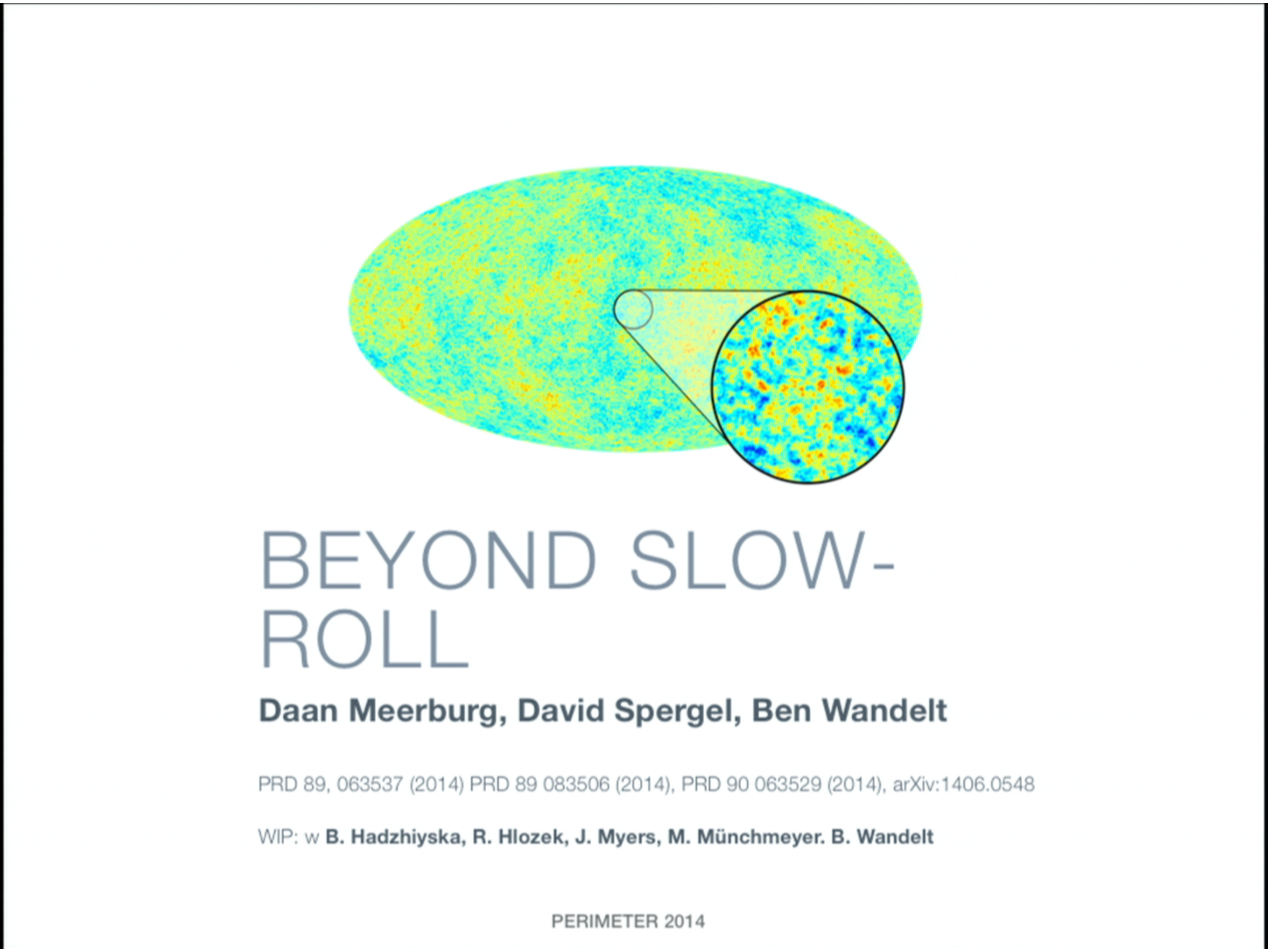
Title: Beyond slow-roll - Daan Meerburg

Date: Oct 28, 2014 11:00 AM

URL: http://pirsa.org/14100119

Abstract: We live in exciting times for cosmologists. There is a plethora of cosmological experiments that allow us to reconstruct the earliest moments in the Universe and test our ideas on how the Universe came into existence. Current data appear to favor an inflationary model that produces adiabatic, scale free, Gaussian fluctuations with an amplitude of 10^-5 in units of mK. WIthin the realm of cosmological models, it appears that such conditions are easily accomplished if we have a single light field slowly rolling down its potential. In this talk, I will investigate the possibility to what extend our current observations would allow for a deviation from slow-roll: several class of models predicts that the fluctuation spectra will contain superimposed features on top of their slow-roll solution. I will discuss these models and explain a novel way of extract these features from the data, both in the power spectrum as well as in the bispectrum. I will give the latest constraints from current cosmological surveys. In light of the possible detection of primordial gravitational waves, I will show that there exists evidence (3 sigma) that the data prefer a long wavelength feature driven by axion monodromy, a model that naturally predicts large tensor modes. From this I will derive a constraint on the axion decay constant. I will conclude with a discussion on how observations of higher order statistics and large scale structure could further constrain these models.



BEYOND SLOW-ROLL

Daan Meerburg, David Spergel, Ben Wandelt

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

WIP: w **B. Hadzhiyska, R. Hlozek, J. Myers, M. Münchmeyer. B. Wandelt**

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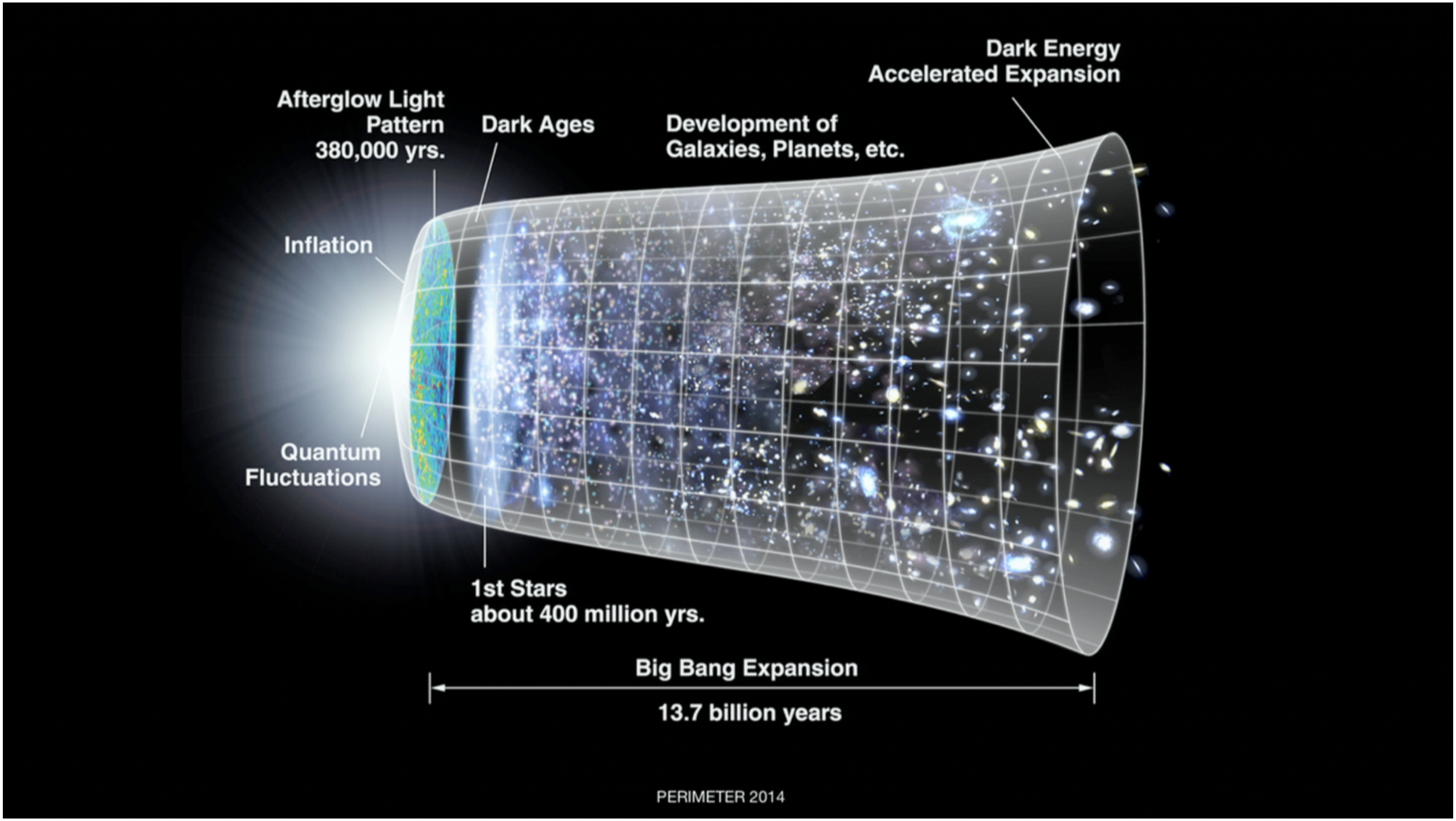
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
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Inflation
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1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
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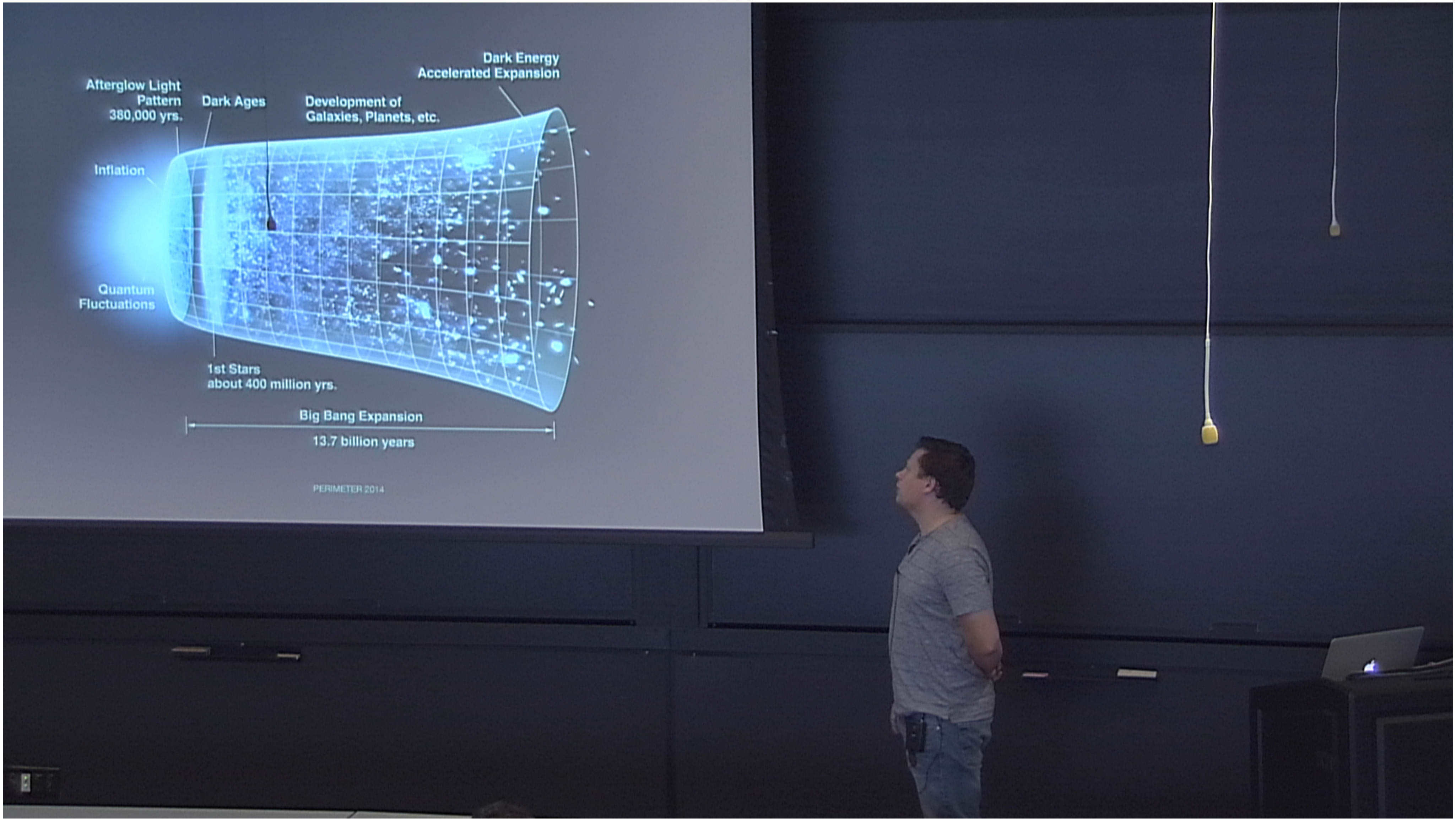
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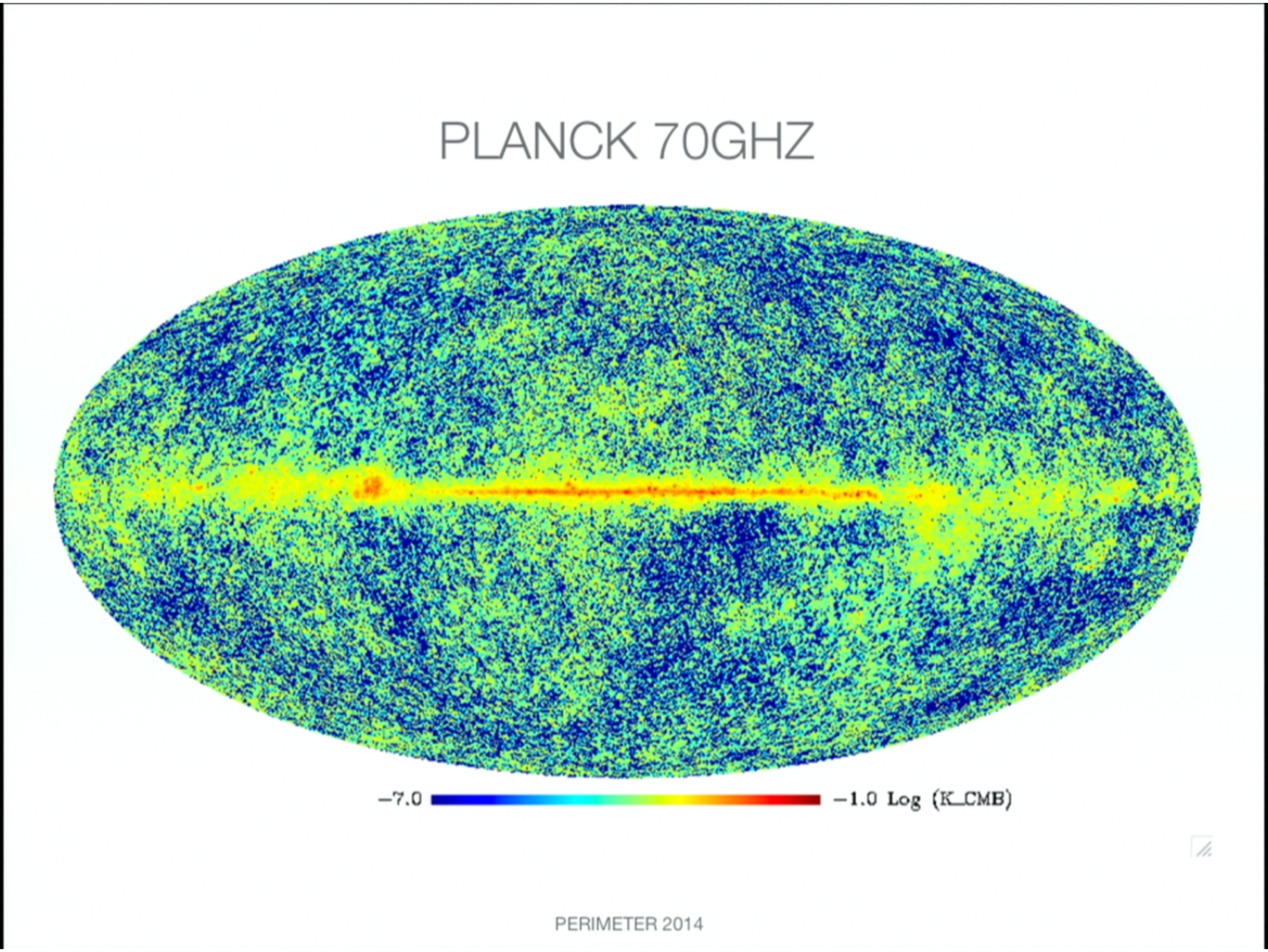

PLANCK 70GHZ

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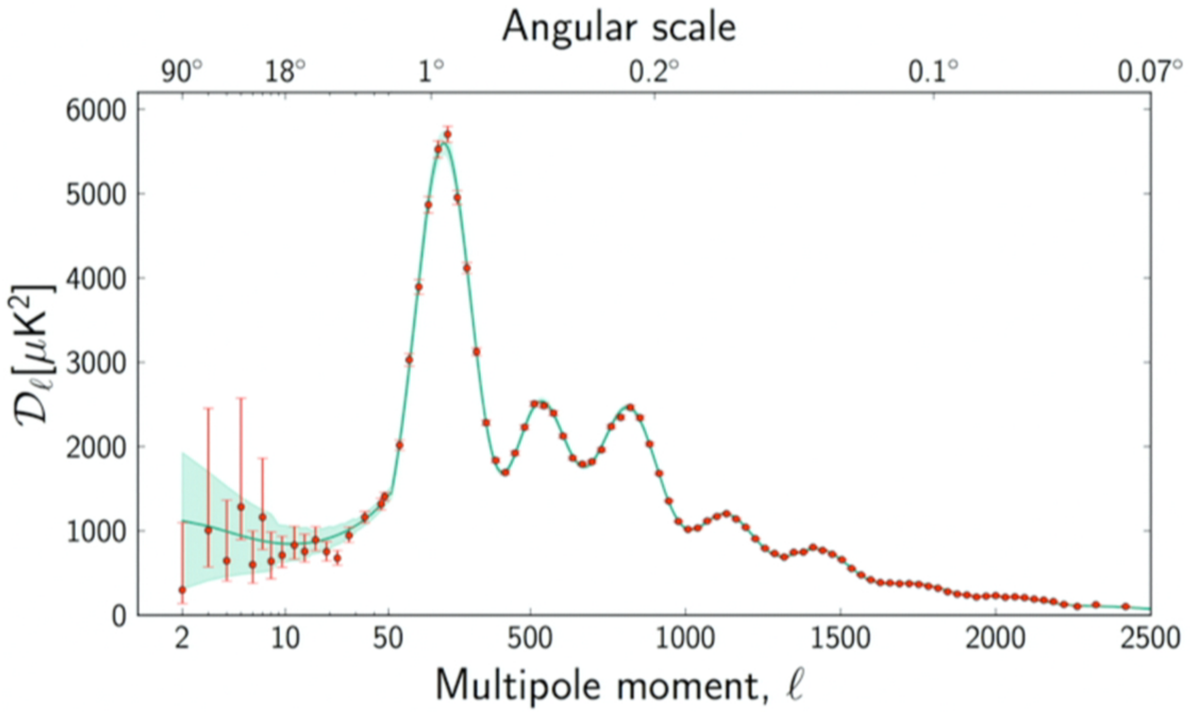

PLANCK COLLABORATION 2013

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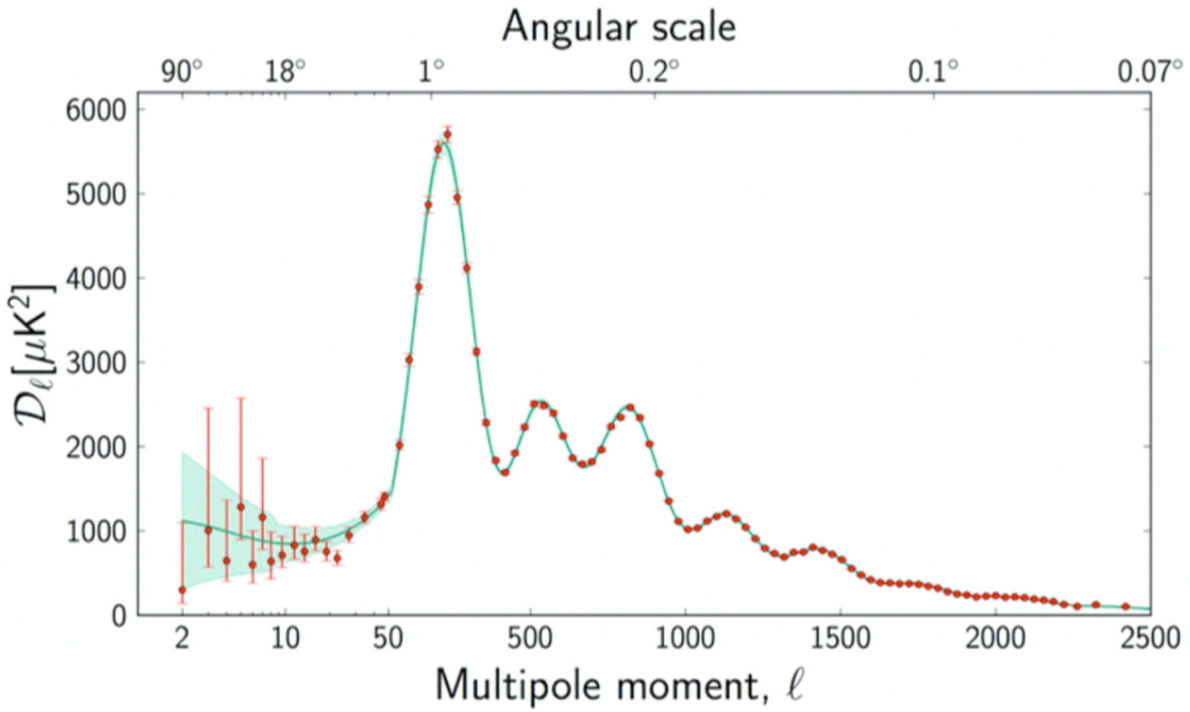

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	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	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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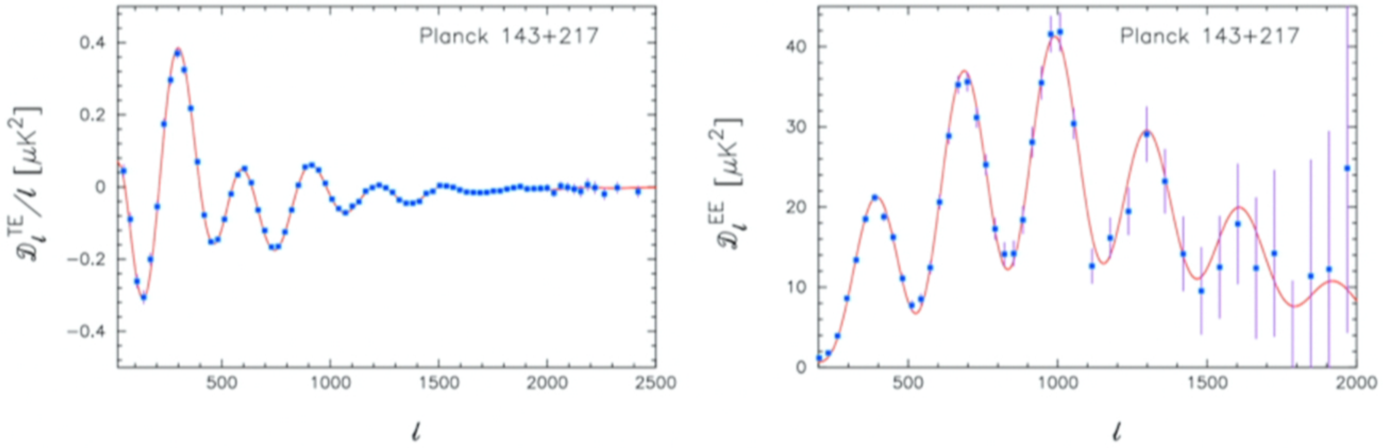
PLANCK COLLABORATION 2013



PLANCK COLLABORATION 2013

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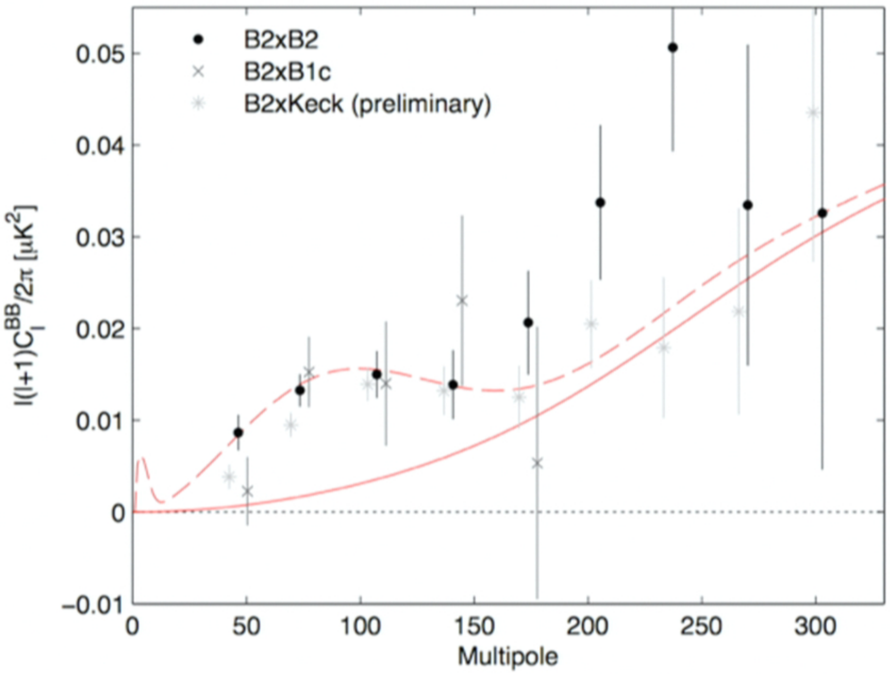

PLANCK COLLABORATION 2013

BICEP COLLABORATION 2014

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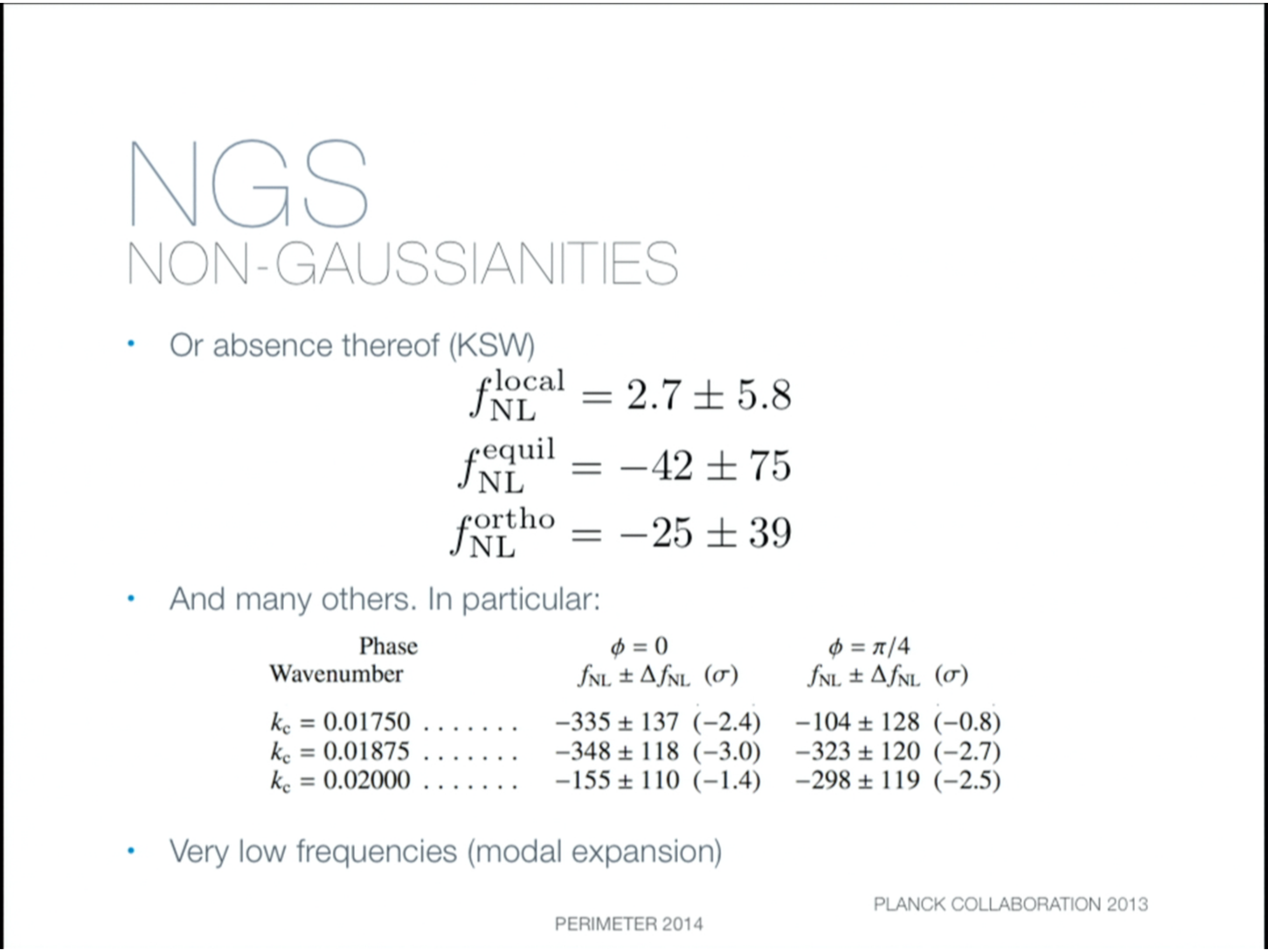

NGS

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	$\phi = 0$	$\phi = \pi/4$
Wavenumber	$f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)	$f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)
$k_{\rm c} = 0.01750$	-335 ± 137 (-2.4)	-104 ± 128 (-0.8)
$k_{\rm c} = 0.01875$	-348 ± 118 (-3.0)	-323 ± 120 (-2.7)
$k_{\rm c} = 0.02000$	-155 ± 110 (-1.4)	-298 ± 119 (-2.5)

- Very low frequencies (modal expansion)

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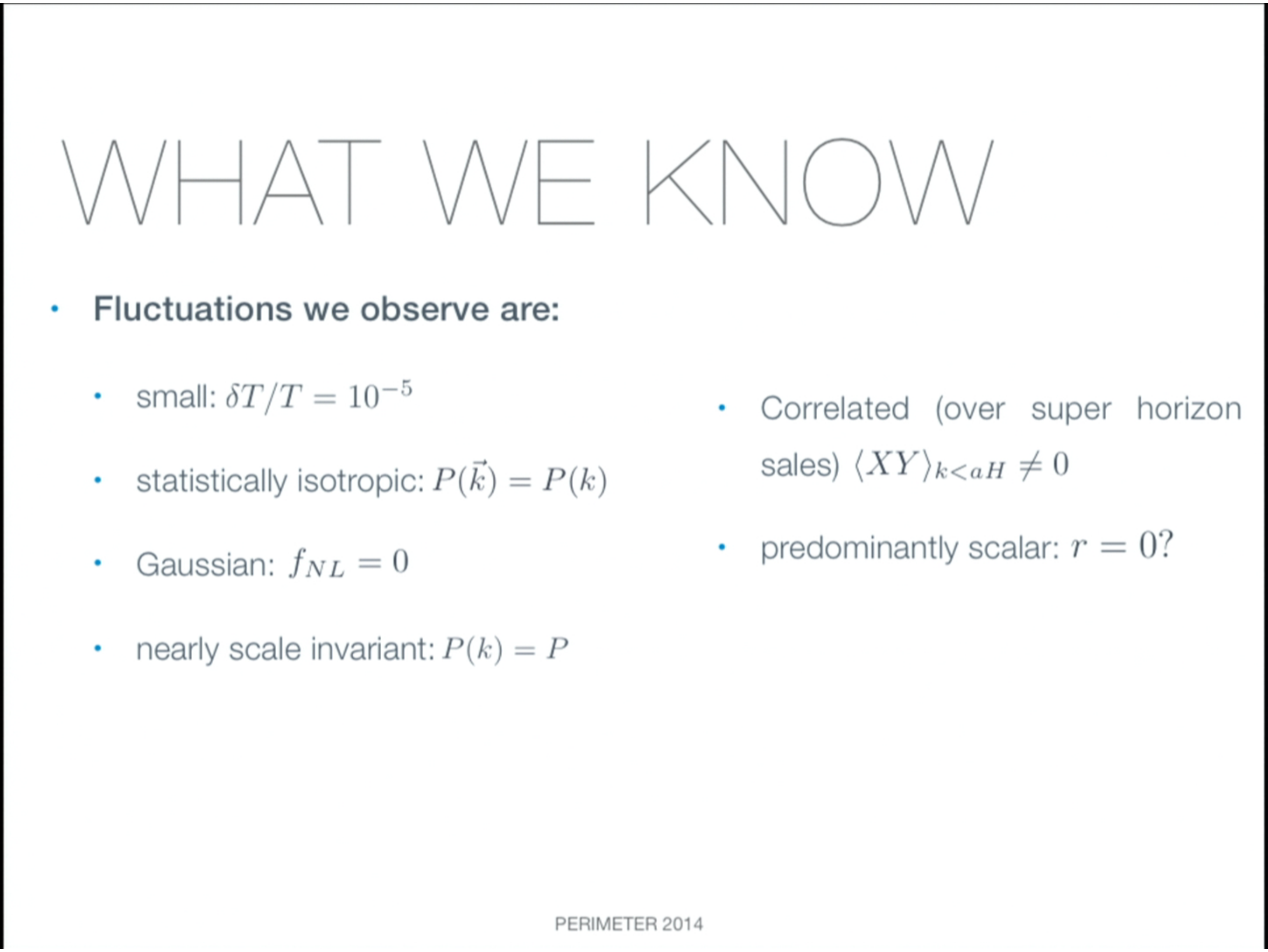
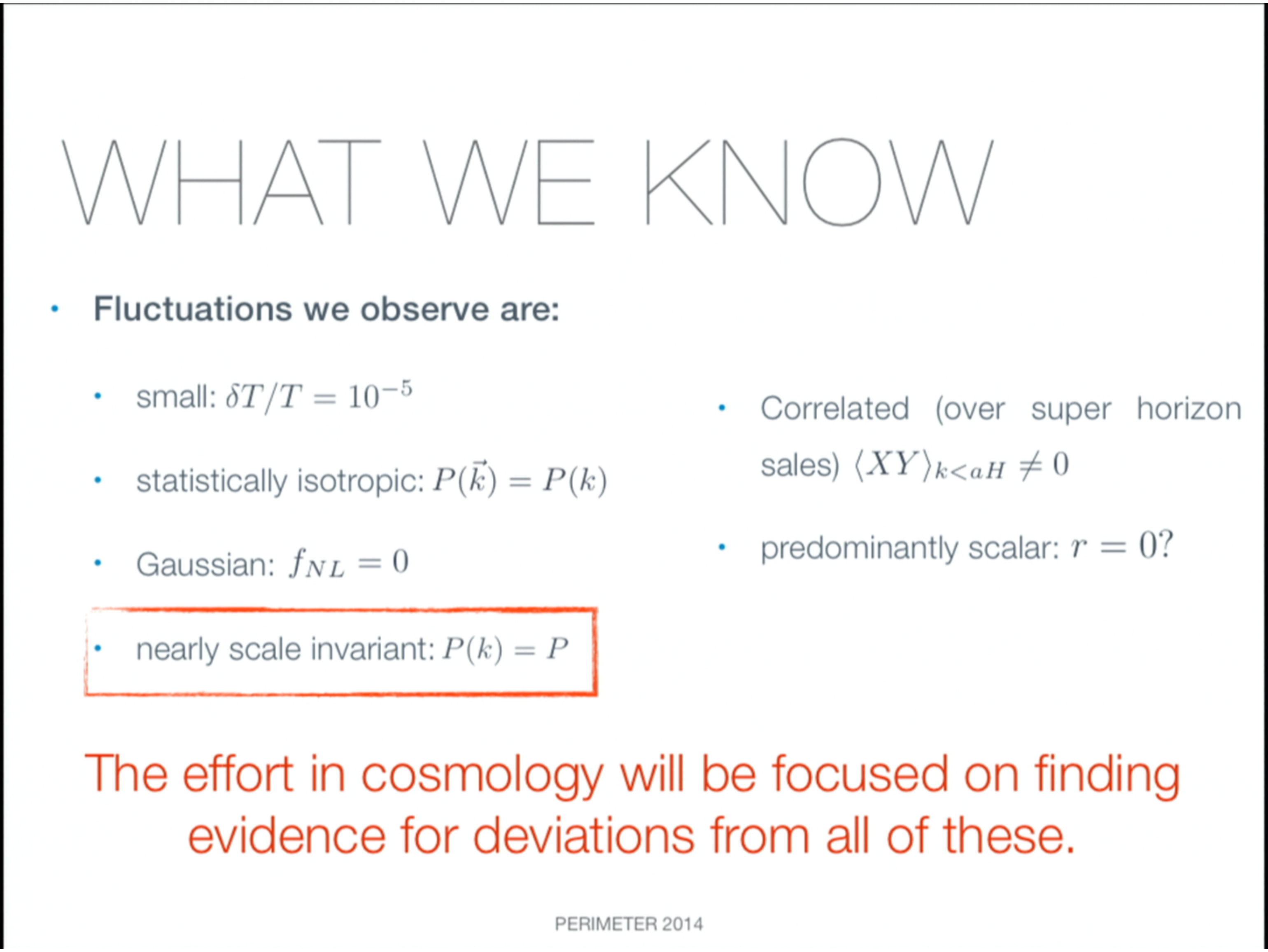


WHAT WE KNOW

- **Fluctuations we observe are:**
  - small: $\delta T/T = 10^{-5}$
  - statistically isotropic: $P(\vec{k}) = P(k)$
  - Gaussian: $f_{NL} = 0$
  - nearly scale invariant: $P(k) = P$
  - Correlated (over super horizon sales) $\langle XY \rangle_{k<aH} \neq 0$
  - predominantly scalar: $r = 0?$



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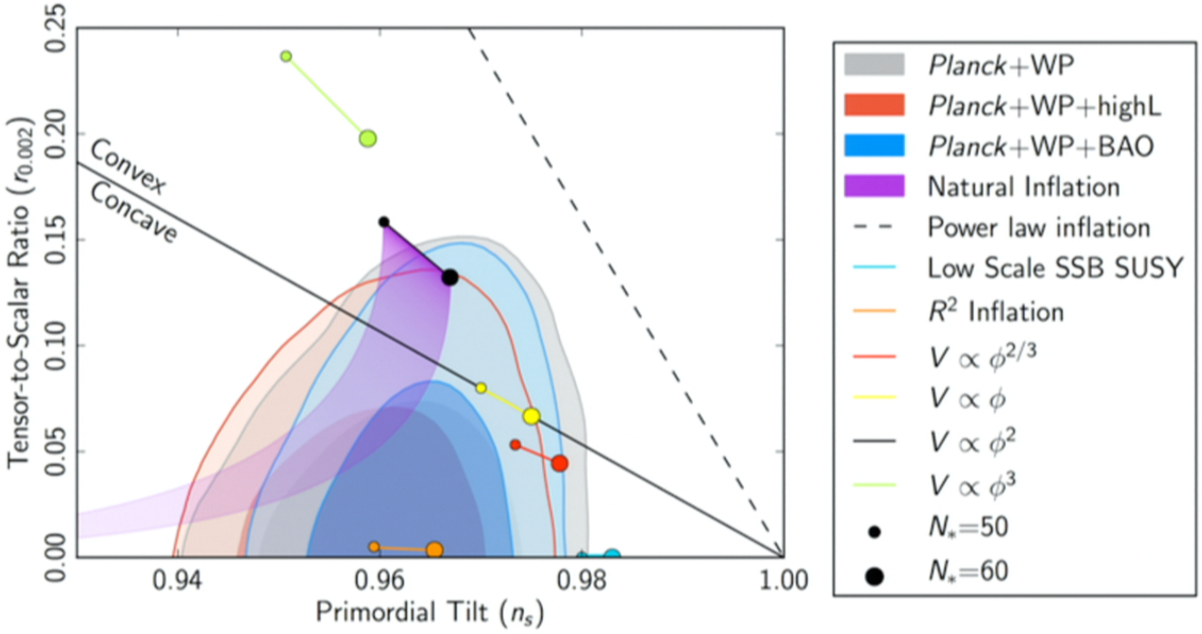
The effort in cosmology will be focused on finding evidence for deviations from all of these.

OUTLINE

- Theoretical motivation for features
- Complication and solutions
- Results
- Discussion
- Non-Gaussianities and BICEP

The Universe Pre-Bicep



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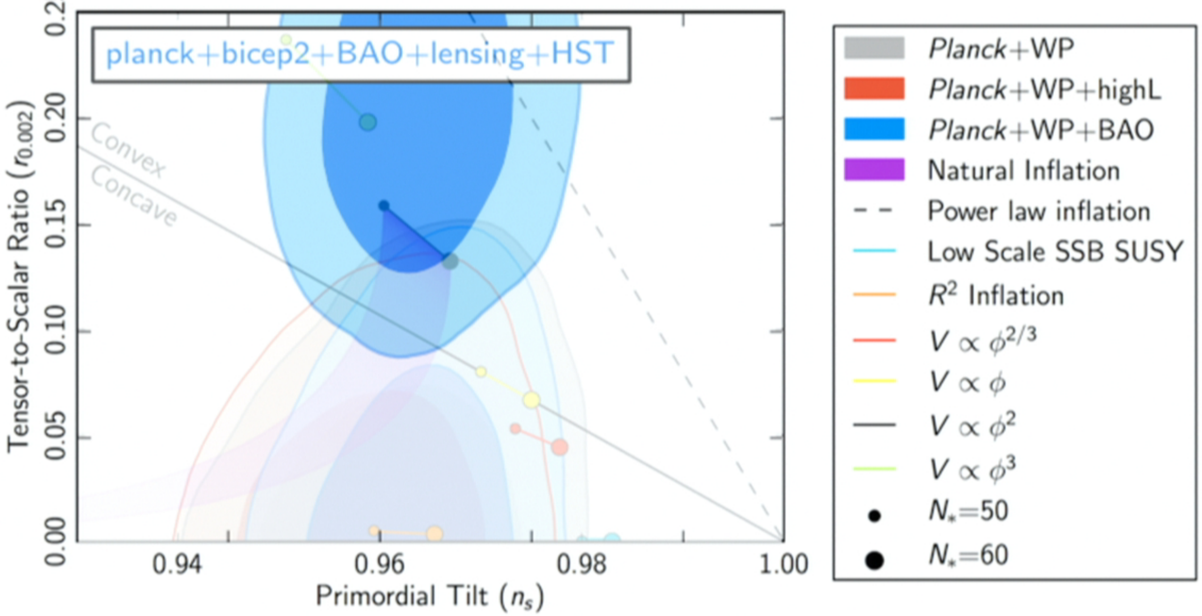
The Universe Post-Bicep (pre-Planck-dust)



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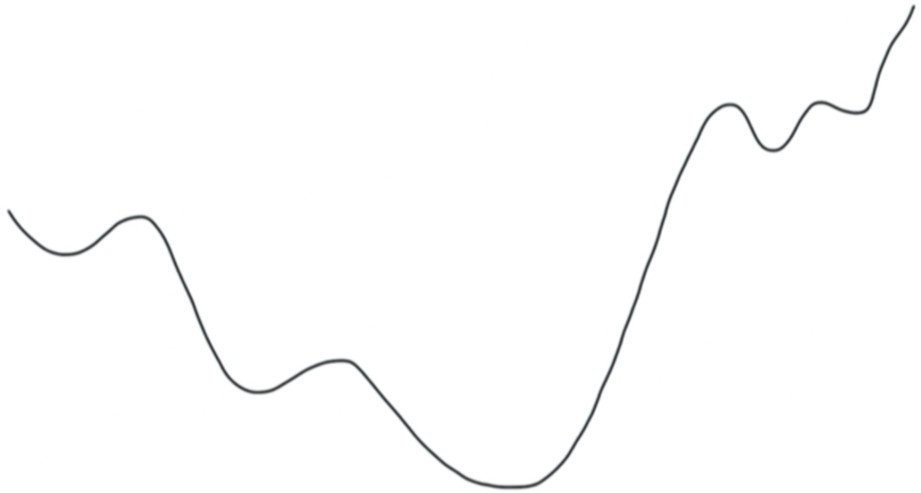
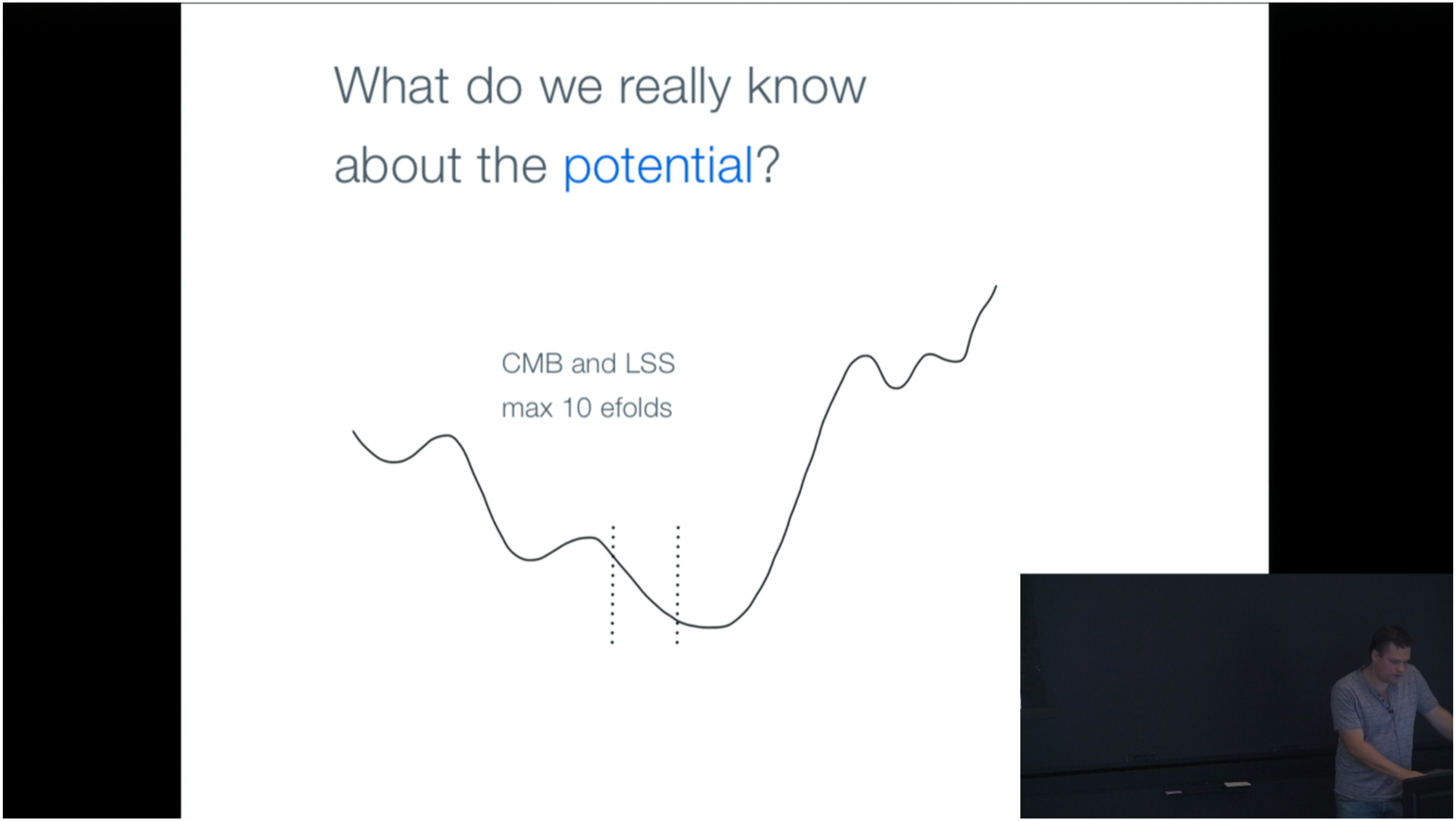
What do we really know about the potential?

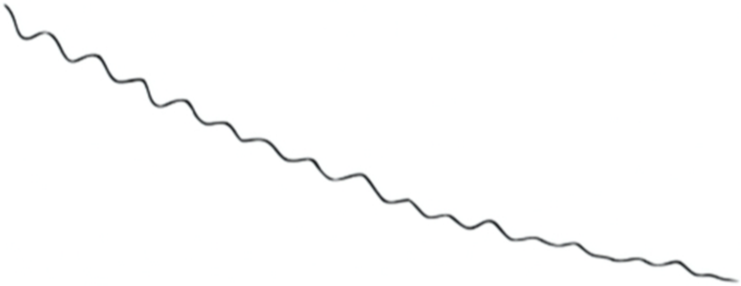


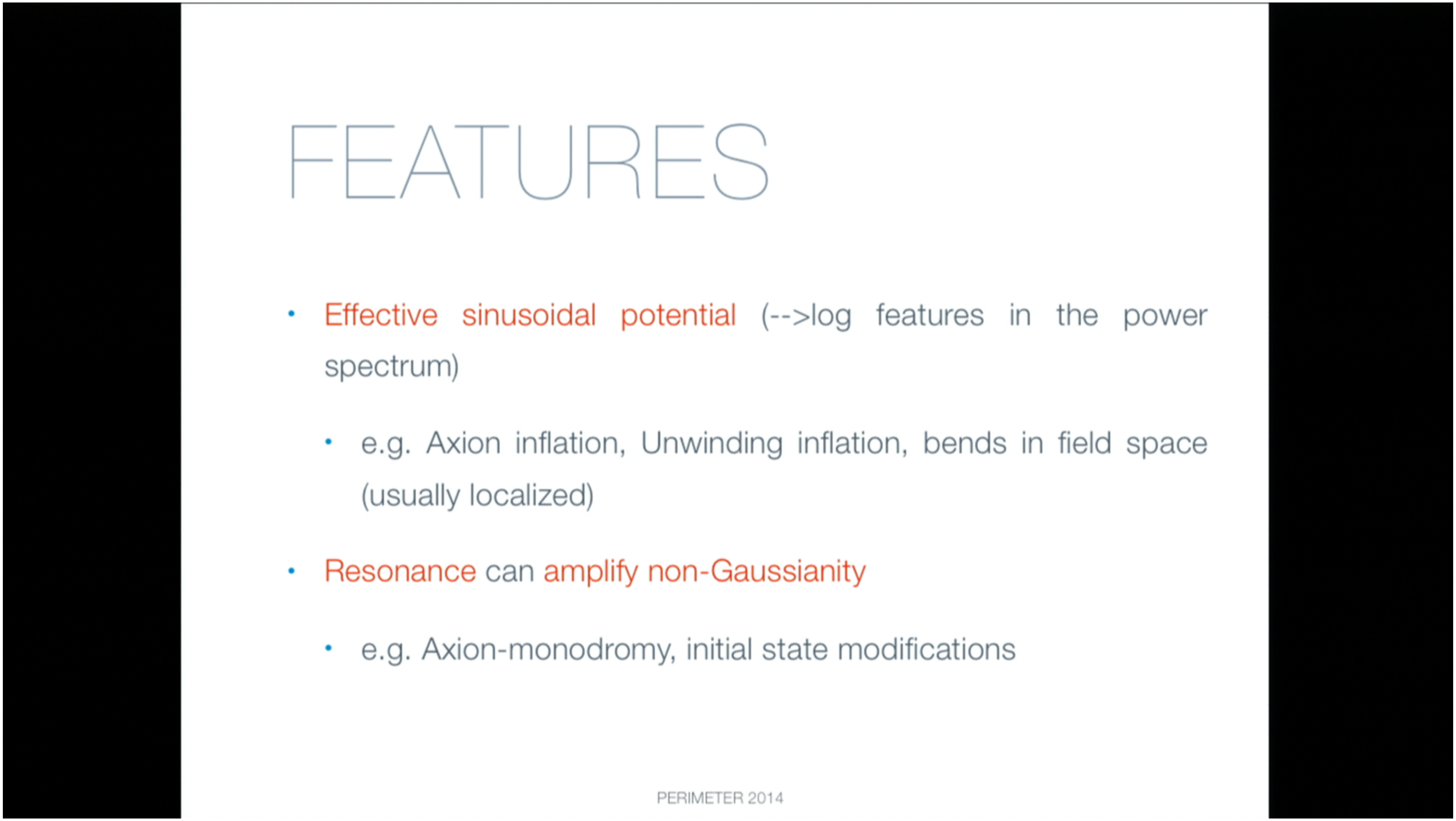


What do we really know about the potential?

CMB and LSS
max 10 efolds

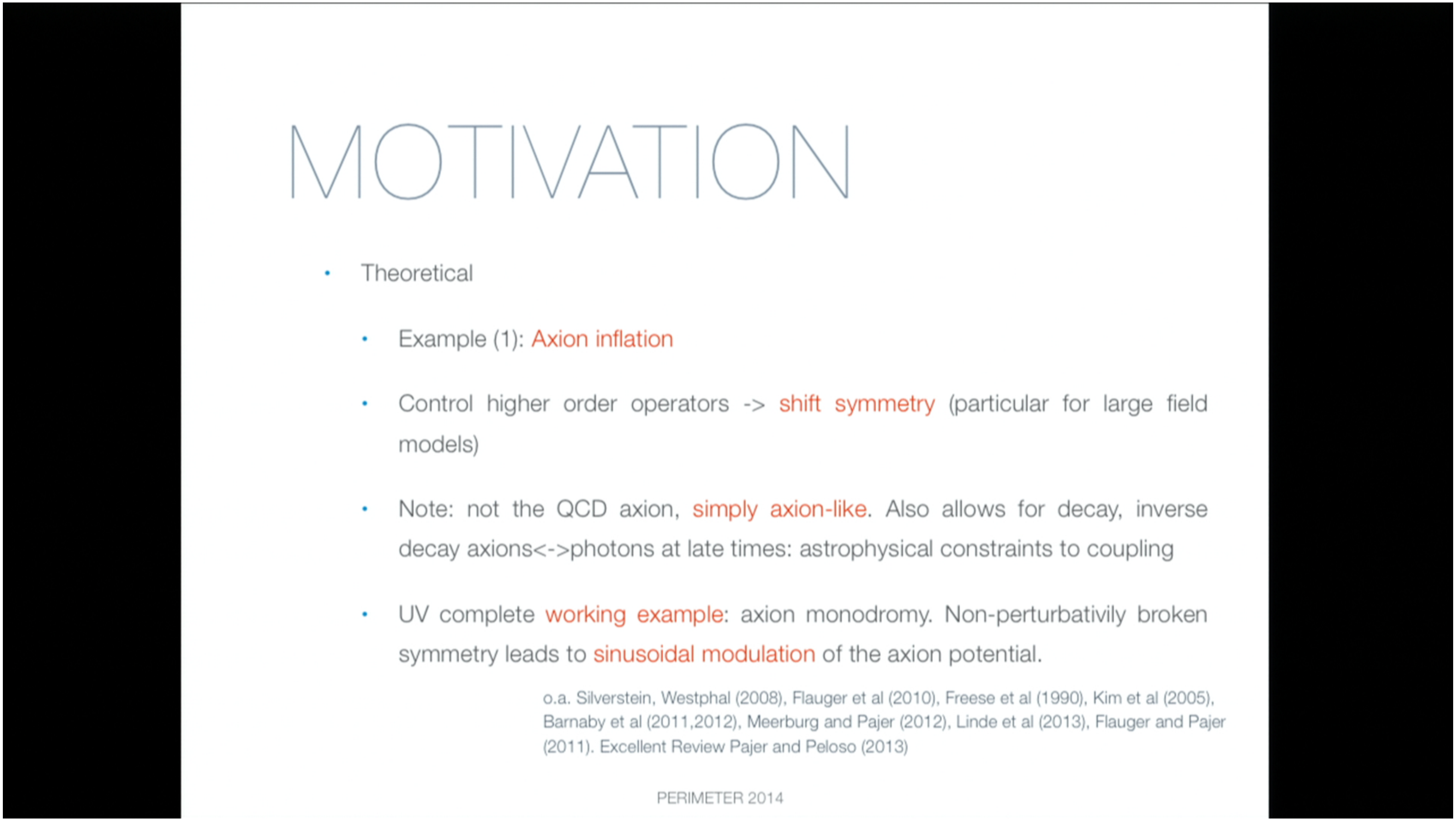
Can we extract anything beyond first few derivatives?





FEATURES

- Effective sinusoidal potential (-->log features in the power spectrum)
  - e.g. Axion inflation, Unwinding inflation, bends in field space (usually localized)
- Resonance can amplify non-Gaussianity
  - e.g. Axion-monodromy, initial state modifications



MOTIVATION

- Theoretical
  - Example (1): Axion inflation
  - Control higher order operators -> shift symmetry (particular for large field models)
  - Note: not the QCD axion, simply axion-like. Also allows for decay, inverse decay axions<->photons at late times: astrophysical constraints to coupling
  - UV complete working example: axion monodromy. Non-perturbativily broken symmetry leads to sinusoidal modulation of the axion potential.

o.a. Silverstein, Westphal (2008), Flauger et al (2010), Freese et al (1990), Kim et al (2005), Barnaby et al (2011,2012), Meerburg and Pajer (2012), Linde et al (2013), Flauger and Pajer (2011). Excellent Review Pajer and Peloso (2013)

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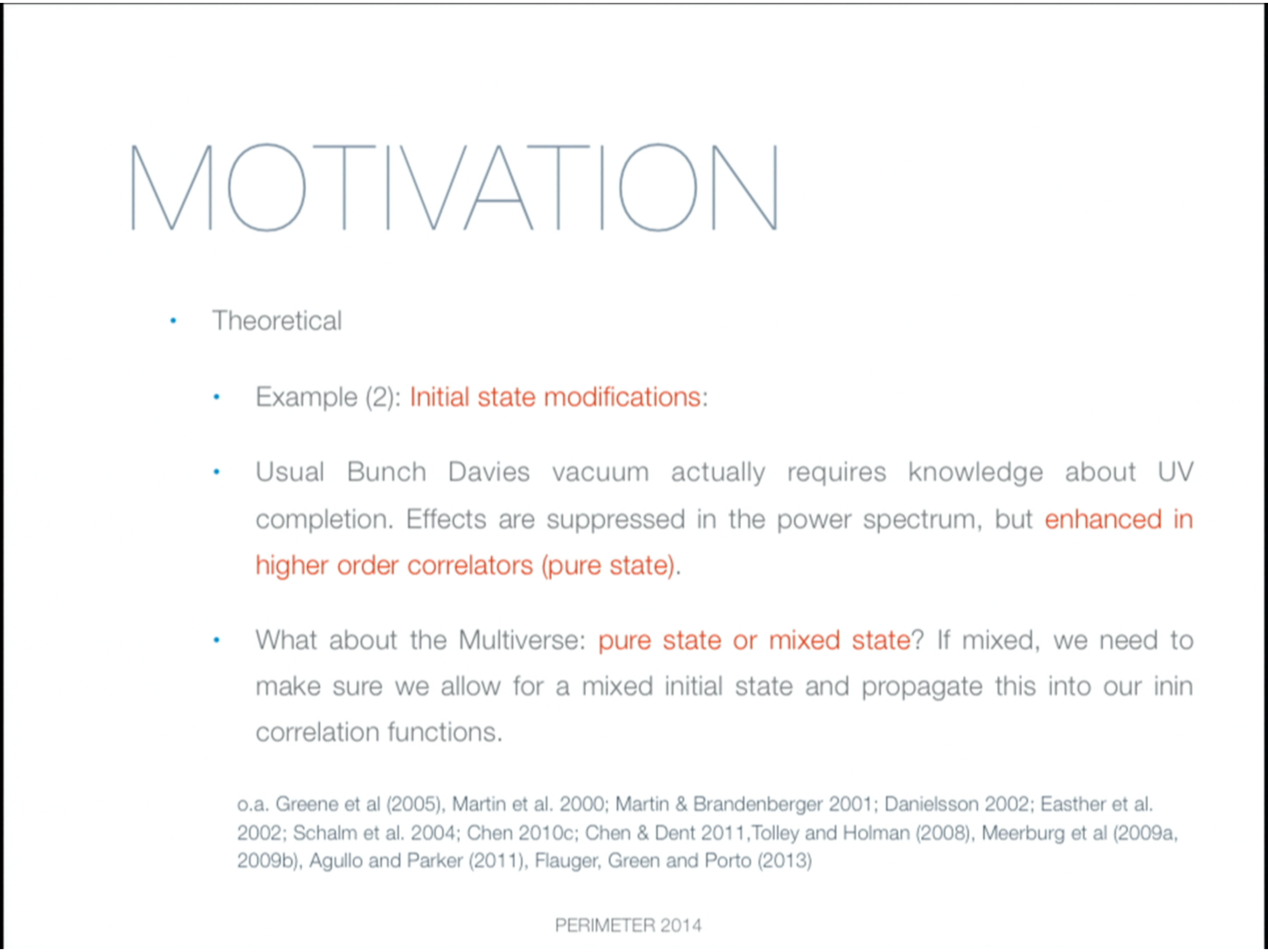

MOTIVATION

- Theoretical
  - Example (2): Initial state modifications:
  - Usual Bunch Davies vacuum actually requires knowledge about UV completion. Effects are suppressed in the power spectrum, but enhanced in higher order correlators (pure state).
  - What about the Multiverse: pure state or mixed state? If mixed, we need to make sure we allow for a mixed initial state and propagate this into our inin correlation functions.

o.a. Greene et al (2005), Martin et al. 2000; Martin & Brandenberger 2001; Danielsson 2002; Easther et al. 2002; Schalm et al. 2004; Chen 2010c; Chen & Dent 2011,Tolley and Holman (2008), Meerburg et al (2009a, 2009b), Agullo and Parker (2011), Flauger, Green and Porto (2013)

MOTIVATION

- More generally:

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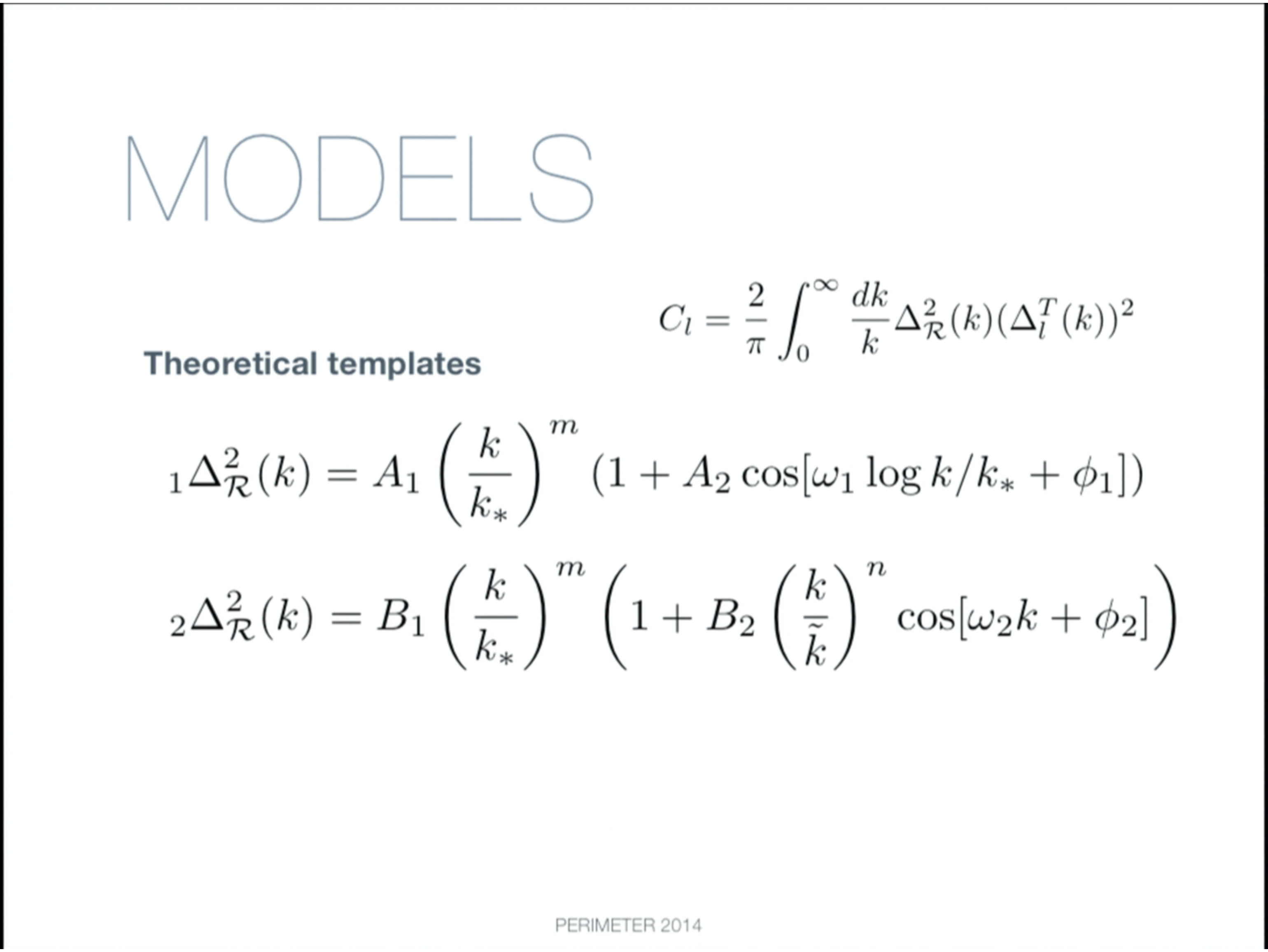
MOTIVATION

- More generally:
    - Phenomenological/Observational
    - Theoretical

Do we learn something more? Observation--->Theory



MODELS

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

Theoretical templates

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

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

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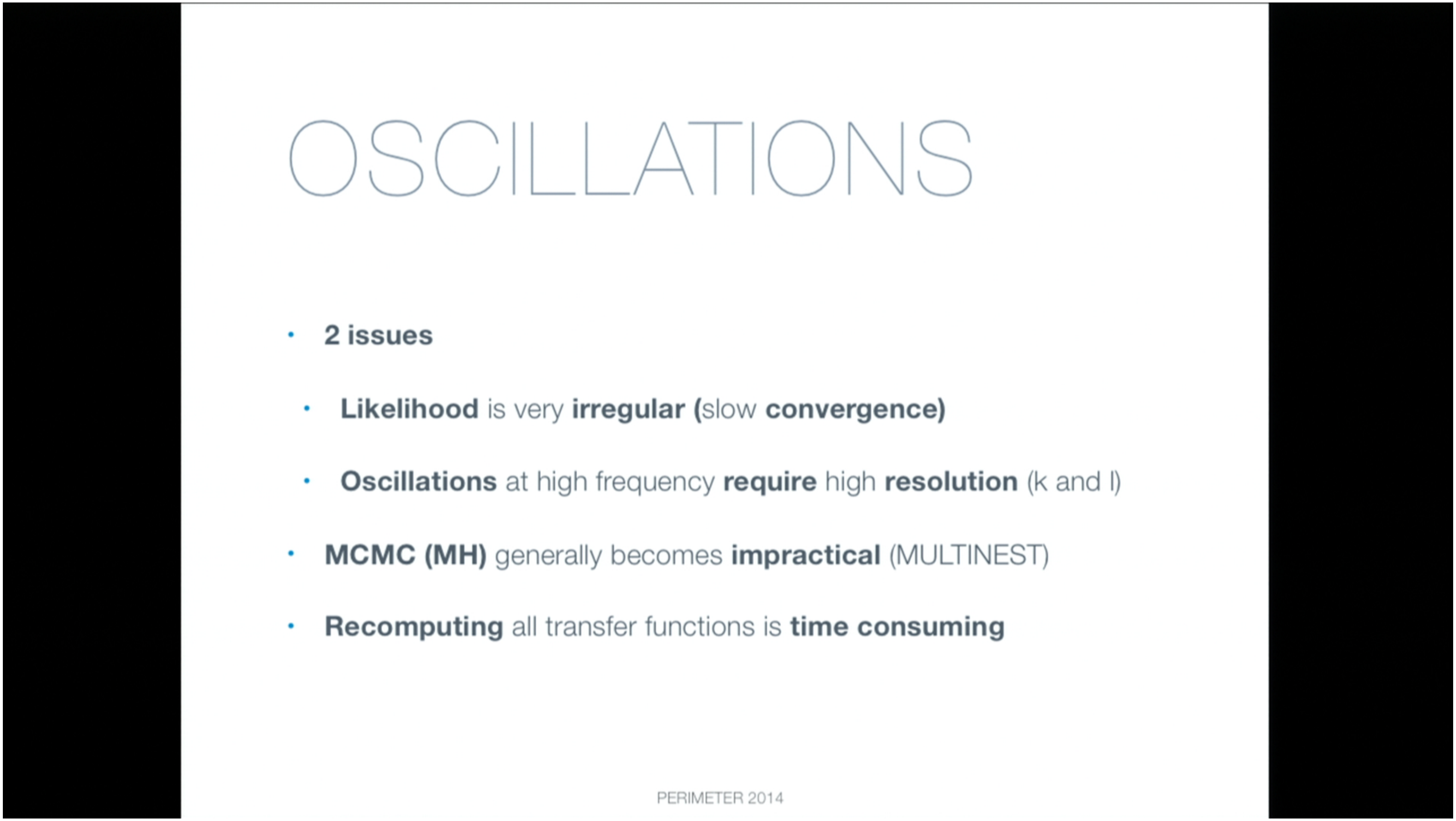

OSCILLATIONS

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

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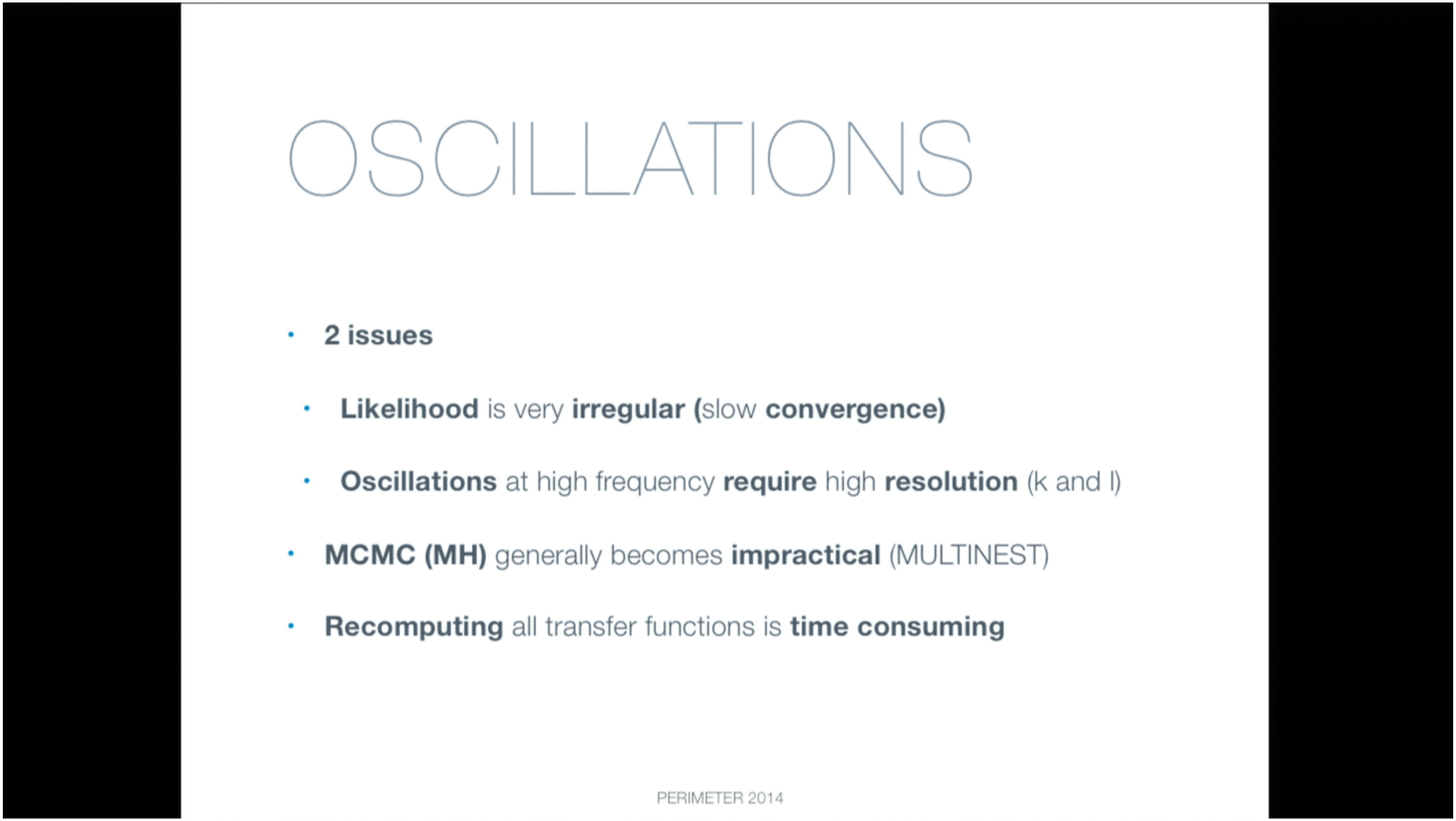

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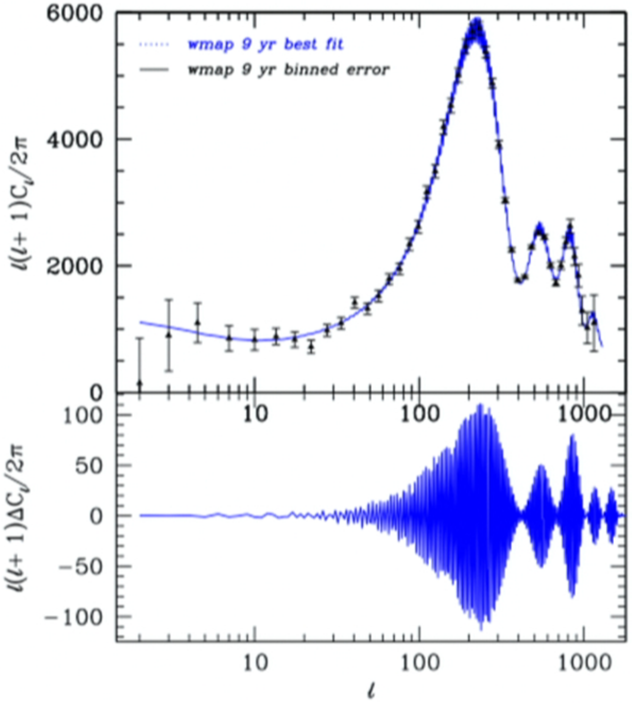
PERTURBATIVE EXPANSION

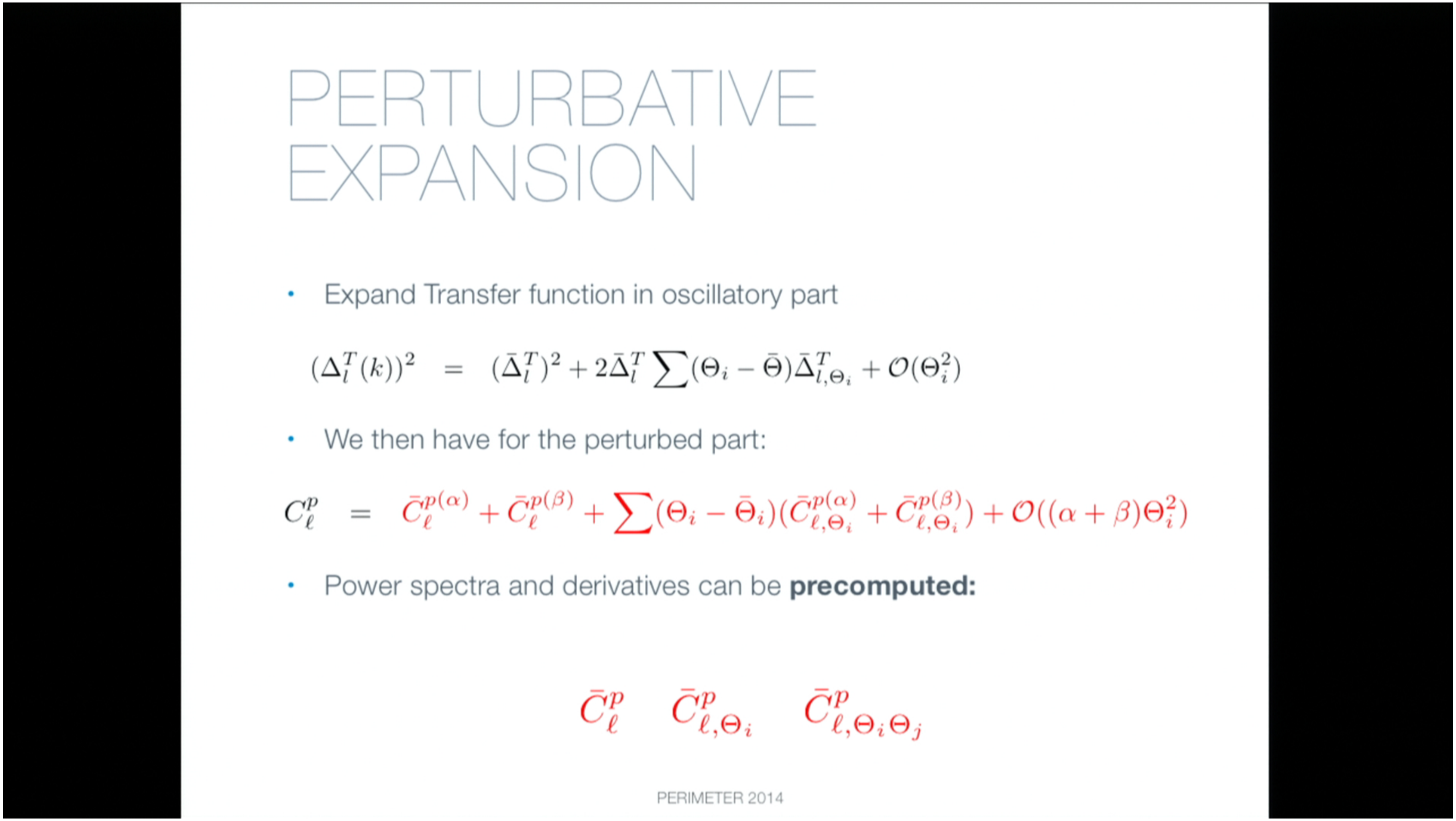


$$C_l = \frac{2}{\pi}\int_0^\infty \frac{dk}{k}\Delta^2_{\mathcal{R}}(k)(\Delta^T_l(k))^2$$

Corrections are small

Perturbative expansion in oscillatory part

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



PERTURBATIVE EXPANSION

- Expand Transfer function in oscillatory part

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

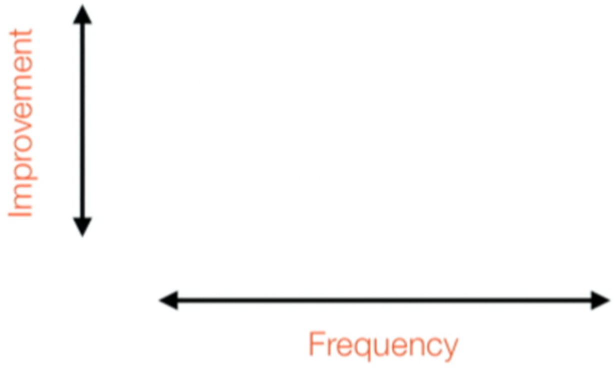
- We then have for the perturbed part:

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

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

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

Next few slides



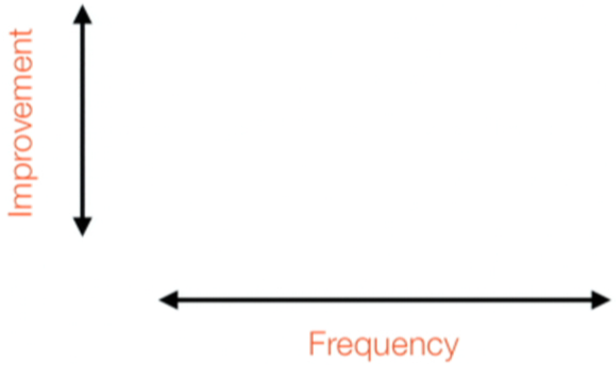
Improvement

Frequency

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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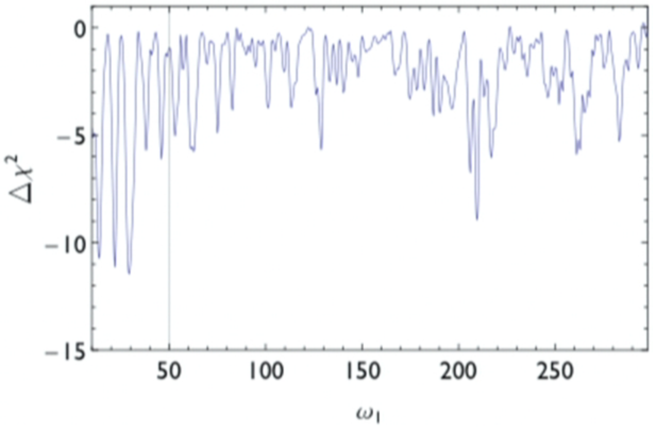
PLANCK BEST FIT



$$A_2 = 0.035$$

$$\phi_1 = 0.15$$

$$\omega_1 = 28.8$$

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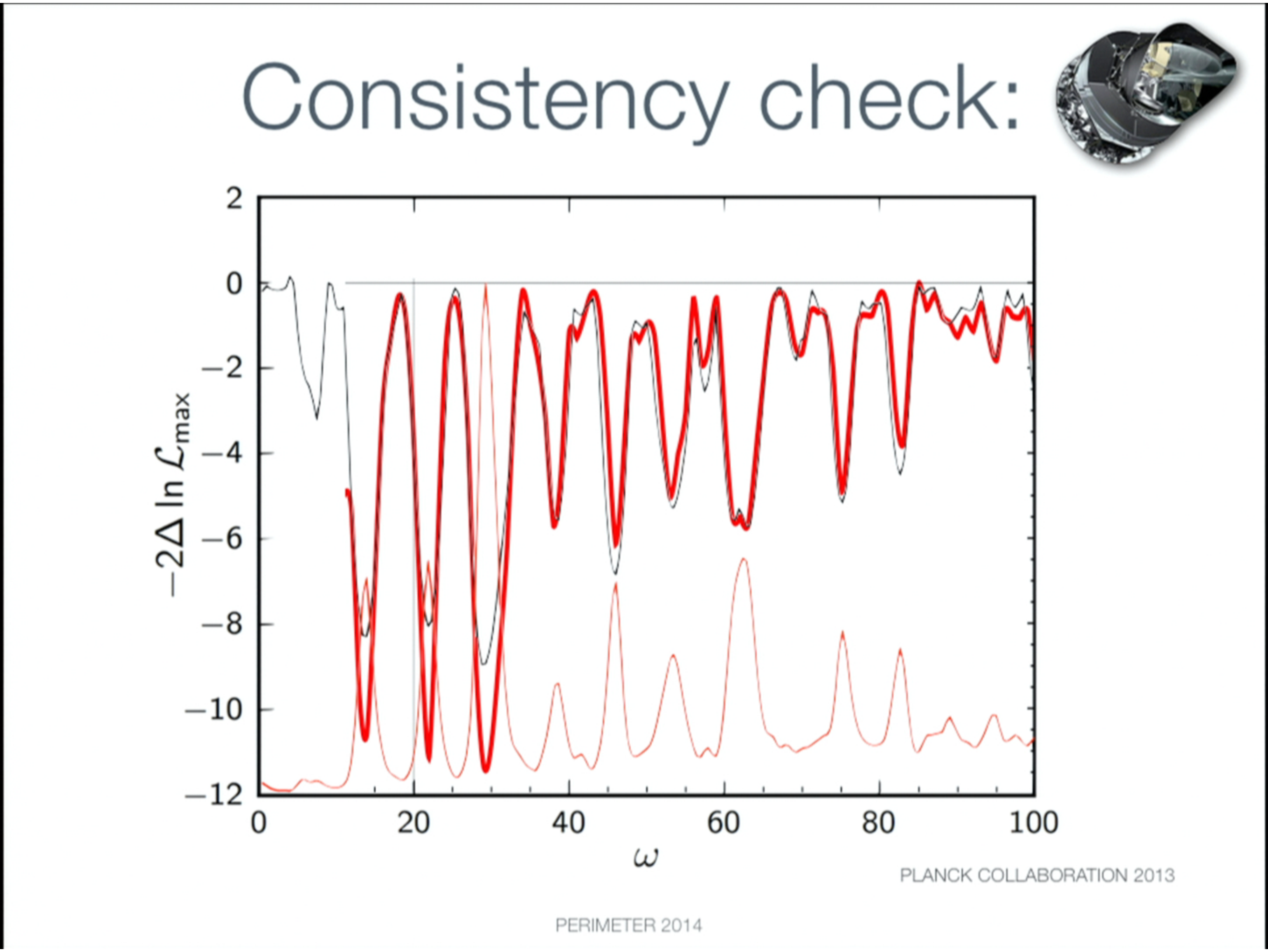

Consistency check:

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PLANCK BEST FIT 2.0

-Higher resolution

-Varied lensing amplitude

Mild Correlation between lensing amplitude and oscillations. Slightly improves fit.

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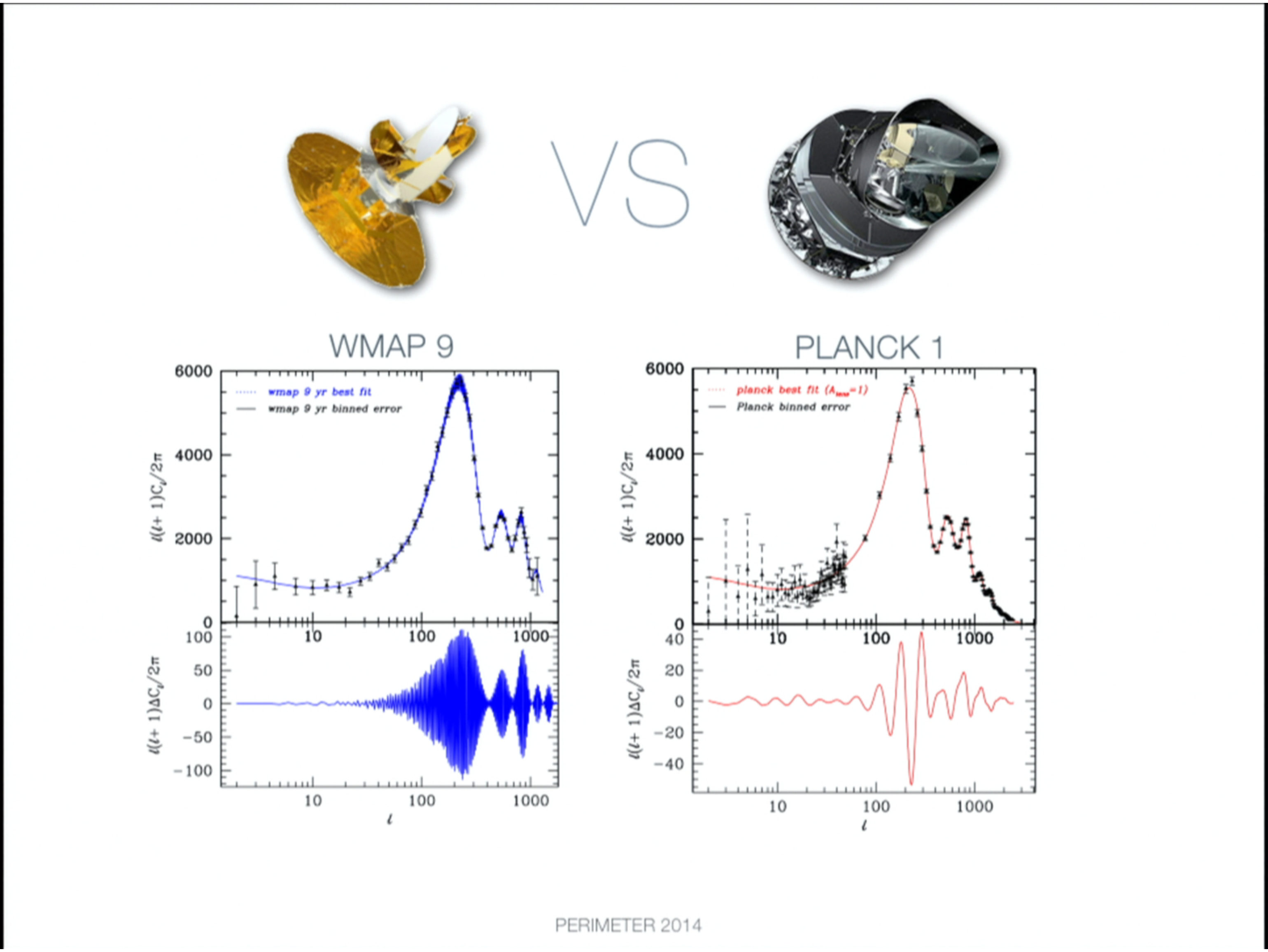

VS

WMAP 9

PLANCK 1

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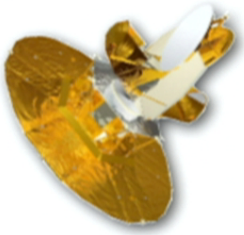

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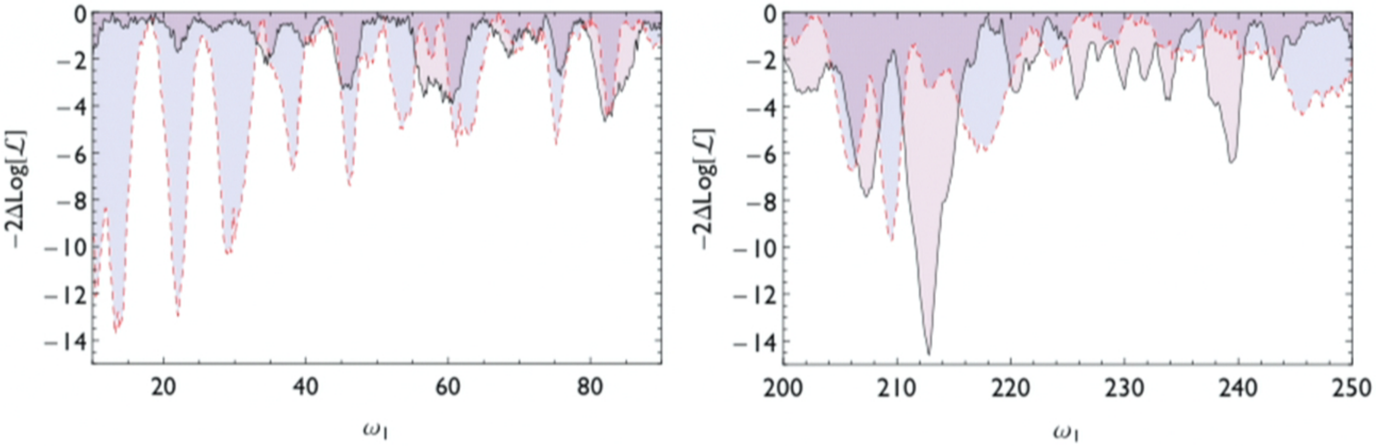
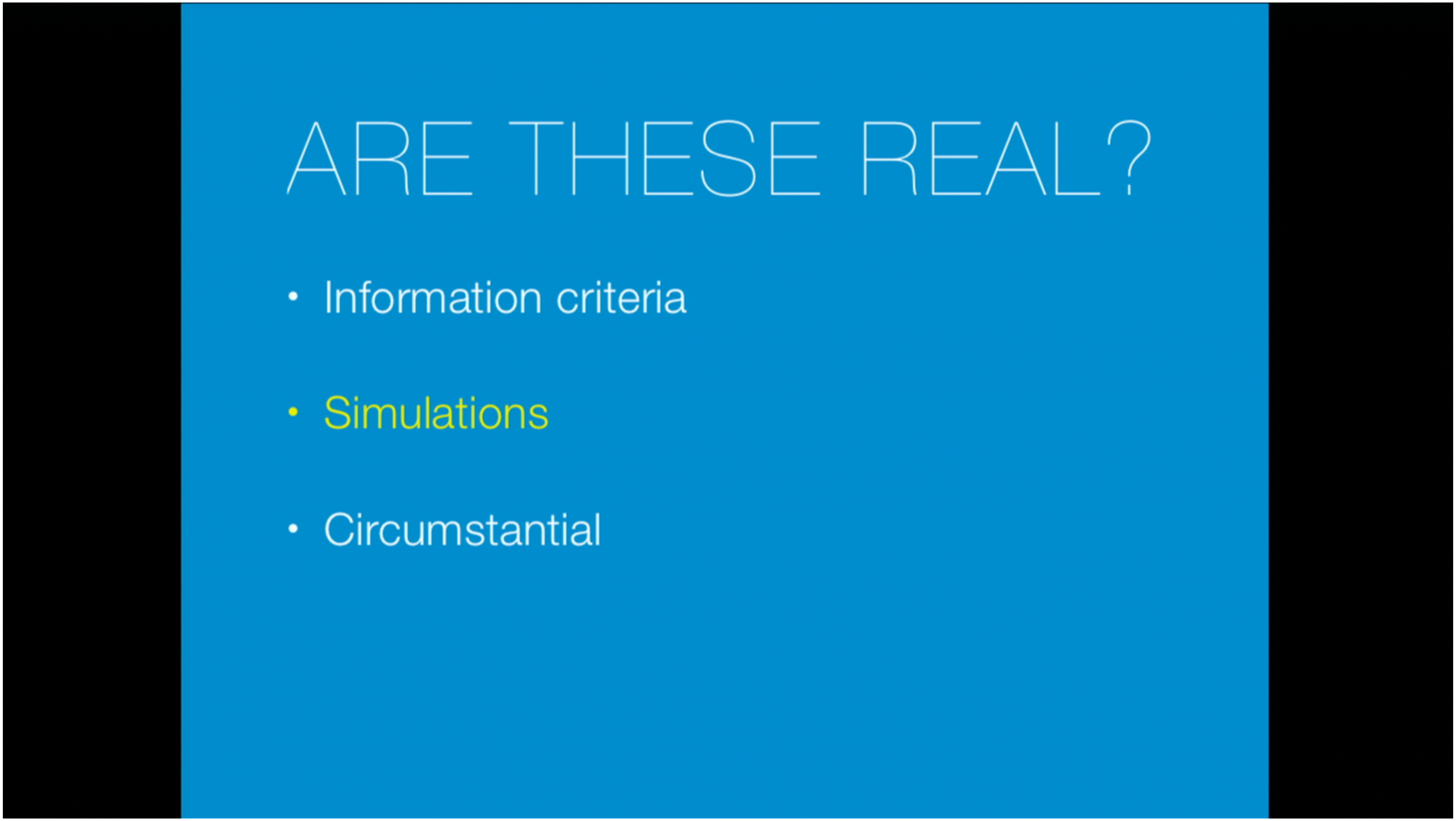
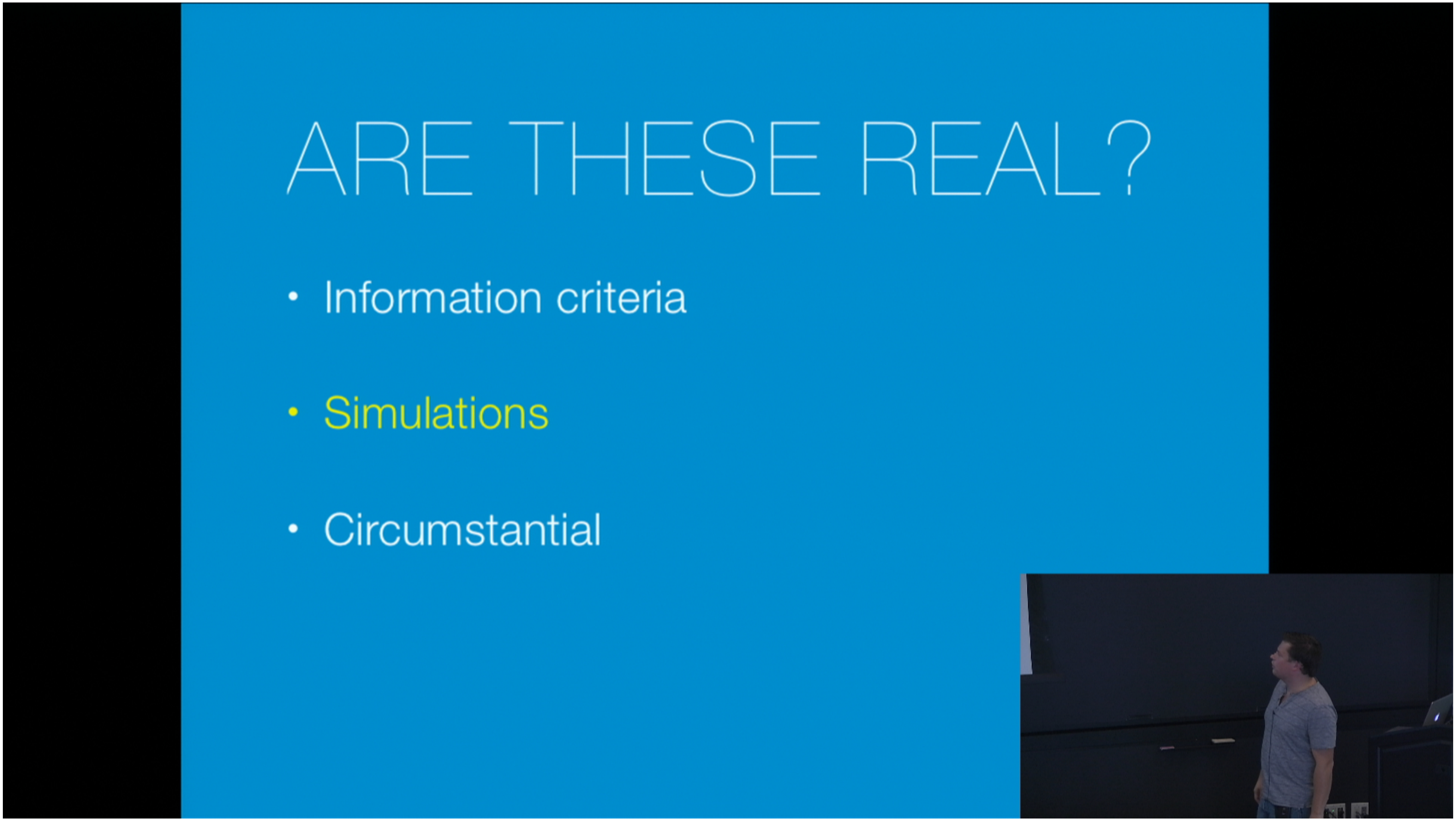


0
−2
−4
−6
−8
−10
−12
−14
$-2\Delta\mathrm{Log}[\mathcal{L}]$
20
40
60
80
ω_1
200
210
220
230
240
250



ARE THESE REAL?

- Information criteria
- Simulations
- Circumstantial



ARE THESE REAL?

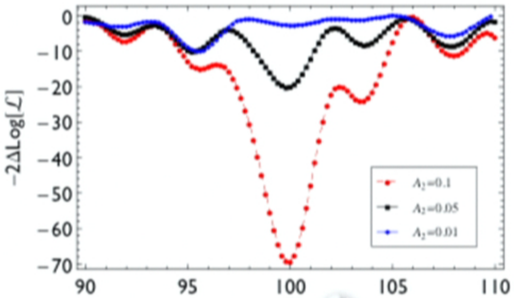
- Information criteria
- Simulations
- Circumstantial

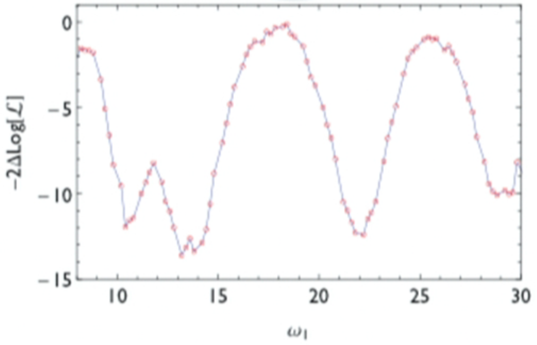
SIMULATIONS

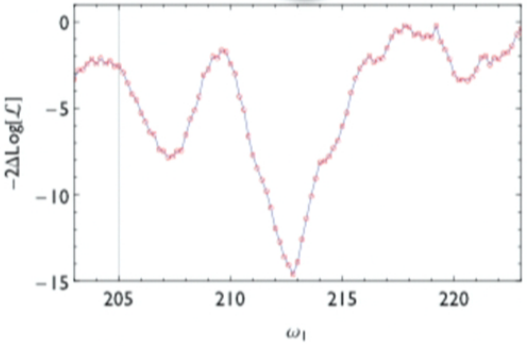
-planck noise

-3 different mock frequencies

-3 different amplitudes







IMPROVEMENT

Log

Notice the difference between high freq and low freq

IMPROVEMENT

Log

Notice the difference between high freq and low freq

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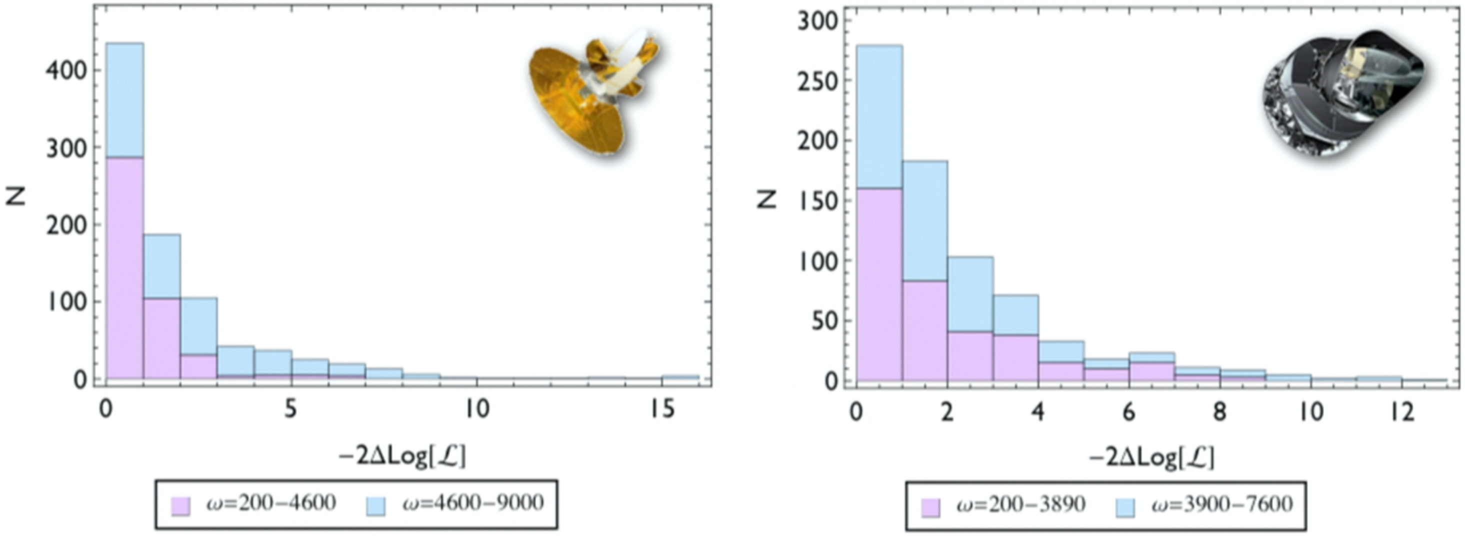
IMPROVEMENT

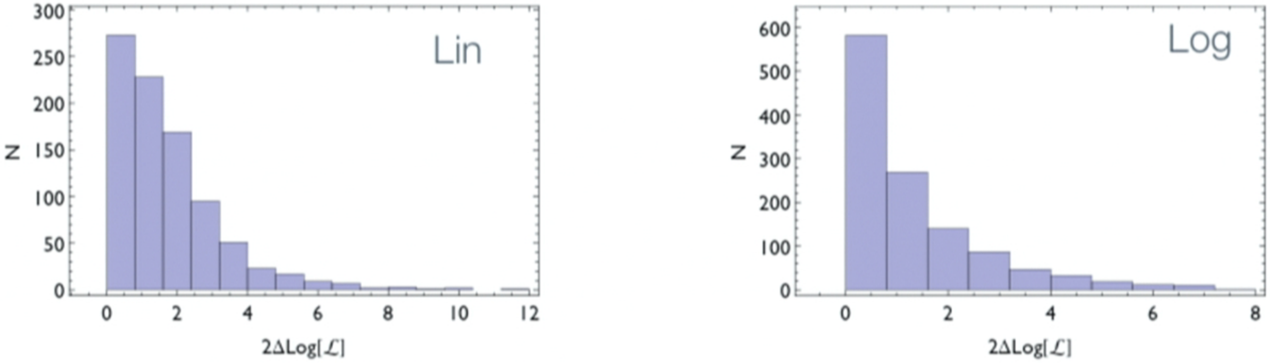
Lin



Notice the difference between high freq and low freq

SIMULATIONS

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



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

SIMULATIONS

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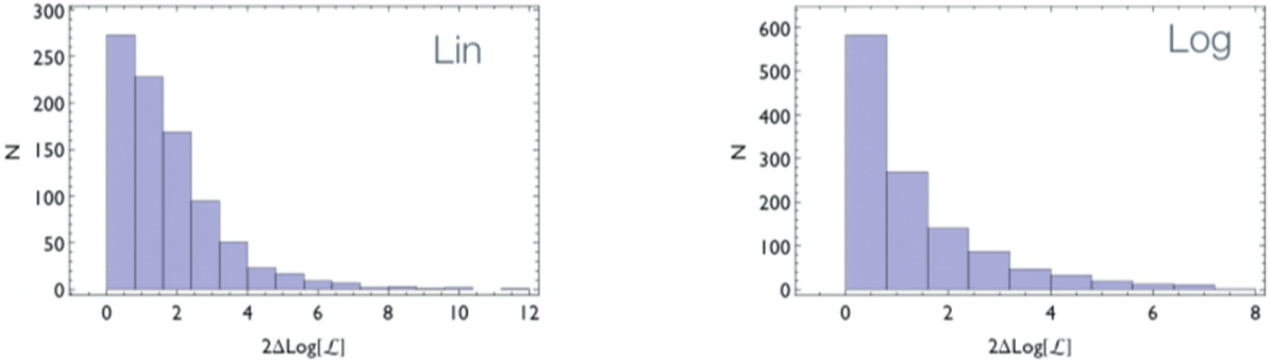
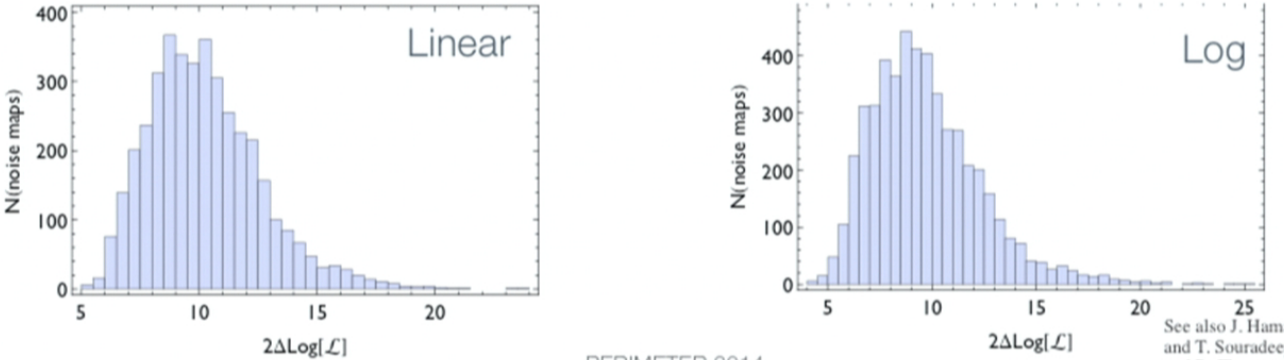


5000 Universes; **WMAP 9 noise** and cosmic variance, no signal



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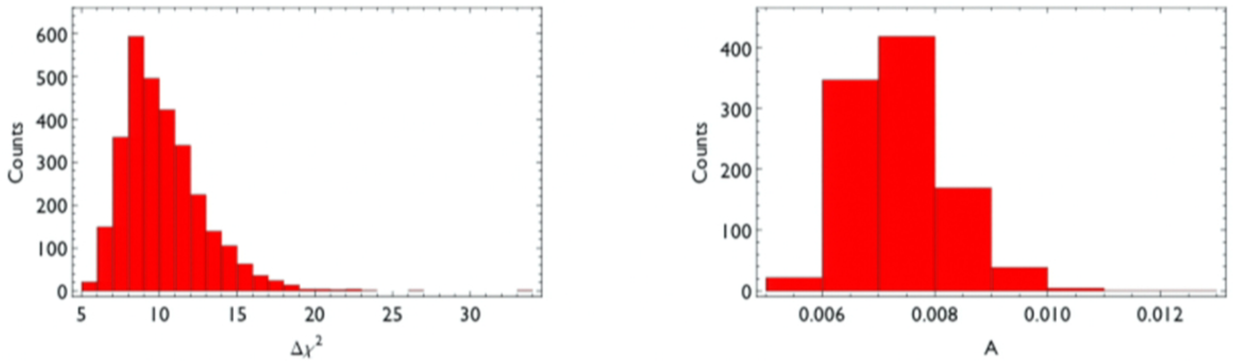
SIMULATIONS

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



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SIMULATIONS

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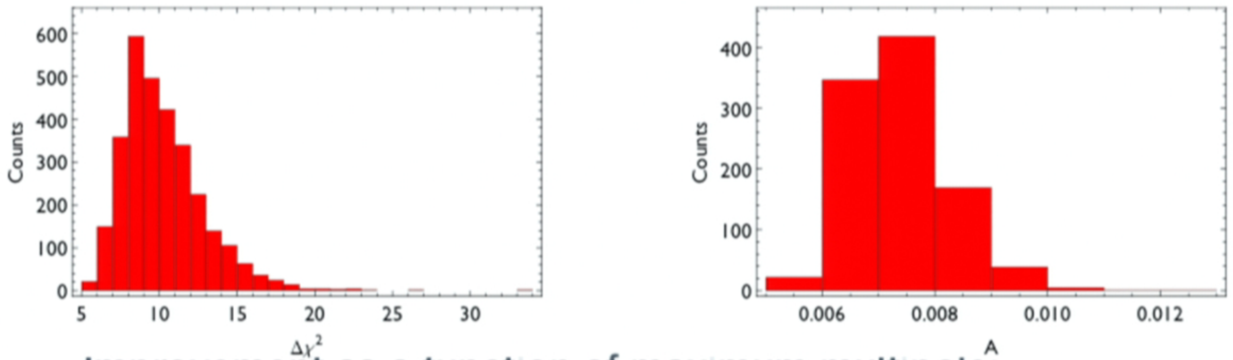
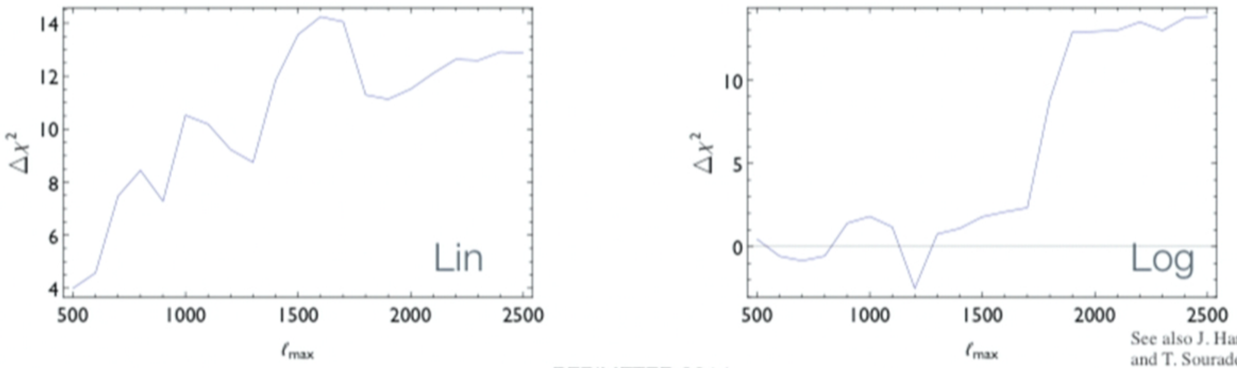


Improvement as a function of maximum multipole:



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SIMULATIONS

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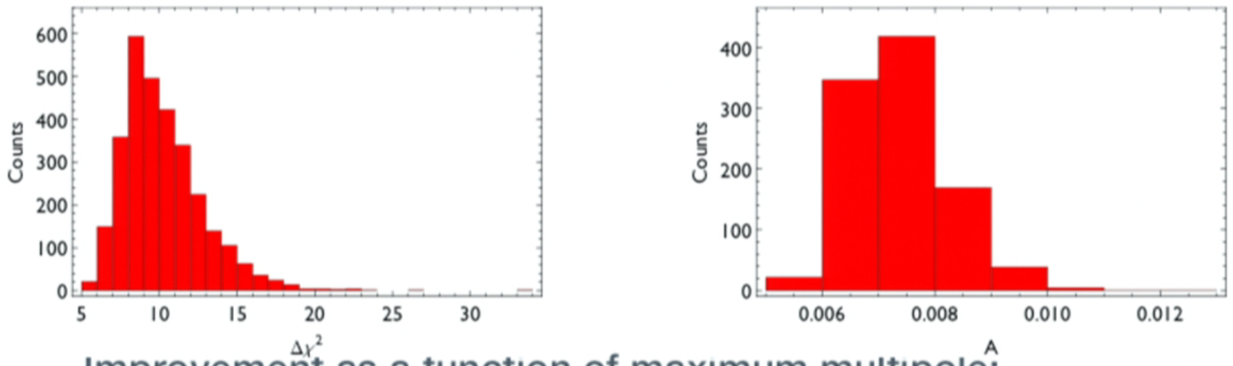

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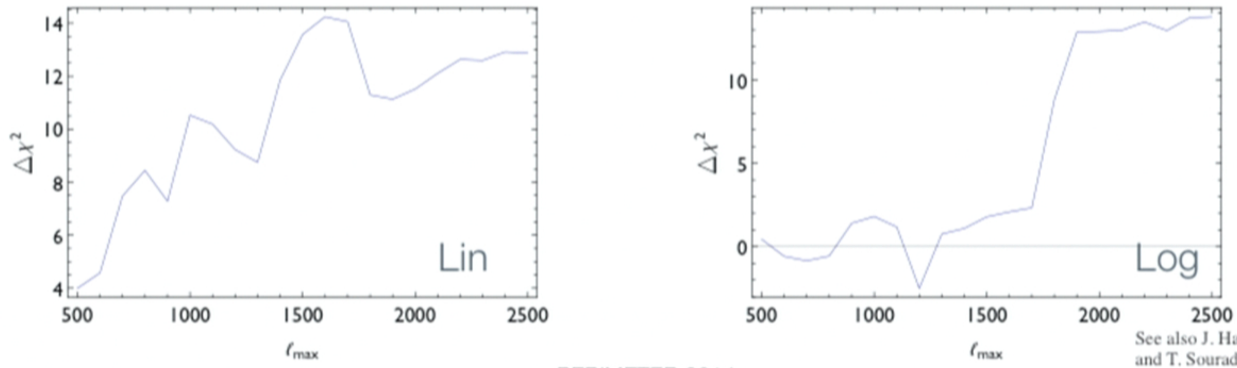

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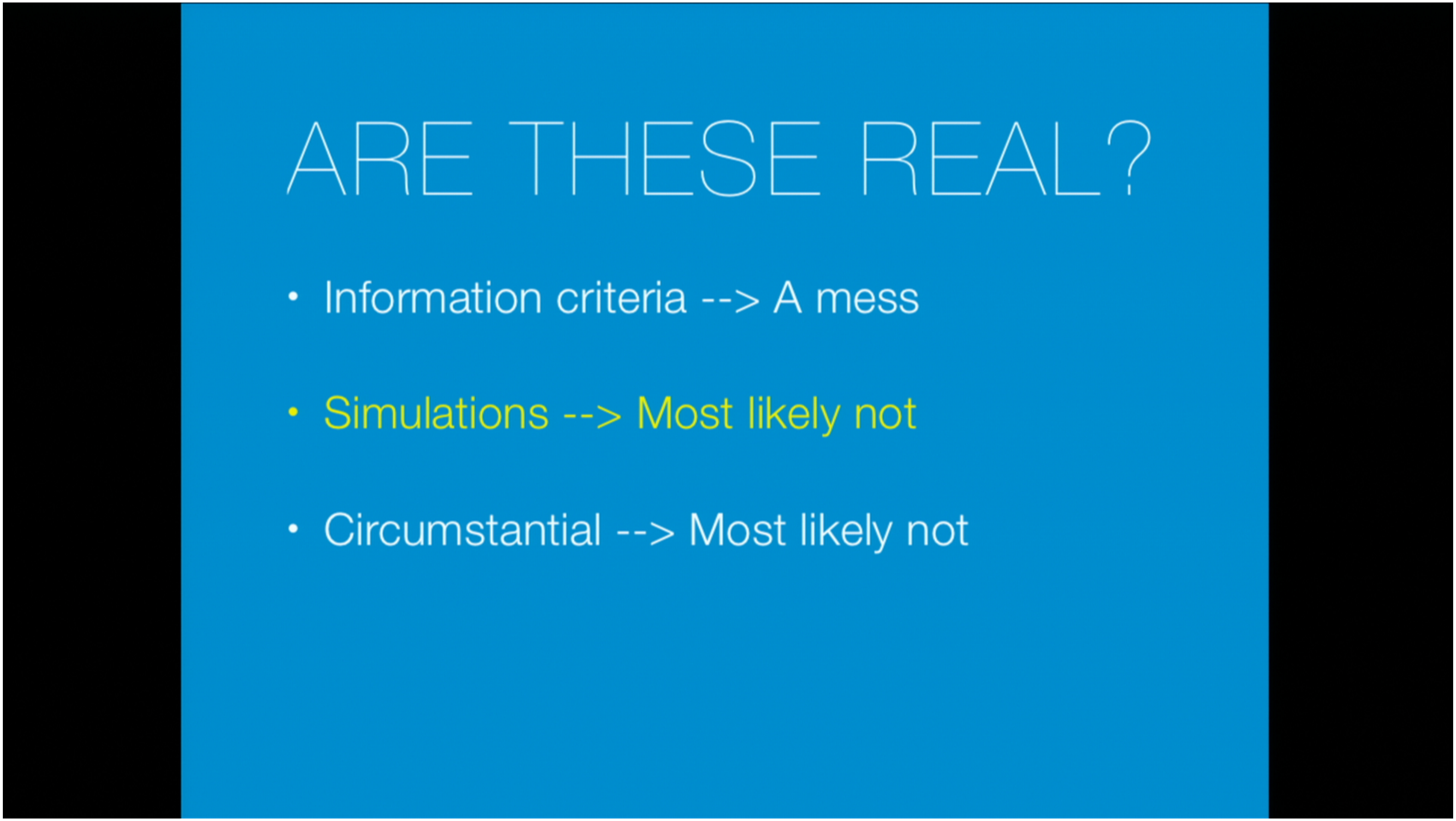
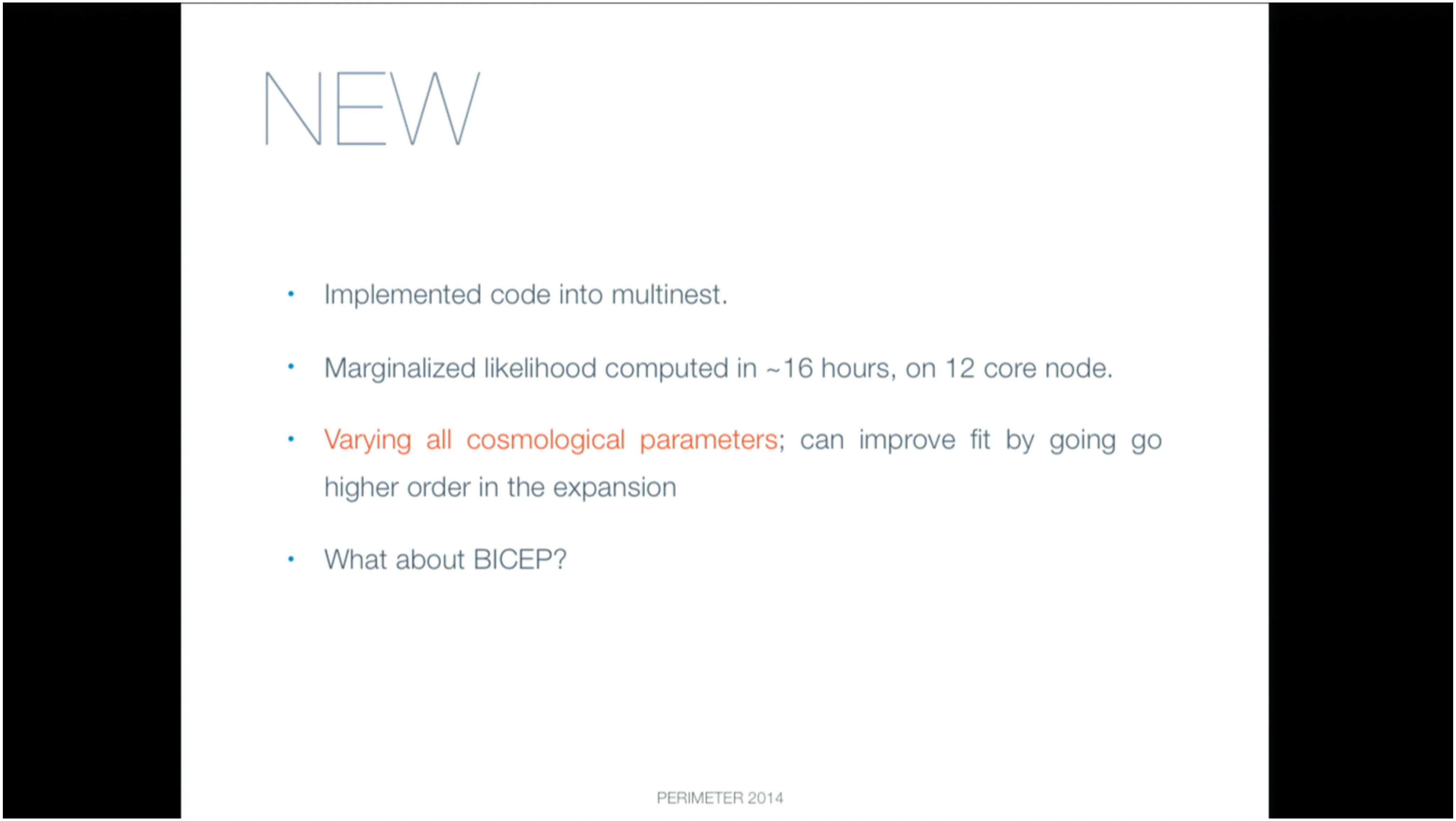


ARE THESE REAL?

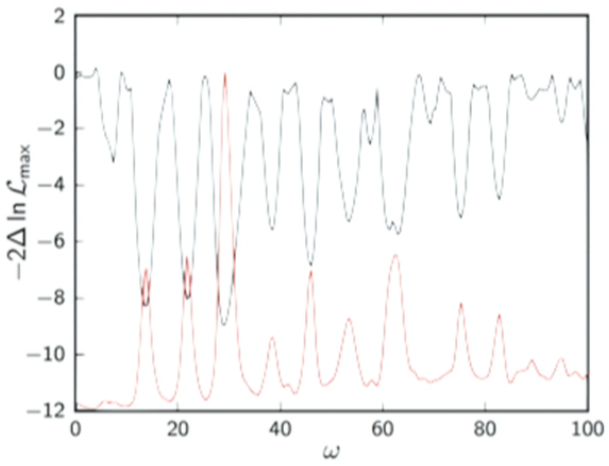
- Information criteria --> A mess
- Simulations --> Most likely not
- Circumstantial --> Most likely not



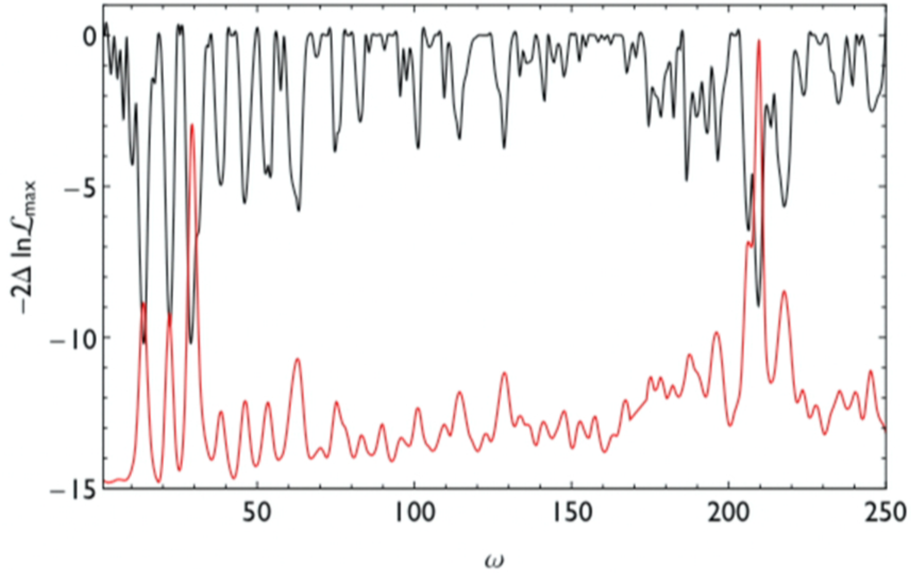
NEW

- Implemented code into multinest.
- Marginalized likelihood computed in ~16 hours, on 12 core node.
- Varying all cosmological parameters; can improve fit by going go higher order in the expansion
- What about BICEP?

Multinest Marginalized prob.

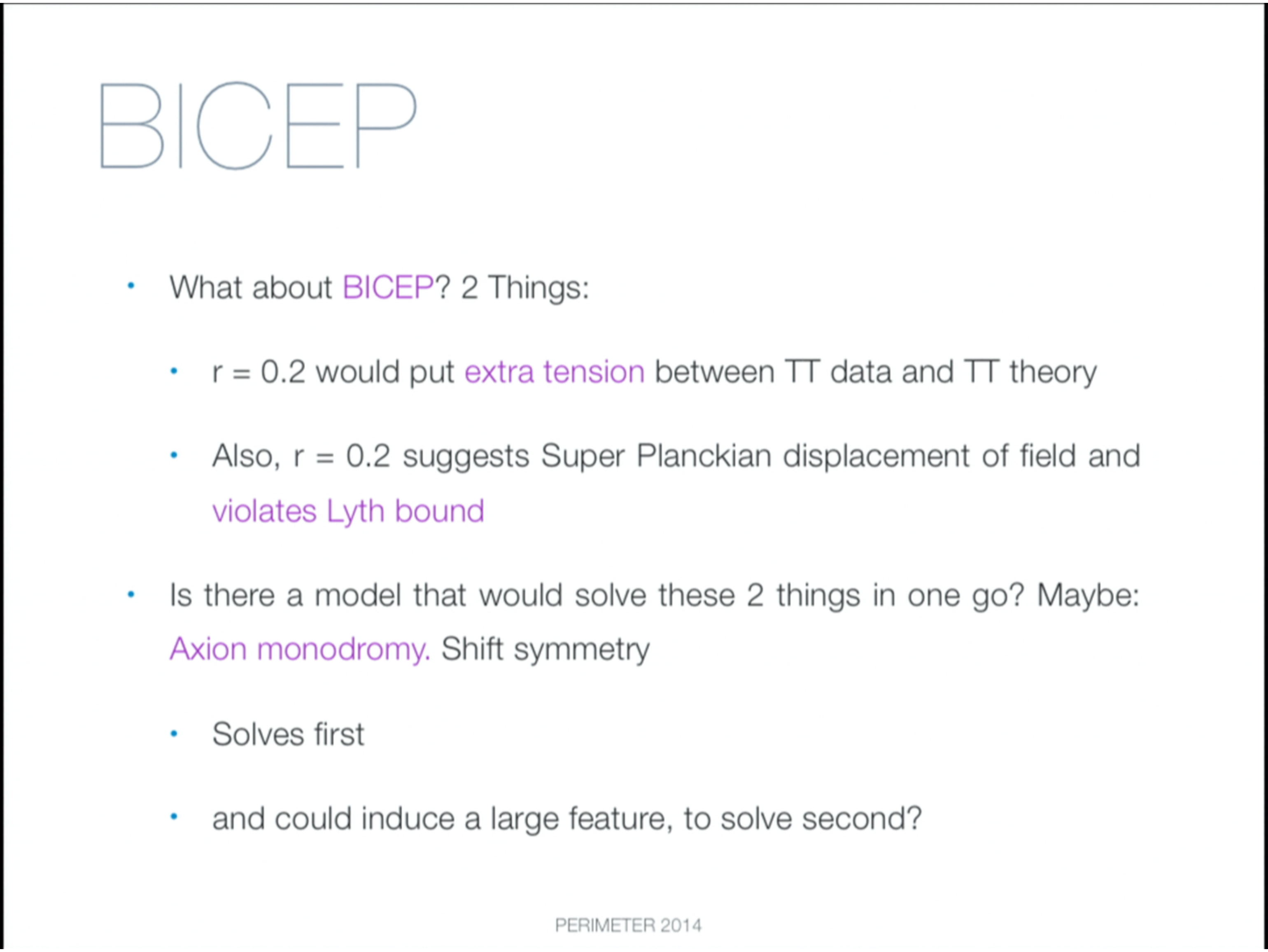


PLANCK COLLABORATION 2013



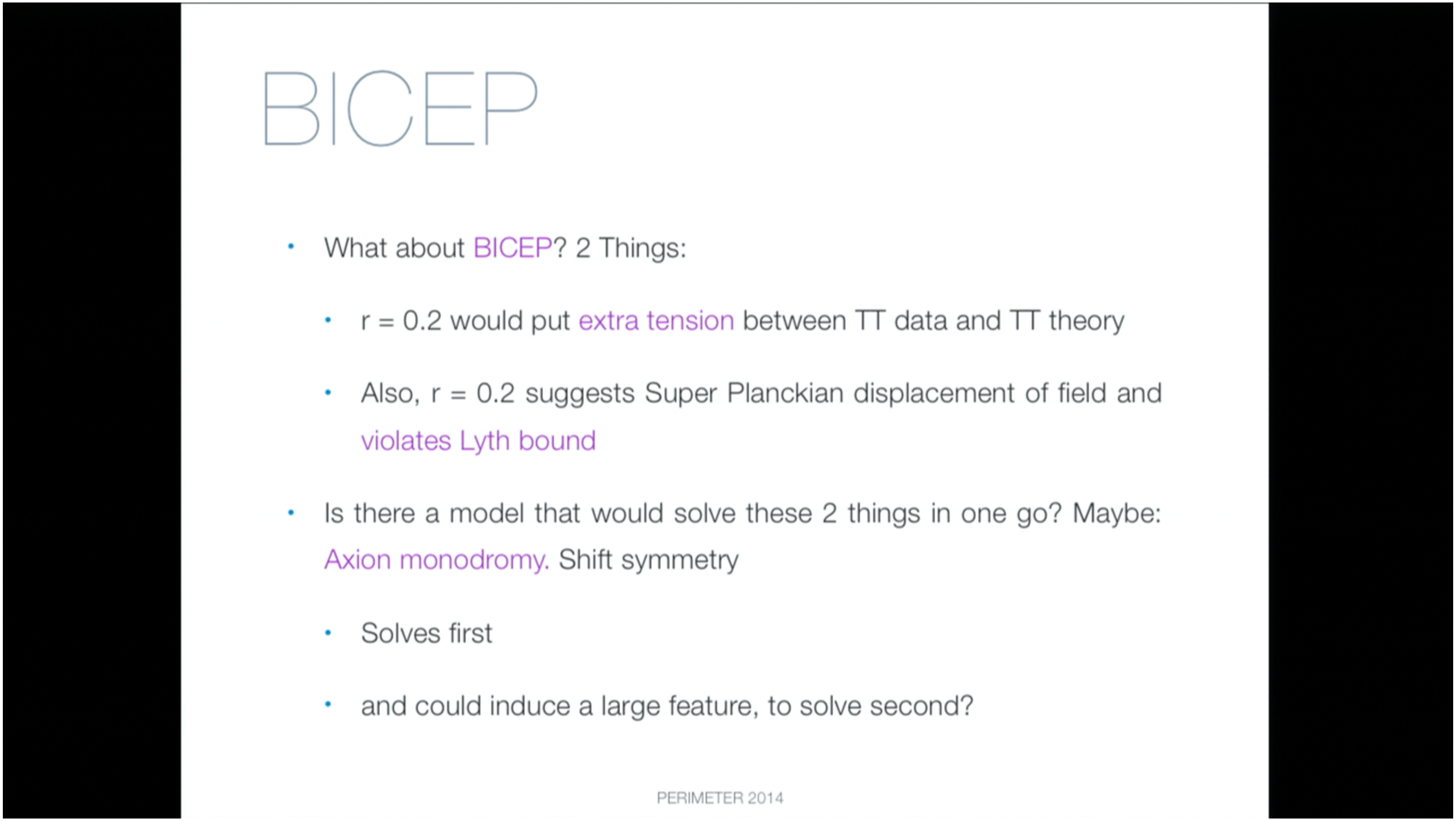
MEERBURG, SPERGEL, WANDELT 2014

PERIMETER 2014



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 and 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?



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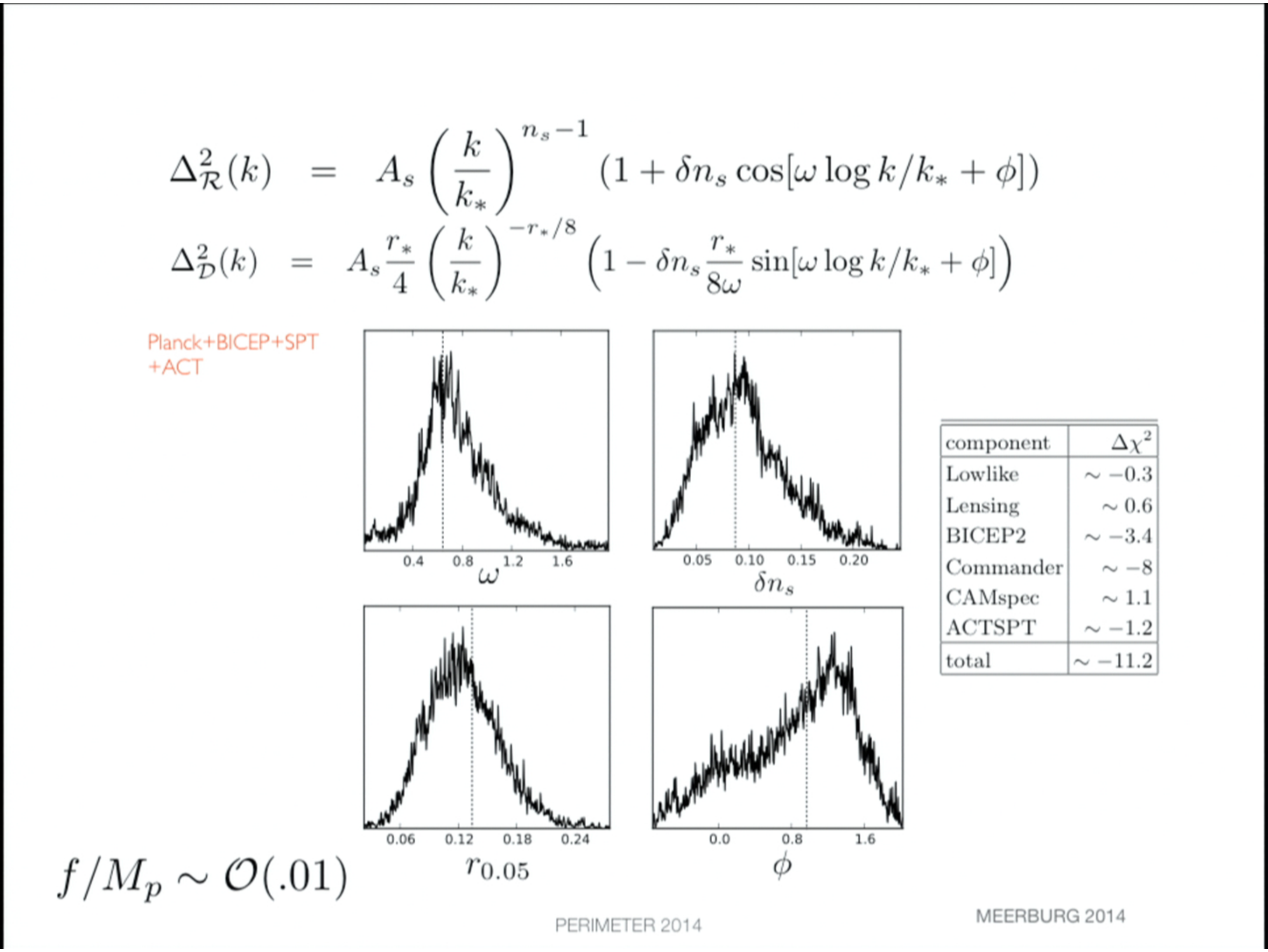

$$\Delta^2_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1} (1 + \delta n_s \cos[\omega \log k/k_* + \phi])$$

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

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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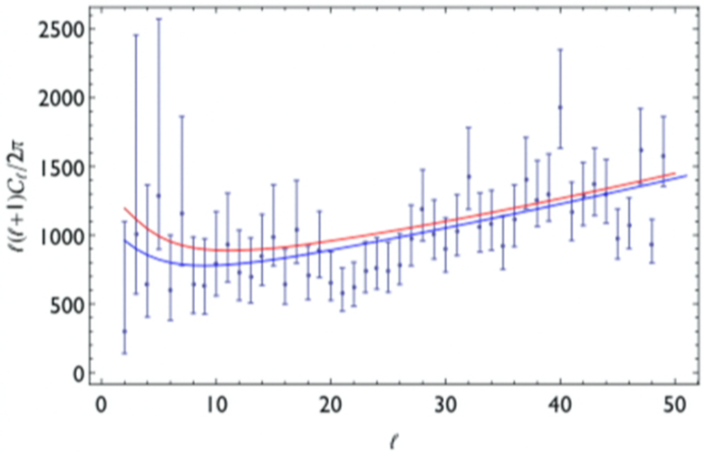
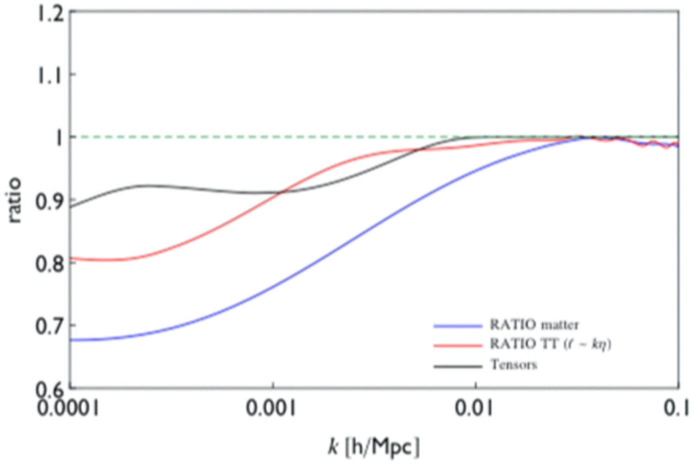
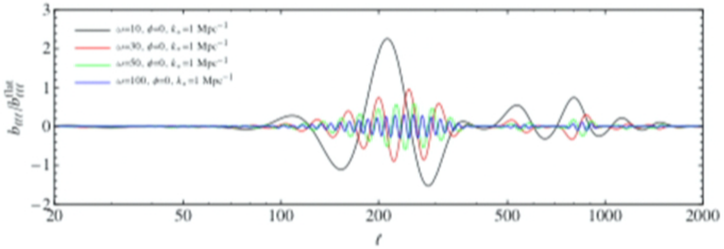
MEERBURG 2014


$\ell(\ell+1)C_\ell/2\pi$
2500
2000
1500
1000
500
0
0
10
20
30
40
50
ℓ


ratio
1.2
1.1
1
0.9
0.8
0.7
0.6
0.0001
0.001
0.01
0.1
k [h/Mpc]
RATIO matter
RATIO TT ($\ell \sim k\eta$)
Tensors

TO DO/IN PROGRESS



- Bispectrum. Difficult

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

  - Too low signal to noise in a single mode: sum over all modes: $\sum_{\text{all } \ell} b_{\ell_1\ell_2\ell_3} \star b^{\text{temp}}_{\ell_1\ell_2\ell_3}$
  - use weighting or template: if template is off, measurement is zero
  - 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
  - Ultimate goal: Joined analysis

W WANDELT AND MÜNCHMEYER

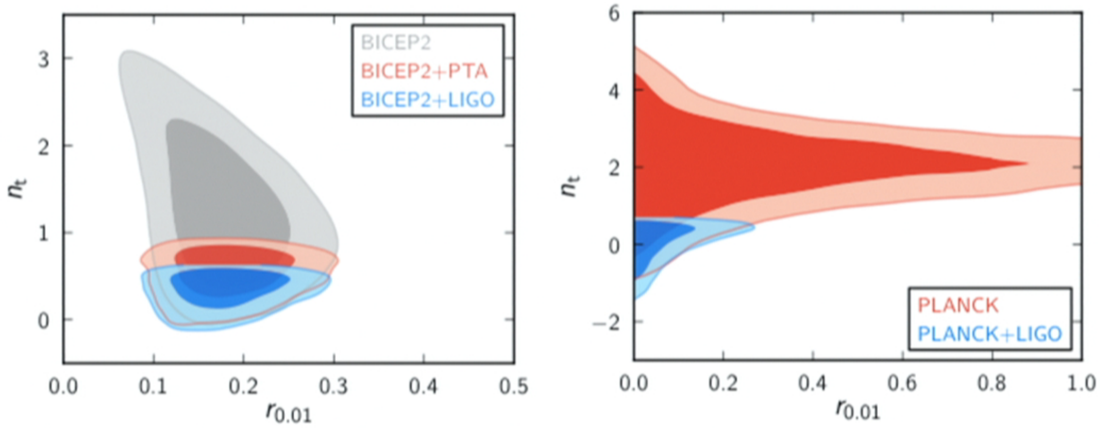
OTHER WORK

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

W B. HADZHIYSKA, R. HLOZEK AND MYERS

OTHER WORK

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



w. and w.out BICEP, $n_t < 0.5$, however ...

W B. HADZHIYSKA, R. HLOZEK AND MYERS

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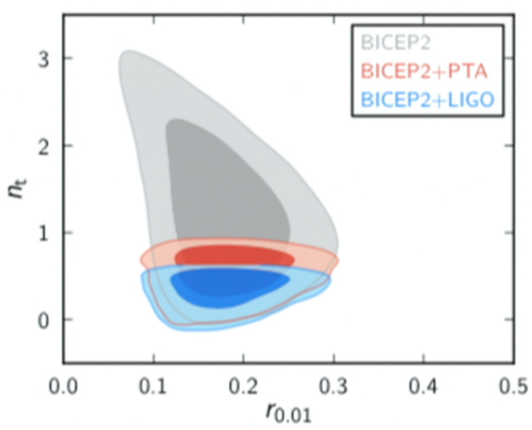

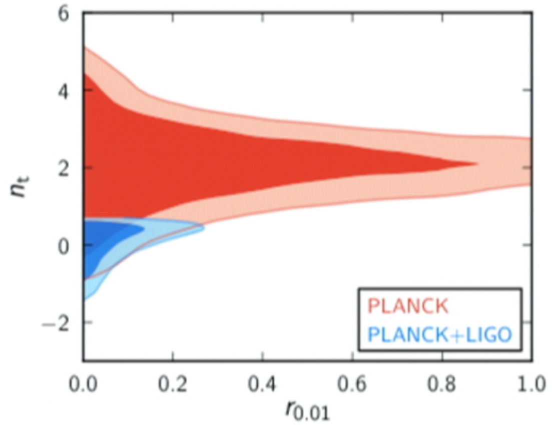

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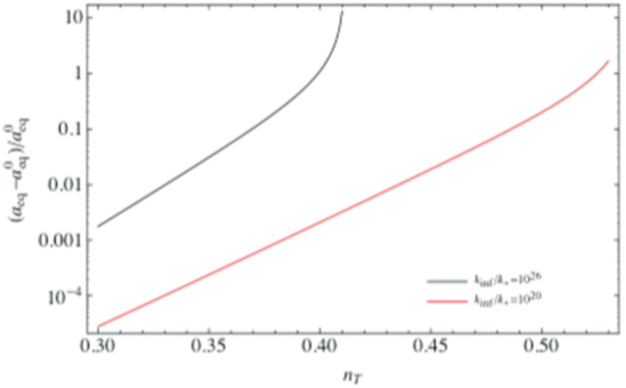
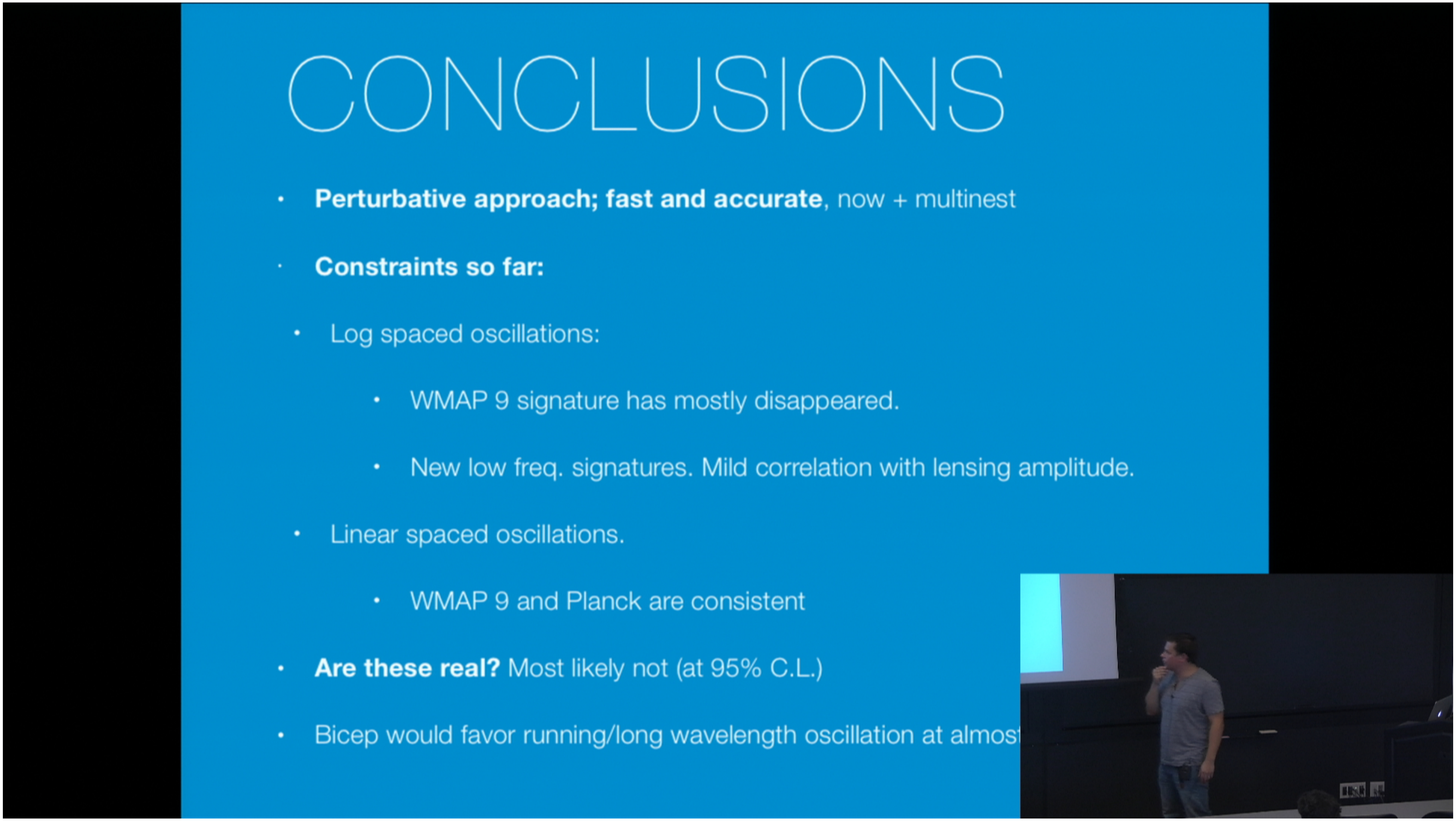


W B. HADZHIYSKA, R. HLOZEK AND MYERS



CONCLUSIONS

- **Perturbative approach; fast and accurate**, now + multinest
- **Constraints so far:**
  - 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 almos