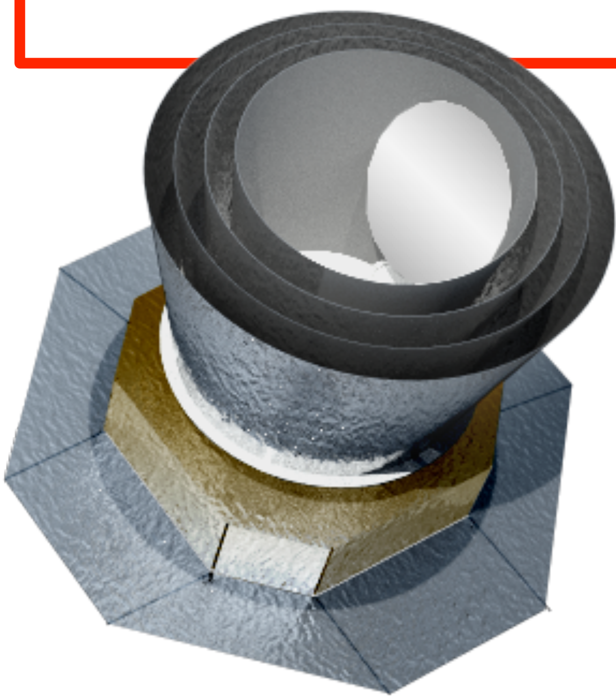
European spaceborne plans



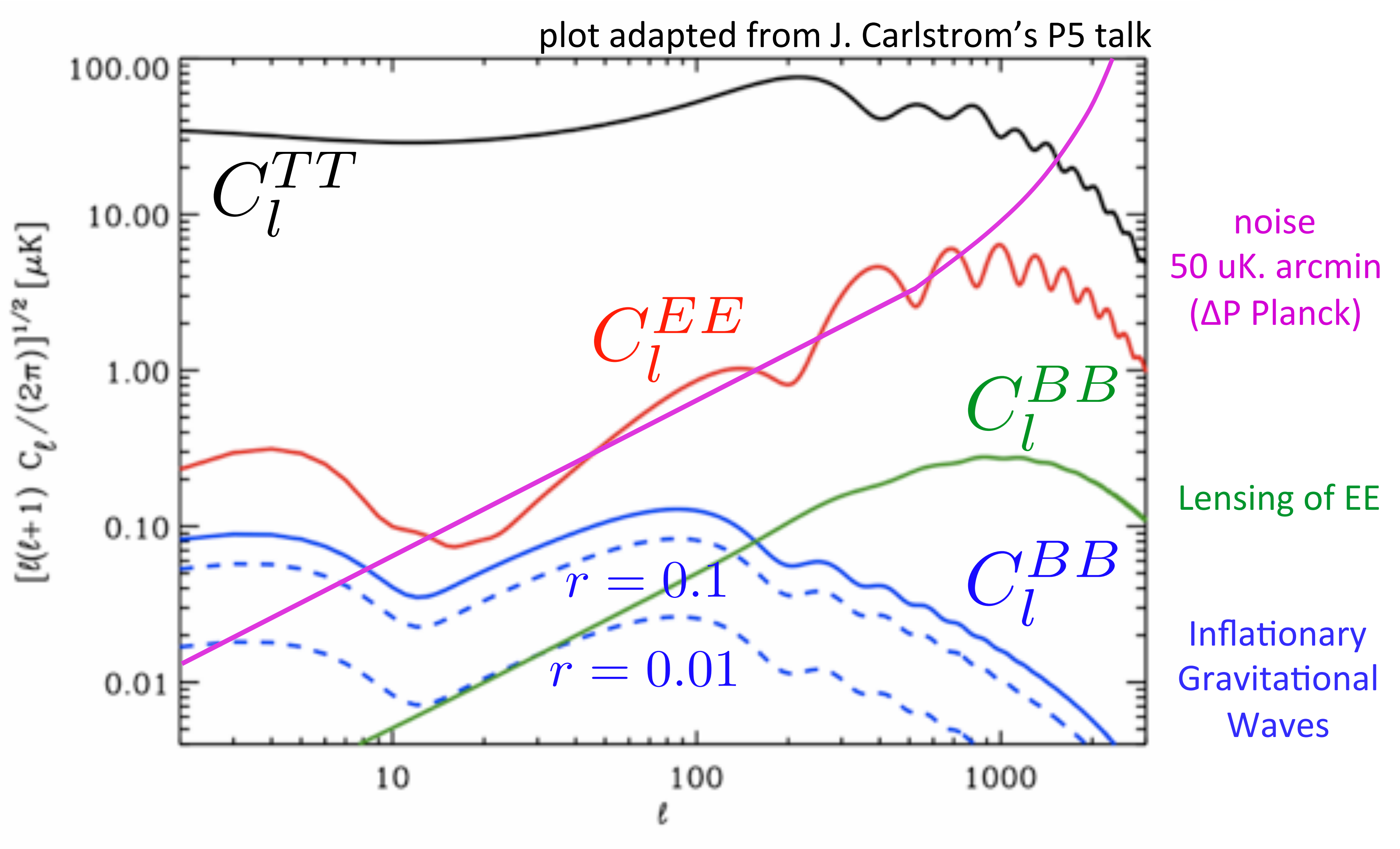
Jacques Delabrouille
Laboratoire APC, Paris, France

For the COrE++ collaboration

Outline

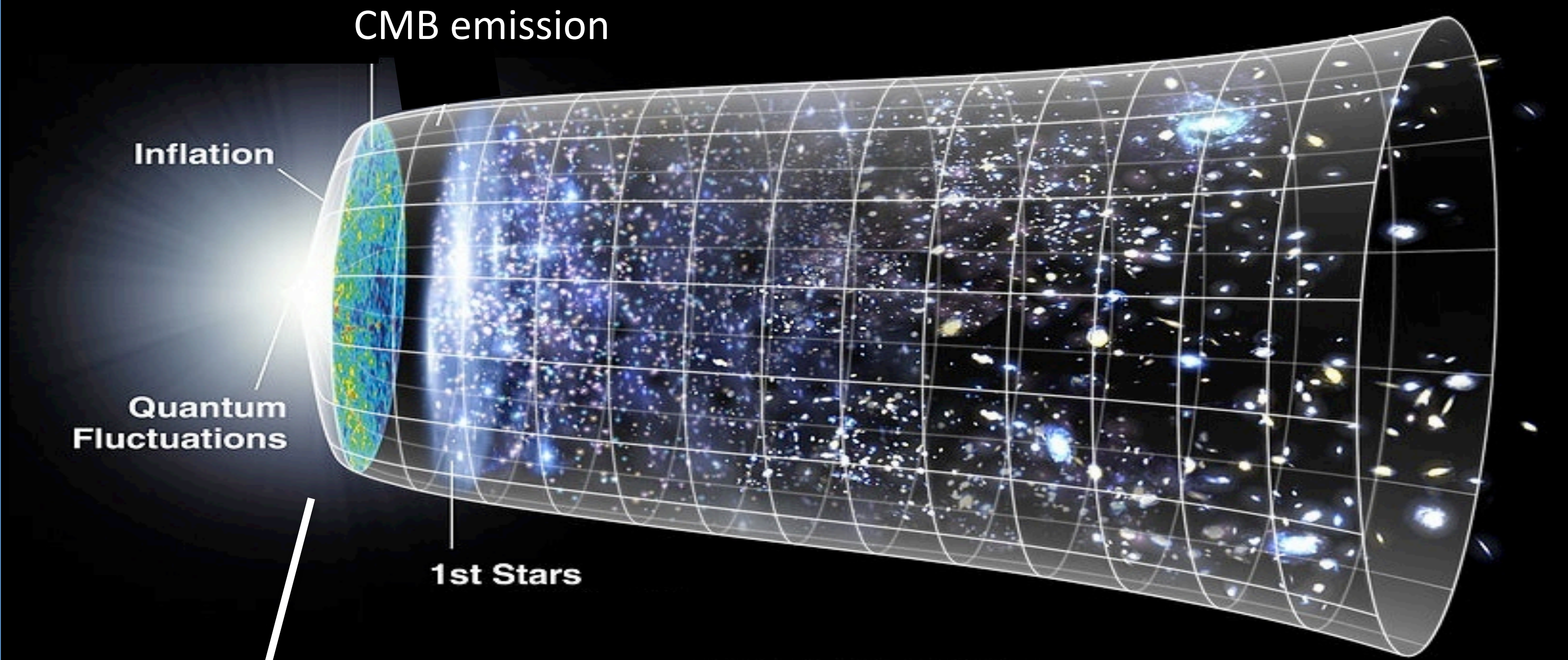
- What CMB science ?
- Why space ?
- What space mission ?
- Strategies and synergies
- Summary

Where are we ?



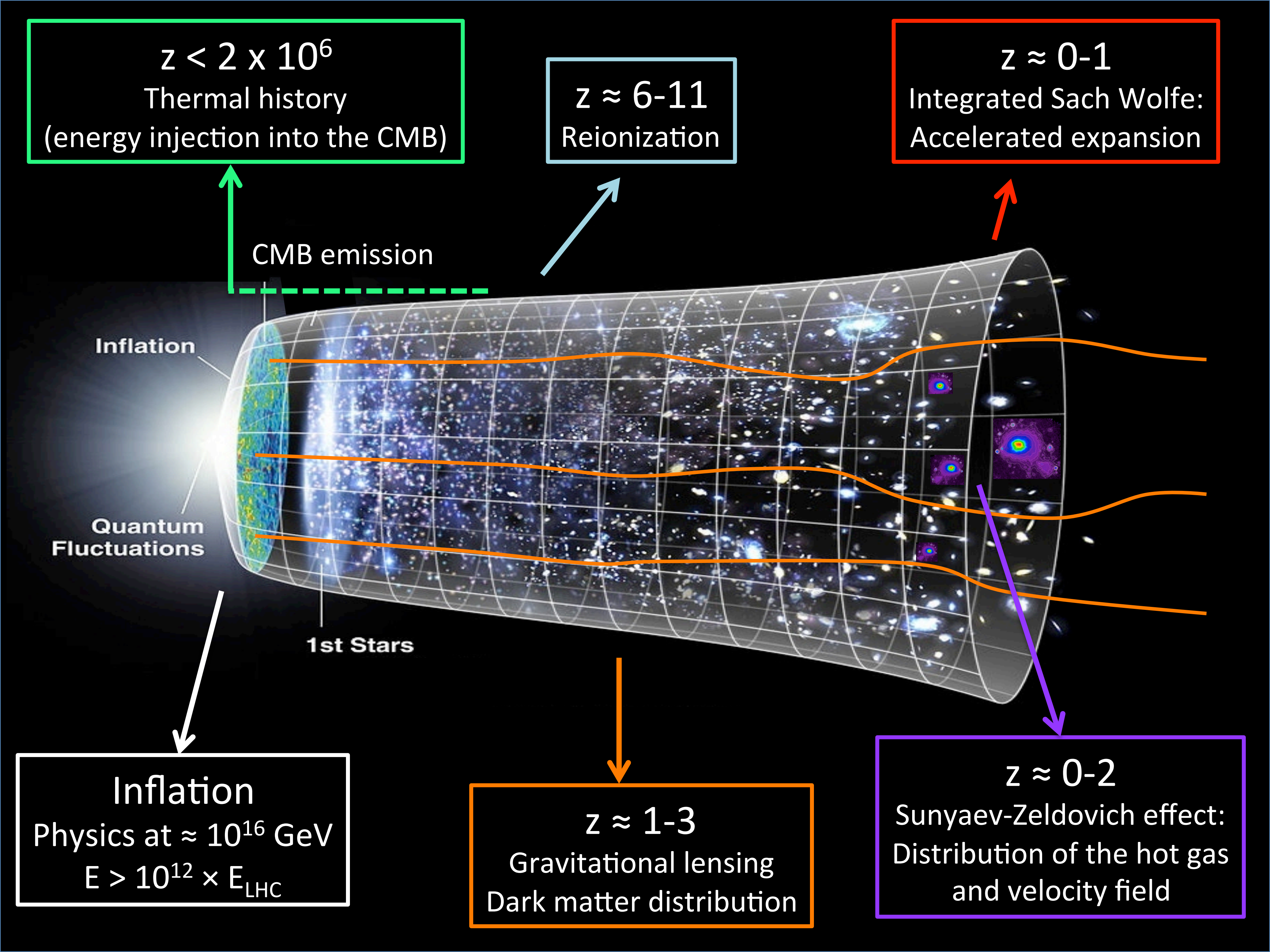
plot adapted from J. Carlstrom's P5 talk
100.00
10.00
1.00
0.10
0.01
[ℓ(ℓ+1) C_ℓ/(2π)]^{1/2} [μK]
10
100
1000
ℓ
C_l^{TT}
C_l^{EE}
C_l^{BB}
C_l^{BB}
$r = 0.1$
$r = 0.01$
noise
50 uK. arcmin
(ΔP Planck)
Lensing of EE
Inflationary
Gravitational
Waves

What is left to be done ?



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

Extremely important and fundamental !



z < 2 x 10^6
Thermal history
(energy injection into the CMB)
z ≈ 6-11
Reionization
z ≈ 0-1
Integrated Sach Wolfe:
Accelerated expansion
CMB emission
Inflation
Quantum
Fluctuations
1st Stars
Inflation
Physics at ≈ 10^16 GeV
E > 10^12 × E_LHC
z ≈ 1-3
Gravitational lensing
Dark matter distribution
z ≈ 0-2
Sunyaev-Zeldovich effect:
Distribution of the hot gas
and velocity field

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; A census of mass) → Requires us to resolve the CMB FWHM < 4'

(A census of hot gas; The cosmic velocity field) → Requires us to resolve clusters FWHM < 1'

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

CMB science

- Inflation – *of course, but also…*
- A census of mass (CMB lensing)

→ Requires us to resolve the CMB FWHM < 4'

- A census of hot gas (thermal SZ)
- The cosmic velocity field (kinetic SZ)

→ Requires us to resolve clusters FWHM < 1'

- Cosmological parameters
- Detailed validation of the model
- Thermal history → Requires absolute calibration with precision ≈ 10^{-8}
- Surprises

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

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

Helium abundance

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

Parameter extensions ?

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Helium abundance

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

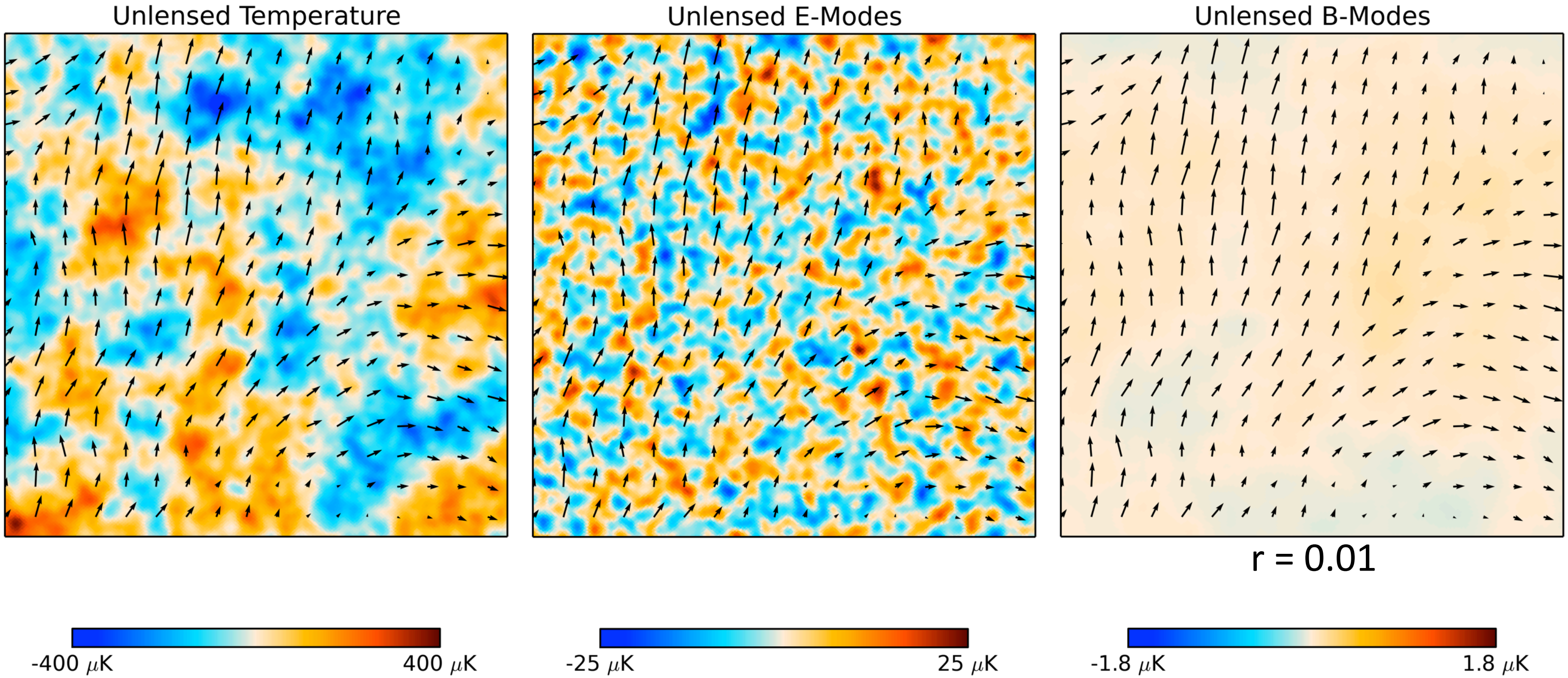
The next space mission can reduce the error box volume

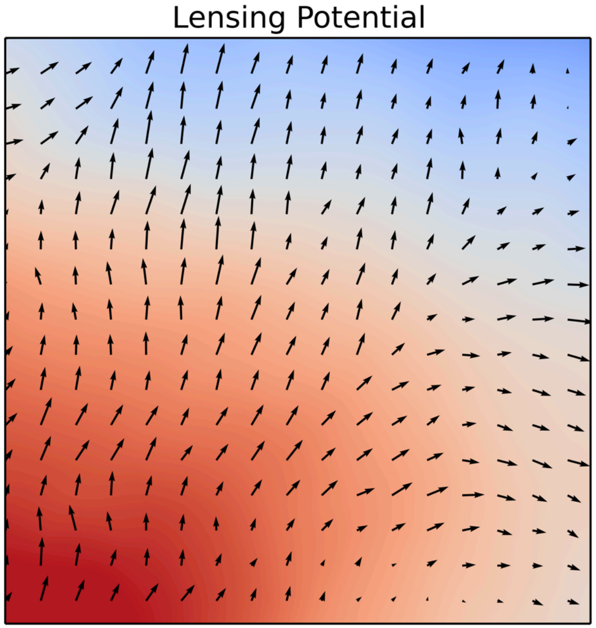
by a factor >10^6

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

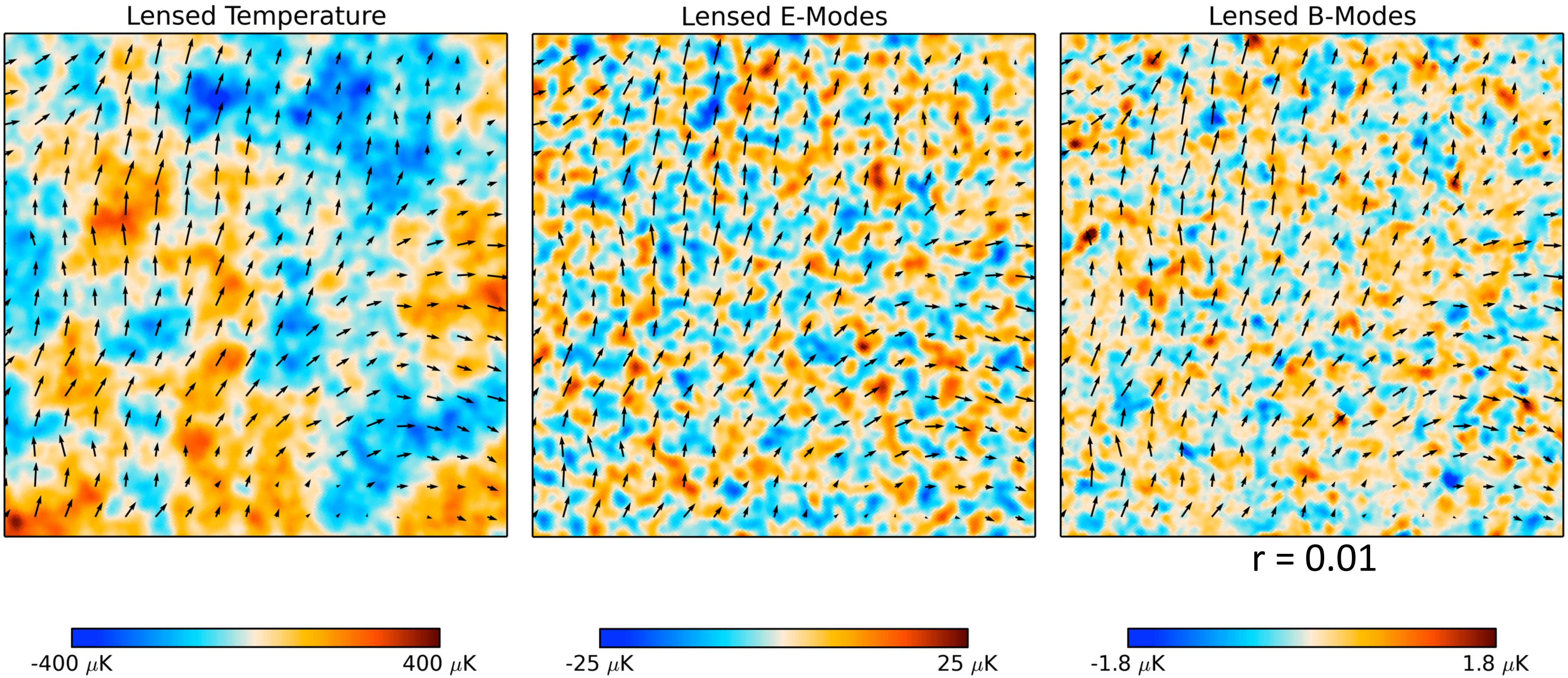
REQUIREMENT:

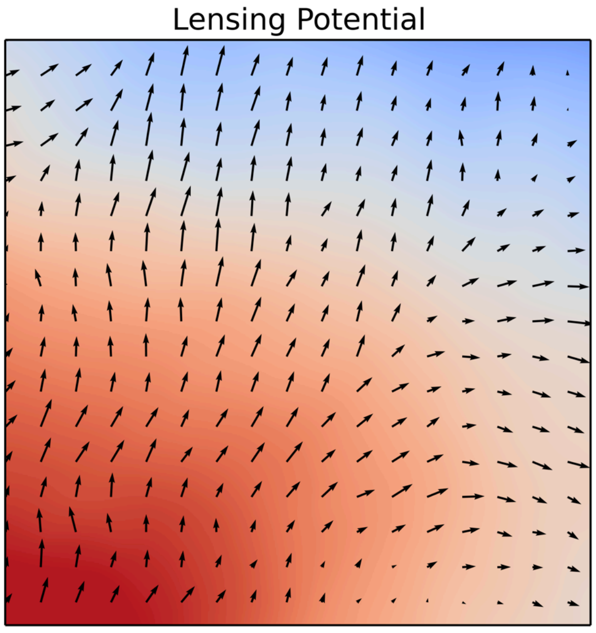
measure all spectra with the best possible accuracy





Gravitational lensing of the CMB





Gravitational lensing of the CMB

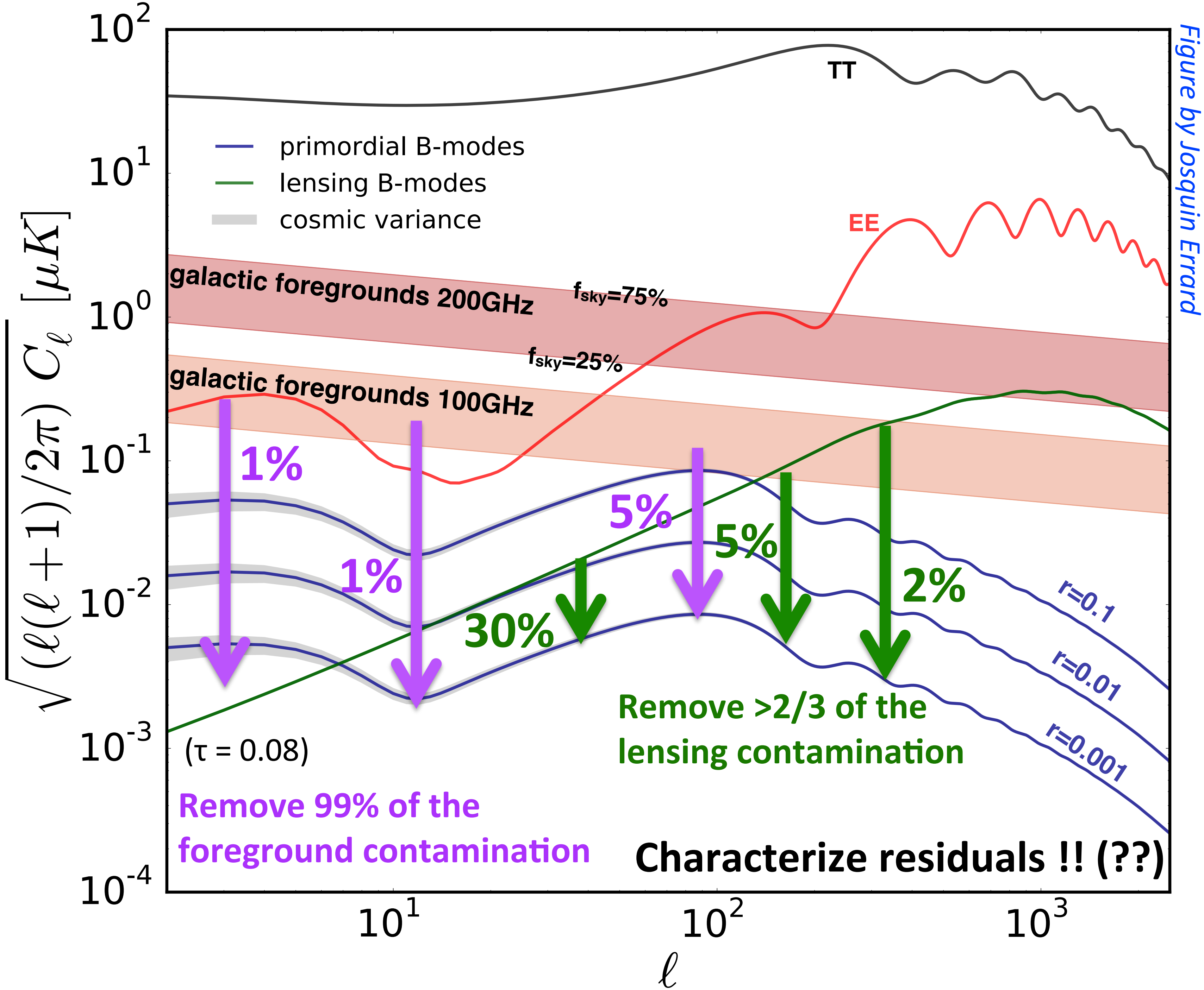
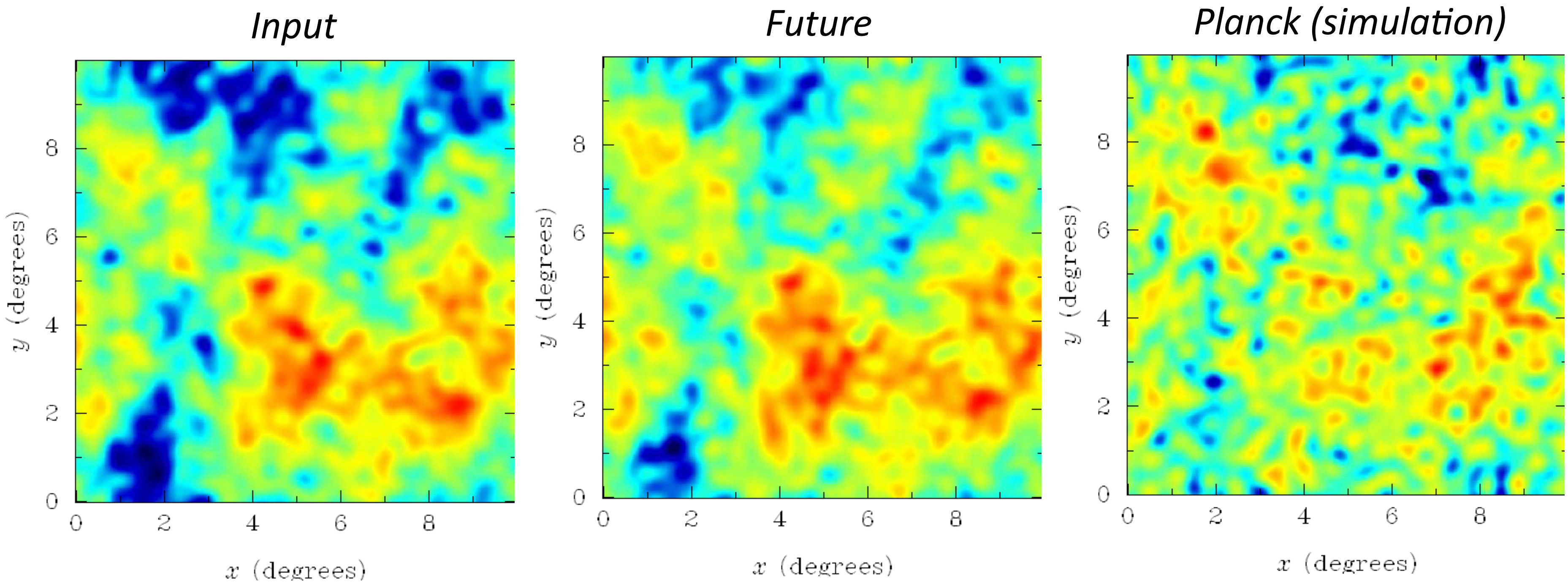


Figure by Josquin Errard
TT
EE
primordial B-modes
lensing B-modes
cosmic variance
galactic foregrounds 200GHz
galactic foregrounds 100GHz
fsky=75%
fsky=25%
1%
1%
5%
5%
30%
2%
r=0.1
r=0.01
r=0.001
(τ = 0.08)
Remove 99% of the foreground contamination
Remove >2/3 of the lensing contamination
Characterize residuals !! (??)
$\sqrt{\ell(\ell+1)/2\pi)\ C_\ell}\ [\mu K]$
ℓ

Mapping (dark) matter structures



Correlations with baryonic tracers of mass for a lot of astrophysical cosmology, 3-D tomography, …

REQUIREMENT:
resolution ≈ 3-4' or better, sensitivity ≈ 2 μk.arcmin or better

In summary: what CMB science?

The CMB is unique !

It is not only an image of the Universe at z=1000,
it also is a source plane that shines on structures
in the whole universe and allows us to probe them

We must seek to learn everything it can tell us.

This is ***MUCH MORE*** *than "just" measuring r=T/S*
(or fitting a 6-parameter cosmological model…)

Outline

- Why the CMB ?
- Why space ?
- What space mission ?
- Strategies and synergies
- Summary

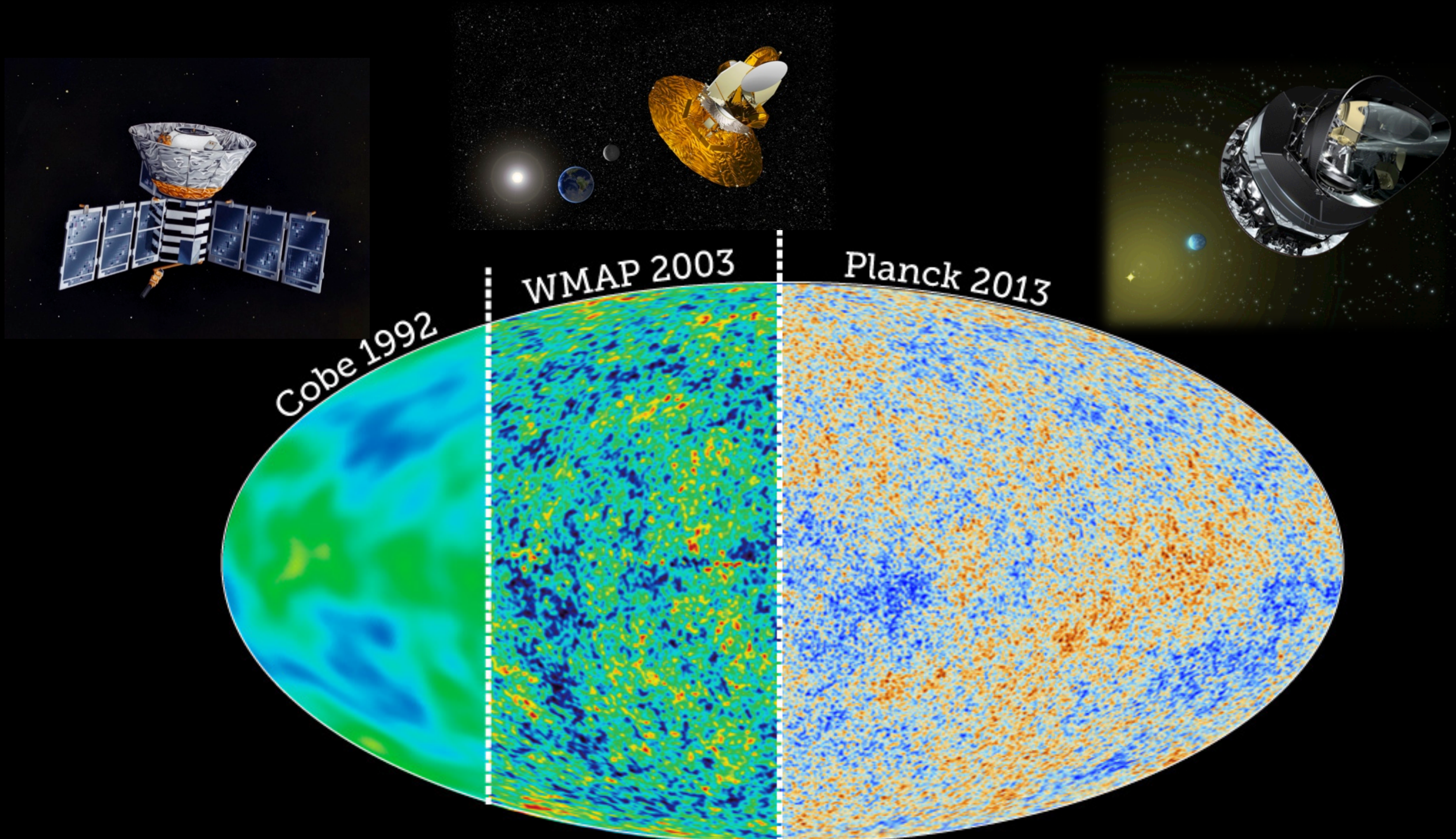
Why space?

Sub-orbital observations have been essential pathfinders:

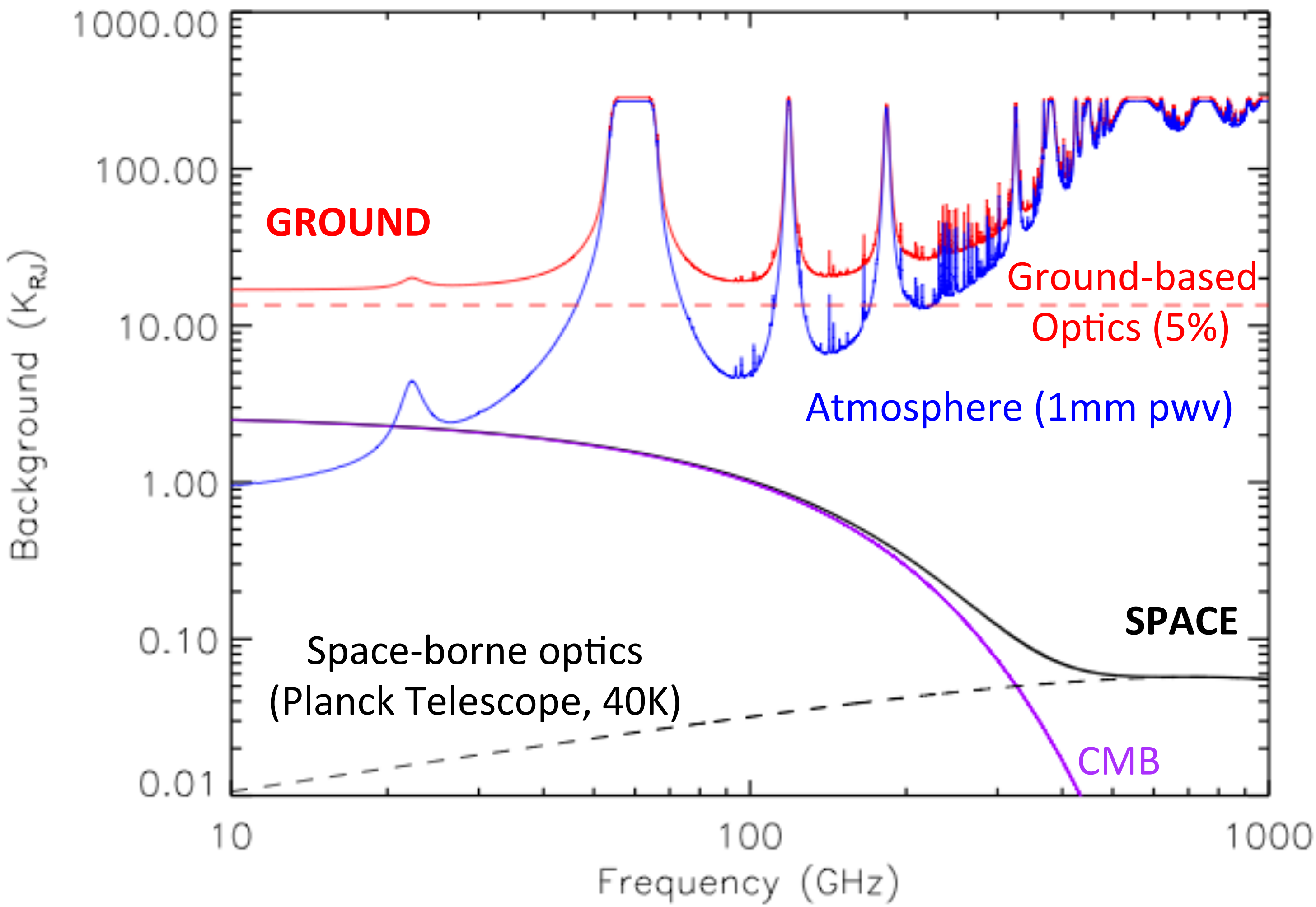
- First detection by Penzias & Wilson;
- Boomerang + Maxima: striking detection of first acoustic peak;
- Archeops: large l-range C_l spectrum;
- DASI: first detection of E-modes (+ CBI);
- Polarbear: first (direct) detection of lensing B-modes (+ BICEP2, SPT…);

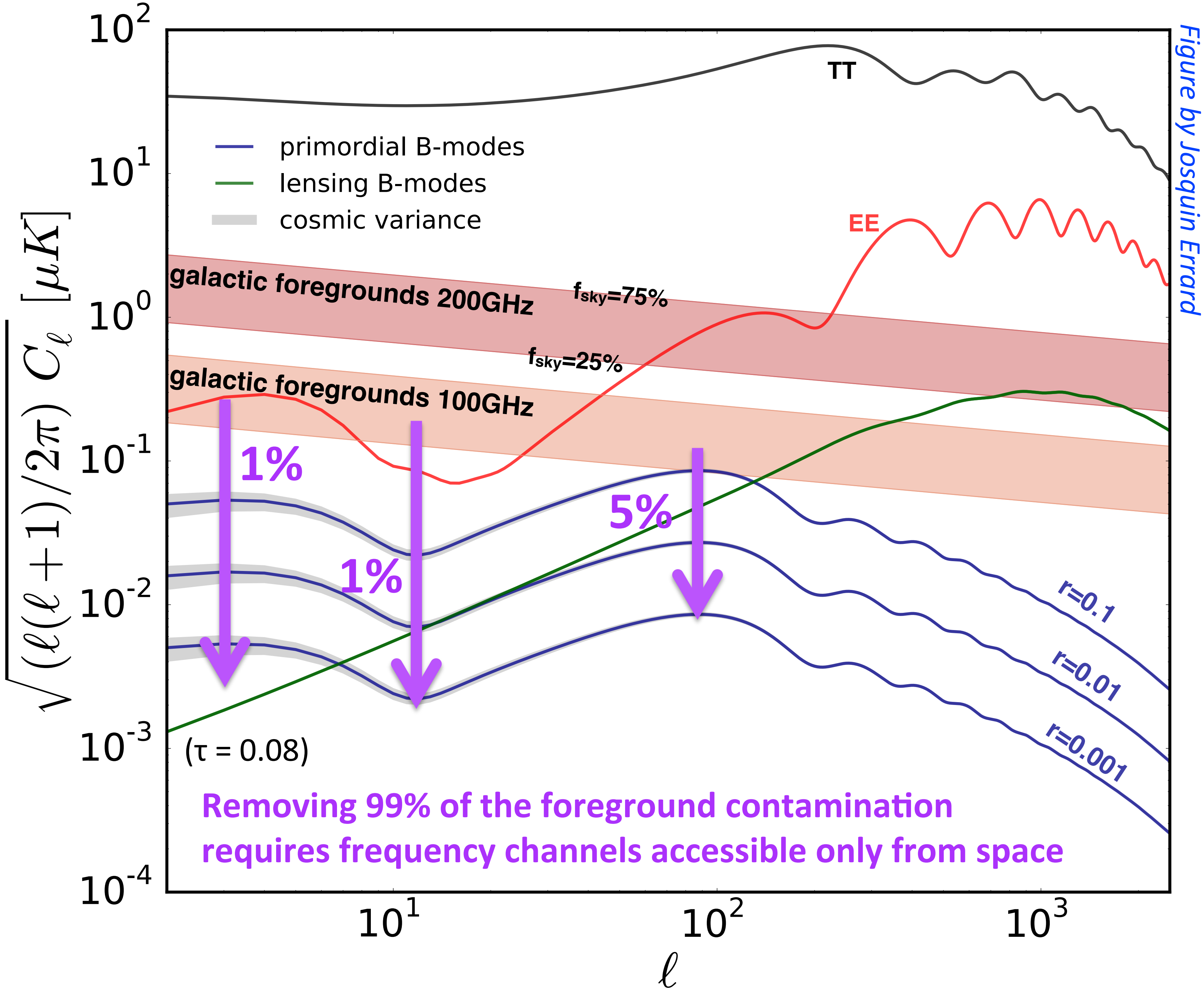
However it is ***space observations*** of the CMB that have enabled ***precision cosmology***, ***unmatched by any suborbital data***:

- FIRAS spectacular blackbody
- DMR first detection of anisotropies, i.e. primordial seeds of structures
- WMAP Temperature and Polarisation fluctuations
- Planck T maps and T+E power spectra, cosmological parameters, f_{NL}, …


Cobe 1992
WMAP 2003
Planck 2013

Space vs. Ground: background comparison





TT
primordial B-modes
lensing B-modes
cosmic variance
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)
Removing 99% of the foreground contamination
requires frequency channels accessible only from space
Figure by Josquin Errard
$\sqrt{\ell(\ell+1)/2\pi)\ C_\ell}\ [\mu K]$
ℓ

Systematic effects from the ground

- Atmospheric emission fluctuations
- Atmospheric absorption (few percent or less)
- Temperature fluctuations of the environment
- Ground pickup with sidelobes
- Lack of stability of observing conditions
- …

All of this makes sensitive ground-based observations challenging

In summary: why space?

Space offers a unique observing environment

- Access to all frequencies (for astrophysical foregrounds)
- Very stable and clean environment (for systematics)
- Lower background (better sensitivity per detector)
- 100% observing time (or close to that)
- Flexibility to observe distant points in short timescales

There is no such place as space !

We will not be done with the CMB until we fly a comprehensive space mission. The sooner the better.

Outline

- Why the CMB ?
- Why space ?
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- Strategies and synergies
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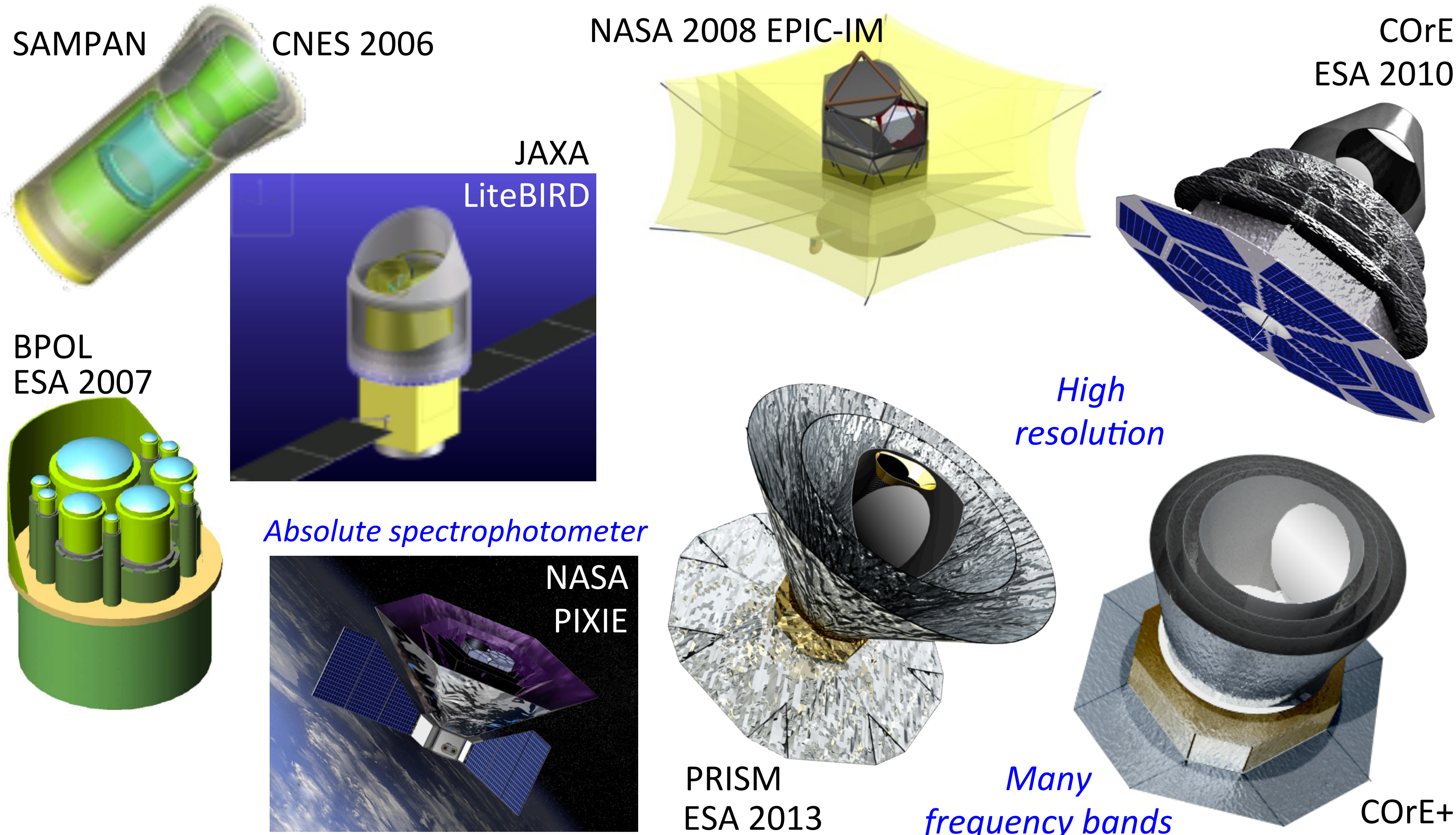
What next? Many proposed CMB missions



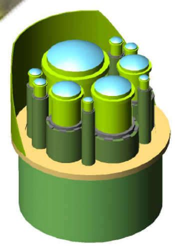
Low resolution
Limited frequency coverage
Primary CMB B-modes

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

CMB mission proposals in Europe

2006: SAMPAN (CNES)

- Small mission focused on Primordial B-modes
- Phase 0 feasibility study: feasible but too expensive for CNES alone

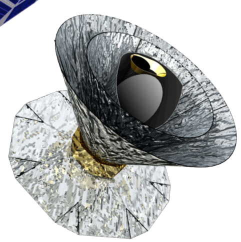


2007: B-POL (ESA M3)

- Similar to SAMPAN (refractive optics, focused on Primordial B-modes
- Before Planck launch…

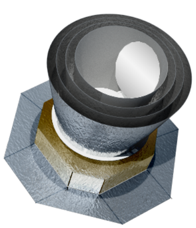
2010: CORE (ESA M4)

- New concept: More channels, better angular resolution
- Well considered, but too early, too complex and costly



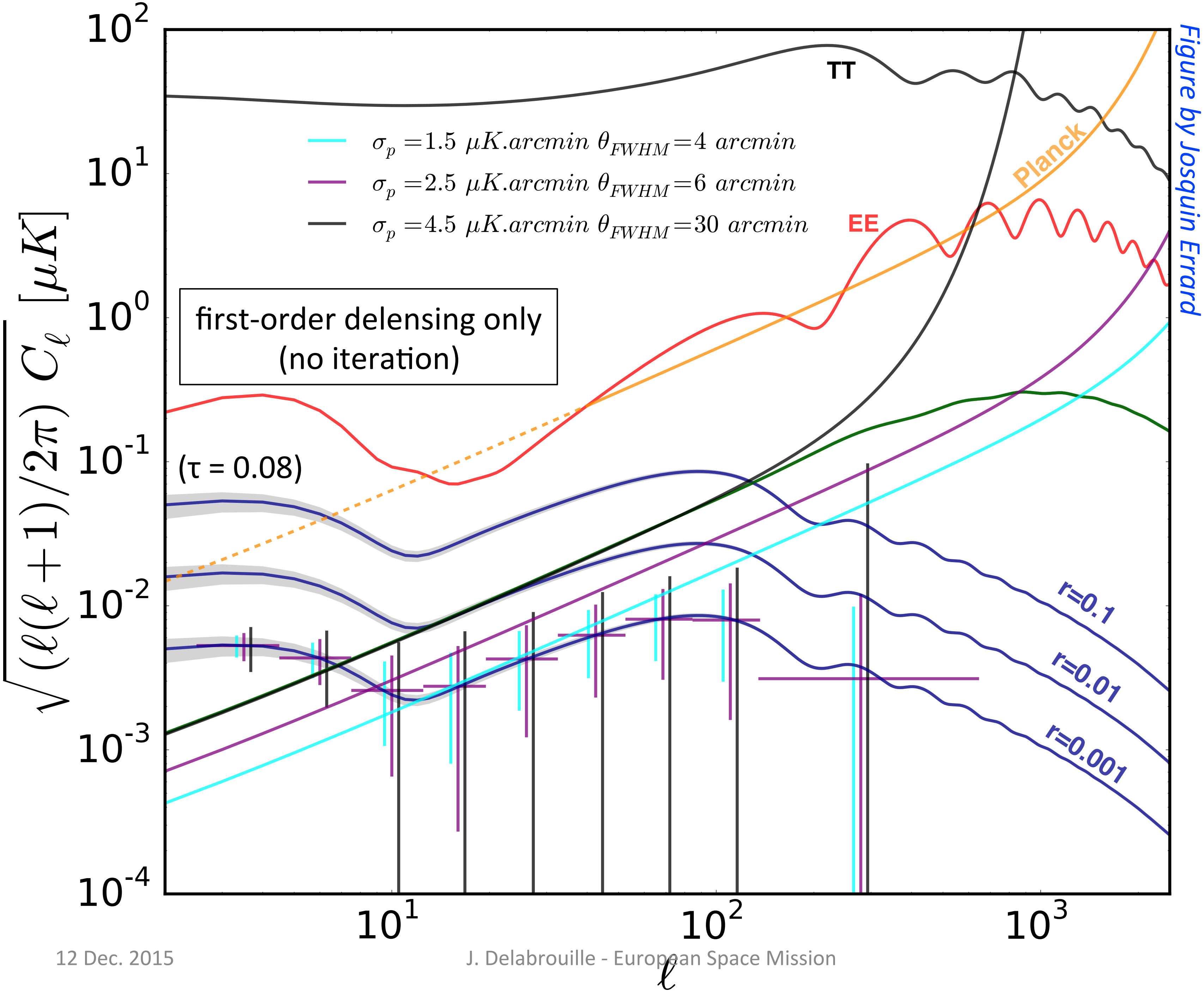
2013: PRISM (ESA L-class)

- Very ambitious mission, imager + spectrophotometer from 30 to 6000 GHz
- Very well considered, but competition too strong



2015: CORE+ (ESA M5 – lower budget M call)

- Similar to CORE, but concept simplified (no rotating HWP)
- Science priority of CNES, feasibility studies with CNES and space industry
- Too expensive, TRL too low for 2025 launch (detector arrays).
- Not evaluated scientifically by ESA.



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

What space mission?

Primordial B-modes may be at any level…

- This makes it hard to define the best strategy to find them!
- **We want to do our best !**

To some extent, it is the lensing B-modes that set the requirement !

- De-lens large scale B-modes for inflationary science
- Map the (dark) mass in the Universe

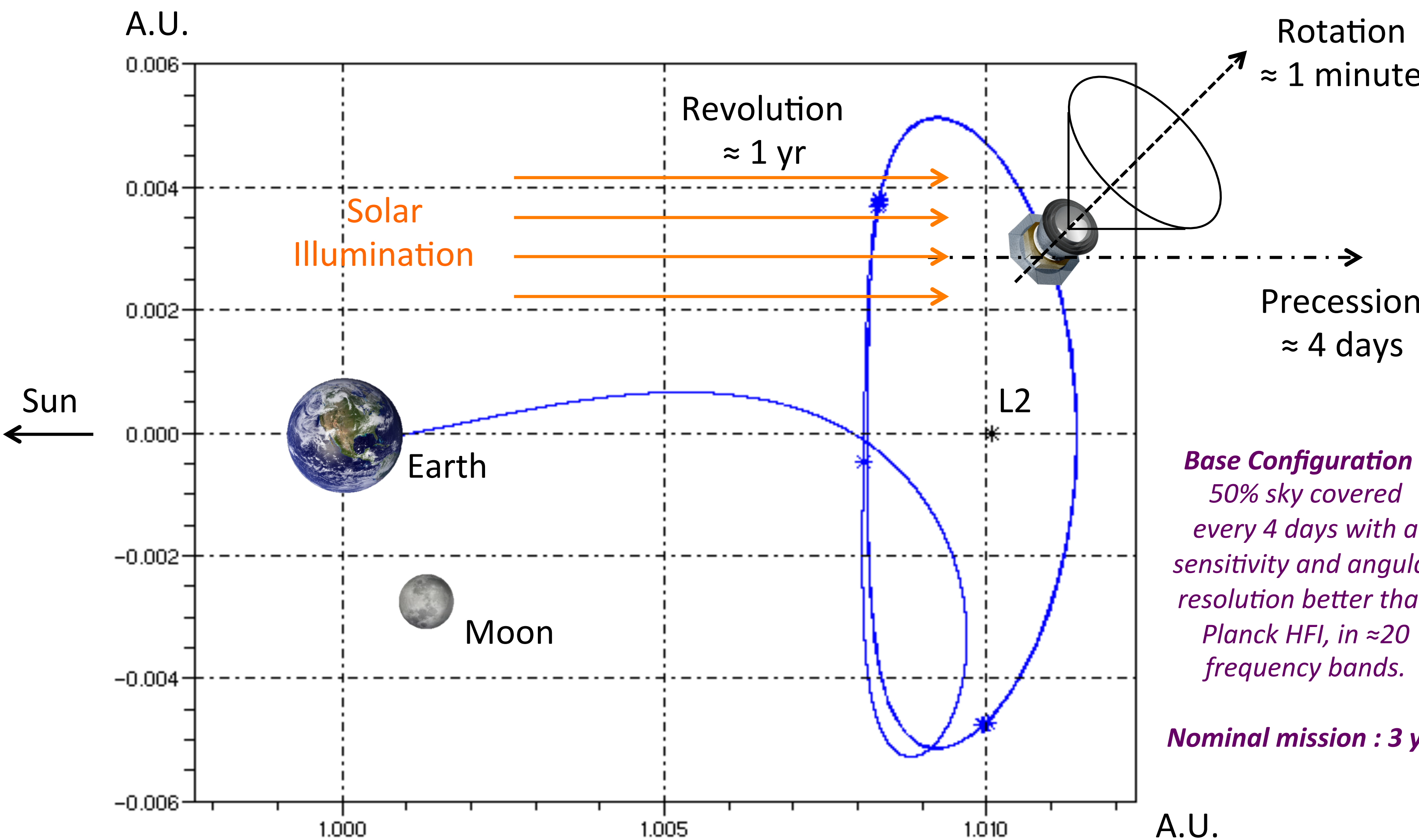
Getting the best out of CMB primary and secondary anisotropies requires a comprehensive space mission.

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.*

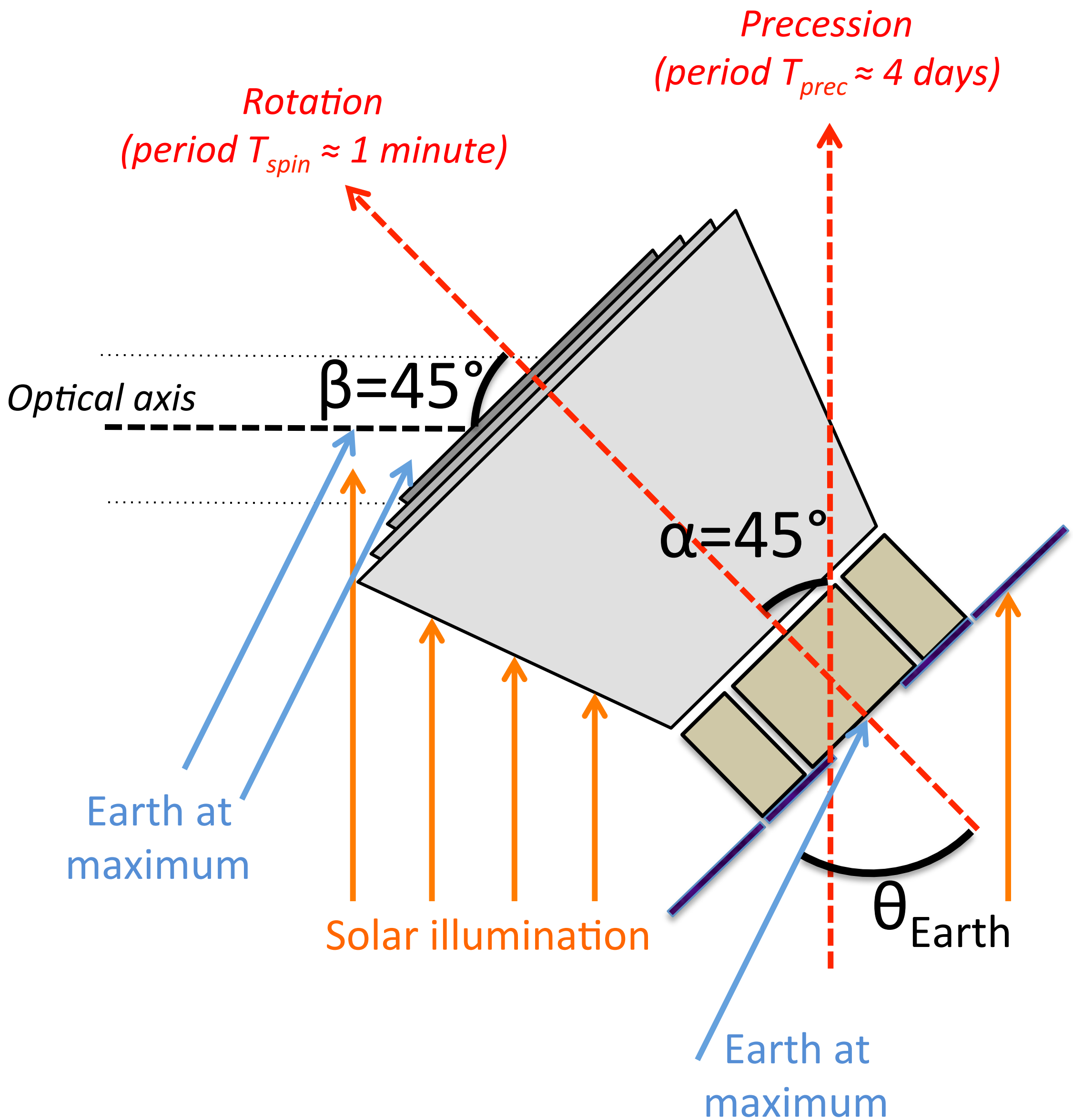
Performance / requirement	***Solution***
Resolve the CMB ≈ 4'-6' resolution or better	Class 1.5m telescope or better ≈ 6' at 135 GHz; ≈ 4' at 200 GHz
Signal dominated data (S/N >2-3 for B_{lens}) σ_P = 1.5-2.5 μK.arcmin on ≈ 100% sky	from ≈ 2500 (base) to 5000 (extension) detectors at ≈ 100 mK
Exquisite 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)

Orbit and Scan strategy



Base Configuration :
50% sky covered every 4 days with a sensitivity and angular resolution better than Planck HFI, in ≈20 frequency bands.

Nominal mission : 3 yrs



Parameter optimisation

Anti-solar precession for thermal stability ;

Constraints on α :
- payload temperature
- power from solar panels

Constraints on θ_{Earth} :
- data transfer
- straylight

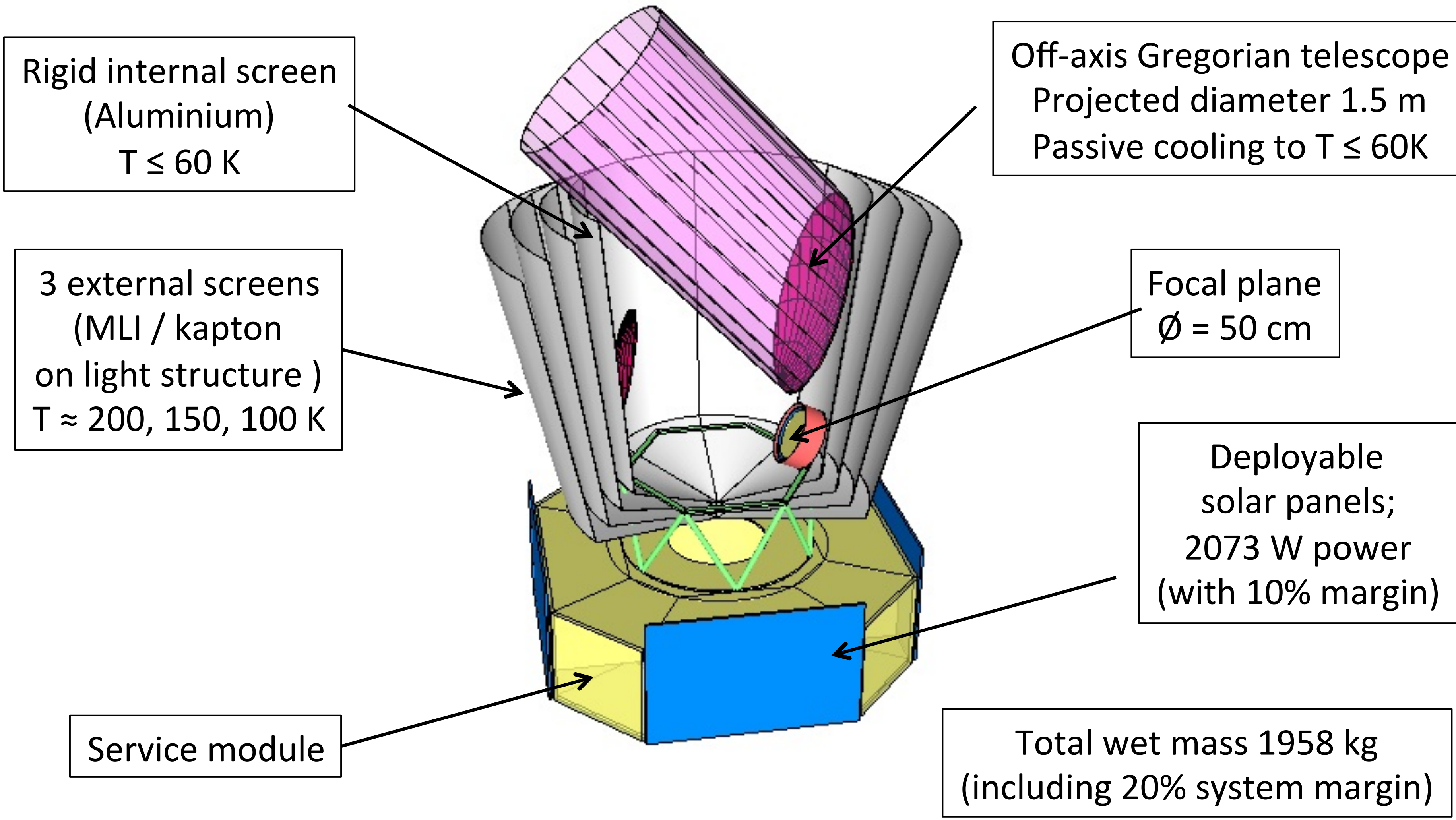
Constraints on β :
- full sky (α+β ≥ 90°)

Constraints on T_{spin} :
- sampling frequency
- data rate

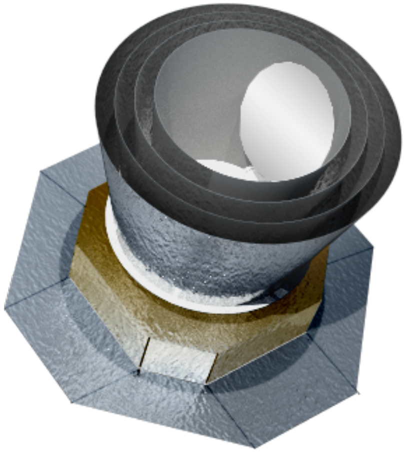
Constraints on T_{prec} :
- cross-scan sampling

(Detailed optimisation of parameters in phase A)

Spacecraft


Rigid internal screen
(Aluminium)
T ≤ 60 K
3 external screens
(MLI / kapton
on light structure)
T ≈ 200, 150, 100 K
Service module
Off-axis Gregorian telescope
Projected diameter 1.5 m
Passive cooling to T ≤ 60K
Focal plane
Ø = 50 cm
Deployable
solar panels;
2073 W power
(with 10% margin)
Total wet mass 1958 kg
(including 20% system margin)

COrE+ fact sheet



Comprehensive CMB experiment: primordial B-modes AND (almost) no compromise on the CMB science (except for spectral distortions).
Drawback for main goals: Not selected yet! (Launch in ≈2029 if selected for M5, ESA only)

Foreseeable science:

- **Precise characterization of tensor modes**
- **(near-) ultimate CMB polarisation experiment**
- **Great legacy value**: Very broad science in many areas of astrophysics and cosmology (***although optimized for CMB only***)

Hundreds of publications

Why was COrE+ not selected ?

- Not evaluated scientifically (by ESA) !!
- TRL of the cooling chain;
- TRL of (European) detector technology;
- The payload architect and cryo-chain architect were not clearly identified;
- Taking these risks into account, the cost at completion, as evaluated by ESA, was of order 700 M€, for an envelope of the order of 500 M€ total (450 M€ from ESA + 50 M€ from Member States); (our estimate 600 M€)

M5: Annoucement on July 20th 2015

- 25 September 2015: statements of interest can be submitted to ESA by the community
- Interaction between ESA and the scientific community during the whole process
- Encouragement from ESA to consider a collaboration with JAXA for CMB polarisation

ESA budget < 550 M€

TENTATIVE SCHEDULE FOR THE M5 CALL

The current tentative schedule is offered for planning purposes, and it's liable to evolve, also based on the responses received in the form of SoI.

Event	Tentative date	
M5 Call release	December 2015	March 2016
Letters of Intent due	January 2016	
Proposals due	April 2016	Fall 2016
Evaluation process	May–June 2016	
Selection of proposals for study phase	June 2016	Early 2017
Phase 0+A completion	June 2018	June 2019
Down-selection to one mission	November 2018	
Phase B1 completion	June 2020	
Mission Adoption Reviews	September 2020	
Mission adoption	November 2020	
Launch (for an ESA-only mission)	Mid–2029 to mid–2030	2029

Launch could be earlier for a joint mission

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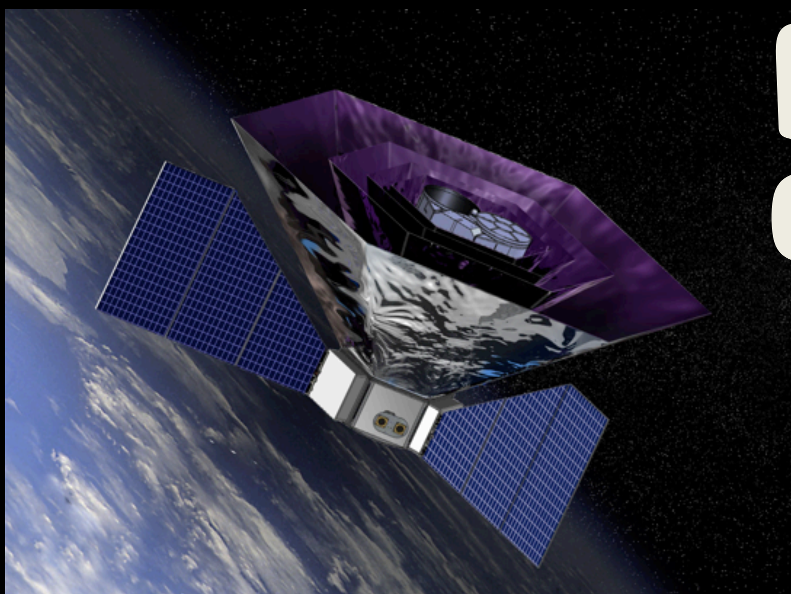
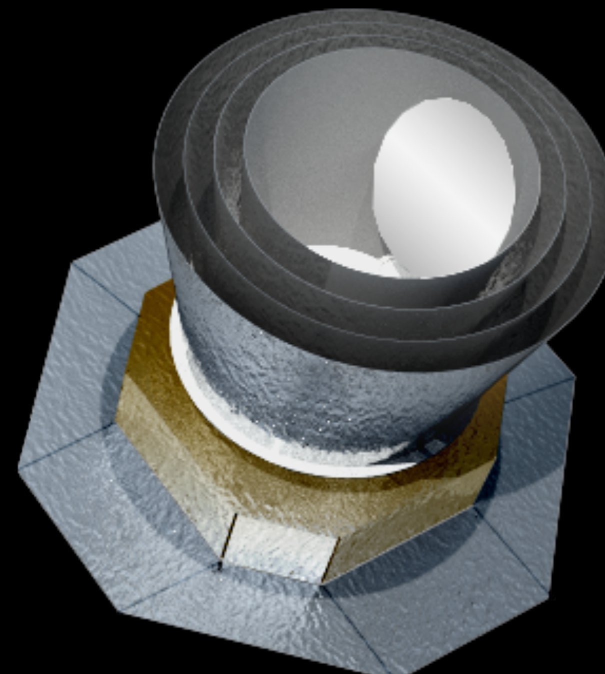
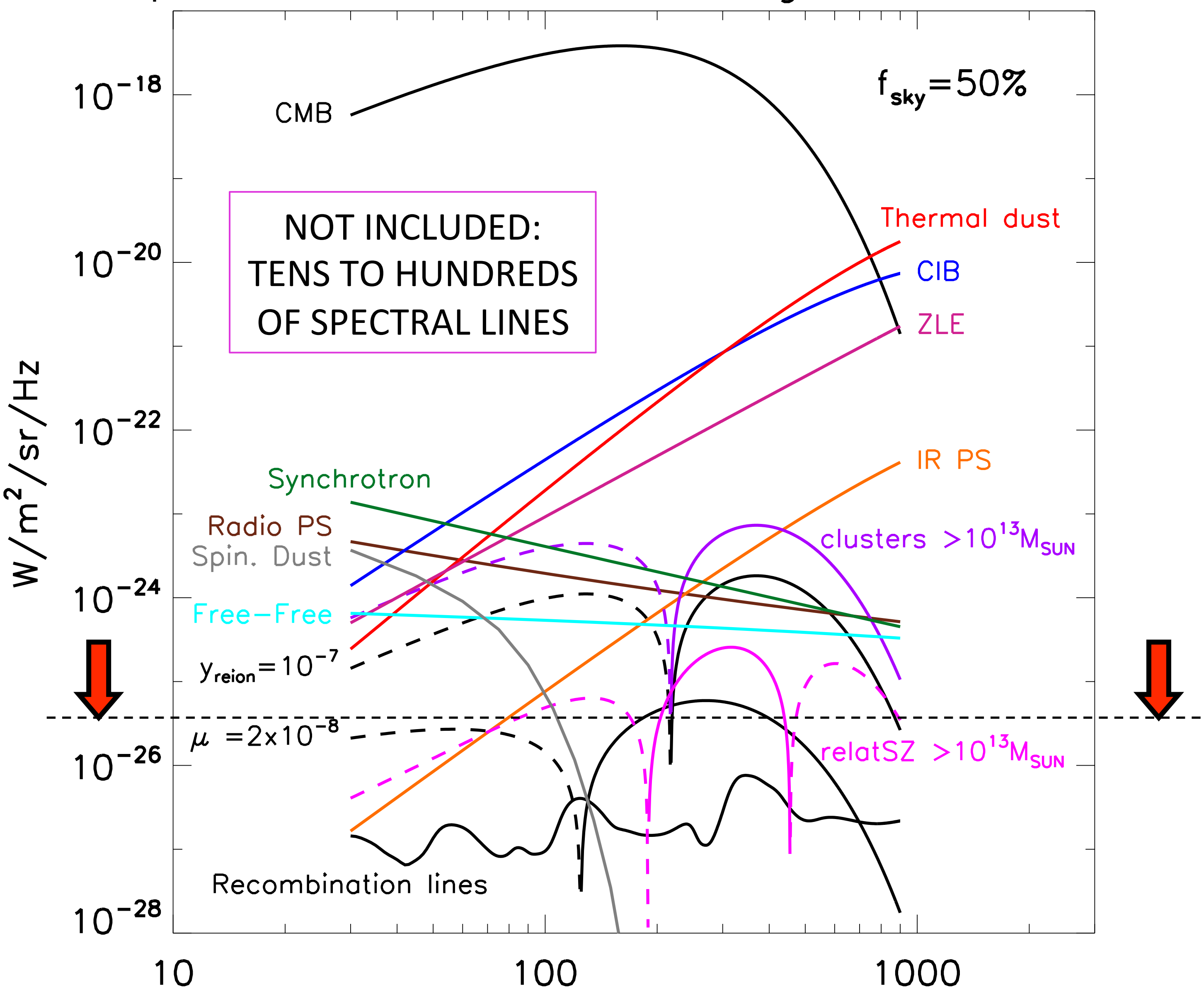
Spectrophotometer or Imager?



?



Spectral distortions and foreground emission



PIXIE 4 years
50% sky used
$\delta I \approx 3\times10^{-26}$

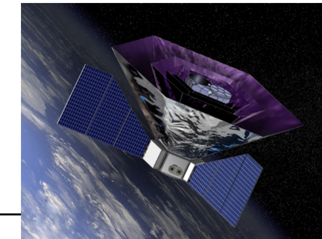
The foreground problem for spectral distortions

- Foregrouds dominate the CMB spectral distortion signals of interest by 4 to 6 orders of magnitude !

- Subtracting these contaminants will be challenging

- The following can help:
  - Better angular resolution and sensitivity
  - More frequency channels in the CMB range
  - Associated imager with high angular resolution (there are 900 4-arcmin, and 3600 2-arcmin "pixels" in a 2° beam)

Complementarity



Ground-based imager
1-2' in atmospheric windows
ν = 40, 95, 150, 220

Foreground monitor
(low frequency small scales)
Small scale complement
in atmospheric windows

Absolute calibrator
(large scales);
Large scale complement;

Absolute FTS
Absolute measurement
1-2° in many frequency bands

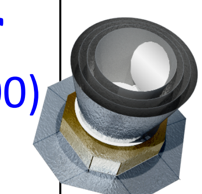
Absolute calibrator
(intermediate scales);
Large scale complement;
Intensity complement.

Small scale complement
at low frequency;
Polarisation sensitivity
complement

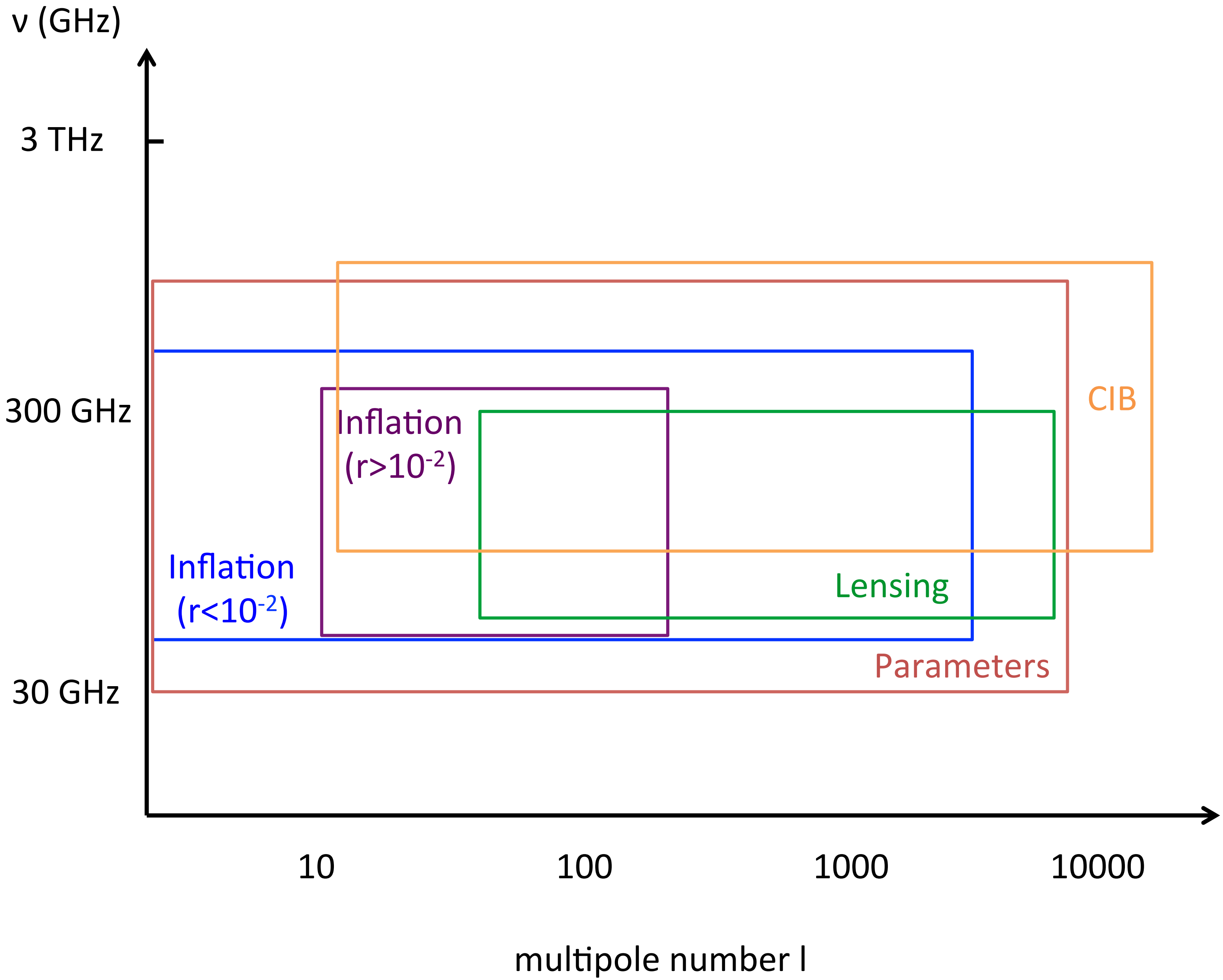
Foreground monitor
(small scales)
Small scale complement

Absolute calibrator
(large scales);
Zero-levels of maps

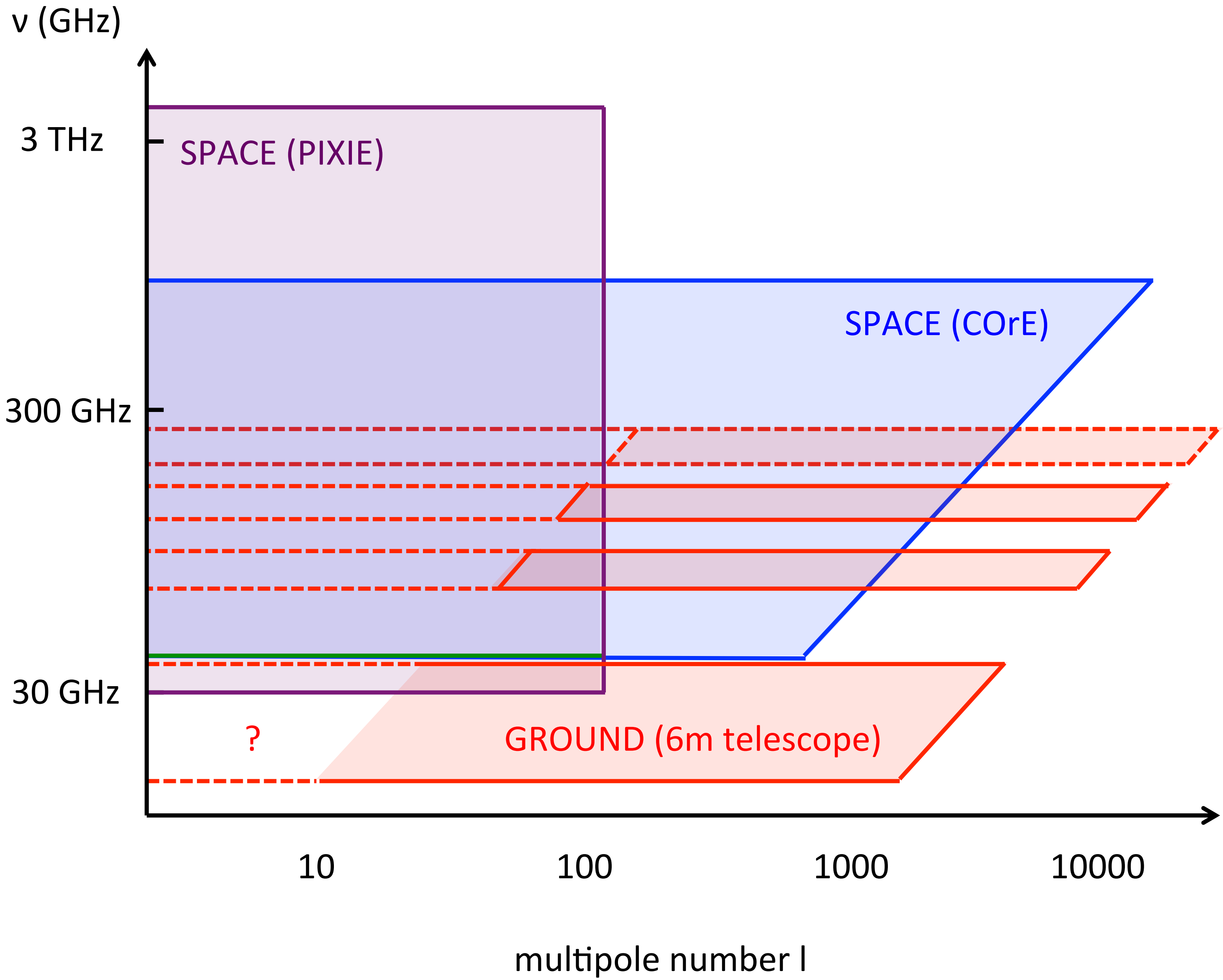
Space-borne imager
1-2' at high frequency (ν ≥ 300)
4'-6' at CMB frequencies
15-20 frequency bands

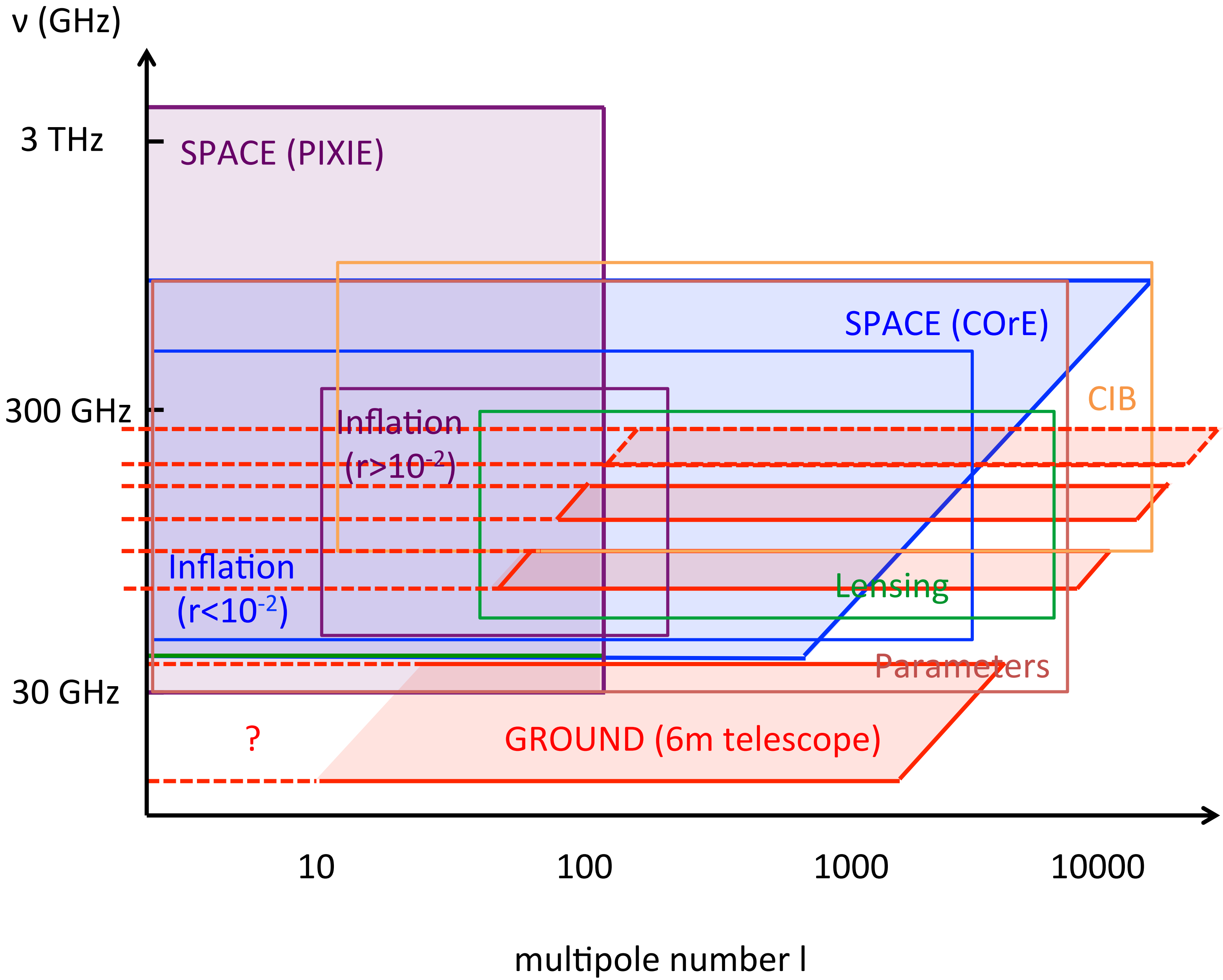


or ?



ν (GHz)
3 THz
300 GHz
30 GHz
CIB
Inflation
(r>10-2)
Inflation
(r<10-2)
Lensing
Parameters
10
100
1000
10000
multipole number l


ν (GHz)
3 THz
SPACE (PIXIE)
SPACE (COrE)
300 GHz
30 GHz
?
GROUND (6m telescope)
10
100
1000
10000
multipole number l


ν (GHz)
3 THz
300 GHz
30 GHz
SPACE (PIXIE)
SPACE (COrE)
CIB
Inflation
(r>10-2)
Inflation
(r<10-2)
Lensing
Parameters
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GROUND (6m telescope)
10
100
1000
10000
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Outline

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Summary

- Only (primary) CMB temperature anisotropies have been measured so far with high S/N.
- E-modes well detected at a statistical level (spectrum) but the best full-sky map still has S/N ≈ 1 per pixel (on all scales larger than about 15')
- B-modes (lensing) just barely detected statistically. Their precise mapping is the key to both inflationary tensor modes, and to precise direct observation of (dark) matter structures in the Hubble volume.

Summary

- There is only one CMB. It is the single observable that sets the stage for precision cosmology. It deserves the best possible observations, which requires comprehensive spaceborne data sets, complemented by ground-based observations if possible.

- Opportunities are opening-up for a joint international strategy to get these observations done.

- ESA is encouraging the European community to submit an international space mission to M5 (in particular with JAXA).

Summary

- A spaceborne imager is required to get high resolution maps across the frequency spectrum.

- Ground-base telescopes are required to reach 1-2' angular resolution at frequencies where the CMB dominates.

- An absolute spectrophotometer is required to get the information encoded in CMB spectral distortions, for measuring zero-level of maps, and for well-calibrated large scale maps.

Summary

- Getting this all done requires joining forces internationally, to get all the required data with a multi-experiment strategy combining the ground and space.

- Let's get organised, and do it.

- The European role in this : a spaceborne imager for CMB polarisation that builds on the Planck legacy, that could possibly be a "COrE+ type" mission done by Europe alone...

- ... but preferably would be a "LiteCOrE" mission with similar CMB goals, but shared by JAXA and ESA, with US contributions welcome!