(Experimental) CMB Activities @ Berkeley: Data Analysis, Systematic Study, and Hardware Deployment of POLARBEAR, Simons Array, and Simons Observatory

Yuji CHINONE (茅根裕司)

University of California, Berkeley

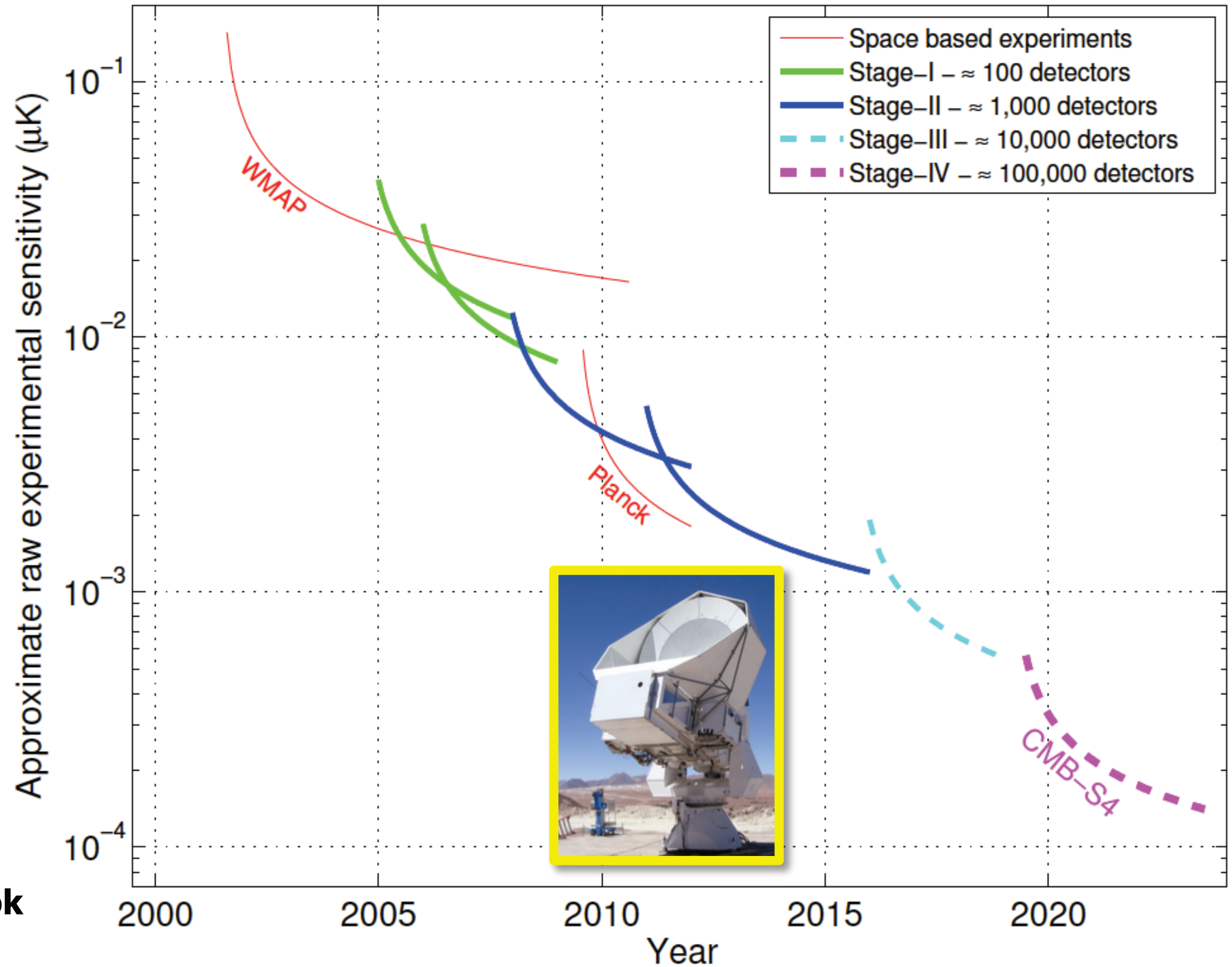
Kavli IPMU

10:10-10:30 (2019-01-16)

Projects We Are Working @ Berkeley

POLARBEAR is a "Stage 2" ground-based CMB experiment

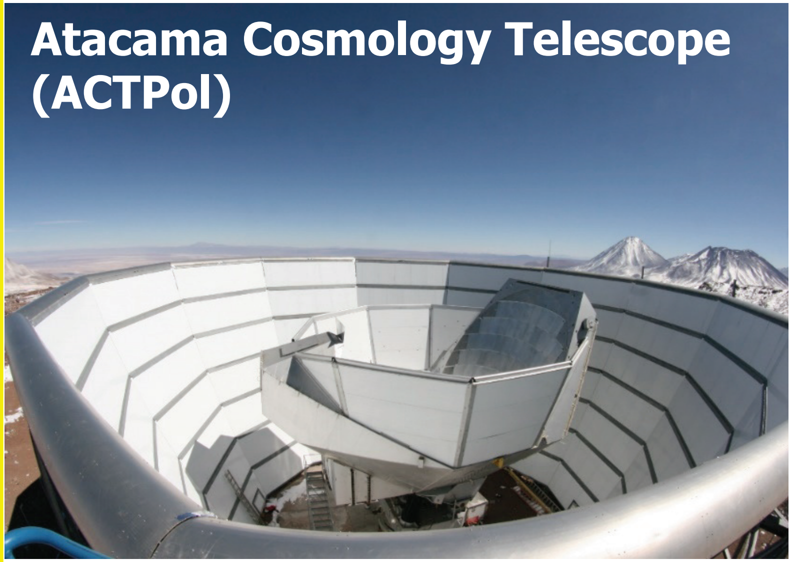
Sensitivity on CMB

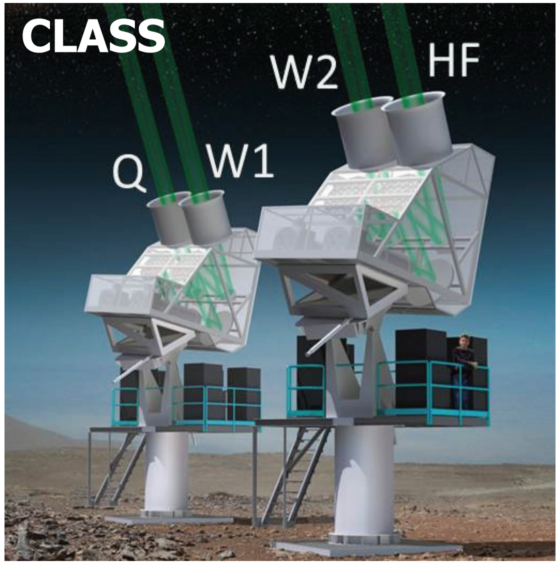


CMB-S4 Science Book (arXiv:1610.02743)

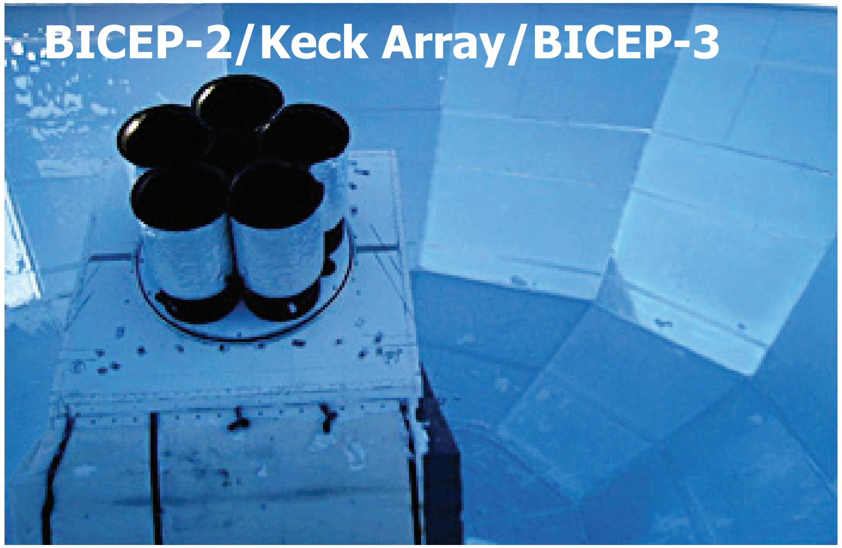
Stage 2 = Current Ground-Based Experiments

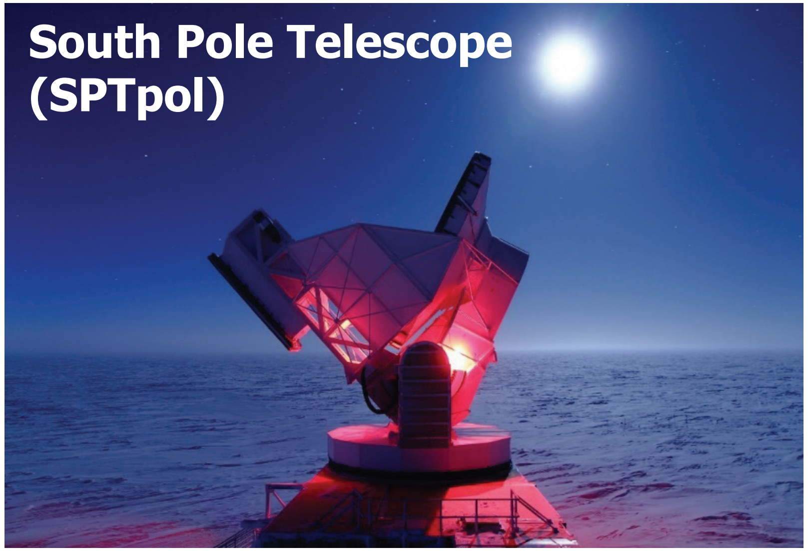
Chile, Atacama

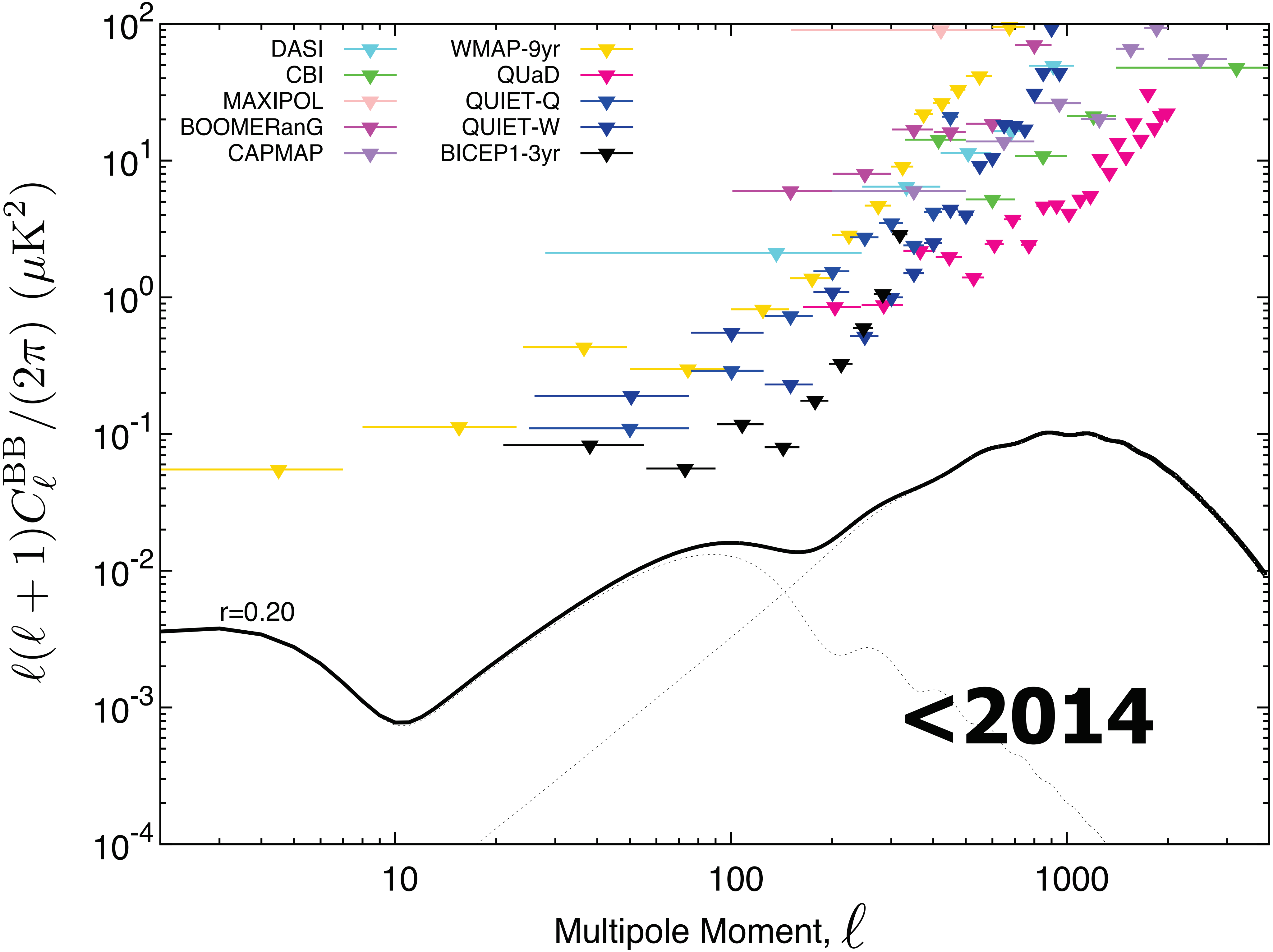


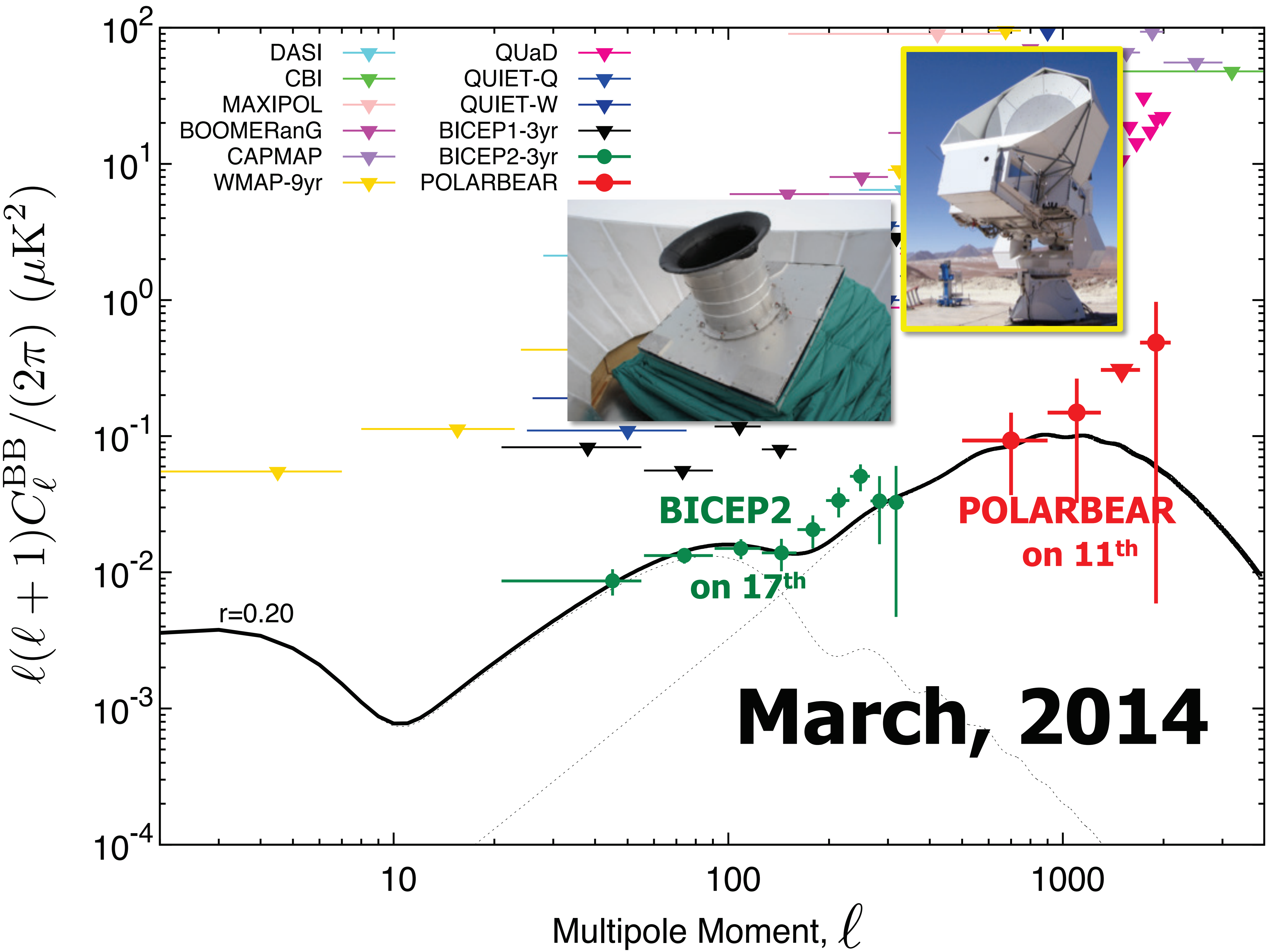


South Pole

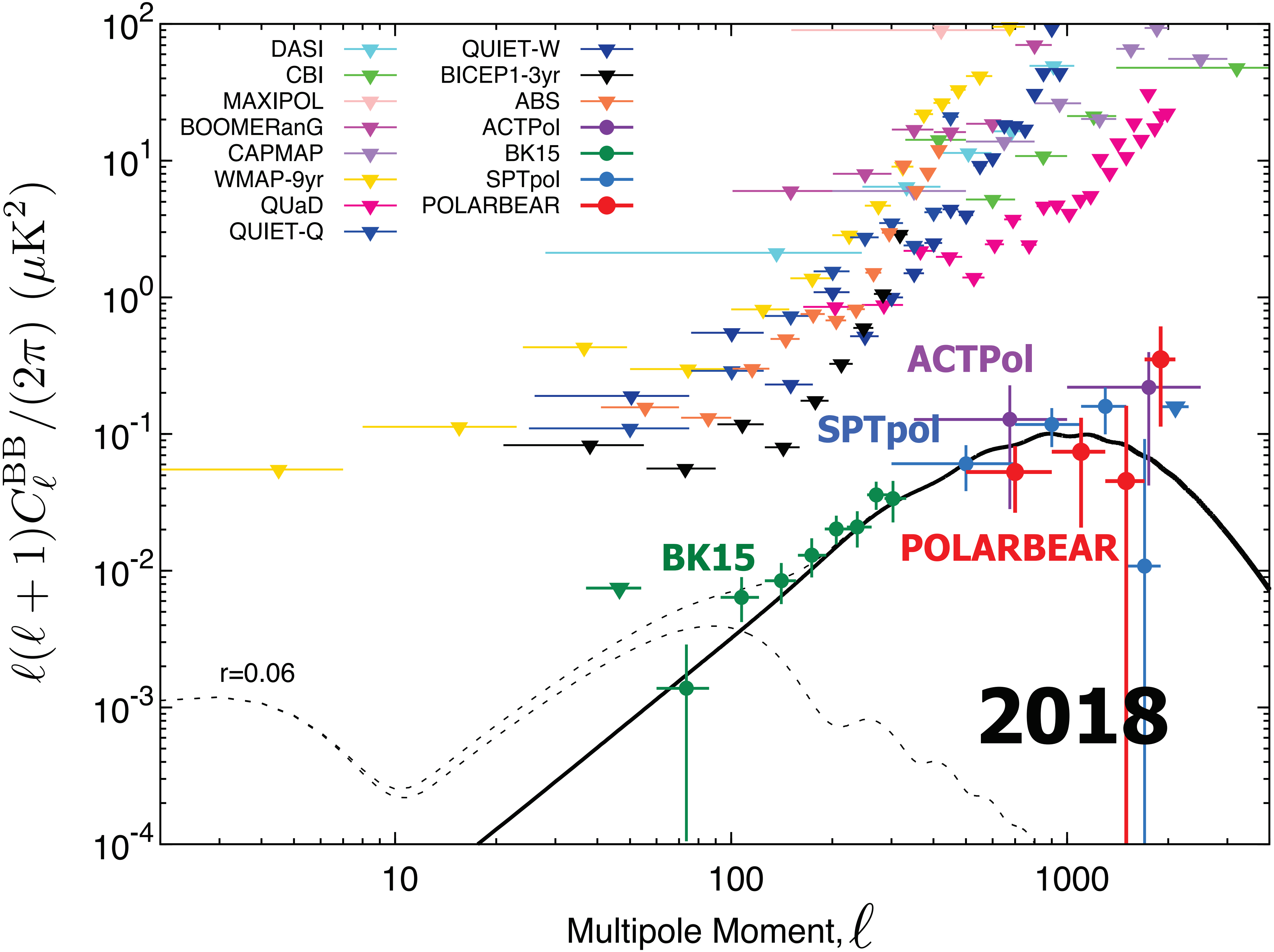





DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
r=0.20
<2014
$\ell(\ell+1)C_\ell^{\rm BB}/(2\pi)$ $(\mu{\rm K}^2)$
Multipole Moment, ℓ
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
100
1000

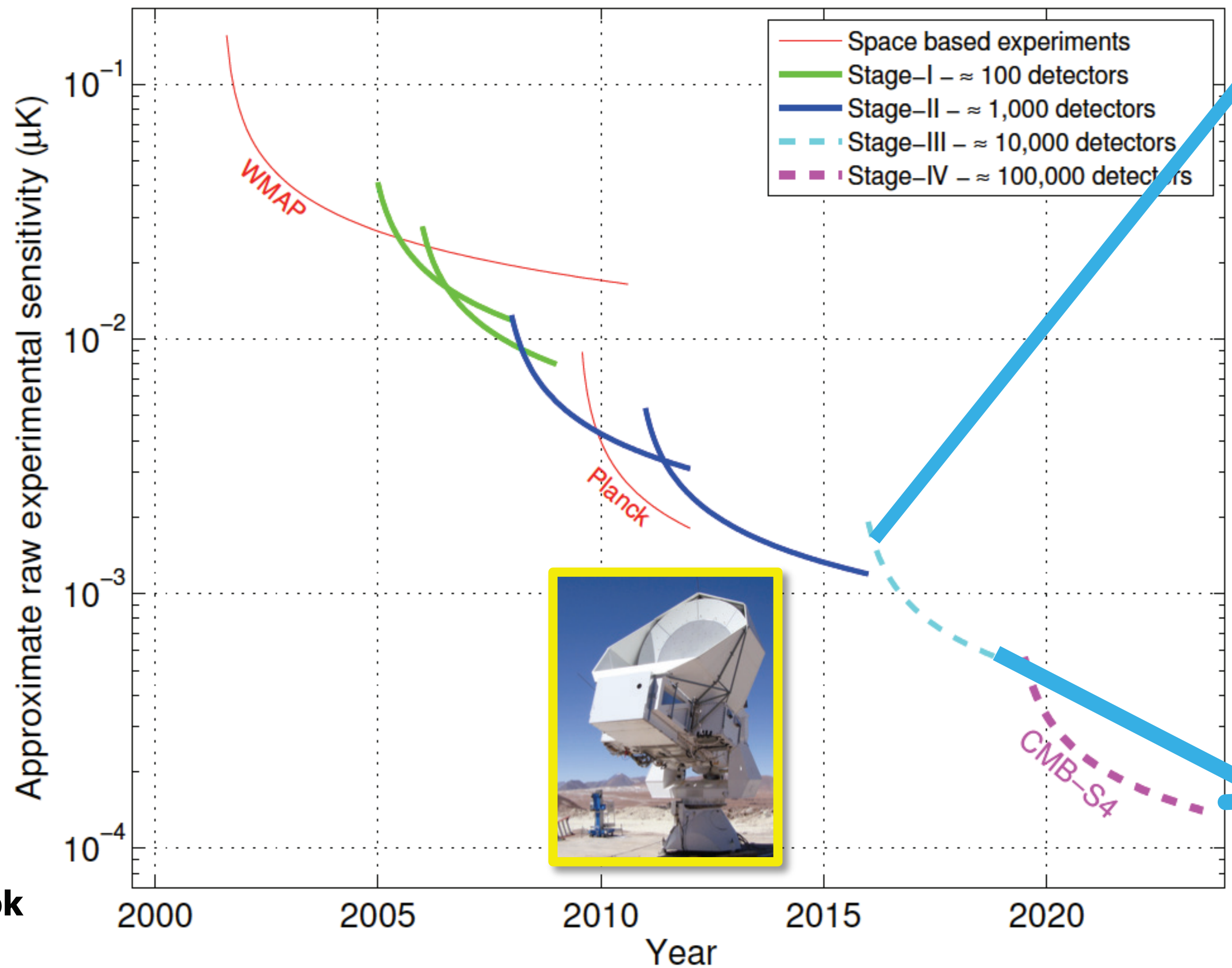


DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
BICEP2-3yr
POLARBEAR
r=0.20
BICEP2
on 17th
POLARBEAR
on 11th
March, 2014
$\ell(\ell+1)C_\ell^{\rm BB}/(2\pi)\ (\mu{\rm K}^2)$
Multipole Moment, ℓ



DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
ABS
ACTPol
BK15
SPTpol
POLARBEAR
ACTPol
SPTpol
BK15
POLARBEAR
r=0.06
2018
$\ell(\ell+1)C_\ell^{\mathrm{BB}}/(2\pi)\ (\mu\mathrm{K}^2)$
Multipole Moment, ℓ
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
100
1000

Simons Array is a "Stage 3" ground-based CMB experiment upgraded from **POLARBEAR**

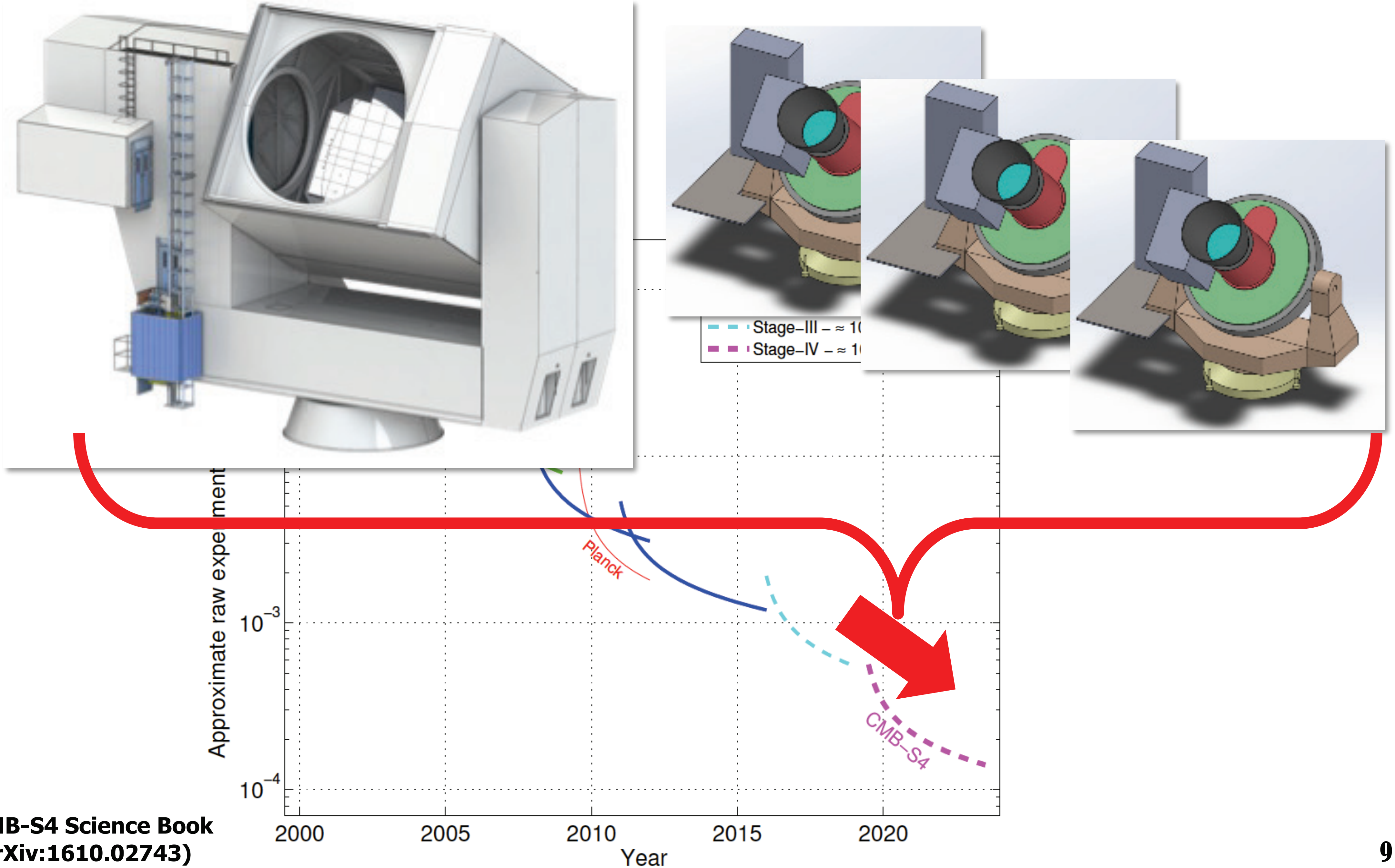


or...

x~20 sensitivity

CMB-S4 Science Book (arXiv:1610.02743)

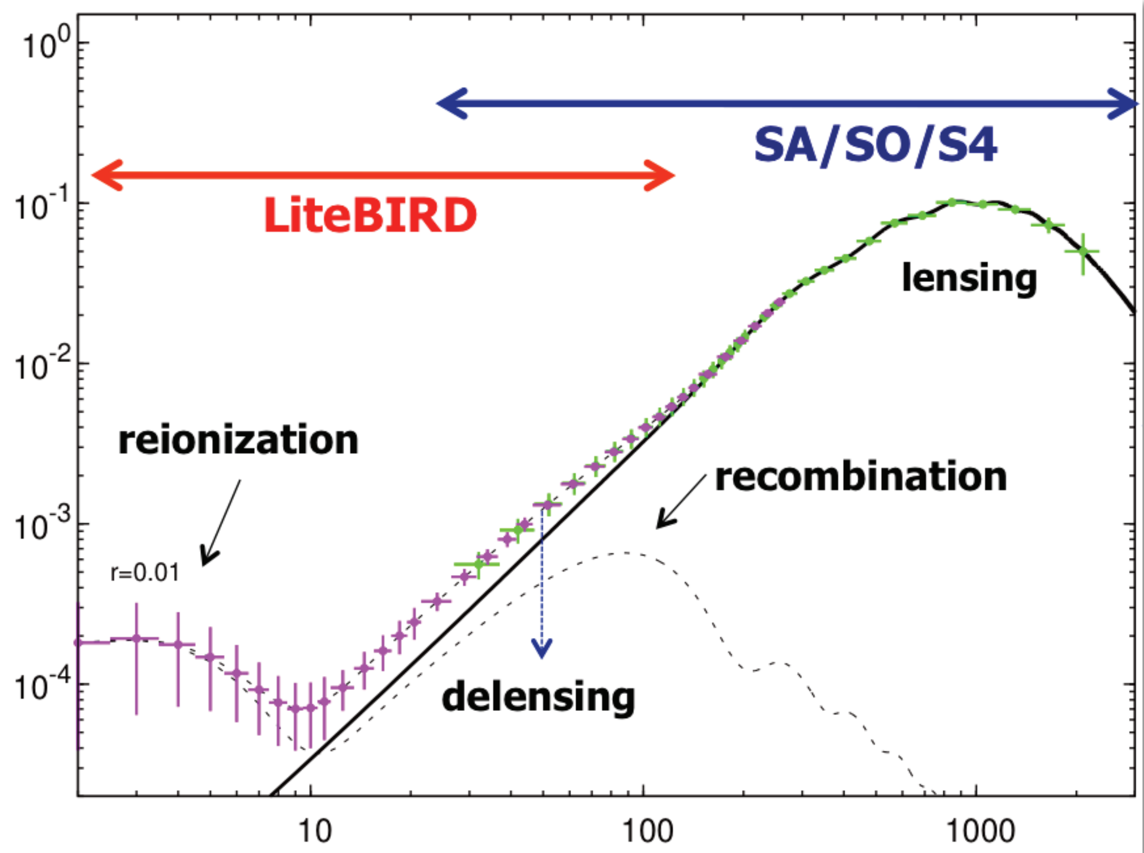
Simons Array to Simons Observatory

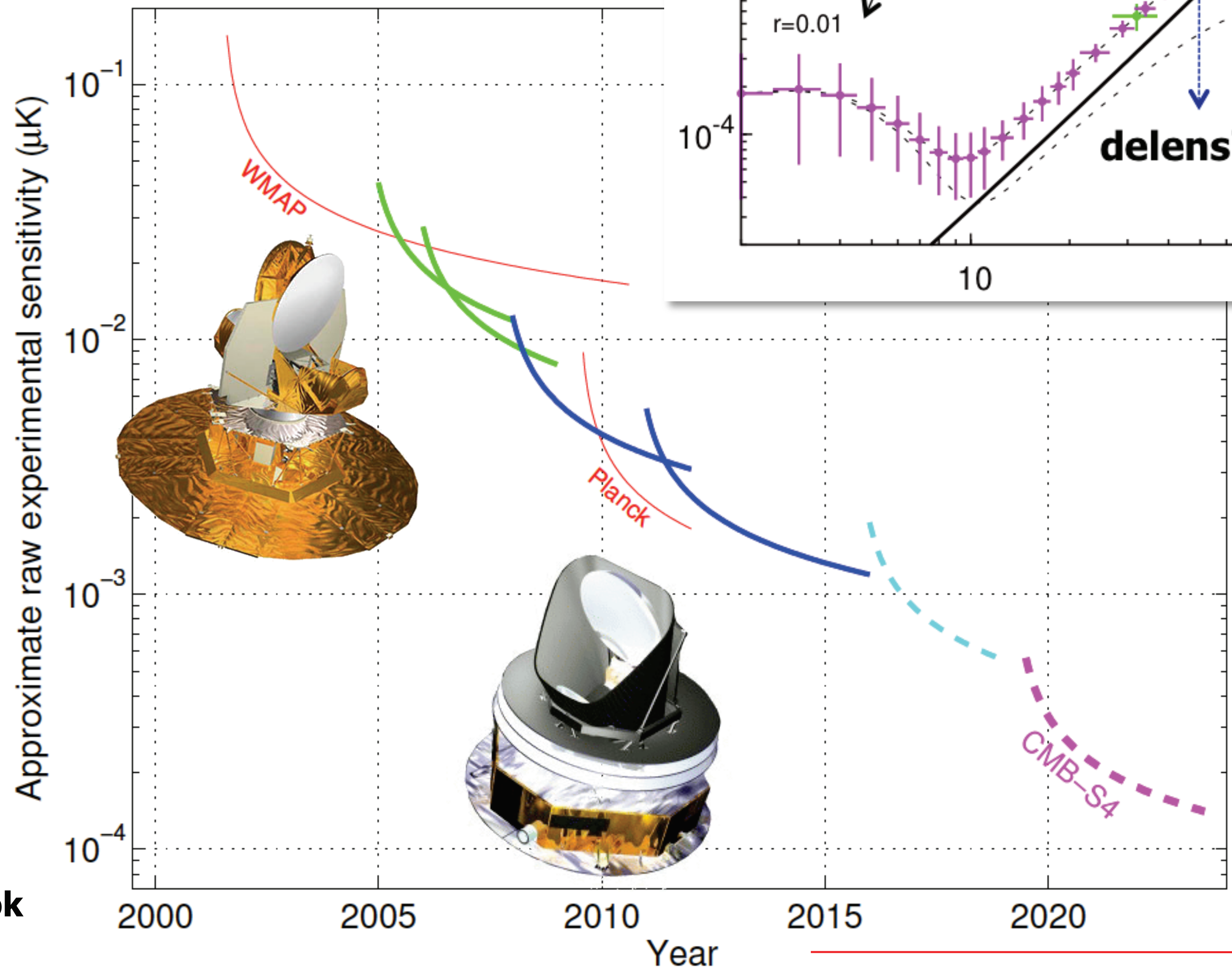


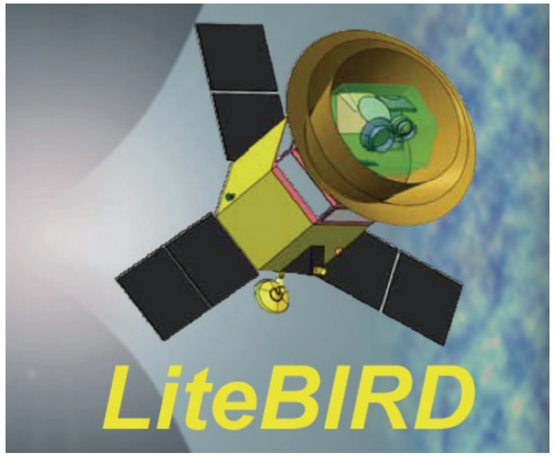
CMB-S4 Science Book (arXiv:1610.02743)

Ground + Satellite

or ultimate satellite?



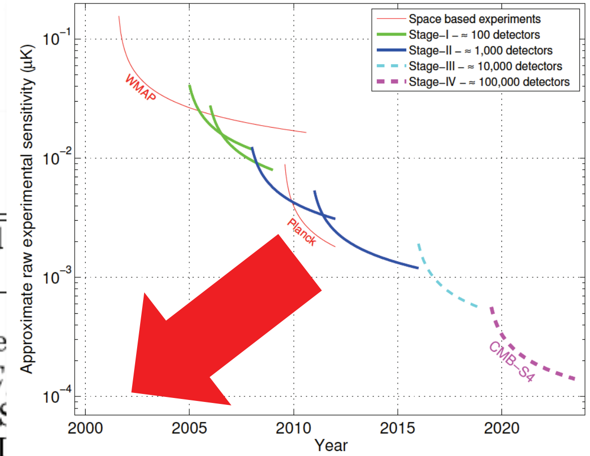




~2027?

CMB-S4 Science Book (arXiv:1610.02743)

Our science targets: e.g. Simons Observatory



SO science forecast paper

Table 9
Summary of SO key science goals[a]

large angular scales

small angular scales

	Parameter	SO-Baseline[b] (no systematics)	**SO-Baseline[c]**	SO-Goal[d]	Current[e]	Method
Primordial perturbations	r	0.0024	**0.003**	0.002	0.03	BB + e
	$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	0.4%	**0.5%**	0.4%	3%	TT/TE
	$f_{\mathrm{NL}}^{\mathrm{local}}$	1.8	**3**	1	5	$\kappa\kappa$ × LS
		1	**2**	1		kSZ + L
Relativistic species	N_{eff}	0.055	**0.07**	0.05	0.2	$TT/TE/EE + \kappa\kappa$
Neutrino mass	Σm_ν	0.033	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO
		0.035	**0.04**	0.03		tSZ-N × LSST-WL
		0.036	**0.05**	0.04		tSZ-Y + DESI-BAO
Deviations from Λ	$\sigma_8(z=1-2)$	1.2%	**2%**	1%	7%	$\kappa\kappa$ + LSST-LSS + DESI-BAO
		1.2%	**2%**	1%		tSZ-N × LSST-WL
	H_0 (ΛCDM)	0.3	**0.4**	0.3	0.5	$TT/TE/EE + \kappa\kappa$
Galaxy evolution	η_{feedback}	2%	**3%**	2%	50-100%	kSZ + tSZ + DESI
	p_{nt}	6%	**8%**	5%	50-100%	kSZ + tSZ + DESI
Reionization	Δz	0.4	**0.6**	0.3	1.4	TT (kSZ)

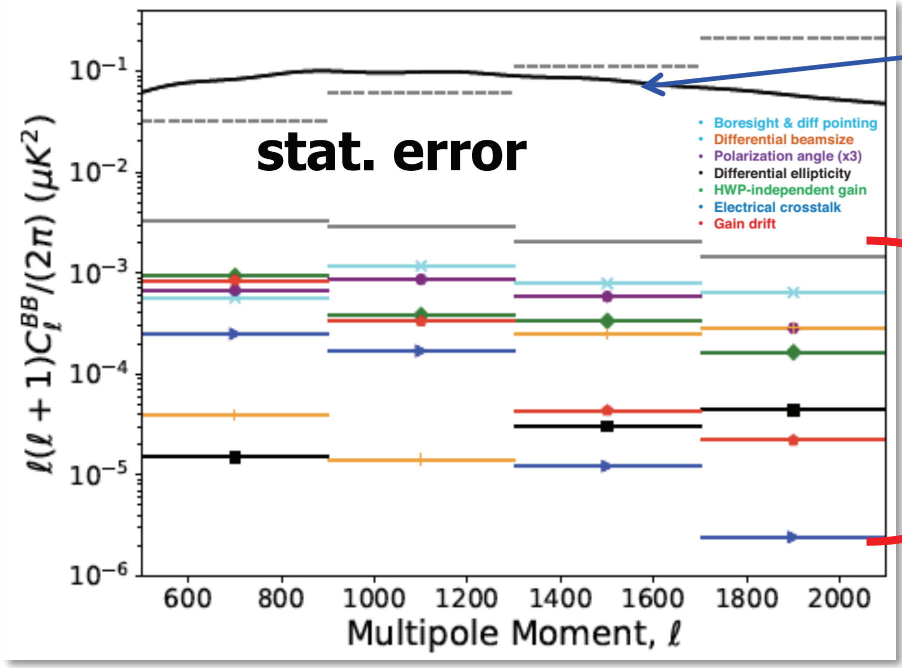
ext delens	Delensing field estimated from large-scale structure surveys	3,5
tSZ-N×LSST-WL	Cluster masses calibrated using LSST weak lensing data	7
$\kappa\kappa$×LSST-LSS	CMB lensing correlated with galaxy density in tomographic slices from 3 years of LSST	2,5
DESI-BAO	BAO measurements from the full DESI survey	2
DESI	Galaxy positions from the full DESI survey	7

- **Angular resolution → large & small aperture telescopes**
- **Sensitivity → more detectors**
- **Suppress any systematic/bias much smaller than stat.**

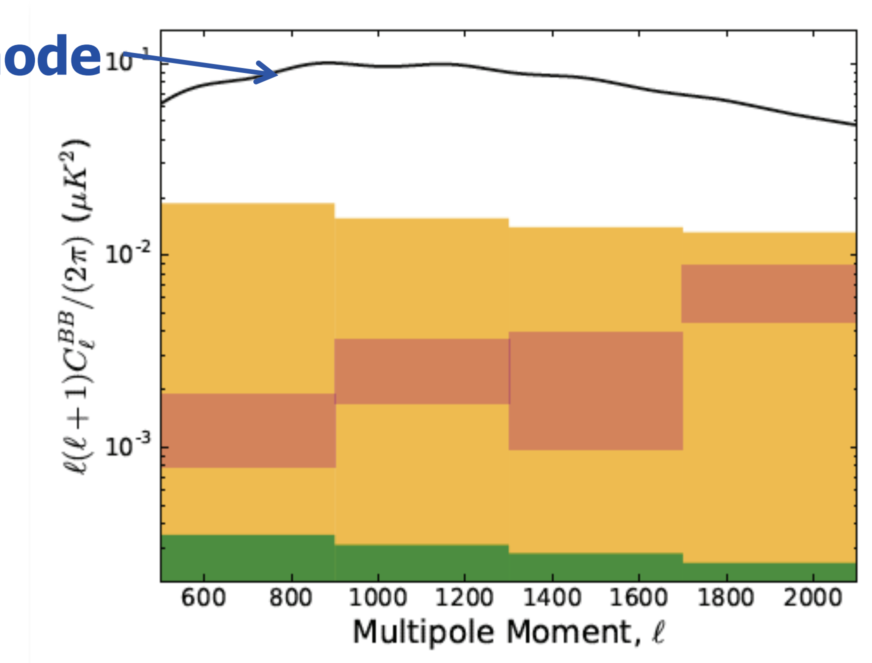
Example: POLARBEAR 2017

- Instrument systematics by realistic simulation
- Foregorund bias from Planck data

B-mode



Instrument sys



Foreground bias

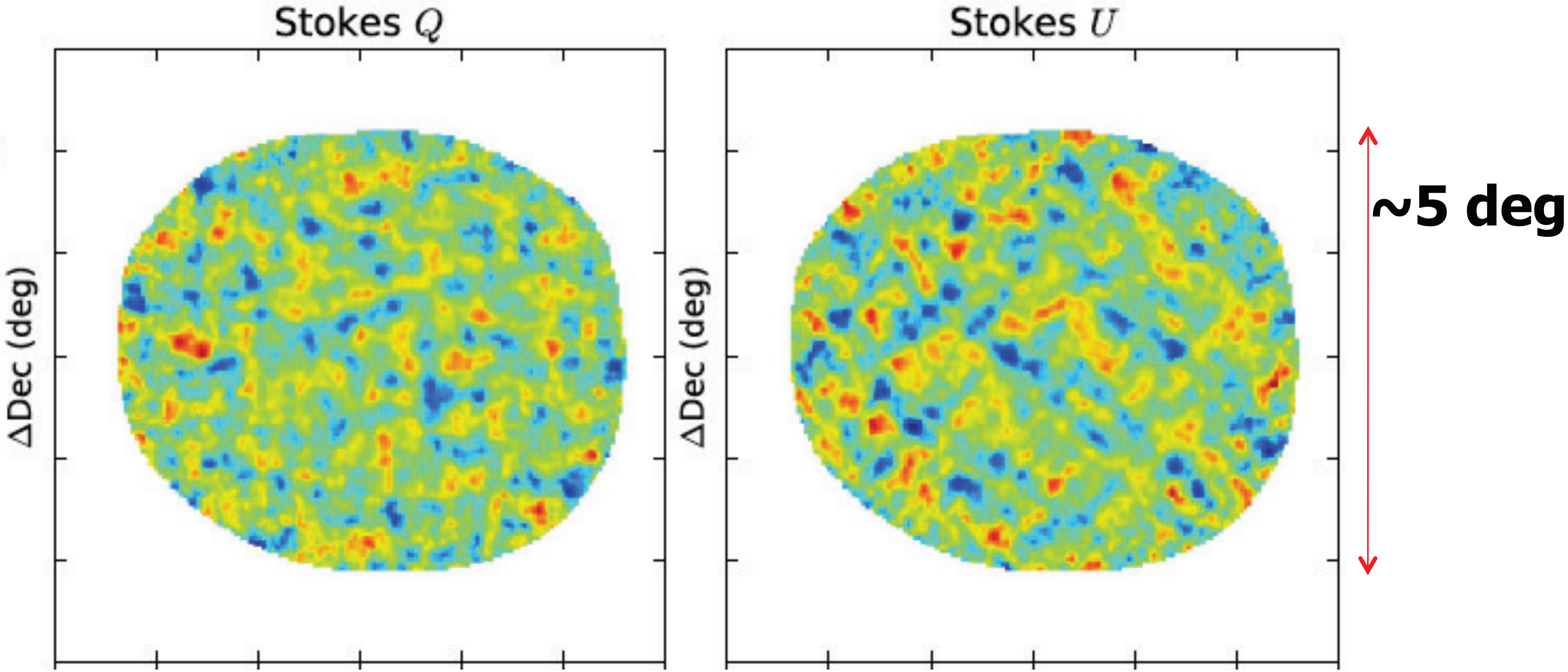
- →These are smaller than the "statistical" errors
- →<u>Stat. error will get improved by O(10-100) in SA/SO/S4</u>
- →<u>Sys. error must be suppressed by the same order</u>

POLARBEAR since 2012 (deployed in 2011)

5,200m @ Atacama Desert, Chile

@150 GHz

Deep Survey @ Sub-Degree Scale



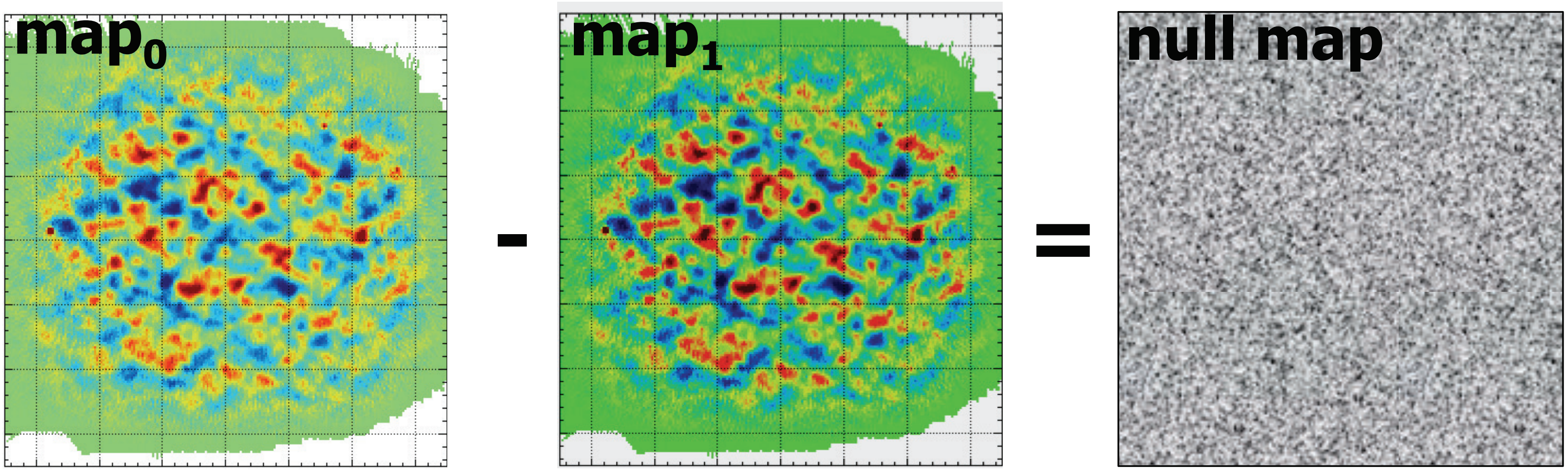
- One of the most "deepest" polarization maps
  - (deepest patch) ~5 μK-′ ~ lensing B-mode signal

finally 3.1σ

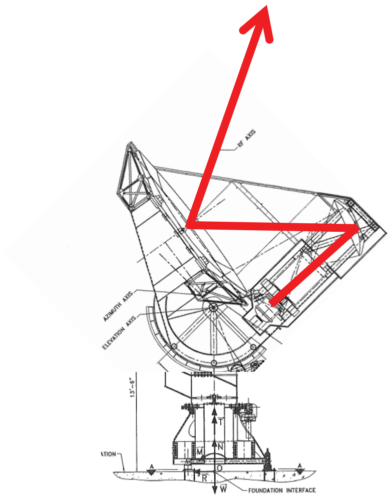
- First measurement & improvement of BB (2014 & 2017)
- **Performed dedicated null tests & systematic validation before unblinding**

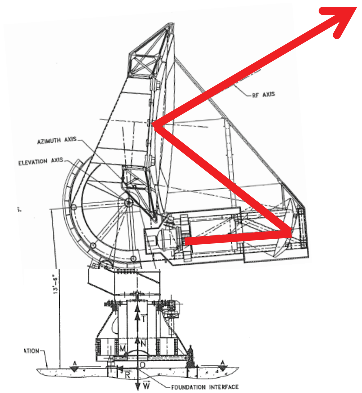
Null Test

- Split data into two, then take the difference to check systematic
  - If no sys, it's just noise; but we would see corresponding sys if not



(**CMB**+**Noise$_1$**) - (**CMB**+**Noise$_2$**) = **Noise**





e.g. high elevation vs. low elevation

Twelve Null Tests

- **1st_season_vs_2nd_season**
- 1st_half_vs_2nd_half
- high_gain_ces_vs_low_gain_ces
- **high_elevation_vs_low_elevation**
- rising_vs_setting
- high_pwv_vs_low_pwv
- far_from_sun_vs_close_to_sun
- far_from_moon_vs_close_to_moon
- sun_above_horizon_vs_sun_below_horizon

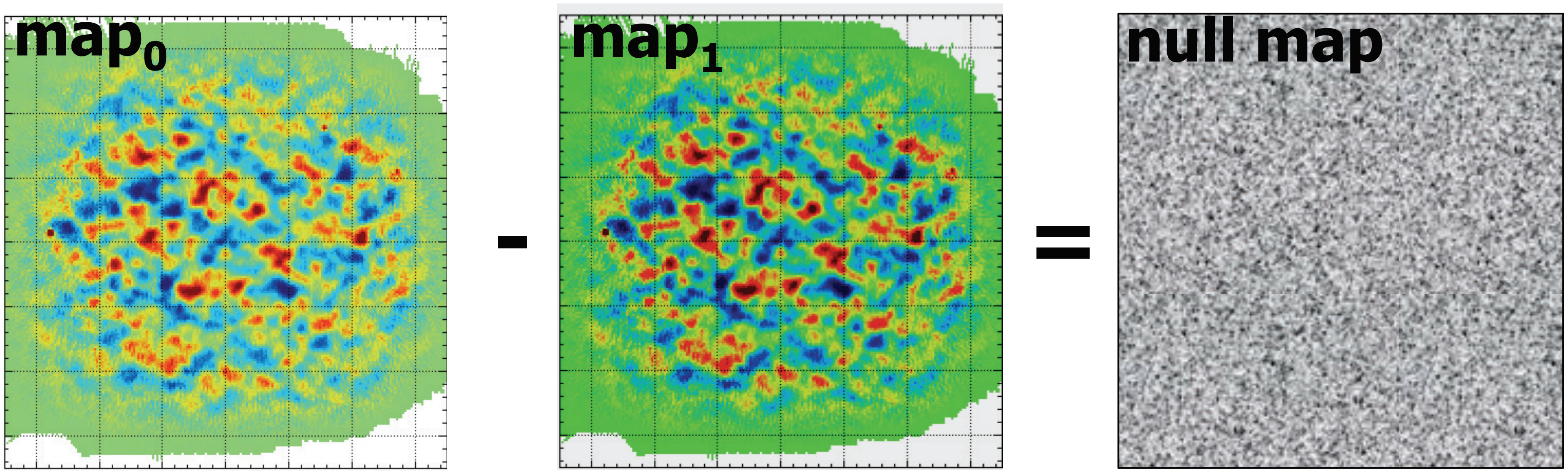
9 different combinations of CES's

- left_going_scan_vs_right_going_scan
- q_pixels_vs_u_pixels
- left_side_pixels_vs_right_side_pixels

2 different splits of FP & L/R scans

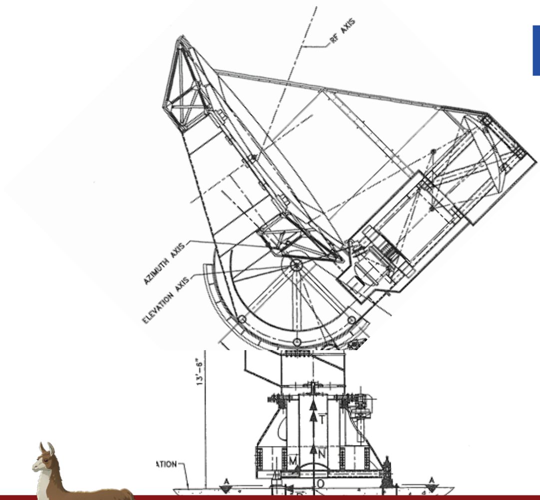
Null Test

- Split data into two, then take the difference to check systematic
  - If no sys, it's just noise; but we would see corresponding sys if not



$(\mathrm{CMB}+\mathrm{Noise}_1) - (\mathrm{CMB}+\mathrm{Noise}_2) = \mathrm{Noise}$

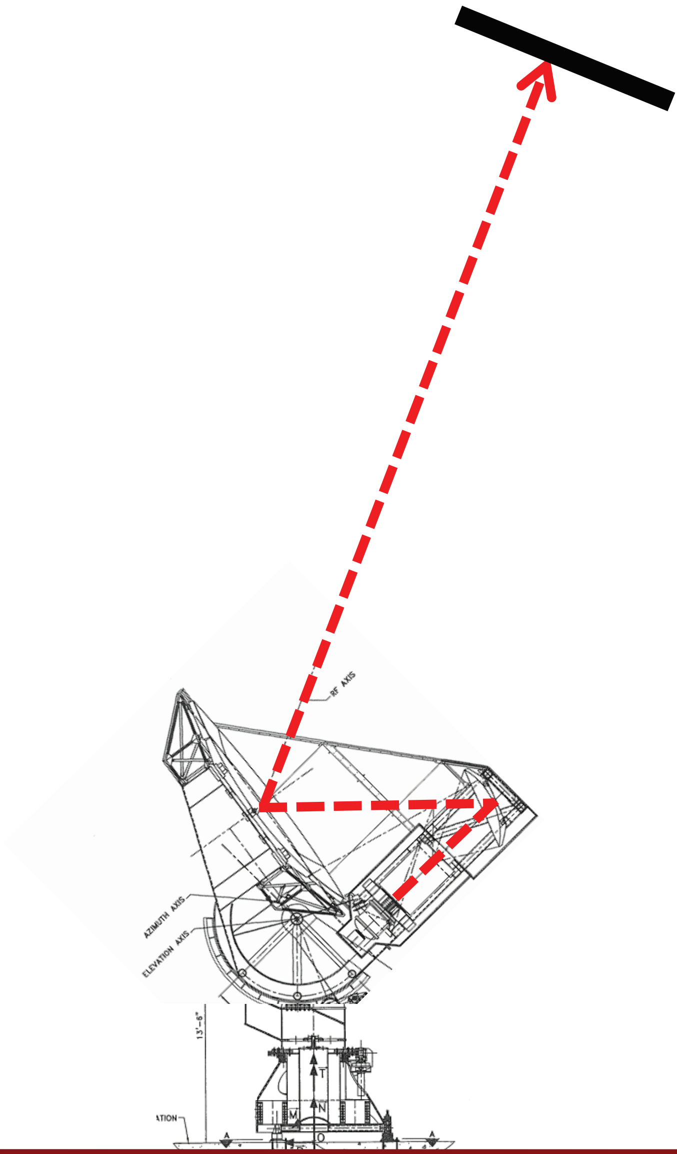
- After several iterations, finally found there is no systematic bias
  - **→Open the "BOX" ("Unblinding")**
- These iterations could tell us **real "problems" we should solve for future experiments** as well as on-going analysis



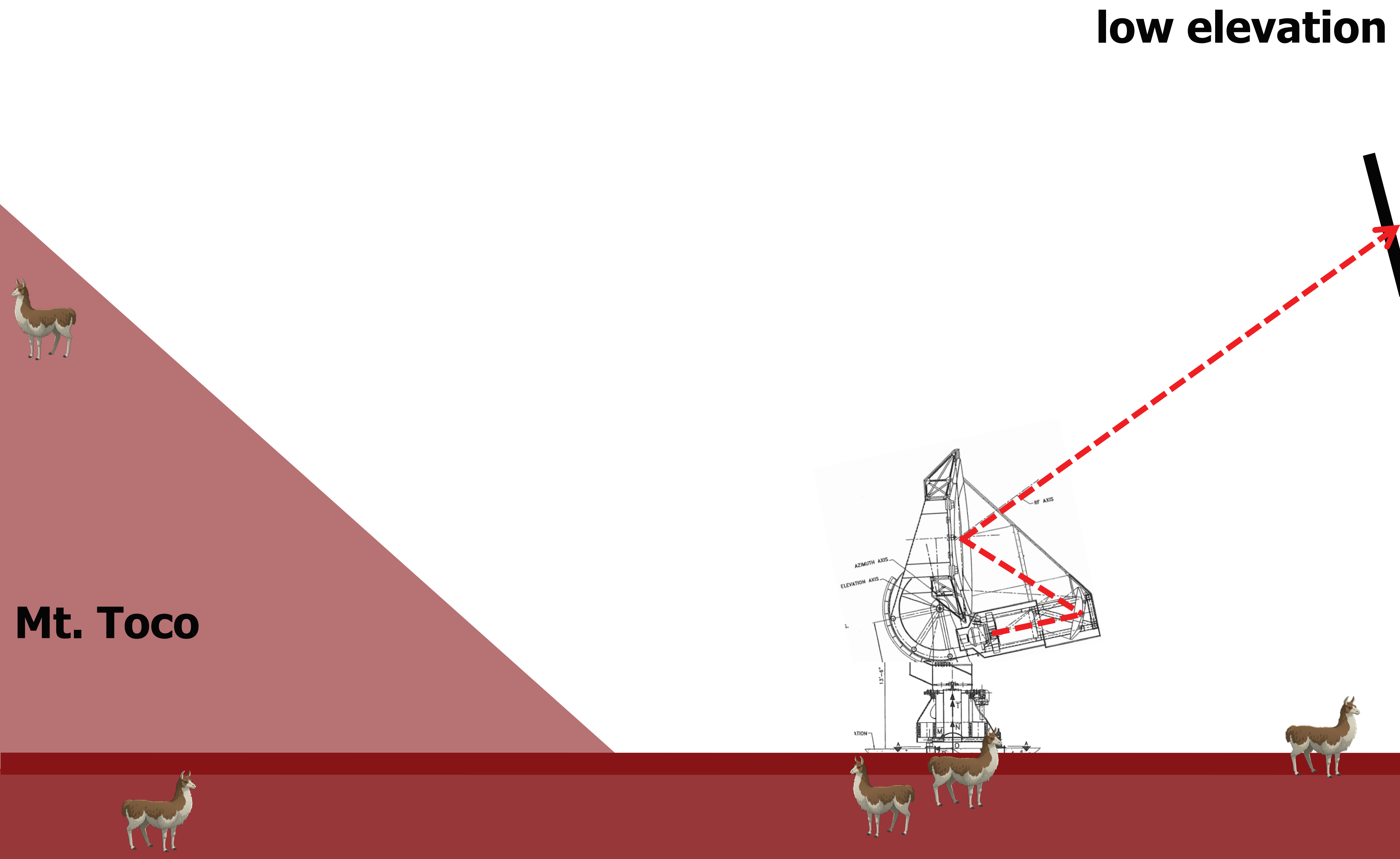
POLARBEAR
@Chile

Mt. Toco

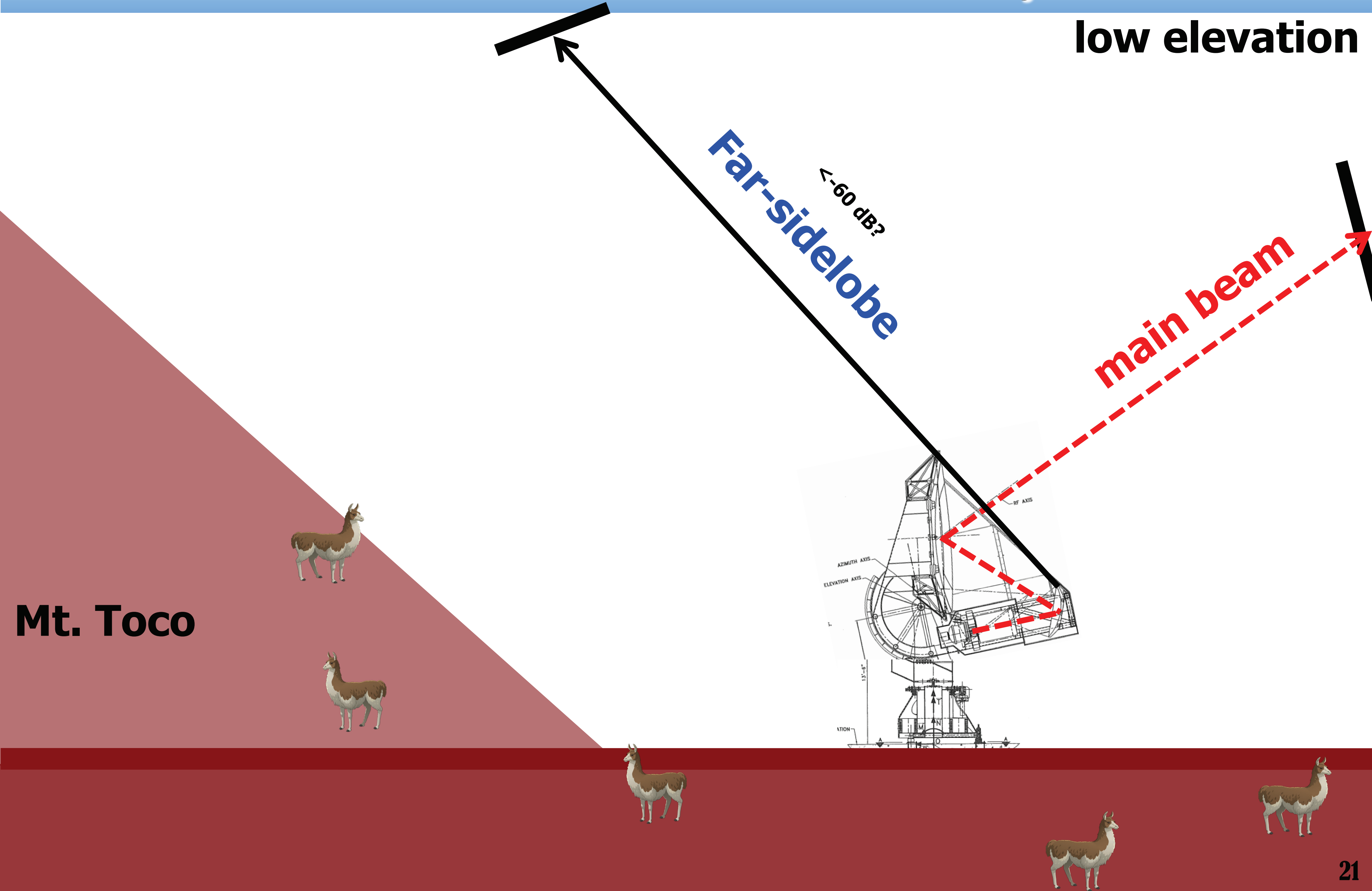
high elevation



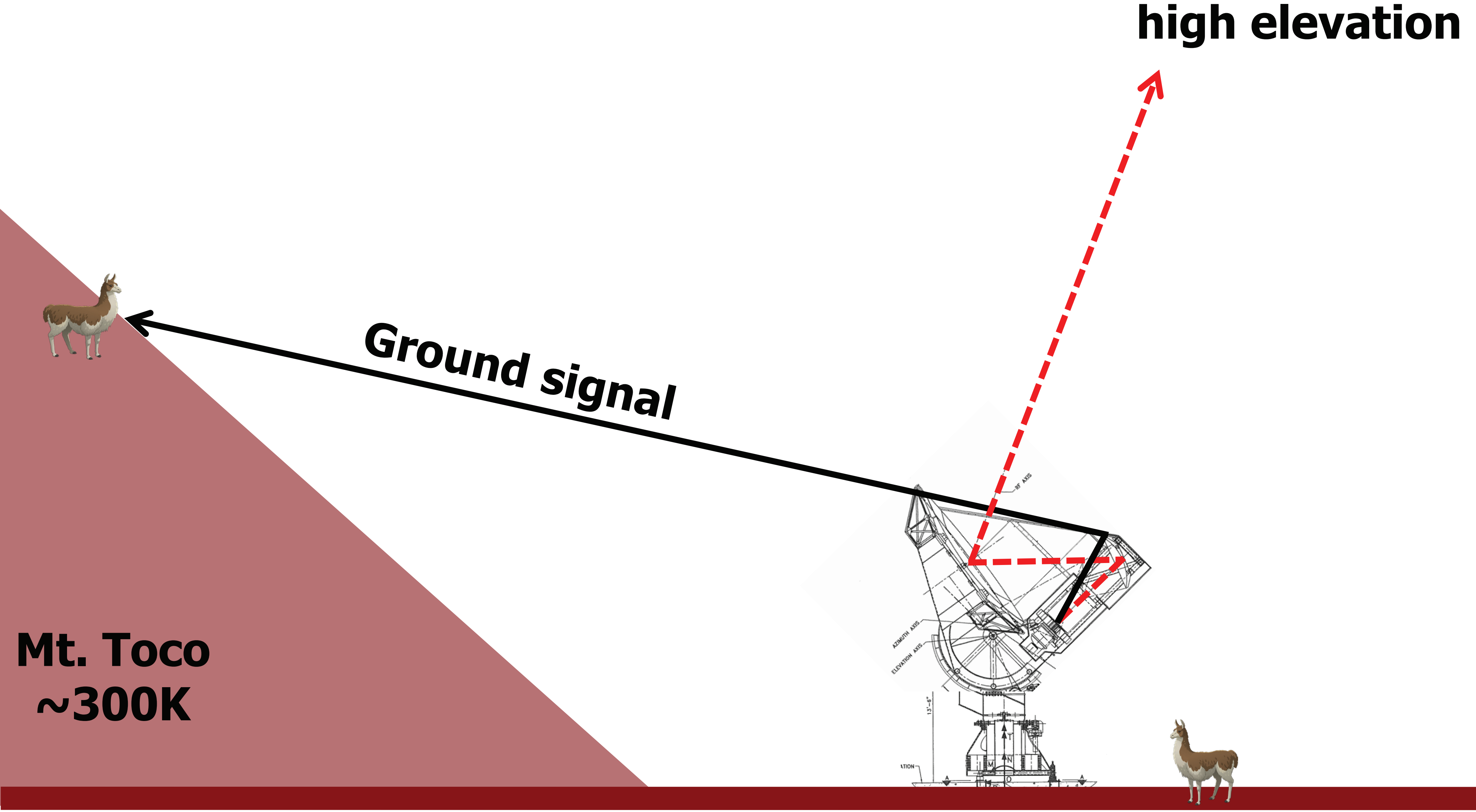
Mt. Toco


low elevation
RF AXIS
AZIMUTH AXIS
ELEVATION AXIS
Mt. Toco

Far-Sidelobe Could Look At Other Sky

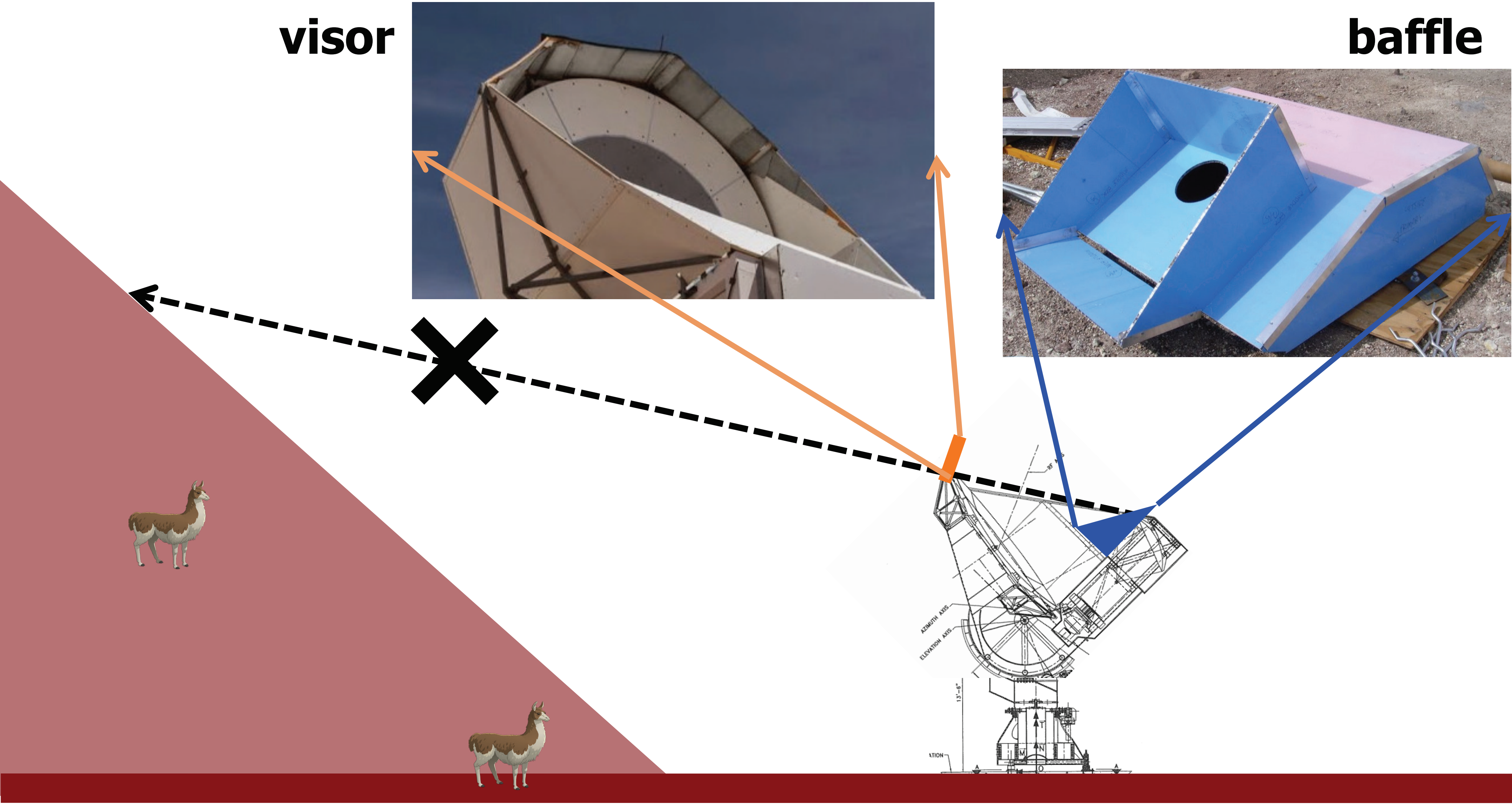


Ground Signal via Far-Sidelobe (Stray Light)



Far-sidelobe could look at ground at high elevation

Feedback to Hardware Design



Feedback from data analysis to hardware design is important

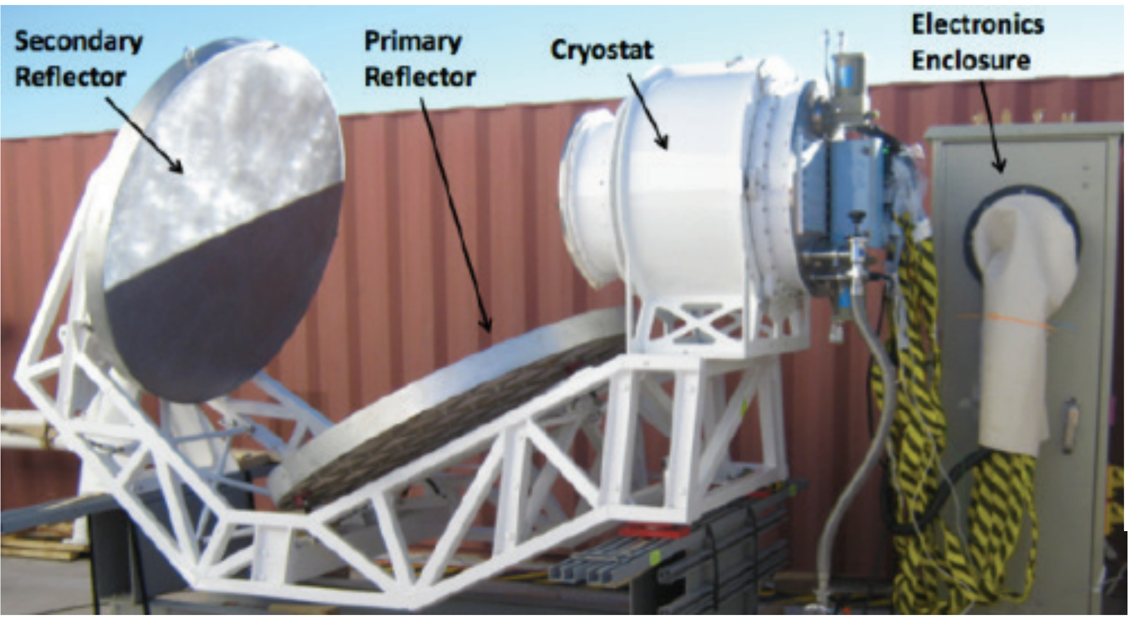
→Feedback to SO/S4 as well as SA

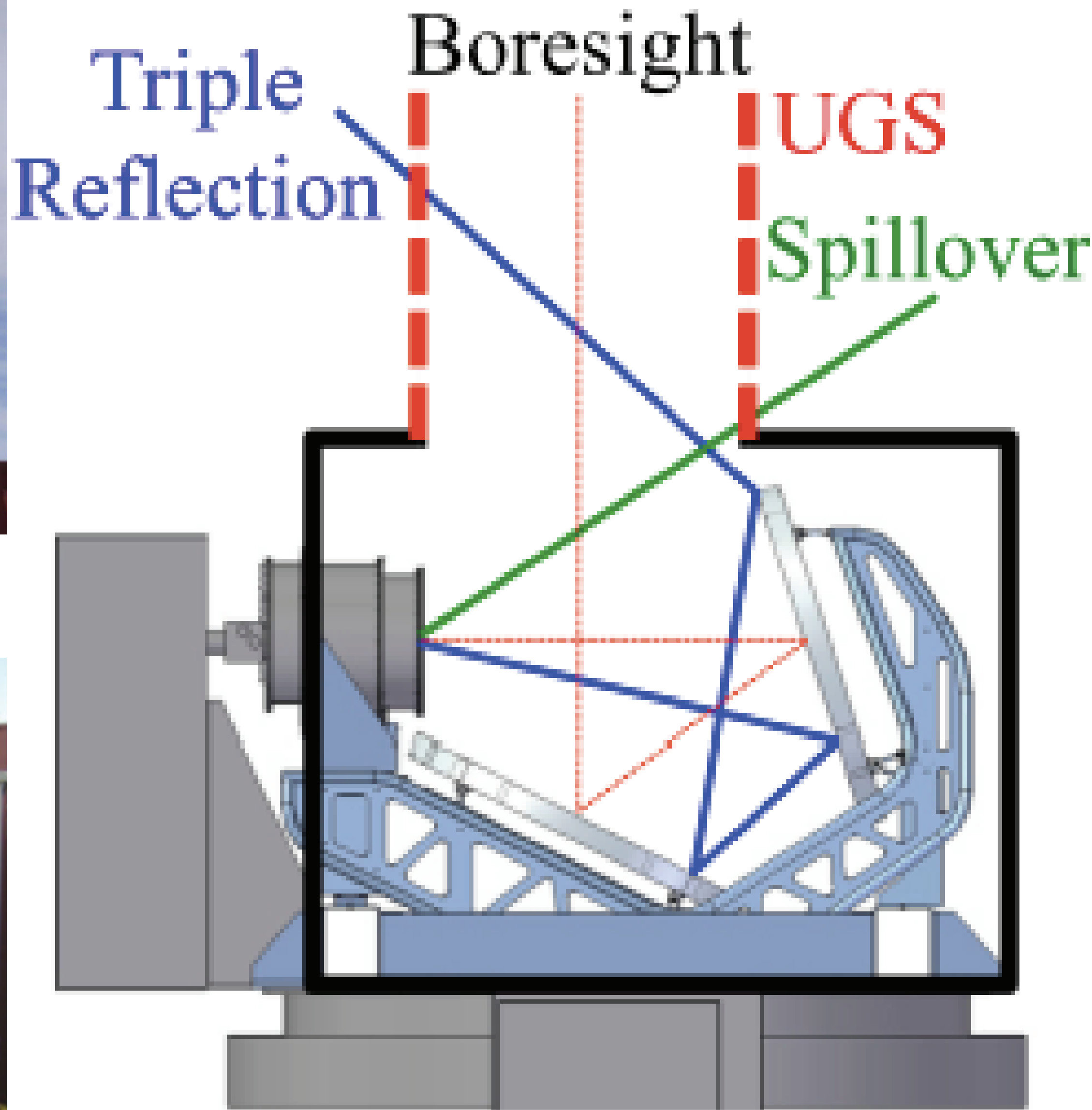
Mitigation of Ground Signal

Ground template subtraction
+
Cross correlations among daily maps

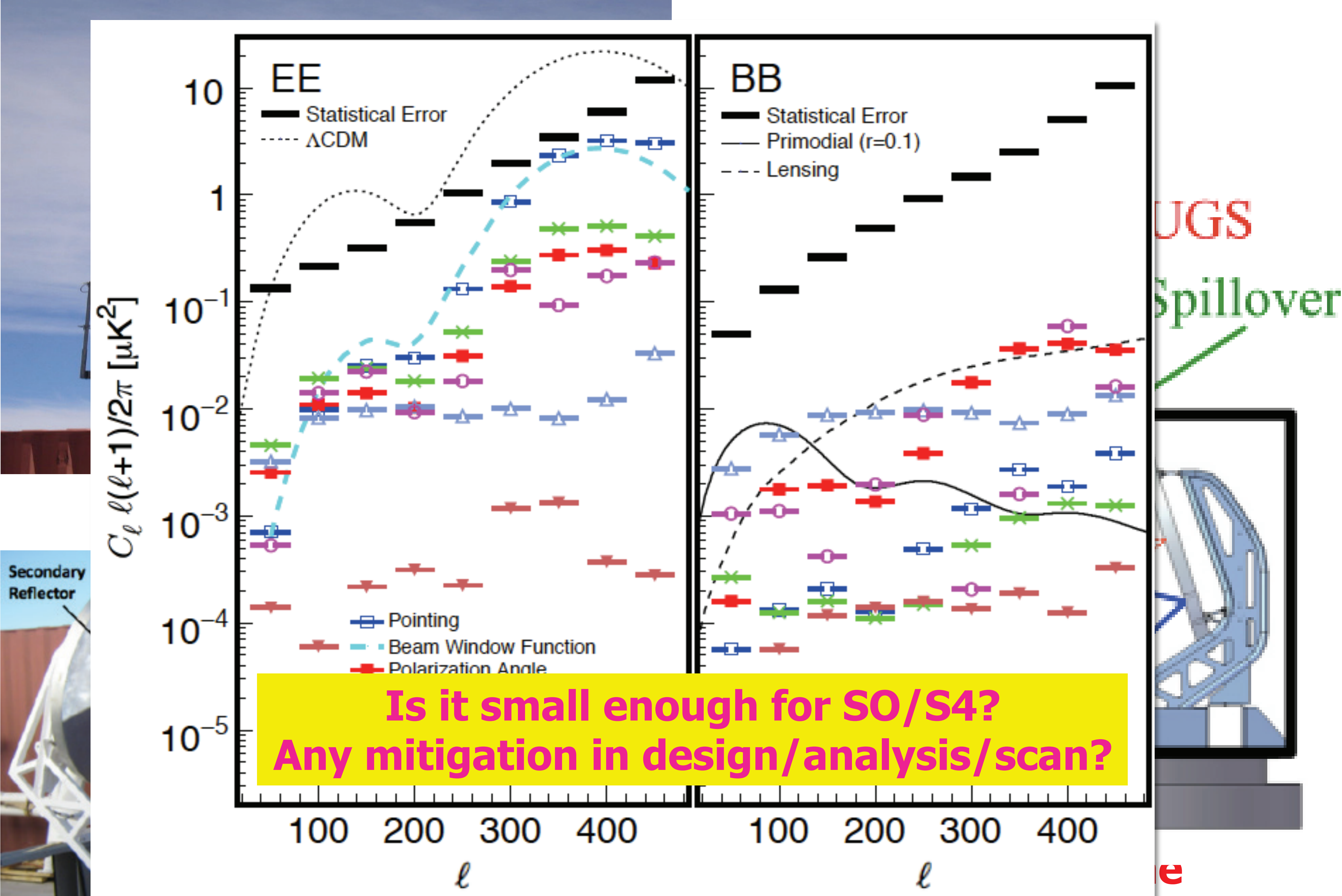
- Mitigation by **new hardware** & **analysis**, i.e. **ground template subtraction & cross-corr**, works well
- *Is it enough/O.K. for SA/SO/S4?*
  - e.g. any residual? any extra bias? applying ground template subtraction could lose certain models in azimuth

1.4m (QUIET) vs. 6m (SO)





Cross-Dragone telescope design



telescope design

Question/Comment

- Likely expect these systematics could be much more suppressed in 4pt estimator than 2pt estimator
  - However, **need realistic estimates/simulation in S3/S4 experiments to confirm it**
    - ✓ In PB/SA, we're studying the application of dedicated null test and systematics simulations for both 2pt & 4pt to do that
- **Which kind of "real" systematic should we worry about in 4pt from theory/science sides as well as experiment side?**
  - Close communication/interface among them is important
- **Cross-correlation w/ other measurement is also powerful as well as for tomography science**

Example: POLARBEAR x HSC

- Detecting cross-correlation BTW PB x HSC by using polarization channel, which has not been done yet

~5 μK-′ in pol
as deep as SO

observes LSS via CMB B mode
(=weak lensing)

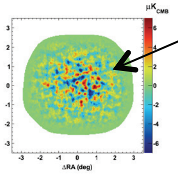
X

observes LSS via shear
(=weak lensing)

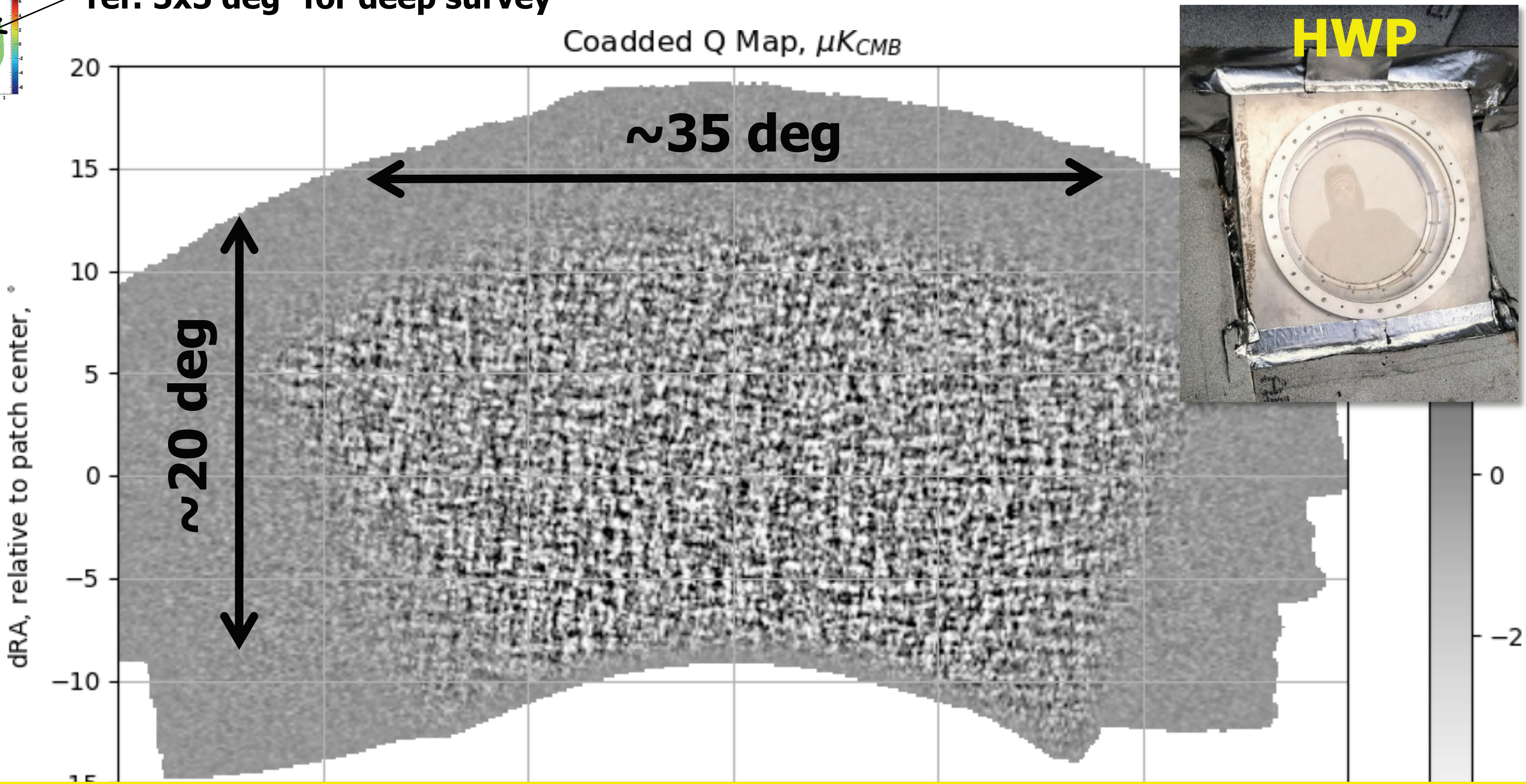
deepest shear map
& can be seen
precursor for LSST

Demonstration by detecting cross-correlation is important

Other Systematic: 1/f Noise on Large Angular Scale



ref: 5x5 deg^2 for deep survey



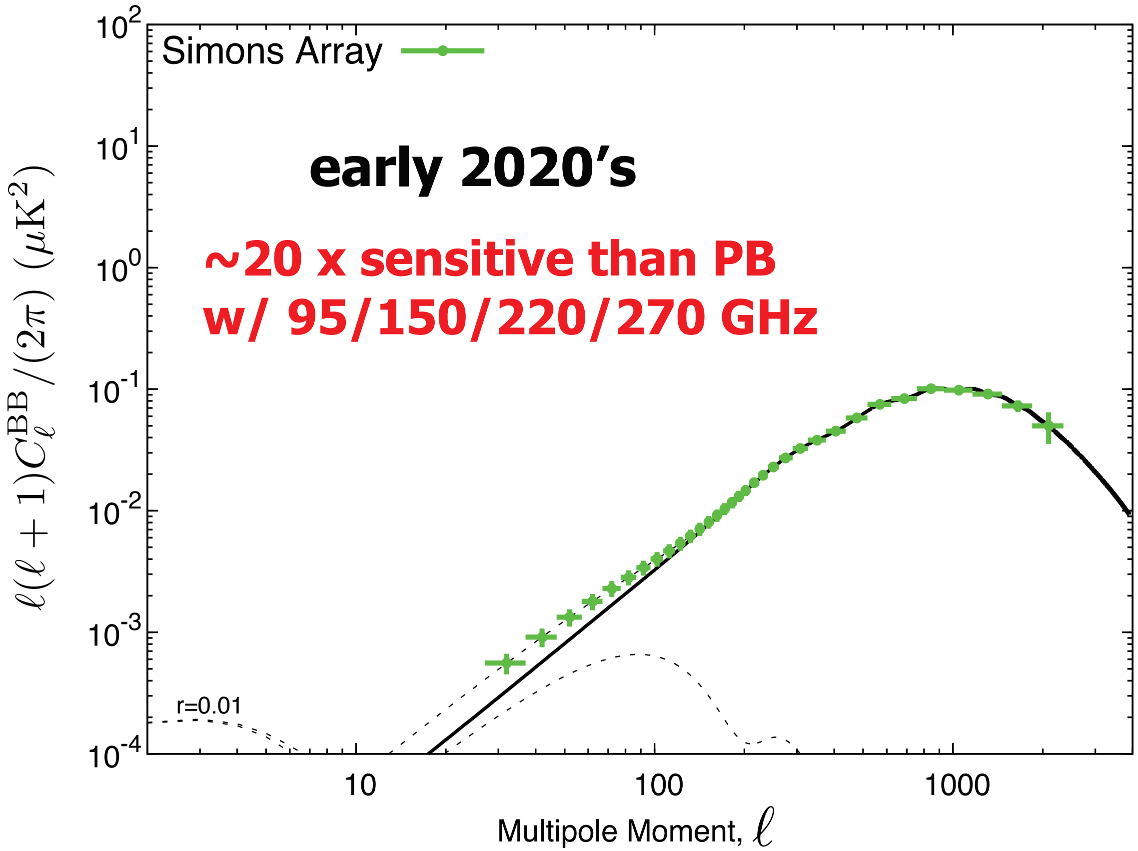
Low-frequency systematic, so-called atmospheric "1/f noise", is the largest.

Suppressing it by rotating Half-wave Plate (HWP) is critical, targeting ell down to ~50

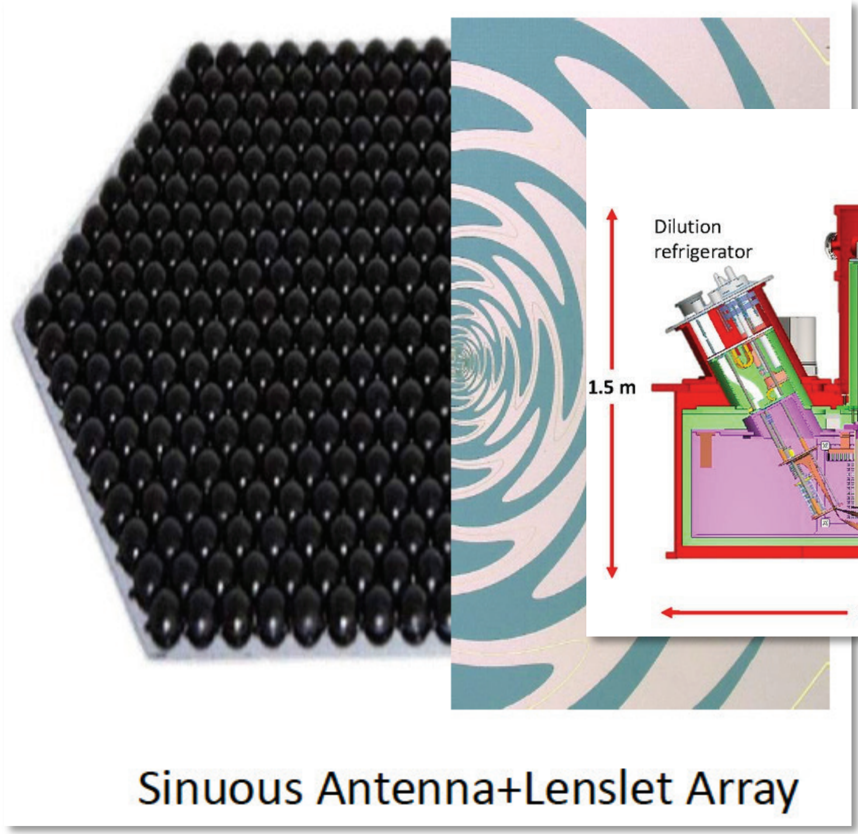
HWP will be used in SA/SO and S4 @ Chile

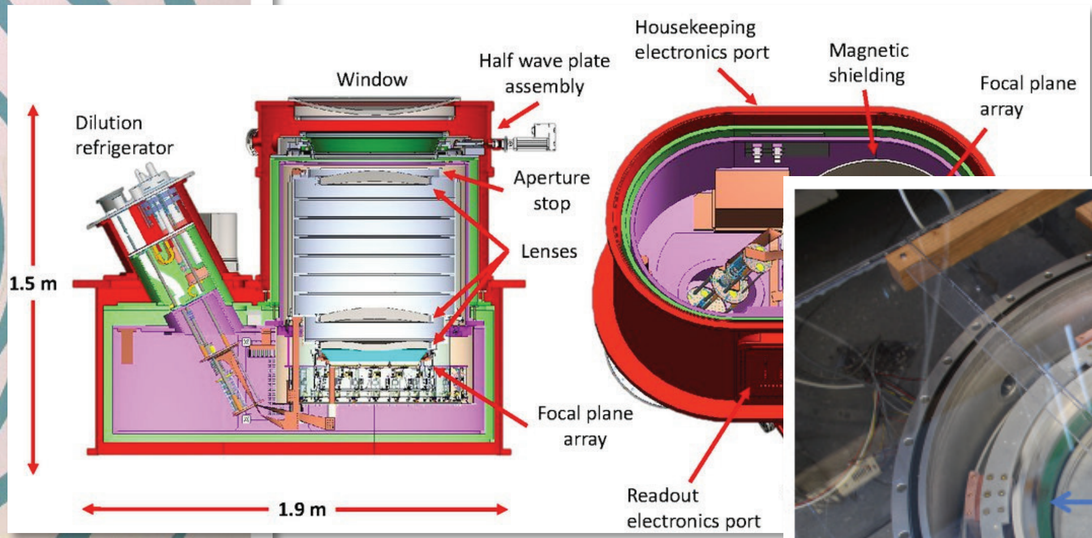
Deploying Simons Array

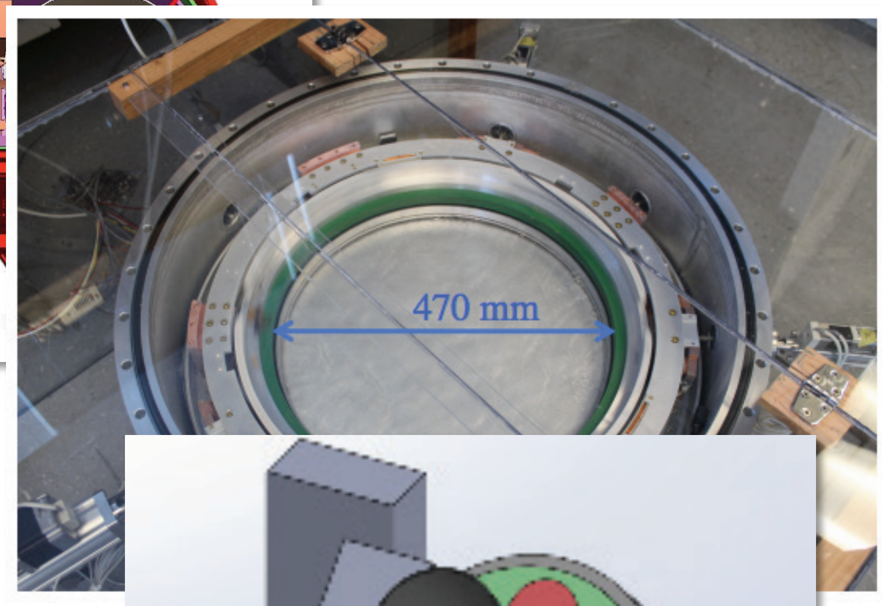
Deploying first receiver

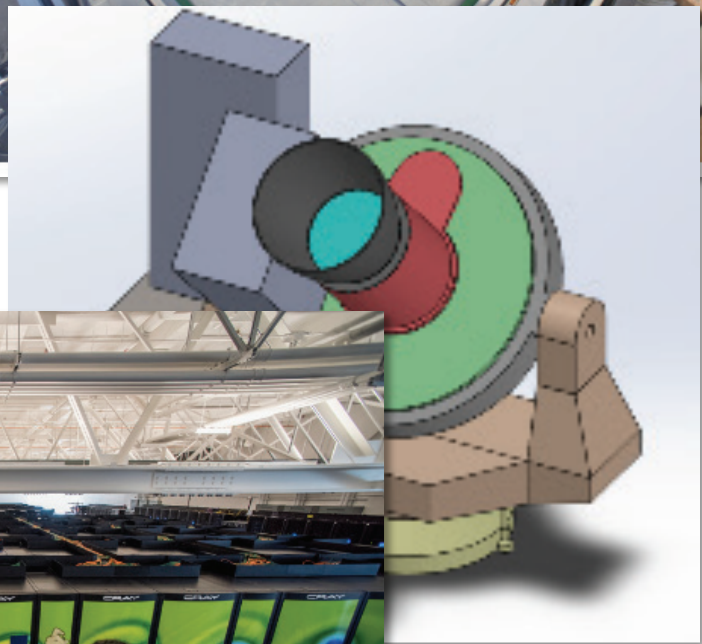


- **We're developing/deploying 3 new receivers by ~2020**
  - **Inflation: $\sigma(r) = 6\times10^{-3}$ (4×10^{-3} stat.)**
  - **Neutrino masses: $\sigma(\Sigma m_\nu)$ = 40 meV (19 meV stat.)** w/ BAO from DESI
- **Stay tuned!?**


Sinuous Antenna+Lenslet Array


Window
Half wave plate assembly
Housekeeping electronics port
Magnetic shielding
Focal plane array
Dilution refrigerator
Aperture stop
Lenses
1.5 m
Focal plane array
Readout electronics port
1.9 m


470 mm



X

Summary

- Working on POLARBEAR, Simons Array, and Simons Observatory
  - CMB-S4 and LiteBIRD are also our main projects
  - To achieve our science goals, better stat. & sys. sensitivity are needed
- Our knowledge/experience from POLARBEAR, especially **"real" systematic**, would be important for SO/CMB-S4; <u>Close communication among science & hardware & analysis is needed</u>
- Deploying Simons Array now; Stay tuned!

Now

$\sigma(r) < O(0.1)$

2019~

$\sigma(r) < 0.01$; $\sigma(\Sigma m_\nu) \sim 40$ meV

2020~

$\sigma(r) < 0.002$; $\sigma(\Sigma m_\nu) \sim 30$ meV