Probing the primordial power spectrum (and non-Gaussianity) with μ-distortions

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In collaboration with:

A. Melchiorri, E. Pajer: Phys. Rev. D 93, 083515 (2016)

E. Pajer and D. van der Woude, in preparation

Upcoming CMB experiments

Main "inflationary" target $\rightarrow$ primordial B-modes:

- primordial tensor modes: smoking gun of inflation
- Lyth bound: constraints on inflationary models (large field vs. small field)
- open possibility of testing $r = -n_{\mathrm{t}}/8$

However:

- large field models (e.g. "natural" $V(\phi) \sim m^2\phi^2$) strongly disfavored by *Planck*
- lower bound $r > 10^{-53}$ from

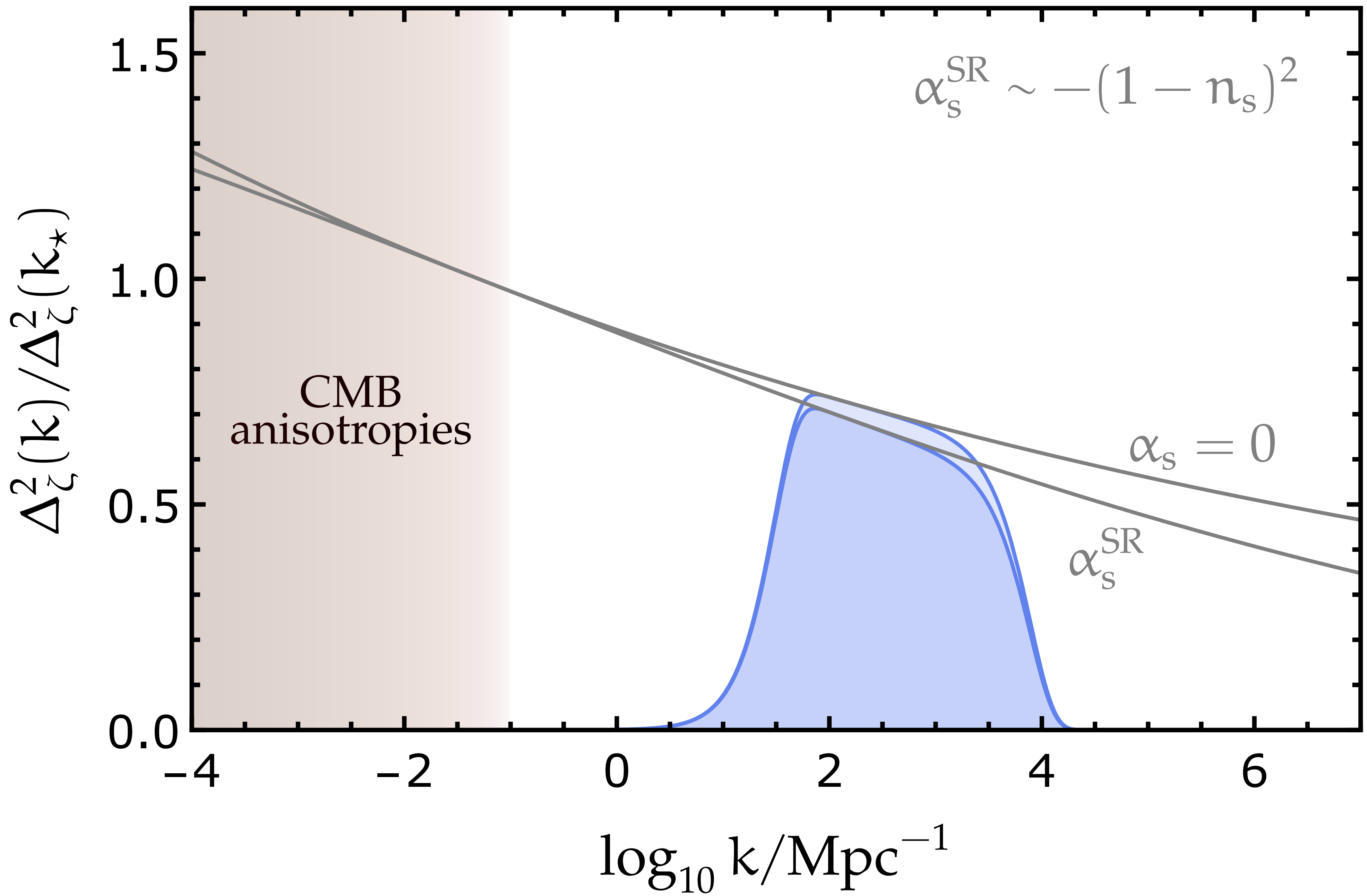
$$A_{\mathrm{s}} \approx 10^{-1} \times \frac{H^2}{M_{\mathrm{P}}^2}\frac{1}{r} \approx 10^{-9},\ M_{\mathrm{P}}^2 H^2 > 10 \times \underbrace{T_{\mathrm{reh}}^4}_{1\,\mathrm{TeV}} \Rightarrow r > 10^{-53}$$

$\Rightarrow$ just scratching the surface of a wide theoretical prior

Scalar modes are still the safest bet? Power spectrum at small scales, primordial NG. . .

Monopole of μ: constraints on the power spectrum

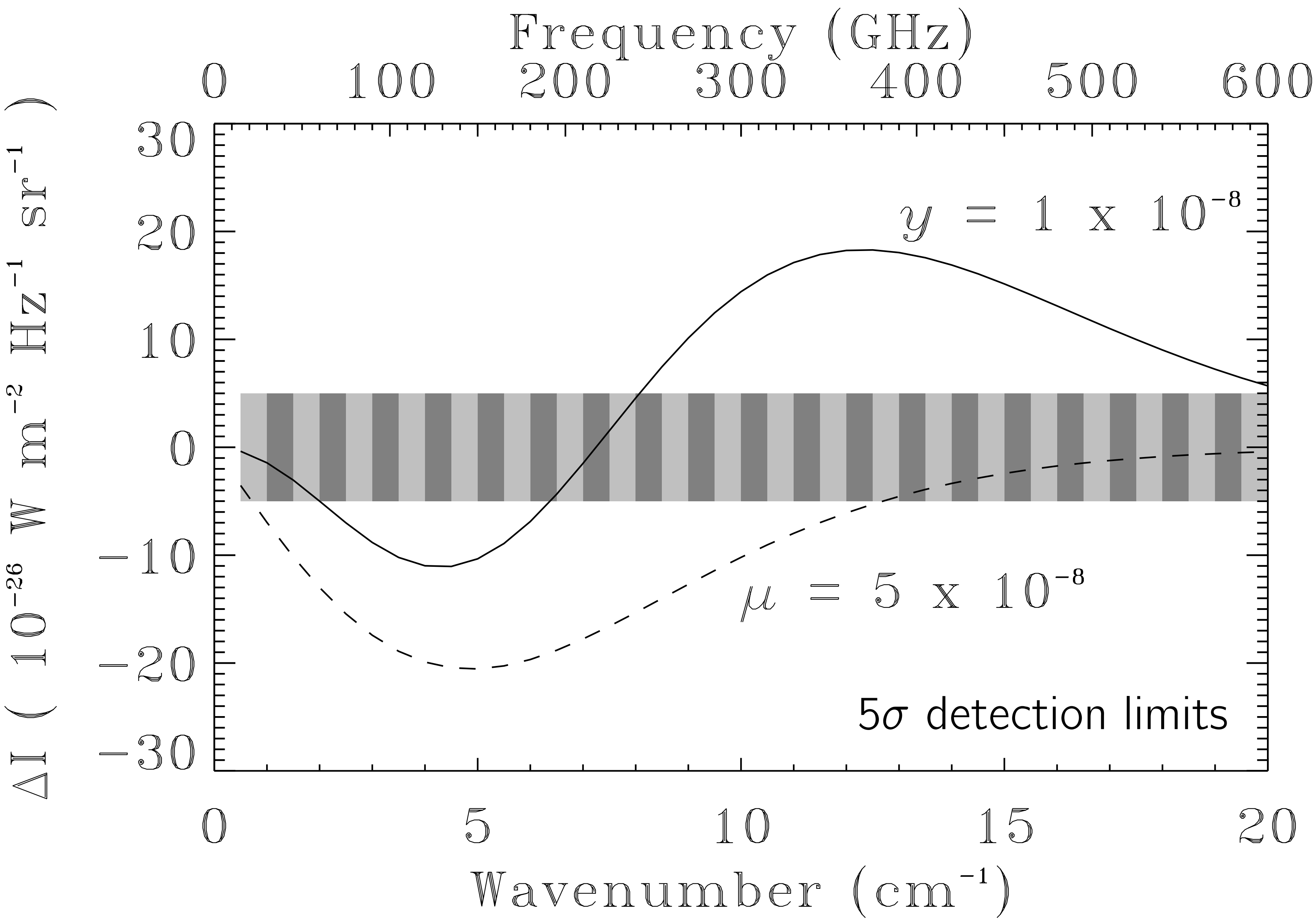
μ-distortions and primordial scalar spectrum



$$\Delta^2_\zeta = A_\zeta \left(\frac{k}{k_\star}\right)^{n_s - 1 + \frac{\alpha_s}{2}\log\frac{k}{k_\star}} \qquad \alpha_s^{SR} \sim -(1-n_s)^2 \ll 1 - n_s \sim 0.04$$

PIXIE

- 400 channels from 30 GHz to 6 THz. $\sigma_\mu = 10^{-8}$ (very optimistic! Taking foregrounds into account: $\sigma_\mu \approx 10^{-7}$ Abitbol, Chluba, Hill, Johnson, 2017)
- $\sim$ three ($\sim$ two) orders of magnitude improvement over FIRAS

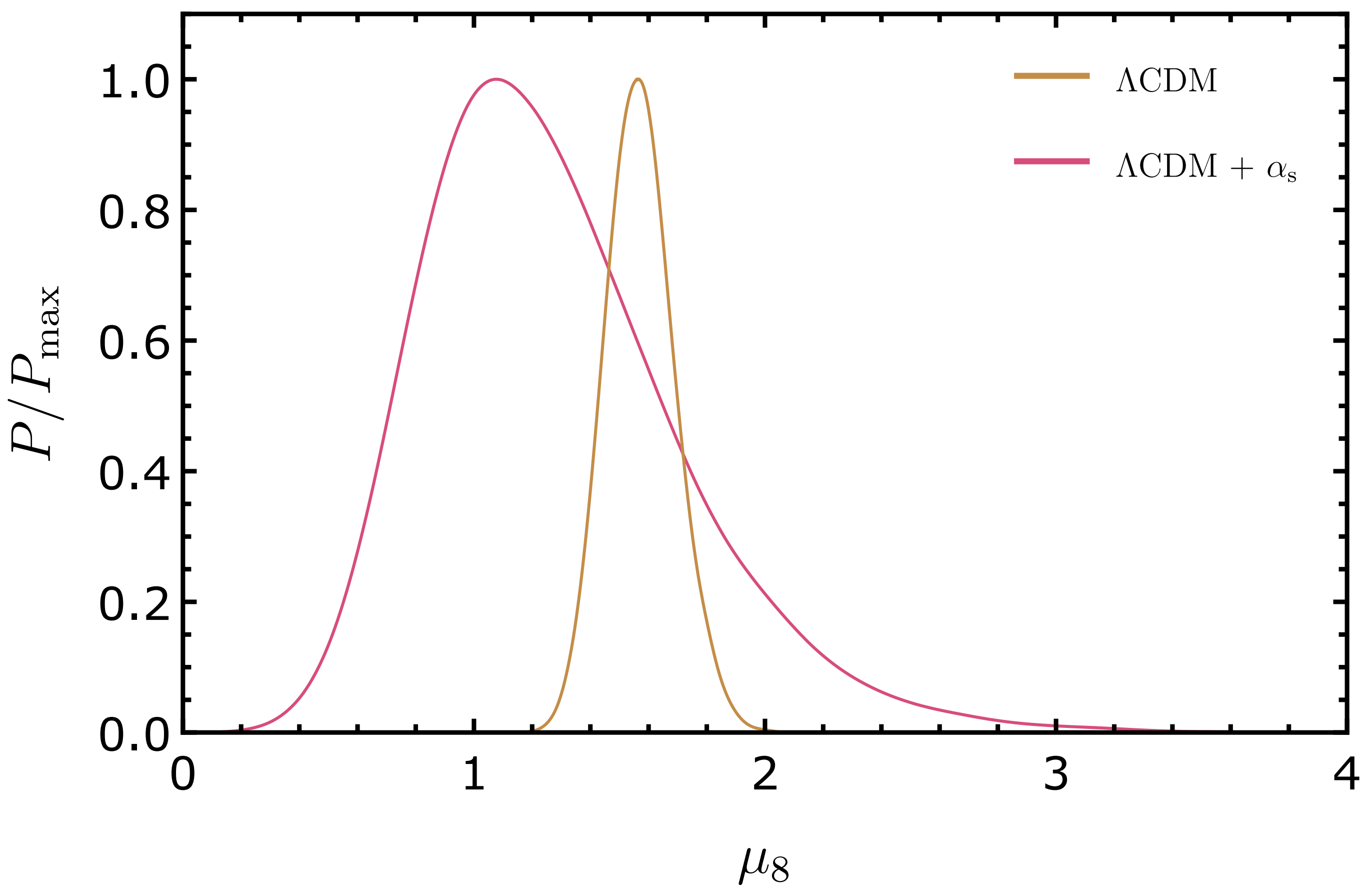


Kogut et al. (2011)

Predictions from CMB anisotropies

`idistort` code used
(Khatri and Sunyaev, 2013)

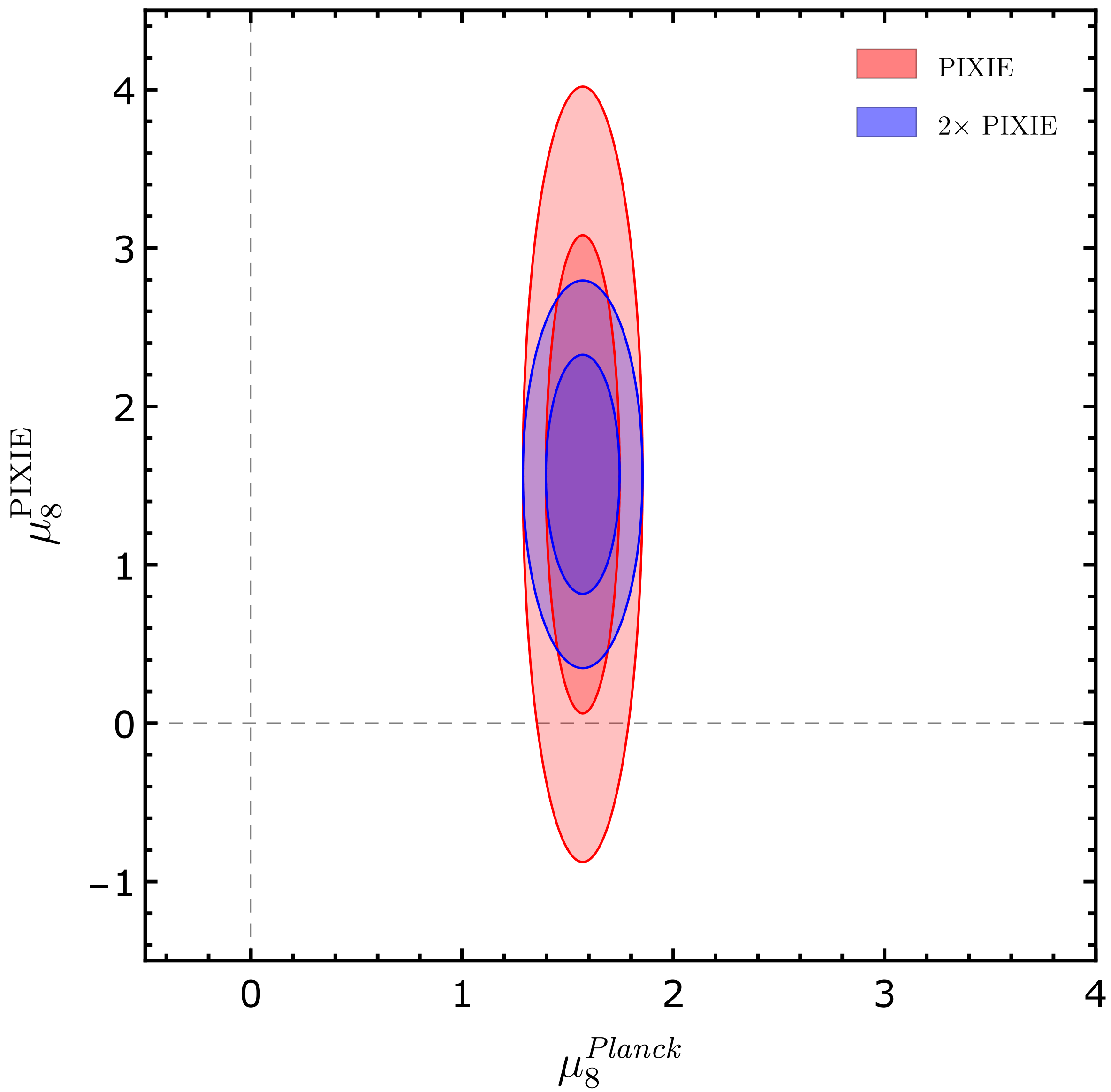
$\sigma_\mu = (1/n) \times 10^{-8} \to$ define $\mu_8 = \mu \times 10^8$



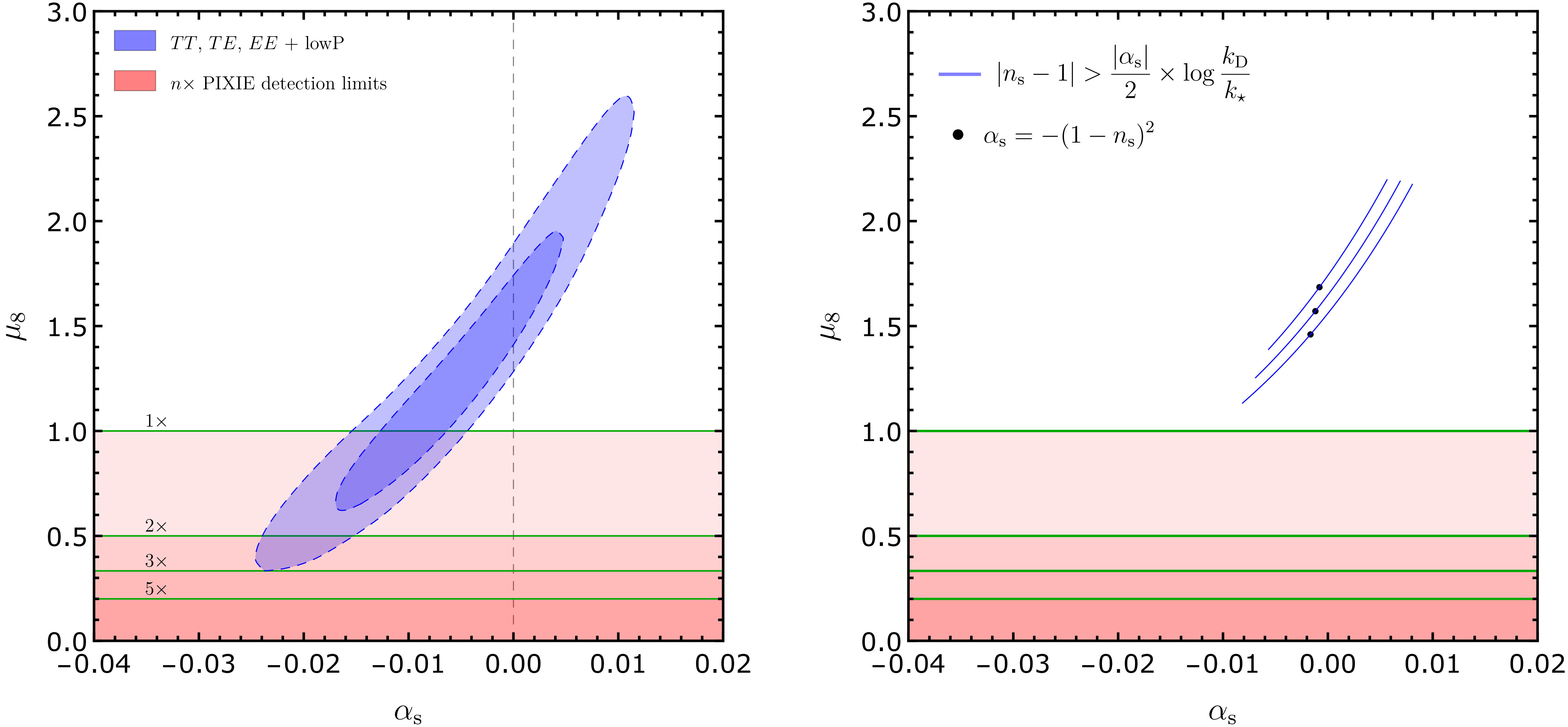
with $\sigma_\mu \sim 0.5 \times 10^{-8} \to$
$\mu_8 \leq 0$ excluded at $\approx 3\sigma$

$\to$ from *Planck* data

$\mu_8 = 1.57^{+0.11}_{-0.13}$ (68% CL)



What about the running?



"Slow-roll prior":

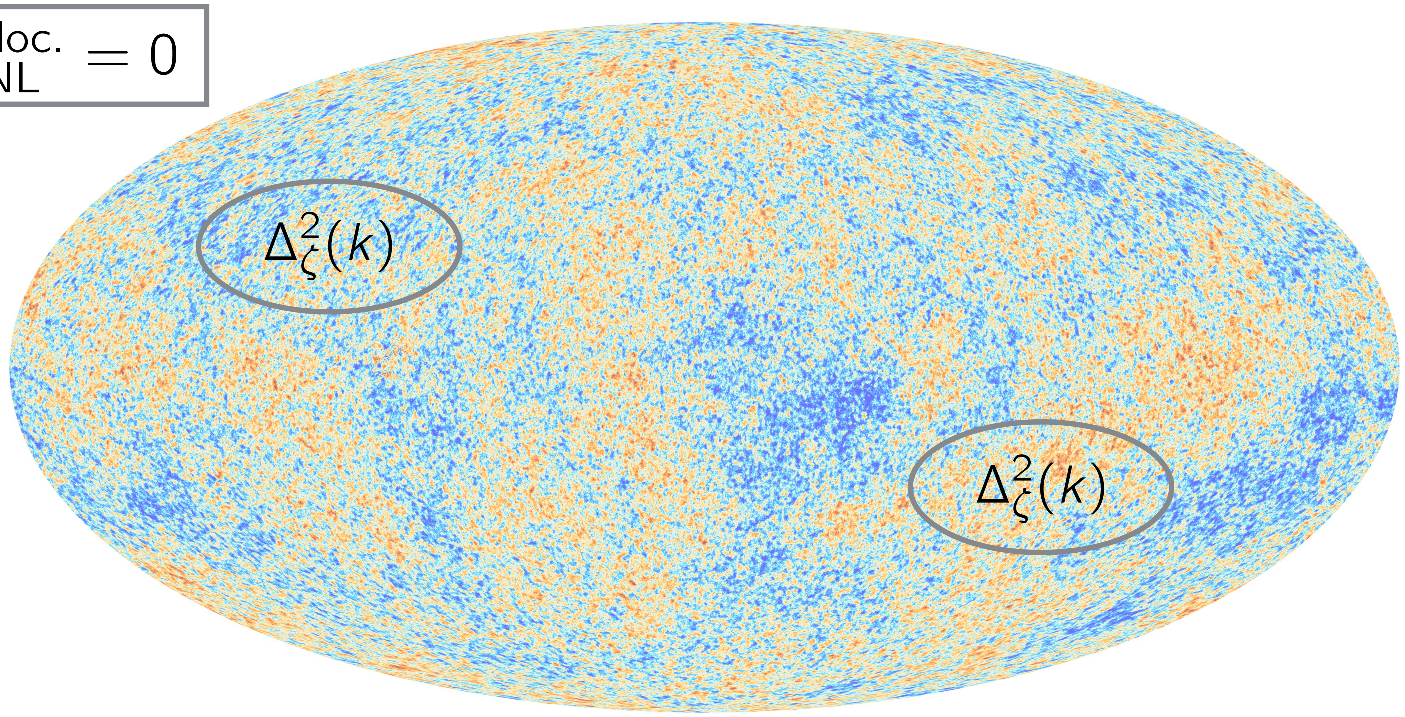
- *Planck*: $n_s = 0.9655 \pm 0.0062$ (68% CL)
- perturbative expansion holds down to k_D
- typical prediction of slow-roll models: $\alpha_s = -(1-n_s)^2$

μ anisotropies and non-Gaussianity

With local non-Gaussianity

In presence of local NG, the heating rate becomes spatially dependent!

$f_{\rm NL}^{\rm loc.} = 0$

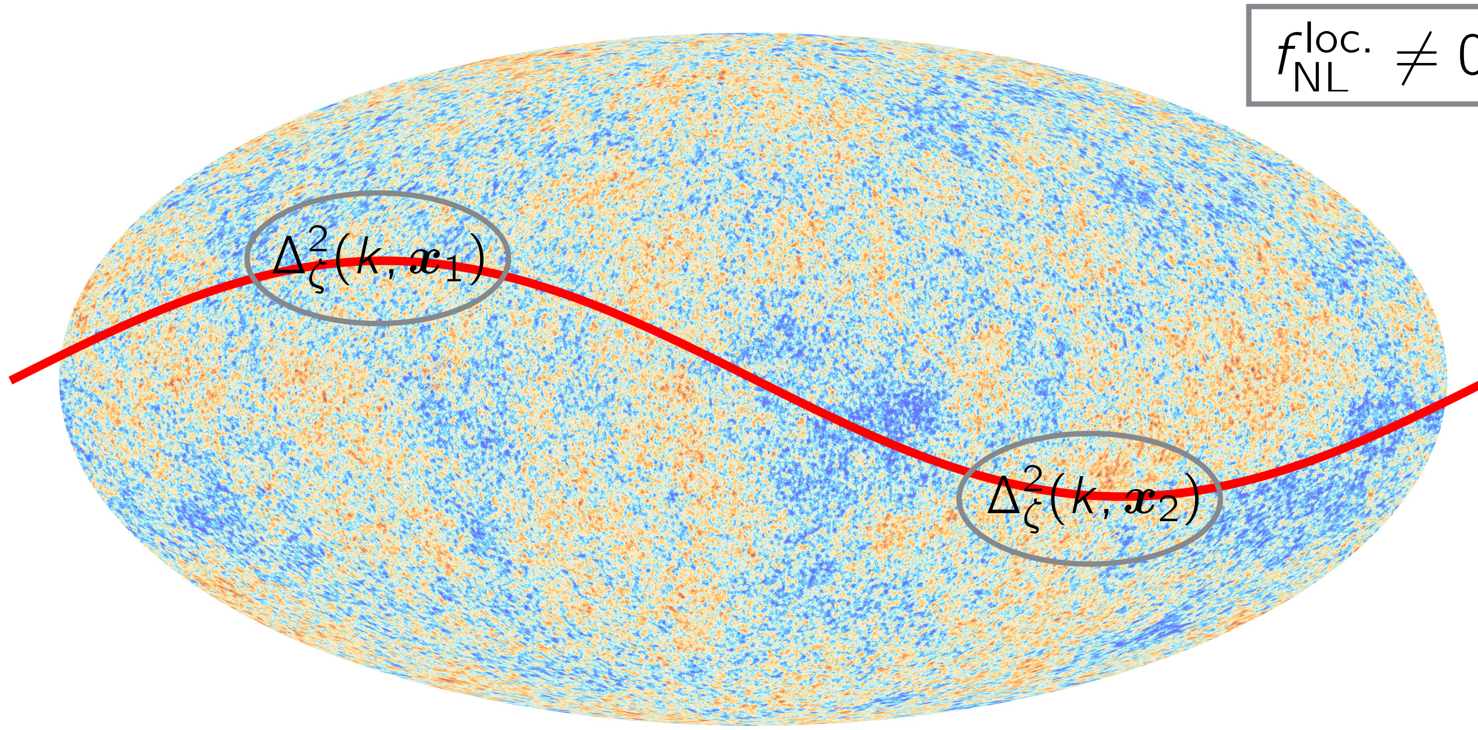


amplitude $\Delta^2_\zeta(k_{\rm small})$ will be the same everywhere

$f_{\rm NL}^{\rm loc.} \neq 0$

amplitude $\Delta^2_\zeta(k_{\rm small})$ will differ from one patch to another

$\to$ correlated with ζ_ℓ



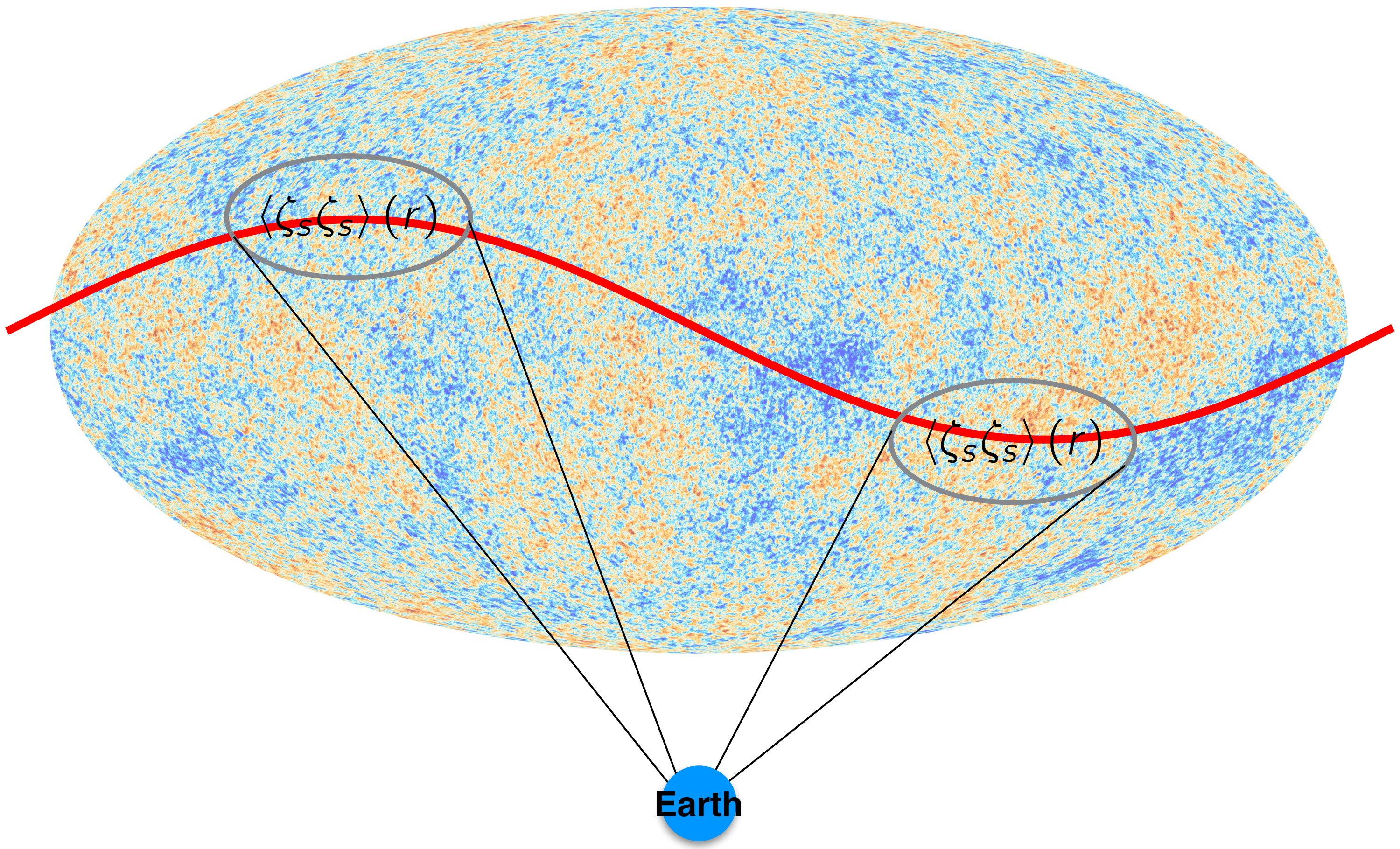
μ-T correlations

Pajer and Zaldarriaga, 2012; Emami, Dimastrogiovanni, Chluba, Kamionkowski, 2015

Short-scale power spectrum is correlated with the long mode $\rightarrow$ is correlated with the long-wavelength T perturbation! *Angular power spectrum* $C^{\mu T}_{\ell \lesssim 100} \approx 12 f^{\text{loc.}}_{\text{NL}} C^{TT}_{\ell}$

However! In every patch a local observer cannot see the coupling with ζ_ℓ in single-field inflation! No μ-T correlations in this case?

But $\rightarrow$ be careful about projection effects! E.g.: CMB squeezed bispectrum



$$B^{TTT}_{\ell_L,\ell_S} = C^{TT}_{\ell_L} C^{TT}_{\ell_S}\left(2 - \frac{\mathrm{d}\log(\ell_S^2 C^{TT}_{\ell_S})}{\mathrm{d}\log \ell_S}\right)$$

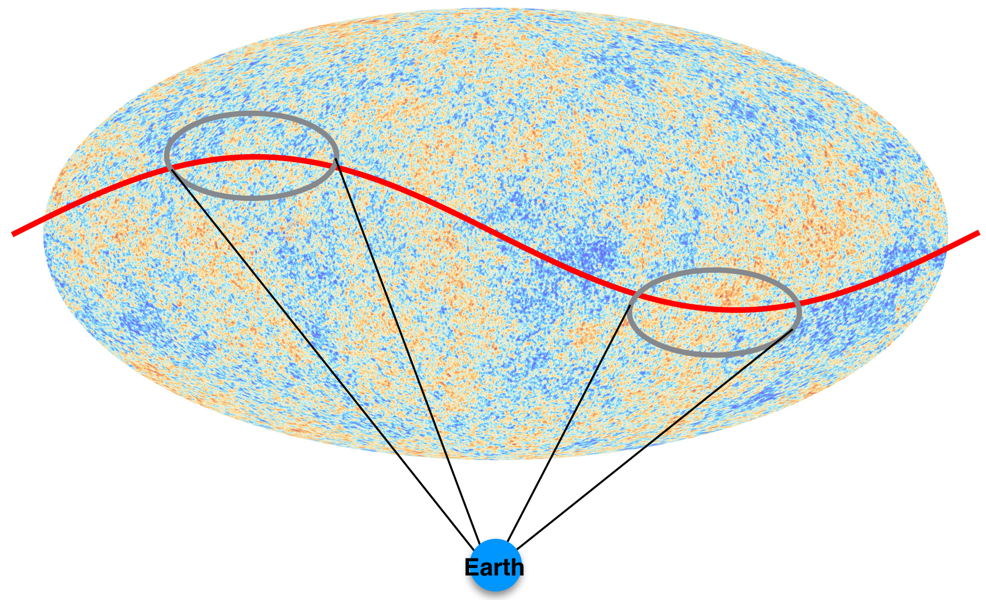
$\ell_L \lesssim 100$

Creminelli, Pitrou, Vernizzi (2011)
Bartolo, Matarrese, Riotto (2011)

any deviation is
$\propto f_{\text{NL}} - (1 - n_{\text{s}})$

e.g.:
Pajer, Schmidt, Zaldarriaga (2013)
Mirbabayi and Zaldarriaga (2014)

Projection effects



1. same physical length in the local patch at recombination appears at different angular sizes to the observer
2. photons experience a different redshift in different directions due to the presence of the long mode

$\Downarrow$ for $C_\ell^{\mu T}$

1. we are looking at the average μ in a patch $\to$ no “ruler” whose length the long mode can perturb
2. μ does not redshift

$$\frac{\mathrm{D}f_\gamma}{\mathrm{d}\lambda} = 0 \Rightarrow \begin{cases} T_{\rm obs} = \frac{E_{\rm obs}}{E_{\rm rec}} T_{\rm rec} \\ \mu_{\rm obs} = \mu_{\rm rec} \end{cases}$$

No correlation from evolution from the LSS to the observer. . . What is the leading effect?

Evolution after the end of the μ-era $\rightarrow$ damping of μ **inhomogeneities**!

Pajer and Zaldarriaga, 2012

⇨ no effect on $\langle\mu\rangle\ldots$

Then $\rightarrow$ effect of long mode on μ creation! In principle, complicated non-linear dynamics...

Exploit another nice difference with CMB bispectrum: horizon at end of μ era is $\approx 10^{-1}\,\mathrm{Mpc}^{-1}$

Up to very high $\ell \gg 100$ we can treat the effect with the separate universe approach!

similarly to halo bias...
e.g.: Dai, Pajer, Schmidt, 2015

Long mode modifies the expansion history and adds curvature $K_F \propto \partial^2\mathcal{R}$ to the FLRW:

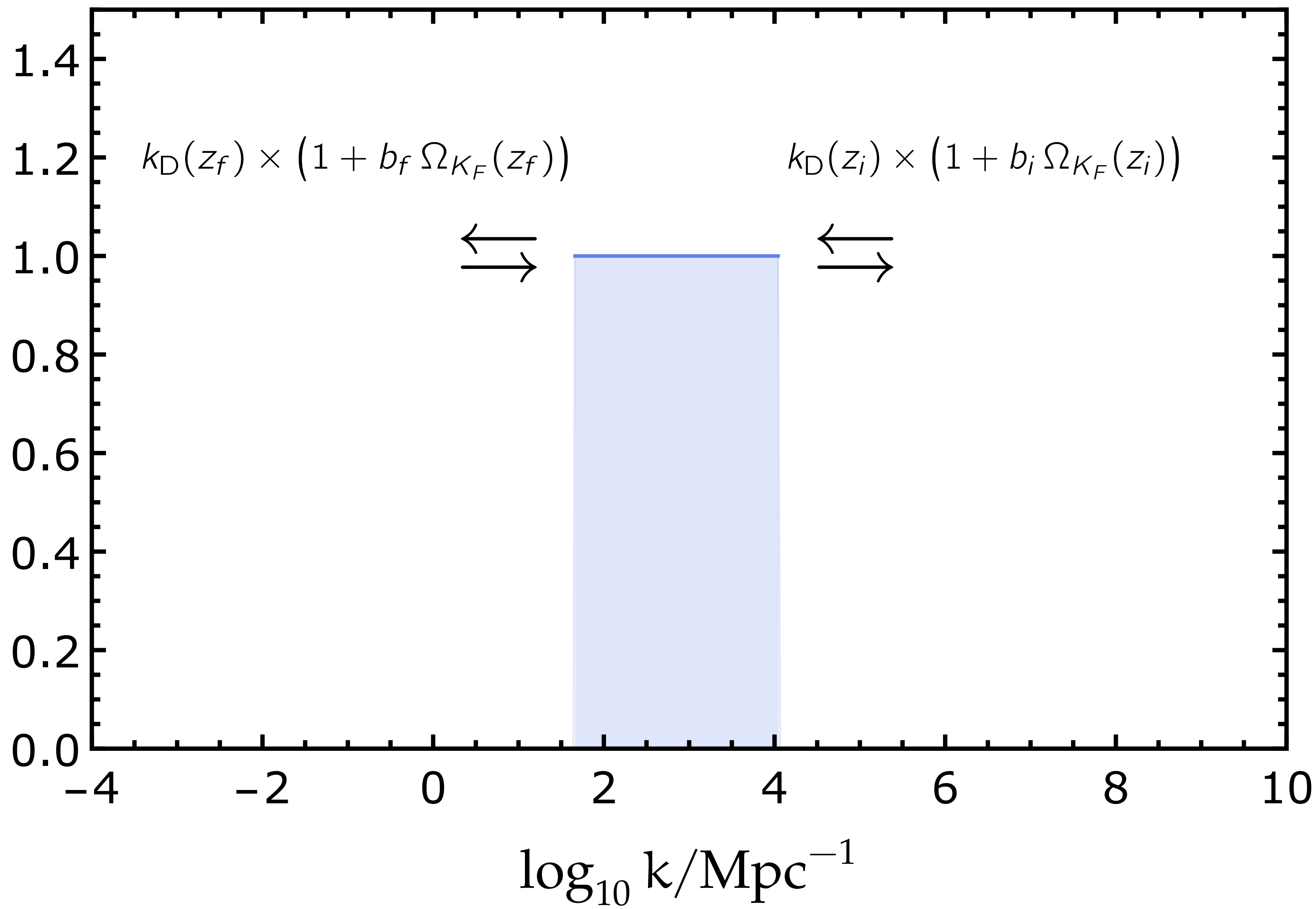
1. modification the duration of the μ era
2. direct effect on the evolution of short modes

GC, Pajer, Schmidt, 2016

3. additional coupling to $K_F \propto \partial^2\mathcal{R}$ from inflation. It is of order $1 - n_s$: can be neglected unless there are (unlikely) cancellations of 1. and 2.

1.

$$\langle \mu \rangle \approx A_s \quad \times$$



2.

Solve for the evolution of δ_γ in a curved FLRW...

A difference with δ_m: $c_s^2 \neq 0 \to$ not only corrections from modification to $a = a(K_F)$

Conclusions

- CMB spectral distortions probe small scales $50\,\mathrm{Mpc}^{-1} < k < 10^4\,\mathrm{Mpc}^{-1}$ $\Rightarrow$ can be used to test scale-dependence of primordial power spectrum and the squeezed bispectrum

- good observable to rule out slow-roll inflation!

- in single-field inflation (practically) no "contamination" on μ-T correlations:
  - no projection effects from last-scattering to observer
  - no effects from tight-coupling evolution
  - only effect: "bias" on μ production. Suppressed by $k_L^2/\mathcal{H}(z_f)^2\ldots$