CMB Polarisation: Toward an Observational Proof of Cosmic Inflation

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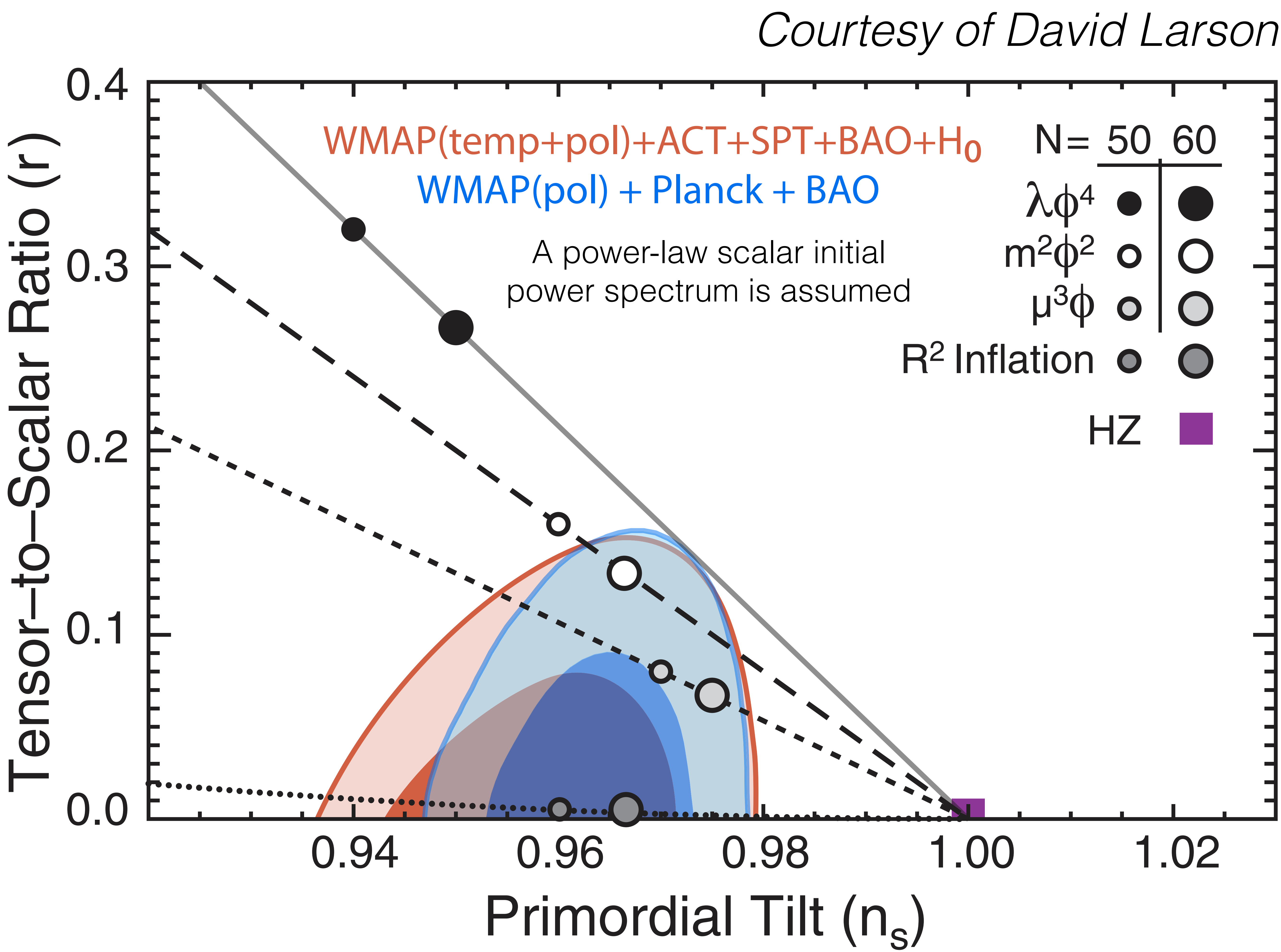
Finding Inflation: Breakthroughs in 2012 and 2013

- *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**


Courtesy of David Larson
WMAP(temp+pol)+ACT+SPT+BAO+H_0
WMAP(pol) + Planck + BAO
A power-law scalar initial
power spectrum is assumed
N= 50 60
$\lambda\phi^4$
$m^2\phi^2$
$\mu^3\phi$
R^2 Inflation
HZ
Tensor-to-Scalar Ratio (r)
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (n_s)

**yet to be confirmed*

Breakthrough* in 2014

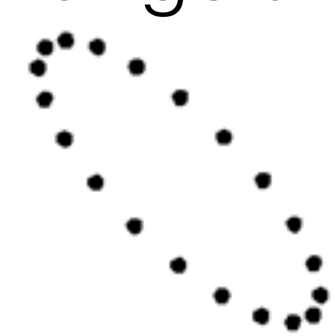
- *Discovery of the primordial* B-modes with more than 5σ by BICEP2*
    - Detection of nearly scale-invariant tensor perturbations proves inflation
    - This requires precise characterisation of the B-mode power spectrum. How are we going to achieve this?

We measure distortions in space

- A distance between two points in space

$$d\ell^2 = a^2(t)[1+2\zeta(\mathbf{x},t)][\delta_{ij}+h_{ij}(\mathbf{x},t)]dx^i dx^j$$

- ζ: “curvature perturbation” (scalar mode)
  - Perturbation to the determinant of the spatial metric
- h_{ij}: “gravitational waves” (tensor mode)
  - Perturbation that does not change the determinant (area)



$$\sum_i h_{ii} = 0$$

Tensor-to-scalar Ratio

$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

- The BICEP2 results suggest **r~0.2**, if we do not subtract any foregrounds

Quantum fluctuations and gravitational waves

- Quantum fluctuations generated during inflation are proportional to the Hubble expansion rate during inflation, **H**
  - Simply a consequence of Uncertainty Principle
- Variance of gravitational waves is then proportional to **H^2**:

$$\langle h_{ij} h^{ij} \rangle \propto H^2$$

Energy Scale of Inflation

$$\langle h_{ij} h^{ij} \rangle \propto H^2$$

- Then, the Friedmann equation relates H^2 to the energy density (or potential) of a scalar field driving inflation:

$$H^2 = \frac{V(\phi)}{3M_{\rm pl}^2}$$

- The BICEP2 result, r~0.2, implies

$$V^{1/4} = 2 \times 10^{16} \left(\frac{r}{0.2}\right)^{1/4} \ \ \mathrm{GeV}$$

Has Inflation Occurred?

- We must see [near] scale invariance of the gravitational wave power spectrum:

$$\langle h_{ij}(\mathbf{k}) h^{ij,*}(\mathbf{k}) \rangle \propto k^{n_t}$$

with

$$n_t = \mathcal{O}(10^{-2})$$

Inflation, defined

- Necessary and sufficient condition for inflation = sustained accelerated expansion in the early universe
- Expansion rate: $H=(da/dt)/a$
- Accelerated expansion: $(d^2a/dt^2)/a = dH/dt + H^2 > 0$
- Thus, **$-(dH/dt)/H^2 < 1$**
- In other words:
    - The rate of change of H must be slow [$n_t \sim 0$]
    - [and H usually decreases slowly, giving $n_t < 0$]

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 x 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!

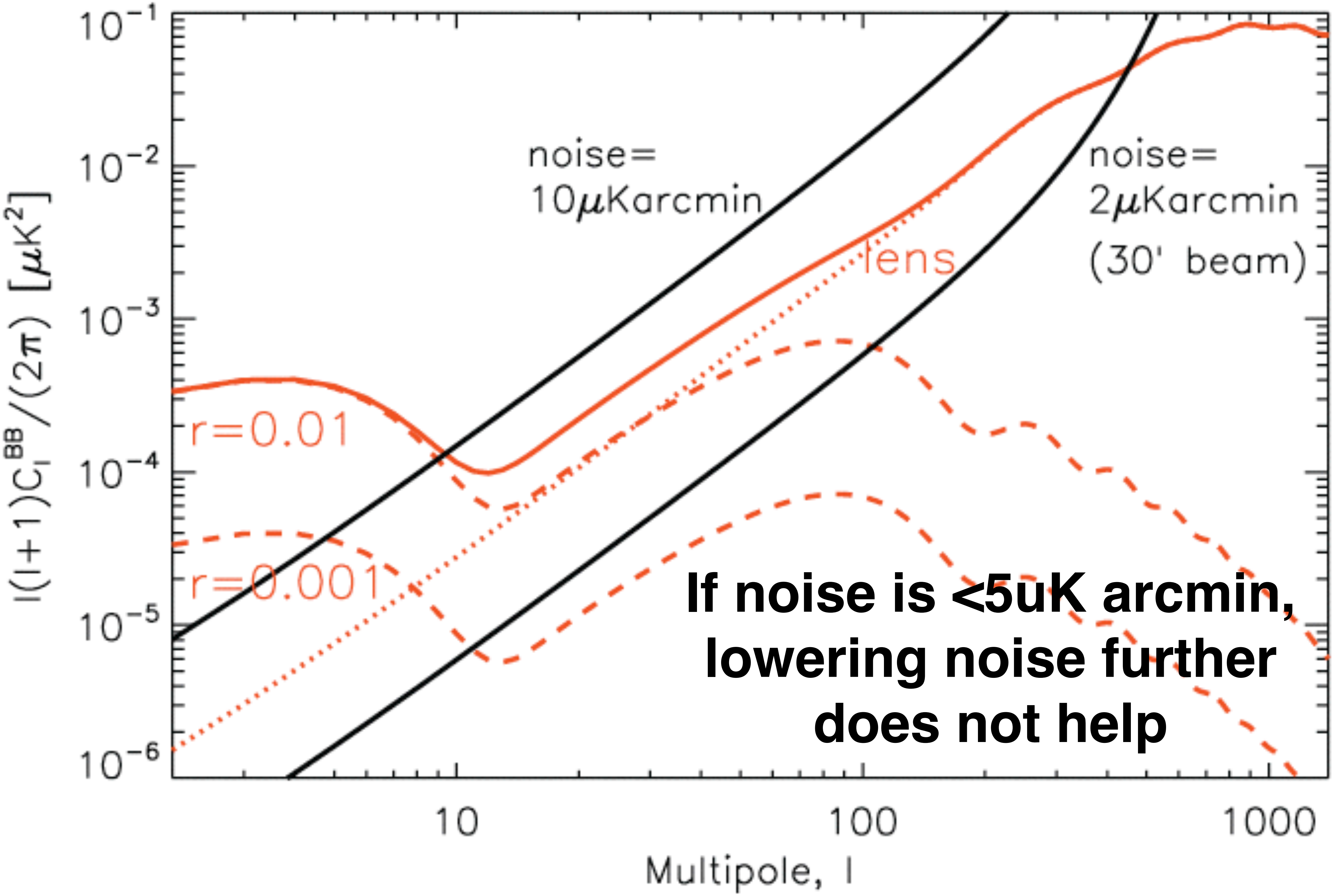
Tensor Tilt, n_t

- 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 **Err[n_t]~0.03 for r=0.1**, which is too large to test the single-field consistency relation, $n_t = -r/8 \sim -0.01(r/0.1)$

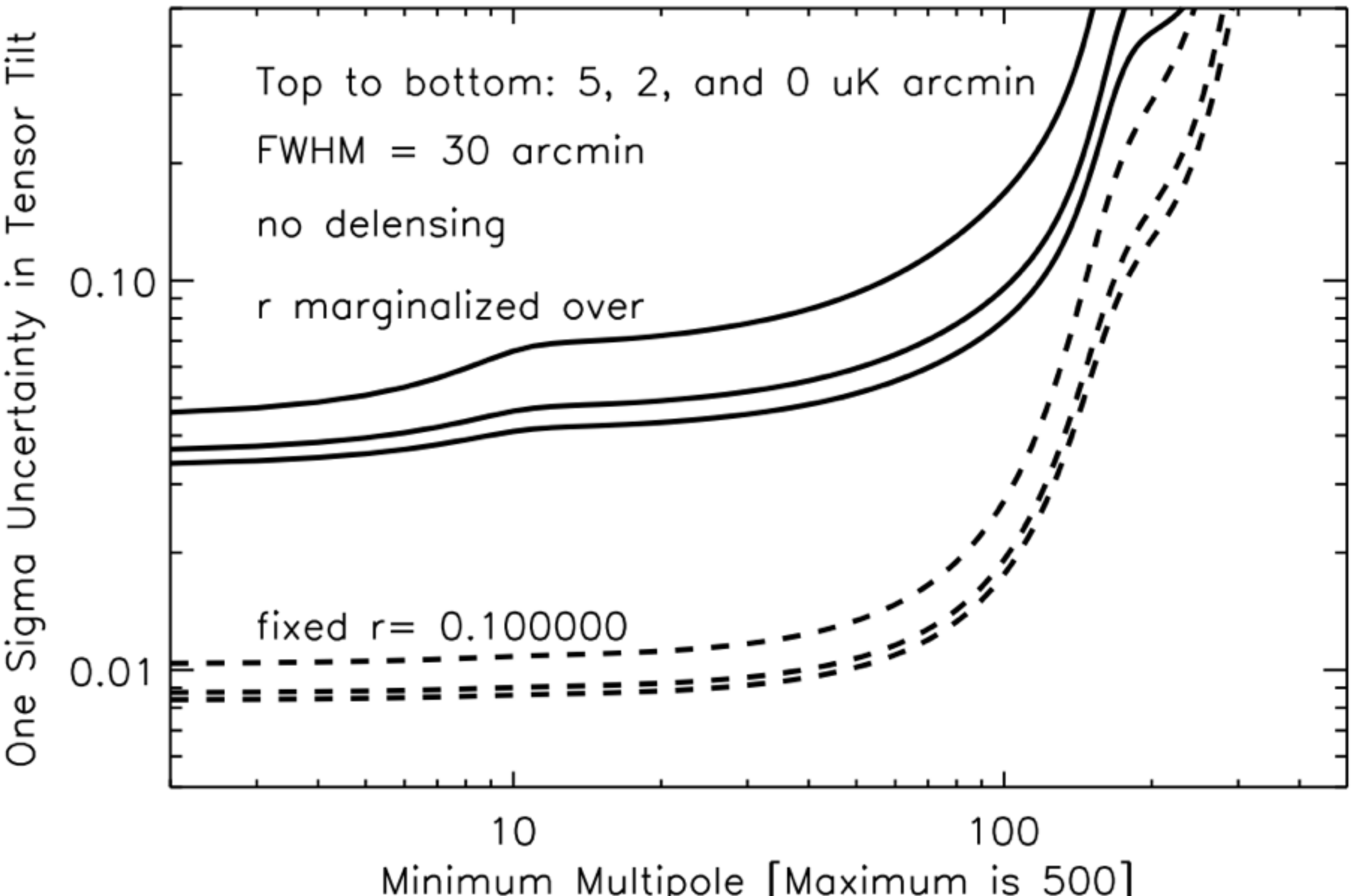
- De-lensing is crucial!

Lensing limits our ability to determine the tensor tilt



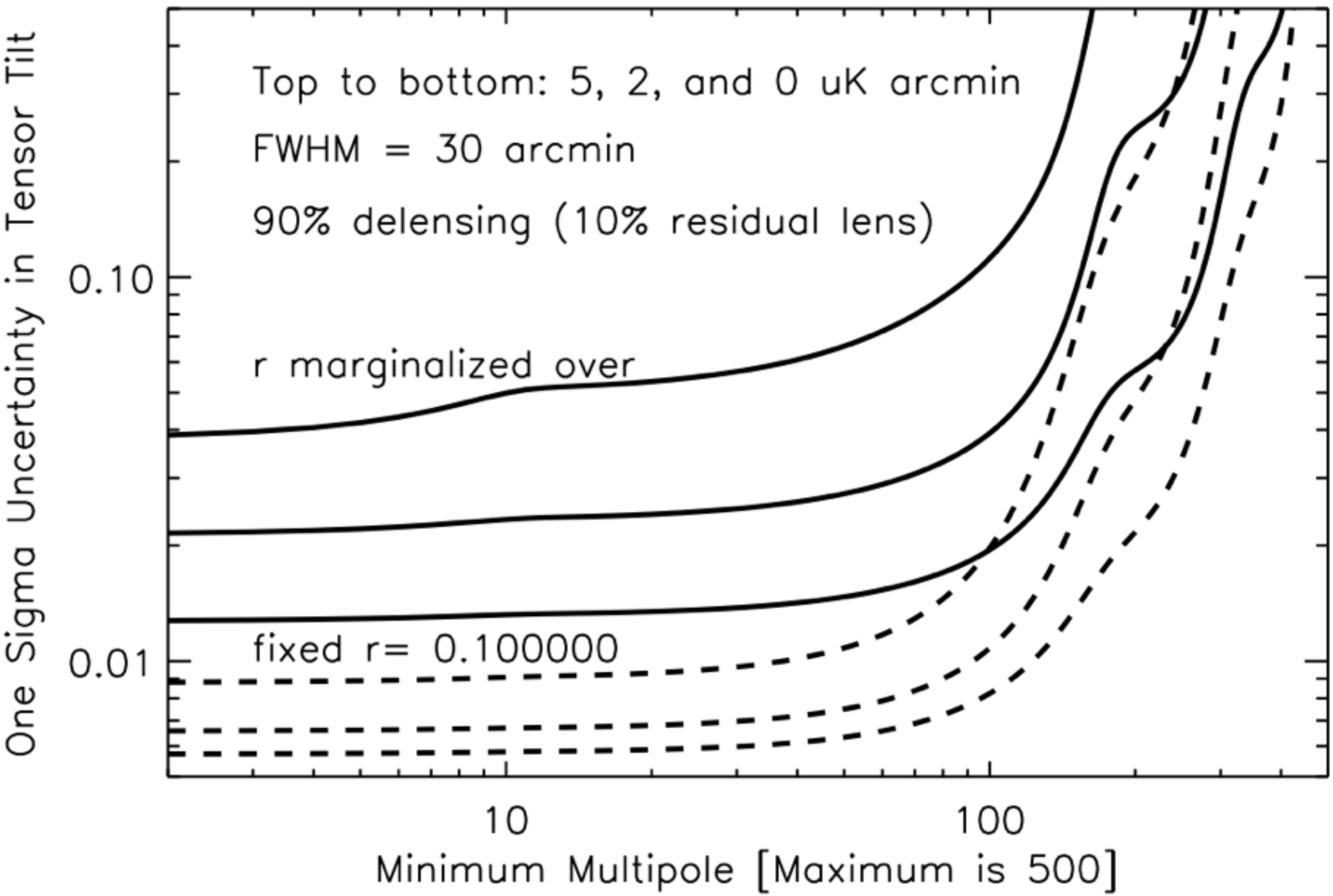
Most optimistic forecast [full sky, white noise, no foreground]

Without de-lensing [r=0.1]



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

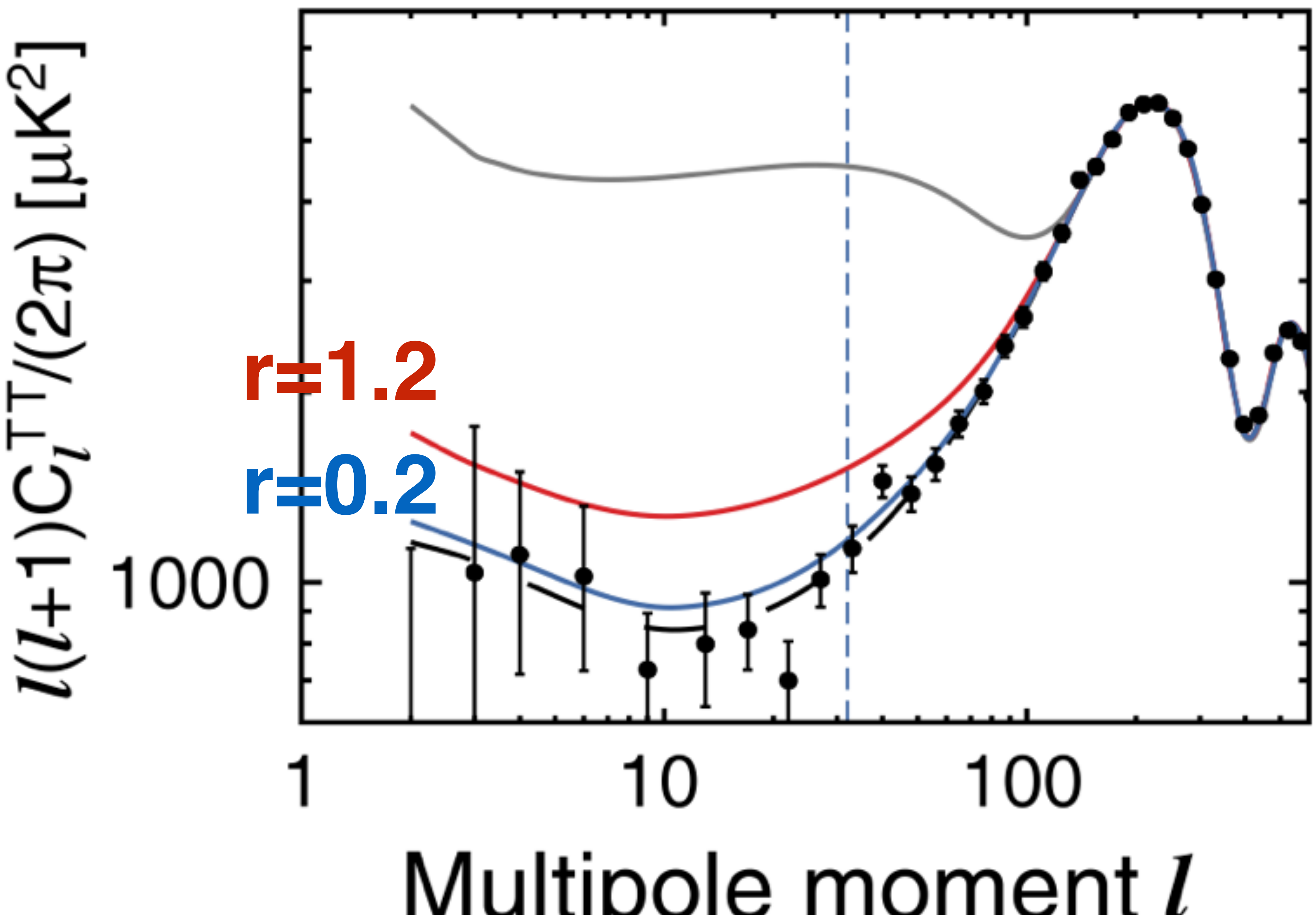
90% de-lensing [r=0.1]



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. *I will come back to this later*

A comment on the tension between r~0.2 and WMAP/Planck



Lowering TT at low multipoles

- Adding a scale-dependent [running] scalar spectral index improves χ^2 by
  - $\Delta\chi^2 = -7.1$ [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]

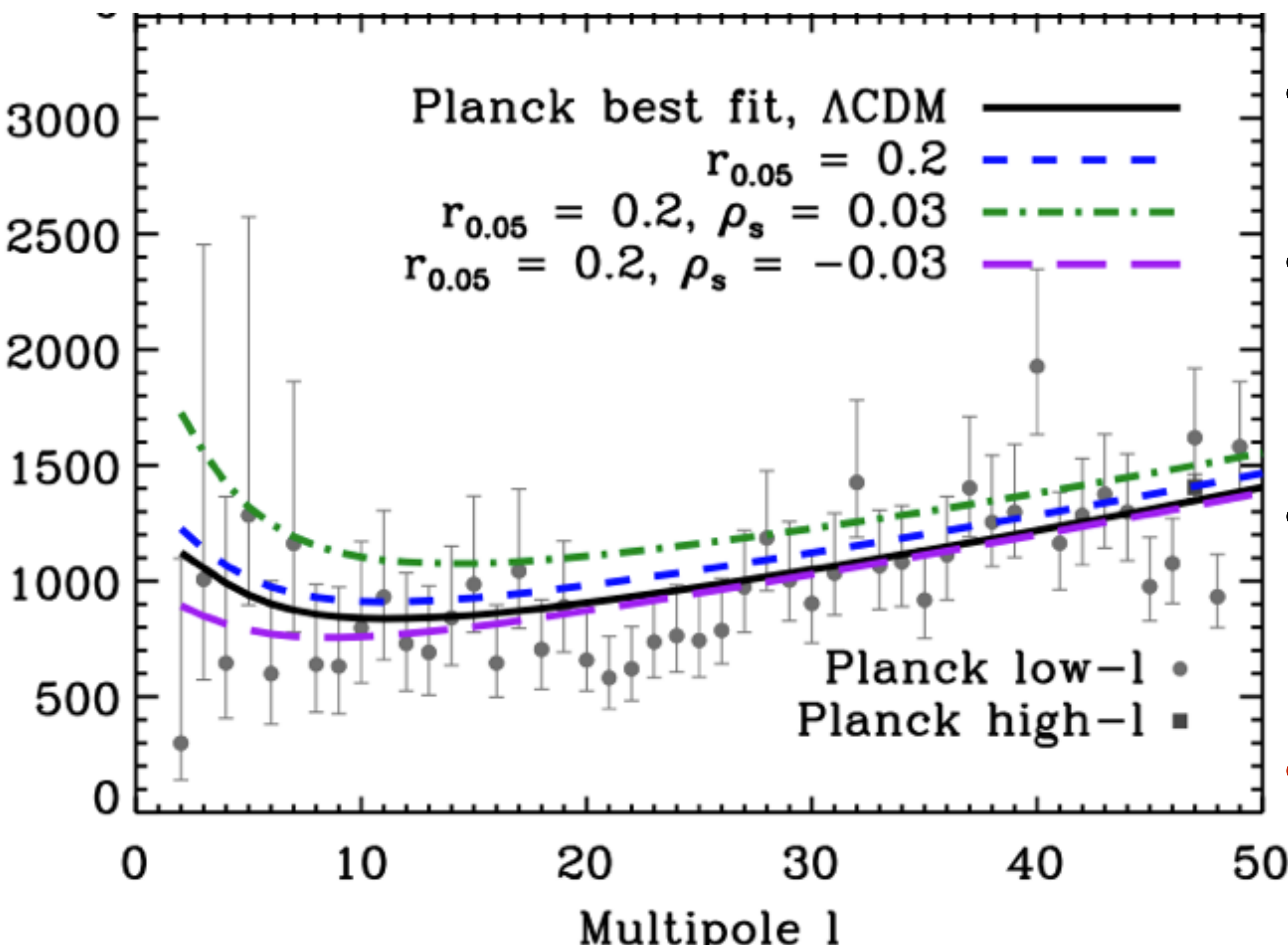
Log[Evidence Ratio]

- 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(Evidence Ratio)=0 to 1 -> no evidence
    - ln(Evidence Ratio)=1 to 2.5 -> weak evidence
    - ln(Evidence Ratio)=2.5 to 5 -> moderate evidence
    - ln(Evidence Ratio)>5 -> strong evidence

Giannantonio & Komatsu, arXiv:1407.4291

Running Index

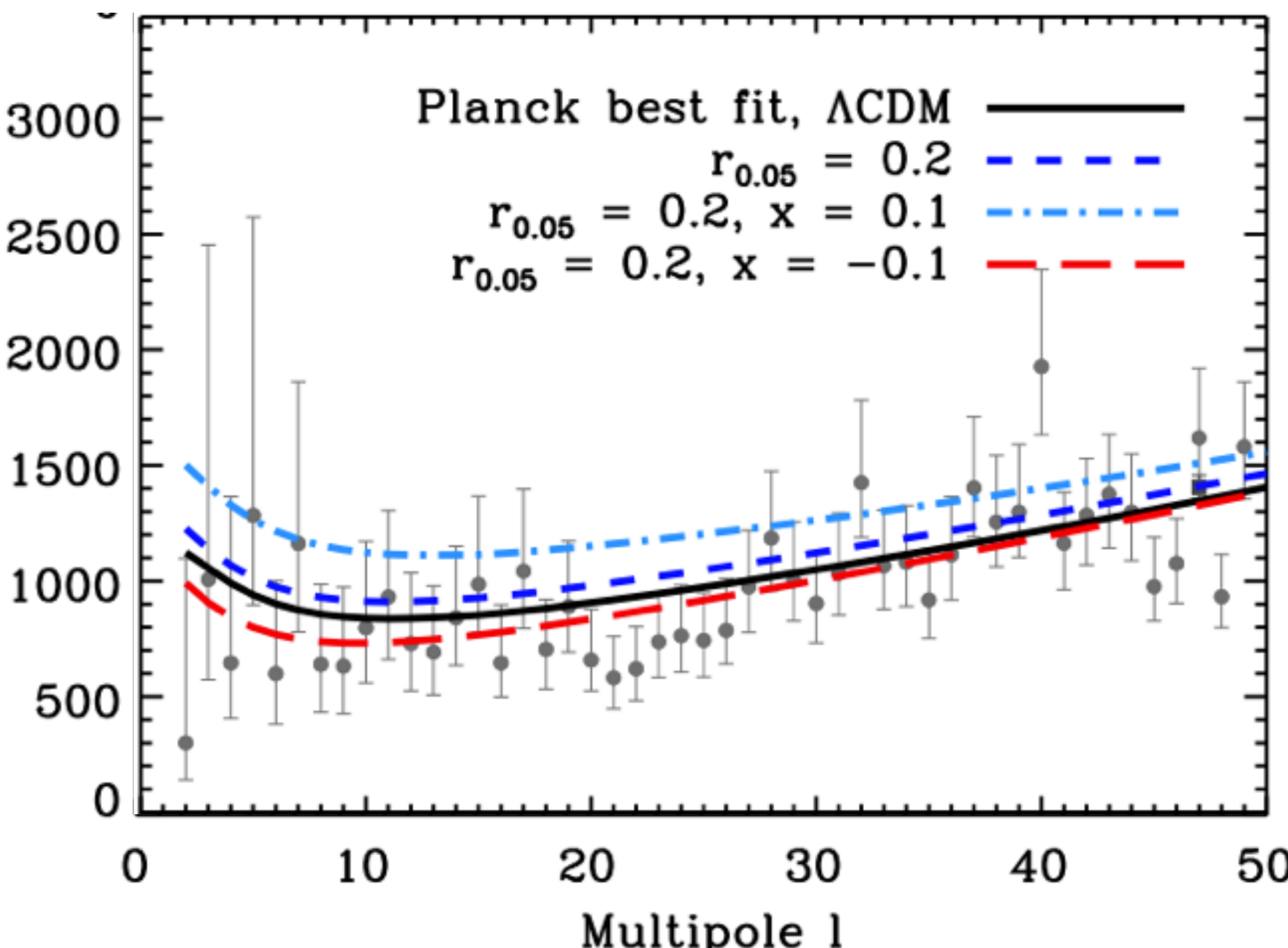
$$k^3 P(k) \propto k^{n_s - 1 + \frac{1}{2}\rho_s \ln(k/k_0)}$$



- Prior: ρ_S=[–0.1,0.1]
- 95% posterior: ρ_S=[–4.4,–0.12]x10^{-2}
- Log[Evidence Ratio wrt LCDM+r] = **2.55**
- Moderately in favour

[Anti] Correlated Isocurvature Perturbation

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



- Prior: α=[0,1]
- 95% posterior: α=[0,1.4]x10^{-2}
- Log[Evidence Ratio wrt LCDM+r] = **–2.1**
- Weakly against

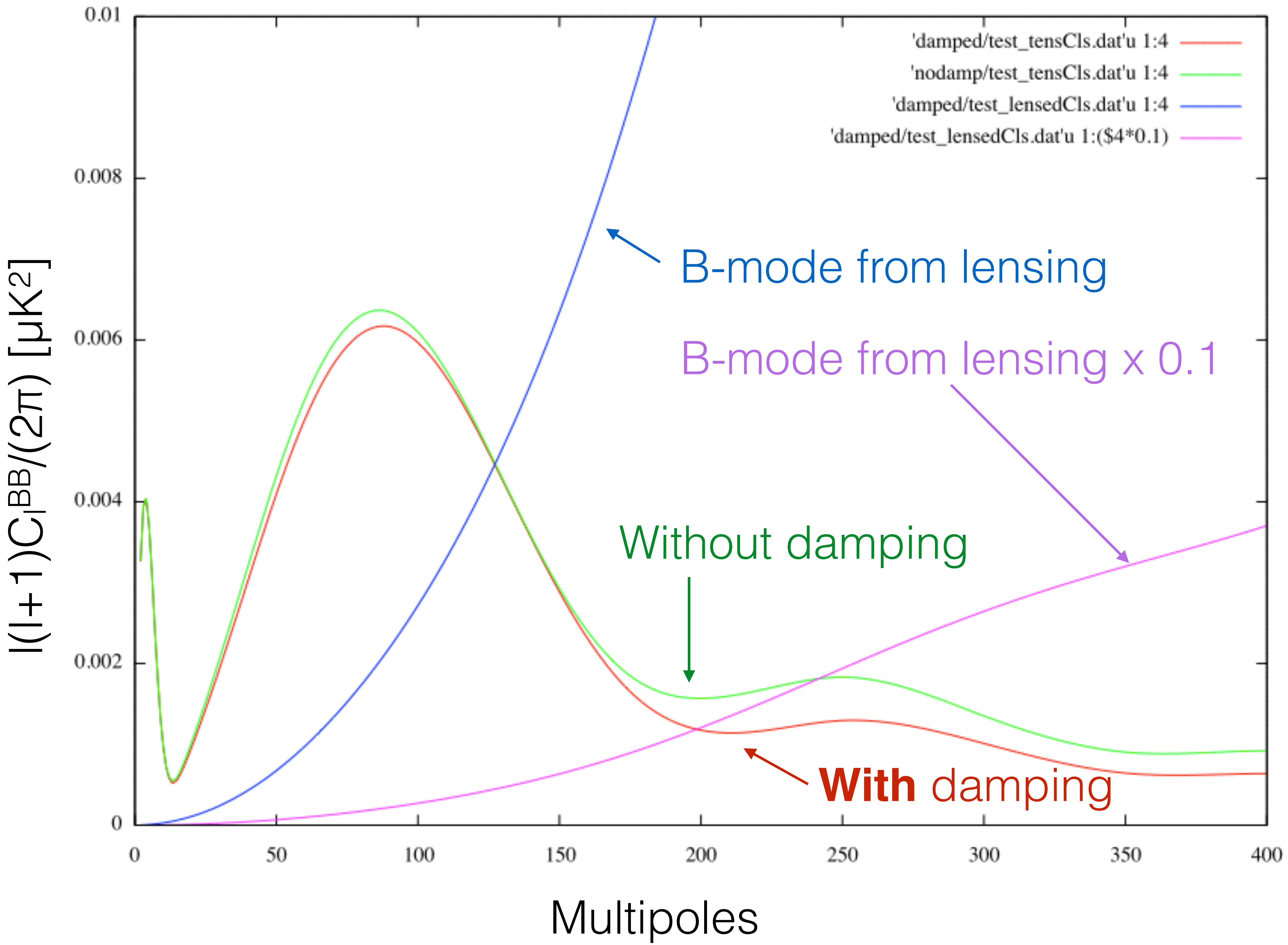
Effect of Relativistic Neutrinos on the B-mode power spectrum

- Gravitational waves are often thought to obey a wave equation in vacuum, simply redshirting away like this: $\Box h_{ij} = 0$

- However, gravitational waves suffer from damping due to anisotropic stress of neutrinos:

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

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



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'nodamp/test_tensCls.dat'u 1:4
'damped/test_lensedCls.dat'u 1:4
'damped/test_lensedCls.dat'u 1:($4*0.1)
B-mode from lensing
B-mode from lensing x 0.1
Without damping
With damping
0.01
0.008
0.006
0.004
0.002
0
0
50
100
150
200
250
300
350
400
l(l+1)C_l^BB/(2π) [μK^2]
Multipoles

Signal-to-noise Estimates

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

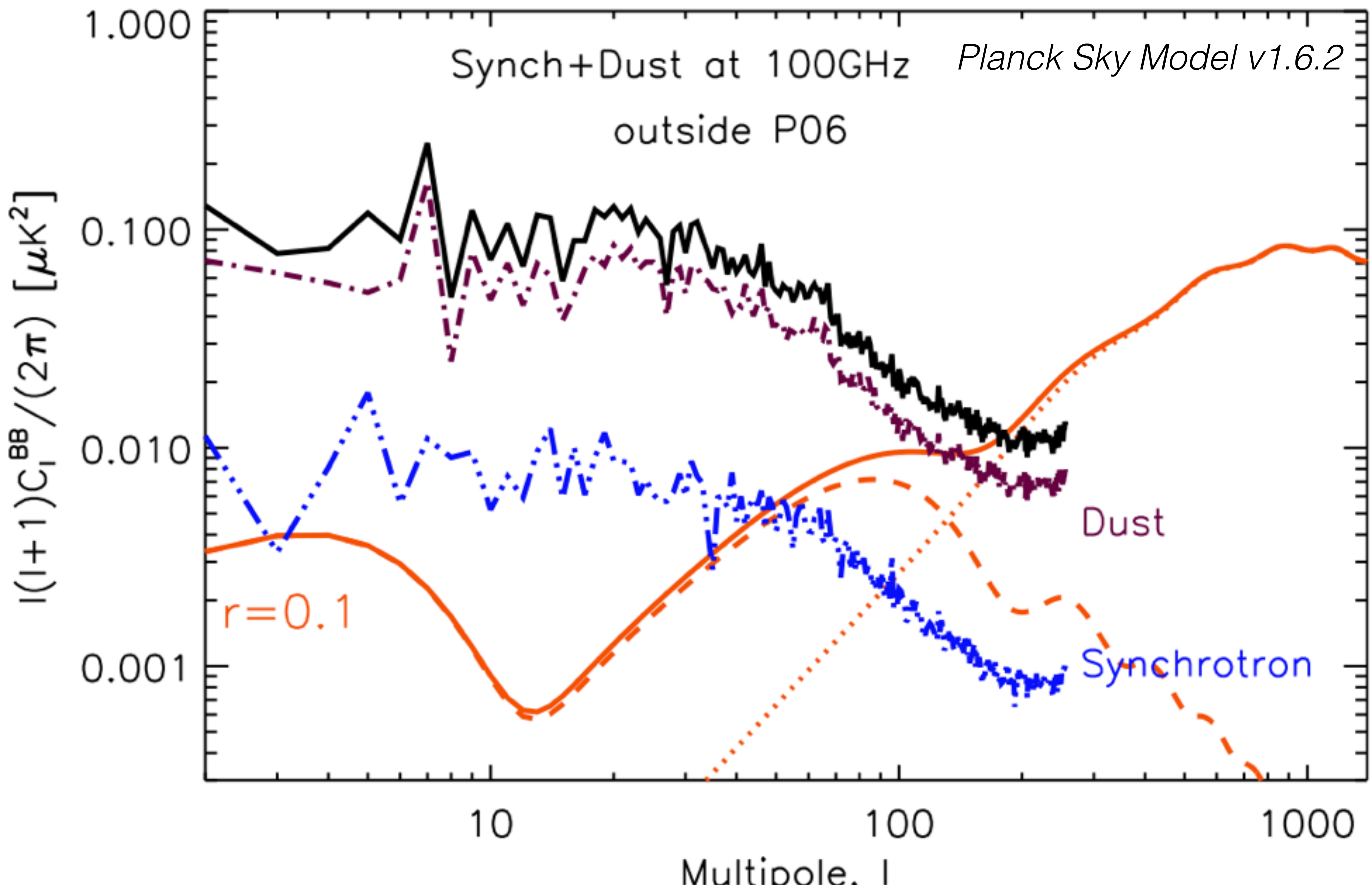
$$\frac{S}{N} = 3.5\frac{r\sqrt{f_{\rm sky}}}{0.1}$$

- With 90% de-lensing

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

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

Galactic Foreground



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

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

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:

$$-2\ln\mathcal{L} = ([\mathrm{data}]_i - [\mathrm{stuff}]_i)^t \underline{(C^{-1})}_{ij} ([\mathrm{data}]_j - [\mathrm{stuff}]_j)$$

2-point function of
CMB plus noise

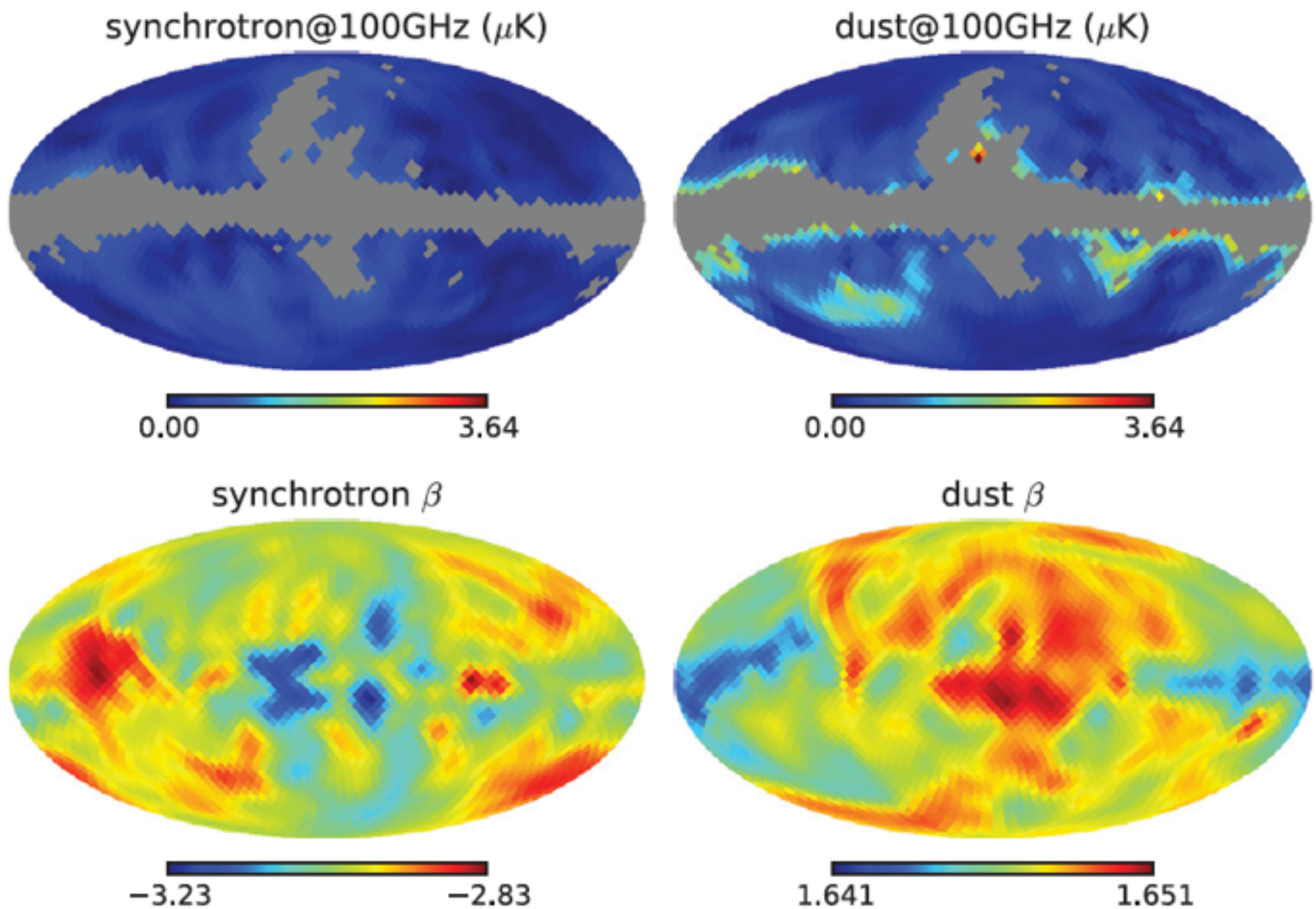
WMAP's Simple Approach

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

- 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:

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

where

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

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

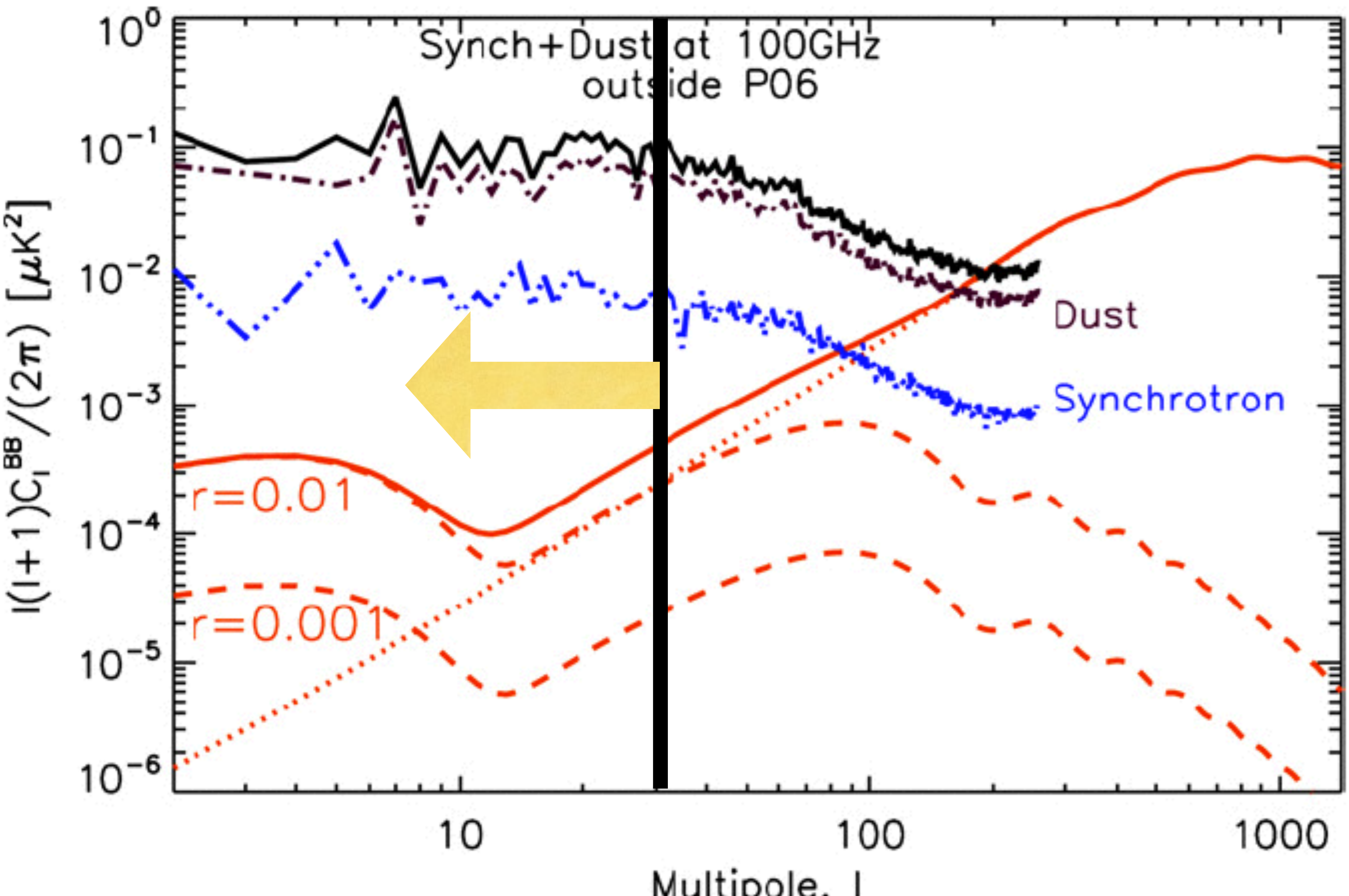
$$\nu = 100\,\text{GHz},$$
$$\nu_{\text{S}}^{\text{template}} = 60\,\text{GHz},$$
$$\nu_{\text{D}}^{\text{template}} = 240\,\text{GHz}.$$

$O(N^3)$

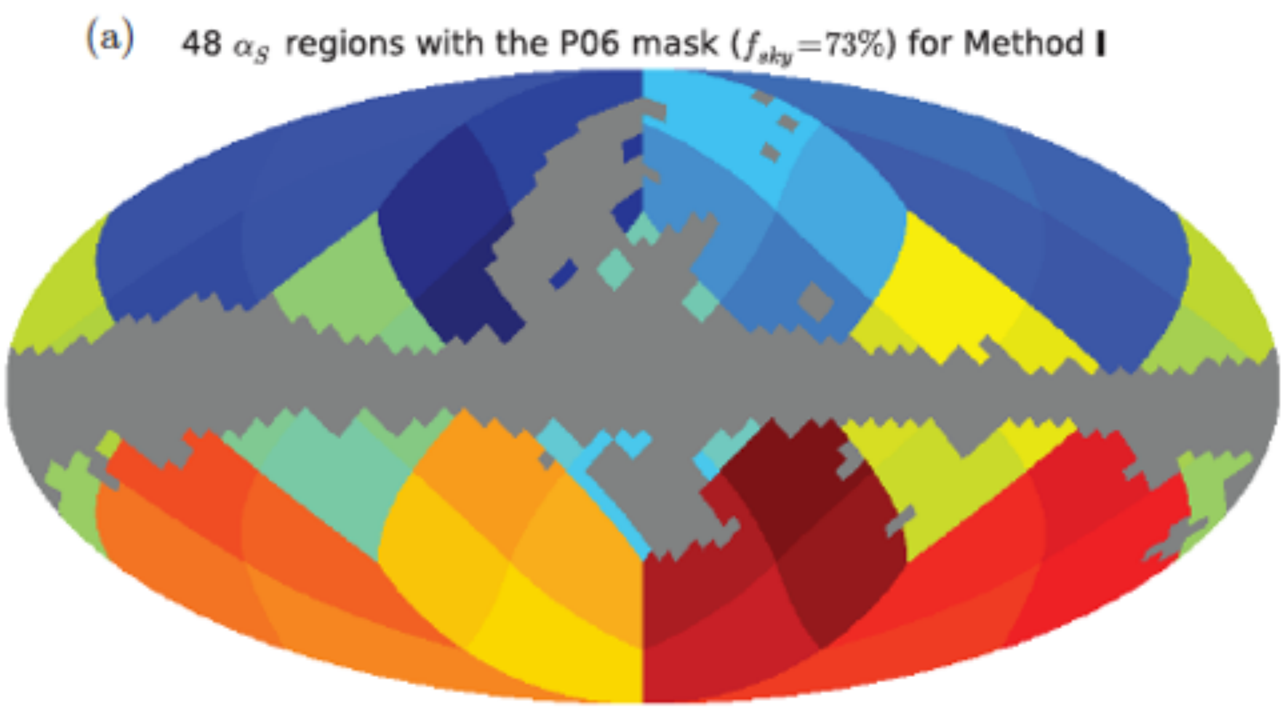
$$\mathcal{L}(r, s, \alpha_i) \propto \frac{\exp\left[-\frac{1}{2}\boldsymbol{x}'(\alpha_i)^T \boldsymbol{C}^{-1}(r, s, \alpha_i)\boldsymbol{x}'(\alpha_i)\right]}{\sqrt{|\boldsymbol{C}(r, s, \alpha_i)|}}$$

- 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]

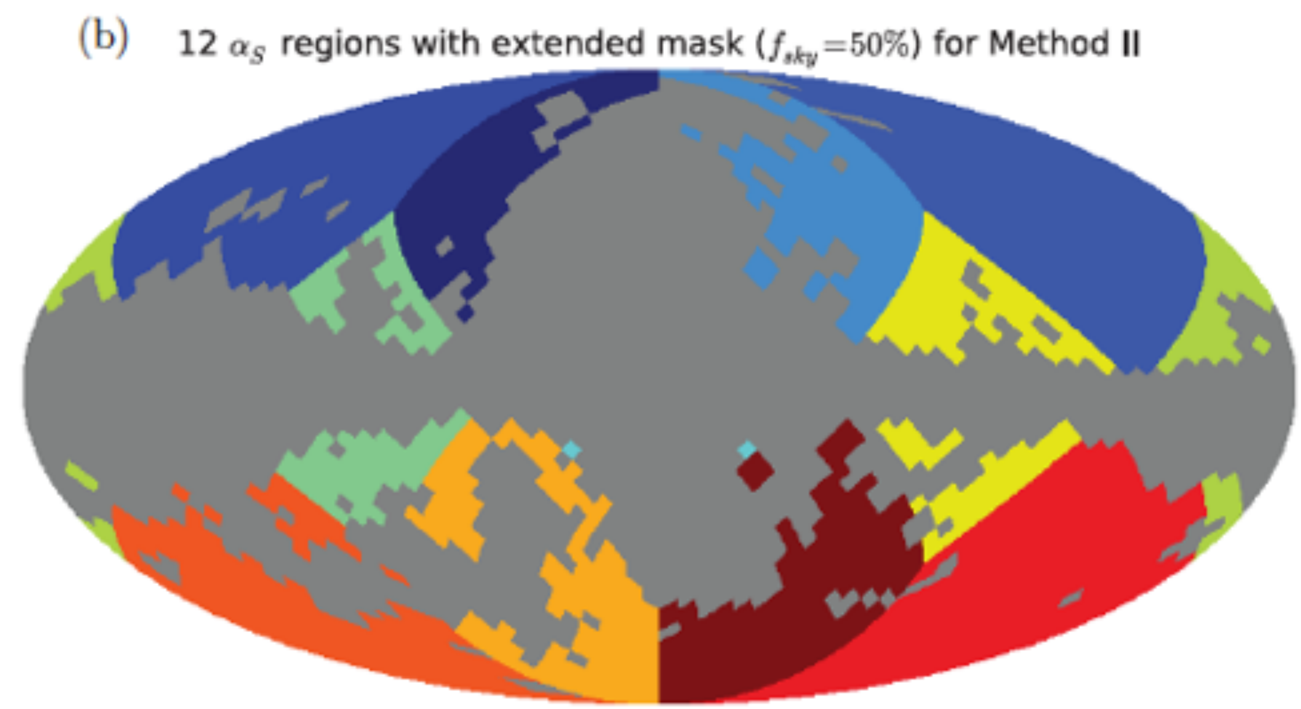
We target the reionisation bump



Two Masks and Choice of Regions for Synch. Index



Method I

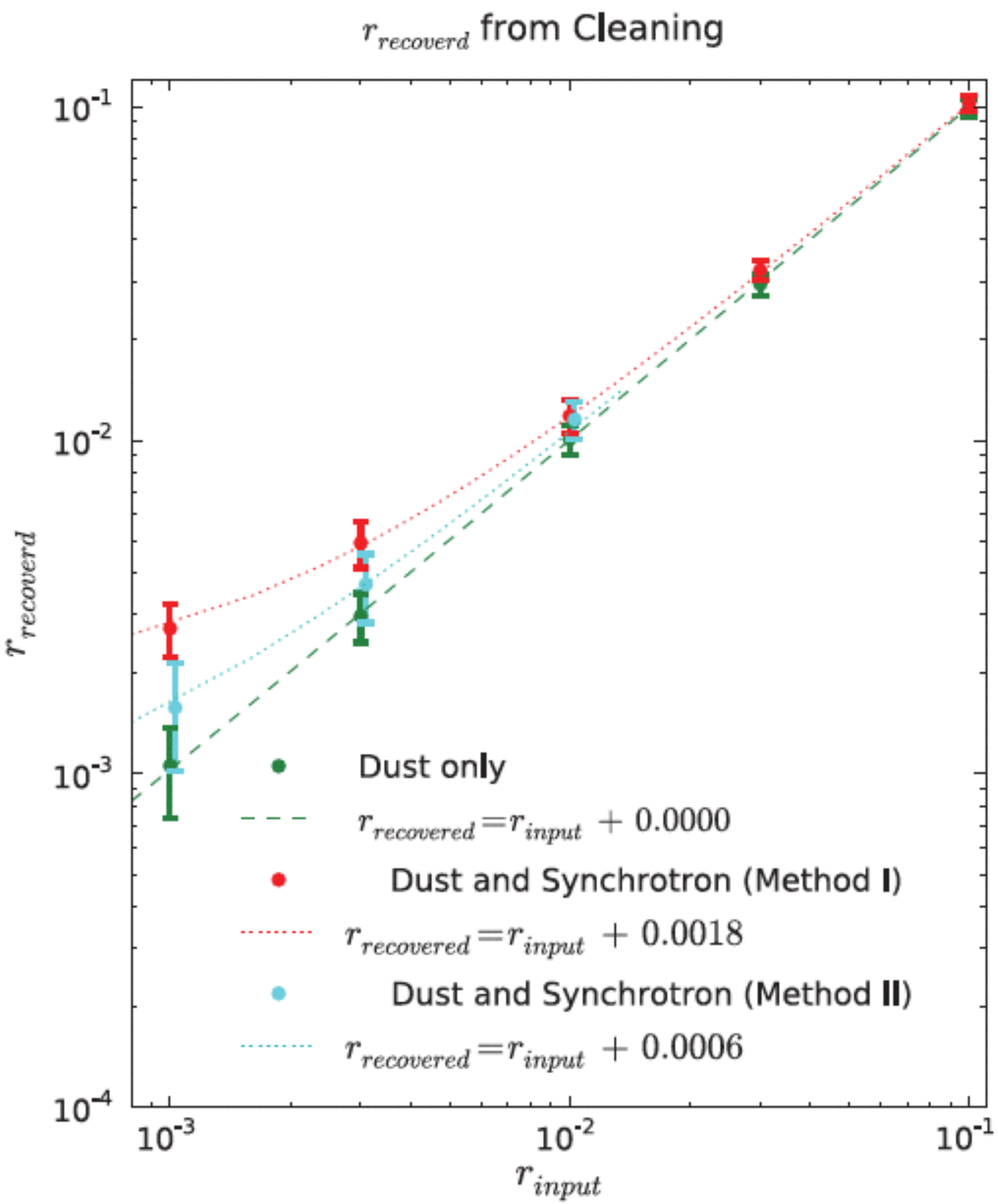


Method II

Katayama & Komatsu, ApJ, 737, 78 (2011)

Results

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



- It works well!
- Method I: the bias is $\delta r = 2\times10^{-3}$
- Method II: the bias is $\delta r = 0.6\times10^{-3}$
- [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

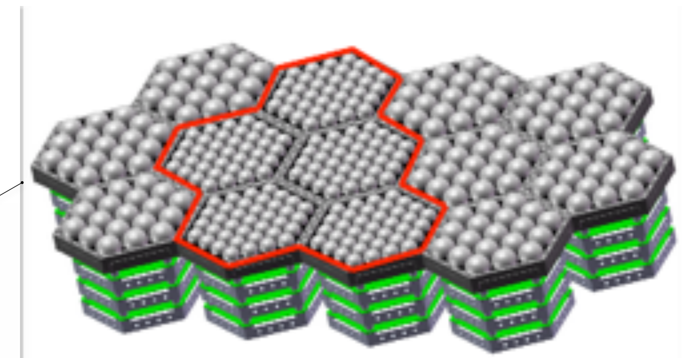
- Next-generation polarisation-sensitive microwave experiment. Target launch date: early 2020
- Led by Prof. Masashi Hazumi (KEK); a collaboration of ~70 scientists in Japan, USA, Canada, and Germany
- **Singular goal**: measurement of the primordial B-mode power spectrum with **Err[r]=0.001**
- **6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

LiteBIRD

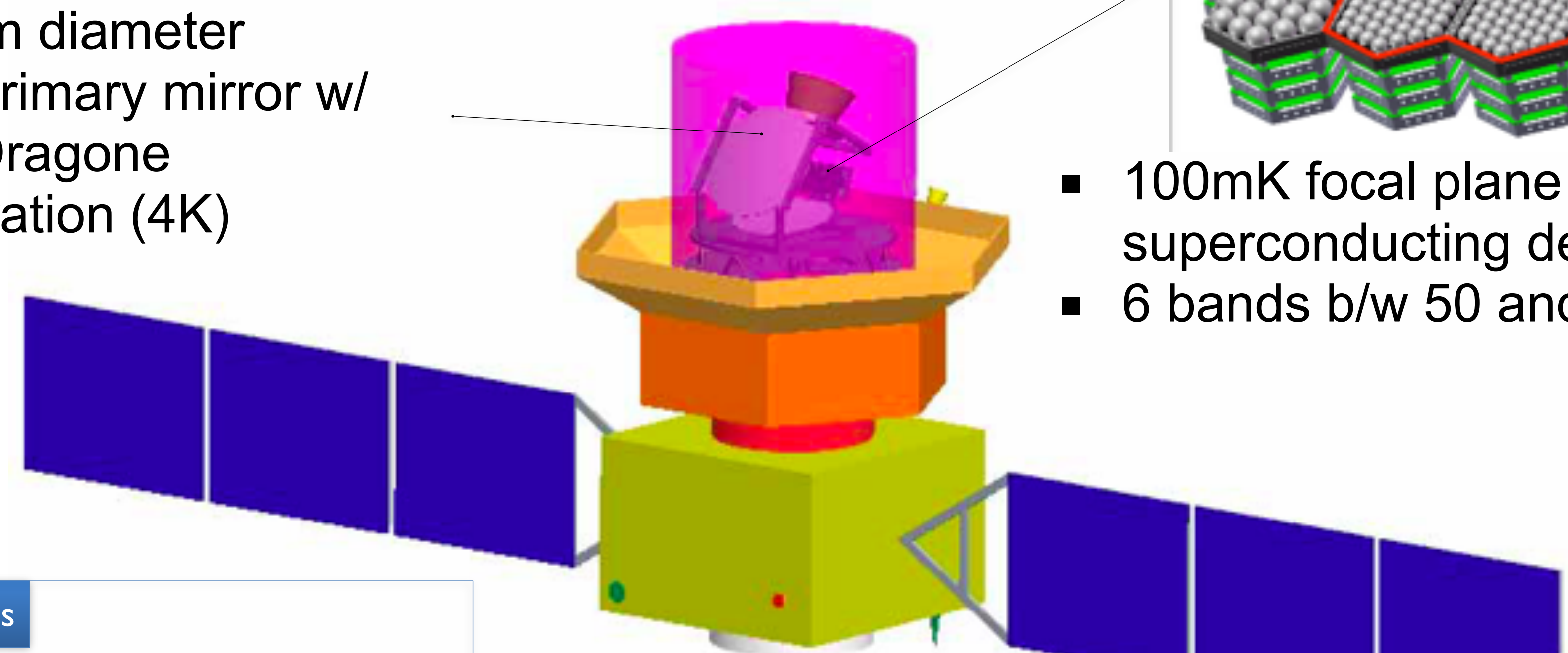
Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection

- 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

McGill U.
M. Dobbs

LBNL
J. Borrill

Tsukuba U.
M. Nagai

Kavli IPMU
N. Katayama
H. Nishino

Yokohama NU.
K. Mizukami
S. Nakamura
K. Natsume

Osaka Pref. U.
K. Kimura
M. Kozu
H. Ogawa

MPA
E. Komatsu

Tohoku U.
M. Hattori
K. Ishidoshiro
K. Morishima

Konan U.
I. Ohta

Saitama U.
M. Naruse

ATC/NAOJ
K. Karatsu
T. Noguchi
Y. Sekimoto
Y. Uzawa

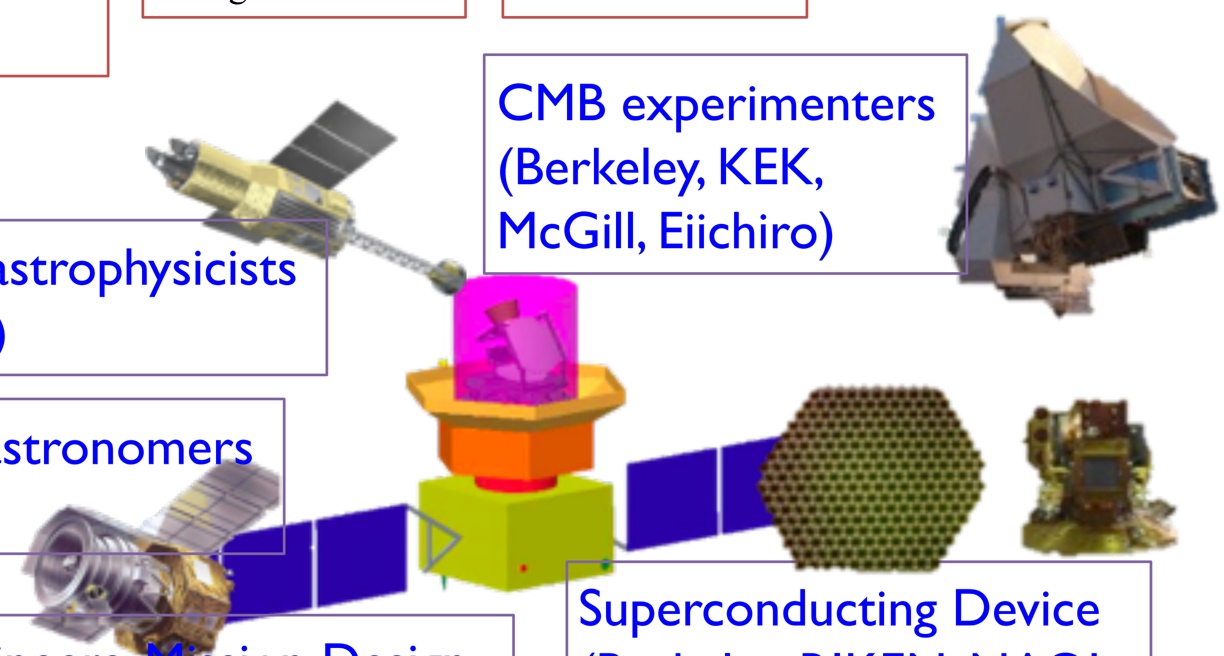
RIKEN
K. Koga
S. Mima
C. Otani

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

Osaka U.
S. Takakura

Okayama U.
H. Ishino
A. Kibayashi
Y. Kibe

NIFS
S. Takada



CMB experimenters (Berkeley, KEK, McGill, Eiichiro)

X-ray astrophysicists (JAXA)

Infrared astronomers (JAXA)

JAXA engineers, Mission Design Support Group, SE office

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

LiteBIRD focal plane design

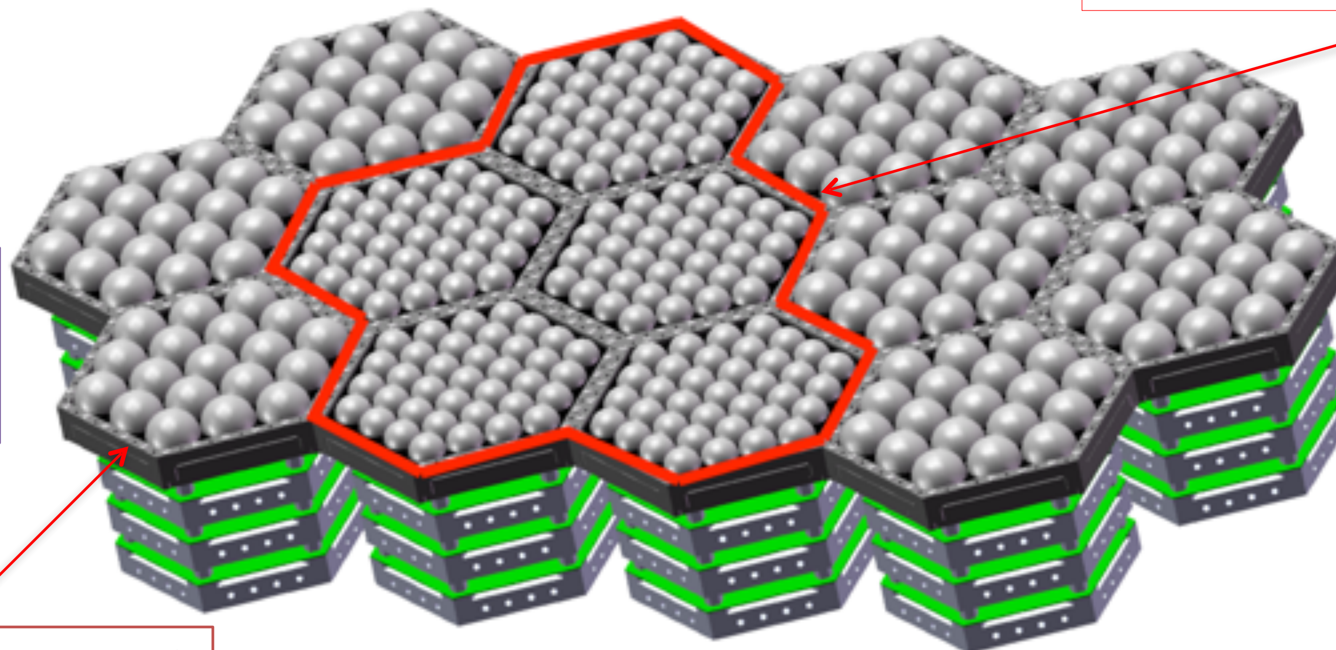
UC Berkeley TES option

2022 TES bolometers

T_{bath} = 100mK

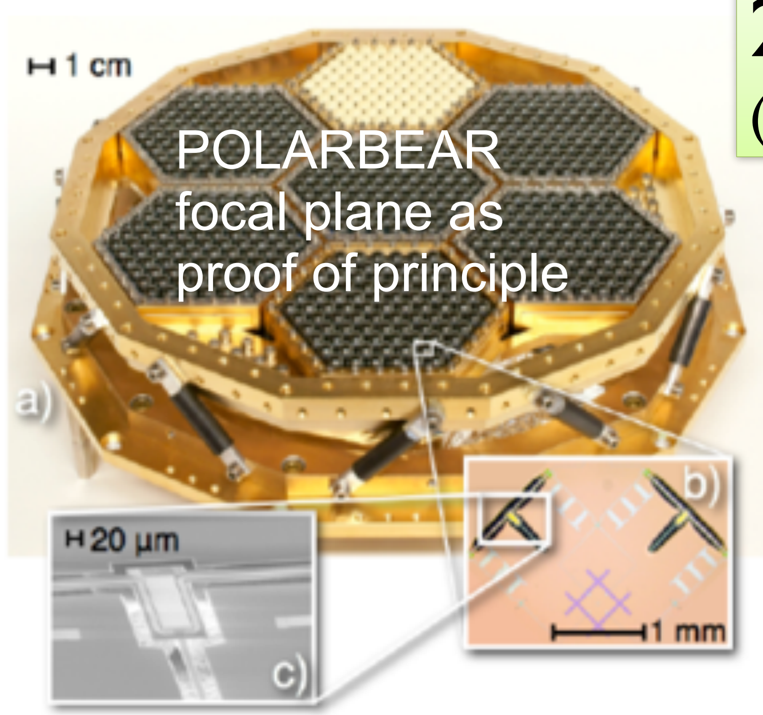
tri-chroic（140/195/280GHz）

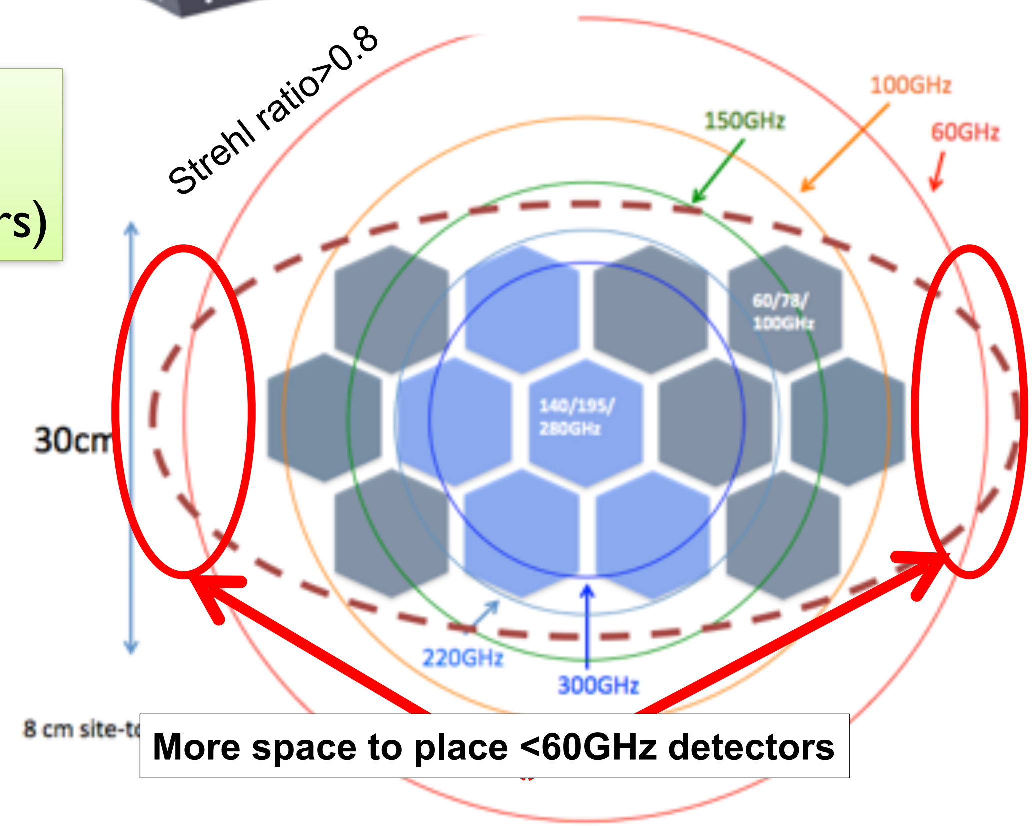
Band centers can be distributed to increase the effective number of bands



tri-chroic（60/78/100GHz）

2μKarcmin
(w/ 2 effective years)





LiteBIRD proposal milestones

- 2012 October - 2014 March
  Feasibility studies & cost estimation with MELCO and NEC
- 2014 March
  Recommendation from Science Council of Japan as one of the top 27 projects
- 2014 July
  Ranked highly in the "Roadmap 2014" of MEXT [Ministry of Education, Culture, Sports, Science & Technology 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
- **Err[n_t]~0.01** possible only with substantial de-lensing
- Neutrino damping observable if r~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