AAS 237
IPSIG Session

Complementarity of Space- and Ground-Based CMB Experiments

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History

- Continuously-improving ground and sub-orbital experiments. . .
- . . .punctuated by comprehensive measurements from space missions

Critical Factors

- Noise
- Angular resolution
- Ability to separate foregrounds
  - Calibration and frequency coverage
- Freedom from systematics

Noise

- Noise is what matters, not sensitivity ($\equiv$ noise per unit time)
  - In the (unrealistic) ideal case,

$$\text{Noise} \propto \frac{\text{“Sensitivity”}}{\text{Integration time}^{1/2}}$$

- Sensitivity per detector is better in space
  - No atmosphere, no ground, cold optics
- Integration time is better in space
  - At L_2, no Sun, no Moon, no Earth, no weather

    In the final “NPIPE” analysis, Planck LFI data were used for 97.5% of four years wall clock time

    For HFI, the equivalent was 80.3%, largely due to cosmic rays
  - Balloon experiments are no longer competitive, largely because of limited integration time
- Advantage space
  - Roughly summarized by the rule of thumb: one detector in space is worth 100 on the ground

Angular Resolution

- Beam size $\propto \frac{\lambda}{\mathrm{D}}$
- Big things in space cost more than little things
- Everything in space costs more than on the ground
  - But launch costs have dropped dramatically, especially for big rockets
- For CMB experiments, when are bigger telescopes necessary?
  - Neutrino work (e.g., N_{eff})
  - Secondary anisotropies (e.g., SZ clusters)
  - At low frequencies, to achieve same beam size as smaller telescopes at higher frequencies

    (This has not yet been dealt with in space experiments)

- Advantage ground

Ability To Separate Foregrounds

- Depends on frequency coverage, noise, calibration accuracy
- Decidedly more challenging at low multipoles
  - Need more (all) sky
  - Foreground fluctuations are larger on large scales
- From the ground, observations are limited to a few discrete windows, which do not cover the foreground minimum
- Advantage space

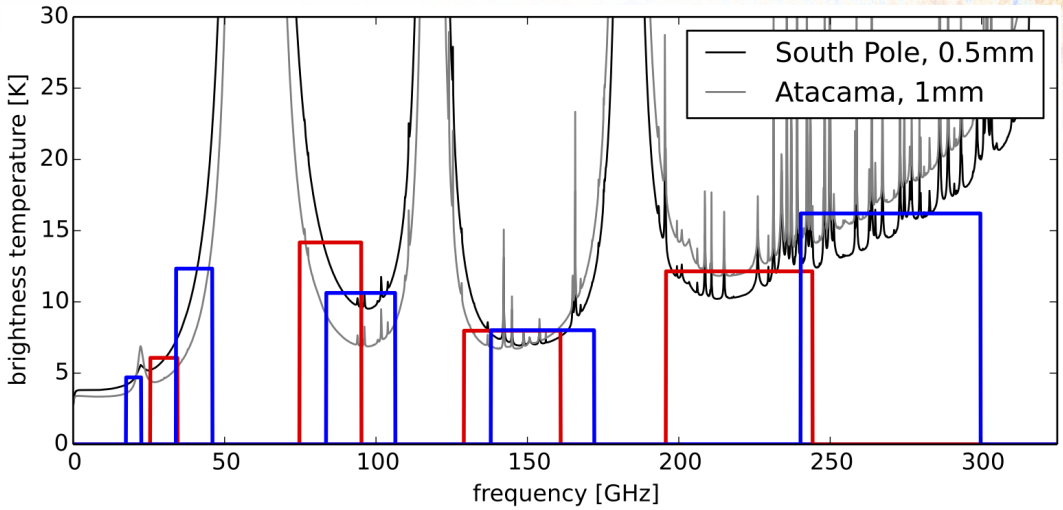
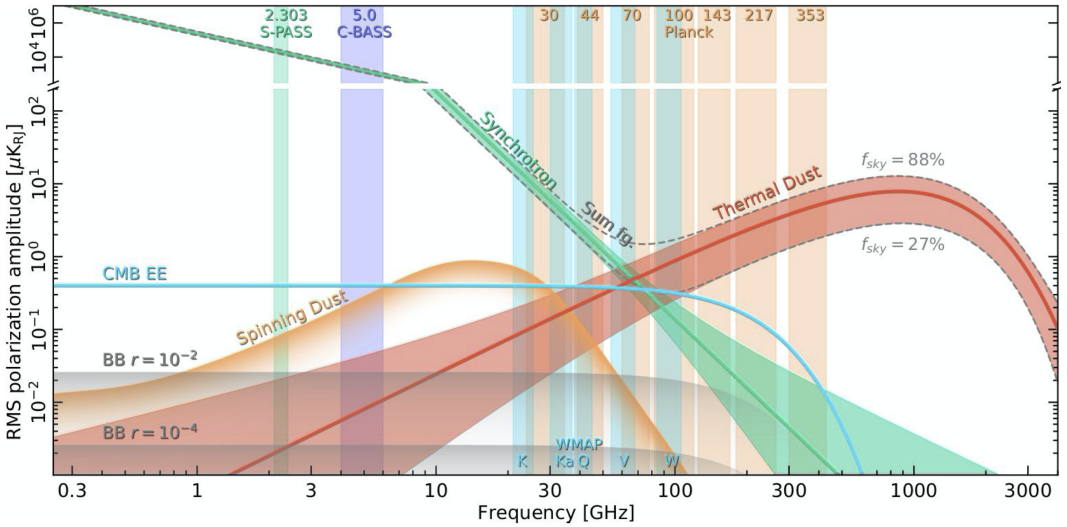


Figure 67. *Calculated atmospheric brightness spectra (at zenith) for the South Pole at 0.5 mm PWV and Atacama at 1.0 mm PWV (both are near median values). Atmospheric spectra are generated using Ref. [563]. The tophat bands are plotted on top of these spectra, with the height of each rectangle equal to the band-averaged brightness temperature using the South Pole spectrum.*

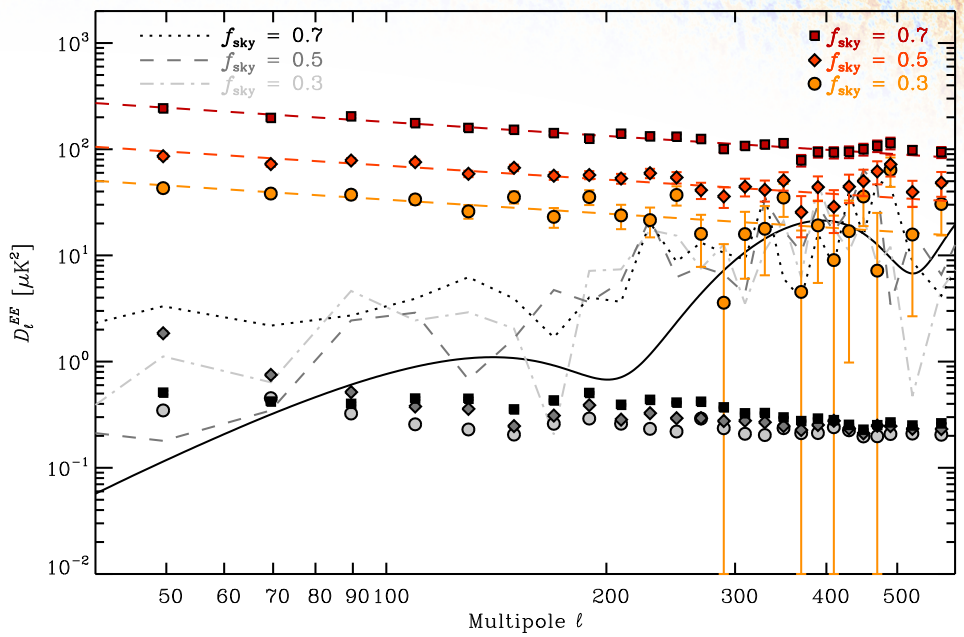
CMB-S4 Decadal Survey Report 2019

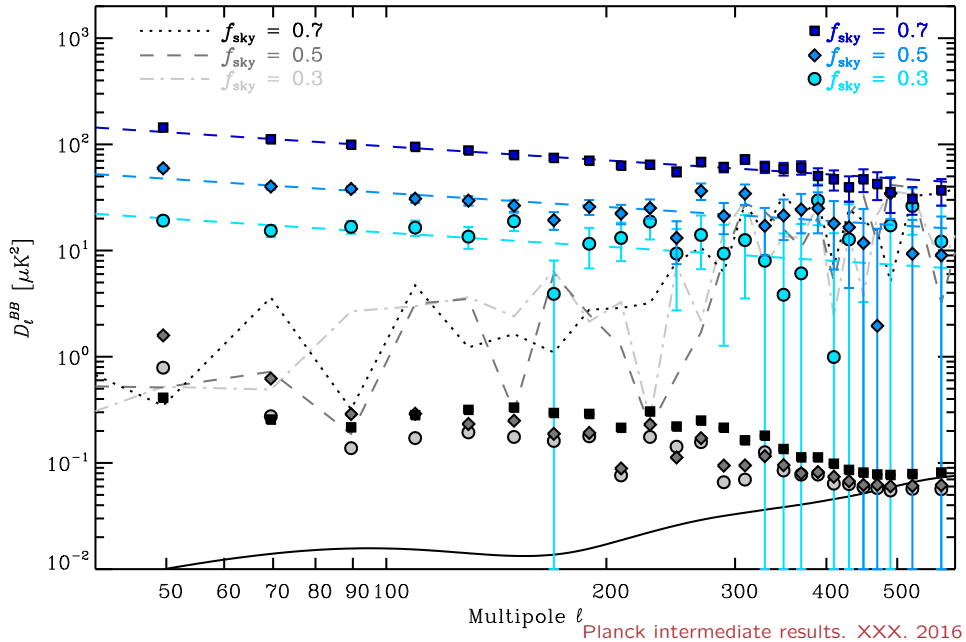


Cosmoglobe project 2020

Foregrounds II

Planck 353 GHz dust power spectra





Planck intermediate results. XXX. 2016

Systematics

space $\equiv L_2$

- Any systematic related to the Sun, Earth (including ground and atmosphere), or Moon is lower or absent in space
- Coverage of the full sky requires multiple sites from the ground, raising many issues
- Anything related to stability and continuity of instrumentation and operations is better in space
- The only drawback of space is the effect of cosmic rays on direct-detection systems

- Advantage space

Other Factors

- Cost and schedule
  - It is more expensive and takes longer to put the "same thing" in space as on the ground
- Ground experiments have historically provided good opportunities for
  - Demonstrating and testing hardware
  - Training of students
- Servicing and repairs are still essentially out of the question in space

Three Science Areas

	r				
	10^{-2}–10^{-3}				
Location	$\ell < 30$	$\ell > 30$	10^{-4}	$N_{\rm eff}$	Clusters
Ground.....	$-$	$+$	$-$	$+$	$+$
Space.....	$+$	$+$	$+$	$+$	\$+\$

Backup on $N_{\rm eff}$

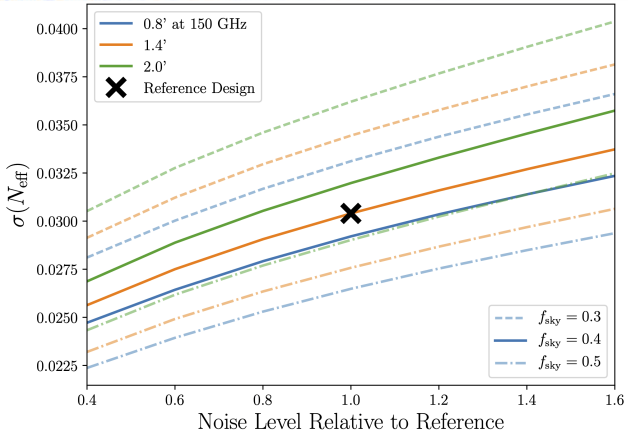


Figure 75. *Impact of changes to the noise level, beam size, and sky fraction on forecasted 1σ constraints on $N_{\rm eff}$ with $Y_{\rm p}$ fixed by BBN consistency. Changes to $f_{\rm sky}$ are taken here at fixed map depth. The forecasts shown in this figure have less detailed modeling of atmospheric effects and foreground cleaning than those shown elsewhere. The results should therefore be taken as a guide to how various experimental design choices impact the constraining power for light relics, but the specific values of the constraints should be taken to be accurate only at the level of about 10%.*

CMB-S4 Decadal Survey Report 2019

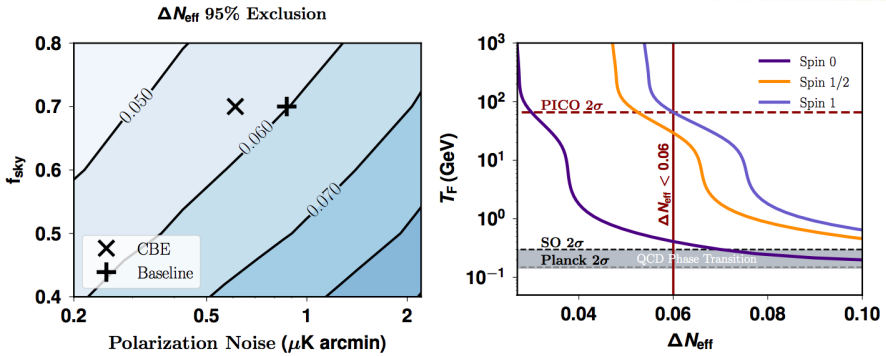


Figure 2.4: PICO will achieve a constraint $\Delta N_{\rm eff} < 0.06\,(95\%)$ (left, 2σ contours shown) in the baseline configuration (cross) using its cosmic-variance-limited measurement of EE for $\ell \leq 2300$, and 21 frequency bands to utilize data over 70% of the sky ($5'$ resolution assumed). This constraint translates to moving up the lowest decoupling temperature T_F for particles with spin 1, 1/2, and 0 by factors of 400, 200, and 6, respectively, relative to *Planck* (right, dashed black, only T_F for vector particles is shown). We also show the projected vector particle limit for the Simons Observatory [35].

PICO Probe Study Report 2019

Summary

- There is much that can be done from the ground, e.g.,
  - r to 10^{-3} or so at $\ell > 30$
  - $N_{\rm eff}$, etc.
  - Cluster science
- Ground will be limited to
  - $\ell > 30$ for $r < 10^{-2}$ or so, with "no chance" of $r \approx 10^{-4}$
- Space ultimately is better for everything, but
  - Costly for high angular resolution

Do what can be done from the ground, from the ground. But for lowest systematics, and to reach the ultimate limits set by foregrounds, space is essential.