

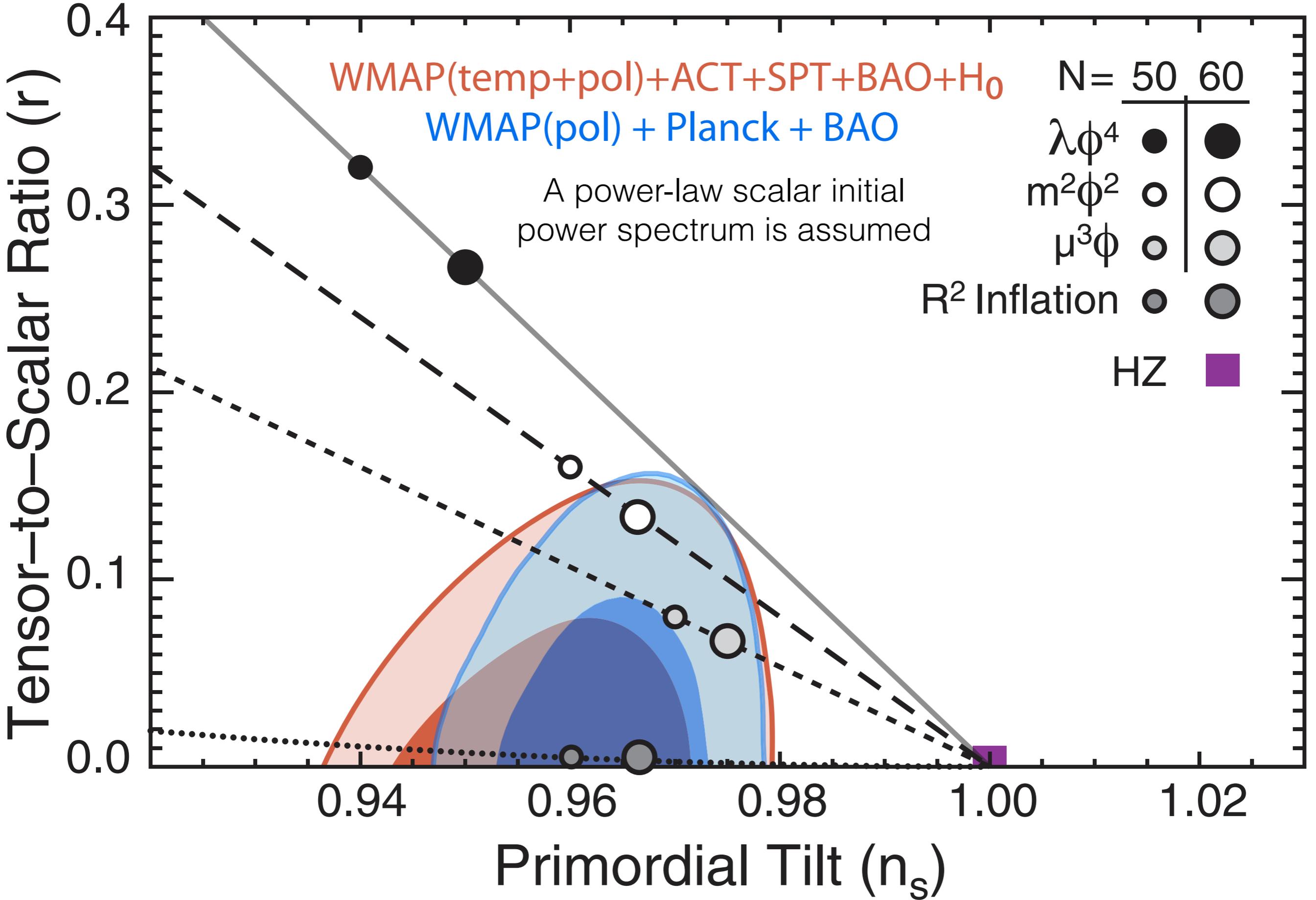
CMB Polarisation: Toward an Observational Proof of Cosmic Inflation

Eiichiro Komatsu, Max-Planck-Institut für Astrophysik
Zel'dovich-100, Space Research Institute (IKI), Moscow
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Finding Inflation: Breakthroughs in 2012 and 2013

- *Discovery of broken scale invariance, $n_s < 1$, with more than 5σ*
 - WMAP+ACT+SPT+BAO [December 2012]
 - WMAP+Planck [March 2013]
- *Remarkable degree of Gaussianity of primordial fluctuations*
 - Non-Gaussianity limited to $<0.2\%$ by WMAP and $<0.04\%$ by Planck [for the local form]
- These are important milestones: **strong evidence for the quantum origin of structures in the universe** [Slava's talk]

Courtesy of David Larson



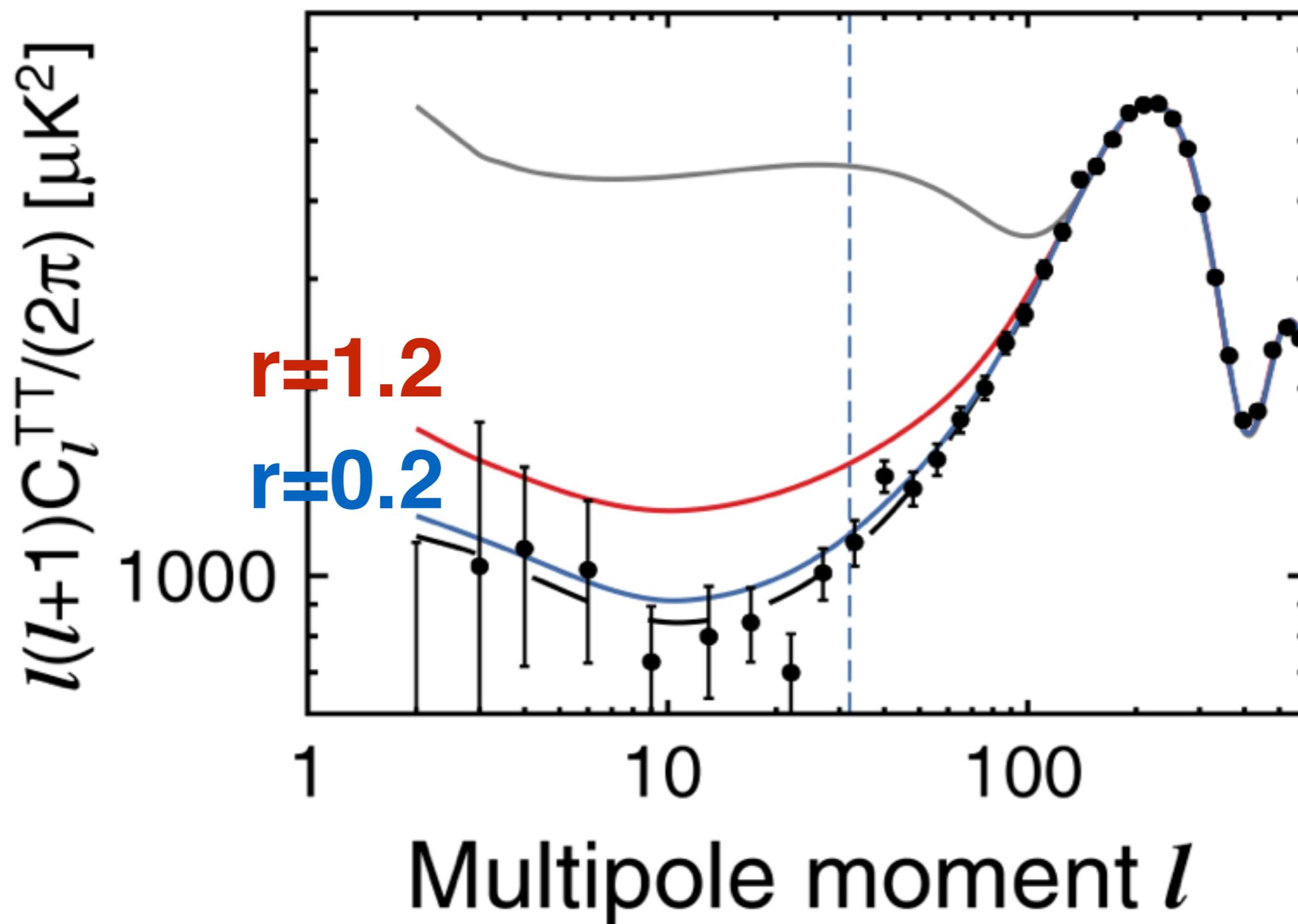
Breakthrough* in 2014

- *Discovery of the primordial* B-modes with more than 5σ by BICEP2*
- Detection of nearly scale-invariant tensor perturbations proves inflation
- This requires precise characterisation of the B-mode power spectrum. How are we going to achieve this?

If BICEP2's discovery of the primordial B-modes is confirmed, what is next?

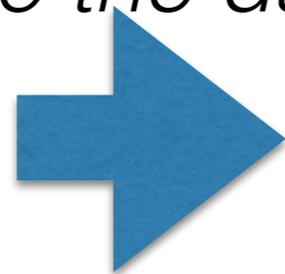
- Prove inflation by characterising the B-mode power spectrum precisely. Specifically:
 - We will find the existence of the predicted “reionisation bump” at $l < 10$
 - We will determine the tensor tilt, n_t , to the precision of a few $\times 10^{-2}$
 - [The exact scale invariance is $n_t=0$]
- **Added bonus:** we may be able to measure the number of neutrino species from the B-mode power spectrum!

A comment on the tension between $r \sim 0.2$ and WMAP/Planck



Lowering TT at low multipoles

- Adding a scale-dependent [running] scalar spectral index improves χ^2 by
 - $\Delta\chi^2 = -6.5$ [one more free parameter]
- Adding isocurvature perturbations totally anti-correlated with adiabatic perturbations improves χ^2 by
 - $\Delta\chi^2 = -4.2$ [one more free parameter]
- Both can lower the temperature power spectrum at low multipoles. But, *do the data require such modifications?*



Bayesian Evidence

Bayesian Evidence

$$\text{Evidence} = \int d^N \theta \underbrace{\mathcal{L}(\text{data}|\vec{\theta})}_{\text{likelihood}} \underbrace{P(\vec{\theta})}_{\text{prior}}$$

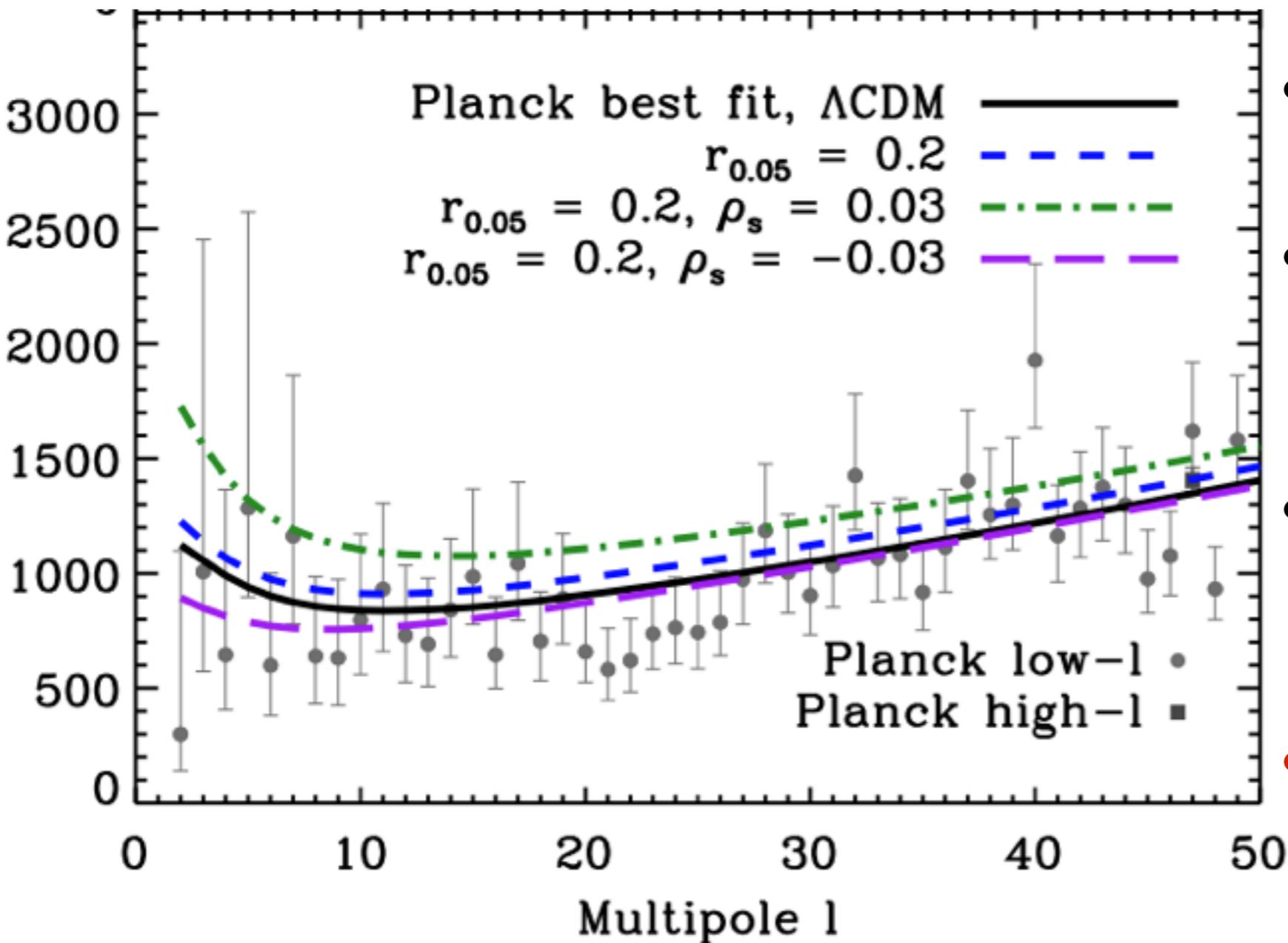
- Bayesian evidence penalises models which have:
 - Too many free parameters
 - Free parameters which have too much freedom [i.e., models are not predictive]

Log[Evidence Ratio]

- Take two models, and compute the Bayesian evidences
- Take the ratio of the evidences, and compute natural logarithm
- Is there evidence that one model is preferred over another?
 - $\ln(\text{Evidence Ratio})=0$ to 1 -> no evidence
 - $\ln(\text{Evidence Ratio})=1$ to 3 -> moderate evidence
 - $\ln(\text{Evidence Ratio})=3$ to 5 -> strong evidence
 - $\ln(\text{Evidence Ratio})>5$ -> decisive evidence

Running Index

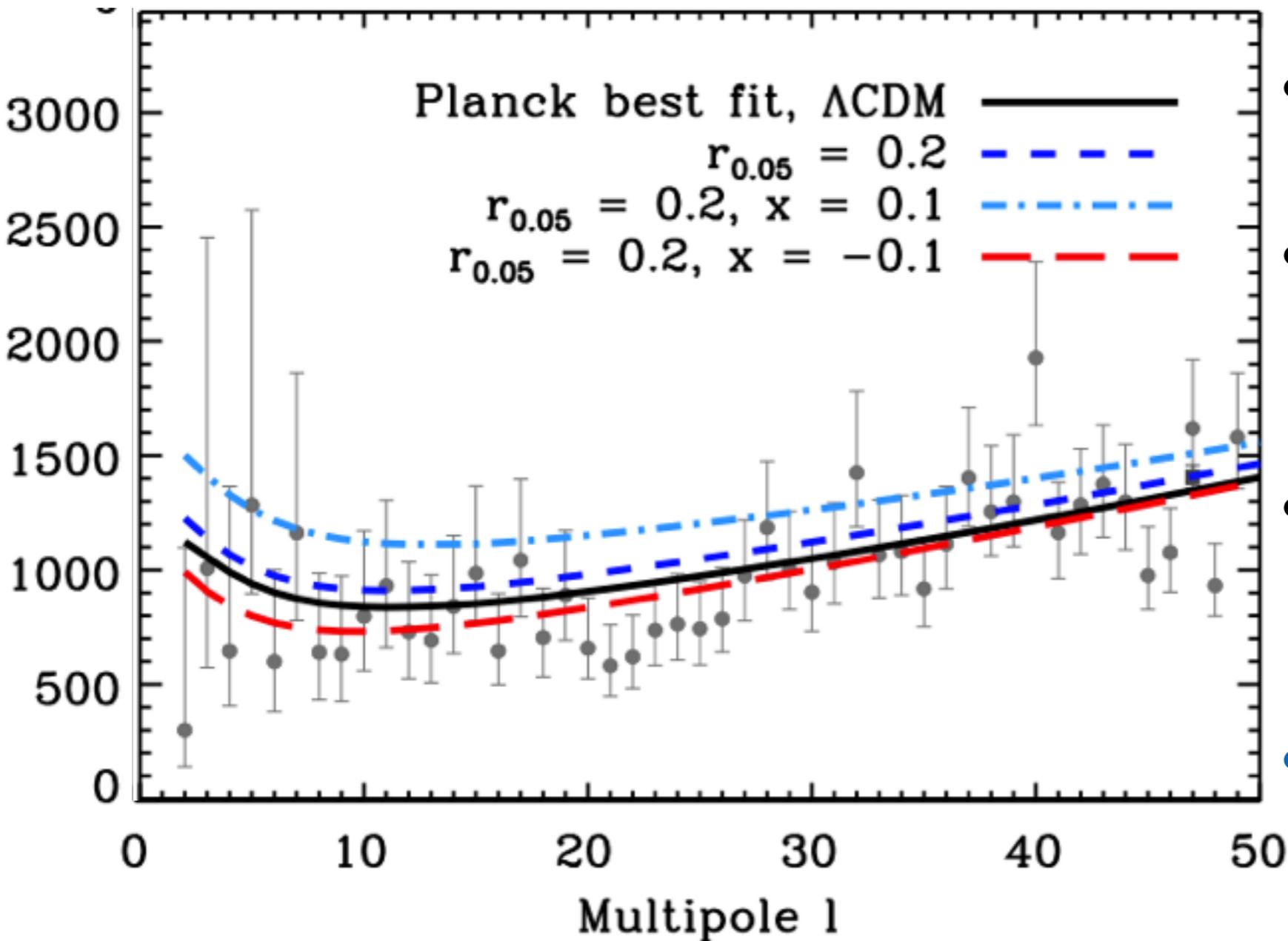
$$k^3 P(k) \propto k^{n_s - 1 + \frac{1}{2} \rho_s \ln(k/k_0)}$$



- Prior: $\rho_s = [-0.1, 0.1]$
- 95% posterior:
 $\rho_s = [-4.4, -0.12] \times 10^{-2}$
- Log[Evidence Ratio
wrt LCDM+r] = **2.55**
- Moderately in favour

[Anti] Correlated Isocurvature Perturbation

$$C_l^{TT,scal} = A^2 \left[(1 - \alpha) \hat{C}_l^{ad2} + \alpha \hat{C}_l^{iso} - \sqrt{\alpha(1 - \alpha)} \hat{C}_l^{cor} \right]$$

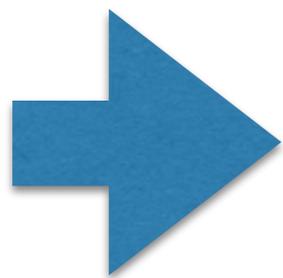


- Prior: $\alpha = [0, 1]$
- 95% posterior: $\alpha = [0, 1.4] \times 10^{-2}$
- Log[Evidence Ratio wrt Λ CDM+r] = **-2.1**
- Moderately against

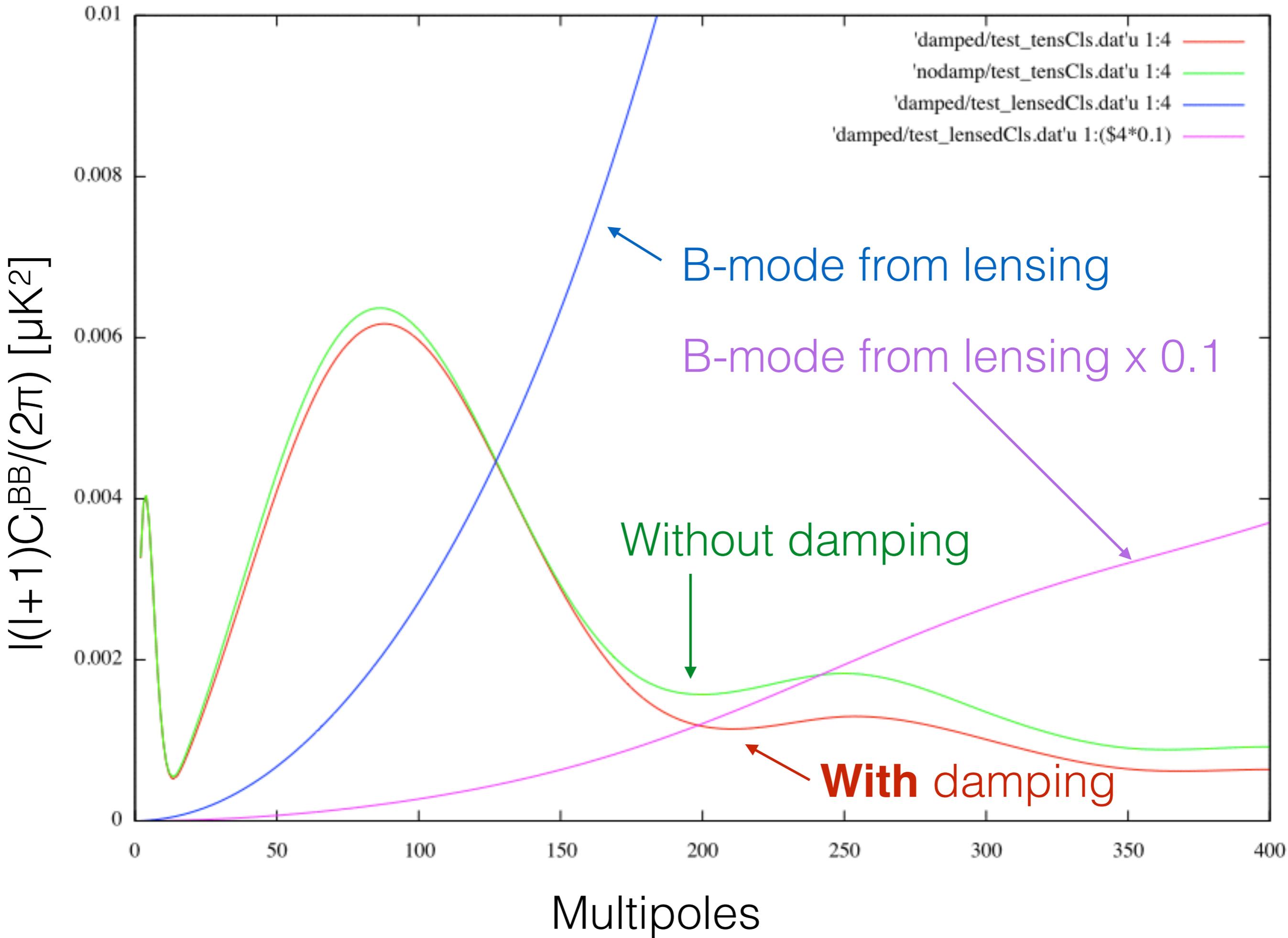
Effect of Relativistic Neutrinos on the B-mode power spectrum

- Gravitational waves are often thought to obey a wave equation in vacuum, simply redshifting away like this: $\square h_{ij} = 0$
- However, gravitational waves suffer from damping due to anisotropic stress of neutrinos:

$$\square h_{ij} = -\frac{16\pi G}{a^2} \delta T_{ij}^{(\nu)}$$



This results in damping of h_{ij} , and the effect is proportional to the energy density of relativistic neutrinos, hence N_{eff} [Weinberg 2004]



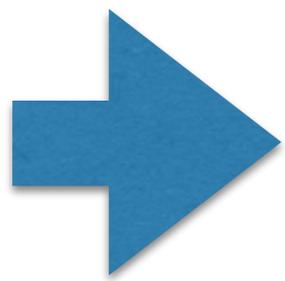
Signal-to-noise Estimates

- With the full lensing B-mode [i.e., no de-lensing]

$$\frac{S}{N} = 3.5 \frac{r \sqrt{f_{\text{sky}}}}{0.1}$$

- With 90% de-lensing

$$\frac{S}{N} = 8 \frac{r \sqrt{f_{\text{sky}}}}{0.1}$$

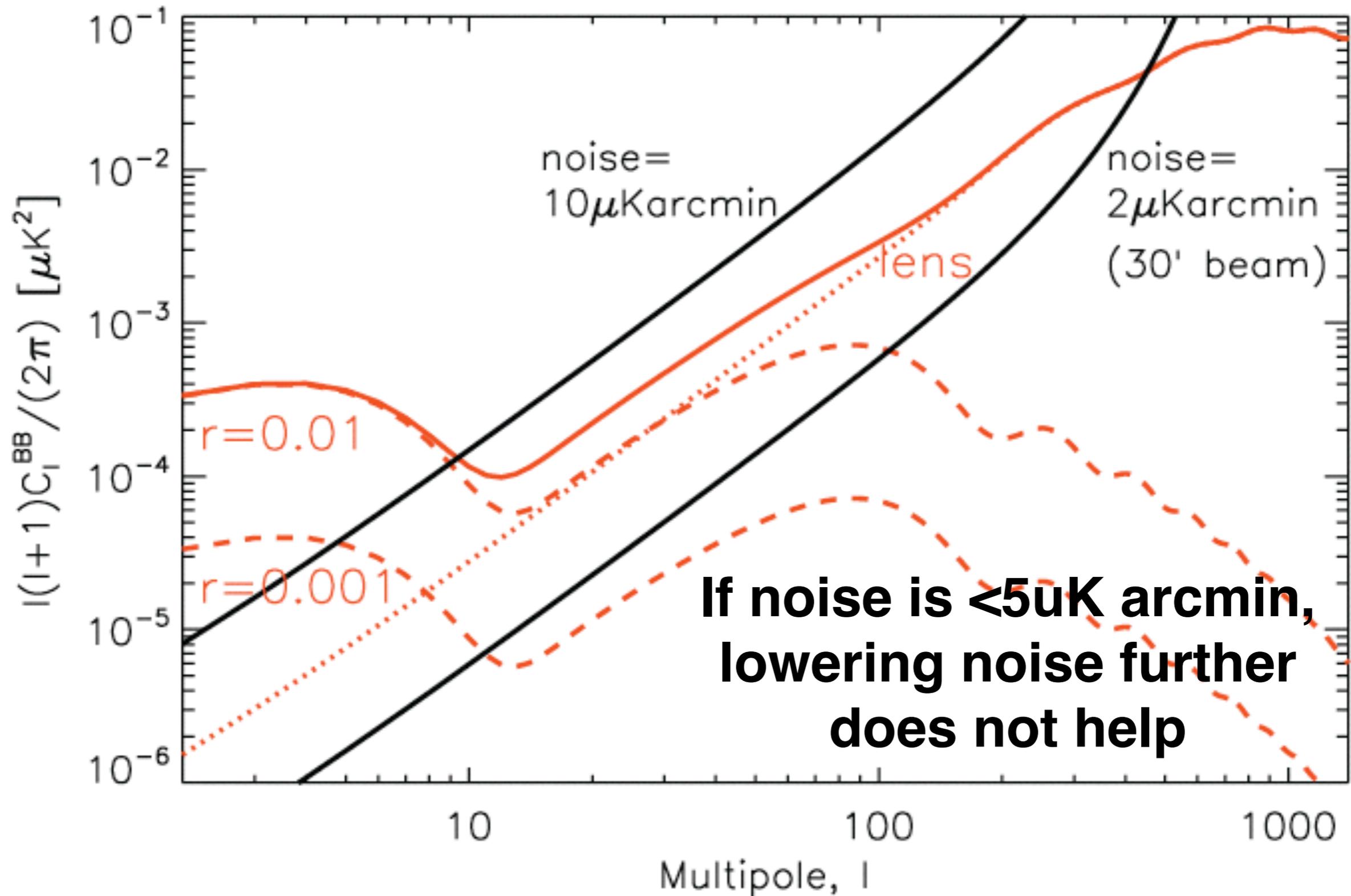


We can use this measurement to constrain the number of effective neutrino species [Zhao, Zhang & Xia 2009]

Tensor Tilt, n_t

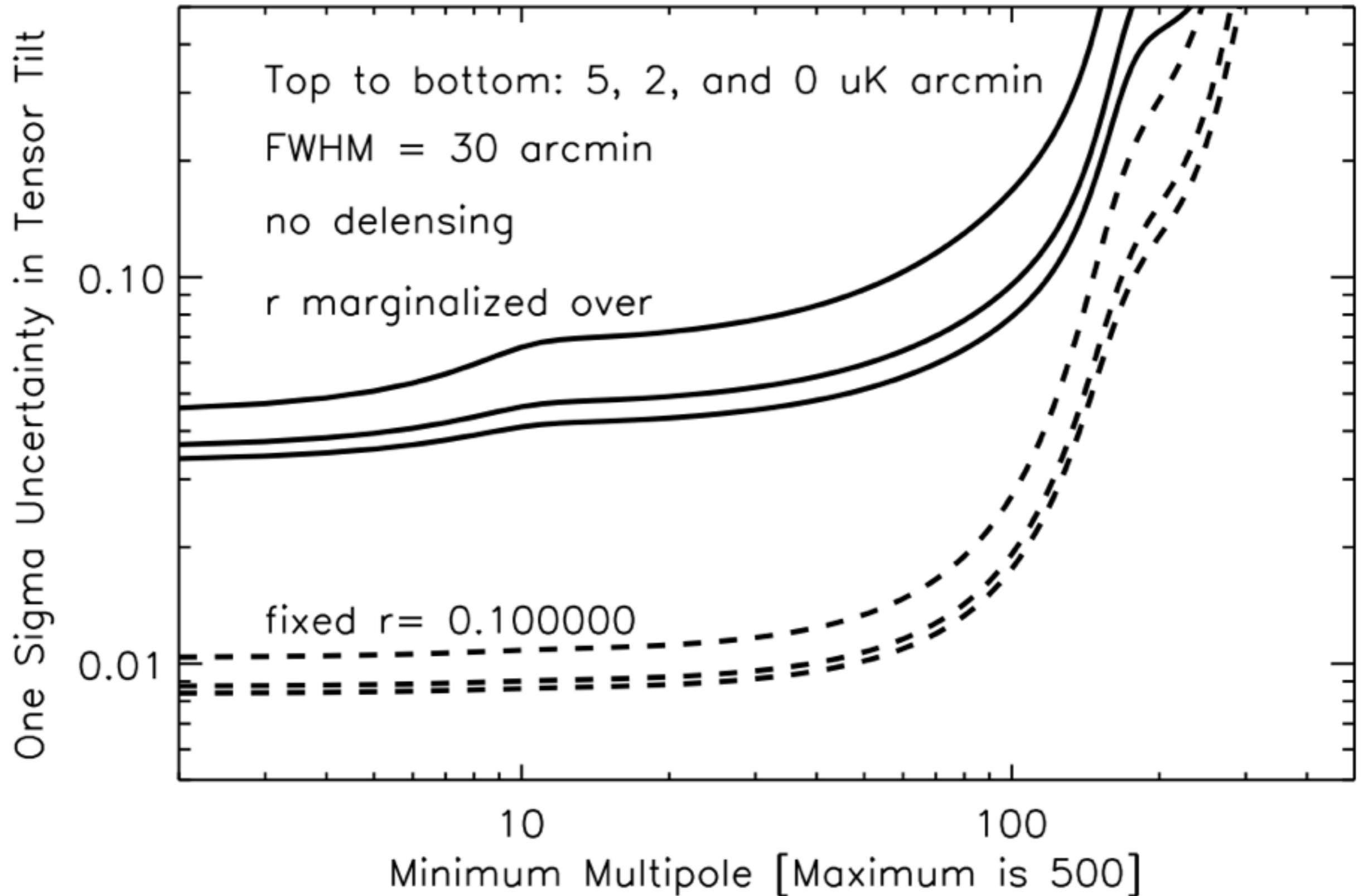
- Unlike the scalar tilt, it is not easy to determine the tensor tilt because the lensing B-mode power spectrum reduces the number of usable modes for measuring the primordial B-mode power spectrum
- **In the best case scenario** without de-lensing, the uncertainty on n_t is **$\text{Err}[n_t] \sim 0.03$ for $r=0.1$** , which is too large to test the single-field consistency relation, $n_t = -r/8 \sim -0.01(r/0.1)$
- De-lensing is crucial!

Lensing limits our ability to determine the tensor tilt



Most optimistic forecast [full sky, white noise, no foreground]

Without de-lensing [$r=0.1$]

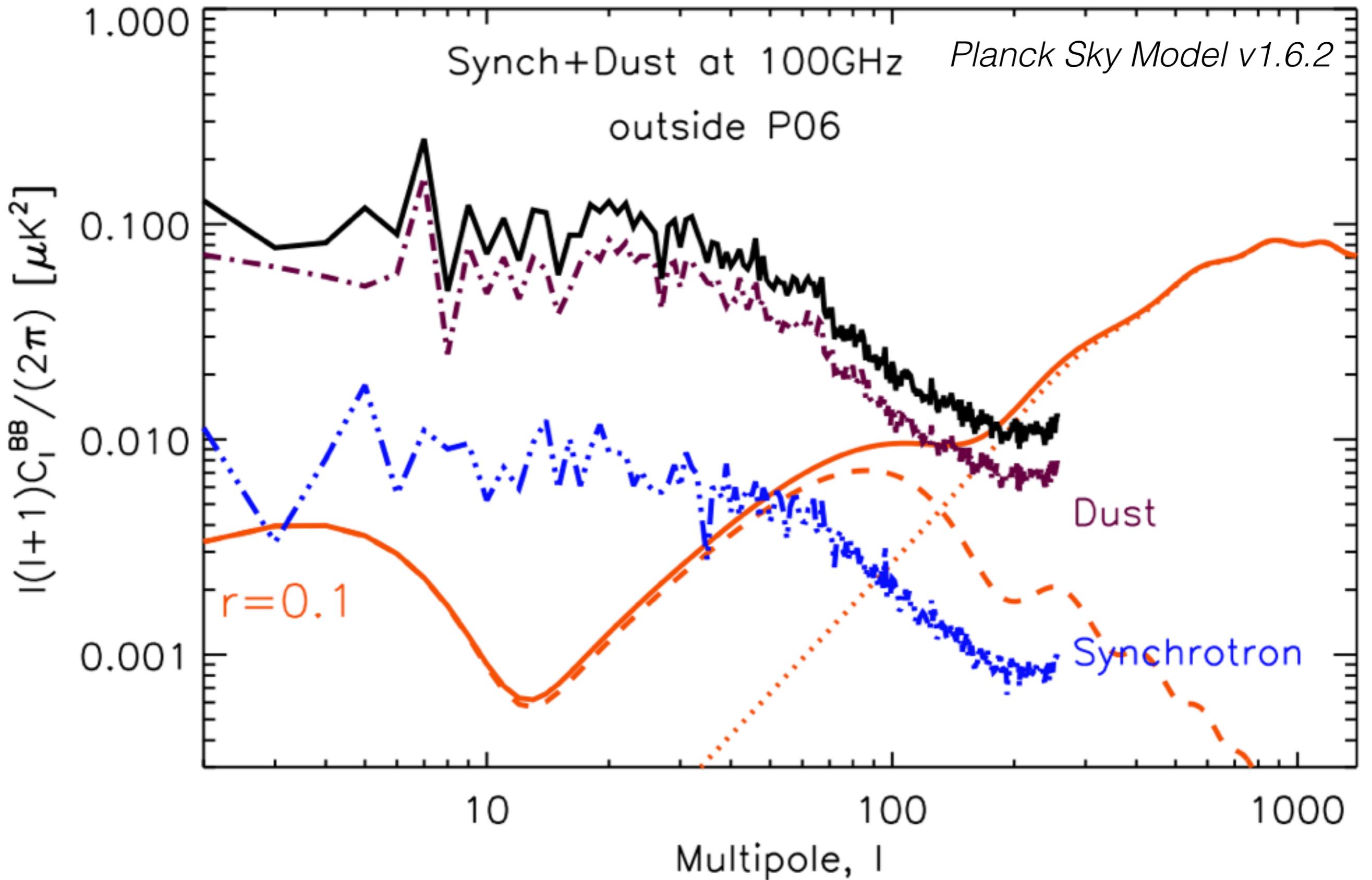


Why reionisation bump?

- Measuring the reionisation bump at $l < 10$ would not improve the precision of the tensor tilt very much
- However, it is an important **qualitative** test of the prediction of inflation
- The measurement of the reionisation bump is a challenging task due to Galactic foreground. How bad can it be?

How many components?

- CMB: $T_\nu \sim \nu^0$
- Synchrotron: $T_\nu \sim \nu^{-3}$
- Dust: $T_\nu \sim \nu^2$
- Therefore, we need **at least** 3 frequencies to separate them



- At 100 GHz, the total foreground emission is a couple of orders of magnitude bigger in power at $l < 10$

Gauss will help us

- The power spectrum captures only a fraction of information
- CMB is very close to Gaussian, while foreground is highly non-Gaussian
- CMB scientist's best friend is this equation:

$$-2 \ln \mathcal{L} = ([\text{data}]_i - [\text{stuff}]_i)^t \underbrace{(C^{-1})_{ij}}_{\text{2-point function of CMB plus noise}} ([\text{data}]_j - [\text{stuff}]_j)$$

2-point function of
CMB plus noise

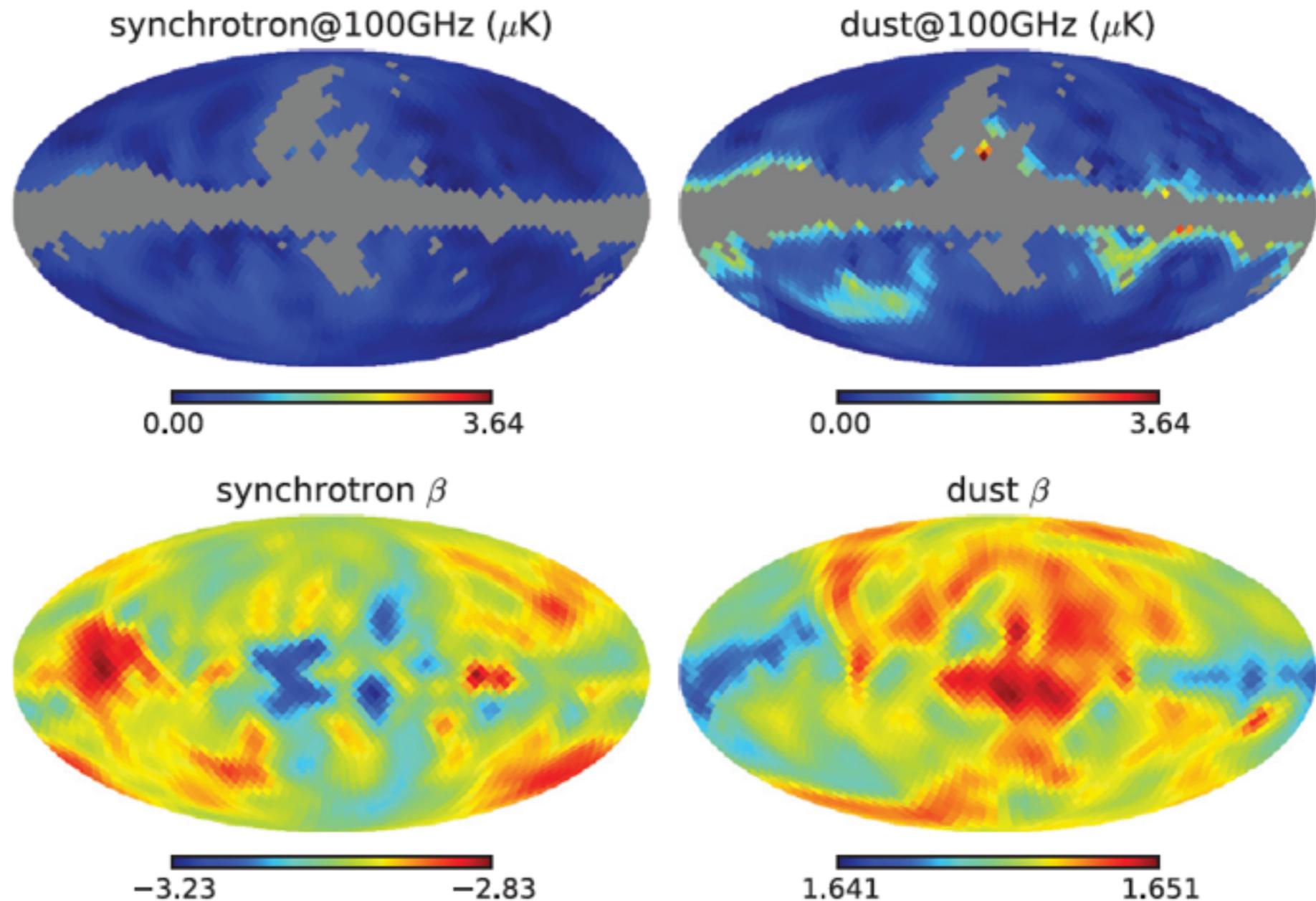
WMAP's Simple Approach

$$[Q', U'](\nu) = \frac{[Q, U](\nu) - \alpha_S(\nu)[Q, U](\nu = 23 \text{ GHz})}{1 - \alpha_S(\nu)}$$

- Use the 23 GHz map as a tracer of synchrotron
- Fit the 23 GHz map to a map at another frequency with a single amplitude α_S , and subtract
- After correcting for the “CMB bias”, this method removes synchrotron completely, **provided that**:
 - Spectral index [$T_\nu \sim \nu^\beta$; $\beta \sim -0.3$ for synchrotron] does not vary across the sky
- Residual foreground emission increases as the index variation increases

Limitation of the Simplest Approach

Planck Sky Model
(ver 1.6.2)



- Synchrotron index **does** vary a lot across the sky

Going with the simplest

- While the synchrotron and dust indices do vary across the sky, let us go ahead with the simplest approach
- Obvious improvements are possible:
 - Fit multiple coefficients to different locations in the sky
 - Use more frequencies to constrain indices simultaneously

Methodology

We shall maximize the following likelihood function for estimating r , s , and α_i :

$$\mathcal{L}(r, s, \alpha_i) \propto \frac{\exp \left[-\frac{1}{2} \mathbf{x}'(\alpha_i)^T \mathbf{C}^{-1}(r, s, \alpha_i) \mathbf{x}'(\alpha_i) \right]}{\sqrt{|\mathbf{C}(r, s, \alpha_i)|}}, \quad (9)$$

where

$$\mathbf{x}' = \frac{[Q, U](\nu) - \sum_i \alpha_i(\nu) [Q, U](\nu_i^{\text{template}})}{1 - \sum_i \alpha_i(\nu)} \quad (10)$$

is a template-cleaned map. This is a generalization of Equation (6) for a multi-component case. In this paper, i takes on “S” and “D” for synchrotron and dust, respectively, unless noted otherwise. For definiteness, we shall choose

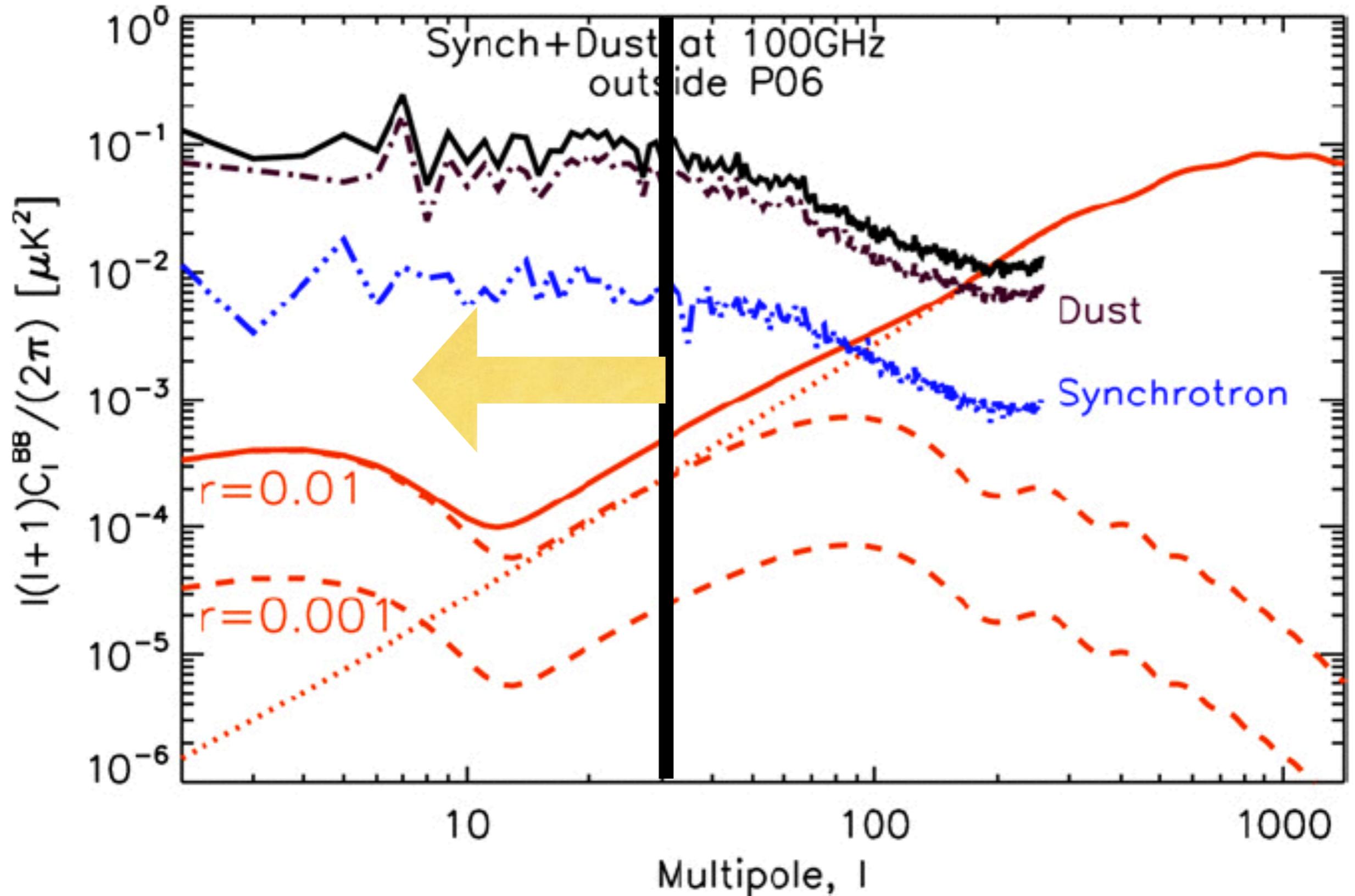
$$\begin{aligned} \nu &= 100 \text{ GHz}, \\ \nu_S^{\text{template}} &= 60 \text{ GHz}, \\ \nu_D^{\text{template}} &= 240 \text{ GHz}. \end{aligned}$$

$$O(N^3)$$

$$\mathcal{L}(r, s, \alpha_i) \propto \frac{\exp \left[-\frac{1}{2} \mathbf{x}'(\alpha_i)^T \mathbf{C}^{-1}(r, s, \alpha_i) \mathbf{x}'(\alpha_i) \right]}{\sqrt{|\mathbf{C}(r, s, \alpha_i)|}}$$

- Since we cannot invert the covariance matrix when the number of pixels is too large, we focus on low-resolution Q and U maps with 3072 pixels per map [N_{side}=16; 3.7-degree pixel]

We target the reionisation bump



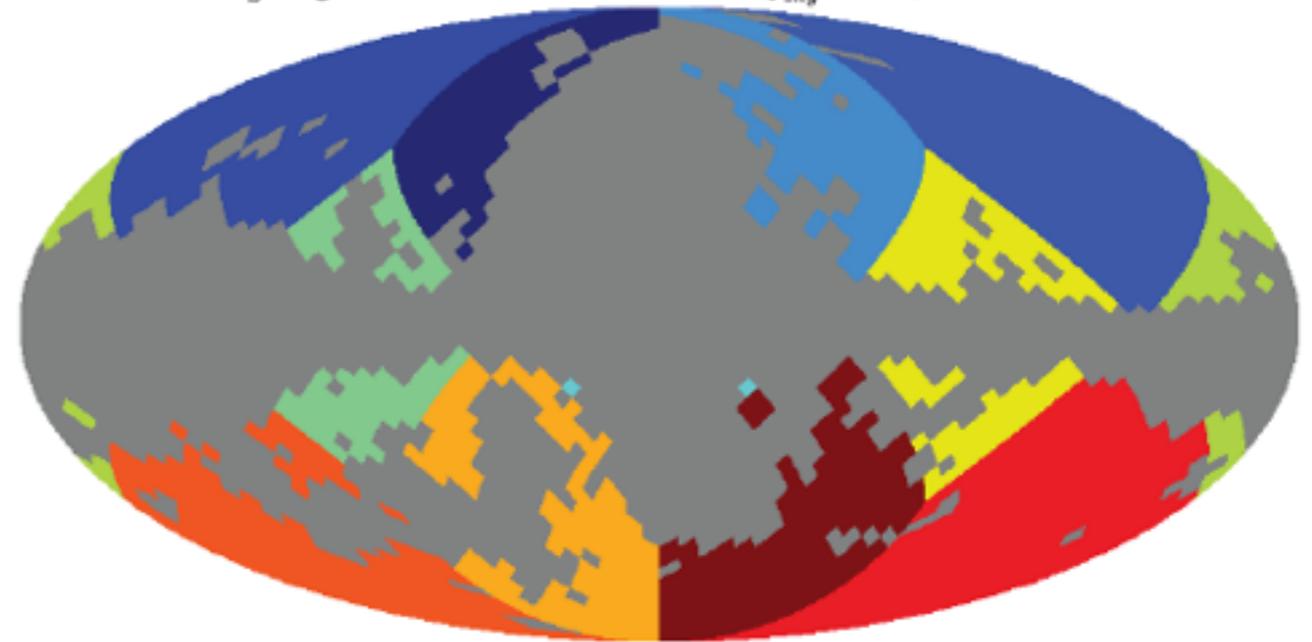
Two Masks and Choice of Regions for Synch. Index

(a) 48 α_S regions with the P06 mask ($f_{sky}=73\%$) for Method I



Method I

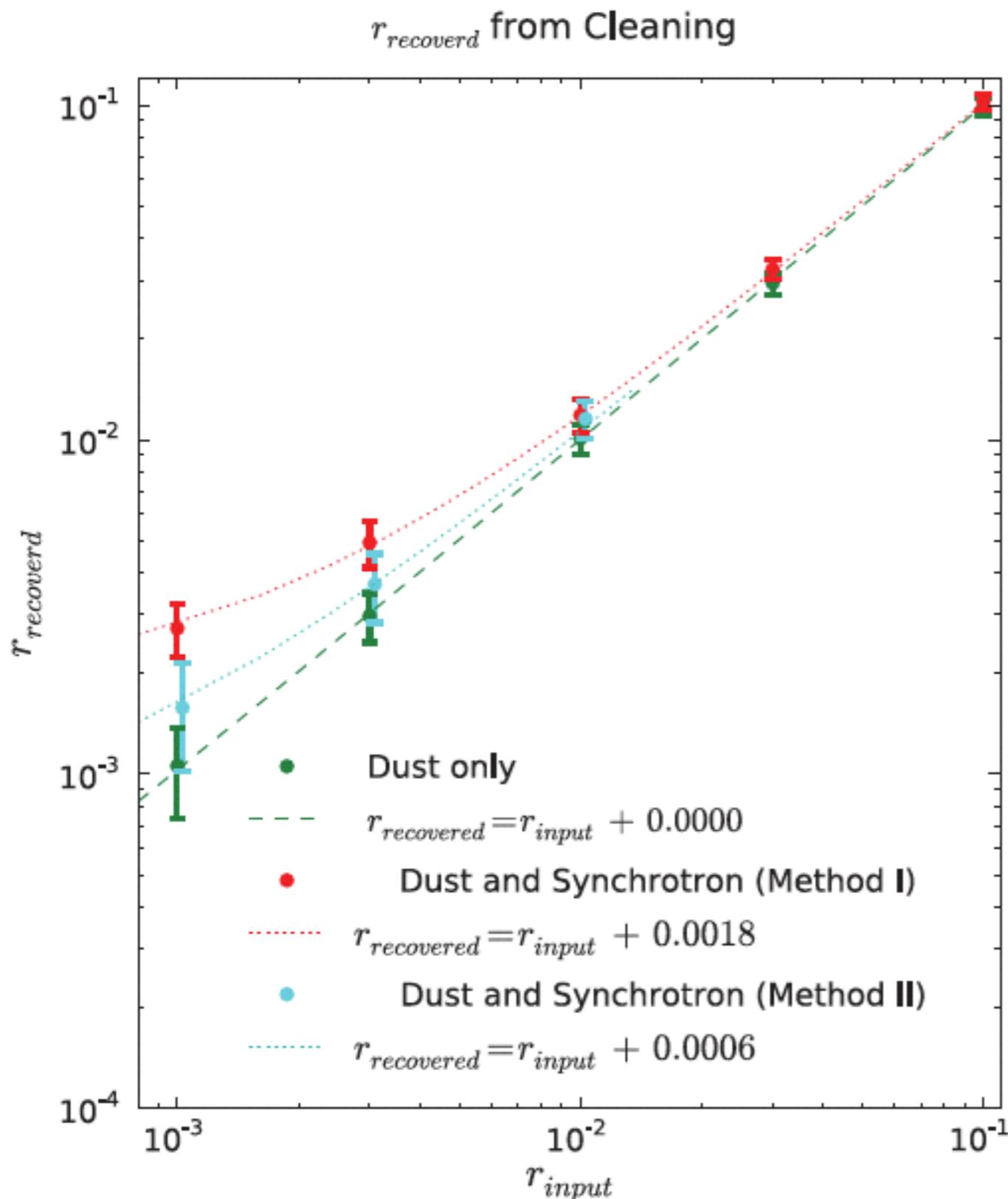
(b) 12 α_S regions with extended mask ($f_{sky}=50\%$) for Method II



Method II

Results

[3 frequency bands: 60, 100, 240 GHz]



- It works well!
- Method I: the bias is $\delta r = 2 \times 10^{-3}$
- Method II: the bias is $\delta r = 0.6 \times 10^{-3}$
- [This analysis needs to be re-done with the dust spectral index from Planck]

Toward precision measurement of B-modes

- $r \sim 10^{-3}$ seems totally possible, even in the presence of synchrotron and dust emissions
- What experiment can we design to achieve this measurement?

LiteBIRD

- Next-generation polarisation-sensitive microwave experiment. Target launch date: early 2020
- Led by Prof. Masashi Hazumi (KEK); a collaboration of ~70 scientists in Japan, USA, Canada, and Germany
- **Singular goal**: measurement of the primordial B-mode power spectrum with **Err[r]=0.001**
- **6 frequency bands** between 50 and 320 GHz

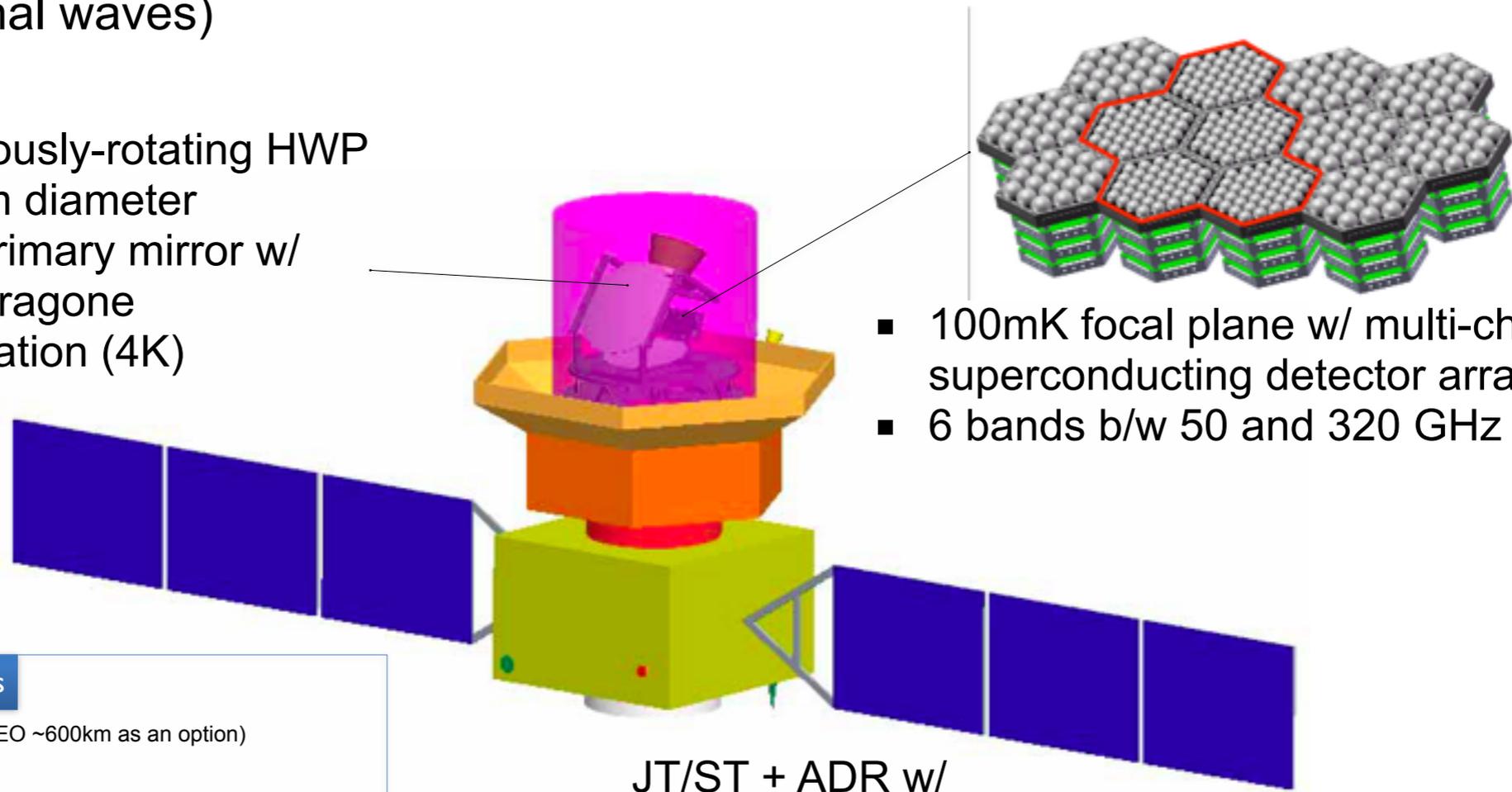
LiteBIRD

Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection

- Candidate for JAXA's future missions on "fundamental physics"
- **Goal:** Search for primordial gravitational waves to the lower bound of well-motivated inflationary models
- **Full success:** $\delta r < 0.001$ (δr is the total uncertainties on tensor-to-scalar ratio, which is a fundamental cosmology parameter related to the power of primordial gravitational waves)

- Continuously-rotating HWP w/ 30 cm diameter
- 60 cm primary mirror w/ Cross-Dragone configuration (4K)

- 100mK focal plane w/ multi-chroic superconducting detector array
- 6 bands b/w 50 and 320 GHz



JT/ST + ADR w/
heritages of X-ray missions

Major specifications

- Orbit: L2 (Twilight LEO ~600km as an option)
- Weight: ~1300kg
- Power: ~2000W
- Observing time: > 2 years
- Spin rate: ~0.1rpm

LiteBIRD working group

❖ 68 members (as of Nov. 21, 2013)

KEK

Y. Chinone
K. Hattori
M. Hazumi (PI)
M. Hasegawa
Y. Hori
N. Kimura
T. Matsumura
H. Morii
R. Nagata
S. Oguri
N. Sato
T. Suzuki
O. Tajima
T. Tomaru
H. Yamaguchi
M. Yoshida

JAXA

H. Fuke
I. Kawano
H. Matsuhara
K. Mitsuda
T. Nishibori
A. Noda
S. Sakai
Y. Sato
K. Shinozaki
H. Sugita
Y. Takei
T. Wada
N. Yamasaki
T. Yoshida
K. Yotsumoto

UC Berkeley

W. Holzapfel
A. Lee (US PI)
P. Richards
A. Suzuki

Kavli IPMU

N. Katayama
H. Nishino

MPA

E. Komatsu

ATC/NAOJ

K. Karatsu
T. Noguchi
Y. Sekimoto
Y. Uzawa

McGill U.

M. Dobbs

Yokohama NU.

K. Mizukami
S. Nakamura
K. Natsume

Tohoku U.

M. Hattori
K. Ishidoshiro
K. Morishima

RIKEN

K. Koga
S. Mima
C. Otani

LBLN

J. Borrill

Osaka Pref. U.

K. Kimura
M. Kozu
H. Ogawa

Konan U.

I. Ohta

Saitama U.

M. Naruse

SOKENDAI

Y. Akiba
Y. Inoue
H. Ishitsuka
H. Watanabe

Okayama U.

H. Ishino
A. Kibayashi
Y. Kibe

NIFS

S. Takada

Osaka U.

S. Takakura

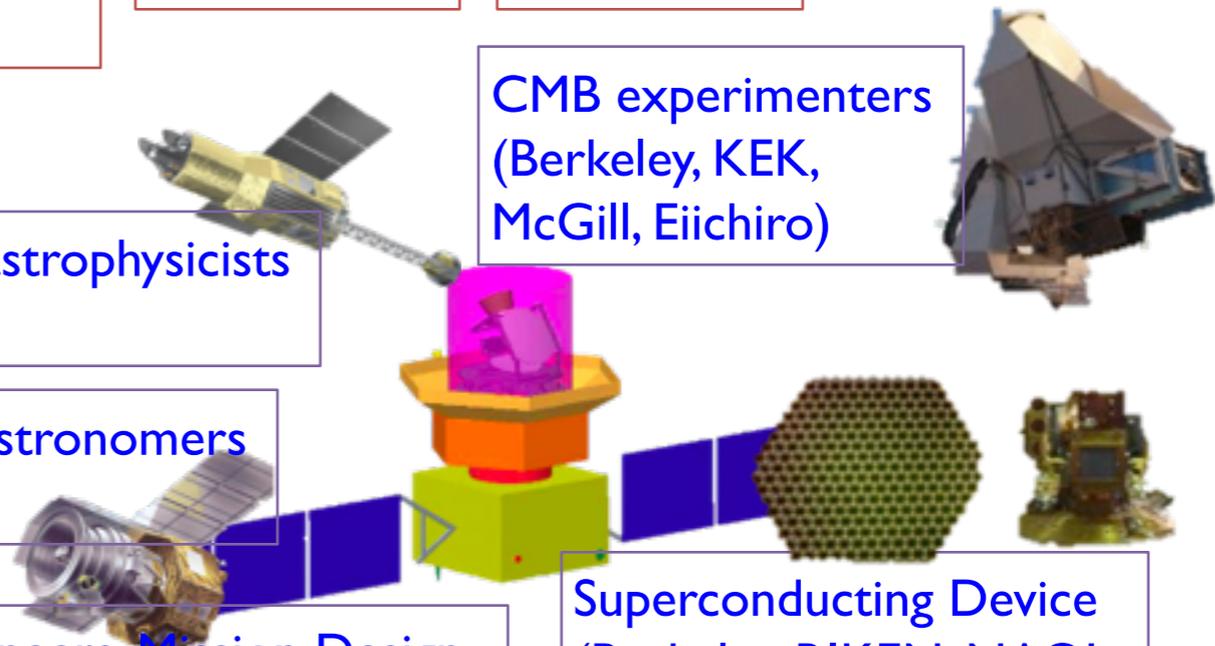
X-ray astrophysicists
(JAXA)

Infrared astronomers
(JAXA)

JAXA engineers, Mission Design
Support Group, SE office

CMB experimenters
(Berkeley, KEK,
McGill, Eiichiro)

Superconducting Device
(Berkeley, RIKEN, NAOJ,
Okayama, KEK etc.)



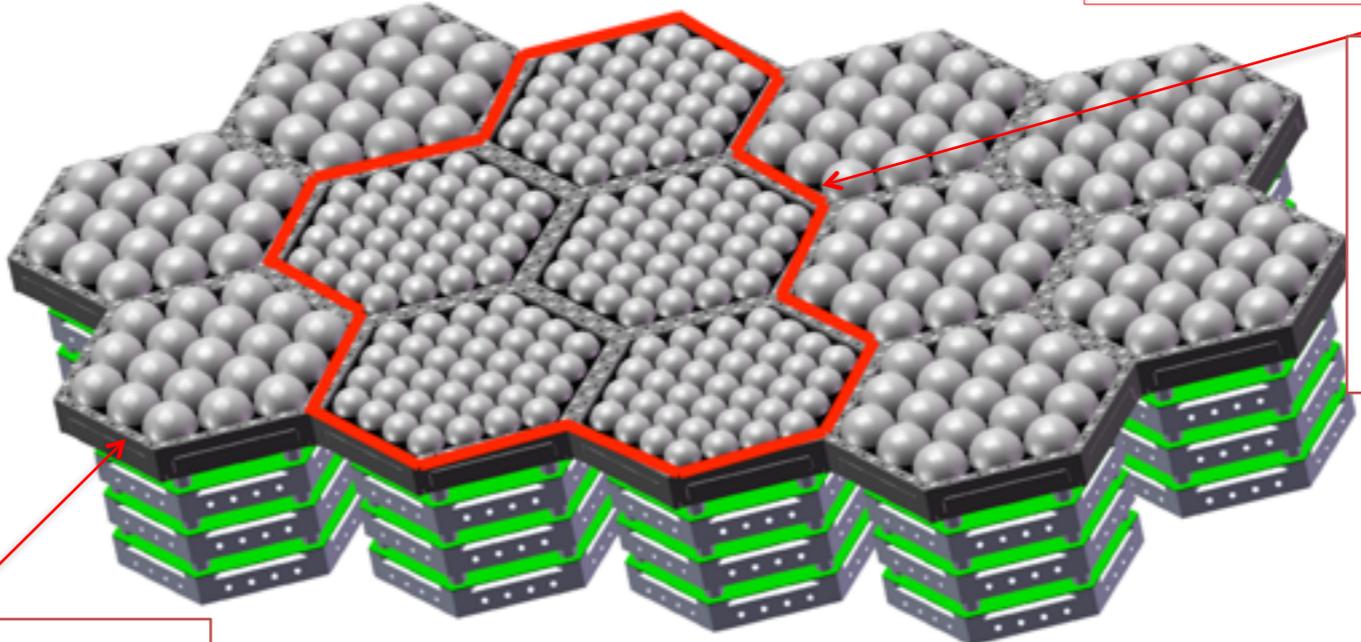
LiteBIRD focal plane design

UC Berkeley TES option

2022 TES bolometers

$T_{\text{bath}} = 100\text{mK}$

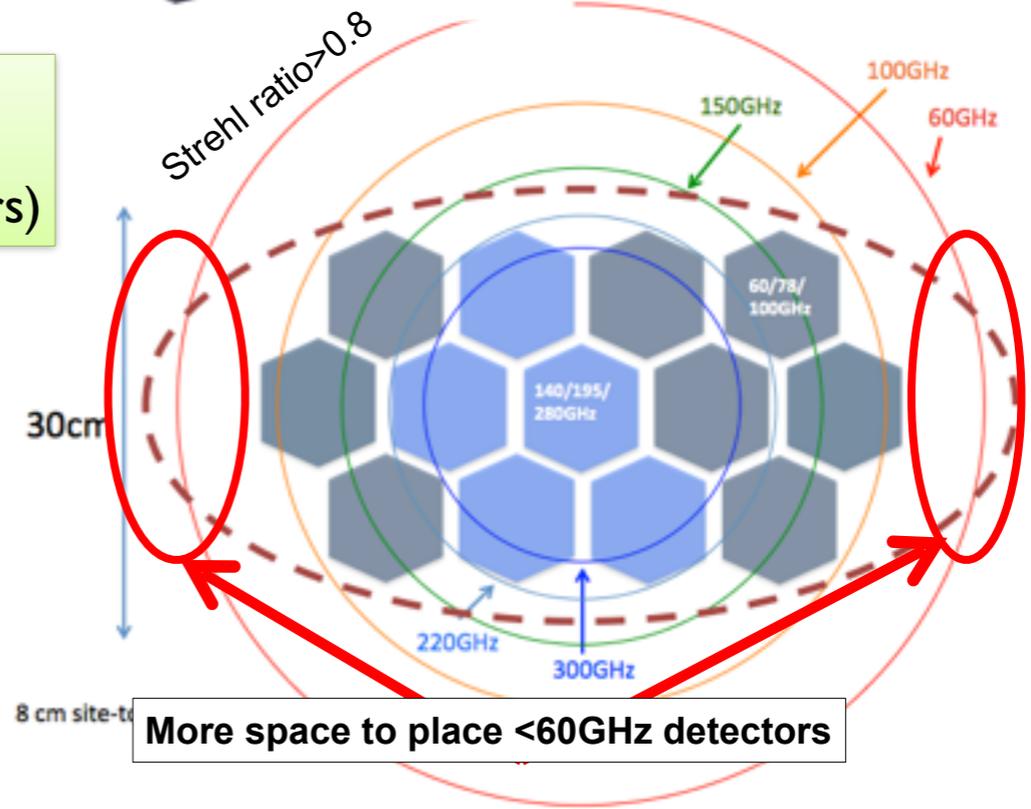
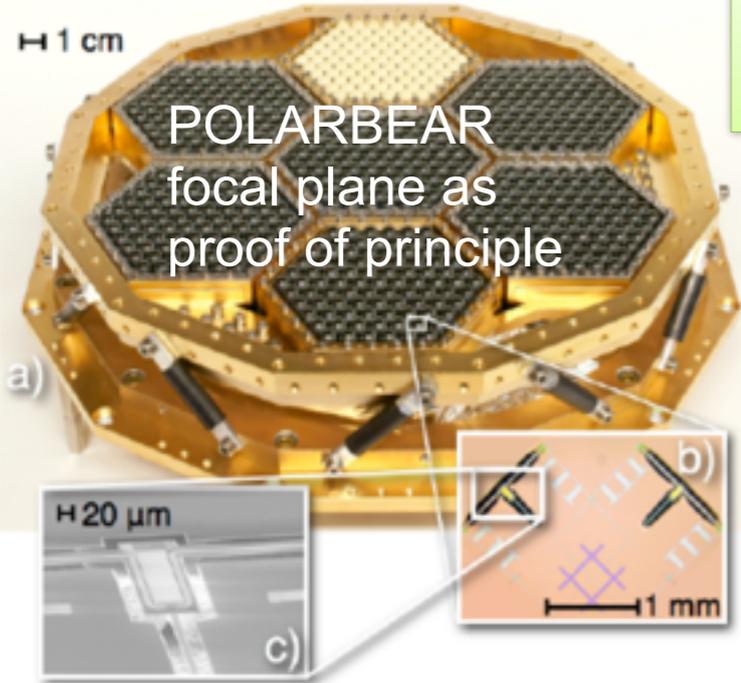
tri-chroic (60/78/100GHz)



tri-chroic (140/195/280GHz)

Band centers can be distributed to increase the effective number of bands

2 μ K arcmin
(w/ 2 effective years)



More space to place <60GHz detectors

LiteBIRD proposal milestones

- 2012 October - 2014 March
Feasibility studies & cost estimation with MELCO and NEC
- 2013 April - 2014 April
Review and recommendation from Science Council of Japan
- late 2014
White Paper (will be published in *Progress of Theoretical and Experimental Physics (PTEP)*)
- 2014 June - December
Proposal and Mission Definition Review (MDR)
- 2015 ~
Phase A

Conclusion

- Important milestones for inflation have been achieved: **$n_s < 1$ with 5σ** ; remarkable Gaussianity
- The next goal: unambiguous measurement of the primordial B-mode polarisation power spectrum
 - A note on the WMAP/Planck–BICEP2 tension: anti-correlated isocurvature does not help
- **$\text{Err}[n_t] \sim 0.01$** possible only with substantial de-lensing
- Neutrino damping observable if $r \sim 0.1$ and de-lensing
- Foreground cleaning with the simplest internal template method is promising, **limiting the bias in r to $< 10^{-3}$**
- **LiteBIRD** proposal: a B-mode CMB polarisation satellite in early 2020