Silk damping at early times: spectral distortion, BBN, and small scale fluctuations

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references: 1306.5751, 1403.3697

Collaborators: Jens Chluba, Josef Pradler, Marc Kamionkowski (JHU)

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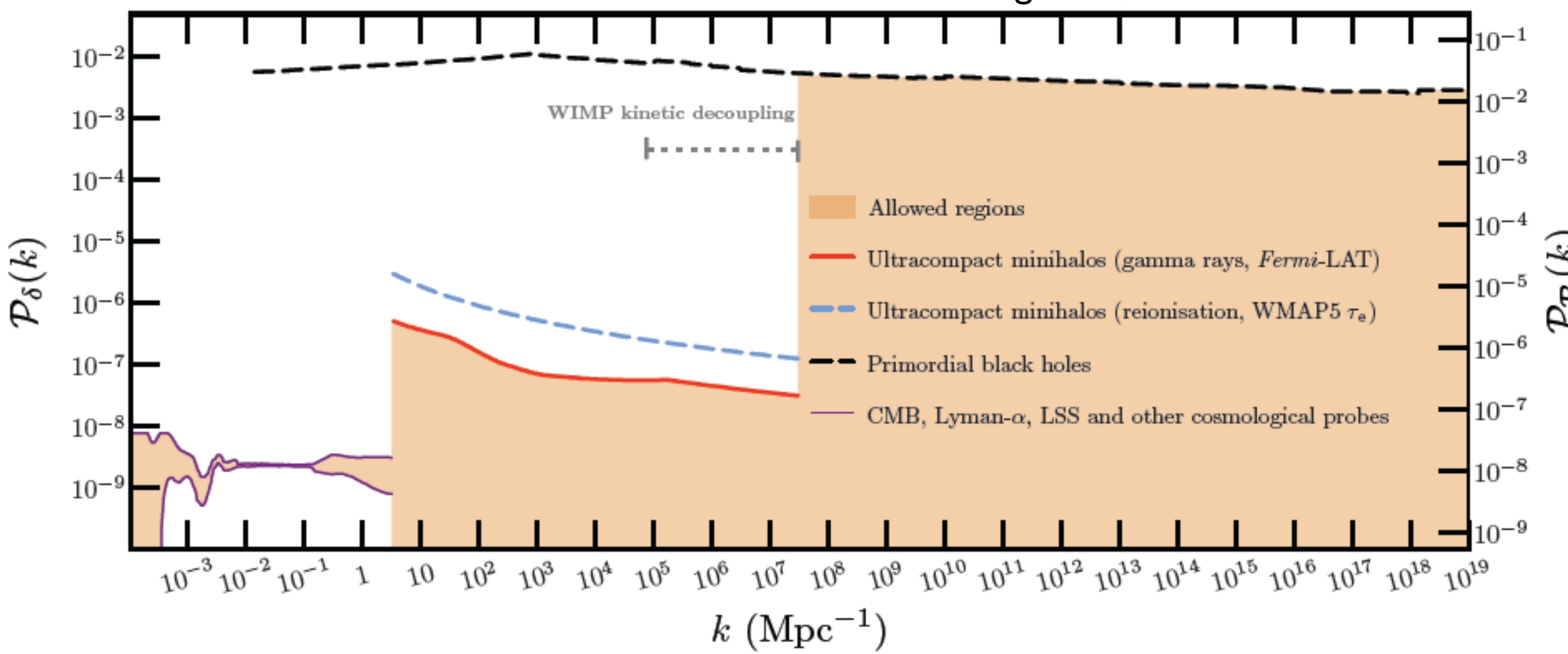
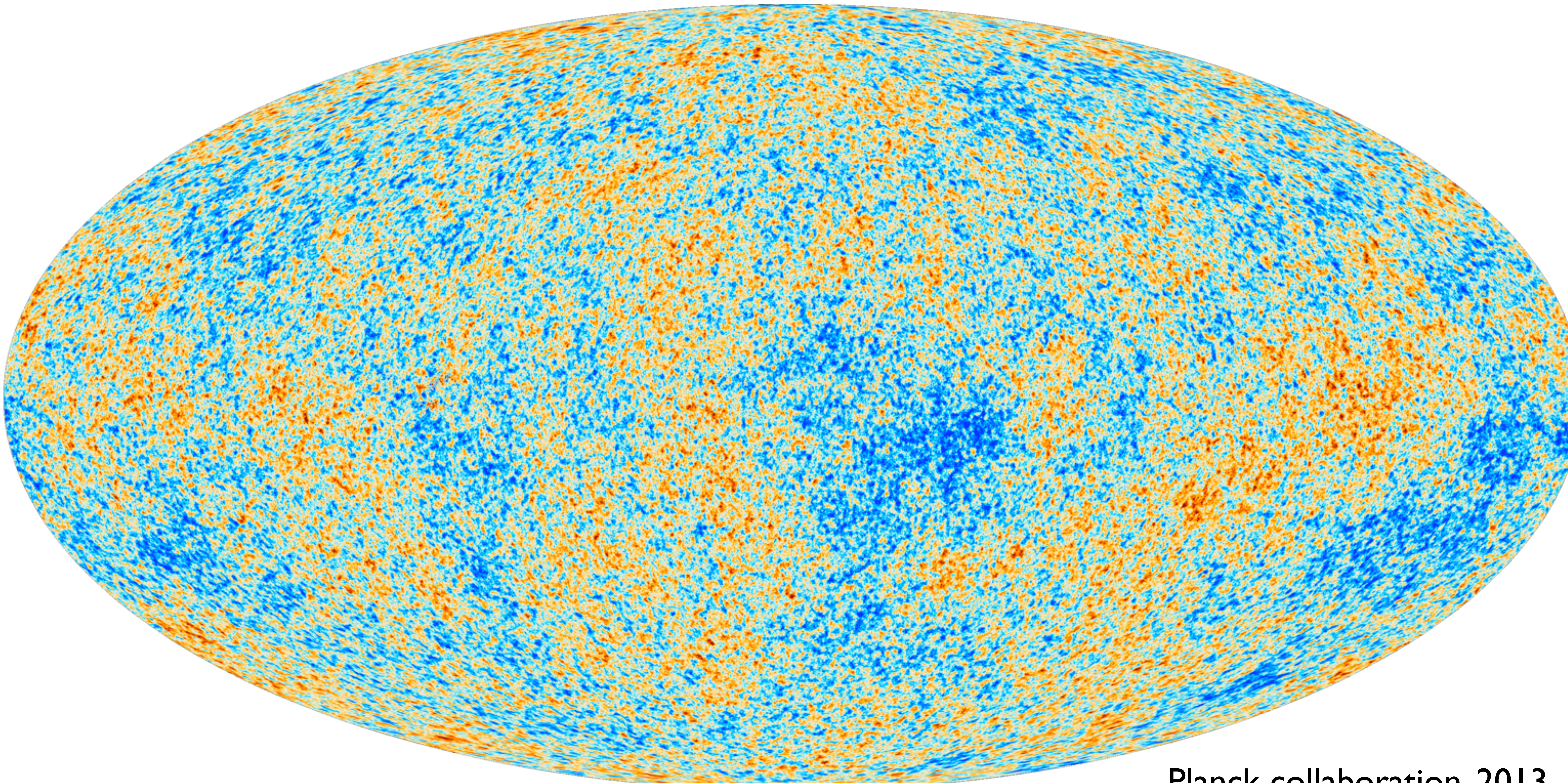
Primordial power spectrum

- is rather unconstrained on small scales ($k \gtrsim 1 \sim 3$ Mpc^{-1})!
- Where else can we look at to put other constraints?

Bringmann, Scott & Akrami 2011



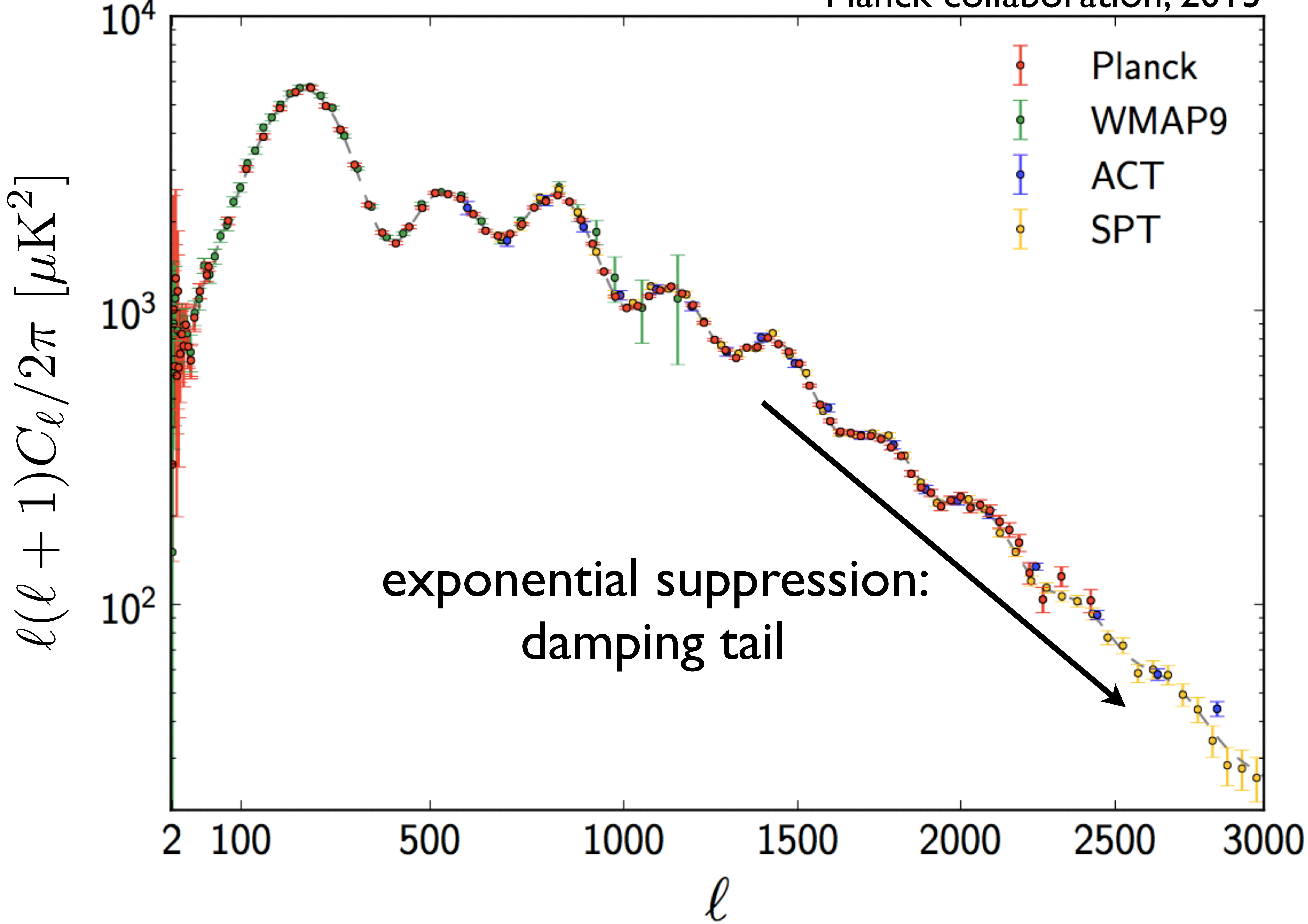
CMB temperature anisotropies



Planck collaboration, 2013

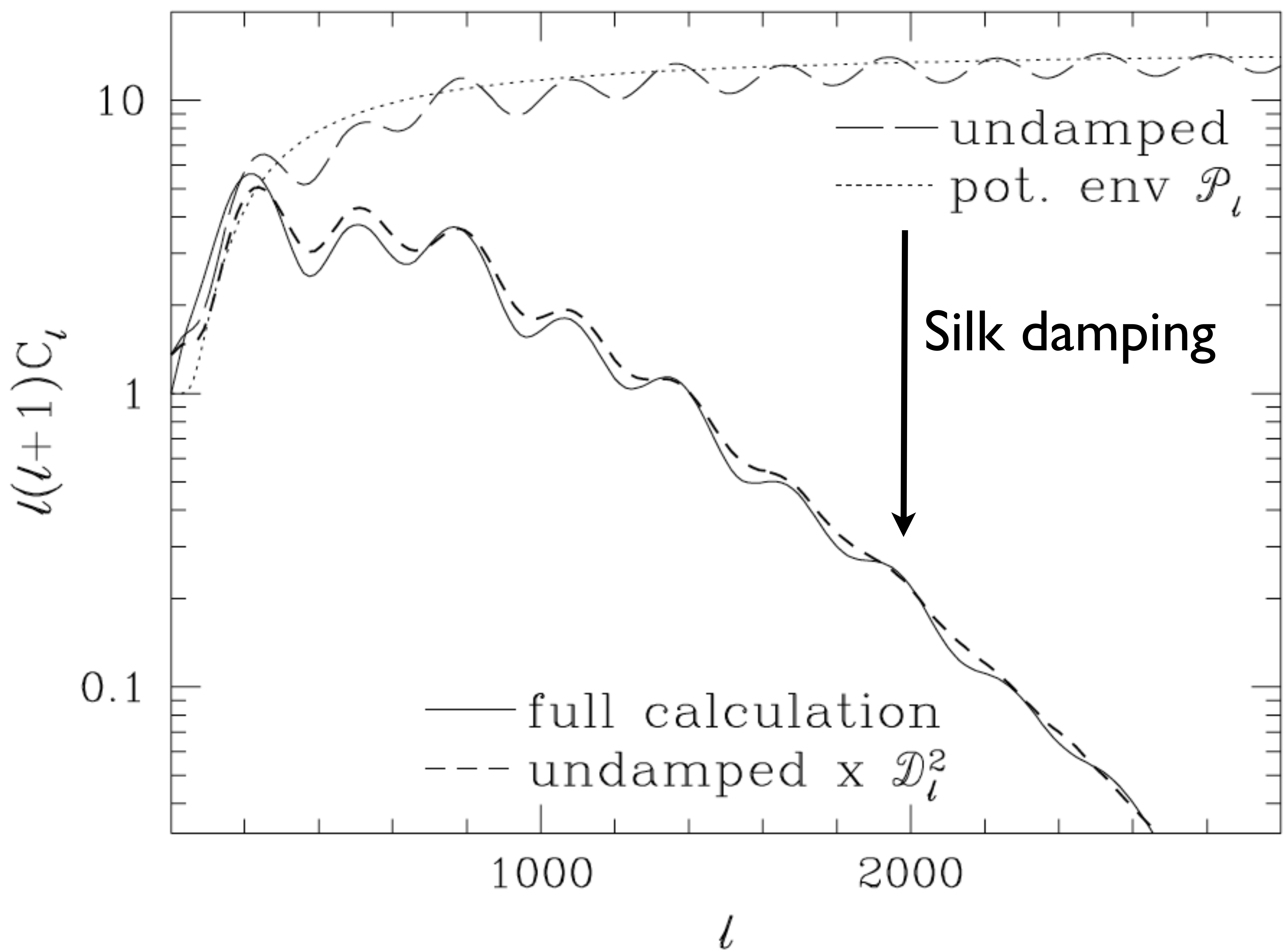
CMB power spectrum C_ℓ

Planck collaboration, 2013

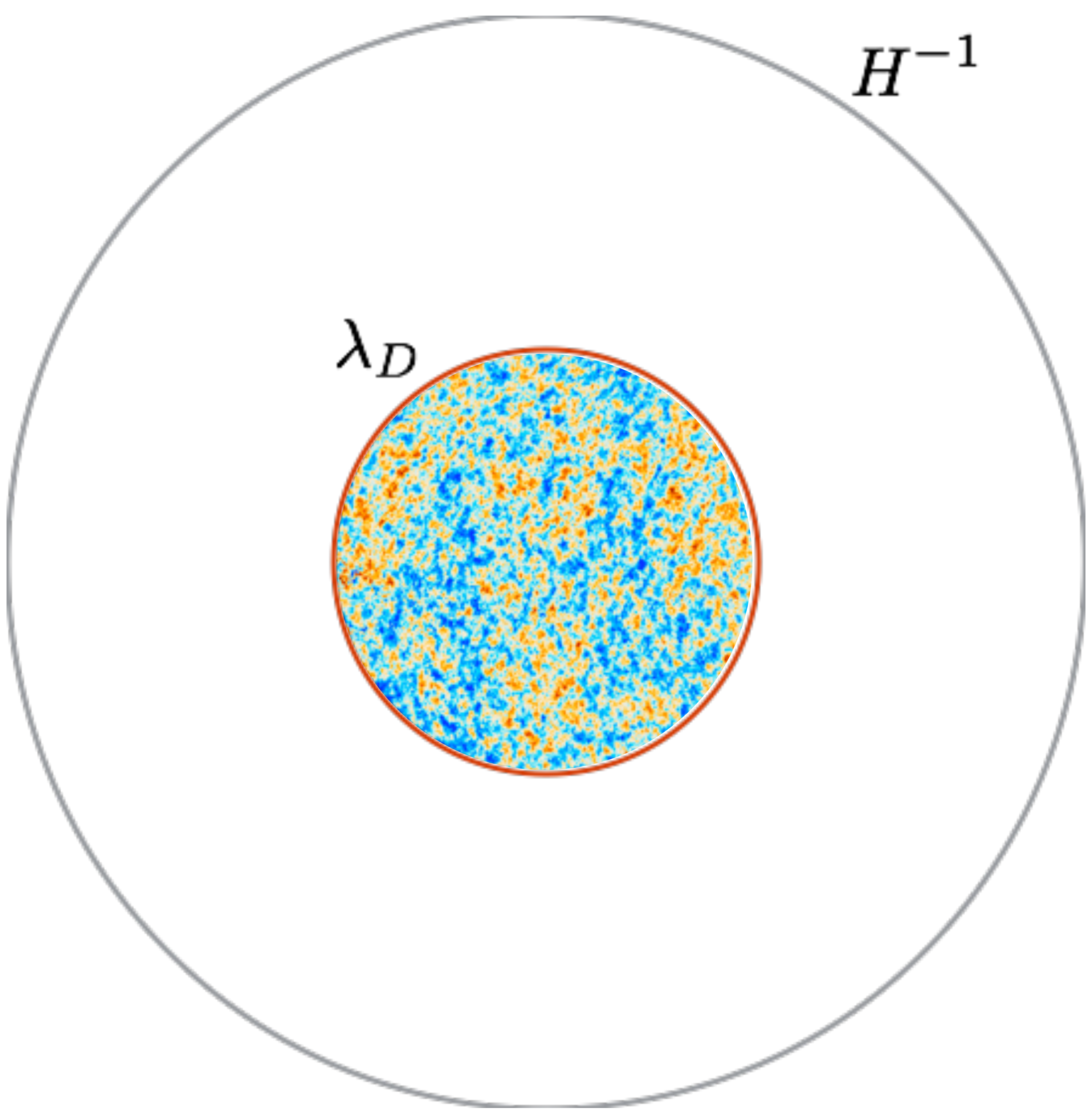


Why call it a damping tail?

Hu & White 1997



Silk damping: diffusion of photon



temperature anisotropies
at ~0.0001” scale

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

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

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

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

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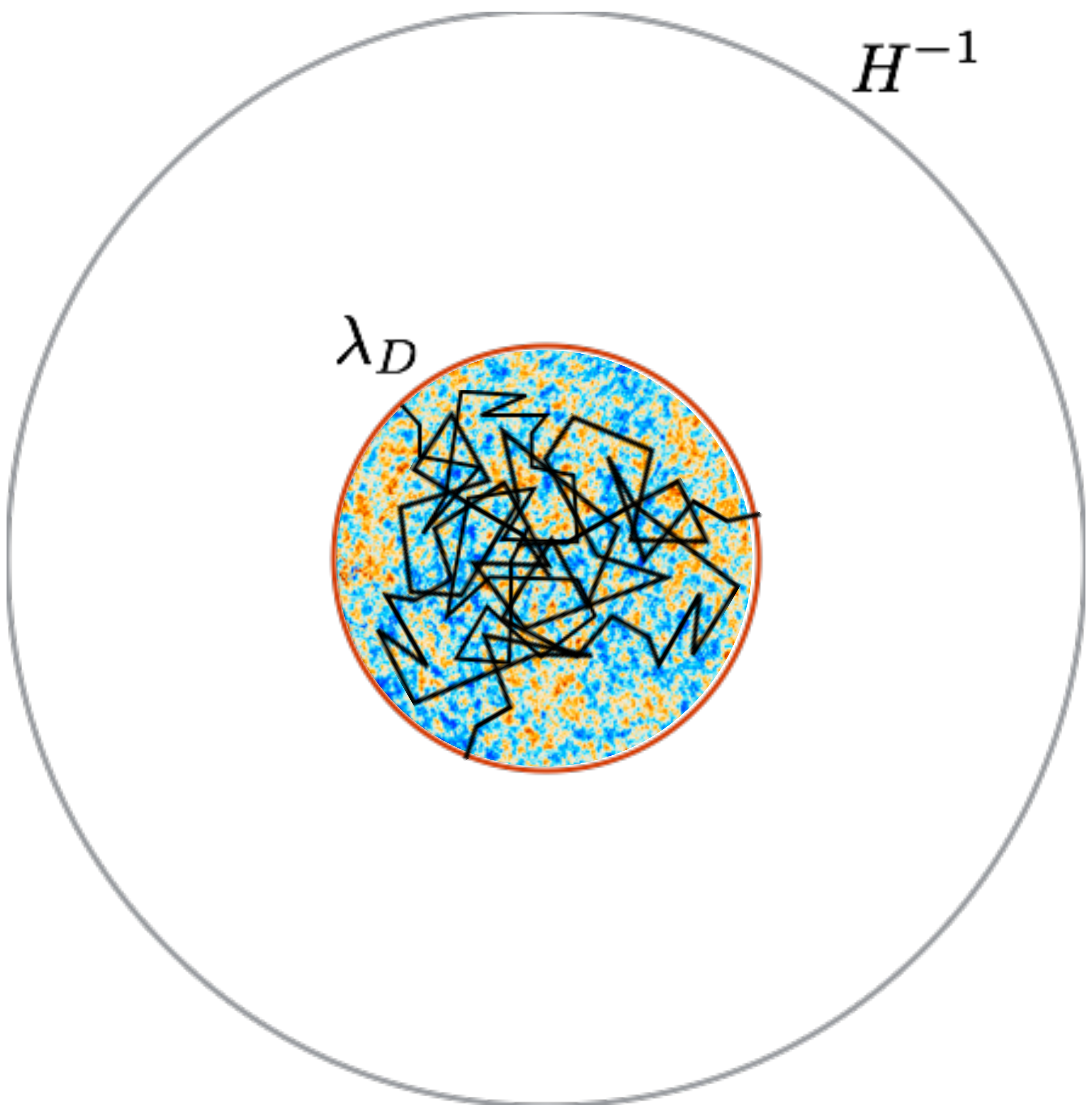

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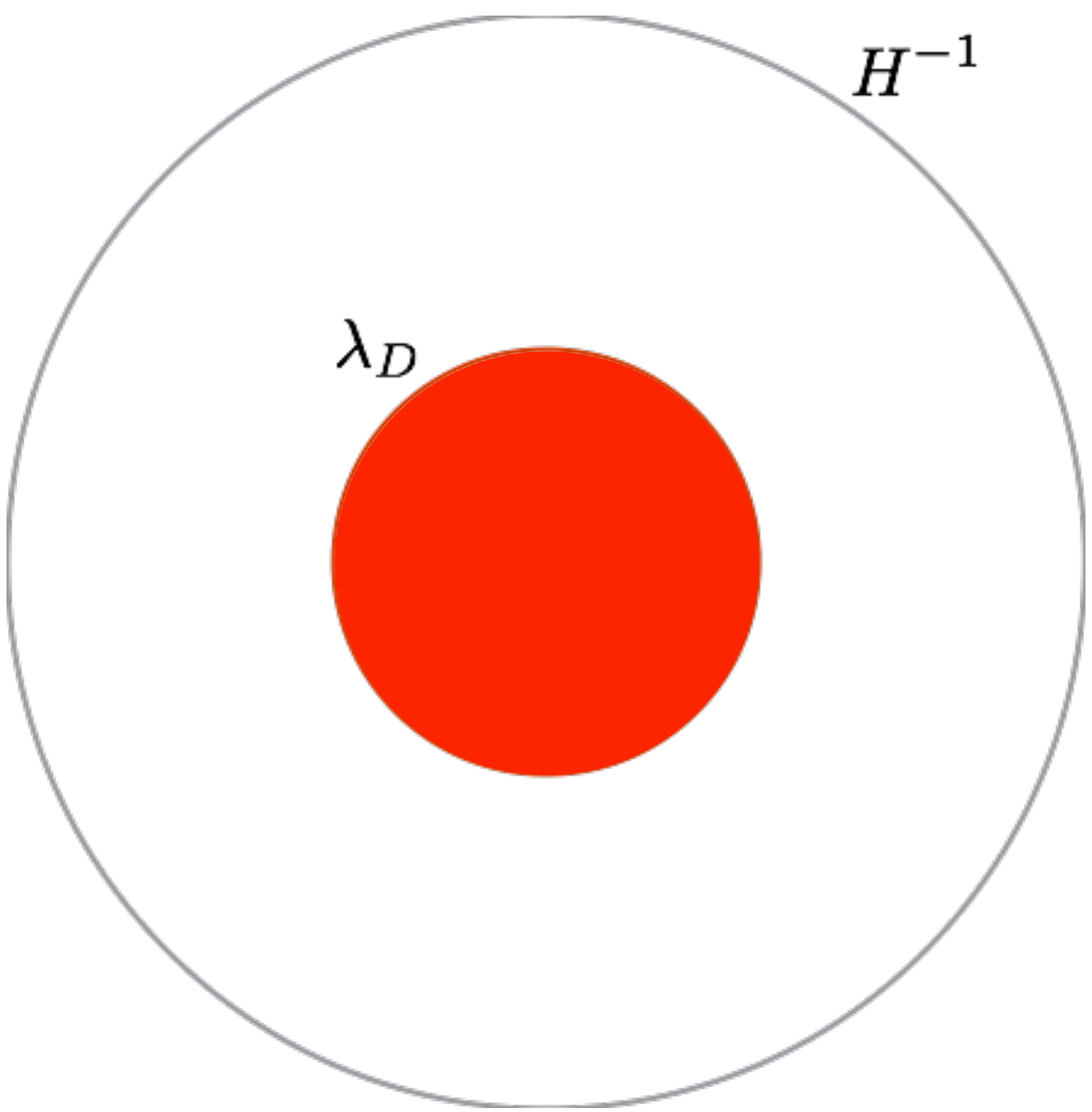

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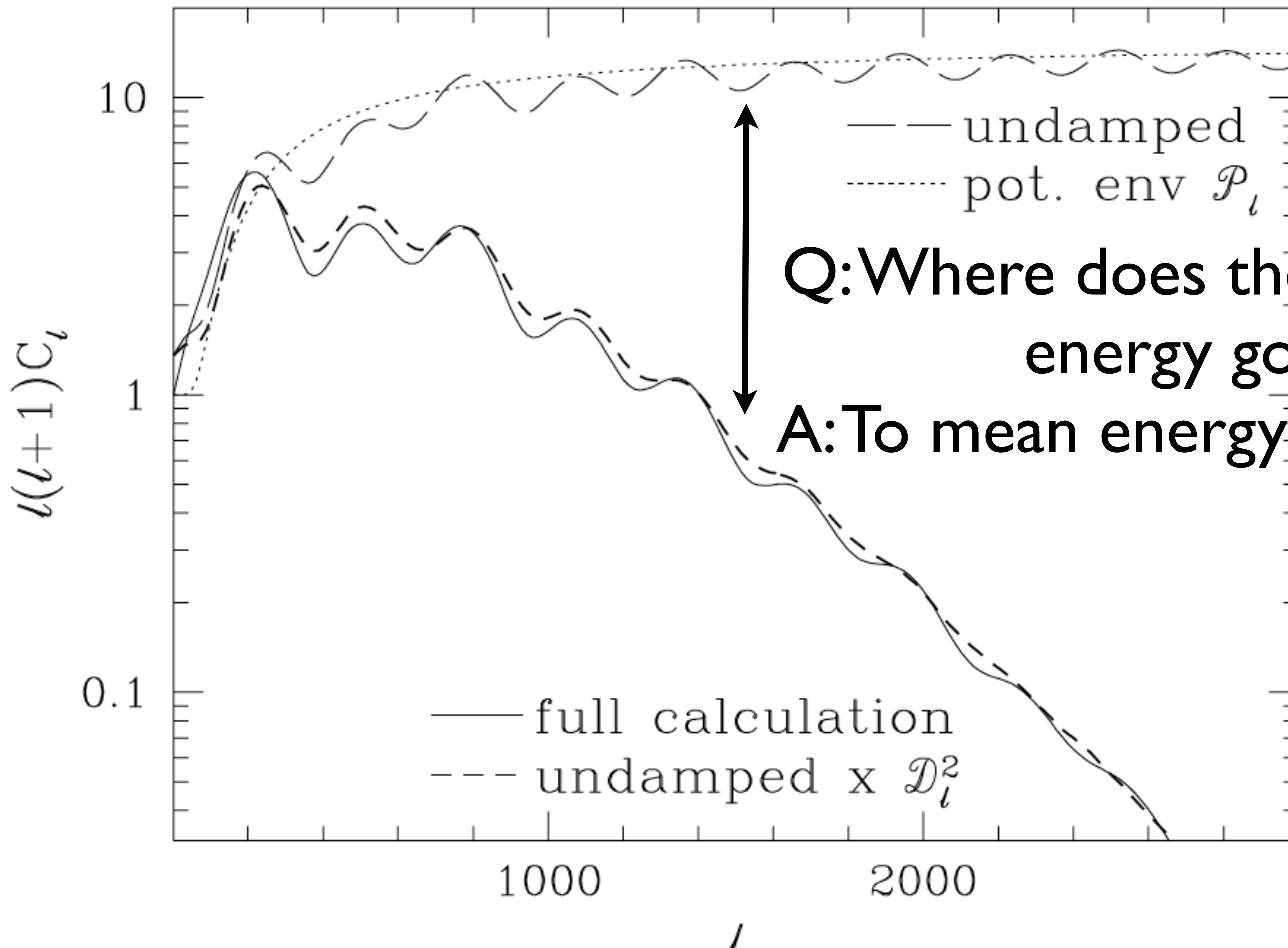
Temperature fluctuations inside of the diffusion scales are smoothed out!

So, it damps the acoustic waves

Hu & White 1997

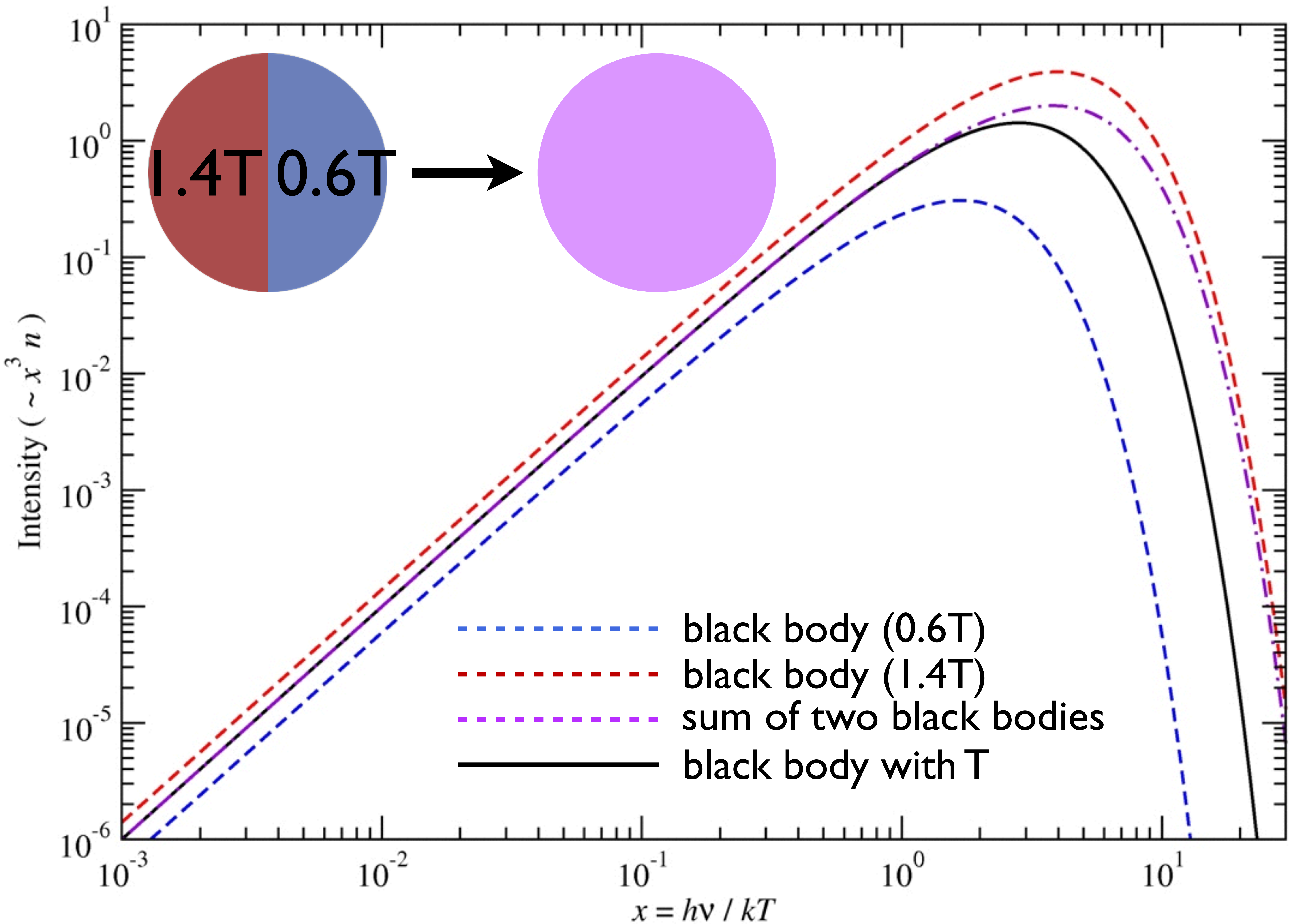


Q: Where does the acoustic energy go?

A: To mean energy spectrum

Smoothed intensity spectrum

is NOT a black body (Zeldovich, Illarionov & Sunyaev 1972)



Energy and Number density

- Smoothing the black bodies with temperature $T = \bar{T}(1+\Theta)$
  - superposed energy density $\rho \propto \left\langle (1+\Theta)^4 \right\rangle = \rho(\bar{T})(1 + 6\left\langle \Theta^2 \right\rangle)$
  - superposed number density $n \propto \left\langle (1+\Theta)^3 \right\rangle = n(\bar{T})(1 + 3\left\langle \Theta^2 \right\rangle)$
- Need to *produce* (It is well known that 3/4x6 - 3 = 3/2.)

$$\frac{\Delta n}{n} = \frac{3}{2}\left\langle \Theta^2 \right\rangle$$

in order to maintain the black body form:

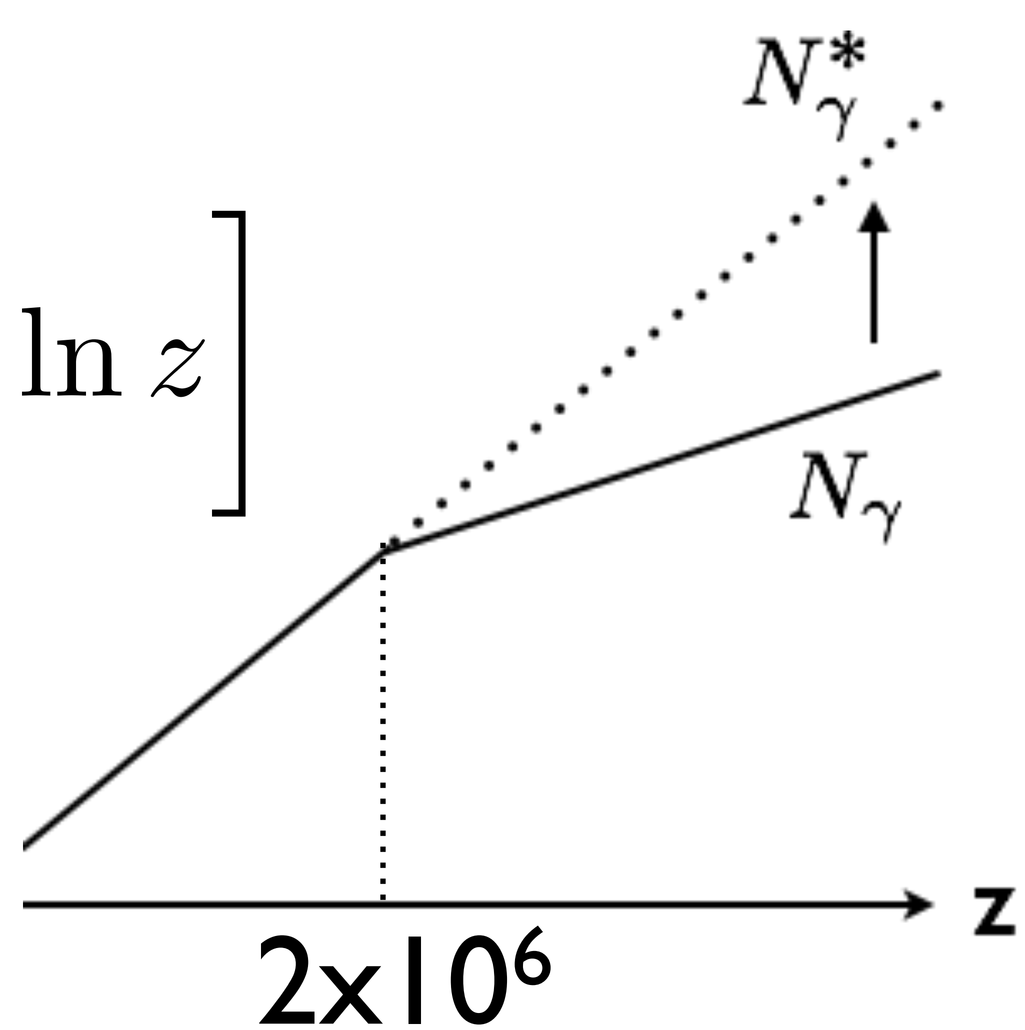
$$\frac{\Delta n}{n} = \frac{3}{4}\frac{\Delta \rho}{\rho}$$

Thermalization at $z \gtrsim 2\times10^6$

- Photon (entropy) production due to double-Compton scattering and Bremsstrahlung + photon transport is efficient
- Thermalization follows immediately after the diffusion process
  - Net entropy production is proportional to the amplitude of primordial power spectrum ($k_D \sim 1/\lambda_D$):

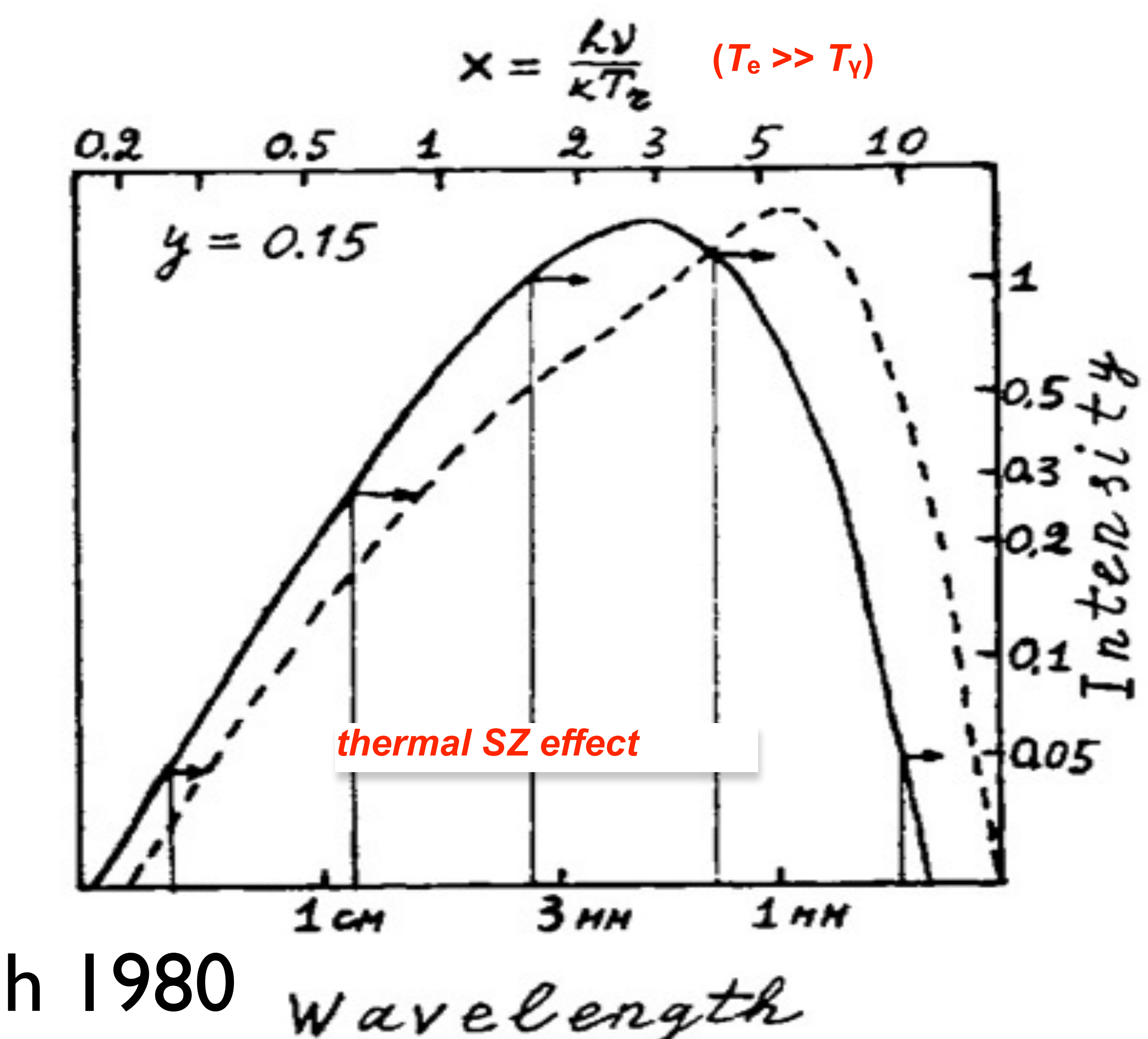
$$N_\gamma(z) \simeq N_\gamma^*(z)\exp\left[-\frac{3}{2}C^2\int_0^z \Delta^2_{\mathcal{R}}(k_D)\frac{d\ln k_D}{d\ln z}\,d\ln z\right]$$

number density extrapolated from 411cm^{-3} today



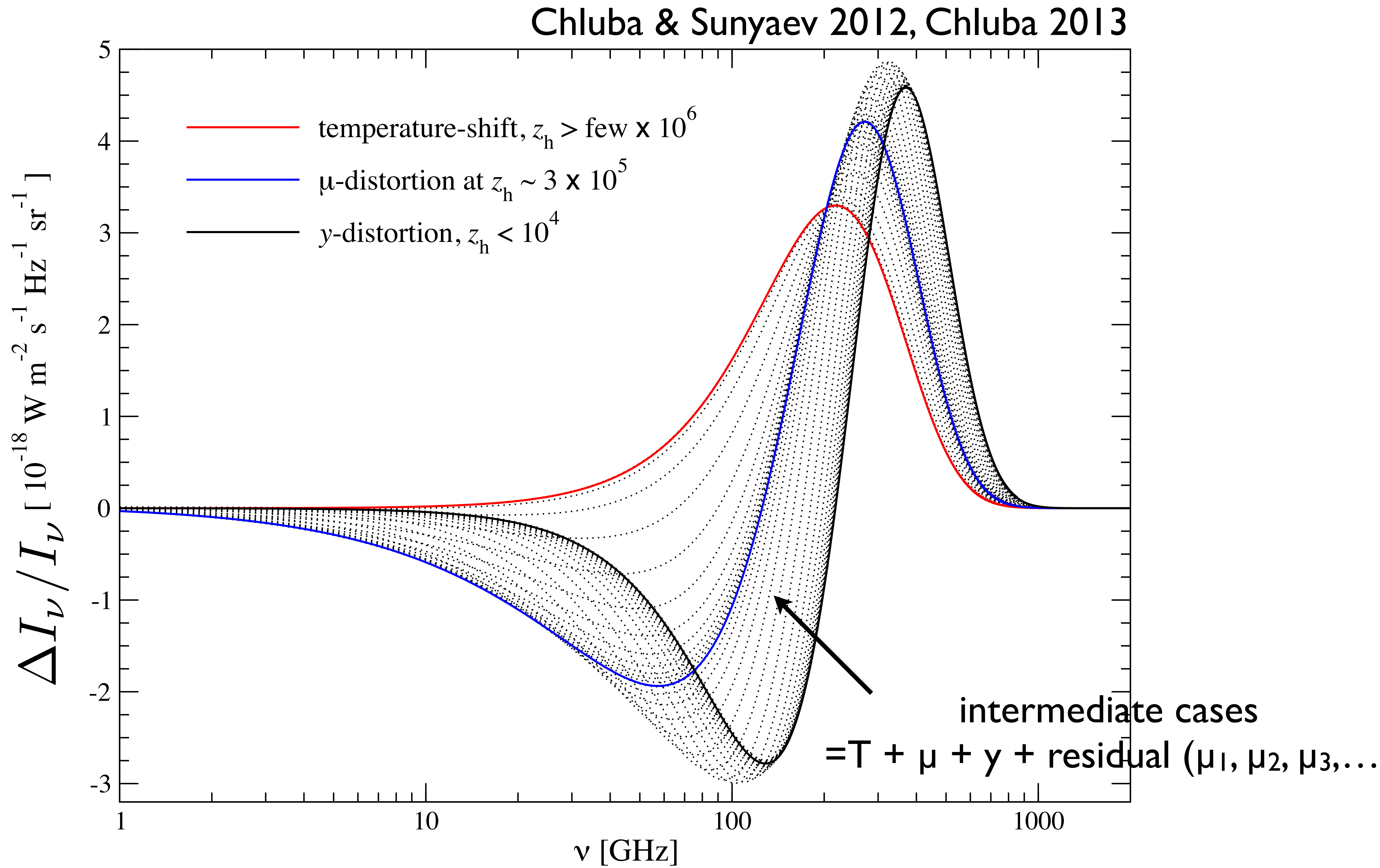
Spectral distortion at $z \lesssim 2\times10^6$

- Two extreme cases with excess energy (compared to number)
- At higher redshifts ($z \gtrsim 3\times10^5$): μ-distortion
  - Interaction is fast enough to relax the intensity spectrum to the Bose-Einstein form with 'effective' chemical potential
- At lower redshifts ($z \lesssim 10^4$): y-distortion
  - inefficient energy exchange leads to the Compton y-type distortion (a.k.a. thermal SZ effect)

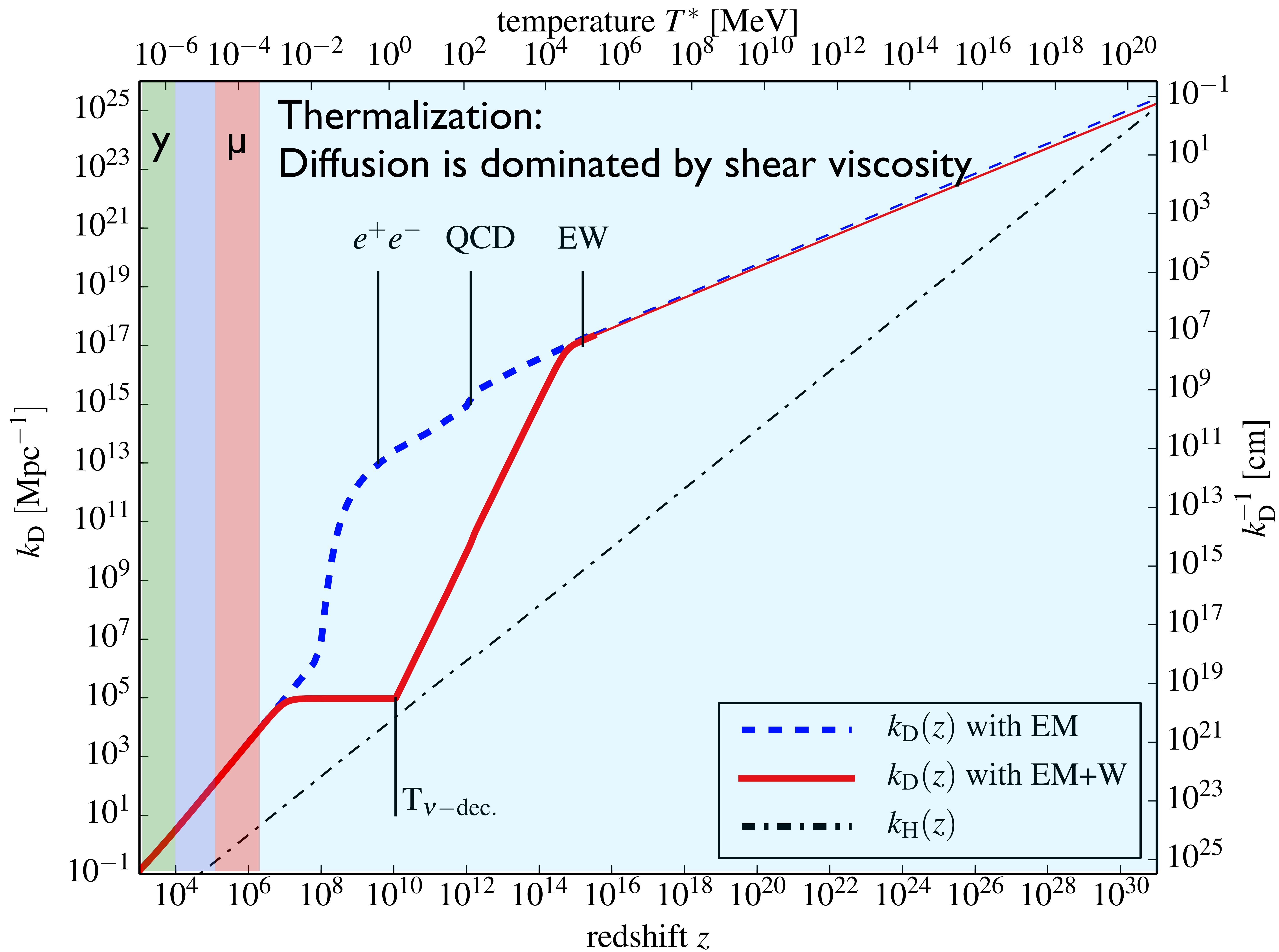


Sunyaev & Zeldovich 1980

How does the distortion look?

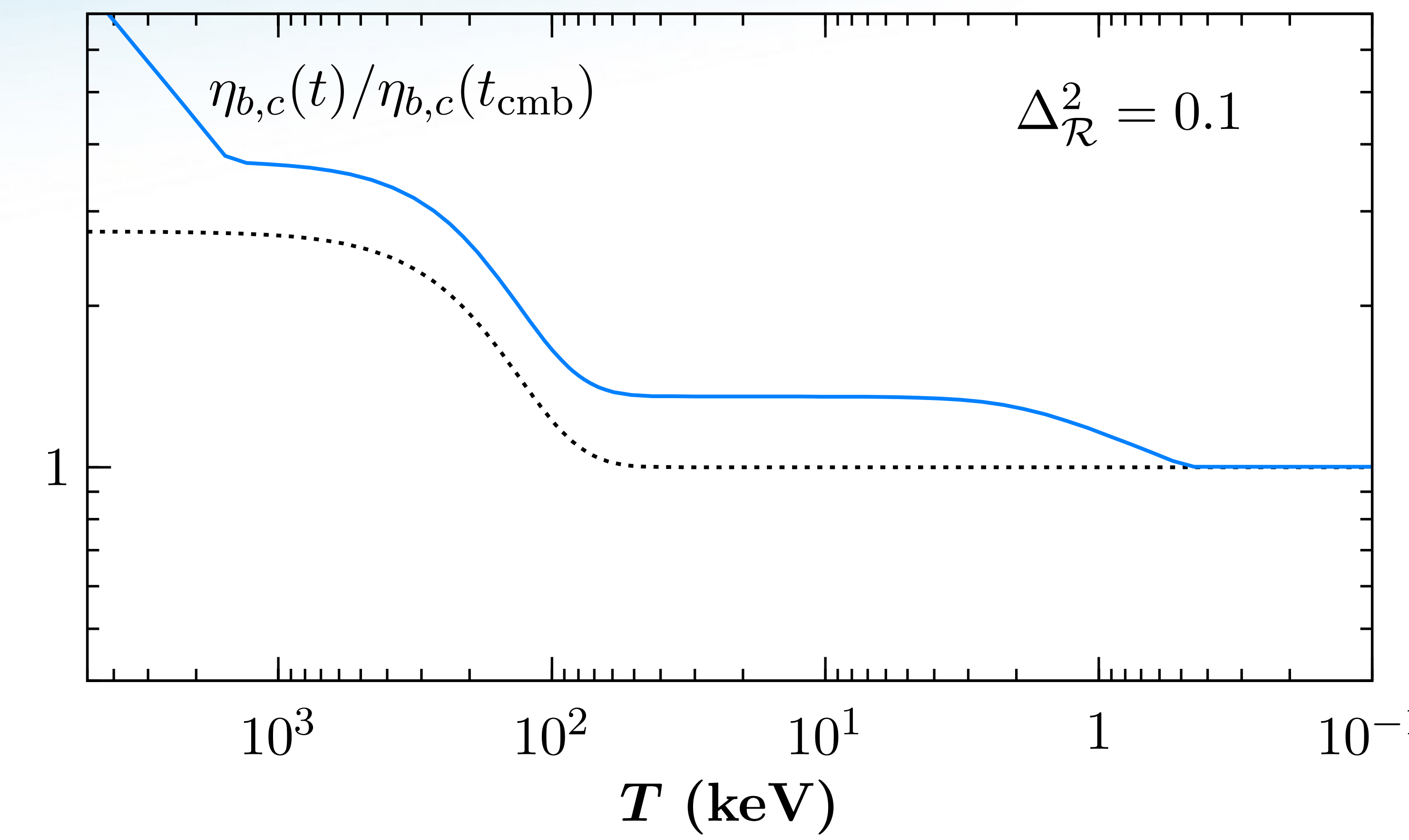


k_D with the Standard Model

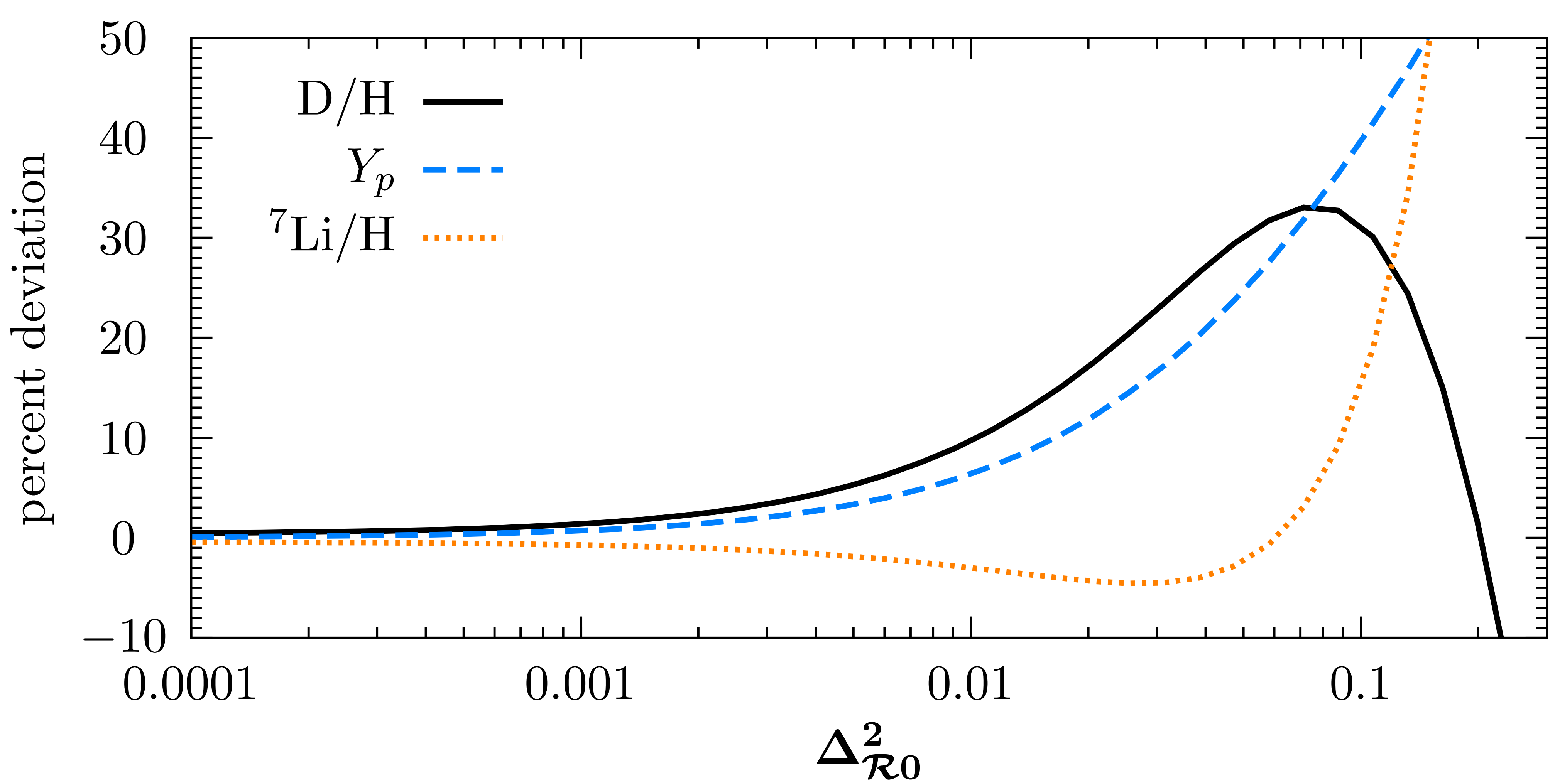


Constraint from BBN

Corrections to BBN come from modes that dissipate *after* BBN (present *during* BBN)



=> elevated baryon asymmetry
=> modified avg. energy/particle
(because of the neutrino spectral distortion!)



$$Y_p : \Delta^2_{\mathcal{R}0} < 0.007$$

$$({\rm D/H})_p : \Delta^2_{\mathcal{R}0} < 0.2$$

$$10^4\,{\rm Mpc}^{-1} \lesssim k \lesssim 10^5\,{\rm Mpc}^{-1}$$

only constraint from *direct* early Universe observable

slide courtesy: Josef Pradler

Constraint from Baryon Asymmetry

Dilution $\frac{\eta_b}{\eta_b^*} = e^{3\Delta^2_{\mathcal{R}0}\Theta_p}$

If quarks are thermalized, principal bound:

$$(N_B - N_{\bar{B}})/N_\gamma \lesssim \mathcal{O}(1)$$

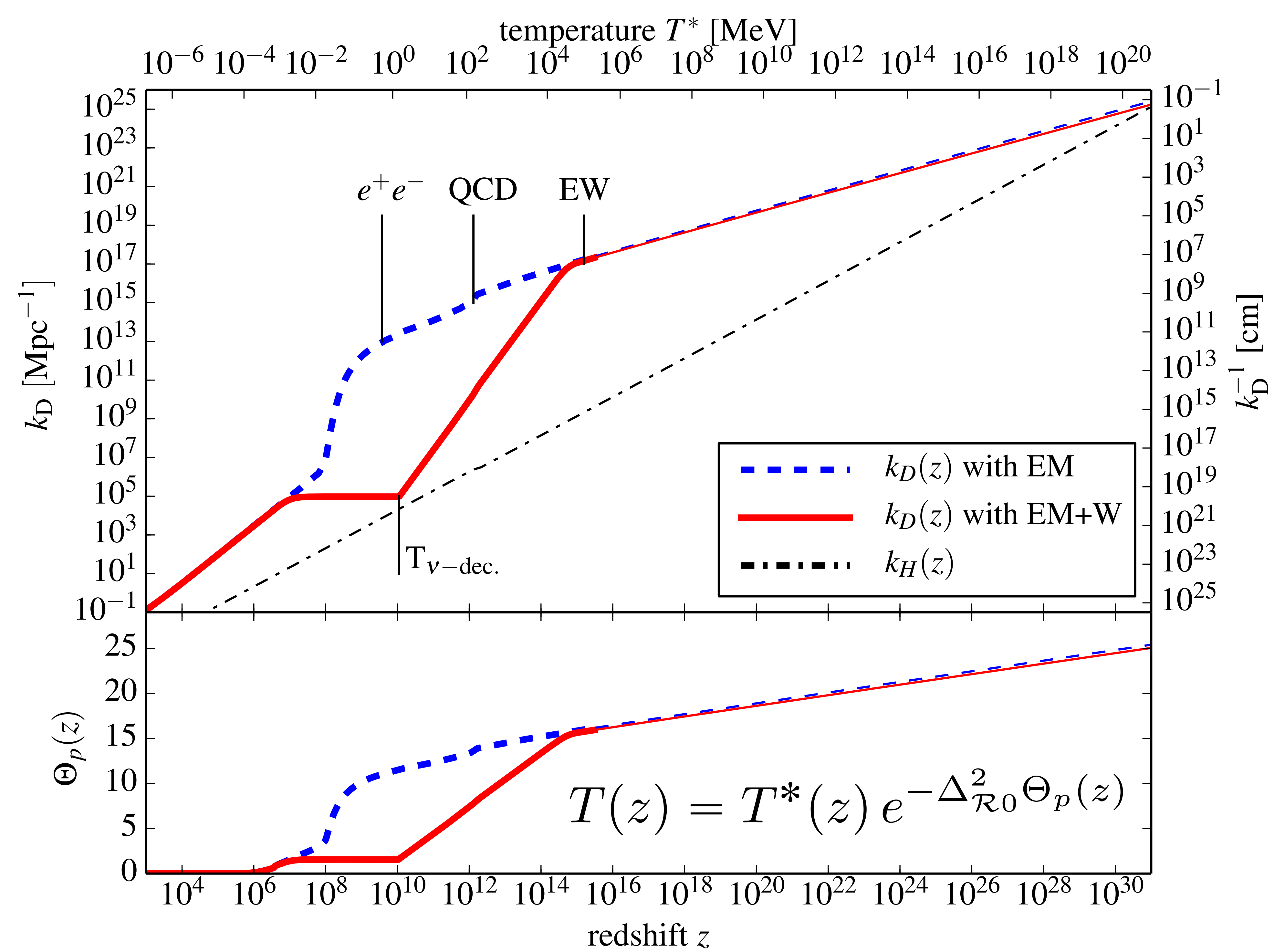
=> $\Delta^2_{\mathcal{R}0} \lesssim 0.3$

If baryogenesis happens above 1 TeV.

Weak bound, but

1. applies on very small scales
2. dilution factor is substantial

Extrapolation for SM



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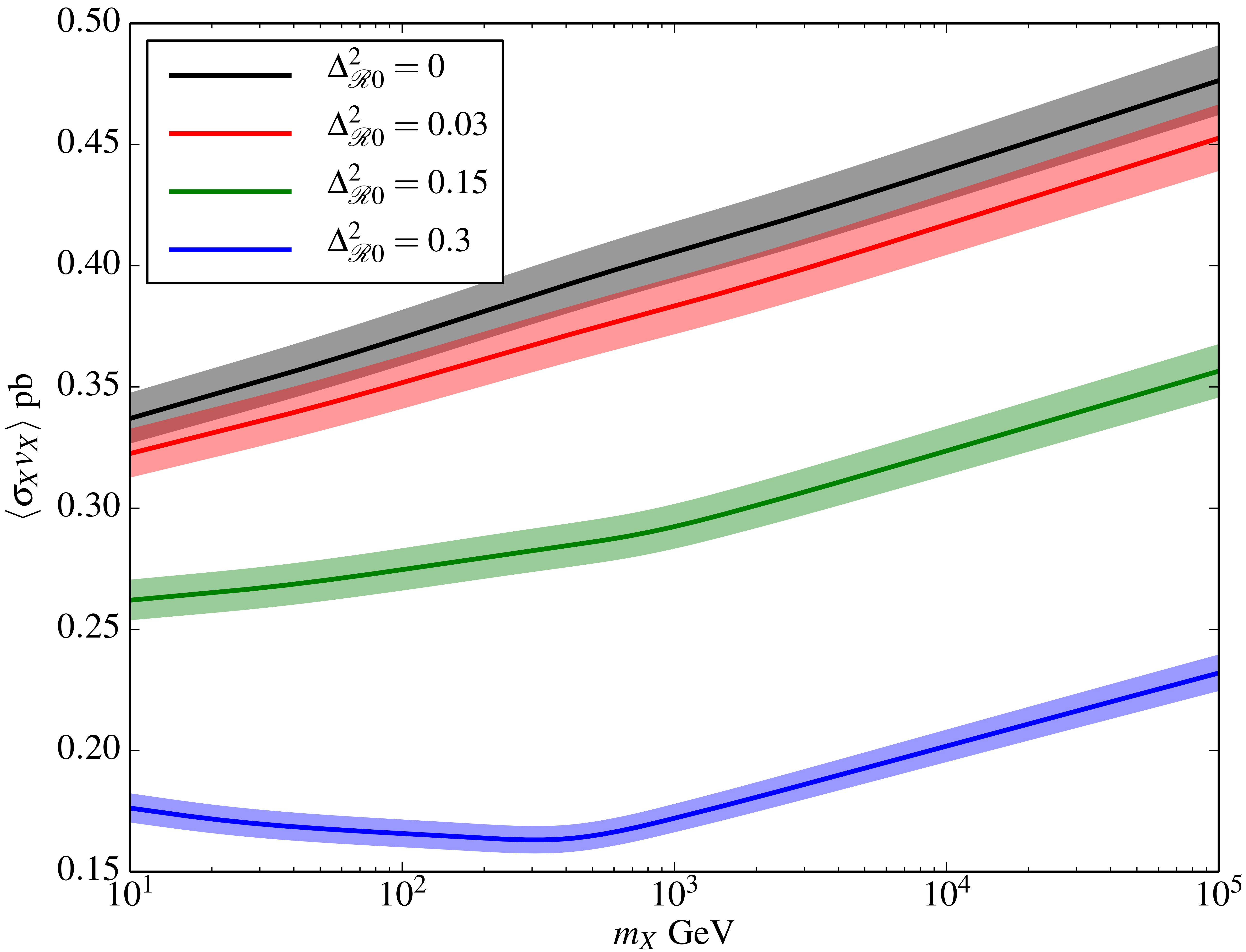
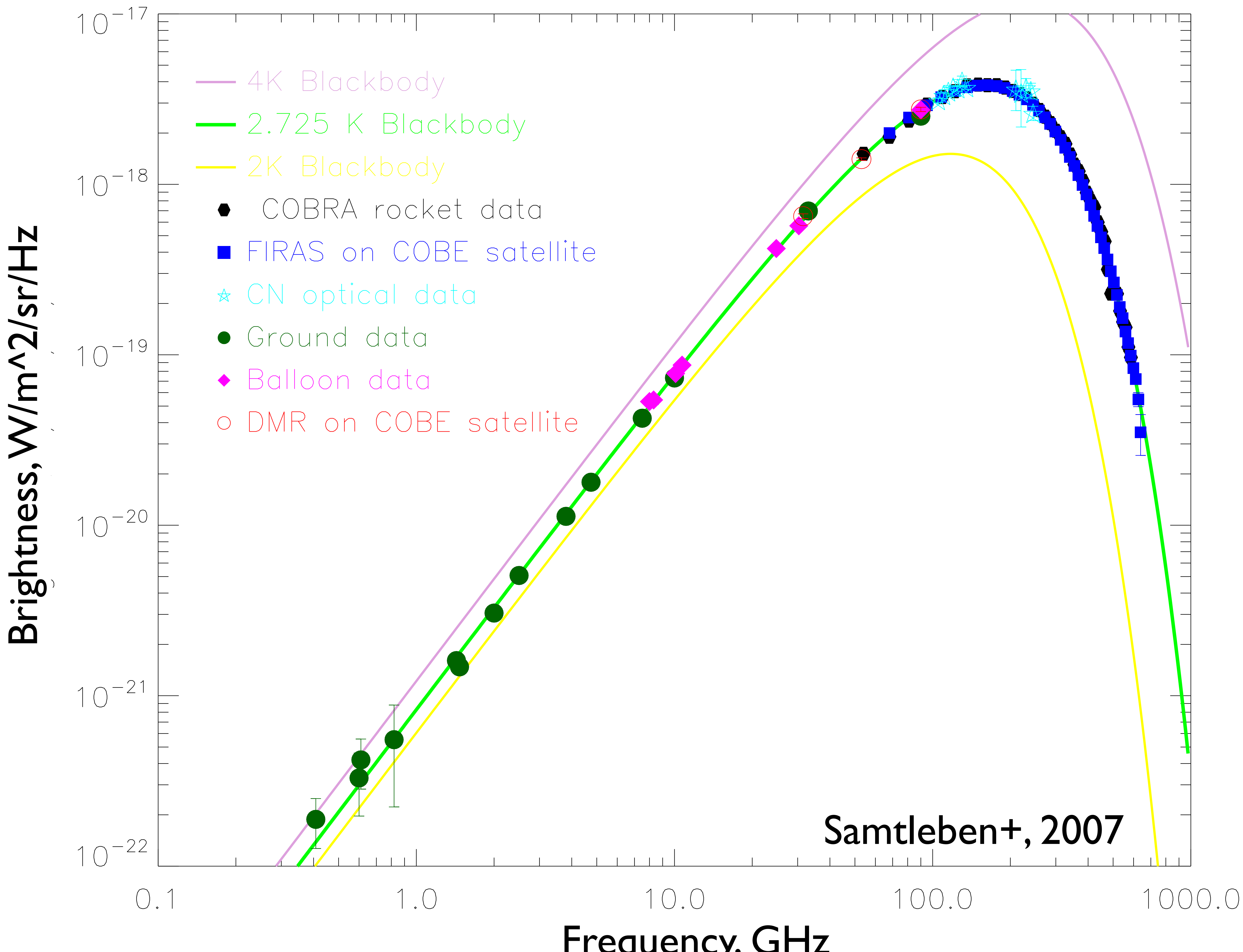
CDM freeze-out (WIMP miracle)



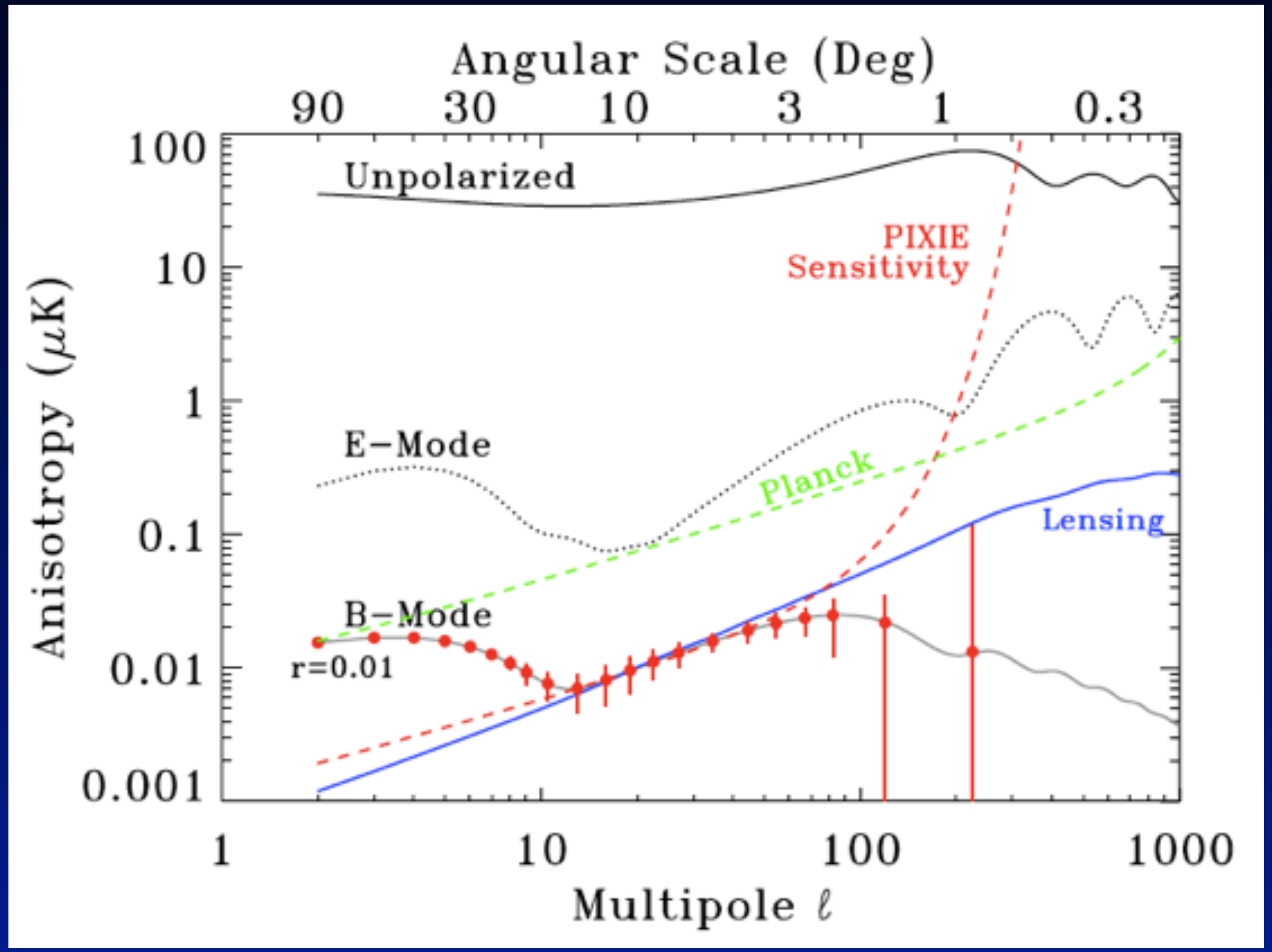
- Effect from revised temperature-redshift relation
- FO density is determined by 'revised' CMB temperature
- Shaded region: Ω_{cdm} = 0.2594±0.0074 (Planck 2-σ)

CMB is very very black-body!

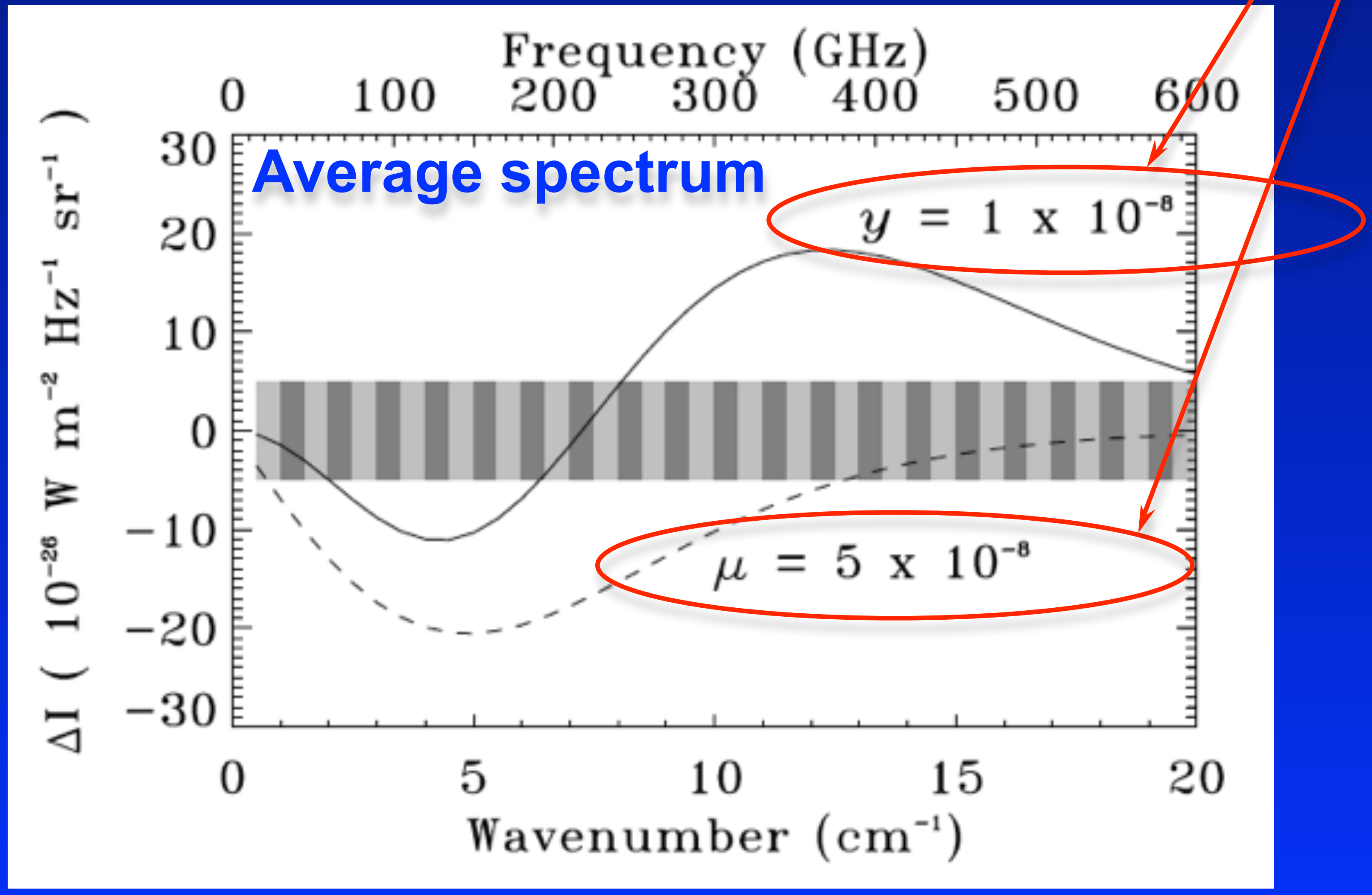


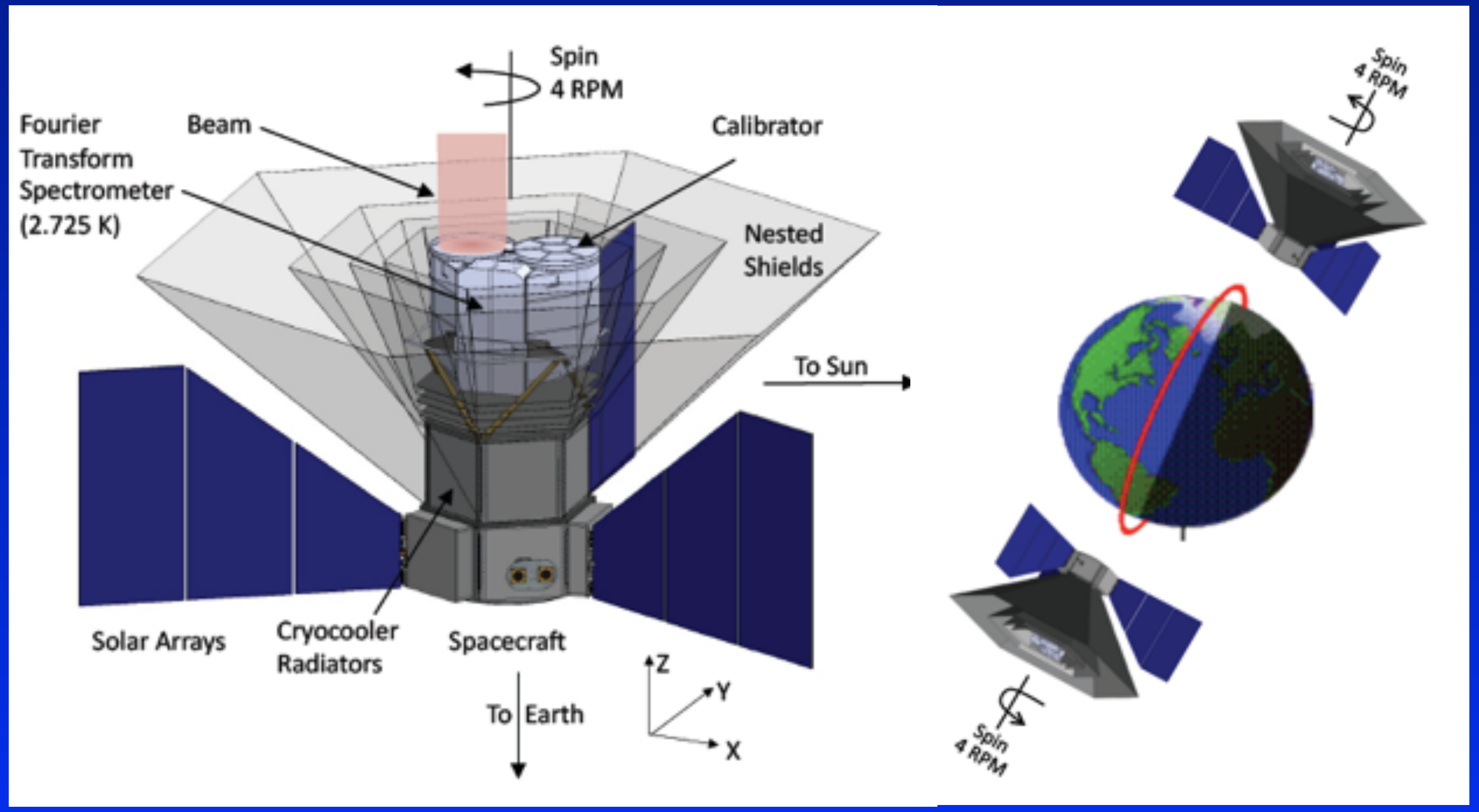
- T_0=2.527±0.001K from COBE/FIRAS (Mather+ 1994, Fixen +1996, Fixen+2003)
- $|y| \leq 1.5\text{x}10^{-5}$
- $|\mu| \leq 9\text{x}10^{-5}$

PIXIE: Primordial Inflation Explorer



- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)

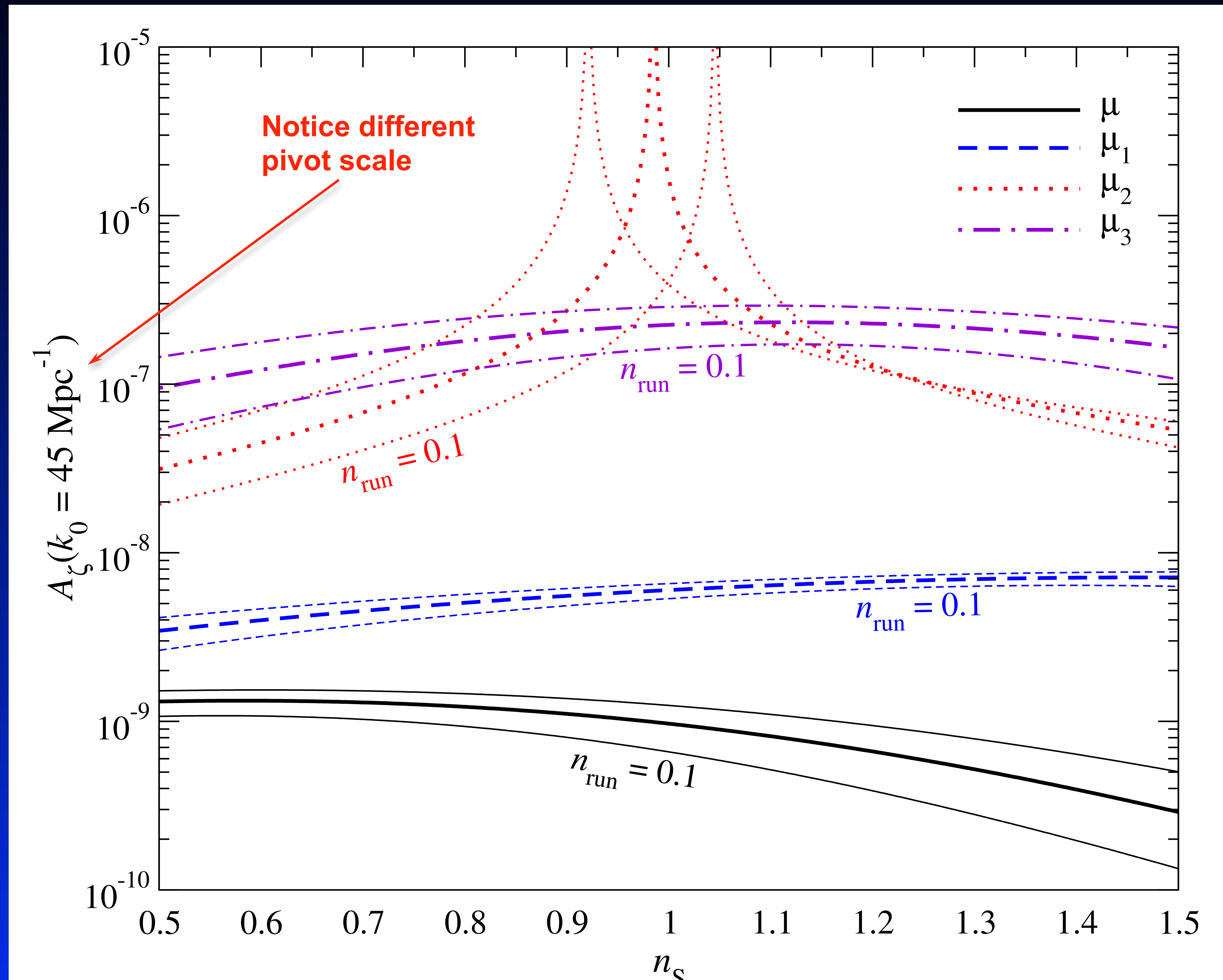




Kogut et al, JCAP, 2011, arXiv:1105.2044

slide courtesy: Jens Chluba

Dissipation scenario: 1σ-detection limits for PIXIE

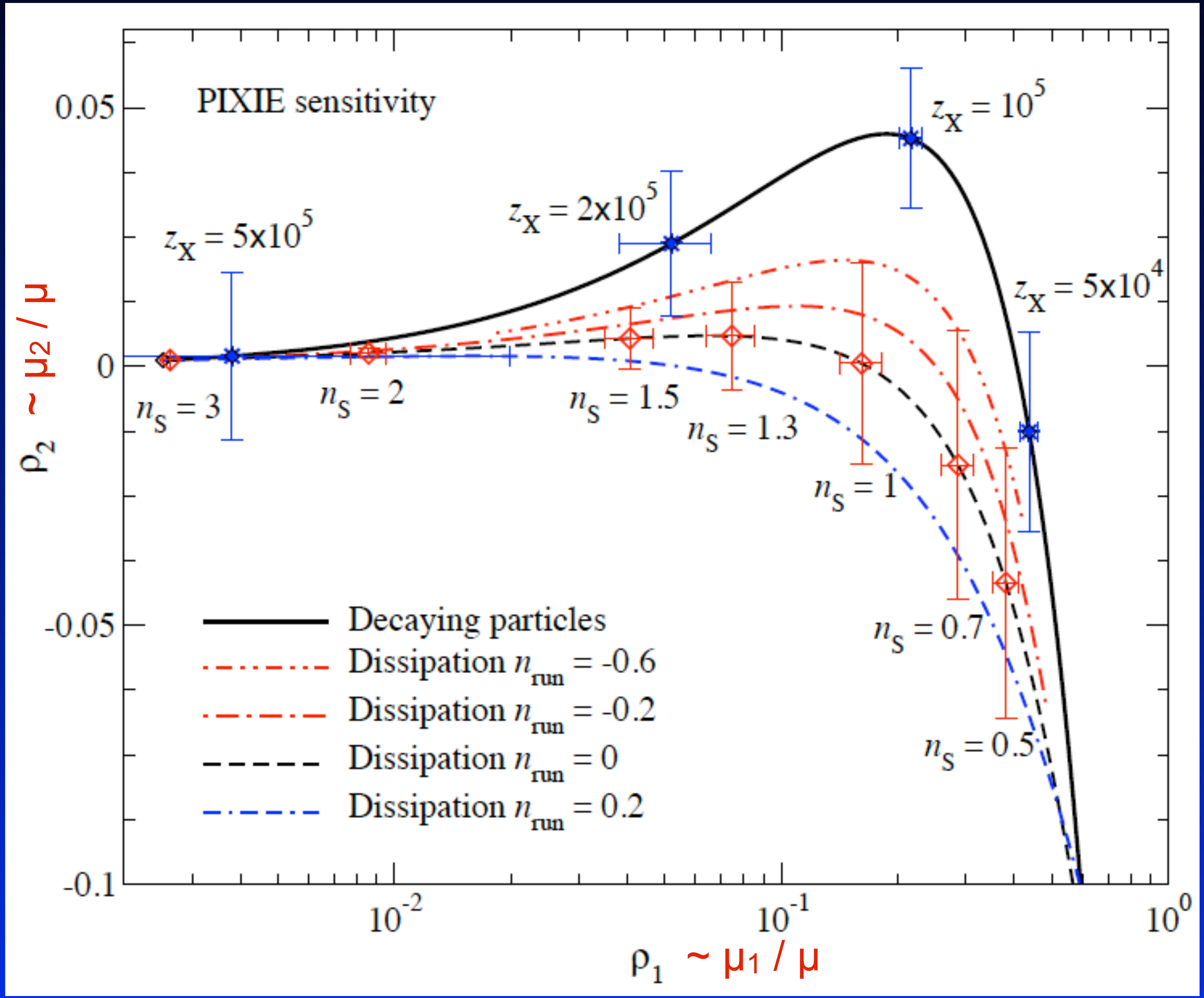


JC & Jeong, 2013

$$P_\zeta(k) = 2\pi^2 A_\zeta k^{-3} (k/k_0)^{n_S - 1 + \frac{1}{2} n_{\rm run} \ln(k/k_0)}$$

slide courtesy: Jens Chluba

Distinguishing dissipation and decaying particle scenarios



- measurement of μ, μ_1 & μ_2
- trajectories of decaying particle and dissipation scenarios differ!
- scenarios can in principle be distinguished

$$A_\zeta = 5 \times 10^{-8}$$

JC & Jeong, 2013

slide courtesy: Jens Chluba

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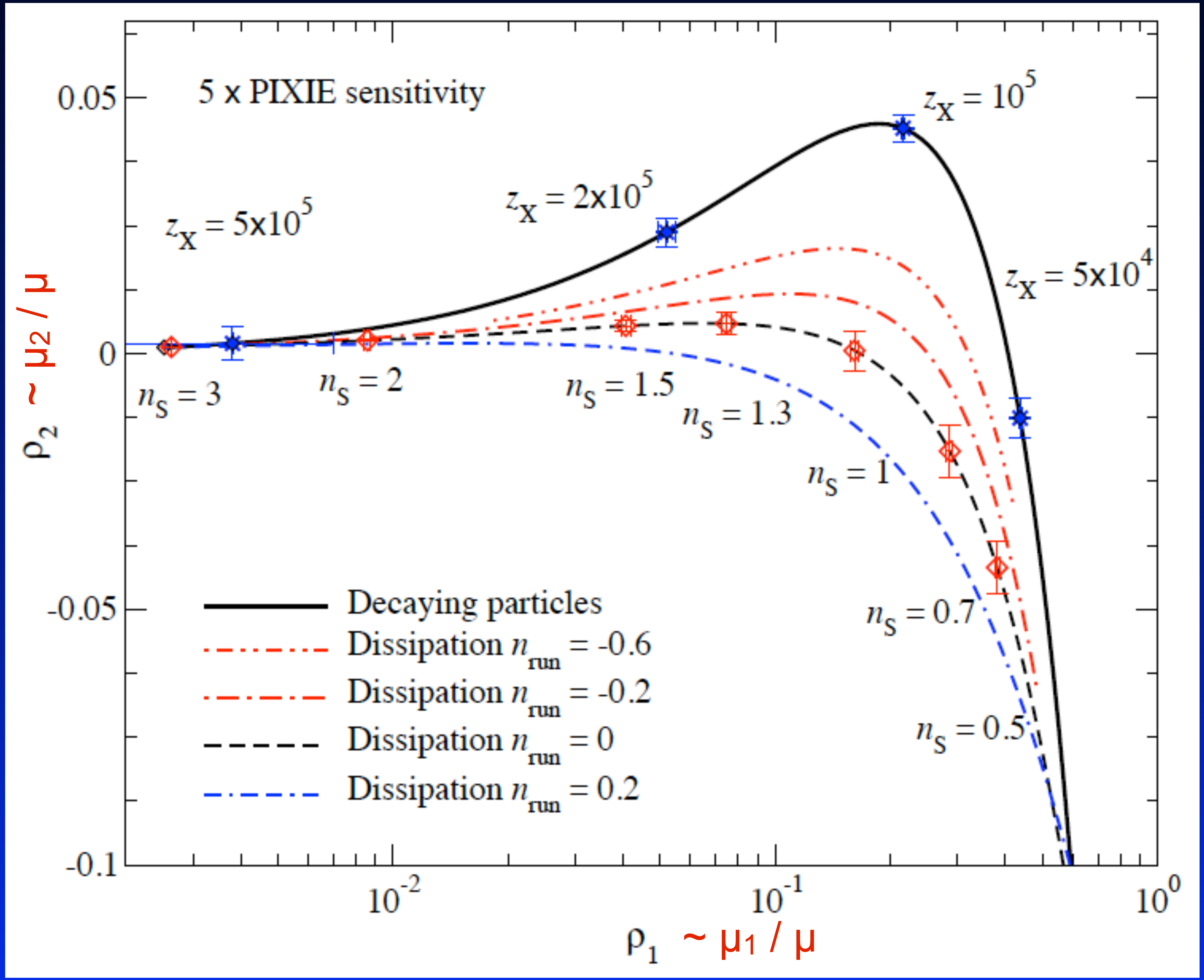

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Conclusion

- Dissipation of small-scale acoustic modes provides yet another way of constraining primordial power spectrum!
- Here, we provide a new limit only using the standard model of particle physics and cosmology. But, extension beyond the standard model is also trivial.
- The thermal history in the early Universe has to be modified with dissipation. Watch out! Too much small-scale power will spoil your thermal history.
- Future CMB spectral distortion measurement (e.g. PIXIE, COrE+) will put a tighter constraint on $10<k<10^4$ Mpc^{-1}.