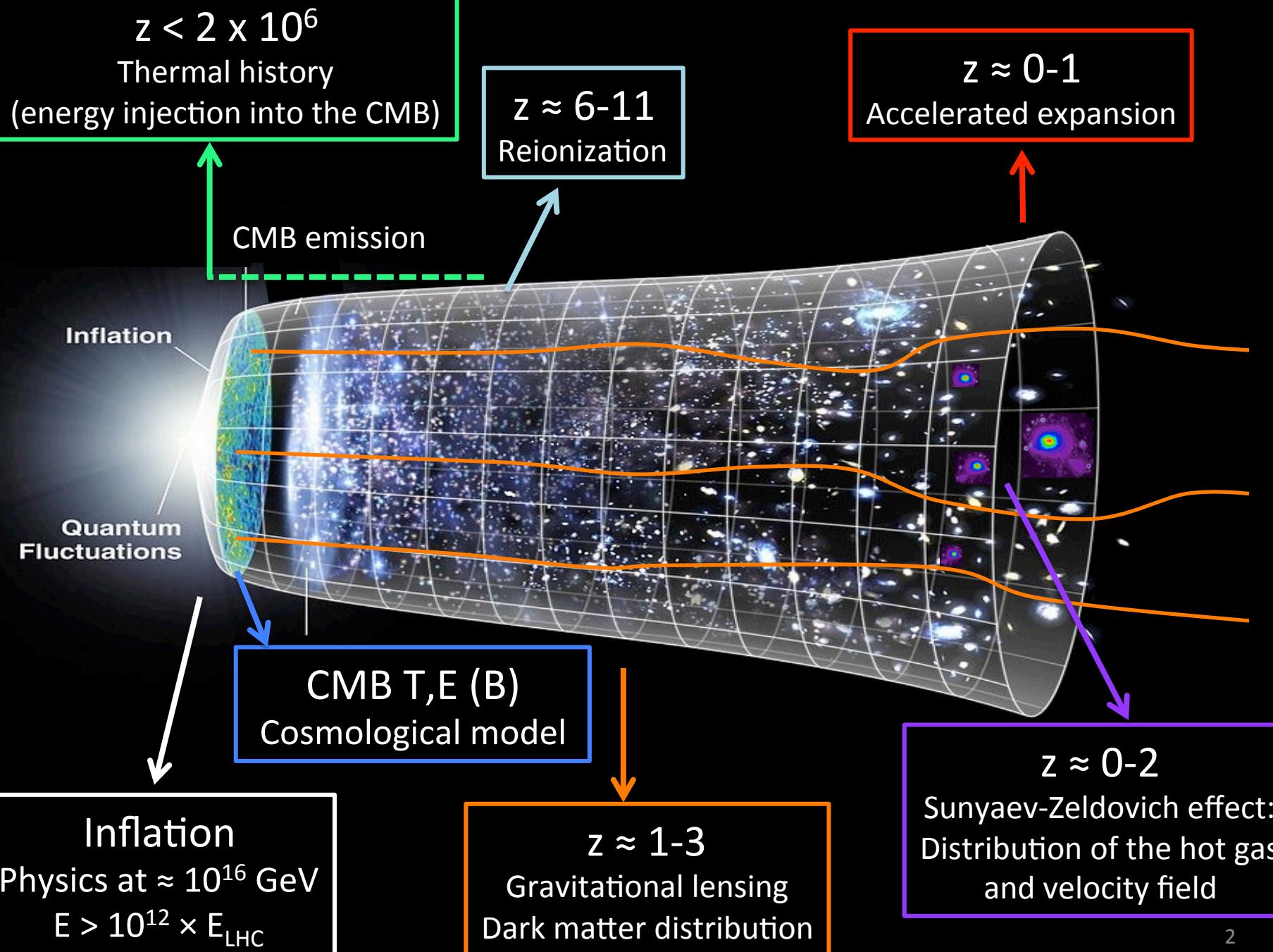


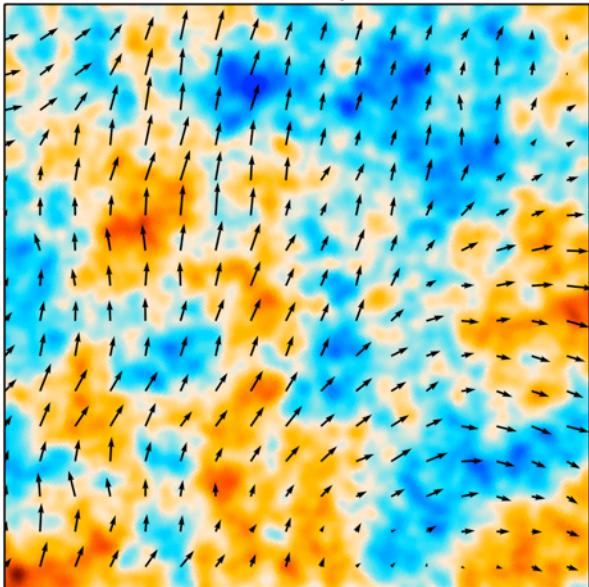
# Future CMB Projects

*Jacques Delabrouille*

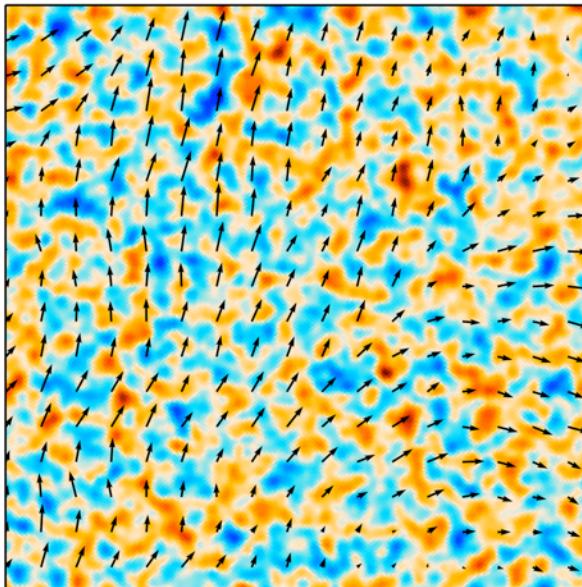
*Laboratoire APC, Paris*



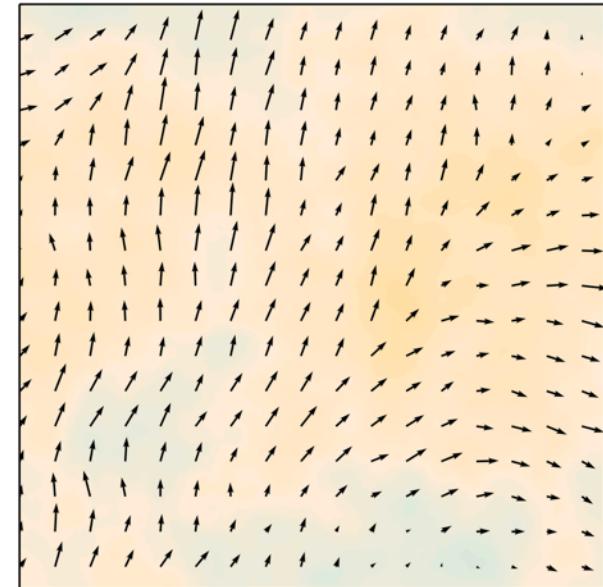
Unlensed Temperature



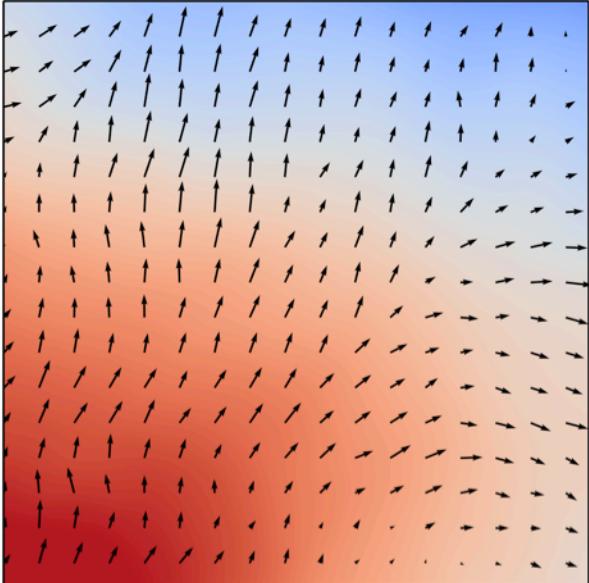
Unlensed E-Modes



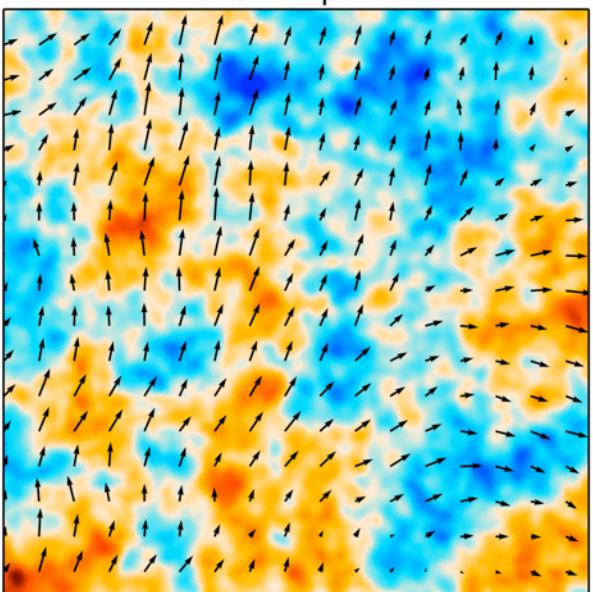
Unlensed B-Modes

 $r = 0.01$ 

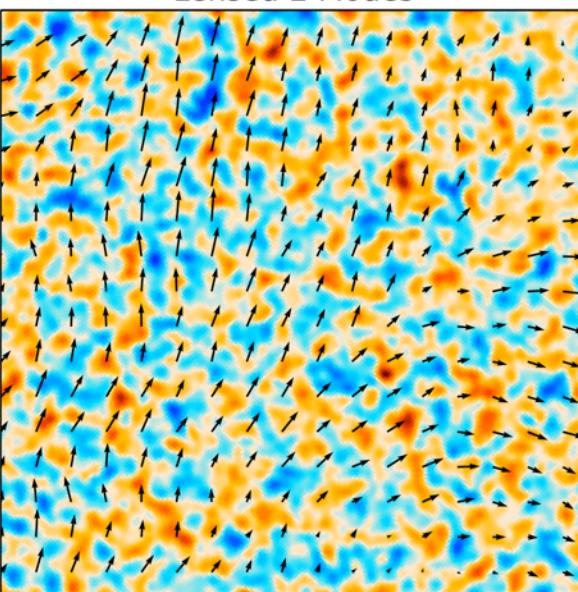
Lensing Potential



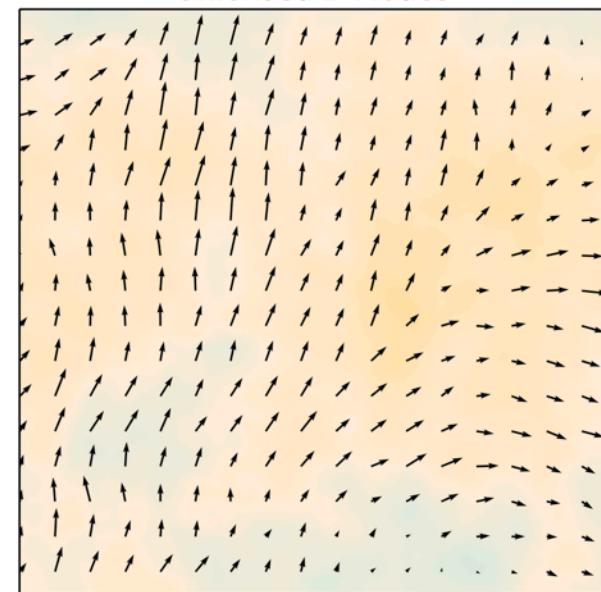
Lensed Temperature



Lensed E-Modes



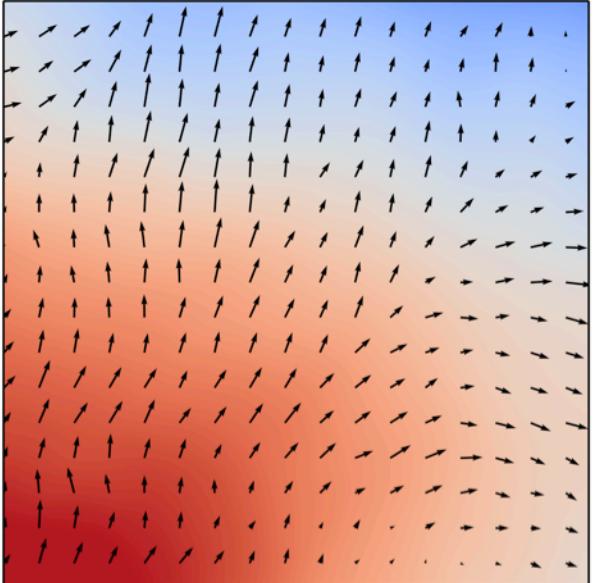
Unlensed B-Modes



$r = 0.01$

-400  $\mu\text{K}$                           400  $\mu\text{K}$

Lensing Potential

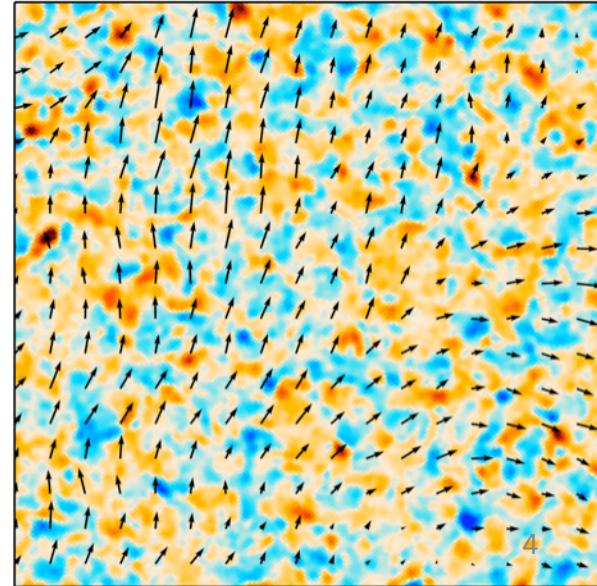


-25  $\mu\text{K}$                           25  $\mu\text{K}$

Gravitational lensing  
of the CMB

-1.8  $\mu\text{K}$                           1.8  $\mu\text{K}$

Lensed B-Modes



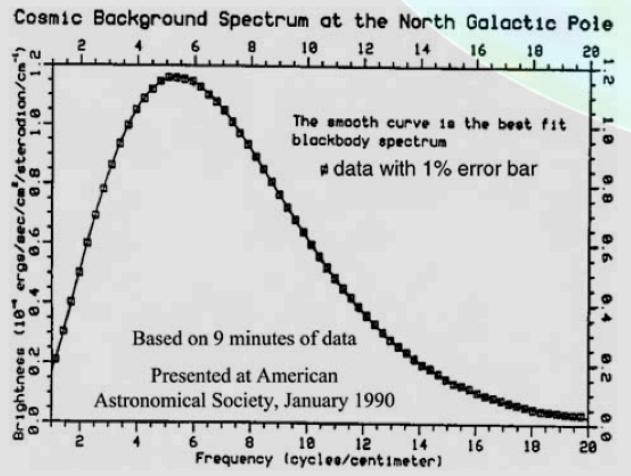
# Outline

- 
- Where are we? What next?
  - Challenges
  - Experiments
  - A strategy for the future
  - Summary



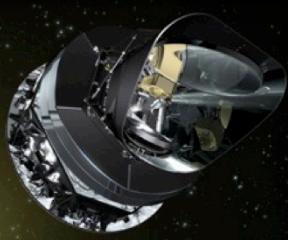
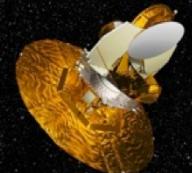
Cobe 1992

## FIRAS



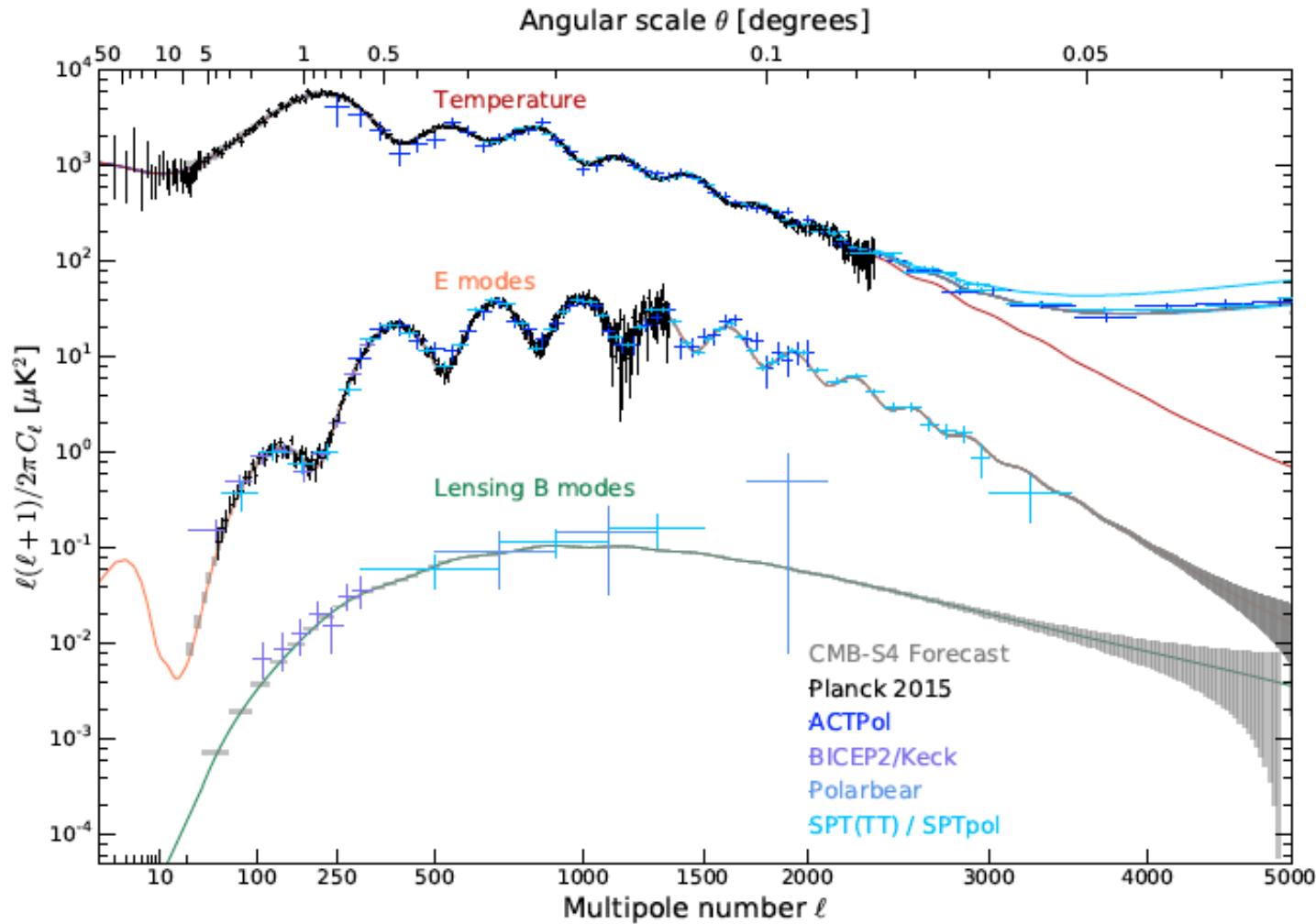
WMAP 2003

Planck 2013



# The CMB: state of the art

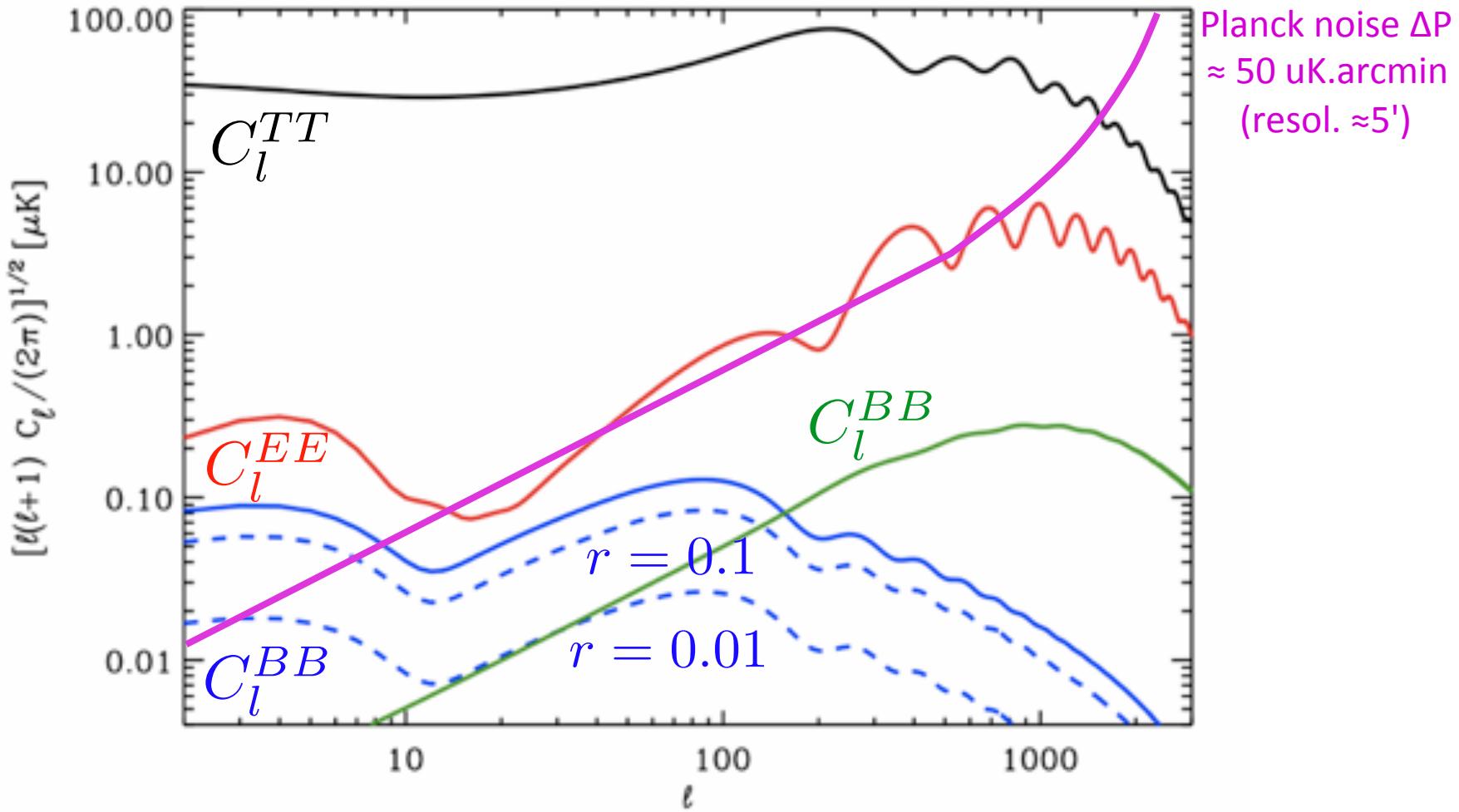
CMB-S4 collaboration arXiv:1610.02743



# The CMB: state of the art

- The CMB "sets the stage" for precision cosmology with  $\Lambda$ CDM
- The reference for CMB observations today comes from
  - COBE/FIRAS (blackbody spectrum at  $l=0$ )
  - the Planck space mission ( $T$  for  $1 < l < 2500$ ,  $E$  for  $2 < l < 1000$ )
  - SPT/SPTPol and ACTPol ( $T$  for  $l > 2500$ ,  $E$  for  $l > 1000$ )
  - SPTPol and Polarbear ( $B$  for  $l > 300$ )
  - BICEP2/Keck array ( $B$  for  $l < 300$ )
- Ground-based experiments so far have observed relatively small patches of sky (e.g. from  $\approx 1\%$  to  $6\%$ );
  - SPT: 2,500 sq. deg. with  $1.2'$  beam and  $\Delta T = 18 \mu\text{K.arcmin}$
  - ACT: 600 sq. deg. with  $1.3'$  beam and  $\Delta T = 17 \mu\text{K.arcmin}$
  - BICE2P-Keck: 400 sq. deg. with  $1.3'$  beam and  $\Delta P = 3 \mu\text{K.arcmin}$

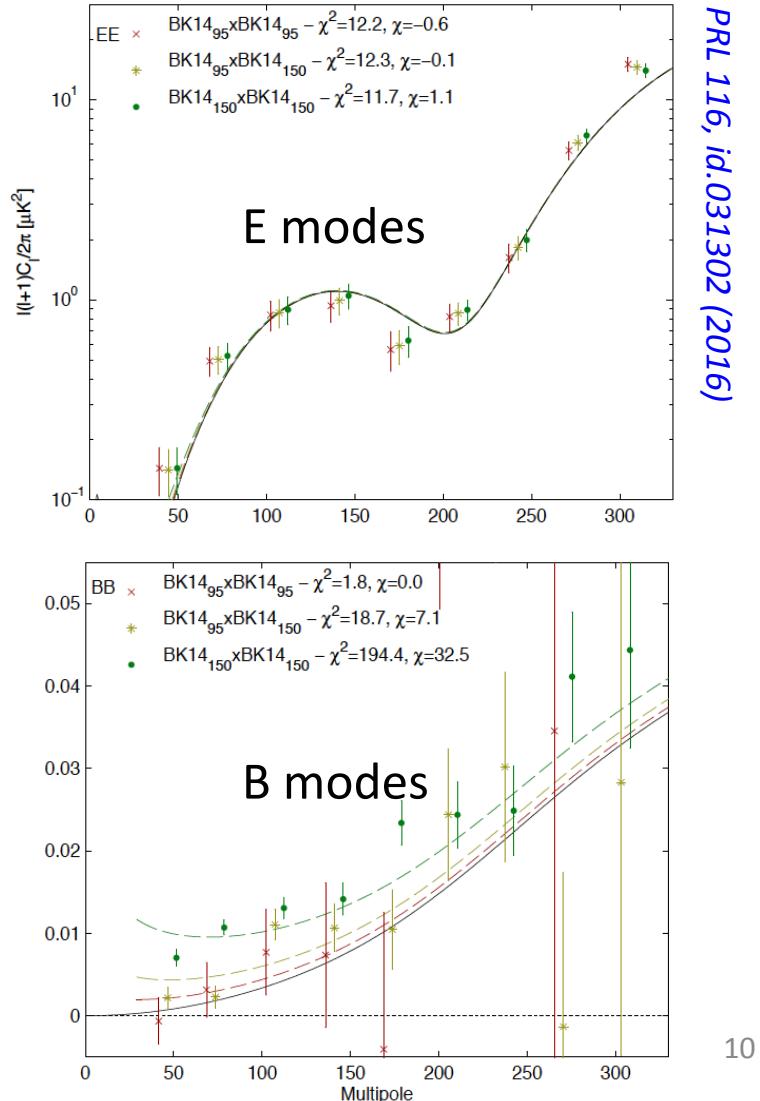
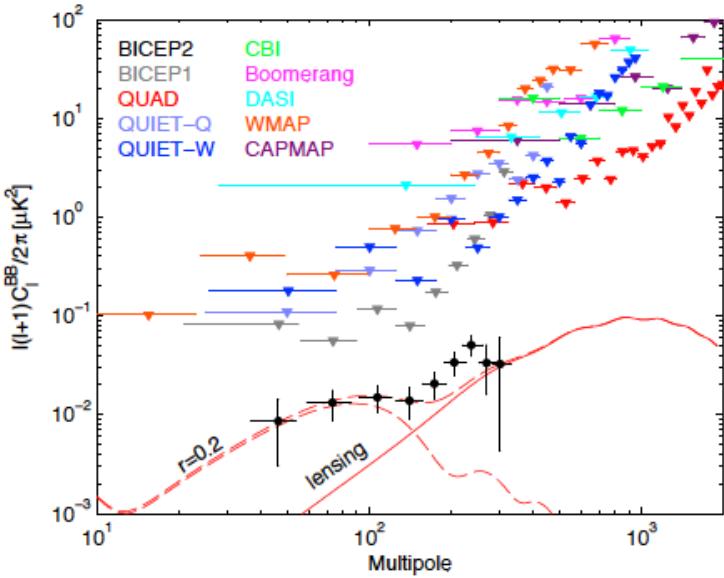
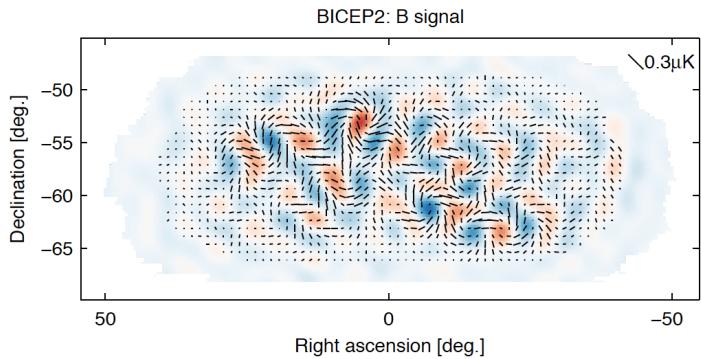
# CMB TEB spectra



# Where the action is: primordial B

BICEP2 hint of B modes: [PRL 112, id.241101 \(2014\)](#)

Revision with Planck: [PRL 114, id.101301 \(2015\)](#)



[PRL 116, id.031302 \(2016\)](#)

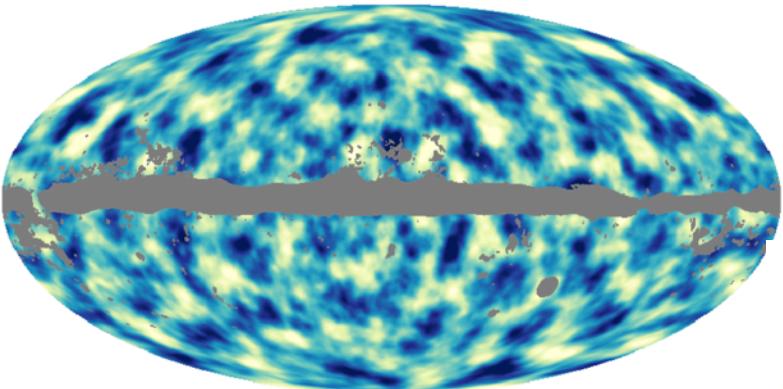
# Where the action is: lensing

Planck lensing:

*Planck Collaboration A&A 571, 17 (2014)*

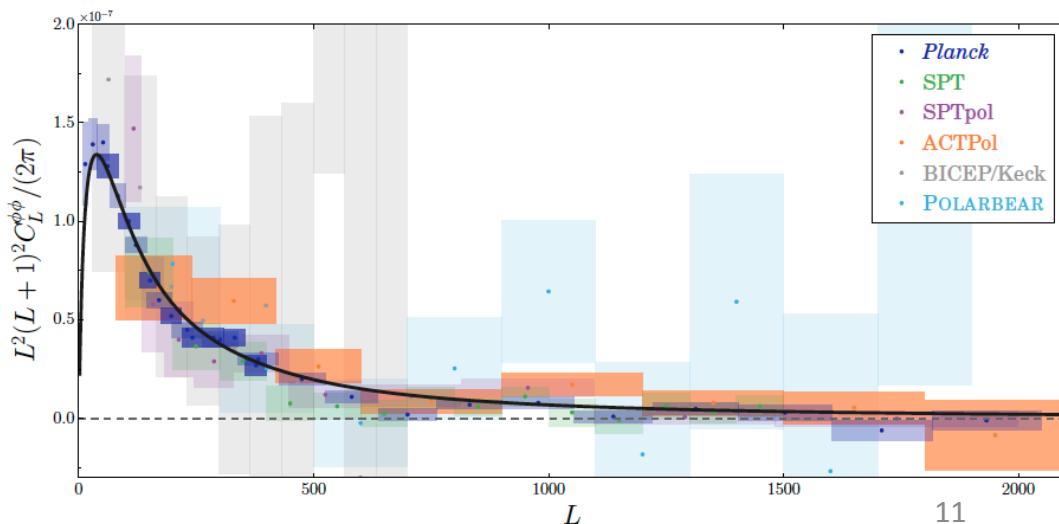
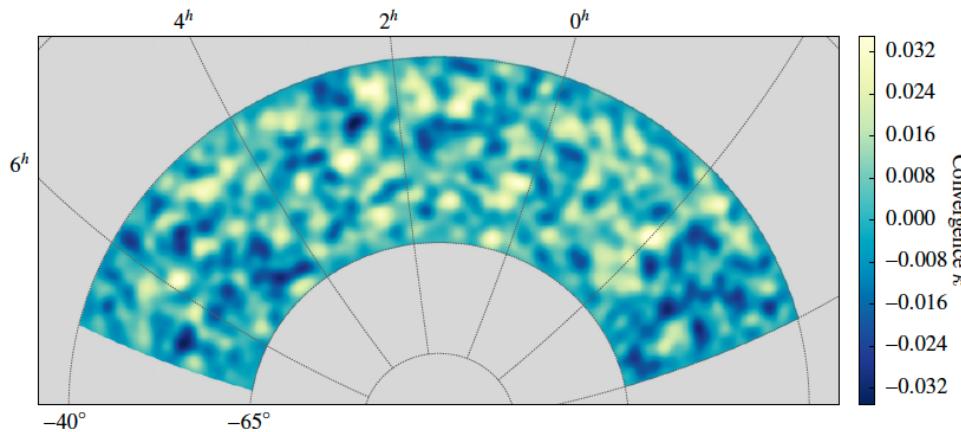
*Planck Collaboration A&A 594, 15 (2016)*

Lensing potential from Planck



COPYRIGHT 2017 © EUROPEAN SPACE AGENCY.

SPT lensing: *PRL 114, id.101301 (2015)*



# Where the action is: "delensing"

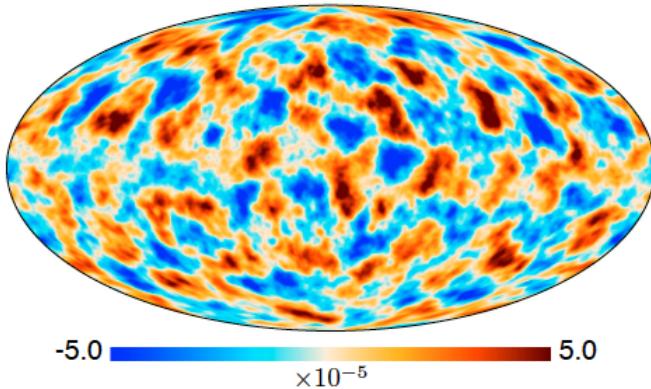
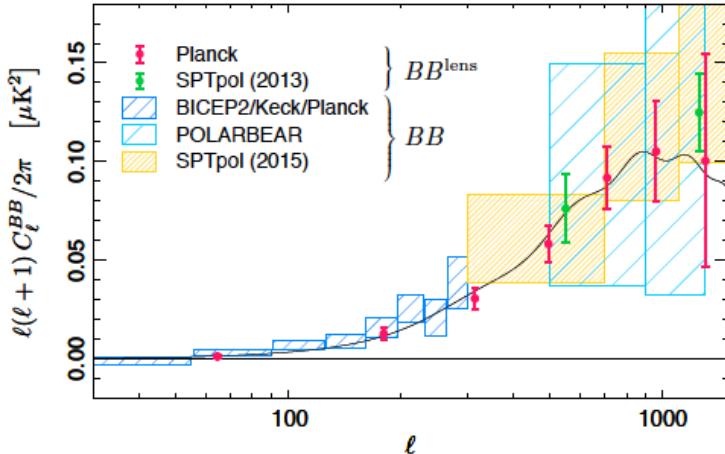


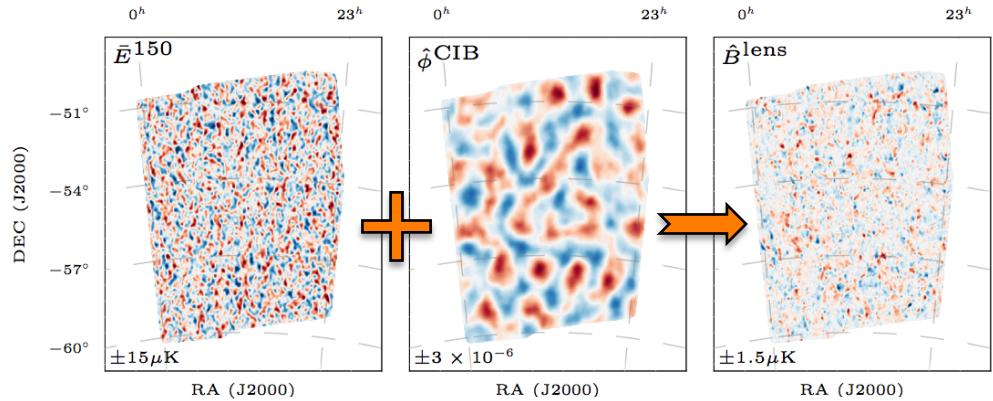
Figure 1. Wiener-filtered lensing potential estimated from the SMICA foreground-cleaned temperature map using the  $f_{\text{sky}} \approx 80\%$  lensing mask.

**Planck**

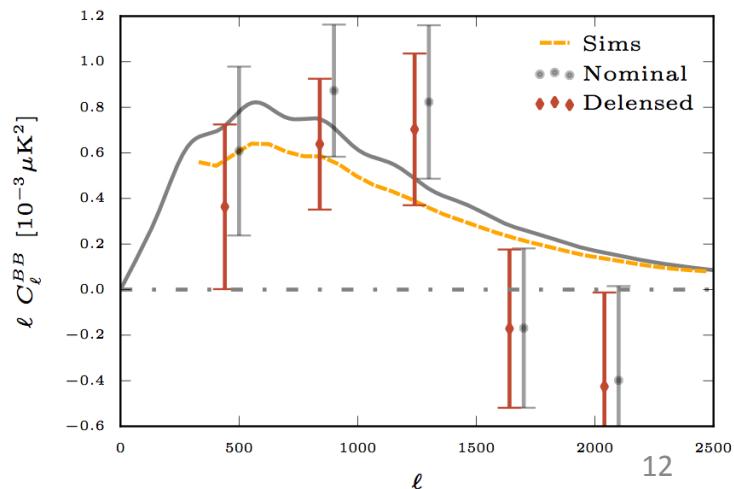


Planck collaboration A&A 596, 102 (2016)

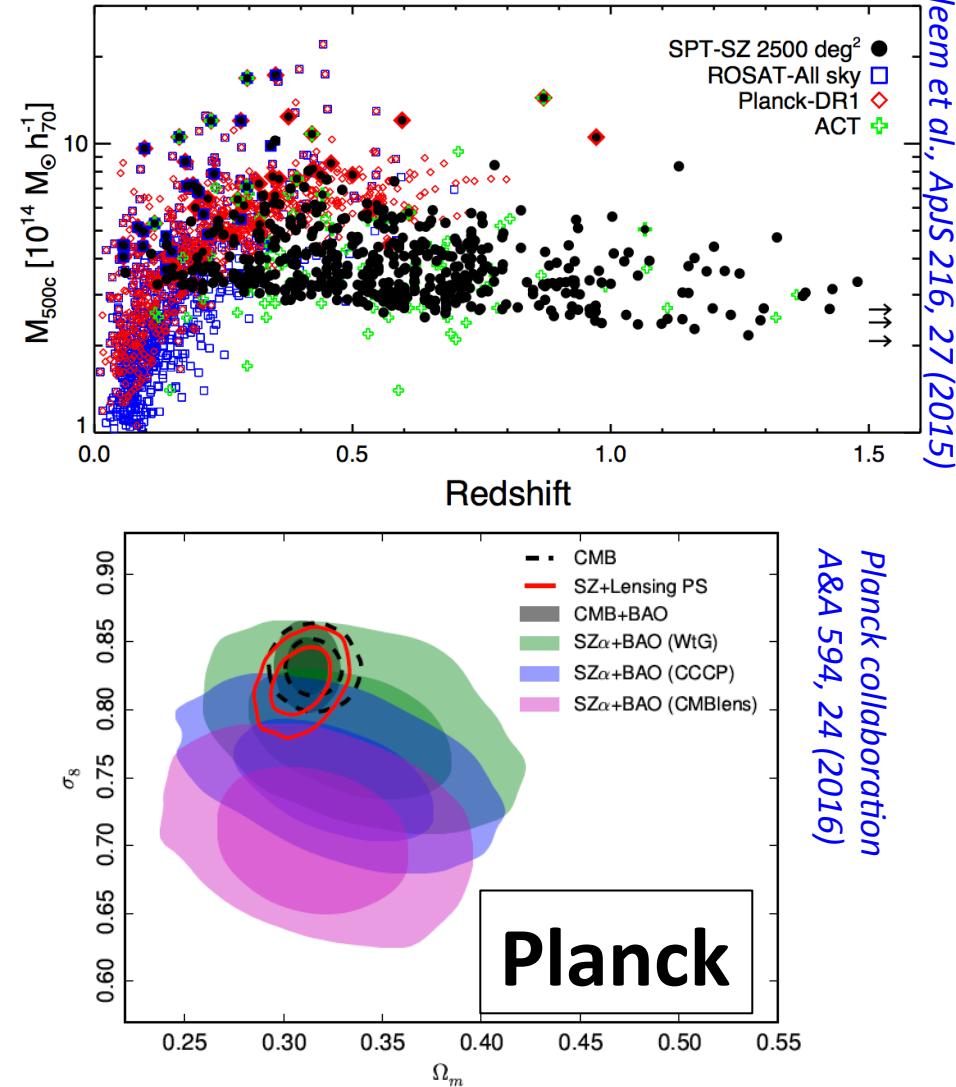
Use lensing potential inferred from dusty galaxies (CIB) and SPT E-modes to infer lensing B-modes



**SPT**

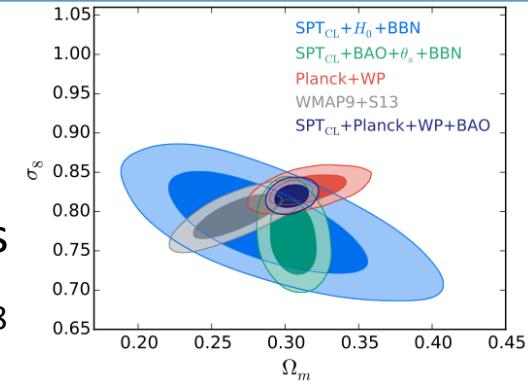


# Where the action is: galaxy clusters

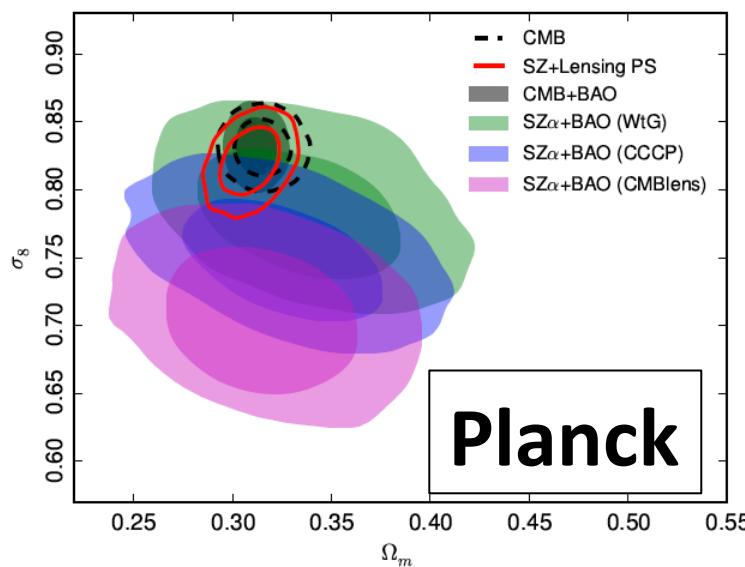


**SPT**

Structures  
 $\Omega_m - \sigma_8$

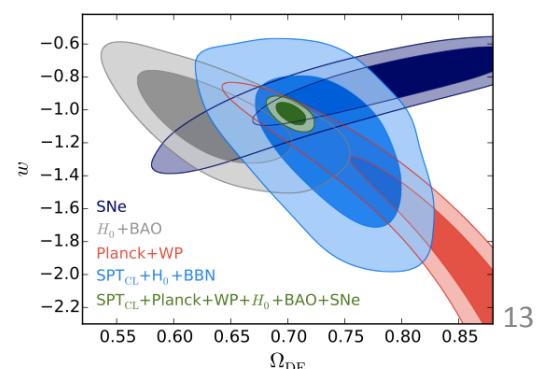
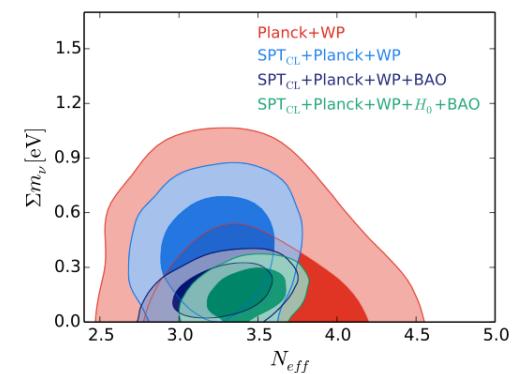


*de Haan et al., ApJ 832, 95 (2016)*



**Planck**

Neutrinos  
 $N_{\text{eff}} - \sum m_\nu$



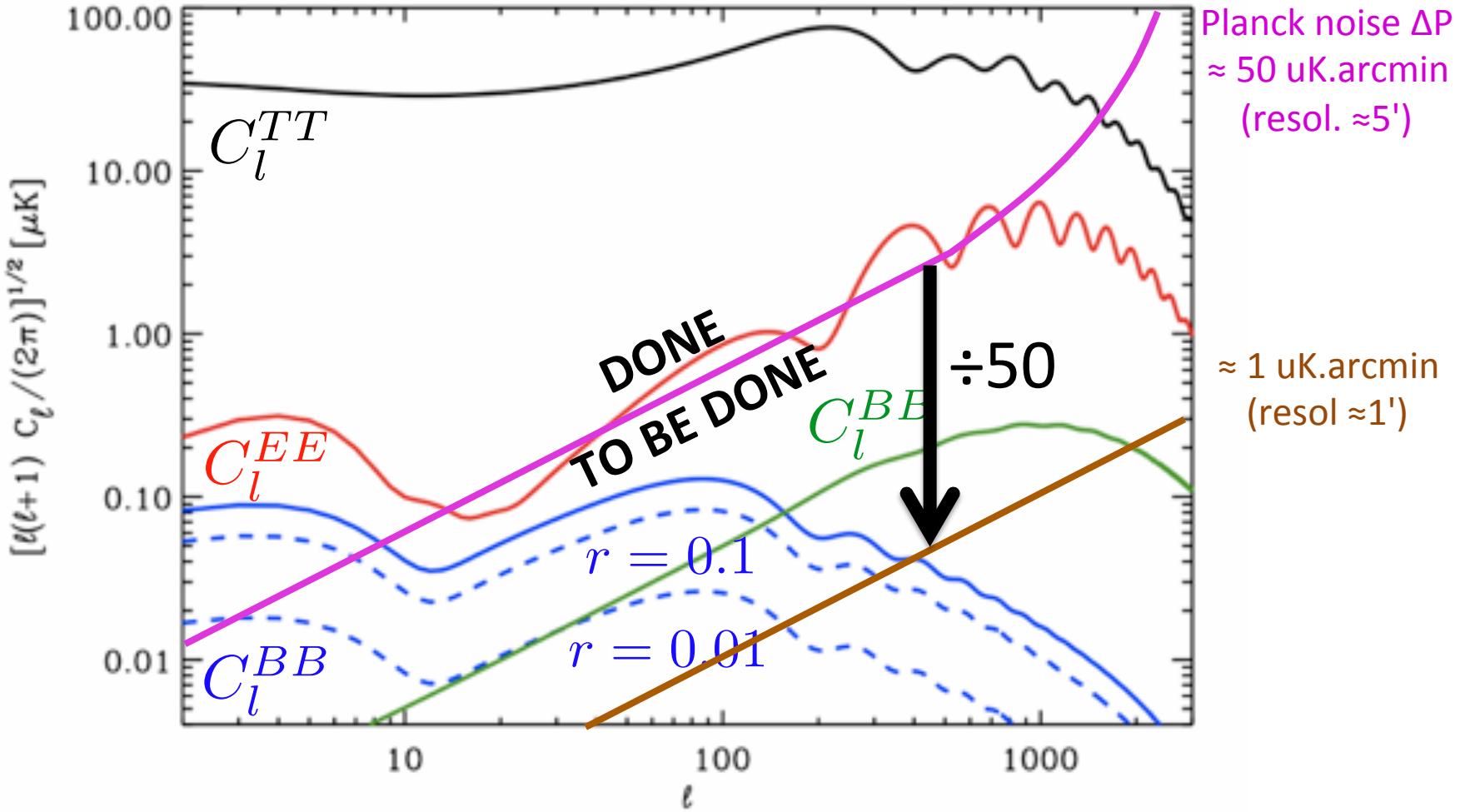
Dark Energy  
 $\Omega_{\text{DE}} - w$

# Scientific Case: what next?

- Very good fit of many cosmological observations ( $H, \Omega_m, \Omega_b, \tau, A_s, n_s, \dots$ ) with mild "tensions" ( $H_0, \sigma_8, \dots$ )
- Did Inflation really happen?
- If so, physics of inflation? ( $r, n_s, \text{running}, n_t, \text{NG\dots?}$ )
- What is Dark Matter? ( $v's, N_{\text{eff}}, \text{decaying DM\dots?}$ )
- What is Dark Energy? ( $\Lambda, w_0, w_1, \dots ?$ )
- Fundamental physics (modified gravity, physics beyond SM)
- Is the CMB a "perfect" blackbody?
- ...
- Is the global  $\Lambda$ CDM picture correct?

Could we ***mine the CMB*** with  **$\approx 50$  times better sensitivity**  
 **$(\approx 2500$  times increased mapping speed) ?**

# The "ultimate" CMB TEB



# Inflation

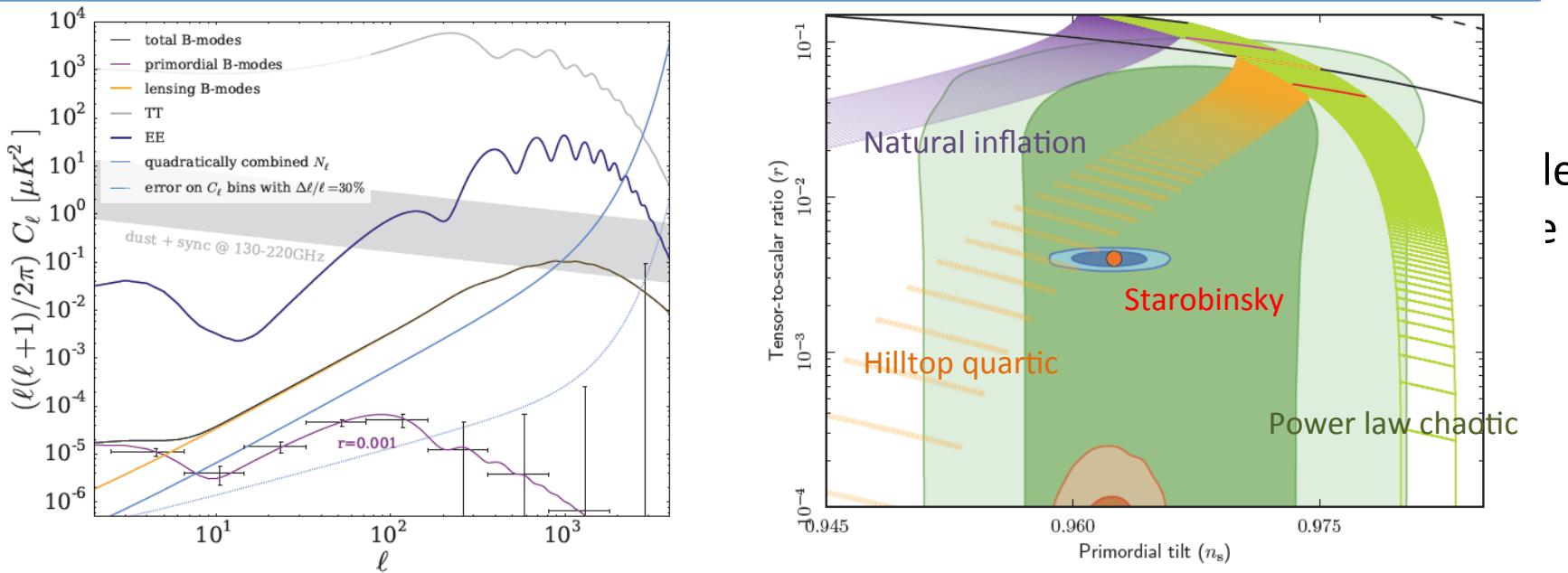
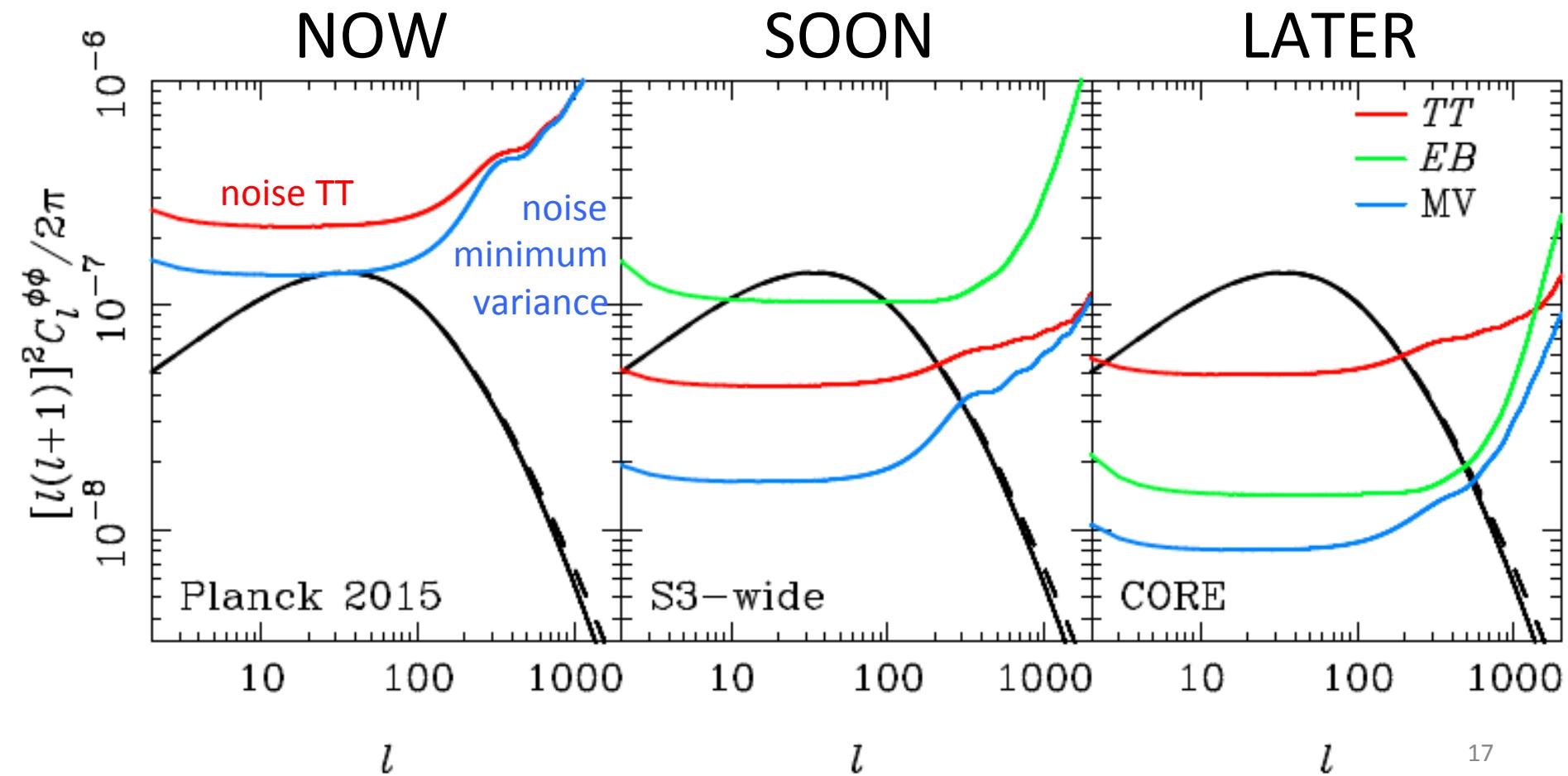


Figure 1: Left: Projected 68% CL error bars (crosses) and the theoretical prediction (purple line) for the primordial B-mode power spectrum with a tensor-to-scalar ratio of  $r = 0.001$ . The orange line shows the secondary B-mode power spectrum from gravitational lensing while the black line shows their sum. The top two lines show the power spectra of the temperature and E-mode polarization, respectively. The solid blue line shows the noise power spectrum, while the dotted line shows the error bar on the B-mode power spectrum due only to noise in the 130-220 channels. Right: Forecasts for marginalized contours for  $(n_s, r)$  at the 68 % and 95 % CL for *CORE* for two scenarios. The fiducial model at the center of the blue marginalized contours (orange dot) has  $r = 0.004$ , a value consistent with the Starobinsky model, and a second fiducial model (red contours) has a level of primordial GW undetectably small for *CORE*. The green contours show the 68 % and 95 % CL for Planck 2015 data combined with the BICEP2-Keck Array-Planck B-mode likelihood [11]. We show the predictions for natural inflation (purple band), hilltop quartic model (orange discrete band) and power law chaotic (light green discrete band) models. These inflationary models consistent with the current data can be ruled out by *CORE*.

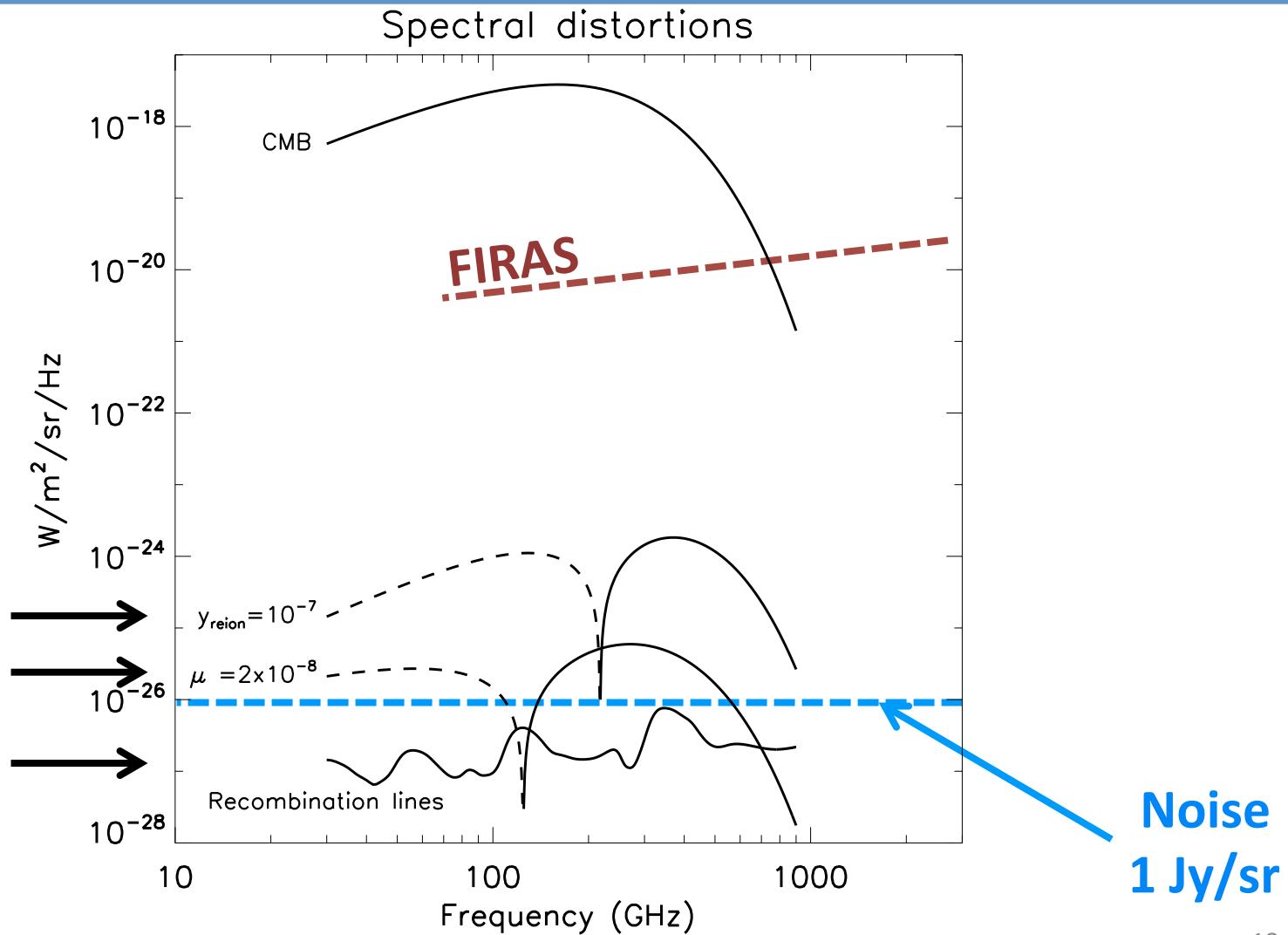
# Lensing spectra : $C_\ell^{\phi\phi}$ ...

Challinor et al. (CORE collaboration) – coming soon



# CMB spectral distortions

CMB  
spectral  
distortions



# Detailed validation of the model

Inflationary parameters (initial conditions)

$$r = \frac{P_t(k_0)}{P_s(k_0)} = 0 \quad n_t \simeq -r/8 = 0 \quad \frac{dn_s}{d \ln k} \simeq 0$$

Spatial curvature

$$\Omega_k h^2 = 0$$

Dark Energy equation of state

$$w_0 = -1 \quad w_1 = 0$$

Neutrino sector

$$N_{\text{eff}} = 3.046 \quad \Omega_\nu h^2 = \frac{\Sigma m_\nu}{93 \text{ eV}} \quad \Sigma m_\nu \simeq 60 \text{ meV}$$

Helium abundance

$$Y_{\text{He}} \simeq 0.25$$

The CMB can still reduce the error box volume

**by a factor  $>10^6$**

(a factor of  $\approx 5$  on each parameter on average)

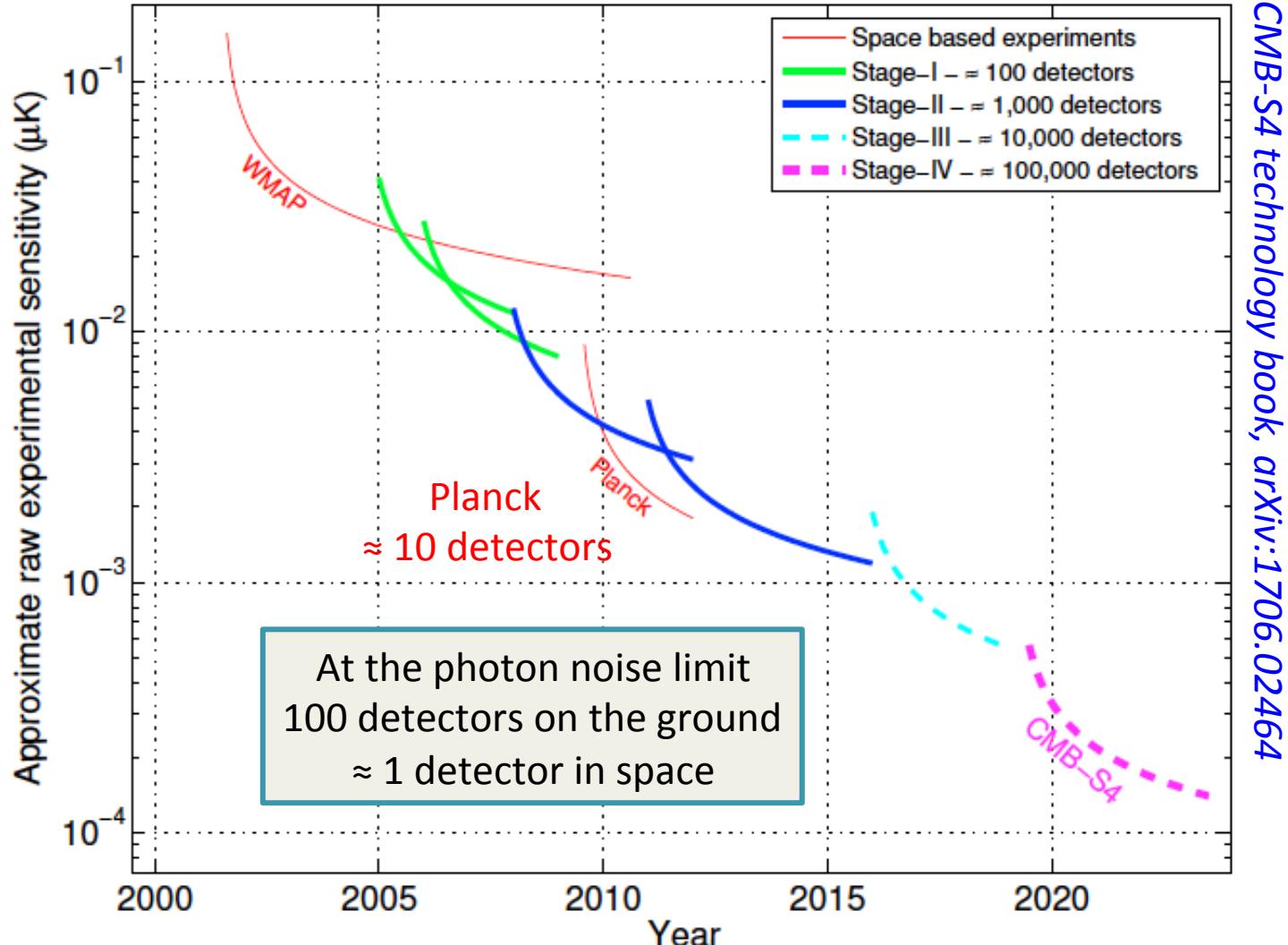
**REQUIREMENT:**

measure all spectra with the best possible accuracy

# Outline

- Where are we? What next?
- ➡ • Challenges
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- Summary

# CMB (polarisation) sensitivity

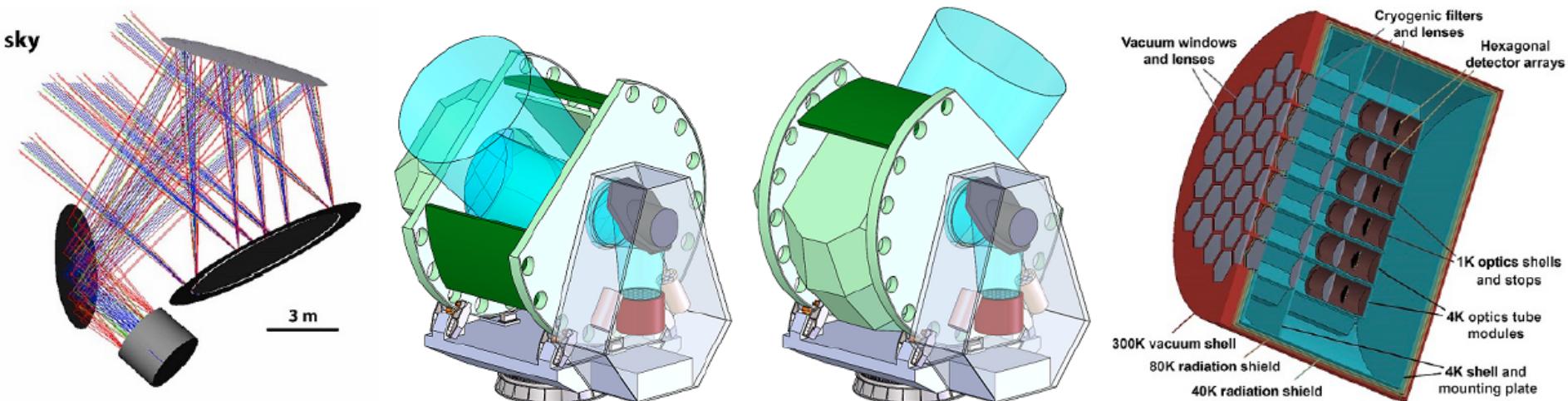


# Need for very large focal planes

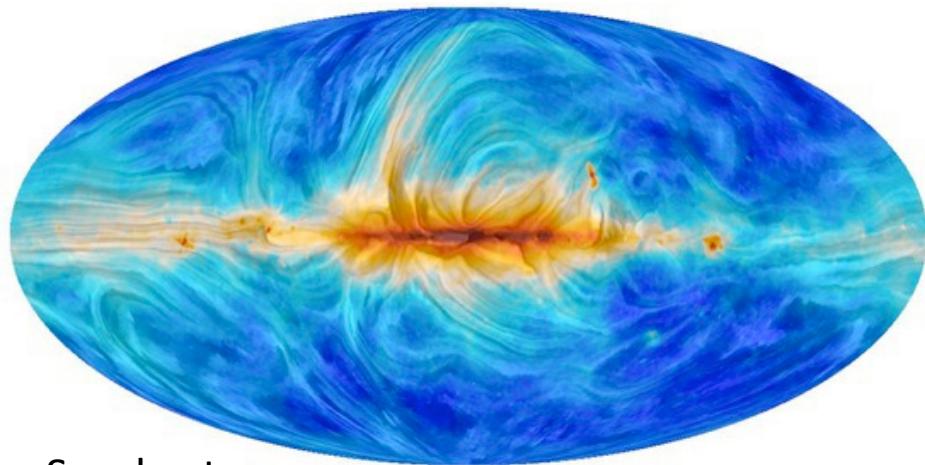
$v = 100 \text{ GHz}$  is  $\lambda = 3 \text{ mm}$   
pixel size about  $1 \text{ cm}^2$   
10,000 detectors require  $1\text{m}^2$  focal plane

multichroic detectors  
+  
dual-polarization

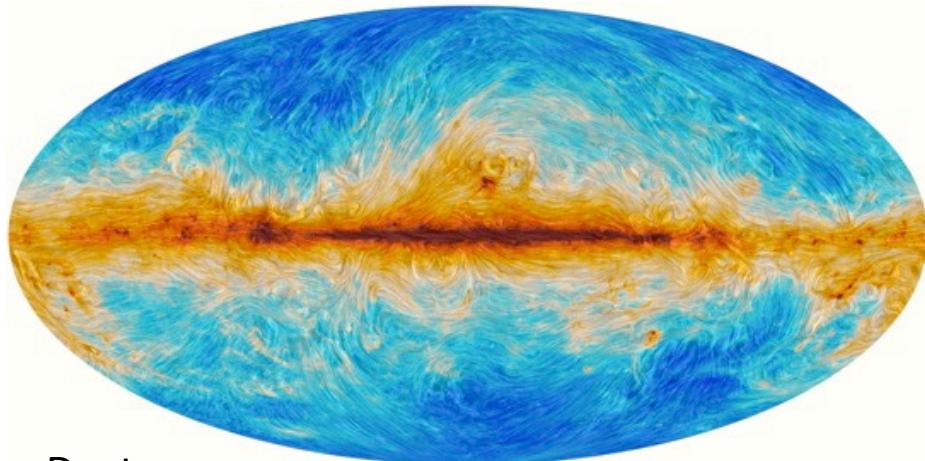
Large telescopes and/or many telescopes



# Foregrounds



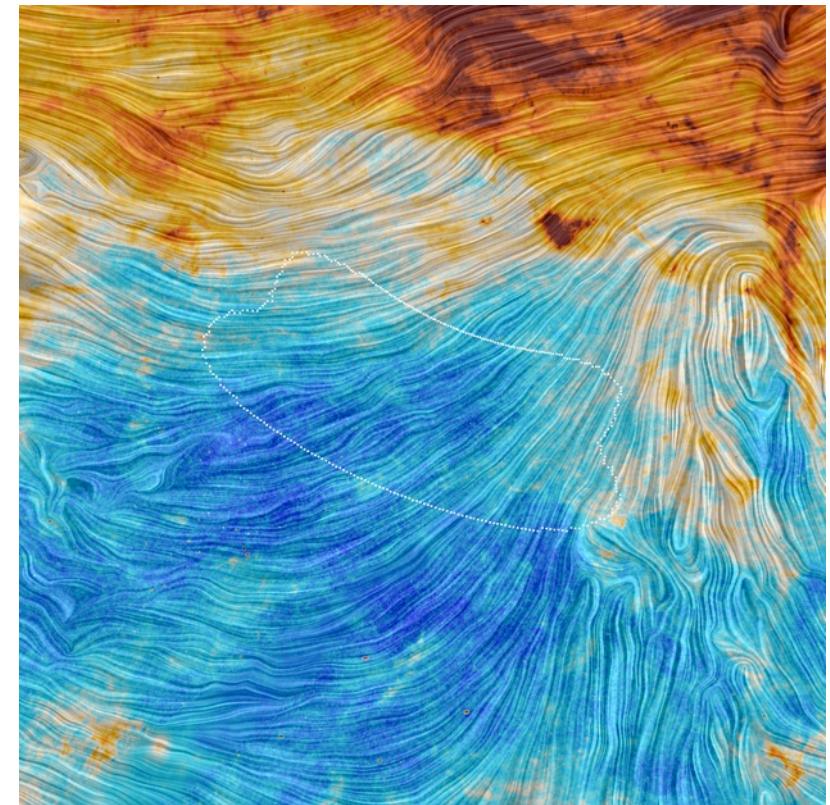
Synchrotron



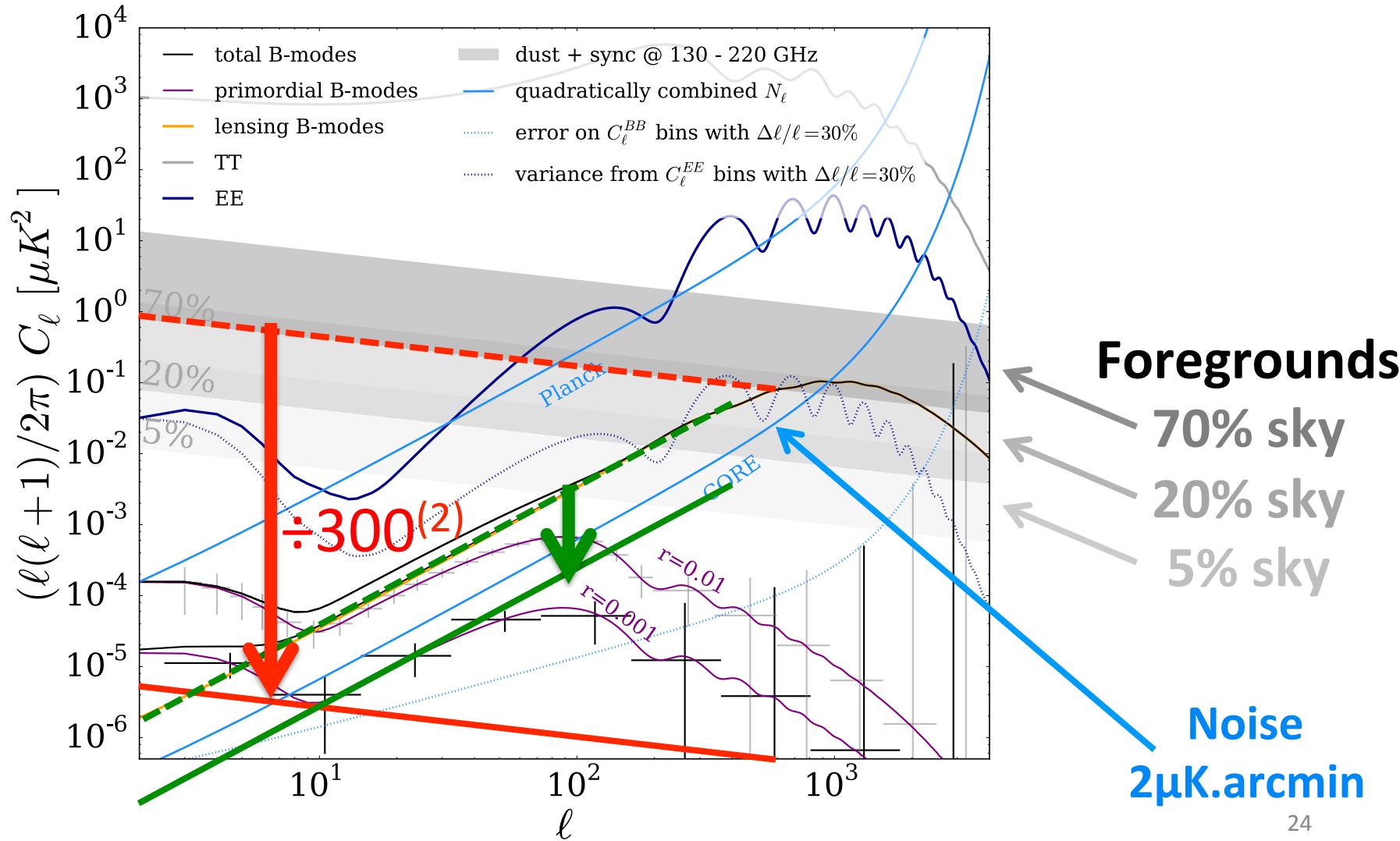
Dust

Credit: ESA, Planck collaboration

Dust in the BICEP2 field

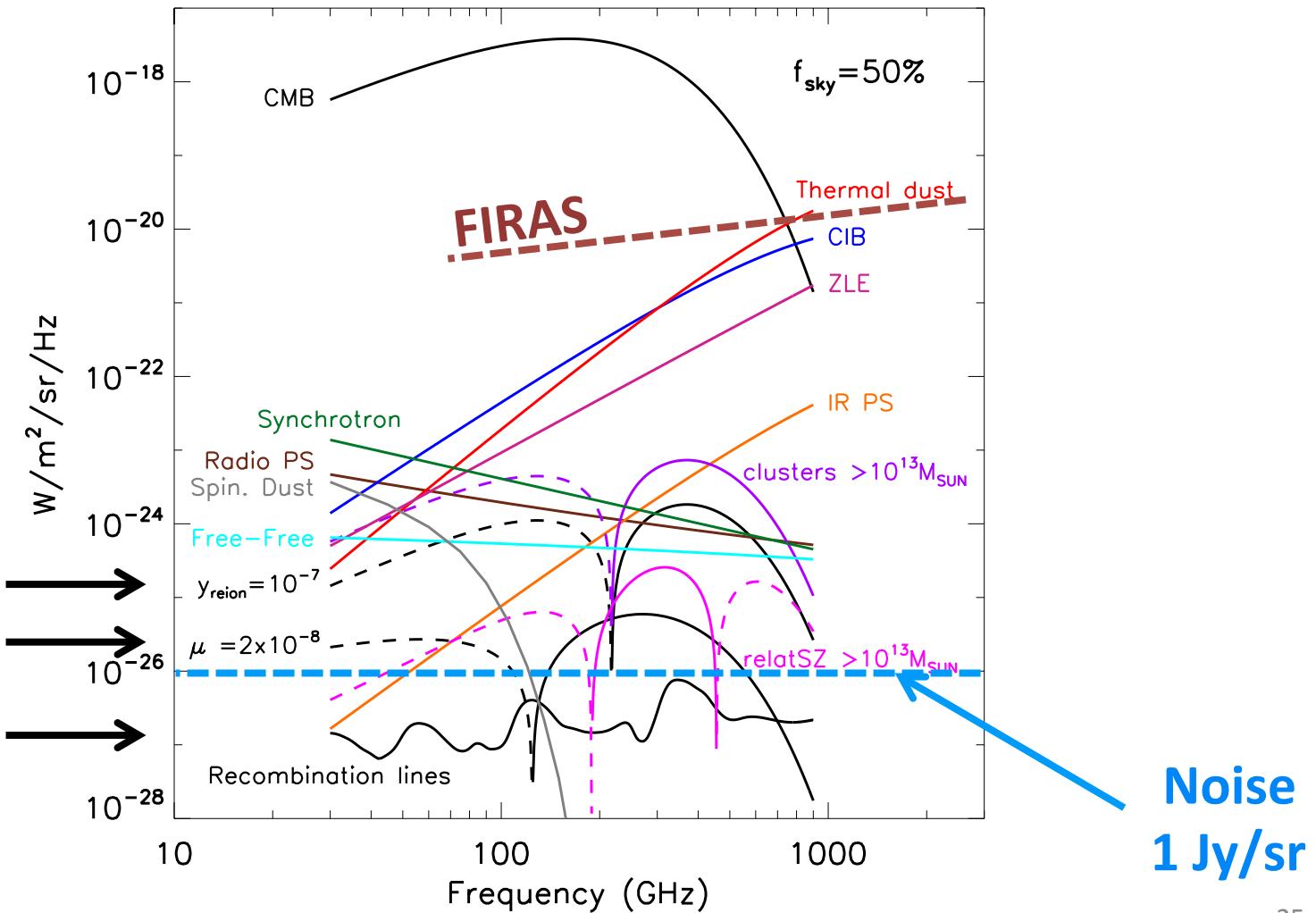


# Foreground + lensing confusion



# Foregrounds & CMB spectral distortions

CMB  
spectral  
distortions



# Outline

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# Ongoing experiments: small aperture

Project	ABS	Keck Array	Spider	Piper	BICEP Array	CLASS
Physical aperture (m)	0.25	0.25	0.27	0.39	0.52	0.6
Illuminated aperture (m)	0.25	0.25	0.27	0.29	0.52	0.35
Telescope f/#	2.5	2.2	2.2	1.55	1.6	2, 2, 1.5, 1.5
f/# at detector array (if different)		2.2	2.2	1.6	1.6	
Minimum Strehl ratio at 150 GHz	0.96		0.97	0.97 (200 GHz)	0.99	
f-lambda spacing at 150 GHz	2.6		1.8	0.5		2.42
A*Omega of illuminated arrays (cm^2 sr)	50			6		92
A*Omega with Strehl > 0.8 at 150 GHz				51		
Field of view per array (deg^2)	315		150	28		315
Useable field of view diameter (deg)			12			
Number of arrays	1	5	6	2 (4 supported)	5	4
Number of telescopes	1	1	1	2	5	4
Observation frequencies (GHz)	150	95, 150, 220	(90, 150) 90, 150, 280	200, 270, 350, 600	35, 95, 150, 220/280	38, 93, 147, 218
Detectors on sky per frequency	480	(288, 512, 512) x # arrays per freq	(816, 1488) 272,992,1488		384, 6106,7776, 9408/9408	72, 1036, 1190, 1190
# Frequencies per array ("multichroic-ness")	1	1	1	1	1,1,1,2	1(40,90), 2(150/220)
Window Material	UHMWPE	Zotefoam HD-30	UHMWPE	None	HDPE	UHMWPE
Illuminated diameter of window (m)	0.28	0.26	0.35	n/a	0.68	0.35
Lens Material	N/A	HDPE	HDPE	Silicon	Alumina	HDPE, silicon
Temperatures of reflective optics (K)	4		N/A	1.4	—	300
Temperatures of refractive optics (K)	N/A	4	4	1.4	4	4, 1
Temperature of cold stop (K)	4	4	2	1.4	4	4
Temperature of detector arrays (K)	0.3	0.25	0.3	0.1	0.25	0.05
Year of initial (or partial) deployment	2012	2012	(flight 1: 2015)	2016	2015	2016
Year of full deployment (all frequencies)	2012	2013	flight 2: 2017	2020	2020	2018

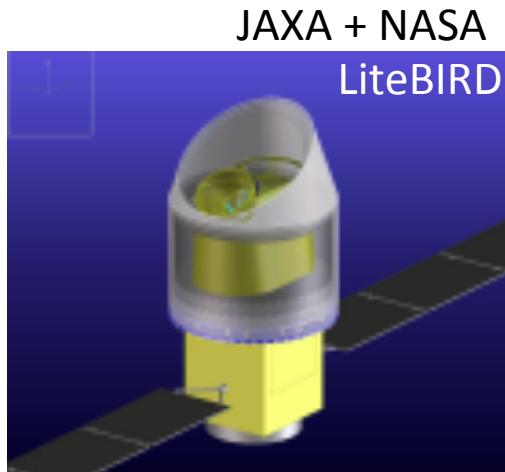
# Ongoing experiments: large aperture

Project	QUIET	EBEX	Simons Array	Adv. ACTPol	CCAT-Prime	SPT-3G
Physical aperture (m)	1.4	1.5	2.5	6	6	10
Illuminated aperture (m)		1.05	2.5	5.6	5.5	7.5
Telescope f/#	1.65	1.9	1.9	2.5	3	1.7
f/# at detector array (if different)		1.9	1.9	1.35	1.5	1.7
Minimum Strehl ratio at 150 GHz		0.9	0.85	0.8 (1 array), 0.93 (2 arrays)	0.81	0.99
f-lambda spacing at 150 GHz		1.74	1.8	1.8	1.3	2
A*Omega of illuminated arrays (cm^2 sr)				180	~2700	250
A*Omega with Strehl > 0.8 at 150 GHz				379	~3000	370
Field of view per array (deg^2)	39 , 53		4 deg on sky	0.8	0.9	1.9
Useable field of view diameter (deg)	7.0, 8.2			2.3	7.5	
Number of arrays	2 (in series)	14	1	3	up to 50	1
Number of telescopes	1	1	1	1	1	1
Observation frequencies (GHz)	42, 90	150, 250, 410	90, 150, 220, 280	28, 41, 90, 150, 230	90 GHz - 1 THz	90, 150, 220
Detectors on sky per frequency	76 diodes, 360 diodes		7588, 7588, 3794, 3794	88, 88, 1712, 2718, 1006	up to ~10^5	5420, 5420, 5420
# Frequencies per array ("multichroic-ness")	1	1	2	2	2 or 3	3
Window Material	UHMWPE	UHMWPE	Zote Foam	UHMWPE		HDPE
Illuminated diameter of window (m)		0.28	0.5	0.31		0.6
Lens Material	N/A	UHMWPE	alumina	silicon		alumina
Temperatures of reflective optics (K)	300	300	300	300	300	300
Temperatures of refractive optics (K)	N/A	4, 1	4	4, 1		4
Temperature of cold stop (K)	N/A	1	4	1		4
Temperature of detector arrays (K)	20K, 27K	0.25	0.25	0.1	0.1	0.25
Year of initial (or partial) deployment	2008	2009 (test flight)	2017	2016	2020	2016
Year of full deployment (all frequencies)	2009	2013	2017	2018	TBD	2016

# Longer-term projects

- The perspectives for the 10-15 years time frame are dominated by plans for:
  - CMB-S4, a large ground-based CMB "stage 4" observatory;
  - A CMB polarization space mission, either focussed on large scale B-modes (LiteBIRD), or addressing all of CMB polarization science (CORE)
  - A post-FIRAS absolute spectrophotometer (PIXIE)

# Recent space mission proposals



*Primordial B-modes mission*

Earliest Launch > 2027  
Phase A not selected by NASA

ONLY large scale  
CMB polarisation

$$\sigma_r \approx 0.001$$

winning bet if:  $0.01 > r > 0.003$

bonus: improve  $\tau$



*Cosmic origins explorer*

Earliest Launch > 2031  
Phase A not selected by ESA for M5

ALL CMB polarisation  
(almost) ultimate

$$\sigma_r \approx 0.0003$$

bonus: a lot of  
guaranteed science



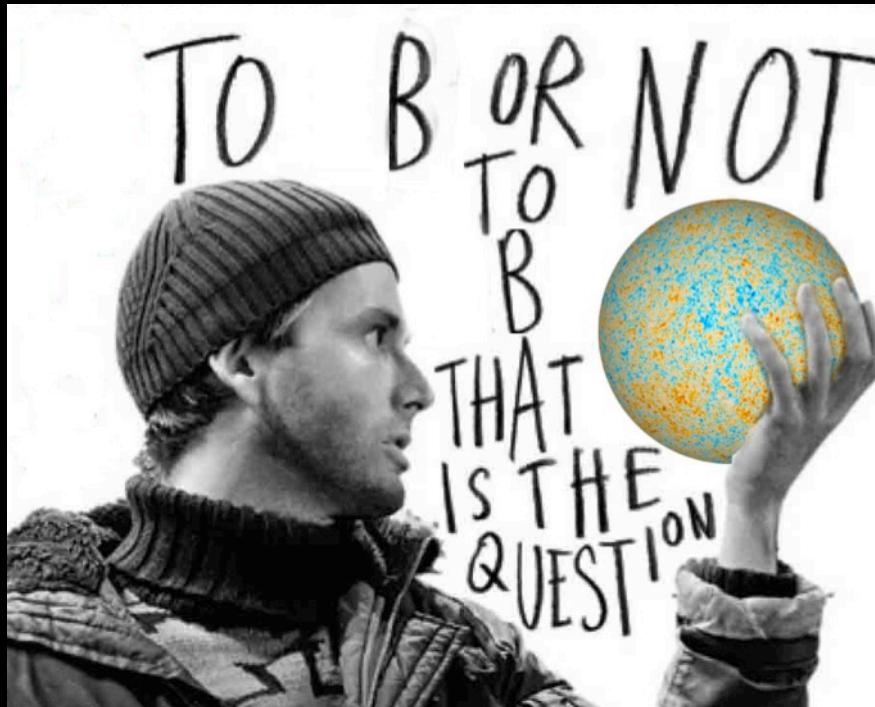
*Absolute spectrophotometer*

Earliest Launch > 2023

very large scale polarisation  
Spectral distortions ?  
bonus: a lot of  
guaranteed foreground science

# Outline

- Where are we? What next?
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- ➡ • A strategy for the future
- Summary



*THE B RACE*

**DILEMMA**

*THE CMB TASK*

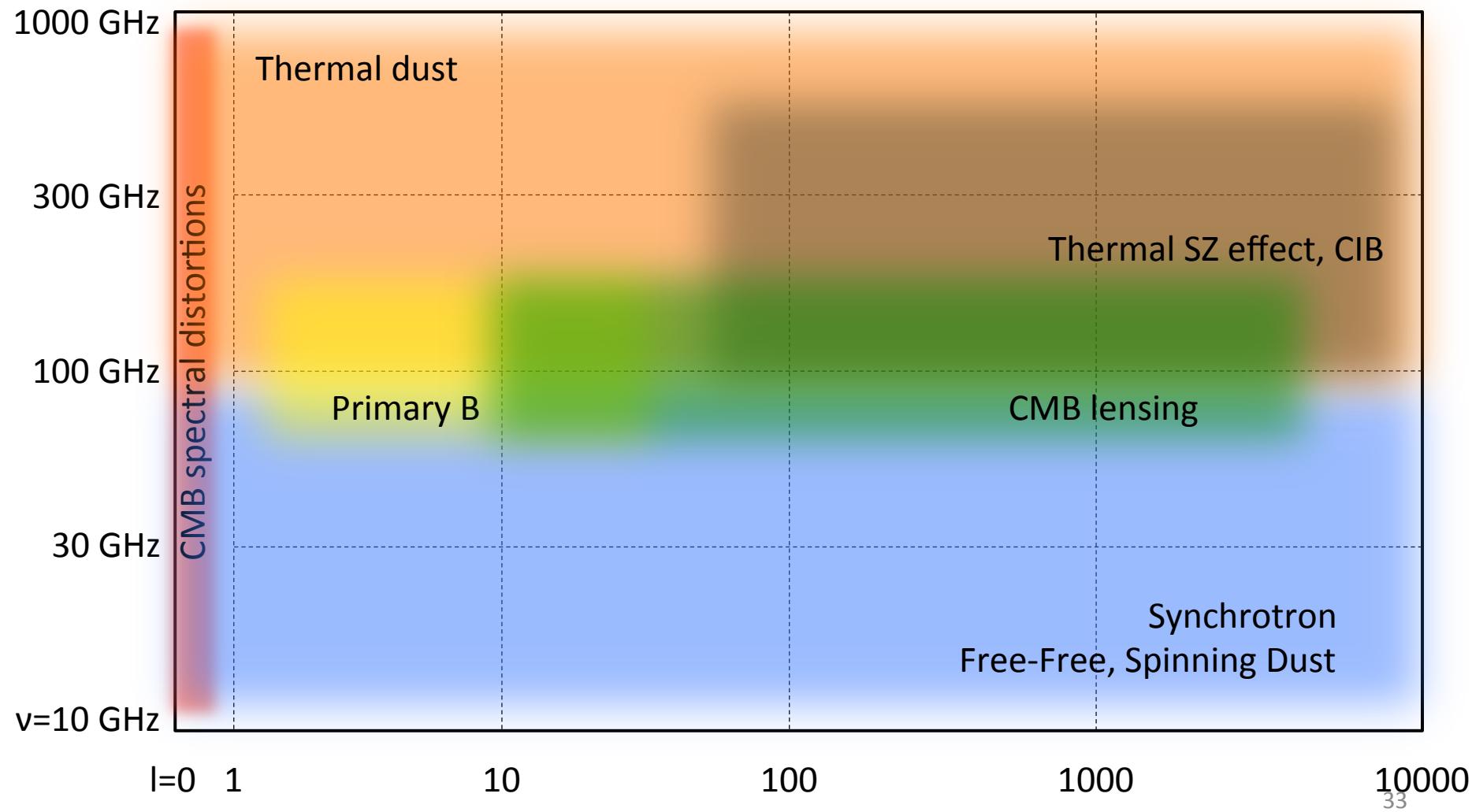
Every small step can yield the first detection of inflationary B-modes.

Lottery ticket for a major discovery (which could happen tomorrow, or in 20 years, or never !)

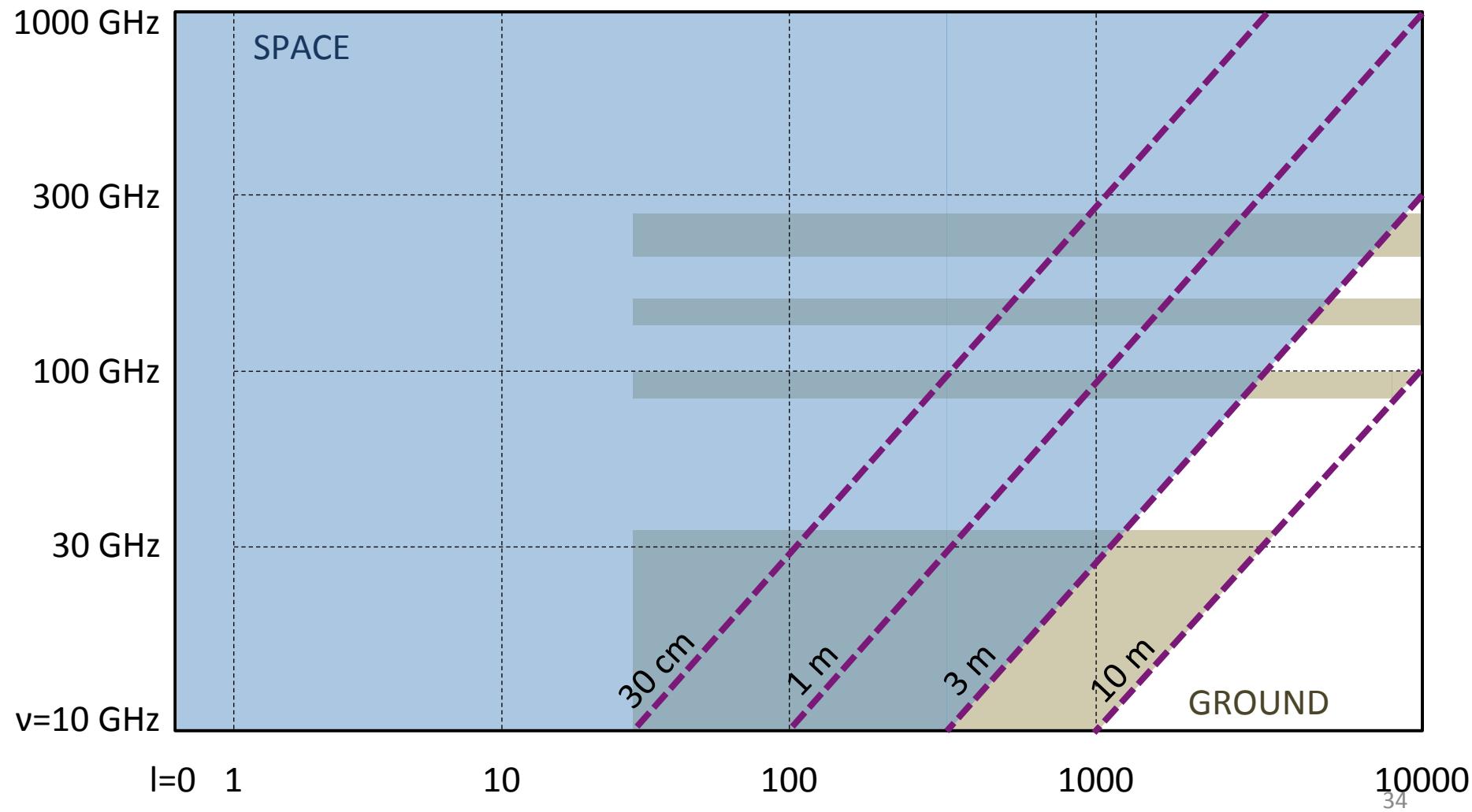
CMB is unique. Getting the best of it is a scientific imperative.

A comprehensive, sensitive and accurate space mission is needed for precision cosmology

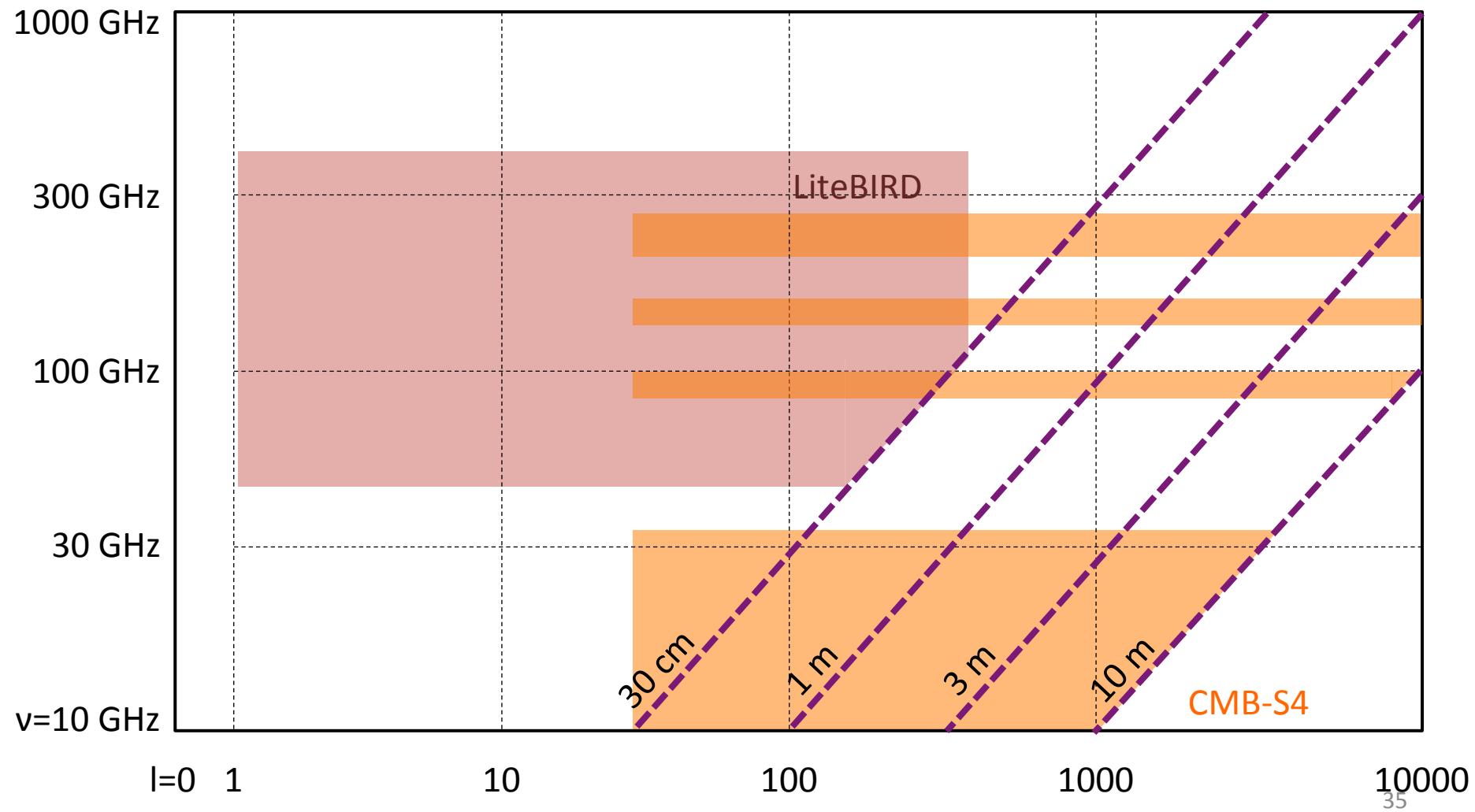
# The battle field



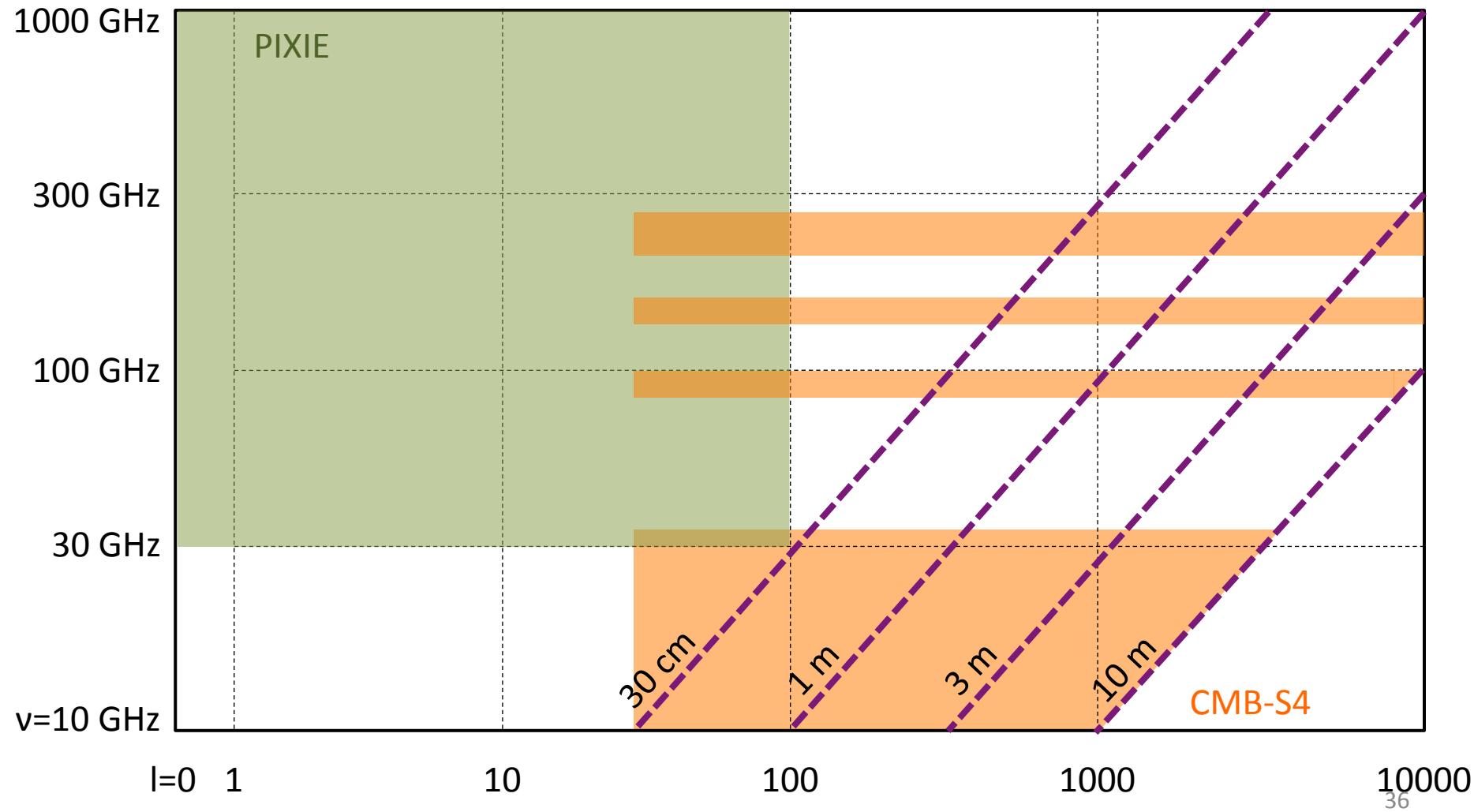
# Ground-space complementarity



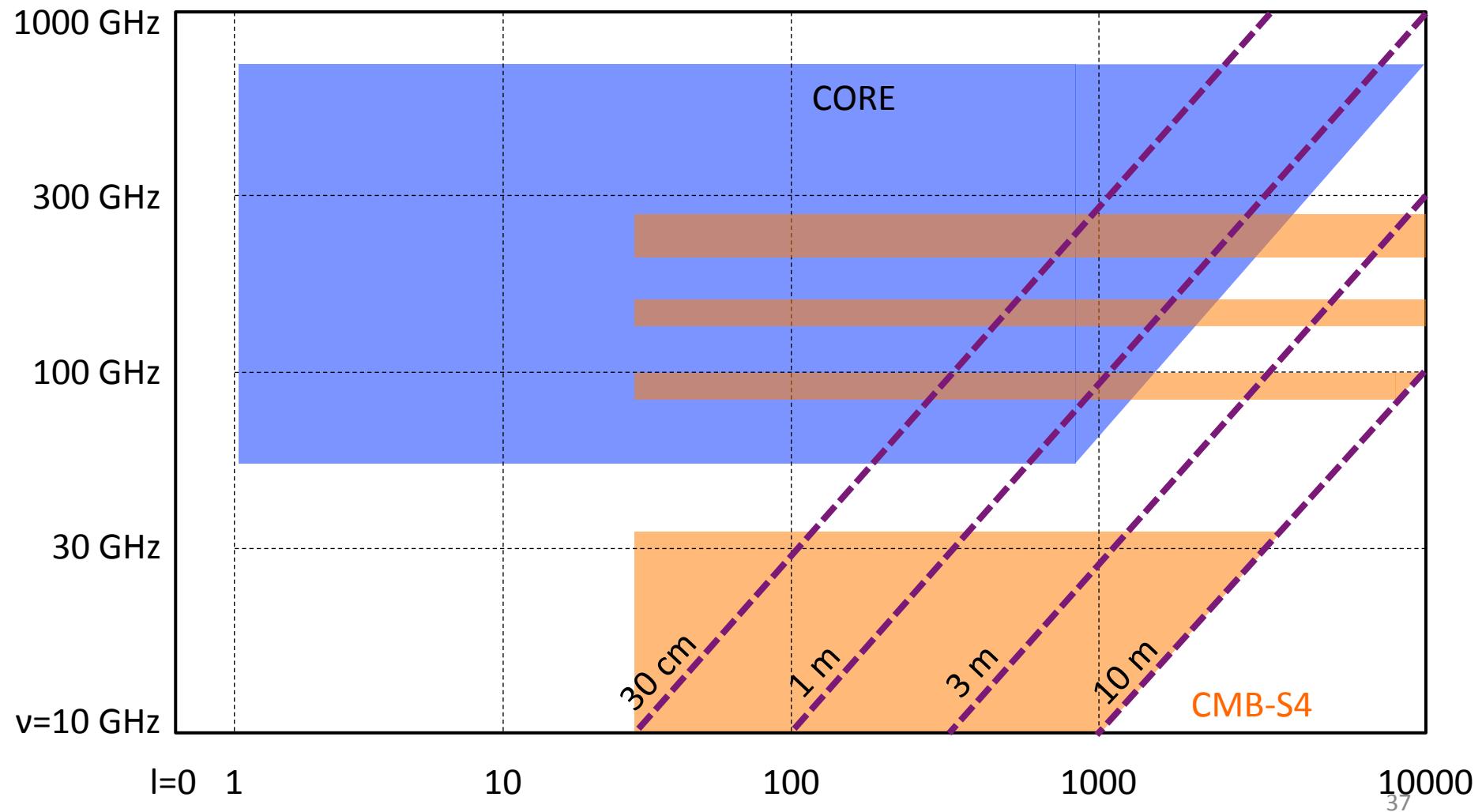
# Ground-space complementarity



# Ground-space complementarity



# Ground-space complementarity



# Complementarity



The suborbital  
roadmap

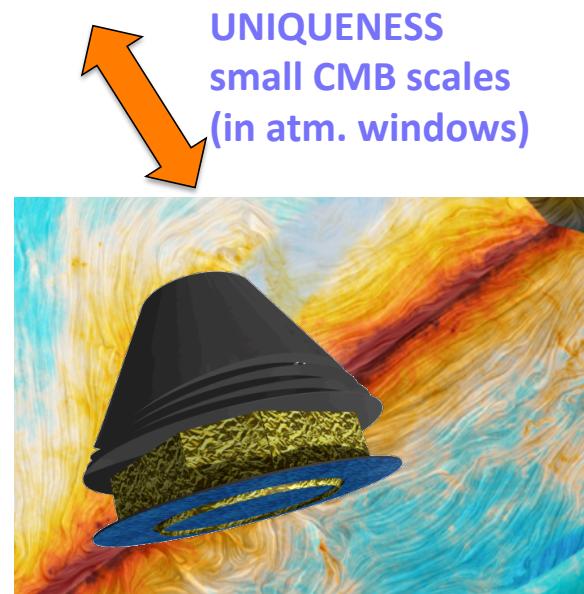


High resolution maps at  $\nu < 200$  GHz

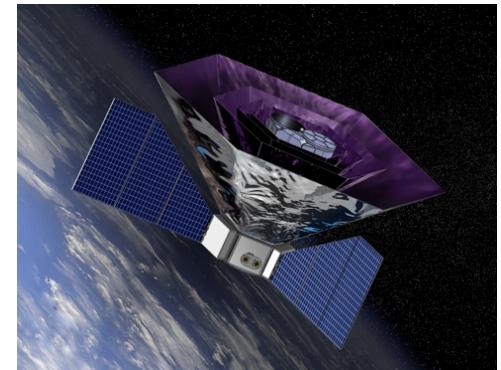
Complementarity  
to get 1-2' resolution  
and no foregrounds



**JOINT OPTIMIZATION  
OF THE DESIGNS**



The CMB spectrum



Absolute spectrophotometry  
**UNIQUENESS**  
absolute measurement

**UNIQUENESS**  
resolved CMB with:  

- many frequencies
- full sky
- systematics control

# Summary

The CMB still provides a fantastic tool for precision cosmology and fundamental physics. Ground-based telescopes and space-borne observations are required.

## Space mission: "Exploring Cosmic Origins (ECO) papers" (special issue of JCAP)

DESIGN

- **Mission:** Delabrouille, de Bernardis, Bouchet et al. arXiv:1706.04516
- **Instrument:** de Bernardis, Ade, Baselmans et al. arXiv:1705.02170

SCIENCE

- **Inflation:** Finelli, Bucher, Achucarro et al. arXiv:1612.08270
- **Lensing:** Challinor, Allison, Carron, et al. coming soon
- **Parameters:** Di Valentino, Brinckmann, Gerbino et al. arXiv:1612.00021
- **Clusters:** Melin, Bonaldi, Remazeilles et al. arXiv:1703.10456
- **Velocity:** Burigana, Carvalho, Trombetti et al. arXiv:1704.05764
- **Sources:** De Zotti, Gonzalez-Nuevo, Lopez-Caniego et al. arXiv:1609.07263

PROCESSING

- **Foregrounds:** Remazeilles, Banday, Baccigalupi et al. arXiv:1704.04501
- **Systematics:** Natoli, Ashdown, Banerji et al. coming soon

## Ground-based: CMB-S4 Science and Technology books

- **Science:** CMB-S4 collaboration arXiv:1610.02743
- **Technology:** CMB-S4 collaboration arXiv:1706.02464