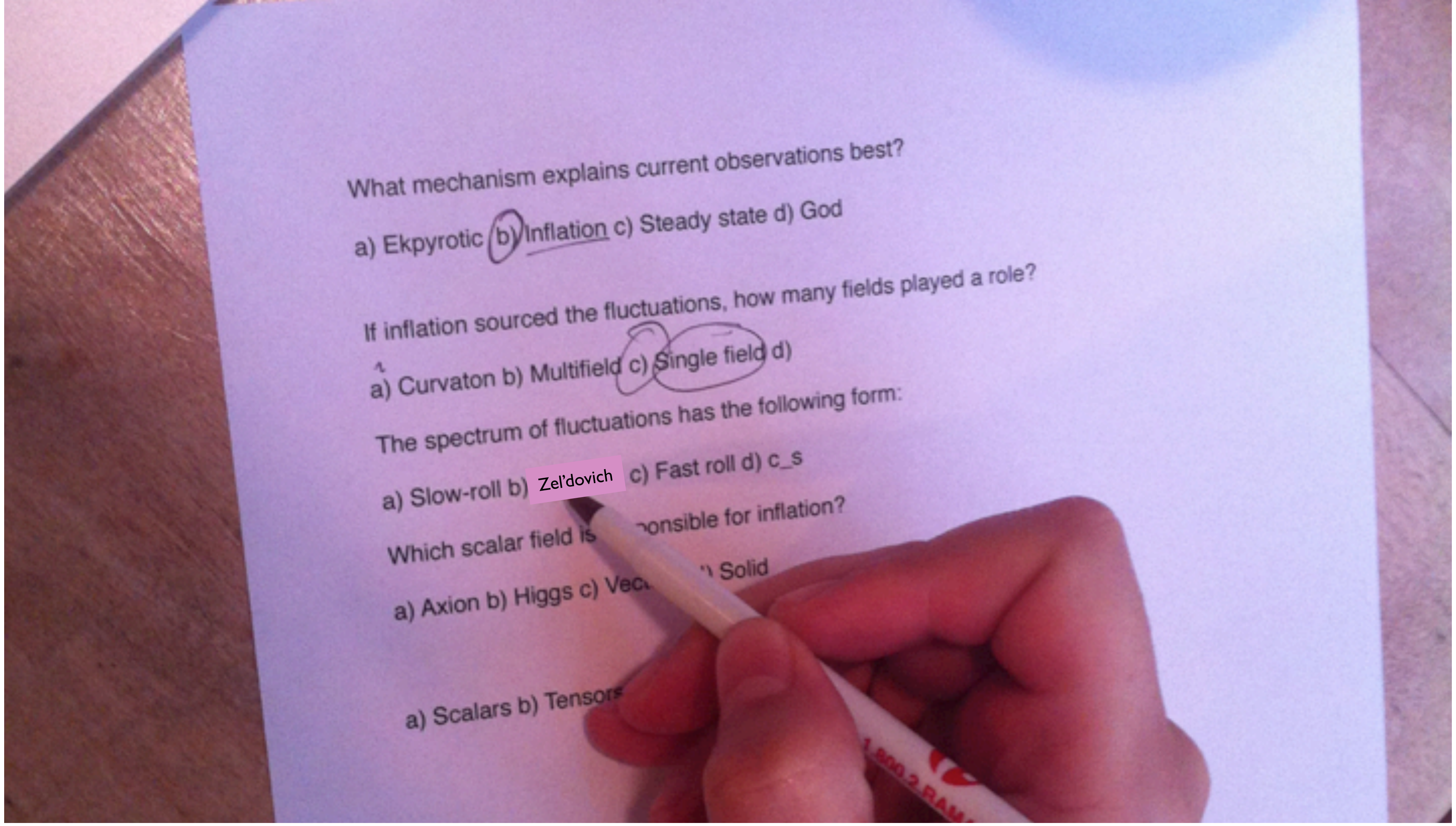

PUTTING INFLATION TO THE TEST

W **David Spergel and Ben Wandelt**

PRD 89, 063537 (2014) PRD 89 083506 (2014), PRD 90 063529 (2014), arXiv:1406.0548

And **B. Hadzhiyska, R. Hlozek, J. Myers,** arXiv:1412.xxxx

M. Münchmeyer. B. Wandelt arXiv:1412.xxxx

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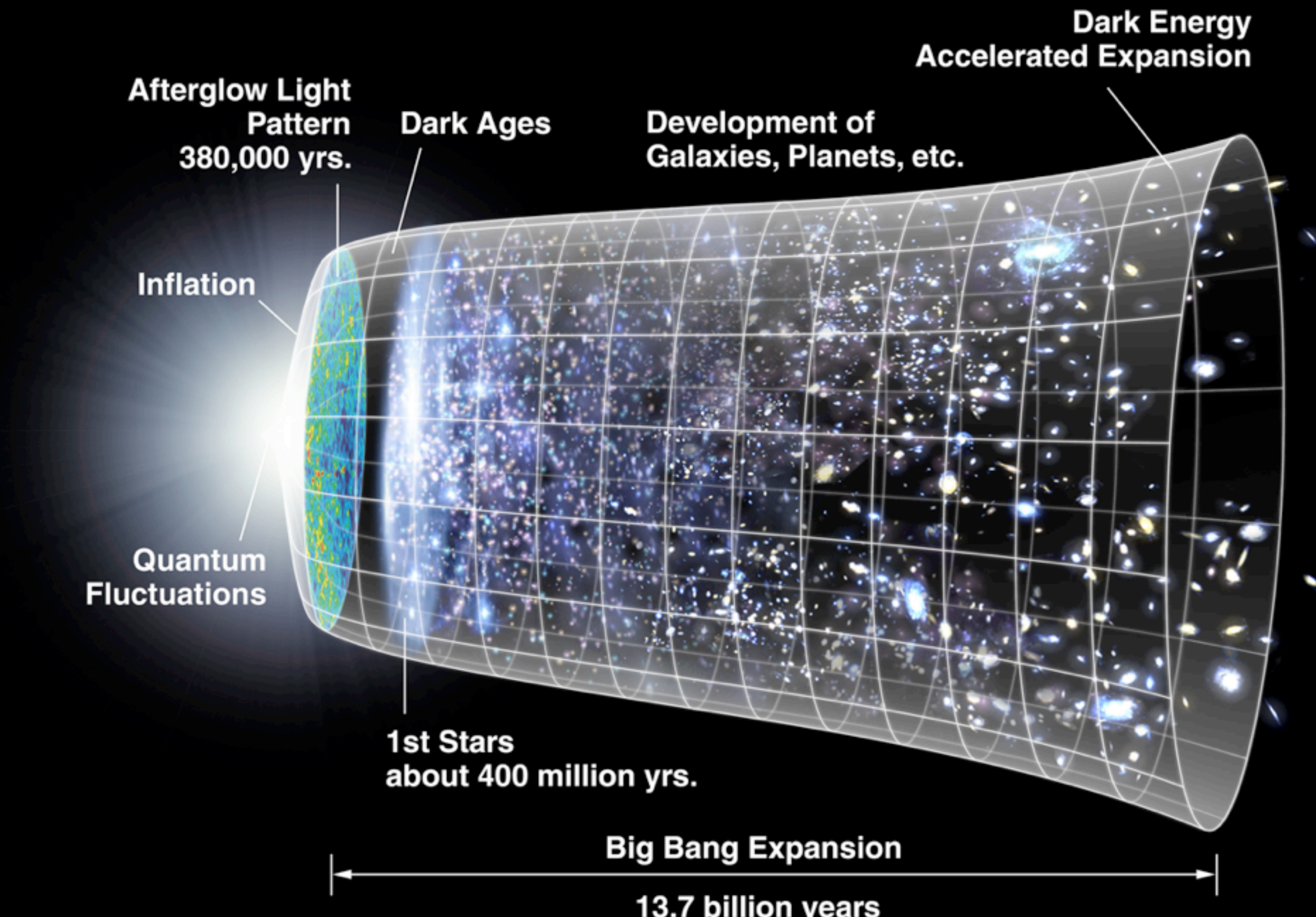
PUTTING INFLATION TO THE TEST:

1) WHAT DRIVES INFLATION?

2) DID INFLATION HAPPEN?



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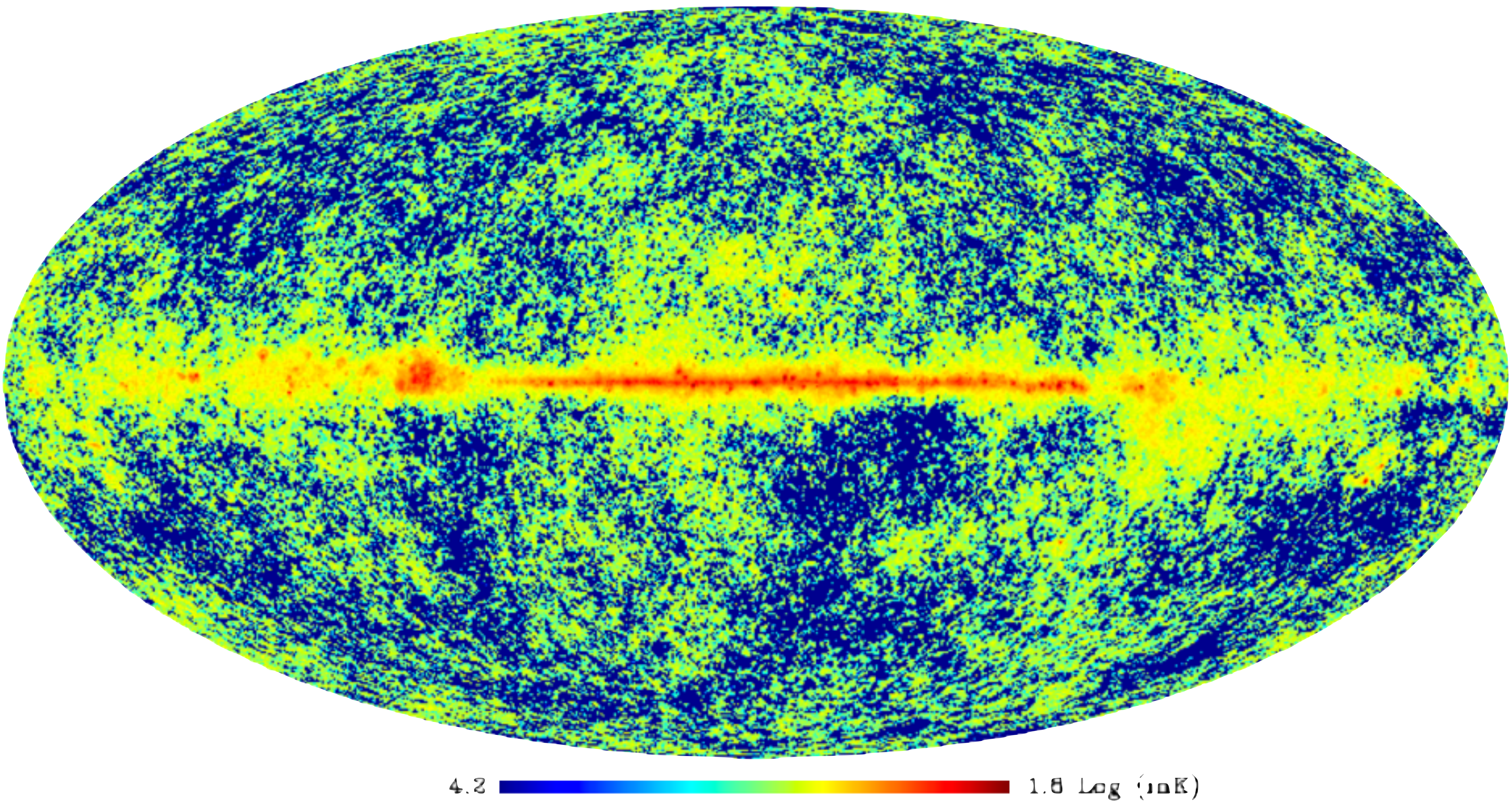
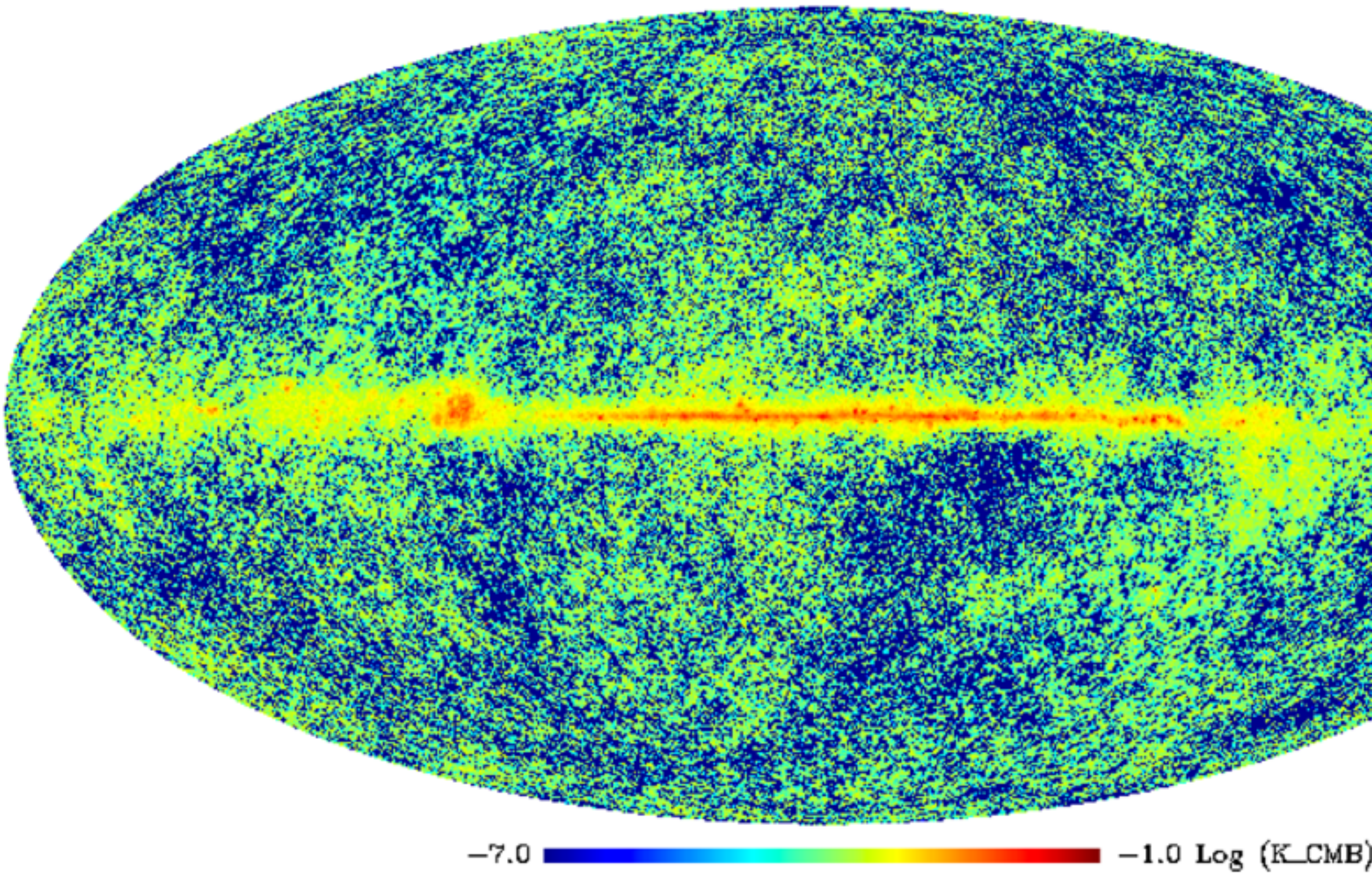
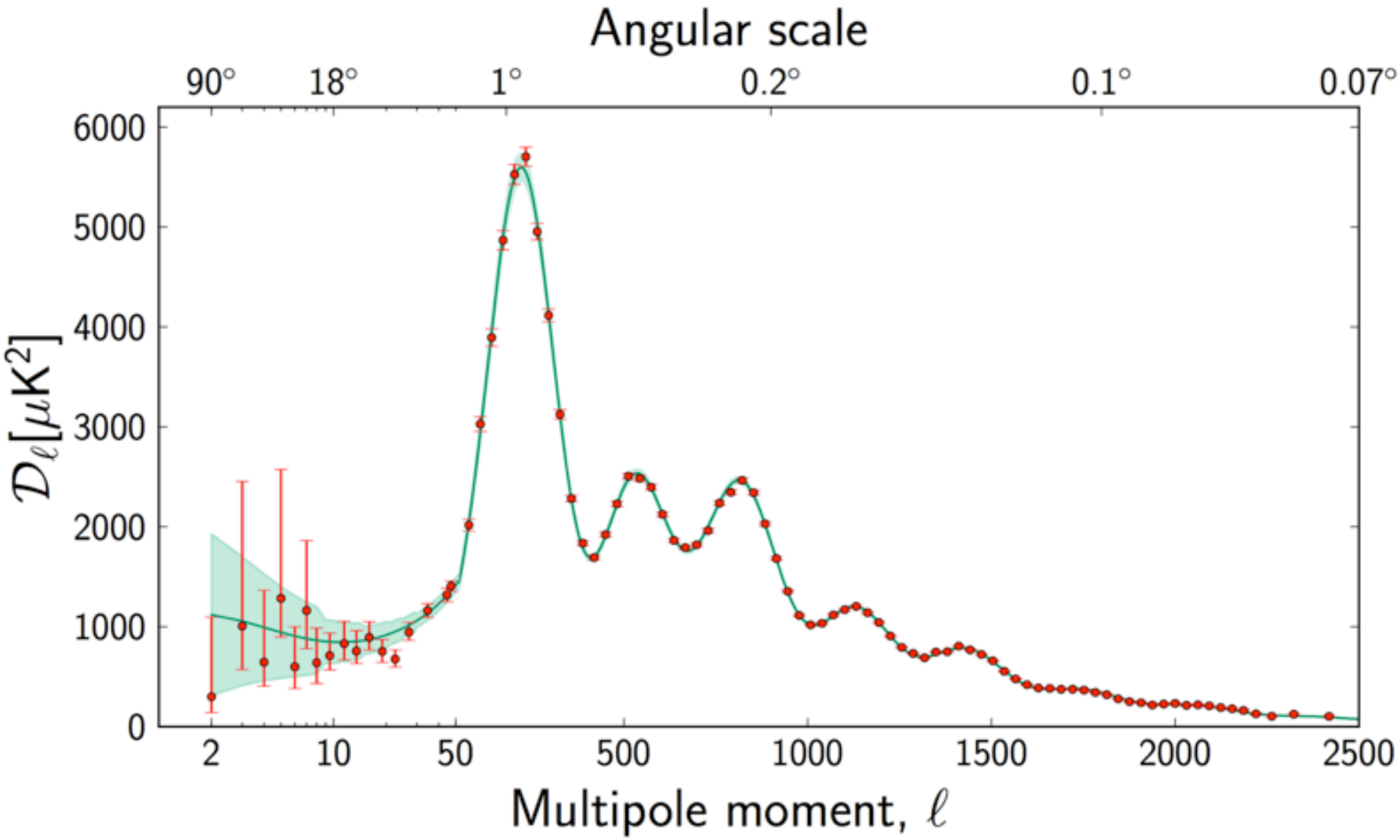
WMAP V BAND

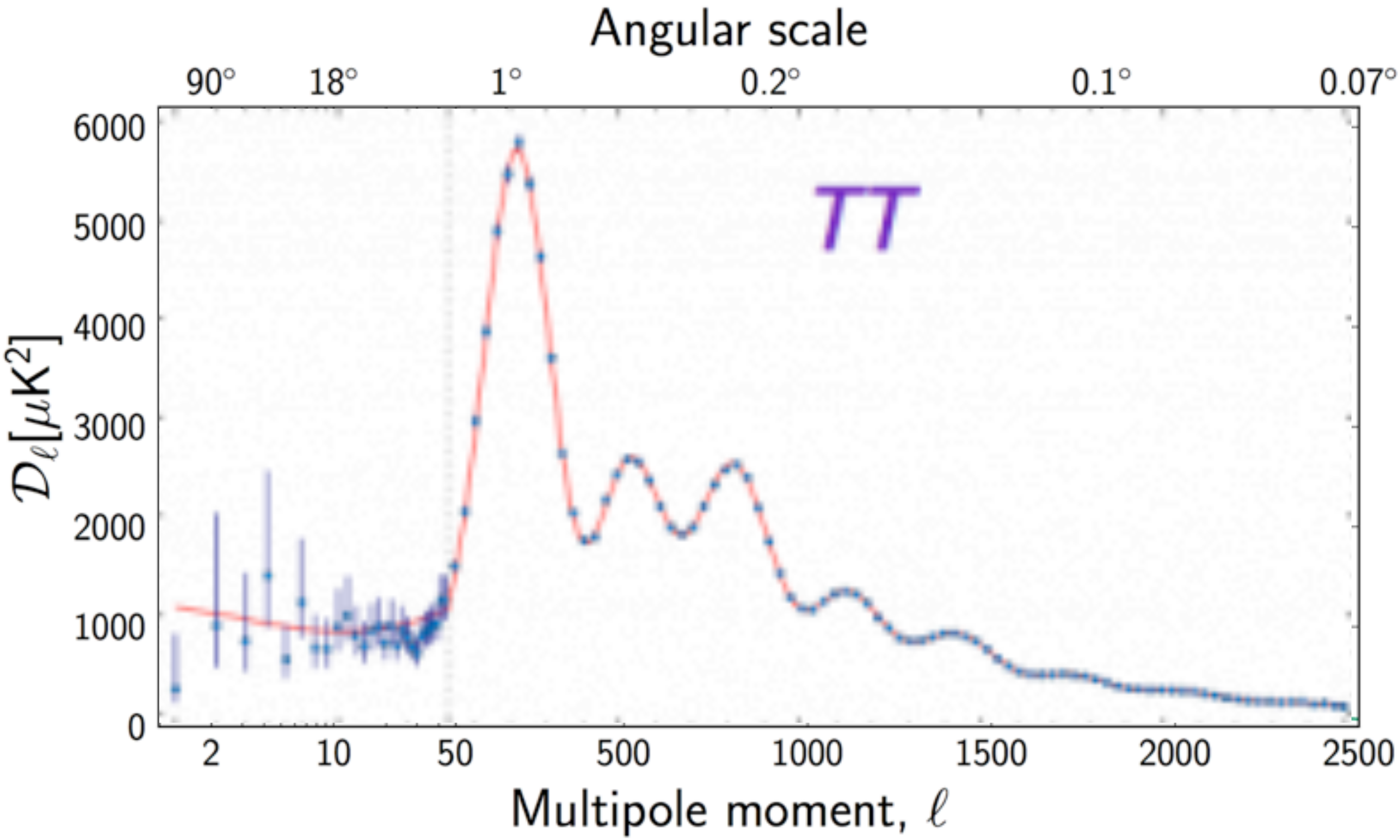


PLANCK 70GHZ





PLANCK COLLABORATION 2013



PLANCK COLLABORATION 2014

Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$

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PLANCK COLLABORATION 2014?

TWITTER 2014

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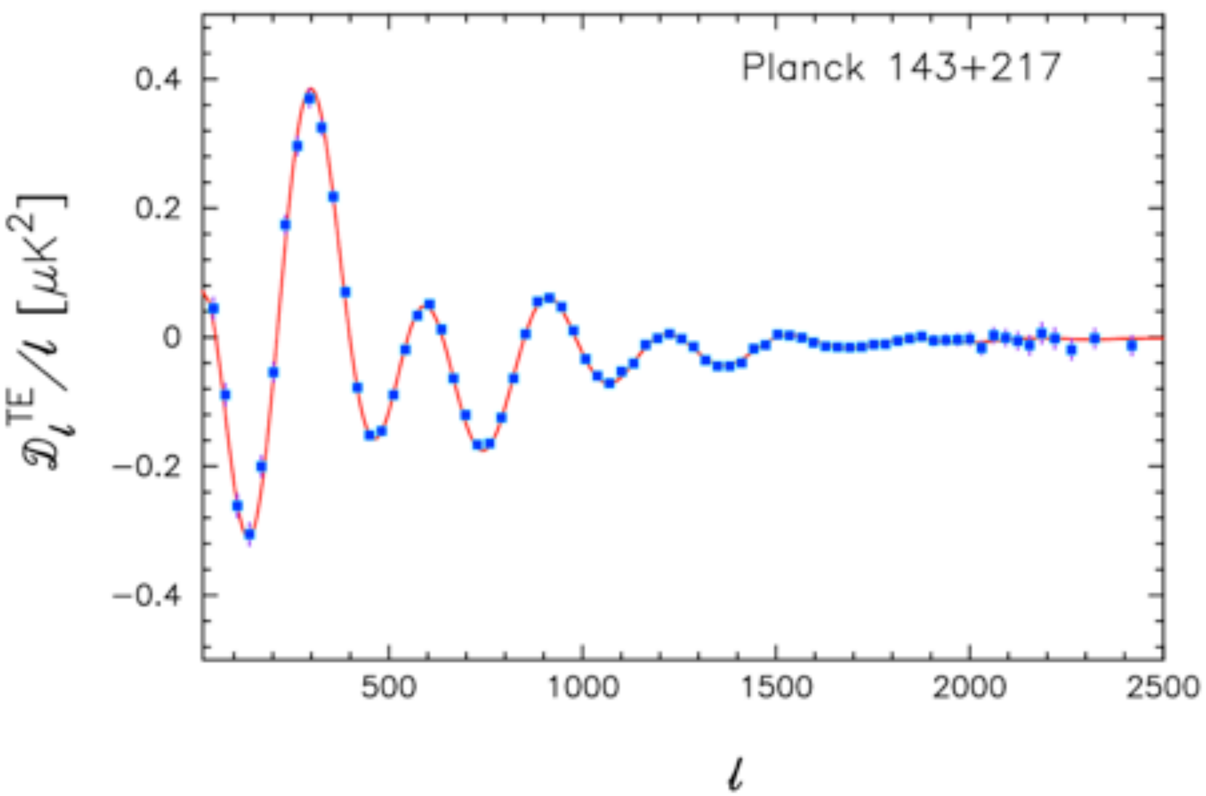
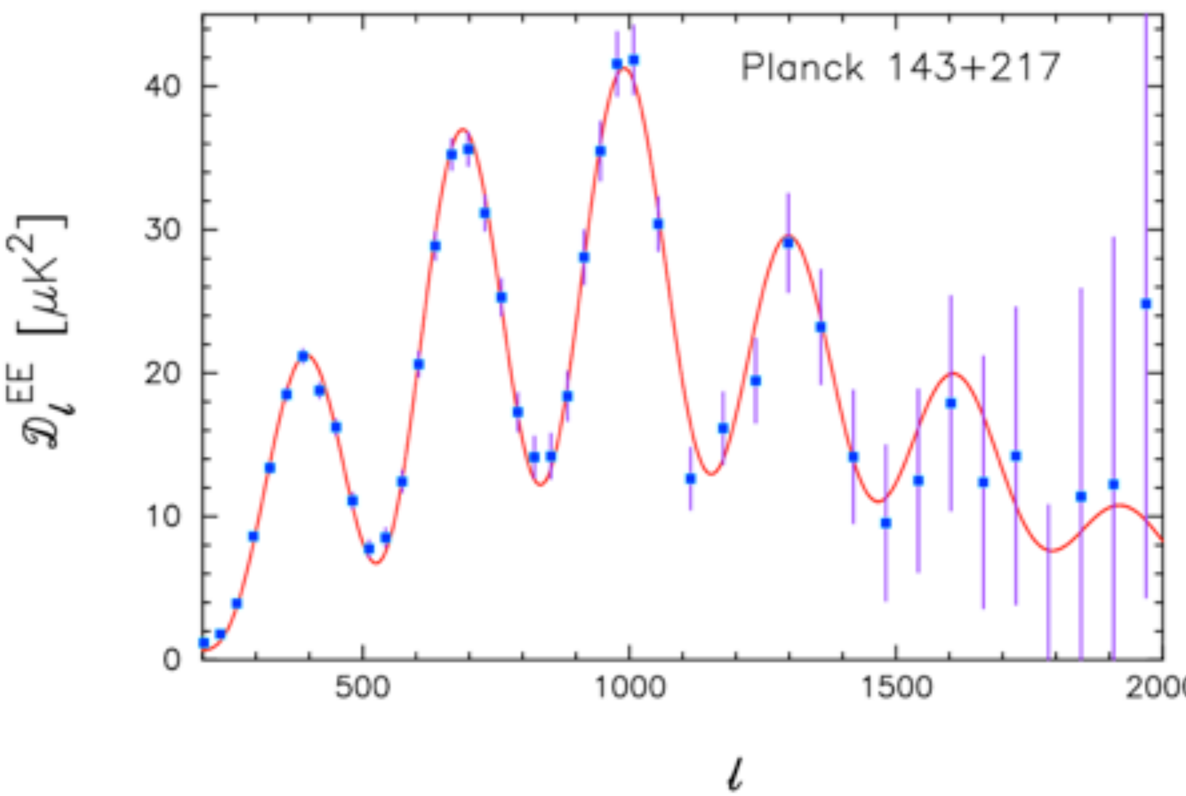
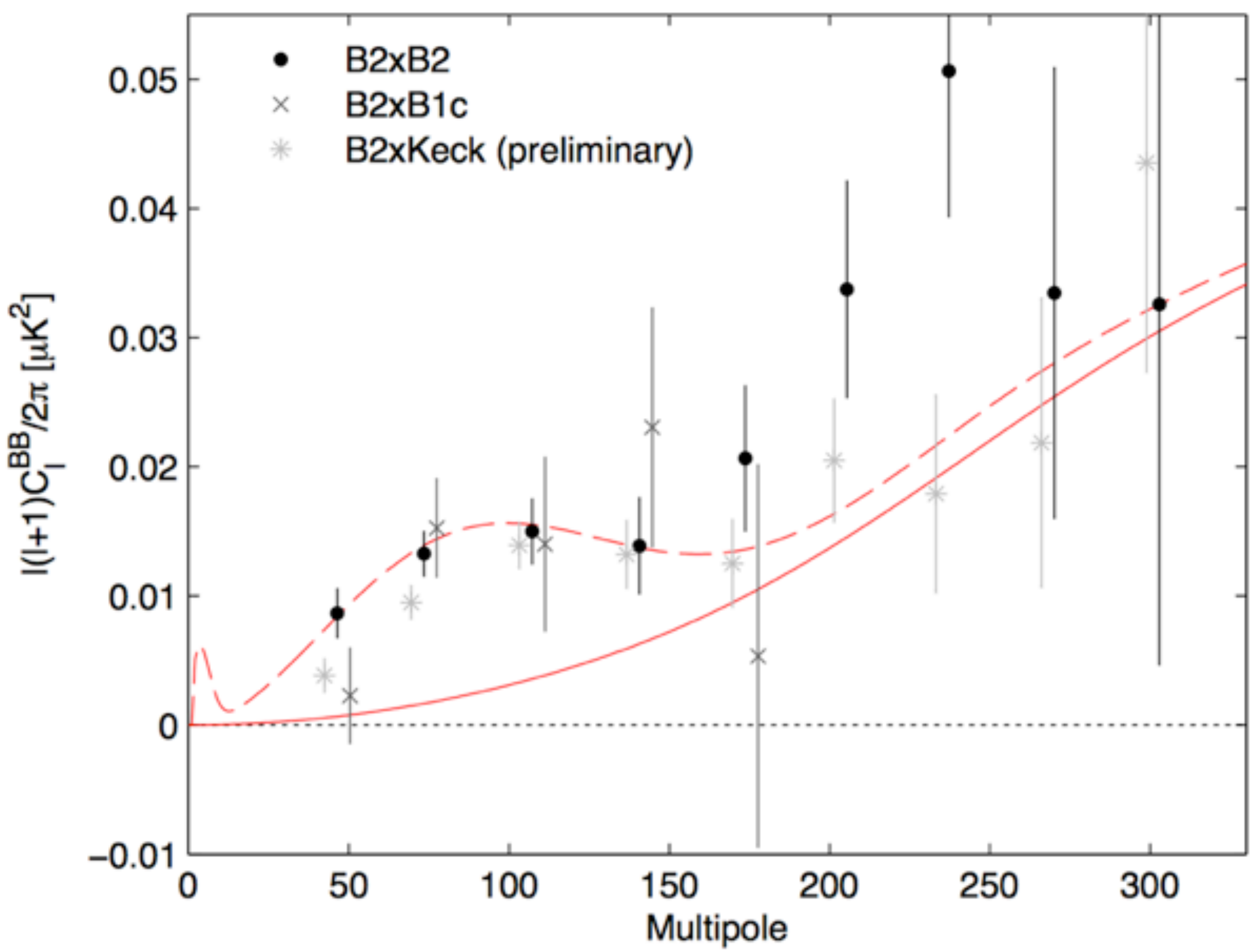
TWITTER 2014



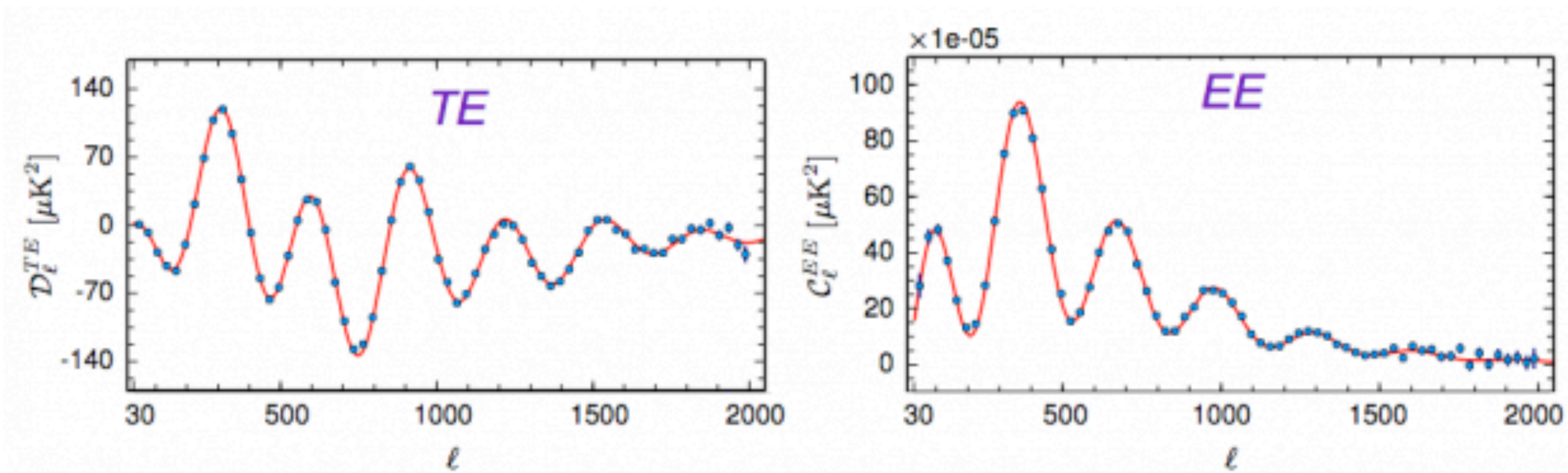


PLANCK COLLABORATION 2013



BICEP COLLABORATION 2014

BERKELEY 2014



PLANCK COLLABORATION 2014

NGS

NON-GAUSSIANITIES

- Or absence thereof (KSW)

$$f_{\rm NL}^{\rm local} = 2.7 \pm 5.8$$

$$f_{\rm NL}^{\rm equil} = -42 \pm 75$$

$$f_{\rm NL}^{\rm ortho} = -25 \pm 39$$

- And many others. In particular:

Phase / Wavenumber	$\phi = 0$ $f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)	$\phi = \pi/4$ $f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)
$k_c = 0.01750$	-335 ± 137 (-2.4)	-104 ± 128 (-0.8)
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PLANCK COLLABORATION 2013

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  - statistically isotropic: $P(\vec{k}) = P(k)$
  - Gaussian: $f_{NL} = 0$
  - nearly scale invariant: $P(k) = P$
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- Motivation for features
- Results from Planck
- Discussion

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- Inflation consistency condition
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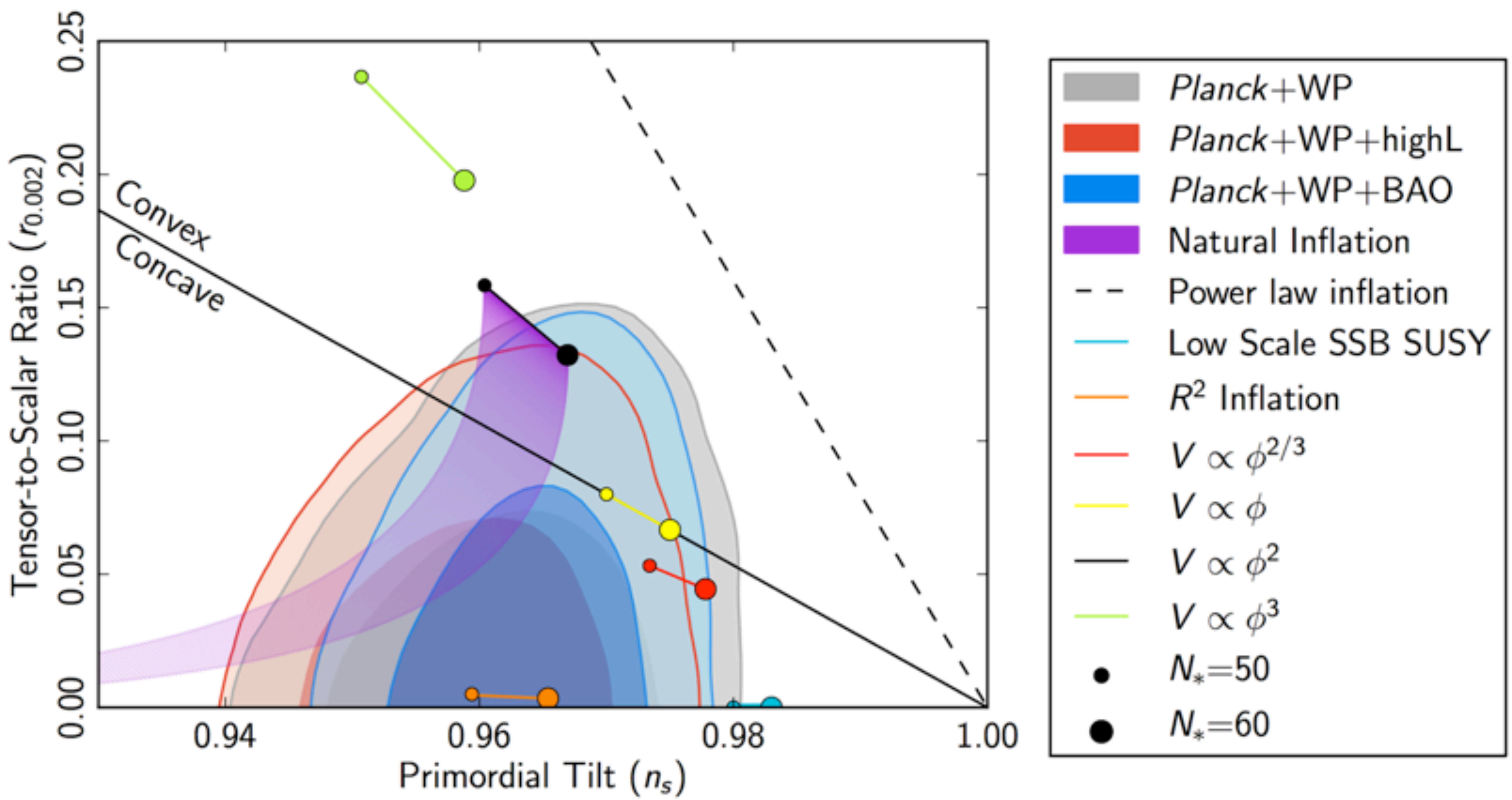
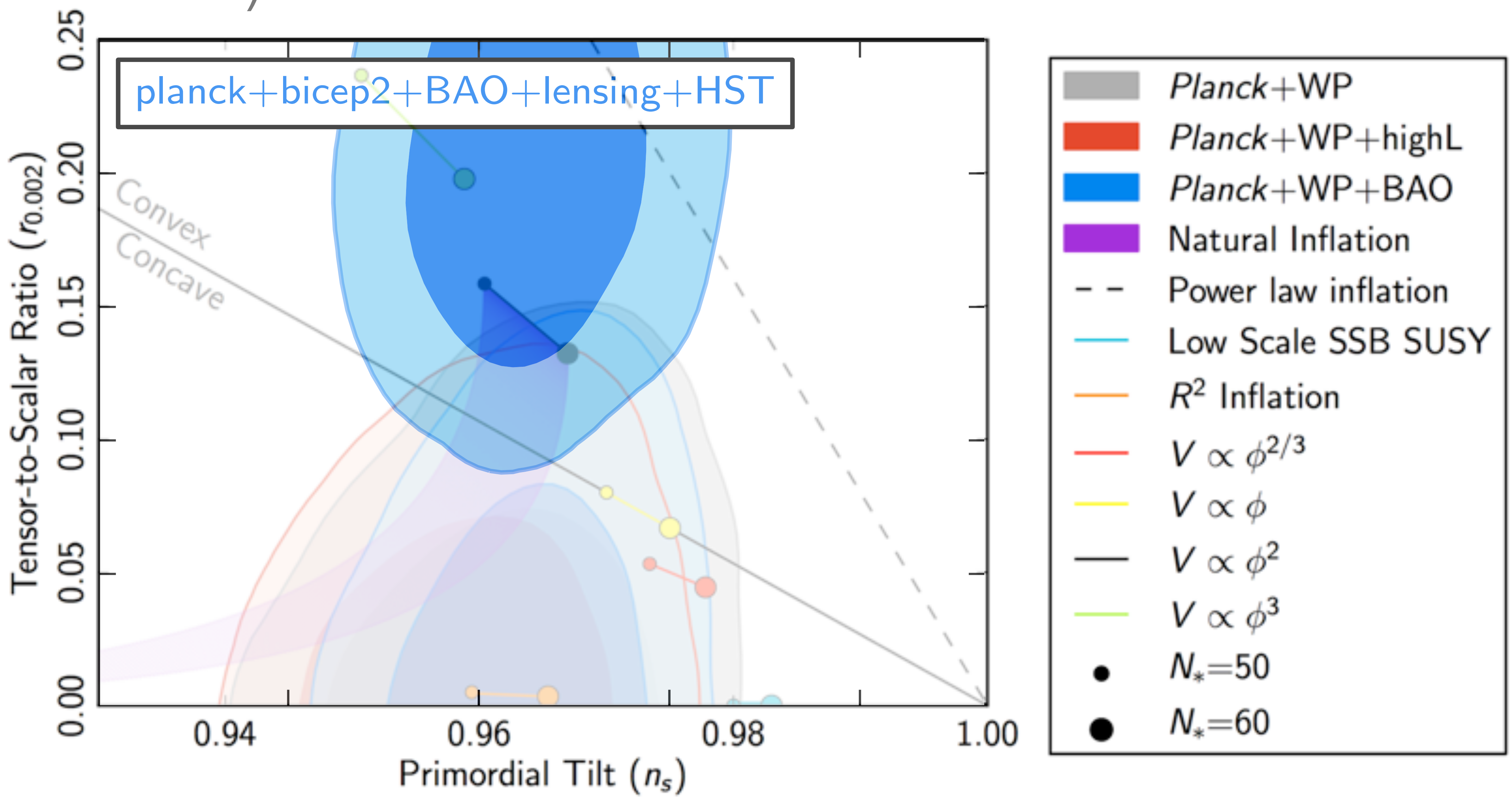
The Universe Pre-Bicep



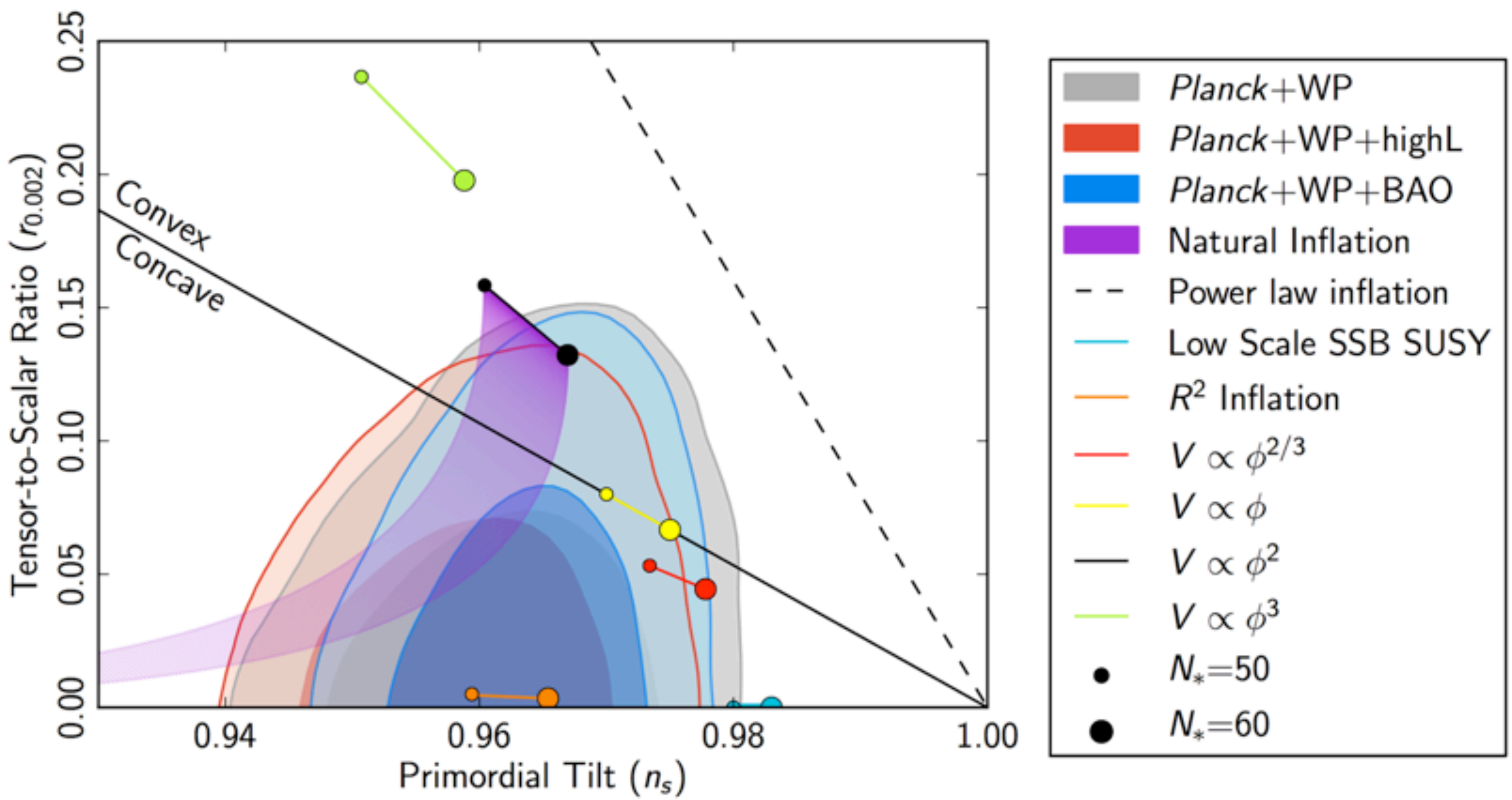
PLANCK COLLABORATION 2013

The Universe Post-Bicep (pre-Planck-dust)



PLANCK COLLABORATION 2013

The Universe Post-Planck-dust?



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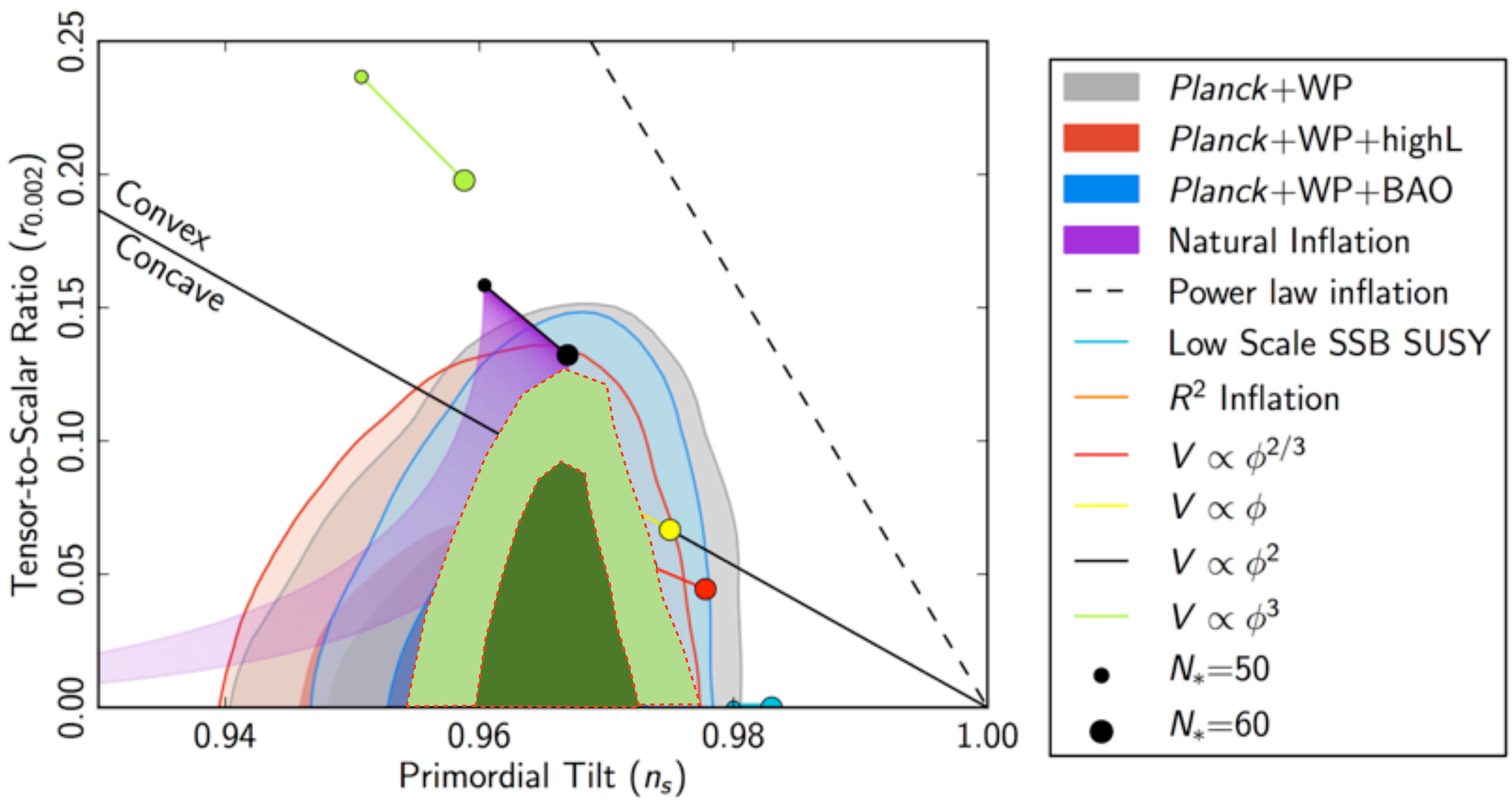
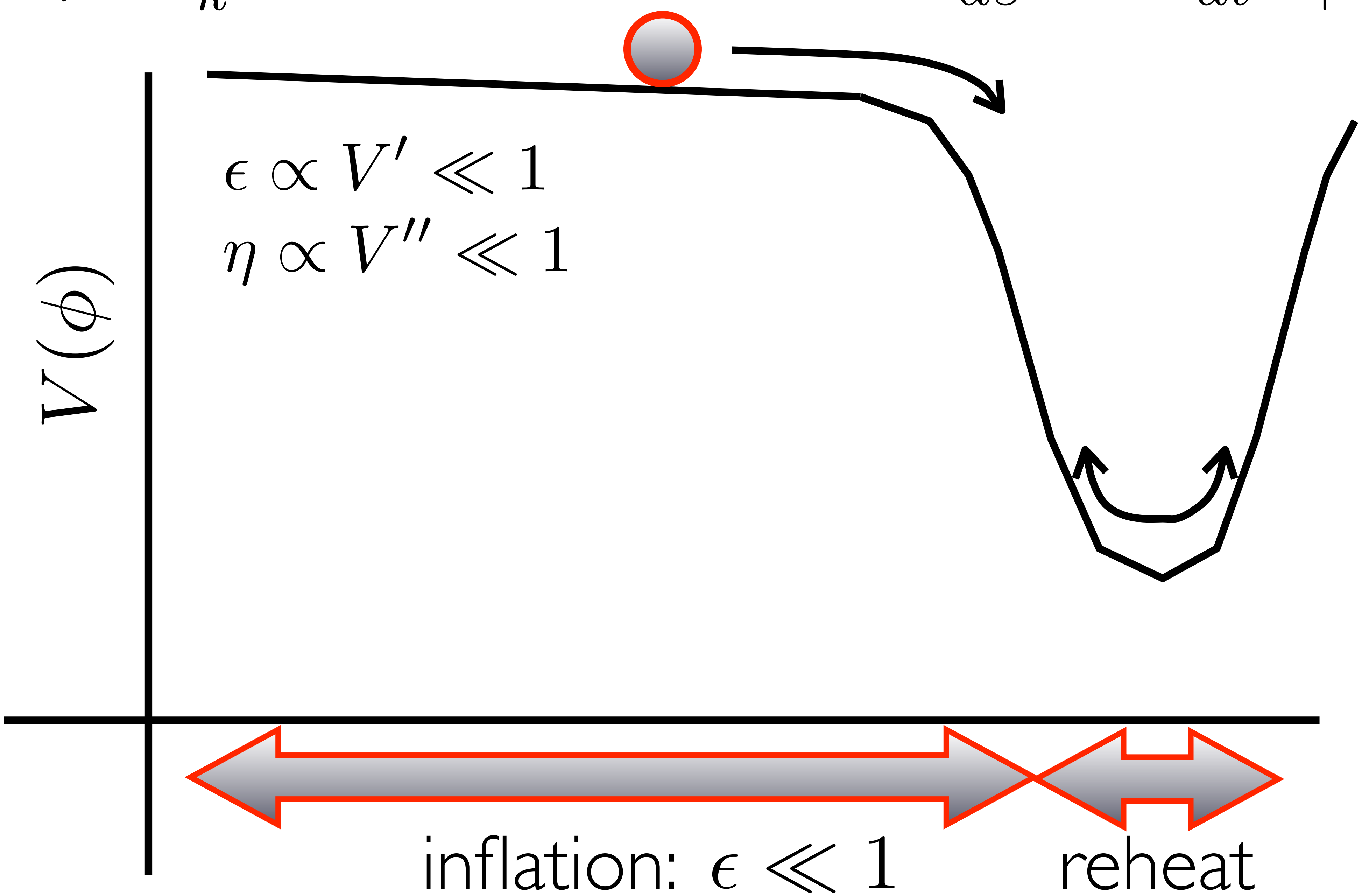


PLANCK COLLABORATION 2014?

TWITTER 2014

Inflation paradigm

$V > E_k$ $\qquad$ $ds^2 = -dt^2 + e^{2Ht} d\mathbf{x}^2$



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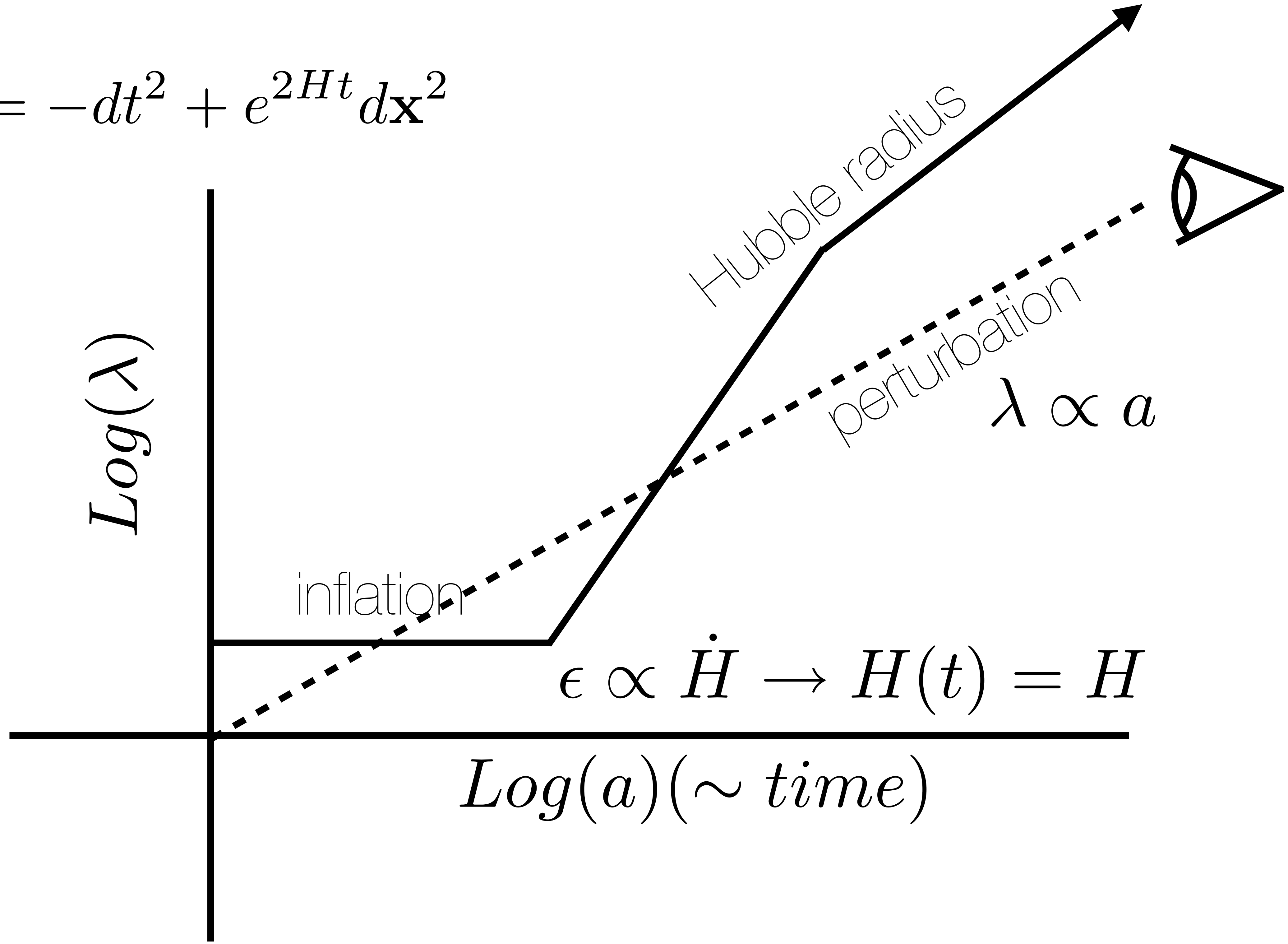
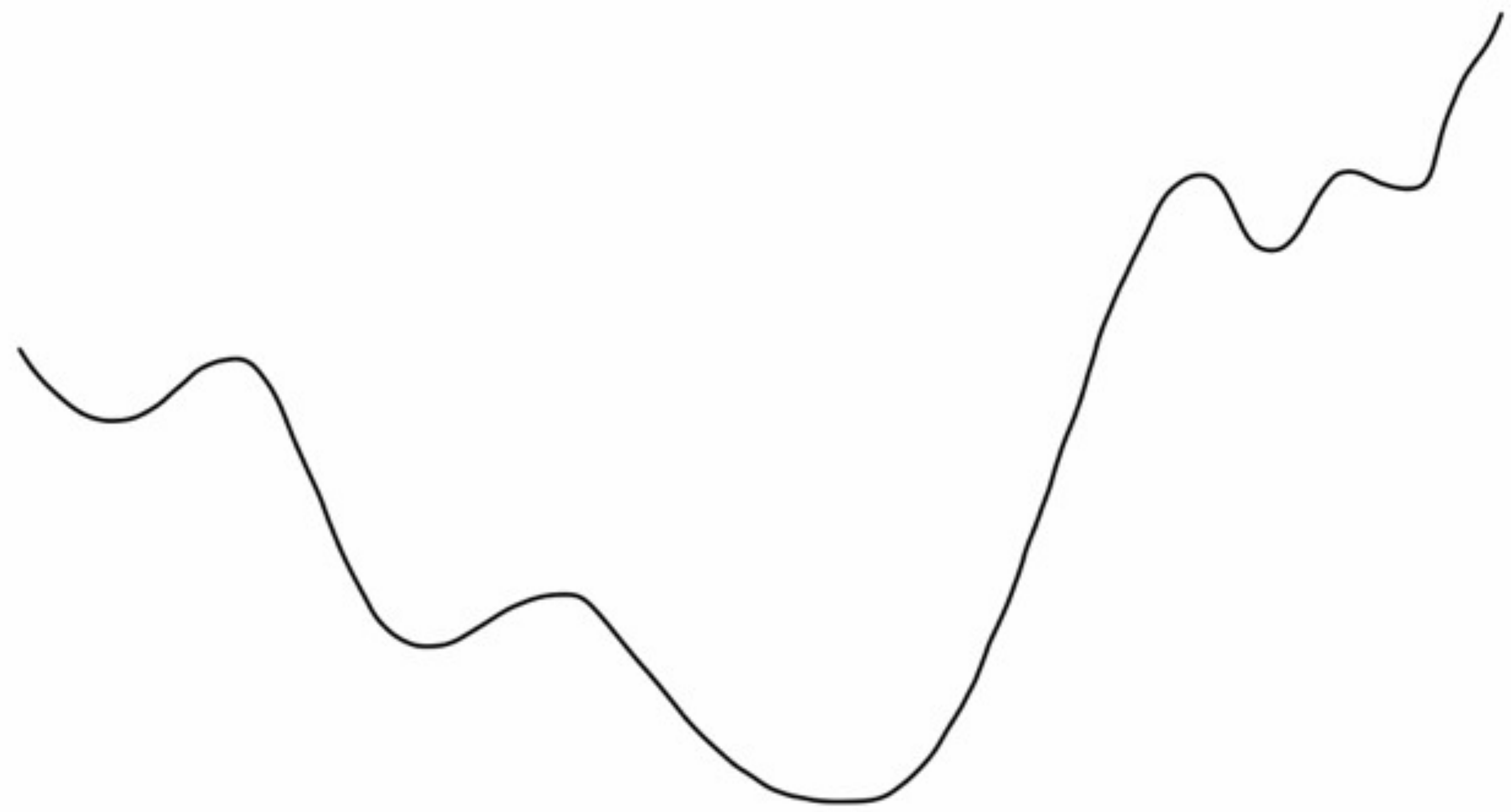


What do we really know about the potential?



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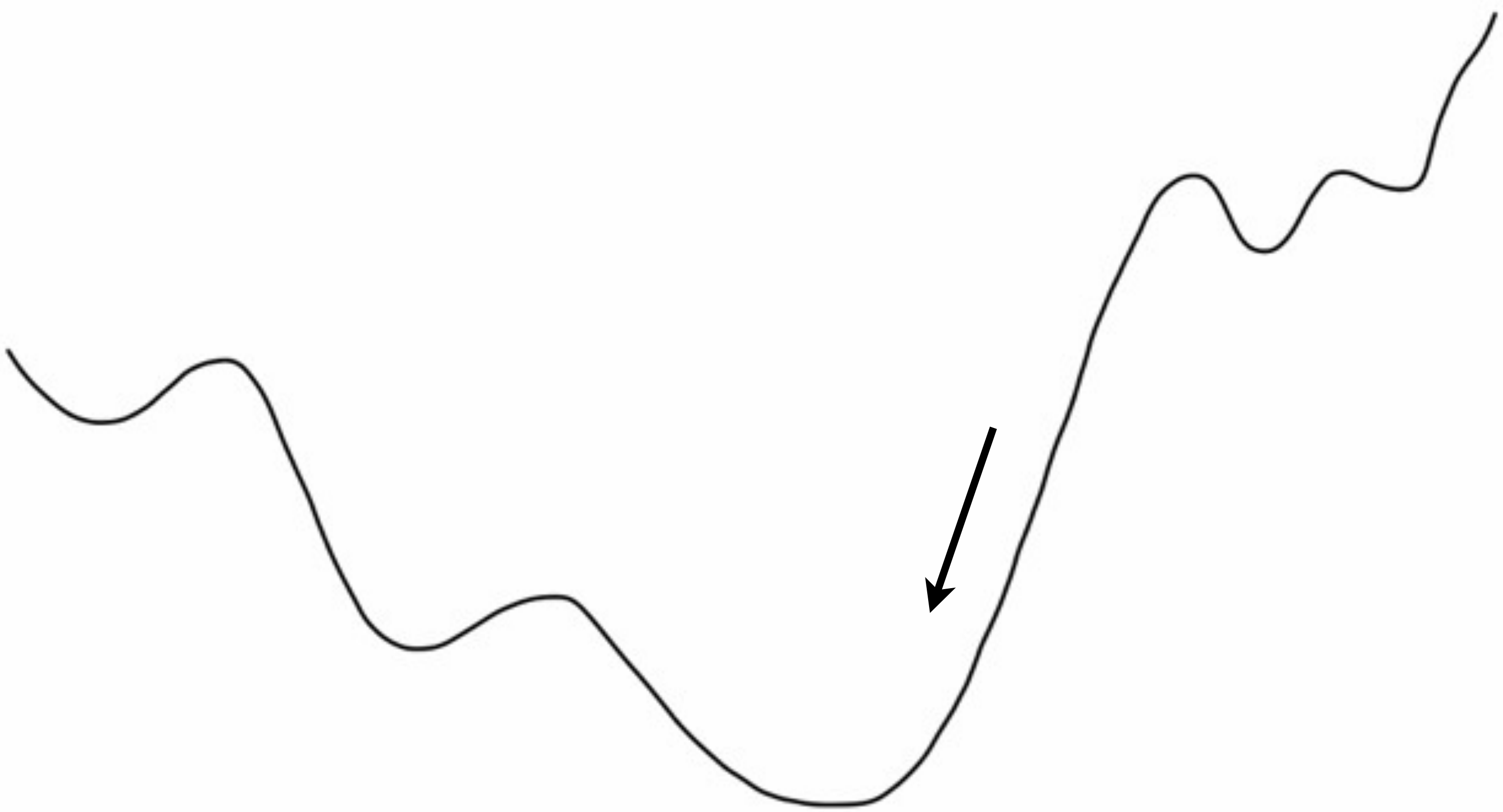

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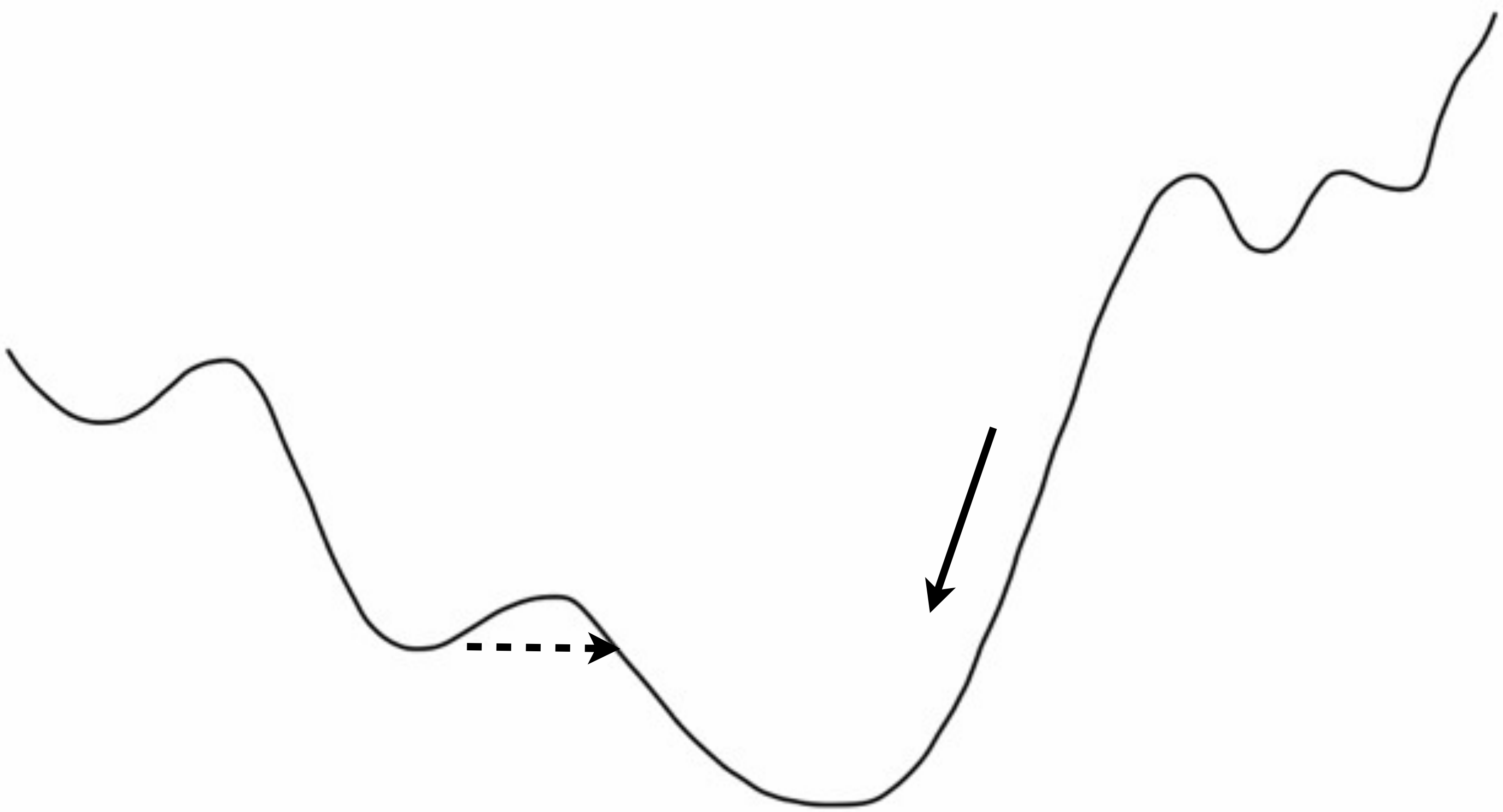

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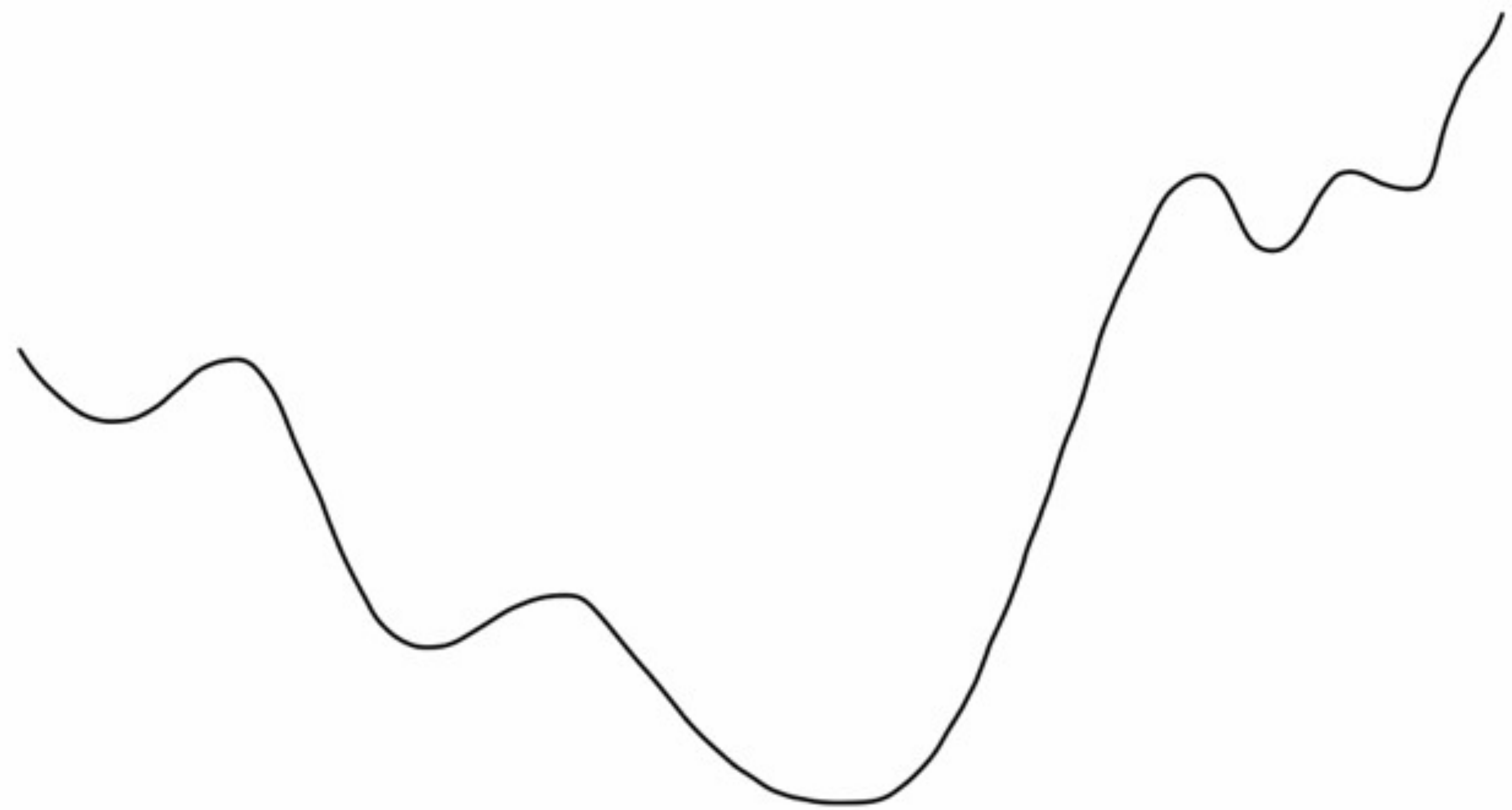

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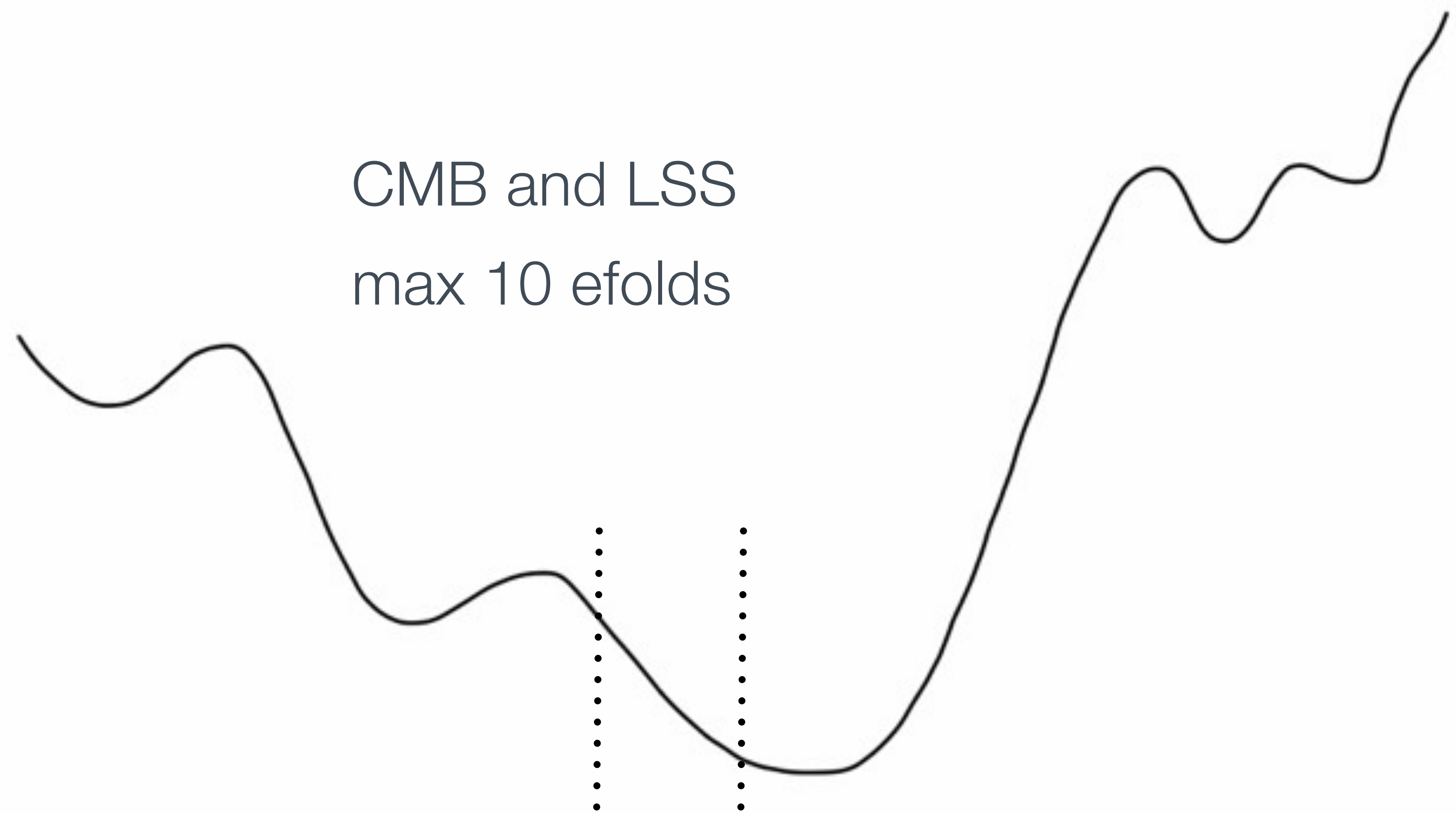

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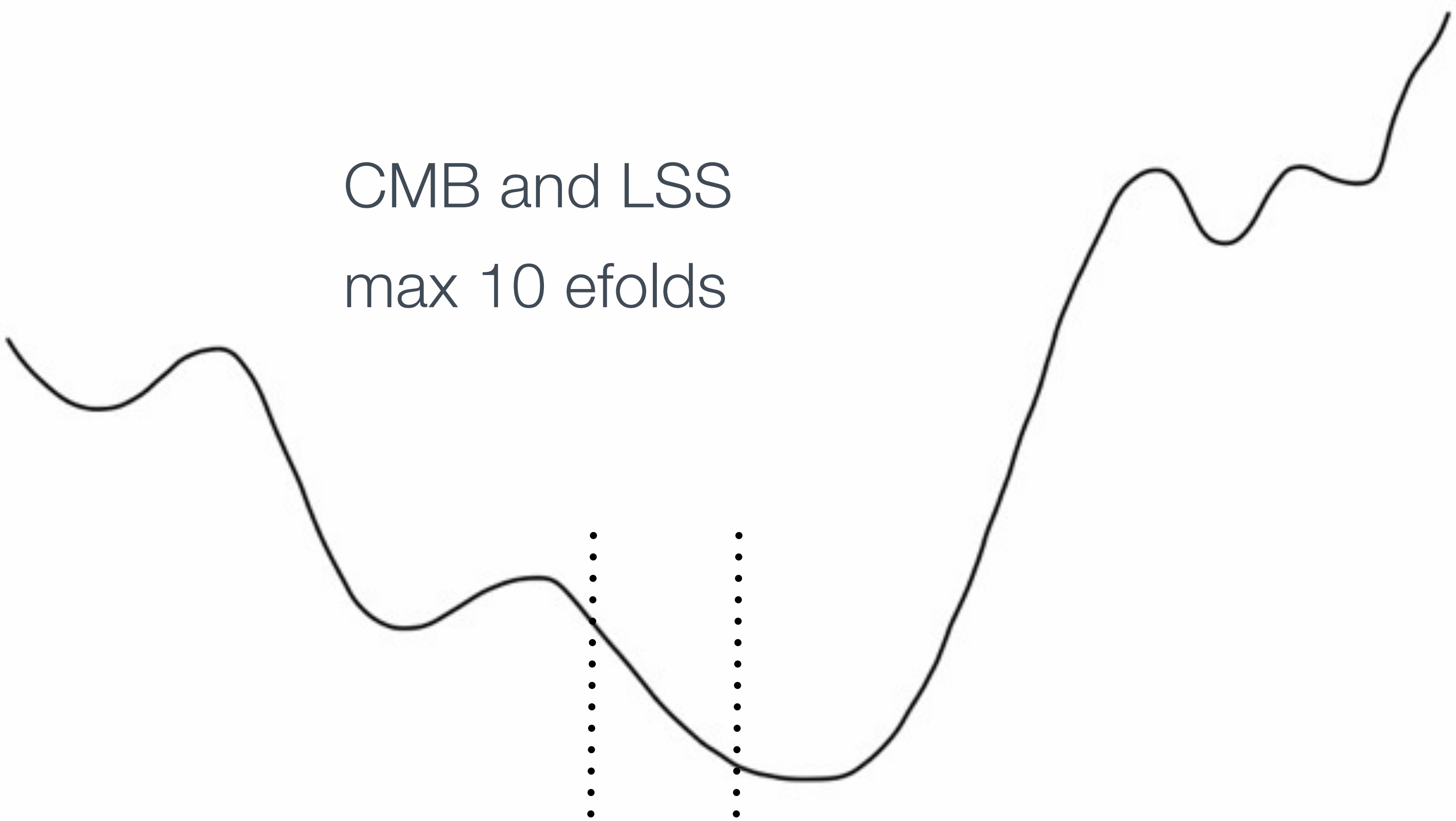

Within these 10 E-folds, red tilt (less power at small scales)

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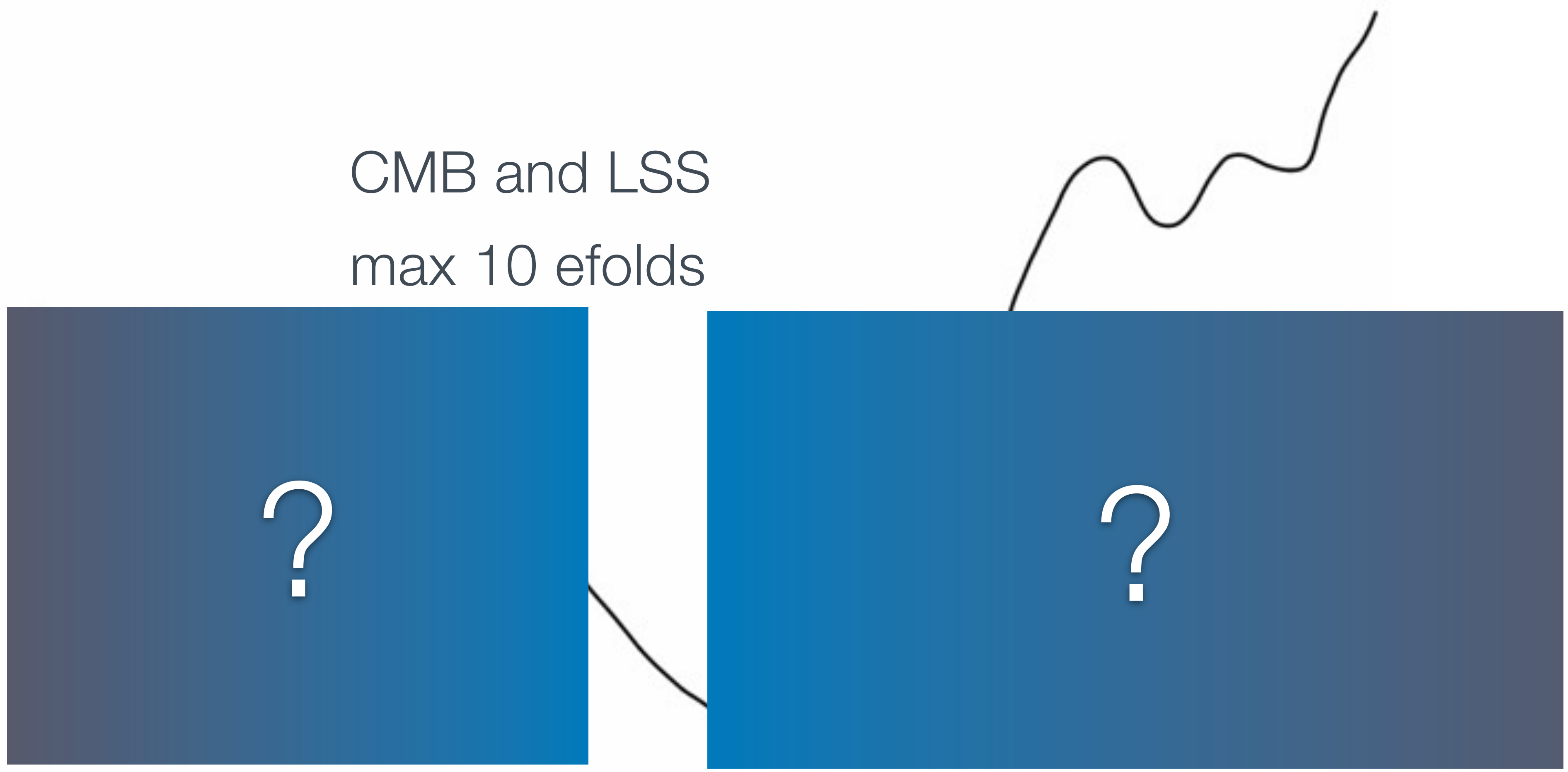

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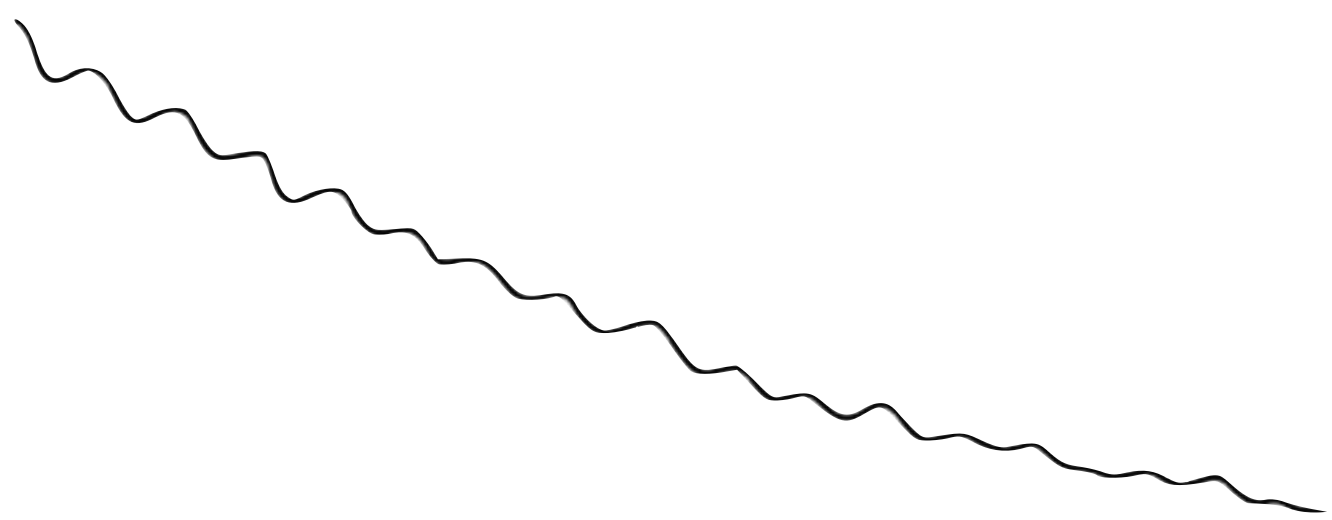
Can we extract anything beyond first few derivatives?



FEATURES

- Roughly (for a single clock):
  - Excitations in time --> Linear oscillations (decaying)
  - Excitations in scale --> Logarithmic oscillations
- Any modification to initial conditions, or e.o.s. during inflation (at fixed time
- Modification of the initial condition at fixed scale, or oscillatory potential (linear).

FEATURES

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- Consider following (general) solution to the e.o.m. :

$$\begin{aligned} \phi_k &= N(k)\left[u_k + \beta(k) u_k^*\right] \\ \phi_k^* &= N(k)\left[u_k^* + \beta(k)^* u_k\right]. \end{aligned}$$

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$$P_\phi(k) \propto \phi\phi^* = \frac{1}{1 - |\beta(k)|^2}\left(1 + |\beta(k)|^2 + e^{2i\psi}\beta(k)^* + e^{-2i\psi}\beta(k)\right)|u_k|^2$$

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- Writing $u_k = |u_k| e^{i\psi}$ and in the limit $\beta \ll 1$

$$P_\phi(k) \simeq P_0\left(1 + 2|\beta(k)|\cos(\alpha(k) + \psi)\right)$$

FEATURES

Non BD vacua

$$\alpha(k) \sim \Lambda/H \sim \Lambda \log k$$

Axion-monodromy

$$\alpha(k) \sim \phi_k/f \sim (\log k)/f$$

MOTIVATION

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    - Phenomenological/Observational
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Do we learn something more? Observation--->Theory

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Generally: Future of early Universe cosmology is **constraining correlated variables**, i.e. Theory ----> {A,B,C,...} observables

MODELS

Derived templates

$$
{}_1\Delta^2_{\mathcal{R}}(k) = A_1\left(\frac{k}{k_*}\right)^m (1 + A_2\cos[\omega_1 \log k/k_* + \phi_1])
$$

$$
{}_2\Delta^2_{\mathcal{R}}(k) = B_1\left(\frac{k}{k_*}\right)^m \left(1 + B_2\left(\frac{k}{\tilde{k}}\right)^n \cos[\omega_2 k + \phi_2]\right)
$$

MODELS

Derived templates

$$ {}_1\Delta^2_{\mathcal{R}}(k) = A_1 \left(\frac{k}{k_*}\right)^m (1 + \boxed{A_2 \cos[\omega_1 \log k/k_* + \phi_1]}) $$

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1) e.g. Axion Monodromy, Natural inflation (similar), non-BD (NPH), unwinding inflation, (e.g. Silverstein & Westphal 2008, Flauger et al 2009, D'Amico et al 2013,Greene et al 2004, Agullo & Parker 2011, Shandera et al. 2012,2013, Battefeld et al 2013)

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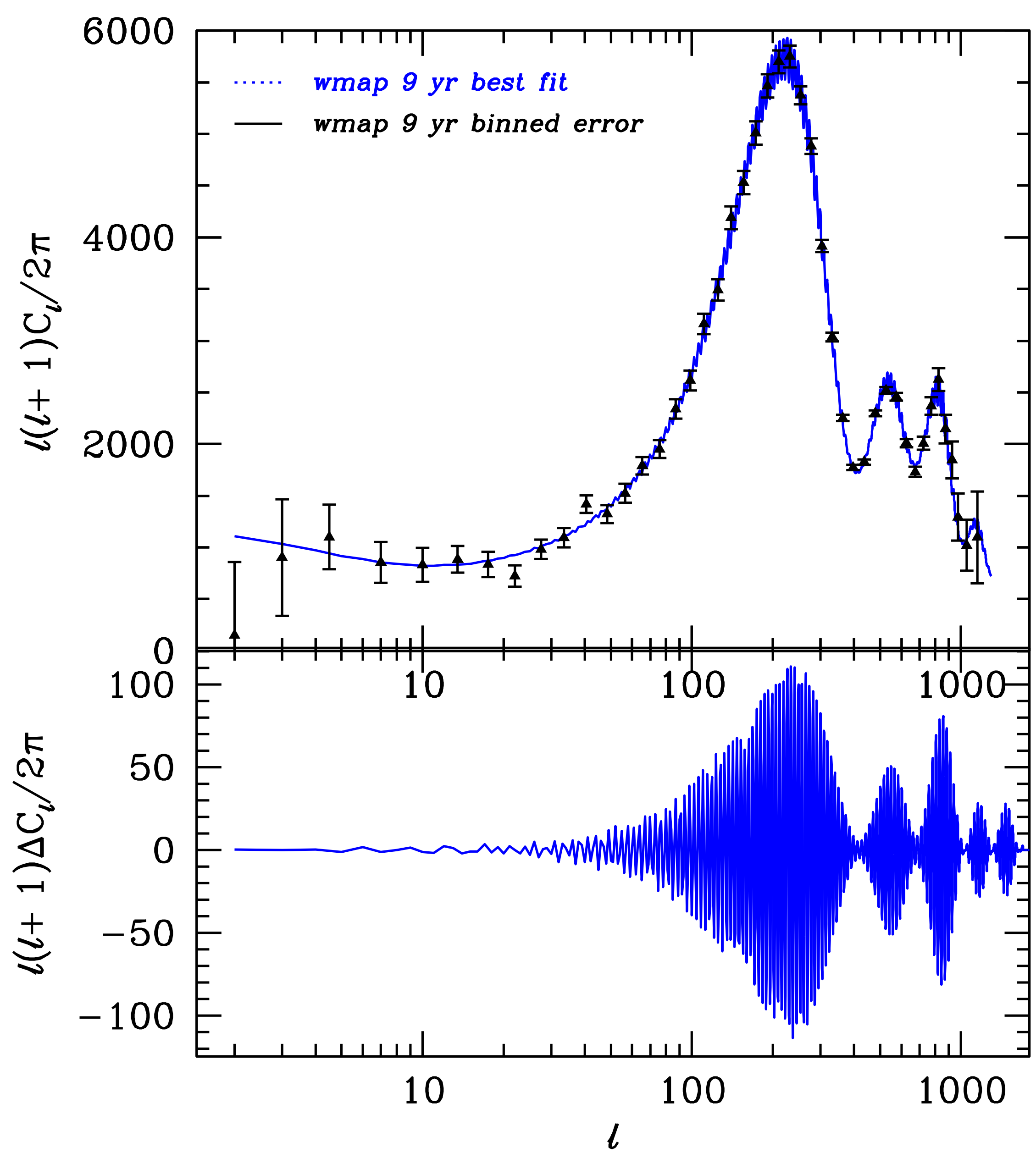
2) e.g. non-BD (BEFT) (e.g. Porrati 2004(2), Greene et al 2004) Change in e.o.s. (e.g. Joy, Sahni, Starobinsky 2007, Battefeld et al 2010, 2014)

DATA ANALYSIS

- 2 Issues:
  - Likelihood is very irregular (slow convergence)
  - Oscillations at high frequency require high resolution (k and ℓ)
- MonteCarloMarkovChain (MH) generally becomes impractical (MULTINEST)
- Recomputing all transfer functions is time consuming

$$C_l = \frac{2}{\pi}\int_0^\infty \frac{dk}{k}\Delta^2_{\mathcal{R}}(k)(\Delta^T_l(k))^2$$

PERTURBATIVE EXPANSION



$$C_l = \frac{2}{\pi}\int_0^\infty \frac{dk}{k}\Delta^2_{\mathcal{R}}(k)(\Delta_l^T(k))^2$$

Corrections are small

Perturbative expansion in oscillatory part

$$C_\ell \quad = \quad C_\ell^u + C_\ell^p$$

PERTURBATIVE EXPANSION

- Expand Transfer function in oscillatory part

$$(\Delta_l^T(k))^2 \quad = \quad (\bar{\Delta}_l^T)^2 + 2\bar{\Delta}_l^T \sum (\Theta_i - \bar{\Theta})\bar{\Delta}_{l,\Theta_i}^T + \mathcal{O}(\Theta_i^2)$$

- We then have for the perturbed part:

$$C_\ell^p \quad = \quad \bar{C}_\ell^{p(\alpha)} + \bar{C}_\ell^{p(\beta)} + \sum (\Theta_i - \bar{\Theta}_i)(\bar{C}_{\ell,\Theta_i}^{p(\alpha)} + \bar{C}_{\ell,\Theta_i}^{p(\beta)}) + \mathcal{O}((\alpha+\beta)\Theta_i^2)$$

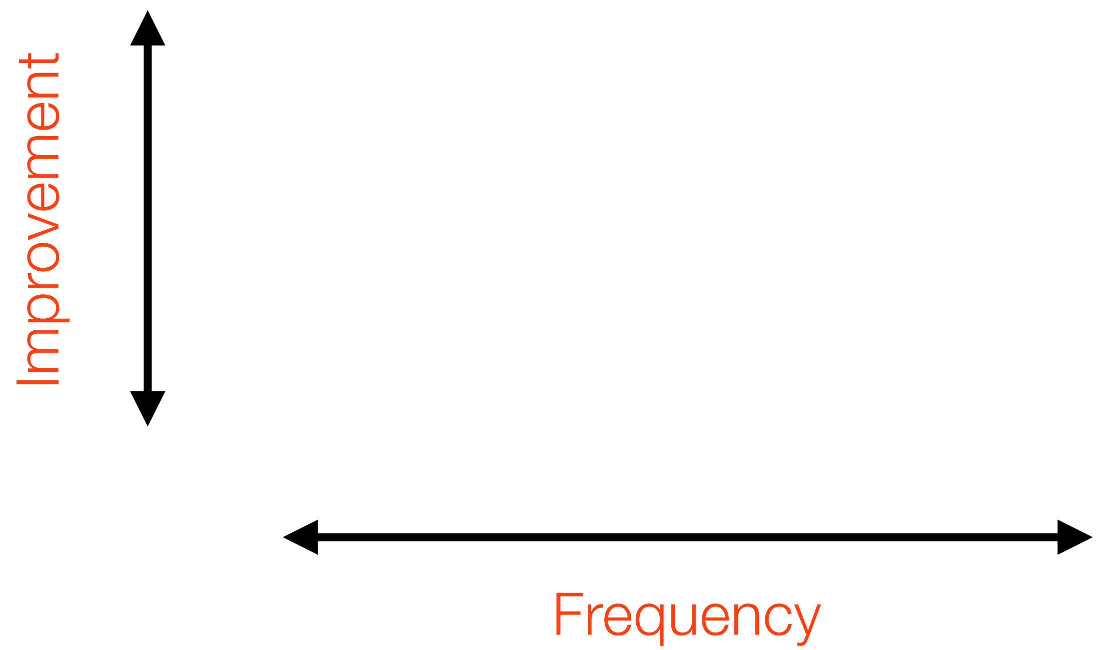
- Power spectra and derivatives can be **precomputed:**

$$\bar{C}_\ell^p \qquad \bar{C}_{\ell,\Theta_i}^p \qquad \bar{C}_{\ell,\Theta_i\Theta_j}^p$$

Improvement in units of $\Delta\chi^2$. Typically, χ^2 distribution of 3 variables, requires $\Delta\chi^2$ of ~11 for 3 sigma significance.

$$-2\Delta \log \mathcal{L} = \Delta\chi^2$$

Next few slides



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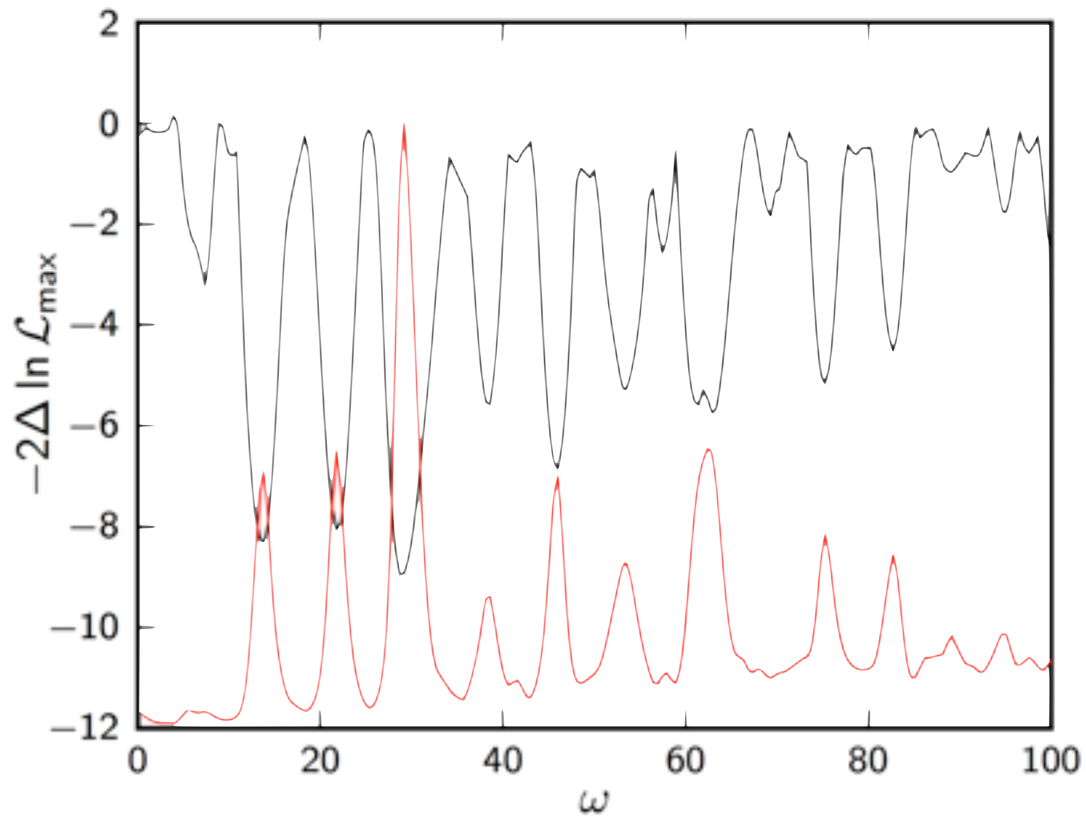
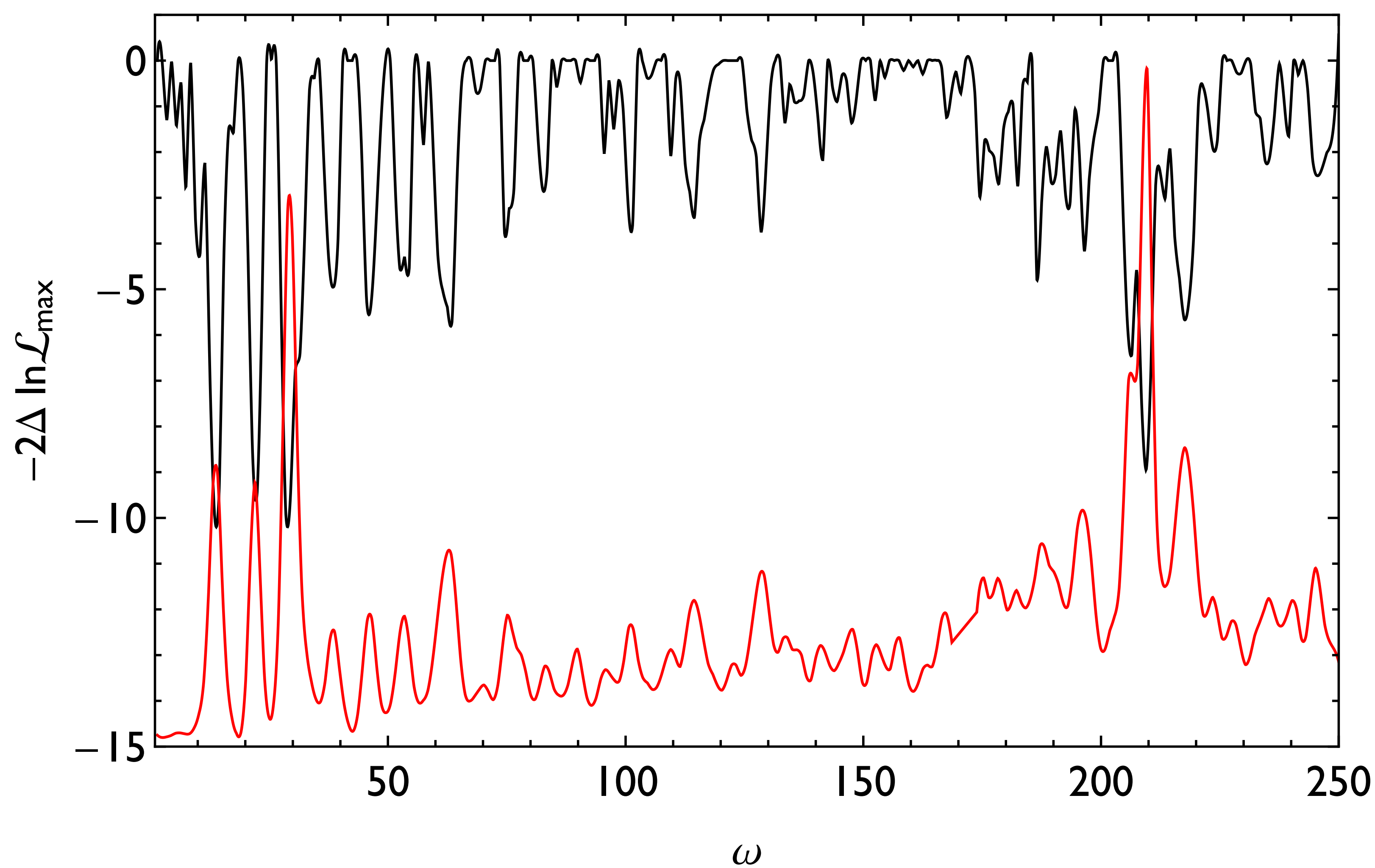


Multinest Marginalized prob.

PLANCK COLLABORATION 2013



- Marginalized likelihood computed in ~16 hours, on 12 core node.

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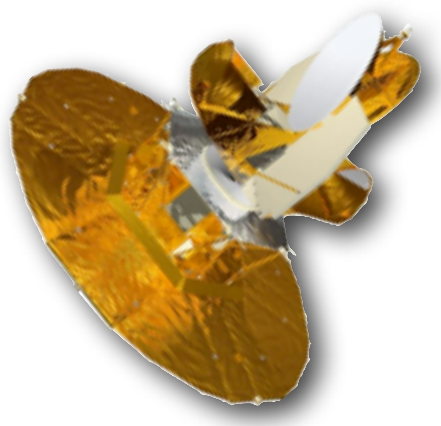
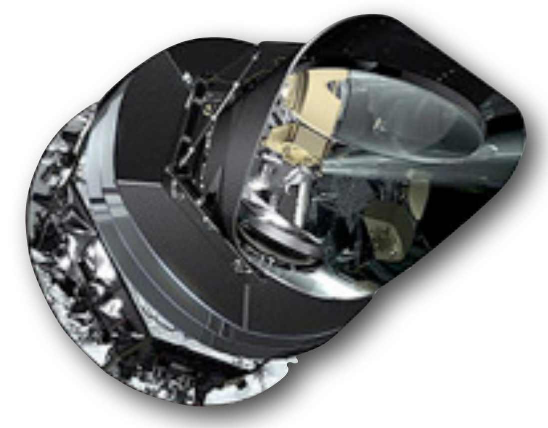
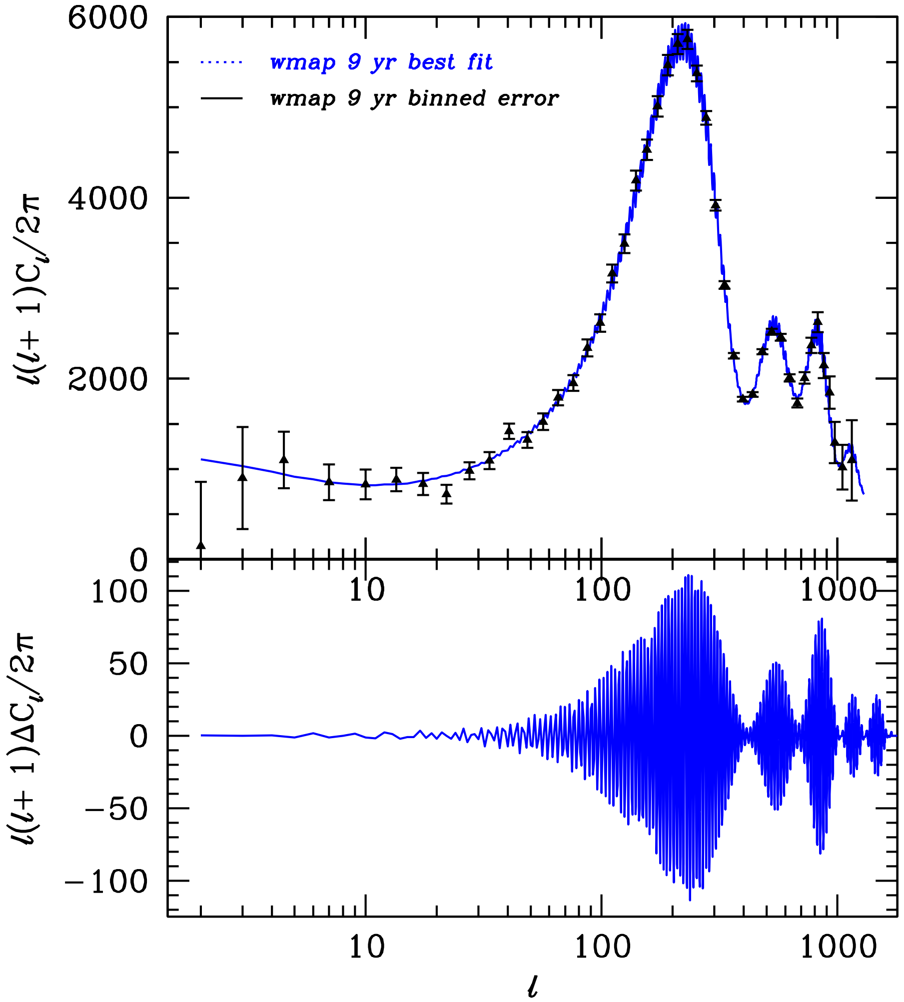


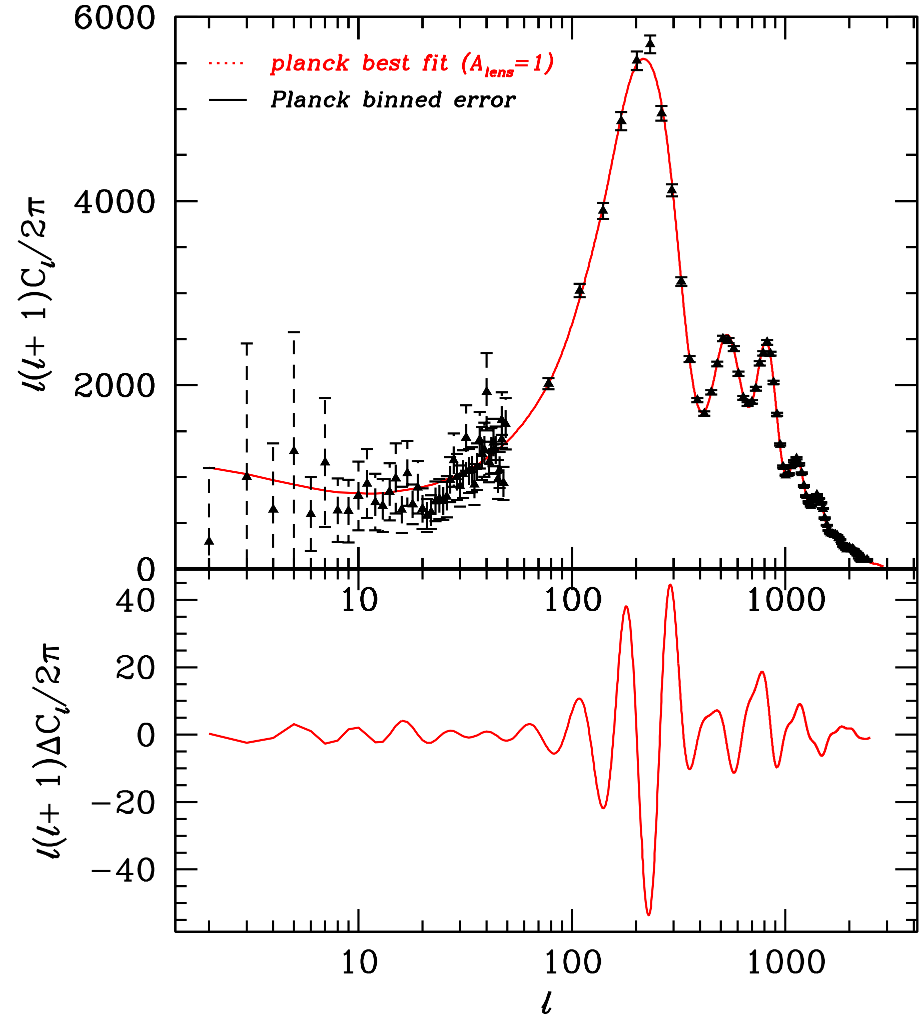
VS



WMAP 9



PLANCK 1



ARE THESE REAL?

- Information criteria
- Simulations
- Circumstantial

SIMULATIONS

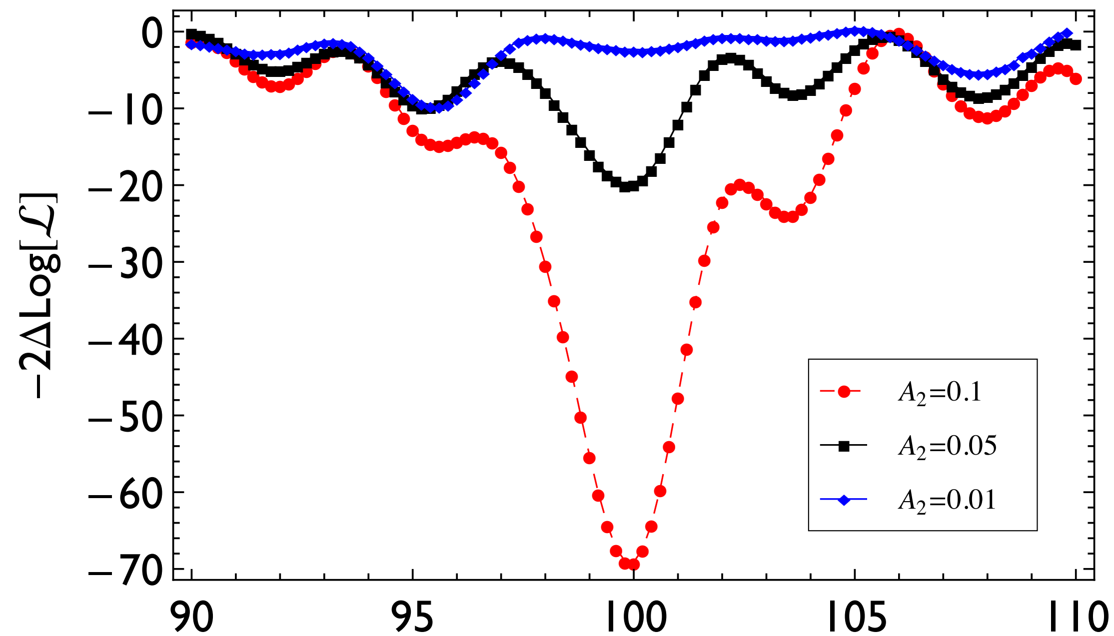
-Planck-like noise

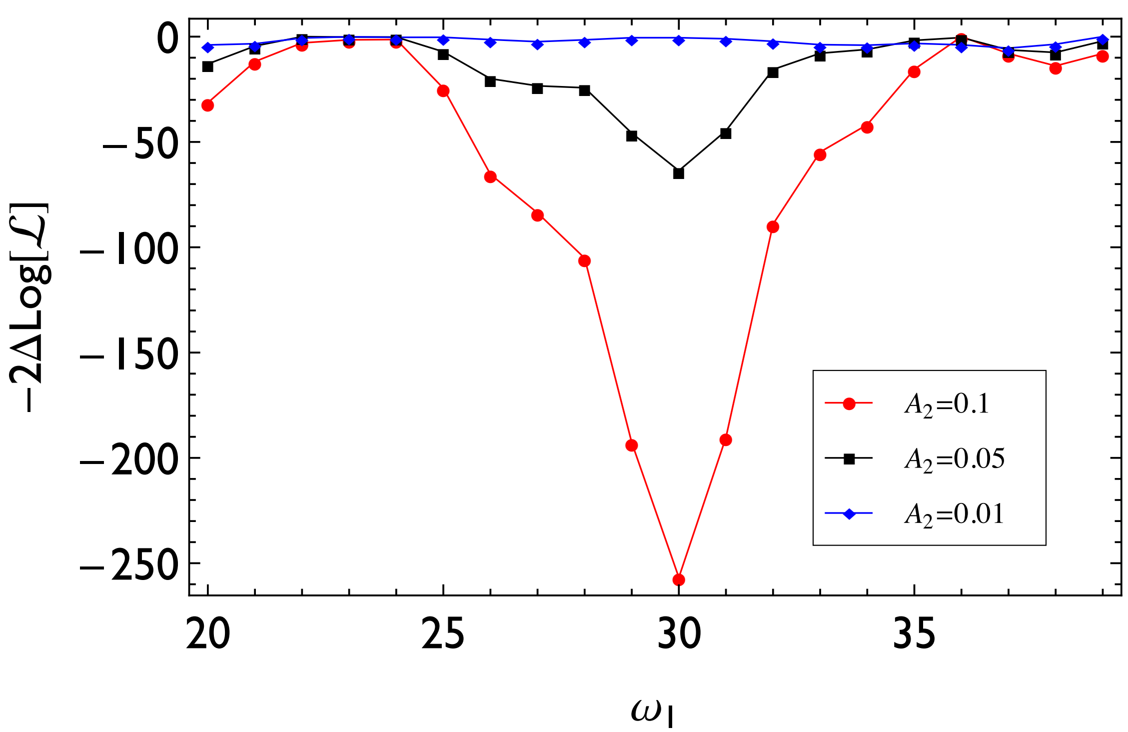
-3 different mock frequencies:

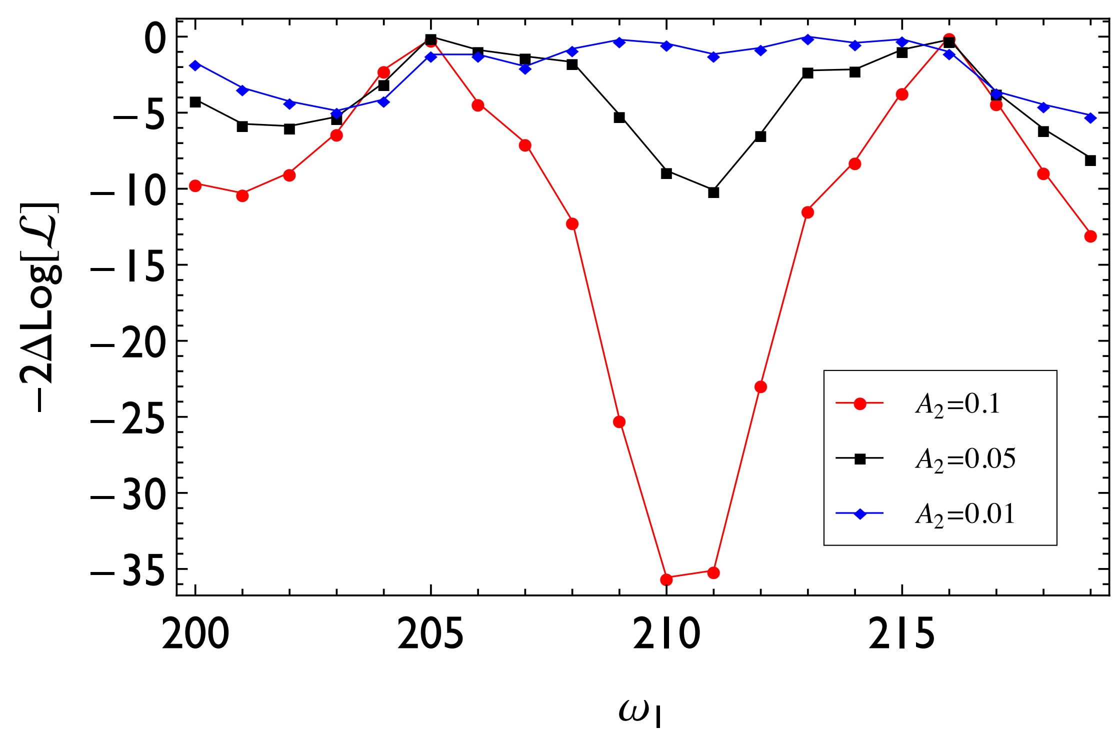
30,100,210

-3 different amplitudes:

0.1%, 1%, 10%

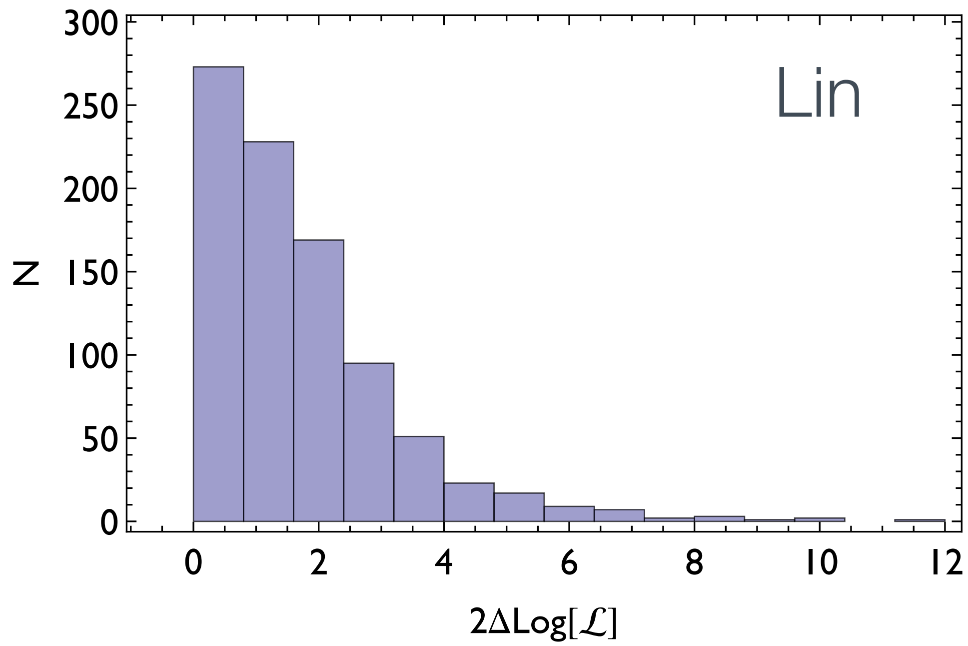


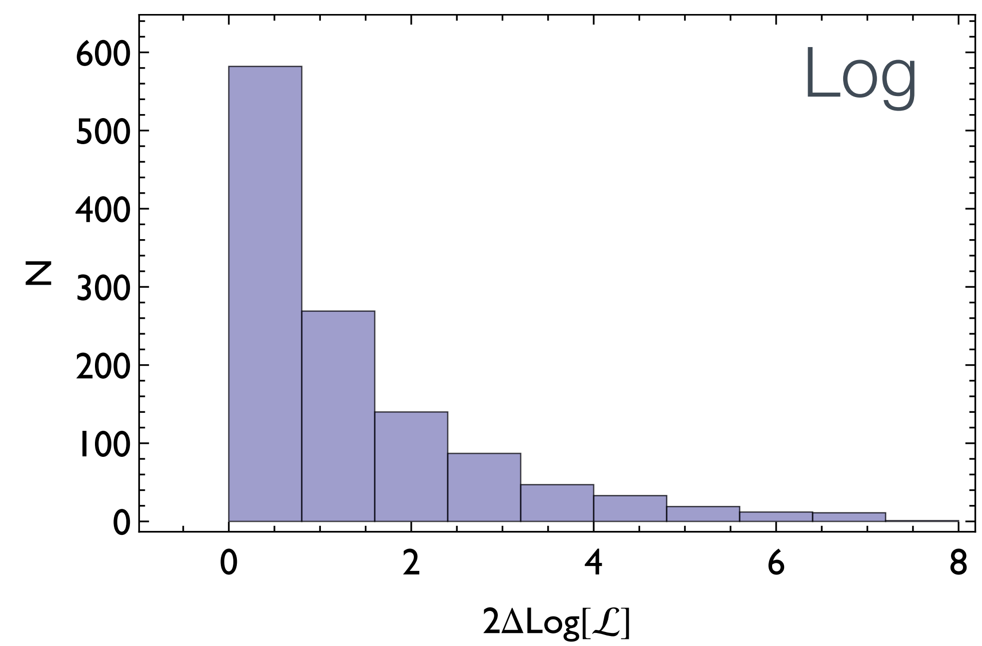




SIMULATIONS

Full MCMC (planck noise) with mock data, no signal





See also J. Hamann, A. Shafieloo, and T. Souradeep (2010), R. Easther and R. Flauger (2013)

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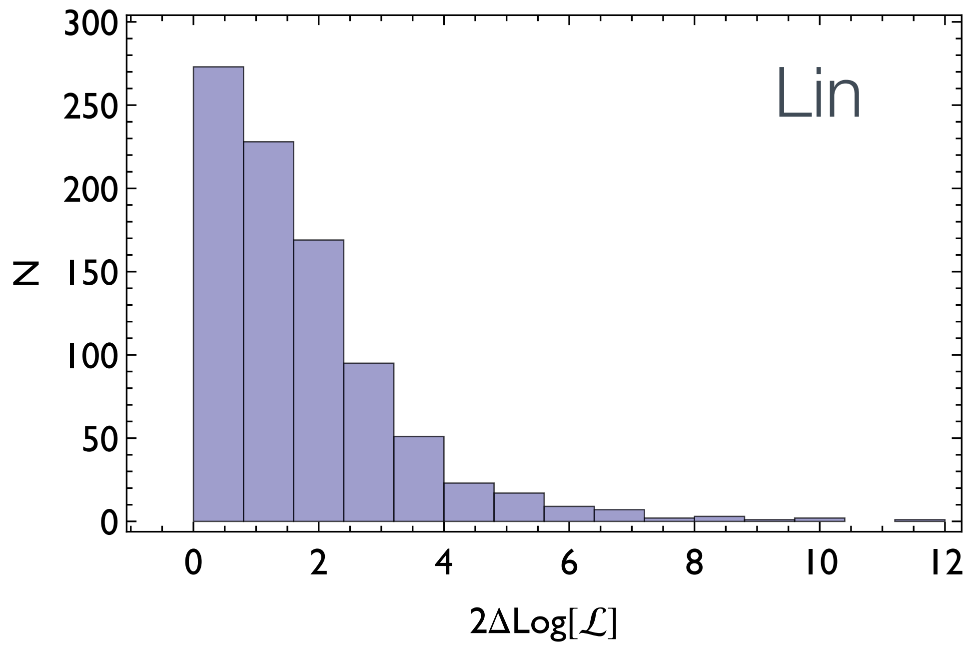
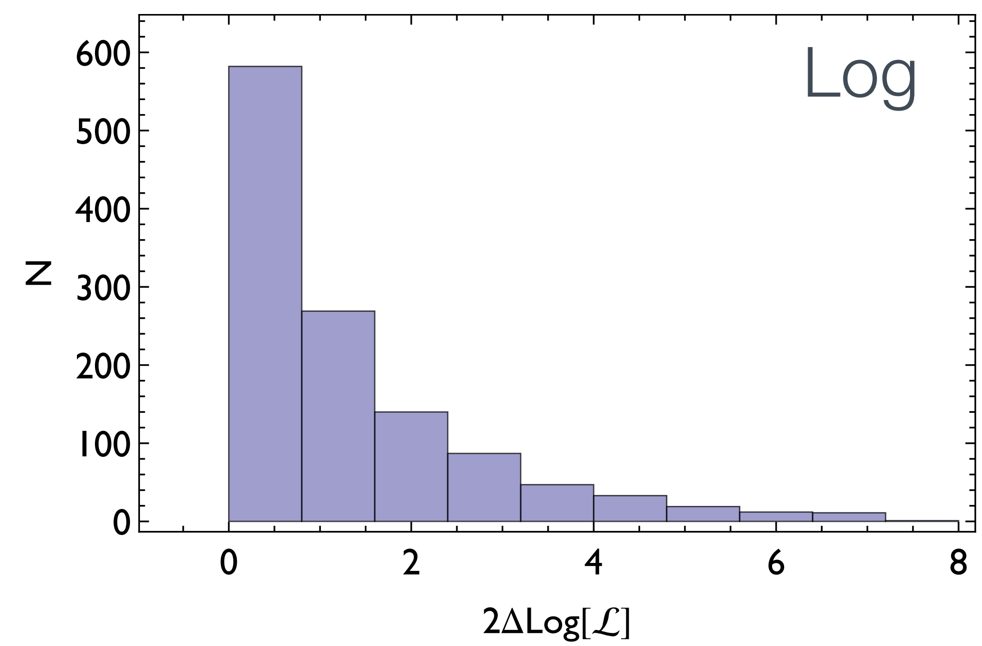
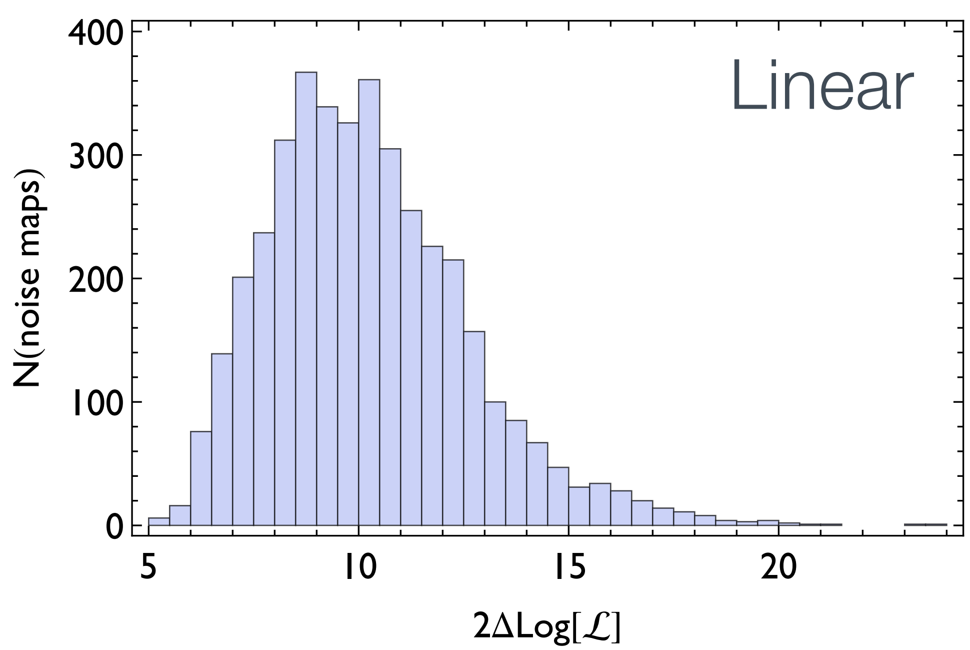
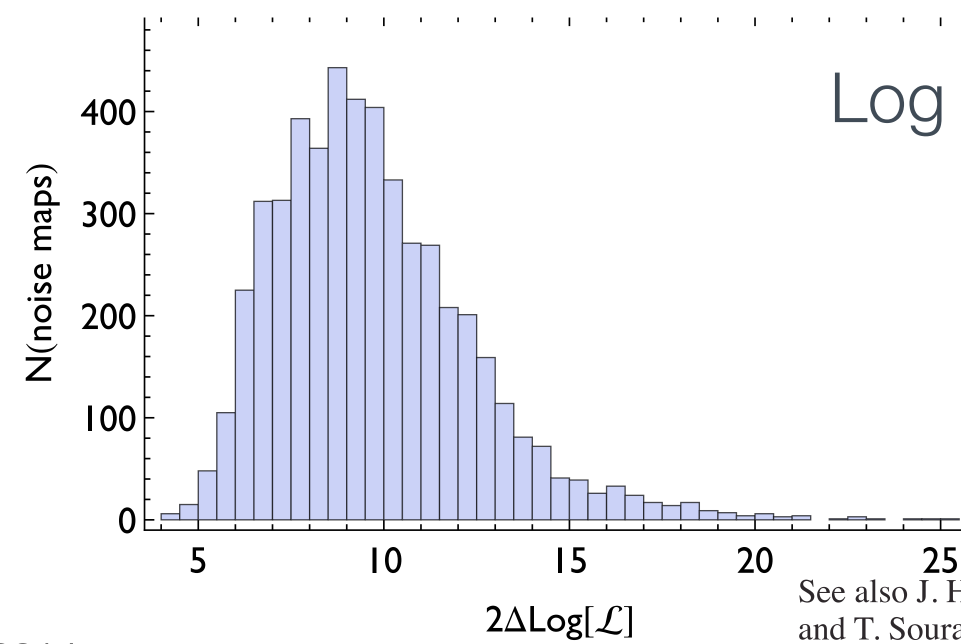




5000 Universes; **WMAP 9 noise** and cosmic variance, no signal





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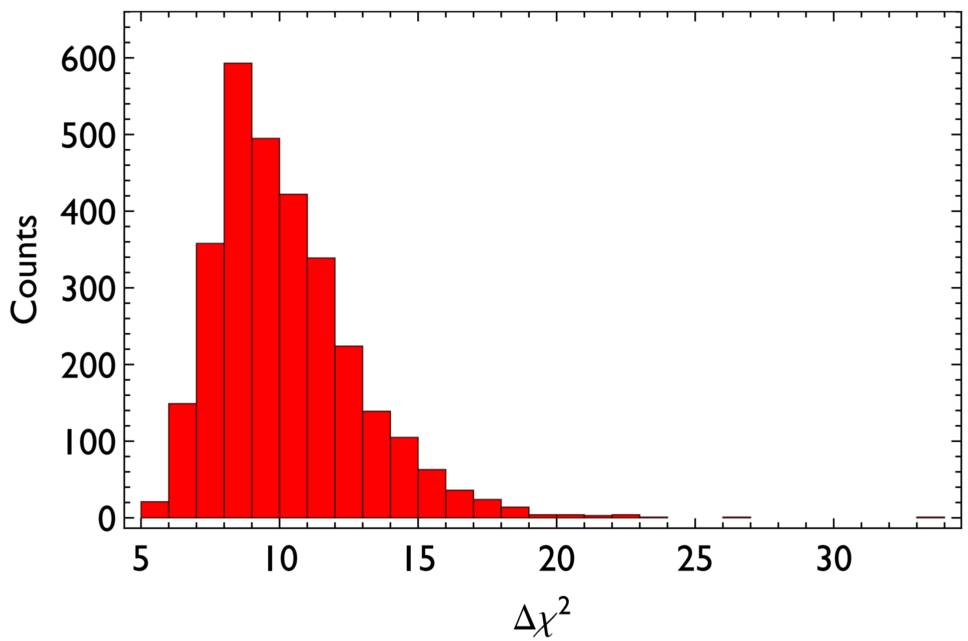
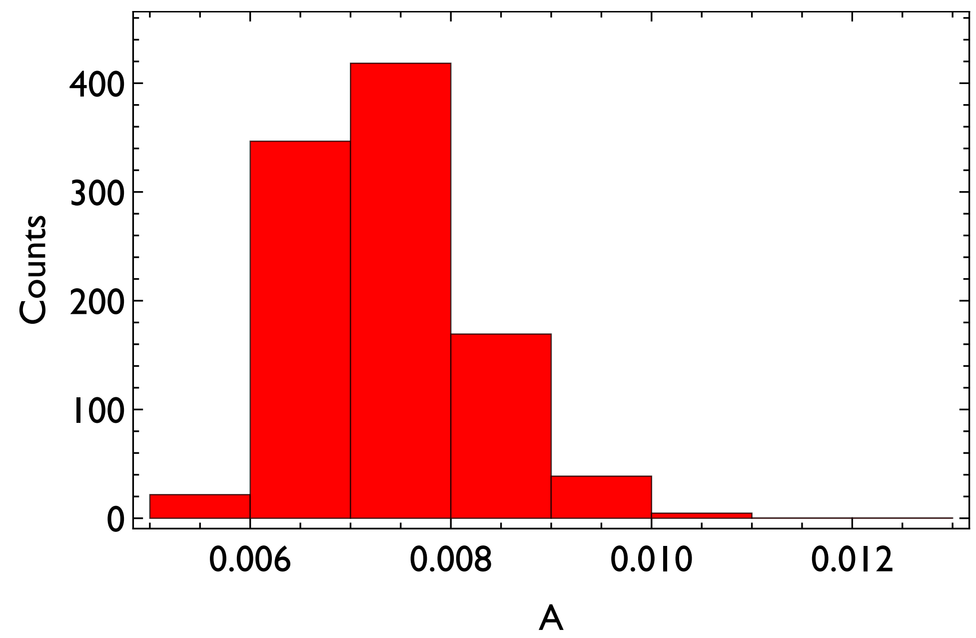
SIMULATIONS

5000 Universes; **Real Planck noise** and cosmic variance, no signal





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SIMULATIONS

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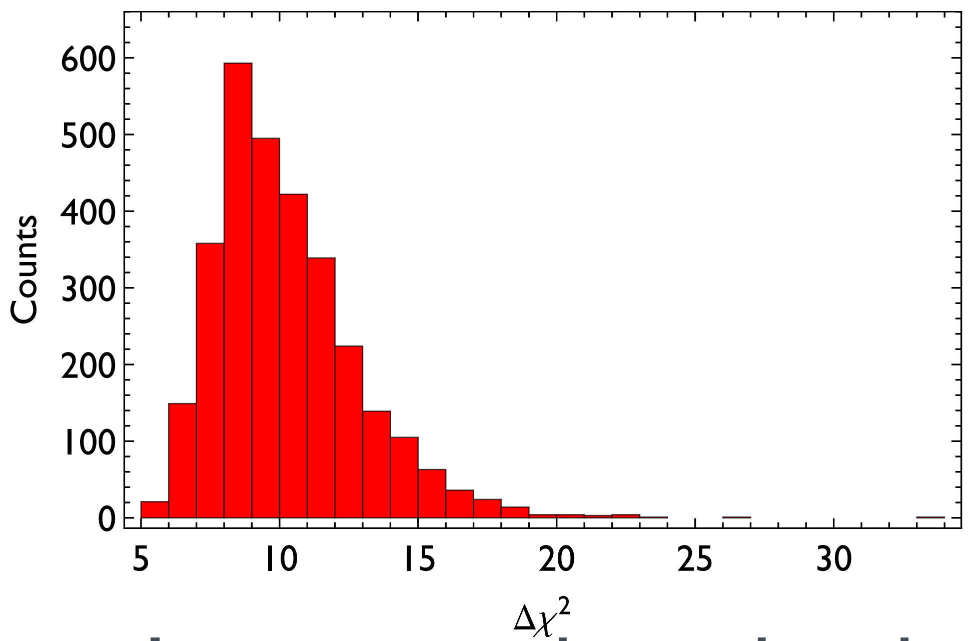
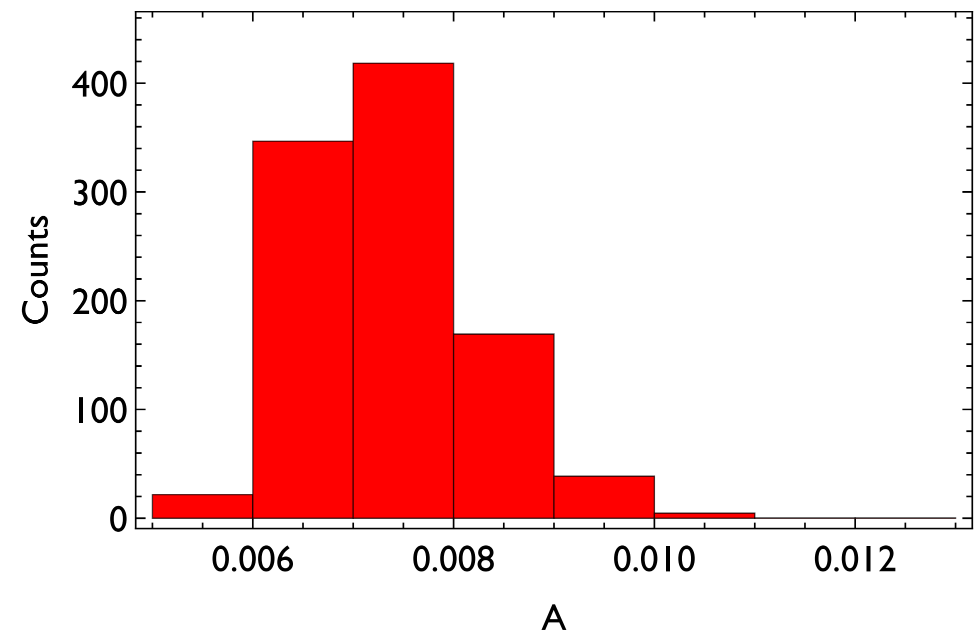
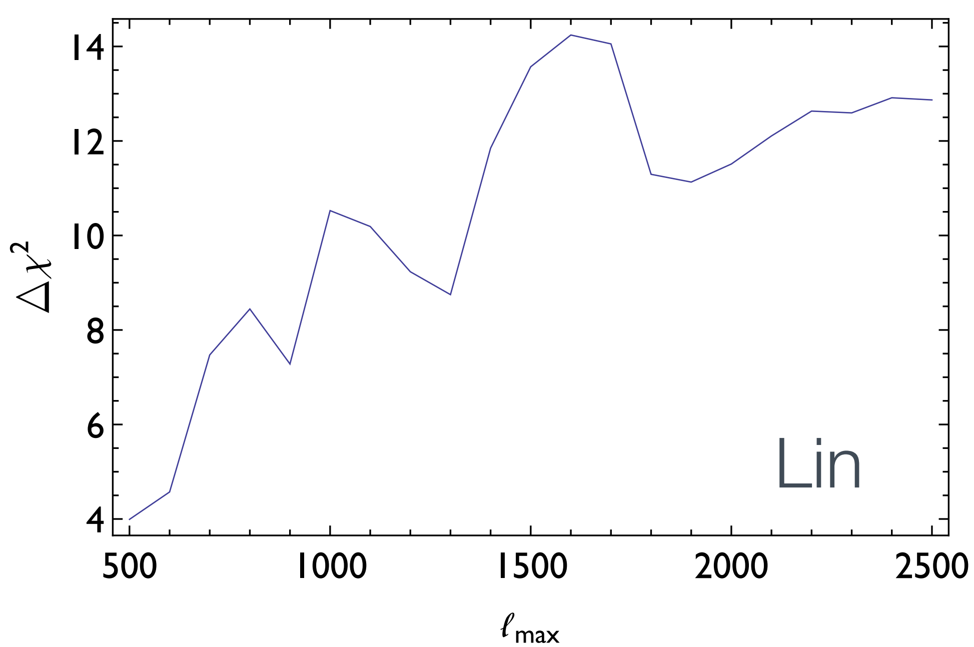
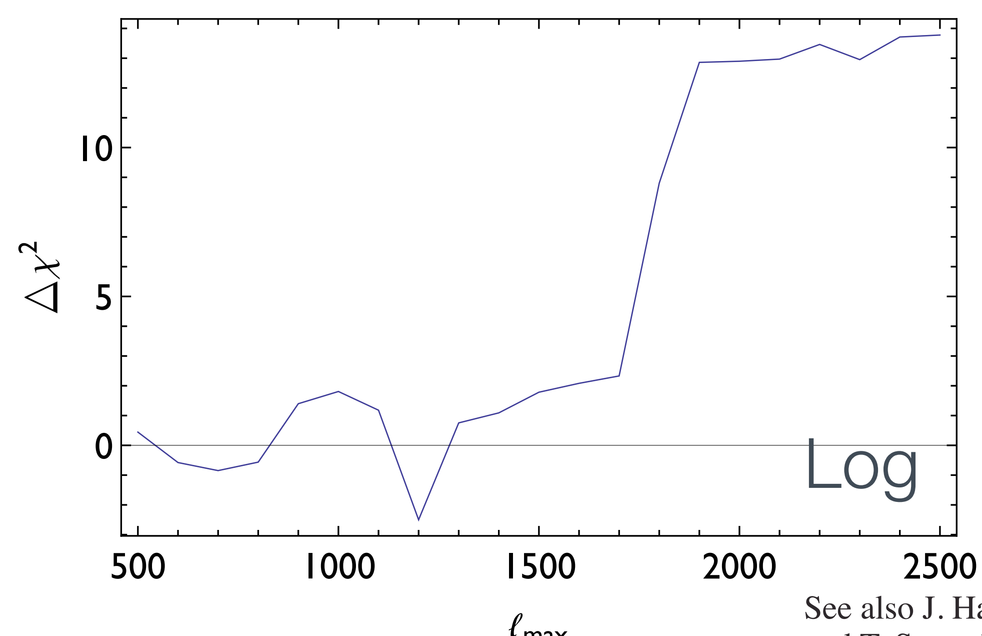




Improvement as a function of maximum multipole:





See also J. Hamann, A. Shafieloo, and T. Souradeep (2010), R. Easther and R. Flauger (2013)

ARE THESE REAL?

- Information criteria --> A mess
- Simulations --> Most likely not
- Circumstantial --> Most likely not

BICEP

- What about BICEP? 2 Things:
  - r = 0.2 would put extra tension between TT data and TT theory
  - Also, r = 0.2 suggests Super Planckian displacement of field / violates Lyth bound
- Is there a model that would solve these 2 things in one go? Maybe: Axion monodromy. Shift symmetry
  - Solves first
  - and could induce a large feature, to solve second?

$$\Delta^2_{\mathcal{R}}(k) \quad = \quad A_s \left(\frac{k}{k_*}\right)^{n_s-1} \left(1 + \delta n_s \cos[\omega \log k/k_* + \phi]\right)$$

$$\Delta^2_{\mathcal{D}}(k) \quad = \quad A_s \frac{r_*}{4} \left(\frac{k}{k_*}\right)^{-r_*/8} \left(1 - \delta n_s \frac{r_*}{8\omega} \sin[\omega \log k/k_* + \phi]\right)$$

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$$\Delta^2_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} (1 + \delta n_s \cos[\omega \log k/k_* + \phi])$$

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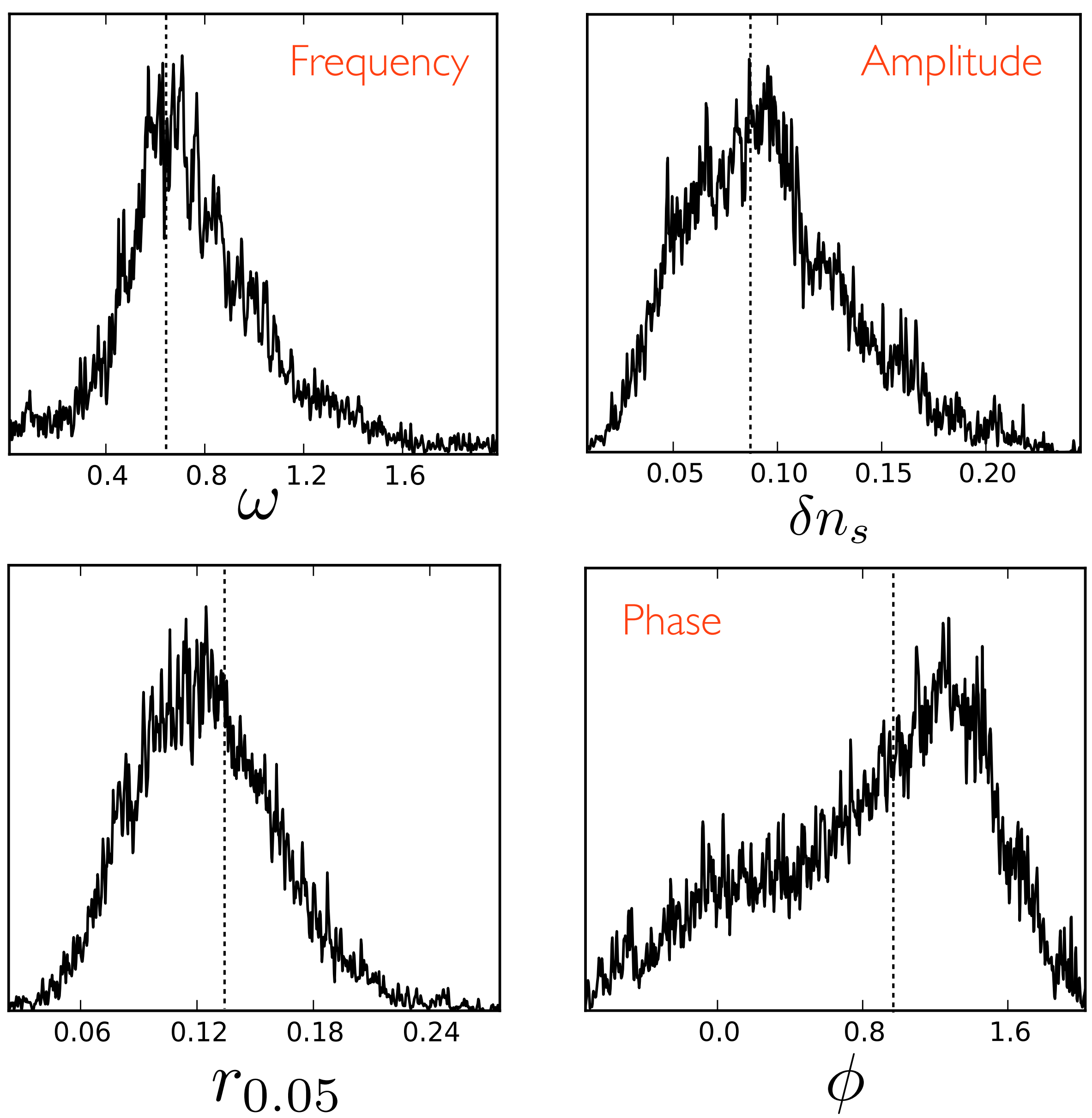

Planck+BICEP+SPT +ACT

$$f/M_p \sim \mathcal{O}(.01)$$

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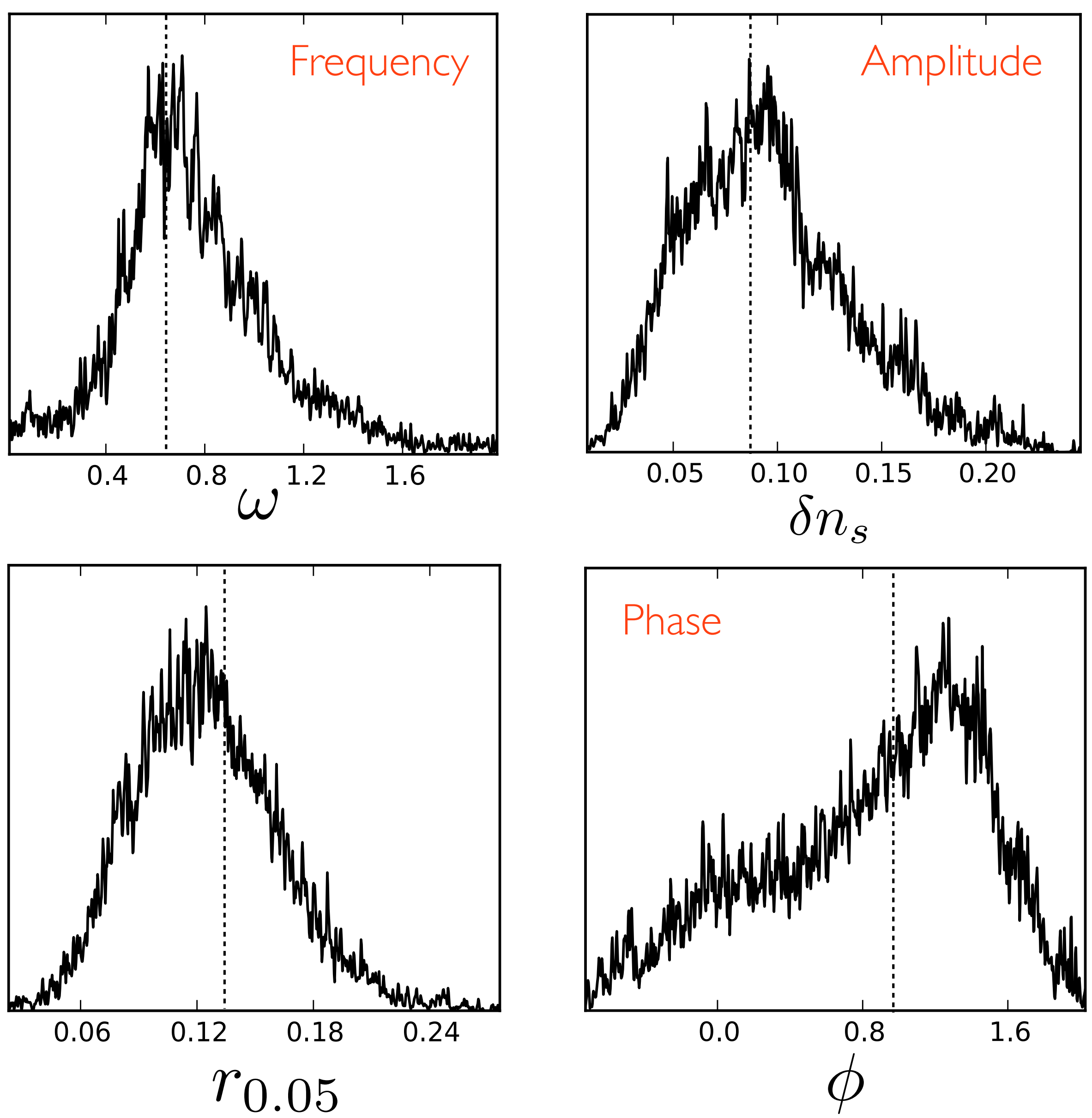

Planck+BICEP+SPT +ACT

component	$\Delta\chi^2$
Lowlike	~ -0.3
Lensing	~ 0.6
BICEP2	~ -3.4
Commander	~ -8
CAMspec	~ 1.1
ACTSPT	~ -1.2
total	~ -11.2

$$f/M_p \sim \mathcal{O}(.01)$$

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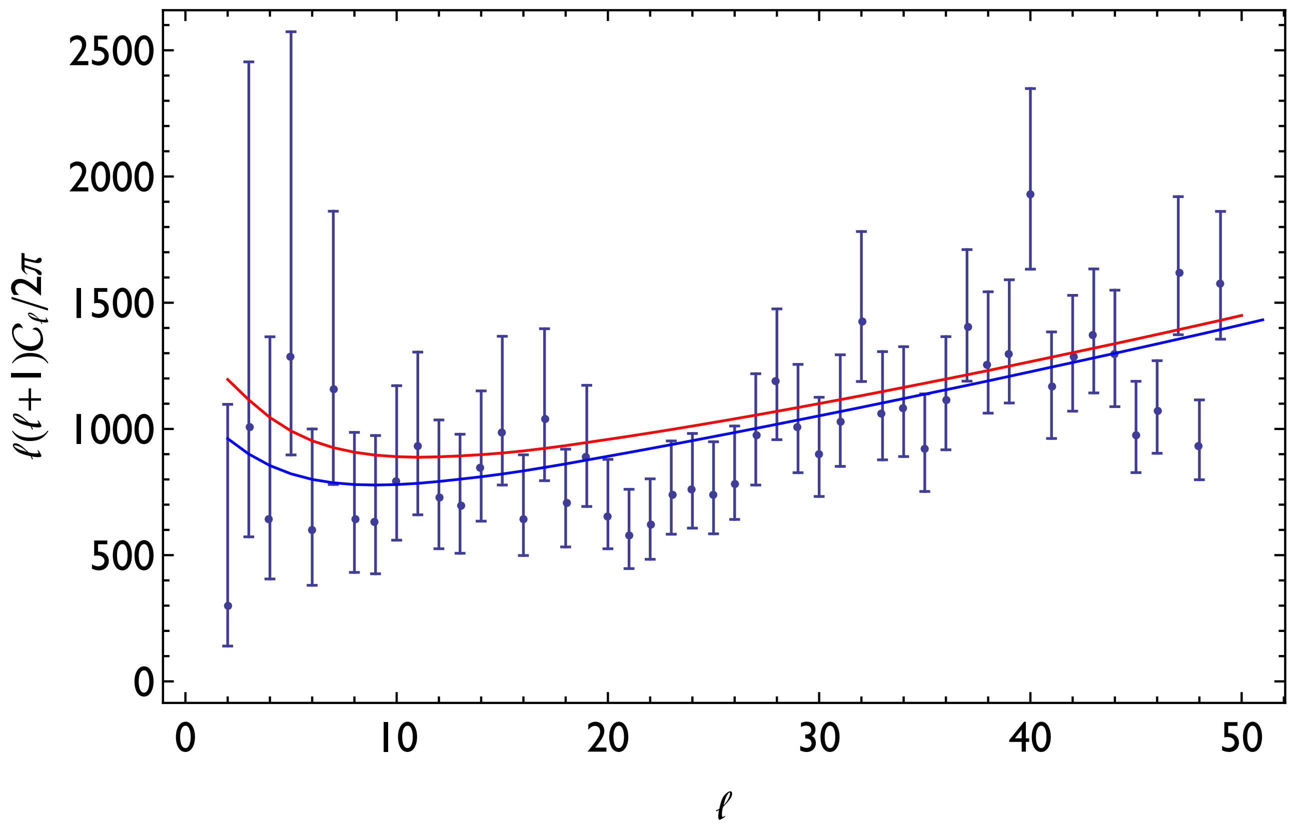

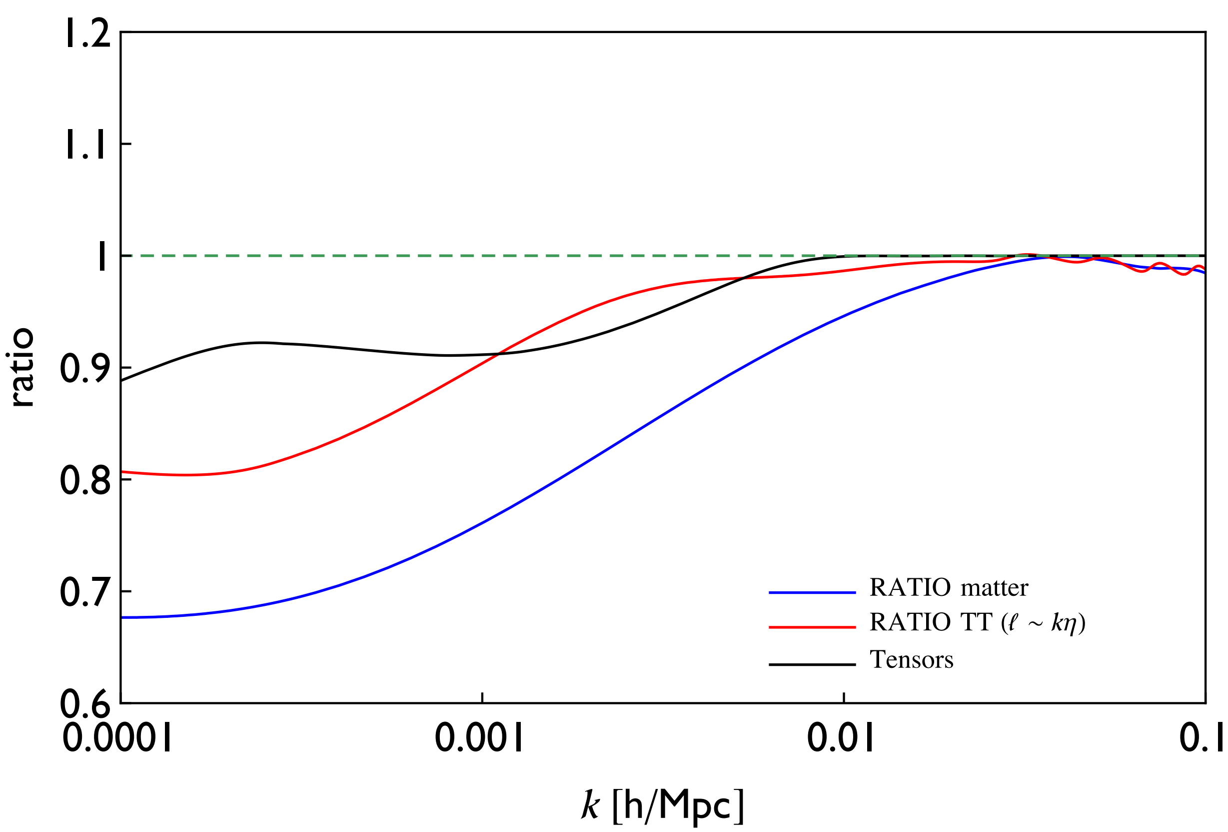

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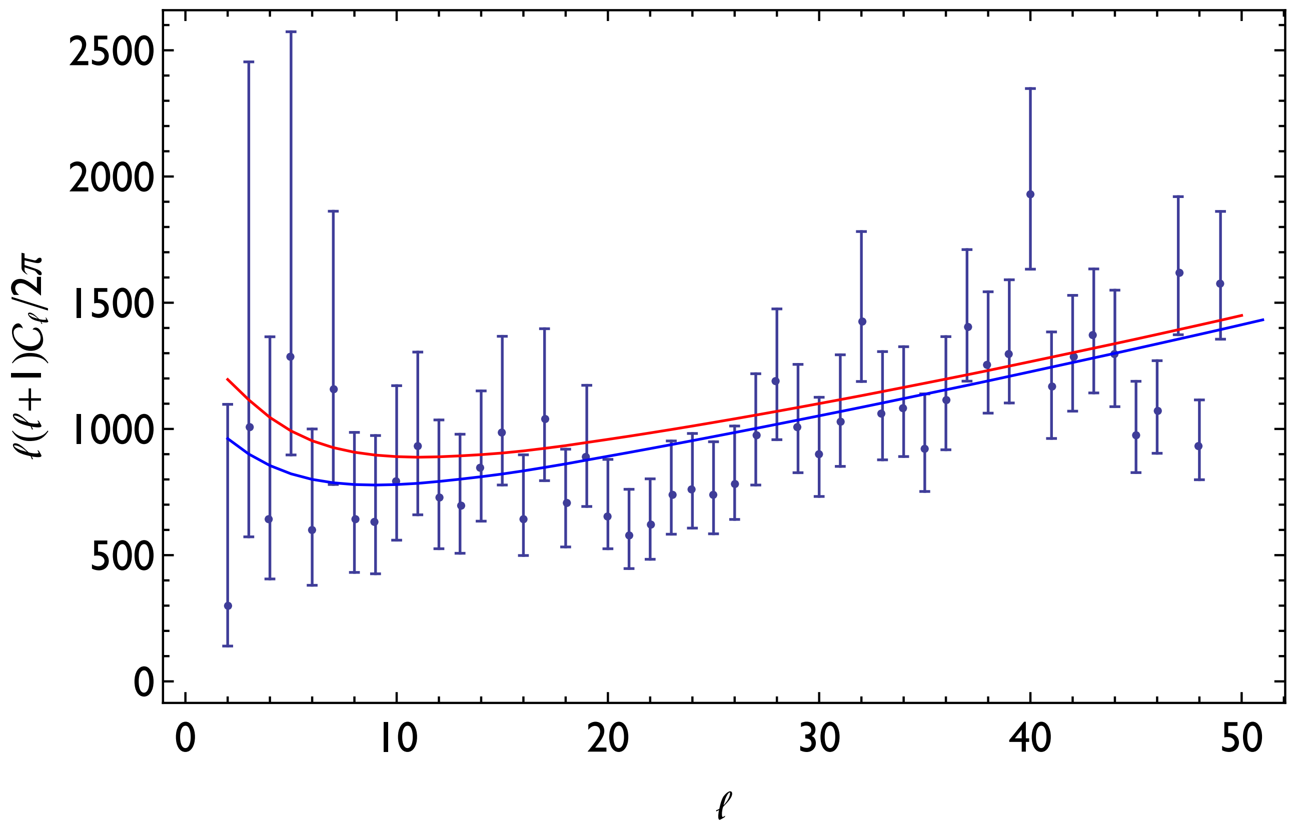
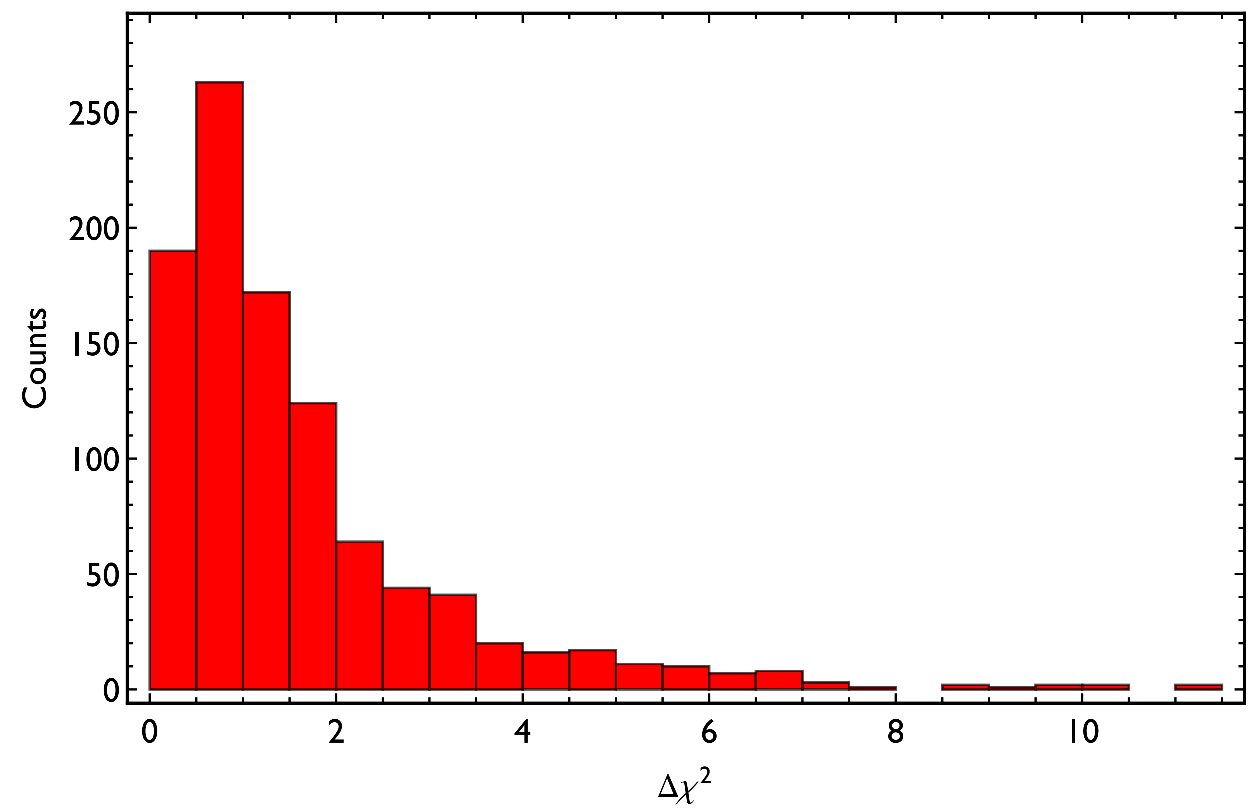
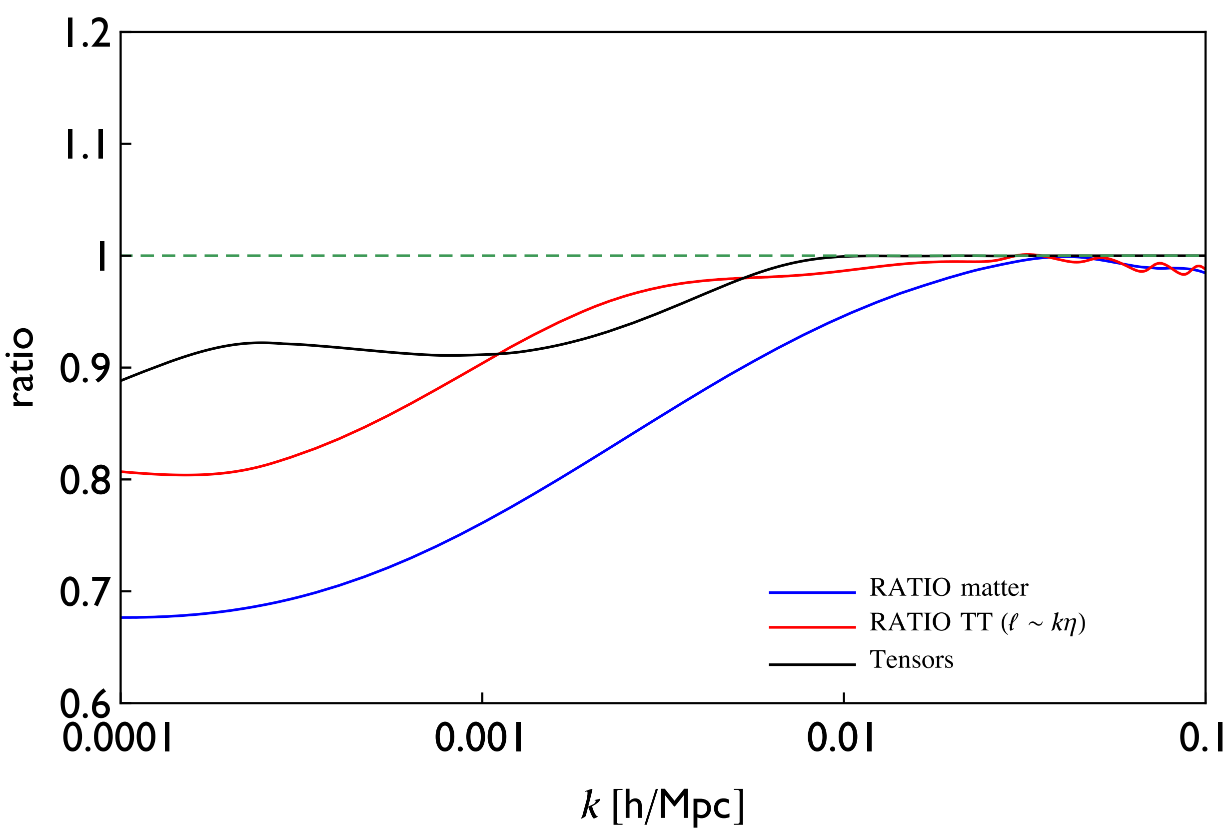
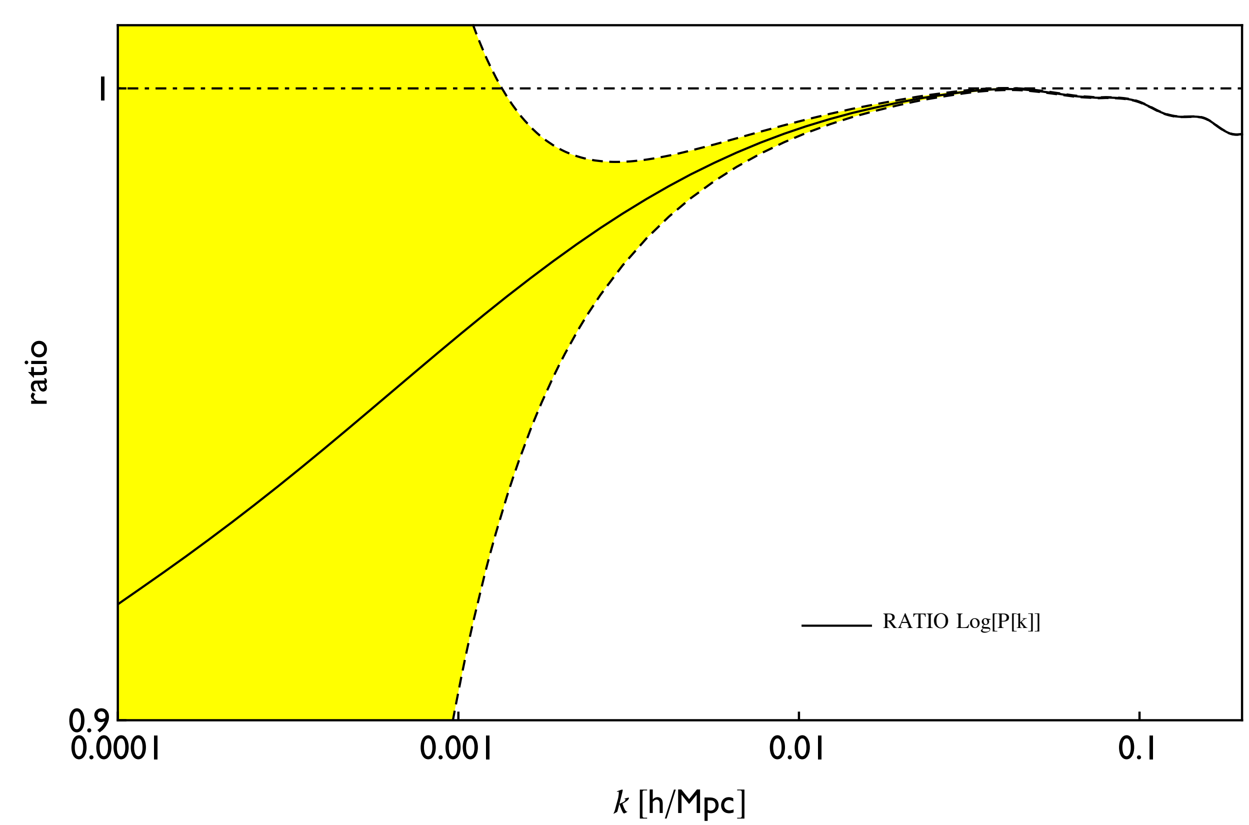






WFIRST



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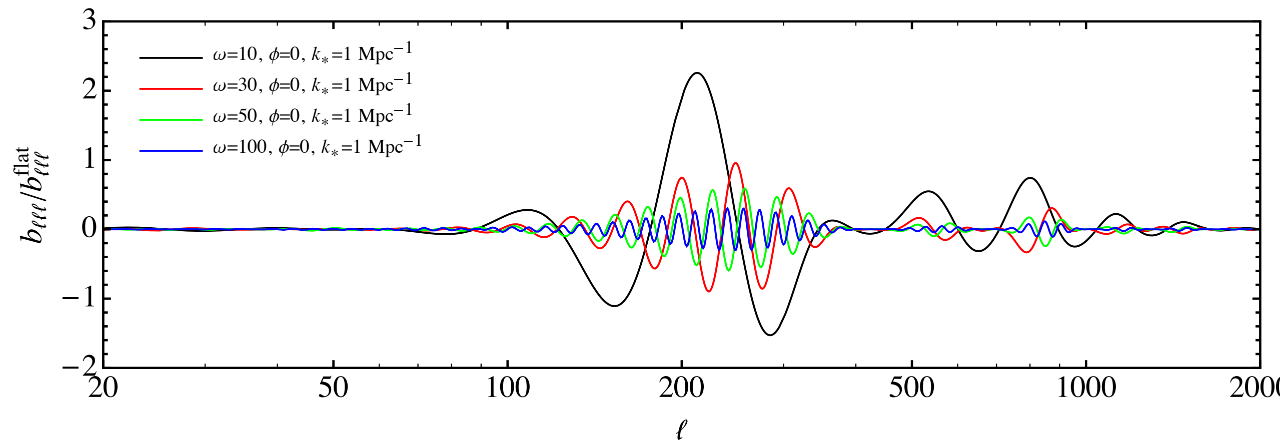
BISPECTRUM



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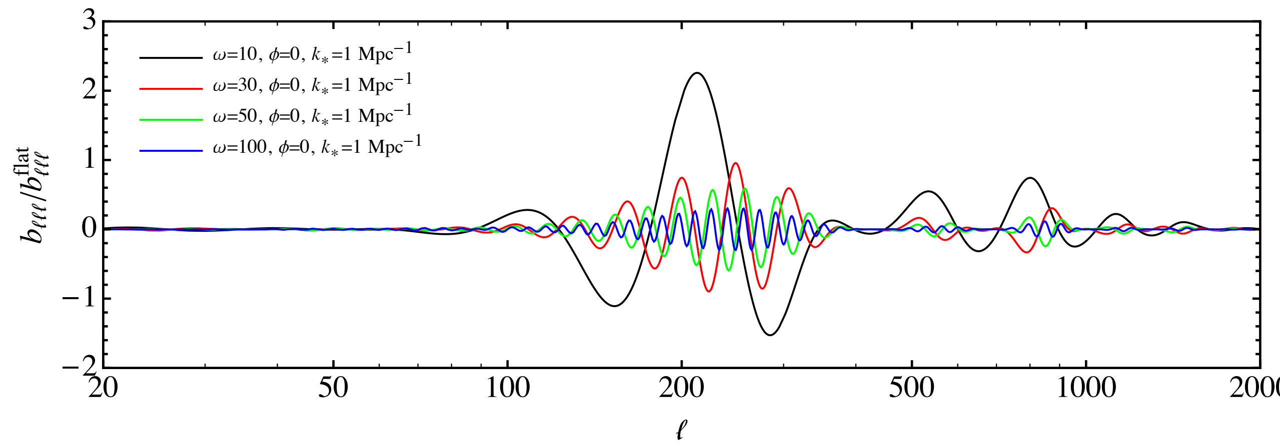
BISPECTRUM



- Bispectrum. Difficult

$$\mathrm{b}_{\ell_1\ell_2\ell_3} = \left(\frac{2}{\pi}\right)^3 \int x^2 dx \prod_i \int dk_i k_i^2 B(k_1,k_2,k_3)^{1/3} \Delta_{\ell_i}(k_i) j_{\ell_i}(k_i x)$$

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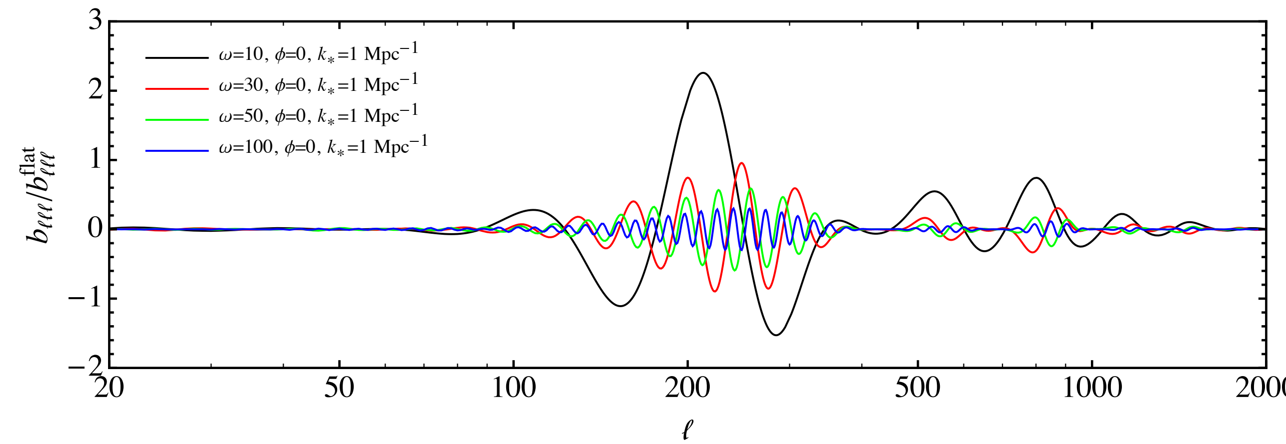
BISPECTRUM



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- Too low signal to noise in a single mode: sum over all modes: $\sum_{\text{all } \ell} b_{\ell_1\ell_2\ell_3} \star b^{\text{temp}}_{\ell_1\ell_2\ell_3}$

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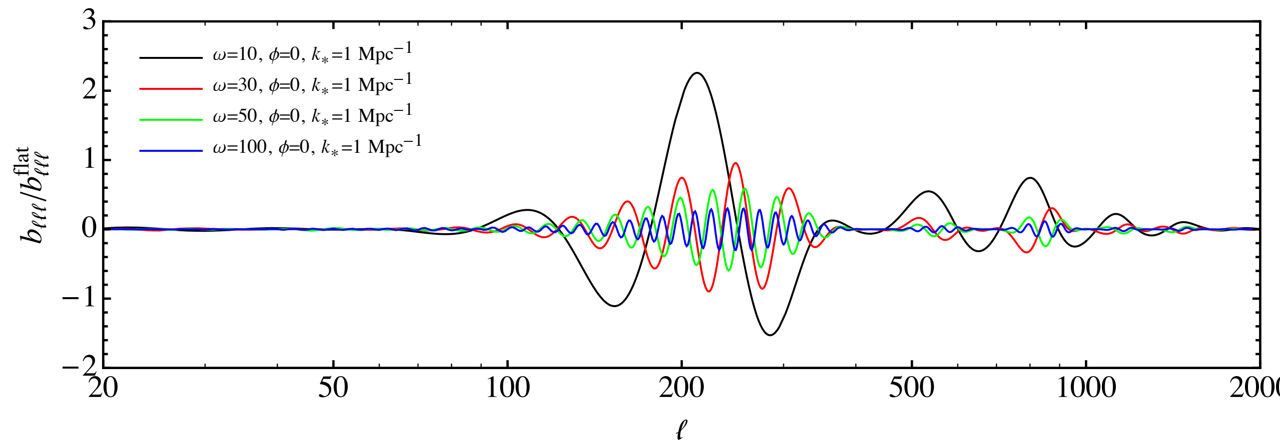
BISPECTRUM



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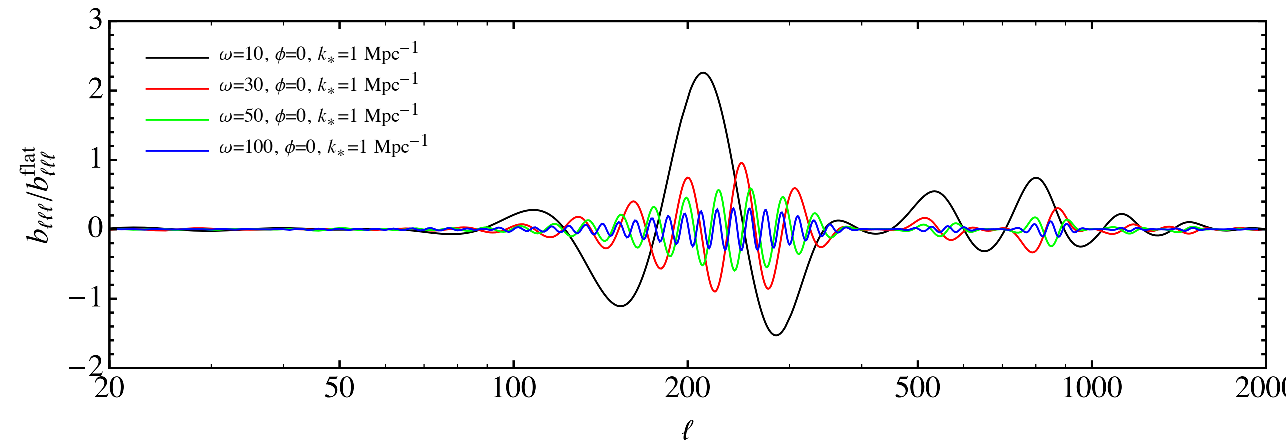

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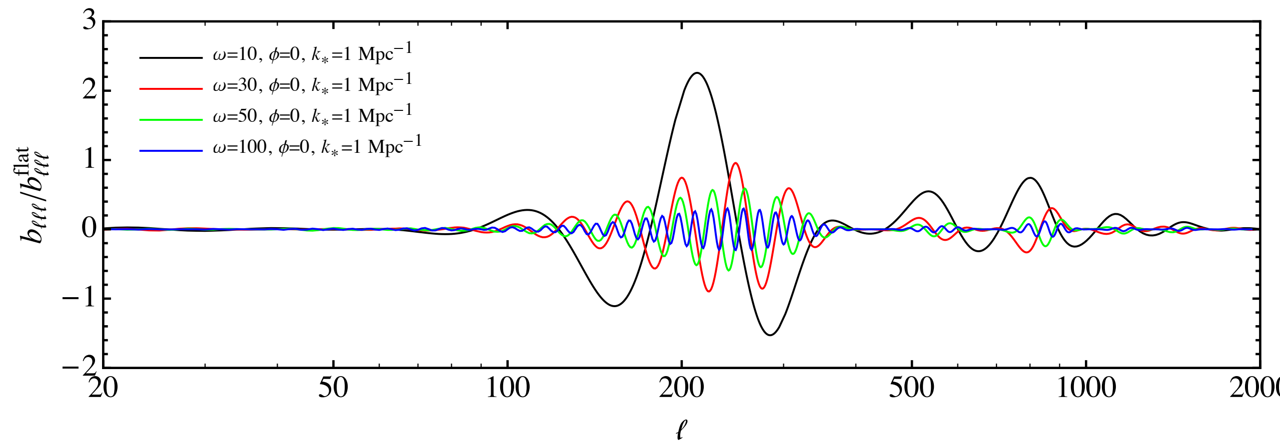
BISPECTRUM



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  - also, computationally, prefer something that is factorizable, because building an estimator would be super slow (i.e. KSW estimator)

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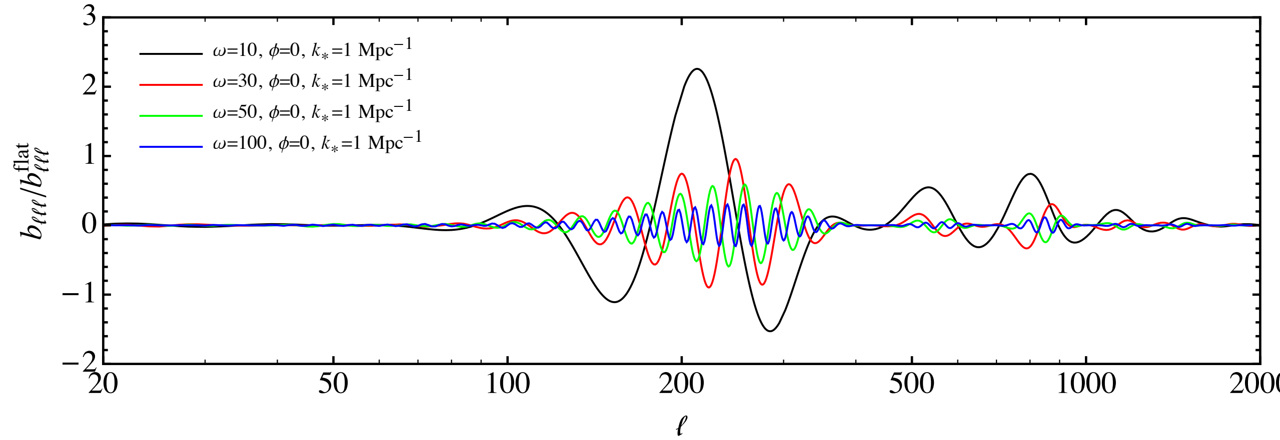
BISPECTRUM



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  - many templates are needed for different frequencies/phases
  - also, computationally, prefer something that is factorizable, because building an estimator would be super slow (i.e. KSW estimator)
  - Using Fourier expansion seems to be the most efficient

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BISPECTRUM

- Bispectra will have preserved scaling argument (log vs lin), but
  - Bispectra measure interactions, so the exact scale dependence will generally be different. Could lead to mixed effects.
  - Simplest is bispectrum of the resonant form:

$$\mathrm{B}_\Phi(k_1, k_2, k_3) = \frac{6\Delta_\Phi^2 f_{\rm NL}}{(k_1 k_2 k_3)^2} \sin\left(\omega \log \frac{k_t}{k_*} + \phi\right).$$

  - Not factorized, several ways, most efficient way:

$$\mathrm{S}(\mathrm{k}_t) = \sum_{n=0}^{N} \left(a_n \cos \frac{2\pi n k_t}{\Delta k_t} + b_n \sin \frac{2\pi n k_t}{\Delta k_t}\right)$$

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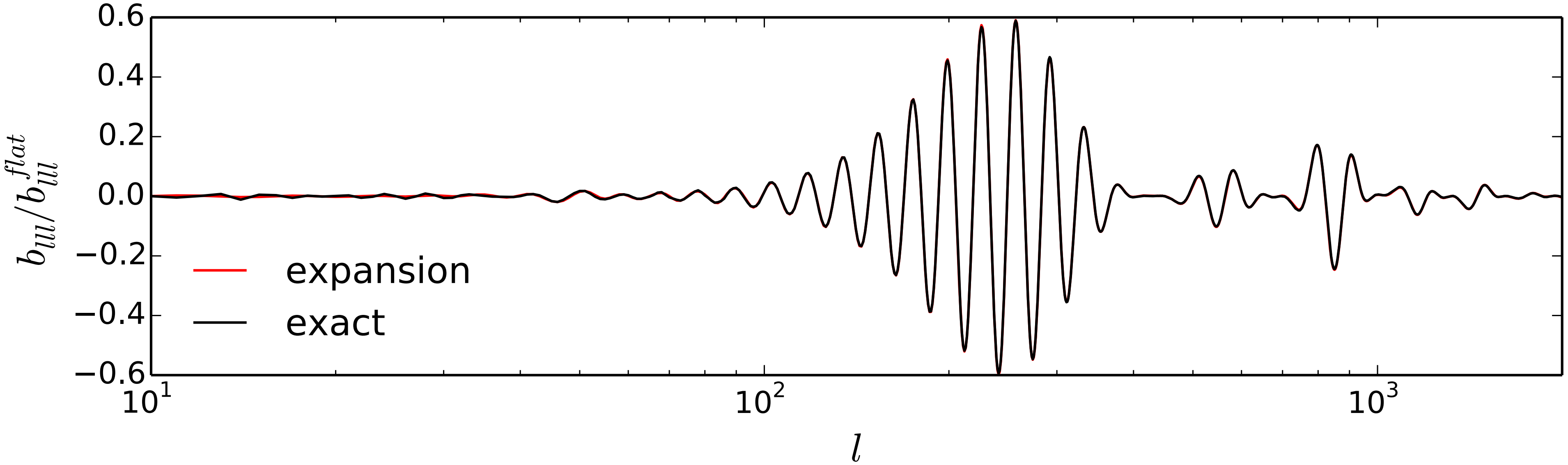
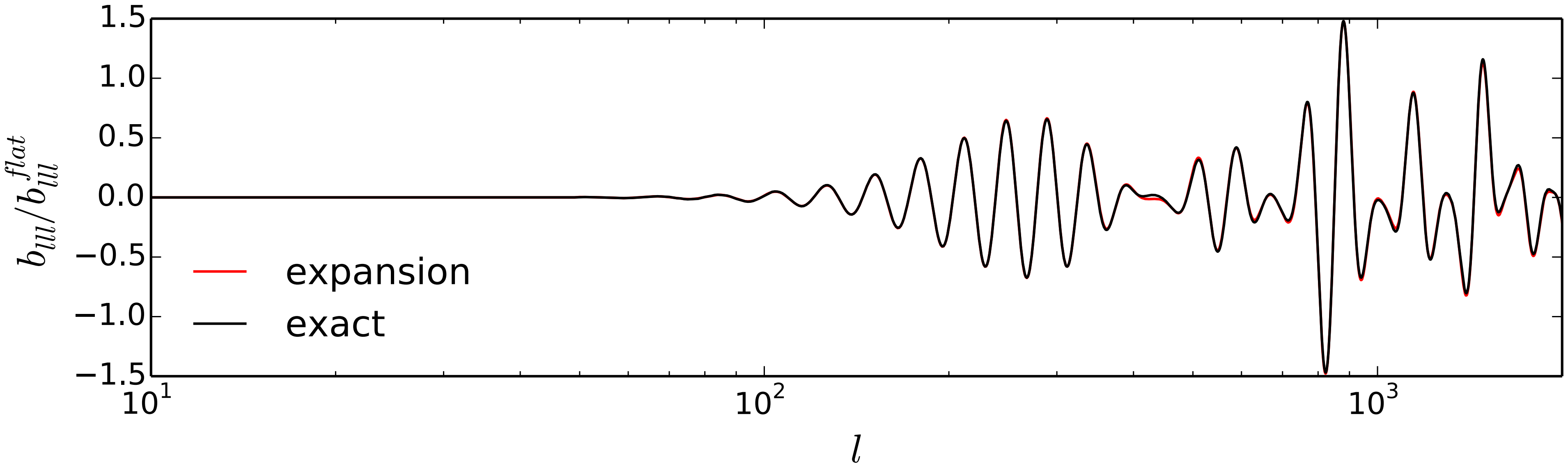
BISPECTRUM





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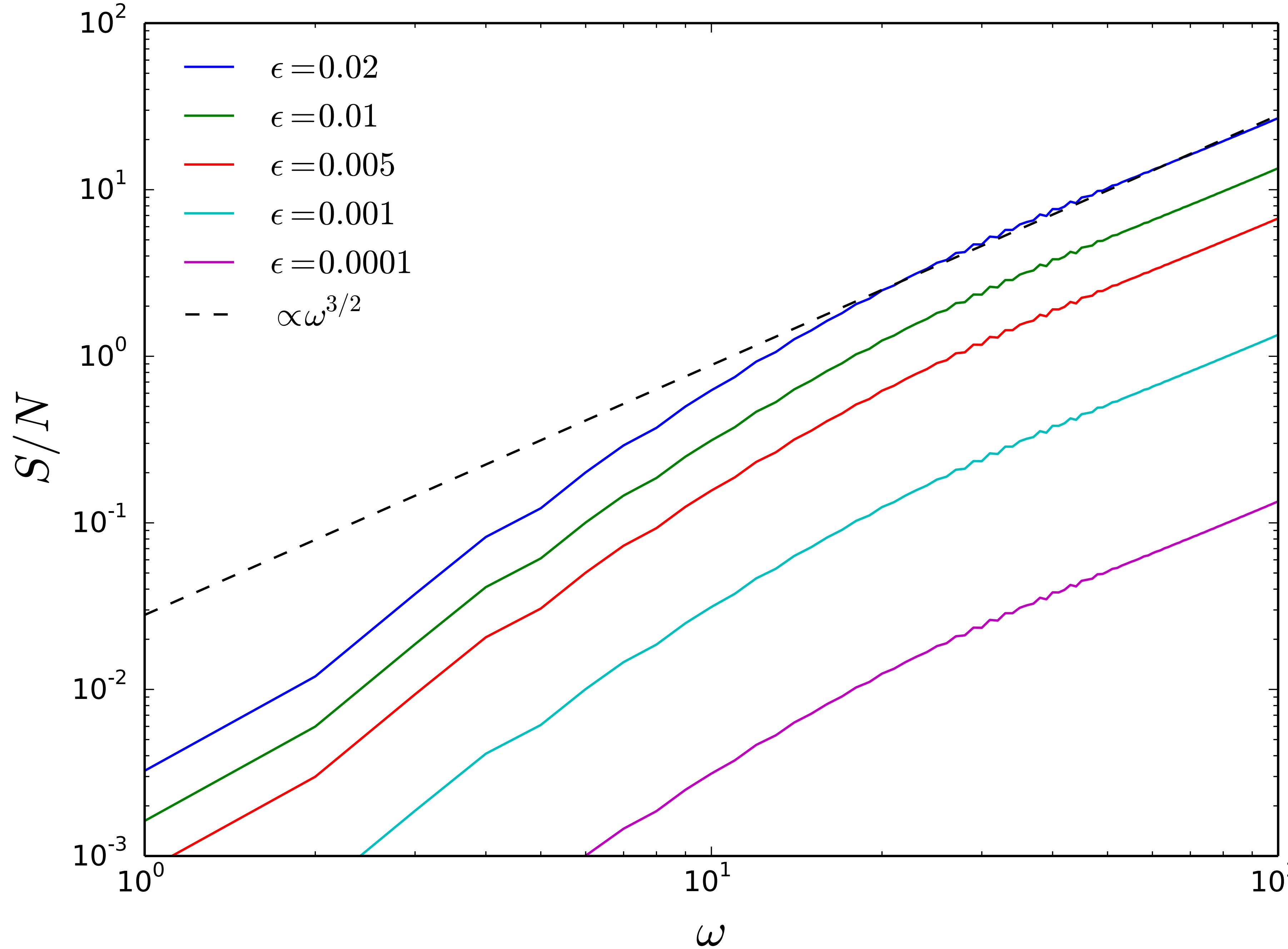

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WHAT DRIVES INFLATION?

- Motivation for features
- Results from Planck
- Discussion

DID INFLATION HAPPEN?

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- Results from Planck/BICEP/ LIGO/PTA/BBN
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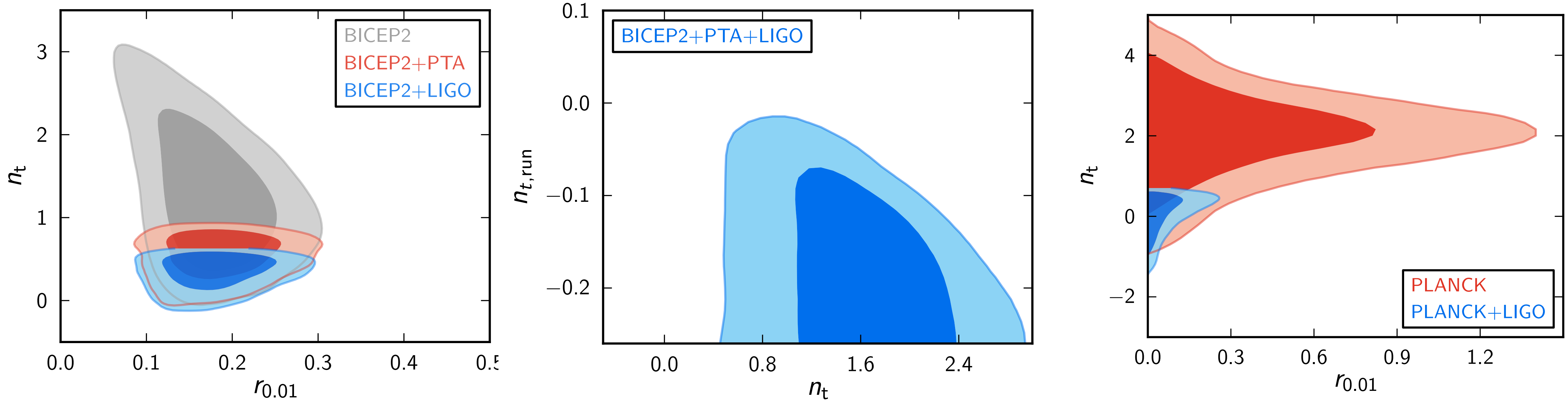
  - Relation between power in tensors and scale dependence in tensors: $\mathrm{n}_t = -r/8$
- Why?
  - Unique prediction from ‘inflation’. Even for more fields. At least tilt is always blue. Would violate null energy condition.
  - Counter examples: Ekpyrotic, or inverse decay of Gauge quanta.

INFLATION CONSISTENCY CONDITION

- For (accurate) tilt measurement (at level of this relation), would need other measures (then CMB).
- Direct detection? Probably. Hard, see e.g. Dodelson (2014), Boyle et al (2014). BBO? Elisa?
- What do we know now?
- CMB only, CMB+LIGO+PTA, CMB++ (BBN?), -BICEP?

RESULTS (1)

Testing inflation consistency condition w current data: $n_t = -r/8$



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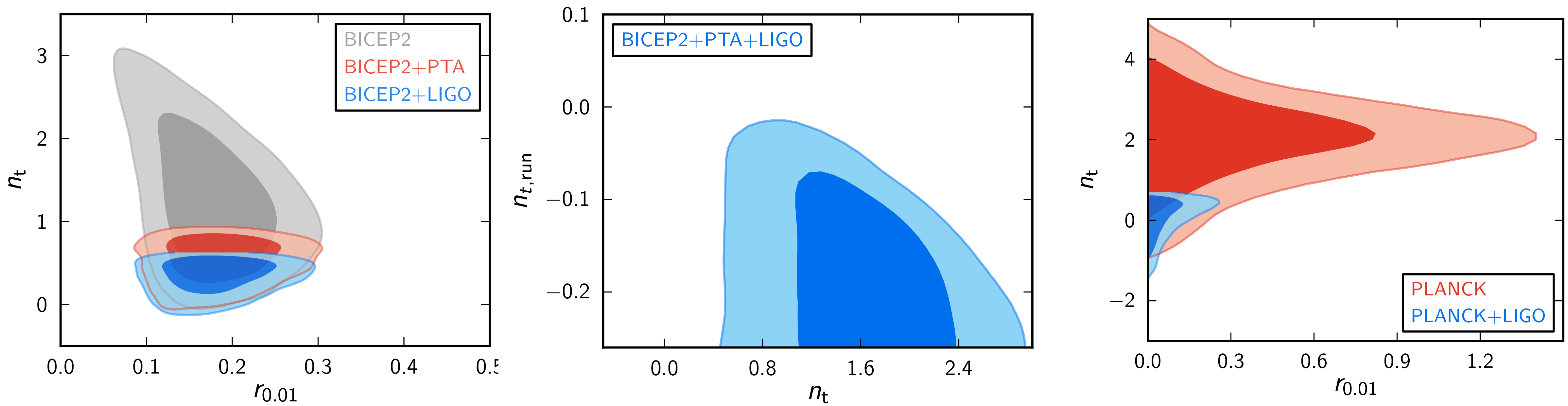

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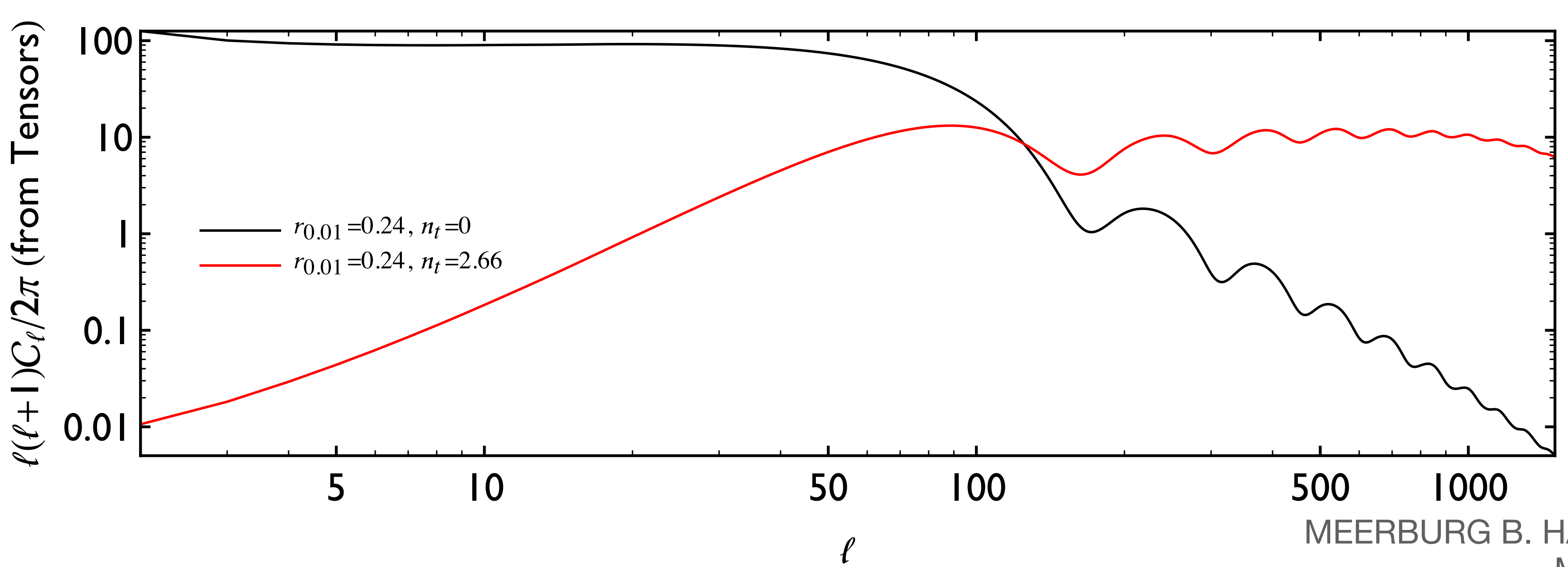

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RESULTS (2)

What about background expansion? Too much GW's would change expansion history, BBN?

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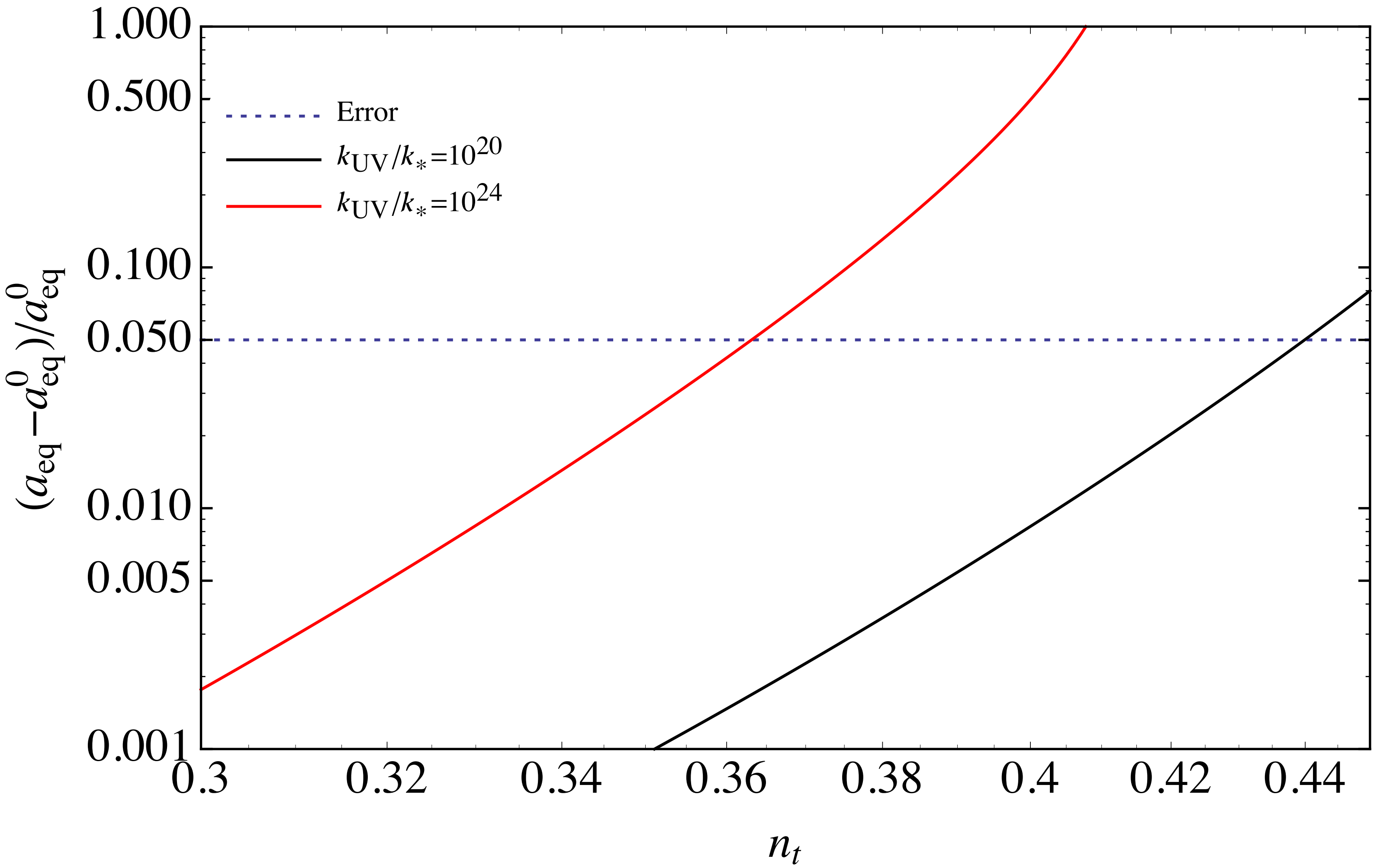

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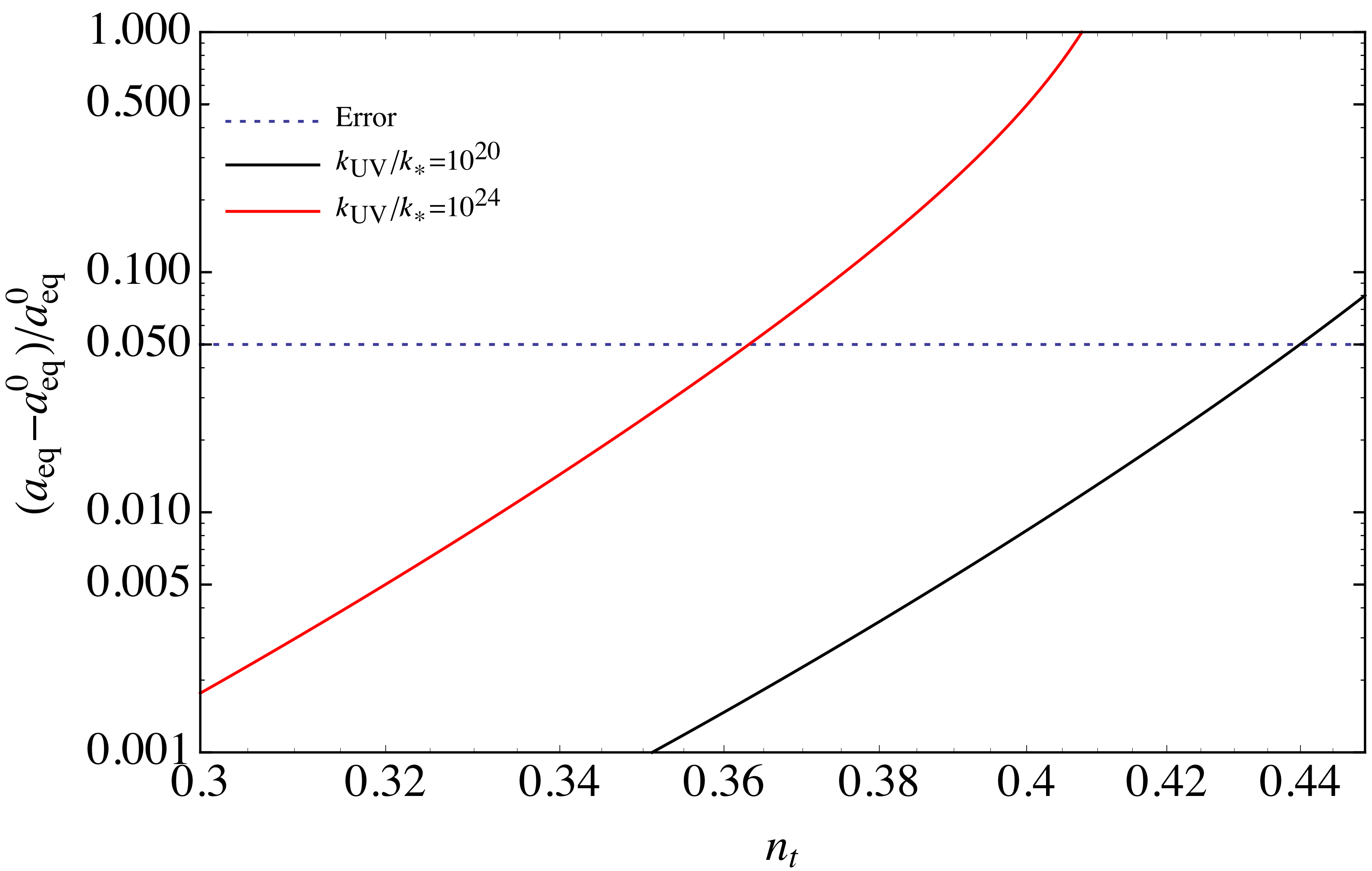

So, yes, matters. But depends strongly on UV cutoff. Also, above constraint should really come from Neff (which is more complicated, see e.g. Bashinsky & Seljak 2003). Error bar is bigger, about 10 percent w Planck 2014.

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WHAT DRIVES INFLATION?

- **Features? Somewhat natural, measurement would be profound.** **Perturbative approach; fast and accurate**
  - Log spaced oscillations:
    - WMAP 9 signature has mostly disappeared.
    - New low freq. signatures. Mild correlation with lensing amplitude.
  - Linear spaced oscillations.
    - WMAP 9 and Planck are consistent
- **Are these real?** Most likely not (at 95% C.L.)
- **Bicep would favor running/long wavelength oscillation** at almost 3 sigma

DID INFLATION HAPPEN?

- **Test inflation consistency condition**
    - LIGO and expansion history give very similar constraints
    - Near future, LIGO will be better. Long term, BBO.
- There exists some model dependence, i.e. cutoff scale etc.
- LIGO will also be dominated by mergers, so constraint is conservative.
- For (too) negative tilt, IR divergence. Is this a bigger problem (what about super horizon modes?) GW energy density no longer well defined? (only back reaction on the metric).