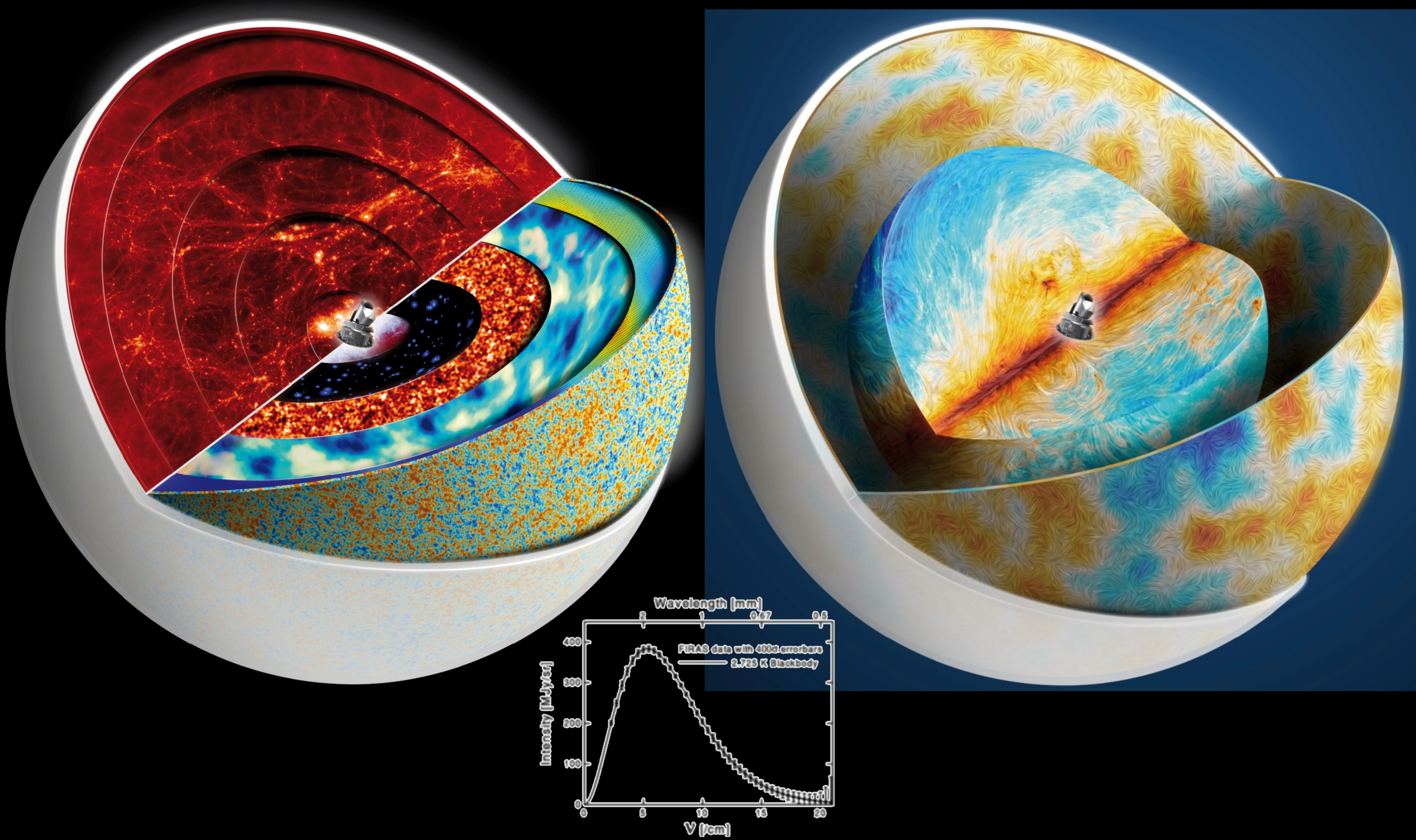
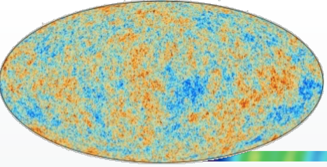
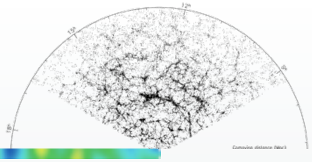
French roadmap to CMB science



François R. Bouchet, Institut d’Astrophysique de Paris, for the roadmapping group



Modus operandi du Groupe de travail

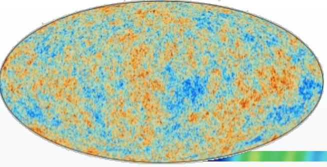


- Le 10/09/2015, mandat est donné par le CNES, l'INSU, l'IN2P3 et le CEA au Programme National Cosmologie et Galaxies d'établir les éléments de la stratégie française en ce domaine (science du CMB), en incluant les aspects sol, ballon et spatiaux dans la feuille de route.

- Le 18/09/2015, composition finalisée du groupe (*Banday[Boulanger], Bernardeau, Bouchet [Président], Désert[Ponthieu], (Douspis), Ganga, Lagache, Rodriguez, Tristram, et ex officio Arnaud [PNCG], Binetruy [CNES-GT Physique fondamentale], Renault [CNES-GT Astrophysique]).*

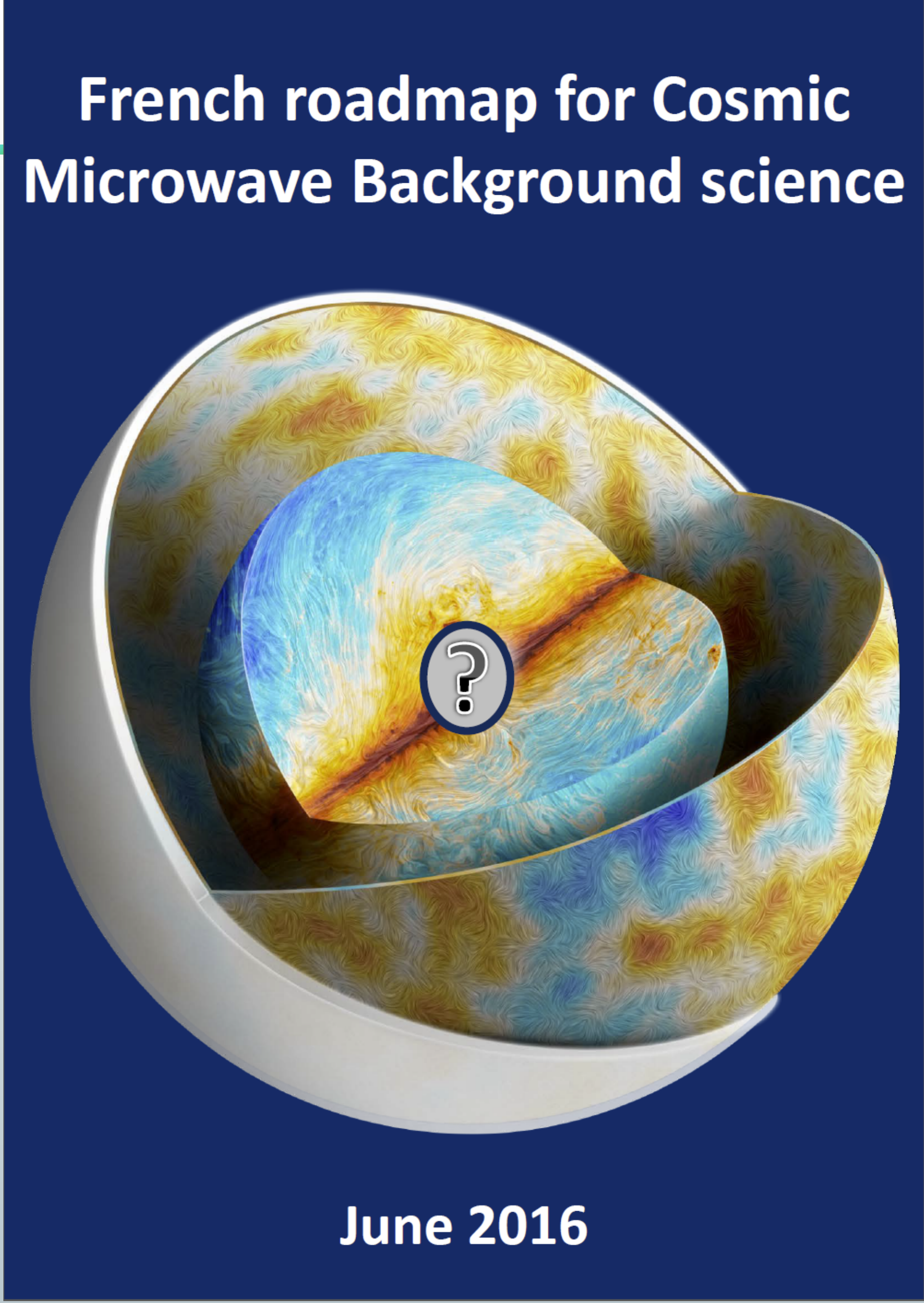
- 6 Réunions Publiques/Fermées (F) les 2015/10/02(F) + 2015/11/26&27(F) + 2016/02/04&05(F) + 2016/04/02&06(F) + 2016/05/13(F) + 2016/06/06&07F
    - *http://prospective.planck.fr/index.php?n=Main.Meetings pour les planches.*

- Rapport (78p., en anglais)
    - *distribué à la communauté pour réactions avant la dernière réunion publique du 2016/06/06.*
    - *Version finale rendue fin Juin 2016; disponible sur le wiki de la prospective http://prospective.planck.fr/uploads/Main/2016-06-30-CMBroute.pdf*



Contenu du rapport

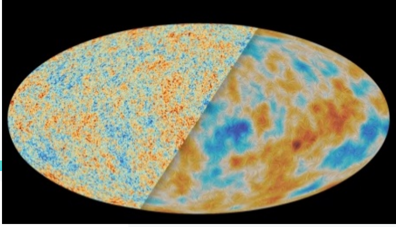
- § 2 & 4: Potentiel scientifique du CMB
- § 3, 5, 6 Défis (astrophysiques/instrumentaux/d'analyse)
- § 7: Paysage expérimental actuel
- § 8: proposition de feuille de route et recommandations
- *Les sections se terminent par un encadré des conclusions et des recommandations (cf. annexe de cette présentation)*

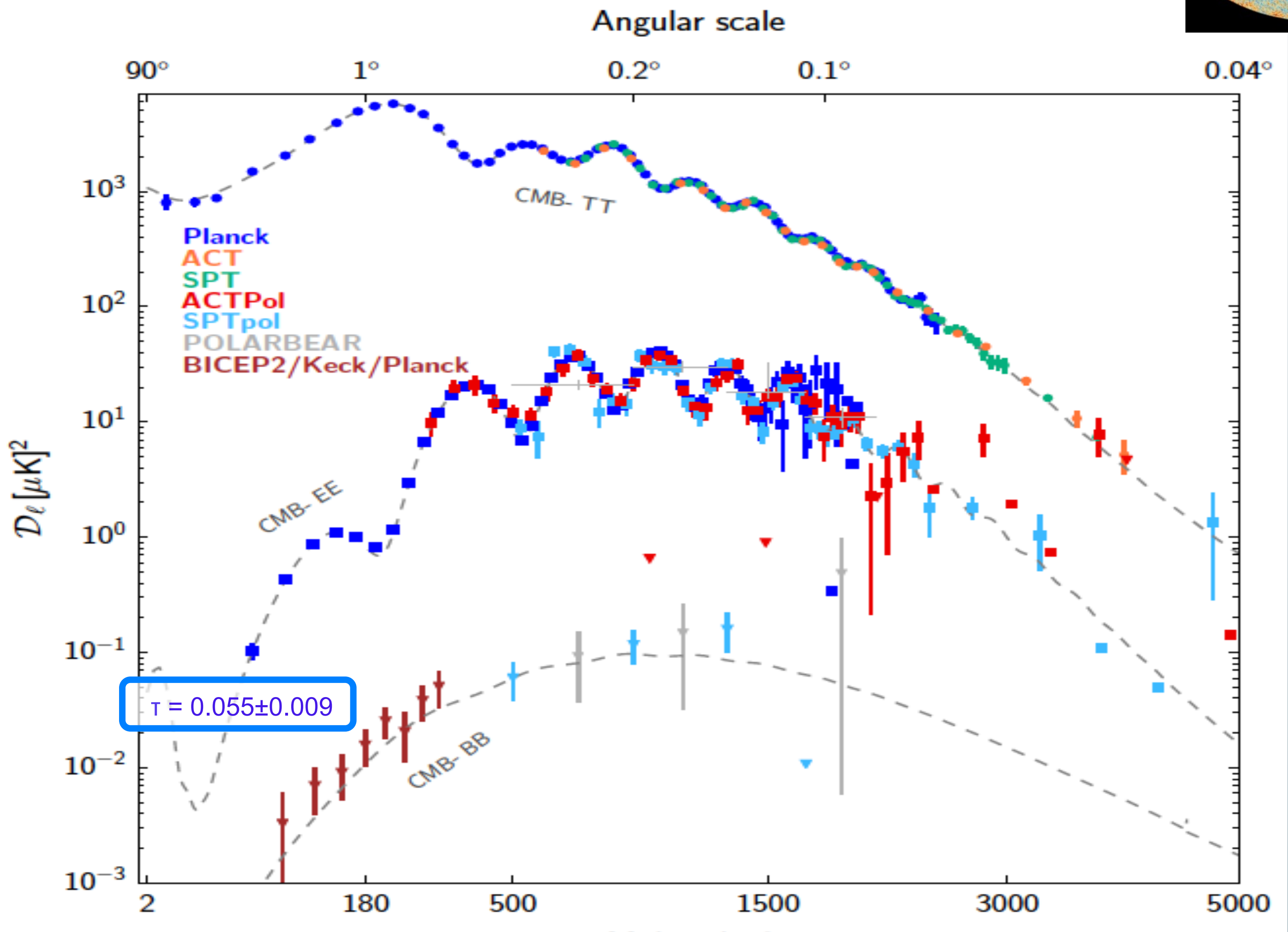


French roadmap for Cosmic Microwave Background science

June 2016

TT, EE, BB – mid 2015 status





τ = 0.055±0.009

Only keeping points w. sufficiently small error bars, Fig. calabrese

1 114 000 Modes measured with **TT**,

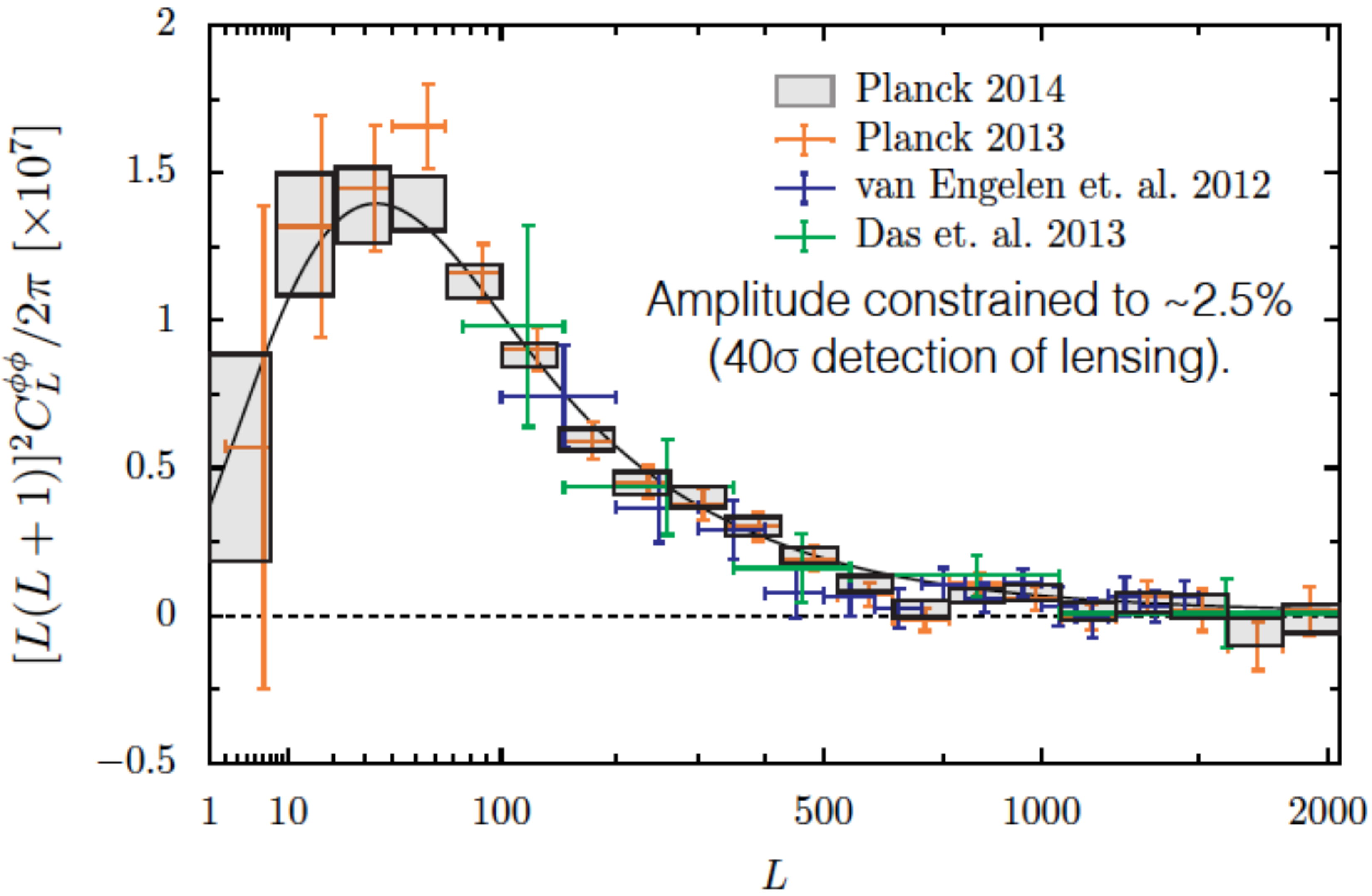
(60 000 with TE)

96 000 with **EE**

… and **10's in BB and φφ**

+ weak constraints with TB and EB

Lensing power spectrum



Amplitude constrained to ~2.5% (40σ detection of lensing).

Planck for the first time measured the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data

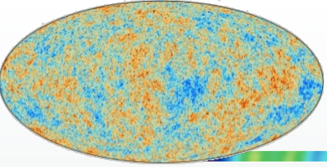
Standard cosmological model - LCDM

- The CMB TT, TE, EE, Φ-Φ, as well as BAO, BBN (but Li7), and SN1a measurements are all consistent, among themselves and across experiments, within LCDM.

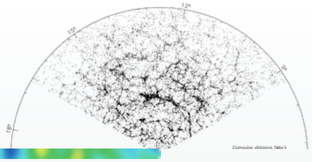
- This network of consistency tests is passed **with per cent level precision.**

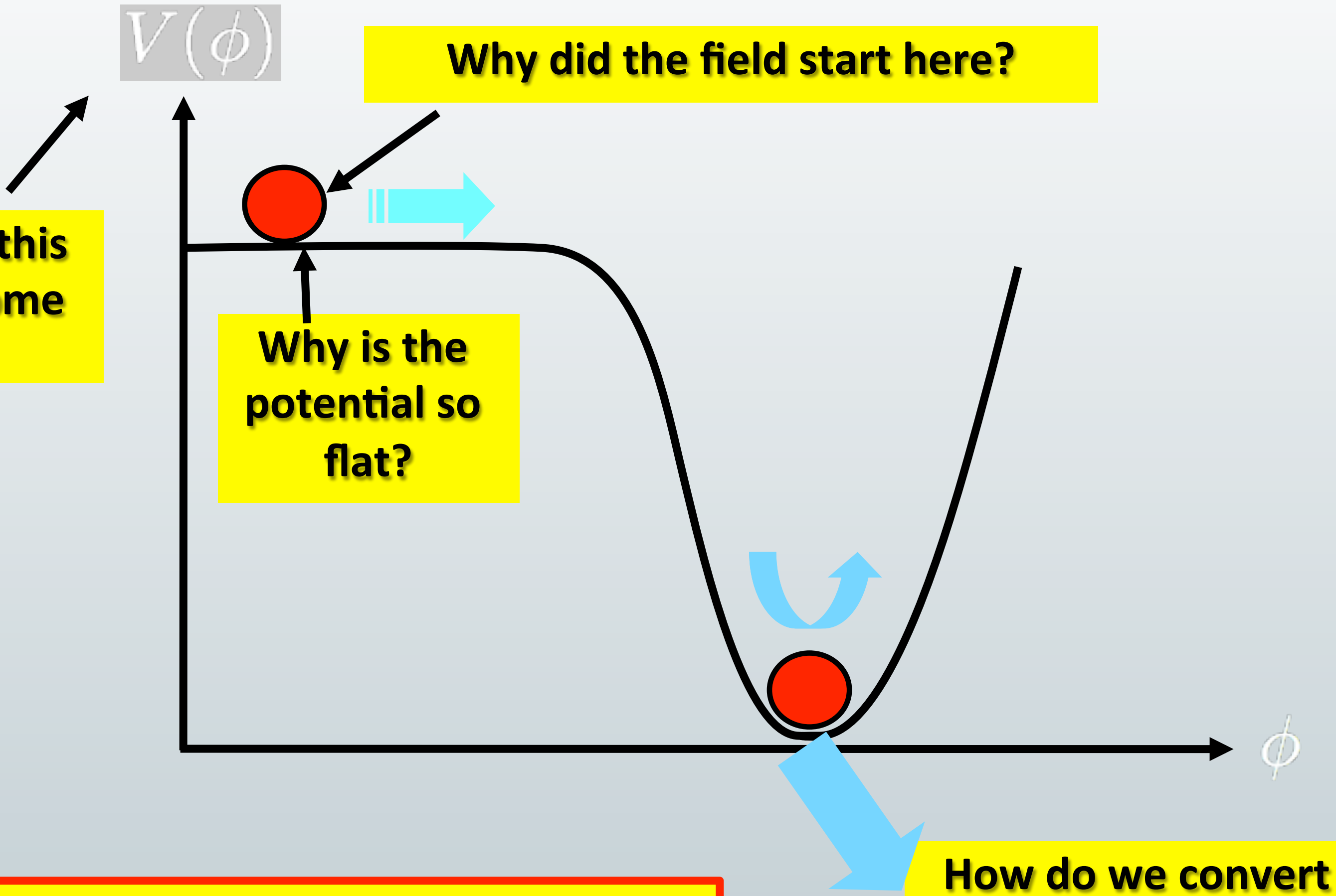
- These tests allow <u>many</u> different checks of the robustness of this base LCDM model and of some of its extensions, including τ constrained two-ways thanks to CMB lensing, flatness at 5 x 10^{-3} level, neutrinos masses and number, DM annihilation limits, w(z), details of the recombination history ($A_{2s\rightarrow 1}$, T_0, and also fundamental constants variation, or any energy input…).

- Some “anomalies/tensions” (large scale, low-z probes)



But what is the physics of inflation?





Why did the field start here?

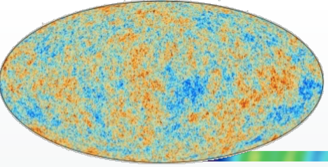
Where did this function come from?

Why is the potential so flat?

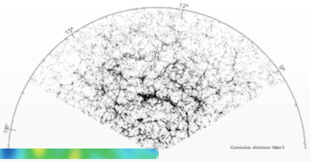
How do we convert the field energy completely into particles?

Is there a completely different paradigm to explain the measurements?

And what are Dark Matter, Dark Energy, neutrinos…?



CMB remains unique and powerful



- Planck has about exhausted, *as promised back in 1996*, the information content of the temperature anisotropies. But only a few per cent of the more tenuous CMB polarisation (B) or lensing modes are known with S/N>1.

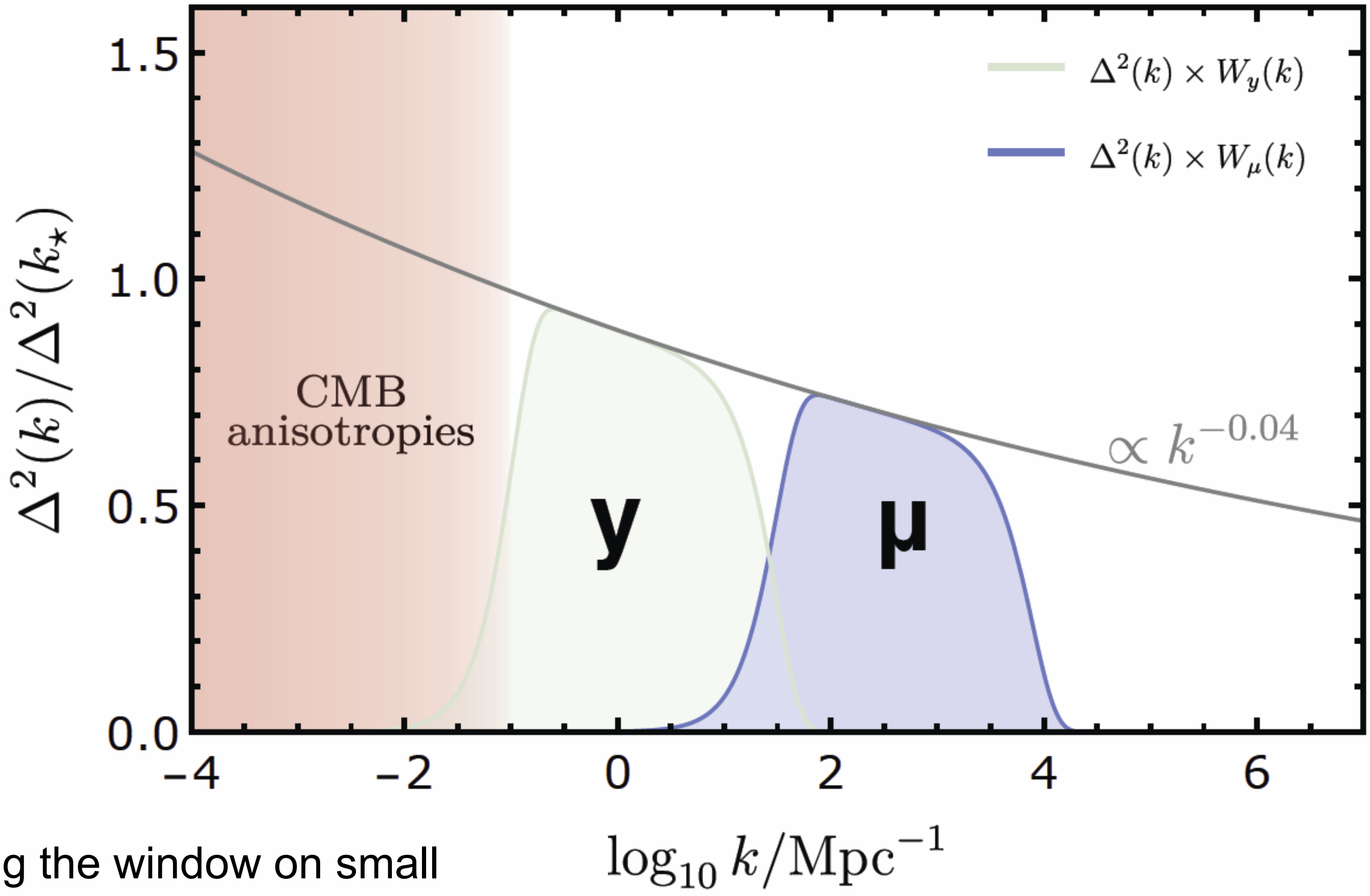
- CMB polarisation is a *unique* source of still unknown cosmological information with unmatched discovery potential: globality (ensemble of parameters, some of which are quasi-inaccessible otherwise (e.g., r, f_{NL}), complementarity with temperature (an independent probe), with other probes of large scale structures (LSS) and particle physics experiments (e.g., Neutrinos Physics), nature (quasi-linearity).

→ *We now have to map all the sky with exacting but achievable requirements of sensitivity and control of systematics, both instrumental and astrophysical (to measure millions of CMB polarisation modes with S/N > 1), in synergy between ground, balloons and space.*

- The CMB polarisation requirements insure great ancillary science.

- *Spectral distortions have not been revisited since FIRAS... Much there too!*

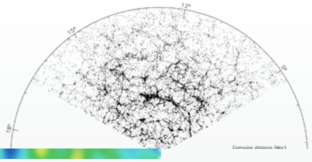
y and mu distorsions from standard inflationary models of the CMB spectrum



Extending the window on small scale scalar primordial power spectrum (+9 e-folds)

Broad band windows.

Also sensitive to any energy input – exotic or astrophysics – a very extended net



Spectral distortions and foreground emission

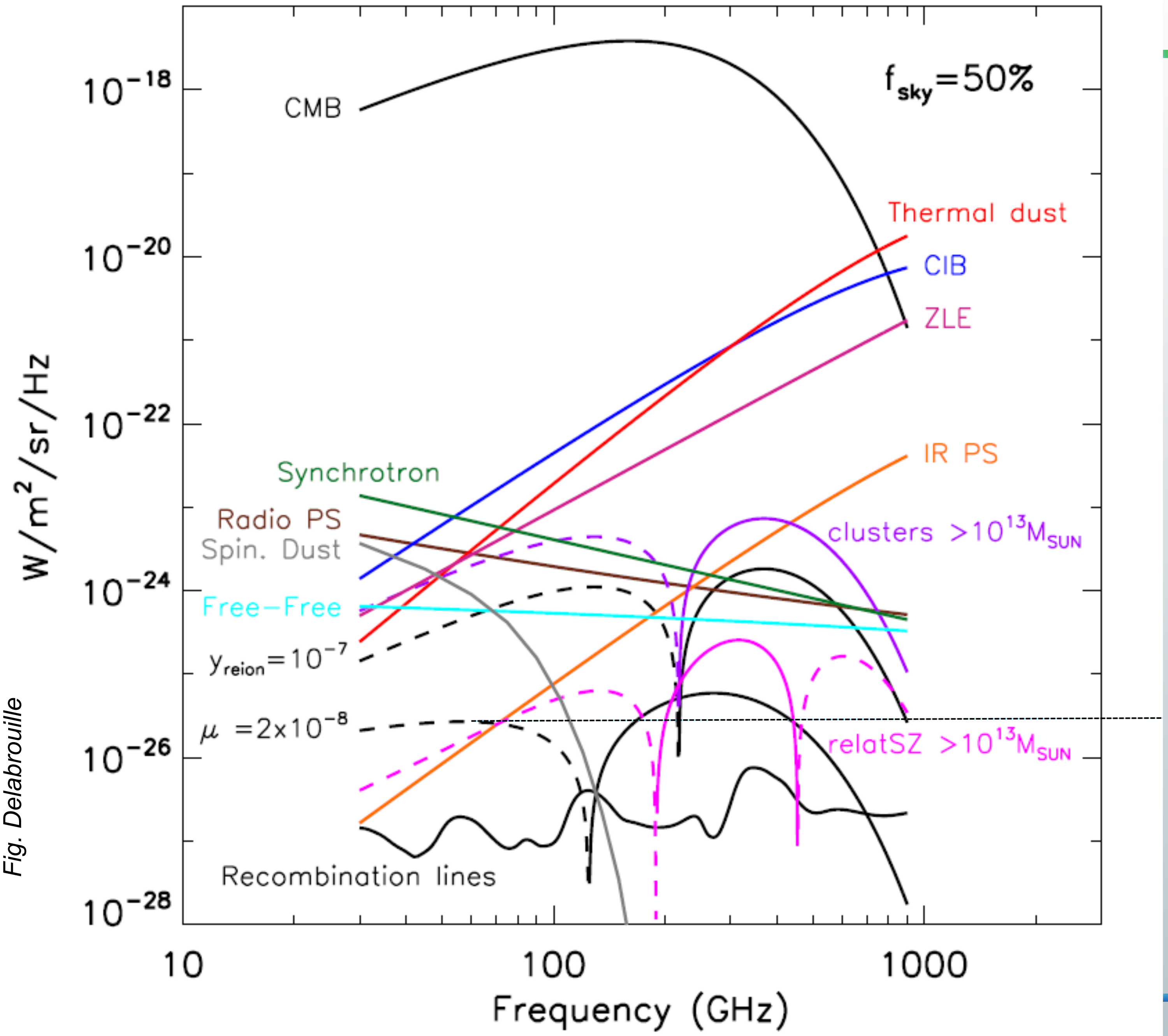


Fig. Delabrouille

Much to be learnt on «late» (z < 1100) distortions & discovery potential on any energy input at z < 10^6

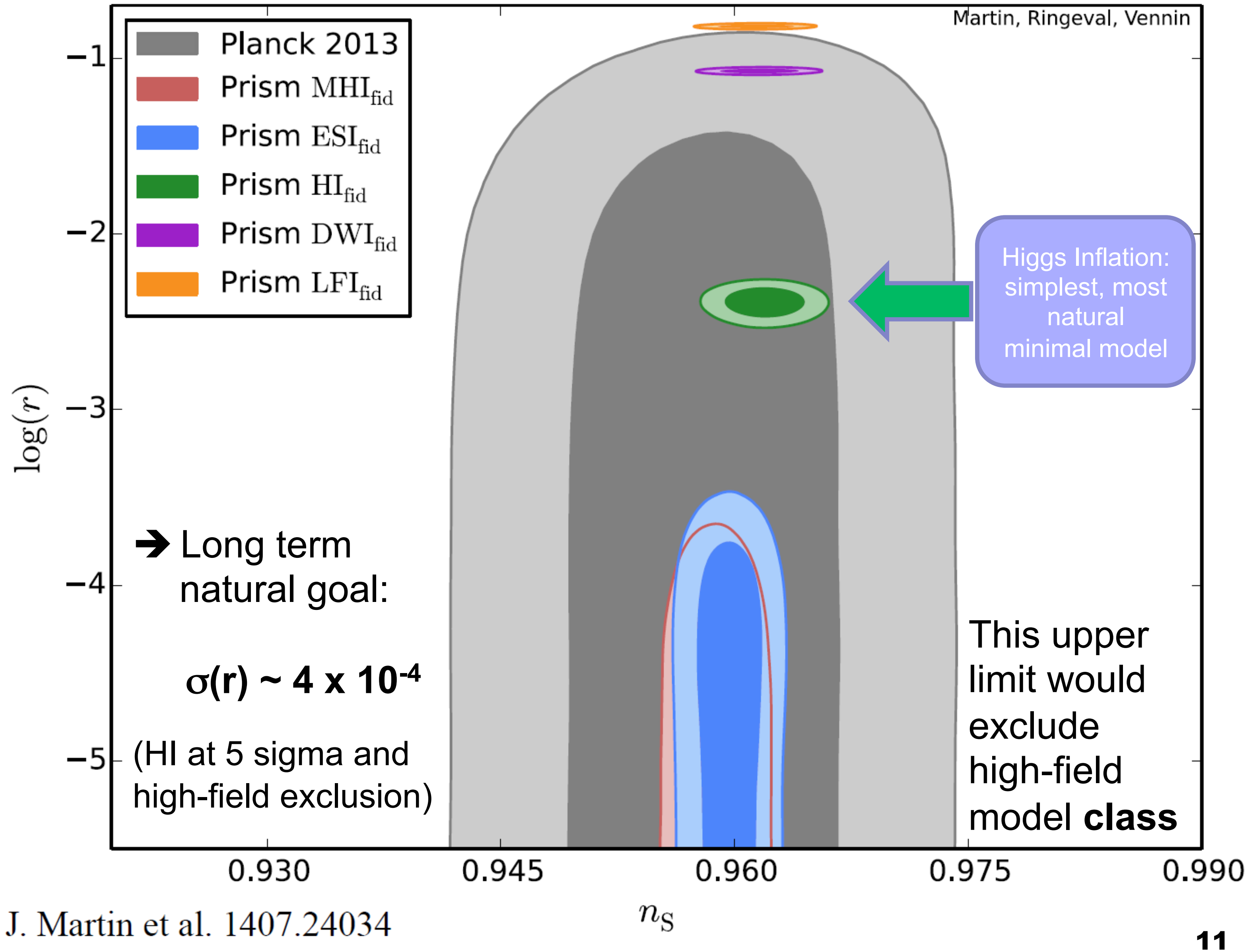
(levels estimated for 50% of the sky)

Pixie - 4 years.
To be proposed to NASA explorer program in 12/2016, for a 2023 launch (with also r capability).

Forecasts for PRISM

Example of reach in (n_s, r) plane, when sigma(r) ~ few 10^{-4}

log(tensor-to-scalar ratio)
⇕level of primoridal gravitational waves



Higgs Inflation: simplest, most natural minimal model

➔ Long term natural goal:

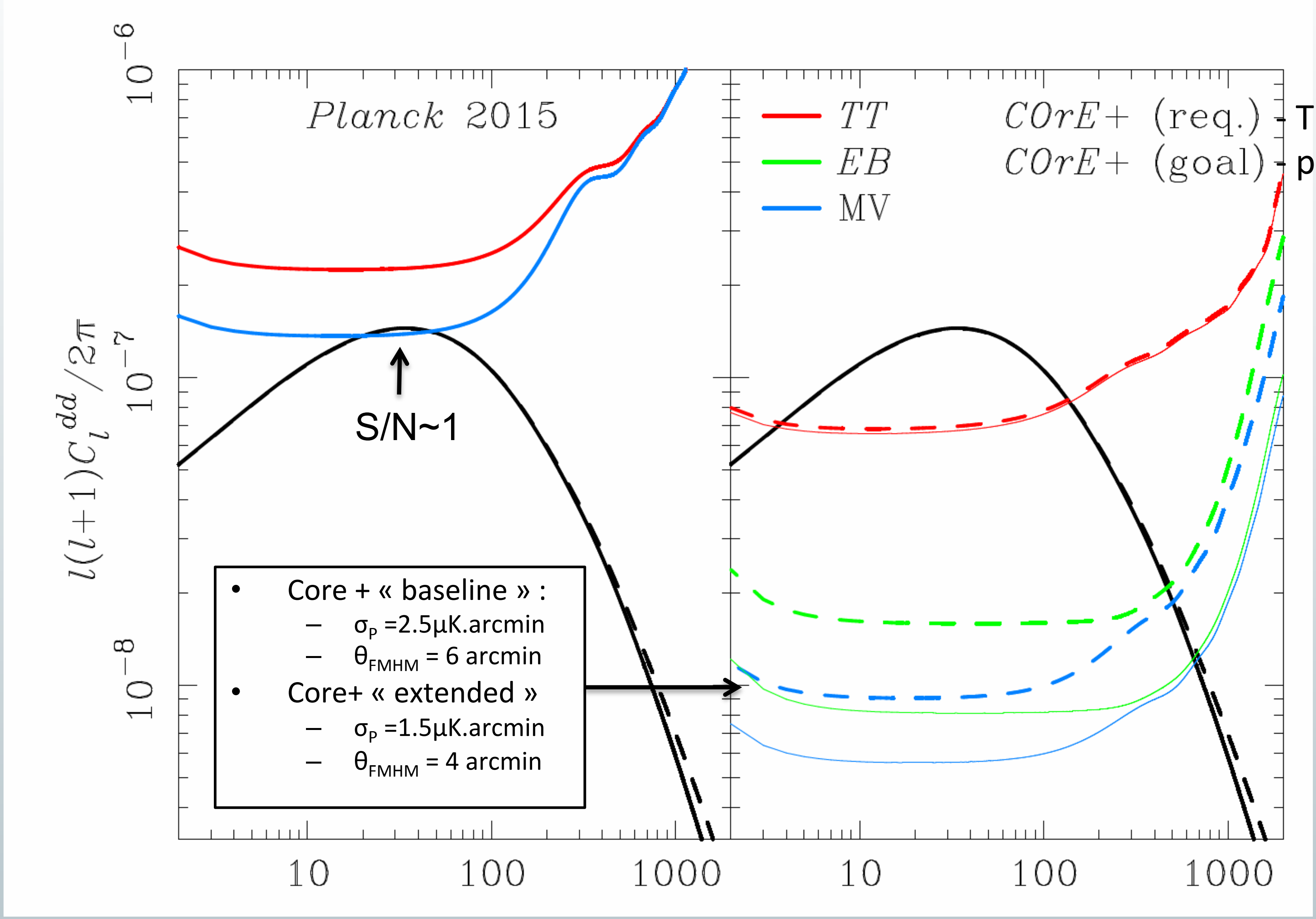
σ(r) ~ 4 x 10^{-4}

(HI at 5 sigma and high-field exclusion)

This upper limit would exclude high-field model **class**

J. Martin et al. 1407.24034

Core+ : Lensing performance

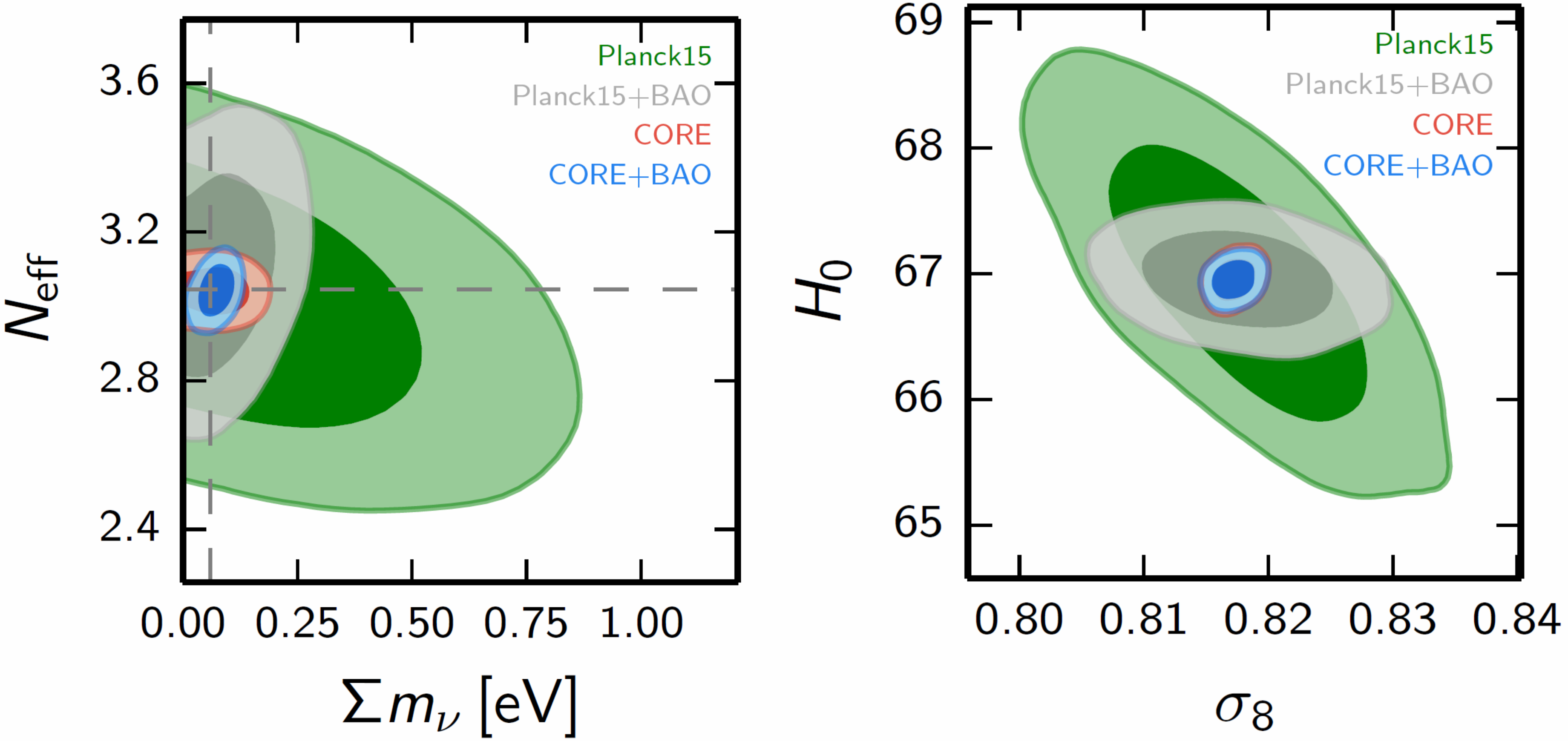


- Core + « baseline » :
  - σ_P =2.5μK.arcmin
  - θ_{FMHM} = 6 arcmin
- Core+ « extended »
  - σ_P =1.5μK.arcmin
  - θ_{FMHM} = 4 arcmin

- Tirets
- pleins

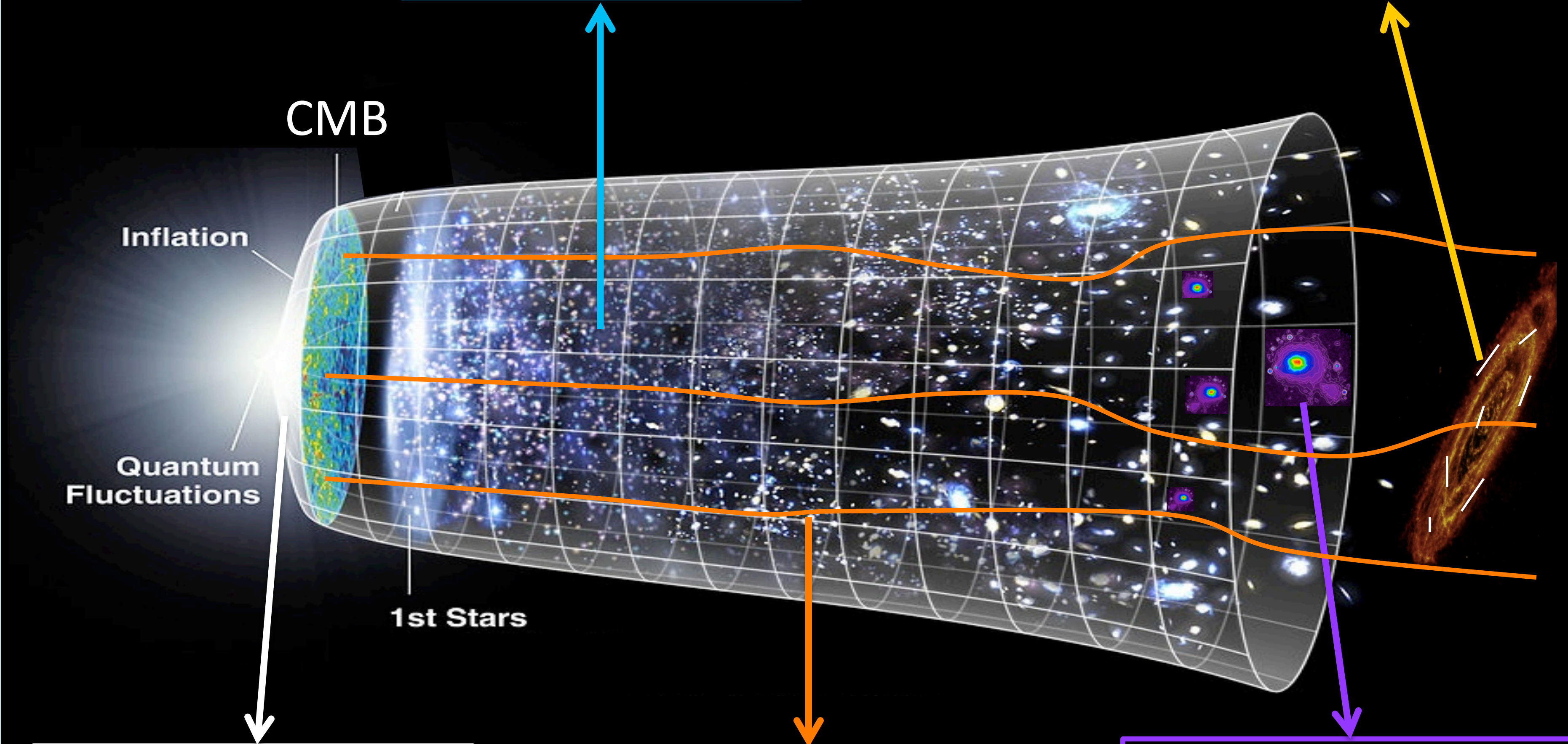
Unique access to Dark Matter distribution at z>2

Examples (from CORE-M5)



Extragalactic
Astrophysics

Interstellar medium
(magnetic field)

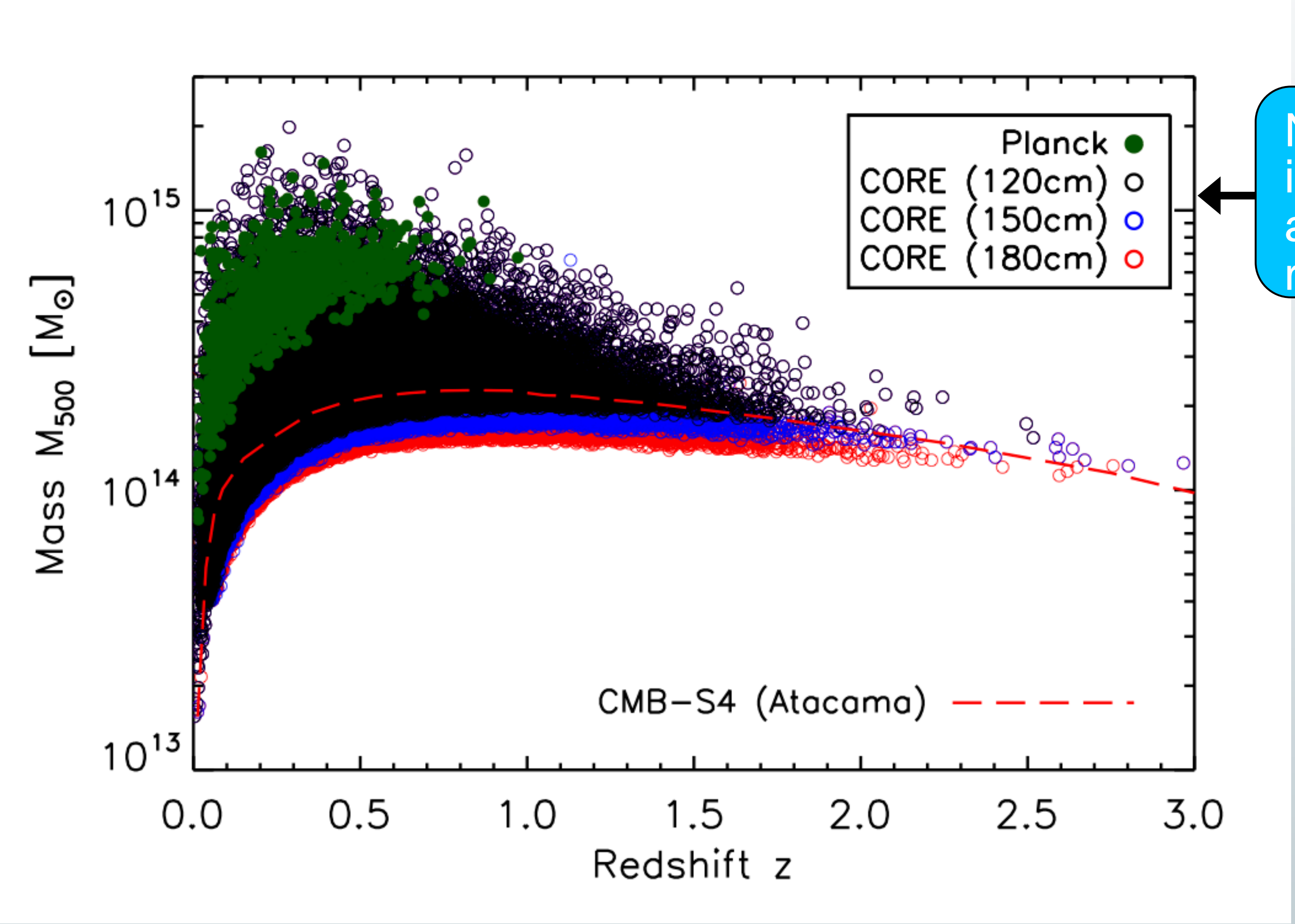


Univers primordial
Physique à ≈ 10^{16} GeV
$E_{CMB} > 10^{12} \times E_{LHC}$

$z \approx 1\text{-}3$
Gravitational lensing
Dark matter distribution

$z \approx 0\text{-}2$
Sunyaev-Zeldovich effect:
Distribution of the hot gas
and velocity field

SZ clusters detection



Note (large) impact of angular resolution

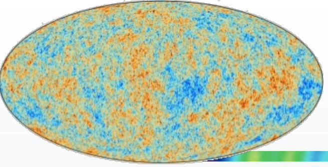
Unique mass proxy via lensing (stacking), Velocity field (kSZ). ***Note high-z tail.***


GRAVITATIONAL
WAVES

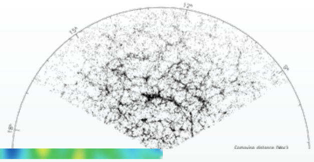
INSTRUMENTAL CHALLENGES

(Orig. S. Staggs, Princeton 06/2015)

- **BEAMS**: in situ measurement of beams, esp. sidelobes (ν & polzn dependence, stability)
- **BANDPASSES:** in situ characterization, matching, polzn dependence, avoiding CO etc
- **GROUND PICKUP**: shielding, sufficient suppression of scan synchronous pickup, stability
- **I → Q/U LEAKAGE**: ν dependence, polarization dependence, stability, spatial dependence
- **SENSITIVITY**: low loading, high optical throughput
- **CALIBRATION**: stability, dynamic range, ν dependence, pointing jitter
- **POLARIZATION ANGLES**: in situ measurement, ν dependence
- **STRIPING**: minimize 1/f with fast modulation
- **& Spectral specific ones**

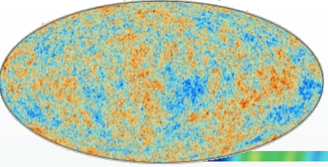


+ Data/Analysis challenges

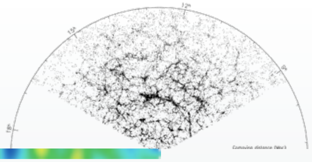


- Extract the most from this expensive data flow
  - *Low level codes not universal, i.e. code share only for high-level analyses*
  - *Moore' s law on cpus unlikely to be enough (smaller final uncertainties tend to increase algorithmic complexity)*
  - *Simulations will become more challenging (and so will be the size of the analysis groups?), but needed for precision science (and even more for accurate science).*
- Sharing the data efficiently?
  - *at TOI level? (e.g. to surround pixelization issues); data size*
  - *X-correlations need a lot of detailed knowledge on both sides (eg Planck x Bicep/Keck)*
  - *Flexible/efficient formats*
- Overall organisation… (we need large integrated teams with varied cultural backgrounds in scattered sites)

- On all those, we gained much experience from Planck!



Etat des lieux & perspectives



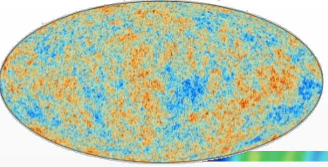
- ➢ Paysage au sol
  - o S3 en cours (US), visant T/S=r=10^{-2} (principalement, mais beaucoup plus)
  - o S4 en développement, visant r=10^{-3} et détection masses ν's

- ➢ Paysage spatial
  - o Pixie/NASA – proposition due dec. 2016, pour lancement 2023.
  - o Litebird/JAXA – recemment passage en A1, pour lancement 2025.
  - o M5/Core/ESA(+?) – pour lancement 2026-2030, prop. pour 10/2016.
    - ▪ Etude CDF ESA(JAXA) début 2016

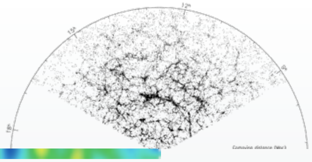
➔ un paysage de possibilités très différentes, (Sciences/Avant-plans/Systés)

- ➢ Des objectifs très ambitieux scientifiquement et expérimentalement, avec des incertitudes substantielles sur
  - o le niveau des modes B primordiaux,
  - o la situation astrophysique (émissions d'avant-plans, inc. Niveau 0),
  - o les performances des différentes solutions expérimentales et leur localisation
- ➢ avec rien de décidé pour le moment…

➔ Une nécessaire complémentarité sol/ballons/espace
  - o Couverture spatiale et angulaire
  - o Temps de mise en œuvre /cout



Logique de la feuille de route



Analyse à partir des objectifs à long terme (plus de 10 ans):

- M5 at ESA (CORE):
  - la proposition spatiale CMB la plus capable,
  - offrant la meilleure possibilité de jouer un rôle central dans ce sujet,
  - impliquant toute la communauté.

  - NB: lancement au mieux entre 2026 et 2030.

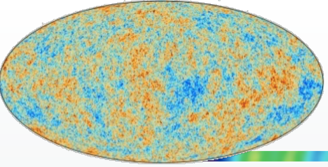
- S4:
  - Quel que soit le sort des diverses propositions spatiales, l'intégralité des nouvelles données, de la science, et des leçons apprises (FG/Instrument) viendront quasi-exclusivement du sol/ballons pendant au moins une décennie (au minimum, i.e. si Litebird ou Pixie sont sélectionnés).

    → Il est donc **vital** que la communauté participe à l'effort sol/ballon.

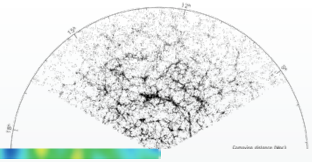
  - La magnitude de l'effort dépendra bien sur du sort des propositions spatiales (que ce soit RH, ou disponibilités techno.).

→Les priorités long terme (> 2025) sont donc **M5 + S4**.

- Ces priorités globale permet de jauger les autres projets/étapes:
  - **Pixie** → excellente opportunité de participation à un « pathfinder » au très fort potentiel (lancement prévu en 2023 si sélectionné par NASA).
  - **Bside** → excellente opportunité de niche, garantie si vol < 2020.
  - **QUBIC** → seule expérience sol en France, mais «fenêtre» étroite autant pour la science qu'en tant qu'étape S4.

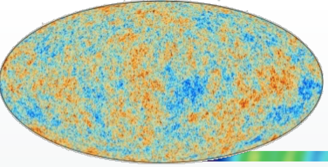


Conclusions

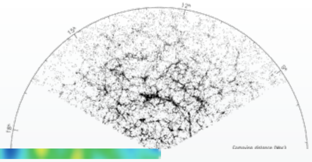


- ➢ The experimental situation in the “post-Planck” era is not yet stable, with most projects not fully determined, and even less decided/funded.
- ➢ Still, as we saw, firm recommendations nevertheless emerge.
- ➢ M5 & S4 participations are the long-term priorities. They set the framework.
- ➢ Participation to S4 would be best at European Level (but not single agency).
- ➢ Also, depending on what happens, in particular regarding M5, some elements of the roadmap may have to be reconsidered to preserve at best the community. i.e. still need a French forum to adapt the roadmap.

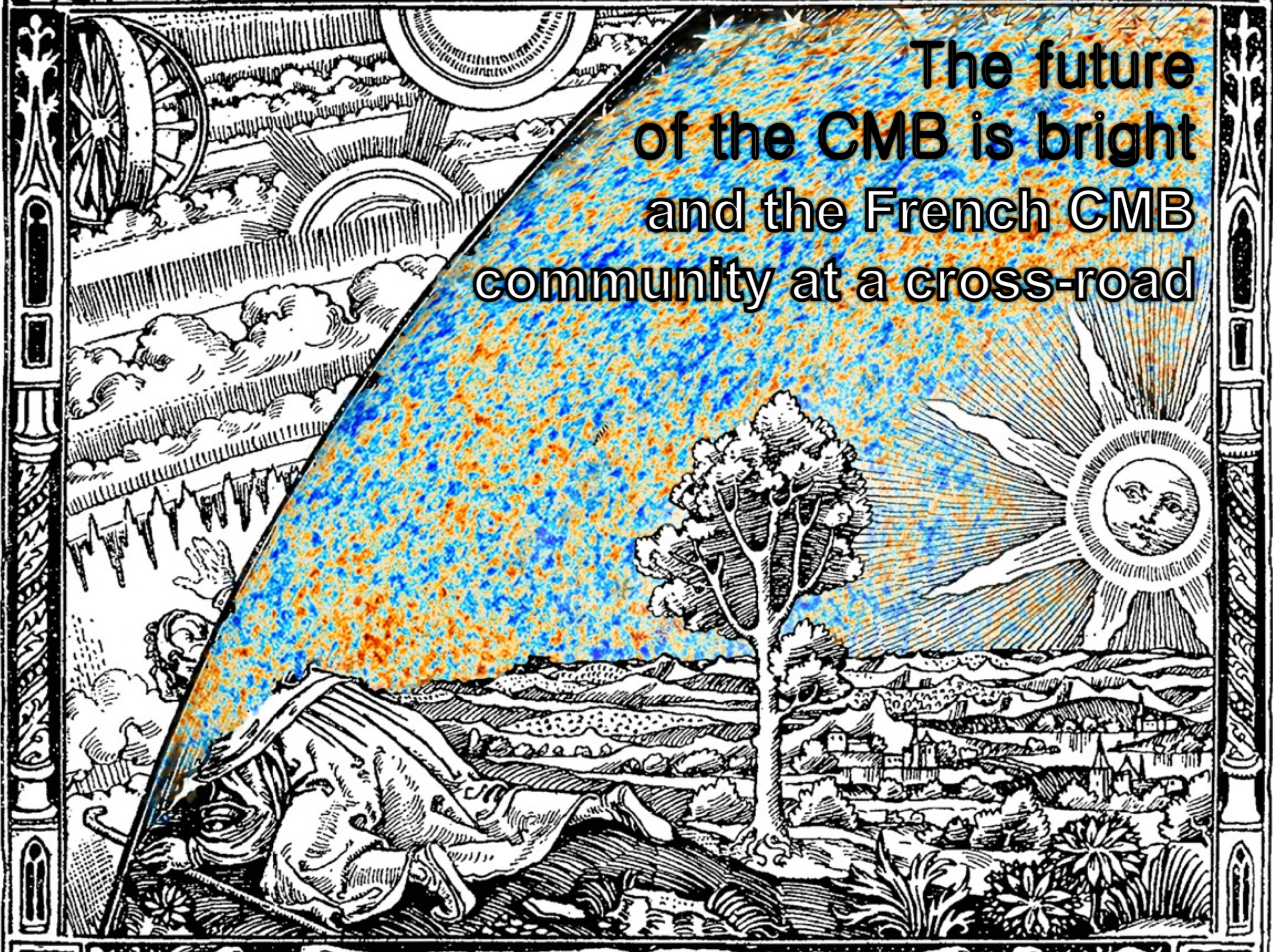
➔ Long term need to coordinate French actions/participations + represent internationally our point of view to maximize returns on actions/participations.



Since June 2016…



- 8-10 Sept – Florence2: “Planning Europe's CMB Future” (with APPEC, Astronet, US representatives attending):
  - ➔ *Broad agreement on perspectives of attending country representatives (in line with our roadmap).*
  - ➔ *Decided to kick-off the set up of a European Scientific Consortium, working towards an MOU with agencies, a European roadmap, coordinated funding proposal, S4 cradle…*
- 19-21 Sept – Chicago: US-CMB Stage4 (S4) meeting:
  - ❖ *FRB invited to give European point of view (following Florence2).*
  - ❖ *S4 science book 1st edition (shortly after), organising drafting of tech. roadmap…*
  - ❖ *Creation of federal “Conceptual Design Team” lead by CRL was announced (now assembled, question of Europe representative posed last week to FRB)*
- Oct 5th – Submission of M5 (CORE) proposal (120cm telescope as baseline)
  - ❖ *with support letters from all S4 lead scientists, JPL (Funding phase A), (+Japan interest).*
- Oct 5th – CIO (CNES, CEA, IN3P3, INSU, PNCG, CSAA…) on report follow-up.
  - ❖ *Need to increase necessary French coordination of all agencies, adding INP, INSMI, INSIS (INRIA?)*
  - ❖ *Foster synergies on all aspects ground/space, PNCG/PCMI/GdR-GW/Madics?, agencies to breed projects.*
  - ❖ *Represent the French CMB community at national agencies level and versus international partners.*
  - ❖ *Possibly in the form of an “action spécifique” capable of bringing large project(s) to funding decision/engagement.*
- Nov 4th – “E-CMB” groundwork meeting @ IAP, w. IT/SP/UK/GE representatives (+FR!)
- Dec 1st – CSAA presentation planned to further shape “CMB-France” !



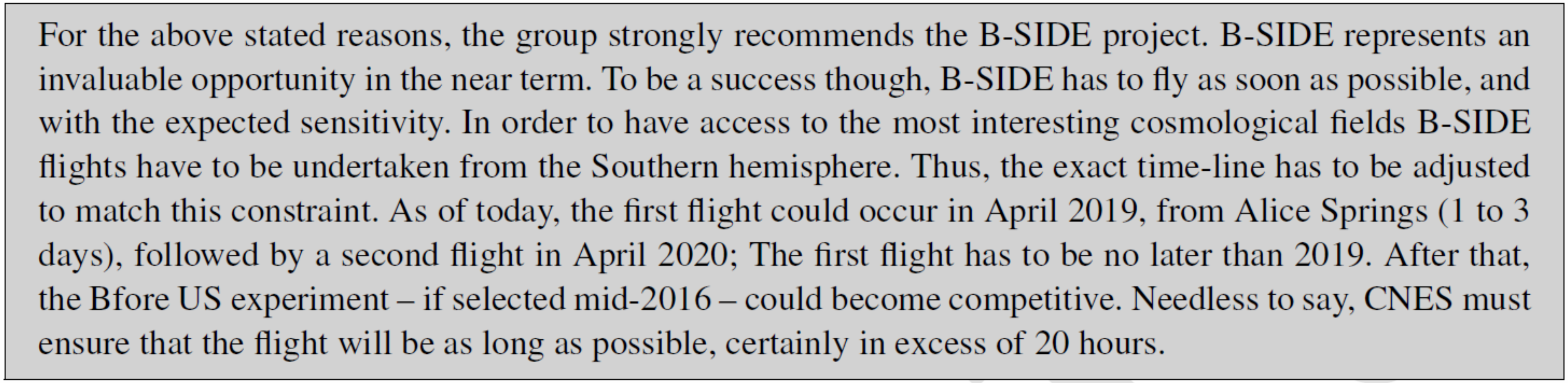
The future of the CMB is bright

and the French CMB community at a cross-road

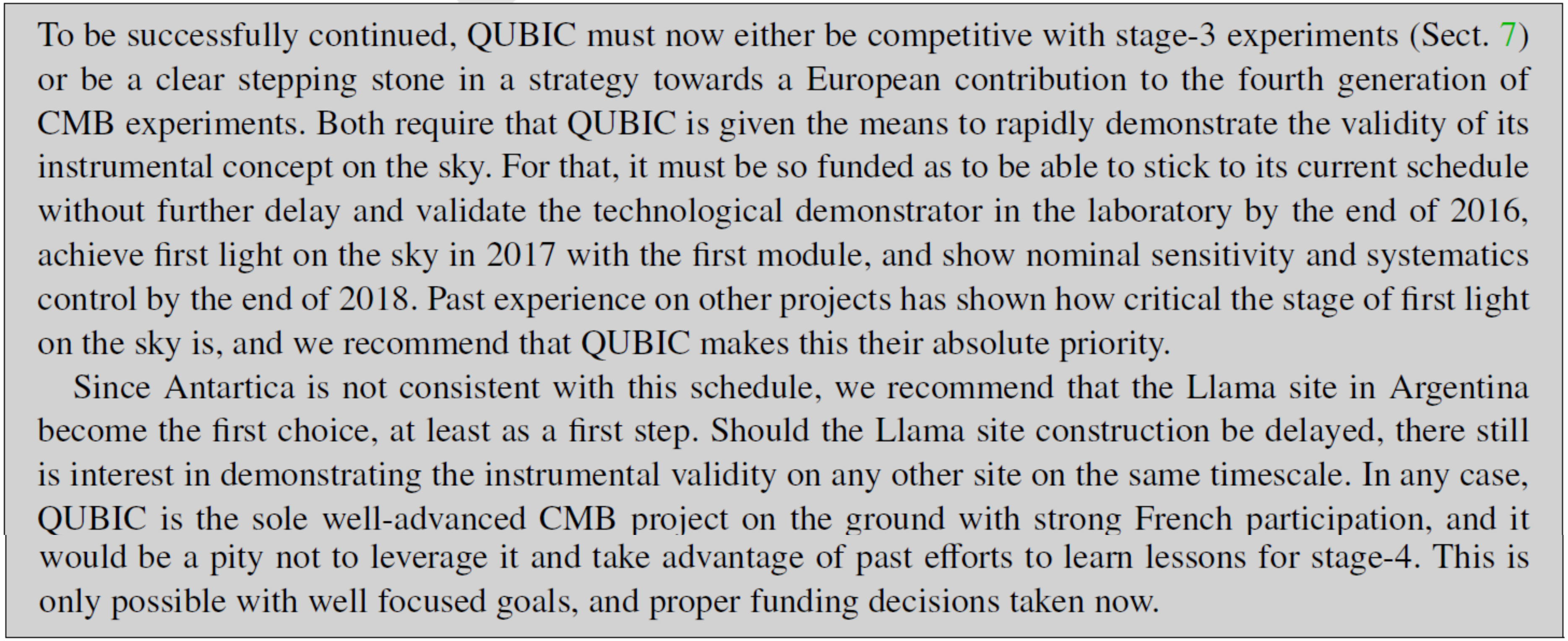
This M5 project is a unique opportunity for the European community to remain at the forefront of CMB research, building on the investment in, and successes of, Planck. In addition to its broad science appeal, it offers the possibility for both developing and using cutting edge technologies of wide-spread interest, including millimetre range detectors, cryogeny, sophisticated data analysis methods, and high performance computing. In addition, developments made for space would be a strategic asset in building a participation to the shorter term effort on the ground (see next). For all these reasons, contributing to the M5 selection and securing a leading role in the mission if selected is the current top priority of the French CMB community.

Given its particular areas of expertise, French participation in PIXIE may actually help to address some of the questions raised above concerning the concept, in particular regarding systematics and component separation. French participation in PIXIE will however be limited to only a fraction of the community, and PIXIE in any case leaves aside the higher resolution science which is addressed by the Stage-4 and CORE experiments. Still, PIXIE would be the first data available from any proposed projects in space and it is in many respect a pioneering project. It has a very reasonable cost for the French community, which is offered proportionately large participation for the proposed financial involvement. We therefore support strongly the proposed French participation.

We recommend encouraging lead CMB scientists in Europe to urgently set up a scientific consortium whose charge will be to provide a forum for discussions within Europe, undertake discussions with the US S4 stakeholders, investigate all funding options, and coordinate all necessary European actions with the help of the European APPEC and Astronet networks of funding agencies in Astroparticle Physics and Astronomy.



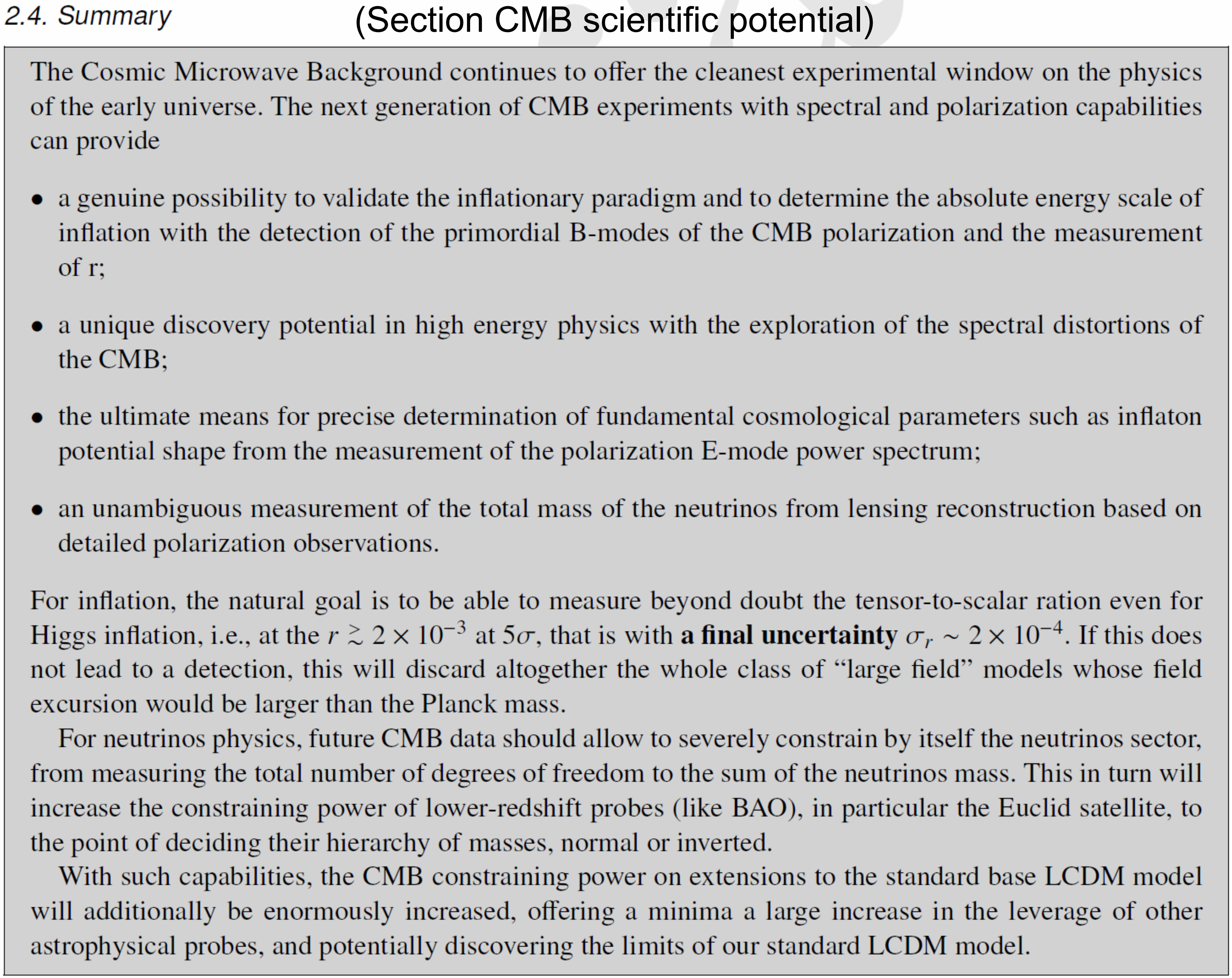
For the above stated reasons, the group strongly recommends the B-SIDE project. B-SIDE represents an invaluable opportunity in the near term. To be a success though, B-SIDE has to fly as soon as possible, and with the expected sensitivity. In order to have access to the most interesting cosmological fields B-SIDE flights have to be undertaken from the Southern hemisphere. Thus, the exact time-line has to be adjusted to match this constraint. As of today, the first flight could occur in April 2019, from Alice Springs (1 to 3 days), followed by a second flight in April 2020; The first flight has to be no later than 2019. After that, the Bfore US experiment – if selected mid-2016 – could become competitive. Needless to say, CNES must ensure that the flight will be as long as possible, certainly in excess of 20 hours.



To be successfully continued, QUBIC must now either be competitive with stage-3 experiments (Sect. 7) or be a clear stepping stone in a strategy towards a European contribution to the fourth generation of CMB experiments. Both require that QUBIC is given the means to rapidly demonstrate the validity of its instrumental concept on the sky. For that, it must be so funded as to be able to stick to its current schedule without further delay and validate the technological demonstrator in the laboratory by the end of 2016, achieve first light on the sky in 2017 with the first module, and show nominal sensitivity and systematics control by the end of 2018. Past experience on other projects has shown how critical the stage of first light on the sky is, and we recommend that QUBIC makes this their absolute priority.

Since Antartica is not consistent with this schedule, we recommend that the Llama site in Argentina become the first choice, at least as a first step. Should the Llama site construction be delayed, there still is interest in demonstrating the instrumental validity on any other site on the same timescale. In any case, QUBIC is the sole well-advanced CMB project on the ground with strong French participation, and it would be a pity not to leverage it and take advantage of past efforts to learn lessons for stage-4. This is only possible with well focused goals, and proper funding decisions taken now.

(Section CMB scientific potential)



2.4. Summary

The Cosmic Microwave Background continues to offer the cleanest experimental window on the physics of the early universe. The next generation of CMB experiments with spectral and polarization capabilities can provide

- a genuine possibility to validate the inflationary paradigm and to determine the absolute energy scale of inflation with the detection of the primordial B-modes of the CMB polarization and the measurement of r;
- a unique discovery potential in high energy physics with the exploration of the spectral distortions of the CMB;
- the ultimate means for precise determination of fundamental cosmological parameters such as inflaton potential shape from the measurement of the polarization E-mode power spectrum;
- an unambiguous measurement of the total mass of the neutrinos from lensing reconstruction based on detailed polarization observations.

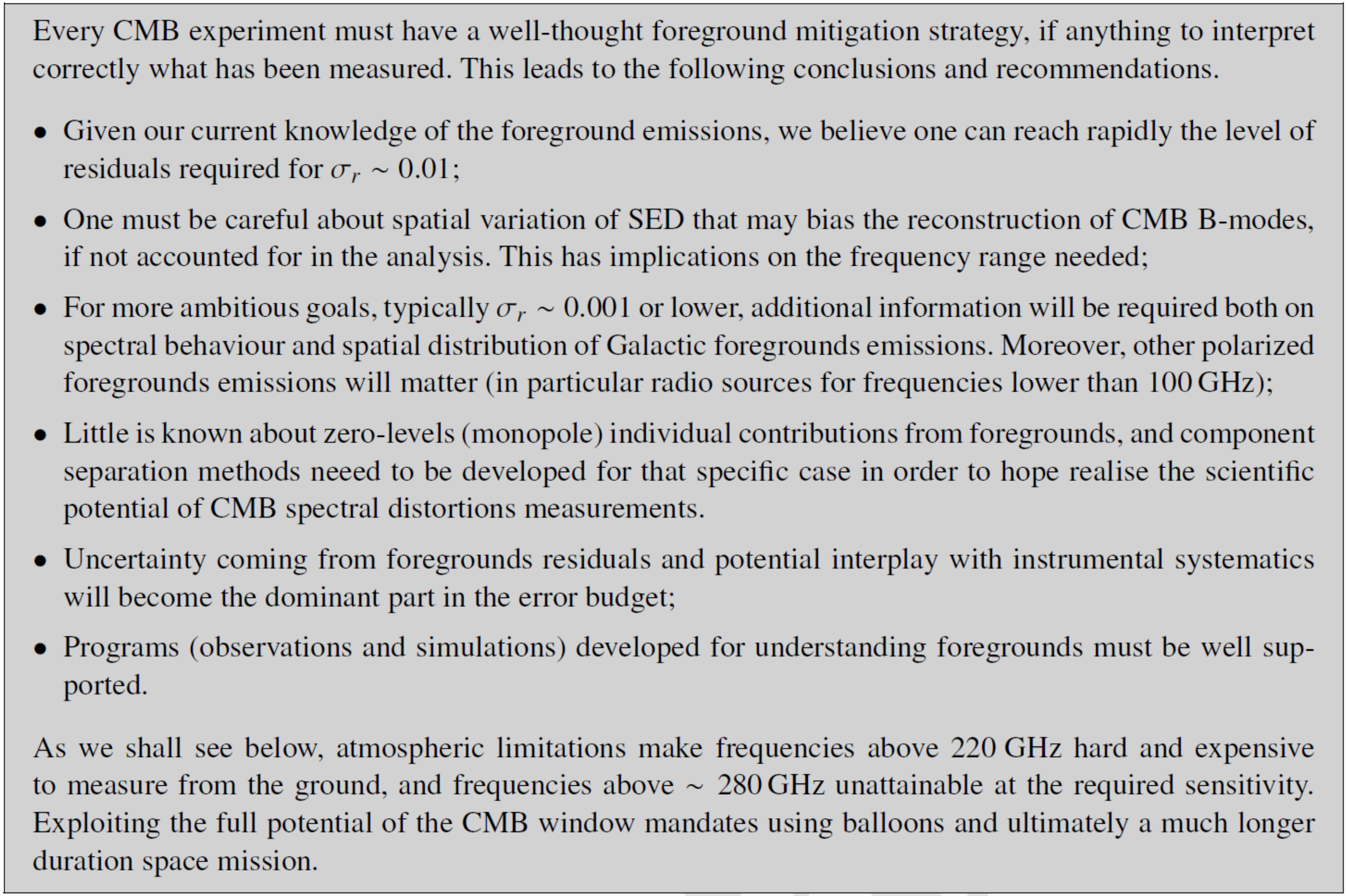
For inflation, the natural goal is to be able to measure beyond doubt the tensor-to-scalar ration even for Higgs inflation, i.e., at the $r \gtrsim 2 \times 10^{-3}$ at 5σ, that is with **a final uncertainty** $\sigma_r \sim 2 \times 10^{-4}$. If this does not lead to a detection, this will discard altogether the whole class of "large field" models whose field excursion would be larger than the Planck mass.

For neutrinos physics, future CMB data should allow to severely constrain by itself the neutrinos sector, from measuring the total number of degrees of freedom to the sum of the neutrinos mass. This in turn will increase the constraining power of lower-redshift probes (like BAO), in particular the Euclid satellite, to the point of deciding their hierarchy of masses, normal or inverted.

With such capabilities, the CMB constraining power on extensions to the standard base LCDM model will additionally be enormously increased, offering a minima a large increase in the leverage of other astrophysical probes, and potentially discovering the limits of our standard LCDM model.

3.4. Summary

(section Foregrounds obstacle)



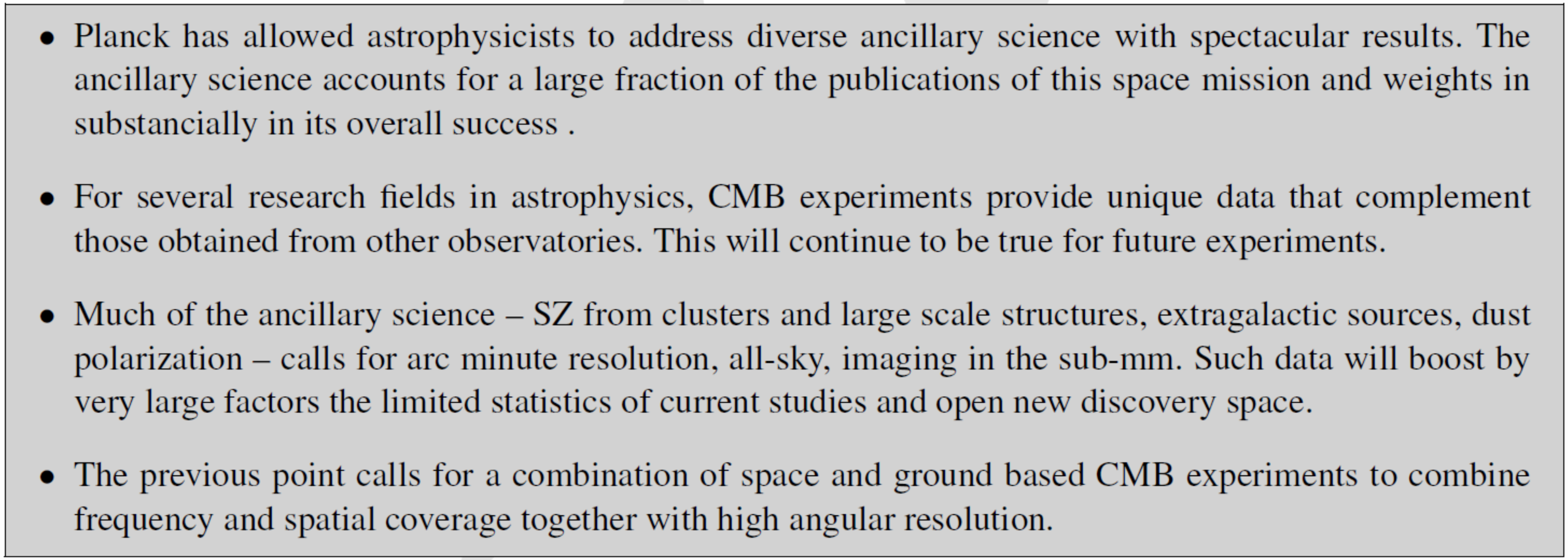
Every CMB experiment must have a well-thought foreground mitigation strategy, if anything to interpret correctly what has been measured. This leads to the following conclusions and recommendations.

- Given our current knowledge of the foreground emissions, we believe one can reach rapidly the level of residuals required for $\sigma_r \sim 0.01$;
- One must be careful about spatial variation of SED that may bias the reconstruction of CMB B-modes, if not accounted for in the analysis. This has implications on the frequency range needed;
- For more ambitious goals, typically $\sigma_r \sim 0.001$ or lower, additional information will be required both on spectral behaviour and spatial distribution of Galactic foregrounds emissions. Moreover, other polarized foregrounds emissions will matter (in particular radio sources for frequencies lower than 100 GHz);
- Little is known about zero-levels (monopole) individual contributions from foregrounds, and component separation methods neeed to be developed for that specific case in order to hope realise the scientific potential of CMB spectral distortions measurements.
- Uncertainty coming from foregrounds residuals and potential interplay with instrumental systematics will become the dominant part in the error budget;
- Programs (observations and simulations) developed for understanding foregrounds must be well supported.

As we shall see below, atmospheric limitations make frequencies above 220 GHz hard and expensive to measure from the ground, and frequencies above ~ 280 GHz unattainable at the required sensitivity. Exploiting the full potential of the CMB window mandates using balloons and ultimately a much longer duration space mission.

4.4. Summary

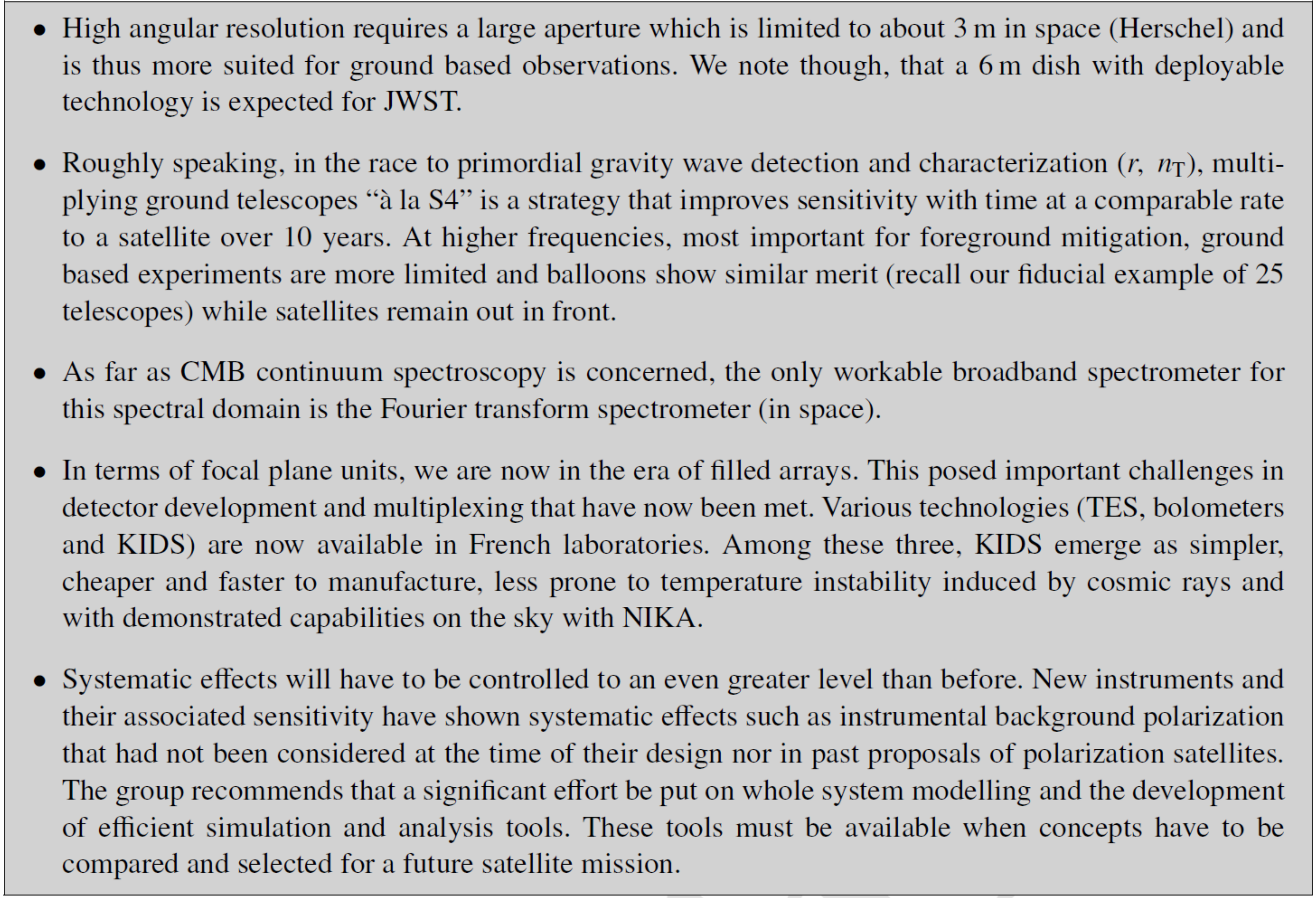
(Section Foregrounds obstacle)



- Planck has allowed astrophysicists to address diverse ancillary science with spectacular results. The ancillary science accounts for a large fraction of the publications of this space mission and weights in substancially in its overall success .
- For several research fields in astrophysics, CMB experiments provide unique data that complement those obtained from other observatories. This will continue to be true for future experiments.
- Much of the ancillary science – SZ from clusters and large scale structures, extragalactic sources, dust polarization – calls for arc minute resolution, all-sky, imaging in the sub-mm. Such data will boost by very large factors the limited statistics of current studies and open new discovery space.
- The previous point calls for a combination of space and ground based CMB experiments to combine frequency and spatial coverage together with high angular resolution.

5.5. Summary

(Section Instrumental aspects)



- High angular resolution requires a large aperture which is limited to about 3 m in space (Herschel) and is thus more suited for ground based observations. We note though, that a 6 m dish with deployable technology is expected for JWST.

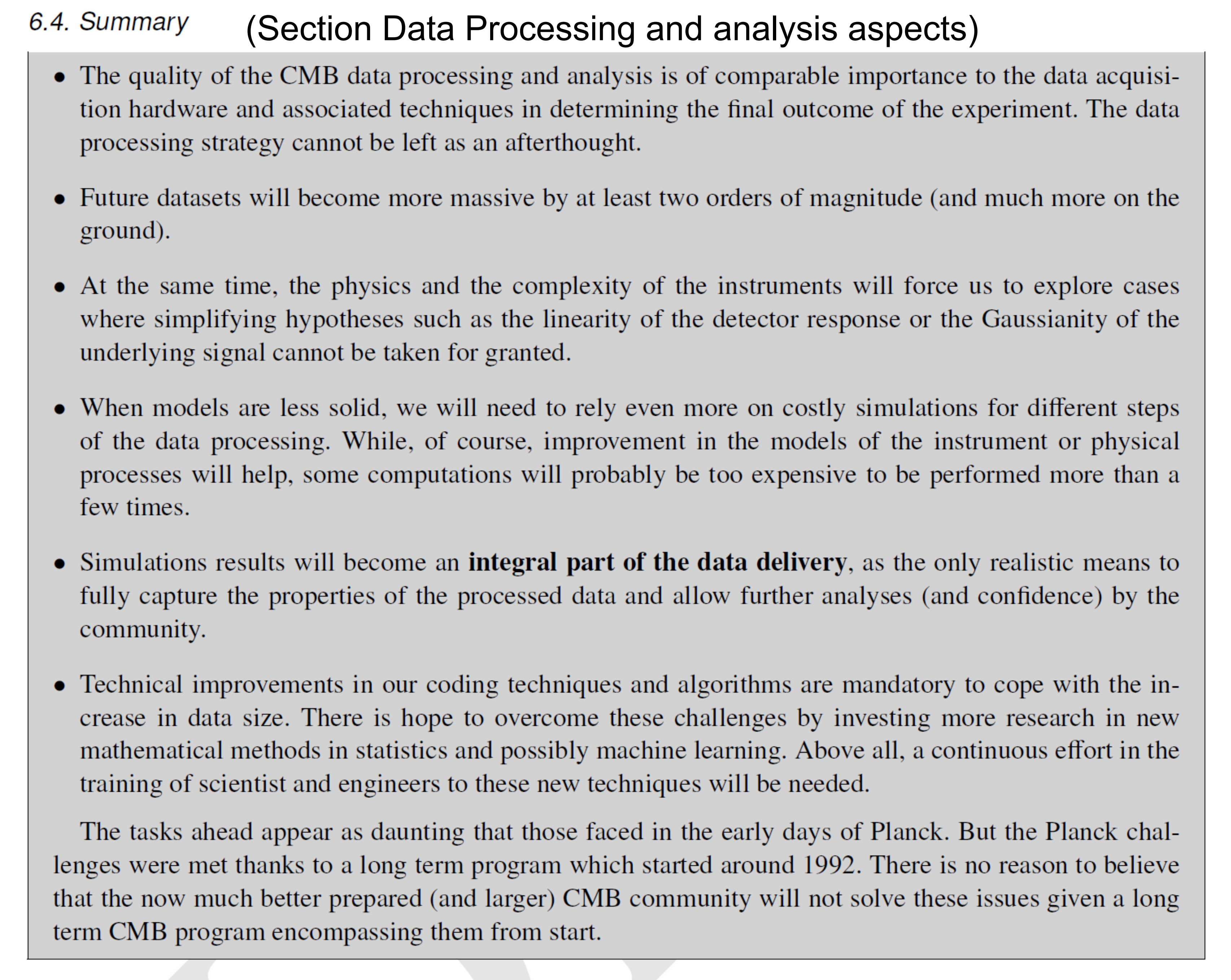
- Roughly speaking, in the race to primordial gravity wave detection and characterization (r, n_T), multiplying ground telescopes “à la S4” is a strategy that improves sensitivity with time at a comparable rate to a satellite over 10 years. At higher frequencies, most important for foreground mitigation, ground based experiments are more limited and balloons show similar merit (recall our fiducial example of 25 telescopes) while satellites remain out in front.

- As far as CMB continuum spectroscopy is concerned, the only workable broadband spectrometer for this spectral domain is the Fourier transform spectrometer (in space).

- In terms of focal plane units, we are now in the era of filled arrays. This posed important challenges in detector development and multiplexing that have now been met. Various technologies (TES, bolometers and KIDS) are now available in French laboratories. Among these three, KIDS emerge as simpler, cheaper and faster to manufacture, less prone to temperature instability induced by cosmic rays and with demonstrated capabilities on the sky with NIKA.

- Systematic effects will have to be controlled to an even greater level than before. New instruments and their associated sensitivity have shown systematic effects such as instrumental background polarization that had not been considered at the time of their design nor in past proposals of polarization satellites. The group recommends that a significant effort be put on whole system modelling and the development of efficient simulation and analysis tools. These tools must be available when concepts have to be compared and selected for a future satellite mission.

(Section Data Processing and analysis aspects)



6.4. Summary

- The quality of the CMB data processing and analysis is of comparable importance to the data acquisition hardware and associated techniques in determining the final outcome of the experiment. The data processing strategy cannot be left as an afterthought.
- Future datasets will become more massive by at least two orders of magnitude (and much more on the ground).
- At the same time, the physics and the complexity of the instruments will force us to explore cases where simplifying hypotheses such as the linearity of the detector response or the Gaussianity of the underlying signal cannot be taken for granted.
- When models are less solid, we will need to rely even more on costly simulations for different steps of the data processing. While, of course, improvement in the models of the instrument or physical processes will help, some computations will probably be too expensive to be performed more than a few times.
- Simulations results will become an **integral part of the data delivery**, as the only realistic means to fully capture the properties of the processed data and allow further analyses (and confidence) by the community.
- Technical improvements in our coding techniques and algorithms are mandatory to cope with the increase in data size. There is hope to overcome these challenges by investing more research in new mathematical methods in statistics and possibly machine learning. Above all, a continuous effort in the training of scientist and engineers to these new techniques will be needed.

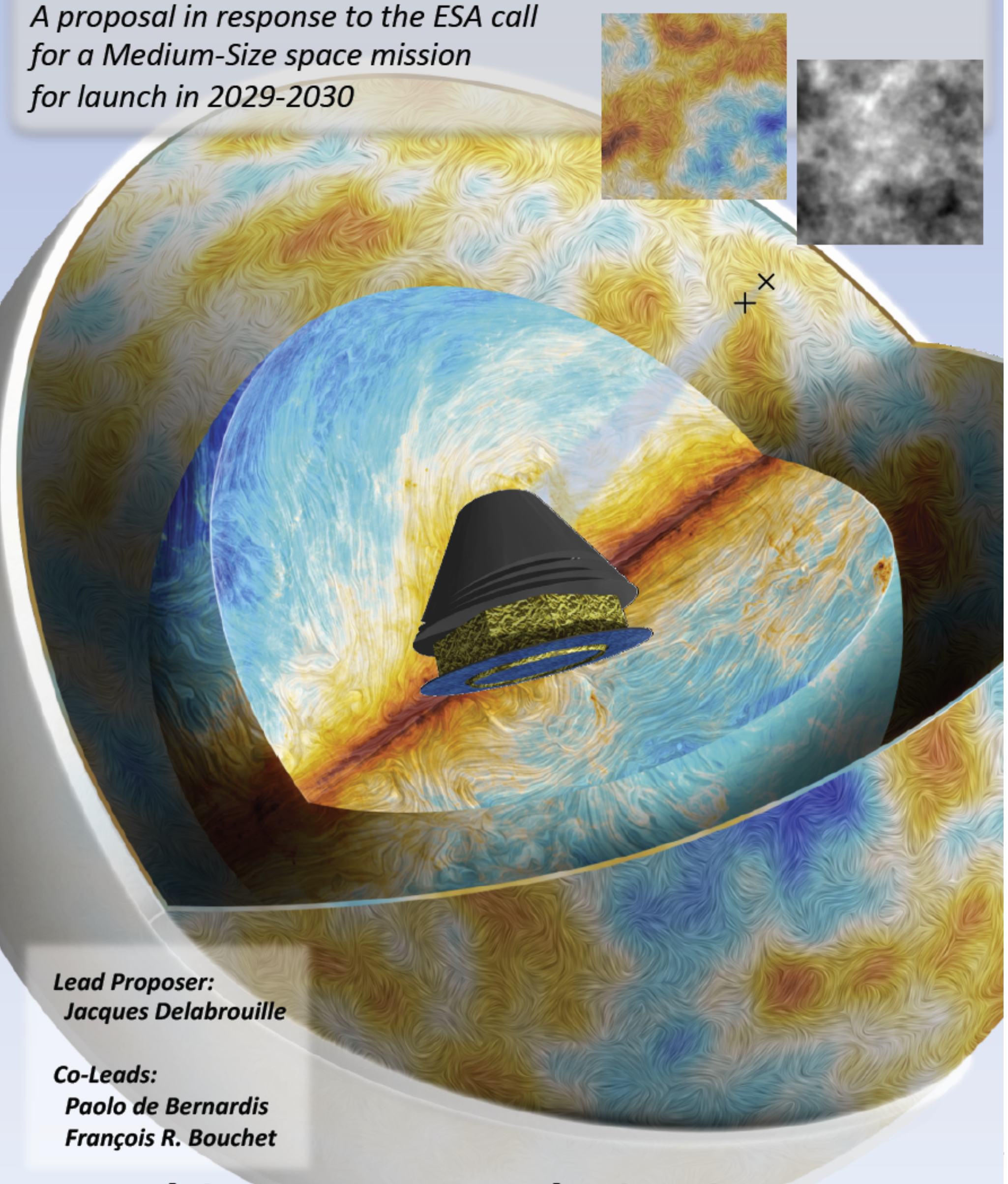
The tasks ahead appear as daunting that those faced in the early days of Planck. But the Planck challenges were met thanks to a long term program which started around 1992. There is no reason to believe that the now much better prepared (and larger) CMB community will not solve these issues given a long term CMB program encompassing them from start.

(Section Outreach)

For the short/mid-term, we recommend to offer visibility to current CMB projects through the well-established `planck.fr` website, at least for the next three years, the time needed for current plans to be approved or otherwise, and to re-orient the content accordingly. This will keep people informed about CMB activities in France. This requires some site reorganisation however, with three areas foreseen, for ground-based, balloon-borne and space-based experiments, in addition to more general material on cosmology and the CMB. This will also require funding to maintain the site.

CORE The Cosmic Origins Explorer

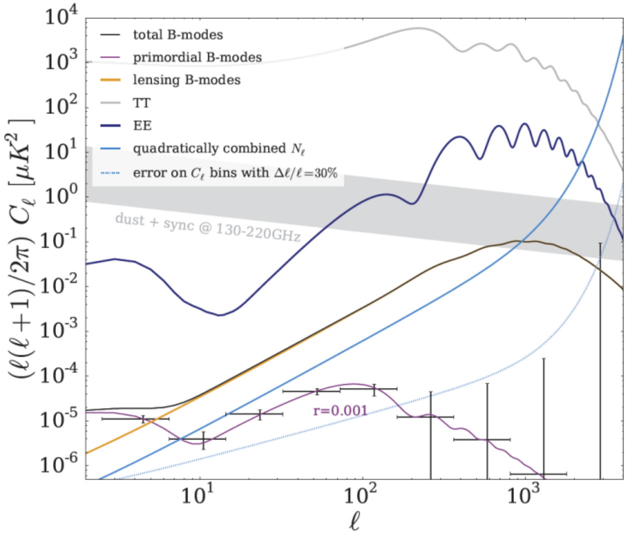
A proposal in response to the ESA call
for a Medium-Size space mission
for launch in 2029-2030

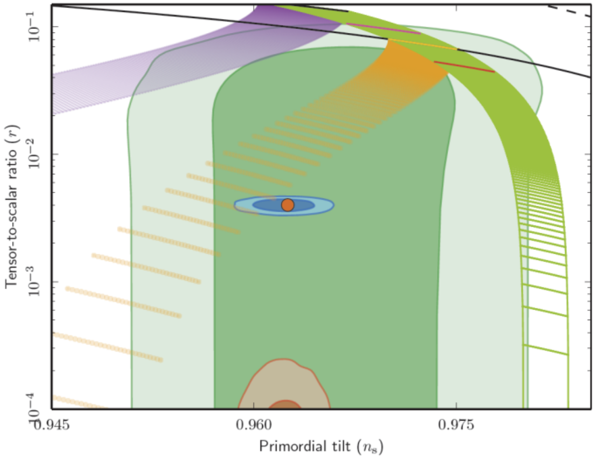


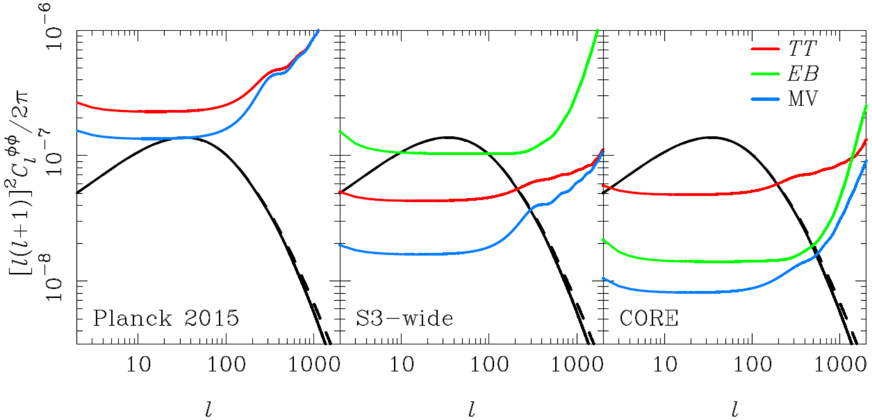
Lead Proposer:
Jacques Delabrouille

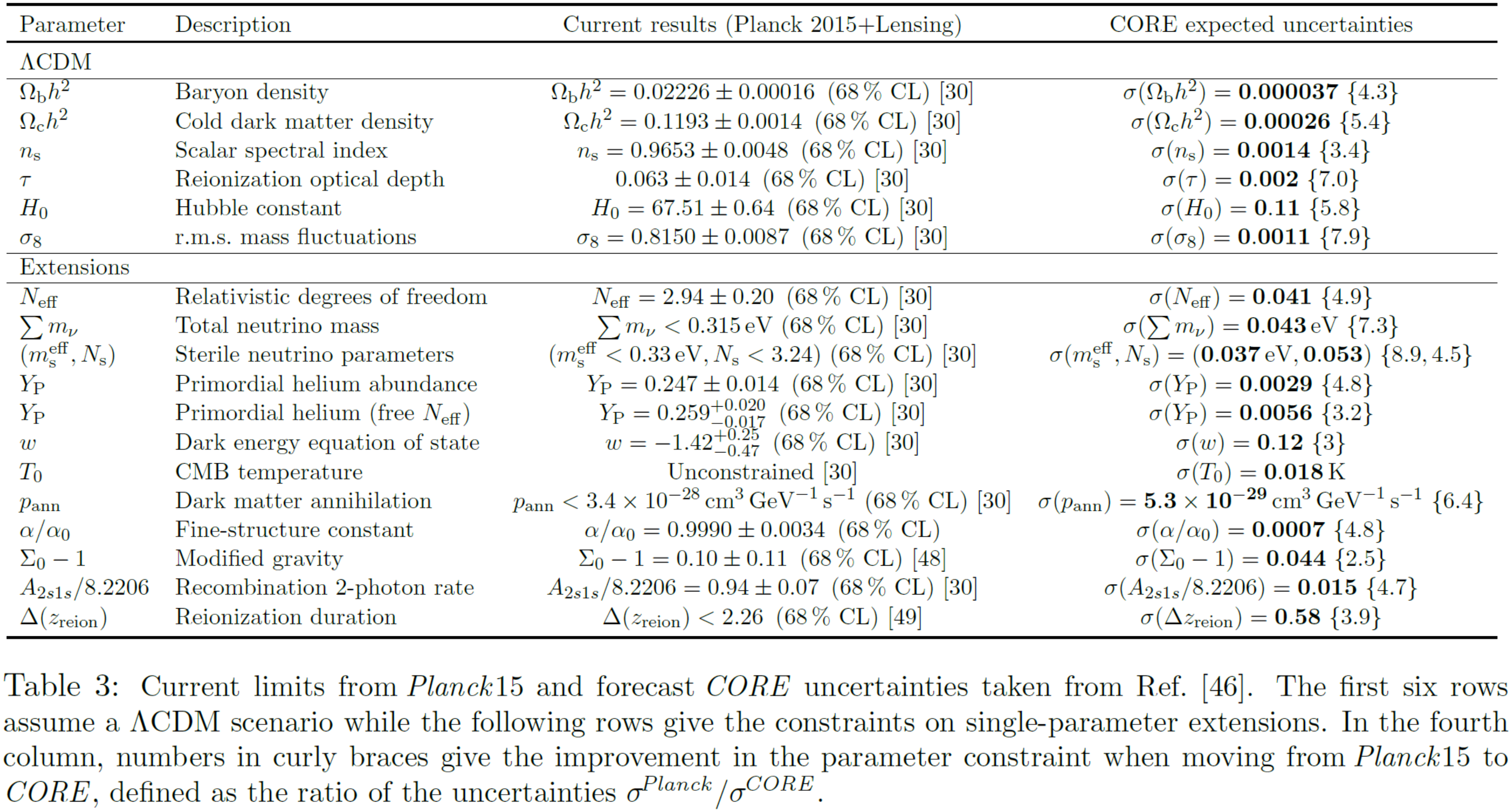
Co-Leads:
Paolo de Bernardis
François R. Bouchet

For ultimate CMB polarisation maps





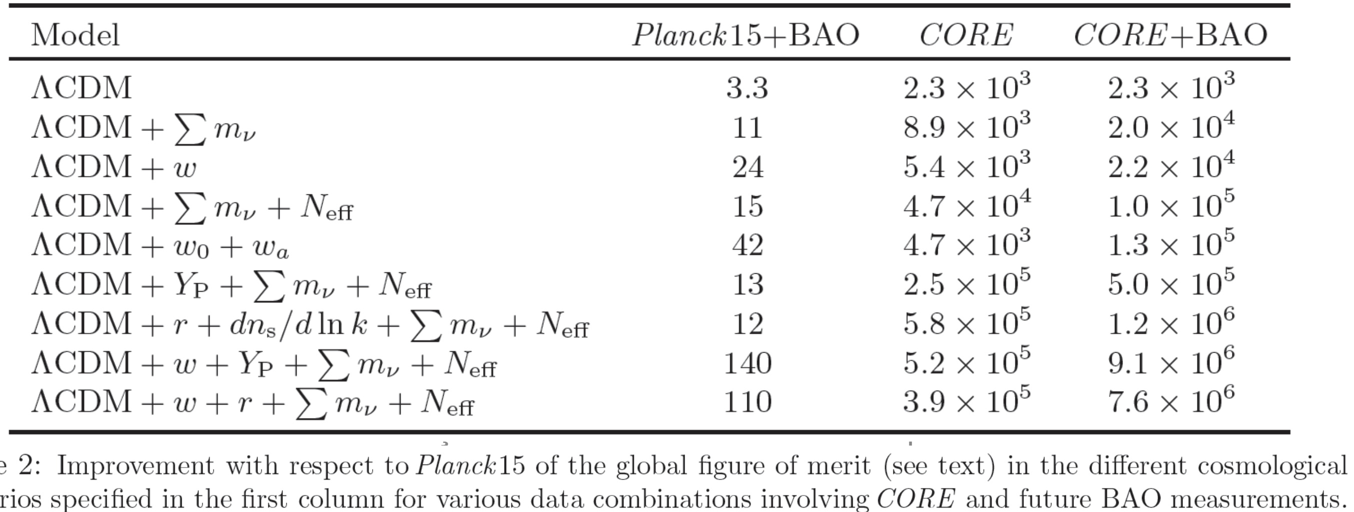




Parameter	Description	Current results (Planck 2015+Lensing)	CORE expected uncertainties
ΛCDM			
$\Omega_b h^2$	Baryon density	$\Omega_b h^2 = 0.02226 \pm 0.00016$ (68 % CL) [30]	$\sigma(\Omega_b h^2) = \mathbf{0.000037}$ {4.3}
$\Omega_c h^2$	Cold dark matter density	$\Omega_c h^2 = 0.1193 \pm 0.0014$ (68 % CL) [30]	$\sigma(\Omega_c h^2) = \mathbf{0.00026}$ {5.4}
n_s	Scalar spectral index	$n_s = 0.9653 \pm 0.0048$ (68 % CL) [30]	$\sigma(n_s) = \mathbf{0.0014}$ {3.4}
τ	Reionization optical depth	0.063 ± 0.014 (68 % CL) [30]	$\sigma(\tau) = \mathbf{0.002}$ {7.0}
H_0	Hubble constant	$H_0 = 67.51 \pm 0.64$ (68 % CL) [30]	$\sigma(H_0) = \mathbf{0.11}$ {5.8}
σ_8	r.m.s. mass fluctuations	$\sigma_8 = 0.8150 \pm 0.0087$ (68 % CL) [30]	$\sigma(\sigma_8) = \mathbf{0.0011}$ {7.9}
Extensions			
$N_{\rm eff}$	Relativistic degrees of freedom	$N_{\rm eff} = 2.94 \pm 0.20$ (68 % CL) [30]	$\sigma(N_{\rm eff}) = \mathbf{0.041}$ {4.9}
$\sum m_\nu$	Total neutrino mass	$\sum m_\nu < 0.315\,\mathrm{eV}$ (68 % CL) [30]	$\sigma(\sum m_\nu) = \mathbf{0.043}\,\mathrm{eV}$ {7.3}
$(m_s^{\rm eff}, N_s)$	Sterile neutrino parameters	$(m_s^{\rm eff} < 0.33\,\mathrm{eV}, N_s < 3.24)$ (68 % CL) [30]	$\sigma(m_s^{\rm eff}, N_s) = (\mathbf{0.037}\,\mathrm{eV}, \mathbf{0.053})$ {8.9, 4.5}
Y_P	Primordial helium abundance	$Y_P = 0.247 \pm 0.014$ (68 % CL) [30]	$\sigma(Y_P) = \mathbf{0.0029}$ {4.8}
Y_P	Primordial helium (free $N_{\rm eff}$)	$Y_P = 0.259^{+0.020}_{-0.017}$ (68 % CL) [30]	$\sigma(Y_P) = \mathbf{0.0056}$ {3.2}
w	Dark energy equation of state	$w = -1.42^{+0.25}_{-0.47}$ (68 % CL) [30]	$\sigma(w) = \mathbf{0.12}$ {3}
T_0	CMB temperature	Unconstrained [30]	$\sigma(T_0) = \mathbf{0.018}\,\mathrm{K}$
$p_{\rm ann}$	Dark matter annihilation	$p_{\rm ann} < 3.4 \times 10^{-28}\,\mathrm{cm^3\,GeV^{-1}\,s^{-1}}$ (68 % CL) [30]	$\sigma(p_{\rm ann}) = \mathbf{5.3 \times 10^{-29}}\,\mathrm{cm^3\,GeV^{-1}\,s^{-1}}$ {6.4}
α/α_0	Fine-structure constant	$\alpha/\alpha_0 = 0.9990 \pm 0.0034$ (68 % CL)	$\sigma(\alpha/\alpha_0) = \mathbf{0.0007}$ {4.8}
$\Sigma_0 - 1$	Modified gravity	$\Sigma_0 - 1 = 0.10 \pm 0.11$ (68 % CL) [48]	$\sigma(\Sigma_0 - 1) = \mathbf{0.044}$ {2.5}
$A_{2s1s}/8.2206$	Recombination 2-photon rate	$A_{2s1s}/8.2206 = 0.94 \pm 0.07$ (68 % CL) [30]	$\sigma(A_{2s1s}/8.2206) = \mathbf{0.015}$ {4.7}
$\Delta(z_{\rm reion})$	Reionization duration	$\Delta(z_{\rm reion}) < 2.26$ (68 % CL) [49]	$\sigma(\Delta z_{\rm reion}) = \mathbf{0.58}$ {3.9}

Table 3: Current limits from *Planck*15 and forecast *CORE* uncertainties taken from Ref. [46]. The first six rows assume a ΛCDM scenario while the following rows give the constraints on single-parameter extensions. In the fourth column, numbers in curly braces give the improvement in the parameter constraint when moving from *Planck*15 to *CORE*, defined as the ratio of the uncertainties $\sigma^{Planck}/\sigma^{CORE}$.

FOM's
wrt
Planck15

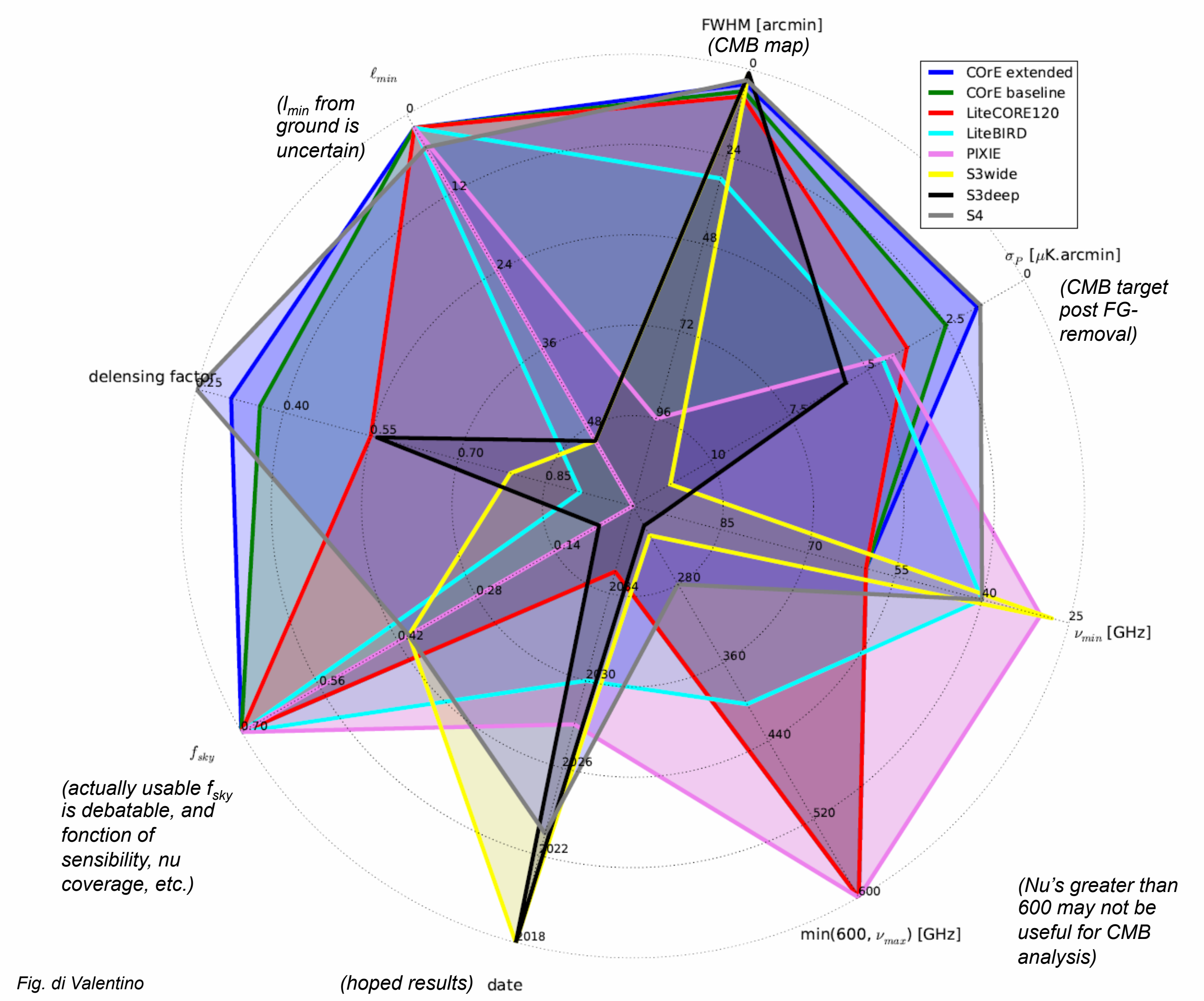


Model	*Planck*15+BAO	*CORE*	*CORE*+BAO
ΛCDM	3.3	2.3×10^3	2.3×10^3
$\Lambda\mathrm{CDM} + \sum m_\nu$	11	8.9×10^3	2.0×10^4
$\Lambda\mathrm{CDM} + w$	24	5.4×10^3	2.2×10^4
$\Lambda\mathrm{CDM} + \sum m_\nu + N_{\rm eff}$	15	4.7×10^4	1.0×10^5
$\Lambda\mathrm{CDM} + w_0 + w_a$	42	4.7×10^3	1.3×10^5
$\Lambda\mathrm{CDM} + Y_P + \sum m_\nu + N_{\rm eff}$	13	2.5×10^5	5.0×10^5
$\Lambda\mathrm{CDM} + r + dn_s/d\ln k + \sum m_\nu + N_{\rm eff}$	12	5.8×10^5	1.2×10^6
$\Lambda\mathrm{CDM} + w + Y_P + \sum m_\nu + N_{\rm eff}$	140	5.2×10^5	9.1×10^6
$\Lambda\mathrm{CDM} + w + r + \sum m_\nu + N_{\rm eff}$	110	3.9×10^5	7.6×10^6

Table 2: Improvement with respect to *Planck*15 of the global figure of merit (see text) in the different cosmological scenarios specified in the first column for various data combinations involving *CORE* and future BAO measurements.

Un espace multi-dimensionnel incertain

Et synergie variable avec autres sondes…



(l_{min} from ground is uncertain)

(CMB target post FG-removal)

(actually usable f_{sky} is debatable, and fonction of sensibility, nu coverage, etc.)

(Nu's greater than 600 may not be useful for CMB analysis)

(hoped results)

Fig. di Valentino

+ Nbands