time: 25min+5min

Scientific challenges expected from future space experiments

T. Matsumura (Kavli IPMU, the Univ. of Tokyo) with various inputs from

Shaul Hanany, Bruno Maffei, Keisuke Yoshihara, Takashi Hasebe, Ryota Takaku, Tommaso Ghigna, Toshiya Namikawa, Thuong Duc. Hoang, Anto Lonappan, Paolo de Bernardis, Adrian Lee, Sophie Henrot-Versillé


PLANCK 2014
THE MICROWAVE SKY IN
TEMPERATURE AND POLARIZATION

Introduction

The goal of my talk is to introduce the nature of **scientific challenges** expected from future space experiments.

I don't necessary provide the answer to them, and ***I believe*** there will be a series of talks that provide the status of the studies in this workshop.

By the end of this workshop, I hope we will share the challenges and foresee some prospects to overcome them without any boundary among space/balloon/ground CMB projects.

Challenge for future space mission?

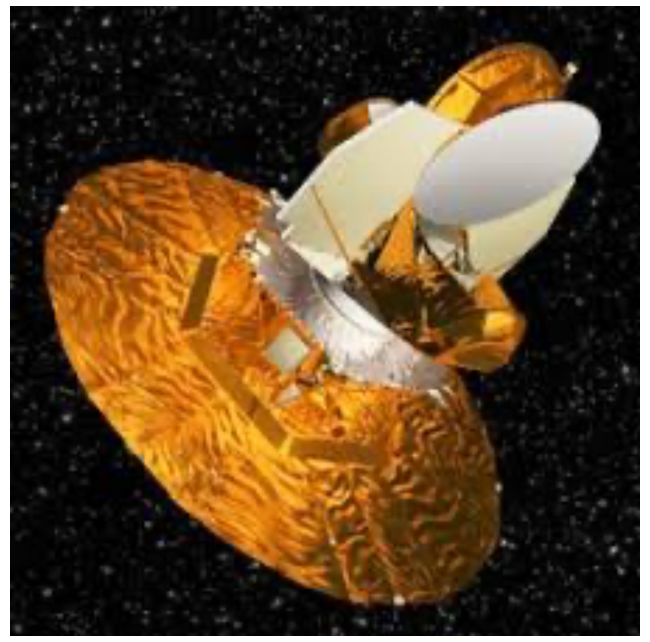
- Choice of the scientific goal?
- Scientific challenge in cosmology itself?
- Foreground challenge?
- Sensitivity challenge?

These are all coupled!

- Systematics and calibration challenge?
- System challenge?
- Instrument component level challenge?
- Computational/Analysis challenge?
- more?

CMB satellites past and future

- **CMB satellites in the past**
  - 1989: NASA COBE
  - 2001: NASA WMAP
  - 2009: ESA Planck



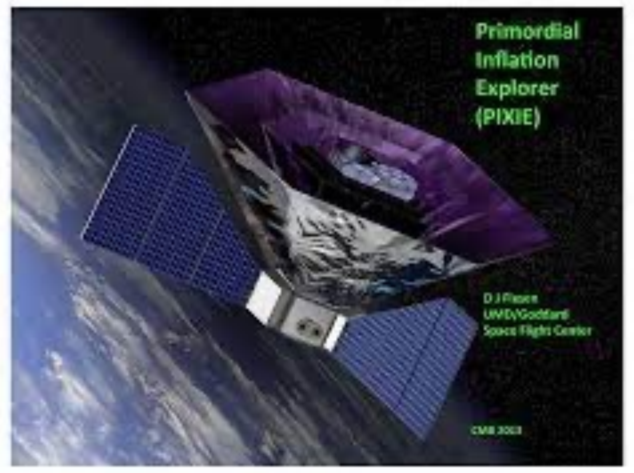
National Aeronautics and Space Administration

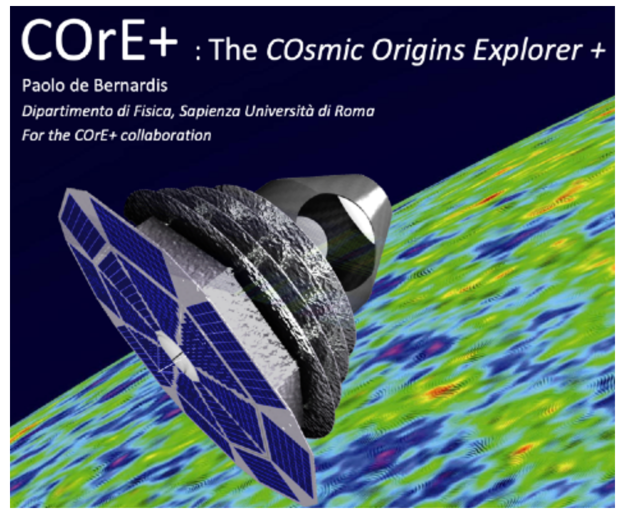
The Experimental Probe of Inflationary Cosmology

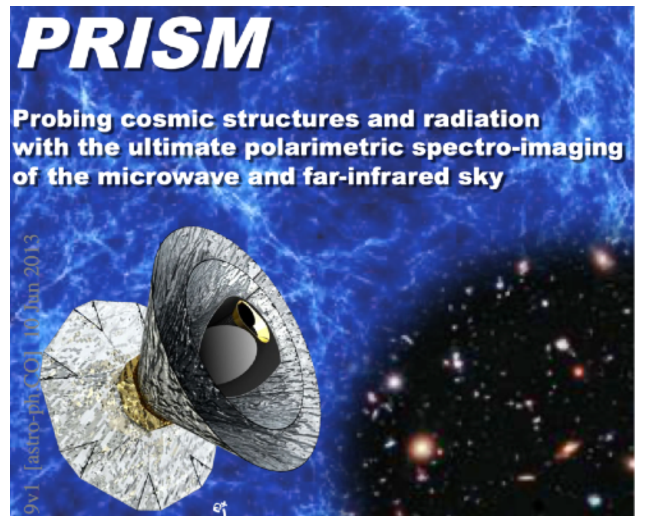
A Mission Concept Study for NASA's Einstein Inflation Probe

COrE
Cosmic Origins Explorer

- **Post Planck mission concept studies**
  - 2010: CMBpol (JPL-led EPIC series…)
  - 201X-2015: COrE/COrE+/PRISM (arXiv:1306.2259)
  - 2019: LiteBIRD - ISAS/JAXA second strategic L-class mission (arXiv:2202.02773)
  - 2020: PICO - NASA Probe scale mission study (arXiv:1902.10541)
  - 201X-: PIXIE (arXiv:1105.2044)
  - 201X-: PRISTINE
  - 201X-: CMB Baharat (arXiv:2110.12362)







PRISTINE

CMB-Bharat
An Indian Cosmology Consortium

LiteBIRD

Great resources to trace what we have been worried in these mission concept studies!

Choice of the scientific goal?

This is the first and probably the biggest branch point for what remaining challenges to face in a CMB space mission. This is true for any projects, but in a space mission there is a clear trade-off: size and mass.

- As seen by the past studies, there are three categories:
  - ***Inflation focus***
    - EPIC-LC/IM?, LiteBIRD
  - ***Inflation + broader science outputs***
    - EPIC-CS/IM?, COrE, COrE+, PRISM, PICO?, CMB-Bharat
  - ***Spectral distortion***
    - PIXIE, PRISTINE

Choice of the scientific goal?

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- As seen by the past studies, there are three categories:
  - ***Inflation focus***
    - EPIC-LC/IM?, LiteBIRD → Potentially compact mission, but science risk?
  - ***Inflation + broader science outputs***
    - EPIC-CS/IM?, COrE, COrE+, PRISM, PICO?, CMB-Bharat → Rich science outcomes but mission feasibility?
  - ***Spectral distortion***
    - PIXIE, PRISTINE → Need space mission, but big jump to make from COBE

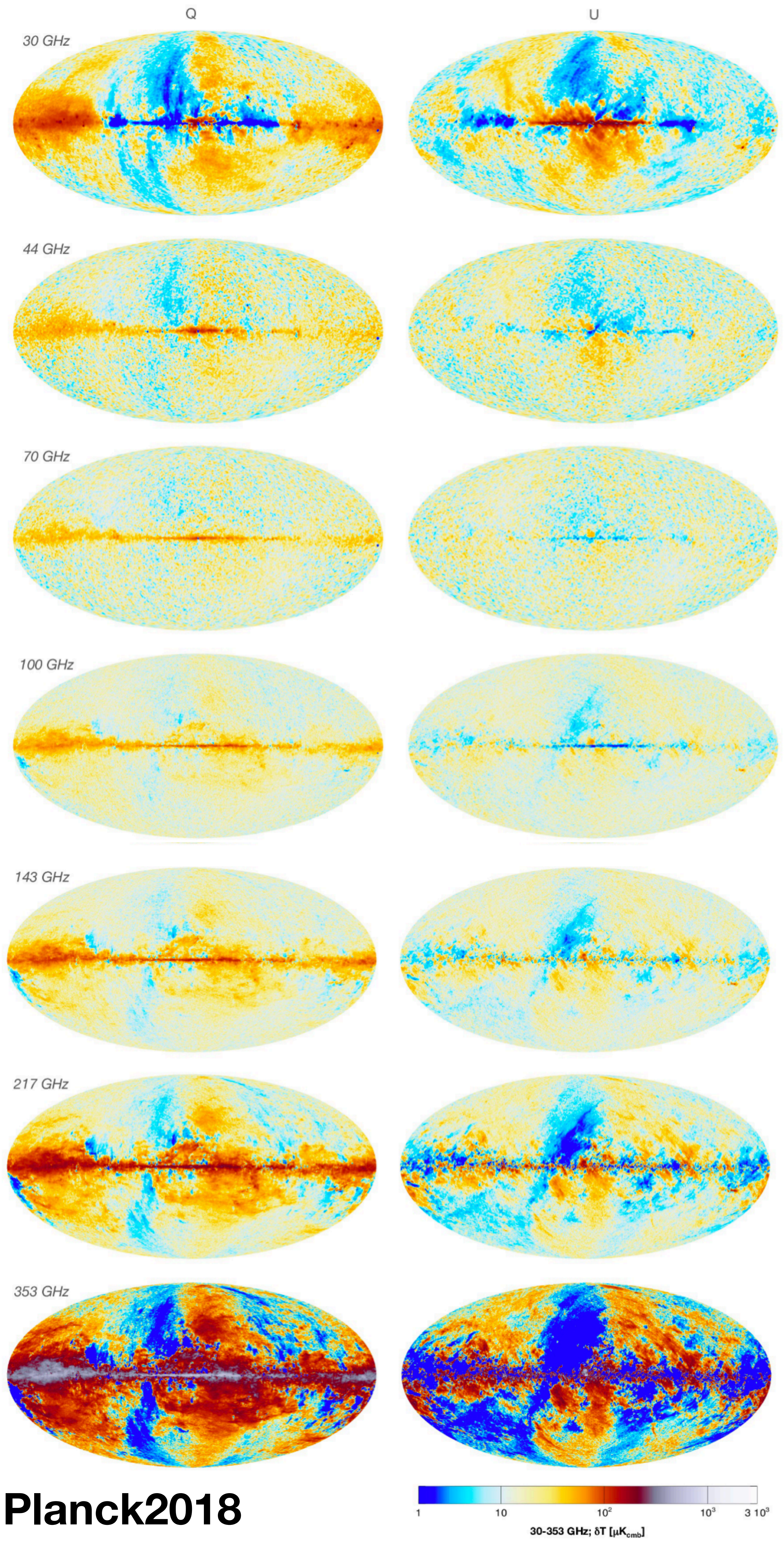
Foreground challenges

Whatever the science goal we set, we need to remove foreground emissions.

``*Within the uncertainties of our analysis, we can conclude that there is no region in the sky where the foreground emission demonstrates to contaminate the CMB B modes at levels lower than a signal with tensor-to-scalar ratio* $r \sim 0.05$.''
N. Krachmalnicoff et al. A&A 588, A65 (2016)

- Planck developed various component separation methods:
  - SMICA, COMMANDER, (G)NILC, SEVEM …
- Any future mission needs to probe deeper than Planck sensitivity, and thus we need to plan for expected and unexpected foreground characteristics.
  - dust single-MBB, synchrotron power-law
  - dust two-MBB, synchrotron curved power-law, AME
  - more…

- **Nicoletta Krachmalnicoff, "Characterization of Foreground emission for CMB experiments: current status and future prospective"**
- **Mathieu Remazeilles, "Next steps in component separation for new CMB observables"**



Planck2018

Sensitivity challenges

For primordial B-modes, the bulk of the power comes from low-ell

CMB only sensitivity argument is as simple as

$$w = \frac{10800}{\pi}\sqrt{\frac{4\pi f_{sky}}{t_{obs}} \cdot \frac{NET^2}{N_{det}/2}}$$

$$2\ \mu K \cdot \textbf{arcmin} = \frac{10800}{\pi}\sqrt{\frac{4\pi \times 1}{3\ \textbf{[year]}} \cdot \frac{50\ \mu K\sqrt{s}}{N_{det}/2}}$$

$N_{det} \sim 2000$

ref: Planck was
LFI: 11 radiometers
HFI: 32 PSBs + 20 SWBs

- The sensitivity to foreground monitor bands + lower f_{sky} adds more detector count.
- Accounting the mission margin adds more detector count.

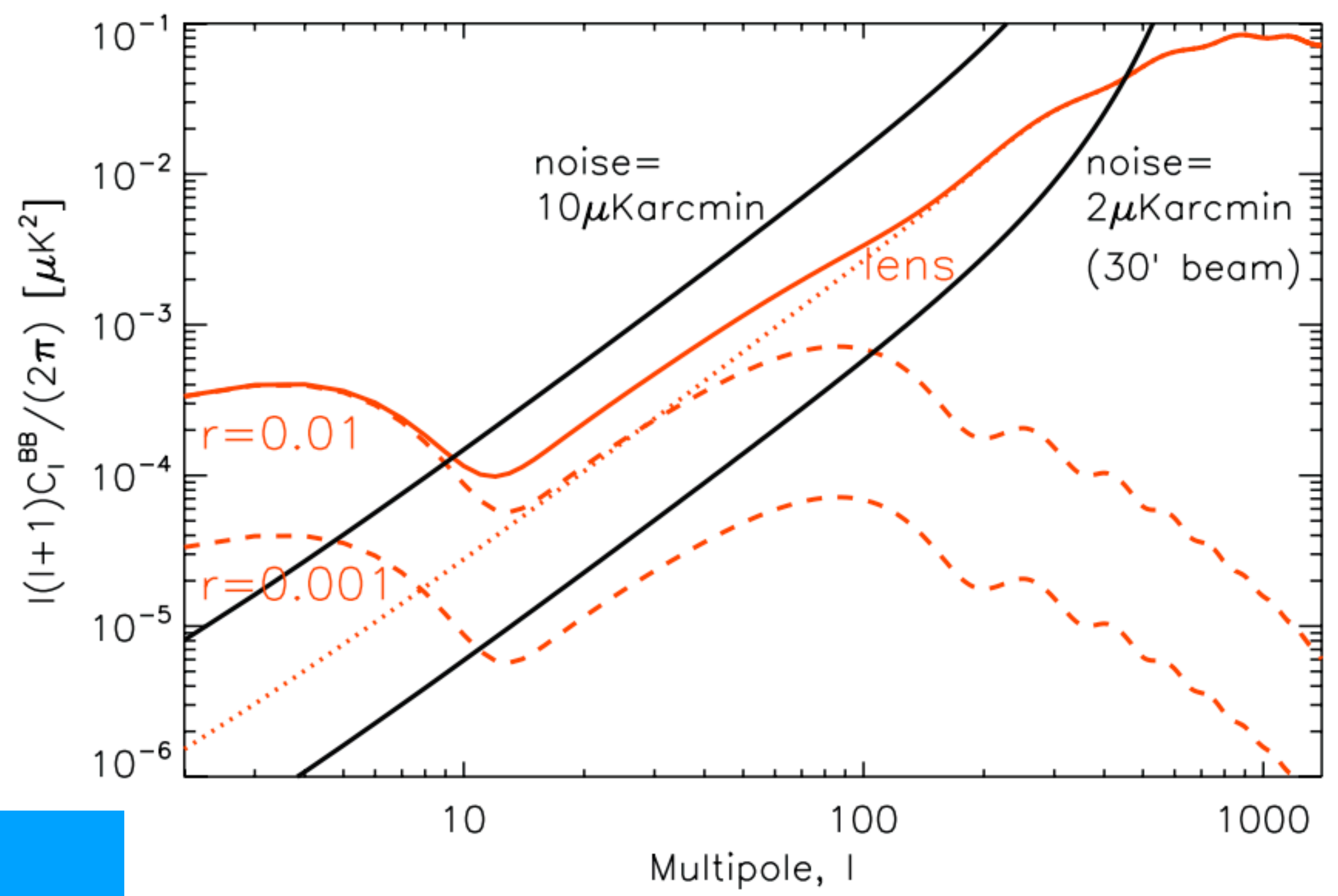
x 2~3?

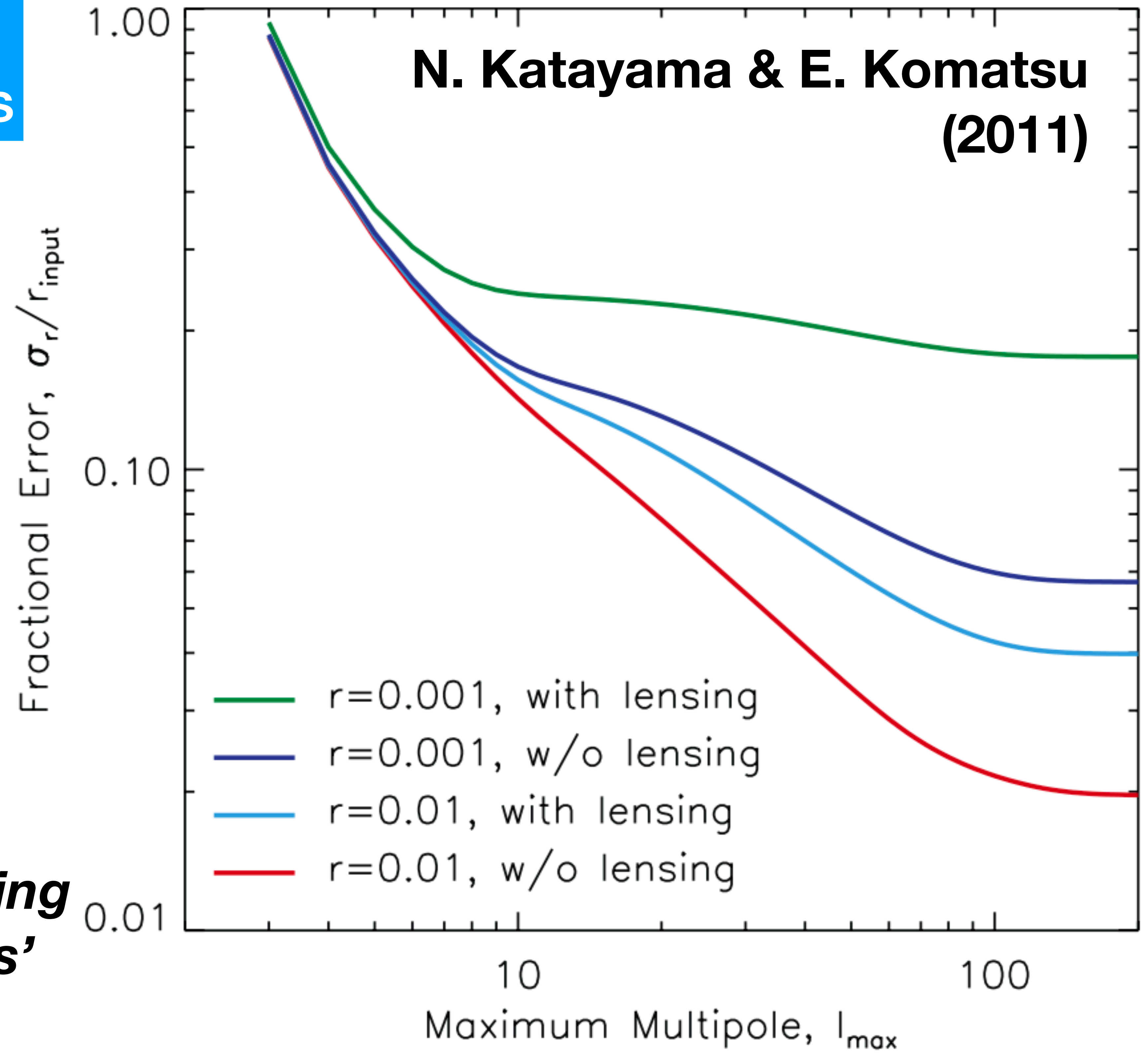
- If one takes into account the self-delensing, a project aims the sensitivity of < 1 μK.arcmin.

x 4-5?

Detector + readout remote fast bias tuning cryogenic challenges' telemetry

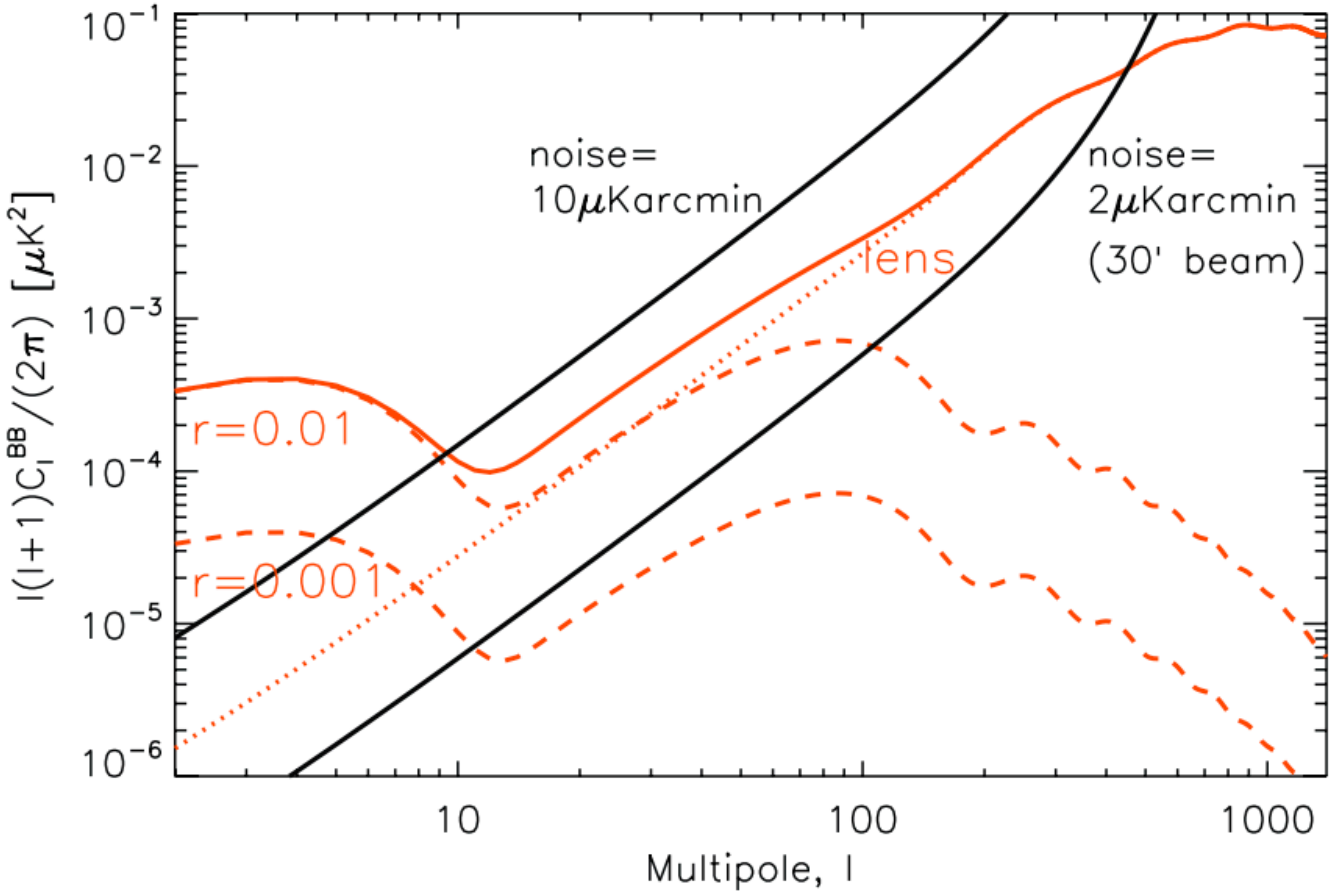
Hannes Hubmayrm, "The shape of CMB focal planes to come"



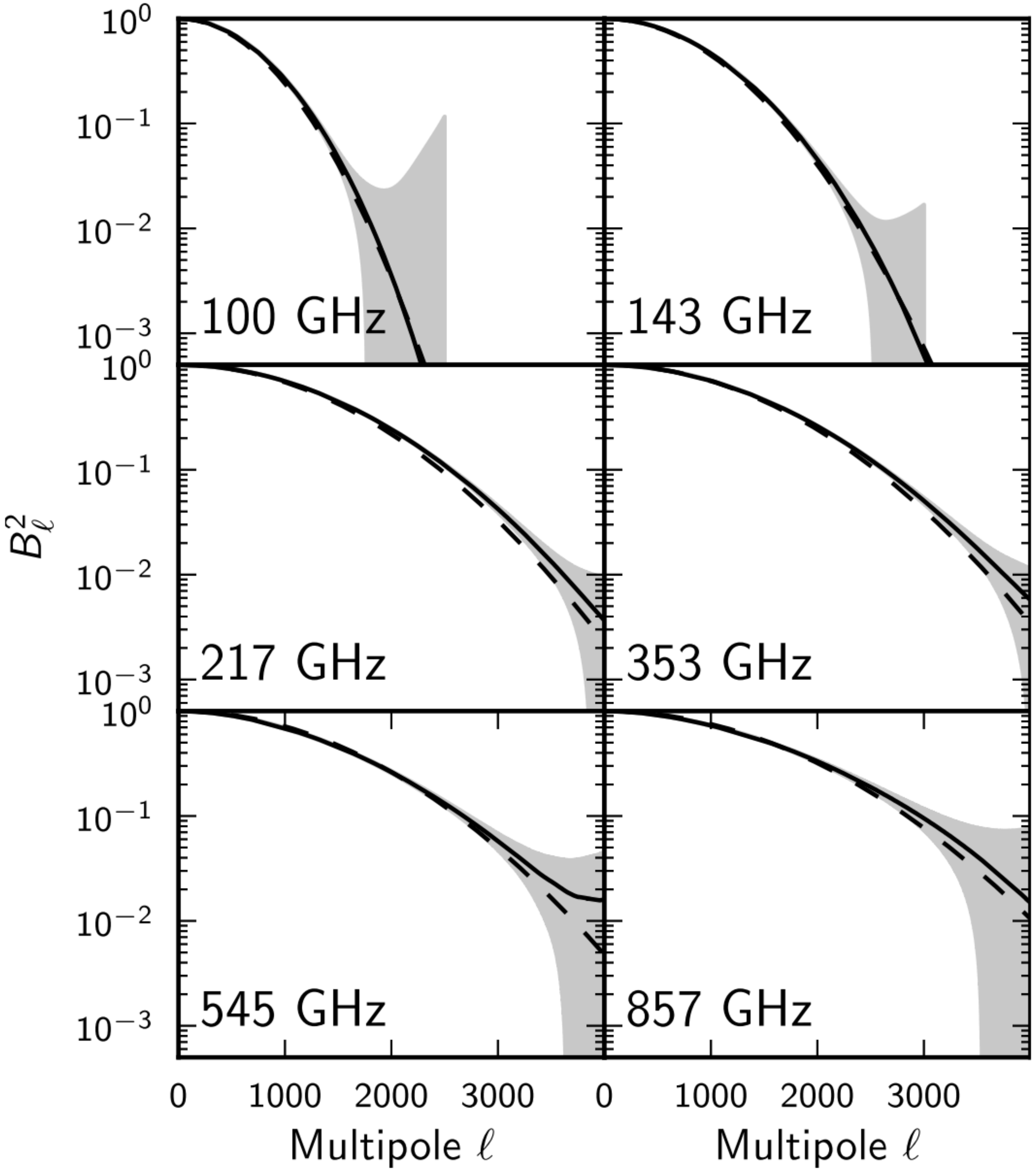


Sensitivity challenges: Angular coverage

N. Katayama & E. Komatsu (2011)



Planck 2013 results. VII



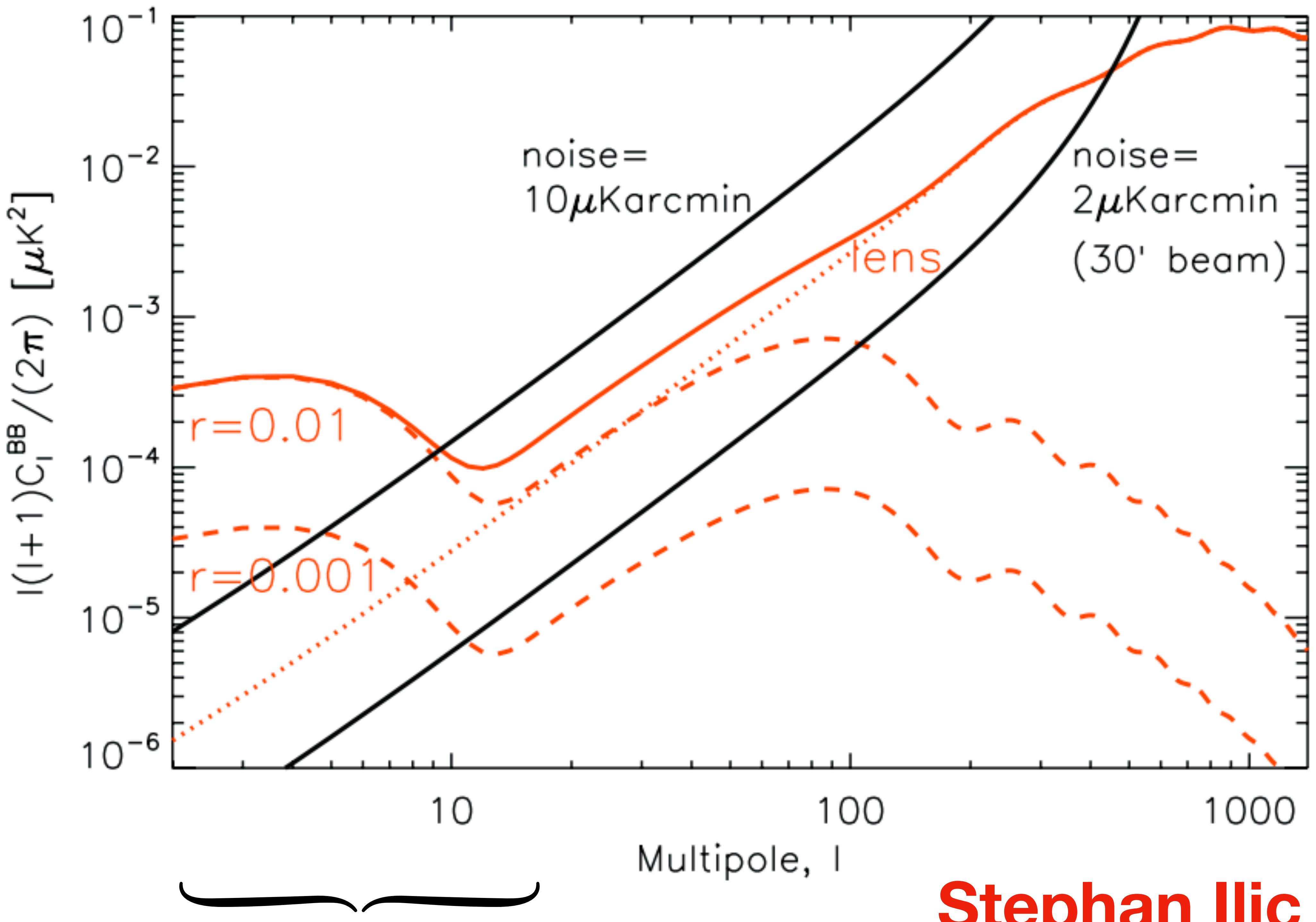
Massimiliano Lattanzi

N_{eff}, **neutrino mass,** n_s, **…** → B_ℓ

The imperfect reconstruction of a detailed beam shape might lead to a false estimation of your science output.

Sensitivity challenges: Angular coverage

N. Katayama & E. Komatsu (2011)



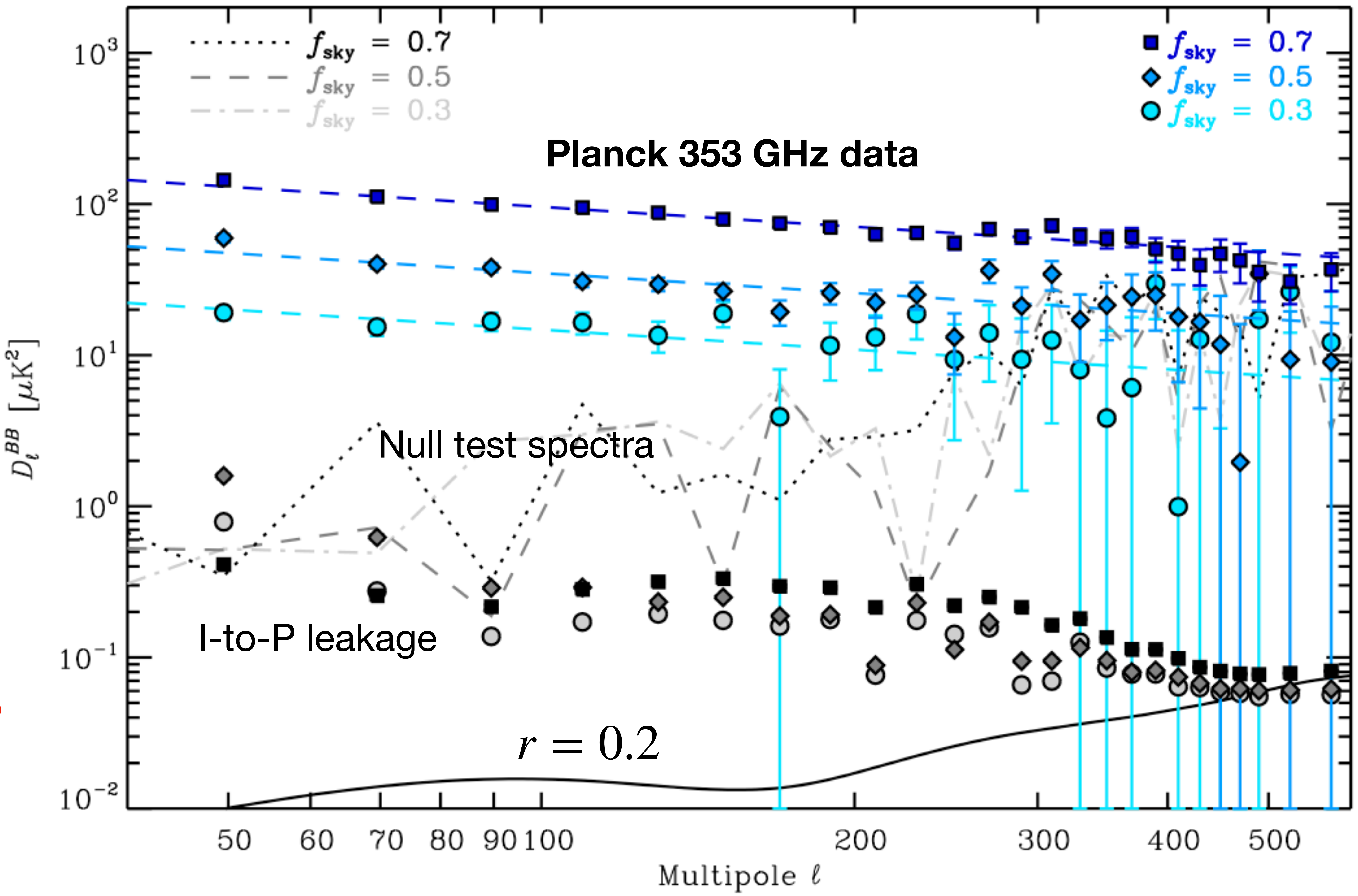
Inflation, reionization

Stephan Ilic
Loris Colombo

Imperfection of the component separation leads to the leakage in

$$T_{cmb}, E_{cmb} \qquad T_{fg}, E_{fg} \rightarrow B_{cmb}$$

Planck intermediate results. XXX



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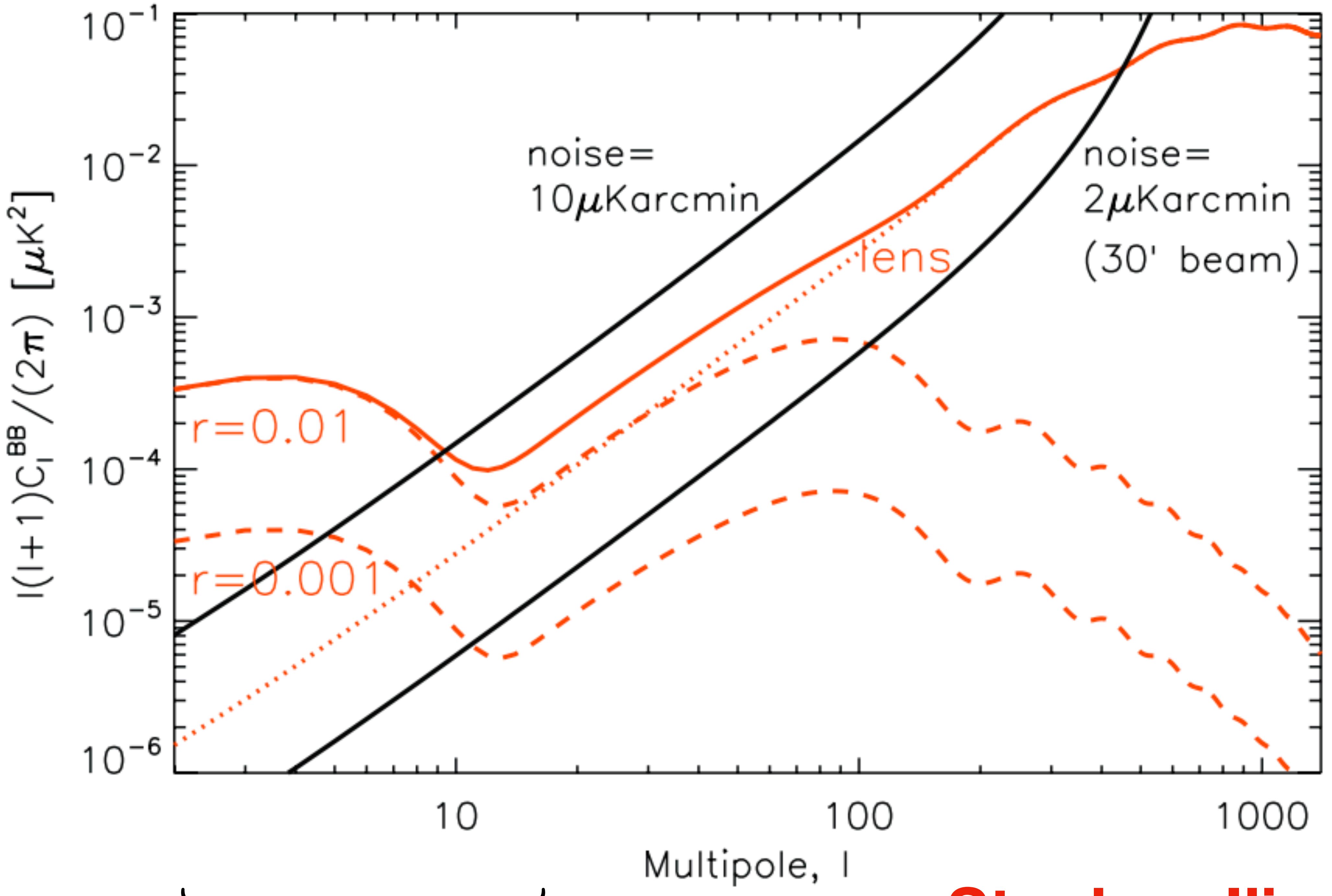

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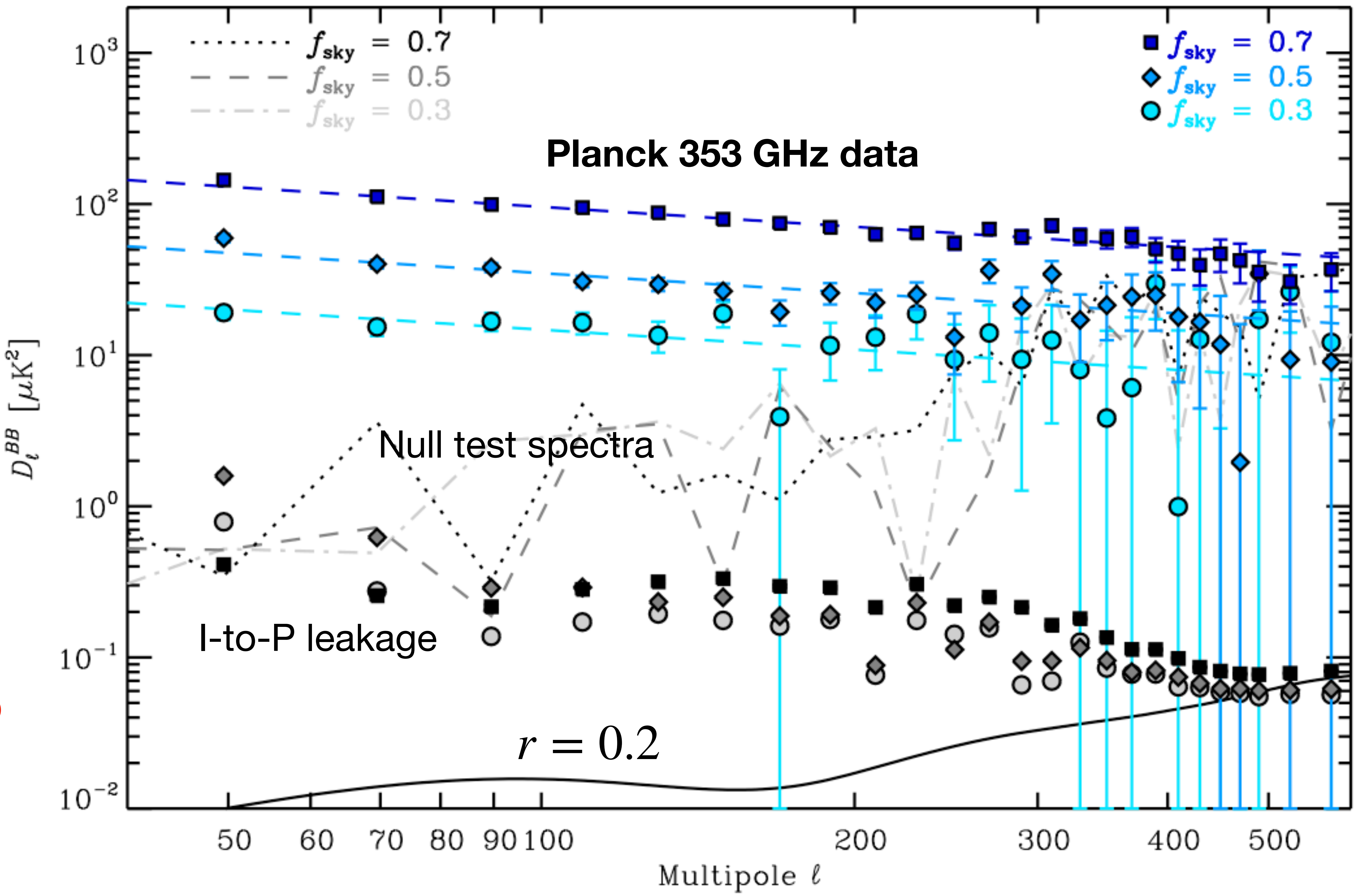


Switching the gear to the systematic effects and calibration

Systematics and calibration challenge?

The required sensitivity becomes so stringent. The systematic effects and calibration uncertainty is the real enemy to fight against.

The space mission has its own nature of systematic effects and calibration challenges. At the same time, the upcoming space mission needs new technology which has never been used. We need to extrapolate from ground and balloon experiences.

- Let's learn from WMAP and Planck → **Charles Lawrence "Lessons from Planck Calibration for Future CMB Experiments"**
- Let's learn from ground-based and balloon-borne experiments.

→ **Paolo de Bernardis (Rome Sapienza University) on "Scientific challenges expected from future balloon experiments"**

Suzanne Staggs (Princeton University) on "Scientific challenges expected from future ground experiments"

Systematics and Calibration: Expected effects

From “Planck pre-launch status: HFI ground calibration” (2010)

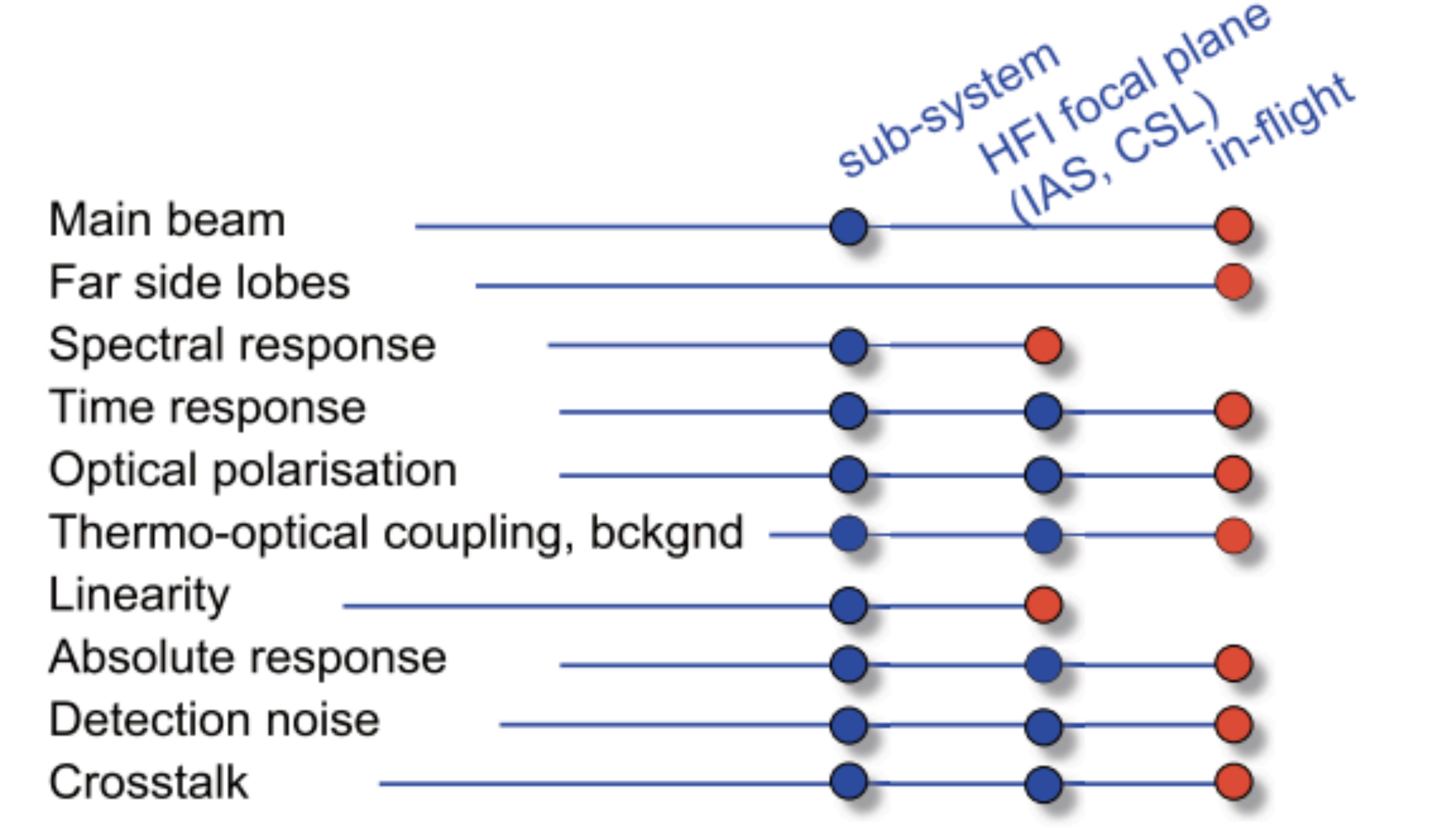
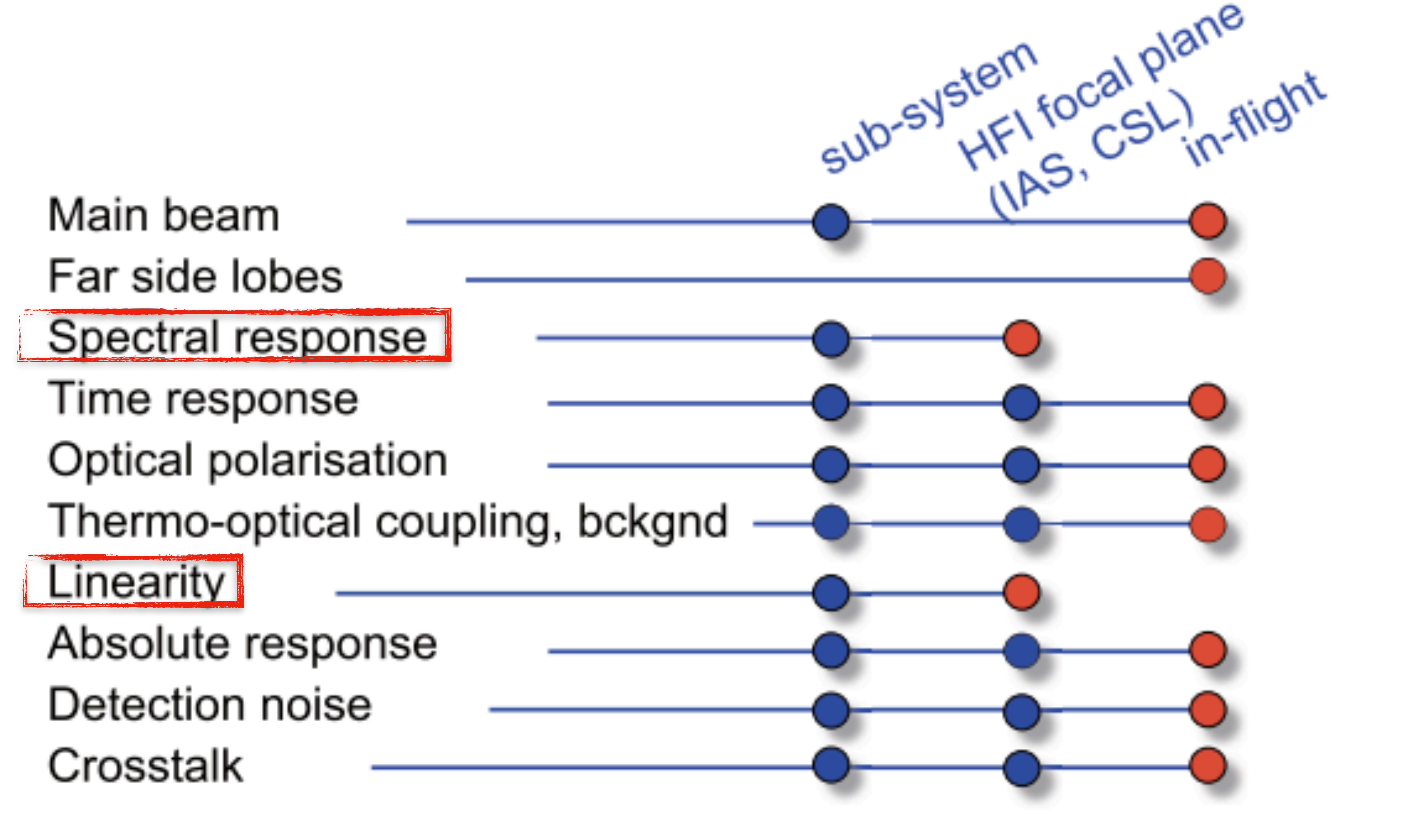


Fig. 1. Calibration philosophy. Blue dots indicate preliminary determinations, red dots indicate final determination.

Systematics and Calibration: Expected effects

From "Planck pre-launch status: HFI ground calibration" (2010)

Two items were not planned to calibrate in-flight.



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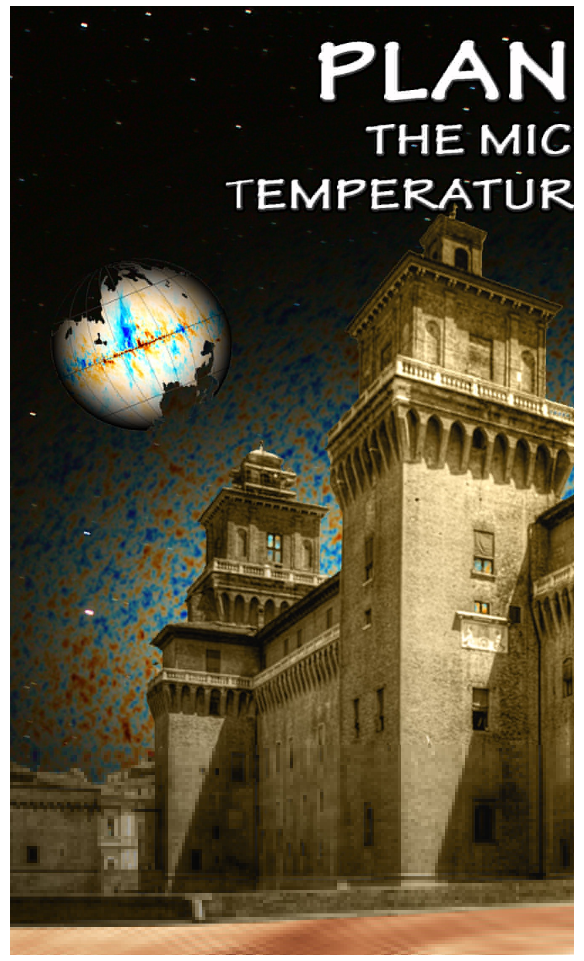
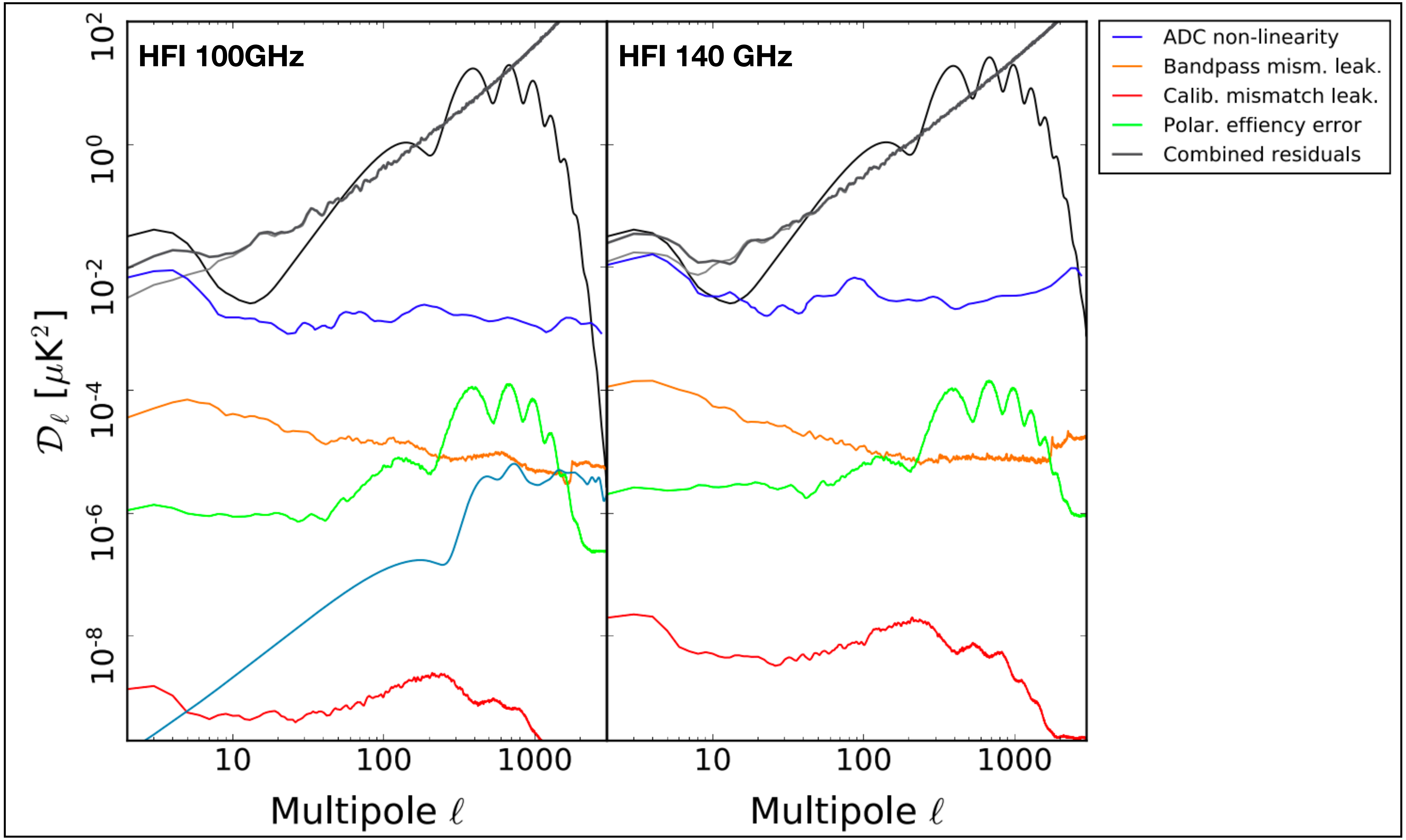
Systematics and Calibration: Expected effects

Two items we
to calibrate ir



Residual systematic effects from Planck 2018 results I



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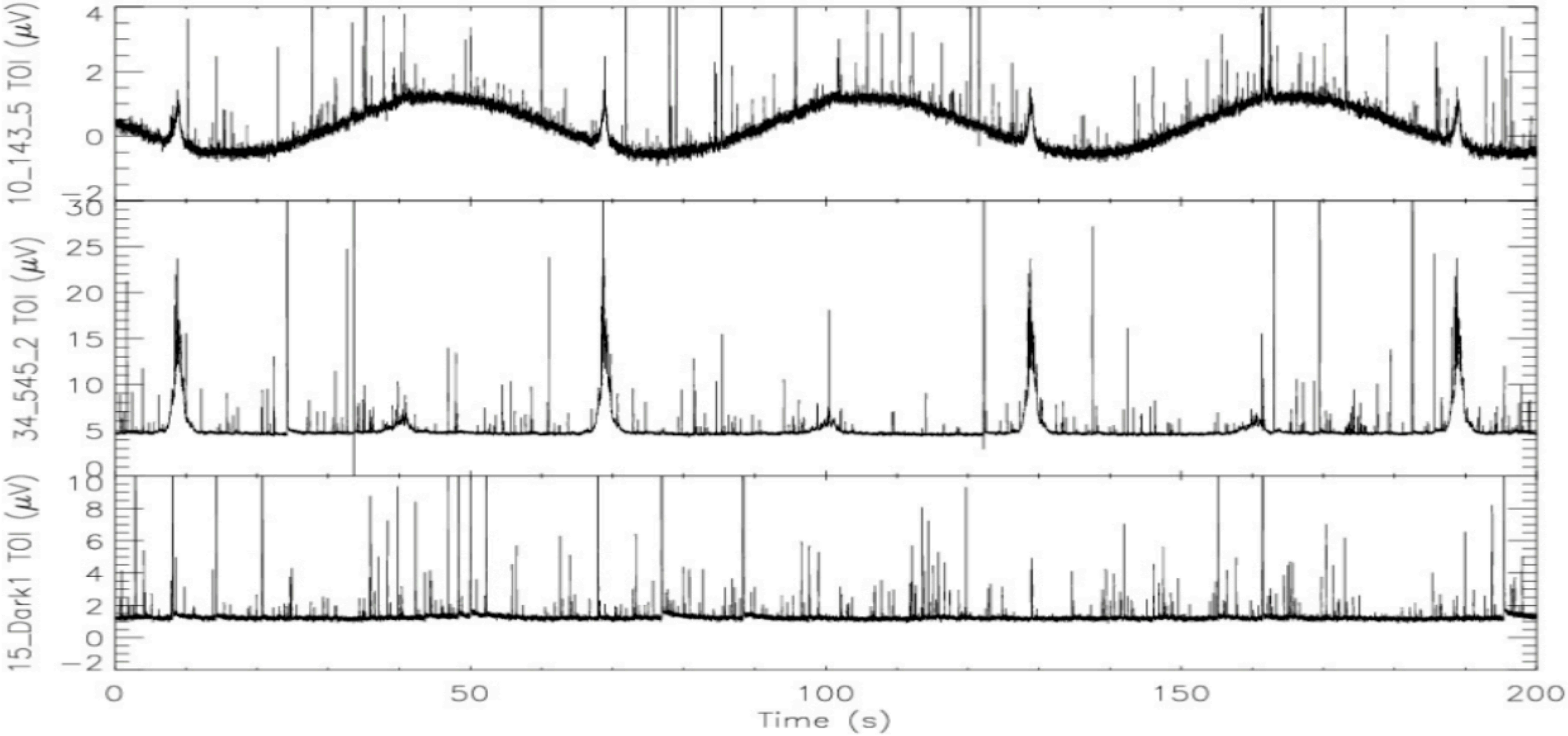
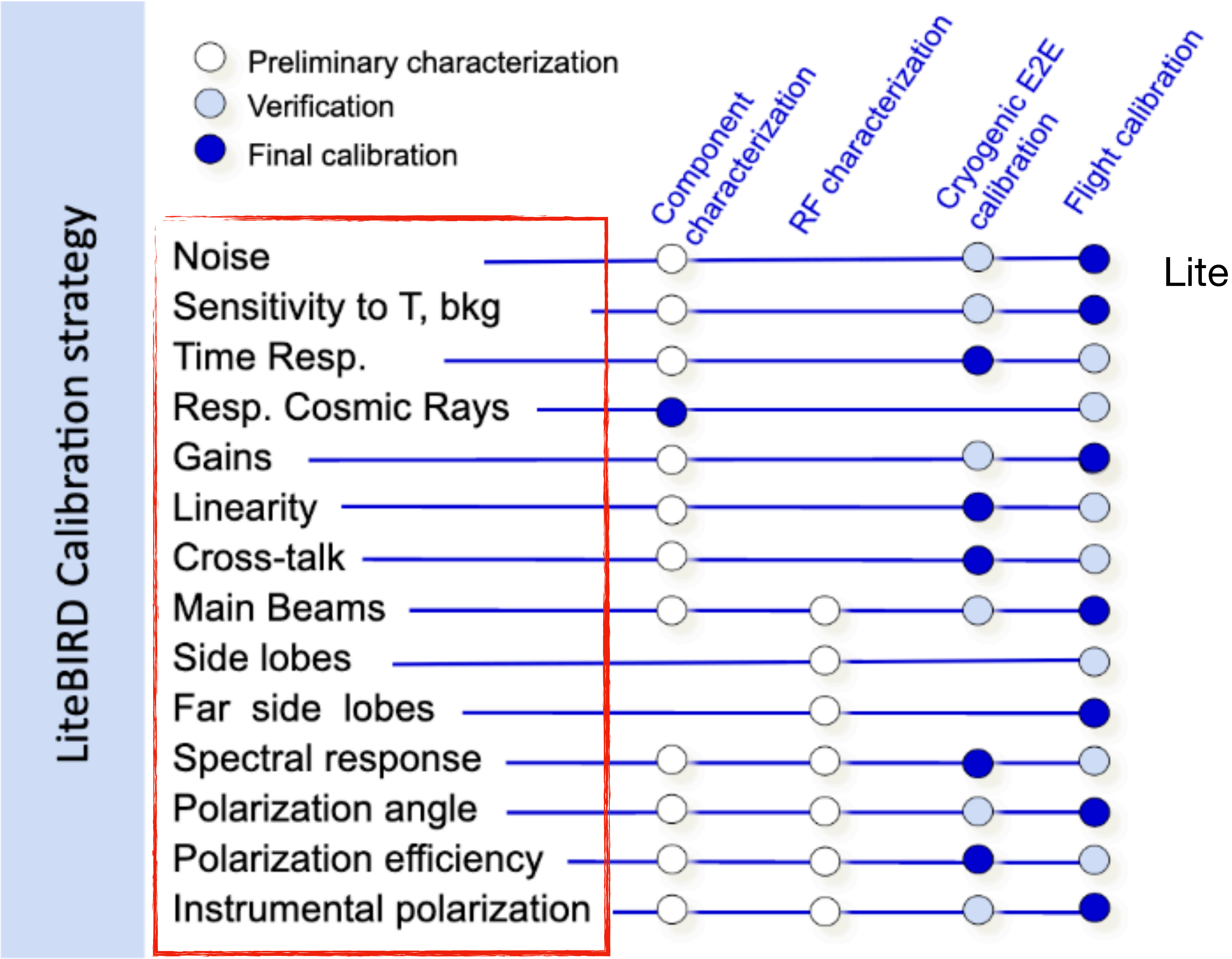
Systematics and Calibration: Unexpected effects

Planck early results (2012)



Estimation of the cosmic ray susceptibility, mitigation by instrument level and/or analysis level?

Systematics and Calibration for future

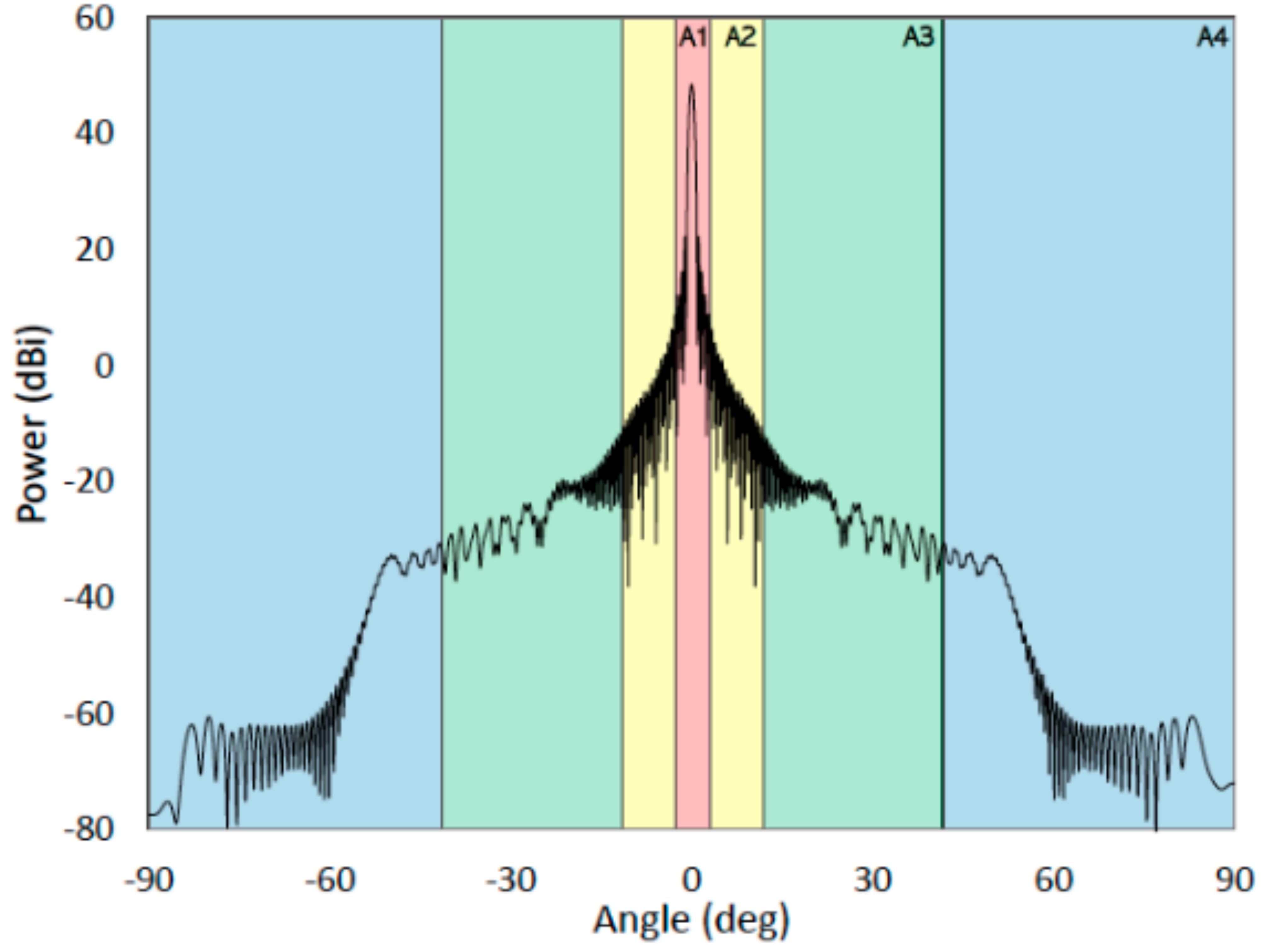


LiteBIRD team listed 70+ systematic effects.

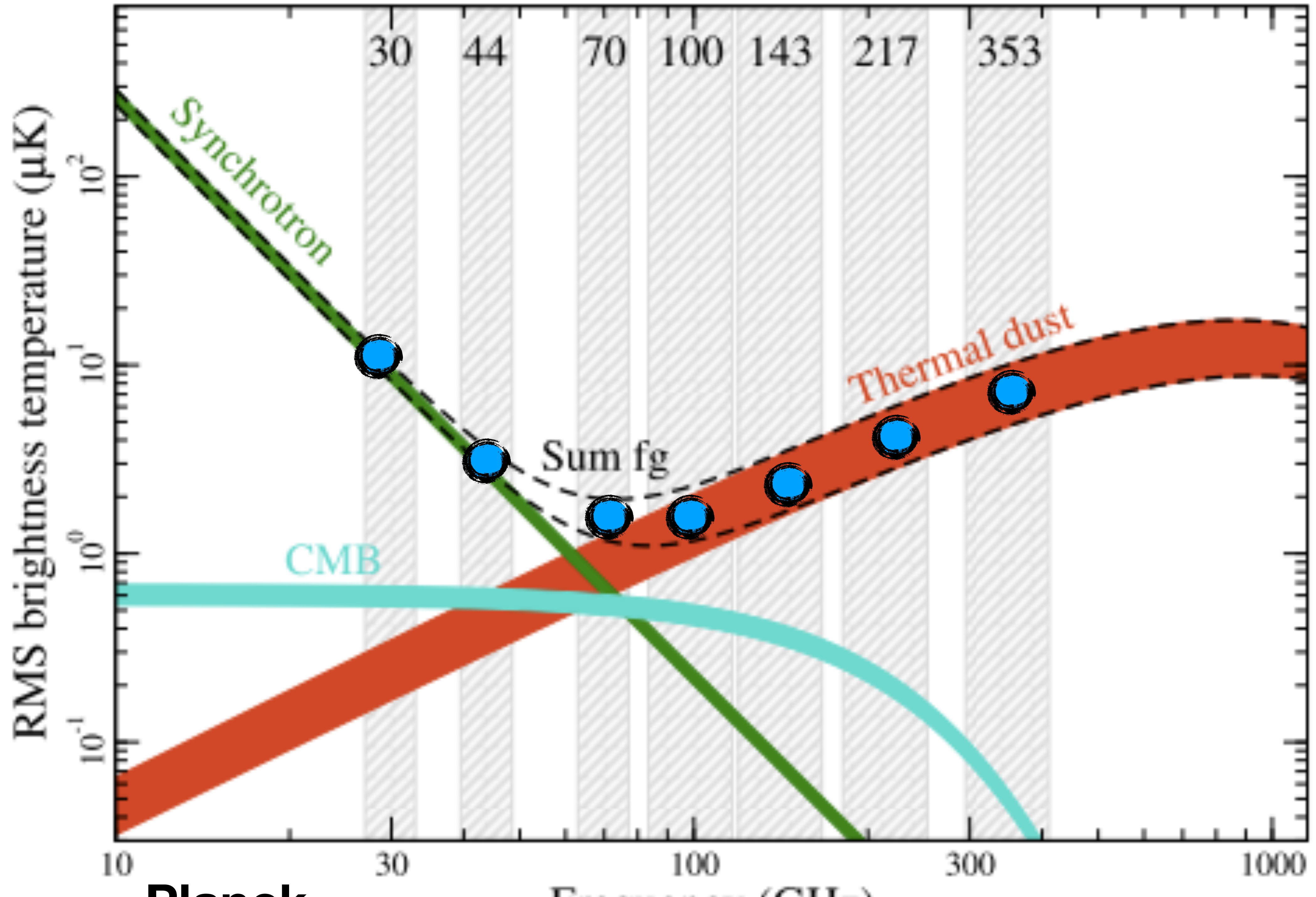
LiteBIRD PTEP 2022, arXiv:2202.02773

Systematics and Calibration: Beam

LiteBIRD PTEP 2022, arXiv:2202.02773



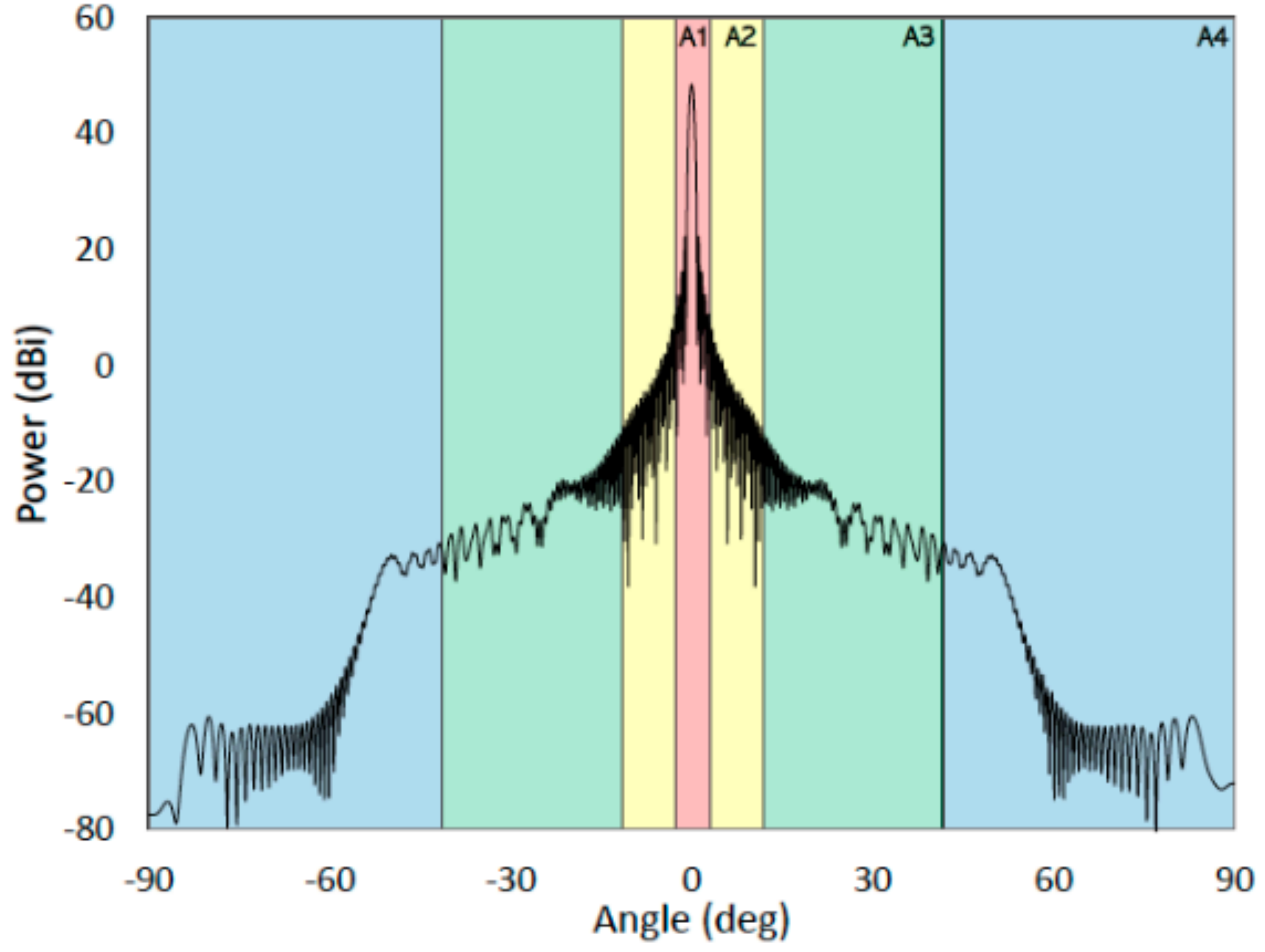
- For a large angular scale recovery, it is important to characterize the beam ***including* the far-sidelobe**.
- We probably need the end-to-end characterization of the far-sidelobe
  - in-flight? -> do we have a source?
  - on the ground? -> can we test in a flight config?
  - rely on a modeling -> can we rely on it? modeling absorber?
  - rely on analysis based mitigation?



Planck

Systematics and Calibration: Beam

LiteBIRD PTEP 2022, arXiv:2202.02773



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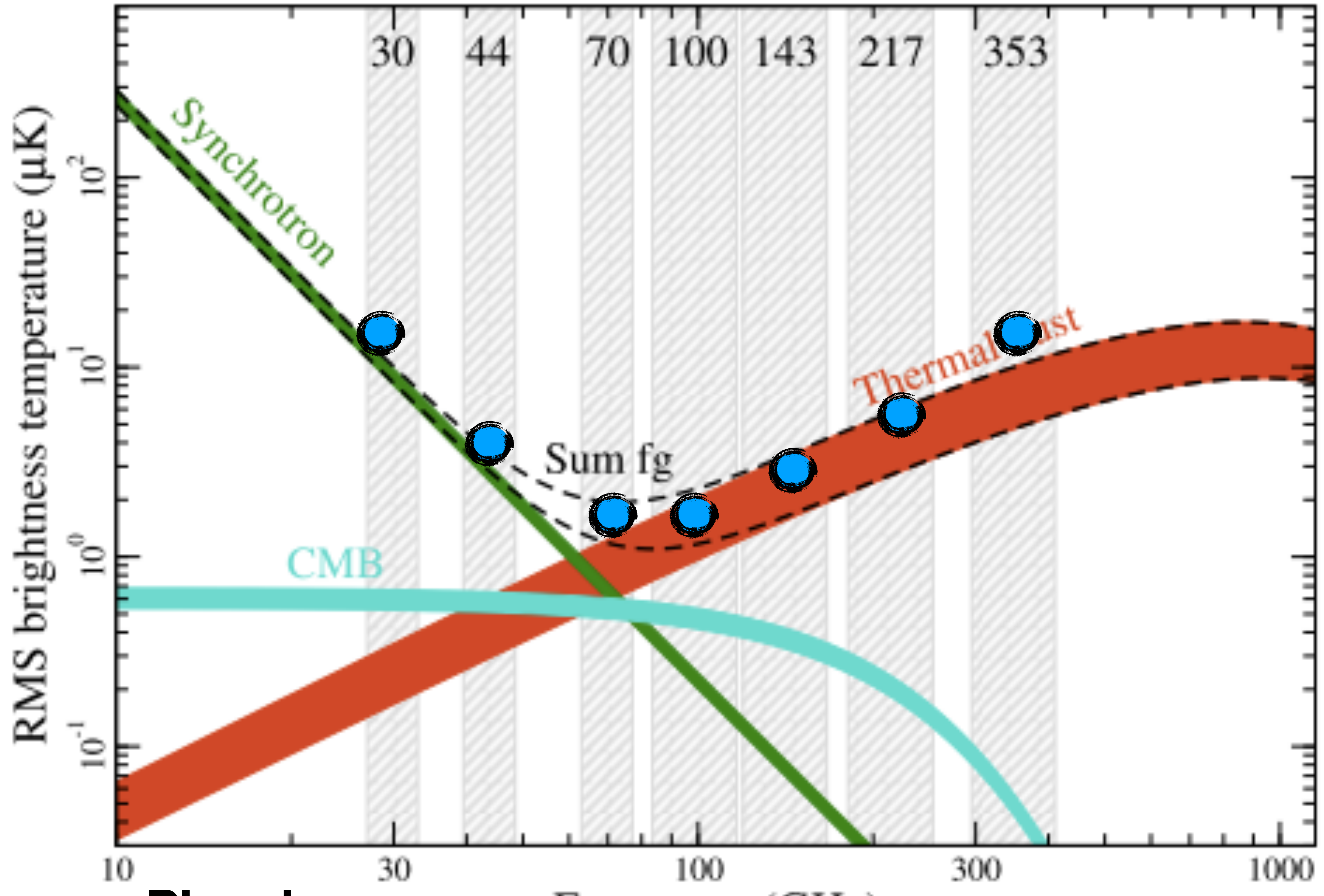

Planck

We need to estimate the systematic effect and calibration feasibility including a component separation step. Not only for beam, but true for all the systematic effects.

Jon Gudmundsson (Stockholm University) on "Knowing your beams"

Systematics and Calibration: Polarization angle

Absolute or relative angle calibration?

Required abs. angle calibration accuracy is about 1 arcmin for $\delta r \sim 1 \times 10^{-3}$.

- in-flight calibration
  - need a sky source that we know well enough
  - C_ℓ^{EB} nulling
    - Can we purely rely on this?

Case	$\Delta\psi_{\rm Gal}$(deg)	$\Delta\psi_{\rm Gal}$(arcmin)
max	3.89	233.5
stddev	1.24	74.6
ground	0.33	20.1
EB	0.28	16.8
TB	0.23	13.8
TB+future	0.12	7.2

Experiment	ν (GHz)	Beam size	$\psi_{\rm Gal}$(deg)	Statistical $\Delta\psi_{\rm Gal}^{\rm stat.}$(deg)	Systematic $\Delta\psi_{\rm Gal}^{\rm sys.}$(deg) Ground	EB	TB
WMAP	23	53′	−88.5	0.1	1.5	–	–
	33	40′	−87.7	0.1	1.5	–	–
	41	31′	−87.3	0.2	1.5	–	–
	61	21′	−87.7	0.4	1.5	–	–
	94	13′	−88.7	0.7	1.5	–	–
XPOL	90	27″	−88.8⋆	0.2	0.5	–	–
PLANCK-LFI	30	33′	−89.26	0.25	0.5	–	–
	44	27′	−88.65	0.79	0.5	–	–
	70	13′	−87.49	1.33	0.5	–	–
PLANCK-HFI	100	10′	−87.52	0.16	1.00	0.63	0.22
	143	7′	−86.61	0.21	1.00	0.42	0.27
	217	5′	−87.93	0.25	1.00	0.51	0.83
	353	5′	−86.76	0.52	1.00	–	–
NIKA	150	18″	−84.3•	0.7	2.3	–	–

J. Aumont et al. A&A 634, A100 (2020)

- **B. Keating et al., ``Self-Calibration of CMB Polarization Experiments", ApJ Letters 762 L23 (2012)**
- **Y. Minami et al., ``Simultaneous determination of the cosmic birefringence and miscalibrated polarisation angles from CMB experiments", PTEP, Vol.2019, 8, Aug. (2019)**

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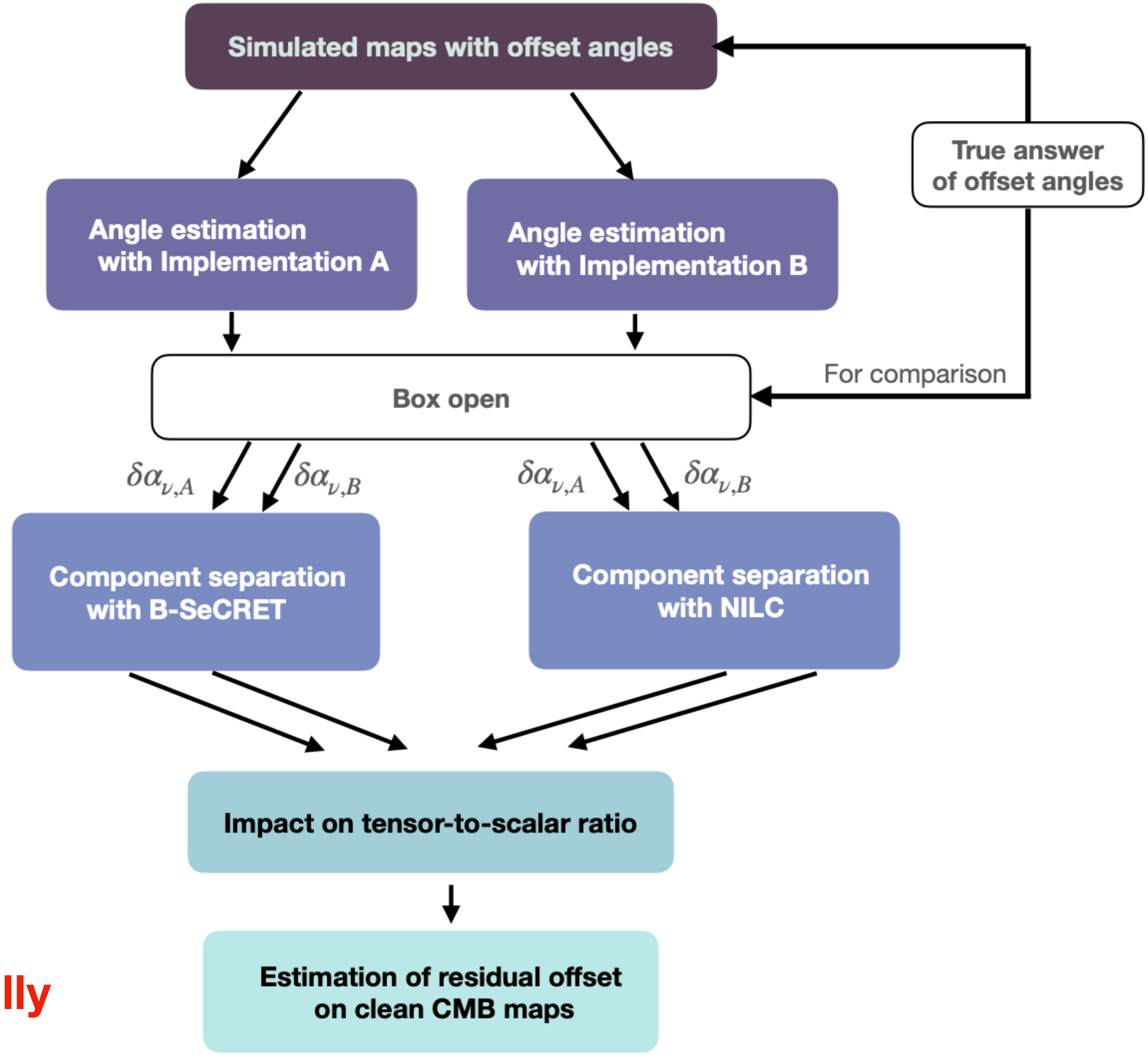

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Blind systematic effect detection test with intentionally introduced offsets.

more complicated blind test!

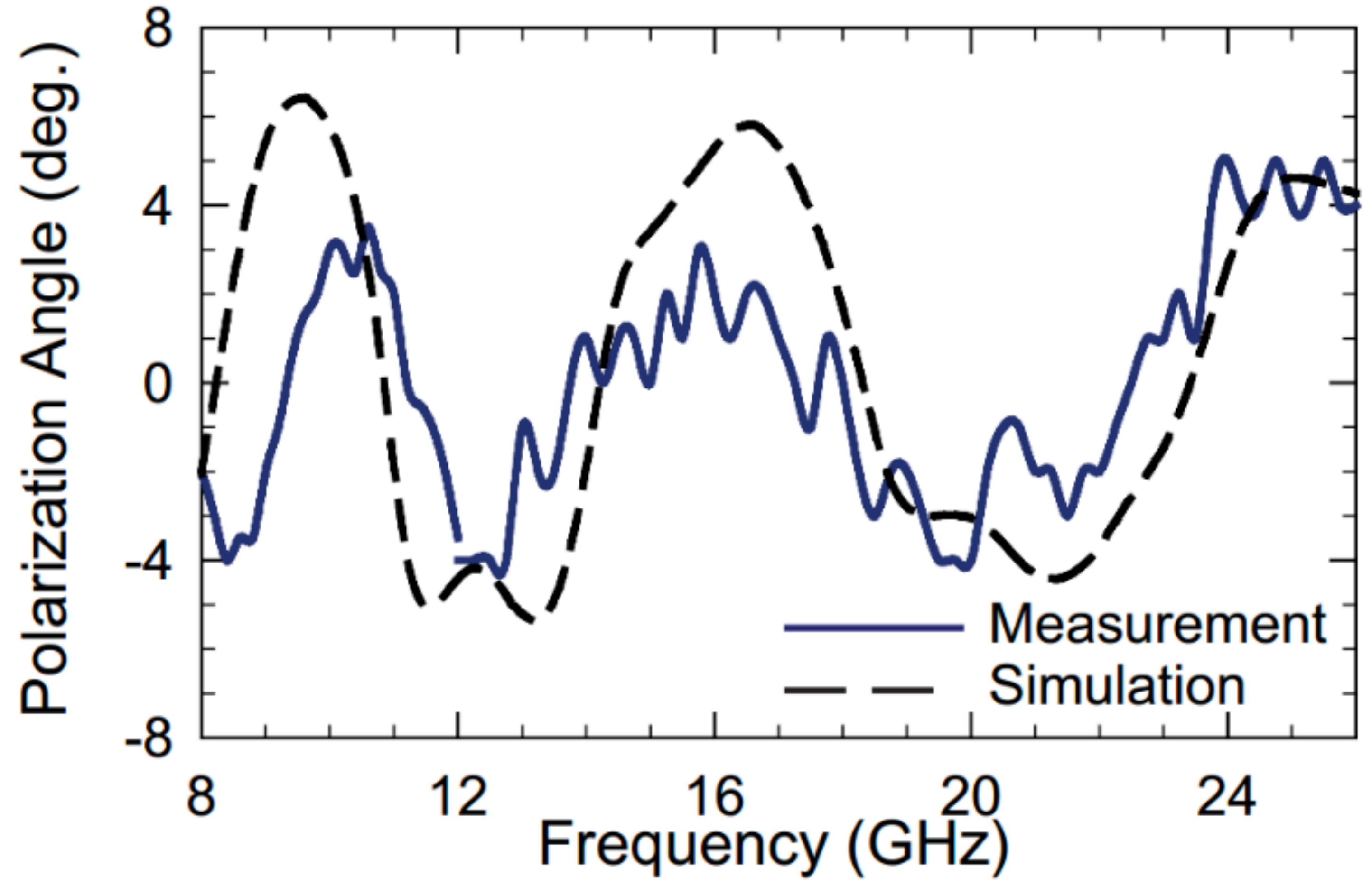
The LiteBIRD collaboration, N. Krachmalnicoff et al., ``In-flight polarization angle calibration for LiteBIRD: blind challenge and cosmological implications", JCAP01(2022)039

Systematics and Calibration: Polarization angle

Absolute or relative angle calibration?

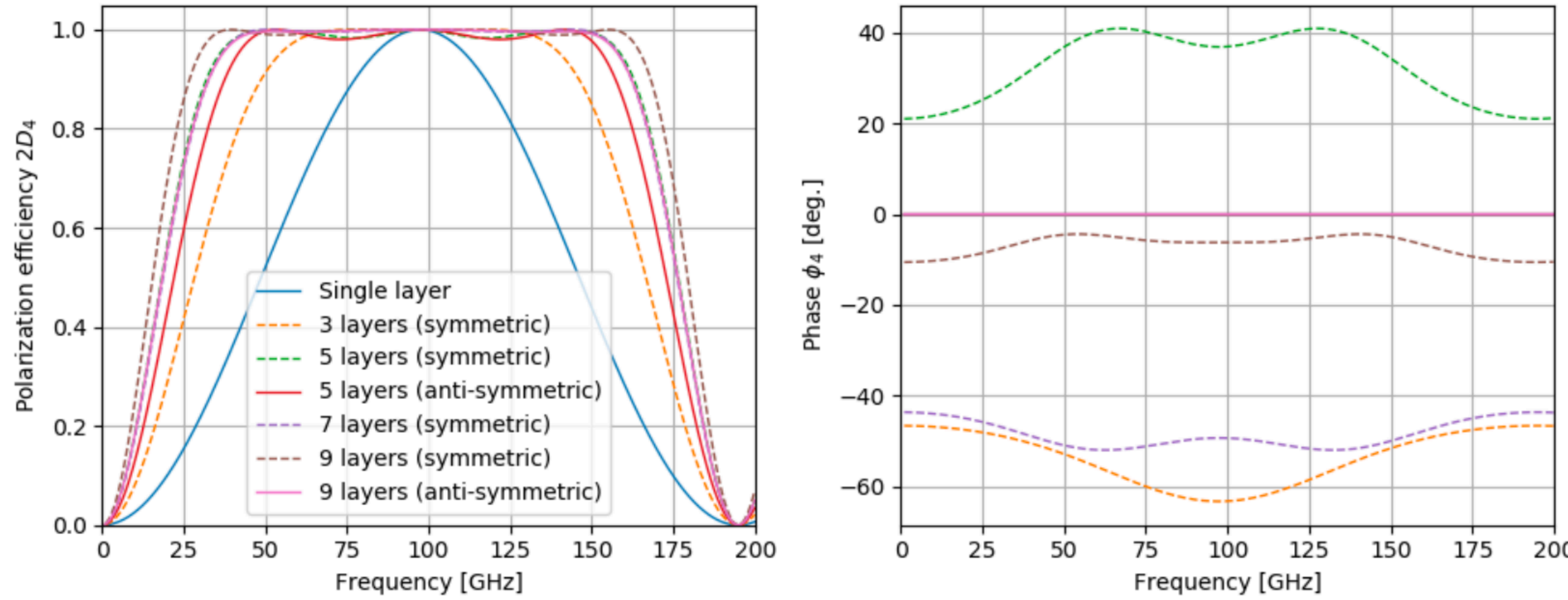
Required abs. angle calibration accuracy is about 1 arcmin for $\delta r \sim 1 \times 10^{-3}$.

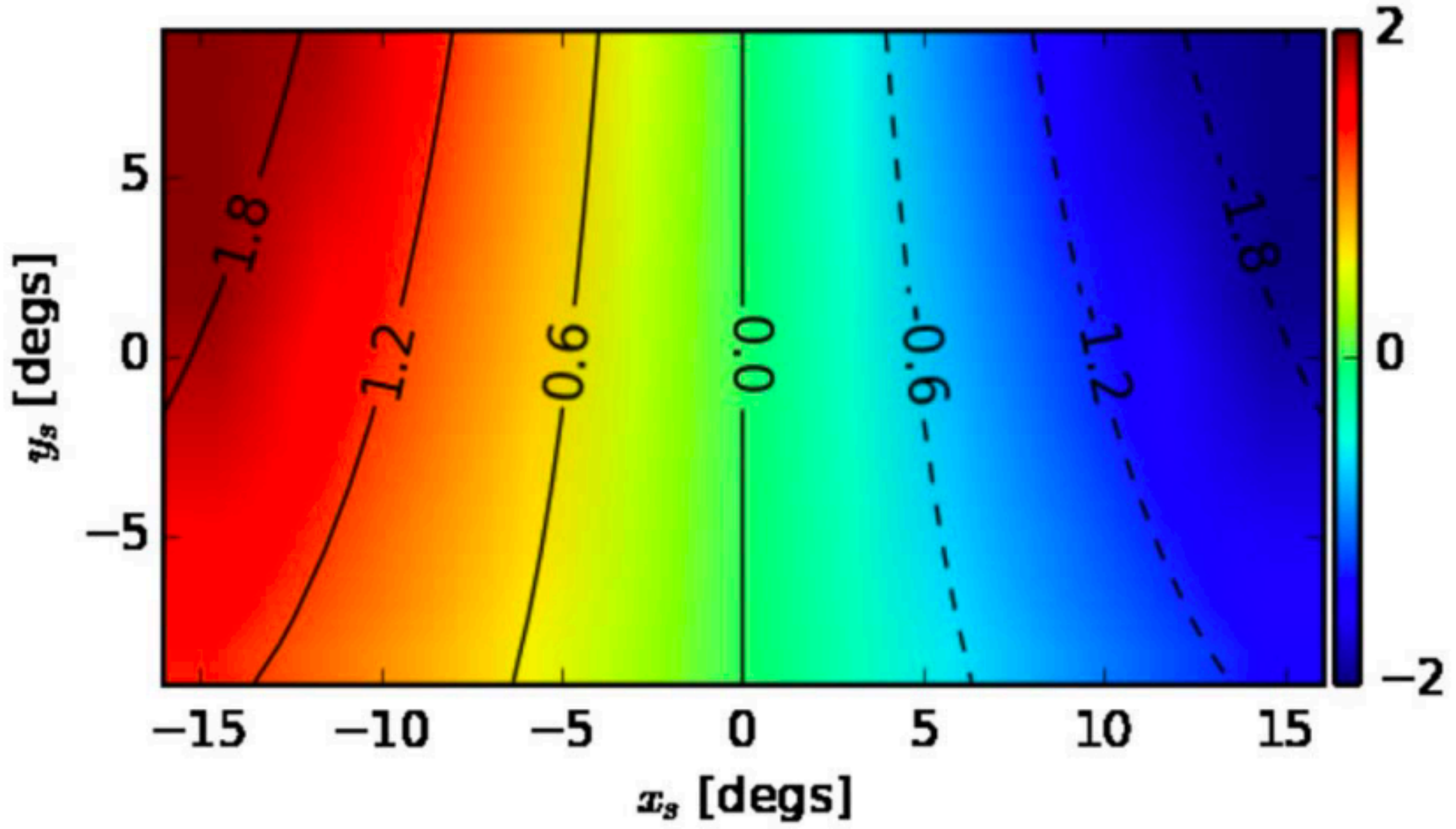
- Component level and analysis level
  - broadband HWP wobble
  - optics rotates the angle over a focal plane
  - sinuous wobble



The hardware migration is proposed by A. Suzuki PhD Thesis (2013)
A pair of sinuous with different parity can cancel the effect.

Flatting the frequency response of the pol. angle in AHWP.
K. Kunimoto et al., SPIE (2020)





Analysis mitigation of the polarization sensitive angle as a function of frequency

- **Clara Vergès et al., arXiv:2009.07814 (2020)**
- **Max Abitbol et al., arXiv:2011.02449 (2020)**

An example of the angle rotation of the cross-Dragone focal plane.
S. Kashima et al. (2018)

System integration, verification, & calibration

System integration, verification, & calibration

Simplified (*and extremely idealized*) project time line

Launch

review | review

Component level development — Design → Fab. → Testing

Engineering model — Design → Fab. → Testing

Flight model — Design → Fab. → Testing

This is the first time you put the entire system:

- optical components, detector, readout,
- cryogenics,
- satellite system.

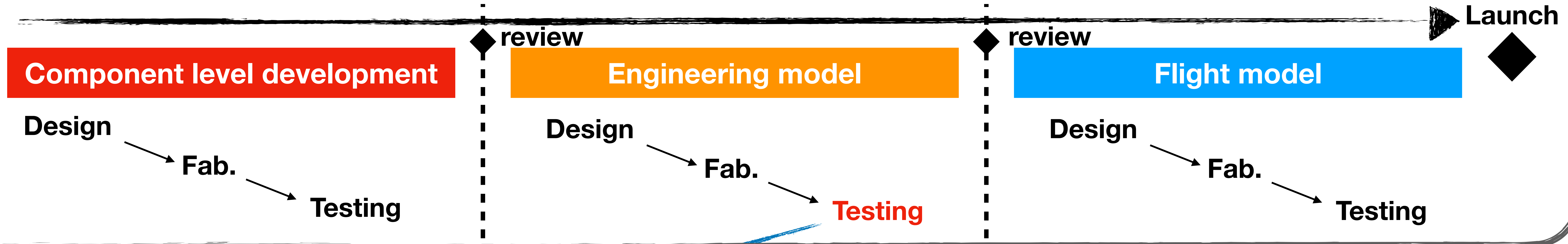
This is the first time encountering the system level end-to-end detector noise and optical characterization, which includes

- **thermal fluctuations**
- **magnetic field interference**
- **vibration**
- **EMI**
- **beam**
- **bandpass**
- **angle…**

- **1/f-like noise**
- **excess white noise**
- **high-freq. excess**
- **line pick up…**

System integration, verification, & calibration

Simplified (*and extremely idealized*) project time line



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- **line pick up…**

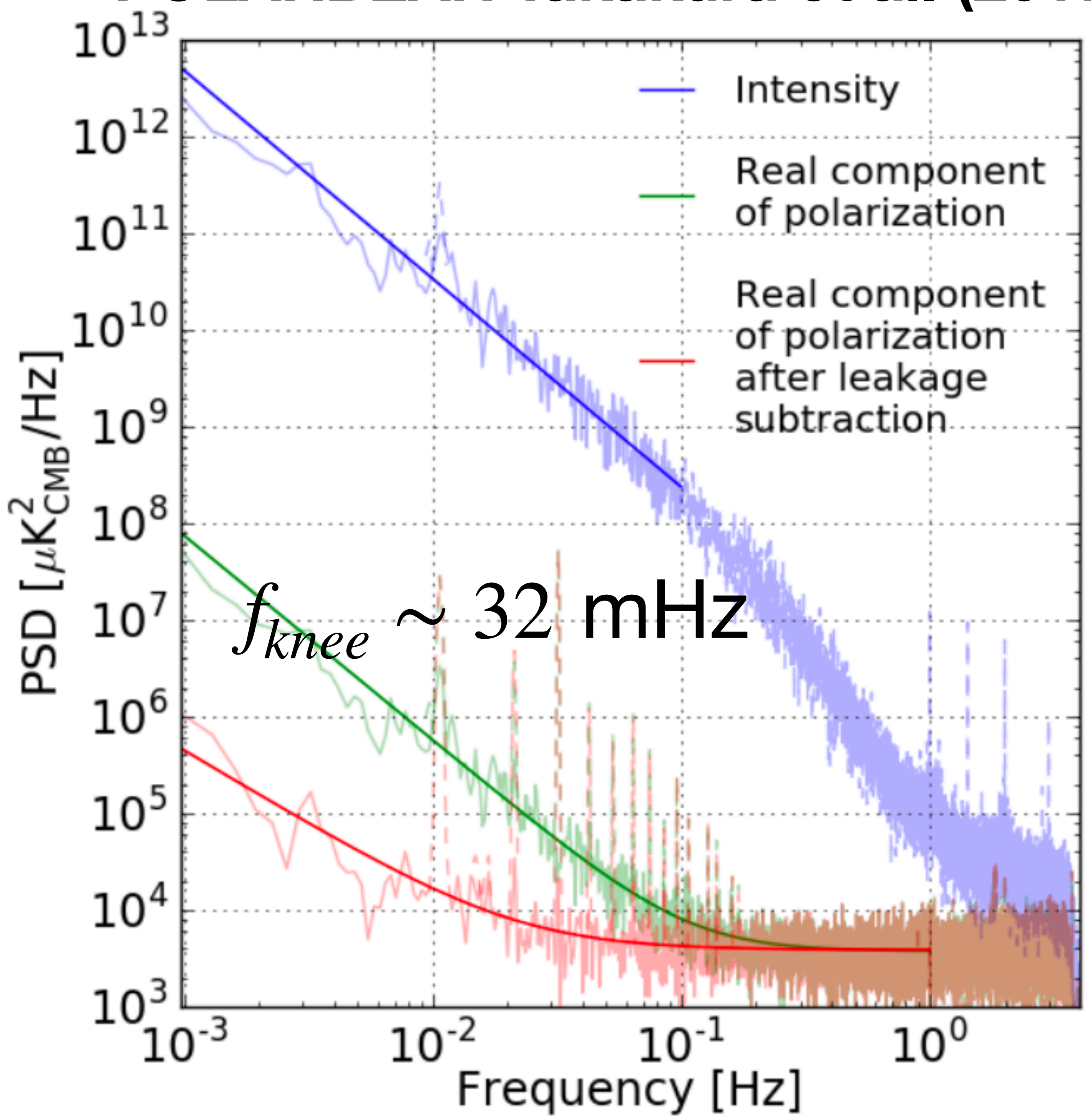
How do we handle any bad surprise at later phase?

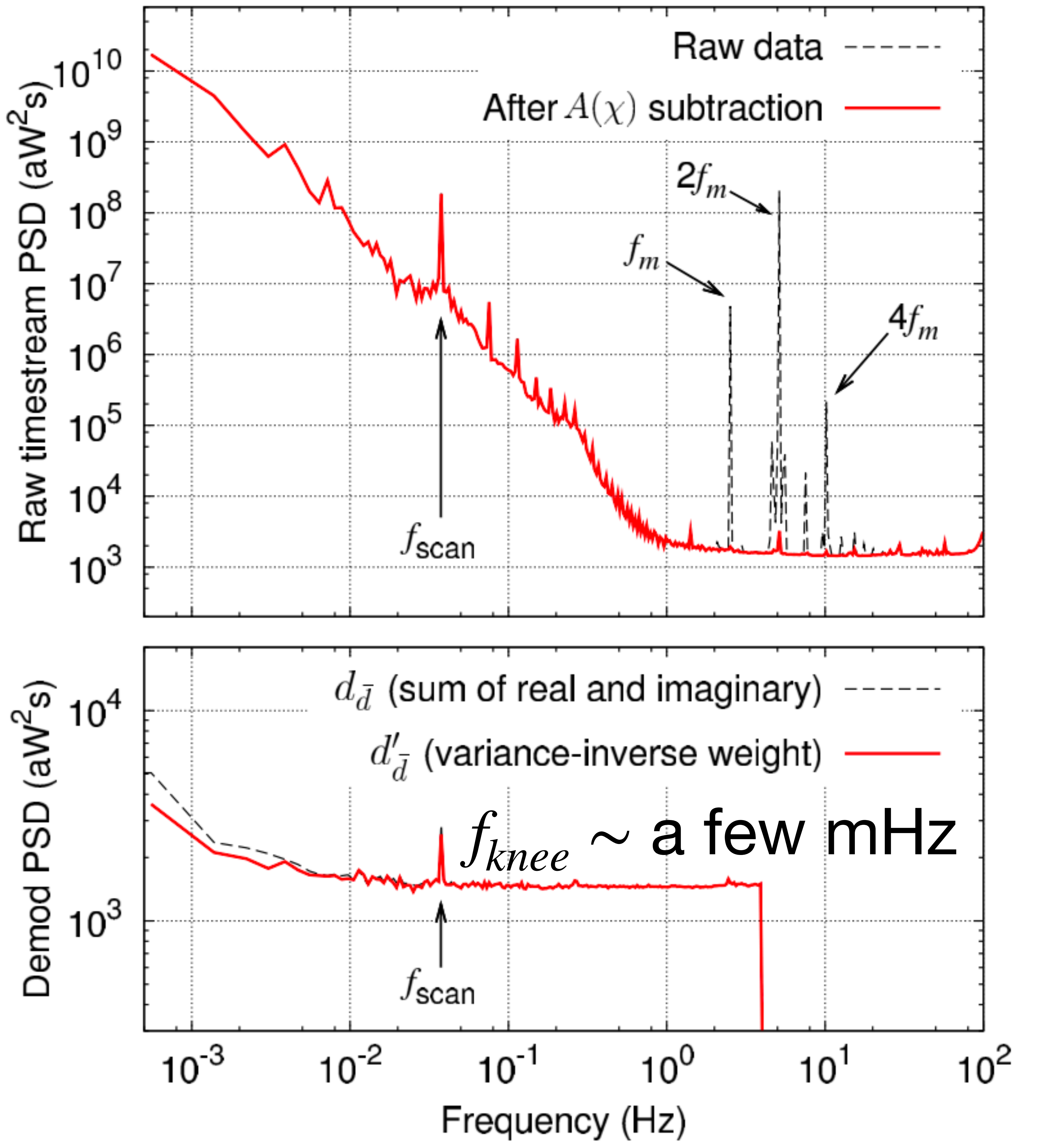
- accept as a risk?
- prepare a backup plan?
- test e2e with a small scale prototype and have a better forecast?
- rely on a model heavily?
- rely on someone's intuition?

Can we avoid 1/f-like effect?

- A modulator is one of the potential solutions to avoid the low-frequency excess noise.
- Among various modulator options, ***a continuously rotating half-wave plate*** polarimeter has deployed in CMB polarization experiments, including MAXIPOL, EBEX, ABS, POLARBEAR, and will plan to deploy by SO-SAT, SWIPE/LSPE, …

POLARBEAR Takakura et al. (2017)





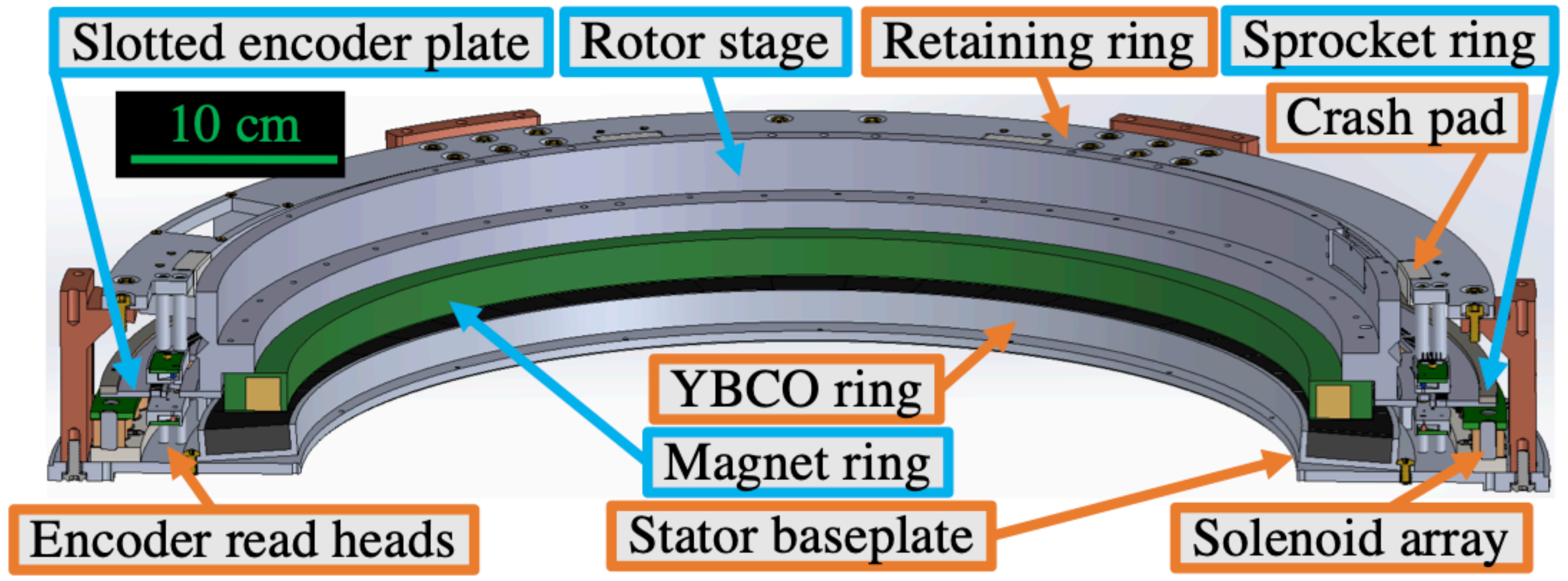
ABS Kusaka et al. (2014)

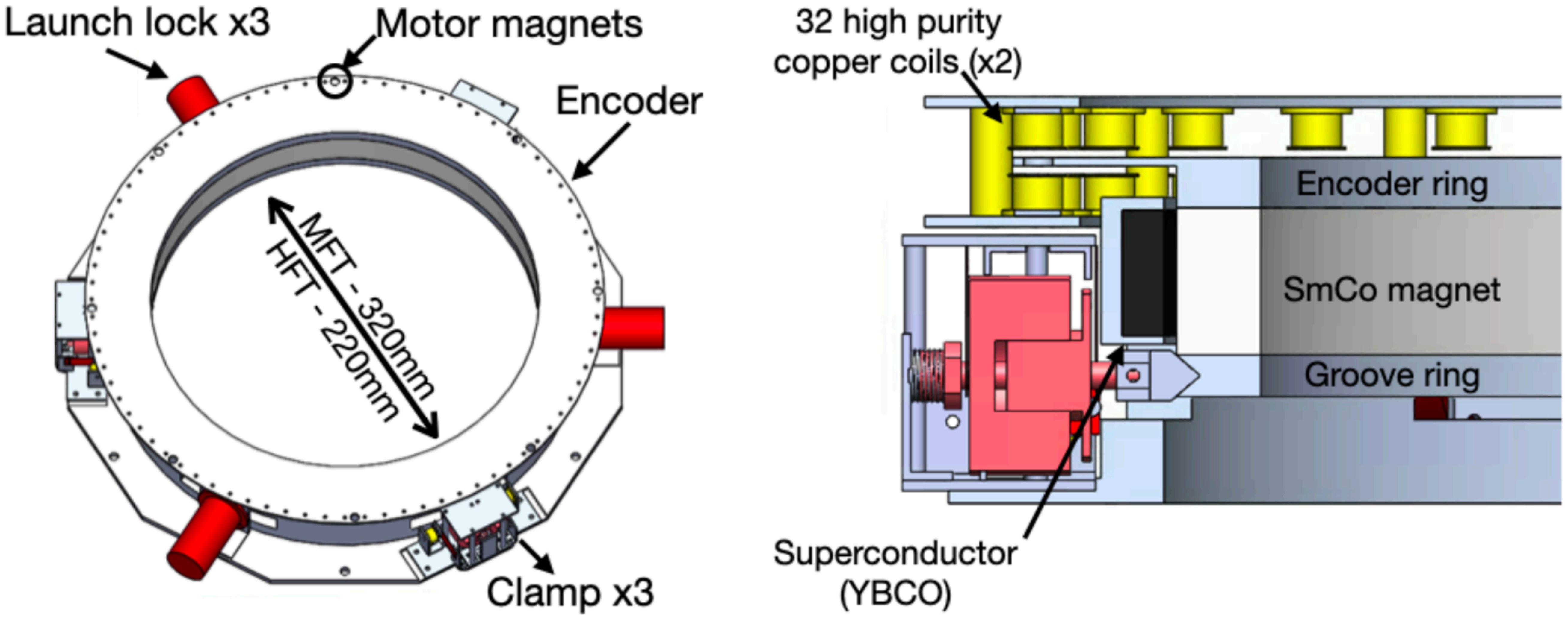
This is an attractive solution, but what does it mean for a space mission?

- never used in a space mission
- broadband
- aperture diameter half-wave plate
- continuous rotation at cryogenic temperature for mission time scale
- low loss in mm-wave and low heat dissipation
- survive launch
- achieve a low f_{knee} with lowest NET detector

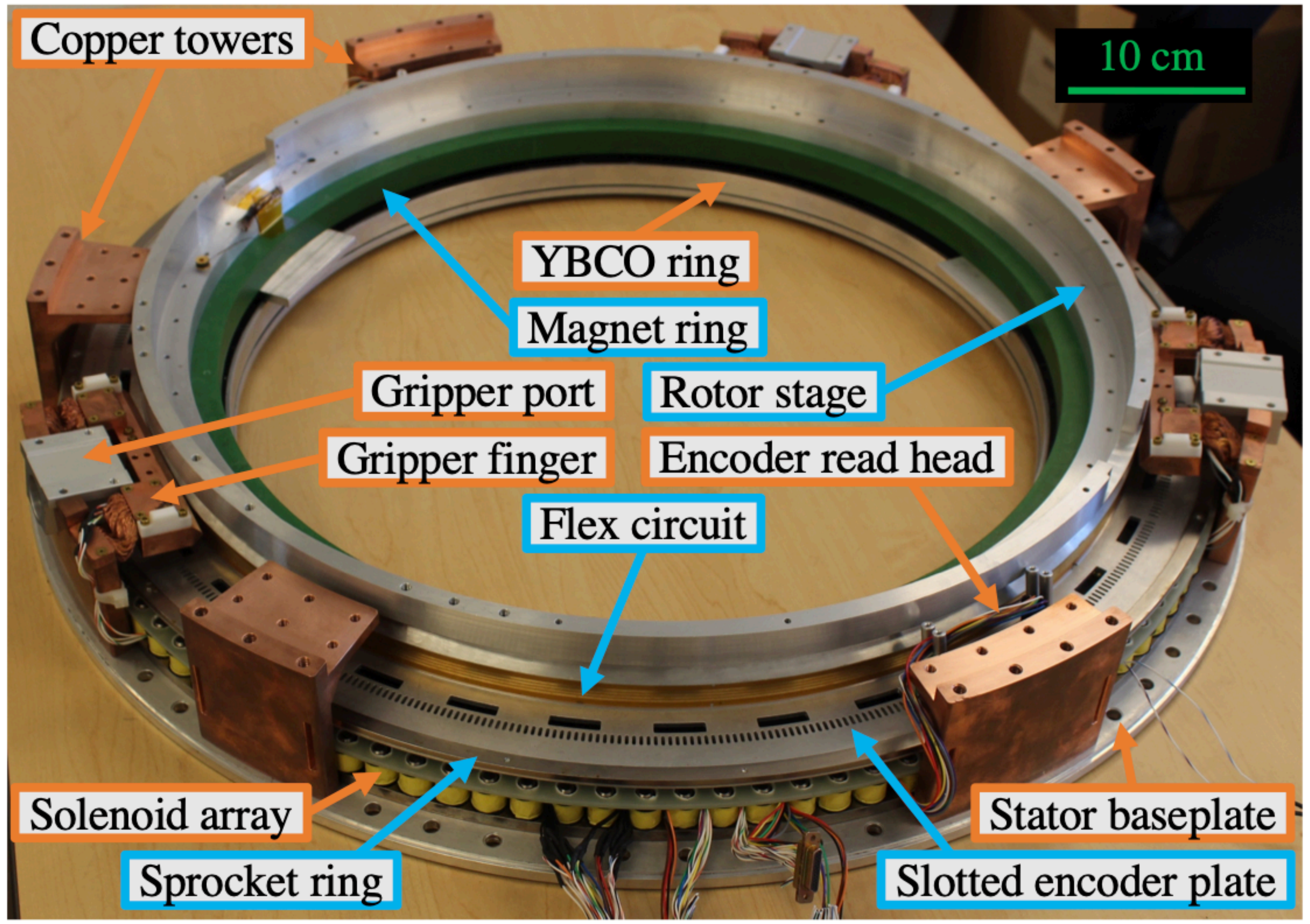
Half-wave plate Rotational mechanism for space?

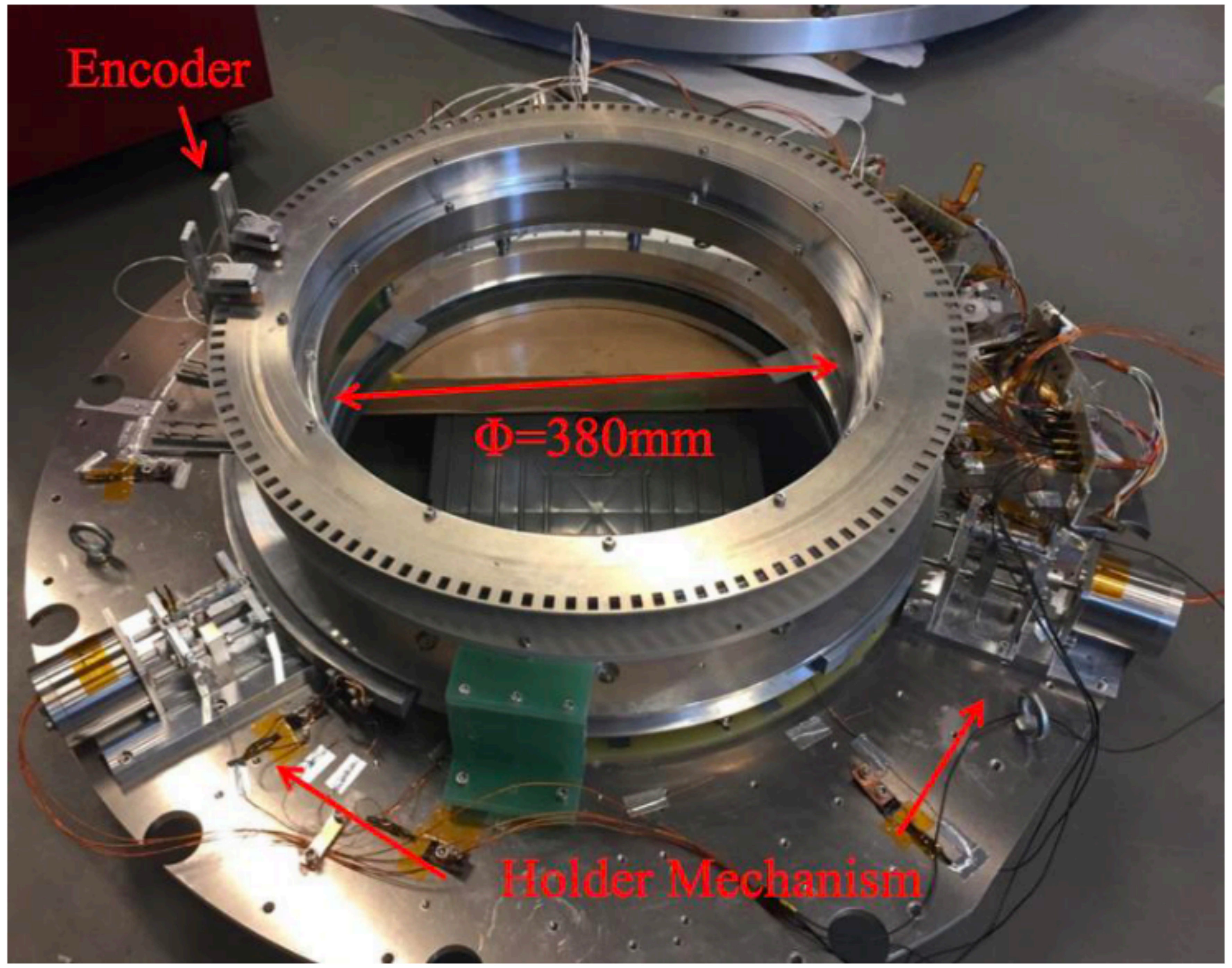
Charles Hill et al. for POLARBAER2





Fabio Columbro et al. for LiteBIRD MHFT





Yuki Sakurai for LiteBIRD LFT

Need to raise TRL w/ extensive development and verification campaigns together with a space manufacture.

Positive unexpected?

There are many things that determines the detector sensitivity.

Q. How would Planck ever be able to meet not just the required sensitivity but the goal sensitivity. What was the allocation of margins?

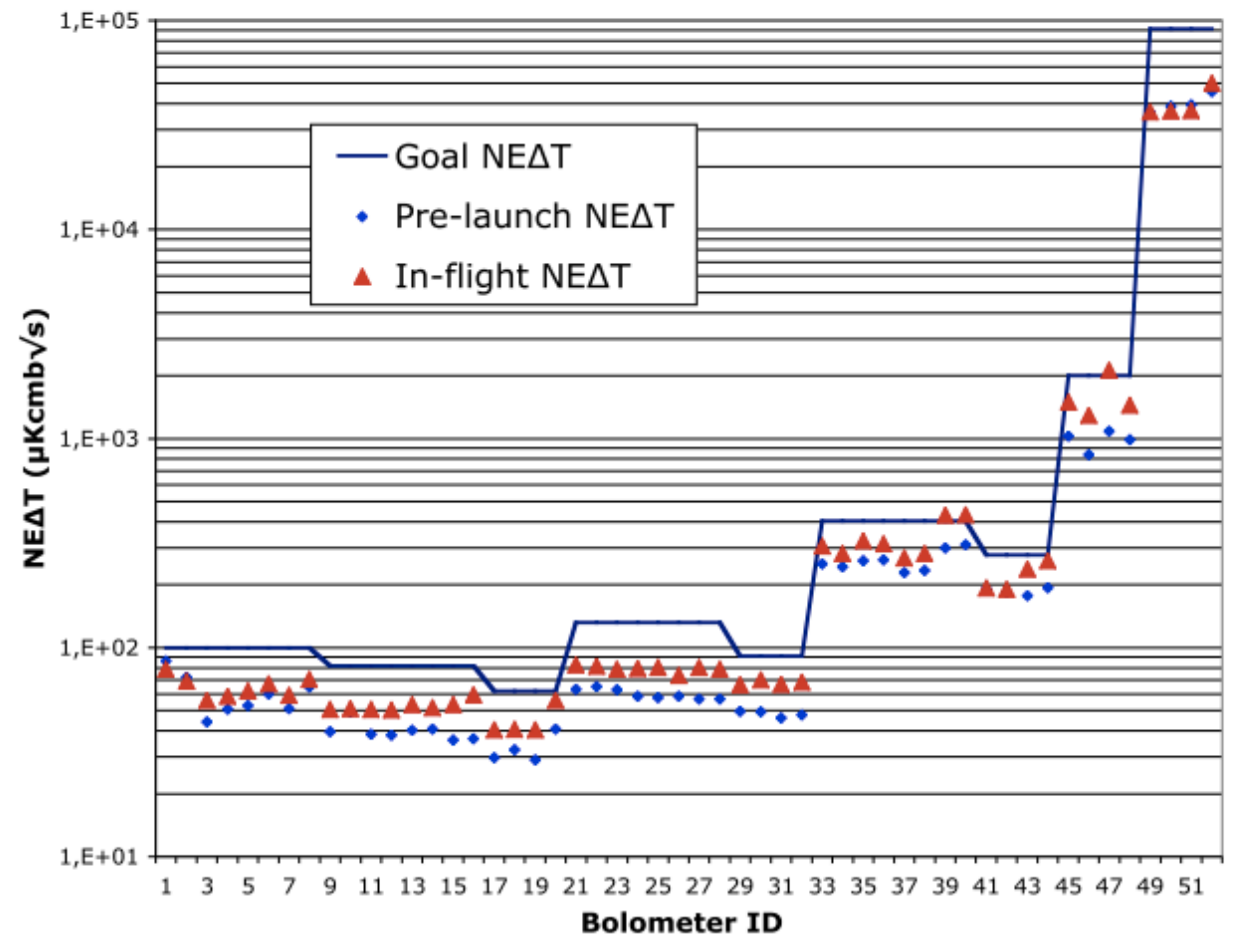
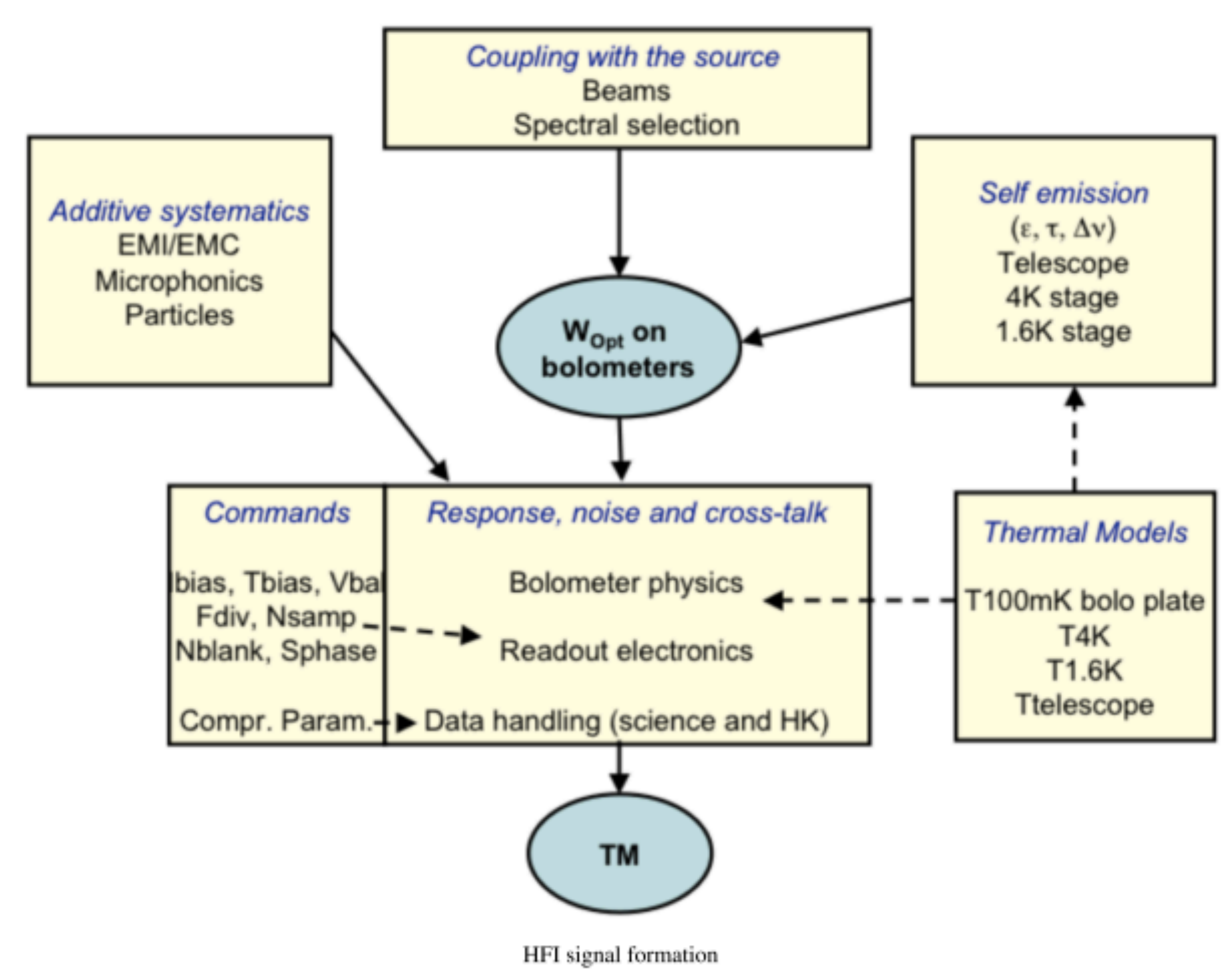


Figure 21. Noise Equivalent Delta Temperature measured on the ground and in-flight with slightly different tools



From PLA explanatory supplement.

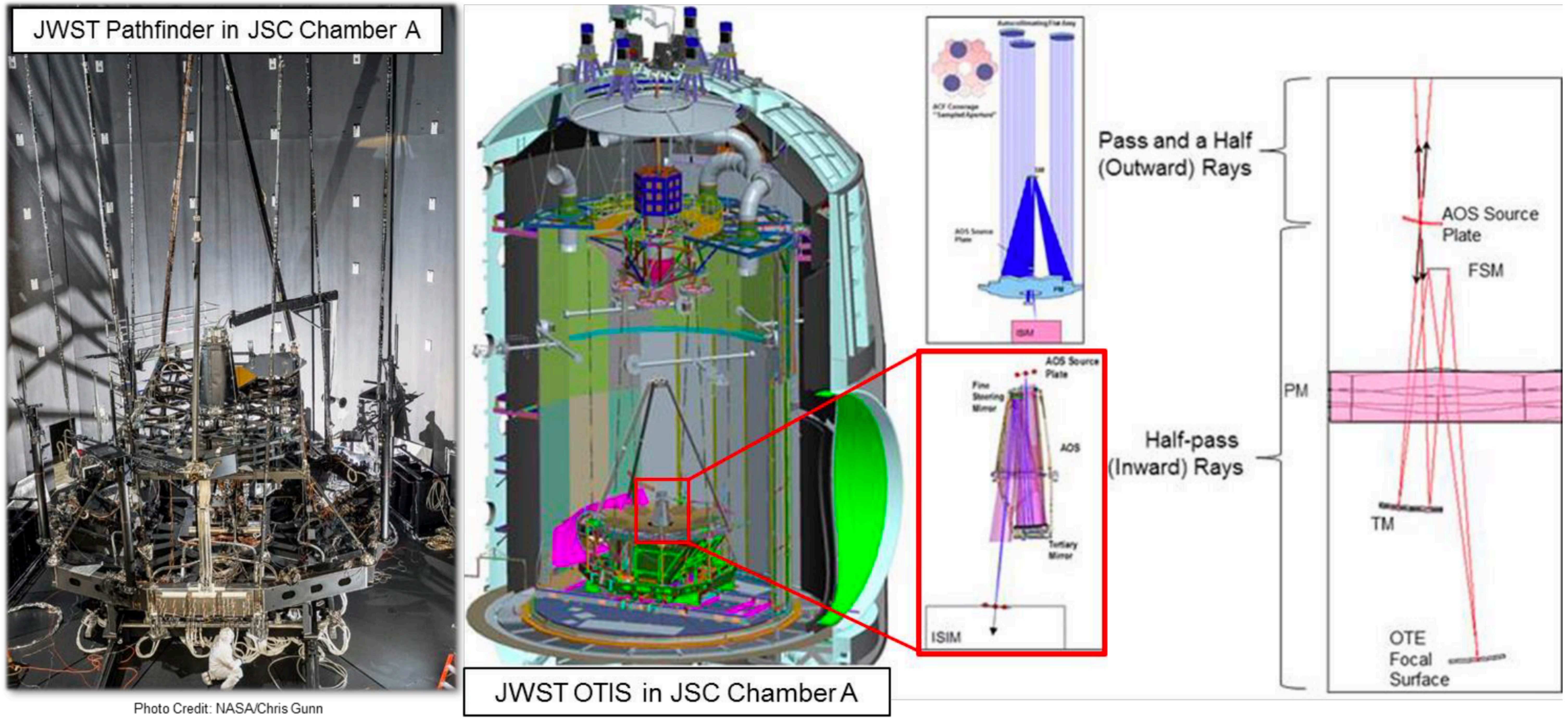
From Planck early results : first assessment of the High Frequency Instrument in-flight performance

System level challenges

Do we need to do this?

Calibration challenges

- the end-to-end calibration
  - noise
  - beam calibration
  - angle
  - bandpass



Koby Z. Smith et al., Calibration results using highly aberrated images for aligning the **JWST** instruments to the telescope

BUS/SVM within a budget

- Spin rate
- Telemetry
- Cryogenics
- Redundancy vs resources

There are many challenges, but it is also find something impossible. There are solutions but it comes with a cost!

Computational/analysis challenges

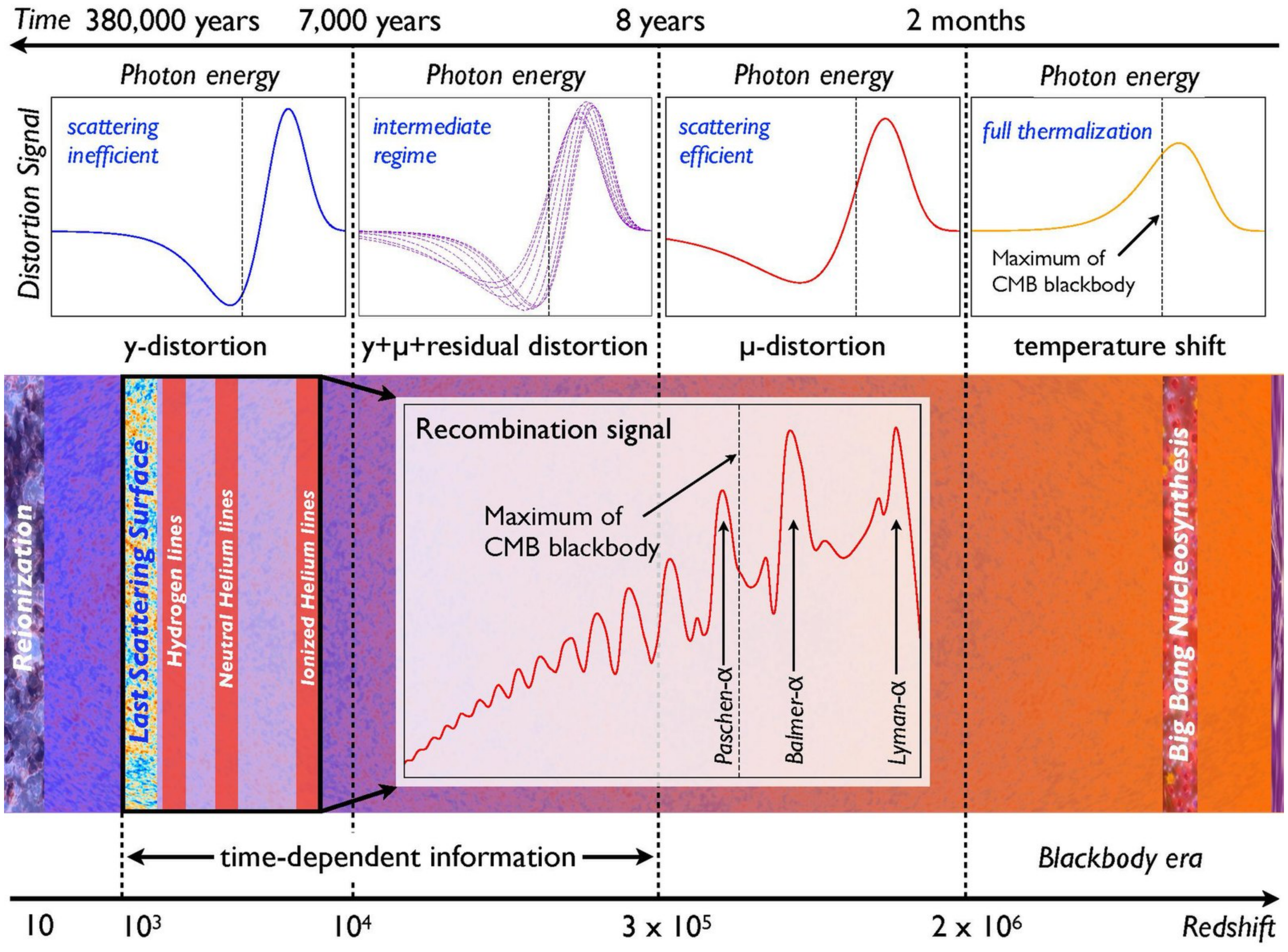
- Ground-based experiments probably drive the computational power at the TOD level due to a fast-sampling $\sim O(10^2)$ and the detector counts $\sim O(10^4 - 10^5)$.

- Do we know how to calibrate and analysis a HWP modulated space mission data?

- TOD simulation with 4pi GRASP beam for $\sim O(10^3)$ detectors. Also, simulating 4pi GRASP beam for $\sim O(10^3)$ itself is challenging.

- Simulating all the systematics in TOD and iterating with component separation and power spectrum estimation can be a challenge.

Challenge in spectrometer from space



- It is essential to go to space for this measurement.
- Many challenges introduced in this talk apply here as well.
- In addition, one of the potential challenges is calibration, i.e. the reference temperature stability, uniformity, and accuracy to monitor over the mission time scale.
- Any development for a imager mission can serve as a TRL raising activity for a spectrometer.

J. Chluba et al. Voyage 2050 Science White Paper

Others? (people, community, budget…)

- Human aspect:
  - a satellite mission involves $\sim 10^3$ people at different levels and expertises.
  - Some are from a space agency and some are from universities. People from a space agency tend to be project-oriented and university is often bottom-up, and plus teaching, supervising students, writing papers… Somehow a group of people from different culture has to come together as one team.
  - Who can look over the entire project end-to-end, a project manager or PI or someone else?
  - Because a project requires various expertise, people tend to work by clustering. Do we have enough bandwidth among the clusters? Even do we share the same terminology?
  - Throughout the project, are we training young scientists for a next generation? Or are we training theorist, data analysis, instrumentalist??
- Community:
  - a ground-based and balloon-borne project also started to become very large too. They tend to be ahead of space mission using new technologies. Do we communicate well enough to learn each other? -> This workshop!
- Budget:
  - I hope scientists do not spend 24/7 thinking of proposals…

Summary

- There are many ways to terminate the mission.
- Many challenges are coupling each tother. The more we advance, the more we need to think of an experiment as a whole with details.
- I was carefully use a world ``a challenge” instead of ``a problem.” But we surely need to sense the problem well in advance, and the feedbacks from the past heritages and the ground-based and balloon-borne experiences are critical.
- Yet, many novel ideas to overcome the existing challenges are proposed, e.g. polarization angle.
- The community is facing such an opportunity to aim the big science(s). I surely hope that we can enjoy this next ~10 years by overcoming the forthcoming and unexpected challenges!