Maps to Power Spectra Update

Francis-Yan Cyr-Racine
On behalf of the Maps to Power Spectra working group

CMB-S4 Spring Collaboration Meeting - May 12, 2022

CMB-S4

Overview

- Review of N_{eff} science case.
- DRAFT overview.
  - Instrument and foreground modelling.
  - Internal linear combination and delensing.
- N_{eff} constraints from CHLATs.
  - Improvement after the inclusion of SPLAT.
- Analysis alternatives for N_{eff} measurements:
  - Considering South Pole only.
  - Joint CMB-S4 and Simons Observatory configurations.
    - Chile-only.
    - Chile + South Pole.
- Beam updates.

N_{eff} Definition and Neutrino Contribution

- N_{eff} probes the abundance of non-photon radiation in the Universe

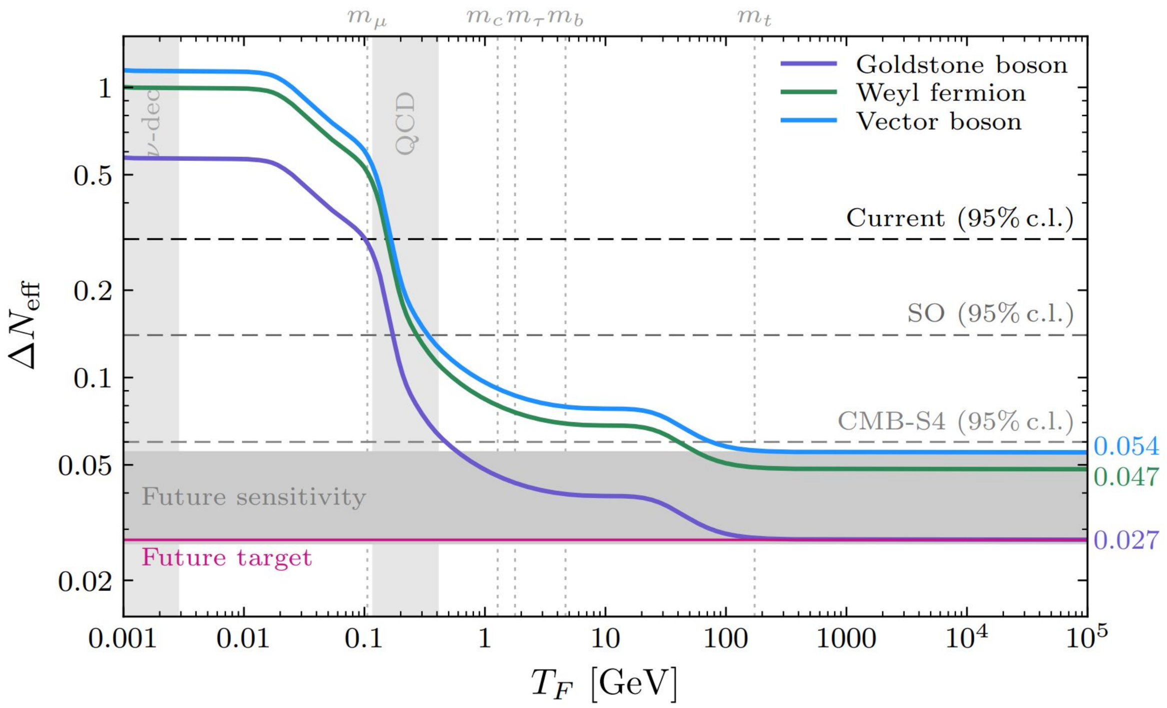
$$\rho_r = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)$$

- The contribution from Standard Model neutrinos is

$$N_{\rm eff}^{\rm SM} = 3.044(1)$$

Escudero Abenza (2020); Akita, Yamaguchi (2020); Froustey, Pitrou, Volpe (2020); Bennett, et al (2021)

Thermal Relics Set N_{eff} Targets



Wallisch (2018); Green, Amin, Meyers, Wallisch, et al (2019); Dvorkin, Meyers, et al (2022)

N_{eff} Impacts CMB Damping Scale

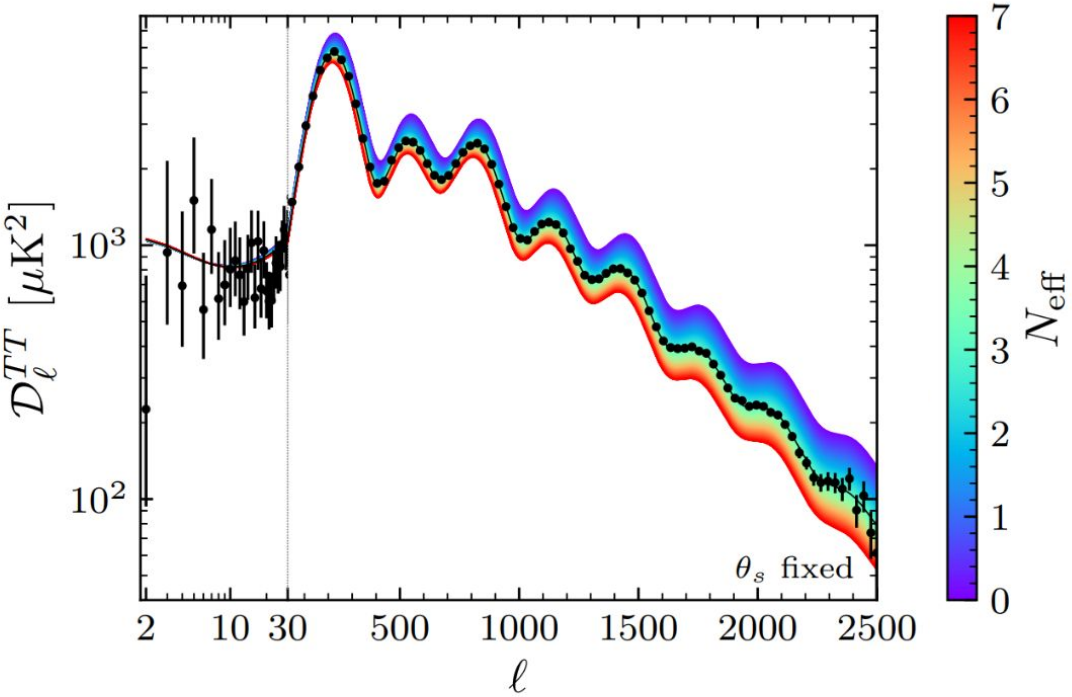
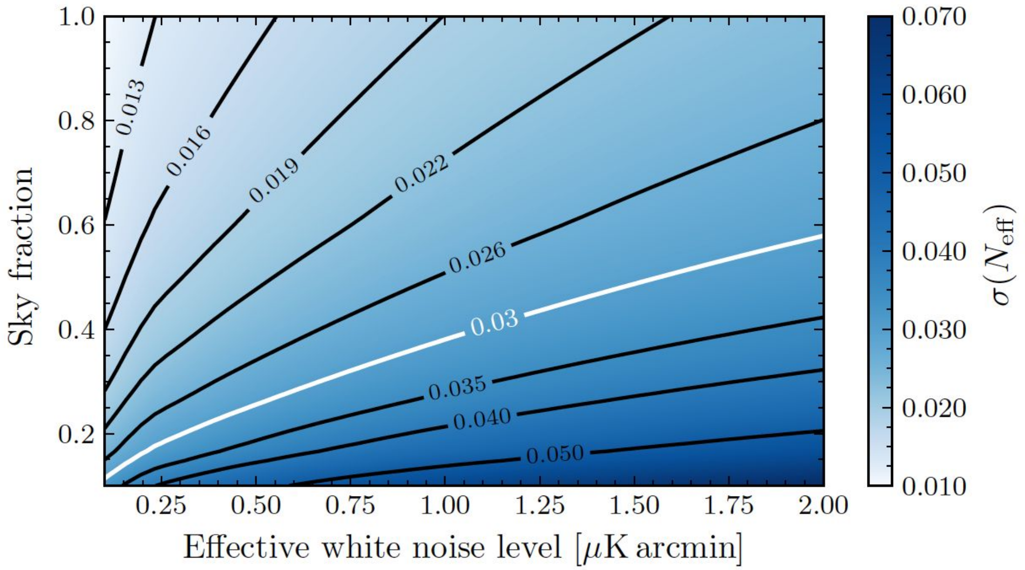


Figure credit: Wallisch (2018)

Measurement of N_{eff} Favors Wide Survey



PBDR Figure 10: Motivating higher f_{sky}

DRAFT summary

DRAFT: Dark Radiation Anisotropy Flowdown Team

Srini Raghunathan
Benjamin Wallisch
Joel Meyers
Cynthia Trendafilova

Inputs:

1. Instrument: Bands/beams/noise levels.
2. Foreground modelling:
   a. Galactic.
   b. Extragalactic.
3. Footprint.

Intermediate:

1. (Spectral) ILC noise curves.
2. Lensing reconstruction noise.
3. Delensed spectra.
4. Lensing: Iterative QE.

Outputs:

1. Cosmological constraints.
   a. Statistical.
   b. Systematic biases.

❖ Github repository: https://github.com/sriniraghunathan/CMB-S4_DRAFT

DRAFT summary

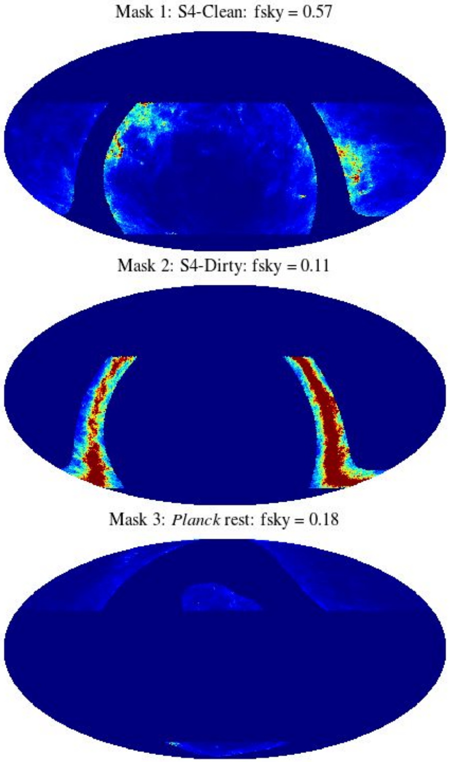
Inputs (Chilean LATs):

- **Bands:** 27, 39, 93, 145, 225 and 278 GHz
- **Noise and Beams:** PBDR values.
- **Nominal observation years:** 7 years.
- **Footprint:** fsky = 0.68 using a minimum observing elevation=40 degrees.
    - Split into **clean (fsky = 0.57)** and **dirty (fsky = 0.11)** regions.
- **Extragalactic foregrounds:** Radio, CIB, tSZ and kSZ power spectra from SPT measurements.
- **Galactic foregrounds:** Dust and Synchrotron power spectra obtained from pySM3 simulations.

Note: We also include *Planck* and information from the delensing LAT (configuration `V3R025`).

Frequency (GHz)	27	39	93	145	225	278
$\theta_{\rm FWHM}$ (arcmin)	7.4	5.1	2.2	1.4	1.0	0.9
Δ_T (μK-arcmin)	21.34	11.67	1.89	2.09	6.9	16.88
$\ell^T_{\rm knee}$	415	391	1932	3917	6740	6792
α_T	3.5	3.5	3.5	3.5	3.5	3.5
Δ_P (μK-arcmin)	30.23	16.53	2.68	2.96	9.78	23.93
$\ell^P_{\rm knee}$	700	700	700	700	700	700
α_P	1.4	1.4	1.4	1.4	1.4	1.4

N_{eff} constraints - CHLATs + *Planck* + SPLAT



S4/*Planck* masks overlayed on galactic dust emission at 145 GHz.

Mask	Sky fraction f_{sky}	σ(Neff)
S4-Clean	0.57	**0.0327**
S4-Dirty	0.11	0.0815
S4-Wide (Clean + Dirty)	0.57 (S4-Clean), 0.11 (S4-Dirty)	0.0303
S4 + *Planck*	0.57 (S4), 0.18 (*Planck*)	0.0324
S4 + Planck + SPLAT	0.54 (CHLAT), 0.18 (*Planck*), and 0.03 (SPLAT)	~0.03

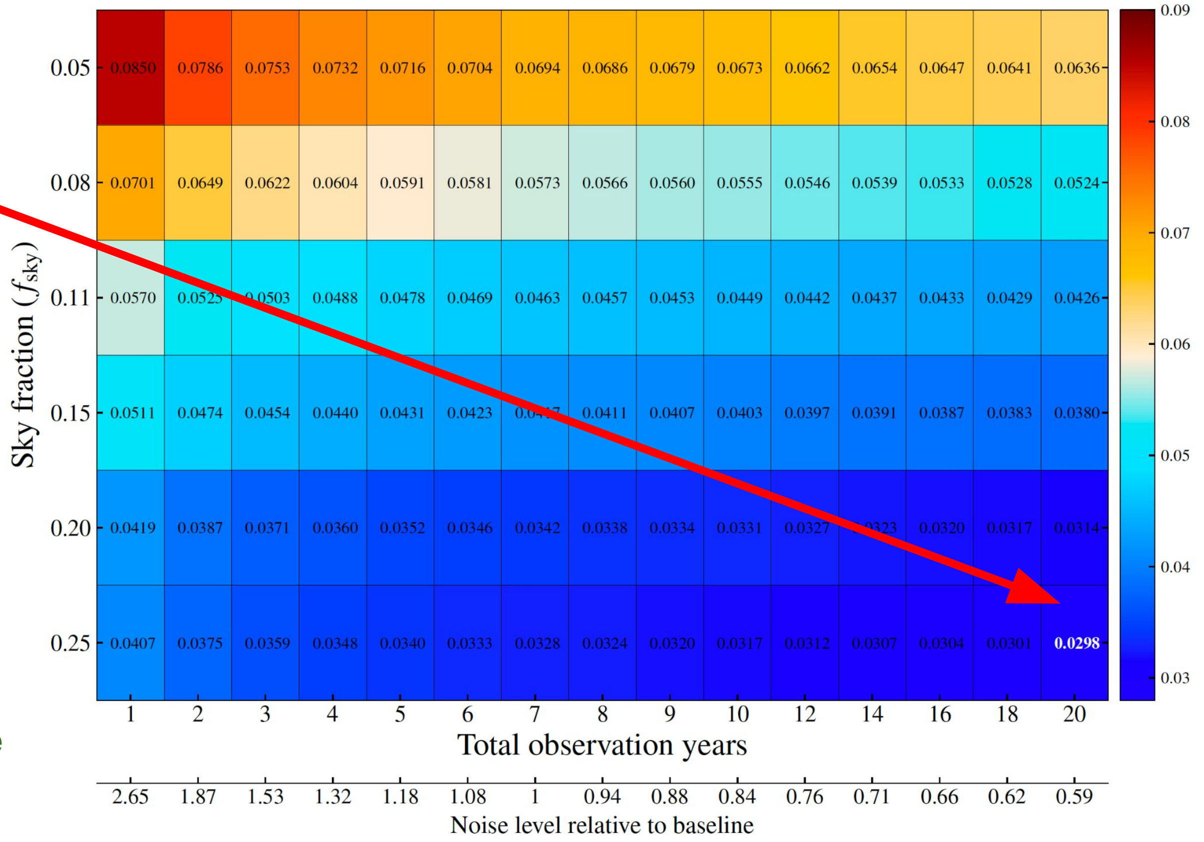
- S4-Clean: delensed S4+*Planck* TT/EE/TE + lensing: $2 \leq \ell \leq 5000$.
  - Here *Planck* is added to S4-CMB data using inverse variance weighting. This helps to remove the S4 1/f noise.
- S4-Dirty: delensed S4 TT/EE/TE + lensing: $30 \leq \ell \leq 5000$.
- *Planck:* TT/EE/TE + lensing: $2 \leq \ell \leq 2500$.
- **Note:** Common sky fractions removed when adding multiple experiments as that introduces covariance between datasets.

CMB-S4

N_{eff} constraints - South Pole-only option

Analysis alternatives: ***South-Pole only N_{eff} constraint is bad,*** ***which is not surprising:***

- Target achieved when we observe f_{sky} = 0.25 from the South Pole for roughly 20 years.
  - Nominal = 7 years.
  - *f_{sky} = 0.25 is the maximum observable sky from the Pole assuming a minimum observable el= 30 degrees.*
- **Equivalent to x25 more effort compared to PBDR (one SPLAT).**
- **6m Crossed-Dragone vs 5m Three-mirror anastigmat telescope designs does not matter.**

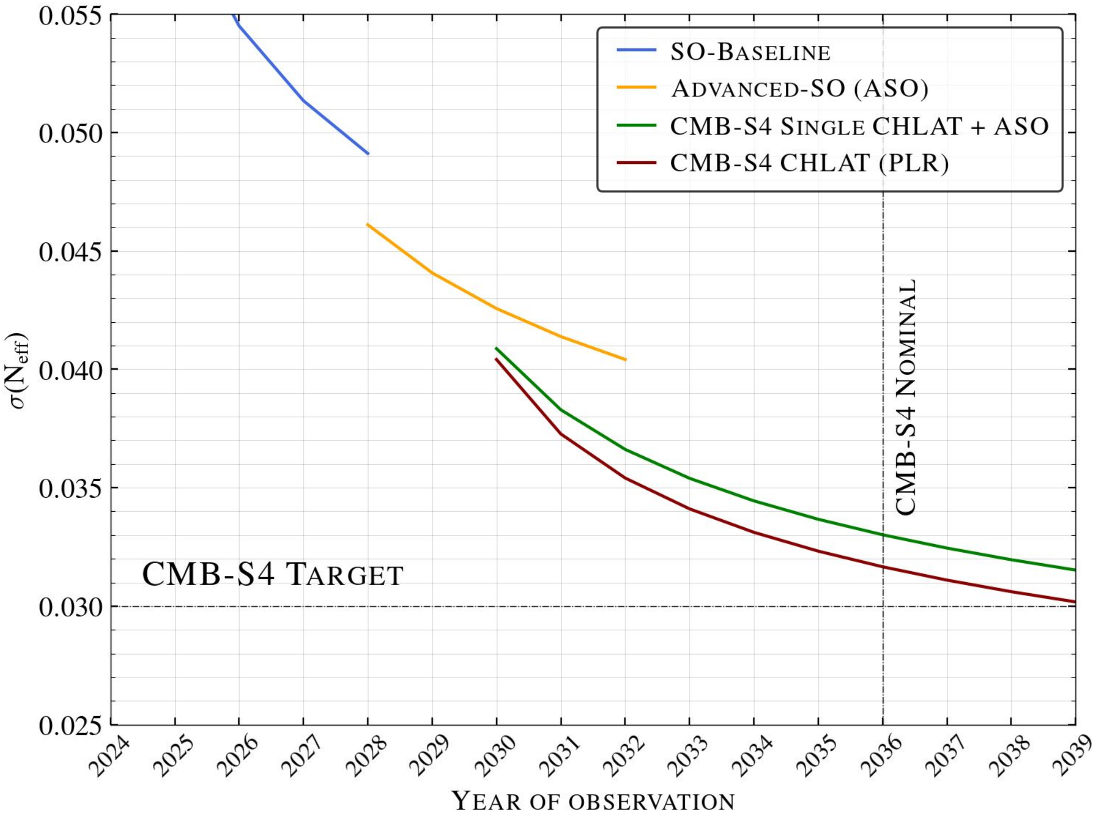


CMB-S4

N_{eff} constraints: CMB-S4 + Advanced SO

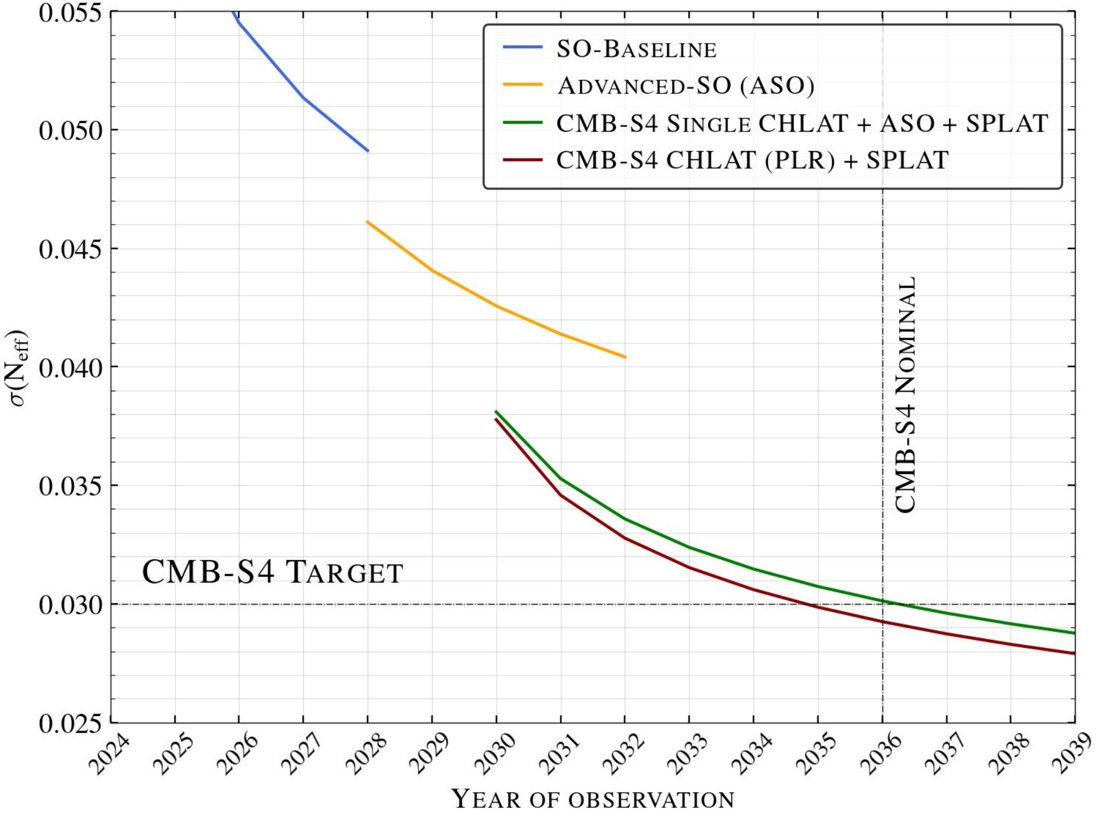
- The other analysis alternative is to replace one of the CMB-S4 Chilean LAT by the Advanced Simons Observatory (ASO) LAT.
- In the following slides we will compare constraints from:
  - **SO-Baseline (4 years of observation).**
  - **Advanced SO (5 years of observation: 2028 start).**
  - **CMB-S4 Single CHLAT + Advanced SO (+ SO-Baseline).**
  - **Nominal CMB-S4 PBDR or PLR configuration (2 CMB-S4 CHLATs).**
  - **Adding CMB-S4 SPLAT to the above configurations.**
- **Note:**
  - *The SO noise levels are not exactly the same as in SO overview paper but a scaled version to include differences in sensitivities.*
  - *SO forecasts assume the same sky fraction as CMB-S4 (f_{sky} = 0.57 ignoring the region with high galactic emissions).*

N_{eff} constraints: CMB-S4 + Advanced SO



- **f_{sky} = 0.57 for both SO and CMB-S4.**
- All curves include SO-Baseline.

N_{eff} constraints: CMB-S4 + Advanced SO



- **f_{sky} = 0.54 for both SO and CMB-S4.**
- **f_{sky} = 0.03 for SPLAT.**
- All curves include SO-Baseline.

Beams and neutrino science

- B(eam)asics $T^{\rm obs}(\hat{n}) = \int d\hat{n}' B(\hat{n},\hat{n}') T(\hat{n}') + \text{noise}$ $\quad$ $\text{Beam deconvolved power spectra} = C_\ell + \frac{N_\ell}{B_\ell^2}$
- Mean beam (e.g. DSR S4 forecast)

Daniel Grin
Frankie Silvers
FYCR

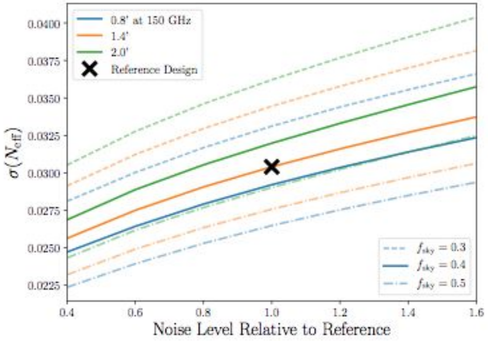


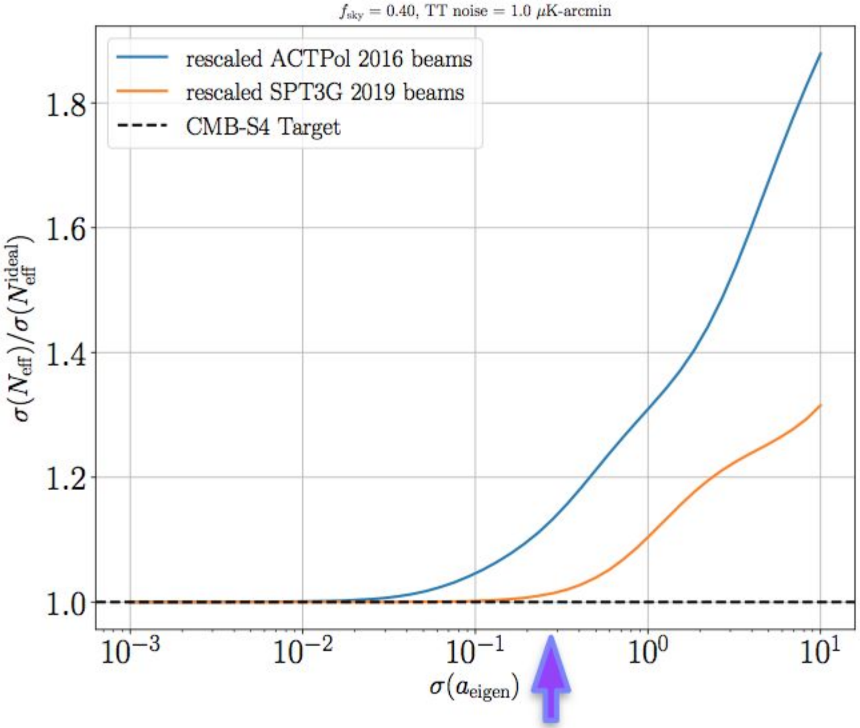
Figure 75. *Impact of changes to the noise level, beam size, and sky fraction on forecasted 1σ constraints on $N_{\rm eff}$ with Y_p fixed by BBN consistency. Changes to $f_{\rm sky}$ are taken here at fixed map depth. The forecasts shown in this figure have less detailed modeling of atmospheric effects 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%.*

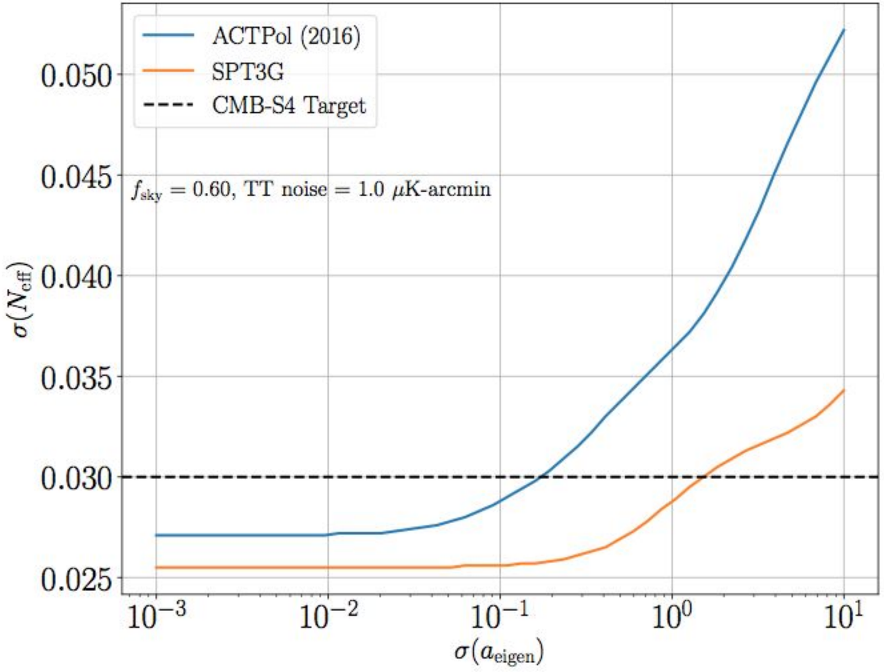
$\theta_{\rm FWHM}$ from arXiv:1907.04473

- Standard model $N_{\rm eff} = 3.045$ — fraction from decoupling details, e. g. 1606.06986

CMB-S4

Hypothetical S4 with 3G/ACTPol-`like' beams



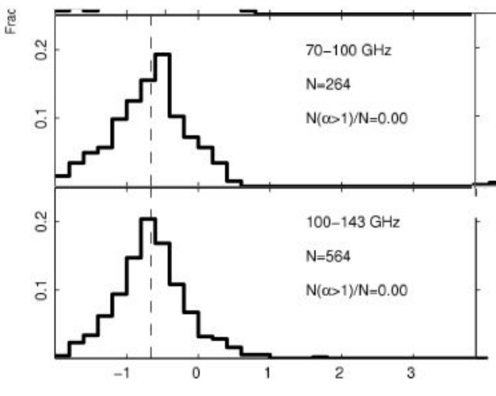


Rough improvement needed in beam uncertainties to hit science targets

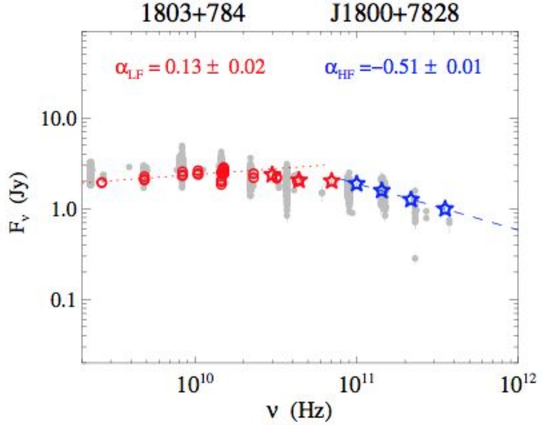
plots here by D.G. and F. C-R.

Spectra of point-source beam calibrators: $I_\nu \propto \nu^\alpha$

from *Ade et al. 2013, A&A V571, 2014*



from Aatrokoski A& A, V536, 2011

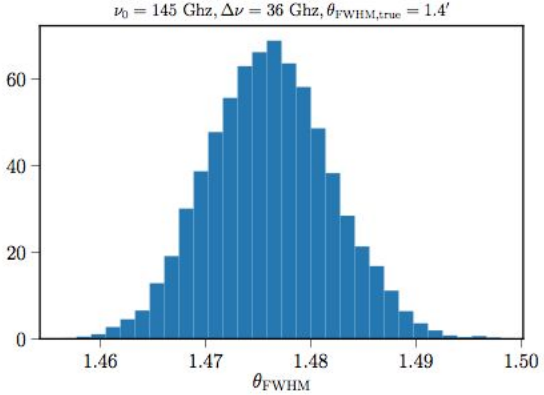


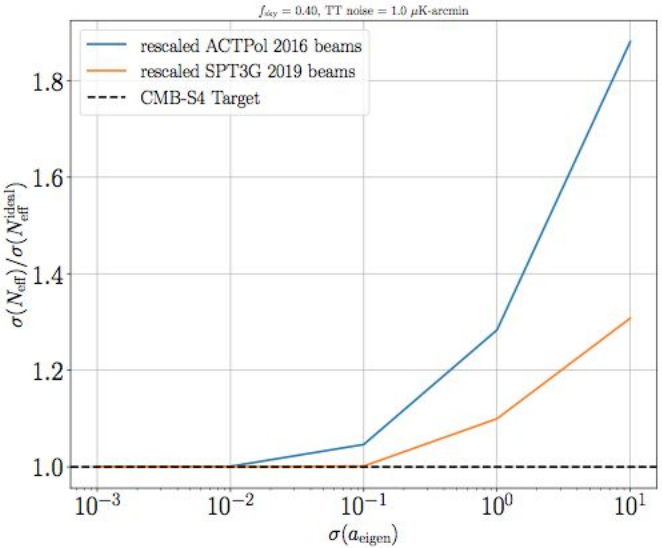
- Beams used are from point sources (AGN, synchrotron), signal of interest is thermal
- Diffraction freq. dep. variation in beams: $\theta_{\rm FWHM} \propto 1/\nu$
- Calibration beam $\neq$ CMB beam

on-thermal point-source beam calibrators: *Preliminary* results

- Diffraction—

$$B(\theta) \to B\left[\theta\left(\frac{\nu}{\nu_c}\right)\right] \qquad \delta B(\theta) = \int_{\nu_c-\Delta\nu/2}^{\nu_c+\Delta\nu/2} d\nu\,[f_\alpha(\nu) - f_{\rm BB}(\nu)]\,B\left(\theta\frac{\nu}{\nu_c}\right)$$





More on non-thermal point-source beam calibrators—

140 GHz preliminary results

F. Silvers senior thesis
(Haverford College)

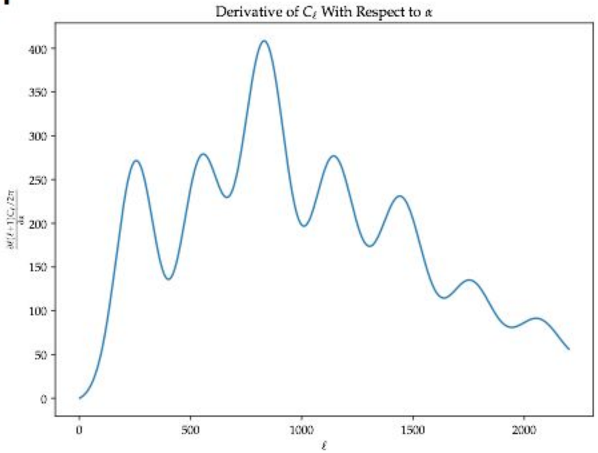
- Harmonic transform of change in beam given by

$$\delta B_\ell = \sum_n B_n \int_{\nu_c-\Delta\nu/2}^{\nu_c+\Delta\nu/2} g_{\ell n}(\nu)\Delta f_\alpha(\nu)d\nu,$$
$$g_{\ell n}(\nu) \equiv \int P_n\left[\cos(\theta)\right] P_\ell \left[\cos\left(\theta\frac{\nu}{\nu_c}\right)\right] \sin\theta d\theta,$$
$$\Delta f_\alpha(\nu) = f_\alpha(\nu) - f_{\rm BB}(\nu).$$

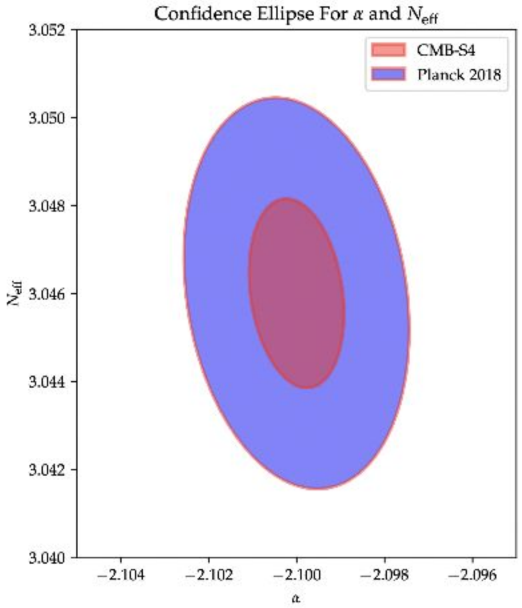
$$\frac{dC_\ell^{\rm XY}}{d\alpha} = \sum_n B_n \int_{\nu_c-\Delta\nu/2}^{\nu_c+\Delta\nu/2} d\nu g_{\ell n}(\nu) h_\alpha(\nu) d\nu,$$

$$h_\alpha = df_\alpha/d\alpha$$

TT



Preliminary TT-only results with 2-param Fisher matrix



— no prior (self-calibration of PS index from CMB)
— other degeneracies likely change story

Conclusions

- Chile-only: We do not hit the target. σ(Neff) = 0.0327.
  - Adding SPLAT takes us pretty close to the target 0.03.
- Analysis alternatives:
  - Pole-only option: Requires x25 more effort compared to the PBDR configuration to reach the target.
  - CMB-S4 + Simons Observatory:
    - Replacing one of the CMB-S4 CHLAT with Advanced SO LAT degrades the constraint at the end of 7 years by ~5 per cent.
    - Excluding SO-Baseline degrades the CMB-S4 constraint by ~2 per cent at the end of 7 years.
    - **SPLAT is required to hit the target in all cases as noted before.**
- Beam updates:
  - Non-thermal calibration point sources can bias the CMB beam.
  - Detailed Fisher forecasts are under way to understand this better.
- Systematics biases:
  - Biases due to unmodelled galactic residuals seem to be important and we are currently exploring multiple options to mitigate them.

Back up slides

$\sigma(N_{eff})$ constraints: $f_{sky} = 0.57$

Total years	SO-Baseline	Advanced-SO		CMB-S4 Single CHLAT + Advanced-SO		CMB-S4 CHLATs (PLR)	
		No SO	With SO	No SO	With SO	No SO	With SO
1	**0.0704**	0.0597	**0.0461**	0.0462	**0.0419**	0.0433	**0.0404**
2	**0.0596**	0.0514	**0.0441**	0.0409	**0.0389**	0.0386	**0.0373**
3	**0.0545**	0.0475	**0.0426**	0.0383	**0.0370**	0.0363	**0.0354**
4	**0.0513**	0.0451	**0.0414**	0.0367	**0.0357**	0.0347	**0.0341**
5	**0.0491**	0.0433	**0.0404**	0.0354	**0.0347**	0.0336	**0.0331**
6	-	-		0.0345	**0.0339**	0.0327	**0.0323**
7	-	-		0.0337	**0.0332**	0.0320	**0.0317**