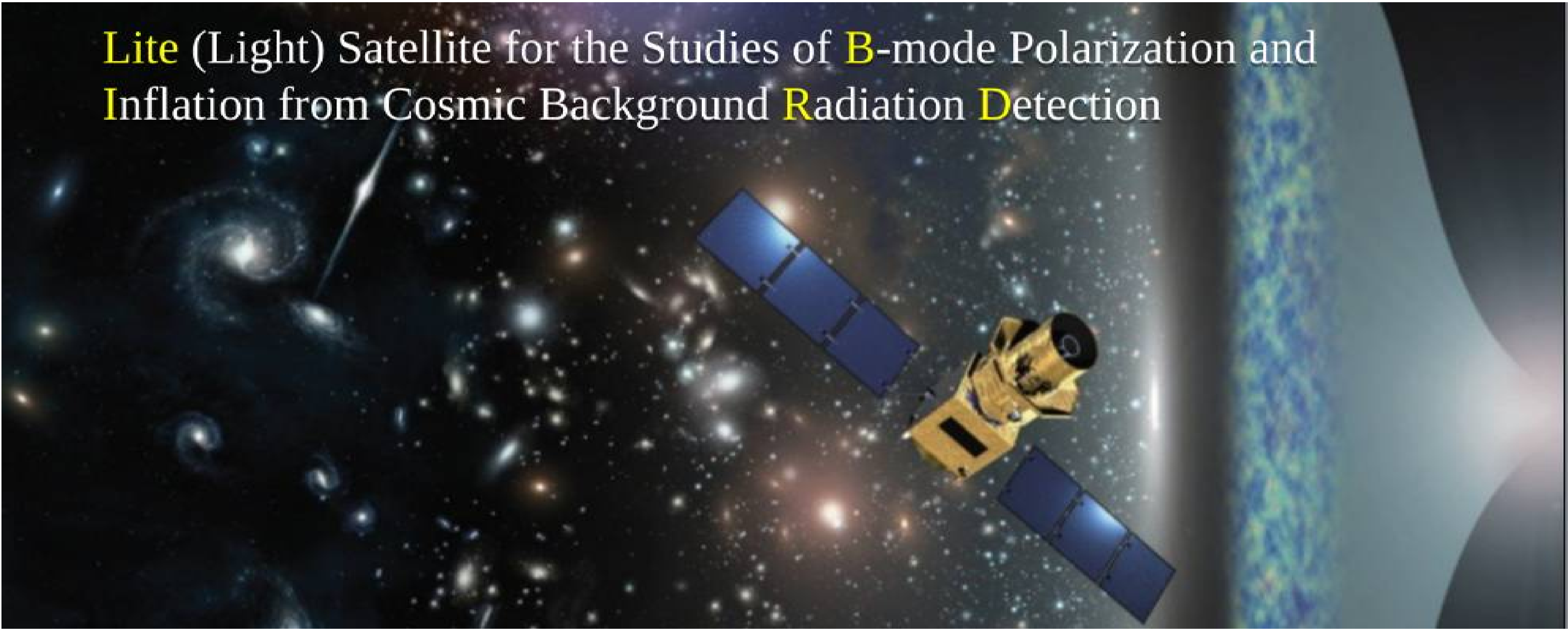



# Cosmology with CMB polarization: current status and future prospects

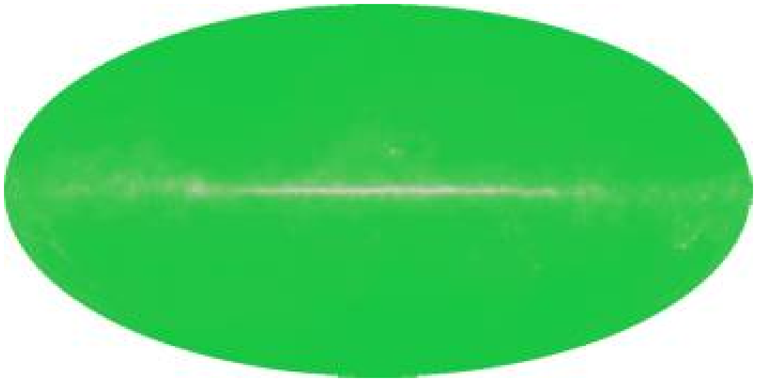
Kiyotomo ICHIKI (Nagoya)

Refs.: KI, Kanai, Katayama & Komatsu, PTEP ‘19
Liu, KI, Tashiro & Sugiyama, MNRAS Letters ‘16
Planck 2018 results V, Meyers+, PRD ‘18
Pagano+(arxiv:1908.09856)

# Contents

- Large scale CMB polarization and optical depth
- Next generation CMB polarization satellite: LiteBIRD
- Future prospects
  - Constraints on reionization history
  - Reconstruct of density fluctuations through cluster CMB polarization
- Summary

# Cosmic Microwave Background

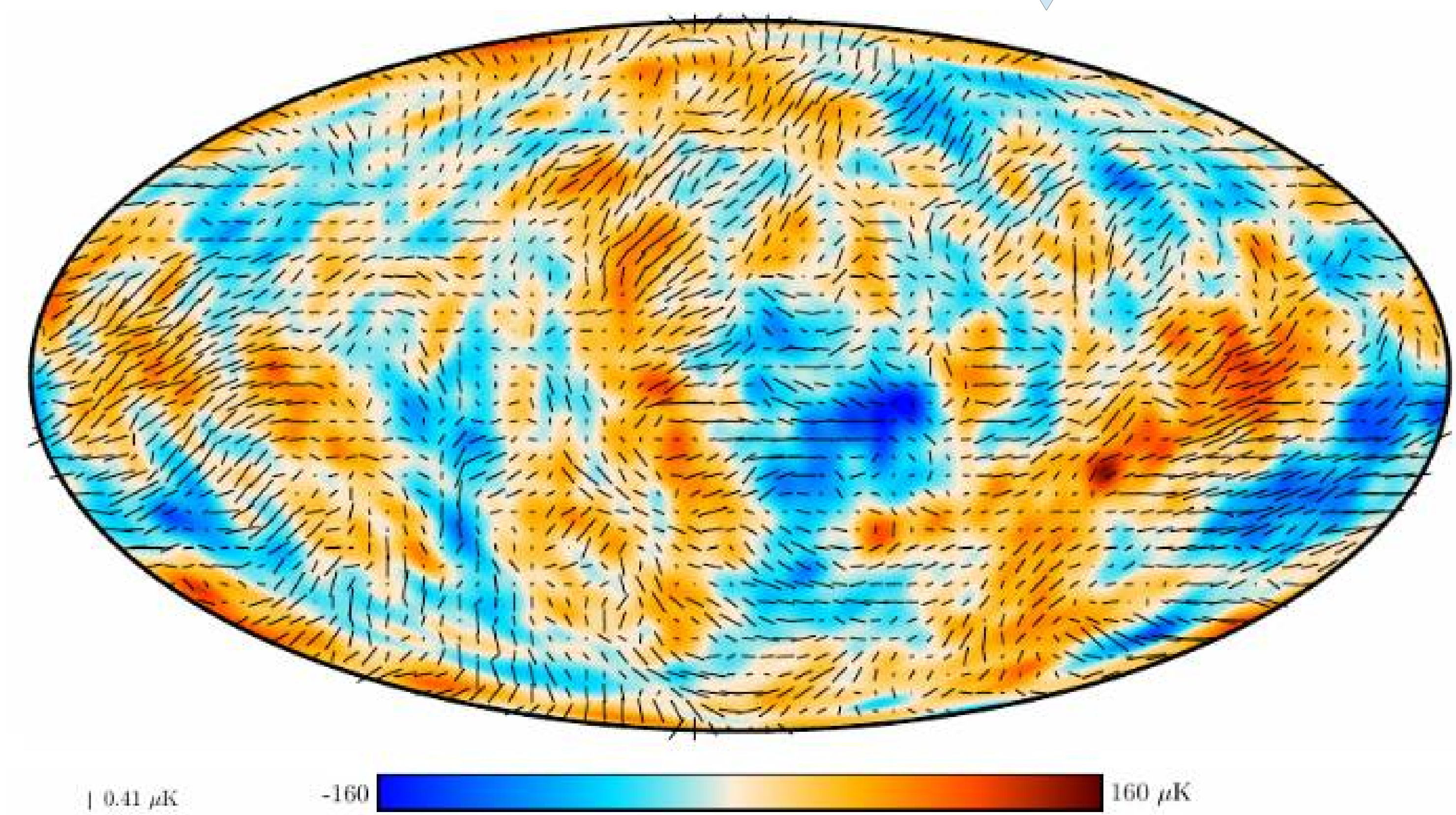


$\sim 3\mathrm{K}$

(Relic of the Big-Bang, 3K black body)

Penzias and Wilson (1965)

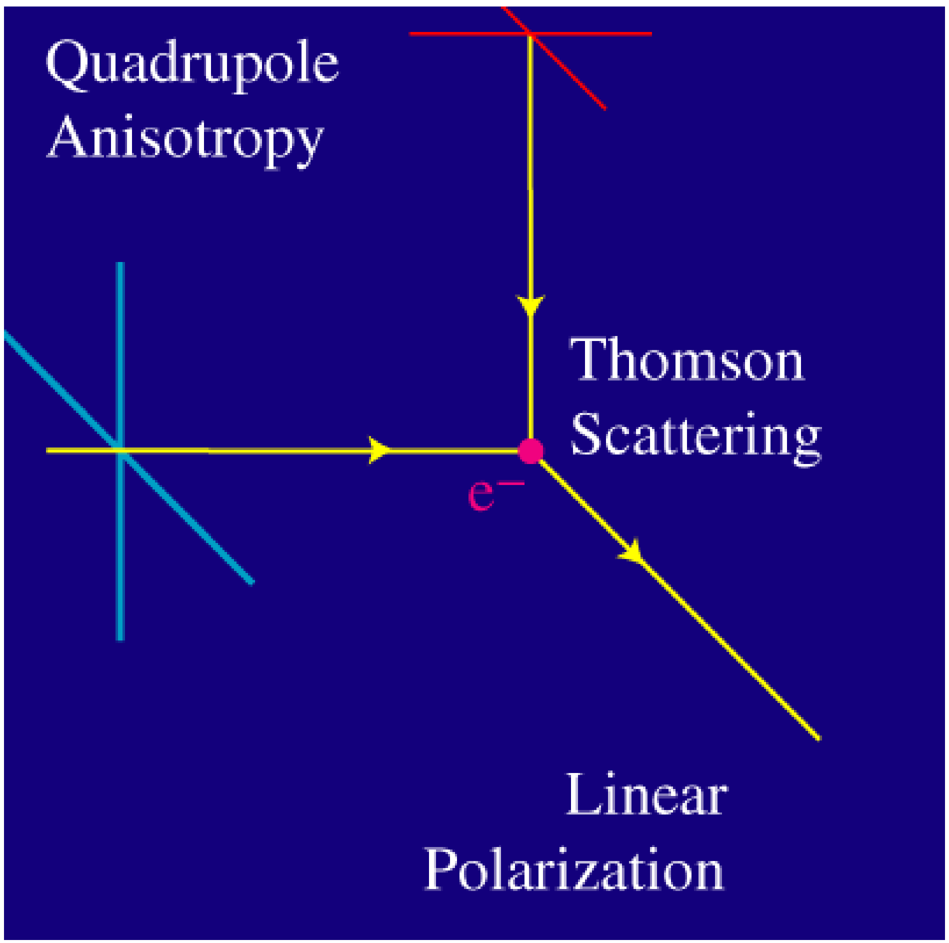
remove the monopole
& dipole



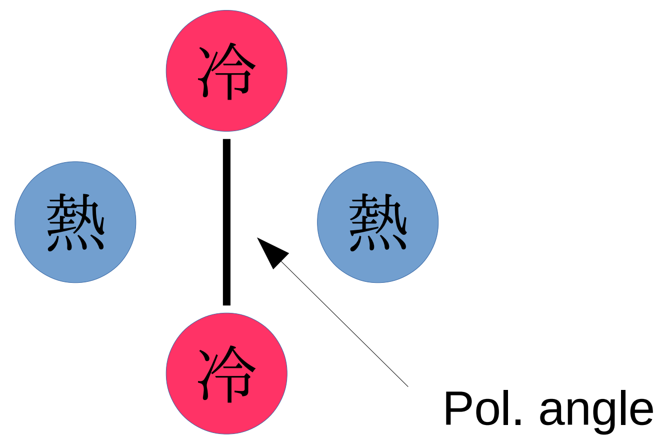

temperature
$\sim 30\mu\mathrm{K}$

polarization
$\sim \mu\mathrm{K}$

# Optical depth tau from CMB E-mode polarization



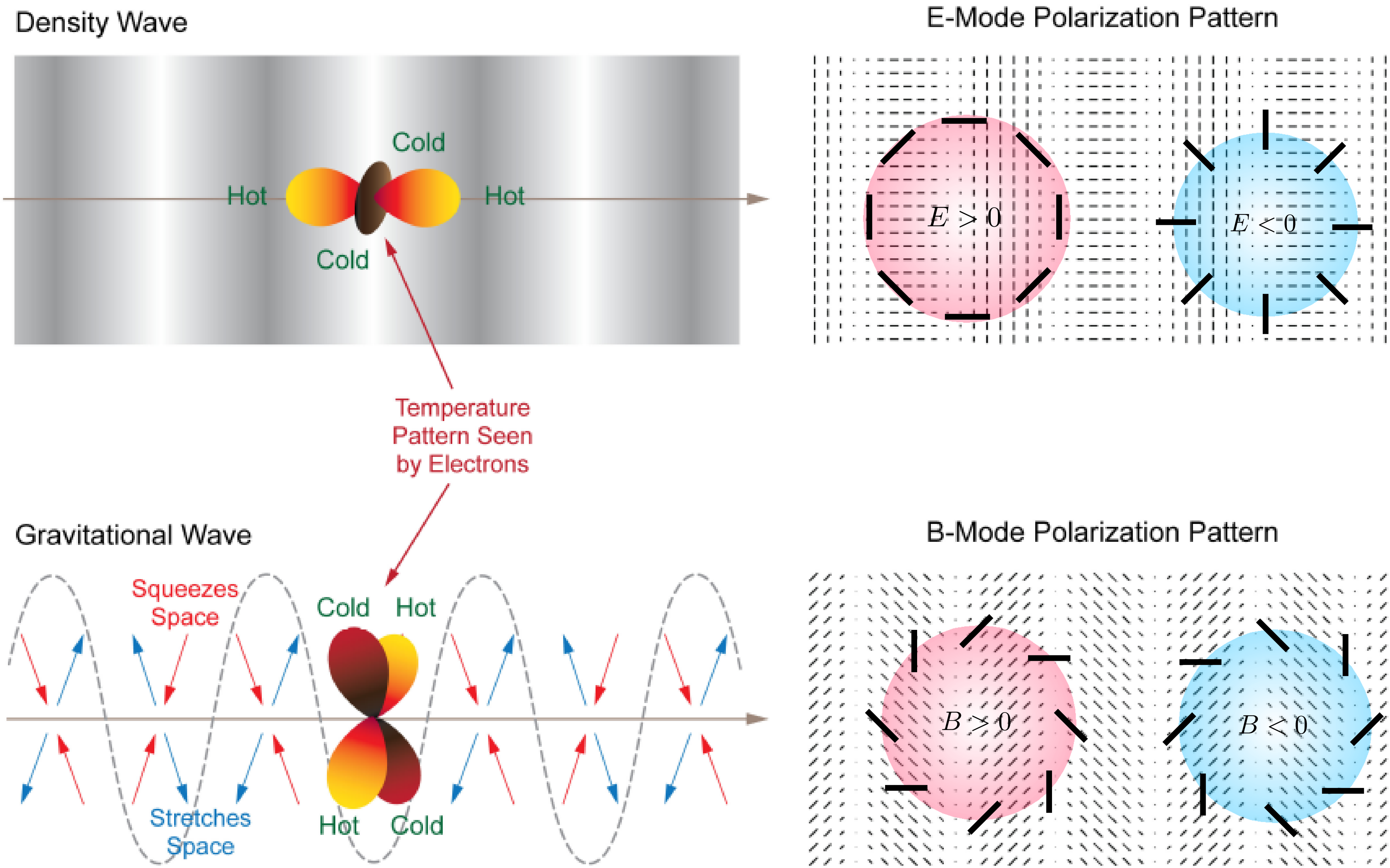

Thomson scattering produces linear polarization if there is quadrupole anisotropy in CMB intensity around the free electrons




Polarization angle follows the CMB quadrupole **seen by the electron**

see W. Hu's tutrial

# E-mode & B-mode

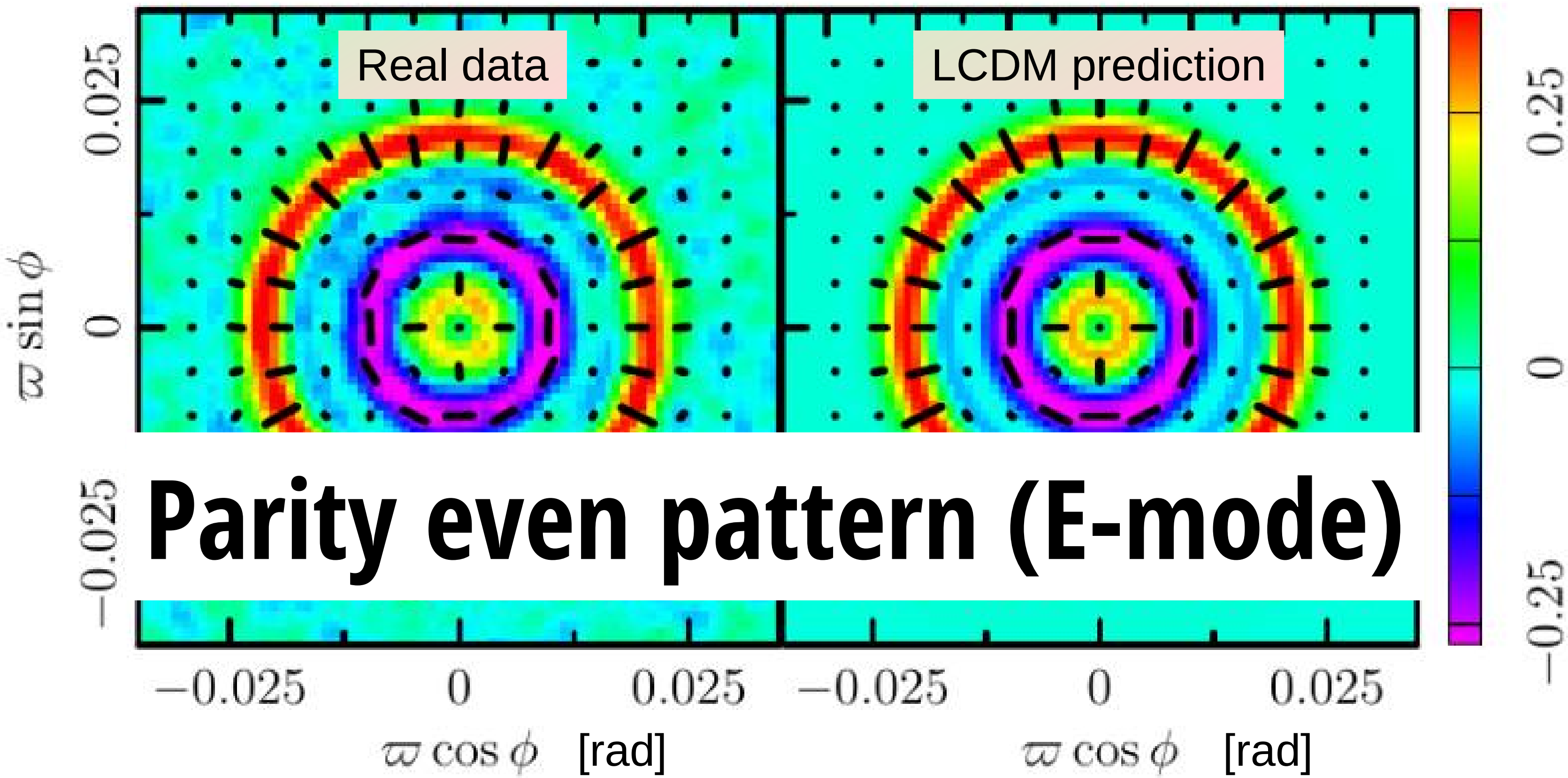





from BICEP2 web page

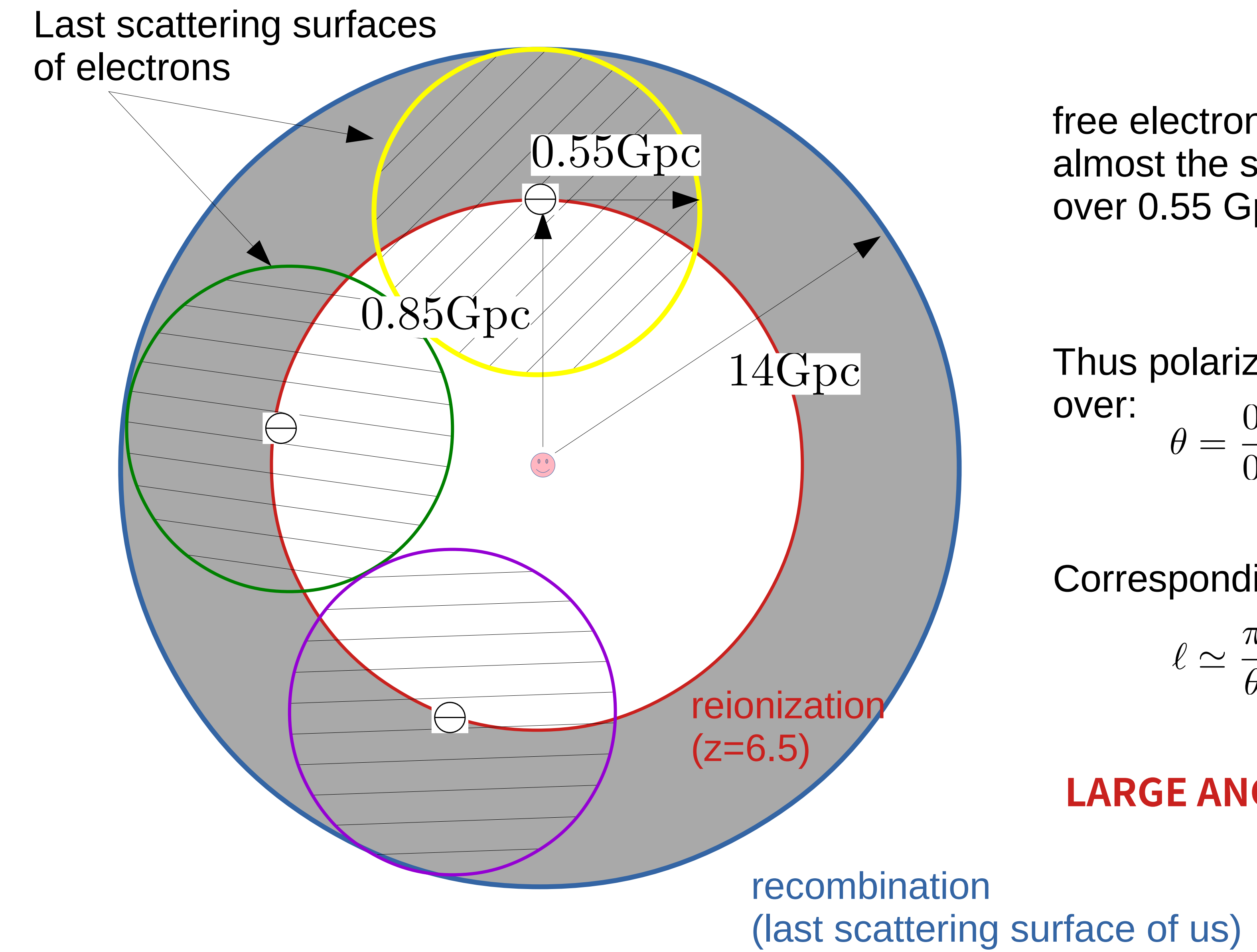
# CMB polarization

Polarization image generated by stacking the polarization pattern around hot spots of temperature anisotropies (clear indication of the sound horizon at recombination)




**Parity even pattern (E-mode)**

# Large angle polarization from reionization




free electrons at re-ionization see almost the same CMB quadropole over 0.55 Gpc scale

Thus polarization pattern is coherent over:

$$\theta = \frac{0.55}{0.85} \simeq 0.65 \text{ rad}$$

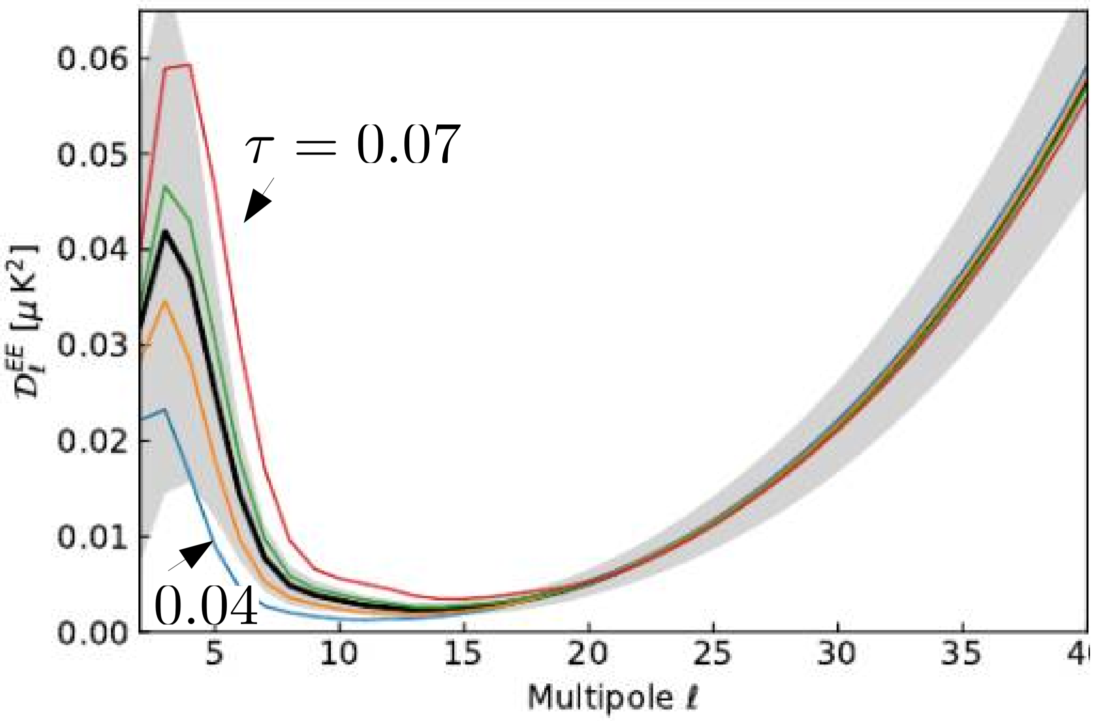
Corresponding multipole is

$$\ell \simeq \frac{\pi}{\theta} \simeq 5$$

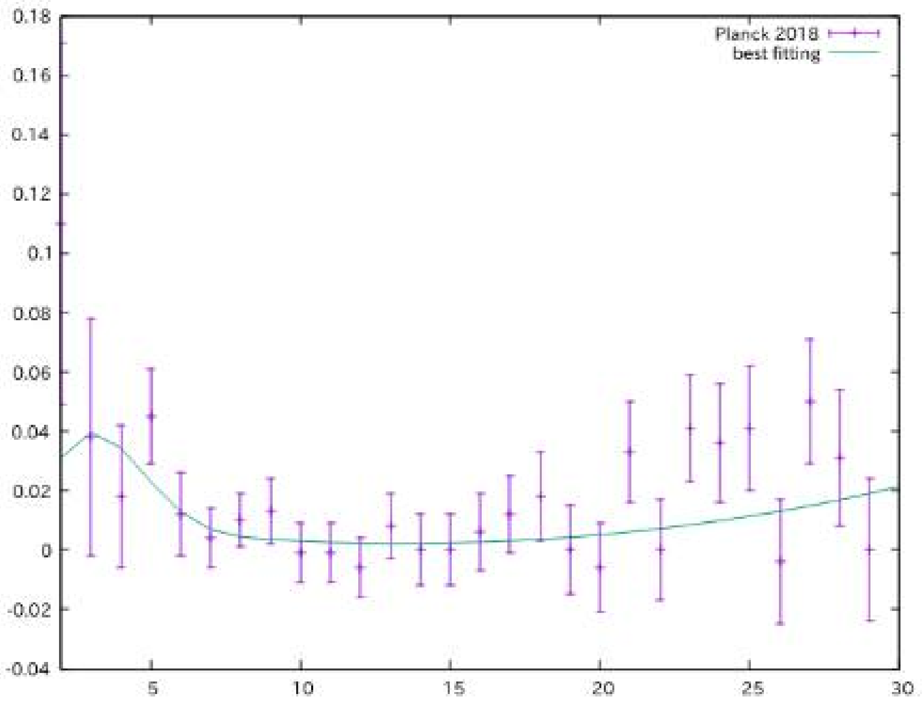
**LARGE ANGULAR SCALE!**

# Planck 2018 results+

Large-scale E-mode power spectrum




Planck 2018 power spectrum

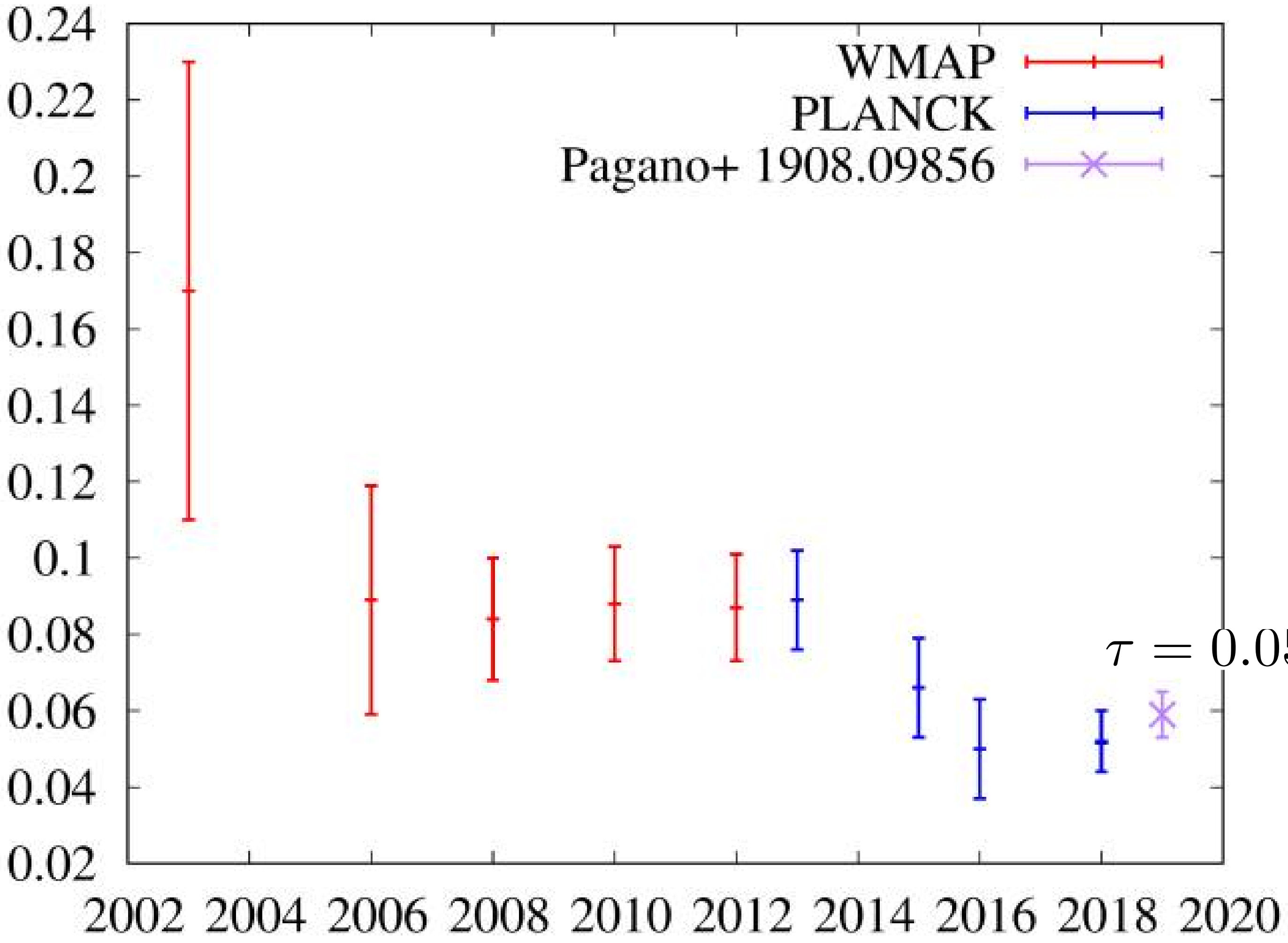


# what’s next?

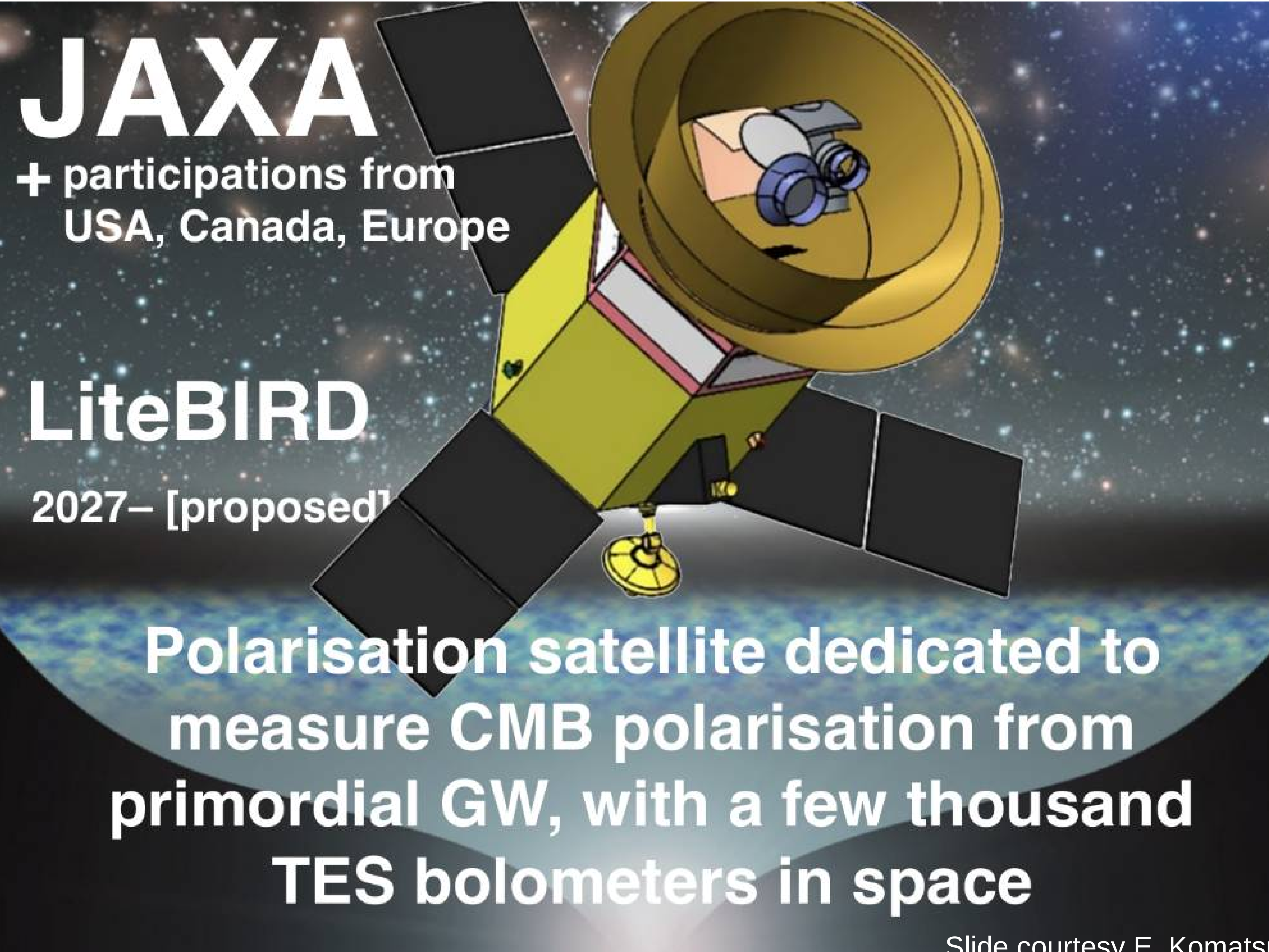
P.Bull+, 2016

| 5. For cosmology, the most valuable/exciting observables over the next decade will probably be: | No. | % |
|---|---|---|
| CMB polarization | 33 | 54 |
| Galaxy redshifts (spectroscopic) | 31 | 51 |
| Weak lensing (shear/convergence) | 30 | 49 |
| 21 cm intensity mapping (EoR) | 29 | 48 |
| Gravitational waves | 25 | 41 |
| 21 cm intensity mapping (late times) | 22 | 36 |
| Galaxy redshifts (photometric) | 18 | 30 |
| CMB lensing | 16 | 26 |
| Peculiar velocities (Kinetic SZ) | 14 | 23 |
| Dark matter direct detection | 14 | 23 |
| High-redshift galaxies | 12 | 20 |
| Matter distribution on ultra-large scales | 12 | 20 |
| Neutrinos | 12 | 20 |
| CMB scattering (Thermal SZ/Rayleigh/spectral distortions) | 11 | 18 |
| Strong lensing | 10 | 16 |
| Various cross-correlations | 10 | 16 |
| Other large-scale structure/matter distribution observables | 8 | 13 |
| Local tests of gravity | 8 | 13 |
| Supernovae | 7 | 12 |
| Cosmic rays | 6 | 10 |
| Particle collisions (LHC) | 5 | 8 |
| Local Hubble rate measurements | 3 | 5 |
| Transients | 3 | 5 |
| Proper motions of stars | 3 | 5 |
| Variation of fundamental constants | 3 | 5 |
| Laboratory tests of gravity | 2 | 3 |
| CMB temperature | 1 | 2 |
| Other | 1 | 2 |

# Planck 2018 results+




$\tau = 0.059 \pm 0.006$

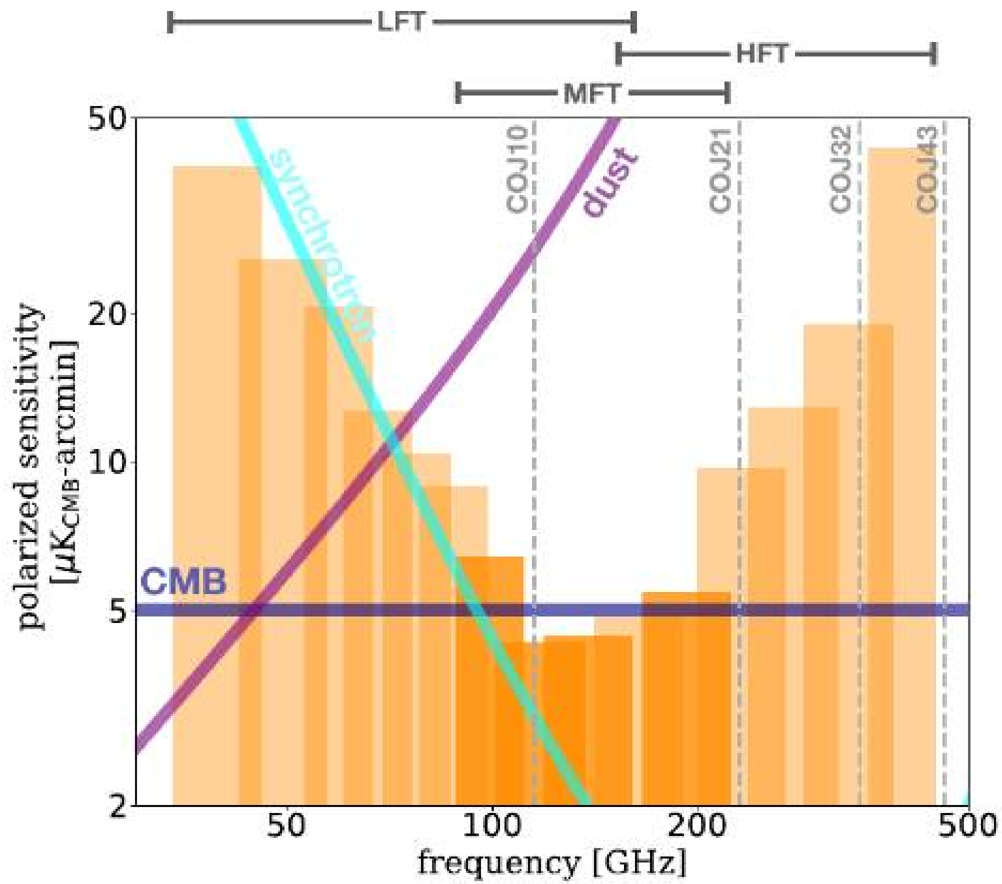

JAXA
+ participations from USA, Canada, Europe
LiteBIRD
2027– [proposed]
Polarisation satellite dedicated to measure CMB polarisation from primordial GW, with a few thousand TES bolometers in space
Slide courtesy E. Komats


JAXA
+ participations from
USA, Canada, Europe
LiteBIRD
2027– Selected!
May 21: JAXA has chosen LiteBIRD
as the strategic large-class mission.
We will go to L2!
Slide courtesy E. Komats

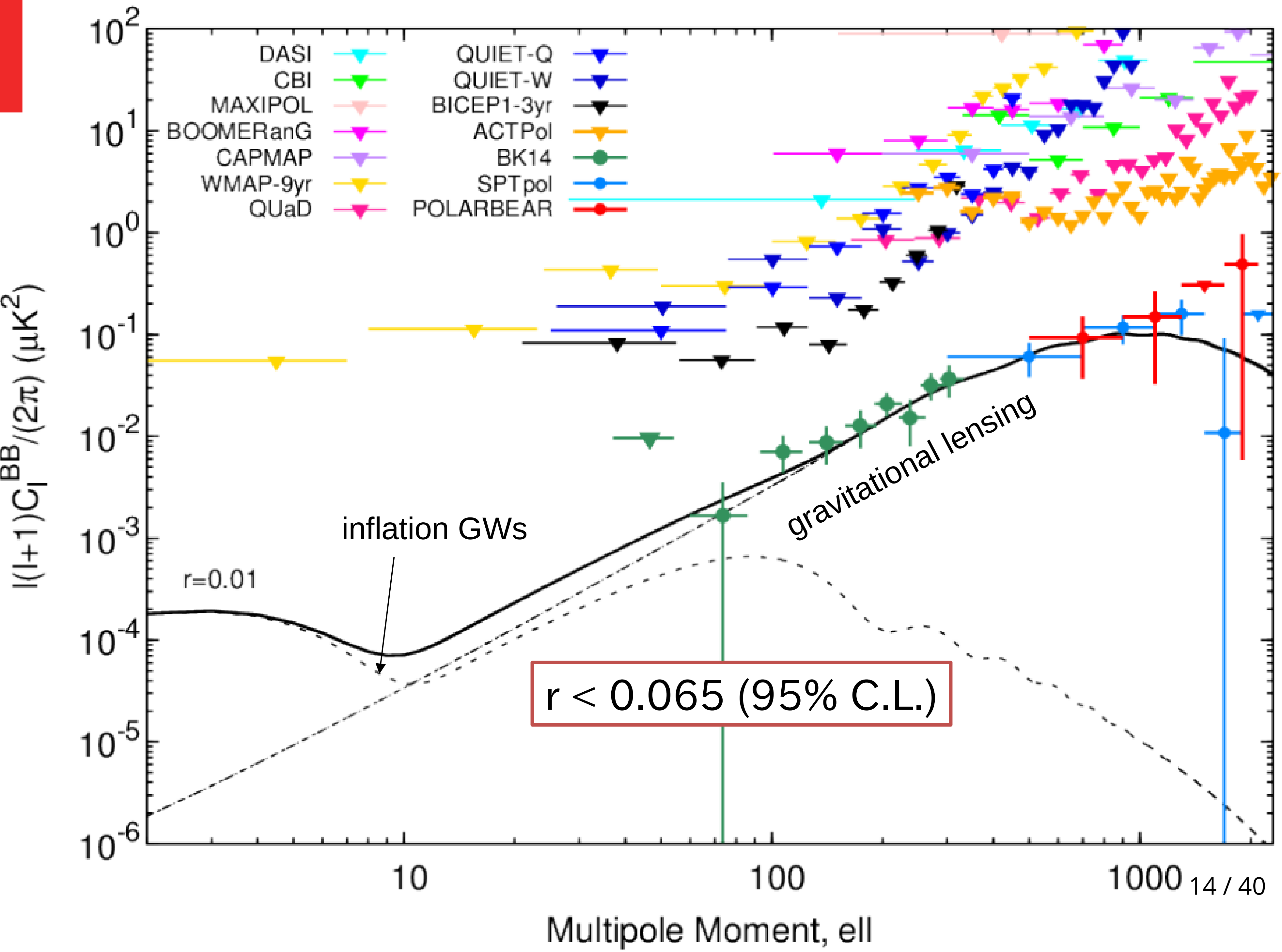
# 15 frequency bands from 40GHz to 400GHz

Mission of Opportunity, A. Lee

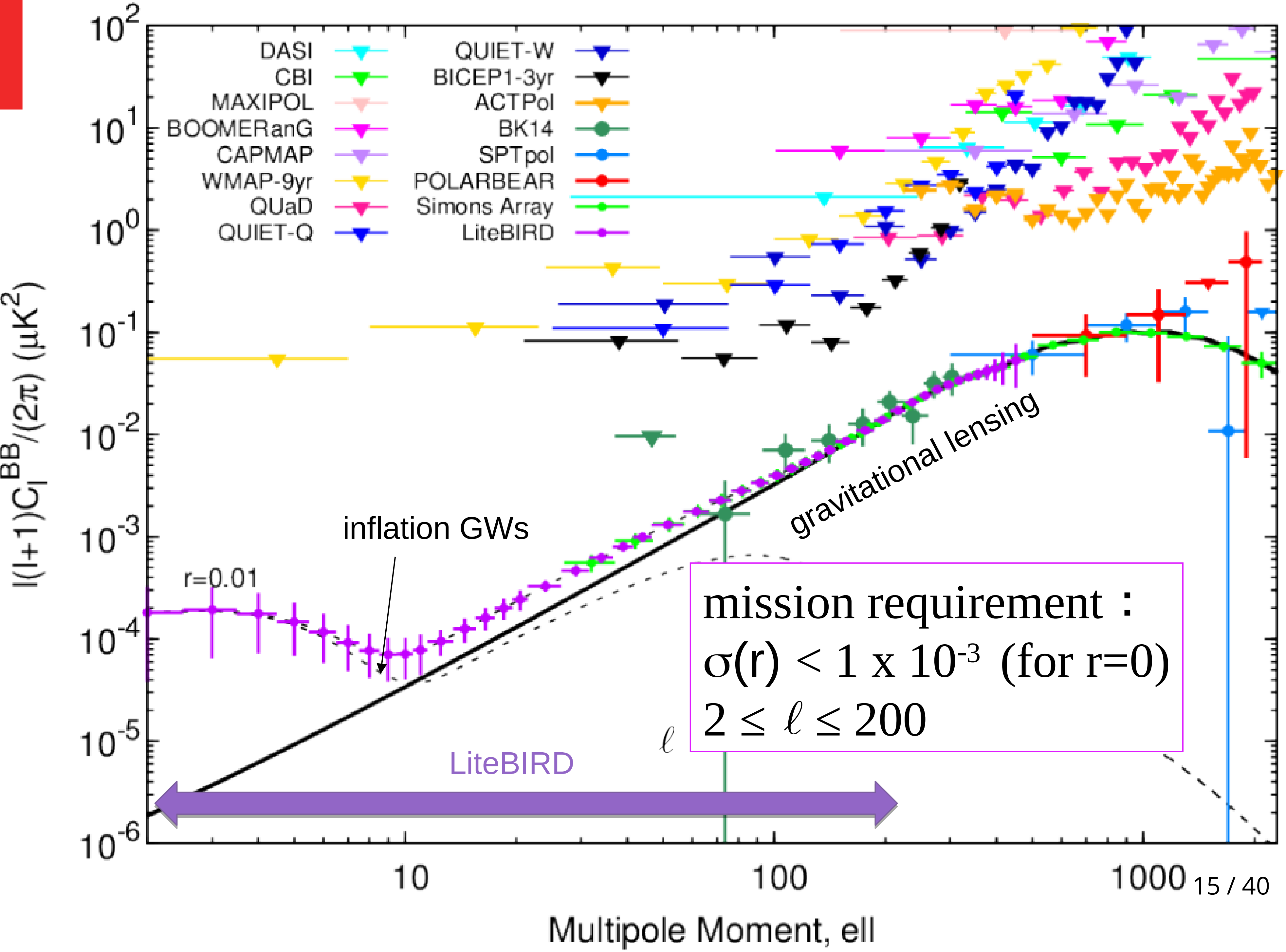
| Band Center [GHz] | Telescope | Number of Bolometers | NET [uK rts] Each Bolometer | | NET [uK rts] Array CBE | Map Noise [uK '] |
|---|---|---|---|---|---|---|
| 40 | LFT | 64 | 133 | | 18.7 | 34.9 |
| 50 | LFT | 64 | 86 | | 12.1 | 22.6 |
| 60 | LFT | 64 | 69 | | 9.7 | 18.1 |
| 68 | LFT | 64/144 | 57 | 96 | 6.0 | 11.2 |
| 78 | LFT | 64/144 | 49 | 74 | 4.9 | 9.2 |
| 89 | LFT | 64/144 | 44 | 61 | 4.2 | 7.8 |
| 100 | LFT/MFT | 144/366 | | 52 | 3.0 | 5.6 |
| 119 | LFT/MFT | 144/488 | | 39 | 2.0 | 3.7 |
| 140 | LFT/MFT | 144/366 | | 37 | 2.1 | 3.9 |
| 166 | MFT | 488 | 45 | | 2.3 | 4.3 |
| 195 | MFT/HFT | 366/254 | 53 | 63 | 2.6 | 4.9 |
| 235 | HFT | 254 | | 65 | 4.6 | 8.6 |
| 280 | HFT | 254 | | 86 | 6.1 | 11.4 |
| 337 | HFT | 254 | | 127 | 9.0 | 16.8 |
| 402 | HFT | 338 | | 334 | 20.5 | 38.3 |



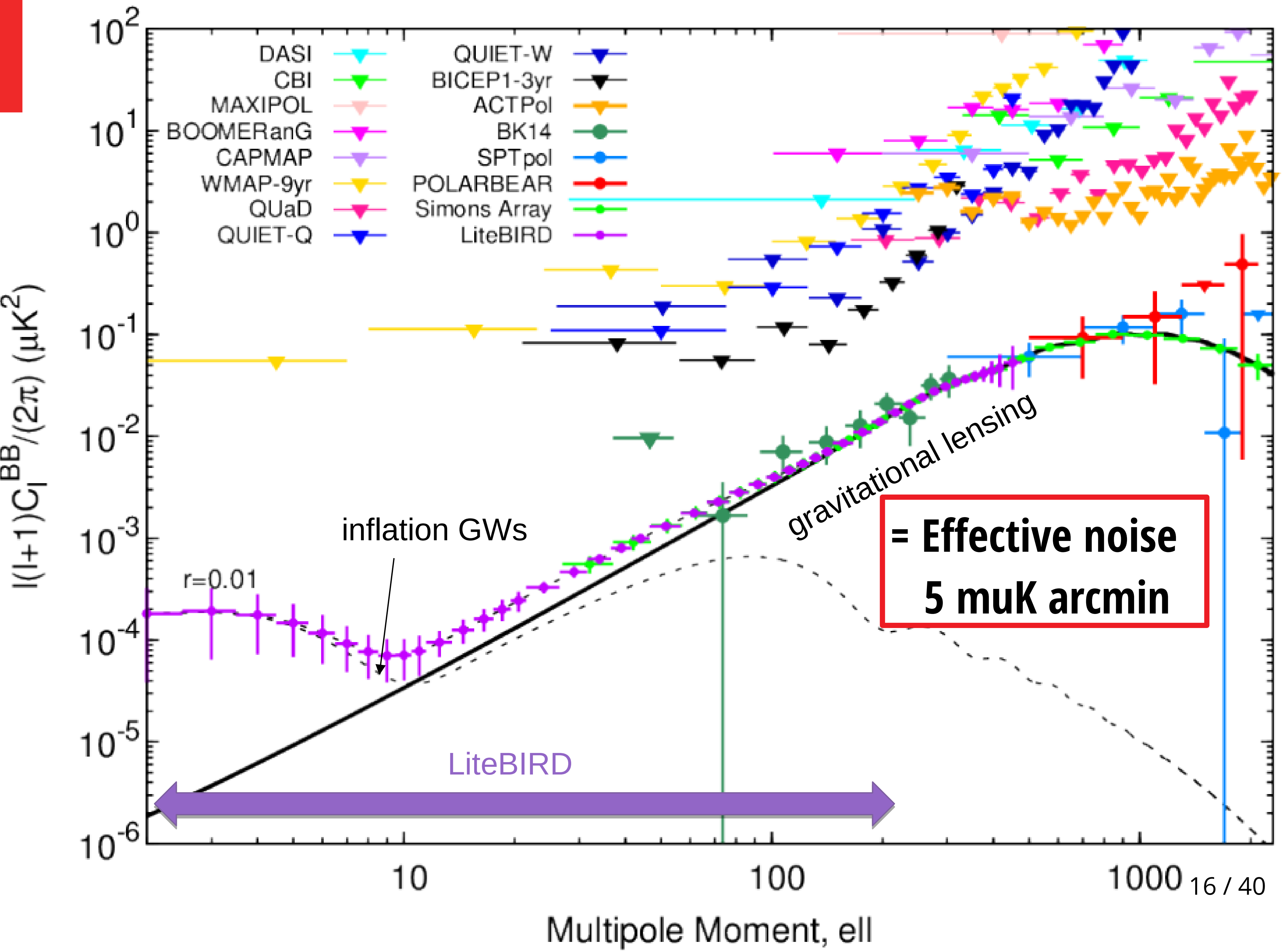

Combined, $\sigma \simeq 2\mu\mathrm{Karcmin}$ FWHM = 30arcmin


DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
ACTPol
BK14
SPTpol
POLARBEAR
r=0.01
inflation GWs
gravitational lensing
$l(l+1)C_l^{BB}/(2\pi)$ ($\mu K^2$)
Multipole Moment, ell

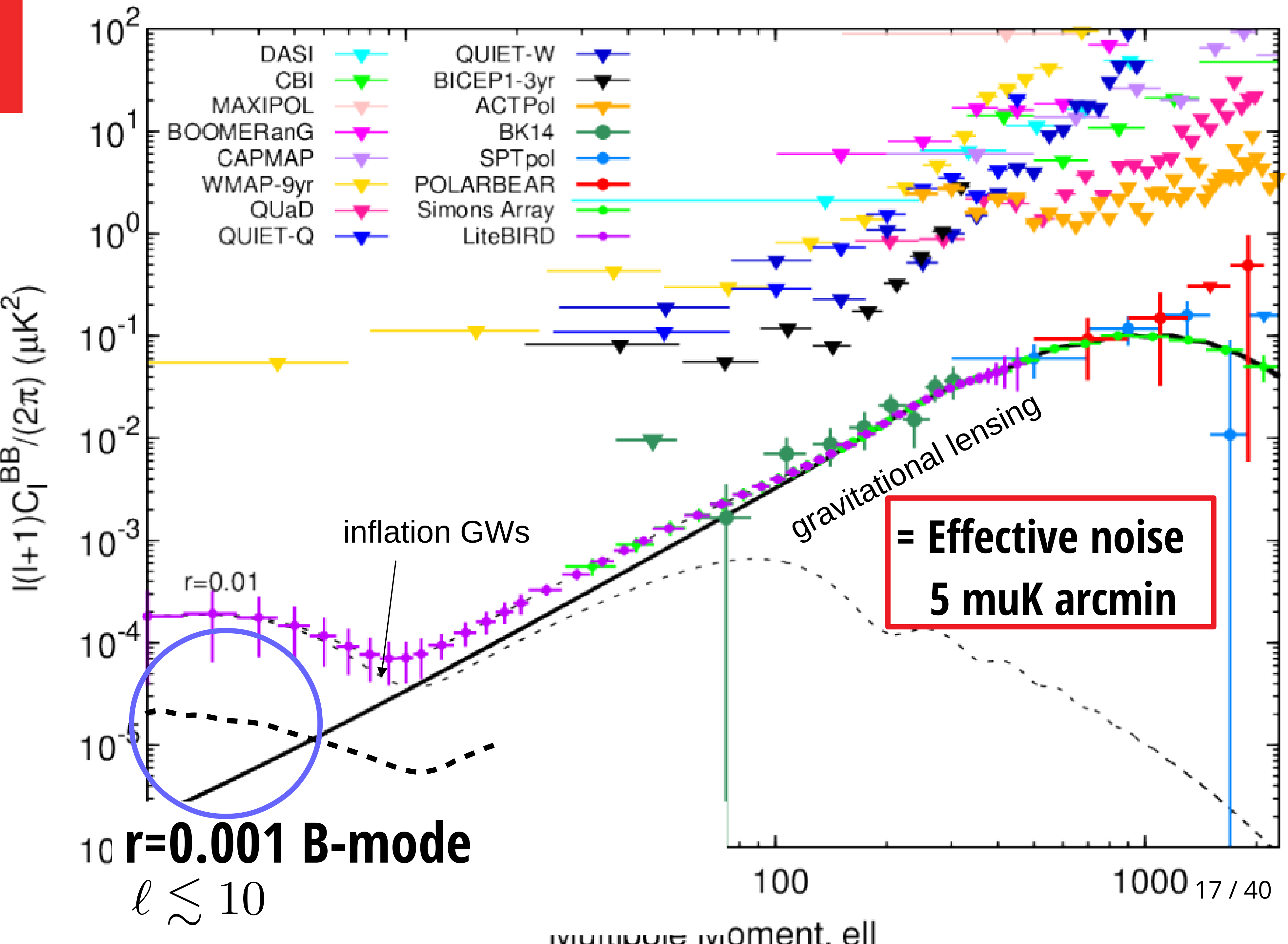
r < 0.065 (95% C.L.)




mission requirement：
$\sigma(r) < 1 \times 10^{-3}$ (for r=0)
$2 \leq \ell \leq 200$



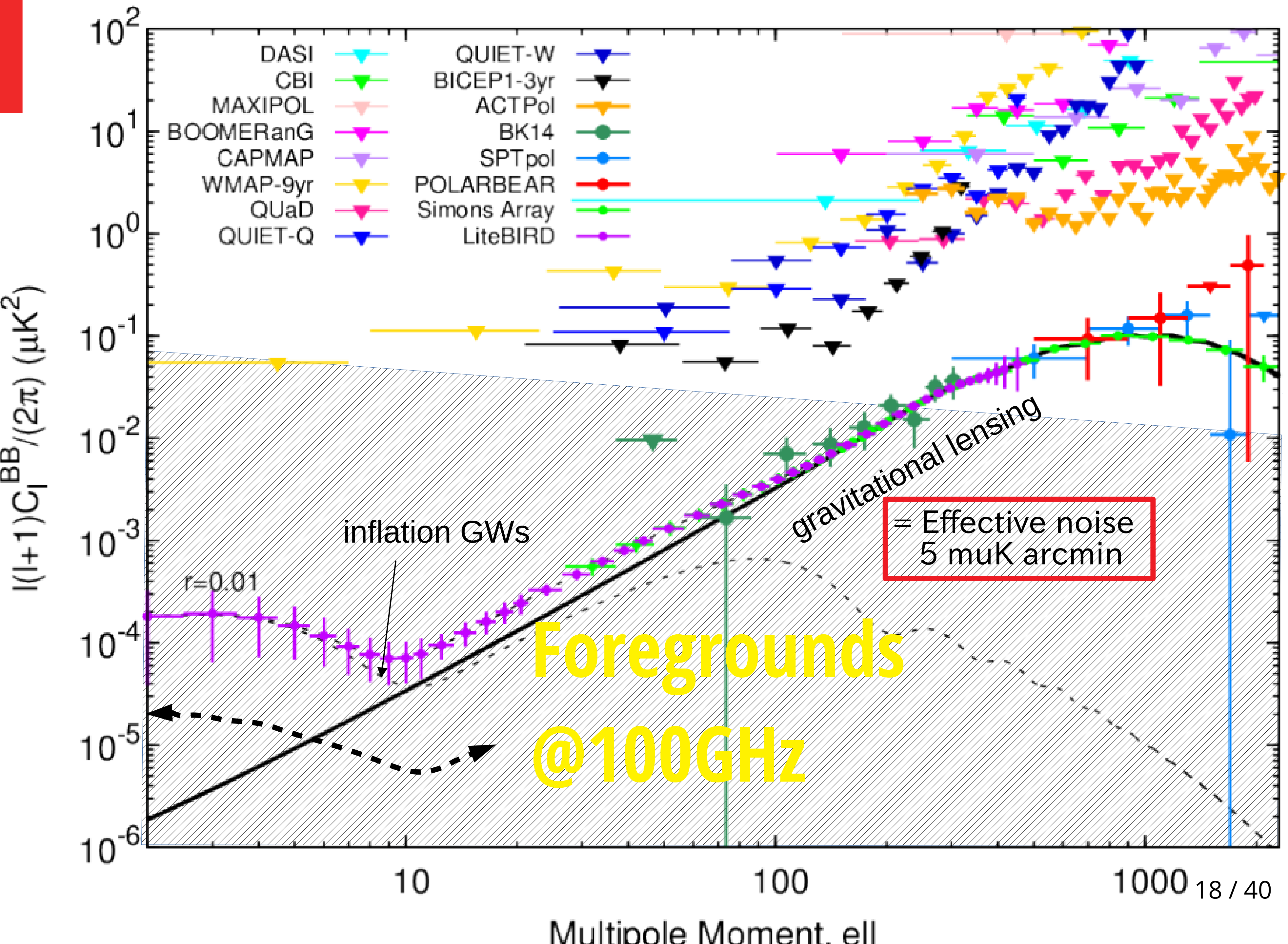

= Effective noise 5 muK arcmin



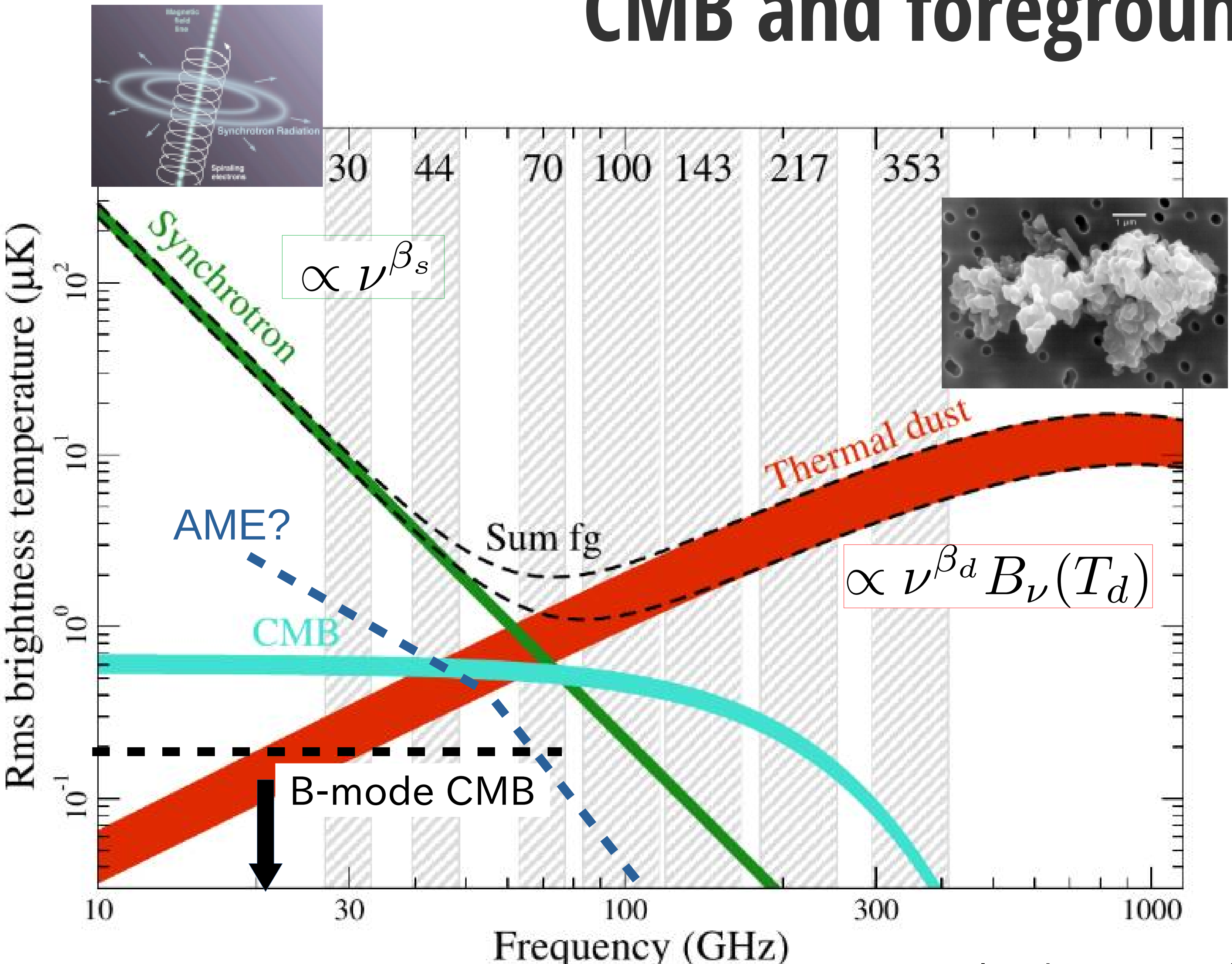

**= Effective noise 5 muK arcmin**

**r=0.001 B-mode**

$\ell \lesssim 10$


DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
ACTPol
BK14
SPTpol
POLARBEAR
Simons Array
LiteBIRD
r=0.01
inflation GWs
gravitational lensing
= Effective noise
5 muK arcmin
Foregrounds
@100GHz
l(l+1)C_l^BB/(2π) (μK^2)
Multipole Moment, ell
10
100
1000
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6

# CMB and foregrounds



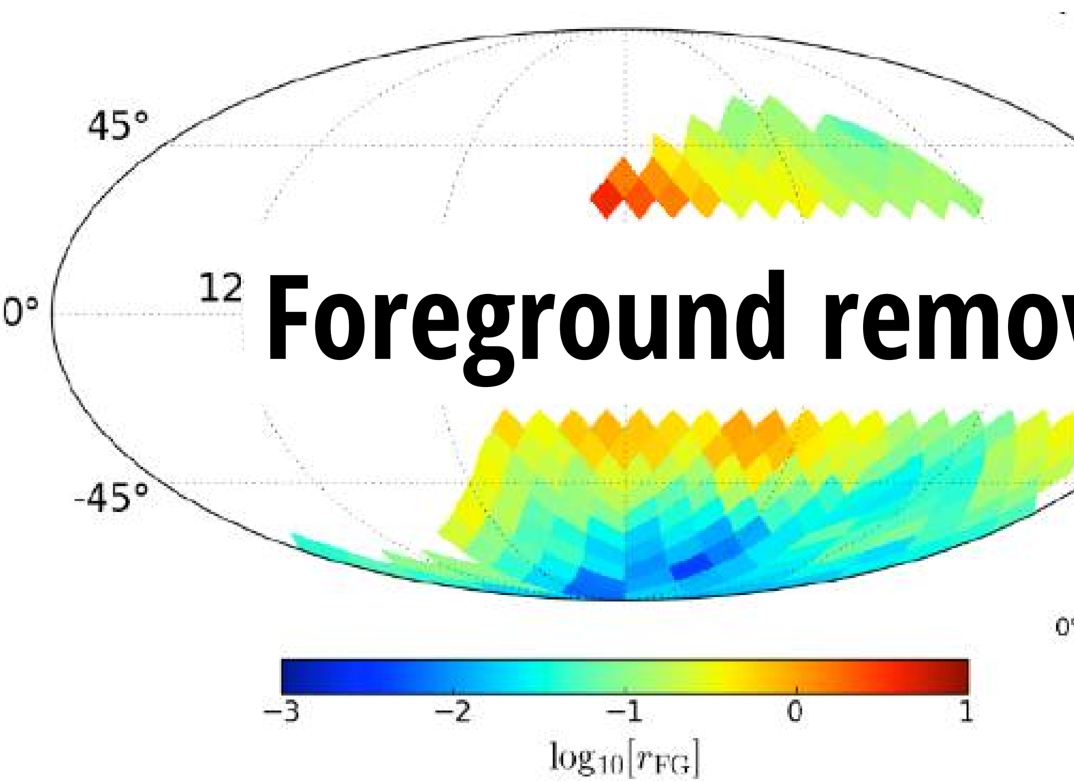


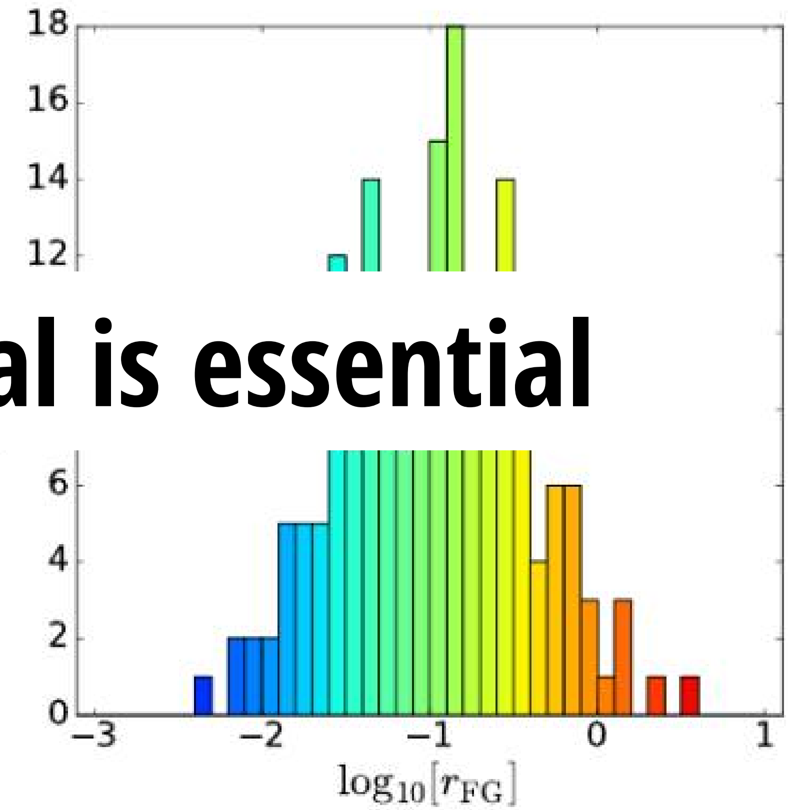

Planck 2015 results. X

# A 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



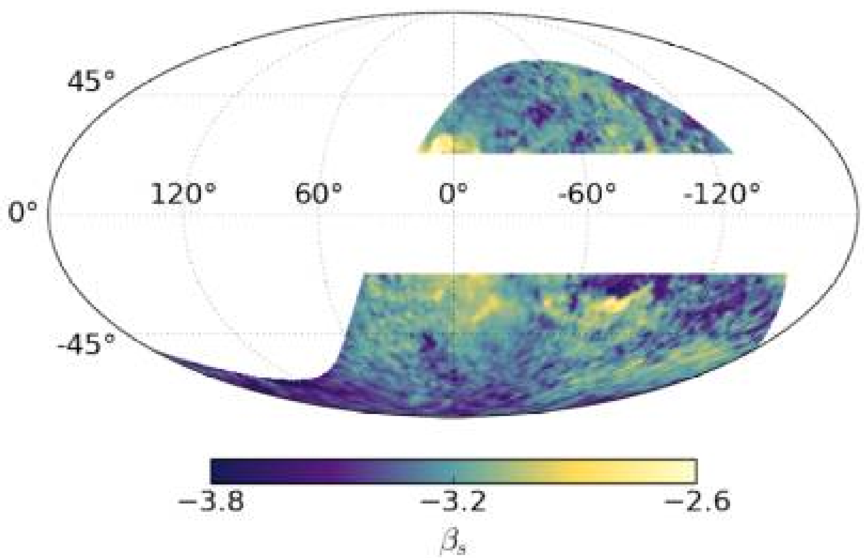

**Foreground removal is essential**

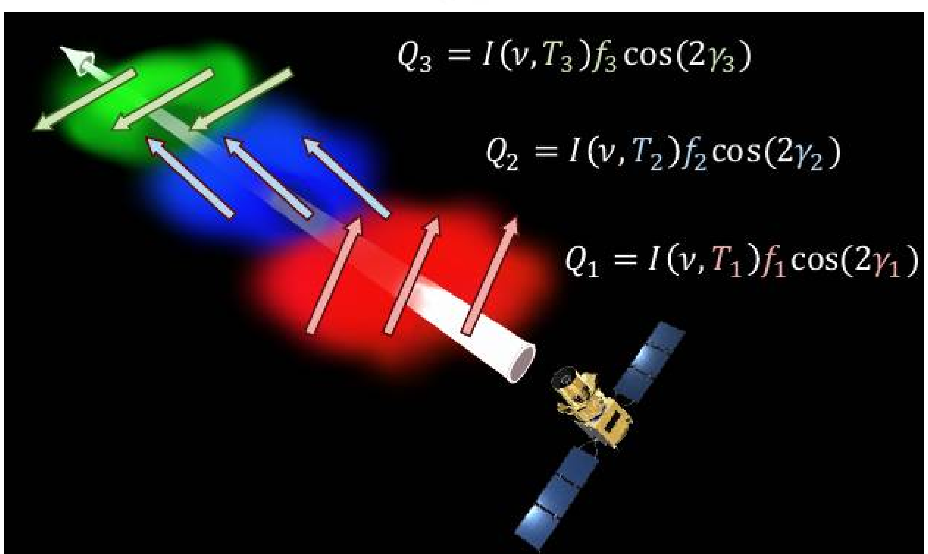


Krachmalnicoff+, arxiv: 1802.01145

# From KK2011 to Deltamap (Katayama & Komatsu, ApJ, '11)

S-PASS (Krachmalnicoff+, arxiv: 1802.01145)




**Three Issues**

**1. varying spectral parameters**

Internal template had to assume that spectral parameters are uniform over the full sky

(e.g. Katayama&Komatsu, ApJ, 2011)

**2. De-correlation effect**

(e.g., Tassis+, MNRAS, '15)

**3. unknown AME component**

**We resolve these issues**

(ICHIKI+, PTEP, '19)

# Results (KI+, PTEP, '19)

Work in Nside=4 resolution

6 or 7 bands used

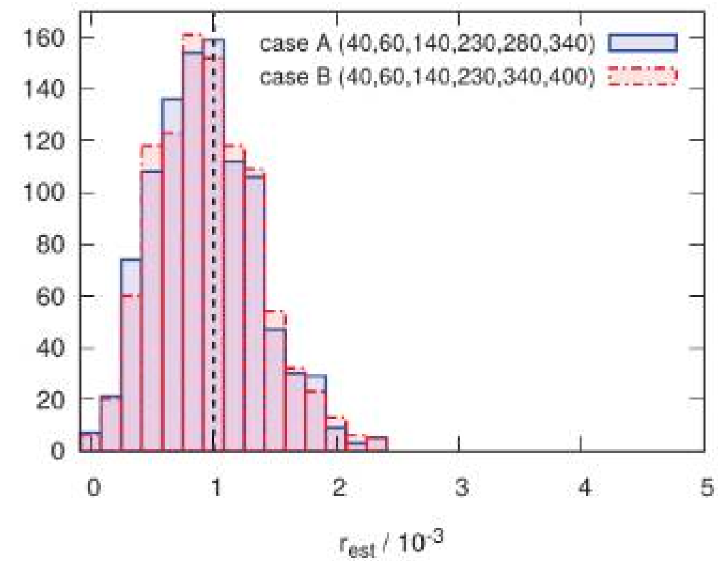
# of parameters = 4 $(r, \bar{\beta}_{\rm s}, \bar{\beta}_{\rm d}, \bar{T}_{\rm d})$

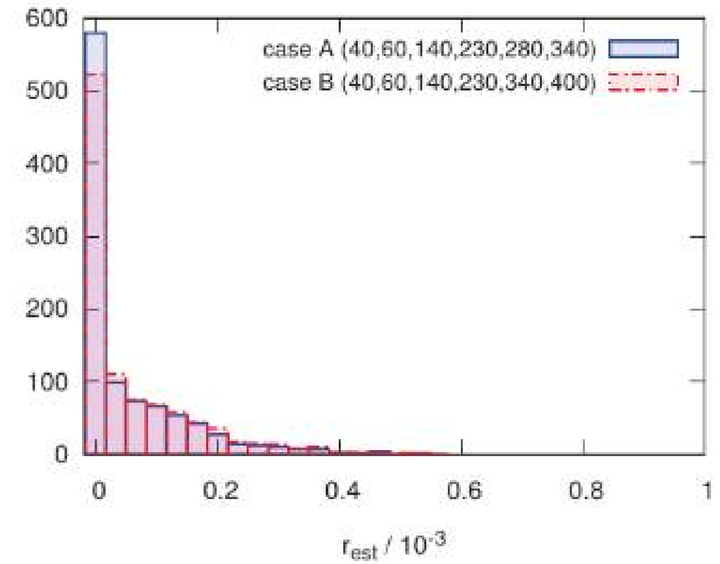
## Appealing points

- **internal & simple**
- **accounting for spatially varying foreground params to 1st order**
- **AME is supported**
- **decorrelation is supported**
- **unbiased**

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

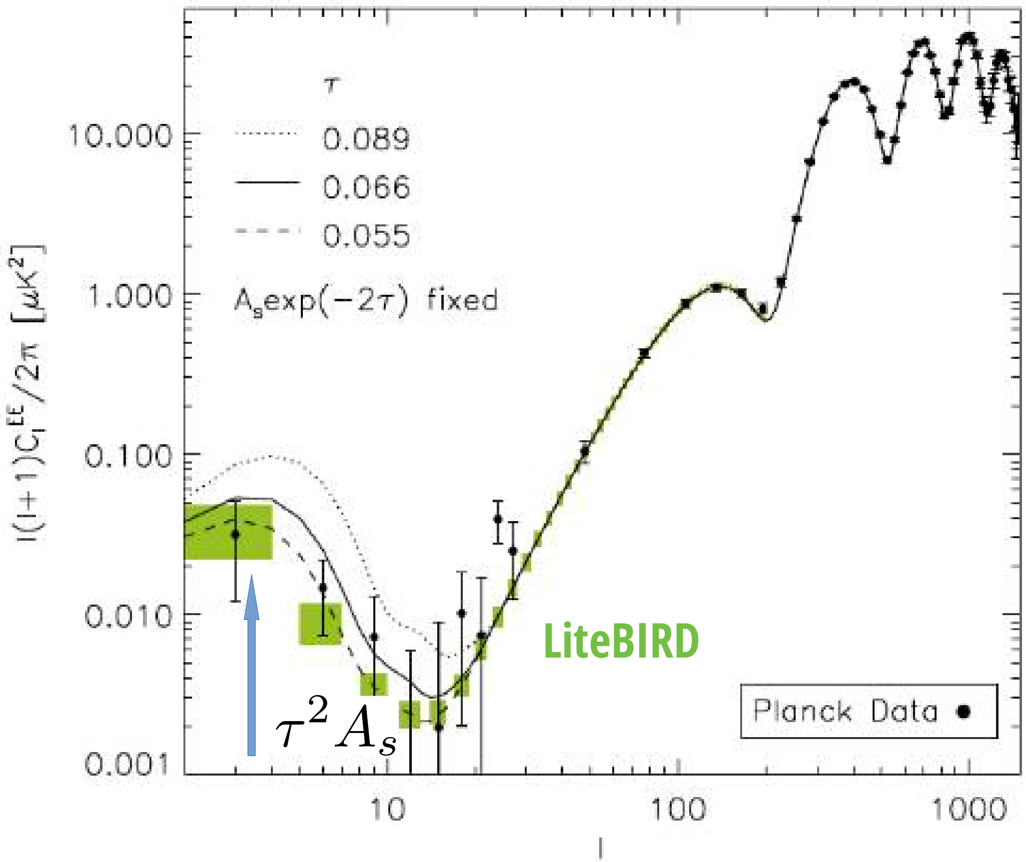
$$\sigma(r) \simeq 0.2 \times 10^{-3} \text{ (noiseless)}$$

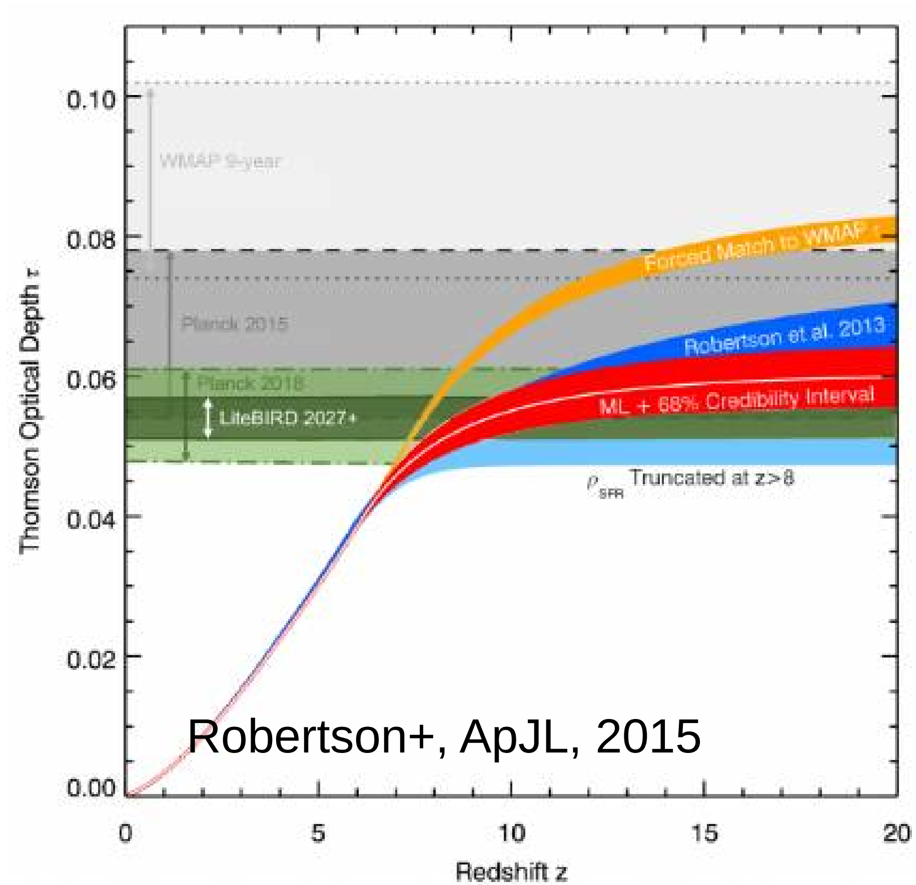


# Even if no GWs were detected

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

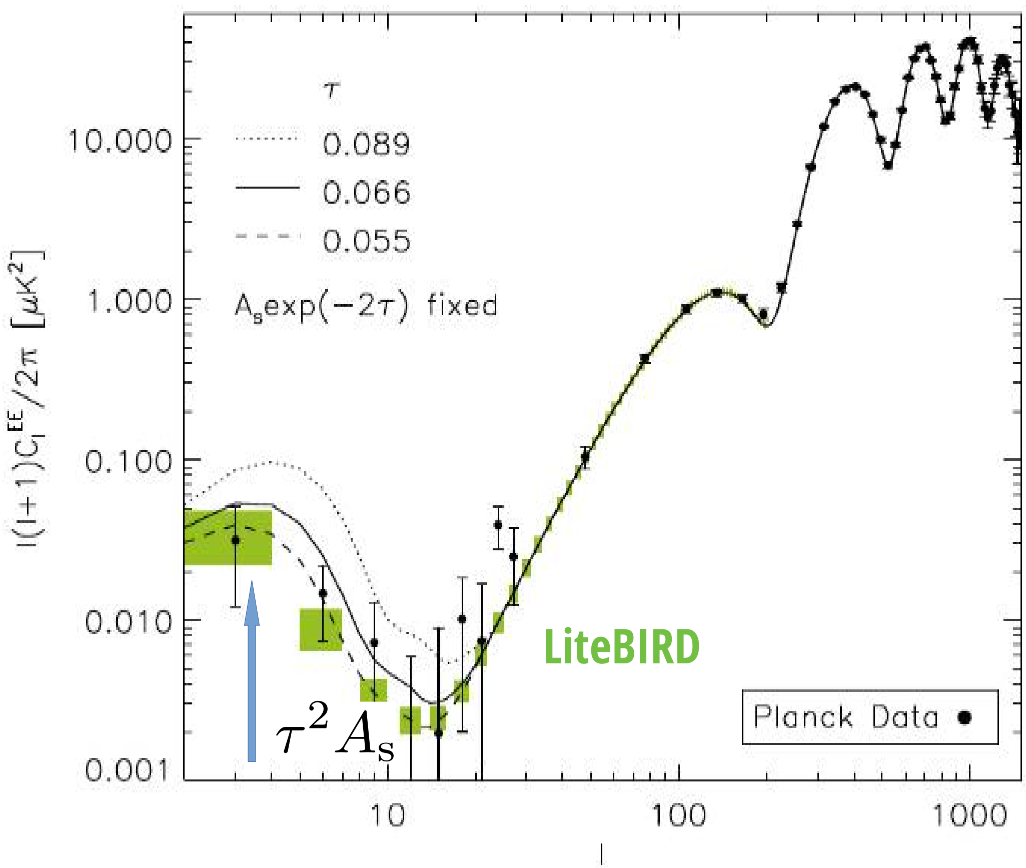


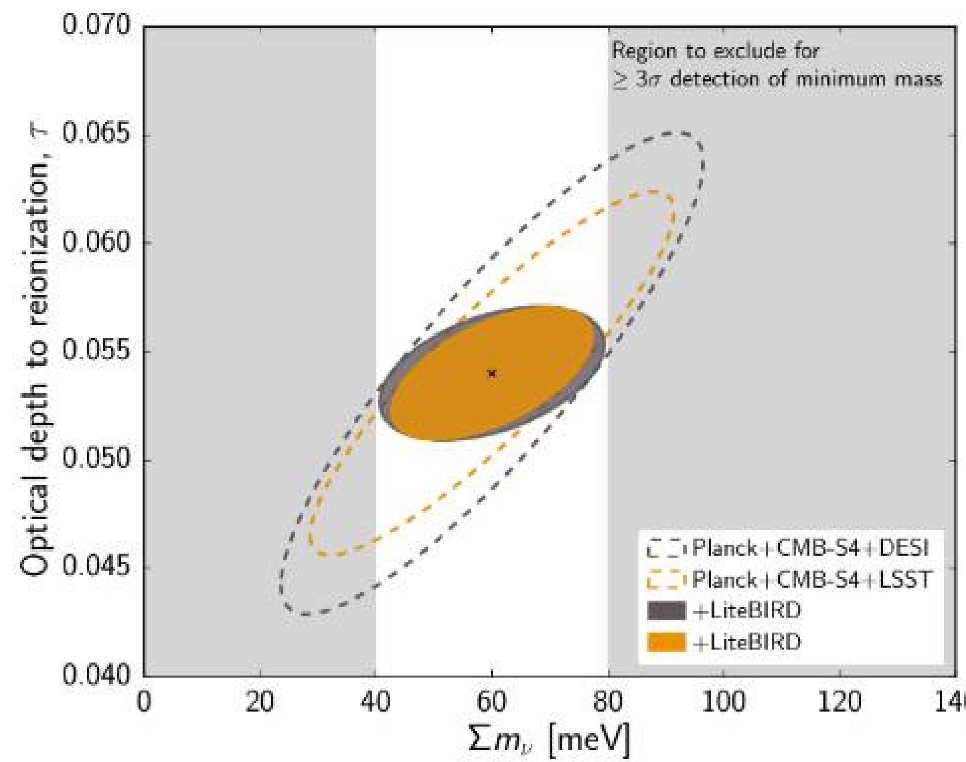




$\sigma(\tau) \approx 0.007$ (planck) → $\sigma(\tau) \approx 0.002$ (LB)

# Even if no GWs were detected

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



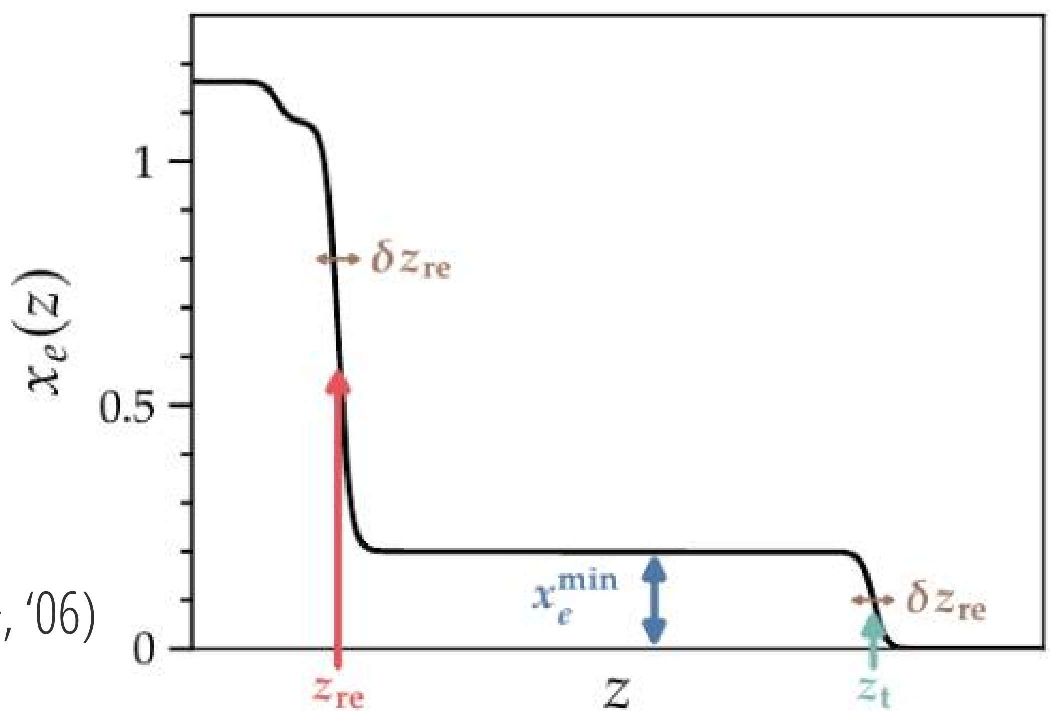

**Breaking degeneracy between** $\tau$ **and** $A_s$ → $5\sigma$ **detection of neutrino mass**



**"Science from LiteBIRD" , Bucher,Komatsu,Hazumi et al., See also Calabrese+, PRD, '16**

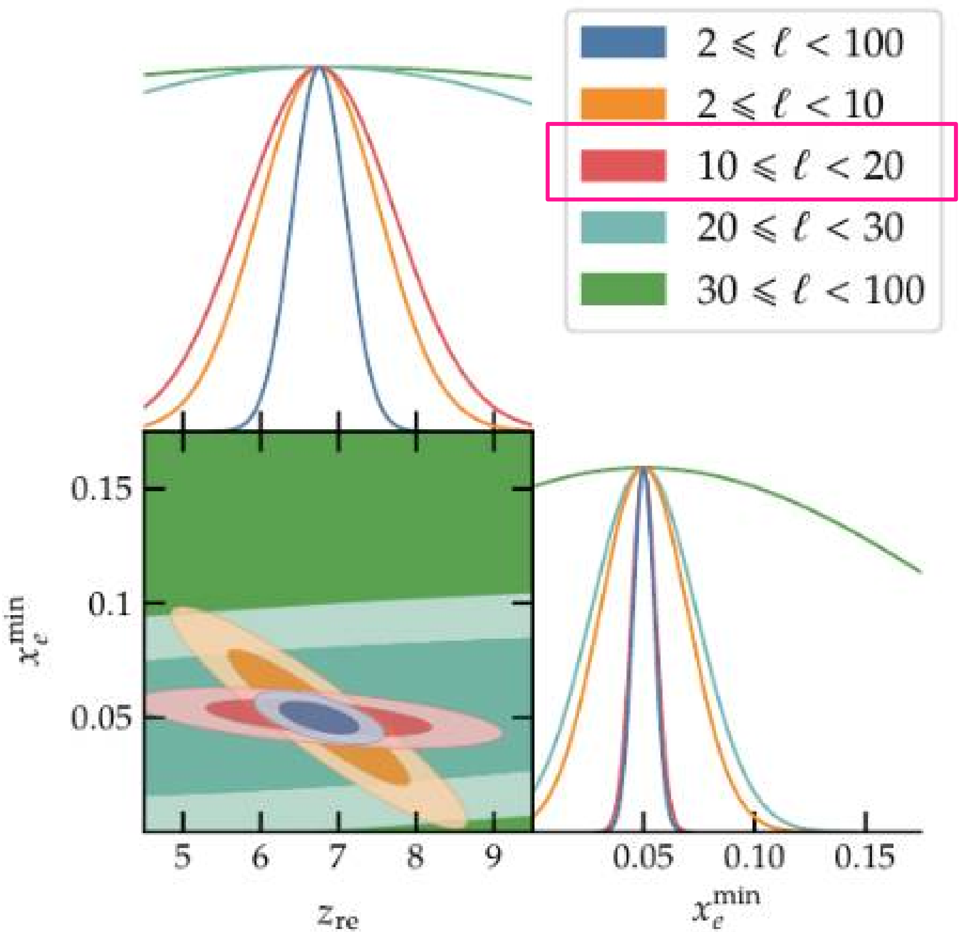
# Optical depth and beyond

- In most CMB analyses, one usually assumes a tanh-like reionization history with a single reionization redshift $z_{re}$ and $dz_{re}$ (=0.5)
- In Watts+ (1910.00590), the authors investigate how the future large-scale E-mode polarization can constrain $x_e(z)$ (Millea&Bouchet, '18)
- Significant $x_e^{min}$ can be expected e.g., from
  - PopIII BBH (Inayoshi+, '16)
  - QSOs (Ewall-Wice+, '18)
  - annihilating particles(Mapelli+, '06)

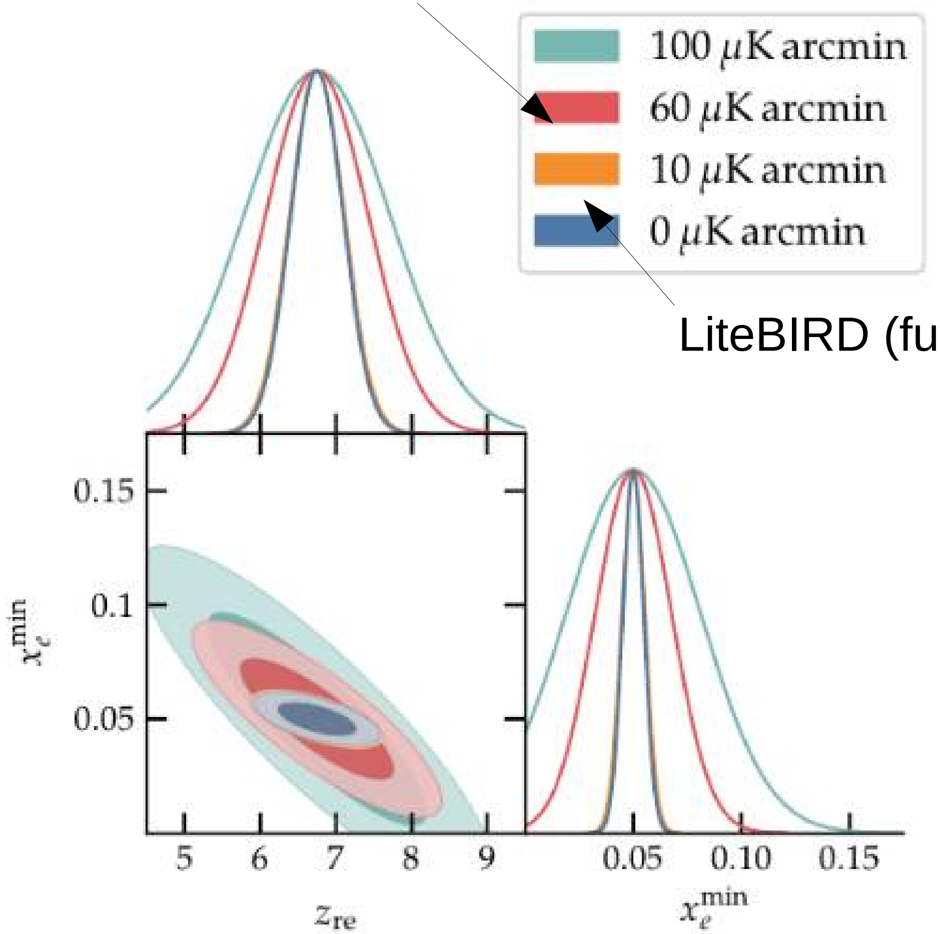


# Future constraints on xe(z) (Watts+,1910.00590)

only from Large-scale E-mode polarization



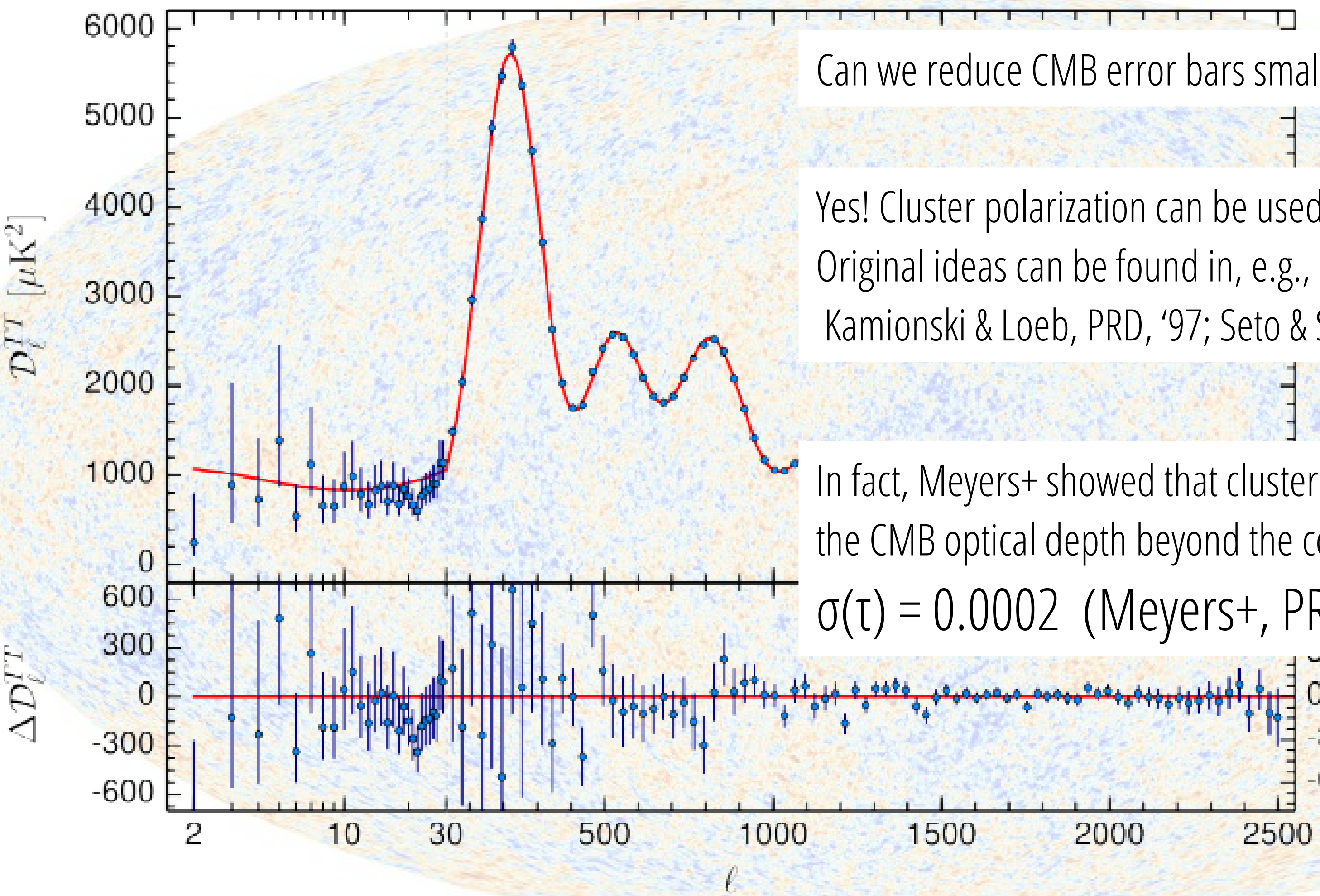

CLASS (on-going) after fore. removal




LiteBIRD (future)

$\sigma(z_{\rm re}) = 0.3$ $\sigma(x_e^{\rm min}) = 0.005$

# Further precision cosmology using CMB polarization



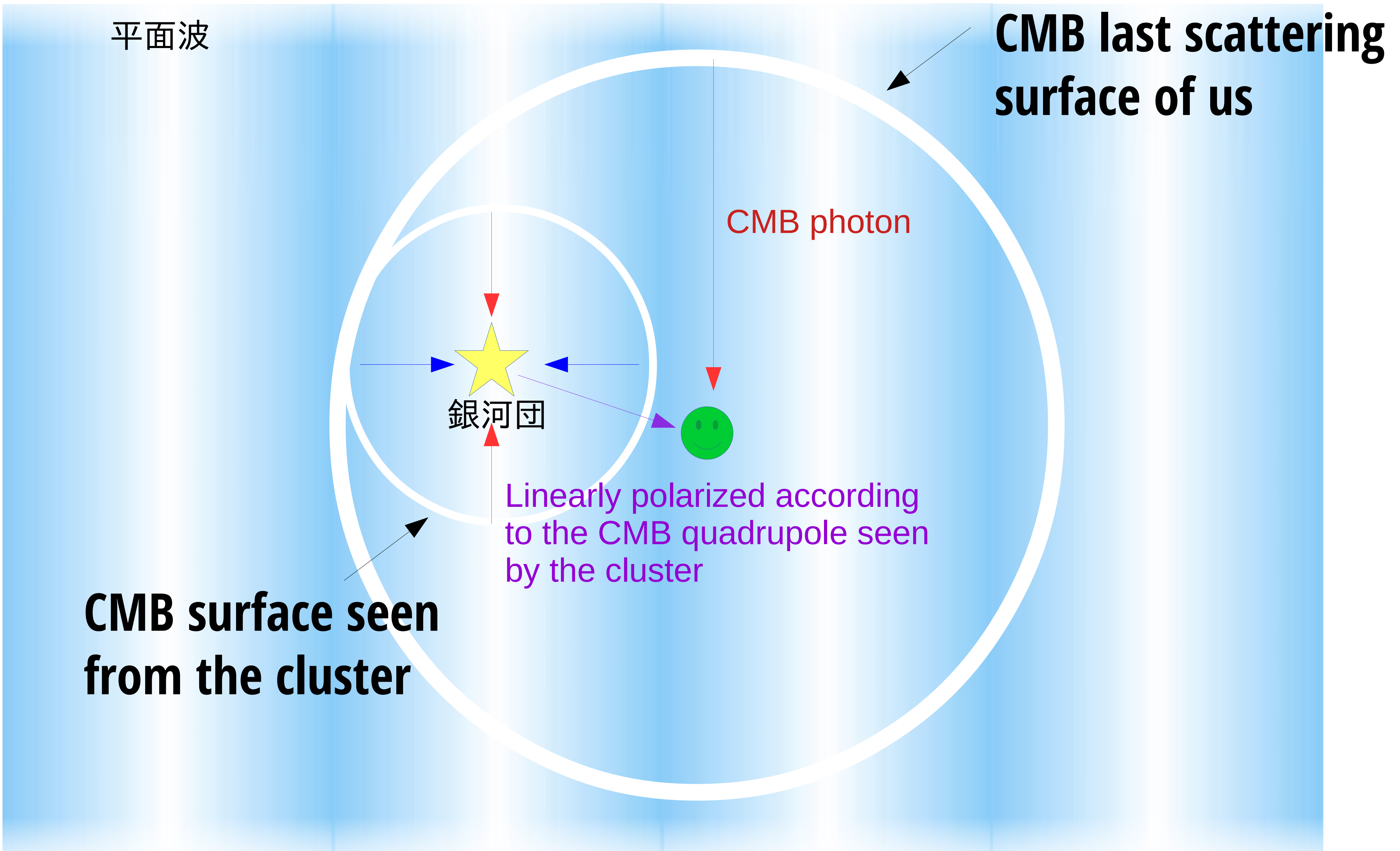

Can we reduce CMB error bars smaller than the cosmic variance?

Yes! Cluster polarization can be used to reduce the cosmic variance
Original ideas can be found in, e.g.,
Kamionski & Loeb, PRD, '97; Seto & Sasaki, PRD, '00

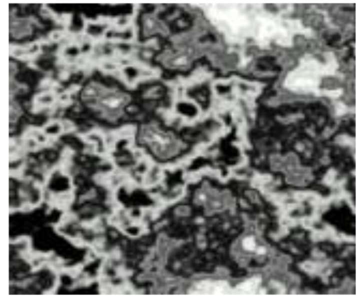
In fact, Meyers+ showed that cluster polarization can be used to constrain the CMB optical depth beyond the cosmic variance to reach

$\sigma(\tau) = 0.0002$ (Meyers+, PRD, '18)

# Kamionkowski & Loeb method

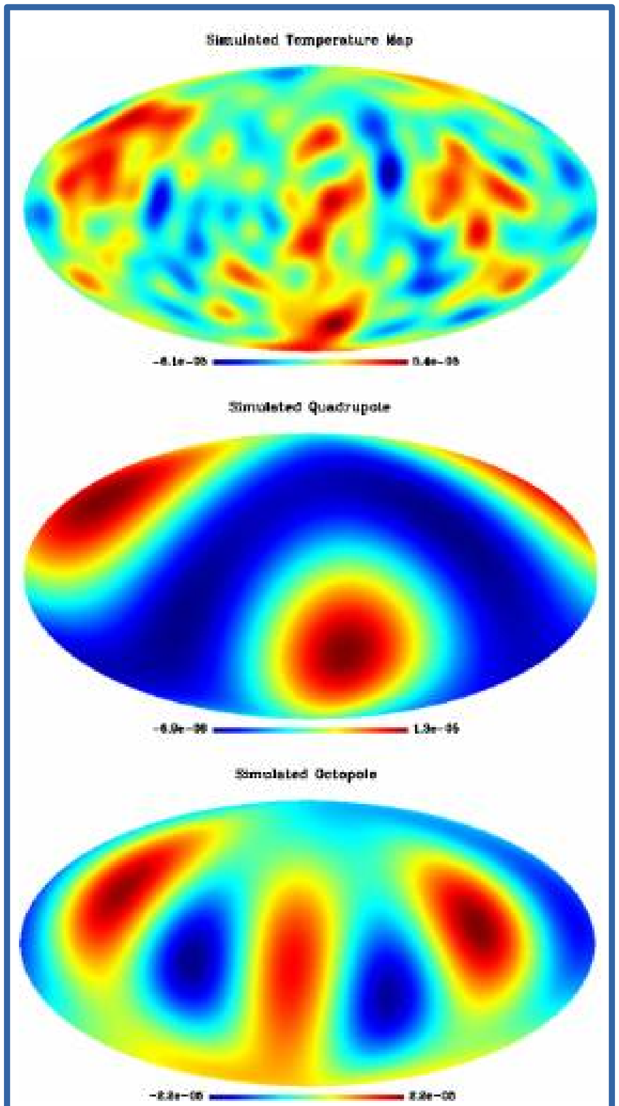


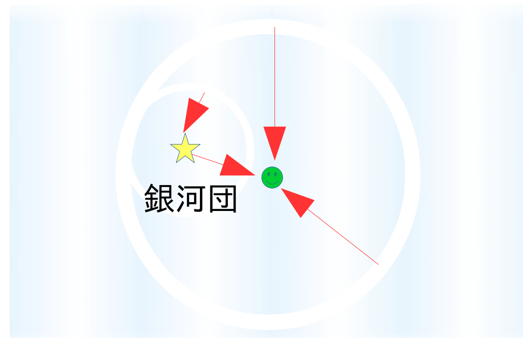
Liu, KI, Tashiro, Sugiyama, MNRAS Letter, ‘16



**3D Initial density fluctuation**

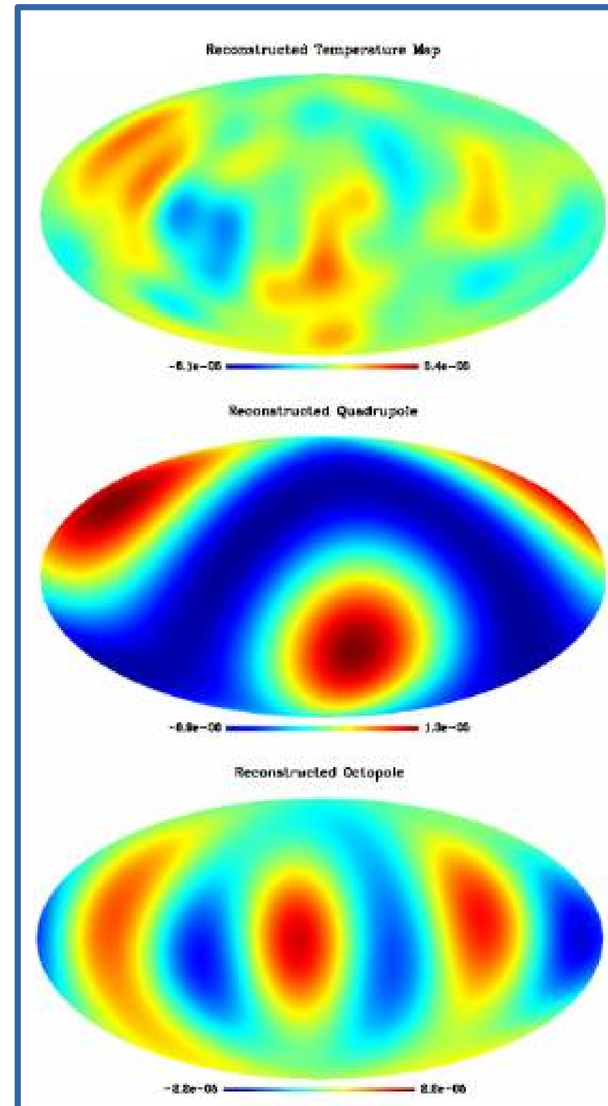
**Direct CMB observation**



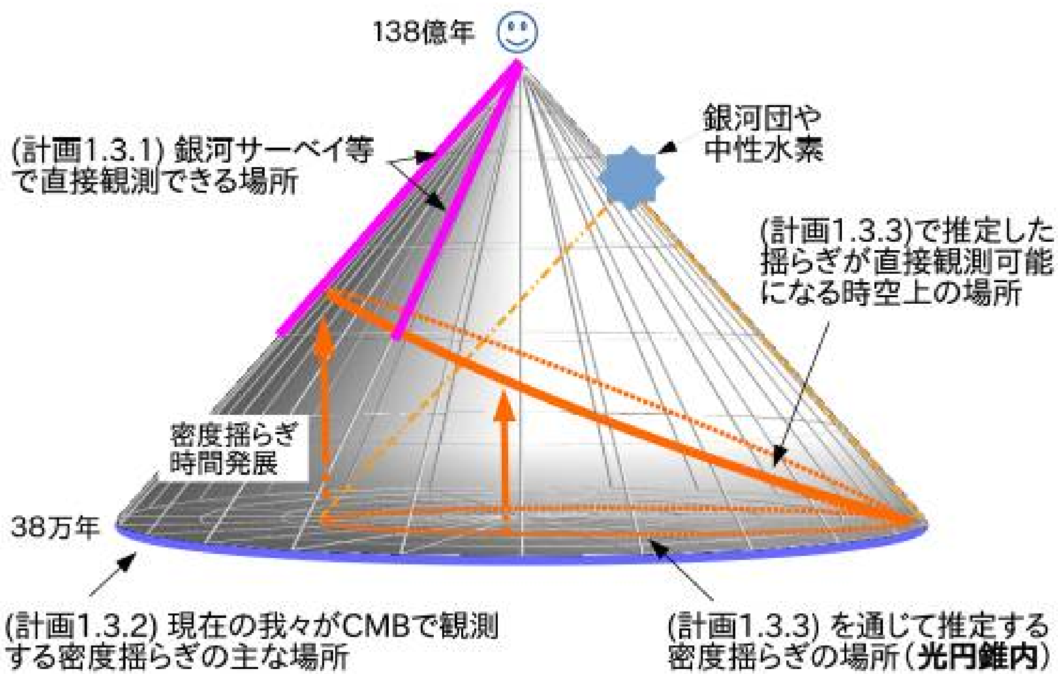




***predict*** **by using remote quadrupole**

We showed that CMB polarization at distant clusters can be used to predict the CMB sky viewed by us!



# Measure cosmological density field twice




Remote quadrupole can be reconstructed by cluster CMB polarizations (K&L, PRD,'97) and 21cm circular polarization (Hirata+, PRD, '18)

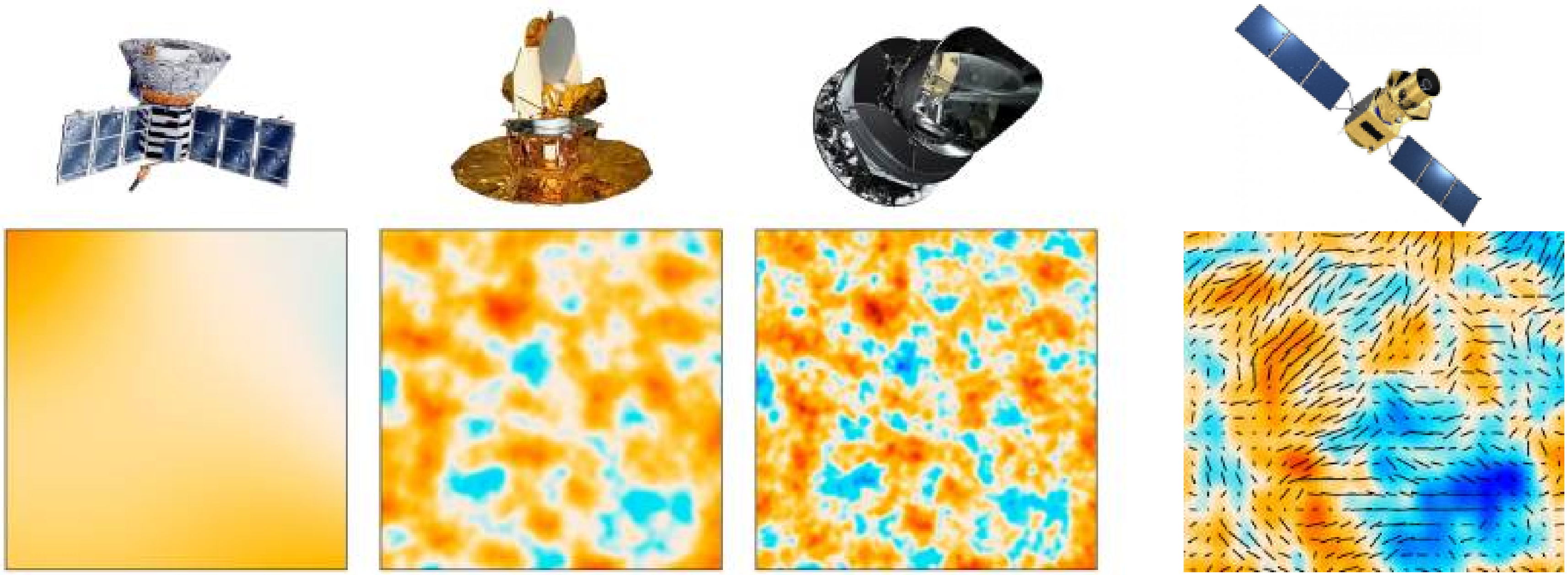
The quadrupole evolve in time and cross our light-cone, and hence it can be directly observed at different redshifts from place to place.

We may be able to observe the same place twice **to beat the cosmic variance** (under investigation)

# summary

- Large-scale E-mode polarization is a clear signature of cosmic reionization
- LiteBIRD is a CMB satellite that aims to detect inflationary GWs with $r>10^{-3}$ and has been selected by JAXA as strategic large mission
- A cosmic variance limited E-mode measurement on large scales will be a legacy for LiteBIRD, giving a detection of neutrino mass with $\sigma(\tau) \approx 0.002$
- Our new internal template foreground removal method supports spatially varying foreground spectra, AME, and dust de-correlation
- Cluster CMB polarization measurements may enable us to observe the density field twice to beat the cosmic variance

# CMB satellites and telescopes



COBE | WMAP | Planck | LiteBIRD

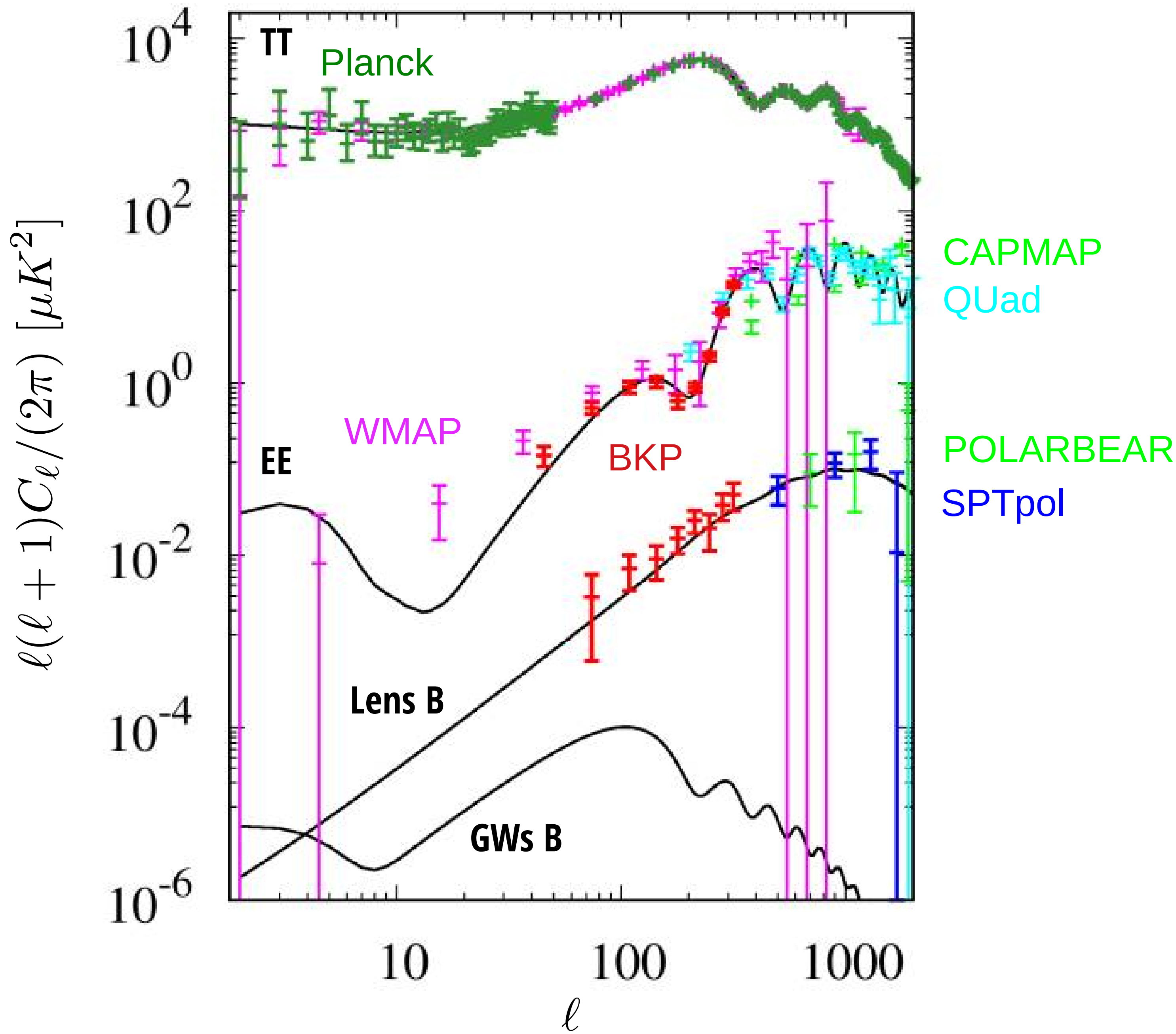
1990s | 2000s | 2010s | 2020s

**Perfect B.B. confirmed**
**large scale fluctuation**

**Clear detection of**
**acoustic peaks**
**LCDM model confirmed**

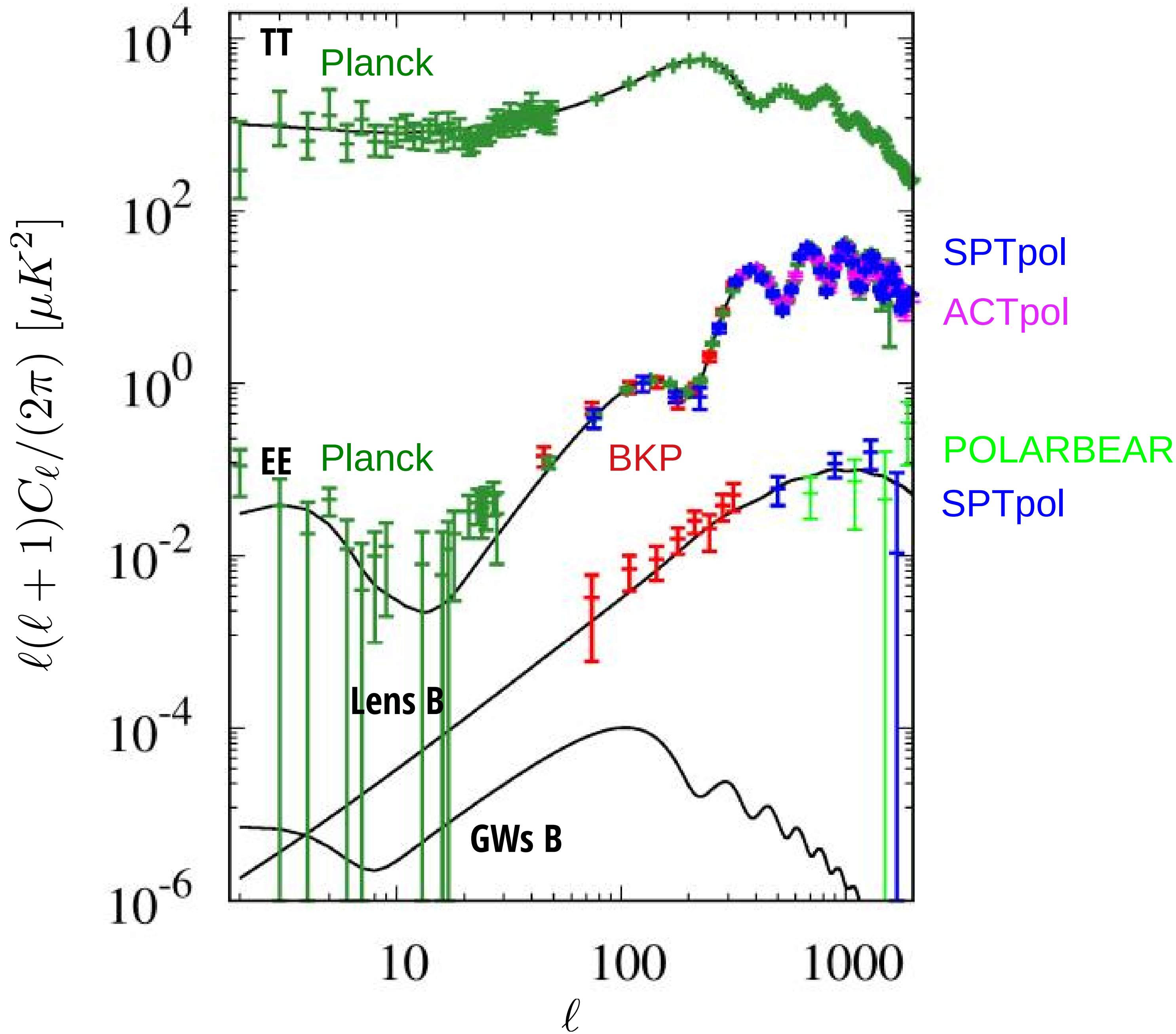
**Finer angular resolution (x3)**
**→ more info. (x9)**
**large scale E-mode**

# 2015

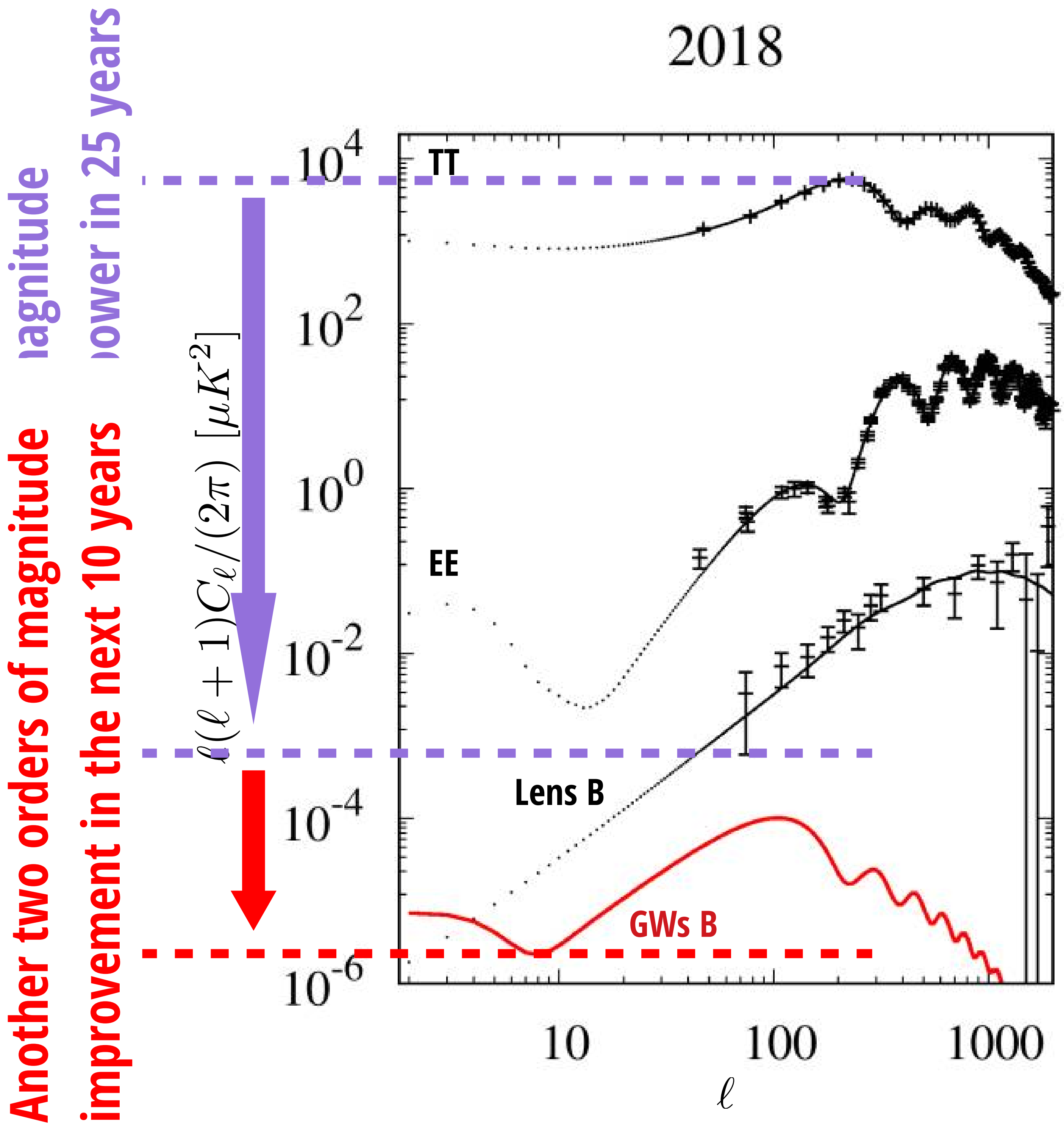


TT
Planck
EE
WMAP
BKP
Lens B
GWs B
CAPMAP
QUad
POLARBEAR
SPTpol
$10^4$
$10^2$
$10^0$
$10^{-2}$
$10^{-4}$
$10^{-6}$
10
100
1000
$\ell$
$\ell(\ell+1)C_\ell/(2\pi)\ [\mu K^2]$

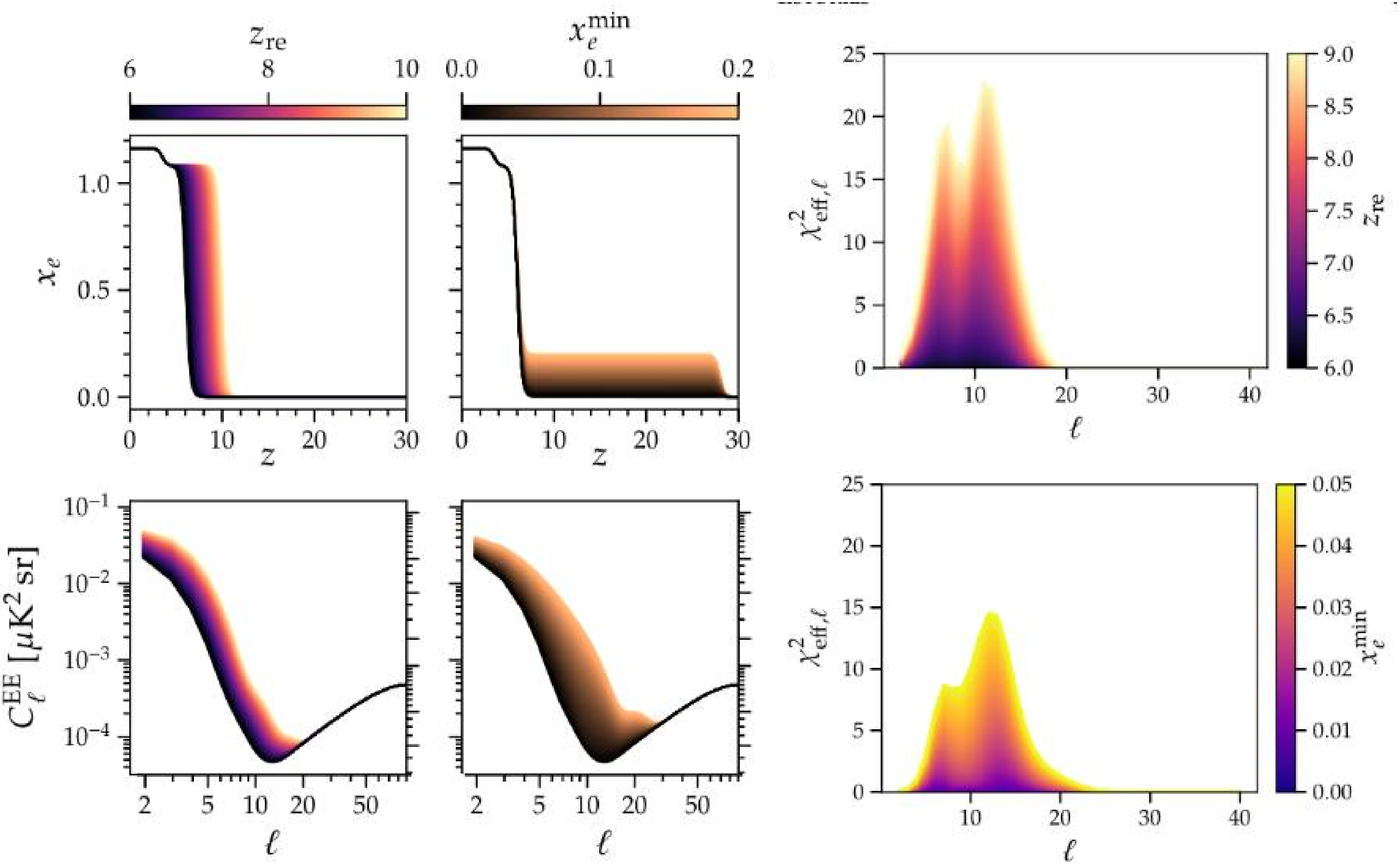
# 2018



TT
Planck
EE
Planck
BKP
SPTpol
ACTpol
POLARBEAR
SPTpol
Lens B
GWs B
$10^4$
$10^2$
$10^0$
$10^{-2}$
$10^{-4}$
$10^{-6}$
10
100
1000
$\ell$
$\ell(\ell+1)C_\ell/(2\pi)\ [\mu K^2]$


2018
TT
EE
Lens B
GWs B
$10^4$
$10^2$
$10^0$
$10^{-2}$
$10^{-4}$
$10^{-6}$
10
100
1000
$\ell$
$\ell(\ell+1)C_\ell/(2\pi)\ [\mu K^2]$
agnitude
ower in 25 years
Another two orders of magnitude
improvement in the next 10 years

# Optical depth and beyond



# S-PASS results

The S-PASS experiment has observed synchrotron emission of our galaxy, and determined synchrotron spectral index

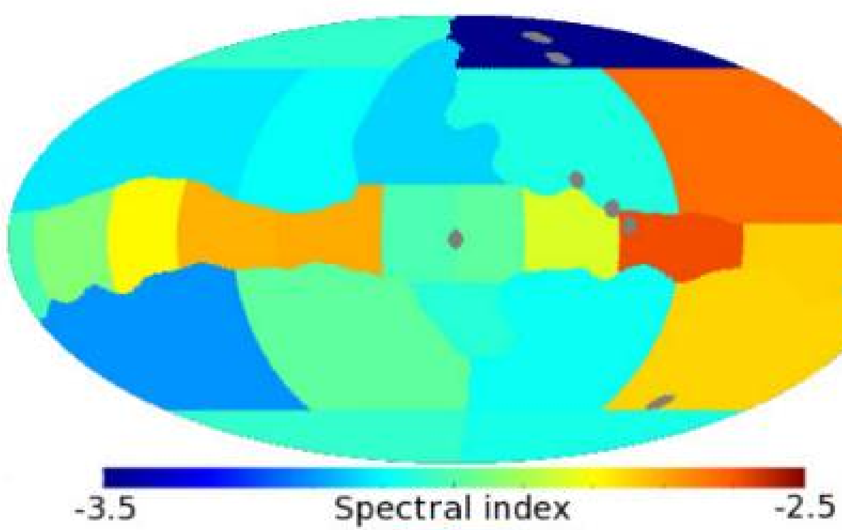
**Parkes 64m (2.3GHz)**

**FWHM = 9’**

**$\sigma_{beam}$ = 1muK**

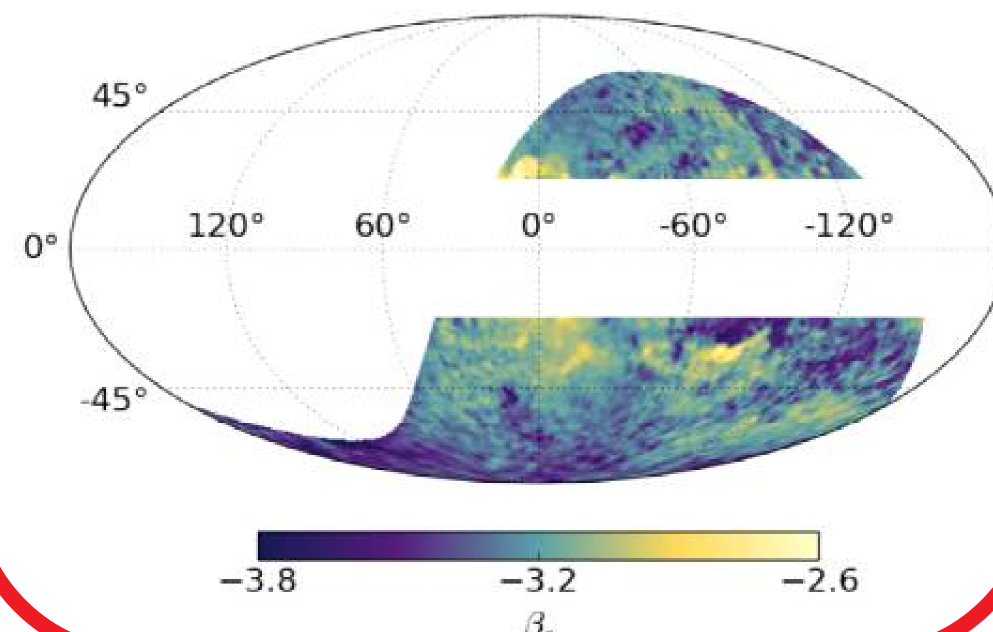
WMAP 9yr

Fuskeland+, ApJ 2014




S-PASS

Krachmalnicoff+, arxiv: 1802.01145



# Delta-map method

$$Q^{\rm synch}(\nu,\hat{n}) = g_\nu \left(\frac{\nu}{\nu_*}\right)^{\beta_{\rm s}(\hat{n})} Q^{\rm synch}(\nu_*,\hat{n})$$

$$\beta_{\rm s}(\hat{n}) = \bar{\beta}_{\rm s} + \delta\beta_{\rm s}(\hat{n}) + C(\hat{n})\ln(\nu/\nu_*)$$ **(Taylor expansion)**

$$Q^{\rm total}(\nu,\hat{n}) \approx {\rm CMB}(\hat{n}) + g_\nu \left(\frac{\nu}{\nu_*}\right)^{\bar{\beta}_{\rm s}} \left[Q^{\rm synch}(\nu_*,\hat{n}) + \ln\left(\frac{\nu}{\nu_*}\right)\delta\beta_s(\hat{n})Q^{\rm synch}(\nu_*,\hat{n}) + \left[\ln\left(\frac{\nu}{\nu_*}\right)\right]^2 C(\hat{n})Q^{\rm synch}(\nu_*,\hat{n})\right]$$

**Delta-map:** two new "foreground maps"

$\delta\beta_s(\hat{n})Q^{\rm synch}(\nu_*,\hat{n})$ & $C(\hat{n})Q^{\rm synch}(\nu_*,\hat{n})$

from spatial variation of spectal parameters, whose frequency dependence does not depend on sky direction.

Now we can remove them by linearly combining different frequency maps

**Synchrotron running:**

**→ absorb AME**

# Let's talk about de-correlation

We show that the multiple dust clouds with different temperatures can be treated
as if Q and U had slightly different dust temperature:

$$Q_\nu = \sum_i Q_{\nu,i} = g_\nu \sum_i I_{d,\nu}(T_{d,i})\Pi_i \cos(2\gamma_i)$$

$$\simeq g_\nu I_{d,\nu}(\bar{T}_d) \underbrace{\sum_i \Pi_i \cos(2\gamma_i)}_{\equiv A} \left(1 + \frac{x_d e^{x_d}}{e^{x_d}-1}\delta_i + \cdots\right) \qquad \text{where } T_{d,i} = \bar{T}_d(1+\delta_i)$$

$$\simeq g_\nu I_{d,\nu}(\bar{T}_d) A \left[1 + \frac{x_d e^{x_d}}{e^{x_d}-1} \underbrace{\frac{\sum_i \delta_i \Pi_i \cos(2\gamma_i)}{A}}_{\equiv \delta_Q}\right] \simeq g_\nu I_{d,\nu}(\bar{T}_d(1+\delta_Q))A$$

(one dust cloud)

Similarly, $U_\nu = g_\nu \sum_i I_{d,\nu}(T_d, i)\Pi_i \sin(2\gamma_i) \simeq g_\nu I_{d,\nu}(\bar{T}_d(1+\delta_U))B$

$$Q_\nu = g_\nu I_{d,\nu}(T_Q)\Pi \cos(2\gamma)$$
$$U_\nu = g_\nu I_{d,\nu}(T_U)\Pi \sin(2\gamma)$$

**Our recipe:** $(r, \bar{\beta}_\mathrm{s}, \bar{\beta}_\mathrm{d}, \bar{T}_\mathrm{d}) \rightarrow (r, \bar{\beta}_\mathrm{s}, \bar{\beta}_\mathrm{d}^\mathrm{Q}, \bar{T}_\mathrm{d}^\mathrm{Q}, \bar{\beta}_\mathrm{d}^\mathrm{U}, \bar{T}_\mathrm{d}^\mathrm{U})$

# Meyers+, PRD, '18