A proposal to ESA-M5 for a CMB polarization mission (COrE++)

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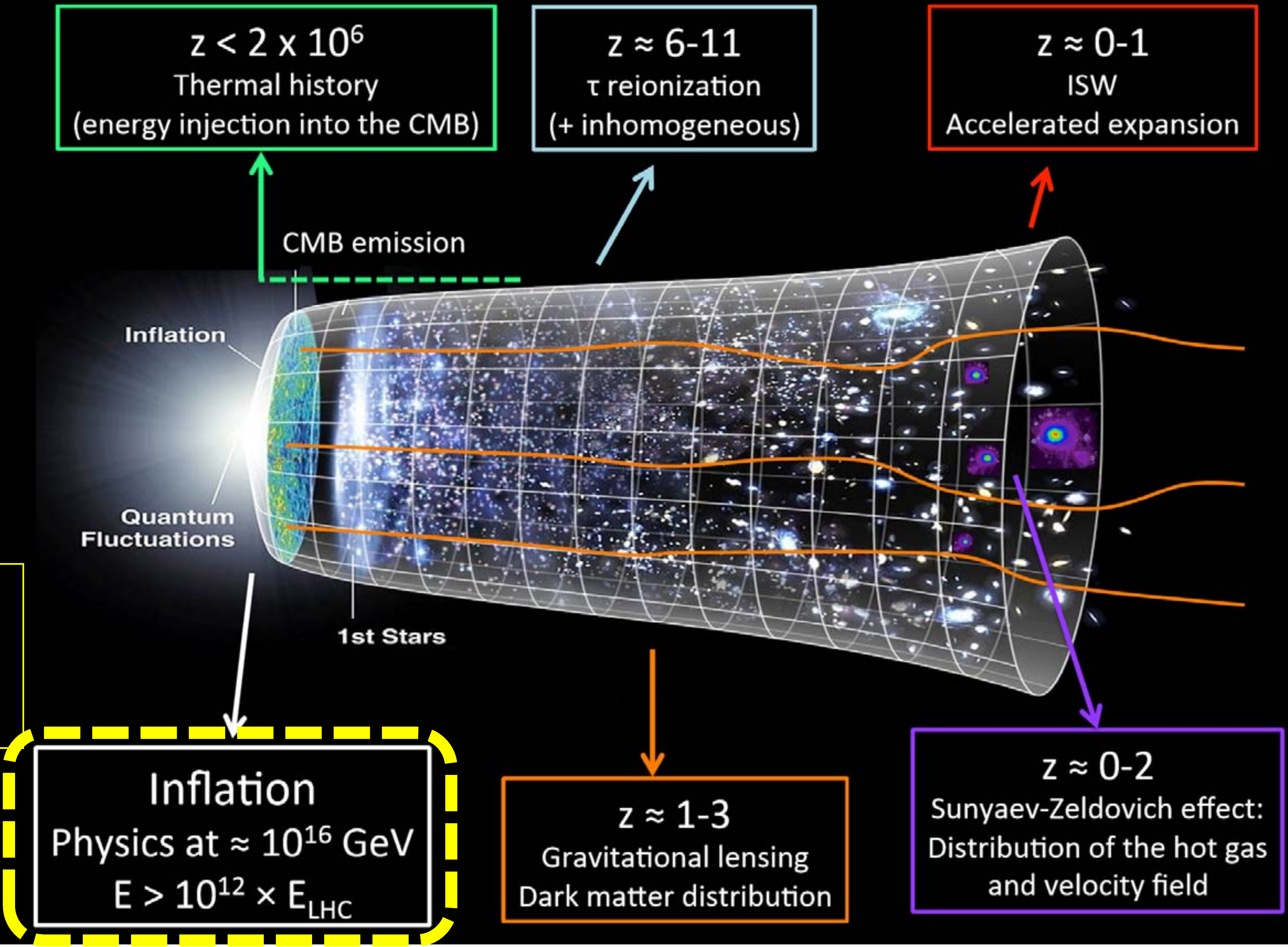
on behalf of the Italian CMB community

Overview

1. Scientific goals of the ESA-M5 CMB polarization mission
2. Why in space
3. Fundamental limits and mission/instrument design
4. Mission implementation
5. Conclusions

COrE++ science



COrE++ is optimized to measure inflationary B-modes

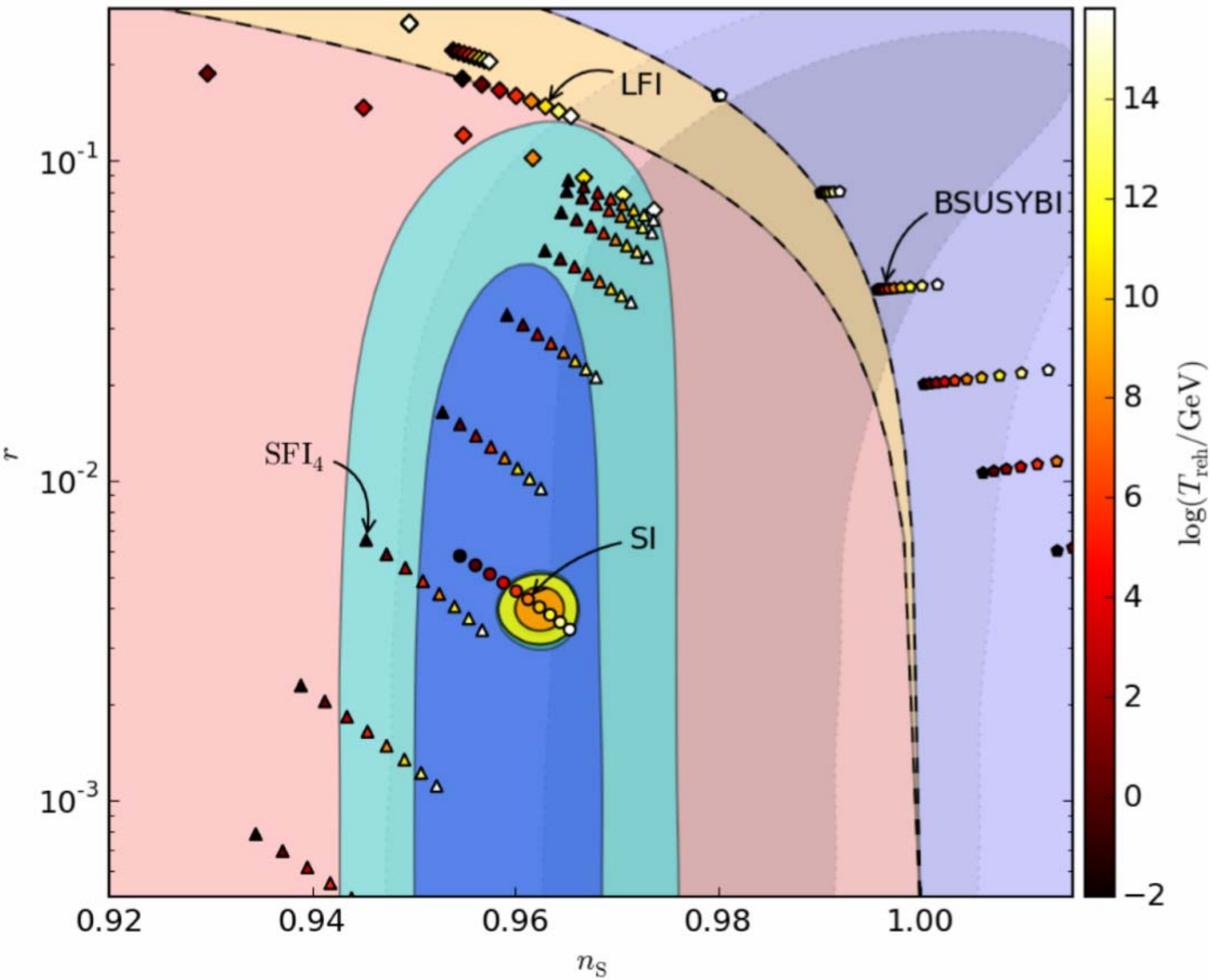
Goals of the CMB polarization mission for M5

- **Final measurement of B-mode polarization**, able to extract the cosmological signal from overwhelming polarized foregrounds.
- Starobinsky model, R^2 (Higgs) inflation have a tensor to scalar ratio $r > 2\times10^{-3}$.
- **The mission should target at $\sigma_r < 4\times10^{-4}$** .
- Such a sensitivity tests Planck-scale physics of the field values in the large-field inflation models:
  - o Lyth bound: $r \leq 2.2\times10^{-3}\left(\frac{\Delta N_{slow}}{60}\right)^{-2}\left(\frac{\Delta\phi_{slow}}{M_P}\right)^{2}$ (Boubeker and Lyth 2005)
  - o A null-result would disfavor the entire class of large-field ($\Delta\phi > M_p$) models, and very few would survive.
- $\sigma_r < 4\times10^{-4}$ should be possibly established without $\ell < 10$.

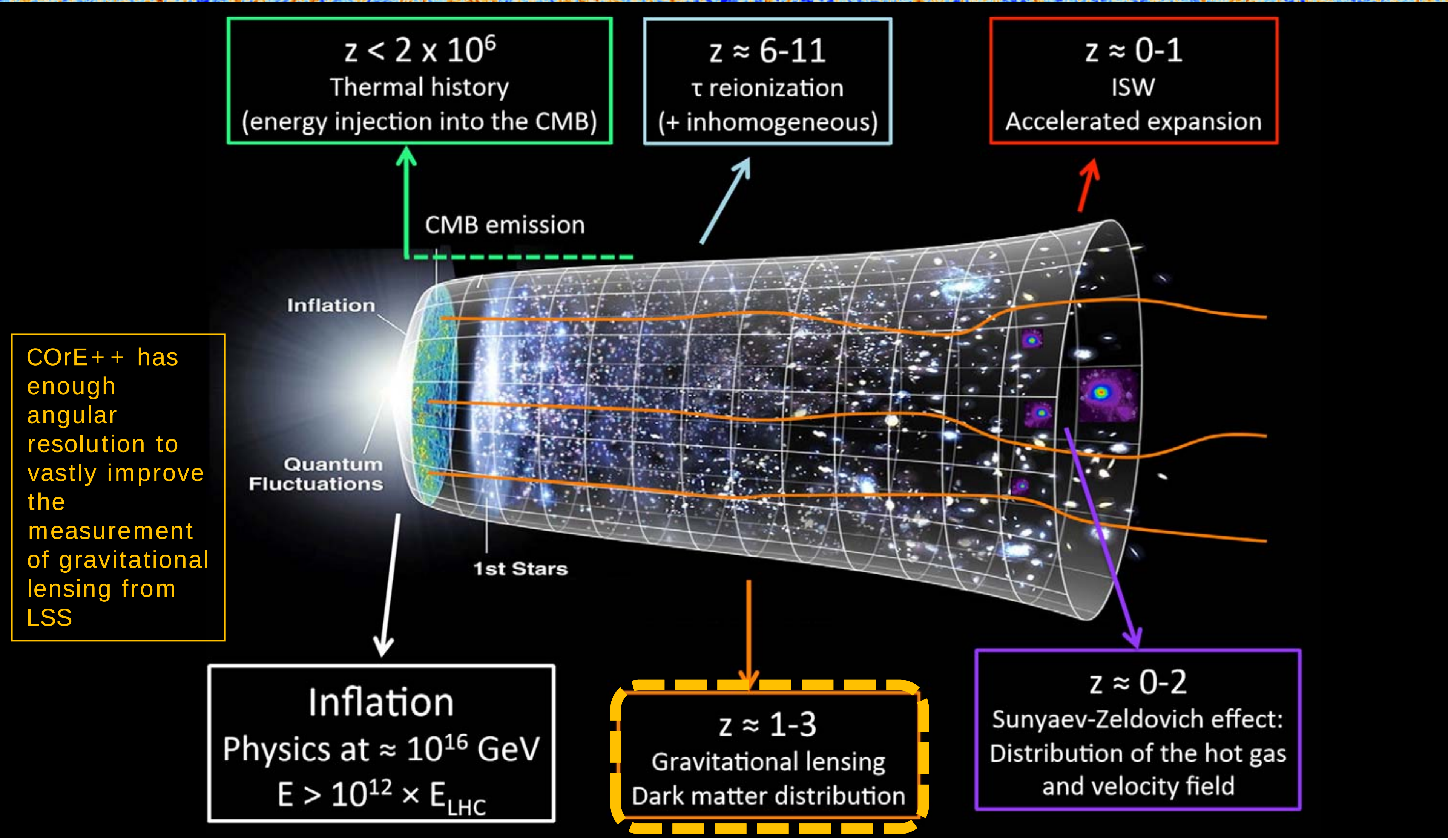
Goals of the CMB polarization mission for M5

n_s would also be measured much better, so that T_{reh} can be estimated.

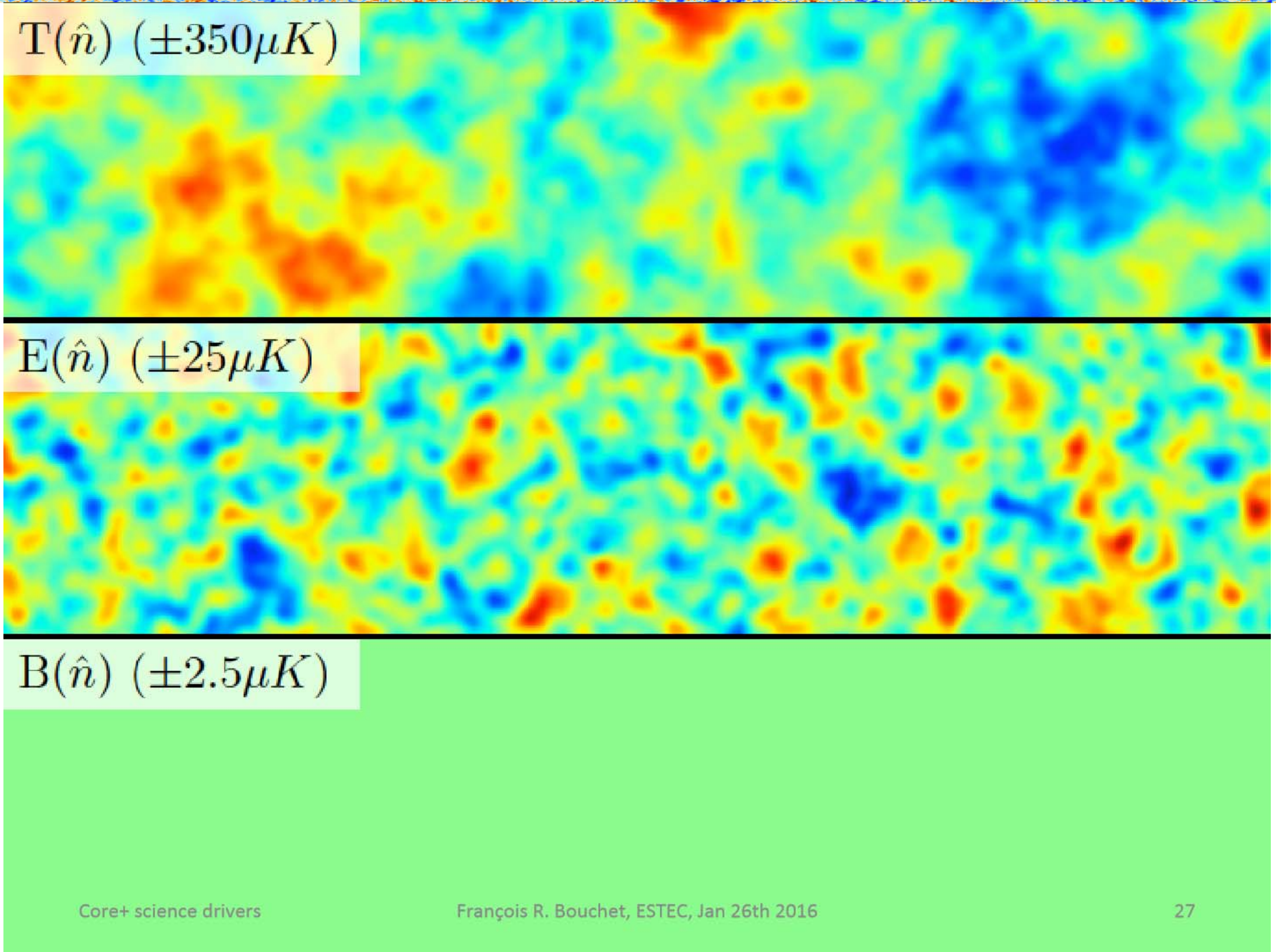
Grey: WMAP
Blue: Planck
Orange: COrE+



Goals of the CMB polarization mission for M5



Gravitational lensing from dark matter structures



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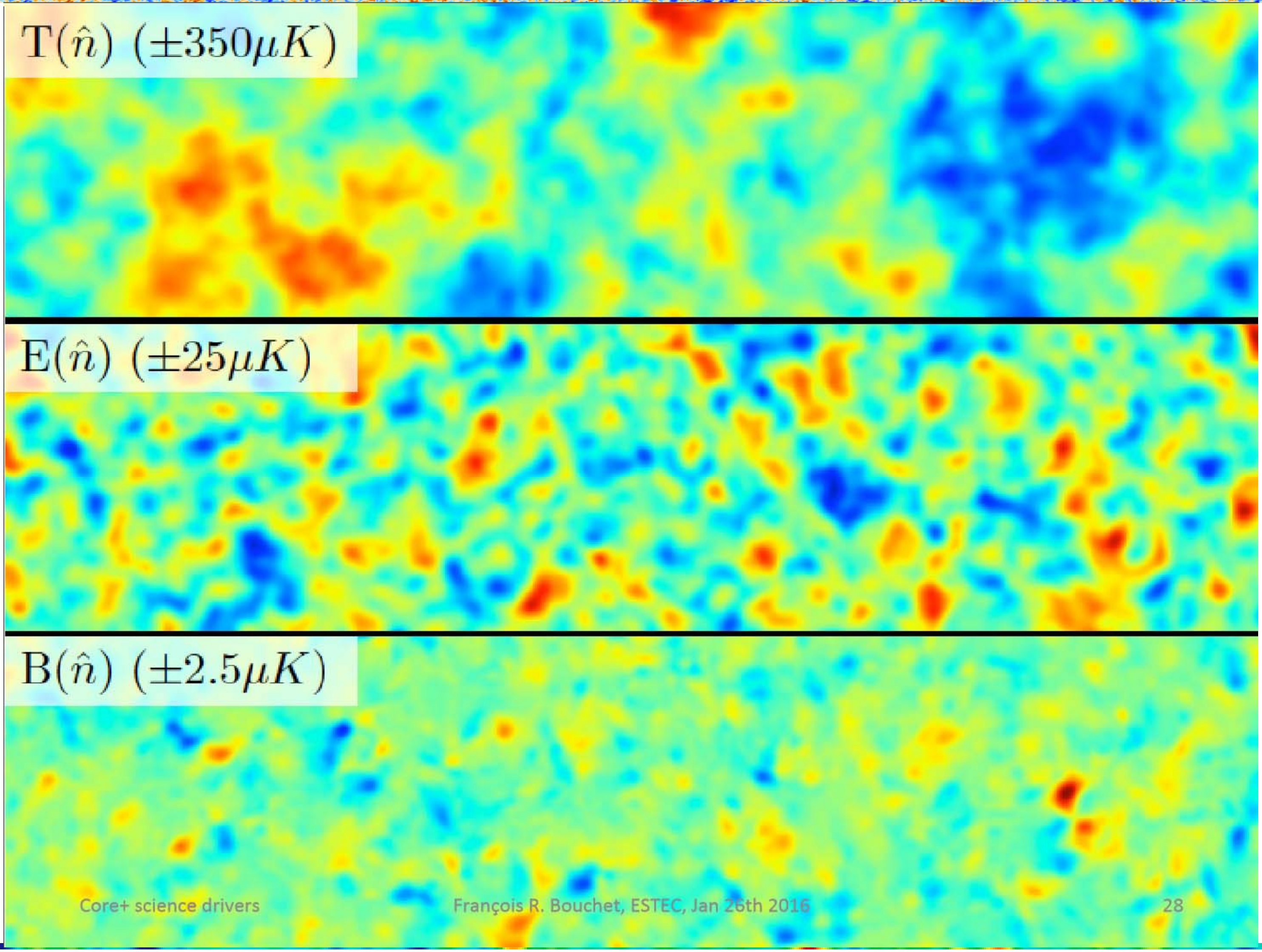
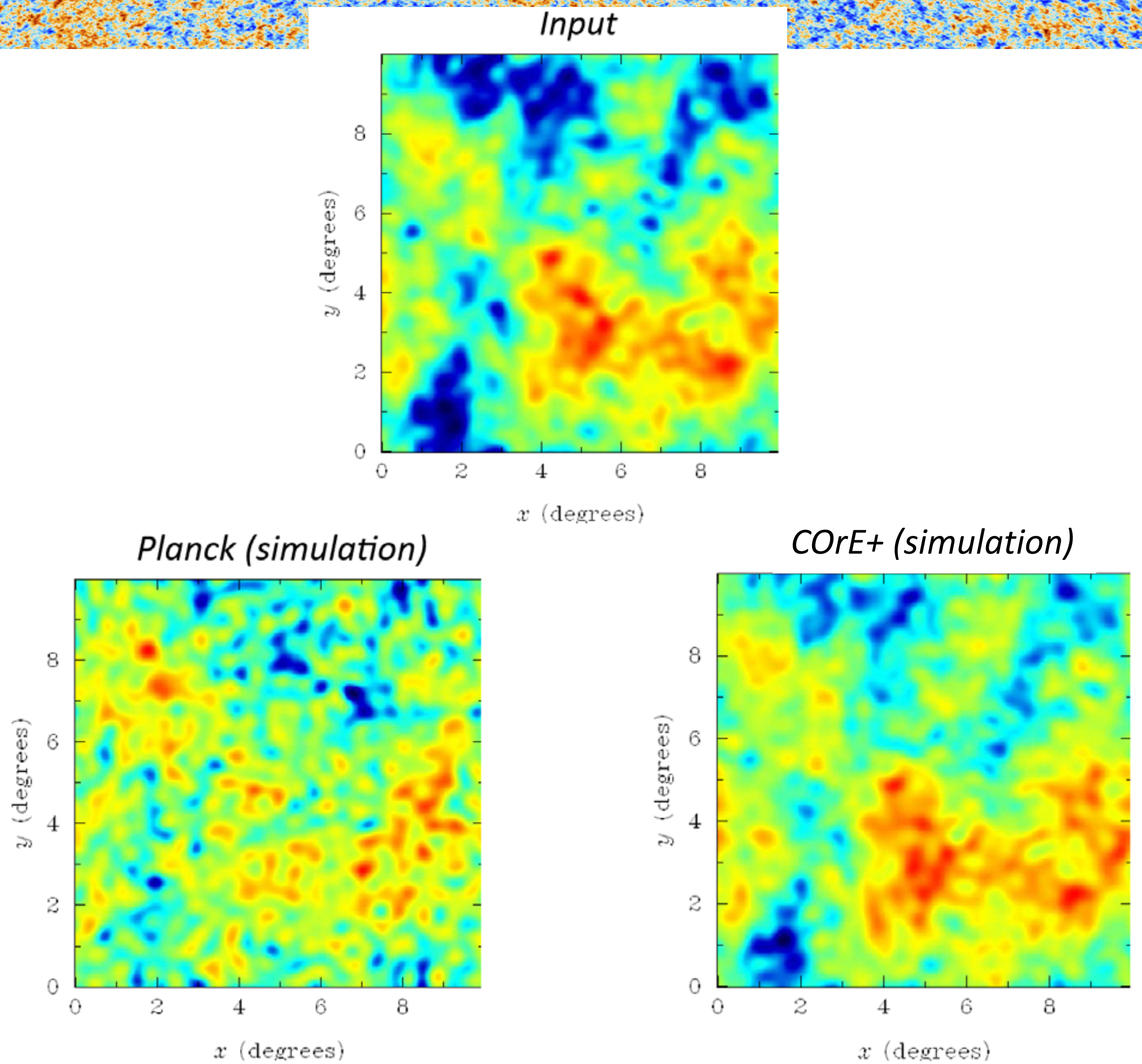


Gravitational lensing from dark matter structures

With the same angular resolution and sensitivity required for the inflationary B-modes, COrE+ produces a **high fidelity map of the gravitational potential integral**, due to dark matter structures from here to recombination: **Direct detection of dark matter structures.**



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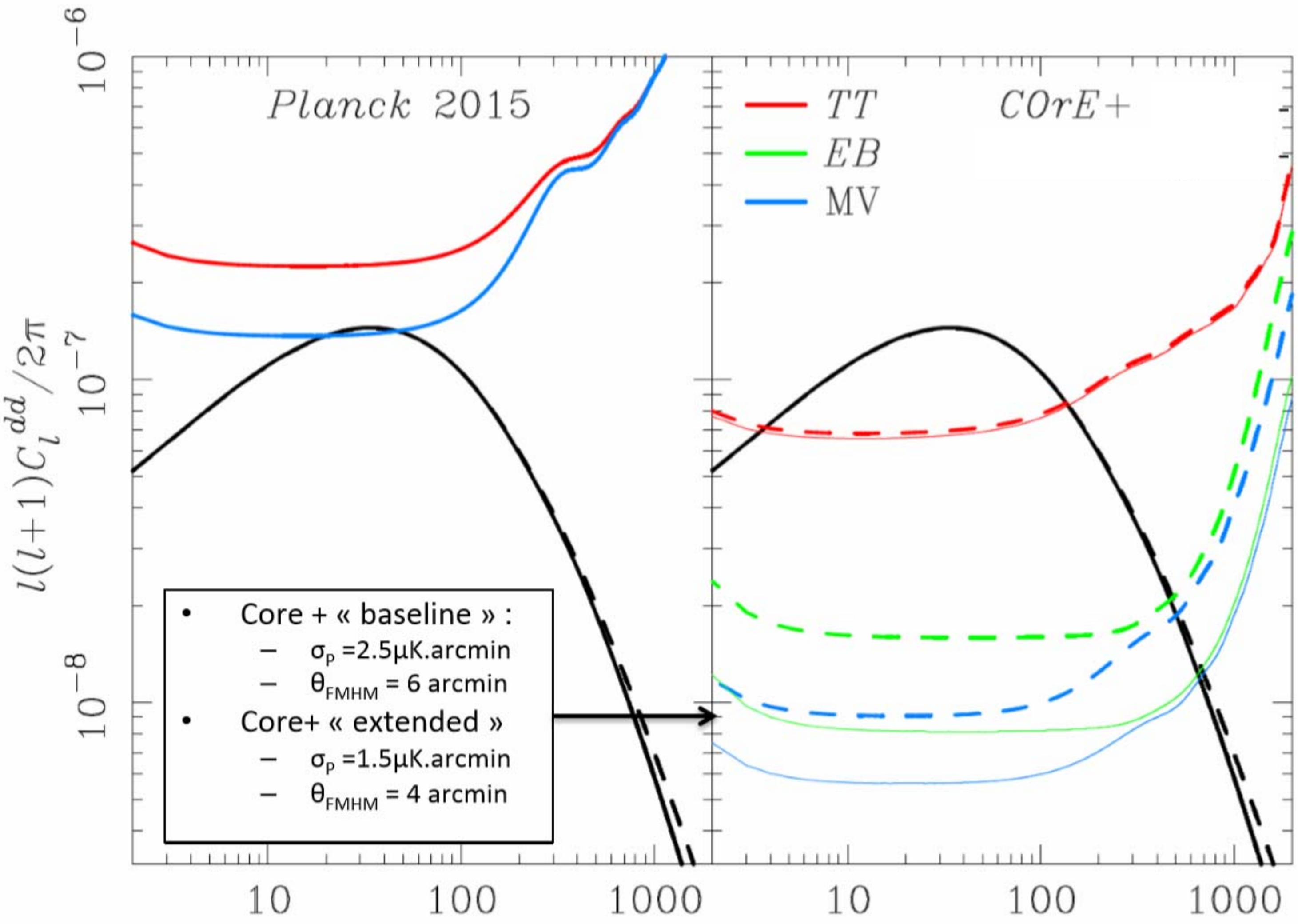
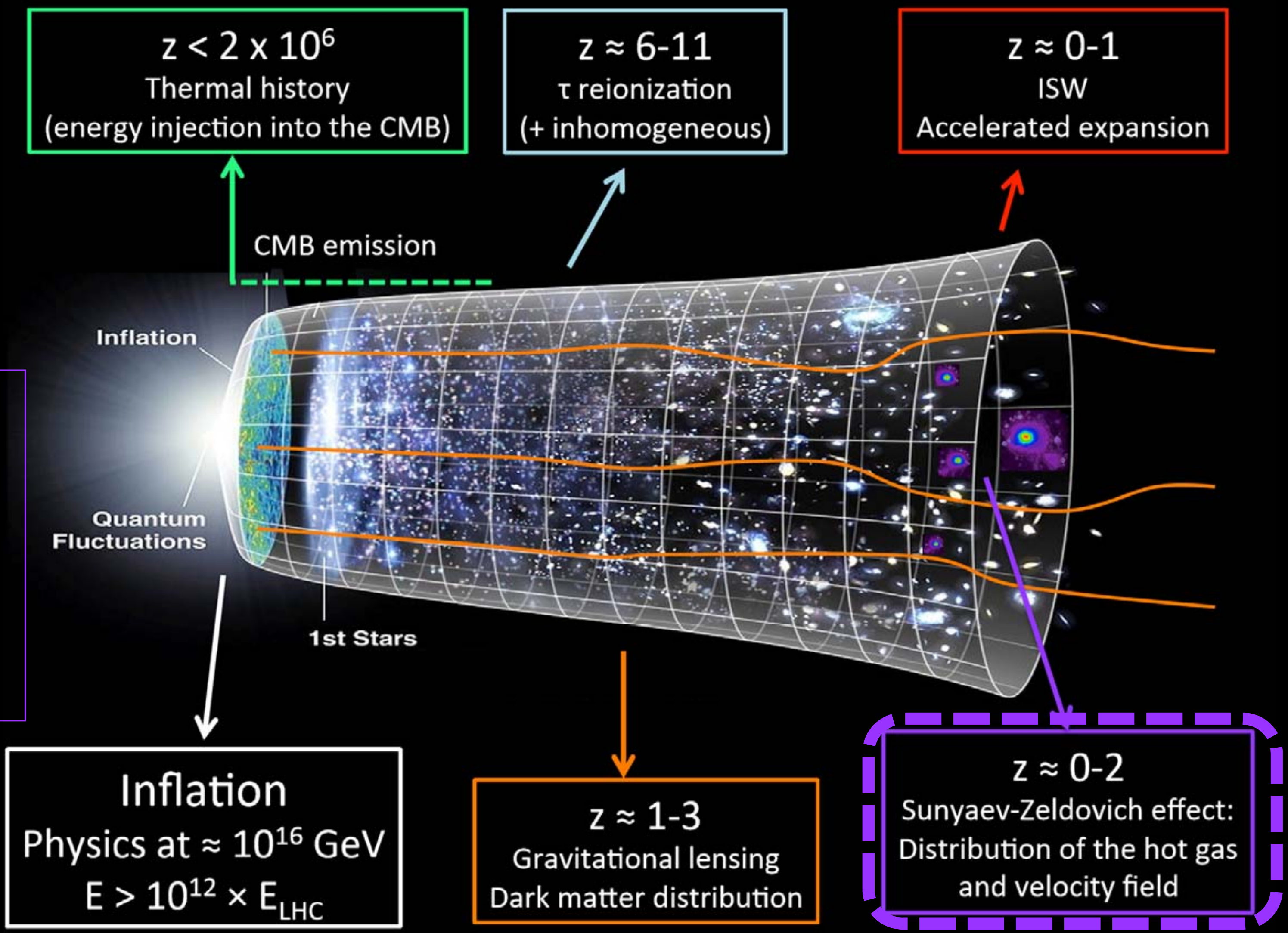


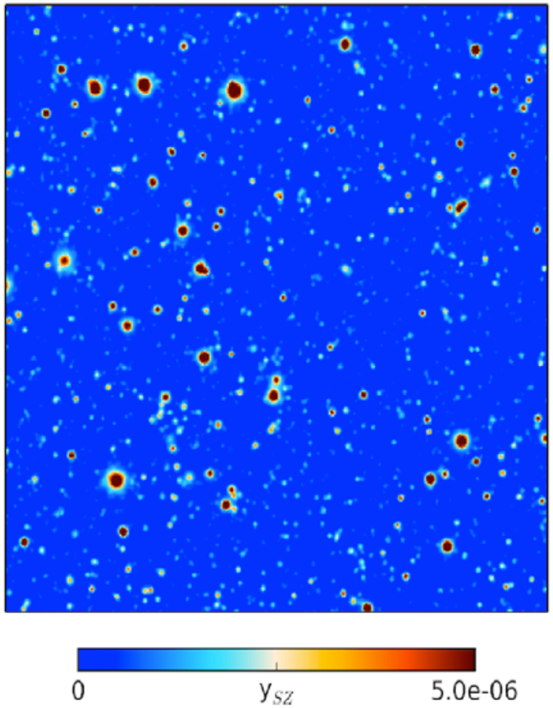
Goals of the CMB polarization mission for M5

COrE++ has enough angular resolution and frequency coverage to extract 100000 SZ clusters from the maps.

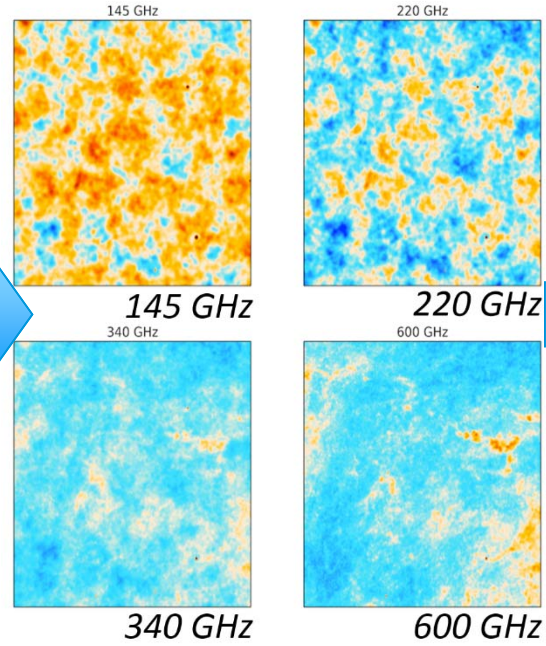


Extract and catalogue 100000 SZ clusters !

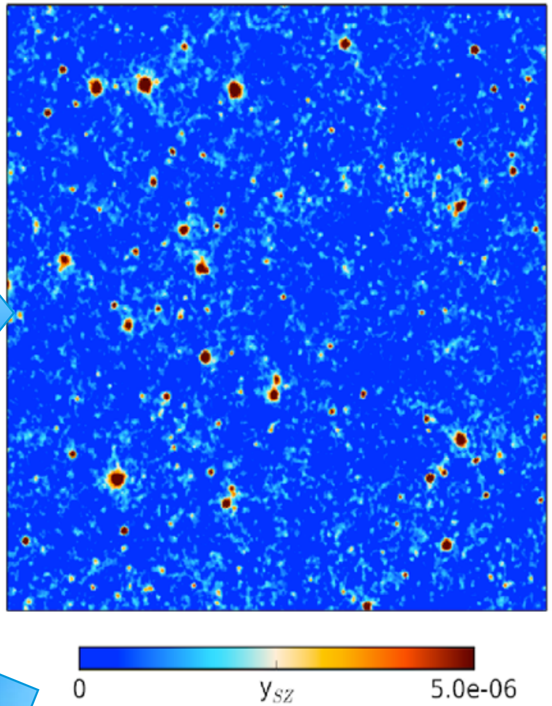
Simulation SZ only (input)

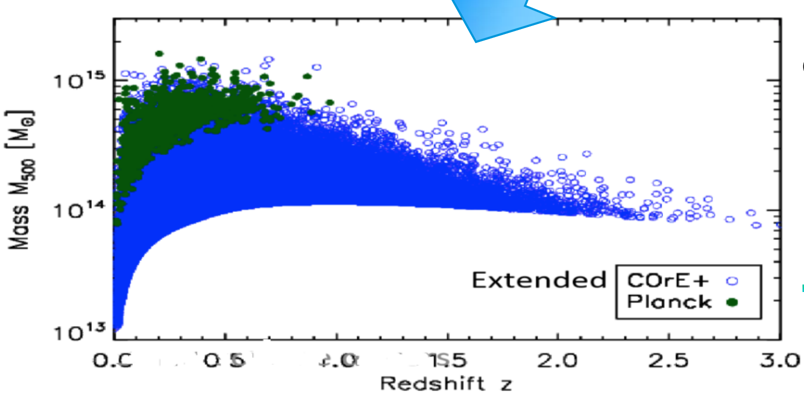


Mixed to other components and noise



Reconstructed after
component separation (output)

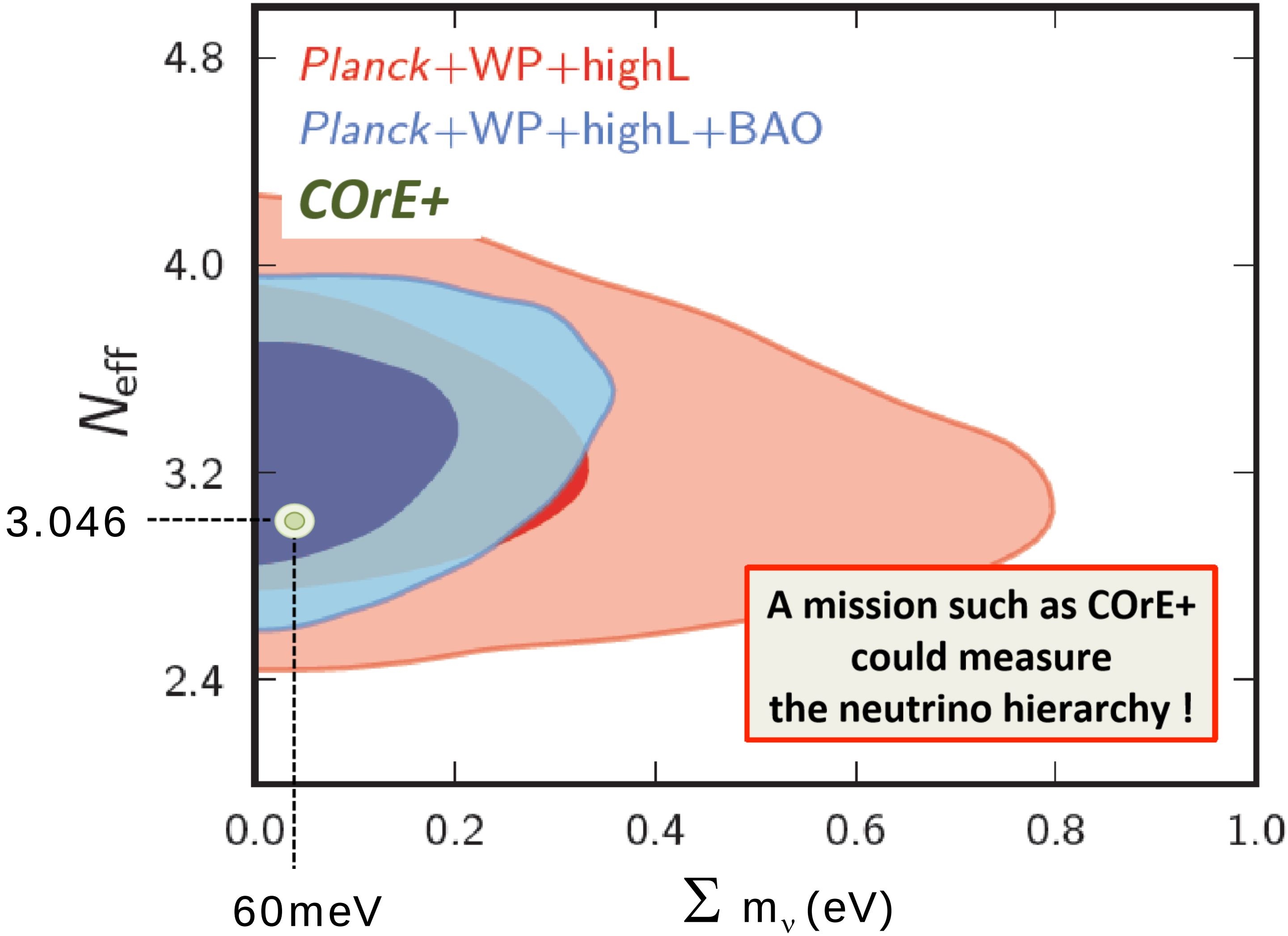


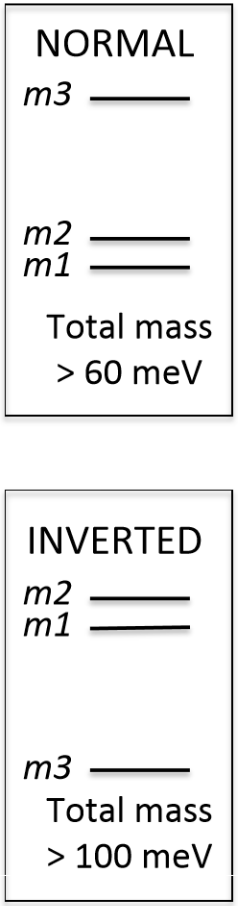


Catalogue

COrE+ simulations
(Remazeilles, Karakci,..)

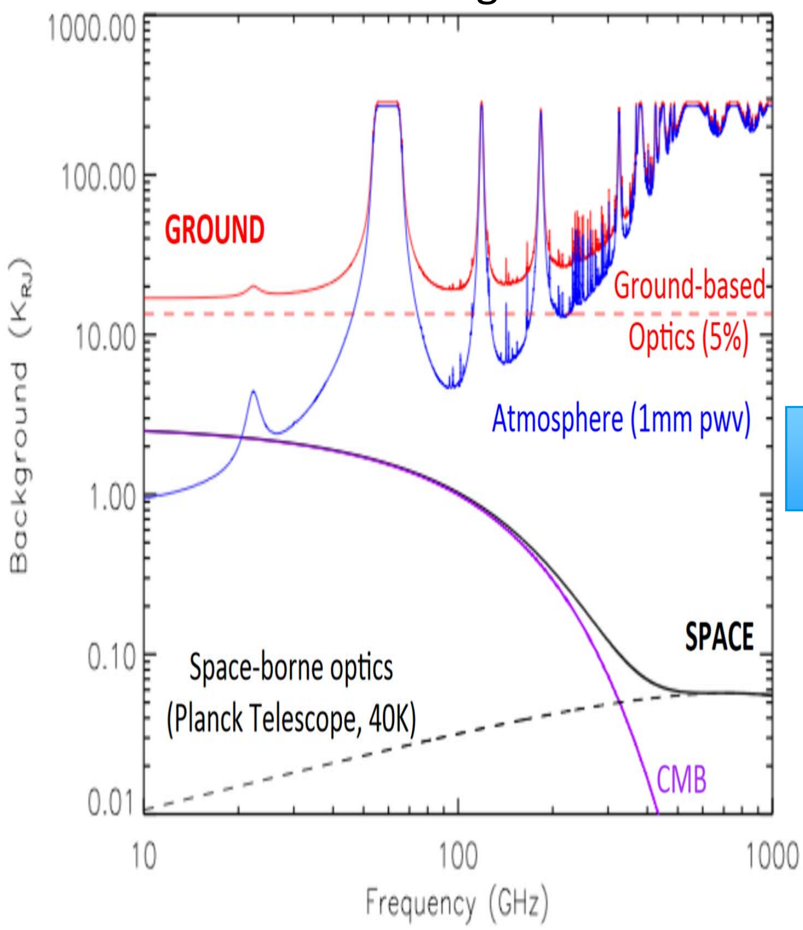
Constraining the neutrino sector



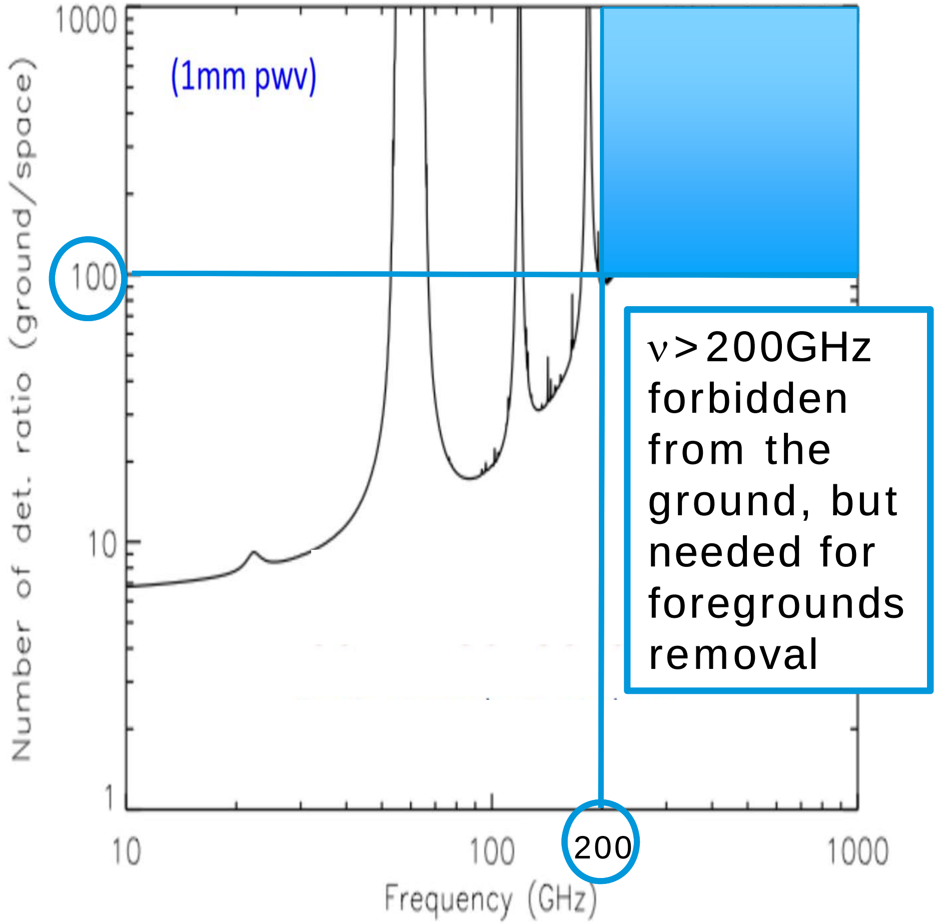


Why in space: 1) background fluctuations

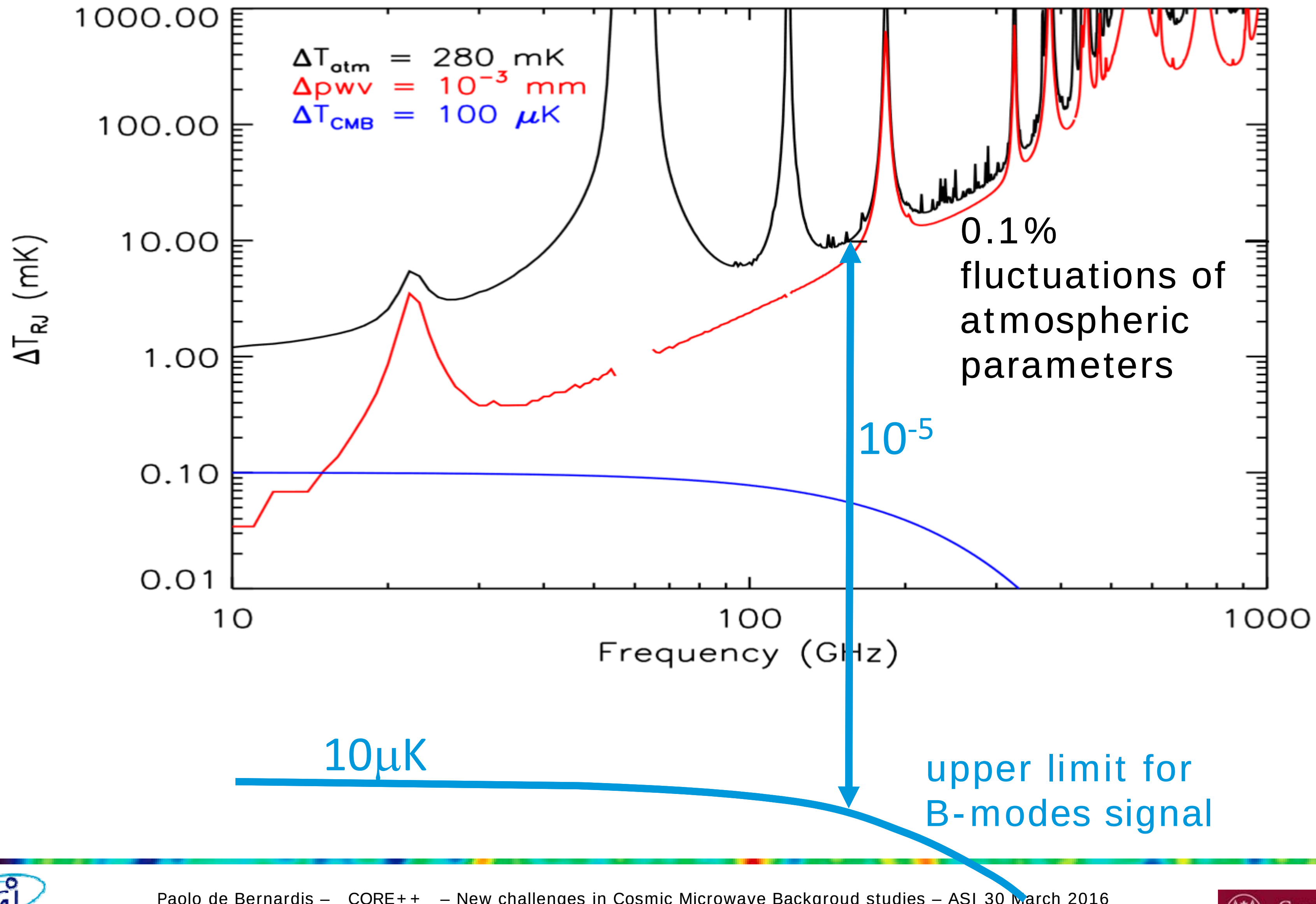
Photon background



Ratio of the number of detectors needed, for a given sensitivity, due to statistical photon background fluctuations.



Why in space: 2) atmospheric instability



Why in space: 3) systematic effects

- Atmospheric fluctuations larger at large scales, where the inflation signal is.
- The effects of ground pickup (from the sidelobes) are larger at large scales.
- The environment temperature is not stable at long timescales
- Duty cycle of ground-based measurements << 100%

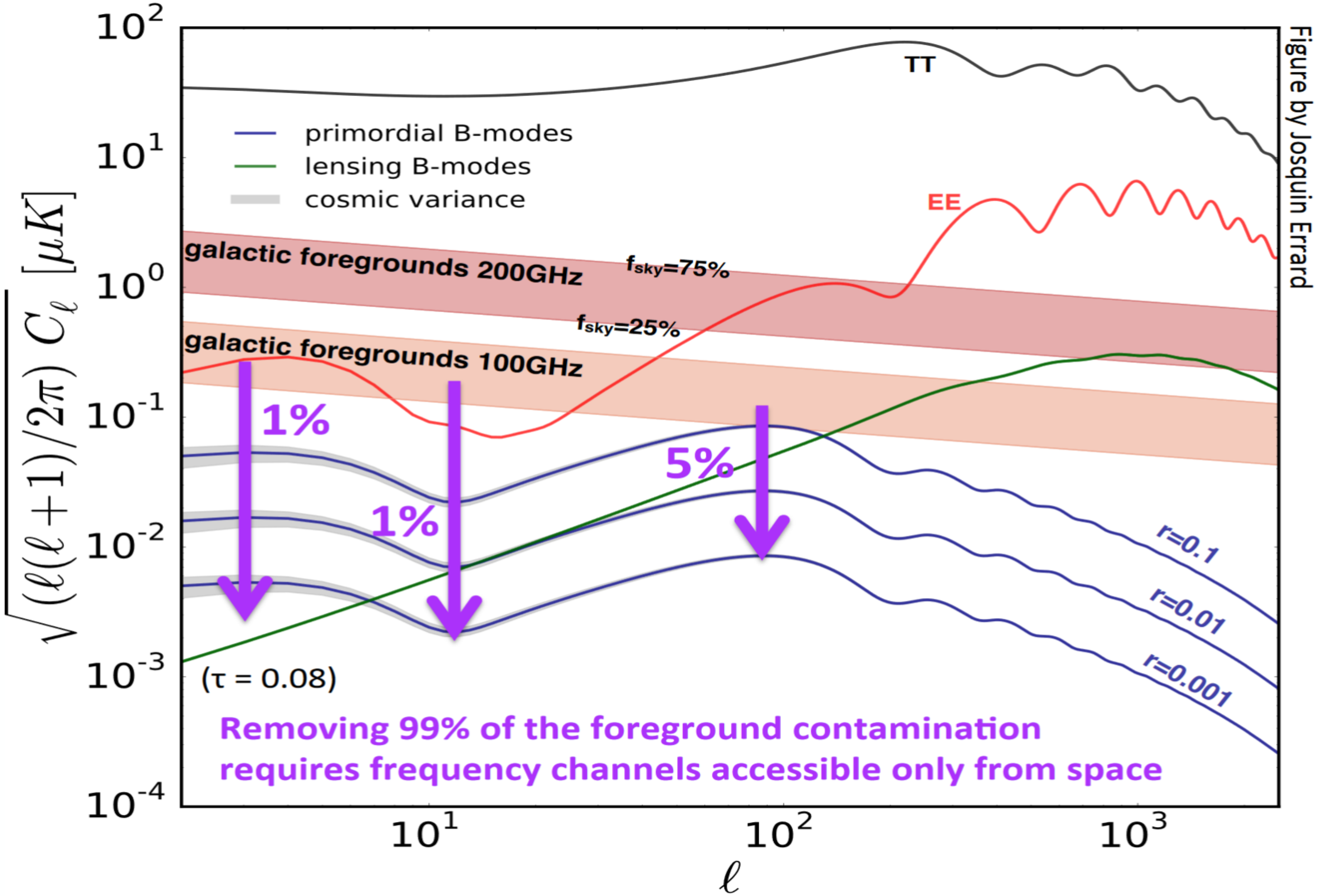
- **All these effects can be vastly reduced with a space mission in L2 (as WMAP, Planck).**
- In L2, the solid angle occupied by the Earth is reduced by a factor 10000.
- Looking at anti-solar directions, the Earth, the Moon and the Sun are very far from the boresight, so that pickup is minimized.
- As long as the solar elongation is kept constant, the environment is extremely stable, and so is the instrument performance.

- The effect of cosmic rays is heavier in space than on the ground, and must be properly mitigated with special detector design, and monitored in the data analysis.

Instrument/mission design driven by fundamental limitations

- Current precision (Planck) σ_r~0.05; our goal σ_r~0.0004
- Fundamental limitations to **Accuracy**:
    - Overwhelming B-mode signals are produced:
    - o Along the path of CMB photons, by gravitational lensing (to be monitored with high angular resolution)
    - o In our Galaxy, by polarized foregrounds (to be monitored with many bands and wide frequency coverage)
    - o In the instrument, if not properly designed (minimize polarizing components in the optical path, use proper optical design)
- Fundamental limitations to **Sensitivity**:
    - Photon noise: the CMB and the emission of the instrument are fluctuating according to photon statistics.
    - Mitigation: work in a stable, low-background environment, for a long time (cold telescope, in space, with active coolers) with many detectors (kilopixel arrays)

Frequency coverage to monitor foregrounds



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

Frequency coverage to monitor foregrounds

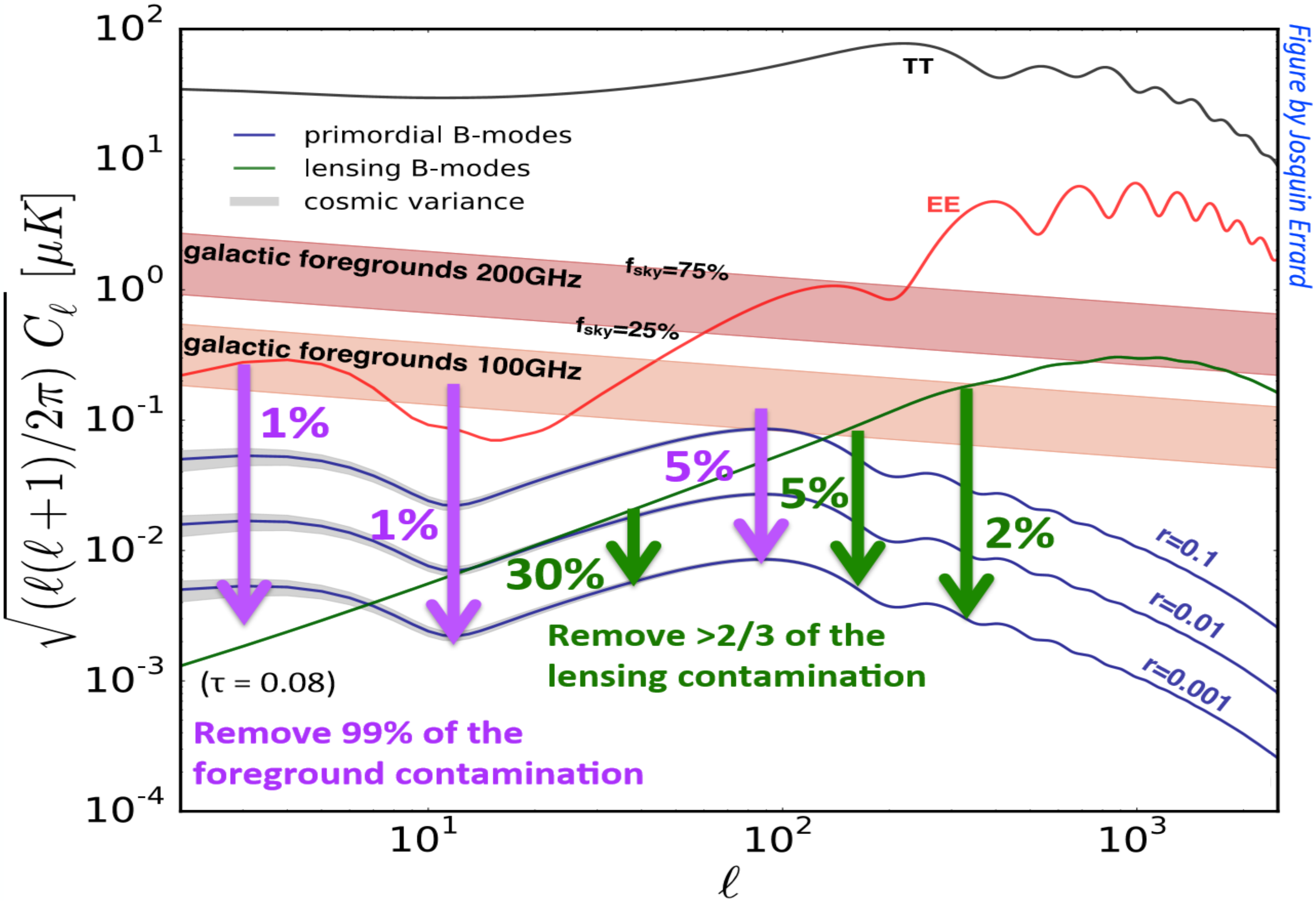
- Results from WMAP show that at low frequency the polarized synchrotron background is strong and has spectral index fluctuations.

- Preliminary results from Planck-HFI show that polarized dust emission must be monitored with great spectral and spatial accuracy to avoid biases in *r*, even at ℓ=100 (fluctuations of the spectral index).

- Monitoring polarized dust at 340 GHz and extrapolating at 140 GHz to remove it (as in BicepKeckPlanck) is only a first approximation, and is not enough for our goal accuracy. Same for monitoring synchrotron at 30 GHz.

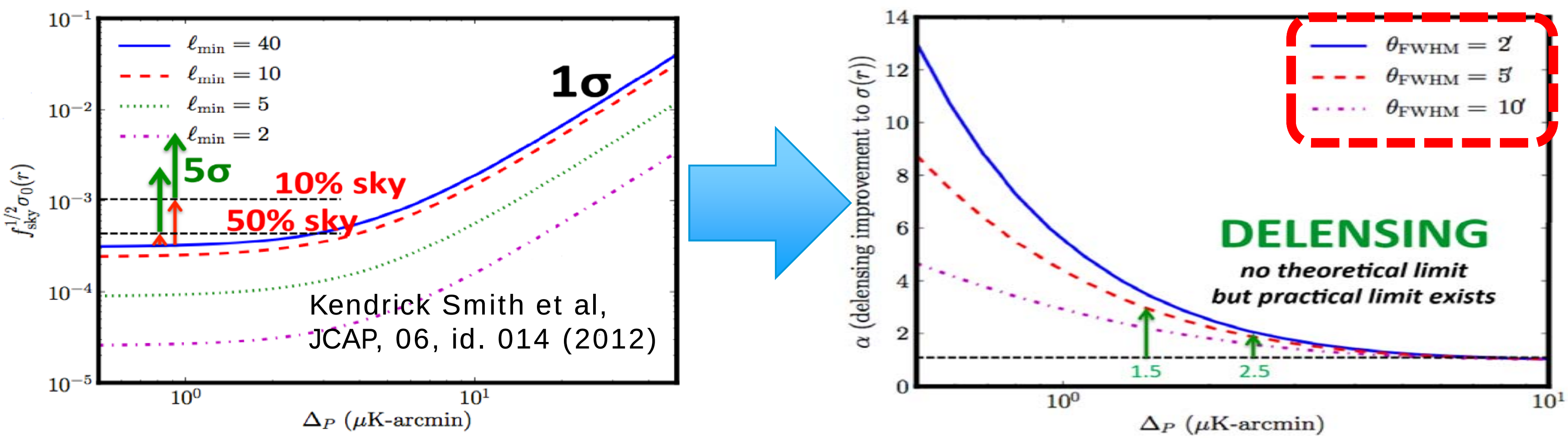
- The final mission must have excellent sensitivity and accuracy in a wide interval of frequencies above 200 GHz (which cannot be monitored from the ground) to extrapolate reliably the polarized emission from interstellar dust at 90-140 GHz.

Multipoles coverage to monitor lensing B-modes



Required sensitivity and resolution

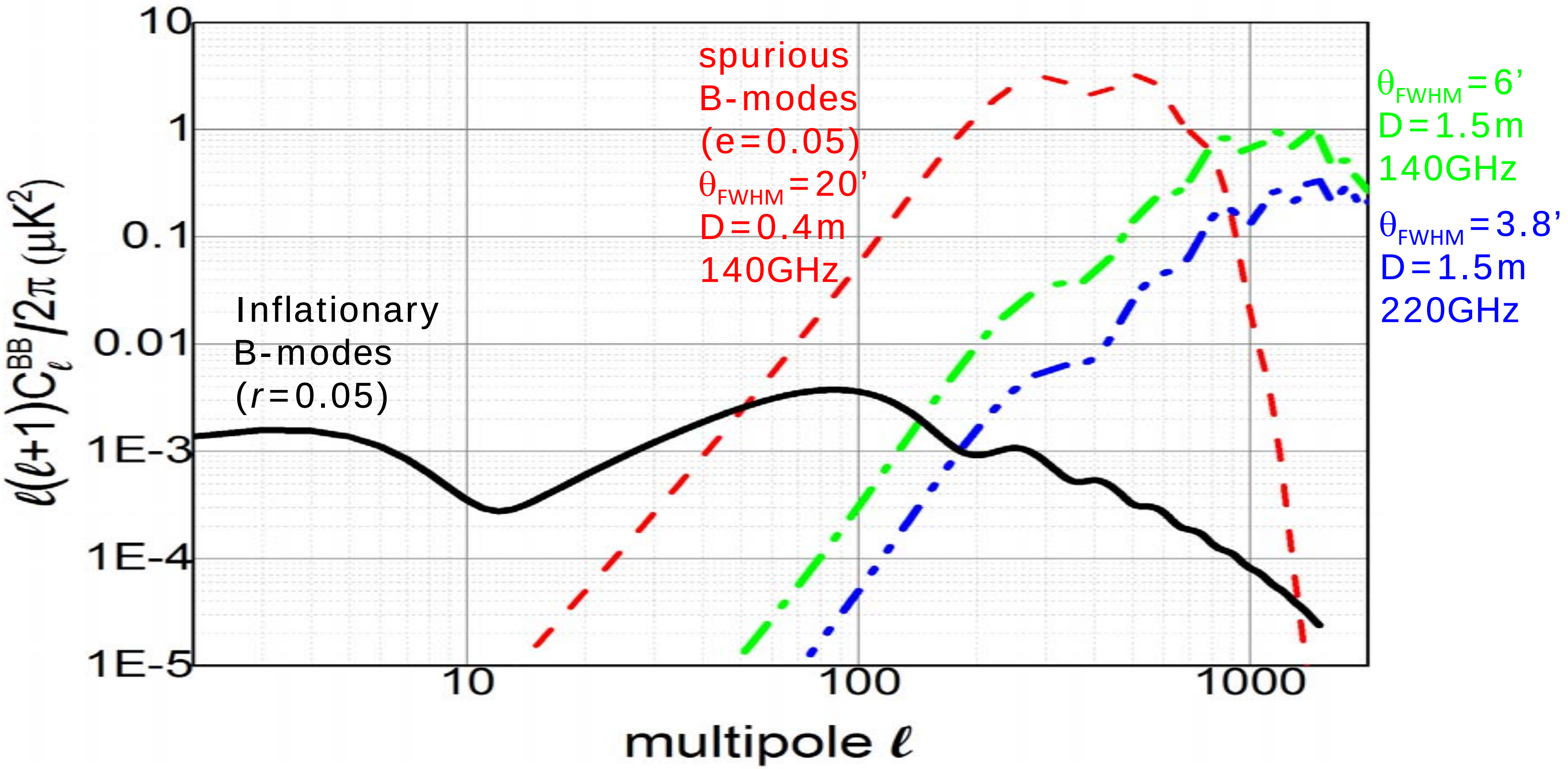
- The survey sensitivity (μK arcmin) depends on total integration time, number of detectors, noise of the detectors.
- Limit on *r* : depends on survey sensitivity, multipoles coverage, *and* lensing confusion (below 4.5μK arcmin the survey becomes lensing-limited).
- De-lensing efficiency depends on the angular resolution of the telescope :



- Requirements: ~ 2 μK arcmin *and* ~ 6' resolution in the CMB channels
- High resolution implies additional science results (SZ, neutrino masses etc.)

Beam ellipticity

- The ellipticity of the beam converts unpolarized CMB anisotropy into spurious polarization. The effect at large scales is mitigated for small beams:

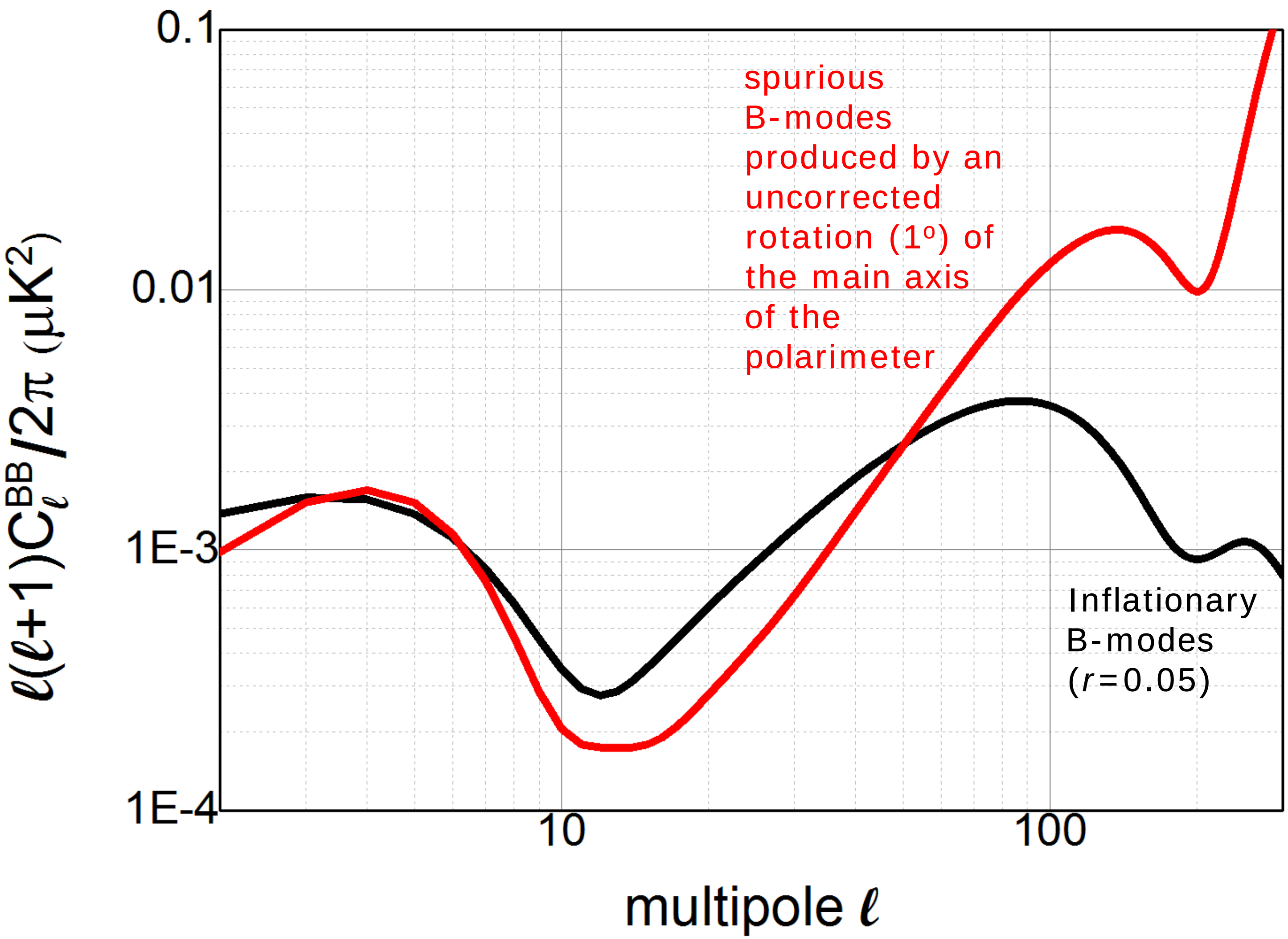


- For small apertures, a Half-Wave Plate is a must (e.g. LITEBIRD, D = 40 cm)

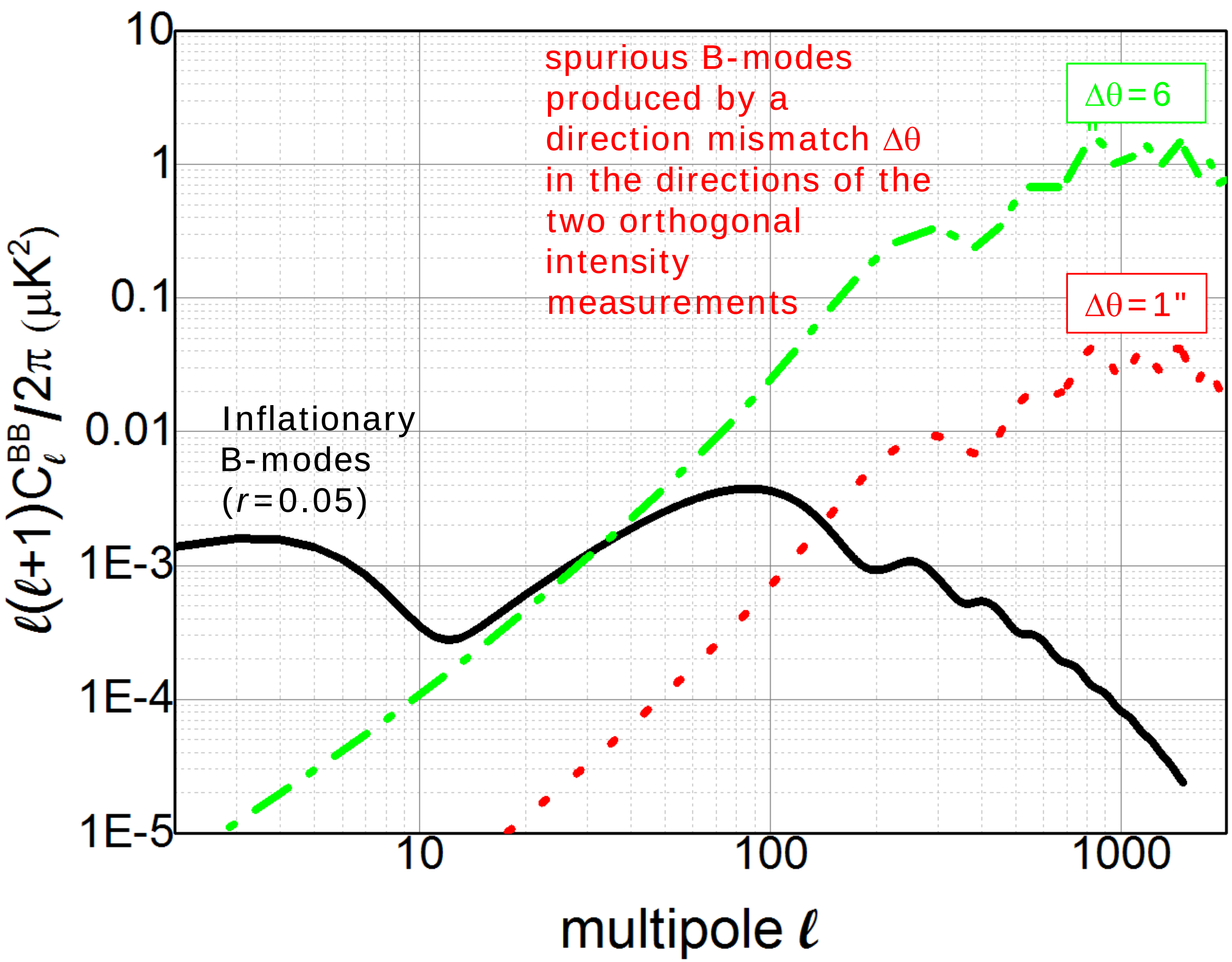
Additional considerations

- We want to detect CMB polarization with more than one channel (preferably 3 channels for cross-spectra, jackknives, comparisons), with enough sensitivity in each CMB channel individually. Long integration time and excellent stability needed.
- We will observe small signals embedded in many polarized local foregrounds and instrumental effects.
    - Need to increase the number of spectral channels above the number of components parameters
    - Need to increase the angular resolution to mask polarized compact sources (radio & IR)
- Very large scales will be hard to measure, since foregrounds increase at large scales. But detection of both the reionization and recombination bumps will be convincing.
- Systematic effects at very low level must be forecasted and monitored.

Systematics: focal plane rotation



Systematics: pointing errors



Mission / instrument implementation

Given all this, we need to implement an imaging polarimeter:

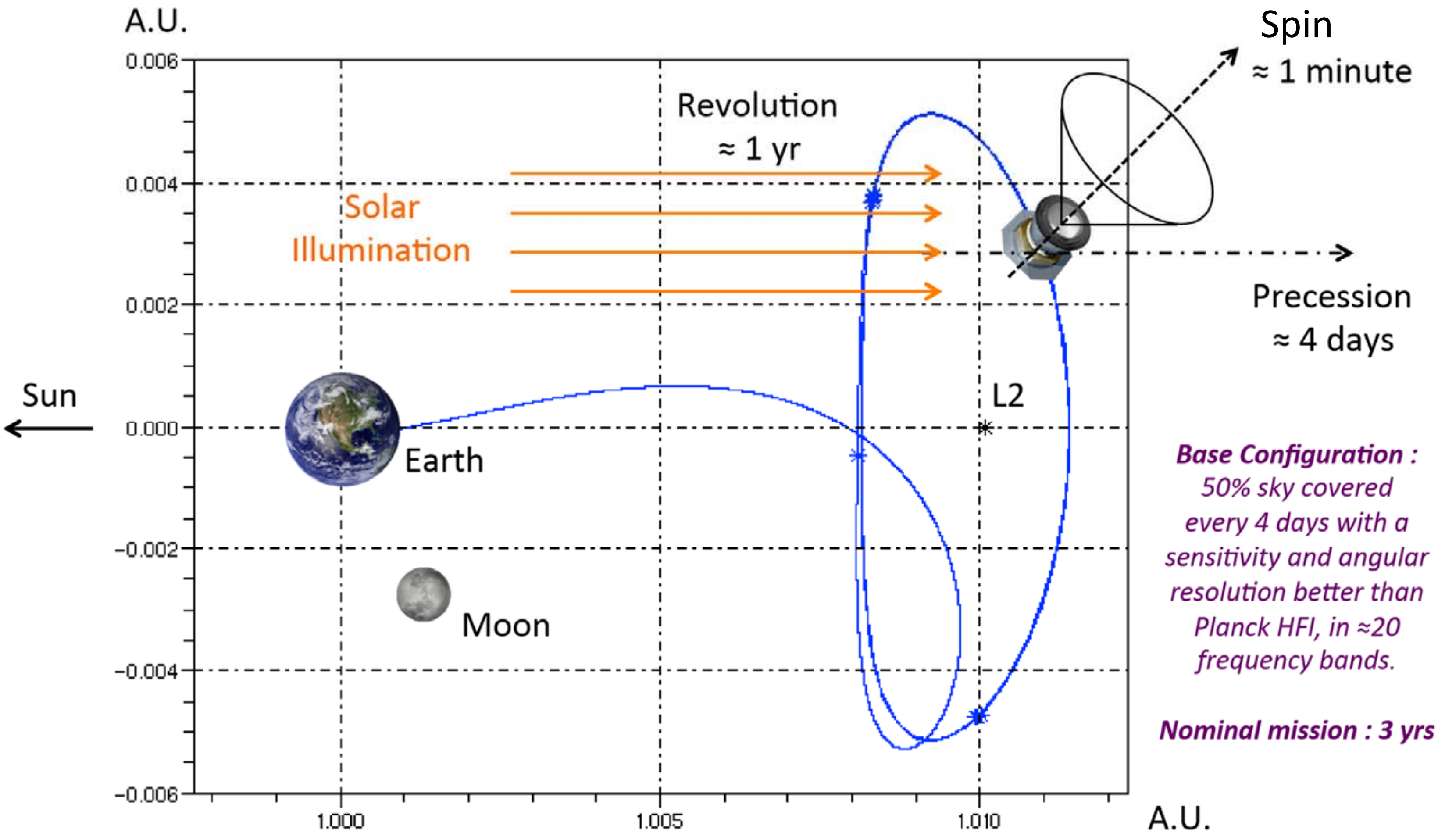
- With a cold (**< 60K**) telescope
- Aperture $\gtrsim$ **1.2m** (4.8'FWHM@220GHz)
- Covering a wide frequency range: **60 to 600 GHz**
- With a large number of single-mode photon-noise-limited detectors optimally distributed among different frequencies, but with several hundred detectors in the CMB bands (90-140-220 GHz). If wide band ($\Delta\lambda/\lambda$ **~ 0.5**), a total of **2000 detectors** will be needed for a survey sensitivity of **2 μK arcmin**.
- The sky survey will be long (**3yrs**) and thermal stability is a must (detectors: continuous dilution cooler at **100 mK**, no ADR; telescope: **passive cooling**)
- The satellite should operate in **L2** (as WMAP and Planck) with a **sky scan** strategy covering a large sky fraction in a short time (days) and observing the same sky pixel with very different orientations of the polarimeter.
- A **rotating HWP** should be **avoided**, to reduce complexity and cost, if at all possible.

Mission / instrument implementation

Performance / requirement	*Solution*
Resolve the CMB ≈ 4'-6' resolution or better	1.2 to 1.5m telescope or better ≈ 6-7' at 135 GHz; ≈ 4-5' 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 to 5000 detectors at ≈ 100 mK
Exquisite control of systematic effets for polarisation measurements	L2 orbit; Polarisation modulation by HWP or scanning strategy
Exquisite control/separation of polarised (and intensity) foregrounds	15-20 frequency bands (or more) covering ≈ 60-600 GHz (or more)

Mission / instrument implementation: scan strategy

The telescope and the polarimeter must be heavily shielded from solar radiation, and solar illumination angle depends on scan strategy.

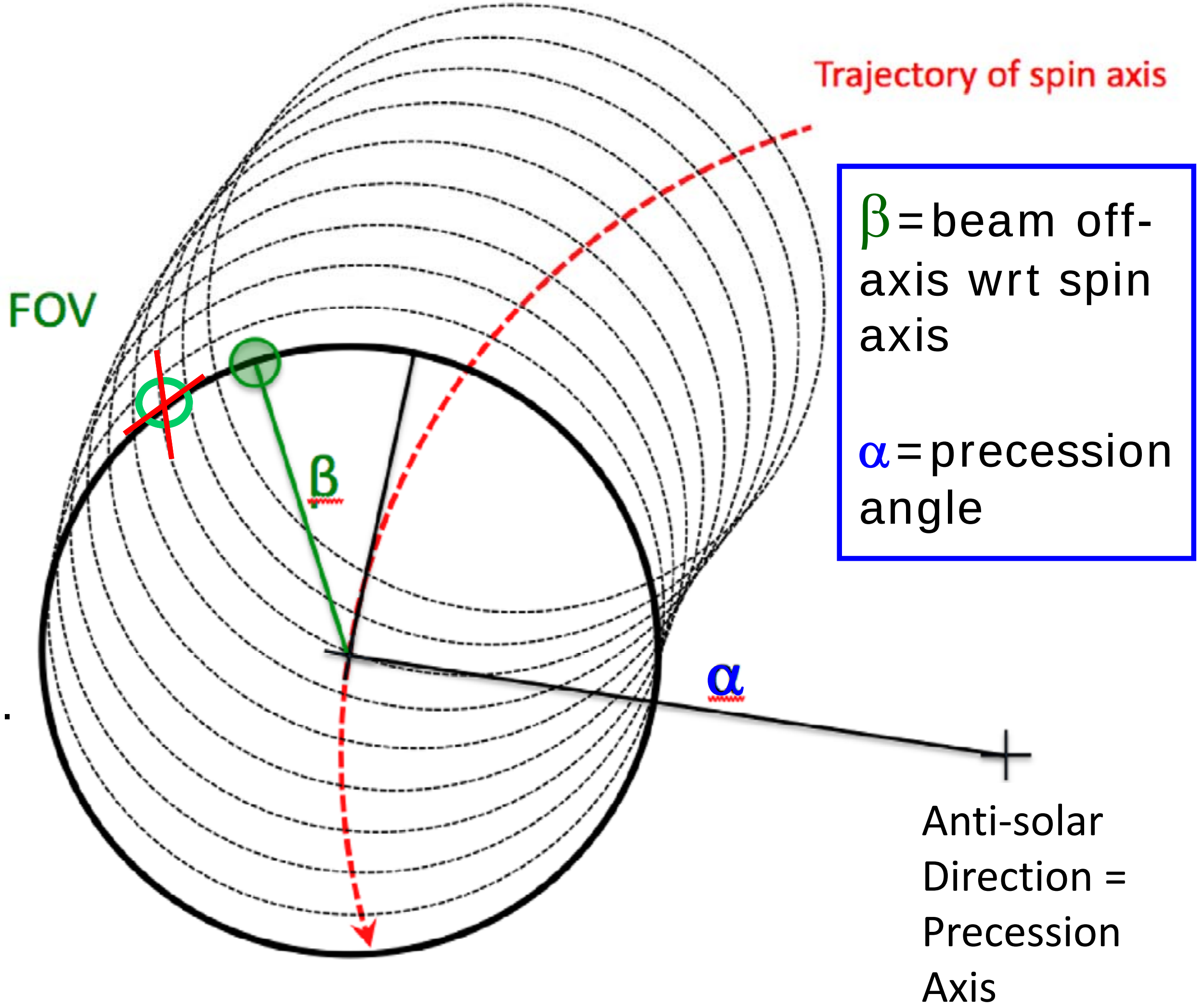


Base Configuration :
50% sky covered every 4 days with a sensitivity and angular resolution better than Planck HFI, in ≈20 frequency bands.

Nominal mission : 3 yrs

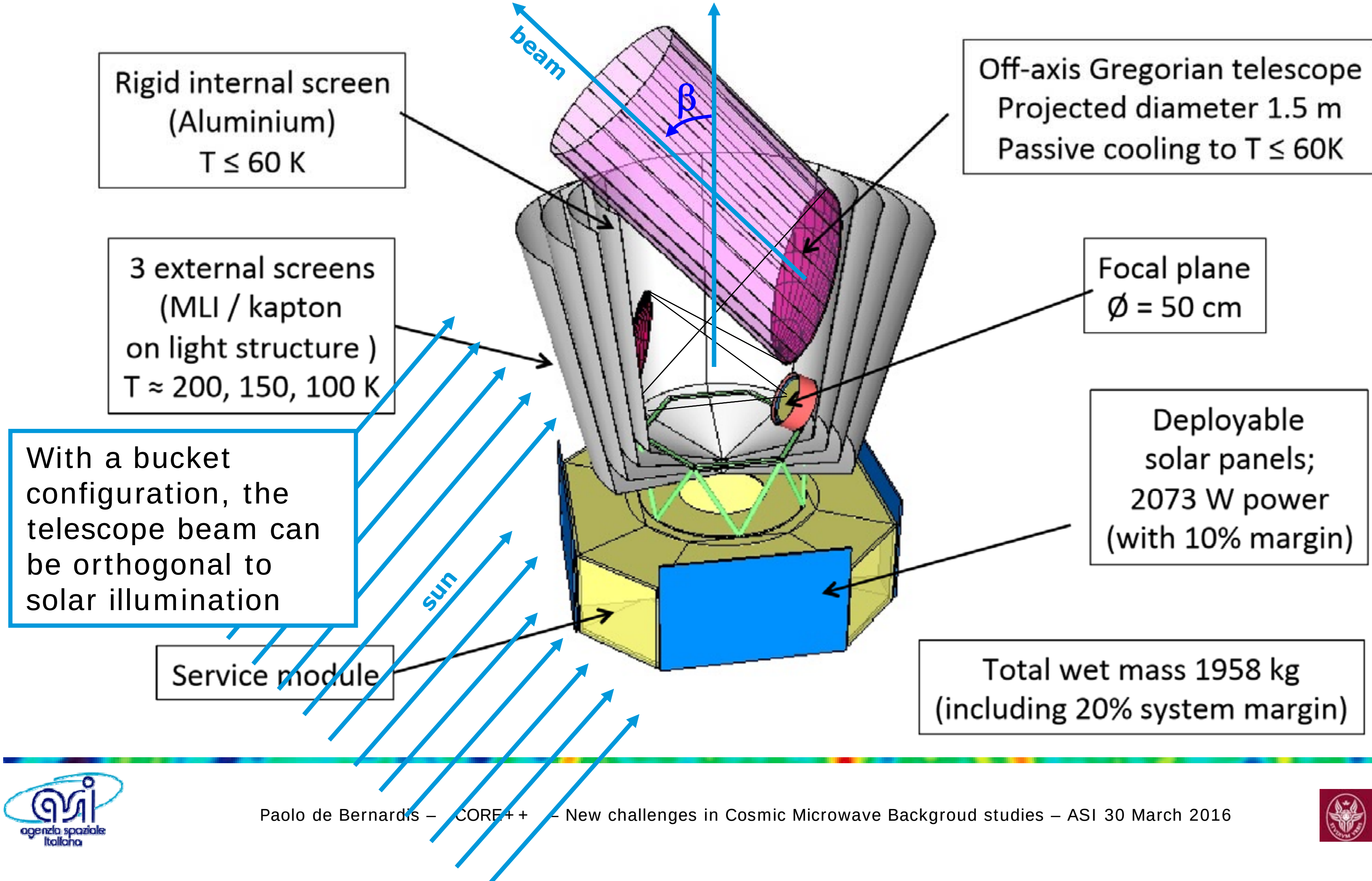
Mission / instrument implementation: scan strategy

- **Spin** (1 rpm) **+ Precession** (0.25 rpd)
- Advantage: with β far from 90^o every pixel is observed with a wide range of orientations of the polarimeter: necessary condition for avoiding the HWP.
- For full sky coverage $\alpha+\beta > 90°$.
- Baseline: $\alpha=\beta=45^o$. cfr: Planck $\beta=80^o$, $\alpha=0^o$.
- To be optimized during phase-A.
- Feasible with large flywheels (5-6).



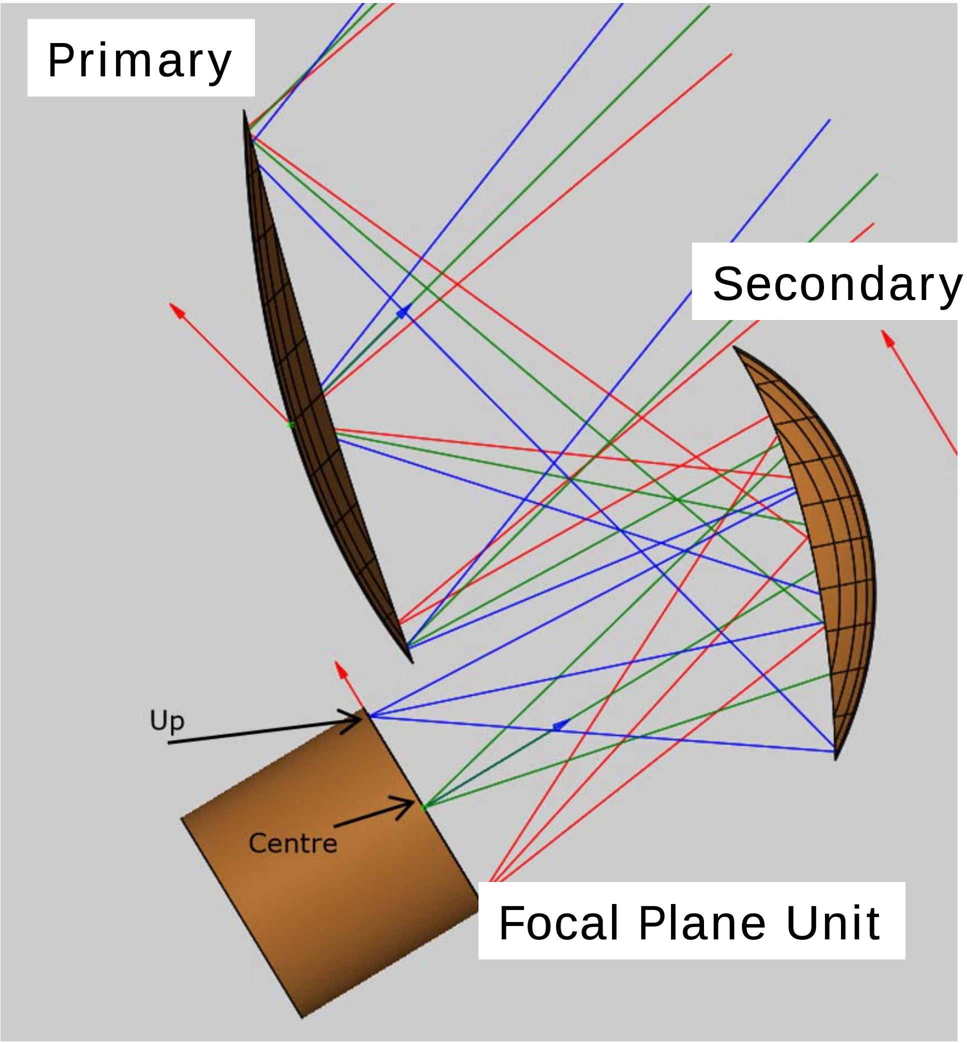
Mission / instrument implementation: shielding

The best way to cool the telescope and the instrument is to use passive cooling V-grooves. Wrt Planck (open V-grooves), β is smaller, and the solar illumination angle has a wider range, so V-grooves must have a «bucket» configuration:



Mission / instrument implementation: telescope

- Aperture: 1.2 – 1.5 m
- Optimized for wide focal plane and polarization purity.
- Considered configurations:
    - Cross-Dragone
    - Open-Dragone
    - Gregorian
- The Gregorian configuration offers the best combination of used volume in the bucket, wide polarization-pure focal plane, and control of straylight.



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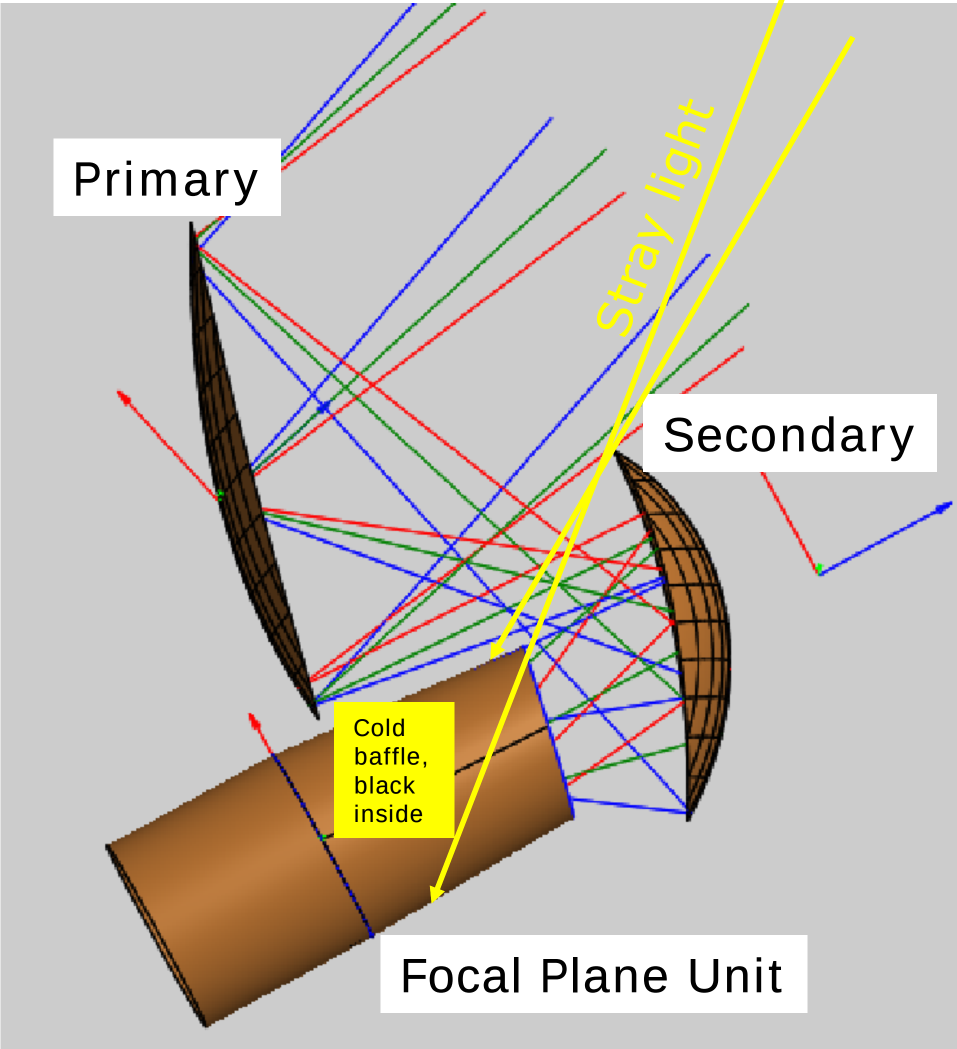
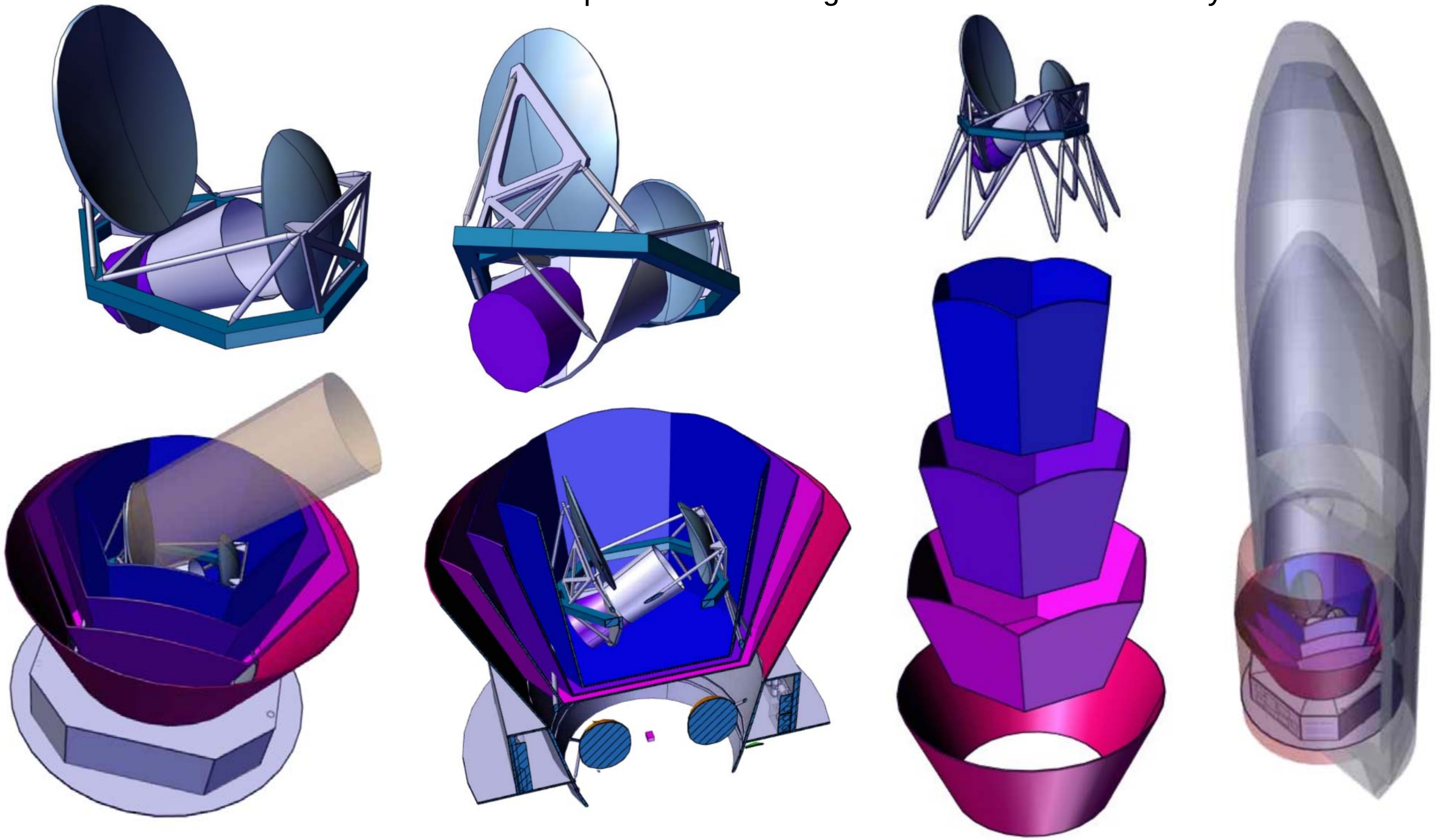


Mission / instrument implementation: telescope

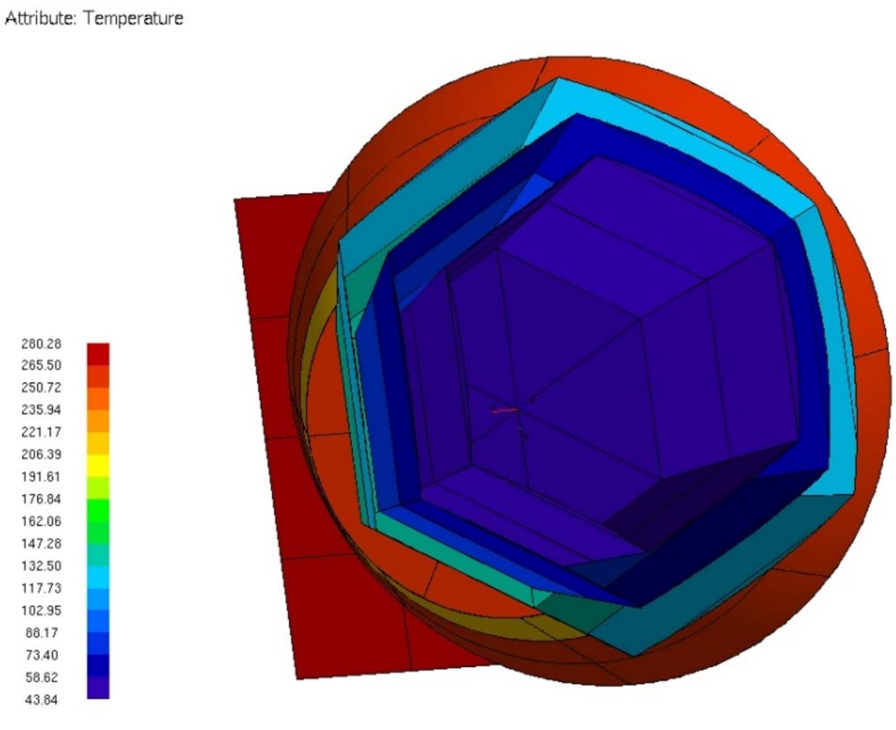
The telescope fits in the V-grooves and the assembly fits in the fairing

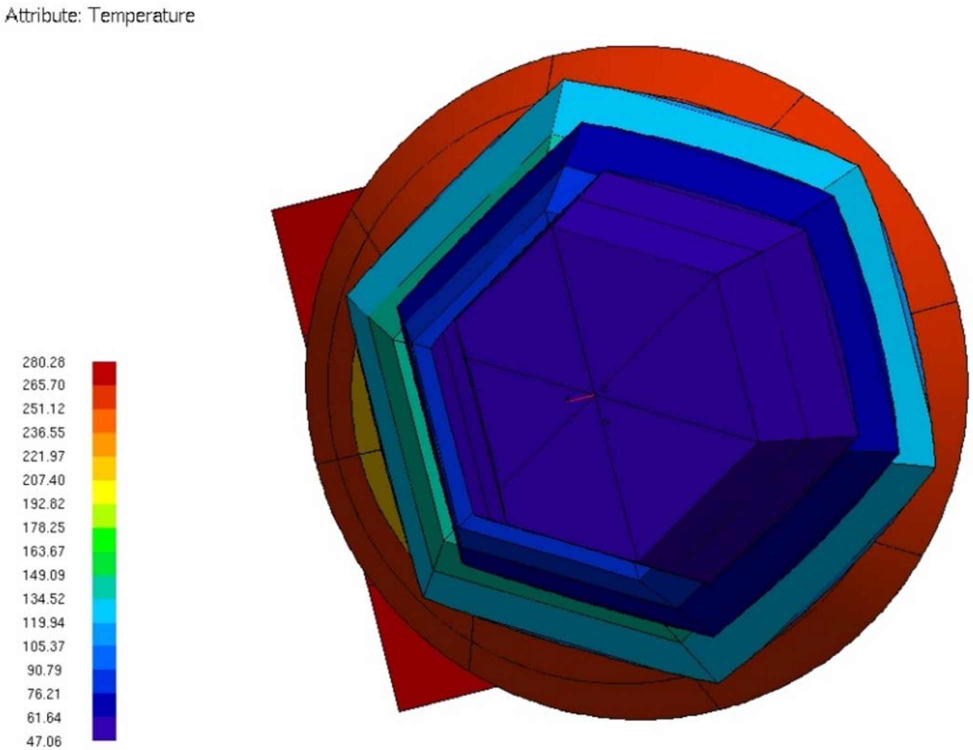


Images from ESA CDF study: «CMB B-modes polarization mission». To be published (April 2016).

Mission / instrument implementation: telescope

The bucket V-grooves radiatively cool the telescope assembly down to < 50K





Images from ESA CDF study: «CMB B-modes polarization mission». To be published (April 2016).

HWP / no HWP tradeoff

Two purposes for the HWP:

1. Move the signal bandwidth above the 1/f noise knee of detectors
2. Modulate polarization so that beam ellipticity and other systematic are mitigated.

M4 approach: No HWP, no mechanisms, wider bandwidths and frequency coverage, no HWP-related systematic effects.

Solve 1. and 2. in the post-processing:

1. Can be solved with good detectors (1/f knee < 0.1Hz) and proper decorrelation/destriping.
2. Can be solved if the aperture of the telescope is large, i.e. the beams are much smaller than the large-scale where B-modes are to be detected.

Mission / instrument implementation: focal plane

- M4 proposal baseline: **horns-coupled** focal plane.
  - Main advantages: high TRL, consolidated technology; clean definition of bolometer FOV and edge-taper on reflectors; reduction of straylight; polarization clean
  - Main disadvantages: high cost, high mass@100mK
  - Recent developments (in Europe):
    - 3D-printed horns in plastic material, metal coated (for low freq. bands)
    - Planar lenses arrays (EAS-ITT study ITT AO/1-7393/12/NL/MH)
- Alternative: **Filled-array** focal plane.
  - Main advantages: Fabrication simplicity; reduced cost; low mass@100mK.
  - Main disadvantages: Nyquist sampling of Airy disk requires 4x sensors and lower detector NEP; requires cold stop in optical system and cold (< 1K) BB box surrounding the focal plane to reduce stray-light and loading.

Mission / instrument implementation: focal plane

channel GHz	beam arcmin	N_{det}	ΔT μK.arcmin	ΔP μK.arcmin	ΔI kJy/sr.arcmin	$\Delta y \times 10^6$ y_{SZ}.arcmin	PS flux (5σ) mJy
60	14	28	11.3	16	1.14	-2.3	6
70	12	30	10.5	14.9	1.4	-2.2	6.3
80	10.5	38	9.1	12.9	1.53	-2.0	6
90	9.33	72	6.5	9.2	1.32	-1.5	4.6
100	8.4	84	6.0	8.5	1.43	-1.5	4.5
115	7.3	124	5.0	7.0	1.45	-1.3	4
130	6.46	180	4.2	5.9	1.43	-1.3	3.5
145	5.79	264	3.6	5.0	1.37	-1.3	3
160	5.25	254	3.8	5.4	1.6	-1.7	3.1
175	4.8	290	3.8	5.3	1.69	-2.2	3.0
195	4.31	346	3.8	5.3	1.79	-4.1	2.9
220	3.82	200	5.8	8.1	2.78	-	4.0
255	3.29	140	8.9	12.6	4.11	5.5	5.1
295	2.85	60	19.4	27.4	7.84	5.7	8.4
340	2.47	60	30.9	43.7	9.91	5.6	9.2
390	2.15	60	55.0	77.8	12.63	7.0	10.2
450	1.87	60	116.6	164.8	16.48	10.9	11.5
520	1.62	60	295.7	418.2	21.71	21.0	13.2
600	1.4	60	899.7	1272.4	28.61	50.3	15.0

CMB channels

Table 3: Proposed *COrE+* frequency channels. The sensitivity is calculated assuming $\Delta\nu/\nu = 25\%$ bandwidth, 50% optical efficiency, total noise of twice the expected photon noise from the sky and the optics of the instrument at 60K temperature. The aggregated CMB sensitivity is 2 μK.arcmin in polarization. This is the *COrE+* baseline configuration, based on single-frequency, dual polarization detectors (Sec. 3.4).

Mission / instrument implementation: focal plane

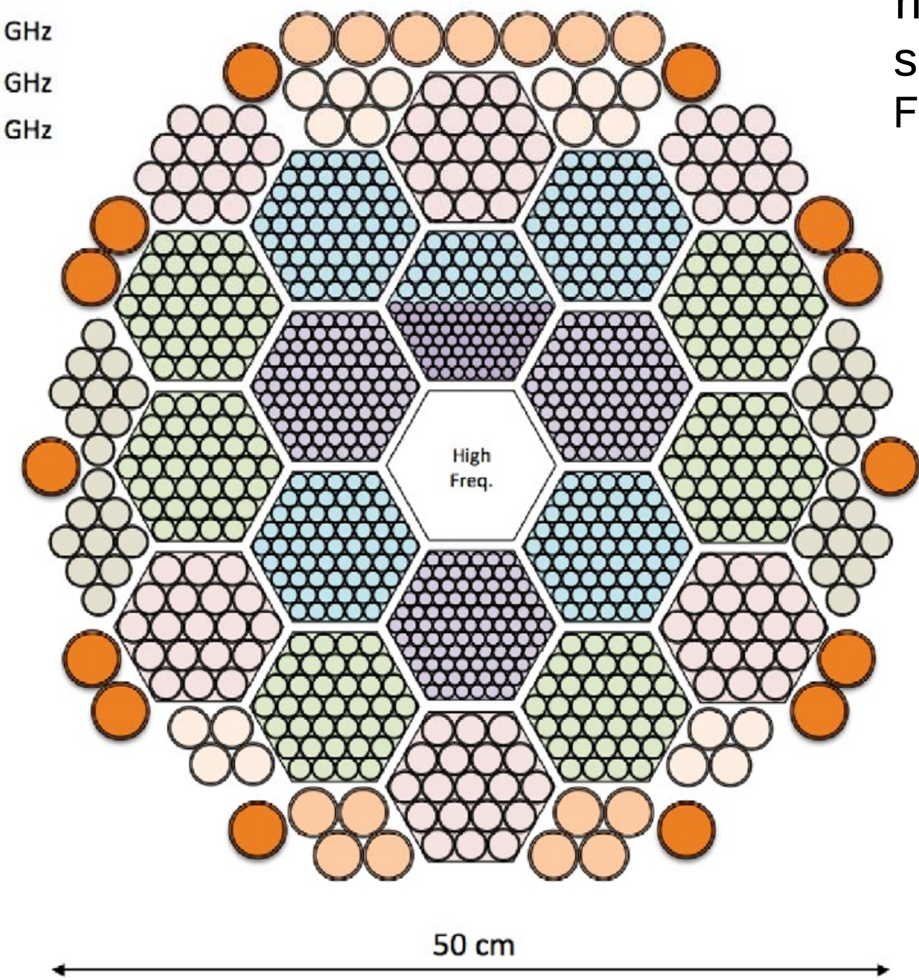
horn-horn spacing = 3Fλ
F/#=2

- 60 GHz
- 70 GHz
- 80 GHz
- 90 GHz
- 100 or 115 GHz
- 130 or 145 GHz
- 160 or 175 GHz
- 195 or 220 GHz
- 255 GHz

ν	$N_{det\ single}$
60	28
70	30
80	36
90	72
100	84
115	124
130	180
145	264
160	254
175	290
195	346
220	200
255	140
295	60
340	60
390	60
450	60
520	60
600	60
700	
800	

Dual polarization, single f pixels

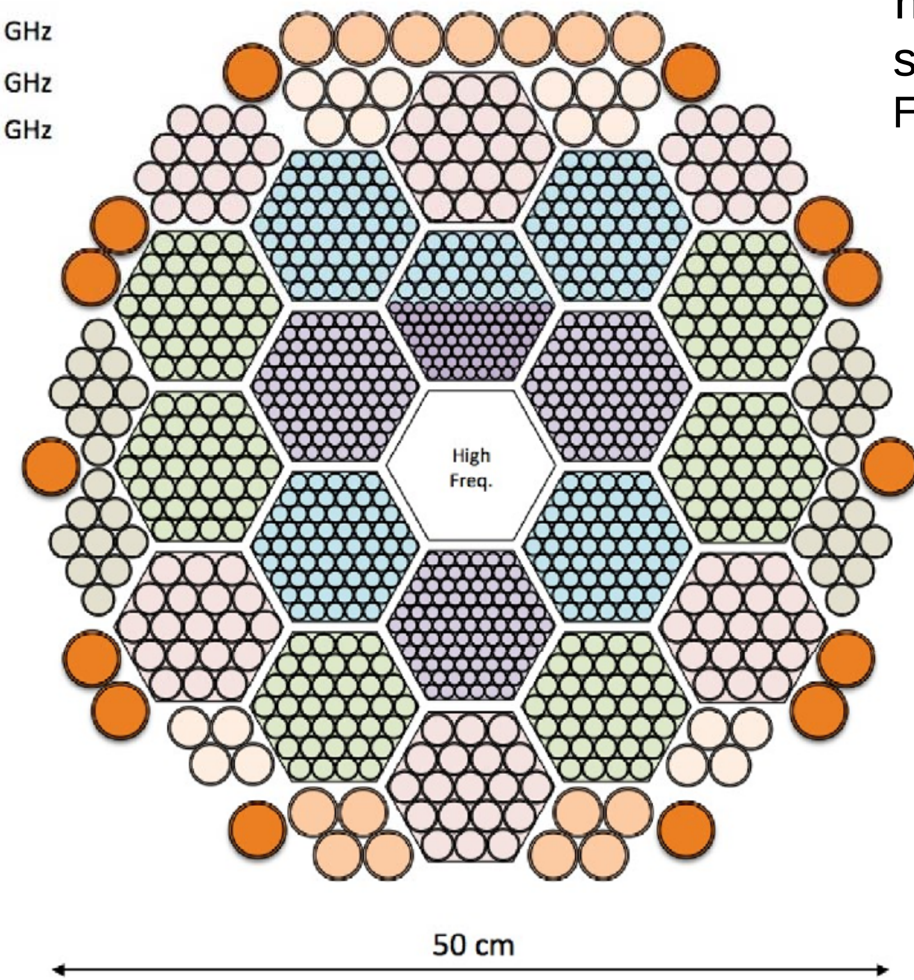
2408



ν	$N_{det\ dual}$
60	28
70	30
80	64
90	102
100	120
115	196
130	264
145	388
160	434
175	554
195	600
220	490
255	486
295	260
340	200
390	120
450	120
520	120
600	120
700	60
800	60

4816

Dual polarization dichroic pixels



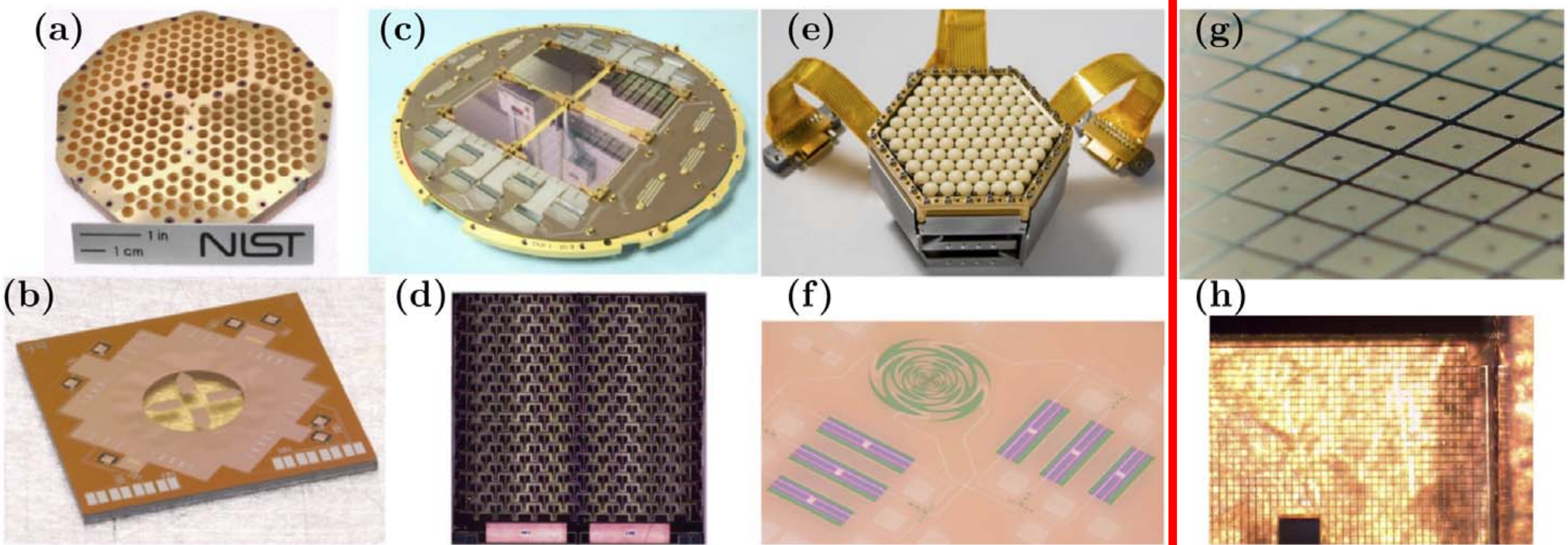
horn-horn spacing = 3Fλ

F/#=2

focal plane: European detectors for CMB

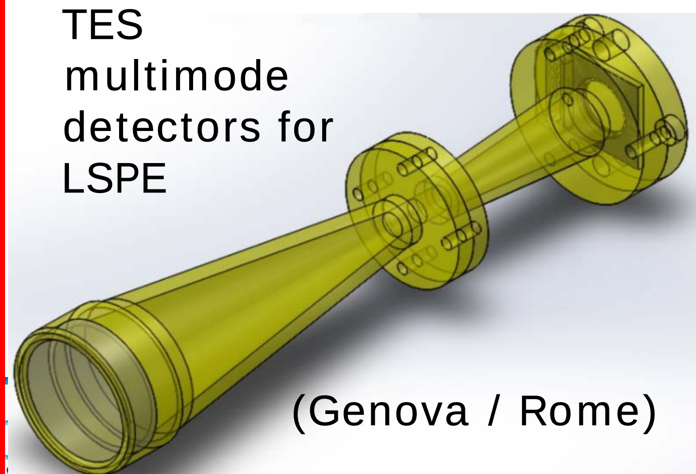
- **TES**
  - Developed in Europe in Paris, Cambridge, Genova …
  - European MUX tecnology demonstrated in the lab (128:1, QUBIC)
  - Single-mode TES successfully operated at telescopes (SPT, ACT, BICEP, ….) and flown on balloons (EBEX, SPIDER) by US teams
  - European multimode TES to be flown on a balloon with LSPE (ASI)
- **KID**
  - Developed in Europe in Grenoble, Groningen, Cambridge, Rome, ….
  - Operation down to 60-80 GHz demostrated (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 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.

focal plane: European detectors for CMB: TES

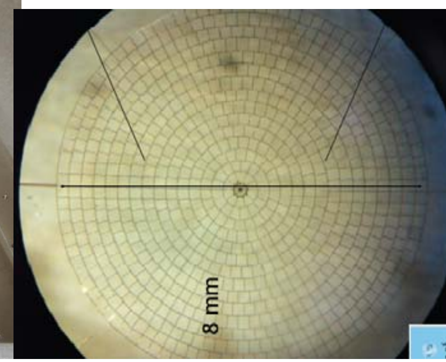


TES detectors for QUBIC (Paris)

TES multimode detectors for LSPE



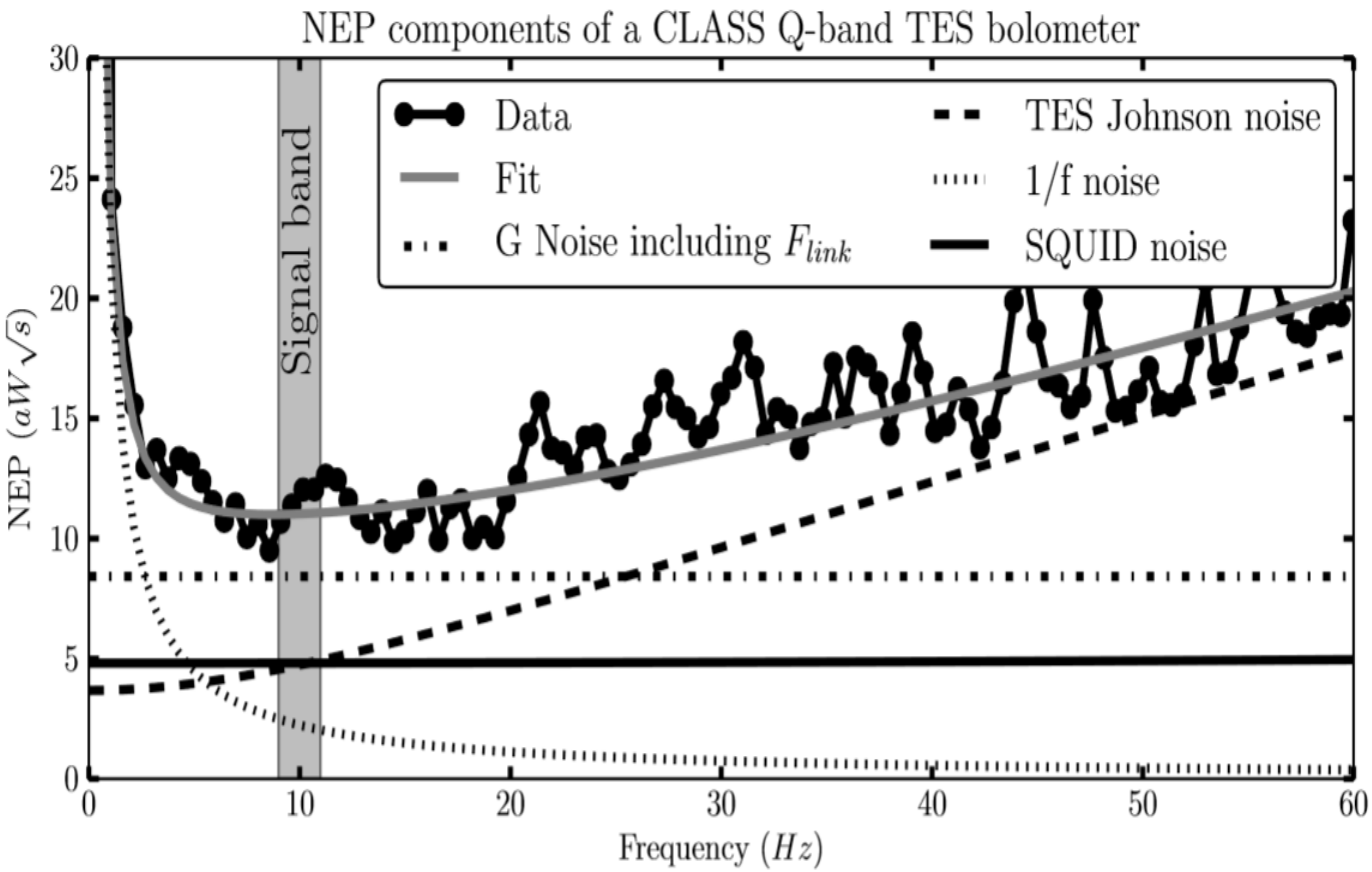
(Genova / Rome)



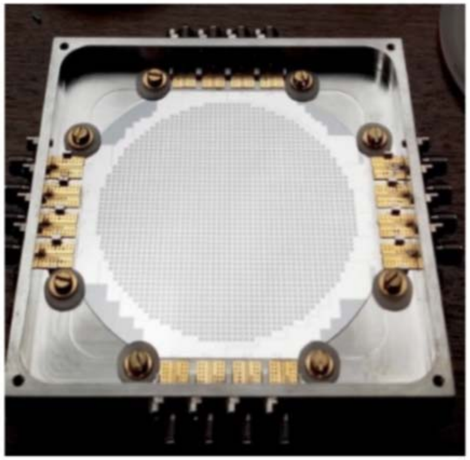
focal plane: European detectors for CMB: TES

Frequency coverage:

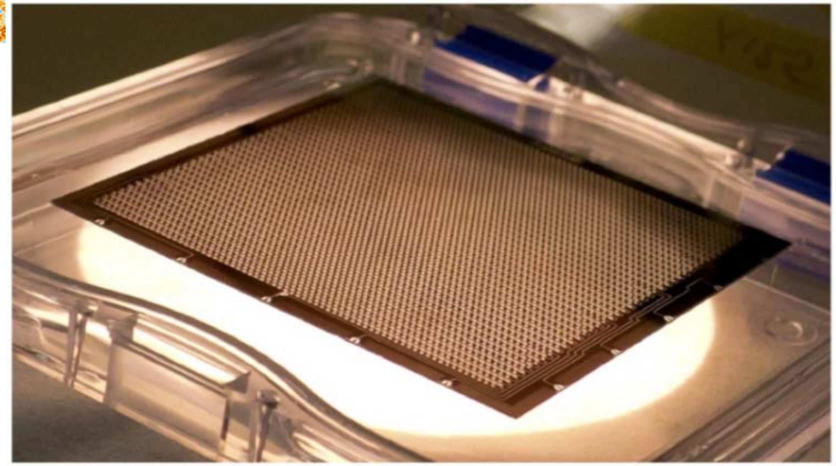
Down to 40 GHz : CLASS, see astro-ph/1408.4789



focal plane: European detectors for CMB: KIDs

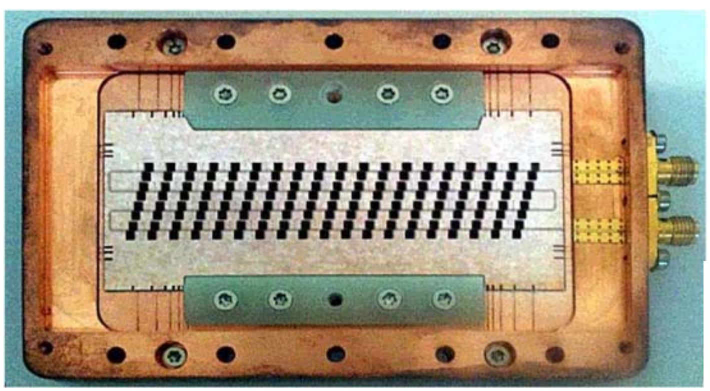


NIKA2 array 200-300 GHz
(Grenoble) -> IRAM30m

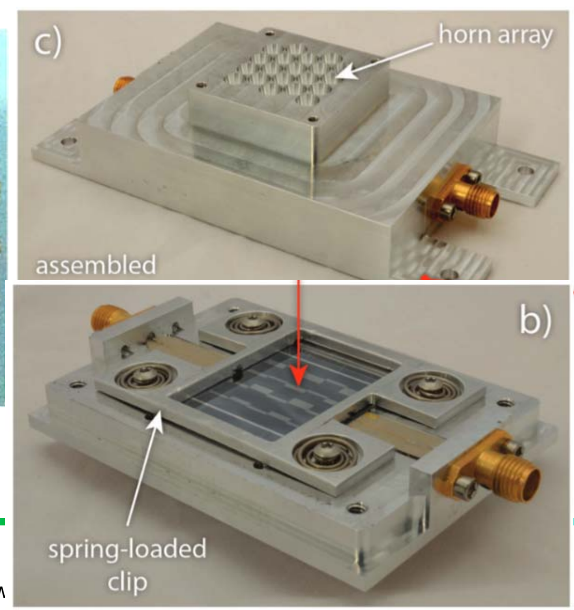


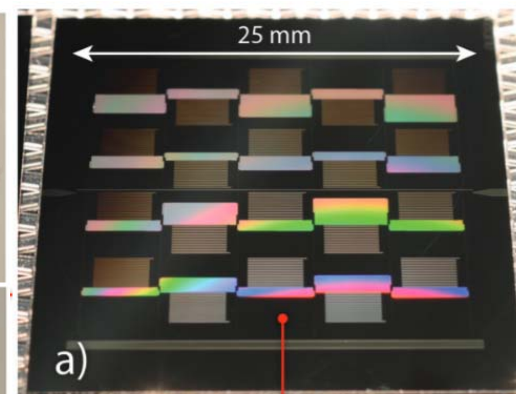
AMKID array - submm
(Groningen) -> APEX ALMA

LEKID for 150 GHz
(Rome)



THz camera for safety scanner
(Cardiff)





Horn-coupled KIDs for CMB
(Cardiff + ASU)

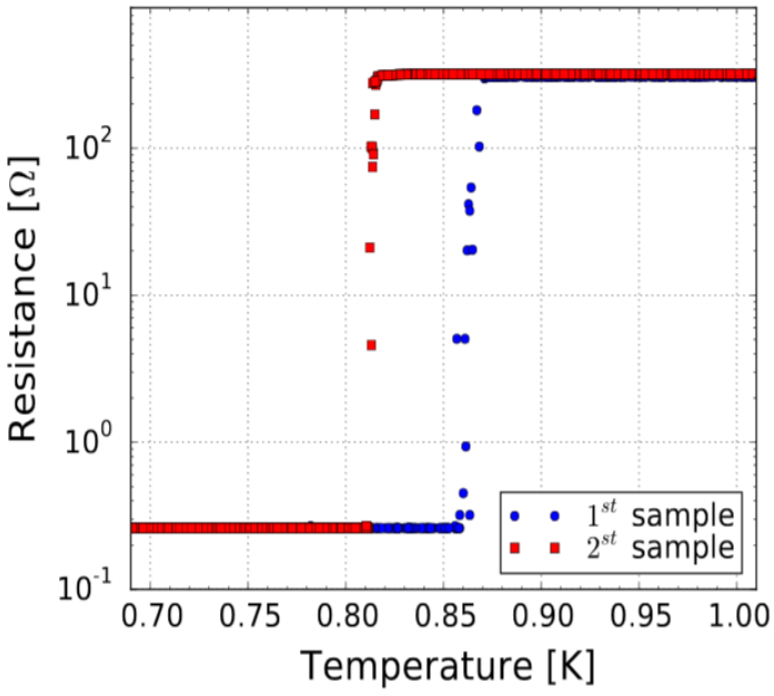
focal plane: European detectors for CMB: KIDs

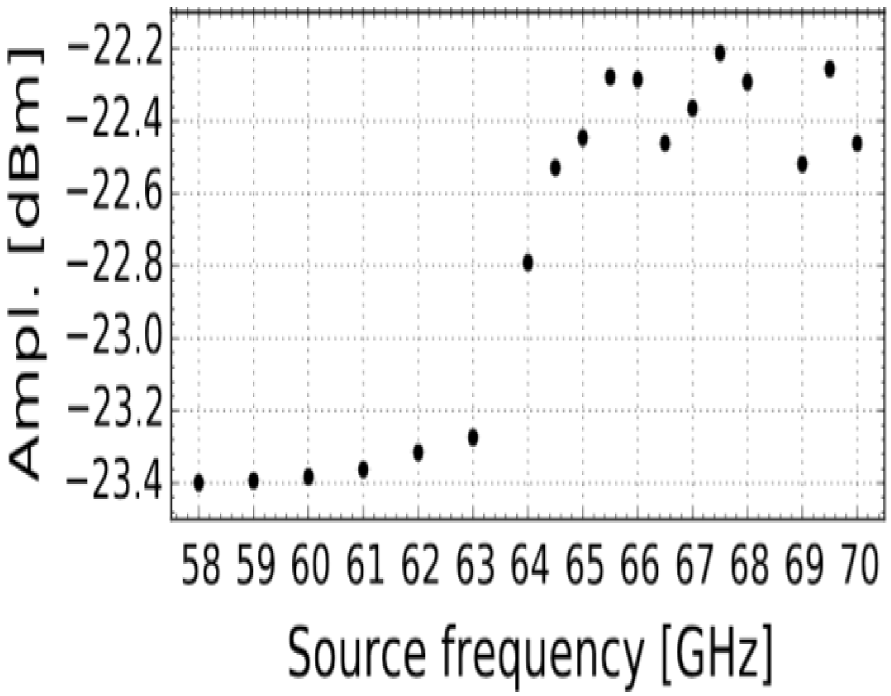
Low-f operation of KIDs demonstrated:

- Catalano et al. A&A 580, A15 (2015)
- Paiella et al. Astro-ph/1601.01466

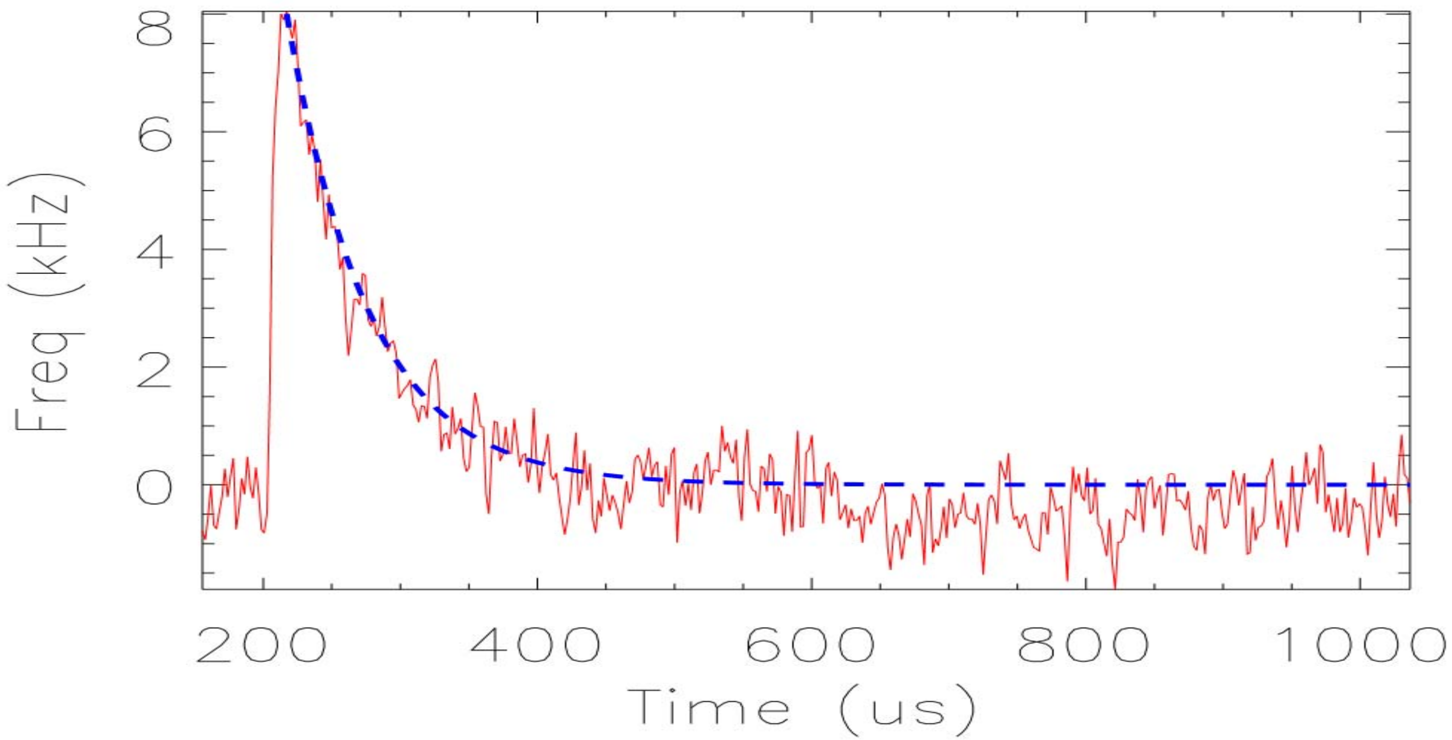
Al-Ti

f > 65 GHz



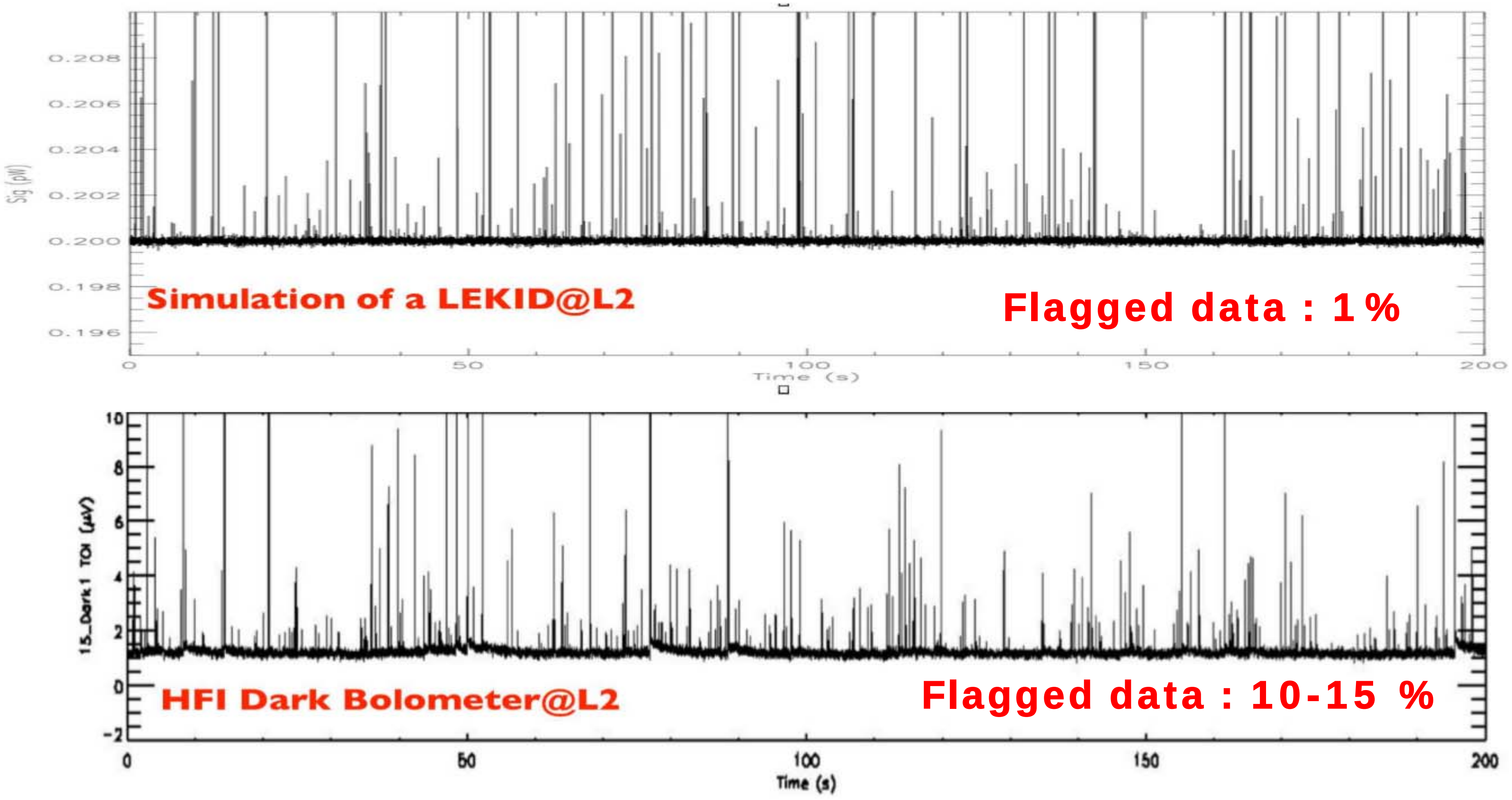


focal plane: European detectors for CMB: KIDs



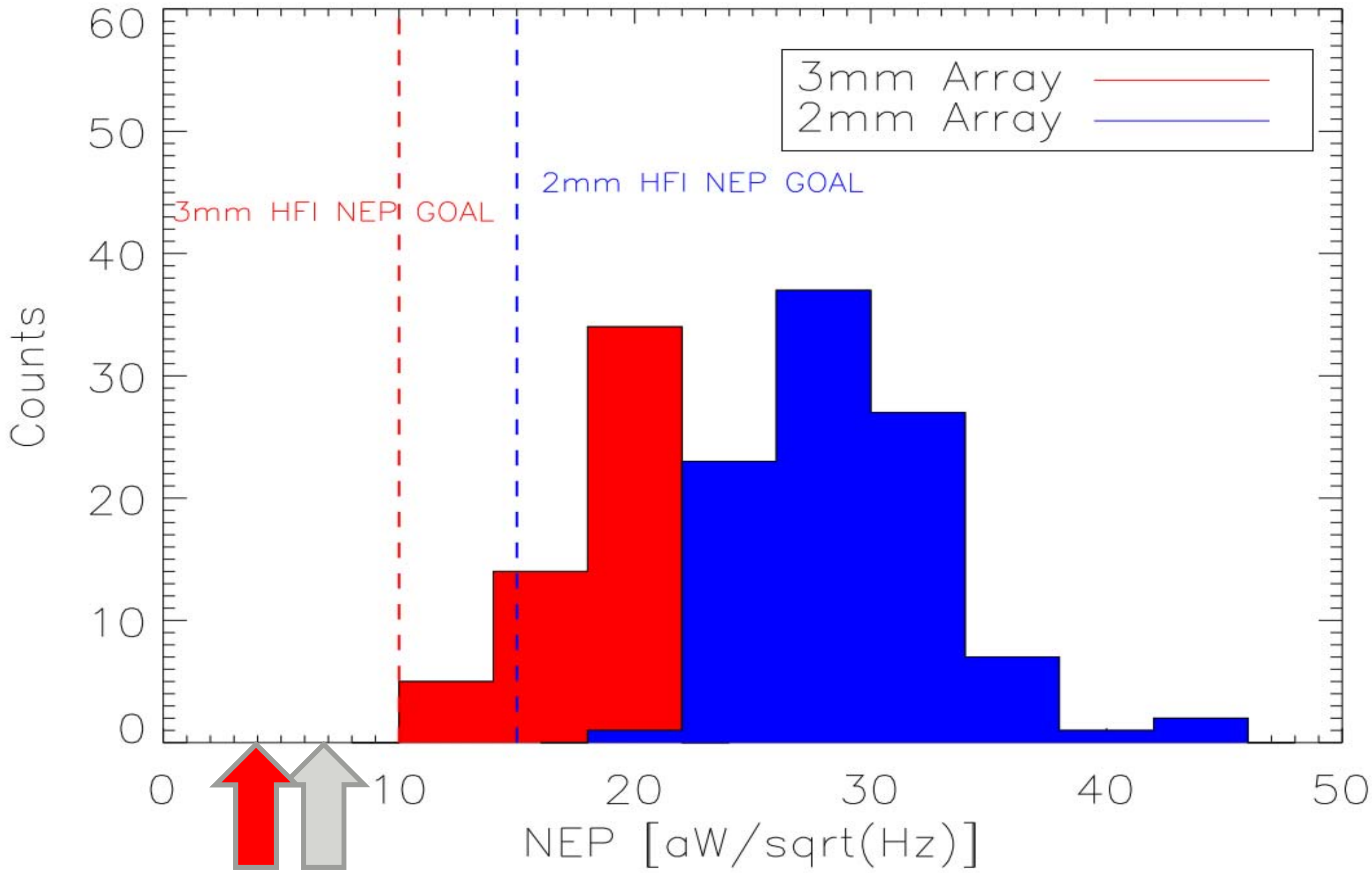
Catalano et al. Astro-ph/1511.02652

focal plane: European detectors for CMB: KIDs



Catalano et al. Astro-ph/1511.02652

focal plane: European detectors for CMB: KIDs



Requirement for COrE+ (filled array)

Requirement for COrE+ (horns-based)

Catalano et al. Astro-ph/1511.02652

cryo chain

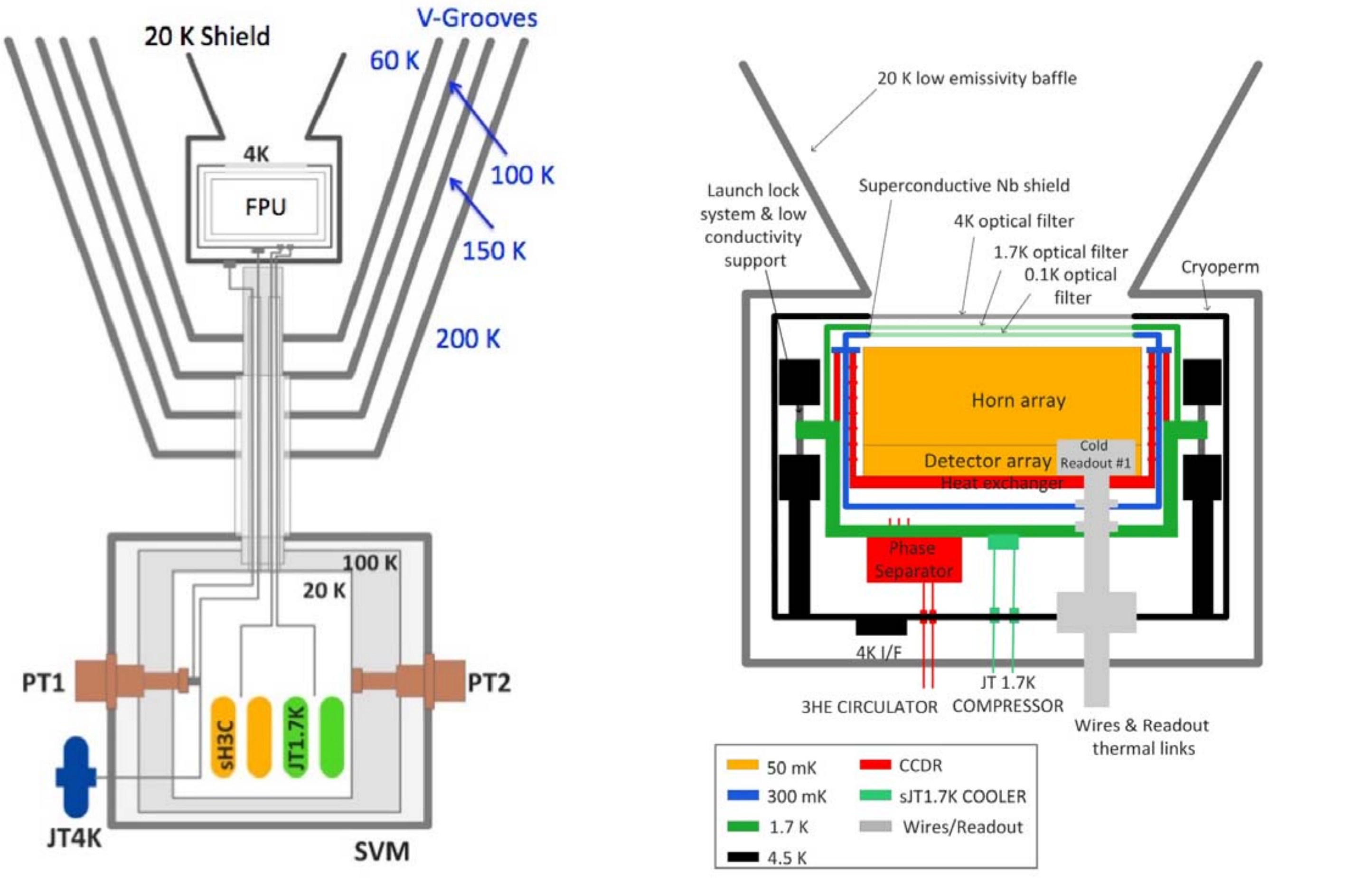
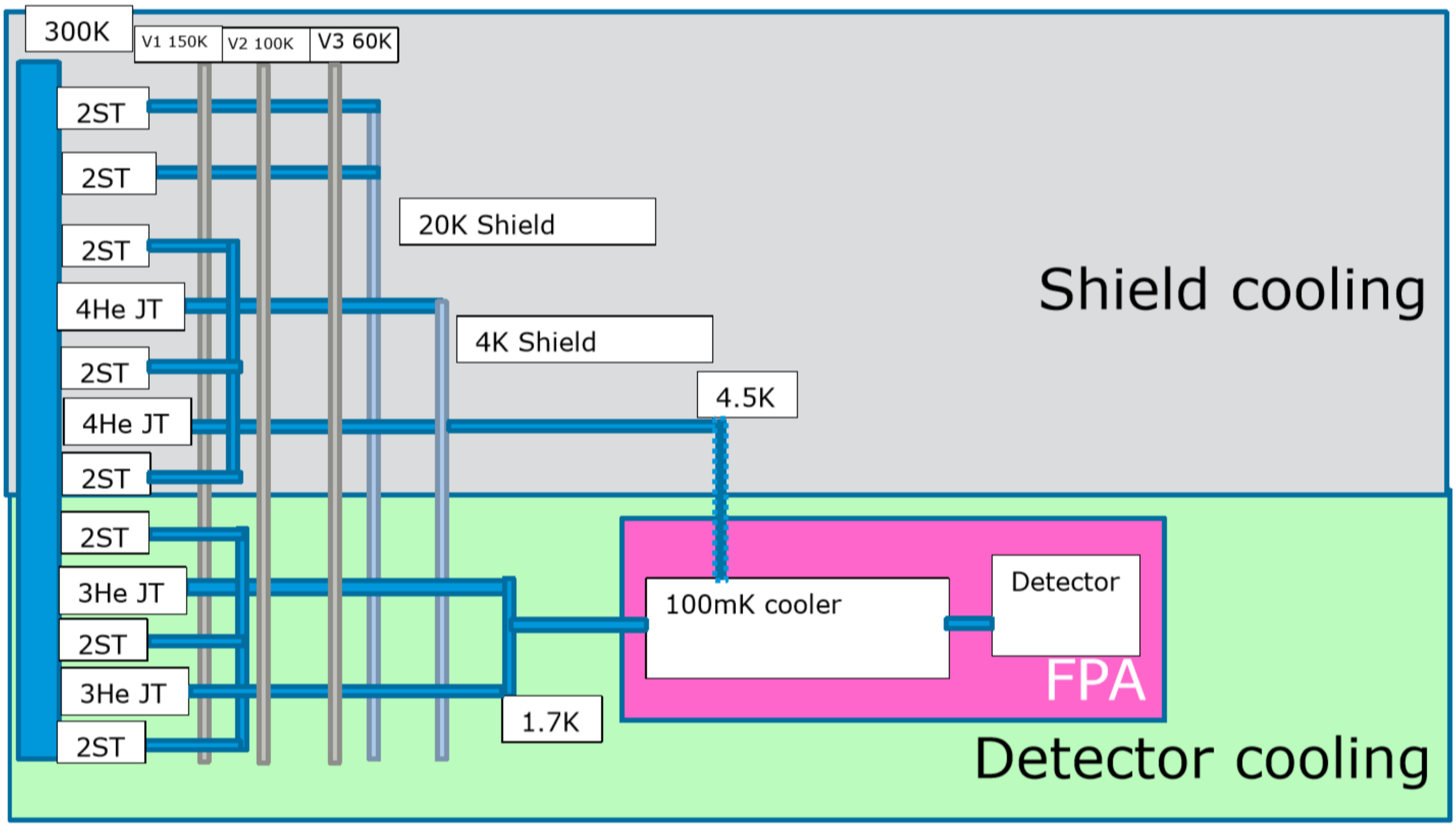


Figure 14: Left: cooling chain overview. Right: side view of the 4 K box and the FPU.

Progress with this design and synergies with ATHENA - Gerard Vermeulen (inst. Néel, Grenoble)

cryo chain



Martin Linder (ESA)

Image from ESA CDF study: «CMB B-modes polarization mission». To be published (April 2016).

Preliminary budgets

- Wet Mass: 2185 kg
- Volume: diameter 4m, h=4.5m
- Momentum: 420 Nms
- Δv: 131 m/s for large amplitude Lissajous orbit around L2
- Power: 1970 W (requires hinged solar panels)
- Communications: 200 Gb/day (K-band, 20 cm derotated antenna)

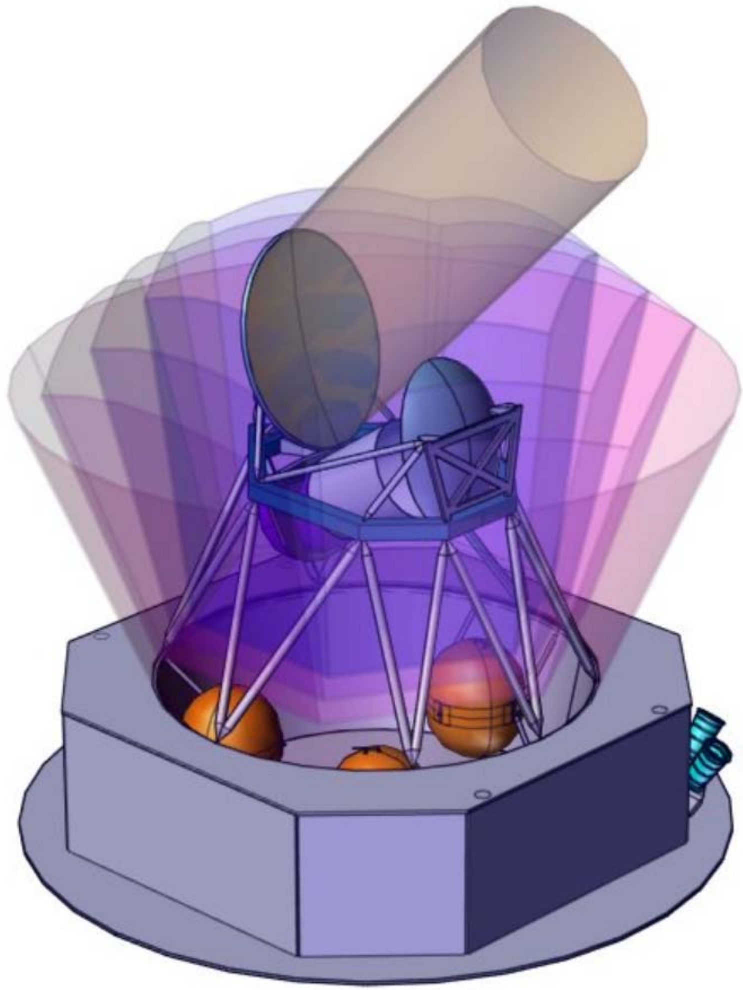


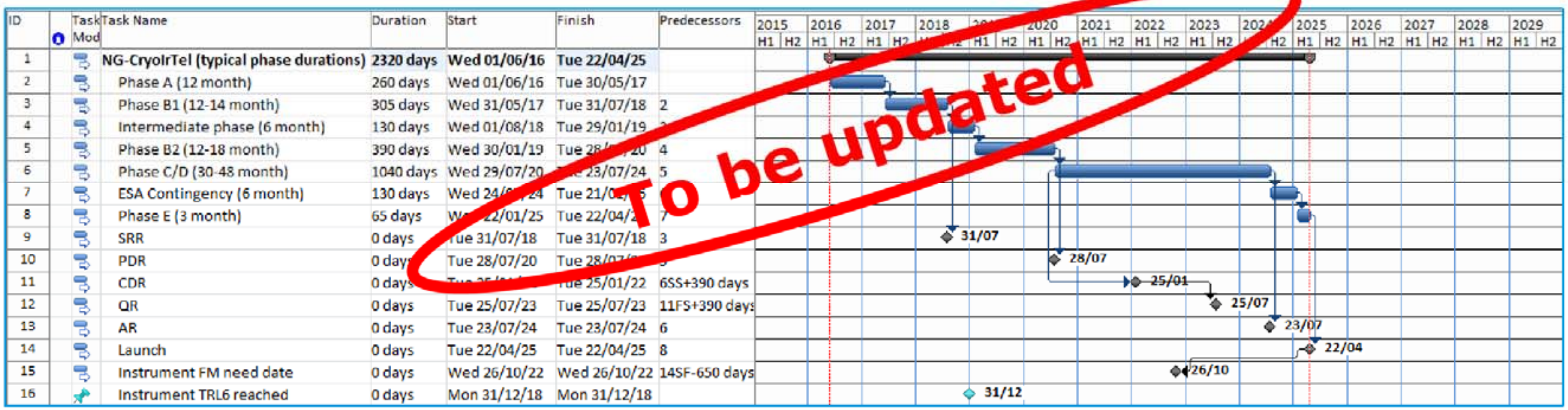
Image from ESA CDF study: «CMB B-modes polarization mission». To be published (April 2016).

COrE++ : Programmatics (very preliminary !)

MODELS:
- Structural Model
- Cryogenic Qualification Model (CQM)
- P/L QM, with a full structure (as for Planck)
- SVM dummy with fittings for the PLM coolers and "PLM warm units“, to be used for the cryogenic test qualifying the chain of cryo stages
- SVM Avionics Model (AVM)
- Protoflight Model (PFM) – New, no refurbishment from other models
- RFQM (refurbished CQM)
- Mirror models: – QM, SM and FM: QM for the CQM and then the RFQM
- Flight spares

INTEGRATION AND VERIFICATION:
(Based on Planck approach)
- Cryogenic tests in CSL
- Optical test in CSL
- Videogrammetry test in LSS
- Spin test in LSS
- PFM TB/TB

SCHEDULE:



ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**NG-CryoIrTel (typical phase durations)**	**2320 days**	**Wed 01/06/16**	**Tue 22/04/25**	
2		Phase A (12 month)	260 days	Wed 01/06/16	Tue 30/05/17	
3		Phase B1 (12-14 month)	305 days	Wed 31/05/17	Tue 31/07/18	2
4		Intermediate phase (6 month)	130 days	Wed 01/08/18	Tue 29/01/19	[illegible]
5		Phase B2 (12-18 month)	390 days	Wed 30/01/19	Tue 28/[illegible]/20	4
6		Phase C/D (30-48 month)	1040 days	Wed 29/07/20	[illegible] 23/07/24	5
7		ESA Contingency (6 month)	130 days	Wed 24/[illegible]/24	Tue 21/[illegible]	[illegible]
8		Phase E (3 month)	65 days	W[illegible] 22/01/25	Tue 22/04/2[illegible]	7
9		SRR	0 days	[illegible]ue 31/07/18	Tue 31/07/18	3
10		PDR	0 day[illegible]	Tue 28/07/20	Tue 28/[illegible]	[illegible]
11		CDR	0 day[illegible]	[illegible]	[illegible]ue 25/01/22	6SS+390 days
12		QR	0 days	Tue 25/07/23	Tue 25/07/23	11FS+390 days
13		AR	0 days	Tue 23/07/24	Tue 23/07/24	6
14		Launch	0 days	Tue 22/04/25	Tue 22/04/25	8
15		Instrument FM need date	0 days	Wed 26/10/22	Wed 26/10/22	14SF-650 days
16		Instrument TRL6 reached	0 days	Mon 31/12/18	Mon 31/12/18	

Image from ESA CDF study: «CMB B-modes polarization mission». To be published (April 2016).

COrE++ : Conclusion

1. A space mission for CMB polarization like CORE++ is the only way to obtain a reliable detection of B-modes. This cannot be done from the ground only.
2. This mission promises outstanding results for cosmology and fundamental physics, and an extremely rich legacy of data for Astrophysics.
3. The mission is technically feasible with current European technology and scientific competence, and within the timeframe 2025-2030.
4. This mission is expensive, and proper support from ESA member states and other partners is mandatory to fit within the budget of M5.
5. The Italian community can have a leading role, but support is required to keep it alive and well.