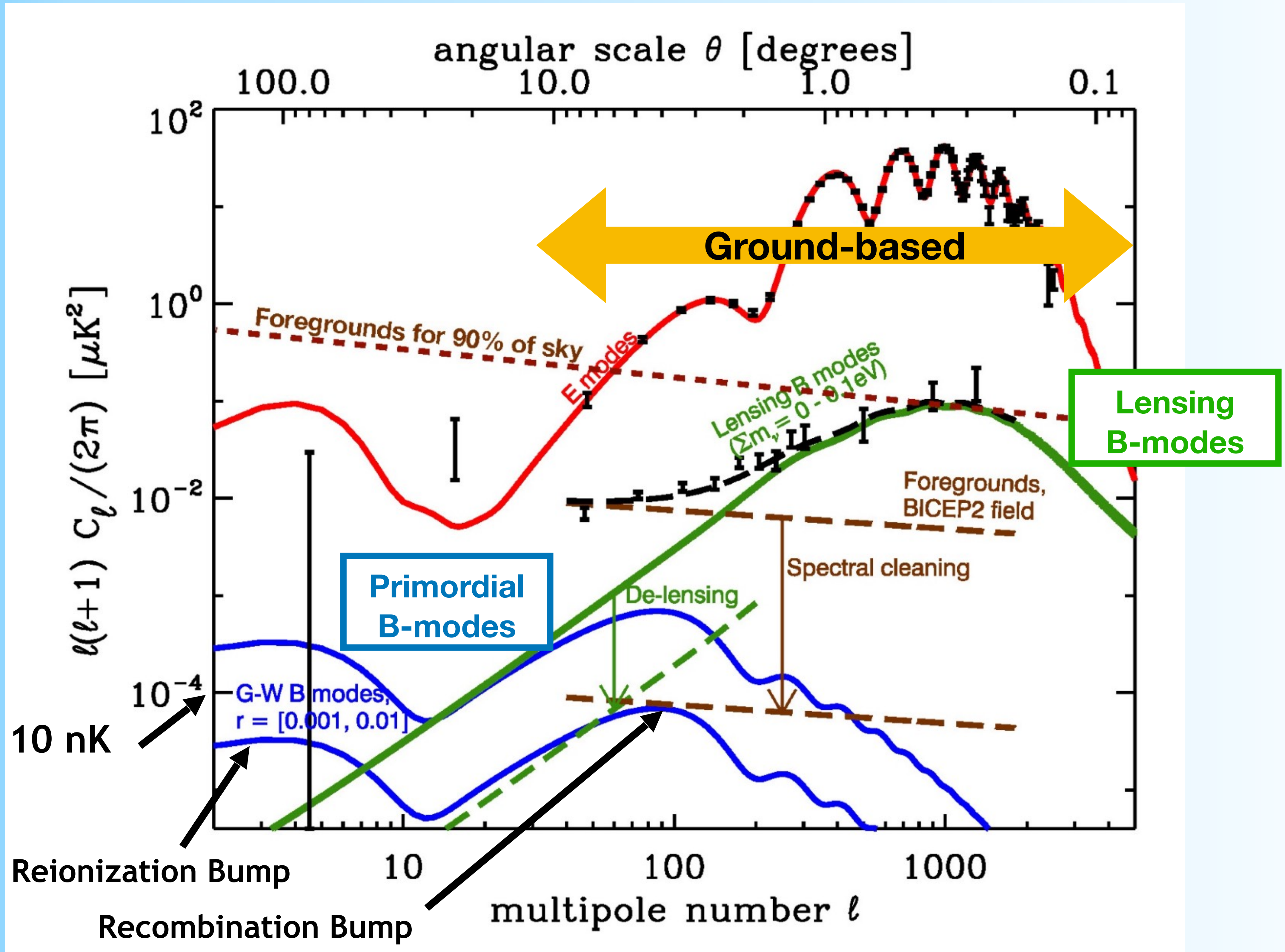
Telescope Baffling Design that Minimizes Stray Light Systematics for Ground-based Experiments, The Simons Observatory Case

Frederick Matsuda
Kavli IPMU

CMB Systematics and Calibration Focus Workshop
Dec. 1, 2020

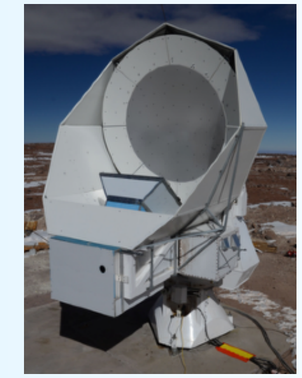
CMB Polarization Power Spectra



Ground-based Measurements

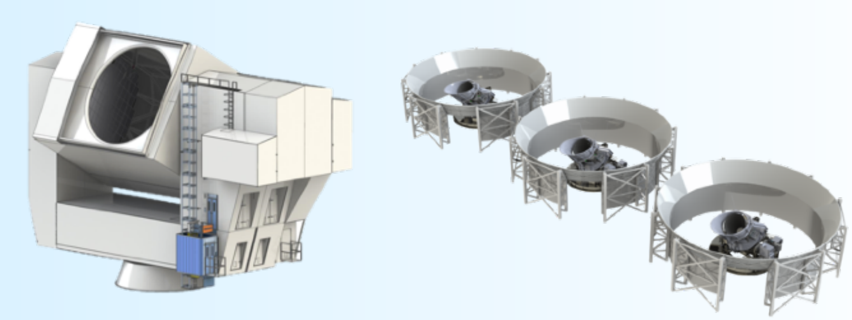
		Sensitivity (μK²)	σ(r)	σ(Σm_ν)	
2015	Stage 2 1000 detectors				Boss BAO prior
2016		≳10^{-5}	0.035	0.15eV	
2017	Stage 3 10,000 detectors				
2018					
2019					Boss BAO prior
2020		10^{-6}	0.006	0.06eV	
2021	Stage 4 CMB-S4 ~500,000 detectors				
2022					
2023					DESI BAO +T_e prior
Target		**10^{-8}**	**0.0005**	**0.015eV**	

POLARBEAR, SPTPol, ACTPol, BICEP2 /Keck Array



Simons Array, SPT-3G, AdvACT, CLASS

Simons Observatory, BICEP Array



CMB-S4

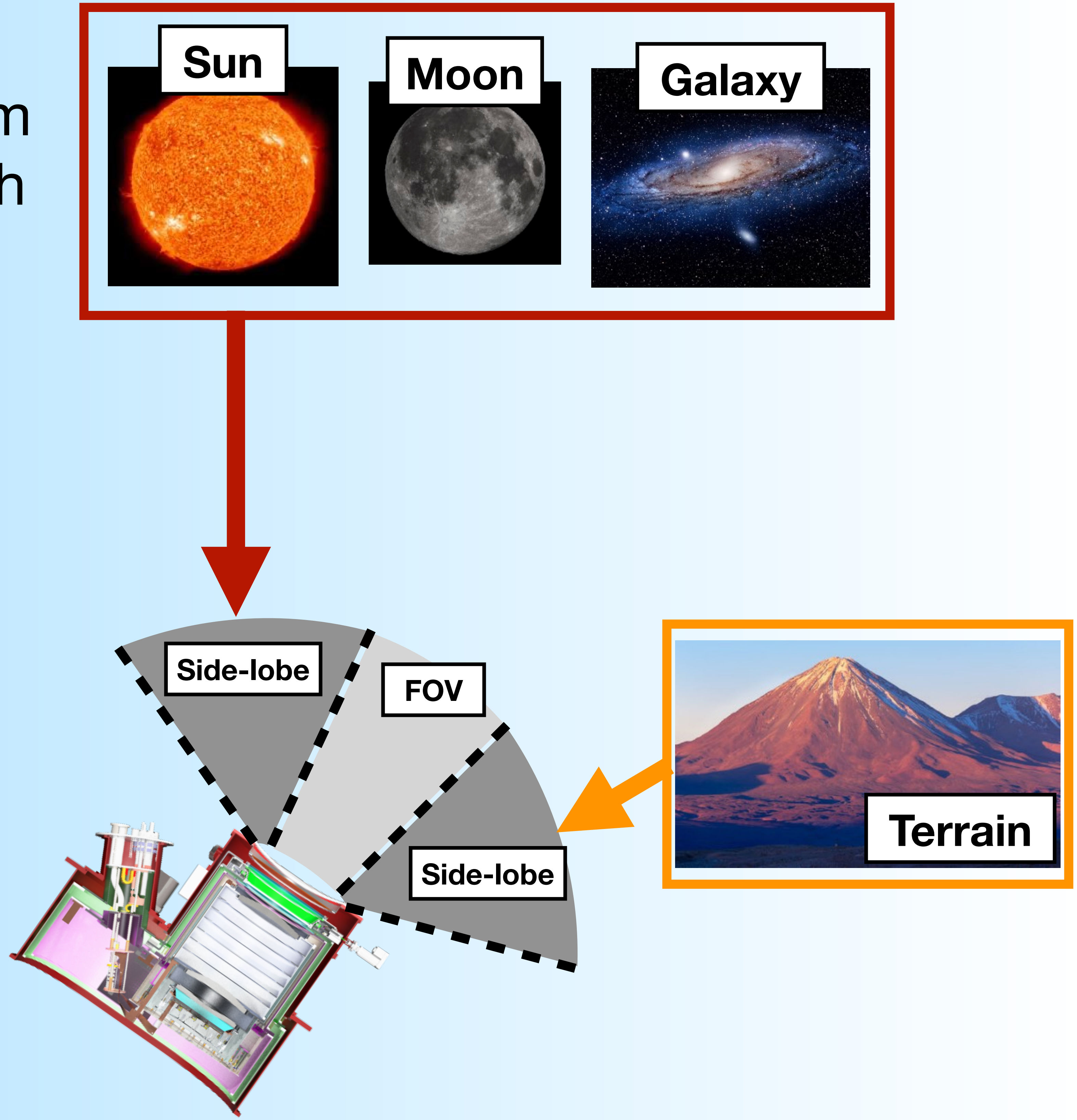
With increasing sensitivity, systematic error mitigation becoming more important

Stray Light Systematics

- Signal contamination from polarized sources through telescope side-lobes

- Typical bright sources
  - Sun, moon, galaxy
  - Terrain (mountains), buildings, other telescopes

- Mitigation strategies
  - Scan strategy
  - Telescope baffling



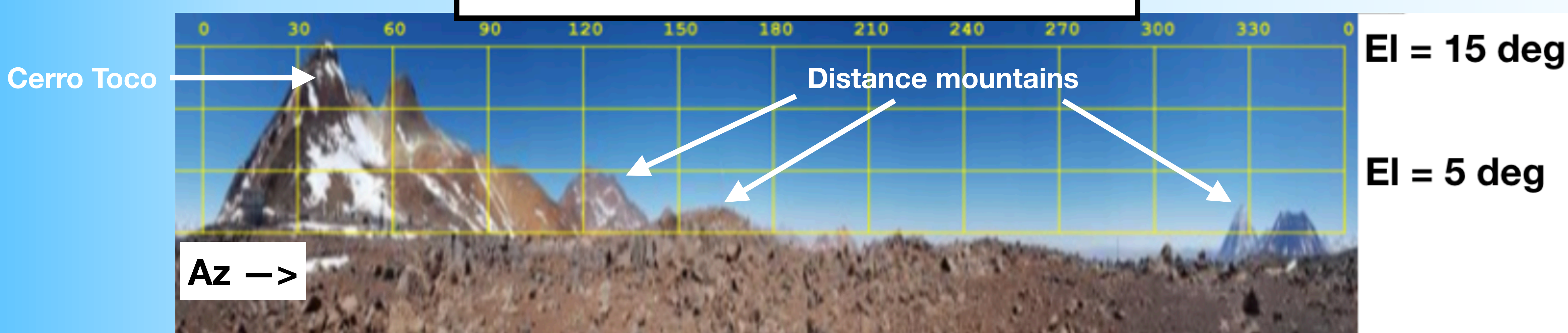
Ground Contamination (Pick-up)

- Most problematic source of stray light for ground-based telescopes
  - Large in magnitude (>300 K)
  - Spatially non-uniform, exists across entire azimuth range
  - Time varying (day/night, season, weather)

- Ground synchronous signal (GSS)
  - Ground template subtraction per scan
  - Difficult to filter-out completely
    - Residue contamination —> systematic error

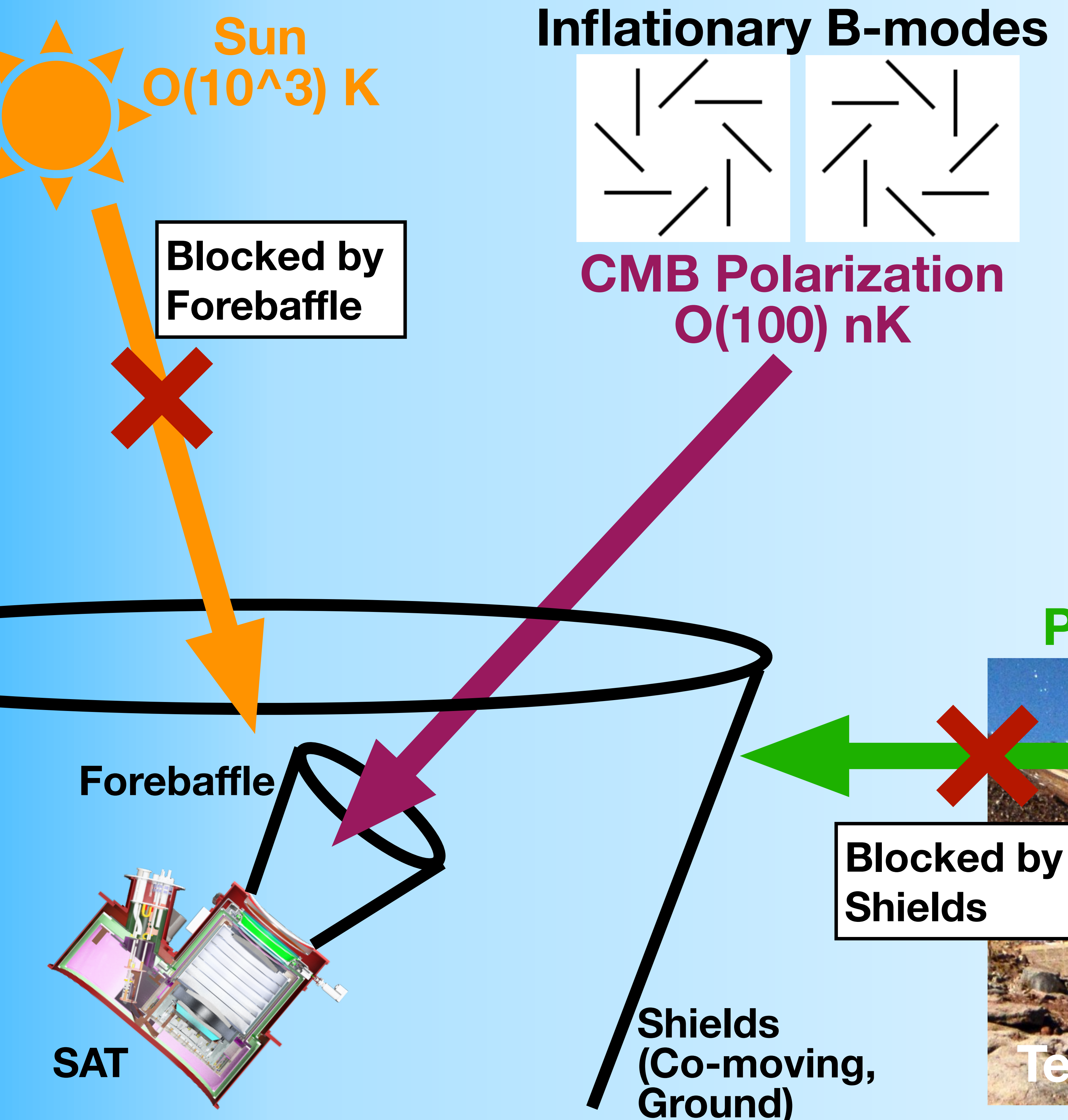
- Chile site has Cerro Toco peak at El ~ 15 deg
  - Distant mountain peaks at El ≤ 5 deg

Terrain at Chile Observation Site



Telescope Baffling

- Reduce stray light systematics using warm baffling
- Ground contamination can reach O(100) μK levels



Telescope Baffling

- Implemented by most ground-based CMB experiments at Chile and South Pole

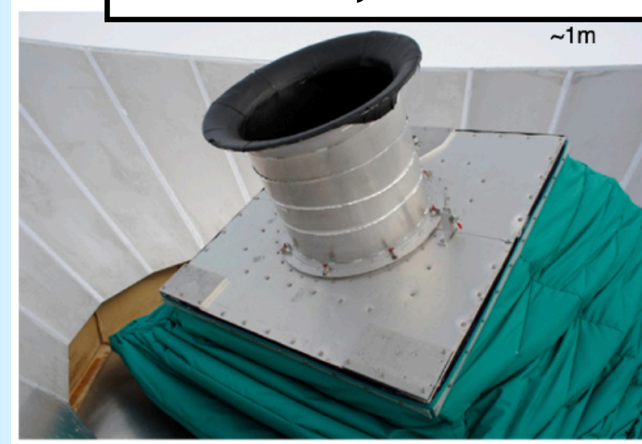
ACT (Chile)

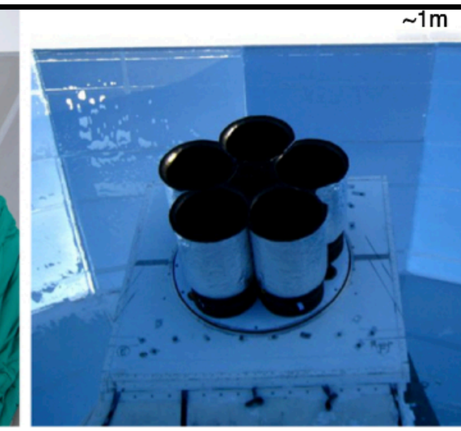
Swetz et al. (2011)
Thornton et al. (2016)

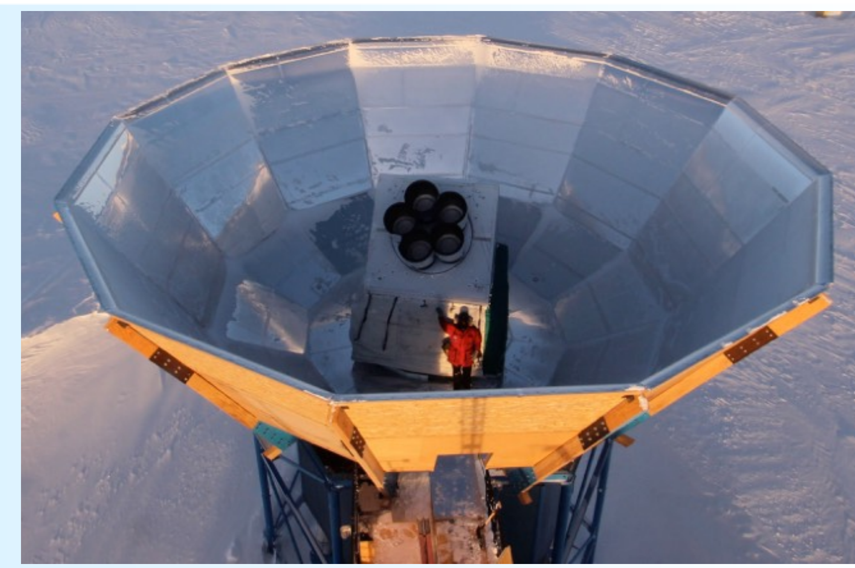
CLASS (Chile)

Appel et al. (2019)

BICEP2, Keck Array (South Pole)



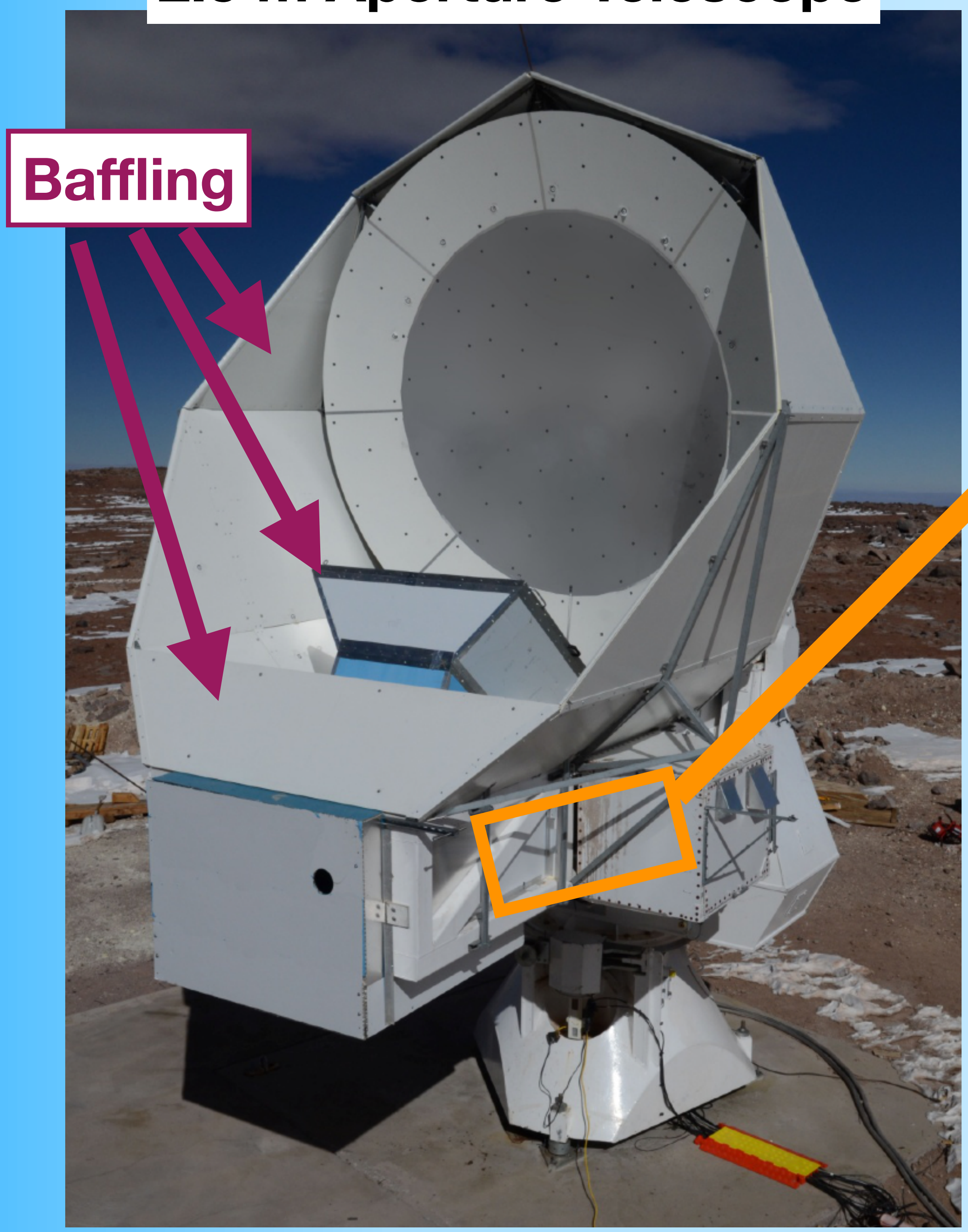




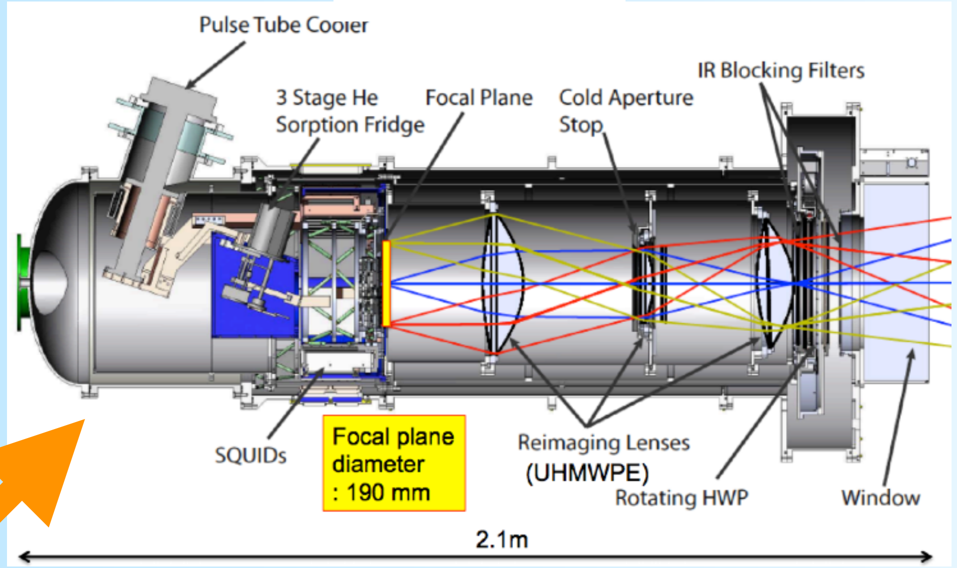
BICEP2 and Keck Array Collaborations (2015)

POLARBEAR Experiment

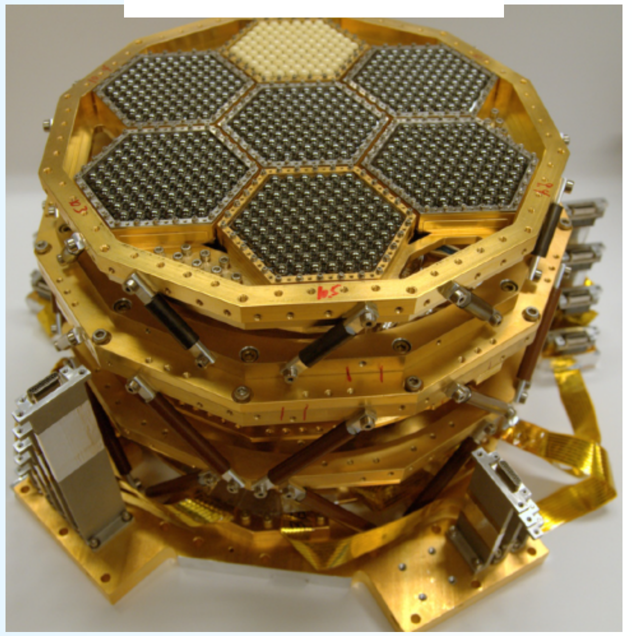
2.5 m Aperture Telescope



Receiver



Focal Plane



- Located Atacama Plateau in Chile
- Observations from 2012-2017
- 1,274 TES detectors @ 150 GHz

- Upgrade to Simons Array
  - 22,764 TES detectors @ 95-270 GHz

POLARBEAR Side-lobe

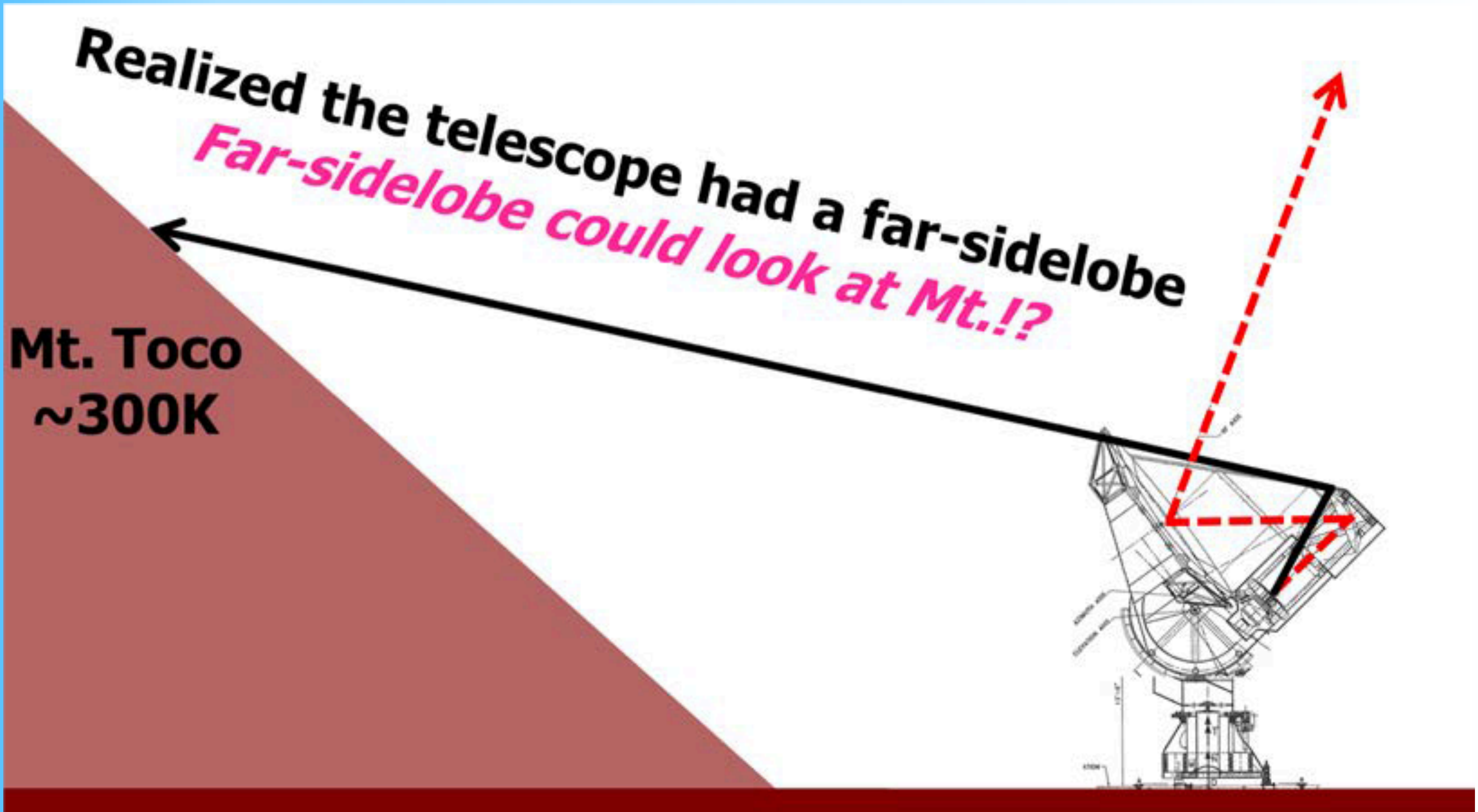


Figure from Yuji Chinone

POLARBEAR Baffling

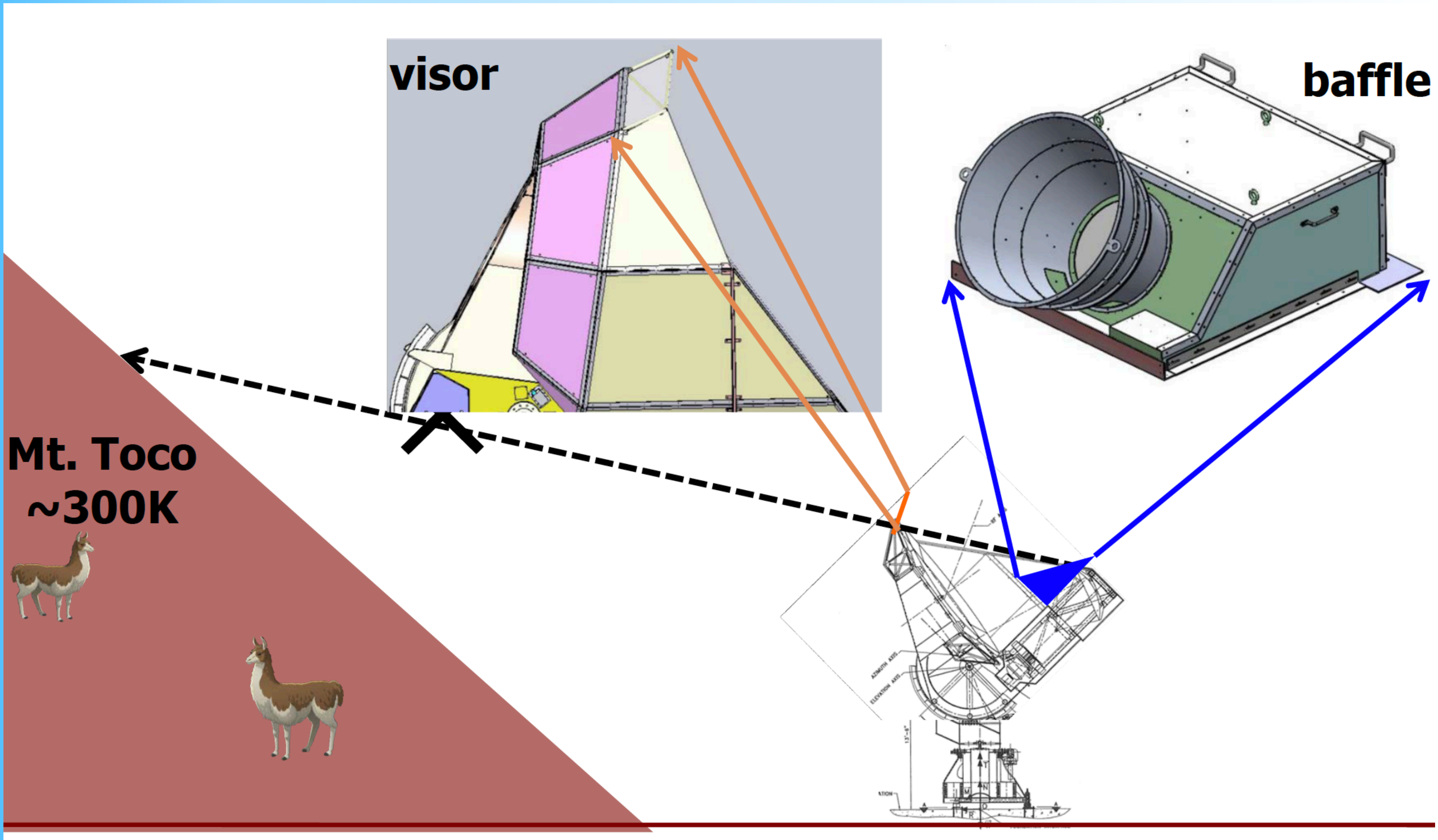
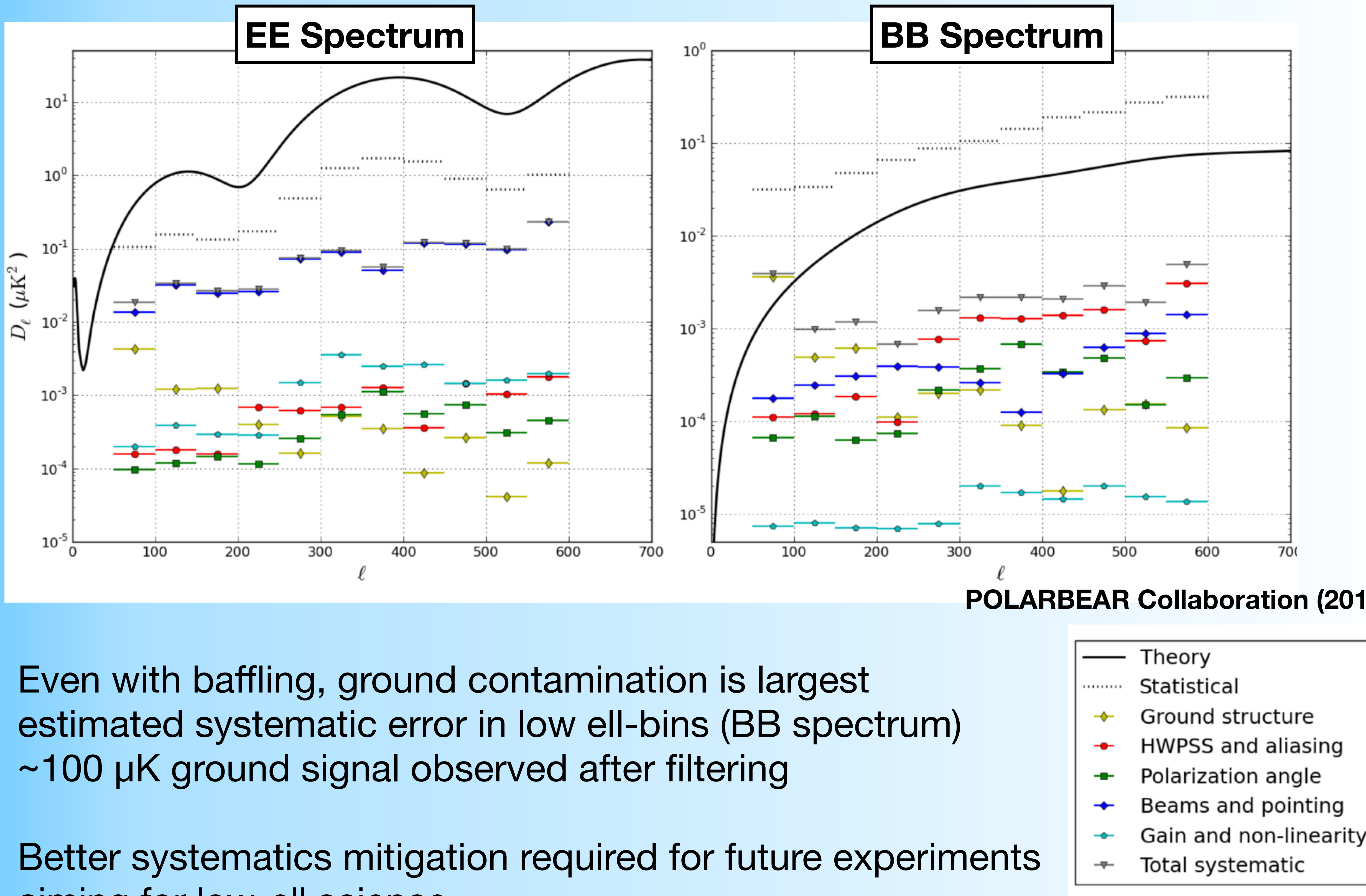


Figure from Yuji Chinone

POLARBEAR Ground Contamination

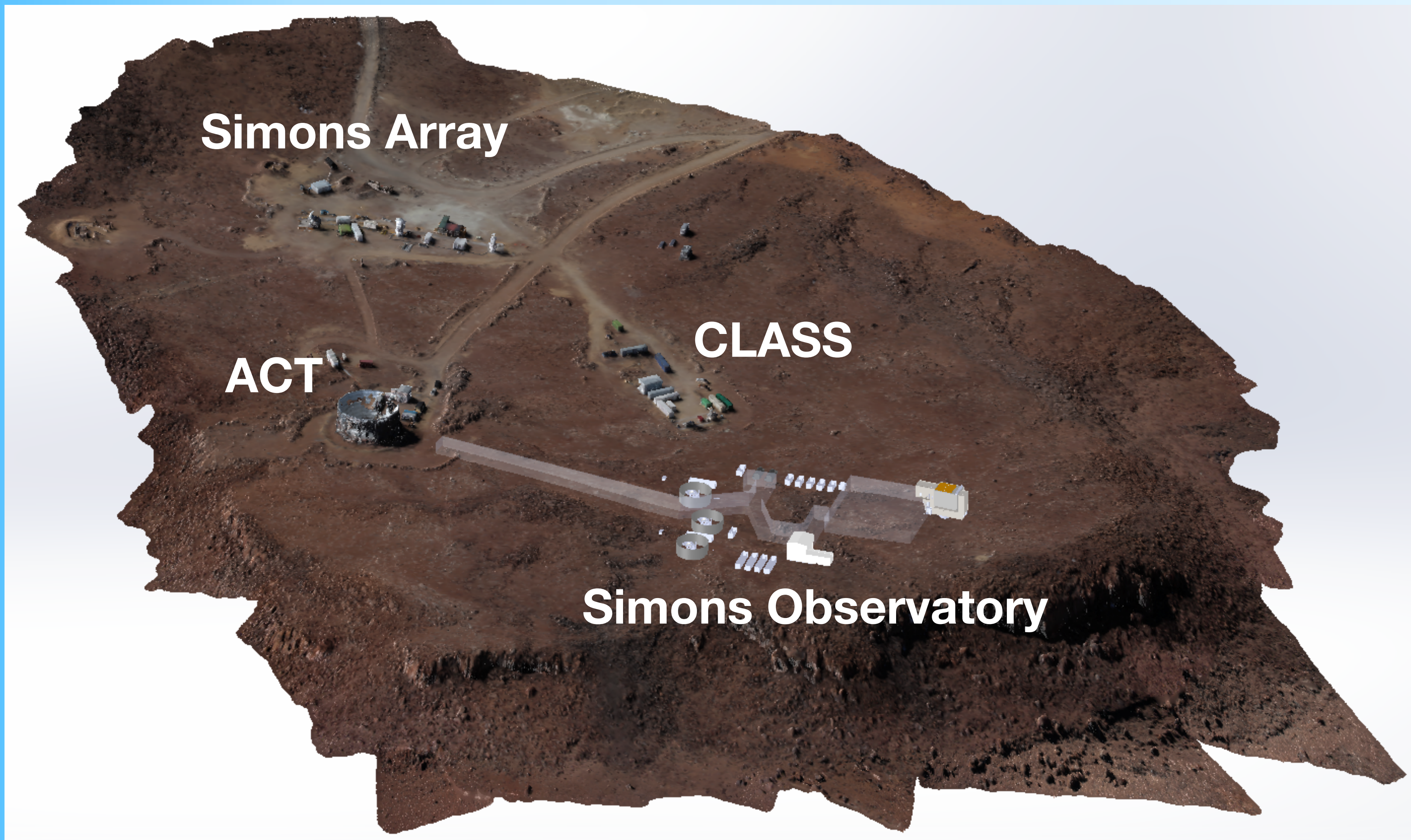


POLARBEAR Collaboration (2019)

- Even with baffling, ground contamination is largest estimated systematic error in low ell-bins (BB spectrum)
- ~100 μK ground signal observed after filtering
- Better systematics mitigation required for future experiments aiming for low-ell science

Simons Observatory Case

Simons Observatory



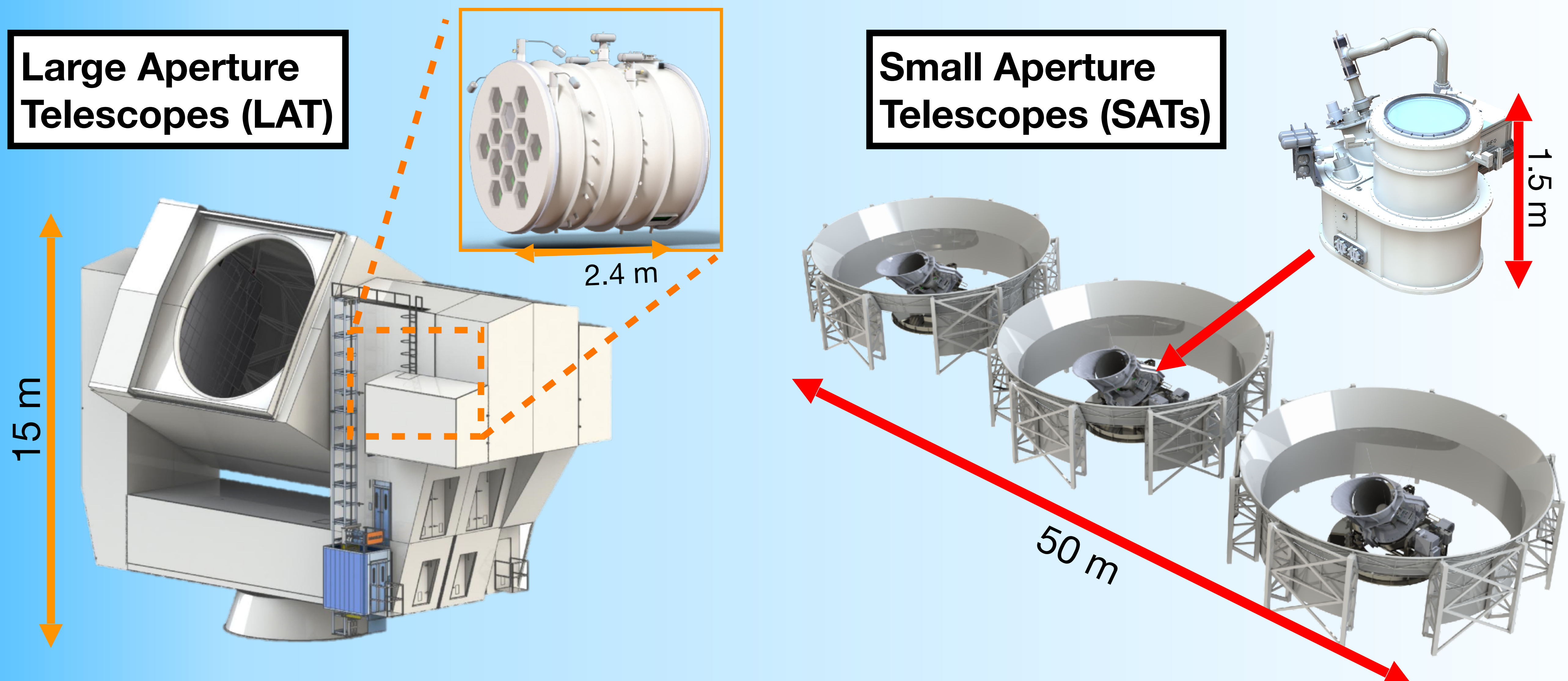
SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION

- International collaboration started off by combining POLARBEAR (Simons Array) + ACT Collaboration members

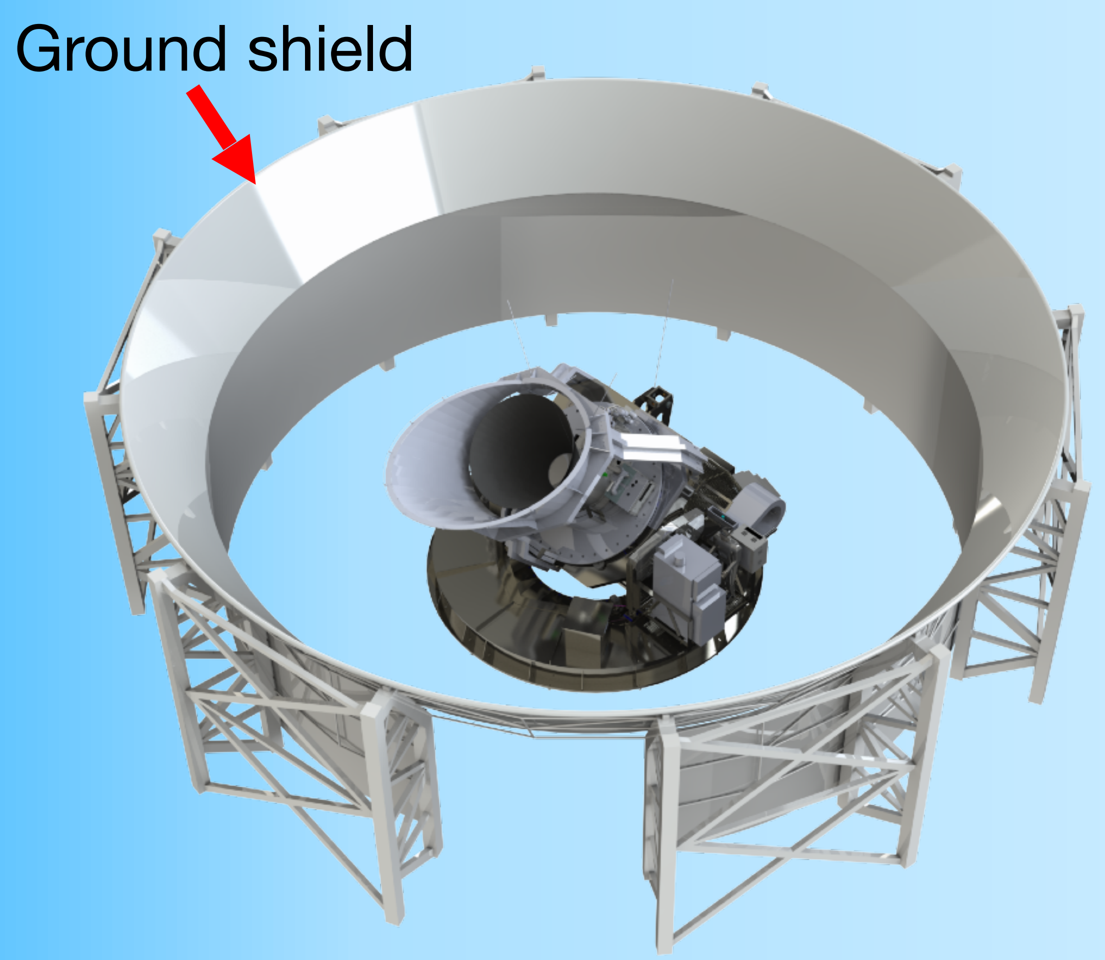
- Observations planned to start ~2021 in Atacama Desert, Chile (altitude 5,190 m)
- Deploy Large Aperture Telescope (6 m) and Small Aperture Telescopes (42 cm)

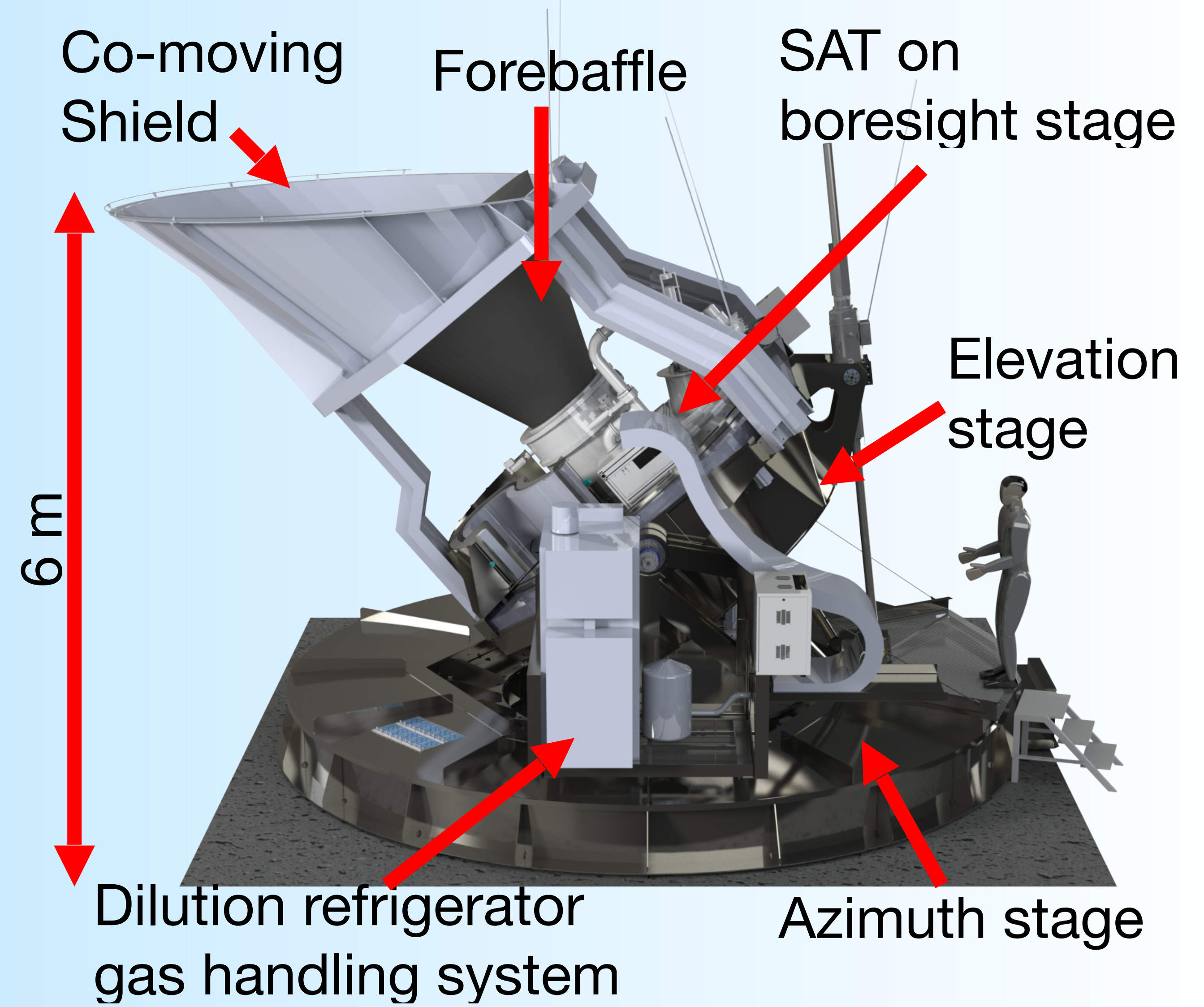
Simons Observatory



- 27-280 GHz observations (6 bands)
- Together implement > 60,000 TES detectors
- Science goals (5 years observation)
  - $\sigma(r) = 0.003$
  - $\sigma(\Sigma m_\nu) = 0.04$ eV

Small Aperture Telescopes

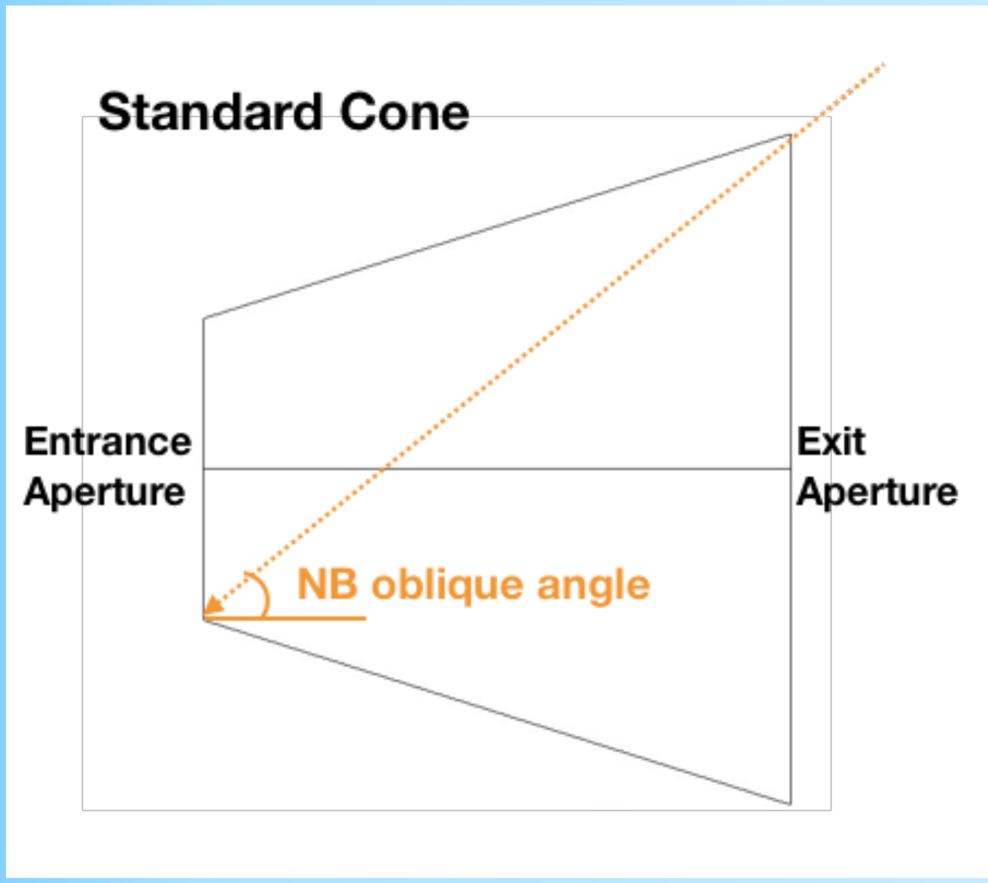


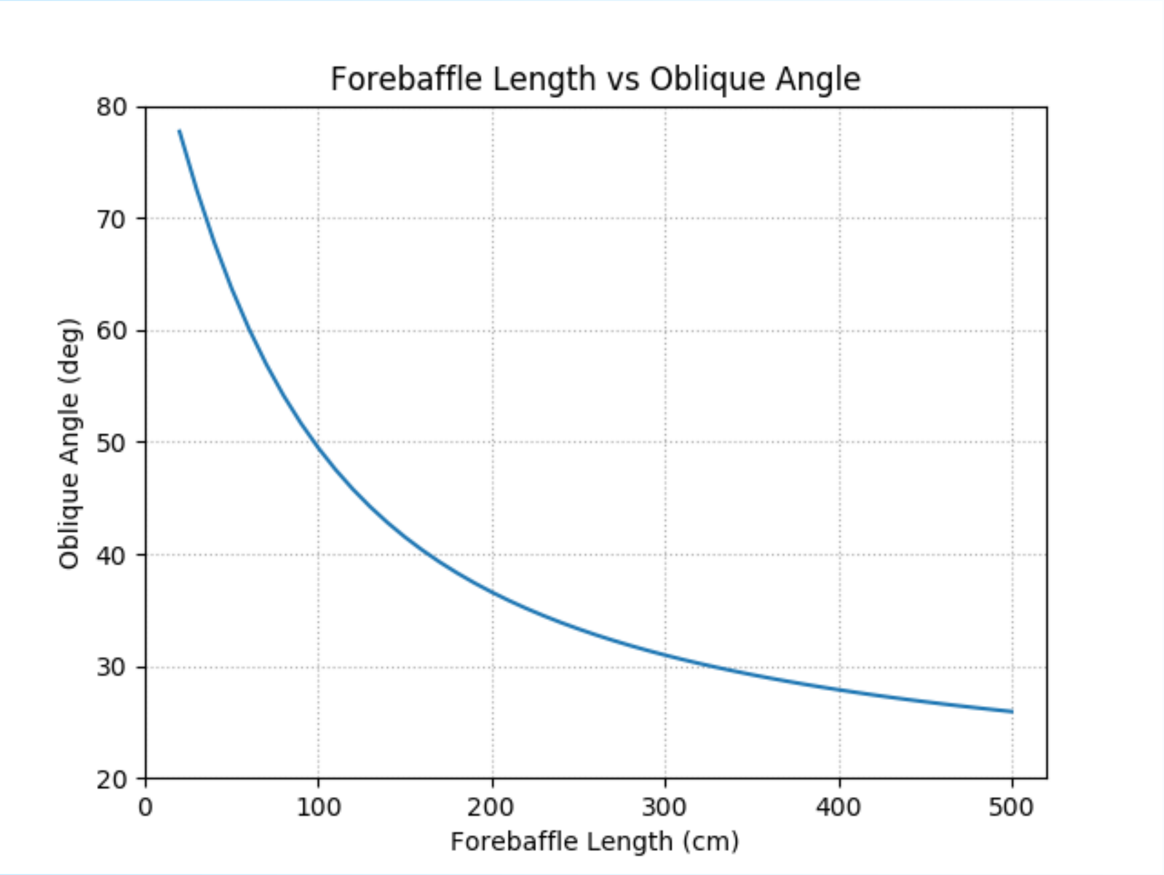


- Target inflationary and low ell science
  - 42 cm aperture 3 Silicon lens refractor telescope
  - 35 degree wide FOV

- 3-Shield Warm Baffling Design
  - Forebaffle, co-moving shield, ground shield
  - **Current SAT baffling design potentially will have the highest optical shielding capabilities compared to other CMB telescopes in Chile**

Forebaffle Optics Design





- Forebaffle reduces side-lobes due to diffraction / scattering from window
  - Blocks direct light from bright sky sources (Sun, Moon) and surrounding environment
  - Trade-off: side-lobes vs observation sensitivity

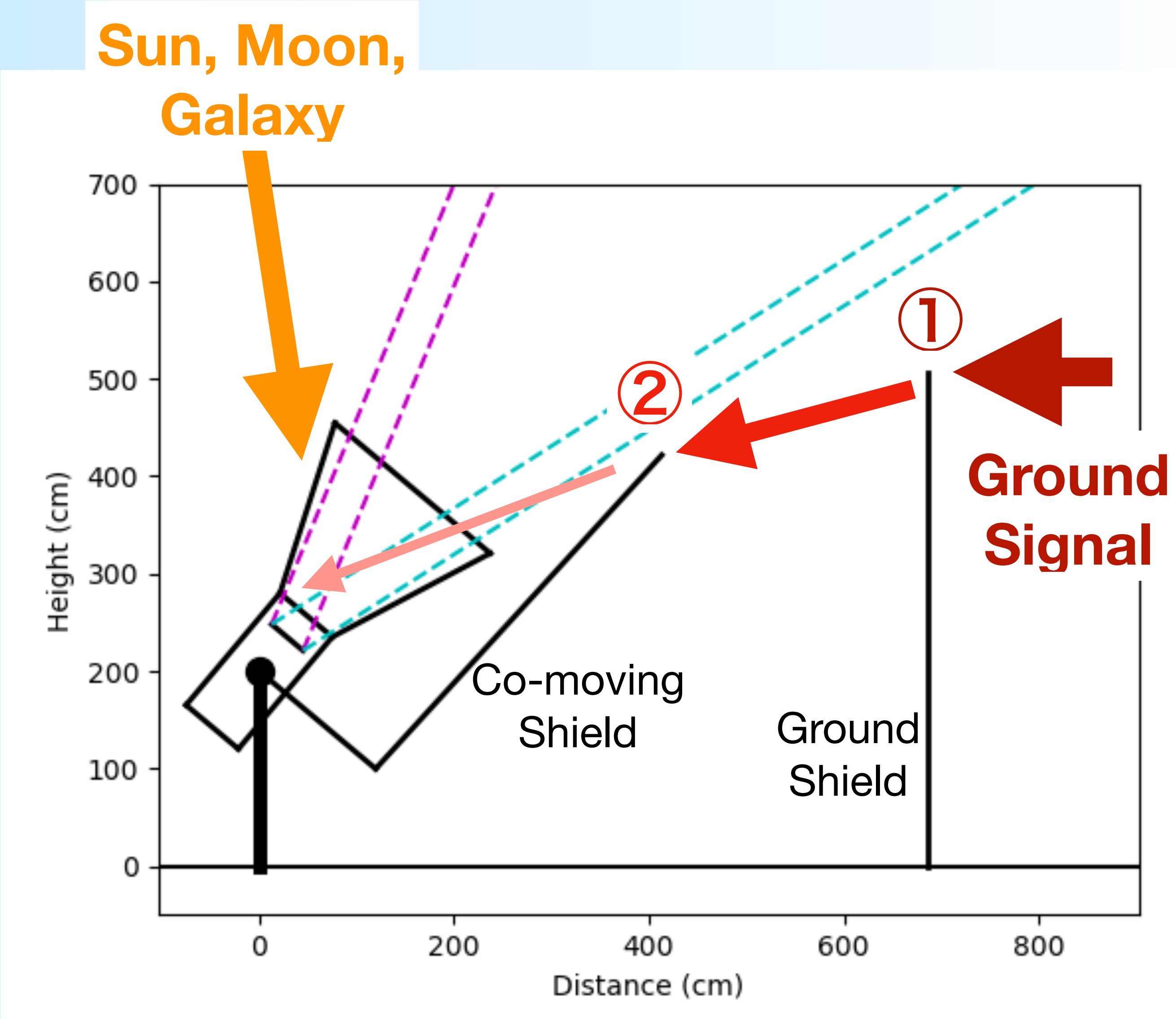
- Forebaffle (Absorptive)
  - 1.7 m long and designed s.t. geometric rays > 40 degrees from boresight cannot enter window
    —> Scan strategy optimized to avoid Sun and Moon by 40 degrees

- **Long forebaffles are more effective at the cost of physical size**

Double-Diffraction Criterion

- **Forebaffle alone is typically insufficient**
  - Long forebaffles difficult to mechanically implement
  - Forebaffle creates side-lobes that can “see” ground

- **Double-diffraction criterion**
  - Any ground signal must diffract at least twice to enter into telescope window
  - Addition baffling
    → lower side-lobe power reaching ground



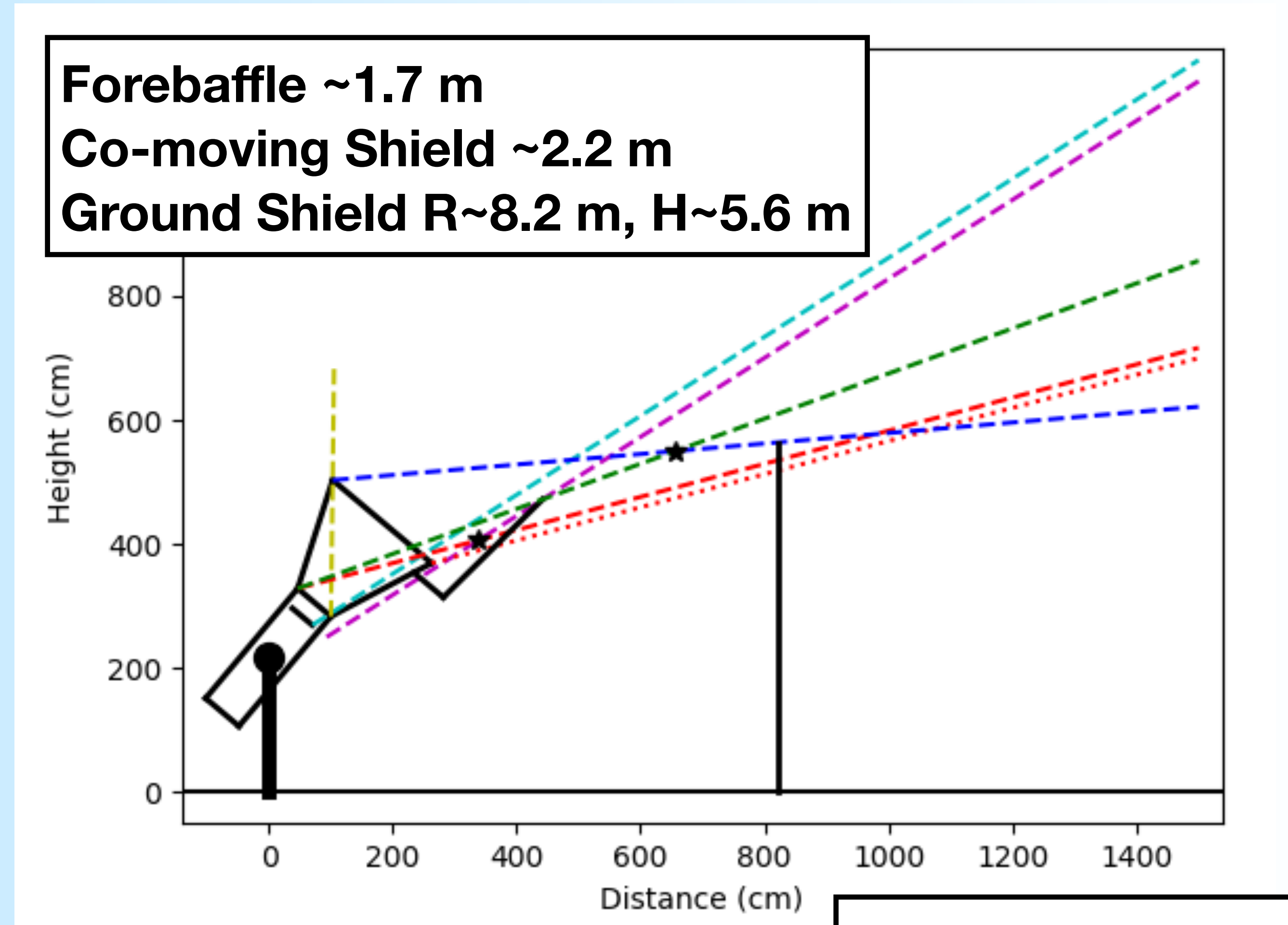
- **SO design**
  - Double-diffraction satisfied for El ≤ 5 deg
  - No direct line-of-sight of window to Cerro Toco for 5 deg < El ≤ 15 deg

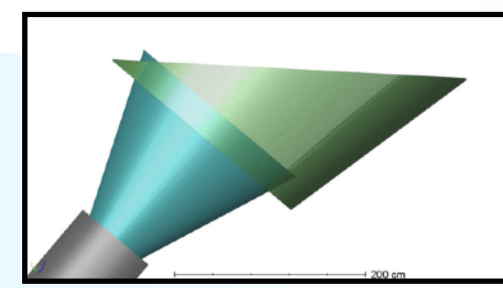
Warm Baffling Optics Design

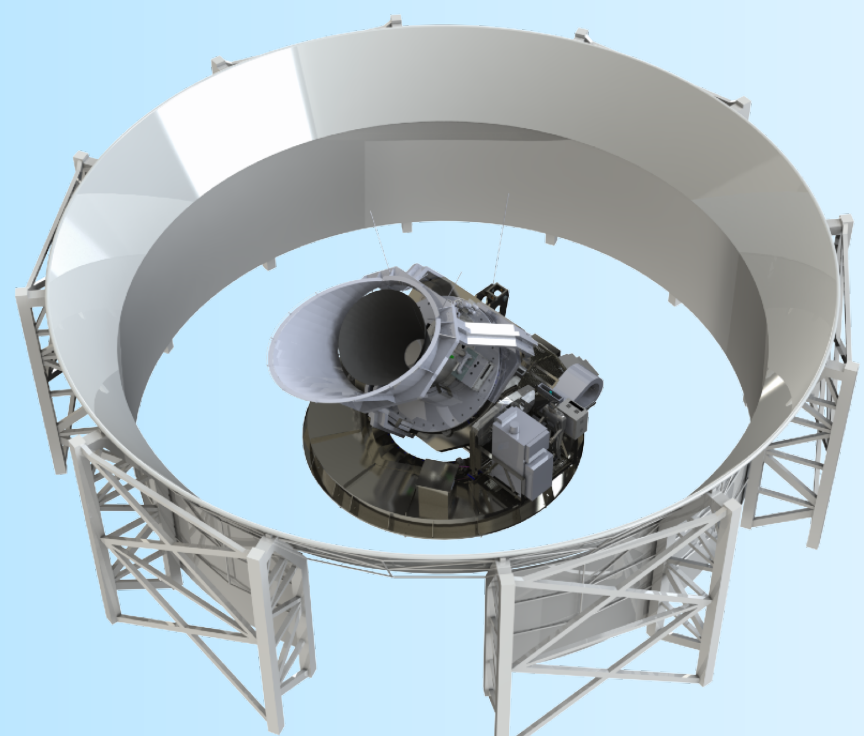
- **Co-moving Shield (Reflective)**
  - Blocks stray light from Cerro Toco
  - Blocks direct light from the ground shield

- **Ground Shield (Reflective)**
  - Block ground signal that can enter through forebaffle side-lobes

- Size optimization between forebaffle / co-moving shield ↔ ground shield

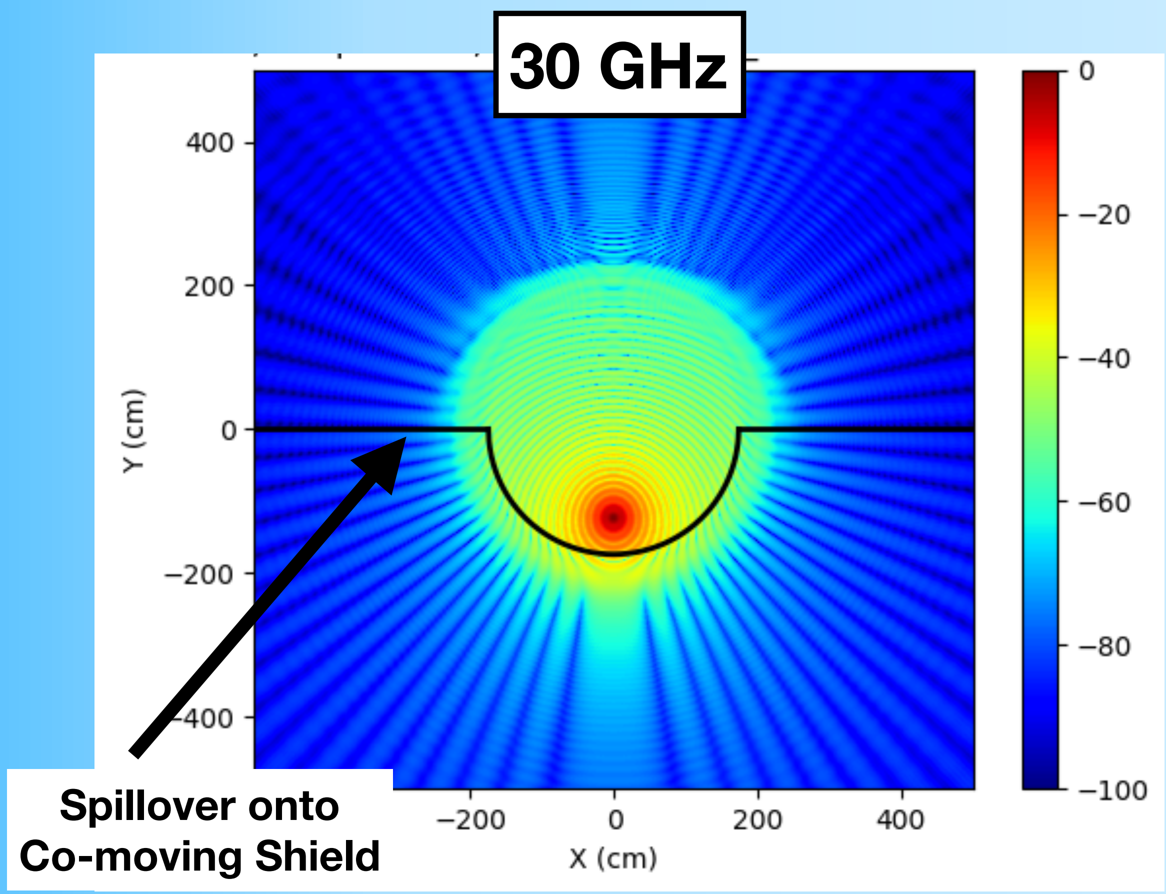


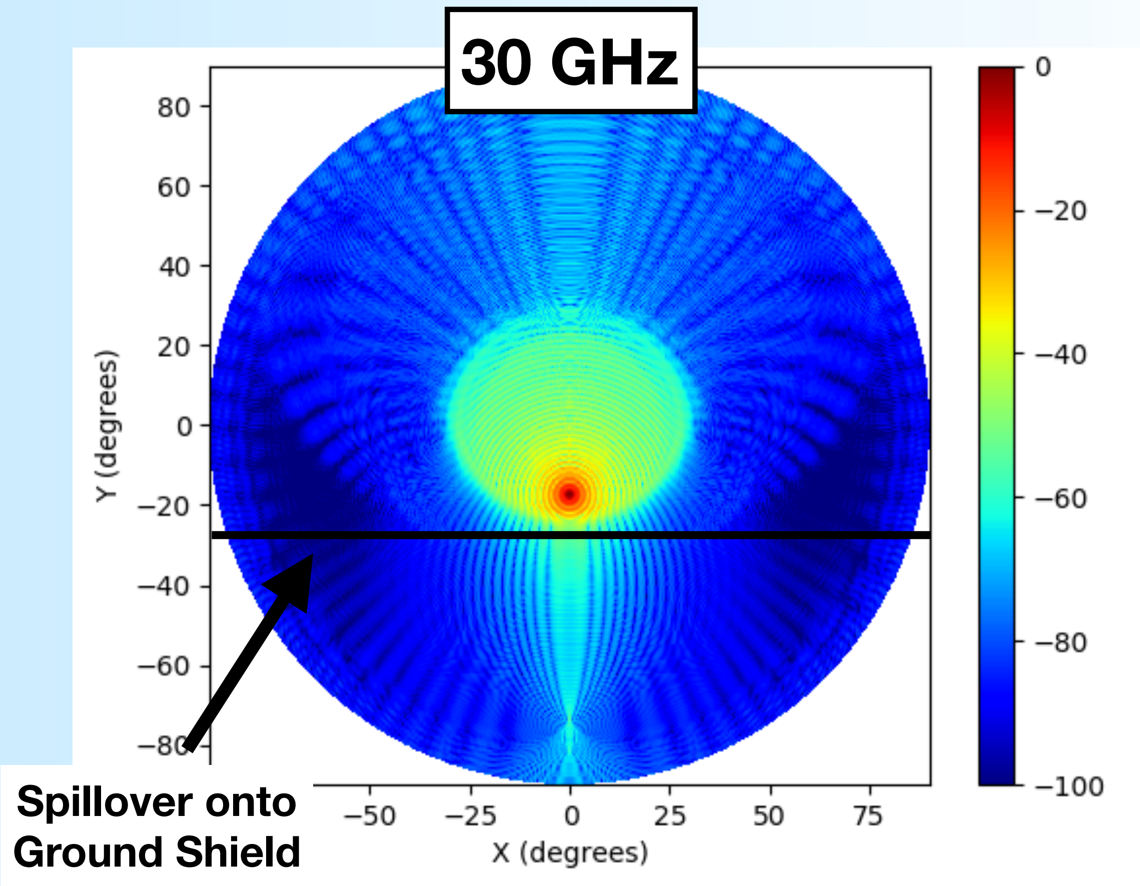




Diffraction Optics Simulations

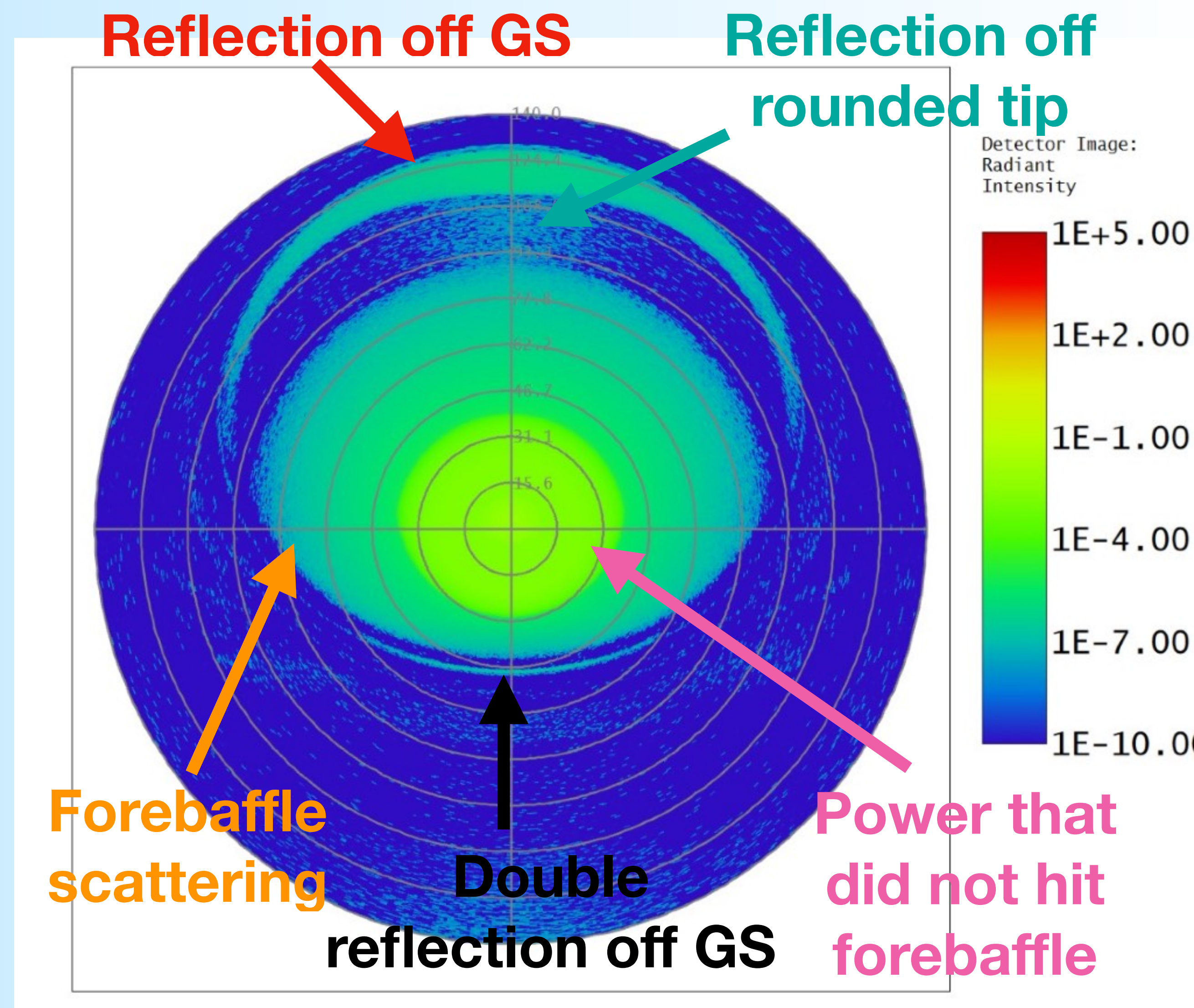
- **Simulated diffraction side-lobes of SO design**
  - Spillover: side-lobe power that does not see sky
- Spillover onto co-moving shield is uniform Az-independent signal
  → constant loading dependent on boresight rotation angle
- Spillover onto ground shield ≤ 0.02% level (total) @ 30 GHz
  - Varying Az-dependent signal → less variable than ground signal
- **Theoretically minimizes spillover onto ground and terrain to < 0.02% level (total) @ 30 GHz**

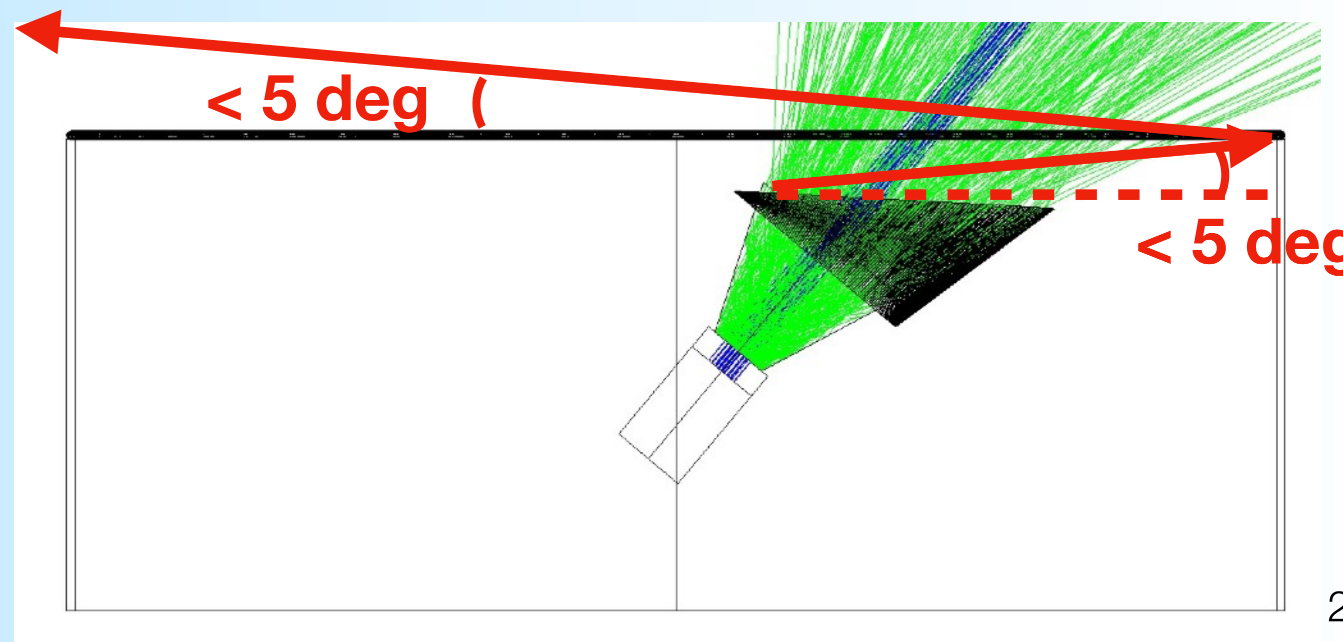




Scattering Optics Simulations

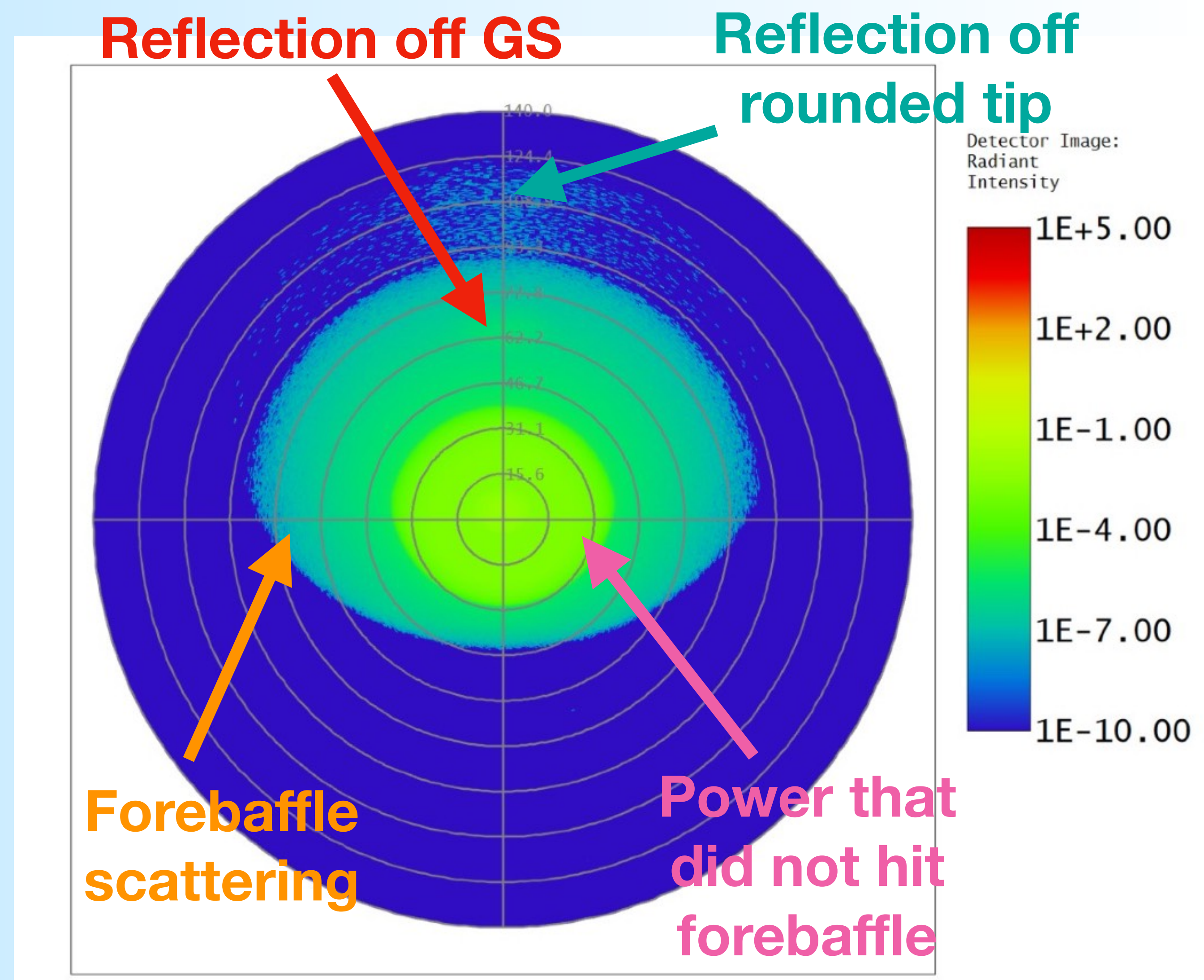
- **Simulated scattering spillover of SO design**
  - Assume 1% window scattering and blackened inner walls
- Diffuse side-lobe has lower magnitude due to scattering off forebaffle (~1e-6% peak level)
- **If ground shield has vertical walls, scattering side-lobe can see behind the telescope (back-lobe)**
  - Can be mitigated by angling ground shield wall

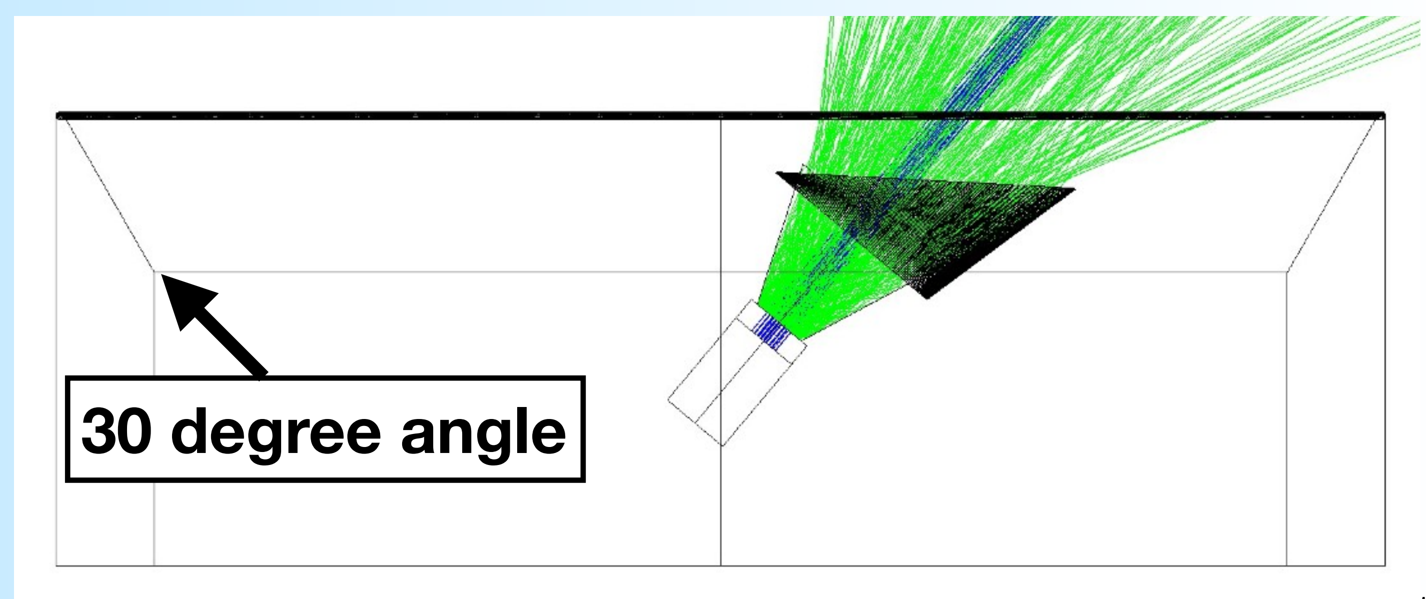




Scattering Optics Simulations

- **Simulated scattering spillover of SO design**
  - Assume 1% window scattering and blackened inner walls
- Diffuse side-lobe has lower magnitude due to scattering off forebaffle (~1e-6% peak level)
- **If ground shield has vertical walls, scattering side-lobe can see behind the telescope (back-lobe)**
  - Can be mitigated by angling ground shield wall





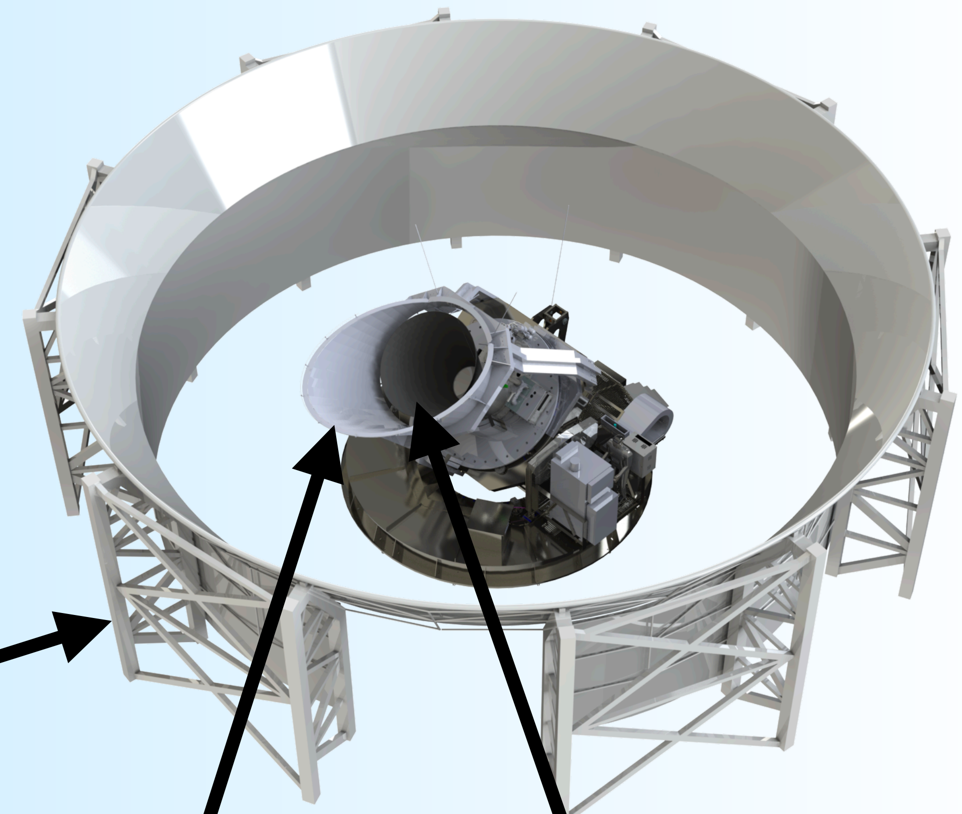
Systematics

- SATs will deploy first 3-shield warm baffling design in CMB field
  - More detailed side-lobe and ground spillover optics simulations in progress

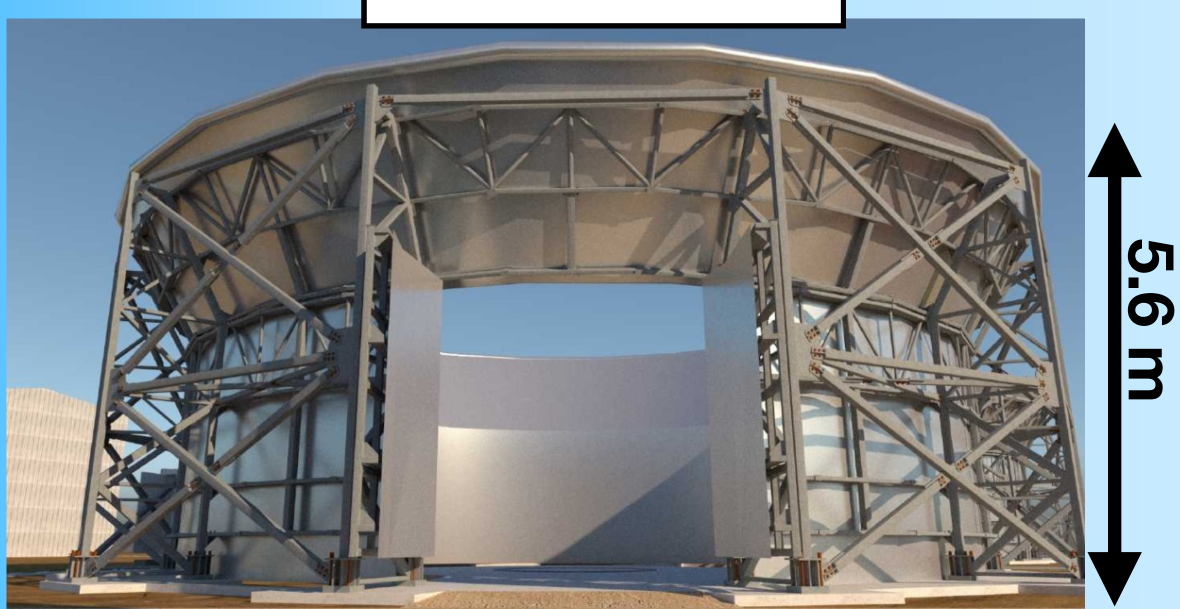
- Effective warm baffling
  → decreased ground synchronous signal
  → more effective ground template subtraction
  → minimize ground contamination systematics

Baffling Development

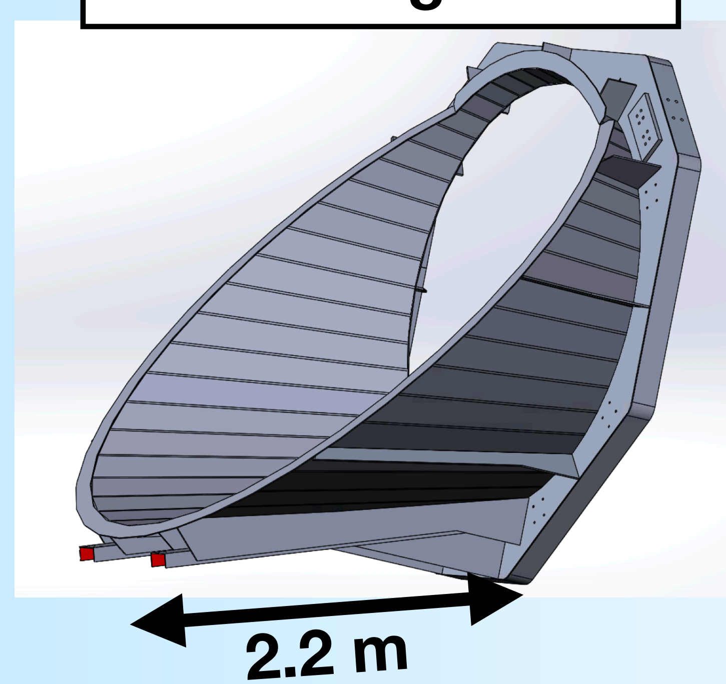
- Forebaffle, co-moving shield, ground shield are currently being fabricated
- Plan to ship first SAT with baffling next year
  - SO baffling studies can provide feedback to future CMB-S4



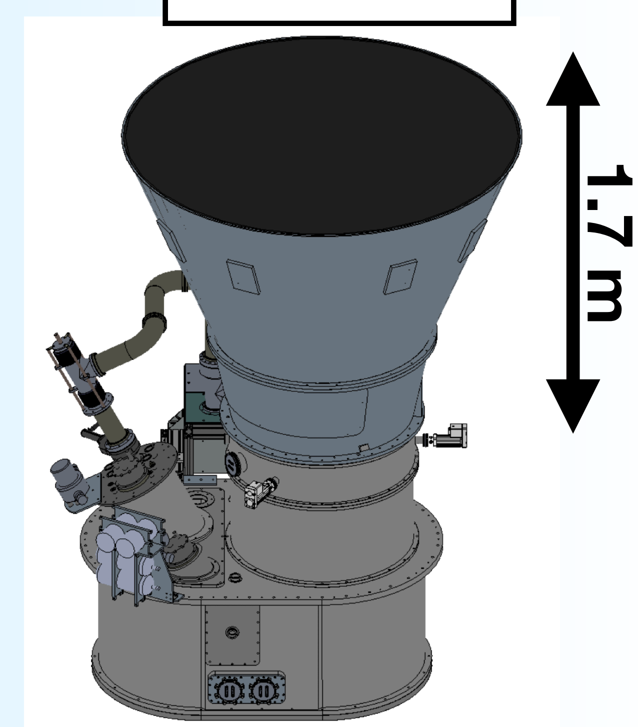
Ground Shield



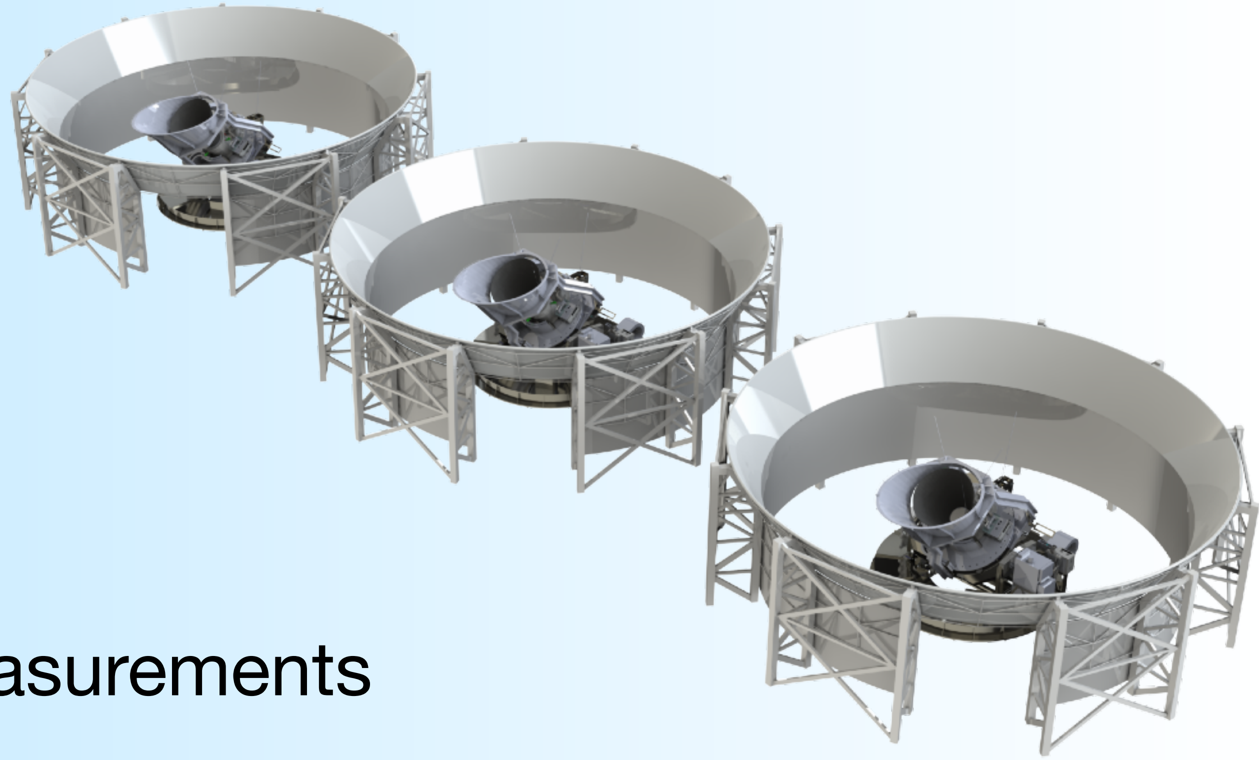
Co-moving Shield



Forebaffle



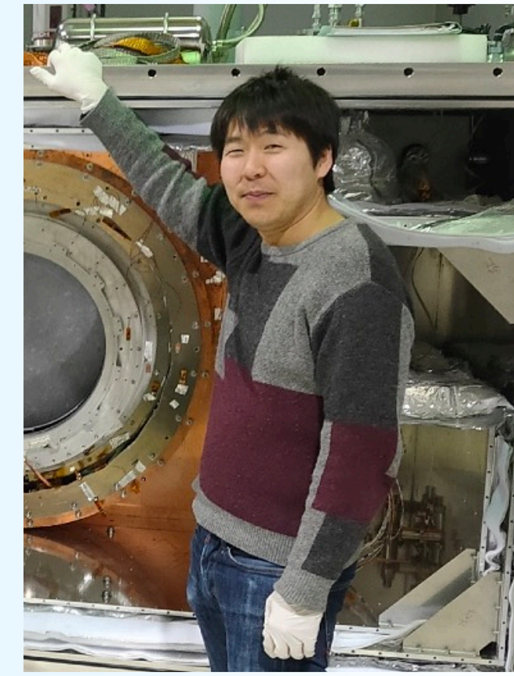
SO Telescope Baffling Summary



- With higher sensitivity, mitigation of stray light systematics becomes vital for ground-based experiments
- Ground contamination continues is one of the most problematic sources of systematic error for low-ell B-mode measurements
  - Contamination on O(100) μK levels
- Simons Observatory SATs implement new 3-shield warm telescope baffling
  - Design based on double-diffraction criterion
  - Potentially highest optical shielding capabilities for CMB experiment in Chile
  - Ground spillover reduced to < 0.02% level (further detailed simulations and calculations in-progress)
- SAT planned to deploy in 2021

Back-up

Introduction

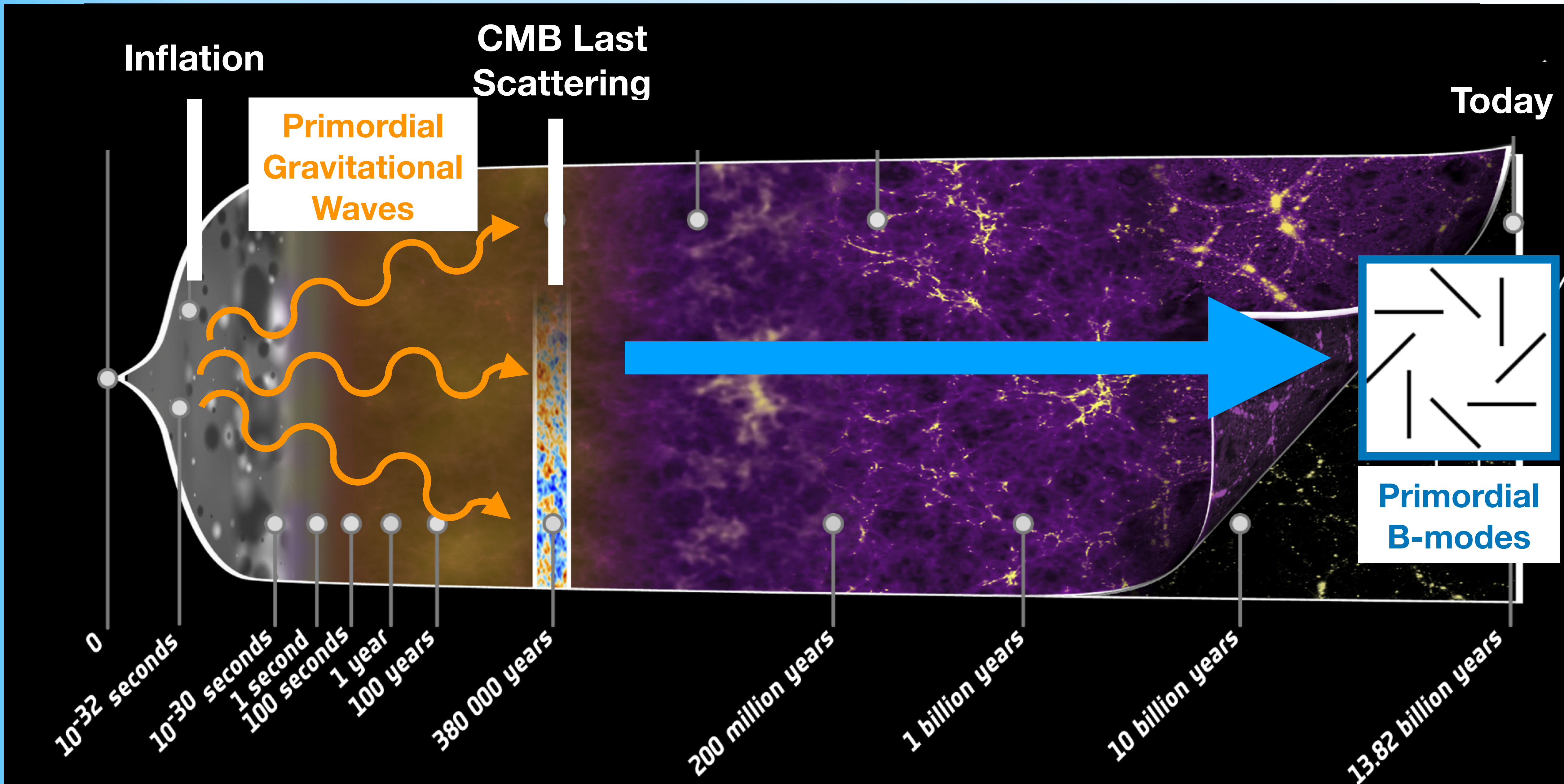


- **Frederick Matsuda**

- Ph.D. at University of California San Diego
- Currently project researcher at Kavli IPMU

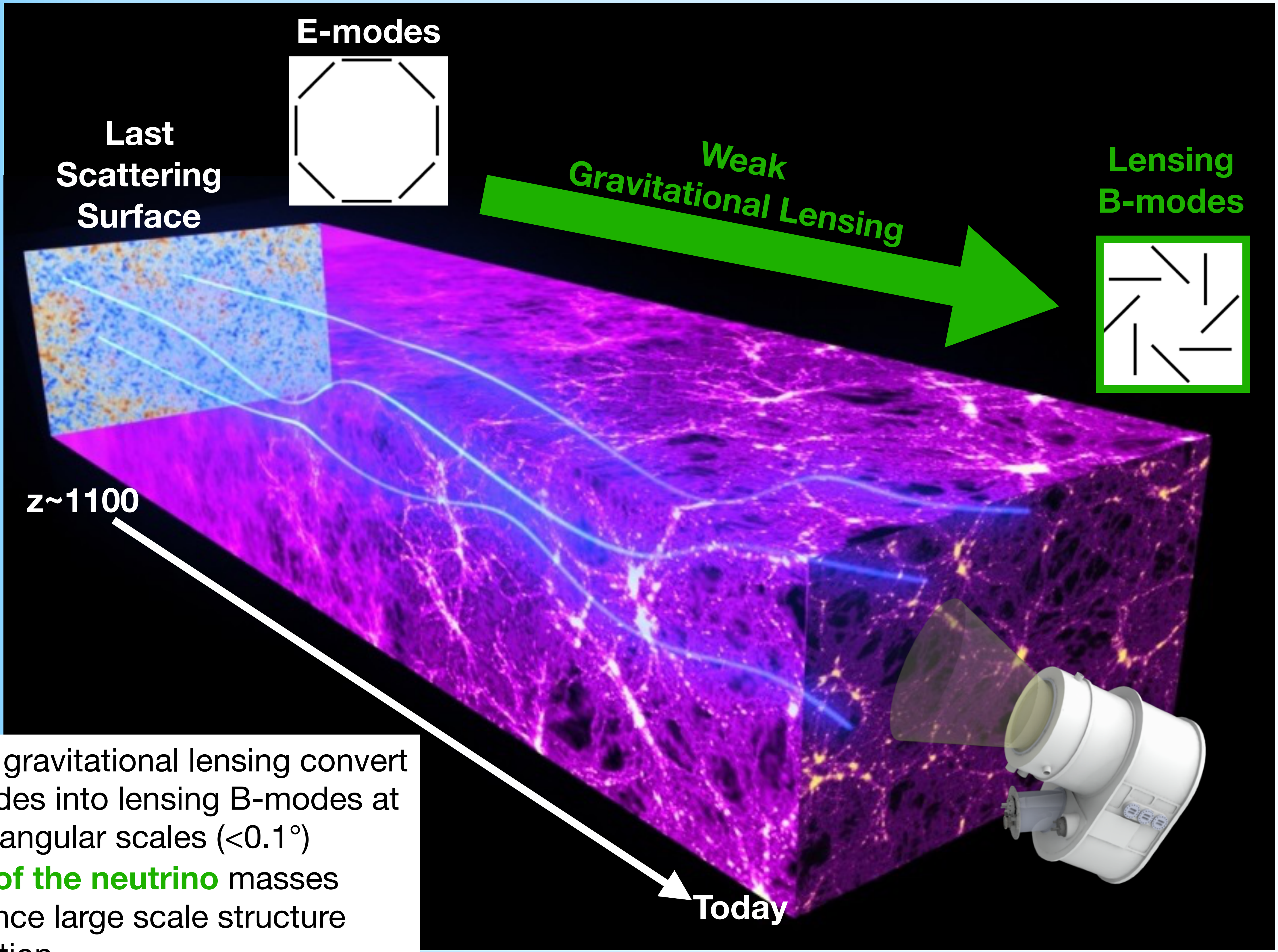
- **Projects** (observations)
  - POLARBEAR (2012-2017)
  - Simons Array (2020~)
  - Simons Observatory (2021~)
  - CMB-S4 (late 2020s)

Inflation



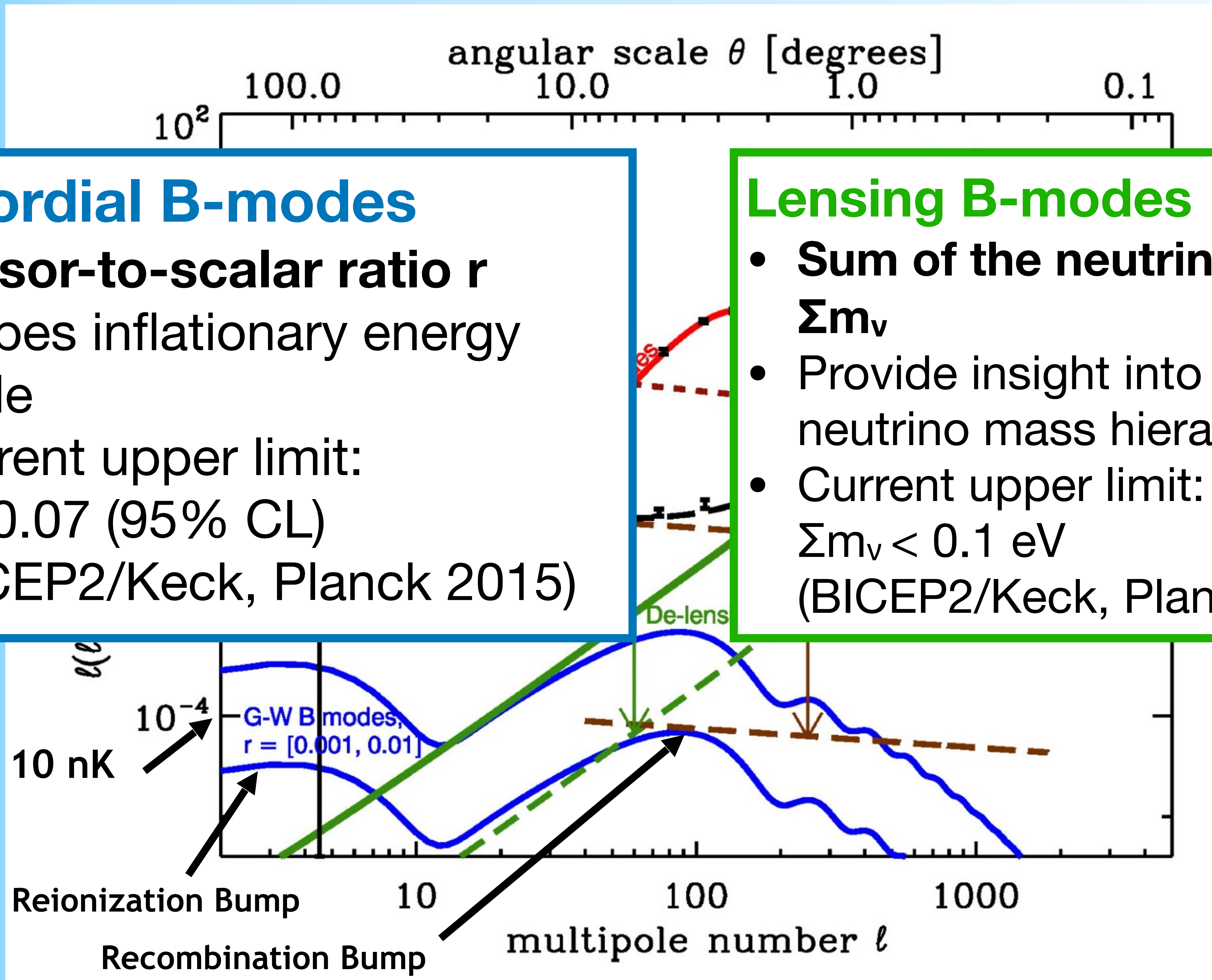
- **Primordial gravitational waves** imprint **primordial B-modes** in the CMB polarization at large angular scales (>1.0°)
- **Primordial B-modes** are considered “smoking gun” evidence of inflation in the early universe

Gravitational Lensing



- Weak gravitational lensing convert E-modes into lensing B-modes at small angular scales (<0.1°)
- **Sum of the neutrino** masses influence large scale structure formation

CMB Polarization Power Spectra



Primordial B-modes

- **Tensor-to-scalar ratio r**
- Probes inflationary energy scale
- Current upper limit:
  $r < 0.07$ (95% CL)
  (BICEP2/Keck, Planck 2015)

Lensing B-modes

- **Sum of the neutrino masses Σm_ν**
- Provide insight into the neutrino mass hierarchy
- Current upper limit:
  $\Sigma m_\nu < 0.1$ eV
  (BICEP2/Keck, Planck 2015)

Membership Institutions

10 Countries
40+ Institutions
306 Researchers

Europe

- APC – France
- Cambridge University
- Cardiff University
- Imperial College
- Manchester University
- Oxford University
- SISSA – Italy
- University of Sussex

Middle East

- Tel Aviv

United States

- Arizona State University
- Carnegie Mellon University
- Center for Computational Astrophysics
- Cornell University
- Florida State
- Haverford College
- Lawrence Berkeley National Laboratory
- NASA/GSFC
- NIST
- Princeton University
- Rutgers University
- Stanford University/SLAC
- Stony Brook
- University of California - Berkeley
- University of California – San Diego
- University of Michigan
- University of Pennsylvania
- University of Pittsburgh
- University of Southern California
- West Chester University
- Yale University

Australia

- Melbourne

Canada

- CITA/Toronto
- Dunlap Institute/Toronto
- McGill University
- Perimeter Institute
- University of British Columbia

Japan

- Kavli IPMU
- KEK
- Kyoto University
- Tohoku University
- University of Tokyo

Chile

- Pontificia Universidad Catolica
- University of Chile

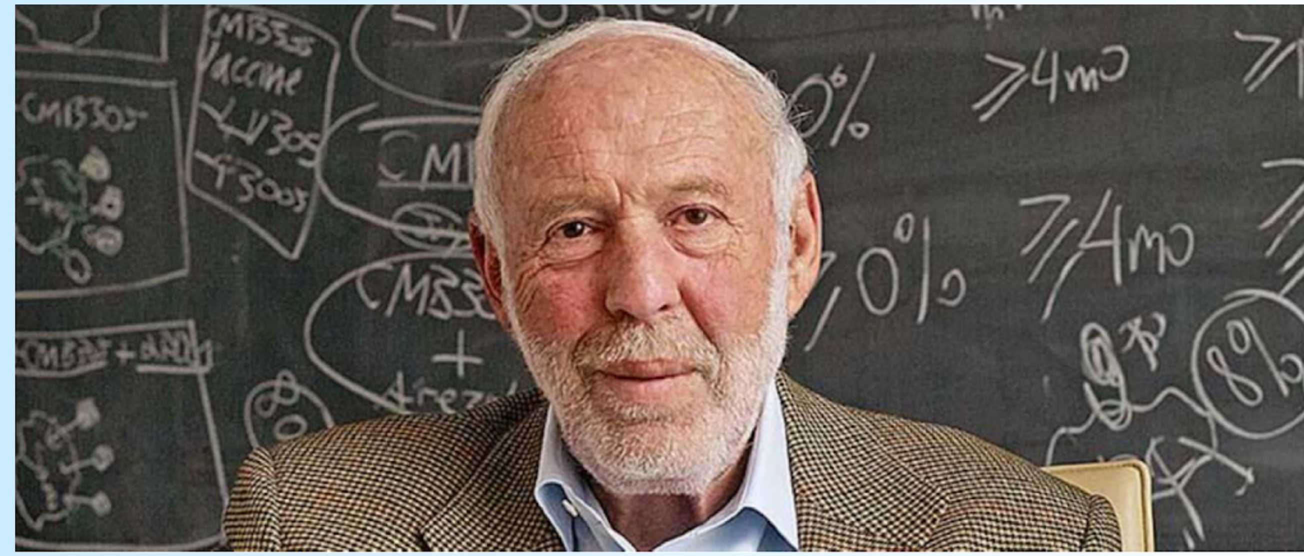
South Africa

- Kwazulu-Natal, SA

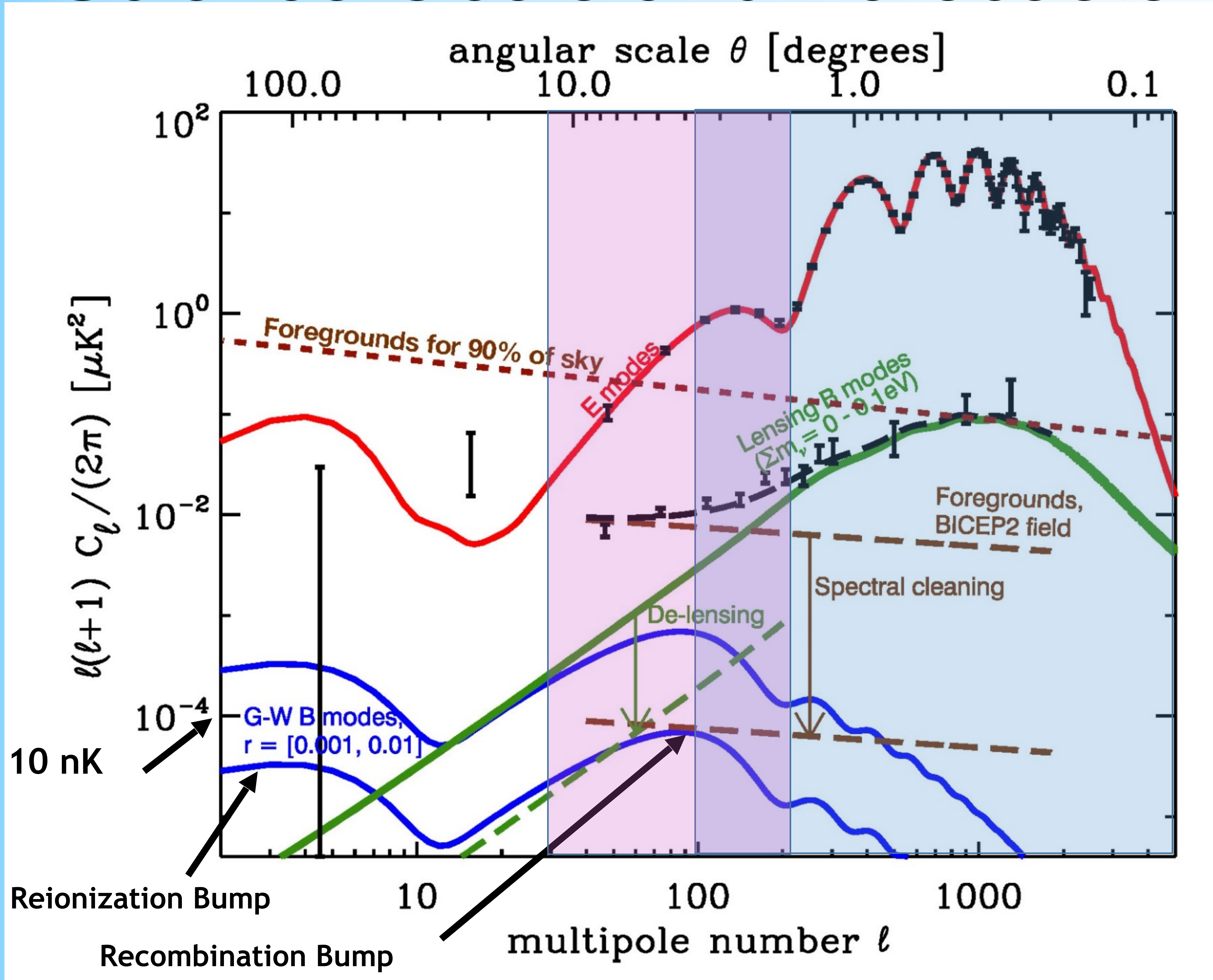
Simons Observatory Collaboration

SIMONS FOUNDATION

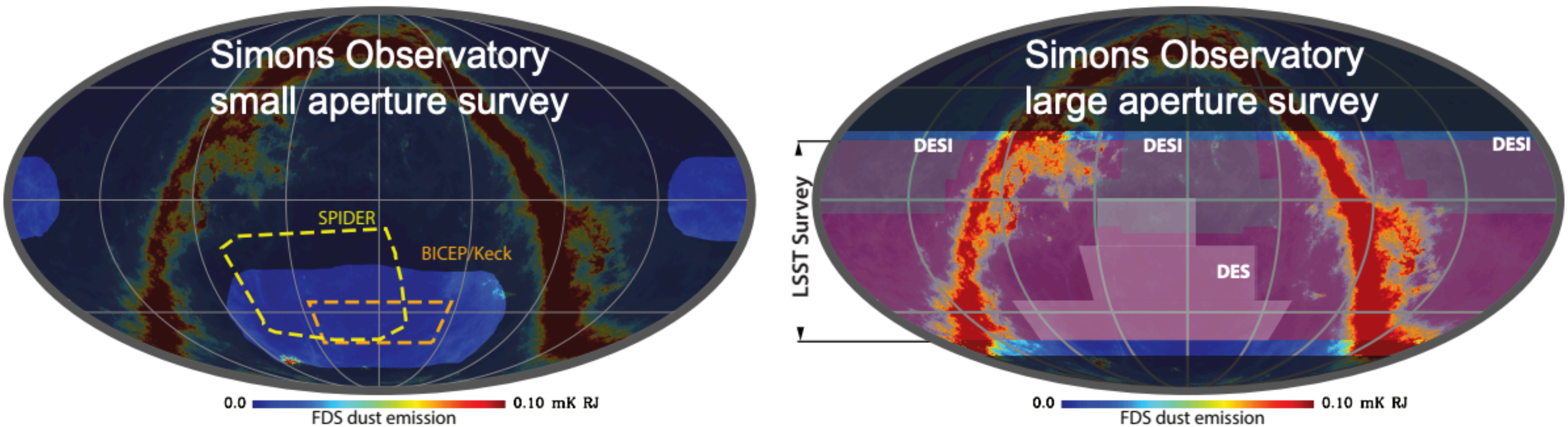
HEISING-SIMONS FOUNDATION



Science Goals and Forecasts



Science Goals and Forecasts



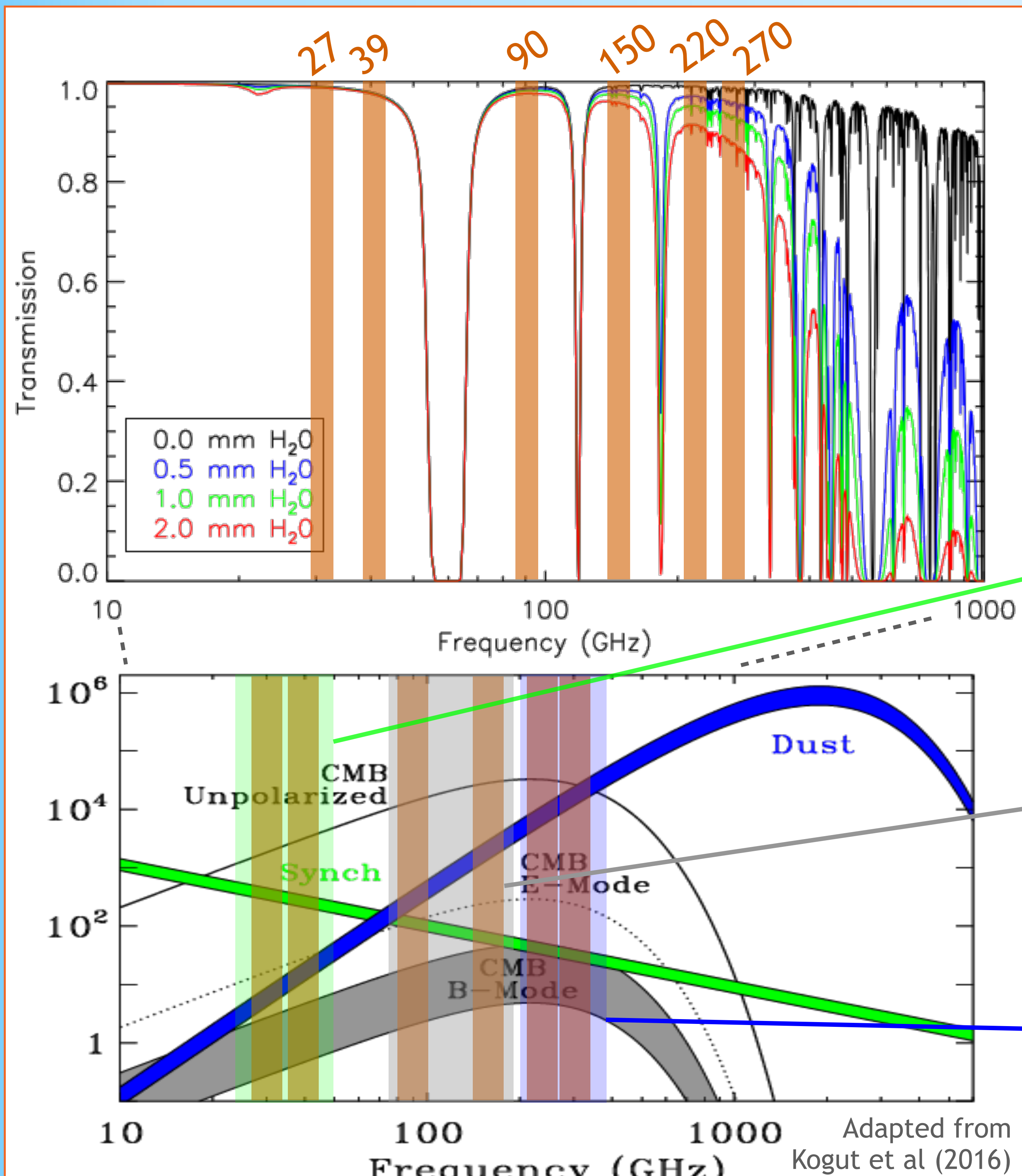
- Effective sky fraction
  - SATs: ~10%
  - LAT: ~40%

- Key Science Goals
  - $\sigma(r) = 0.003$ for $r = 0$
  - $\sigma(N_{eff}) = 0.07$
  - $\sigma(\Sigma m_\nu) = 0.04$ eV (DESI, LSST combined)

The Simons Observatory Collaboration, 2018
The Simons Observatory: Science Goals and Forecasts
https://arxiv.org/abs/1808.07445

Dichroic Optics Tubes
LF (27/39 GHz), **MF** (90/150 GHz), **UHF** (220/270 GHz)

Observation Frequencies



- SO will implement dichroic optics tube
  - LF (27/39 GHz)
  - MF (90/150 GHz)
  - UHF (220/270 GHz)
- Bands chosen based on sensitivity calculations to meet requirements for foreground removal and science goals

Synchrotron spectral indices, synchrotron template

CMB

+ realistic correlated noise
+ instrumental systematics

Dust spectral indices, dust template

+ Planck + C-BASS + SPASS

Future Experiments

- CMB-S4
  - "Ultimate" (stage 4) ground-based CMB experiment that plans to deploy telescope arrays to Chile and South Pole
  - SAT optical / mechanical design currently being developed
    - Carefully planning of warm baffling is proceeding