PROBING THE ANISOTROPIC EARLY UNIVERSE

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Cluster of Excellence PRiSMA+

PORTOROZ 2023:
Particle Physics from Early Universe to Future Colliders

Portoroz **April 13, 2023**

Probing the anisotropic early Universe

The early Universe as window to new physics

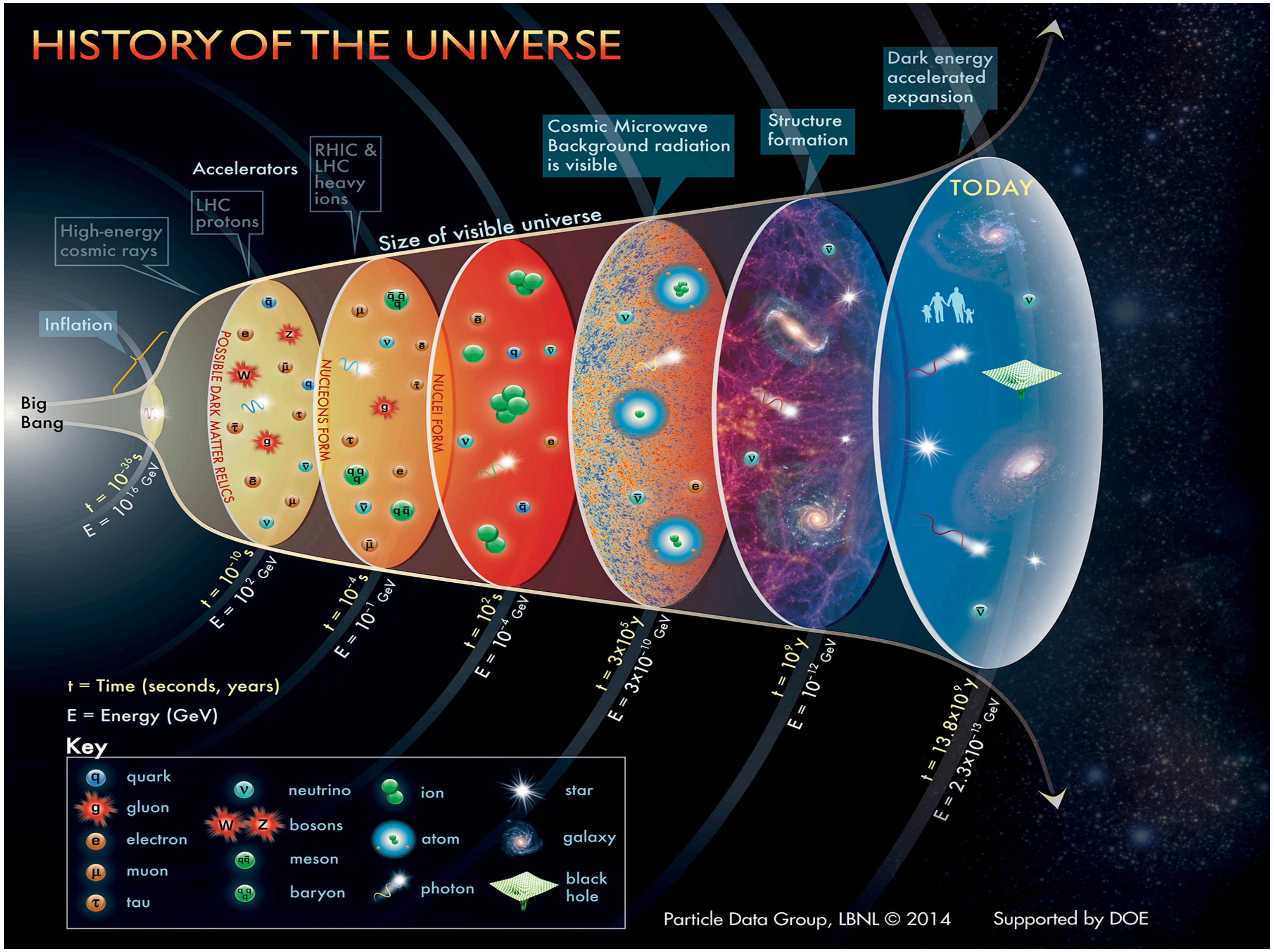
Gravitational waves

- Phase transitions at strong coupling
- The NANOGrav hint for a stochastic GW signal

CMB spectral distortions

- Complementary probe of GW sources

Thermal history and particle physics

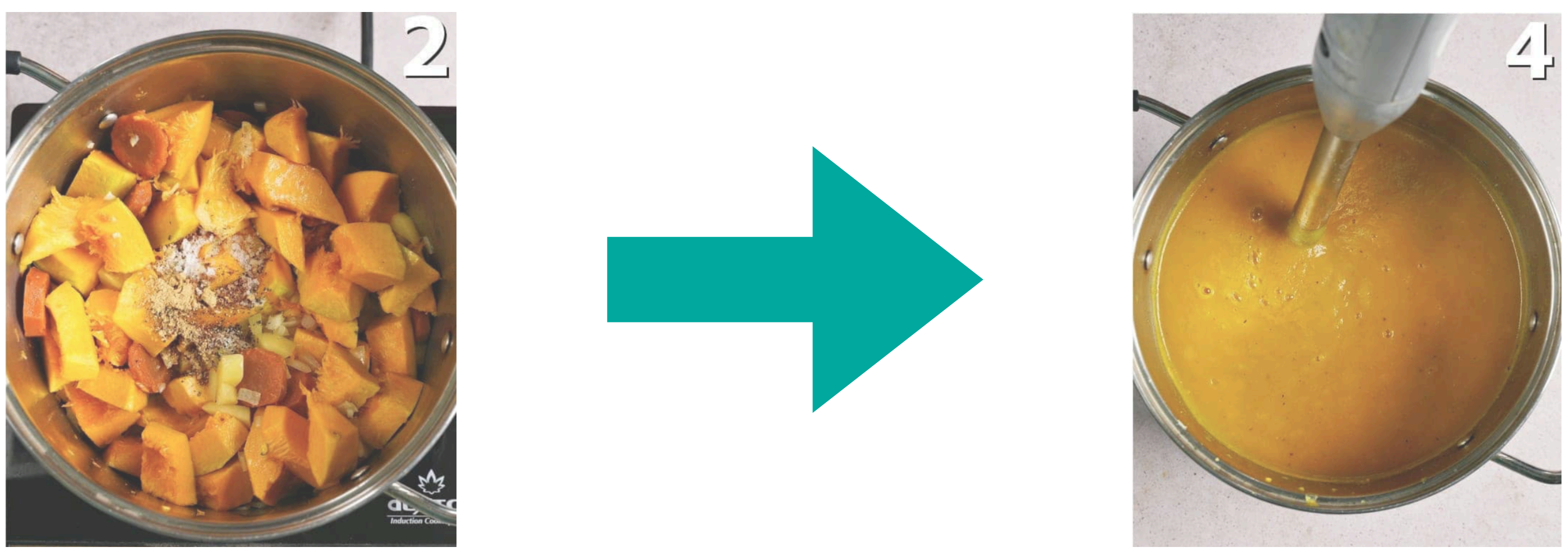


The early Universe

Key to many open questions in particle physics

- What is dark matter, and how is it made
- What is the origin of matter
- What is the dynamics of inflation and reheating

Thermal equilibrium wipes out information



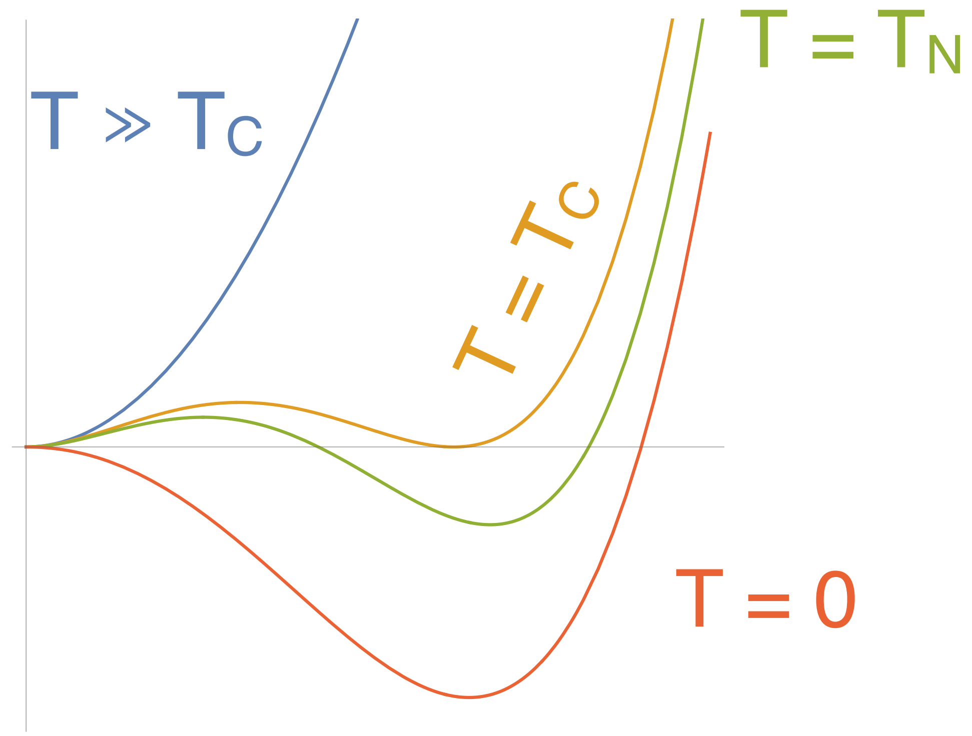
Observable traces from anisotropies and non-equilibrium

Example: Gravitational waves from phase transitions

Broken symmetries are restored at high T

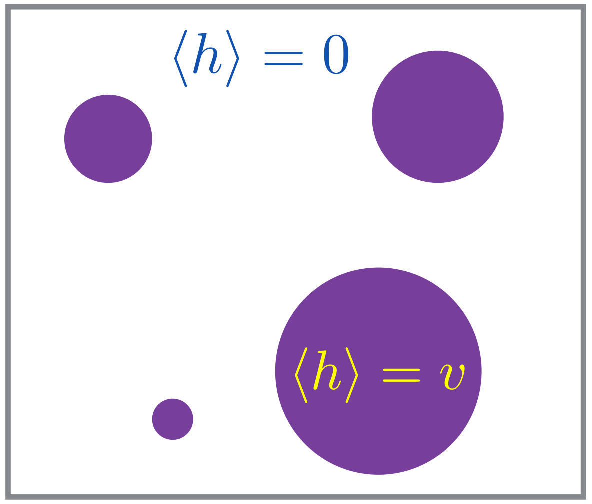
Symmetry breaking phase transitions

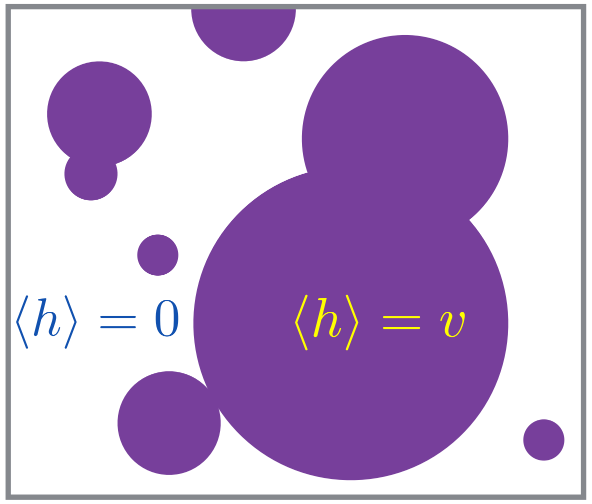
- Cross-over in SM
- First order possible in BSM



FOPT source GWs

Cosmological GW background observable today!





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QCD like dark sectors

Nonabelian $SU(N)$ dark sector, confinement scale Λ_d

n_f light/massless **dark** quarks

$n_f = 0$	$n_f > 0$
Glueball DM	Dark Baryons or Dark Pions
PT from center symmetry restoration	Chiral Symmetry Breaking
First order	First order for $n_f \geq 3$

Quantitative predictions?

Neither lattice nor holography alone suitable

We use improved holographic QCD

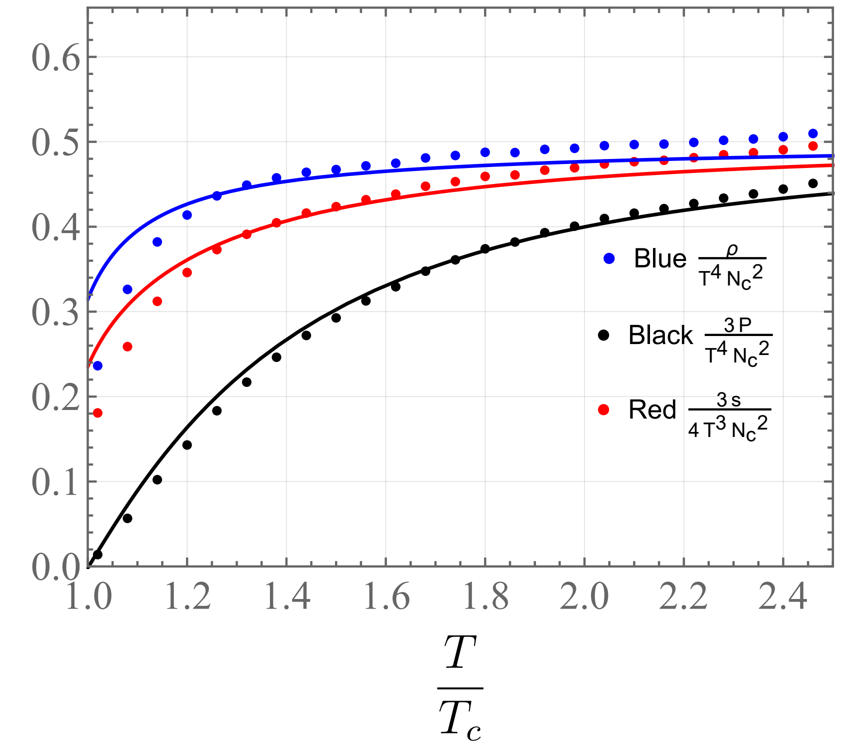
Gürsoy, Kiritsis, Mazzanti, Nitti
0707.1324, 0707.1349, 0812.0792, 0903.2859, ...

- Confinement in IR ($\lambda \to \infty$)
- Yang Mills beta function in UV ($\lambda \to 0$)

$$V(\lambda) = \frac{12}{\ell^2}\left\{1 + V_0\lambda + V_1\lambda^{4/3}[\log(1 + V_2\lambda^{4/3} + V_3\lambda^2)]^{1/2}\right\}$$

Fix parameters:

- V_0, V_2 to reproduce 2 loop YM running in UV
- V_1, V_3 fit to reproduce SU(3) lattice thermodynamics in IR



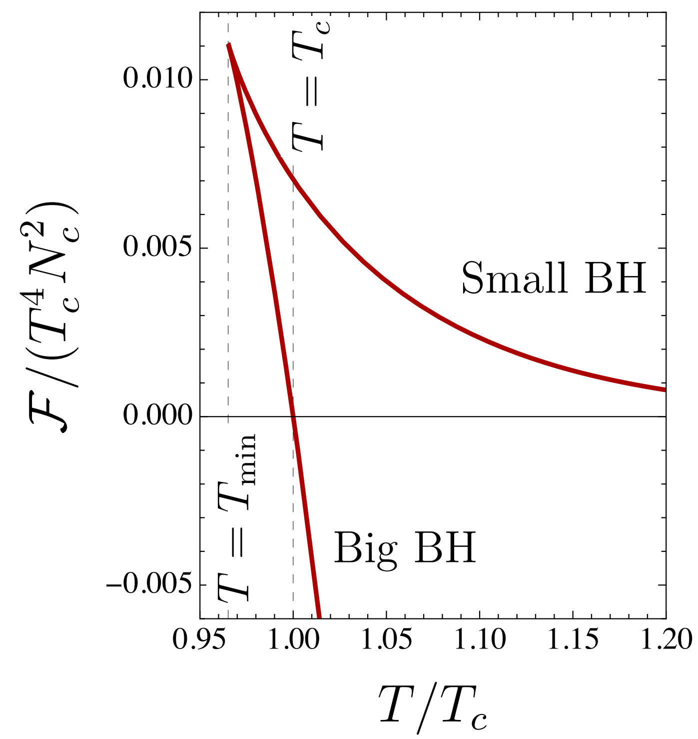
The phase transition in ihQCD

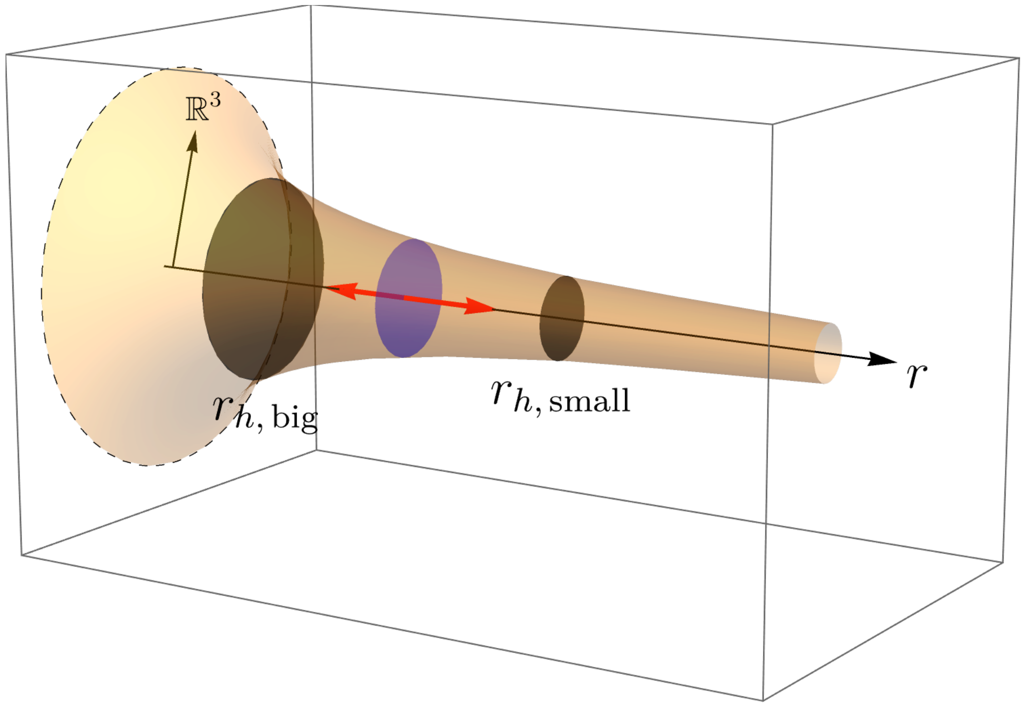
Hawking Page transition, with small BH acting as instanton

To compute bounce action, need effective action (or free energy) along the full path

Interpolate between big and small BH solutions

- Do some hard work…
- Win :)





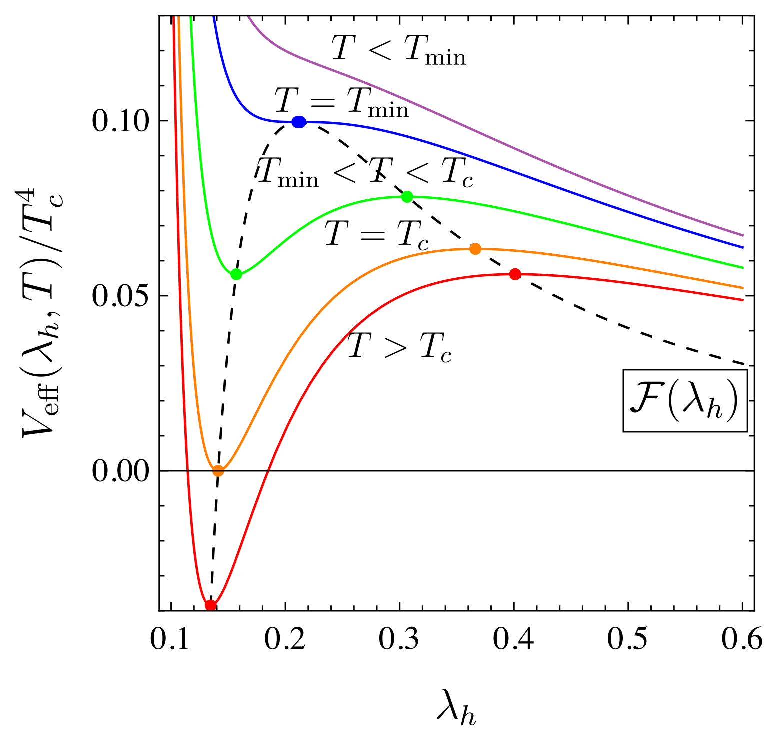
Morgante, Ramberg, PS, 2210.11821

Effective potential and GW spectrum

Morgante, Ramberg, PS, 2210.11821

Bounce action

$$\mathcal{S}_{\rm eff} = \frac{4\pi}{T}\int d\rho\rho^2\left[c\frac{N_c^2}{16\pi^2}(\partial_r\lambda_h(r))^2 + V_{\rm eff}(\lambda_h(r))\right]$$

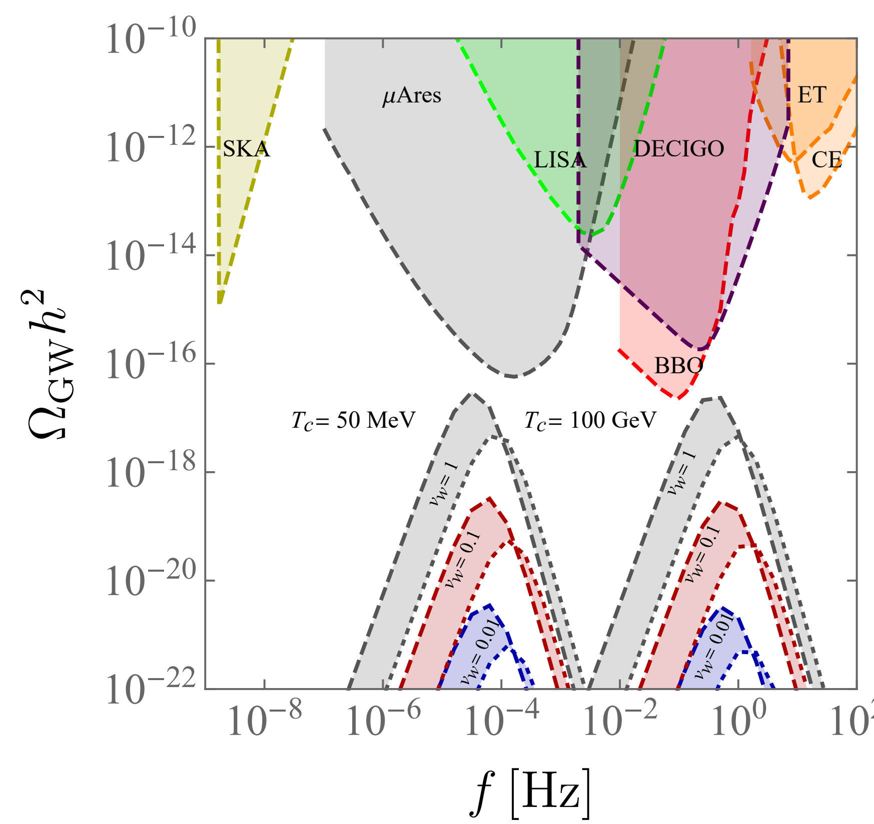


Tunneling rate

$$\Gamma = T^4\left(\frac{\mathcal{S}_B}{2\pi}\right)^{3/2} e^{-\mathcal{S}_B}$$

Allows us to compute GW parameters

- So far: $N_c = 3$, $n_f = 0$
- Agrees with estimates based on effective theories and lattice data
  (e.g. Halverson+ 2012.04071, Huang+ 2012.11614, March-Russell+ 1505.07109)



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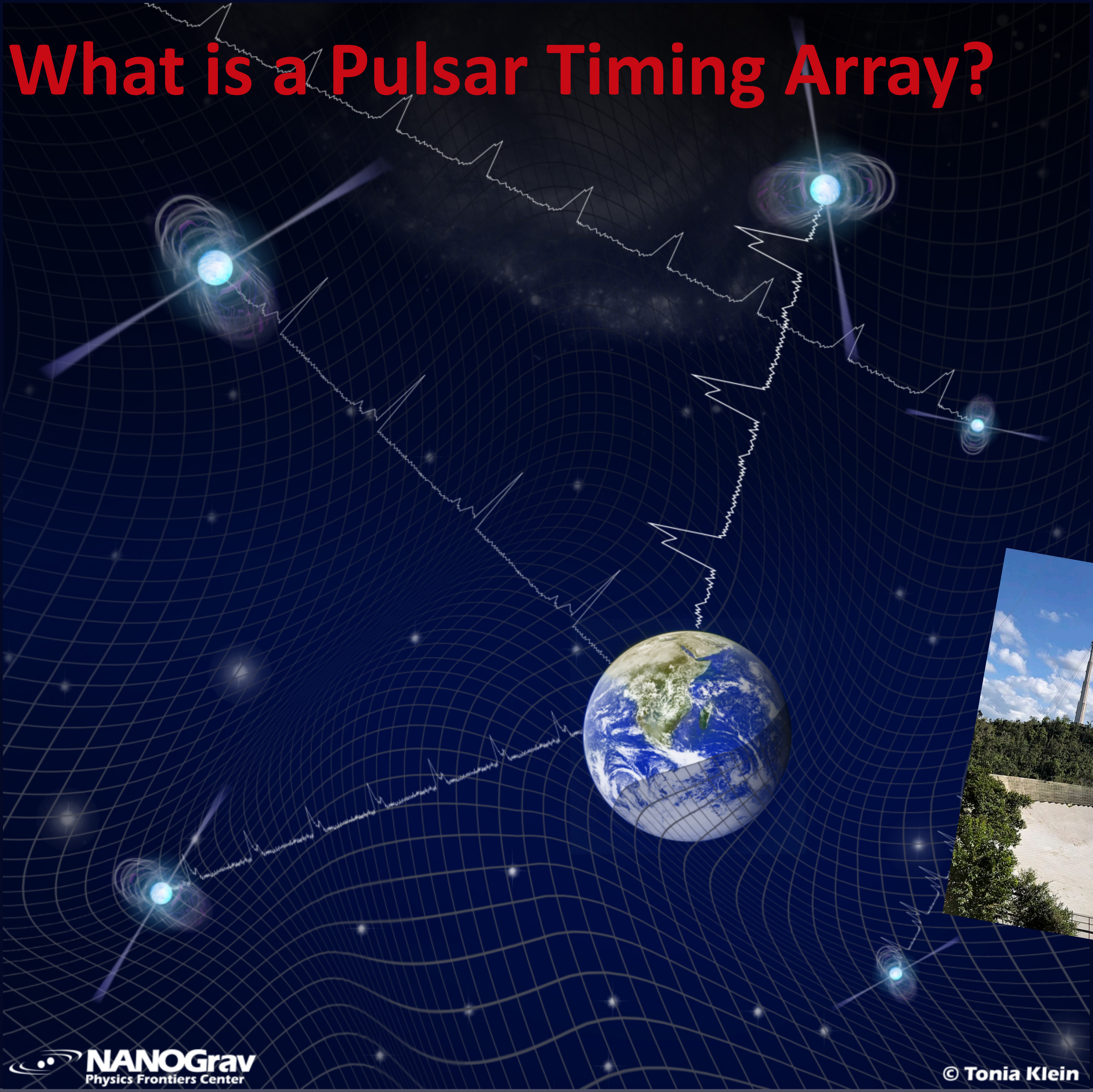
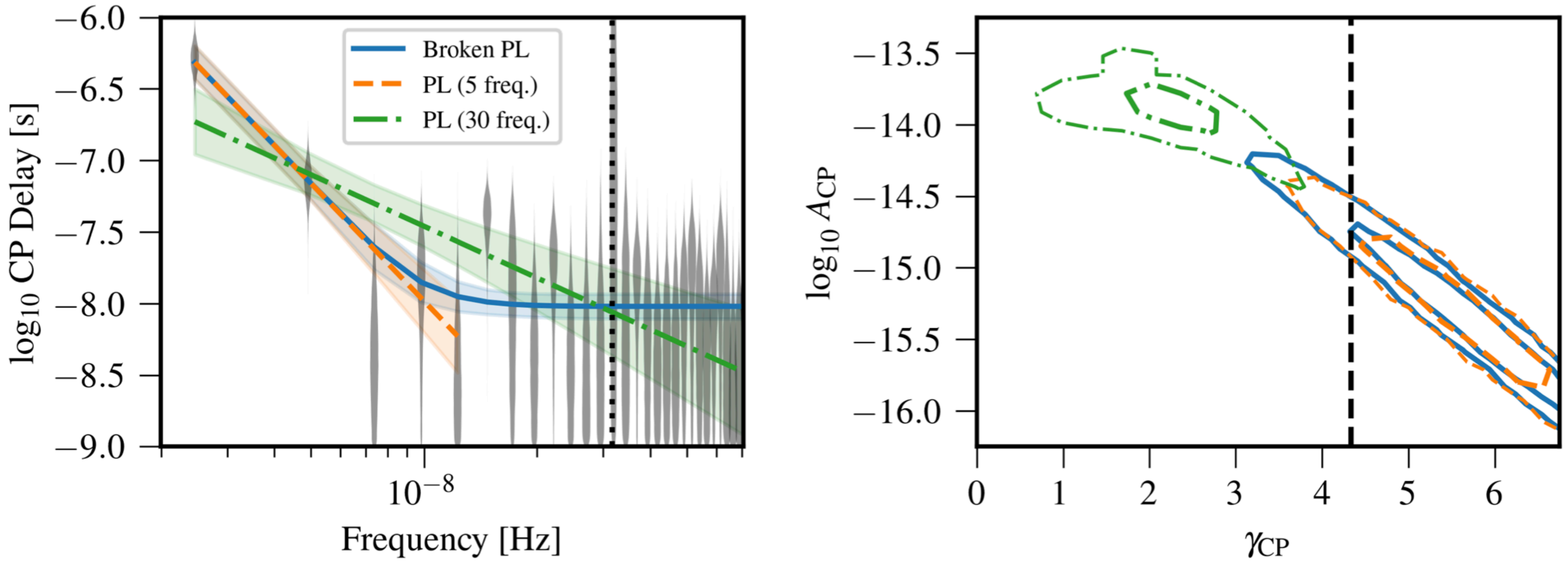
What is a Pulsar Timing Array?



NANOGrav Finds Possible ‘First Hints’ of Low-Frequency Gravitational Wave Background

arXiv:2009.04496



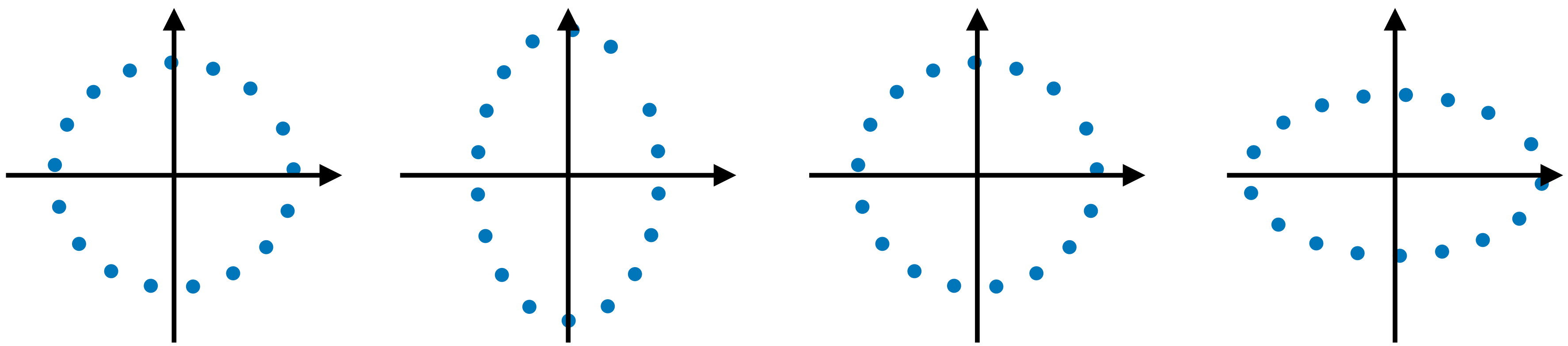
Fit with free spectrum (violins) or simple power law signals

Strong preference over BG only hypothesis (Bayes factor > 10’000)

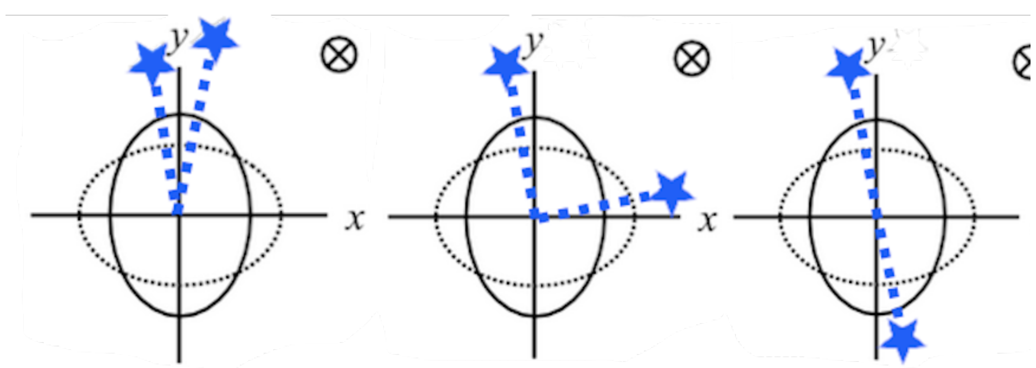
$$h_c(f) = A_{GWB}\left(\frac{f}{f_{year}}\right)^{\alpha}$$

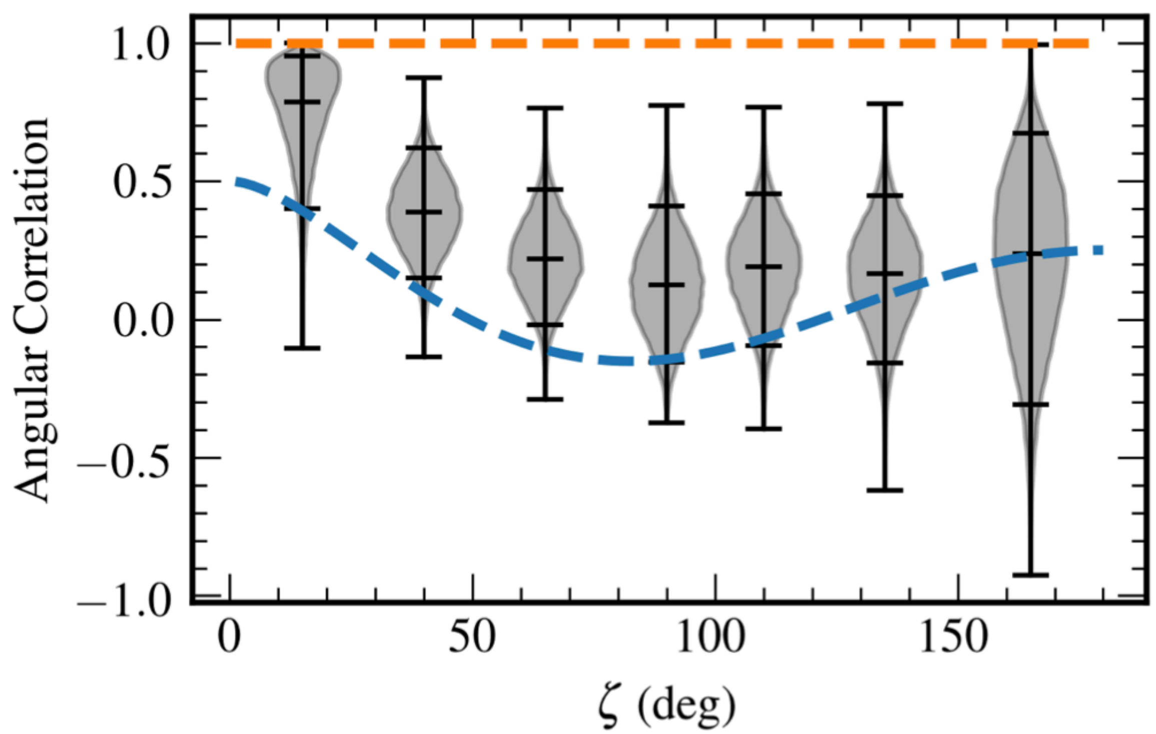
$$\gamma = 3 - 2\alpha$$

GWs are quadrupole radiation



Angular correlation in pulsar response (Helling Downs)

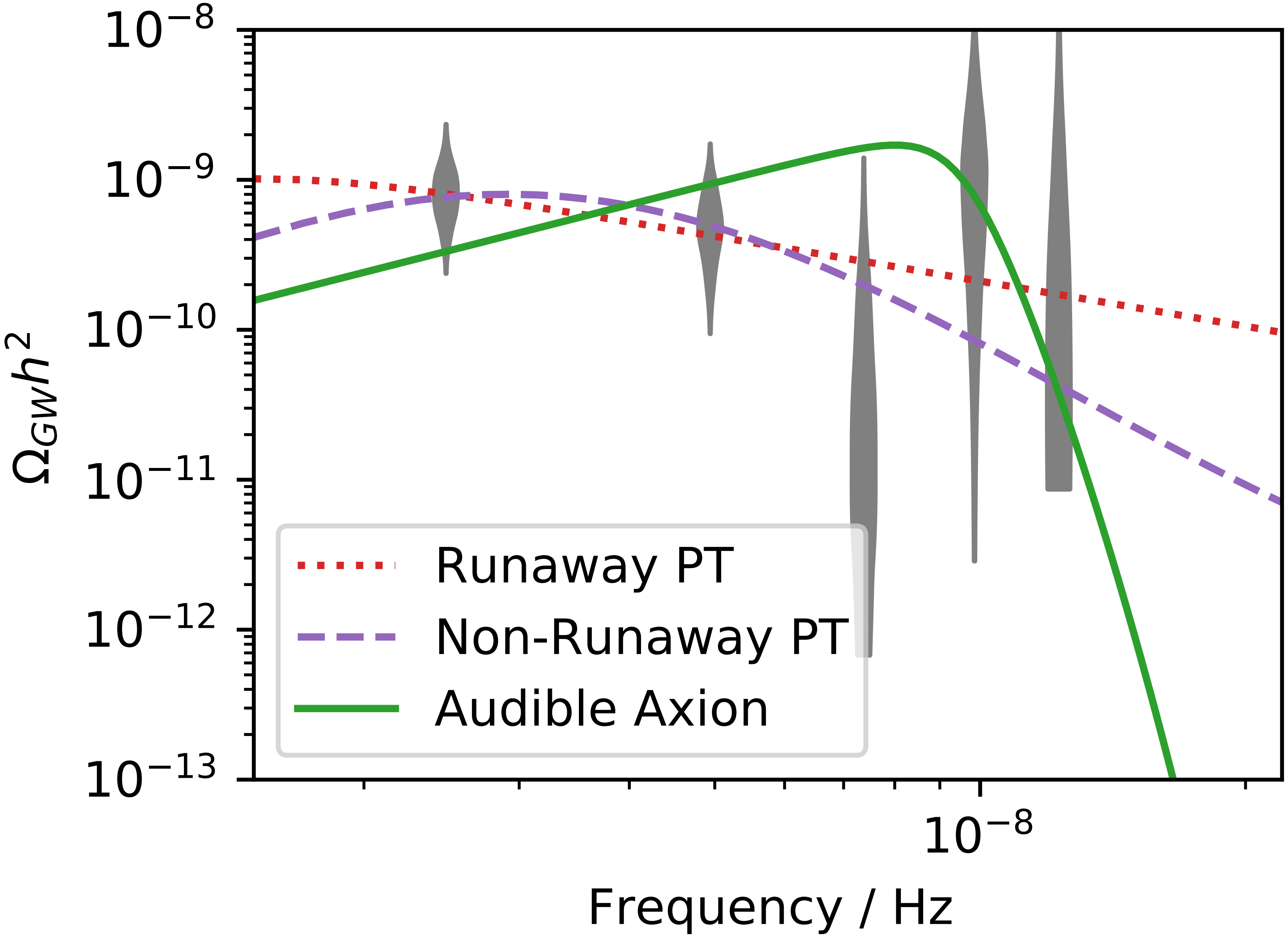




No conclusive evidence for HD correlation (yet)

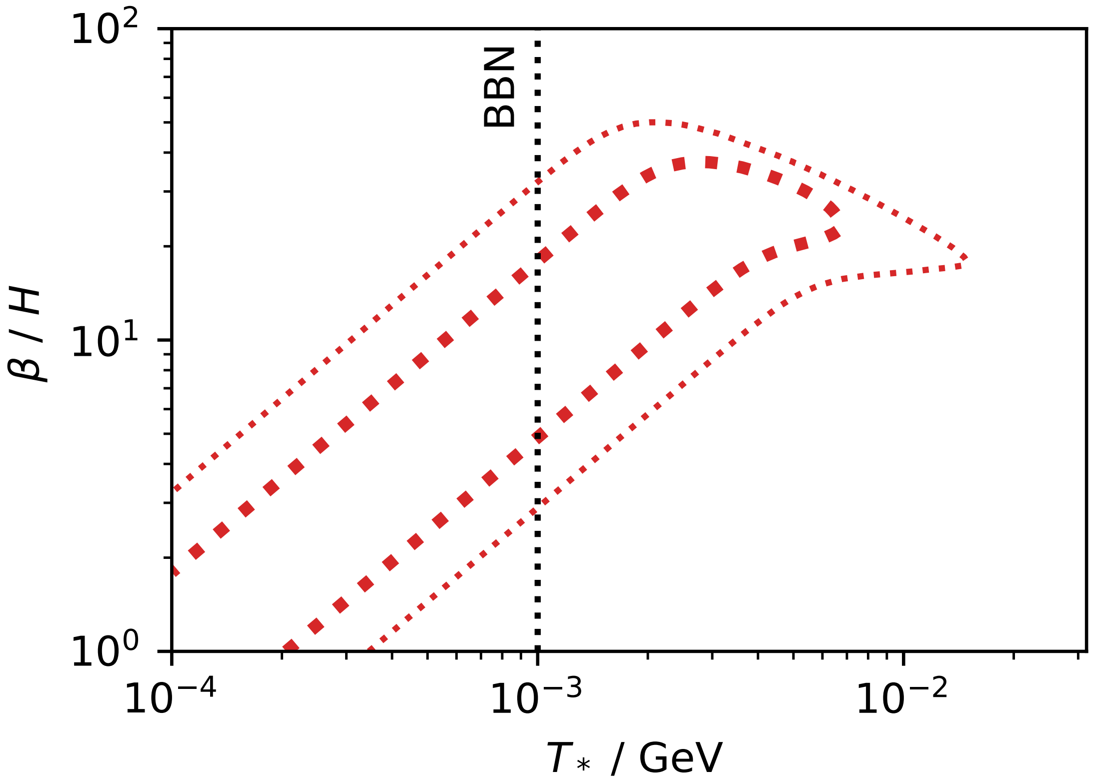
Signal/hint also seen in PPTA, EPTA and IPTA now - waiting for more data!

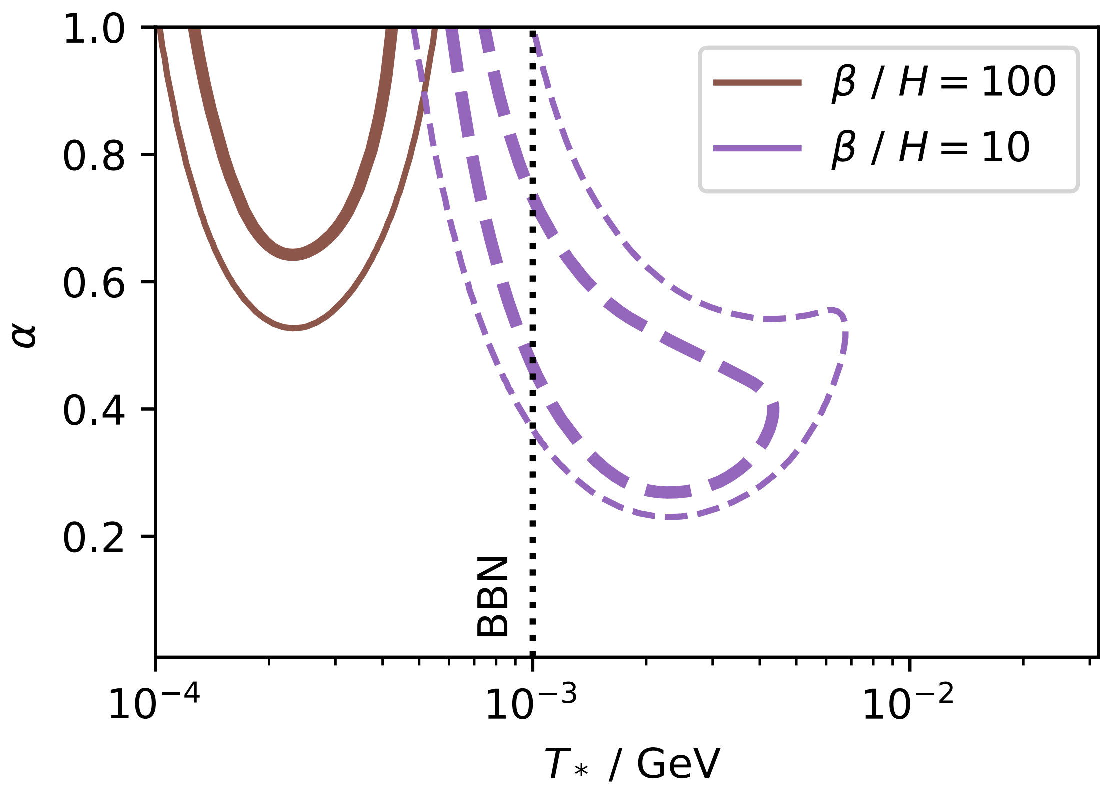
Fit with broken power laws: PTs and axions



Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition





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

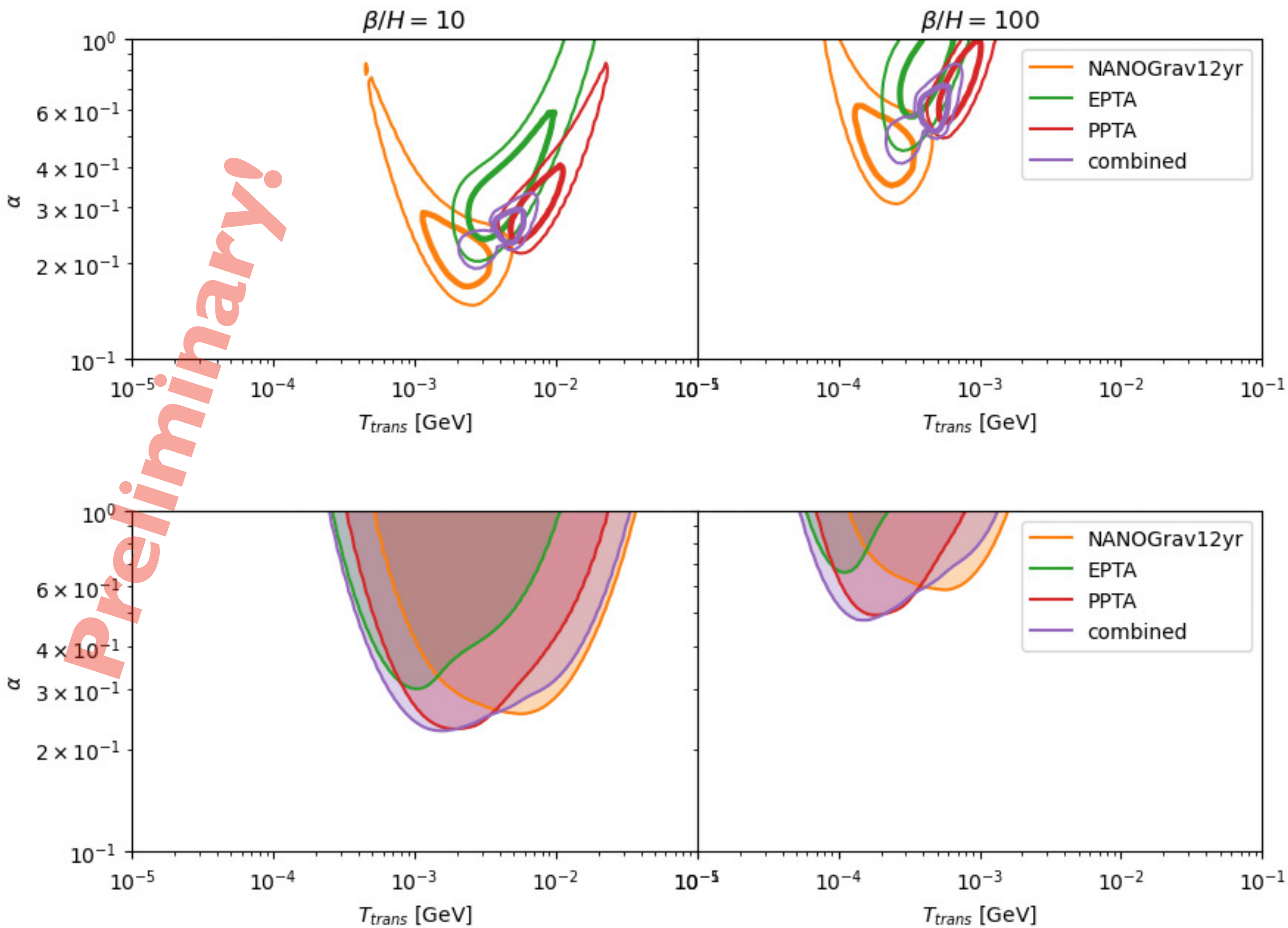
A dark sector at the few MeV scale? X17?!? Neutrino masses?

Wolfram Ratzinger & PS, 2009.11875

Phase transitions revisited

Fit to all PTA data

Also: Model exclusion



Madge, Morgante, Puchades, Ramberg, Ratzinger, Schenk, PS, in preparation

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CMB spectral distortions

- Complementary probe of GW sources

Model discrimination

GW spectra, chirality

- With more PTA data (+ other GW detectors)

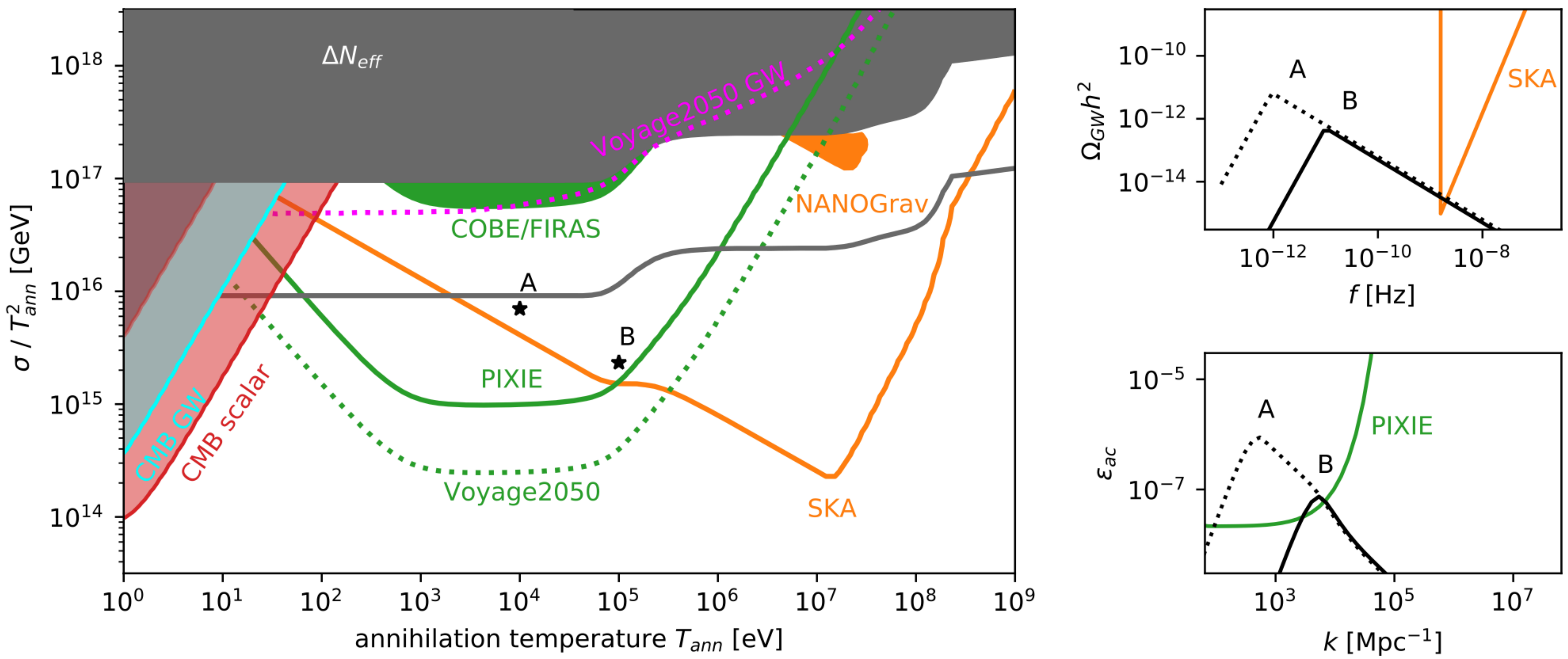
Cosmology

- Many sources contribute to N_{eff} , should not upset BBN
- Requires concrete models

CMB spectral distortions

- Strong GW sources imply large anisotropies “somewhere”
- Anisotropies couple at least gravitationally to SM plasma
- We are close to CMB decoupling → spectral distortions

Example GW source: Annihilating domain walls



Spectral distortions already probe parameter space

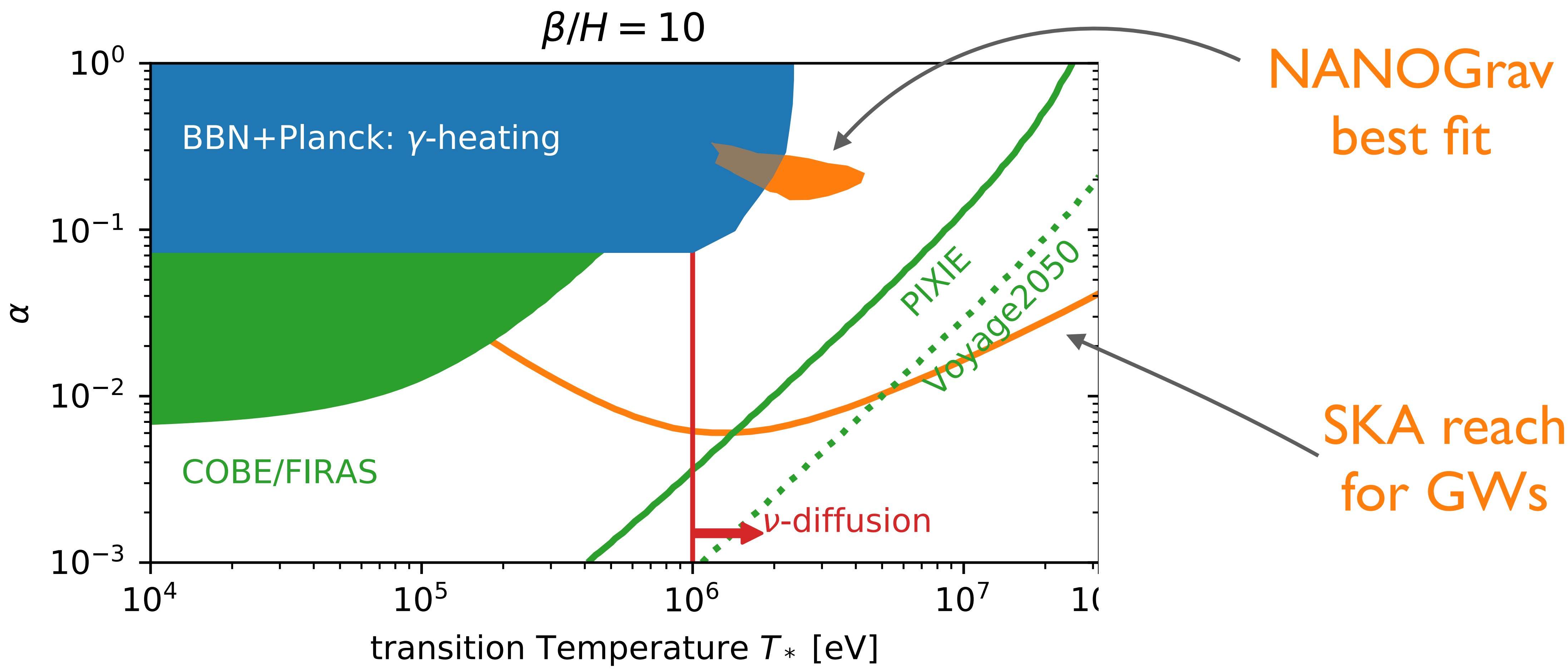
Complementary to GW probes, can break degeneracy

- Multi-messenger cosmology

Ramberg, Ratzinger & PS, 2209.14313

Probing sub-MeV phase transitions

Can also directly probe the scalar (density) fluctuations induced by PTs in a dark or visible sector



More sensitive! Multi-messenger cosmology!

Ramberg, Ratzinger & PS, 2209.14313

Probing the anisotropic early Universe - Summary

GWs and CMB spectral distortions probe non-equilibrium dynamics in the early Universe

Progress understanding strongly coupled PTs using improved holographic QCD

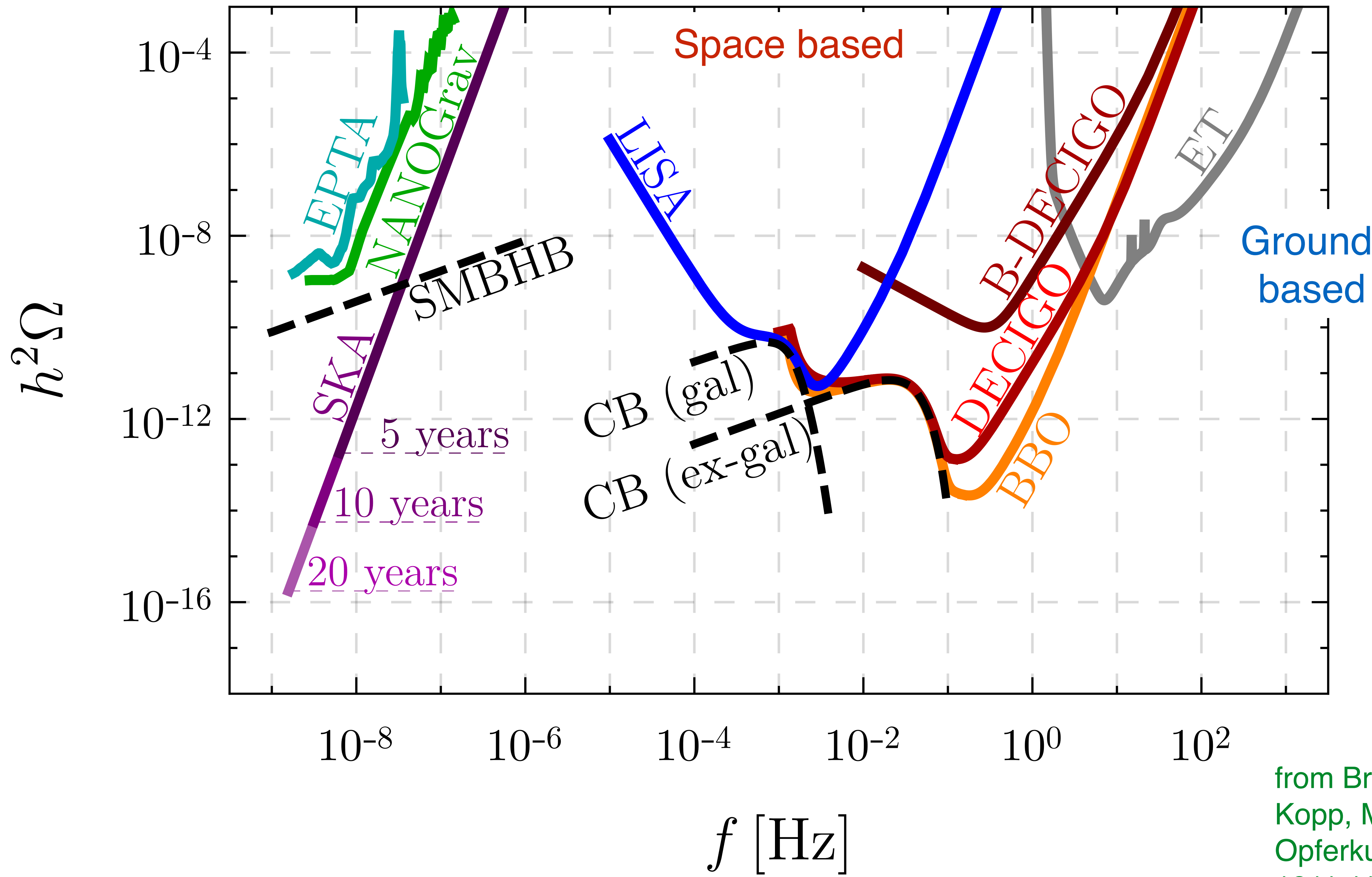
Interesting hints for a stochastic GW background at very low frequencies (MeV scale new physics)

CMB spectral distortions provide a complementary probe of GW sources

Supplemental material

Frequency ranges

New physics scale   GeV   TeV   PeV



from Breitbach, Kopp, Madge, Opferkuch, PS 1811.11175

Messengers II: Photons

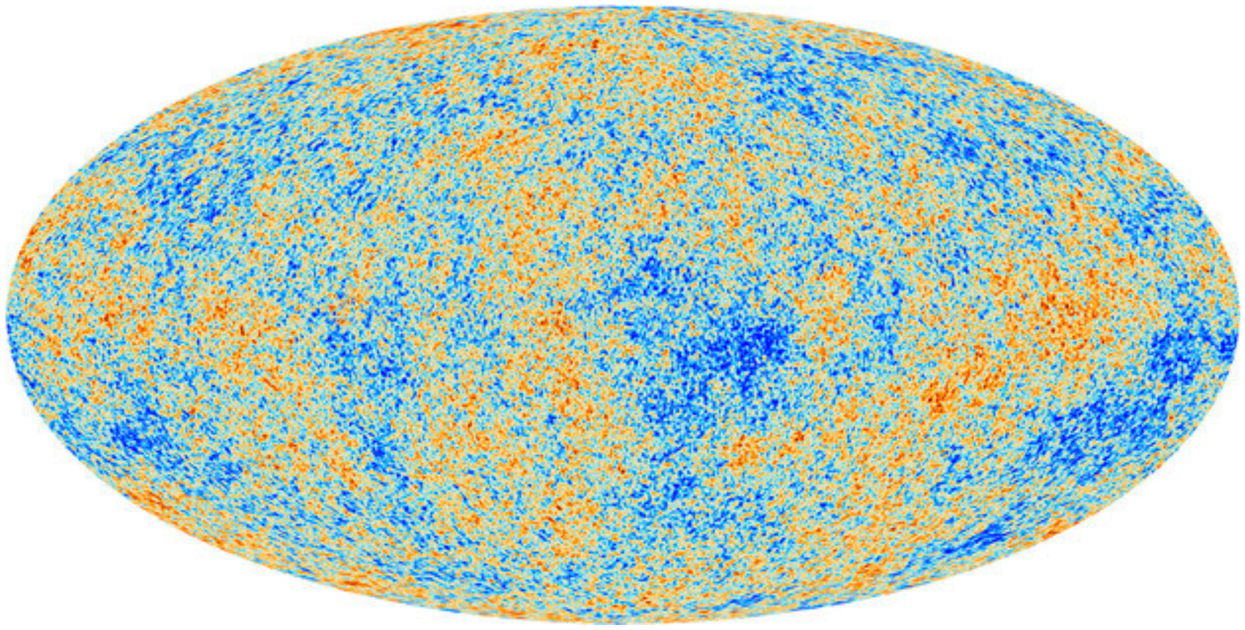
Emitted at $T \sim 1\,\mathrm{eV}$

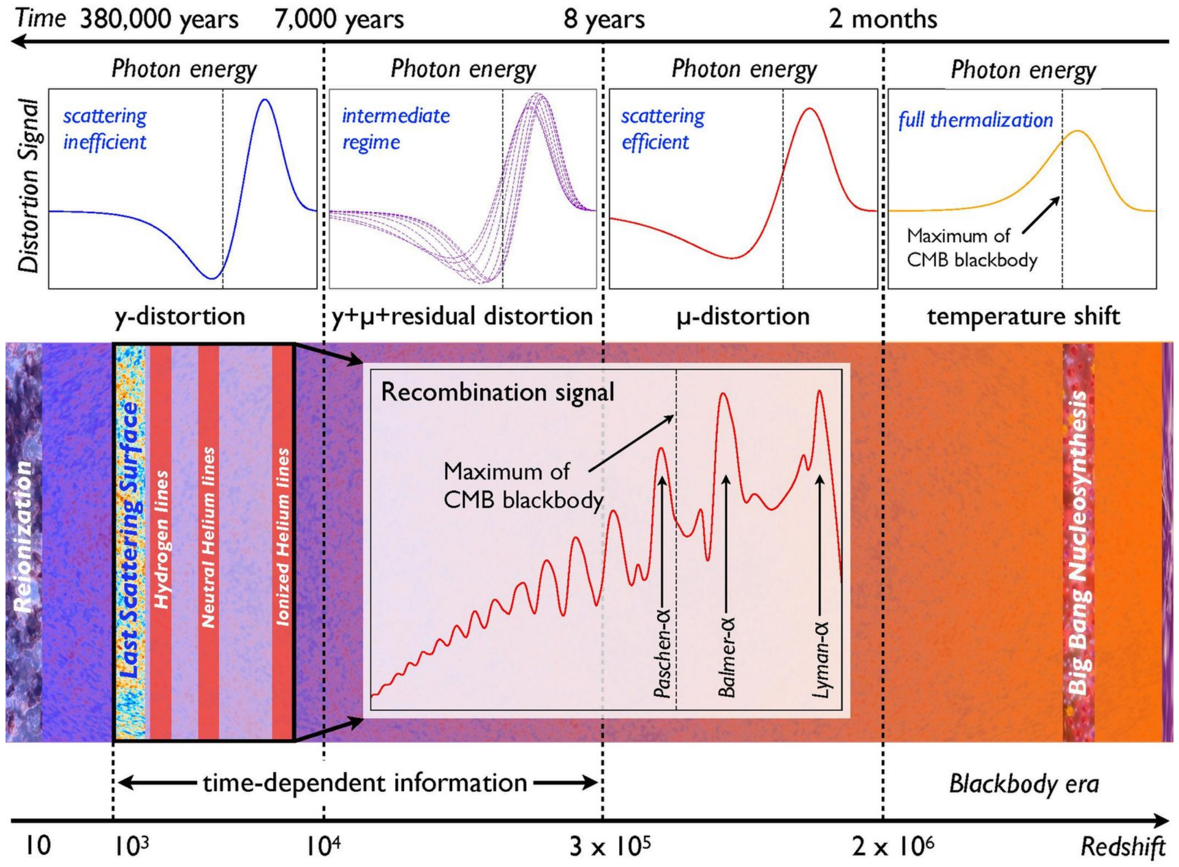
Equilibrium phyiscs

- almost perfect black body spectrum

Non-equilibrium physics can distort the spectrum

- Probe of $\mathrm{keV} - \mathrm{MeV}$ temperatures



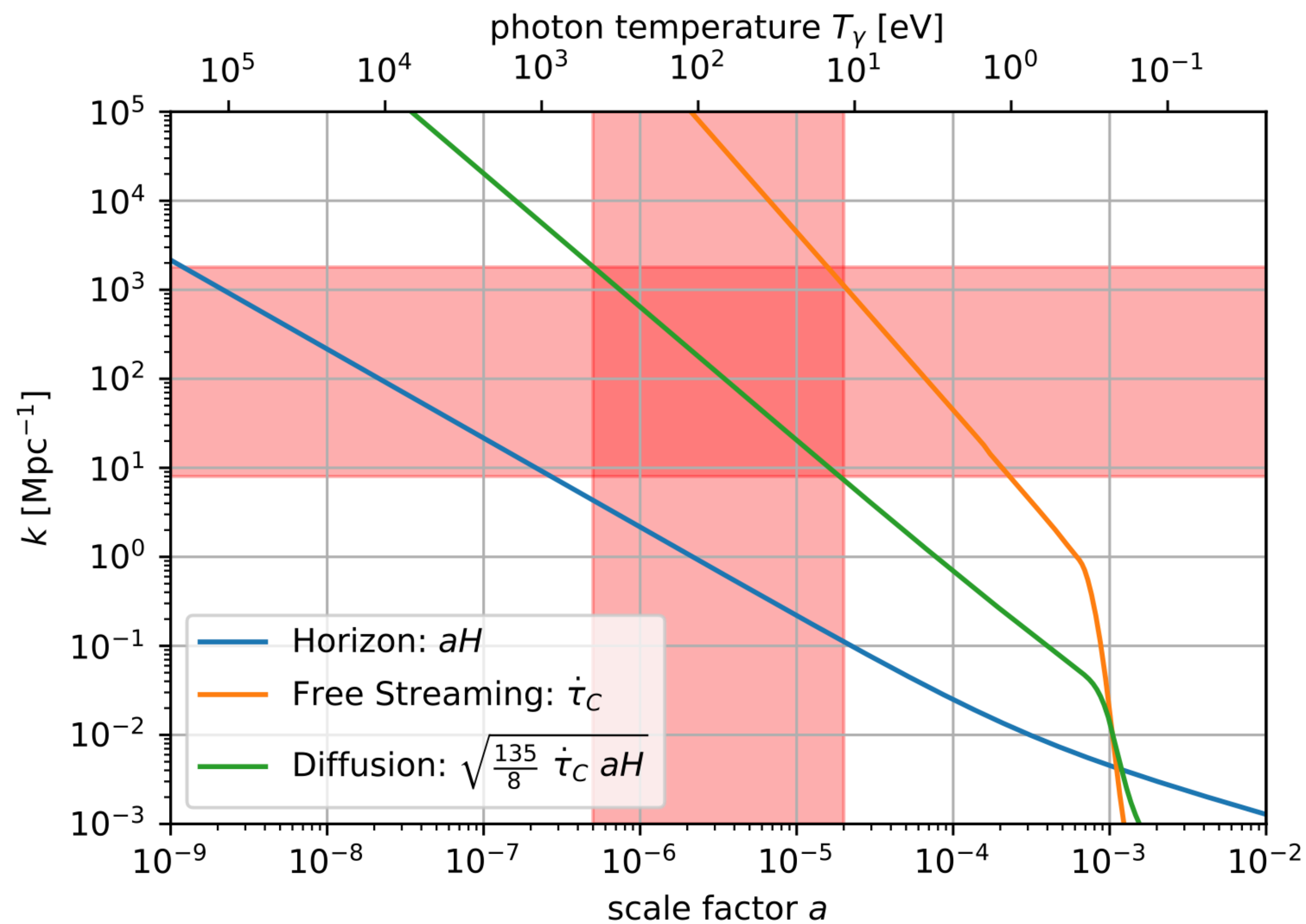


Spectral distortions?

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

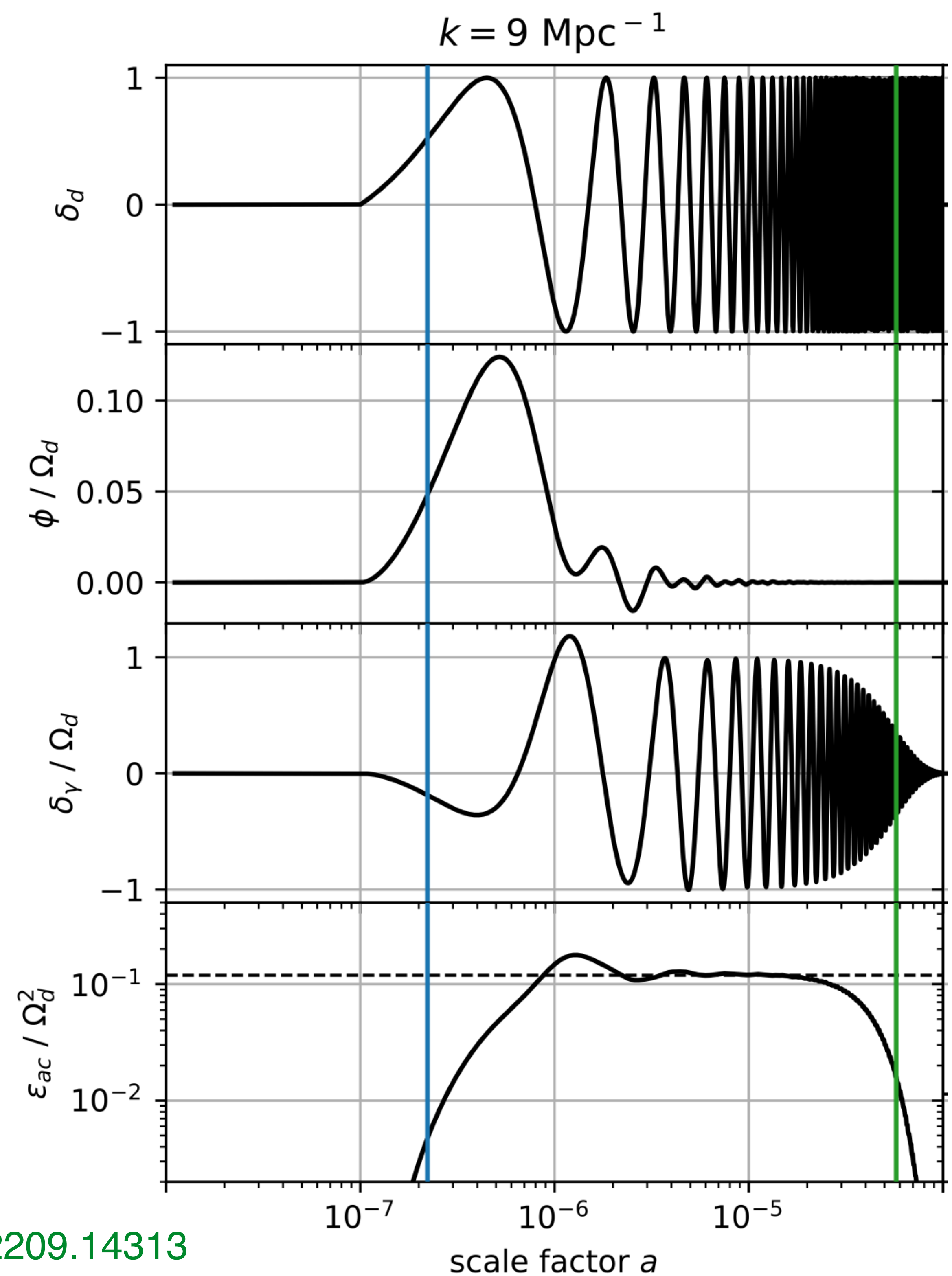
Assume decoupled dark sector, $\Omega_d \ll 1$

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

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

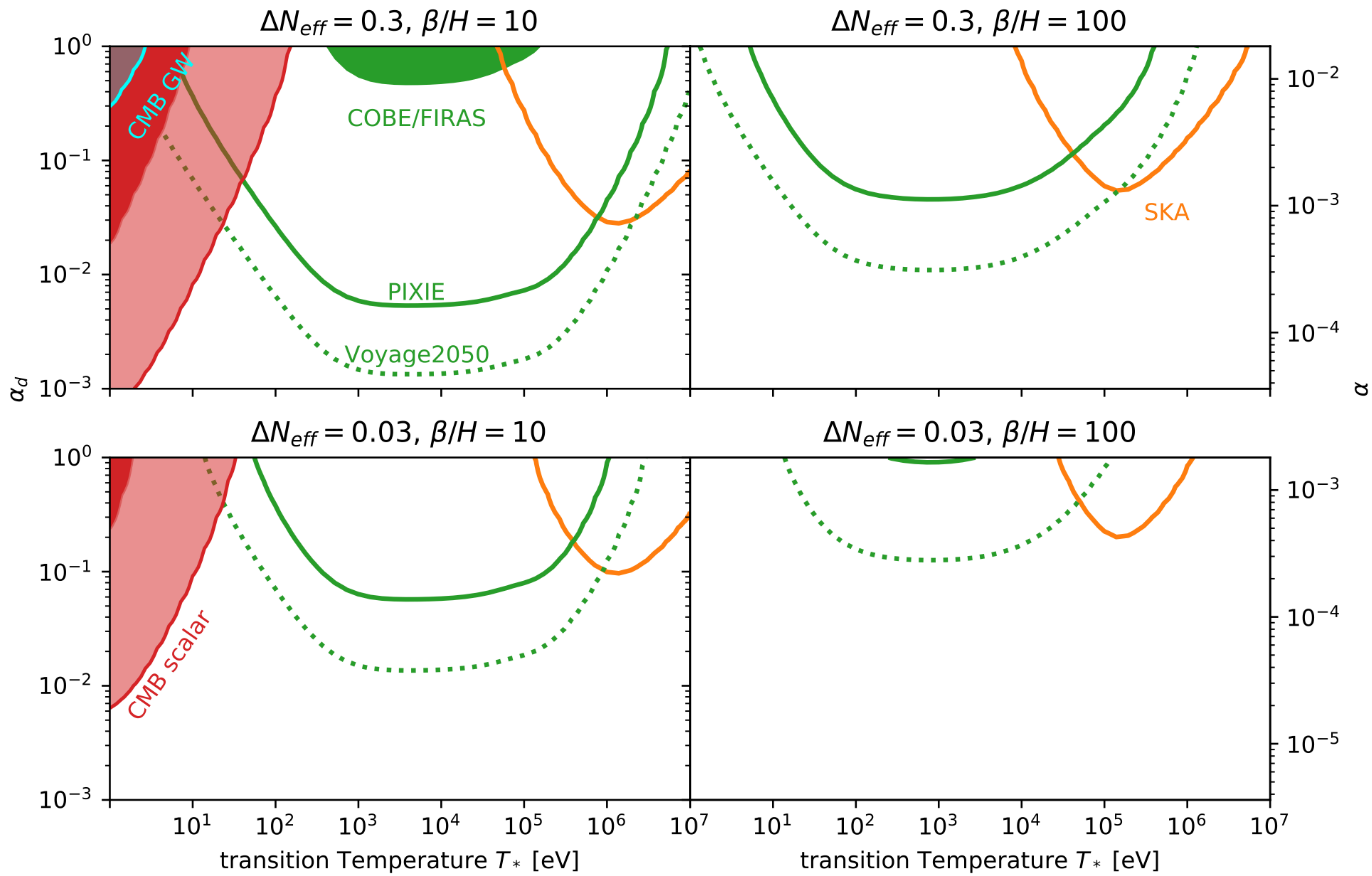
Resulting μ distortions

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



Ramberg, Ratzinger & PS, 2209.14313

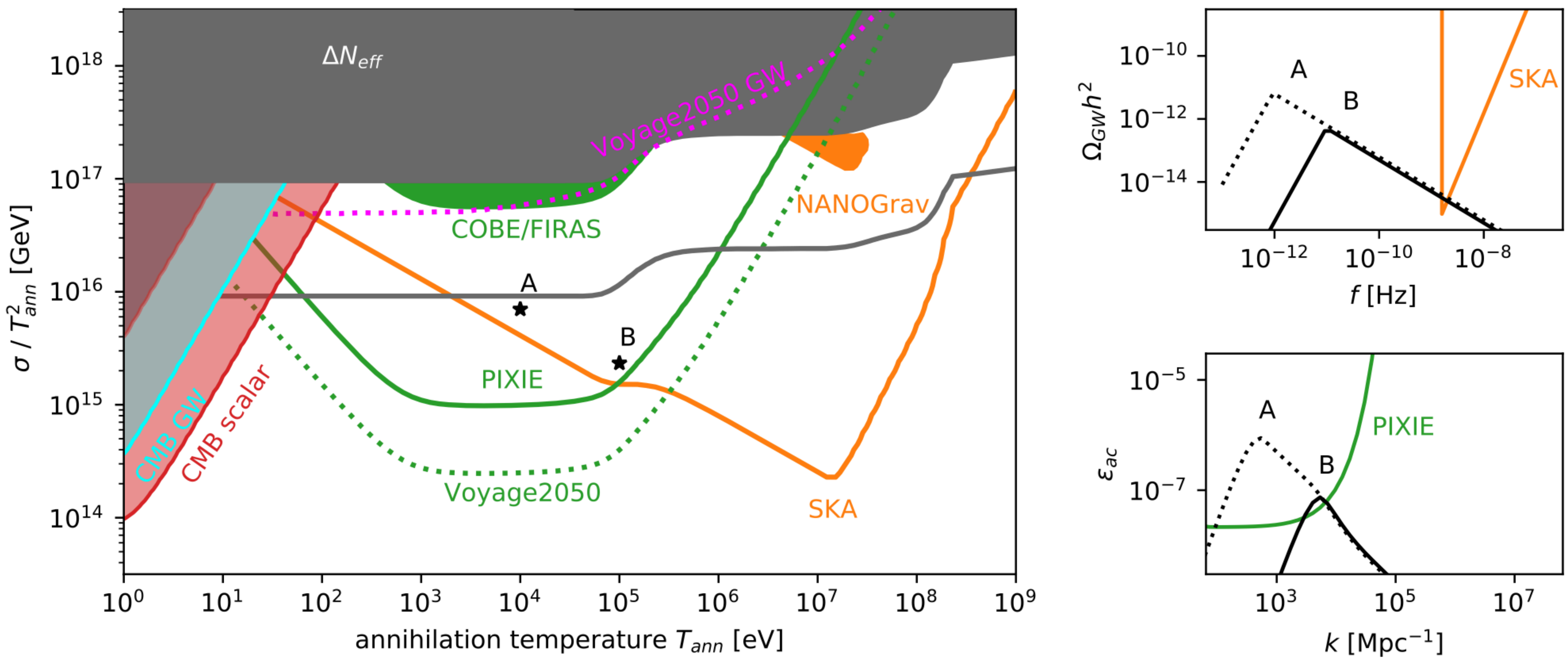
Example source I: Dark sector phase transition



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

Ramberg, Ratzinger & PS, 2209.14313

Example source II: Annihilating domain walls



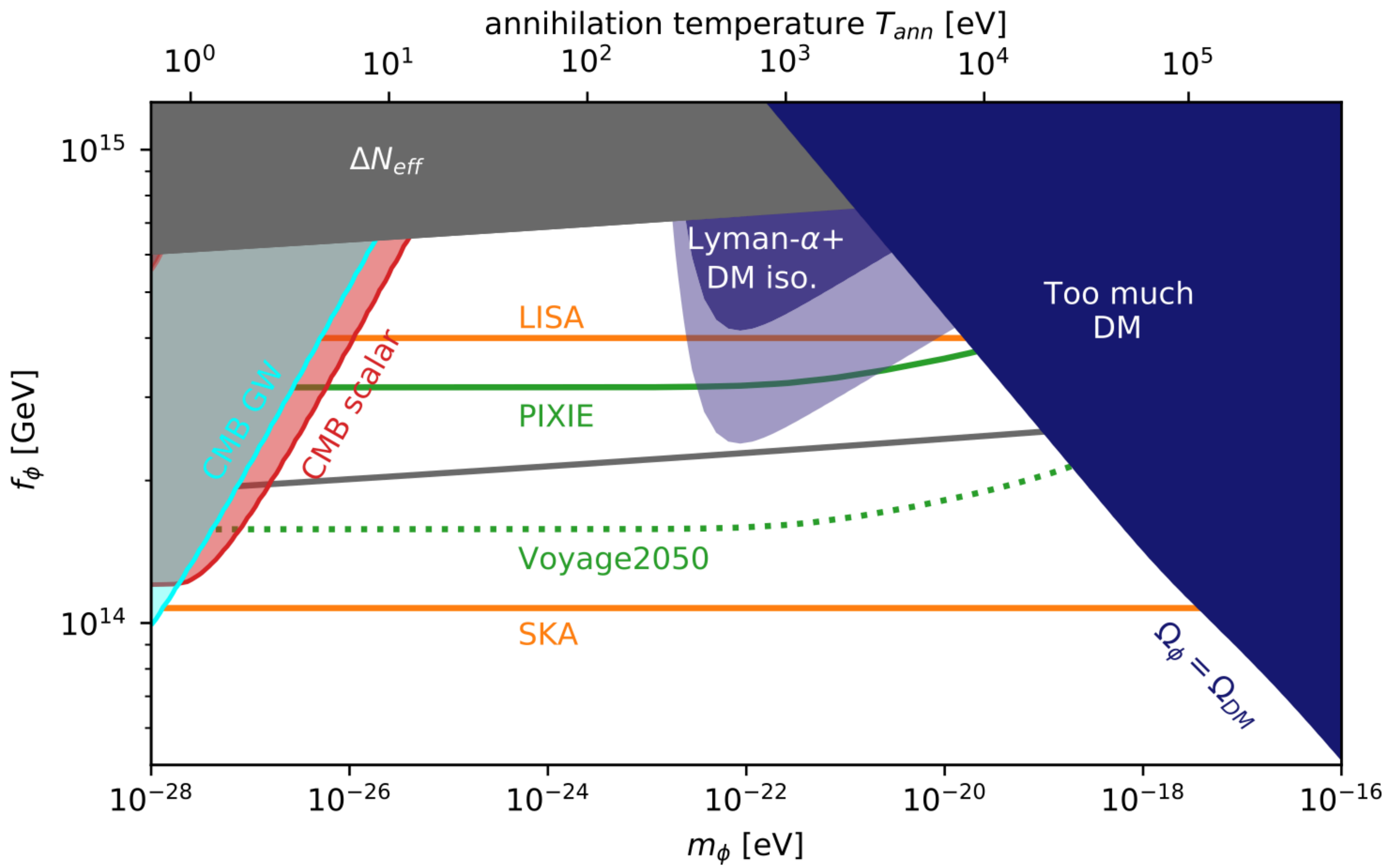
Already probes allowed parameter space

Complementary to GW probes, can break degeneracy

- Multi-messenger cosmology

Ramberg, Ratzinger & PS, 2209.14313

Source III: (global) cosmic strings



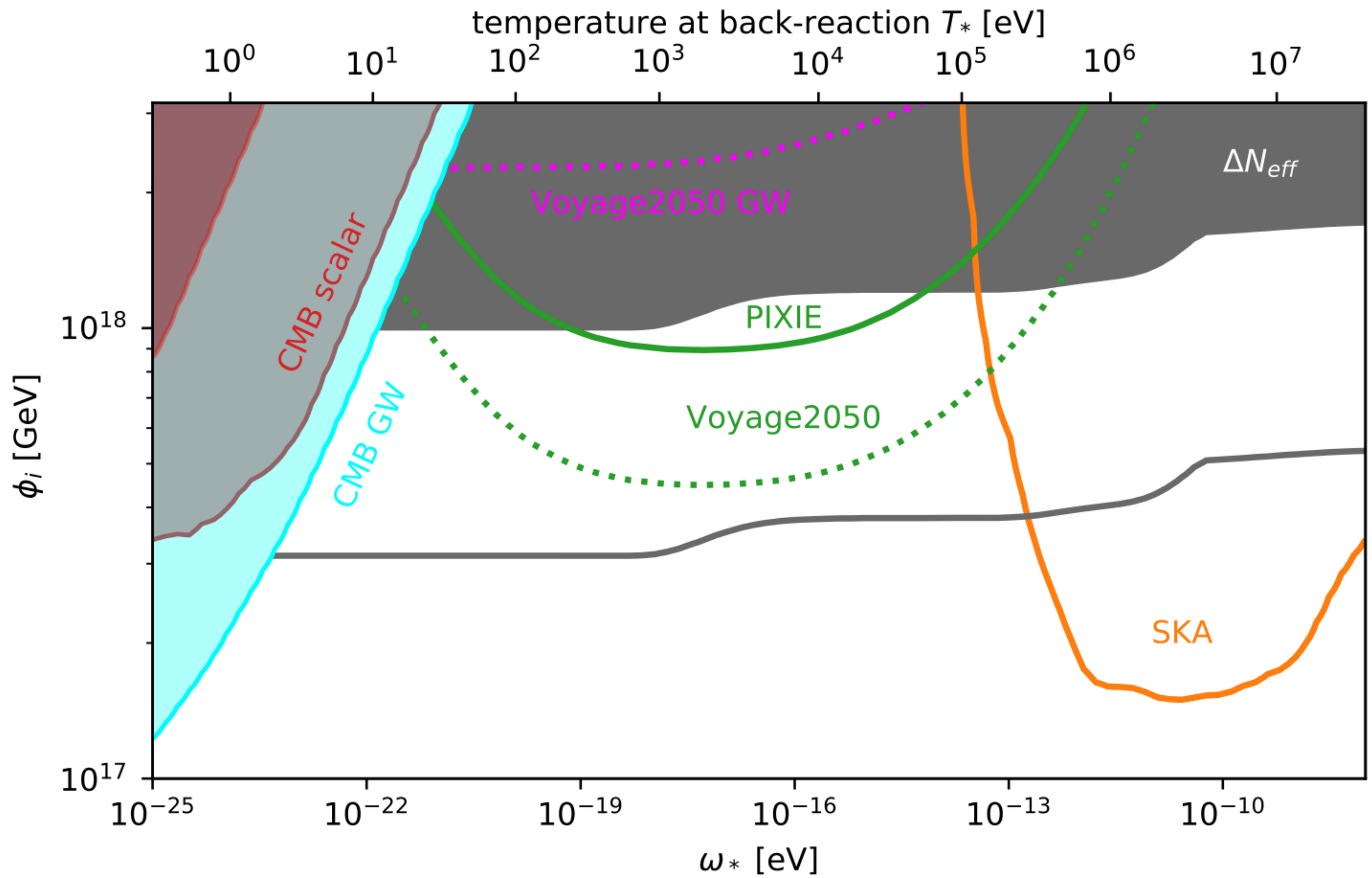
Note: Local strings mainly radiate from small loops and are thus NOT an efficient source of spectral distortions

Example source IV: Audible axions…

Not yet…

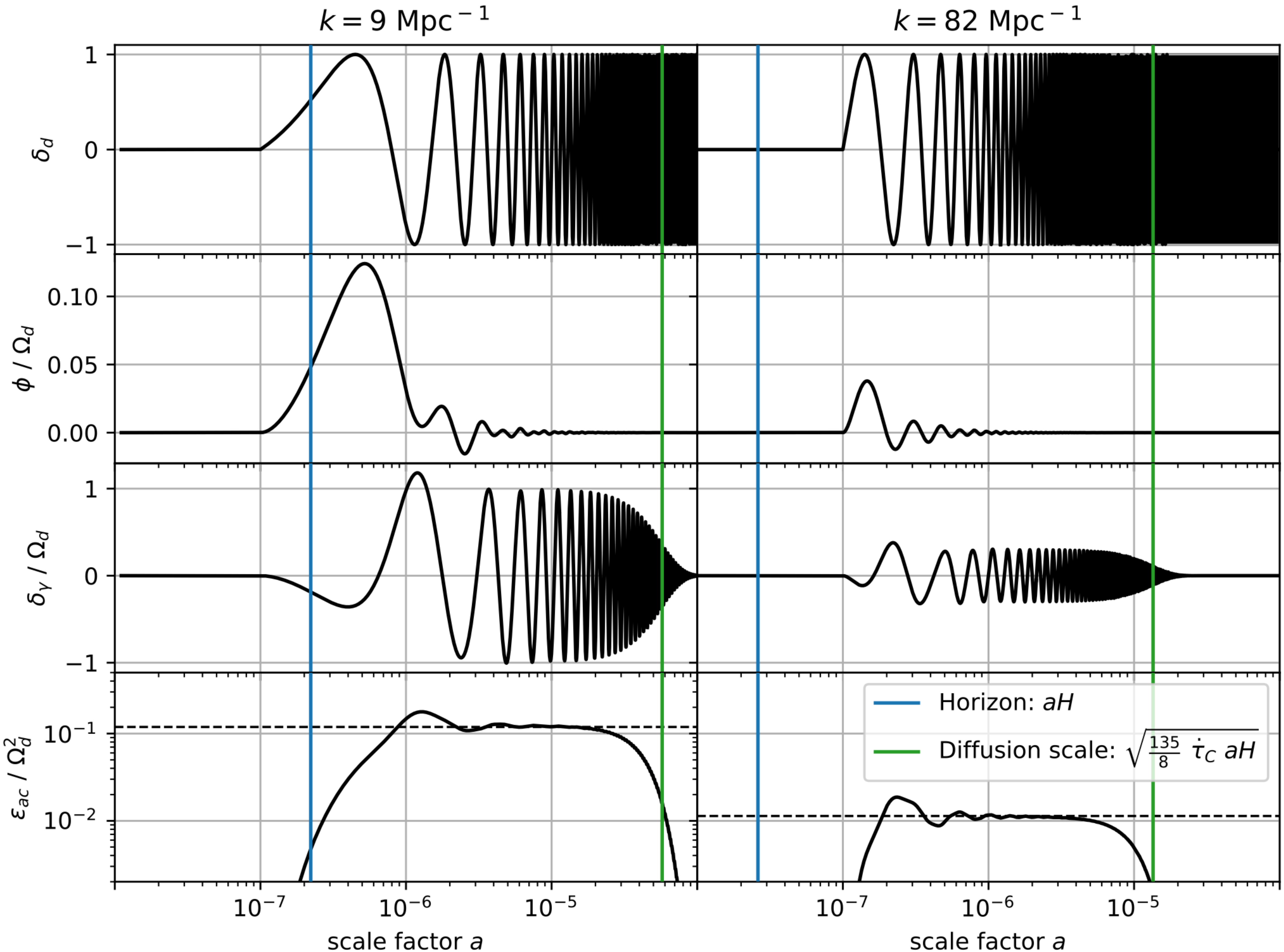
Results for scalar toy model

Constraints not as strong since fluctuations are not horizon size

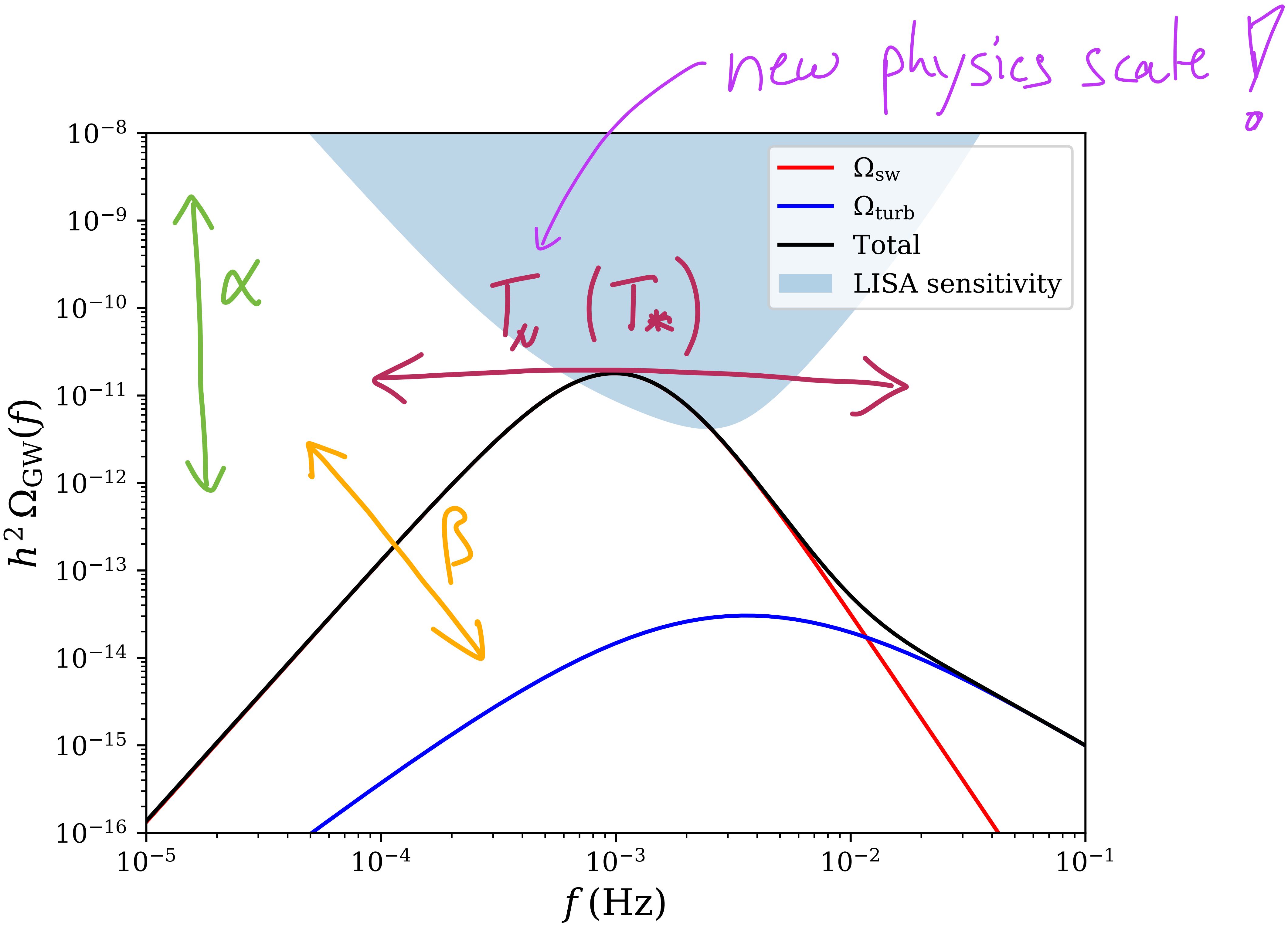


Expect better sensitivity for axion fragmentation

Ramberg, Ratzinger & PS, 2209.14313


$k = 9$ Mpc^{-1}
$k = 82$ Mpc^{-1}
δ_d
ϕ / Ω_d
δ_γ / Ω_d
ε_{ac} / Ω_d^2
1
0
−1
0.10
0.05
0.00
10^{-1}
10^{-2}
10^{-7}
10^{-6}
10^{-5}
scale factor a
Horizon: aH
Diffusion scale: $\sqrt{\frac{135}{8}\ \dot{\tau}_C\ aH}$

Signal properties



Combine both approaches

Improved holographic QCD

$$\mathcal{S}_5 = -M_P^3 N_c^2 \int d^5x \sqrt{g} \left[R - \frac{4}{3}(\partial\Phi)^2 + V(\Phi) \right] + 2M_P^3 N_c^2 \int_{\partial M} d^4x \sqrt{h} K$$

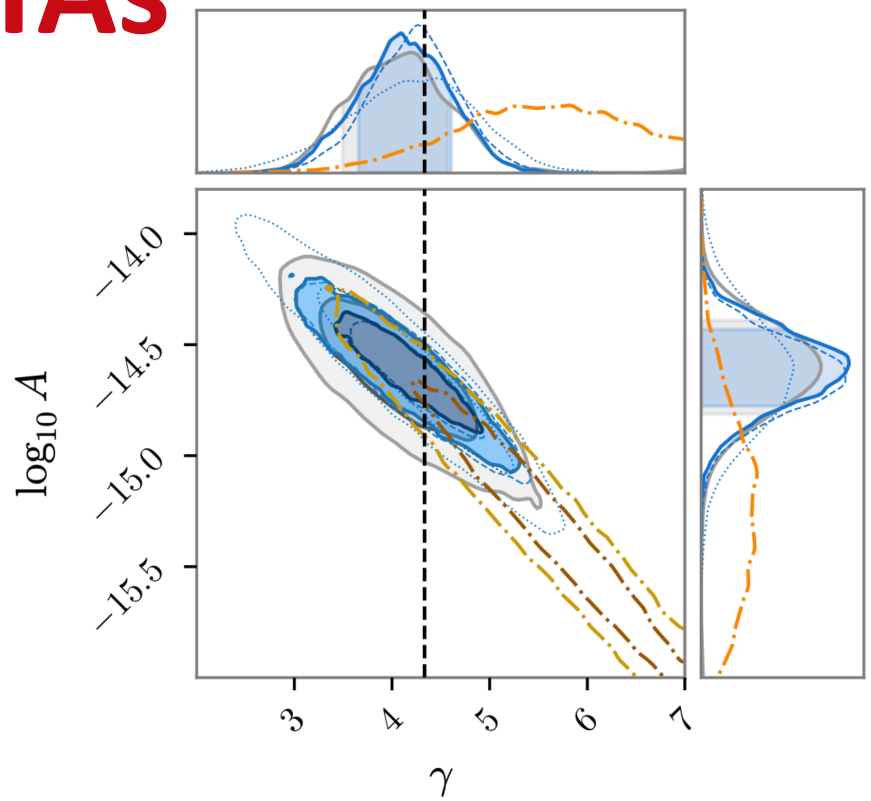
- AdS Einstein-dilaton gravity $\leftrightarrow$ 4D CFT
- Dilaton potential $V(\Phi)$
- Dilaton $\lambda = \exp\Phi$ $\leftrightarrow$ 't Hooft coupling $\lambda_t = N_c g_{YM}^2$
- …
- Solutions of EOM $\leftrightarrow$ phases of SU(N)

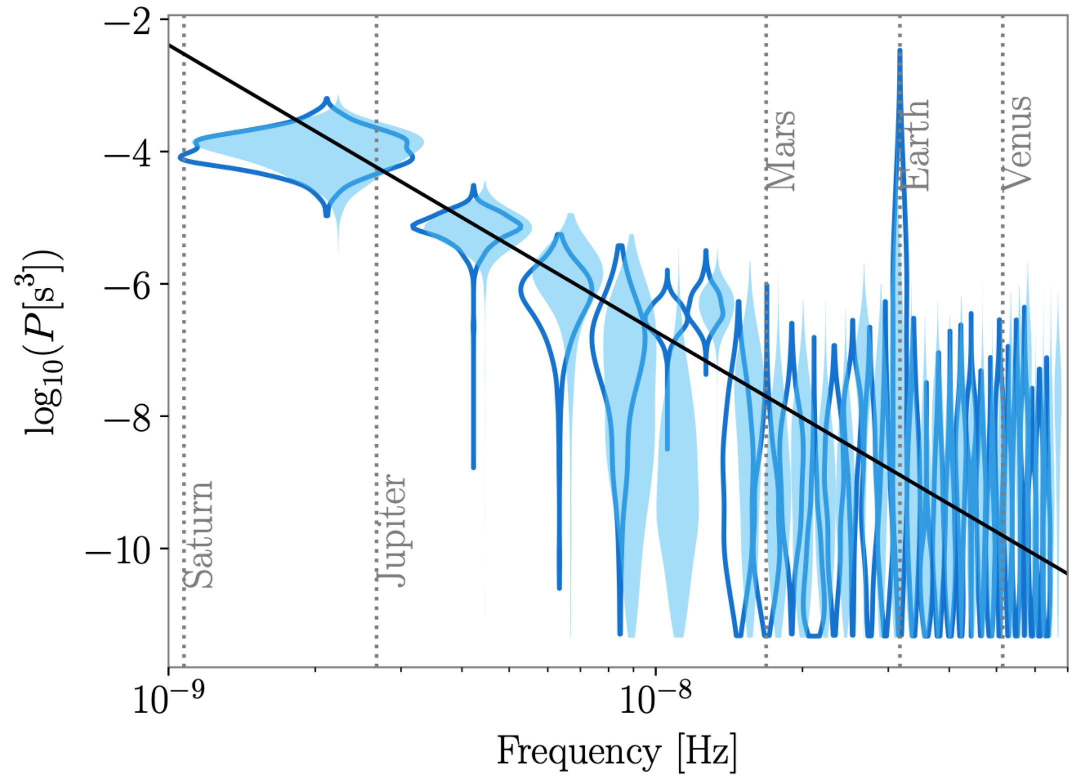
Gürsoy, Kiritsis, Mazzanti, Nitti
0707.1324, 0707.1349, 0812.0792, 0903.2859, ...

Other PTAs

Parkes PTA (Australia)

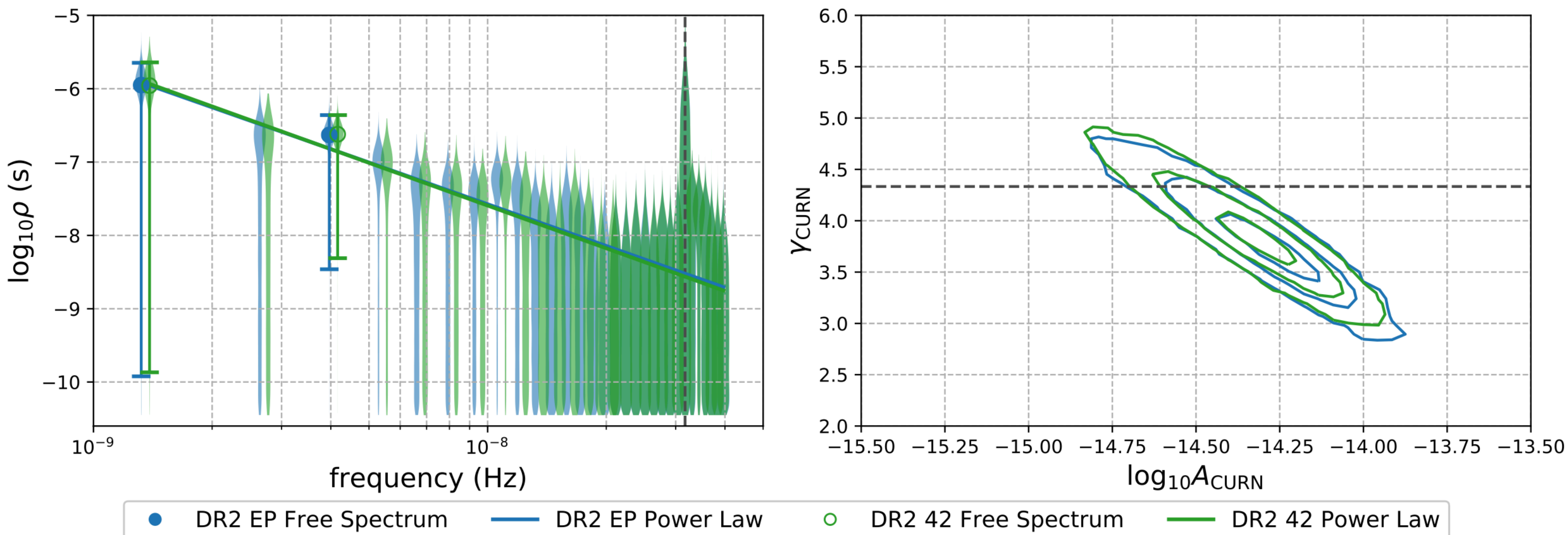
arXiv:2107.12112





European PTA

arXiv:2110.13184



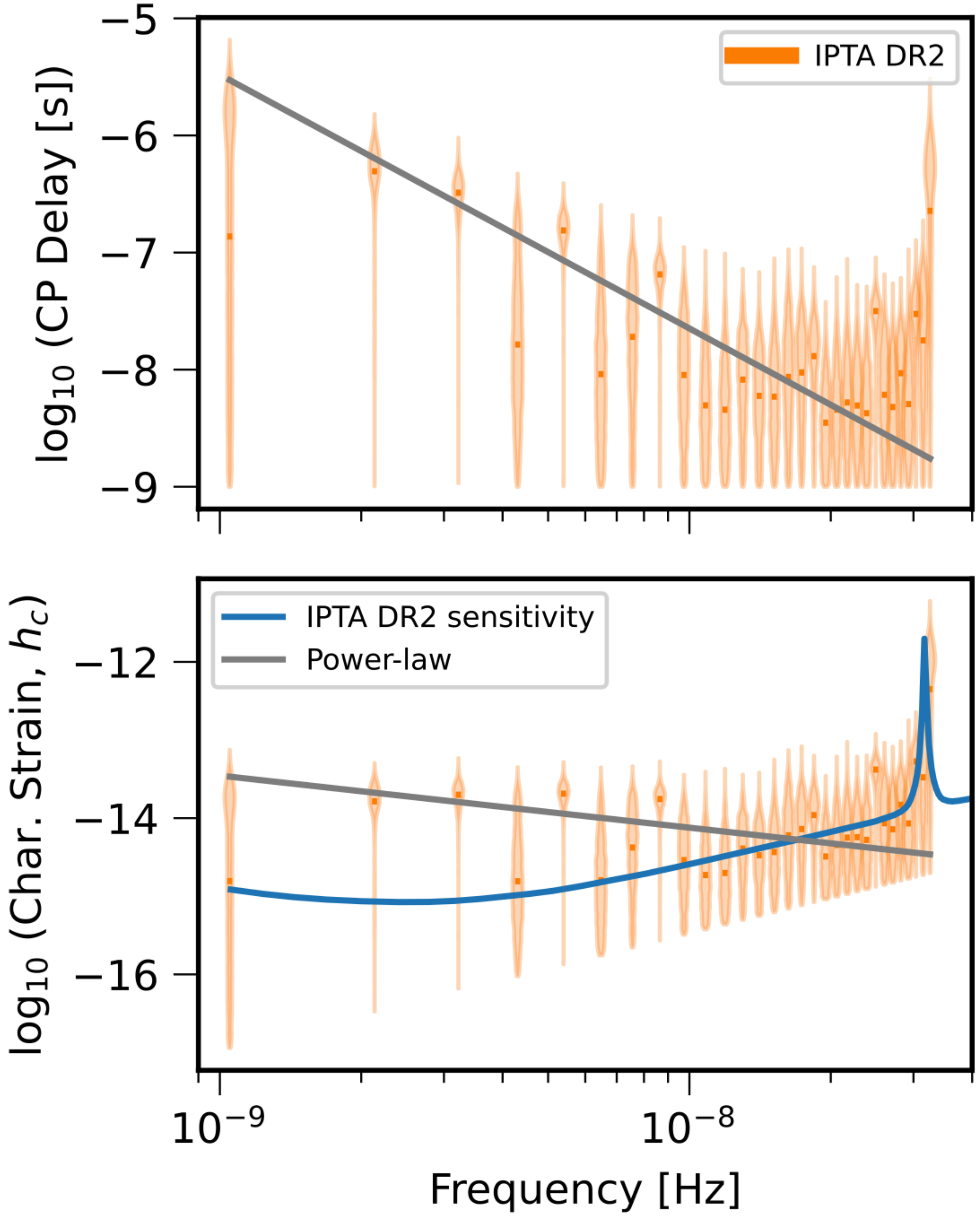
International PTA

Combination of data, but using older data

Again strong evidence for "something", but no conclusive evidence for quadrupole correlation

Model comparison	$\log_{10}$ BF
HD vs CP	0.3111(6)
CP vs Pulsar Noise	8.2*
CP vs Monopole	4.67(2)
CP vs Dipole	2.28(3)

arXiv:2201.03980

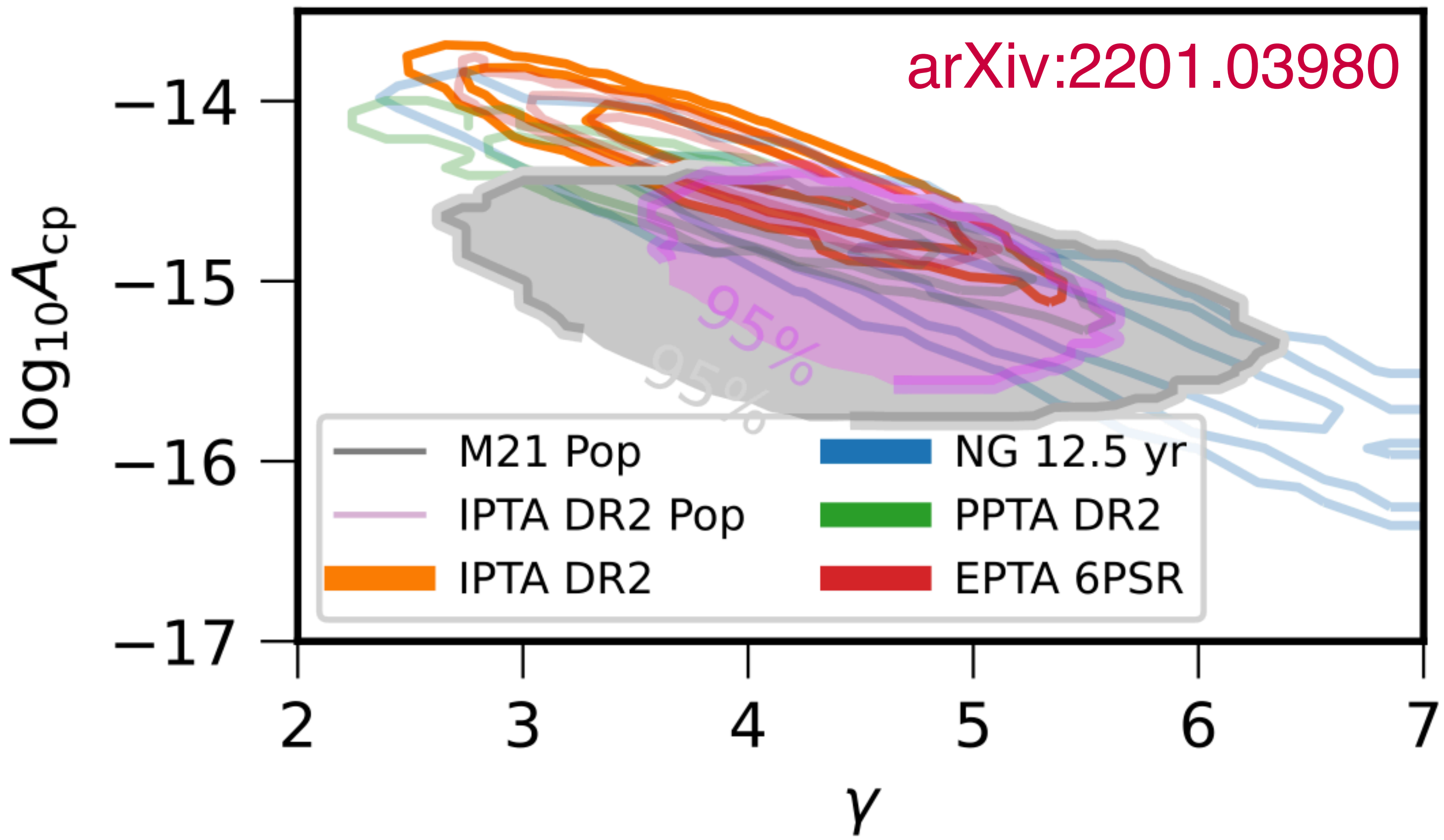


Not an anomaly?

There is an expected background from supermassive black hole binaries (SMBHB)!

Expected slope of $\gamma = 13/3$, but can vary in practice

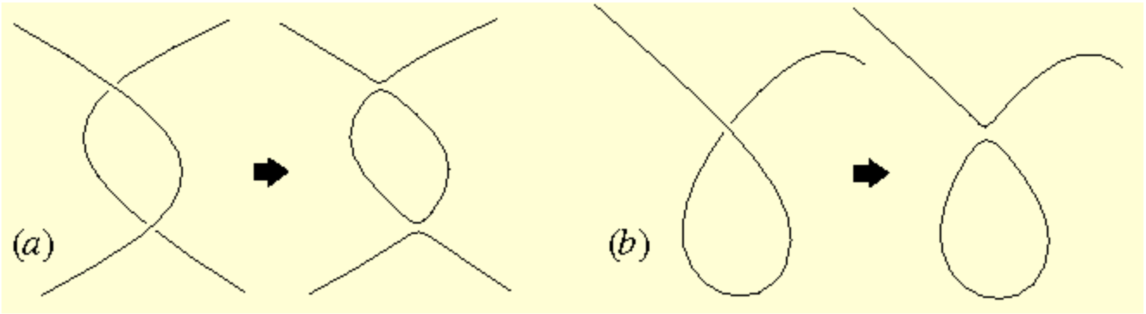
Amplitude a bit high for pure Astro signal

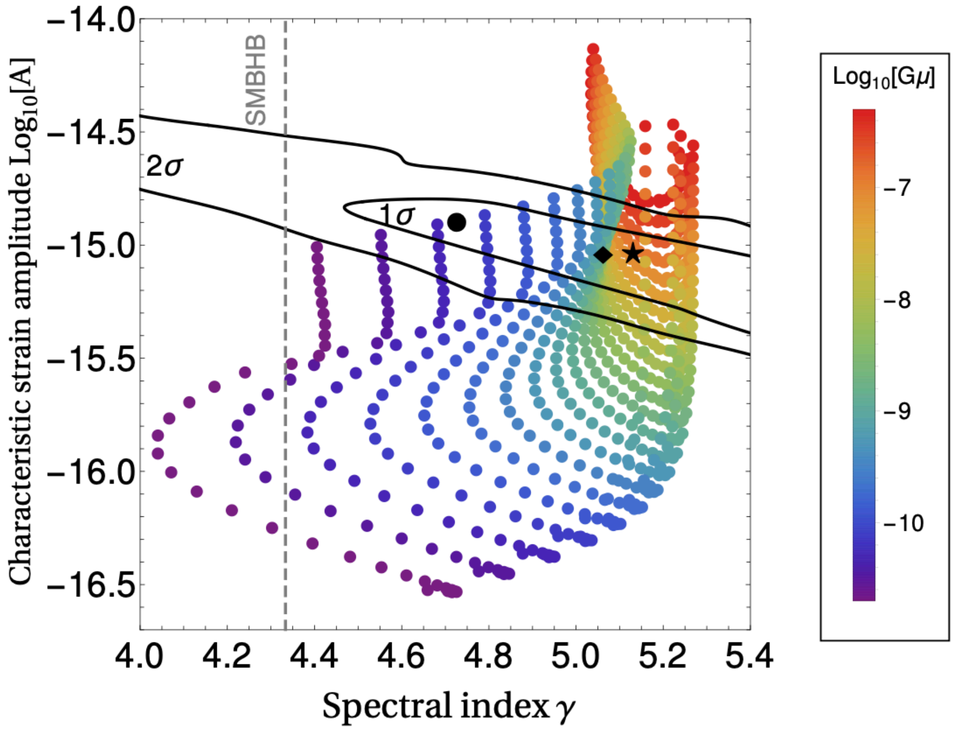


- Room for new physics contribution!

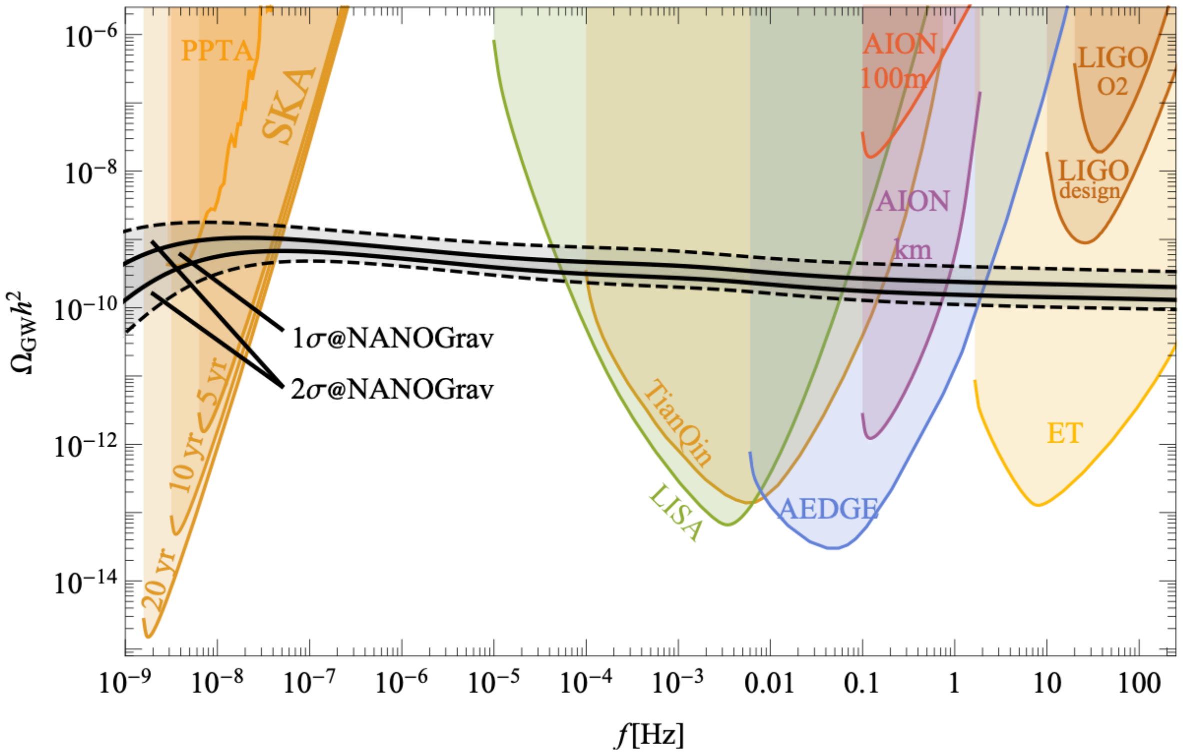
Simple power laws: Inflation or cosmic strings

Strings work better though!





Blasi, Brdar, Schmitz, 2009.06607



Ellis, Lewicki, 2009.06555

More BHs?

Signal from mergers “stupendously” large primordial BH?

Atal, Sanglas, Triantafyllou, 2012.14721

Only possible with large clustering!

Depta, Schmidt-Hoberg, PS, Tasillo, in preparation