW probes of audible ALPs

Machado, Ratzinger, Stefanek, PS, 1912.01107

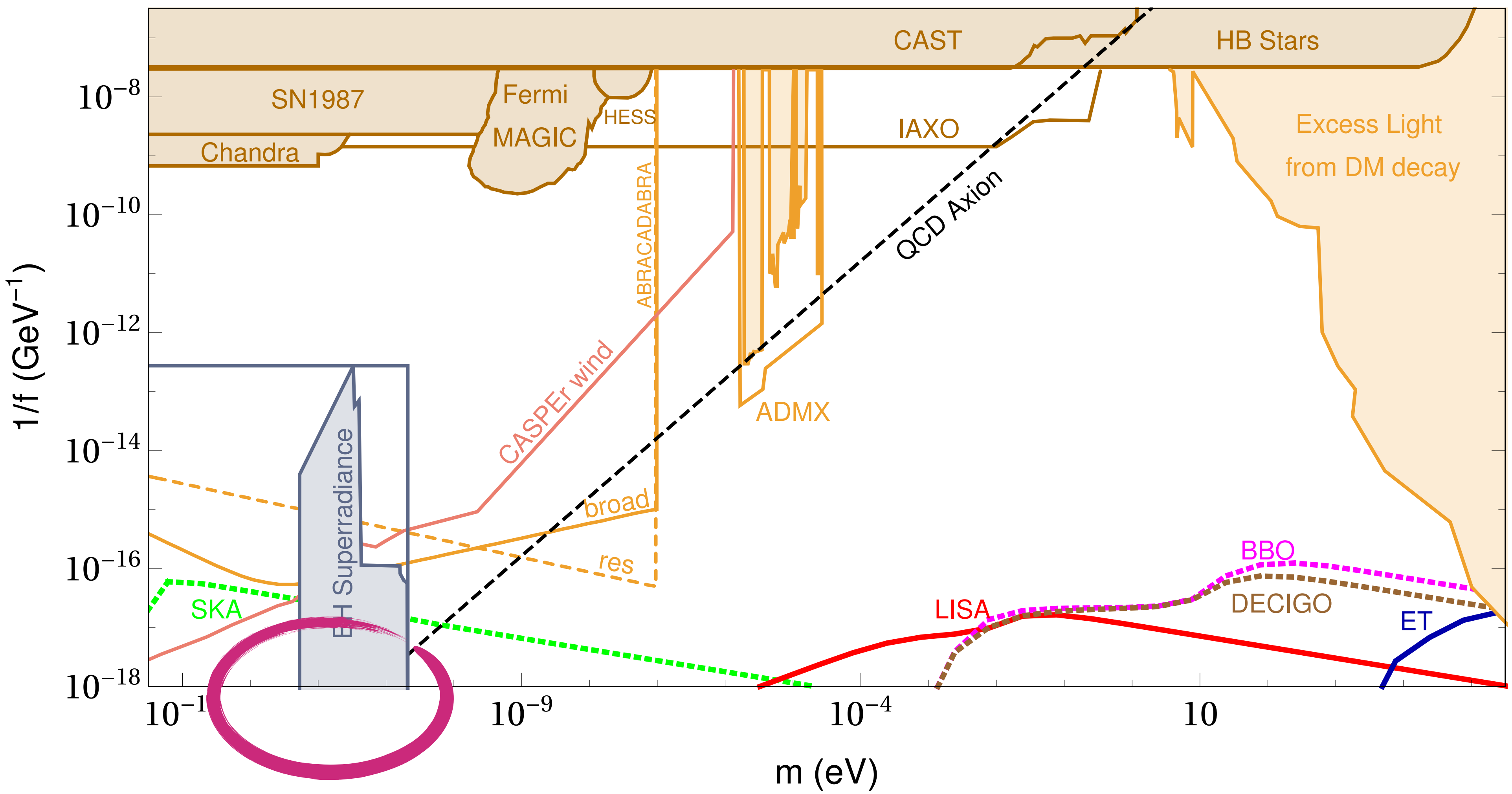


Mainly sensitive to high scale ALPs, since

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

GW probes of audible ALPs

Machado, Ratzinger, Stefanek, PS, 1912.01107

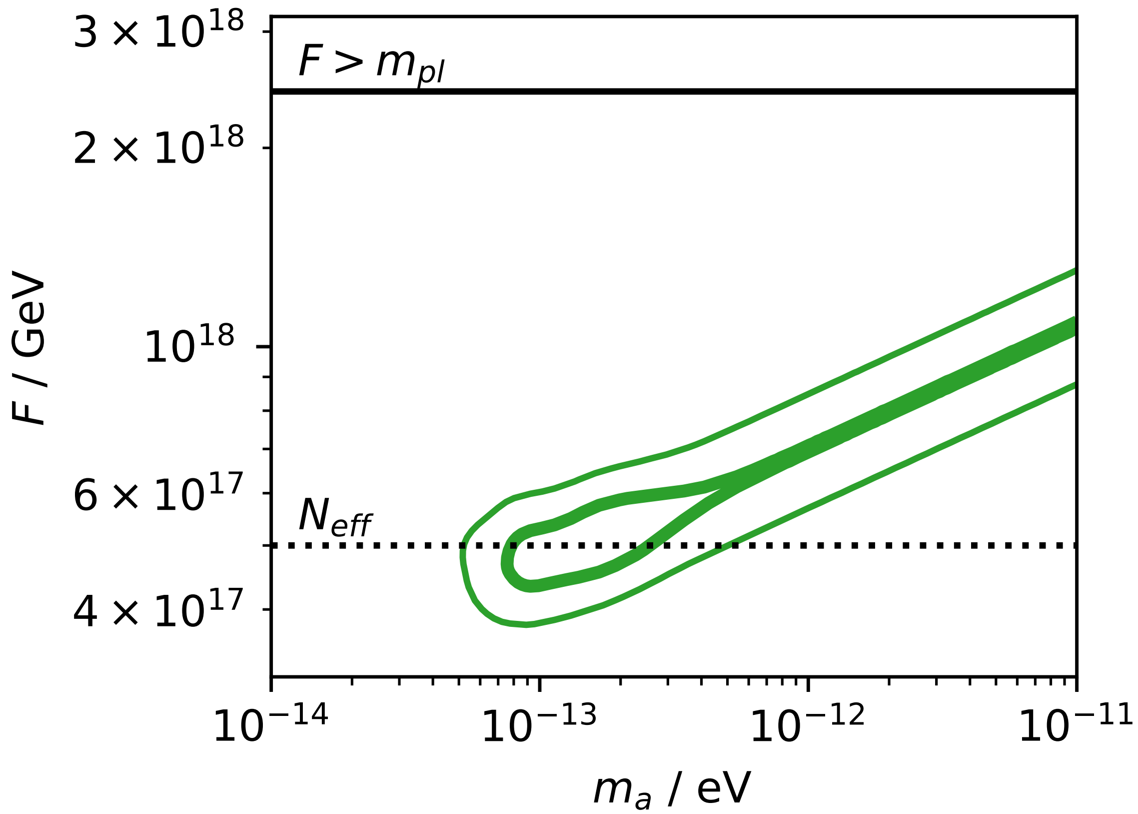


PTA region

Did PTAs hear the audible axion?

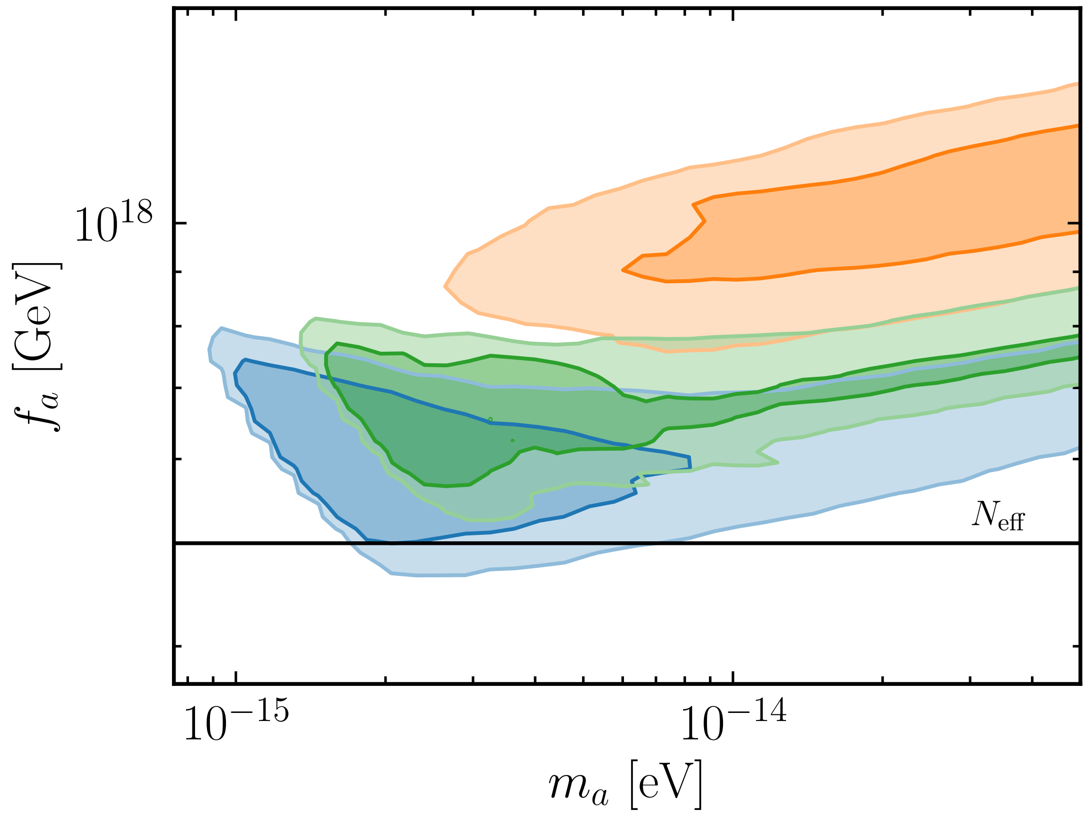
2020: Maybe

Wolfram Ratzinger & PS, 2009.11875



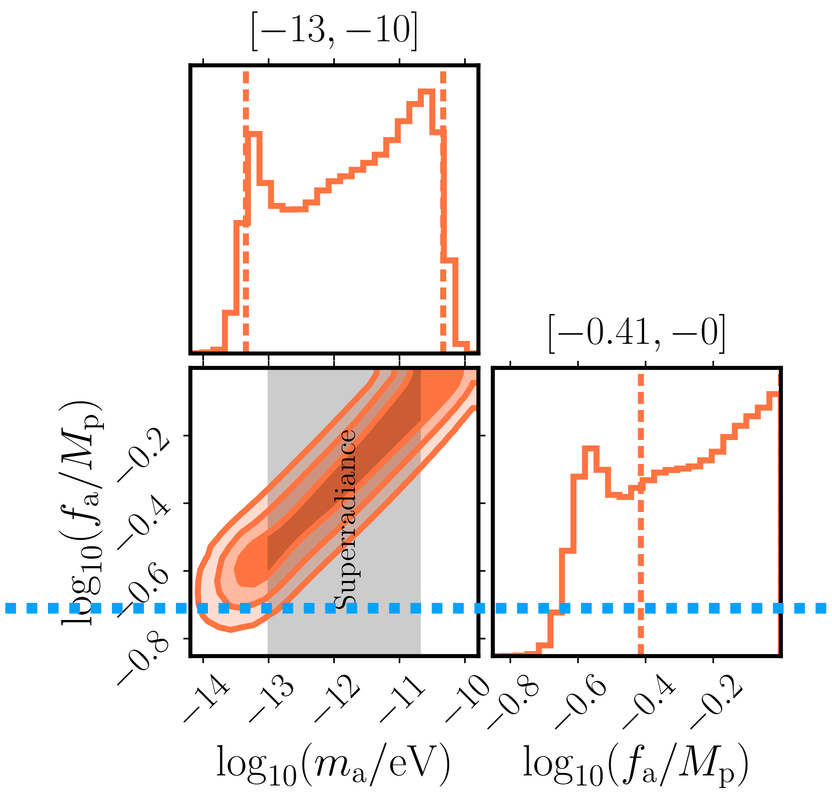
2023:

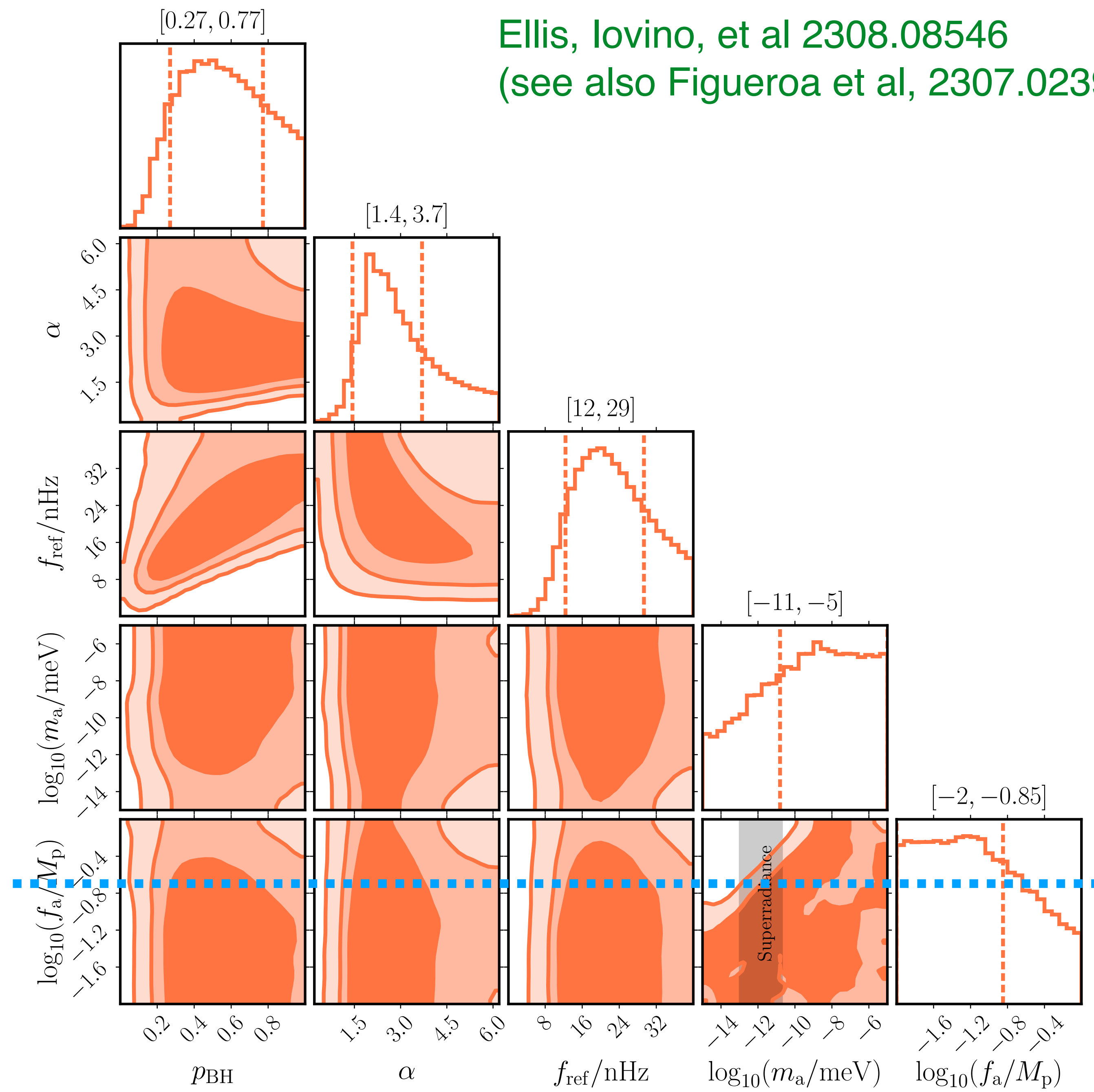
- Barely consistent with $N_{\rm eff}$
- Not all of signal from AA
- OK since we also expect an astrophysical contribution



Madge et al, 2306.14856

Fits including SMBHB (from 2308.08546)





Ellis, Iovino, et al 2308.08546
(see also Figueroa et al, 2307.02399)

Fit moves to lower f_a

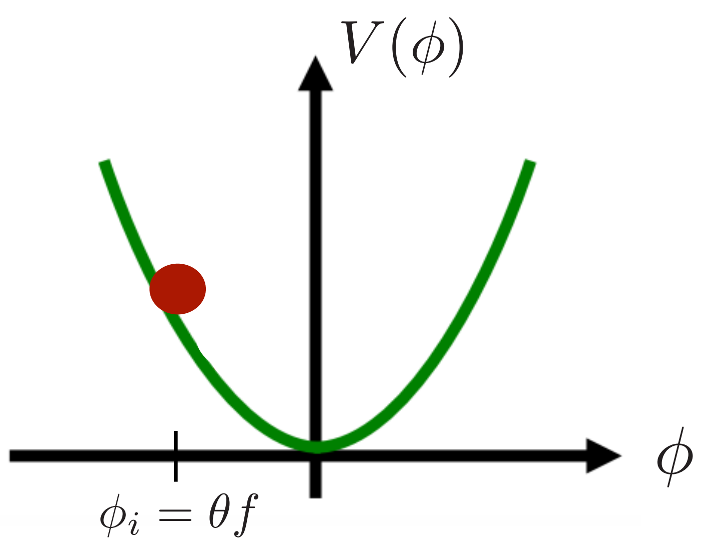
Consistent with $N_{\rm eff}$

Using template w/o backreaction

ALP dynamics - once more

Equation of motion

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

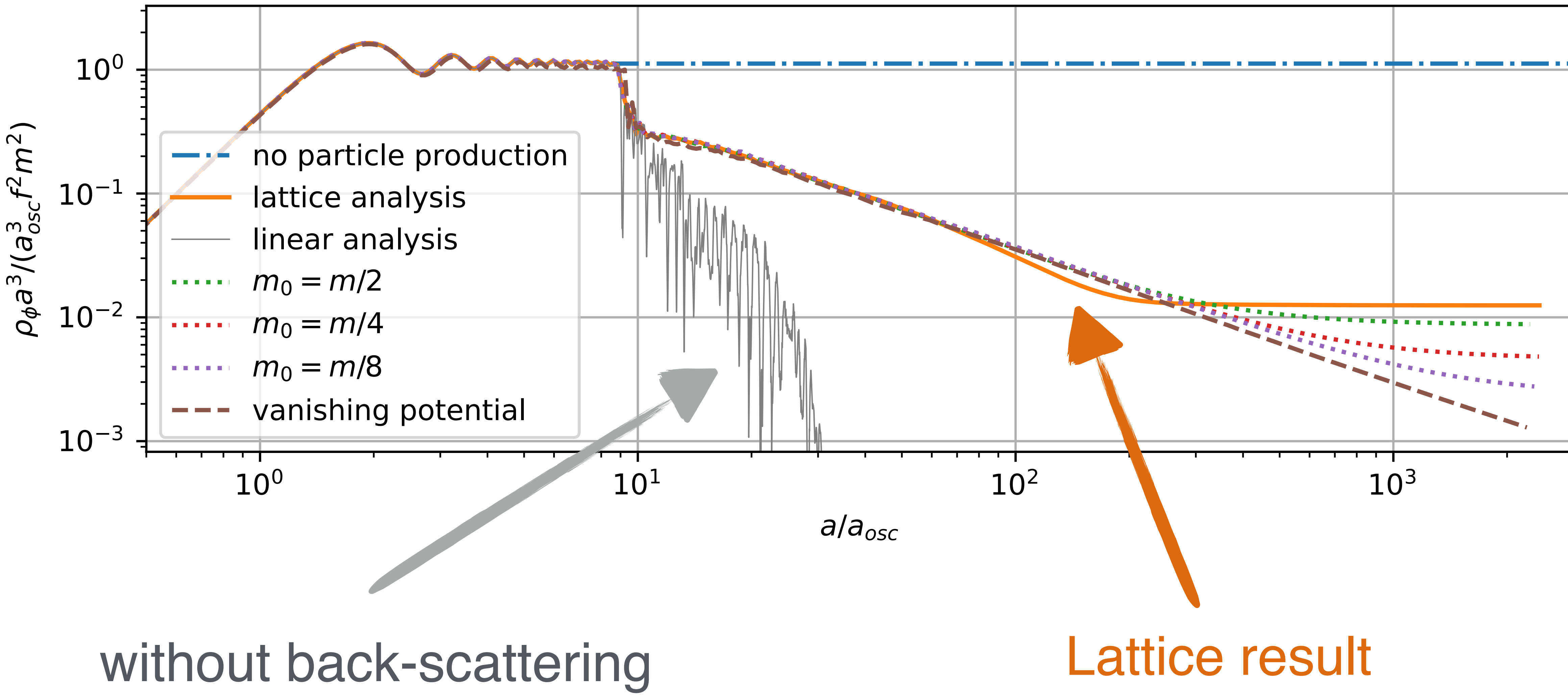


Once a significant population of dark photons is produced, the back-scattering into ALP fluctuations becomes non-negligible

Requires fully numerical treatment on the lattice

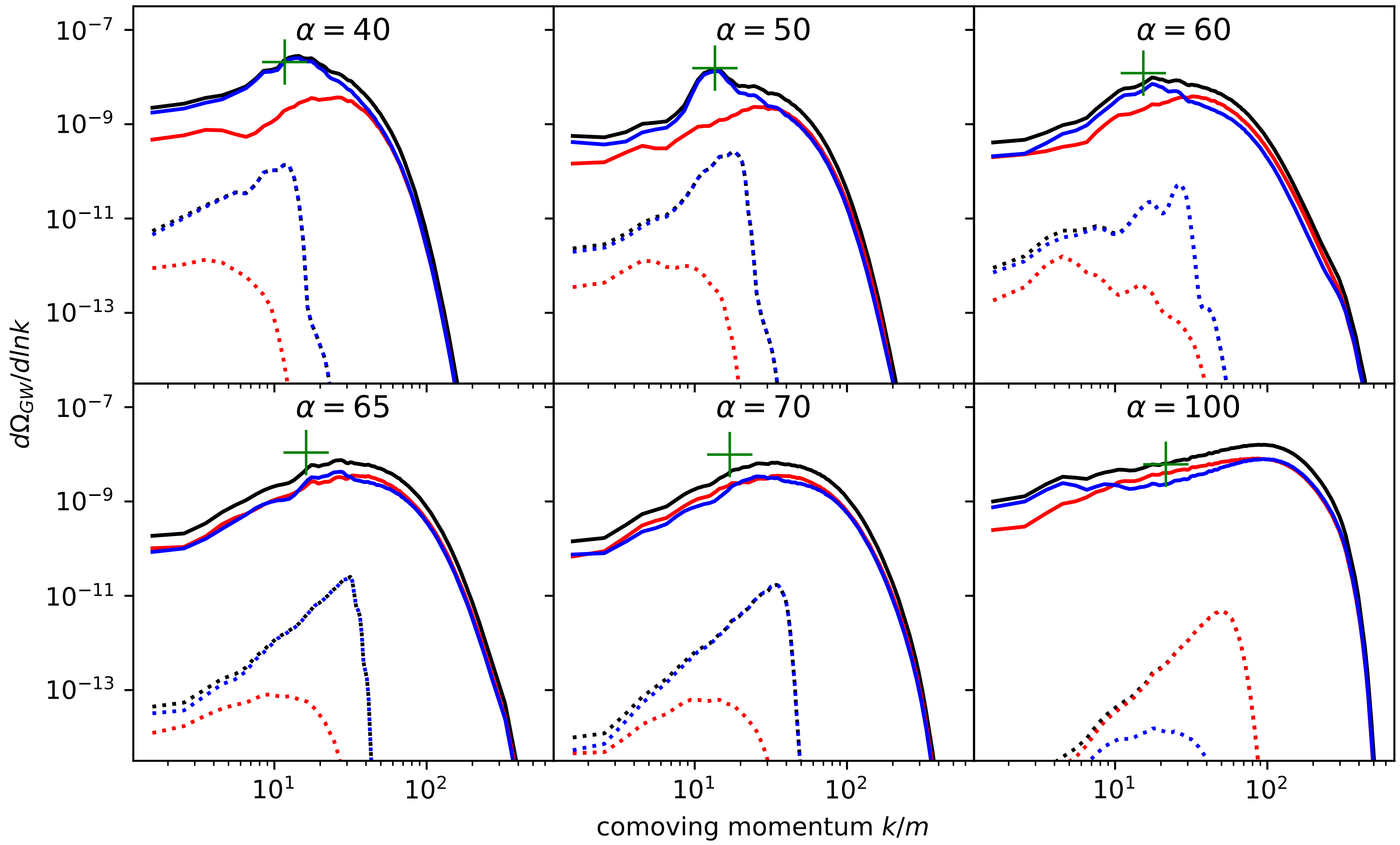
Important to get correct relic abundance prediction

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)

Notes

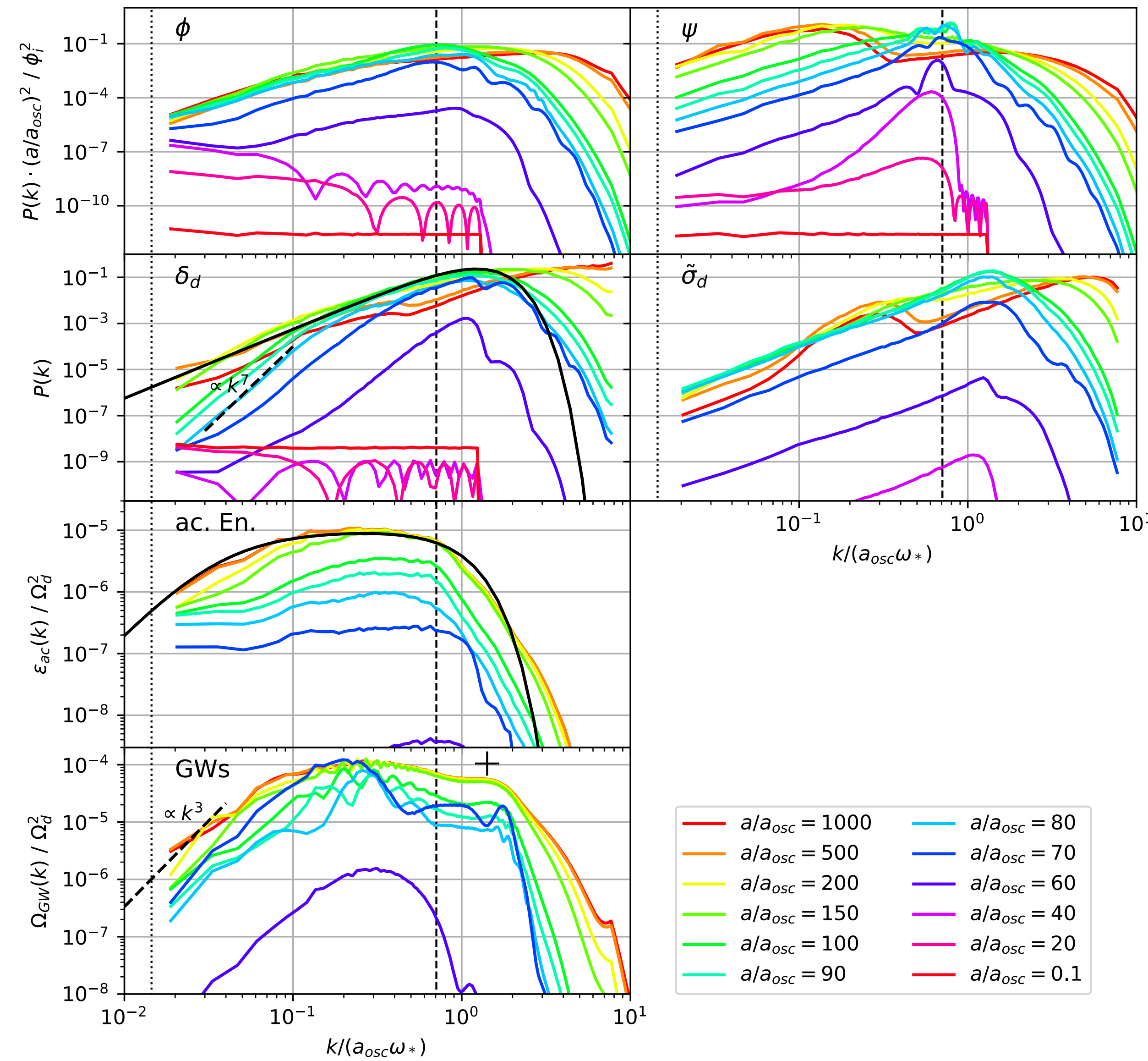
Model variations: Audible Relaxion, Axion kinetic misalignment (see extra slides)

Also works for:

- Scalar dark sectors, e.g.

$$V(\phi,\psi) = \frac{1}{4}\lambda\phi^4 + \frac{1}{2}g^2\phi^2\psi^2$$

Ramberg, Ratzinger & PS, 2209.14313
see also Cui et al, 2310.13060



- single field models (e.g. axion fragmentation)

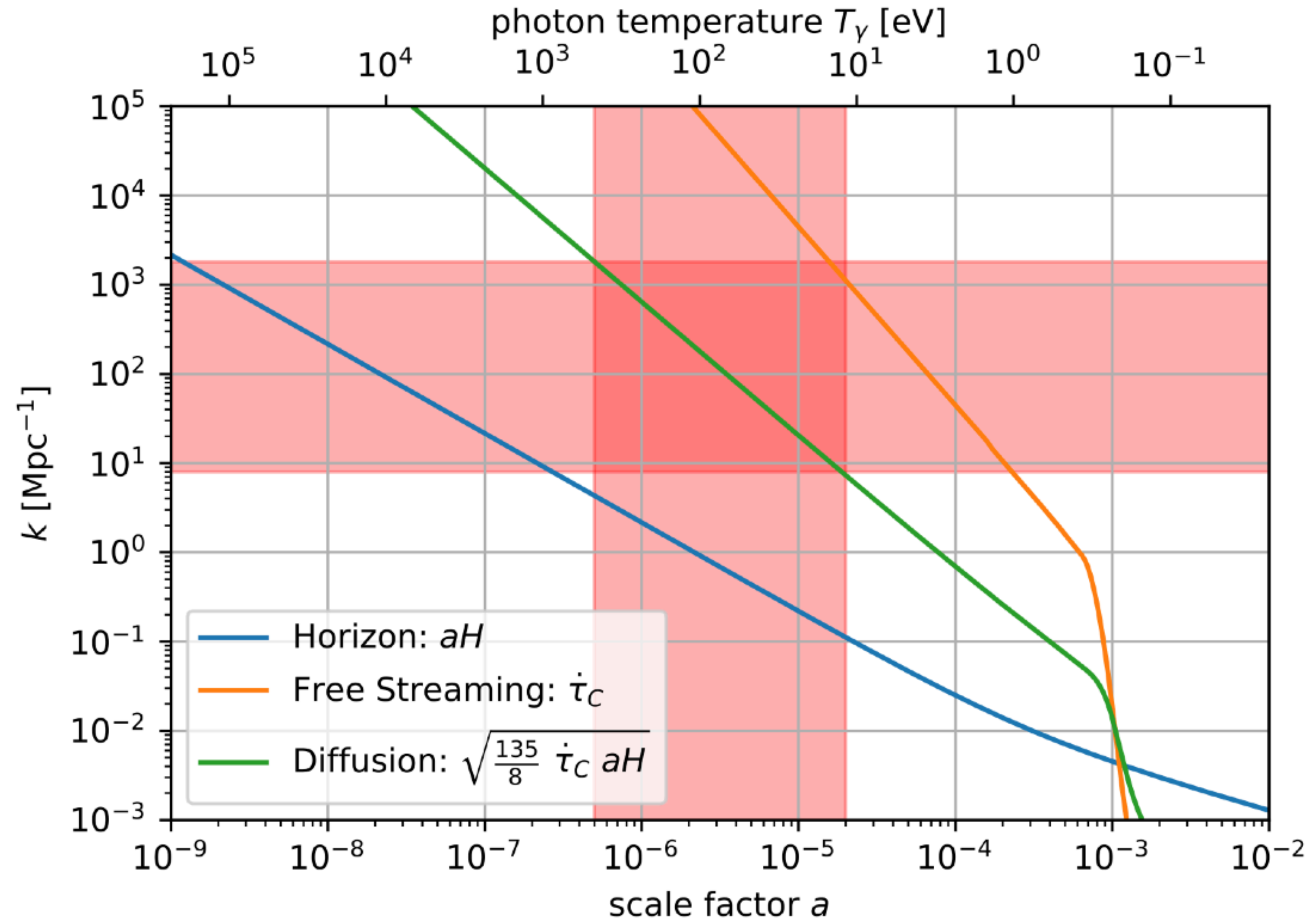
see e.g. Chatrchyan, Jaeckel, 2004.07844, Fonseca, Morgante, Sato, Servant, 1911.08472, …

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 from dark sector anisotropies

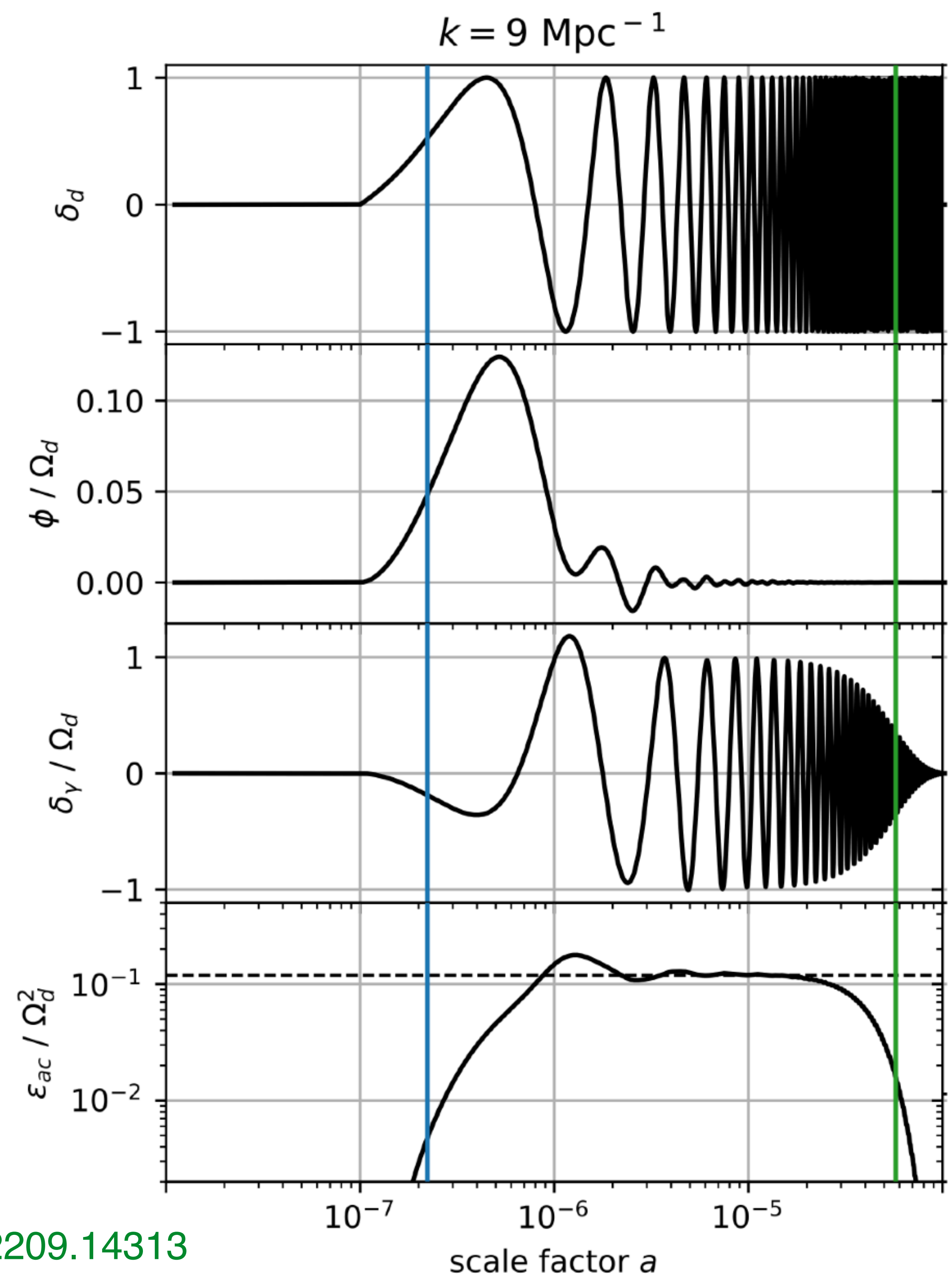
Assume decoupled dark sector, $\Omega_d \ll 1$

Large fluctuations $\delta_d = \delta\rho_d/\rho_d \sim 1$

- Gravitationally induced sound waves in photons $\epsilon_{\rm ac}$

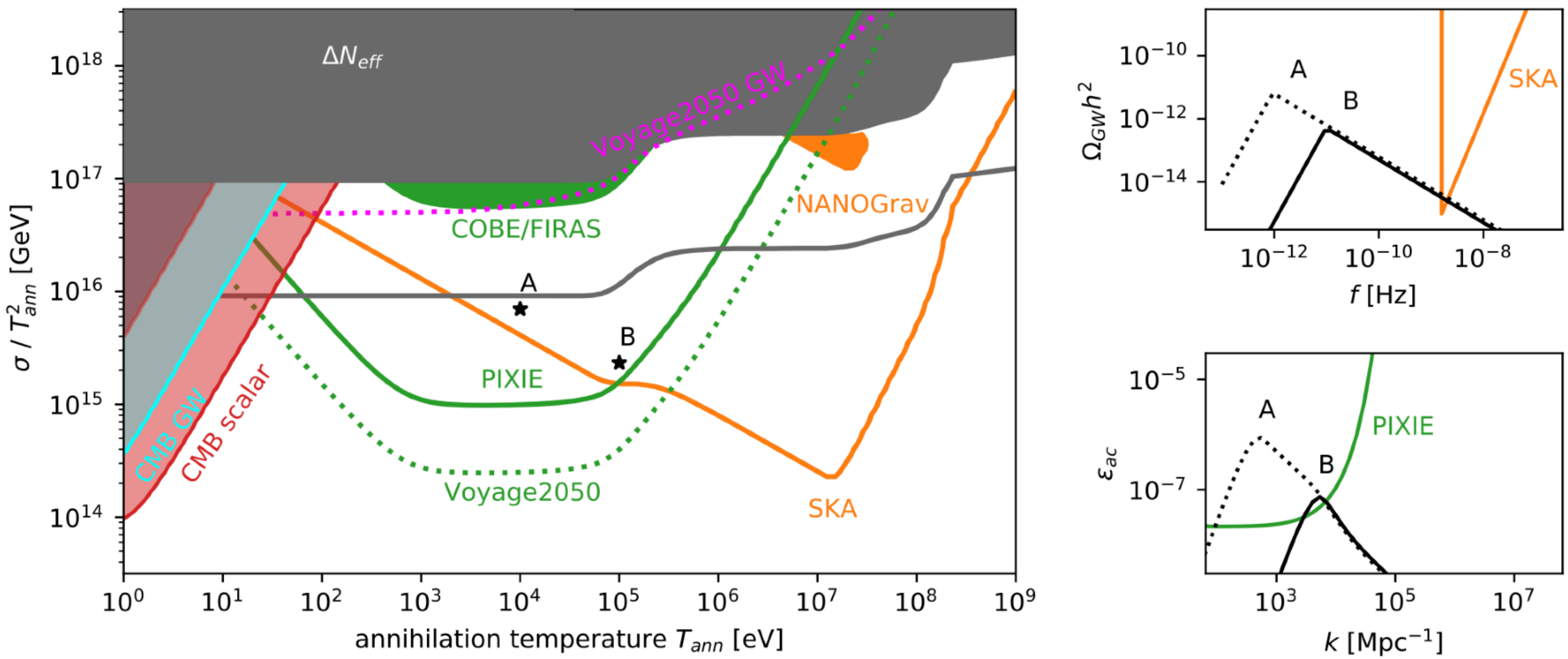
Resulting μ distortions

$$\mu = \int d\log k \; \epsilon_{ac}^{\lim}(k)\mathcal{W}(k),$$



Ramberg, Ratzinger & PS, 2209.14313

Example source: Annihilating domain walls



Already probes allowed parameter space

Complementary to GW probes, can break degeneracy

- For all low scale sources (PTs, strings, AA,...)

Ramberg, Ratzinger & PS, 2209.14313

Axion/ALP domain walls

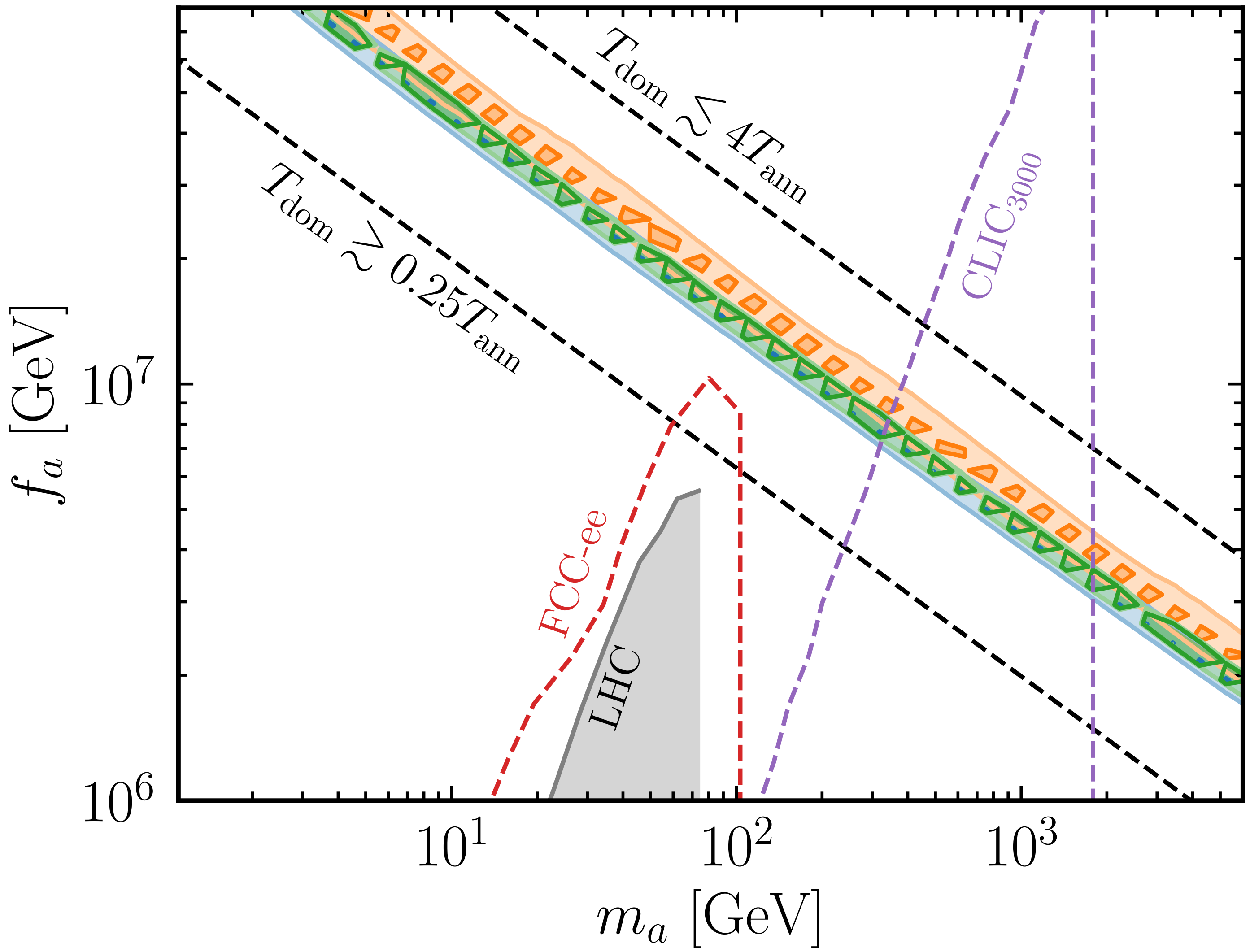
Madge et al, 2306.14856

Concrete model: Aligned/clockwork Axions Higaki et al, 1606.05552

Heavy axion "partners" at weak scale

In reach of future colliders Bauer et al, 1808.10323

Visible, no spectral distortions



Invisibly decaying DWs

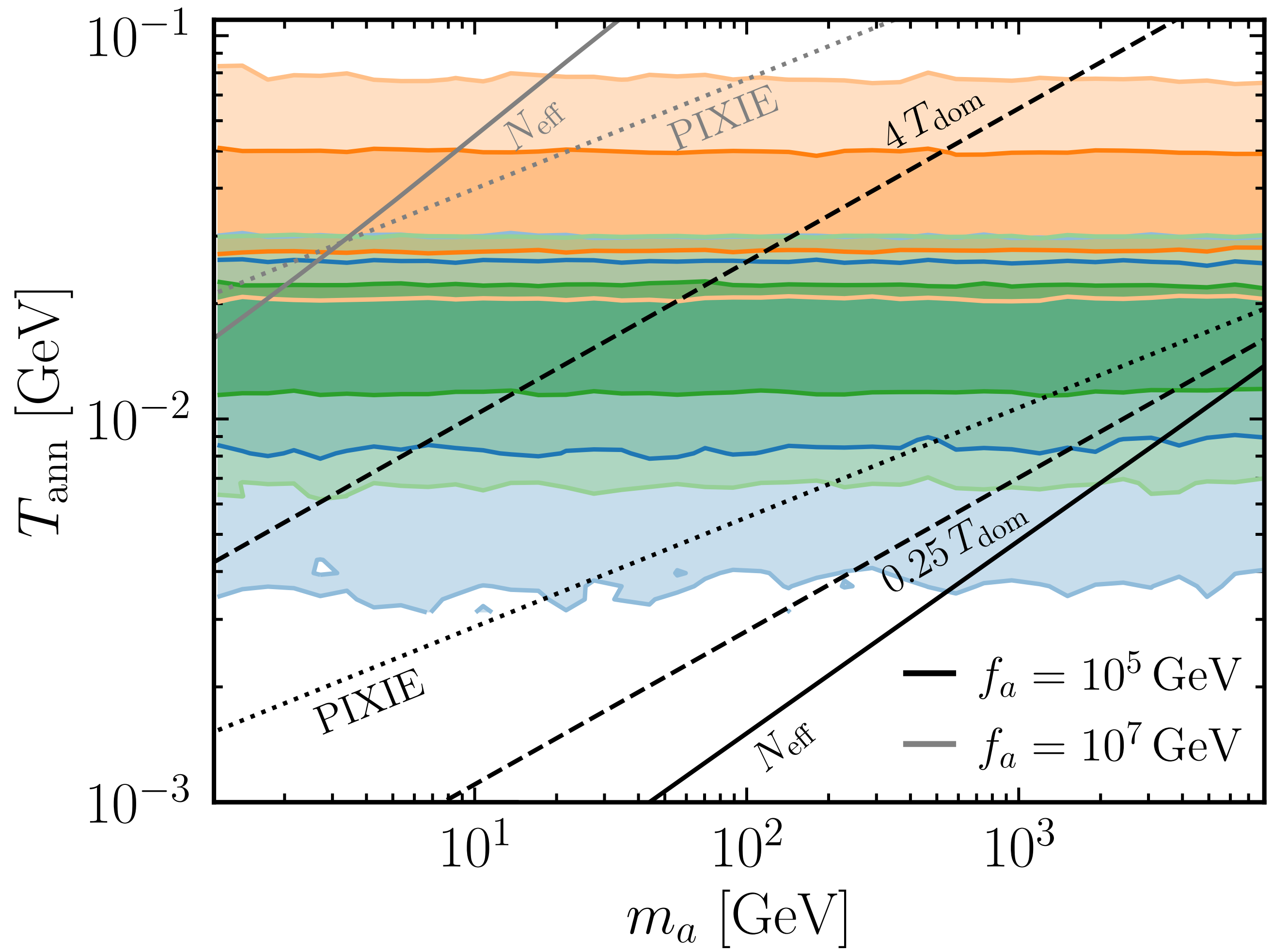
Madge et al, 2306.14856

DWs annihilate to dark radiation

- N_{eff} ok mostly

Dark sector anisotropies induce CMB spectral distortions

- In reach of future experiments (PIXIE)



Also: PBH formation (Y. Gouttenoire 2023)

One more: Primordial black holes

Depta et al, 2306.17836

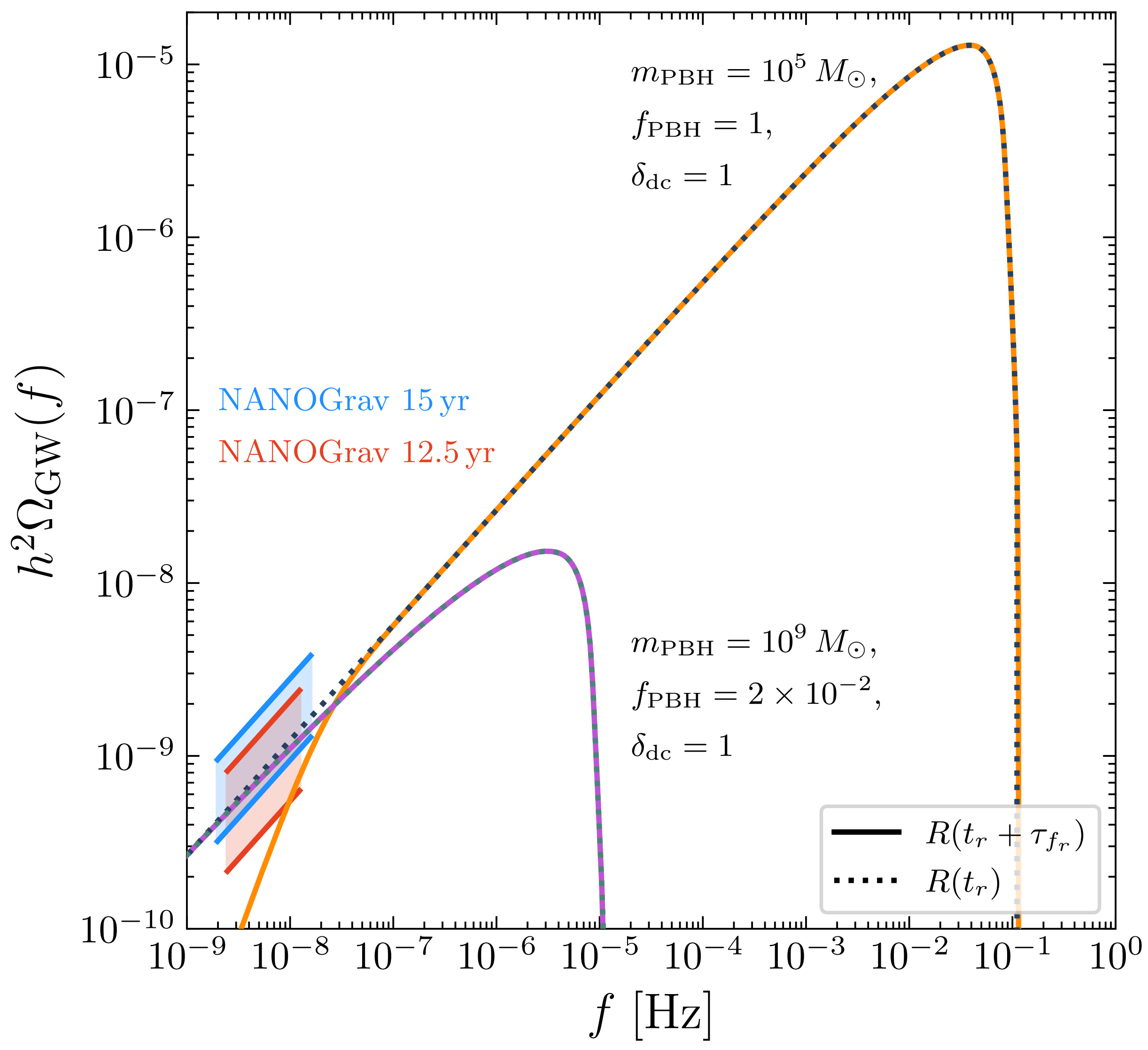
Binaries of supermassive PBH produce a stochastic GWB

Parameters:

- Mass m_{PBH}
- DM fraction f_{PBH}
- Clustering δ_c

Approximations:

- Circular orbits, monochromatic mass distribution, no environmental effects



PBH: No clustering

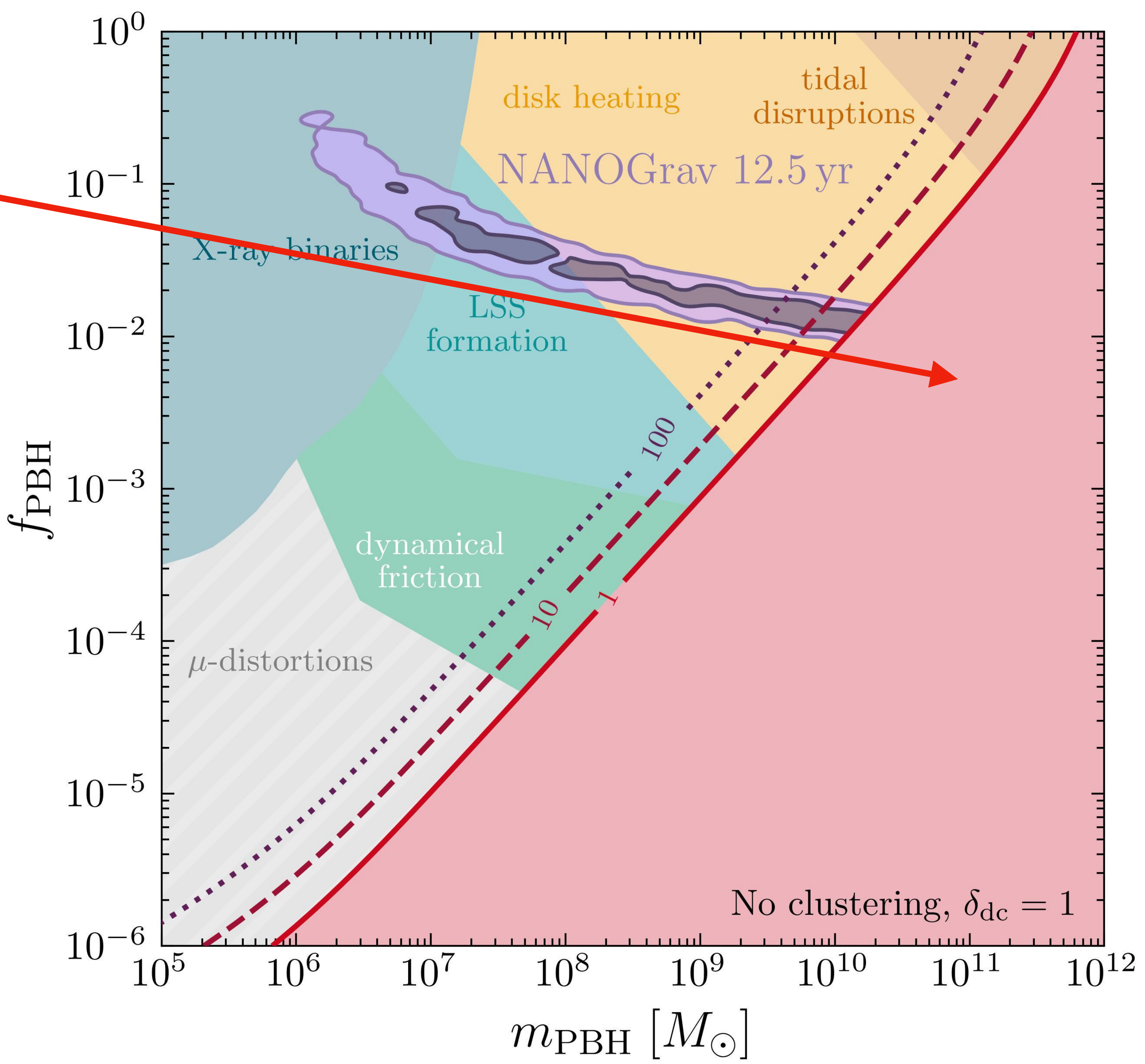
Depta et al, 2306.17836

Viable region at very large masses

already pointed out by Atal, Sanglas, Triantafyllou, 2012.14721

However: Fewer than one pBH contributes to signal on average there

- Not a stochastic BG
- Not even a signal most of the time



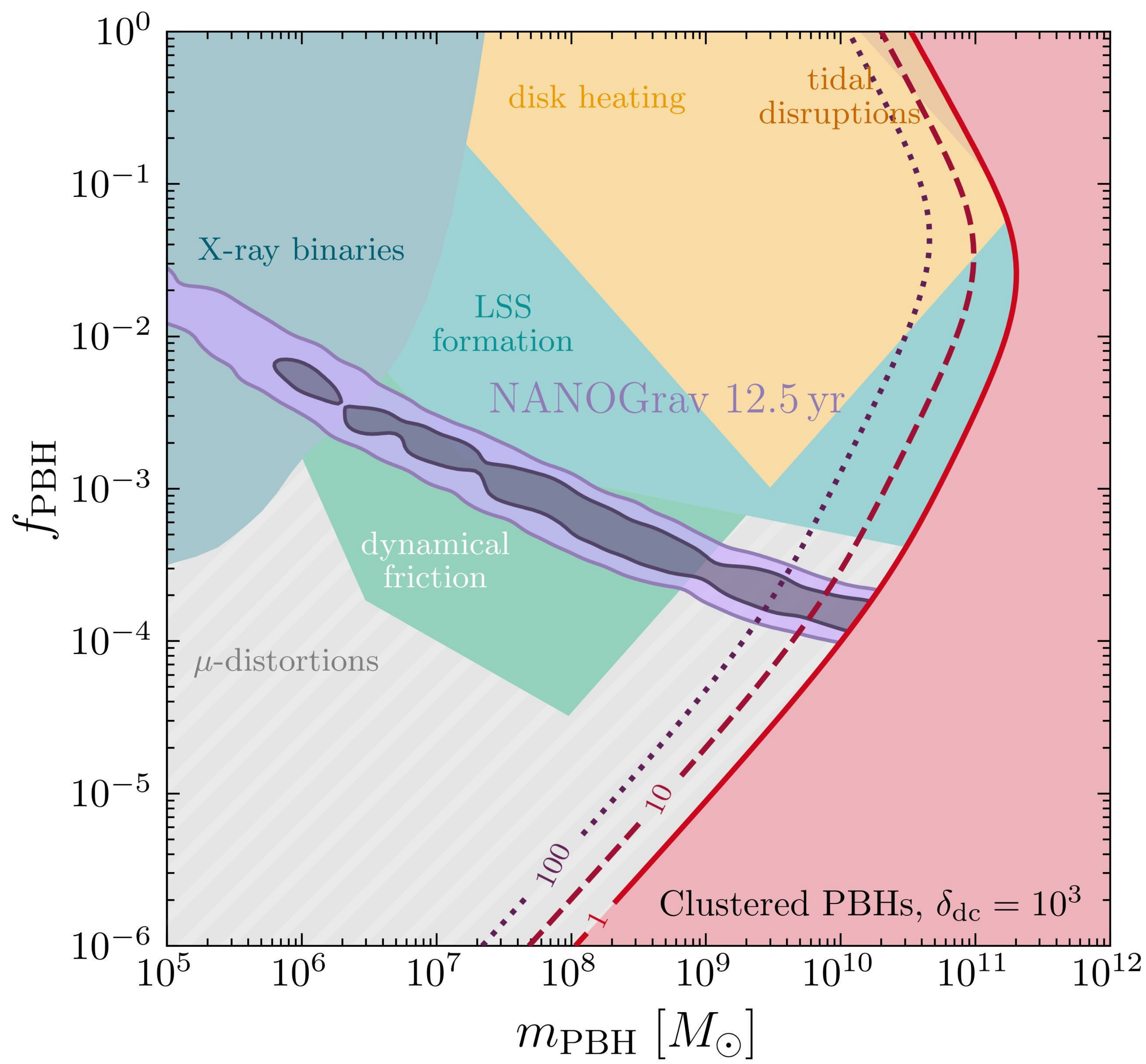
PBH: With clustering

Depta et al, 2306.17836

Now an actually viable region emerges

Assuming a suitable production mechanism

- Needs to evade mu distortion bounds
- Non-gaussian!

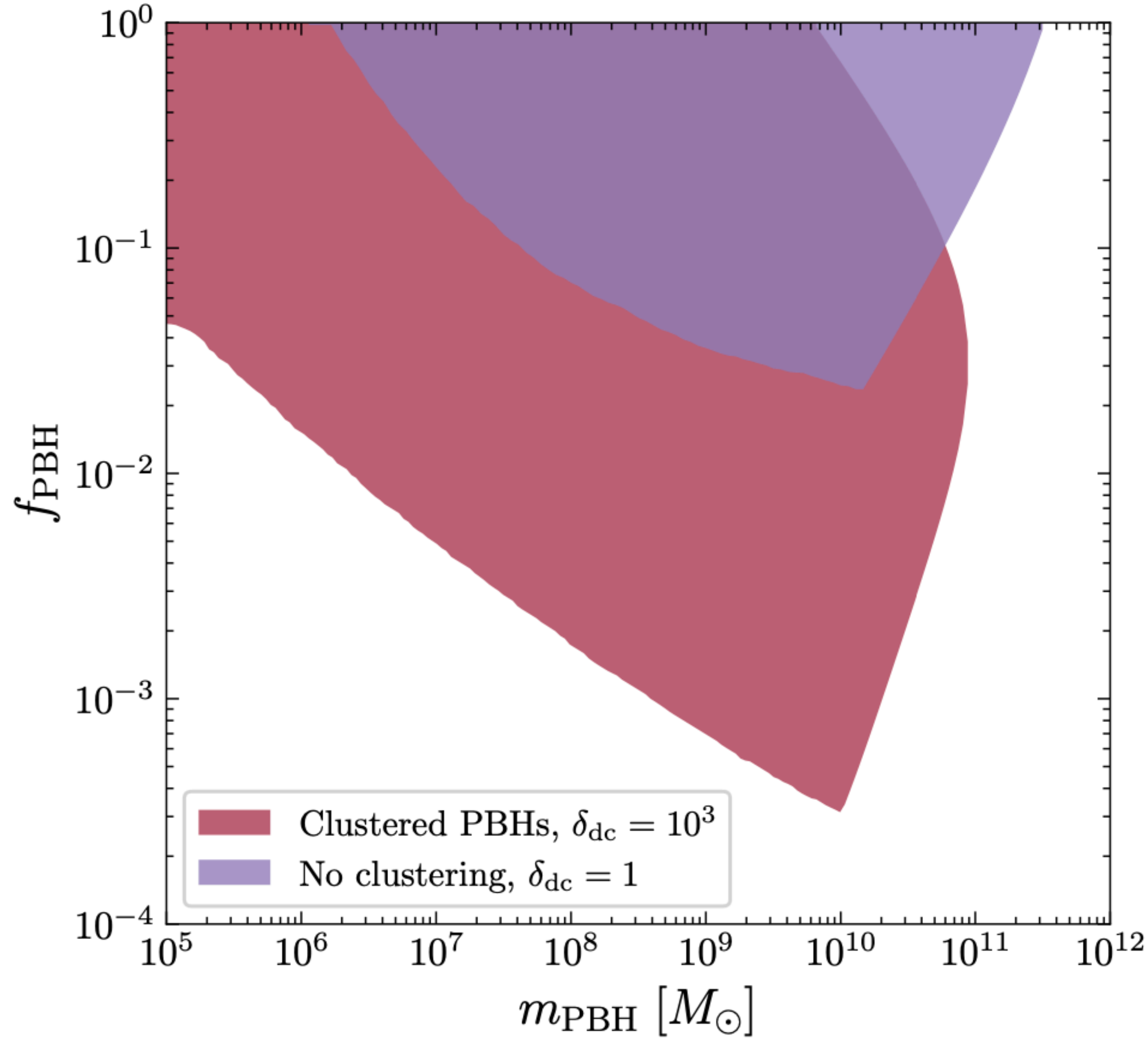


Superlarge PBH

Depta et al, 2306.17836

Less crazy: Astro-independent bounds on clustered pBH from PTAs

Expect anisotropies in GW background :)



Summary

GWs are new window to early, dark Universe

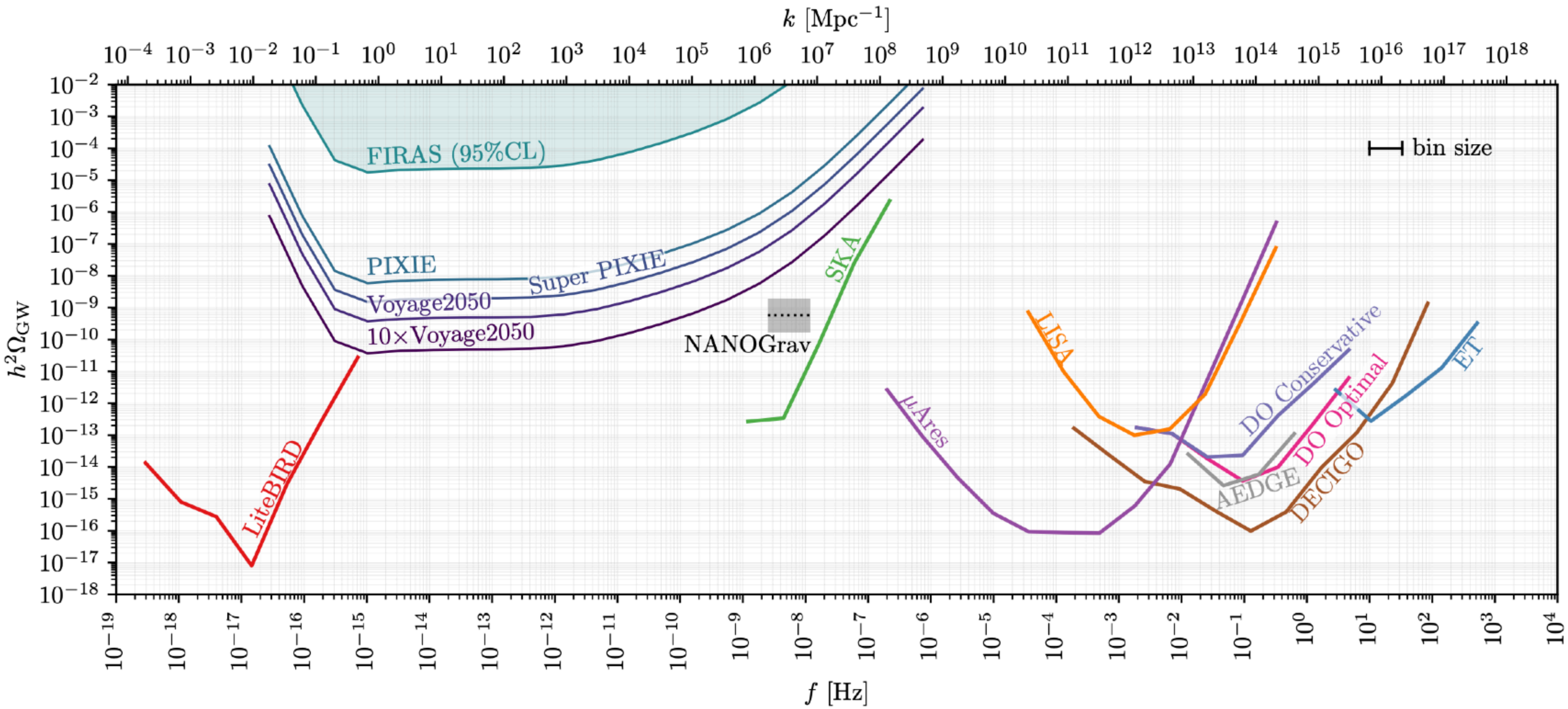
Today:

- Audible axions are cool
- Spectral distortions are cool
- Supermassive pBH are also cool, but maybe a bit crazy ;)

Many things to be done (simulations!), much data will come in the future -> Exciting times!

Extra slides :)

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)

High frequency GW searches

Higher Frequency → shorter wavelength

- Experiment may fit in your laboratory

Gravity couples to everything

- Any very sensitive device could potentially be a detector

Current interest:

- Cavities for axion searches
- Gertsenshtein effect:
  GWs convert to photons in strong magnetic field

Berlin et al, 2112.11465

Sources? Primordial BH, superradiance, or…?

E&M on curved backgrounds is confusing however

E and B fields not uniquely defined everywhere in detector, depend on chosen coordinate frame

$$E_a = F_{a0} ?$$

$$E_{\underline{a}} = \hat{e}^{\mu}_{\underline{a}} F_{\mu\nu} u^{\nu} \; !$$

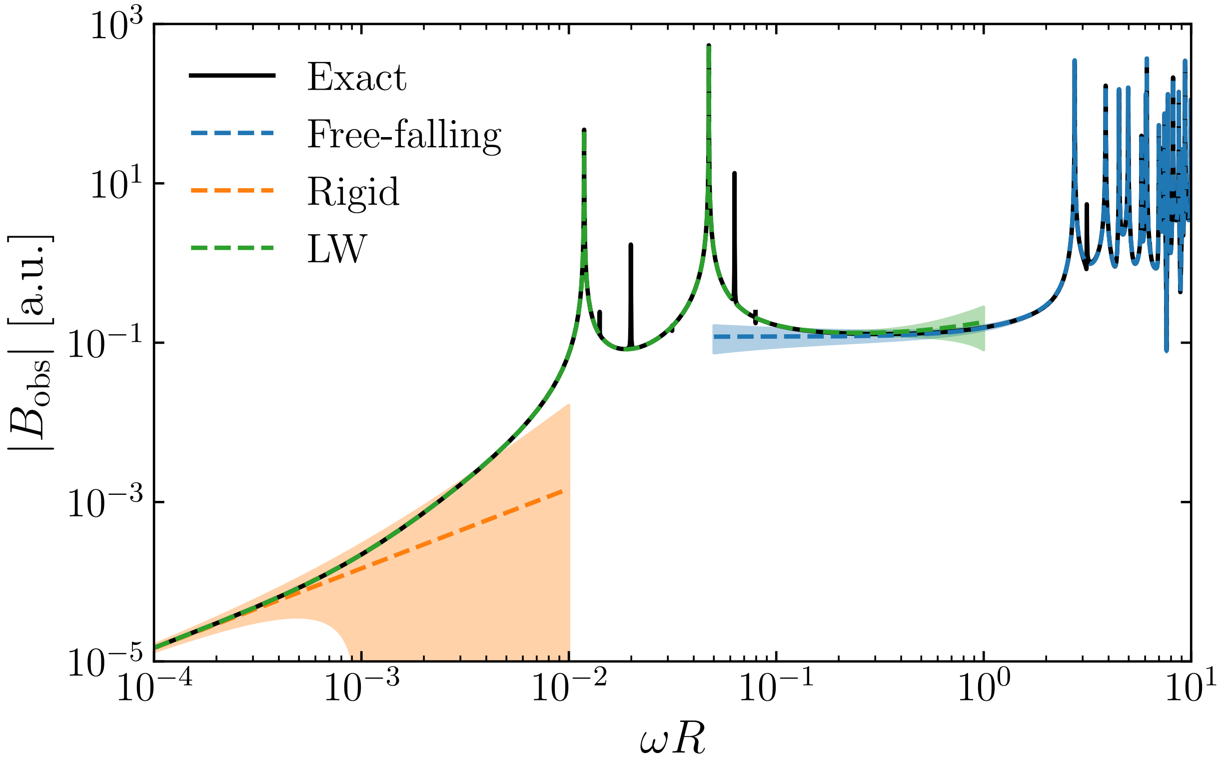
Observables should be independent!

Proposed coordinate independent perturbation scheme

Applied to:

- Thin rod
- Sphere

Including mechanical deformations



Compared with commonly used approximations → can identify range of validity and provide error estimate

Wolfram Ratzinger, Sebastian Schenk, PS, 2404.08572

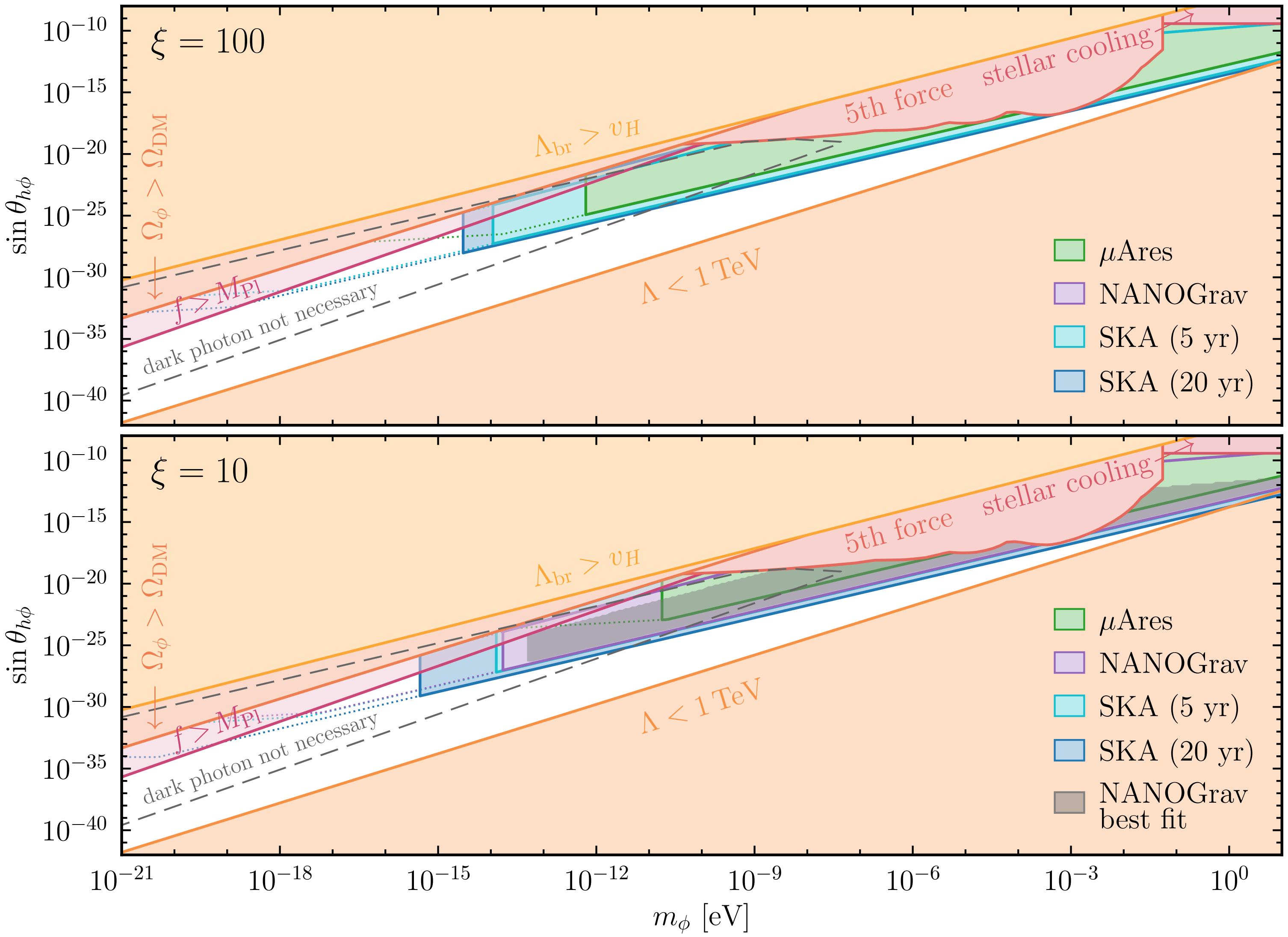
Audible relaxion

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

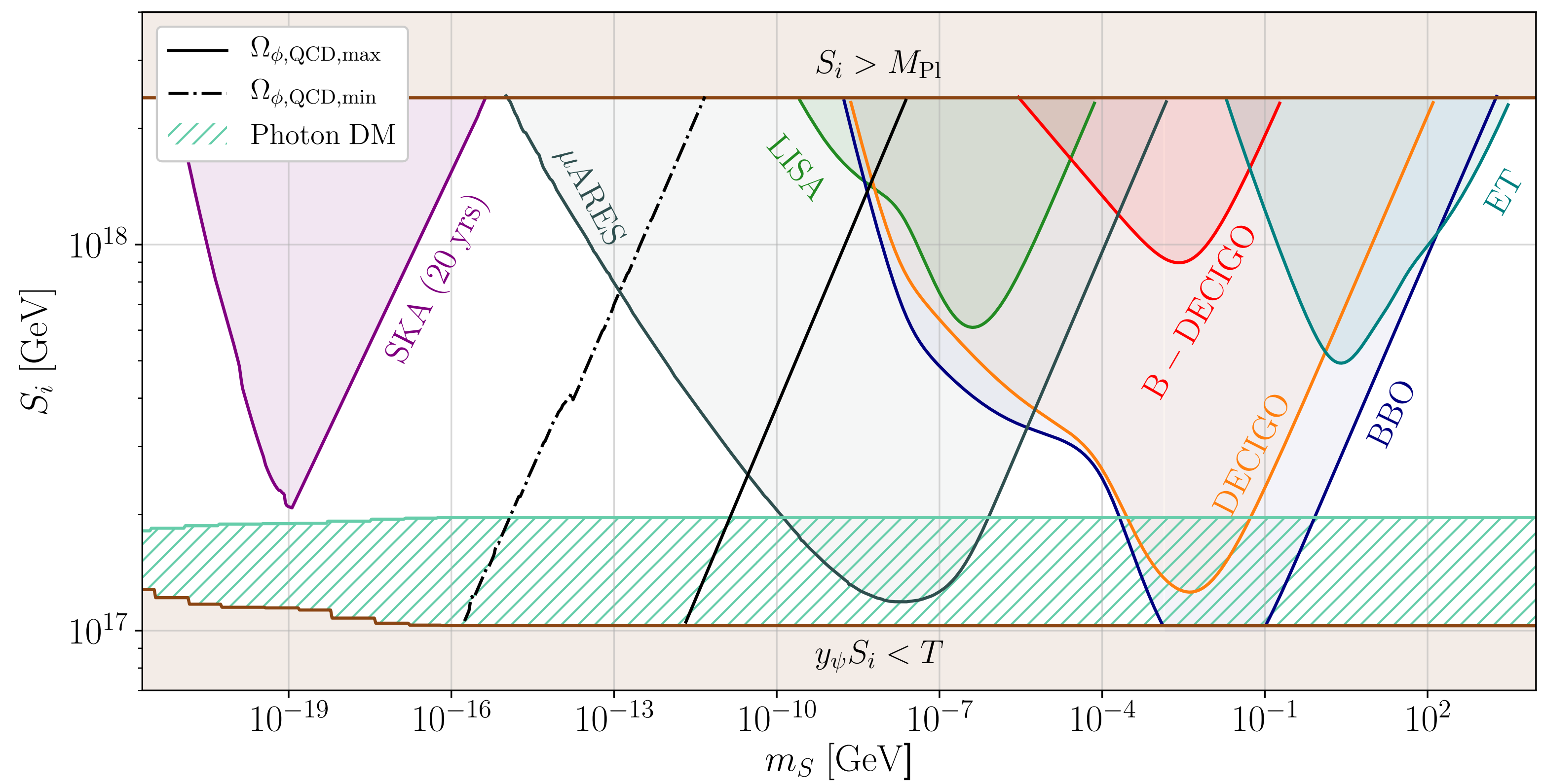
GWs from kinetic misalignment

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

Detectable signal also for smaller decay constants

Fix ALP mass to fit DM relic abundance

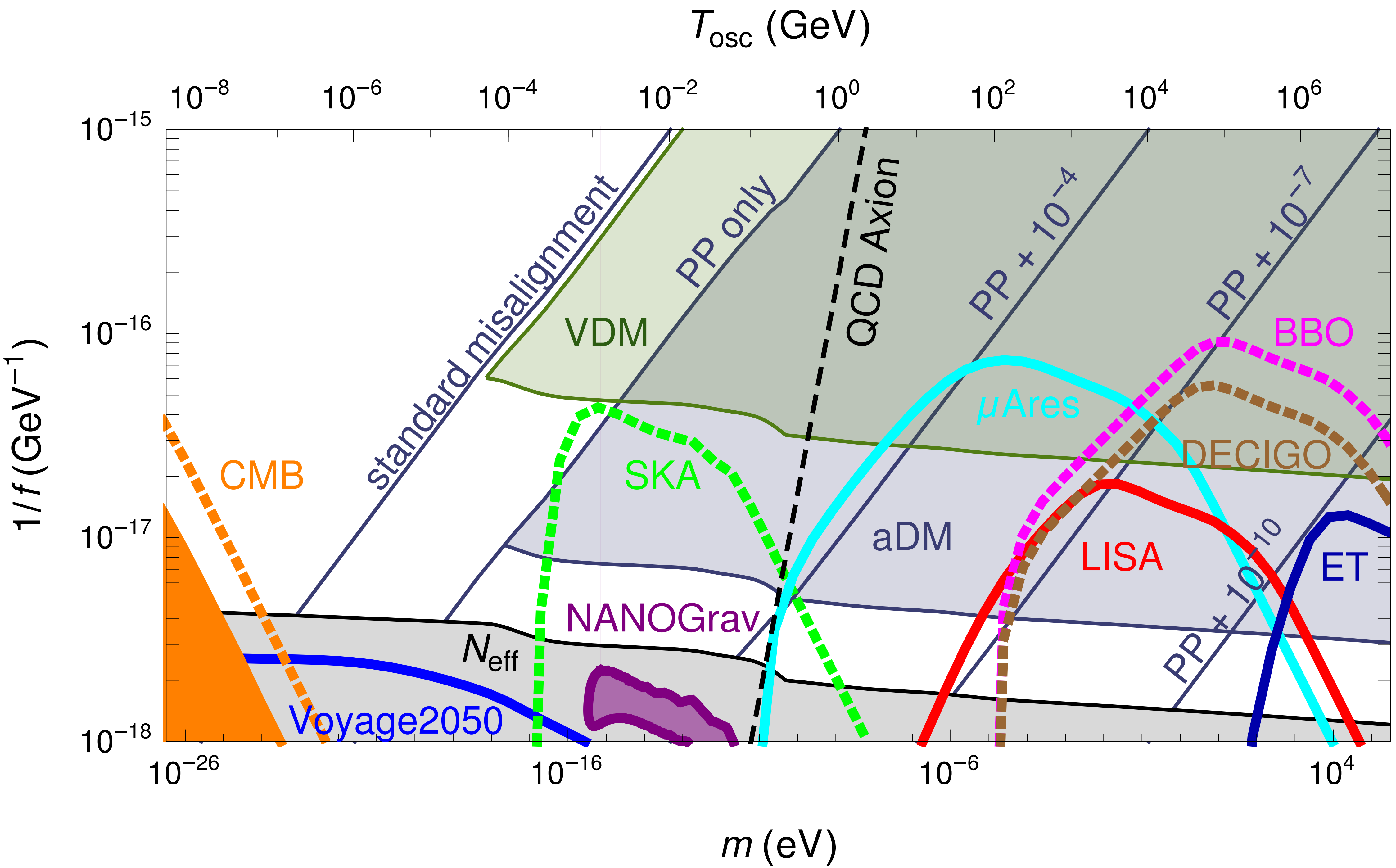
Also consistent with Axiogenesis!



From Madge, Ratzinger, Schmitt, PS, 2111.12730

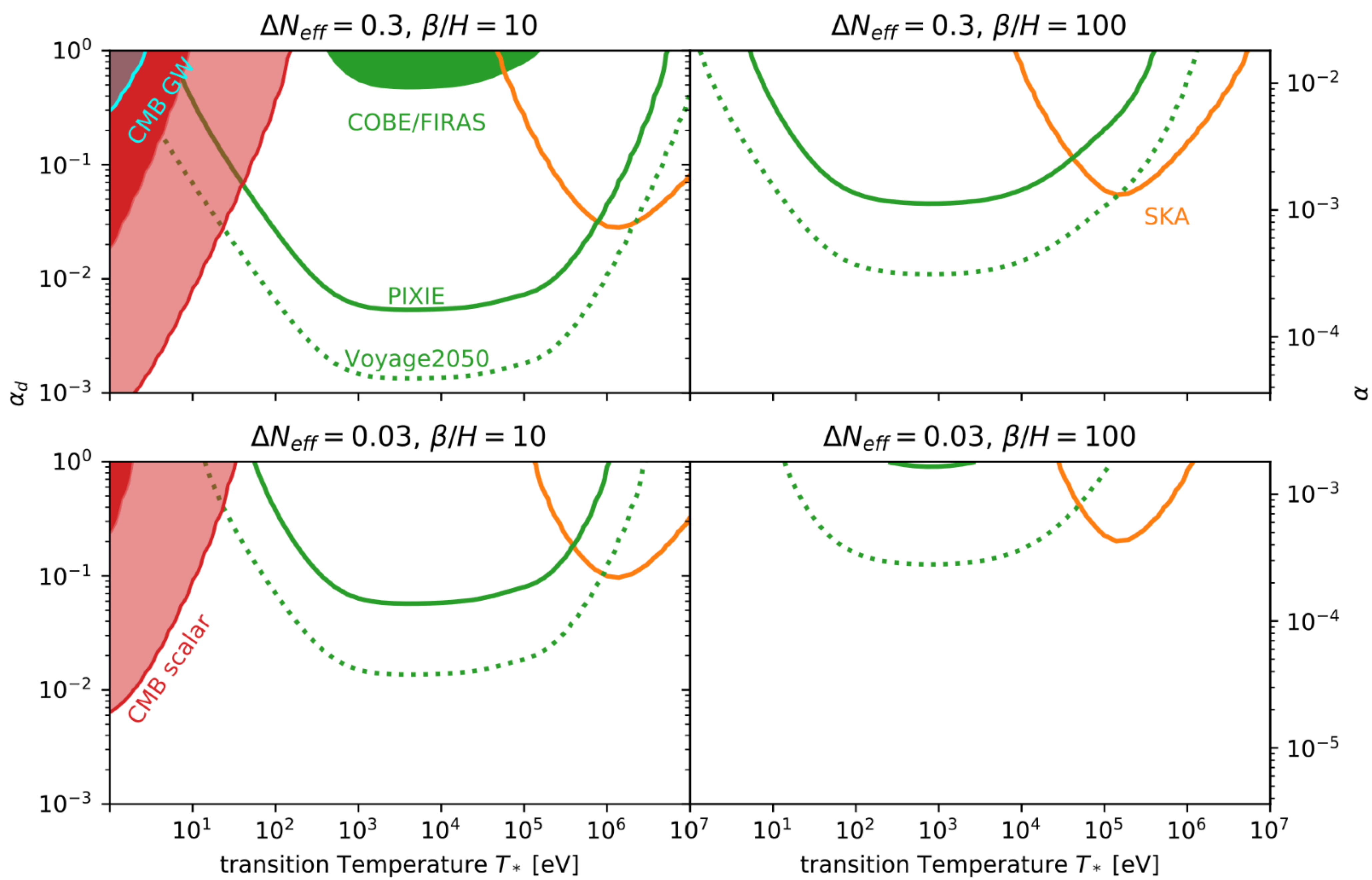
See also Co, Harigaya, Pierce, 2104.02077

Detectable region - update



From 2012.11584 with W. Ratzinger, B. Stefanek

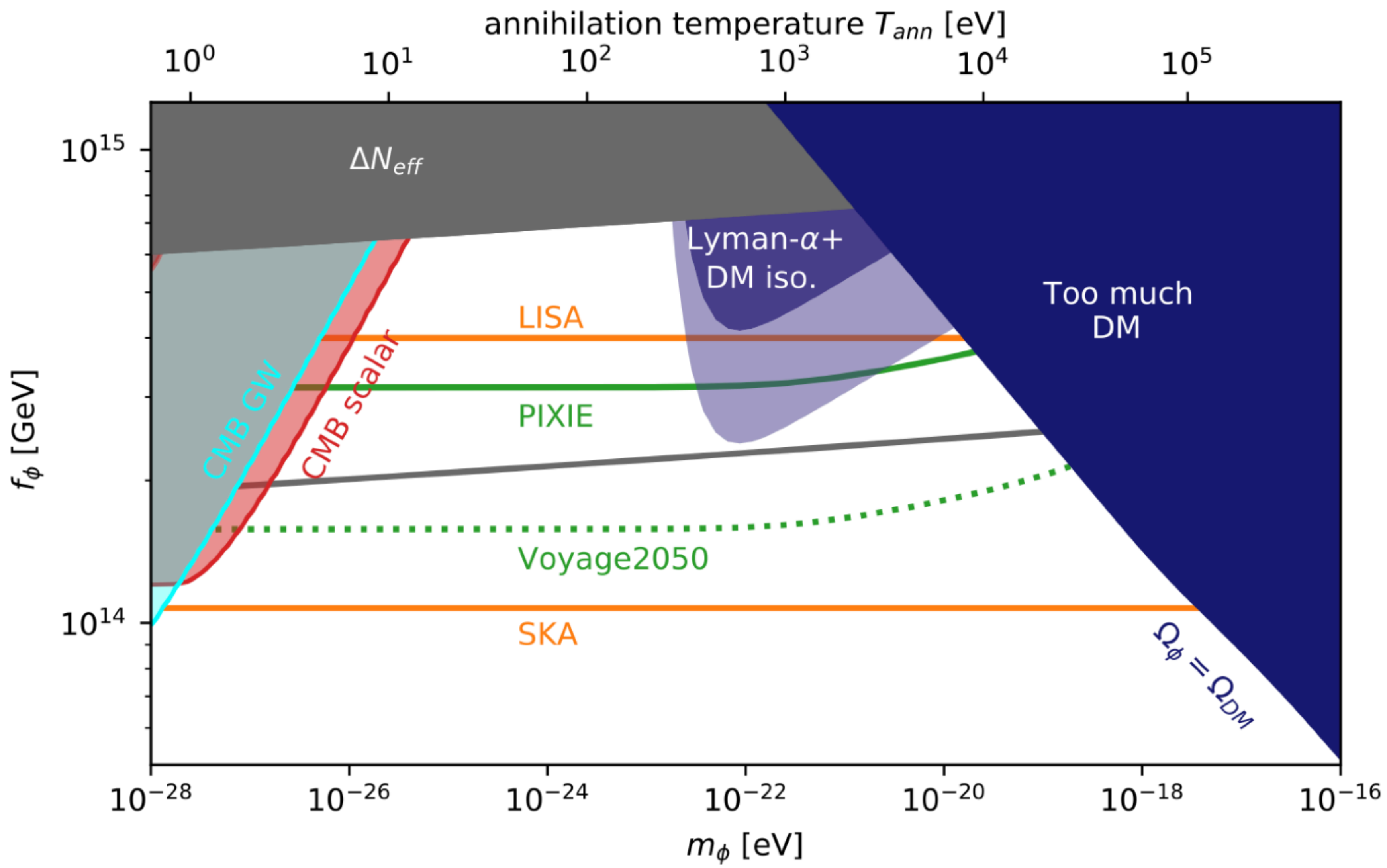
Example source I: Dark sector phase transition



Note: Ω_d fixed to satisfy N_{eff} constraints

Ramberg, Ratzinger & PS, 2209.14313

Source III: (global) cosmic strings



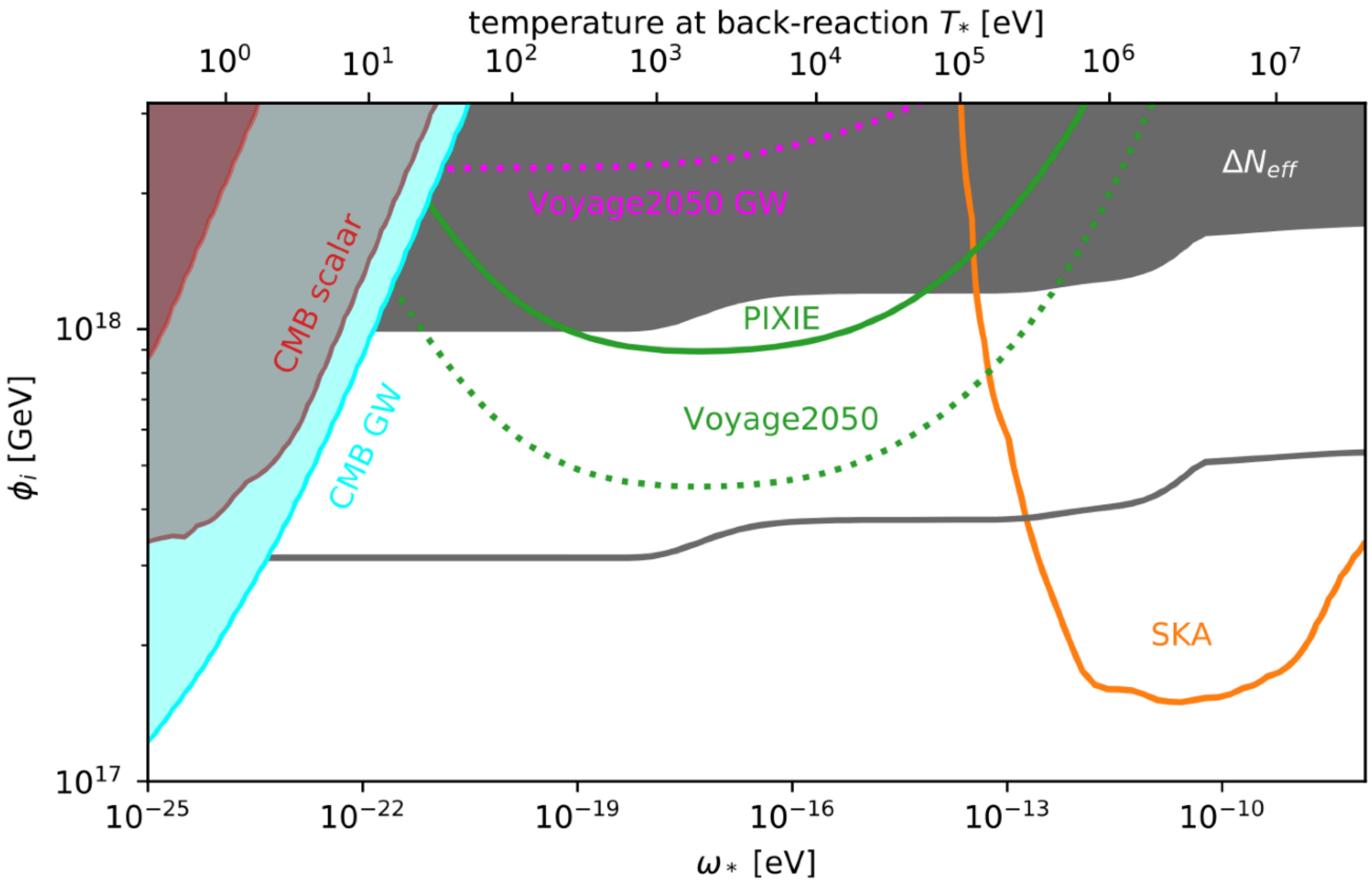
Note: Local strings mainly radiate from small loops and are thus NOT an efficient source of spectral distortions

Example source IV: Audible axions…

Not yet…

Results for scalar toy model

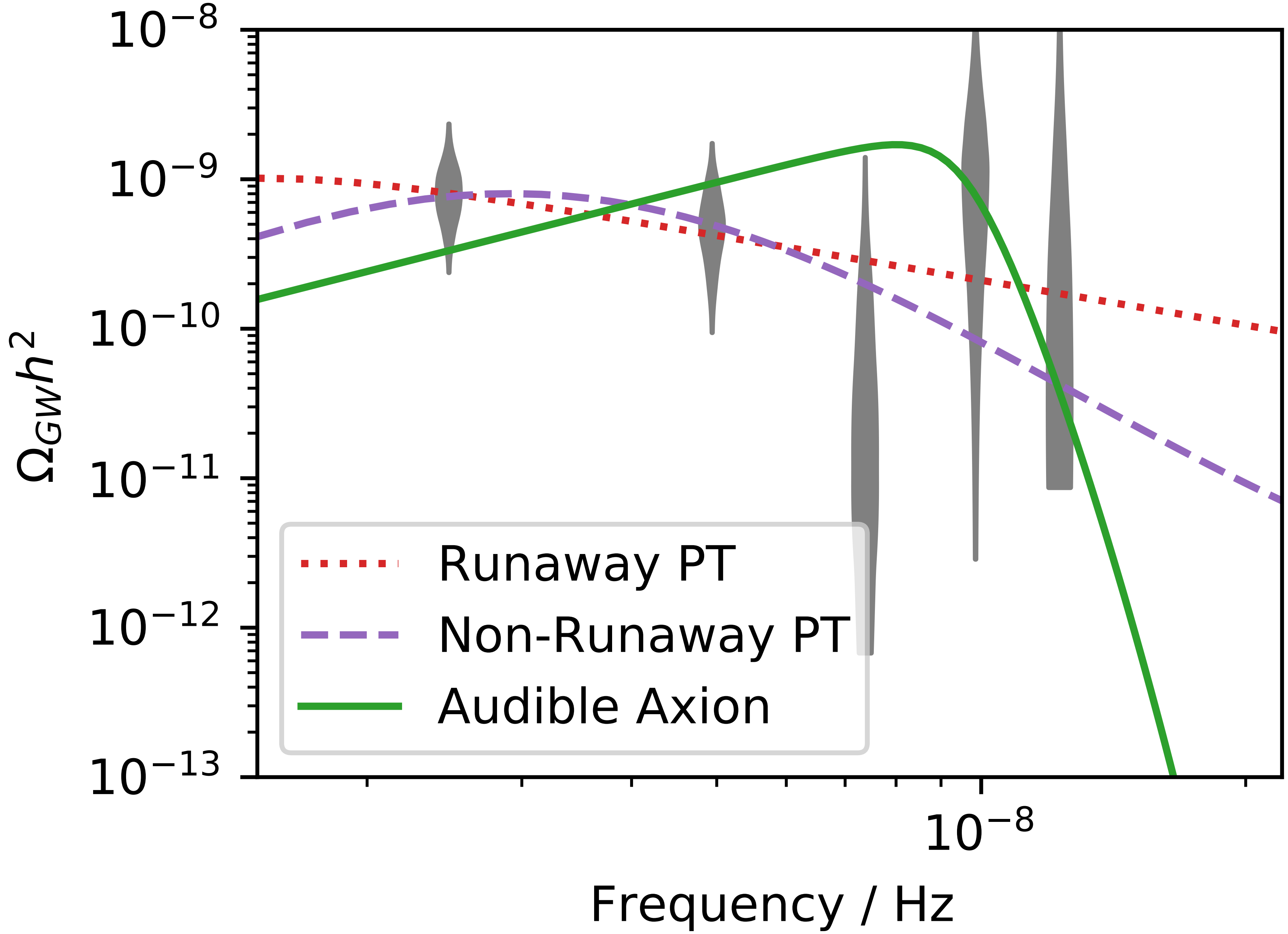
Constraints not as strong since fluctuations are not horizon size



Expect better sensitivity for axion fragmentation

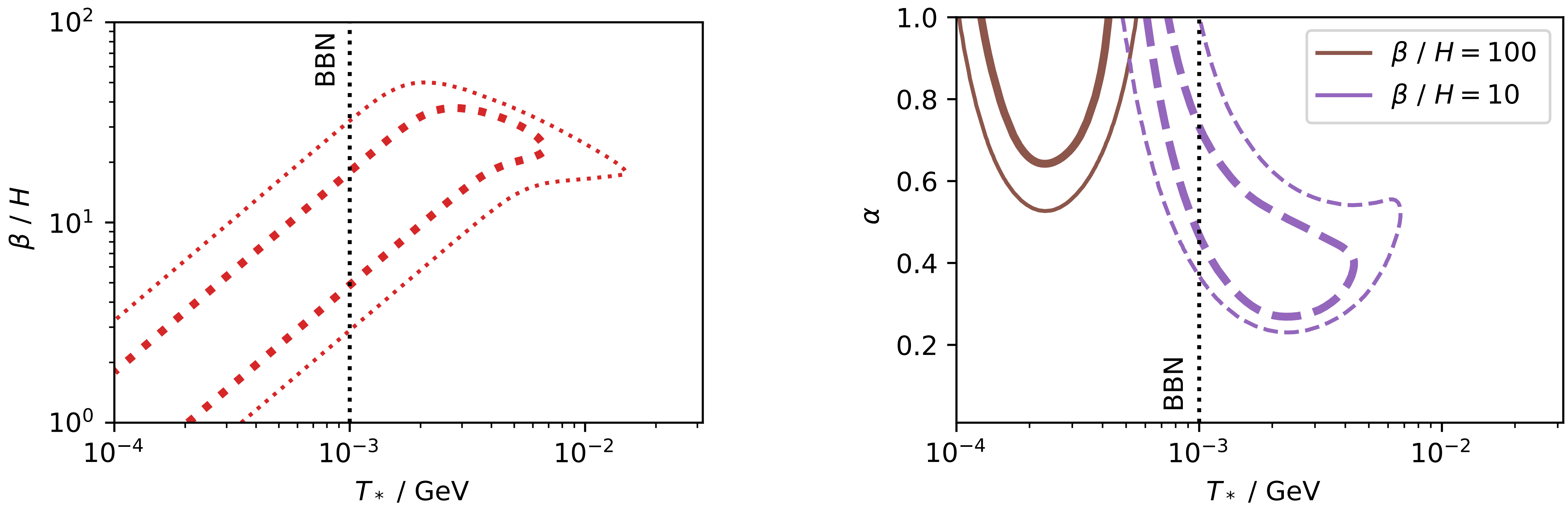
Ramberg, Ratzinger & PS, 2209.14313

Fit with broken power law signals



Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition

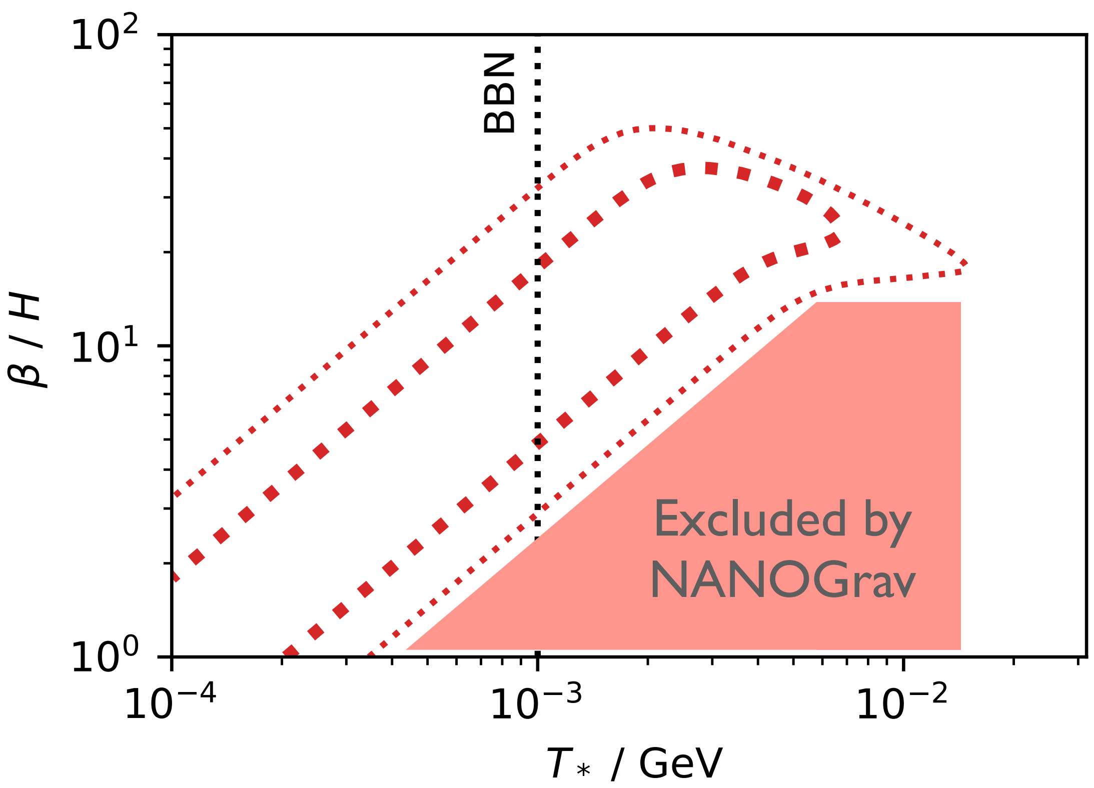


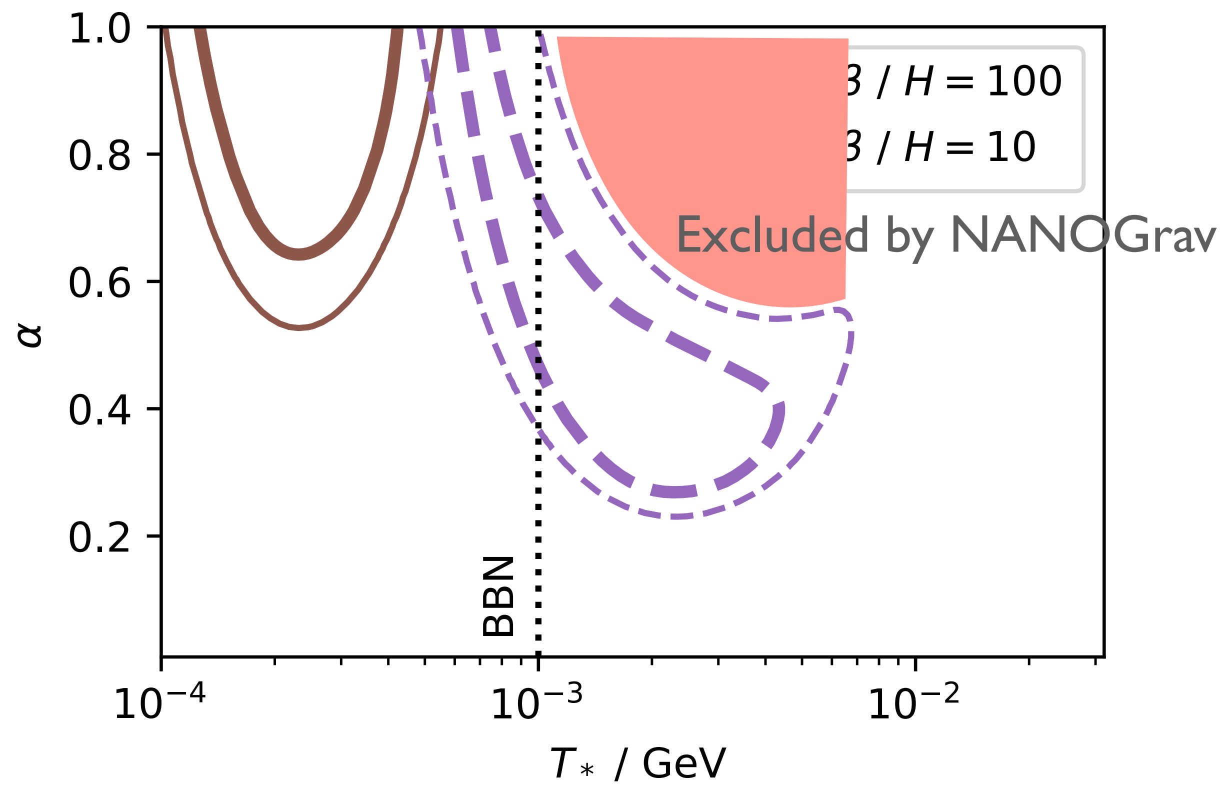
Generic PT parameterisation, best fit with PT at temperatures in few MeV range

Challenge for model building → Hint for dark sector

Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition





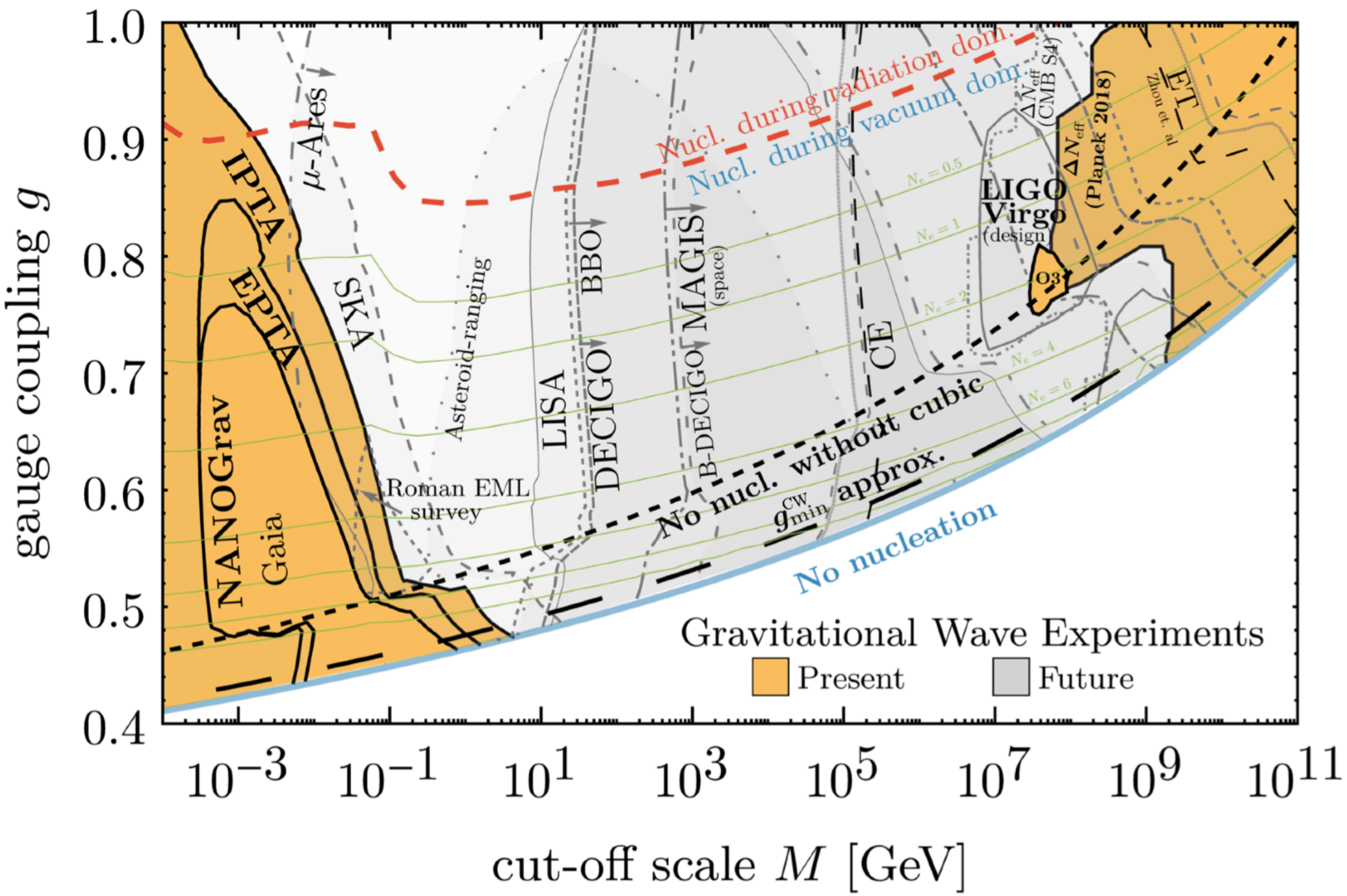
Generic PT parameterisation, best fit with PT at temperatures in few MeV range

Some model parameters excluded by PTA data now!

Wolfram Ratzinger & PS, 2009.11875

At higher frequencies

Levi, Opferkuch, Redigolo, 2212.08085



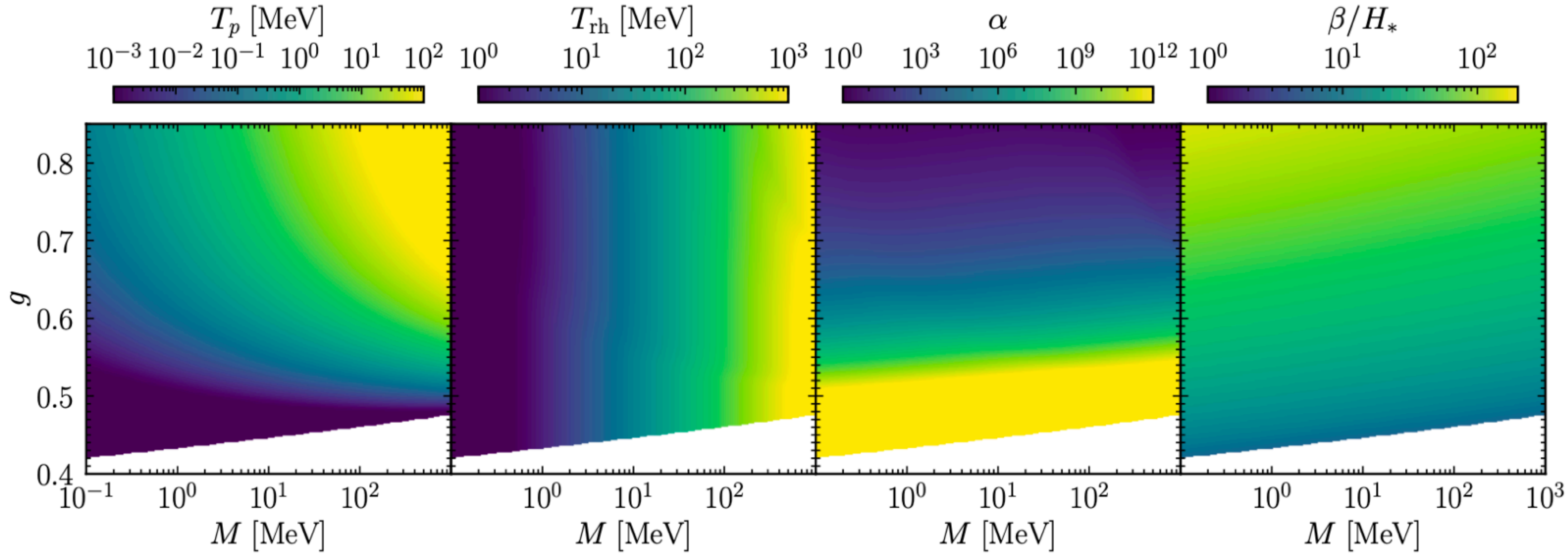
LISA will probe above 10 GeV, colliders could fill gap

Supercooled phase transitions

Benchmark model: Coleman-Weinberg model with vanishing tree level potential

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi, T)$$

Two parameter model: Mass scale M and coupling g



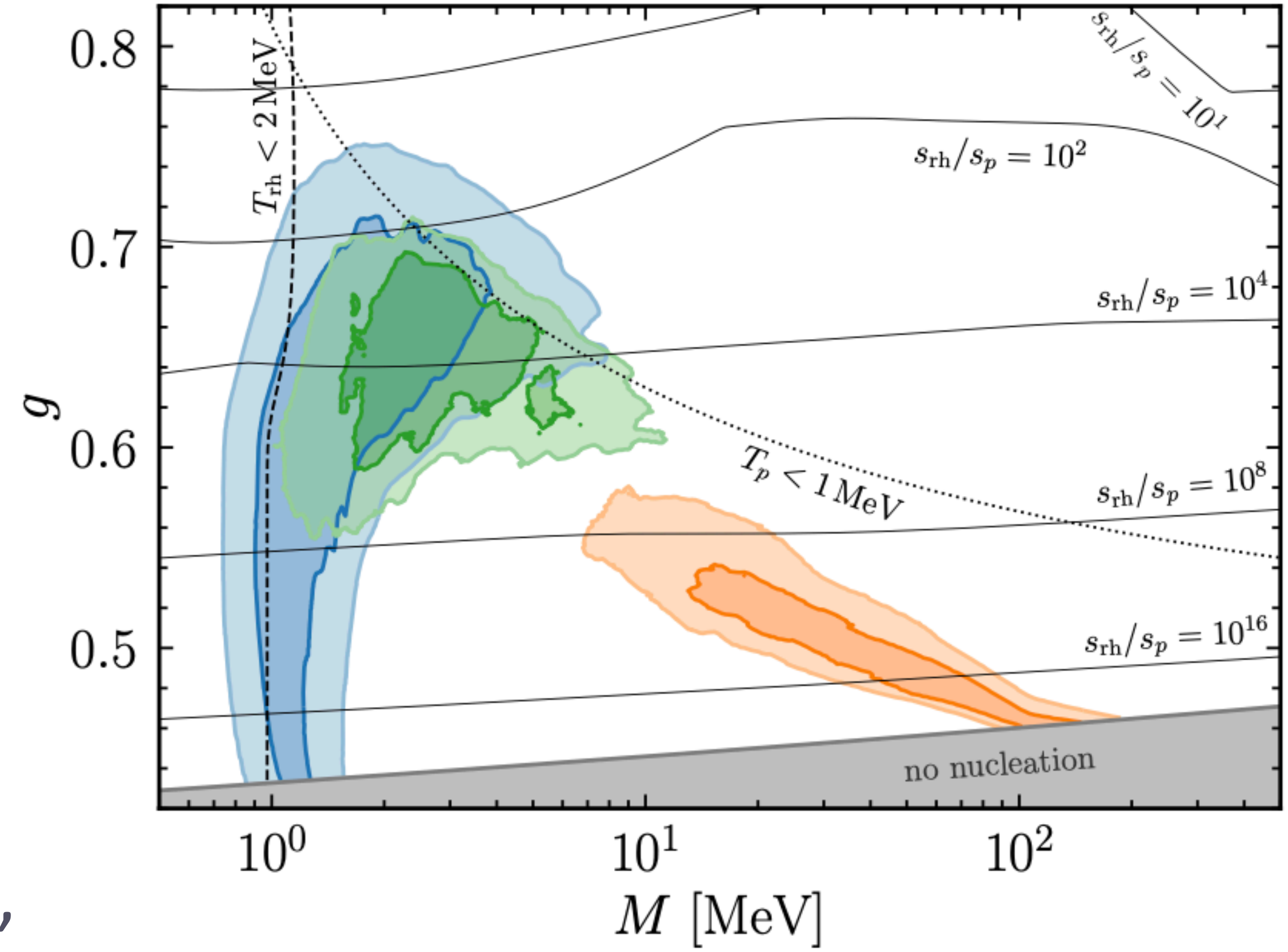
Madge et al, [2306.14856](2306.14856)

Signal dominated by colliding bubbles and sound shells

Simulated by Lewicki and Vaskonen, 2208.11697

Supercooled phase transitions

Madge et al, 2306.14856



Comparison with 12 year data

Large supercooling and reheating

- Dilution of baryons, dark matter
- Two BBNs

Pheno: Light scalar $m_\phi \approx M$, decay to electrons and photons

Higgs portal not viable, instead

$$\mathcal{L} \supset c_{ee}\frac{|\Phi|^2}{\Lambda^2} LH\bar{e} + c_{\gamma\gamma}\frac{|\Phi|^2}{\Lambda^2} F_{\mu\nu}F^{\mu\nu}$$

FCC? Or low energy e+e- machine (e.g. MESA in Mainz)

Axion/ALP domain walls

Domain walls appear when discrete symmetries are spontaneously broken to degenerate ground states

Long lasting GW source, until DWs annihilate, before dominating the Universe ideally

Review: Saikawa, 1703.02576

Axion DW: $U(1)_{\rm PQ} \to Z_N$

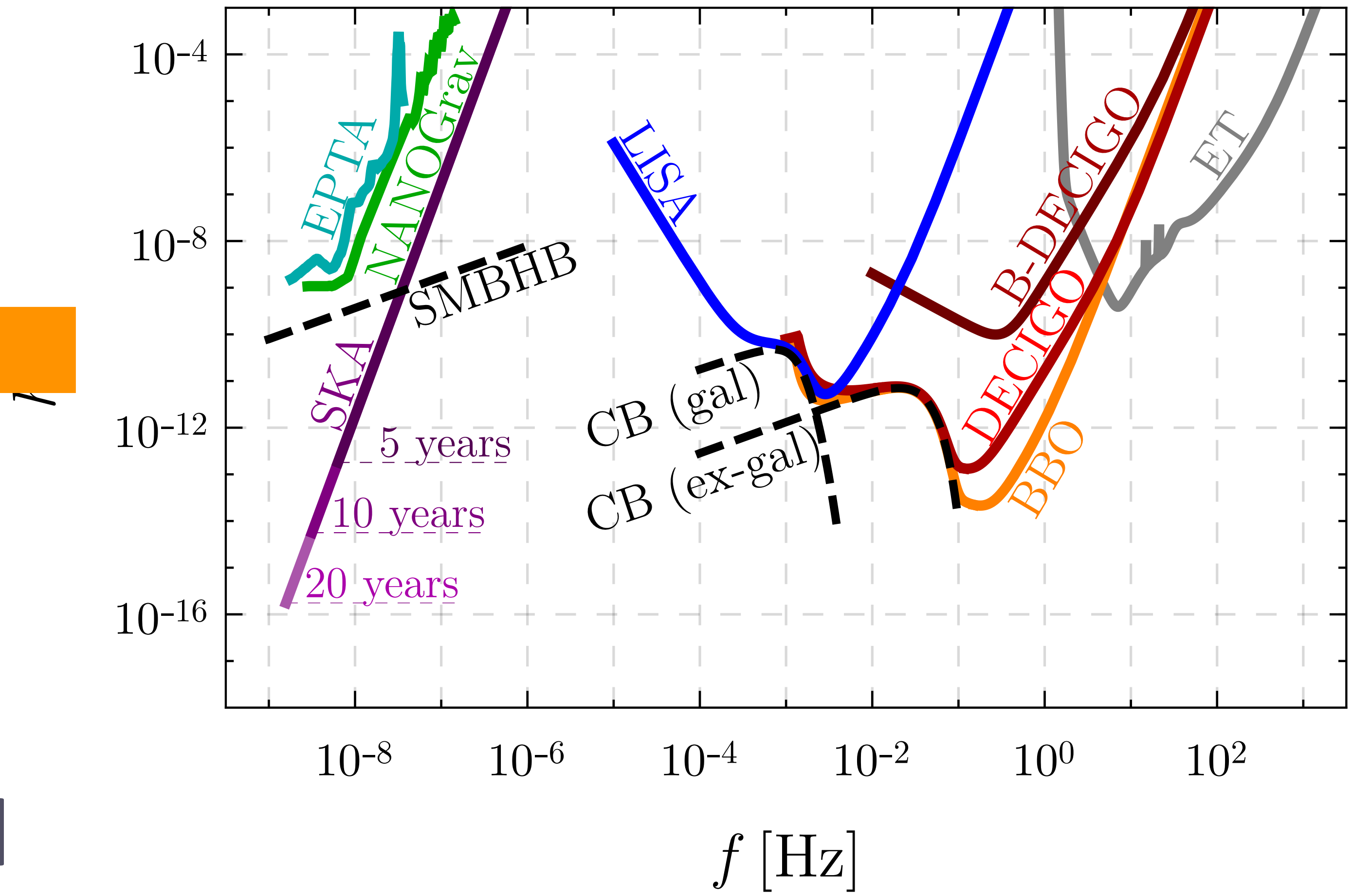
Surface tension $\sigma = 8 m_a f_a^2$

Annihilation triggered by QCD instantons

$$T_{\rm ann} \sim 1\,{\rm GeV} \left(\frac{g_*(T_{\rm ann})}{80}\right)^{-\frac{1}{4}} \left(\frac{\Lambda_{\rm QCD}}{400\,{\rm MeV}}\right)^2 \left(\frac{10^7\,{\rm GeV}}{f_a}\right) \sqrt{\frac{10\,{\rm GeV}}{m_a}}$$

Madge et al, 2306.14856

Pushing the limits



CMB spectral distortions

High frequency GW detectors