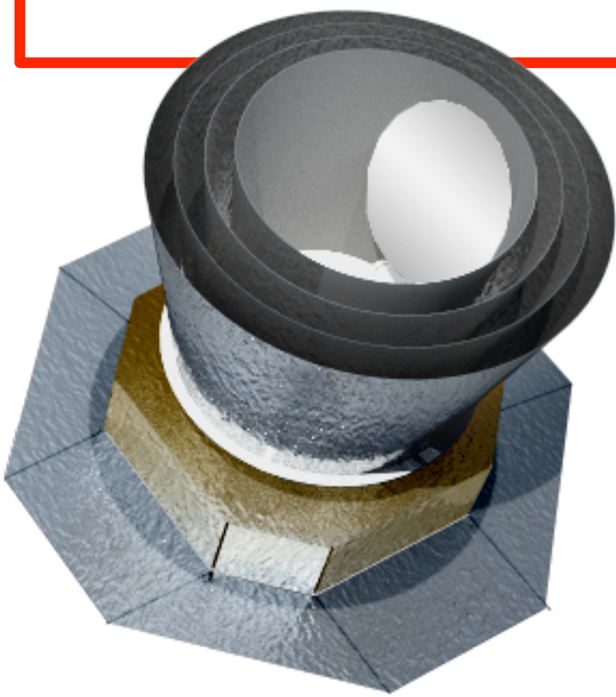
B-modes from space



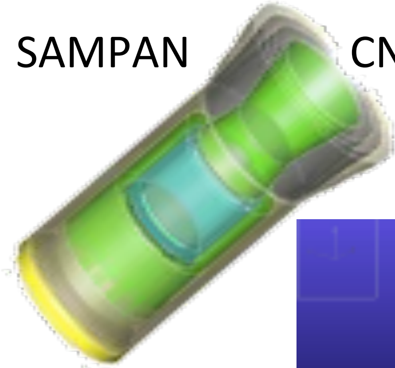
Jacques Delabrouille
Laboratoire APC, Paris, France

Outline

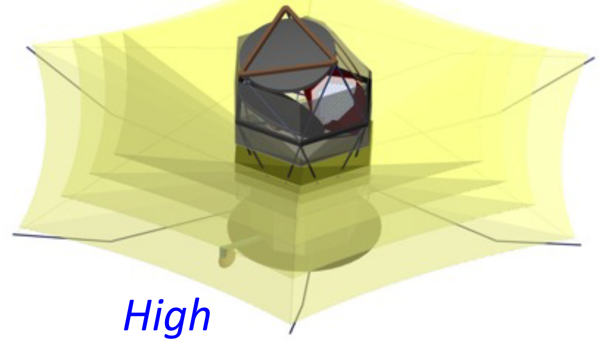
- Tensor modes with a future mission?
- Beyond primary CMB science
- Why a space mission ?
- COrE+
- Conclusion

Many proposed Post-Planck CMB missions

SAMPAN CNES 2006



NASA 2008 EPIC-IM

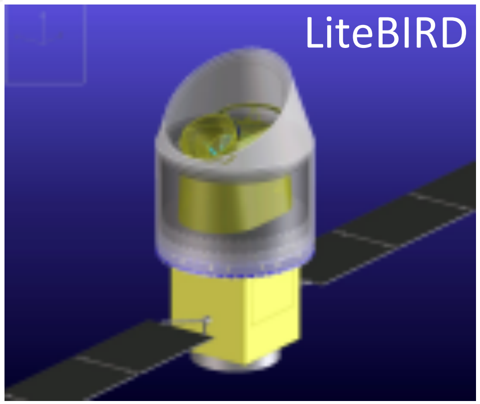


High resolution

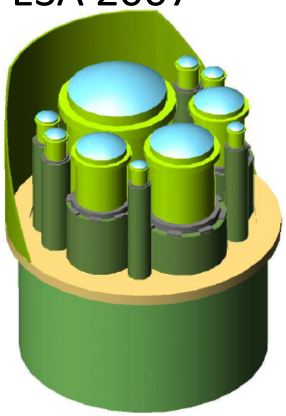
COrE
ESA 2010

Many frequency bands

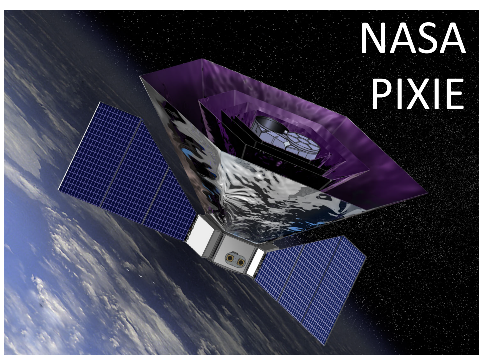
JAXA 2008

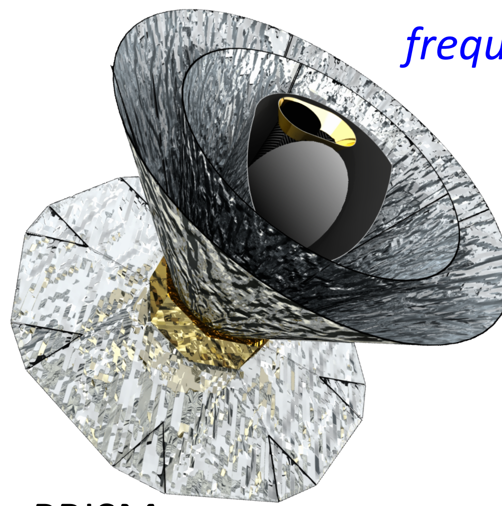


BPOL
ESA 2007

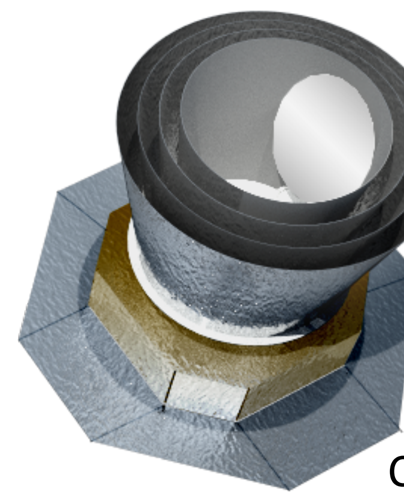


Absolute spectrophotometer





PRISM
ESA 2013



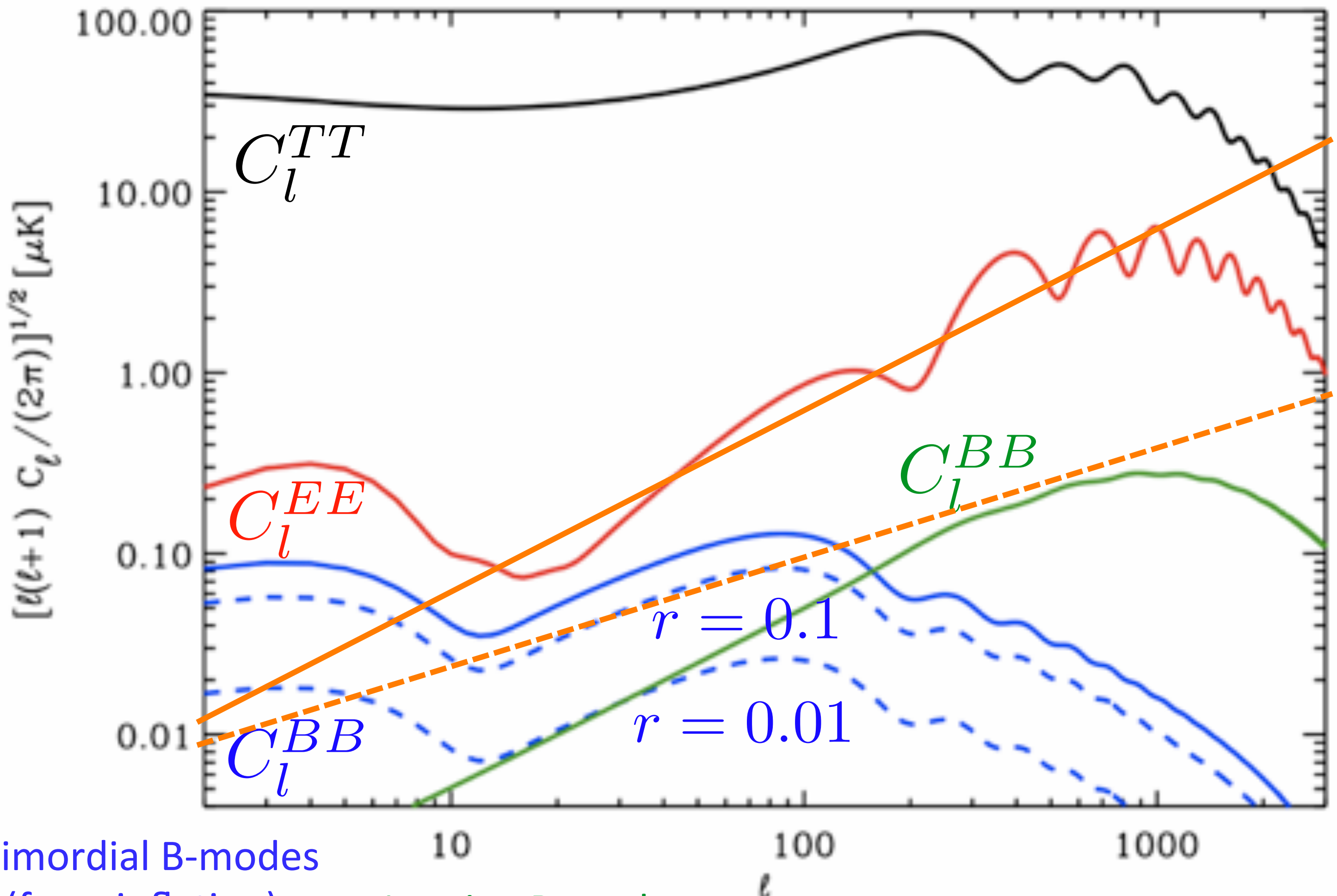
COrE+
ESA 2015

Low resolution
Limited frequency coverage
Primary CMB B-modes

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

Polarisation B-modes

Objective: CMB B-modes (primordial and lensing)



Planck noise
≈ 50 uK.arcmin
(no beam)
(no systematics)
(no foregrounds)

divided by $l^{1/2}$

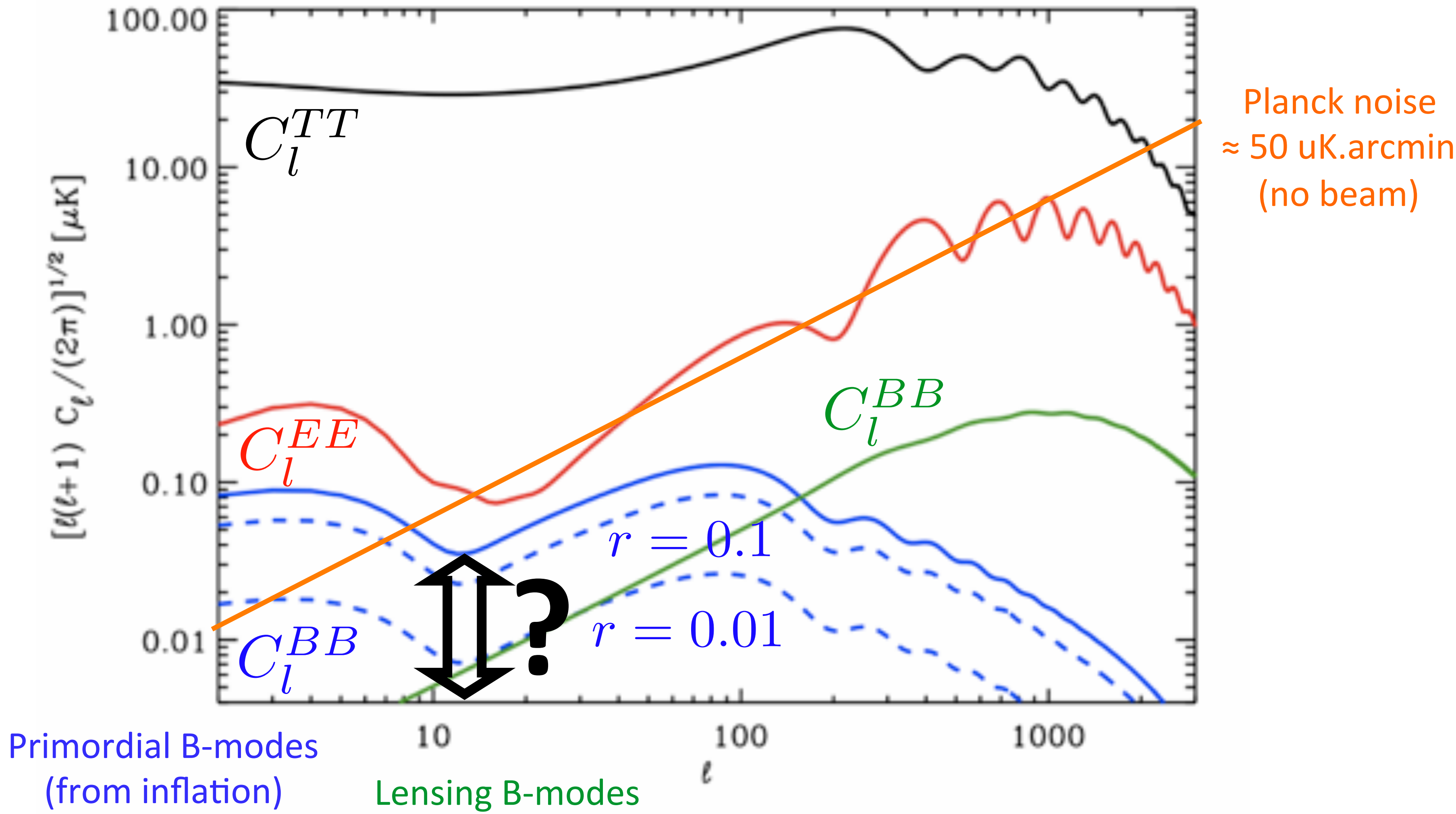
N.B.: plot in amplitude

Primordial B-modes (from inflation)

Lensing B-modes

Polarisation B-modes

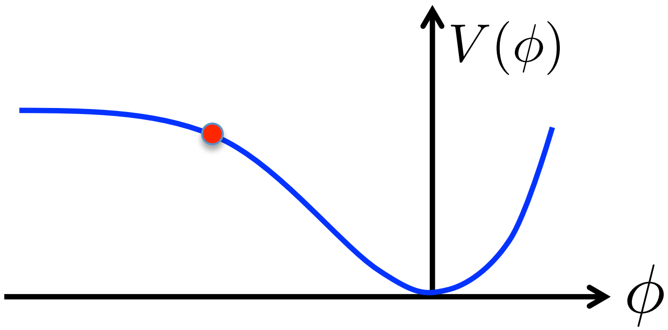
Objective: CMB B-modes (primordial and lensing)



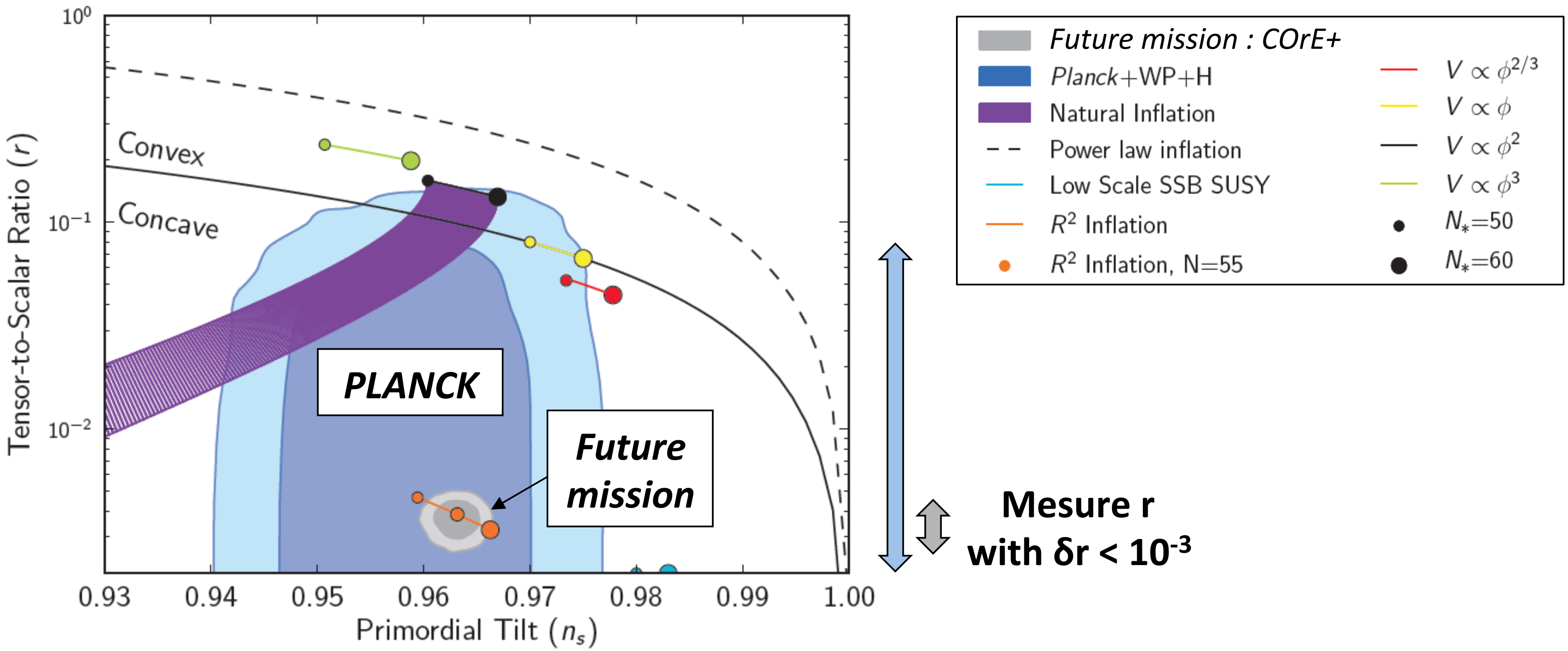
Early Universe : physics at 10^{16} GeV

Initial perturbations
- scalar (density)
- tensor (gravity waves)

depend on the potential $V(\phi)$ and derivatives:



- scalar spectral index $n_S - 1$
- running $\dfrac{\mathrm{d}n_S}{\mathrm{d}\ln k}$
- tensor/scalar ratio $r = T/S$
- tensor spectral index n_T



Improve mesurement of n_s

Particularly interesting values of r

- r ≈ 0.1-0.15
- r ≈ 2-3 × 10^{-3}

Evaluation of PRISM L-scale mission proposed science (early 2014):
" The SSC was fully convinced of the great importance of the core CMB science and encourages the CMB community to consider proposing this science for a future M-class mission.”

Fundamental limitations

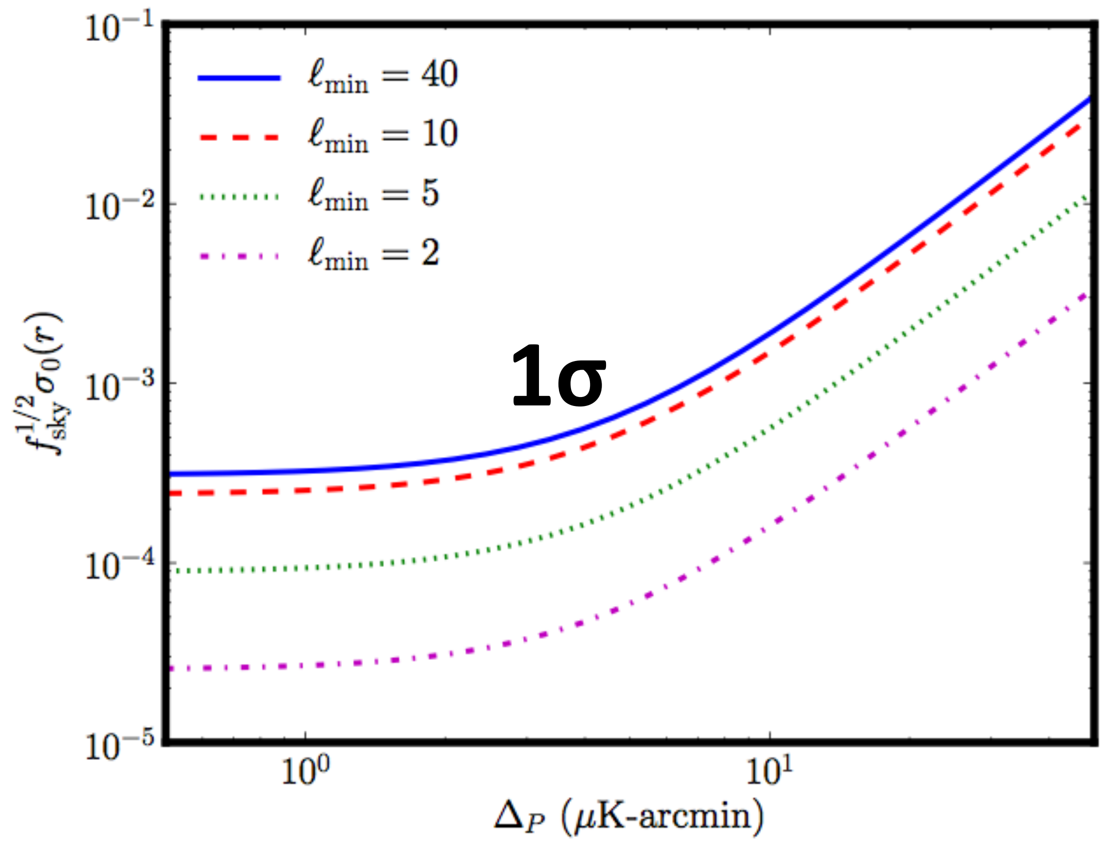
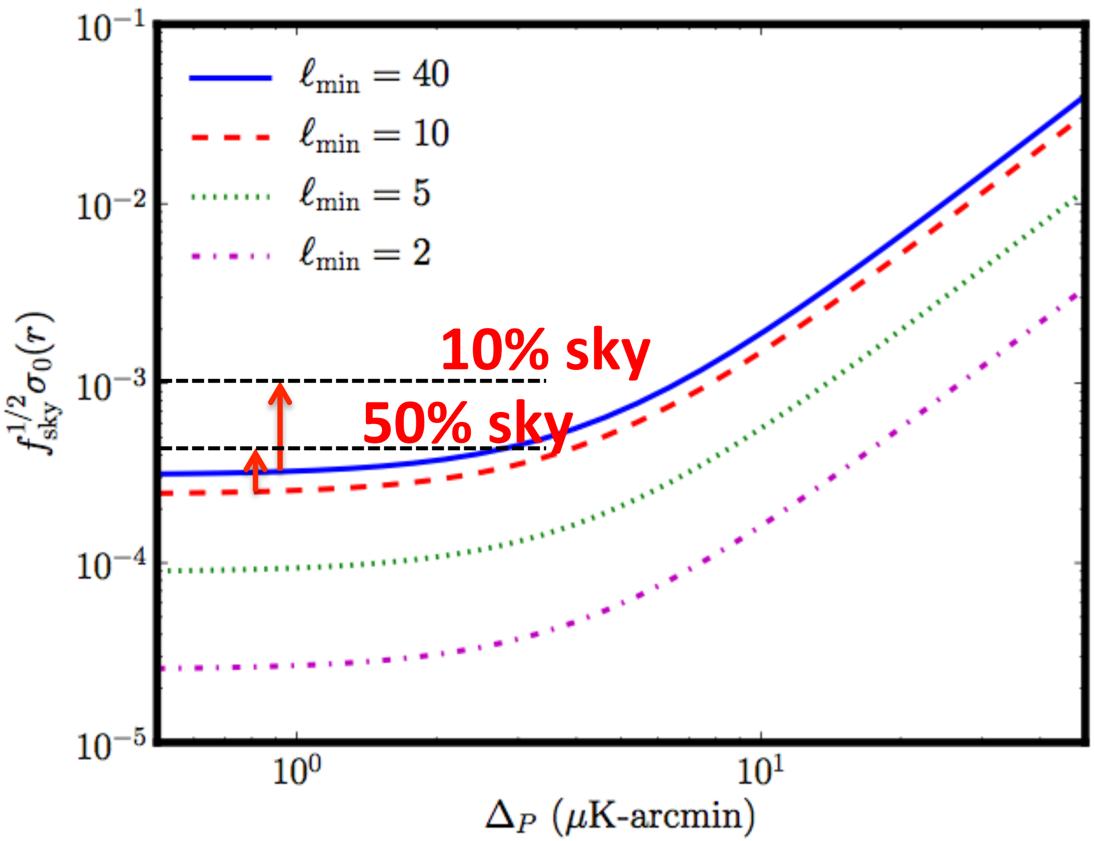


Figure 2: Statistical error $\sigma_0(r)$ on the tensor-to-scalar ratio for varying noise level, assuming no delensing has been done. The forecast is strongly dependent on whether the reionization B-mode signal at $\ell \lesssim 10$ is assumed measureable in the presence of sky cuts and Galactic foregrounds. The value of $\sigma_0(r)$ levels off for noise levels $\lesssim 4.4$ μK-arcmin since the observations have become lensing-limited.

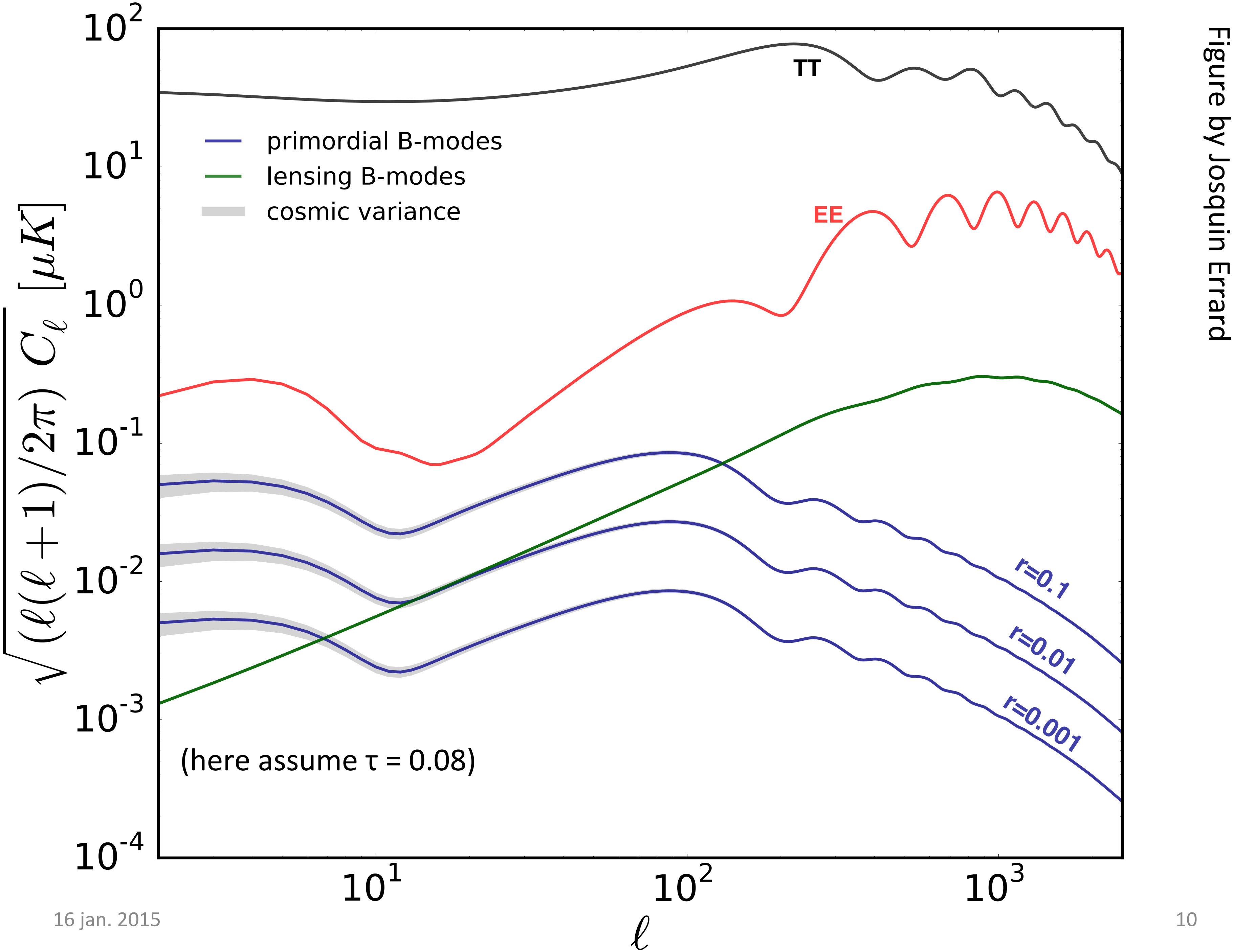
Kendrick Smith et al, JCAP, Issue 06, id. 014 (2012)

Fundamental limitations: lensing confusion



Kendrick Smith et al, JCAP, Issue 06, id. 014 (2012)

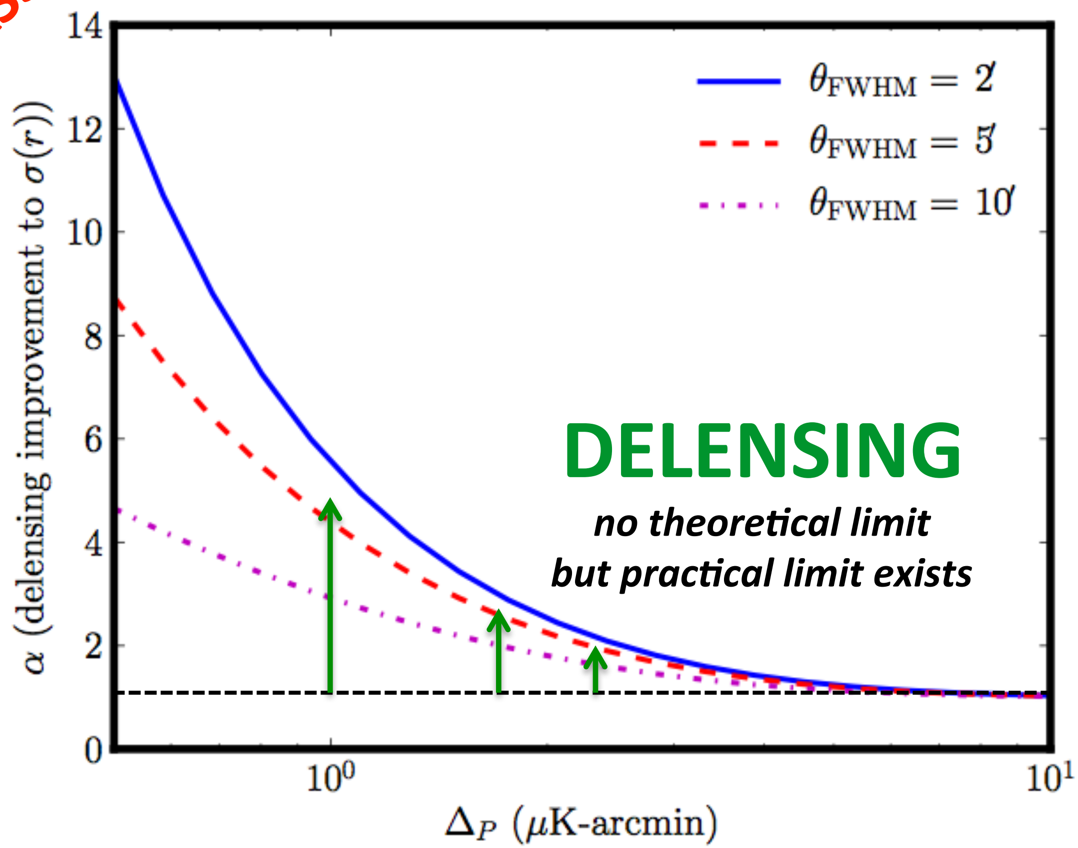
Figure 2: Statistical error $\sigma_0(r)$ on the tensor-to-scalar ratio for varying noise level, assuming no delensing has been done. The forecast is strongly dependent on whether the reionization B-mode signal at $\ell \lesssim 10$ is assumed measureable in the presence of sky cuts and Galactic foregrounds. The value of $\sigma_0(r)$ levels off for noise levels $\lesssim 4.4$ μK-arcmin since the observations have become lensing-limited.



$\sqrt{\ell(\ell+1)/2\pi)\ C_\ell}\ [\mu K]$
ℓ
TT
EE
primordial B-modes
lensing B-modes
cosmic variance
r=0.1
r=0.01
r=0.001
(here assume τ = 0.08)
Figure by Josquin Errard

Fundamental limitations

OTHER OPTION
USE TRACER OF MASS

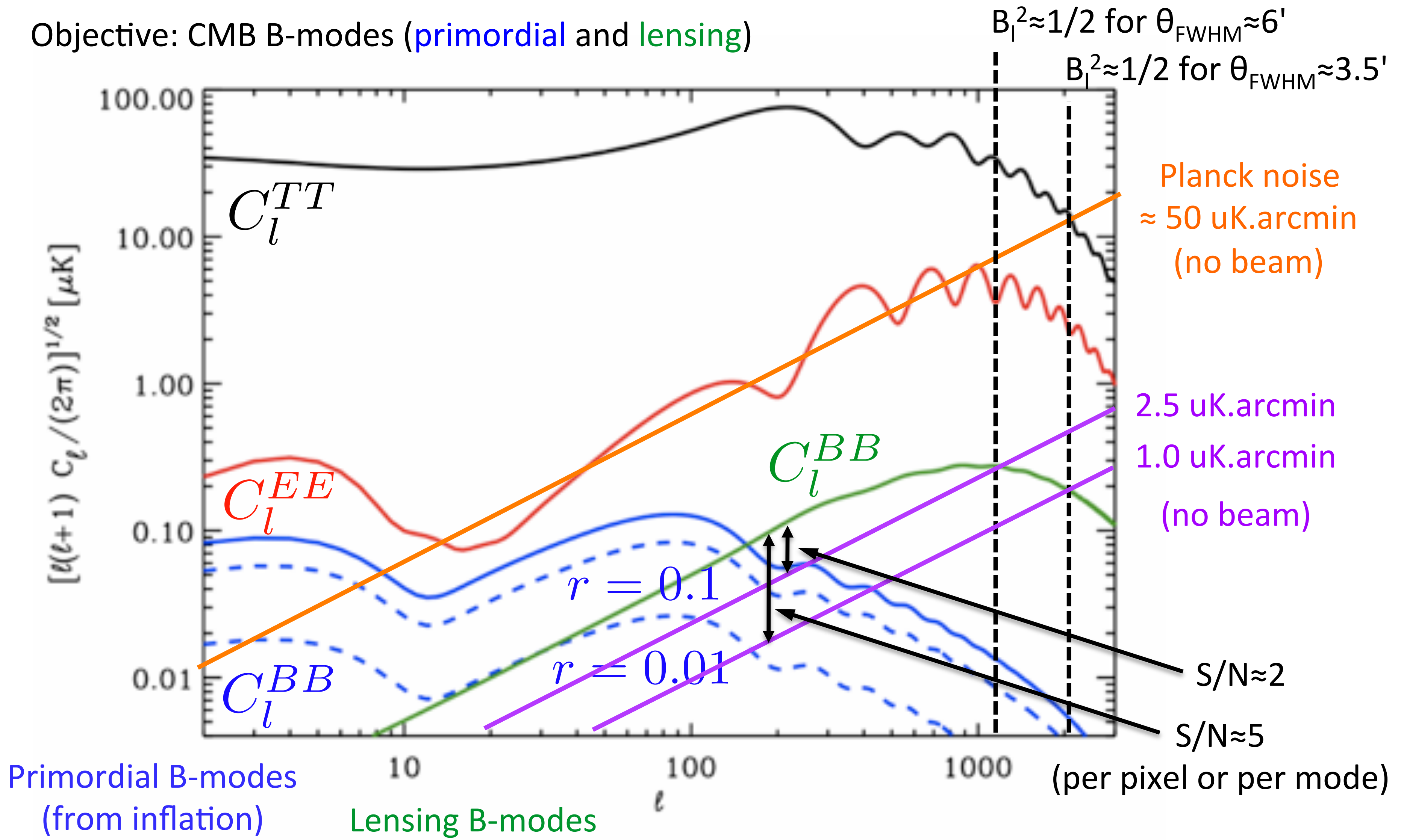


Kendrick Smith et al, JCAP, Issue 06, id. 014 (2012)

Figure 3: Forecasted improvement $\alpha = \sigma_0(r)/\sigma(r)$ in the statistical error on r due to polarization delensing, for varying noise level and beam. In the limit of low noise and high resolution, we find no limit (from delensing residuals alone) to how well r can be measured.

Next : Polarisation B-modes

Objective: CMB B-modes (primordial and lensing)



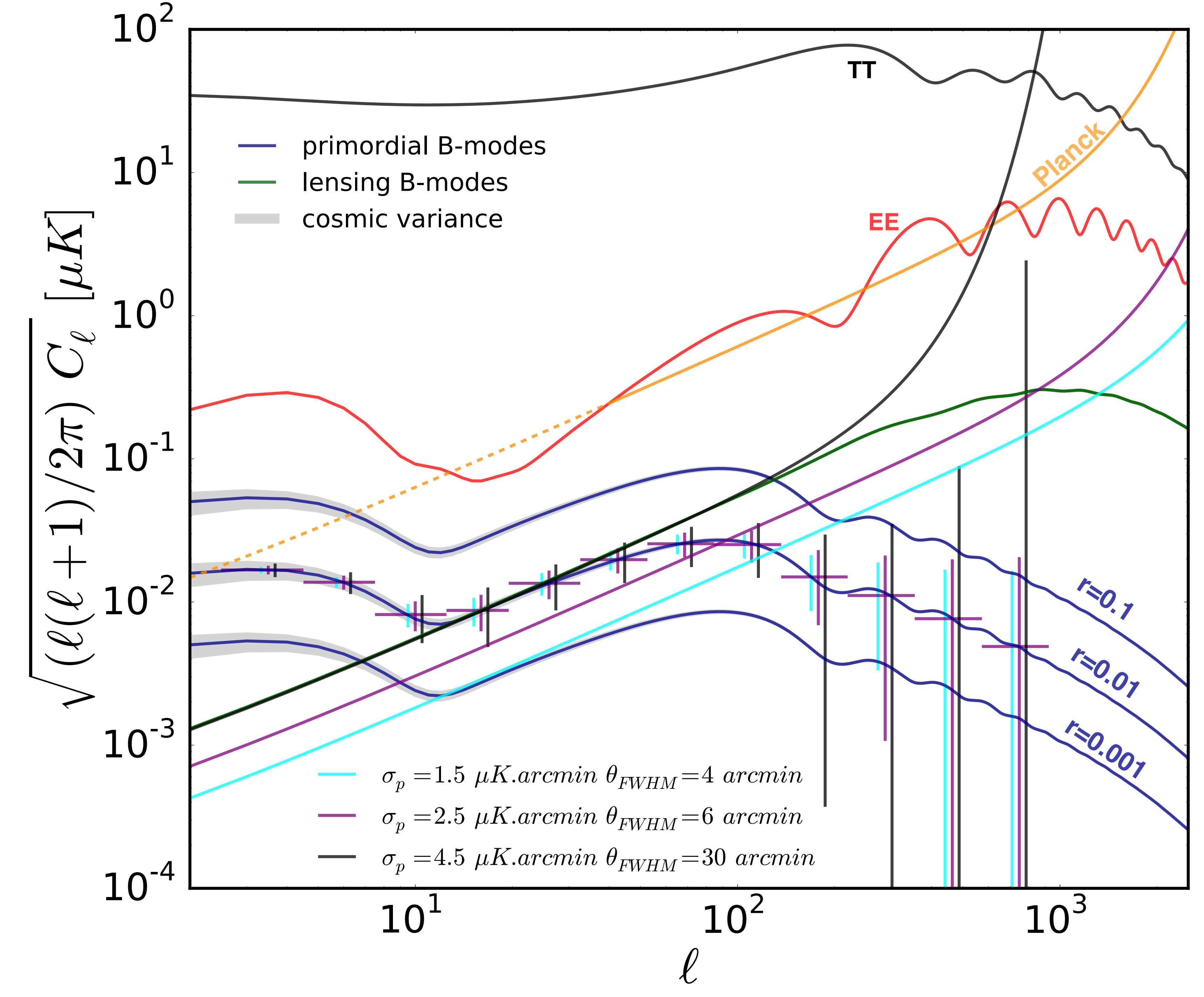


Figure by Josquin Errard

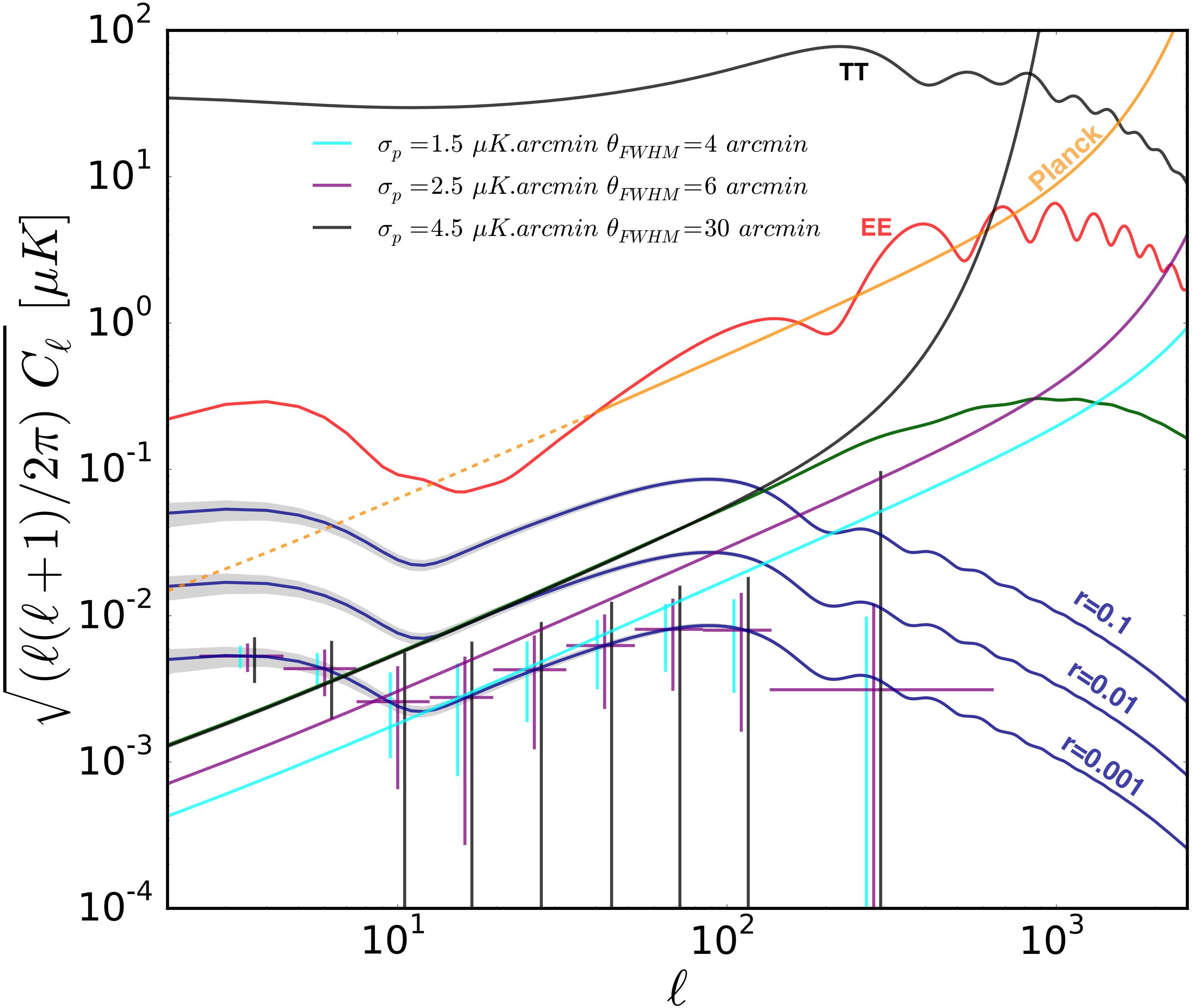


Figure by Josquin Errard

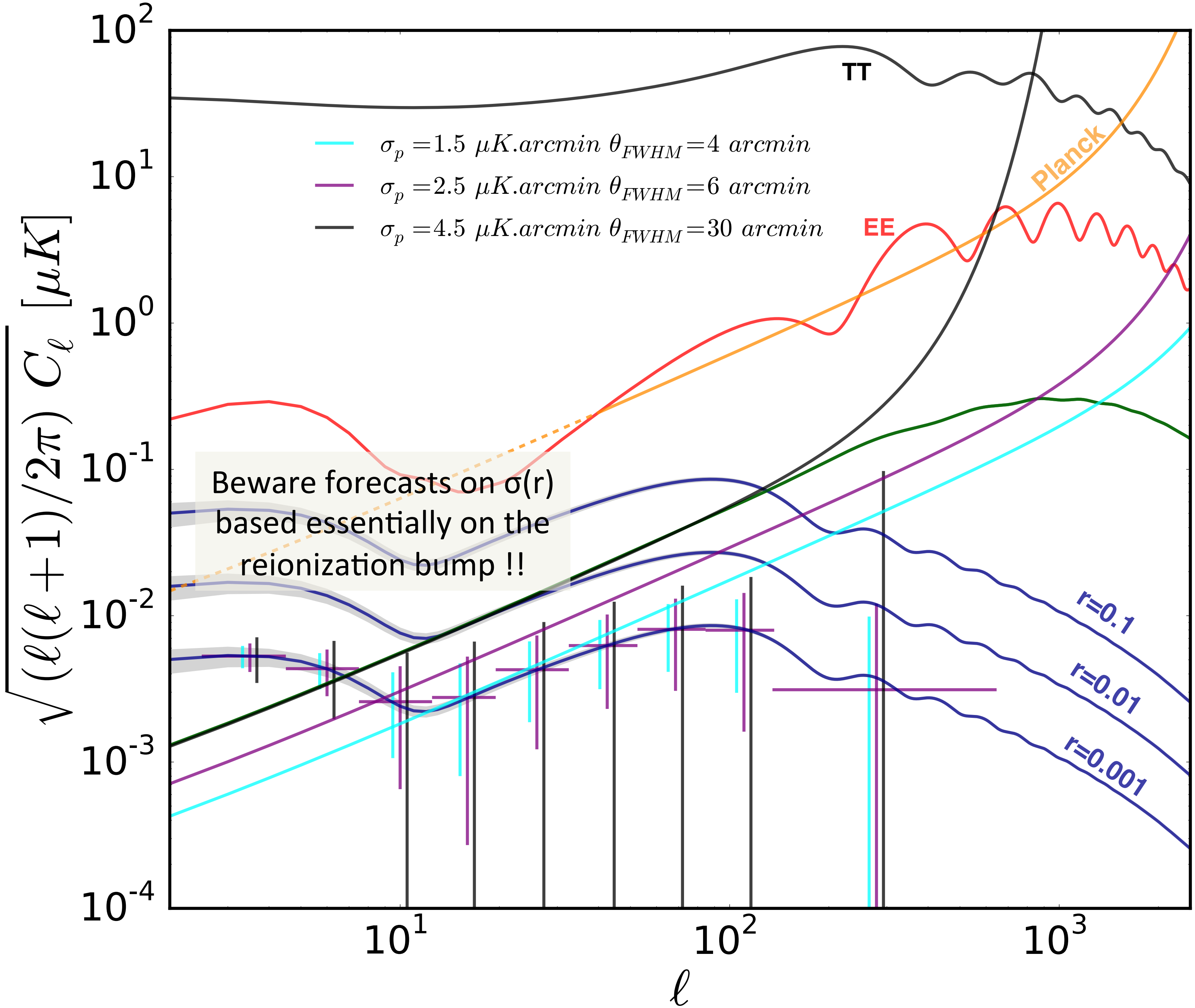


Figure by Josquin Errard

What space mission ?

There is a strong incentive to reach
$r \approx 2\text{-}3 \times 10^{-3}$ at 5σ

This can be achieved with a reasonably-sized space mission with large sky coverage and some de-lensing.

Sensitivity between 1.5 et 2.5 μK.arcmin
≈ 2000-6000 detectors in space

CMB angular resolution between 4' et 6'
(class ≈ 1.5 m telescope)

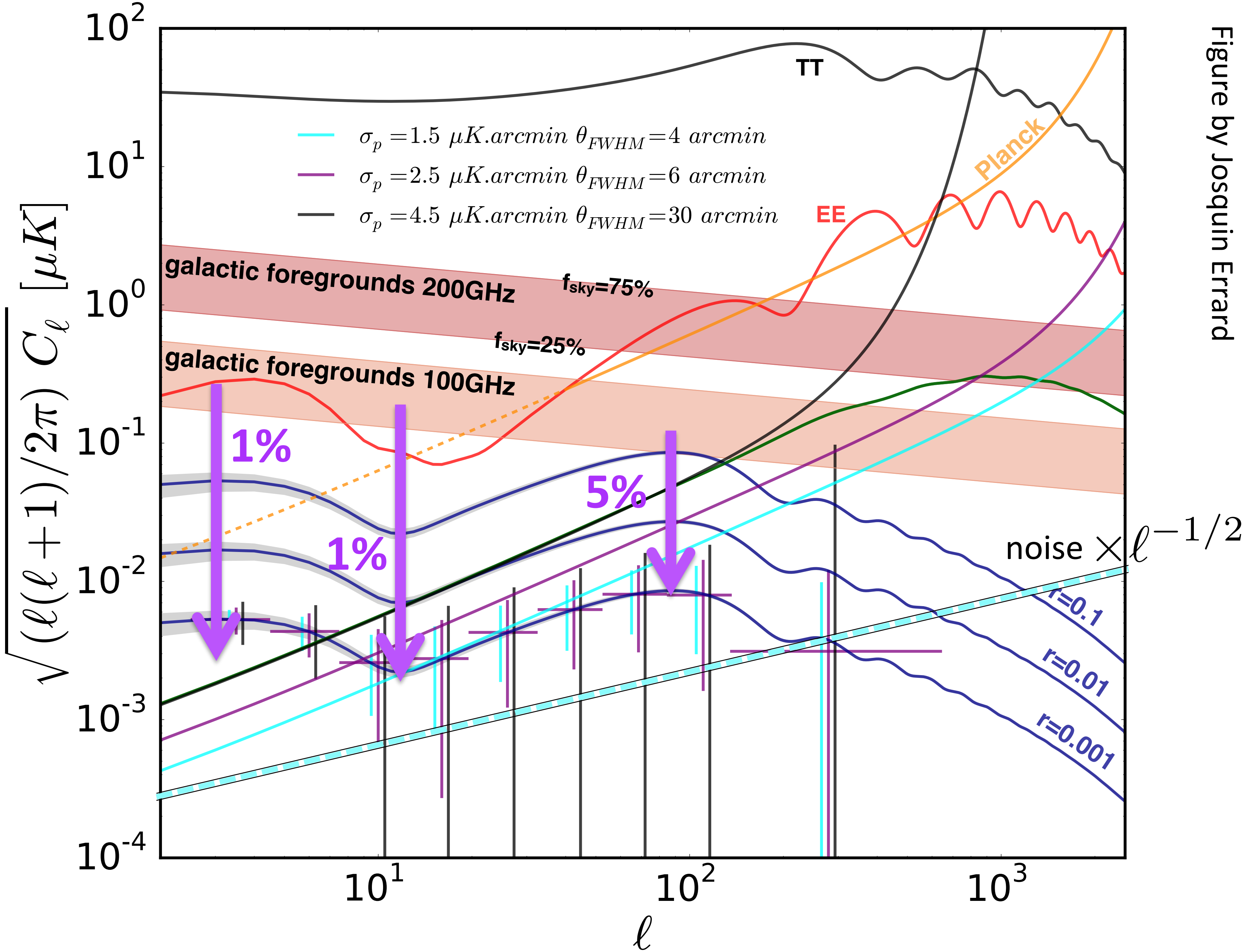


Figure by Josquin Errard
$\sigma_p = 1.5\ \mu K.arcmin\ \theta_{FWHM} = 4\ arcmin$
$\sigma_p = 2.5\ \mu K.arcmin\ \theta_{FWHM} = 6\ arcmin$
$\sigma_p = 4.5\ \mu K.arcmin\ \theta_{FWHM} = 30\ arcmin$
TT
EE
Planck
galactic foregrounds 200GHz
galactic foregrounds 100GHz
f_{sky}=75%
f_{sky}=25%
1%
1%
5%
noise $\times \ell^{-1/2}$
r=0.1
r=0.01
r=0.001
$\sqrt{\ell(\ell+1)/2\pi)\ C_\ell}\ [\mu K]$
ℓ

What space mission ?

Enough channels to separate CMB from foregrounds

Well motivated target for r, but
exceptional science guaranteed for all values of r
(inflation + lensing + foreground science).

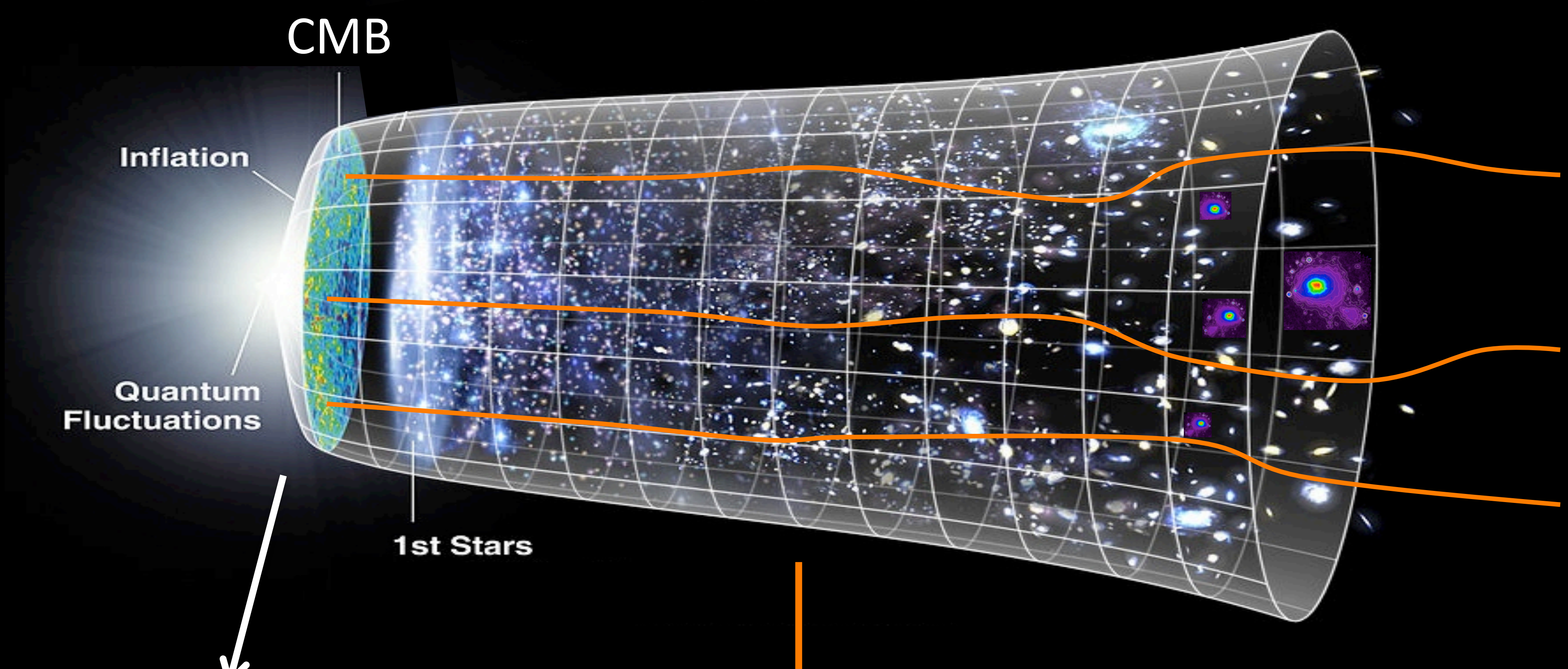
The (near-) ultimate CMB polarisation mission also
requires few-arcminute angular resolution.

Other options: spectral distortions of the continuum
(PIXIE), large scales only (LiteBIRD)

Outline

- Tensor modes with a future mission?
- Beyond primary CMB science
- Why a space mission ?
- COrE+
- Conclusion

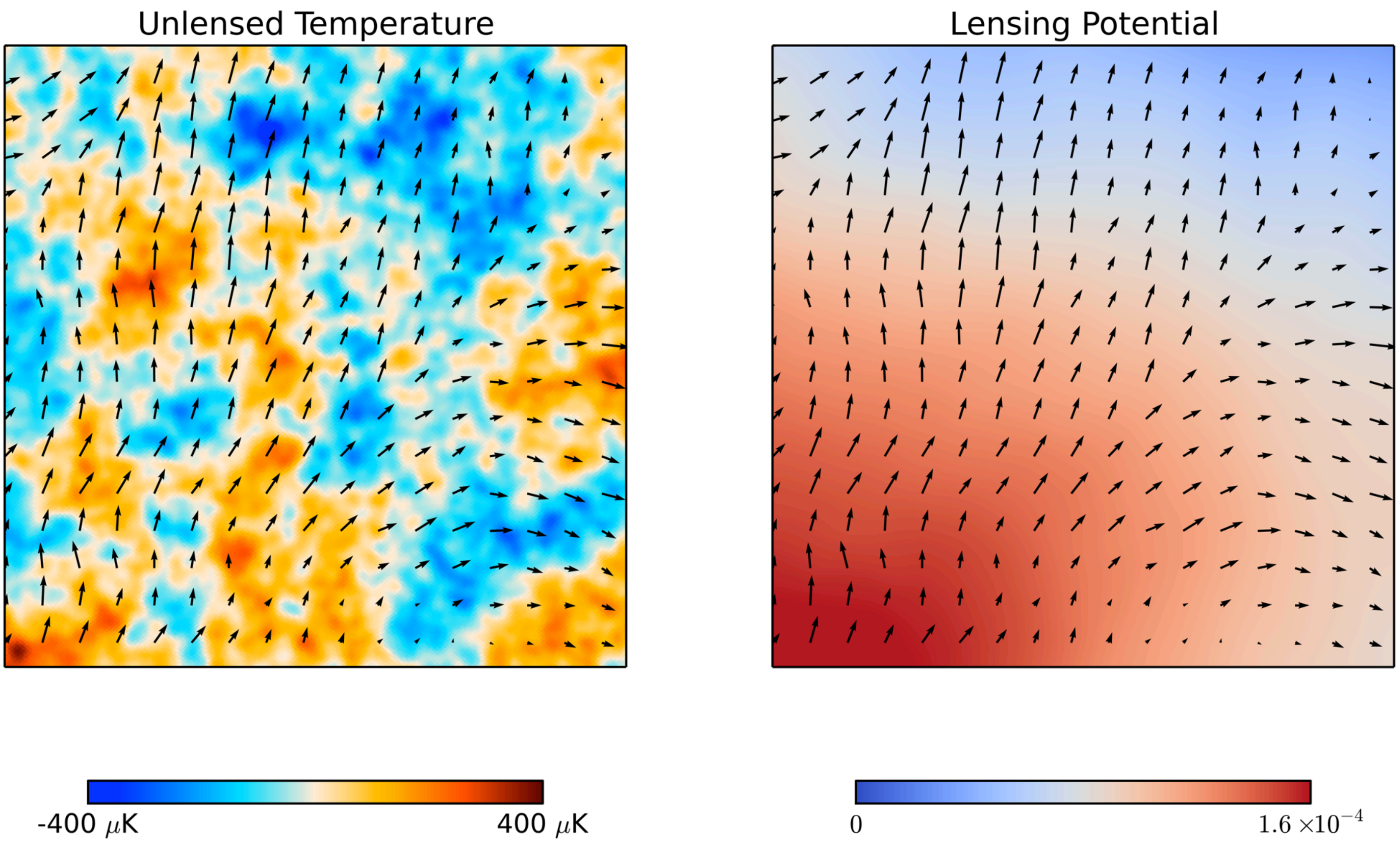
CMB lensing



Inflation
Physics at ≈ 10^{16} GeV
$E_{COrE+} > 10^{12} \times E_{LHC}$

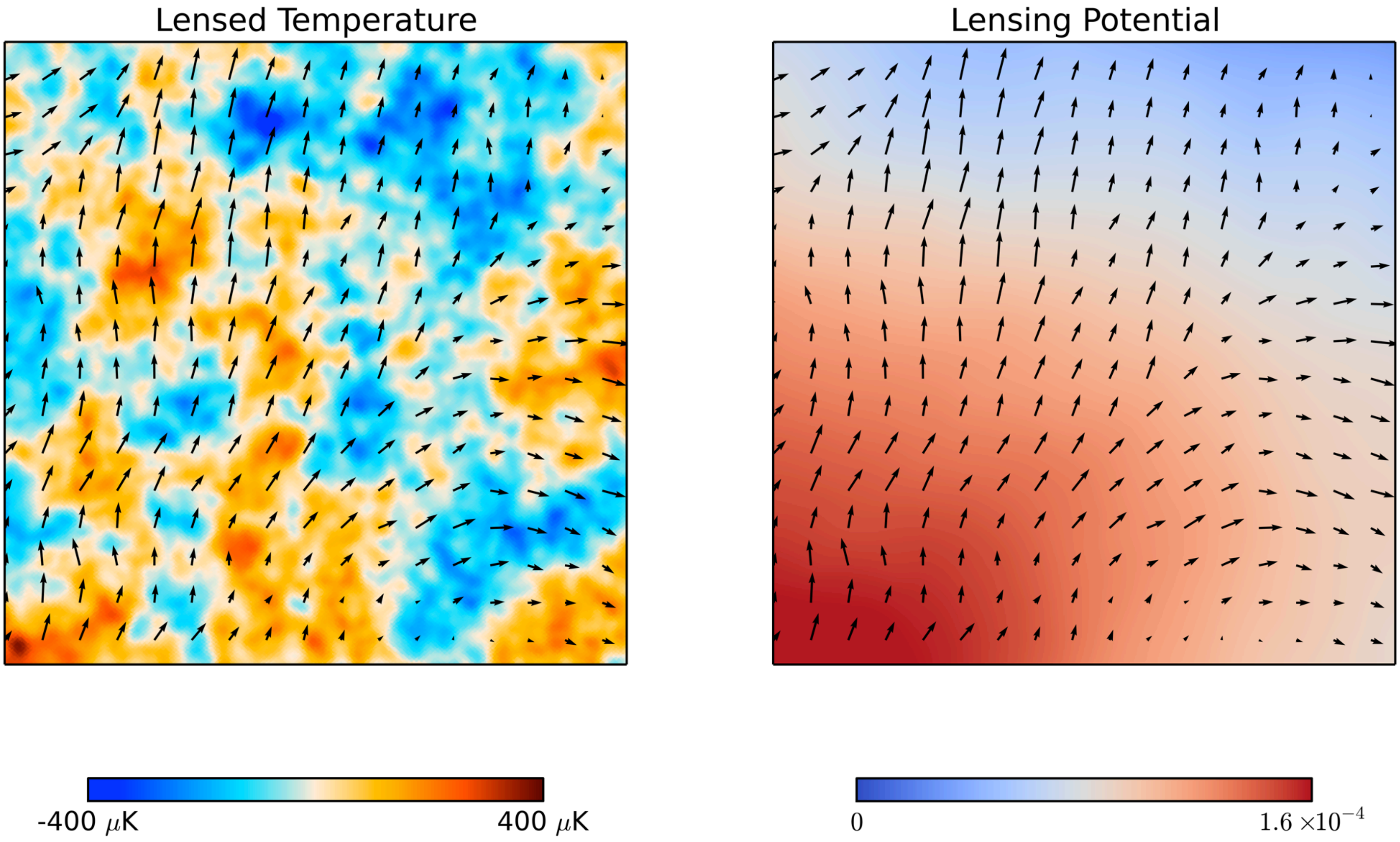
z ≈ 1-3
Gravitational lensing
Dark matter distribution

T (unlensed) and lensing potential



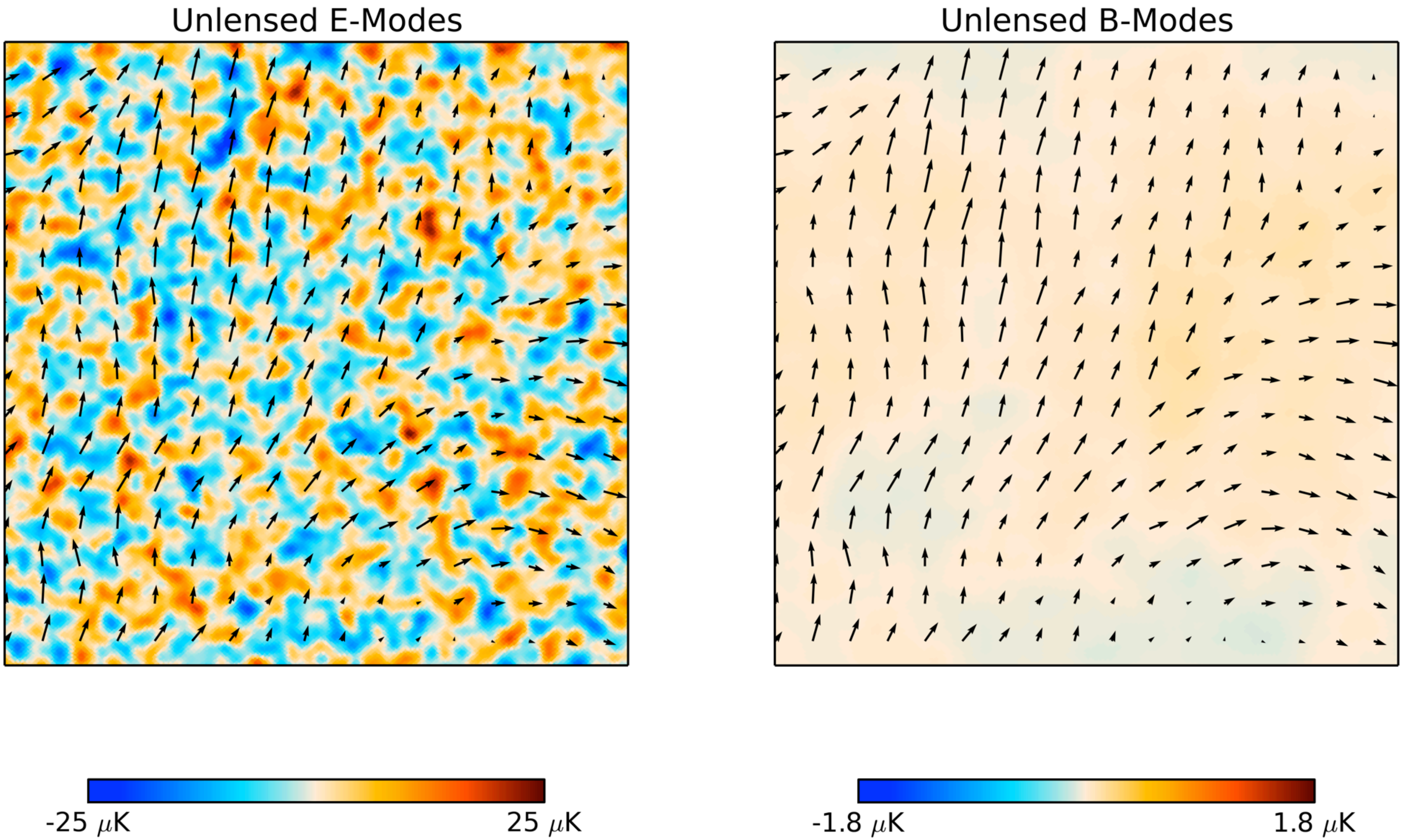
Figures by Ata Karakci

T (lensed) and lensing potential



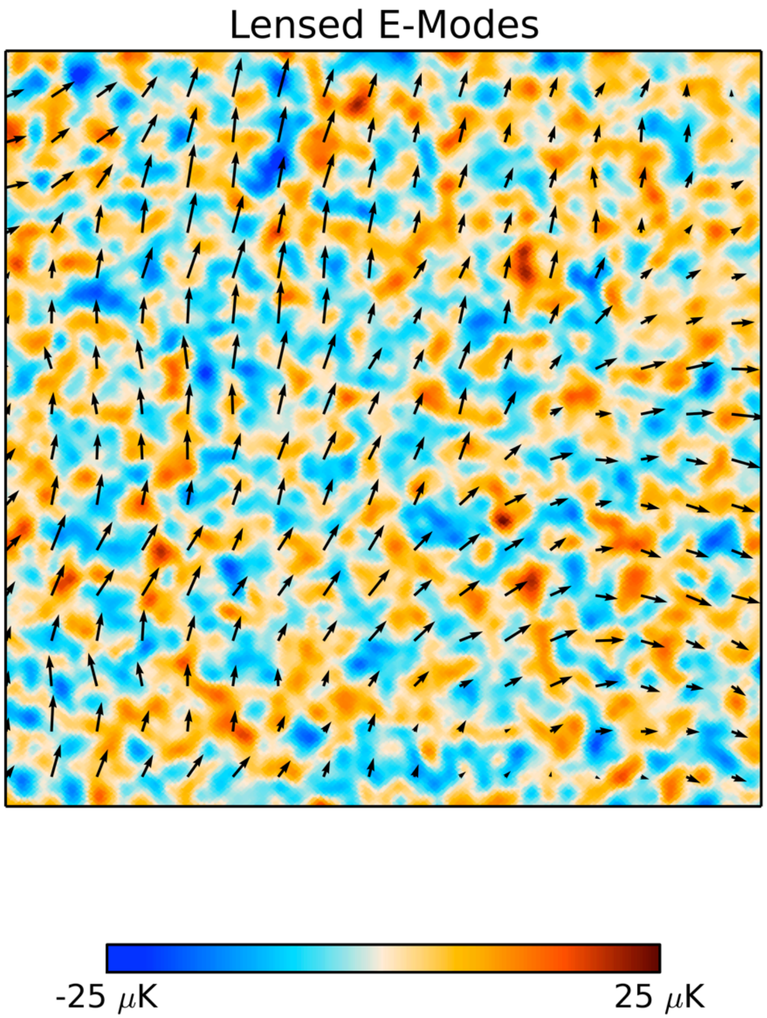
Figures by Ata Karakci

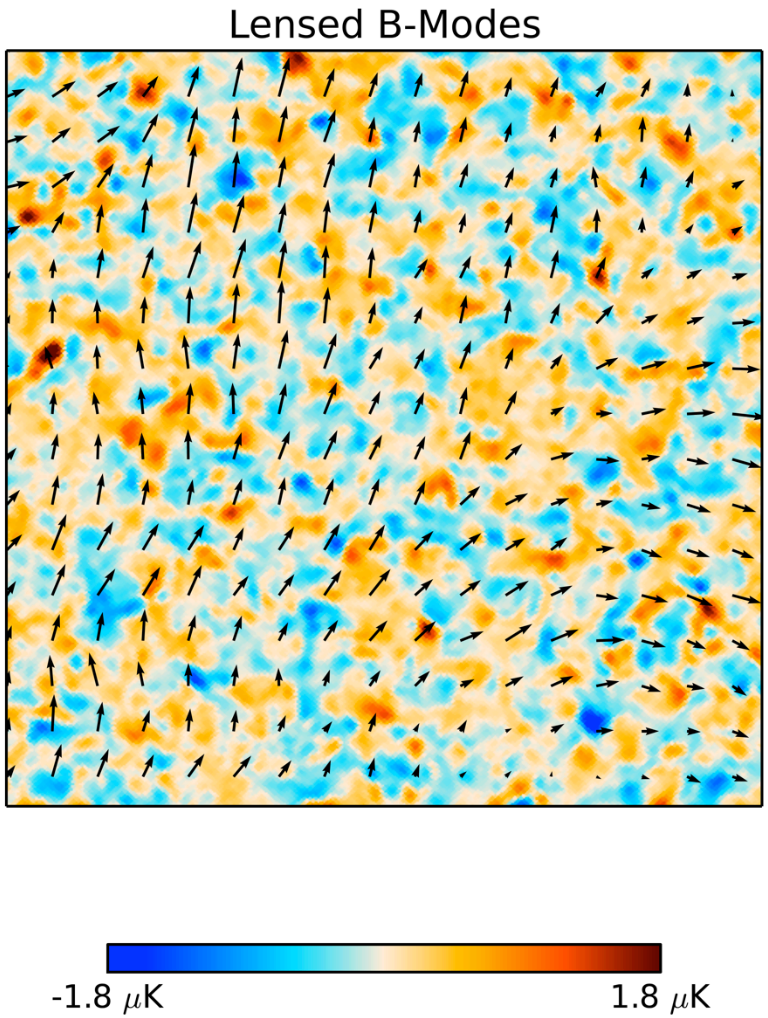
E, B (unlensed) r=0.01



Figures by Ata Karakci

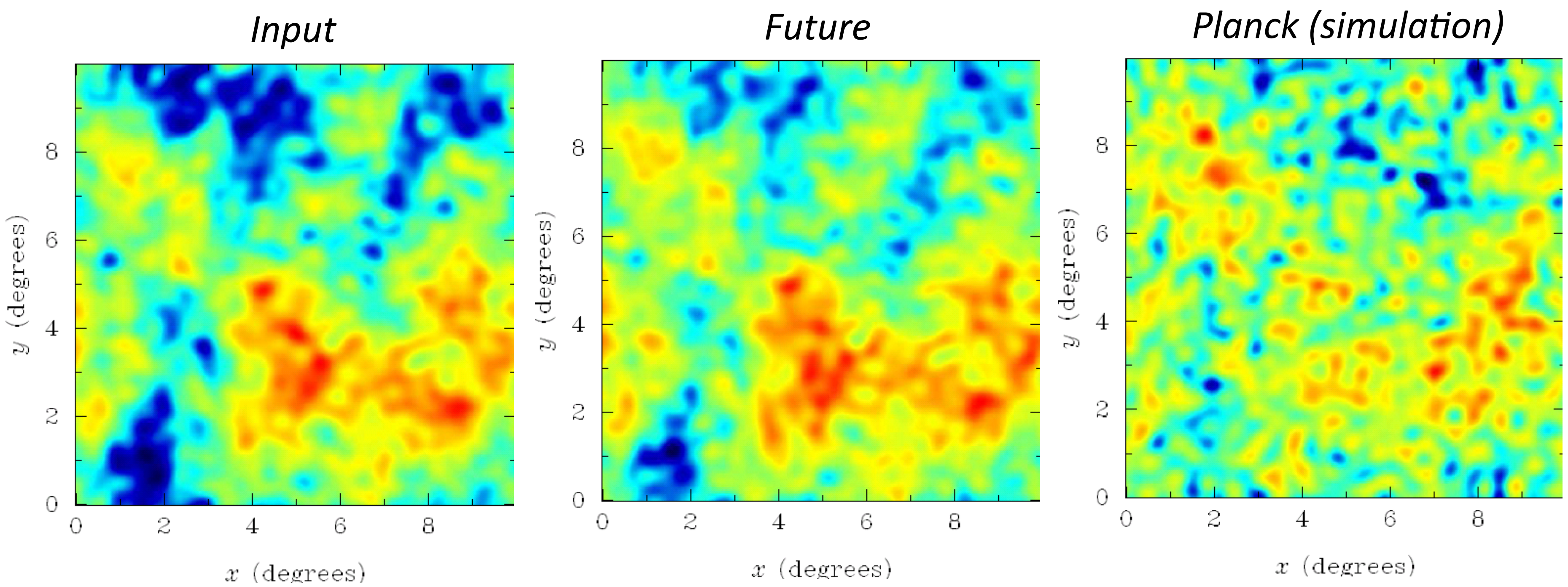
E, B (lensed) r=0.01





Figures by Ata Karakci

Reconstruction of the lensing potential



- **COrE+** : High-fidelity reconstruction of the integral of the gravitational potential all the way to recombination.
- Direct detection of dark matter structures…

Reconstruction of the lensing potential

3 unknowns

Φ

T_{LSS}

E_{LSS}

3 observations

T_{OBS}

E_{OBS}

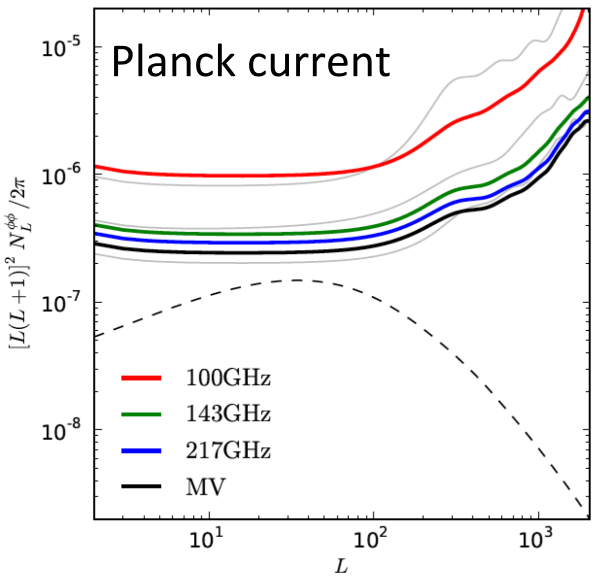
B_{OBS}

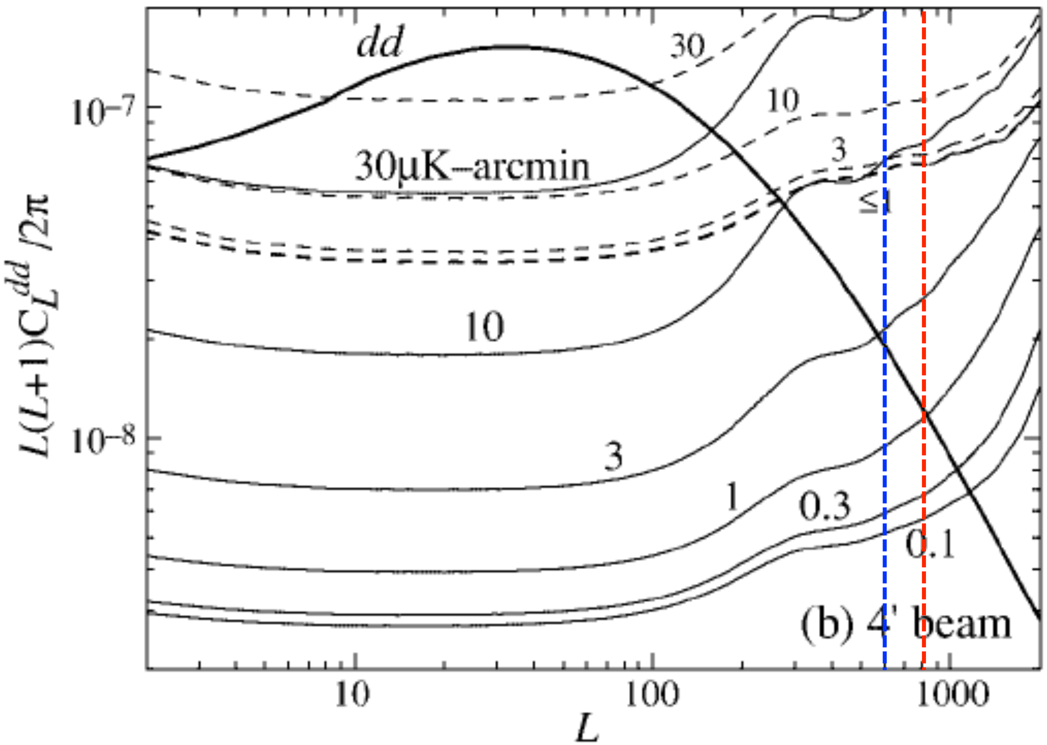
Reconstruction of the lensing potential

Impact of sensitivity ΔT=ΔP/√2

Hu & Okamoto, 2002, ApJ 574, 566

- - - - - Temperature only
——— Polarisation (E-B correlation)





Objective: ΔT≈1 μK. arcmin

20' 15'

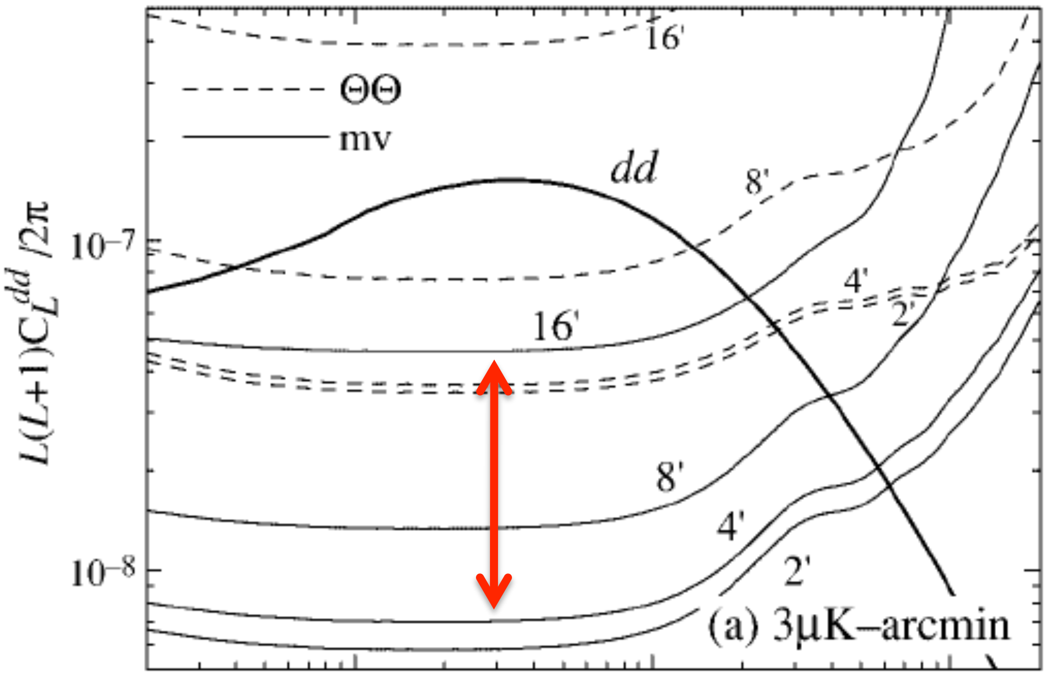
Reconstruction of the lensing potential

Impact of angular resolution

Hu & Okamoto, 2002, ApJ 574, 566

- - - - - Temperature only

——— Polarisation (E-B correlation)



Objective: 4' resolution

Reconstruction of the lensing potential

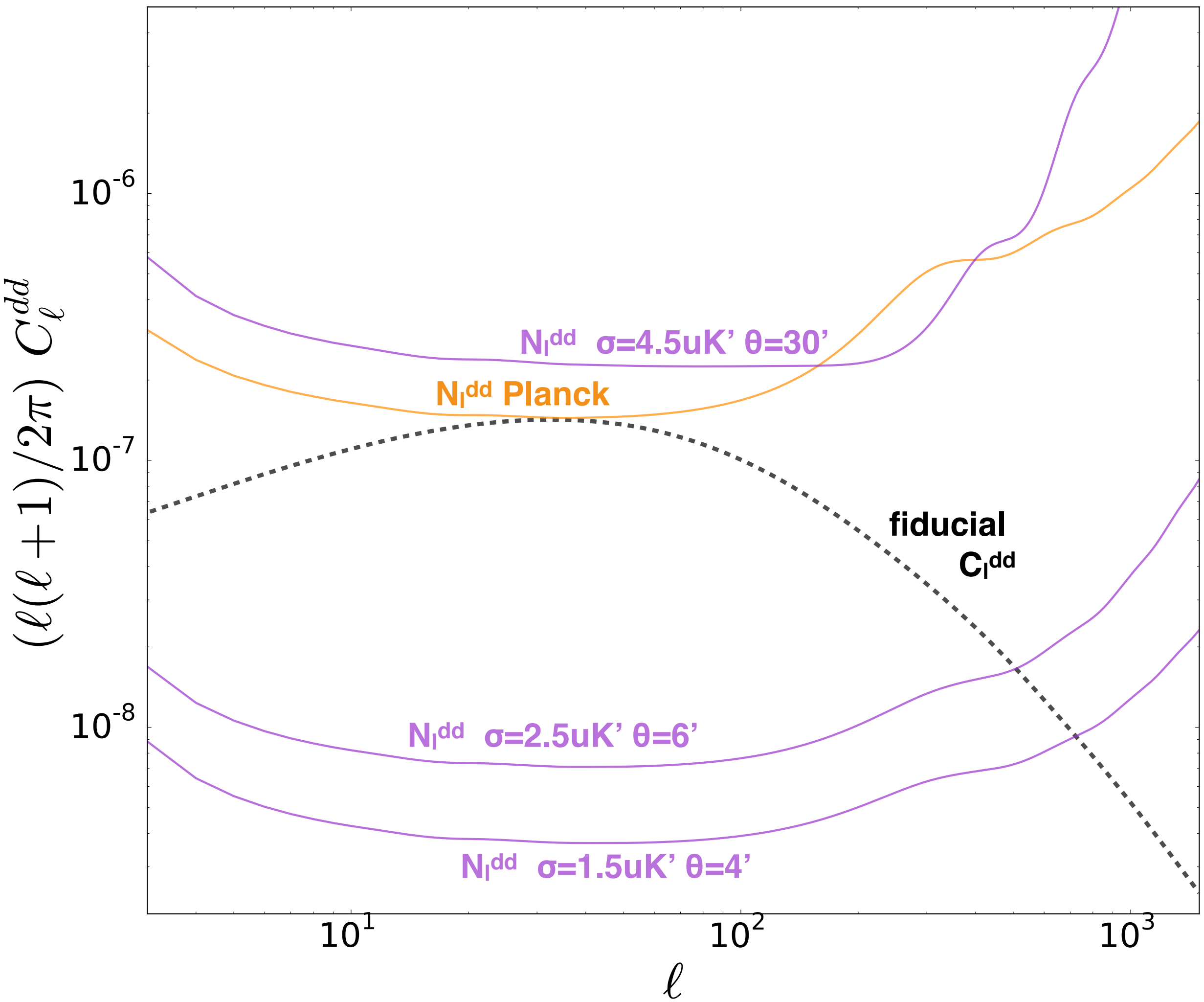
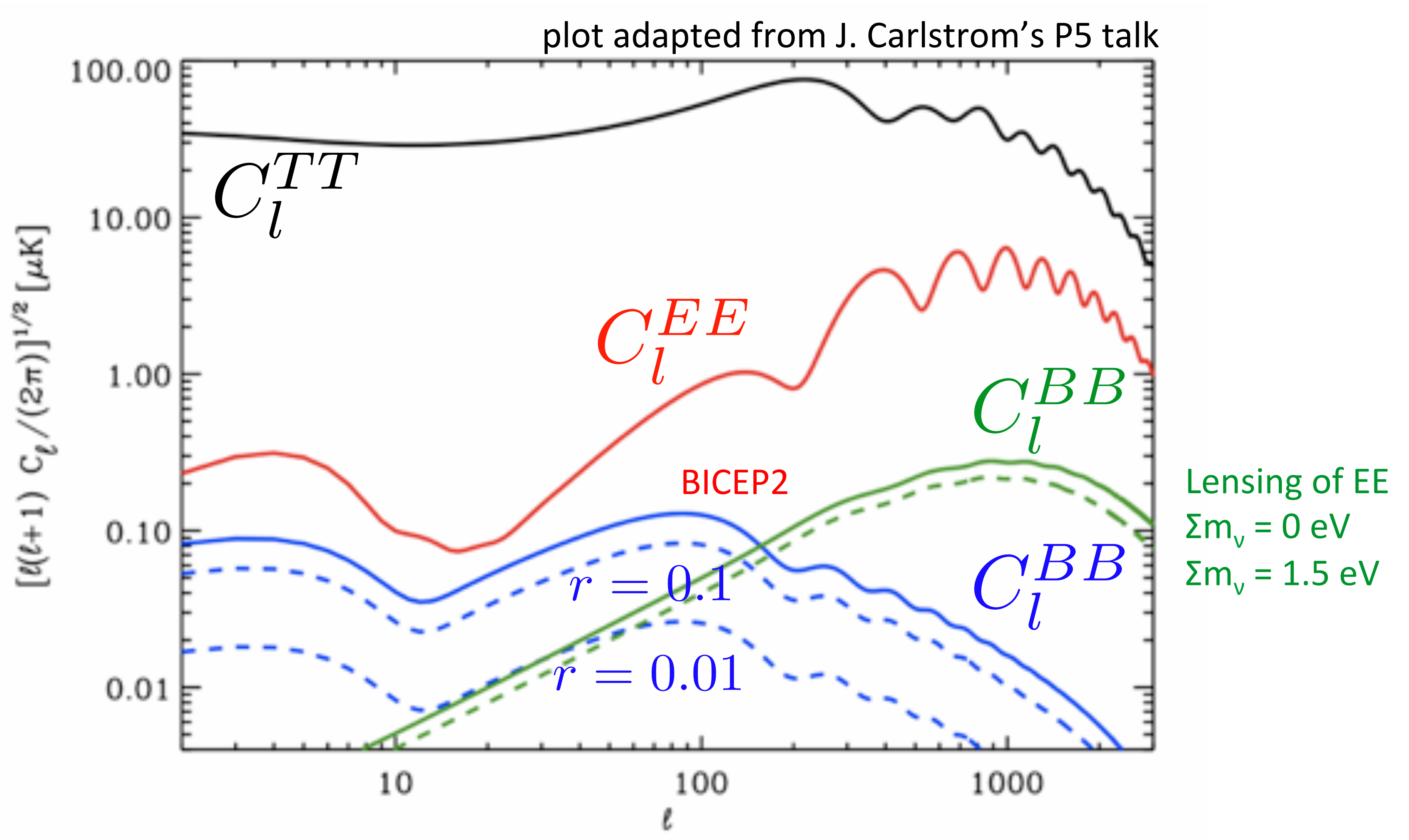
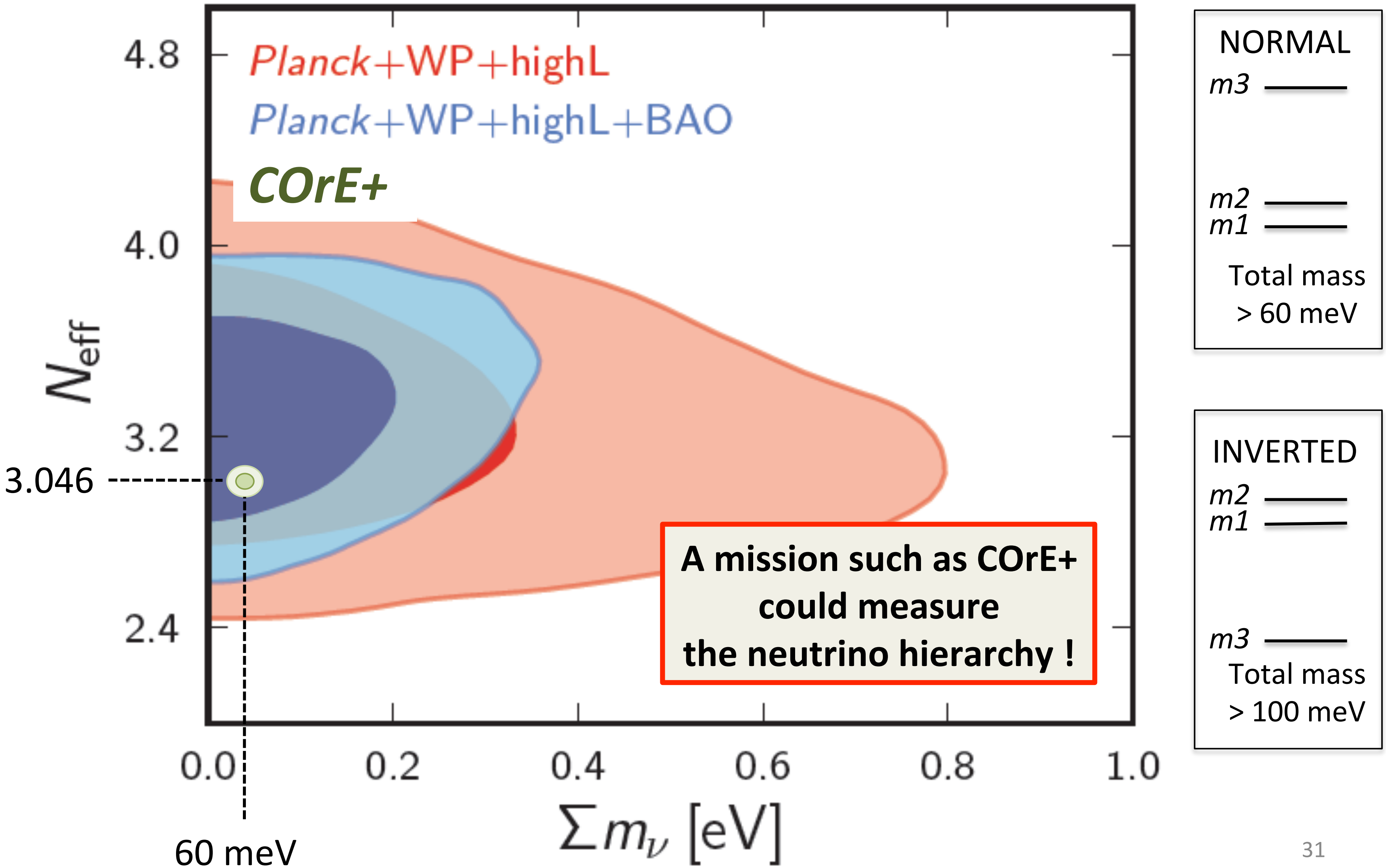


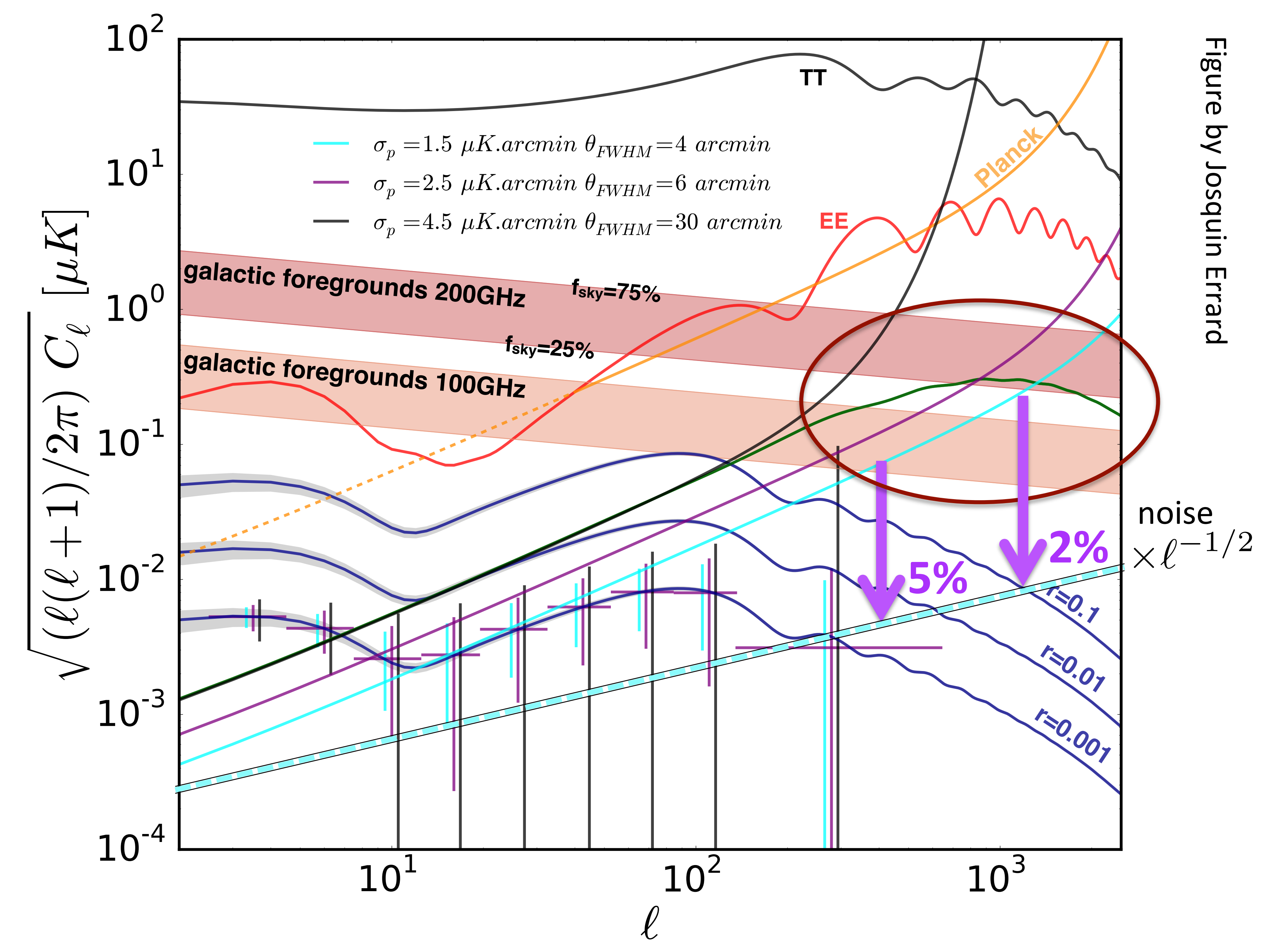
Figure by Josquin Errard

Temperature & Polarisation CMB C_l



Constraining the neutrino sector





$\sqrt{\ell(\ell+1)/2\pi)\ C_\ell}\ [\mu K]$
ℓ
TT
EE
Planck
$\sigma_p = 1.5\ \mu K.arcmin\ \theta_{FWHM} = 4\ arcmin$
$\sigma_p = 2.5\ \mu K.arcmin\ \theta_{FWHM} = 6\ arcmin$
$\sigma_p = 4.5\ \mu K.arcmin\ \theta_{FWHM} = 30\ arcmin$
galactic foregrounds 200GHz
galactic foregrounds 100GHz
f_{sky}=75%
f_{sky}=25%
noise
$\times \ell^{-1/2}$
5%
2%
r=0.1
r=0.01
r=0.001
Figure by Josquin Errard

What space mission ?

COrE+

(quasi-) ultimate mission for CMB polarisation anisotropies

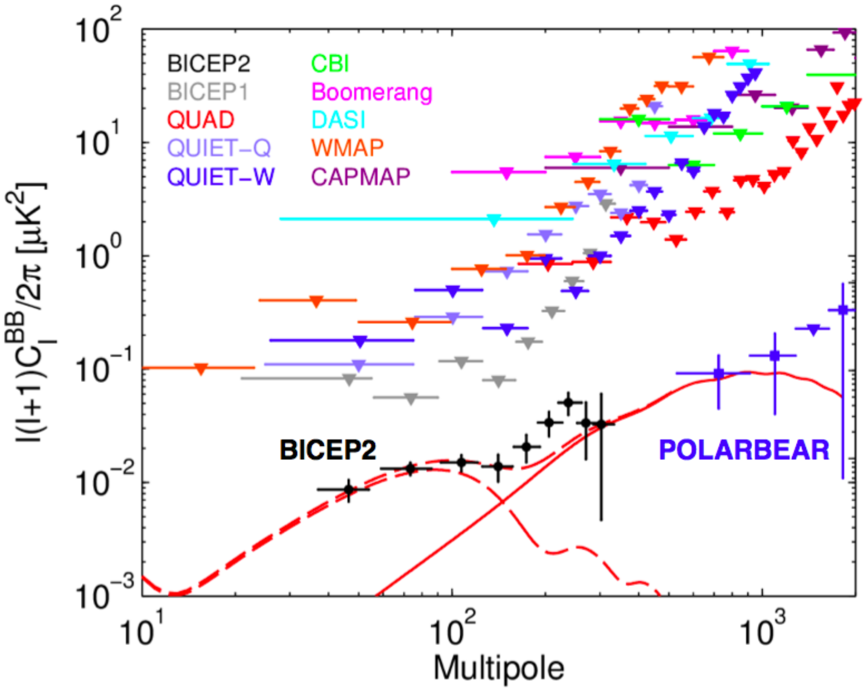
(fit 15 cosmological parameters)

This is true irrespective of the value of r.

Outline

- Tensor modes with a future mission?
- Beyond primary CMB science
- ➡ Why a space mission ?
- COrE+
- Conclusion

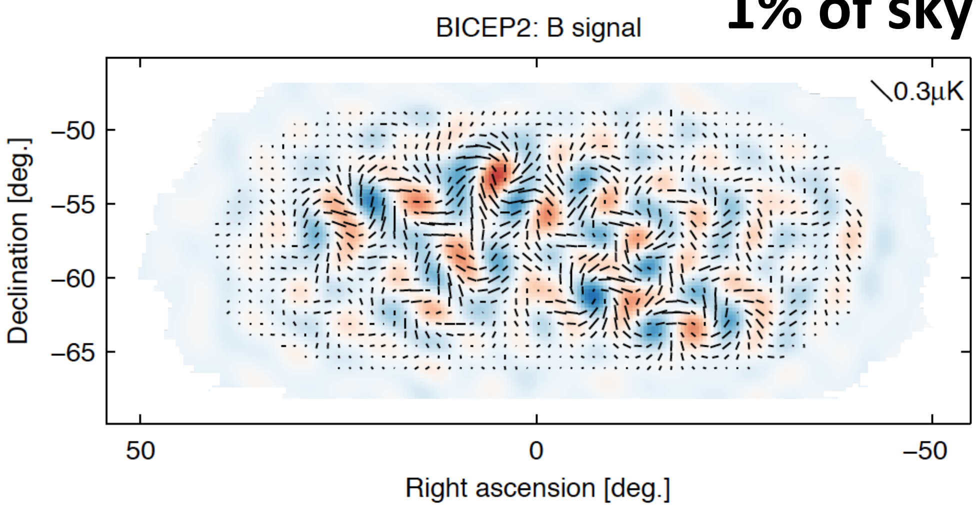
B-modes detected…

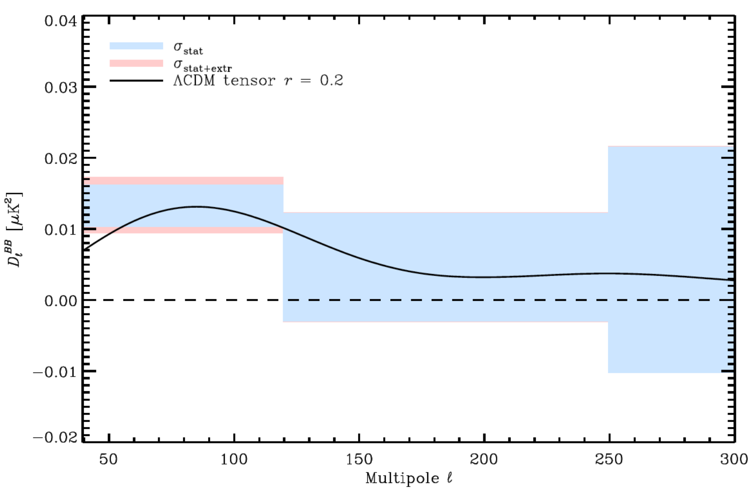


BICEP2: Ade et al., PRL 112, 24, id.241101 arXiv:1403.3985

POLARBEAR
Ade et al., ApJ 794, issue 2, Article id. 171

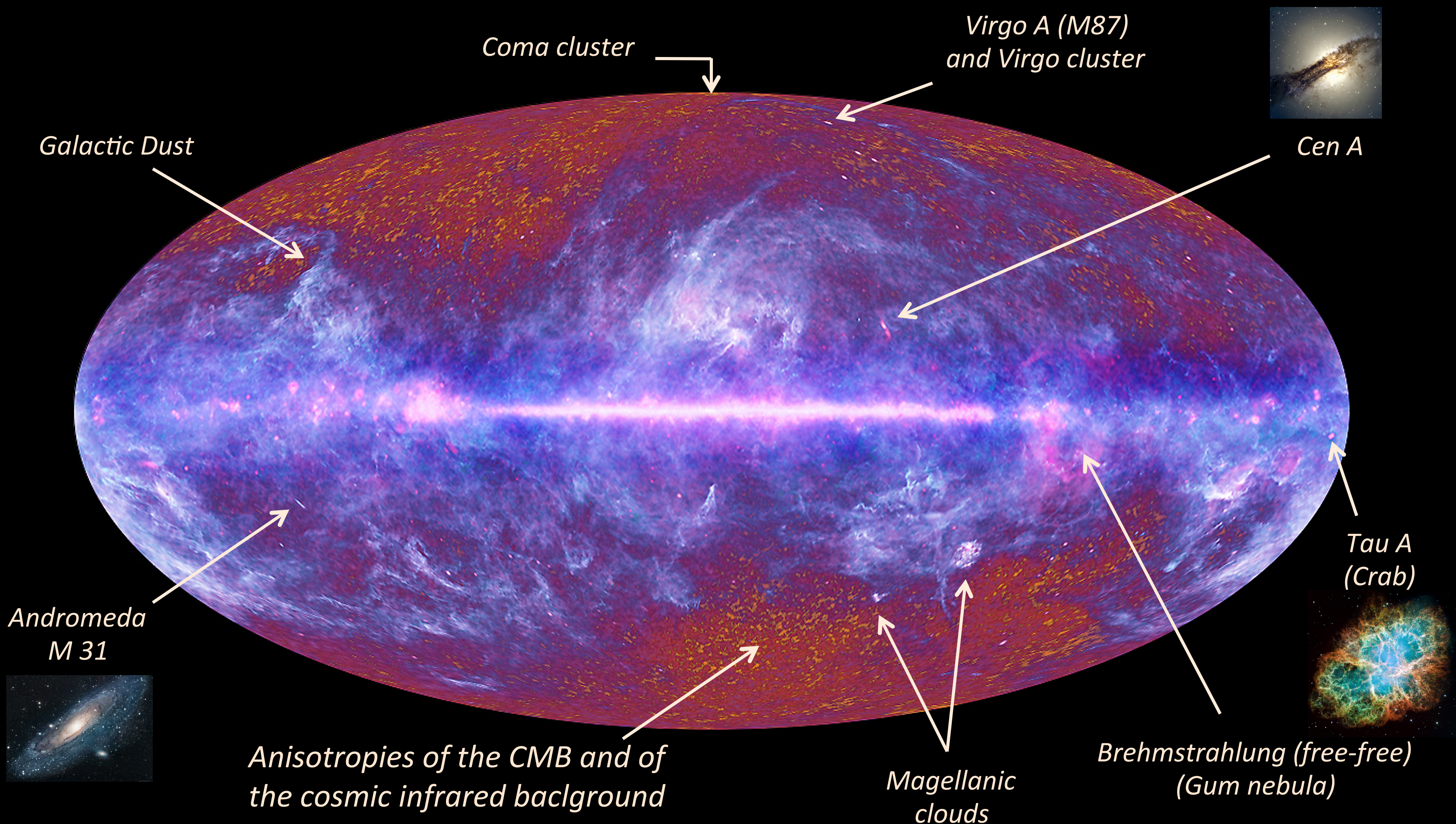
1% of sky



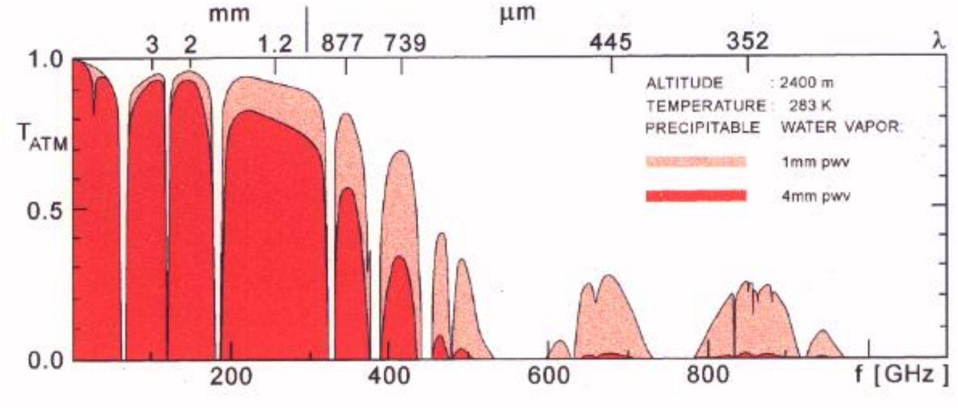


Planck collaboration, Planck intermediate results XXX.

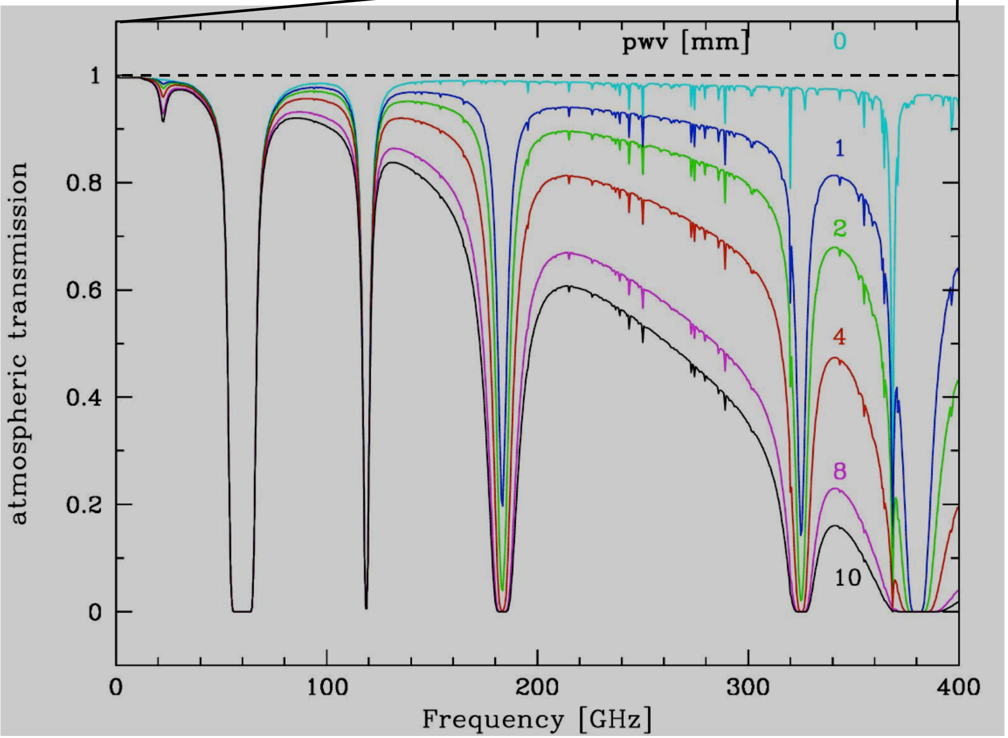
Foreground emission



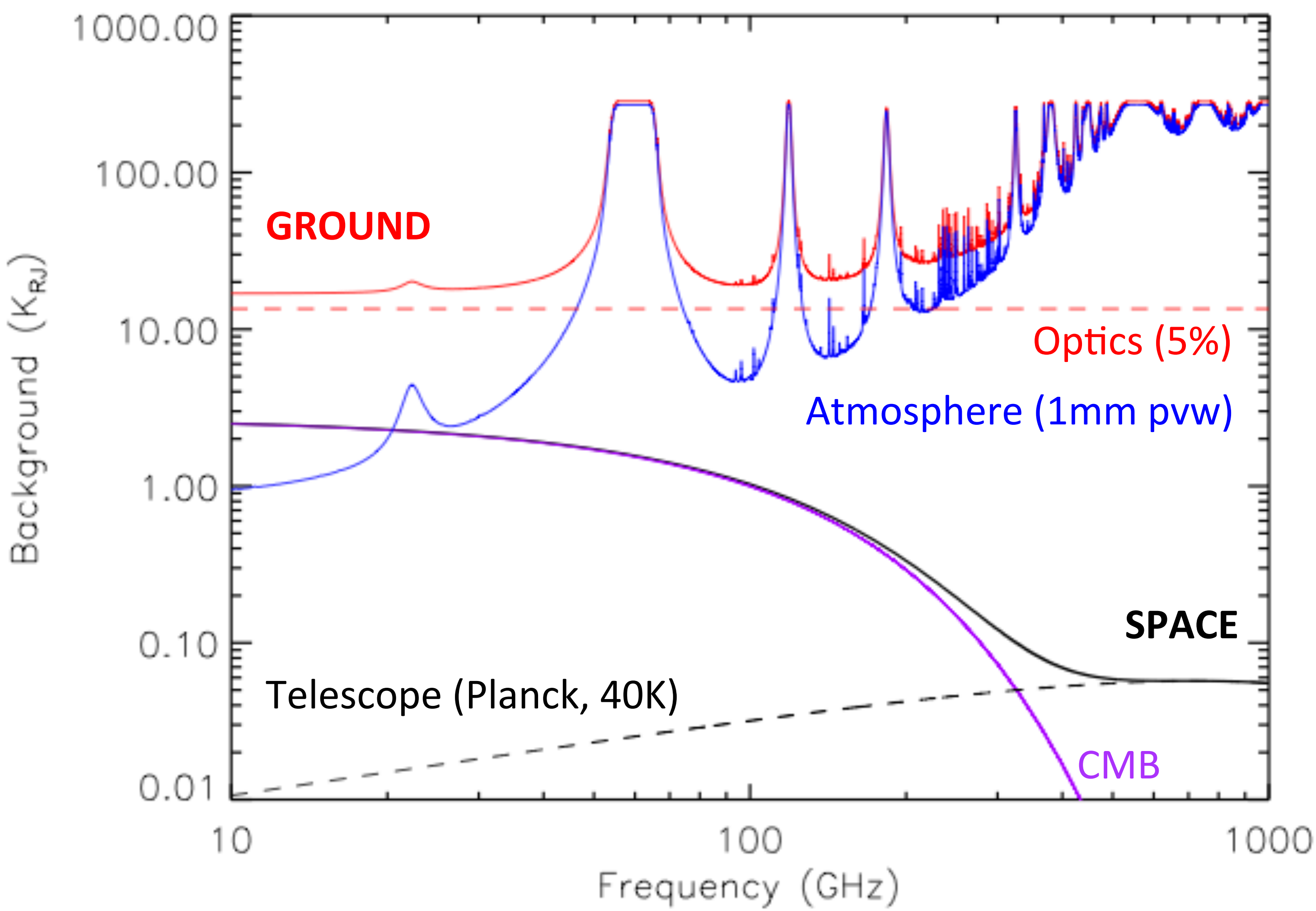
Atmosphere !



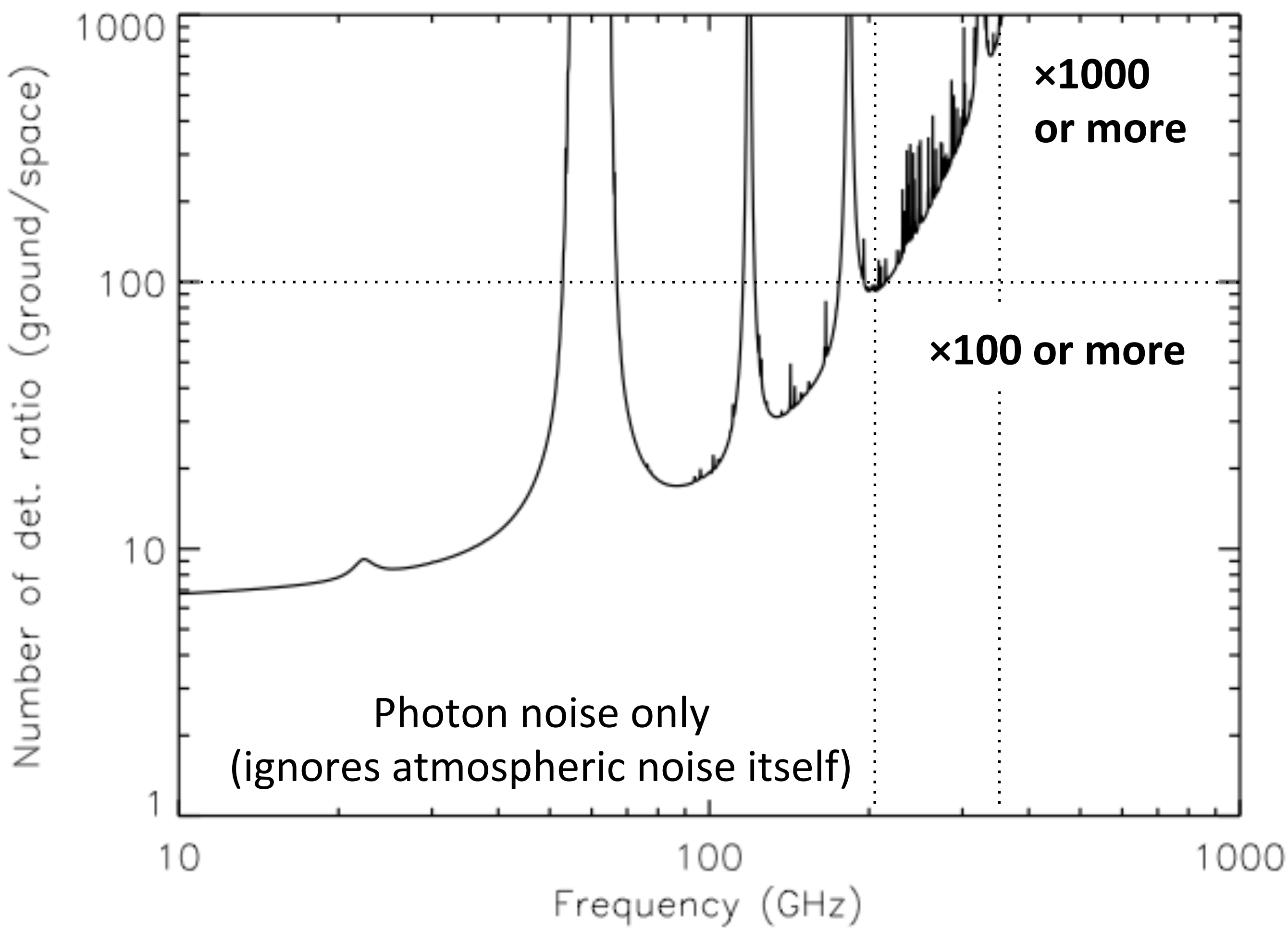
transmission and emission



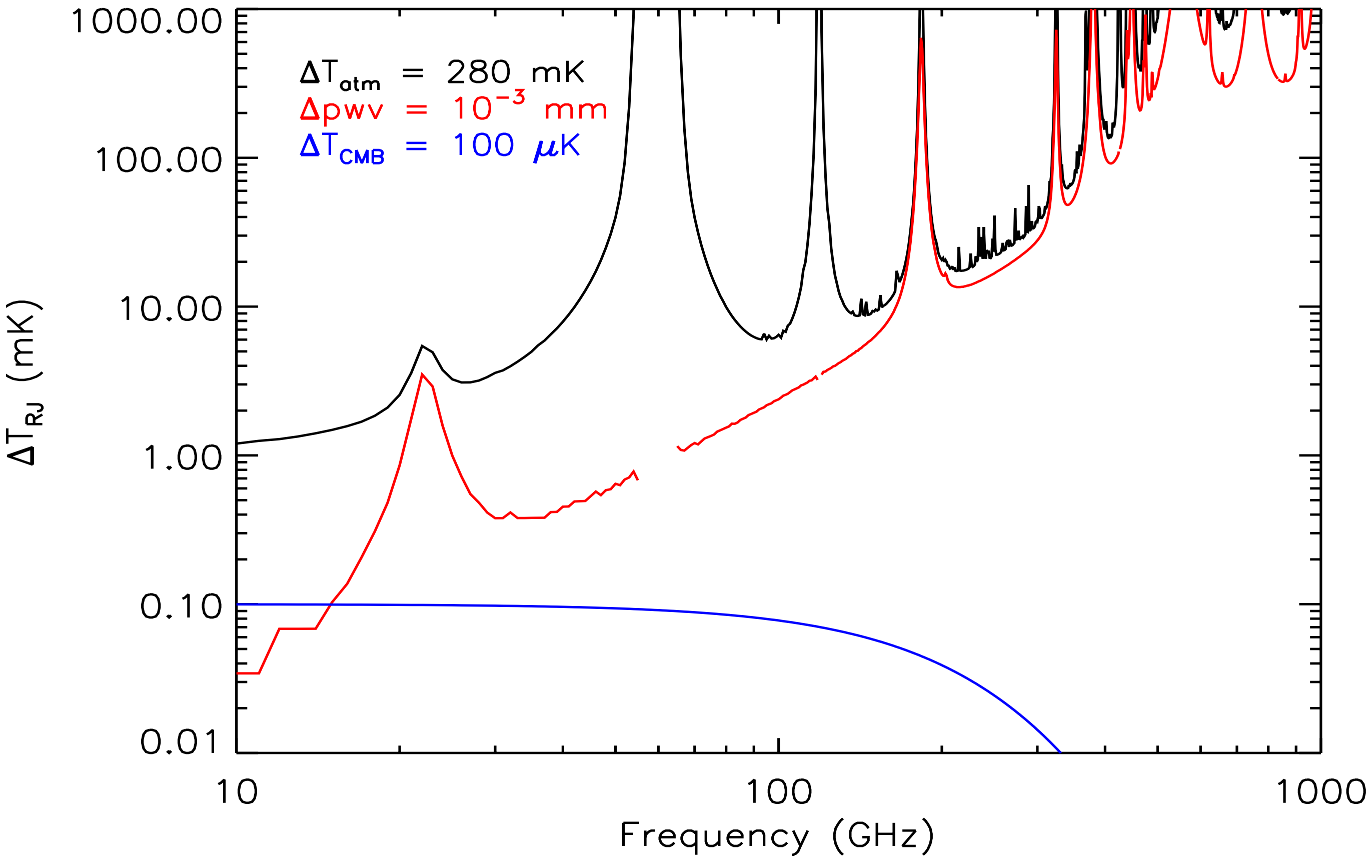
Comparison of the sky background



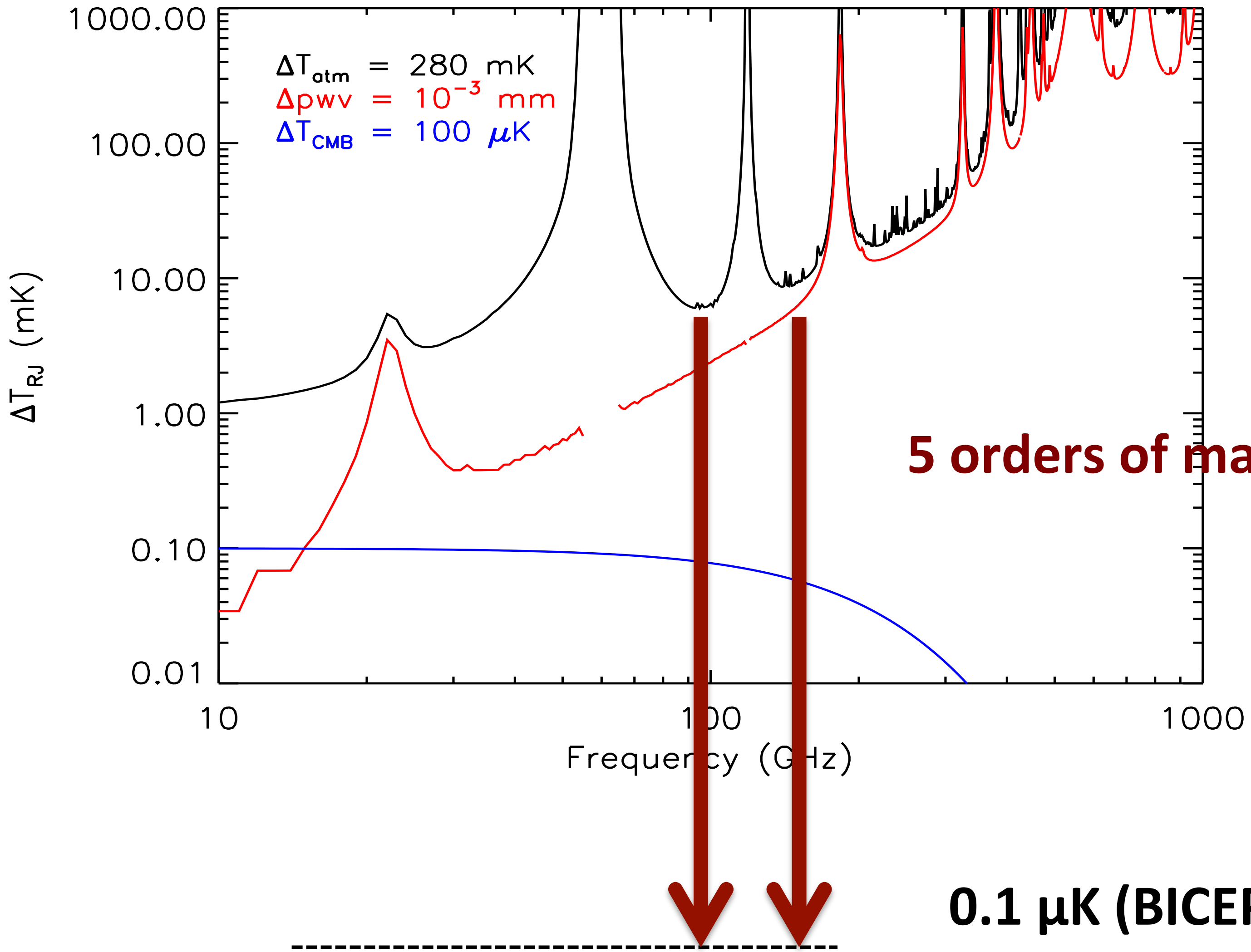
Sensitivity comparison



Atmospheric emission



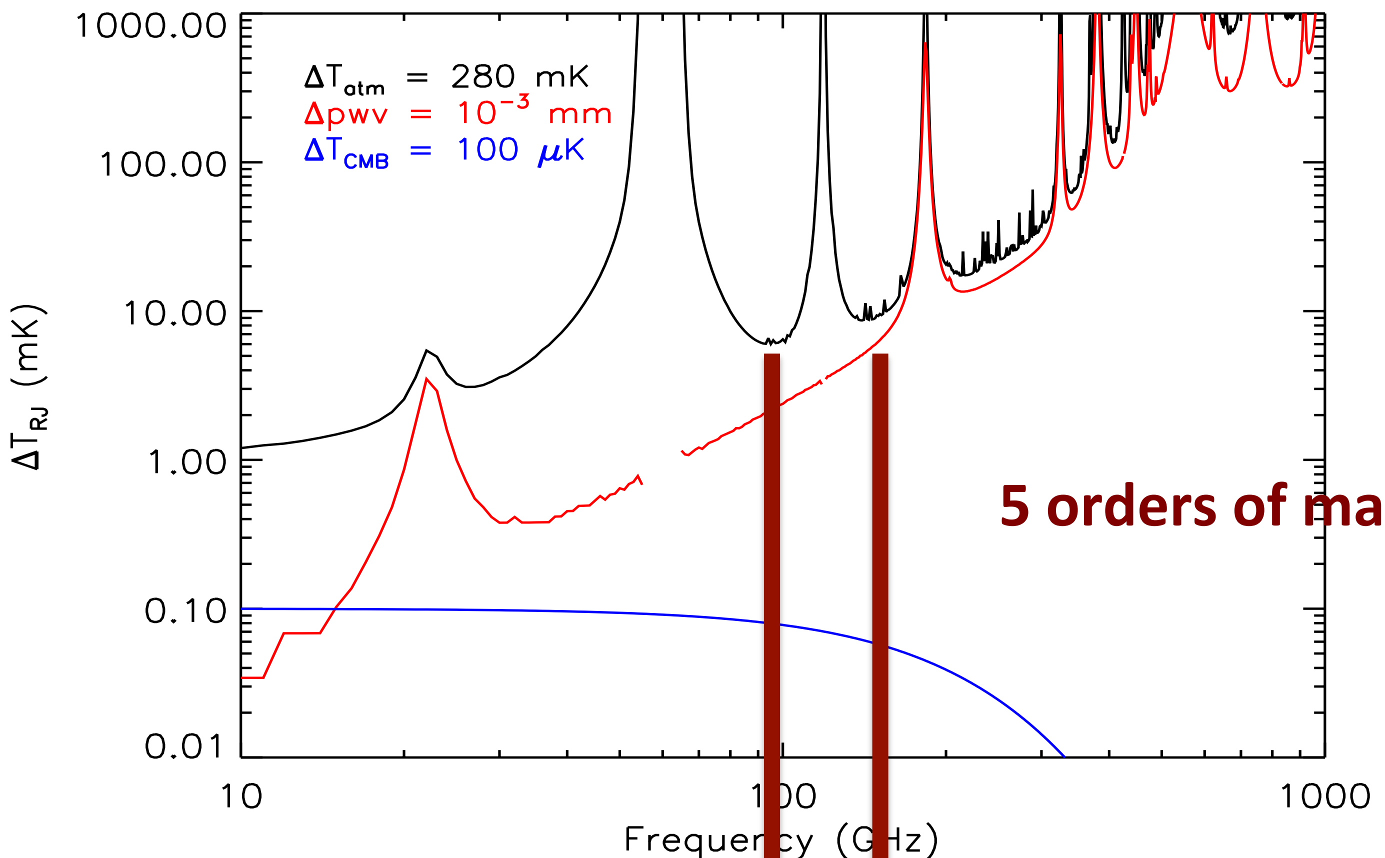
Atmospheric emission



5 orders of magnitude

0.1 μK (BICEP 2 signal)

Atmospheric emission



5 orders of magnitude

0.1 μK (BICEP 2 signal)

One more (only) but *on larger scales*

Outline

- Tensor modes with a future mission?
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- Why a space mission ?
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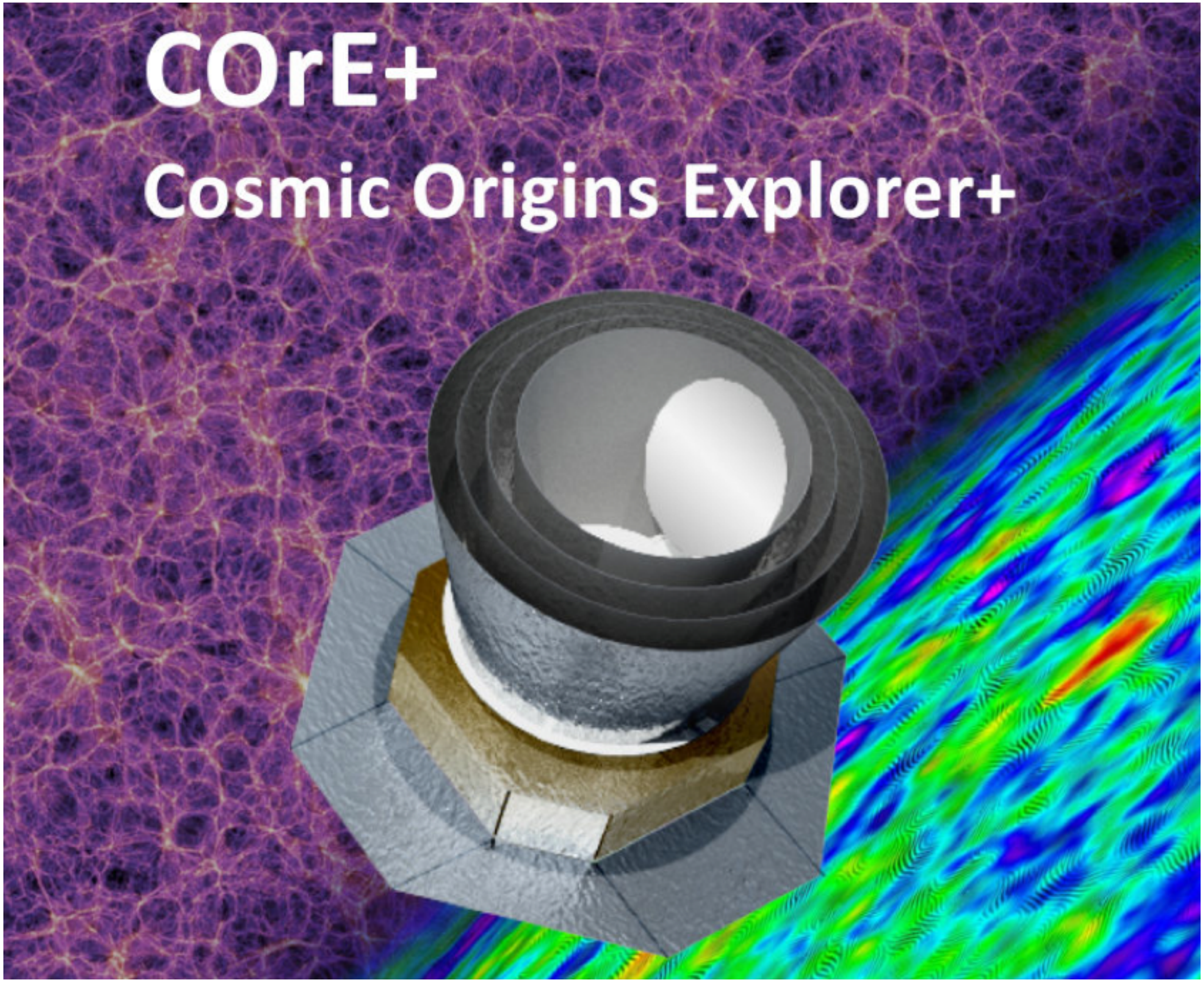
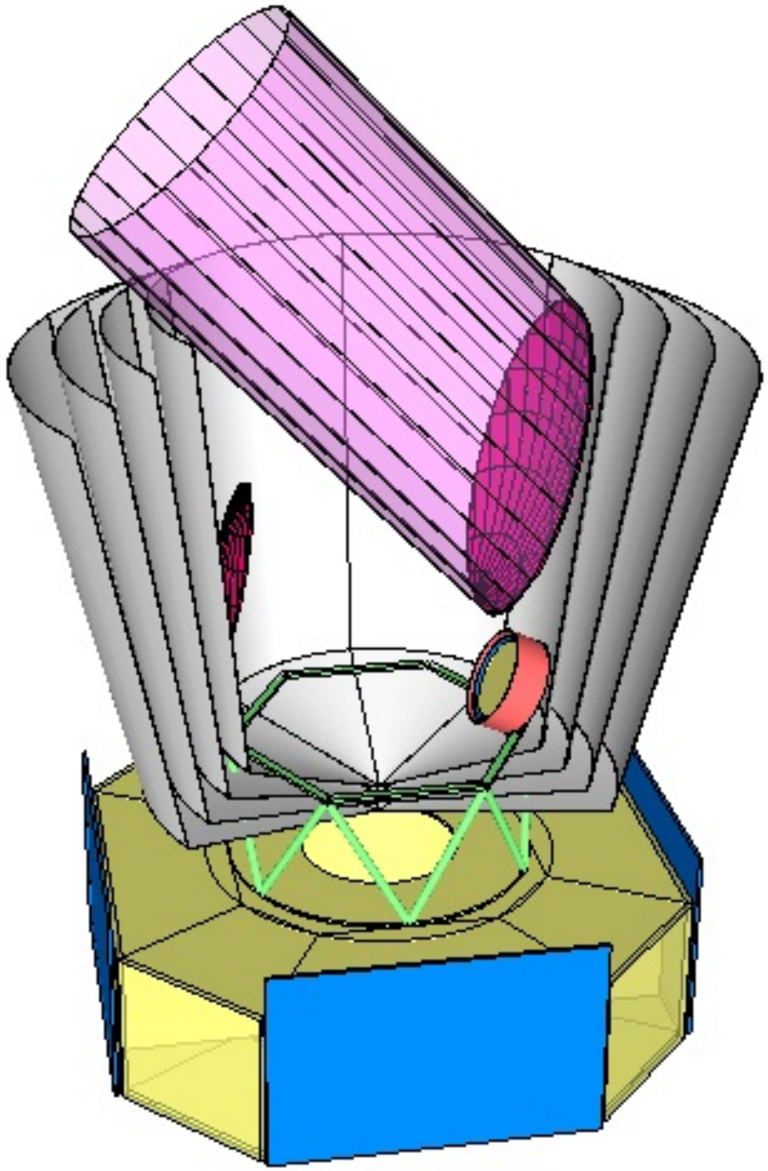
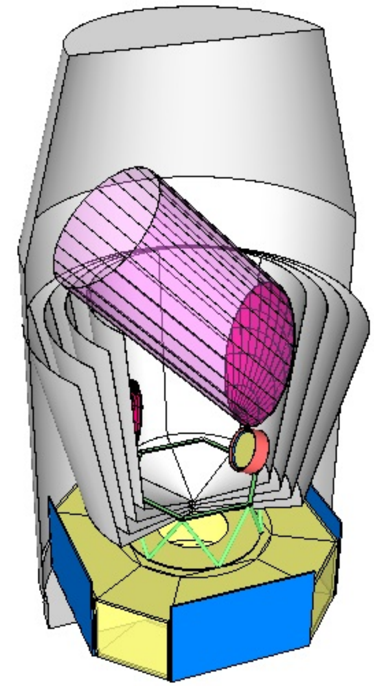
COrE+ and ESA M4 call

- ESA M4 call for a medium mission.
  - Budget 450 M€ (ESA) + National contributions for the science payload (including international contributions, e.g. from NASA);
  - Call issued August 19th, 2014; Proposal submitted January 15th, 2015;
  - CoRE+ NOT SELECTED. Did not pass the programmatic and technical screening. considered as too expensive and too low payload TRL.

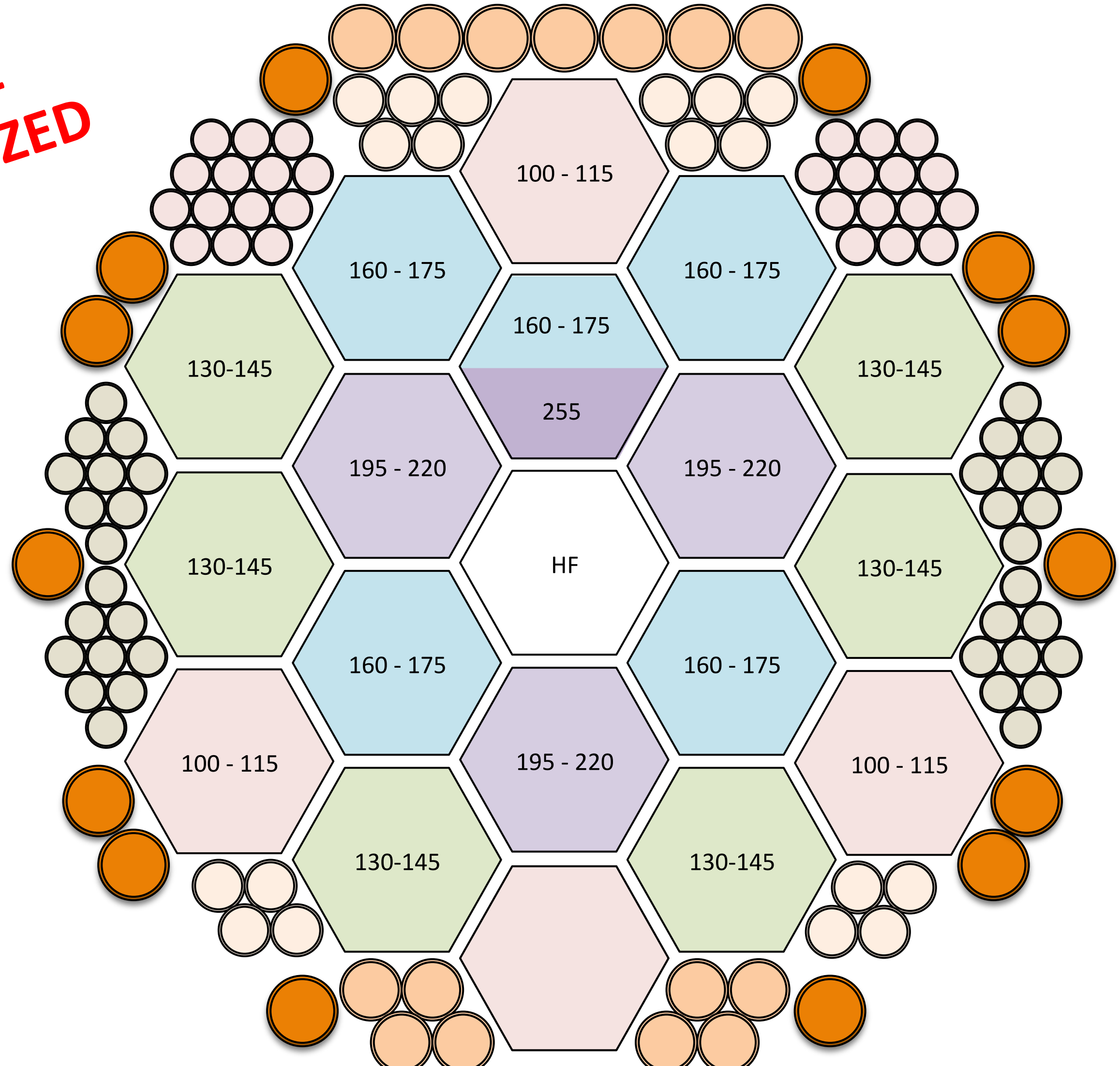

COrE+
Cosmic Origins Explorer+





Launch configuration
COrE+ in Soyuz fairing

TO BE OPTIMIZED



ν	$N_{det\ single}$	$N_{det\ dual}$
60	28	28
70	30	30
80	36	64
90	72	102
100	84	120
115	124	196
130	180	244
145	264	444
160	254	434
175	290	554
195	346	600
220	200	490
255	140	486
295	60	260
340	60	200
390	60	120
450	60	120
520	60	120
600	60	120
700		60
800		60

2410 (5028) detectors

63% (58%) in CMB channels

1.85 (1.2) μK.arcmin sensitivity

COrE+ proposed baseline

(50% opt. eff., Δν/ν=25%, 60K payload, single frequency pixels)

channel GHz	beam arcmin	$N_{\rm det}$	ΔT μK.arcmin	ΔP μK.arcmin	ΔI kJy/sr.arcmin	$\Delta y \times 10^6$ $y_{\rm SZ}$.arcmin	PS flux (5σ) mJy
60	14	28	11.3	16	1.14	-2.3	6
70	12	30	10.5	14.9	1.4	-2.2	6.3
80	10.5	38	9.1	12.9	1.53	-2.0	6
90	9.33	72	6.5	9.2	1.32	-1.5	4.6
100	8.4	84	6.0	8.5	1.43	-1.5	4.5
115	7.3	124	5.0	7.0	1.45	-1.3	4
130	6.46	180	4.2	5.9	1.43	-1.3	3.5
145	5.79	264	3.6	5.0	1.37	-1.3	3
160	5.25	254	3.8	5.4	1.6	-1.7	3.1
175	4.8	290	3.8	5.3	1.69	-2.2	3.0
195	4.31	346	3.8	5.3	1.79	-4.1	2.9
220	3.82	200	5.8	8.1	2.78	-	4.0
255	3.29	140	8.9	12.6	4.11	5.5	5.1
295	2.85	60	19.4	27.4	7.84	5.7	8.4
340	2.47	60	30.9	43.7	9.91	5.6	9.2
390	2.15	60	55.0	77.8	12.63	7.0	10.2
450	1.87	60	116.6	164.8	16.48	10.9	11.5
520	1.62	60	295.7	418.2	21.71	21.0	13.2
600	1.4	60	899.7	1272.4	28.61	50.3	15.0

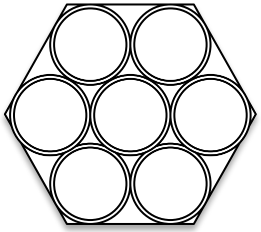
Table 3: Proposed *COrE+* frequency channels. The sensitivity is calculated assuming $\Delta\nu/\nu = 25\%$ bandwidth, 50% optical efficiency, total noise of twice the expected photon noise from the sky and the optics of the instrument at 60K temperature. The aggregated CMB sensitivity is $2\,\mu$K.arcmin in polarization. This is the *COrE+* baseline

COrE+ proposed extension
(50% opt. eff., Δν/ν=25%, 60K payload, dual-frequency pixels)

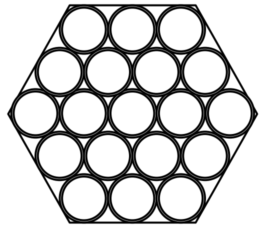
channel GHz	beam arcmin	$N_{\rm det}$	ΔT $\mu K\cdot$arcmin	ΔP $\mu K\cdot$arcmin	ΔI (kJy/sr)·arcmin	$\Delta y \times 10^6$ $y_{\rm SZ}\cdot$arcmin	PS flux (5σ) mJy
60	14	28	9.8	13.8	0.99	-2.0	5.2
70	12	30	9.1	12.9	1.21	-1.9	5.5
80	10.5	64	6.1	8.6	1.02	-1.3	4.0
90	9.33	102	4.8	6.7	0.96	-1.1	3.4
100	8.4	120	4.3	6.1	1.04	-1.1	3.3
115	7.3	196	3.4	4.8	1.00	-0.9	2.7
130	6.46	264	3.0	4.2	1.02	-0.9	2.5
145	5.79	388	2.5	3.6	0.98	-0.9	2.1
160	5.25	534	2.3	3.2	0.96	-1.0	1.9
175	4.8	554	2.4	3.3	1.06	-1.4	1.9
195	4.31	600	2.5	3.5	1.18	-2.7	1.9
220	3.82	490	3.2	4.5	1.54	-	2.2
255	3.29	486	4.1	5.8	1.91	2.6	2.4
295	2.85	260	8.1	11.4	3.26	2.4	3.5
340	2.47	200	14.6	20.7	4.70	2.7	4.4
390	2.15	120	33.7	47.6	7.74	4.3	6.2
450	1.87	120	71.4	100.9	10.09	6.7	7.1
520	1.62	120	181.1	256.1	13.3	12.9	8.1
600	1.4	120	551	779.2	17.52	30.8	9.2
700	1.2	60	3293.5	4657.8	33.35	145.1	15.0
800	1.05	60	14499.8	20505.9	43.04	527.4	16.9

Table 4: *COrE+* frequency channels for a possible extension of the proposed baseline, based on dual-frequency, dual polarization detectors. Each pixel feeds detectors at frequency ν_n and ν_{n+2}, i.e. (60 and 80 GHz), (70 and 90 GHz), (80 and 100 GHz), etc.

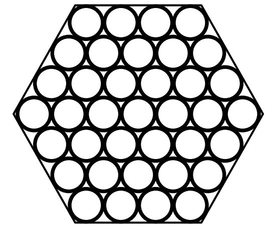
Focal plane wafers



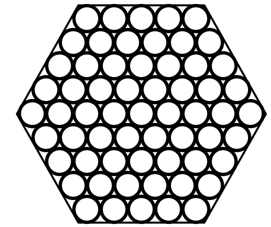
7 horns
14 detectors
h = 8.2 Fλ



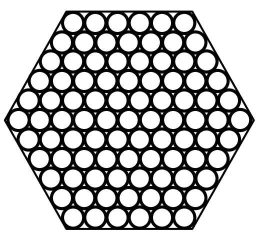
19 horns
38 detectors
h = 13.4 Fλ
100 – 115 GHz



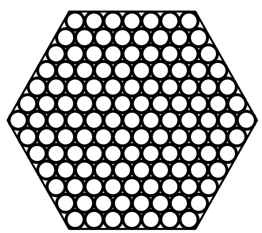
37 horns
74 detectors
h = 18.6 Fλ
130 – 145 GHz



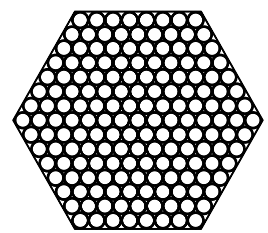
61 horns
122 detectors
h =23.8 Fλ
160 – 175 GHz



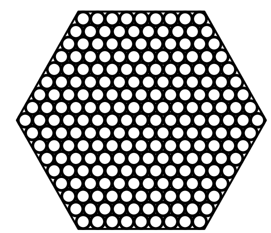
91 horns
182 detectors
h = 29.0 Fλ
195 – 220 GHz



127 horns
254 detectors
h = 34.2 Fλ
255 GHz



169 horns
338 detectors
h = 39.4 Fλ
295 GHz



217 horns
434 detectors
h = 44.6 Fλ
High frequencies

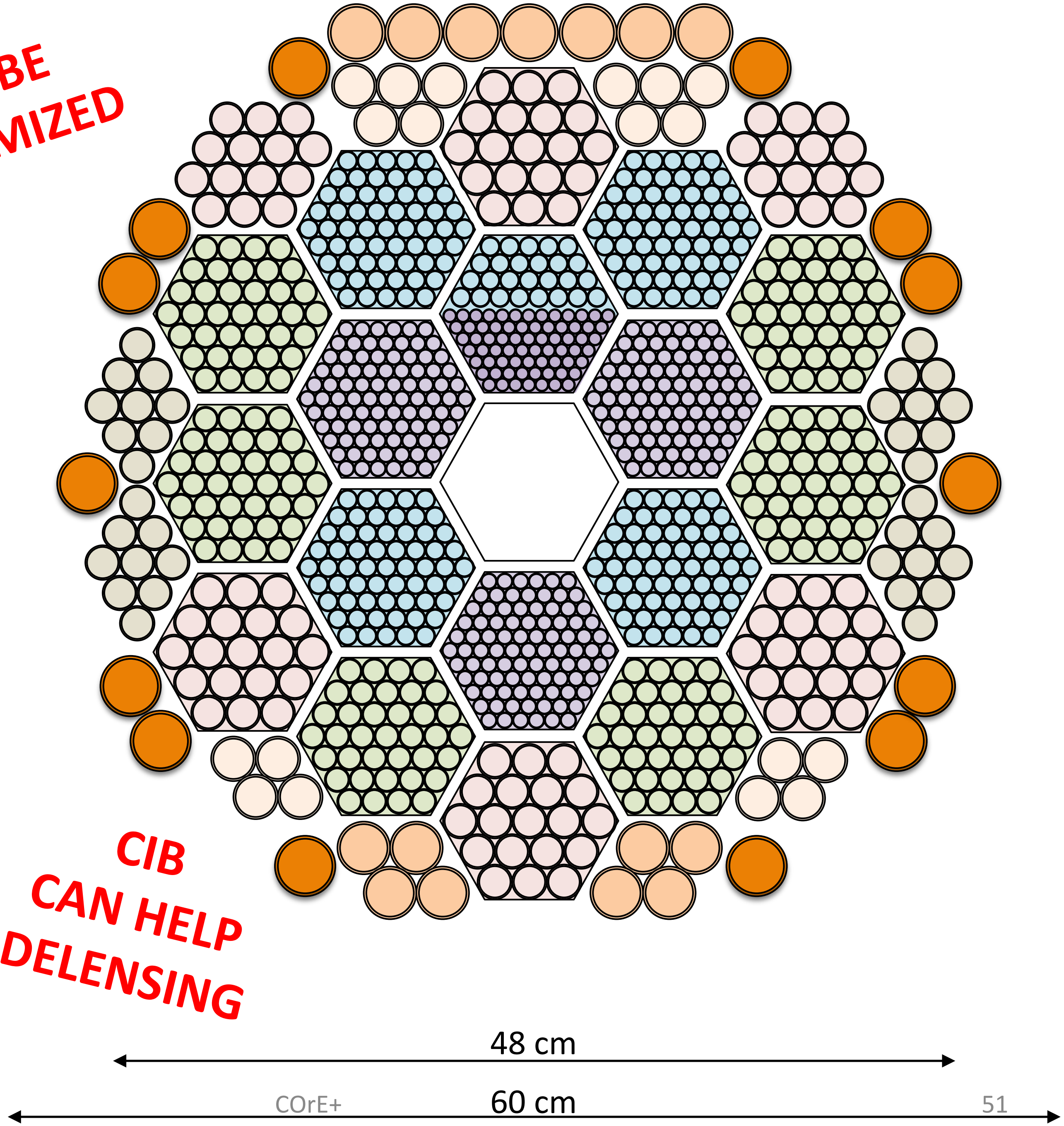
h = Height of the hexagons for horn diameter of 3 Fλ (-20 dB edge taper)

- 60 GHz
- 70 GHz
- 80 GHz
- 90 GHz
- 100 or 115 GHz

TO BE OPTIMIZED

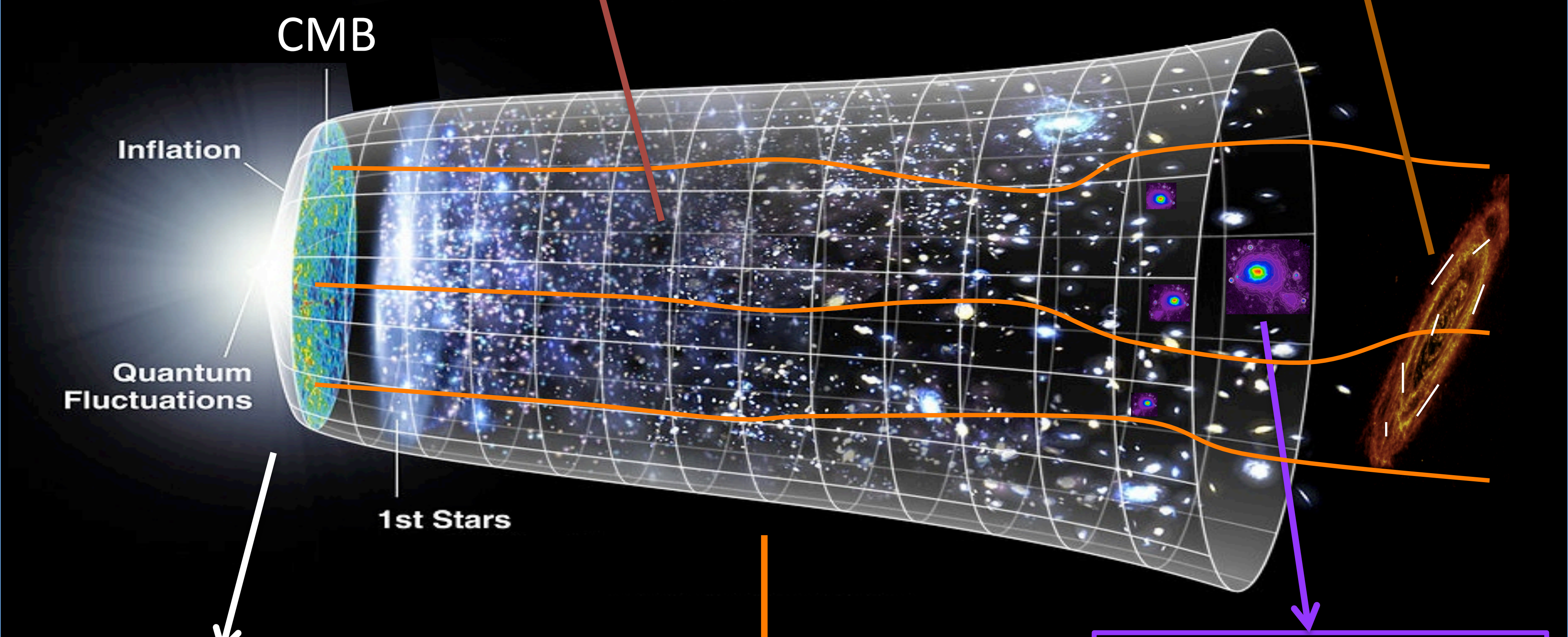
ν	$N_{det\ single}$	$N_{det\ dual}$
60	28	28
70	30	30
80	36	64
90	72	102
100	84	120
115	124	196
130	180	244
145	264	444
160	254	434
175	290	554
195	346	600
220	200	490
255	140	486
295	60	260
340	60	200
390	60	120
450	60	120
520	60	120
600	60	120
700		60
800		60

CIB CAN HELP DELENSING



Extragalactic Astrophysics

Interstellar medium (magnetic field)



Univers primordial

Physique à ≈ 10^{16} GeV

$E_{COrE+} > 10^{12} \times E_{LHC}$

z ≈ 1-3

Gravitational lensing

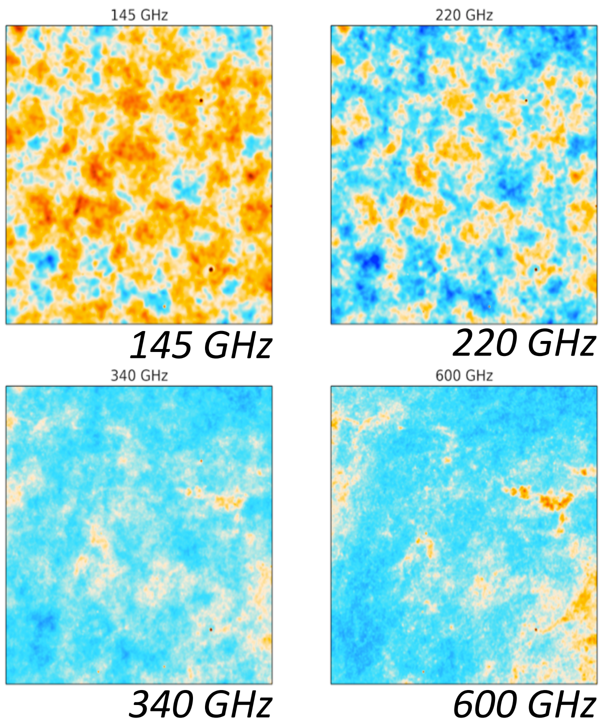
Dark matter distribution

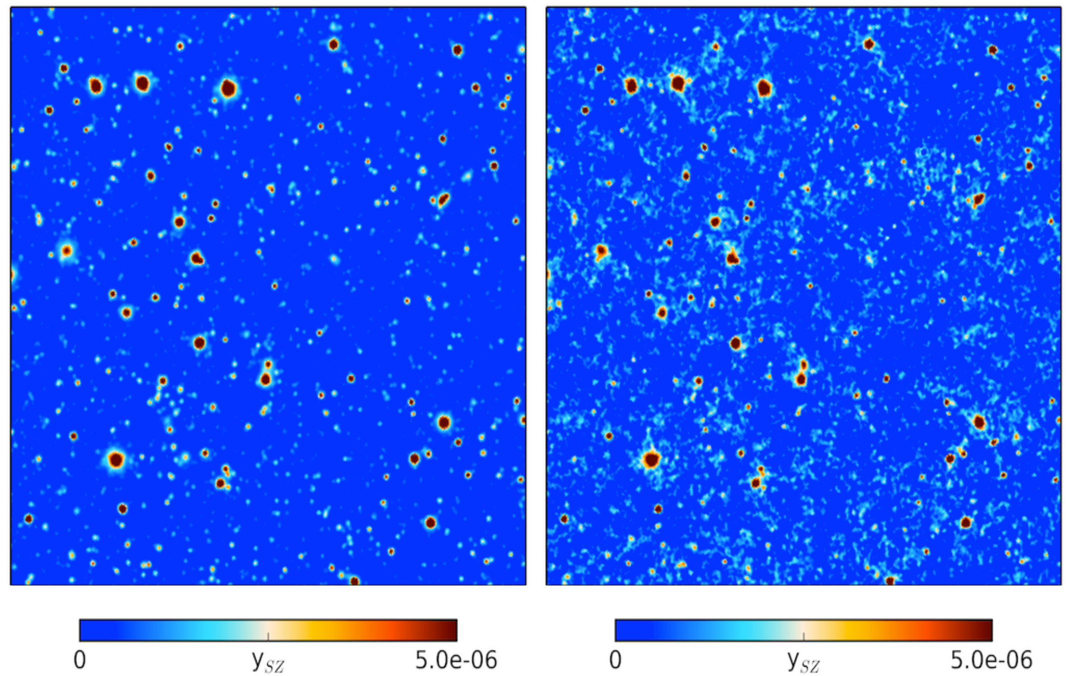
z ≈ 0-2

Sunyaev-Zeldovich effect:

Distribution of the hot gas and velocity field

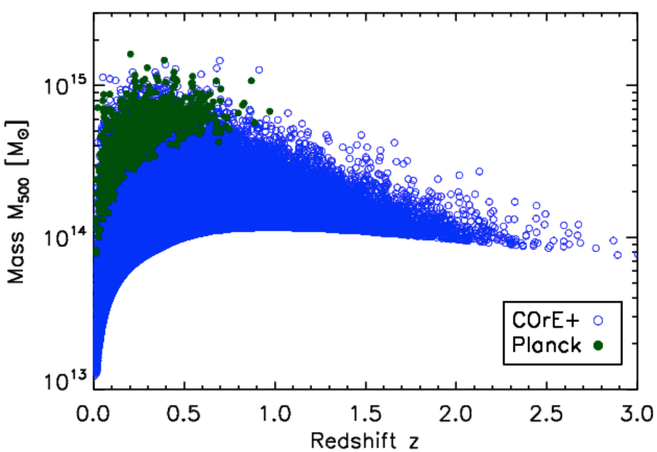
Observation of >100,000 Galaxy clusters





SZ map reconstruction

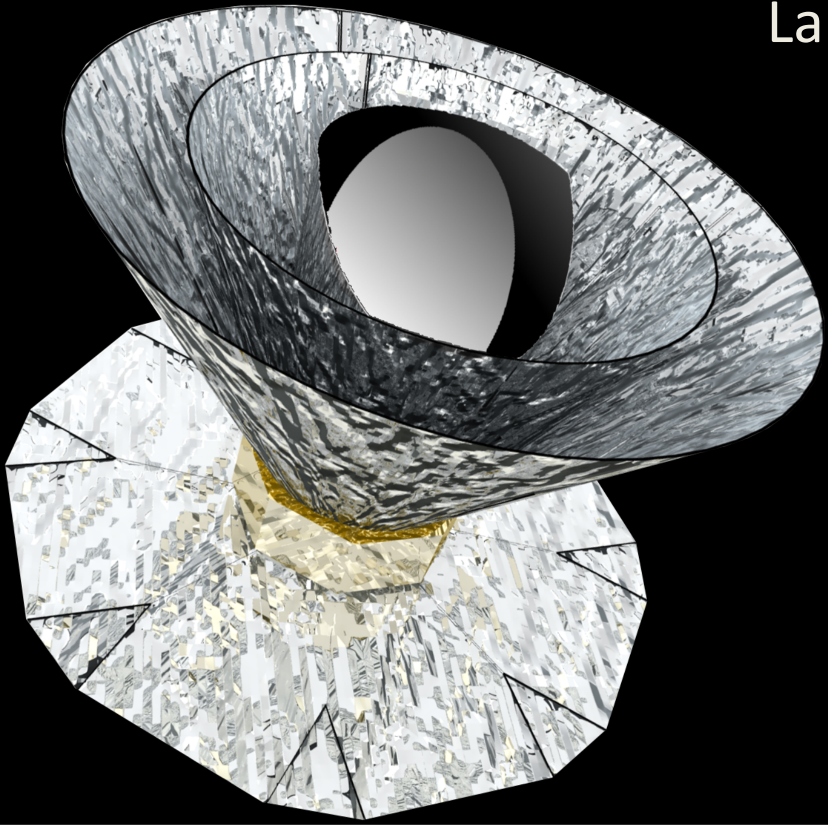
Needlet ILC (Mathieu Remazeilles)
on PSM simulations (Ata Karakci)



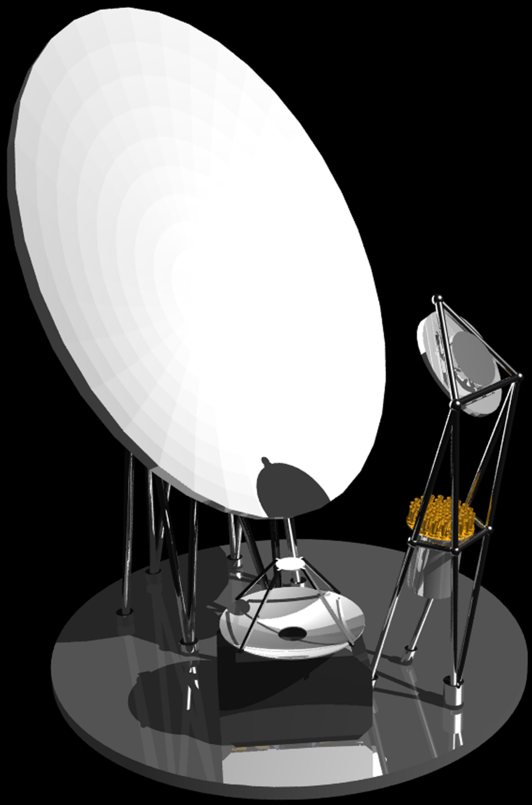
Limit mass as a function of redshift (Jean-Baptiste Melin)

PRISM

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



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



Two instruments

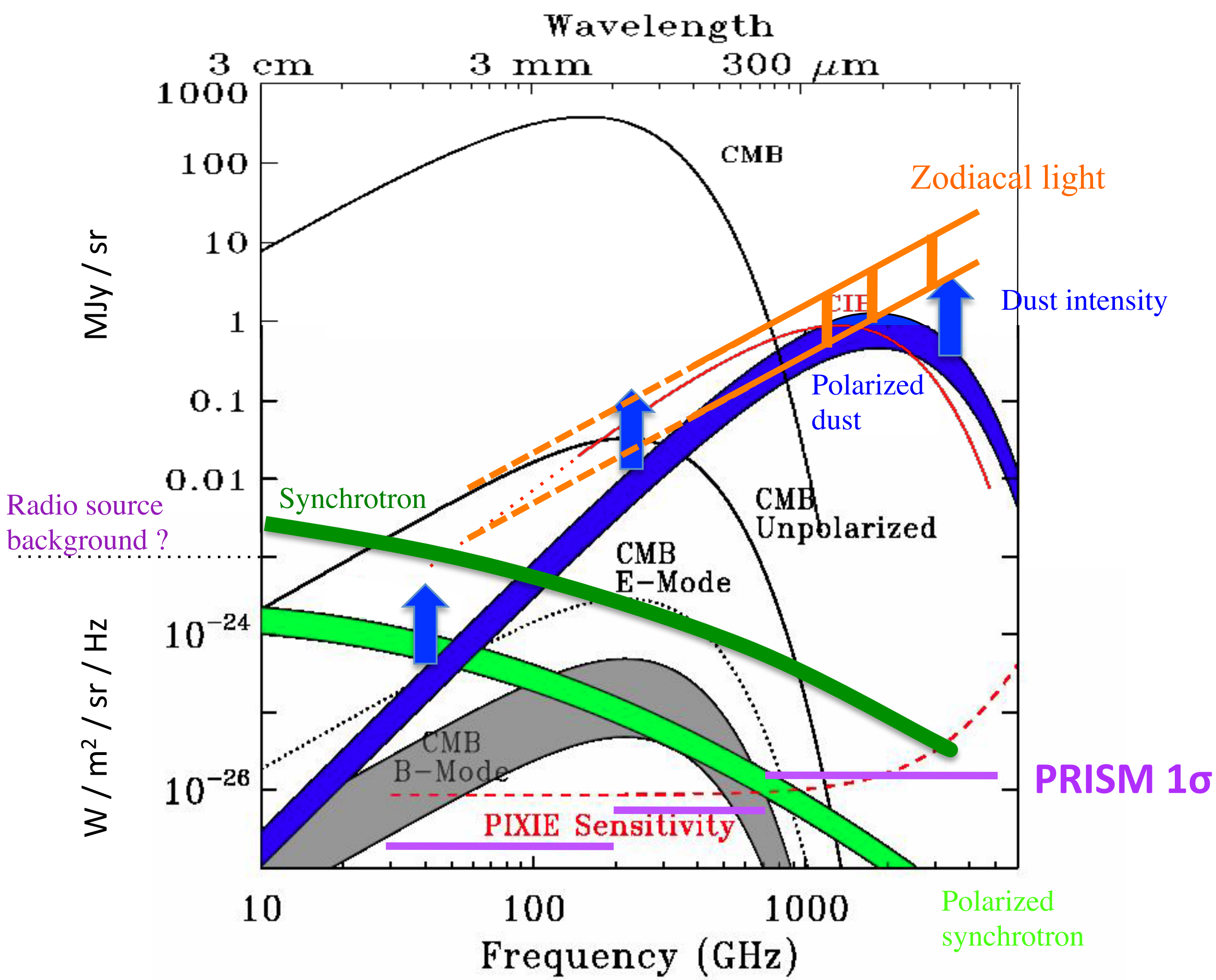
Why imager + spectrophotometer ?

SPECTROPHOTOMETER:
Big foreground problem

Component separation (e.g. template fitting) on absolute emission is not possible…

spectral emission at
l=0 and at l>1
are different.

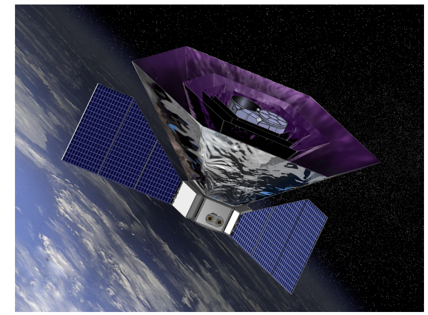
We need a complete physical model of *all* components down to the sensitivity limits



A goal and a strategy for the CMB community

CMB S4
Ground-based:
1-2' in atmospheric windows
ν = 40, 95, 150, 220
Good on small scales

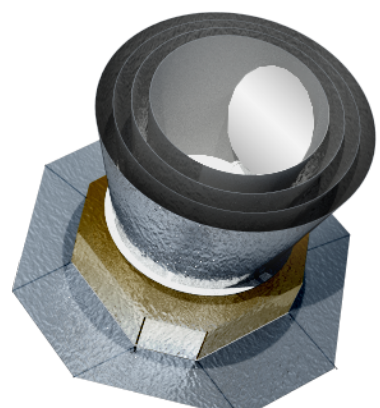
High angular resolution



PIXIE
Absolute measurement
1-2° in many bands
Clean large scales

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

COrE+
Space-borne, many frequencies
1-2' at high frequency (ν ≥ 300)
4'-6' at CMB frequencies
Clean large scales



Absolute calibration & zero-level of maps