GRAVITATIONAL WAVE PROBES OF DARK SECTORS

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Gravitational waves and dark sectors

Gravitational waves as windows into the early, **dark** Universe

Primordial gravitational wave sources

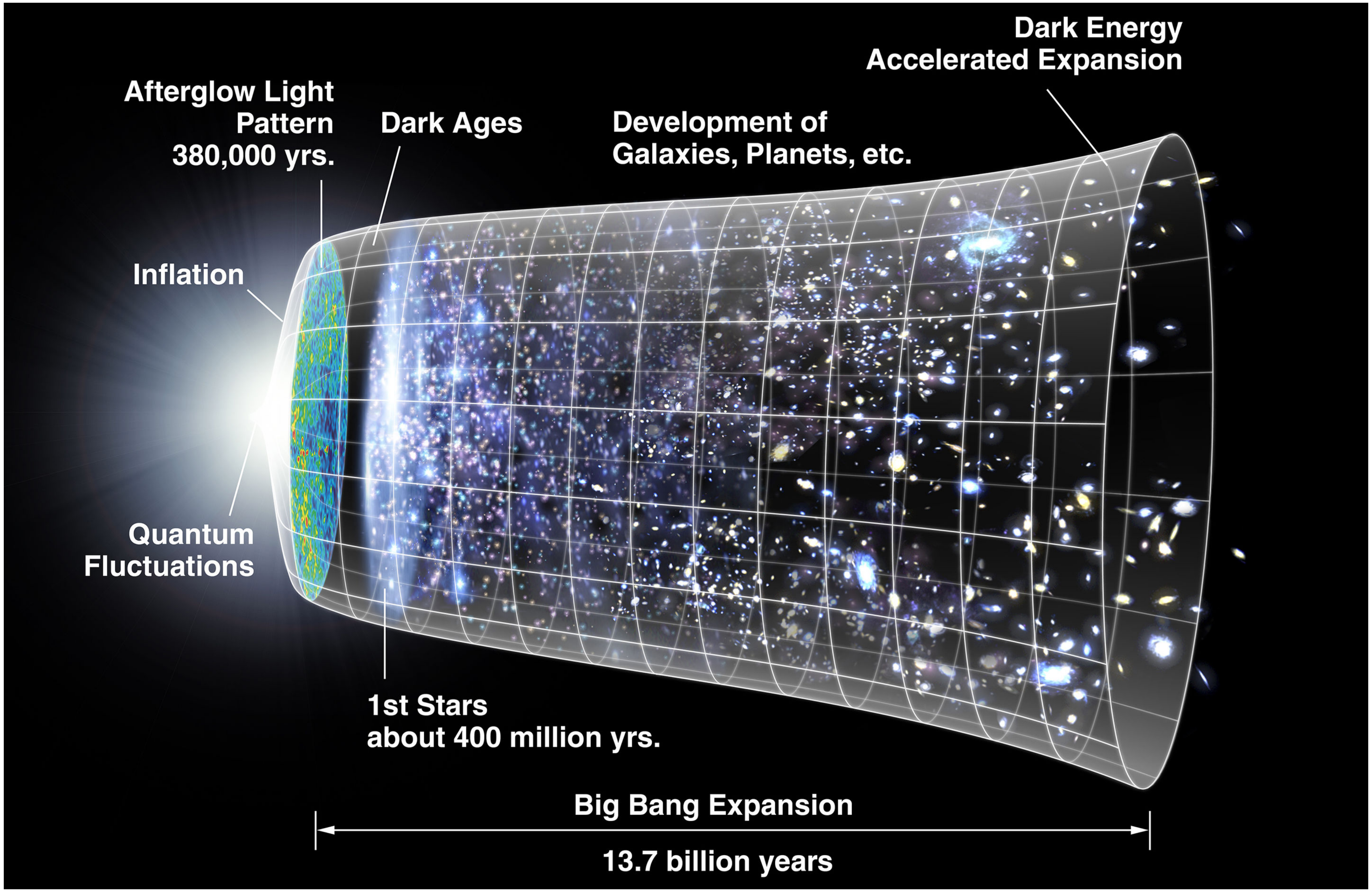
- Overview
- Audible axions

Thoughts on the PTA signal

Complementary probes via CMB spectral distortions

What do we know about the early Universe?

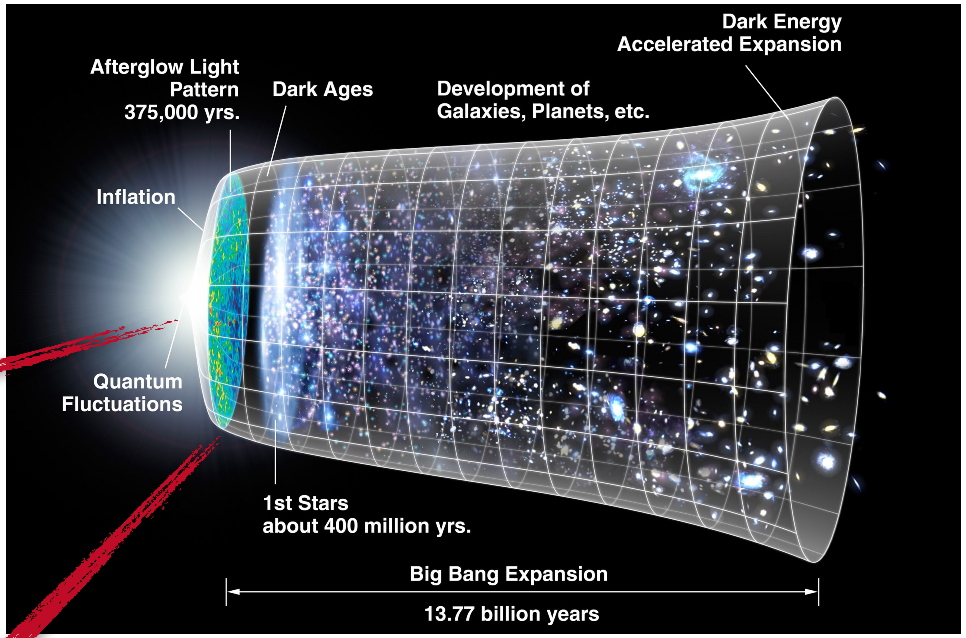
Thermal History

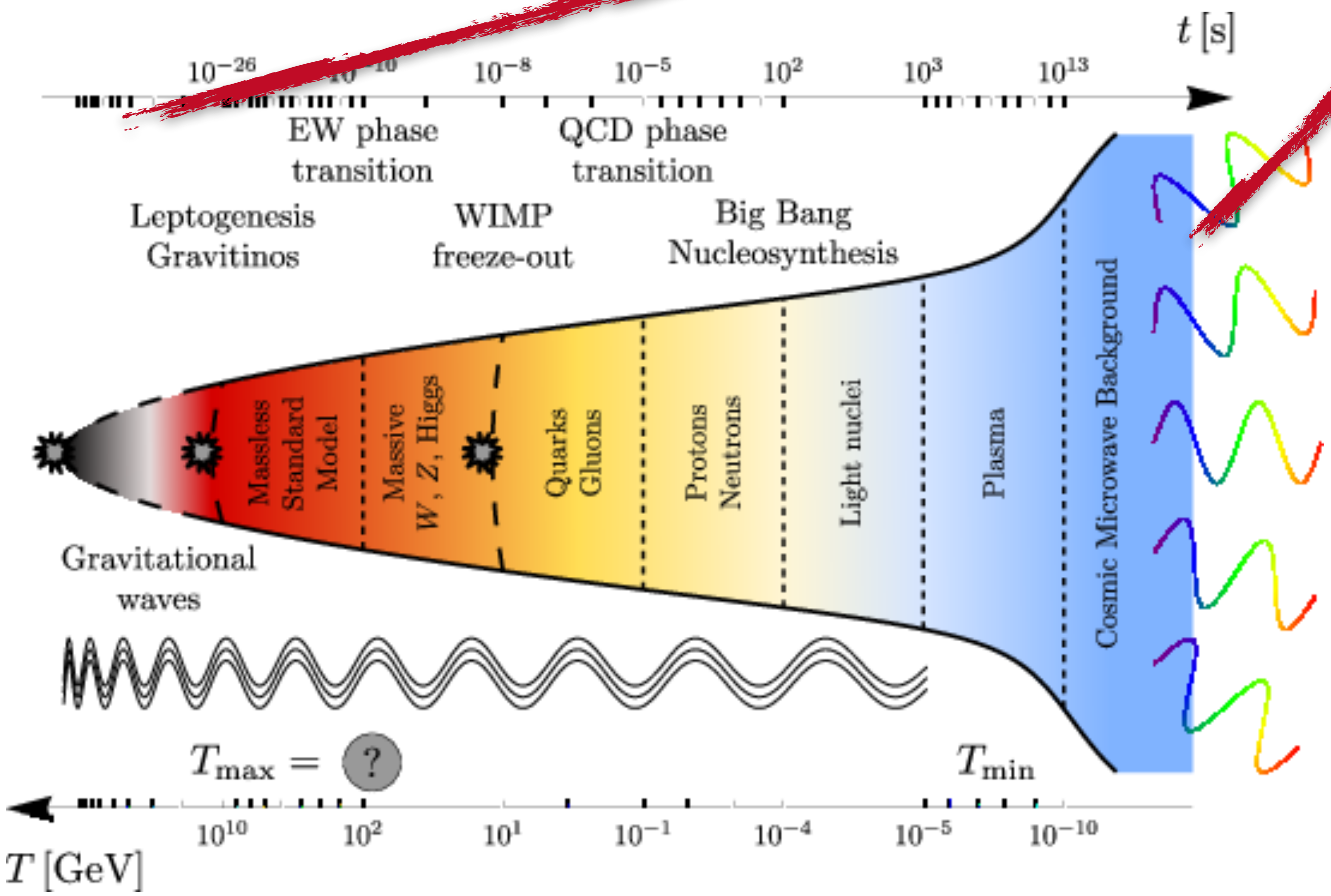


Gravitational Waves?

Zoom into interesting region

New window into early universe





e.g.

Electroweak symmetry breaking

Baryogenesis

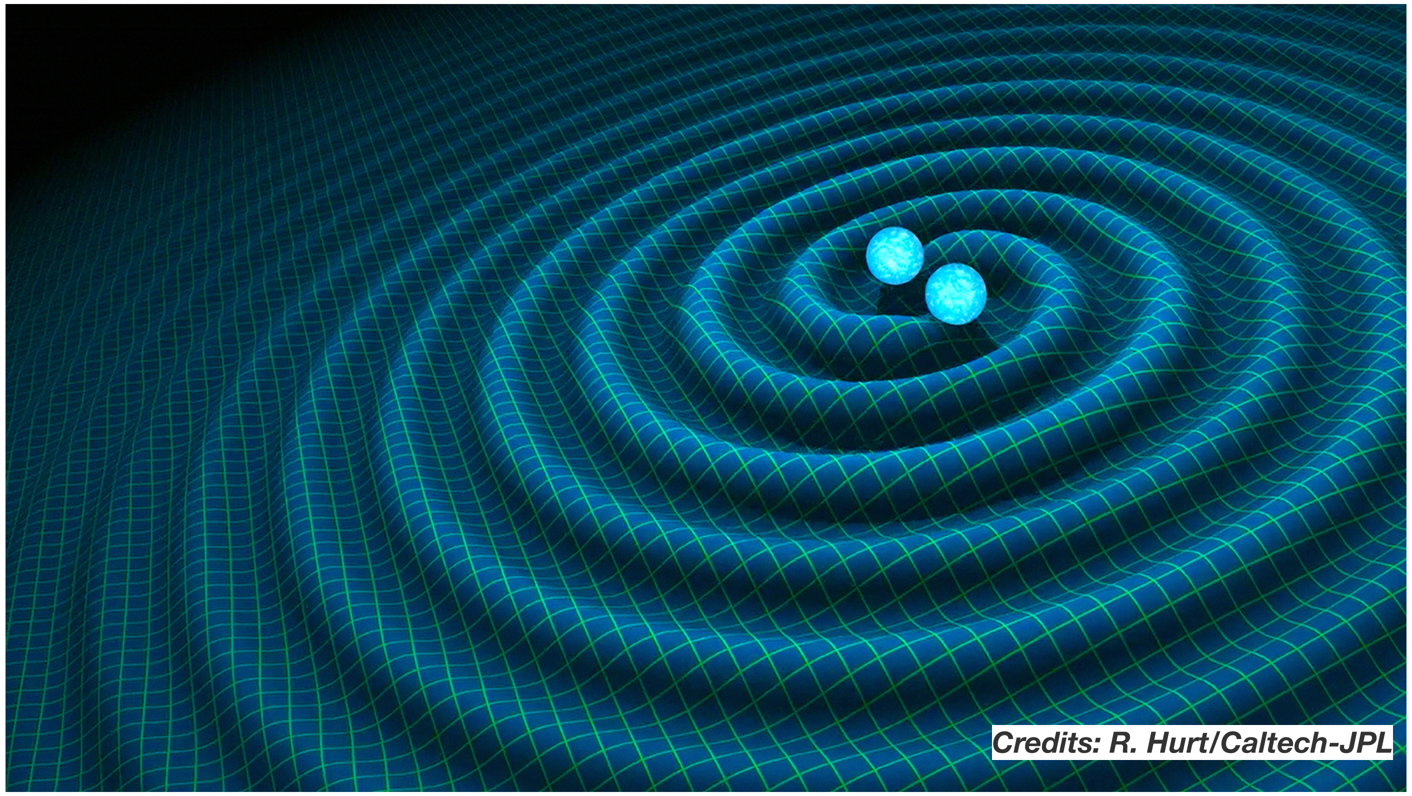
Dark matter production

Gravitational waves as messengers from the early Universe

Travel undisturbed from earliest times

Only produced by violent, non-equilibrium physics

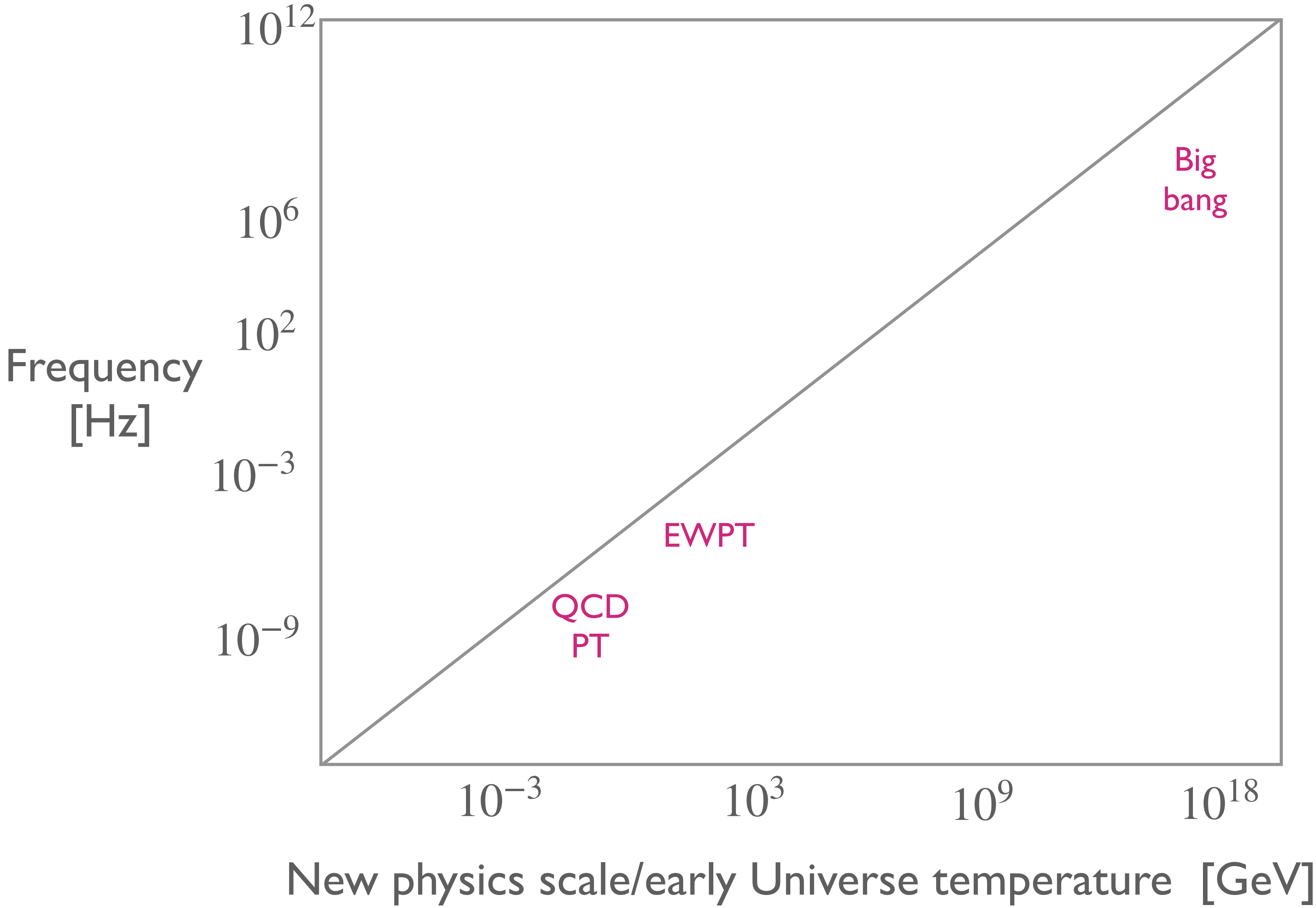
- Stochastic GW background



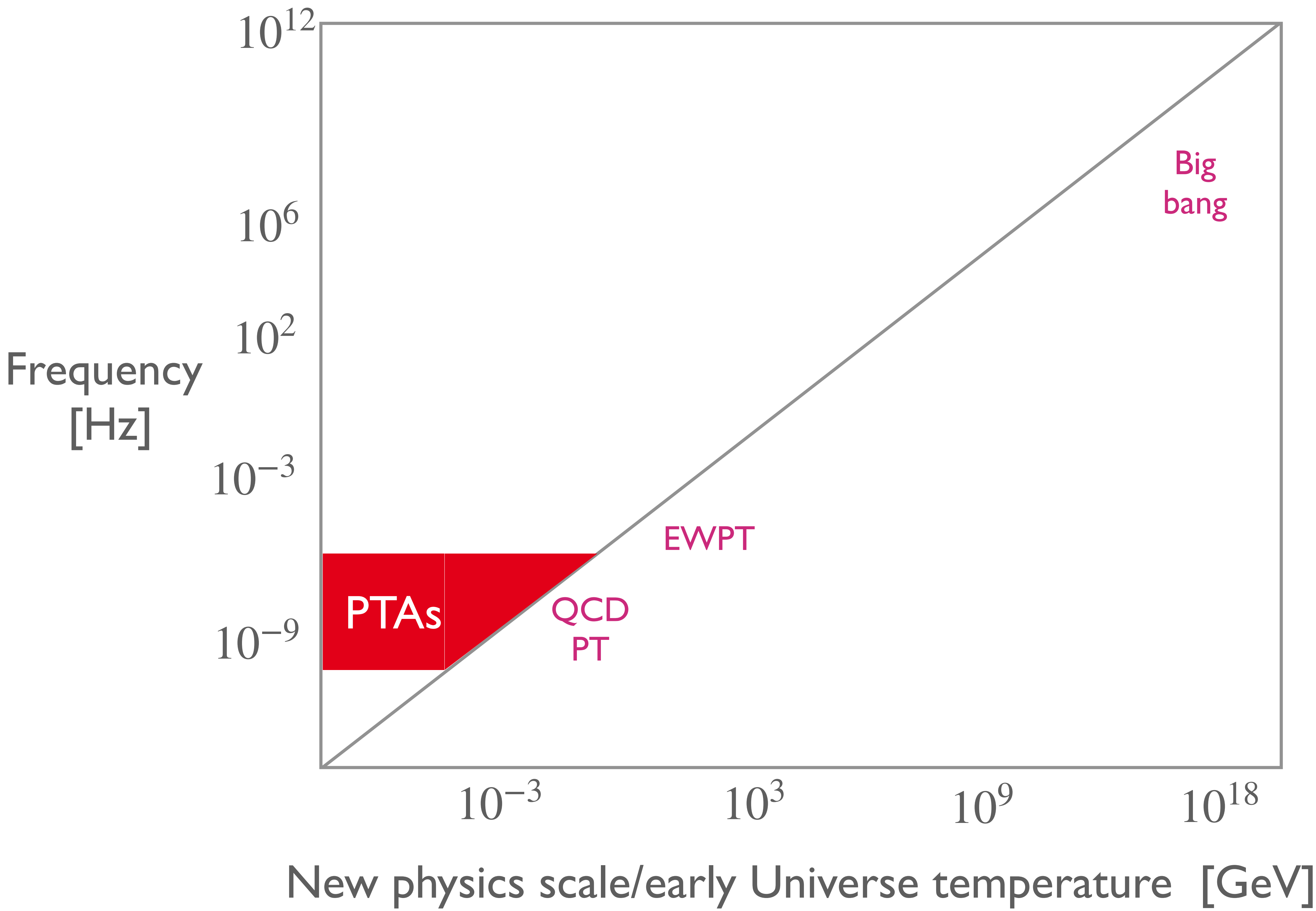
Relevant scale: Hubble radius ↔ GW wavelength

GW frequency $$f_{\rm GW} \sim T_*$$ Age of Universe

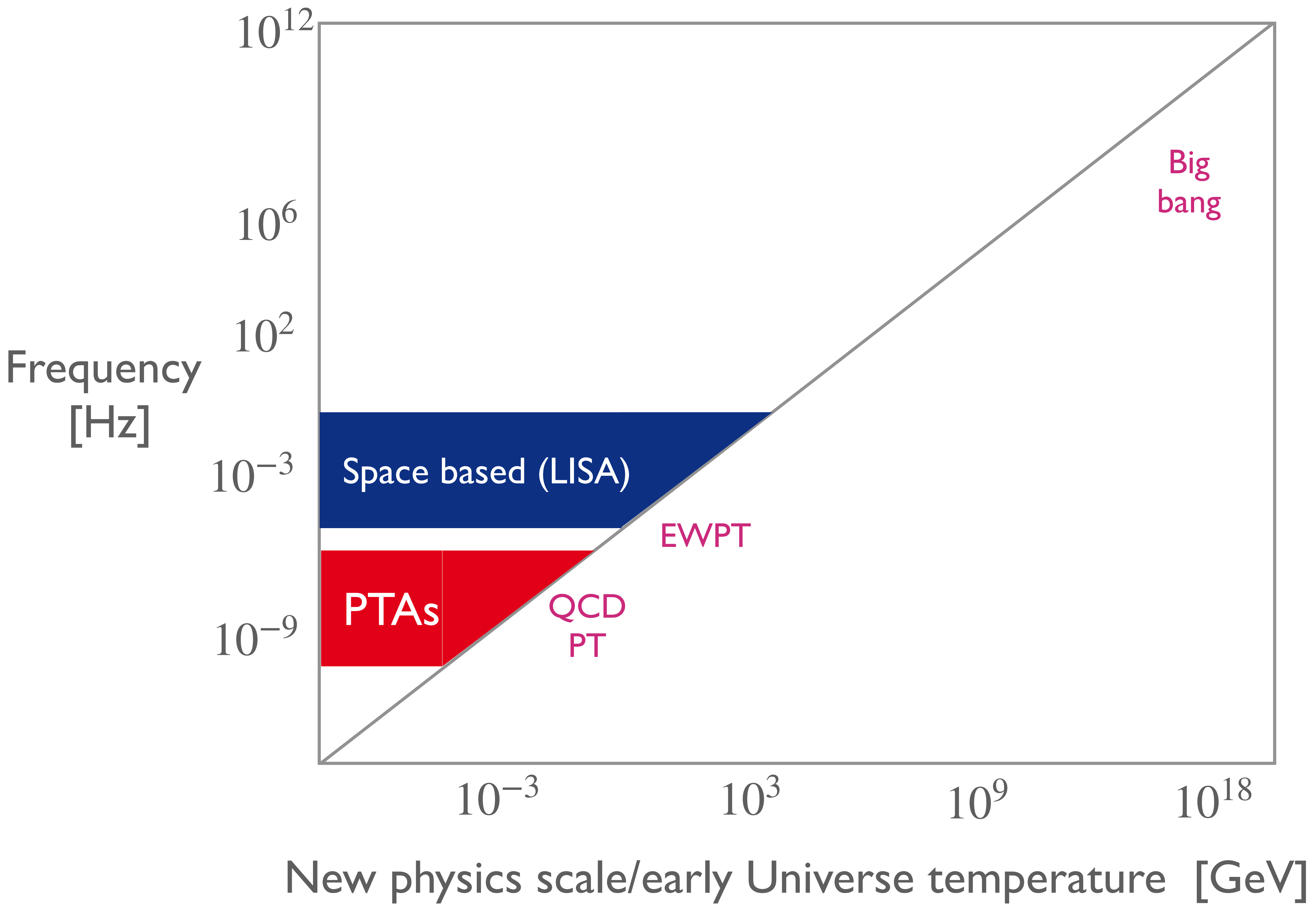
Frequencies of interest



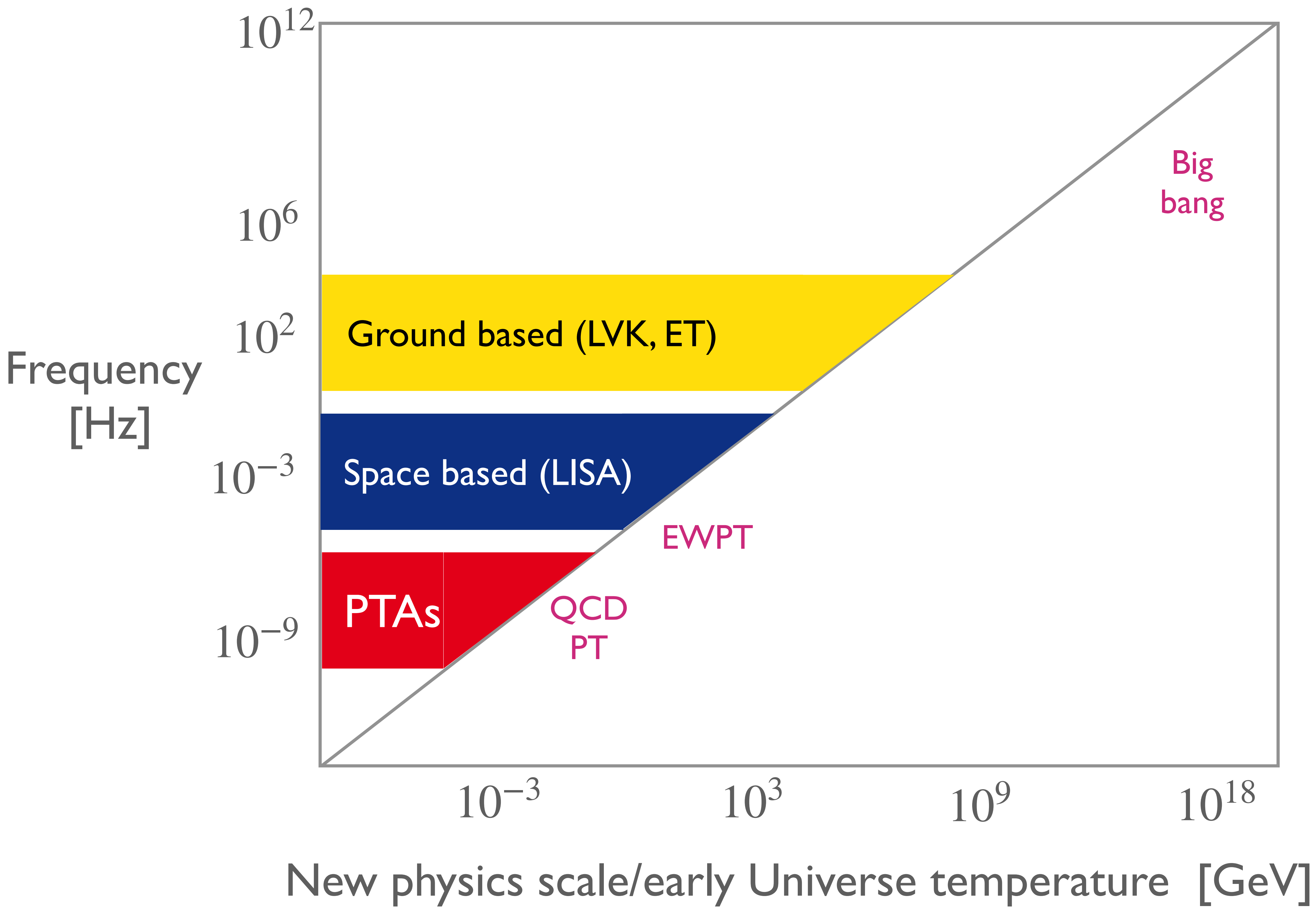
Frequencies of interest



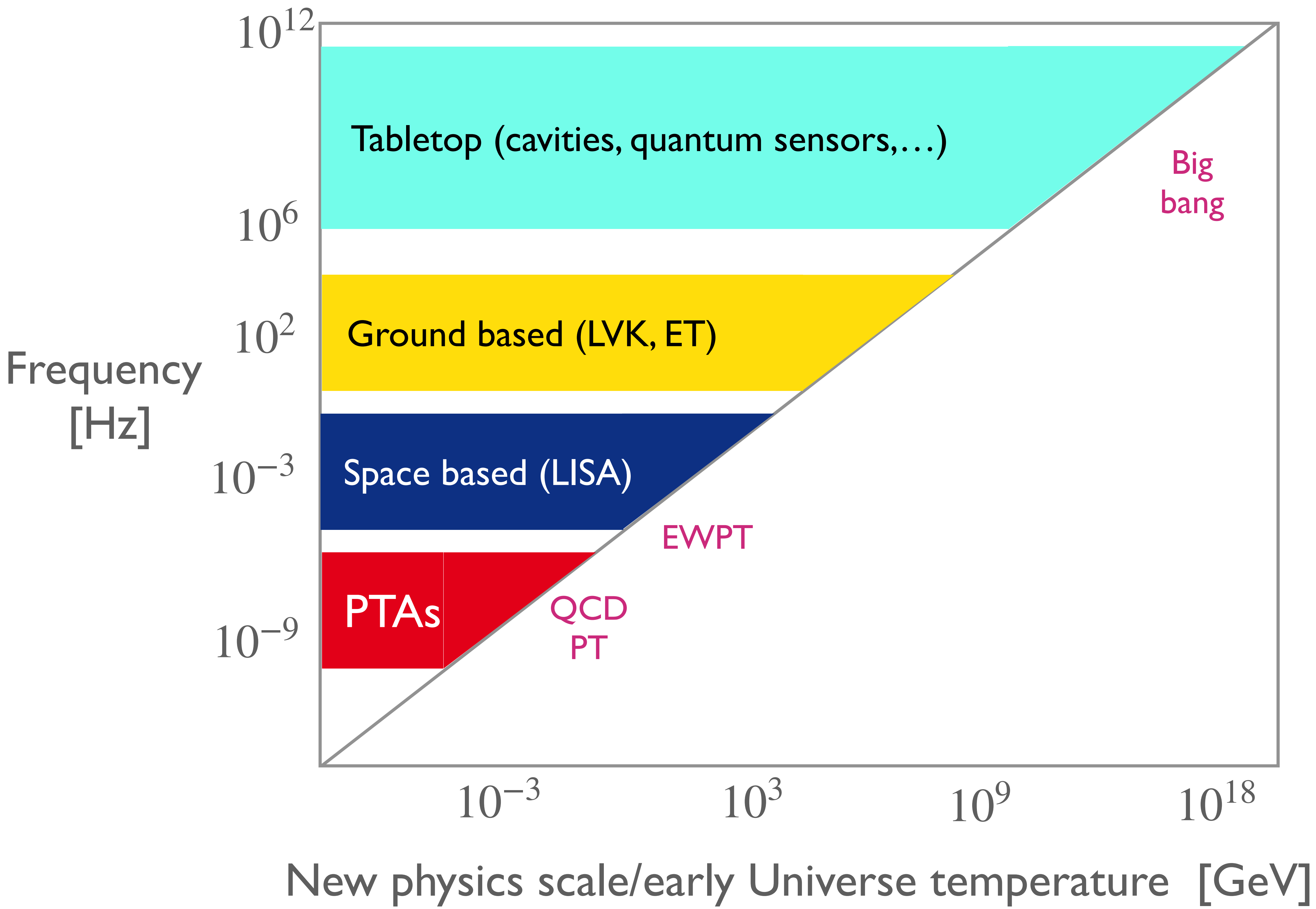
Frequencies of interest



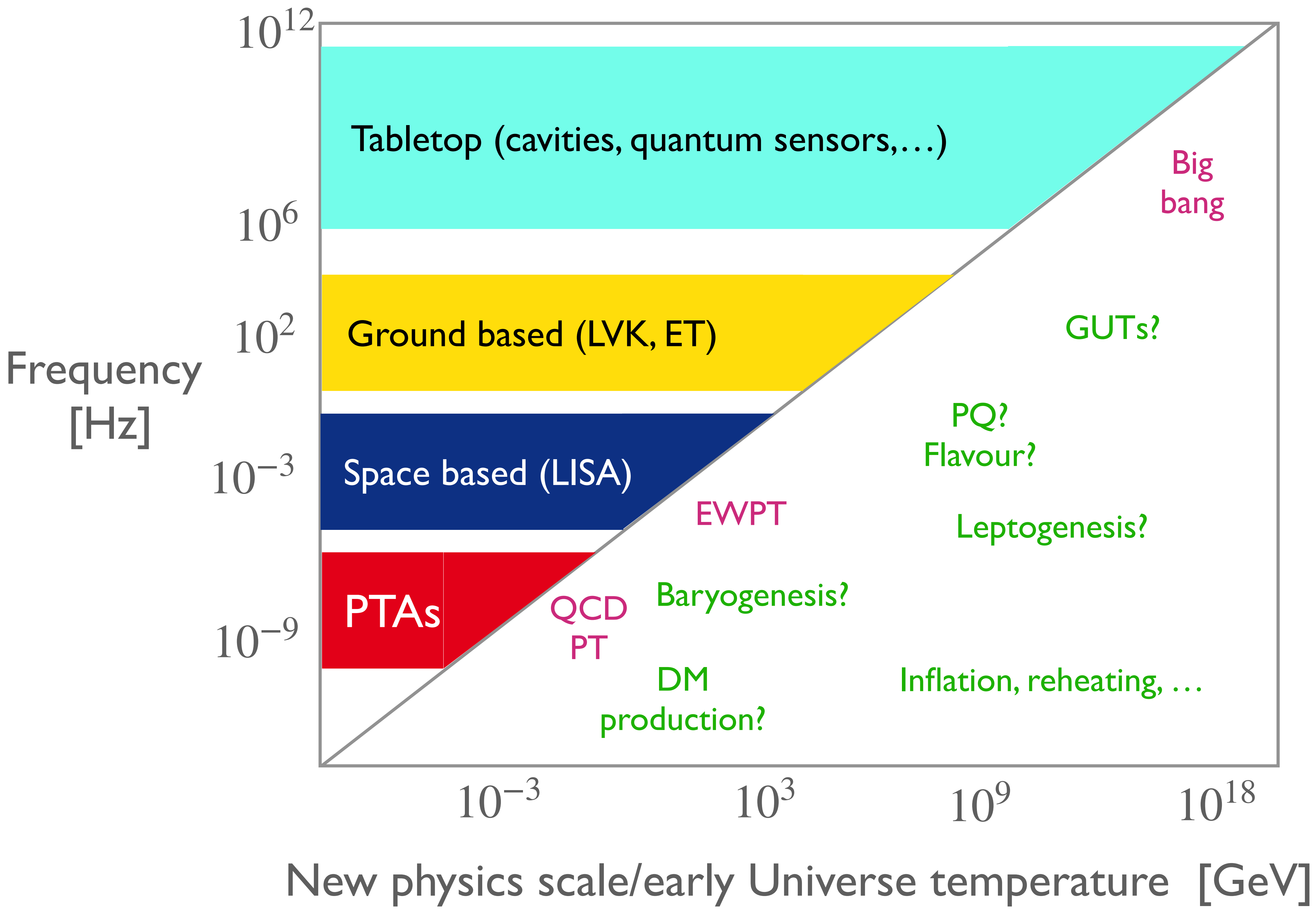
Frequencies of interest



Frequencies of interest

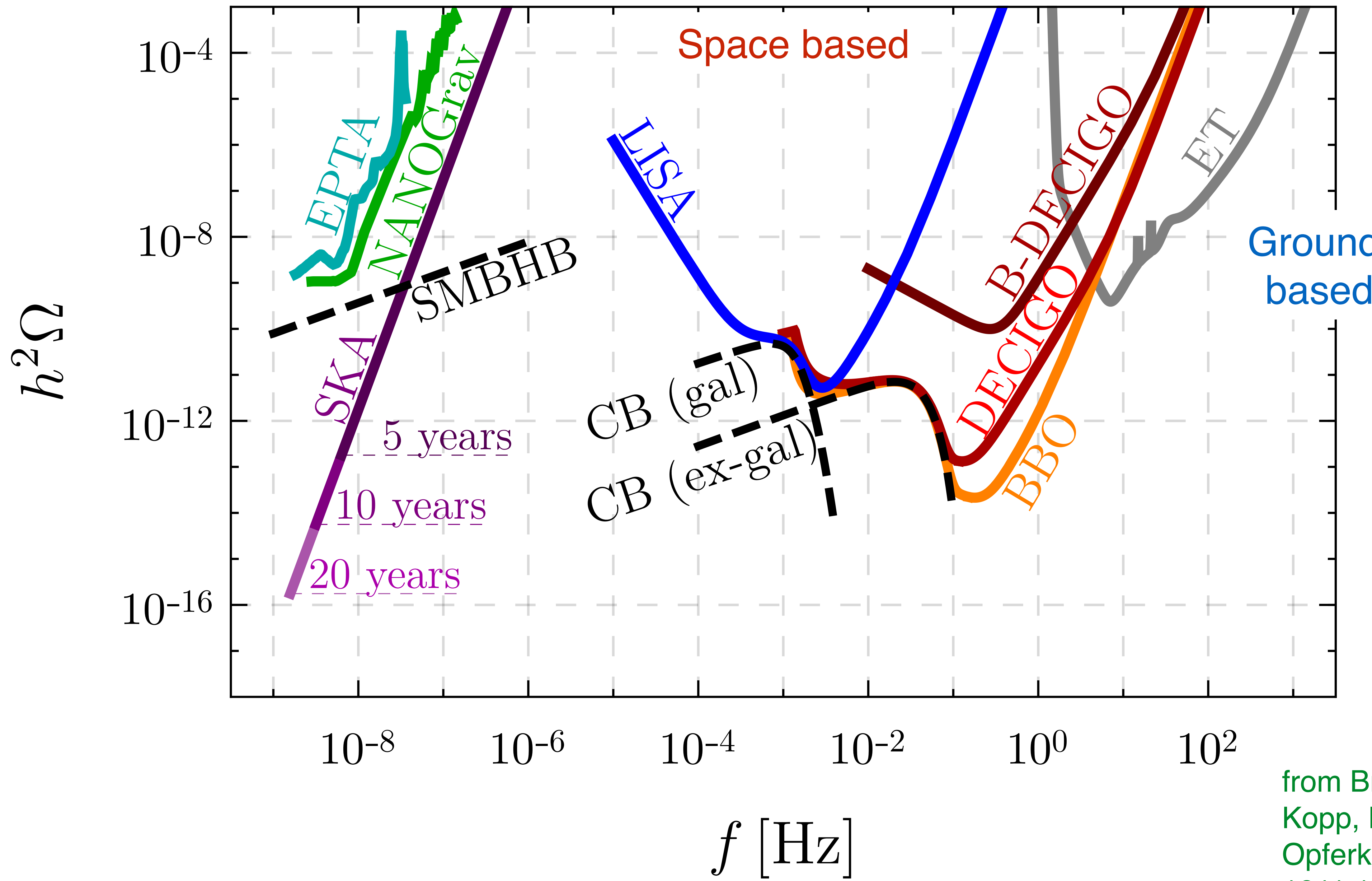


Frequencies of interest



Multiband GW searches

New physics scale GeV TeV PeV

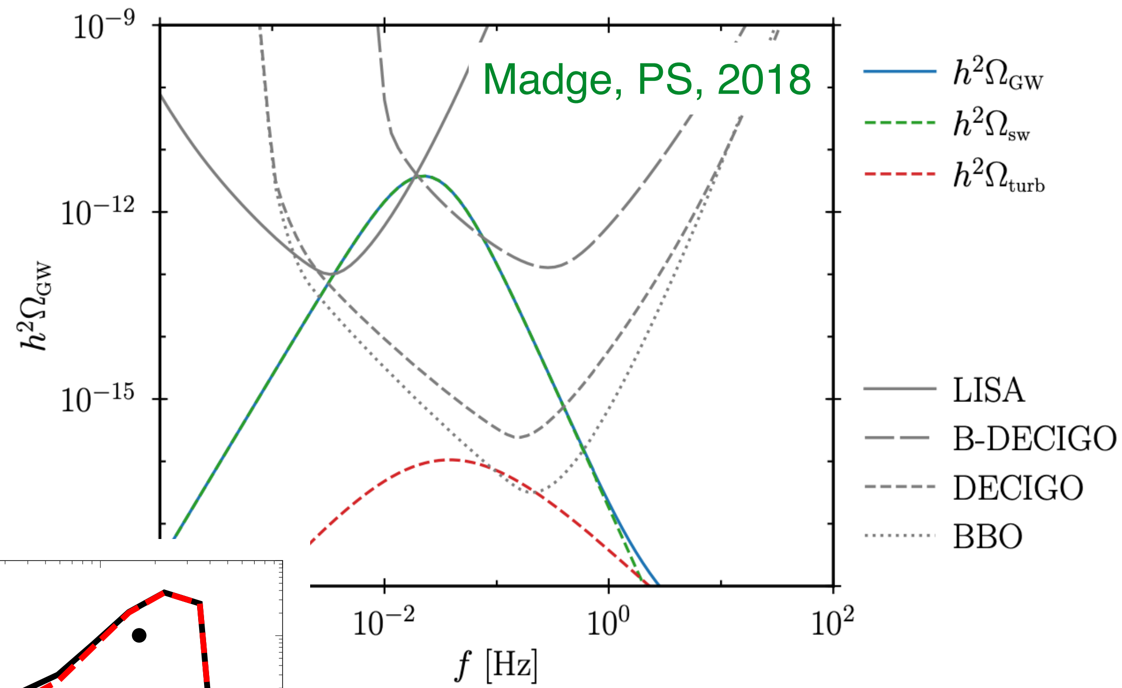


from Breitbach, Kopp, Madge, Opferkuch, PS 1811.11175

GW sources and their signal shapes

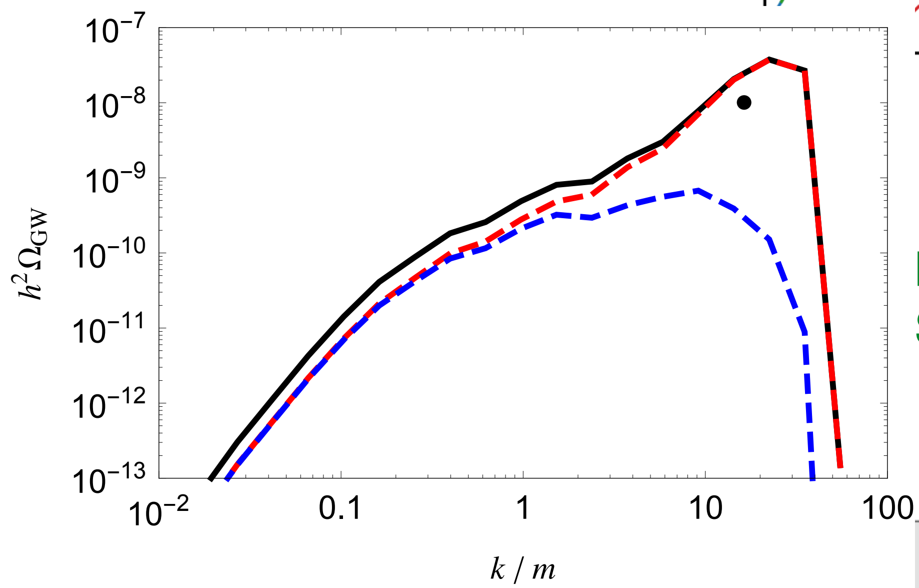
Phase transition

- Peak position depends on critical temperature



Audible axions:

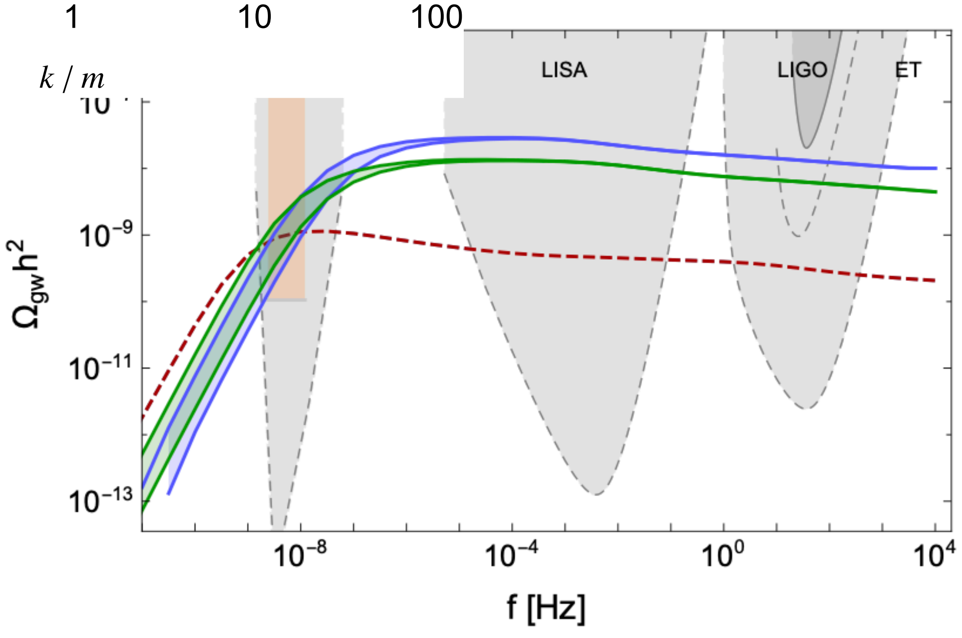
- Peaked
  but chiral



Machado, Ratzinger, Stefanek, PS, 2018/19

Cosmic strings

- Flatter spectrum



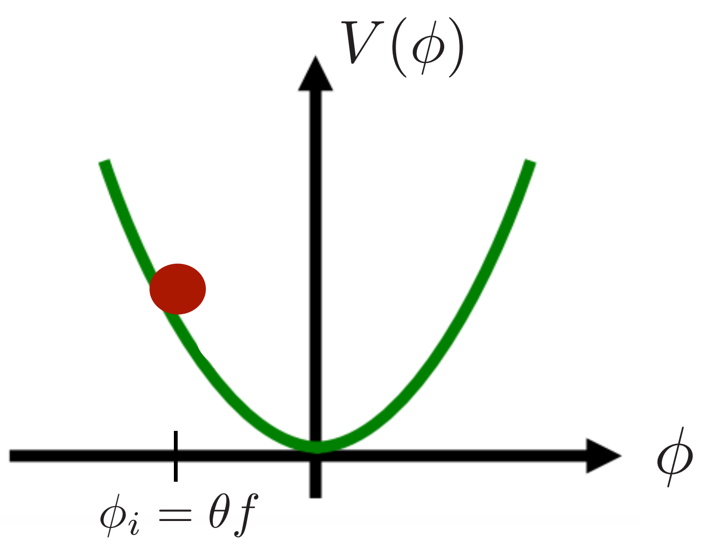
Buchmuller, Domcke, Schmitz, 2021

Audible Axions

Axion misalignment and DM

Axion EOM

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



Starts rolling when $H \sim m_\phi$

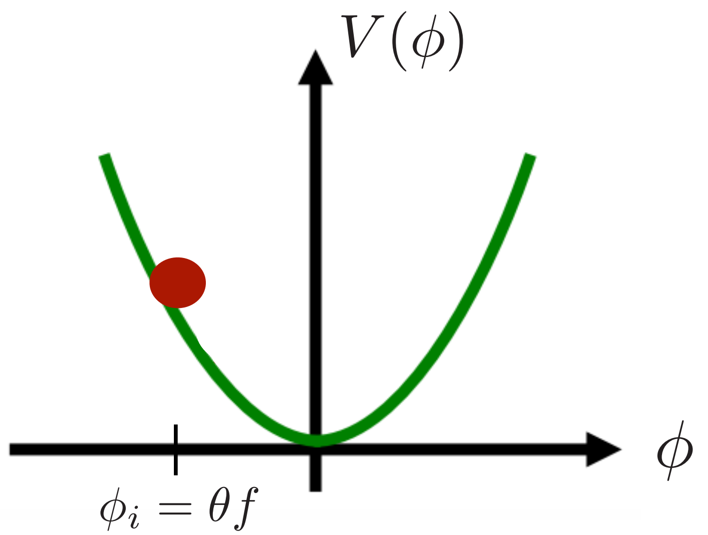
Redshifts with a^{-3}, i.e. like non-relativistic matter

Candidate for non-particle dark matter

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 - enlarge natural DM parameter space
- Or production of vector DM

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

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)

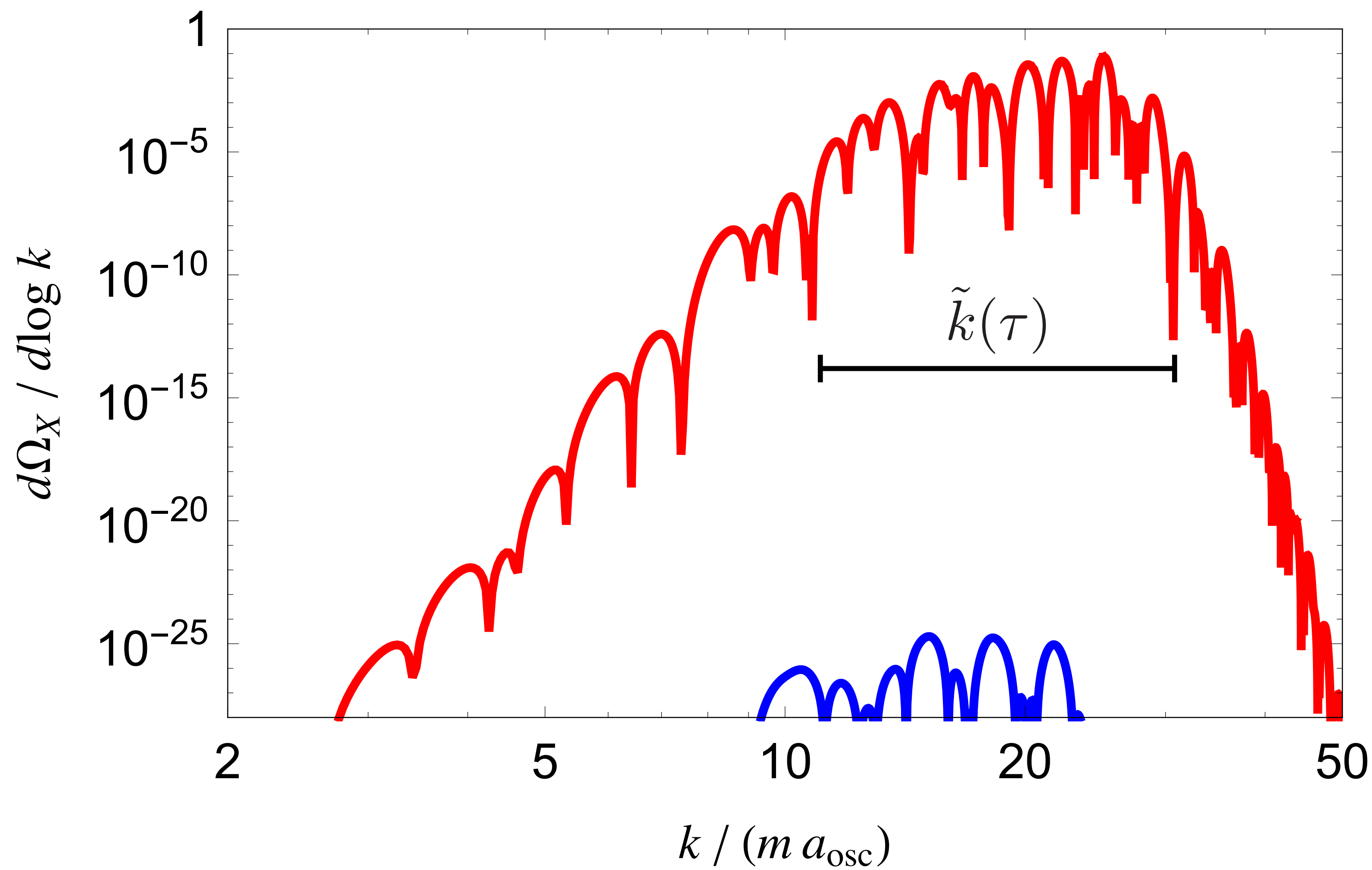
Dark photon spectrum

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

One dark photon helicity dominates

A certain range of modes undergoes growth

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

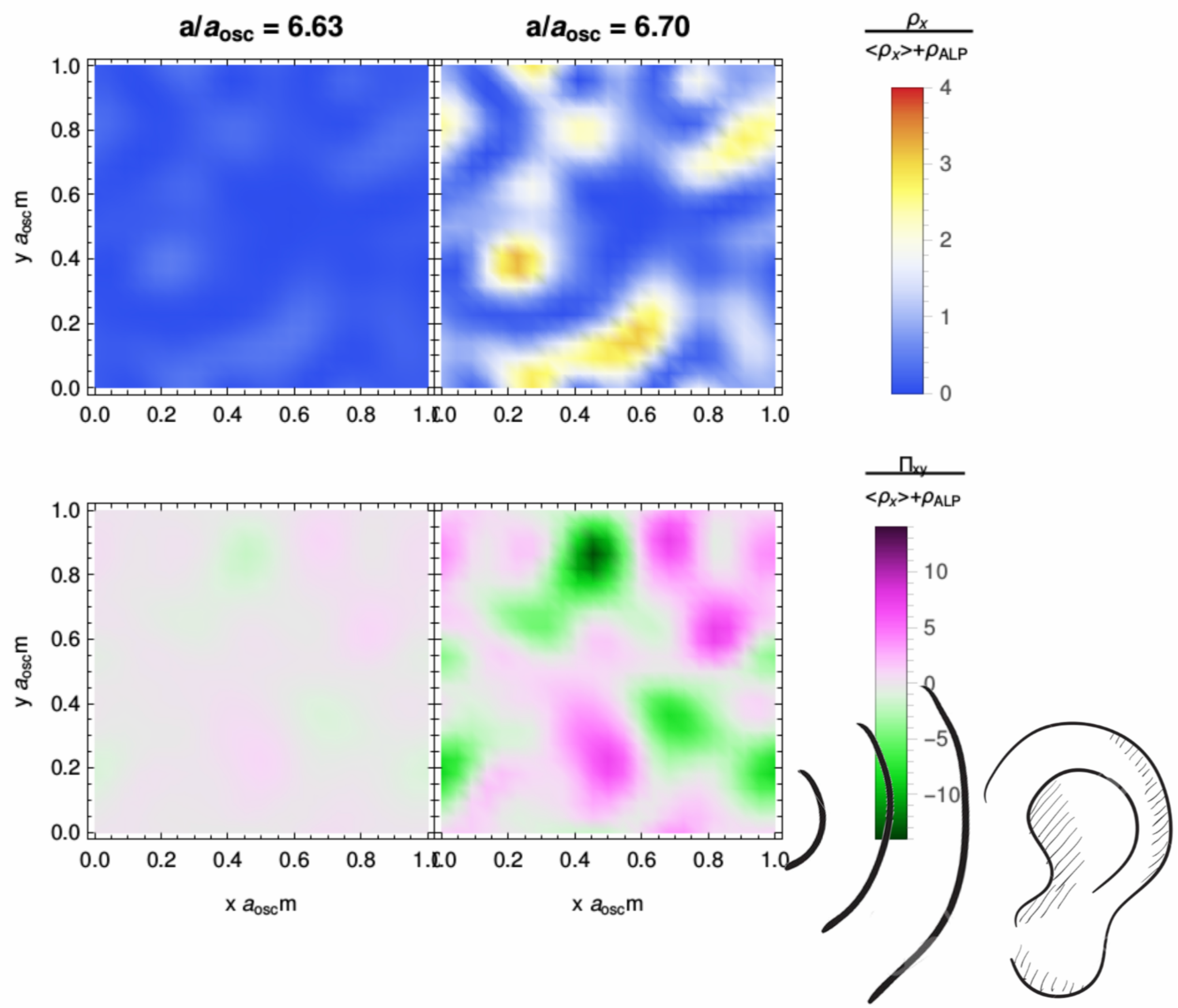


Machado, Ratzinger, Stefanek, PS, 1811.01950

GW production

Energy Density of Dark Photon

Anisotropic Stress

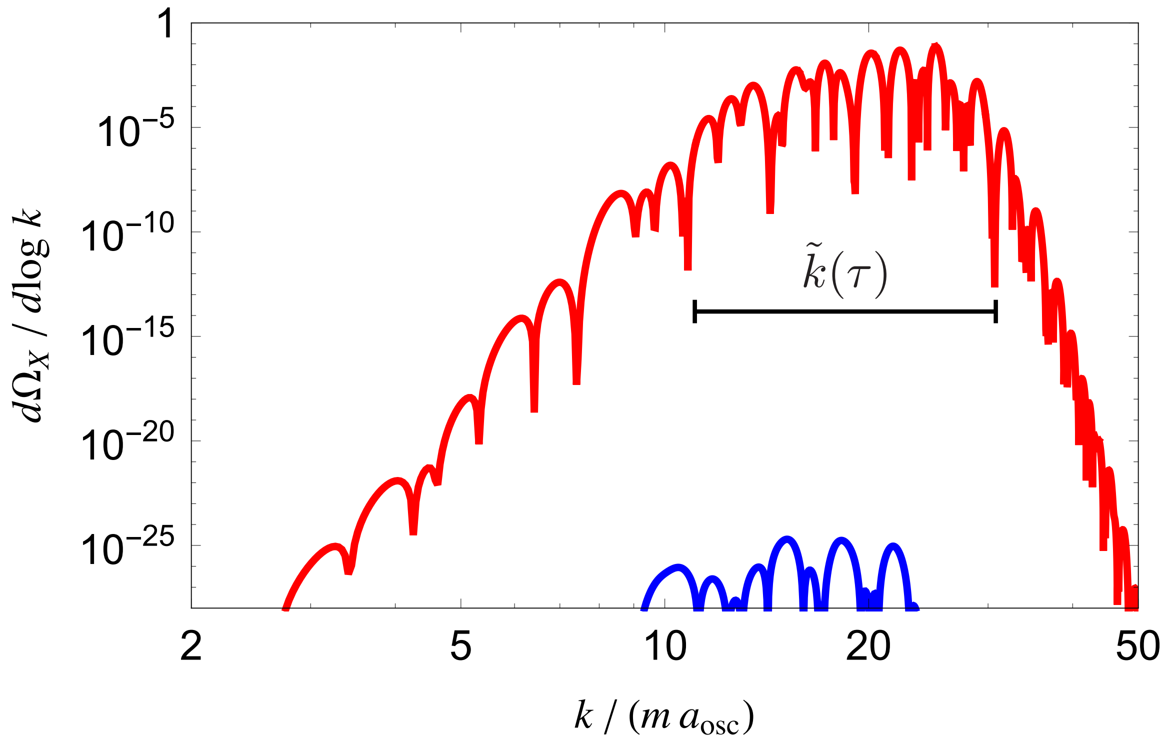


Gravity Waves → $$h''_{ij}(\mathbf{k},\tau) + k^2 h_{ij}(\mathbf{k},\tau) = \frac{2}{M_P^2}\Pi_{ij}(\mathbf{k},\tau)\,,$$ ← Anisotropic stress

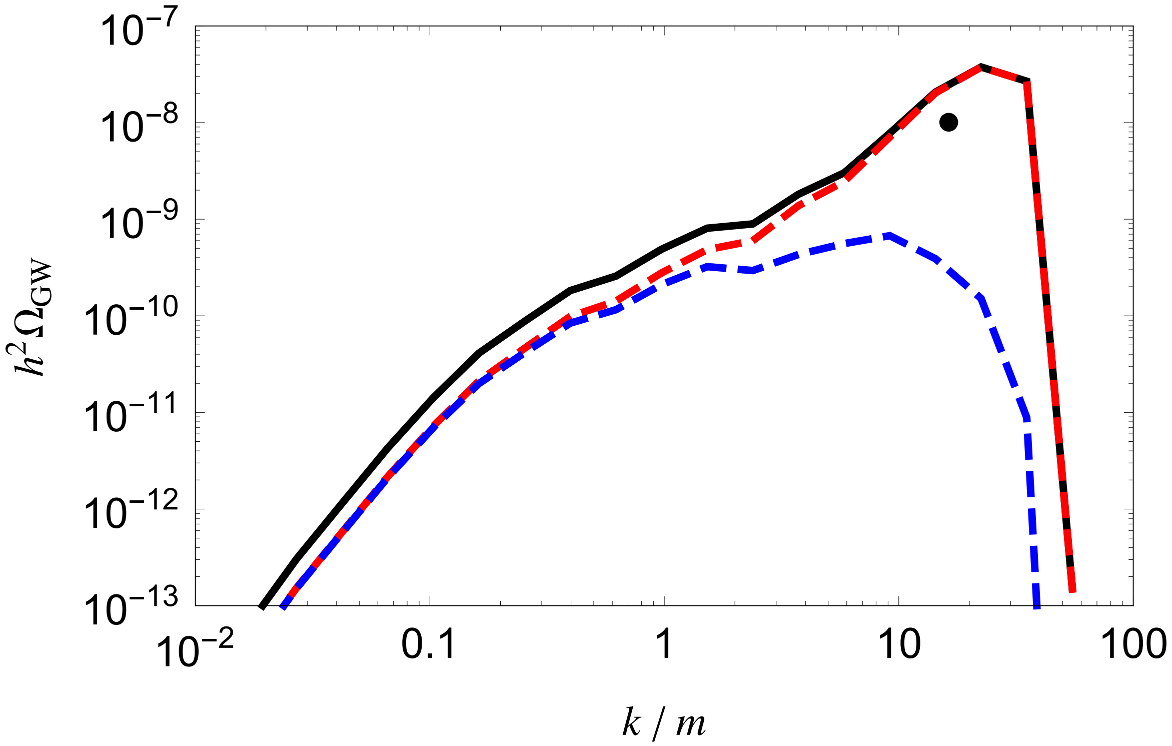
$$\hat{\Pi}_{ij}(\mathbf{k},\tau) = \frac{\Lambda_{ij}^{kl}}{a^2}\int\frac{d^3q}{(2\pi)^3}\left[\hat{E}_k(\mathbf{q},\tau)\hat{E}_l(\mathbf{k}-\mathbf{q},\tau) + \hat{B}_k(\mathbf{q},\tau)\hat{B}_l(\mathbf{k}-\mathbf{q},\tau)\right].$$

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

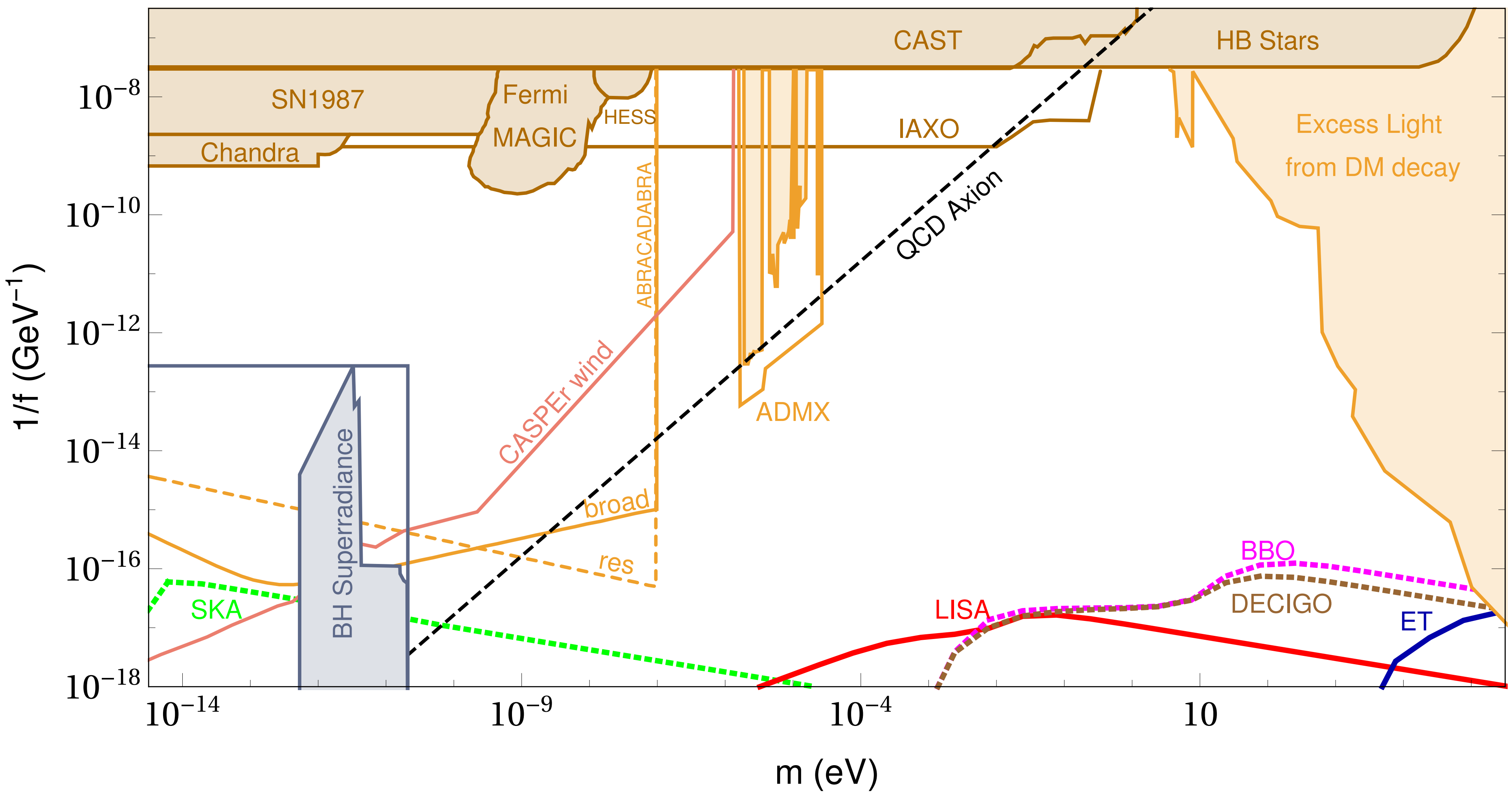


GW spectrum

Machado, Ratzinger, Stefanek, PS, 1811.01950

GW probes of audible ALPs

Machado, Ratzinger, Stefanek, PS, 1912.01107



Mainly sensitive to high scale ALPs, since

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

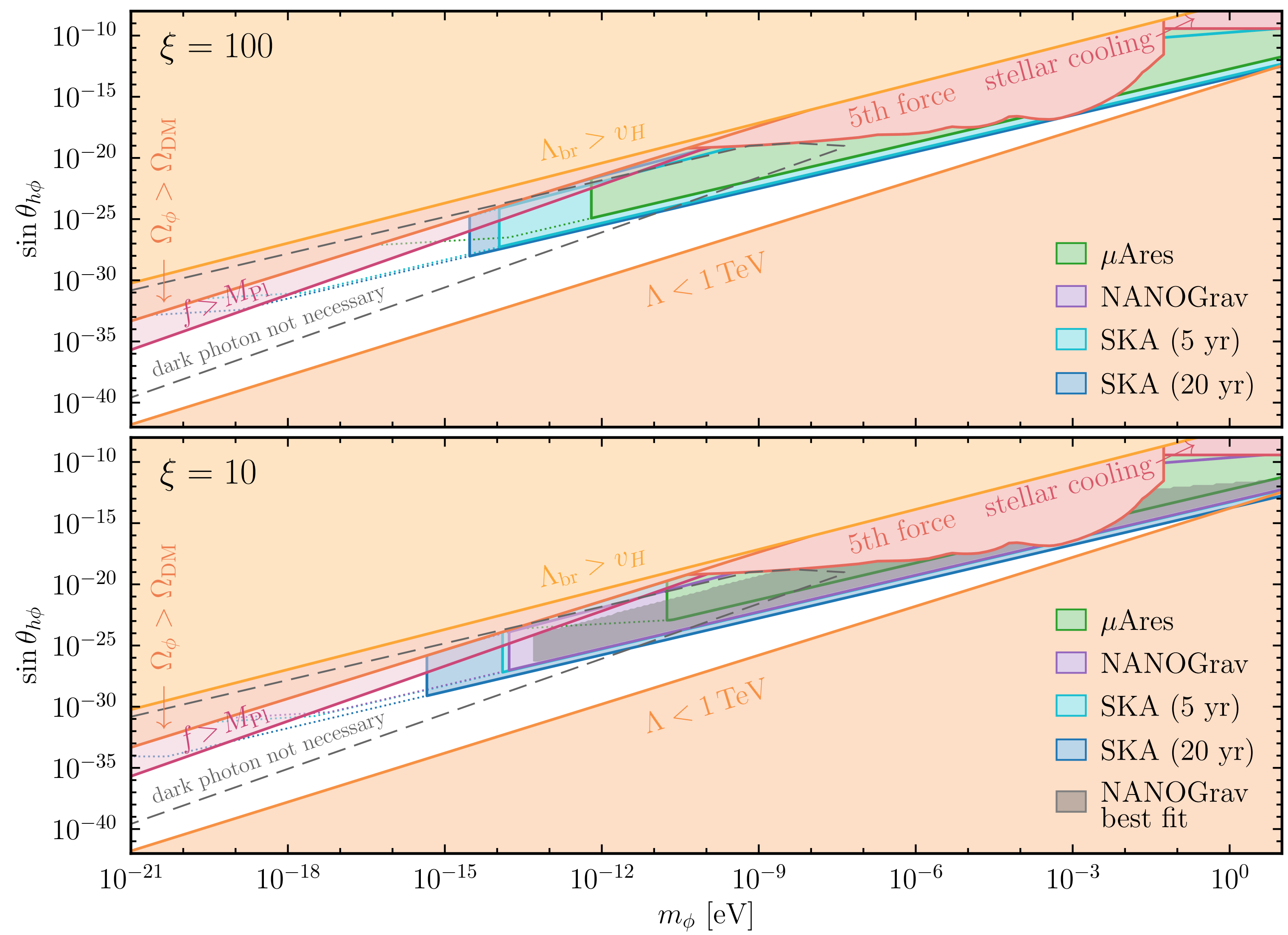
Audible relaxion

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

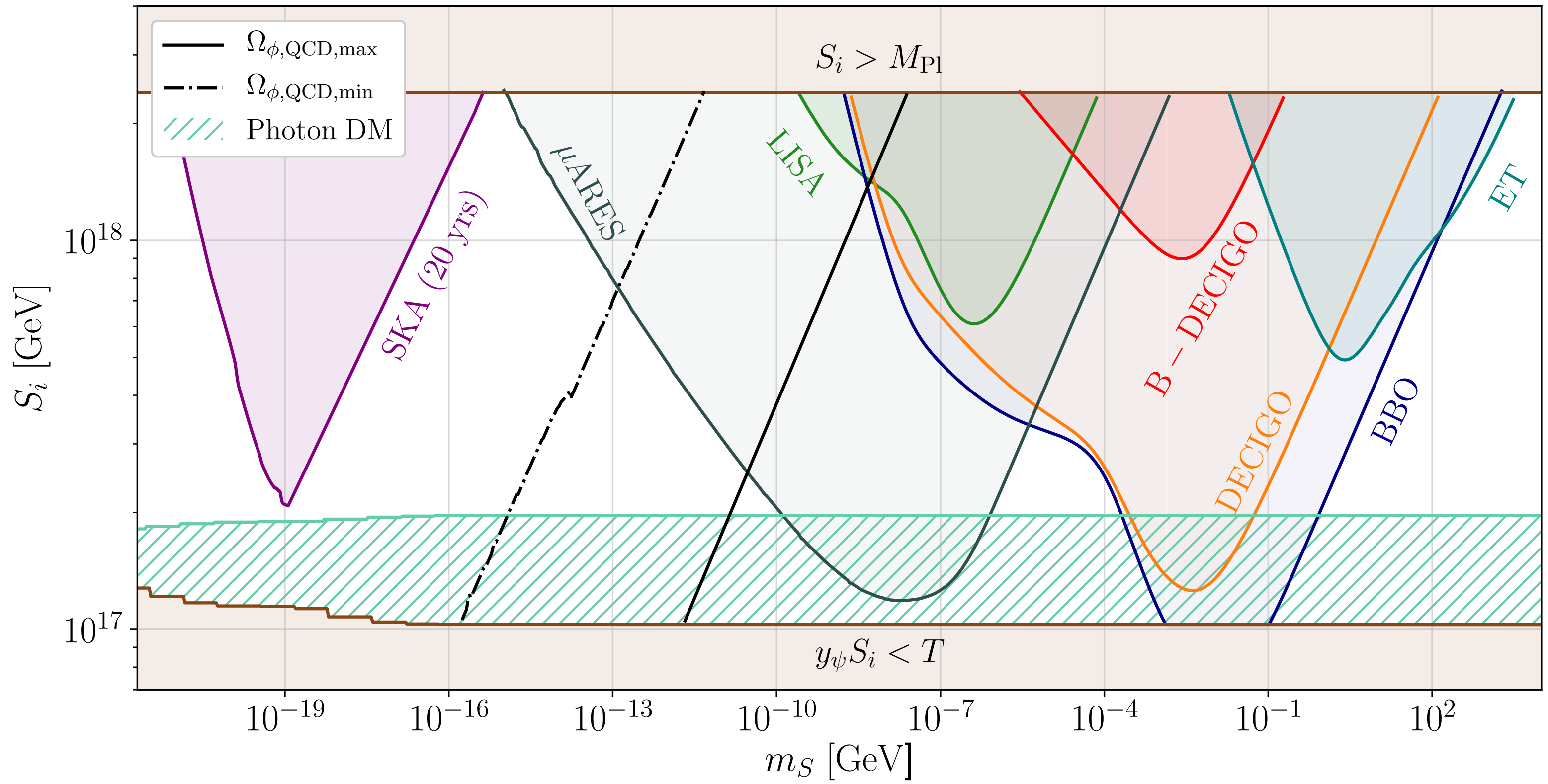
GWs from kinetic misalignment

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

Supercool audible axions

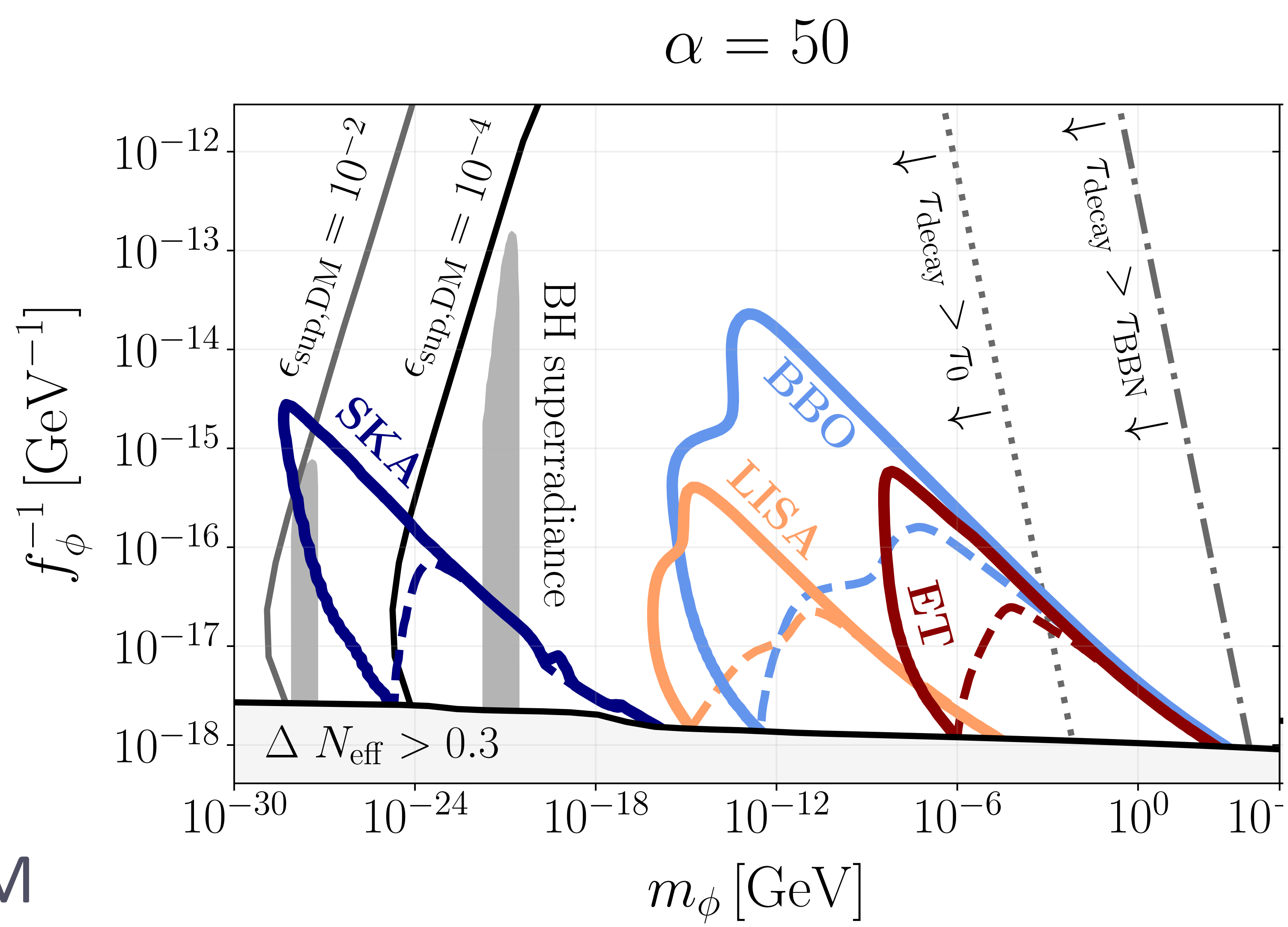
Assume ϕ is trapped initially (e.g. trapped misalignment)

Rolling delayed below

$m_\phi \sim H$

Benefits:

- Observable GWs at smaller f_ϕ
- Also for smaller ALP coupling
- Potentially even with SM photon



Christopher Gerlach, Daniel Schmitt, PS, in progress

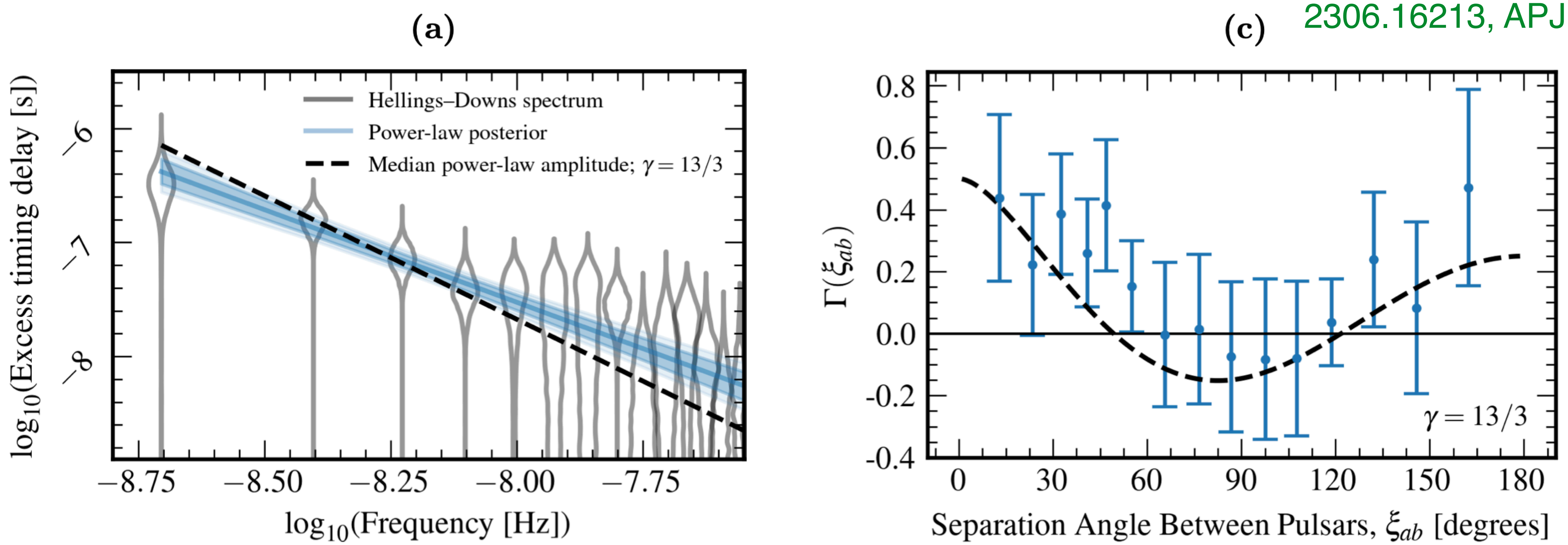
Pulsar Timing Arrays

What is a Pulsar Timing Array?

Pulsar timing arrays

NANOGrav has observed evidence for a stochastic GW background at nano-Hz frequencies:

NANOGrav Collaboration, 2306.16213, APJL 951



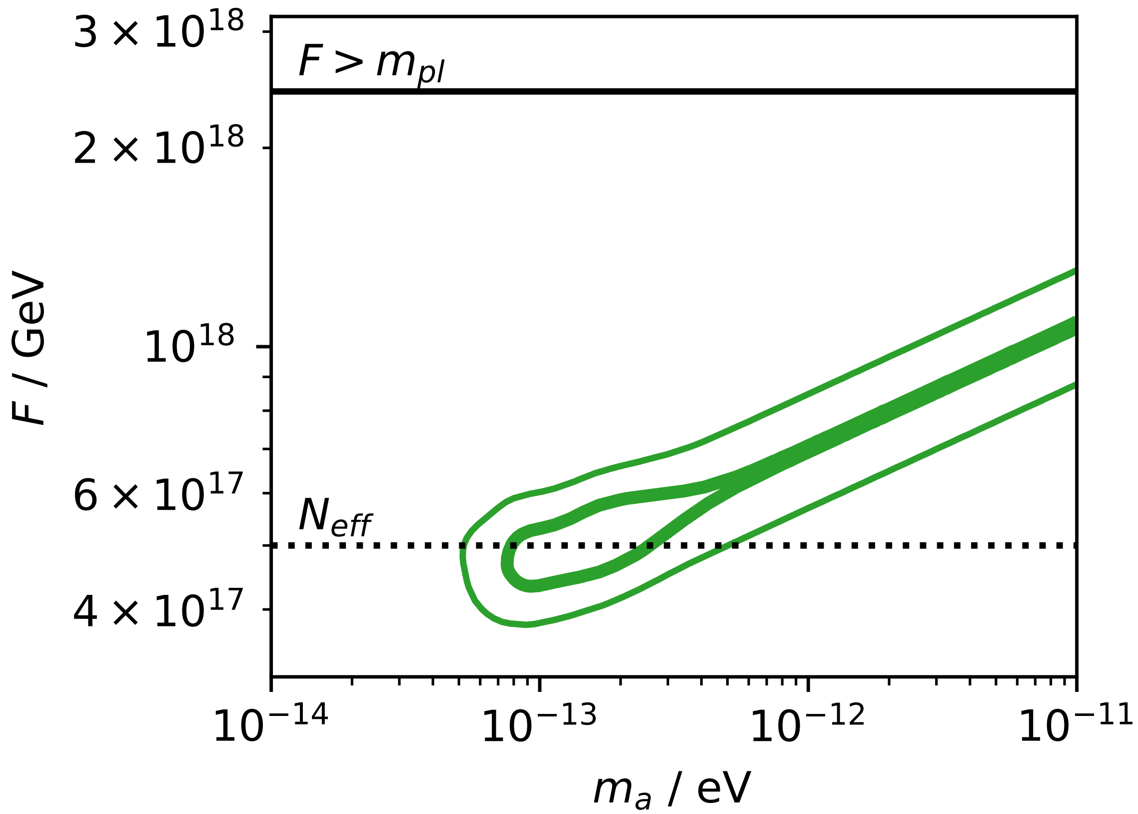
Strong evidence for Hellings-Downs correlation

Also supported by new EPTA+InPTA, CPTA data (PPTA less)

Did PTAs hear the audible axion?

2020: Maybe

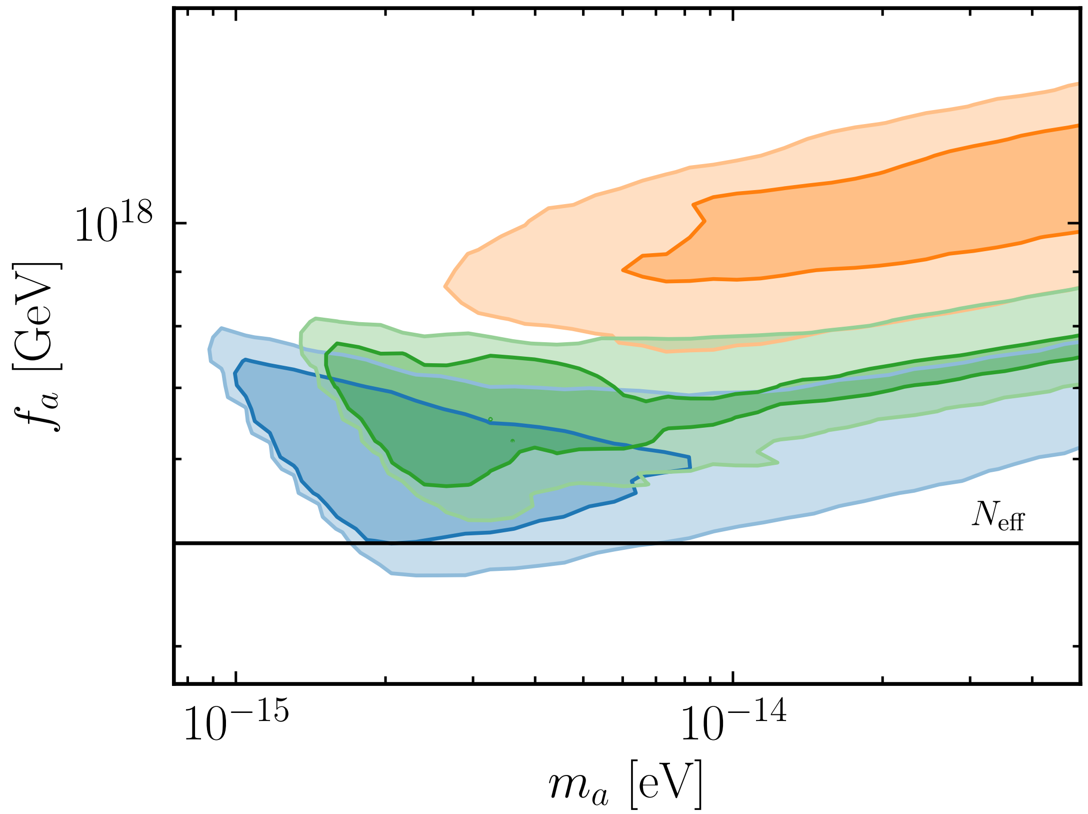
Wolfram Ratzinger & PS, 2009.11875



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



What about other models?

This is a very strong signal!

$$\Omega_{\text{GW, today}} \sim 10^{-9}$$

Comparison: The photon density today is $\Omega_\gamma \sim 10^{-5}$, but photons were in thermal equilibrium in early Universe

Any source that can explain this must:

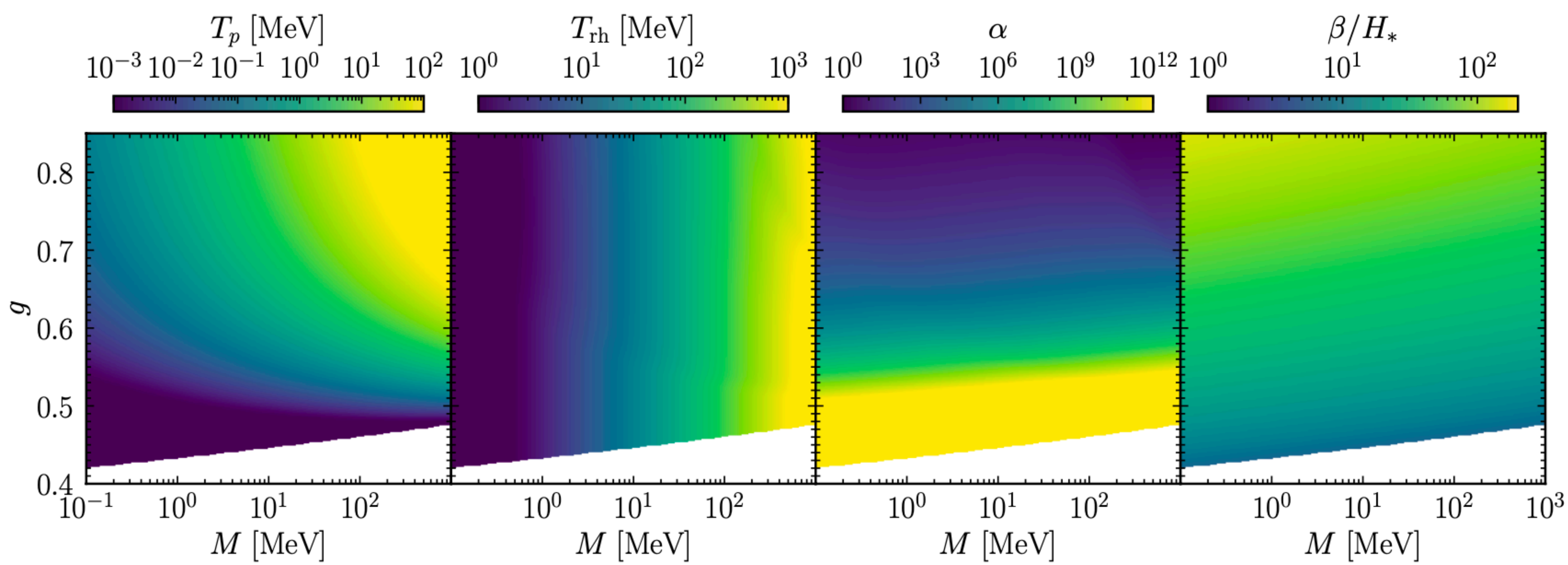
- Represent a significant fraction of the total energy density at the time of production, $T_* \sim (10 - 1000)\,\text{MeV}$
- Be very efficient at converting that energy to GW radiation
- Then disappear before onset of BBN, $T \sim 1\,\text{MeV}$

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]

Signal dominated by colliding bubbles and sound shells

Simulated by Lewicki and Vaskonen, 2208.11697

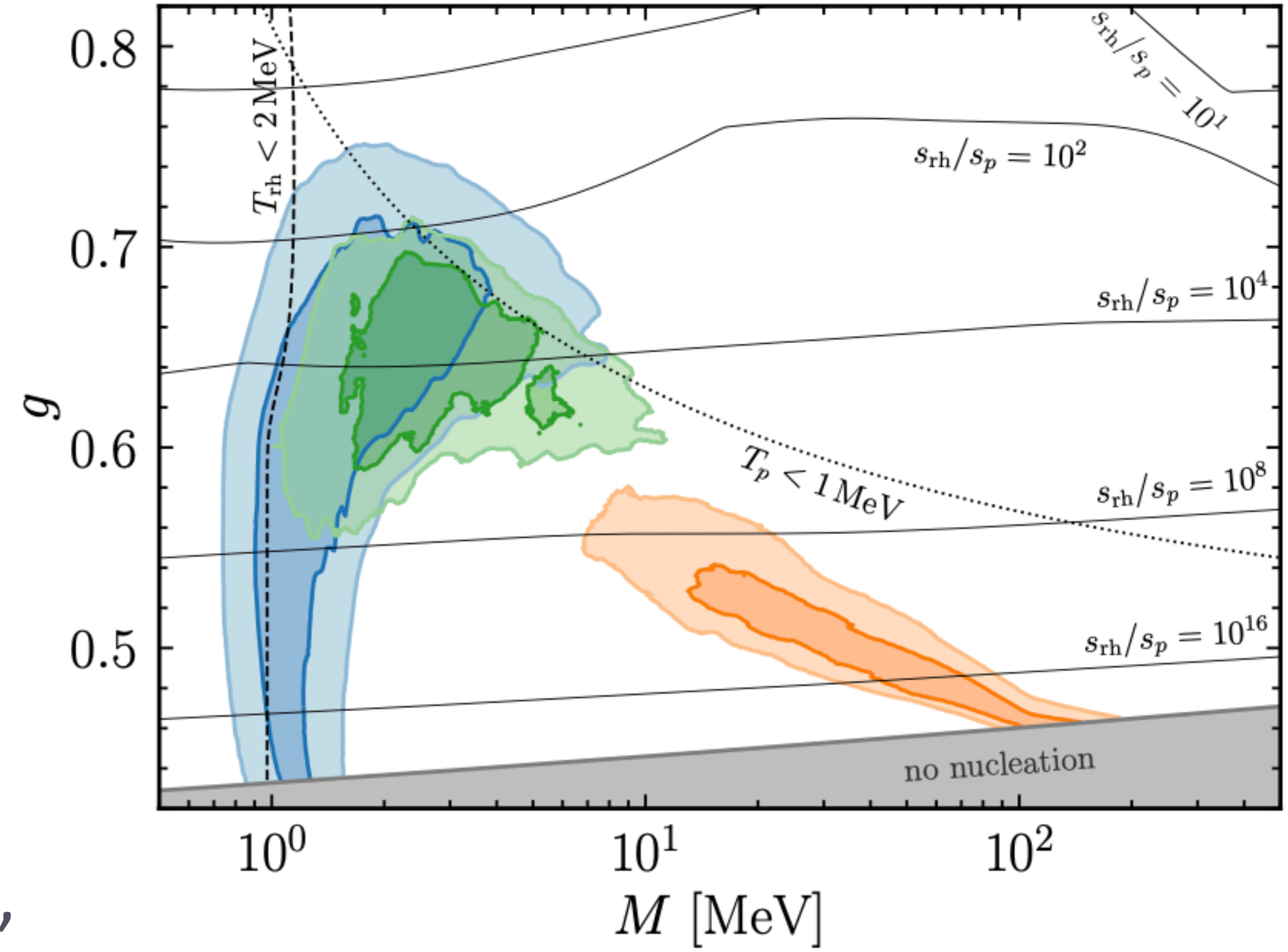
Supercooled phase transitions

Madge et al, [2306.14856](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

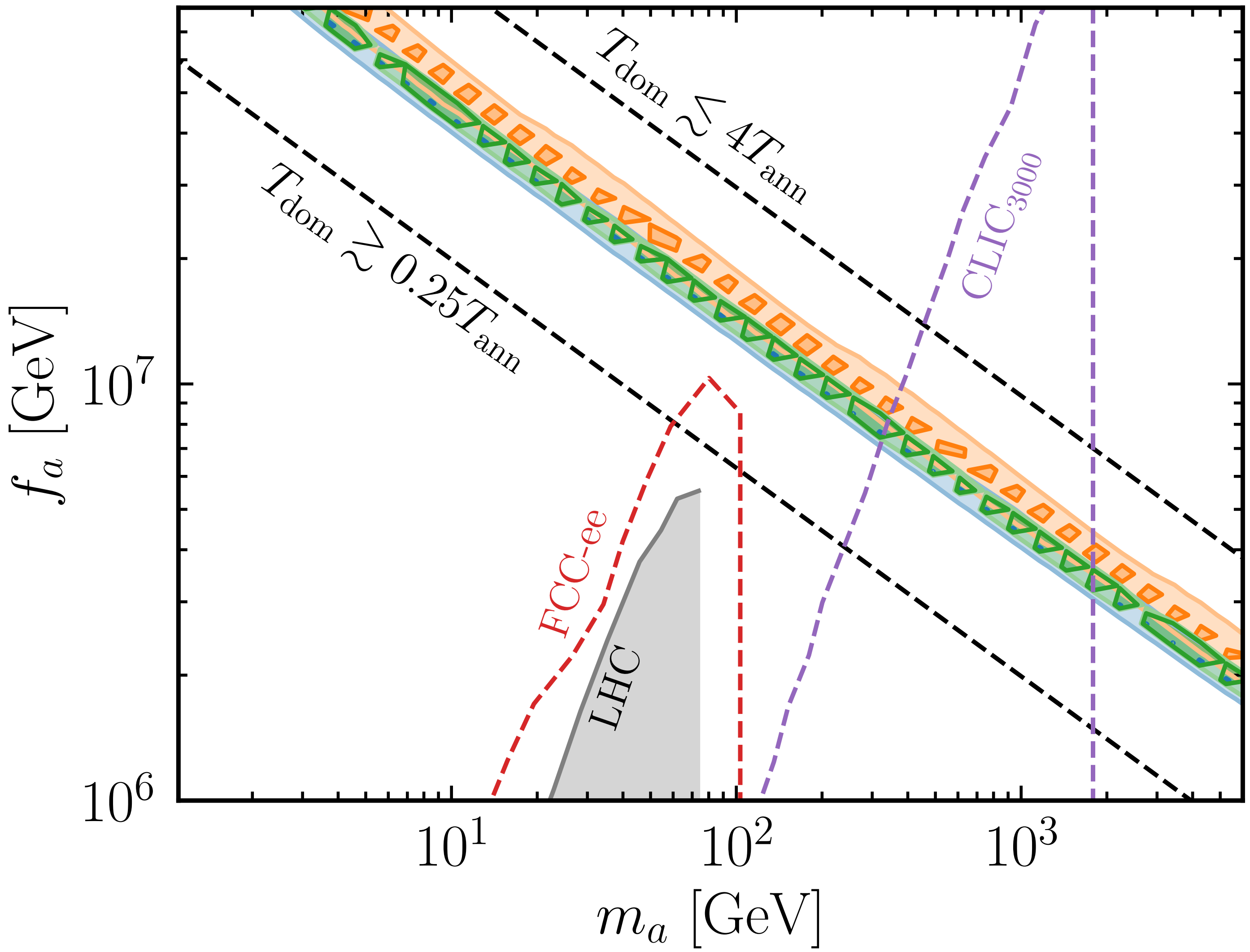
Axion/ALP domain walls

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



- Maybe room for improvement (FCC-hh?)

Invisibly decaying DWs

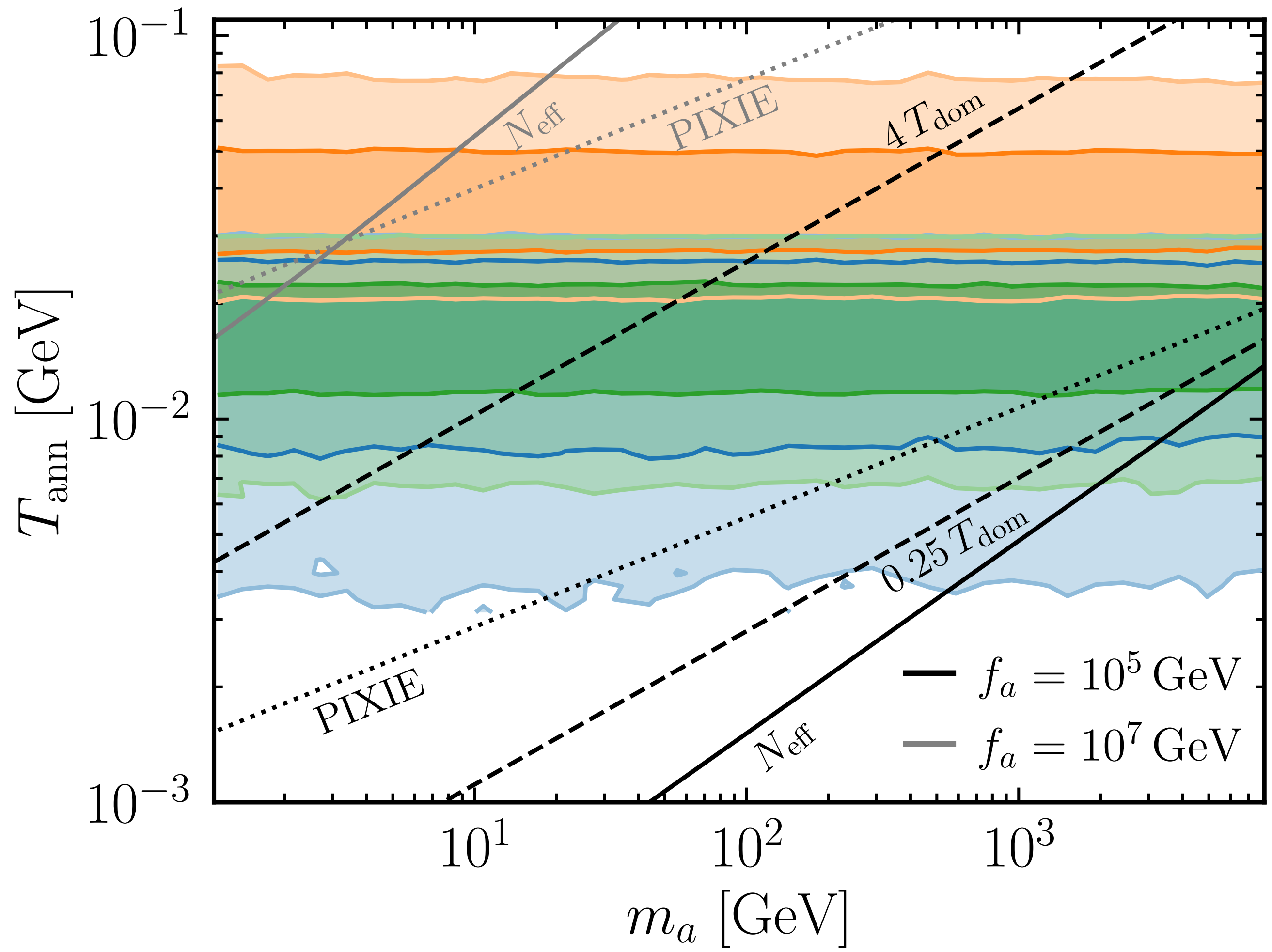
Madge et al, 2306.14856

DWs annihilate to dark radiation

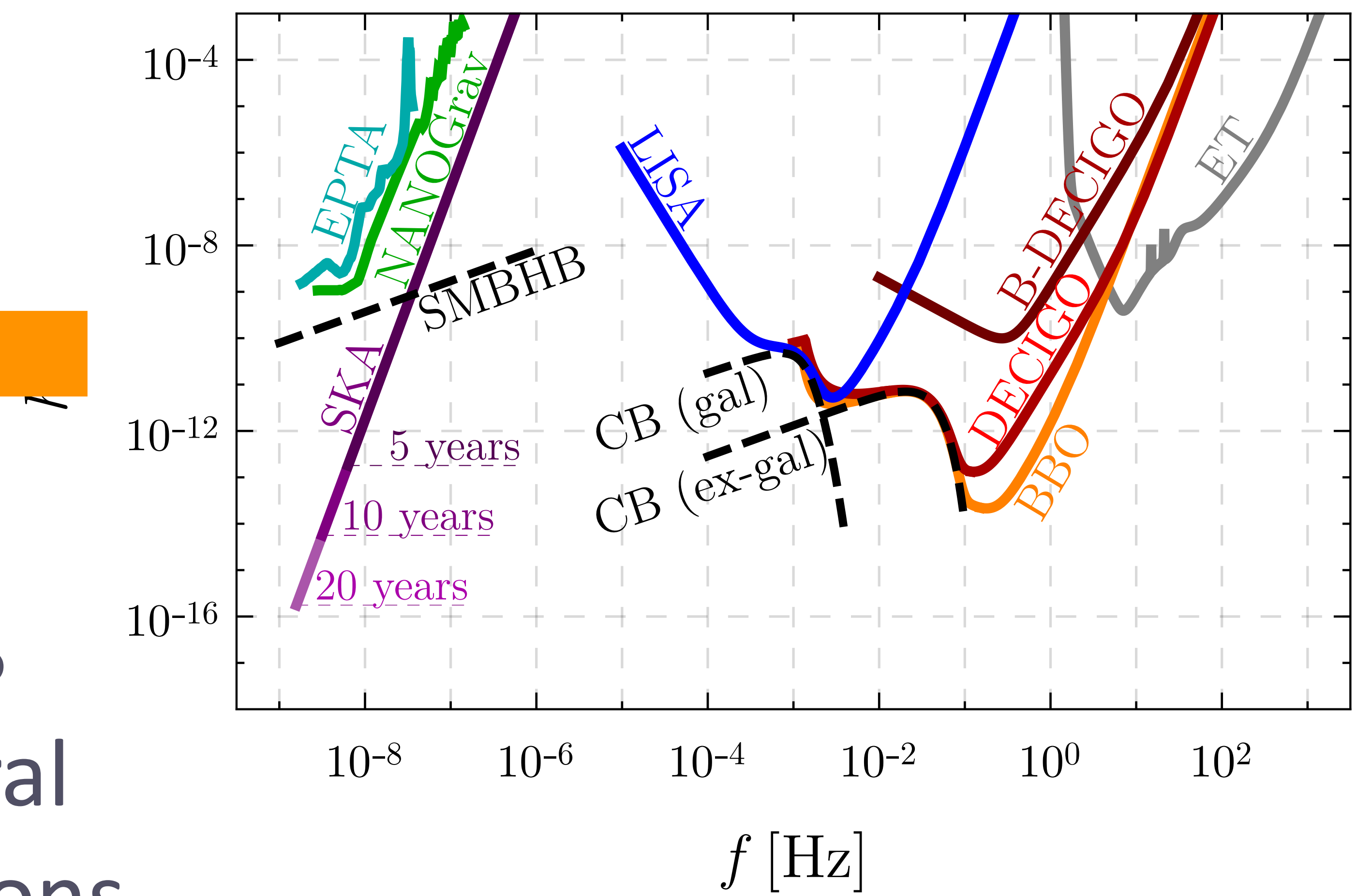
- $N_{\rm eff}$ ok mostly

Dark sector anisotropies induce CMB spectral distortions

- In reach of future experiments (PIXIE)



Pushing the limits



CMB spectral distortions

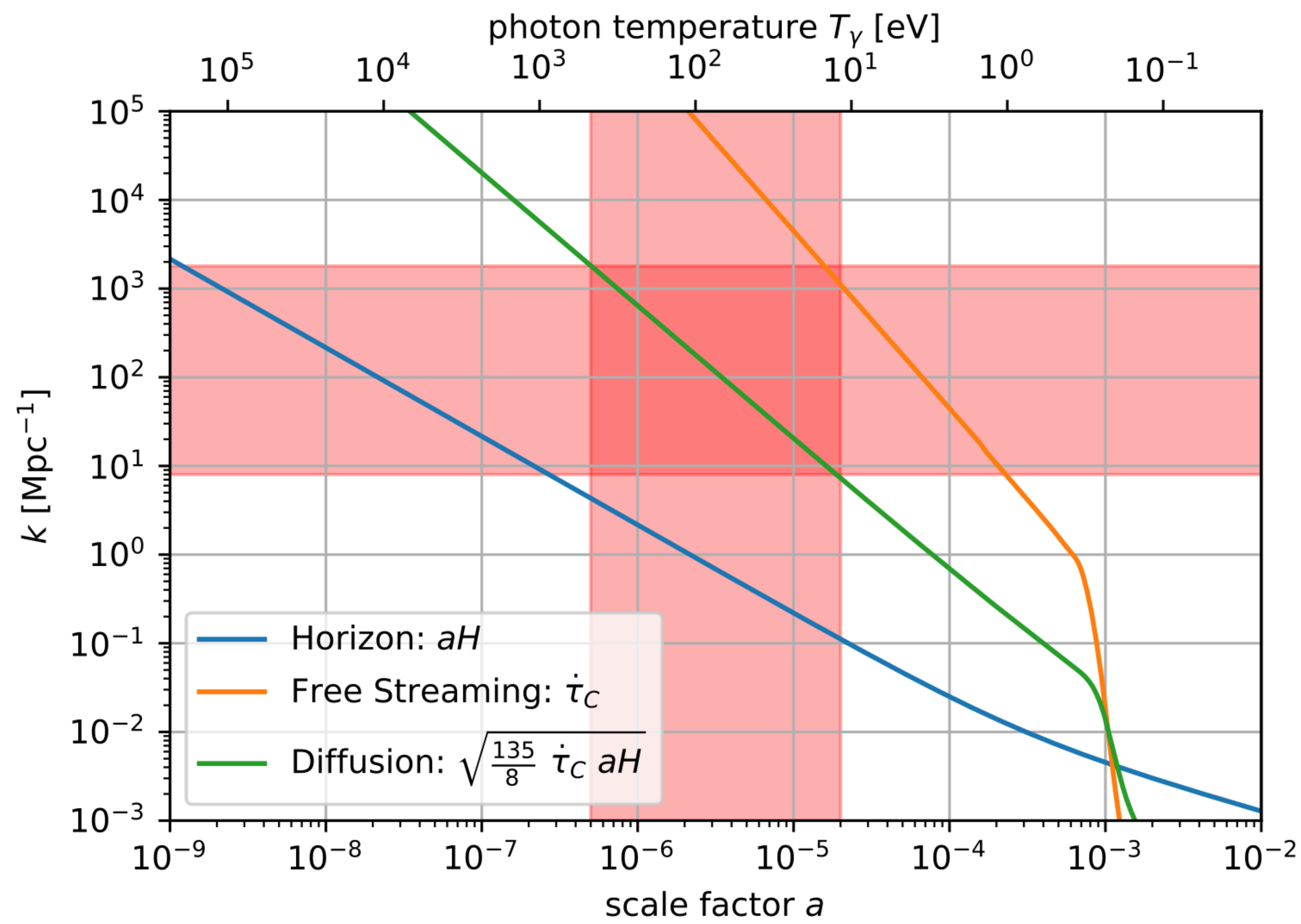
High frequency GW detectors

Spectral distortions?

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

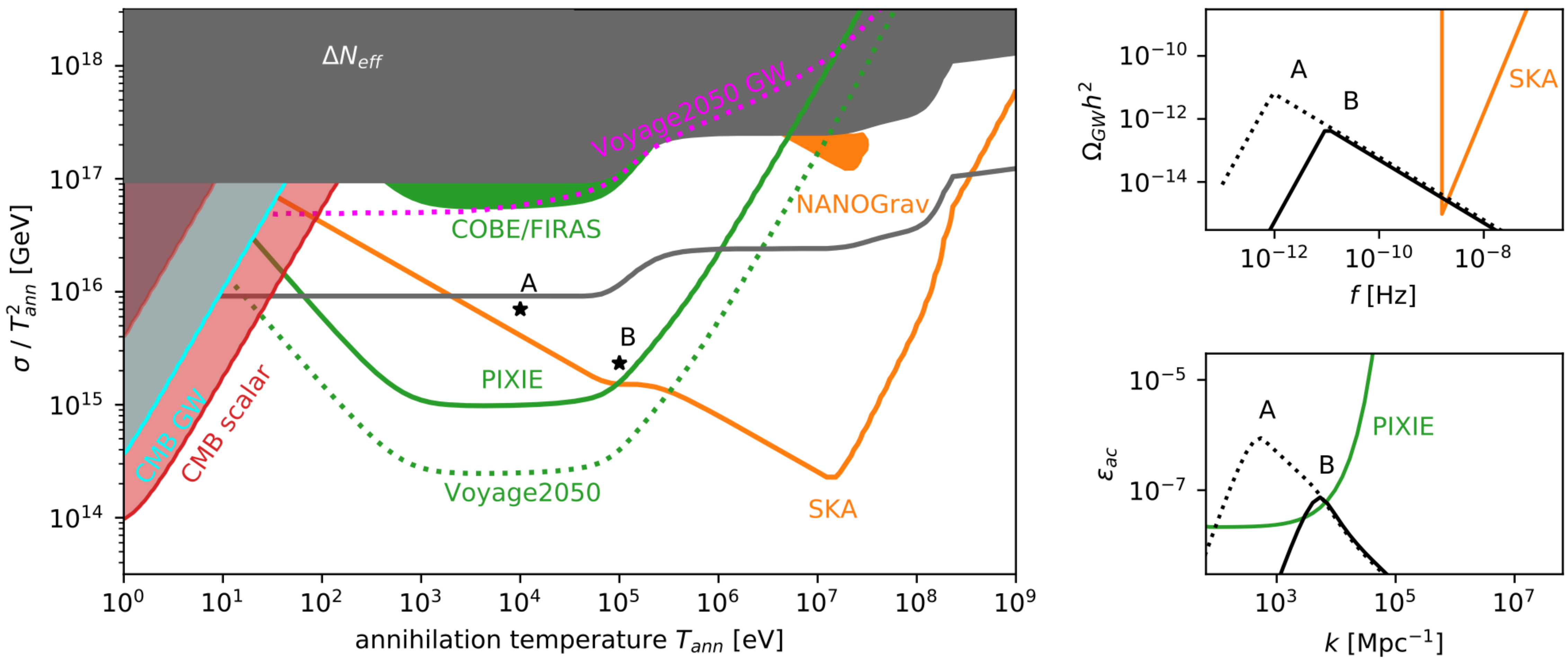
Any energy added to the photons leads to a so called μ distortion

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



Ramberg, Ratzinger & PS, 2209.14313

Example source: Annihilating domain walls



Already probes allowed parameter space

Complementary to GW probes, can break degeneracy

- Multi-messenger cosmology

Ramberg, Ratzinger & PS, 2209.14313

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

$$E_a = F_{a0} ?$$

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

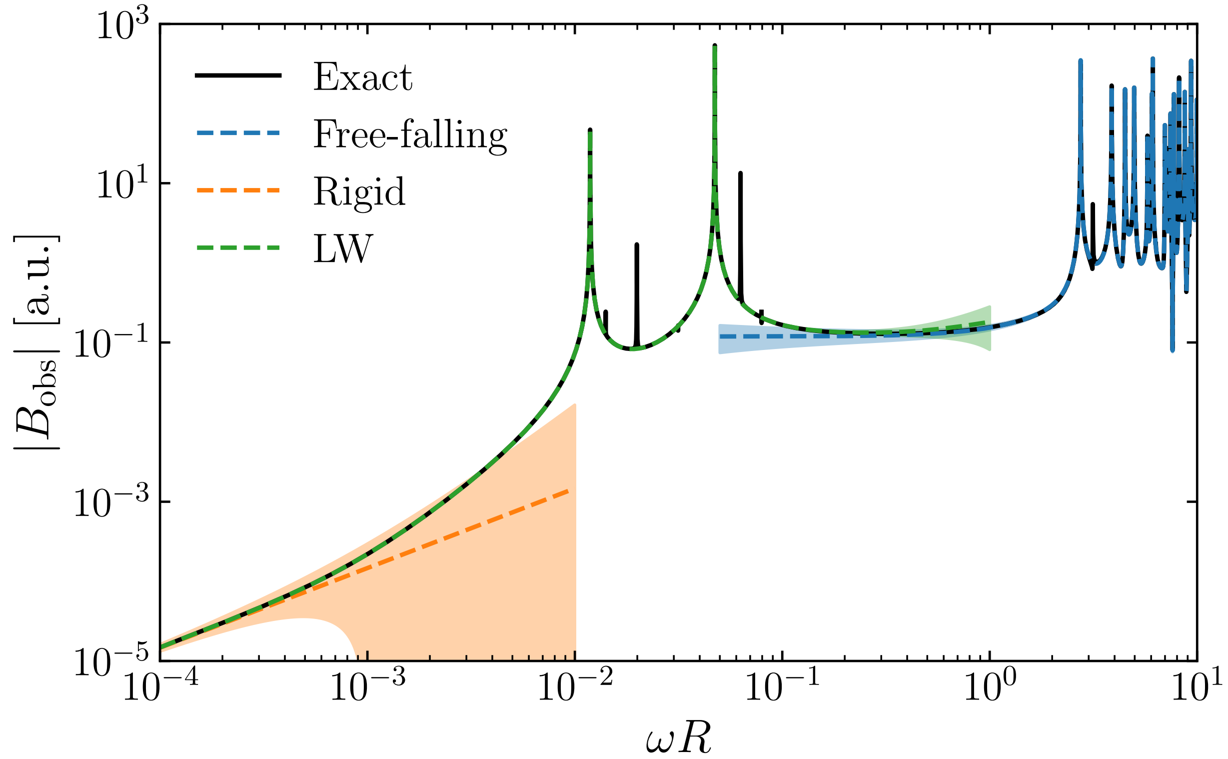
Observables should be independent!

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

Summary

GWs are new window to early, dark Universe

Future GW measurements will (start to) probe unknown dynamics in the early Universe

- Phase transitions, scalar field (axion) dynamics, cosmic strings, domain walls

Evidence for stochastic GW background in nano-Hz range, consistent with several new physics scenarios

Combination of laboratory, GW and astro/cosmo measurements required to identify sources - spectral distortions can help in PTA range

High-frequency GW searches emerging as new frontier

Exciting times :)

Extra slides :)

E&M on curved backgrounds is confusing however

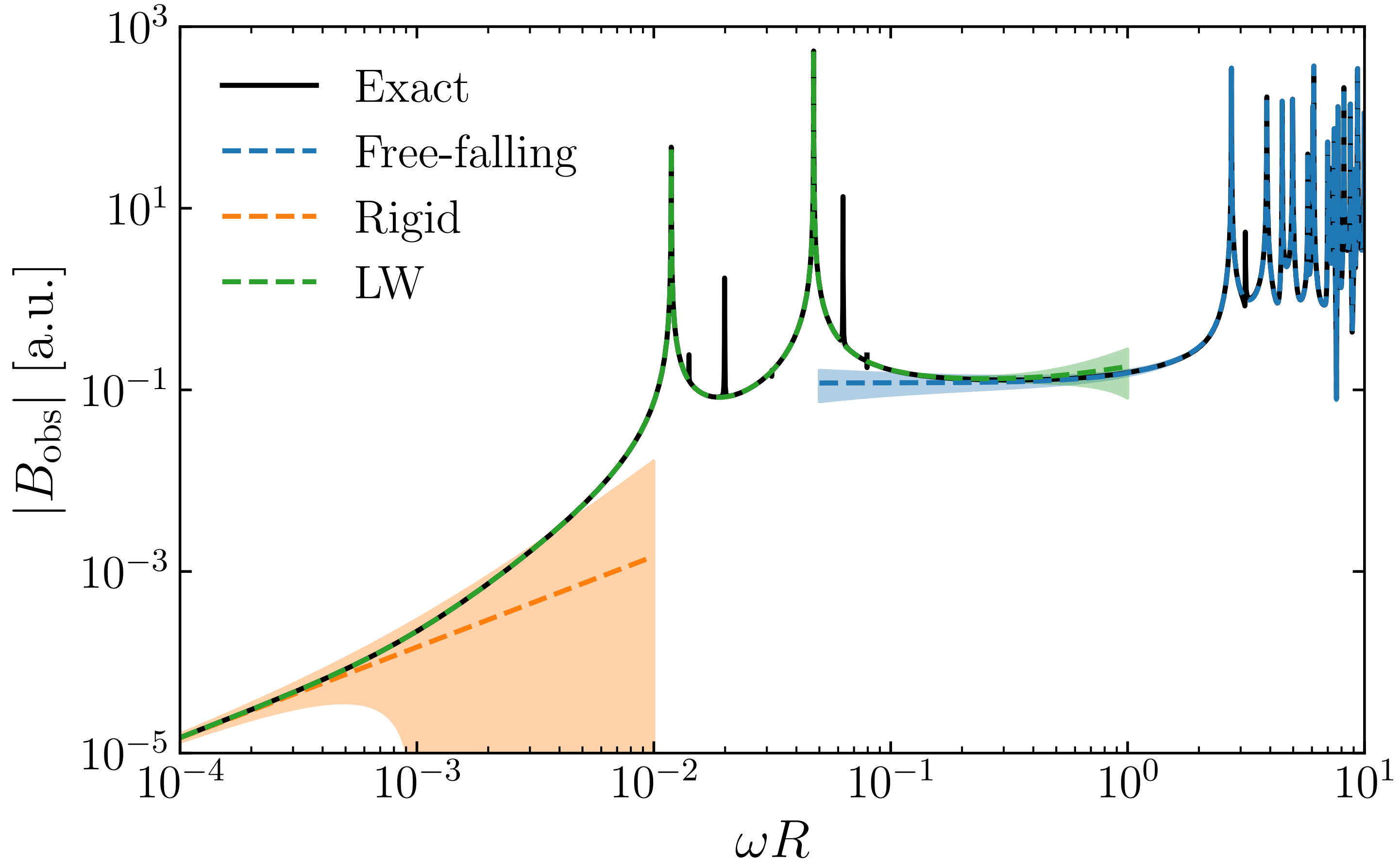


Figure 2: Amplitude of the observed magnetic field measured by a pickup loop attached to the spherical cavity of radius R, as a function of ωR. Here, the sound velocity is chosen to be $v_s = 10^{-2}$. Furthermore, the (relative) wall thickness is $\Delta R/R = 1/100$, and we have chosen only a plus polarisation of the gravitational wave, $h^+ = 1$ and $h^- = 0$. As an example, the pickup loop is located at angles of $\theta = \pi/5$ and $\varphi = 0$, such that in a spherical basis $d^- = 0.572$, $d^0 = -0.588$ and $d^+ = -0.572$. Similarly, in our example, the magnetic background field in this basis is given by $\overline{B}^- = 0.416$, $\overline{B}^0 = 0.81$ and $\overline{B}^+ = -0.416$, respectively.

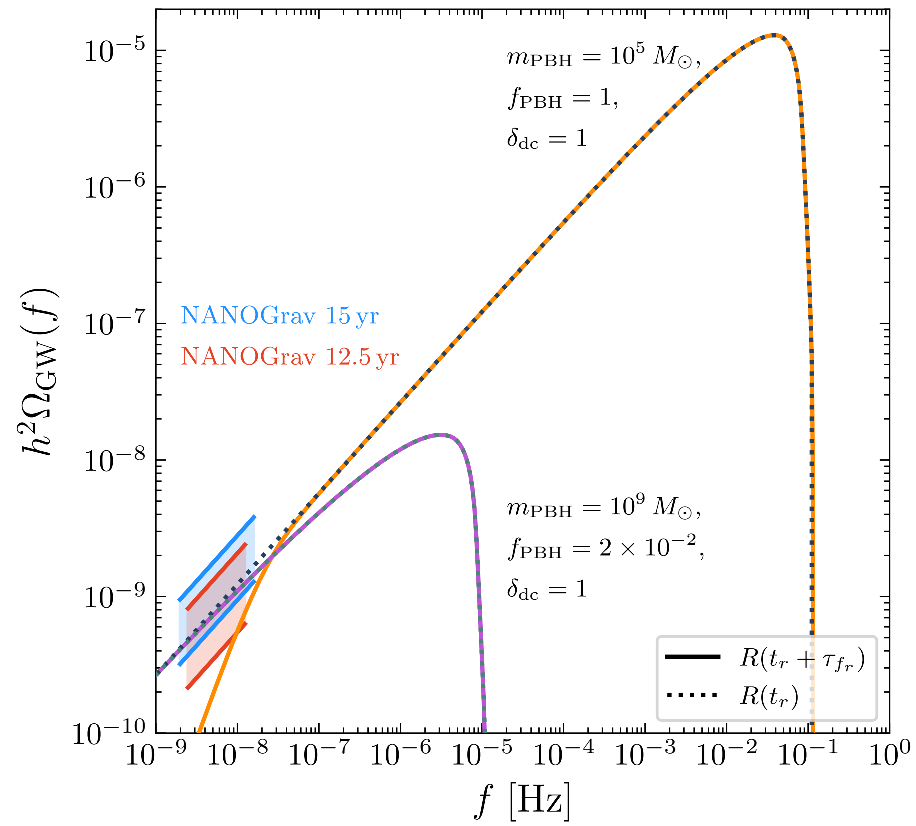
One more: Primordial black holes

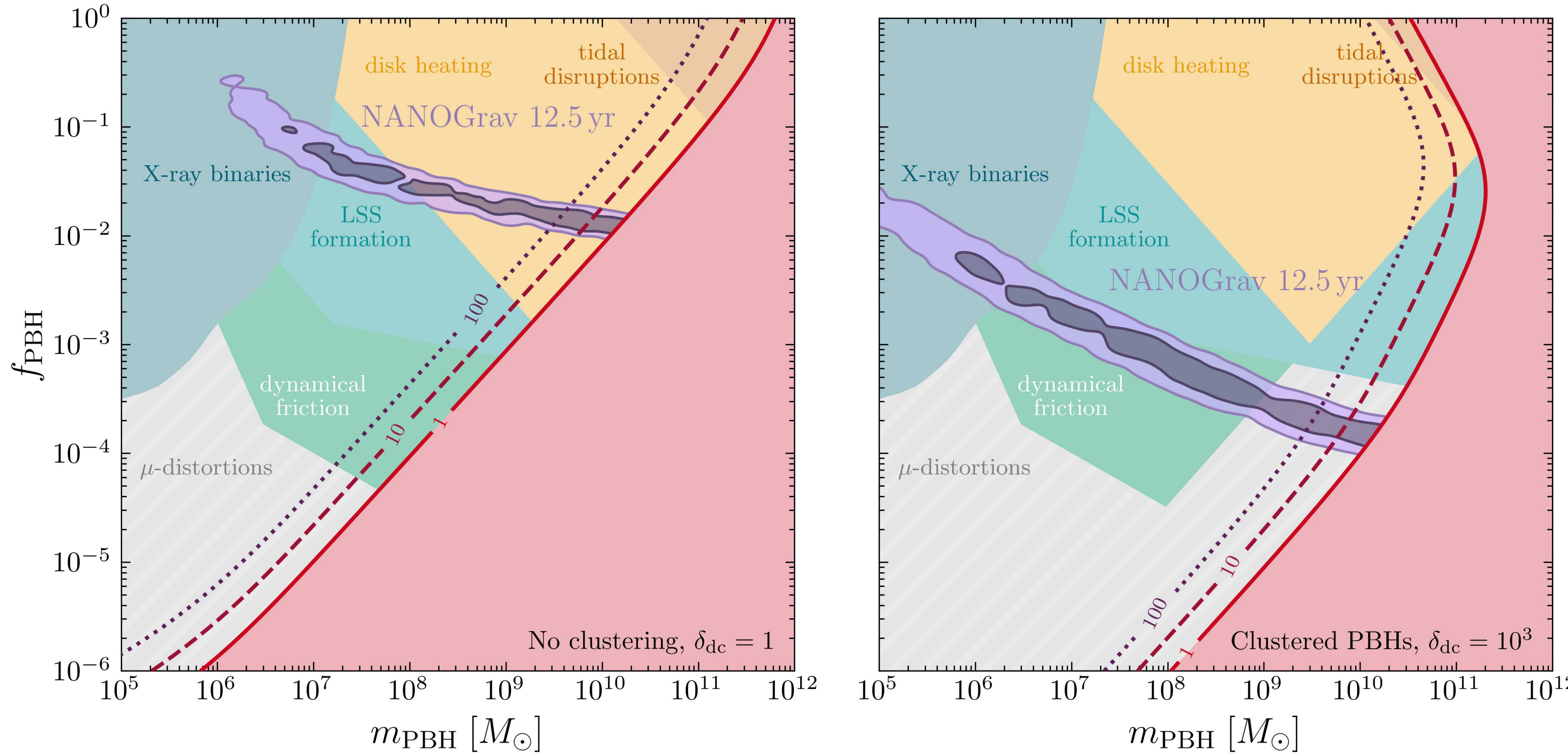
Depta et al, 2306.17836

pBH mergers can explain the data

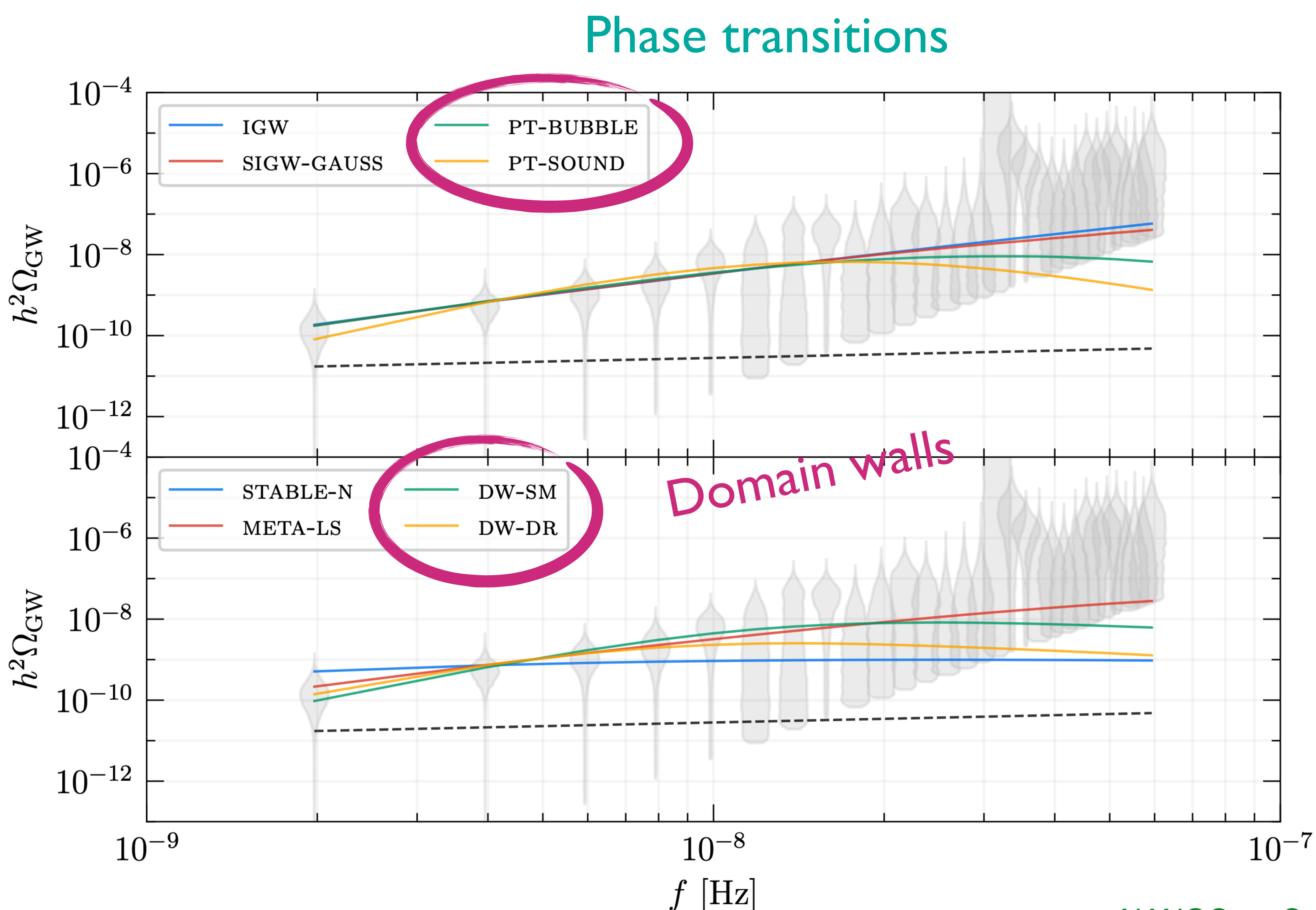
Clustering needed to evade most stringent bounds

Expect larger anisotropies than from primordial sources





Compatible with primordial GWs from new physics

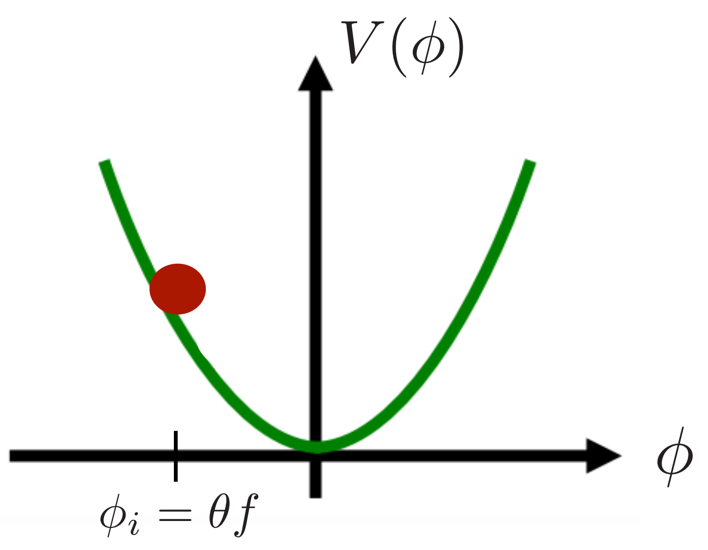


NANOGrav Collaboration,
2306.16219, APJL 951

ALP dynamics - once more

Equation of motion

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

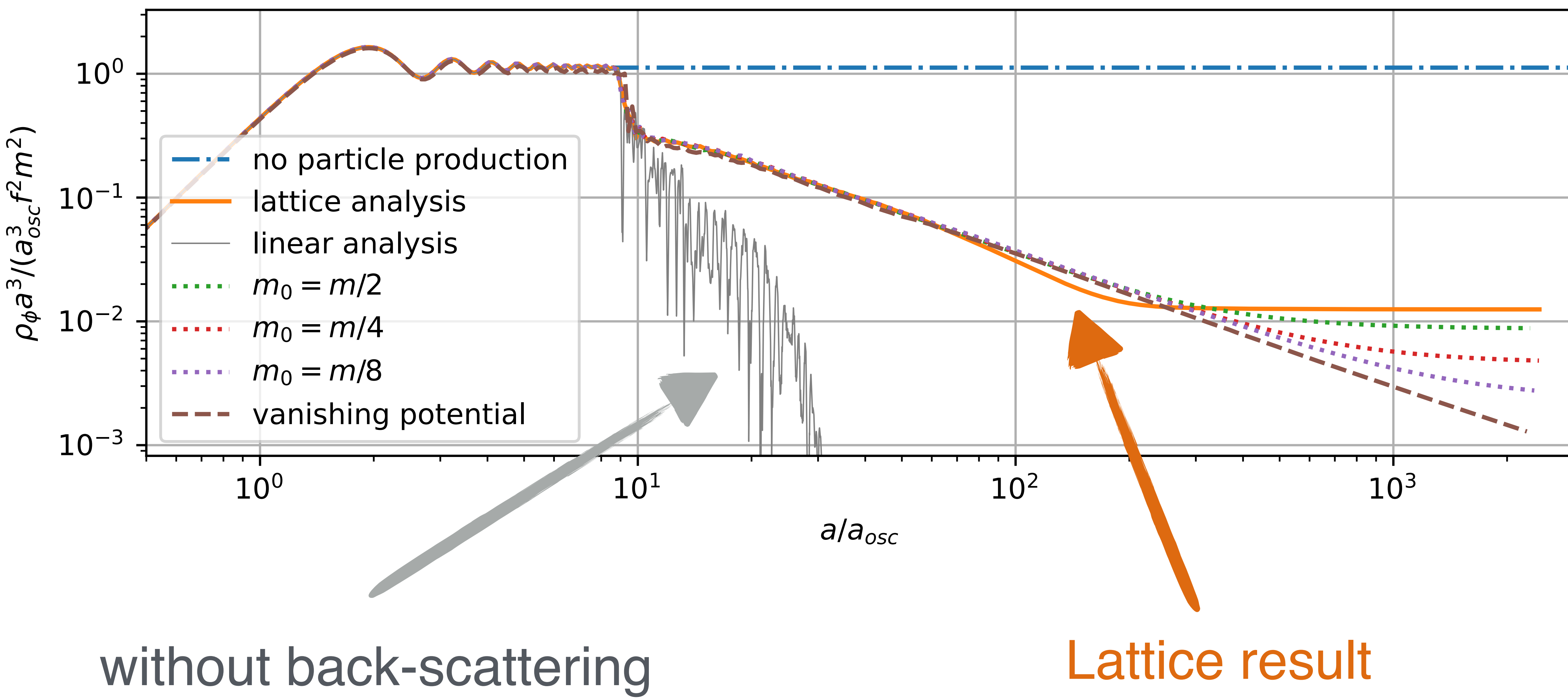


Once a significant population of dark photons is produced, the back-scattering into ALP fluctuations becomes non-negligible

Requires fully numerical treatment on the lattice

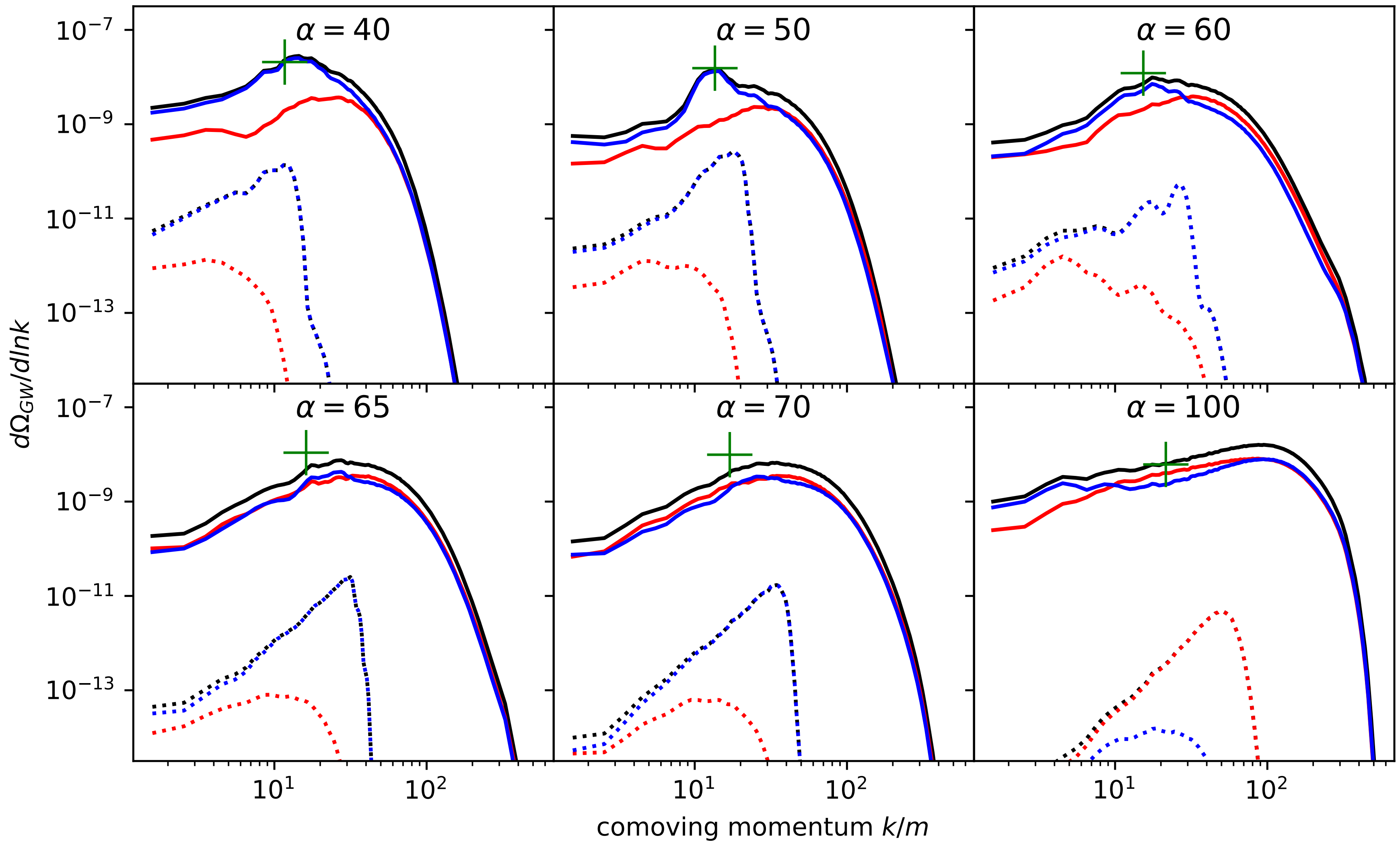
Important to get correct relic abundance prediction

From 2012.11584 with W. Ratzinger, B. Stefanek



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

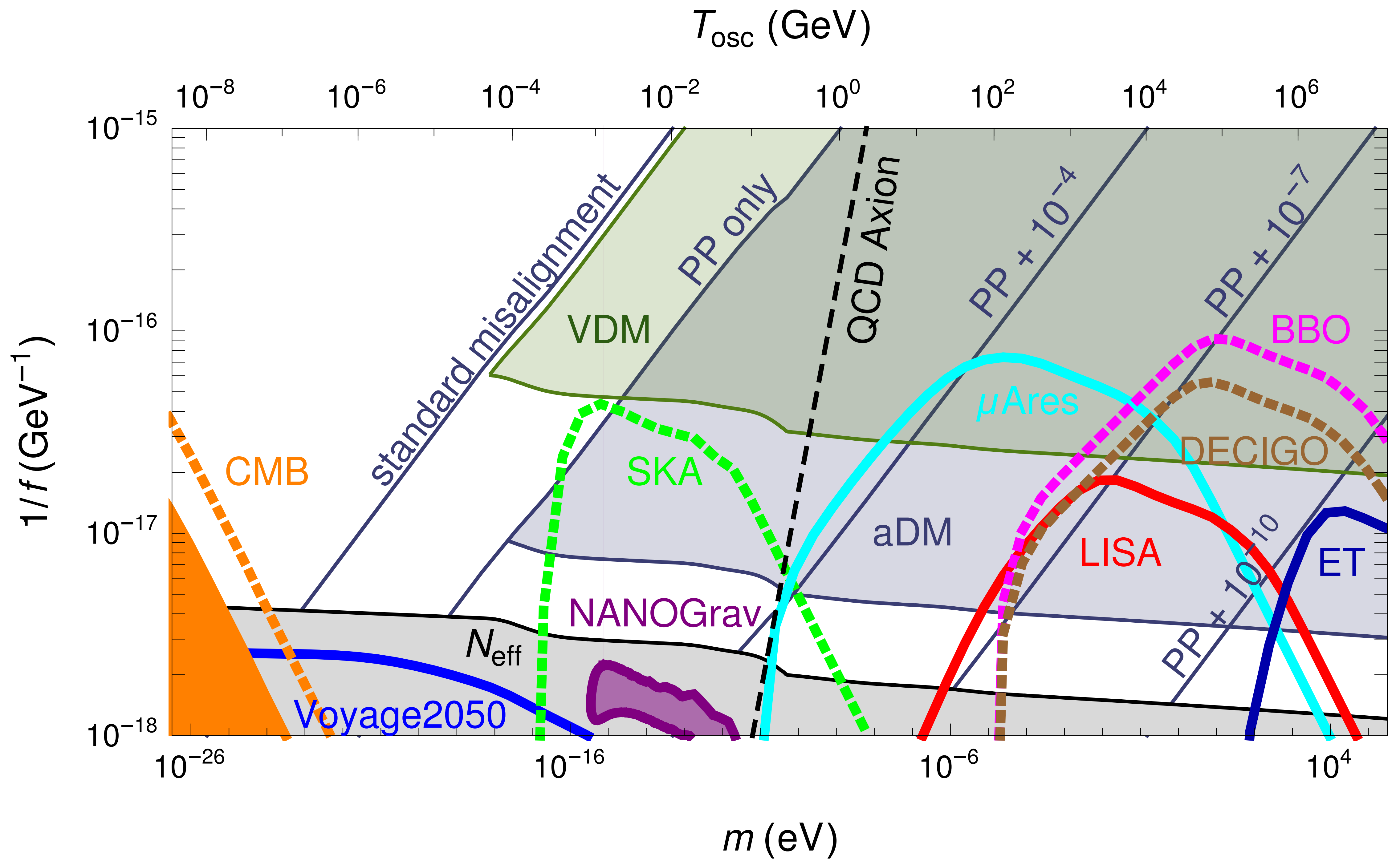
Corrections to GW signal



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

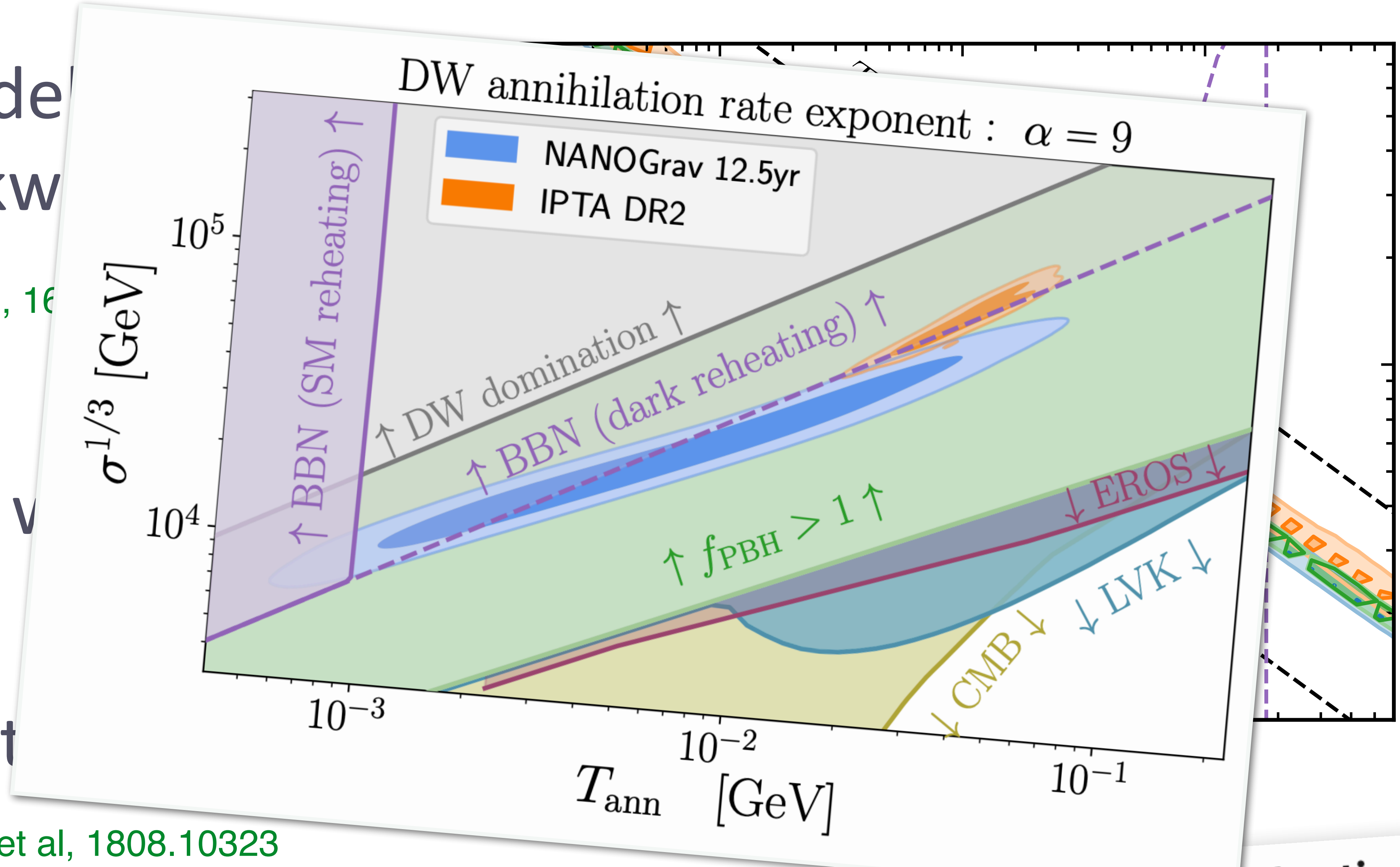
Axion/ALP domain walls

Madge et al, 2306.14856

Concrete mode
Aligned/clockw
Axions Higaki et al, 16

Heavy axion
“partners” at v
scale

In reach of fut
colliders Bauer et al, 1808.10323



Domain wall interpretation of the PTA signal confronting black hole overproduction

Yann Gouttenoire (Tel Aviv U.), Edoardo Vitagliano (Hebrew U.)

Jun 30, 2023

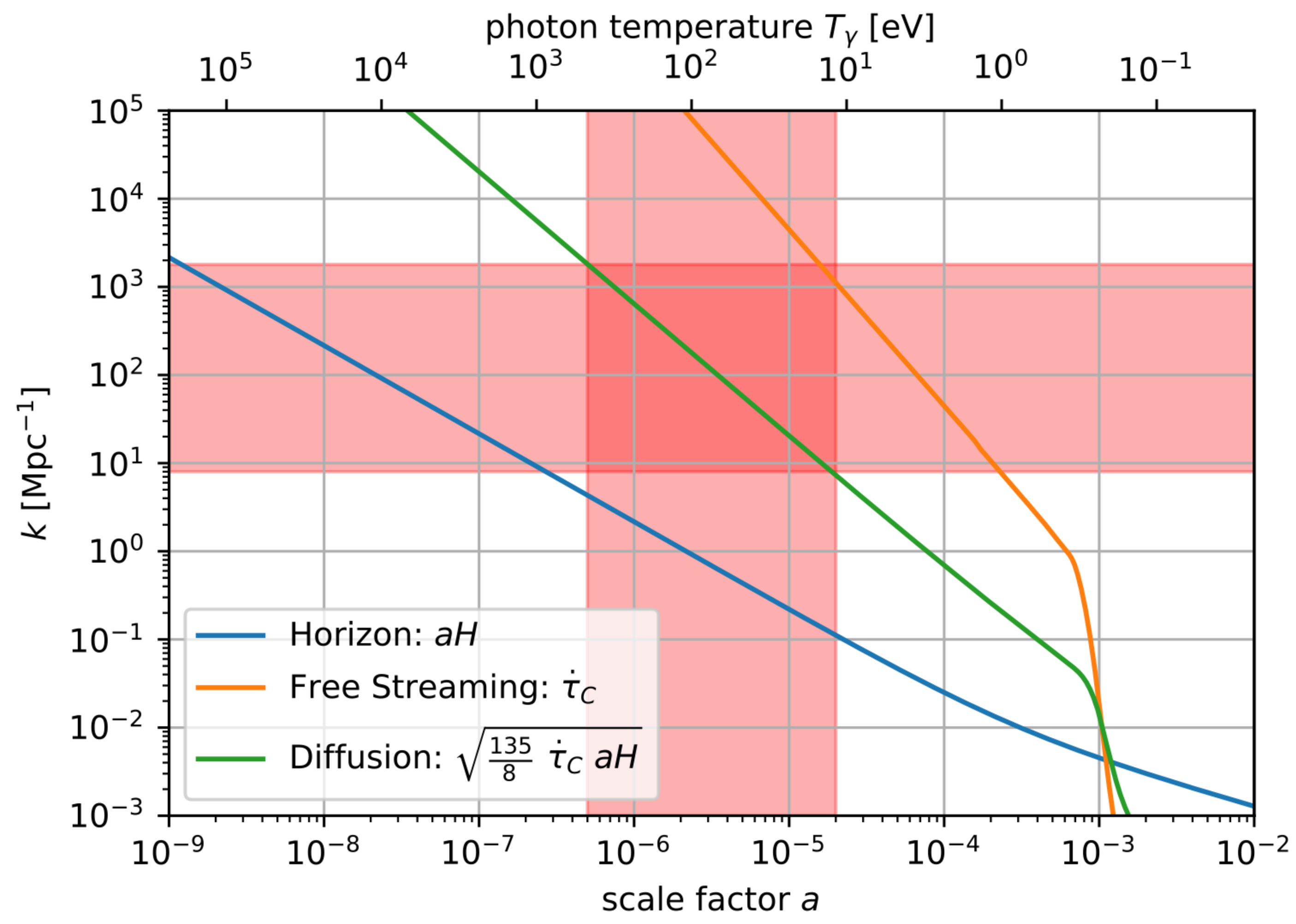
Now what about the spectral distortions?

Spectral distortions?

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

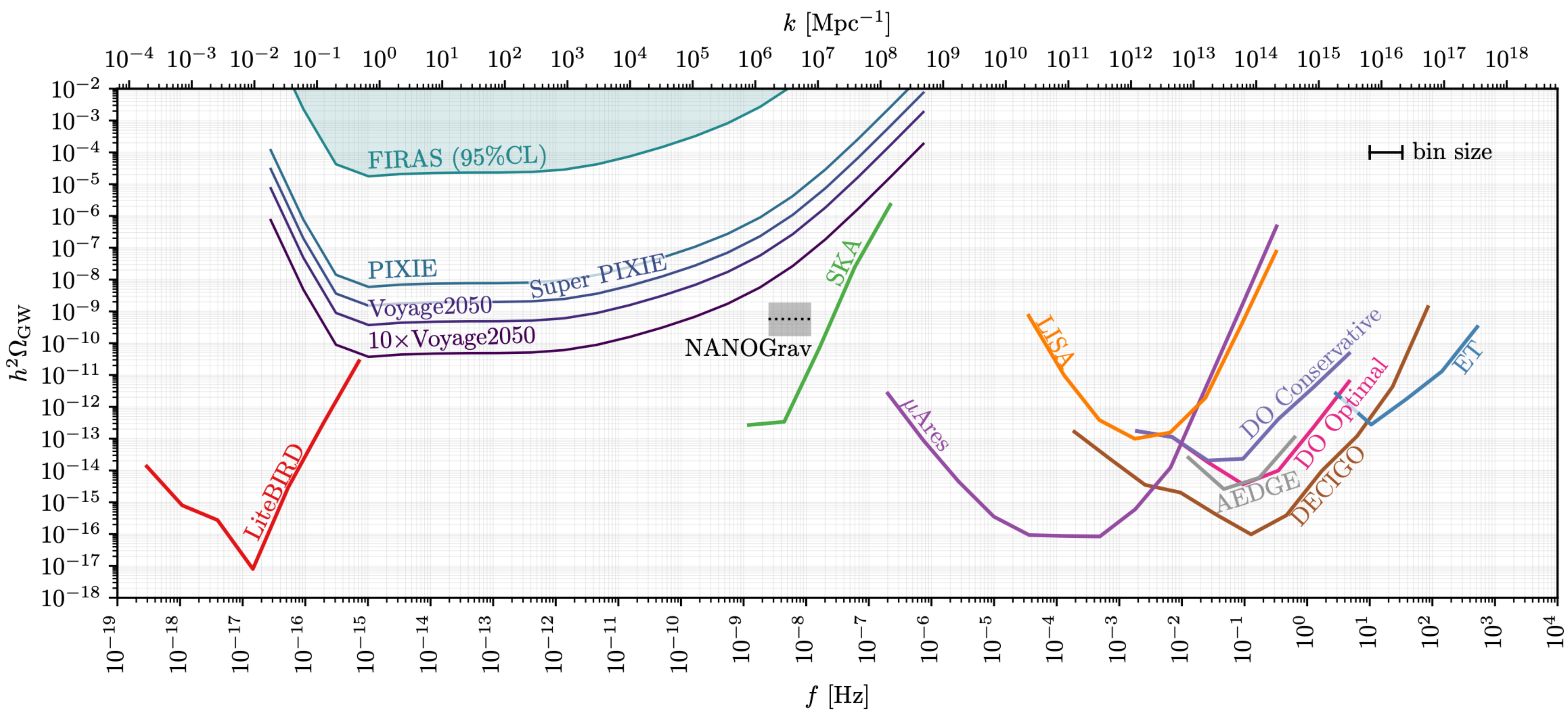
Any energy added to the photons leads to a so called μ distortion

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)

Spectral distortions from dark sector anisotropies

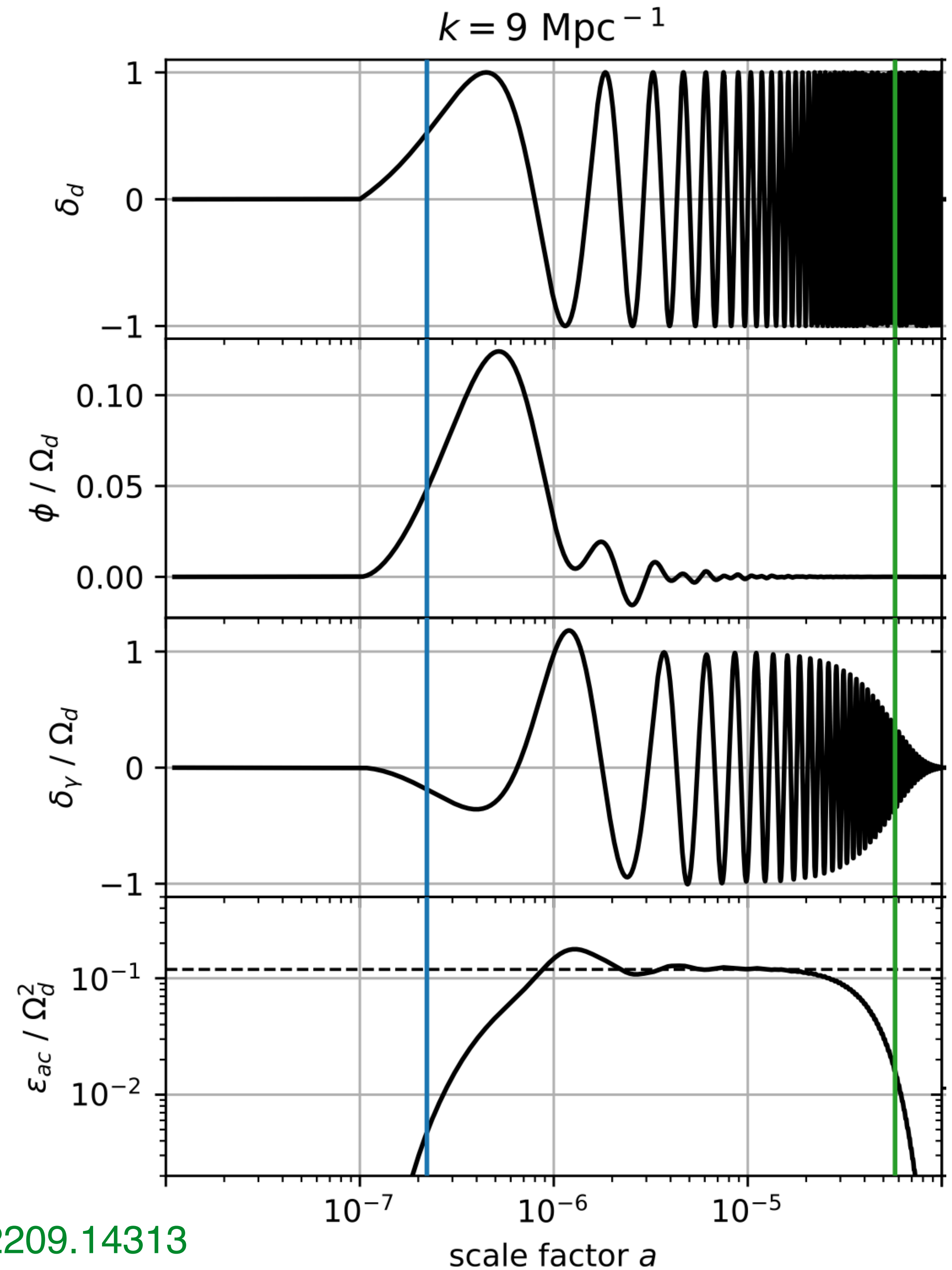
Assume decoupled dark sector, $\Omega_d \ll 1$

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

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

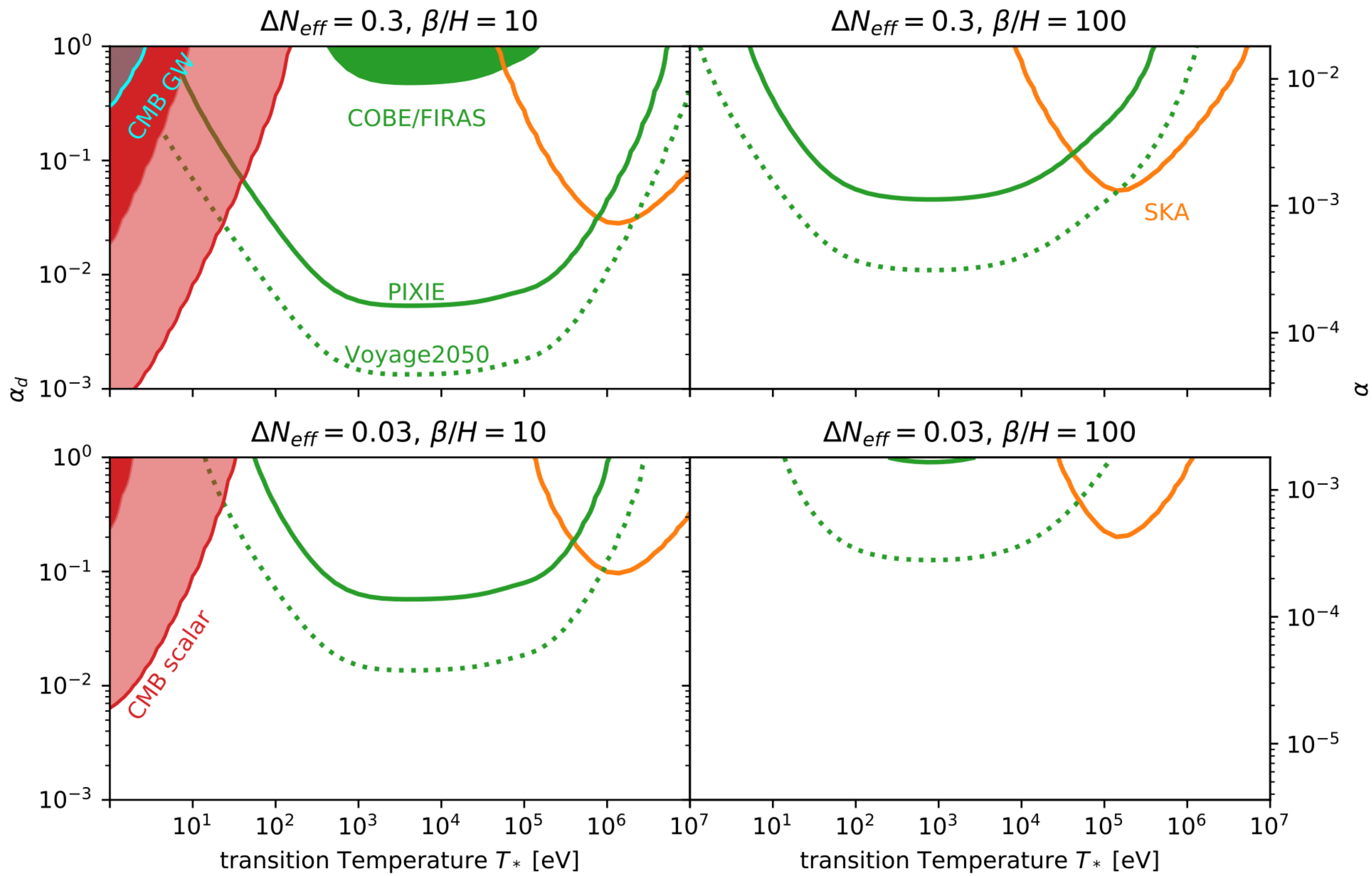
Resulting μ distortions

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



Ramberg, Ratzinger & PS, 2209.14313

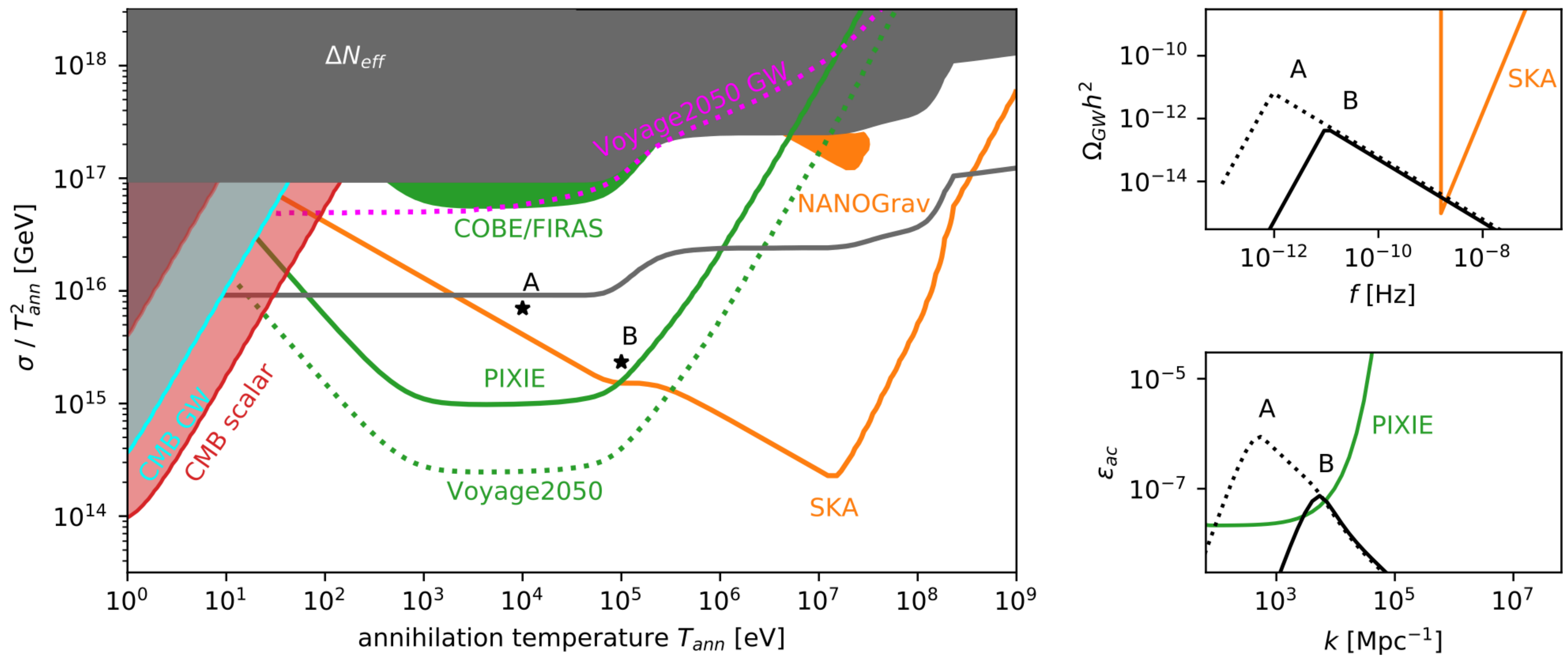
Example source I: Dark sector phase transition



Note: Ω_d fixed to satisfy $N_{\rm eff}$ constraints

Ramberg, Ratzinger & PS, 2209.14313

Example source II: Annihilating domain walls



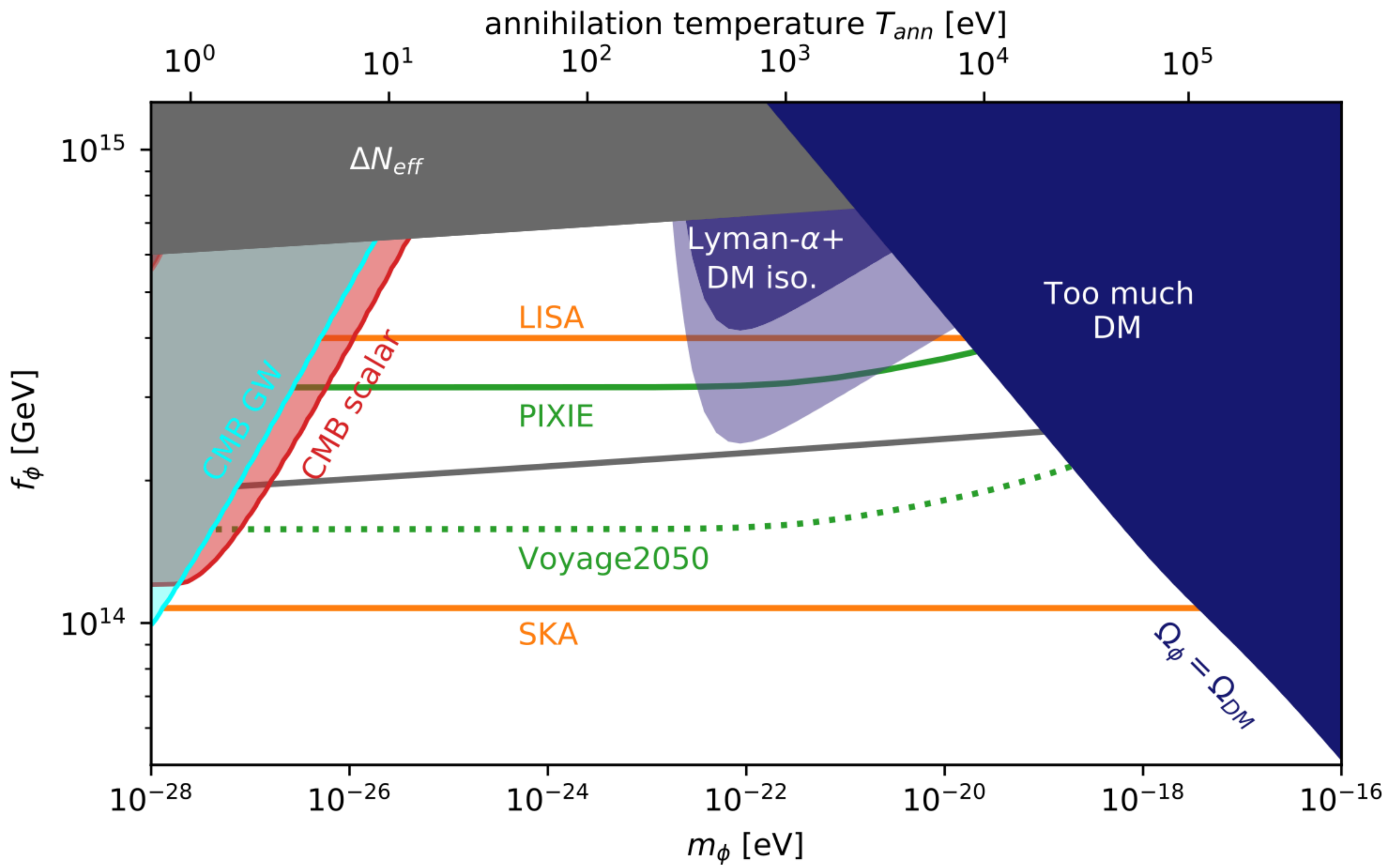
Already probes allowed parameter space

Complementary to GW probes, can break degeneracy

- Multi-messenger cosmology

Ramberg, Ratzinger & PS, 2209.14313

Source III: (global) cosmic strings



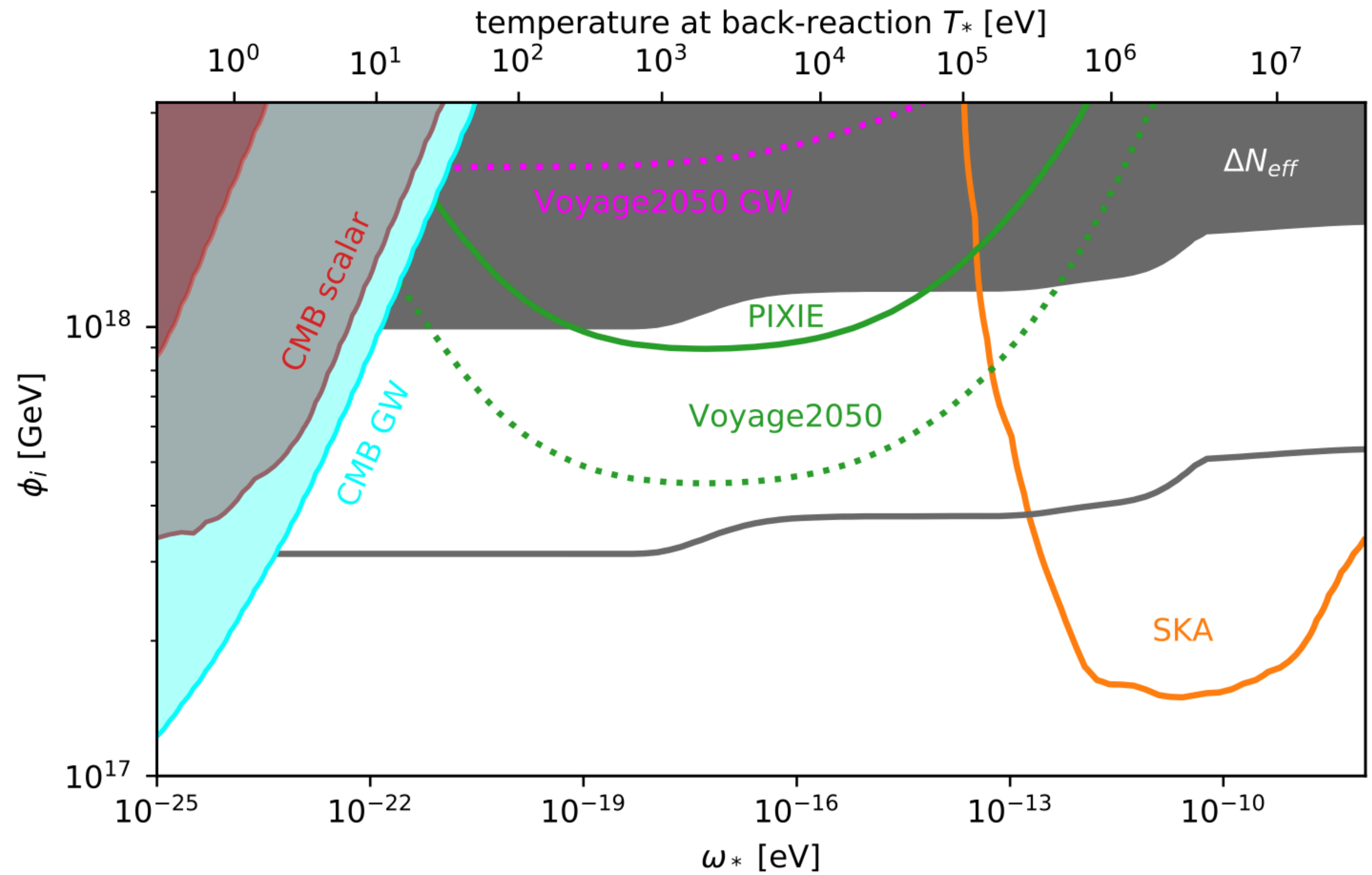
Note: Local strings mainly radiate from small loops and are thus NOT an efficient source of spectral distortions

Example source IV: Audible axions…

Not yet…

Results for scalar toy model

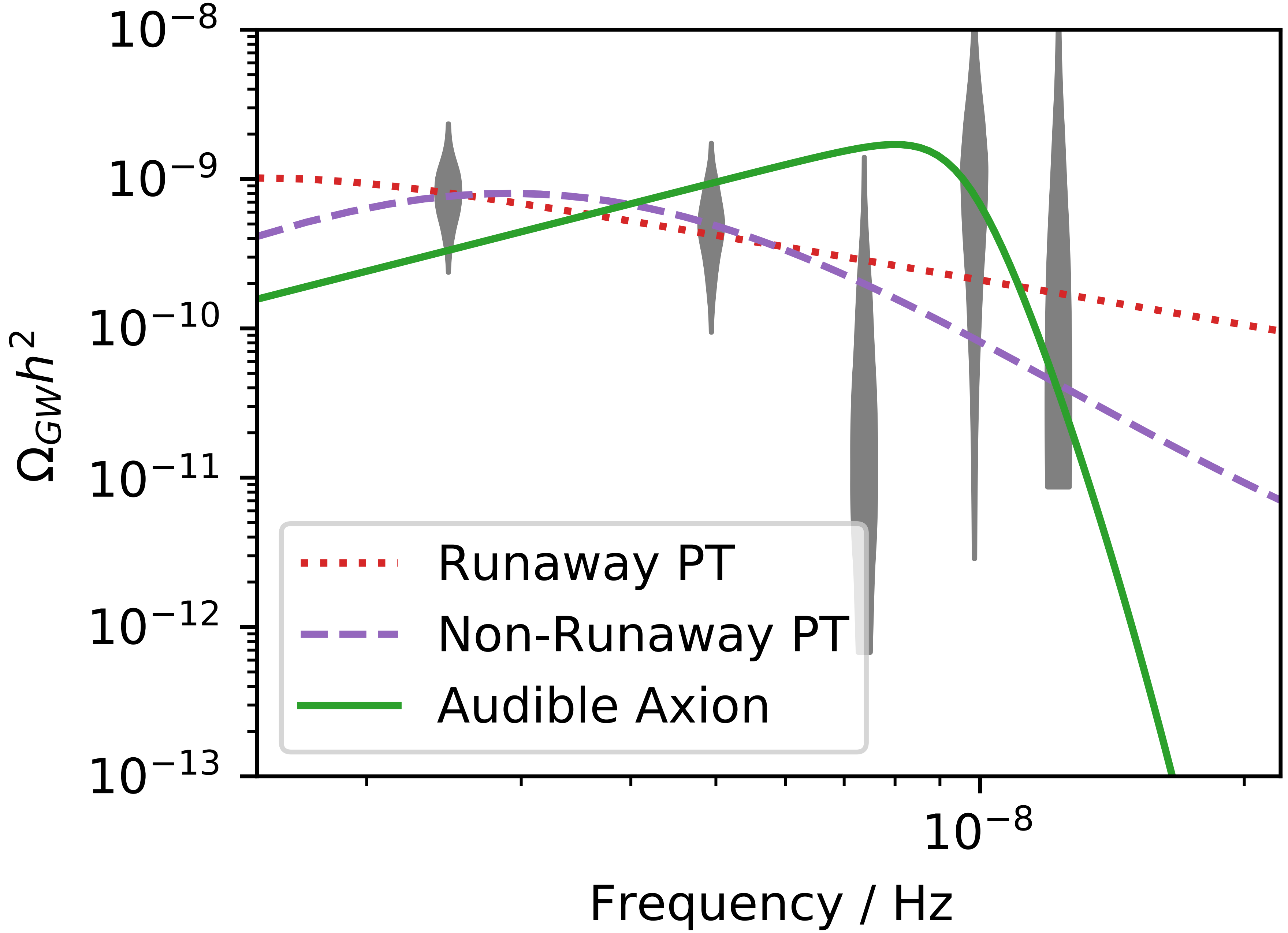
Constraints not as strong since fluctuations are not horizon size



Expect better sensitivity for axion fragmentation

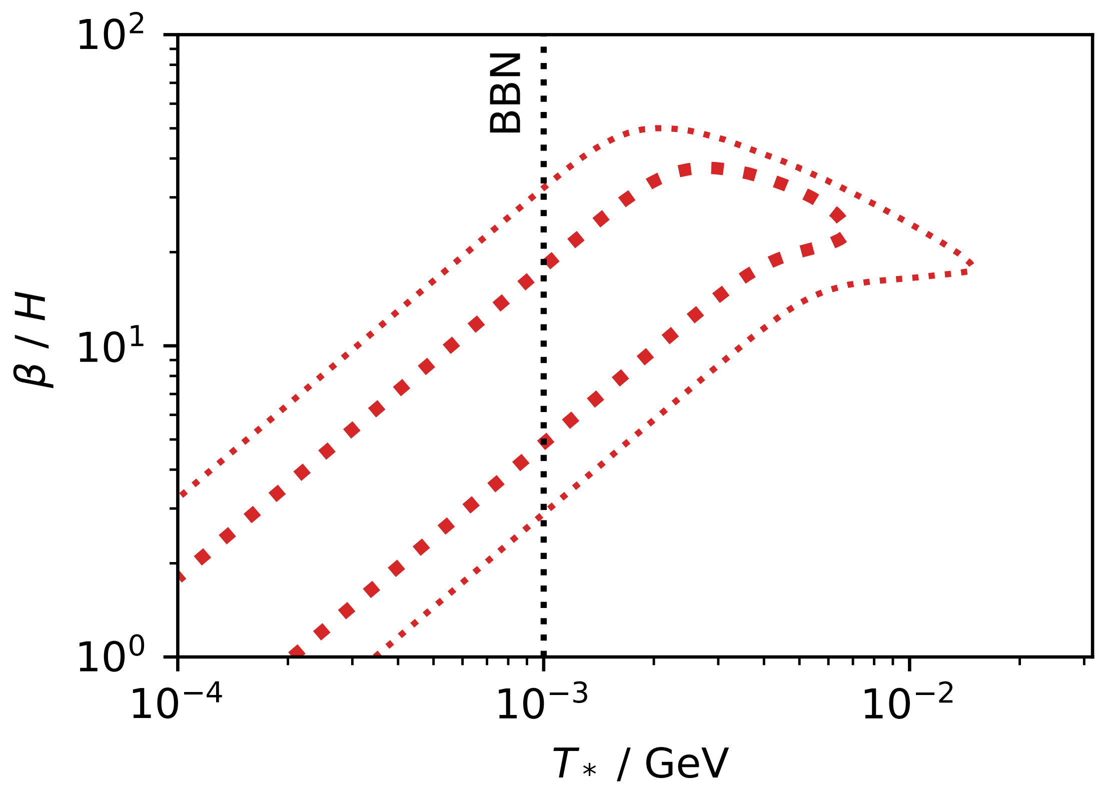
Ramberg, Ratzinger & PS, 2209.14313

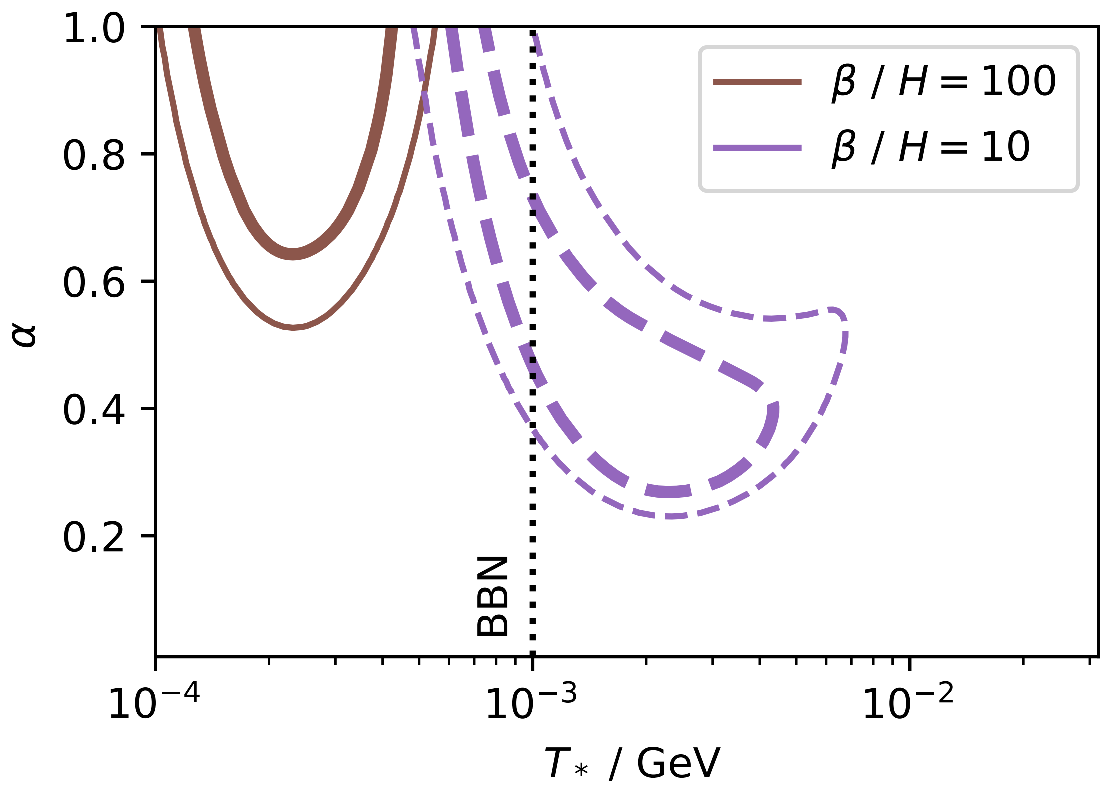
Fit with broken power law signals



Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition



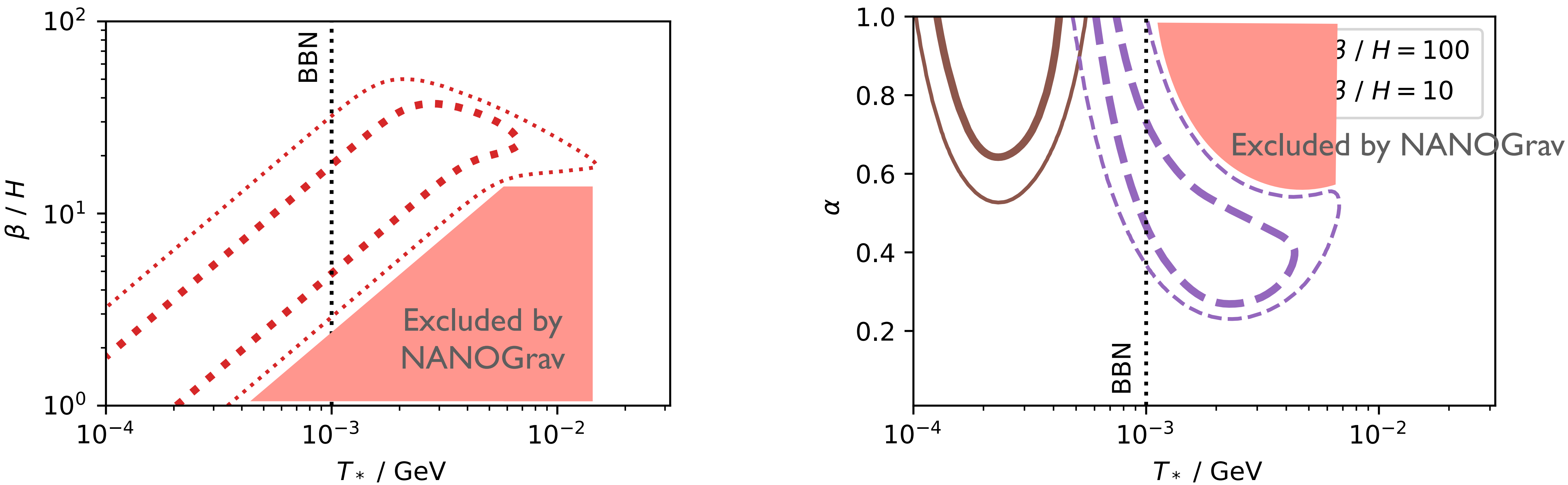


Generic PT parameterisation, best fit with PT at temperatures in few MeV range

Challenge for model building → Hint for dark sector

Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition



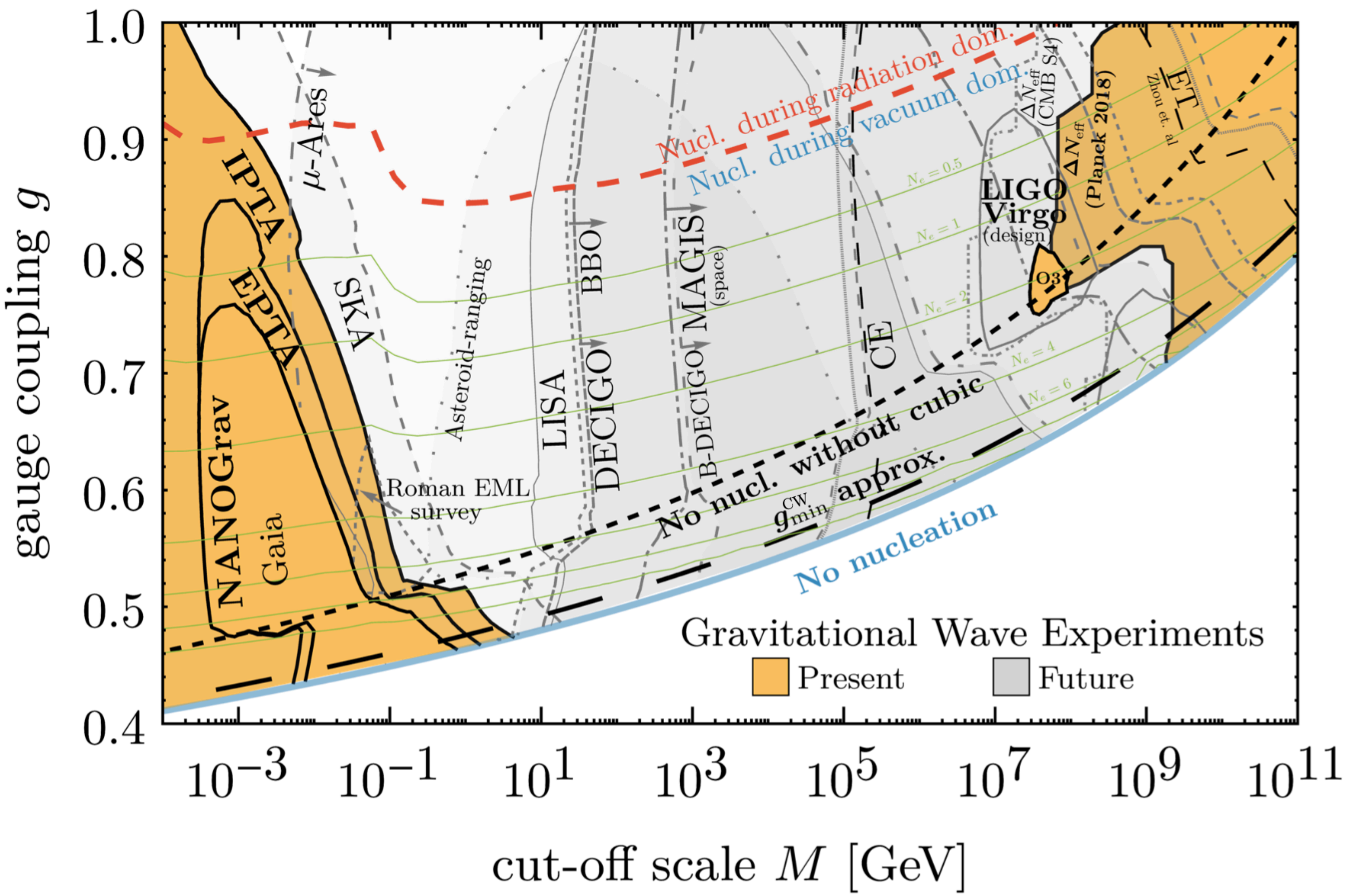
Generic PT parameterisation, best fit with PT at temperatures in few MeV range

Some model parameters excluded by PTA data now!

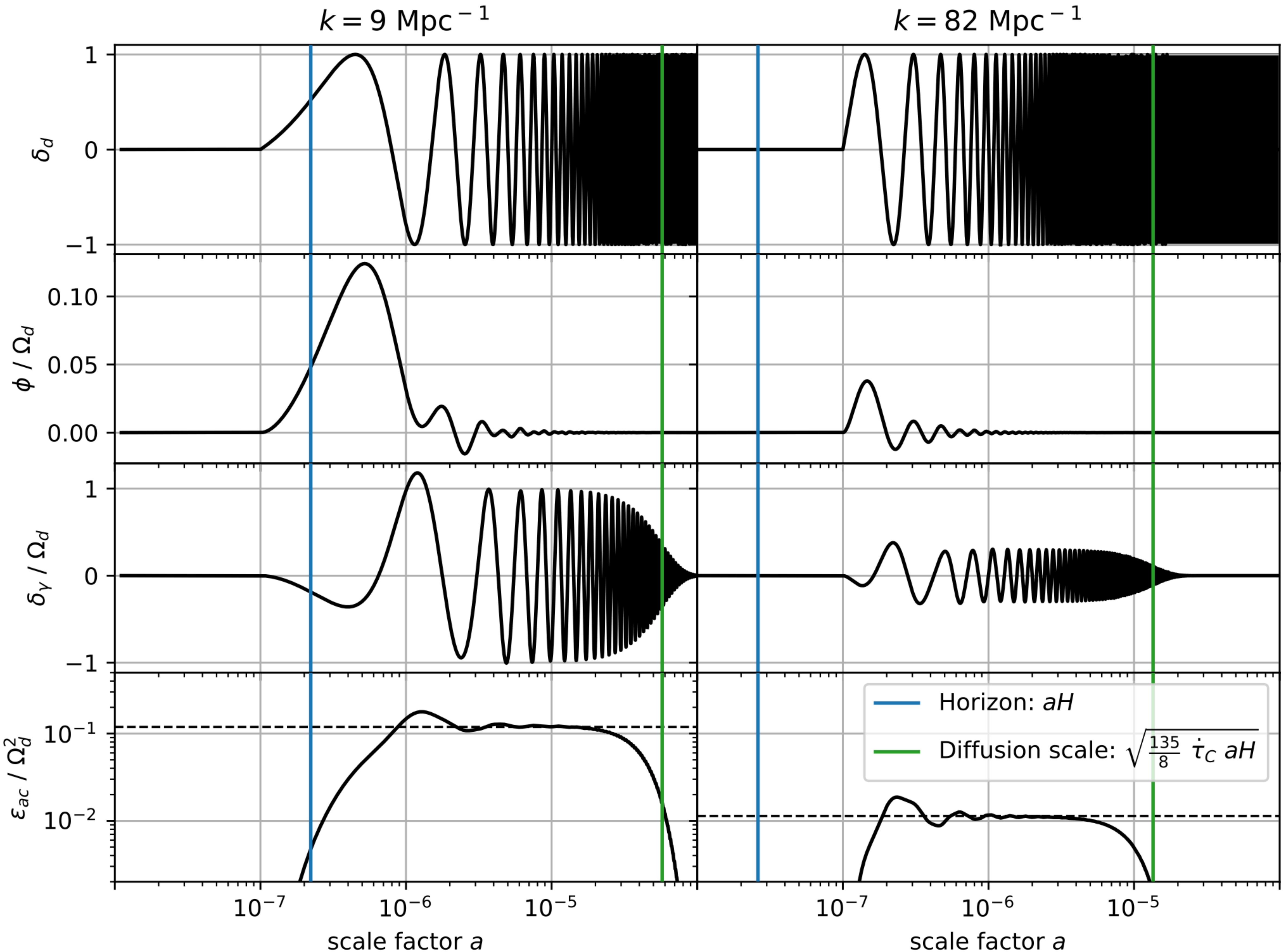
Wolfram Ratzinger & PS, 2009.11875

At higher frequencies

Levi, Opferkuch, Redigolo, 2212.08085



LISA will probe above 10 GeV, colliders could fill gap

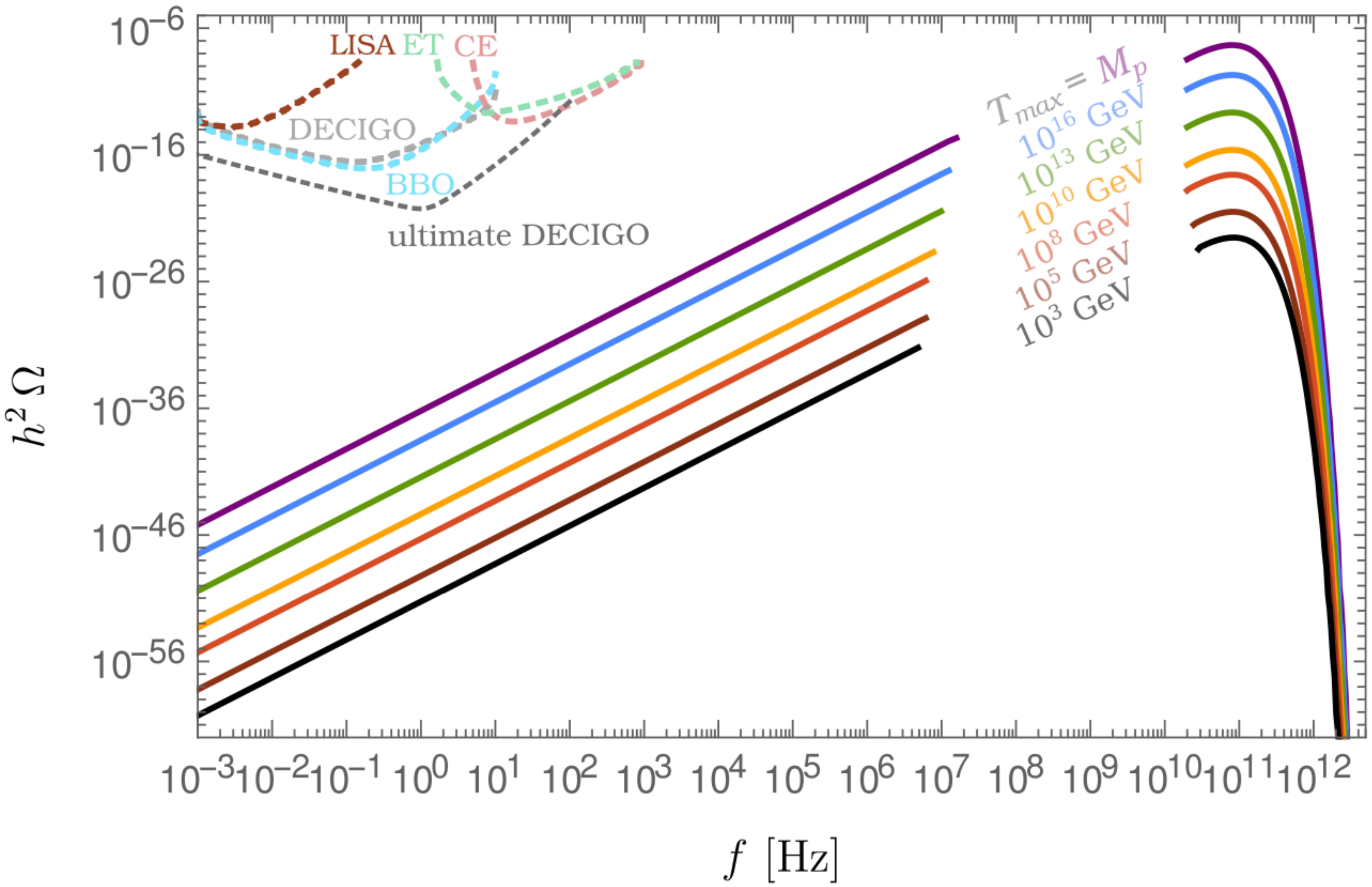


$k = 9\ \mathrm{Mpc}^{-1}$
$k = 82\ \mathrm{Mpc}^{-1}$
δ_d
$\phi\ /\ \Omega_d$
$\delta_\gamma\ /\ \Omega_d$
$\varepsilon_{ac}\ /\ \Omega_d^2$
Horizon: aH
Diffusion scale: $\sqrt{\frac{135}{8}\ \dot{\tau}_C\ aH}$
scale factor a
scale factor a

Standard model

The hot early Universe sources GWs!

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



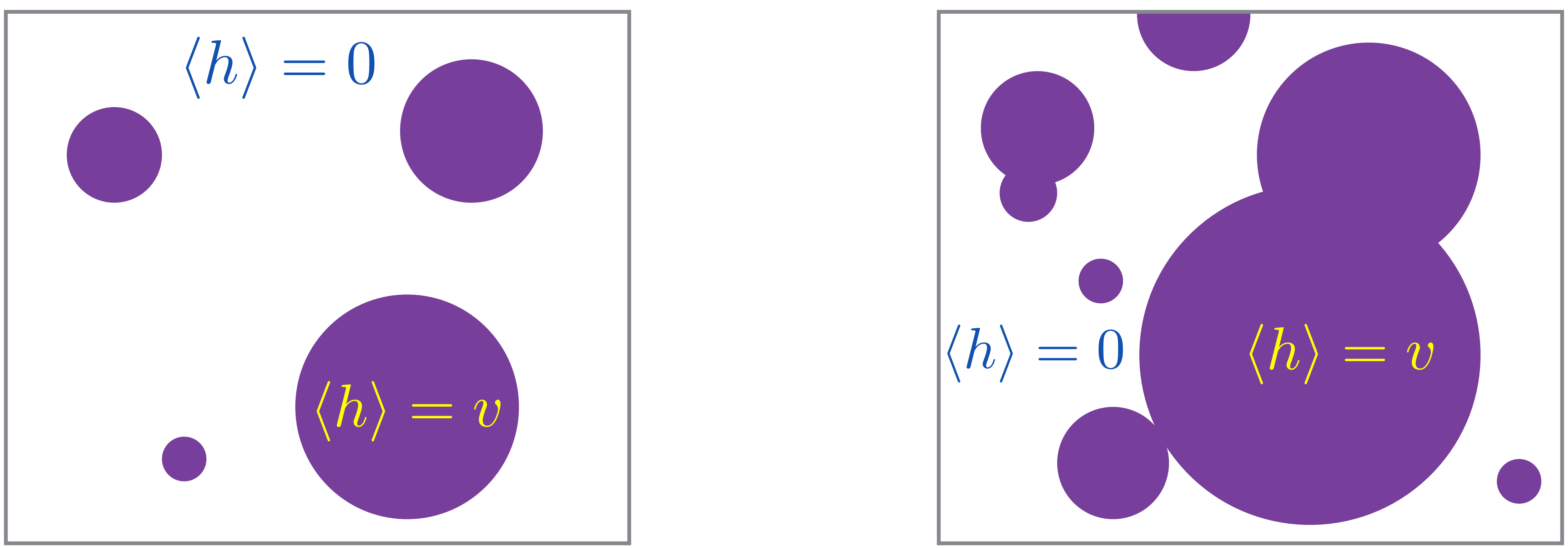
From Ringwald,
Schütte-Engel, Tamarit, 2020

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

GWs from Phase Transitions

First order PT → Bubbles nucleate, expand

Bubble collisions → Gravitational Waves



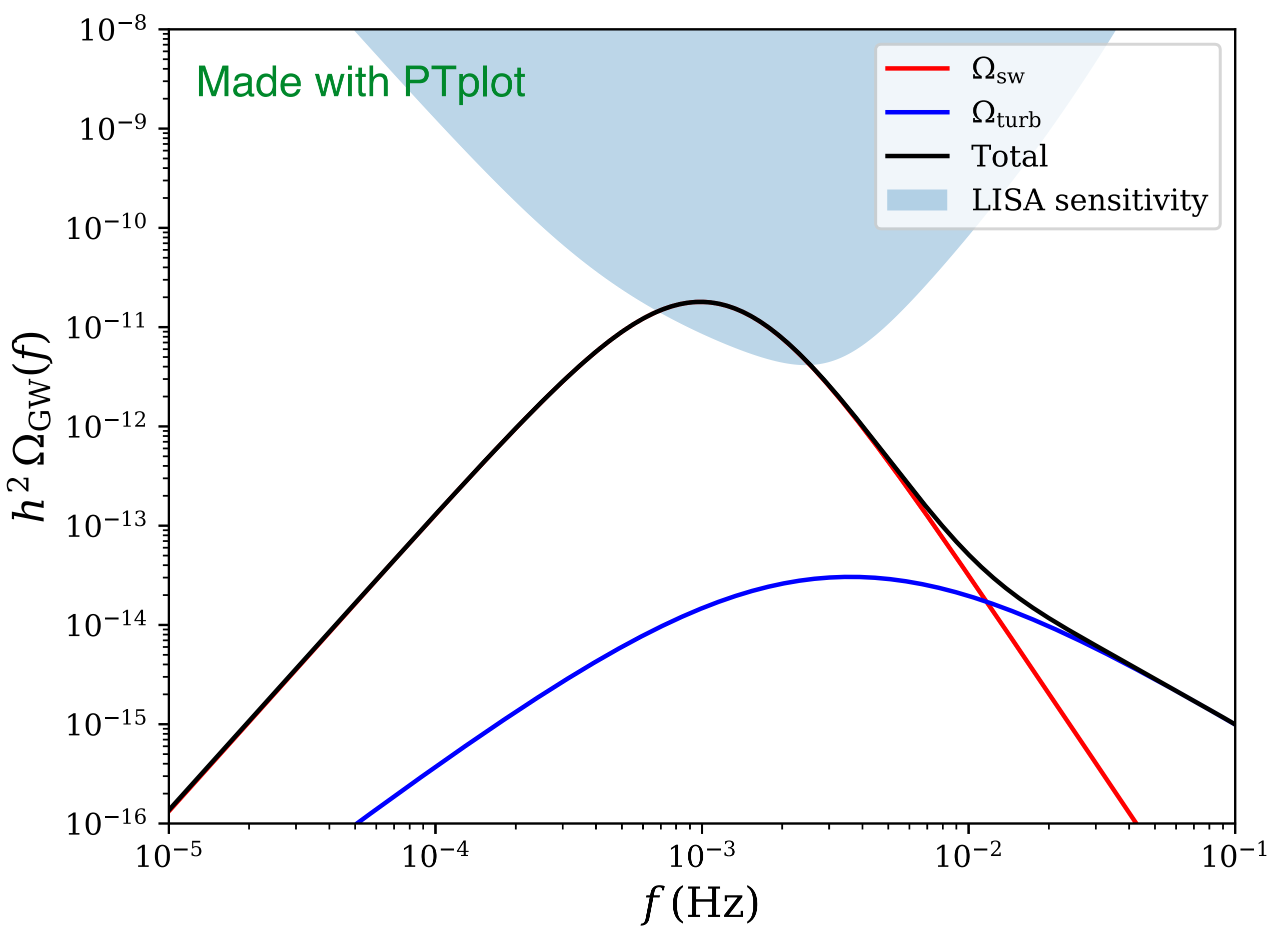
PT signal

PT characterised by few parameters:

- Latent heat $\alpha \approx \frac{\Omega_{\rm vacuum}}{\Omega_{\rm rad}}$
- Bubble wall velocity v
- Bubble nucleation rate β
- PT temperature T_*

More details, see e.g.:

Summary and recommendations:
1910.13125
(LISA Cosmology WG)



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)

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