Design Validation: Measurement to Science - Light Relics
Systematic studies: beam effects

Daniel Grin (Haverford)/Francis-Yan Cyr-Racine (UNM)
Maps to Power Spectra Working Group
+ *T. Crawford, A. Crites, N. Goeckner-Wald, D. Green, J. Meyers, S. Raghunathan, C. Reichardt…*
+ *useful conversations with R. B. Partridge*

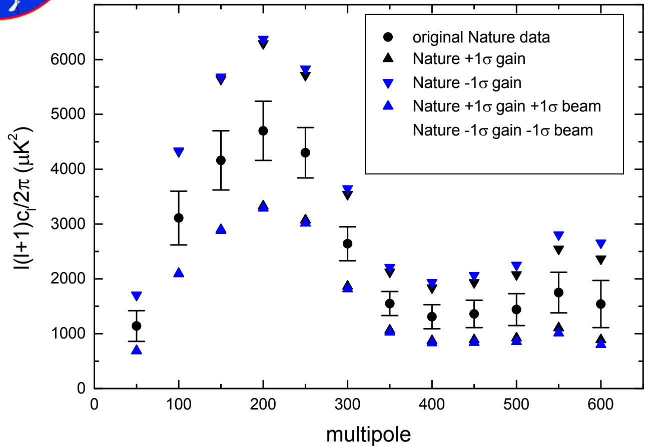
building on past efforts by Calabrese, van Engelen Green, Meyers 5/2017 +Green, Crawford, Hasselfield, van Engelen 8/2017

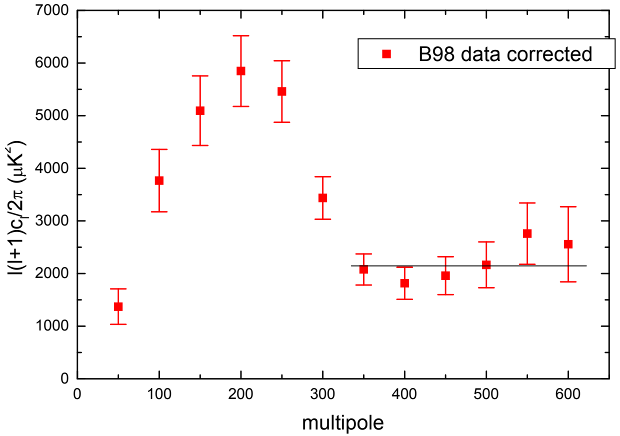
CMB-S4 Spring Collaboration Meeting - March 11th, 2021

CMB-S4

You shouldn't beam at the history of this topic …

Boomerang and the second acoustic peak ….





Telescope pointing jitter and change in effective beam by 2'!

P. de Bernardis *et al.* Nature 404, 955–959 (2000), presentation slides from P. de Bernardis

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)

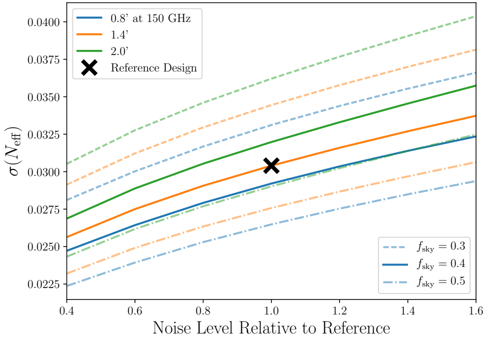


Figure 75. *Impact of changes to the noise level, beam size, and sky fraction on forecasted 1σ constraints on $N_{\rm eff}$ with $Y_{\rm p}$ fixed by BBN consistency. Changes to $f_{\rm sky}$ are taken here at fixed map depth. The forecasts shown in this figure have less detailed modeling of atmospheric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

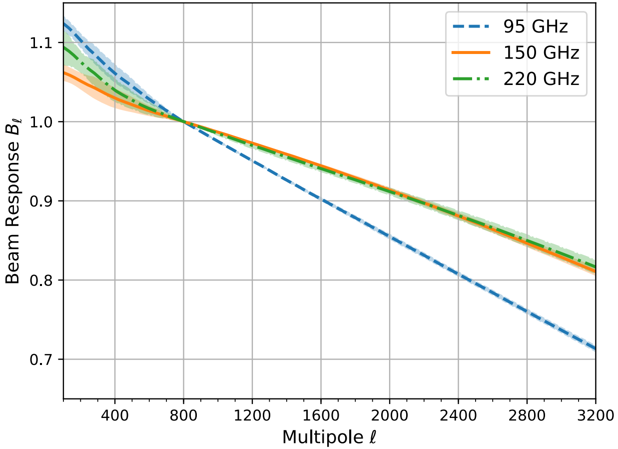
$\theta_{\rm FWHM}$ from arXiv:1907.04473

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

ACT/SPT-3G beams

- Roughly a Central Gaussian with ~$1/\theta^3$ sidelobe

Dutcher et al. 2021 (2018 data)



from Choi et al. 2020, 2007.07289, Aiola et al. 2020, 2007.07288

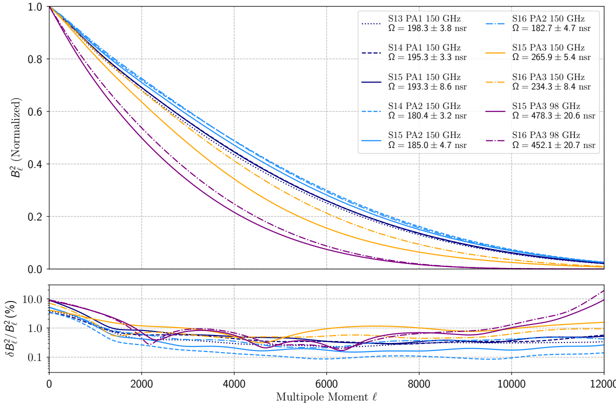


FIG. 2.— Window functions for the mean *instantaneous* beam of each array and band in each season. The window functions used for interpretation of the survey maps are slightly modified to account for residual pointing variance in the observations contributing to each map. The window function errors shown in the bottom panel are strongly correlated between multipoles.

- SPT Beams calibrated using brightest QSOs and dedicated planetary obs. *Dutcher et al. 2021, arxiv: 2101.01684, techniques of Schaffer et al. 2011, Story et al. 2013, Crites et al. 2015*

- Beam error driven by residual atmospheric noise in planetary flux, fitting noise, CMB fluctuations, + others…
- FWHM of ~1.0’ at 150 Ghz (~target for S4-LATS), **~1% uncertainty**

Beam uncertainty as a nuisance parameter

- Beam parameters can be treated as other parameters for Fisher forecasting purposes

$$C_\ell^{\rm map} = C_\ell^{\rm theory} B_\ell^2 + N_\ell \rightarrow \hat{C}_\ell^{\rm theory} = \left\{ 1 - \frac{2\delta B_\ell}{B_\ell} \right\} C_\ell^{\rm theory}$$

- Beam expanded in terms of eigen-modes of beam covariance:

$$\delta B_\ell = \sum_i a_i f_\ell^i \qquad \Sigma_{\ell\ell'} \equiv \langle \delta B_\ell \delta B_{\ell'} \rangle$$

- Fisher analysis with beam uncertainty folded in —

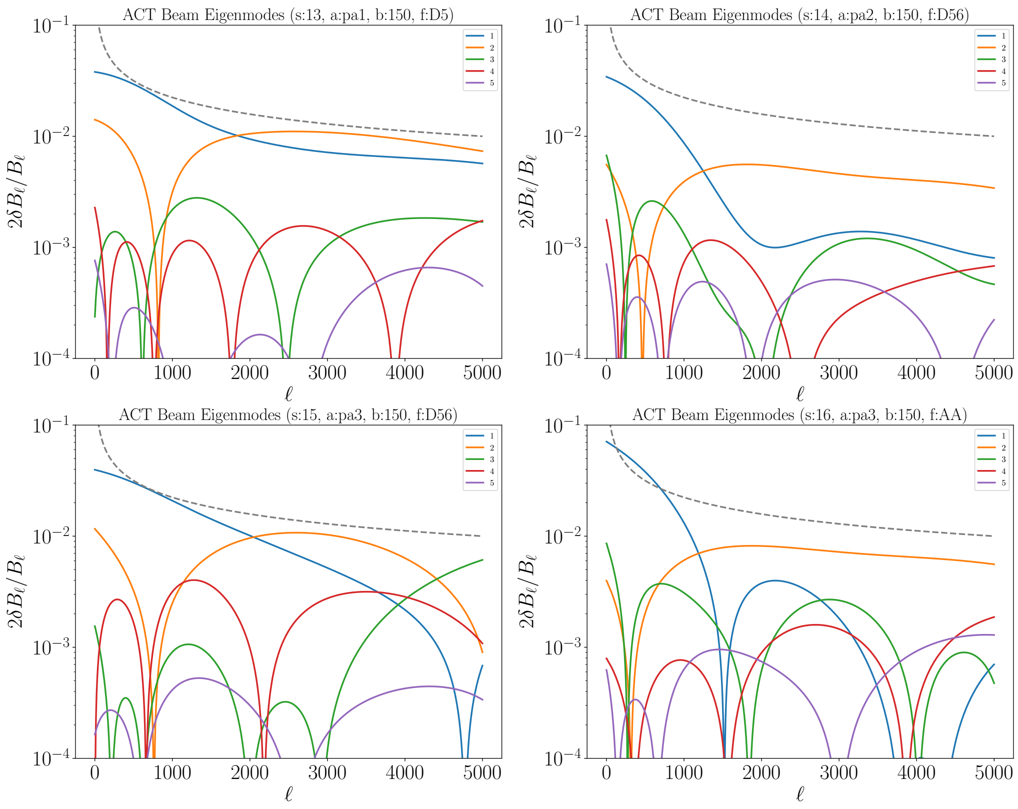
$$\vec{\theta} = \{\Omega_c h^2, \Omega_b h^2, A_s, n_s, N_\nu, \tau, H_0\} \rightarrow \{\Omega_c h^2, \Omega_b h^2, A_s, n_s, N_\nu, \tau, H_0, [a_1, ..., a_n]\}$$

$$F_{\alpha\beta}^{\rm use} = F_{\alpha\beta} + \frac{\delta_{\alpha\beta}}{\sigma_{i=\alpha}^2}$$

Forecasts done with modified Fisher module from DRAFT tool, S. Raghunathan
https://github.com/sriniraghunathan/cmbs4_fisher_forecasting

- Explore SPT/ACTPol type beams, with better uncertainties

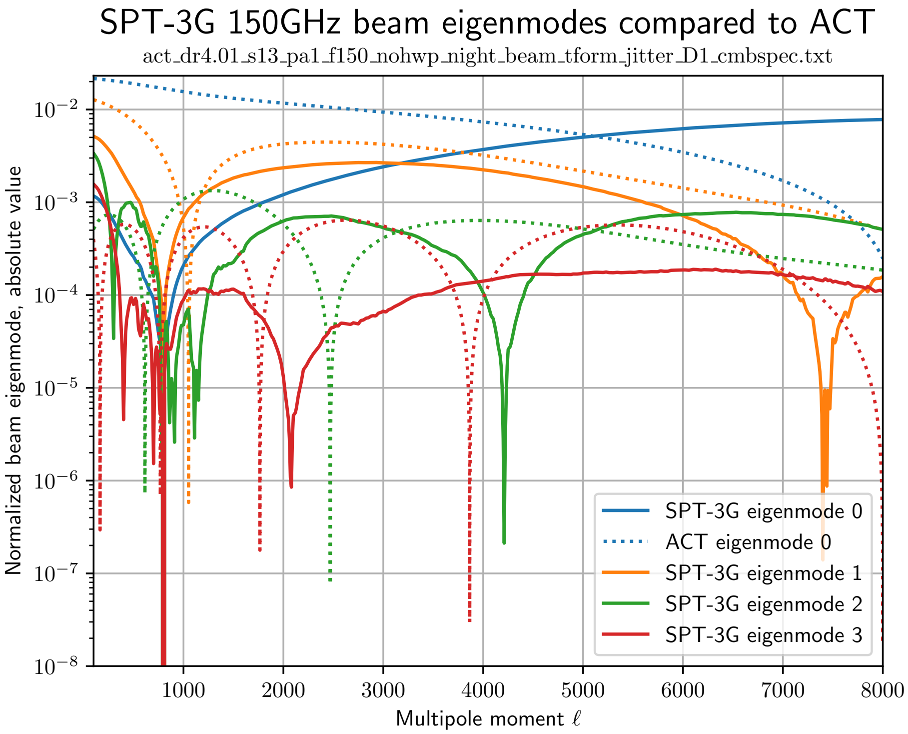
Seasonal/detector/field driven beam variations



- Beam data products from https://lambda.gsfc.nasa.gov/product/act/actpol_prod_table.cfm

ACT — 2008-2018 data, 2020 papers

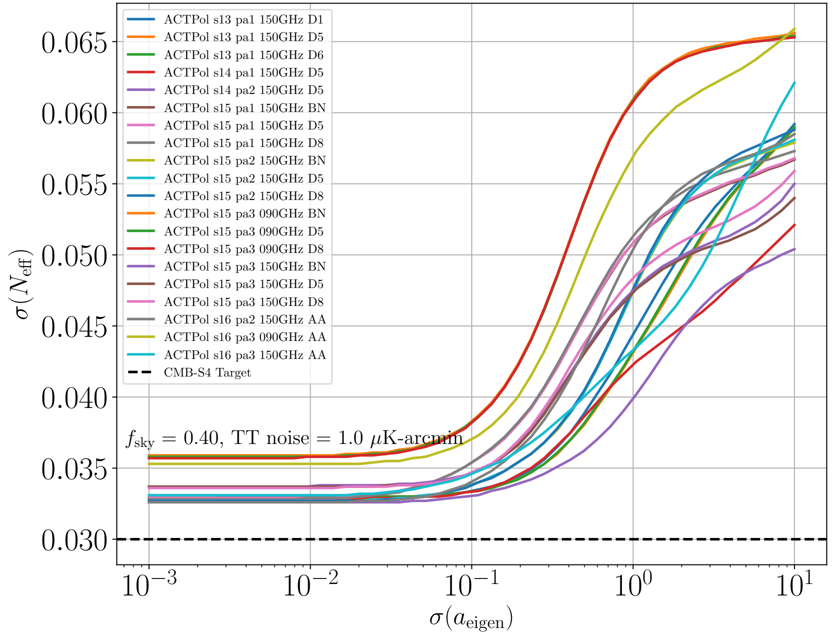
Ongoing efforts have noticeably different eigenmodes: *(3G vs. ACTPol)*

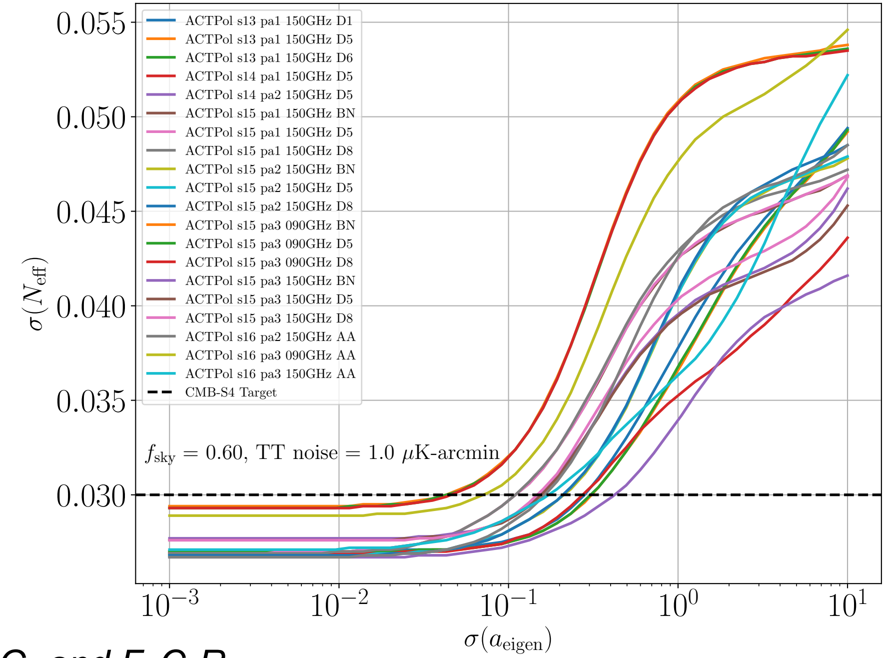


- Preliminary beams provided for analysis by SPT-3G collaboration

- *Eigenmode Plot by N. G-Wald, F. Cyr-Racine*

Seasonal/detector/field driven beam variations- effect on N_{eff}

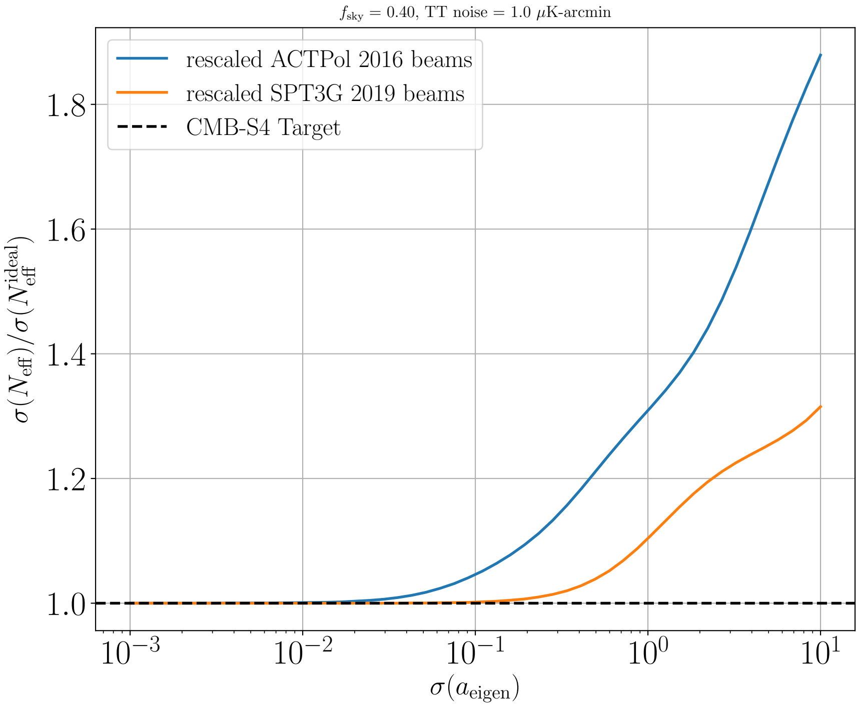


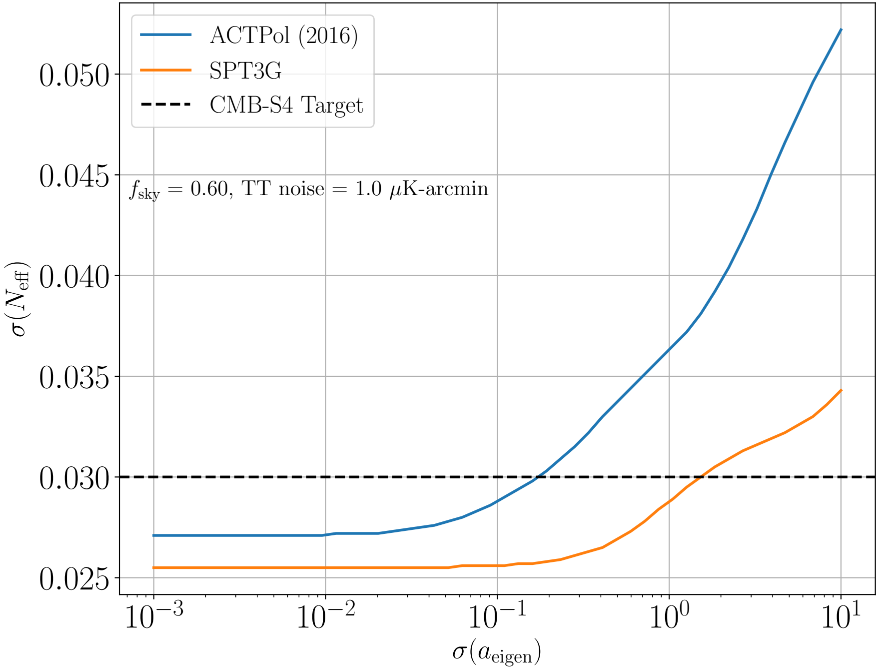


plots here by D.G. and F. C-R.

- Normalization chosen so that $\{\sigma_i = 1\}\,\forall i \rightarrow$ reproduces fiducial experimental error

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





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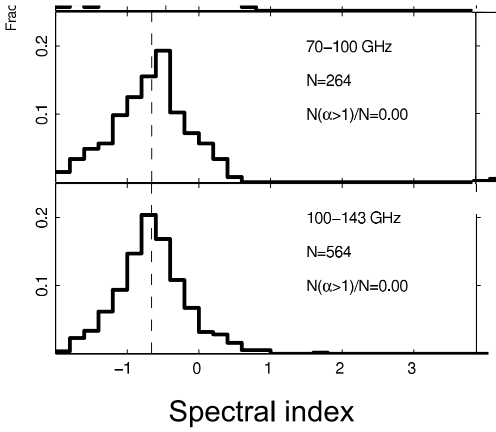
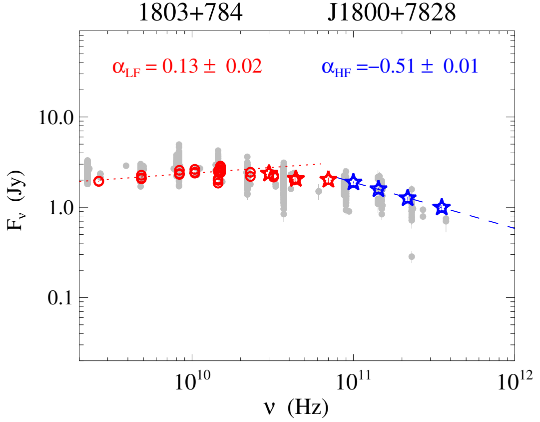
Spectra of point-source beam calibrators

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: $\theta_{\mathrm{FWHM}} \propto 1/\nu$

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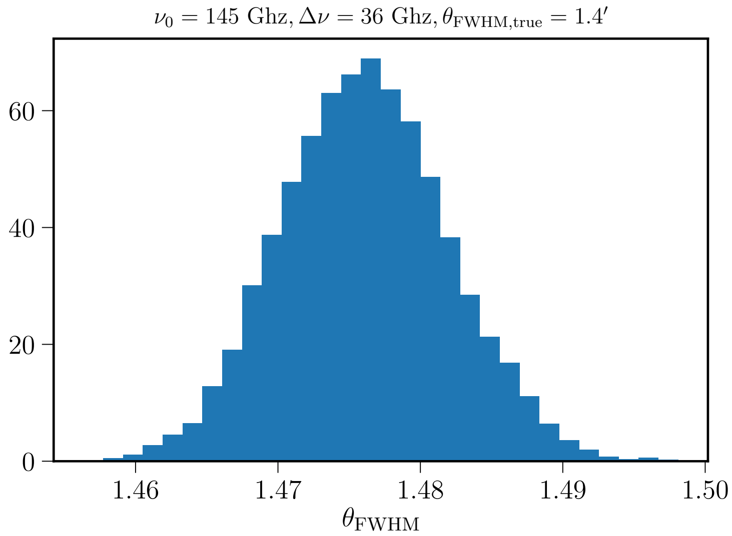
Impact of non-thermal point-source beam calibrators: *Preliminary* results

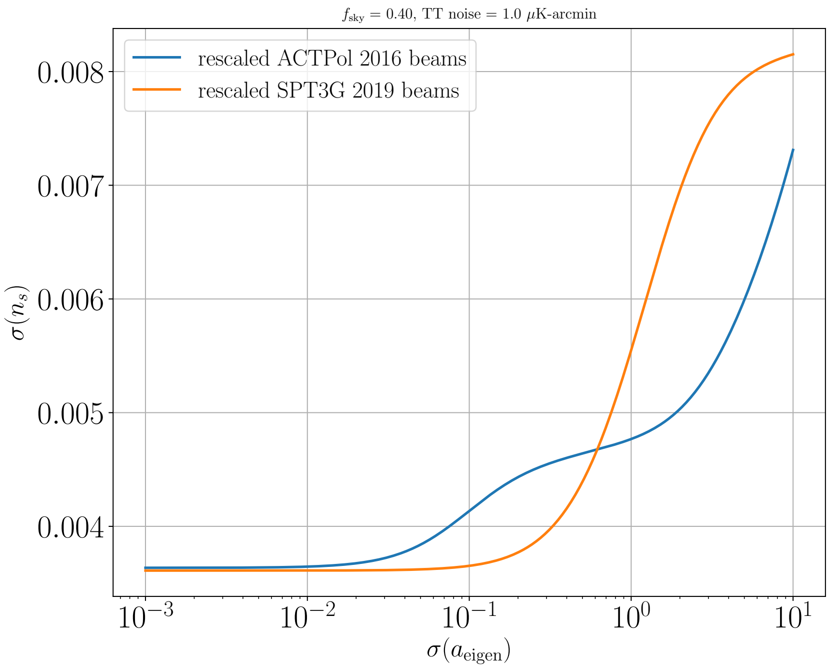


- Next step - fold into cosmological parameter sensitivity forecasting

Take-aways and next steps…

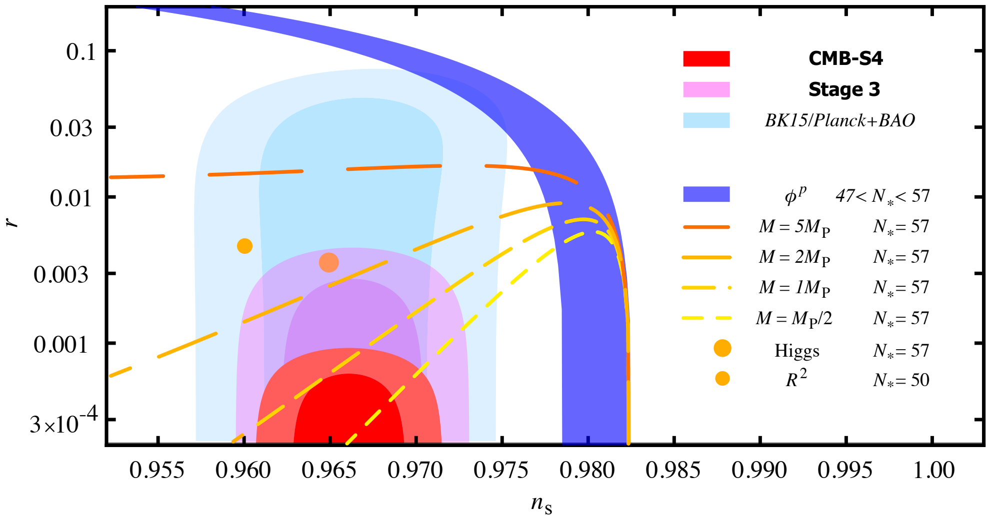
- Moderate (factor of 3-10) improvement in beam calibration needed to meet hot relic science goals
- *More realistic follow-up:* Use DRAFT tool to run full sky cut, secondary, point source, parameter forecasts, “observe” with different beams used sampling from existing eigenmodes with varying prior
- Explore additional effects - Non-thermal source calibration, Jitter-convolved beams, temperature-polarization leakage

Other science targets (inflation, primordial power spectrum)



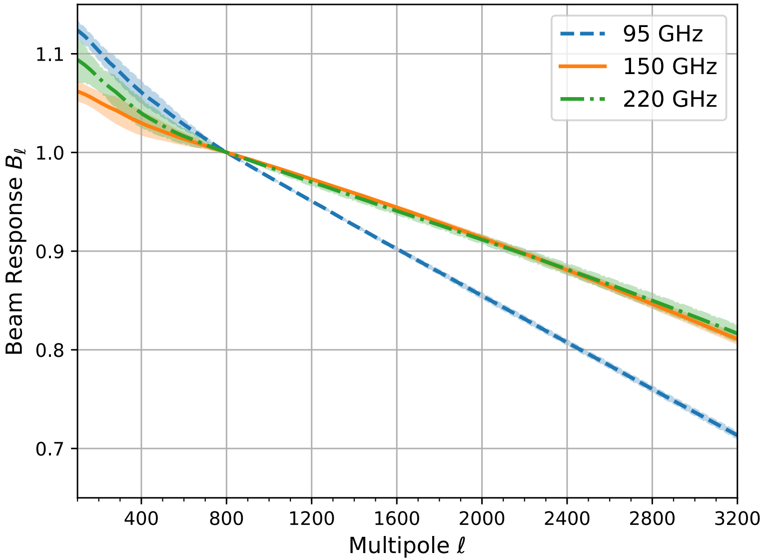
plots here by D.G. and F. C-R.

✳ *More generally ….*



arXiv:1907.04473

SPT-3G beam calibration



- *Dutcher et al. 2021 (2019 data)*

- Roughly a Central Gaussian with ~$1/\theta^3$ sidelobe
- Beams calibrated using brightest QSOs in the 1500 deg^2 field and five dedicated Mars observations (2018), convolved with pointing jitter. *Dutcher et al. 2021, arxiv: 2101.01684, applying stitching technique of Schaffer et al. 2011, Story et al. 2013, Crites et al. 2015*
- Beam error driven by residual atmospheric noise in planetary flux, fitting noise, CMB fluctuations, + others…
- FWHM of 1.0’ at 90 Ghz, 1.4’ at 150 Ghz, 1.2’ at 220 GhZ (~target for S4-LATS), **1.5% uncertainty**

Beams and neutrino science

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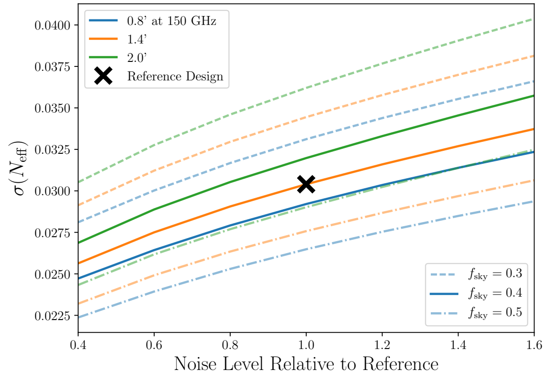

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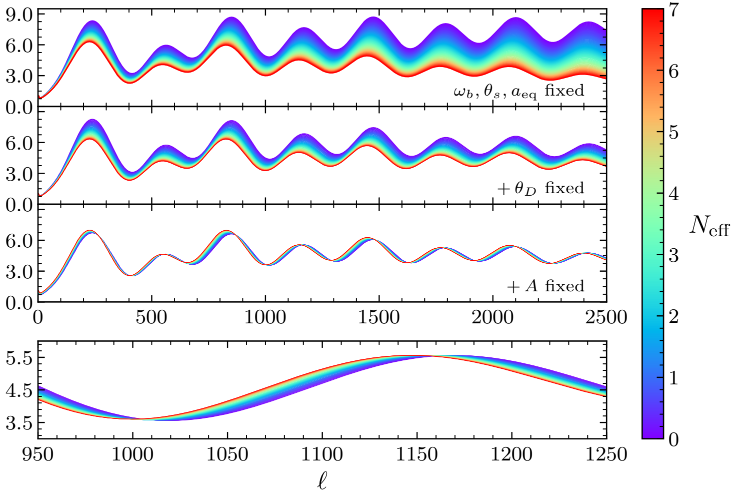

Wallisch 2018, 1810.02800

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

Mean beams but not beam errors included in DSR forecasts, even though beam covariance enters any real-life data analysis (e.g. SPT-3G 2020, ACTPol 2020)

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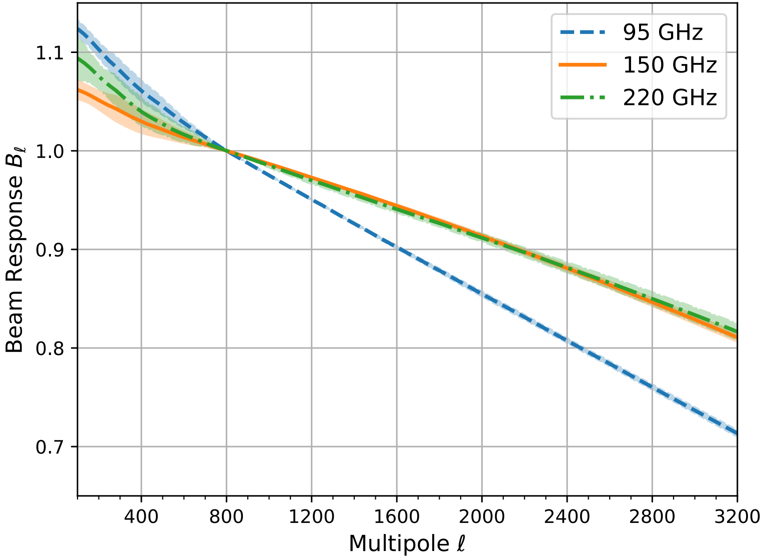
SPT-3G beam calibration



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ACTPol beam calibration

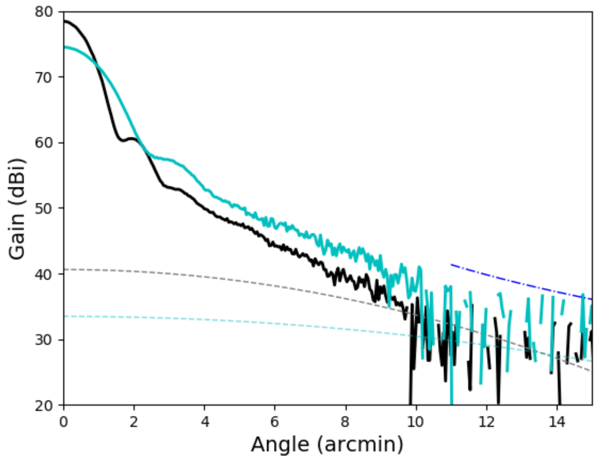

FIG. 1.— The average 98 GHz (cyan) and 150 GHz (black) beam profiles in "gain above isotropic" $(4\pi/\Omega_B)$. The forward gains are 74.5 and 78.4 dBi respectively. The two dashed curves on the bottom show the scattering beam due to the surface roughness. For reference, the blue dash-dot line, offset for clarity, shows the slope of a $1/\theta^3$ profile. Negative values due to noise fluctuations are not plotted.

- Roughly a Central Gaussian with ~ $1/\theta^3$ sidelobe
- Observations of Uranus, Saturn
- Aiola et al. 2020, JCAP 12/2020, Choi et al. 2020, JCAP 12/2020, Louis + 2016, Hasselfield 2013
- FWHM of 1.4' at 140 Ghz (~target for S4-LATS)

Past collaboration work

- Calabrese, van Engelen Green, Meyers 5/2017

$$B_\ell = e^{\ell(\ell+1)\sigma^2\{b_1+b_2(\ell/3000)+b_3(\ell/3000)^2\}}$$

Point-source secondaries

$$D_\ell^{\mathrm{TT,ps}} \simeq 6\left(\frac{\ell}{3000}\right)^2 (\mu\mathrm{K})^2$$

$$D_\ell^{\mathrm{EE,ps}} \simeq 3\times10^{-3}\times D_\ell^{\mathrm{TT,ps}}$$

Atmospheric noise

$$N_\ell^{\mathrm{TT}} \to N_\ell^{\mathrm{TT}}\left[1+\left(\frac{l}{3400}\right)^{-4.7}\right]$$

$$N_\ell^{\mathrm{EE}} \to N_\ell^{\mathrm{EE}}\left[1+\left(\frac{l}{340}\right)^{-4.7}\right]$$

- Green, Crawford, Hasselfield van Engelen 8/2017

using ACT 2013 eigenmodes