Cosmic Microwave Background as Laboratory for Fundamental Physics

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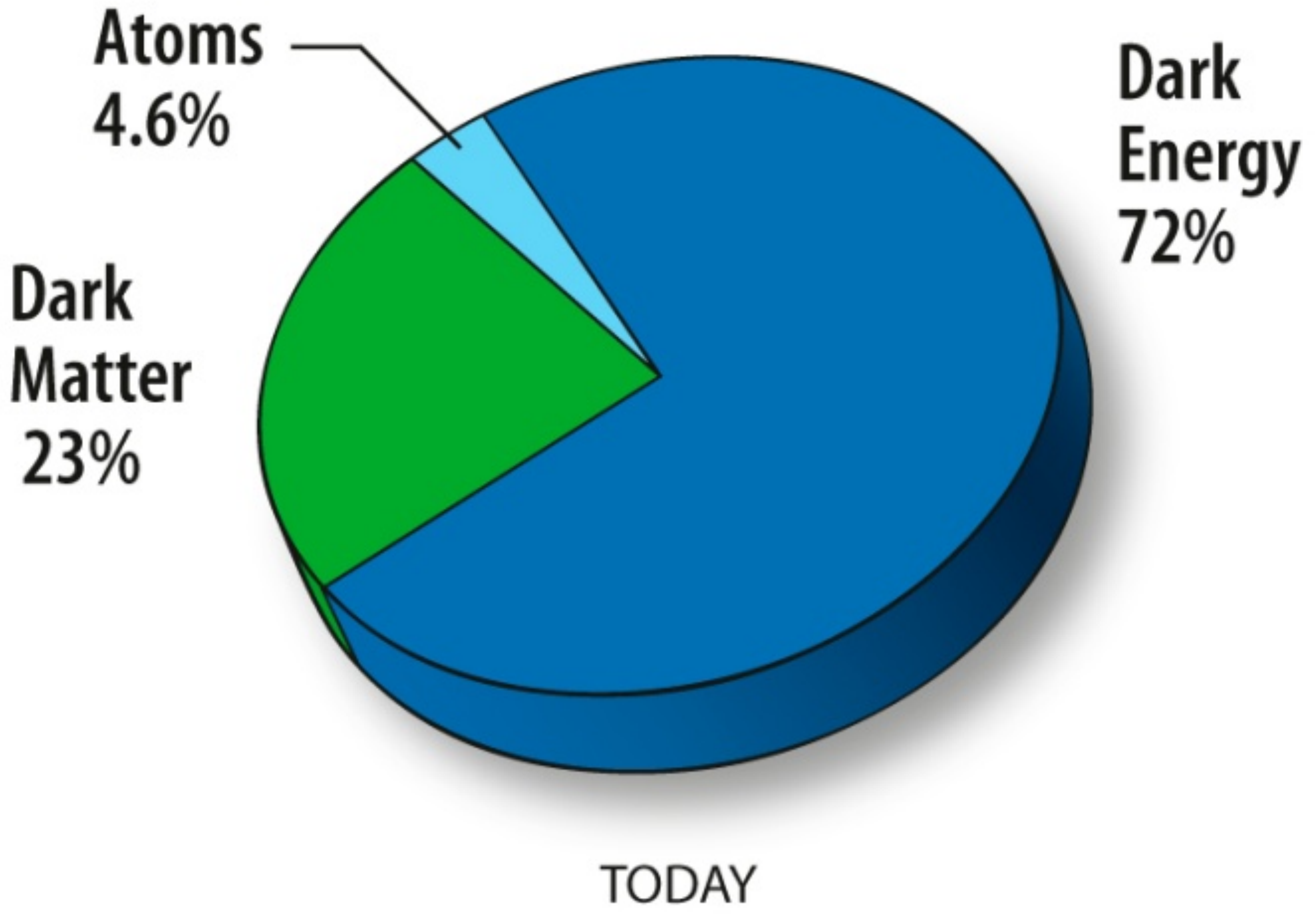
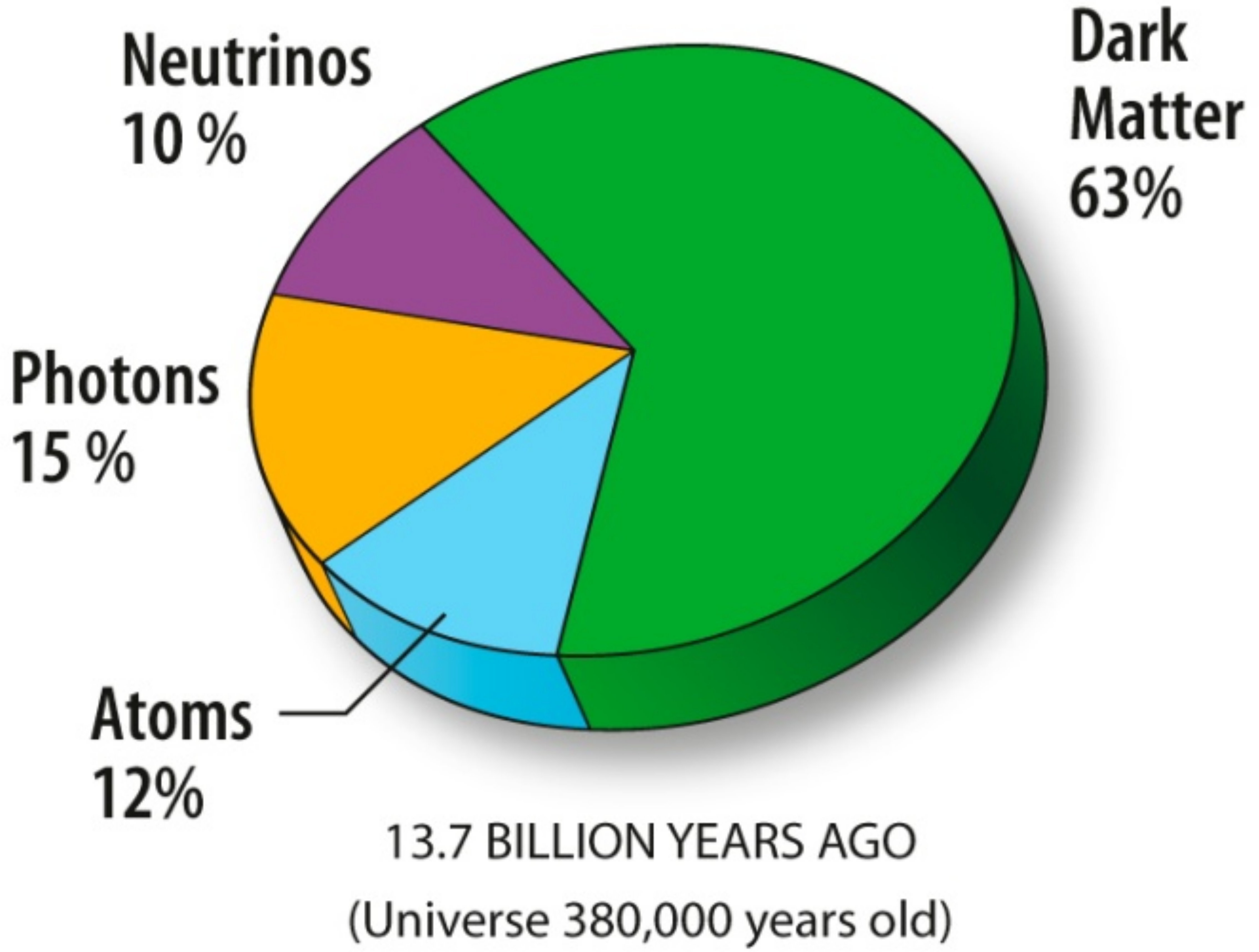
CMB shapes our physical cosmology

- The Universe is spatially flat, and the expansion is accelerating.





Source: NASA/WMAP science team

Remaining big questions

- ASTRO2010, 2020 decadal review panel questions are all related to the *nature of the building blocks* of the concordance model:
  - **Dark energy:** Why is the Universe accelerating now?
  - **Inflation:** How did the Universe begin?
  - **Dark matter:** What is dark matter?
  - **Neutrinos:** What are the properties of neutrinos?
- *We have been addressing all these questions using the CMB!*

CMB is a relic from hot Big-Bang

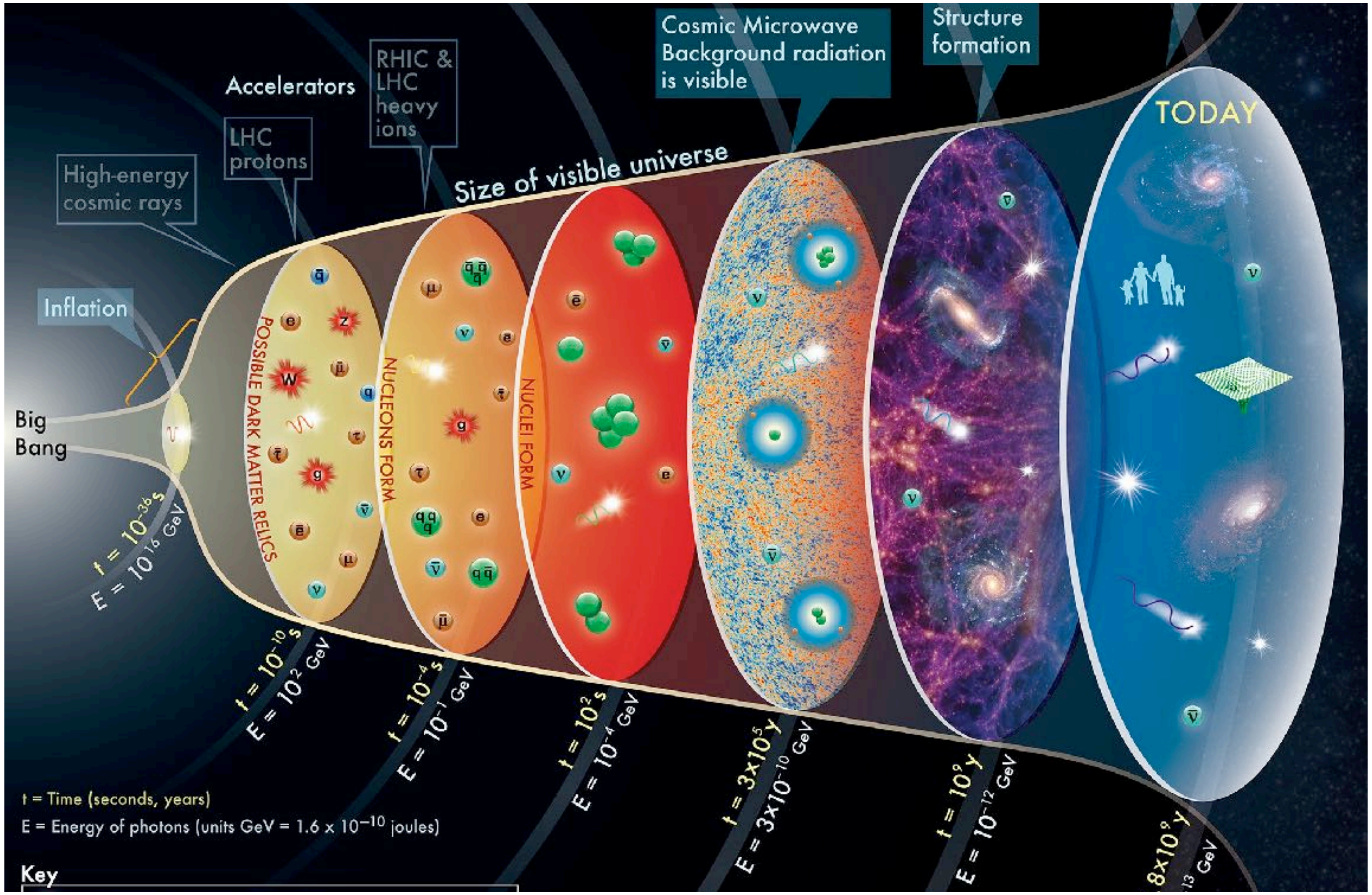


Figure from Particle Data Group, LBNL @ 2015

CMB is a relic from hot Big-Bang

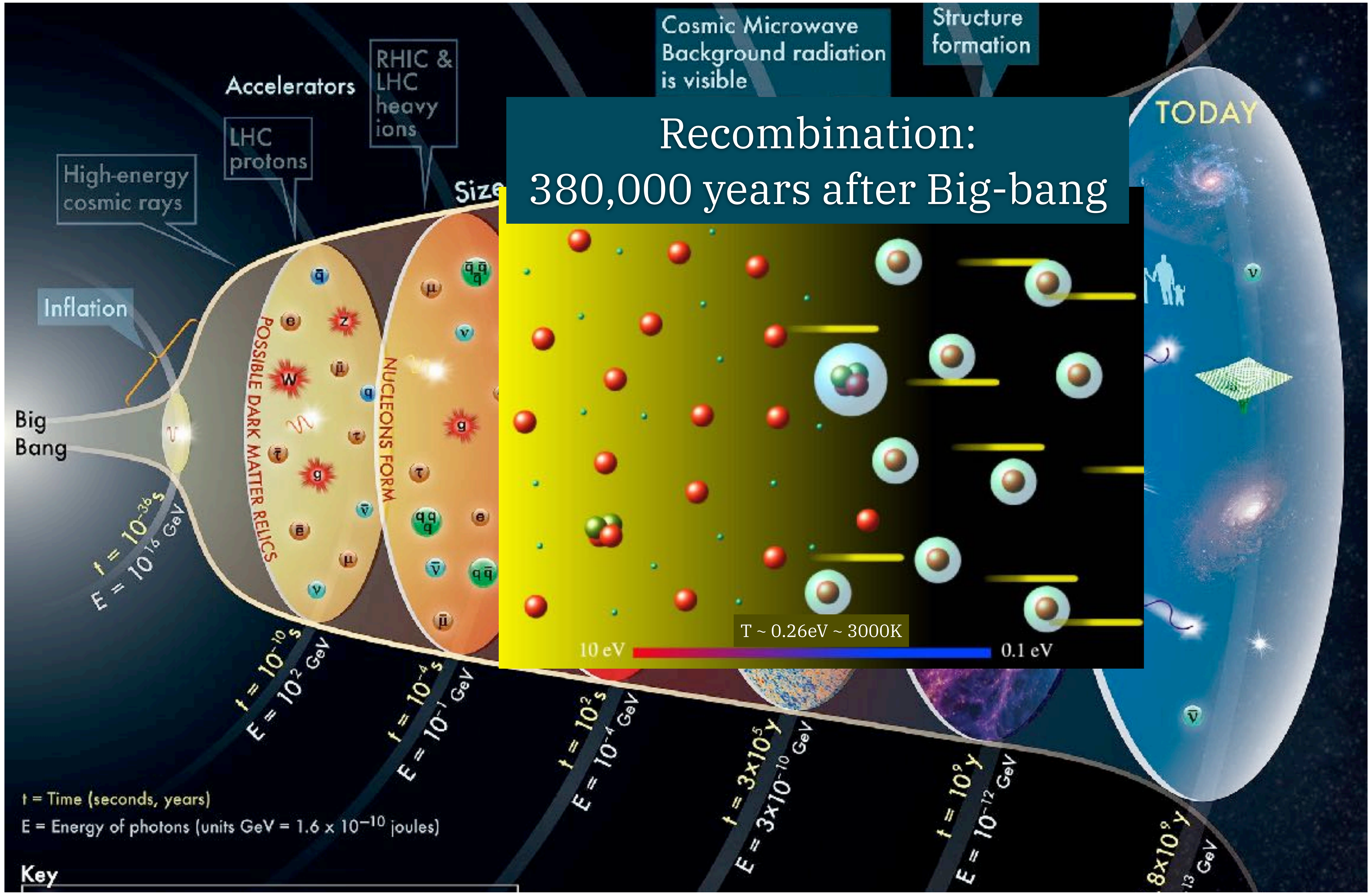
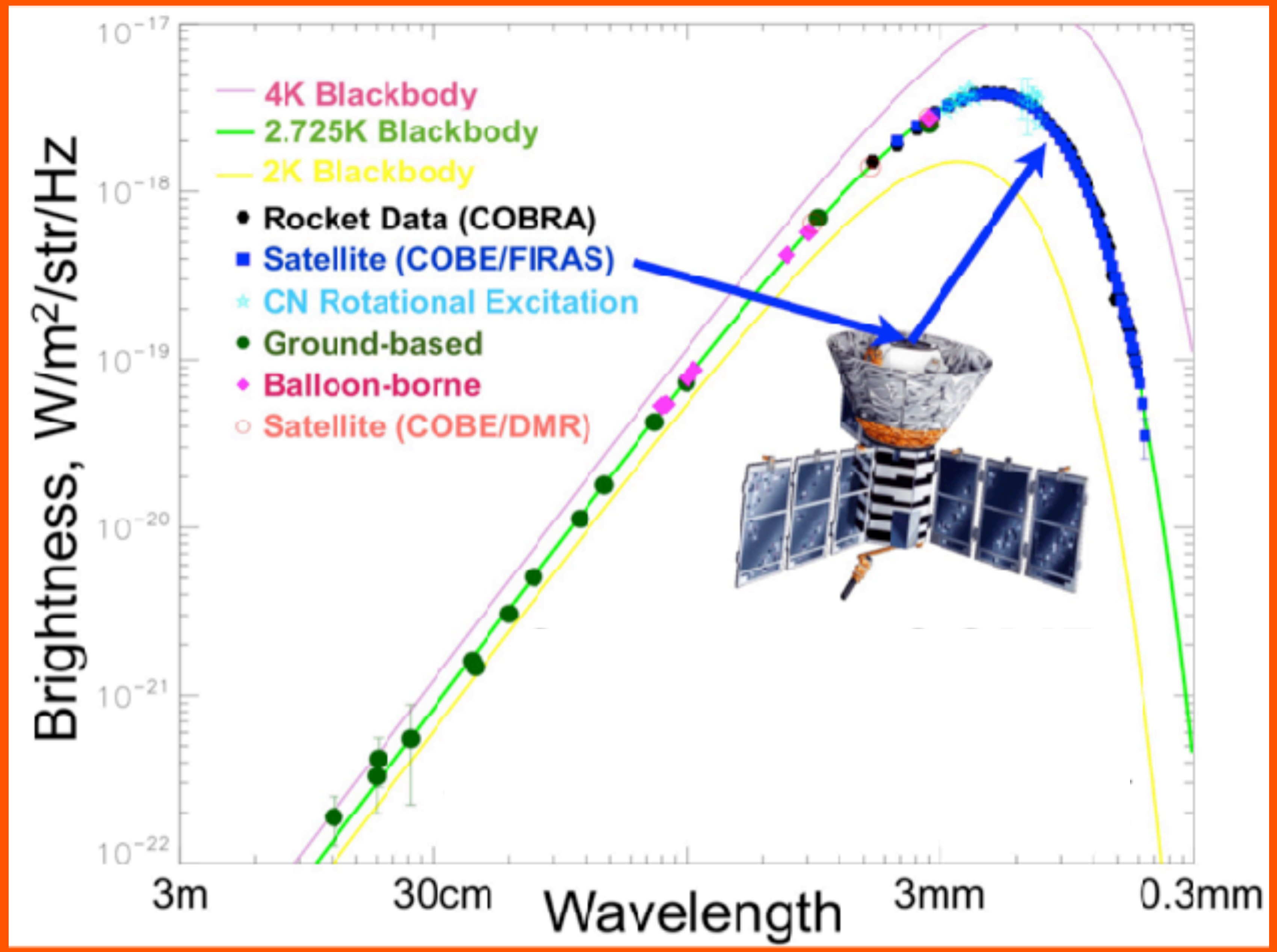


Figure from Particle Data Group, LBNL @ 2015

CMB = isotropic

Full-sky CMB intensity map at 1mm

CMB = isotropic black-body

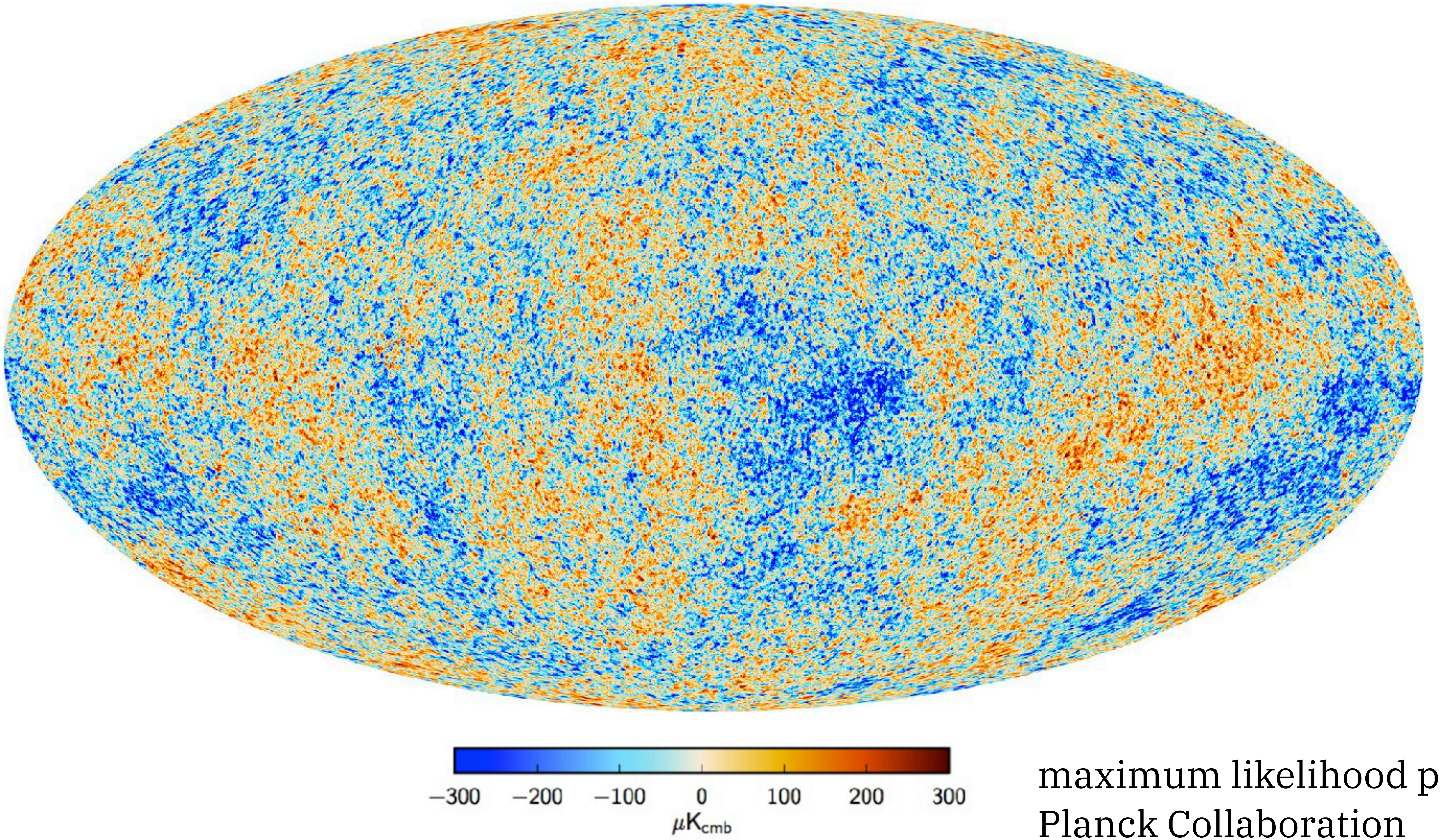


$T_{CMB} = 2.7260 \pm 0.0013$ K

(Fixen+2009, COBE/FIRAS)

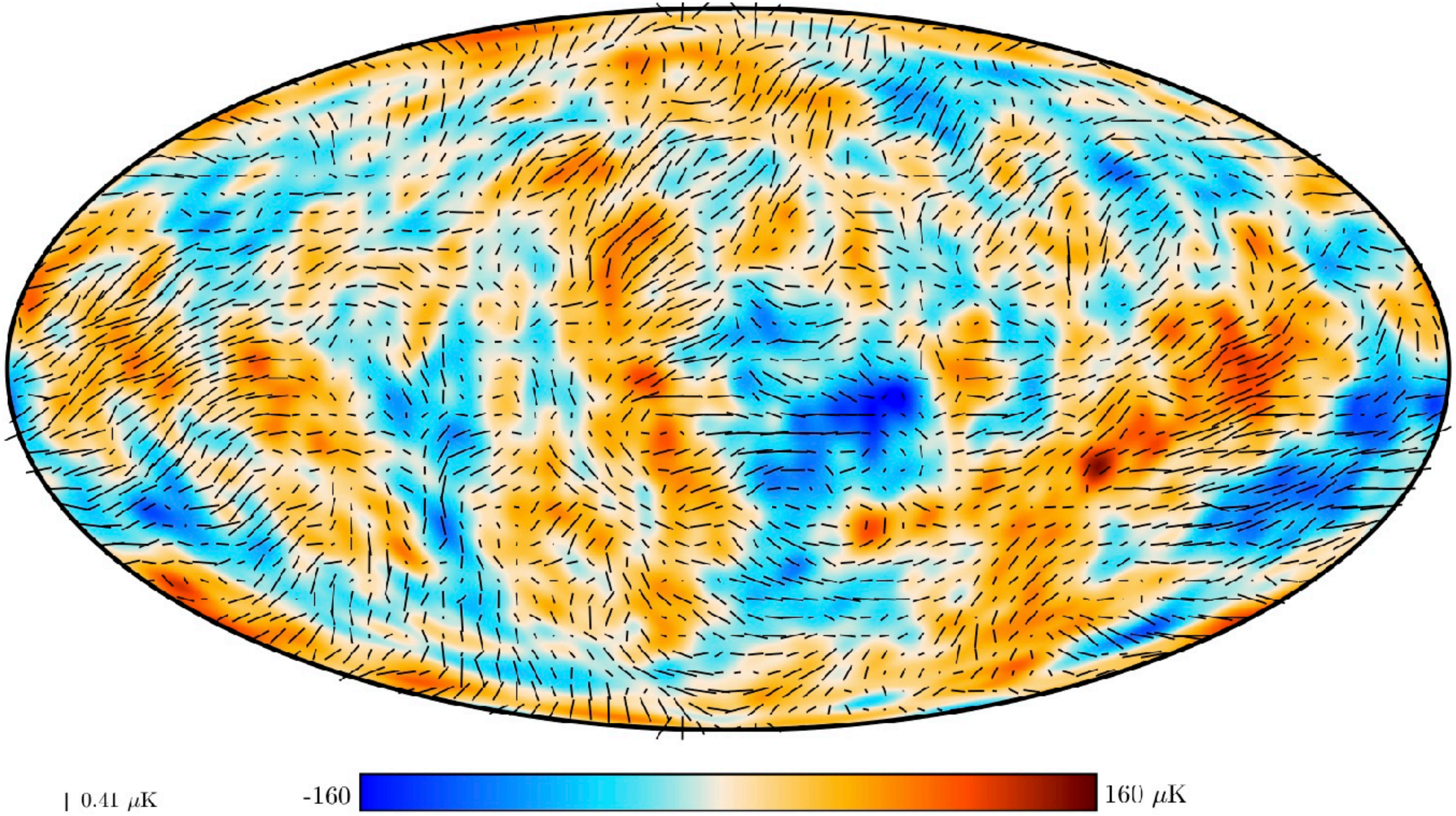
Limits on spectral distortions: $|y|<1.5\times10^{-5}$, $|\mu|<9\times10^{-5}$

CMB is anisotropic



maximum likelihood posterior map
Planck Collaboration

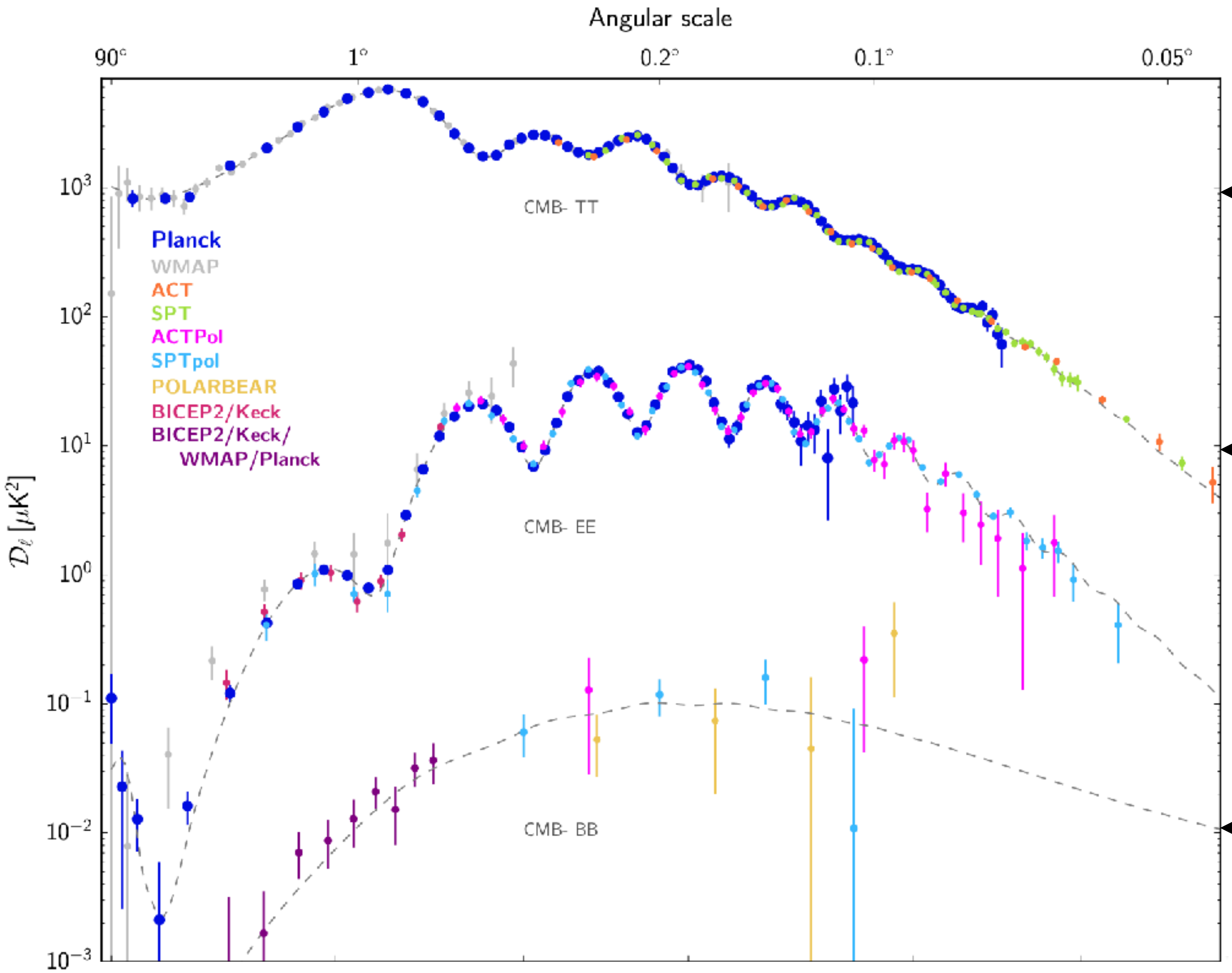
CMB is polarized



Planck map smoothed with 5° filter

Power spectra quantify anisotropies

Angular power spectrum $\ell(\ell+1)C_\ell/2\pi$



$(30\ \mu K)^2$

$(3\ \mu K)^2$

$(0.1\ \mu K)^2$

2 150 500 1000 2000 3000 4000 Multipole moment ℓ

Planck collaboration (2018)

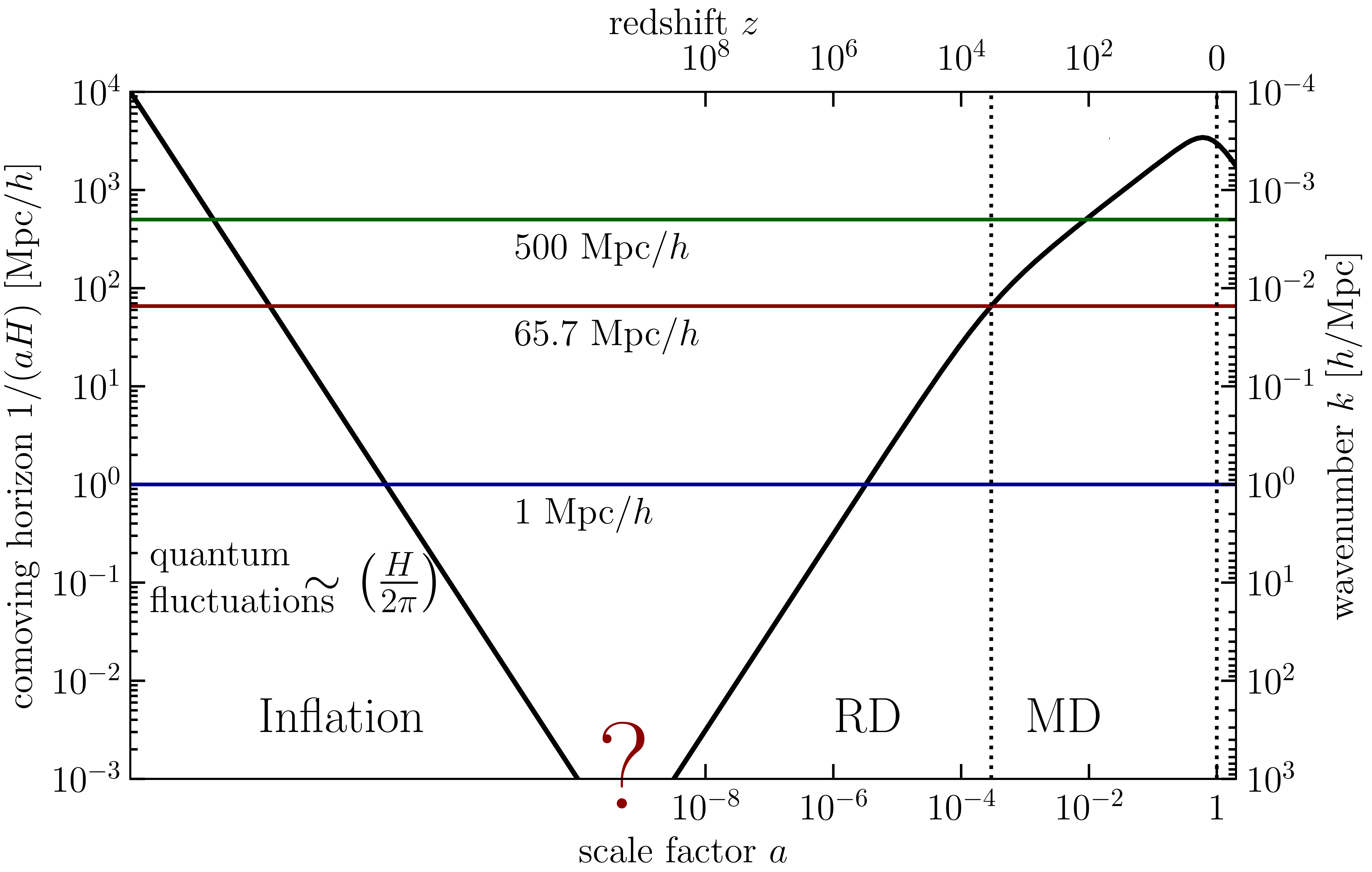
6 parameters fit ~10^6 multipoles!

Assuming plain ΛCDM model

Parameter	Best-fitting value	68% C.L.	
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	Baryon density
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	Cold dark matter density
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	Acoustic scale
τ	0.0543	0.0544 ± 0.0073	Optical depth
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	Amplitude of primordial power spectrum
n_s	0.96605	0.9649 ± 0.0042	Tilt of primordial power spectrum

Why only six parameters? Let’s look into the details!

Inflationary perturbation theory



Story of CMB anisotropies I

- It is seeded by the quantum fluctuation generated during inflation, stretched outside *the horizon*. We call this ζ.

$$\mathcal{P}_\zeta(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

$n_s = 1$: scale-invariant power spectrum

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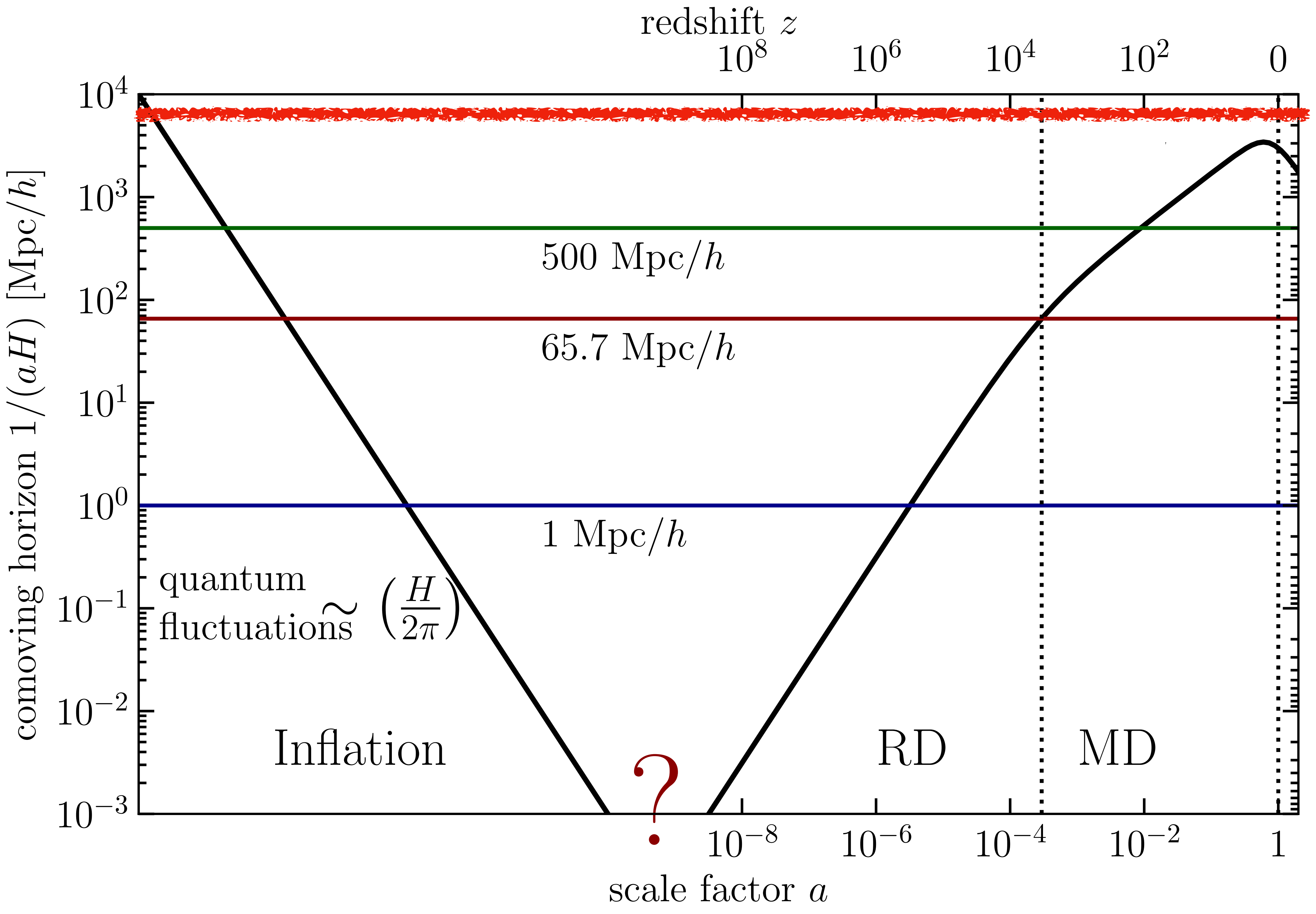
Story of CMB anisotropies II

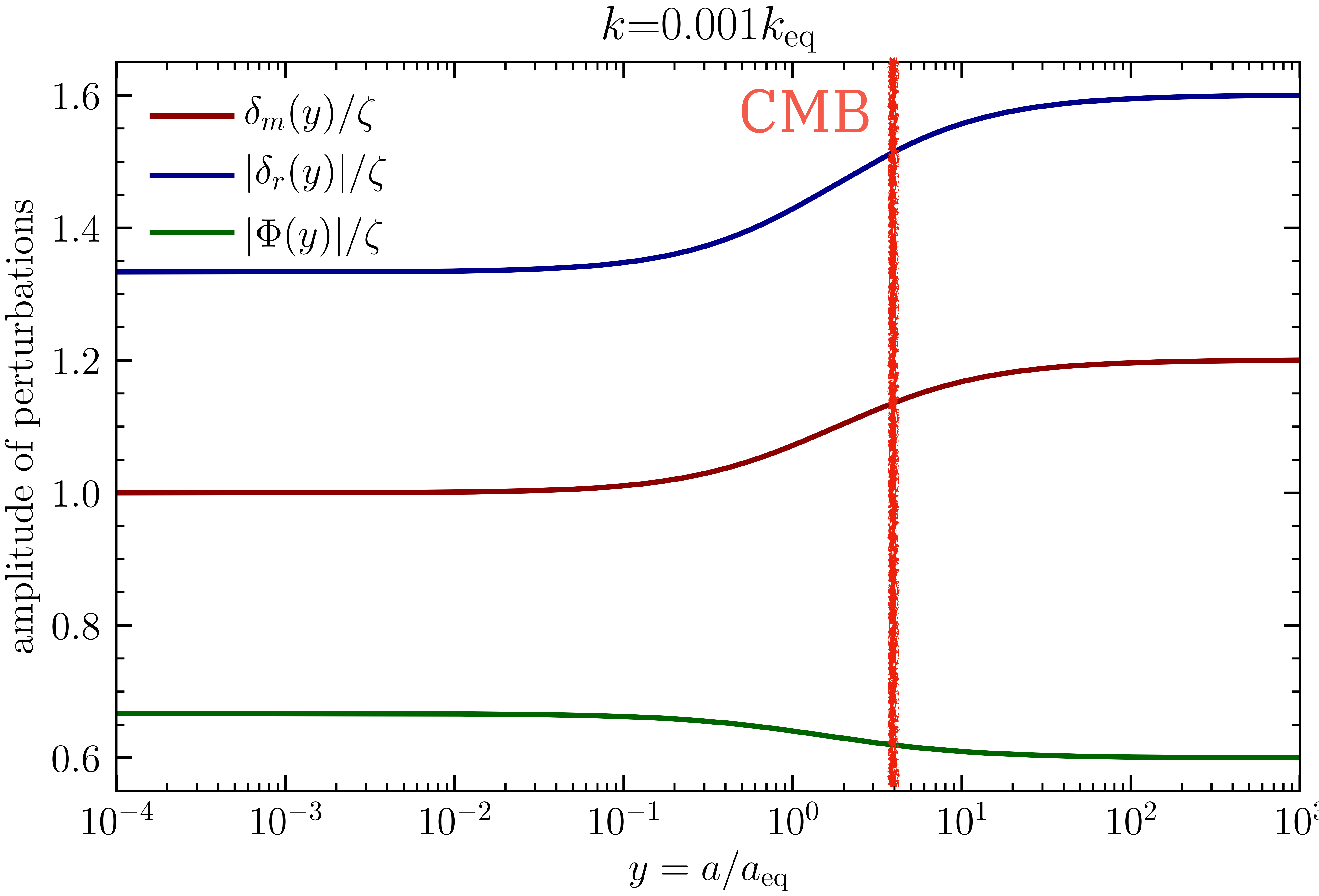
- It is seeded by the quantum fluctuation generated during inflation, stretched outside *the horizon*. We call this ζ.

- For the large-scale modes that are still outside of the horizon at the CMB decoupling time, anisotropies are determined by competition between the photon perturbation and gravitational potential (Sachs-Wolfe effect, mind the sign!)

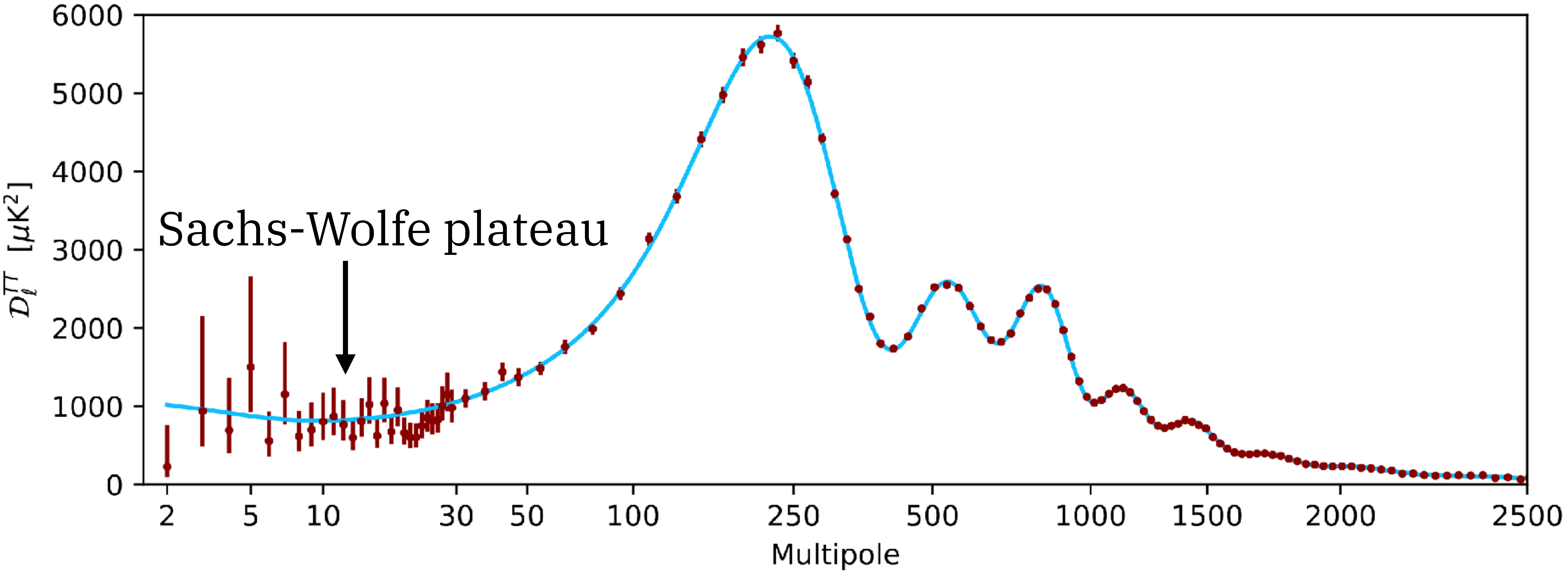
$$\left(\frac{\delta T}{T}\right)_{\rm obs} = -\frac{1}{5}\zeta$$

Linear evolution @ super-horizon





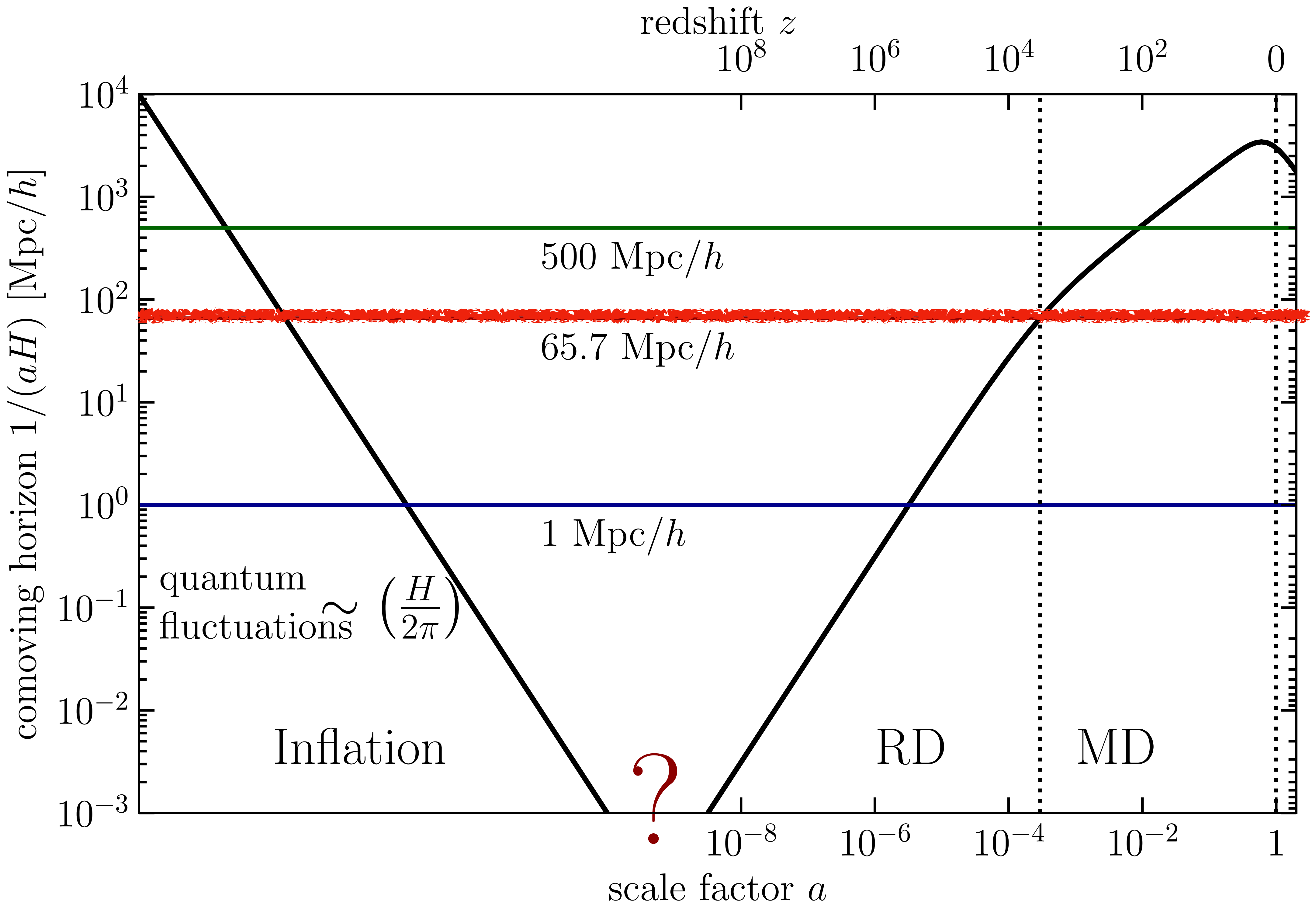
Temperature power spectrum

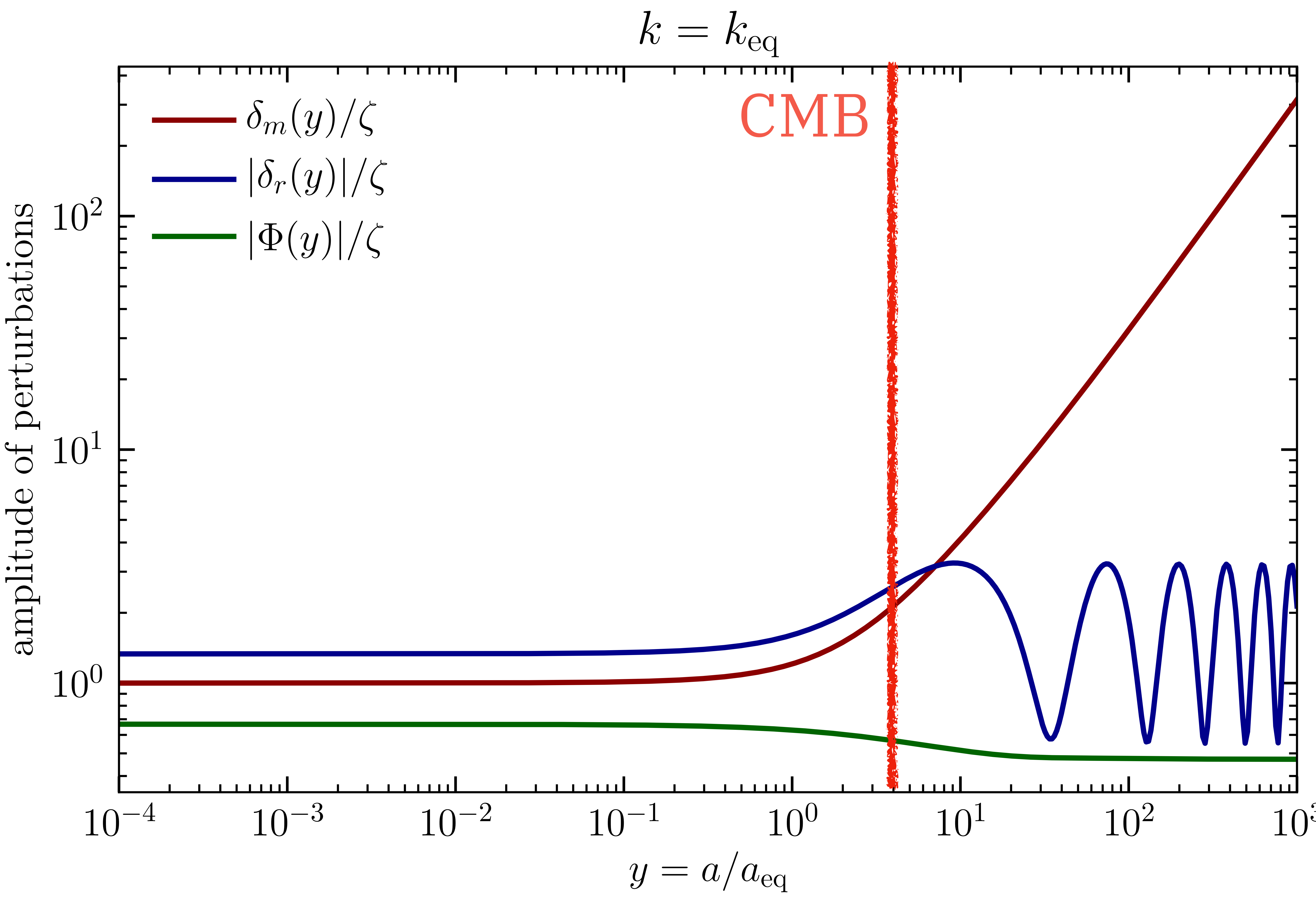


Story of CMB anisotropies II

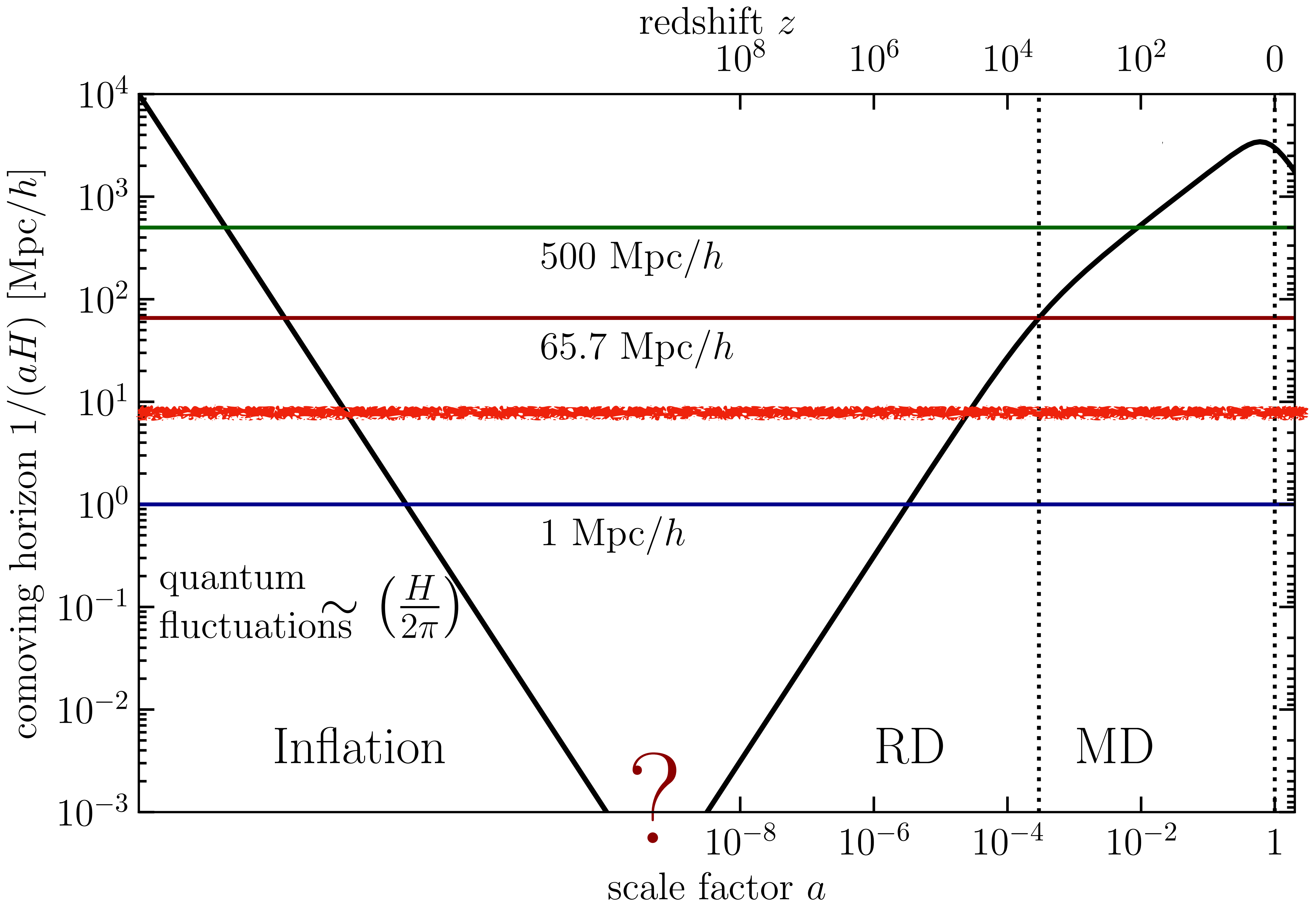
- For the small-scale modes that were inside the horizon, tightly coupled baryon-photon plasma evolves as the pressure wave in the external gravitational field provided by dark matter perturbations: ***Acoustic oscillation***

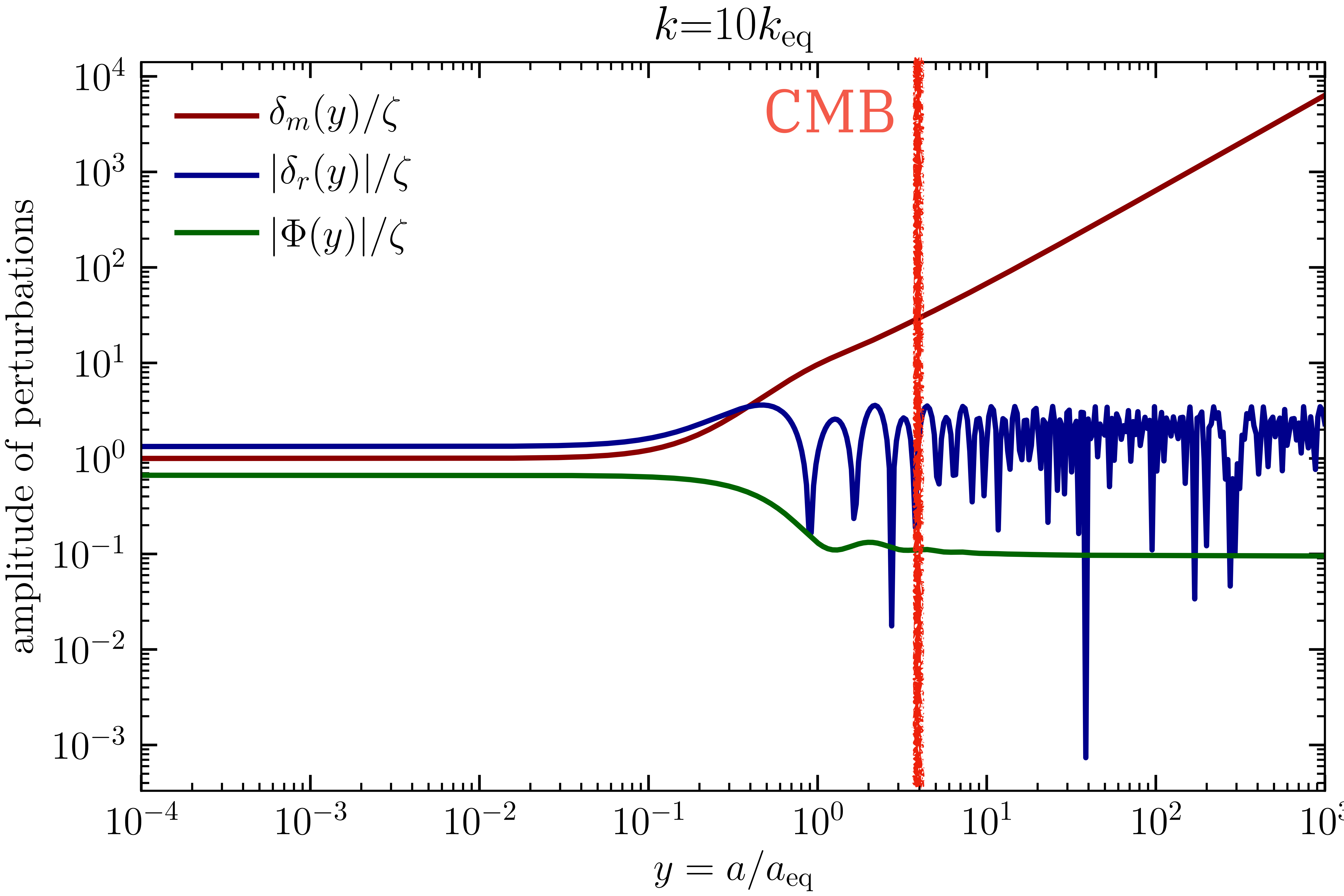
Linear evolution @ k_{eq}





Linear evolution @ 10 k_{eq}





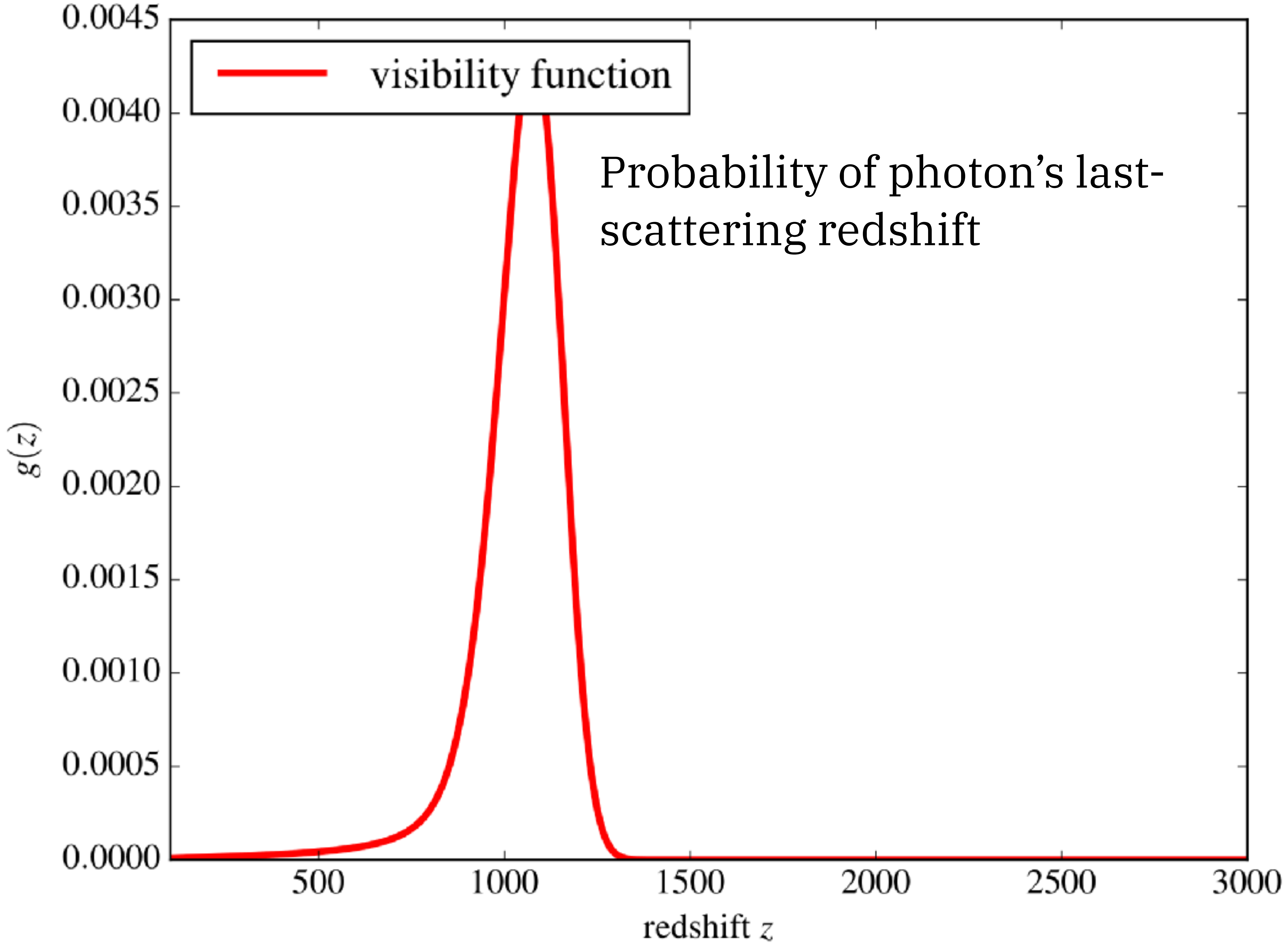
Story of CMB anisotropies III

- The comoving sound horizon of the pressure wave is modified from the usual 1/√3 (photon fluid) because of the *extra inertia*

$$r_s = \int_0^{t_{\rm dec}} c_s(t) \frac{dt}{a(t)} \qquad c_s = \frac{1}{\sqrt{3(1+3\bar{\rho}_b/4\bar{\rho}_\gamma)}}$$

- Expansion rate determined by Friedman: $3H^2 = 8\pi G\left(\bar{\rho}_{\rm r} + \bar{\rho}_{\rm m}\right)$
- The amplitude of the gravitational potential is determined by the cold dark matter density : $\bar{\rho}_{\rm c}$

Story of CMB anisotropies IV



- Of course, the decoupling epoch (t_{dec}) also depends on
  - **baryon density**:
    how many hydrogen to break
  - **matter density**:
    how fast the photons loose energy by cosmological redshift

Planck collaboration (2018)

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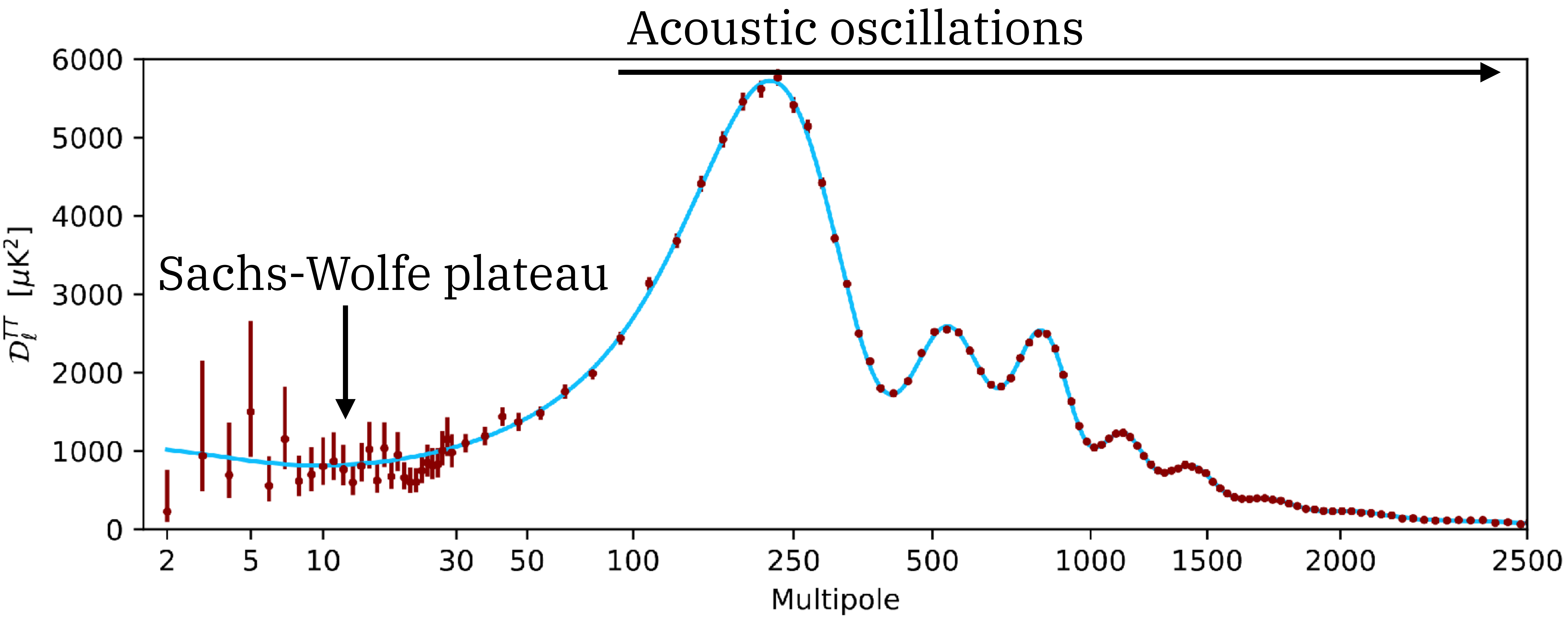
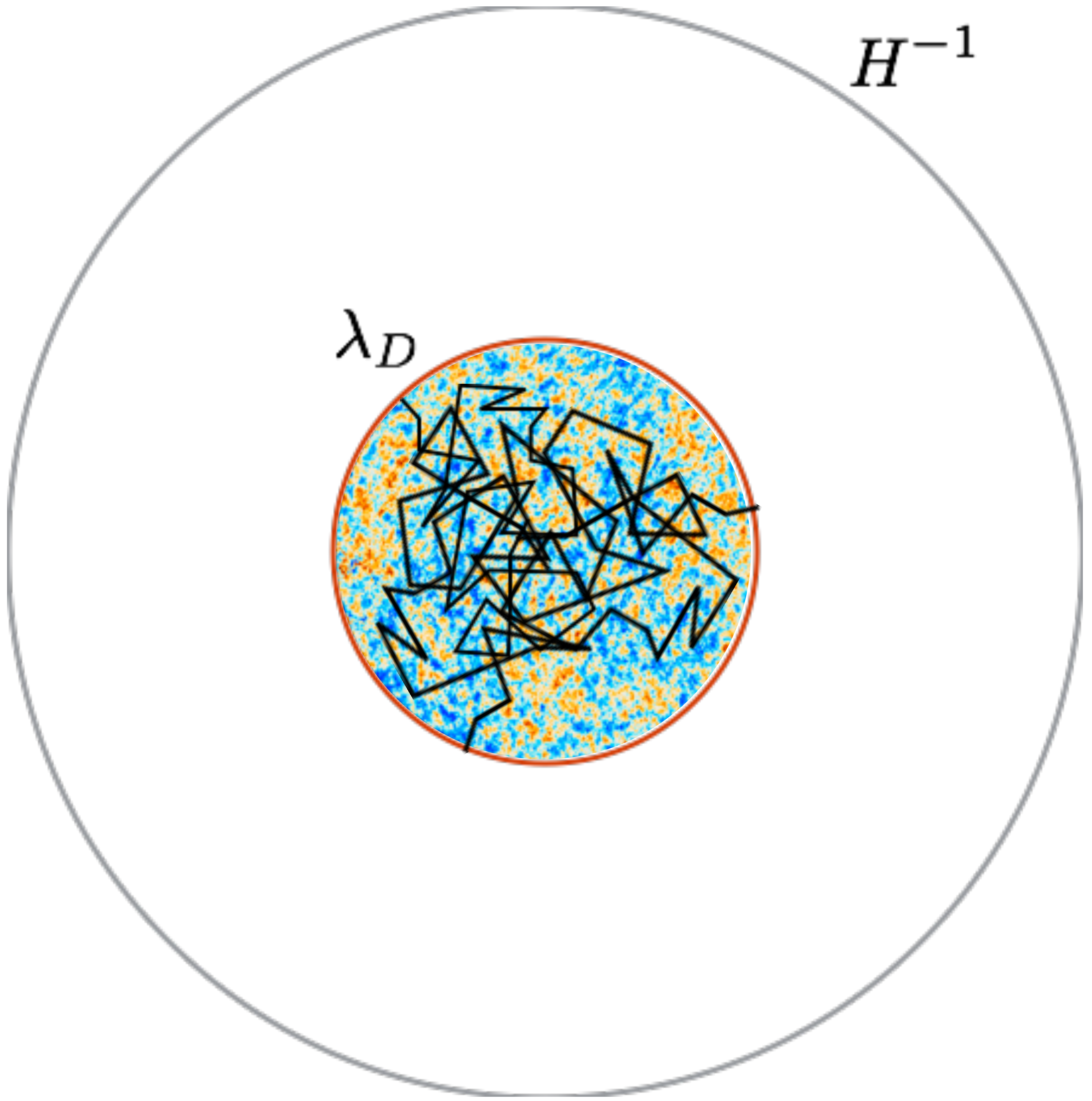


Silk damping and Diffusion scale



temperature anisotropies
at ~0.0001'' scale, ***at early time***

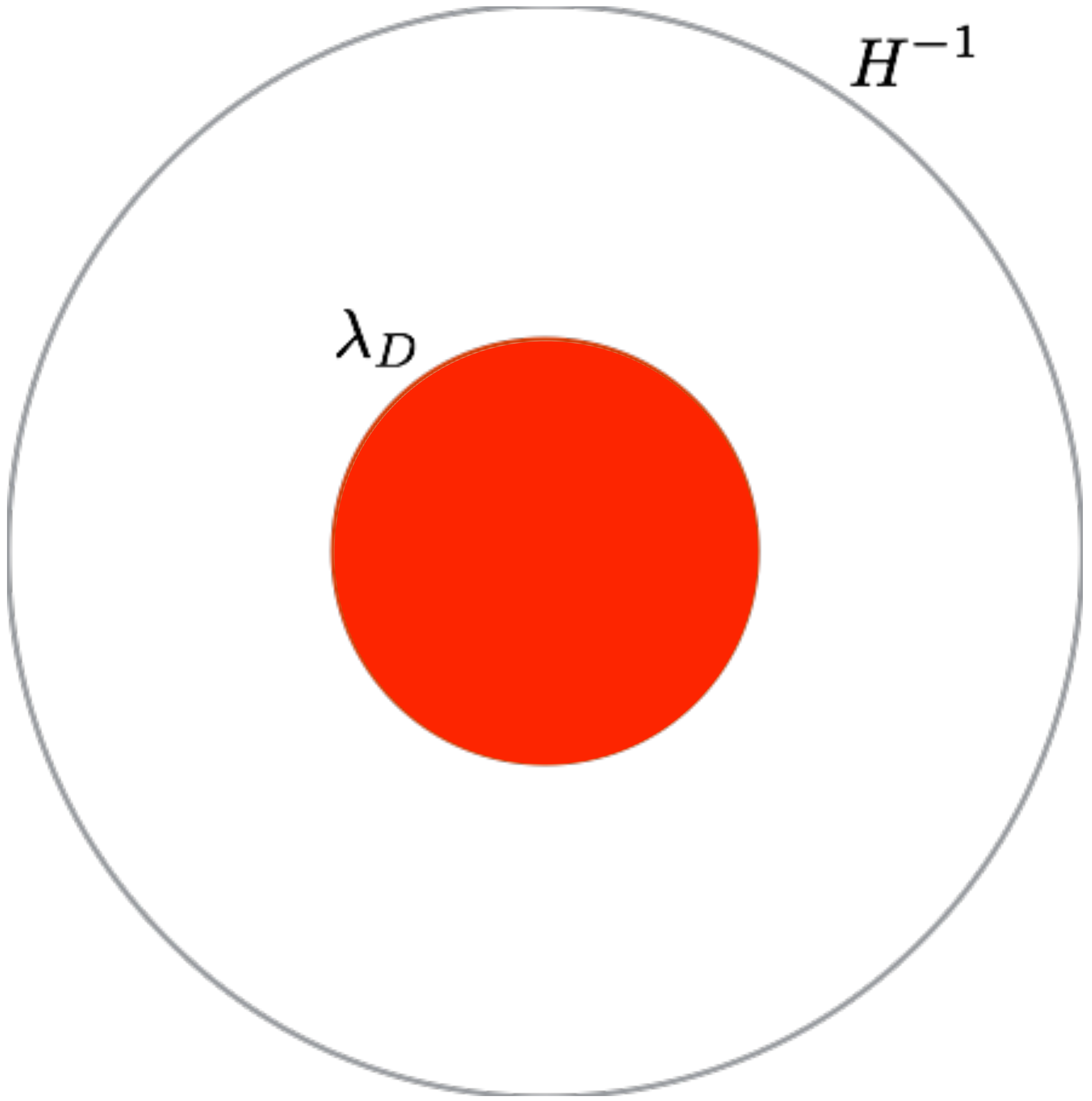
mean free path: $\lambda_{\rm mfp} \simeq \dfrac{1}{\sigma_{\rm e\gamma} n_e}$

# of scatters: $N \simeq \sigma_{e\gamma} n_e H^{-1}$

diffusion scale (r.m.s. of random walk):

$$\lambda_D \simeq \lambda_{\rm mfp}\sqrt{N} \simeq \frac{1}{\sqrt{\sigma_{\rm e\gamma} n_e H}}$$

Silk damping and Diffusion scale



temperature anisotropies
at ~1'' scale, ***observed***

mean free path: $\lambda_{\rm mfp} \simeq \dfrac{1}{\sigma_{\rm e\gamma} n_e}$

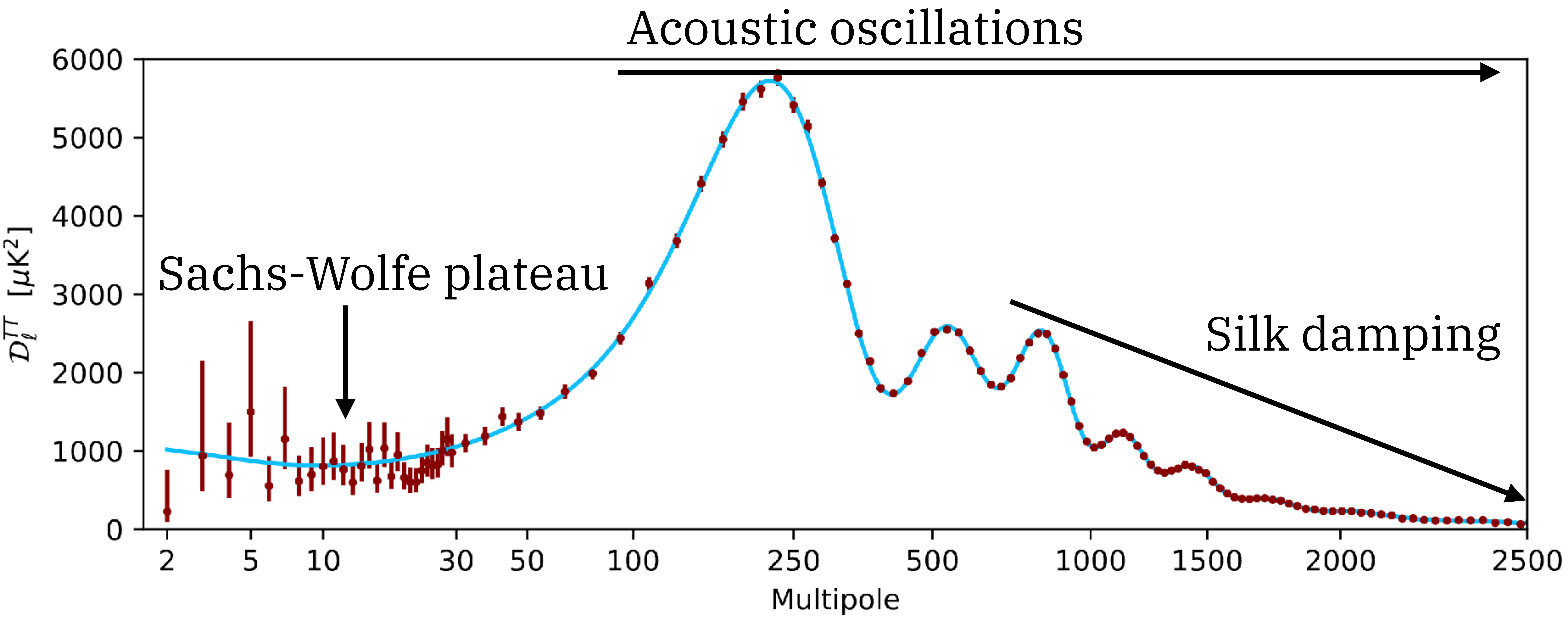
# of scatters: $N \simeq \sigma_{e\gamma} n_e H^{-1}$

diffusion scale (r.m.s. of random walk):

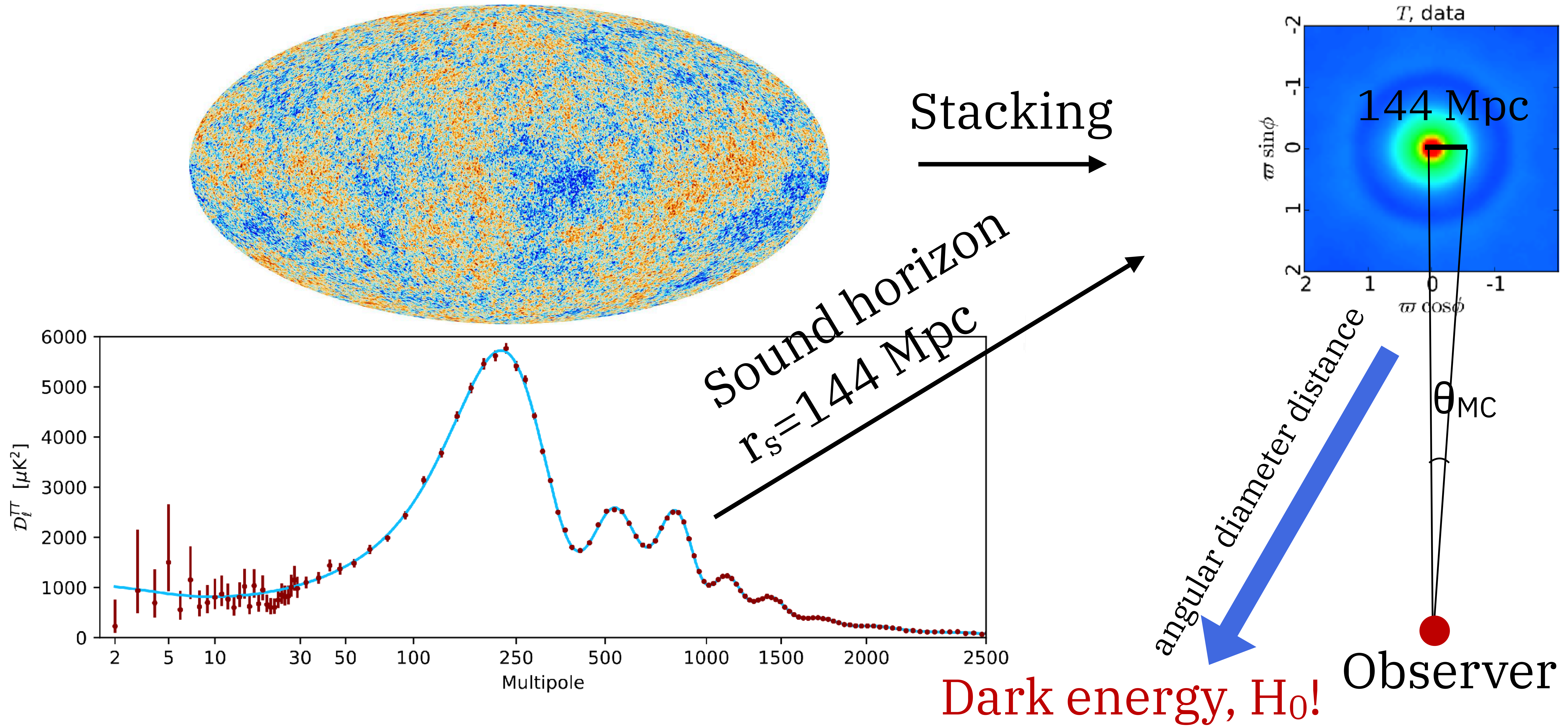
$$\lambda_D \simeq \lambda_{\rm mfp}\sqrt{N} \simeq \frac{1}{\sqrt{\sigma_{\rm e\gamma} n_e H}}$$

Diffusion = temperature equalizer
Diffusion length scale ~ <u>**10 Mpc**</u>!!

Temperature power spectrum



Sound horizon and acoustic scale



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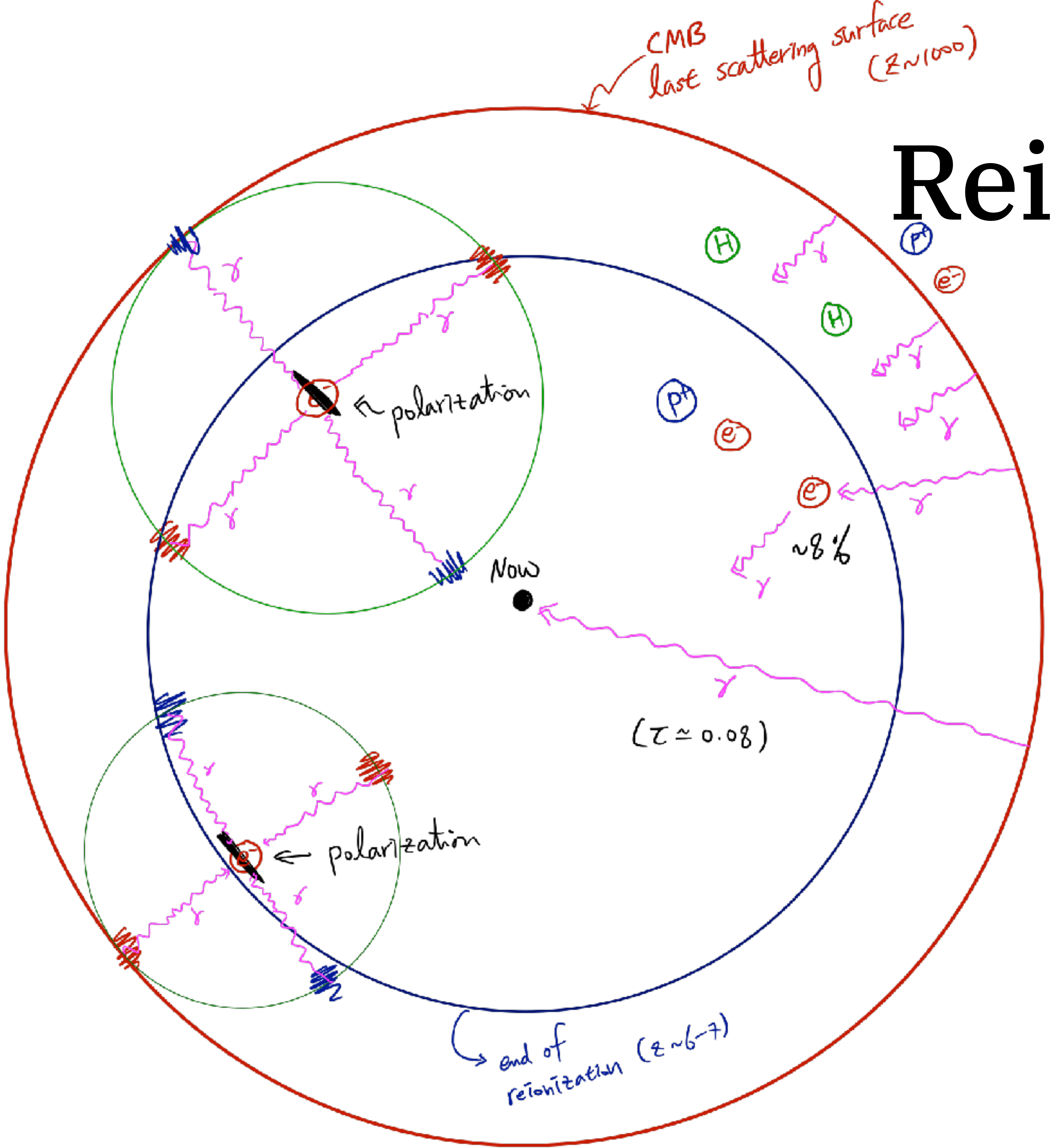

Reionization and CMB

- Reionization Optical depth ~ 0.05 (Planck), 0.08(WMAP): 5~8% of CMB re-scatter
- Three effects:
  - Damping the temperature anisotropies on small scales
  - Polarization on large scales.
  - kSZ from reionization patches

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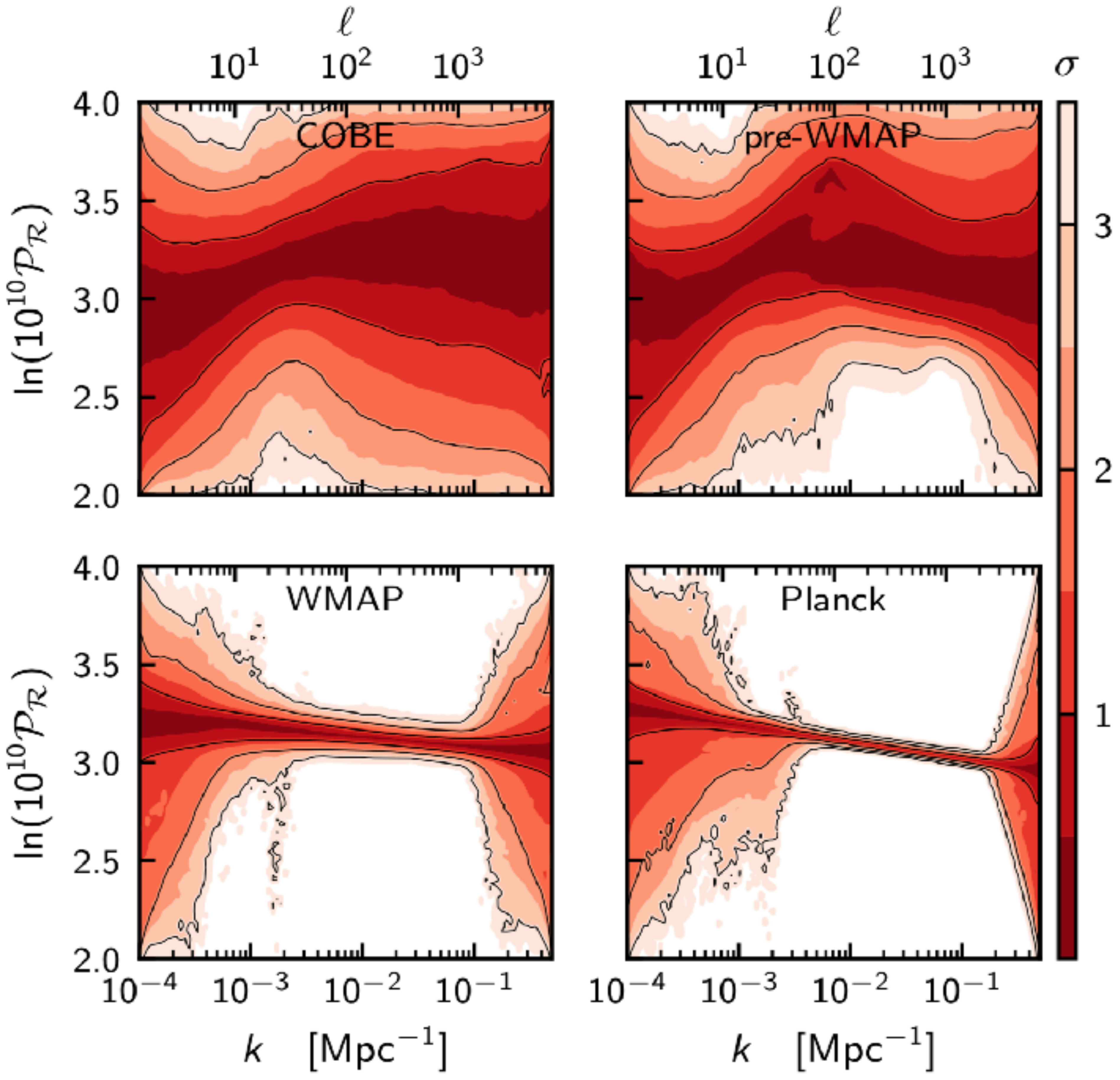
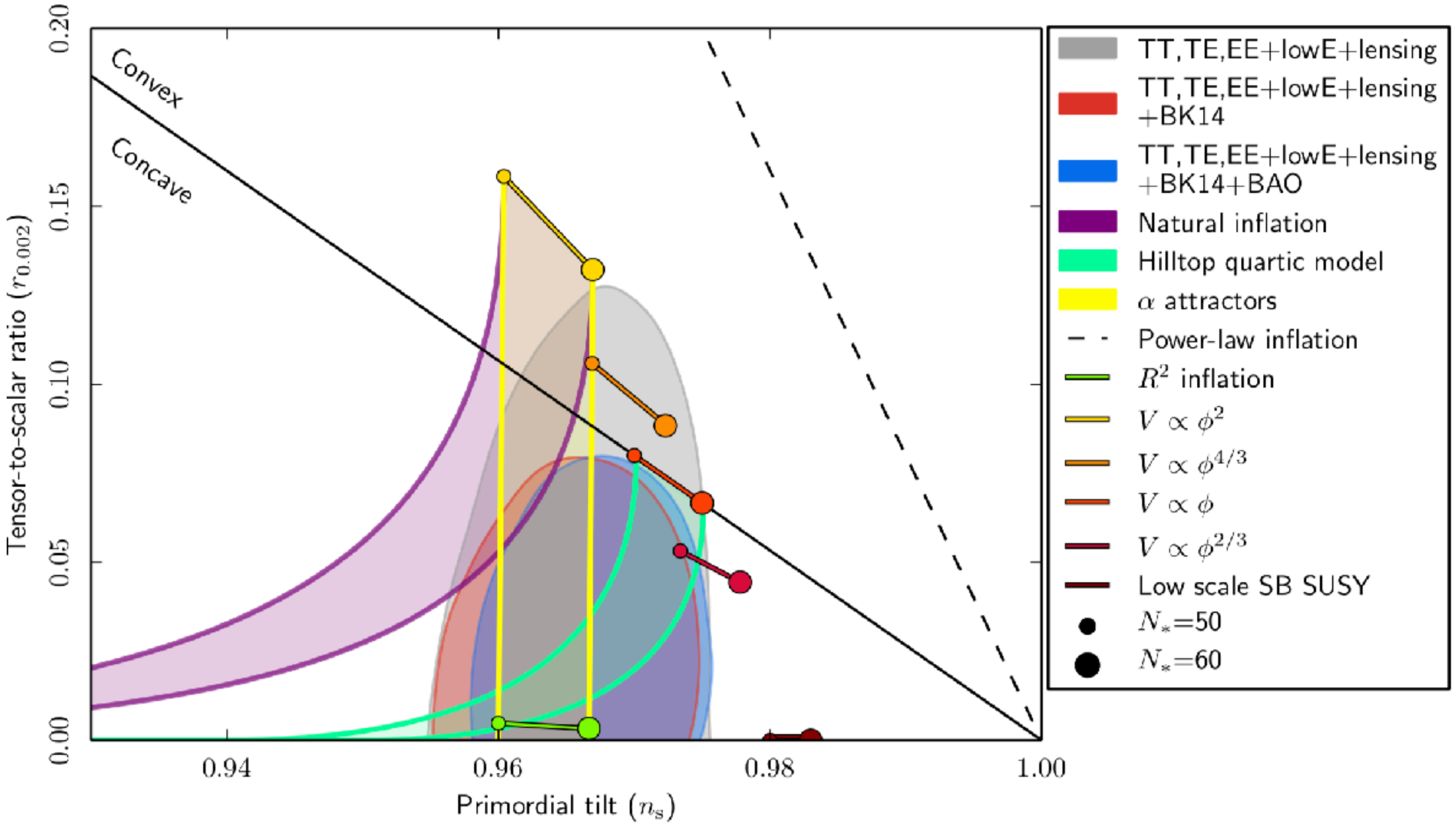
Undo evolution to constrain the *I.C.*

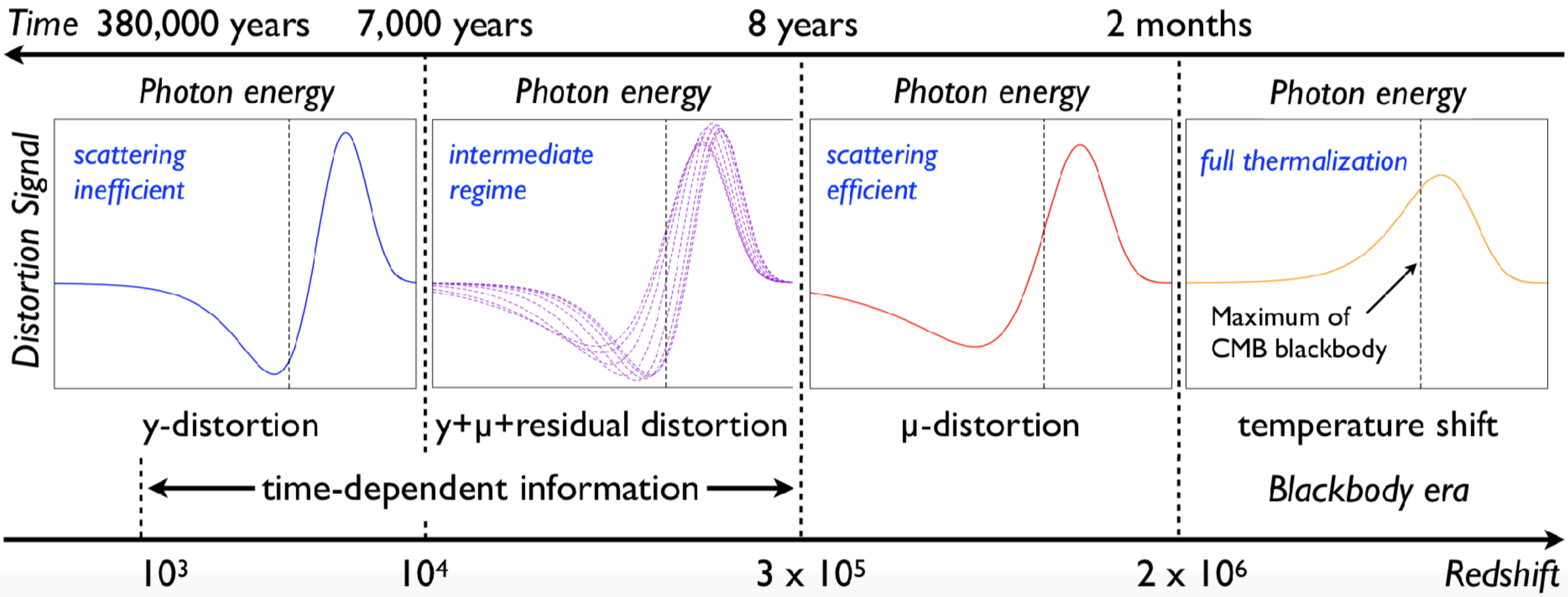


r=(tensor)^2/(scalar)^2



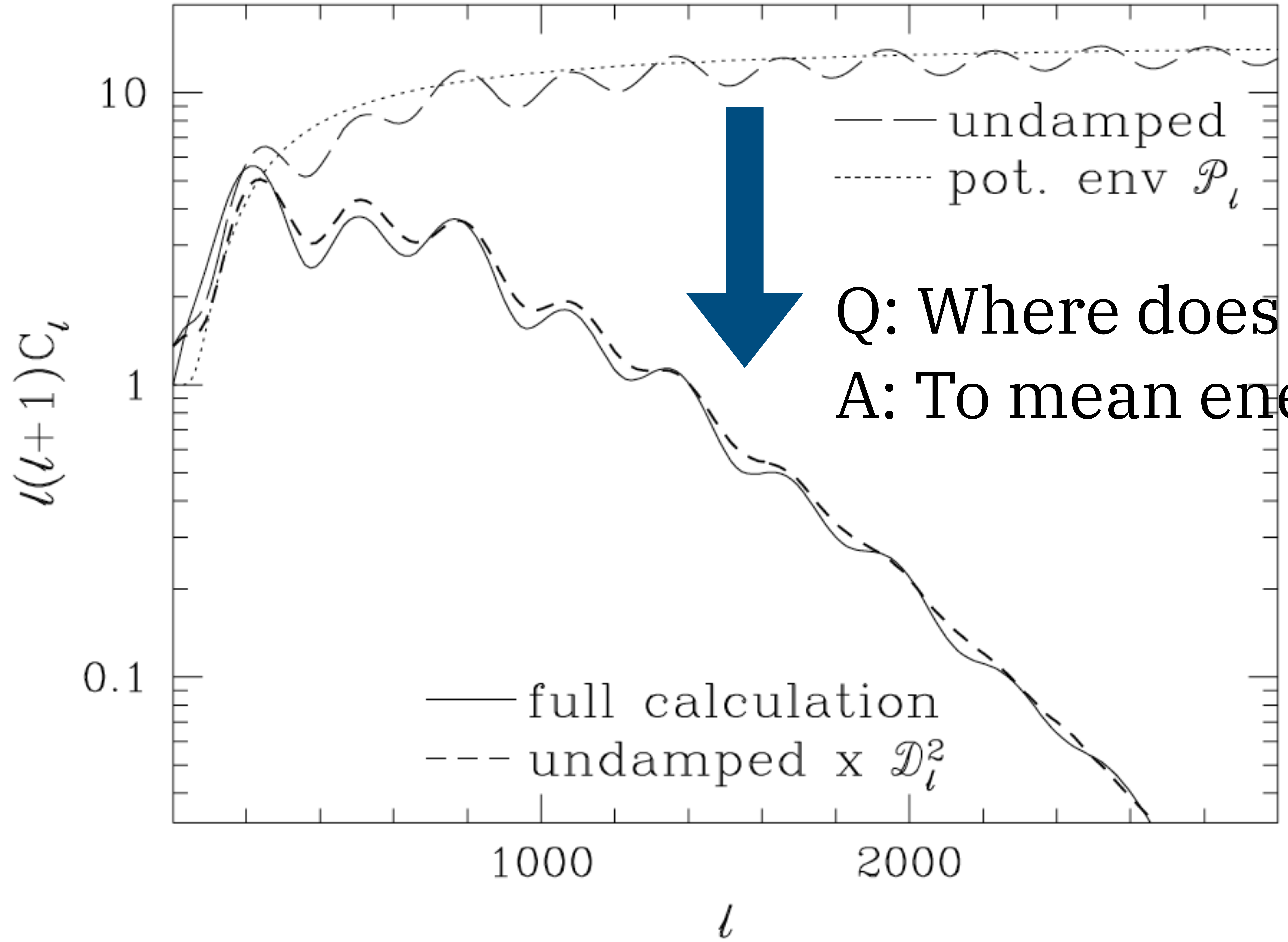
Chluba+ (2019)

CMB spectrum and energy injection



Silk damping to heat up the spectrum

Hu & White 1997

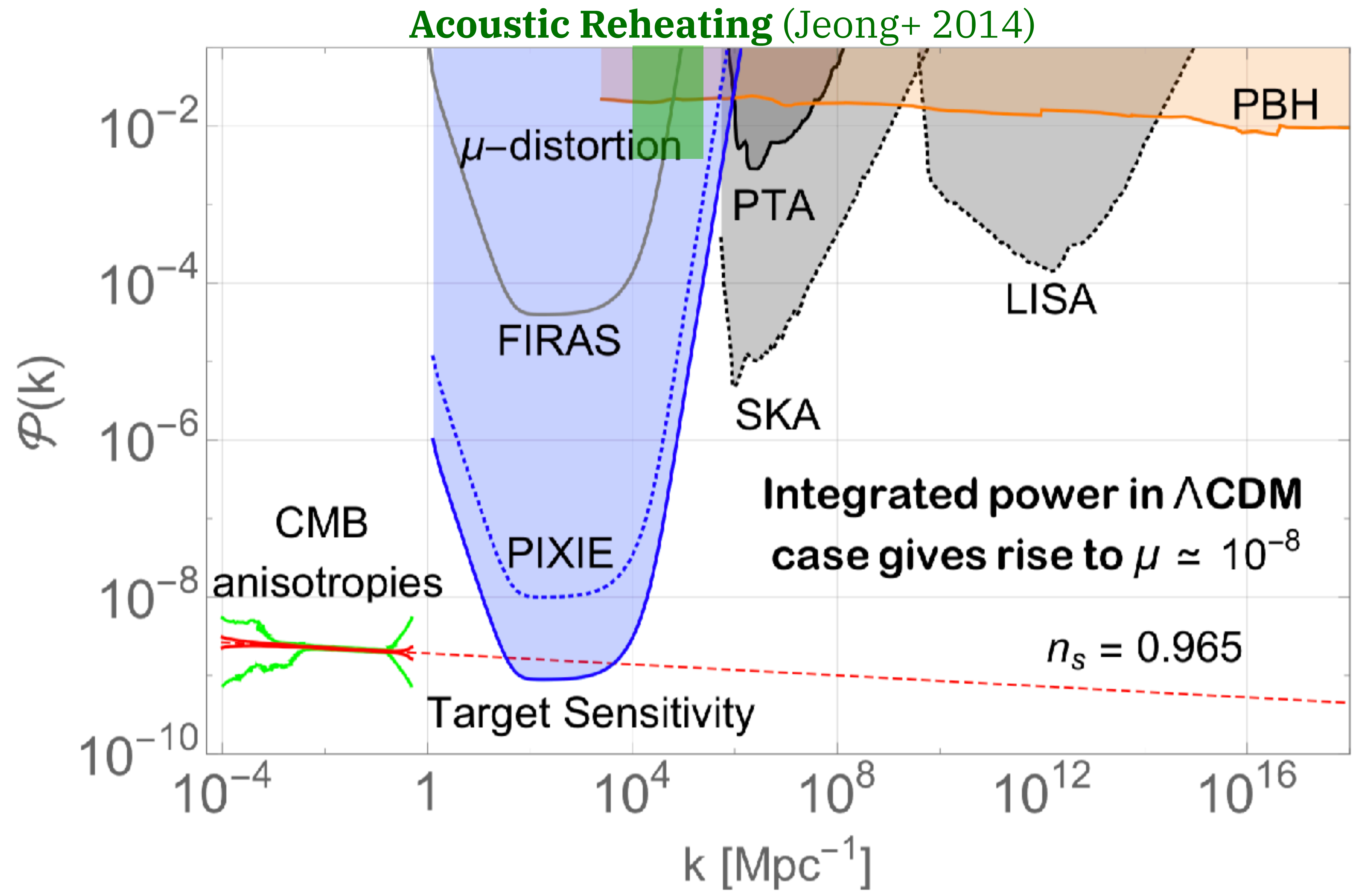


Q: Where does the acoustic energy go?

A: To mean energy spectrum

Chluba+ (2019)

μ-distortion can probe small-scales



Primordial GW (PGW)

- de Sitter spacetime generates stochastic gravitational waves with amplitude of (here, $m_{pl} = \sqrt{G_N}$):

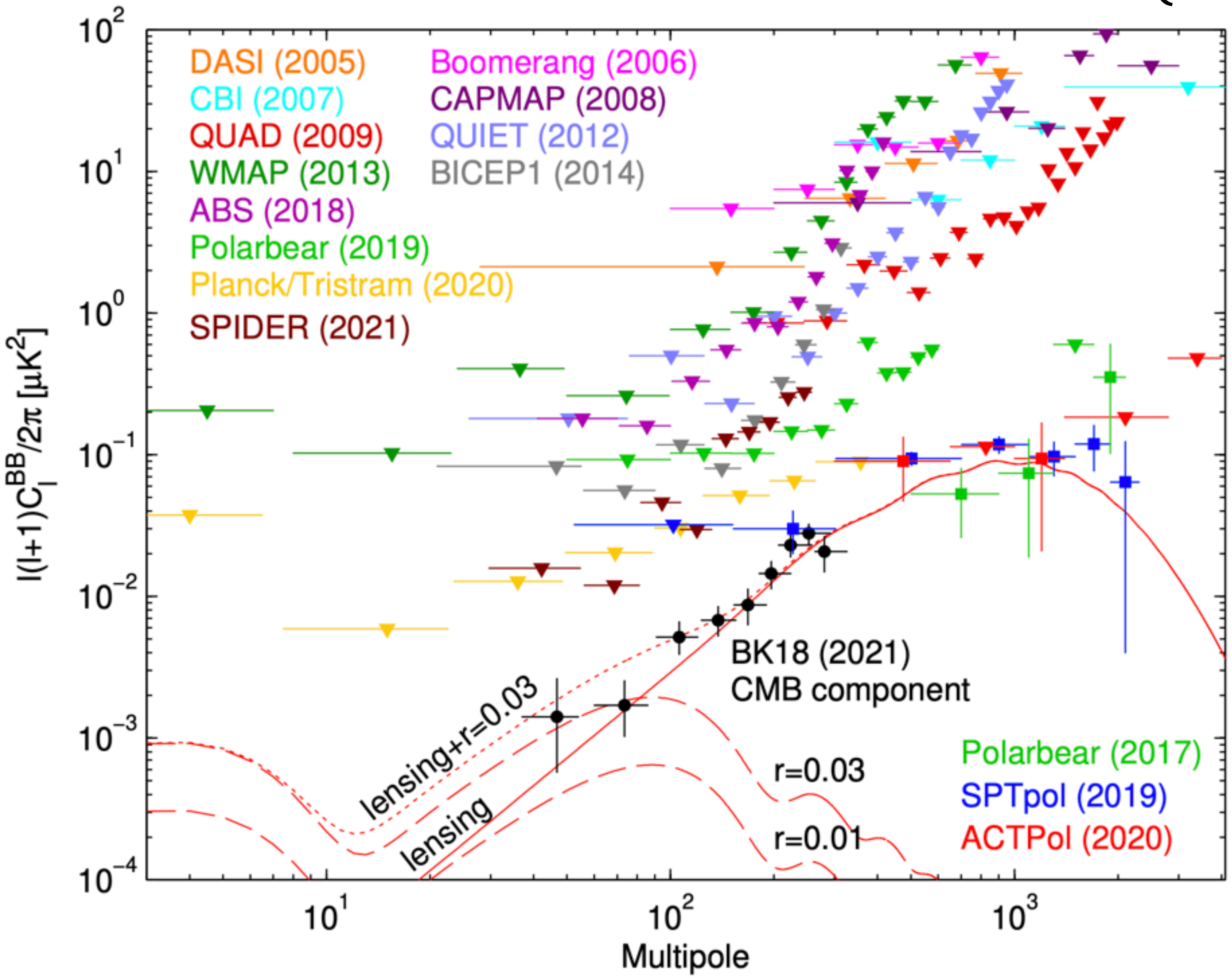
$$\Delta_h^2(k) = \frac{k^3 P_T(k)}{2\pi^2} = \frac{64\pi}{m_{\mathrm{pl}}^2} \left. \boxed{\left(\frac{H}{2\pi}\right)}^2 \right|_{k=aH}$$

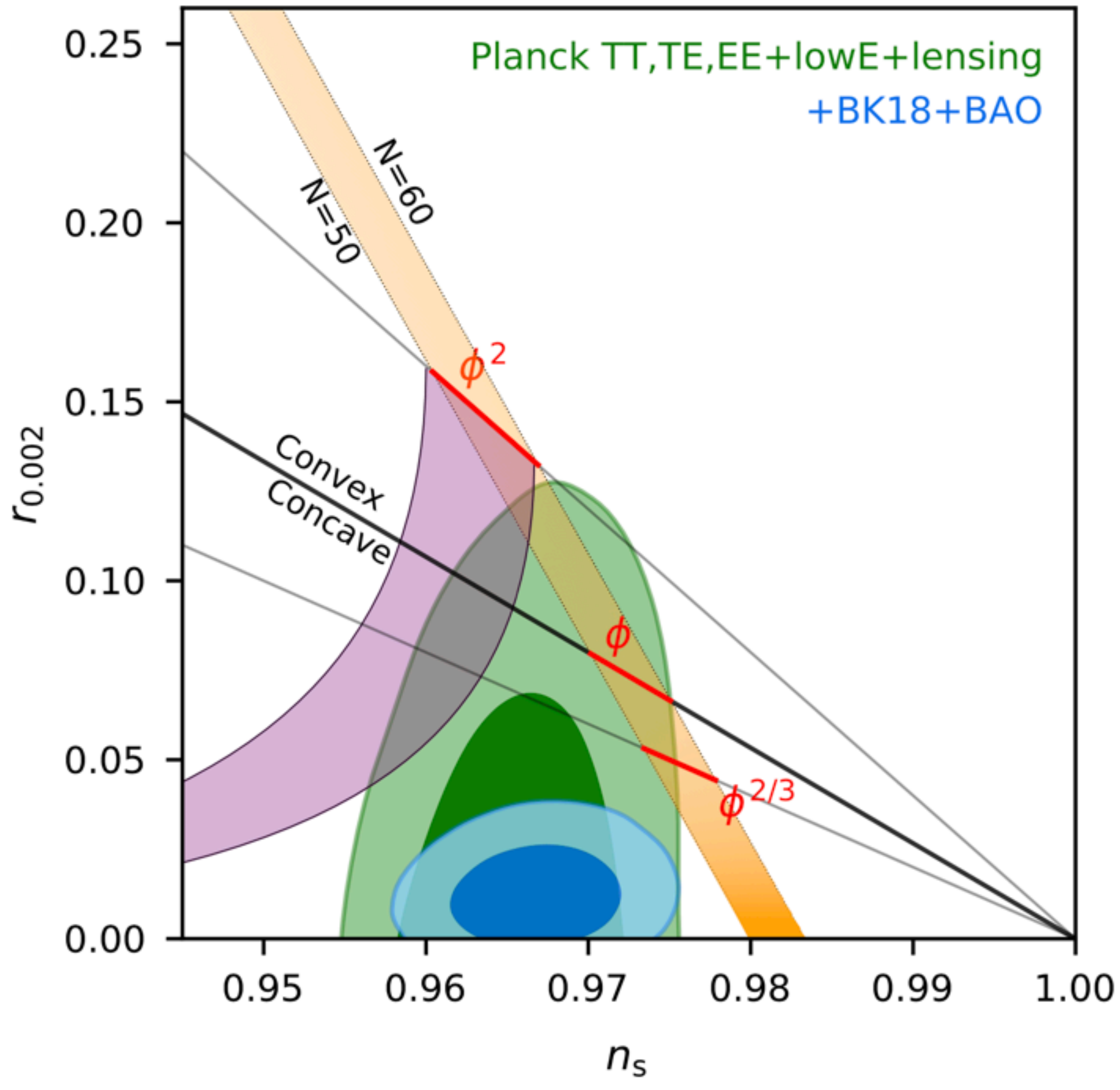
+ Friedmann equation: $3H^2 \sim 8\pi G\rho$

- ***PGW = energy scale*** of inflation: $E \sim (r/0.01)^{1/4} 10^{16}$GeV!
- ***PGW = expansion rate*** during inflation: ***the proof of inflation!***

B-mode polarization, status

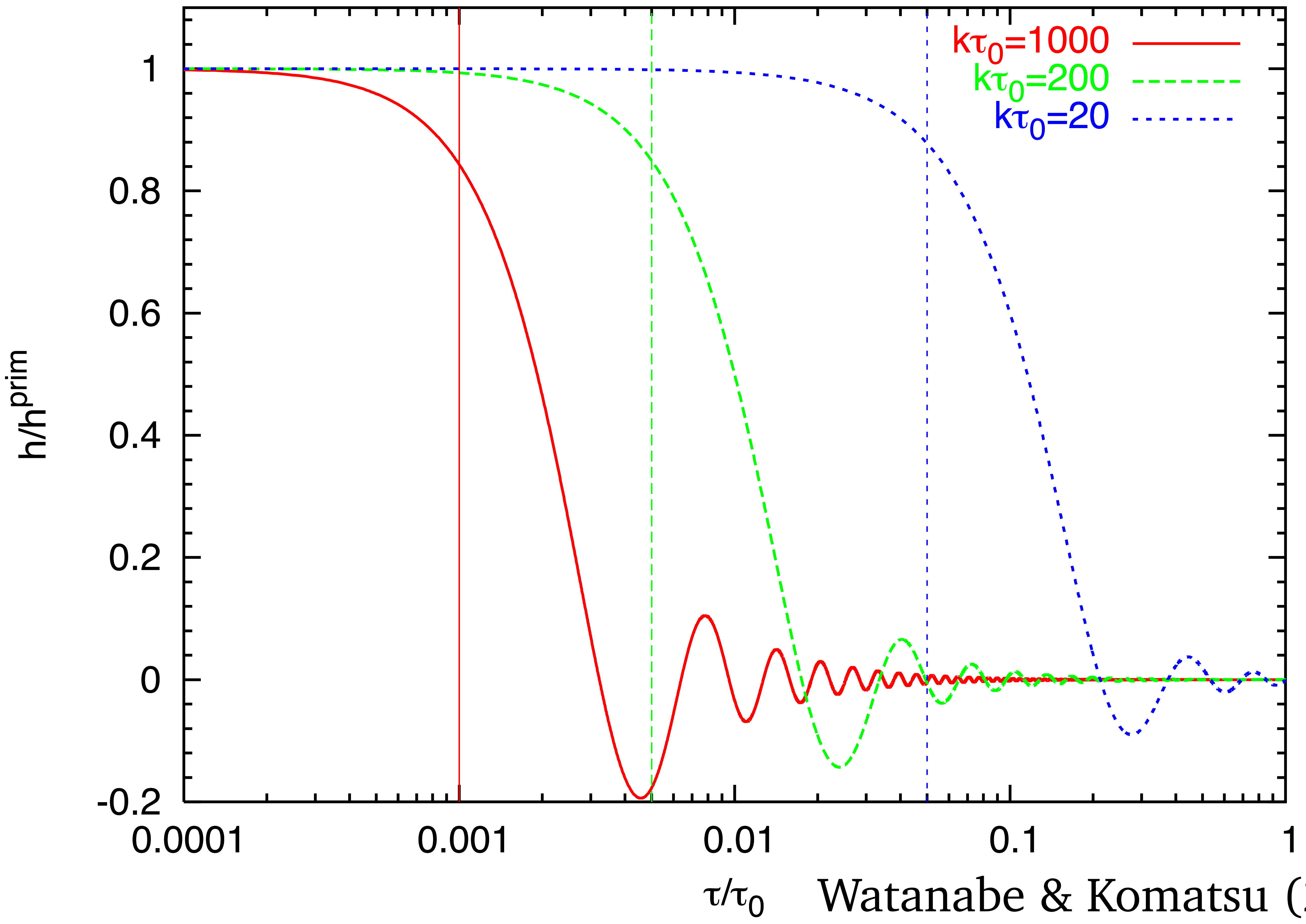
$r<0.036$ (95% C.L.)





Evolution of PGW w/o sources

$$-\Box h_{ij} = h_p''(\boldsymbol{k}) + 2\mathcal{H}h_p'(\boldsymbol{k}) + k^2 h_p(\boldsymbol{k}) = 0$$

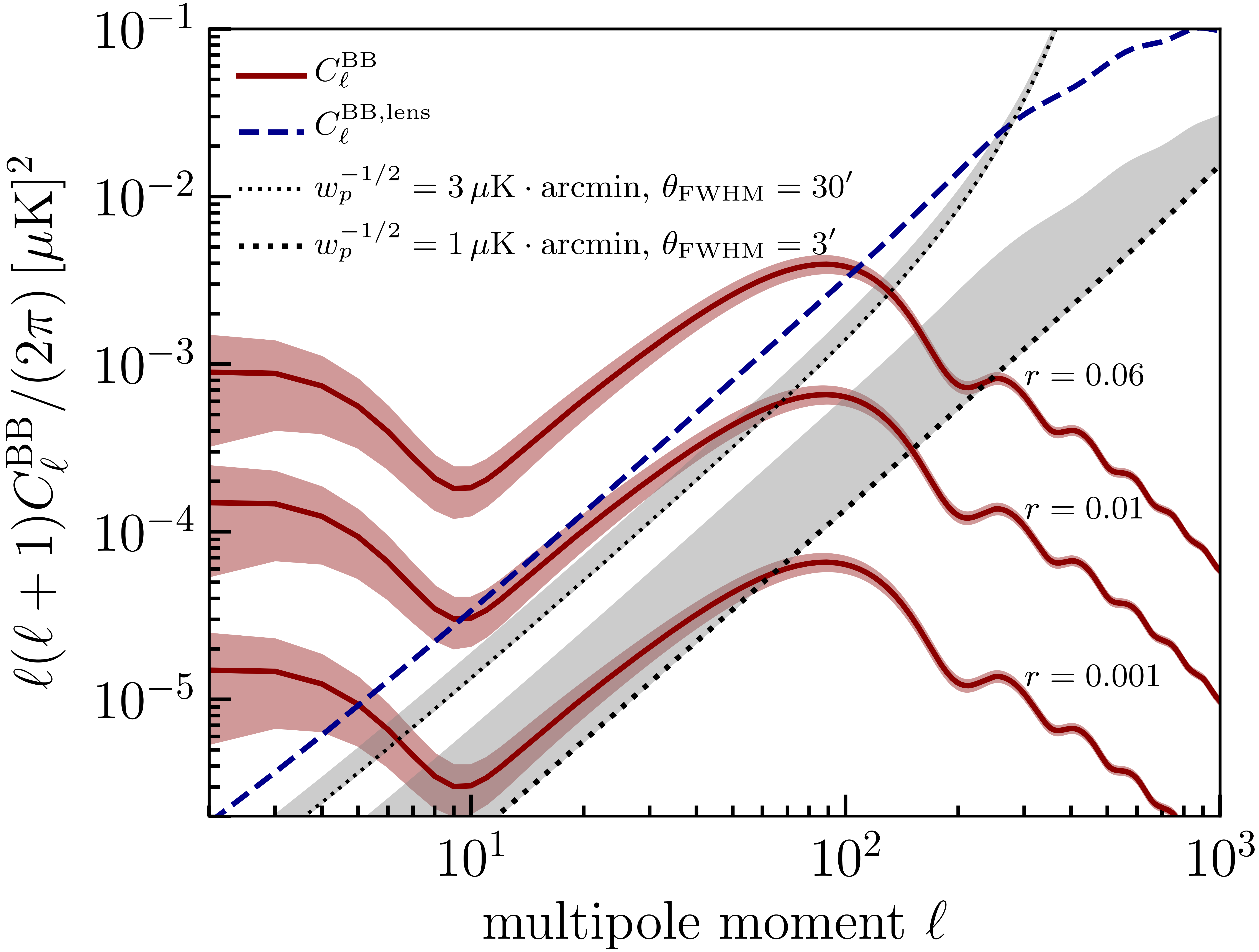


Watanabe & Komatsu (2006)

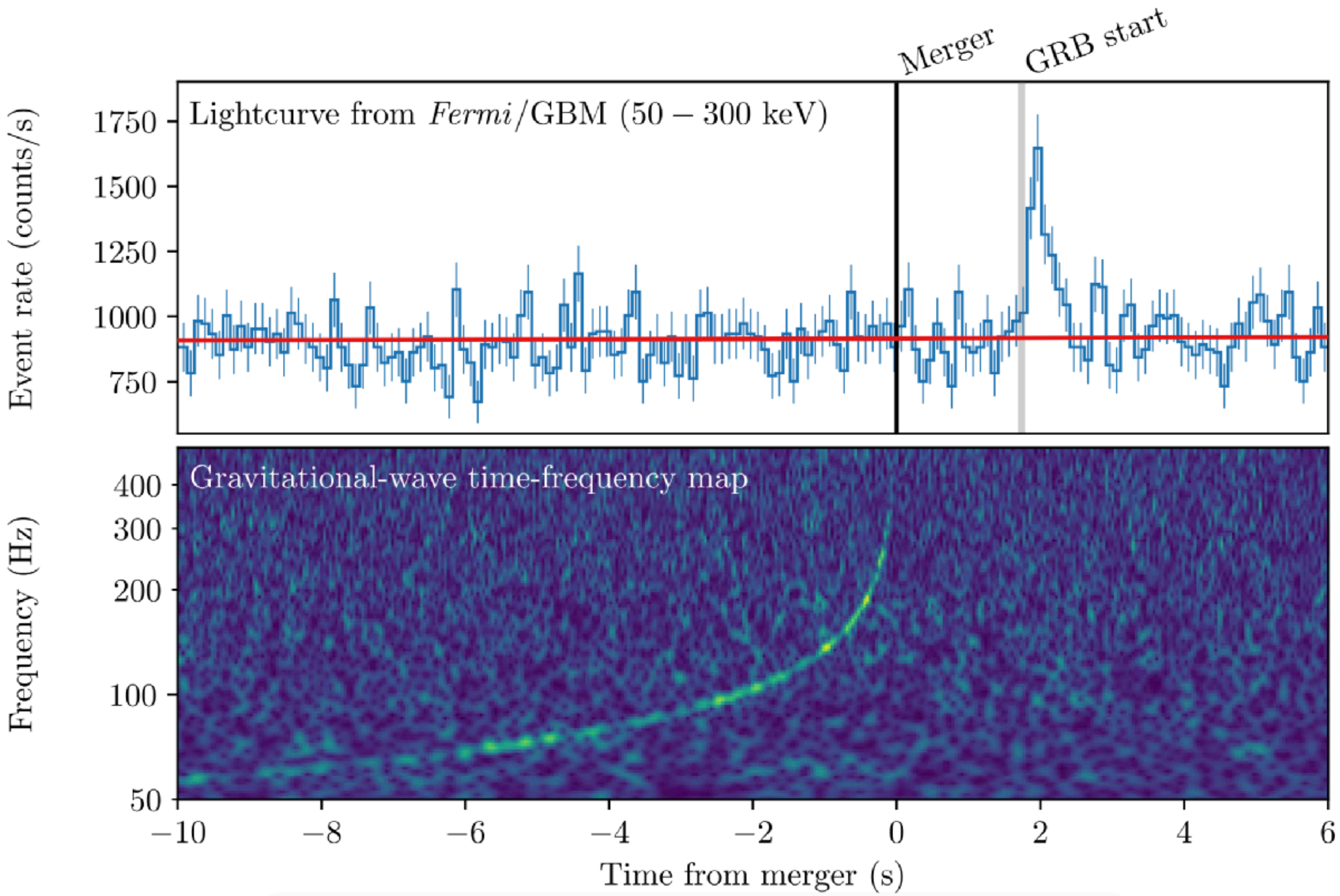
- PGW stays constant outside of horizon, but decays once the mode enters the horizon.
- *cf.* scalar perturbations grow inside of horizon.

Jeong & Kamionkowski (2019)

B-mode power spectrum



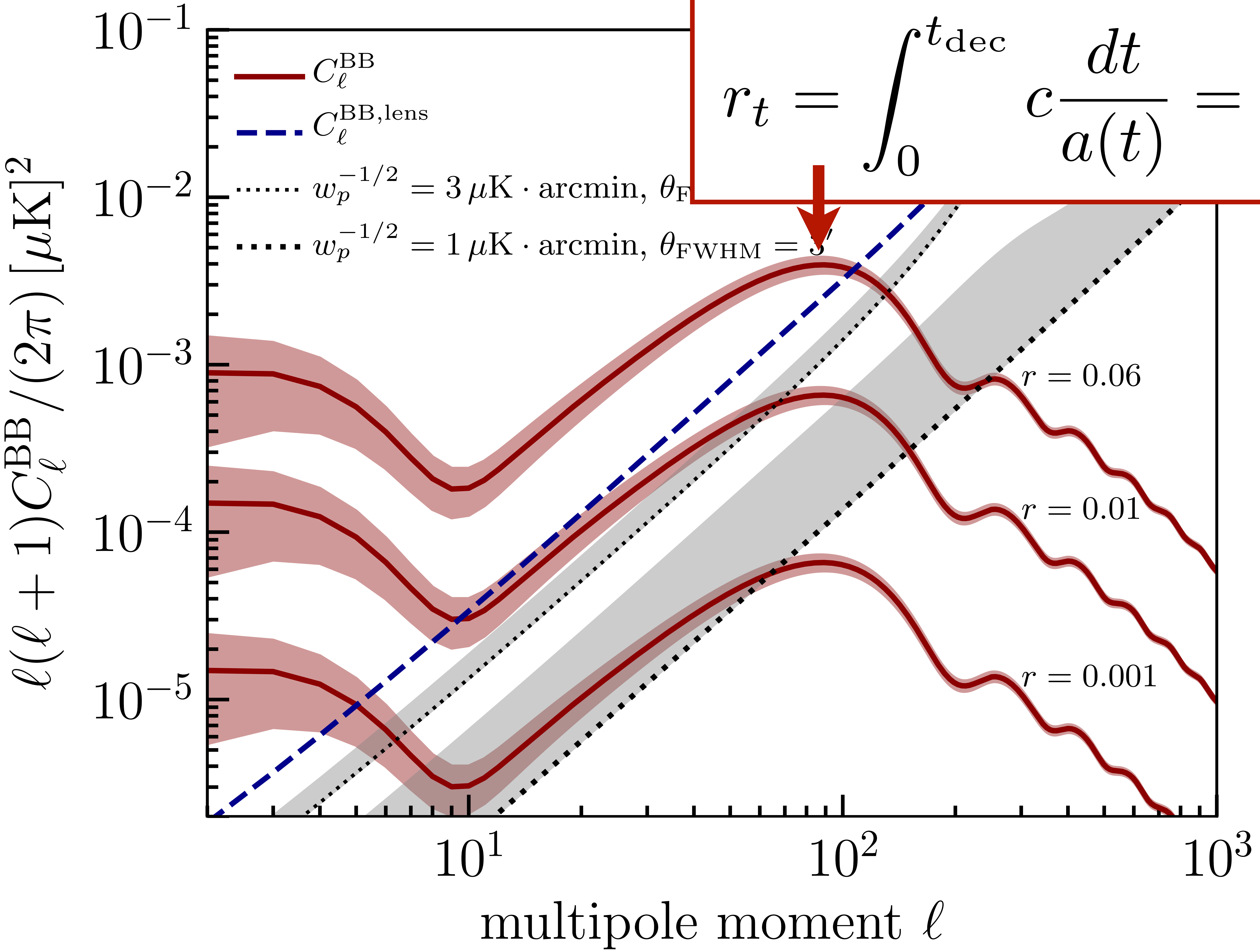
GW170817 and GRB 170817A



Jeong & Kamionkowski (2019)

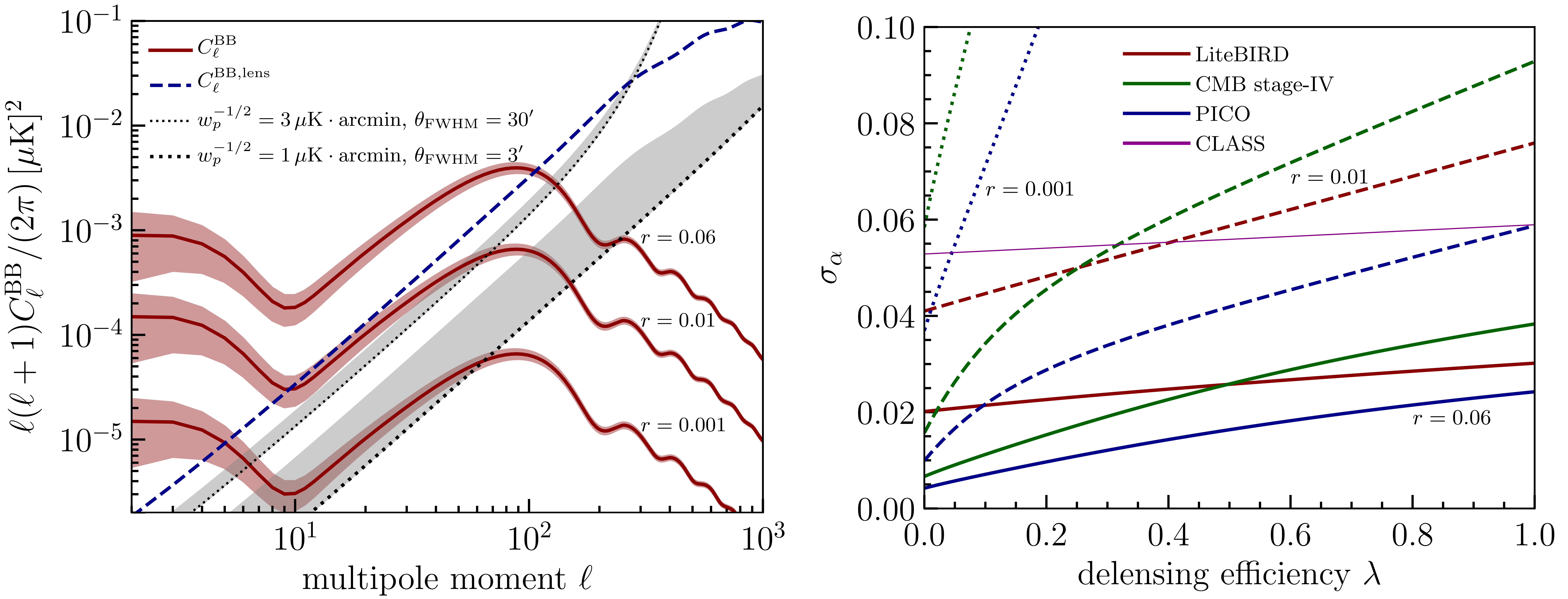
Turn-over scale r_t

$$r_t = \int_0^{t_{\rm dec}} c\frac{dt}{a(t)} = \int_0^{a_{\rm dec}} c\frac{da}{a^2H(a)}$$



Jeong & Kamionkowski (2019)

We can measure r_t, if r>0.001!

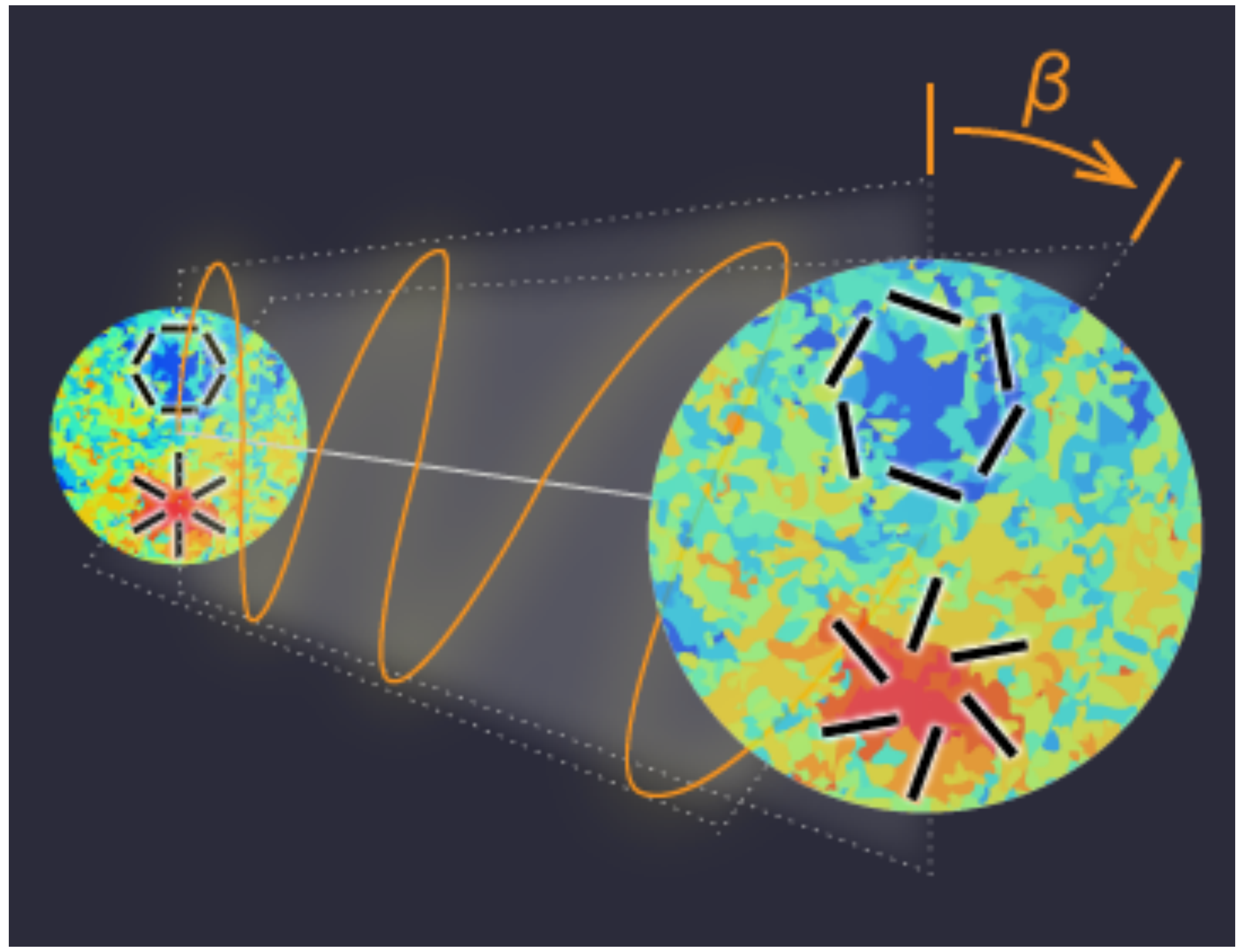


Lue, Wang & Kamionkowski (1999); Feng et al. (2005, 2006); Liu, Lee & Ng (2006)

The Cosmic Birefringence

E <-> B conversion by rotation of the linear polarization plane

- The intrinsic EE, BB, and EB power spectra 13.8 billion years ago would yield the observed EB as



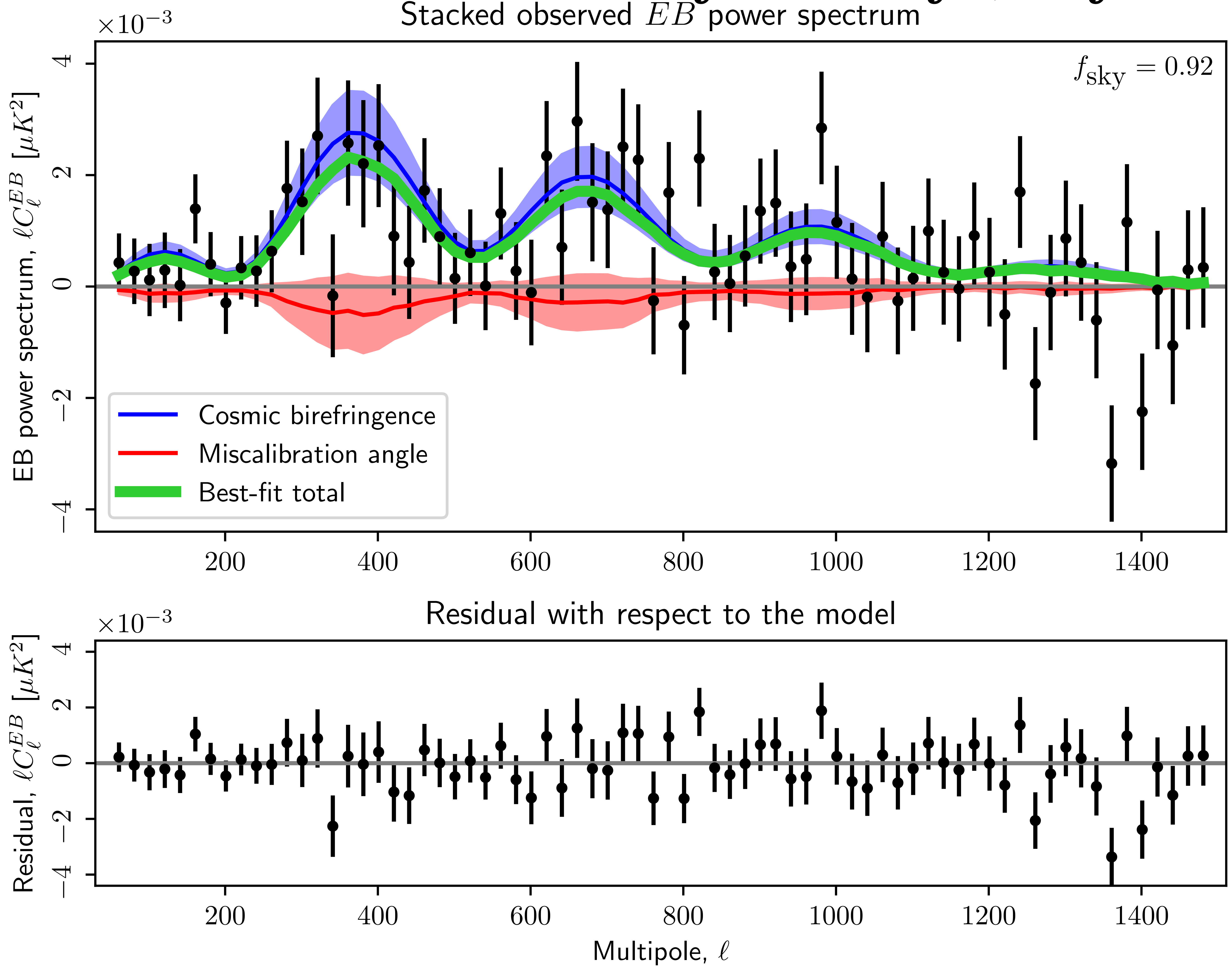
$$C_\ell^{EB,\mathrm{obs}} = \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\beta) + C_\ell^{EB}\cos(4\beta)$$

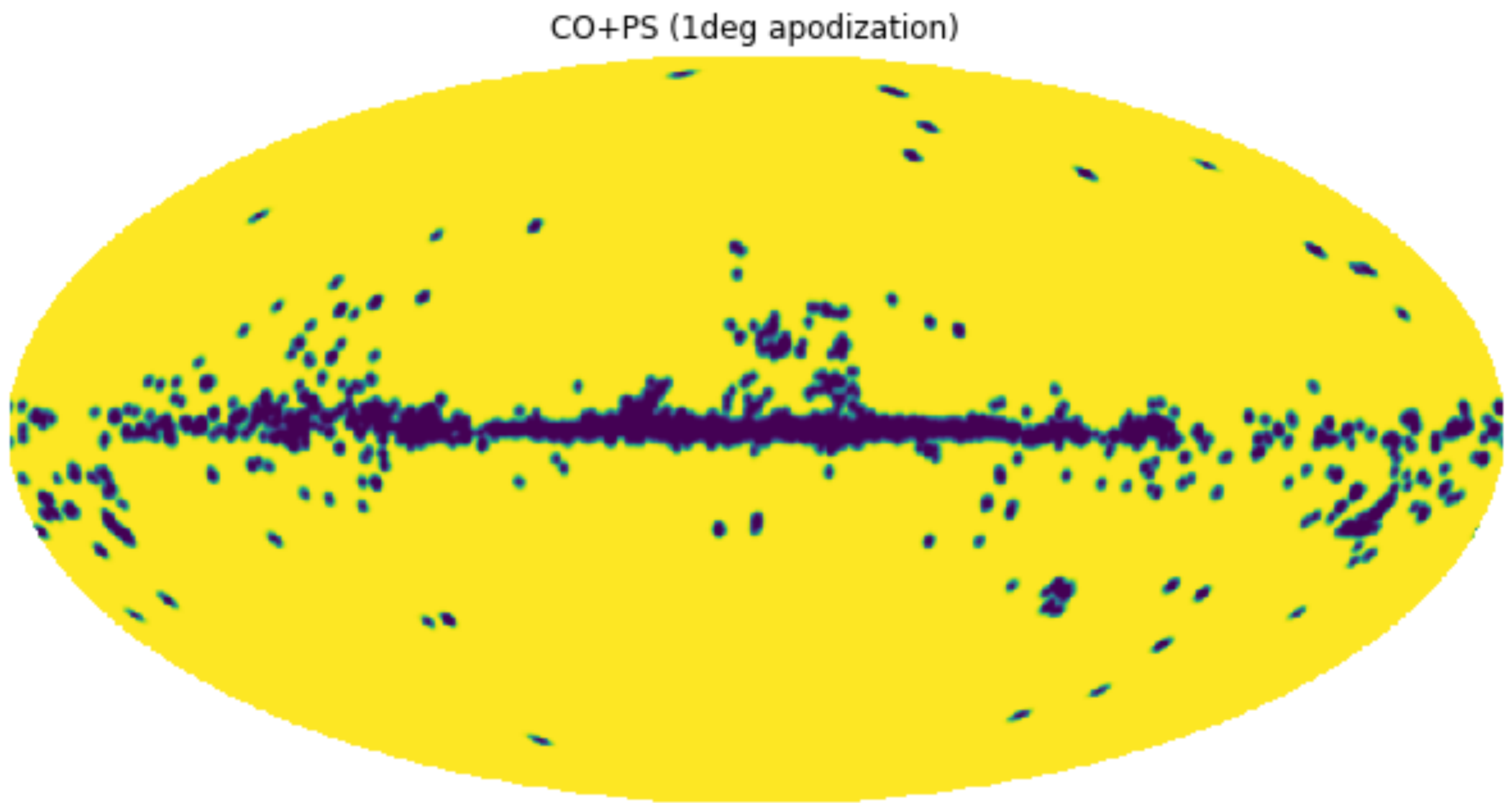
- One would find β by fitting $C_l^{EE,CMB} - C_l^{BB,CMB}$ to the observed $C_l^{EB,obs}$ using the best-fitting CMB model, and <u>assuming the intrinsic EB to vanish, $C_l^{EB}=0$</u>.

Eskilt & Komatsu (2022)

Cosmic Birefringence in WMAP+Planck

Nearly full sky (fsky = 92%) analysis



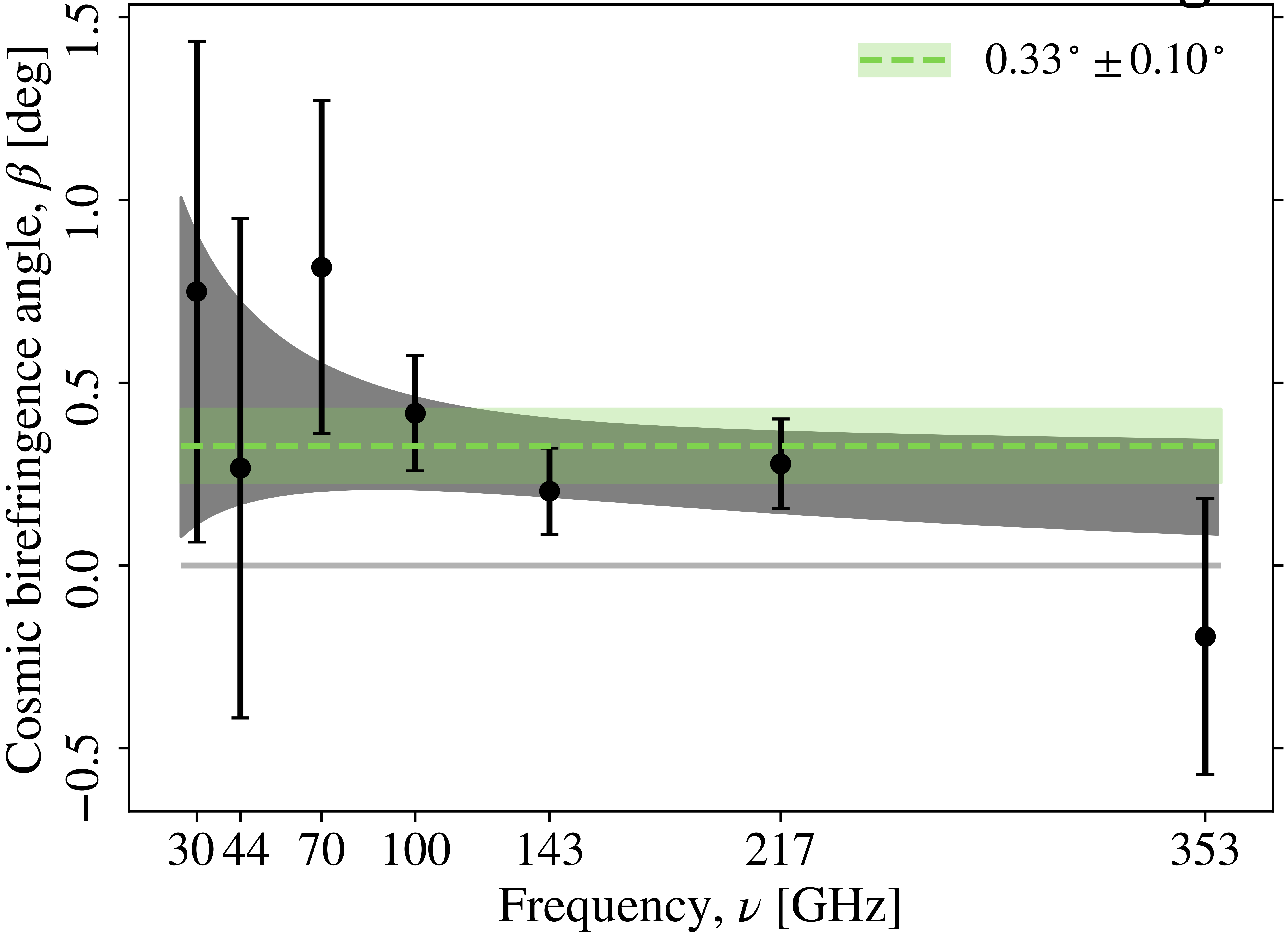


- **Mis-calibration angles** make only small contributions thanks to the cancellation.
- **β = 0.34 ± 0.09 deg** $\boxed{3.6\sigma!!}$
- χ^2 = 65.3 for DOF=72

Sekilt (2022), Eskilt & Komatsu (2022)

No strong frequency dependence

Consistent with cosmic birefringence due to $\mathscr{L} \ni \theta F\tilde{F}$



- No evidence for frequency dependence:
  - For $\beta \sim (\nu/150\mathrm{GHz})^n$, $\mathbf{n = -0.20^{+0.41}_{-0.39}}$ (68% CL)
  - Faraday rotation (n=−2) is disfavored.

Lee, Kang, Gong, Jeong, Jung, and Park (In prep)

Kinetic coupling with Dark-U(1)?

$$\mathcal{L} = -\frac{1}{4}\hat{F}^{\mu\nu}\hat{F}_{\mu\nu} - \frac{1}{4}\hat{F}_X^{\mu\nu}\hat{F}_{X\mu\nu} - \frac{\varepsilon}{2}\hat{F}_{\mu\nu}\hat{F}_X^{\mu\nu}$$

$$\beta_\nu \propto \varepsilon\sqrt{\frac{I_{\mathrm{D}\gamma}}{I_{\mathrm{CMB}}}}\sin\beta_{\mathrm{D}\gamma}$$

- The frequency dependence is weak as long as $T_{\text{dark-U(1)}} \lesssim T_{\text{CMB}}$.
- Dark recombination preceded the baryonic recombination:
  - Unless we have a strong coupling to correlate the polarization of dark U(1) at dark recombination to the CMB's linear polarization, the relative linear polarization is *random*.
  - The random angle removed the average birefringence signal.
  - Leading contribution = Spectral distortion and <EEBB> trispectrum.

Summary & Conclusion

- With WMAP and Planck, the CMB has been providing most accurate measurement of cosmological parameters.
- The CMB is still a valuable source of clues for puzzles that we are facing now. Three examples:
  - Amplitude of small-scale power spectrum from spectral distortion
  - B-mode polarization turn-over for testing early dark energy models
  - EB cross correlation for possible parity breaking sinatures