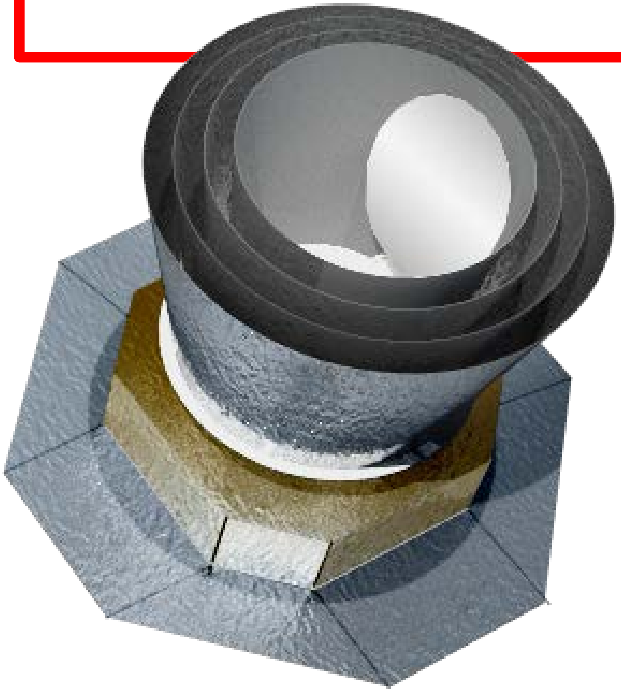
From fundamental physics to the CMB:

Prospects and challenges
for a next-generation CMB space mission



Jacques Delabrouille

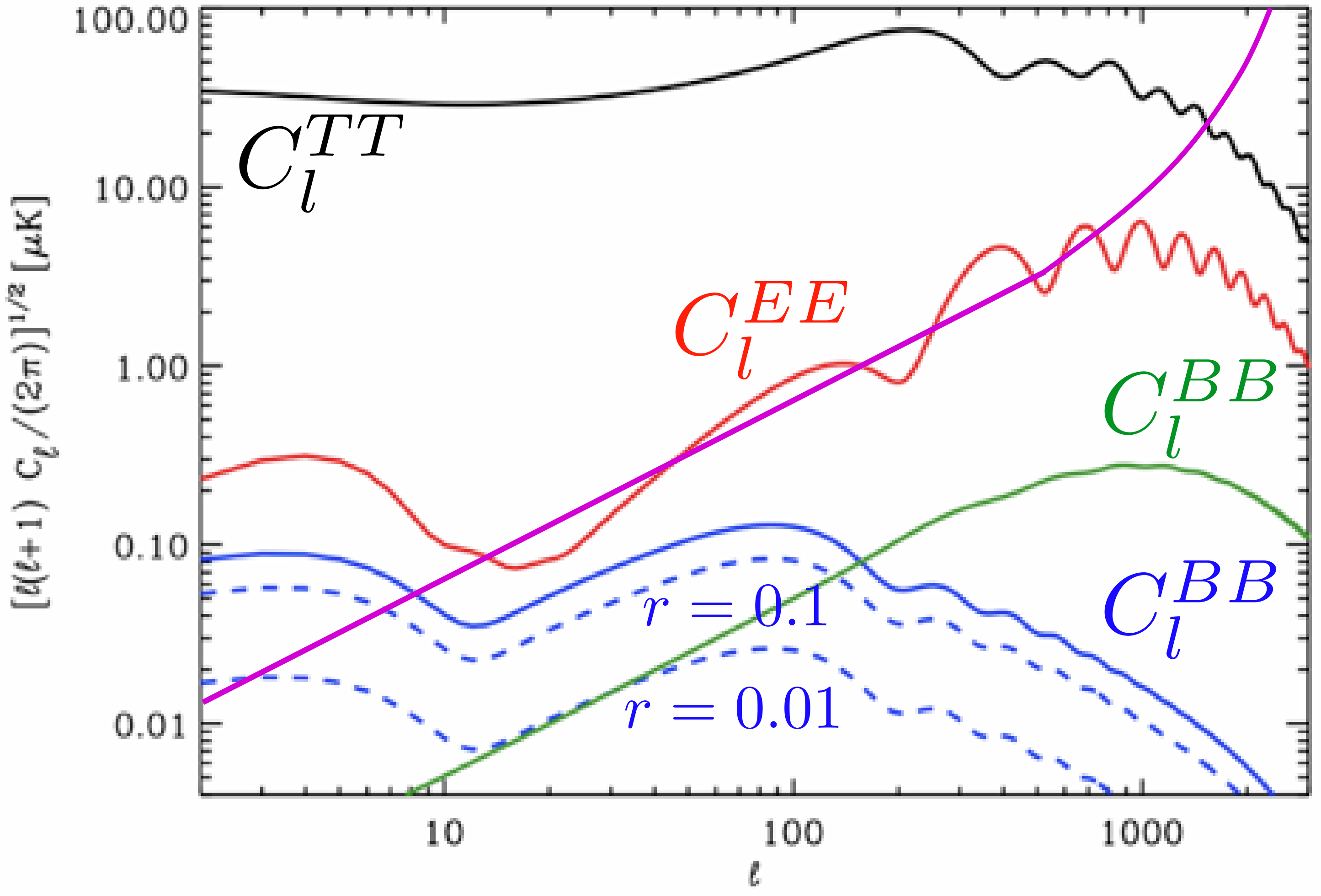
Laboratoire APC, Paris, France

Outline

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

Where are we ?

plot adapted from J. Carlstrom's P5 talk

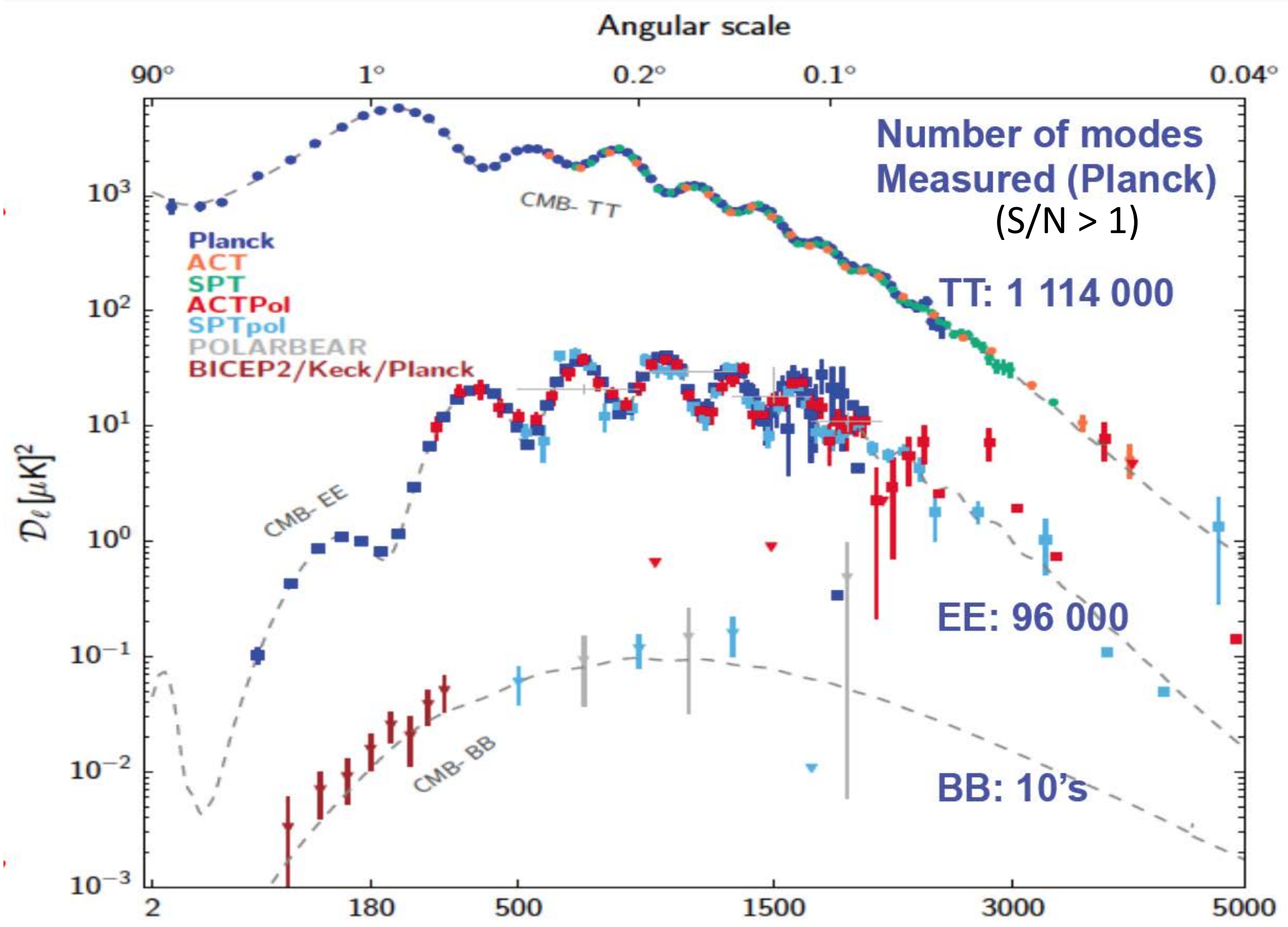


noise
50 uK. arcmin
(ΔP Planck)

Lensing of EE

Inflationary
Gravitational
Waves

Where are we ?



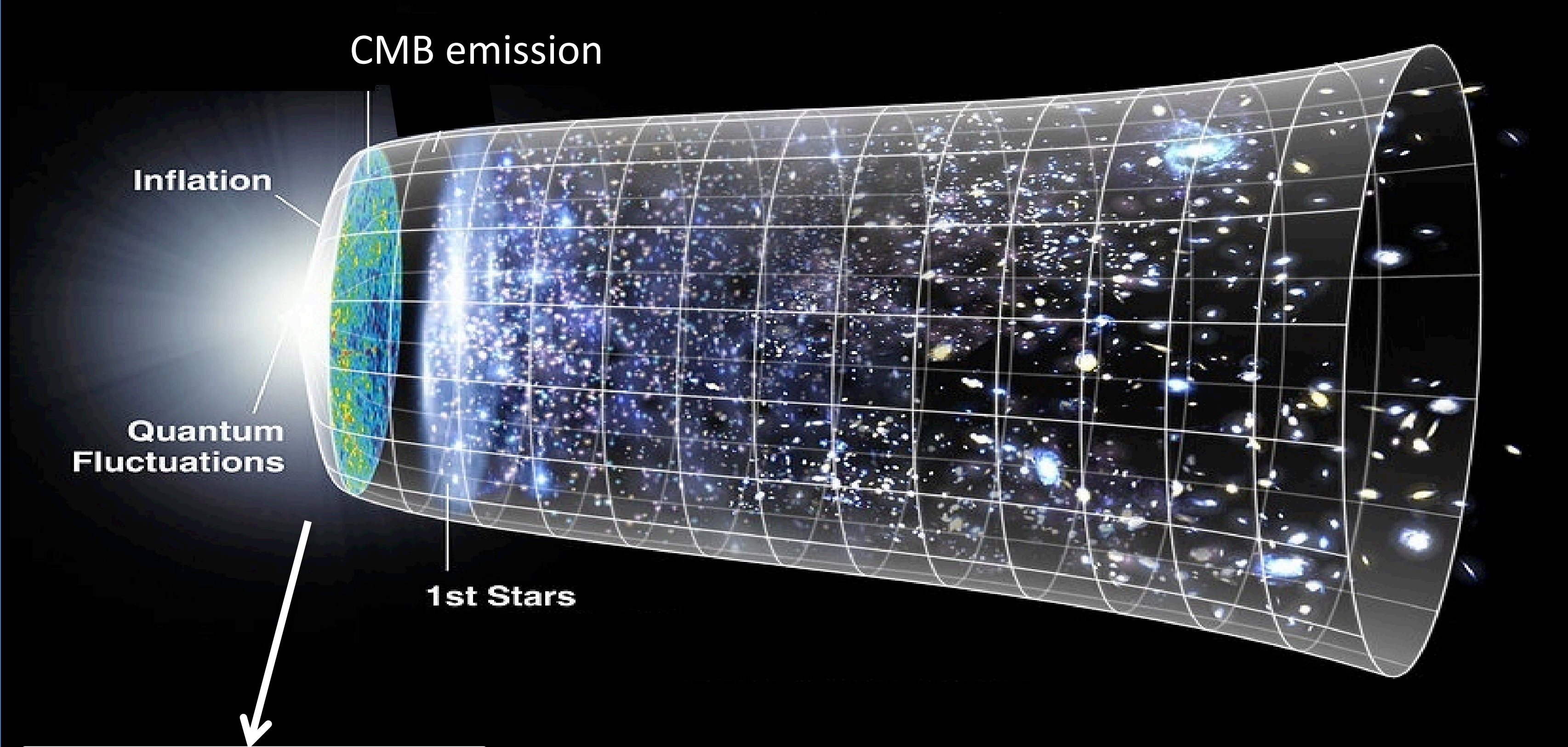
Number of modes Measured (Planck)
(S/N > 1)

TT: 1 114 000

EE: 96 000

BB: 10's

What is left to be done ?



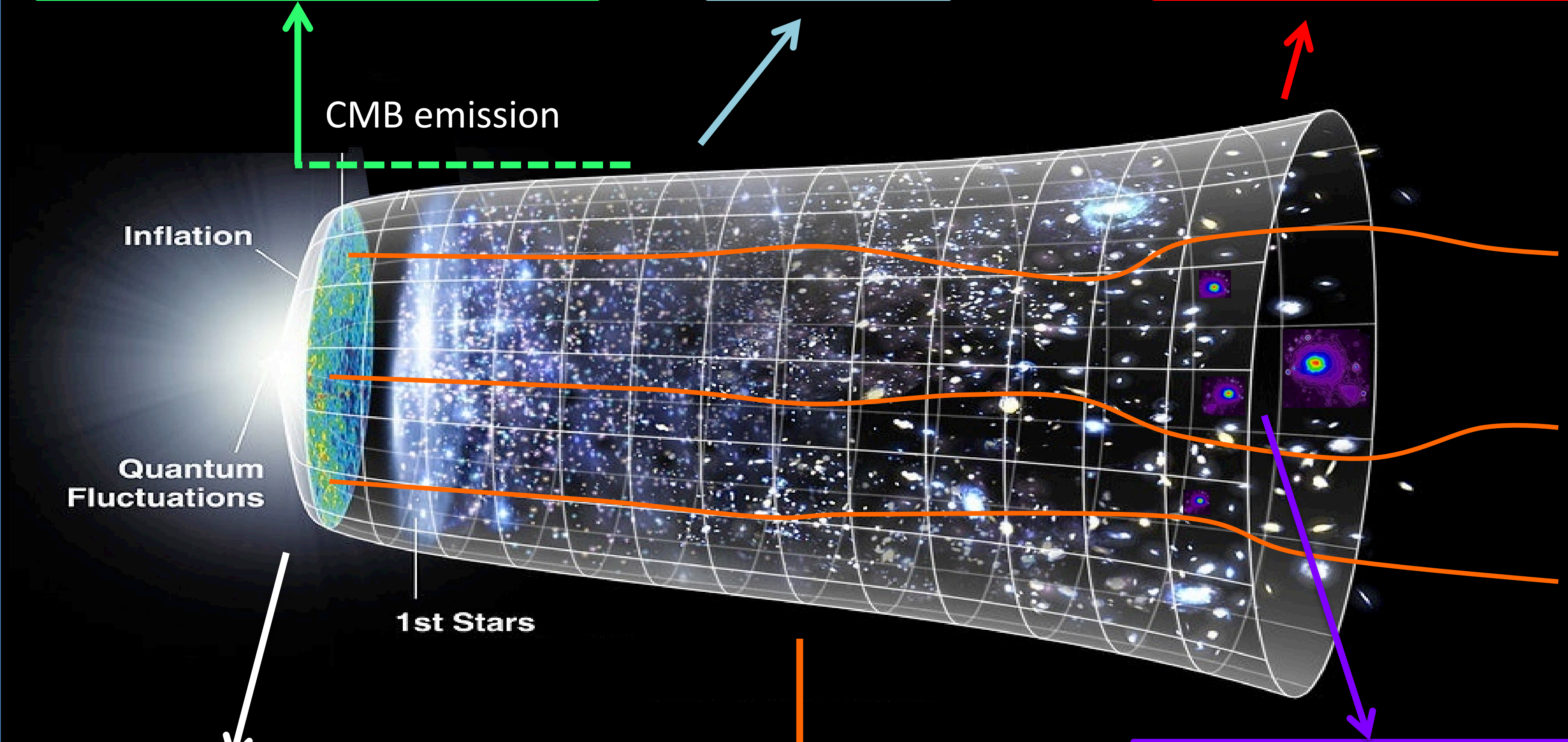
Inflation
Physics at ≈ 10^{16} GeV
$E > 10^{12} \times E_{LHC}$

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



Inflation
Physics at ≈ 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

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

Requires us to resolve the CMB FWHM < 4'

Requires us to resolve clusters FWHM < 1'

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

Parameter extensions ?

?

Inflationary parameters (initial conditions)

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

Spatial curvature

$$\Omega_k h^2 = 0$$

Dark Energy equation of state

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

Neutrino sector

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

Helium abundance

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

Parameter extensions ?

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The next space mission can reduce the error box volume

by a factor >10^6

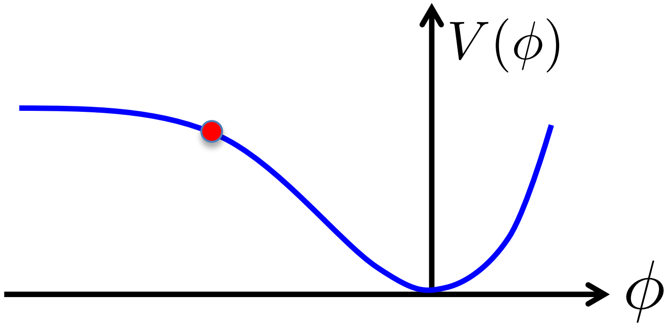
(a factor of ≈5 on each parameter on average)

REQUIREMENT:

measure all spectra with the best accuracy possible

Inflation – slow roll models

Single scalar field inflation
in the slow roll approximation:



Equation of motion $$\ddot{\phi} + 3H\dot{\phi} + V_\phi = 0$$

Friedmann equation $$H^2 = \frac{1}{3{M_{\rm pl}}^2}\left(\frac{1}{2}\dot{\phi}^2 + V\right)$$

Slow roll parameters

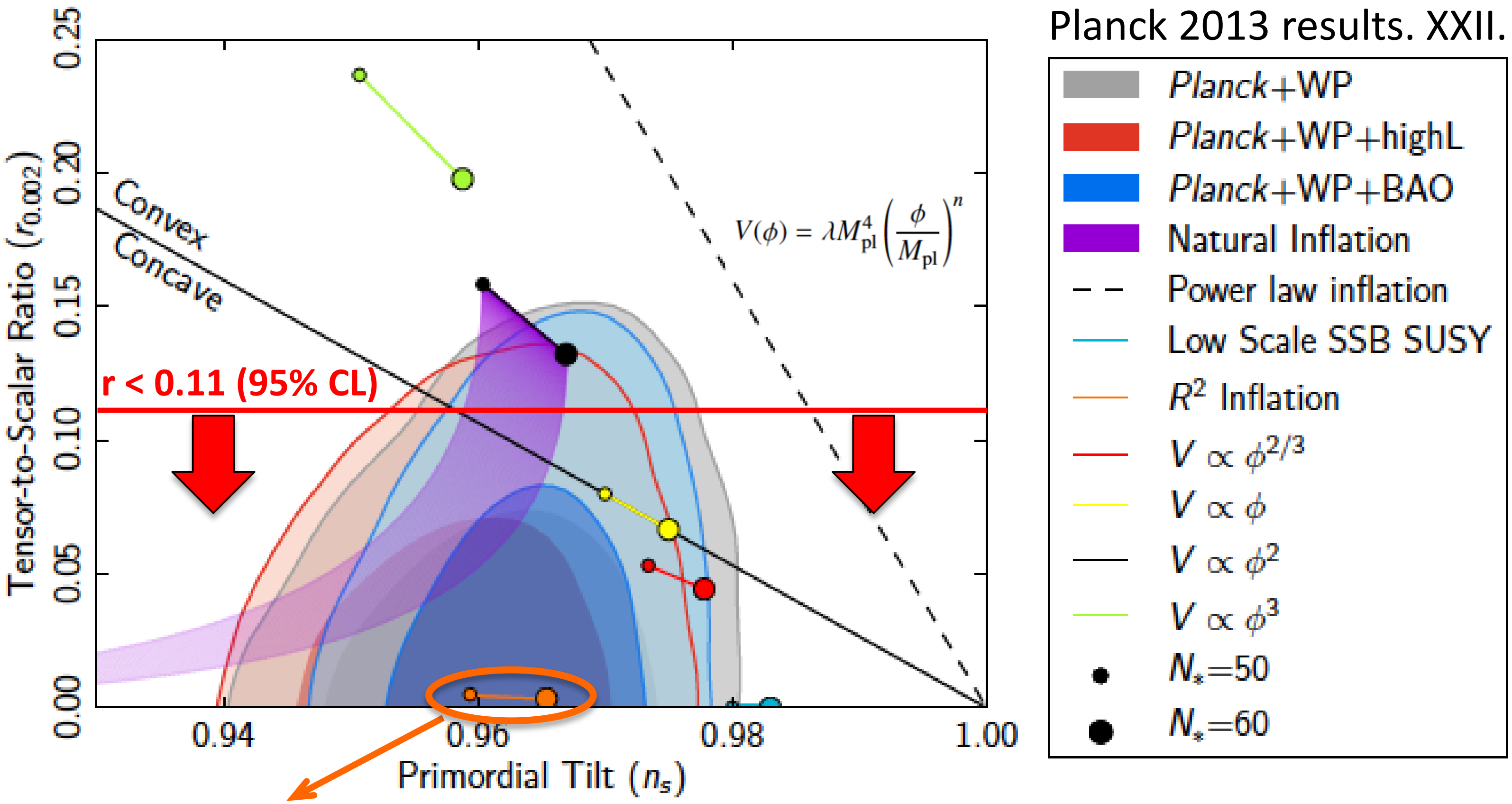
$$\epsilon = \frac{{M_{\rm pl}}^2 V_\phi^2}{2V^2} \qquad \eta = \frac{{M_{\rm pl}}^2 V_{\phi\phi}}{V} \qquad \xi^2 = \frac{{M_{\rm pl}}^4 V_\phi V_{\phi\phi\phi}}{V^2}$$

Inflation – slow roll models

The slow roll parameters are connected to the primordial spectra of scalar (density) and tensor (gravitational waves) perturbations

scalar spectral index	$n_s - 1 = 2\eta - 6\epsilon$
tensor spectral index	$n_t = -2\epsilon$
running	$\frac{\mathrm{d}n_s}{\mathrm{d}\ln k} = -16\epsilon\eta + 24\epsilon^2 + 2\xi^2$
tensor/scalar ratio & consistency relation	$r \simeq 16\epsilon \simeq -8n_t$

Planck constraints on inflation (2013)



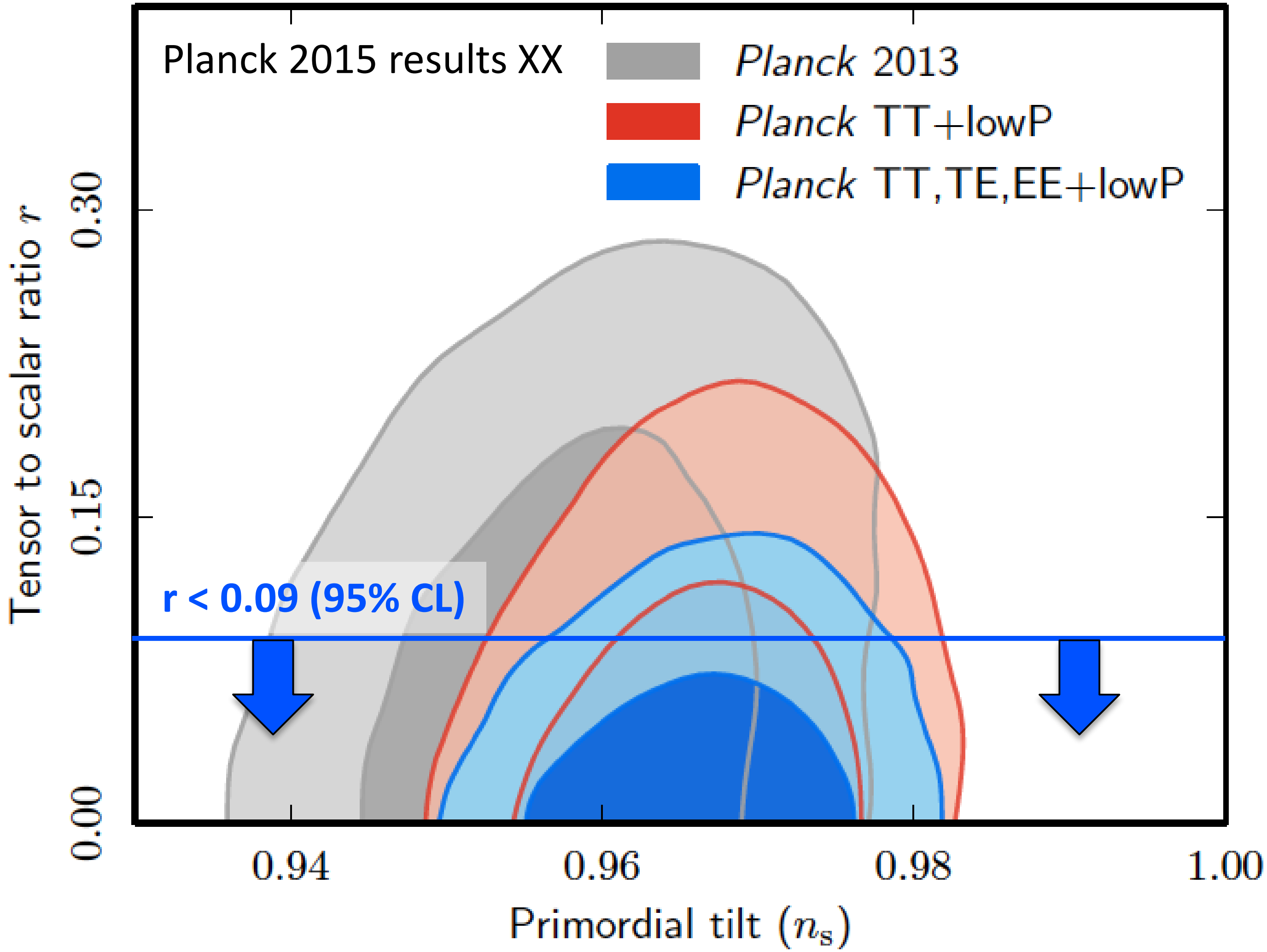
Planck 2013 results. XXII.

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

$r \approx 12/N_*^2$

and hence low tensor modes

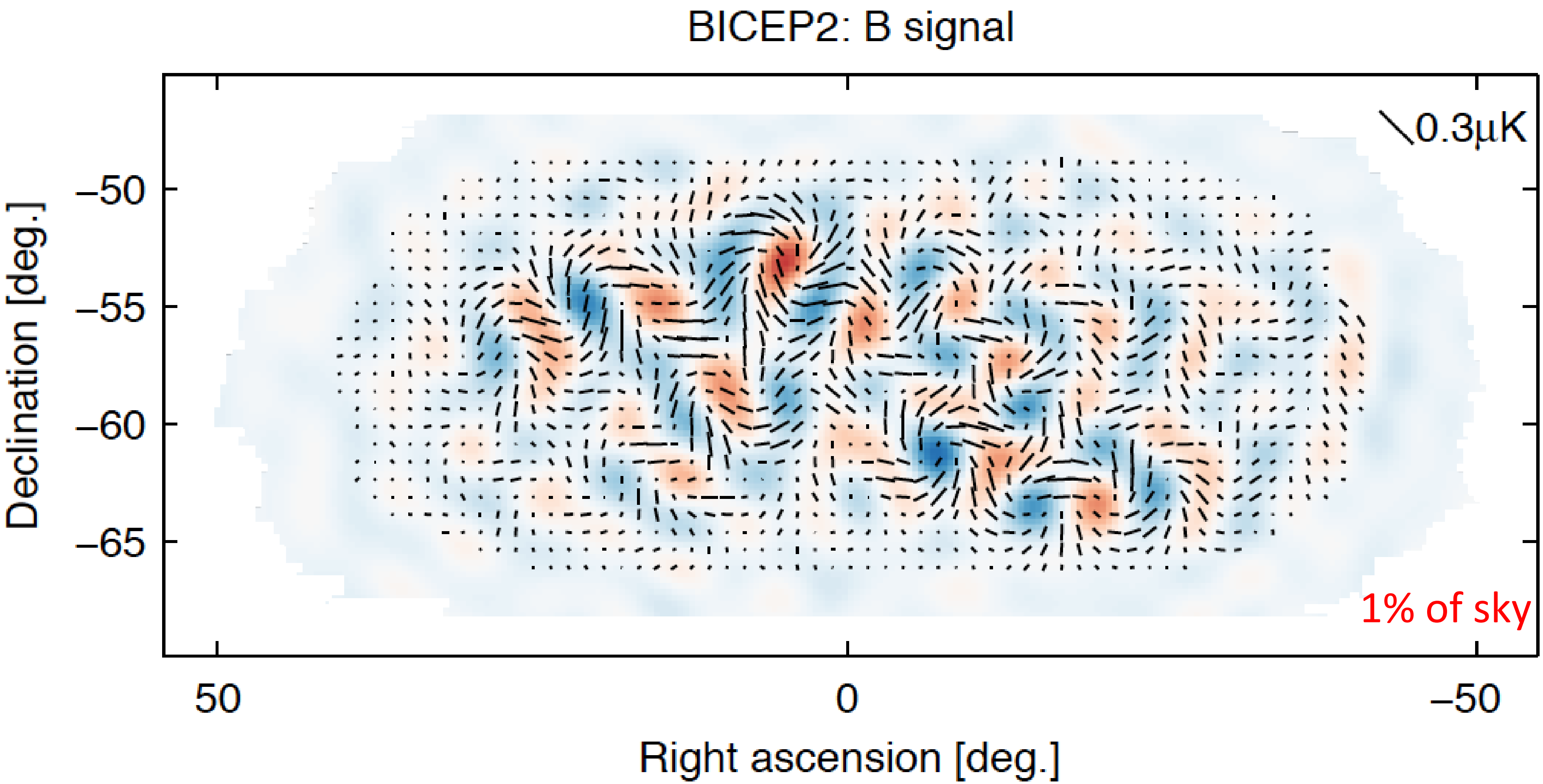
New contours from Planck 2015



Ground-based developments: BICEP2

BICEP2 detects B-modes !

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

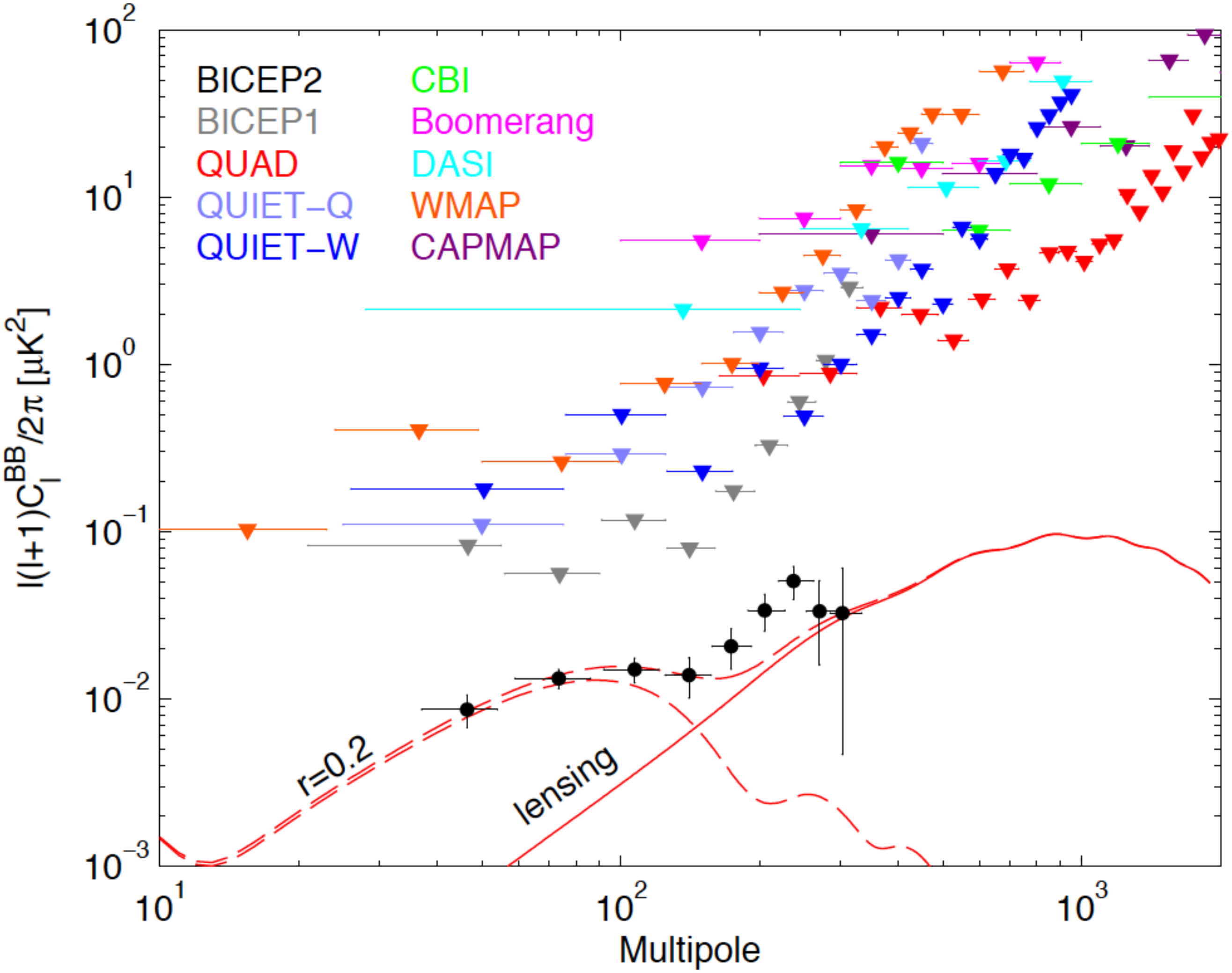


1% of sky

Amplitude of signal = about 0.1 μK

BICEP2 detects B-modes !

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

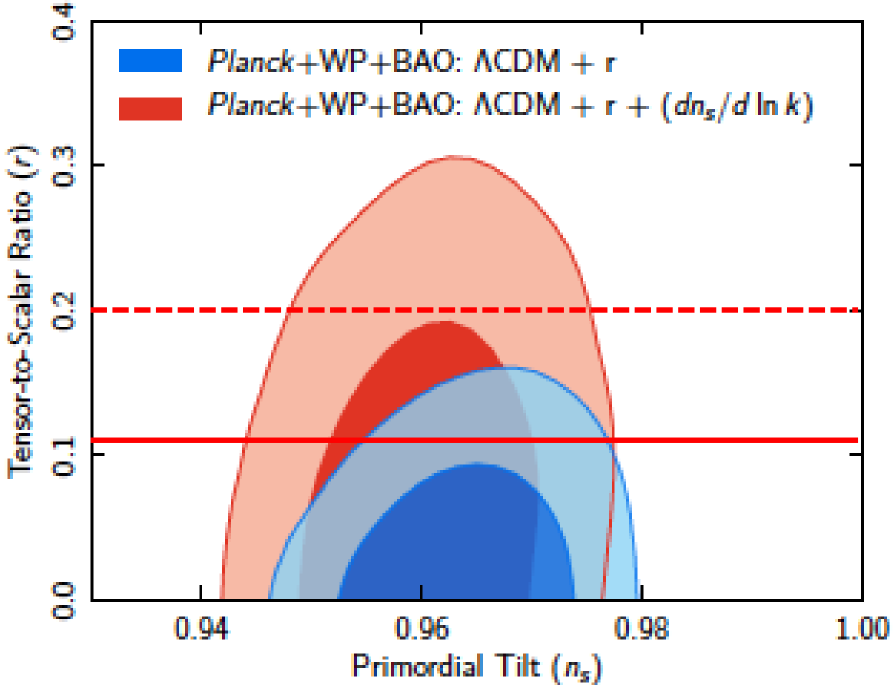


Running of the spectral index ?

Planck 2013 results. XXII.

$$P_s(k) = A_s \left(\frac{k}{k_0}\right)^{(n_s-1)+\frac{1}{2}\frac{\mathrm{d}n_s}{\mathrm{d}\ln k}\ln(k/k_0)}$$

Depends on next-order slow-roll parameter



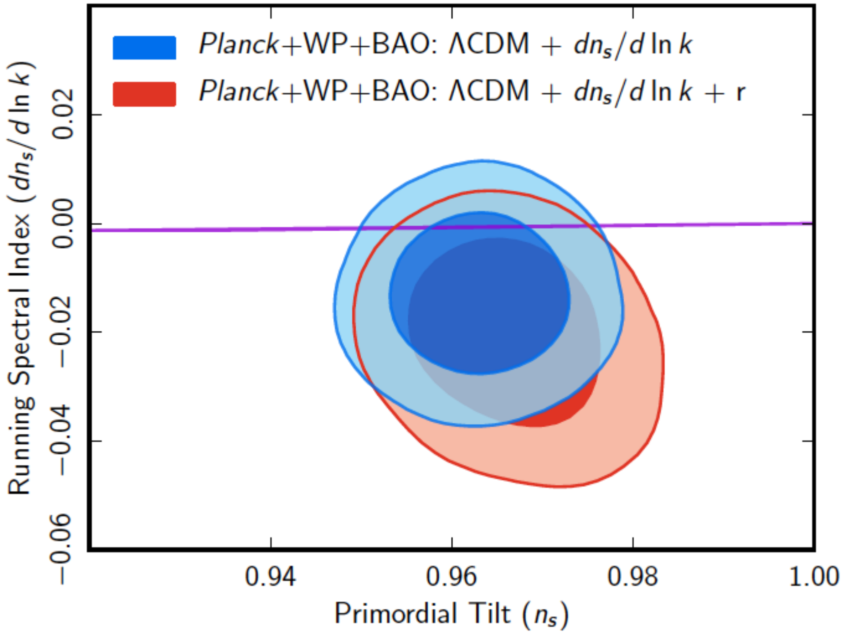
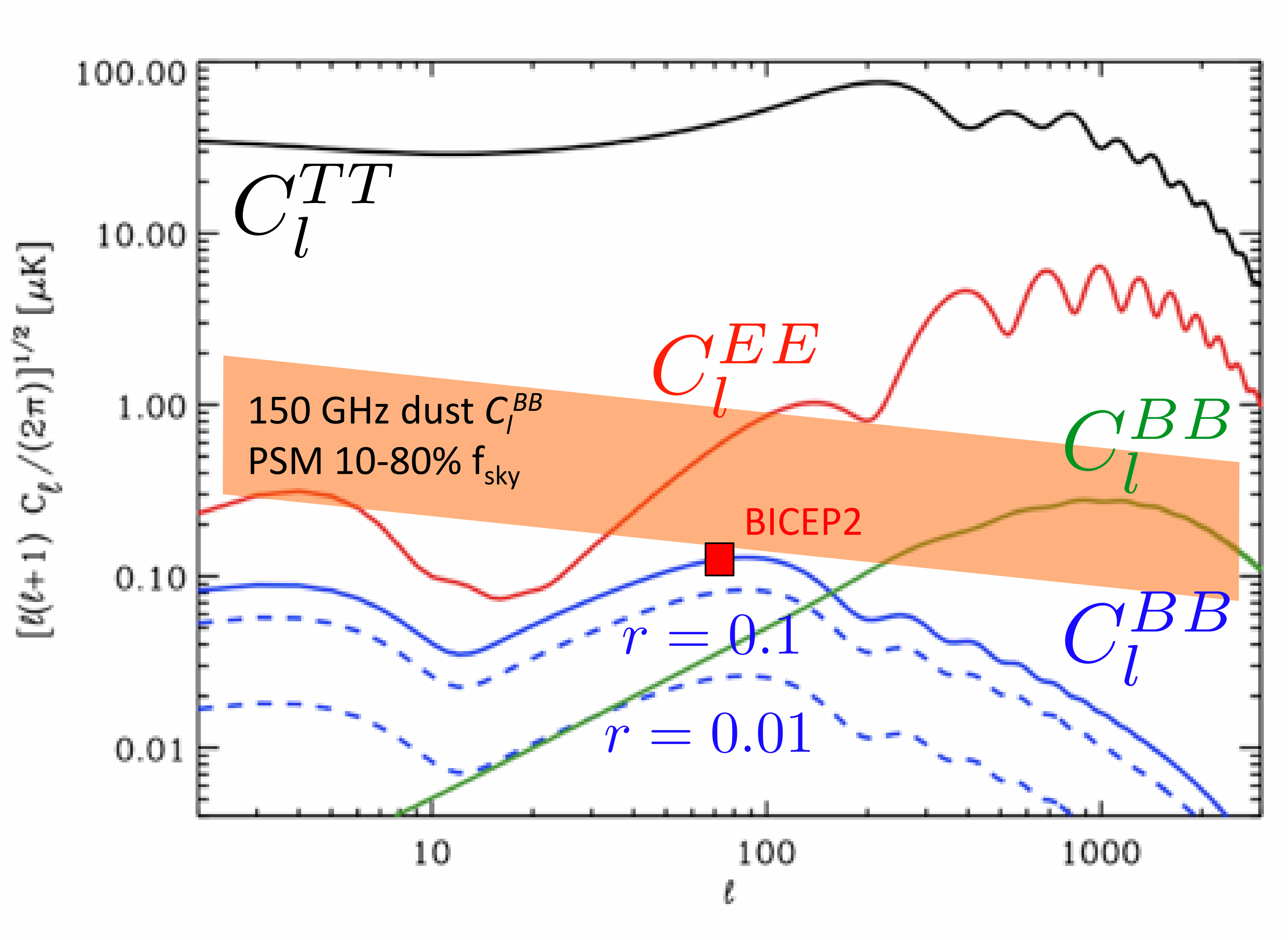


Fig. 2. Marginalized joint 68% and 95% CL for $(\mathrm{d}n_s/\mathrm{d}\ln k\,, n_s)$ using *Planck*+WP+BAO, either marginalizing over r or fixing $r = 0$ at $k_* = 0.038\ \mathrm{Mpc}^{-1}$. The purple strip shows the prediction for single monomial chaotic inflationary models with $50 < N_* < 60$ for comparison.

Dust B-mode C_l

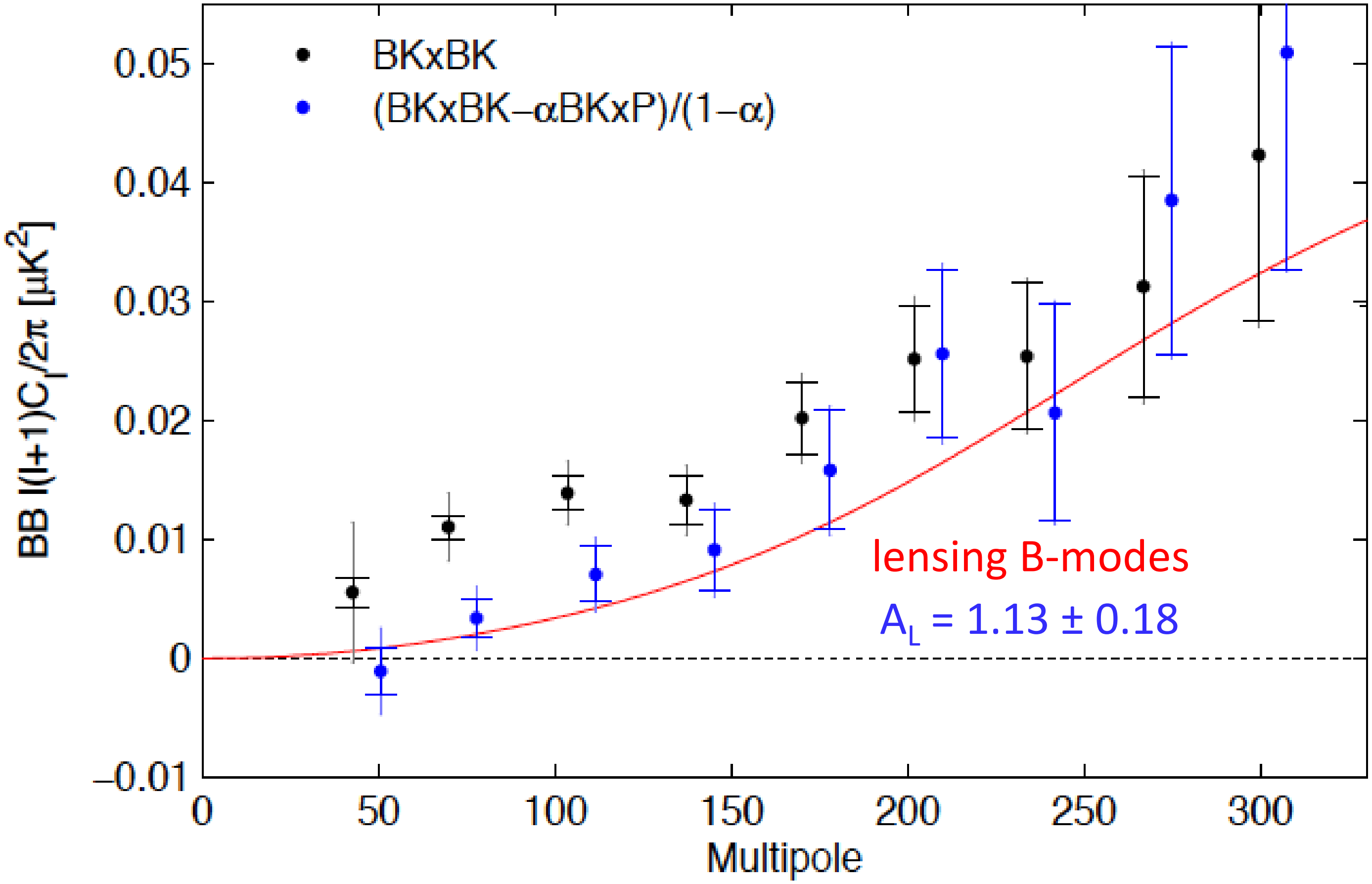


150 GHz dust C_l^{BB}
PSM 10-80% f_{sky}

Lensing of EE

Inflationary
Gravitational
Waves

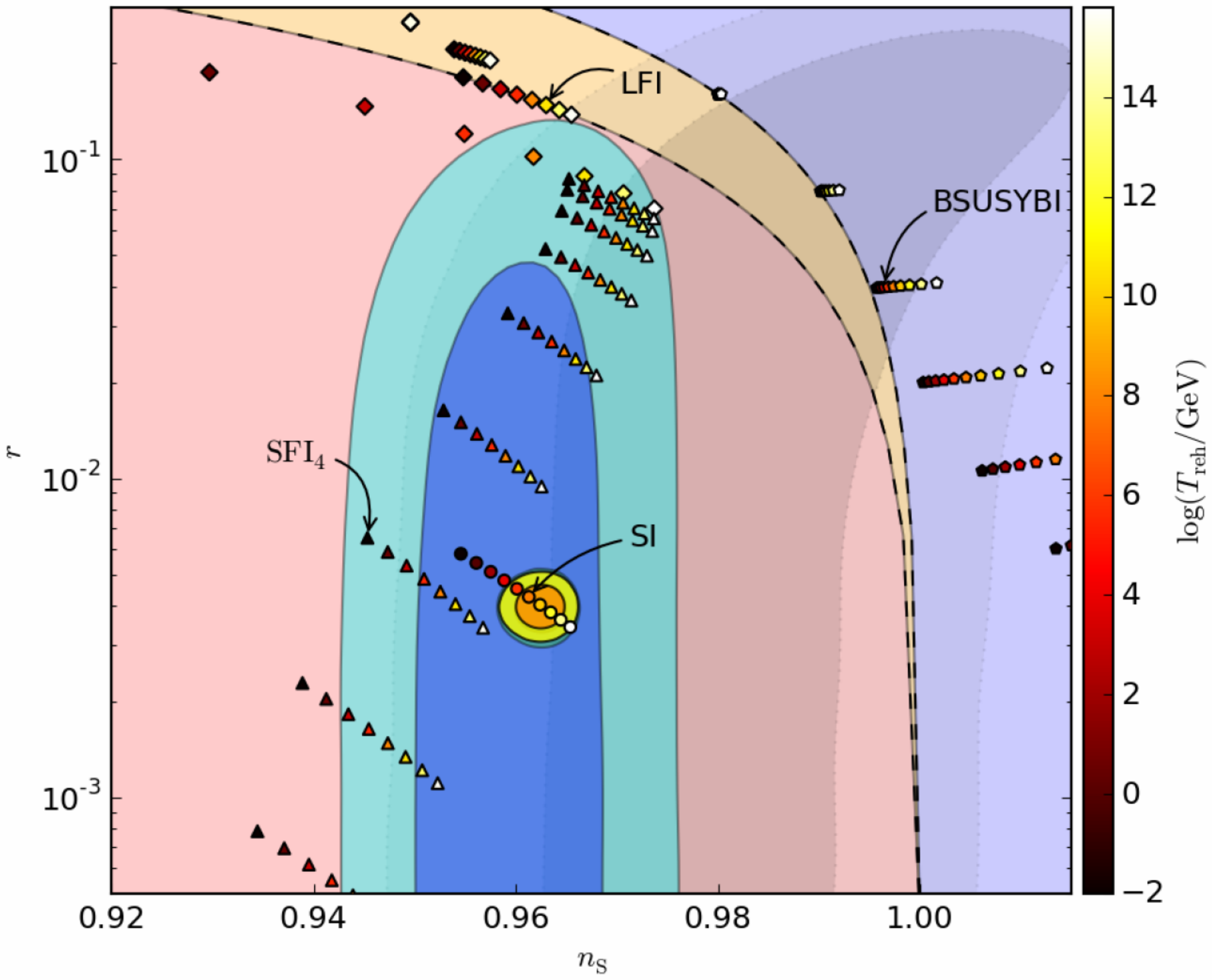
Joint analysis from Planck + BICEP2/Keck



lensing B-modes

$A_L = 1.13 \pm 0.18$

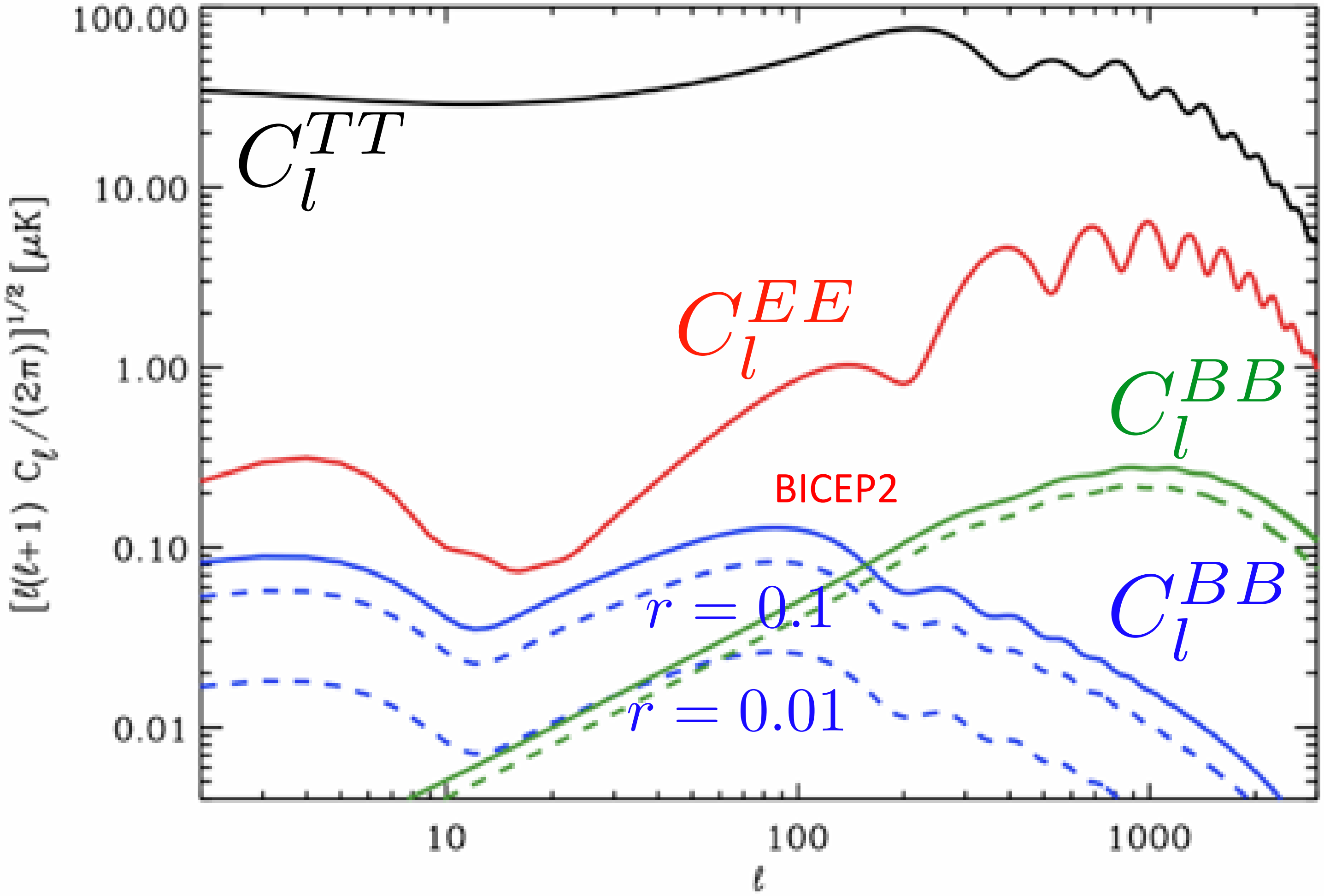
Inflationary constraints



- Fiducial = R^2 Starobinsky
- Grey = WMAP9
- Blue = Planck 2013
- Orange = Core+ baseline (no delensing)
- Improving n_s gives constraints on T_{reh}
- $r = 10^{-3}$ is a natural target (limit between weak and strong field).

Temperature & Polarisation CMB C_l

plot adapted from J. Carlstrom's P5 talk



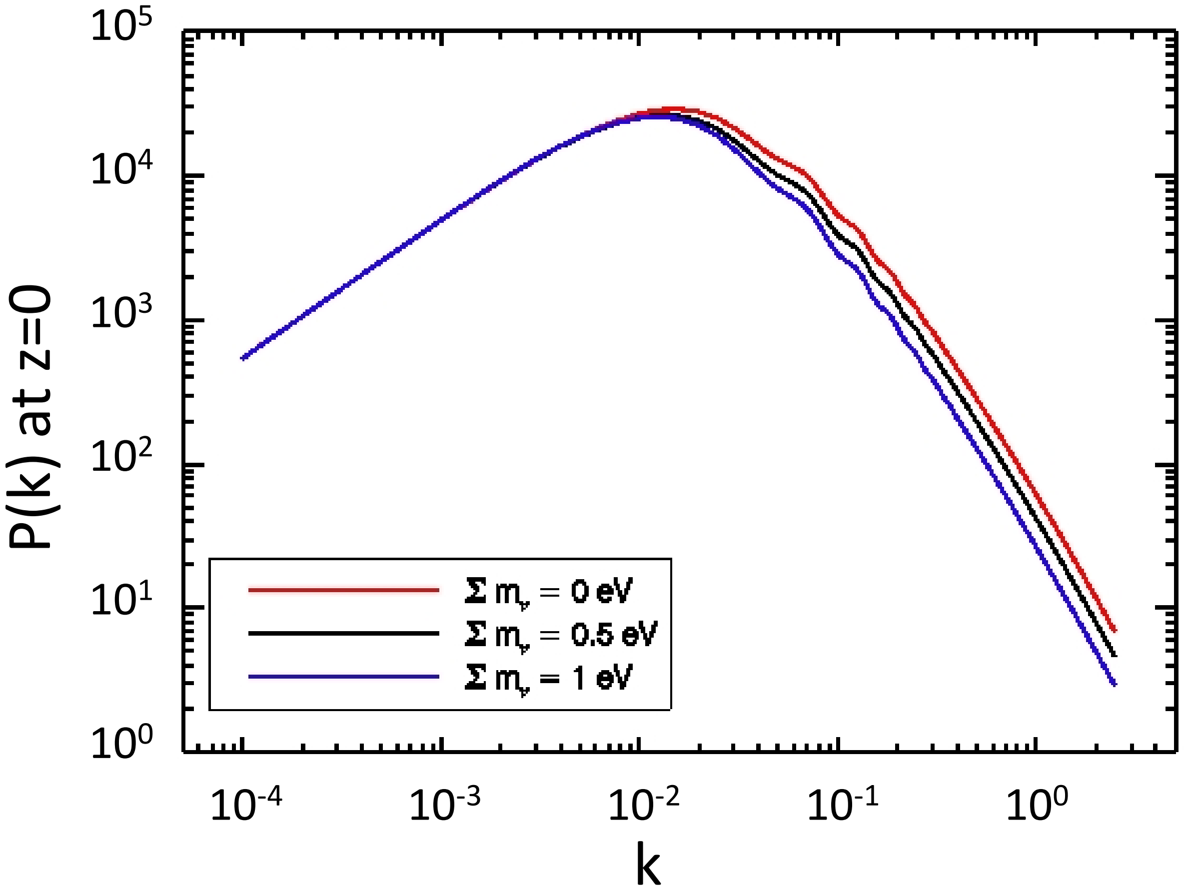
Lensing of EE

$\Sigma m_\nu = 0$ eV

$\Sigma m_\nu = 1.5$ eV

Inflationary Gravitational Waves

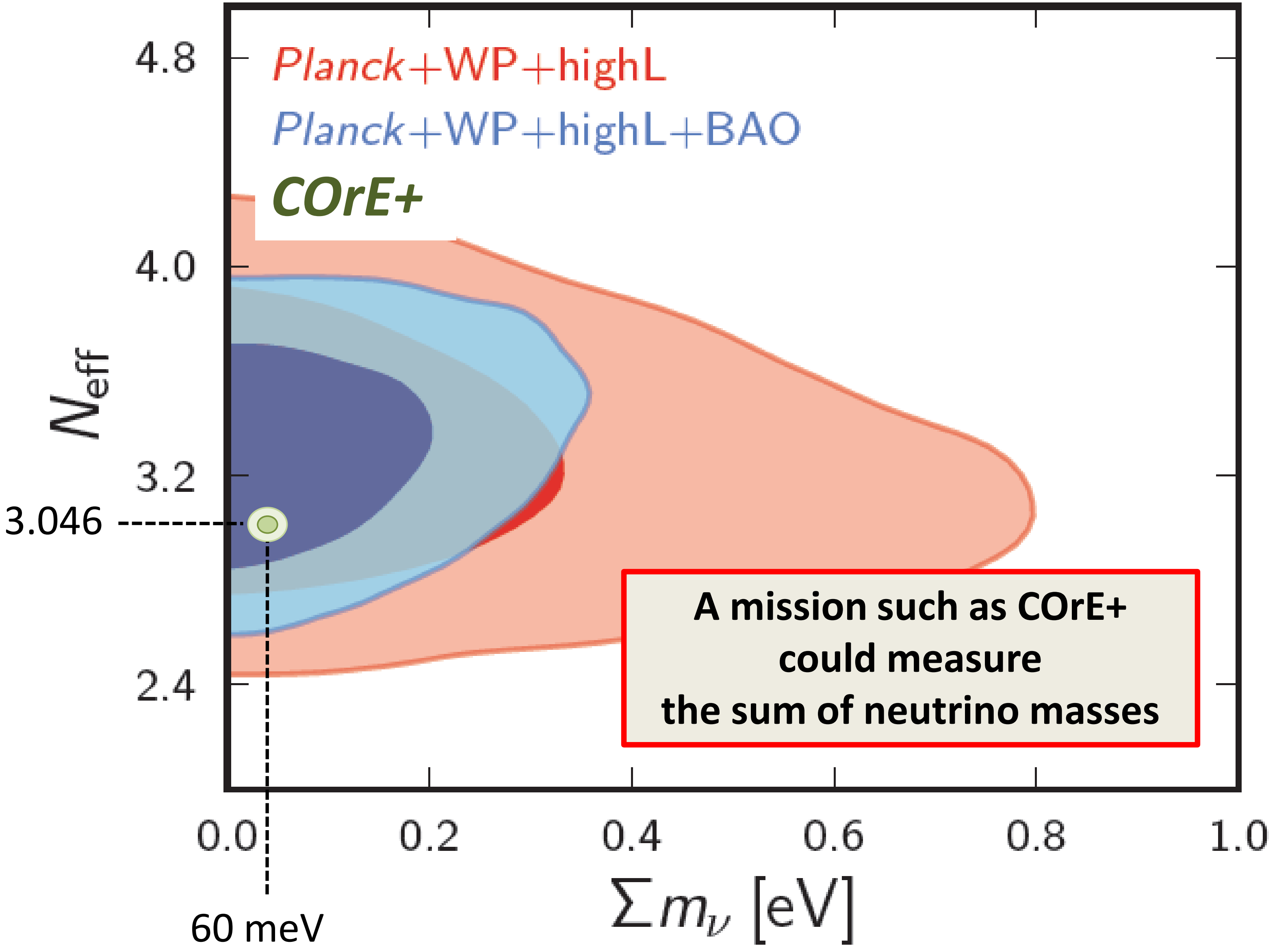
A handle on neutrino masses



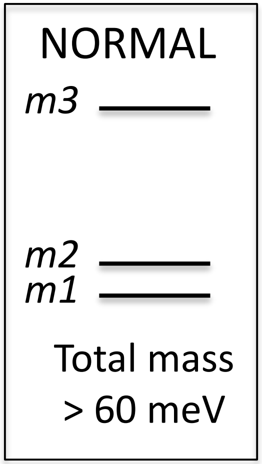
A fundamental question:
Absolute neutrino masses

Neutrino hierarchy (3 species)
normal: $\Sigma m_\nu > 0.06$ eV
inverted: $\Sigma m_\nu > 0.1$ eV

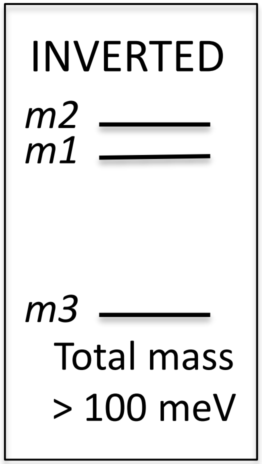
Constraining the neutrino sector



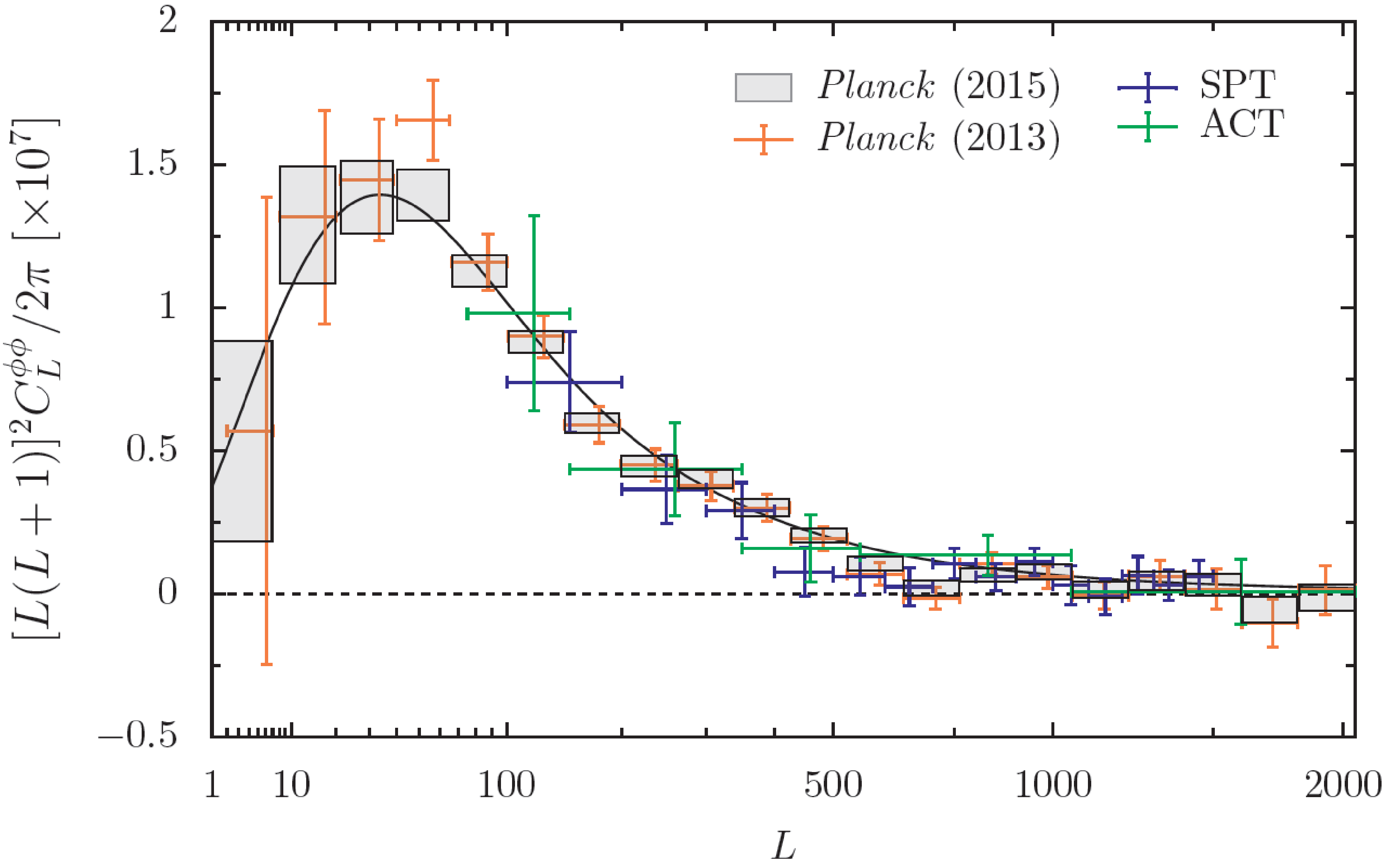
A mission such as COrE+ could measure the sum of neutrino masses



Total mass > 60 meV



Total mass > 100 meV


$[L(L+1)]^2 C_L^{\phi\phi}/2\pi\ [\times 10^7]$
2
1.5
1
0.5
0
−0.5
1
10
100
500
1000
2000
L
Planck (2015)
Planck (2013)
SPT
ACT

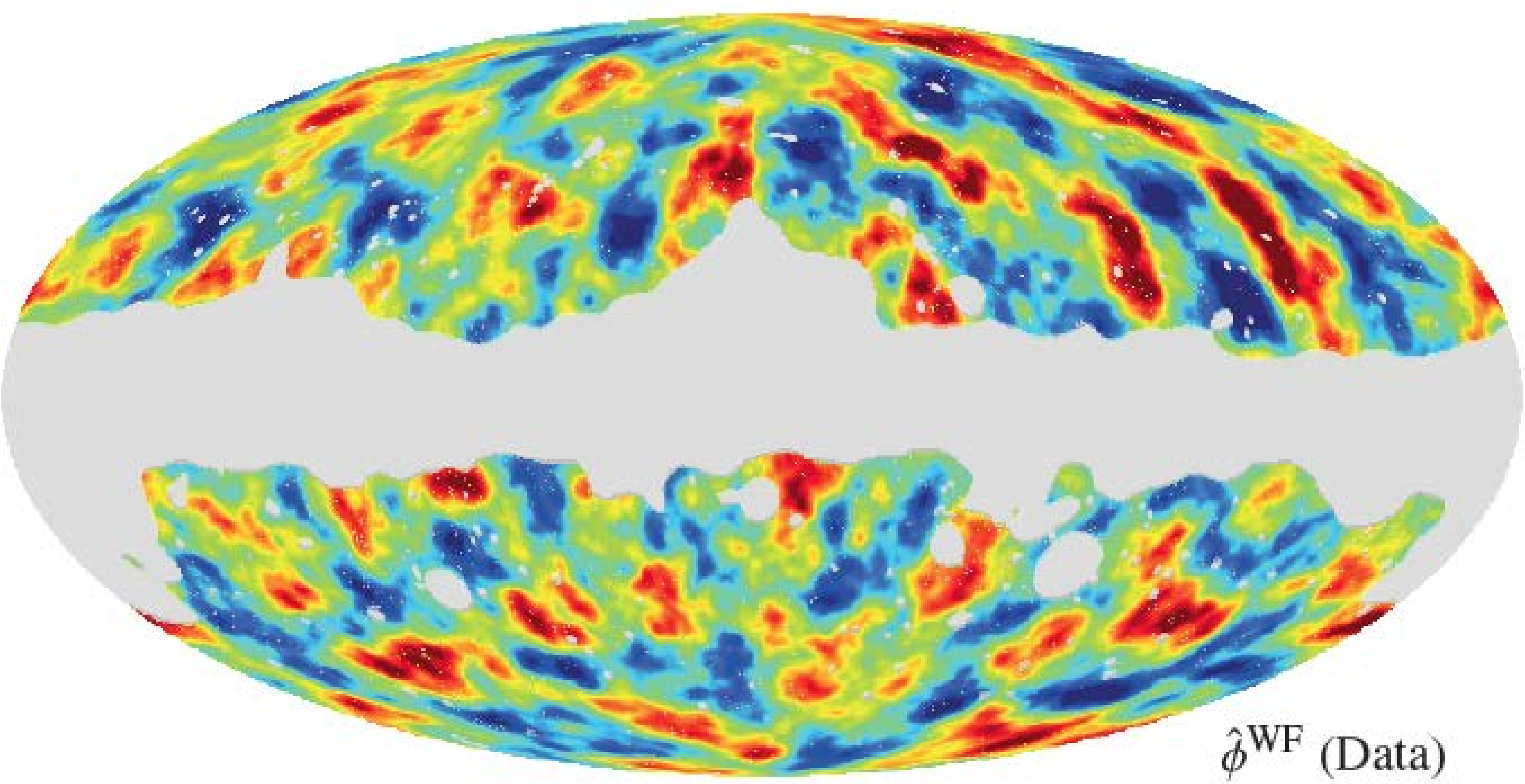
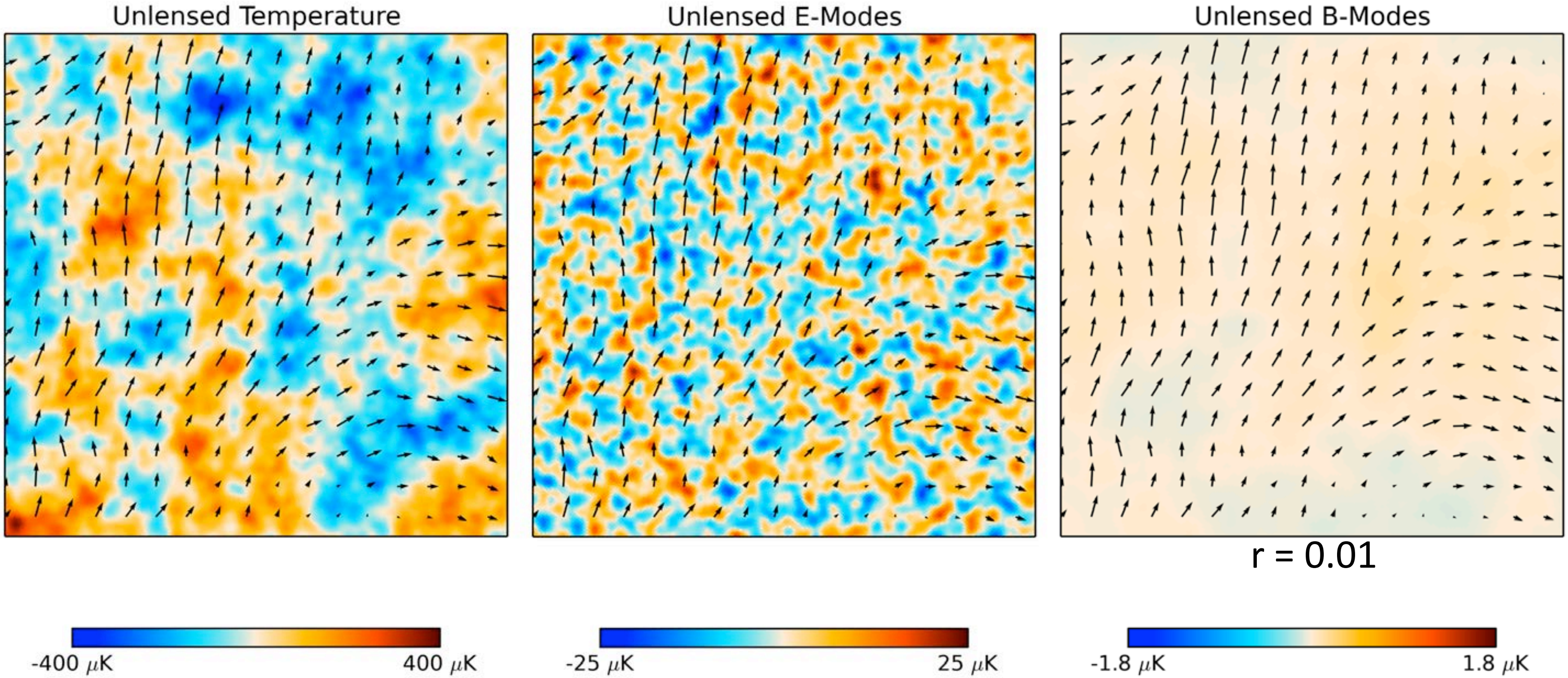
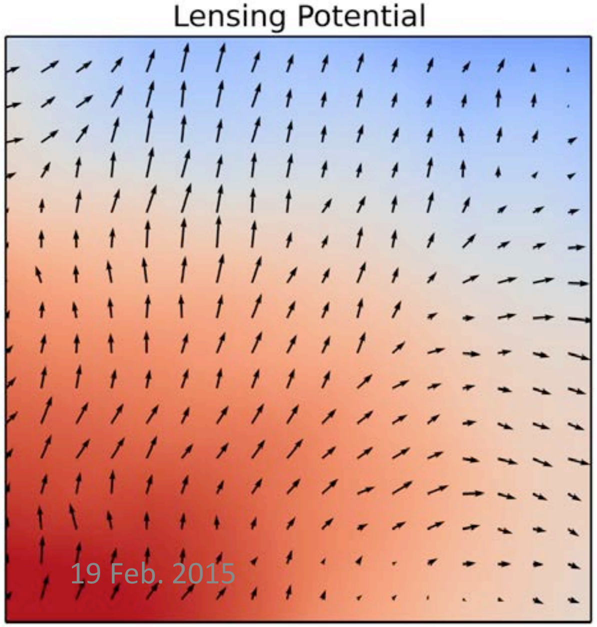
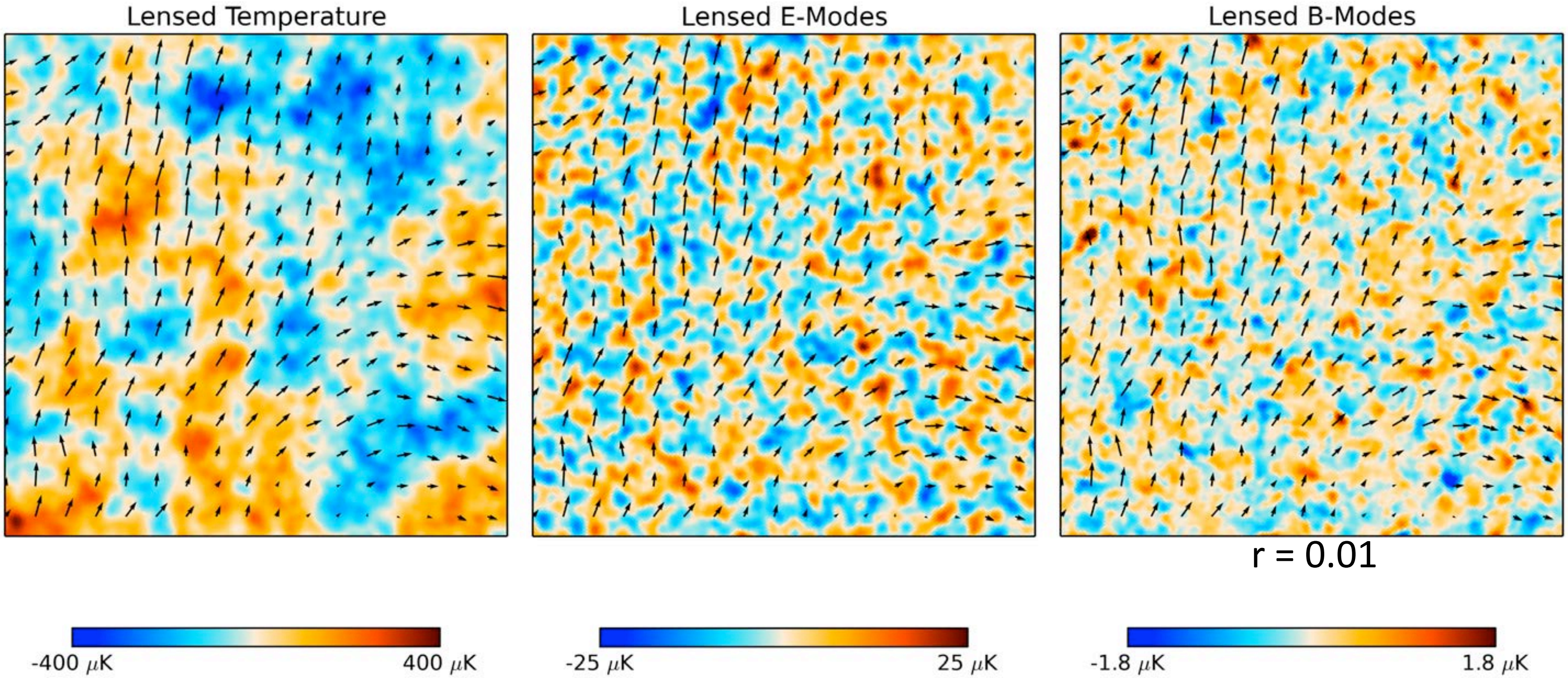


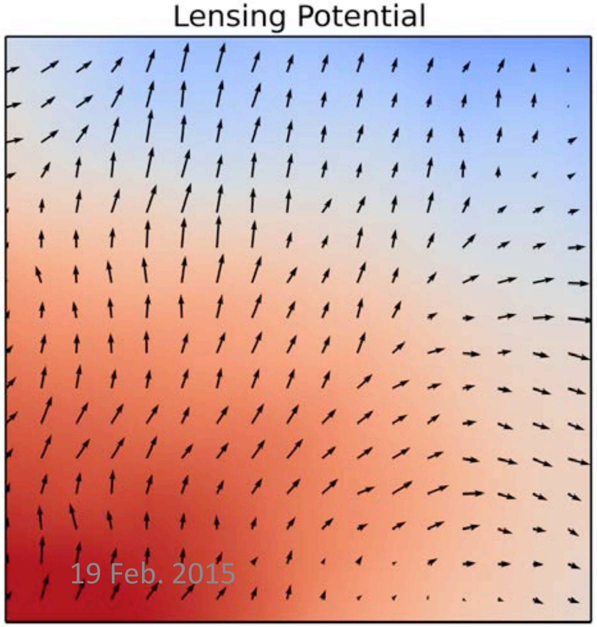
Fig. 2 Lensing potential estimated from the `SMICA` full-mission CMB maps using the MV estimator. The power spectrum of this map forms the basis of our lensing likelihood. The estimate has been Wiener filtered following Eq. (5), and band-limited to $8 \leq L \leq 2048$.





Gravitational lensing of the CMB

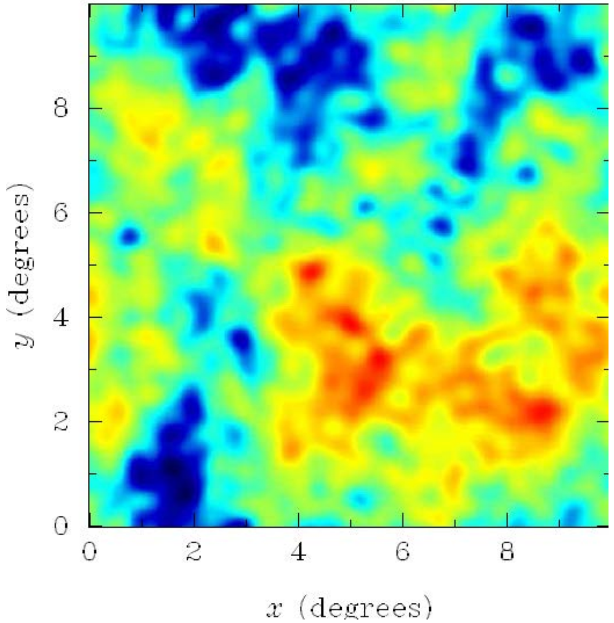




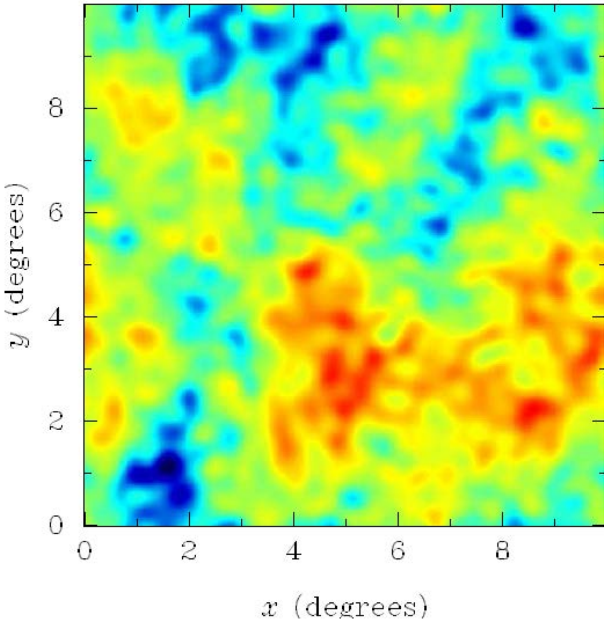
Gravitational lensing of the CMB

Mapping (dark) matter structures

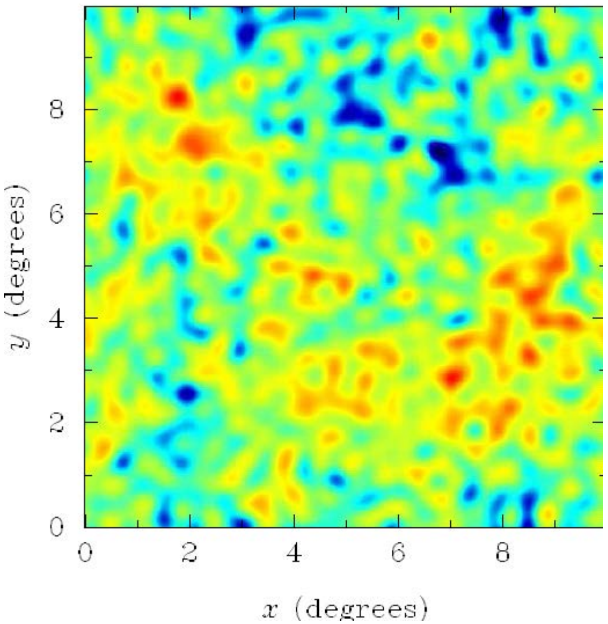
Input



Future



Planck (simulation)



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

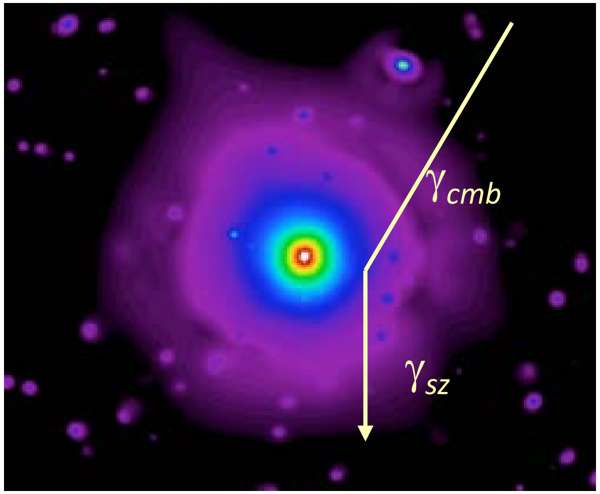
Reconstruction of the lensing potential

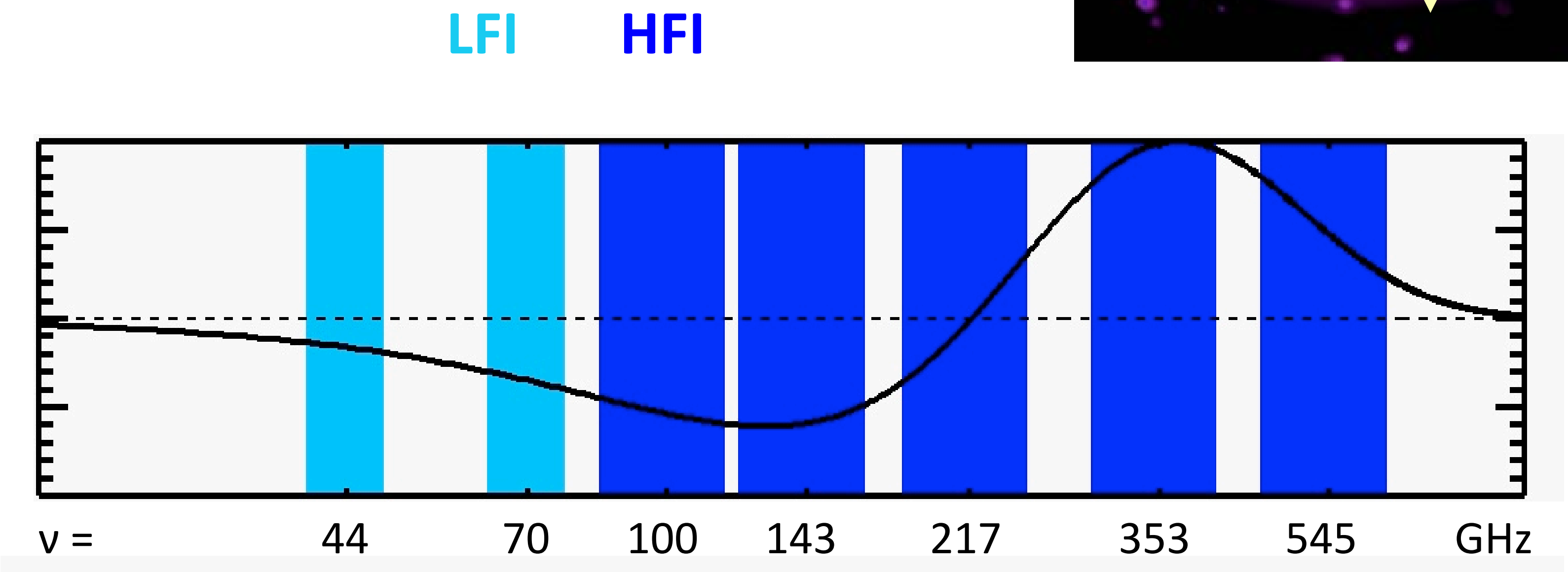
3 unknown maps	3 observed maps
Φ	T_{OBS}
T_{LSS}	E_{OBS}
E_{LSS}	B_{OBS}

Thermal SZ effect

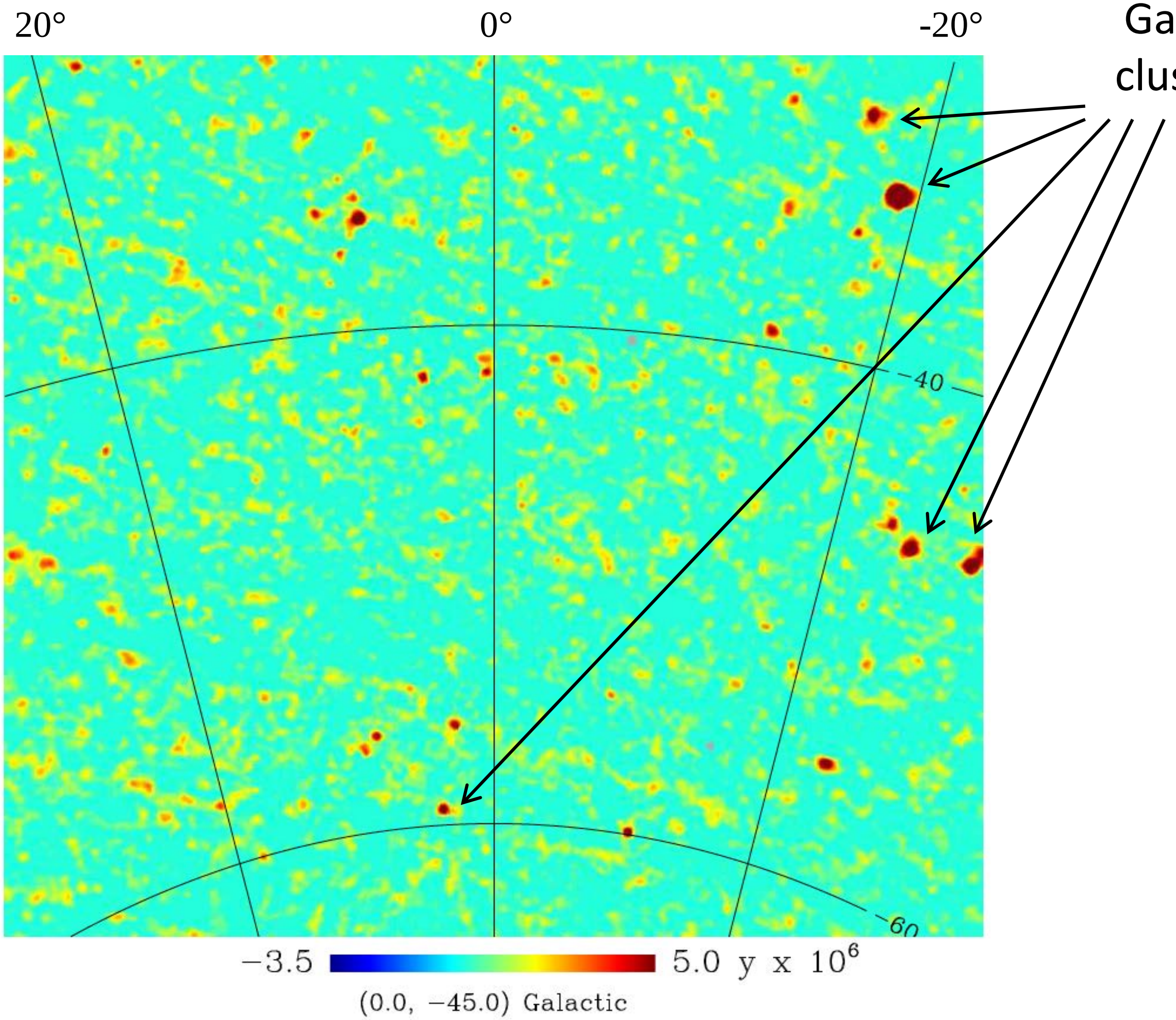
Clusters of galaxies are the largest gravitationally bound structures

- 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

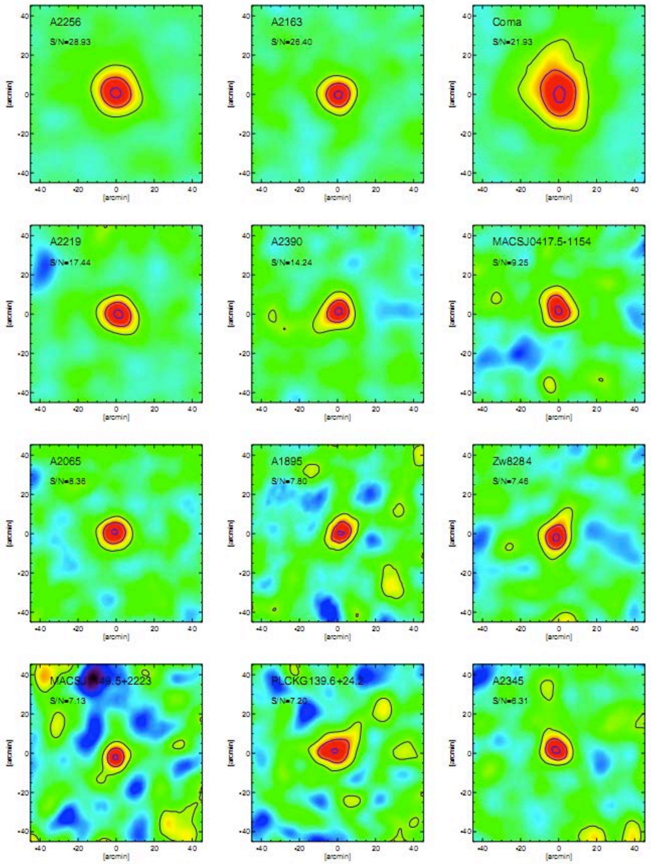




Planck maps of SZ clusters



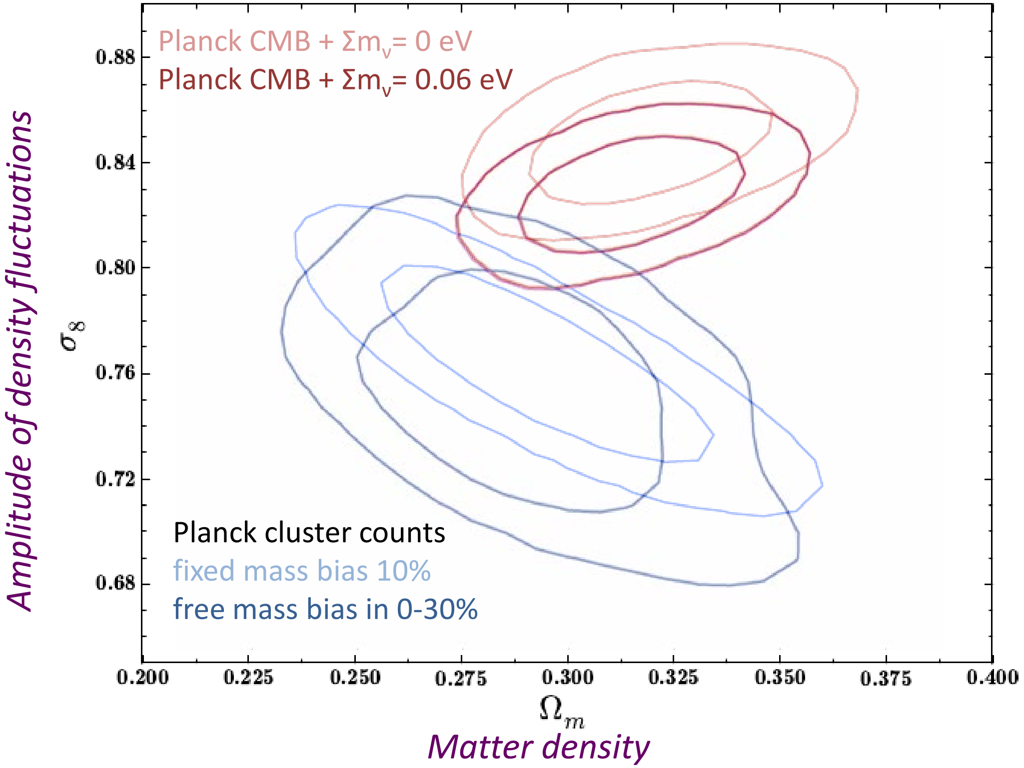
Galaxy clusters

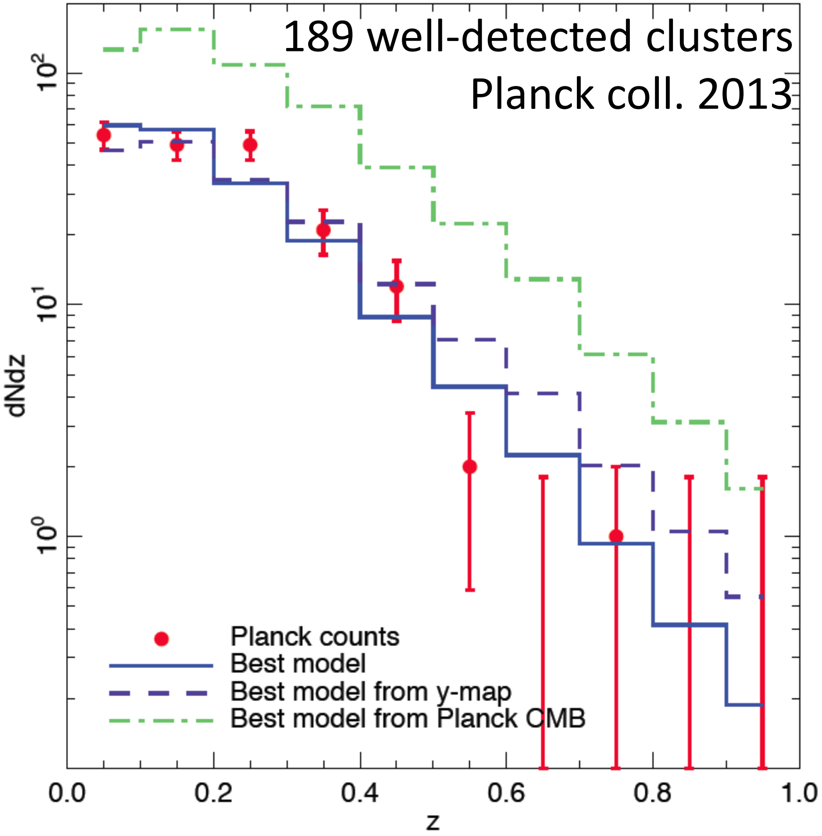


Cosmological information from clusters

- 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

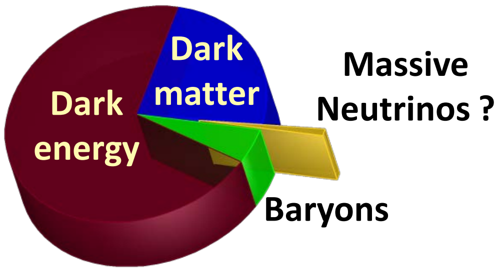
Cosmological constraints from clusters




189 well-detected clusters
Planck coll. 2013

CMB best fit cosmology overpredicts the number of observed clusters

Revise cluster physics ?
Revise matter and energy content?



Uses Canadian Cluster Comparison Project (CCCP) priors on (1-b):

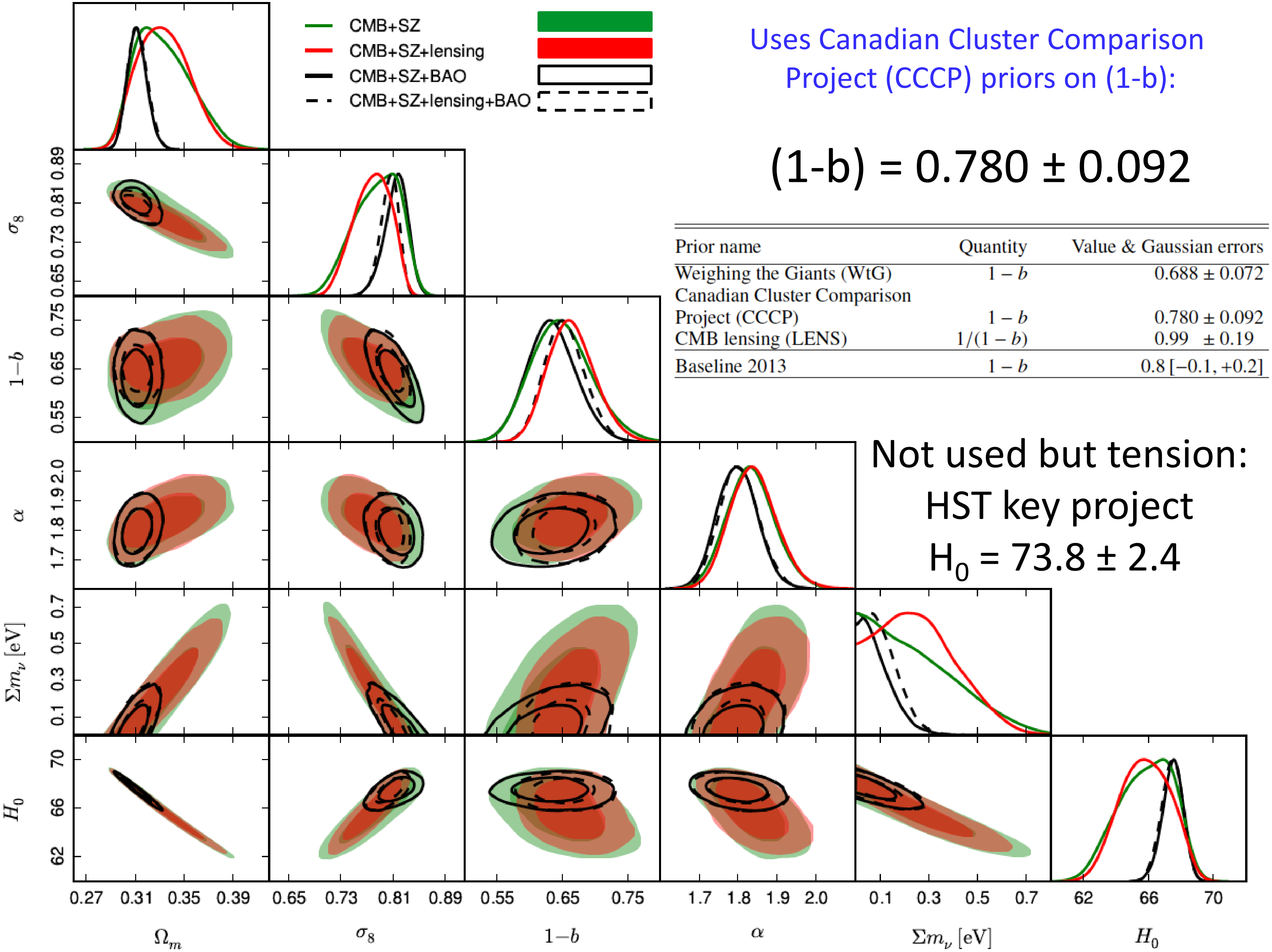
$$(1\text{-}b) = 0.780 \pm 0.092$$

Prior name	Quantity	Value & Gaussian errors
Weighing the Giants (WtG)	$1-b$	0.688 ± 0.072
Canadian Cluster Comparison Project (CCCP)	$1-b$	0.780 ± 0.092
CMB lensing (LENS)	$1/(1-b)$	0.99 ± 0.19
Baseline 2013	$1-b$	$0.8\,[-0.1, +0.2]$

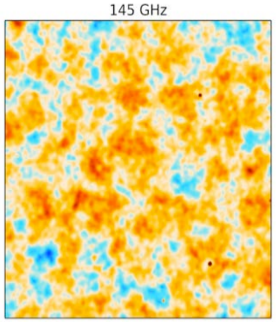
Not used but tension:

HST key project

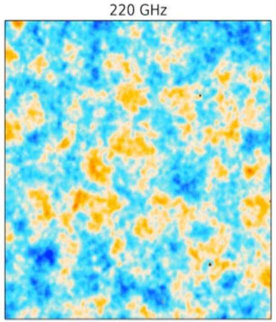
$H_0 = 73.8 \pm 2.4$



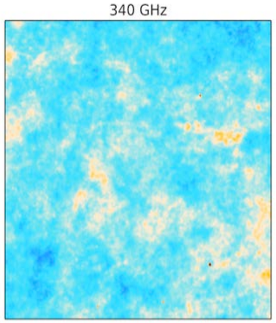
Observation of >100,000 Galaxy clusters



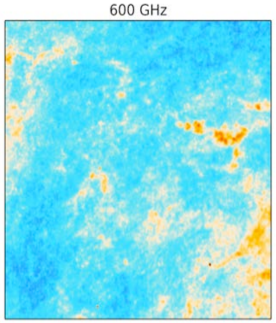
145 GHz



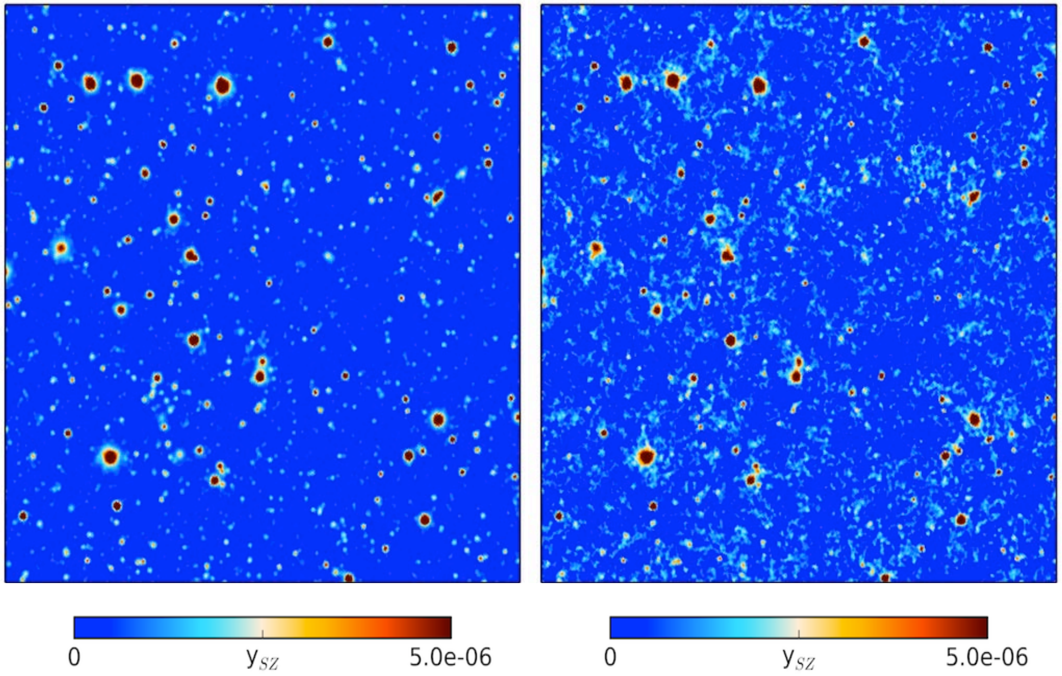
220 GHz



340 GHz

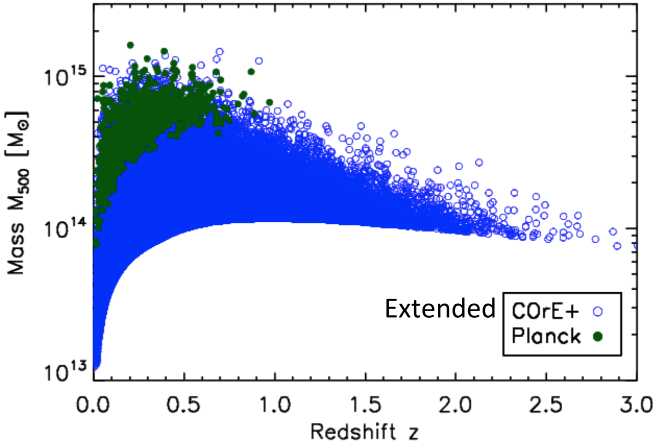


600 GHz



SZ map reconstruction

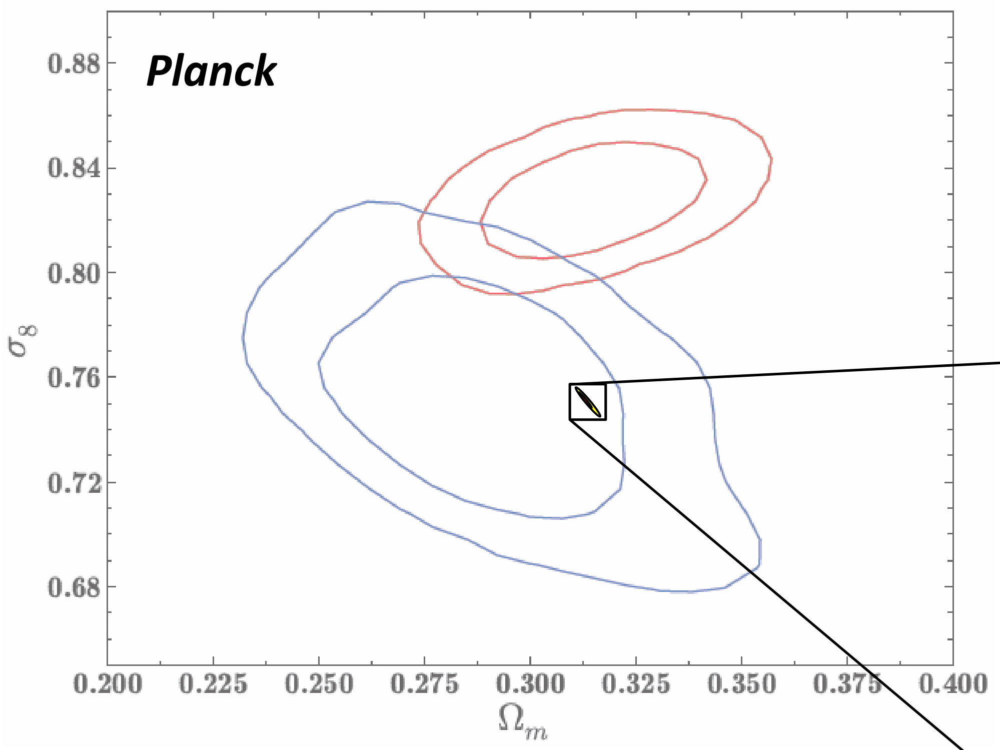
Needlet ILC (Mathieu Remazeilles)
on PSM simulations (Ata Karakci)

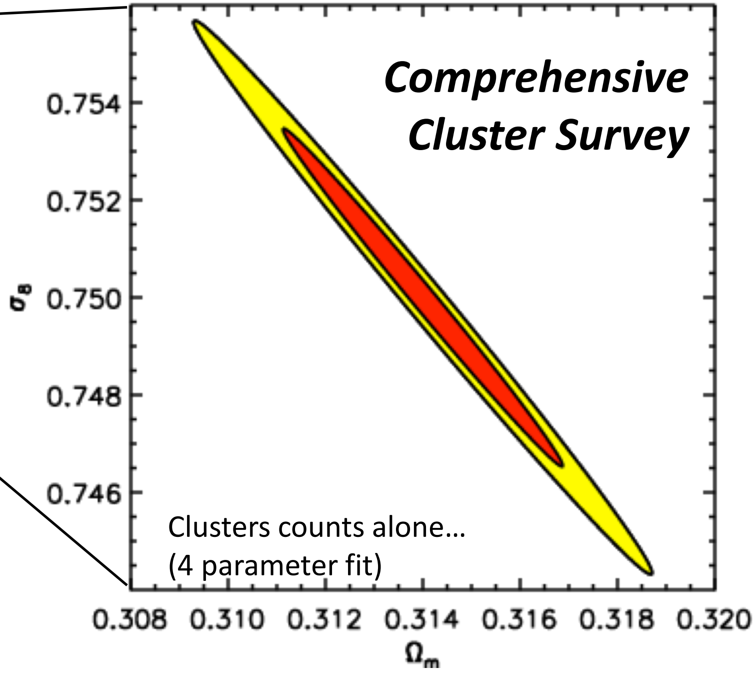


Limit mass as a function of redshift (Jean-Baptiste Melin)

Ω_m and σ_8 with galaxy clusters

COrE+ alone is not quite good enough. Contours here are computed for a very ambitious mission (PRISM). However, ground+space may do about as well…(TBC)

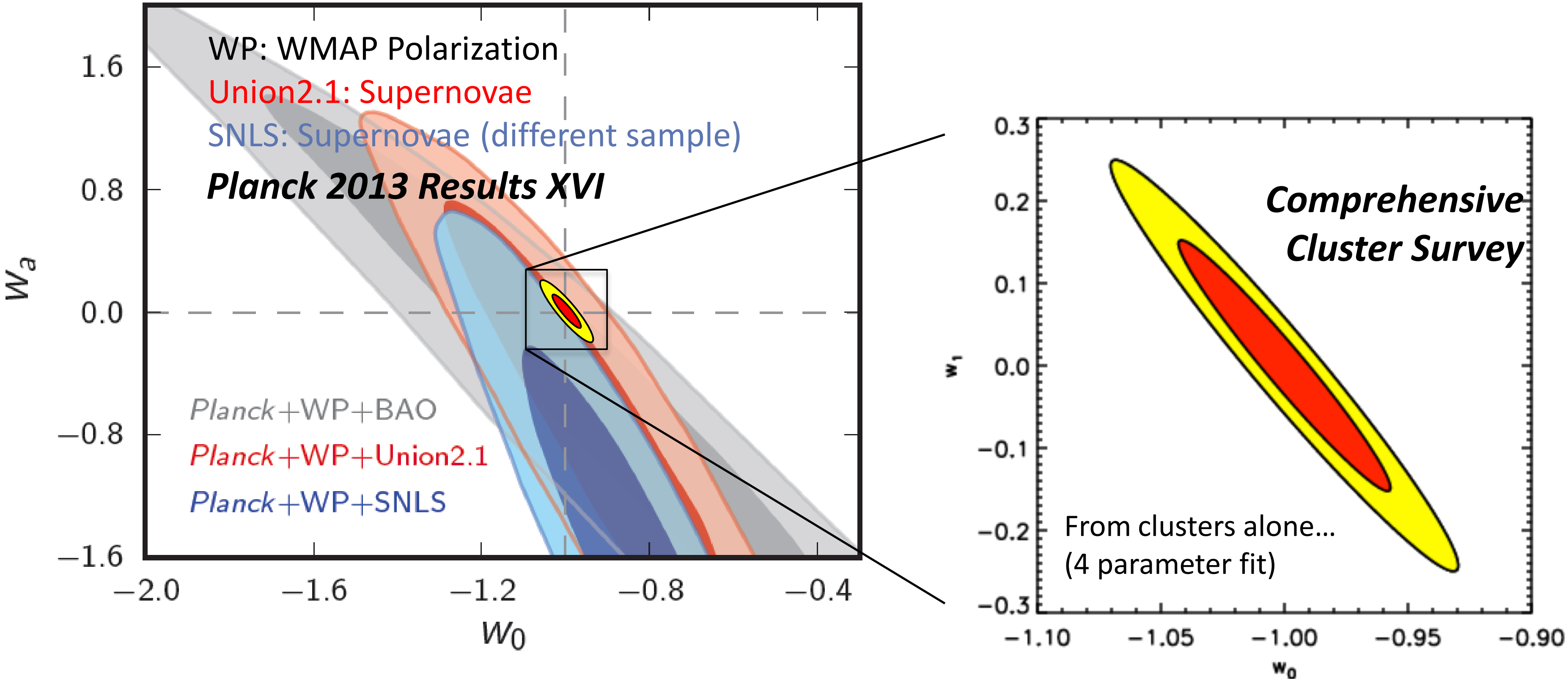




Clusters counts alone…
(4 parameter fit)

Assuming that the scaling relation is calibrated

w_0 and w_a with galaxy clusters



REQUIREMENT:

resolution ≈ 1-2', high sensitivity. Many channels to avoid confusion with sources and separate kSZ, tSZ, and relativistic corrections.

In summary: why the CMB?

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

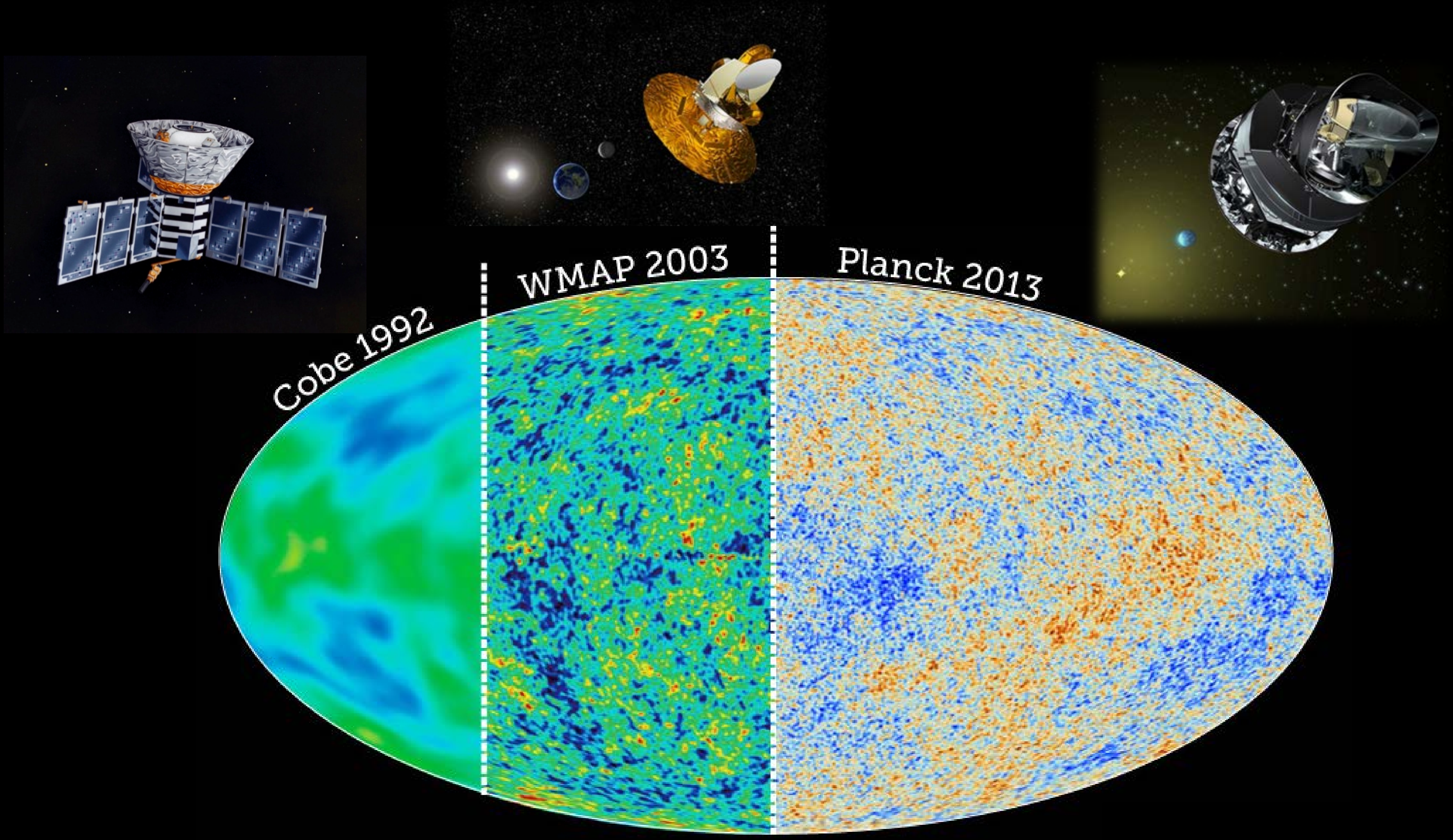
Why space?

Sub-orbital observations have been essential pathfinders:

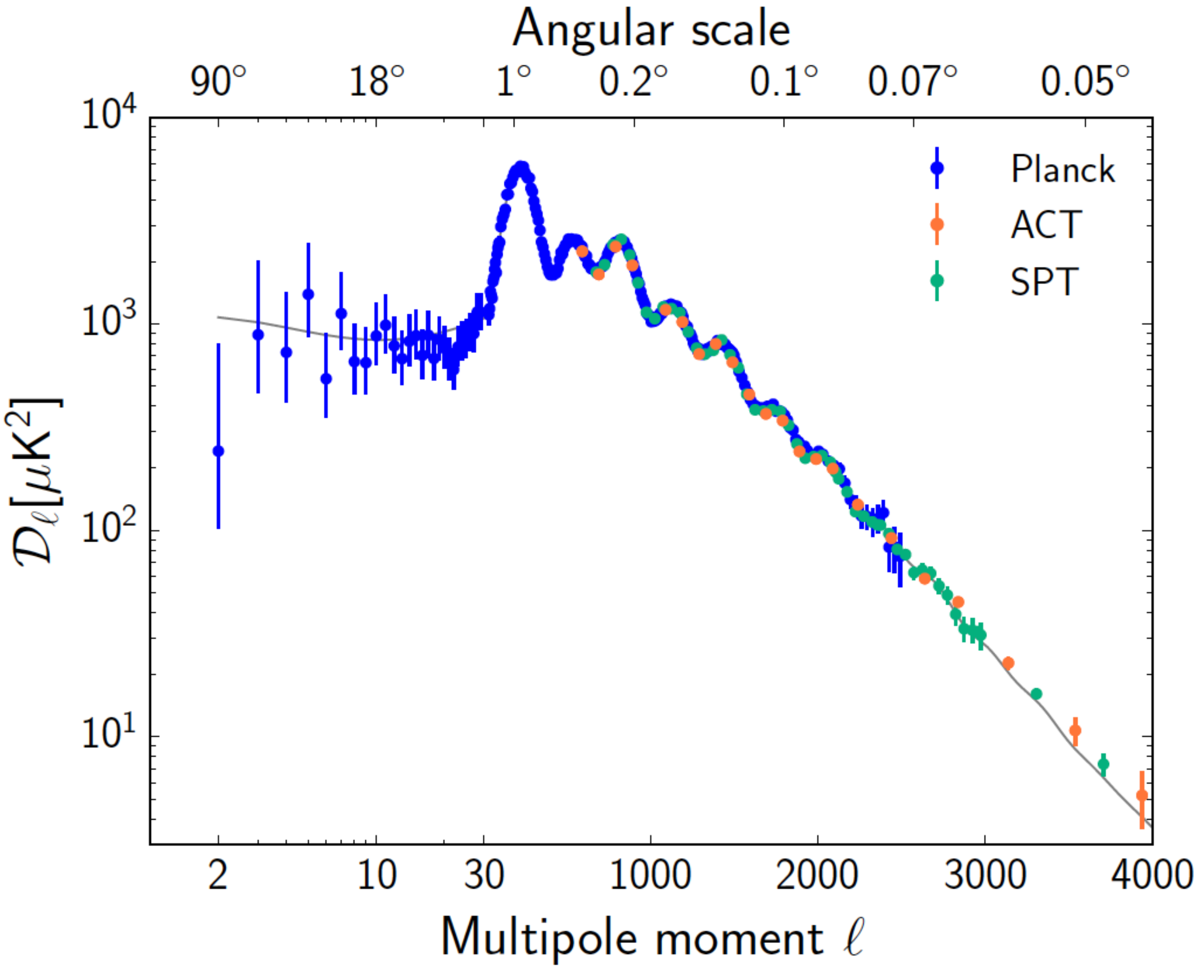
- First detection by Penzias & Wilson;
- Boomerang + Maxima: first striking detection of main acoustic peak;
- Archeops: first large l-range C_l spectrum;
- DASI: first detection of E-modes (+ CBI);
- Polarbear: first (direct) detection of lensing B-modes (+ BICEP2, SPT…);

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}, …

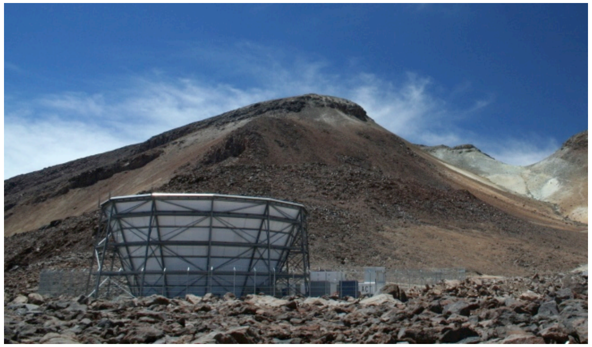

Cobe 1992
WMAP 2003
Planck 2013

The temperature spectrum



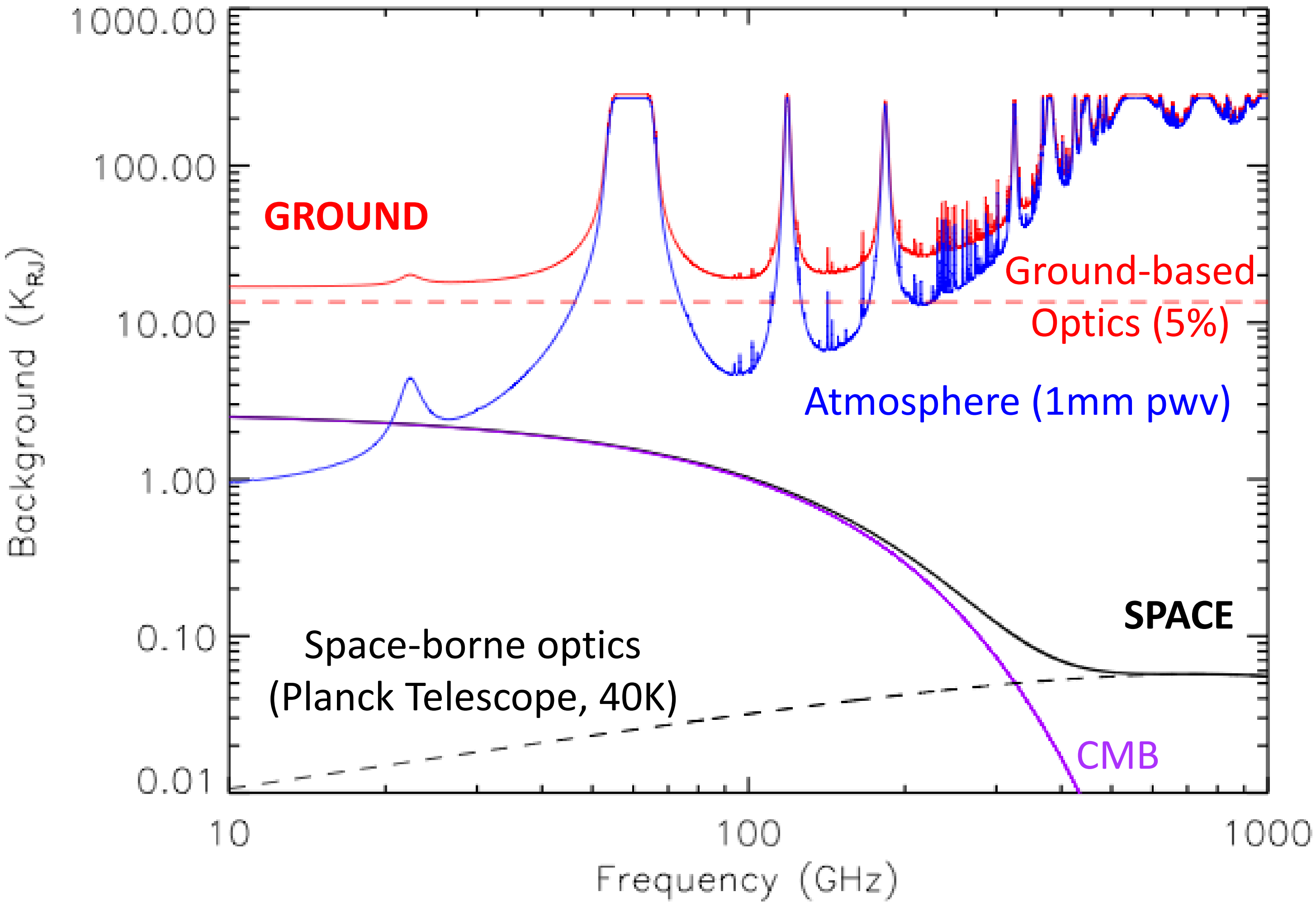
Planck 2015 results XI

ACT: Das et al. (2014)

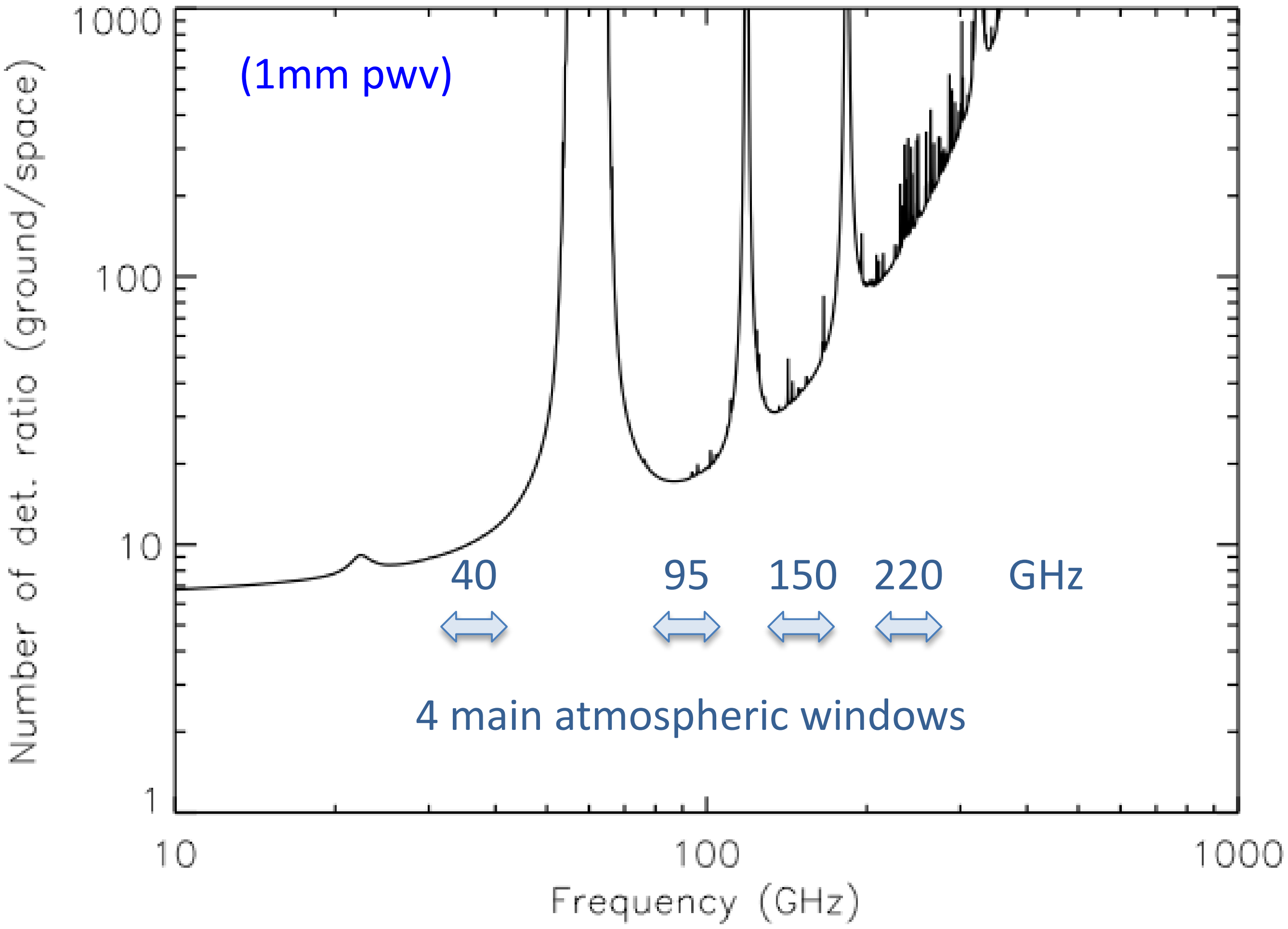


SPT: Story et al. (2012)
George et al. (2015)

Space vs. Ground: background comparison



Sensitivity comparison

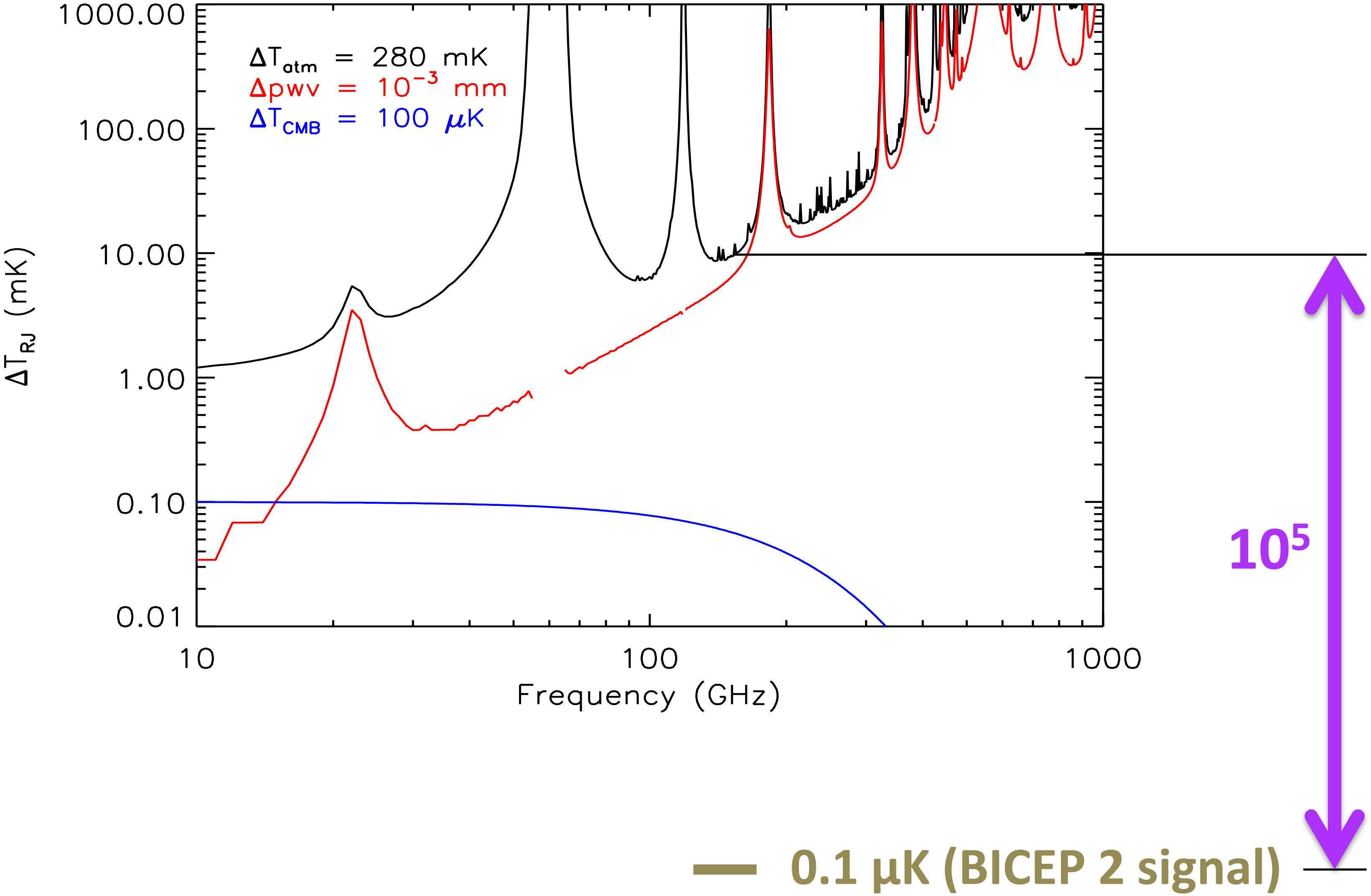


(1mm pwv)

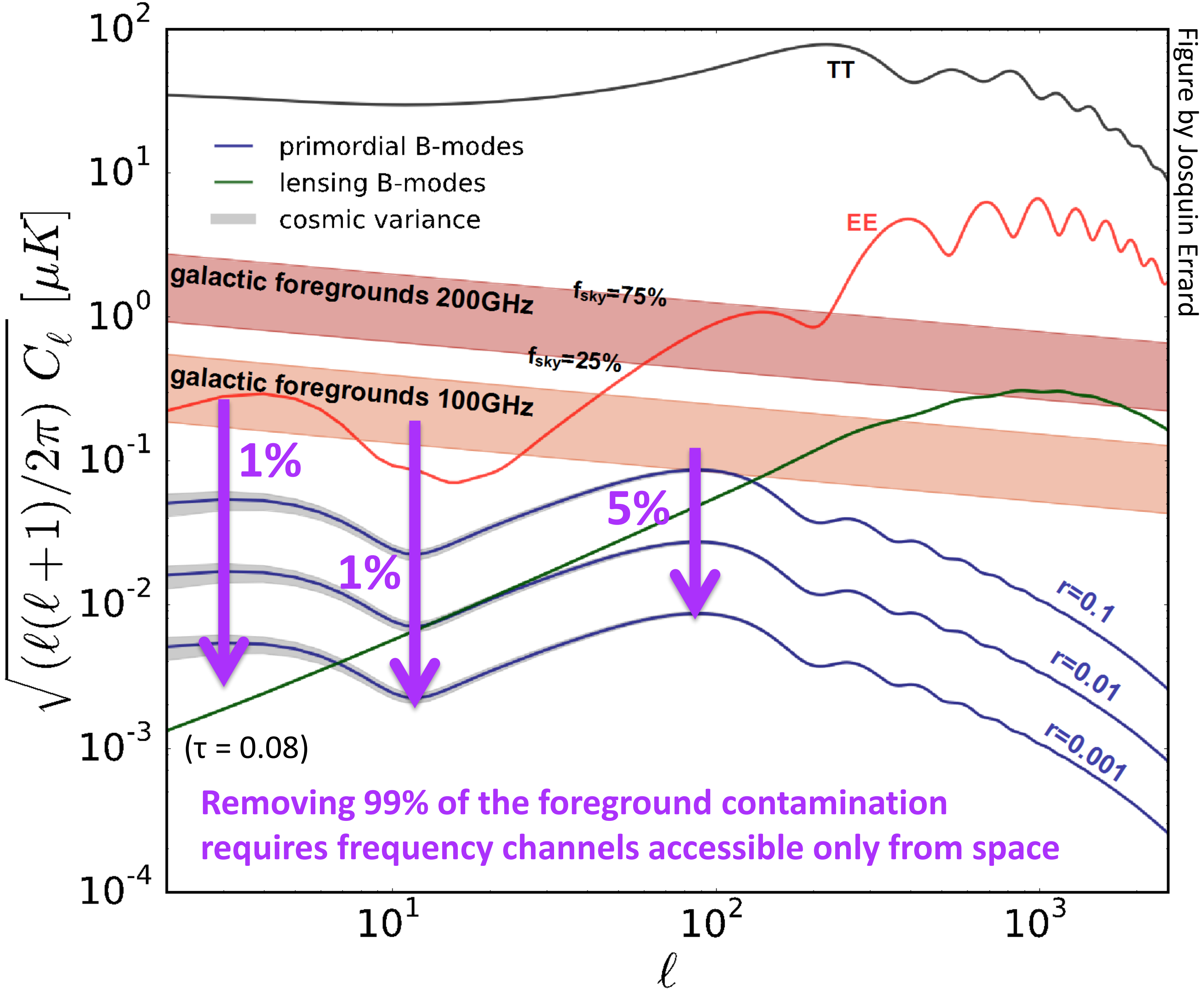
40 95 150 220 GHz

4 main atmospheric windows

Atmospheric emission



0.1 µK (BICEP 2 signal)



Removing 99% of the foreground contamination requires frequency channels accessible only from space

Figure by Josquin Errard

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 ground-based observations extremely challenging, in particular on large scales

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

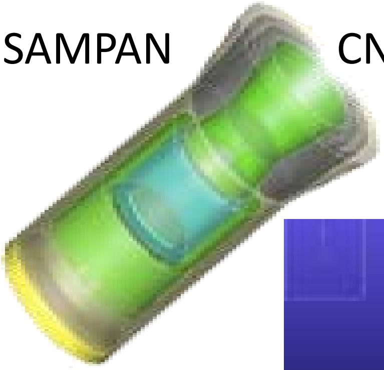
We will not be done with the CMB until we fly a comprehensive space mission. The sooner the better.

Outline

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

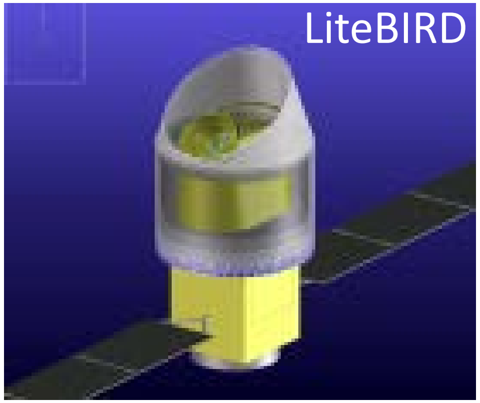
What next? Many proposed CMB missions

SAMPAN



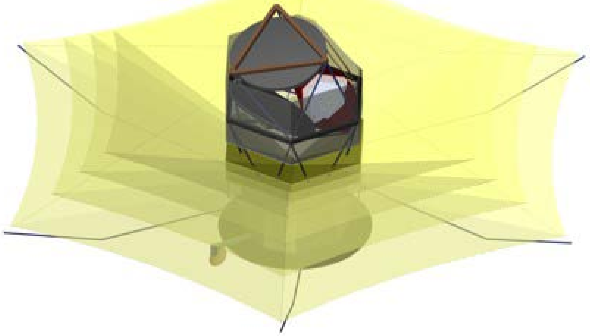
CNES 2006

JAXA

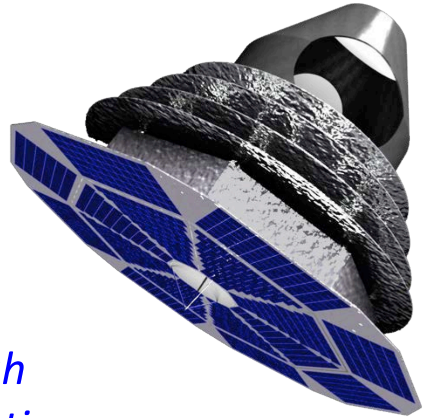


LiteBIRD

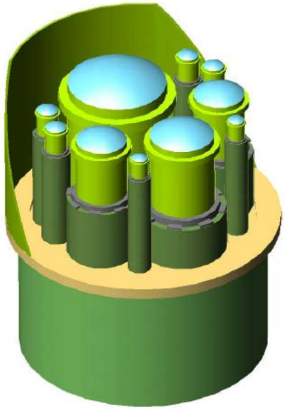
NASA 2008 EPIC-IM



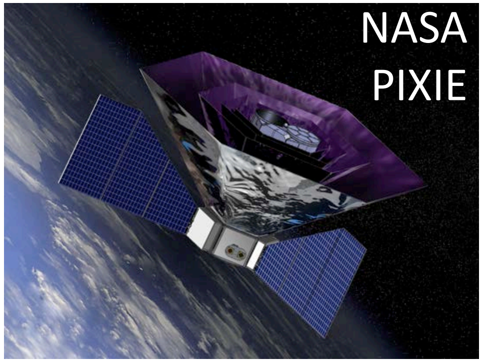
COrE
ESA 2010



BPOL
ESA 2007

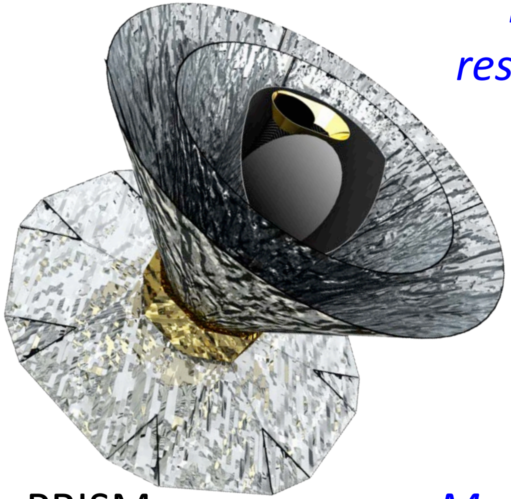


Absolute spectrophotometer

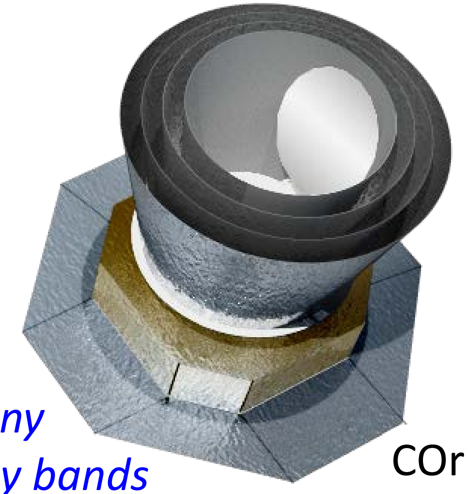


NASA
PIXIE

High resolution



PRISM
ESA 2013



Many frequency bands

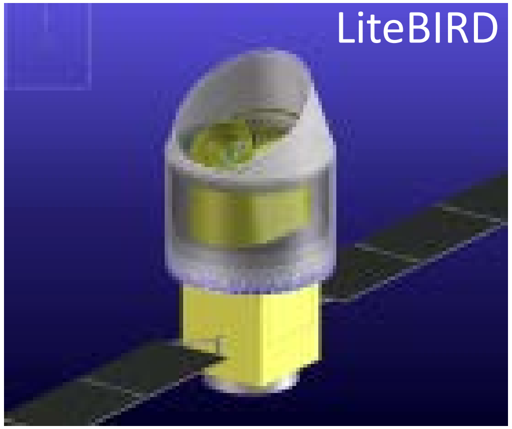
COrE+
ESA

Low resolution
Limited frequency coverage
Primary CMB B-modes

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

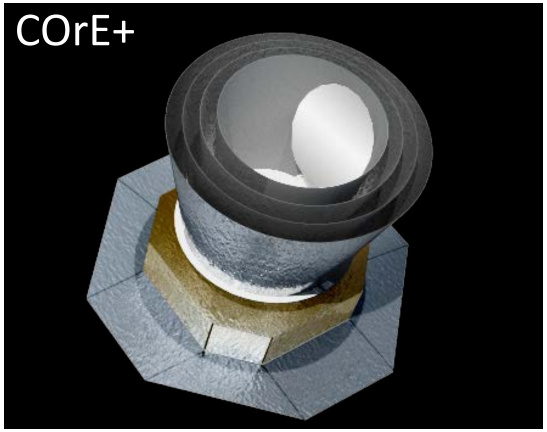
Recently proposed CMB missions

JAXA


LiteBIRD

Primordial B-modes mission

ESA


COrE+

Cosmic origins explorer

NASA


PIXIE

Absolute spectrophotometer

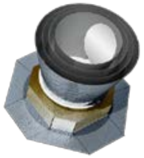
"LiteCOrE"

A joint ESA-JAXA CMB polarization imager ?

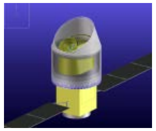
DISCUSSIONS ONGOING

Our M5 proposal
builds on several
previous concepts
(B-Pol, COrE, PRISM, COrE+
led by P. de Bernardis)

Legacy value & discovery potential

COrE+ (extended): 

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

Litebird (new, extended): 

- 15 channels with angular resolution ranging from 18' to 106', 3 million data samples
- x 15 sensitivity improvement in 10-15 years

PIXIE: 

- 400 channels with fixed angular resolution of 2.6°, 3 million data samples
- x 1000 sensitivity improvement (for absolute spectrum) in 10 years

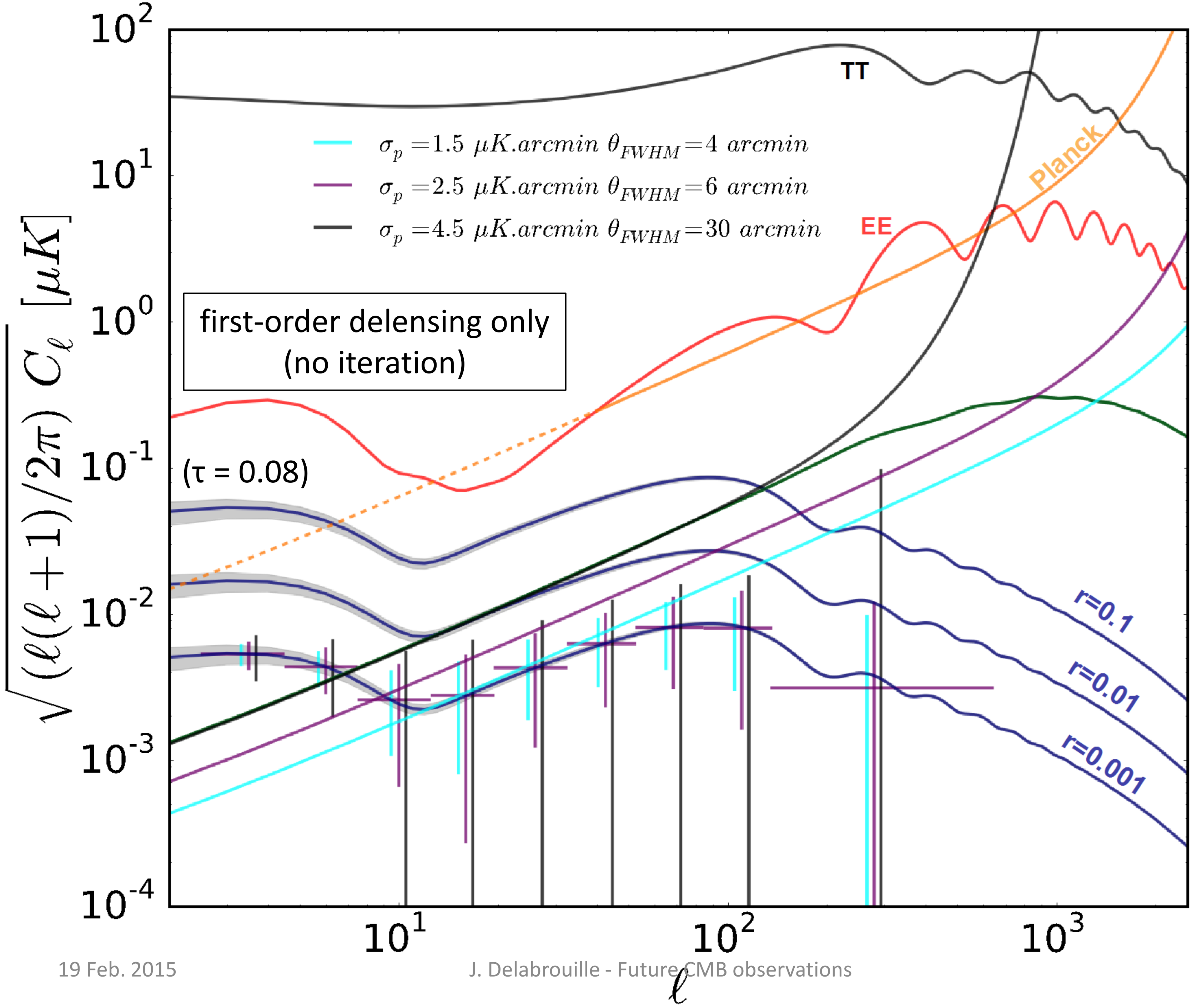


Figure by Josquin Errard

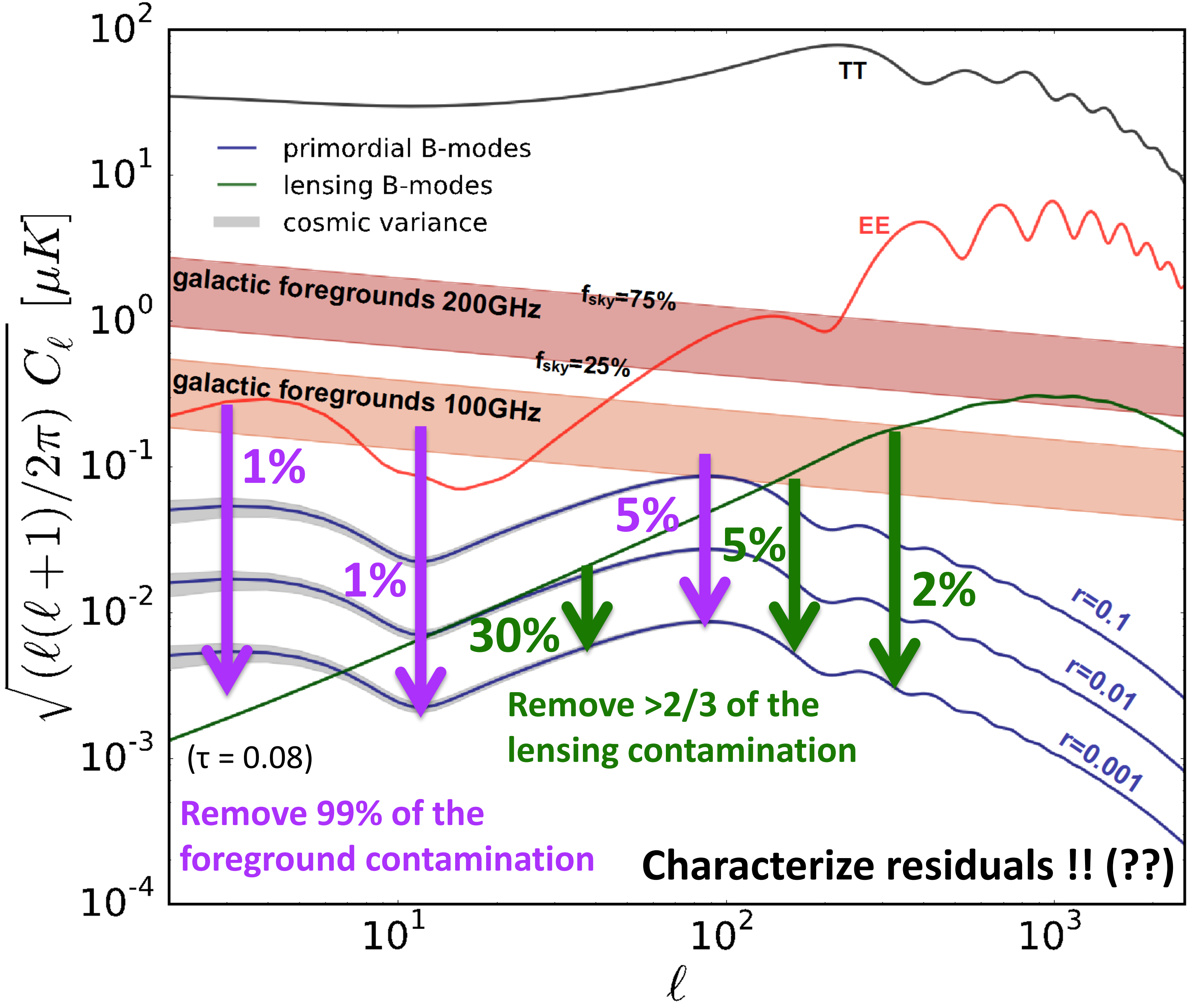


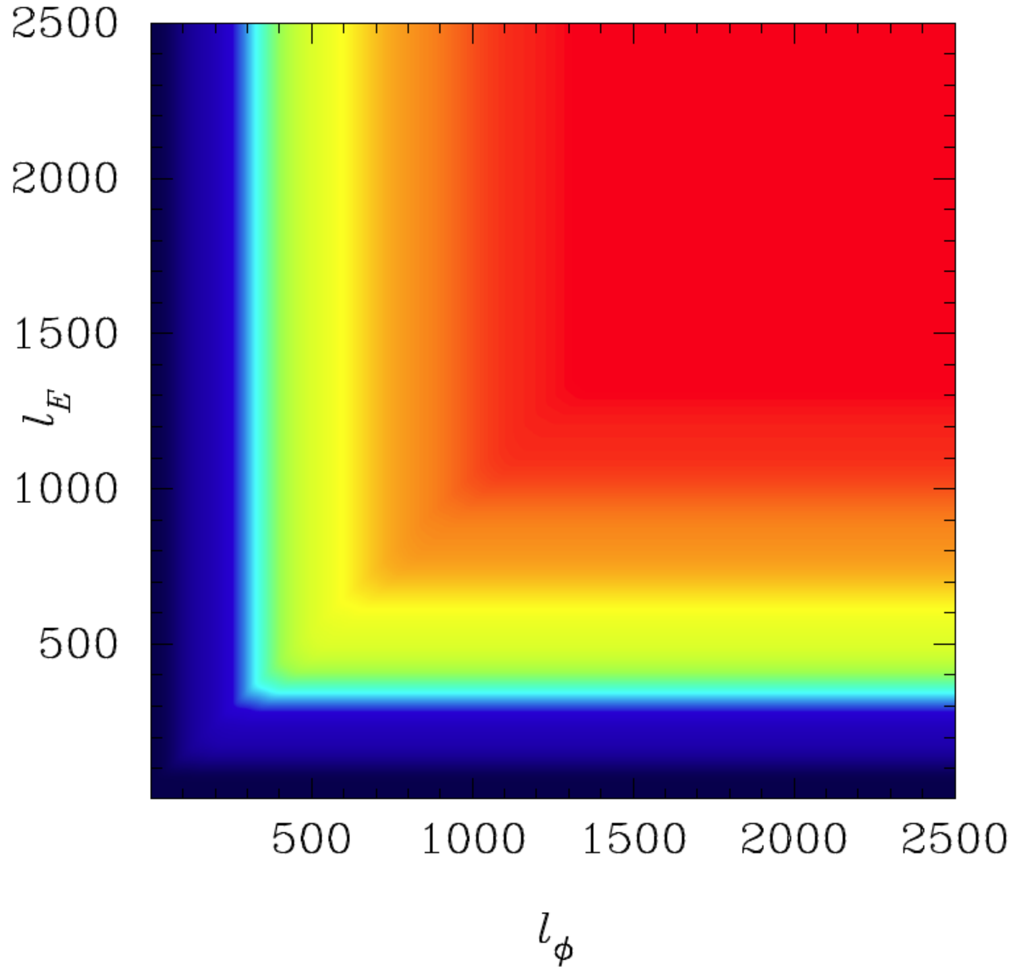
Figure by Josquin Errard

Remove 99% of the foreground contamination

Remove >2/3 of the lensing contamination

Characterize residuals !! (??)

Fractional contribution to C_l^BB at multipole l=60 from lenses with multipole less than l_phi and from E-modes with multipole less than l_E.
One can also interpret this as the fraction of C_l^BB at l=60 that can be removed by delensing using a perfect lens reconstruction (or proxy) at multipoles less than l_phi and perfect E-modes at multipoles less than l_E, and nothing at smaller scales.



Anthony Challinor

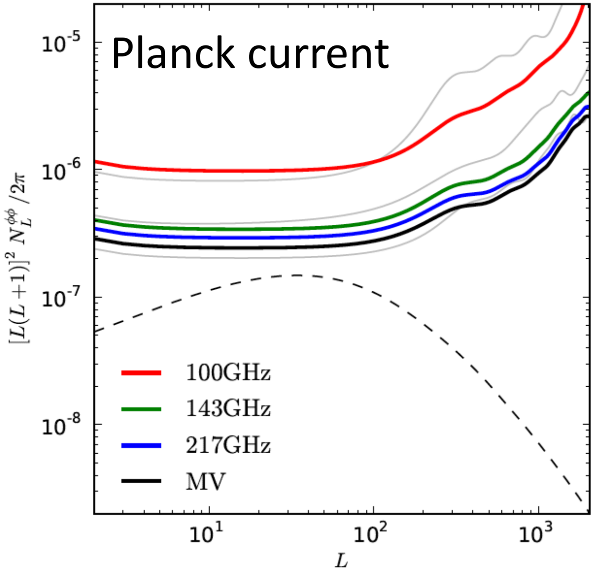
Reconstruction of the lensing potential

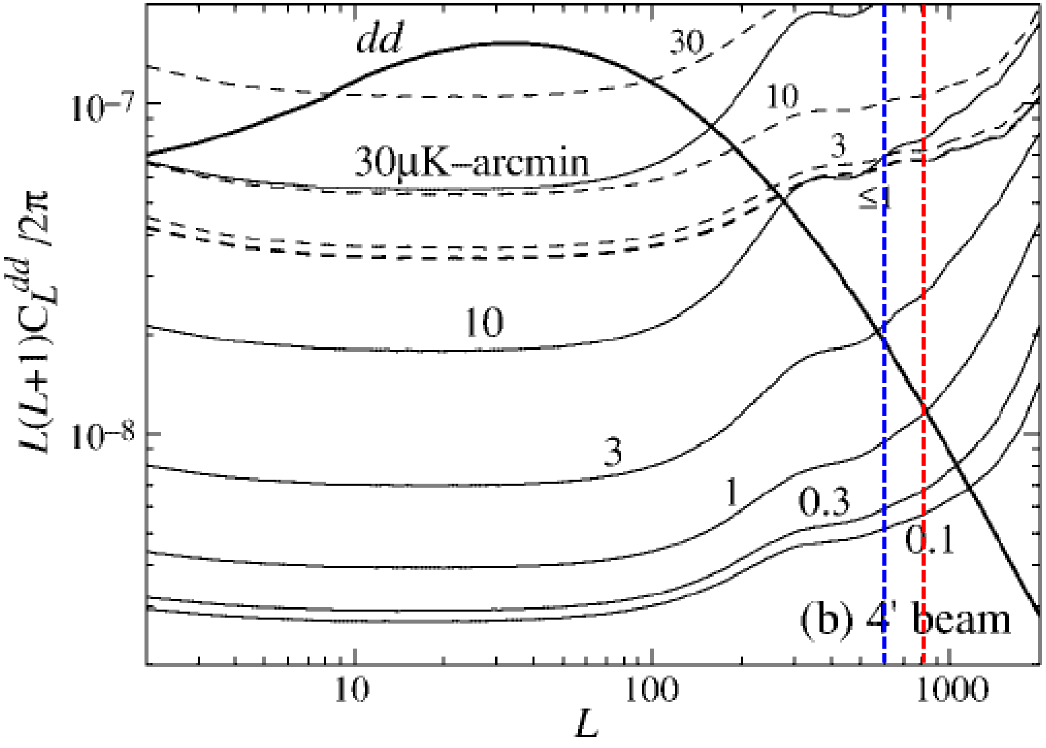
Impact of sensitivity

Hu & Okamoto, 2002, ApJ 574, 566

╌╌╌ Temperature only

── Polarisation (E-B correlation)





20' 15'

Objective: 1-3 μK. arcmin sensitivity or better

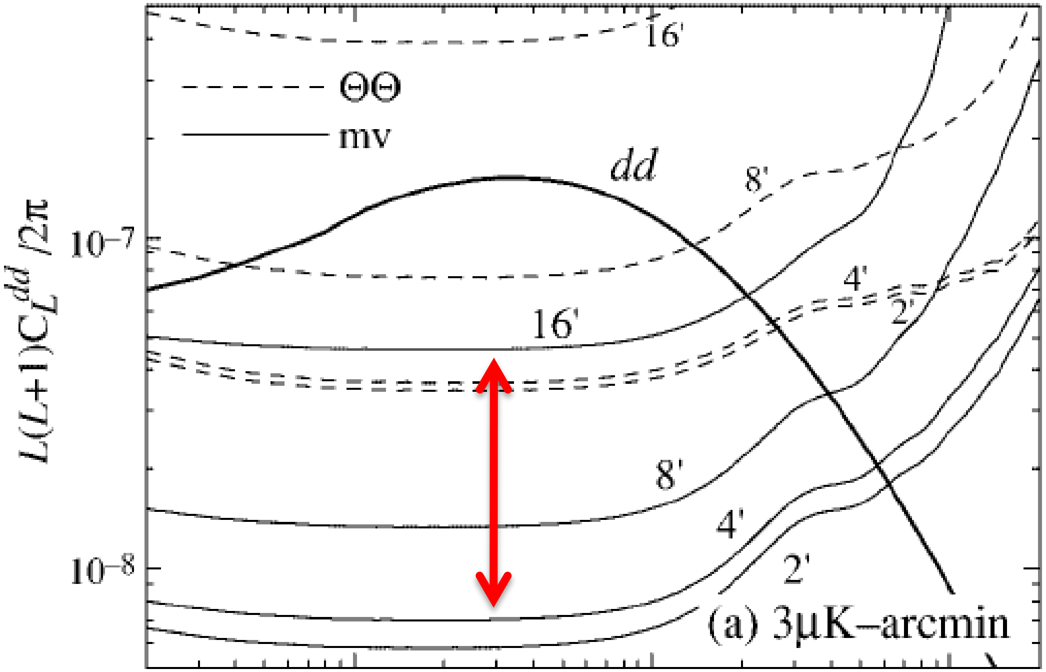
Reconstruction of the lensing potential

Impact of angular resolution

Hu & Okamoto, 2002, ApJ 574, 566

- - - - - Temperature only

——— Polarisation (E-B correlation)



Objective: 4-8' resolution or better

What space mission?

Primordial B-modes may be at any level…

- This makes it hard to define the best strategy to find them!

… but for a comprehensive polarisation mission, the lensing B-modes set the requirement !

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

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

CMB mission proposals in Europe

2006: SAMPAN (CNES)

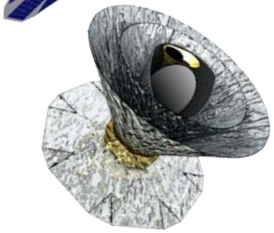
- Small mission focused on Primordial B-modes
- Phase 0 feasibility study: feasible but too expensive for CNES alone

2007: B-POL (ESA M3)

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

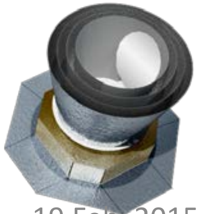
2010: CORE (ESA M4)

- 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.

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

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
Letters of Intent due	January 2016
Proposals due	April 2016
Evaluation process	May–June 2016
Selection of proposals for study phase	June 2016
Phase 0+A completion	June 2018
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

Launch could be earlier for a joint mission

Outline

- Why the CMB ?
- Why space ?
- What space mission ?
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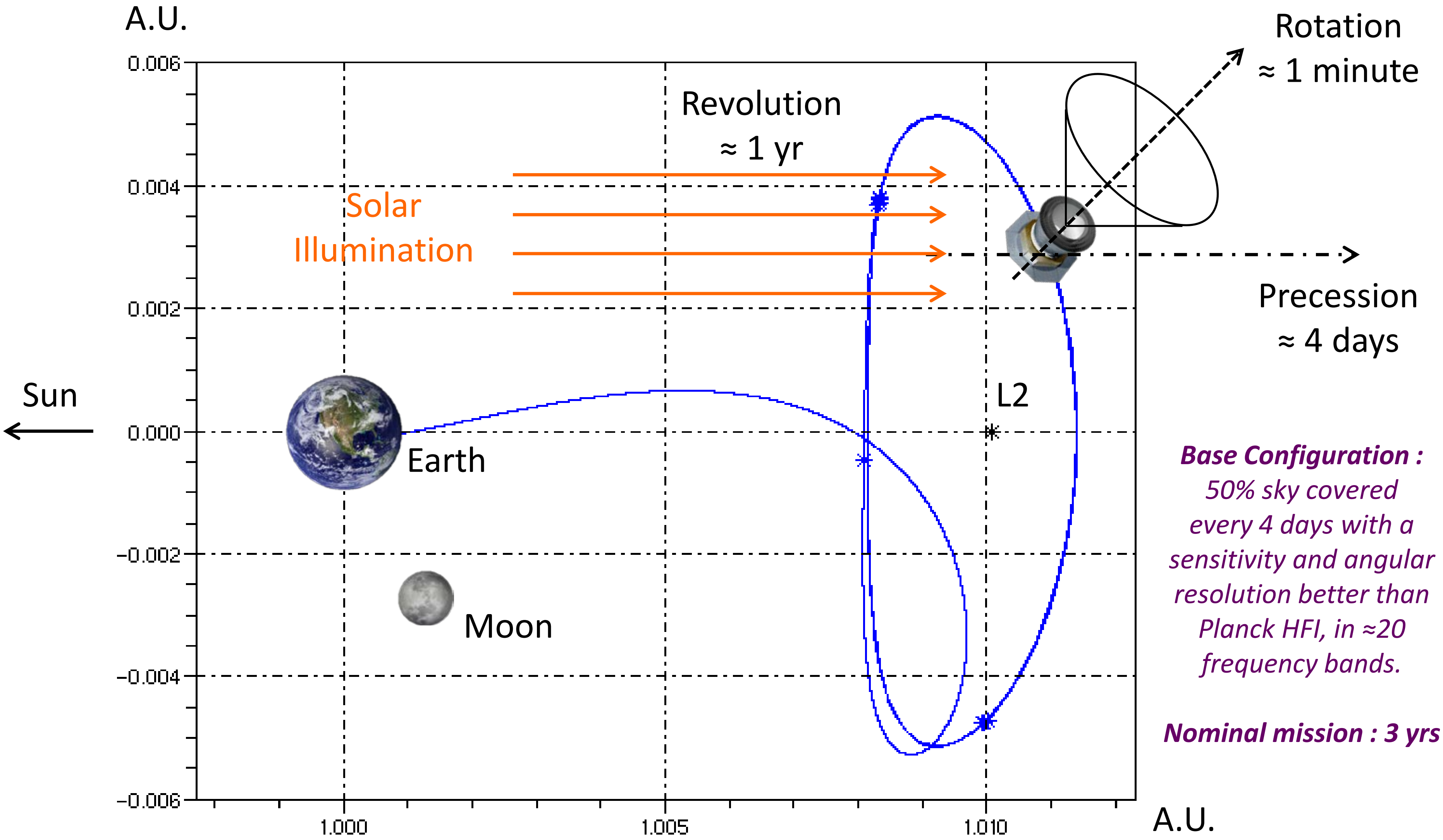
COrE+ concept and strategy

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.*

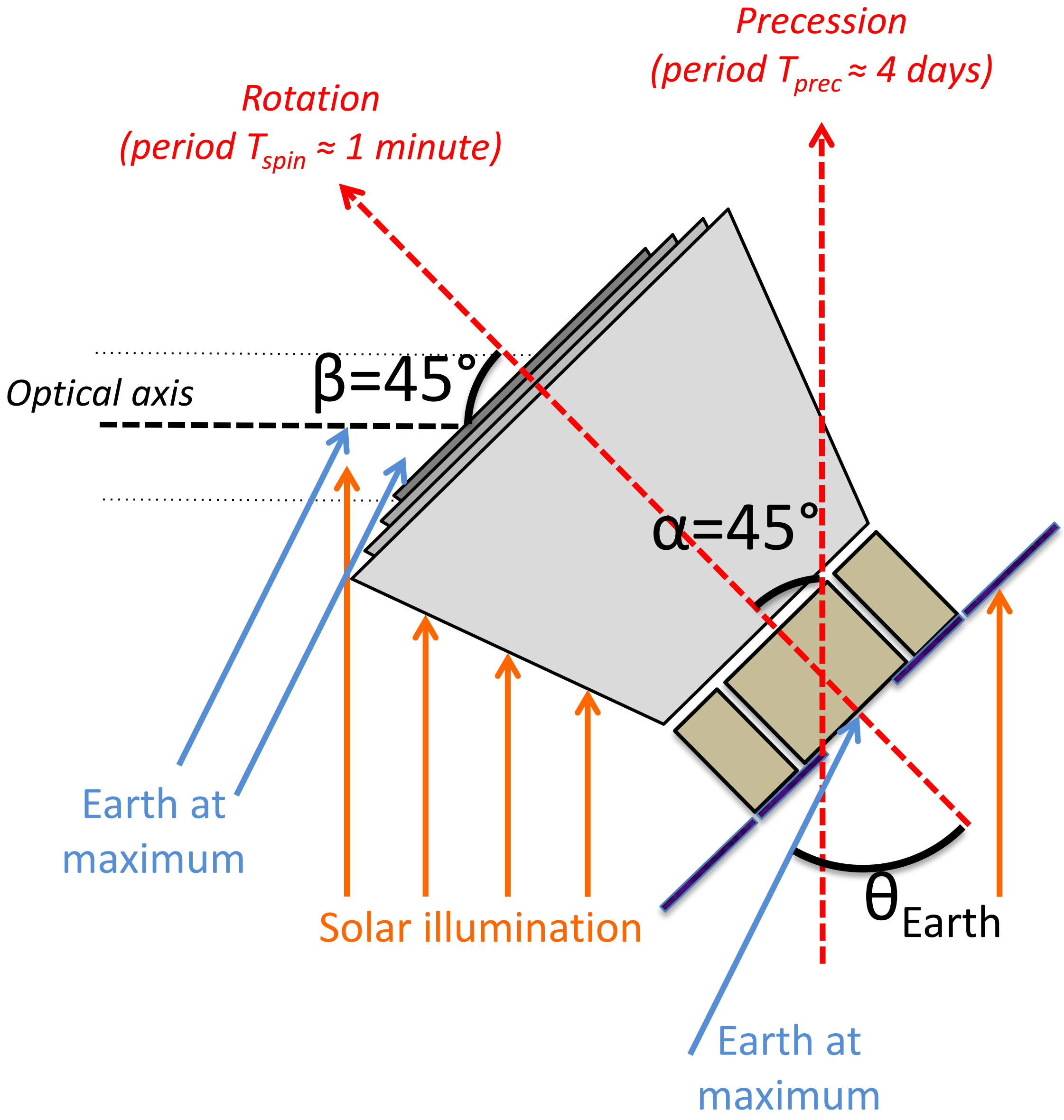
Performance / requirement	***Solution***
Resolve the CMB ≈ 4'-6' resolution or better	Class 1.5m telescope or better ≈ 6' at 135 GHz; ≈ 4' at 200 GHz
Signal dominated data (S/N >2-3 for B_{lens}) σ_P = 1.5-2.5 μK.arcmin on ≈ 100% sky	from ≈ 2500 (base) to 5000 (extension) detectors at ≈ 100 mK
Exquisite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



(Detailed optimisation of parameters in phase A)

Parameter optimisation

Anti-solarprecession for thermal stability ;

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

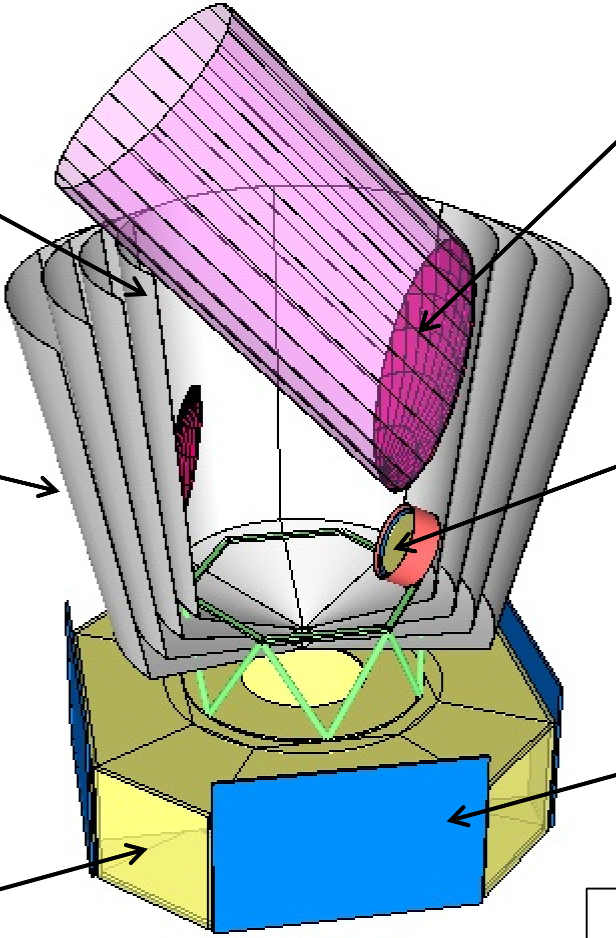
Constraints on θ_{Earth} :
- data transfer
- straylight

Constraints on β :
- full sky ($\alpha+\beta \geq 90°$)

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

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

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+ Collaboration (baseline)

Austria: J. Alves; **Denmark:** J. Ambjorn, P.H. Damgaard, A.M. Frejsel, P. Naselsky, N. Obers; **Finland:** E. Keihanen, H. Kurki-Suonio **France:** N. Aghanim, J. Aumont, A. Banday, R. Banerji, J. Bartlett, K. Benabed, J.-P. Bernard, J. Bobin, F.R. Bouchet, F. Boulanger, M. Bucher, M. Calvo, Ph. Camus, C. Caprini, A. Catalano, J.-F. Cardoso, I. Charles, C. Combet, F. Couchot, J. Delabrouille, F.-X. Désert, M. Douspis, L. Duband, J.-M. Duval, J. Errard, K. Ganga, M. Giard, J. Grain, J.-C. Hamilton, S. Henrot-Versillé, E. Hivon, G. Lavaux, J.F Macias-Perez, J. Martin, F. Mayet, J.-B. Melin, M.-A. Miville-Deschênes, A. Monfardini, L. Montier, G. Patanchon, O. Perdereau, L. Perotto, P. Peter, M. Piat, N. Ponthieu, V. Revéret, I. Ristorcelli, L. Rodriguez, R. Stompor, J.-F. Sygnet, A. Tartari, S. Triquenaux, M. Tristram, B. Van Tent, G. Vermeulen, B. Wandelt; **Germany:** R. Guesten, E. Komatsu, K. Menten, J. Lesgourgues, J. Mohr, R. Sunyaev, J. Weller; **Ireland:** A. Murphy, C. O'Sullivan, D. McCarthy, N. Trappe; **Italy:** M. Ballardini, N. Bartolo, P. Battaglia, E. Battistelli, M. Bersanelli, C. Burigana, C. Baccigalupi, S. Basak, P. Bielewicz, V. Casasola, G. Castex, F. Cavaliere, M. Clemens, F. Cuttaia, G. DAlessandro, P. de Bernardis, F. Del Torto, M. De Petris, A. De Rosa, G. de Zotti, G. Fabbian, F. Finelli, C. Franceschet F. Gatti, M. Gervasi, A. Gregorio, A. Gruppuso, N. Krachmalnicoff, L. Lamagna, M. Lattanzi, M. Liguori, D. Maino, S. Masi, M. Massardi, S. Matarrese, A. Melchiorri, A. Mennella, D. Molinari, G. Morgante, F. Nati, P. Natoli, M. Negrello, F. Paci, L. Pagano, D. Paoletti, F. Piacentini, G. Polenta, G. Puglisi, S. Ricciardi, M. Rossetti, M. Salatino, A. Schillaci, L. Terenzi, M. Tomasi, T. Trombetti, N. Vittorio, A. Zacchei, M. Zannoni; **The Netherlands:** A. Achucarro, A. Baryshev, P. Decowski, B. Freivogel, F. Freire, M. Haverkorn, F. Helmich, H. Hoekstra, K. Kuijken, E. Pajer, M. Postma, T. Prokopec, D. Roest, D. Samtleben, J.P. van der Schaar, K. Schalm, J. Schaye, W. Valkenburg, C. Weniger, R. van de Weygaert, S. Zaroubi; **Norway:** H.K. Eriksen, I. Wehus; **Poland:** M. Biesiada, M. Blicki, M. Demianski, W. Hellwing, A. Janiuk, J. Krywult, B. Lew, J. Mielczarek, P. Orleanski, W. Piechocki, A. Pollo, B. Roukema, R. Szczerba; **Portugal:** M.A. de Avillez, D.S. Barbosa, C.S. Carvalho, A.J.C. da Silva, C.J.A.P. Martins; **Spain:** B. Barreiro, E. Battaner, F. Casas, J.M. Diego, J. García-Bellido, J. Gonzalez-Nuevo, C. Hernandez-Monteagudo, D. Herranz, M. Lopez-Caniego, J.A. Rubiño-Martín, L. Toffolatti, L. Verde, P. Vielva; **Switzerland:** S. Antusch, D. Blas, C. Bonvin P. Dubath, R. Durrer, D. Eckert, M. Kunz, S. Paltani, S. Patil A. Rassat, M. Tucci, M. Turler; **United Kingdom:** P. Ade, M. Ashdown, R. Battye, A. Bonaldi, T. Bradshaw, M. Brown, A. Challinor, J. Chluba, D. Clements, M. Crook, R. Davis, C. Dickinson, J. Dunkley, B. Ellison, A. Heavens, A. Jaffe, M. Jones, T. Kitching, A. Lewis, B. Maffei, F. Noviello, E. Pascale, M. Peel, H. Peiris, G. Pisano, M. Remazeilles, G. Savini, P. Shellard, A. N. Taylor, V. Vennin, S. Withington.

Technological challenges

- Detectors
  - Need for thousands of background-limited detectors in 15-20 frequency channels ranging from 60 to 600 GHz

- Cooling chain
  - Continuous cooling of a large focal plane to 100 mK

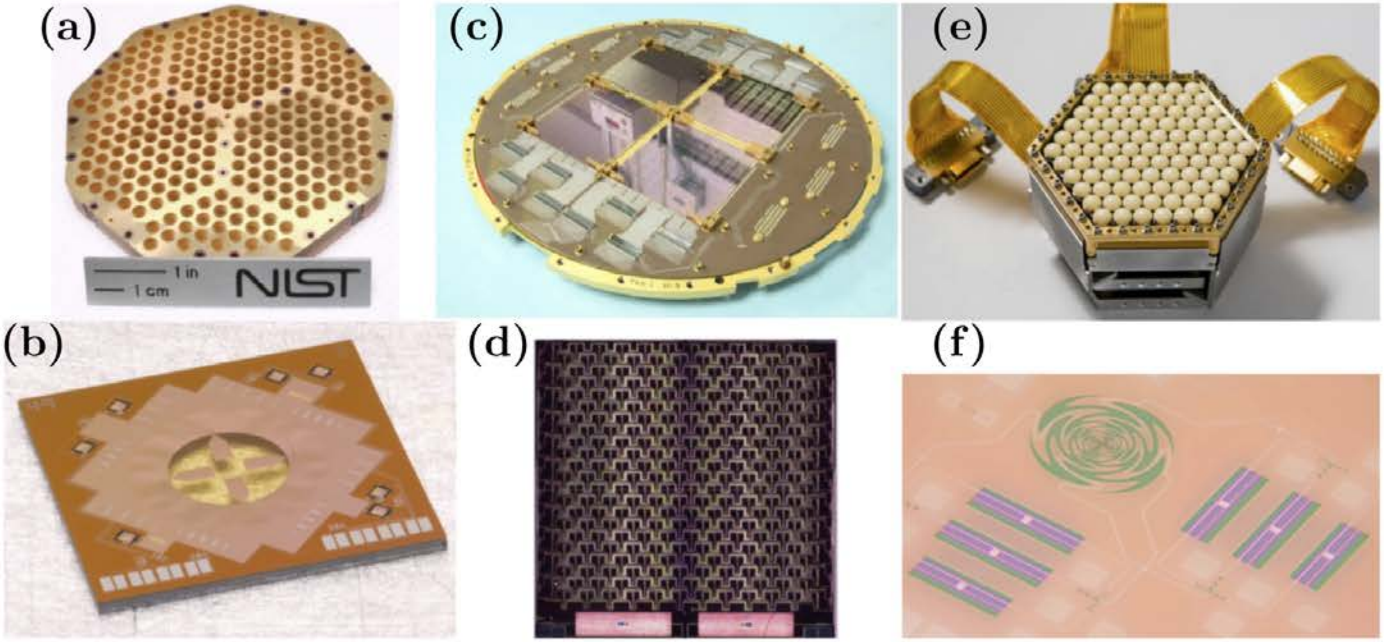
- Simulations / data analysis
  - Modelling sky emission
  - Analysis of data sets from several thousand detectors

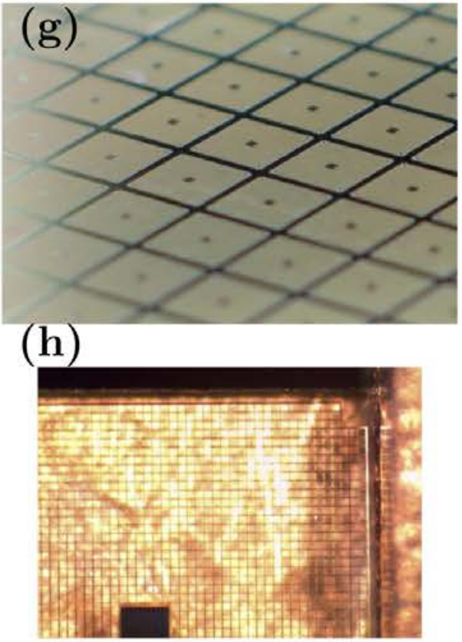
European detectors for CMB polarization measurements

- TES
  - Developed in Europe in Paris, Cambridge, Genova …
  - European MUX tecnology demonstrated in the lab (128:1, QUBIC)
  - Single-mode TES successfully operated at telescopes (SPT, ACT, BICEP, ….) and flown on balloons (EBEX, SPIDER) by US teams
  - European multimode TES to be flown on a balloon with LSPE (ASI+INFN)
- KID
  - Developed in Europe in Grenoble, Groningen, Cambridge, Rome, ….
  - Operation down to 60-80 GHz demonstrated (A&A 580, A15 (2015), Astro-ph/1601.01466)
  - Large European matrix already operated at a telescope (NIKA & NIKA2)
  - For a filled array, 10 aW/sqrt(Hz) sensitivity demonstrated in a laboratory setup simulating the radiative background in L2 and 30% bands @100 and 150 GHz - Astro-ph/1511.02652; The sensitivity target for use in COrE+ is around 3 aW/sqrt(Hz) for a 35% band.
  - Study of cosmic ray effects on-going (space-KIDs, see e.g. Astro-ph/1511.02652). Glitches are very short; cross section slightly larger than for TESs.
  - To be flown on balloons (Adv. Blastpol in the USA, OLIMPO and Plan-B / B-SIDE in Europe)
- MID
  - MEMS metal insulator detectors developed at CEA-Leti for Herschel-PACS have been improved to reach aW/sqrt(Hz) sensitivity operating at <100 mK, and in-pixel polarization measurements. European program CESAR developed suitable readout electronics.
  - Still to be operated at telescopes
- CEB
  - Developed in Chalmers
  - Instrinsically insensitive to Cosmic Rays
  - Still to be operated at telescopes.

Slide from Paolo de Bernardis

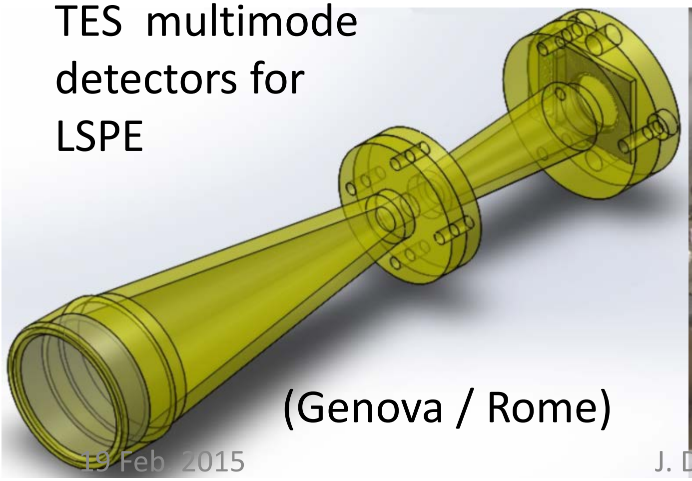
TES detectors



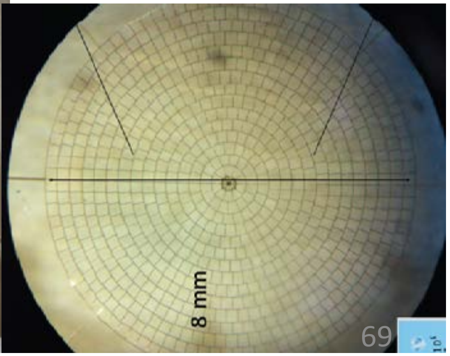


TES detectors
for QUBIC
(Paris)

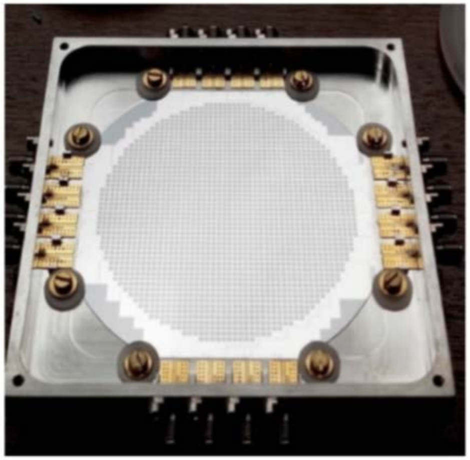
TES multimode
detectors for
LSPE



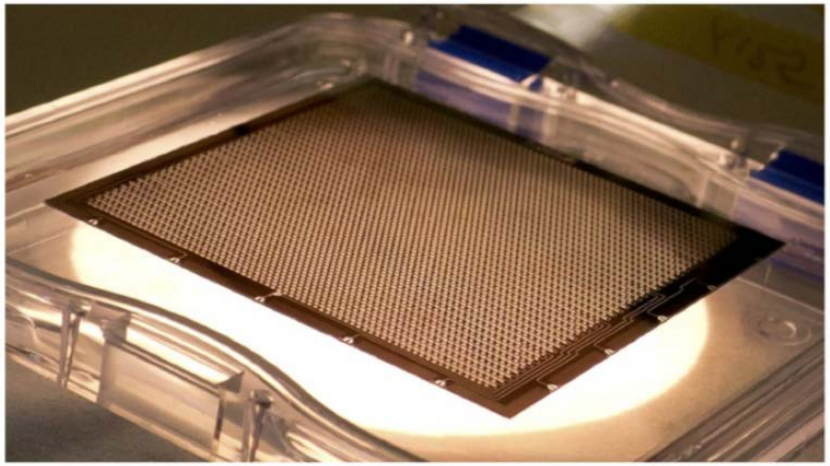
(Genova / Rome)



KID detectors in Europe

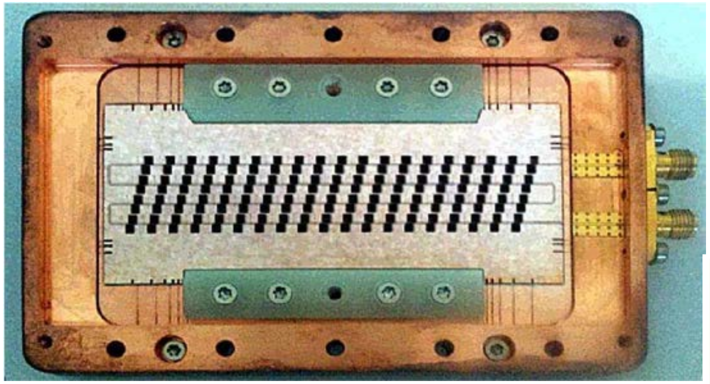


NIKA2 array 200-300 GHz
(Grenoble) -> IRAM30m

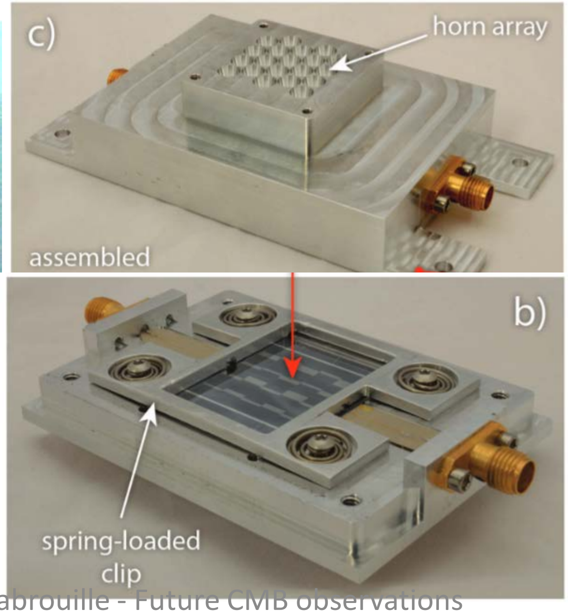


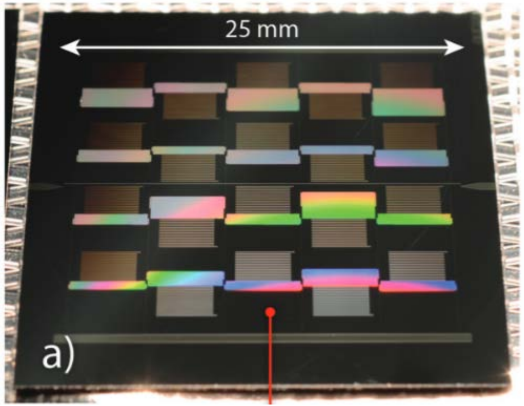
AMKID array - submm
(Groningen) -> APEX ALMA

LEKID for 150 GHz
(Rome)



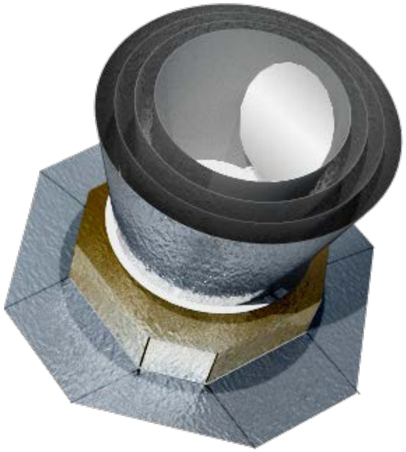
THz camera for safety scanner
(Cardiff)





Horn-coupled KIDs for CMB
(Cardiff + ASU)

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:

Hundreds of publications

- **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)

My wish list:

Get it selected and launched as soon as possible!

From Tomotake Matsumura

ISAS/JAXA mission categories

Space Policy Commission under cabinet office intends to guarantee predetermined ***steady annual budget*** for space science and exploration for ISAS/JAXA to maintain its excellent scientific activities

Strategic Large Missions (300M$ class) for JAXA-led flagship science mission with HIIA vehicle (3 in ten years)

Phobos/Deimos

LiteBIRD

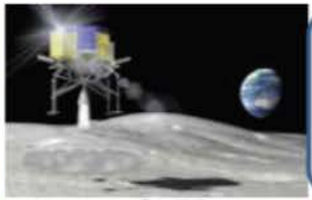
Solar Sail

SPICA

We do not exclude the other candidates.

Competitively-chosen medium-sized focused missions (<150M$ class) with Epsilon rocket (every 2 year)

ERG



SLIM

#4, #5
AO

Missions of opportunity (10M$ per year) for foreign agency-led mission, sounding rocket, ISS

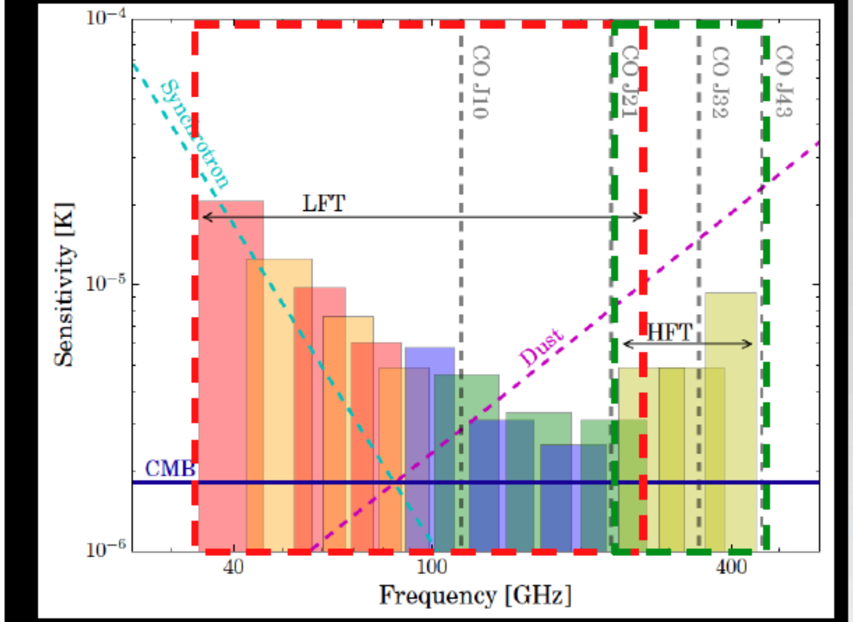
JUICE

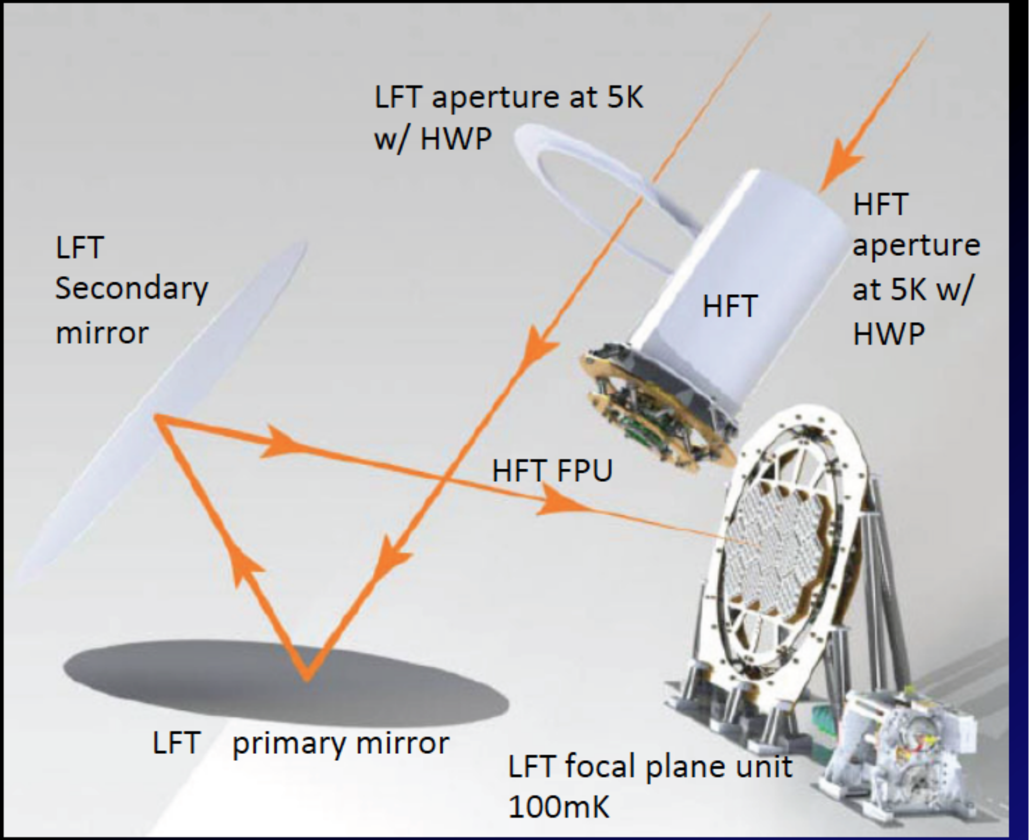
ATHENA

From Tomotake Matsumura

Mission system overview

Observing band



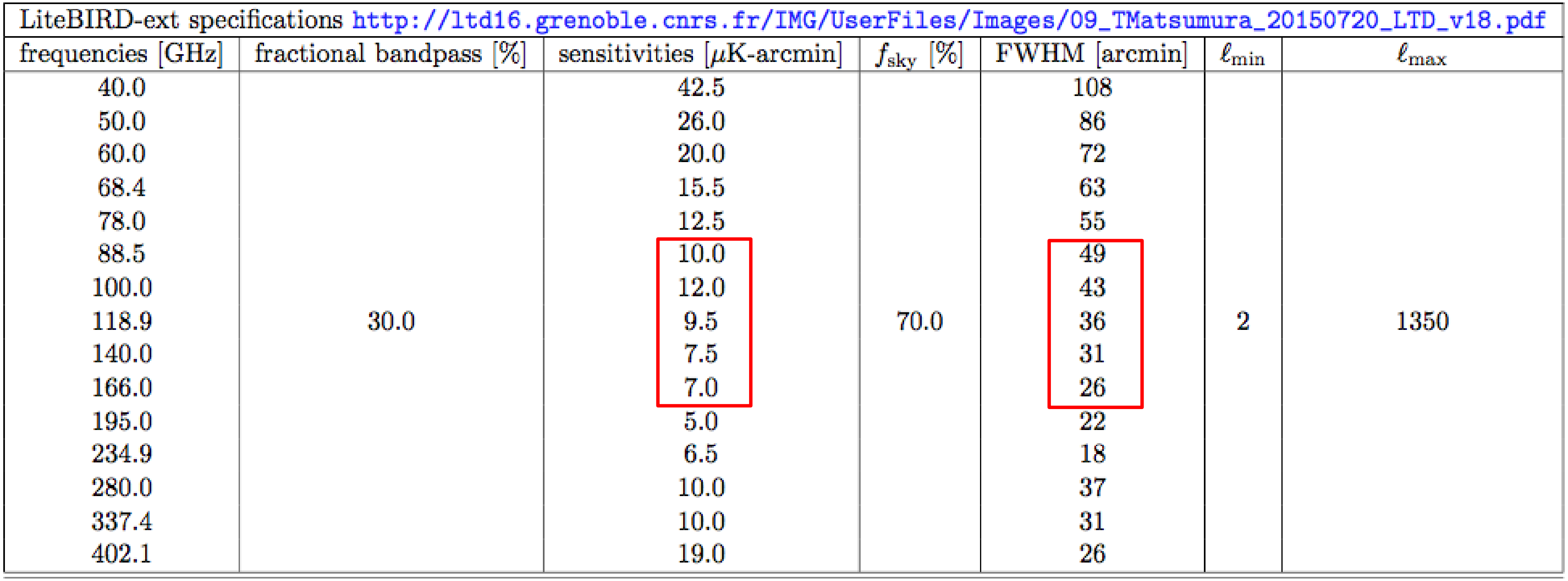


Obs. band : 40～402 GHz
The obs. band is split into two.

- Lower freq.: 40～235 GHz（Low frequency telescope: LFT）
- Higher freq.: 280～402 GHz（High frequency telescope: HFT）

Superconducting detector array: TES bolometer or MKID.

Main LiteBIRD (extended) characteristics



LiteBIRD-ext specifications `http://ltd16.grenoble.cnrs.fr/IMG/UserFiles/Images/09_TMatsumura_20150720_LTD_v18.pdf`

frequencies [GHz]	fractional bandpass [%]	sensitivities [μK-arcmin]	$f_{\rm sky}$ [%]	FWHM [arcmin]	$\ell_{\rm min}$	$\ell_{\rm max}$
40.0	30.0	42.5	70.0	108	2	1350
50.0		26.0		86		
60.0		20.0		72		
68.4		15.5		63		
78.0		12.5		55		
88.5		10.0		49		
100.0		12.0		43		
118.9		9.5		36		
140.0		7.5		31		
166.0		7.0		26		
195.0		5.0		22		
234.9		6.5		18		
280.0		10.0		37		
337.4		10.0		31		
402.1		19.0		26		

Assumes 30% bandwidth with 70% optical efficiency
CMB resolution from about 26' to about 49' (in CMB channels)
Low frequency foregrounds monitored with resolution from 55 to 108'
High frequency foreground monitored with resolution from 18 to 37'

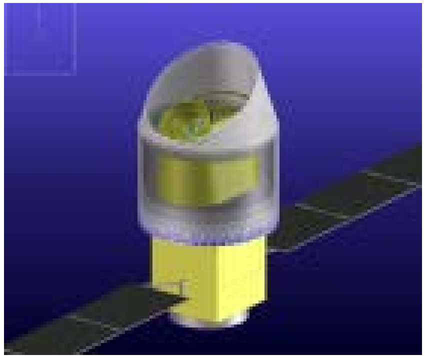
LiteBIRD status

Ongoing phase A for the US contribution to LiteBIRD (focal plane, sub-K cooler)

Phase A1 in Japan now supposed to start in April 2016

Joint study initiated by ESA and JAXA for a common mission (more on this later)

LiteBIRD *(JAXA+NASA selected for phase A!)*



Very targeted experiment: Detect primordial B-modes as soon as possible.

Drawback for main goal: No de-lensing because of low angular resolution (30').

Limited frequency bands and coverage.

Foreseeable science:

- **Detection of r** (or confirmation or upper limit)
- **Stationarity / anomalies of polarisation on large scales**
- (Constraint on tau from the reionisation bump in E-modes)

Risk:

Moderate success if no detection of r and marginal improvement over ground-based upper limits

PIXIE

Two-purpose experiment: primordial B-modes AND spectral distortions (FIRAS x 1000 !).

Drawback for main goals: No de-lensing possible AND low angular resolution (2.5°) – only 8000 independent pixels on the sky. Sensitivity somewhat too low for CMB spectral distortions…

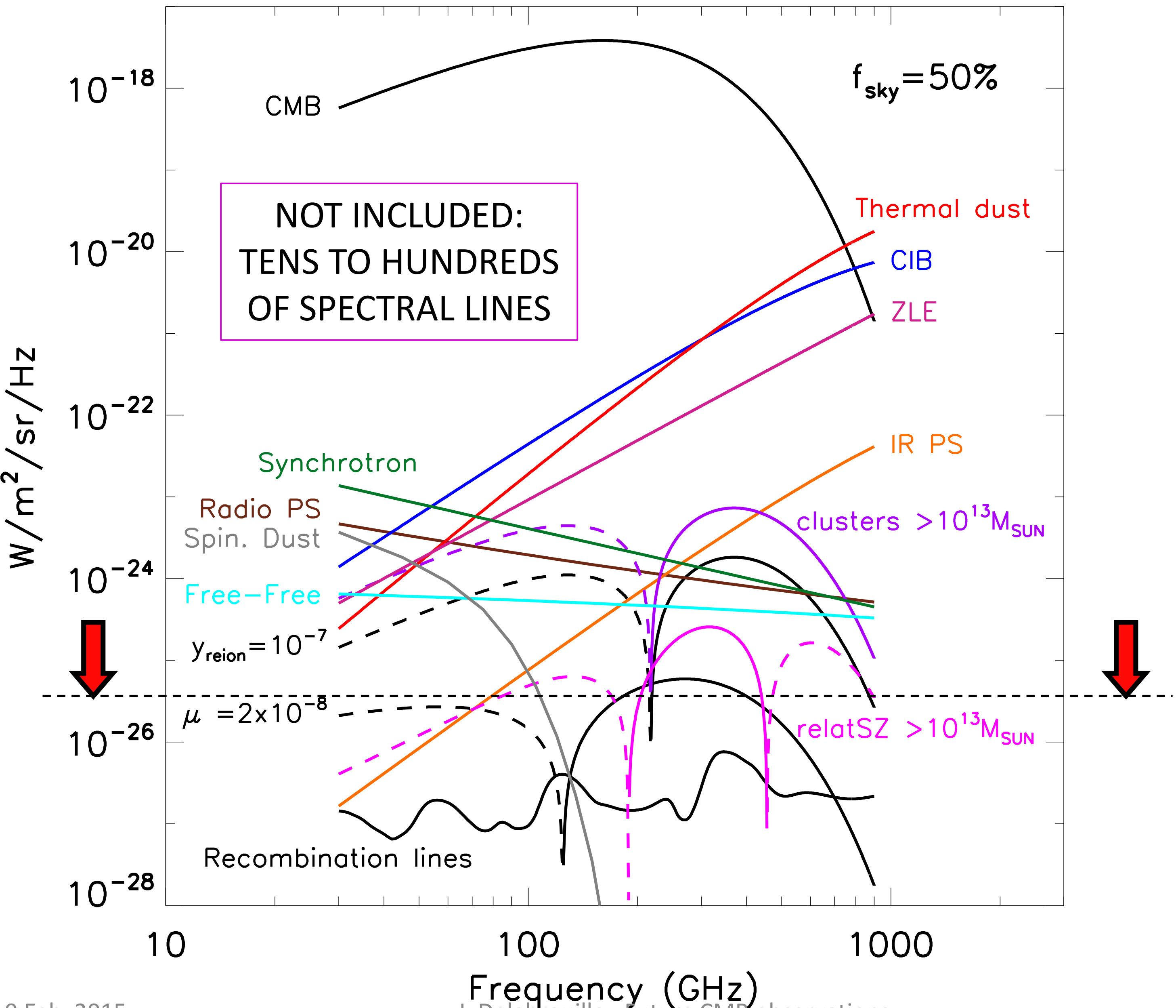
Foreseeable science:

- **Most of LiteBIRD science AND**
- Spectral distortions (**1000 x FIRAS**) **AND**
- Absolute emission of many astrophysical sources of radiation

Limitations:

Low angular resolution and sensitivity, too few channels at low ν.

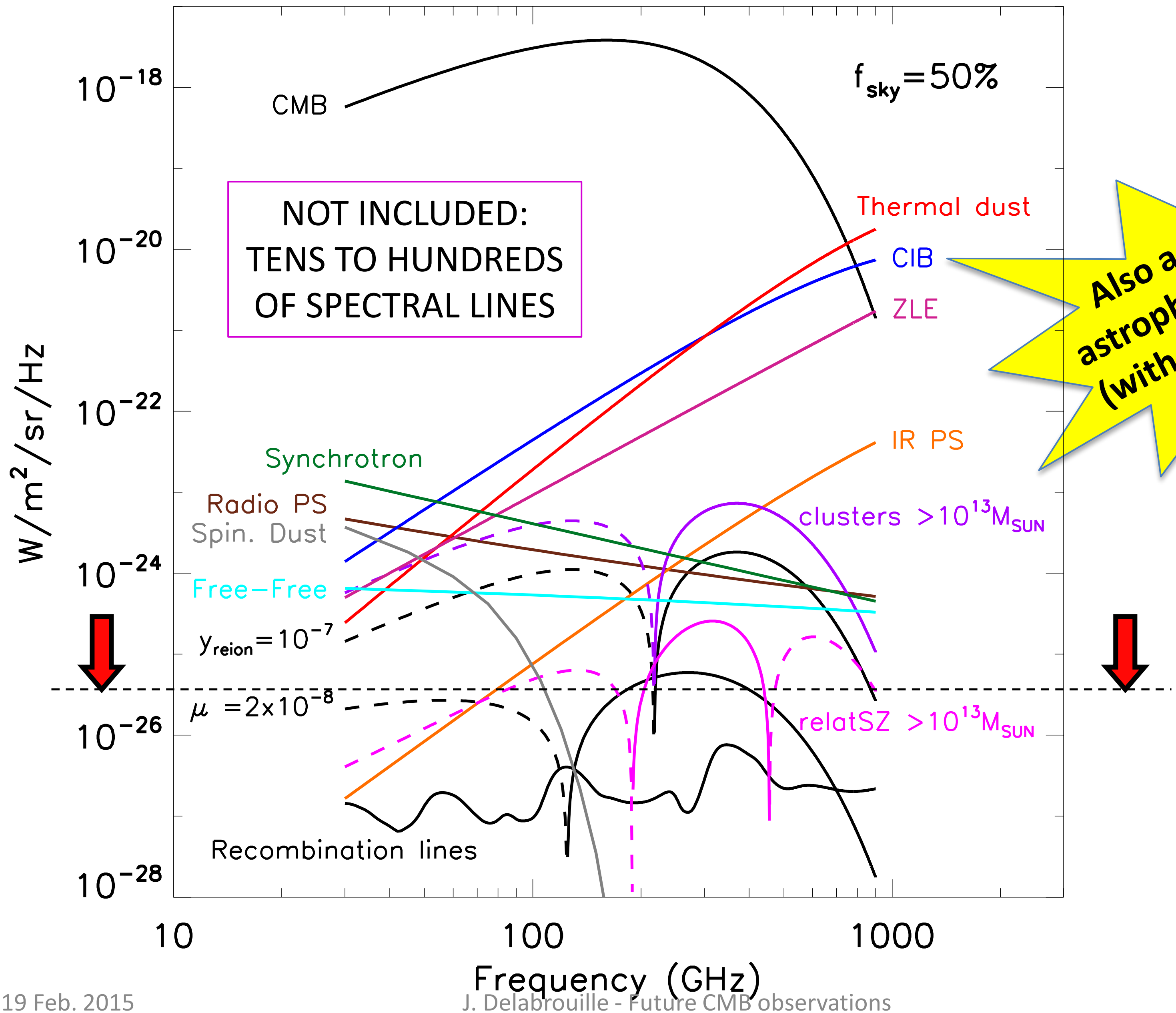
Spectral distortions and foreground emission



NOT INCLUDED:
TENS TO HUNDREDS
OF SPECTRAL LINES

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

Spectral distortions and foreground emission



NOT INCLUDED:
TENS TO HUNDREDS
OF SPECTRAL LINES

Also a fantastic astrophysics mission (with better FWHM)

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

The foreground problem for spectral distortions

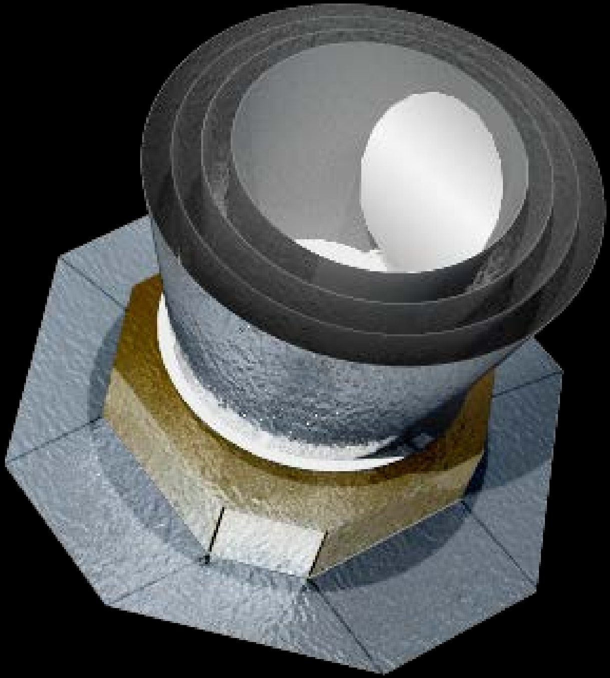
- Foregrouds dominate the CMB spectral distortion signals of interest by 4 to 6 orders of magnitude !

- Subtracting these contaminants will be challenging

- The following can help:
  - Better angular resolution and sensitivity
  - More frequency channels in the CMB range
  - An associated imager with high angular resolution

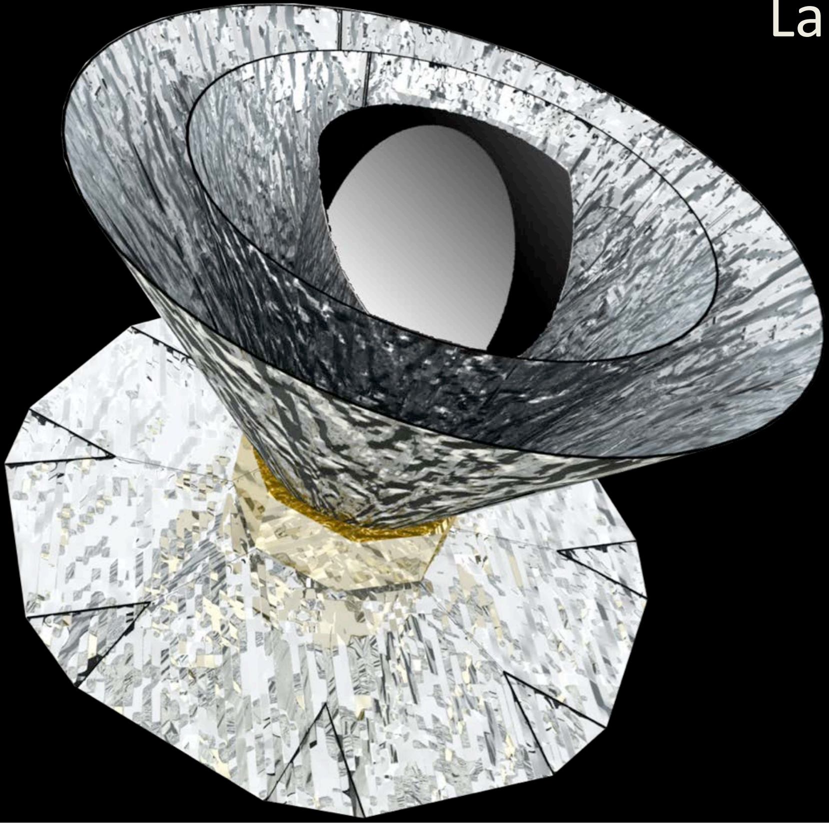
Spectrophotometer or Imager?

?

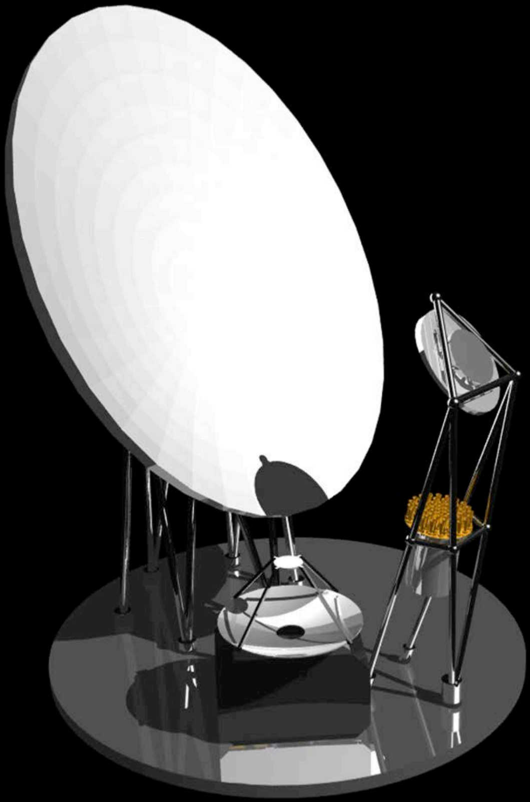


PRISM

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

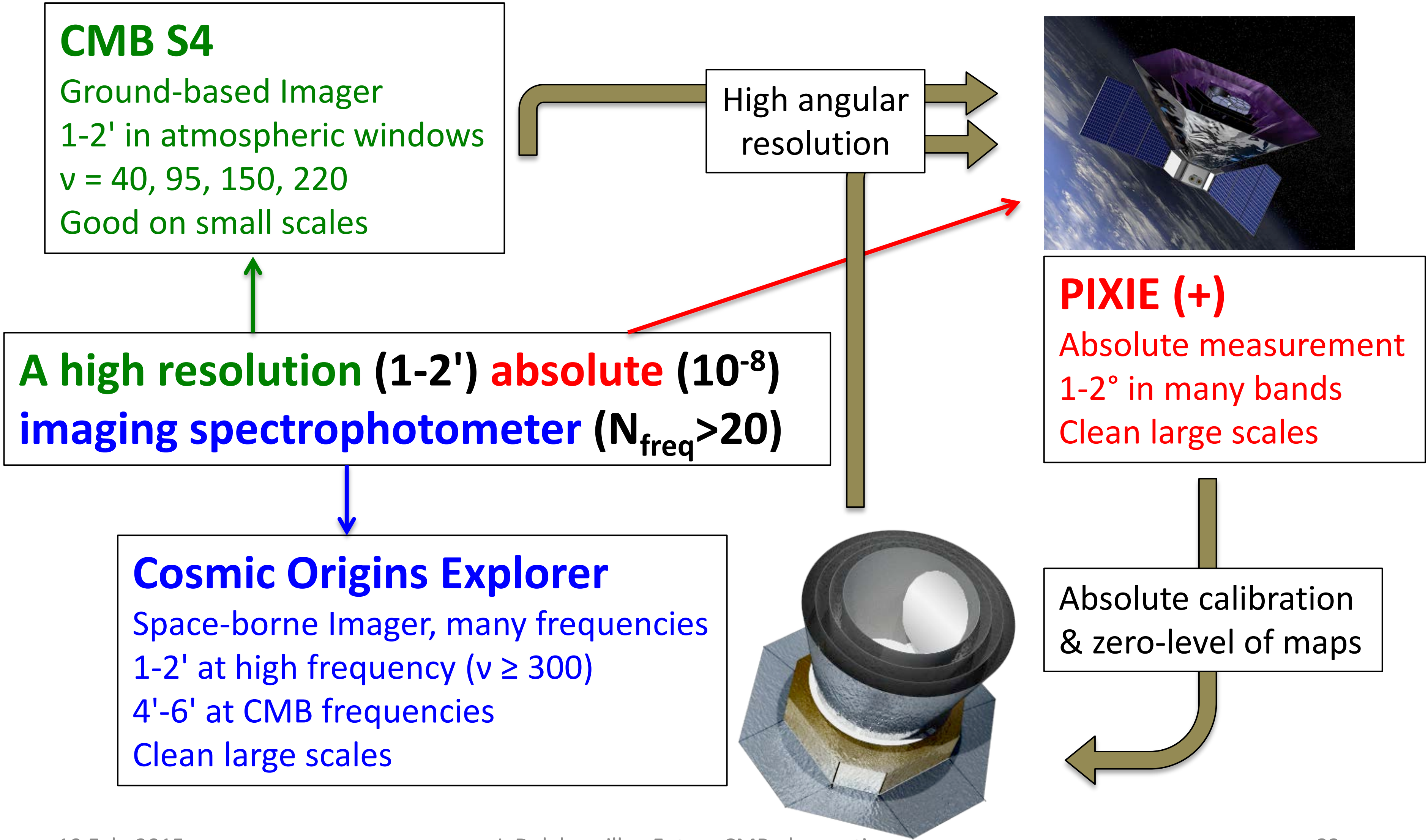


A high resolution (1-2') **absolute** (10^{-8})
imaging spectrophotometer (N_{freq}>20)



Two instruments

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 (+)

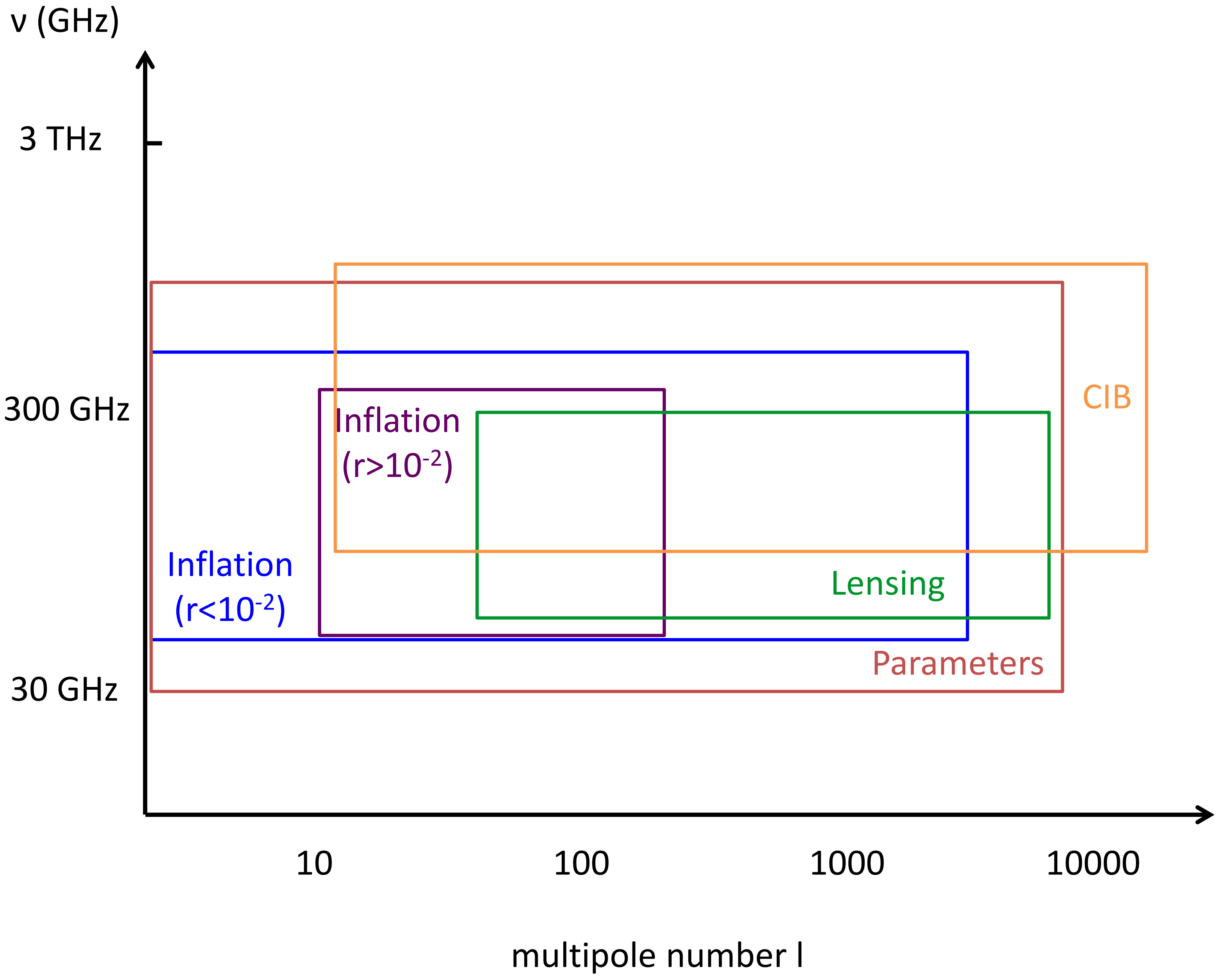
Absolute measurement
1-2° in many bands
Clean large scales

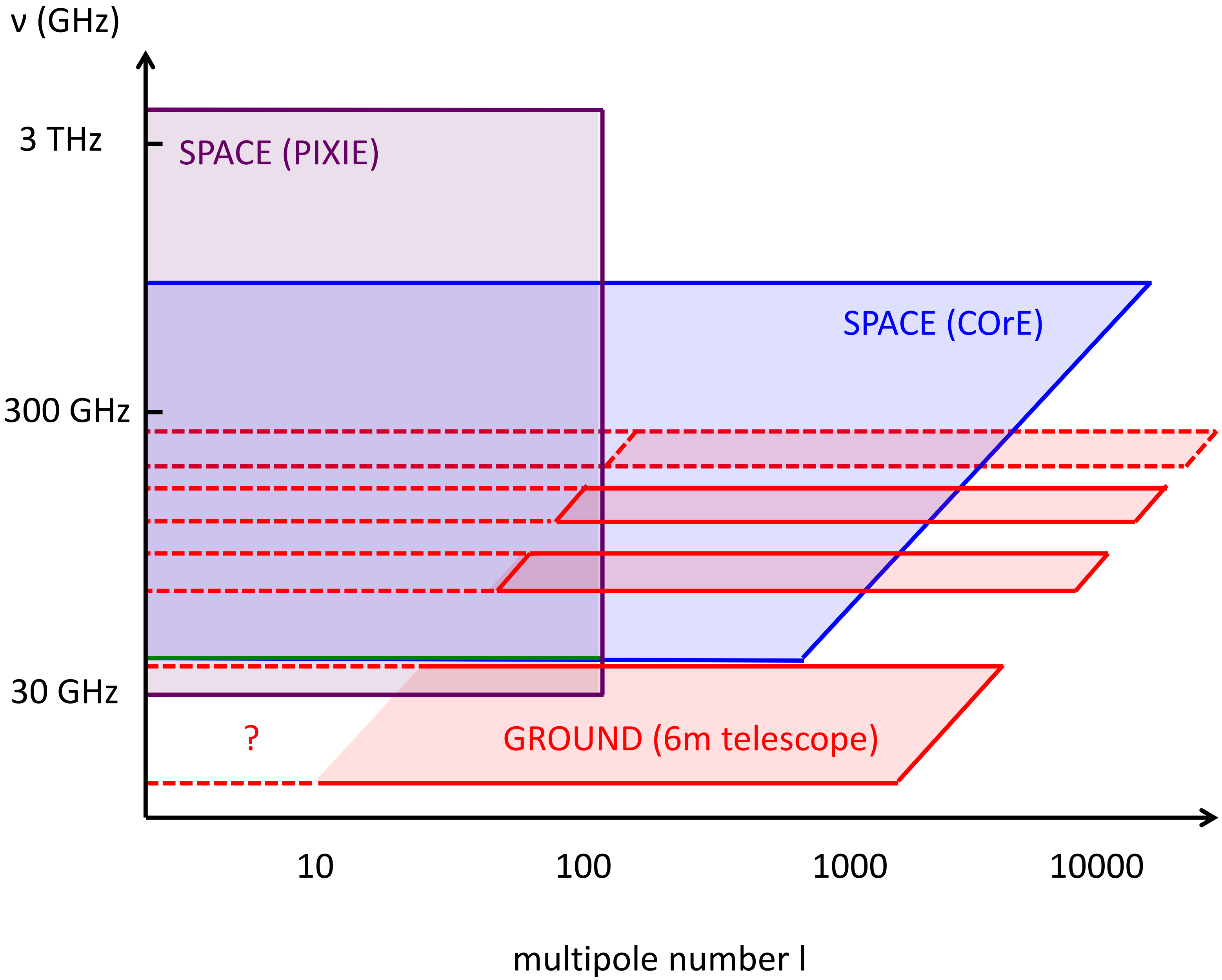
A high resolution (1-2') absolute (10^{-8}) imaging spectrophotometer (N_{freq}>20)

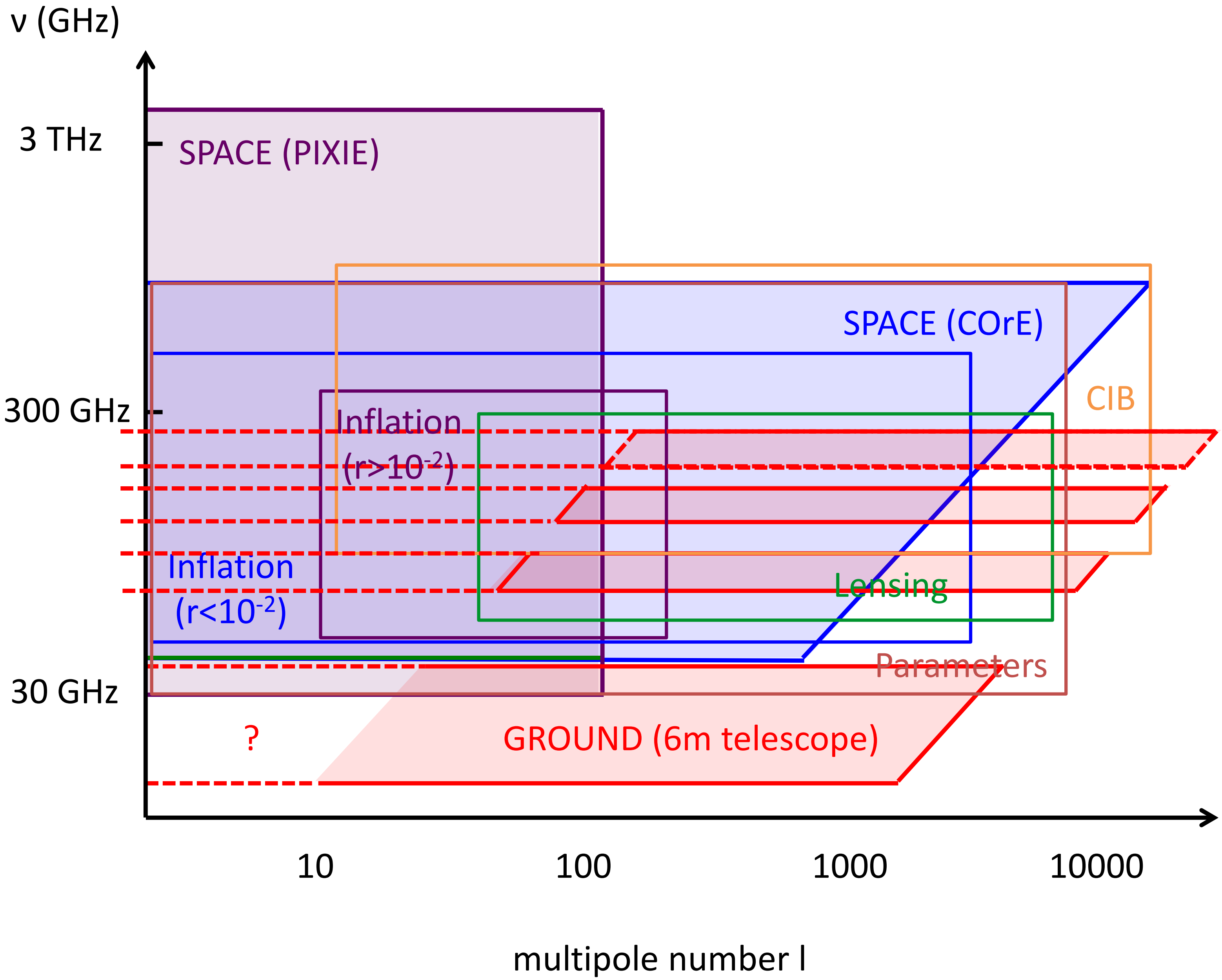
Cosmic Origins Explorer

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

Absolute calibration & zero-level of maps

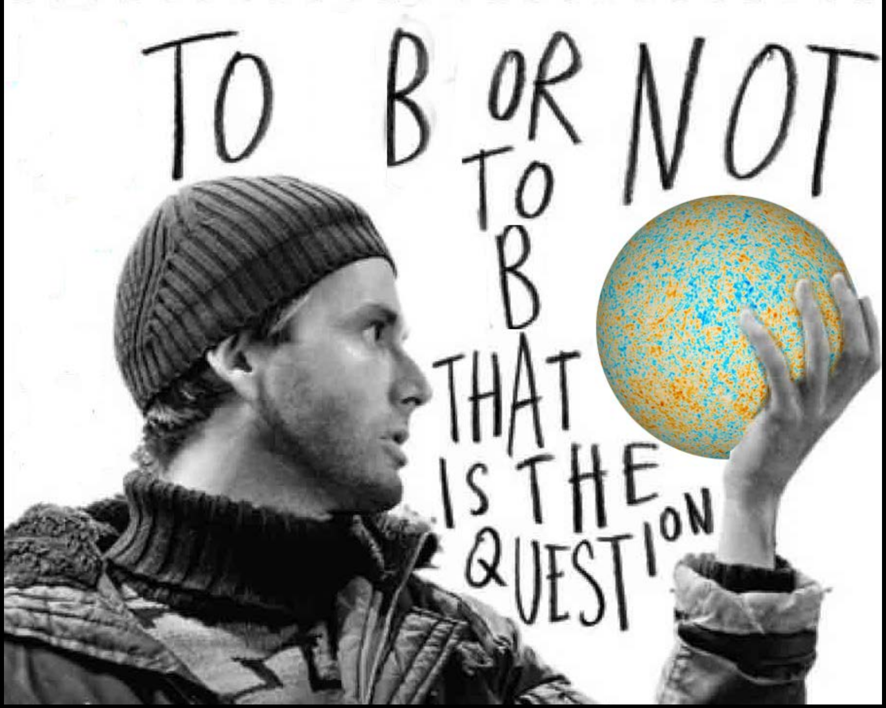

ν (GHz)
3 THz
300 GHz
30 GHz
Inflation
(r>10^-2)
Inflation
(r<10^-2)
CIB
Lensing
Parameters
10
100
1000
10000
multipole number l


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

Outline

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



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THE B RACE

DILEMMA

THE CMB TASK

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

Individual 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.

It now requires coordination, expensive instruments, large teams, and time…

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.
- A lot can also be learnt from CMB spectral distortions.

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 a major contribution from JAXA).

- On the spectral distortions side, it is now possible to improve the FIRAS measurement by 3 or 4 orders of magnitude.

Summary

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

- Ground-based telescopes are required to reach 1' angular resolution at frequencies where the CMB dominates, and where SZ effects are measured.

- An absolute spectrophotometer is required to get the information encoded in CMB spectral distortions.

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.
- Europe is ideally positioned to do a comprehensive multi-frequency polarised imager.
- Let's get organised, and do it.