Challenges in optics design, calibration, and systematic control

CMB-Cal @ BICOCCA, 6 Nov 2024

Jón E. Guðmundsson, University of Iceland

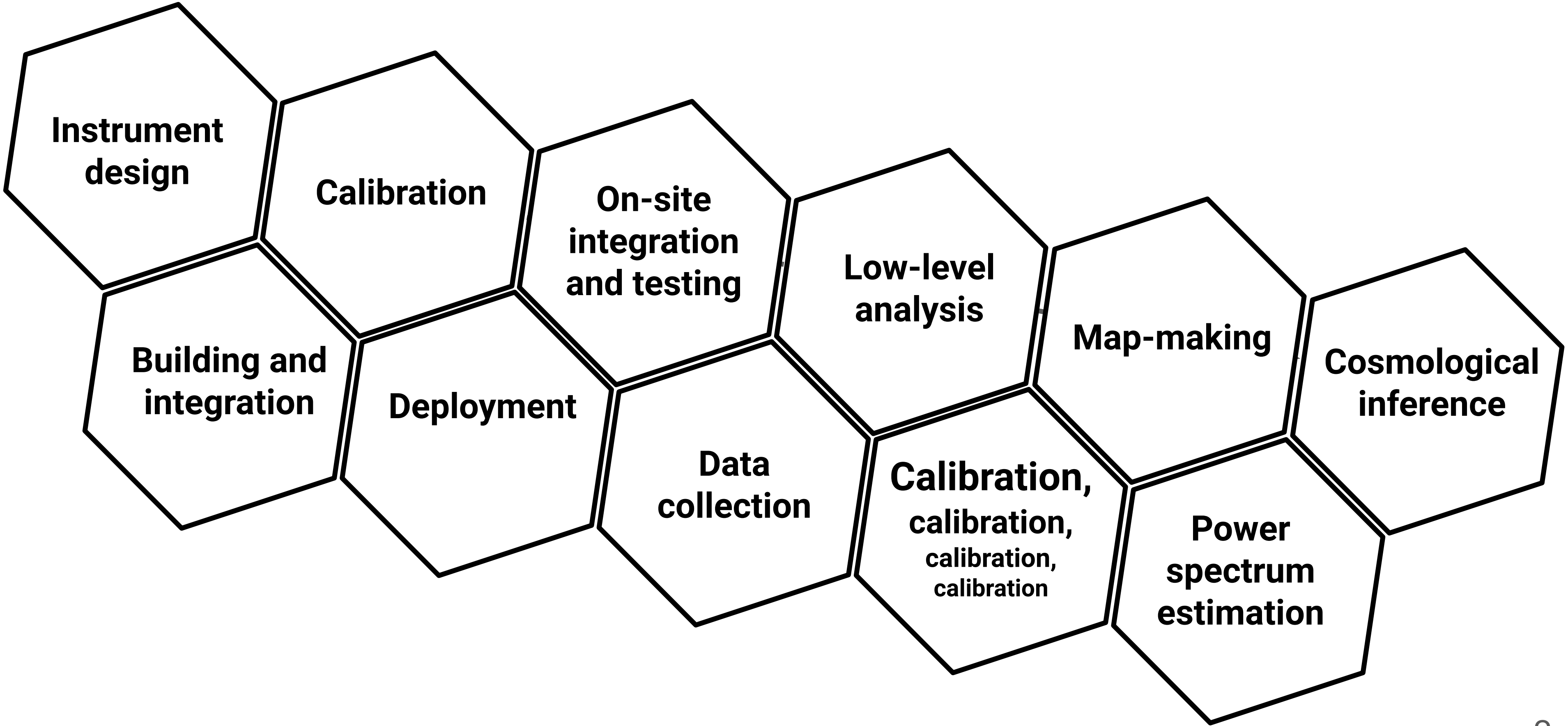
CMBeam project
funded by:

**Funded by
the European Union**

erc
European Research Council
Established by the European Commission

"It's always about the beams"
— A person at this conference

A “day” in the life of an experimentalist



Instrument design

Building and integration

Calibration

Deployment

On-site integration and testing

Data collection

Low-level analysis

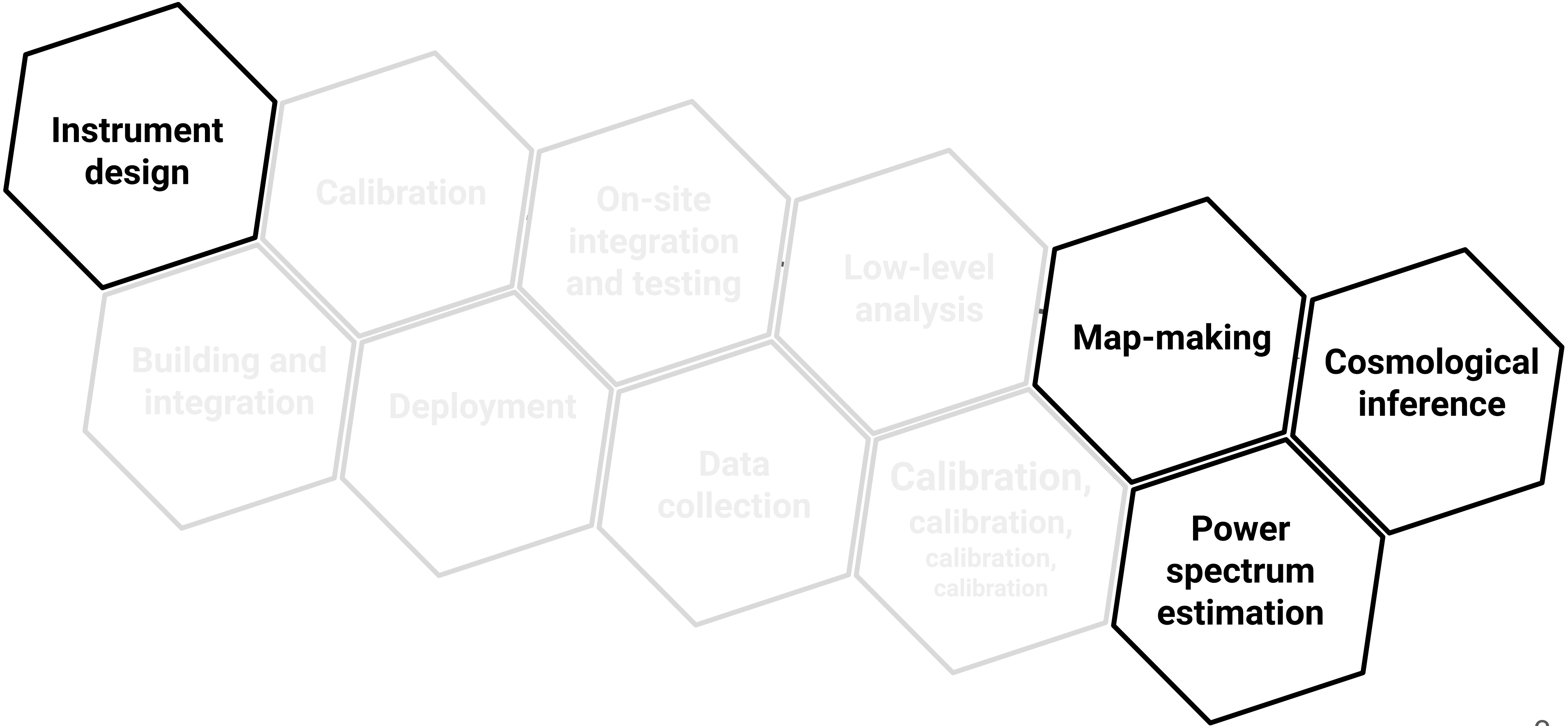
Calibration, calibration, calibration, calibration

Map-making

Power spectrum estimation

Cosmological inference

Why can't we just simulate these experiments?



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From ray traces to final design:
The Simons Observatory Large Aperture Telescope

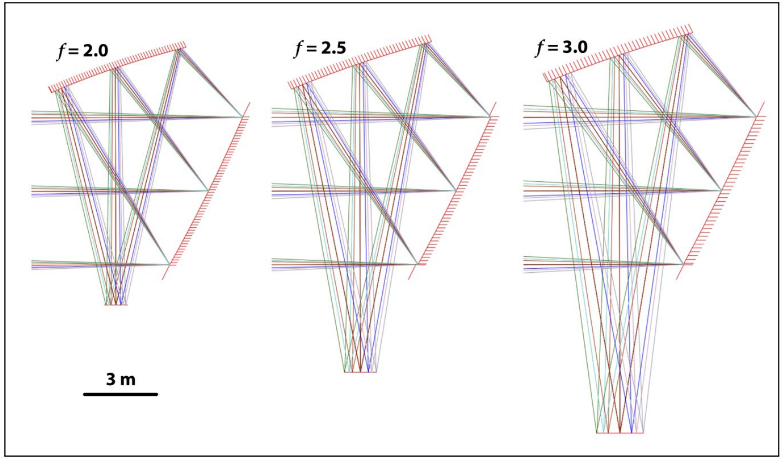
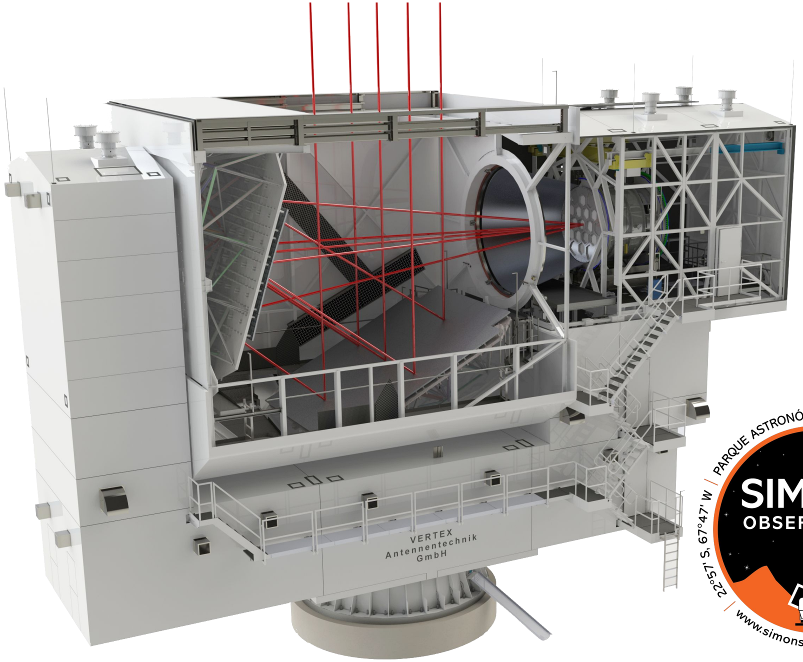


Fig. 1. Three 6 m aperture telescope designs with different f. Plotted rays span the 150 GHz CFOV with Strehl ratios > 0.70.

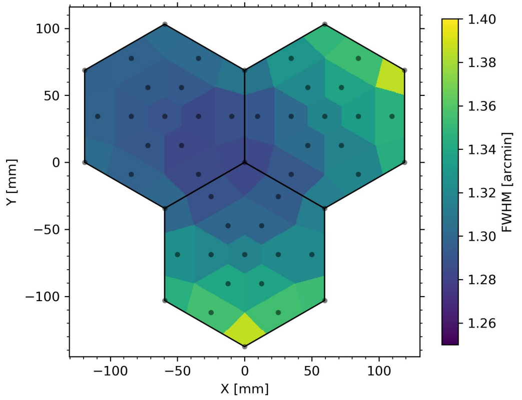
Niemack, Applied Optics, vol. 55 (2016)



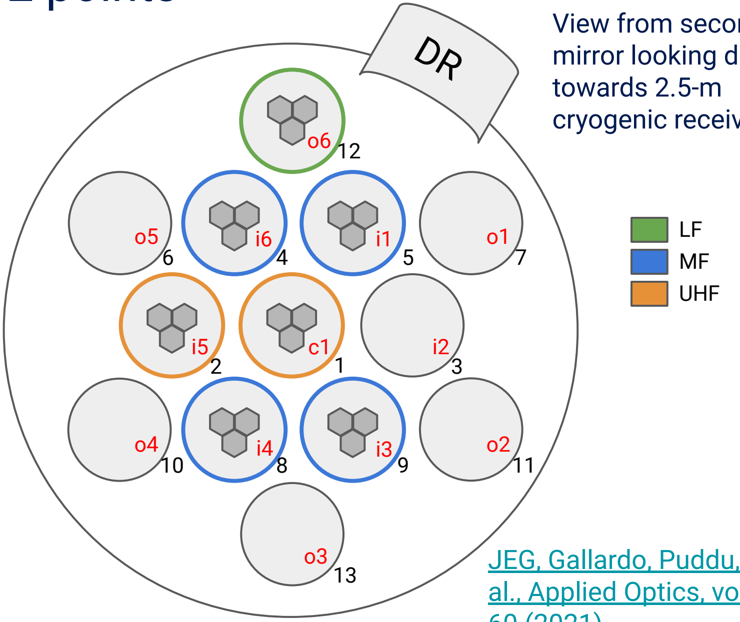
JEG, Gallardo, Puddu, et al., Applied Optics, vol. 60 (2021)

SO LAT physical optics simulations

- **Goal**: **Provide quantitative predictions for far-field beam response** that can be used to assess impact on mapping speed and science
- Using GRASP: Electric fields emitted from 52 points on the FPU and propagated through three lenses, window and reflectors
- Simulations for 90, 150, 220, and 270 GHz; taking weeks of computing on a 36-core workstation



Distribution of 150-GHz beam FWHM for the i4 optics tube

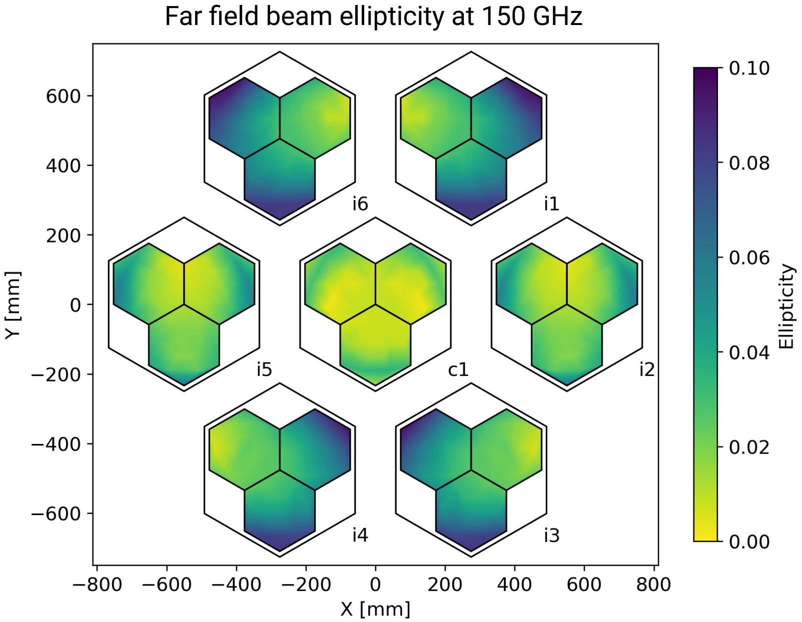


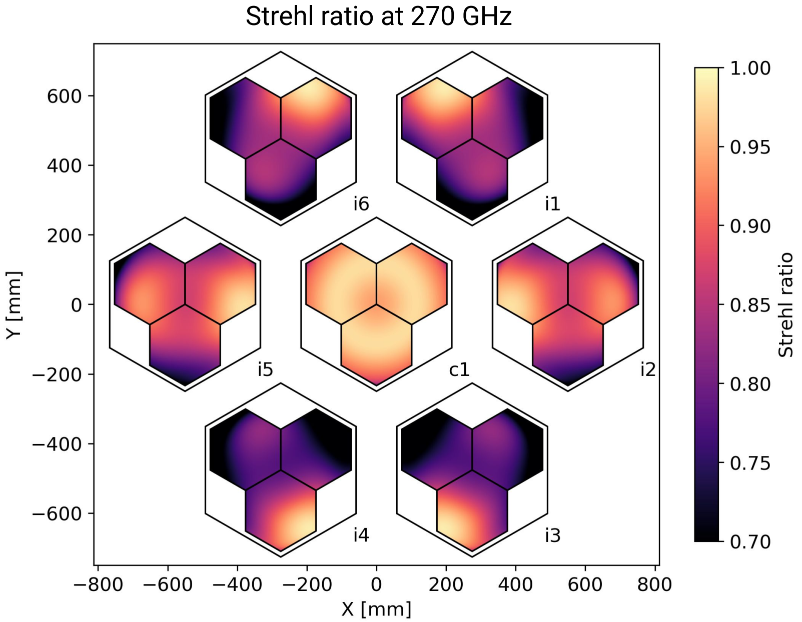
View from secondary mirror looking down towards 2.5-m cryogenic receiver

[JEG, Gallardo, Puddu, et al., Applied Optics, vol. 60 (2021)]

Ellipticity vs Strehl ratios

- Beam ellipticity at **150 GHz** as predicted by PO sims (left) correlates with Strehl ratio as calculated using ray tracing in Zemax (right)


Far field beam ellipticity at 150 GHz

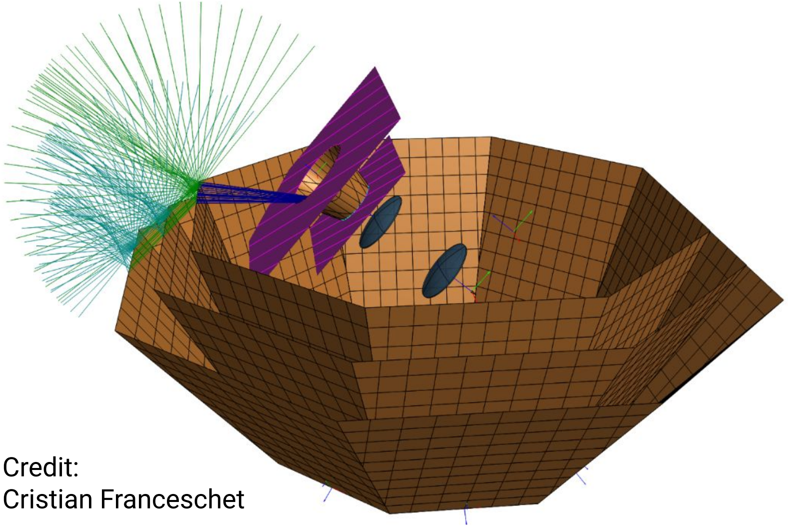

Strehl ratio at 270 GHz

JEG, Gallardo, Puddu, et al., Applied Optics, vol. 60 (2021)

Simulating an experiment

Duivenvoorden, JEG, & Rahlin, MNRAS (2018)
Duivenvoorden et al., MNRAS (2021)

- There exist multiple codes that allow us to generate time-domain simulations of CMB experiments scanning the sky (e.g., TOAST, beamconv)
  - We can inject realistic noise and detector correlations, use arbitrary scan strategies, simulate somewhat realistic atmospheric conditions, etc.
  - We can simulate hundreds of realizations of O(100–1000) detectors, sampled at O(100) Hz, scanning for O(1 years)
- The hard part is accurately capturing critical details about the beam and frequency response; these include:
  - Lenses with metamaterial anti-reflection coatings, broadband absorbers, reflective focal planes, filters, half-wave plates, ground screens, multiple reflections
- Accurately capturing small angular scales, $\ell > 1000$, is still quite computationally expensive



Credit:
Cristian Franceschet

Calibrating on *Planck* HFI

Planck (30–353 GHz) is calibrated on the orbital dipole…
….and it turns out all of the other experiments calibrate on *Planck*.
What if the Planck absolute calibration is biased?
Is there a way to independently verify the Planck absolute calibrations?

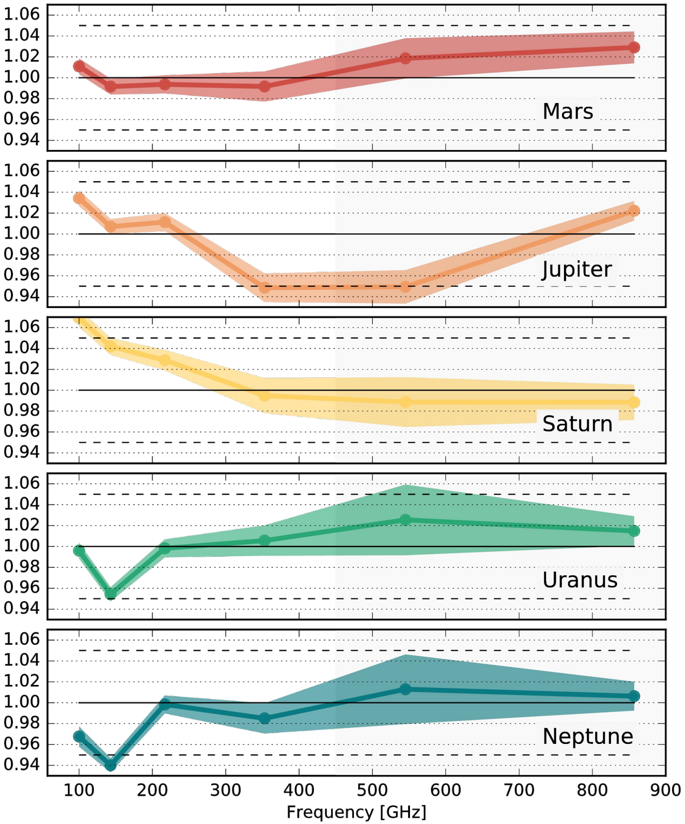
Yes! Planet observations depend on accurate spectral response estimates and provide a powerful constraint on the 4π detector solid angle

$$\begin{aligned} s_i &= \iint \mathrm{d}\Omega \mathrm{d}\nu \tau'(\nu) P(\theta_i, \phi_i) A_{\mathrm{eff}}(\nu) B(\nu, T) \\ &= \frac{c^2}{\Omega_{\mathrm{b}}} \iint \mathrm{d}\Omega \mathrm{d}\nu N \tau'(\nu) P(\theta_i, \phi_i) B(\nu, T)/\nu^2 \\ &\approx \underbrace{\frac{\Omega_{\mathrm{p},i}}{\Omega_{\mathrm{b}}}}_{\text{Dilution factor}} \int \mathrm{d}\nu \underbrace{\tau(\nu)}_{\text{Spectral response}} \underbrace{B(\nu, T)}_{\text{Source spectrum}} \qquad \left[\mathrm{W\,m^{-2}\,sr^{-1}}\right]. \end{aligned}$$

If the absolute calibration [ADU2K$_{\mathrm{cmb}}$], source spectral dependence, $B(\nu,T)$, spectral response function, $\tau(\nu)$, and planet solid angle, Ω_{p}, are known, the signal amplitude from point source observations will bracket the detector 4π beam solid angle.

Planck intermediate results LII. Planet flux densities
https://www.aanda.org/articles/aa/pdf/2017/11/aa30311-16.pdf

Comparison with models



Comparison with WMAP

- Planck observations of Jupiter at 100 GHz and WMAP at 94 GHz give T_P=172.3 ± 0.8 K and T_W=172.3 ± 0.8 K, respectively, suggesting agreement at the T_P/T_W = 0.984 ± 0.007 level
- Similar comparison with Saturn gives γ_P/γ_W = 1.007 ± 0.010
- Similar comparison with Mars gives ζ_P/ζ_W= 1.012 with a difficult-to-estimate error due to Mars temporal effects

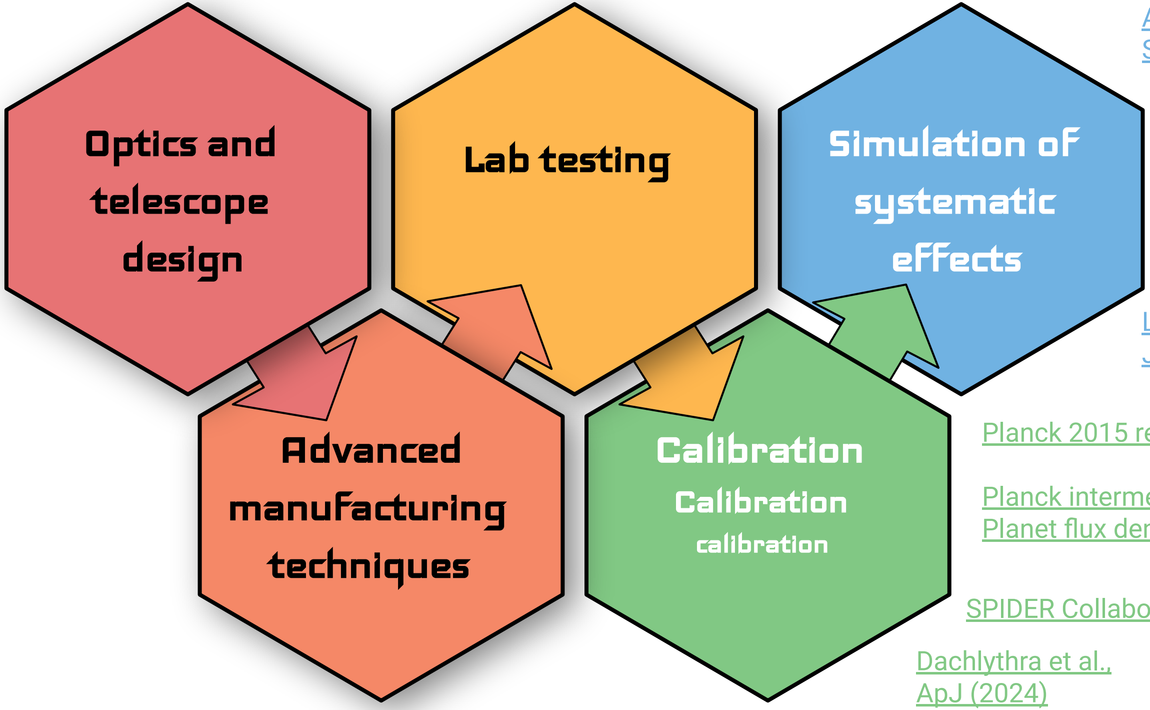
<u>Planck and WMAP agree at the ~1% level</u>

Note: generally speaking, the planet experts/model indicate non-trivial temporal effects; absolute accuracy of these models quoted at the 5% level with no clear error analysis (that I know of)

Planck intermediate results LII. Planet flux densities
https://www.aanda.org/articles/aa/pdf/2017/11/aa30311-16.pdf

Knowing your beams implies…

…GRASPing a number of concepts



Optics and telescope design

Lab testing

Simulation of systematic effects

Advanced manufacturing techniques

Calibration

Calibration

calibration

Adler and JEG.
SPIE (2020)

JEG, AO, (2020)

JEG, Gallardo,
Puddu et al.,
AO (2021)

Duivenvoorden, JEG, & Rahlin, MNRAS (2018)
Duivenvoorden et al., MNRAS (2021)

Adler et al,.
SPIE (2022)

Dachlythra et al.,
upcoming publication

Adler et al,.
JCAP (2024)

Leloup et al,.
JCAP (2024)

Planck 2015 results VII., A&A (2016)

Planck intermediate results LII.
Planet flux densities, A&A (2017)

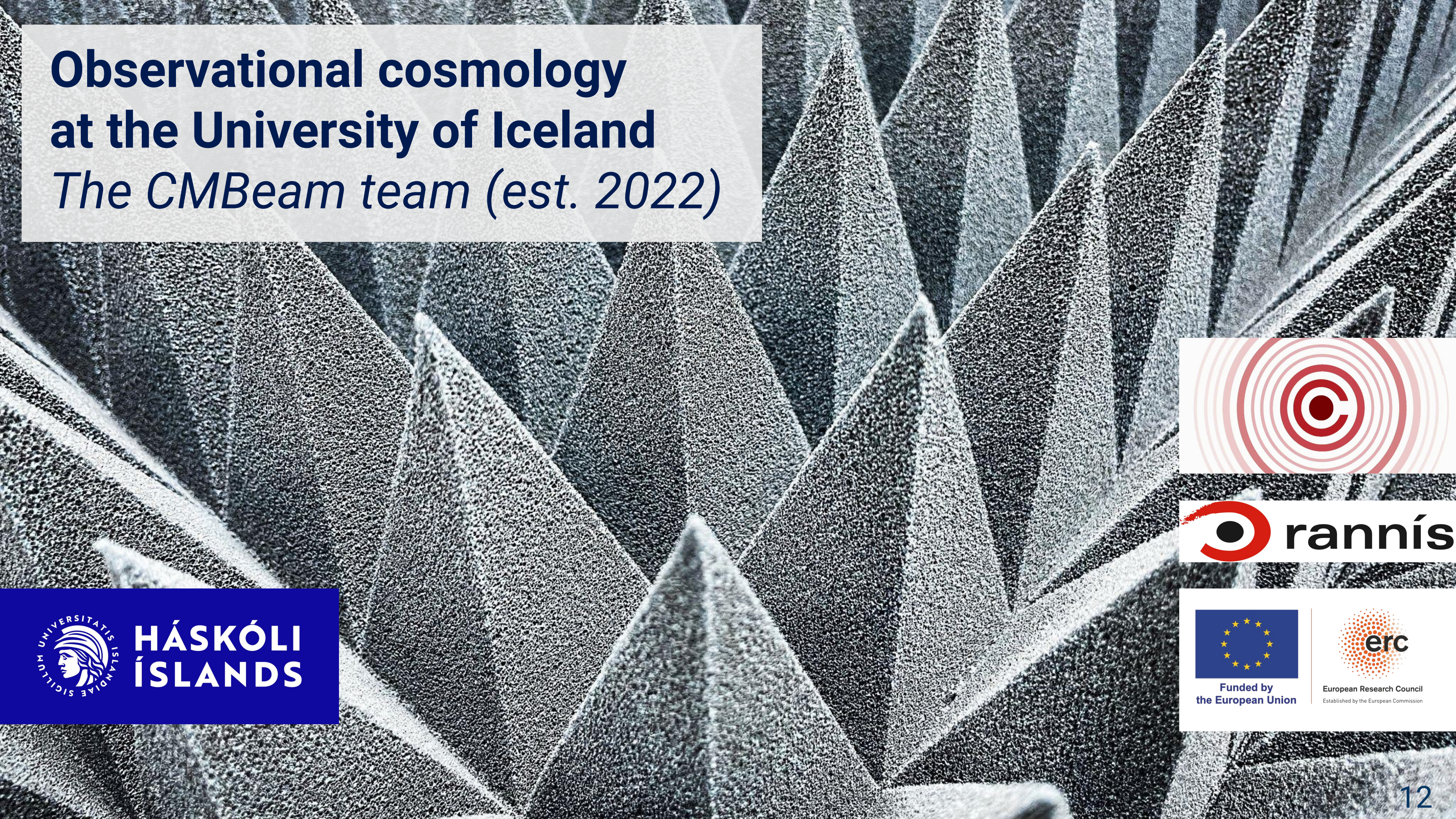
SPIDER Collaboration, ApJ (2022)

Dachlythra et al.,
ApJ (2024)

The CMBeam team

…has a firm GRASP of optics

Lots of people thinking about beams and calibrations 💙



Observational cosmology at the University of Iceland

The CMBeam team (est. 2022)

HÁSKÓLI ÍSLANDS

rannís

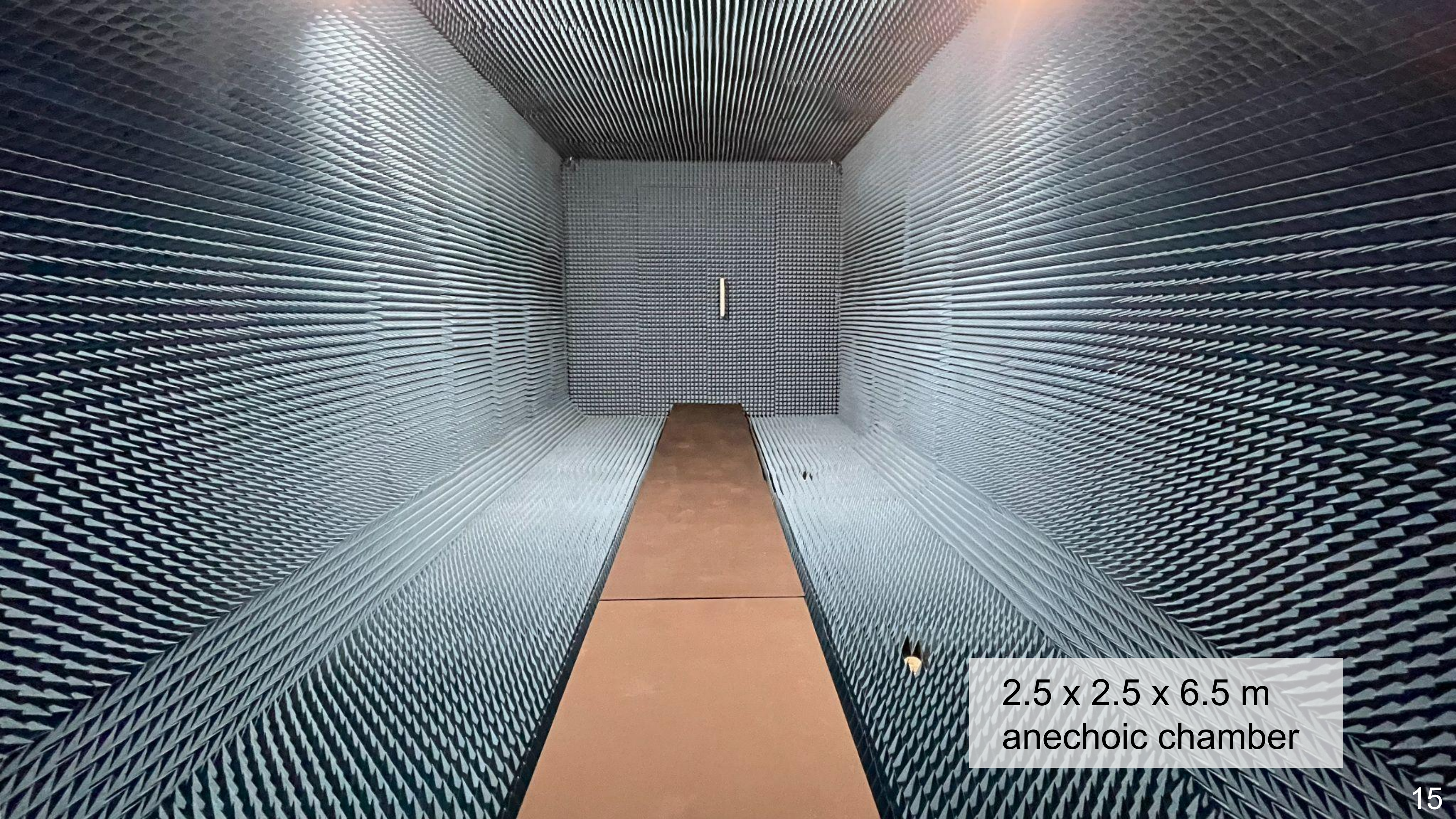
Funded by the European Union

European Research Council
Established by the European Commission

19 Jan 2023

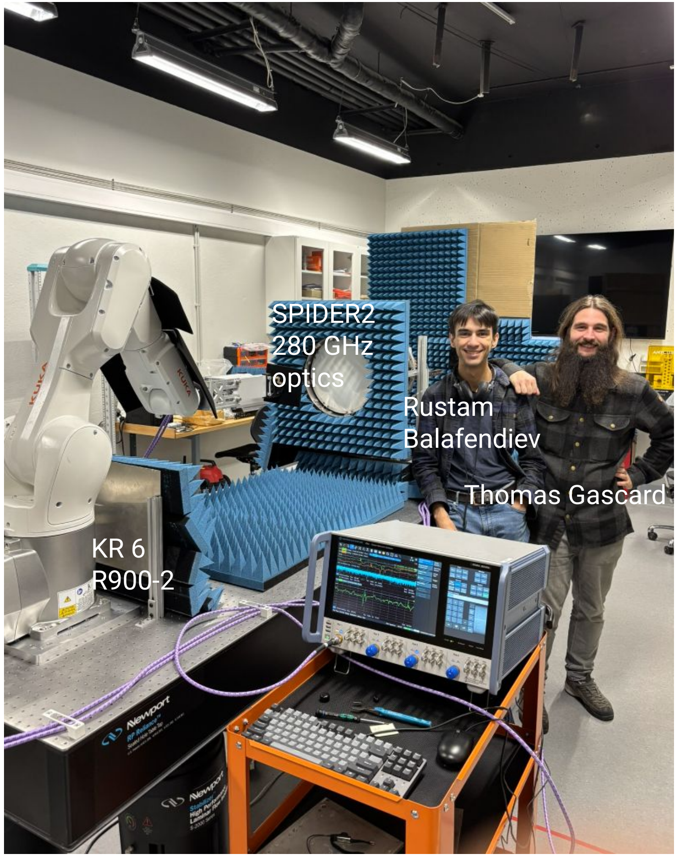
VR III lab space under construction

25 May 2023



2.5 x 2.5 x 6.5 m
anechoic chamber

Holography at the University of Iceland



- Phase-sensitive measurements at 75–110 and 220–330 GHz now up and running
- Warm testing of a SPIDER2, 280-GHz, optics tube ongoing
- Combination of warm measurements and GRASP simulations will help inform cosmological analysis
- Cryogenic measurements to follow in 2025

Beam estimates at ~ 3 mm wavelengths

Simple feedhorn-to-feedhorn transmission measurement gives good agreement with theory after we have implemented a rotation of 0.61 deg.

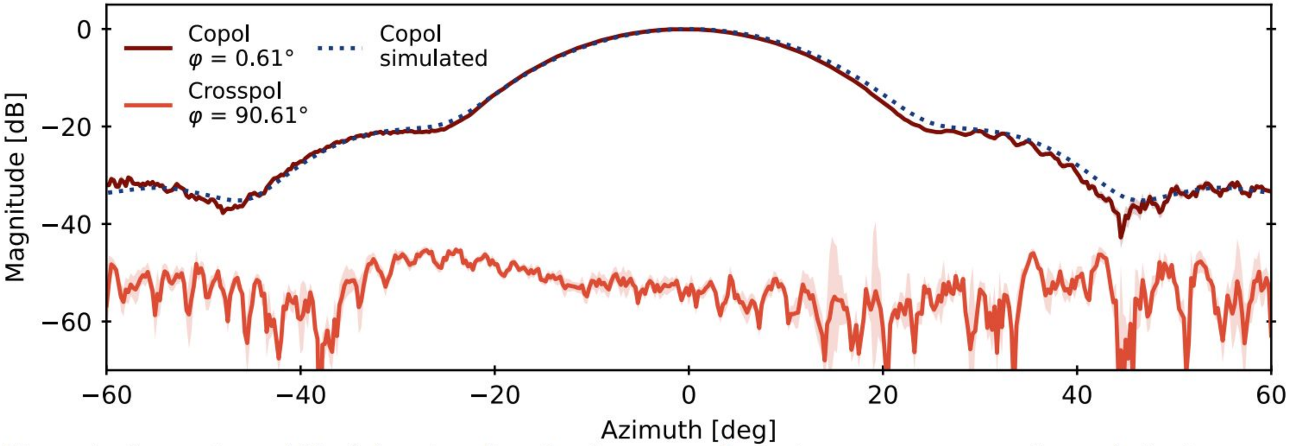
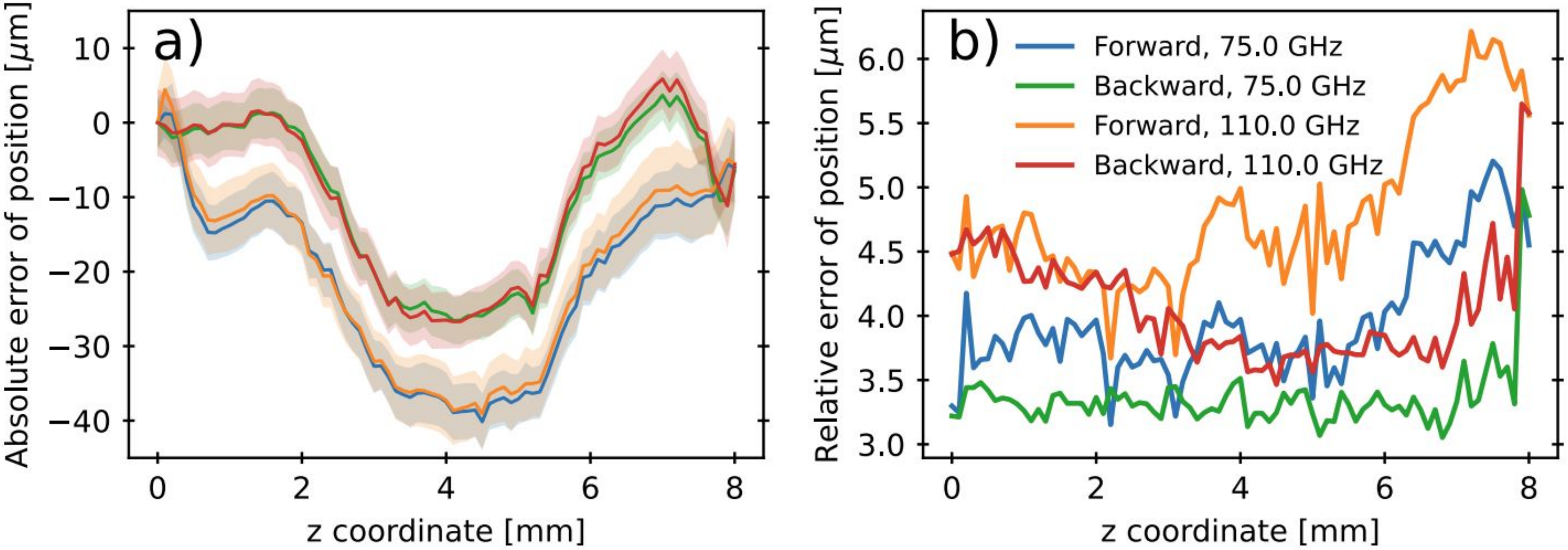


Figure 4: Comparison of 0° of elevation slices for the cross-polarisation measurement and co-polarisation measurement and simulation. A 3σ deviation envelope obtained from 40 identical measurements is plotted over the experimental data. The simulated data has been obtained using a model of the horn in CST MWS.[14] A rotation 0.61° was added to ϕ in the process of minimising the cross-polarisation response. The measured result matches well with the simulated one, with notable discrepancies being due to standing waves between the transmitter and the receiver and some degree of non-ideality of alignment. The normalised cross-polarisation measurement averages at about $-54\,\mathrm{dB}$, with some points going as low as $-70\,\mathrm{dB}$. This suggests a comparable dynamic range of about $-70\,\mathrm{dB}$ for this system.

Positional repeatability

Note: 1σ-variation in commanded vs realized position based on 100 scans. **The spec sheet states that this number should be 20-30 µm!**



Note: Absolute position error based on expected phase shift relative to measured shift,

Balafendiev, Gascard, and JEG, SPIE (2024)

Positional repeatability

We performed 100 planar scans over a 60 ✕ 60 cm region sampled at 2-cm intervals with each scan lasting for approx. 30 minutes.

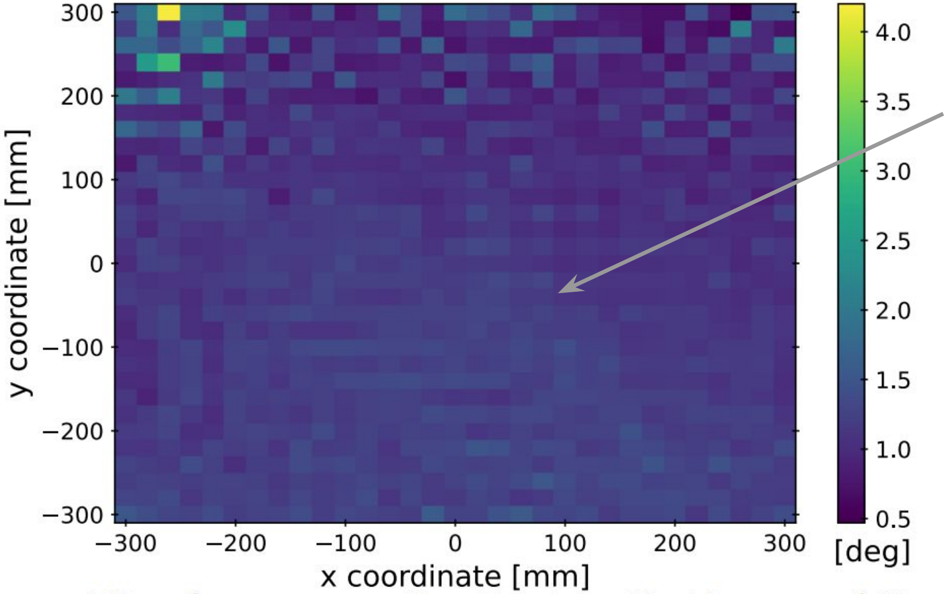


Figure 6: Positional repeatability of a scan over a 31 × 31 point grid with a span of 60 × 60 cm at the lowest frequency of 75 GHz, calculated by the 1σ standard deviation from 50 samples at each point.

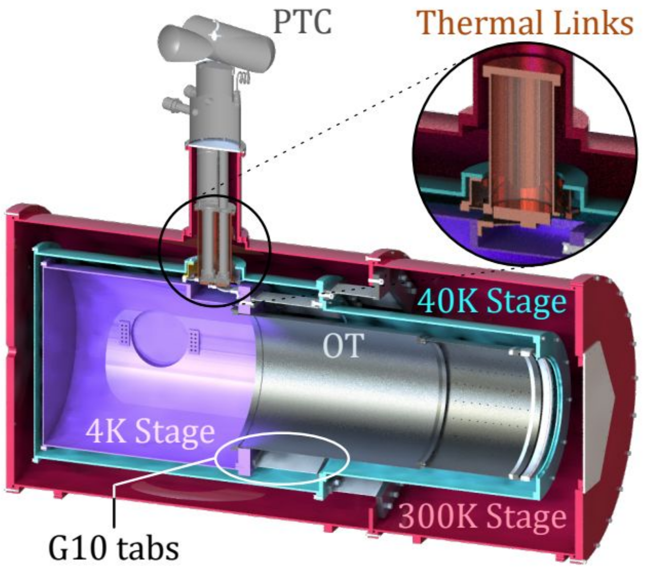
Mean phase error ~ 1 deg at 75 GHz, corresponding to ~ 10 μm

Note that this is an **upper limit on error** in positional repeatability

Balafendiev, Gascard, and JEG, SPIE (2024)

CryoBEAM

https://github.com/Skuggsja-Lab/skuggsja-cryobeam/



(a) The Mod-Cam cryostat

Gascard et al., SPIE (2024)
https://arxiv.org/pdf/2407.04613

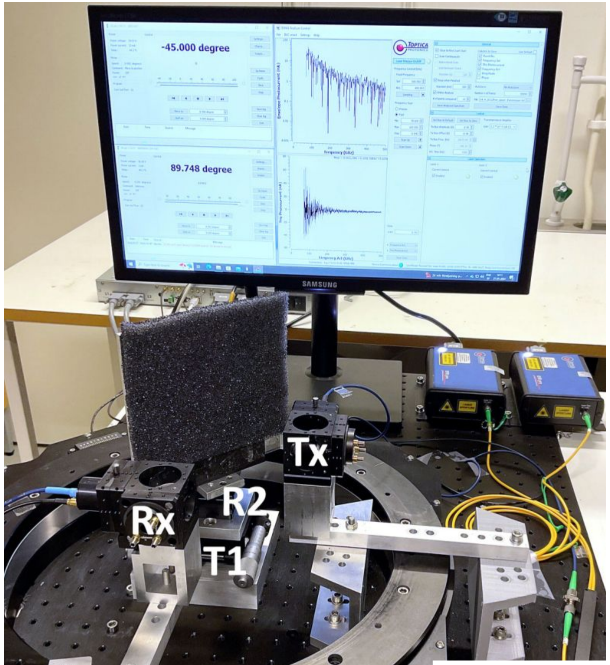
Thomas Gascard

- A fully parameterized Solidworks model coupled to Comsol thermal analysis via Livelink
- Building a 4K cryostat that can accommodate most optics tubes implemented by current and future-generation experiments
- Goal is cryogenic holography to inform telescope designs and constrain optical properties of real instruments
  - Modeled after work done by pioneers in the field: Chesmore, Takakura, McMahon, Sekimoto, Yates, and many others
- Assembled and tested phase-sensitive microwave circuits for 75–110 and 220–330 GHz, with more frequency bands on the way

Terascan FSL systems

See also talks from Lessler (Tue) and Sutarya (Thu)

TKRam unit cell size: 4 mm
PMA unit cell size: 6 mm
Stycast is flat



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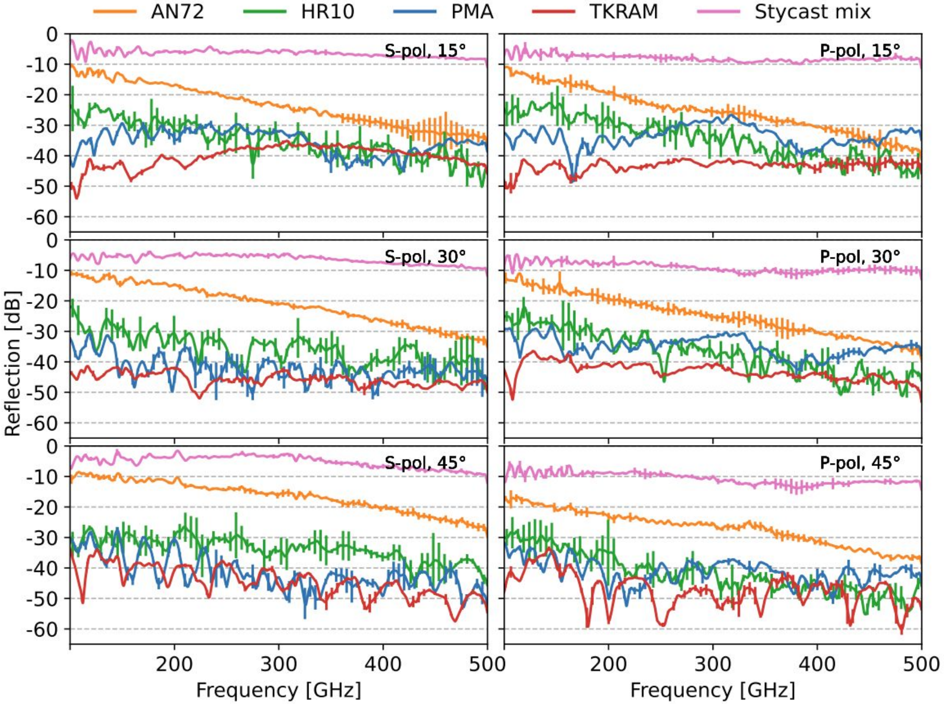


Figure 3. Comparison of specular reflection response from various absorbers at different angle of incidence ($\phi_1 = 15°$, $30°$, and $45°$) for the two polarizations, S-polarization (left column) and P-polarization (right column).

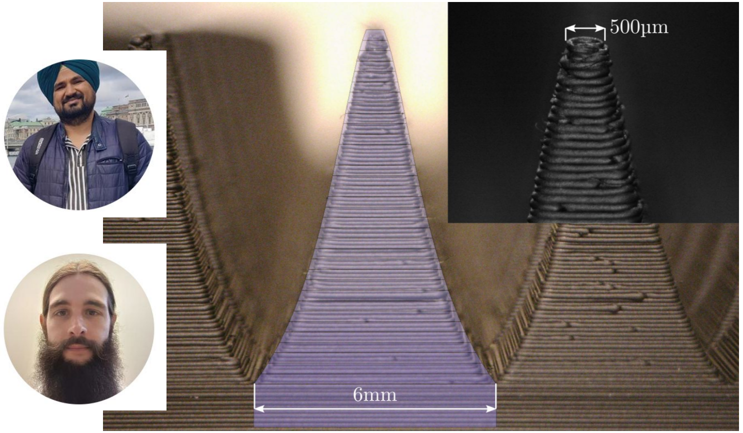
Singh et al., SPIE (2024)
https://arxiv.org/pdf/2407.05512

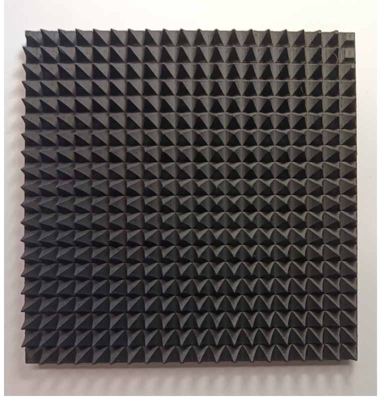
What is the optimal absorber geometry?

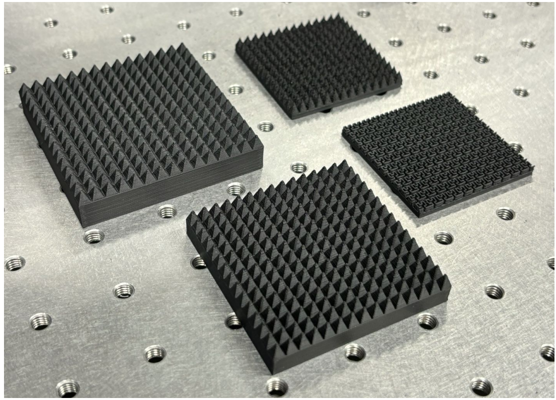
- Optimal absorber geometry depends on frequency range, incidence angles, and material properties
- What is the optimal geometry?
  see e.g. Kubitsky (‘12) or Wollack (‘14)
- FDM 3D printing produces arbitrary geometries with limited artifacts and details down to 500 µm
- TKRAM: ε = 3.7 + 0.5i
  PMA: ε = 5.1 + 0.8i
  Stycast: ε = 5.2 + 0.02i
- To be minimized:

Reflectance

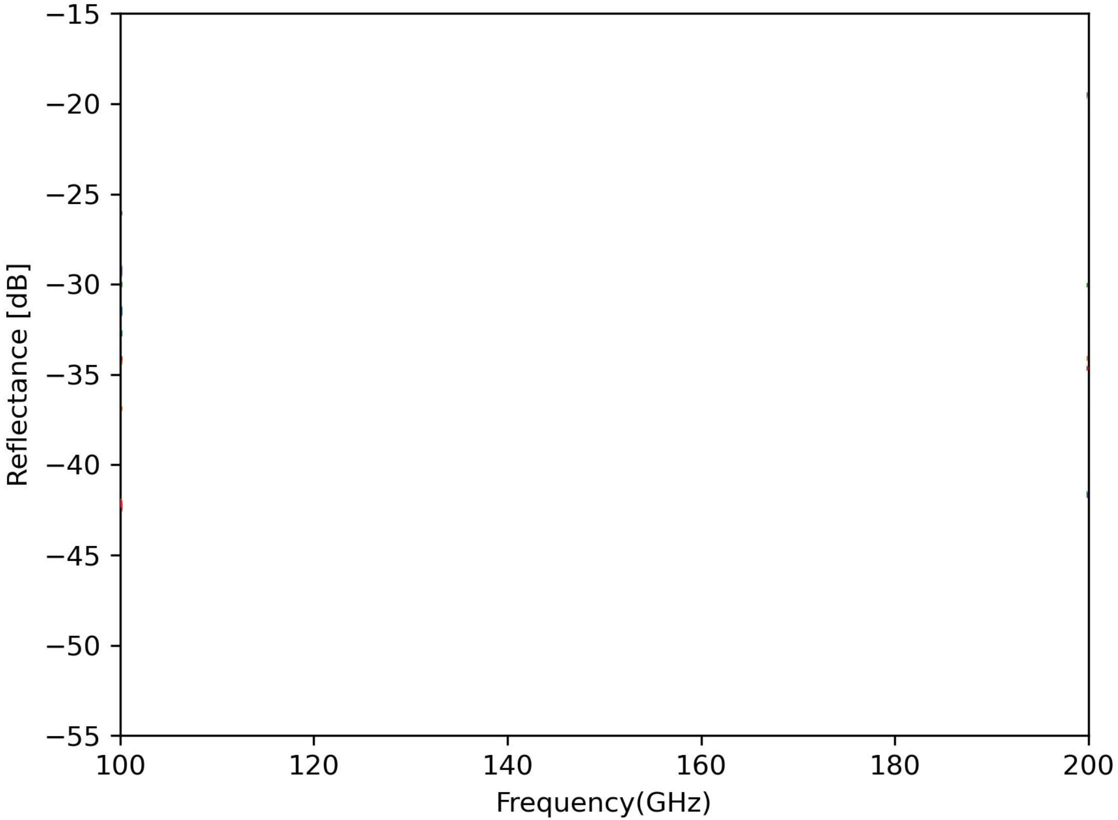
$$\mathrm{FoM} = \iint R(\nu,\theta)\,d\nu\,d\theta$$

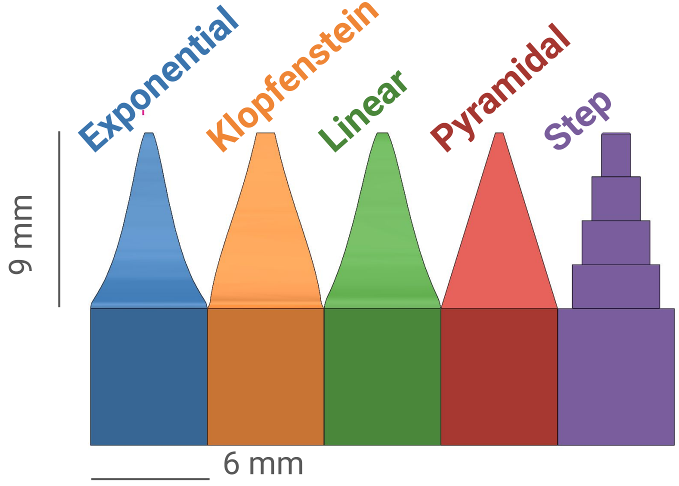






Measurement results at 15-deg angle of incidence





Note: Same material, different geometries
Material: ε = 5.1 + 0.8i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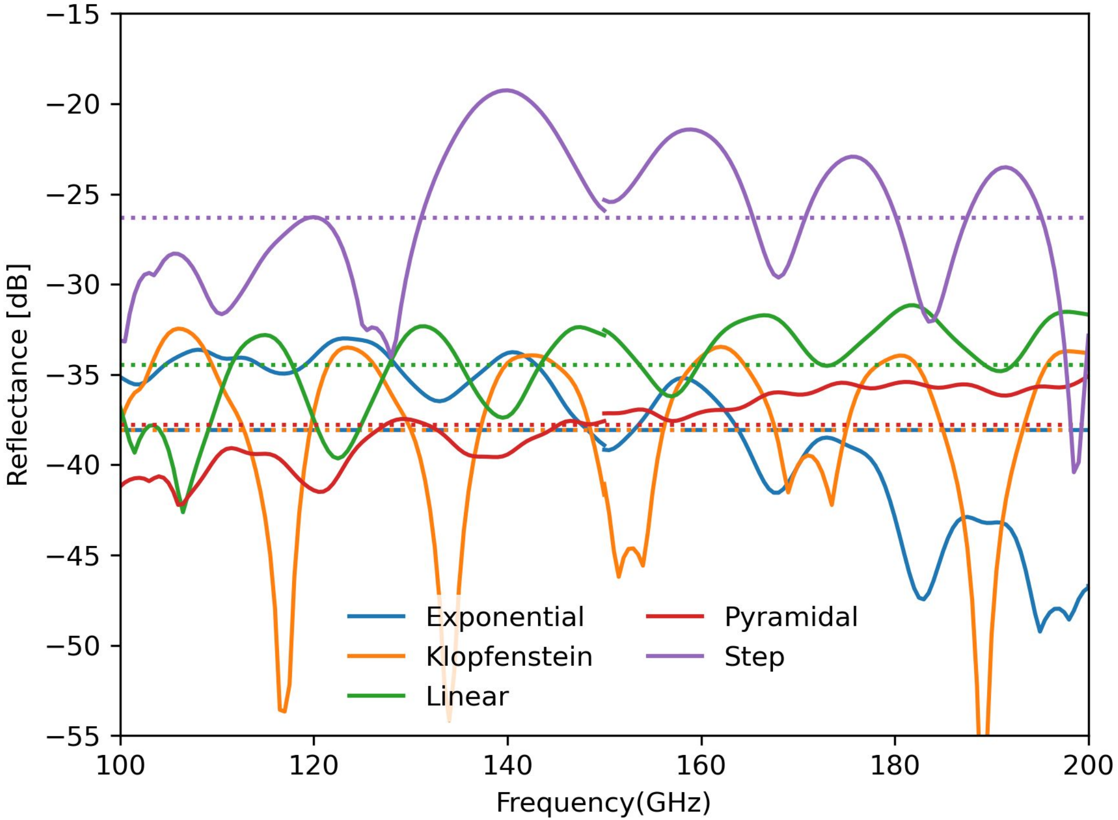
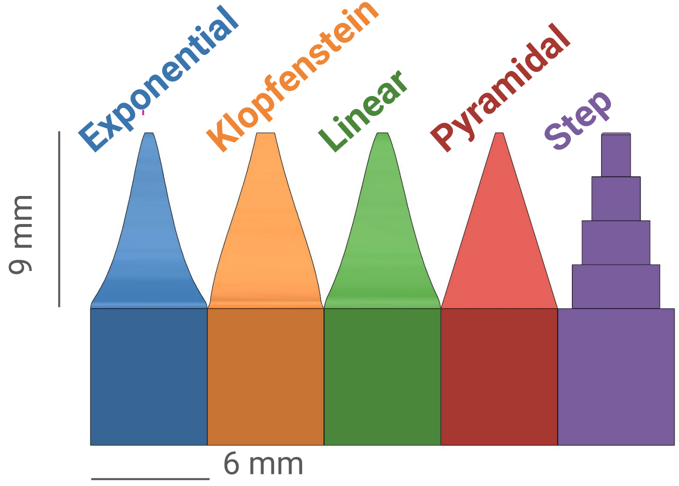
Best performance compares quite favorably with Petroff et al. (2019), Xu et al. (2020)

Simulation results





Note: Same material, different geometries
Material: ε = 5.1 + 0.8i

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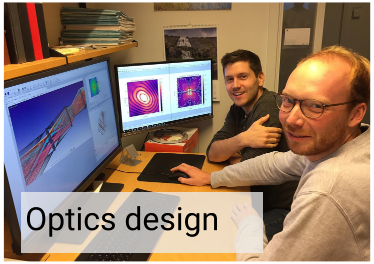
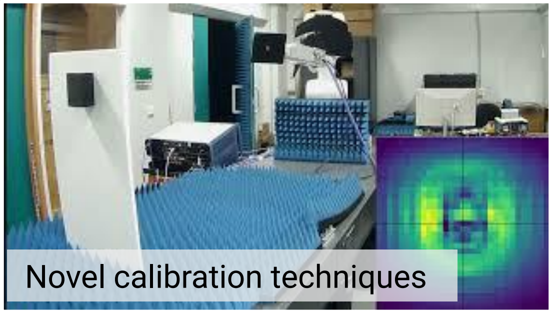
Two new positions:
PhD student (3-year minimum)
Postdoctoral researcher (3-year)
Application deadline December 2
https://english.hi.is/vacancies
https://cmbeam.com/

Potential research projects include efforts relating to data analysis, calibration and instrument development for past, current, and future experiments. This includes Planck, SPIDER, Taurus, Simons Observatory, and LiteBIRD.


Optics design


Instrument development


Novel calibration techniques

In conclusion

We have made a lot of progress in the last 5–10 years, but there is a long way to go!

The community is now largely aware just how important our understanding of the instrument is for extracting future science results.

A new CMB group in Iceland is doing cool stuff!

Big hurdles in advanced optical modeling remain.

Working on beams might get you published in the New York Times!

Nadia Dachlythra et al.
ApJ (2024)

In Scandinavia, unearthing a ship burial that predates the Viking Age.

A look at a claim by online influencers about delaying your morning coffee.

ScienceTimes

The New York Times

Seeking Clues From the Big Bang

A Chilean observatory's study of cosmic microwaves could offer insights on theories of space-time.