



CMB からの背景重力波への制限 の現状と将来への展望

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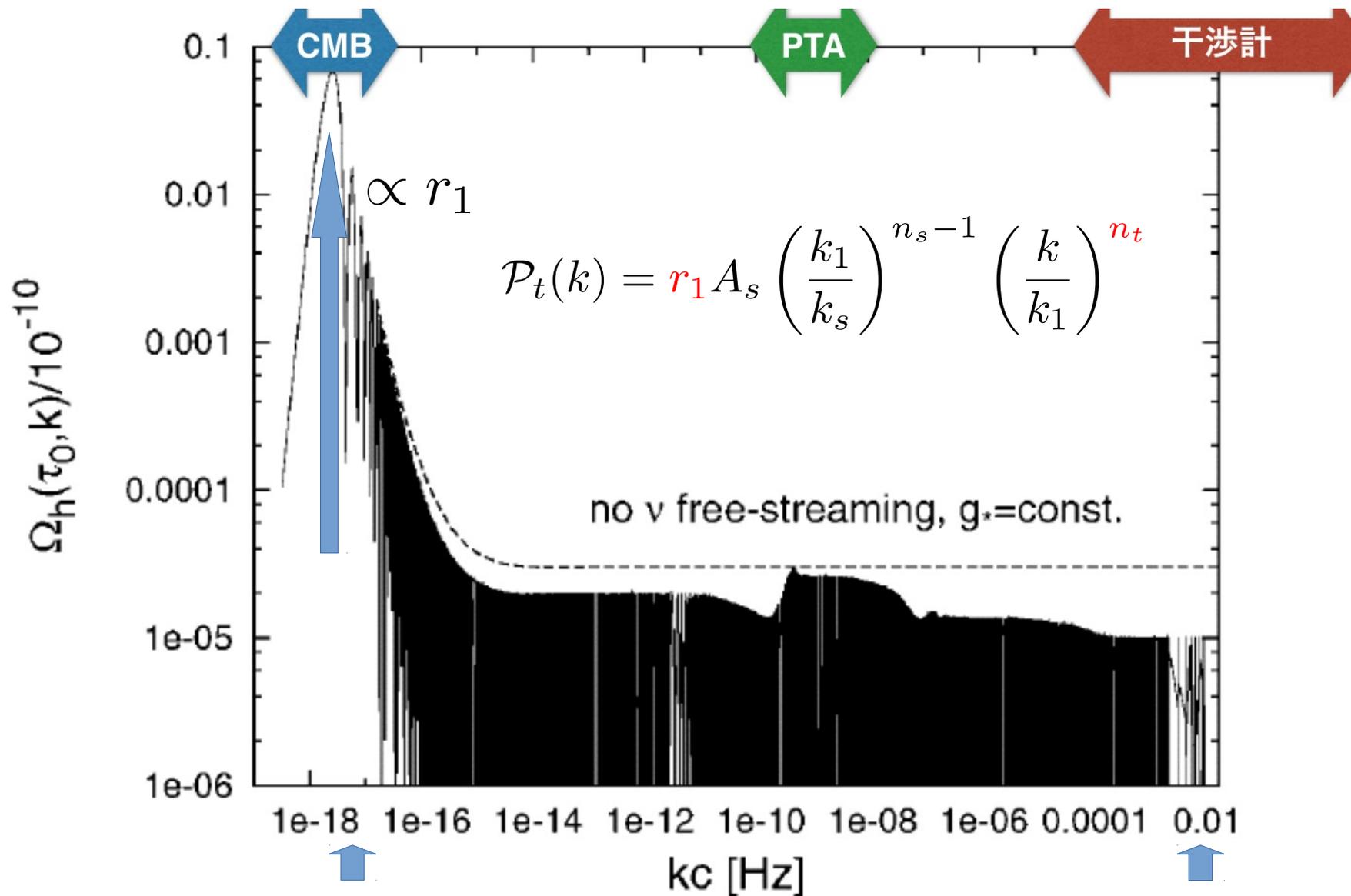
アウトライン

- **CMB と背景重力波**
 - Planck 2018 results と BICEP15 results
 - Road to inflation physics (Dodelson'15 に沿って)
- **LiteBIRD experiment と前景放射問題**
 - 前景放射除去への取り組み , S-PASS results, LiteBIRD で確実にできる science
- **summary**

現在の背景重力波スペクトル

Watanabe & Komatsu, PRD, '06

重力波のエネルギースペクトル



宇宙年齢で揺らぐ重力波

人間の時間スケールで揺らぐ重力波

Useful relations (planck 2018 results より)

- 波数と周波数

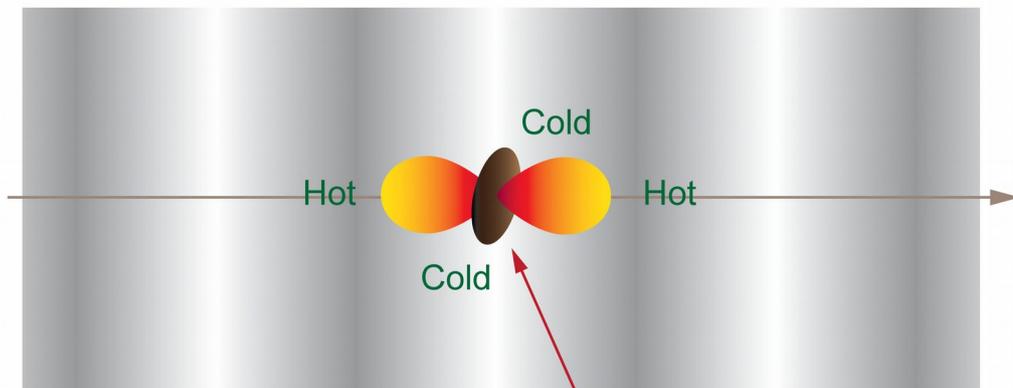
$$\left(\frac{f}{\text{Hz}} \right) = \left(\frac{k}{6.5 \times 10^{15} [\text{Mpc}^{-1}]} \right)$$

- From r to Ω_{GW}

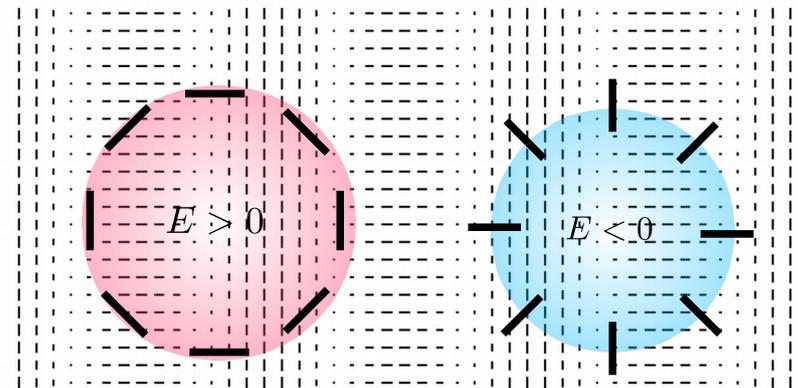
$$\Omega_{\text{GW}}(k) < 2.3 \times 10^{-15} \left(\frac{r_{0.002}}{0.1} \right) \left(\frac{k}{0.002 [\text{Mpc}^{-1}]} \right)^{n_t}$$

E-mode と B-mode

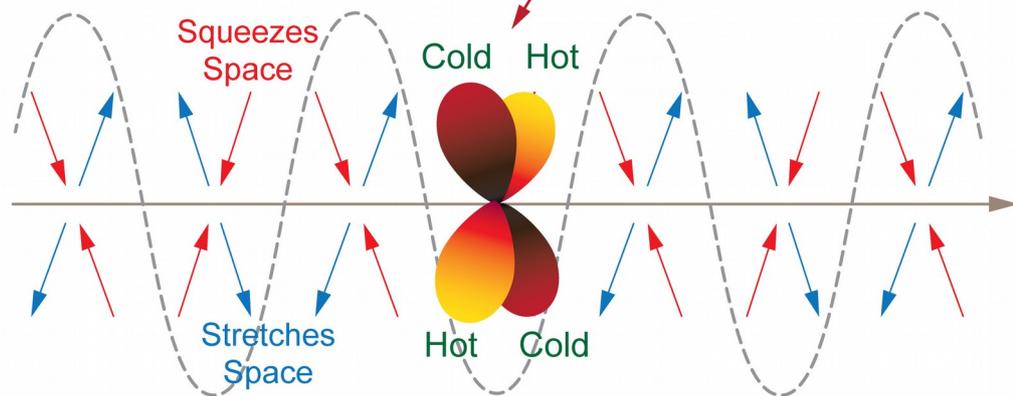
Density Wave



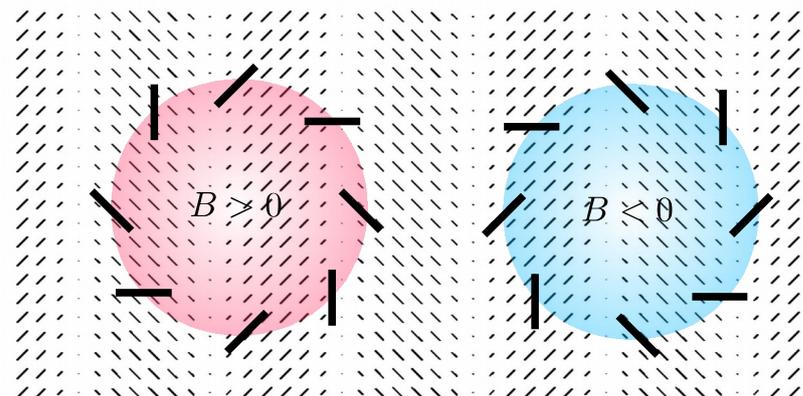
E-Mode Polarization Pattern



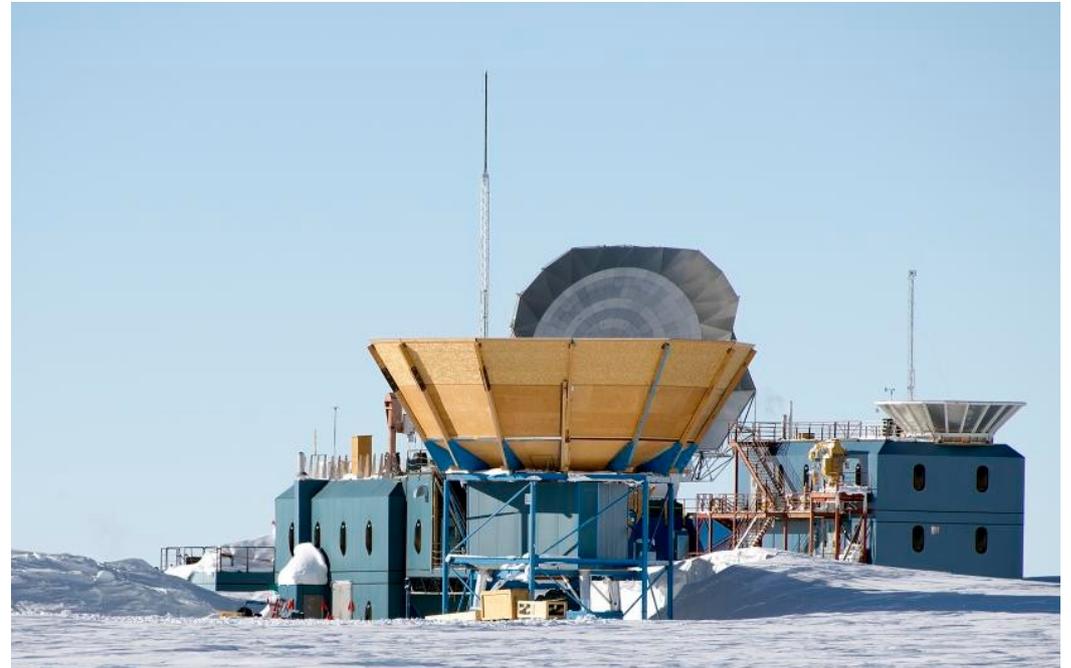
Gravitational Wave



B-Mode Polarization Pattern



Planck satellite & BICEP2/Keck



全天観測

9 bands (30GHz – 857GHz)

2009 (打上) – 2013 (観測終了)

感度： ~60 $\mu\text{K arcmin}$

分解能： ~7 arcmin

CV limited な温度ゆらぎの観測

400 平方度観測

95GHz, 150GHz, 220GHz

2015 年観測データ

感度： 5.2, 2.9, 26 $\mu\text{K arcmin}$

分解能： ~12 arcmin

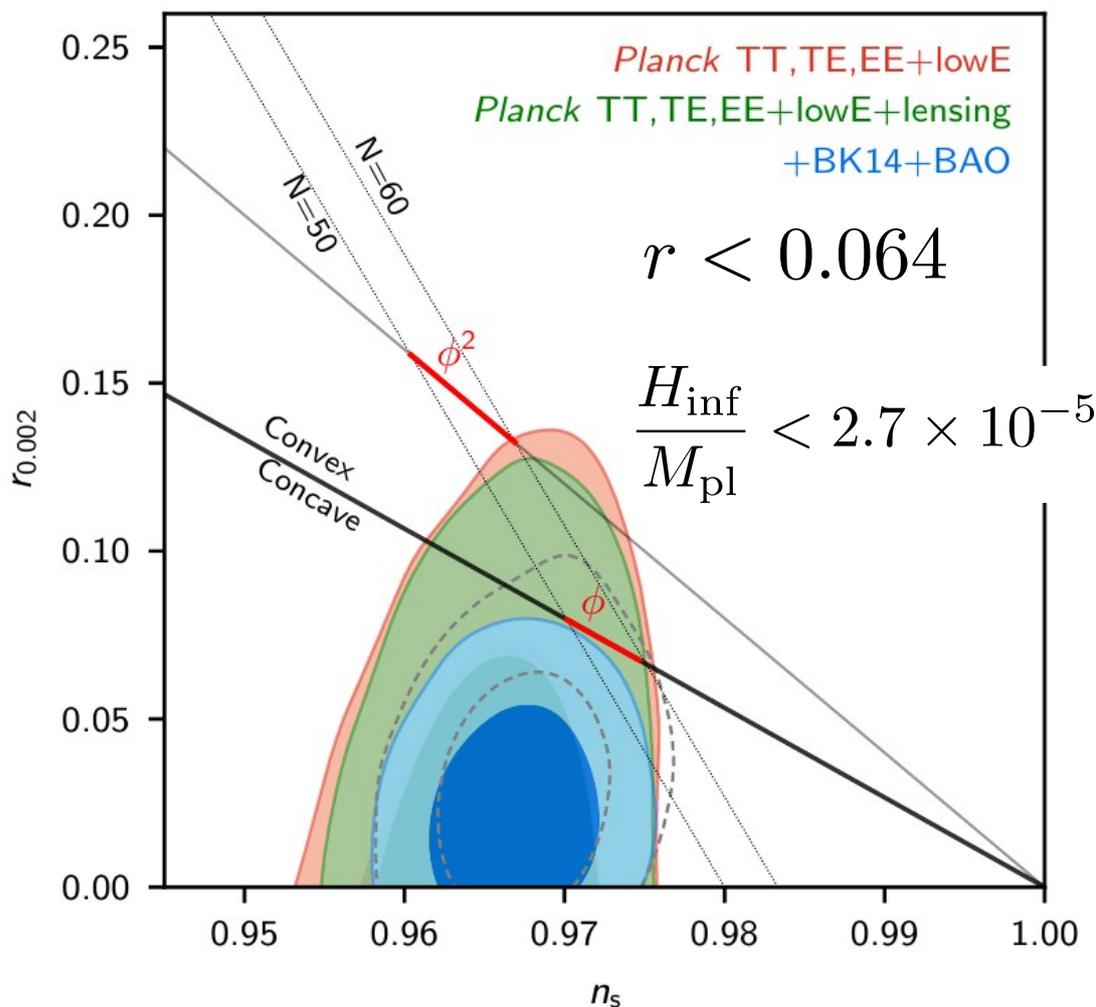
8.8 σ detection of lensing B

Road to inflation physics

- 1st stage – detection & confirmation
 - 再電離期からのシグナル・前景除去・全天からのシグナルか？
- 2nd stage – (r, n_s) の精密観測
 - DESI, LSST, SKA などの大規模構造観測から n_s 測定精密化
- 3rd stage – n_t の観測
 - 重力レンズの除去が必須。低ノイズ，広視野，高角度分解能
 - r が十分大きい場合にのみ可能→ 背景重力波の干渉計観測が必要

1st stage

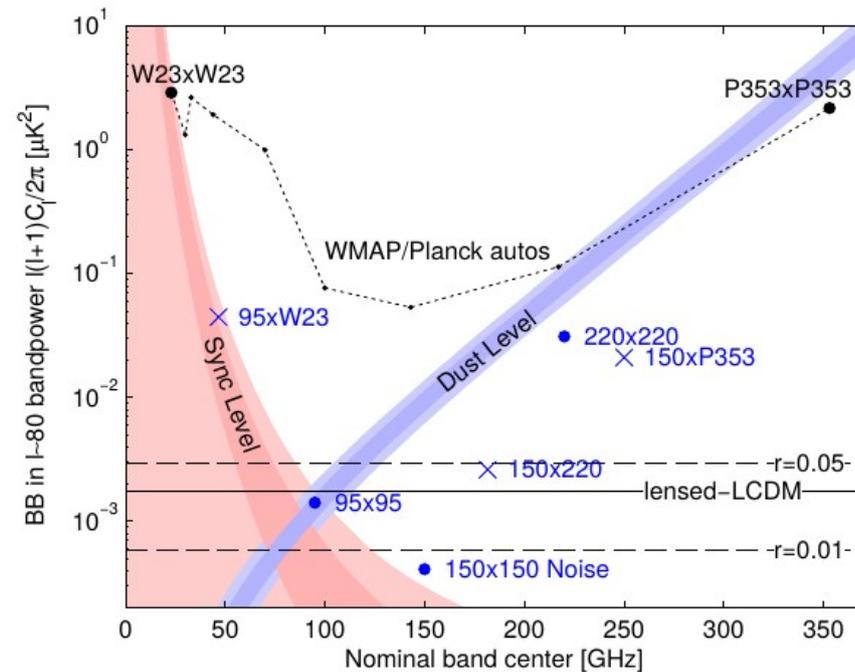
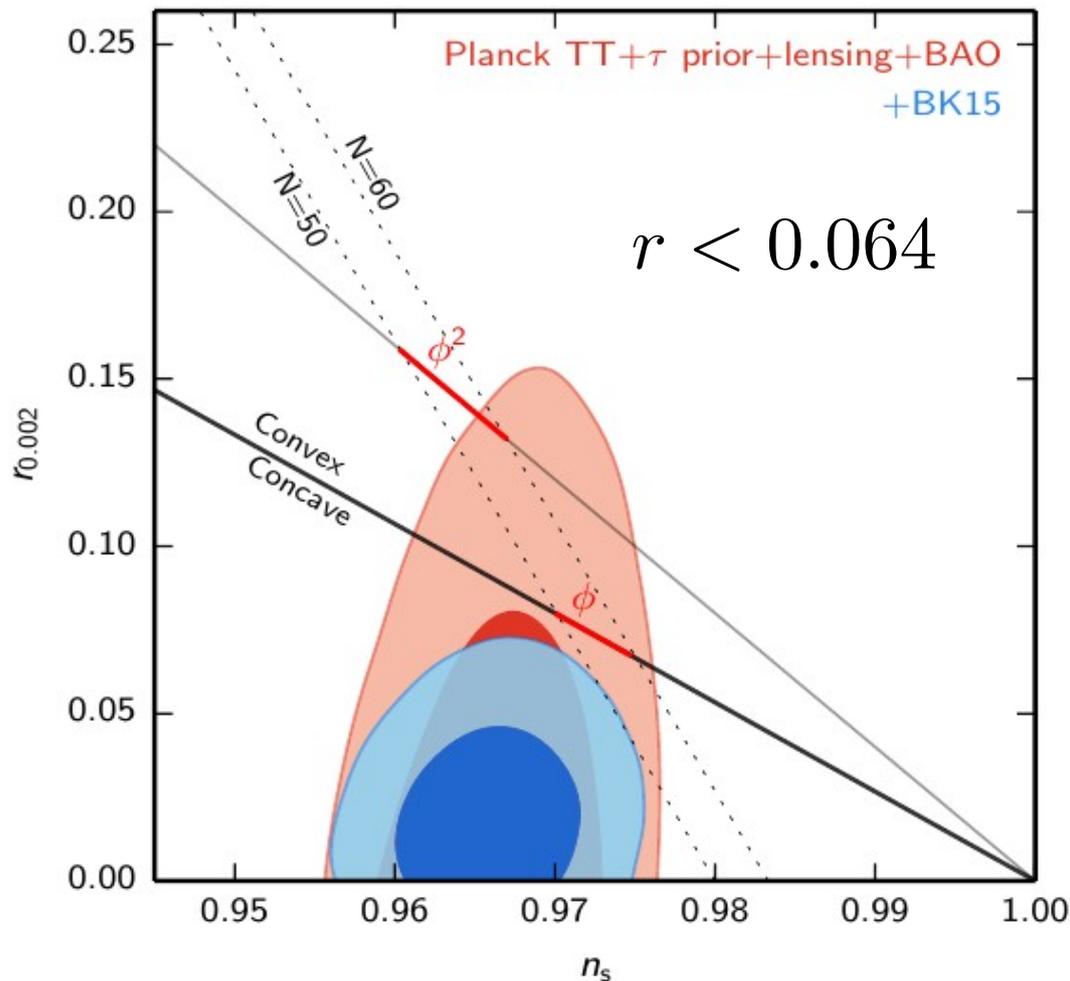
Planck 2018 results VI, 1807.06209



Potential $V(\phi)$	$\Delta\chi^2$	$\ln B$
$\Lambda^4 (1 - e^{-\sqrt{2/3}\phi/M_{\text{Pl}}})^2$
$\lambda M_{\text{Pl}}^{10/3} \phi^{2/3}$	2.8	-2.6
$\lambda M_{\text{Pl}}^3 \phi$	2.5	-1.9
$\lambda M_{\text{Pl}}^{8/3} \phi^{4/3}$	10.4	-4.5
$\lambda M_{\text{Pl}}^2 \phi^2$	22.3	-7.1
$\lambda M_{\text{Pl}} \phi^3$	40.9	-19.2
$\lambda \phi^4$	89.1	-33.3
$\lambda^4 \phi^4 + \xi \phi^2 R/2$	3.1	-1.6
$\Lambda^4 [1 + \cos(\phi/f)]$	9.4	-4.2
$\Lambda^4 (1 - \phi^2/\mu_2^2 + \dots)$	1.7	-2.0
$\Lambda^4 (1 - \phi^4/\mu_4^4 + \dots)$	-0.3	-1.4
$\Lambda^4 (1 - \mu_{\text{D}2}^2/\phi^p + \dots)$	-2.3	1.6
$\Lambda^4 (1 - \mu_{\text{D}4}^4/\phi^p + \dots)$	-2.2	0.8
$\Lambda^4 [1 - \exp(-q\phi/M_{\text{Pl}}) + \dots]$	-0.5	-1.0
$\Lambda^4 [1 + \alpha_h \log(\phi/M_{\text{Pl}}) + \dots]$	9.0	-5.0
$\Lambda^4 \left\{ 1 - \exp \left[-\sqrt{2}\phi \left(\sqrt{3\alpha_1^{\text{E}}} M_{\text{Pl}} \right)^{-1} \right] \right\}^{2n}$	0.2	-1.0
$\Lambda^4 \left\{ 1 - \exp \left[-\sqrt{2}\phi \left(\sqrt{3\alpha_2^{\text{E}}} M_{\text{Pl}} \right)^{-1} \right] \right\}^{2n}$	-0.1	0.7
$\Lambda^4 \tanh^{2m} \left[\phi \left(\sqrt{6\alpha_1^{\text{T}}} M_{\text{Pl}} \right)^{-1} \right]$	-0.1	0.1
$\Lambda^4 \tanh^{2m} \left[\phi \left(\sqrt{6\alpha_2^{\text{T}}} M_{\text{Pl}} \right)^{-1} \right]$	-0.4	0.1

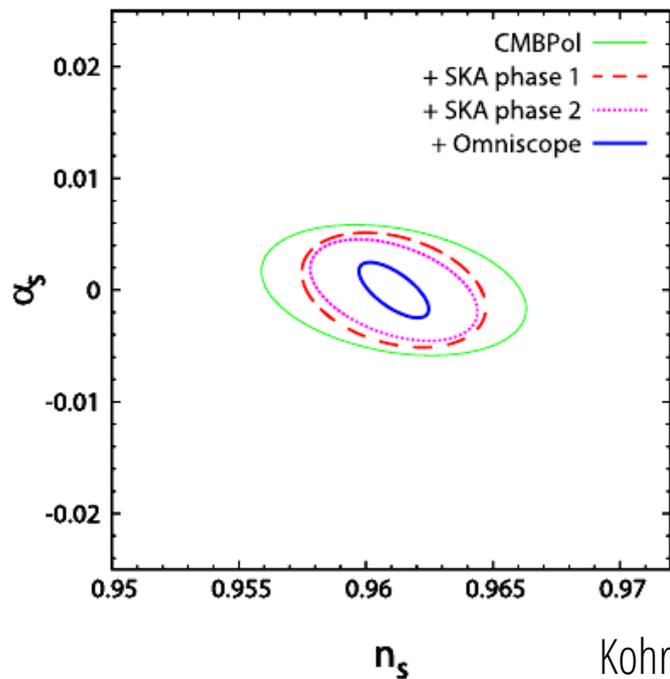
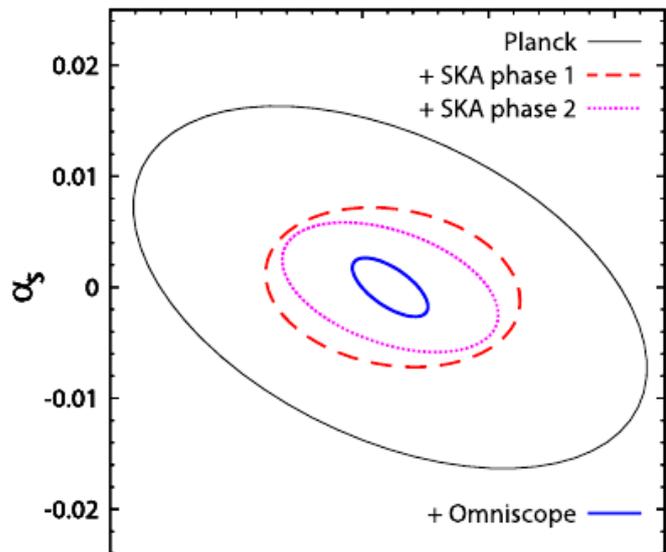
1st stage

BICEP2/Keck results, 1810.05216



- ノイズは $r=0.01$ レベル
- ここからは FG(と lensing) との戦い

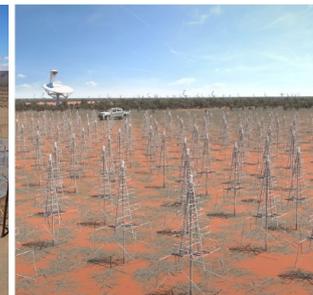
2nd stage



MWA2('16-)



HERA('17-)



SKA1 ('20-)



SKA2 ('28?-)

$$\sigma(n_s) = 2.20 \times 10^{-3} \text{ DESI}$$

arxiv:1308.0847

$$\sigma(n_s) = 1.90 \times 10^{-3} \text{ CMB-S4}$$

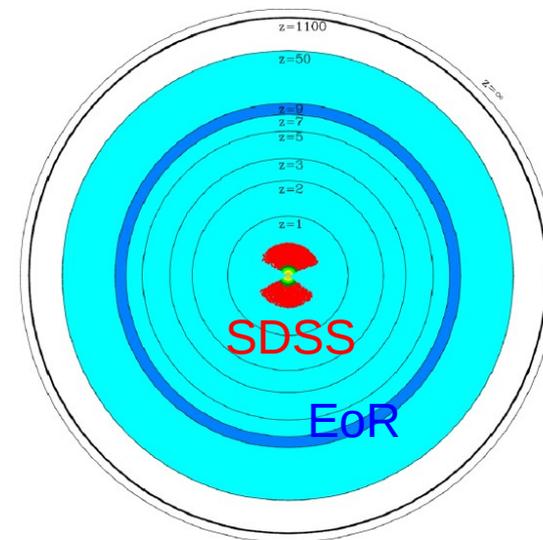
arxiv:1610.02743

$$\sigma(n_s) = 1.33 \times 10^{-3} \text{ SKA2}$$

$$\text{CMB info} = \left(\frac{\ell_{\text{max}}}{\ell_{\text{min}}} \right)^2 \approx 2000^2 = 4 \times 10^6$$

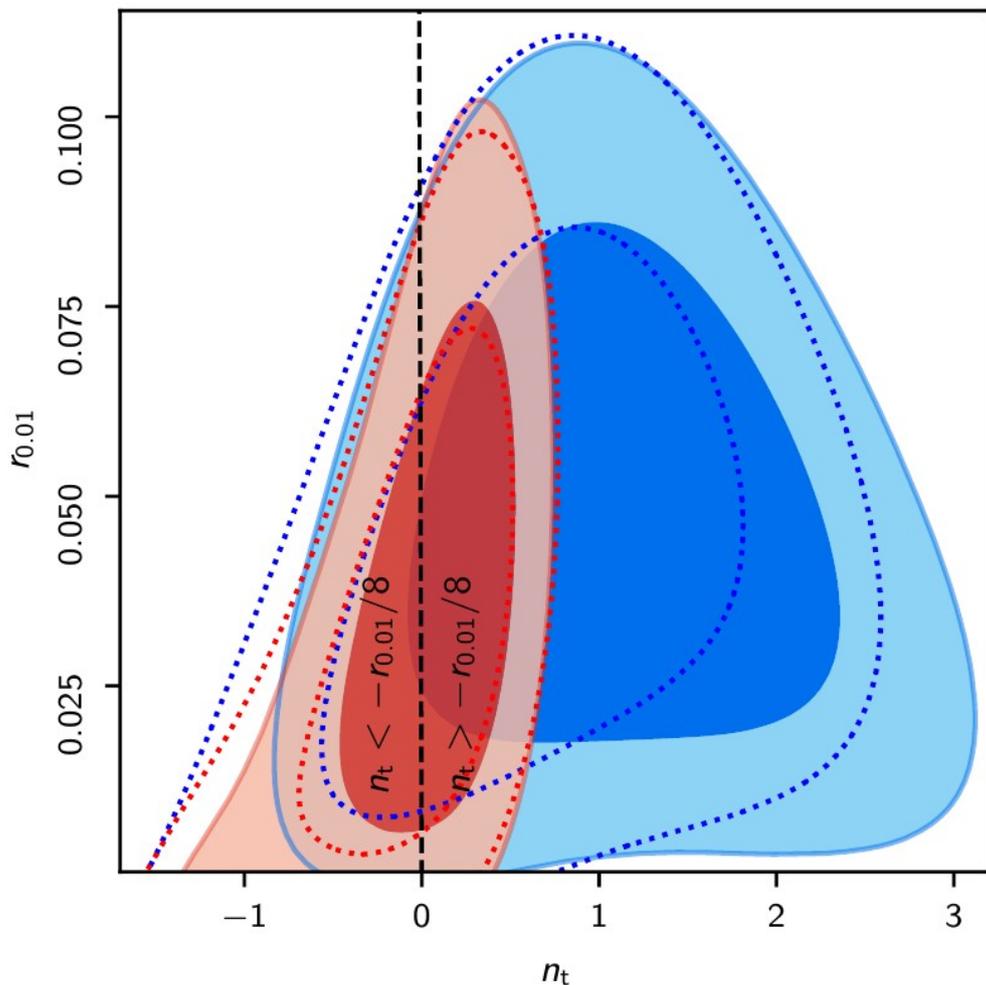
8 桁

$$\text{LSS info} = \left(\frac{k_{\text{max}}}{k_{\text{min}}} \right)^3 \sim \left(\frac{10\text{Gpc}}{100\text{kpc}} \right)^3 = 10^{15}$$



3rd stage

- Planck TT,TE,EE+lowE+lensing+BK14
- +LIGO&Virgo2016



$$\mathcal{P}_t(k) = r_{k_1} A_s \left(\frac{k_1}{k_s} \right)^{n_s - 1} \left(\frac{k}{k_1} \right)^{n_t}$$

$$n_t \simeq -r/8$$

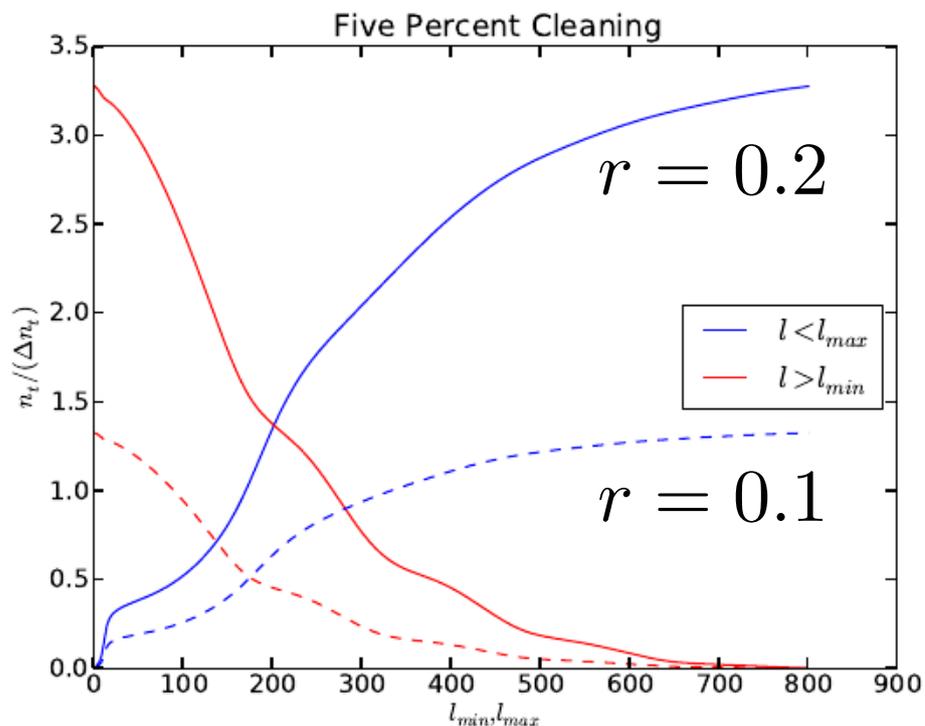
現状 CMB だけでは n_t は決まらない



- 直接観測から大きな n_t は棄却
- inflation model は矛盾なし

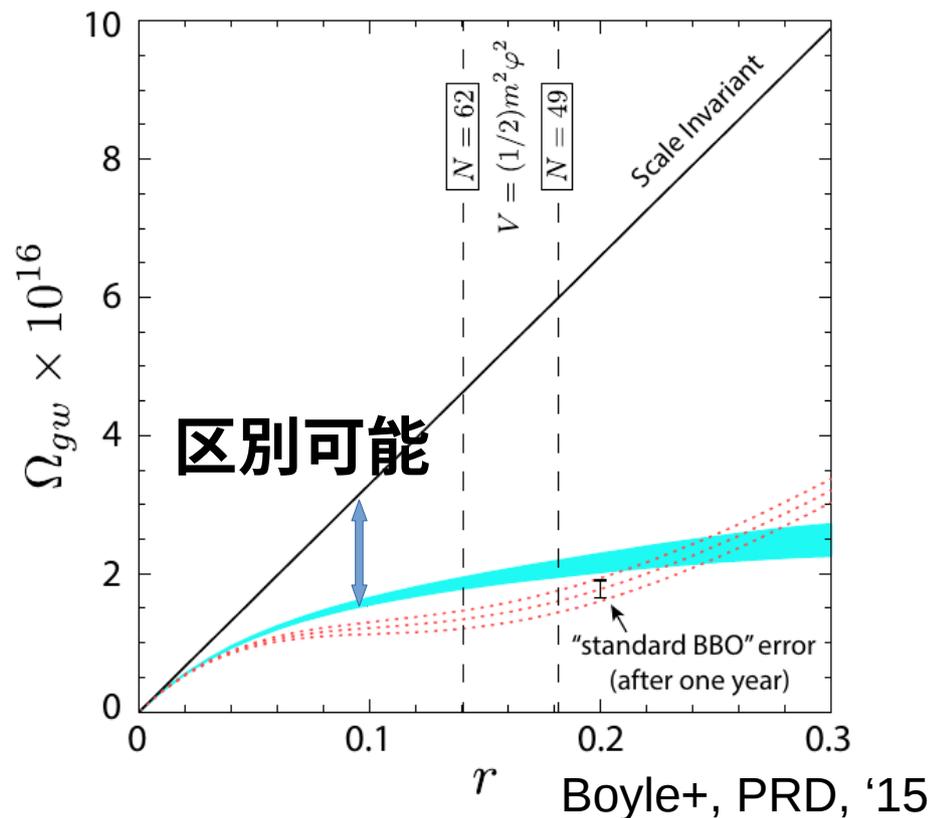
3rd stage

CMB のみの場合



Dodelson, PRL, '14

CMB + 重力波干渉計



Boyle+, PRD, '15

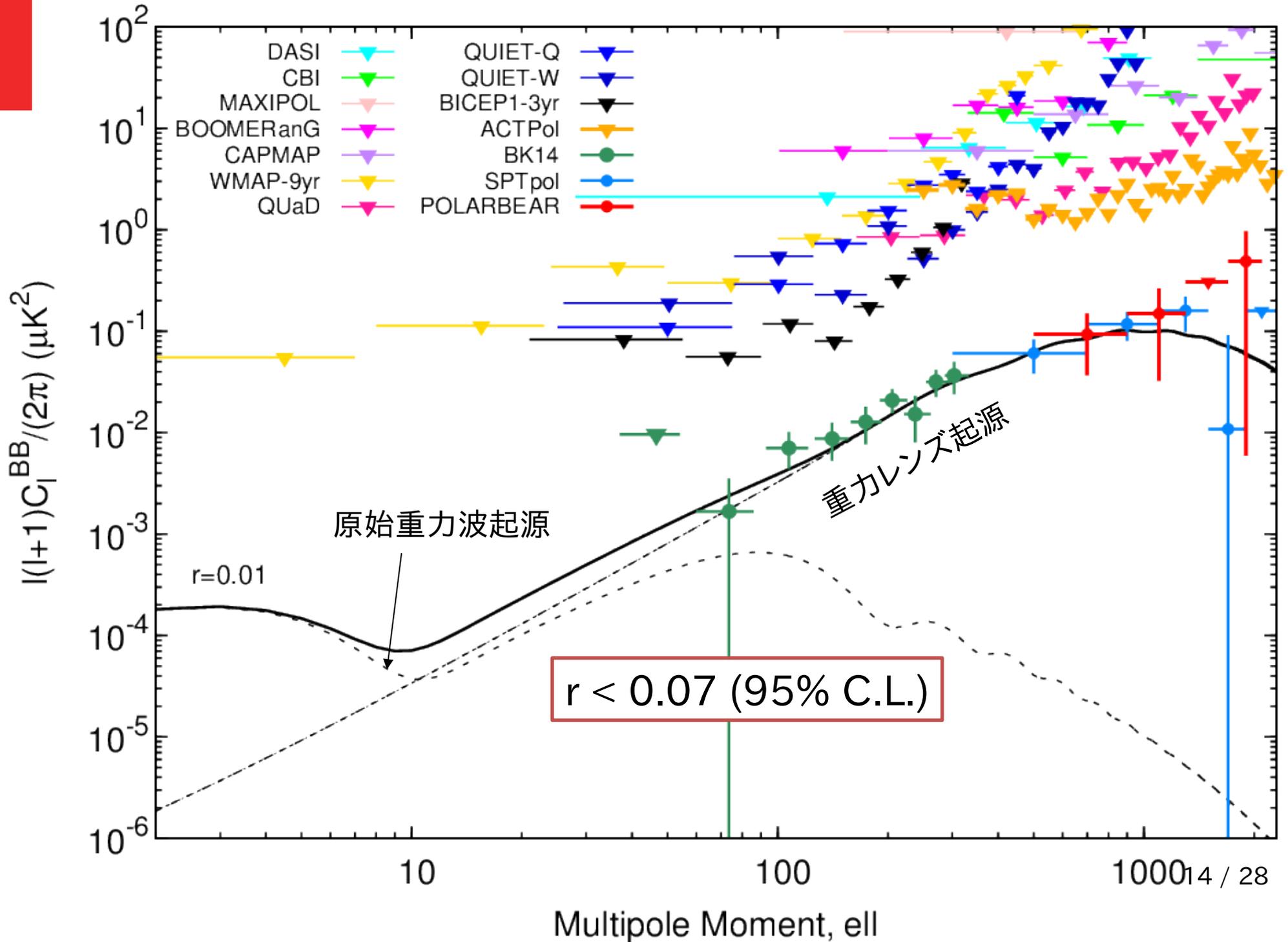
CMB では $r < 0.1$ だと de-lens しても 1σ 以下
重力波干渉計が必須

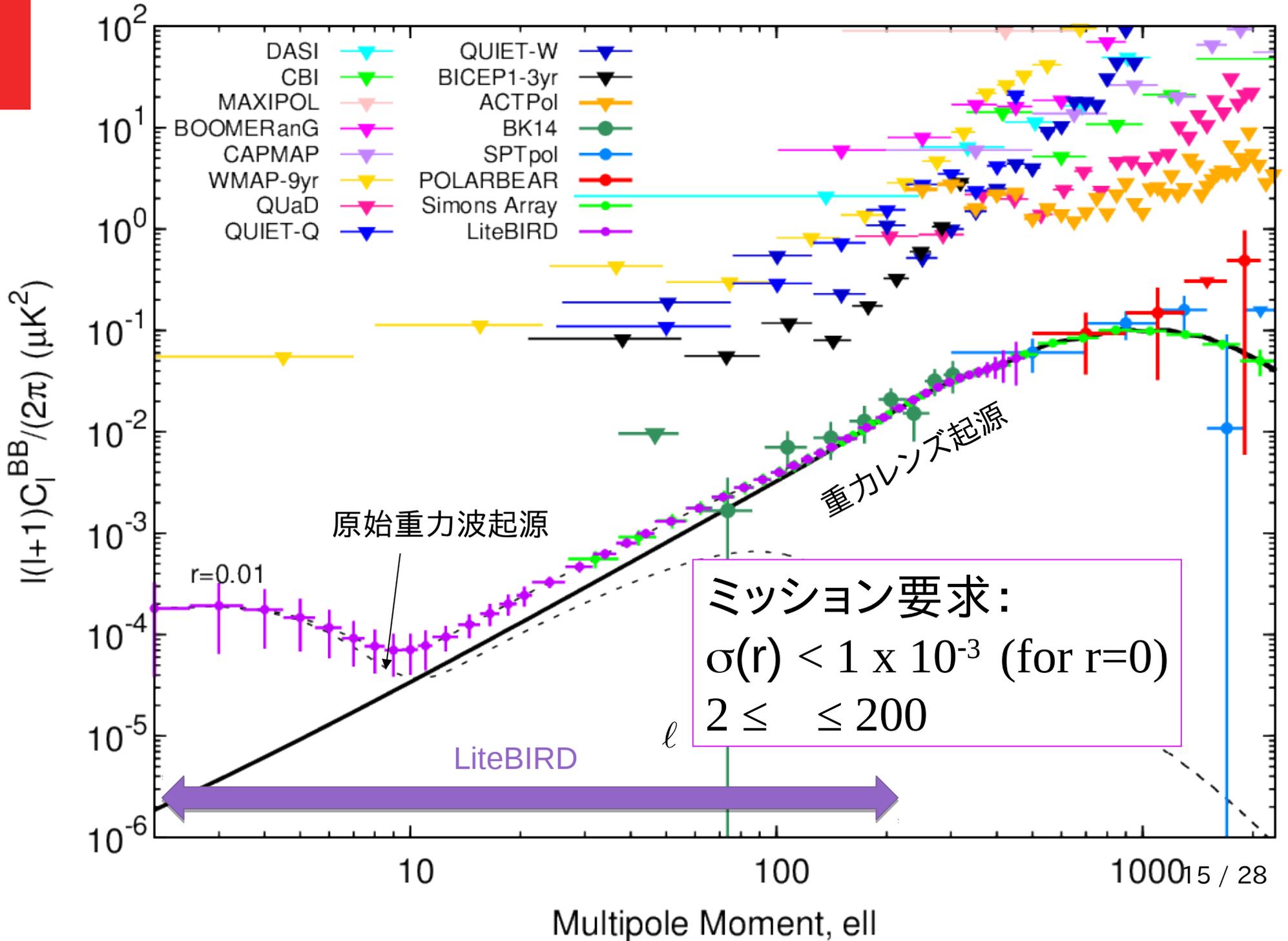
LiteBIRD

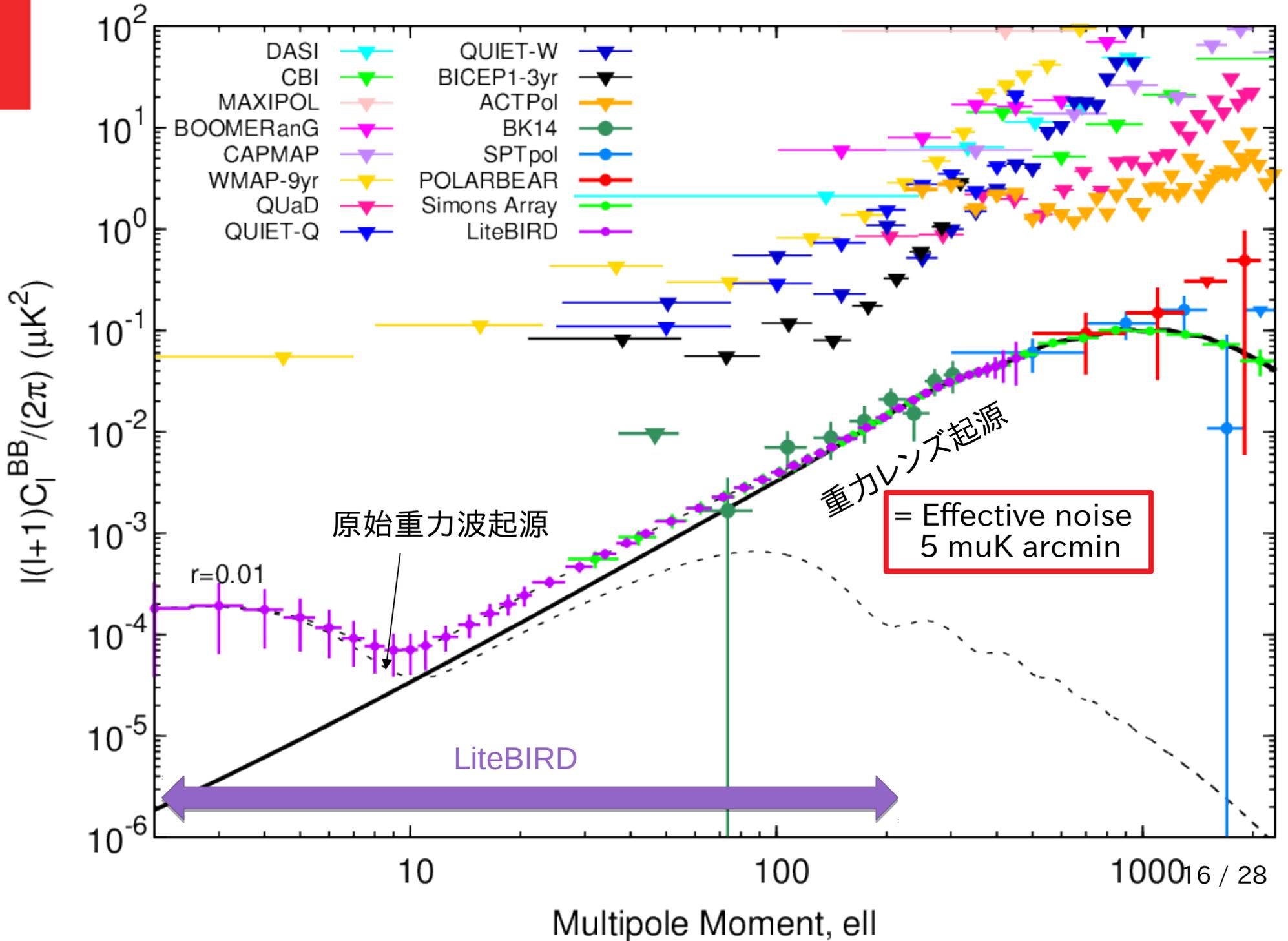
Lite (Light) Satellite for the Studies of **B**-mode Polarization and Inflation from Cosmic Background **R**adiation **D**etection

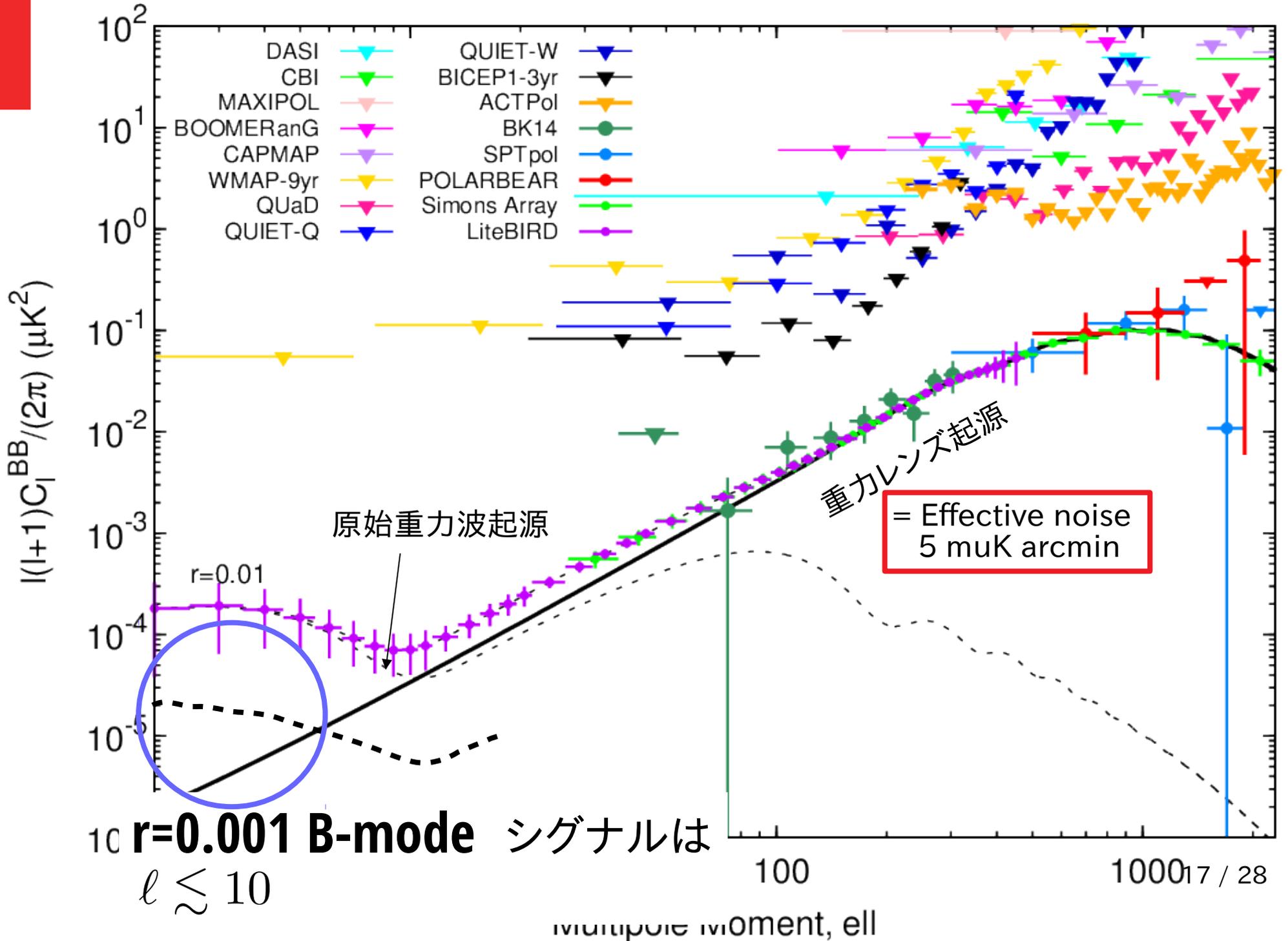
インフレーション宇宙を検証する

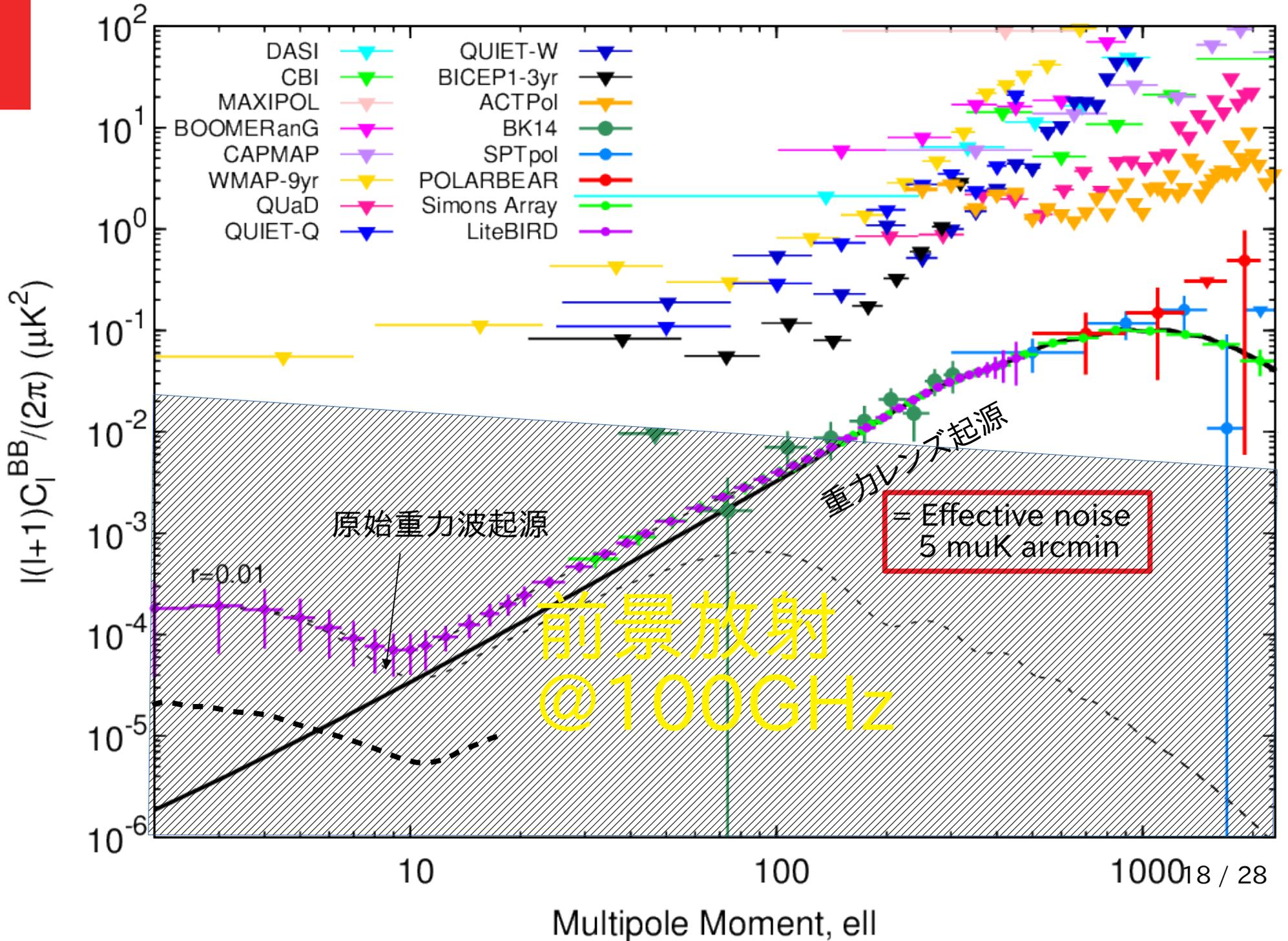
羽澄昌史氏 (KEK/Kavli IPMU/ 総研大) スライドより











Foreground Modeling

H. KANAI



E. KOMATSU

N. KATAYAMA

Foreground Cleaning

K. ICHIKI



T. Matsumura



H. Ochi



Y. Minami

We discuss once a week through zoom

angle calibration

Japan team's methodology

PTEP

11月9日投稿予定 (28 pages)
000000000

Delta-map method to remove CMB foregrounds with spatially varying spectra

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³Graduate School of Engineering, Yokohama National University, 79-5 Tokiwadai, Hodogaya-ku, Yokohama 240-8501 JAPAN

⁴Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), Todai Institutes for Advanced Study, The University of Tokyo, Kashiwa 277-8583, Japan

⁵Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, D-85748 Garching, Germany

特徴

- map 上で直接推定
- 前景放射パラメタの方向依存性を考慮
- AME を考慮
- de-correlation を考慮
- unbiased, but not minimal variance

これまで我々の方法は最終エラーが大きくなってしまおうと思っていたが、最近、すべての観測バンドを最大限うまく使う方法を発見
やり方の方針については論文に記載

LiteBIRD 国際チーム標準方法との比較

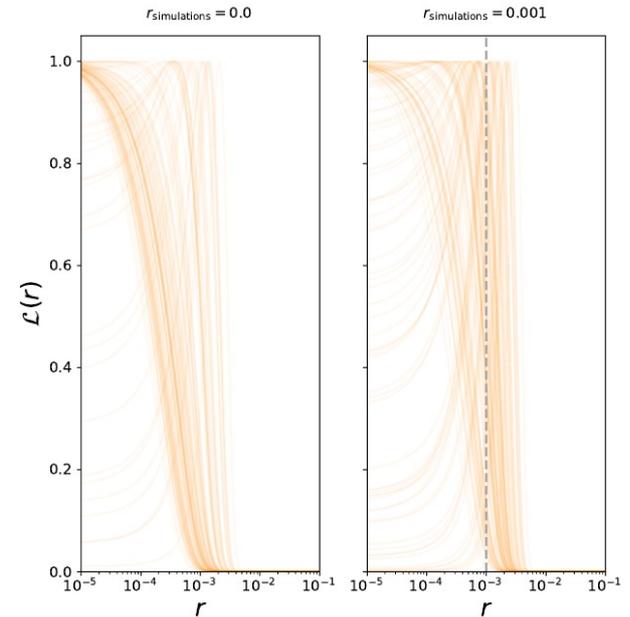
Baseline (from Concept Design Report)

Work in Nside=8 resolution

of FG parameters = 6144

15 bands used

$$\sigma(r) \simeq 0.4 \times 10^{-3}$$



Deltamap (internal template) K. Ichiki+, to be submitted

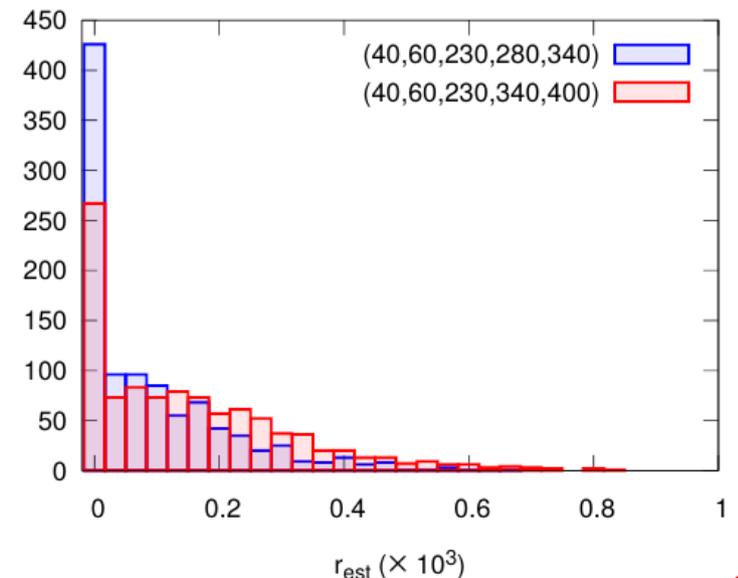
Work in Nside=4 resolution

of FG parameters = 4

6 or 7 bands used

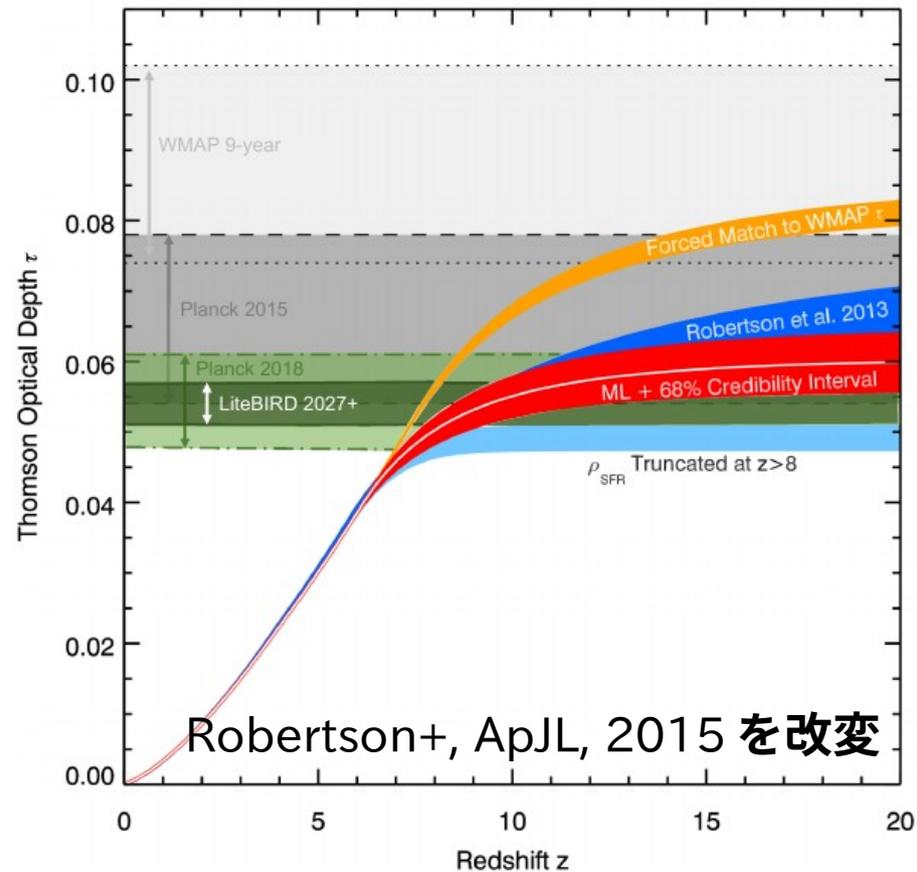
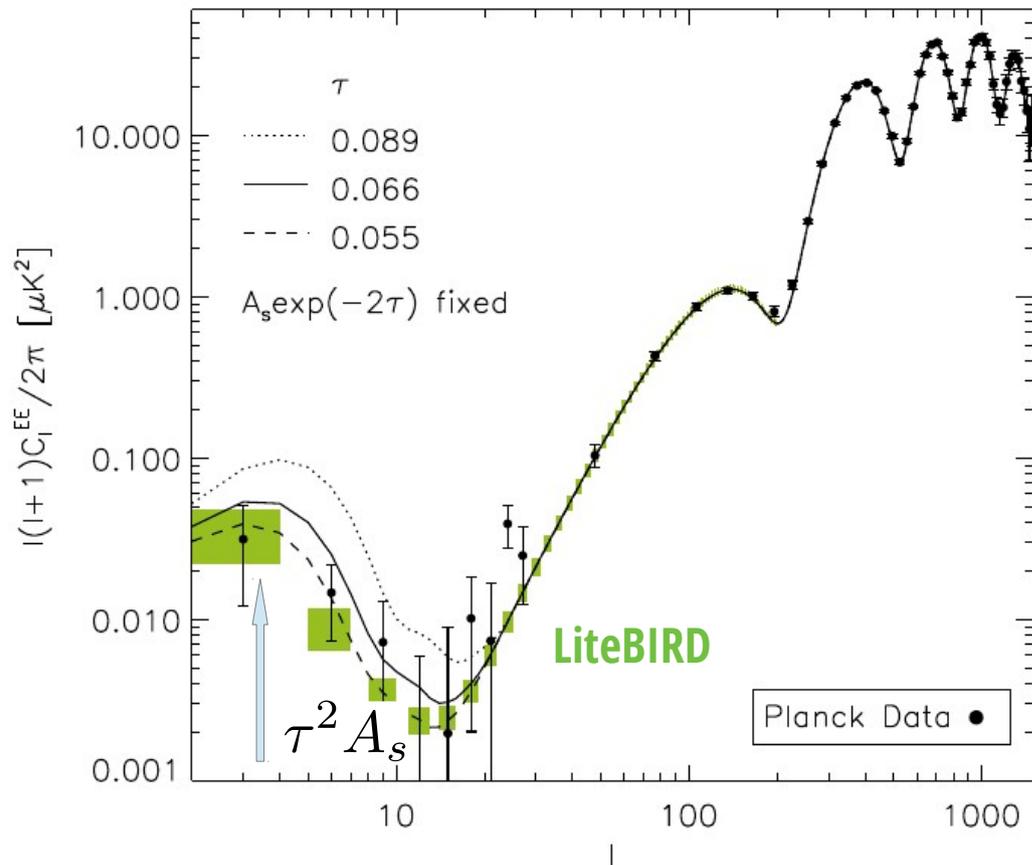
$$\sigma(r) \simeq 0.9 \times 10^{-3}$$

$$\sigma(r) \simeq 0.2 \times 10^{-3} (\text{noiseless})$$



もし重力波が受からなくても

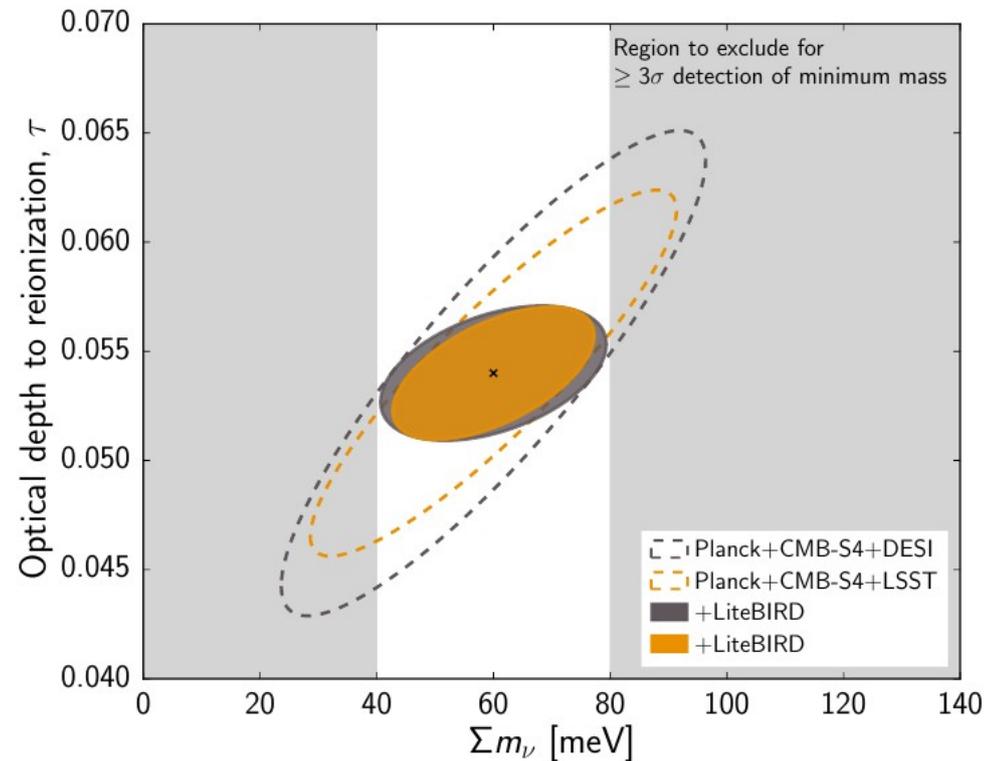
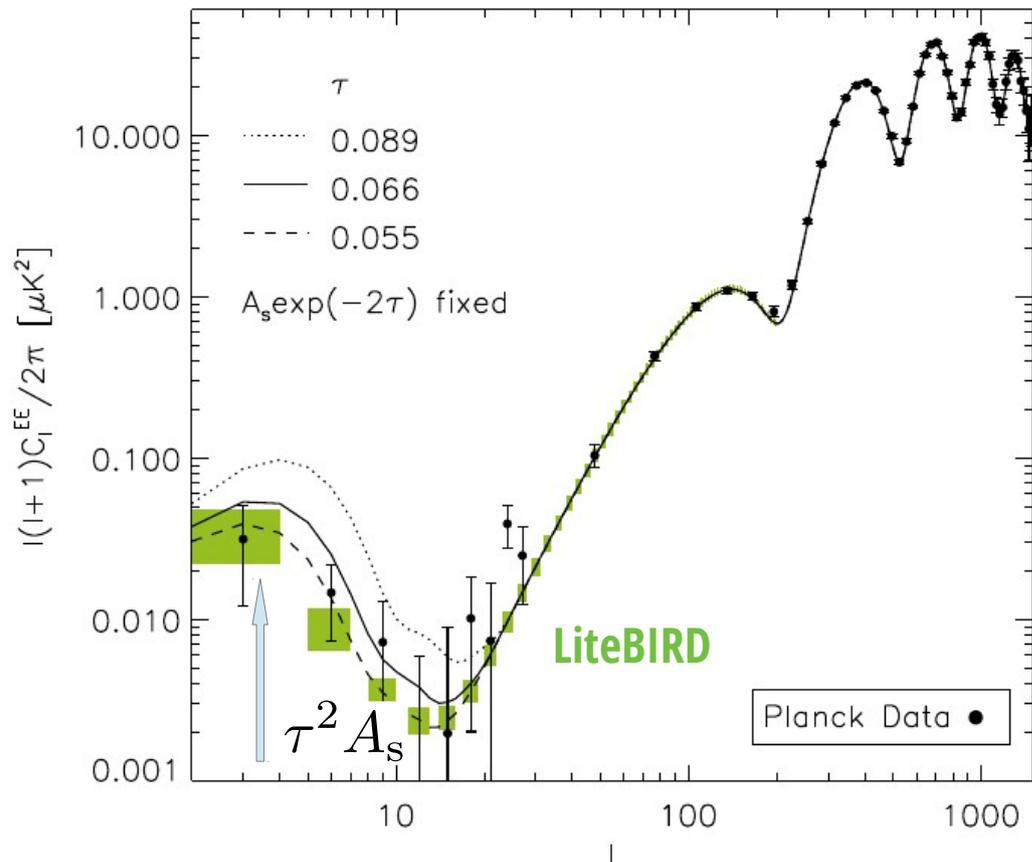
“A cosmic variance limited measurement of EE on large angular scales will be an important, and guaranteed, legacy for LiteBIRD.” (external international science review)



$$\sigma(\tau) = 0.002$$

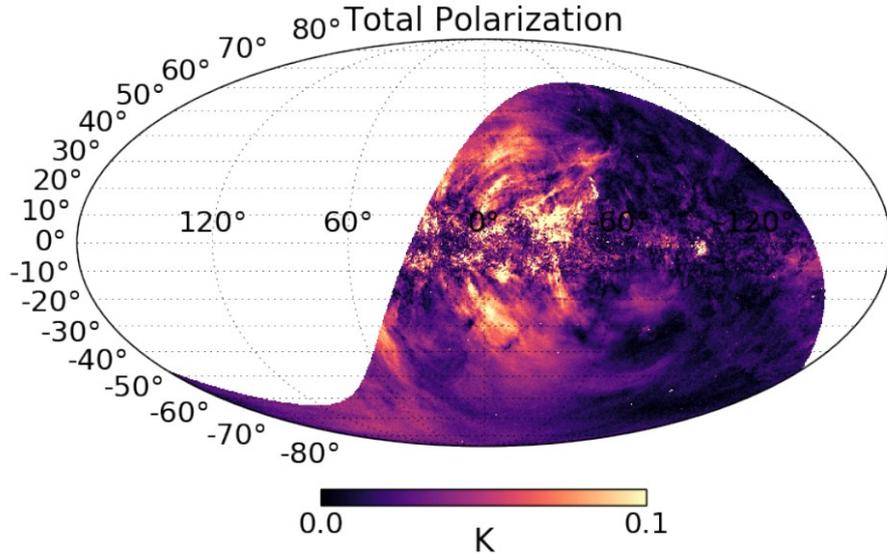
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“A cosmic variance limited measurement of EE on large angular scales will be an important, and guaranteed, legacy for LiteBIRD.” (external international science review)

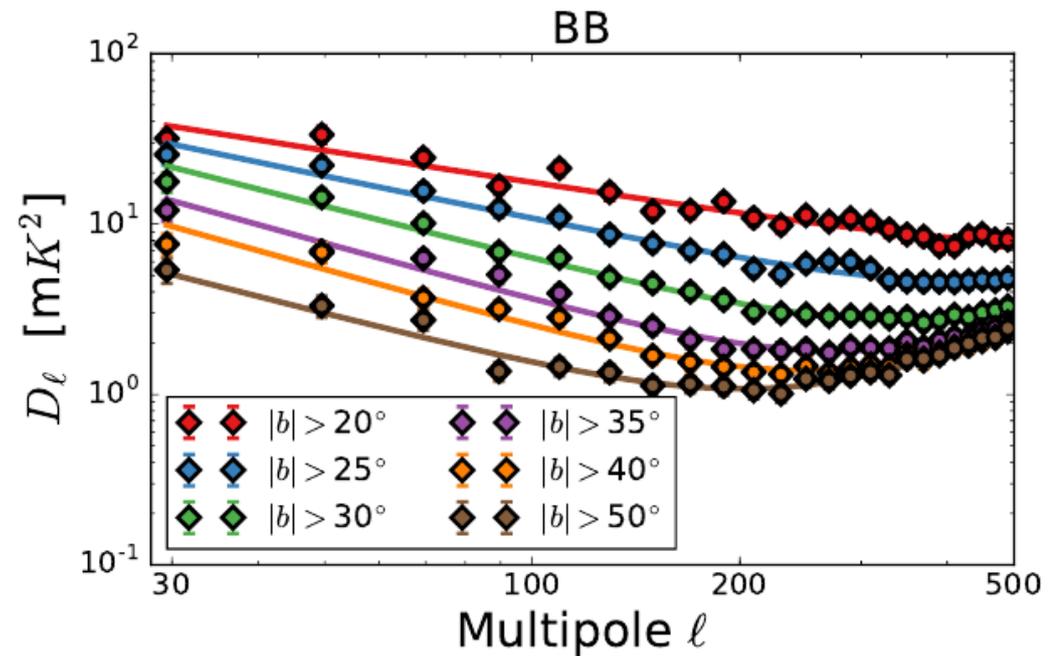
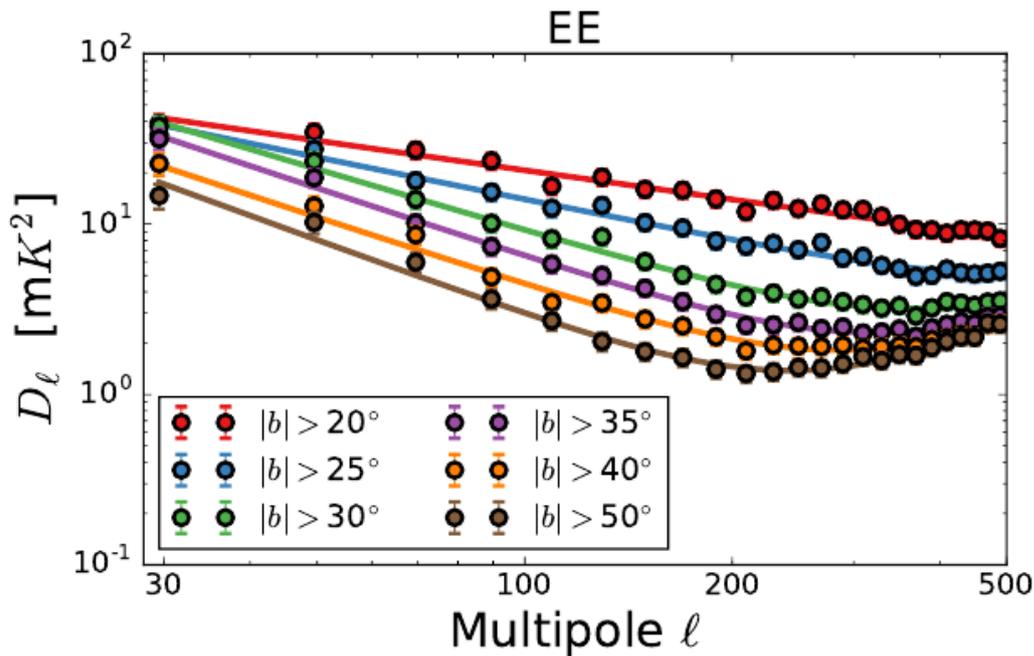


Breaking degeneracy between τ and A_s \rightarrow 5σ detection of neutrino mass

S-PASS results

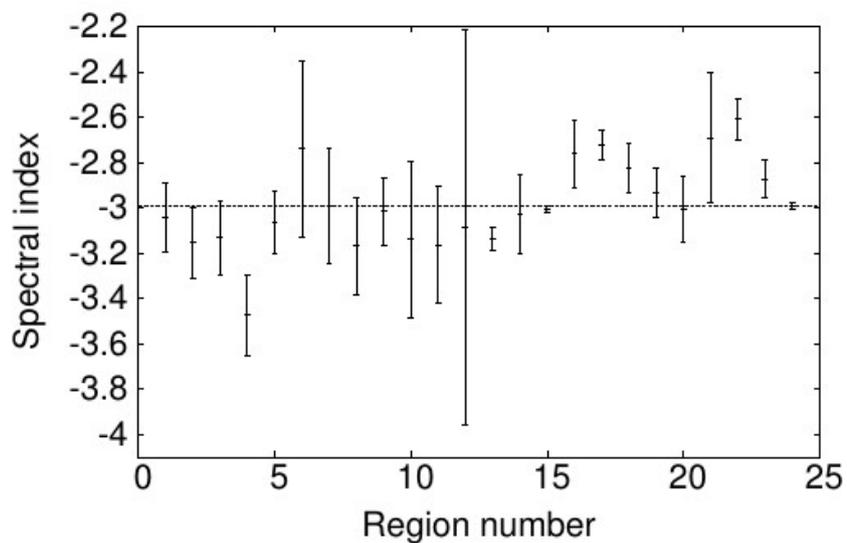
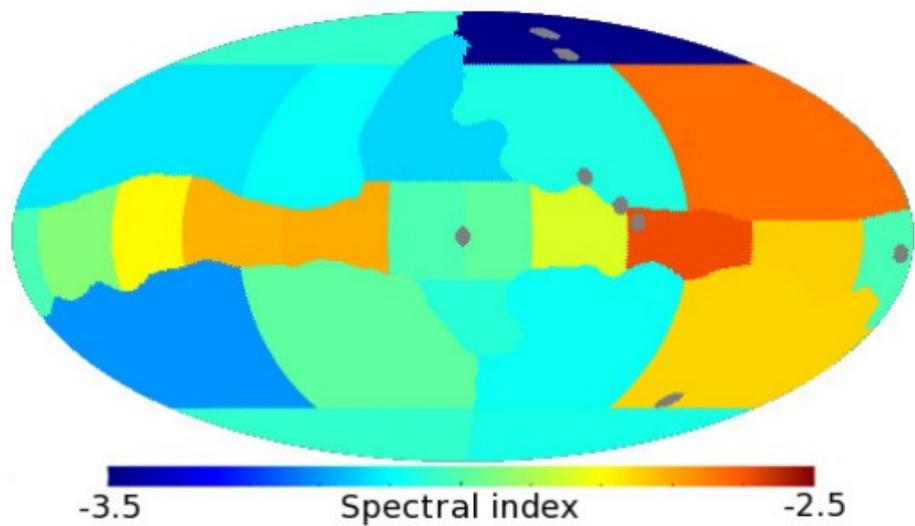


Parkes 64m (2.3GHz)
FWHM = 9'
 $\sigma_{\text{beam}} = 1\text{m}\mu\text{K}$



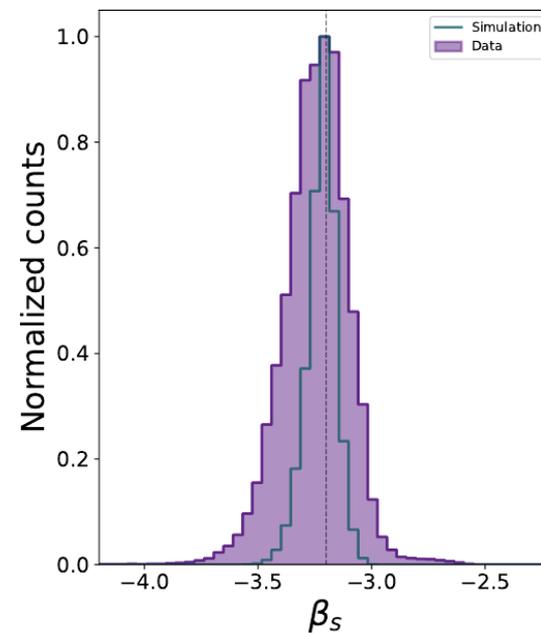
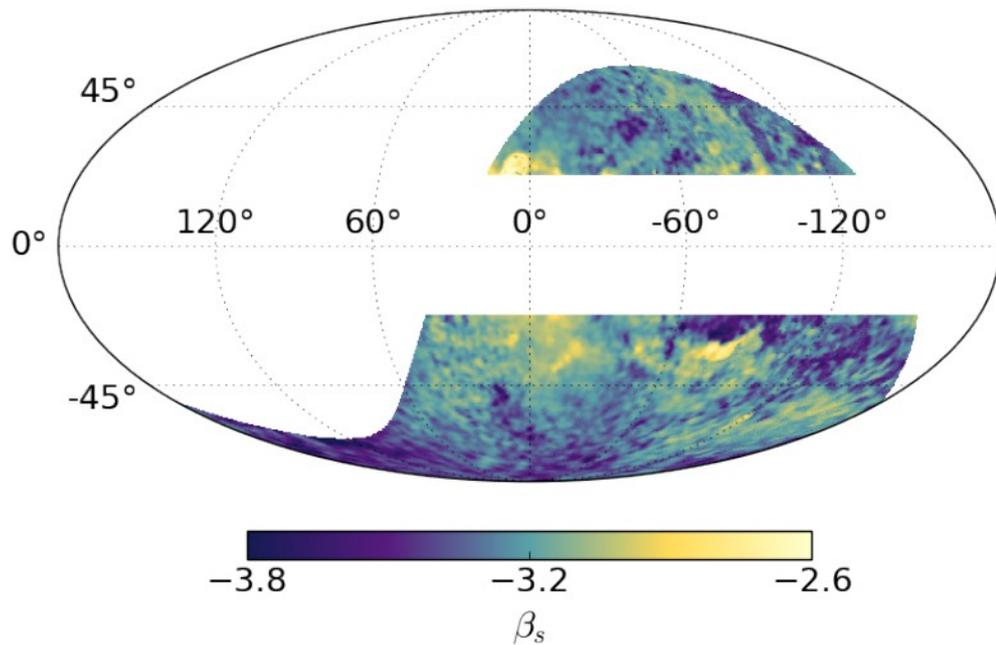
WMAP 9yr

Fuskeland+, ApJ 2014



S-PASS

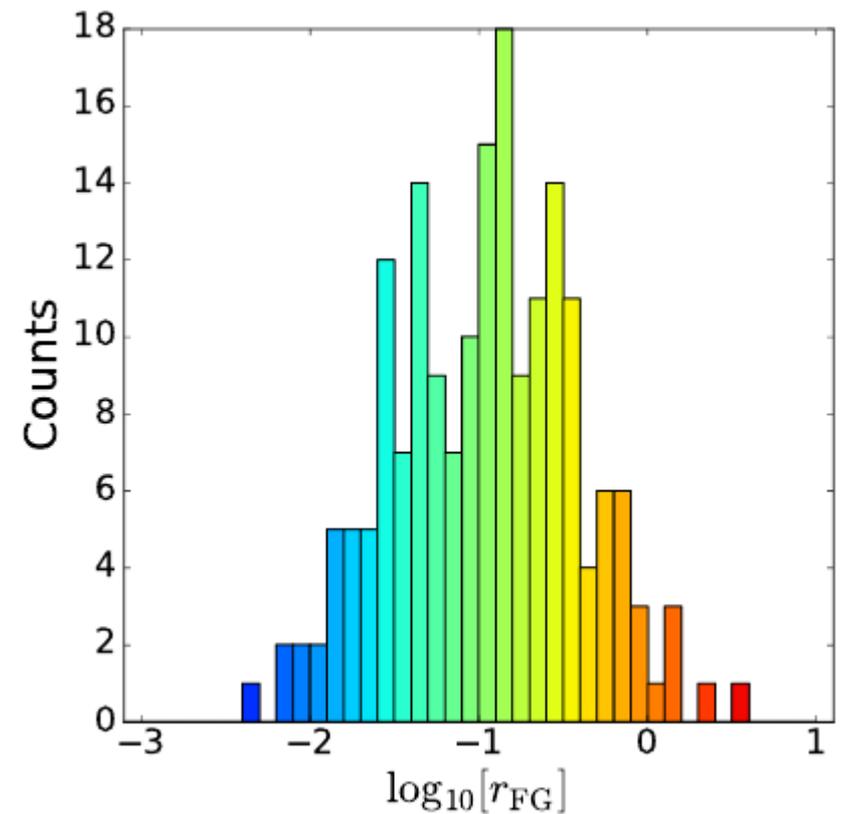
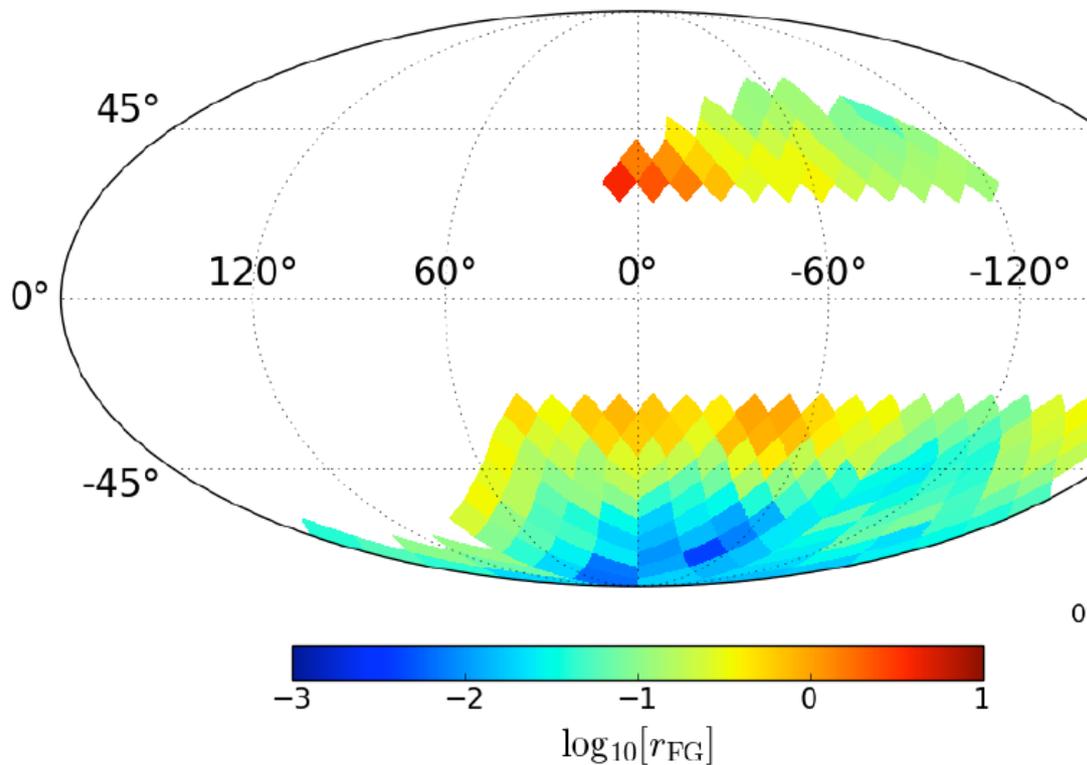
Krachmalnicoff+, arxiv: 1802.01145



Message from S-PASS

Synchrotron ... S-PASS
Dust ... Planck 353

Our findings, confirm, once again, that there is no region of the sky (among the sky portion covered by the S-PASS survey) nor frequency where the foreground amplitude (at the degree angular scales) lie below a CMB B -mode signal with $r \simeq 10^{-3}$, and



まとめ

- 現在の背景重力波への制限は $r < 0.06$ (Planck2015+BK15)
 - 全天どの方向も前景放射が卓越 (S-PASS + Planck 353)
 - 上限は前景放射 (dust) のモデリングの精度で決まっている
- LiteBIRD で期待される感度は $r < 0.001$
 - 前景放射除去に要求される精度 $r < 0.57 \times 10^{-3}$ は達成可能
 - 日本版除去アルゴリズム `deltamap` 法の開発
 - consistency relation は CMB のみでは困難 → decigo などの重力波干渉計による直接検出
 - 受からなかったら $\Omega_{\text{GW}} \lesssim 2 \times 10^{-17}$

