Next-generation CMB projects

Jean-Baptiste Melin

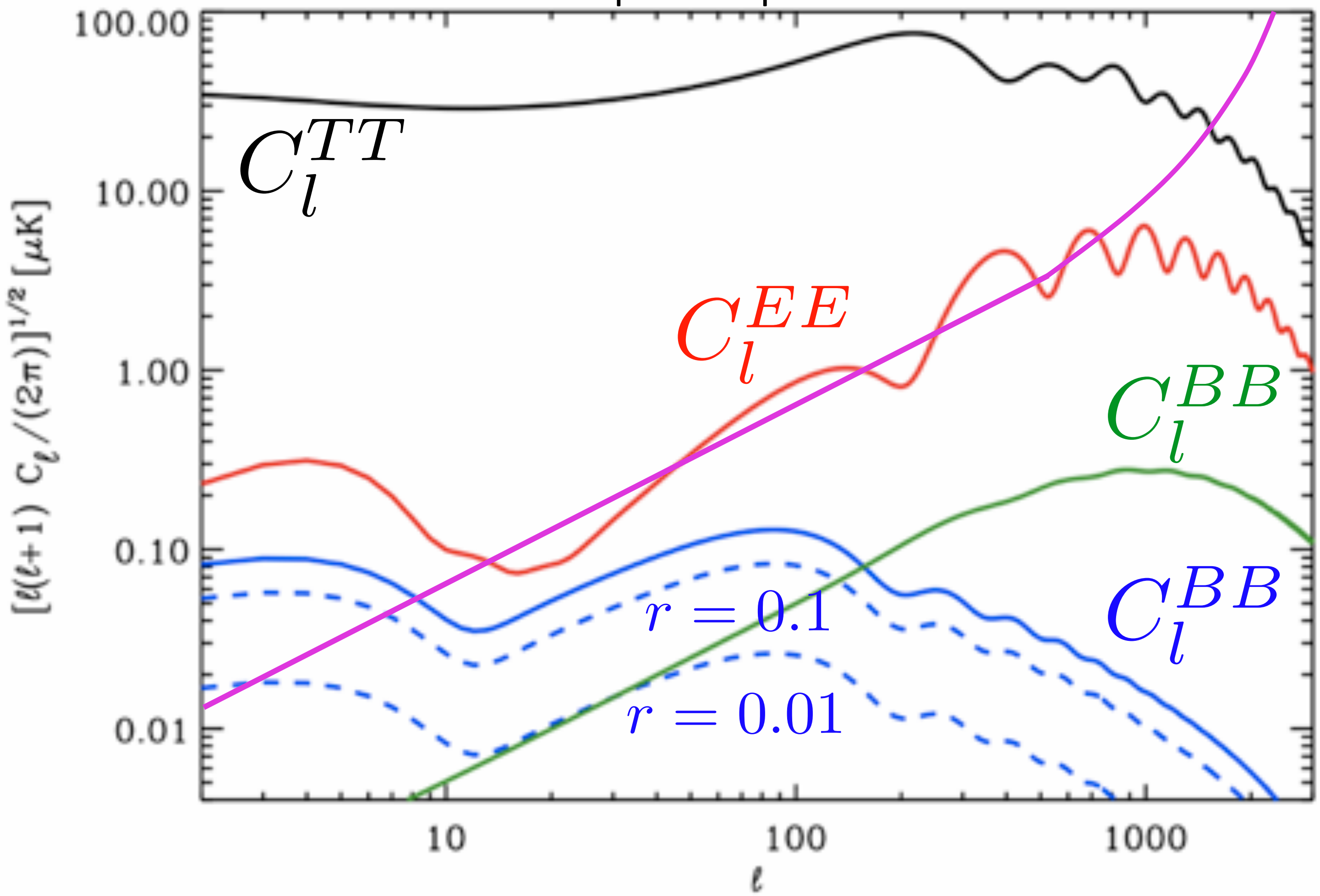
October 27, 2015

The Planck mission is ending

- Towards the European Coordination of the CMB programme (Florence, 31 Aug. and 1 Sept. 2015)
  https://indico.cern.ch/event/376392/timetable/#20150831
- Cosmology with CMB-S4 workshop (Ann Arbor, 21 and 22 Sept. 2015)
- COrE++ meeting in preparation for the M5 call (Paris, 28 and 29 Sept. 2015)
- Conseil scientifique de l'IN2P3 (22 oct. 2015)
- …

Where are we ?

plot adapted from J. Carlstrom's P5 talk



noise
50 uK. arcmin
(ΔP Planck)

Lensing of EE

Inflationary
Gravitational
Waves

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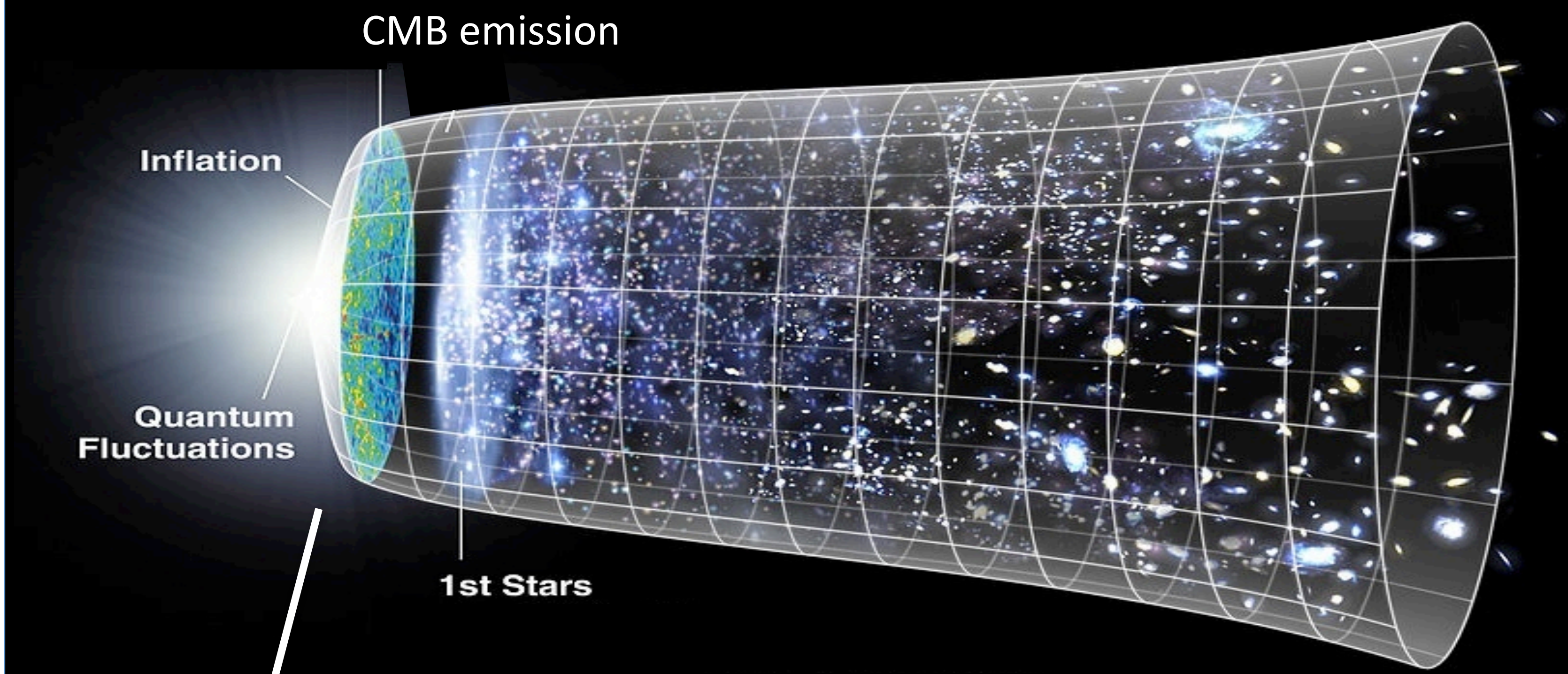
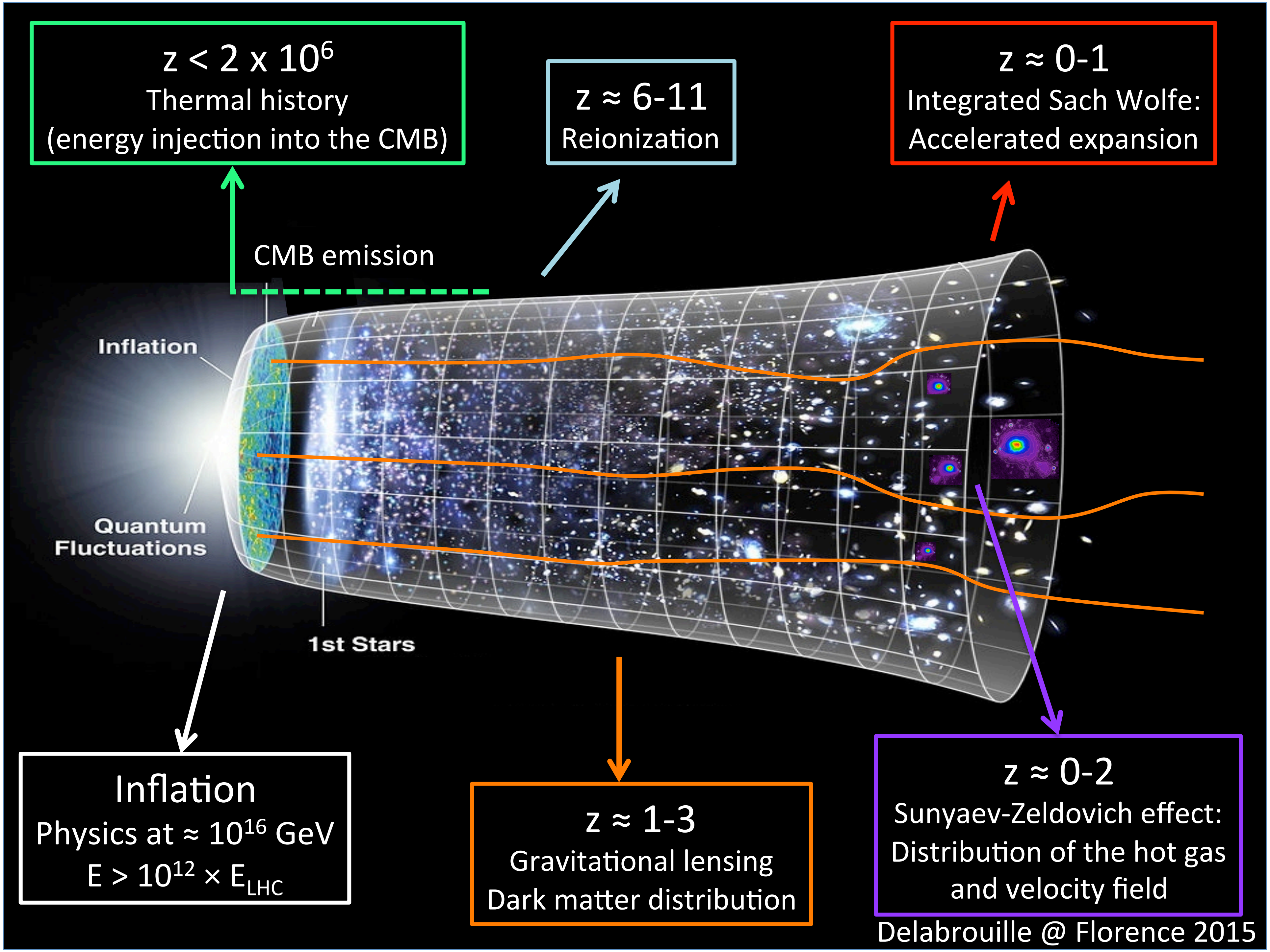
What is left to be done ?



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

Extremely important and fundamental !



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

- Inflation – *of course, but also…*
- A census of mass (CMB lensing)
- A census of hot gas (thermal SZ)
- The cosmic velocity field (kinetic SZ)
- Cosmological parameters
- Detailed validation of the model
- Thermal history
- Surprises

Inflation and CMB lensing → Requires us to resolve the CMB FWHM < 4'

Thermal SZ and kinetic SZ → Requires us to resolve clusters FWHM < 1'

Thermal history → Requires absolute calibration with precision ≈ 10^{-8}

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Parameter extensions ?

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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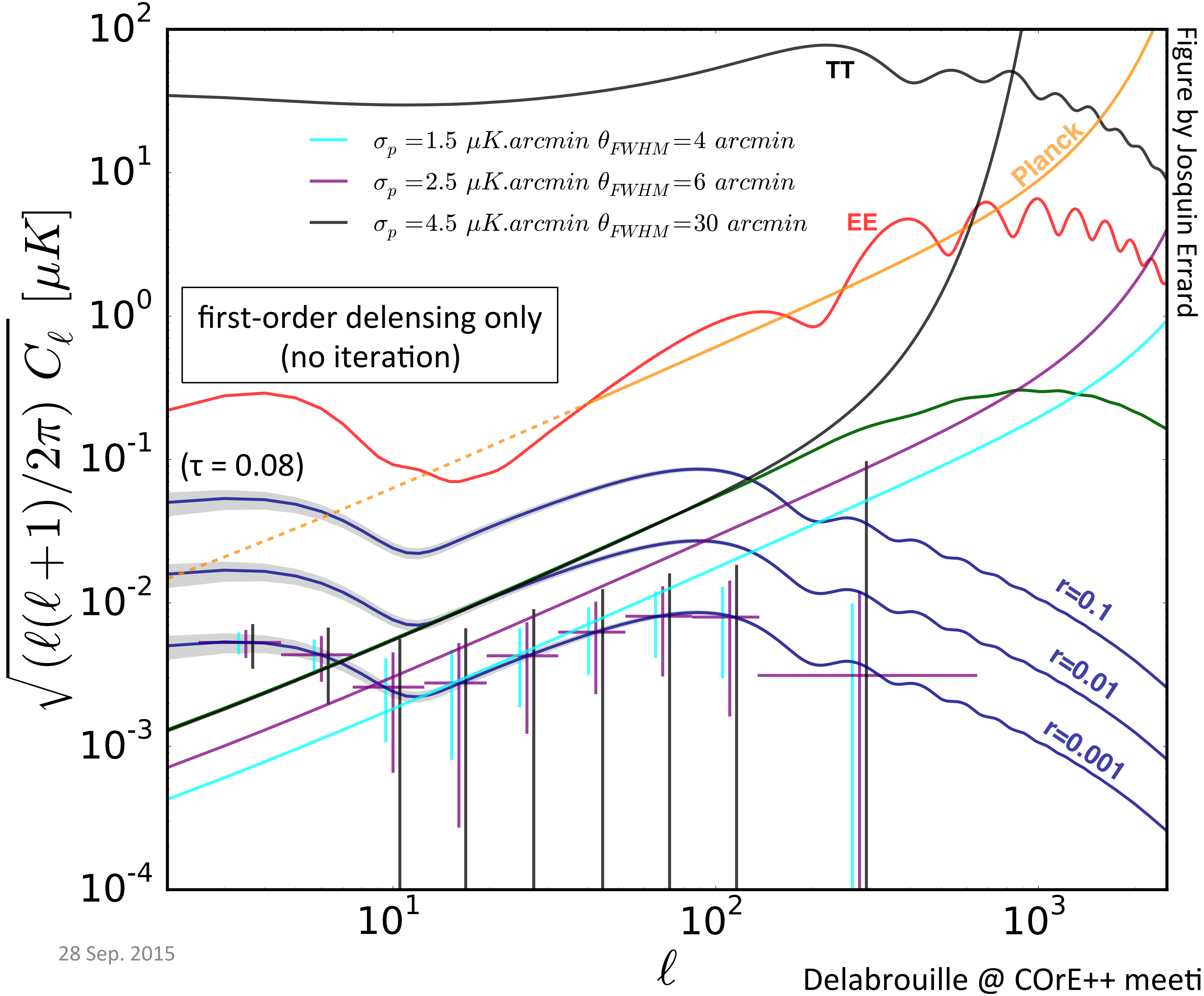
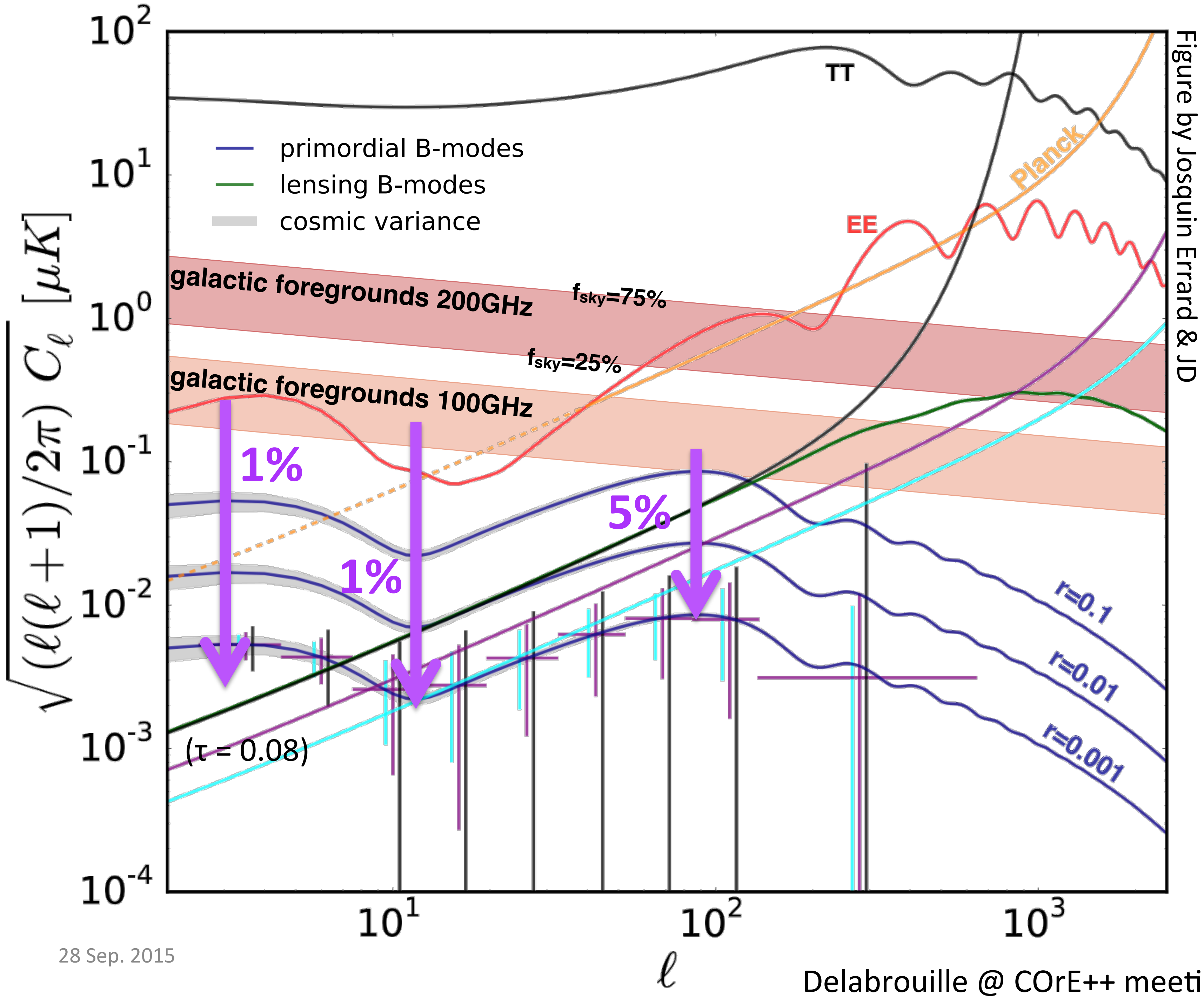
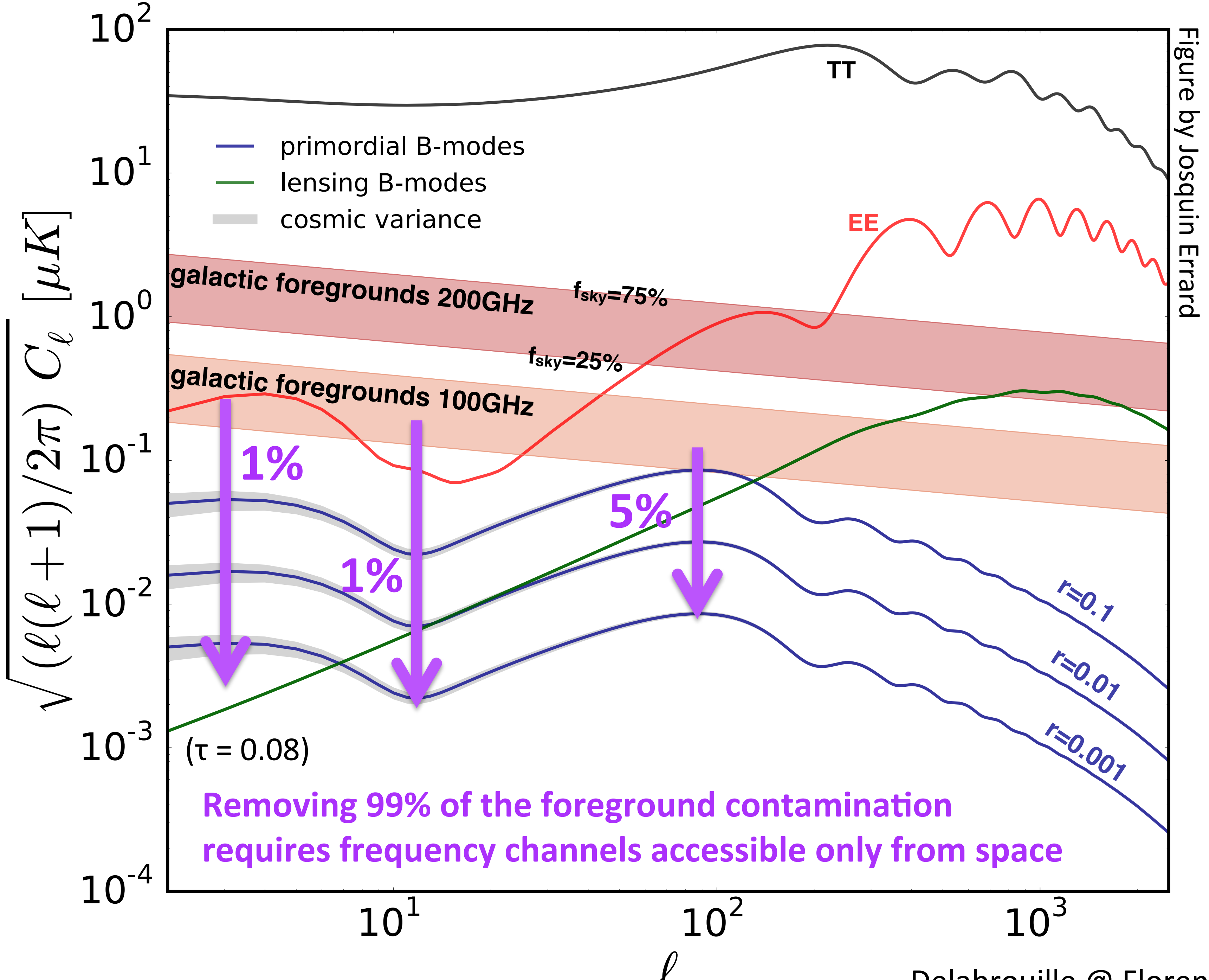
The next space mission can reduce the error box volume
by a factor >10^6
(a factor of ≈5 on each parameter on average)

REQUIREMENT:
measure all spectra with the best accuracy possible



10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3
ℓ
$\sqrt{\ell(\ell+1)/2\pi)\ C_\ell}\ [\mu K]$
$\sigma_p = 1.5\ \mu K.arcmin\ \theta_{FWHM} = 4\ arcmin$
$\sigma_p = 2.5\ \mu K.arcmin\ \theta_{FWHM} = 6\ arcmin$
$\sigma_p = 4.5\ \mu K.arcmin\ \theta_{FWHM} = 30\ arcmin$
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


TT
primordial B-modes
lensing B-modes
cosmic variance
Planck
EE
galactic foregrounds 200GHz
f_{sky}=75%
f_{sky}=25%
galactic foregrounds 100GHz
1%
1%
5%
r=0.1
r=0.01
r=0.001
(τ = 0.08)
Figure by Josquin Errard & JD
$\sqrt{\ell(\ell+1)/2\pi)\ C_\ell}\ [\mu K]$
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{1}
10^{2}
10^{3}
ℓ



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Experiments/Projects

- Current ground Europe : QUBIC and NIKA2 in France, QUIJOTE in Spain
- Balloons Europe : LSPE and Olimpo in Italy
- Balloons US : EBEX, SPIDER, PIPER, BFORE
- Future space : LiteBIRD (Japan & US), CorE++ (Europe), PIXIE (US)
- Future ground US : CMB-S4

Summary

- ## QUBIC is a novel instrumental concept
  - ★ Bolometric Interferometer optimized to handle systematics (**self-calibration**)
    - *Synthesized imager observing a selected range of spatial frequencies that can be* ***accurately*** *calibrated*
  - ★ Dedicated to CMB polarimetry and inflationary physics
  - ★ High sensitivity with ~2000 TES bolometers
  - ★ Dual Band (150 / 220 GHz): Dust contamination control
  - ★ Location: Dome C, Antarctica
  - ★ <u>Target :</u>
    - First module (150 & 220 GHz, 2 yrs): r < 0.04 at 95% C.L. (incl. dust + eff.)
    - Six modules (90, 150, 220 GHz) : r ~ 0.002 at 95% C.L.
- ## Current difficulties
  - ★ Installation at Concordia appears more difficult than expected
    - *Exploring another possible site on the Argentinian side of the Atacama Plateau*
  - ★ Budget is not fully secured (detection chain, mount)
    - *New partners are welcome!*

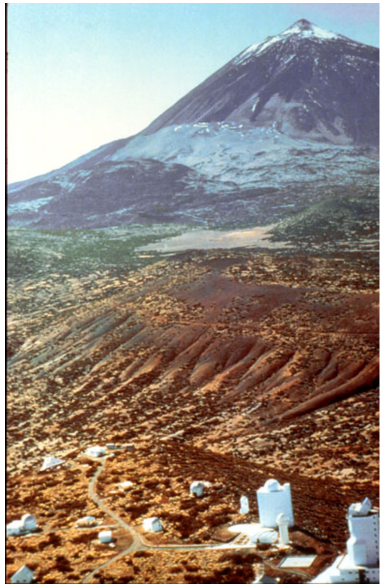
NIKA2 scientific objectifs

- **Resident multipurpose** instrument at the IRAM 30 m telescope

\+

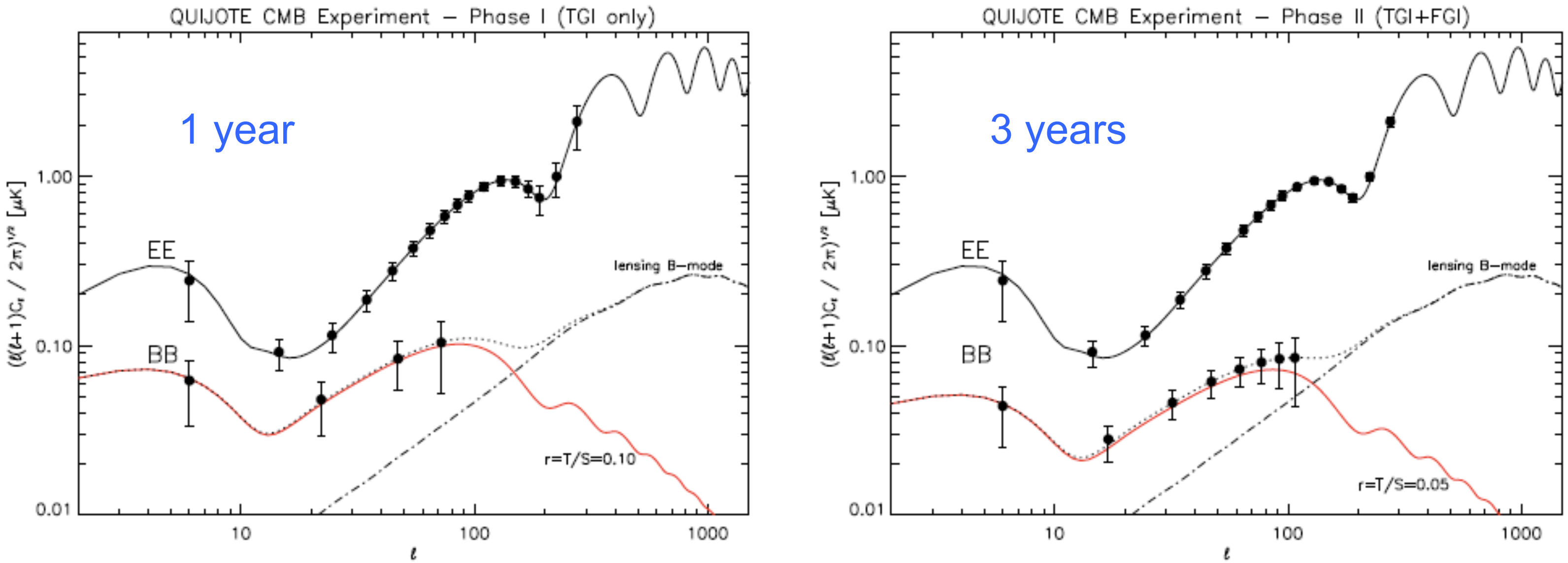
- **NIKA2 Large programs**:
  - ***thermal Sunyaev-Zeldovich (SZ)*** effect on high redshift clusters
  - deep cosmological survey
  - early stage of star formation in the galaxy
  - study of nearby galaxies
  - polarisation

QUIJOTE: Project baseline



- **Site**: Teide Observatory (altitude 2400 m, 28.3º N, 16.5 W)
- **Frequencies**: 11, 13, 17, 19, 30 and 42 GHz.
- **Angular resolution**: 0.92º to 0.26º
- **Sky coverage**: -32º < Dec. < 88º (fsky=0.65).
- **Telescopes and instruments: two phases, fully funded.**
  - **Phase I.**
    - First telescope (QT1). In operation since Nov 2012.
    - Multi-Frequency Instrument (MFI) with 4 polarimeters at 10-20 GHz. In operation (Nov12)
    - Second Instrument (TGI) with 31 polarimeters @ 30 GHz. Starting fall 2015.
  - **Phase II.**
    - Second telescope (QT2). Installed since July 2014.
    - Third instrument (FGI) at 42 GHz (31 polarimeters). Late 2015/2016.
- **Technology:** Coherent detectors.
- **Polarization detection**: modulation (mechanical for MFI; phase switches for TGI and FGI).
- **Observing strategy**: Deep observations in selected areas using raster scans, plus wide survey using "nominal mode".
- **Scientific operation plan**: 2012-2020.

Science with QUIJOTE second (TGI) and third (FGI) instruments



Left: Example of the QUIJOTE scientific goal after the Phase I: <u>1 year (effective)</u> observing time, and a sky coverage of 3,000 deg^2. The red line corresponds to r = 0.1.

Right: QUIJOTE Phase II. Here we consider <u>3 years of effective operations</u> with the TGI, and that during the last 2 years, the FGI will be also operative. The red line now corresponds to r = 0.05.

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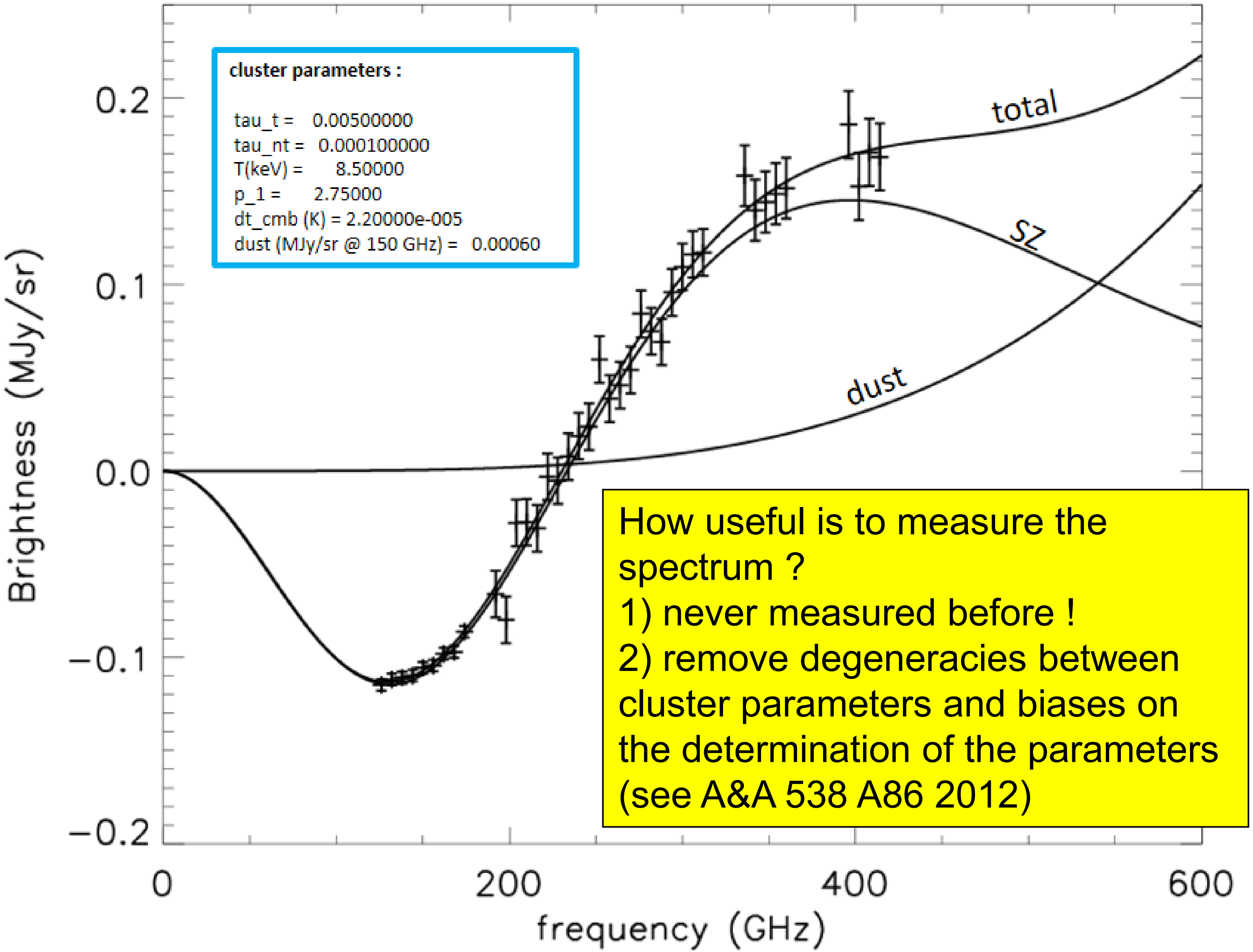
LSPE in a nutshell

- The Large-Scale Polarization Explorer is :
  - an instrument to measure the polarization of the CMB at large angular scales
  - using a spinning stratospheric balloon payload
  - flying long-duration (> 10 days), in the polar night
- Frequency coverage: 40 – 250 GHz (2 instruments: STRIP & SWIPE)
- Angular resolution: 1.4° FWHM
- Sky coverage: 20-25% of the sky per flight
- Use a polarization modulator or OMT to achieve high stability
- Combined sensitivity: 10 μK/arcmin per flight
- See arXiv:1208.0298, 1208.0281, 1208.0164
- Current collaboration: Italian Universities, INAF, INFN + UK



How useful is to measure the spectrum ?
1) never measured before !
2) remove degeneracies between cluster parameters and biases on the determination of the parameters (see A&A 538 A86 2012)

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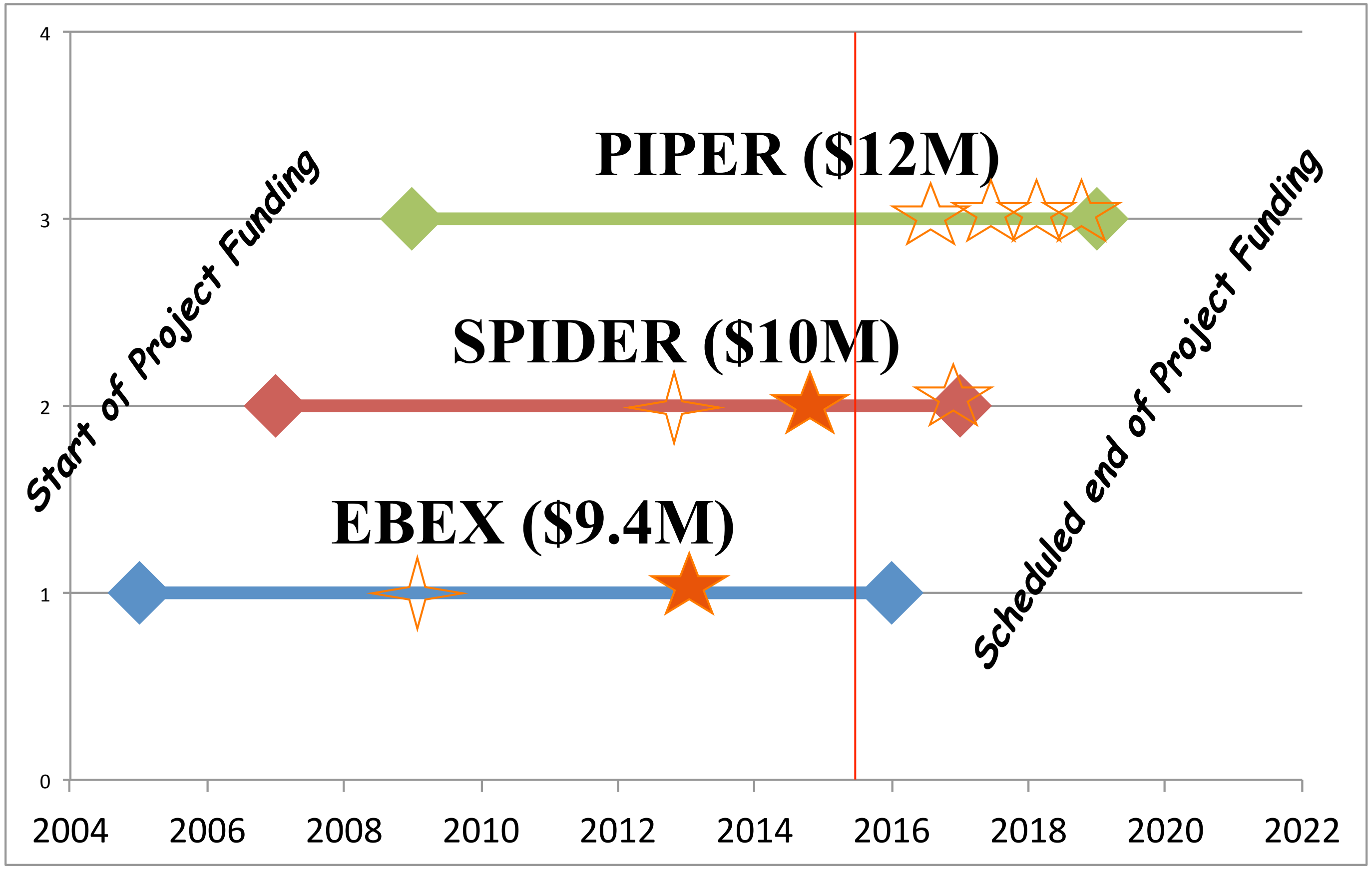
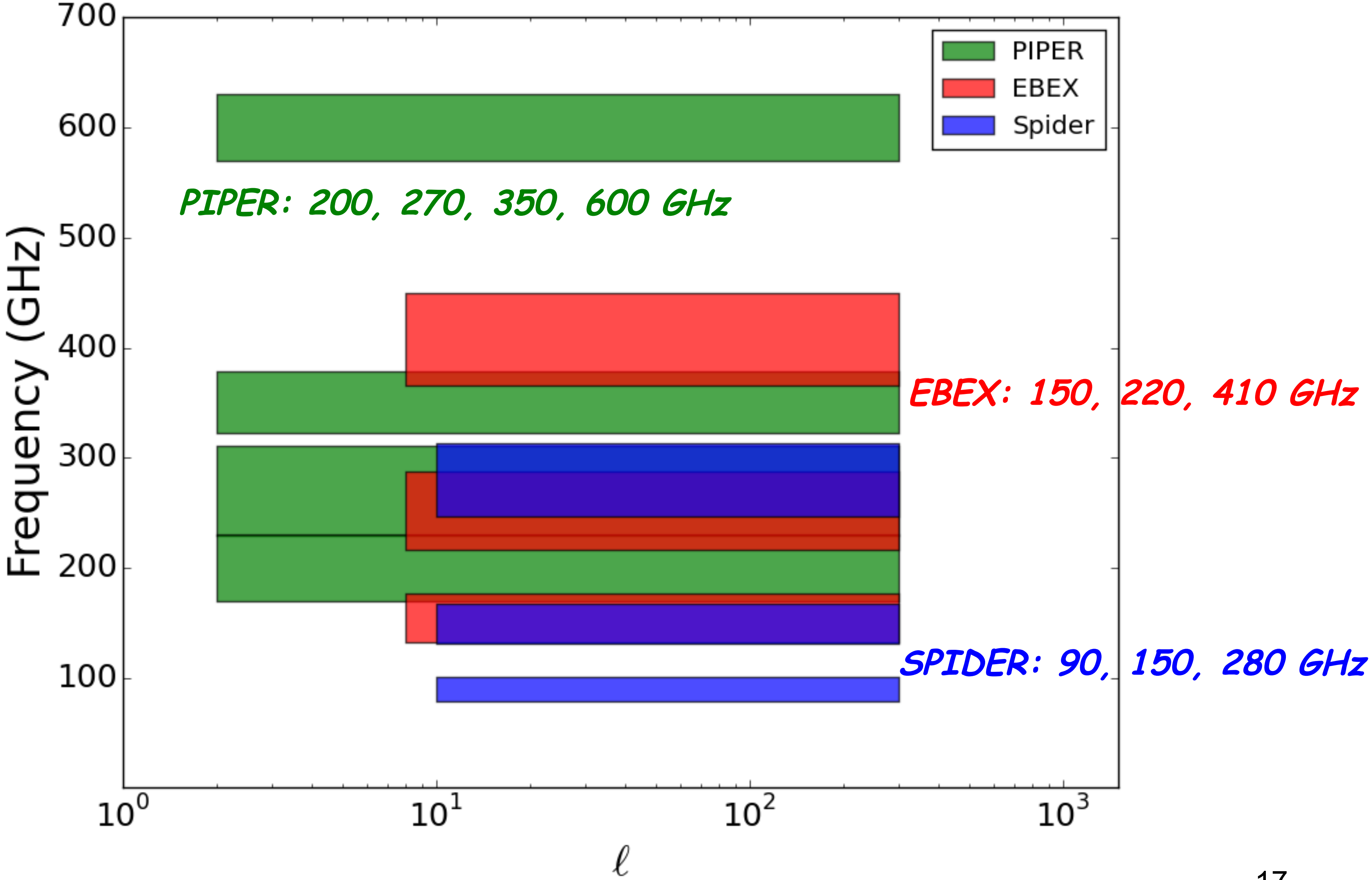
Currently Funded CMB - Timelines

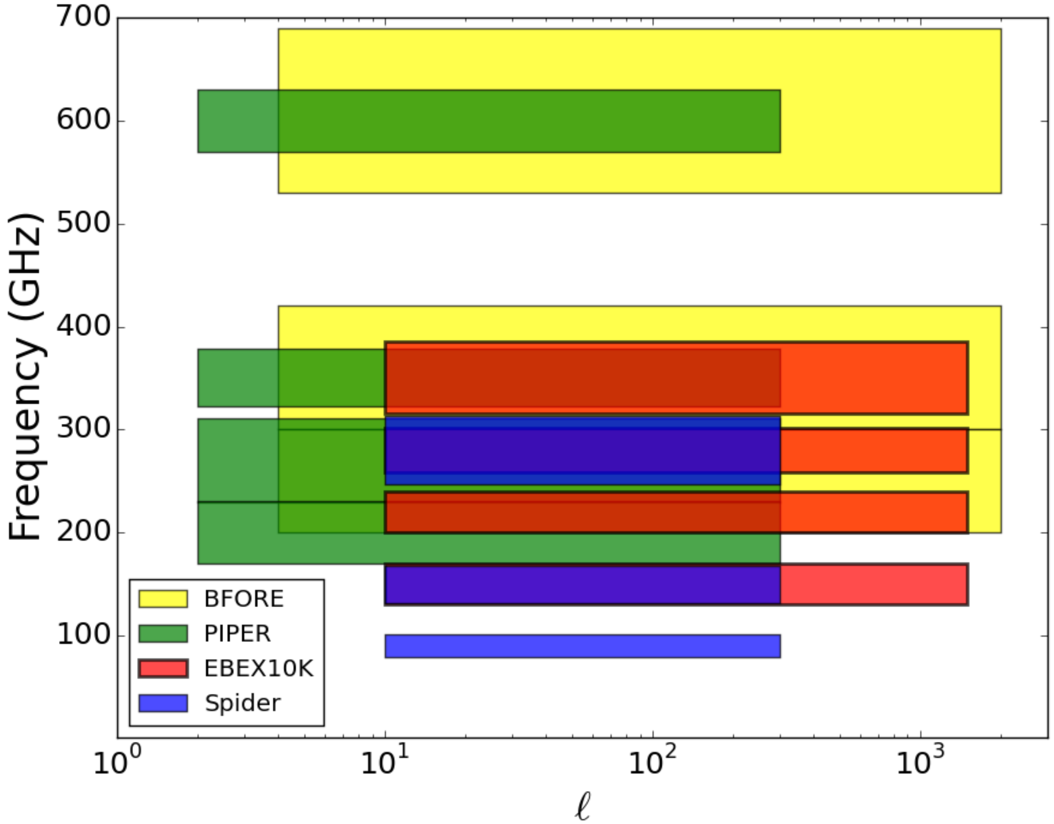


- ~$1M/year/project; ~8 years to first dataset
- Compared to 20 years ago, complexity has increased (much) more than funding
- MO: $35M/7 years; Partner Mission: $65M; SMEX: $100M; EX: $230M; Probe: $1B; (Large>$1B)

Frequency and \ell coverage



EBEX10K and BFORE



EBEX10K / BFORE

Both probing high freq.
(4 bands / 3 bands)

Both extending coverage to high ell

Both complementing ground measurements

Both achieving >x5 deeper than Planck on dust

Both using latest focal plane tech. with ~11,000 detectors

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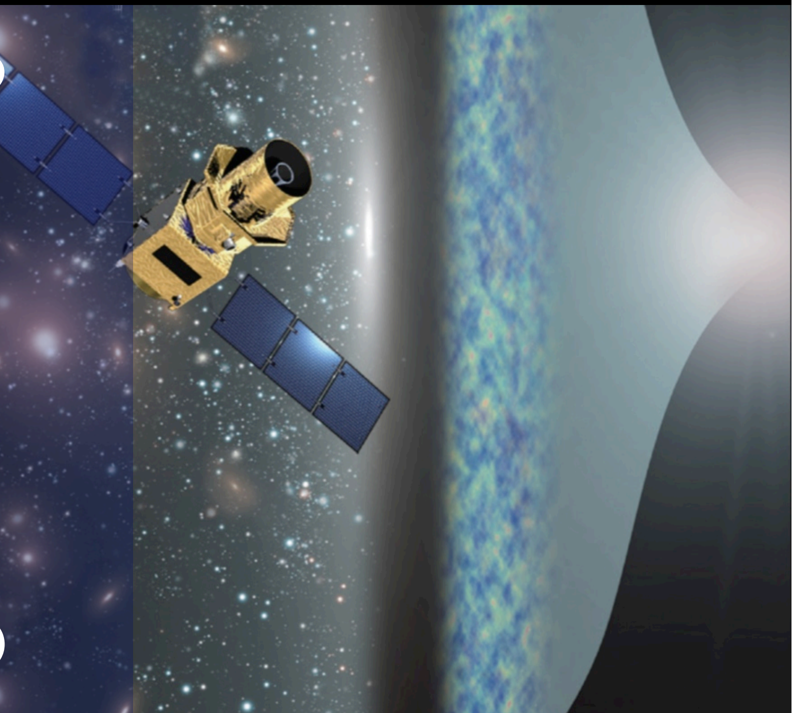
LiteBIRD Overview

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

- CMB B-mode satellite proposed to JAXA and NASA
- Proposed launch year: JFY 2022
- Success criteria
  - Total uncertainty on r: $\sigma(r) < 0.001$*
  - Multipole coverage: $2 \le \ell \le 200$
    - Each bump (reionization, recombination) with >5sigma if r > 0.01
- Orbit: L2
- Observing time: ≥3 years



*Our current studies yield $\sigma(r) = 2 \times 10^{-4}$ for 3 year observation

COrE+ concept and strategy

*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 1.5m 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	from ≈ 2500 (base) to 5000 (extension) 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)

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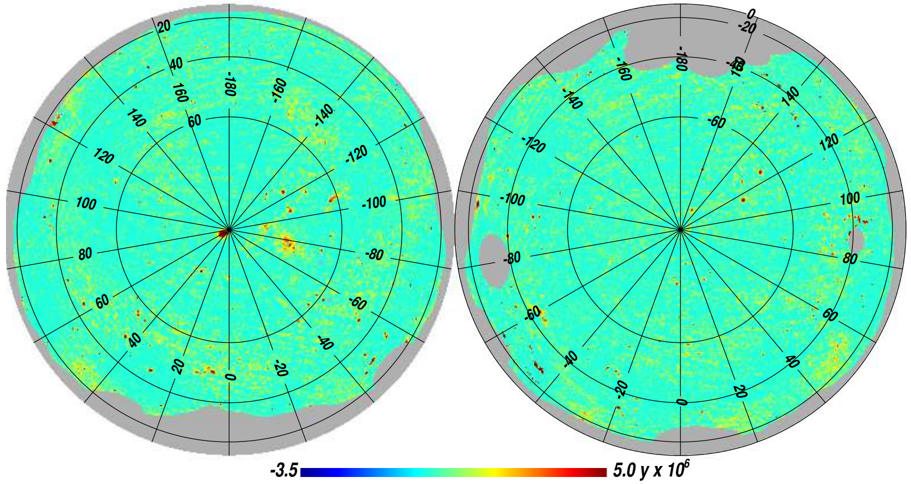
Spectral Distortions: Structure Formation



Planck measures thermal SZ effect

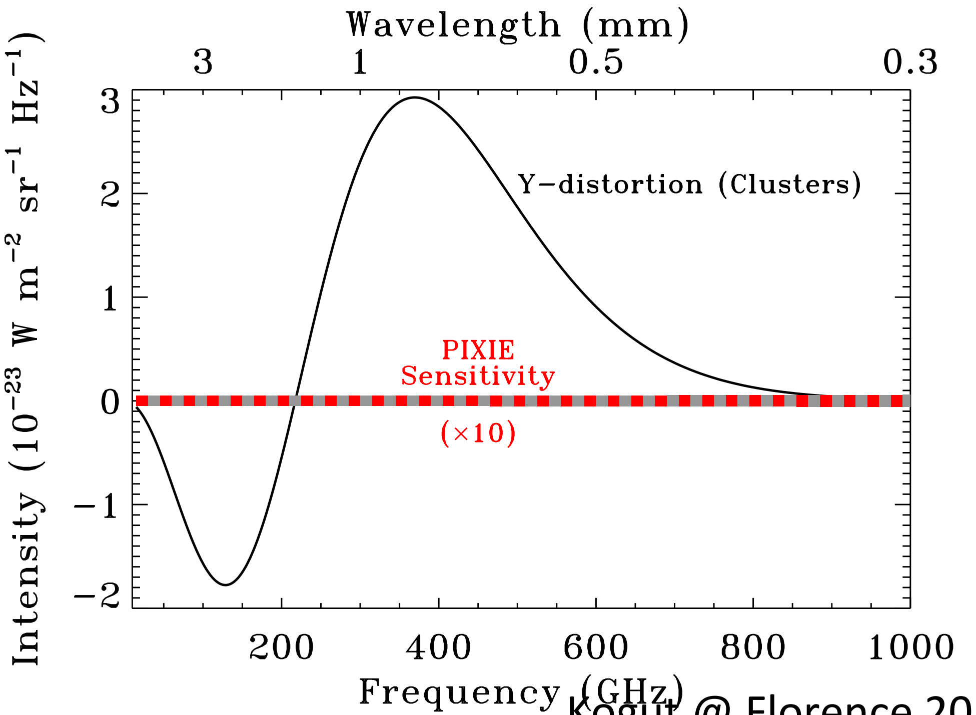
Monopole floor: y > 5.4 x 10^{-8}
PIXIE 50-sigma detection

Contribution from unresolved sources

Total monopole: y = 1.6 x 10^{-6}
PIXIE 1500-sigma detection

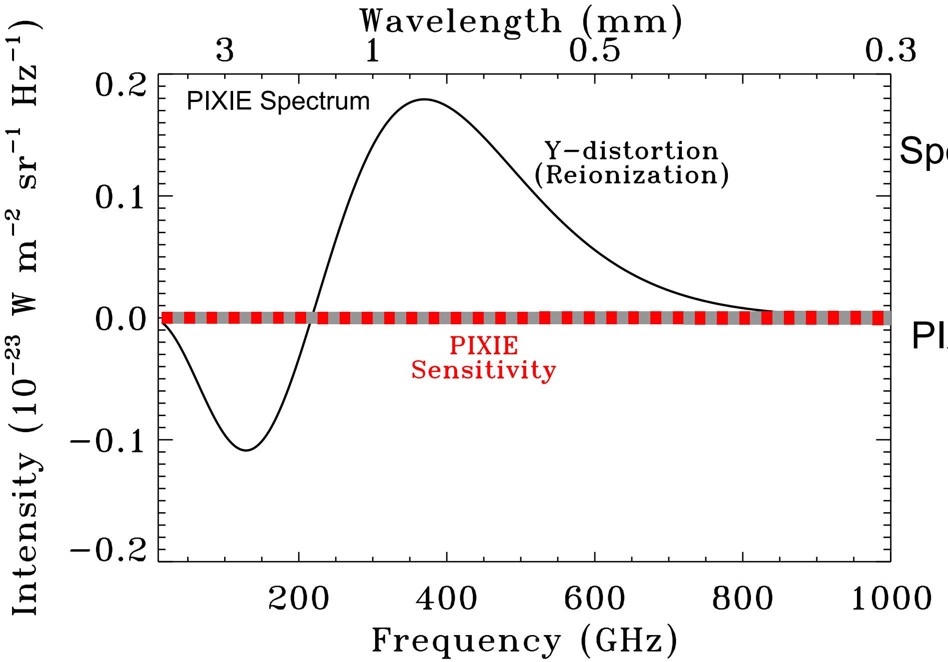
- *Dipole: Compare to CMB at z=1000*
  Gravitational accelerations

- *Cross-correlate vs redshift surveys*
  Growth of structure



Planck 2015 XXII, arXiv:1502.01596
Khatri & Sunyaev 2015, arXiv:1505.00781
Hill et al. 2015, PRL, in prep

Spectral Distortions: Reionization



Spectrum: y distortion ~ Electron pressure $\int nkT_e$

- PIXIE limit $y < 5 \times 10^{-9}$
- Signal $y \sim 10^{-7}$

PIXIE 95-sigma detection (but buried under IGM)

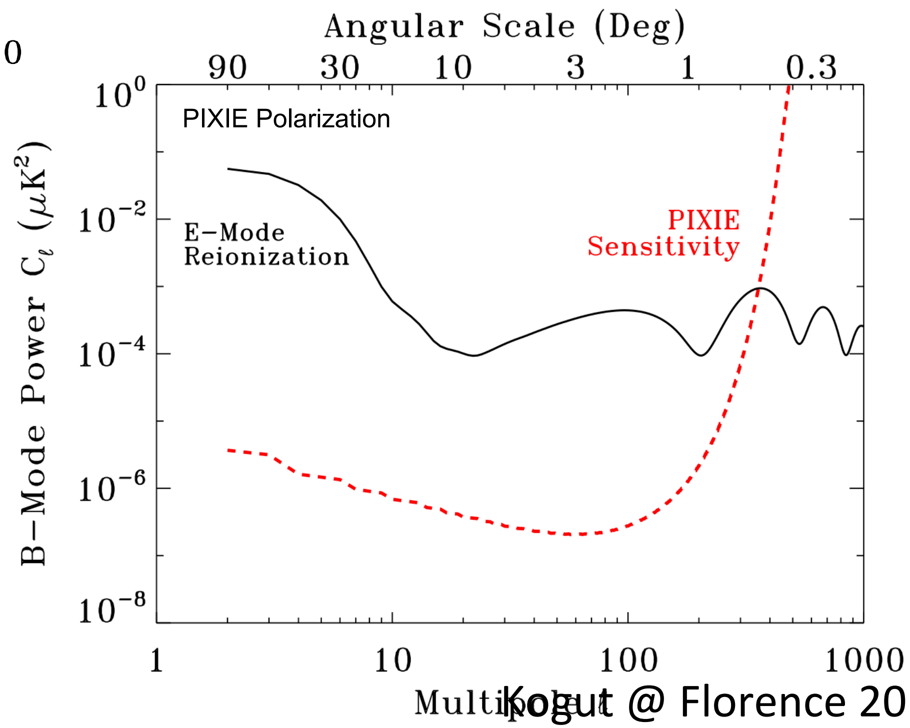
E-mode optical depth ~ Electron density n

Same scattering for both signals

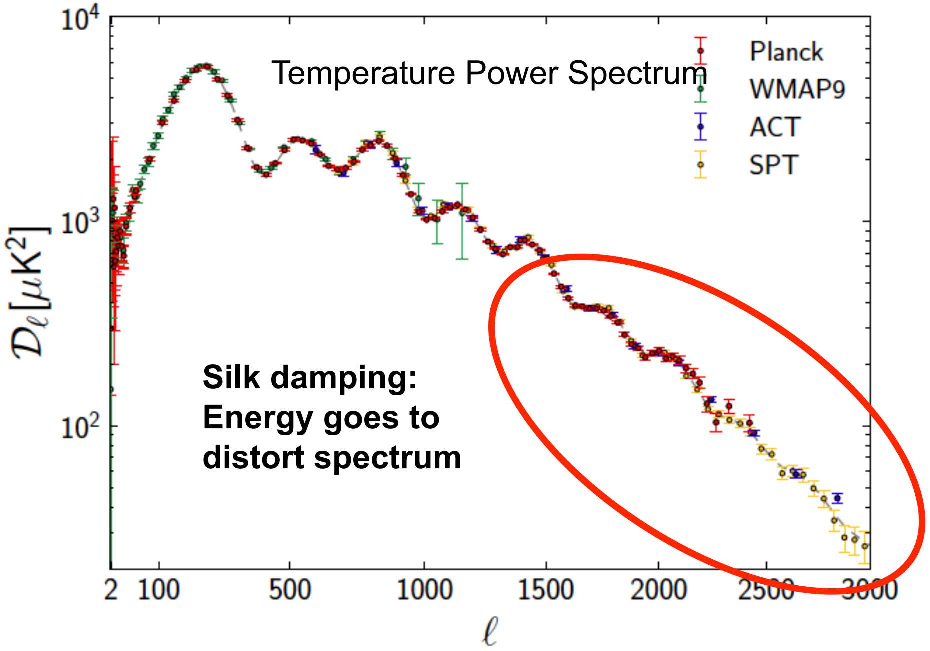
Combine to get n and T_e

- T_e probes ionizing spectrum
- Distinguish Pop III, Pop II, AGN

Determine nature of first luminous objects



Spectral Distortions: Inflation



Silk damping of primordial perturbations

- Scalar index n_s and running $d\ln n_s/d\ln k$
- Non-Gaussian f_{NL}
- Physical scale ~1 kpc ($1M_\odot$)

Spectral distortions extend tests of inflation by 4 orders of magnitude in physical scale

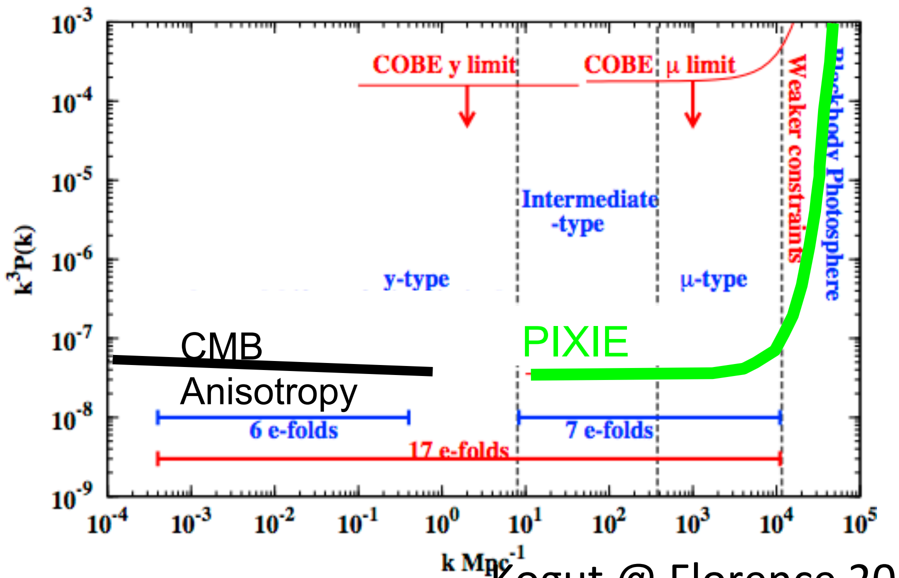
Daly 1991
Hu, Scott, & Silk 1994
Chluba, Erickcek, & Ben-Dayan 2012

Energy release at $10^4 < z < 10^6$

Chemical potential $\mu = 1.4 \frac{\Delta E}{E}$

PIXIE limit $\mu < 10^{-8}$

~3 sigma detection, depending on ops



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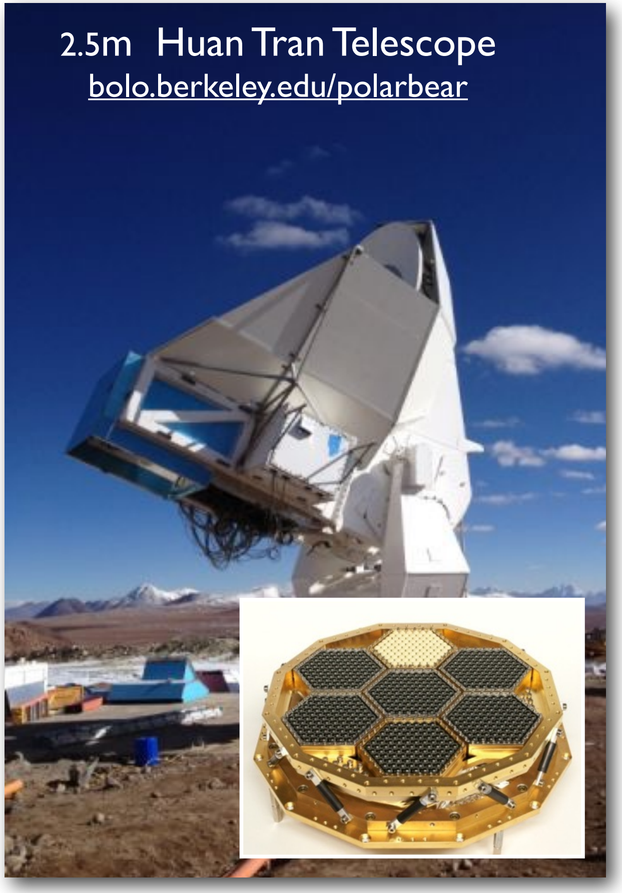
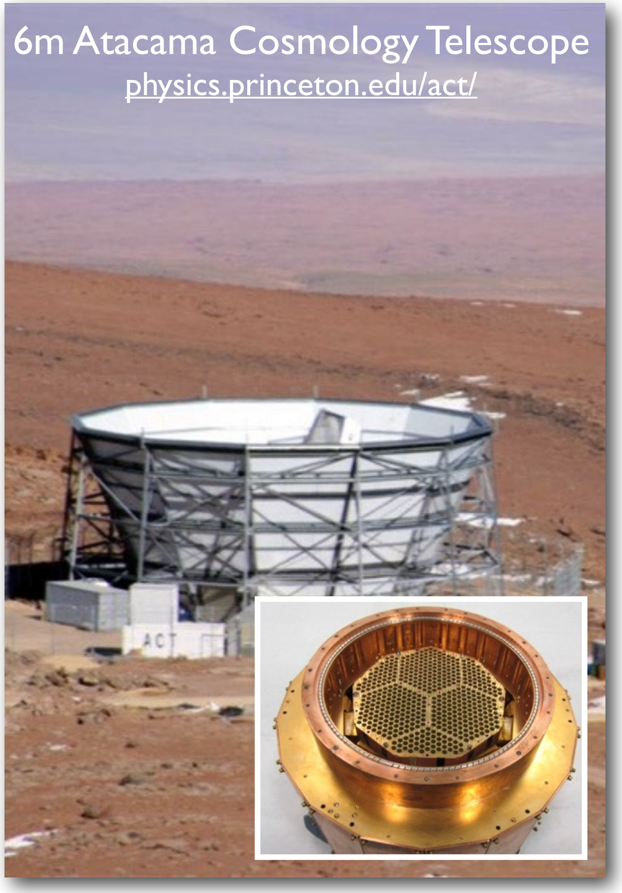
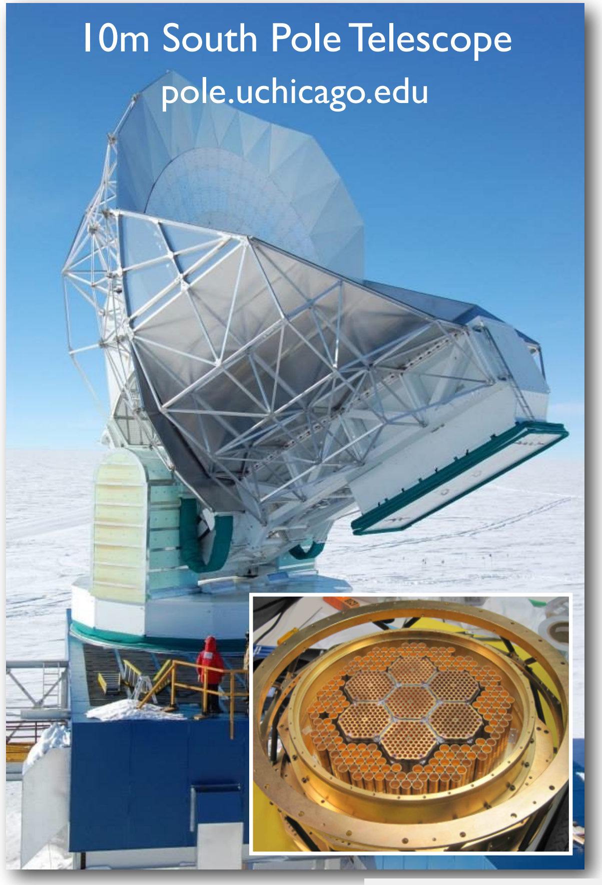
Current generation of large aperture CMB telescopes







Exceptional high and dry sites for dedicated CMB observations.
Exploiting and driving ongoing revolution in low-noise bolometer cameras

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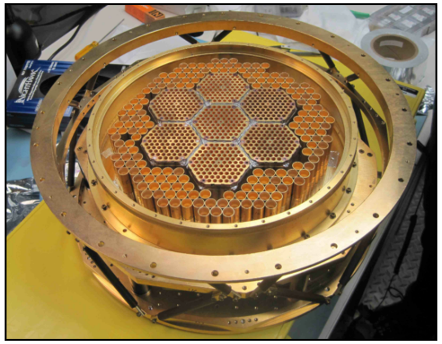
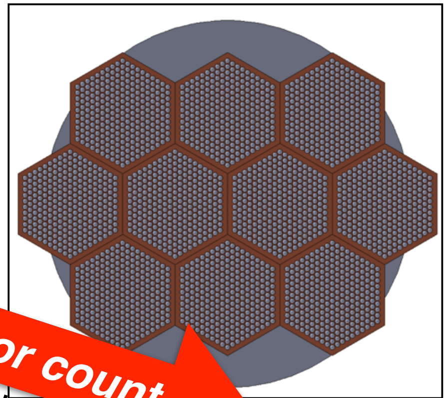
Maintaining Moore's Law: focal planes are saturated so must use parallel processing and multiple telescopes.

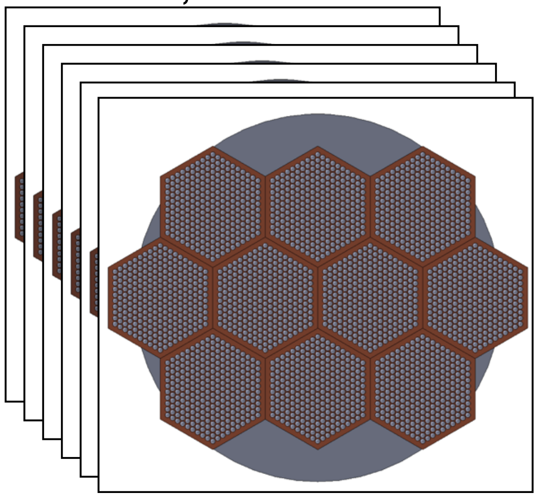
Stage II
Now
~1000 detectors



Stage III
ramping up
~10,000 detectors



Stage IV
~2020 - CMB-S4
~500,000 detectors



increasing detector count
(the trend being followed by all CMB projects, not just SPT)

CMB-S4: A coordinated community wide program to put order 500,000 detectors spanning 30 - 300 GHz using multiple telescopes and sites to map ≳70% of sky.

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Stage IV experiment: CMB-S4

CMB-S4: a ground-based program working with, and building on, CMB stage II & III projects.

Participation includes, ***but is not limited to:***

- the ACT, BICEP/KECK, CLASS, POLARBEAR, SPT, … CMB Stage II & III teams and their international partners.
- Argonne, FNAL, LBNL, SLAC, NIST U.S. national labs and the high energy physics community.

International partnerships encouraged.

Strive to be complementary with balloon and space-based instruments.

Nominal CMB-S4 specifications

- **Survey:**

  - Inflation, Neutrino, and Dark Energy science requires an optimized survey which includes a range of resolution and sky coverage from deep to wide

- **Sensitivity:**

  - 1 uK-arcm over ≳70% of the sky

- **Configuration:**

  - O(500,000) detectors on multiple telescopes (small and large aperture)
  - spanning 30 - 300 GHz for foreground removal (split atmospheric bands?)
  - ≲ **3 arcmin resolution** required for CMB lensing & neutrino science
  - ***higher resolution leads to amazing and complementary dark energy constraints, gravity tests on large scales via the SZ effects, and mapping the universe in momentum.***

CMB polarization timeline

- 2013: Stage II experiments detect lensing B-modes (SPTpol)
- now: $r \lesssim 0.12$ from B-modes (BICEP2/KECK with *Planck*)
- 2013-2016: Stage II experiments
  $\sigma(r)$~0.03, $\sigma(N_{eff})$~0.1, $\sigma(\Sigma m_\nu)$~0.1eV
- 2016-2020: Stage III experiments
  $\sigma(r)$~0.01, $\sigma(N_{eff})$~0.06, $\sigma(\Sigma m_\nu)$~0.06eV*

- 2020-2025: Stage IV experiment, **CMB-S4**
  $\sigma(r) \lesssim 0.001$, $\sigma(N_{eff}) = 0.020$, $\sigma(\Sigma m_\nu)$ =16 meV*
  each crosses a critical threshold

* includes BOSS prior
* includes DESI prior

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Summary

Legacy value & discovery potential

COrE+:

- 21 channels with angular resolution ranging from 1' to 14', 700 million data samples
- x 30 sensitivity improvement in 15 years

Litebird (baseline):

- 6 channels with angular resolution ranging from 16' to 75', 1.4 million data samples
- x 15 sensitivity improvement in 10 years

PIXIE:

- 400 channels with fixed angular resolution of 2.5°, 3.4 million data samples
- x 1000 sensitivity improvement (for absolute spectrum) in 10 years

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CMB-S4:

- 4 main channels with angular resolution 0.8 - 4.4', 50% sky, 250 million data samples
- x 10 sensitivity improvement in 10 years

(Take with a pinch of salt)

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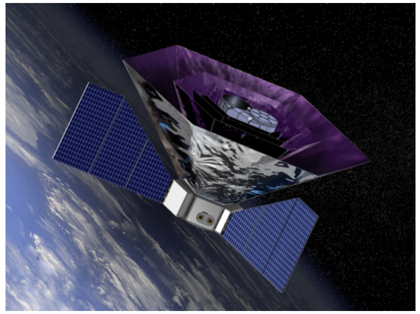
A goal and a strategy for the CMB community

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

High angular resolution

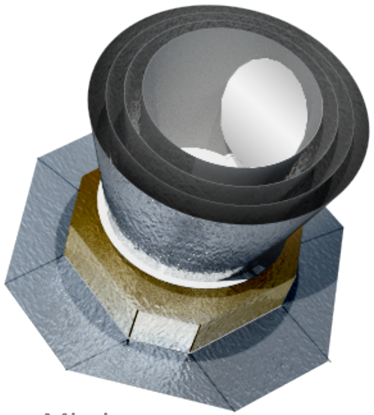


PIXIE (+)
Absolute measurement
1-2° in many bands
Clean large scales

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

Absolute calibration & zero-level of maps

Cosmic Origins Explorer
Space-borne Imager, many frequencies
1-2' at high frequency (ν ≥ 300)
4'-6' at CMB frequencies
Clean large scales



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