CMB experiments

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Outline

- Introduction
- Where are we?
- Science case: what next
- Challenges
  - sensitivity
  - atmosphere
  - systematics
  - foregrounds
- Suborbital experiments
- Space experiments
  - PIXIE
  - LiteBIRD
  - CORE
  - PRISM
- A strategy for the future
- Summary

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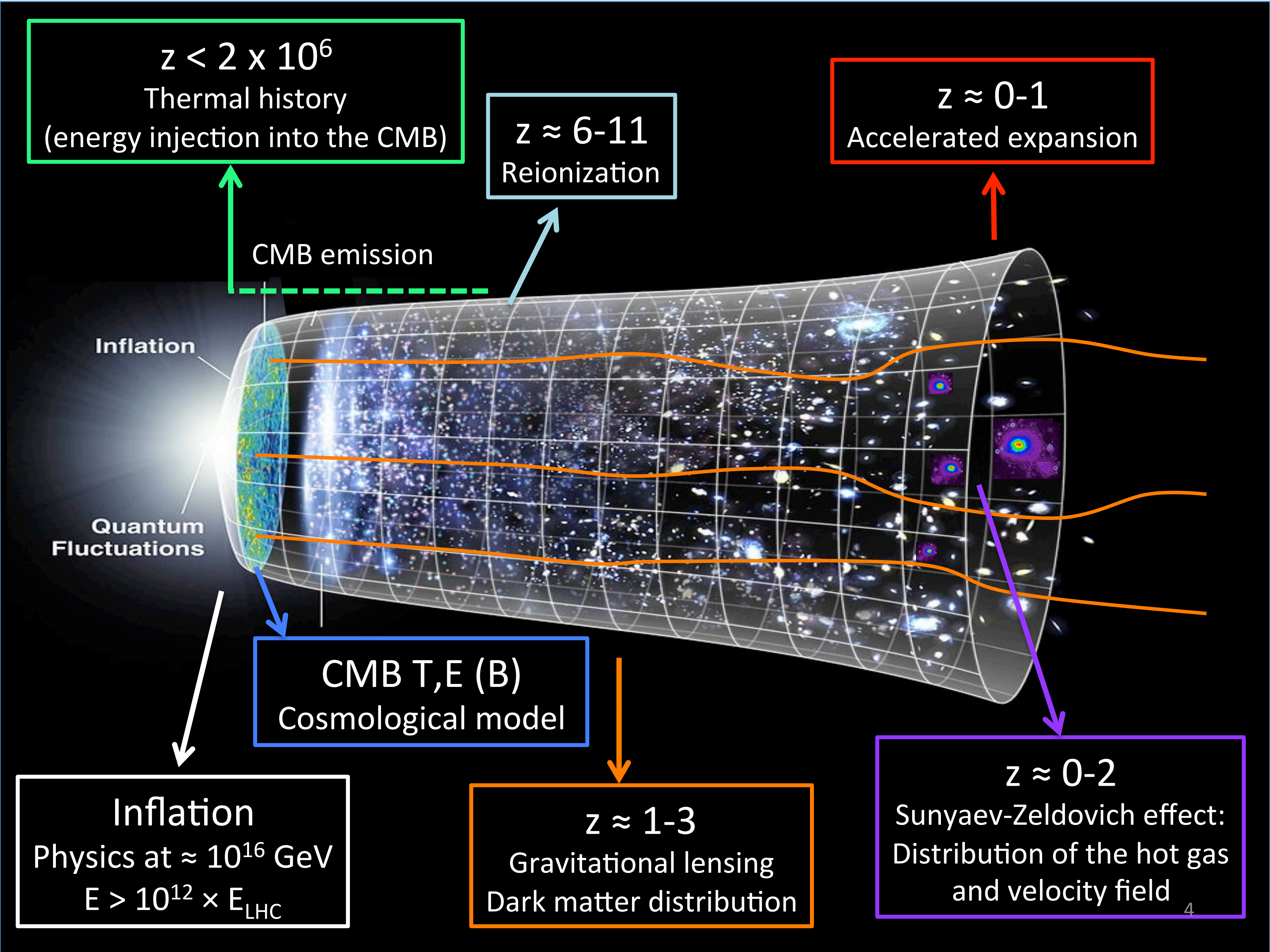
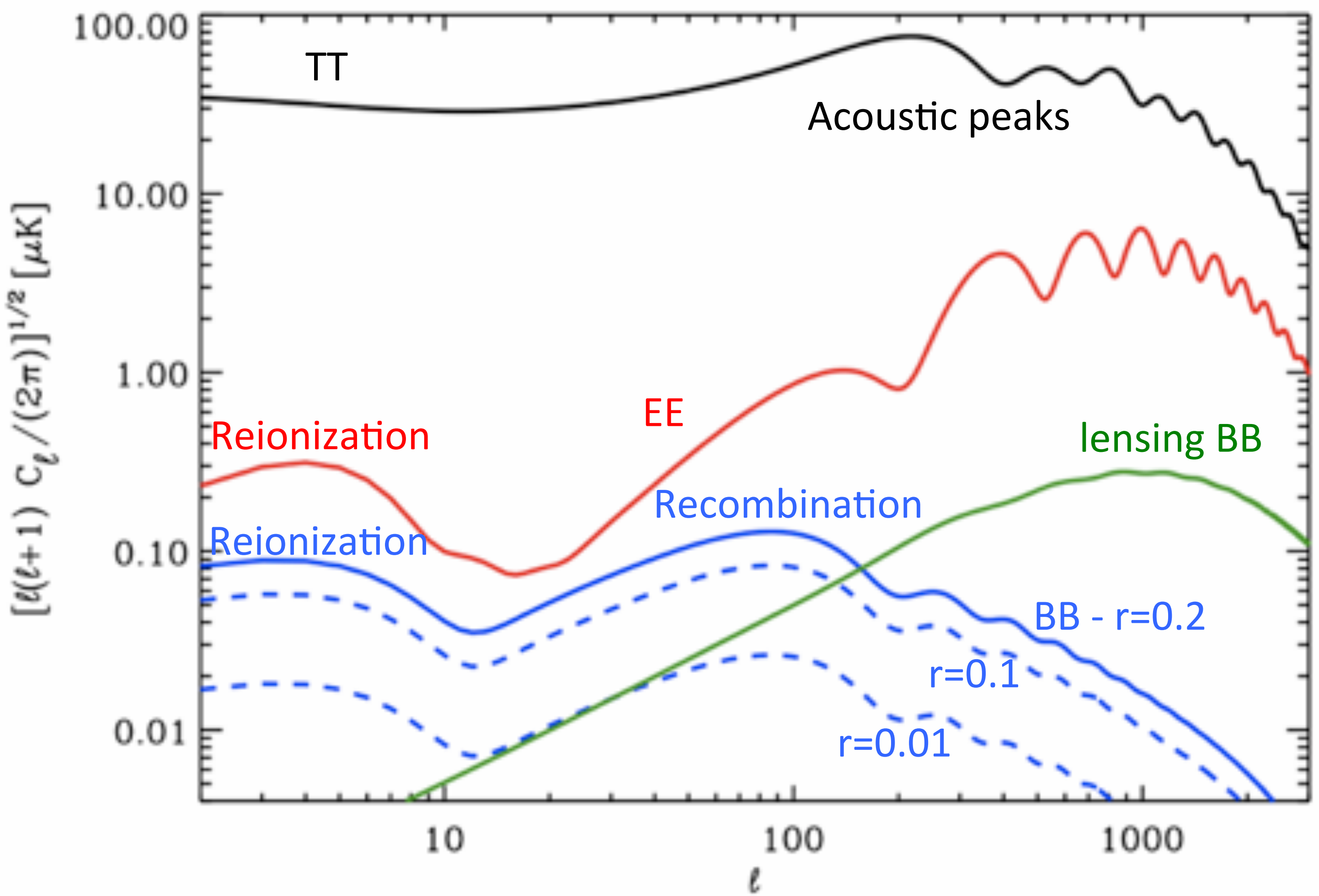
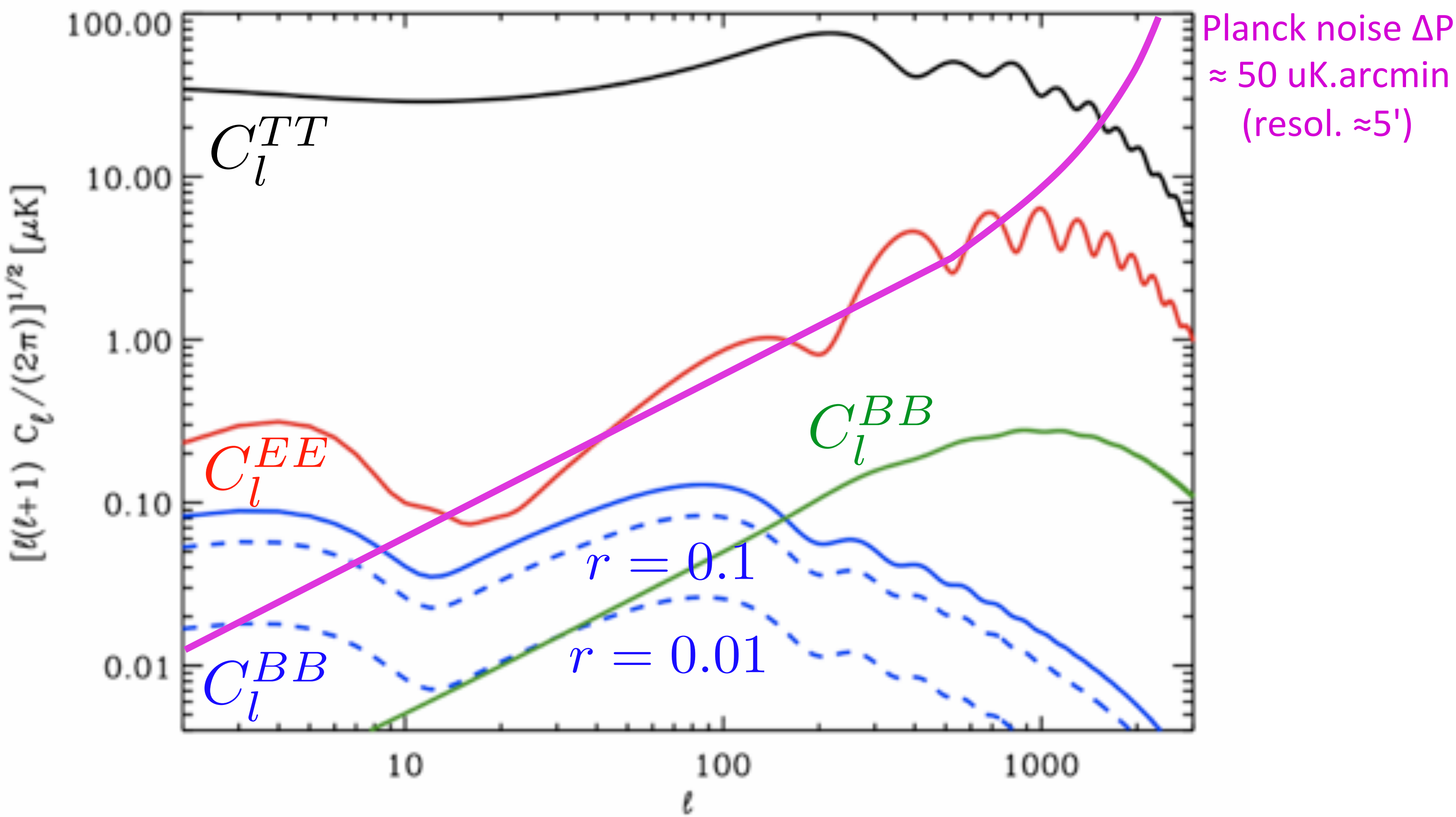


$z < 2 \times 10^6$
Thermal history
(energy injection into the CMB)
$z \approx 6$-11
Reionization
$z \approx 0$-1
Accelerated expansion
CMB emission
Inflation
Quantum Fluctuations
CMB T,E (B)
Cosmological model
Inflation
Physics at $\approx 10^{16}$ GeV
$E > 10^{12} \times E_{LHC}$
$z \approx 1$-3
Gravitational lensing
Dark matter distribution
$z \approx 0$-2
Sunyaev-Zeldovich effect:
Distribution of the hot gas
and velocity field

CMB TEB spectra



CMB TEB spectra



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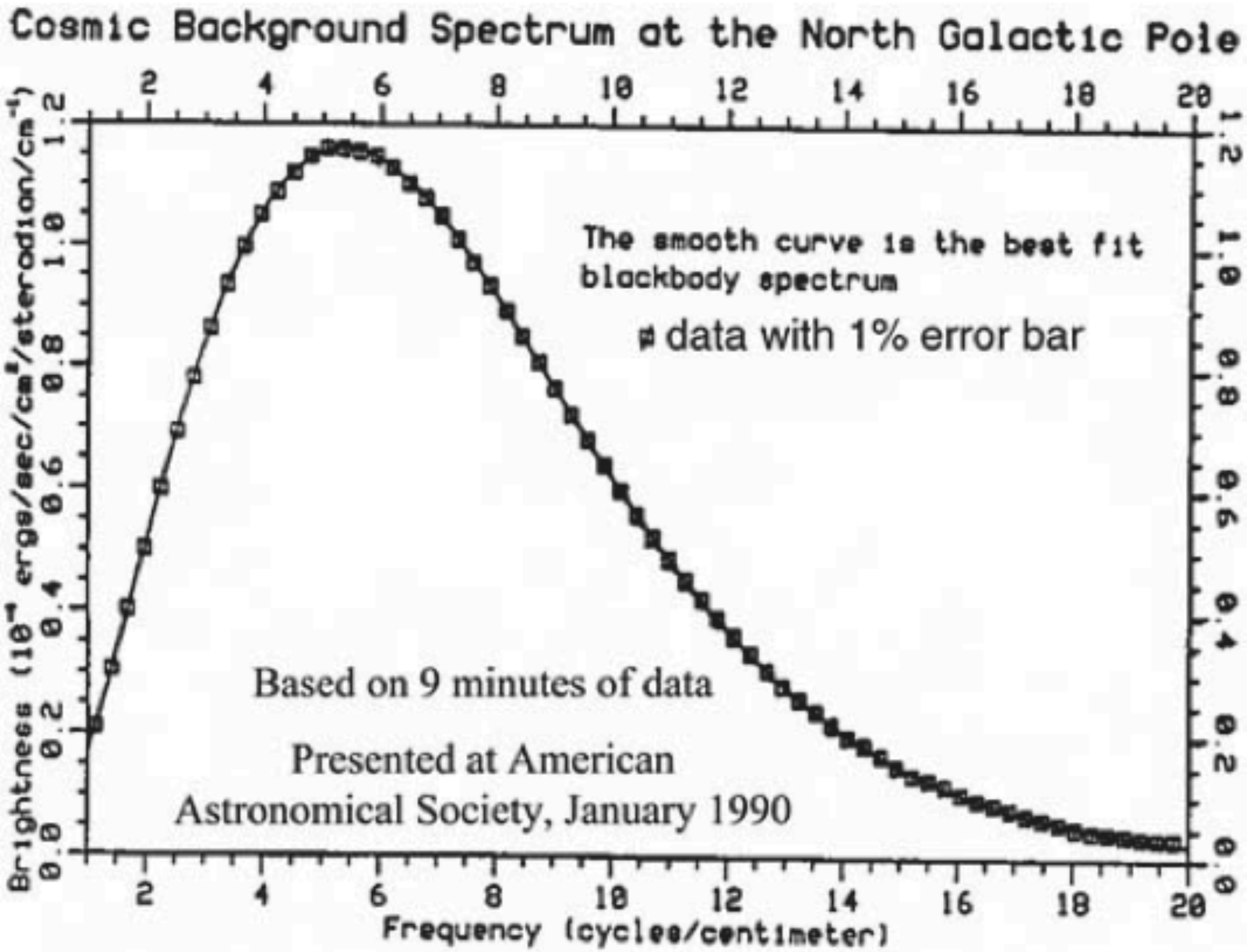
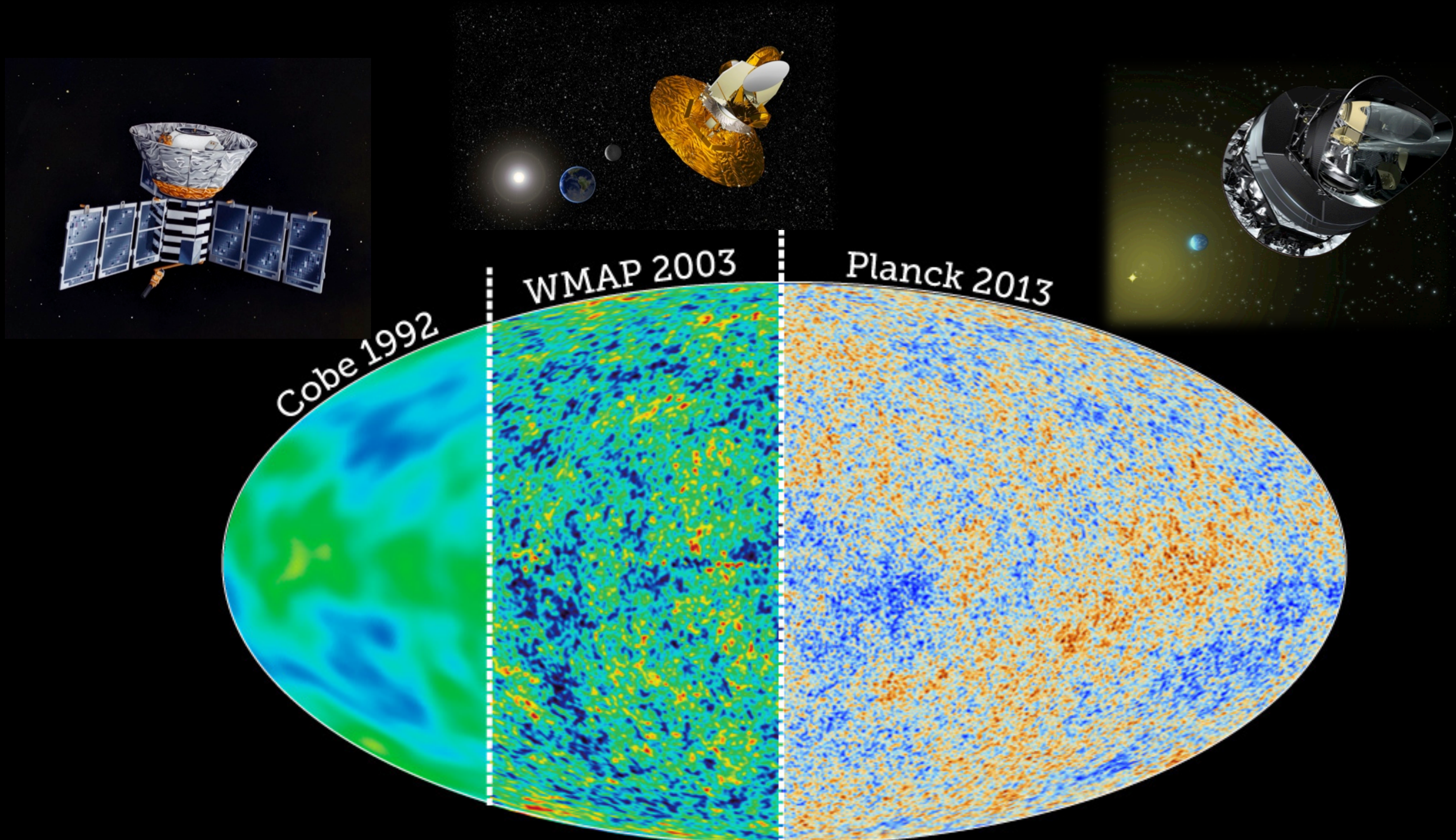
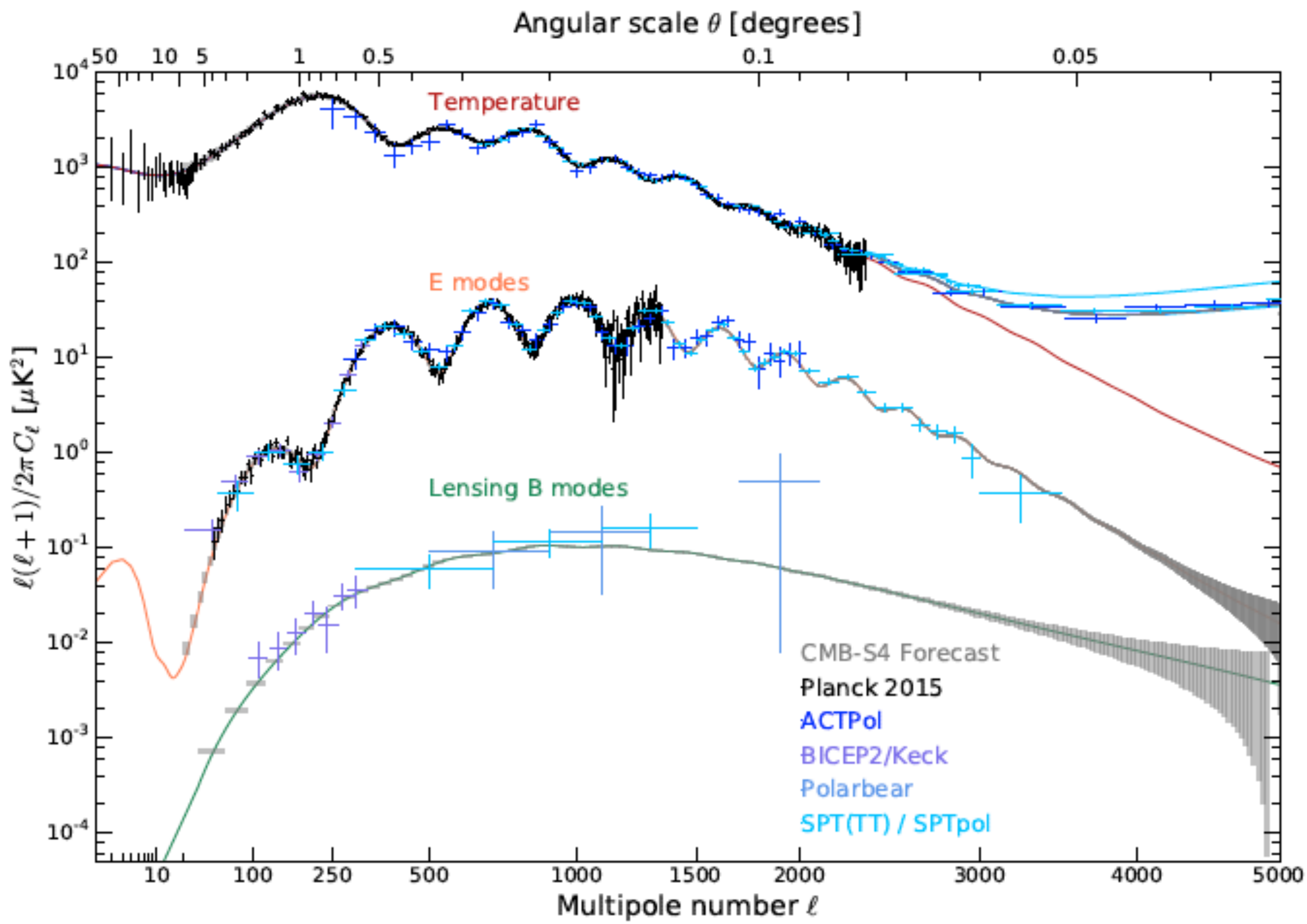
The CMB blackbody




Cobe 1992
WMAP 2003
Planck 2013

The CMB: state of the art



CMB-S4 collaboration arXiv:1610.02743

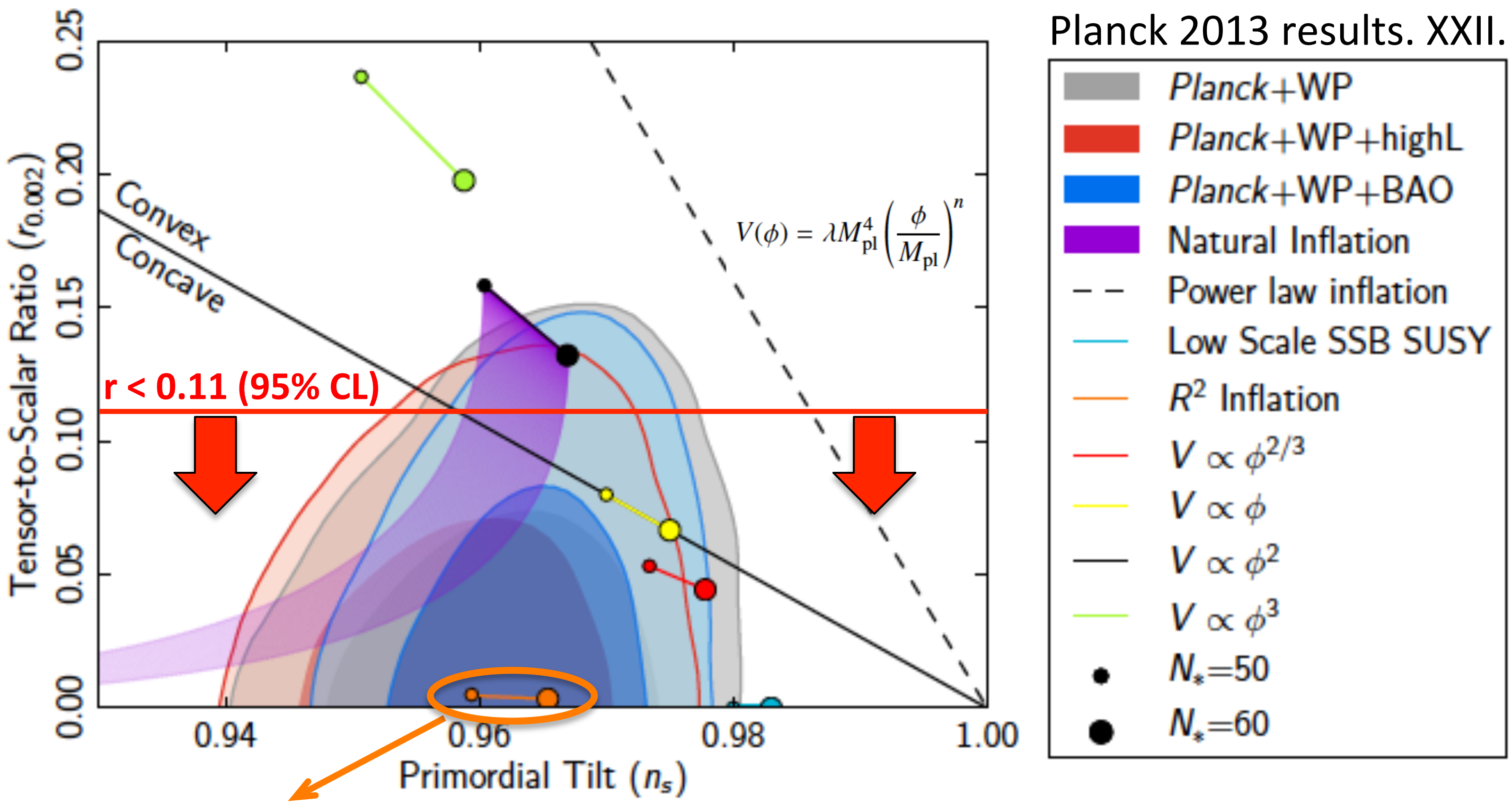
The CMB: state of the art

- 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 ≈ 1% to 6%);
  - SPT: 2,500 sq. deg. with 1.2' beam and $\Delta T = 18$ μK.arcmin
  - ACT: 600 sq. deg. with 1.3' beam and $\Delta T = 17$ μK.arcmin
  - BICE2P-Keck: 400 sq. deg. with 1.3' beam and $\Delta P = 3$ μK.arcmin

Where the action is: primordial B

Planck 2013 results. XXII.

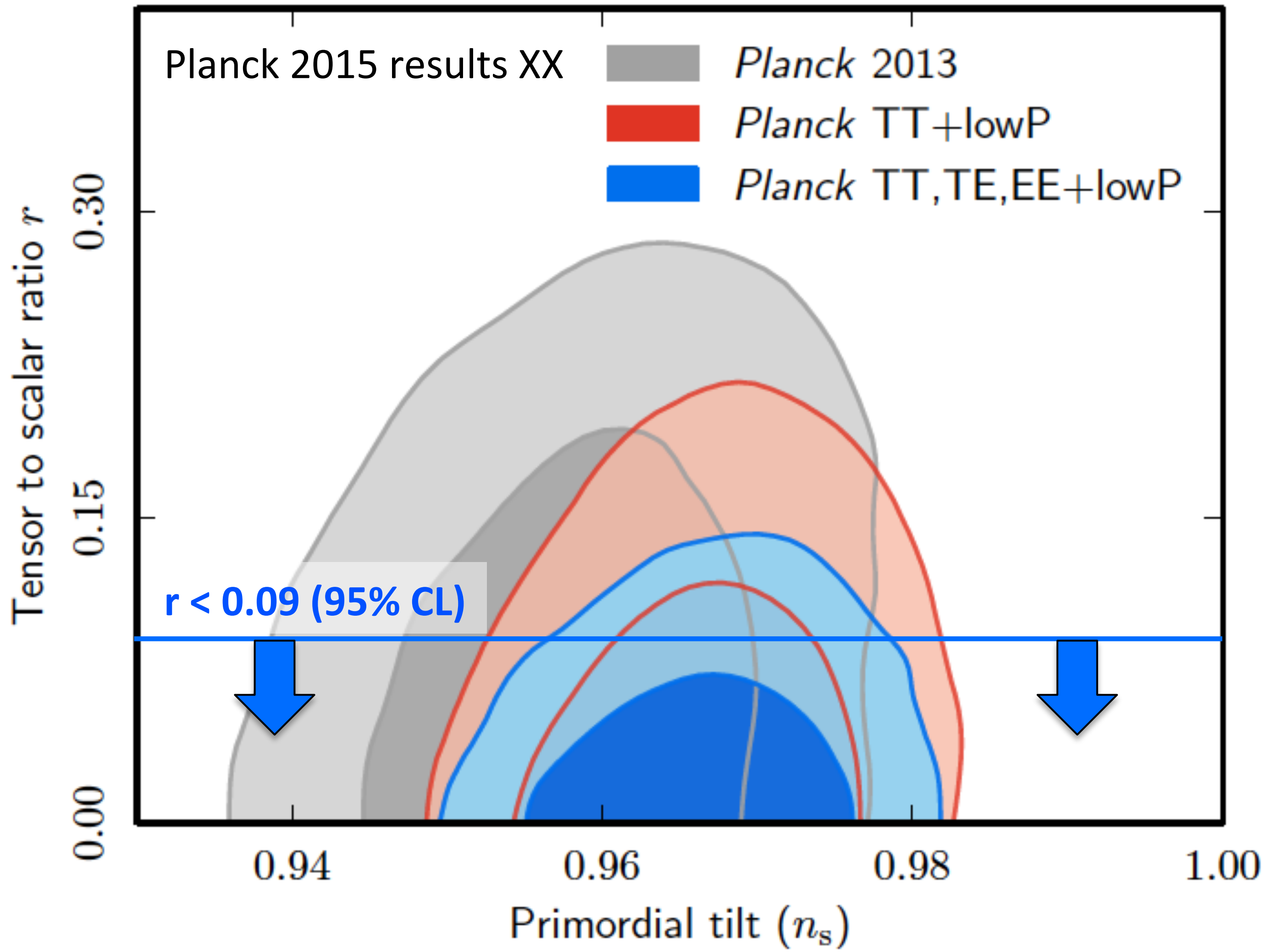


R^2 inflation: $n_s - 1 \approx -2/N_*$

$r \approx 12/N_*^2$

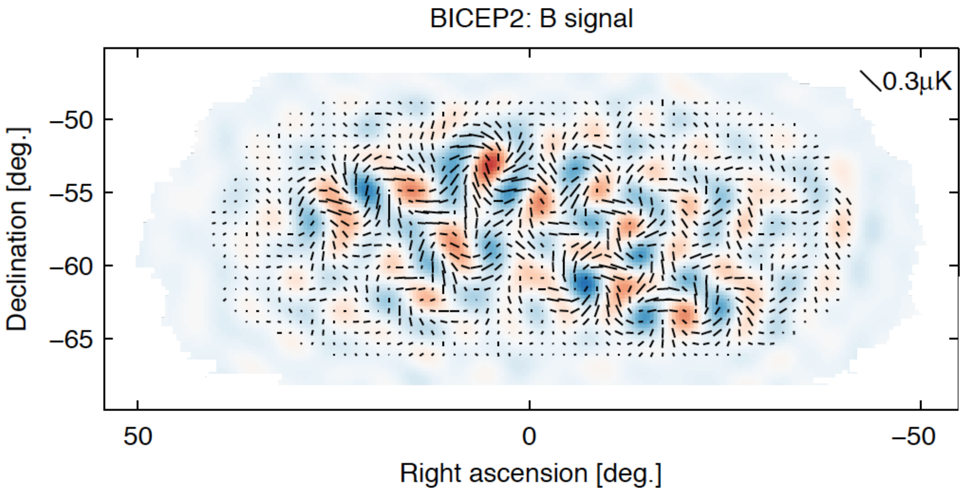
and hence low tensor modes

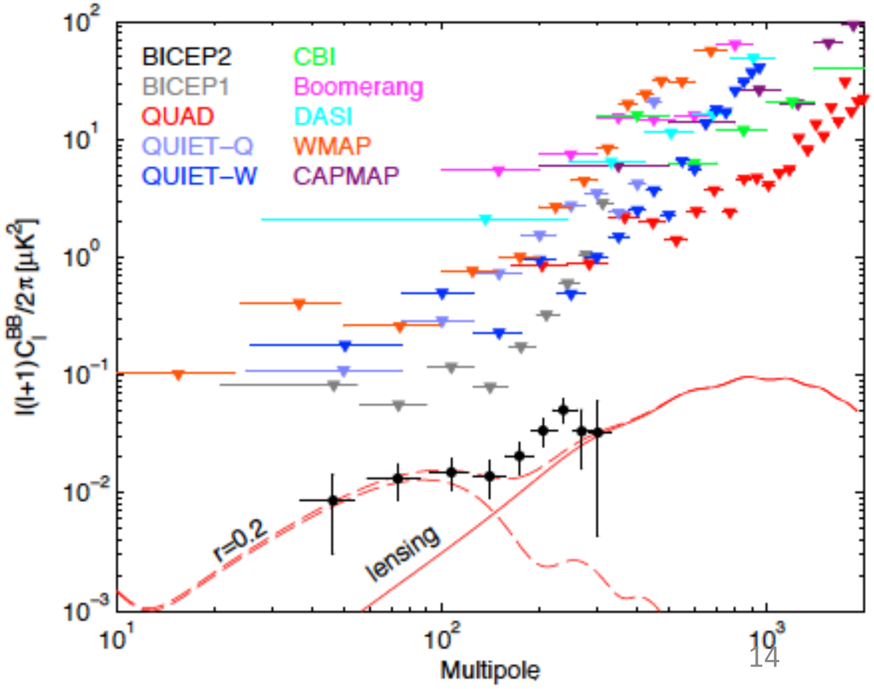
Where the action is: primordial B



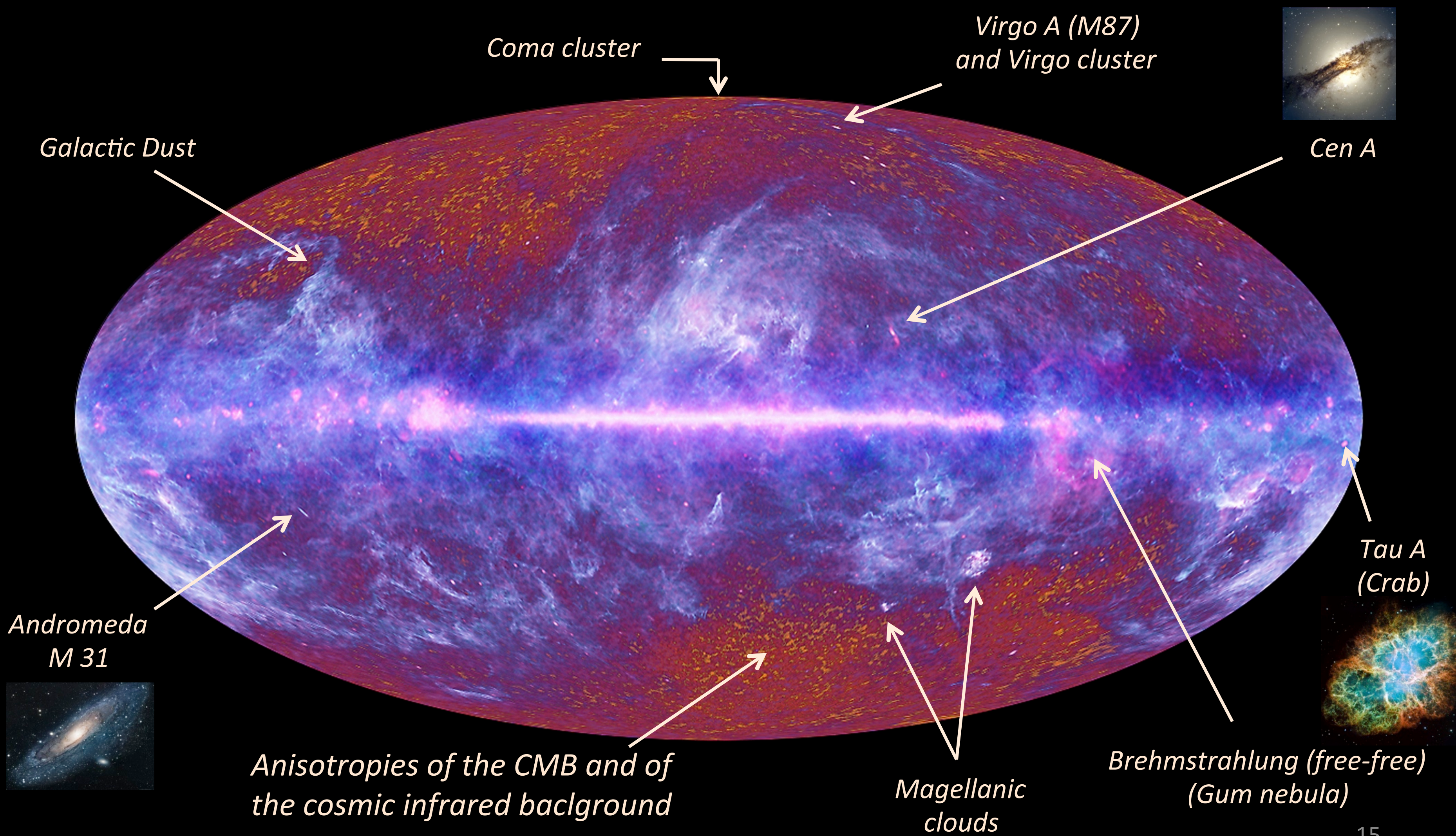
Where the action is: primordial B

BICEP2 hint of B modes: *PRL 112, id.241101 (2014)*
Revision with Planck: *PRL 114, id.101301 (2015)*





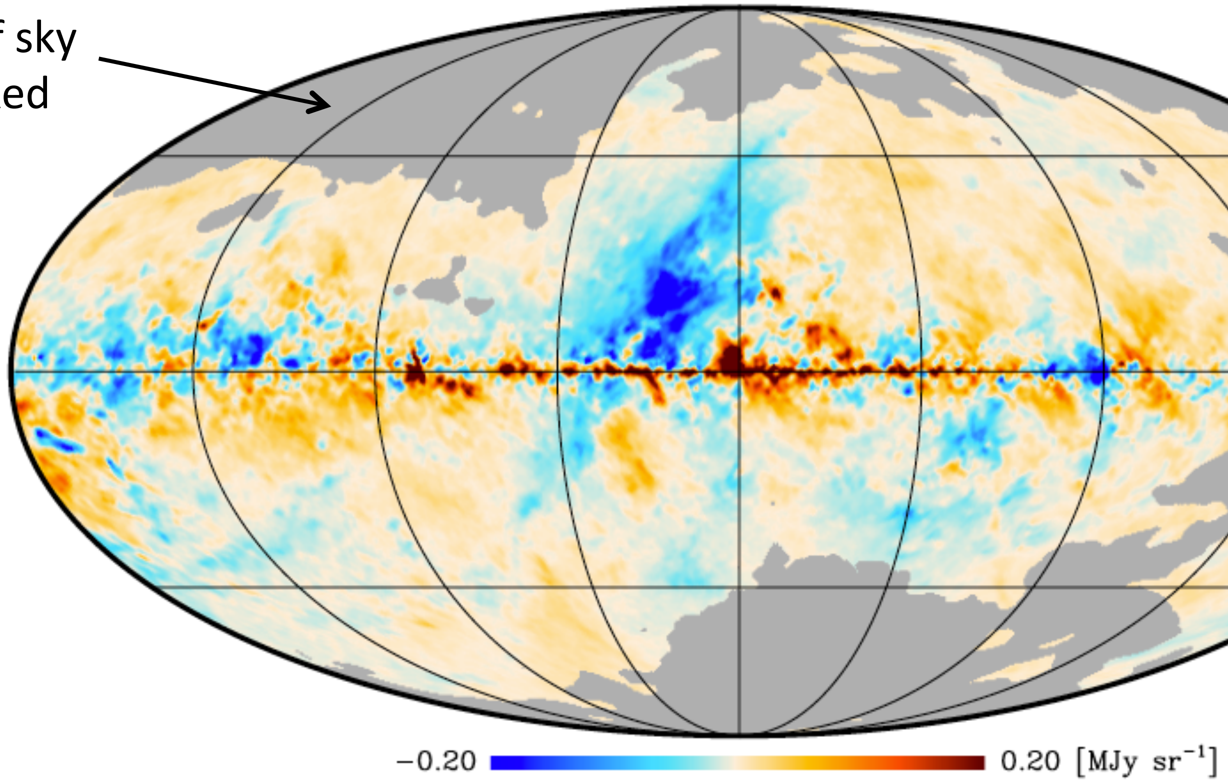
Foreground emission



Dust contamination ?

Planck U Stokes parameter at **353 GHz** (Planck collaboration, PIP XIX).

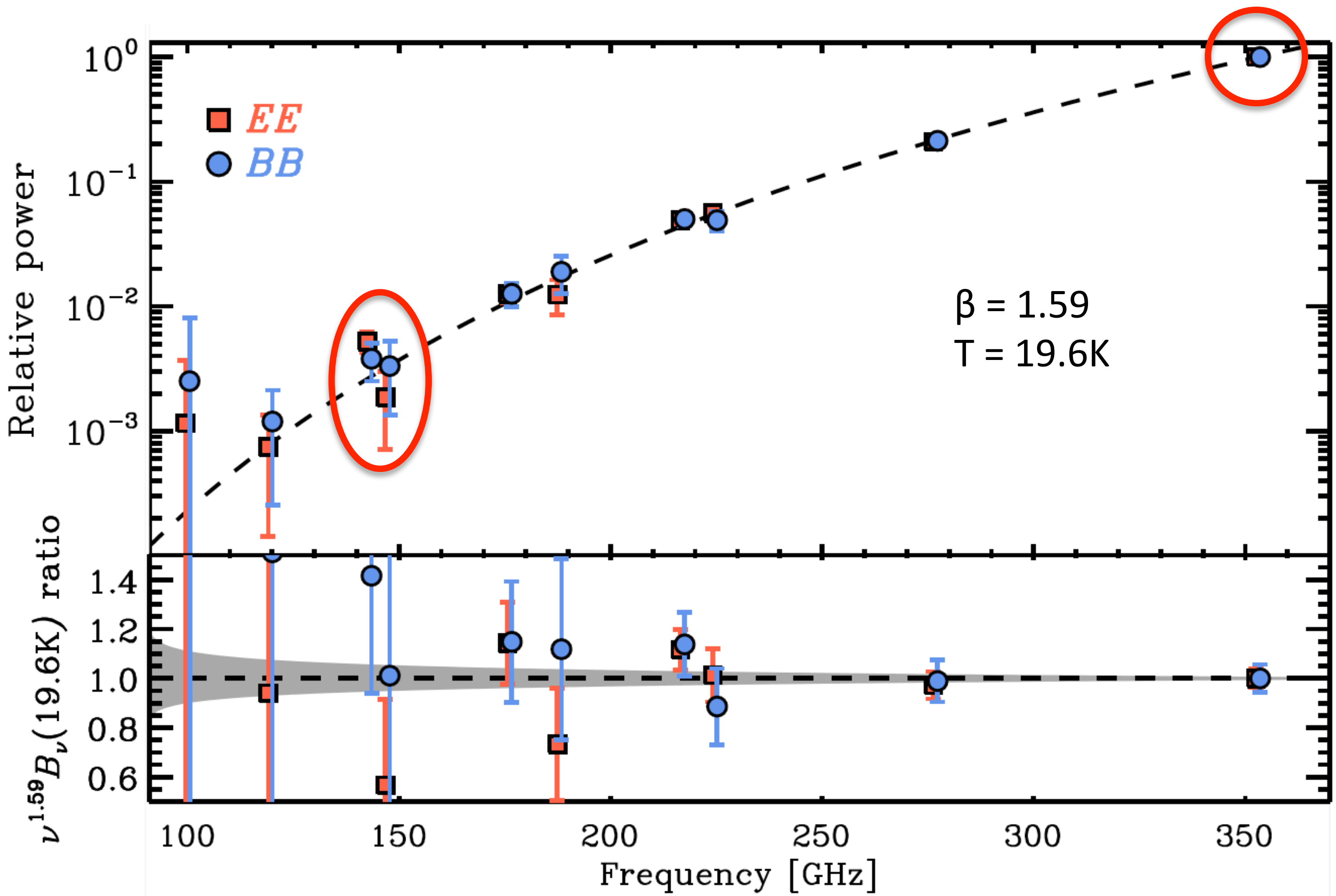
21% of sky masked



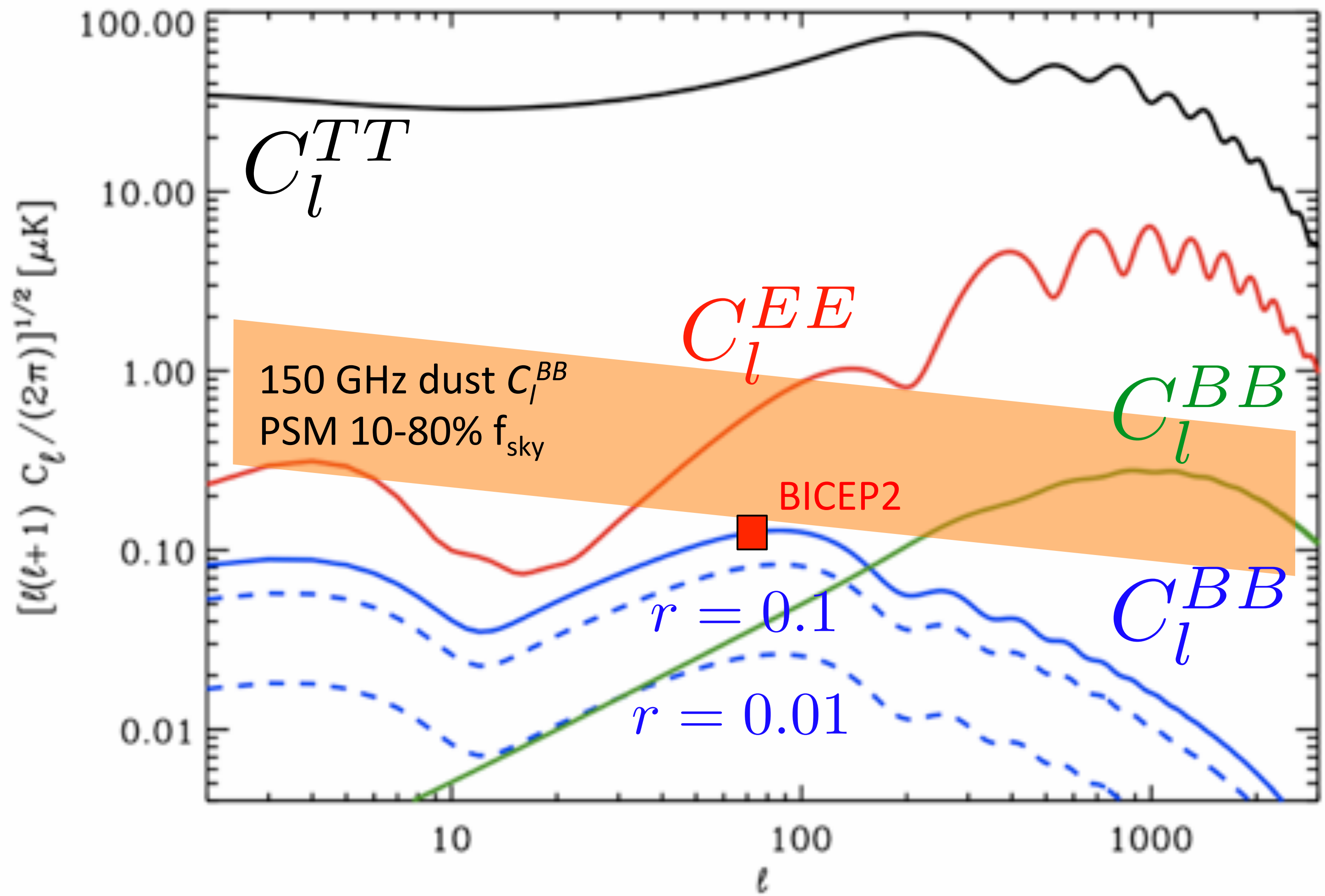
Polarised emission from elongated dust grains aligned in the galactic magnetic field

Dust contamination !

Planck Intermediate Results XXX



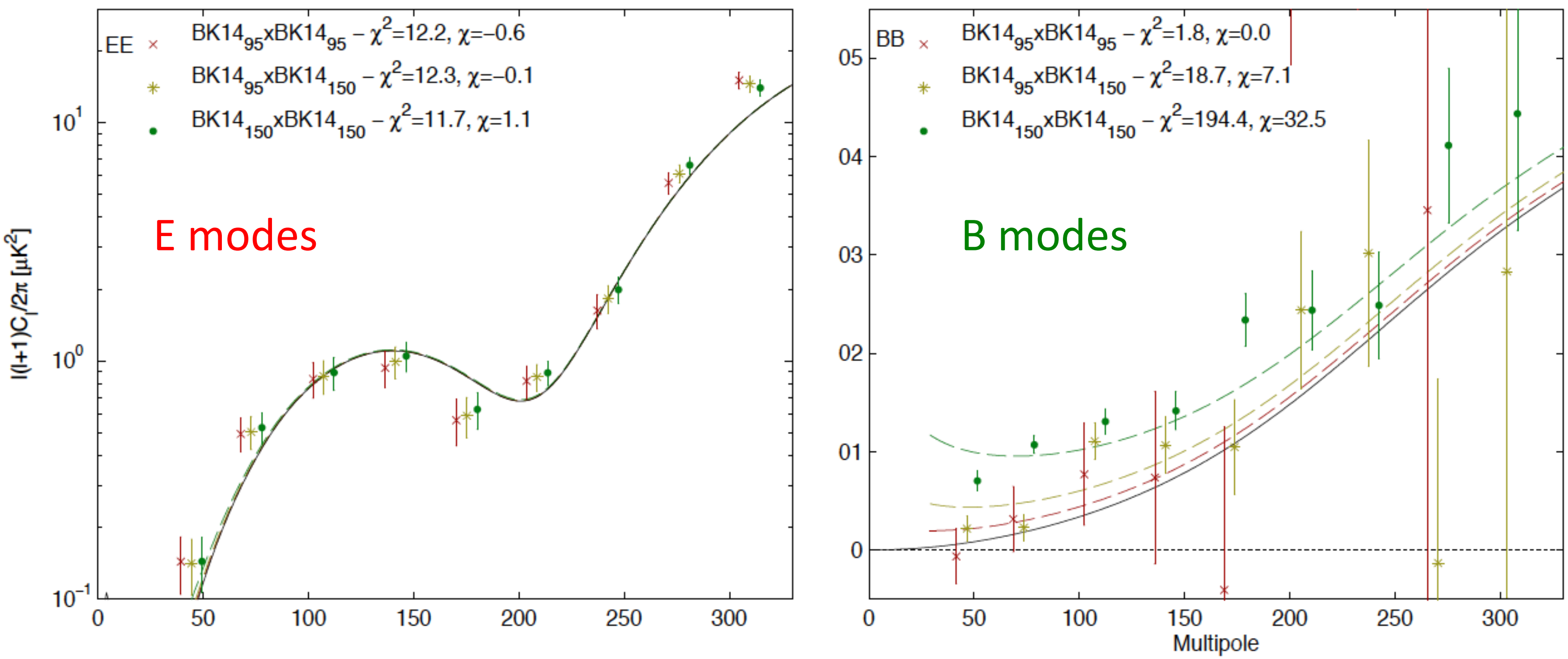
Dust B-mode C_l



Lensing of EE

Inflationary Gravitational Waves

Where the action is: primordial B



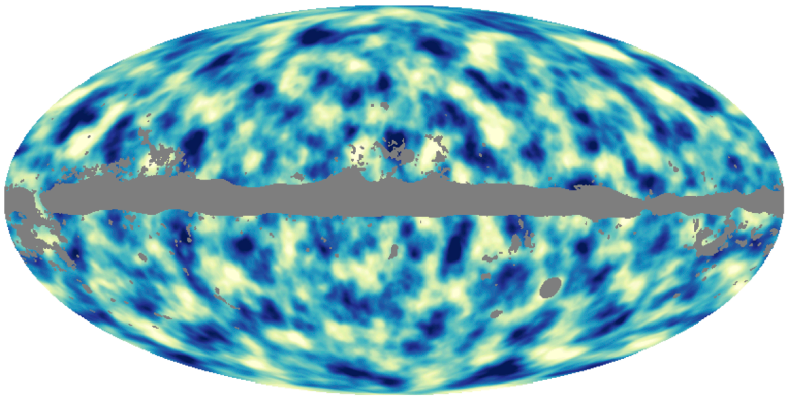
PRL 116, id.031302 (2016)

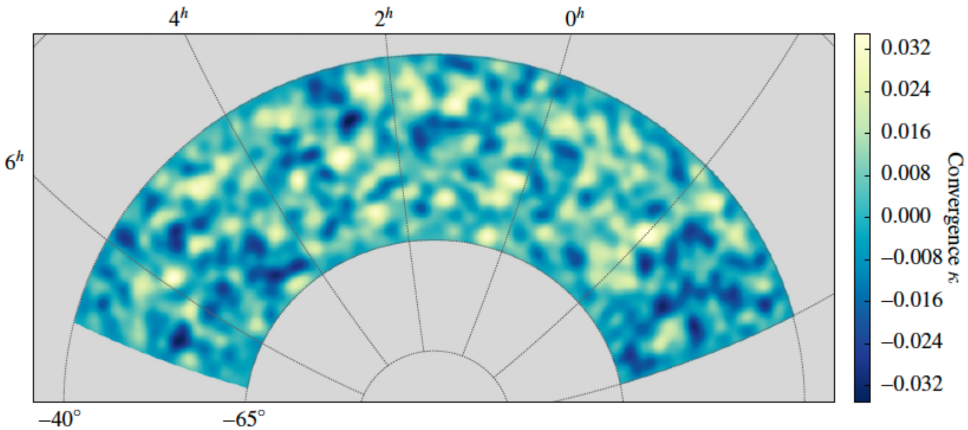
Where the action is: lensing

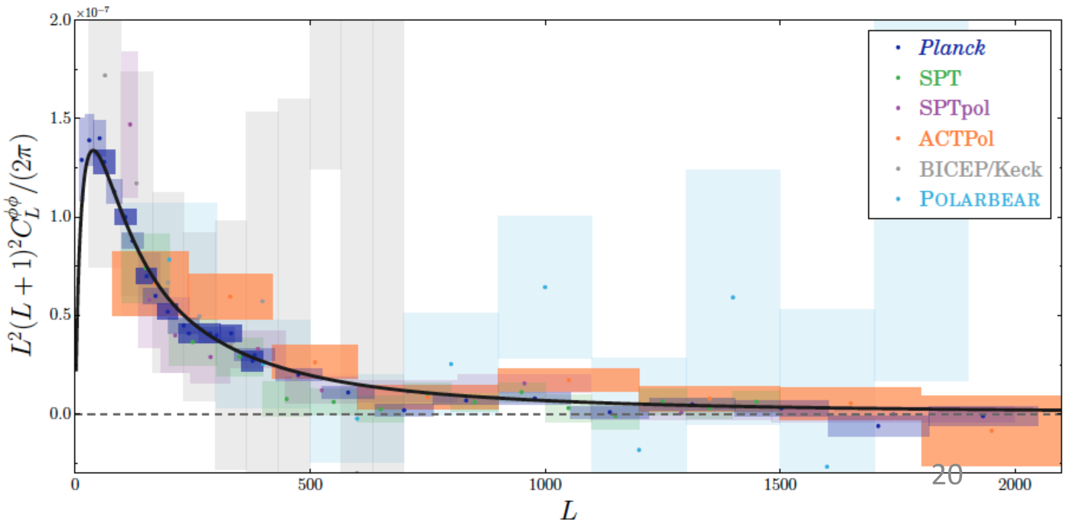
Planck lensing:
Planck Collaboration A&A 571, 17 (2014)
Planck Collaboration A&A 594, 15 (2016)

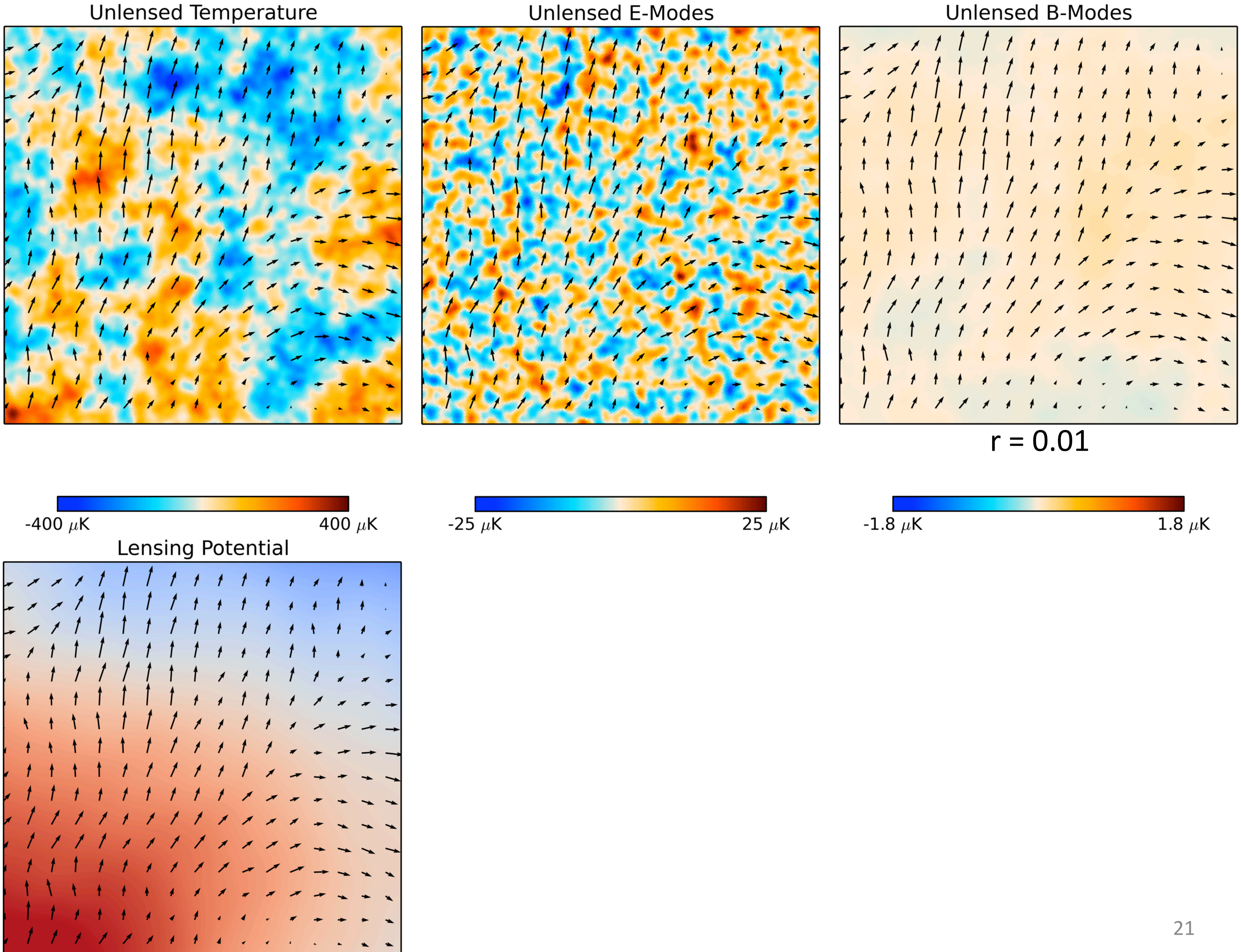
SPT lensing: *PRL 114, id.101301 (2015)*

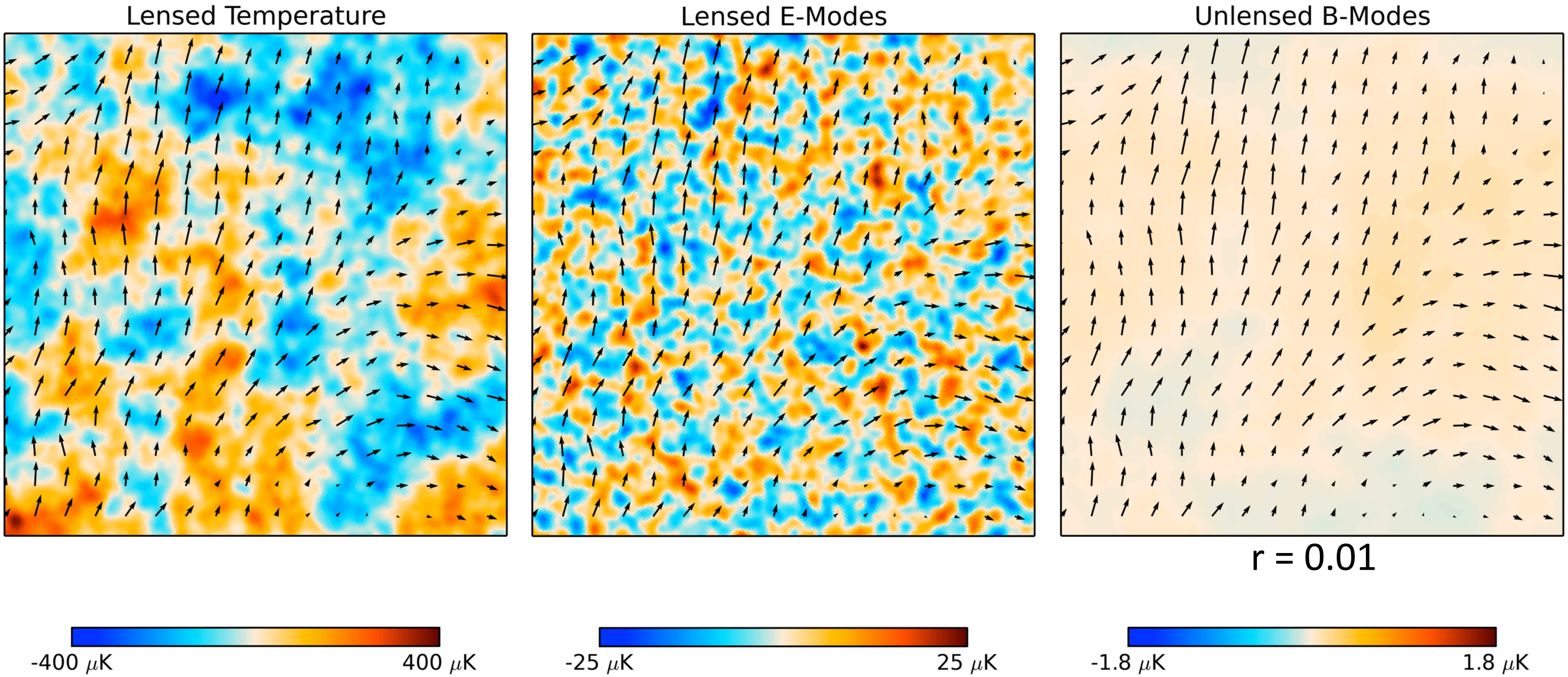
Lensing potential from Planck

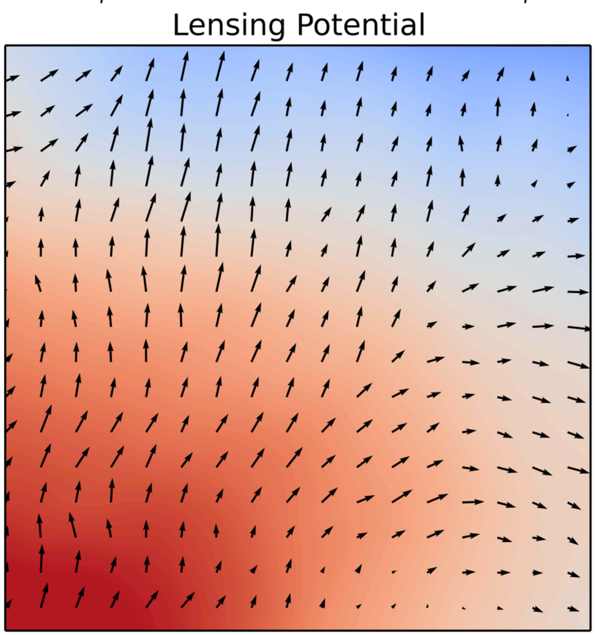




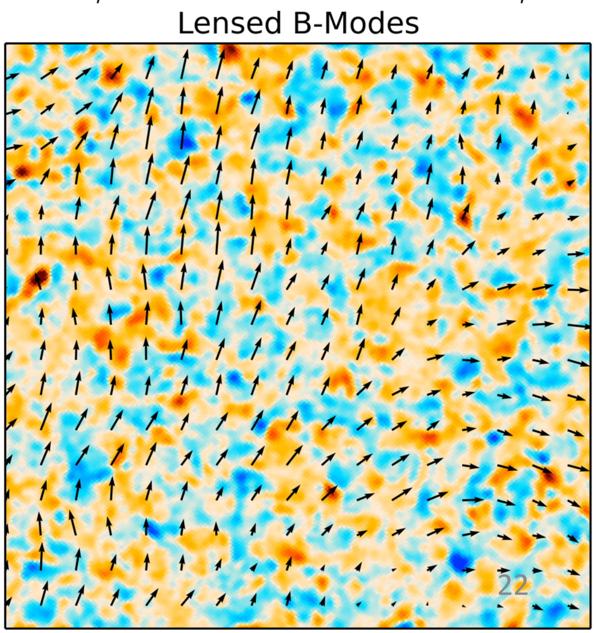



Unlensed Temperature
Unlensed E-Modes
Unlensed B-Modes
r = 0.01
-400 μK
400 μK
-25 μK
25 μK
-1.8 μK
1.8 μK
Lensing Potential





Gravitational lensing of the CMB



Where the action is: "delensing"

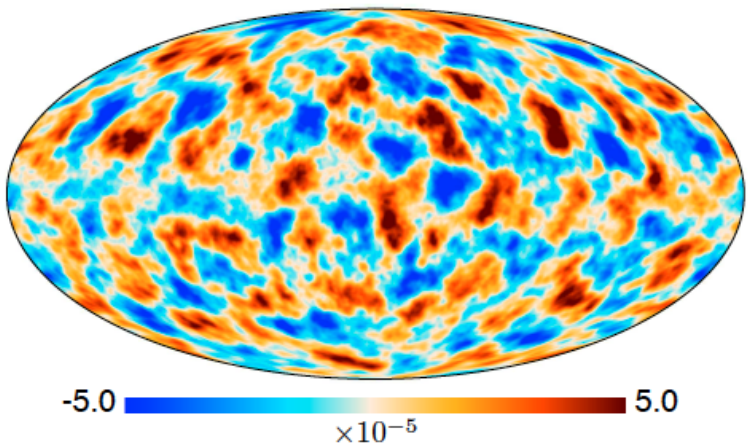
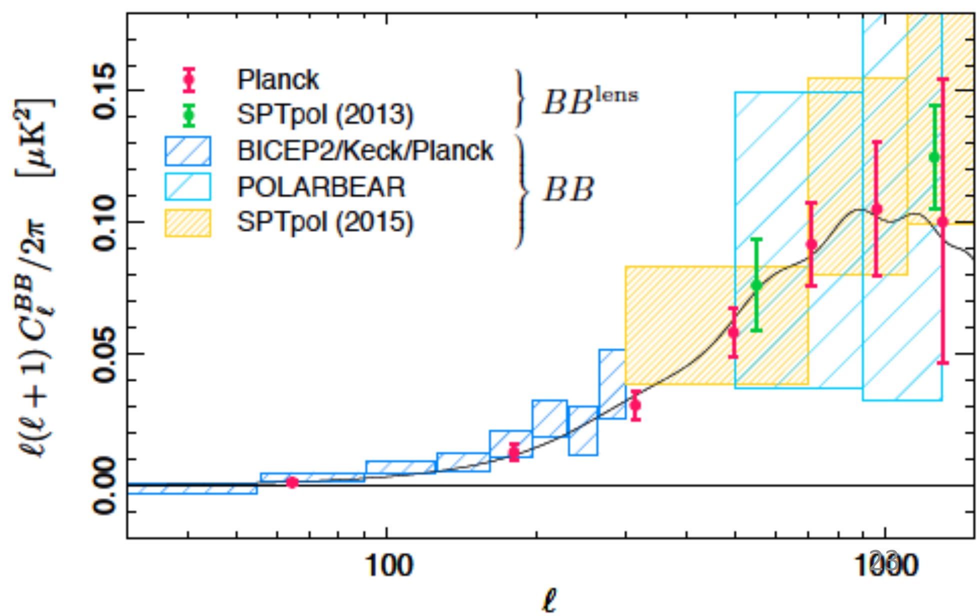


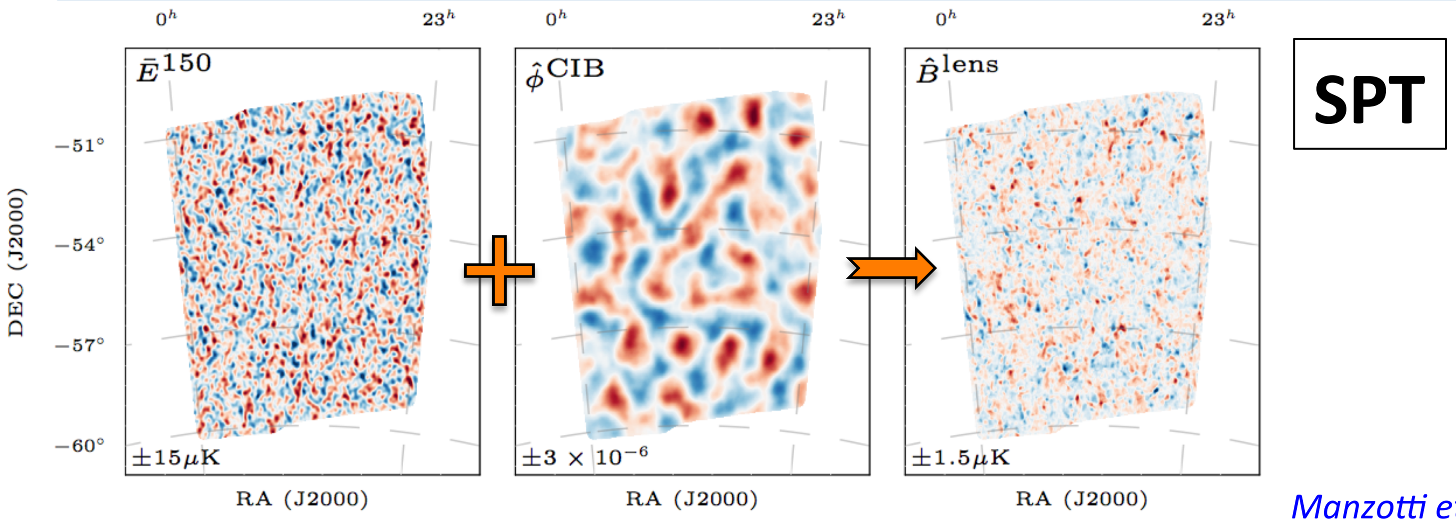
Figure 1. Wiener-filtered lensing potential estimated from the SMICA foreground-cleaned temperature map using the $f_{sky} \simeq$ 80 % lensing mask. ı is

Planck

Planck collaboration A&A 596, 102 (2016)

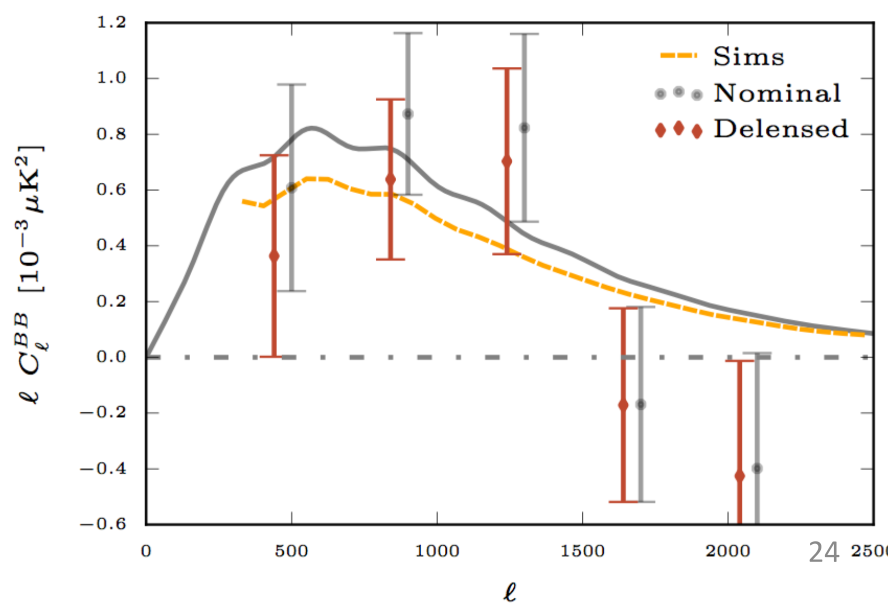


Where the action is: "delensing"



Manzotti et al. arXiv:1701.04396

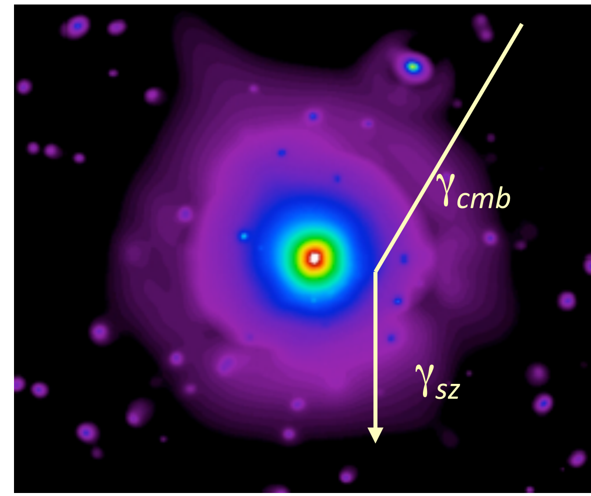
Use lensing potential inferred from dusty galaxies (CIB) and SPT E-modes to infer lensing B-modes



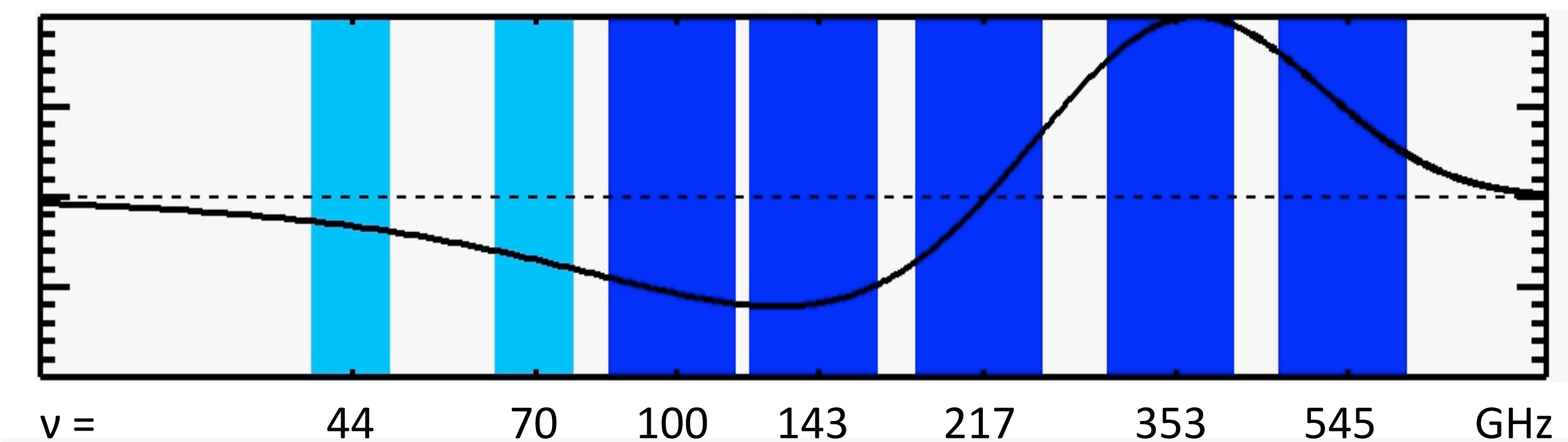
Thermal SZ effect

Clusters of galaxies are the largest gravitationally bound structures

- Sunyaev and Zel'dovich
  - Compton Interaction on ***hot electron gas***
  - Detection possible at high redshift *z*
  - The SZ distortion is a very good mass proxy

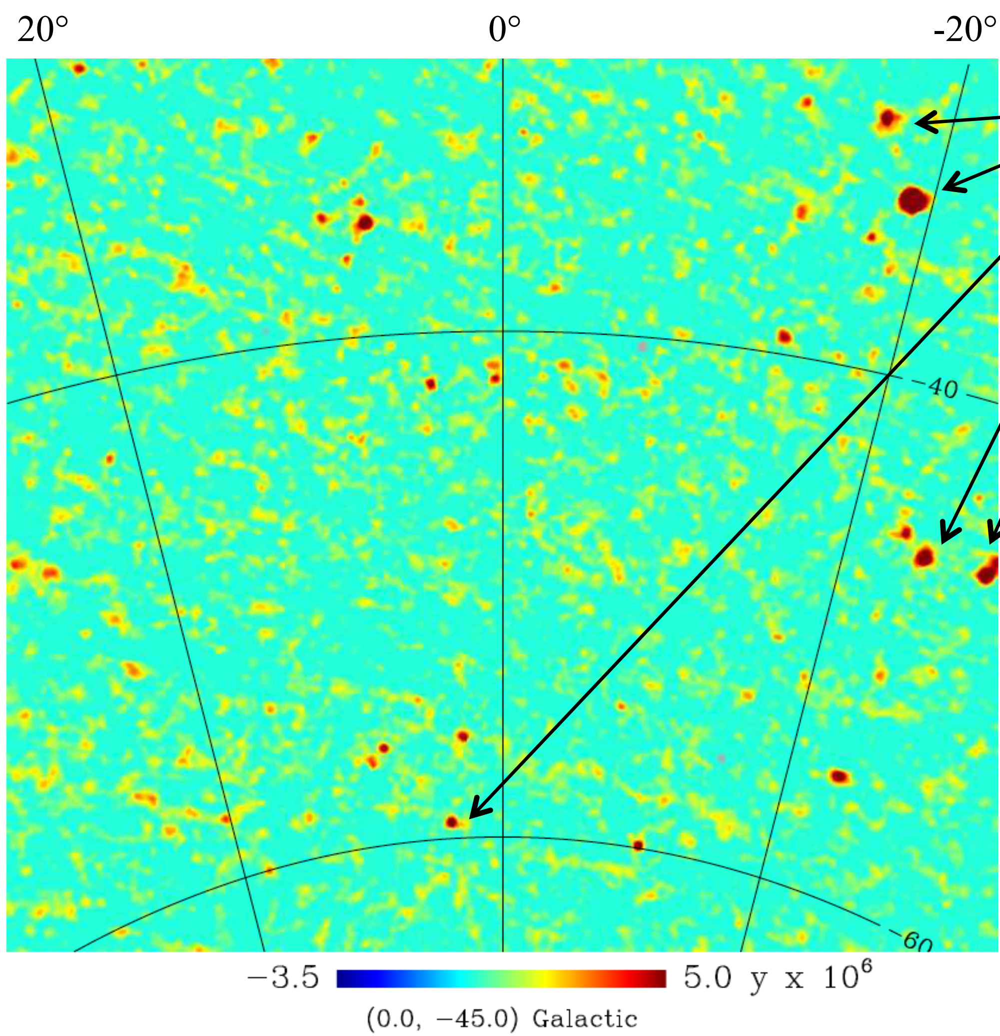


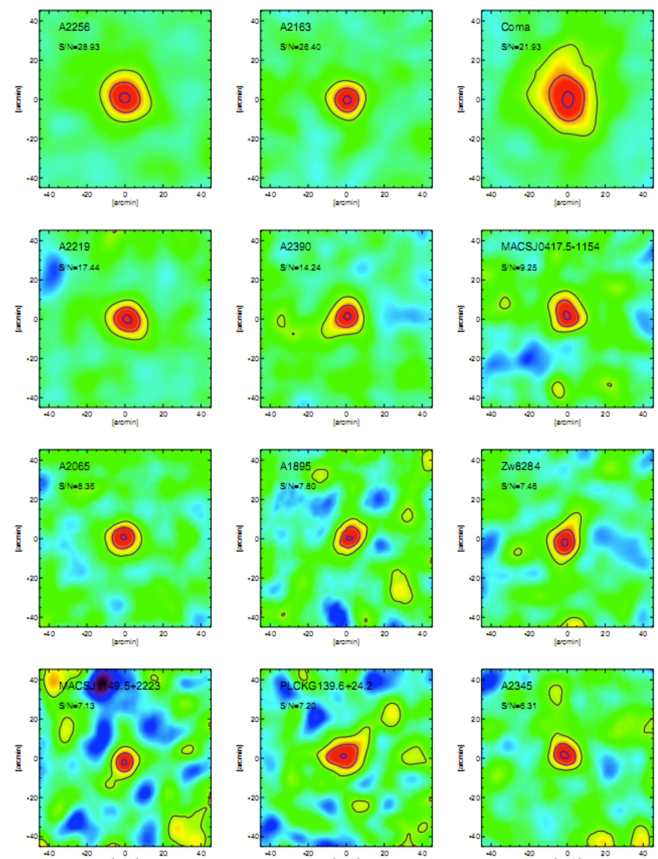
LFI **HFI**



Planck maps of SZ clusters

Galaxy clusters

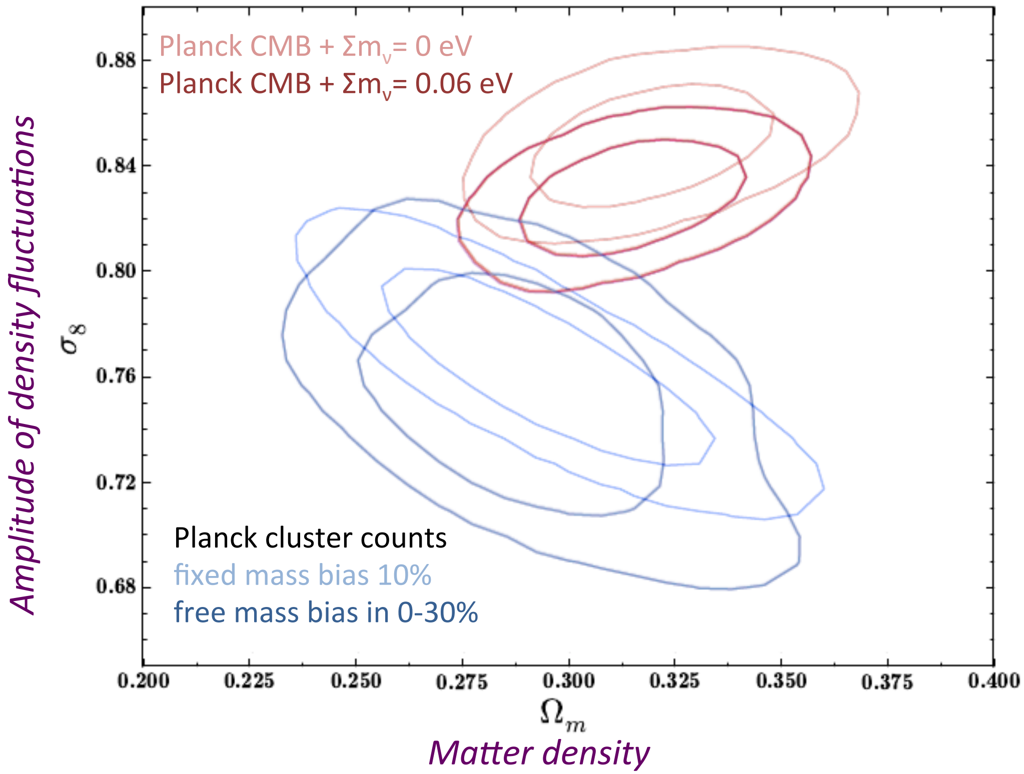


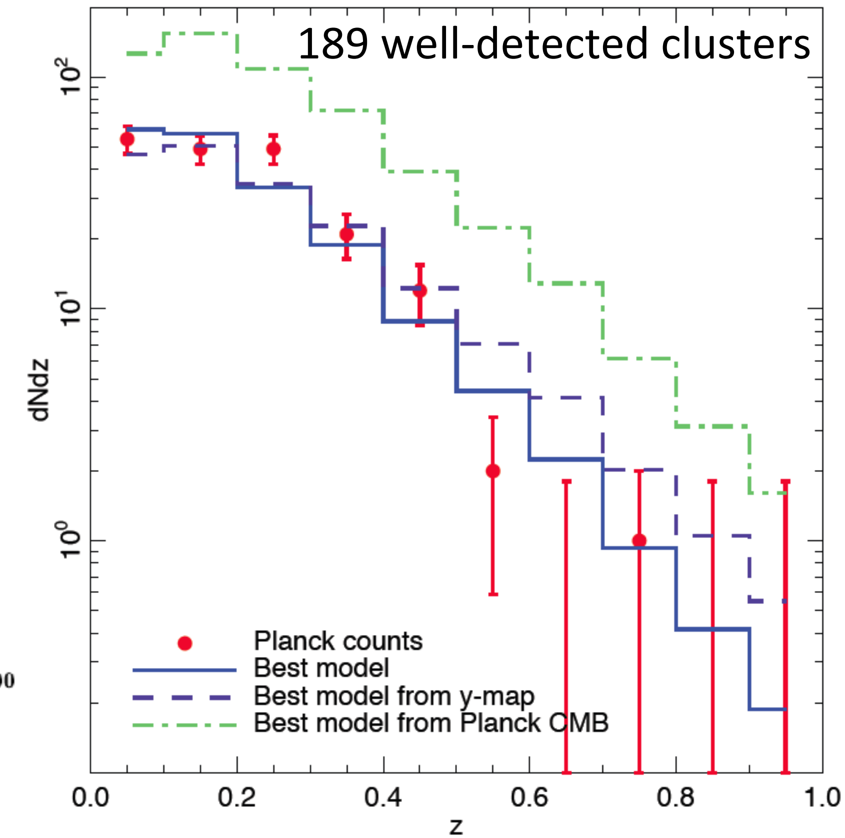


Cosmological information from clusters

- Number counts *dN/dMdV*
  - Growth of structures Ω_m, Λ (dark sector in general)
  - Spectrum *P(k)* (σ_8)
- Number counts *dN/dMdz(dΩ)*
  - Geometry $D_A(z)$, $H(z)$
- Cosmological tests
  - Velocity flows (modified gravity)
  - Correlations (SZ, ISW, lensing…)
  - Power spectrum of thermal and kinetic SZ
- Angular vs. physical size
- Gas fraction M_g/M_{tot}
- Cluster physics

Cosmological constraints from clusters 2013





CMB best fit cosmology overpredicts the number of observed clusters

Revise cluster physics (Y_{SZ}-M scaling) ?

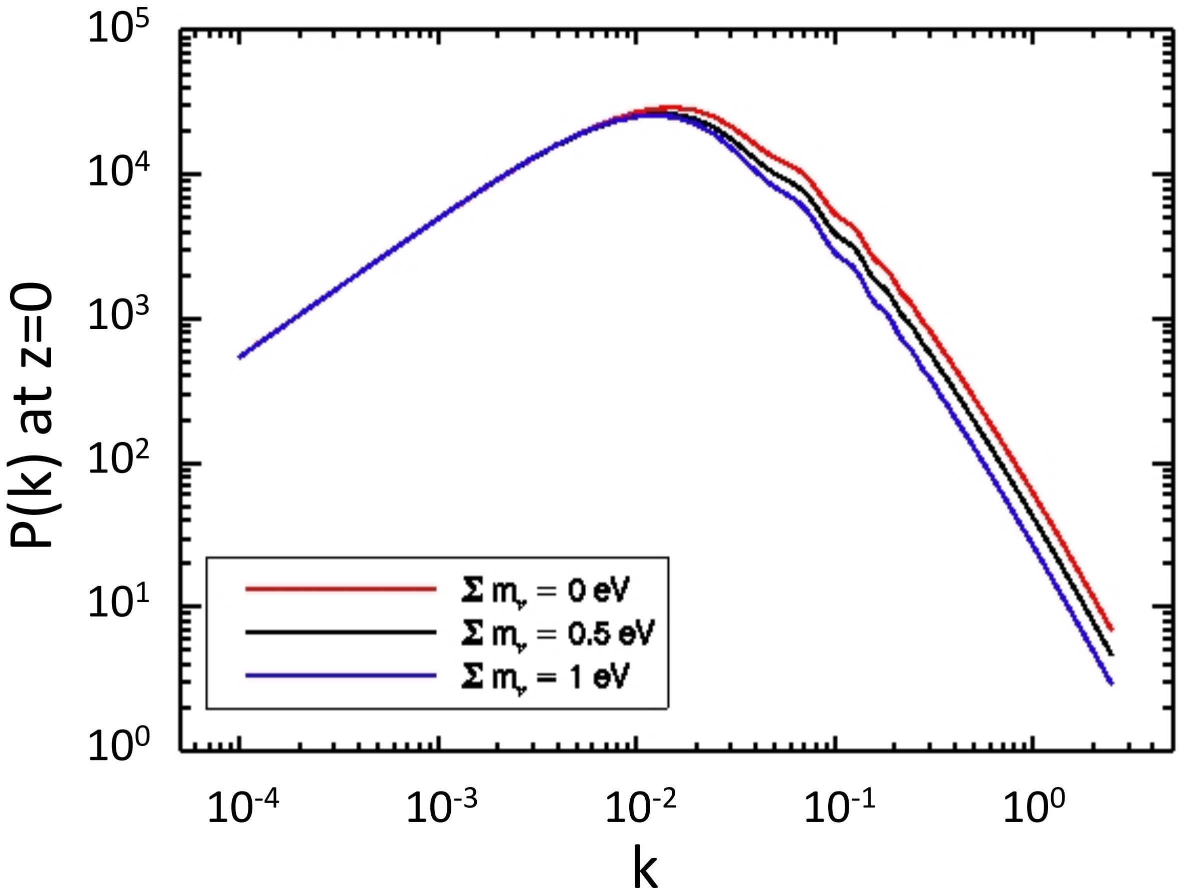
Revise matter and energy content?

$$Y_{SZ} = f(M)$$

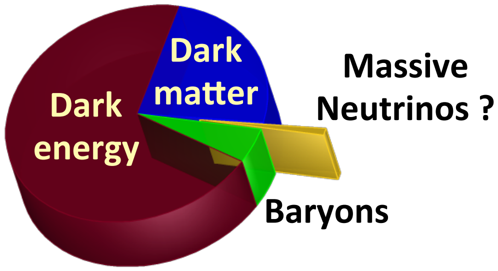
⇓

$$Y_{SZ} = (1-b) \times f(M)$$

A handle on neutrino masses



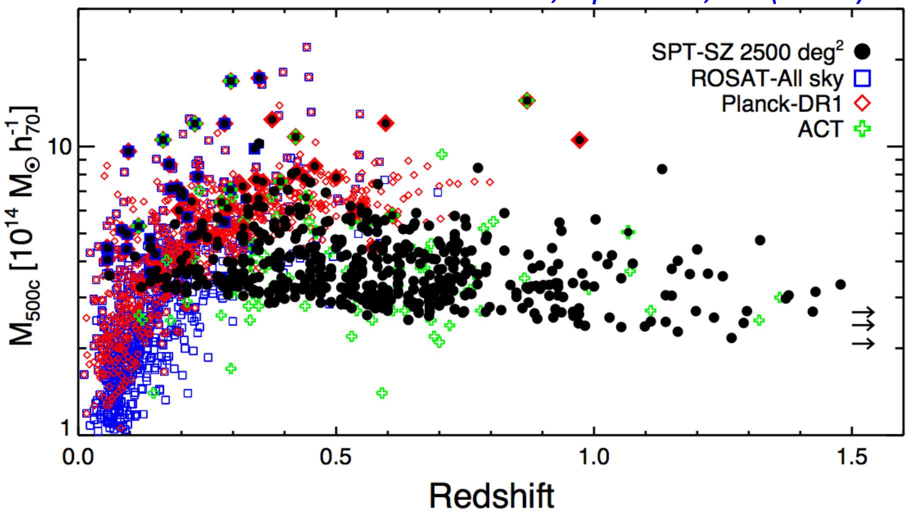
A fundamental question:
Absolute neutrino masses



A total mass of light neutrino species of 0.3 eV would solve the discrepancy

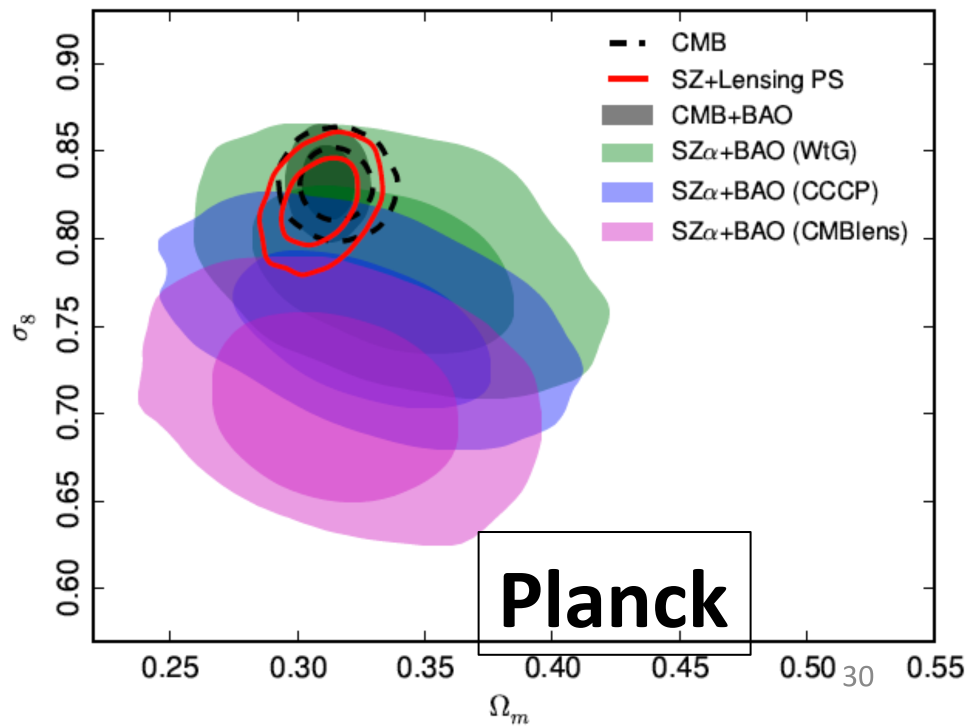
Where the action is: galaxy clusters

Bleem et al., ApJS 216, 27 (2015)



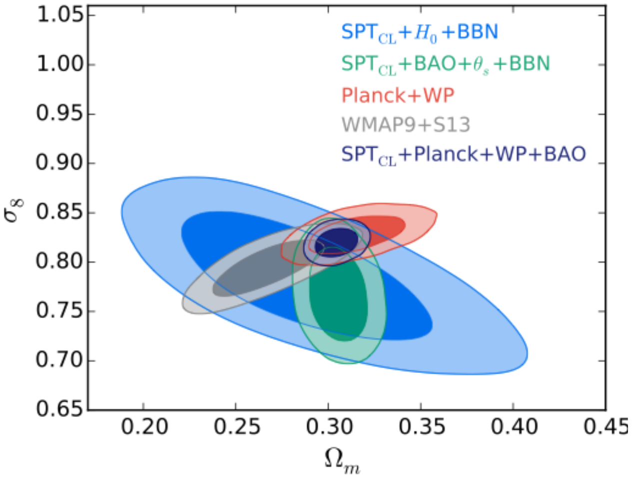
Clusters detected through the Sunyaev-Zel'dovich (SZ) effect

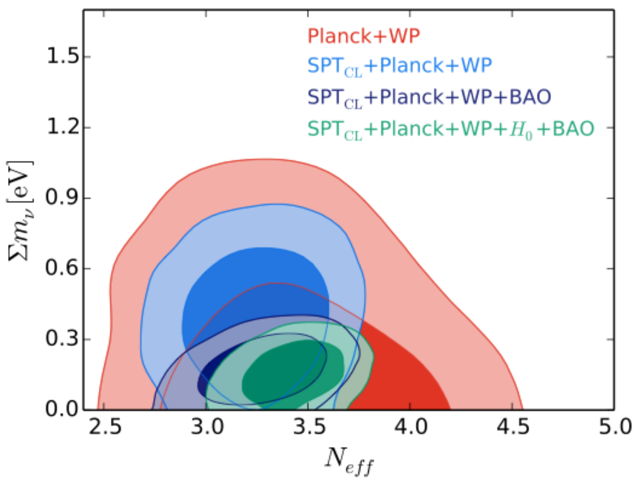
Planck collaboration A&A 594, 24 (2016)

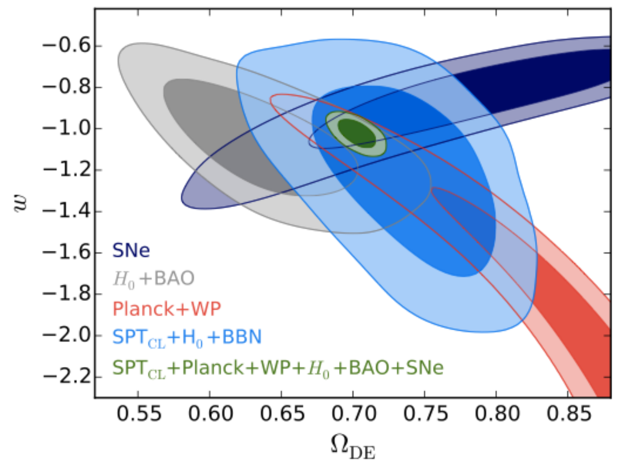


Where the action is: galaxy clusters

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







Structures
$\Omega_m - \sigma_8$

Neutrinos
$N_{eff} - \Sigma m_\nu$

Dark Energy
$\Omega_{DE} - w$

SPT

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Scientific Case: what next?

- Very good fit of many cosmological observations ($H, \Omega_m, \Omega_b, \tau, A_s, n_s, \ldots$) in spite of mild "tensions" (H_0, σ_8, A_L...) and of possible anomalies (large scale power, alignments...)

- Did Inflation really happen?
- If so, physics of inflation? (r, n_s, running, n_t, NG...?)
- What is Dark Matter? (ν's, N_{eff}, decaying DM...?)
- What is Dark Energy? (Λ, w_0, w_1,...?)
- Fundamental physics (gravity, physics beyond SM)
- (Is the CMB a "perfect" blackbody?)
- ...
- Is the global ΛCDM picture correct?

Inflation

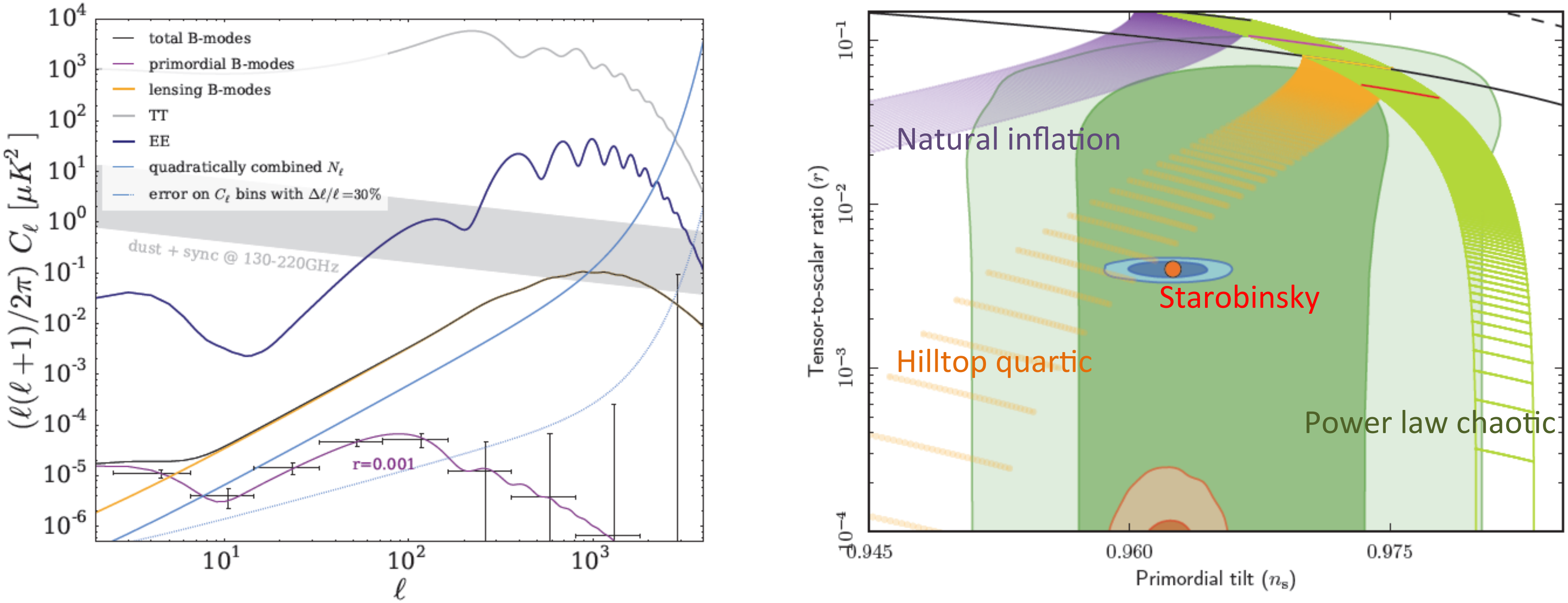
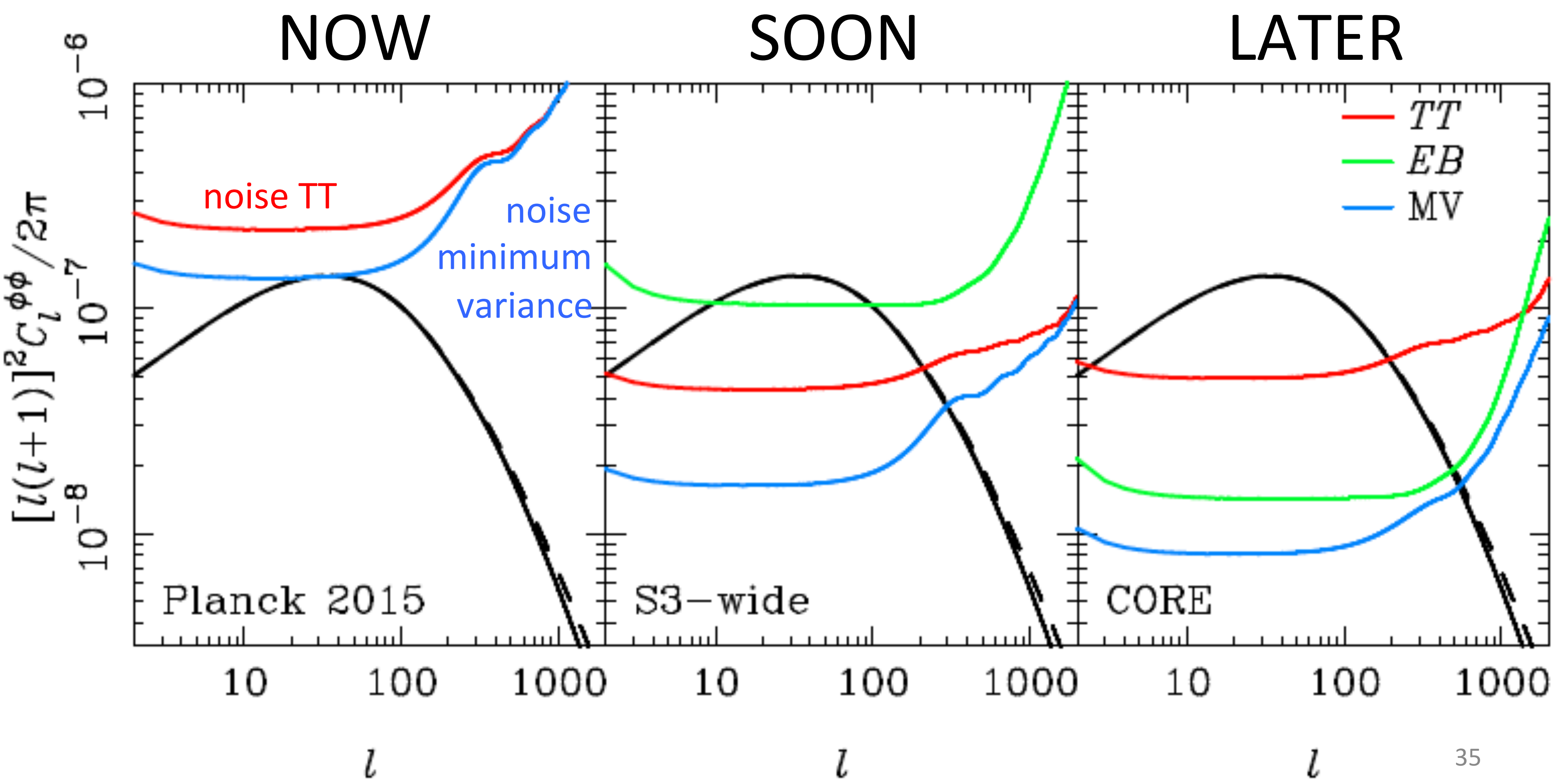


Figure 1: Left: Projected 68% CL error bars (crosses) and the theoretical prediction (purple line) for the primordial B-mode power spectrum with a tensor-to-scalar ratio of $r = 0.001$. The orange line shows the secondary B-mode power spectrum from gravitational lensing while the black line shows their 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



Detailed validation of the model

Inflationary parameters (initial conditions)

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

Spatial curvature

$$\Omega_k h^2 = 0$$

Dark Energy equation of state

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

Neutrino sector

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

Helium abundance

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

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The CMB can still reduce the error box volume

by a factor >10^6

(a factor of ≈5 on each parameter on average)

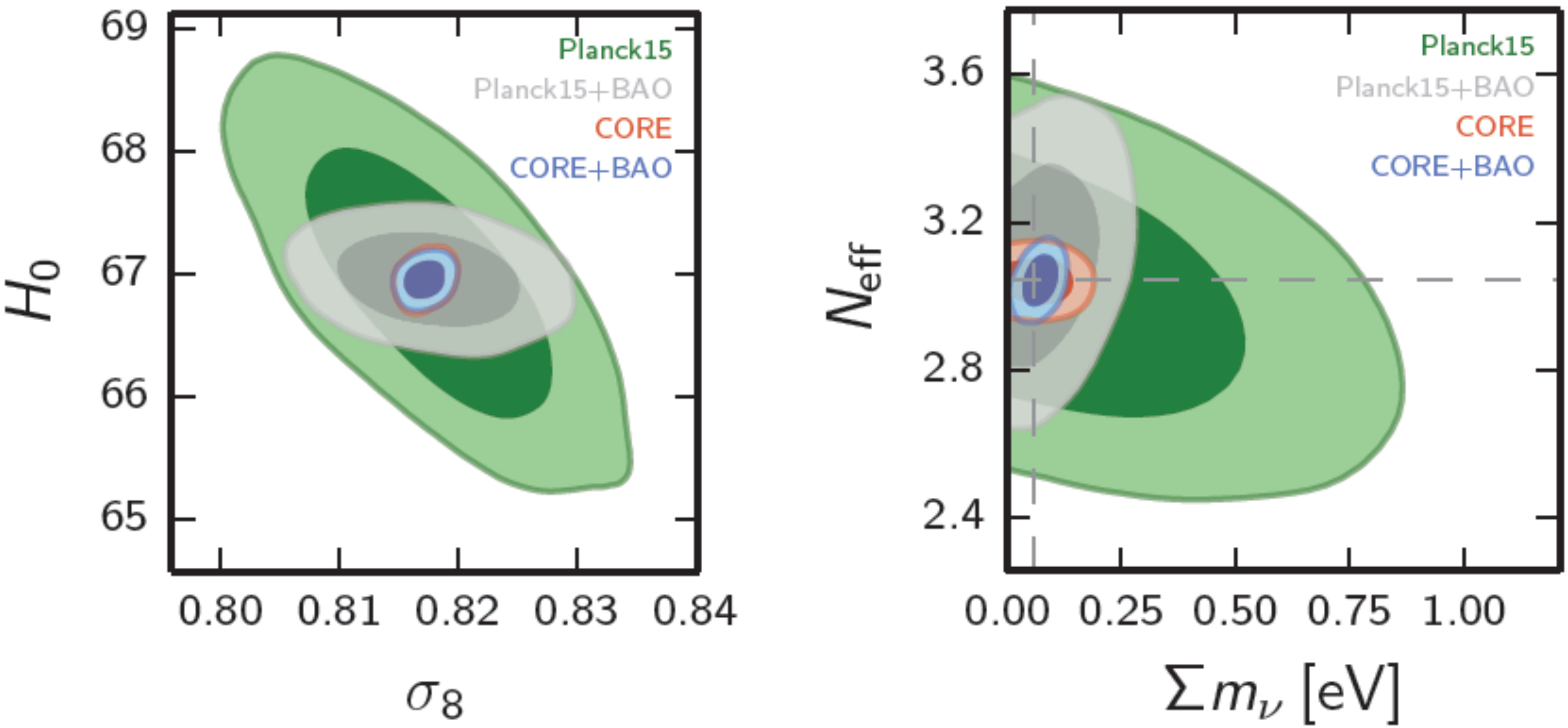
REQUIREMENT:

measure all spectra with the best possible accuracy

Cosmological constraints

See ECO parameters paper

Current tension at 2.5σ with
H_0 = 73.8 ± 2.4 km/s/Mpc (Riess et al. 2011, HST)



Cosmological constraints

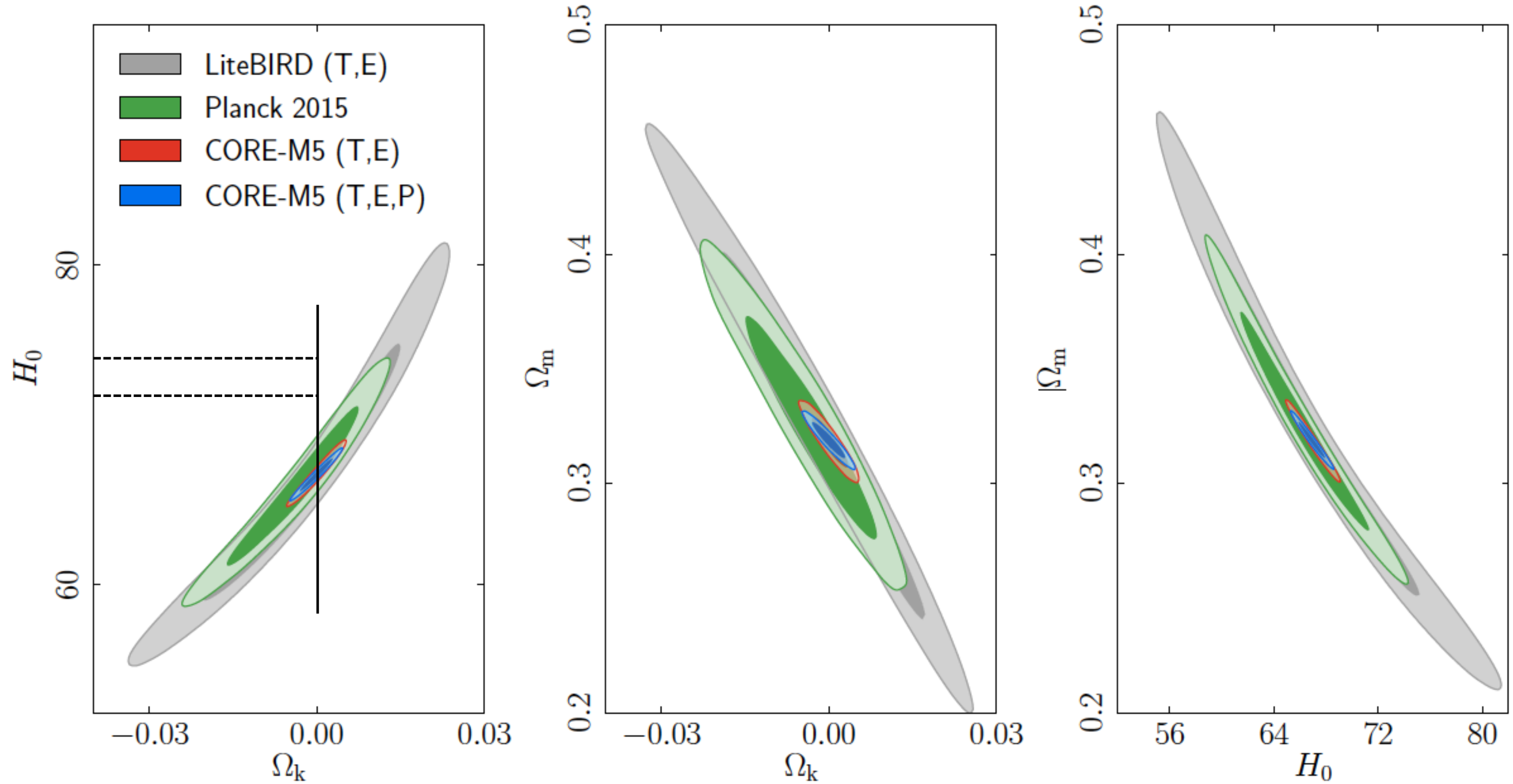


Figure 12: Forecast 68 % and 95 % CL marginalized regions for (Ω_k, H_0) (left panel), (Ω_k, Ω_m) (middle panel) and (H_0, Ω_m) (right panel) for LiteBIRD (grey) and CORE-M5 (blue) obtained by allowing Ω_k to vary. These forecasts assume $\Omega_k = 0$ as fiducial value. The 68 % and 95 % CL marginalized contours for Planck 2015 TT,TE,EE + lowP + lensing (green) are shown for comparison [4]. Note that the Planck 2015 contours are based on real data whose best-fit is different from the fiducial cosmology used.

ECO inflation paper (arXiv:1612.08270)

Scientific Case: what next?

- **Mine the CMB** : extract essentially *all* the information it carries about our Universe.
  - Detect primary B-modes and probe the physics of inflation;
  - Map the (dark) matter structures in the Hubble volume;
  - Constrain fundamental physics (dark sector physics, modified gravity, light relics, …);
  - Test the cosmological scenario to exquisite precision (dark matter? dark energy? curvature? neutrinos? isotropy?)

- This is within reach in the next 1-2 decades.

- The name of the game is :
  - reach full-sky ΔP = 1 μK.arcmin and 1 arcmin angular resolution
  - control foreground astrophysical emission
  - control systematics
  - redundancy !

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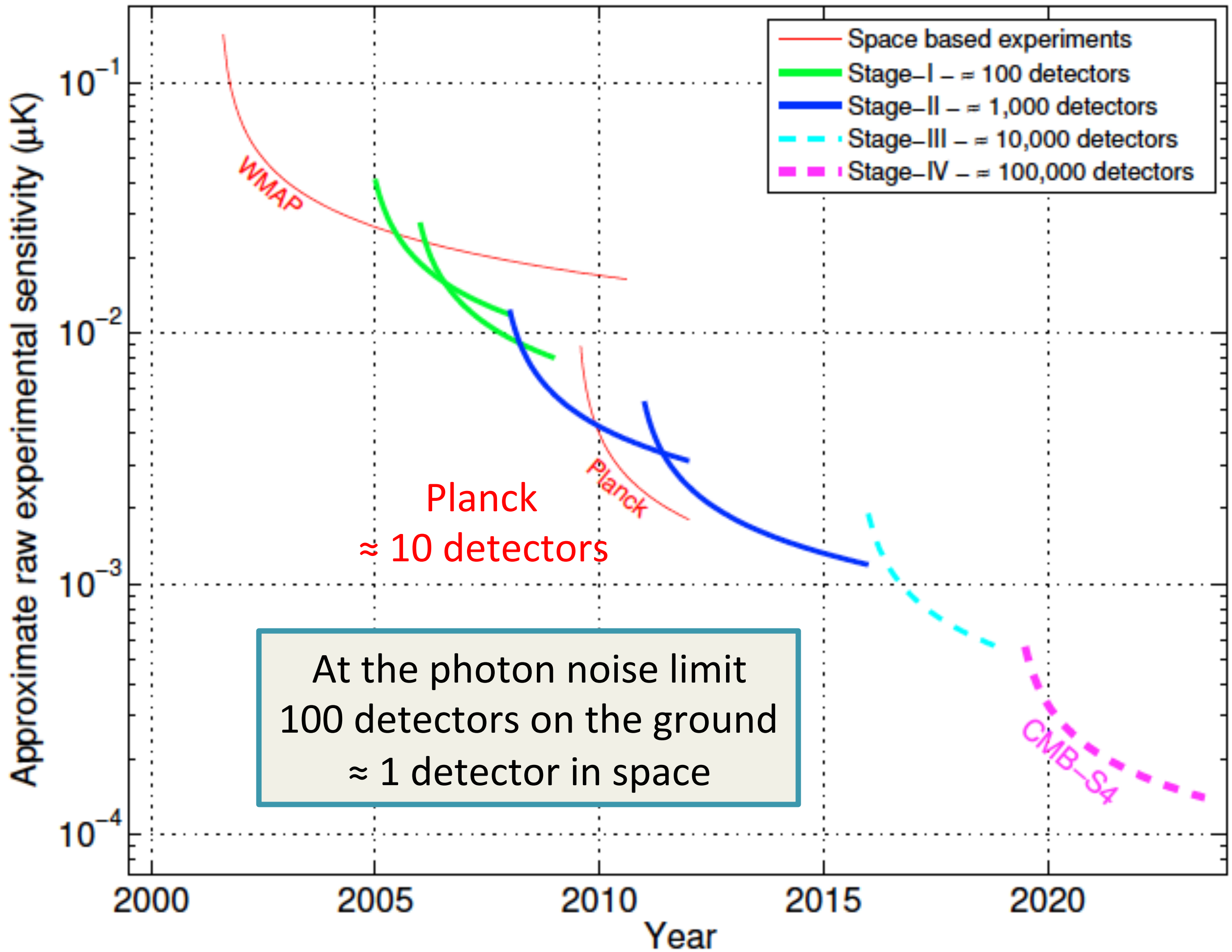
Sensitivity



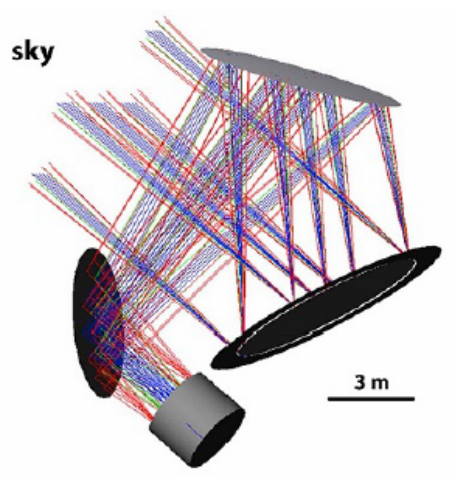
CMB-S4 technology book, arXiv:1706.02464

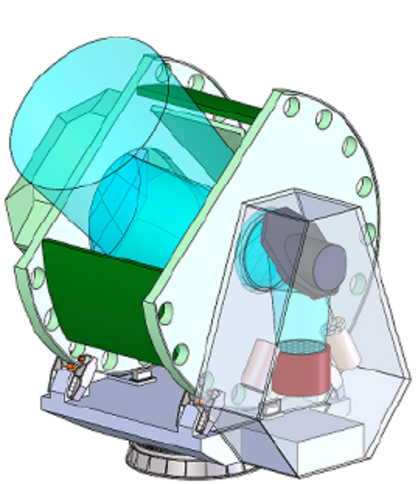
Need for very large focal planes

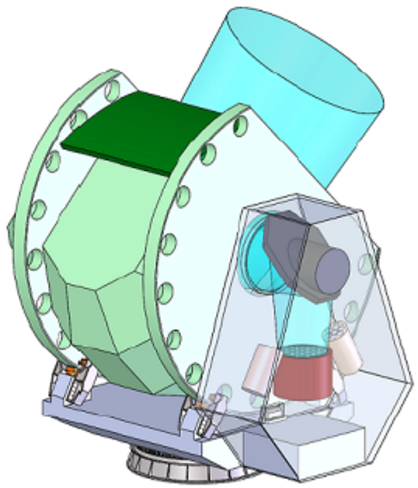
ν = 100 GHz is λ = 3 mm
pixel size about 1 cm^2
10,000 detectors require 1m^2 focal plane

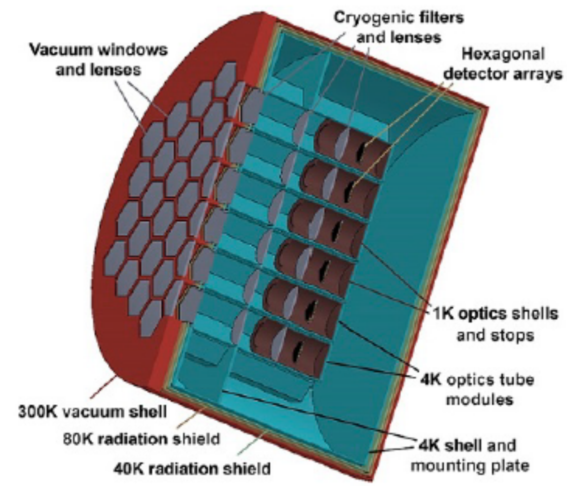
Large telescopes and/or many telescopes

multichroic detectors
+
dual-polarization









CMB-S4 technology book, arXiv:1706.02464

Outline

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  - atmosphere
  - systematics
  - foregrounds
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  - PIXIE
  - CORE
  - PRISM
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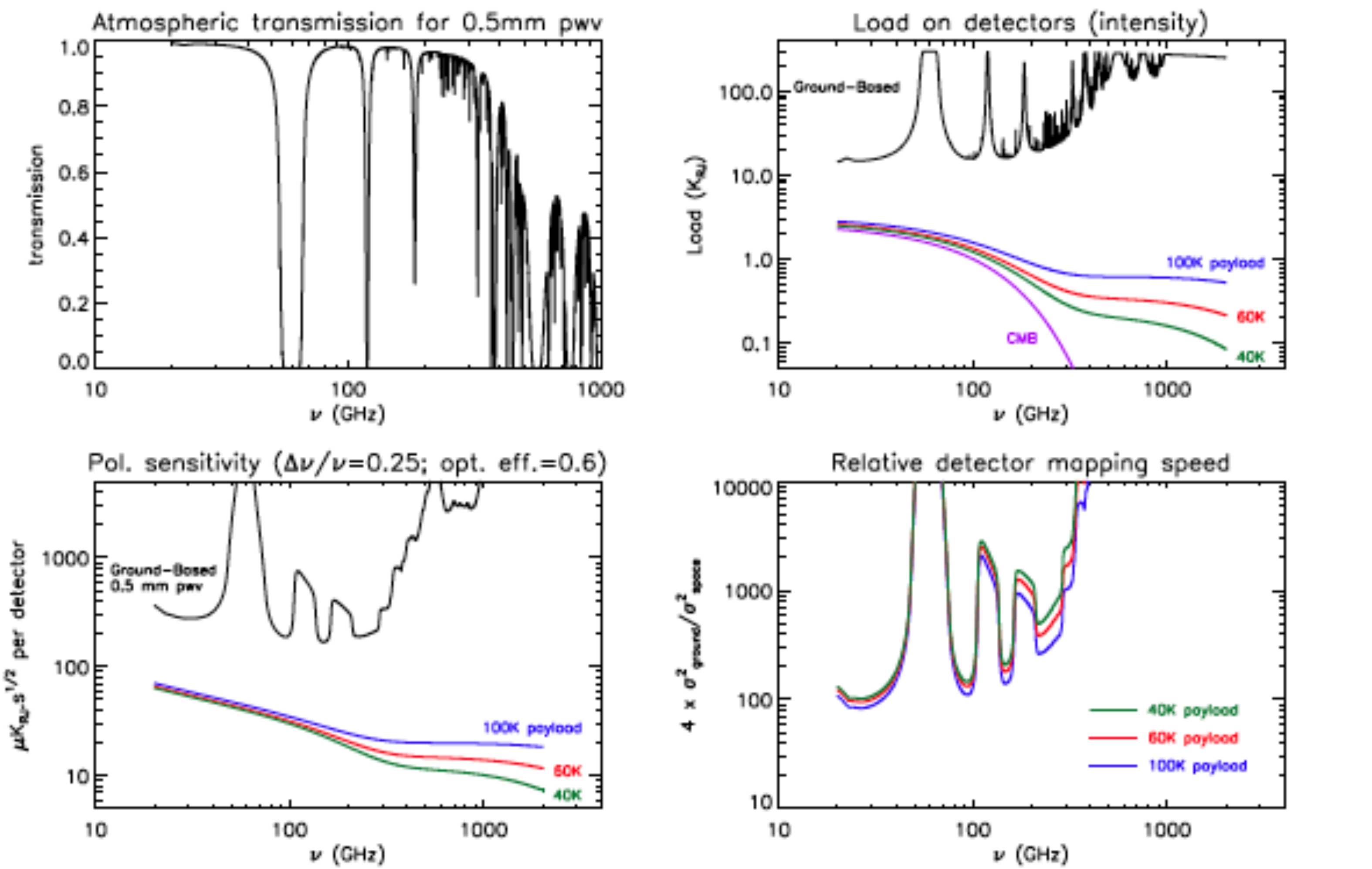
Atmosphere : load



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Systematics

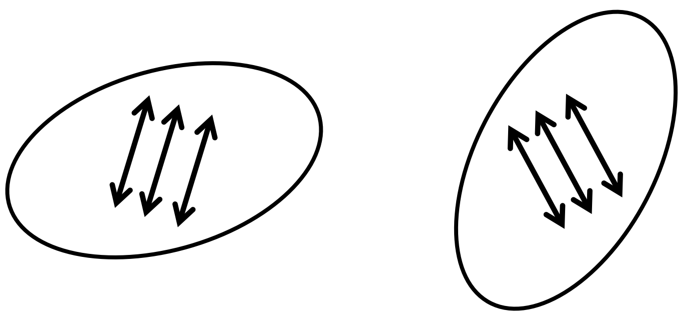
$$s = I + Q\cos 2\psi + U\sin 2\psi$$

- Systematic effects !
  - Perhaps the biggest challenge
  - Let less than ≈ 10^{-4} of intensity can leak into Q and U
  - Let less than ≈ 10^{-2} of E can leak into B (Q-U mixing)
  - Space observations much better than ground-based
  - Use or not a rotating HWP to mitigate systematic effects?

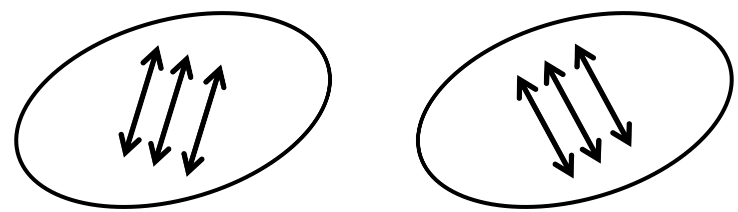
HWP or no HWP

$$s = I + Q\cos 2\psi + U\sin 2\psi$$

- The question of a Half wave plate…

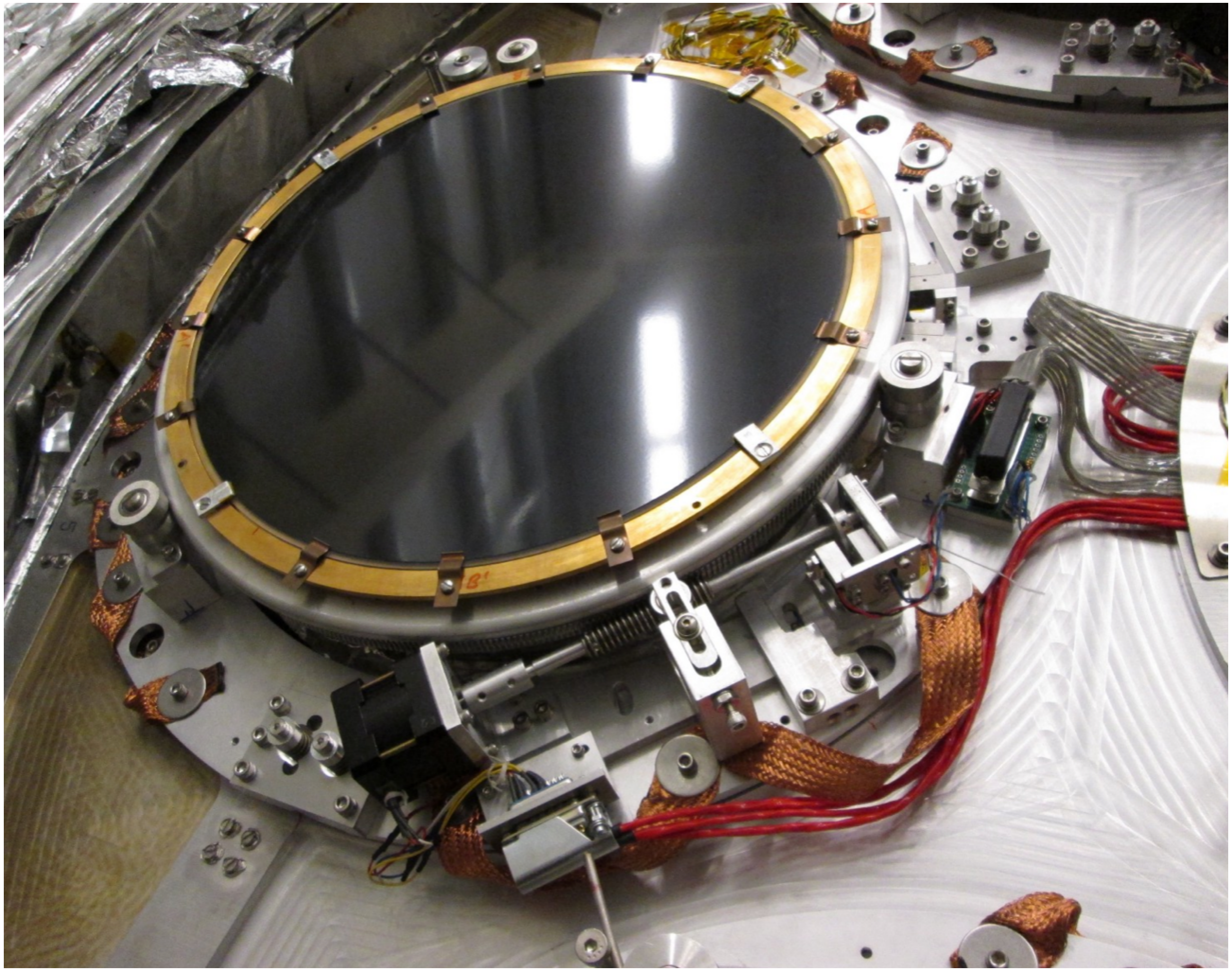


No HWP
rotate the whole instrument



HWP
rotate only polarization

HWP or no HWP



150 GHz HWP

built for the SPIDER balloon

Picture from Sean Bryan

HWPs are not perfect either

- They emit radiation
- They are not homogeneous
- Response changes while they rotate
- Far sidelobes change while they rotate
- Hard to do broad band HWPs

- Do they do more harm or more good?

Alternative: model + deproject

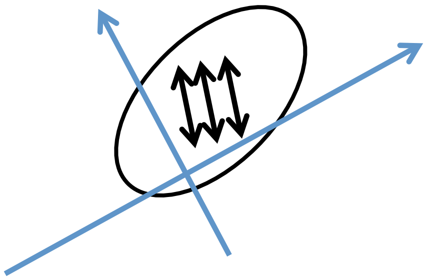
$$s(p) \simeq I(p) + \eta \left(Q_{||}(p)\cos 2\psi + U_{||}(p)\sin 2\psi\right)$$

⇓

$$\begin{aligned} s(p) \simeq\ & I(p) + \eta \left(Q_{||}(p)\cos 2\psi + U_{||}(p)\sin 2\psi\right) \\ &+ a_{||}\nabla^2_{||} I(p) + a_{\perp}\nabla^2_{\perp} I(p) + a_{\times}\nabla_{\perp}\nabla_{||} I(p) \\ &+ b_{||}\nabla_{||}\left[I(p) + \eta\left(Q_{||}(p)\cos 2\psi + U_{||}(p)\sin 2\psi\right)\right] \\ &+ b_{\perp}\nabla_{\perp}\left[I(p) + \eta\left(Q_{||}(p)\cos 2\psi + U_{||}(p)\sin 2\psi\right)\right] \\ &+ 2\delta\,\eta\left[-Q_{||}(p)\sin 2\psi + U_{||}(p)\cos 2\psi\right] \\ &+ \epsilon I(p) + \xi\left[Q_{||}(p)\cos 2\psi + U_{||}(p)\sin 2\psi\right], \end{aligned}$$

Alternative: model + deproject

polarization efficiency



$$
\begin{aligned}
s(p) \simeq\ & I(p) + \eta\left(Q_{\|}(p)\cos 2\psi + U_{\|}(p)\sin 2\psi\right) \\
& + a_{\|}\nabla_{\|}^{2} I(p) + a_{\perp}\nabla_{\perp}^{2} I(p) + a_{\times}\nabla_{\perp}\nabla_{\|} I(p) \\
& + b_{\|}\nabla_{\|}\left[I(p) + \eta\left(Q_{\|}(p)\cos 2\psi + U_{\|}(p)\sin 2\psi\right)\right] \\
& + b_{\perp}\nabla_{\perp}\left[I(p) + \eta\left(Q_{\|}(p)\cos 2\psi + U_{\|}(p)\sin 2\psi\right)\right] \\
& + 2\delta\eta\left[-Q_{\|}(p)\sin 2\psi + U_{\|}(p)\cos 2\psi\right] \\
& + \epsilon I(p) + \xi\left[Q_{\|}(p)\cos 2\psi + U_{\|}(p)\sin 2\psi\right],
\end{aligned}
$$

beam ellipticity ($a_{\|}$, $a_{\perp}$, $a_{\times}$)

pointing error ($b_{\|}$, $b_{\perp}$)

polar angle error (δ)

calibration and polarization efficiency errors (ϵ, ξ)

Past experience

- No Half Wave Plate
  - Planck (satellite)
  - BICEP2 and Keck array (at South Pole)
  - SPTPol (at South Pole)
  - …

- With HWP
  - ACTPol (in Atacama)
  - Polarbear (in Atacama)
  - SPIDER (balloon)
  - …

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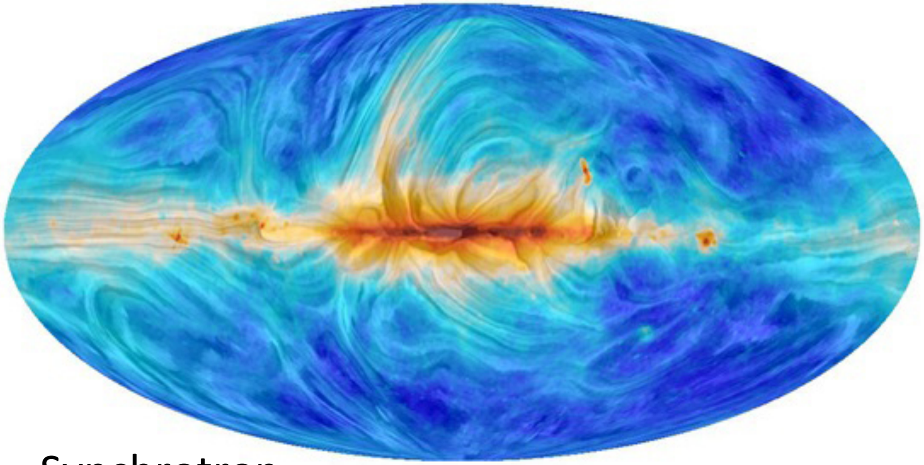
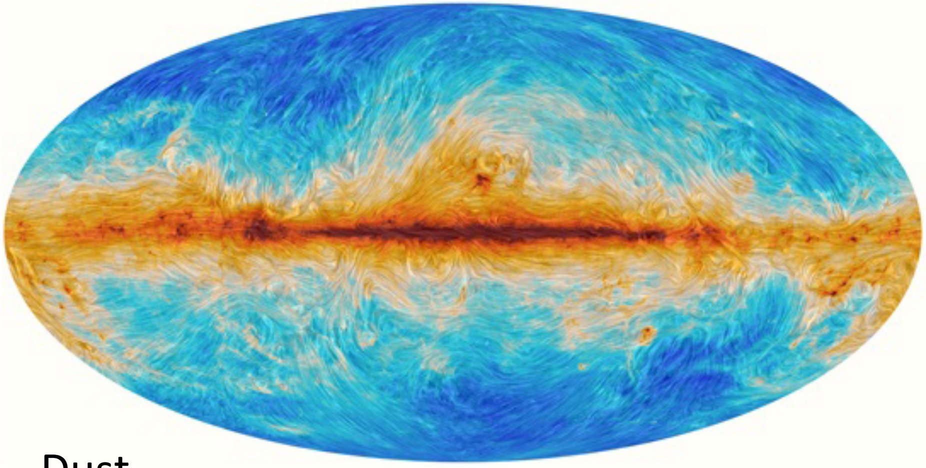
Foregrounds

Credit: ESA, Planck collaboration

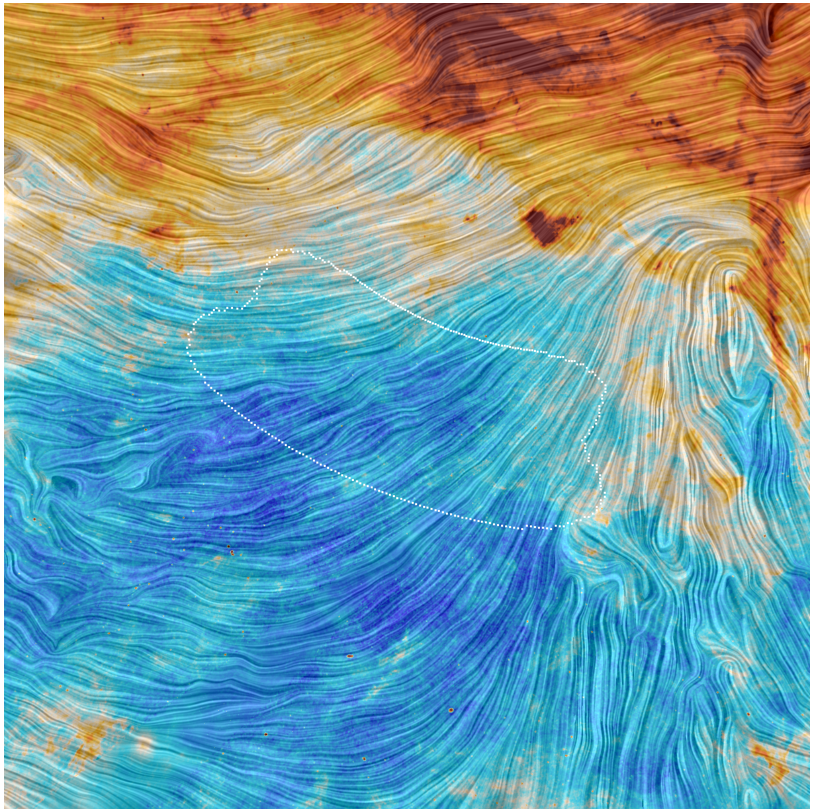


Synchrotron

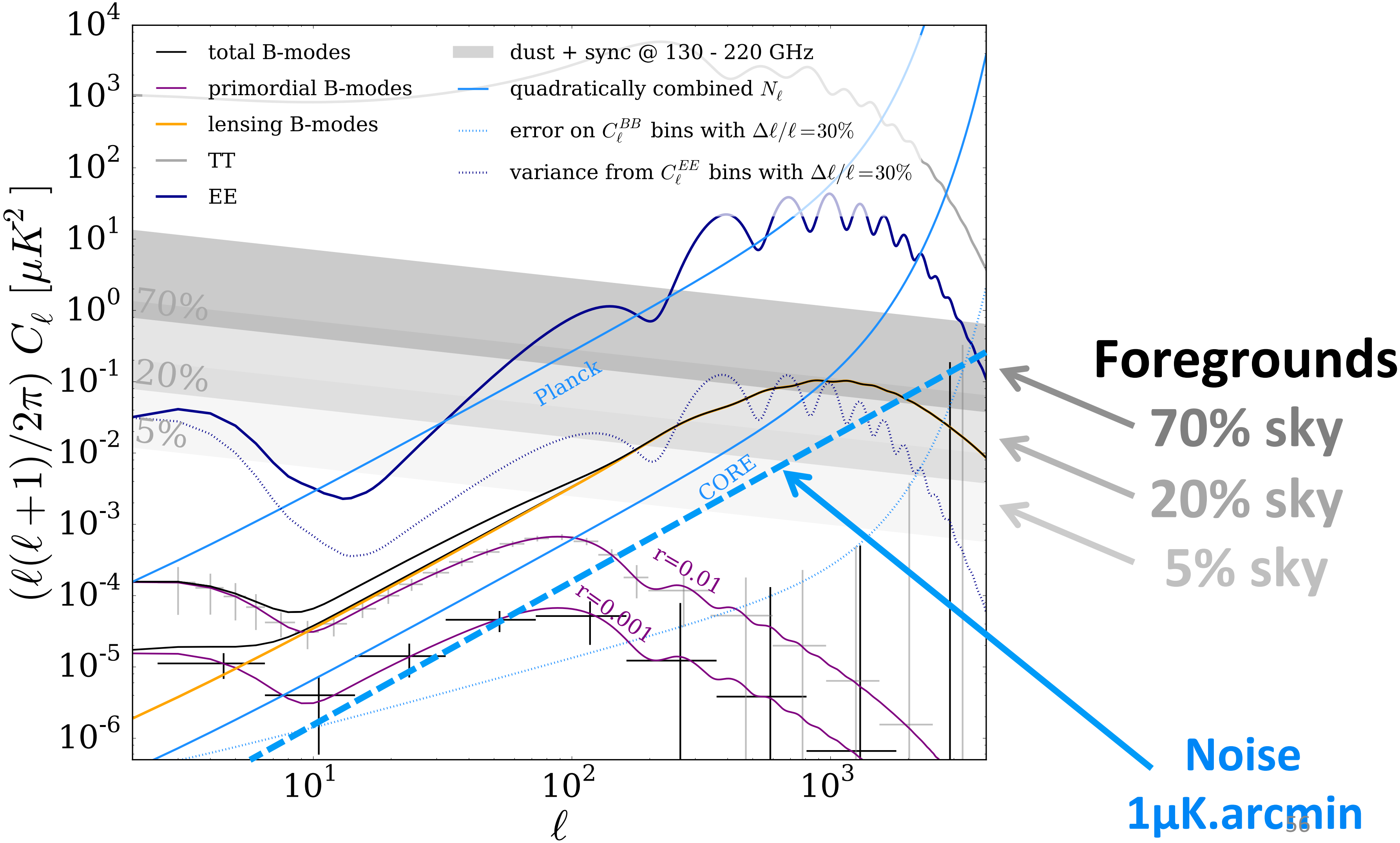


Dust

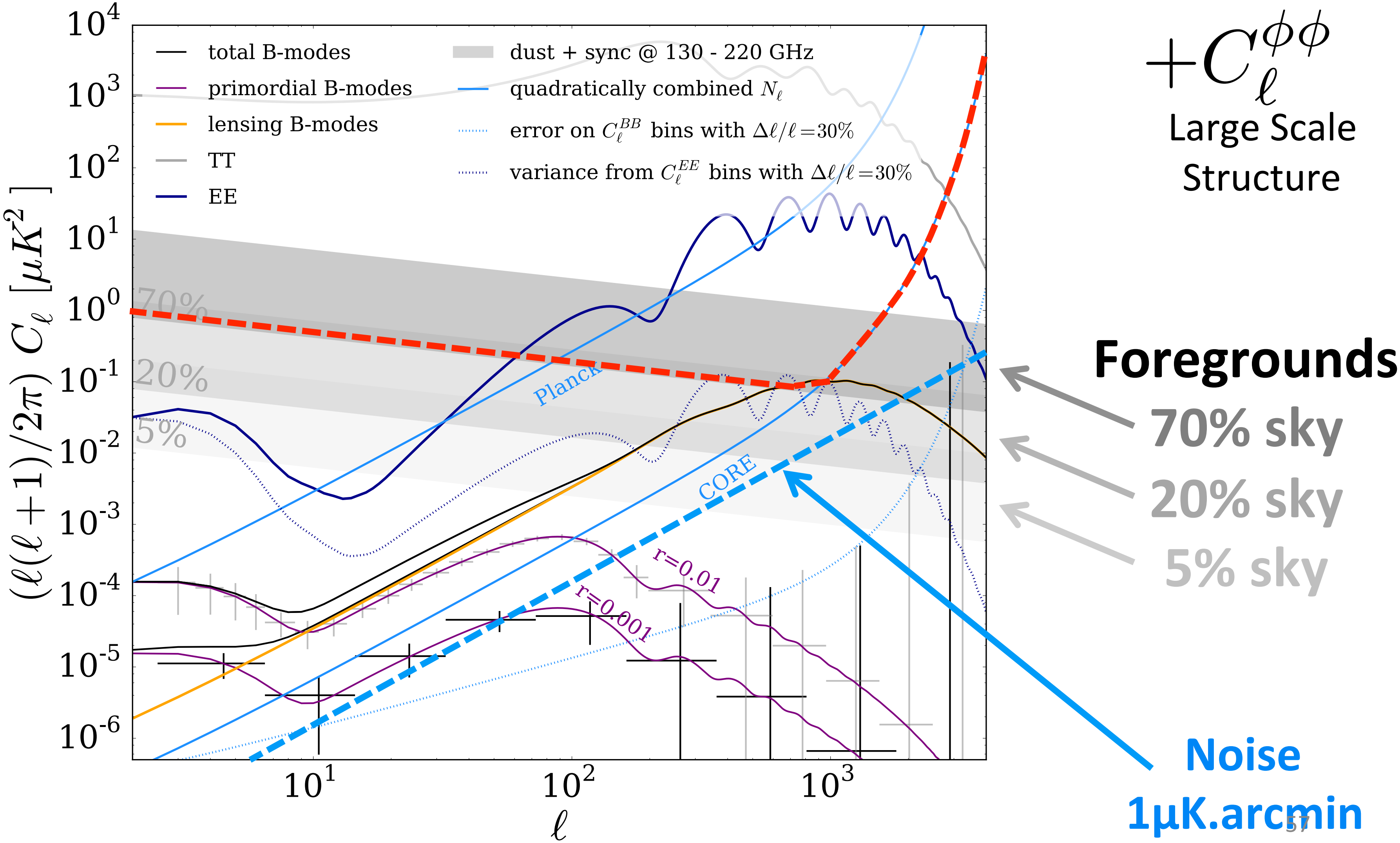
Dust in the BICEP2 field



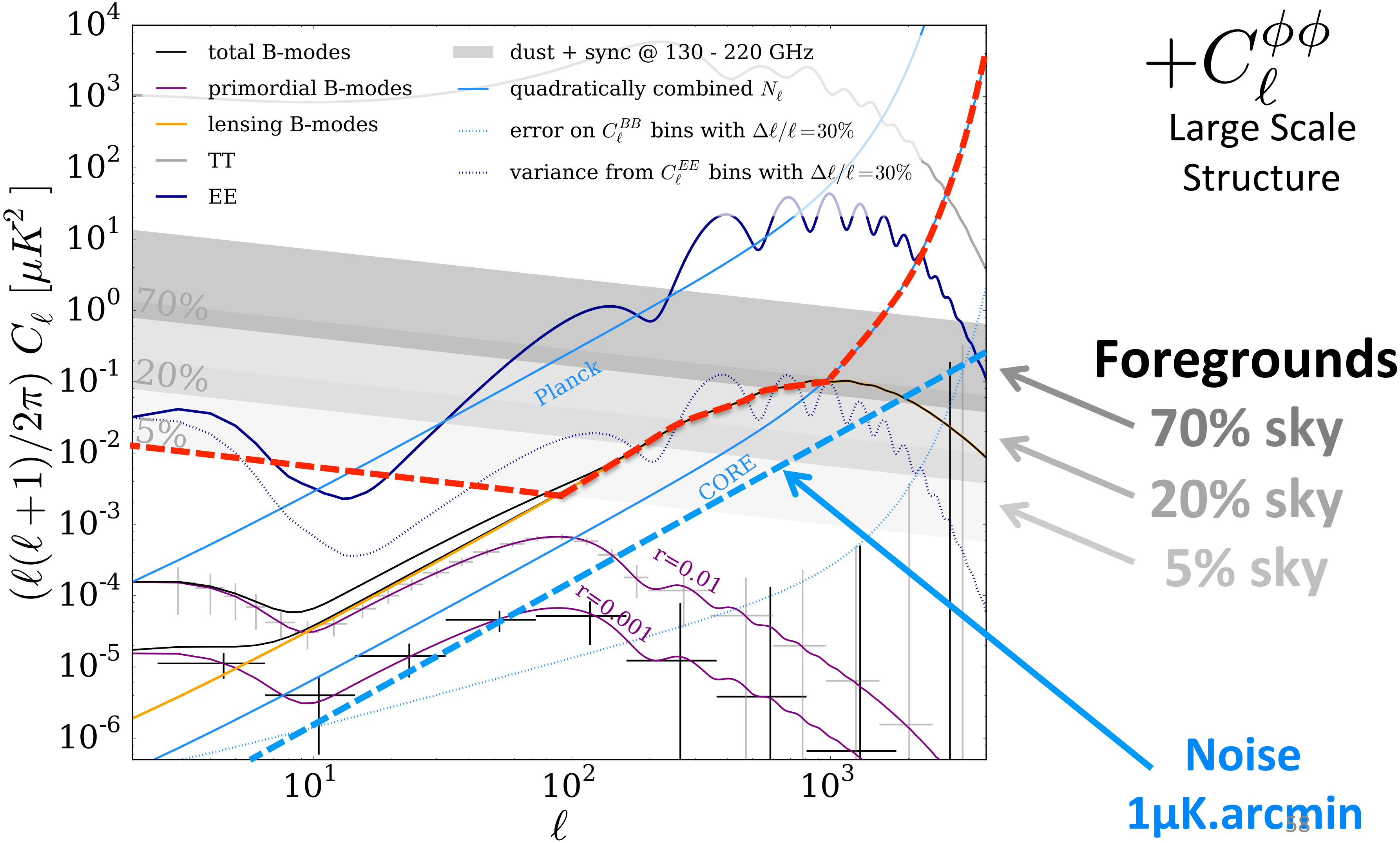
T, E and B maps and spectra



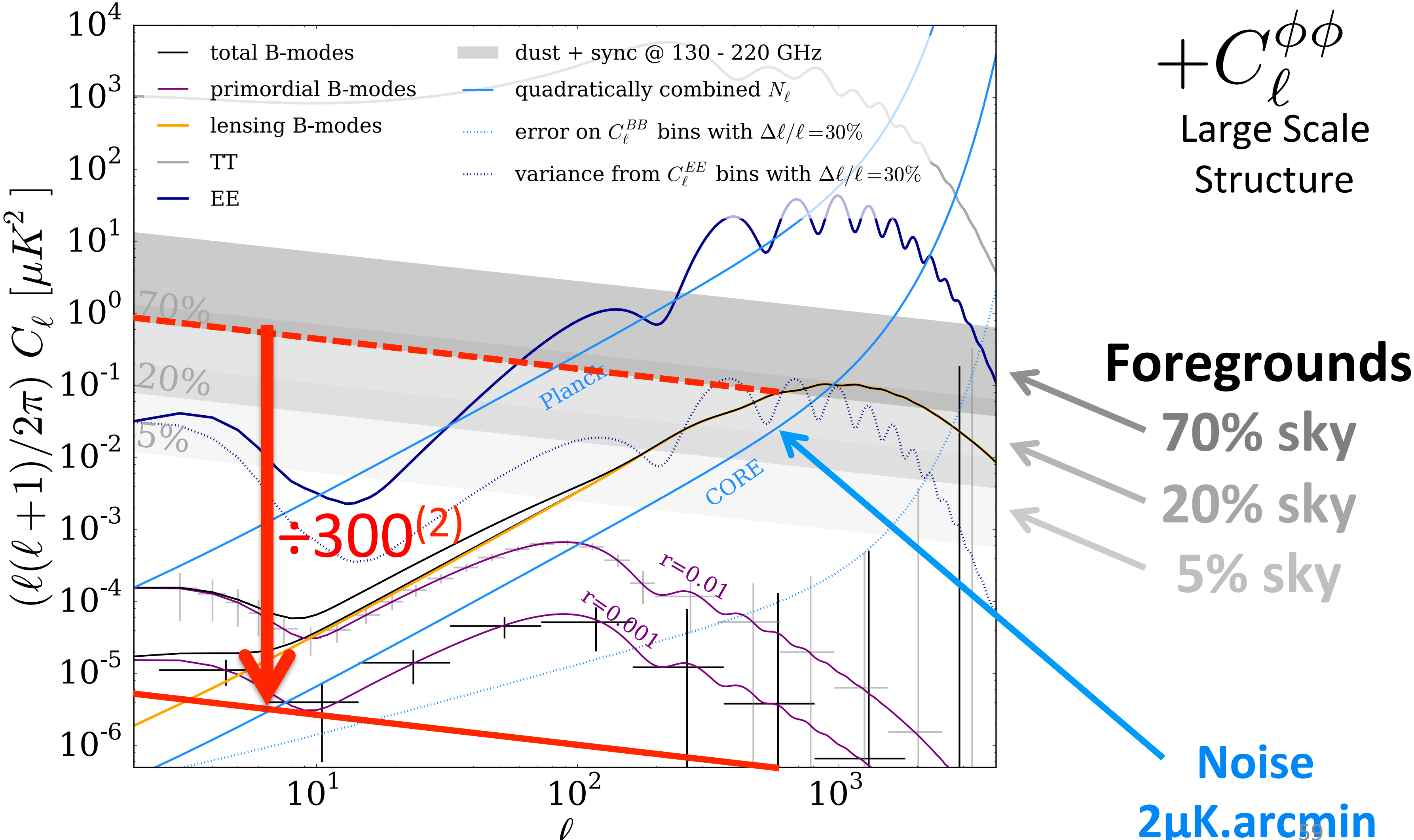
T, E and B maps and spectra



T, E and B maps and spectra



Foreground + lensing confusion



How many channels?

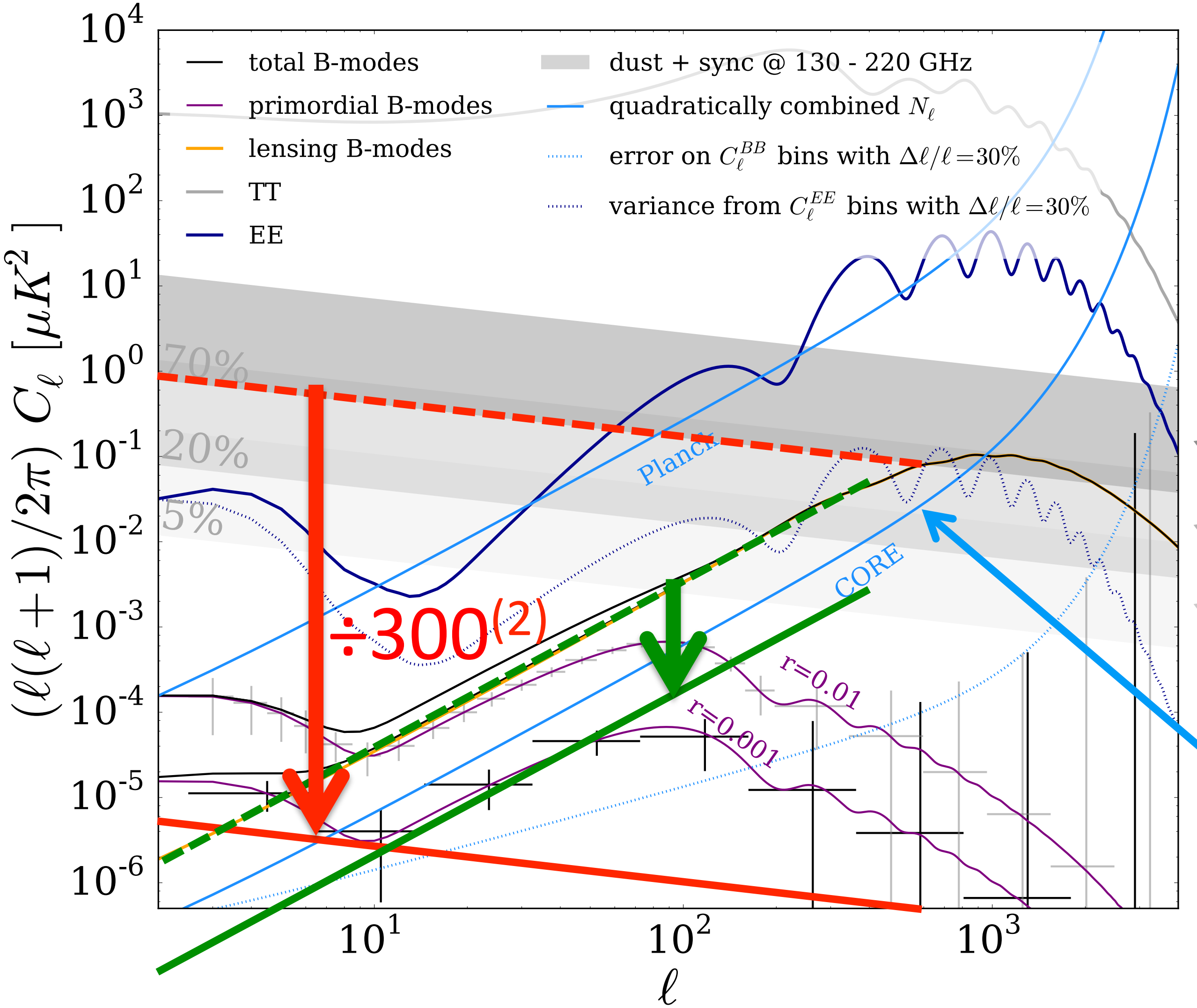
- Enough to model the foreground contamination and correct for it…

• Synchrotron (Amplitude, spectral index)	2+1
• Thermal dust (Amplitude, spectral index, temperature)	3+1
• CMB	3
• thermal SZ	1+1
• free-free	1+1
• spinning dust	a few
• CIB	a few
• Zodiacal light	a few
• point sources	4
• surprises	2

TOTAL for Polarization : >15 channels

TOTAL for Intensity: >20 channels

Foreground + lensing confusion



$+C_\ell^{\phi\phi}$

Large Scale Structure

Foregrounds

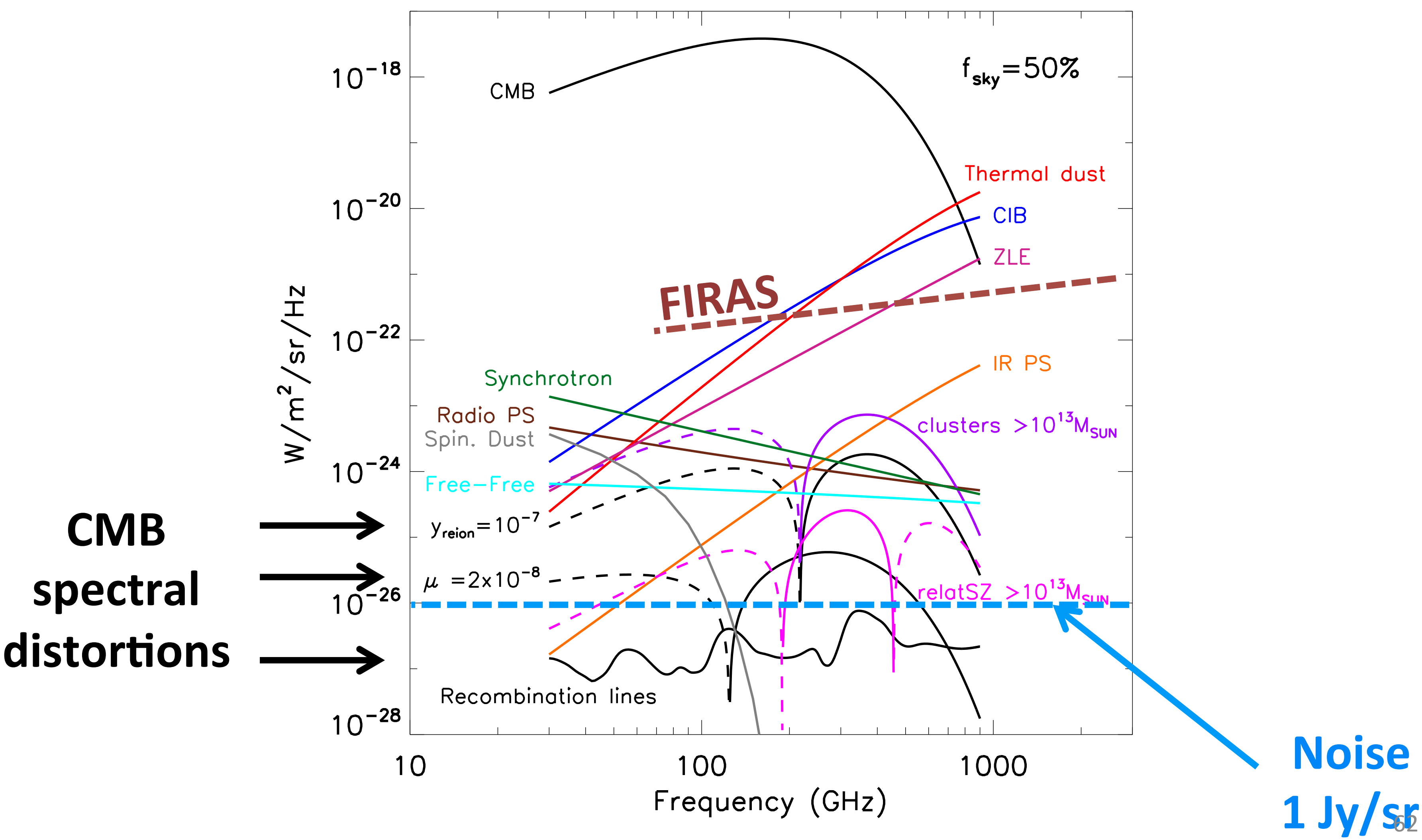
70% sky

20% sky

5% sky

Noise 2μK.arcmin

Foregrounds & CMB spectral distortions



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At the south pole

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

CMB-S4 technology book, arXiv:1706.02464

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

CMB-S4 technology book, arXiv:1706.02464

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 European proposal to study a European version, or a participation to CMB-S4, has been submitted.

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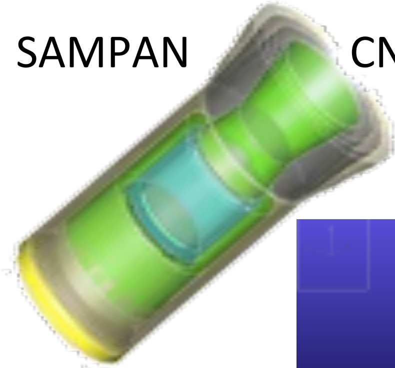
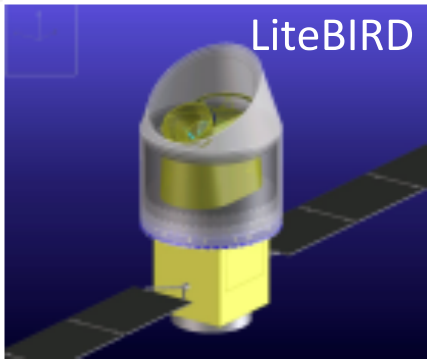
What next? Many proposed CMB missions

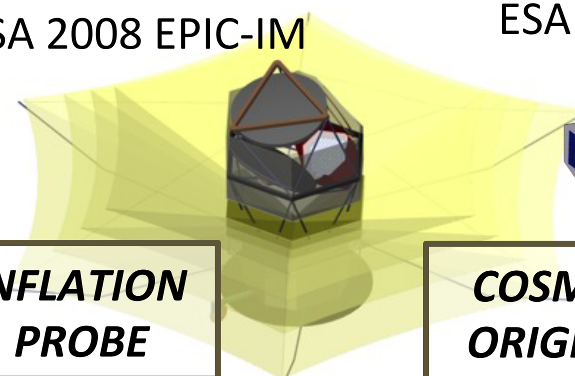
SAMPAN CNES 2006



JAXA 2008



NASA 2008 EPIC-IM



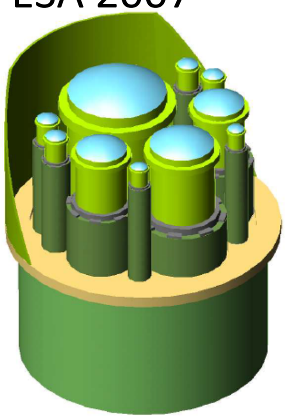
INFLATION PROBE

ESA 2010 COrE

COSMIC ORIGINS EXPLORER

High resolution

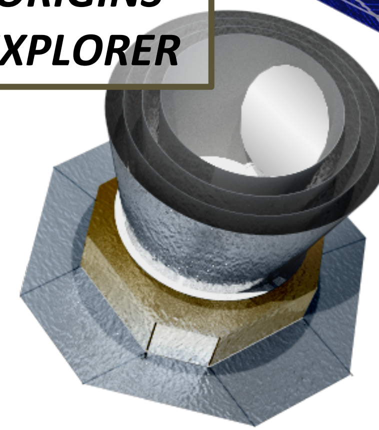
BPOL
ESA 2007



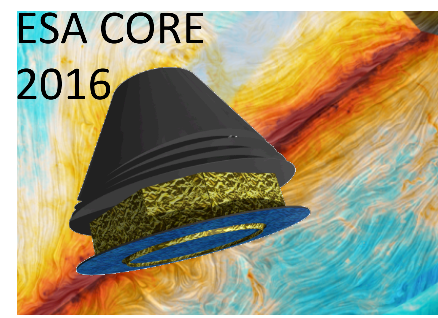
Absolute spectrophotometer

Many frequency bands

PRISM
ESA 2013



COrE+
ESA 2015

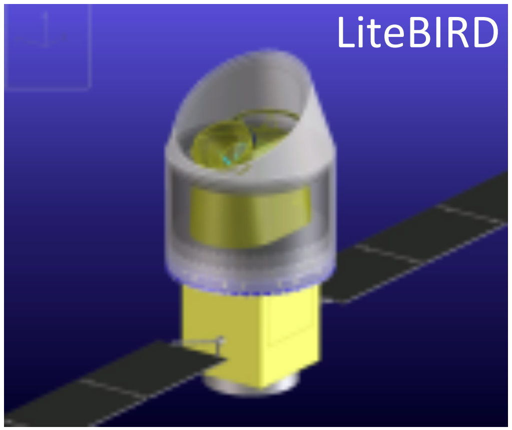


Low resolution
Limited frequency coverage
Primary CMB B-modes

More comprehensive science cases
(spectroscopy, sub-mm astronomy, astrophysical cosmology)

Recent space mission proposals

JAXA + NASA



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 τ

ESA

Cosmic origins explorer

Earliest Launch > 2031

Phase A not selected by ESA

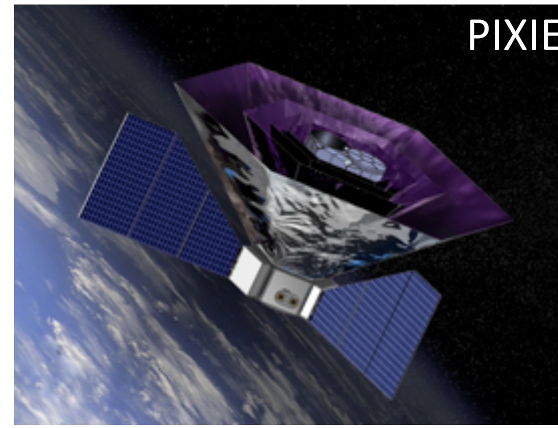
ALL CMB polarisation (almost) ultimate

$\sigma_r \approx 0.0003$

---

bonus: a lot of guaranteed science

NASA



Absolute spectrophotometer

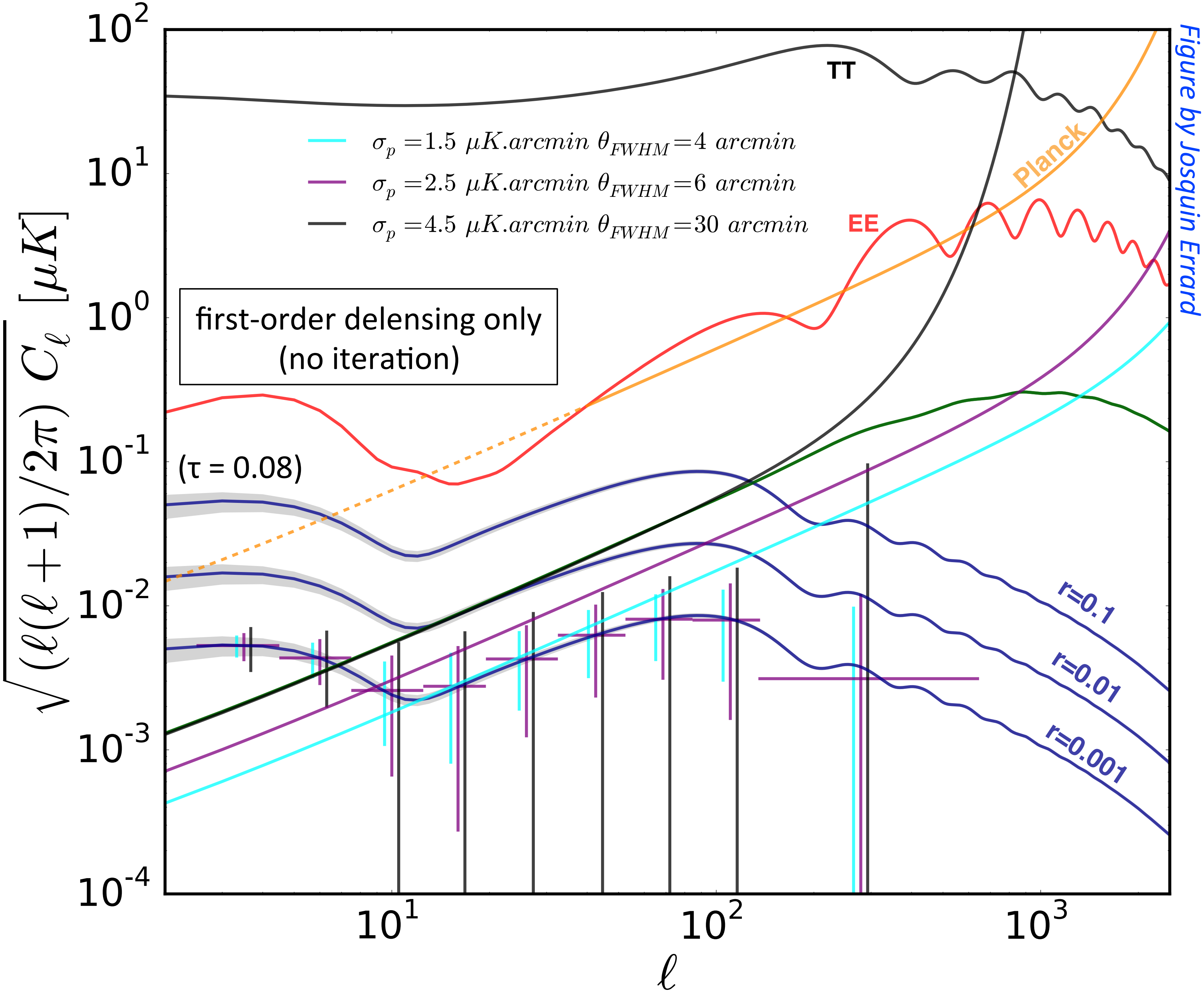
Earliest Launch > 2023

very large scale polarisation

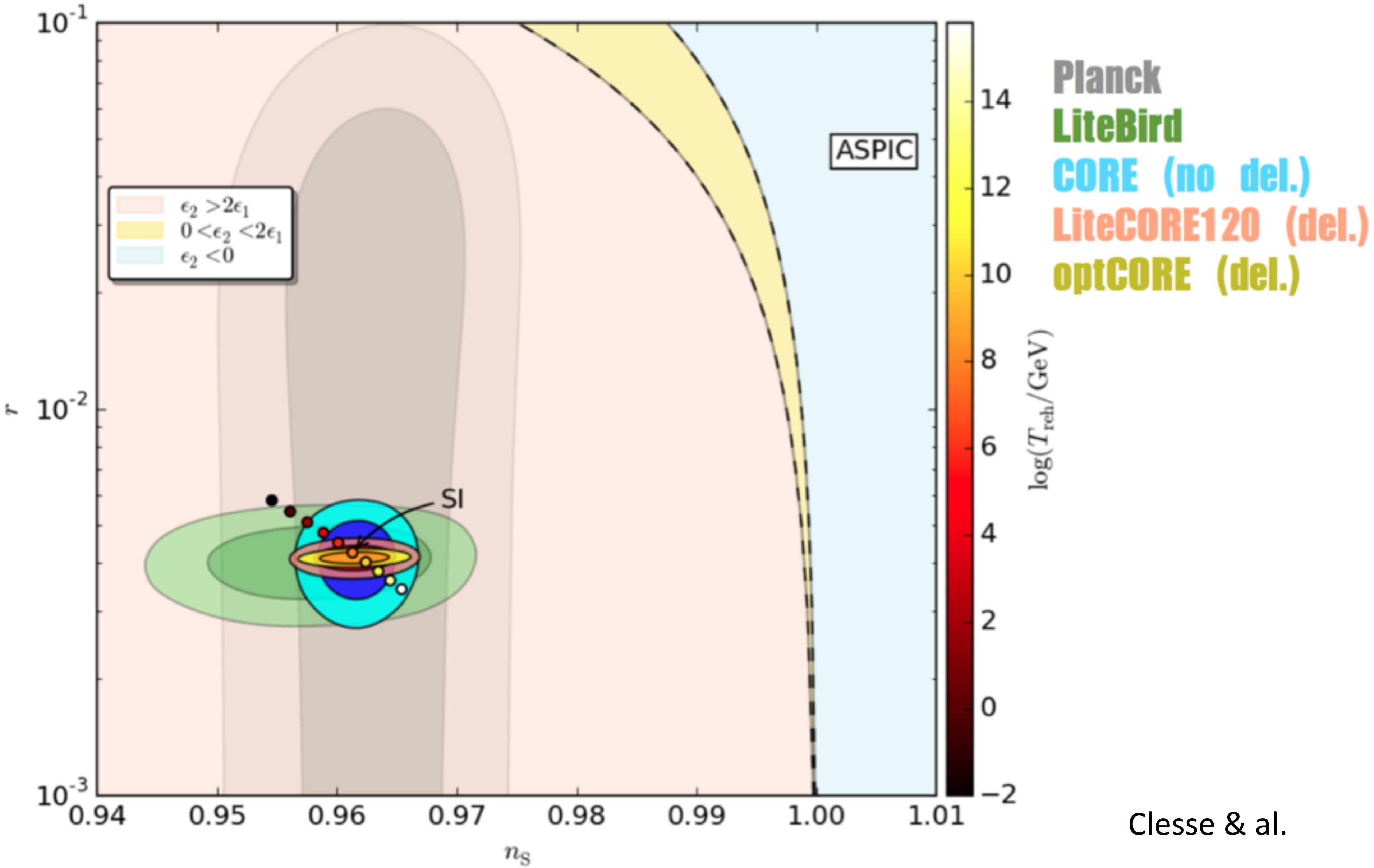
Spectral distortions ?

---

bonus: a lot of guaranteed foreground science



$\sqrt{\ell(\ell+1)/2\pi)\ C_\ell}\ [\mu K]$
ℓ
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3
$\sigma_p = 1.5\ \mu K.arcmin\ \theta_{FWHM} = 4\ arcmin$
$\sigma_p = 2.5\ \mu K.arcmin\ \theta_{FWHM} = 6\ arcmin$
$\sigma_p = 4.5\ \mu K.arcmin\ \theta_{FWHM} = 30\ arcmin$
TT
Planck
EE
first-order delensing only
(no iteration)
(τ = 0.08)
r=0.1
r=0.01
r=0.001
Figure by Josquin Errard



10^{-1}
10^{-2}
10^{-3}
r
0.94
0.95
0.96
0.97
0.98
0.99
1.00
1.01
n_S
$\epsilon_2 > 2\epsilon_1$
$0 < \epsilon_2 < 2\epsilon_1$
$\epsilon_2 < 0$
ASPIC
SI
14
12
10
8
6
4
2
0
−2
$\log(T_{\rm reh}/\rm GeV)$
Planck
LiteBird
CORE (no del.)
LiteCORE120 (del.)
optCORE (del.)

Clesse & al.

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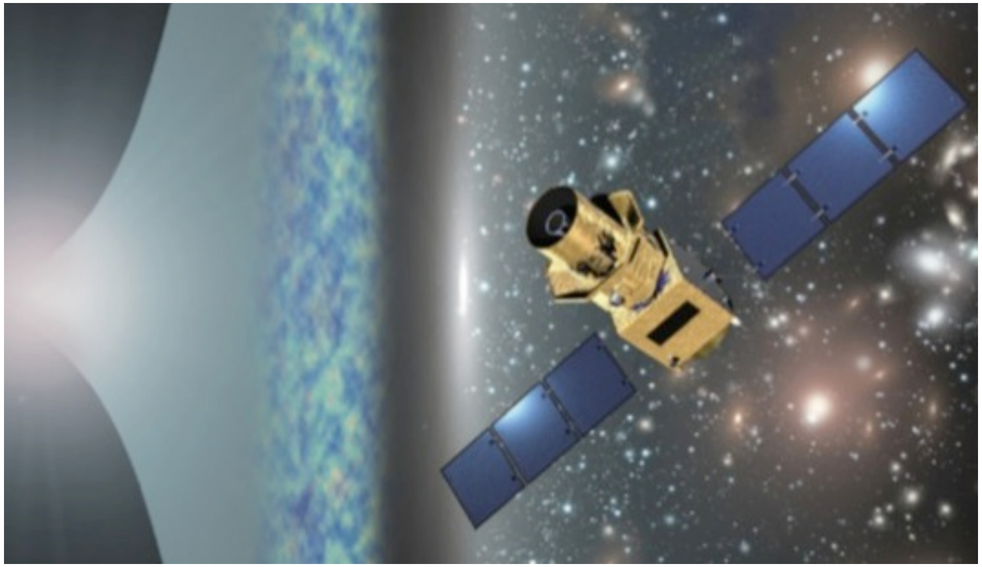
LiteBIRD

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

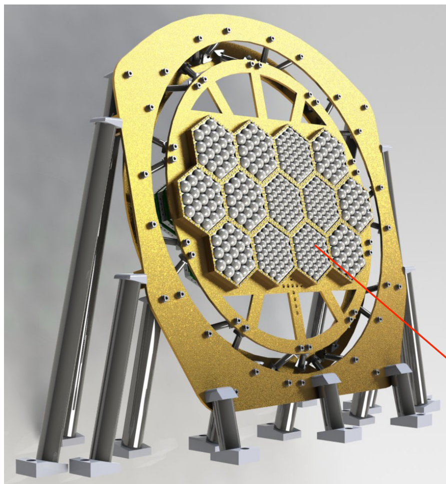


- CMB polarization all-sky survey proposed to JAXA (Feb. 2015)
  - Also to NASA MO for U.S. participation (Dec. 2014)
  - Both proposals passed initial down-selections
  - However, NASA contribution not selected for phase A
  - ISAS/JAXA Phase-A studies have started (Aug. 2016)
- Objective : to test major large-field inflation models and quantum gravity
  - Total uncertainty on tensor-to-scalar ratio, r, $\sigma(r=0) < 0.001$
  - Multipole coverage: $2 \leq \ell \leq 200$
- Launch in ~2027 (post Hitomi) with JAXA's H3 for 3-year observations at L2
  - Currently the only CMB polarization space project in Phase-A status

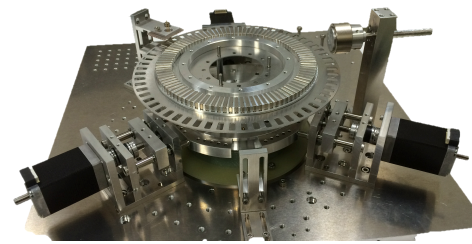
Adapted from
Masashi Hazumi

LiteBIRD instrument

Slide from Adrian Lee



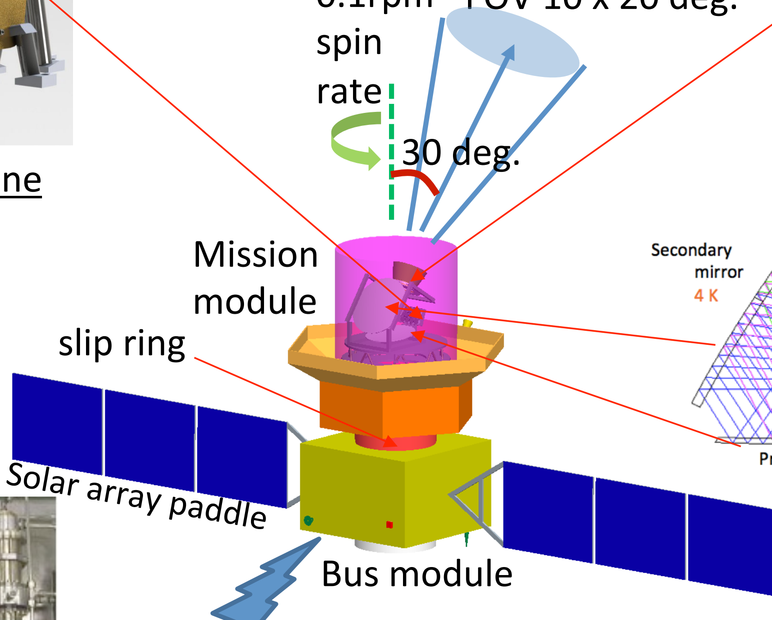
Multi-chroic focal plane



Continuously-rotating half wave plate (HWP)

Line of sight
FOV 10 x 20 deg.

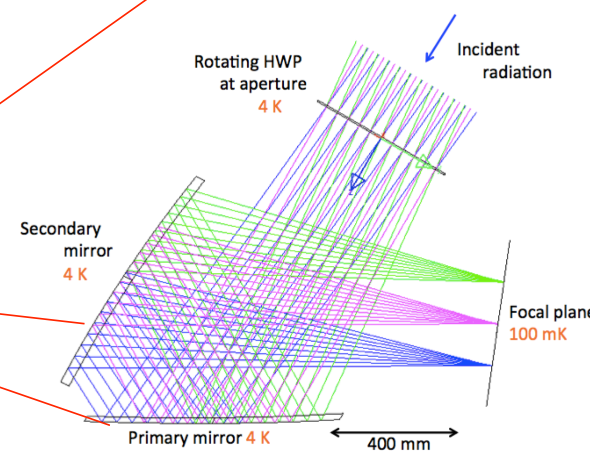
0.1rpm spin rate



Mission module

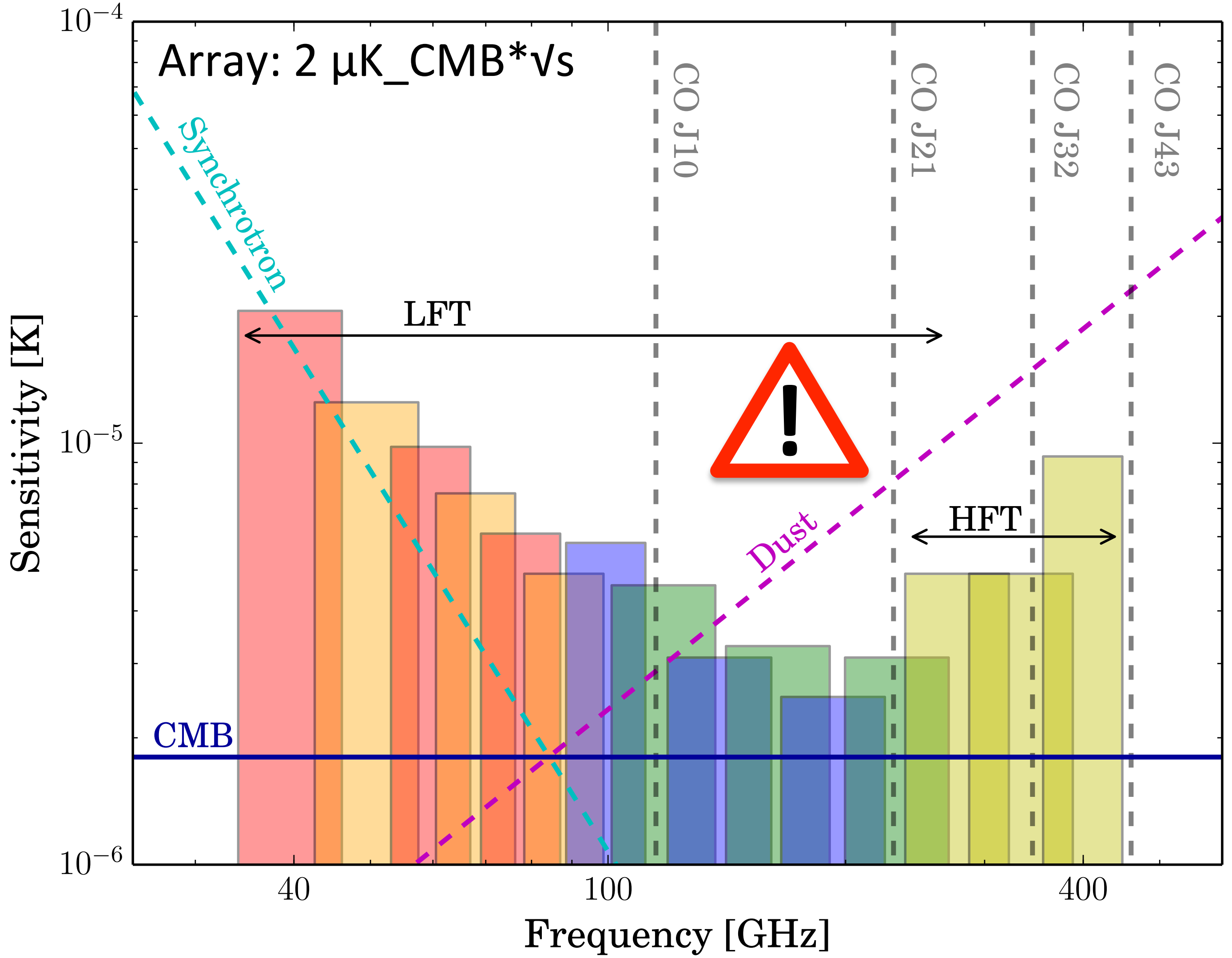
HGA : X band data transfer to the ground

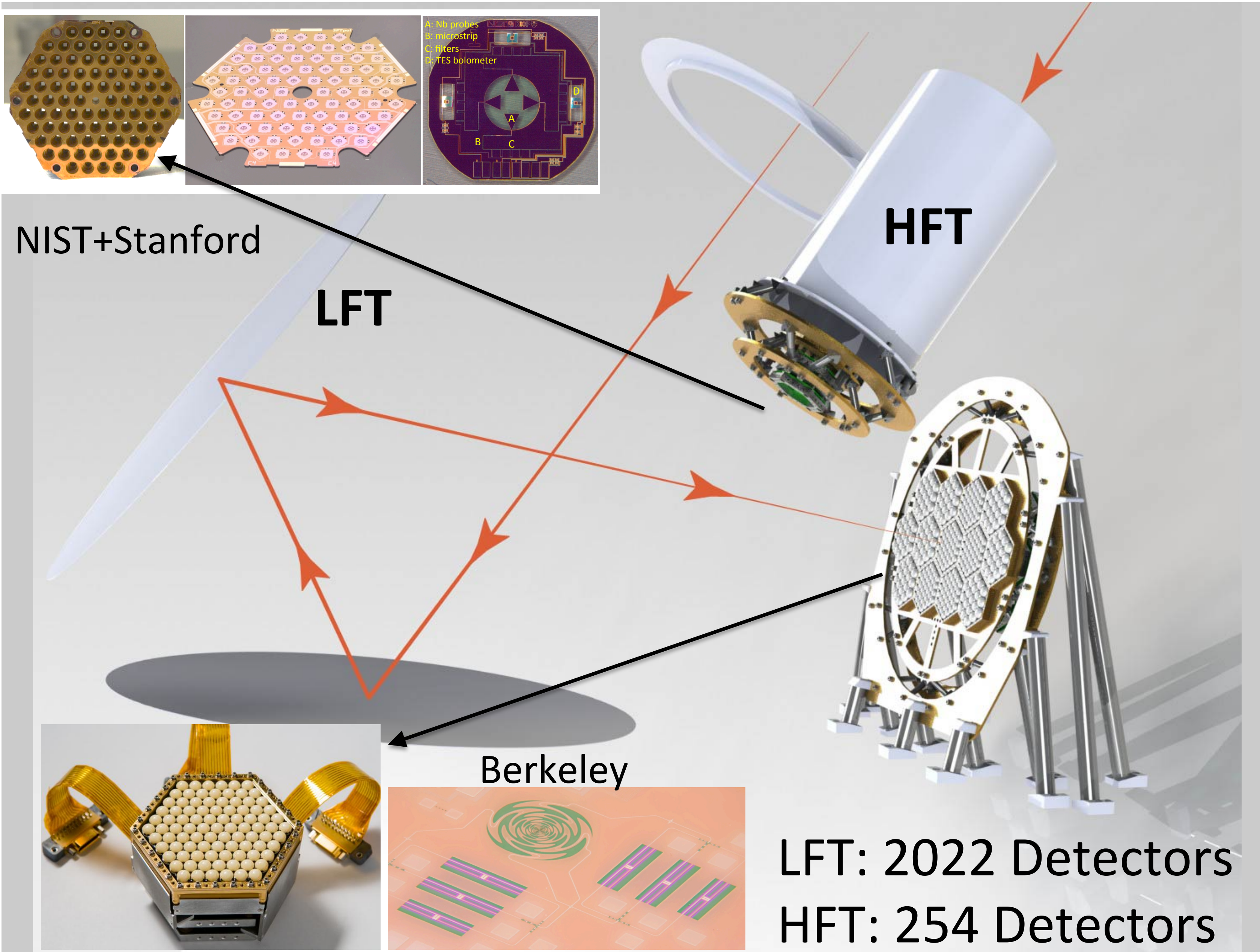
Cryogenics
- JT/ST and ADR (Astro-H heritage)



Mirrors at 4K

Frequency bands





Slide from Adrian Lee

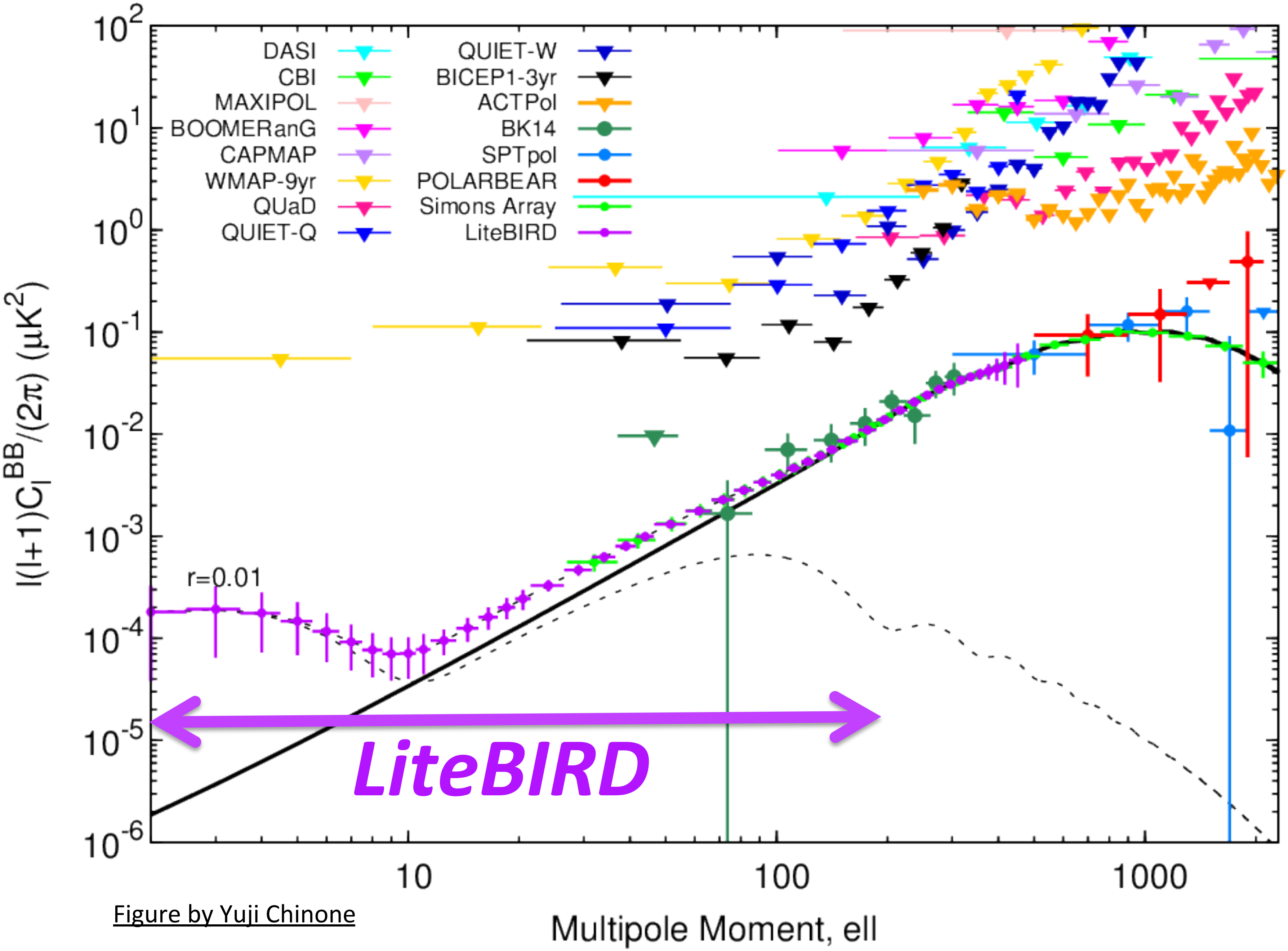


Figure by Yuji Chinone

Slide from Masashi Hazumi

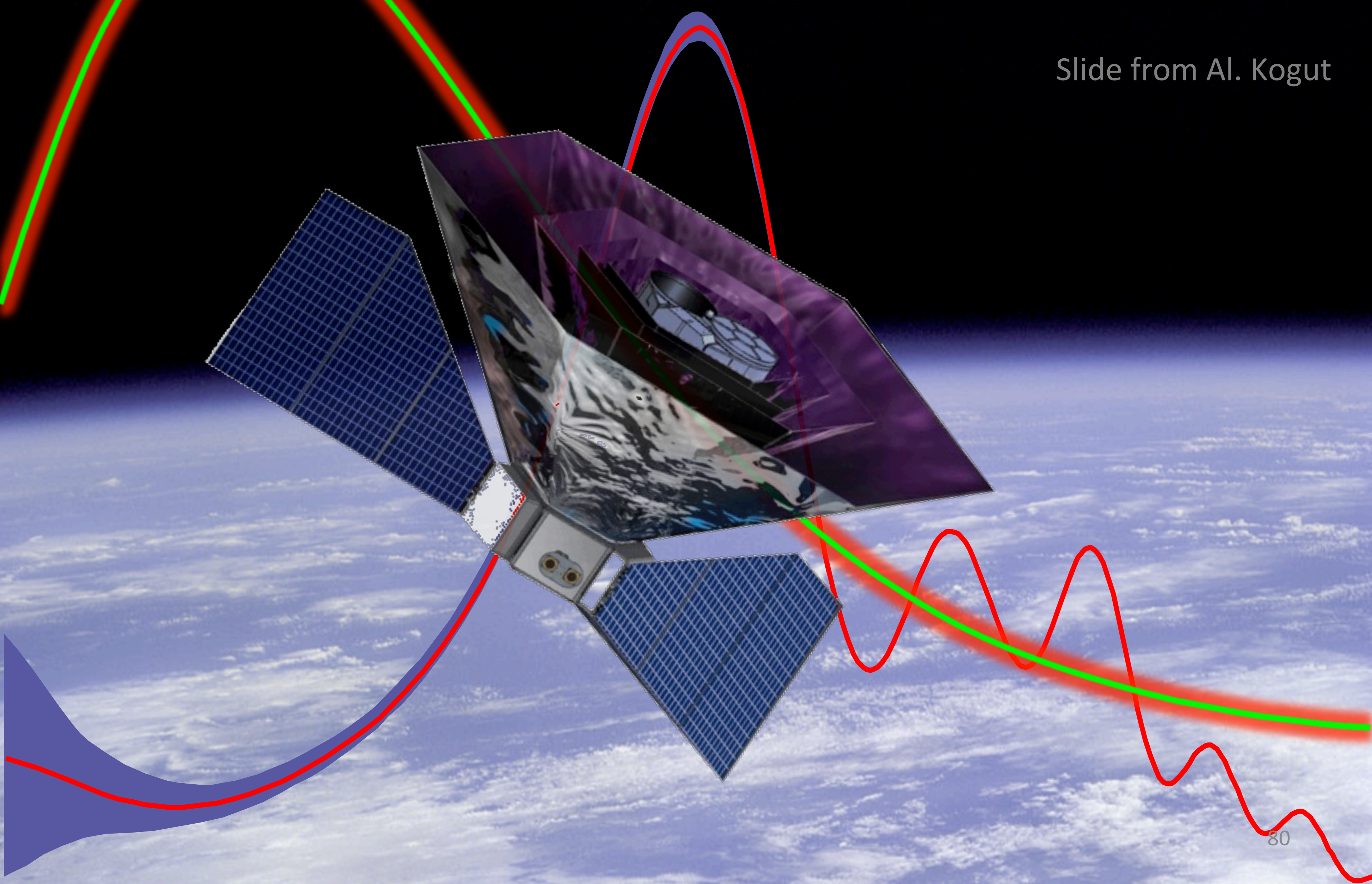
Outline

- Introduction
- Where are we?
- Science case: what next
- Challenges
  - sensitivity
  - atmosphere
  - systematics
  - foregrounds
- Suborbital experiments
- Space experiments
  - PIXIE
  - LiteBIRD
  - CORE
  - PRISM
- A strategy for the future
- Summary

The Primordial Inflation Explorer

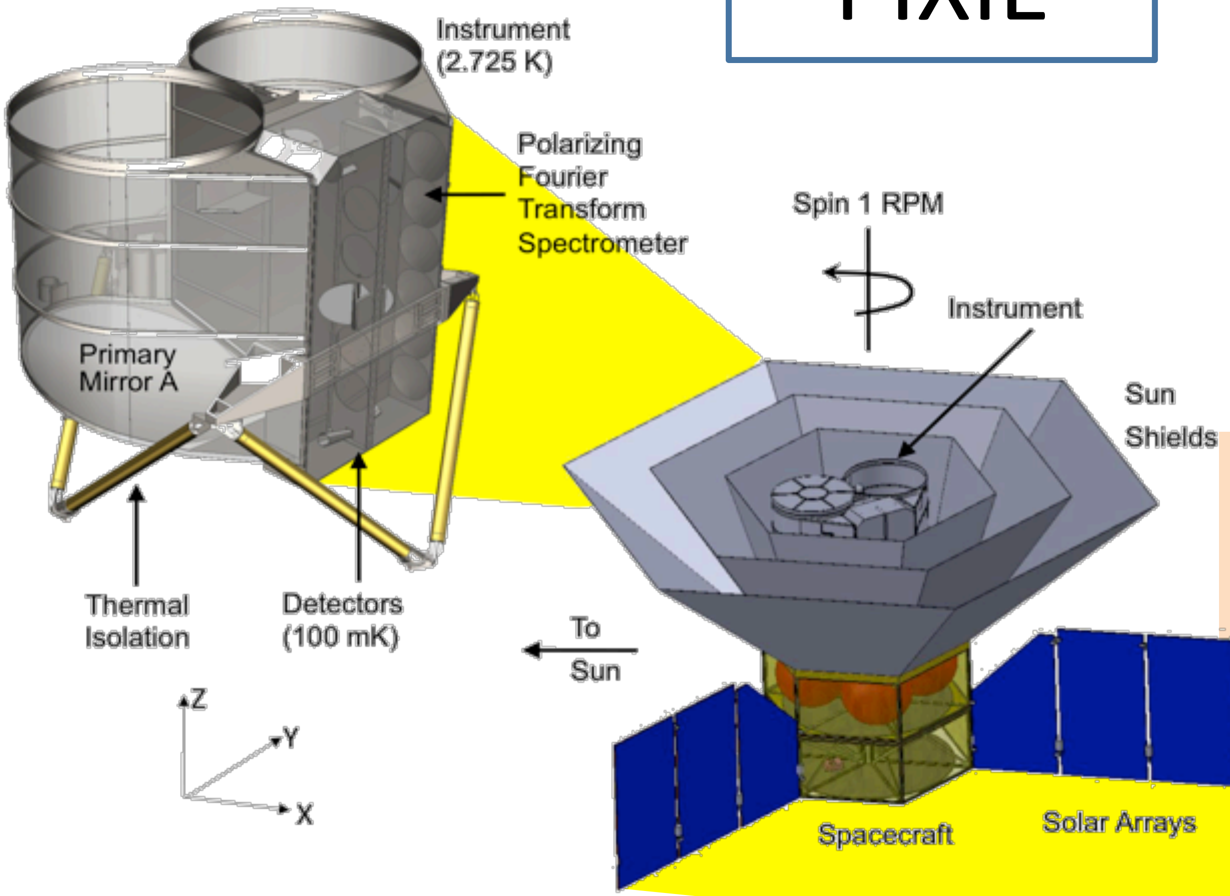
Beyond the Power Spectrum

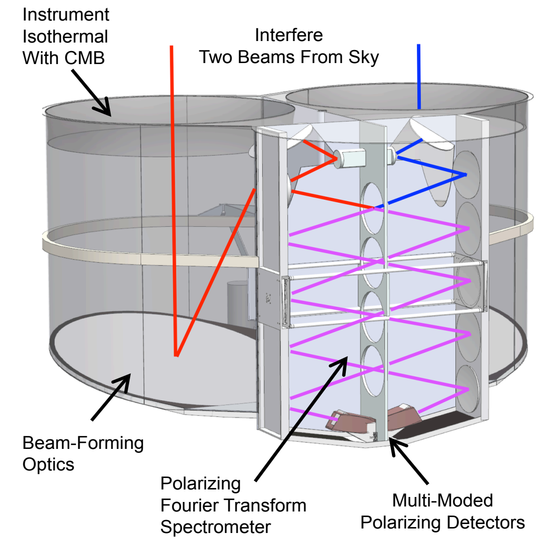
Slide from Al. Kogut



Slide from Al. Kogut

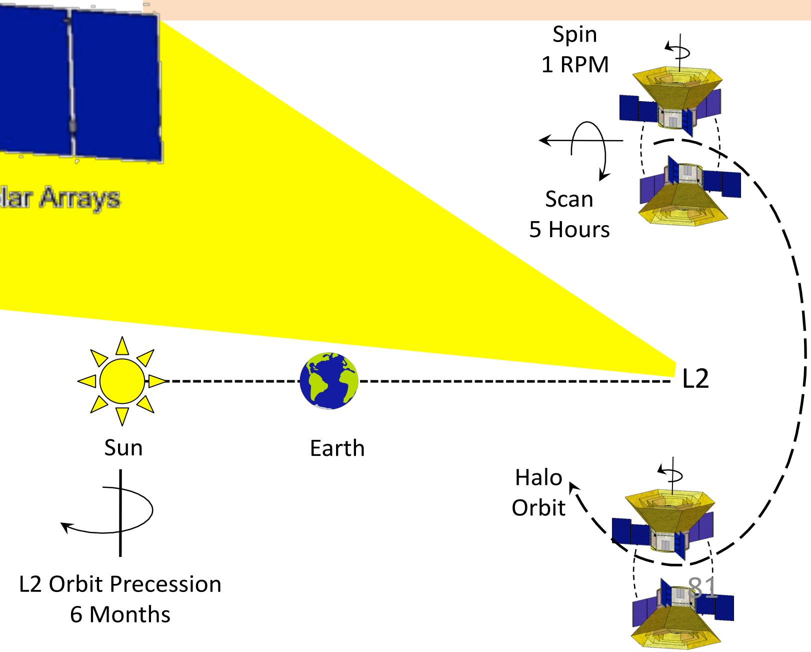
PIXIE





Cryogenic instrument at L2 halo orbit

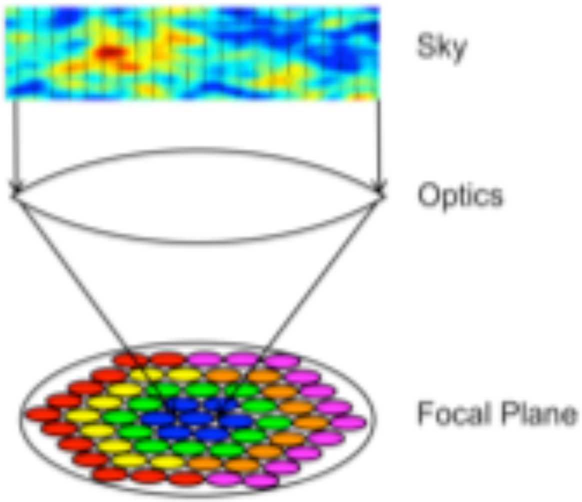
- Spin at 1 RPM
- Precession 5 hours about sun line



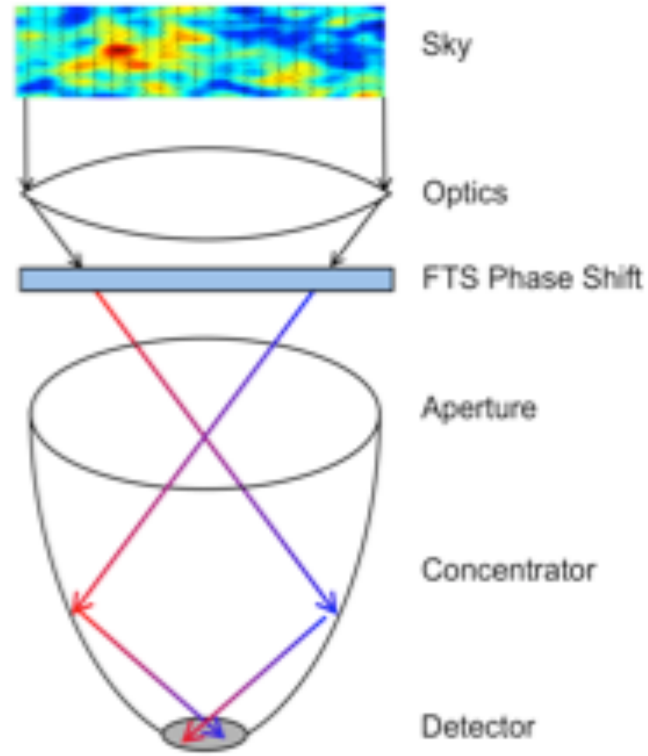
L2 Halo Orbit

- Spin axis 91 deg to sun line
- Precess scan plane to follow sun line
- Full-sky coverage every 6 months

Single-Moded

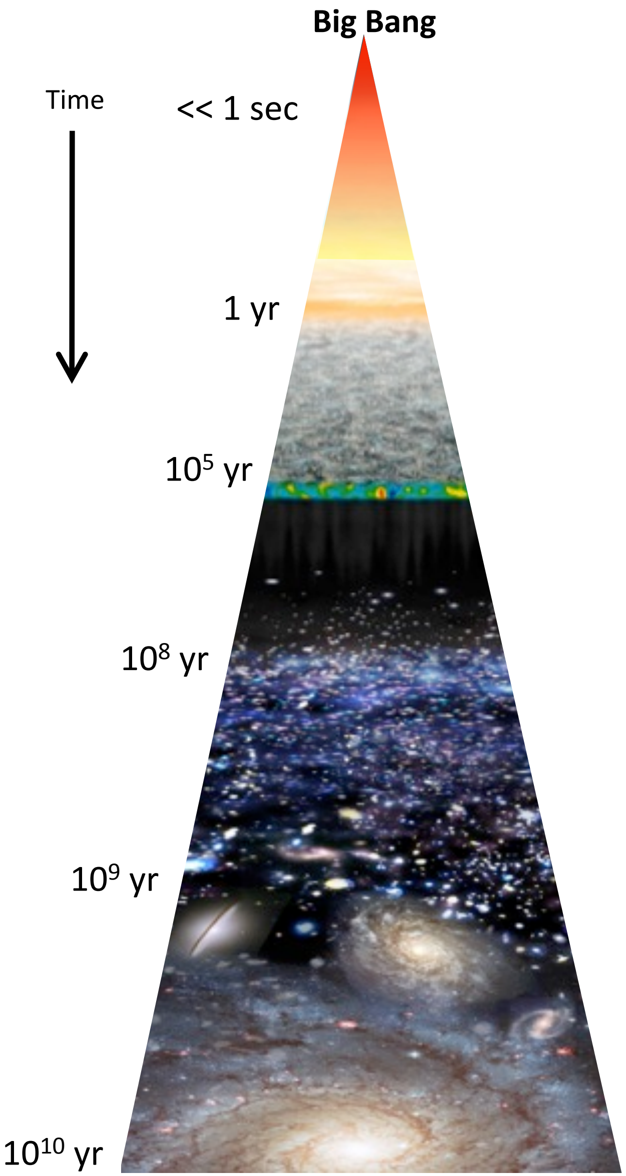


Multi-Moded



Slide from Al. Kogut

PIXIE Samples History of the Universe



Big Bang Cosmology
- Inflation
- Grand Unification physics
- Quantum gravity

Early Universe
- Dark matter decay/annihilation
- Primordial density perturbations

Reionization and First Stars
- Detection of neutrino mass
- Nature of first stars

Large-scale Structure
- Cosmic tomography
- Star formation history

Galactic Structure
- Assembly history of the Galaxy
- Dust & chemical separation

All this science with single instrument

Questions specifically called out in Astro-2010 Decadal Survey

Slide from Al. Kogut

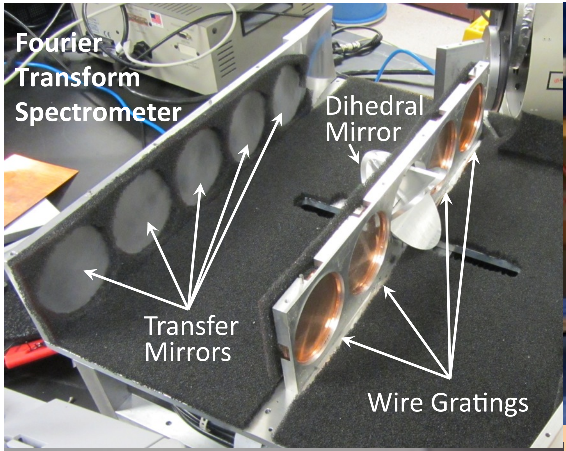
NASA Explorer Program

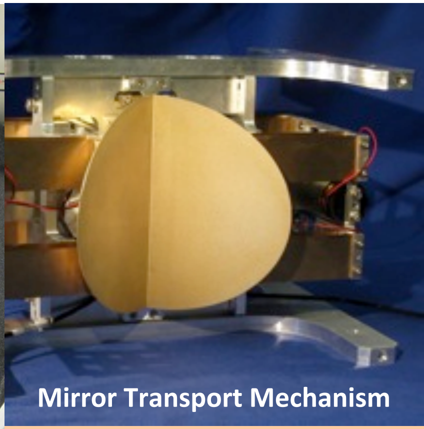
Small PI-led missions
- 22 full missions proposed Feb 2011
- $200M Cost Cap + launch vehicle

PIXIE not selected; urged to re-propose
- Top (Category I) science rating
- Broad recognition of science appeal

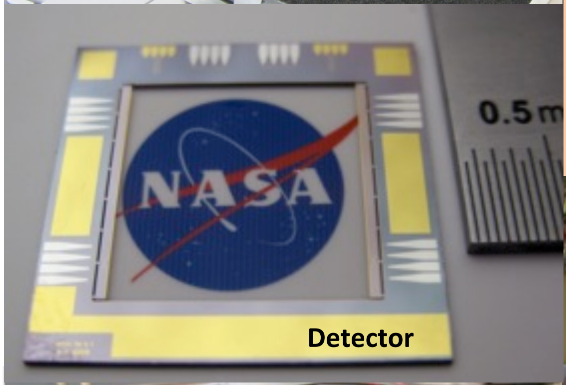
Re-propose to next MIDEX AO (2016)
- Technology is mature
- Launch early next decade

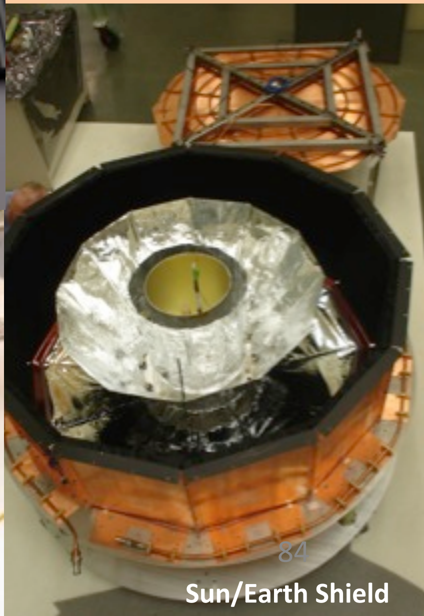
"PIXIE's spectral measurements alone
justify the program"
-- NASA review panel





Mature technology





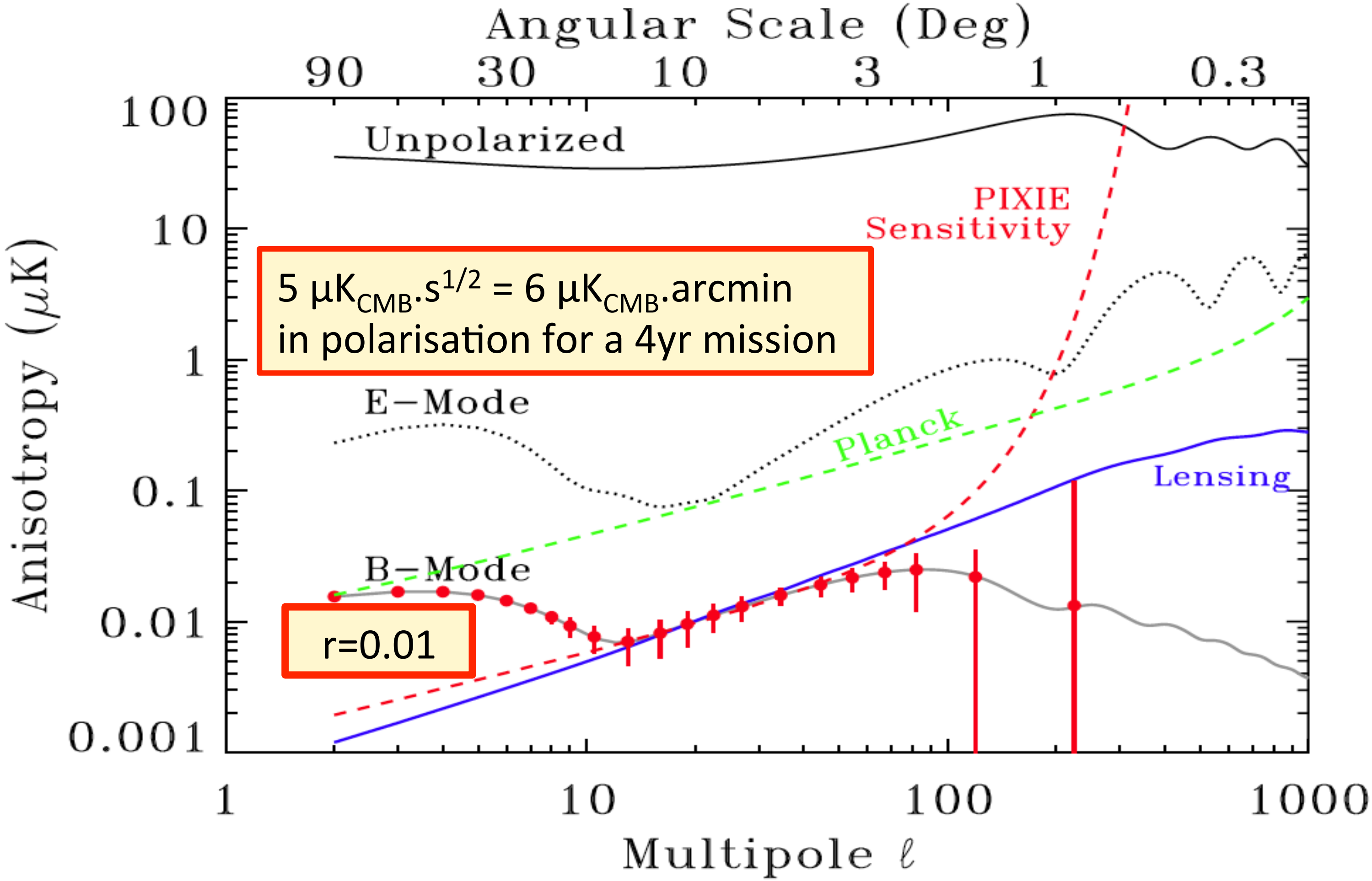


Figure 1. Angular power spectra for unpolarized, E-mode, and B-mode polarization in the cosmic microwave background. The dashed red line shows the PIXIE sensitivity to B-mode polarization at each multipole moment $\ell \sim 180°/\theta$. The sensitivity estimate assumes a 4-year mission and includes the effects of foreground subtraction within the cleanest 75% of the sky combining PIXIE data at frequencies $\nu < 600$ GHz. Red points and error bars show the response within broader ℓ bins to a B-mode power spectrum with amplitude $r = 0.01$. PIXIE will reach the confusion noise (blue curve) from the gravitational lensing of the E-mode signal by cosmic shear along each line of sight, and has the sensitivity and angular response to measure even the minimum predicted B-mode power spectrum at high statistical confidence.

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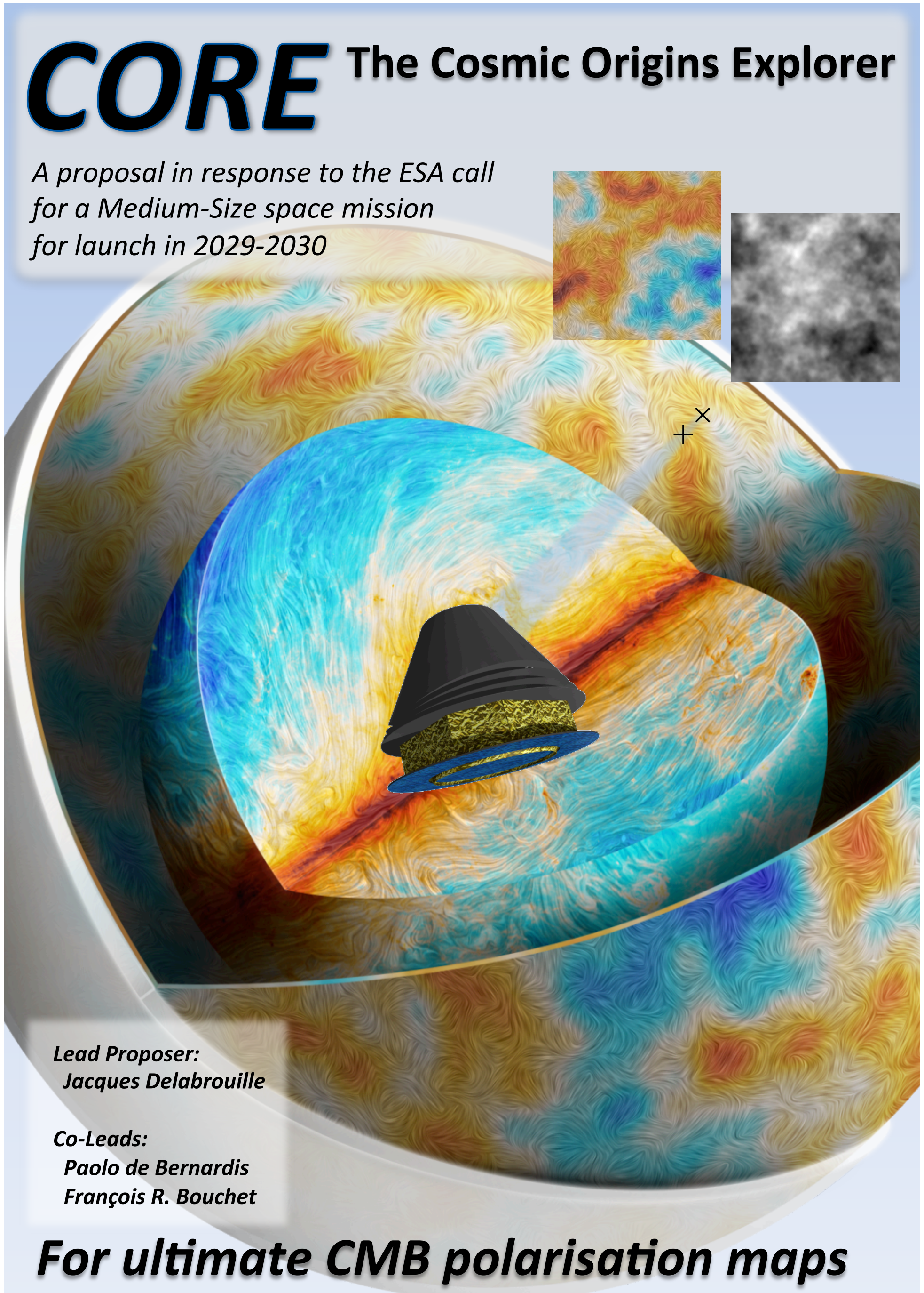

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350 proposers from 15+1 countries

CORE mission concept

Think the mission as the ***(near)-ultimate CMB*** *polarisation mission, with* ***guaranteed science*** *whatever the value of r, and* ***great legacy value*** *and discovery potential.*

Performance / requirement	***Solution***
Resolve the CMB ≈ 4'-6' resolution or better	Class 1.2-1.5m telescope or better ≈ 6' at 135 GHz; ≈ 4' at 200 GHz
Signal dominated data (S/N >2-3 for B_{lens}) σ_P = 1.5-2.5 μK.arcmin on ≈ 100% sky	a few thousand detectors at ≈ 100 mK
Exquisite control of systematic effets for polarisation measurements	L2 orbit; Redundancy and polarisation modulation by scanning strategy
Exquisite control/separation of polarised (and intensity) foregrounds	15-20 frequency bands (or more) covering ≈ 60-600 GHz (or more)

CORE in a nutshell

1) Sensitivity 2 uK.arcmin

- sufficient for signal-dominated lensing maps and for r=0.001

2) 19 frequency channels

- 6 for low-frequency foregrounds (synchrotron…) below 115 GHz
- 6 for the CMB, between 130 and 220 GHz
- Good sensitivity in each CMB channel individually
- 7 for high-frequency foregrounds (dust…) above 250 GHz

3) Angular resolution ranging from 2 to 20 arcminute

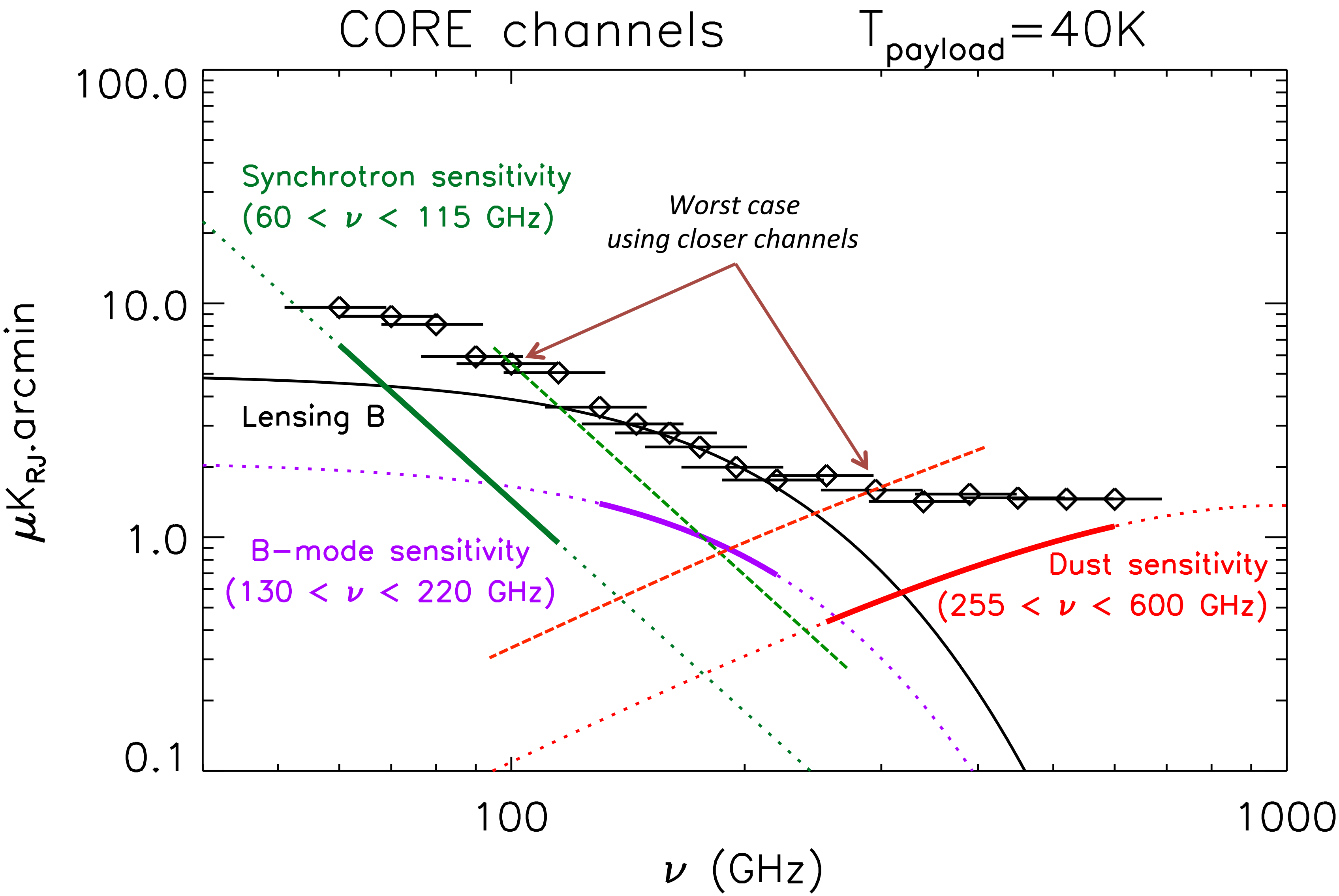
- 5-10' in CMB channels

4) Control of systematic effects

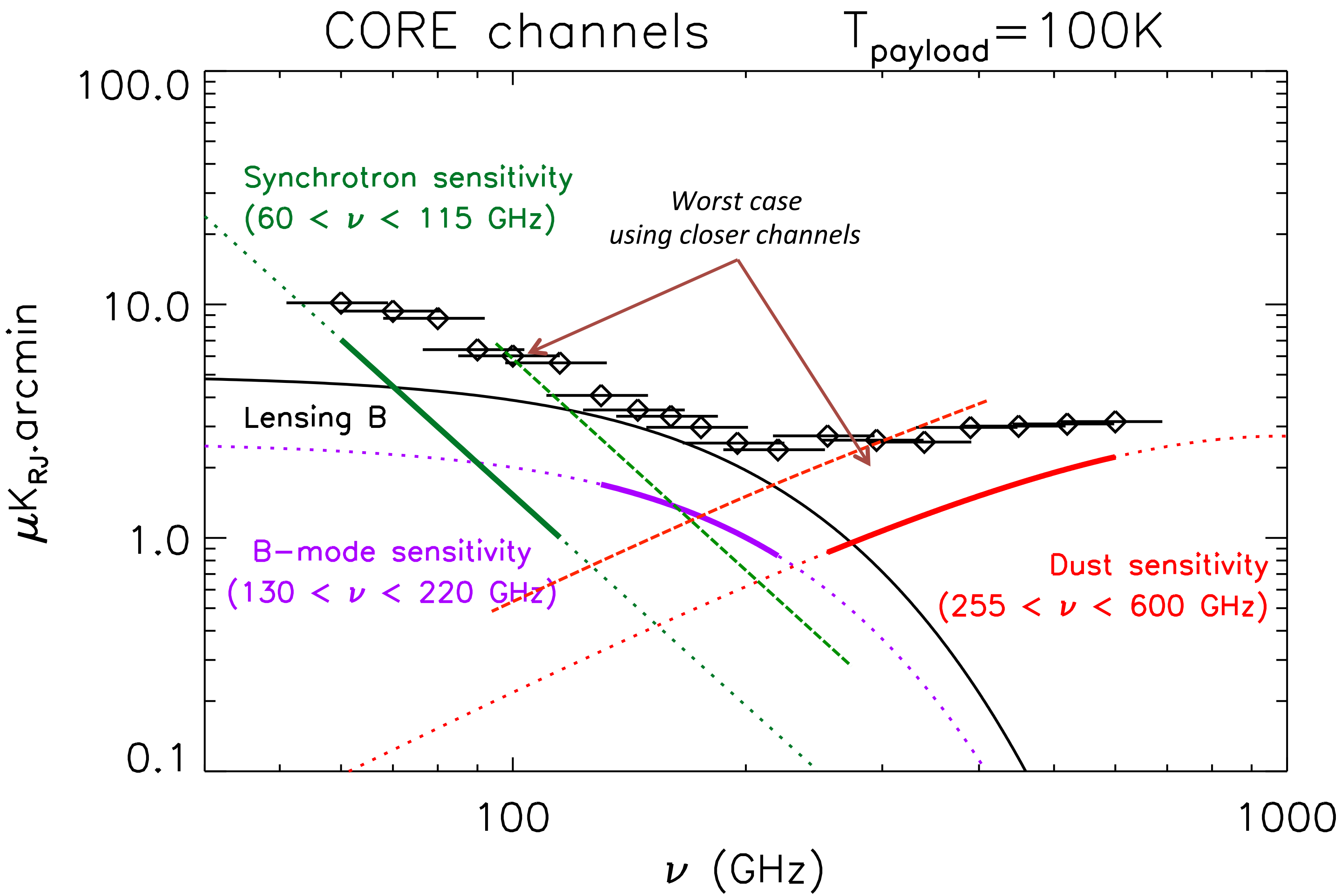
- Very stable observing conditions
- Dedicated scan strategy to modulate polarisation

CORE channels

channel GHz	beam arcmin	$N_{\rm det}$	ΔT μK.arcmin	ΔP μK.arcmin	ΔI $\mu K_{\rm RJ}$.arcmin	ΔI kJy/sr.arcmin	$\Delta y \times 10^6$ $y_{\rm SZ}$.arcmin	PS (5σ) mJy
60	17.87	48	7.5	10.6	6.81	0.75	-1.5	5.0
70	15.39	48	7.1	10	6.23	0.94	-1.5	5.4
80	13.52	48	6.8	9.6	5.76	1.13	-1.5	5.7
90	12.08	78	5.1	7.3	4.19	1.04	-1.2	4.7
100	10.92	78	5.0	7.1	3.90	1.2	-1.2	4.9
115	9.56	76	5.0	7.0	3.58	1.45	-1.3	5.2
130	8.51	124	3.9	5.5	2.55	1.32	-1.2	4.2
145	7.68	144	3.6	5.1	2.16	1.39	-1.3	4.0
160	7.01	144	3.7	5.2	1.98	1.55	-1.6	4.1
175	6.45	160	3.6	5.1	1.72	1.62	-2.1	3.9
195	5.84	192	3.5	4.9	1.41	1.65	-3.8	3.6
220	5.23	192	3.8	5.4	1.24	1.85	-	3.6
255	4.57	128	5.6	7.9	1.30	2.59	3.5	4.4
295	3.99	128	7.4	10.5	1.12	3.01	2.2	4.5
340	3.49	128	11.1	15.7	1.01	3.57	2.0	4.7
390	3.06	96	22.0	31.1	1.08	5.05	2.8	5.8
450	2.65	96	45.9	64.9	1.04	6.48	4.3	6.5
520	2.29	96	116.6	164.8	1.03	8.56	8.3	7.4
600	1.98	96	358.3	506.7	1.03	11.4	20.0	8.5
Array		2100	1.2	1.7			0.41	

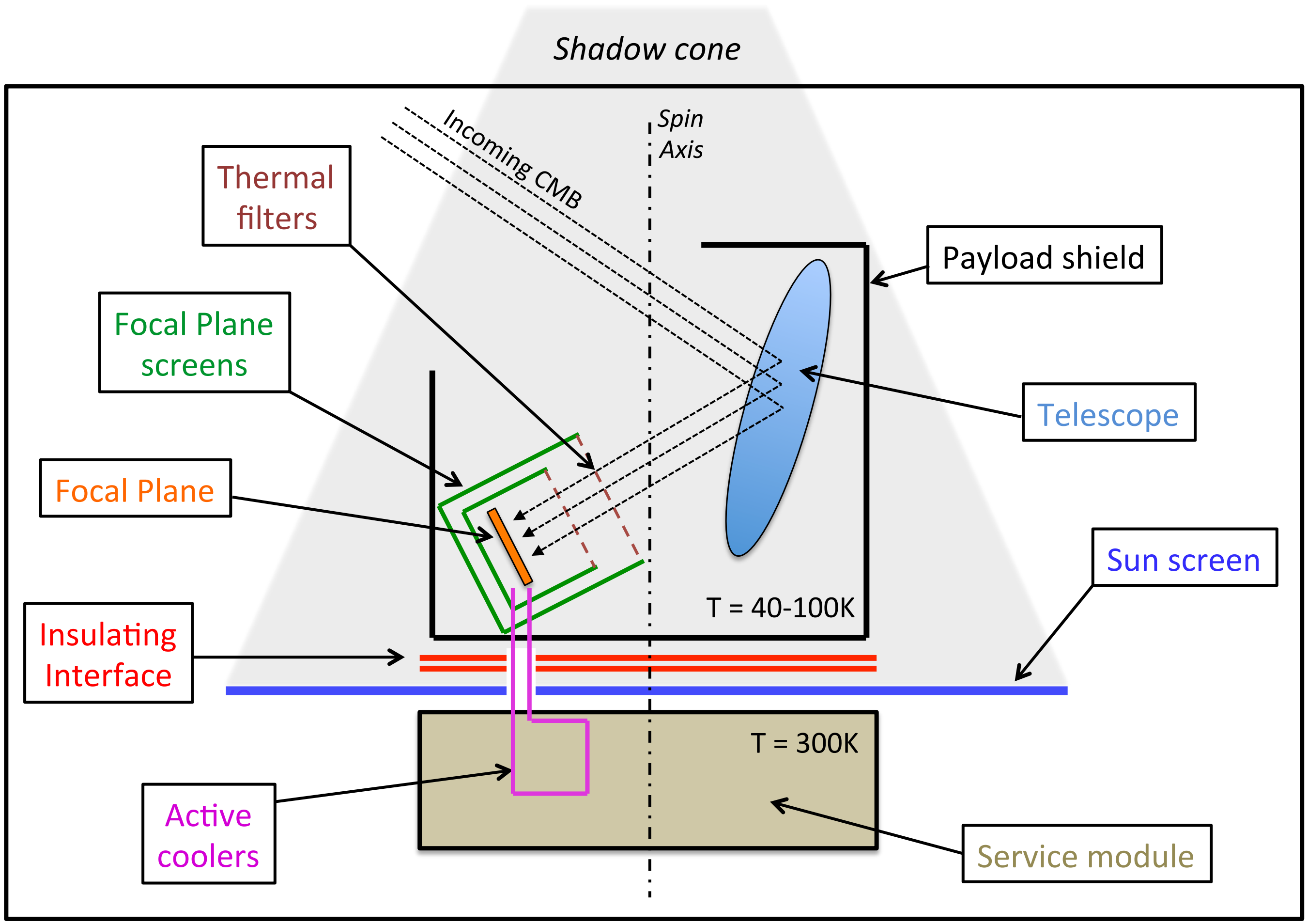


CMB polarization sensitivity	2.05 uK.arcmin
Synchrotron extrapolation at 130 GHz	1.00 uK.arcmin
Dust extrapolation at 220 GHz	1.10 uK.arcmin



CMB polarization sensitivity	2.58 uK.arcmin
Synchrotron extrapolation at 130 GHz	1.06 uK.arcmin
Dust extrapolation at 220 GHz	2.18 uK.arcmin

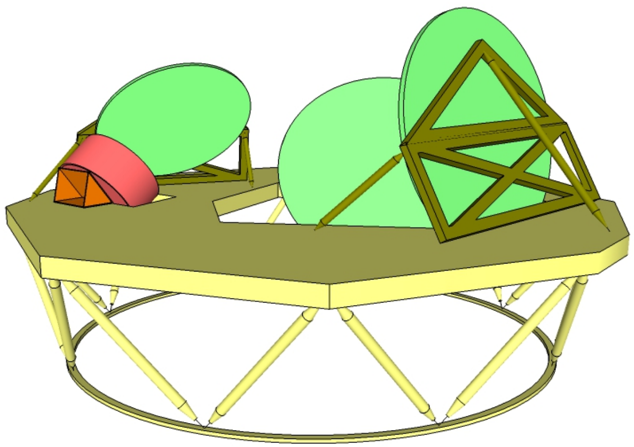
CORE functional design

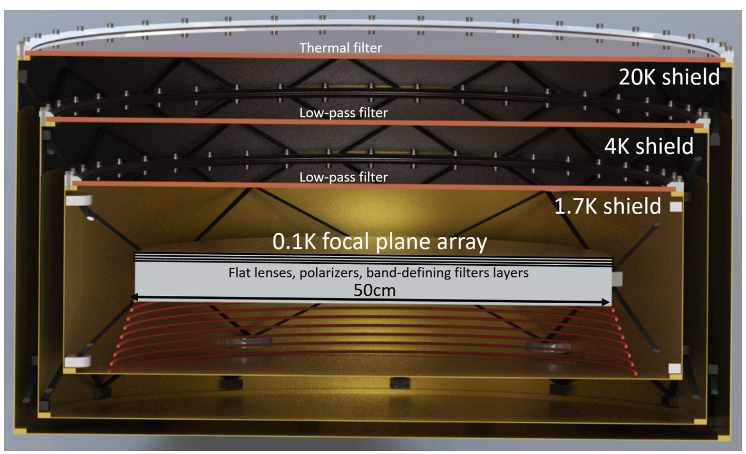


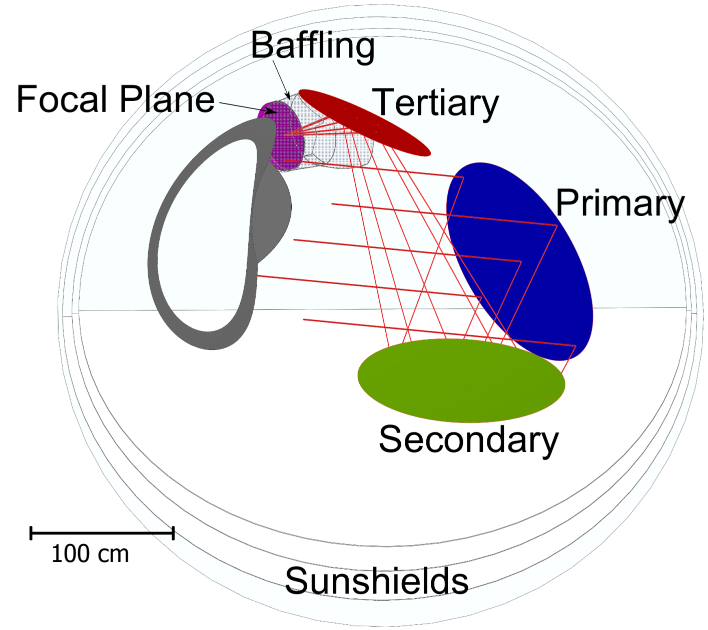
Optics

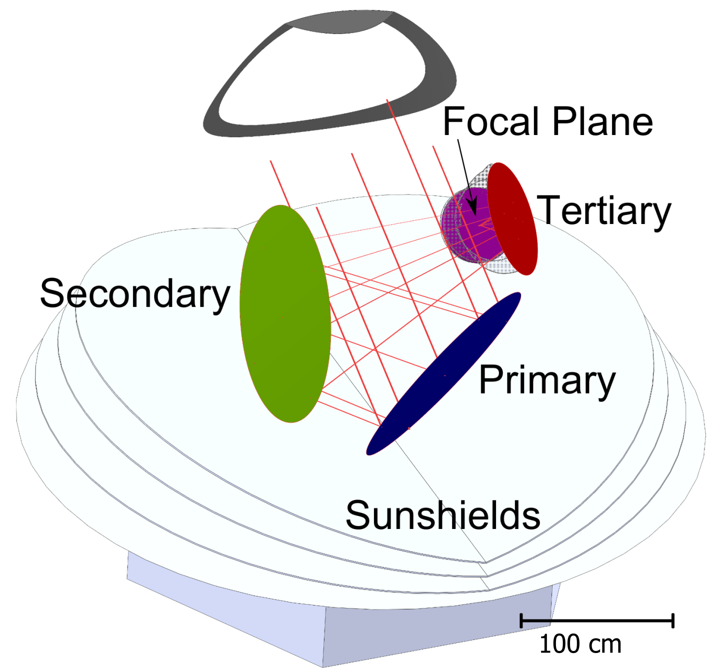
Crossed-Dragone Telescope

- Excellent polarisation properties
- Large, flat, telecentric focal plane



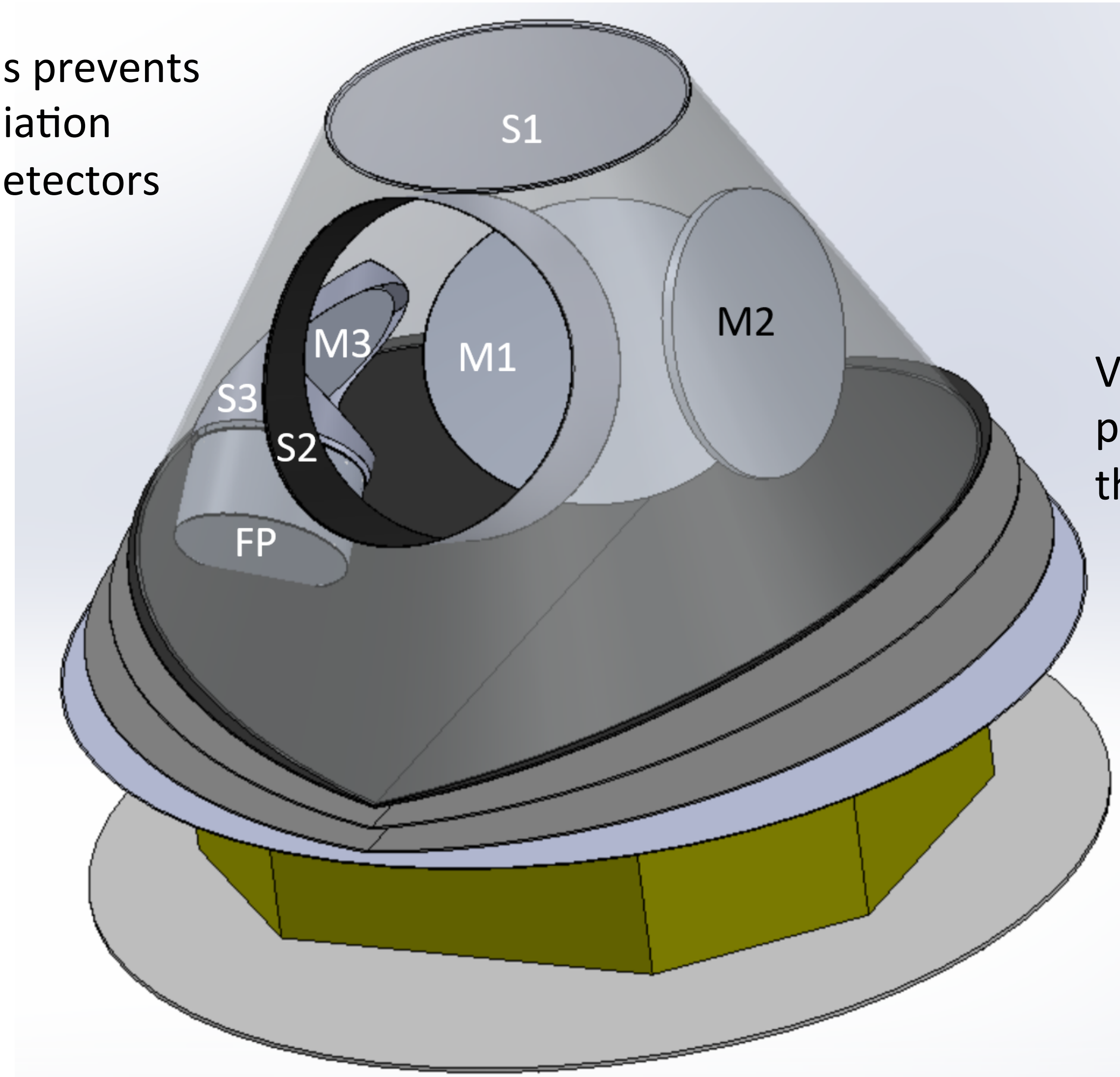






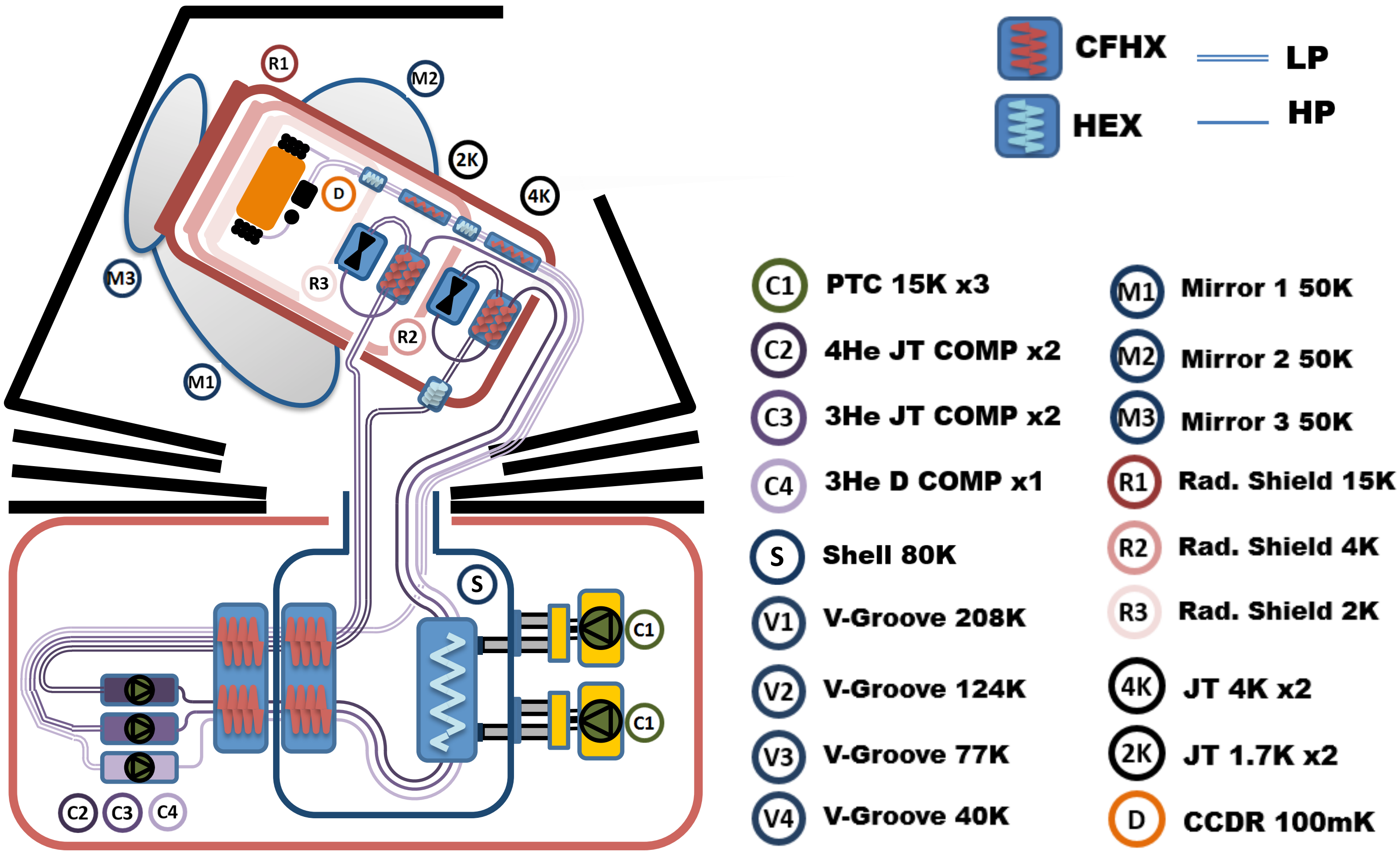
CORE shielding

A set of shields prevents unwanted radiation to reach the detectors



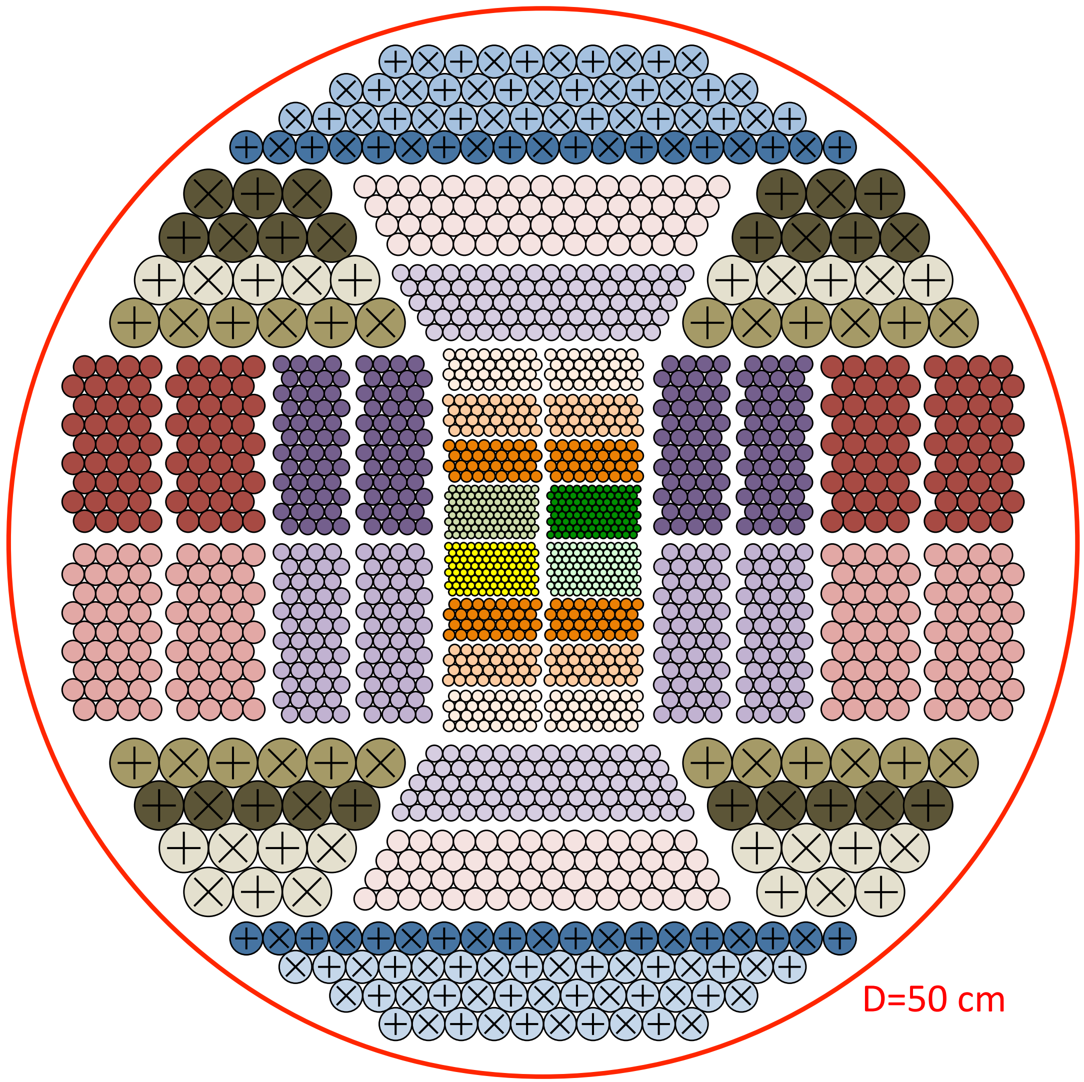
V-grooves provide passive cooling of the payload to 40K

Cooling chain

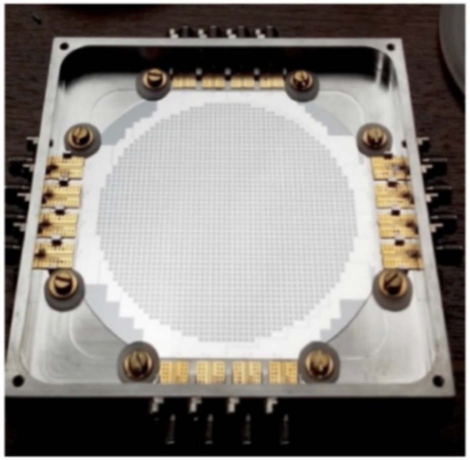


Focal plane

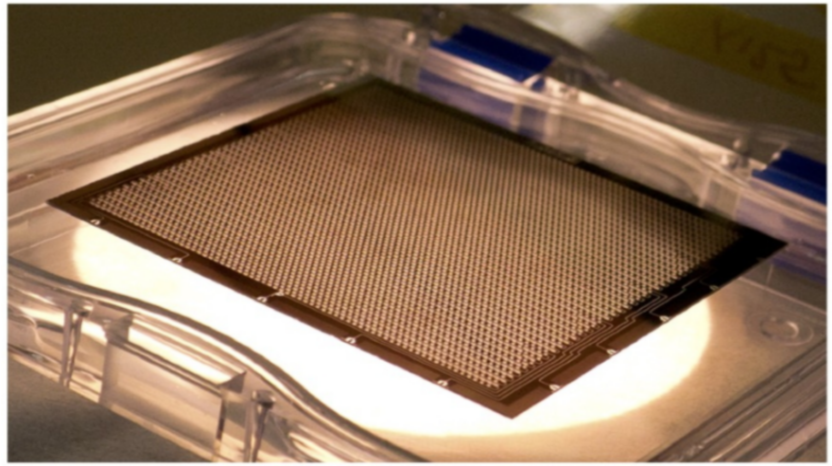
GHz	N_{det}
60	24×2
70	24×2
80	24×2
90	39×2
100	39×2
115	38×2
130	124
145	144
160	144
175	160
195	192
220	192
255	128
295	128
340	128
390	96
450	96
520	96
600	96
TOTAL	2100



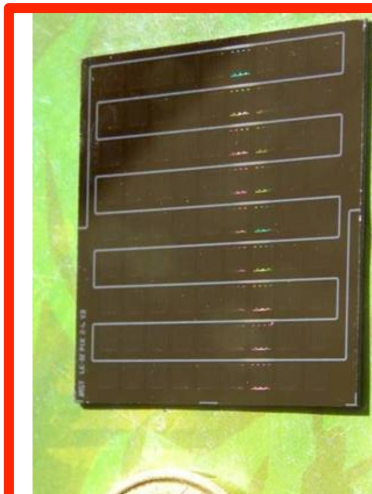
KID detectors in Europe



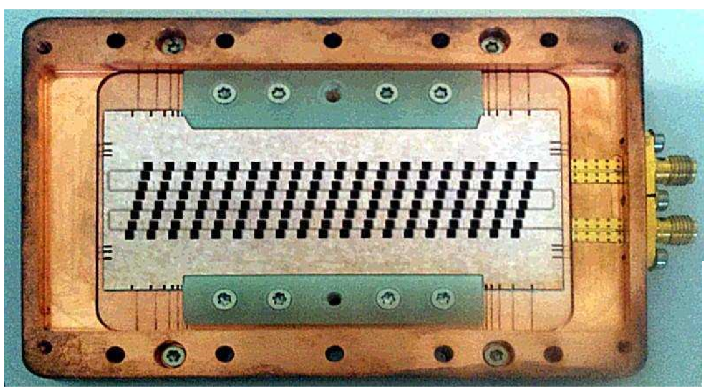
NIKA2 array 200-300 GHz
(Grenoble) -> IRAM30m



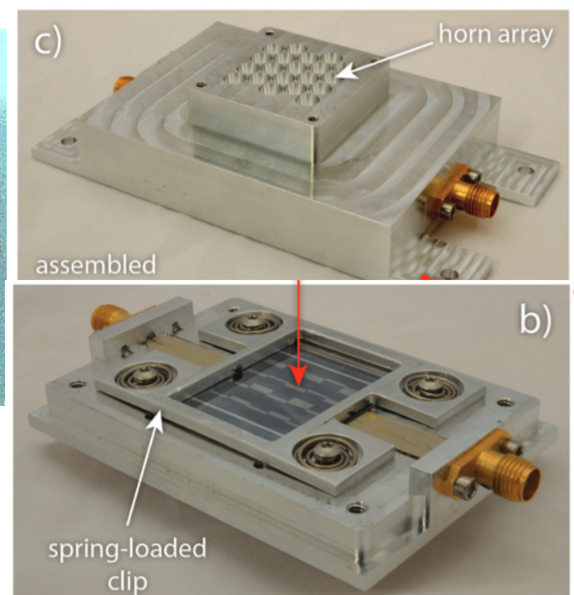
AMKID array - submm
(Groningen) -> APEX ALMA

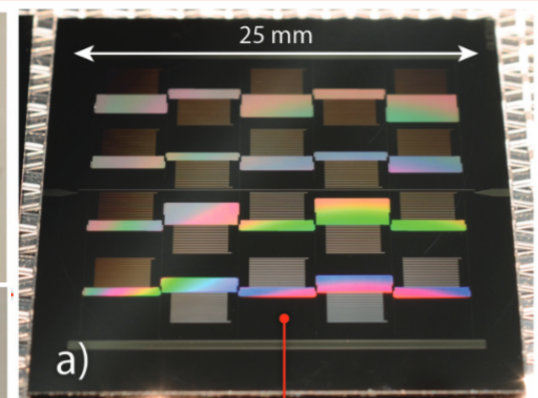


LEKID for 150 GHz
(Rome)



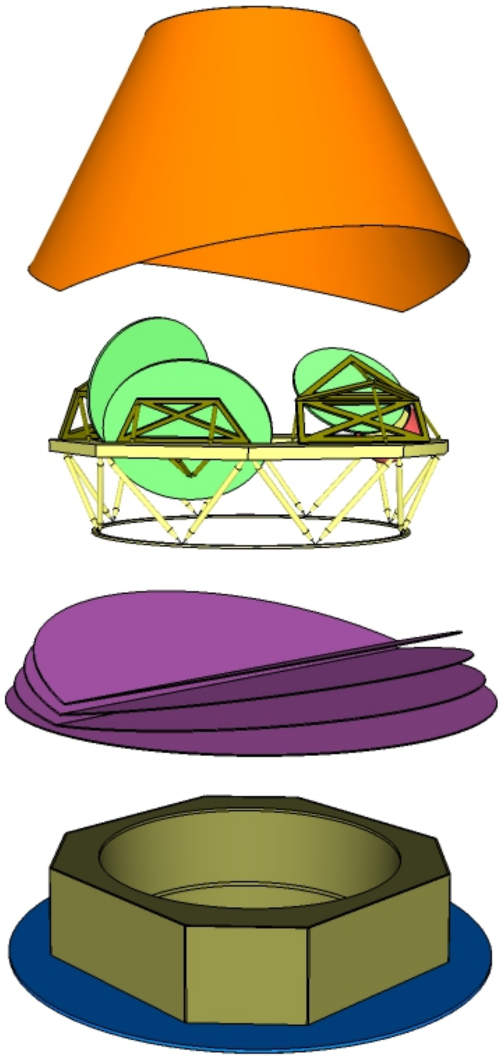
THz camera for safety scanner
(Cardiff)

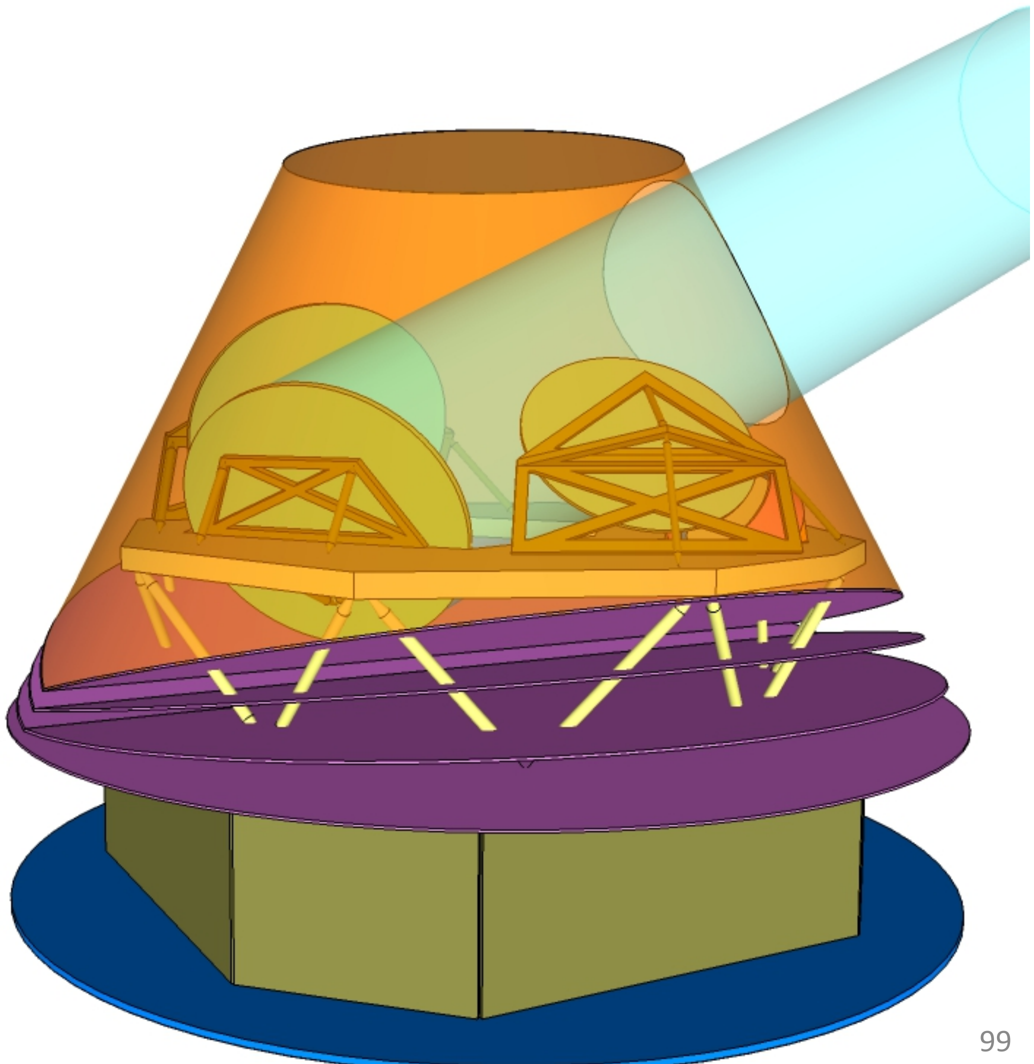




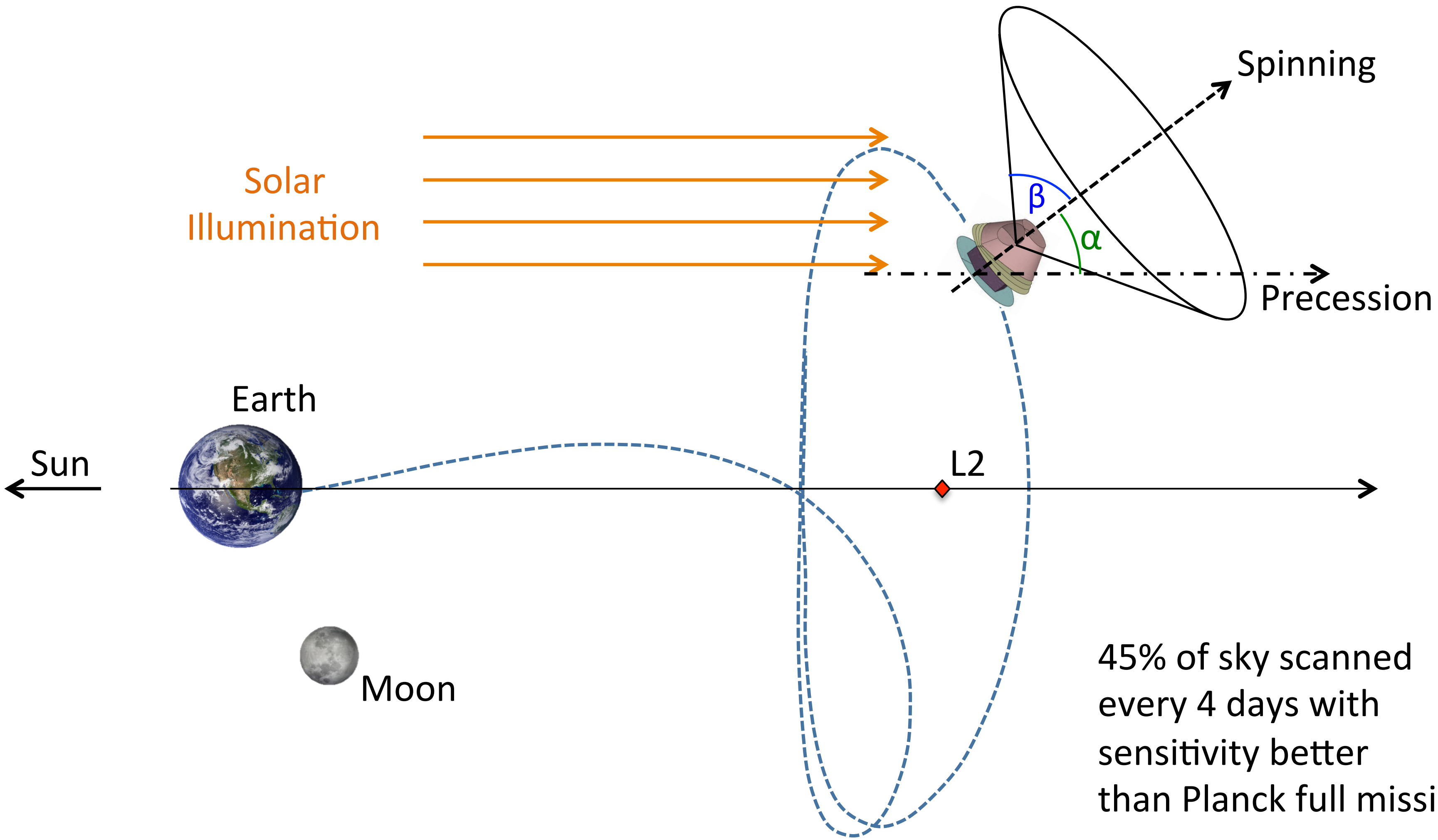
Horn-coupled KIDs for CMB
(Cardiff + ASU)

Spacecraft





Scanning



45% of sky scanned every 4 days with sensitivity better than Planck full mission

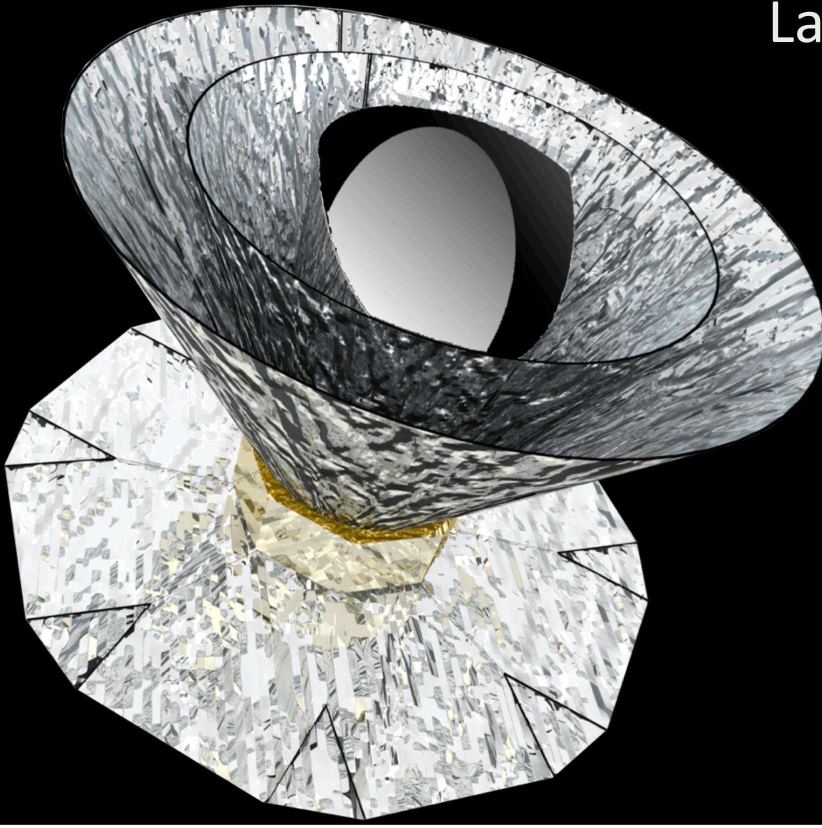
	CORE	LiteBIRD
Orbit	L2	L2
Launch year	>2030	2027 ?
Observation time	3 years	3 years
Mass	2.2 tons	2.2 tons
Power	2.2 kW	2.5 kW
Main telescope	Gregorian, 1.2m aperture, 60-100K passive	Cross Dragone 40cm aperture, <10K active
Secondary telescope + instrument	No	Yes
Frequencies	≈ 60-600 (19 bands)	≈ 40-400 (12+3 = 15 bands)
Detectors	≈ 2000 single band single-polar, 100mK, One focal plane	≈ 2000 tri-chroic dual-polar, 100 mK, Two focal planes
Cooling system	ST/JT/CCDR or ADR	ST/JT/ADR or CCDR
Data size	100-400 Gbit/day	4 Gbit/day
Moving parts in PLM	none	2 CRHWPs, cooled to <10K Slip ring between PLM and SVM
Moving parts in SVM	Steerable antenna	Deployable solar panels Steerable antenna
Sensitivity	≈ 2 μK.arcmin	≈ 3 μK.arcmin (assumes 0.8 yield + 25% margin)
Angular resolution	10' @ 100 GHz	>30' @ 100 GHz

Outline

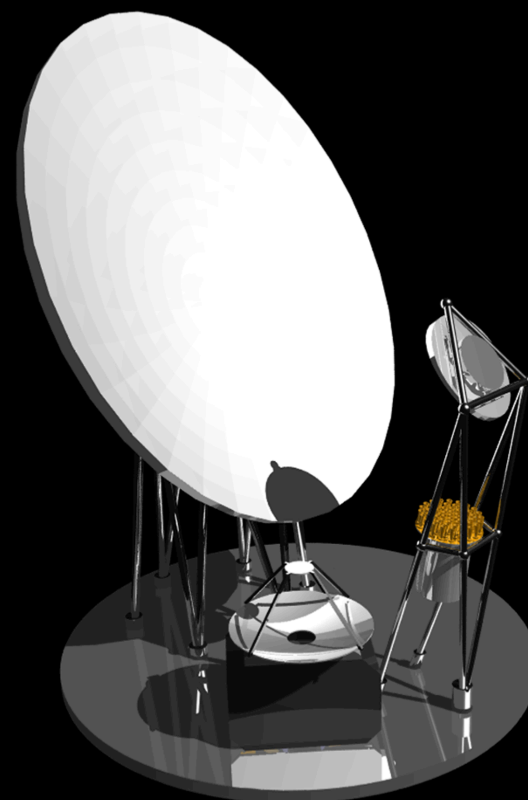
- Introduction
- Where are we?
- Science case: what next
- Challenges
  - sensitivity
  - atmosphere
  - systematics
  - foregrounds
- Suborbital experiments
- Space experiments
  - PIXIE
  - LiteBIRD
  - CORE
  - PRISM
- A strategy for the future
- Summary

PRISM

Large ESA mission (1B€) (not selected)



A high resolution (1-2') absolute (10^{-8}) imaging spectrophotometer (N_{freq}>20)



Two instruments

Outline

- Introduction
- Where are we?
- Science case: what next
- Challenges
  - sensitivity
  - atmosphere
  - systematics
  - foregrounds
- Suborbital experiments
- Space experiments
  - PIXIE
  - LiteBIRD
  - CORE
  - PRISM
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THE B RACE

DILEMMA

THE CMB TASK

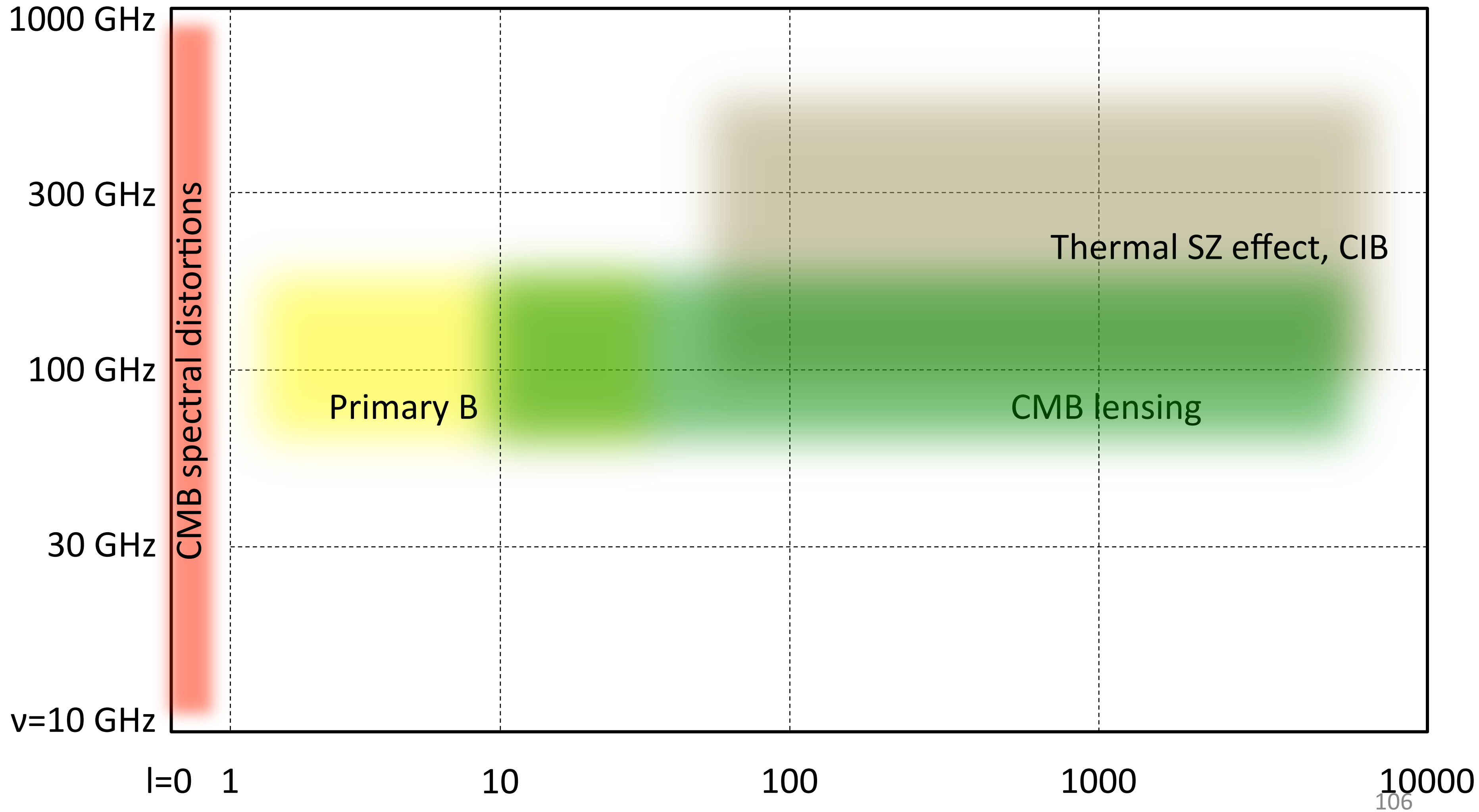
Every small step can yield the first detection of inflationary B-modes.

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

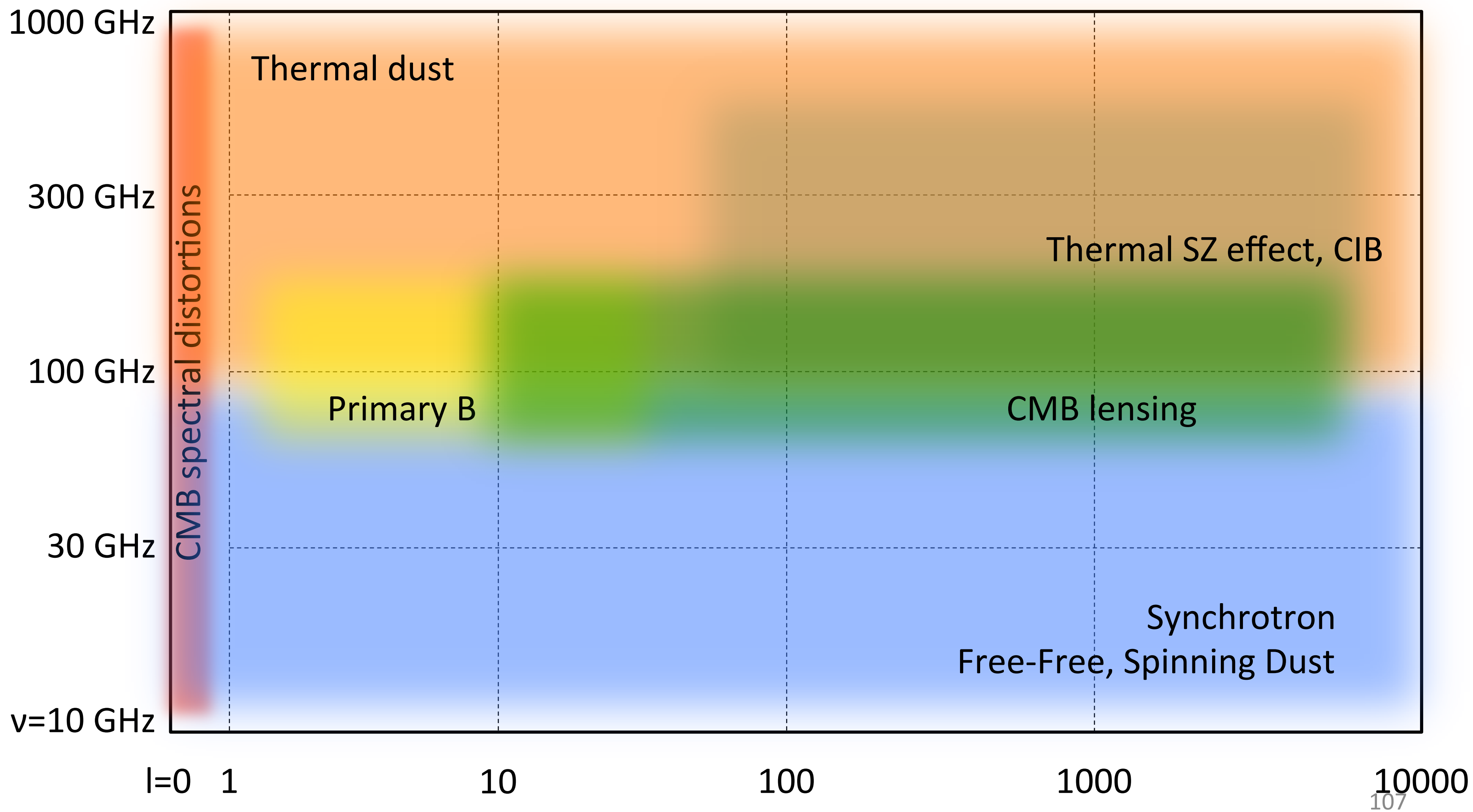
CMB is unique. Getting the best of it is a scientific imperative.

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

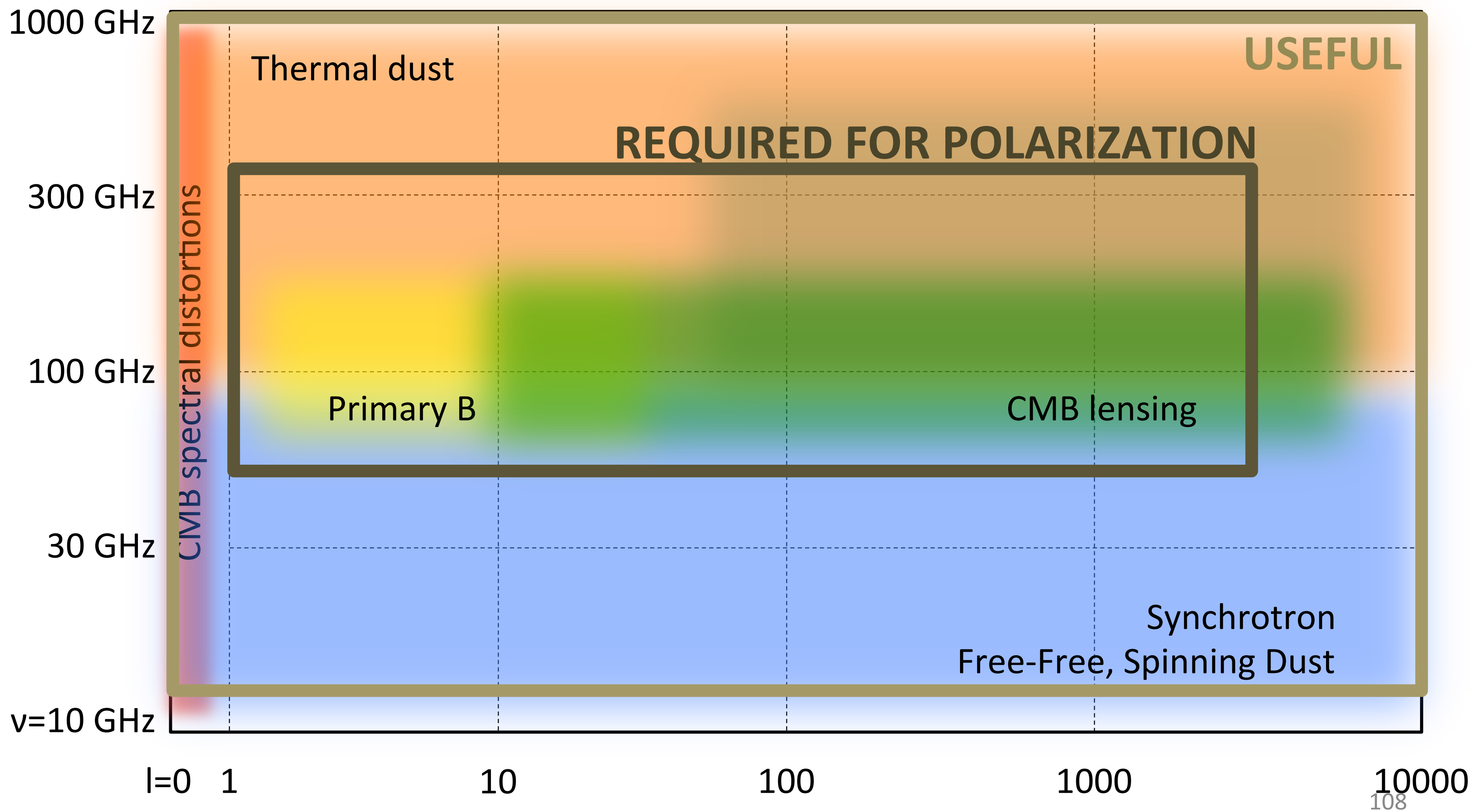
The battle field



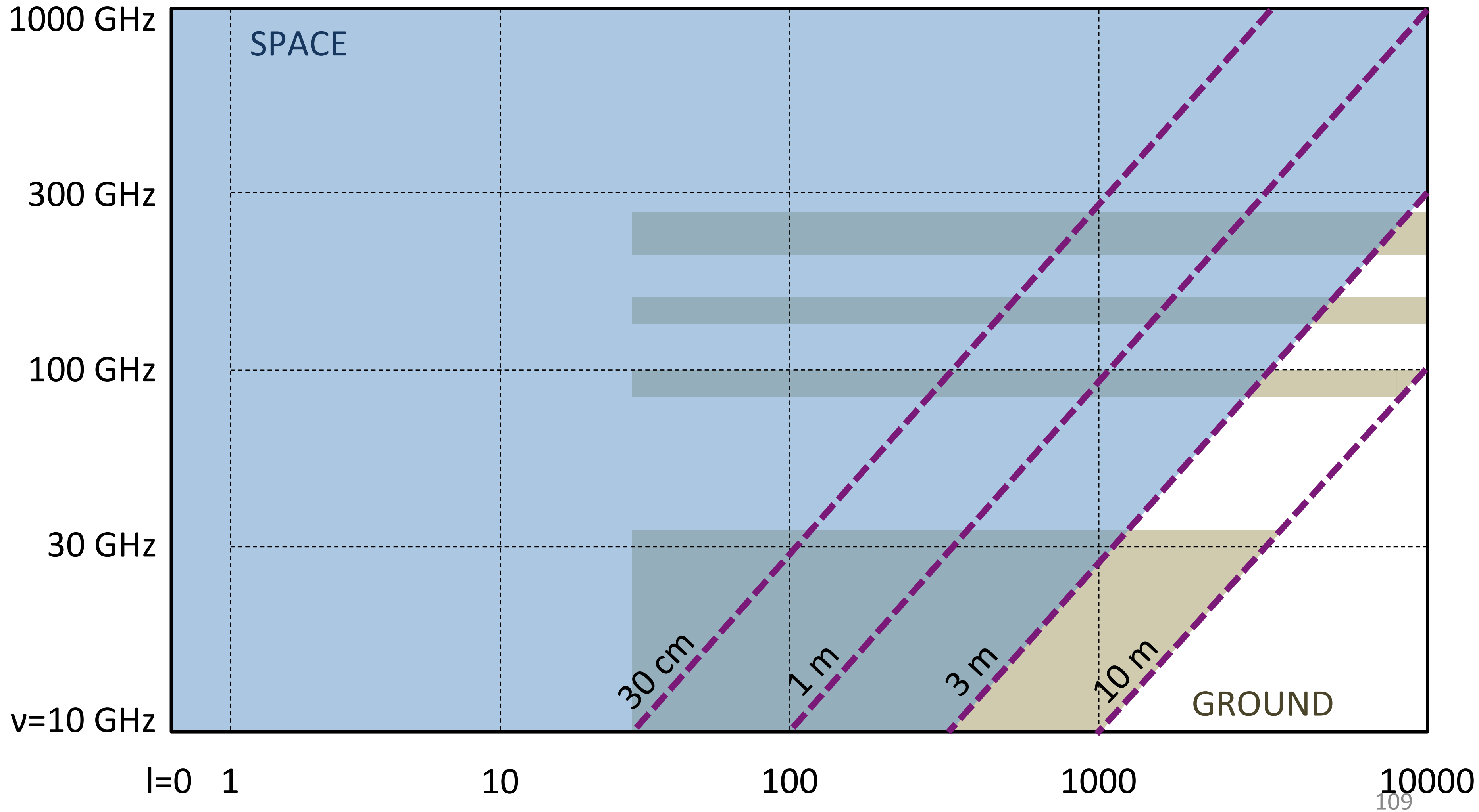
The battle field



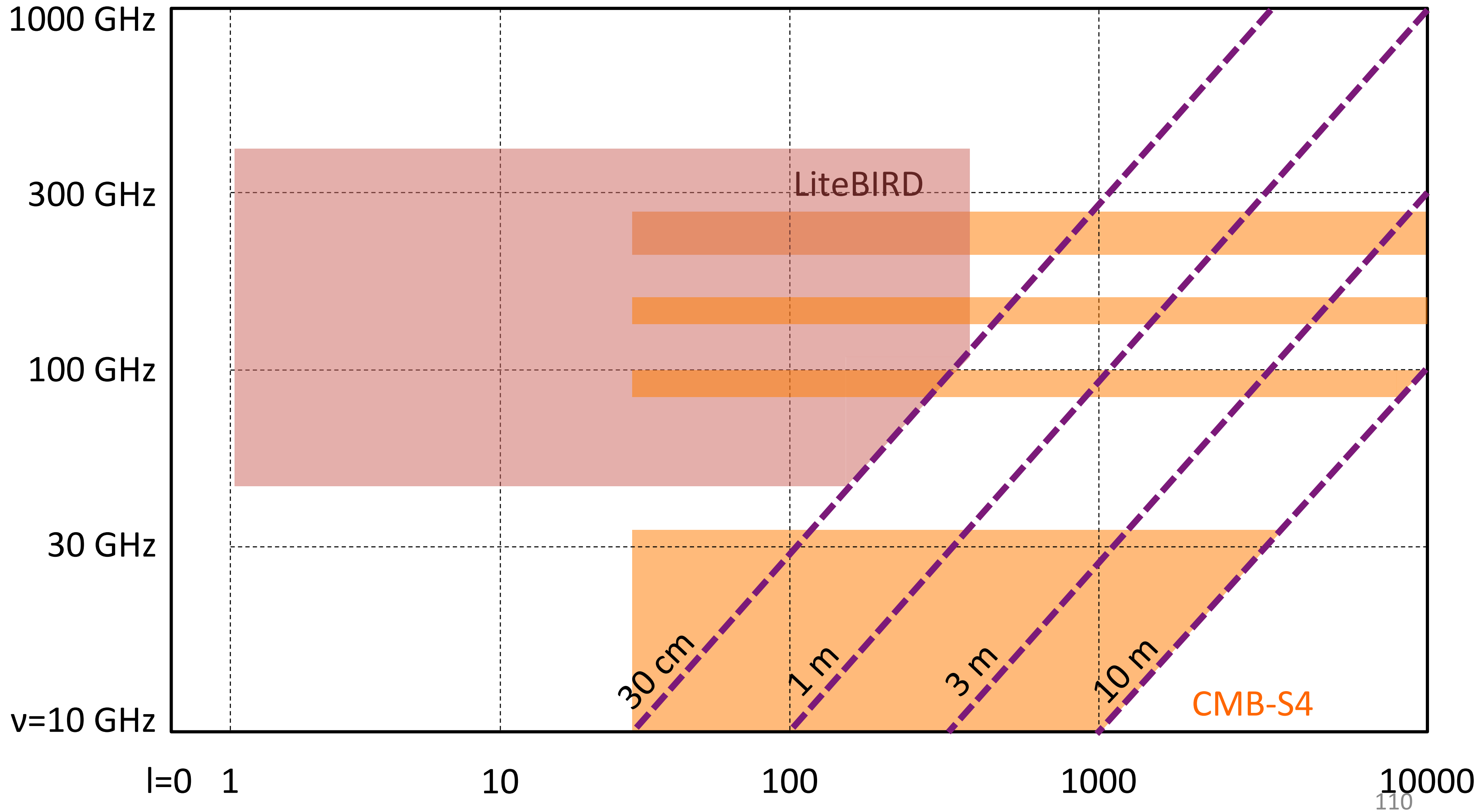
The battle field



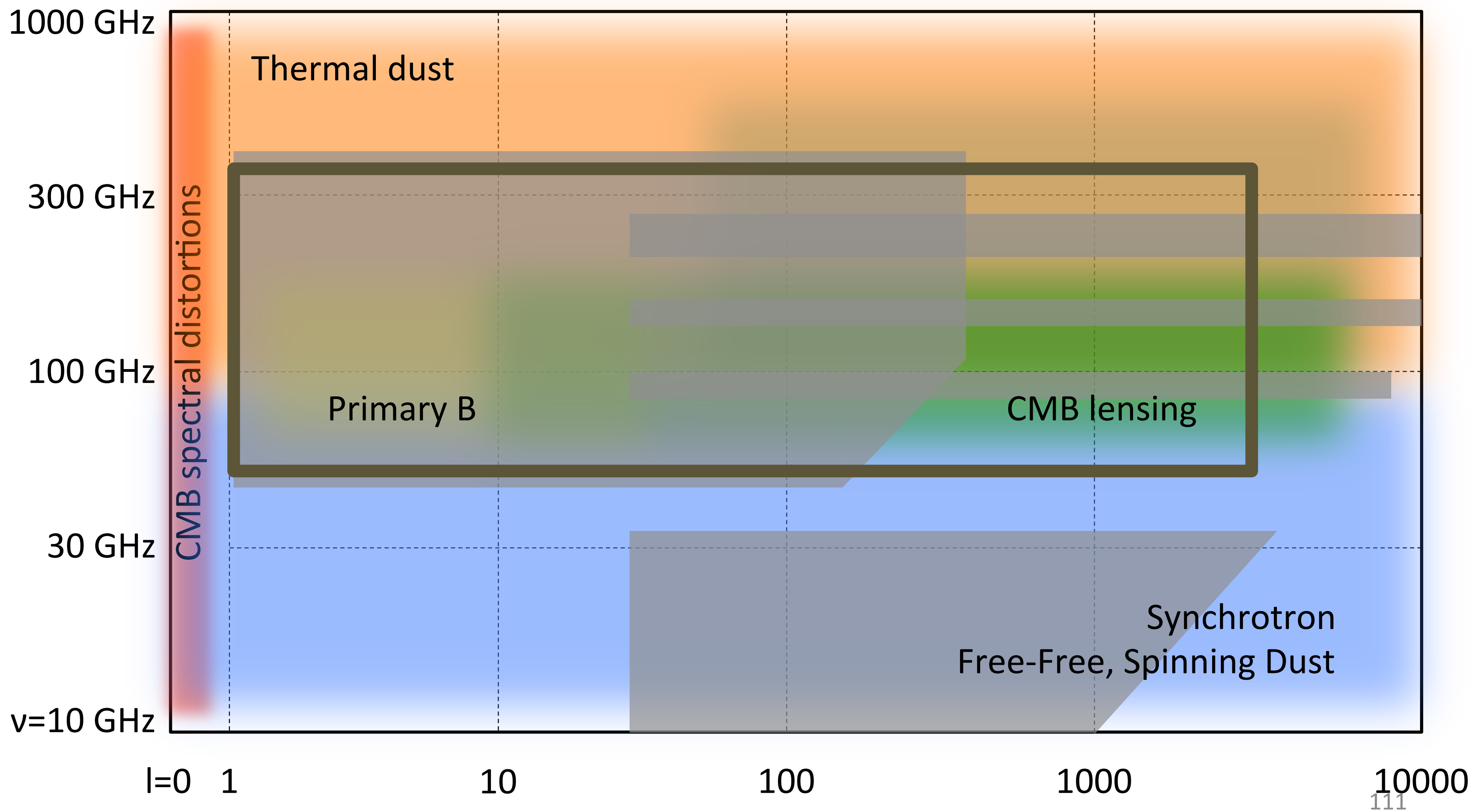
Ground-space complementarity



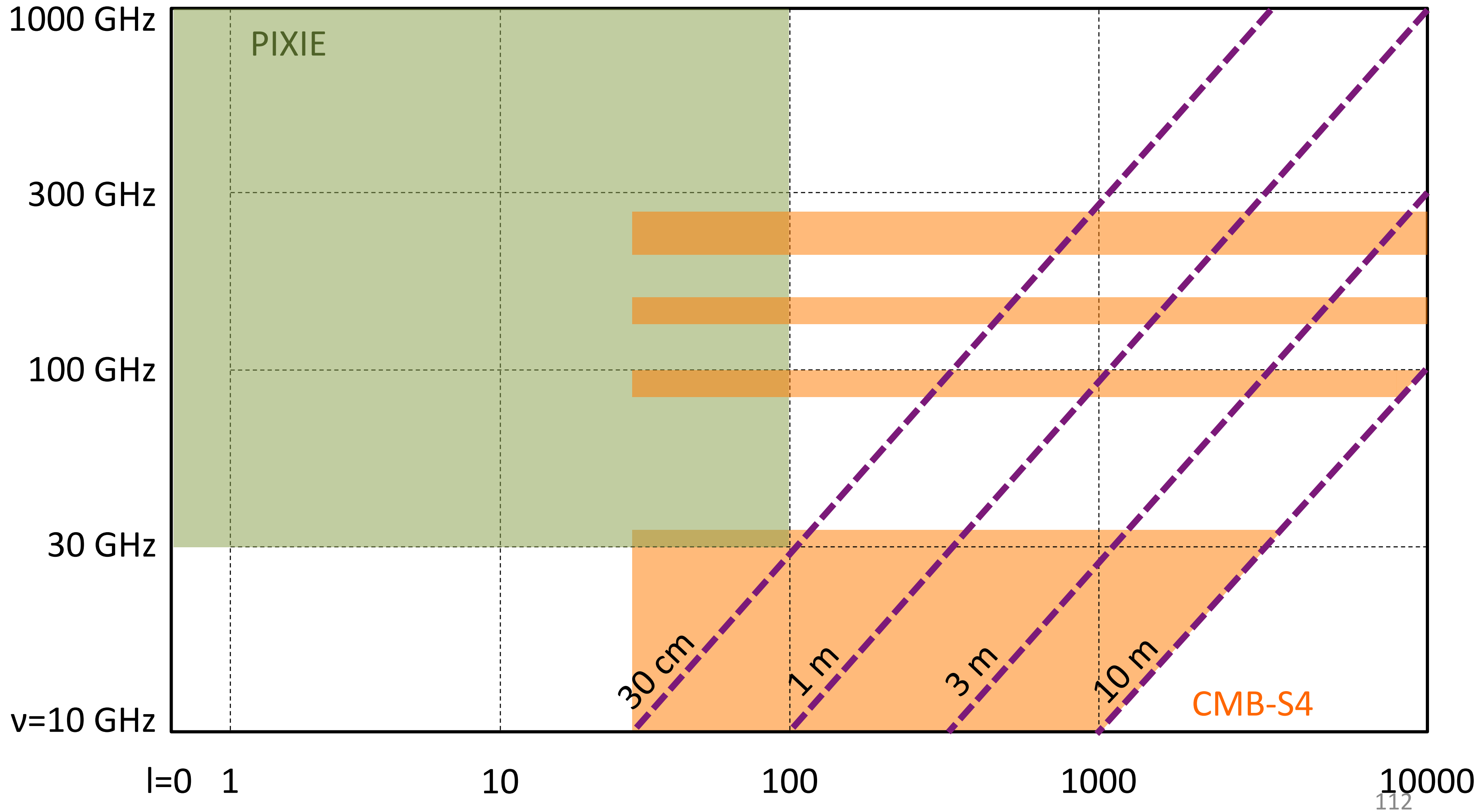
Ground-space complementarity



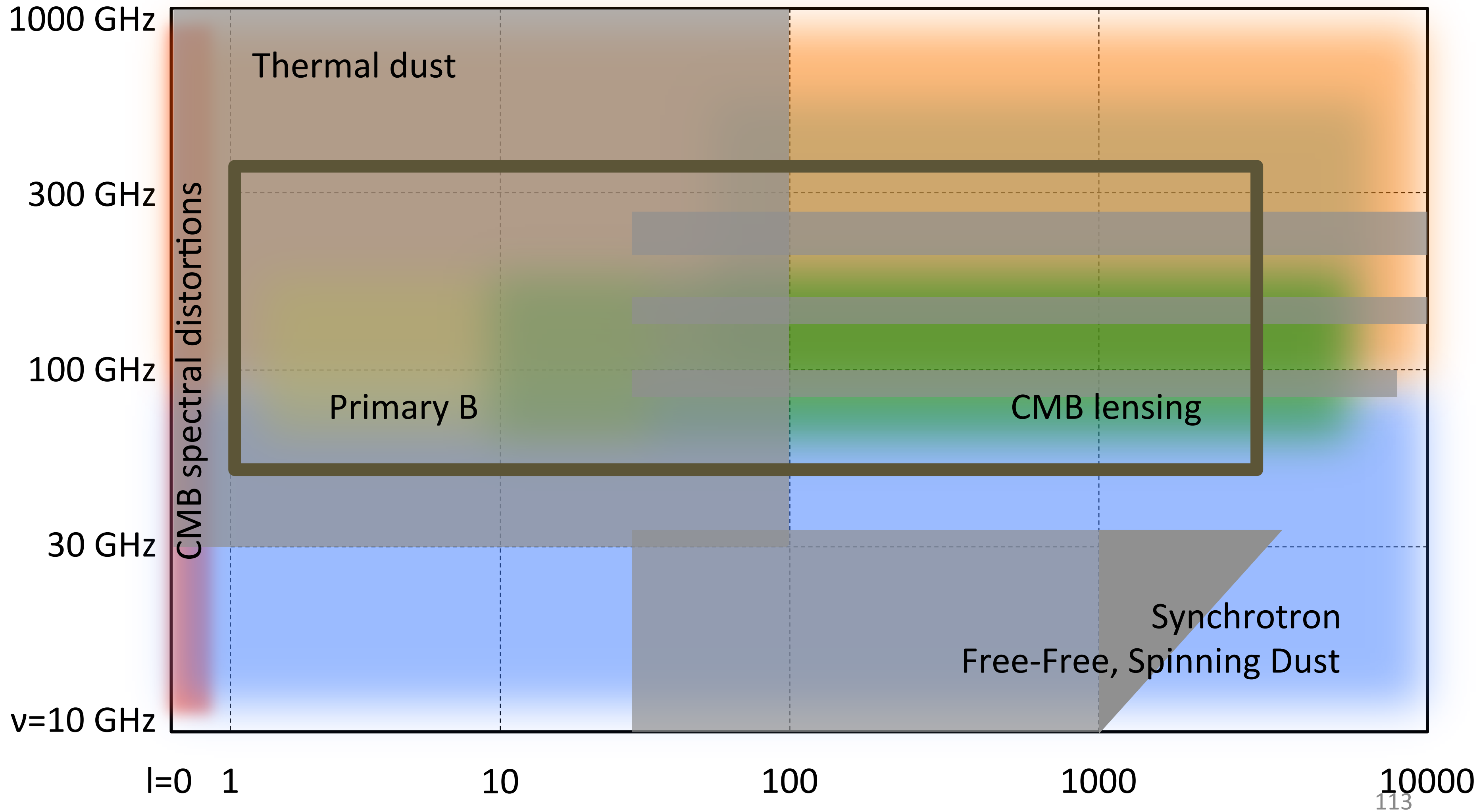
The battle field



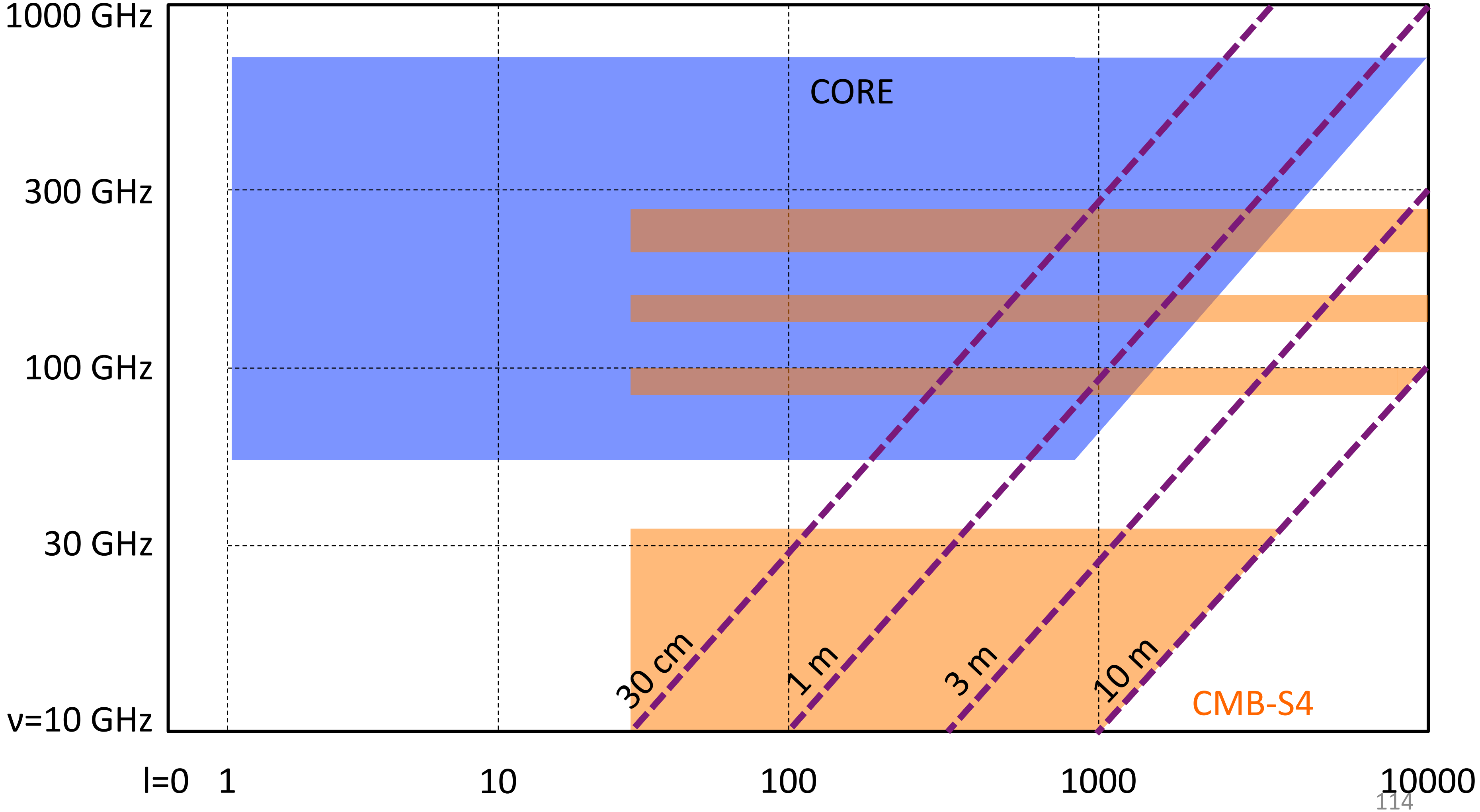
Ground-space complementarity



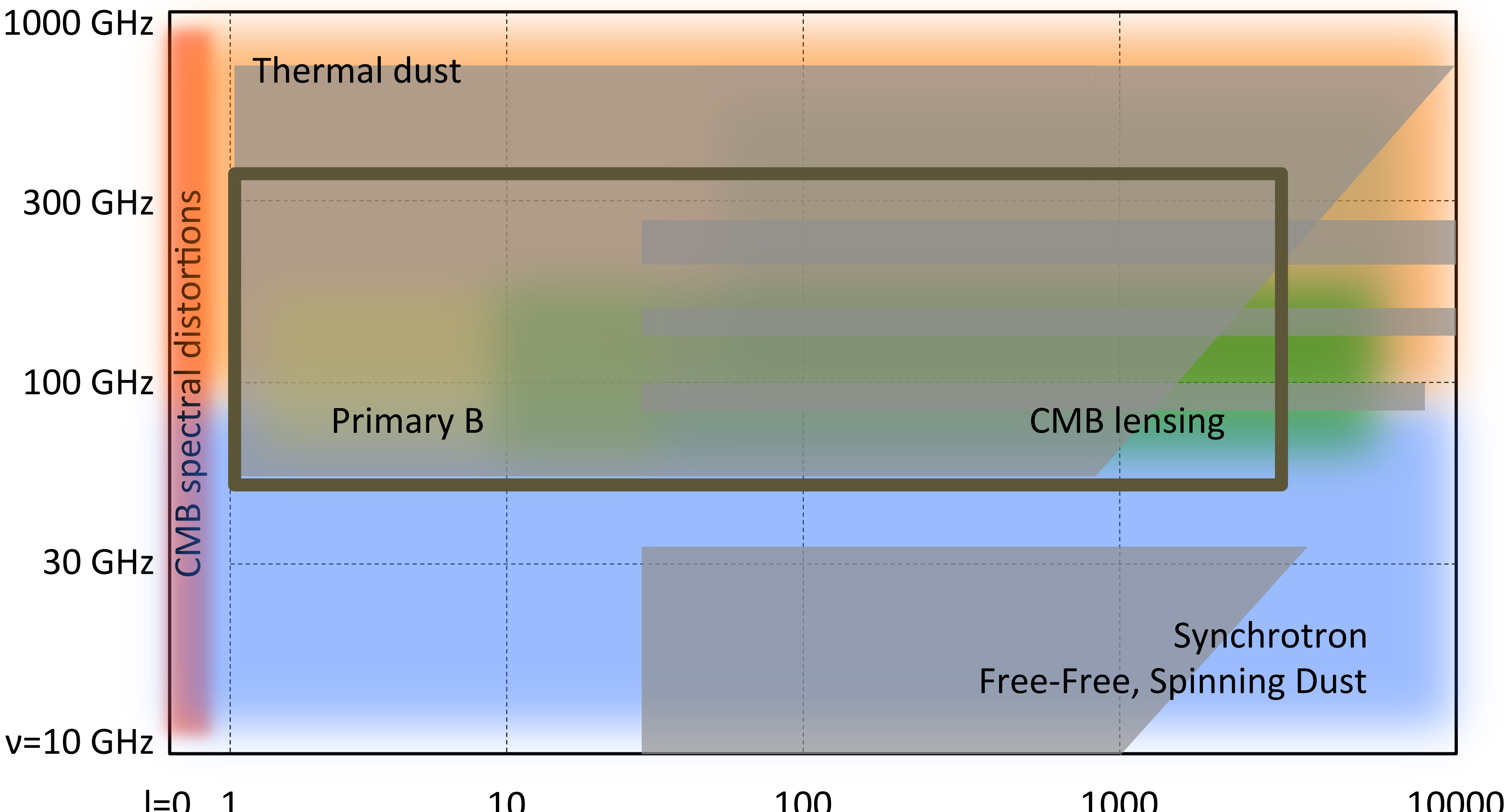
The battle field



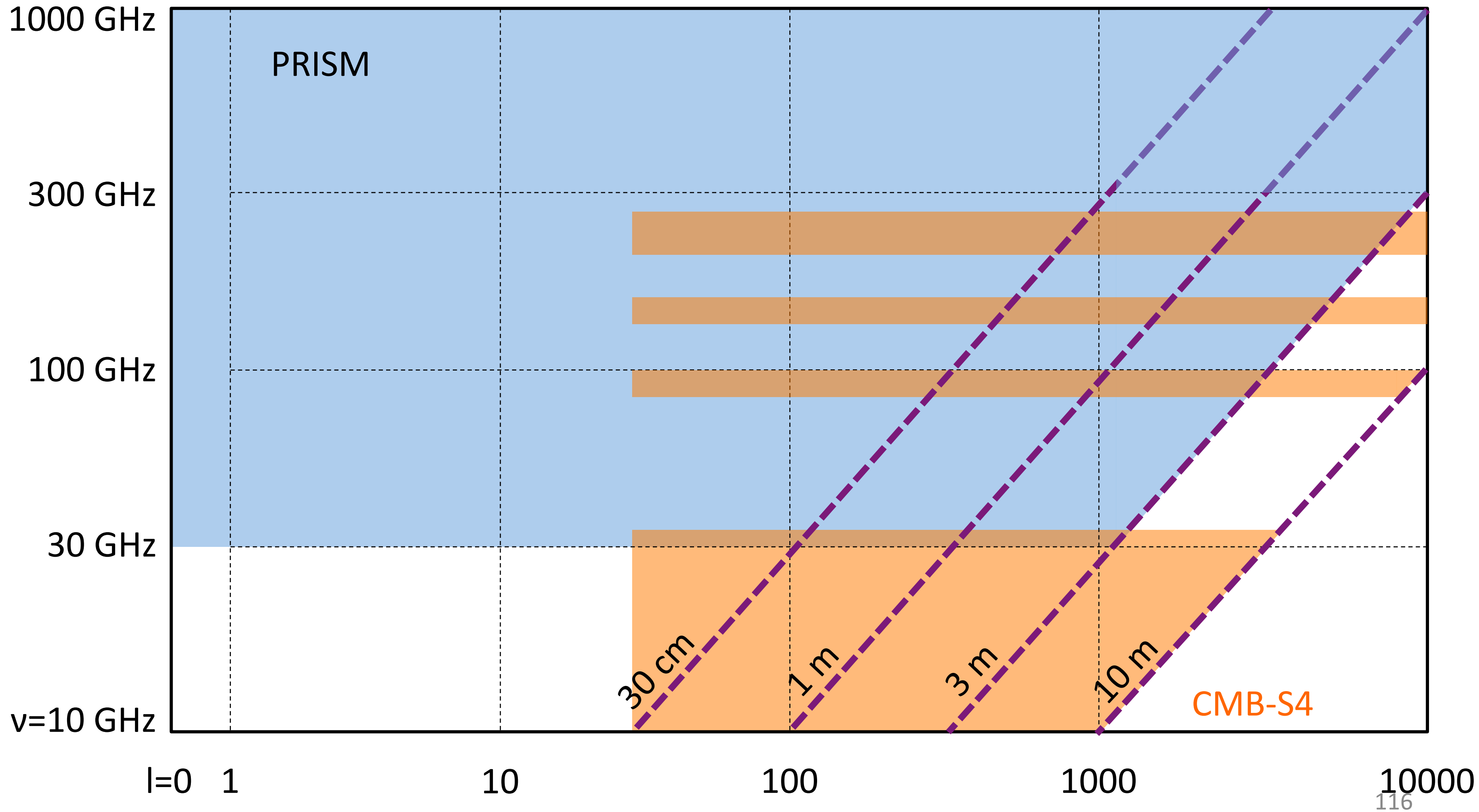
Ground-space complementarity



The battle field

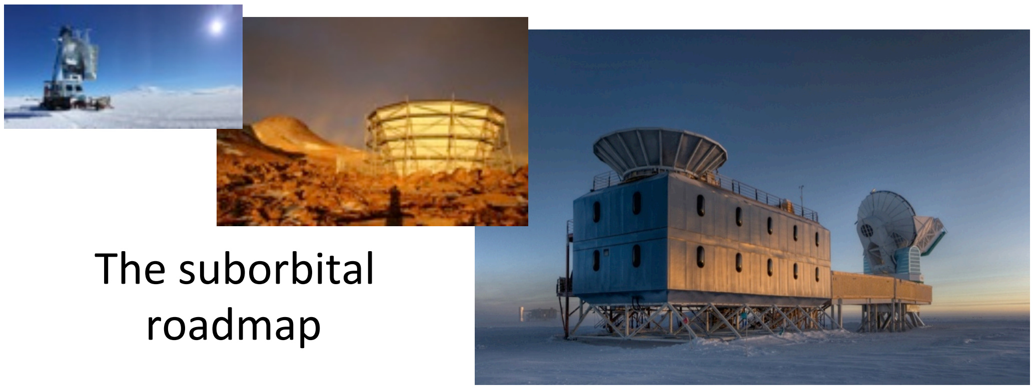


Ground-space complementarity



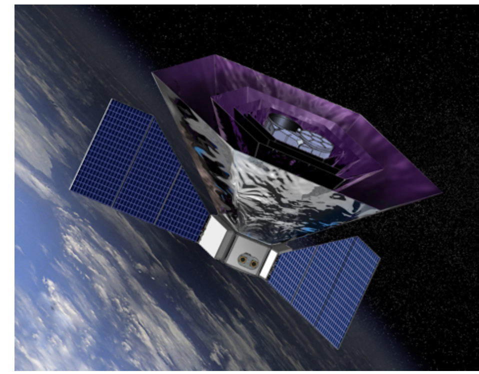
Complementarity

The CMB spectrum



The suborbital roadmap

High resolution maps at ν < 200 GHz



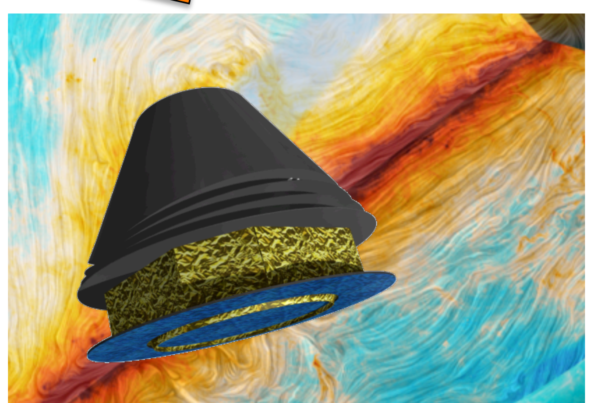
Absolute spectrophotometry

UNIQUENESS
small CMB scales
(in atm. windows)

UNIQUENESS
absolute measurement

Complementarity
to get 1-2' resolution
and no foregrounds

JOINT OPTIMIZATION OF THE DESIGNS



UNIQUENESS
resolved CMB with:

- many frequencies
- full sky
- systematics control

Summary

- Still a lot of information for precision cosmology with the CMB
- Time to plan the "CMB mining"
- This requires both space and ground
- Careful synergetic designing + long timescale (10-20 yrs)
- A lot of ongoing activity with pathfinder experiments!

To learn more

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