On-sky Calibration of CMB Experiments

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New Perspectives Conference

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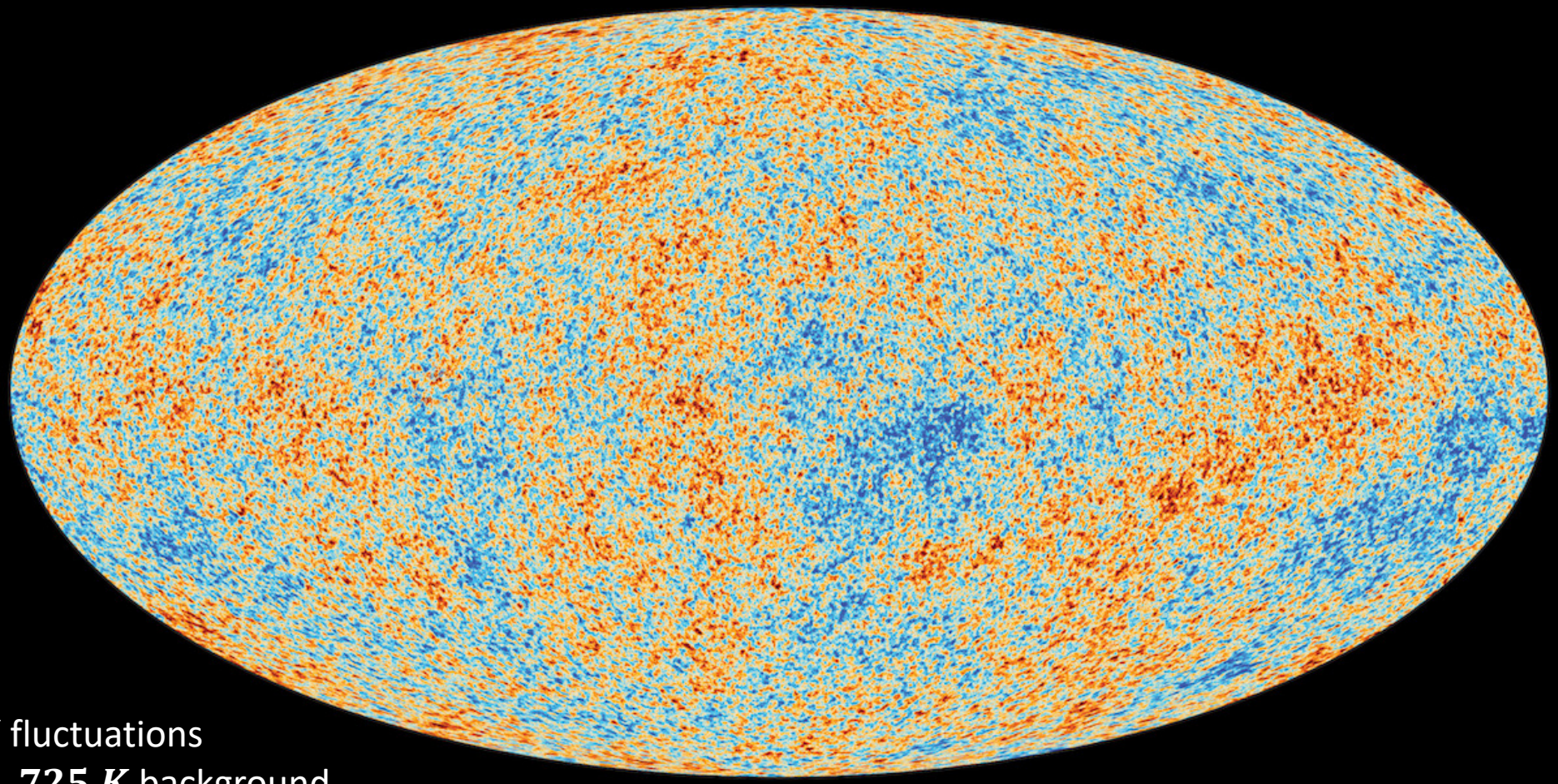
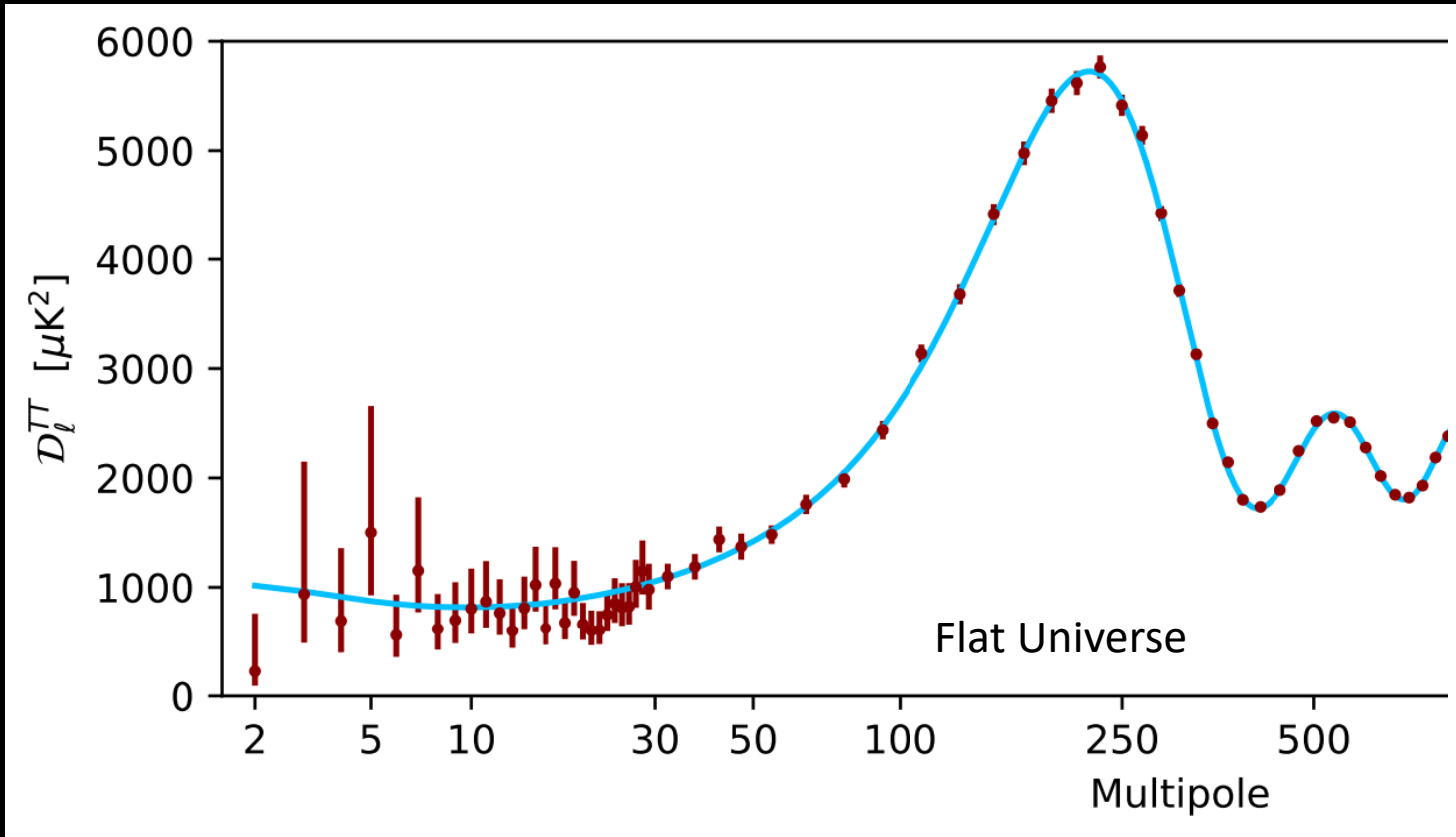
The CMB Temperature (Ani)sotropy



$\pm 300\ \mu K$ fluctuations
over the $2.725\ K$ background,
1/10,000.

Figure credits: Planck 2018

Temperature Anisotropy Power Spectrum



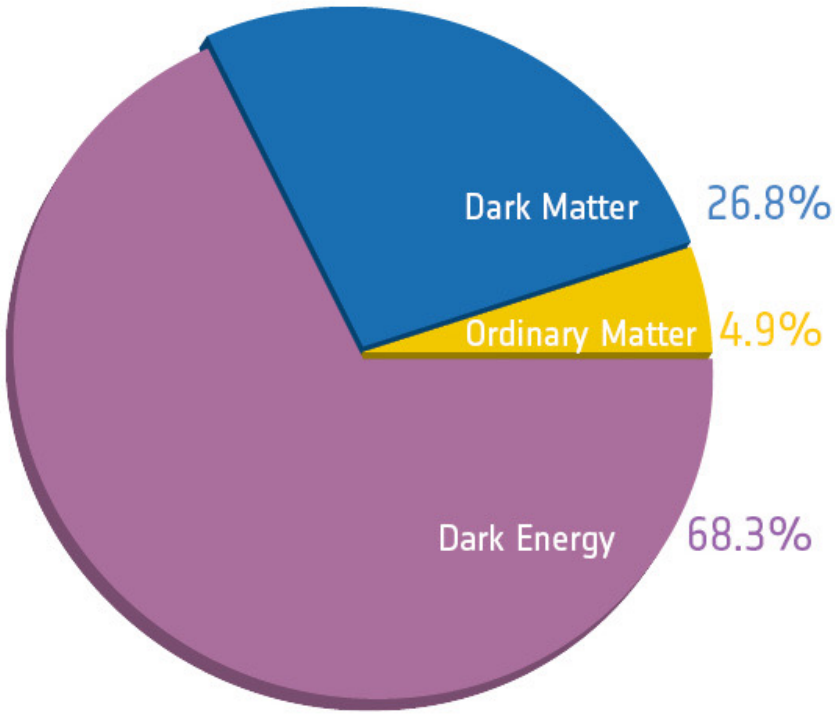


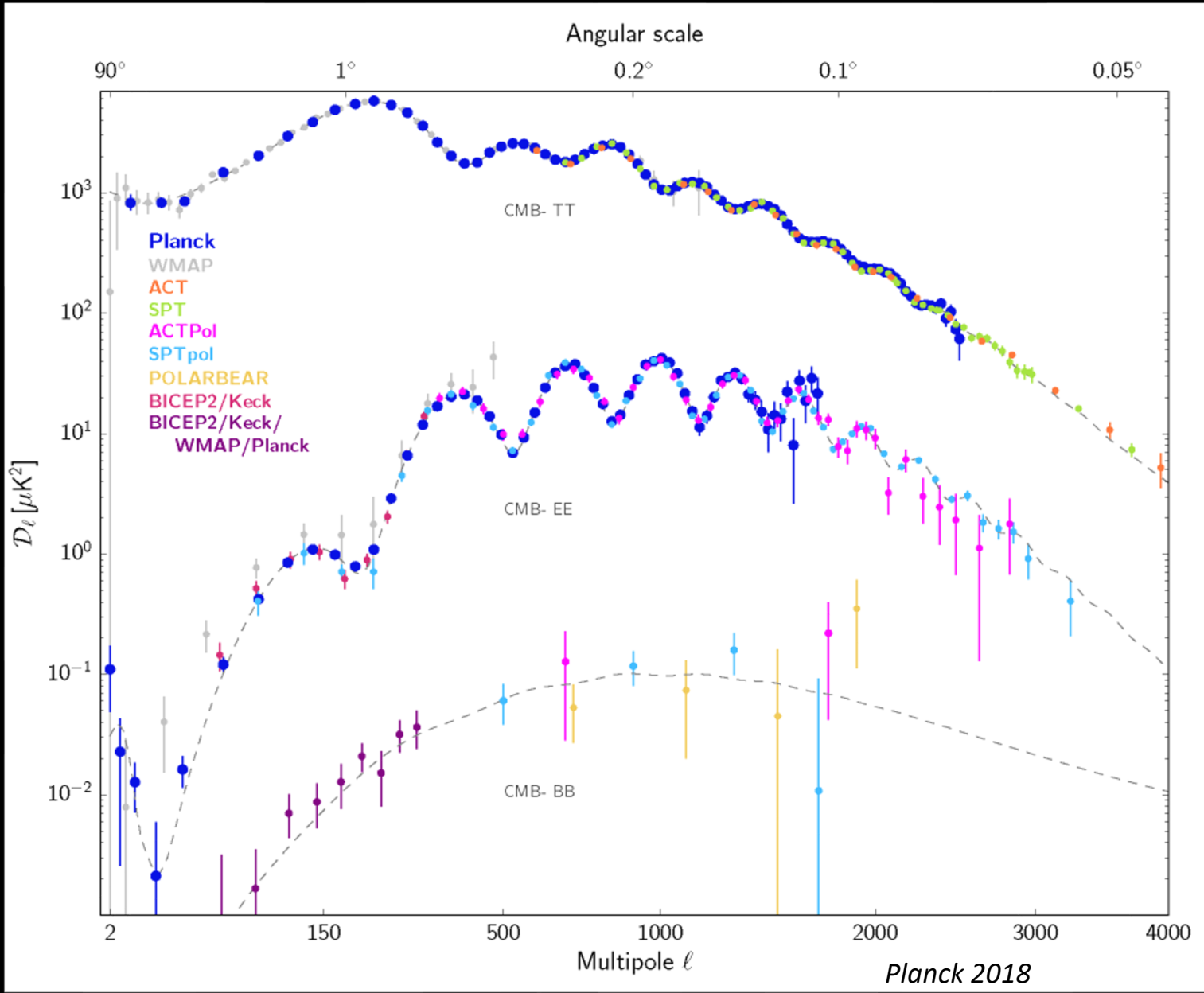
Figure credits: Planck 2018

Cosmic Inflation: an exponential expansion of the Universe at the first 10^{-35} s

Solves horizon problem, flatness problem, and explains initial perturbation

CMB polarization can be decomposed into curl-free E-mode and curly B-mode.

Only the inflationary gravitational wave (tensor perturbation) generates B-mode polarization at the largest scales.



Planck 2018

Importance of Calibration

- Build instruments → make measurements
- Build instruments → <u>know the instruments</u> → make measurements

- Raw data from different experiments are digitalized numbers.
- <u>Calibration</u> provides the knowledge of the instrument to interpret <u>digital numbers</u> into <u>physical meanings</u>
- As important as building the instrument

Cosmology Large Angular Scale Surveyor (CLASS)

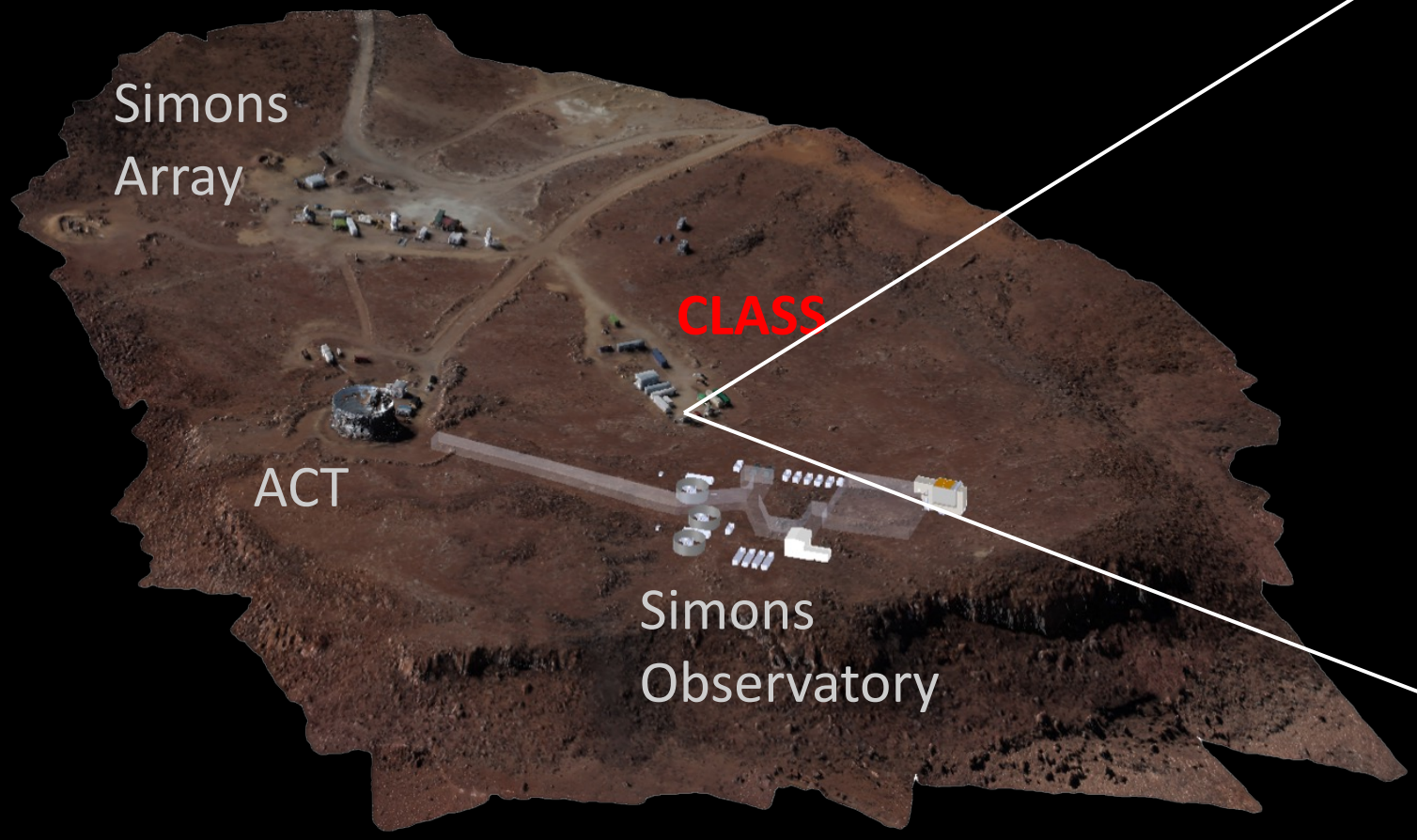


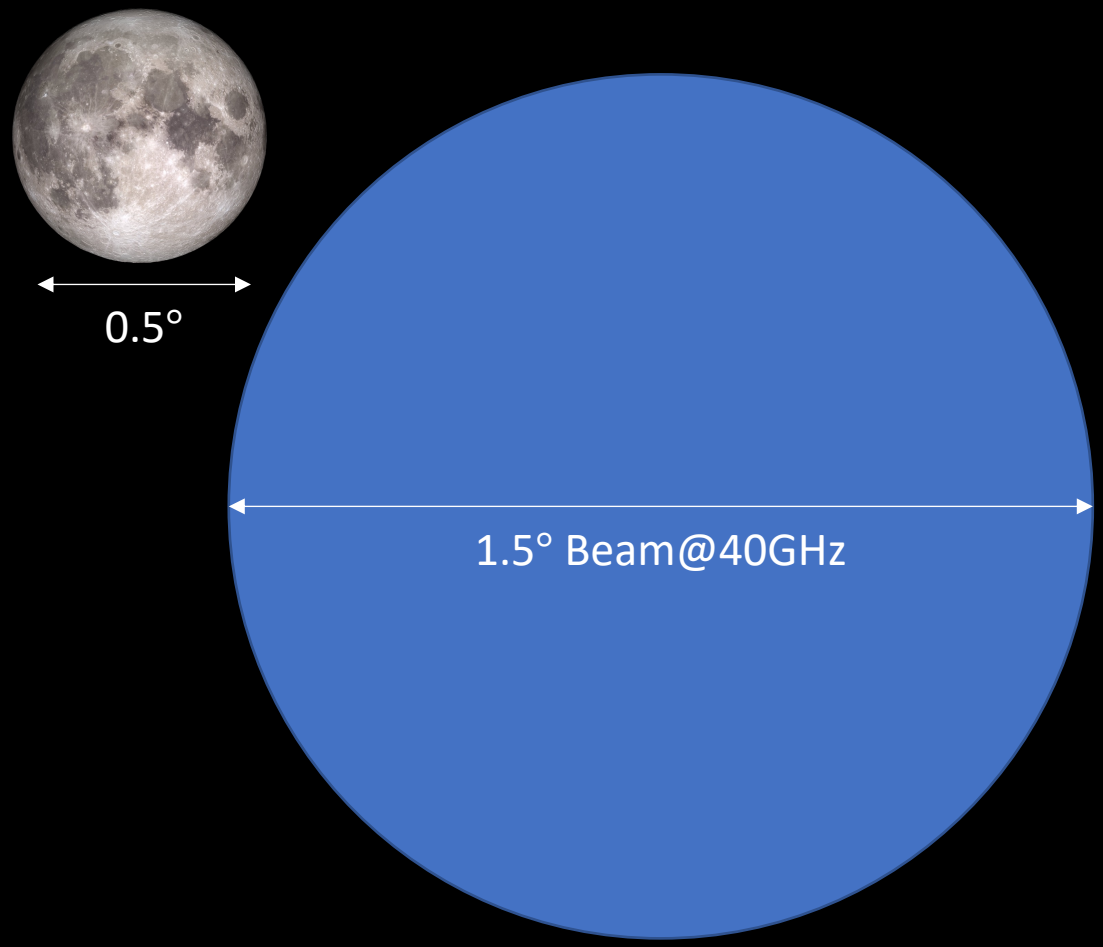
Figure credits: SO and CLASS Collaboration

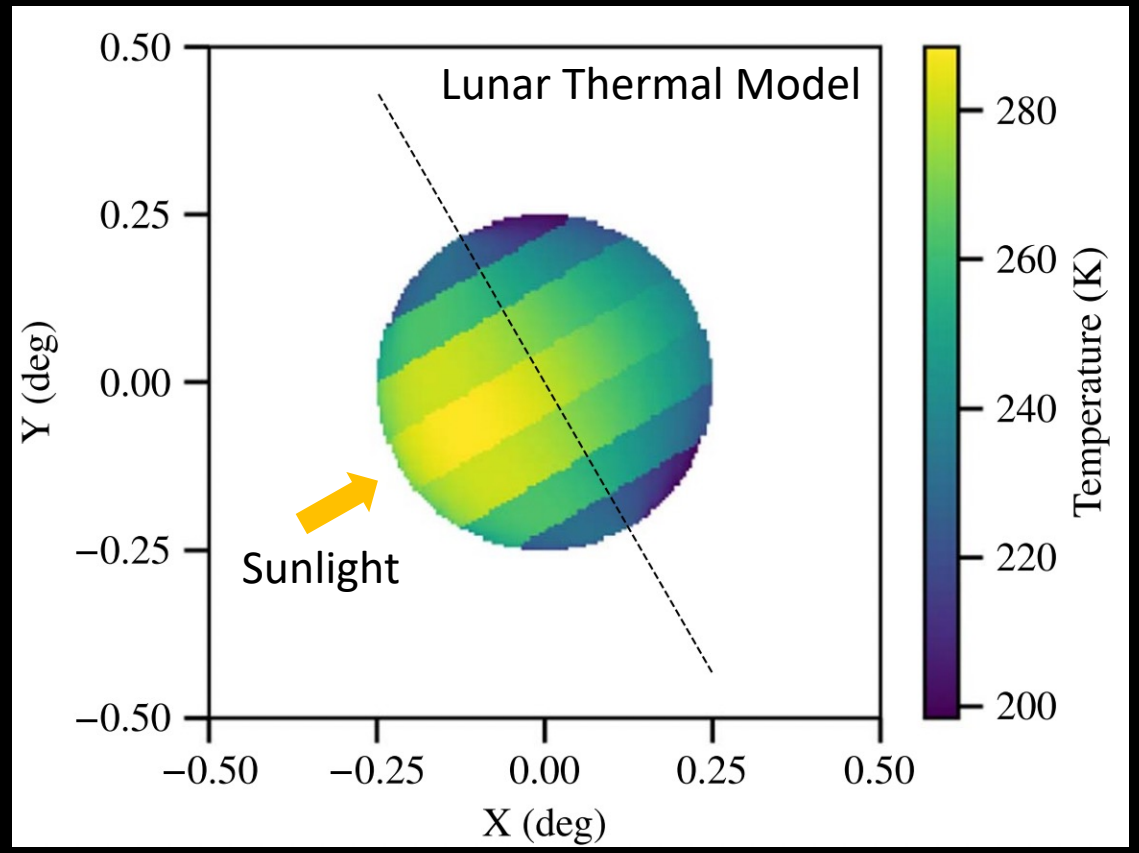
Calibration Analysis (intensity)

- System efficiency: testing the efficiency of all optical components
- Pointing & Beam: testing the alignment of all the optical components
- Far sidelobes: testing the suppression of optical systematics

Calibration Analysis (intensity)

Moon as the calibrator

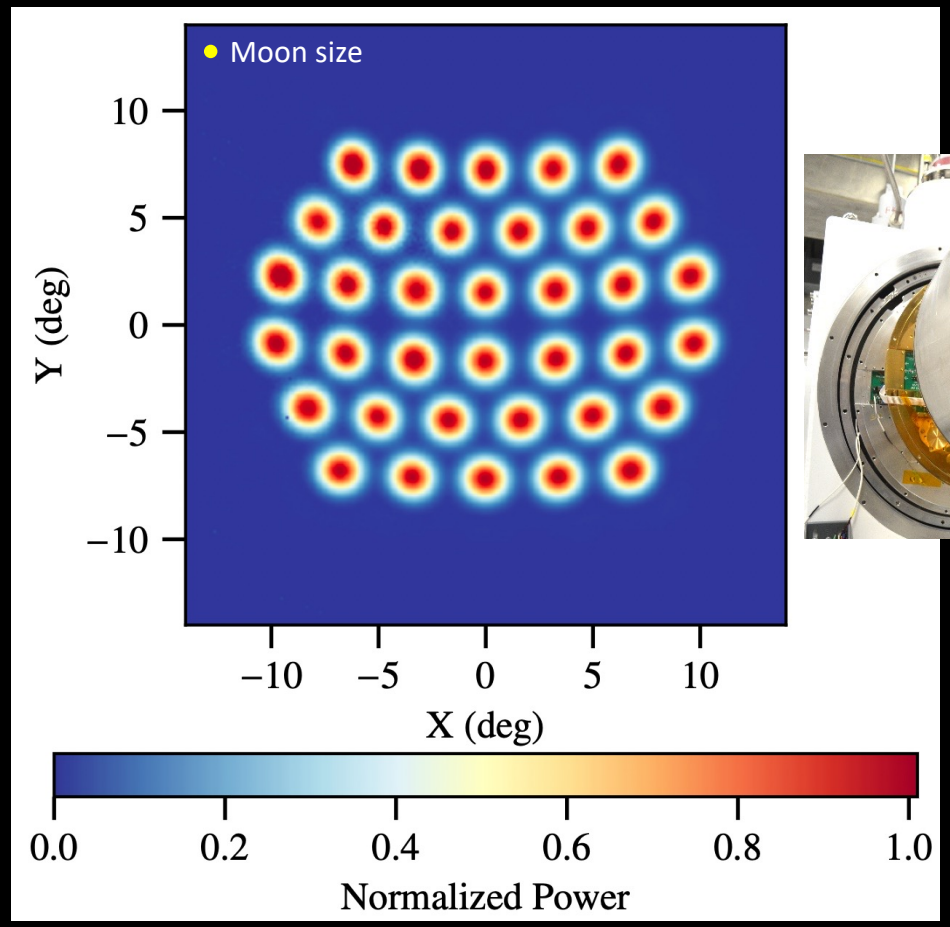


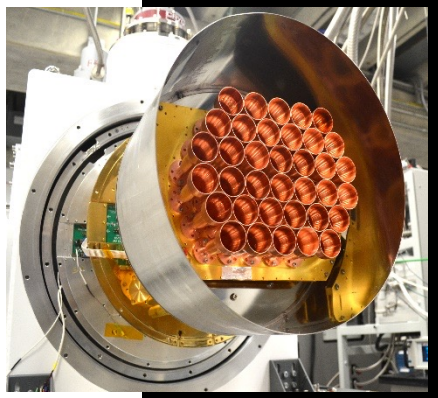


$\eta = 48\%$

(Appel, Xu, et al., 2019)

Calibration Analysis (intensity)





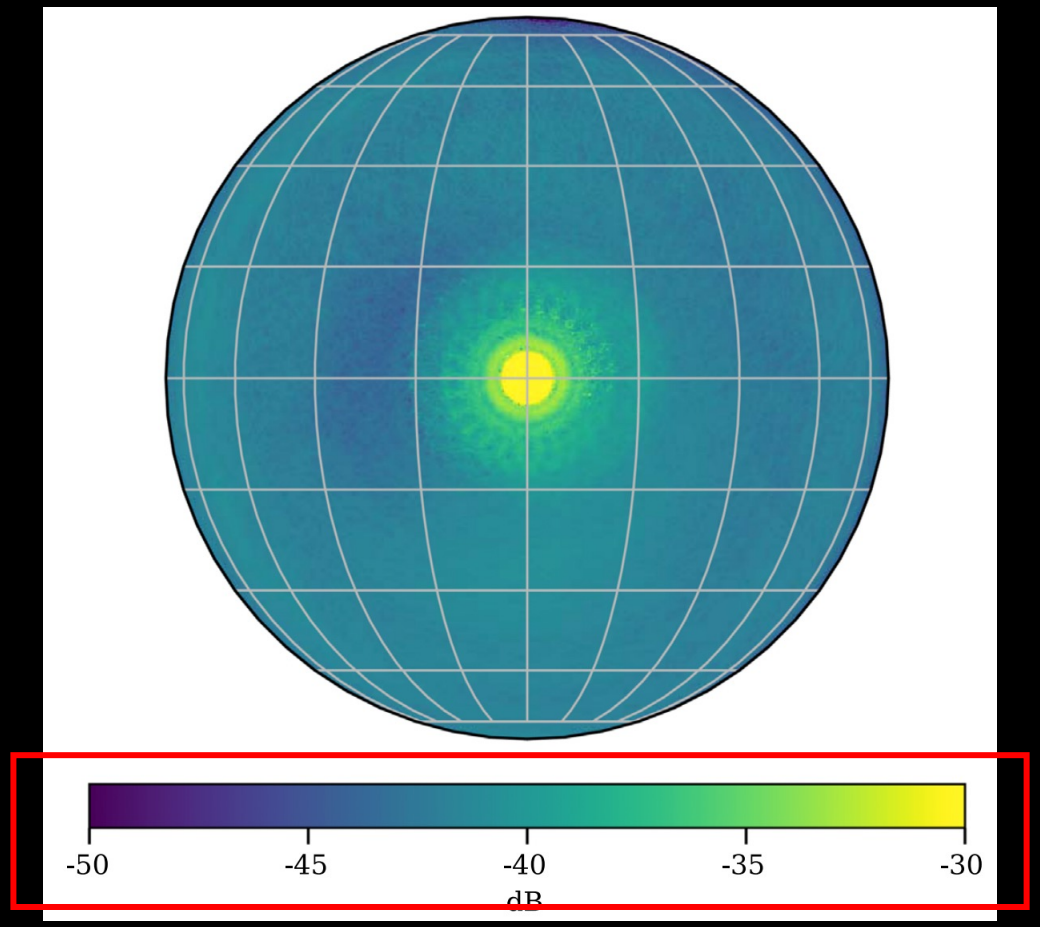
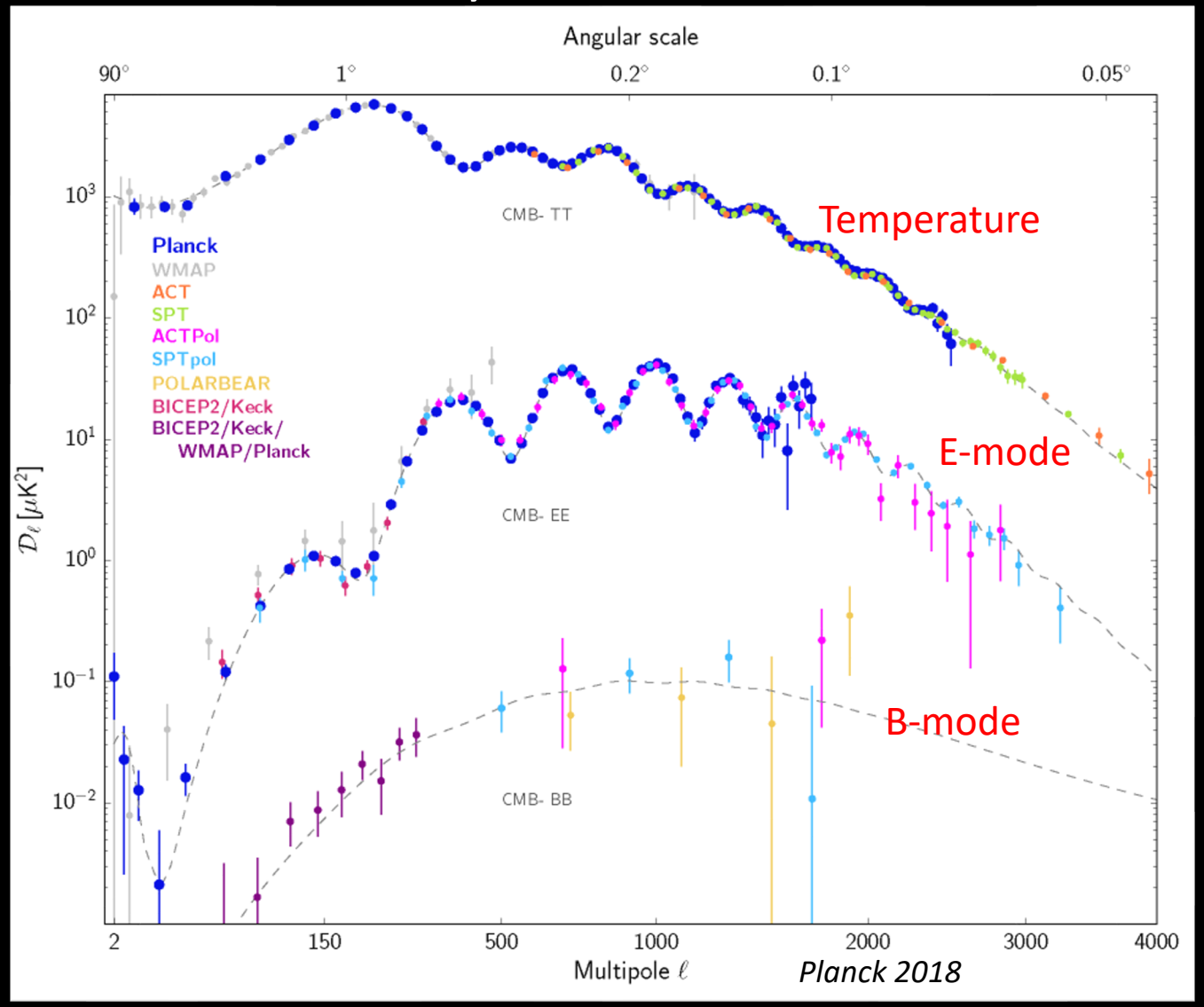


Photo credits: CLASS Collaboration

Xu et al., 2020

Calibration Analysis (Polarization)

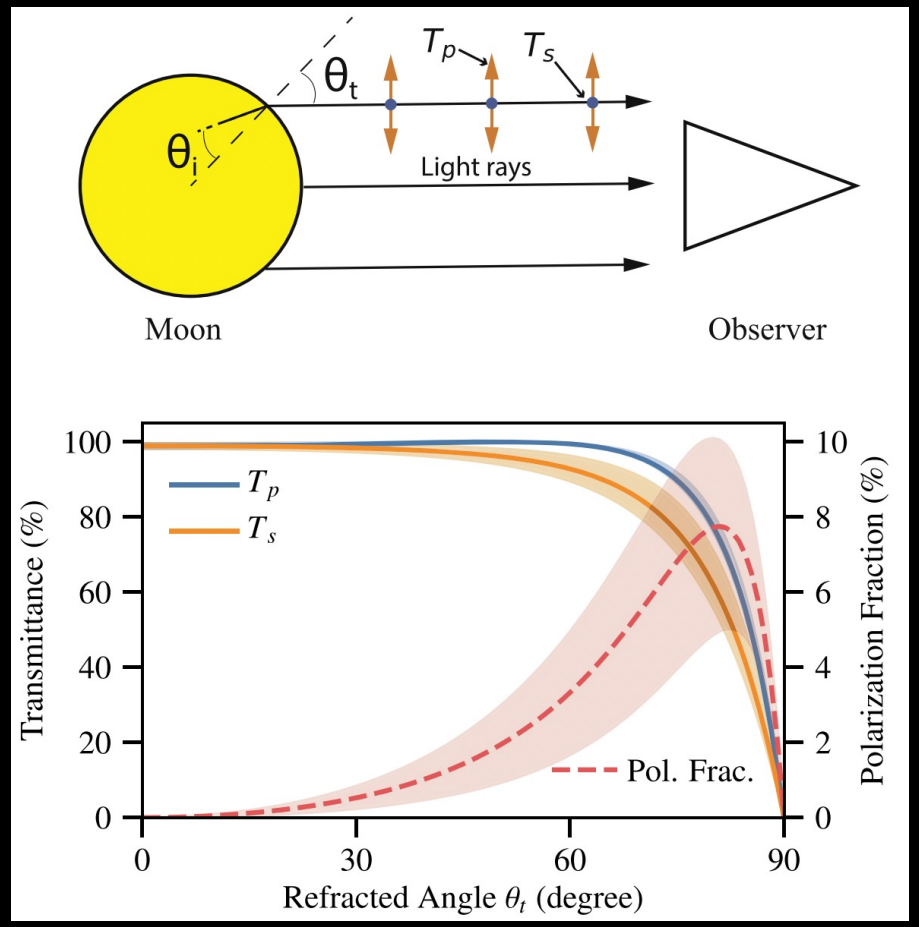
- Polarization calibration is <u>important</u>
  - Temperature—polarization leakage
  - E—B Leakage: det polarization angle
- Polarization calibration is <u>hard</u>
  - Not many significantly-polarized celestial sources
  - The polarized celestial sources are NOT well understood



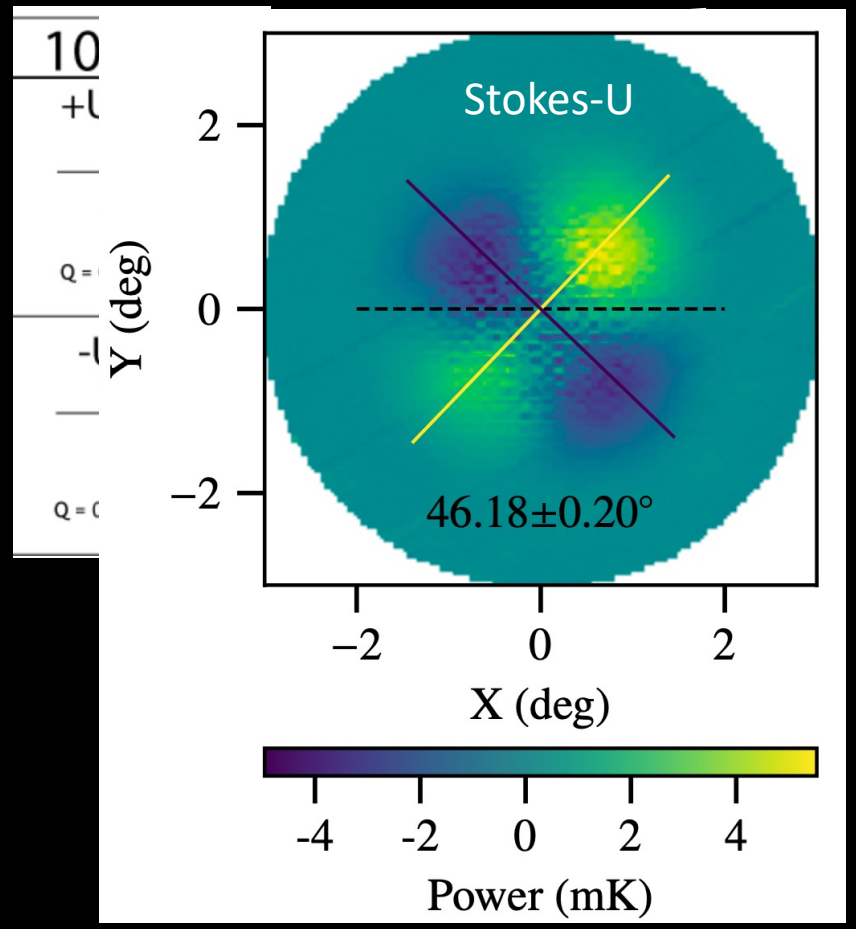
Planck 2018

Calibration Analysis (Polarization)

Moon as the calibrator

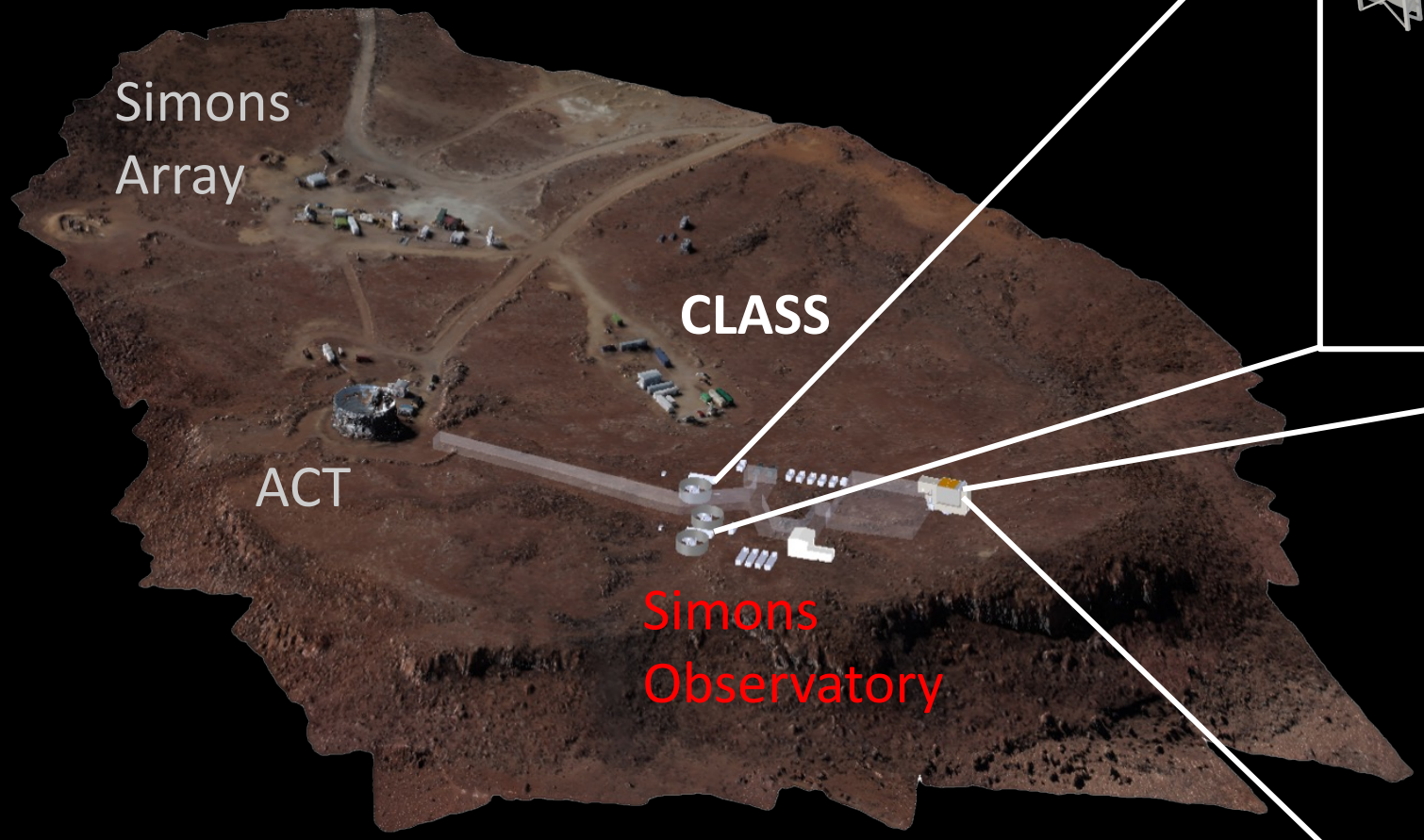


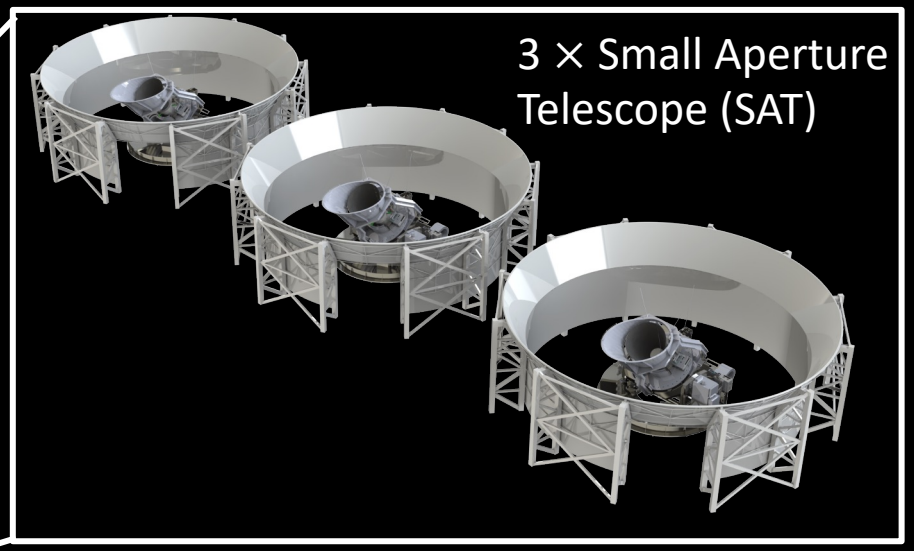
- Measured the temperature-to-polarization leakage at $4.4 \pm 2.6\times 10^{-5}$ $(68\%\ C.L.)$
- Polarization angle
  - Distinguishing E and B modes
  - <u>Sub-deg</u> precision

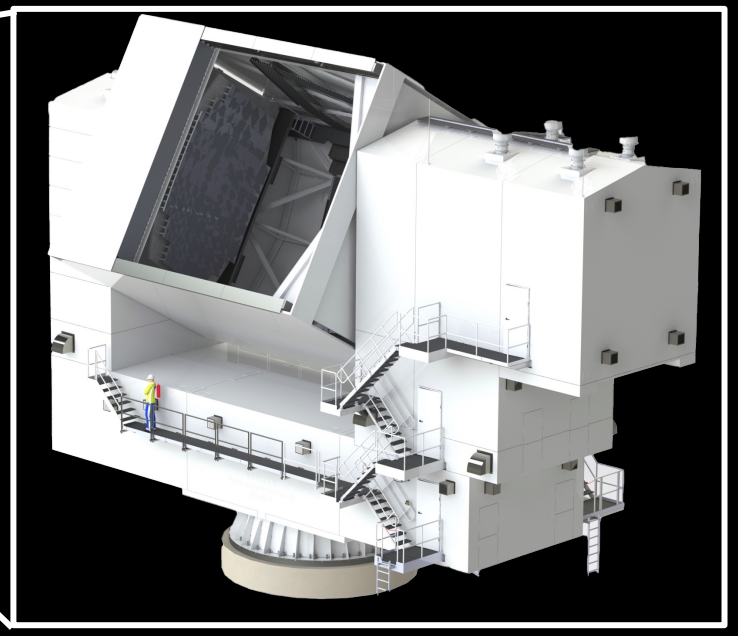


Xu et al, 2020

Simons Observatory (SO)







1 × Large Aperture Telescope (LAT)

Figures Credits: SO Collaboration

Calibration Analysis

- Learning from previous experiments
- Simulated raw data
  - Detector noise
  - Atmospheric noise
- Calibration analysis is underway
- Drone Calibration

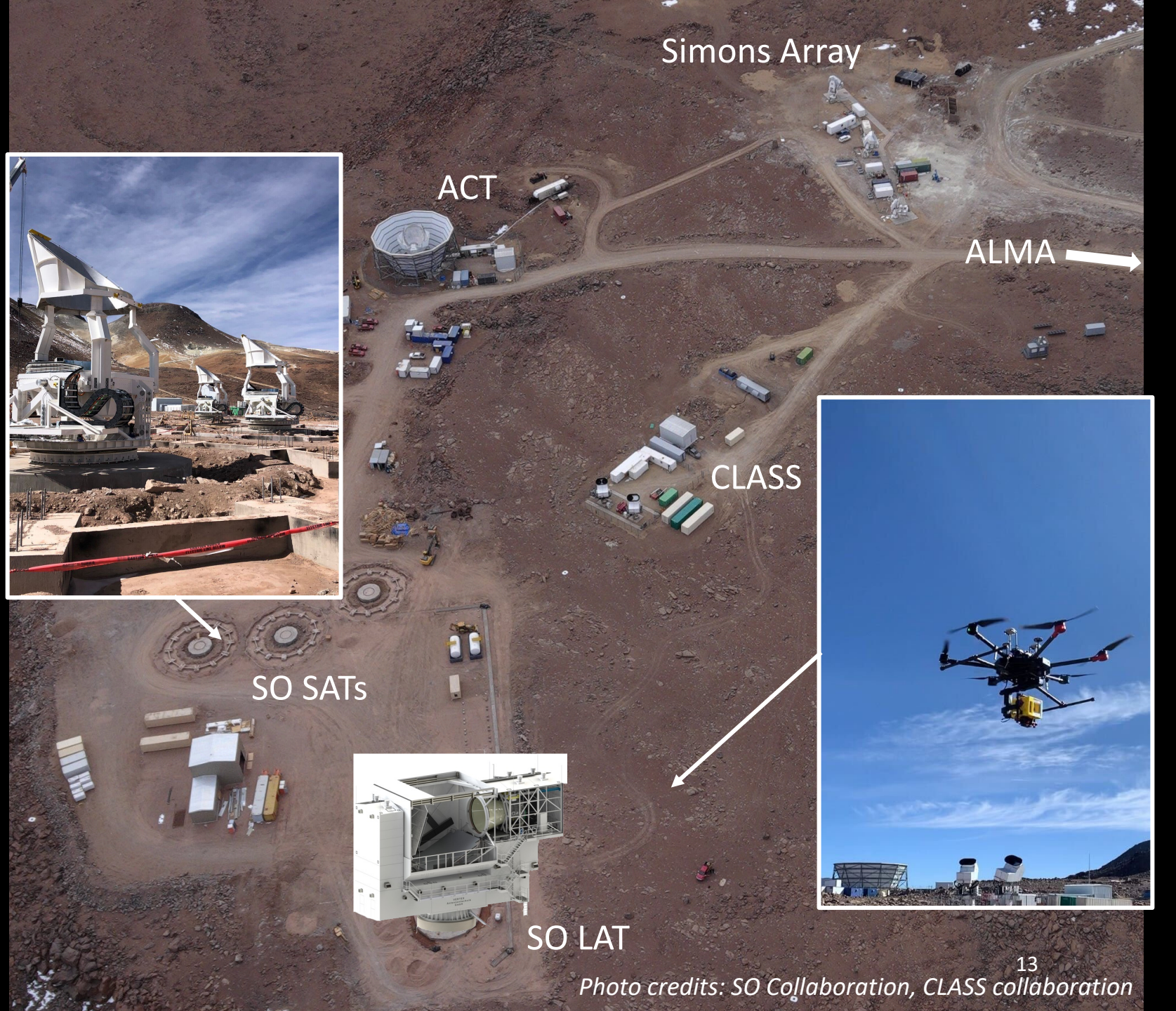


Photo credits: SO Collaboration, CLASS collaboration

Conclusion

- Calibration is as important as building the instrument itself and has become the bottleneck for CMB experiments.

- We have demonstrated that we could calibrate the 40GHz telescope with the Moon within CLASS:
  - Intensity: efficiency, pointing, beam, far sidelobes
  - Polarization: temperature-to-polarization leakage, detector polarization angle

- We are developing the calibration pipeline and strategy for Simons Observatory.