LiteBIRD as a unique opportunity for CMB

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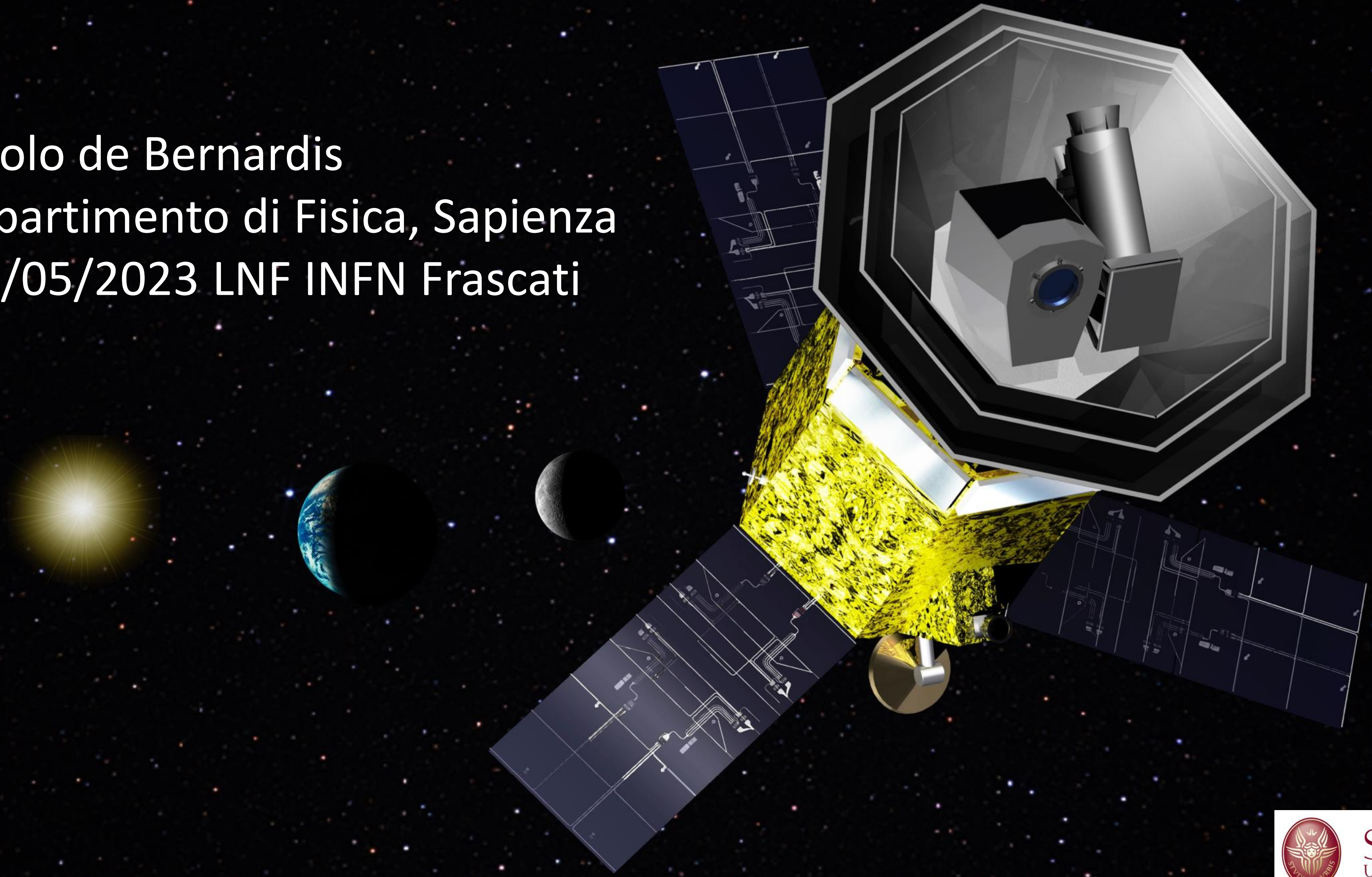


The hidden treasure of CMB polarization

- The large scale structure of the universe is believed to be originated by **early quantum fluctuations**, boosted to cosmological scales by the **inflation process**.
- Accurate measurements of the CMB are among the best tools to test this hypothesis.
- Measured temperature anisotropies are consistent and support the scenario above.
- CMB anisotropy data probe scales $0.001\ Mpc^{-1} < k < 0.1\ Mpc^{-1}$. In this range single-field slow-roll models for cosmological inflation are expected to produce a primordial spectrum of **scalar perturbations** close to scale-invariant :

$$P(k) = A_s(k/k_o)^{(n_s-1)}$$

- This parametrization is perfectly consistent with CMB anisotropy measurements from Planck, which constrain

$$\ln(10^{10}A_s) = 3.045 \pm 0.016$$
$$n_s = 0.9649 \pm 0.0044.$$

- Different models produce spectra with different $(n_s - 1)$, and current data are already ruling out some of these models.

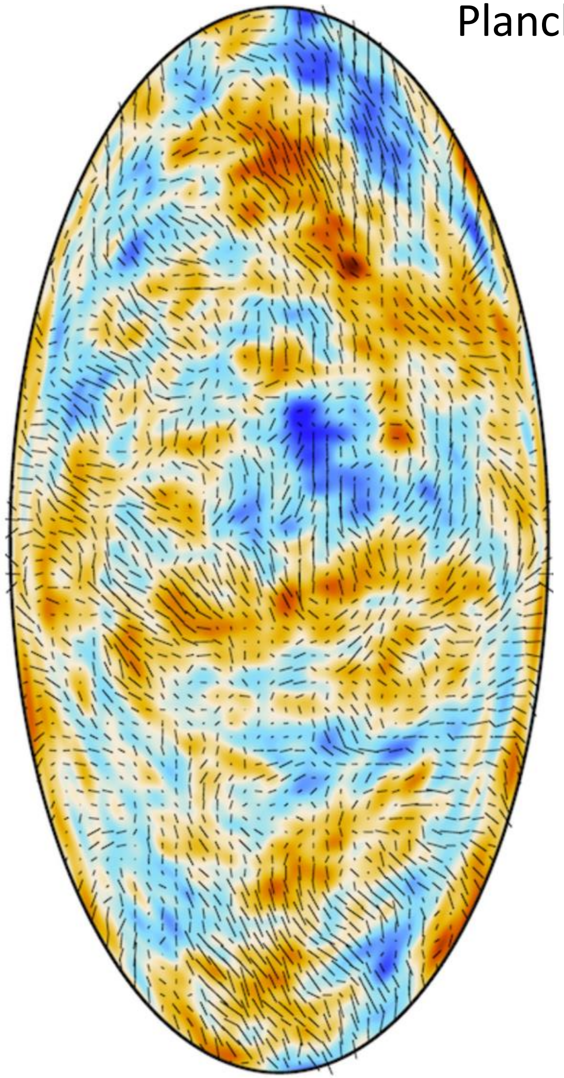
The hidden treasure of CMB polarization

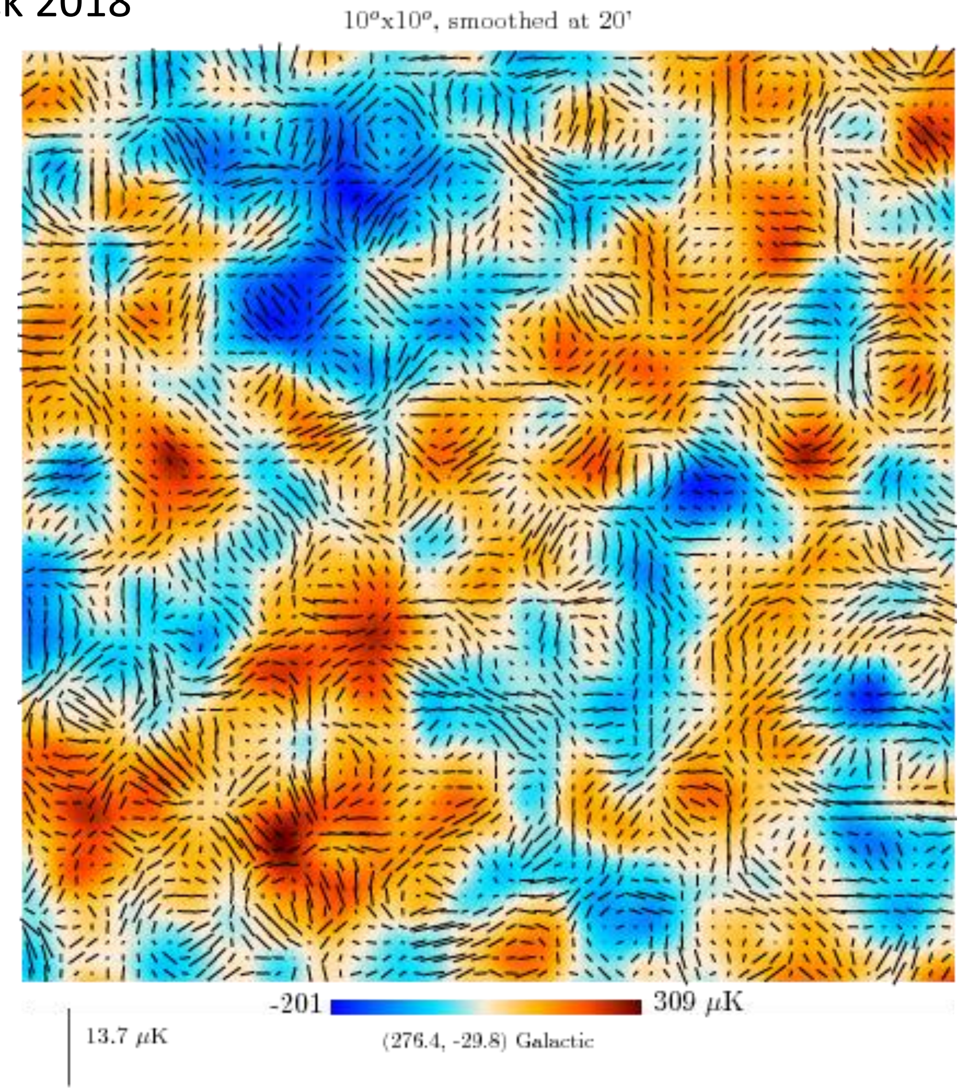
- Another prediction of all cosmological inflation models is the production of a background of gravitational waves (i.e. ***tensor perturbations***).
- These interact with the CMB at recombination and at reionization, producing ***B-mode polarization***.
- This is ***small*** with respect to the E-mode polarization due to scalar perturbations and visible in the two Planck maps on the right.
- The ratio between tensor and scalar modes amplitudes is called *r*.
- Planck with BICEP-Keck contrains this parameter to be

$$\boldsymbol{r < 0.036}\ (@95\% CL).$$

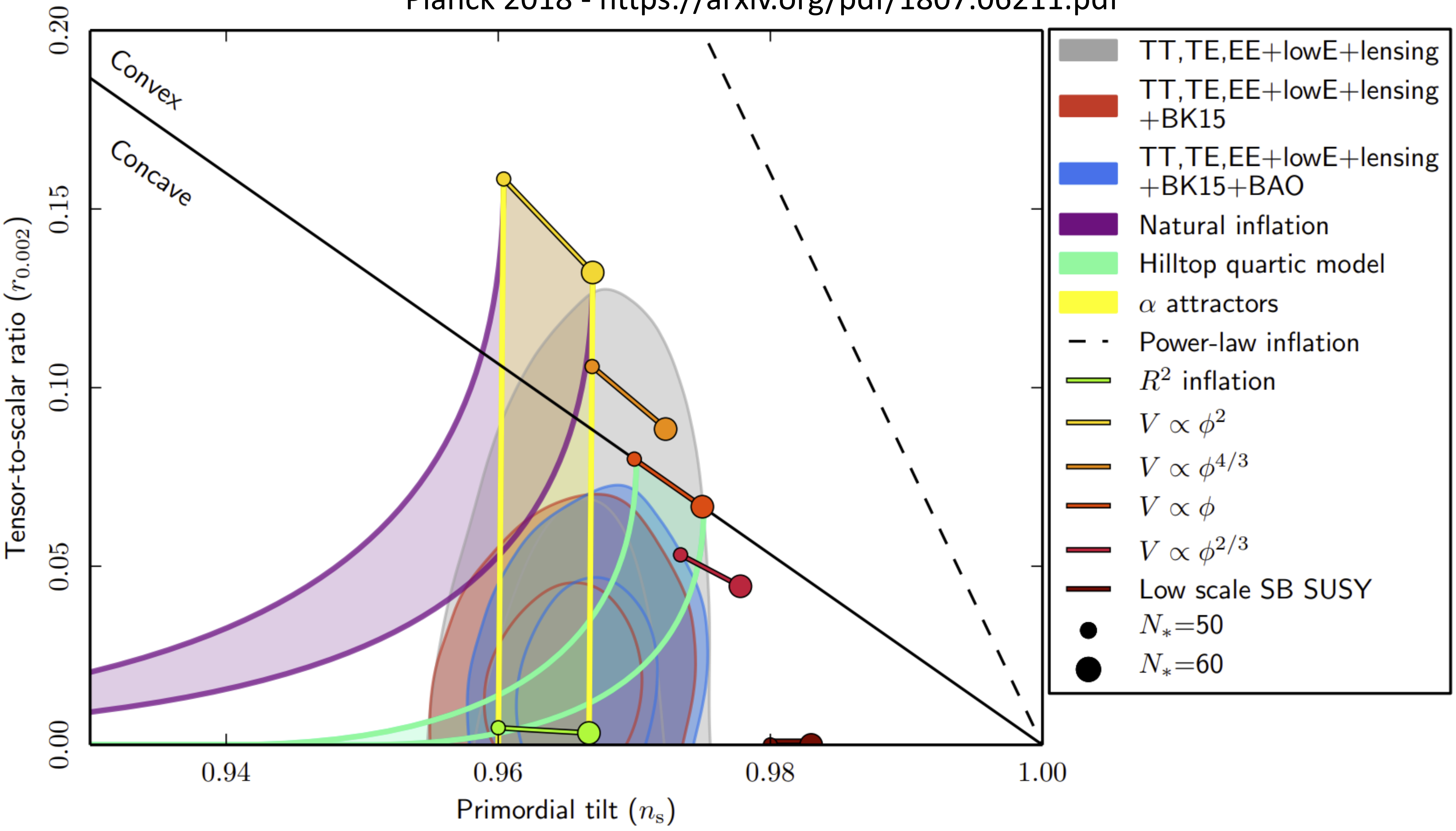
- Using both measurements (n_s and r) we can constrain the inflaton potential and, in turn, physics at ultra-high energies.

Planck 2018





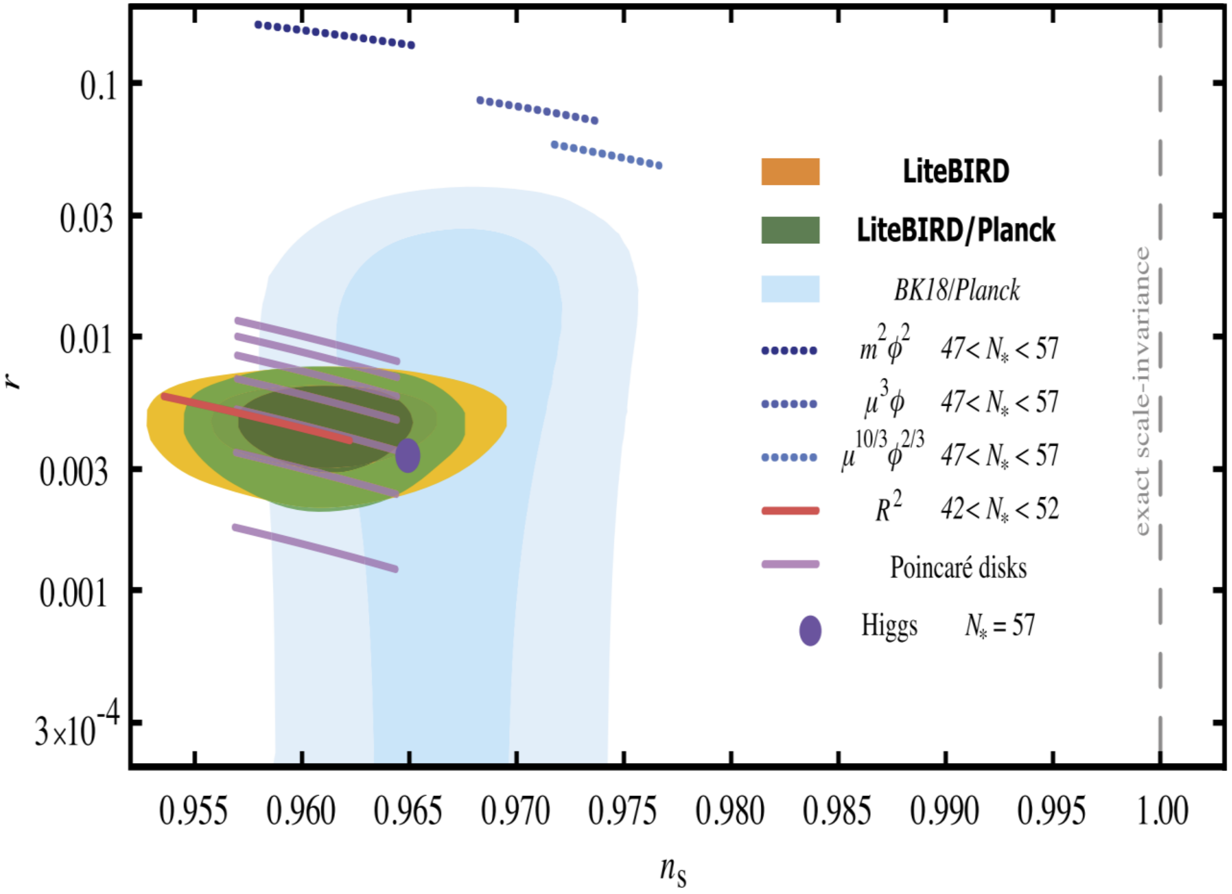
Planck 2018 - https://arxiv.org/pdf/1807.06211.pdf



Improving the polarization measurements wrt Planck is the only way to shrink these contours and better constrain inflation models.

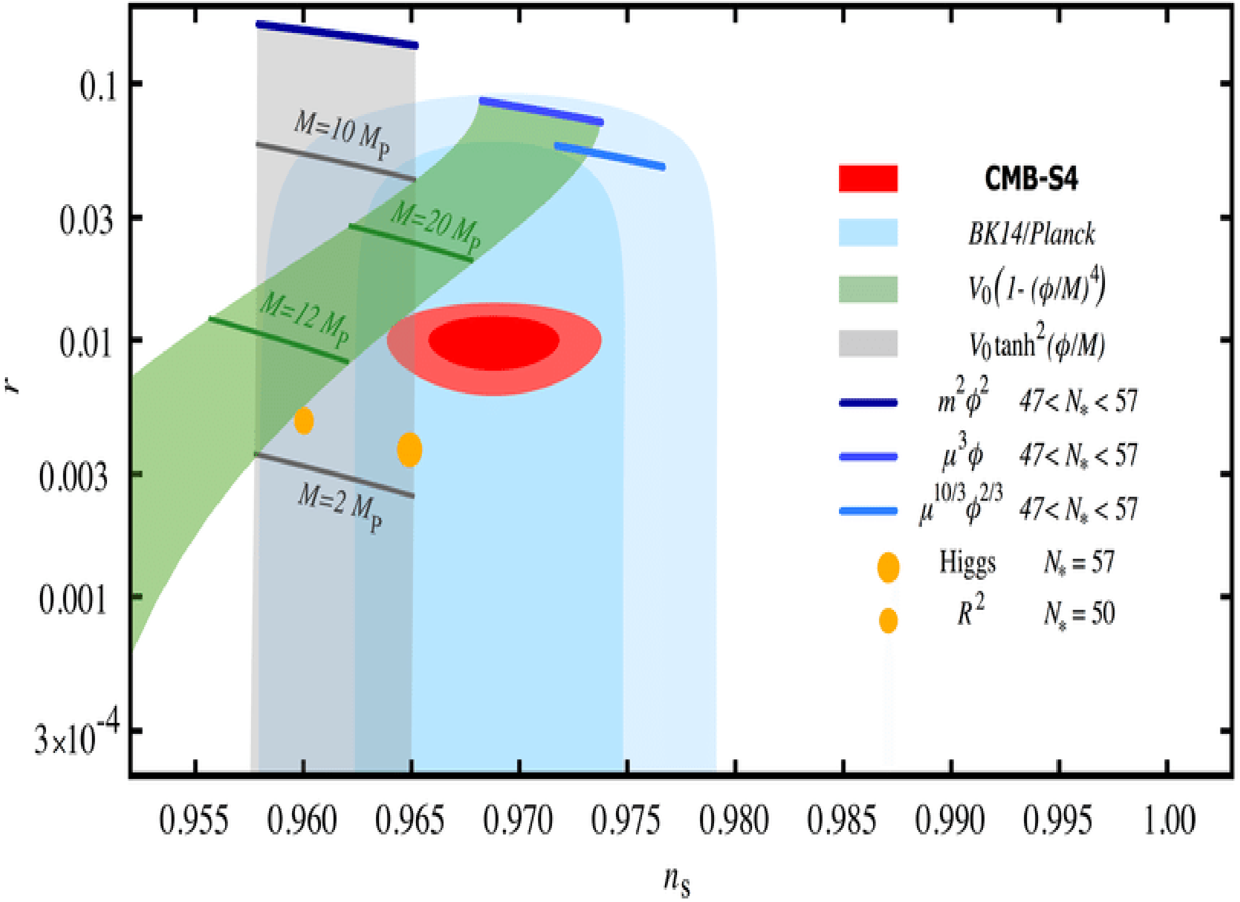
LiteBIRD – Space based

https://arxiv.org/abs/2202.02773



CMB-S4 – ground based

https://arxiv.org/abs/1610.02743

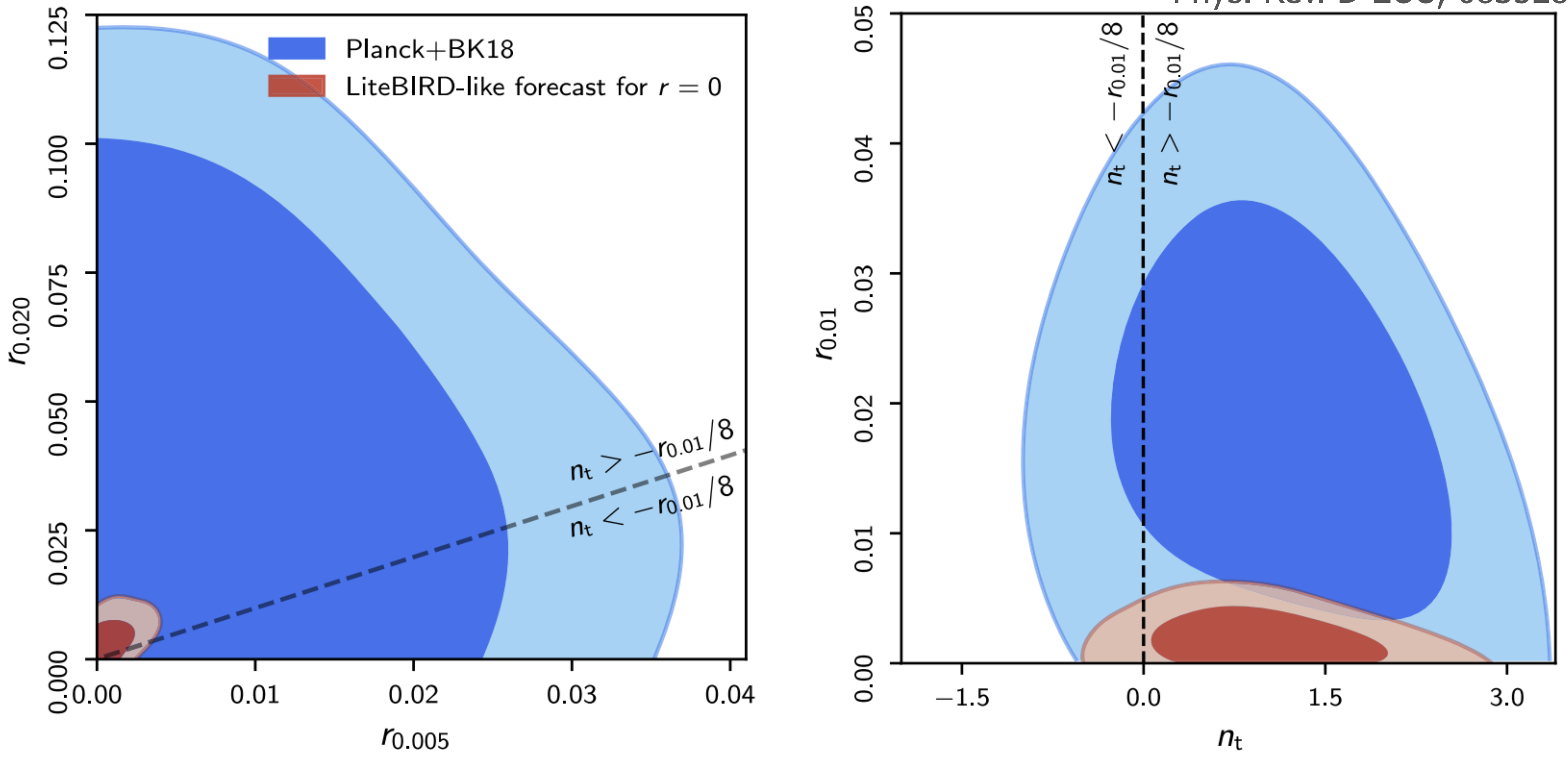


- These are two ambitious and expensive experiments, with similar discriminating power.
- Do we need both ? The answer, in my view, is yes. To be discussed later.

Beyond n_s vs r

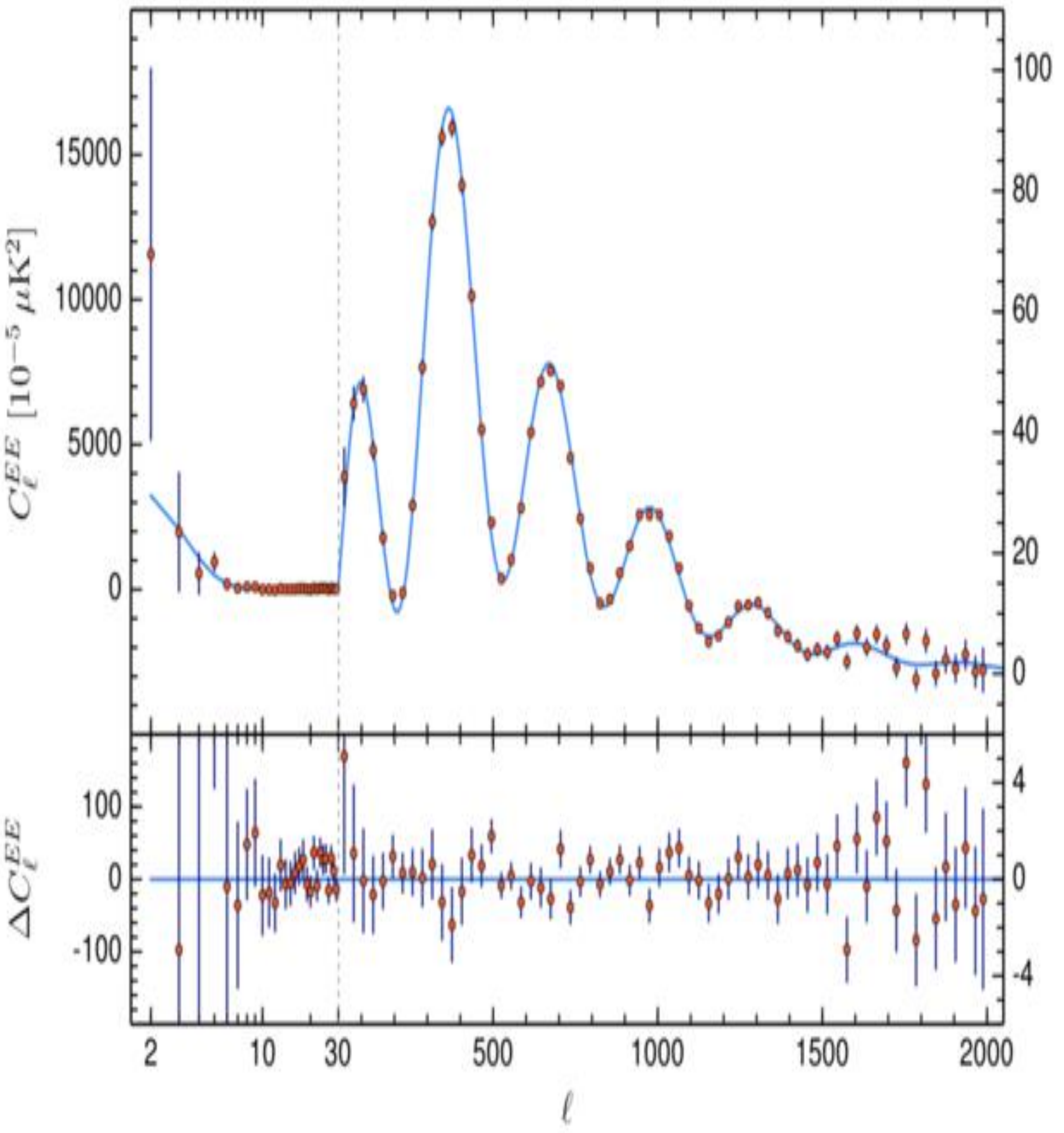
- We heard from Fabio what happens if we allow for $n_t \neq r/8$
- The discriminating power of LiteBIRD is impressive.

Phys. Rev. D **106**, 083528 2022



Beyond n_s vs r

- An important, well known concern is that there is no firm prediction for the amplitude of tensor modes produced by inflation, in its broadest implementations.
- This reflects our ignorance about ultra-high energy physics, and this alone should justify any attempt to sample physics at those energies.
- But, again, there are small-field slow-roll models with r << 0.001. This means that the (n_s vs r) contour cannot be the only target of CMB polarization measurements, and indeed there are others.
- One important observable is the **precision** determination of **E-mode** polarization. The measurement from Planck is already very good, but is not cosmic variance limited.
- Deviations from slow-roll (**primordial features**) are expected to produce a periodic modulation in the power spectrum, which in turn produces features in the TT and, even more, in the EE spectra. (see e.g. Finelli+ https://arxiv.org/abs/1612.08270 and Braglia+ https://arxiv.org/abs/2210.07028).
- These carry information on ultra-high energy physics and the very early universe, so are another important target for the next generation of CMB polarimeters.



The unique opportunity of LiteBIRD

- A space-borne survey is the only way to ***extend sensitive measurements of CMB power spectra down to*** $\boldsymbol{\ell < 40}$.
- This is a very important range, due to
  - Reionization bump and physics of reionization
  - Separation of primordial B-mode from lensing B-mode
- Ground-based measurements are not optimal for large-scale measurements due to
  - The sky coverage, which cannot be full-sky
  - The spectrum of atmospheric emission fluctuations, strongly increasing at large spatial and temporal scales, implying $1/f$ noise in the timestreams and large-scale features in the maps
  - The existence of elongated, horizontally aligned ice-crystals in the atmosphere, producing large polarized signal spikes when present in the LOS (see e.g. MNRAS, 376, 645 (2007) and ApJ 870 102 (2019))
  - The anisotropy of ground-pickup, resulting in noise and large-scale features in the maps
  - The long-term instability of the environment, producing drifts in the measurements, $1/f$ noise and large-scale features
- As a matter of facts, while WMAP and Planck have produced very accurate measurements of low multipoles, all ground-based experiments had to high-pass filter the data taken during the scans, resulting in a lack of sensitivity to the largest scales. SO and CMB-S4 wisely aim at $\boldsymbol{\ell > 40}$.
- The measurement of large scales better than Planck is a very difficult one, even for space-based measurements, and I'll focus in the following on the instrumental challenges implied for LiteBIRD by such a target.

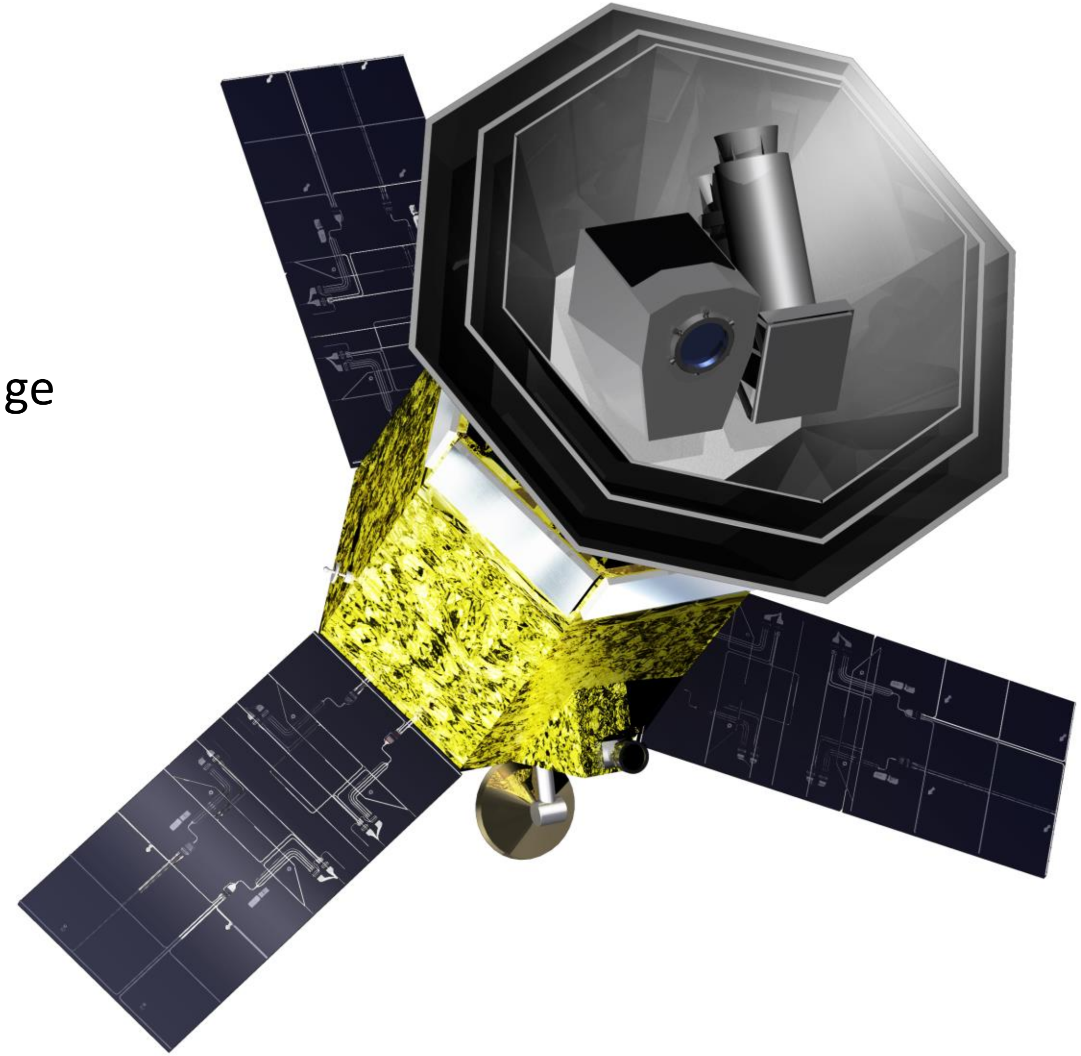
Instrumental Challenges for LiteBIRD

LiteBIRD is an incredibly challenging experiment, for both HW and SW developments.

Here I'll focus on a few among many challenges for instrument design and development, showing that the configuration we have is likely to be optimized, but there is a number issues which will require the energy and dedication of an entire generation of CMB experimentalists.

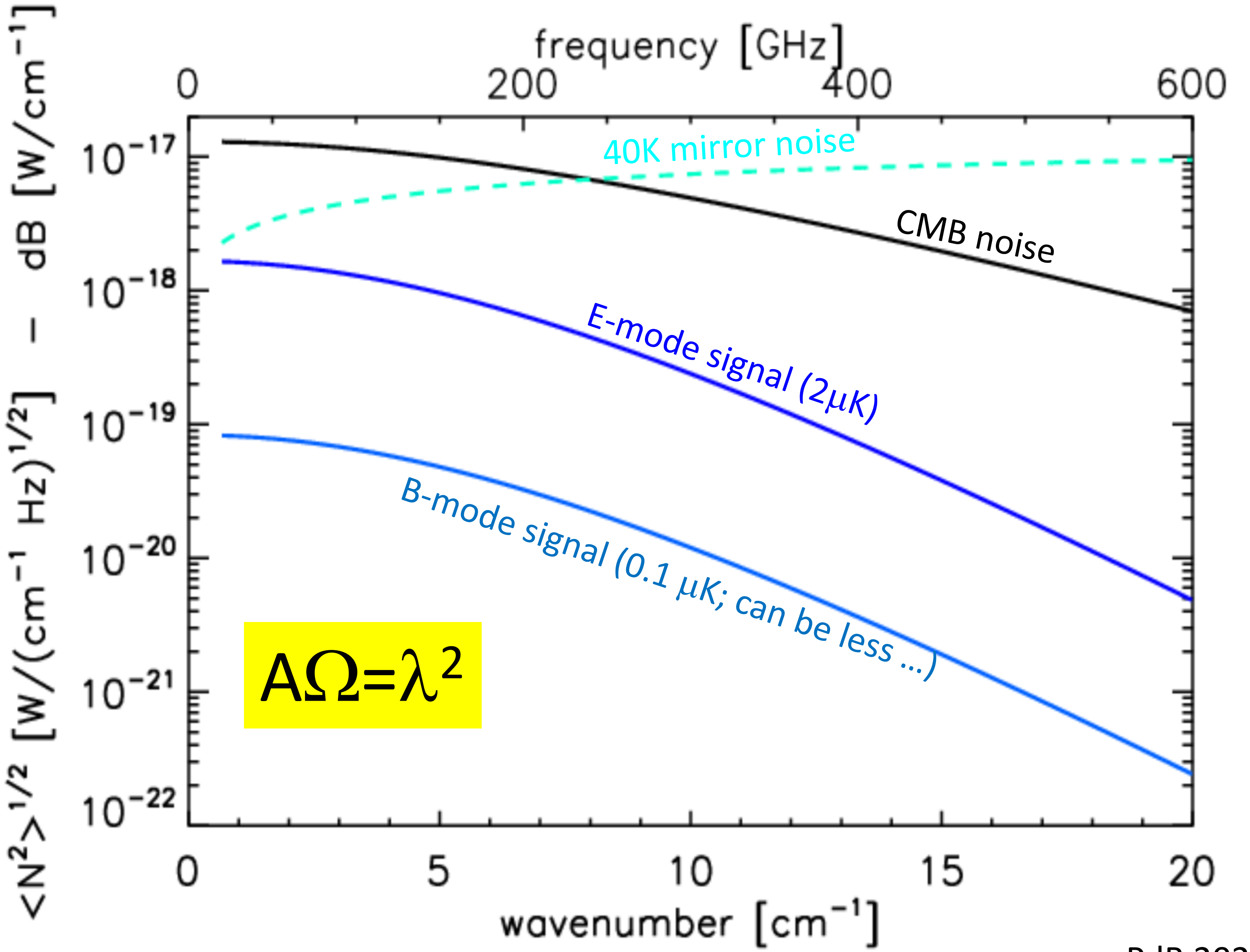
A certainly incomplete list is as follows:

- Sensitivity
  - number of detectors
  - noise characteristics (white, 1/f, CR)
- Systematic Effects
  - Foregrounds: sky coverage / frequency coverage
  - Optical (HWP & its rotation, ghosts)
  - Magnetic
- Calibration
  - Polarimetry
    - on-sky: Calibration of targets
      - effects of atmosphere, ice crystals ...
      - confusion from foregrounds
    - Artificial source
  - Gains
  - Beams (main beam, sidelobes)
  - Pointing



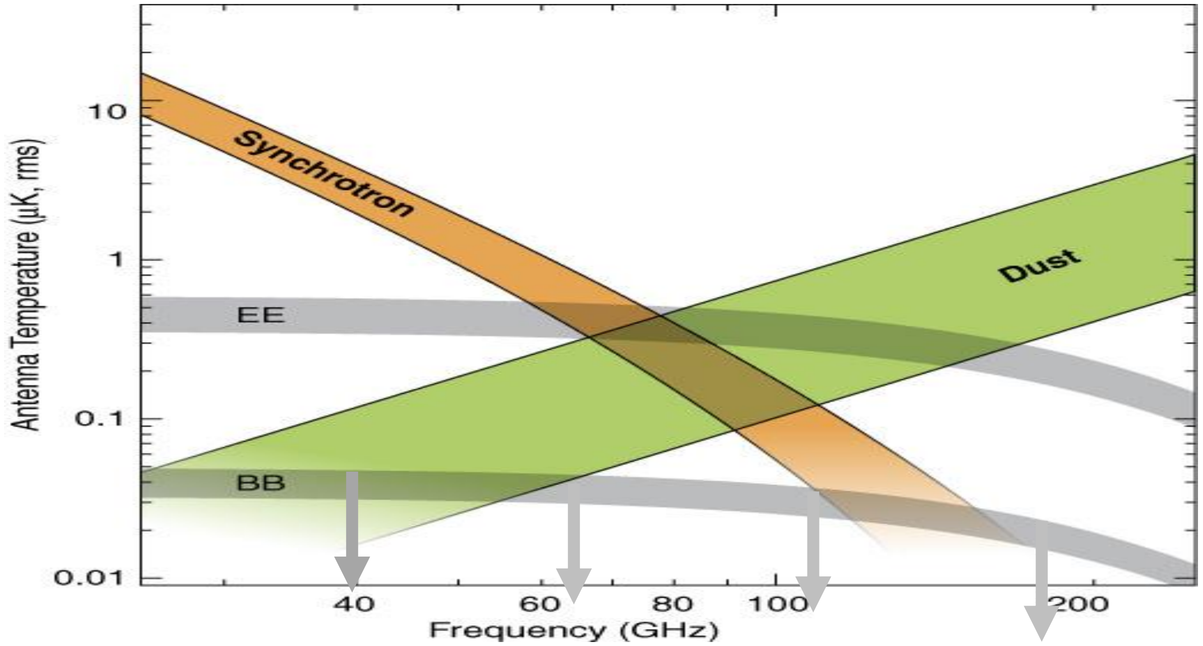
Raw sensitivity

- Target B-mode polarization signal very faint (< 0.1 μK) with respect to CMB E-mode & CMB photon noise
- Implications:
  - Long integration time required, even in CMB-BLIP conditions.
  - High S/N per pixel not achievable (>1Ms/px). High S/N on angular power spectra achievable, with limitations on pixel-based analysis of systematics/foregrounds effects.
  - Optical system has to be colder than in Planck. 5K required for coverage up to 450 GHz.



Raw sensitivity

- Target B-mode polarization signal very faint (< 0.1 μK) with respect to CMB E-mode & CMB photon noise
- Target polarization signal embedded in overwhelming polarized foregrounds
- Need to have many detectors *times* many frequency bands, i.e. very large focal plane
- Low frequency bands very expensive in terms of focal plane area



- Solution:
  - **CMB-BLIP detectors**, no warm optics -> challenges for the cryogenic system
  - Optics optimized for **wide focal planes** -> at the cost of some polarization distortion at the edges of the field (to be carefully calibrated)
  - **3 telescopes** to multiply focal plane area, covering different frequency bands (with overlaps), accommodating a total of 15 bands –> feasible, but implies large, heavy payload
  - **Diplexing and Triplexing pixels** to increase detectors density in the focal planes -> feasible, but implying wafer complexity and demanding requirements for polarization modulator achromaticity

Raw sensitivity

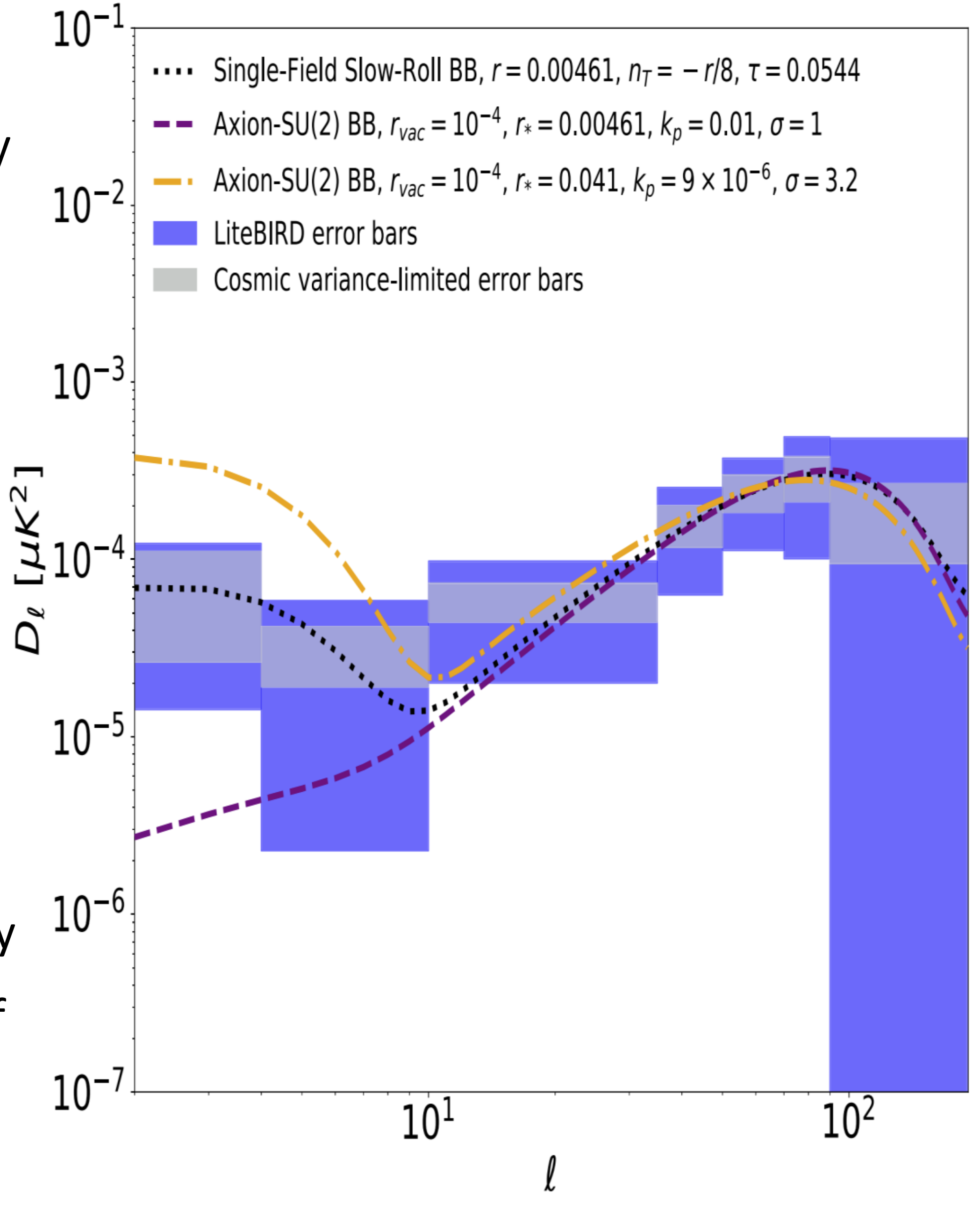
- We need to achieve single detector performance limited only by the intrinsic noise of the observable (CMB photons statistics), and obtain fast ***mapping speed using a suitable number of detectors.***
- Survey depth formula:
  - noise per pixel:

$$w^{-1/2}[\mu K\ arcmin] \sim 3.1\sqrt{\frac{f_{sky}}{t_{survey}[yrs]}}\ \frac{NET_{det}[\mu K_{CMB}/\sqrt{Hz}]}{\sqrt{N_{det}}}$$

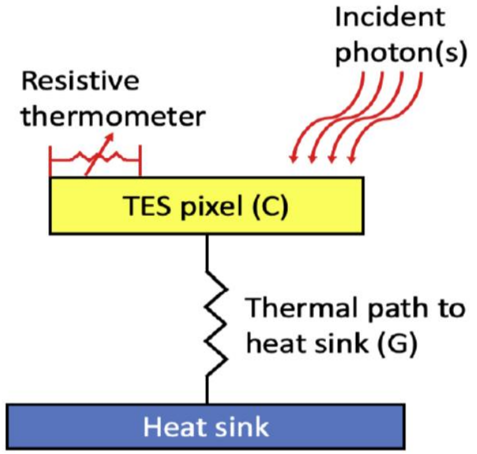
  - Error on the power spectrum:

$$\Delta C_\ell^{BB}[\mu K^2] = \sqrt{\frac{2}{(2\ell+1)f_{sky}}}[C_\ell^{BB} + w^{-1}W_\ell^{-1}]$$

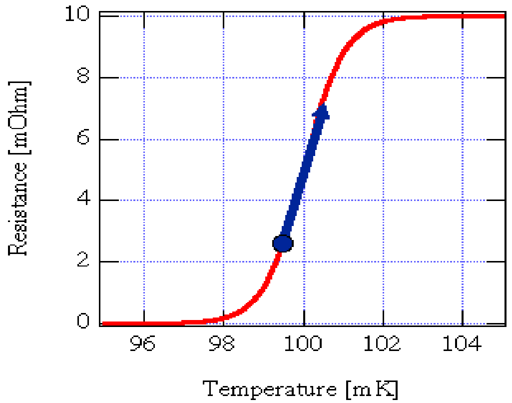
  - where $W_\ell = e^{-\ell(\ell+1)\sigma_\theta^2}$ is the beam window function
- The first term is due to cosmic variance, the second one to the noise of the detectors (assumed to be white).
- For a full sky BB survey with a given observation time and 4π sky coverage, the survey depth can be improved only by reducing the *NET* at the photon noise limit, and increasing the number of detectors until we basically reach cosmic variance limited performance.
- To achieve sufficient S/N for large scale B-modes in a 3 years mission, **about 4000 detectors are needed**.

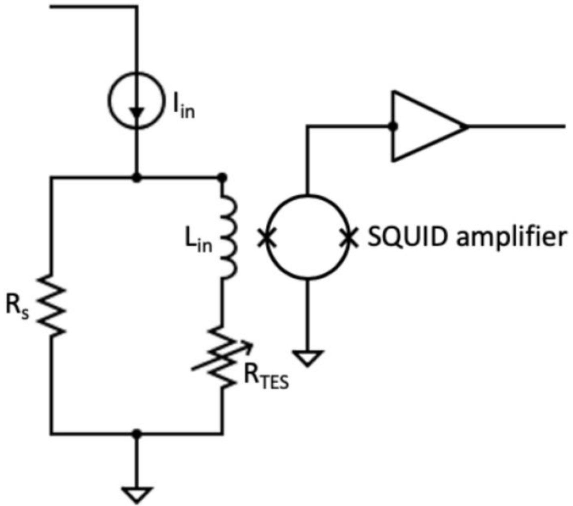


Raw sensitivity



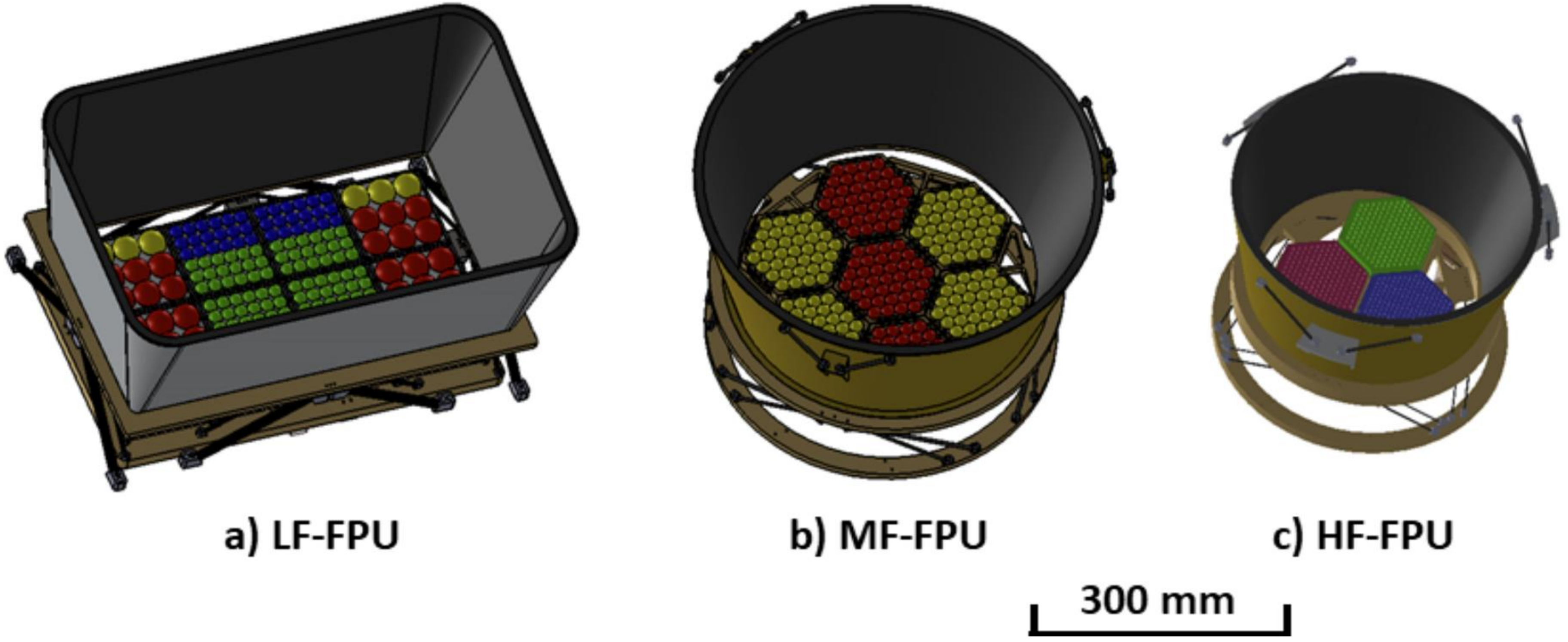
- For the reasons above, not only detectors must be limited only by the intrinsic noise of the observable (CMB photons statistics), but also must be easily replicable in large arrays.
- Cryogenic bolometers are the detectors of choice for broad-band thermal radiation. They must be assembled in high-count pixels arrays to achieve sufficient mapping speed.
- Transition-edge sensors (TES) with SQUID MUX readout is a complex but mature technology for ***large-format bolometric arrays***, as validated in modern ground-based CMB measurements (see e.g. PolarBEAR, SPT-3G, ..)
- Large-format arrays (1000s pixels) are possible with TESs because
  - Fabrication totally based on automatic wafer processing techniques
  - Multiplexing (FDM or TDM) made possible by extremely low-power SQUID ammeters with FLL electronics.
- Their use in space has been validated in the stratosphere (SPIDER, EBEX), but not in orbit, yet.
- Main issues:
  - Extreme cryogenics required (0.1K, a la Planck, better than Planck for the optical system)
  - Mitigation of magnetic pickup requires careful magnetic shielding
  - Mitigation of cosmic rays hits badly required
  - Control of 1/f or telegraphic noise badly needed (mitigated by polarized signal modulation, see below)





Focal plane units (FPUs)

Arrays of di/tri-plexing TES pixels for LiteBIRD



Detectors real estate

Telescope	Detector Type	FPM	Pixel Name	Frequency $[GHz]$	Frequency Range $[GHz]$	Pixel Size (mm)	Pixel Count	N_{det}
LFT	Lenslet/ Sinuous	LF12	LF-1	40/60/78	34 - 87 (Δ53)	32	12	72
			LF-2	50/68/89	43 - 99 (Δ56)	32	24	144
		LF34	LF-3	68/89/119	60 - 133 (Δ73)	16	72	432
			LF-4	78/100/140	69 - 162 (Δ93)	16	72	432
MFT	Lenslet/ Sinuous	MF1	MF-1	100/140/195	77 - 224 (Δ147)	12	183	1098
		MF2	MF-2	119/166	105 - 216 (Δ111)	12	244	976
HFT	Horn/ OMT	HF1	HF-1	195/280	166 - 322 (Δ156)	7	127	508
		HF2	HF-2	235/337	200 - 388 (Δ188)	7	127	508
		HF3	HF-3	402	366 - 448 (Δ92)	6.1	169	338

Table 1. Focal plane configurations for the LF-FPU, MF-FPU, and HF-FPU. The colors of the frequency schedule correspond to those in figure 2. The detector count is simply the pixel count multiplied by the number of bands in the pixel and the two orthogonal polarization states sense by each pixel.

https://arxiv.org/pdf/2101.05306.pdf

di/tri-plexing TES pixels for LiteBIRD

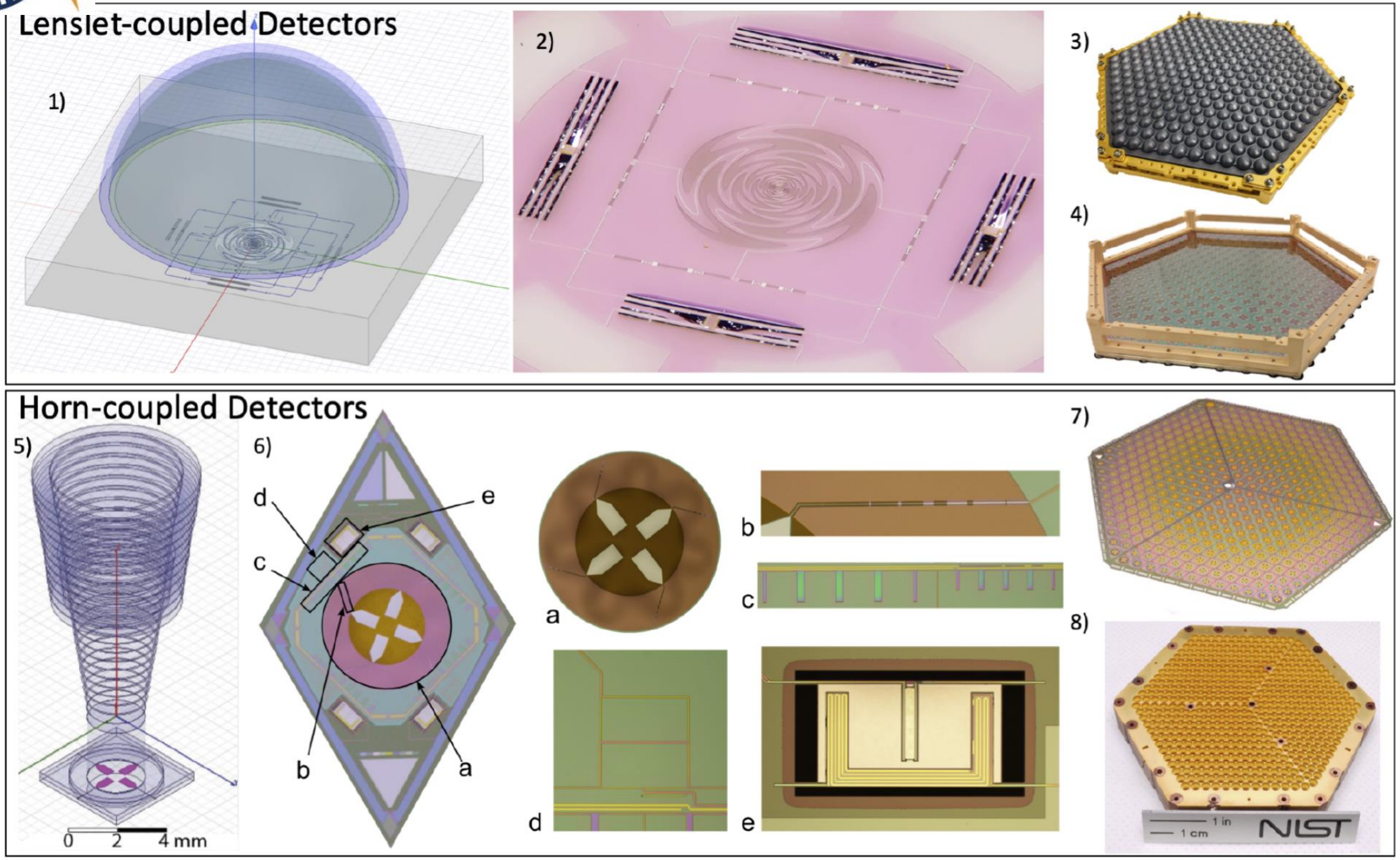


Figure 4. LiteBIRD detector arrays consist of lenslet-coupled arrays for the LF-FPU and MF-FPU and horn-coupled detector arrays for the HF-FPU. 1) Single lenslet-coupled detector. 2) Photograph of microfabricated sinuous antenna coupled detector. 3) Machined monolithic silicon lenslet array and 4) microfabricated detector array in a gold plated detector holder. 5) Single horn-coupled detector. 6) Optical micrograph of detector with labeled components a) planar OMT, b) CPW to microstrip transition, c) diplexer, d) 180 hybrid, e) TES bolometer.7) Photograph of 432 element array of dichroic horn-coupled detectors and mating 8) silicon platelet feedhorn array.

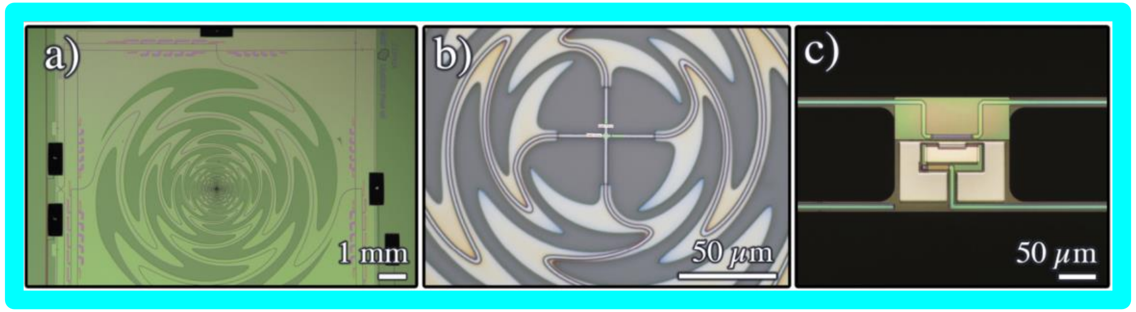
Two technologies: lenslets (LFT, MFT) vs feedhorns (HFT).
Common characteristics:

Design	Goal
Pixel in-band optical efficiency	$\geq 80\%$
Minimum Operating Power	2-3X optical power
On-sky end-to-end yield	$\geq 80\%$
FPU T_b	$100\ mK$
Cross wafer T_c variation	$\leq 7\%$
TES operating resistance	0.6 to 0.8 Ω
Parasitic series resistance	0.05 to 0.2 Ω
Intrinsic Time Constant (τ_0)	$33\ ms$
Loopgain during operation	≥ 10
Common 1/f-knee	$\leq 20\ mHz$
FPU lifetime	≥ 3 years

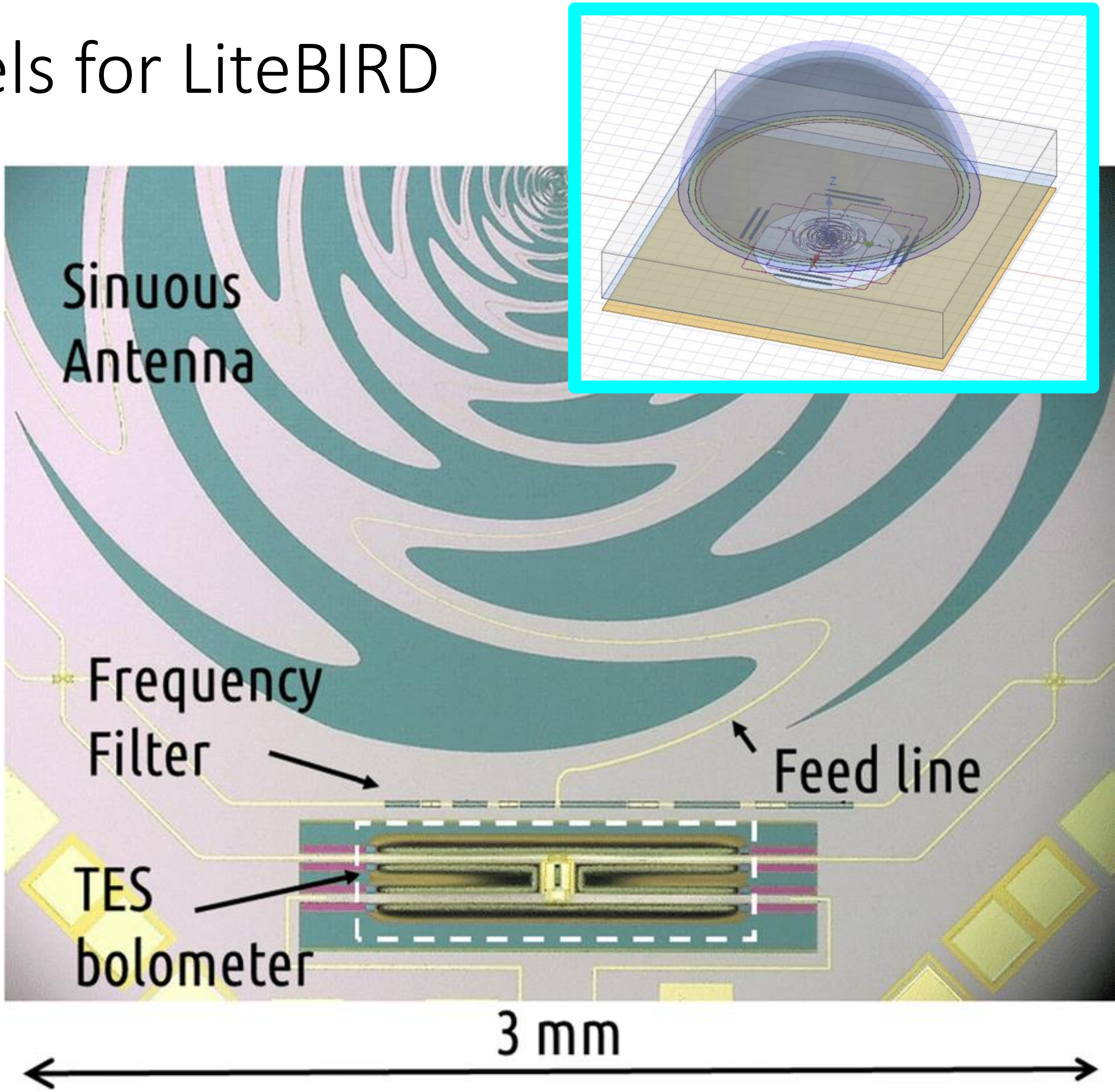
di/tri-plexing TES pixels for LiteBIRD

Complexity of wafer ! For each pixel:

- Hemispherical Lenslet with metamaterial anti reflection surface (MARS)
- dual-polarization sinuous antenna with central probes
- Two feedlines
- Frequency filters (di/tri-plexing)
- Small detector island with tiny resistor and TES sensor (small C) and long support legs (small G)

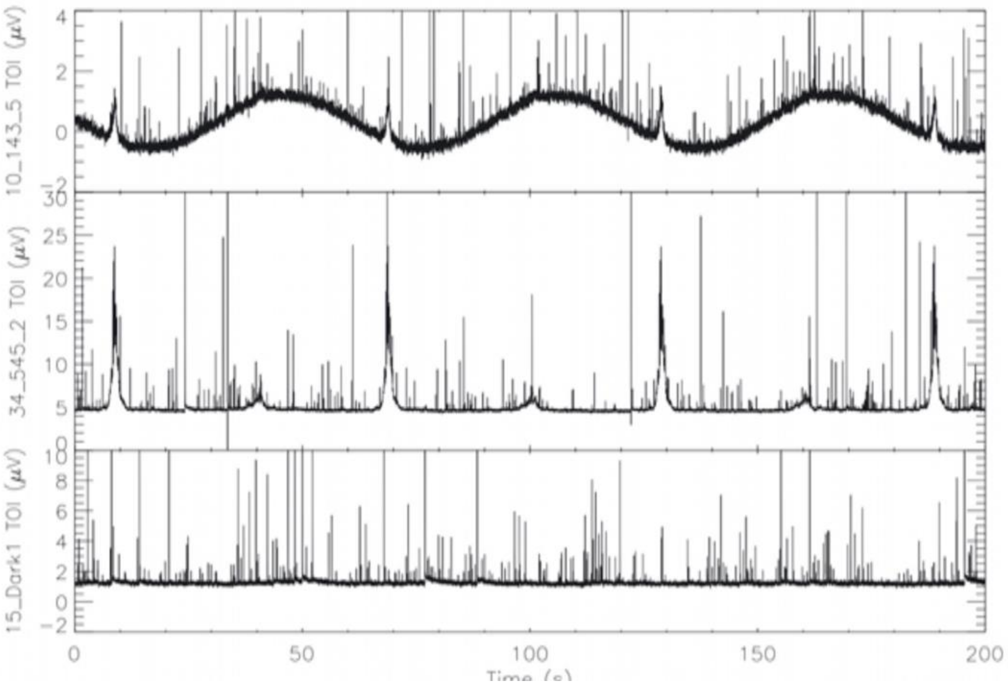


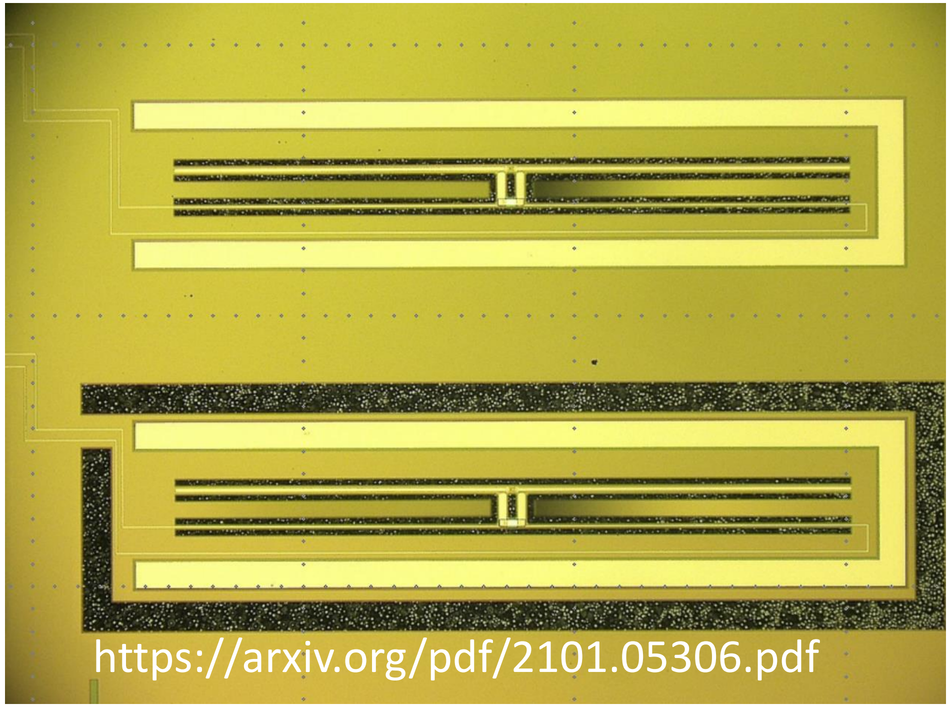
See Journal of Low Temperature Physics (2020) 199:1137–1147
https://arxiv.org/pdf/2101.05306.pdf
https://arxiv.org/pdf/2209.09864.pdf



Raw sensitivity: CR hits mitigation

- Additional wafer complexity due to cosmic ray hits mitigation.
- From Planck HFI data:
  - Short thermal spike glitch, when a CR hits a component of the bolometer
  - Long glitch when CR hits the silicon die
  - High coincidence events, when a showers of high energy CR hits coincidentally many detectors, producing a temperature increase
- Mitigations for LiteBIRD (work in progress):
  - Increase the thermal conductivity between the silicon die and the focal plane structures to reduce long time scale thermal fluctuations;
  - Make the suspended TES island as small as possible to reduce the number of short glitches;
  - Block ballistic phonon propagation to the TES: surround the bolometer island with a Pd layer and/or etch away the wafer around the island.





Raw sensitivity : 1/f noise

- 1/f noise does exist, independently of the technology used for the detector. Typical knee frequency around 0.1 Hz.
- Nasty because its effect averages out much slower than $1/\sqrt{t}$
- Mitigation with detrending / destriping removes useful signal at large scales.
- Fast (few Hz) polarization modulation very effective in removing 1/f. Polarization modulator units with spinning HWP adopted for this reason (and for removing asymmetric beam systematics)

Planck-HFI in-flight
single semiconductor bolometers

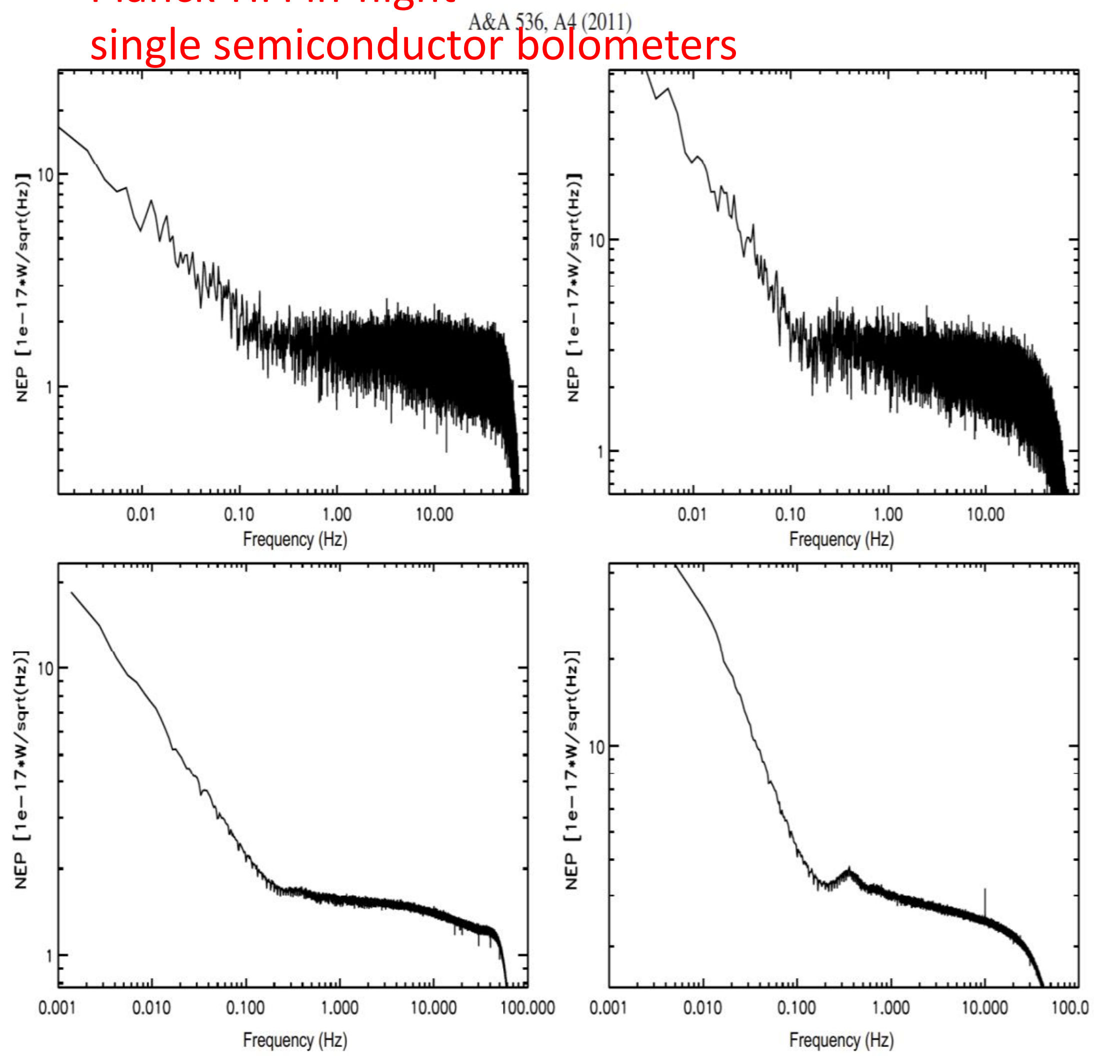
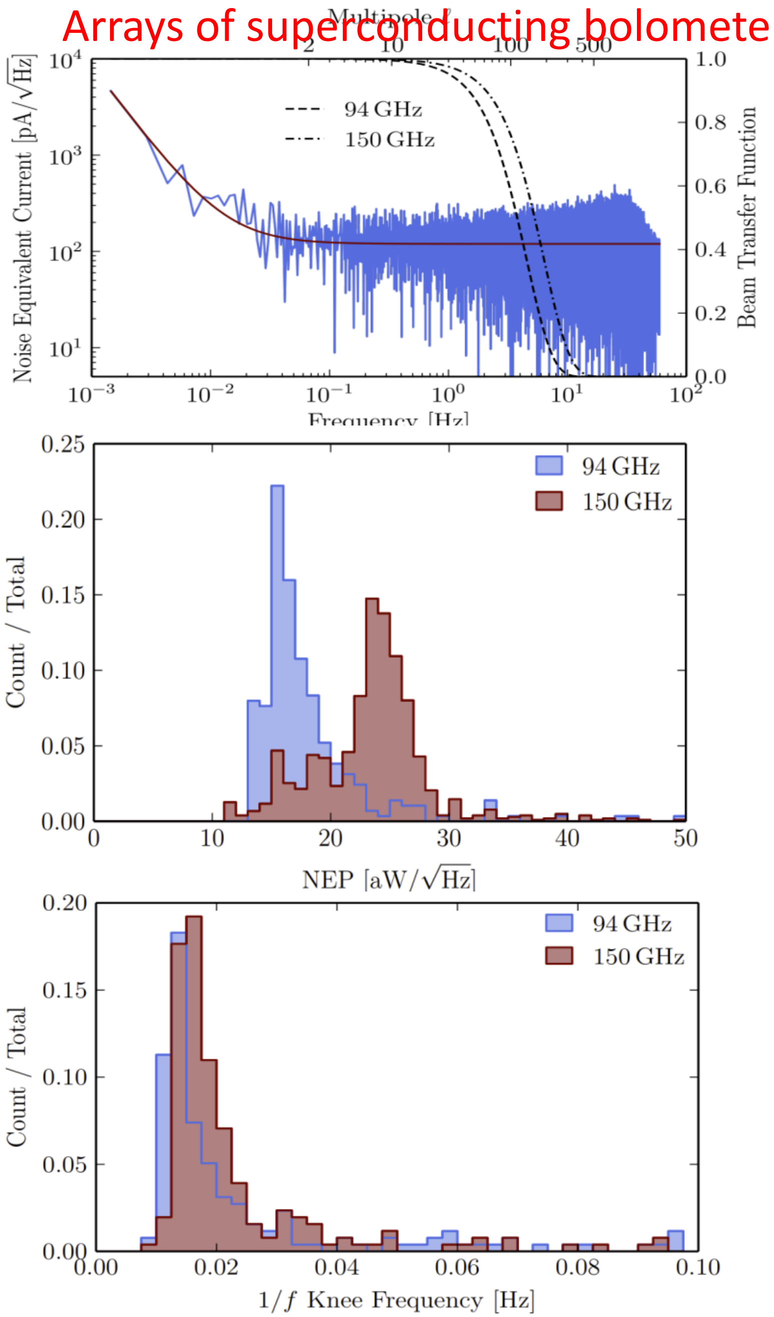


Fig. 14. Typical power spectrum amplitude of bolometers 143-5 and 545-2. For *the upper panels*, this is the power spectrum density of valid samples, after an average ring (the sky signal) has been subtracted from the TOI. Stacking of the result for 200 rings is shown in *the lower panel*. Here, the instrument time response is not deconvolved from the data.

https://www.aanda.org/articles/aa/pdf/2011/12/aa16487-11.pdf

SPIDER - pre-flight
Arrays of superconducting bolometers



https://arxiv.org/pdf/1407.2906.pdf

Raw sensitivity: PMU to mitigate 1/f noise

- The sky scan of LiteBIRD is optimized for full-sky coverage, with a slow scan of the detector boresight resulting from spin (20 min) and precession of the spin axis (3.2058 hours).
- In order to
  - obtain a uniform coverage of the polarization directions,
  - mitigate systematics due to the ellipticity of the beams,
  - mitigate 1/f noise ..
- a relatively fast (40-80 rpm) HWP is inserted as the first optical element (skywise) for the three telescopes.
- In this way the instrument becomes a Stokes polarimeter. The power collected by detectors maximally sensitive to horizontal and vertical polarizations is, to first order,

$$W_H = DP_H R(-\gamma(t)) H R(\gamma(t)) S = \frac{1}{2}[I_s + Q_s \cos(4\gamma(t) + 2\theta) + U_s \sin(4\gamma(t) + 2\theta)]$$

$$W_V = DP_V R(-\gamma(t)) H R(\gamma(t)) S = \frac{1}{2}[I_s - Q_s \cos(4\gamma(t) + 2\theta) - U_s \sin(4\gamma(t) + 2\theta)]$$

- Polarization information present in the scan is upconverted in the sidebands of $4f$, where $f = \dot{\gamma}/2\pi$ is the mechanical spin frequency of the HWP.
- This means that polarization signals initially encoded by the spin of the satellite at a frequency of 10^{-3} Hz (hidden in 1/f noise) are upconverted to near 4 Hz, well above the 1/f noise knee.

Raw sensitivity: PMU to mitigate 1/f noise

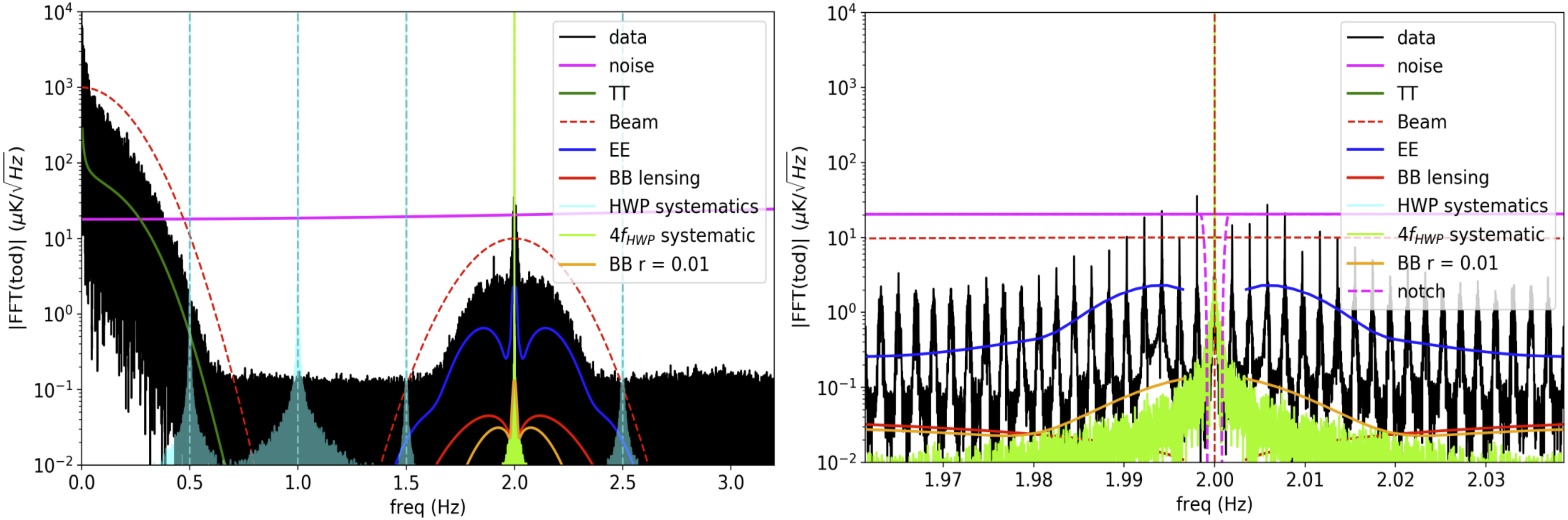
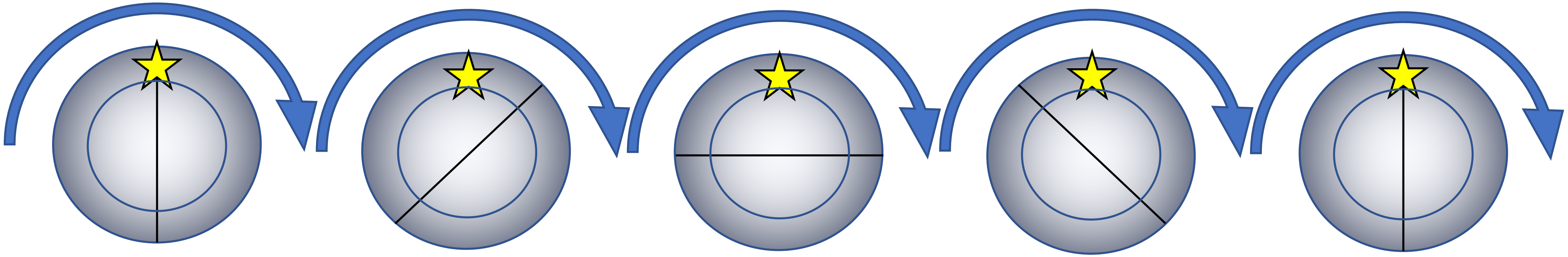


Figure 21. LSPE-SWIPE frequency spectrum (*top*), and zoom-in near modulation frequency (*bottom*), for a 16 hours noise-free CMB-only simulated timestream. The black curve represents the data; CMB temperature data are centered around 0 frequency, and polarization data around $4f_{\rm HWP}$. The magenta line is the noise for a single detector at 145 GHz. The magenta dashed line, is the noise multiplied by the notch filter. Vertical dashed lines represent harmonics of the HWP spin frequency. The dark green curve is the expected signal for a temperature CMB angular power spectrum, blue curve for E-mode power spectrum, red for B-mode (lensing only) and orange for inflationary B-mode. The light-green curve, visible in the bottom plot, is a systematic effect at $4f_{\rm HWP}$, with an amplitude of 1 mK, spread in frequency due to the uncertainty in the HWP angular velocity $\sigma_{\omega_{\rm HWP}}/\omega_{\rm HWP} = 0.6 \times 10^{-6}$. The cyan clear curves are the systematic effects at 1, 2, 3, $5f_{\rm HWP}$, as discussed in section 4.3.3. Since the signal is quasi-periodic, with period $T_{\rm payload}$, its Fourier transform peaks at the modulation frequency $4f_{\rm HWP}$ and then in frequency shifts equal to $\Delta f = 1/T_{\rm payload}$, clearly visible in the bottom figure.

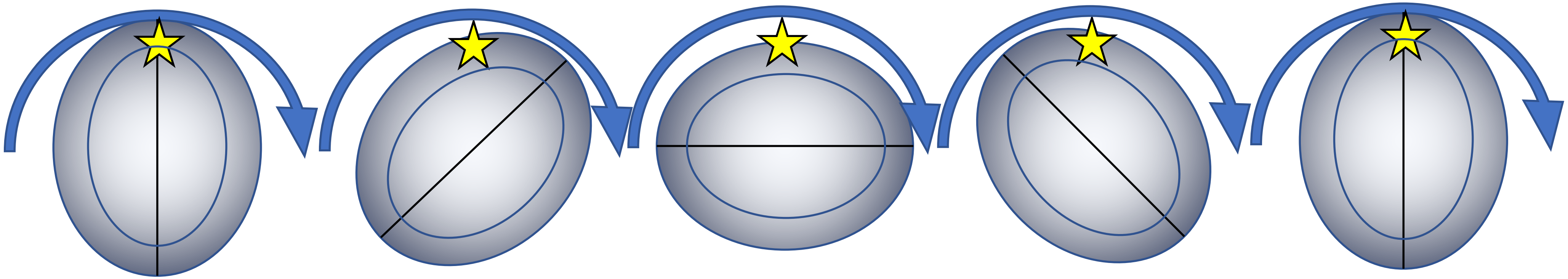
https://arxiv.org/pdf/2008.11049.pdf

PMU to mitigate beam systematics

- If an unpolarized source is anisotropic or off axis, and the detector beam is elliptical, when the telescope rotates around its boerisght to explore different polarization directions a signal mimiking a polarized source (spurious polarization) is detected, even if the source is unpolarized.
- This is called intensity to polarization leakage (IP)
- A rotating HWP rotates the main polarimetric axis without rotating the beam, effectively reducing IP.



Circular beam: constant signal from an unpolarized off-axis/anisotropic source



Elliptical beam: modulated signal from an unpolarized off-axis/anisotropic source, mimiking a polarized source

PMU complexity (implementation)

- This HWP modulator looks like a great idea, however has a big cost.
- The HWP emissivity can be of the order of 1-2% so must be cooled cryogenically to reduce the radiative background on the detectors
- Moreover, the HWP is not ideal. This means that it produces emission signals synchronous with its rotation. These must be minimized, which, again, calls for a cryogenic implementation.
- So the rotation mechanism has to be cold, and frictionless, to avoid extra heat loads on the cryogenic system.
- In the cryogenic environment of LiteBIRD the solution comes from superconductive magnetic bearings.
- Thoroughly investigated by US and Japanese colleagues, as well as in Italy in the contest of the SWIPE-LSPE experiment.
- It remains a high cost, high risk, single point failure subsystem, but the gain is well worth the investment and risk.
- Hear Giampaolo Pisano and Fabio Columbro later, on real-world implementation of the PMU for MHFT.

PTEP **2023**, 042F01 E. Allys et al.

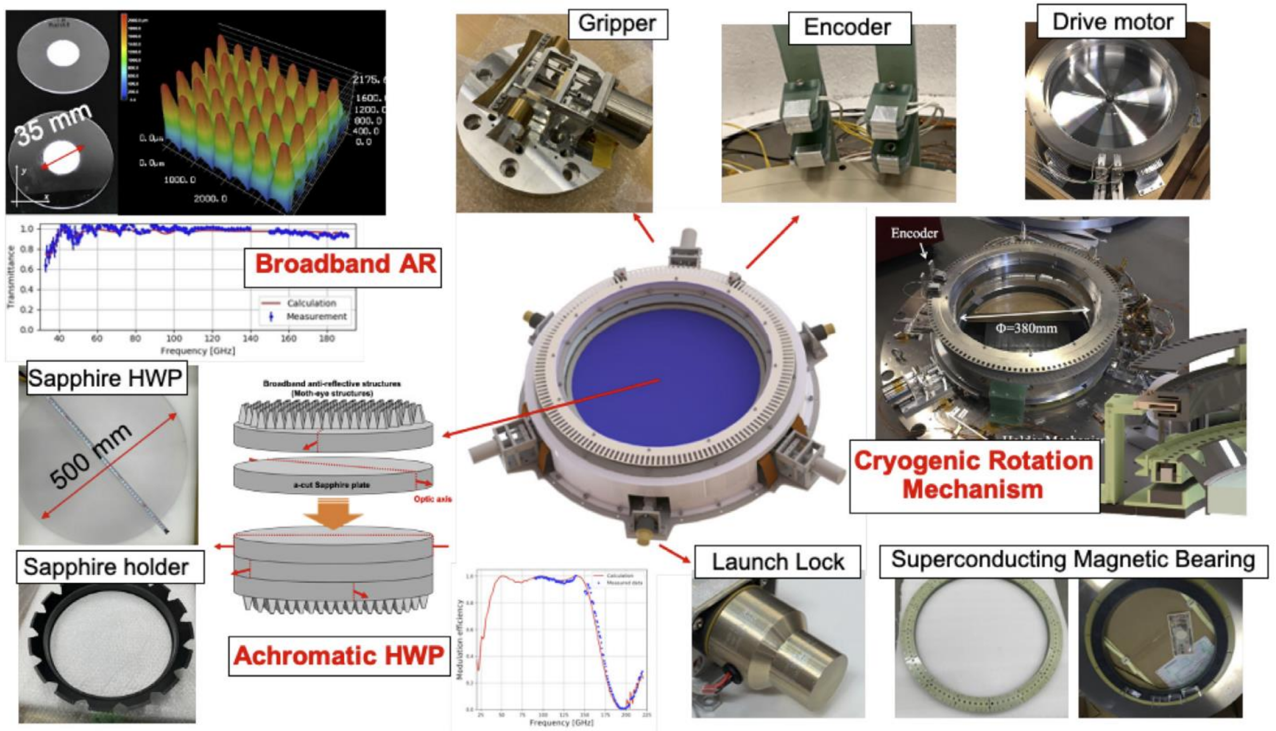


Fig. 14. Overview and components of the *LiteBIRD* LFT PMU BBM. The AHWP is composed of five-layer sapphire plates that are about 500 mm in diameter with moth-eye sub-wavelength grating structures for anti-reflection on two outer surfaces. The entire AHWP is held in a leaf-like holder, which accounts for the differential thermal contact and yet is strong enough to survive the launch impact and vibration. The rotational mechanism is composed of the cryogenic holder mechanism (called the “gripper”), the optical encoder for monitoring the rotor position, and the drive motor mechanism to drive the rotor. The rotation is supported by the superconducting bearing, ring magnet, and ring YBCO. The entire rotor is held by the launch lock in order to survive the launch impact.

PMU complexity (performance)

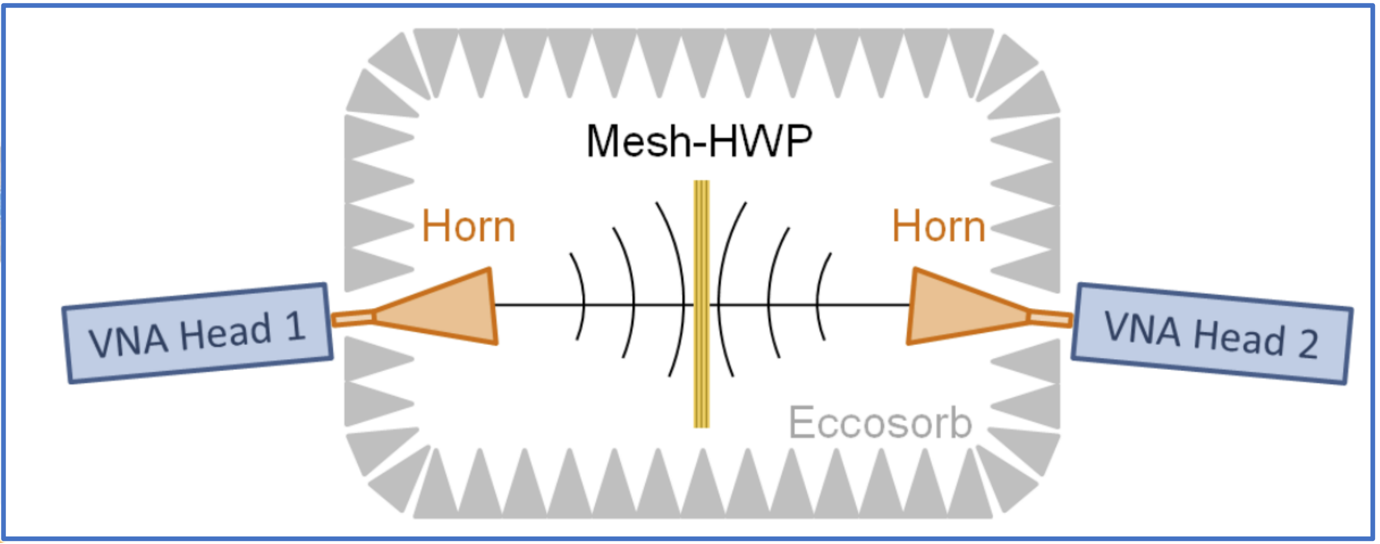
- Small non idealities are certainly present in the PMU
- For the rotator:
  - Knowledge of the rotation angle (offset and random errors)
  - Stability of the rotation (modulation of detectors time response)
  - Equilibrium temperature (loading, synchronous signals)
  - …

$$W_H = DP_H R(-\gamma(t)) H R(\gamma(t)) S = \frac{1}{2}[I_s + Q_s \cos(4\gamma(t) + 2\theta) + U_s \sin(4\gamma(t) + 2\theta)]$$

- For the HWP:
  - Device nonideality
    - Deviation from ideal: $H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \rightarrow H = \begin{bmatrix} T & \rho & 0 & 0 \\ \rho & T & 0 & 0 \\ 0 & 0 & c & -s \\ 0 & 0 & s & c \end{bmatrix}$ or $H = \begin{bmatrix} M_{II} & M_{IQ} & M_{IU} & M_{IV} \\ M_{QI} & M_{QQ} & M_{QU} & M_{QV} \\ M_{UI} & M_{UQ} & M_{UU} & M_{UV} \\ M_{VI} & M_{VQ} & M_{VU} & M_{VV} \end{bmatrix}$
    - Chromaticity
    - Non-orthogonal incidence
    - …
  - Interaction with other optical components (multiple reflections, ghosts, &)
- Can we *calibrate* all this, at the required level ?

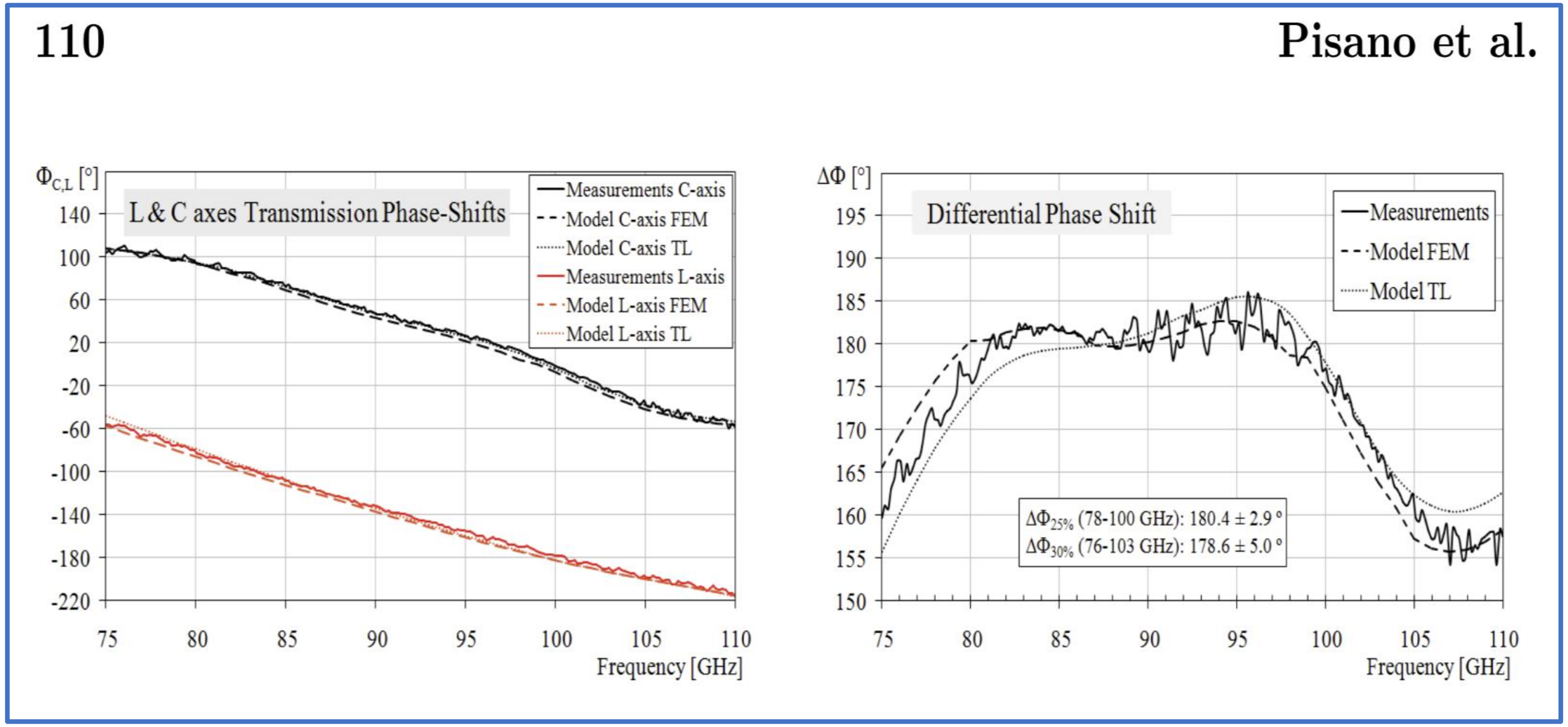
PMU complexity (performance)

- Small non idealities are certainly present in the PMU
- For the rotator:
  - Knowledge of the rotation angle (offset and random errors) Cryogenic optical encoder (<10”)
  - Stability of the rotation (modulation of detectors time response) Inertia, optimal Kalman reconstruction ($<10^{-5}$)
  - Equilibrium temperature (loading, synchronous signals) Design, emissivity optimization (<20K)
  - …
- For the HWP:
  - Device nonideality   Can be marginalized using a specialized map making, in conjunction with initial values from calibration
    - Deviation from model: $H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \rightarrow H = \begin{bmatrix} T & \rho & 0 & 0 \\ \rho & T & 0 & 0 \\ 0 & 0 & c & -s \\ 0 & 0 & s & c \end{bmatrix}$ or $H = \begin{bmatrix} M_{II} & M_{IQ} & M_{IU} & M_{IV} \\ M_{QI} & M_{QQ} & M_{QU} & M_{QV} \\ M_{UI} & M_{UQ} & M_{UU} & M_{UV} \\ M_{VI} & M_{VQ} & M_{VU} & M_{VV} \end{bmatrix}$
    - Chromaticity Special map making: from map with averaged response to averaged maps from $\neq$ sub-bands
    - Non orthogonal incidence Special map making: from map with averaged response to averaged maps at $\neq$ incidence
    - …
  - Interaction with other optical components (multiple reflections, ghosts, &) Reduced by tilting the HWP, exposing the curved face of the lens, with optimized ARCs
- Wide literature: see e.g. O’Dea+ 2007, Salatino & PdB 2010, D’Alessandro+ 2019, Giardiello+ 2022, Monelli+ 2023, no comprehensive treatment yet.
- Calibration is the key.



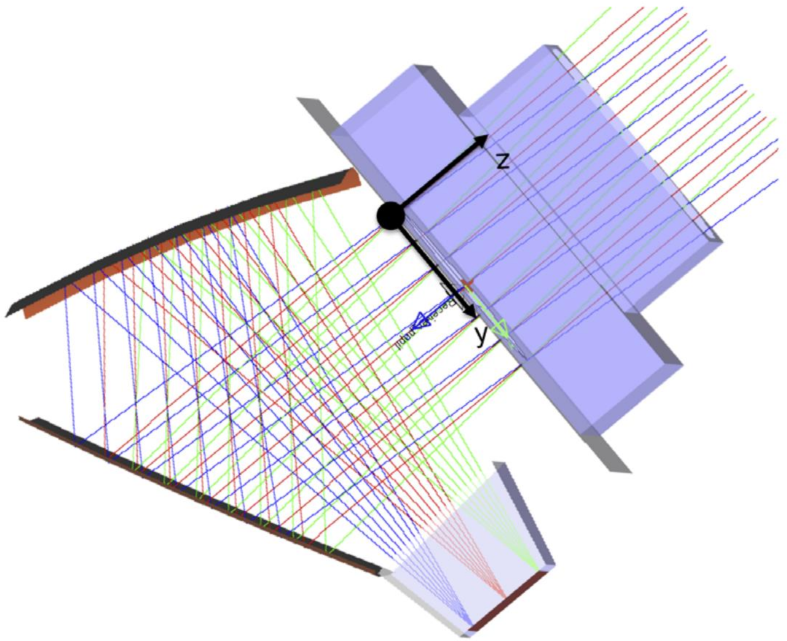
Pisano+, Progress In Electromagnetics Research M · January 2012

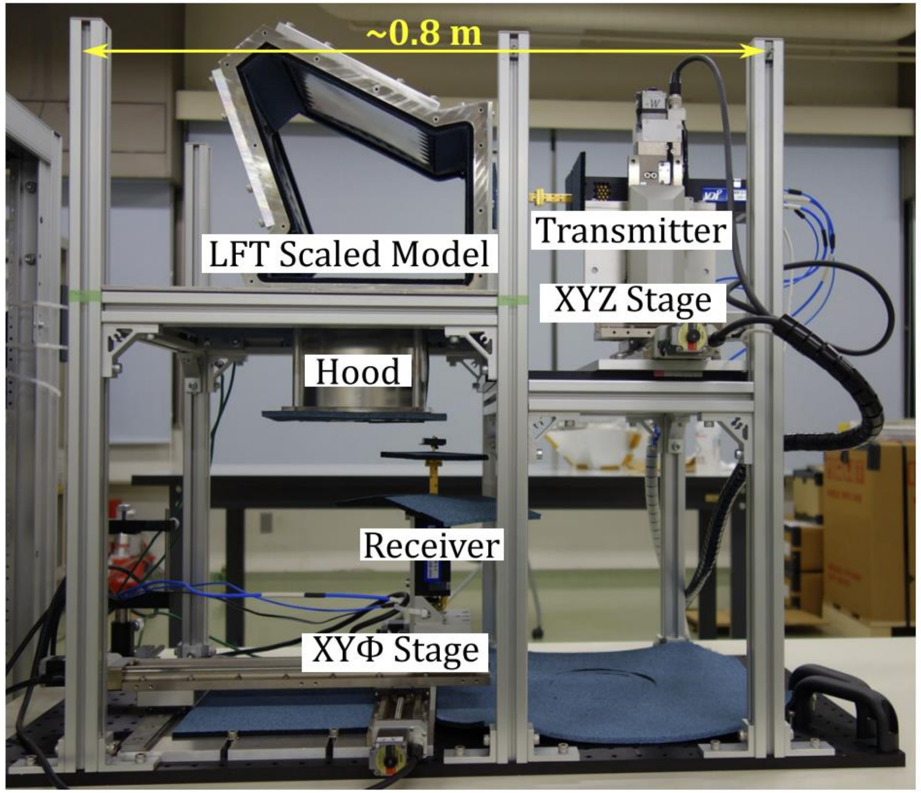
- VNA measurements are extremely detailed.
- Wide coverage VNA needed to cover all the MHFT bands (Sapienza, Grandi Attrezzature, funded)
- Care must be taken to limit systematic effects (reflections, standing waves). The setup limits crosspol measurements to around -45 dB.
- Phase drifts in the VNA limit the accuracy of the phase shift measurement to a fraction of a degree.
- To be complemented by FTS measurements for validation.

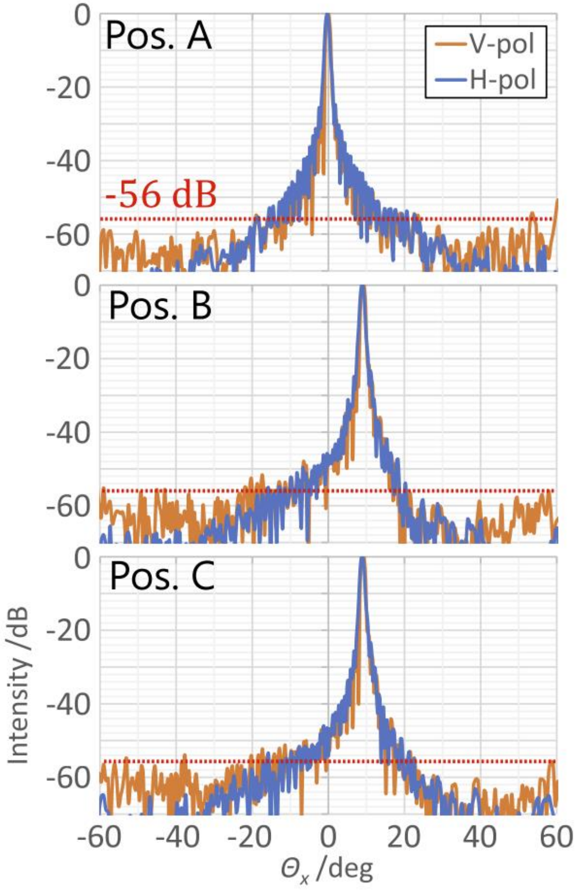


Raw sensitivity: large focal planes -> special telescopes

- Both reflective Cross-Dragone (LFT) and 2-lenses telecentric refractor (MHFT) provide good polarimetric and aberration performance over a very wide focal plane (similar in size to the input aperture !).
- A penalty to pay is the rotation of the polarization at the periphery of the field for the cross-dragone (up to 1.5o for LFT), and the presence of ghosts in the refractor (minimized by accurate ARC in MHFT). This must be accurately calibrated.





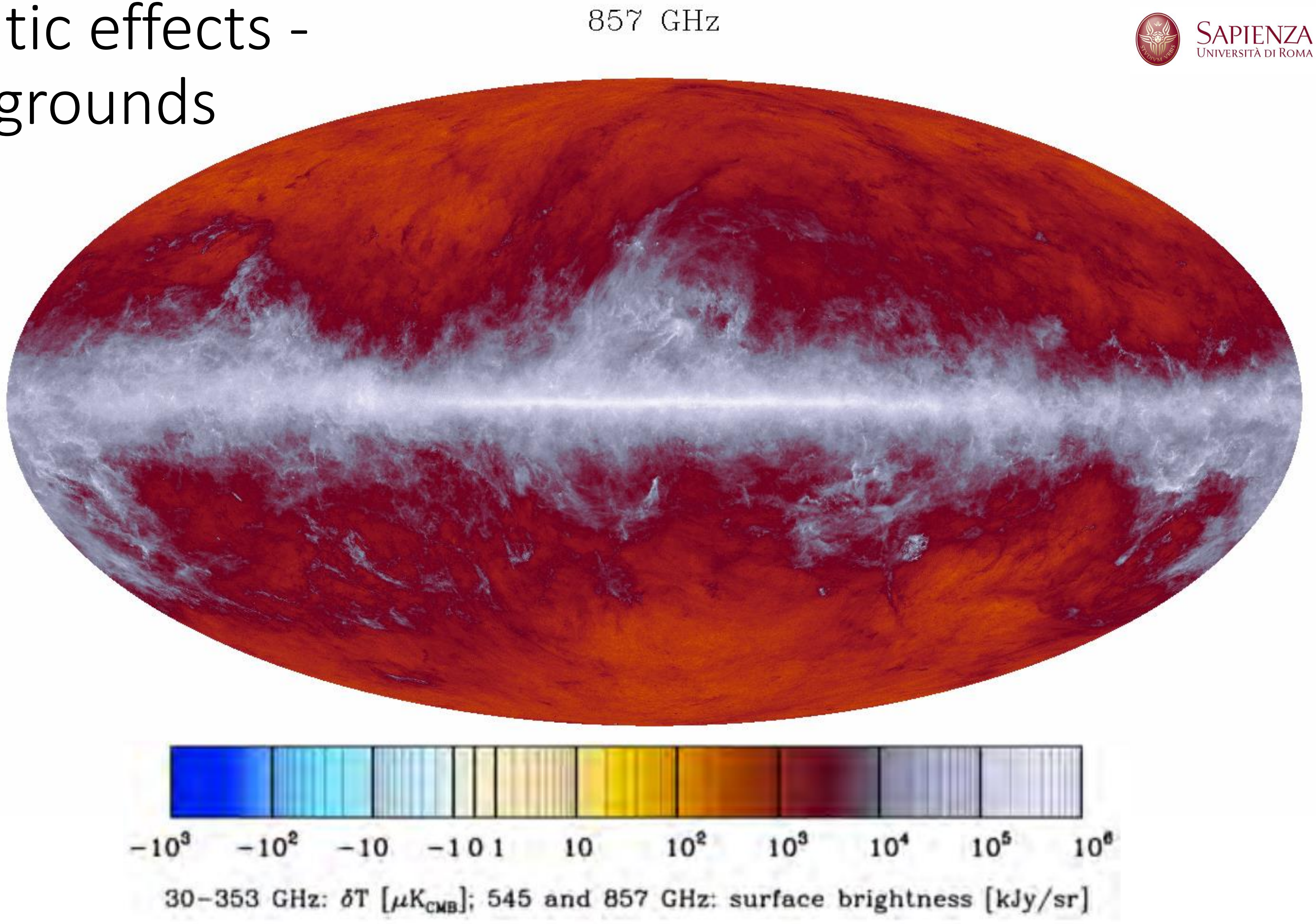


Systematic effects - Foregrounds

Intensity maps from Planck:

- ISM Synchrotron dominates the mm-wave sky at low frequencies (<40 GHz)
- ISM thermal dust dominates the sky at high frequencies (>140 GHz).

Both are polarized, and CMB polarization is much fainter than CMB anisotropy.



Systematic effects – Polarized Foregrounds from Planck

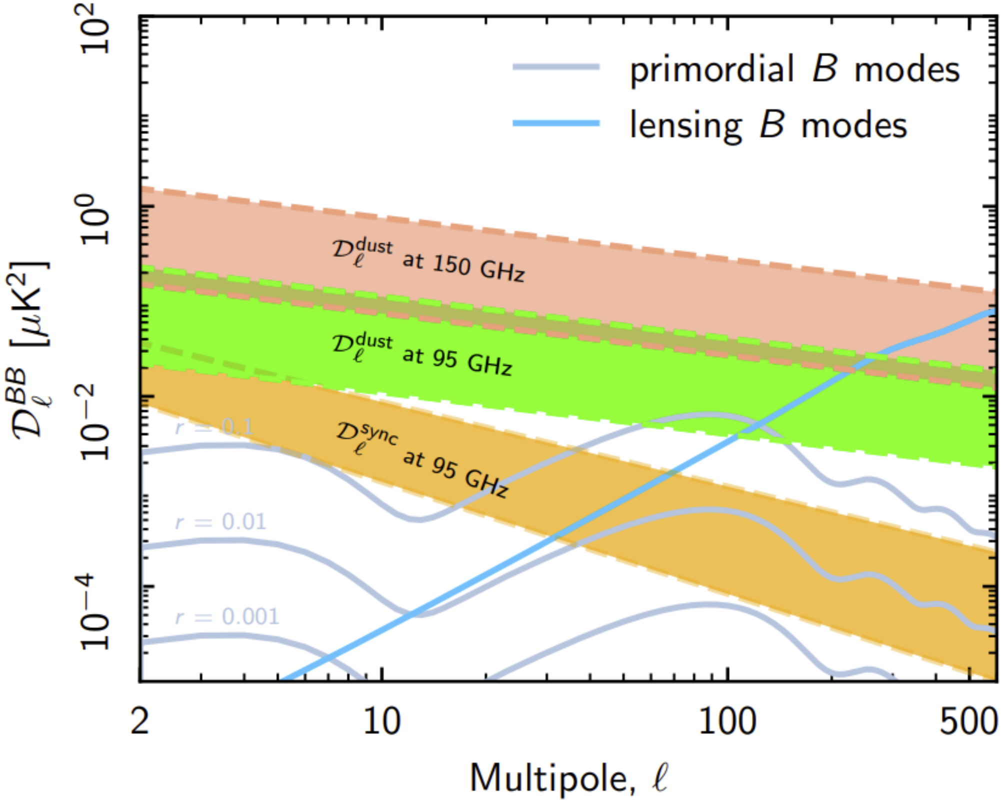
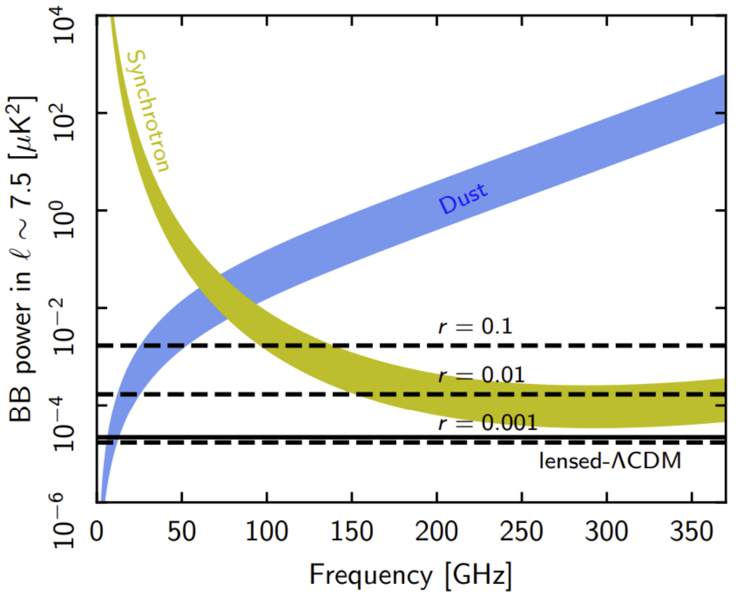


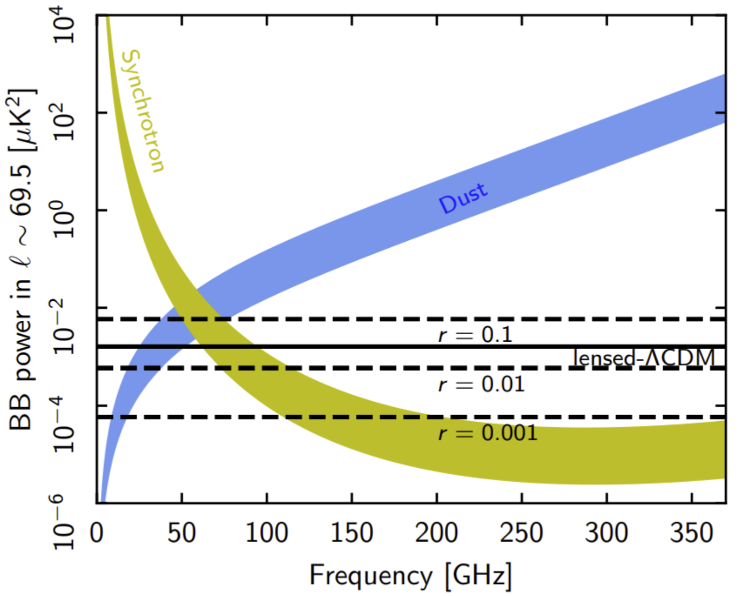
Fig. 12. Dust and synchrotron B-mode power versus multipole. The dust power at 95 and 150 GHz, and that of synchrotron at 95 GHz are compared with CMB B modes from primordial gravitational waves (grey lines) for three values of the tensor-to-scalar ratio, r = 0.1, 0.01, and 0.001, and from lensing (blue line) for the *Planck* 2015 ΛCDM model (Planck Collaboration XIII 2016). The coloured bands show the range of power measured from the smallest (LR24) to the largest (LR71) sky regions in our analysis. The lower limit of the synchrotron band is derived from the S-PASS data analysis in Krachmalnicoff et al. (2018).

From Planck 2018 results - XI. Polarized dust foregrounds

Fig. 13. Dust and synchrotron B-mode power versus frequency for two multipole bins: ℓ = 4–11 (*top*) and 60–79 (*bottom*). The coloured bands show the range of power measured from the smallest (LR24) to the largest (LR71) sky regions in our analysis. The lower limit of the synchrotron band is derived from the S-PASS data analysis in Krachmalnicoff et al. (2018). The primordial CMB B-mode signal, averaged within the appropriate ℓ bin, is plotted with dashed lines for three values of the tensor-to-scalar ratio: r = 0.1; 10^{-2}; and 10^{-3}. The solid line represents the lensing B-mode signal for the *Planck* 2015 ΛCDM model (Planck Collaboration XIII 2016).

- Take away message: B-mode subdominant wrt galactic polarization at all frequencies.
- Only solution: make multiband measurements, estimate and subtract (polarized components separation, many methods).
- **1) Need many observation bands to do this.**
- **2) beware of *decorrelations***

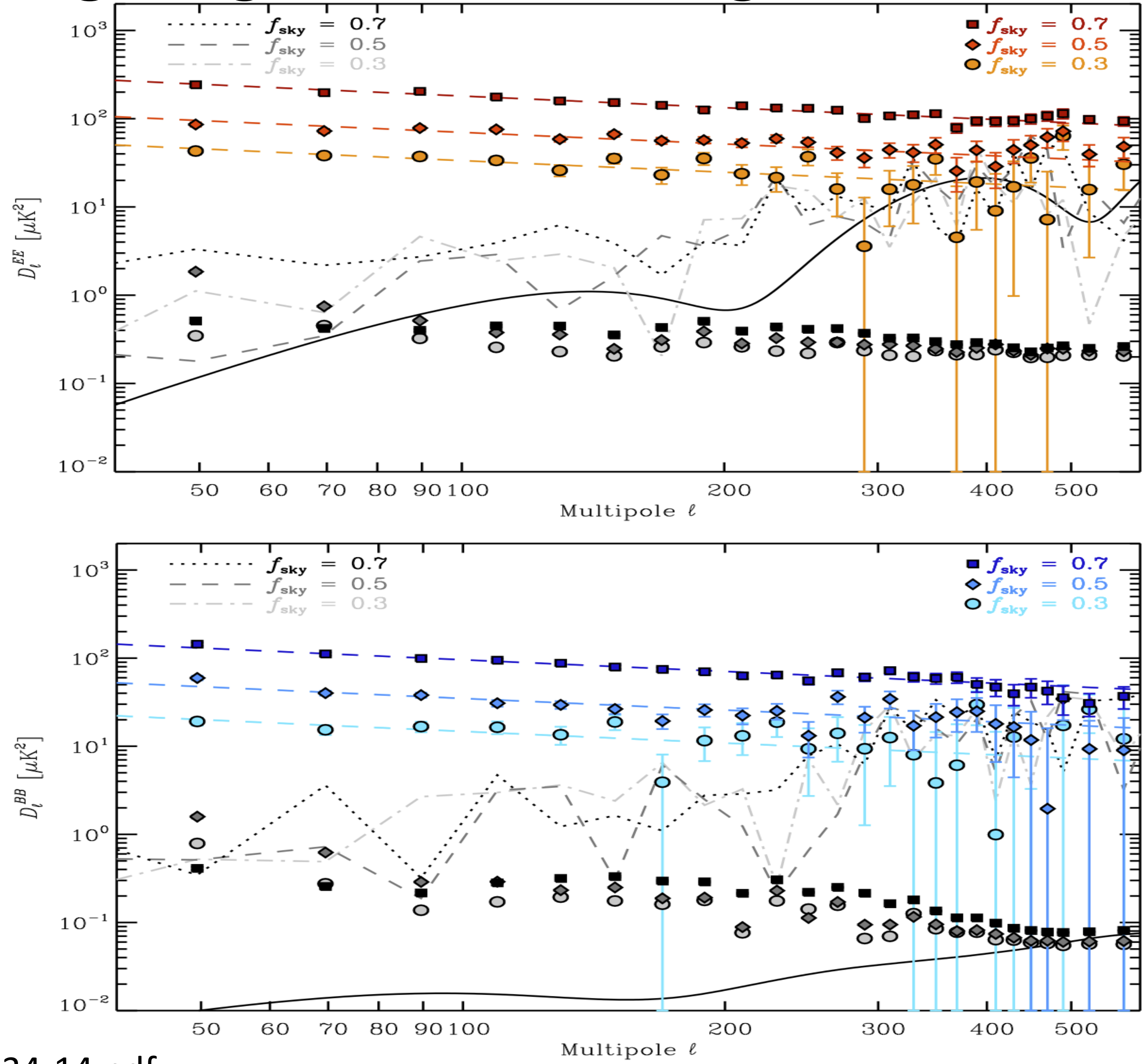




https://www.aanda.org/articles/aa/pdf/2020/09/aa32618-18.pdf

Systematic effects – Mitigating Polarized Foregrounds

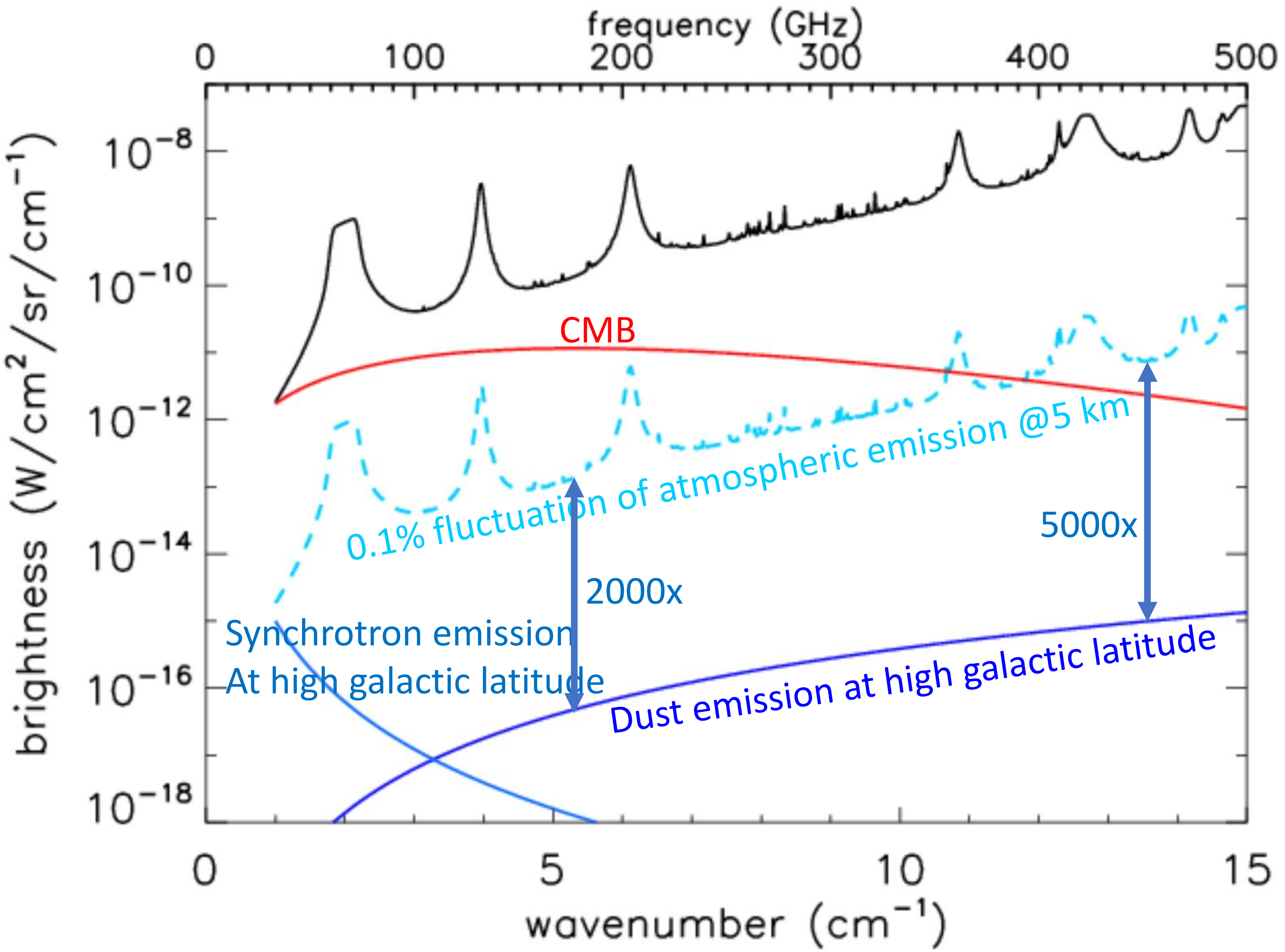
- Interstellar dust emission is an important polarized foreground, with spectrum steeply rising with frequency.
- Note EE similar to BB for the 353 GHz sky …



https://www.aanda.org/articles/aa/pdf/2016/02/aa25034-14.pdf

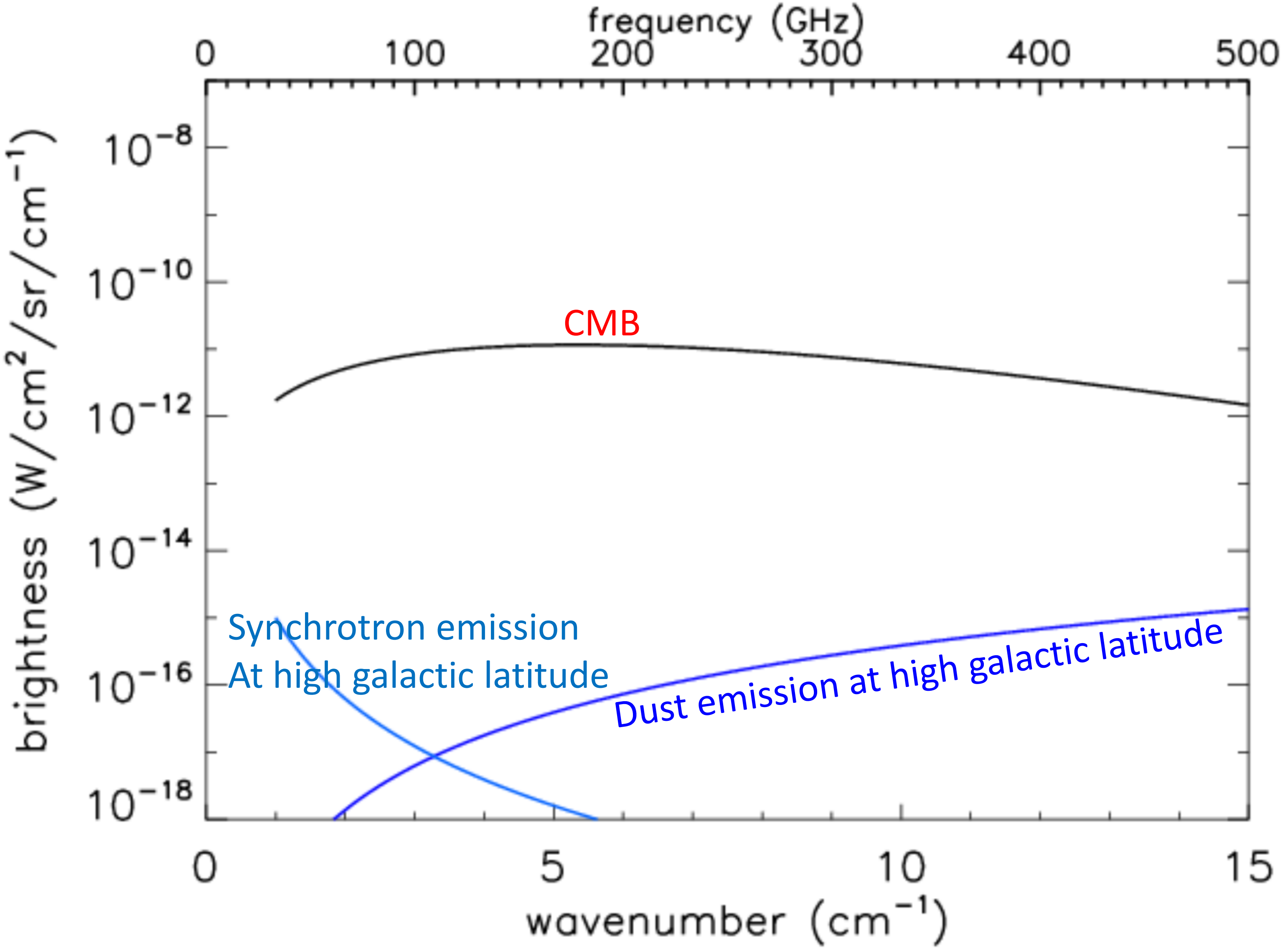
Systematic effects – Mitigating Polarized Foregrounds

- Very difficult to monitor it with the required accuracy from the ground, due to overwhelming and variable atmospheric emission, expecially at the largest scales, where dust polarization is larger.
- However, high frequency measurements are essential to monitor and subtract the tiny, yet important, dust polarization signal at low frequency.
- This measurement simply cannot be done from the ground.



Systematic effects – Mitigating Polarized Foregrounds

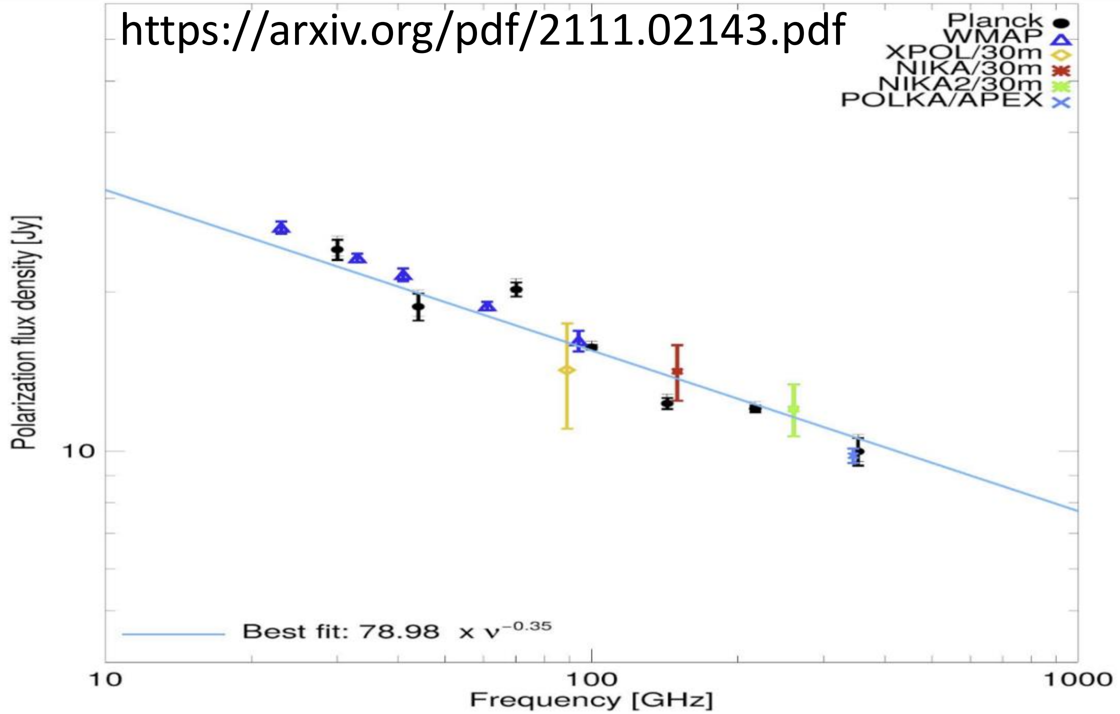
- Very difficult to monitor it with the required accuracy from the ground, due to overwhelming and variable atmospheric emission, expecially at the largest scales, where dust polarization is larger.
- However, high frequency measurements are essential to monitor and subtract the tiny, yet important, dust polarization signal at low frequency.
- This measurement simply cannot be done from the ground.
- This clearly calls for a space mission with several bands above 180 GHz (the largest usable frequency from ground).
- Also in this sense, LiteBIRD represents a ***unique opportunity*** for CMB polarization measurements: ***it's the only way to obtain a full sky, sensitive and accurate map of dust polarization, while performing the most sensitive survey yet of CMB polarization.***

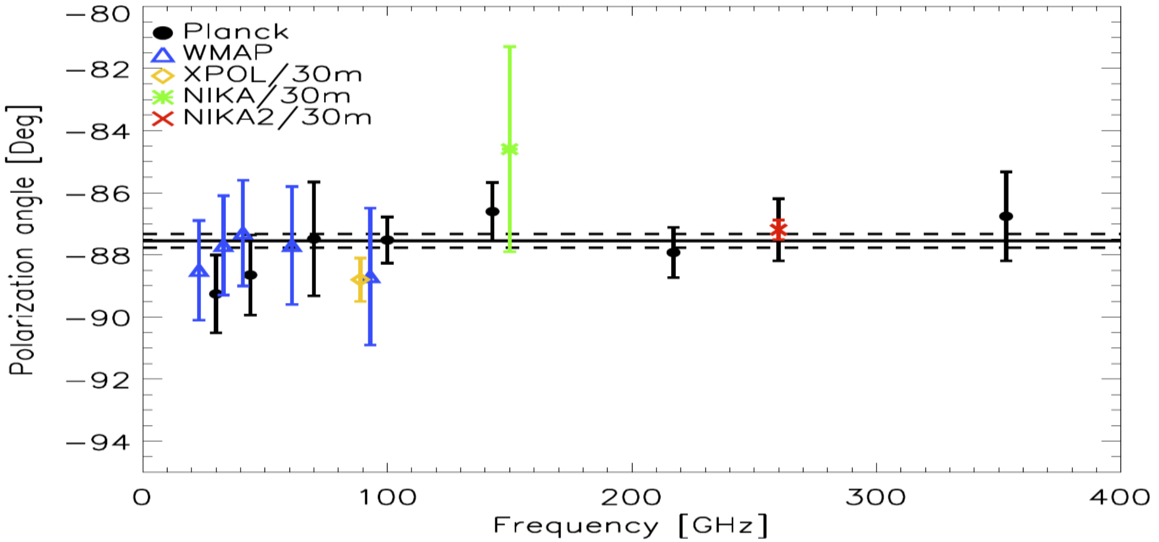


Gain and Polarimetric Calibration

- Best way to calibrate a polarimeter: look at a well characterized source during the survey.
- To date, there's no such thing. We have to work hard to procure one in time for the LiteBIRD survey.
- The largest polarized signal in the mm-wave sky comes from the ***Crab Nebula***.
- To date, its polarization signal and polarization angle are known with insufficient accuracy (we need ~1')
- The measurement errors might be improved by ***better calibrating the instruments***, with a drone/satellite source.

https://arxiv.org/pdf/2111.02143.pdf

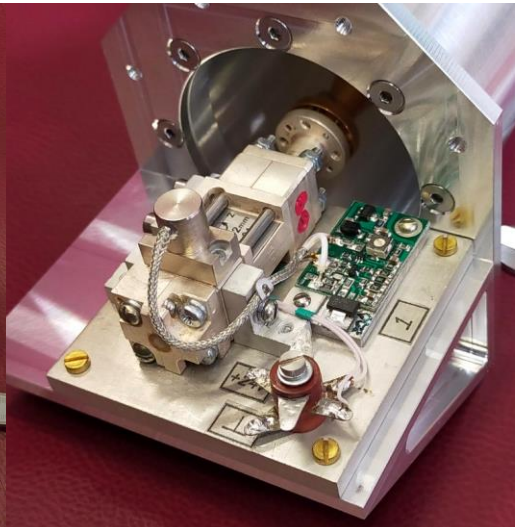


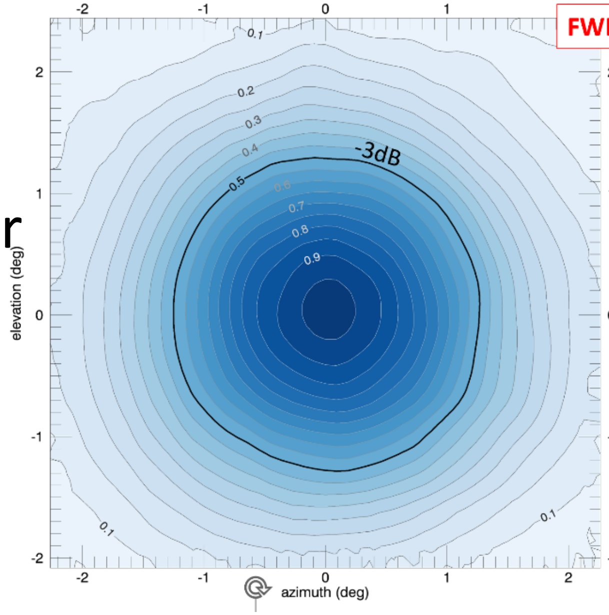


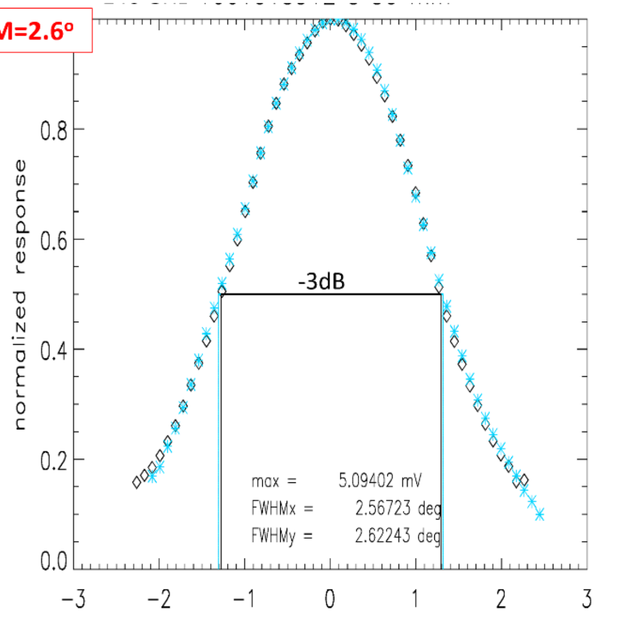
Gain and Polarimetric Calibration

SAPIENZA
UNIVERSITÀ DI ROMA

- Using an air/space borne high purity polarized source to calibrate ground/balloon borne polarimeters was proposed long ago. *Johnson, B., et al., Journal of Astronomical Instrumentation, 4, 1550007-65, (2015) – arXiv 1505.07033*
- Drone-based sources have been developed by the Torino group and by the Milano Bicocca group. A concern due to drone altitude limitations is the resulting ground pickup, due to the low elevation pointings of the telescope to be calibrated. This can be mitigated performing the measurements in the near field and correcting.
- Satellite based sources have been proposed by several groups. These suffer for the short scan time and demanding ACS requirement for the LEO implementation, and for the limited number of sites to be served in the geostationary implementation.
- In Sapienza we have built two of such sources (95 and 140 GHz) as a contribution to an industrial study with TASI.
- A coordination effort within LiteBIRD is underway.







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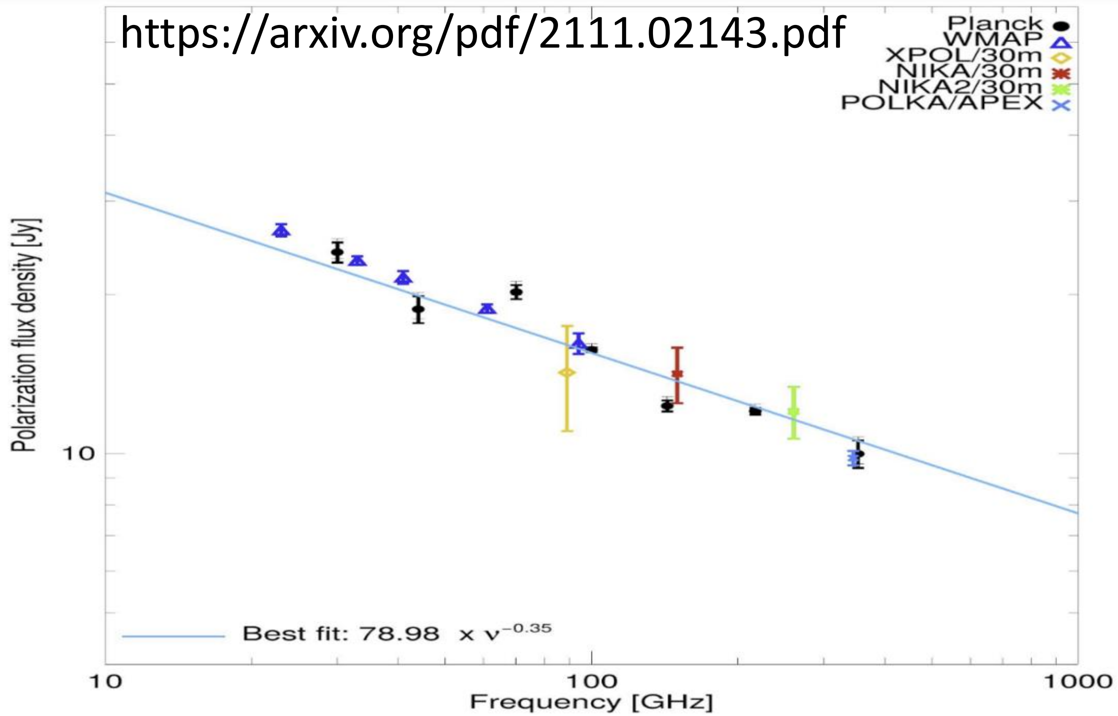
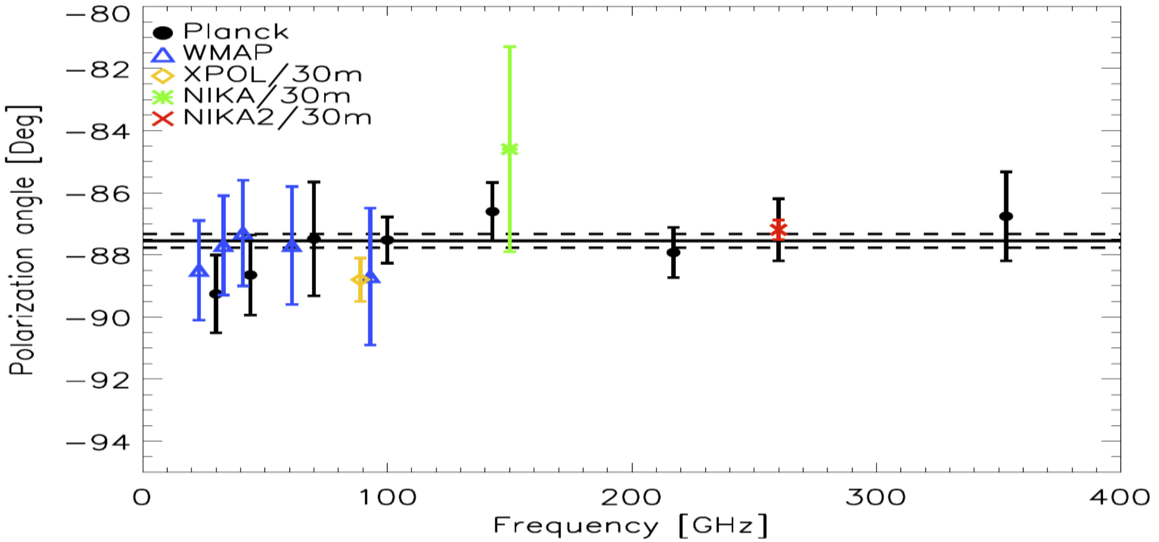
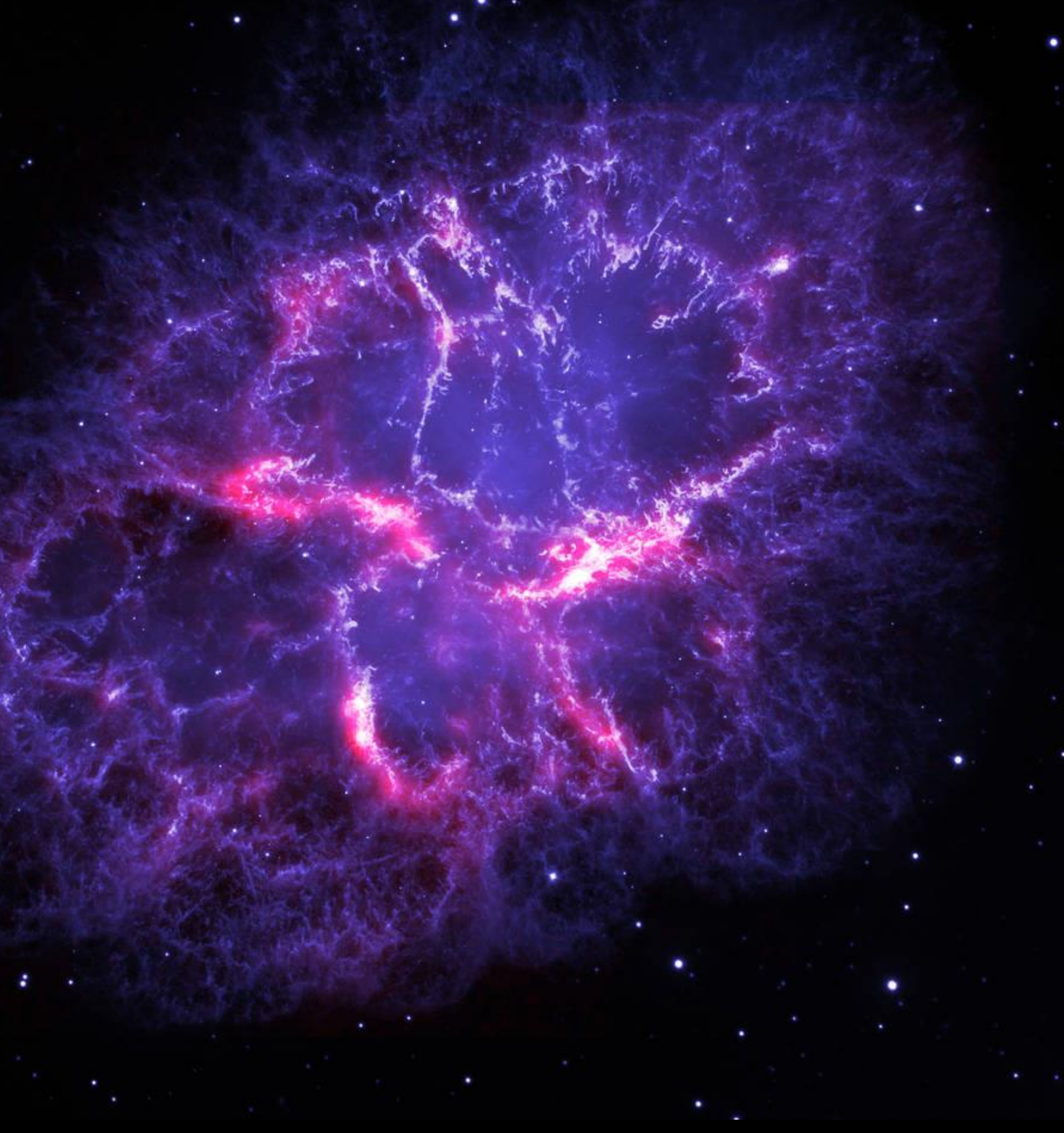
- The largest polarized signal in the mm-wave sky comes from the ***Crab Nebula***.
- To date, its polarization signal and polarization angle are known with insufficient accuracy (we need ~1')
- The measurement errors might be improved by ***better calibrating the instruments***, with a drone/satellite source.
- But there is an additional fundamental issue, related to the fact that ***the Crab lies close to the galactic plane, where diffuse polarized emission from the ISM is not negligible***.





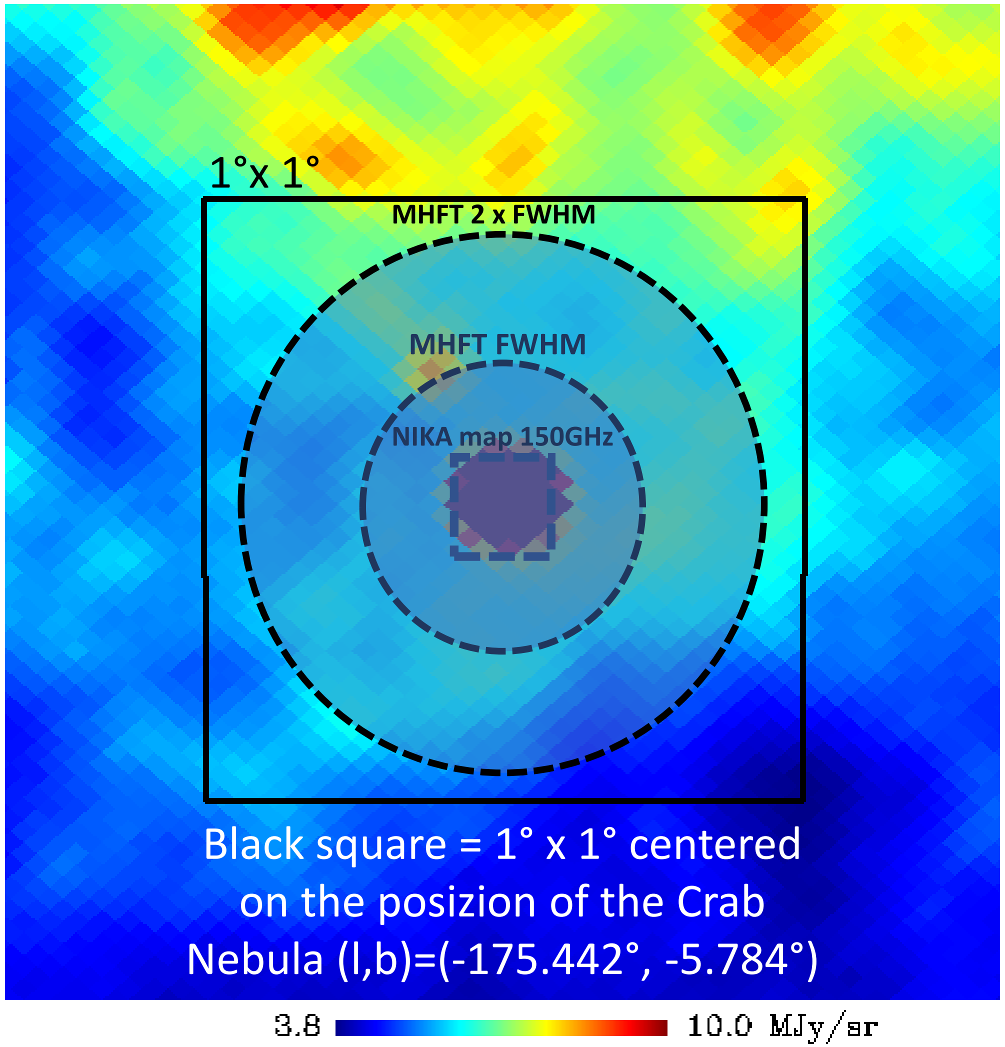
Gain and Polarimetric Calibration

- Masi+ (2021 ApJ 921 34) have analyzed the problem of contamination of the polarized signal from the CRAB, due to the polarized diffuse emission of the ISM. The study uses polarized Planck maps to assess the issue.
- This is relevant for instruments with beamwidth larger than the source, like LiteBIRD.
- The main conclusion is that diffuse polarized emission affects the measurements of the polarization angle ψ in the Crab direction, when observed with a wide beam instrument like LiteBIRD, especially at high frequency. This requires wide (1°- 2° diameter), accurate reference maps to use the Crab as an angle calibrator.

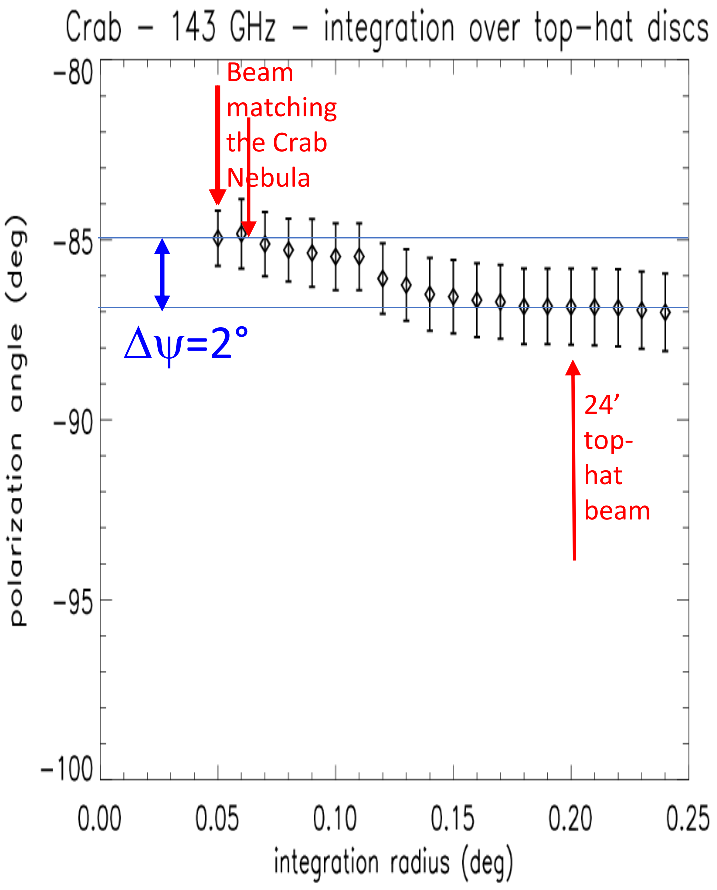


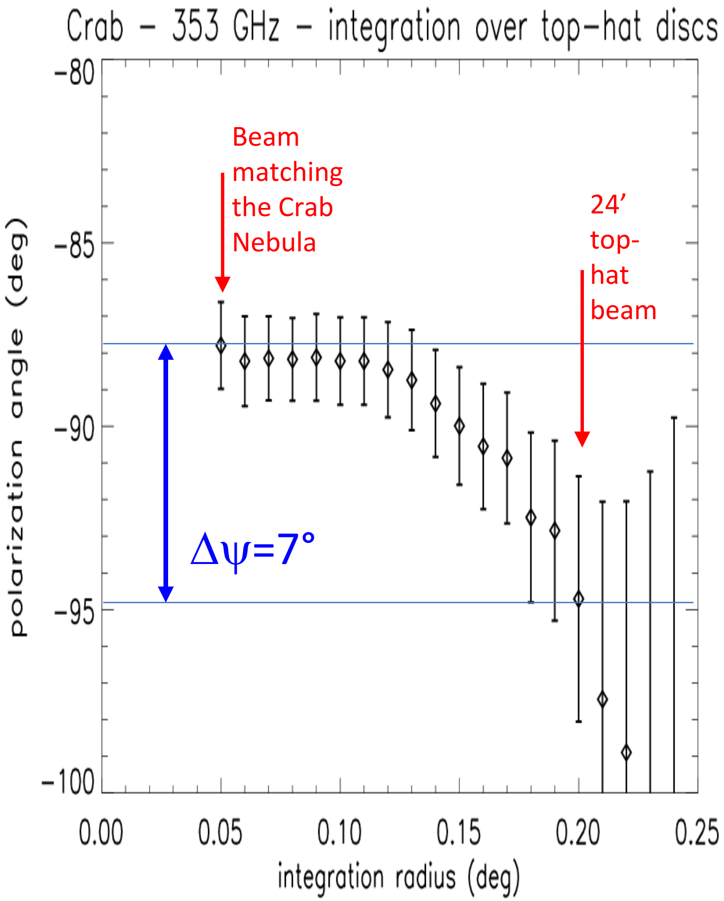
Gain and Polarimetric Calibration

Planck 545 GHz – Stokes I



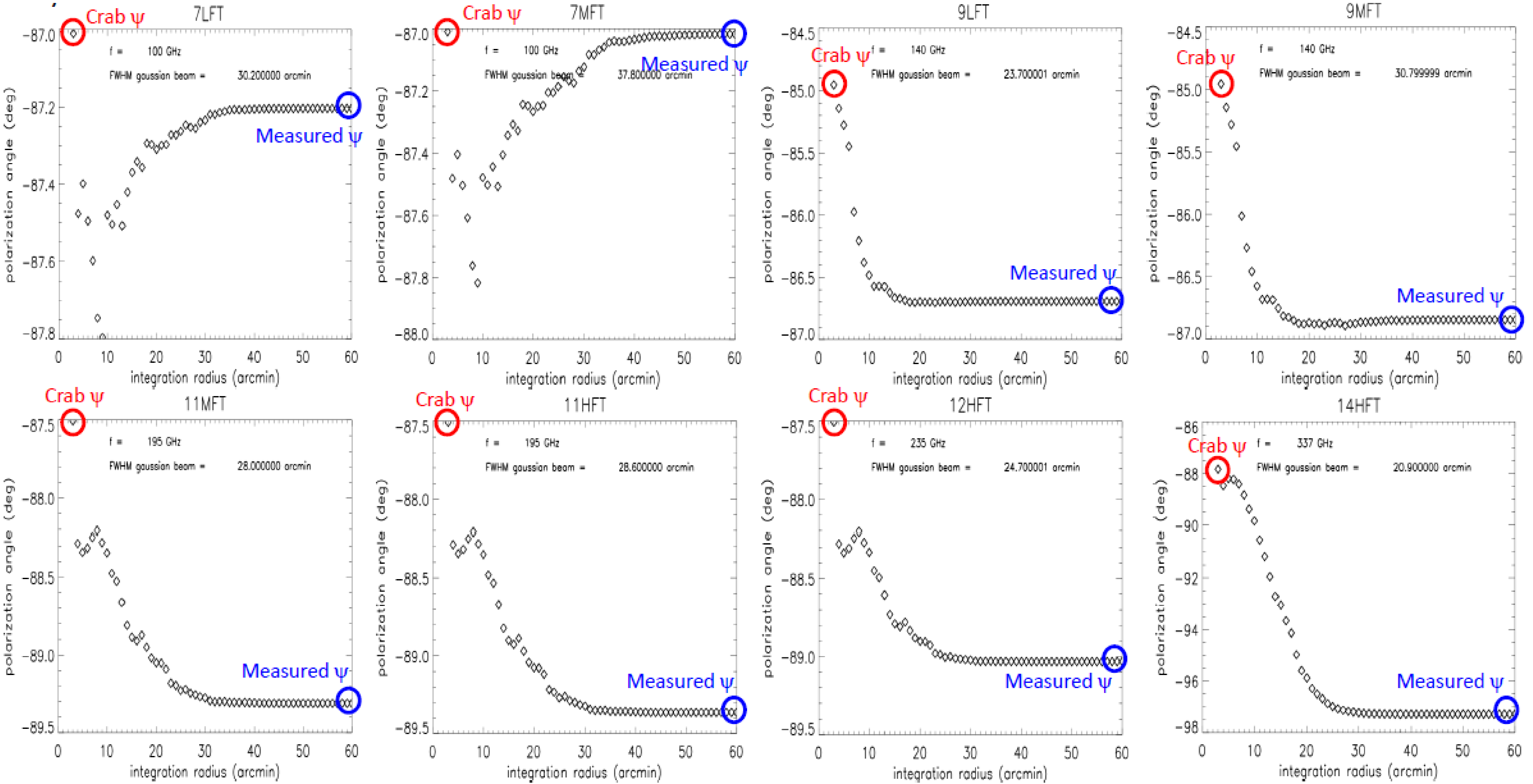
$$\psi = \frac{1}{2}\tan^{-1}\left(\frac{U_m}{Q_m}\right) \qquad Q_m = \int_{\Omega_b} Q(l,b)d\Omega\,,\ U_m = \int_{\Omega_b} U(l,b)d\Omega$$





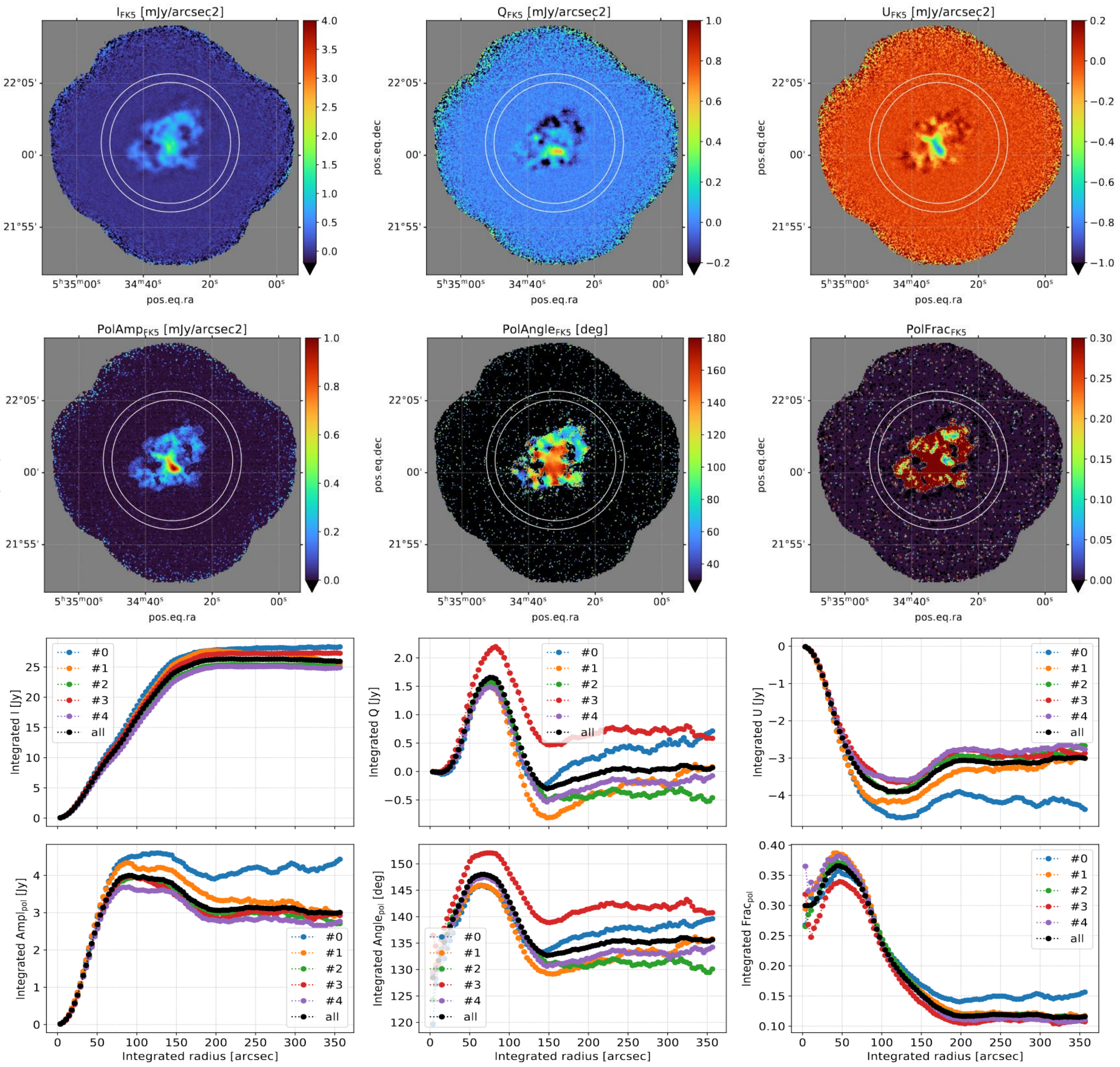
Gain and Polarimetric Calibration

- In the Gaussian beam approximation, for all channels, accurate knowledge of the sky is required over a 2° diameter disk (where the ψ angle change becomes < 1’). Note that different instruments will measure different polarization angles at the same frequency.



Gain and Polarimetric Calibration

- Procuring high fidelity polarization maps centered on the Crab nebula for all the frequencies of interest of LiteBIRD will be very challenging.
- A very first effort started with a proposal to observe tau-A with scuba-2 at Mauna Kea (Douglas Scott &) at 850μm (350 GHz).
- Time was allocated (2.6h) and data were taken.
- The preliminary, demanding analysis (Shunsuke Honda &, Daniel Rodrigues &) demonstrates how difficult it is to obtain this kind of information from ground-based experiments.
- Note the size of the maps (very small) and the day-to-day dispersion of the results.
- This program will require very large dedicated efforts !



Summary

- LiteBIRD covers the entire sky with extreme sensitivity, in a wide frequency range, in an extremely stable operating environment.
- This allows for coverage of the low-multipoles ($\ell < 40$) range, which is not accessible to ground-based experiments, and the measurement of dust polarization, which, again, is not accessible to ground-based experiments.
- For these reasons LiteBIRD is the best candidate to convincingly detect B-mode polarization of primordial origin.
- However, the experiment is extremely ambitious, and poses challenging problems:
  - requires the coordinated operation of extremely ***advanced and complex*** subsystems: most noticeablylarge arrays of multichroic photon-noise limited detectors and cryogenic polarization modulators.
  - Several potentially devastating systematic effects have been identified, and mitigation strategies are in place, requiring dedicated efforts to reach extreme calibration accuracy and custom developed procedures and analysis pipelines.
- The development will be long. Strategies must be implemented to support the effort of ***all*** the contributors (***HW specialists***, data analysis experts, theorists), especially the new post-Planck generation which cannot wait for mission data for their carreers, in order to reach the goal.