The Cosmic Microwave Background

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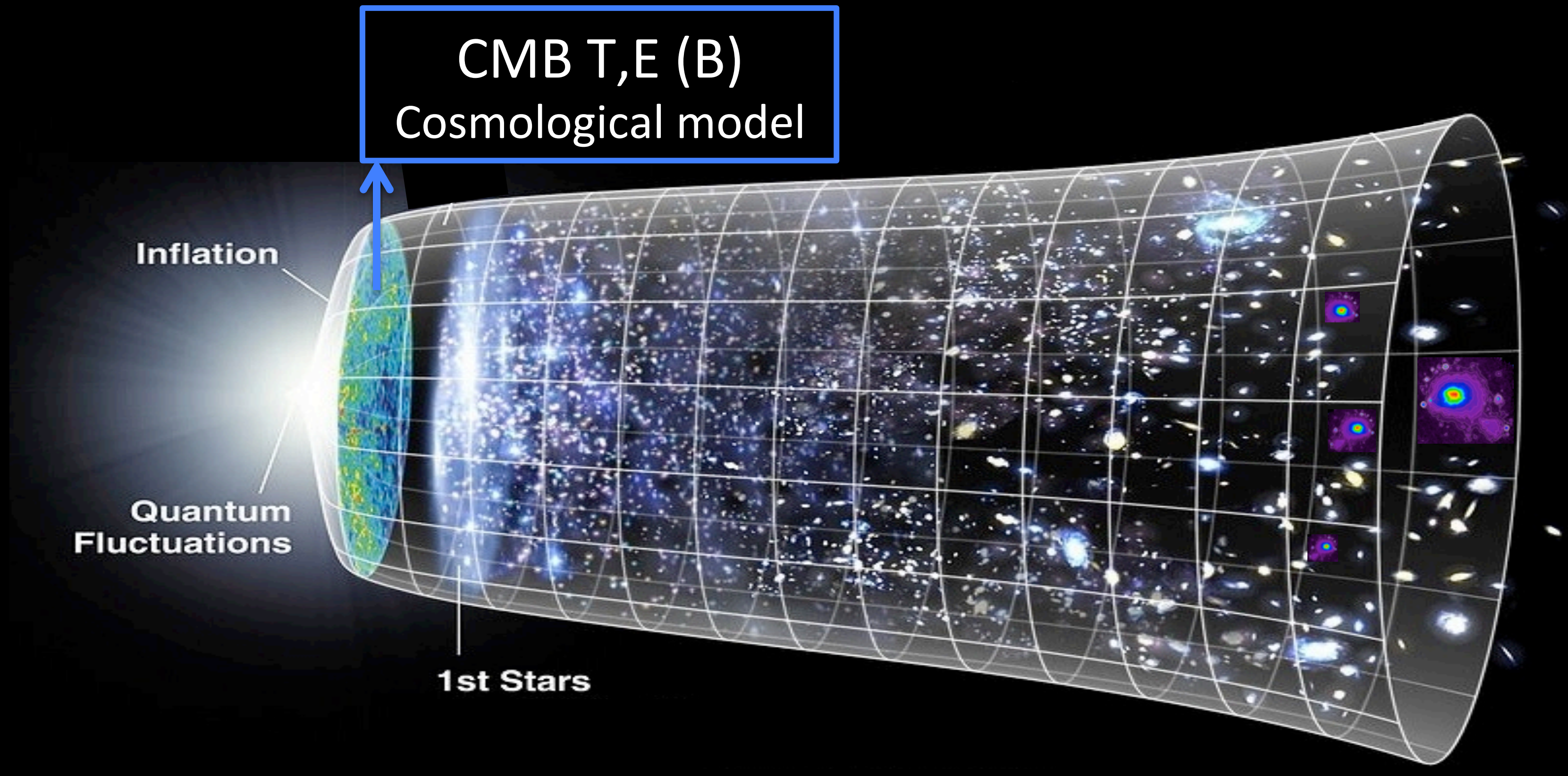
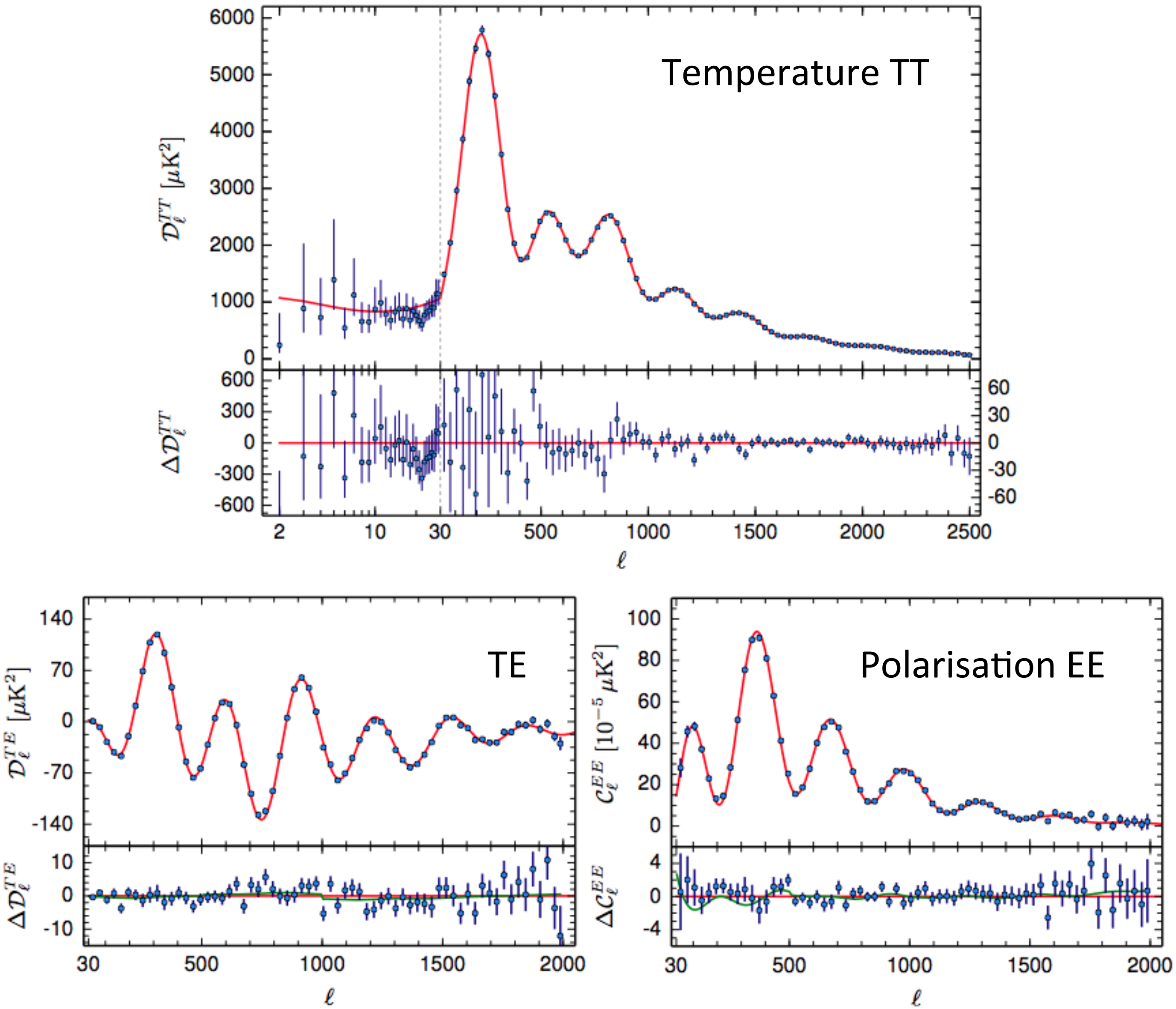
Outline

- CMB science and challenges
- Hot CMB topics
- The CORE space mission
  - *Context*
  - *Scientific objectives*
  - *Mission design*
  - *Status and feedback*
- What next?
  - *Evolving context*
  - *Option of a mission with India ?*
- Summary



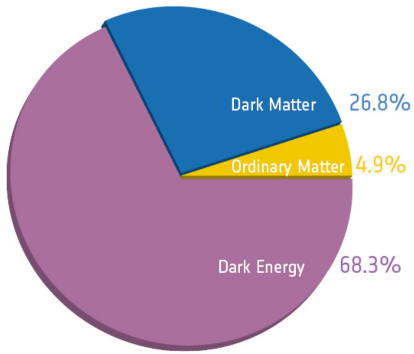
- *simple initial perturbation spectrum (power law)*
- *acoustic oscillations in the hot and dense plasma*

CMB spectra – Planck mission results (2015)



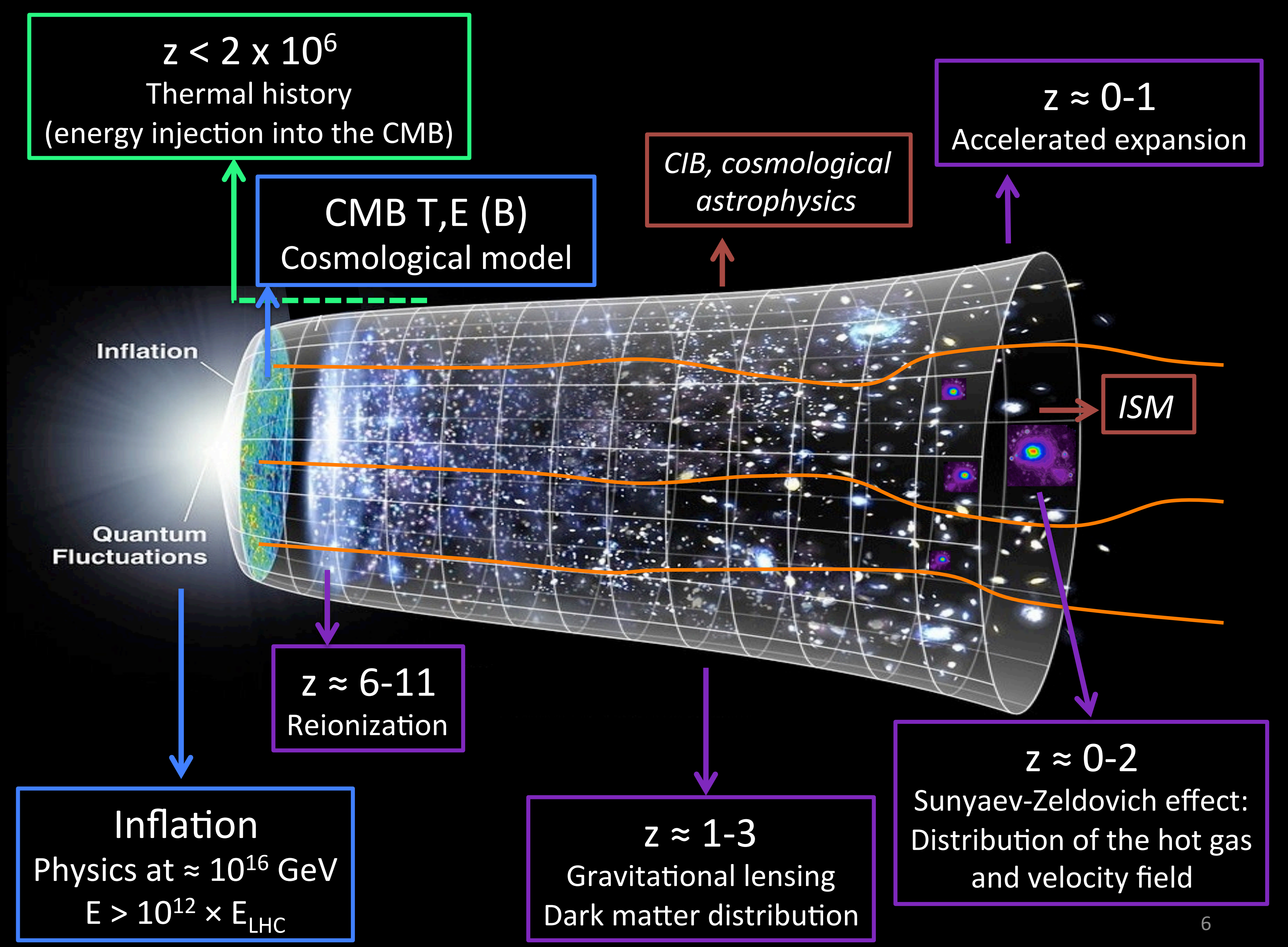
Success ?

- A "standard model of cosmology" has emerged: ΛCDM



- Very good fit of many cosmological observations ($H,\Omega_m,\Omega_b,\tau,A_s,n_s$,...) with mild "tensions" (H_0, σ_8, ...)

- Open questions !
  - Initial perturbations : did Inflation really happen?
  - If so, physics of inflation? (r, n_s, running, n_t, NG...?)
  - What is Dark Matter? (ν's, decaying DM...?)
  - What is Dark Energy? (Λ, w_0, w_1,...?)
  - Any Dark radiation / light relics? (N_{eff}, ...?)
  - Fundamental physics (modified gravity, physics beyond SM)
  - ...
  - Is the global ΛCDM picture correct?


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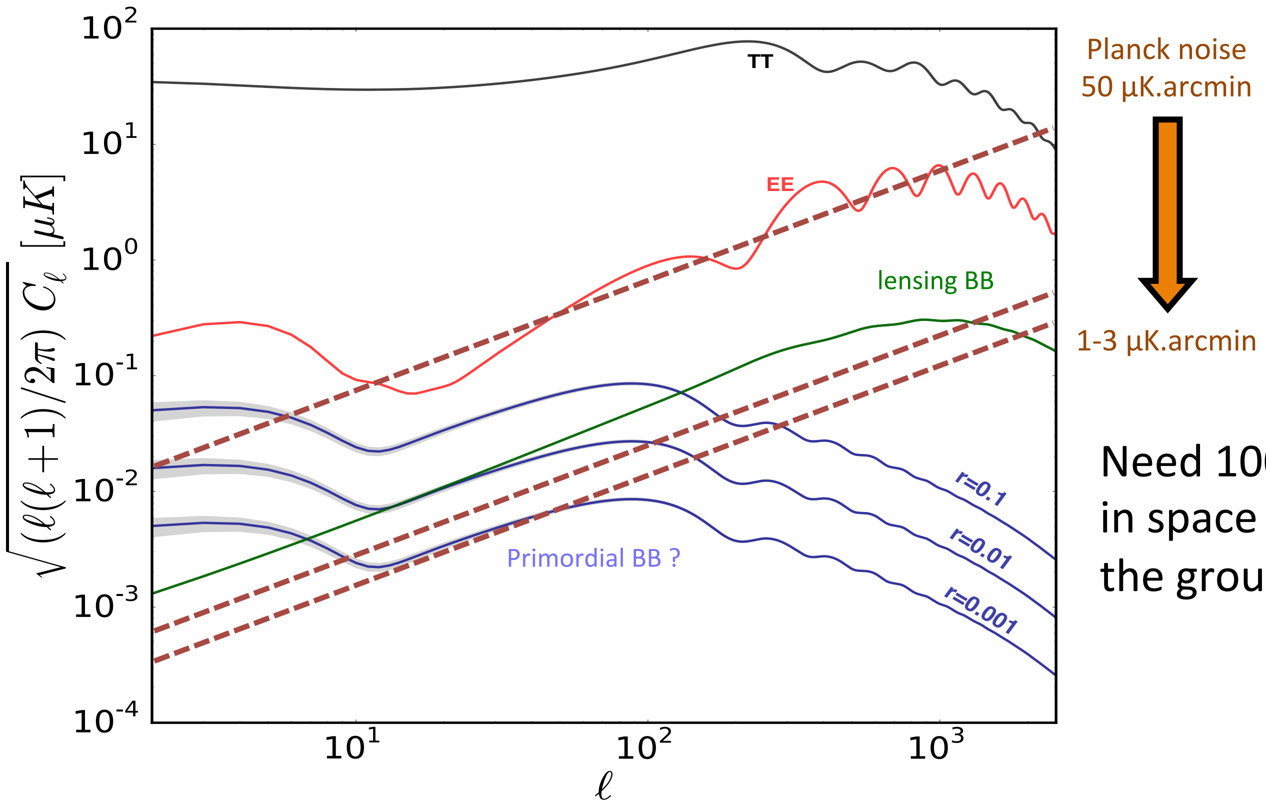
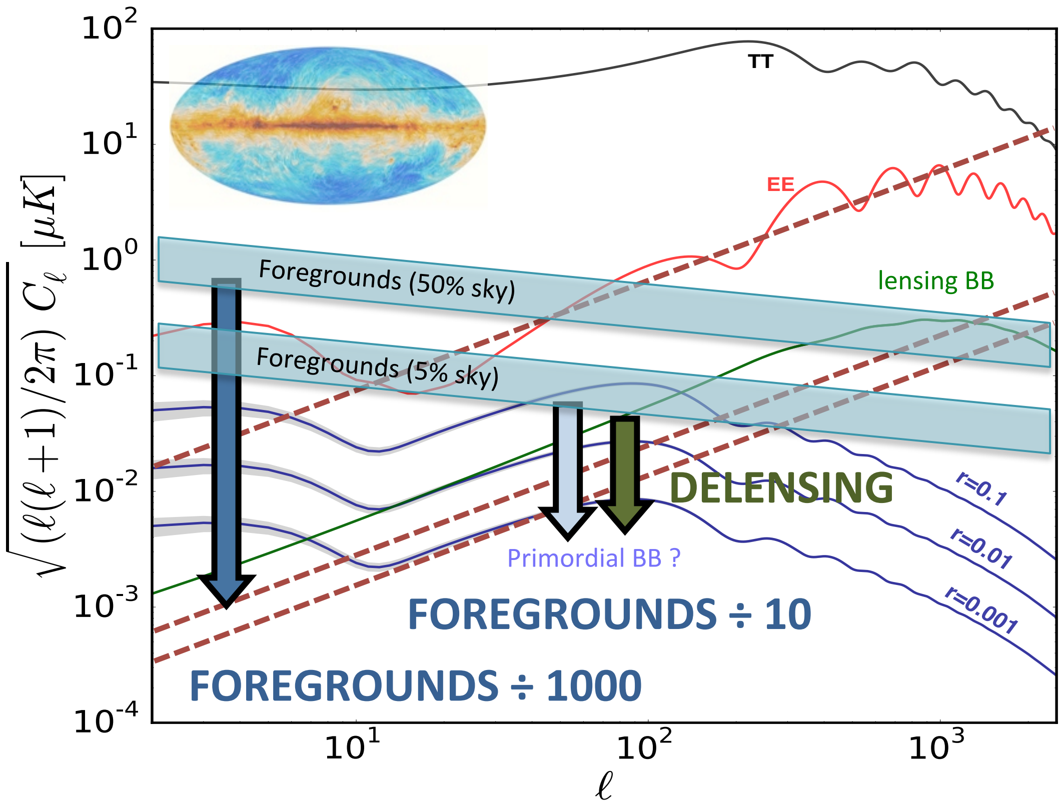
Physics at $\approx 10^{16}$ GeV
$E > 10^{12} \times E_{LHC}$
$z \approx 1\text{-}3$
Gravitational lensing
Dark matter distribution
$z \approx 0\text{-}2$
Sunyaev-Zeldovich effect:
Distribution of the hot gas and velocity field

Challenges: Primordial B-modes ?



Need 1000s of detectors in space (or 100,000s on the ground).

Challenges: Primordial B-modes ?

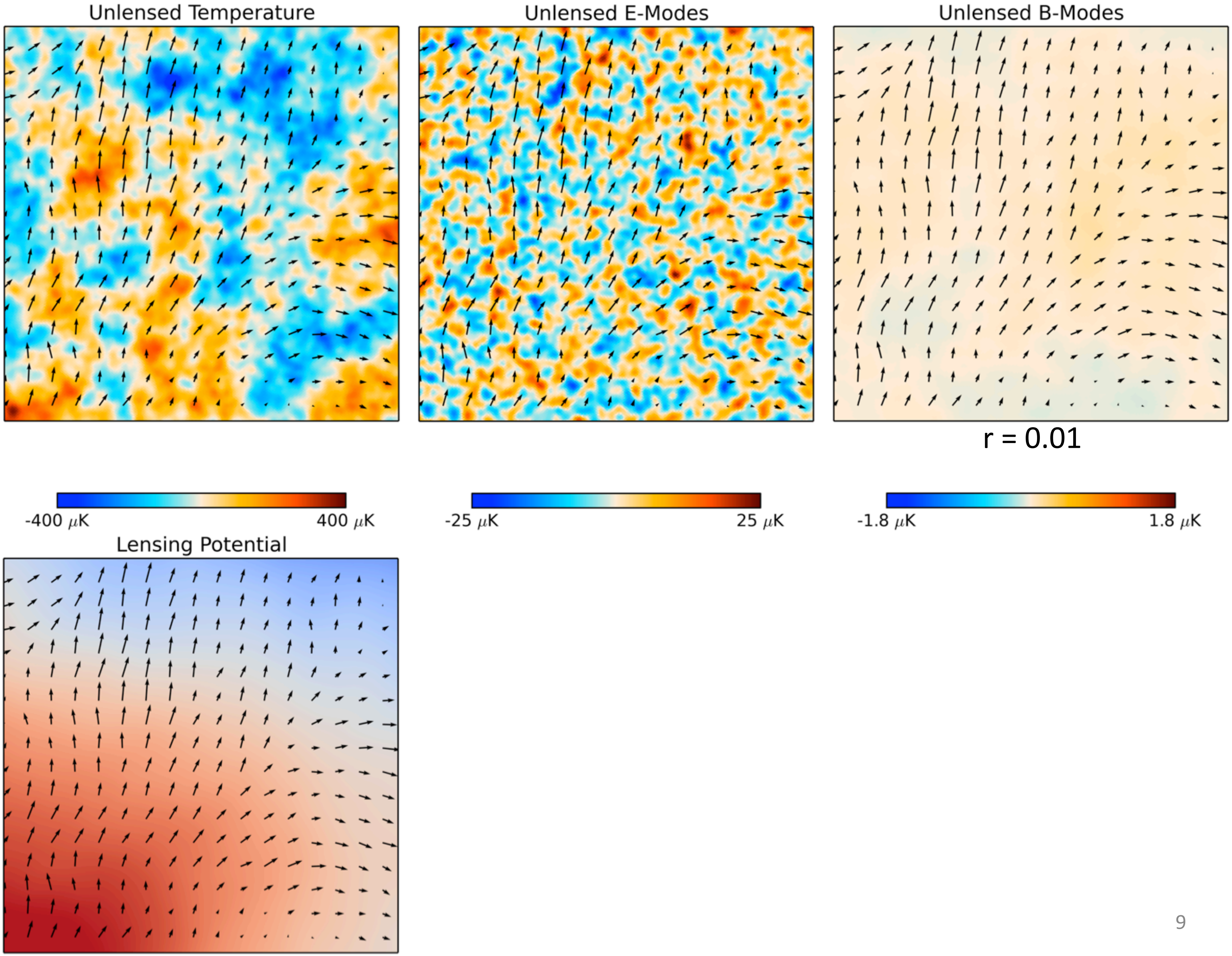


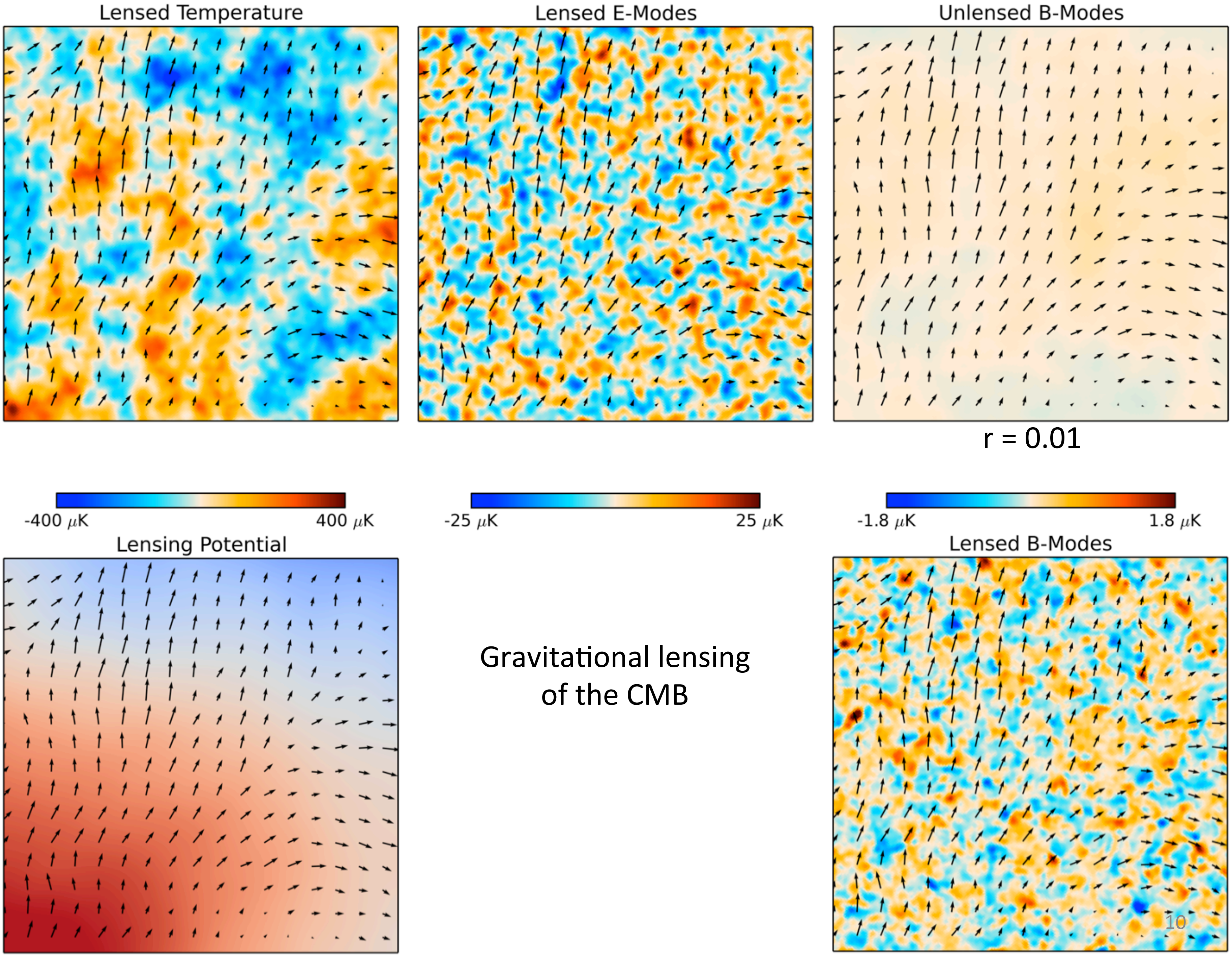
Need 1000s of detectors in space (or 100,000s on the ground).

The level of primordial B-modes is unknown

The feasibility of reducing foregrounds to 1‰ is unknown

Difficult to do better
- Size of Focal Plane
- Foregrounds
- De-lensing

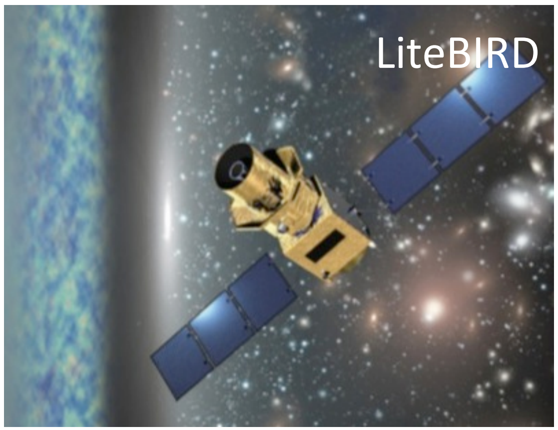

Unlensed Temperature
Unlensed E-Modes
Unlensed B-Modes
r = 0.01
-400 μK
400 μK
-25 μK
25 μK
-1.8 μK
1.8 μK
Lensing Potential



Gravitational lensing of the CMB

Space missions

JAXA + NASA



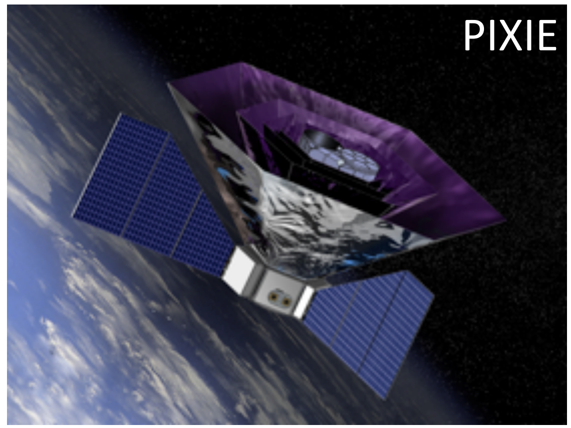
Primordial B-modes mission

Earliest Launch > 2027

Phase A ongoing in Japan

ONLY large scale CMB polarisation

NASA



Absolute spectrophotometer

Earliest Launch > ?

Phase A not selected by NASA

Very large scale polarisation and spectral distortions

ESA

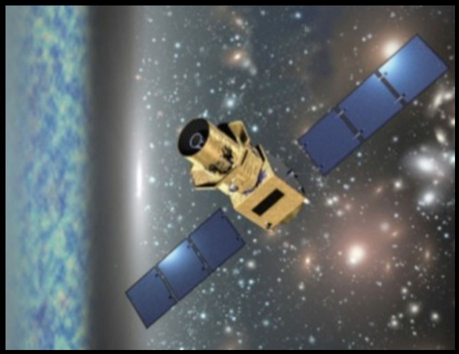
Cosmic origins explorer

Earliest Launch > 2031

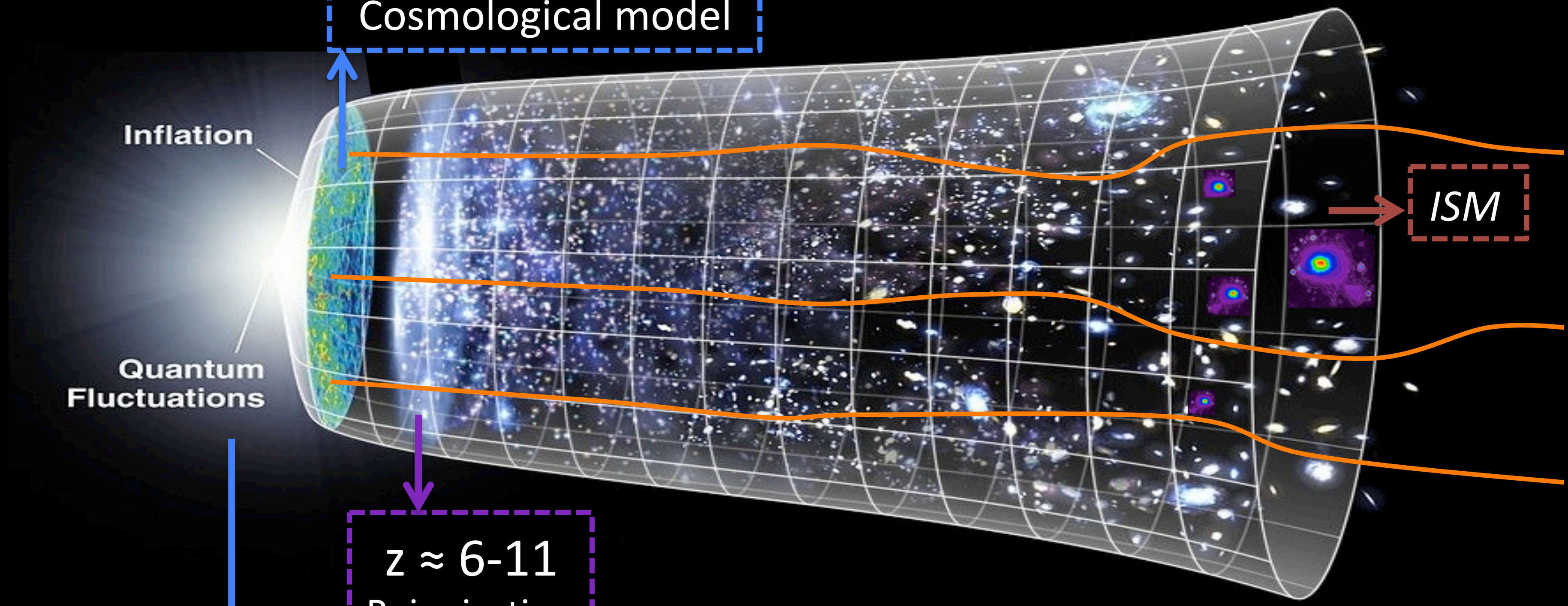
Phase A not selected by ESA

ALL CMB polarisation (almost) ultimate

LiteBIRD



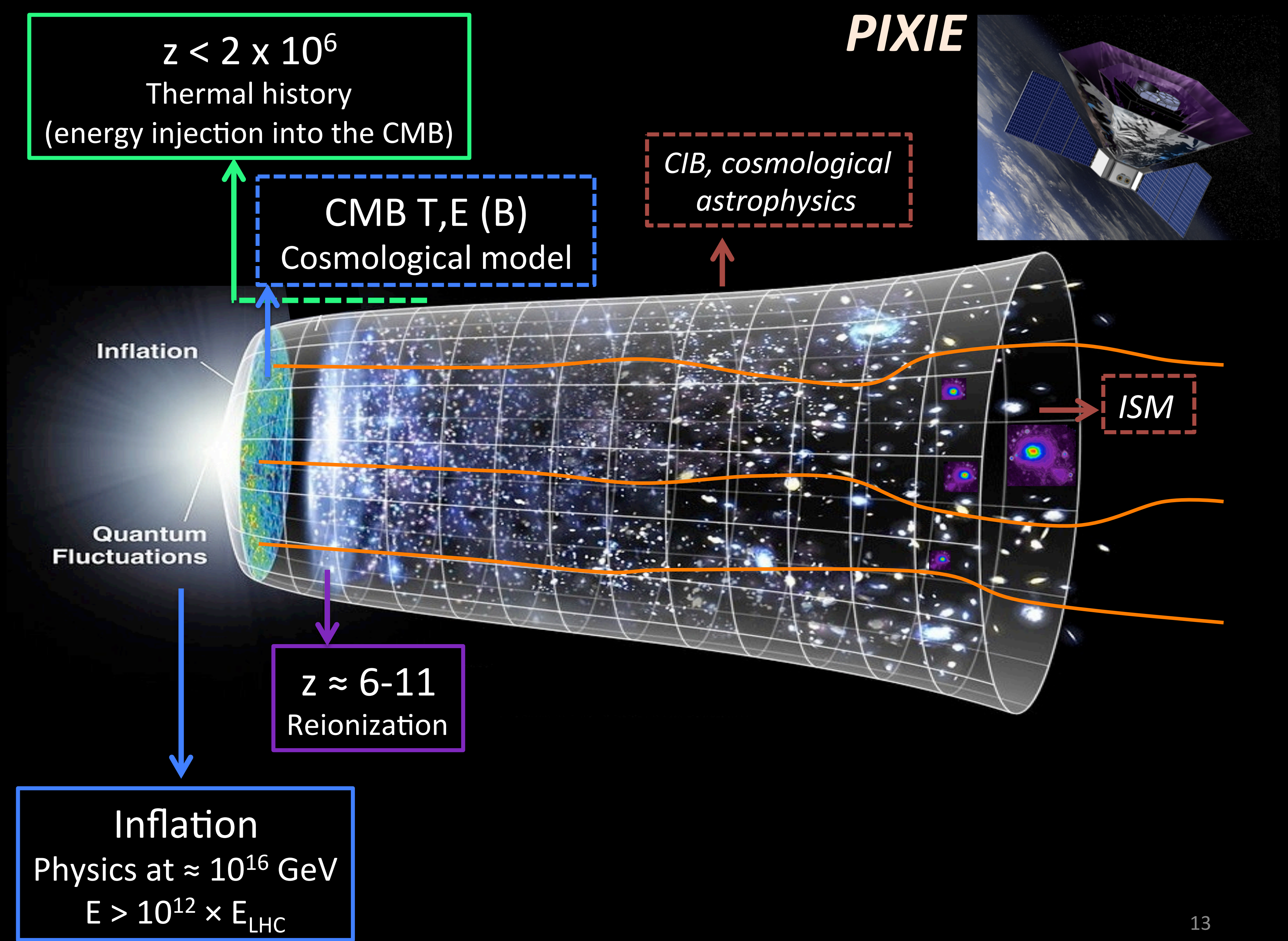
CMB T,E (B)
Cosmological model



ISM

$z \approx 6\text{-}11$
Reionization

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



z < 2 x 10^6
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CIB, cosmological astrophysics
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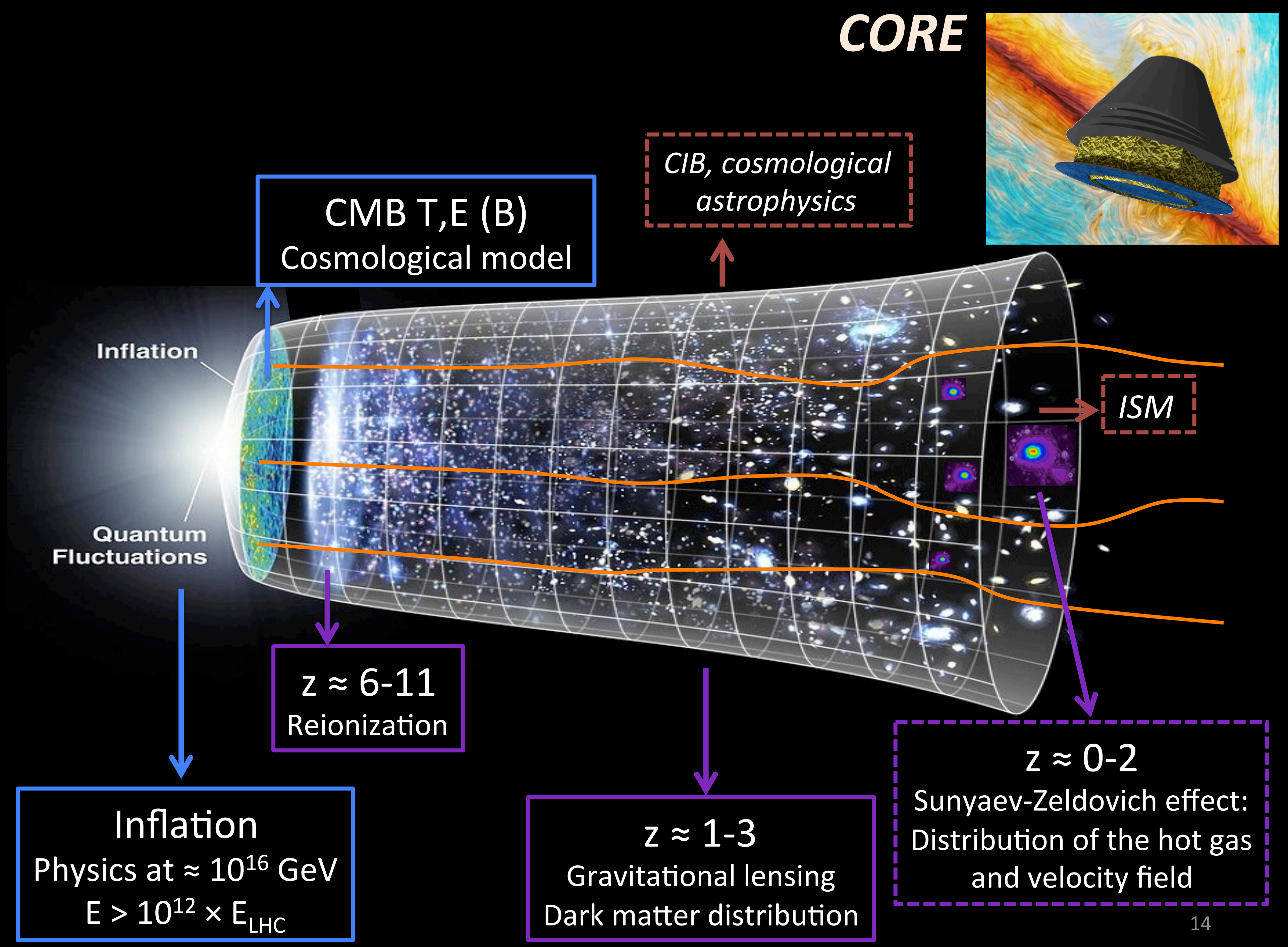
CORE
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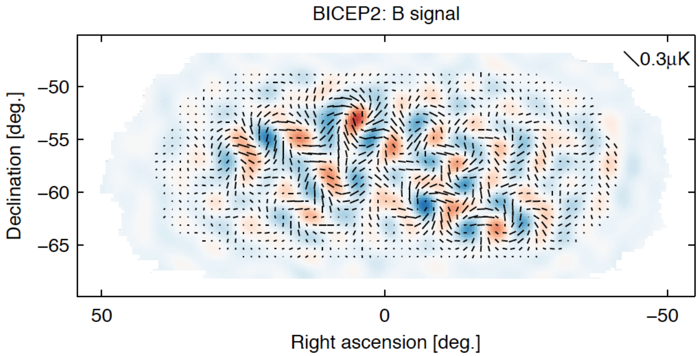
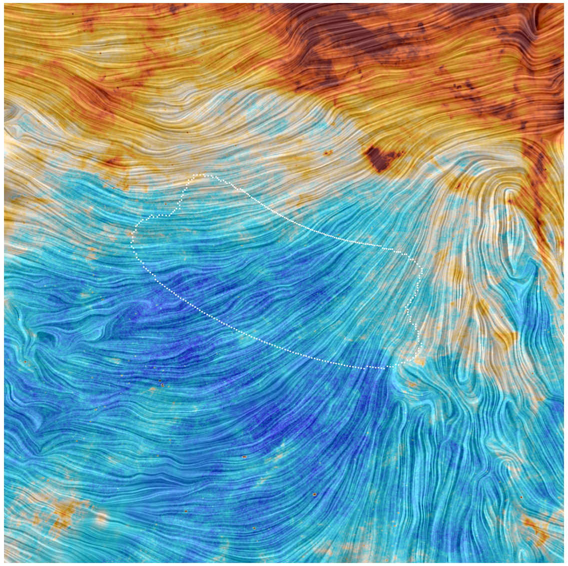
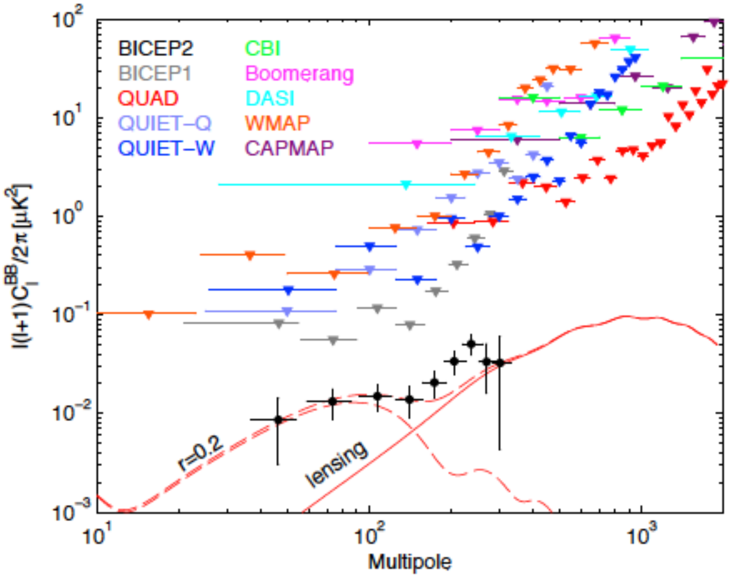
Primordial B-modes ?

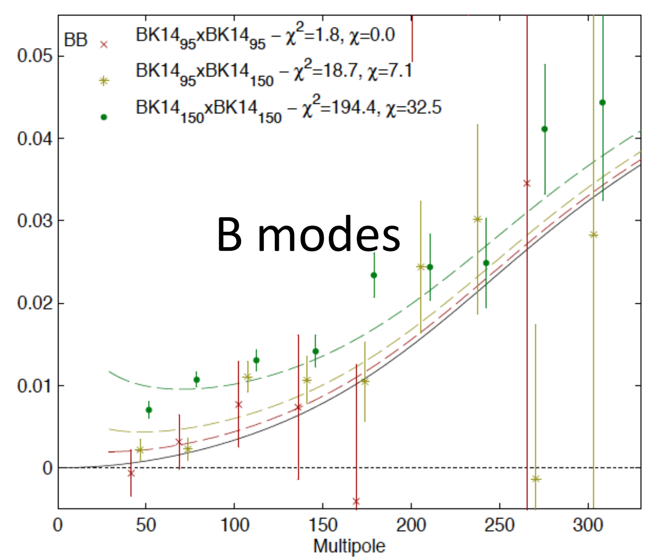
BICEP2 hint of B modes: *PRL 112, id.241101 (2014)*
Revision with Planck: *PRL 114, id.101301 (2015)*



Dust in the BICEP2 field





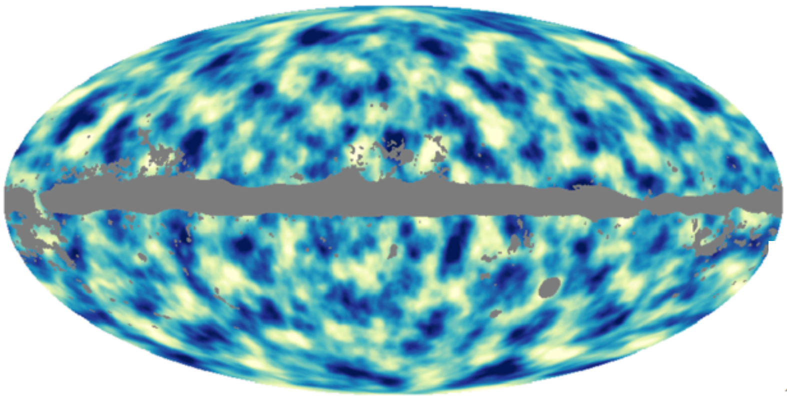


Lensing

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



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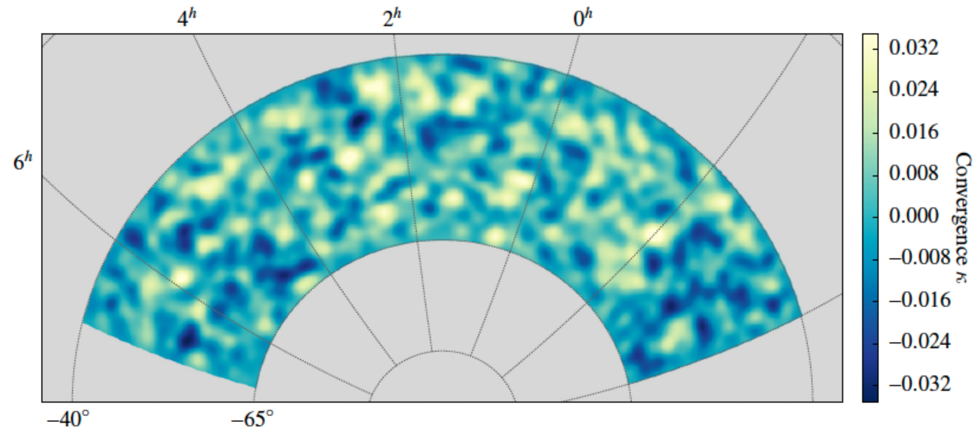
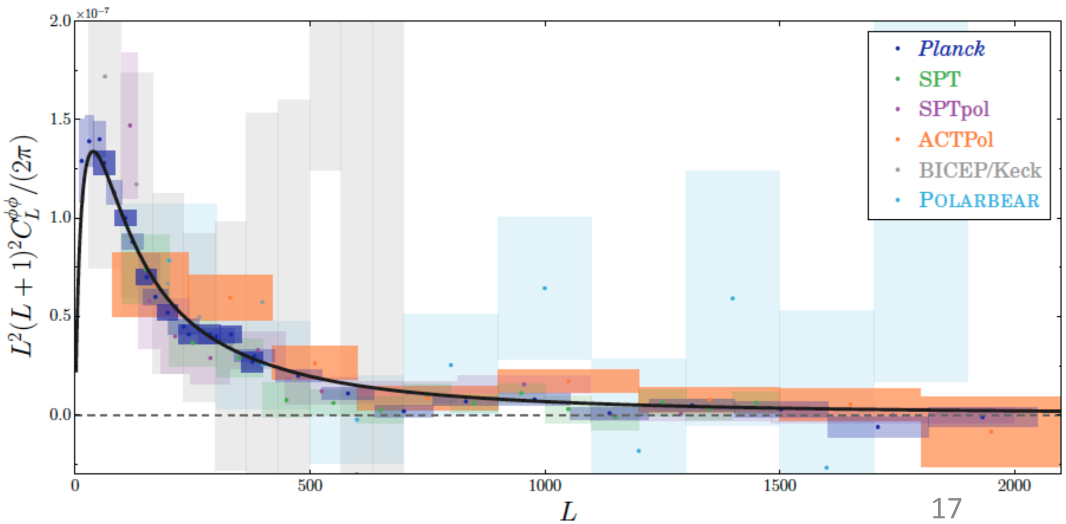




De-lensing

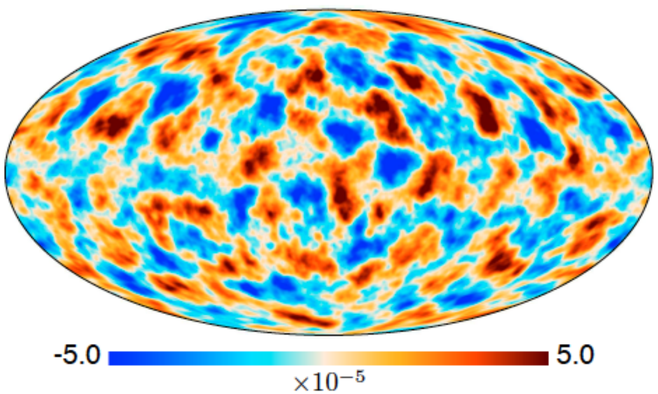
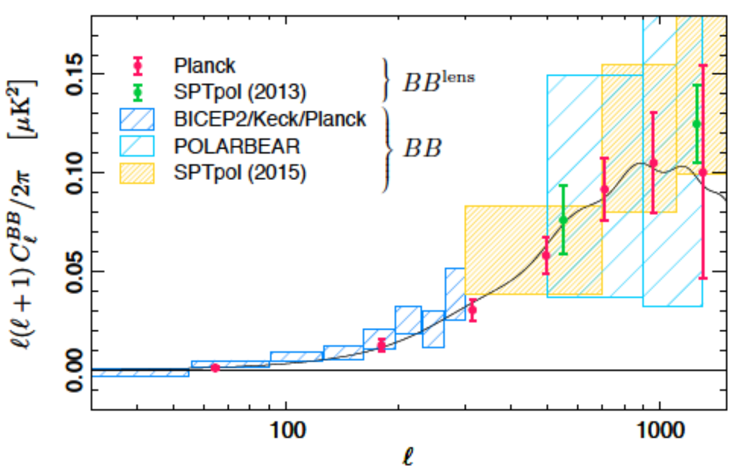


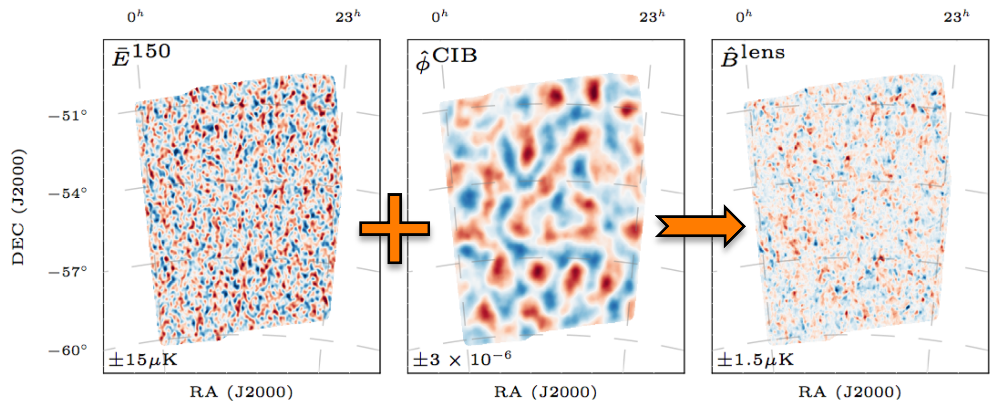
Figure 1. Wiener-filtered lensing potential estimated from the SMICA foreground-cleaned temperature map using the $f_{\rm sky} \simeq 80\,\%$ lensing mask.

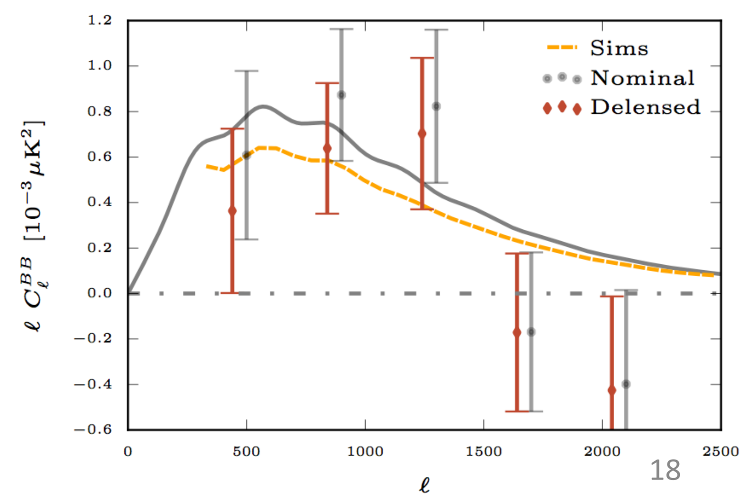
Planck



Planck collaboration A&A 596, 102 (2016)

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

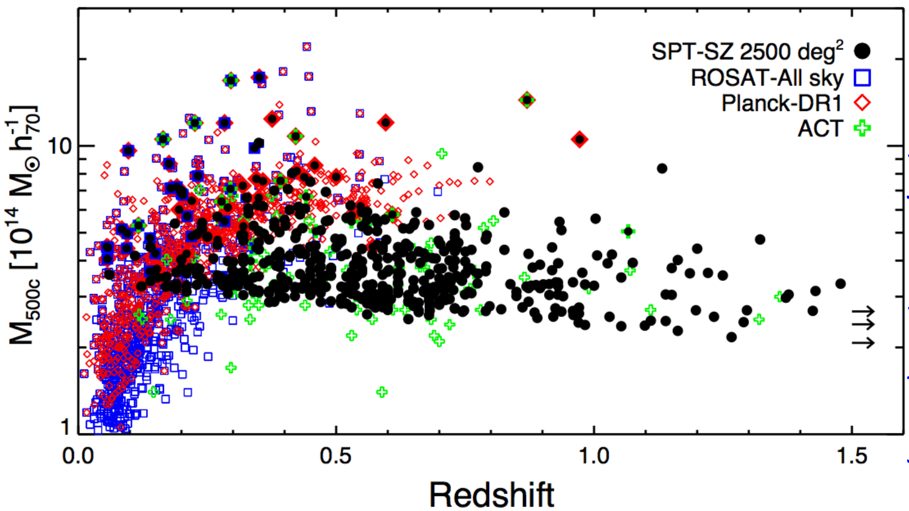




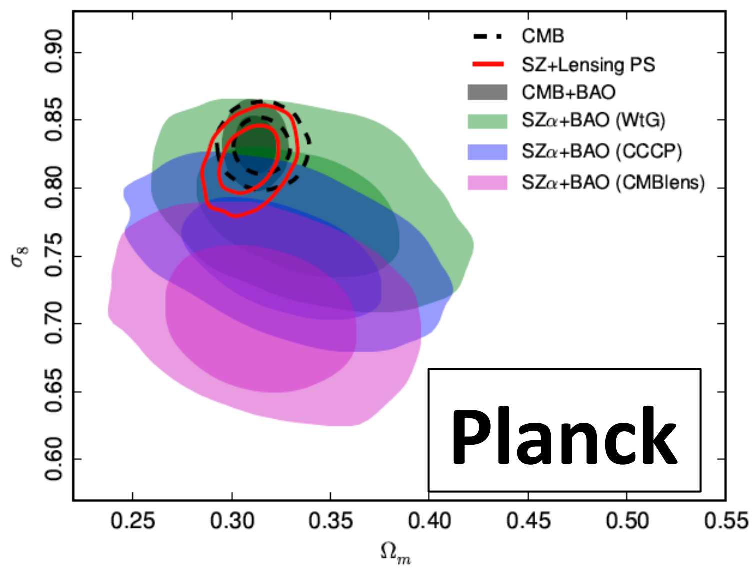
SPT

Manzotti et al. arXiv:1701.04396

Galaxy clusters



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

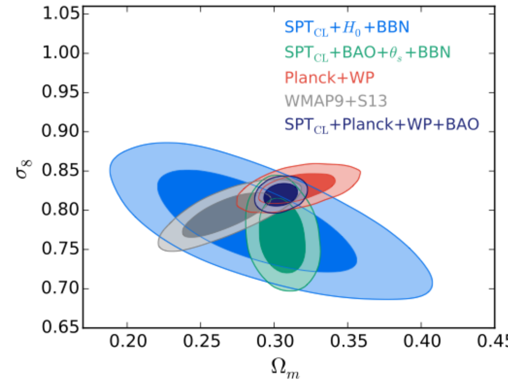


Planck collaboration A&A 594, 24 (2016)

SPT

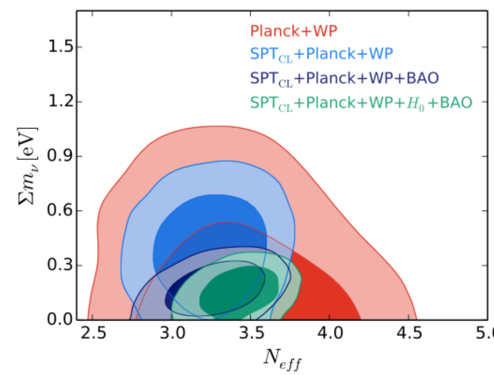
Structures

$\Omega_m - \sigma_8$



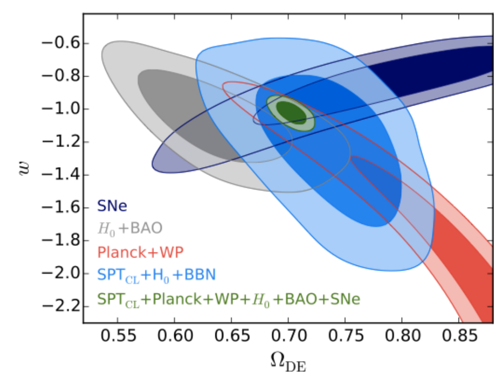
Neutrinos

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

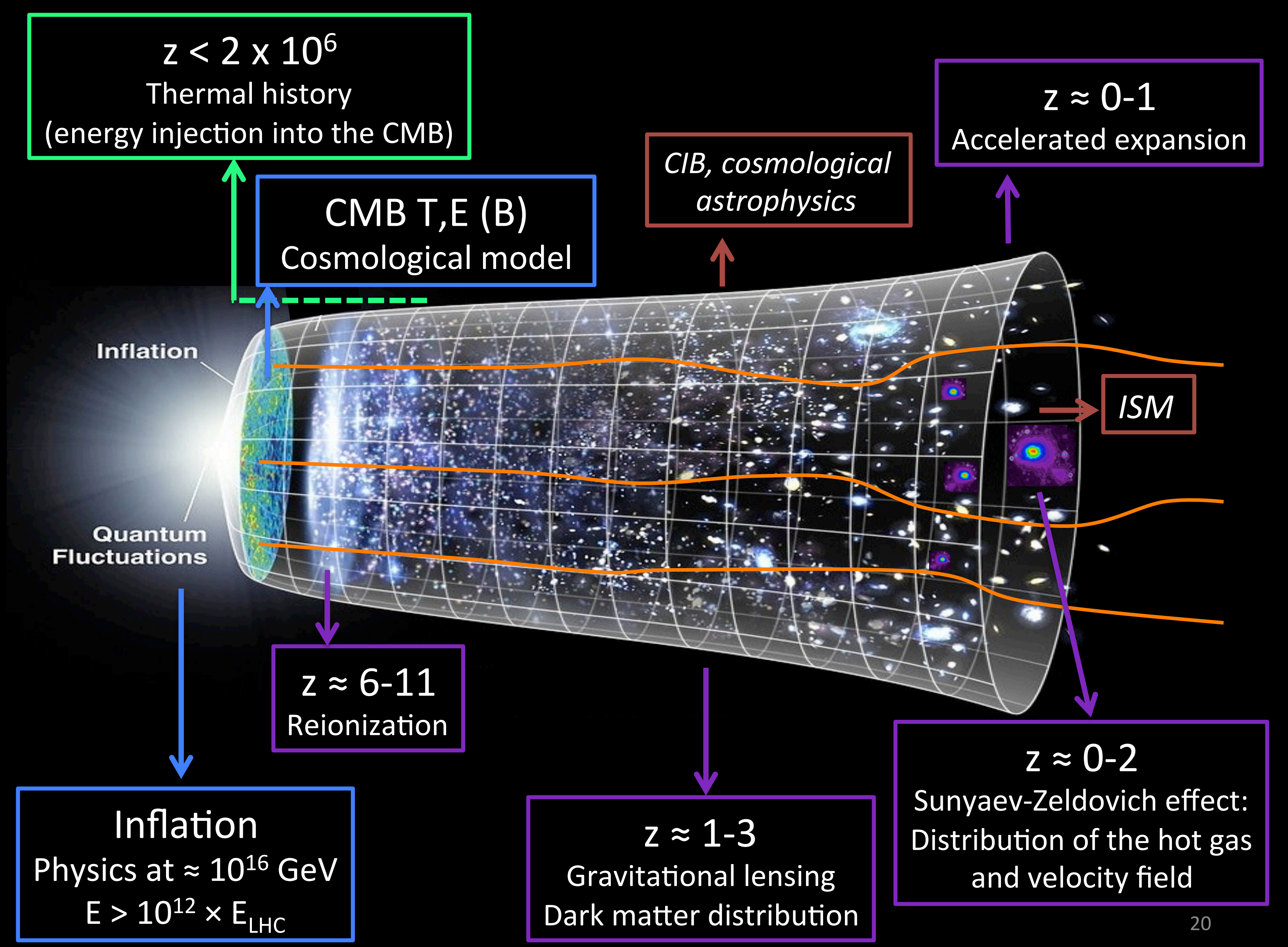


Dark Energy

$\Omega_{DE} - w$



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



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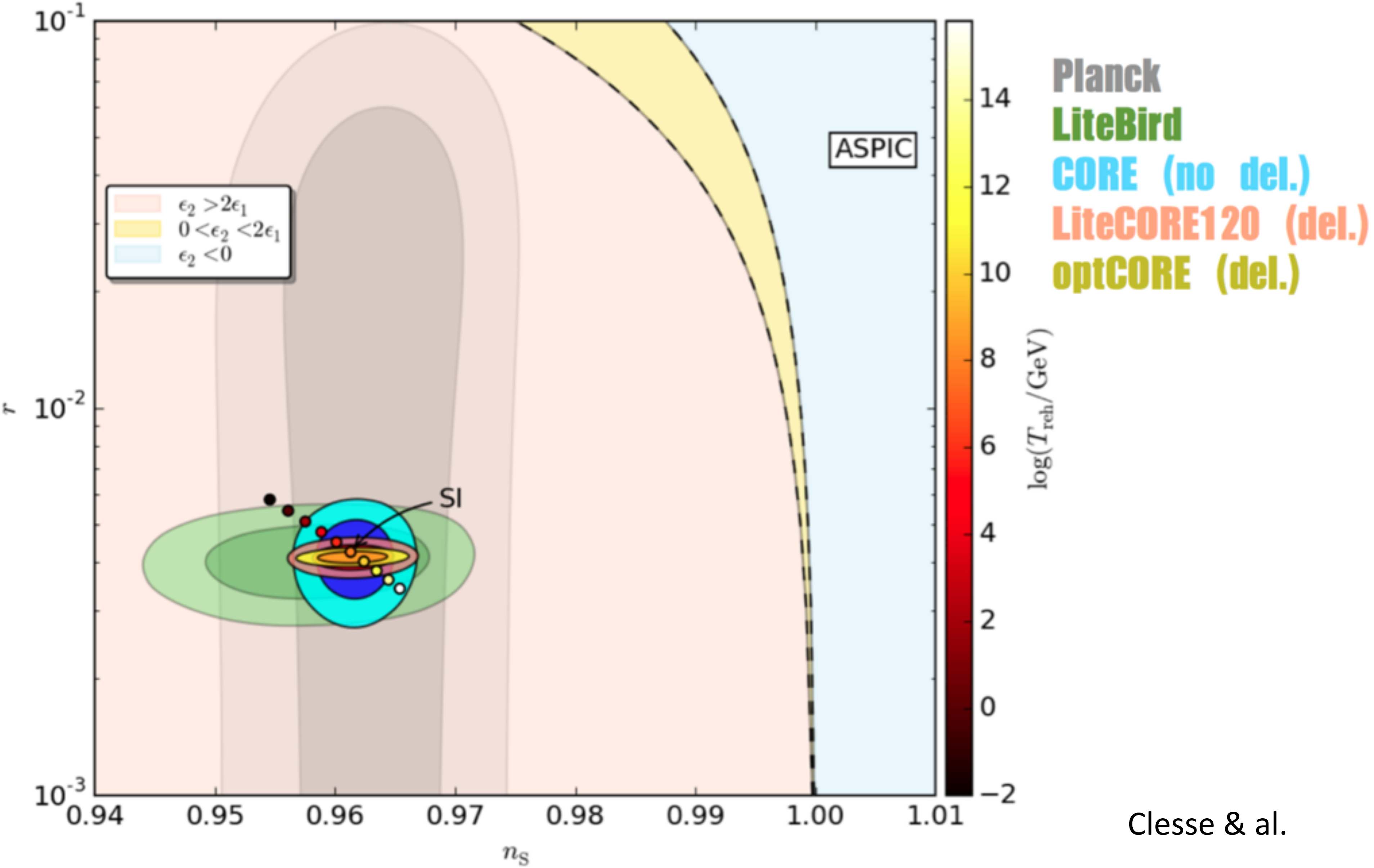


10^{-1}
10^{-2}
10^{-3}
r
0.94
0.95
0.96
0.97
0.98
0.99
1.00
1.01
n_S
$\epsilon_2 > 2\epsilon_1$
$0 < \epsilon_2 < 2\epsilon_1$
$\epsilon_2 < 0$
ASPIC
SI
14
12
10
8
6
4
2
0
−2
$\log(T_{reh}/GeV)$
Planck
LiteBird
CORE (no del.)
LiteCORE120 (del.)
optCORE (del.)

Clesse & al.

CMB polarization with CORE (M-class)

Primordial BB modes are very important but uncertain:

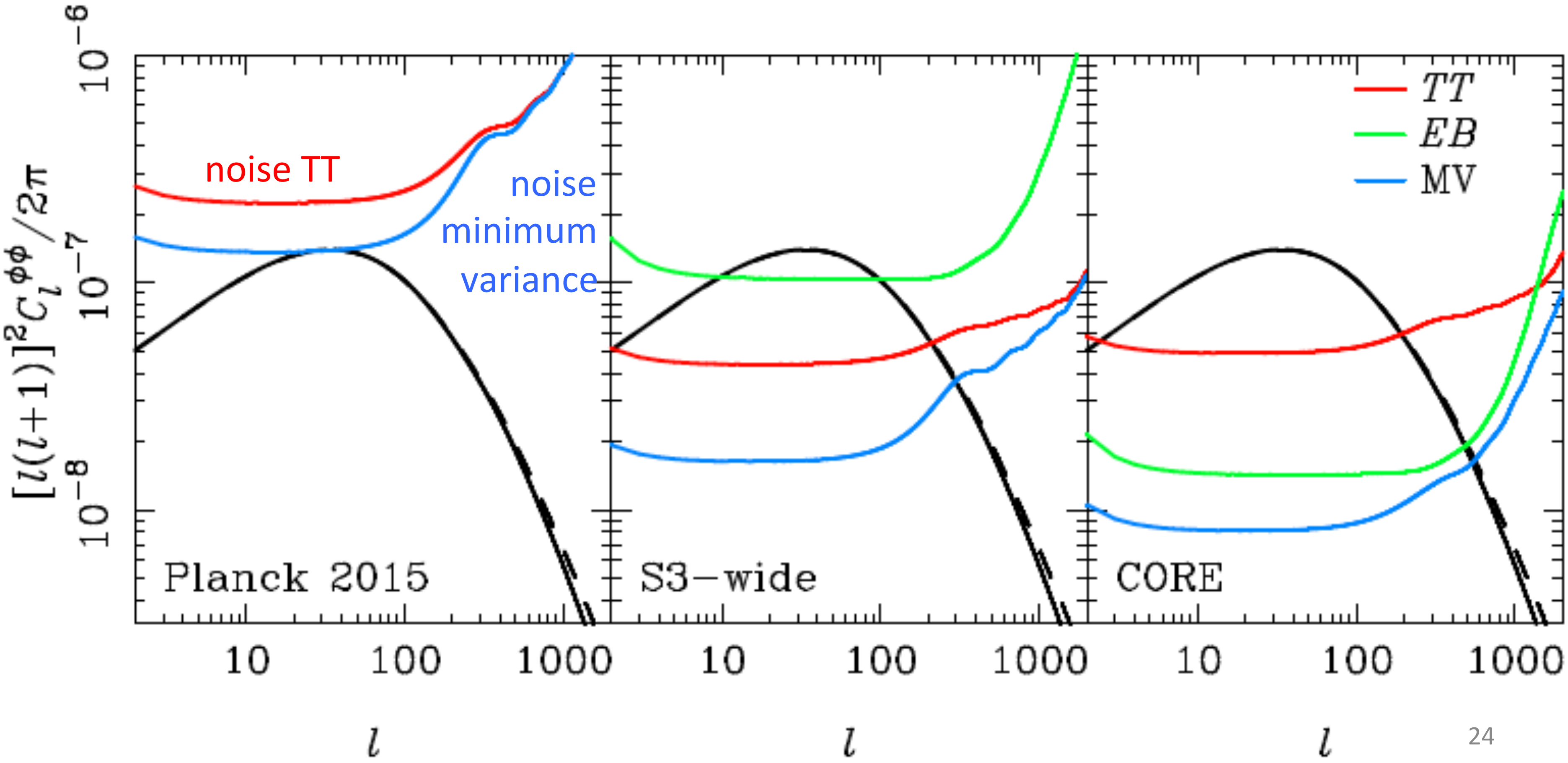
- *foregrounds* are a potential killer at l < 10;
- *lensing* and foregrounds are issues at l≈80;
- ground observations will improve in the next 10 years (r ≈ 0.005-0.01 ?);
- *r could be << 0.001,* beyond detection capability;
- the risk of "detecting" r = 0.002 ± 0.001 should be avoided.

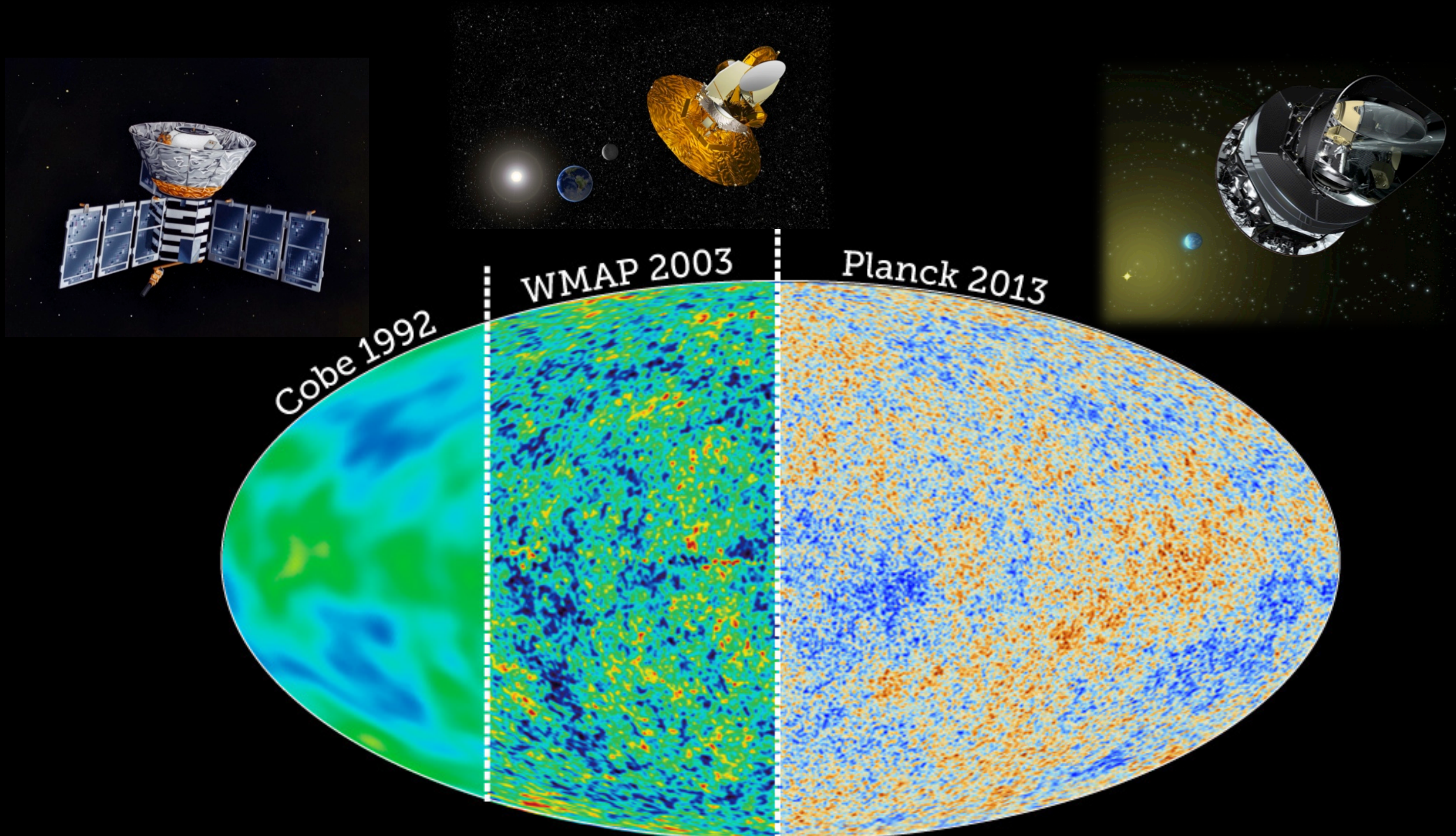
CORE avoids these risks with:

- targeting primordial B-modes *down to "reasonable" fundamental limits,* after ***both*** de-lensing & foreground subtraction (error on r ≈ 0.0004);
- *guaranteed* high-value "near-optimal" **CMB polarization** science;
- *guaranteed* rich legacy.

Signal to noise in lensing maps

- CORE can make signal-dominated full-sky maps of the lensing potential down to 20'
- Improvement comparable to COBE-DMR to WMAP for anisotropies




Cobe 1992
WMAP 2003
Planck 2013

Discovery space

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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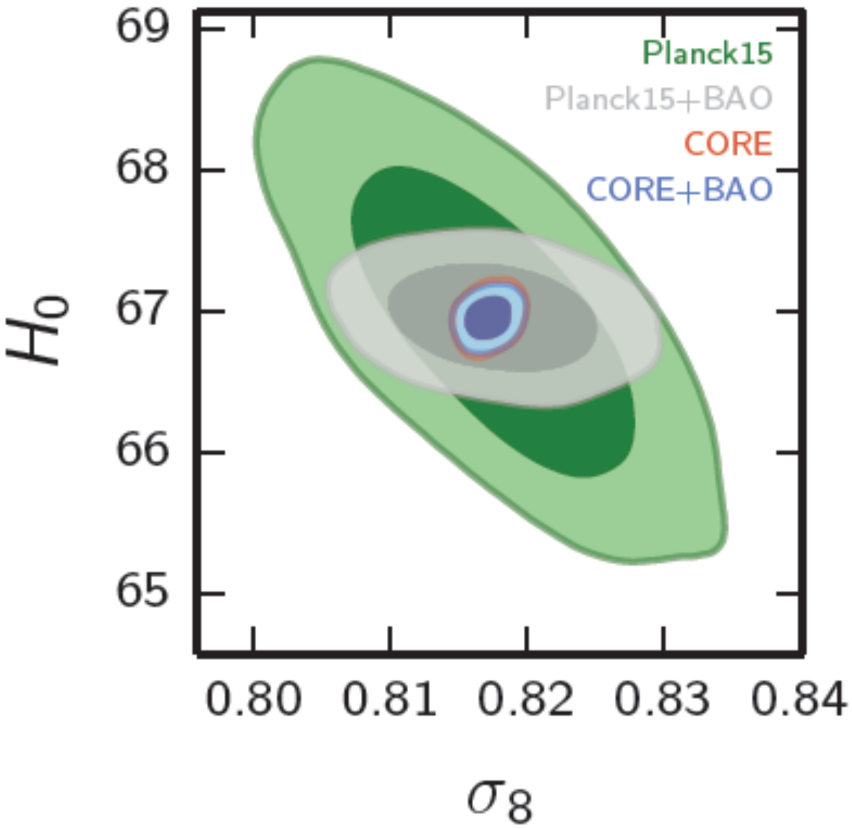
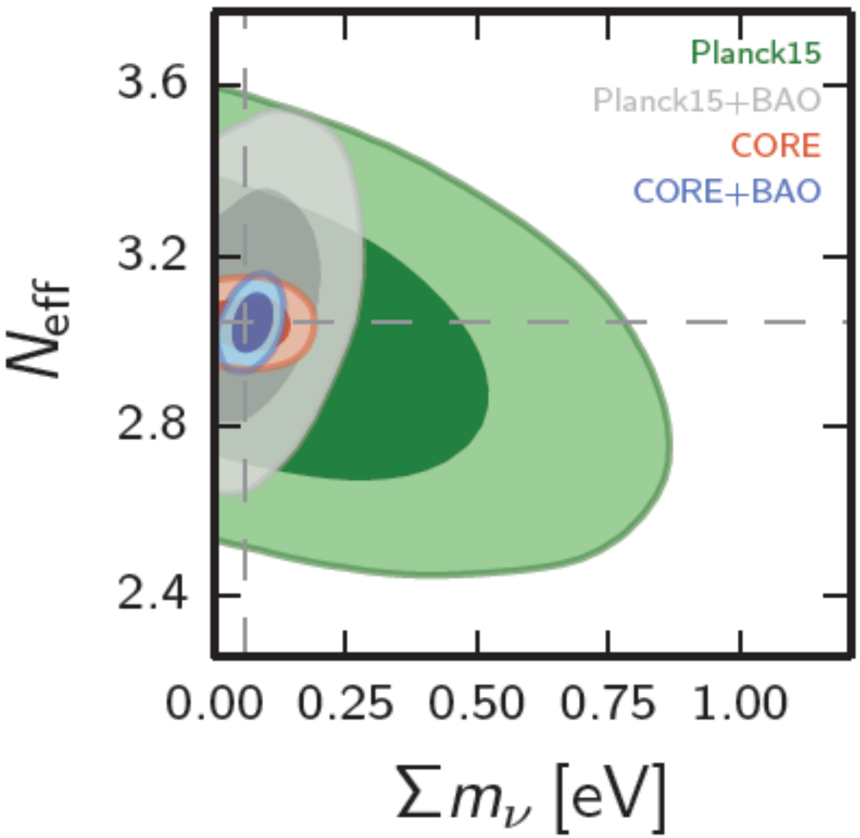
The CMB can still reduce the error box volume **by a factor >10^6**

Parameter constraints

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





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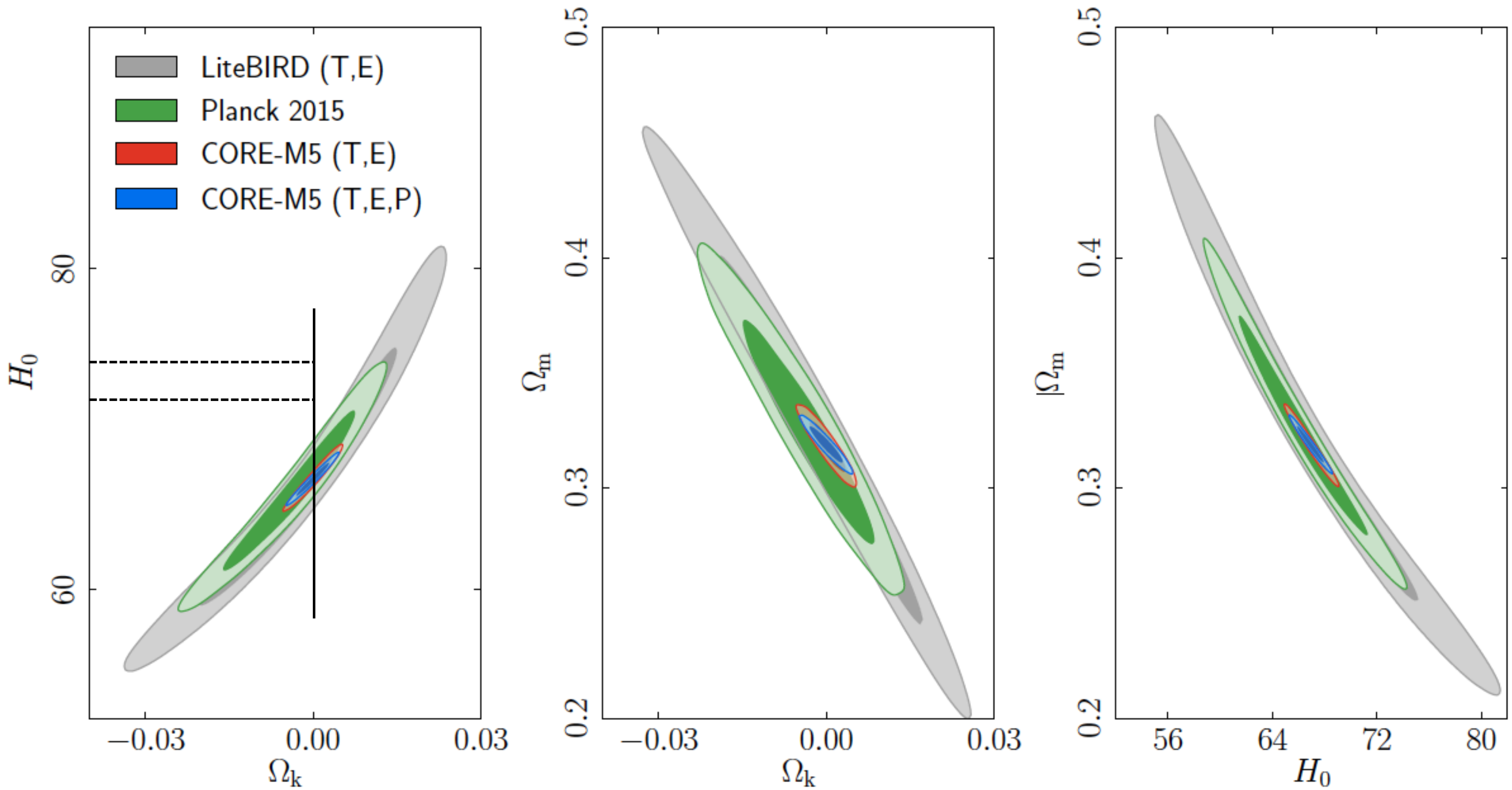
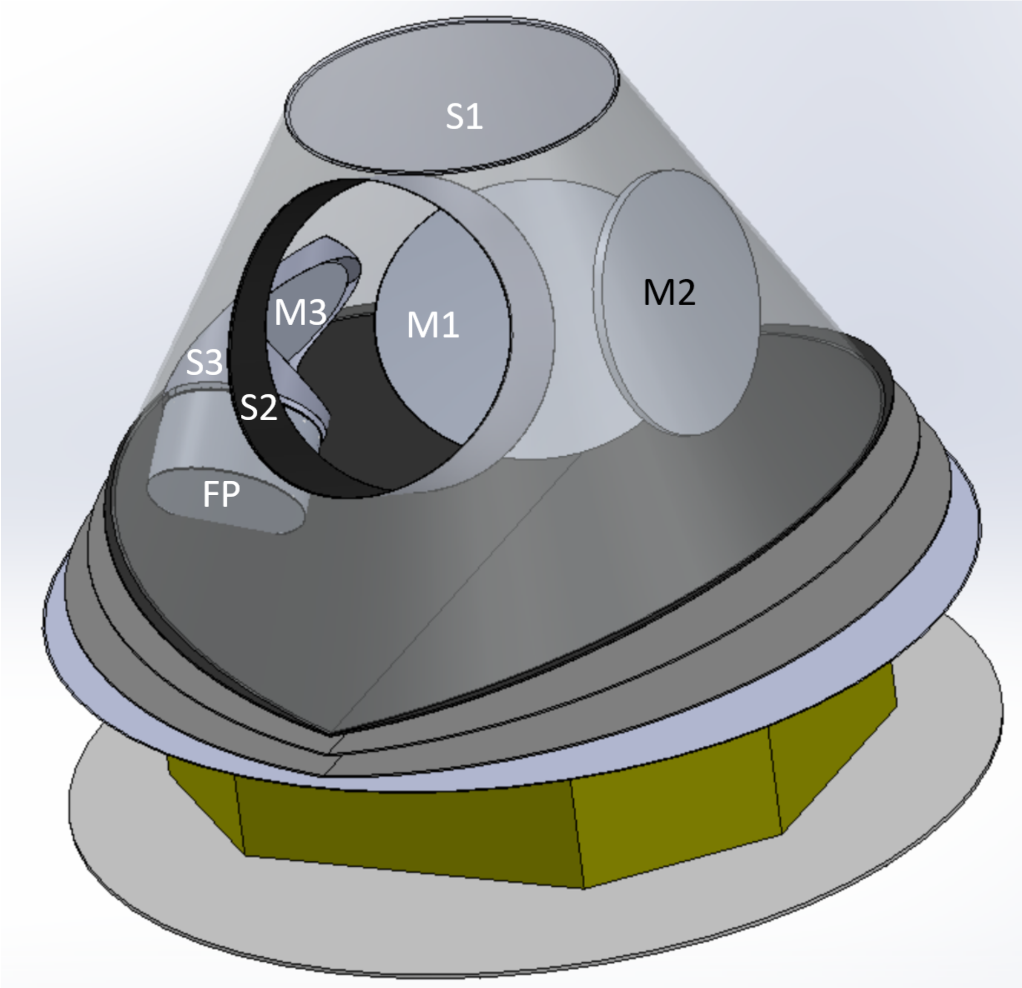


Figure 12: Forecast 68 % and 95 % CL marginalized regions for (Ω_k, H_0) (left panel), (Ω_k, Ω_m) (middle panel) and (H_0, Ω_m) (right panel) for LiteBIRD (grey) and CORE-M5 (blue) obtained by allowing Ω_k to vary. These forecasts assume $\Omega_k = 0$ as fiducial value. The 68 % and 95 % CL marginalized 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.

CORE: a simple and robust design for M5

- One single instrument
- Passively cooled PLM
- Single frequency, single polarization detectors[a]
- No moving part in the cold payload
- Spinning at ½ rpm
- 19 frequency bands
- A ***lot*** of redundancy
- Sensitivity margins
- Guaranteed science



(a) Safest option taking into account European technological readiness at time of submission

References

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. arXiv:1707.02259
- 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. arXiv:1707.04224

Over 500 useful pages of discussion and comparison of options constitute a reference for the optimization of the mission scientific scope and design.

Status

- After the M4 proposal (CORE+), guidance was provided by the ESA-(JAXA) CDF study
  - No technical showstopper, but developments needed;
  - Suitable for a collaboration at ≈20% level;
  - Recommendations for simplification;
  - Joint mission with JAXA would have been a logical outcome, but did not materialize.

- With no firm commitment from an international partner, CORE was proposed as a (simplified) standalone mission.

- It did not pass the initial ESA screening. The main issue was cost (ESA estimated overcost ≈ 30%).

- Solutions
  - Simplify drastically (hard to envisage without compromising the science);
  - Find an international partner (interest in India, ongoing study in the US).

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Other CMB polarization projects

- **CMB-S4 (ground-based) in preparation in the US**
  - Objective: detect $r \geq 0.003$ or constrain $r < 0.001$ (95% CL)
  - 3 to 8% sky coverage for r, using fourteen 0.5m telescopes and one 6m telescope, 4x2 channels from 20 to 270 GHz; 240,000 detectors;
  - 40% sky coverage using two 6m telescopes (for N_{eff}); 140,000 detectors;
  - Budget 412 M$ + running costs; If funded, observations in 2027+ (Source: CDT document);

- **LiteBIRD is in phase A in Japan**
  - Objective: $\sigma_r = 0.001$
  - Frequency coverage 40-400 GHz in 15 bands, most of CMB sensitivity between 140 and 200 GHz (where dust is the dominating foreground); Large scales only (FWHM 30'-60');
  - If selected by JAXA (decision ≈ early 2019?), launch foreseen in 2027+;

- **Missing:**
  - **Full sky coverage with resolved CMB polarization (i.e. FWHM ≈ 5');**
  - **Channels to monitor and map thermal dust polarization and the CIB;**
  - **Spectroscopy;**
  - **A role for Europe!**

A CMB mission in partnership with India ?

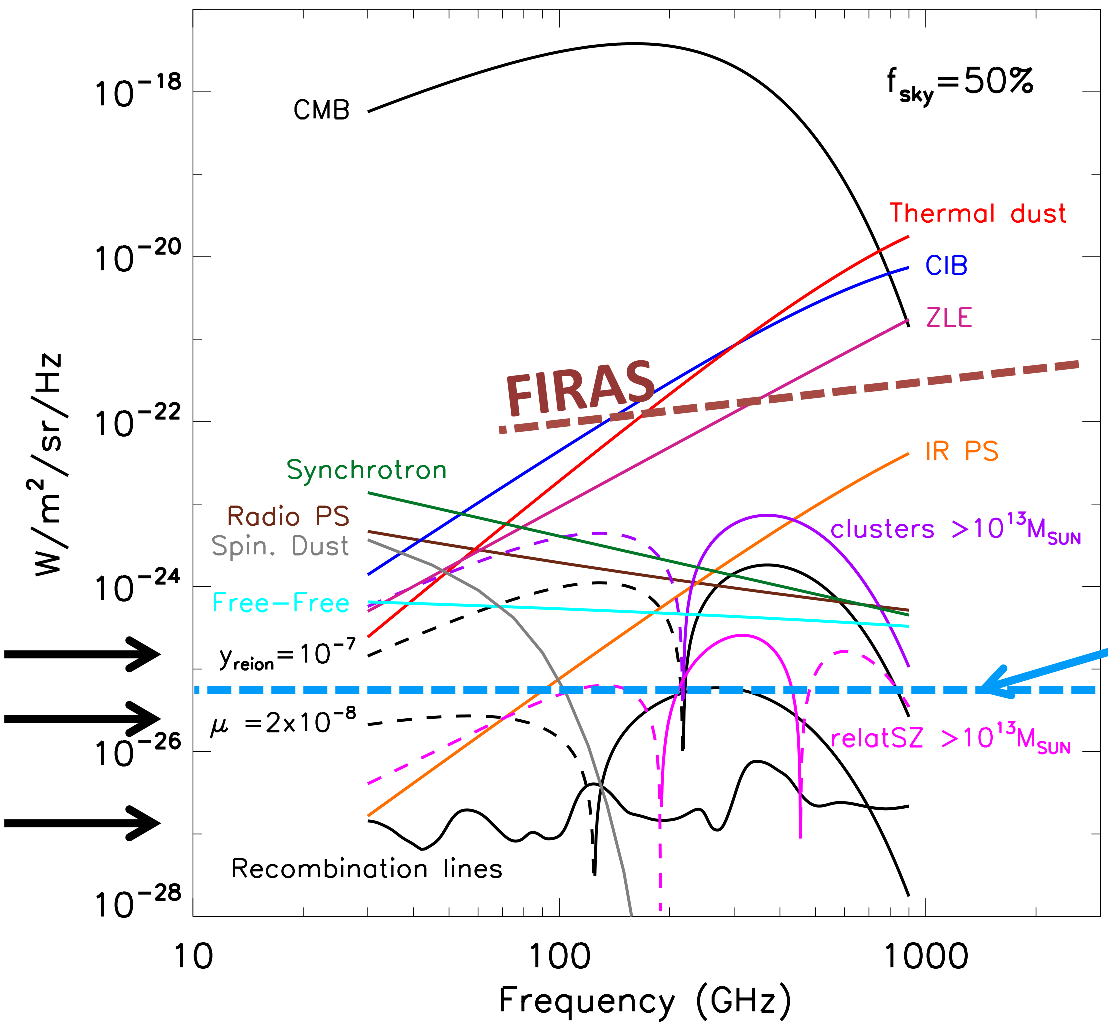
- ISRO launcher GSLV Mrk-III seems adequate for CORE.

- ISRO scientific satellites:
  - Successful Moon and Mars orbiters;
  - Successful Astrosat mission;
  - Planned solar mission to L1;
  - Past experience of a mission with CNES (Megha-Tropiques).

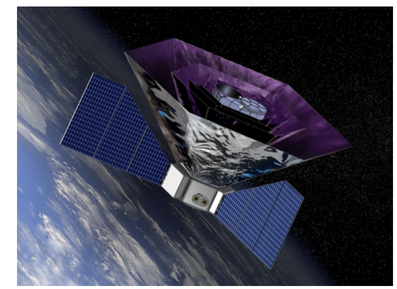
- Preliminary discussions for a CMB mission are encouraging.

- Some options:
  - Refocus for optimized complementarity with LiteBIRD and S4;
  - Pointed observation mode;
  - MiniCORE + Absolute spectrometer (smaller than PIXIE).

Spectral distortions ?

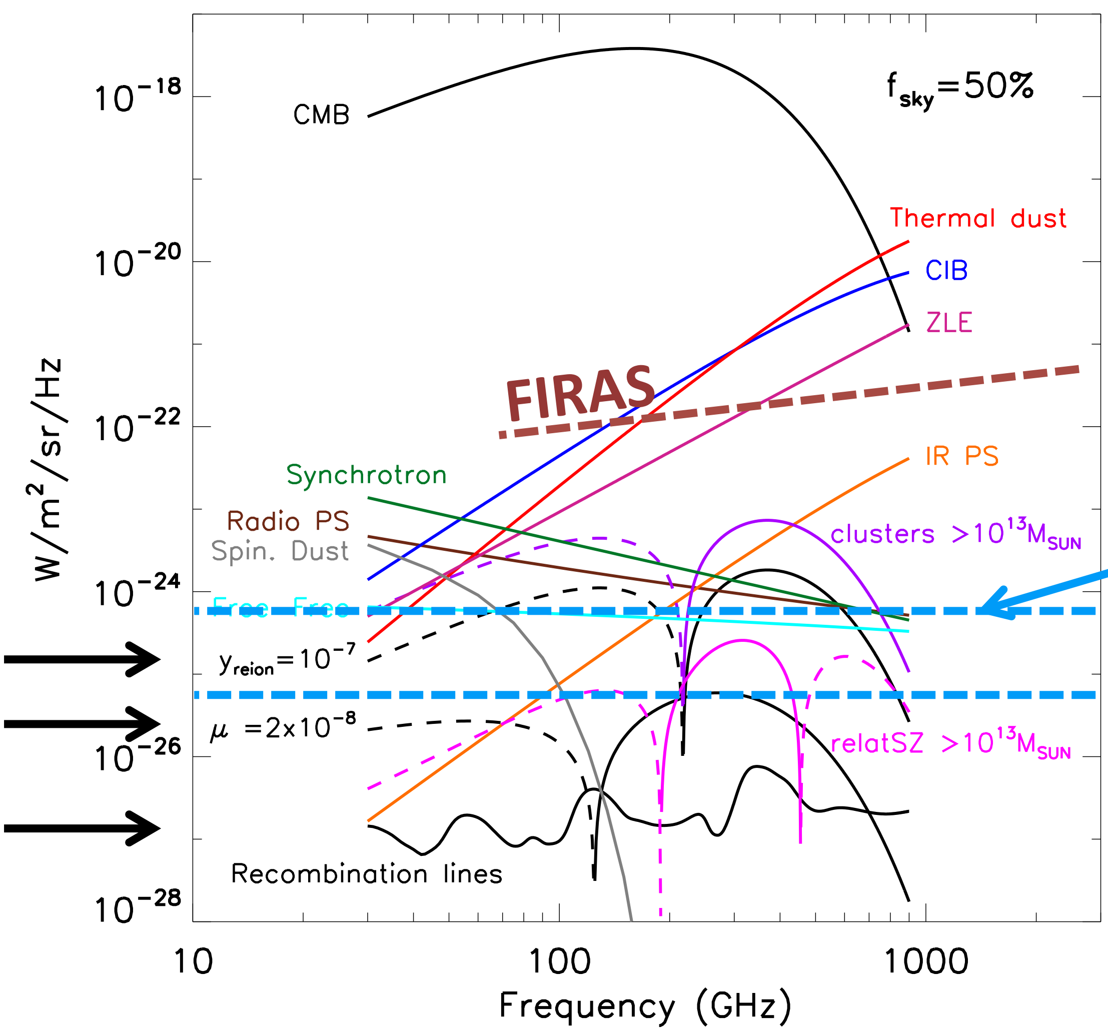


CMB spectral distortions



Noise 5 Jy/sr (PIXIE)

Spectral distortions ?



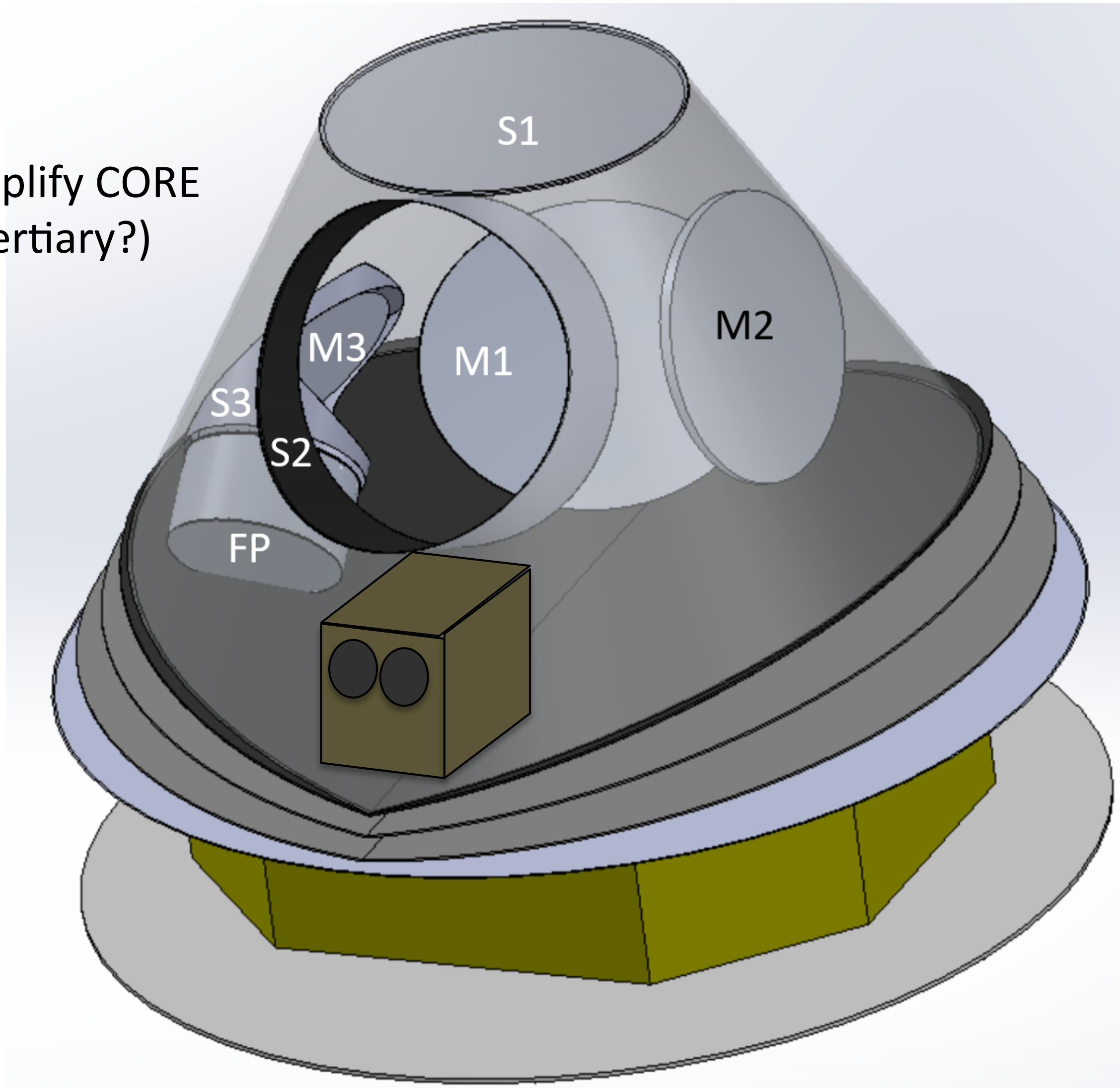
CMB spectral distortions

Noise 50 Jy/sr

MiniCORE + MiniPIXIE ?

Reduce / simplify CORE
(remove tertiary?)

Small absolute
spectrometer?



Outline

- CMB science and challenges
- Hot CMB topics
- The CORE space mission
  - *Context*
  - *Scientific objectives*
  - *Mission design*
  - *Status and feedback*
- What next?
  - *Evolving context*
  - *Option of a mission with India ?*
- Summary

Summary

- A very rich science case towards primordial B-modes and beyond.
- To address it, CORE and PIXIE were strongly recommended in the French 2016 CMB roadmap (for good reasons).
- Their non-selection leaves **crucial gaps** in the CMB programme, not covered by CMB-S4 or LiteBIRD as currently proposed:
  - full sky coverage on scales smaller than ≈1 degree is lacking;
  - full-sky de-lensing capability is lacking;
  - high frequency foregrounds monitoring must be improved;
  - absolute spectroscopy reference is now 25 years old (FIRAS).
- A space mission (or possibly two!) is needed to cover these gaps.
- We must prepare this future now.