Improving constraints on primordial B-modes by measuring high frequency polarisation

Eiichiro Komatsu (Max Planck Institute for Astrophysics), April 8, 2020

The question to answer

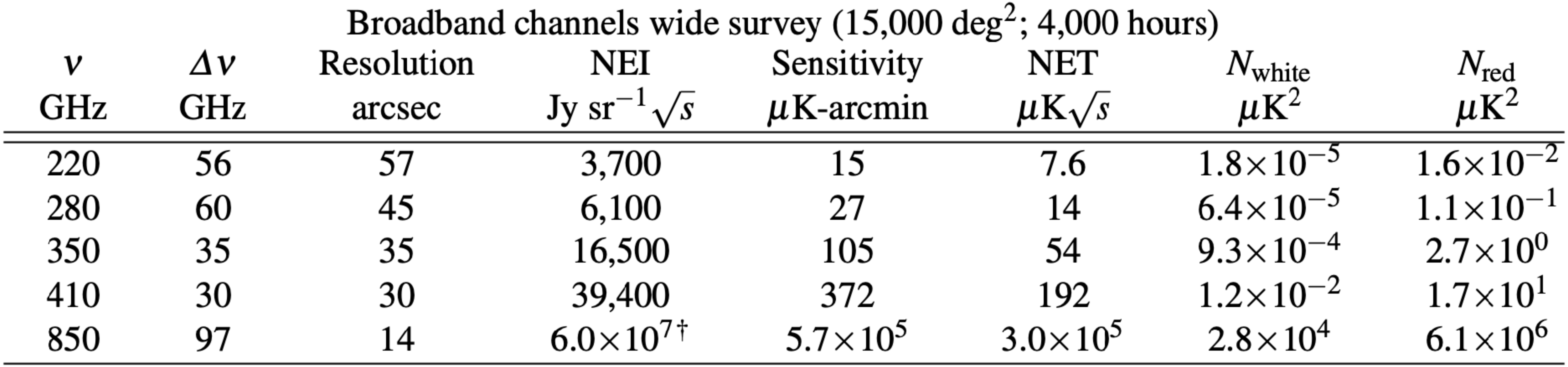
(But I don’t have an answer yet)

- *How much would CCAT-prime data at* ***225, 280, 350, 410 and 850 GHz*** *help improve cleaning dust for Simons Observatory’s Small Aperture Telescope (SAT)?*
  - Why SO? Because the time scale is similar and we are working together

Input data

CCAT-prime sensitivity

- CCAT-prime sensitivity is taken from Table 1 of the JLT paper (Choi et al.)



Broadband channels wide survey (15,000 deg^2; 4,000 hours)

ν GHz	$\Delta\nu$ GHz	Resolution arcsec	NEI Jy sr$^{-1}\sqrt{s}$	Sensitivity μK-arcmin	NET μK$\sqrt{s}$	N_{white} μK^2	N_{red} μK^2
220	56	57	3,700	15	7.6	1.8×10^{-5}	1.6×10^{-2}
280	60	45	6,100	27	14	6.4×10^{-5}	1.1×10^{-1}
350	35	35	16,500	105	54	9.3×10^{-4}	2.7×10^{0}
410	30	30	39,400	372	192	1.2×10^{-2}	1.7×10^{1}
850	97	14	$6.0\times10^{7\dagger}$	5.7×10^{5}	3.0×10^{5}	2.8×10^{4}	6.1×10^{6}

- Temperature sensitivity (uK arcmin) will be **multiplied by sqrt(2)** for polarisation sensitivity
- **Will also try a 4 times deeper survey**, i.e., fsky=0.4 -> 0.1 and N_{white} -> $N_{\mathrm{white}}/4$, to see a trade off (SO-SAT's survey is fsky=0.1)

Input data

CCAT-prime sensitivity

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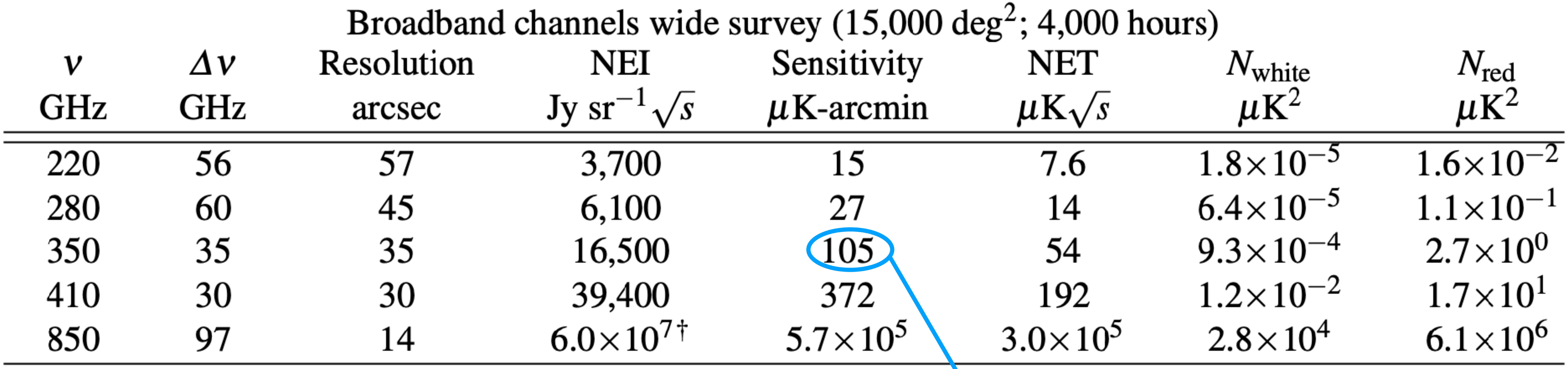

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~1/4 of Planck HFI

Input data

SO sensitivity

- SO-SAT and LAT sensitivities are taken from “**baseline**” in Table 1 of the “Science Goals and Forecasts” paper (1808.07445v2)

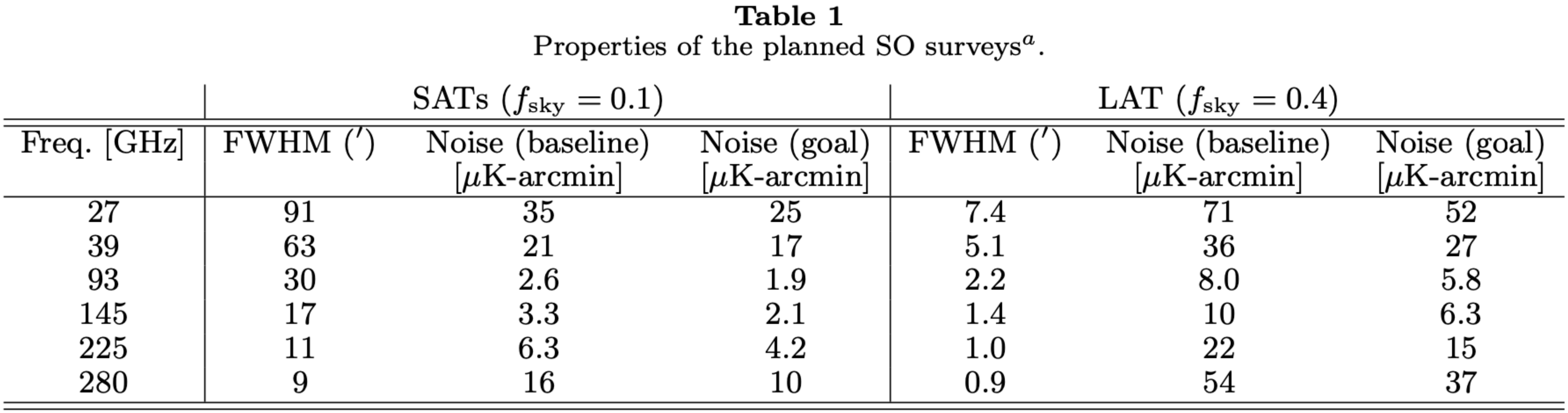


Table 1

Properties of the planned SO surveys^a.

	SATs ($f_{\mathrm{sky}} = 0.1$)			LAT ($f_{\mathrm{sky}} = 0.4$)		
Freq. [GHz]	FWHM ($'$)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]	FWHM ($'$)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
27	91	35	25	7.4	71	52
39	63	21	17	5.1	36	27
93	30	2.6	1.9	2.2	8.0	5.8
145	17	3.3	2.1	1.4	10	6.3
225	11	6.3	4.2	1.0	22	15
280	9	16	10	0.9	54	37

Input data

Model for noise power spectrum with 1/f

- For CCAT-prime and SO-LAT, the noise power spectrum is given by

$$N_\ell = N_{\rm red}\left(\frac{\ell}{\ell_{\rm knee}}\right)^{\alpha_{\rm knee}} + N_{\rm white}.$$

$$= \left[\left(\frac{\ell}{700}\right)^{-1.4} + 1\right] N_{\rm white}$$

- For SO-SAT, use information given in Table 2 of the forecast paper

Input data

Model for B-mode dust polarisation power spectrum

- B-mode dust polarization power spectrum is given by

$$\frac{\ell(\ell+1)C_\ell^{BB,d}}{2\pi} = A_{d,353}\left(\frac{\ell}{80}\right)^{\alpha_d}\left[\frac{g(\nu)}{g(353)}\left(\frac{\nu}{353}\right)^{\beta_d+1}\frac{\exp(h\cdot 353/k_B T_d)-1}{\exp(h\nu/k_B T_d)-1}\right]^2$$

$$A_{d,353} = 4.6\ \mu\mathrm{K}^2 \quad \text{(In BICEP2 patch, BICEP2/Keck Array collab, 2018)}$$

$$\alpha_d = -0.4, \quad \beta_d = 1.6, \quad T_d = 19.6\ \mathrm{K}$$

$$g(\nu) = (e^x-1)^2/(x^2e^x), \quad \text{with } x = h\nu/(k_B T_{\mathrm{CMB}})$$

- **Will also try 10x more dust power,** A$_d$=46 uK^2, to be more representative of fsky=0.4

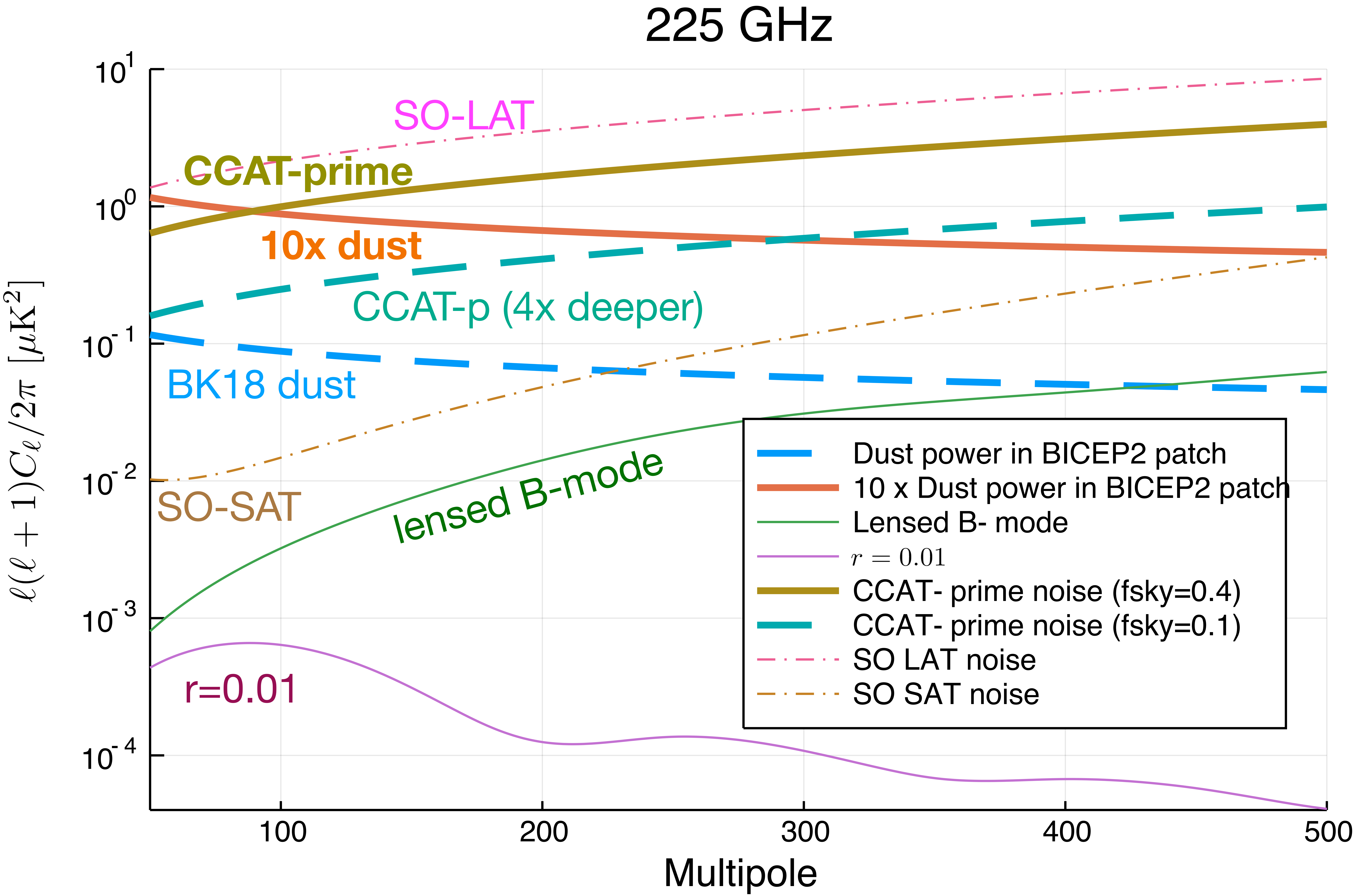
Input data

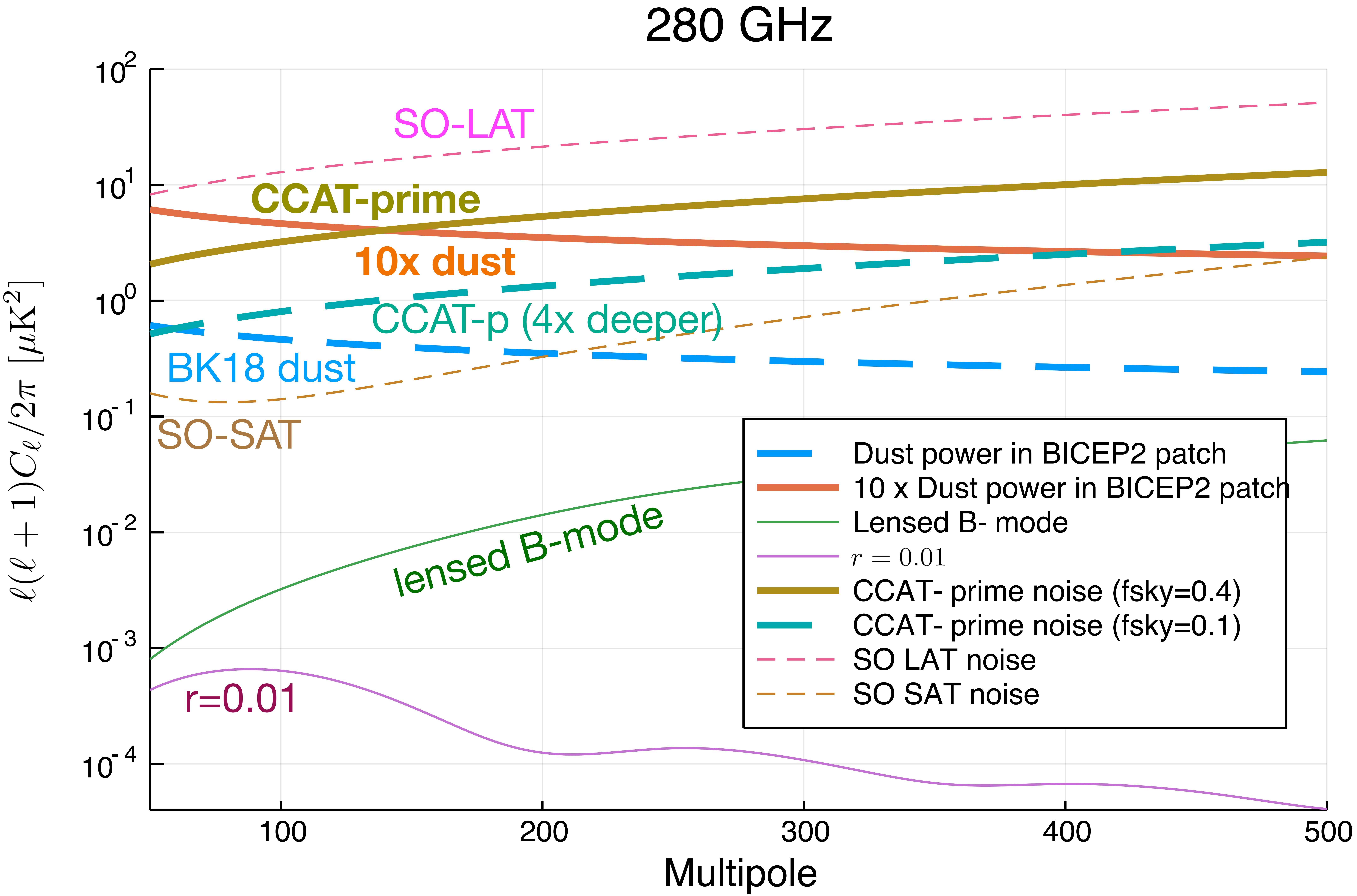
Power spectrum error

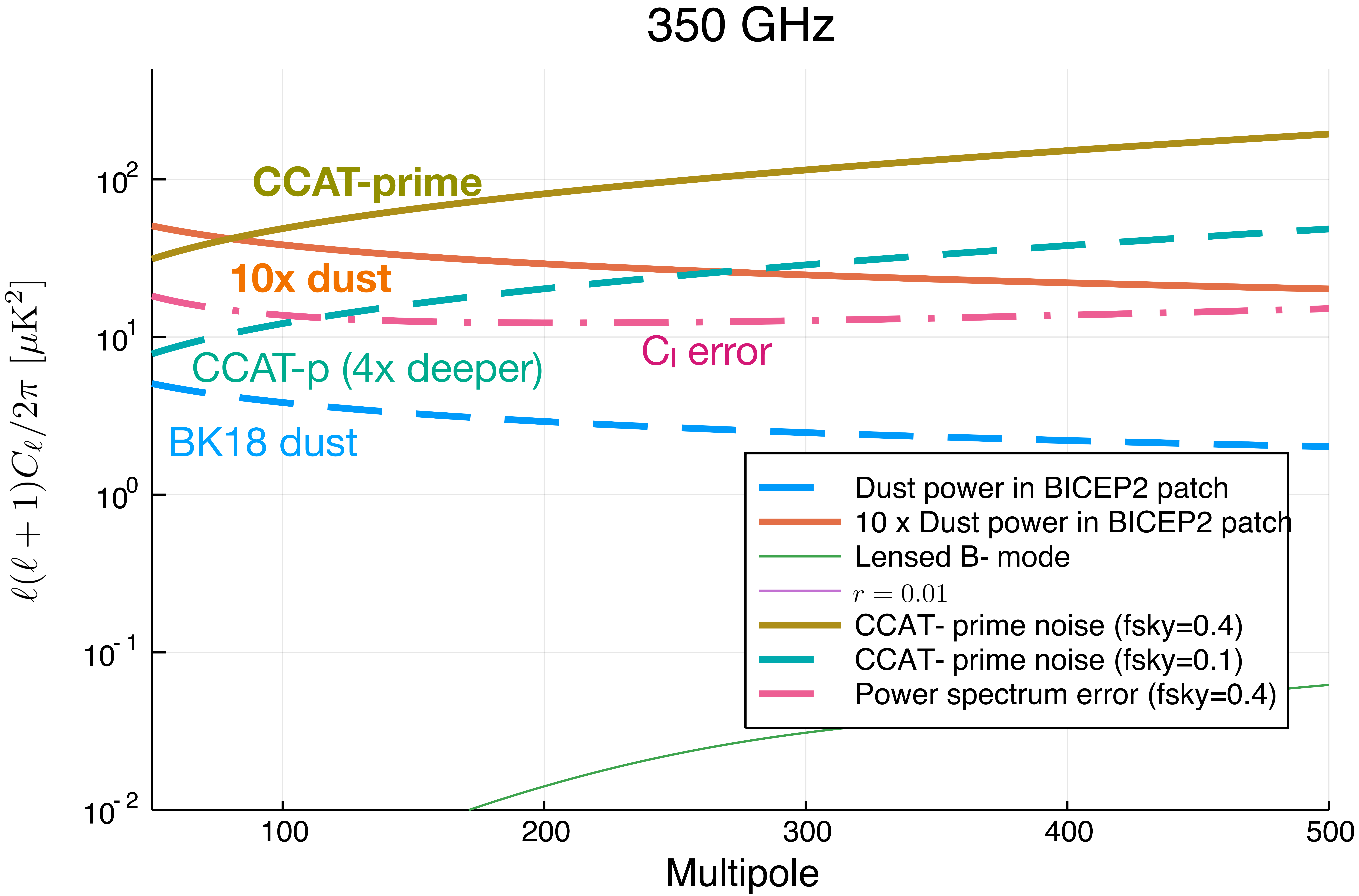
- The power spectrum error is given by

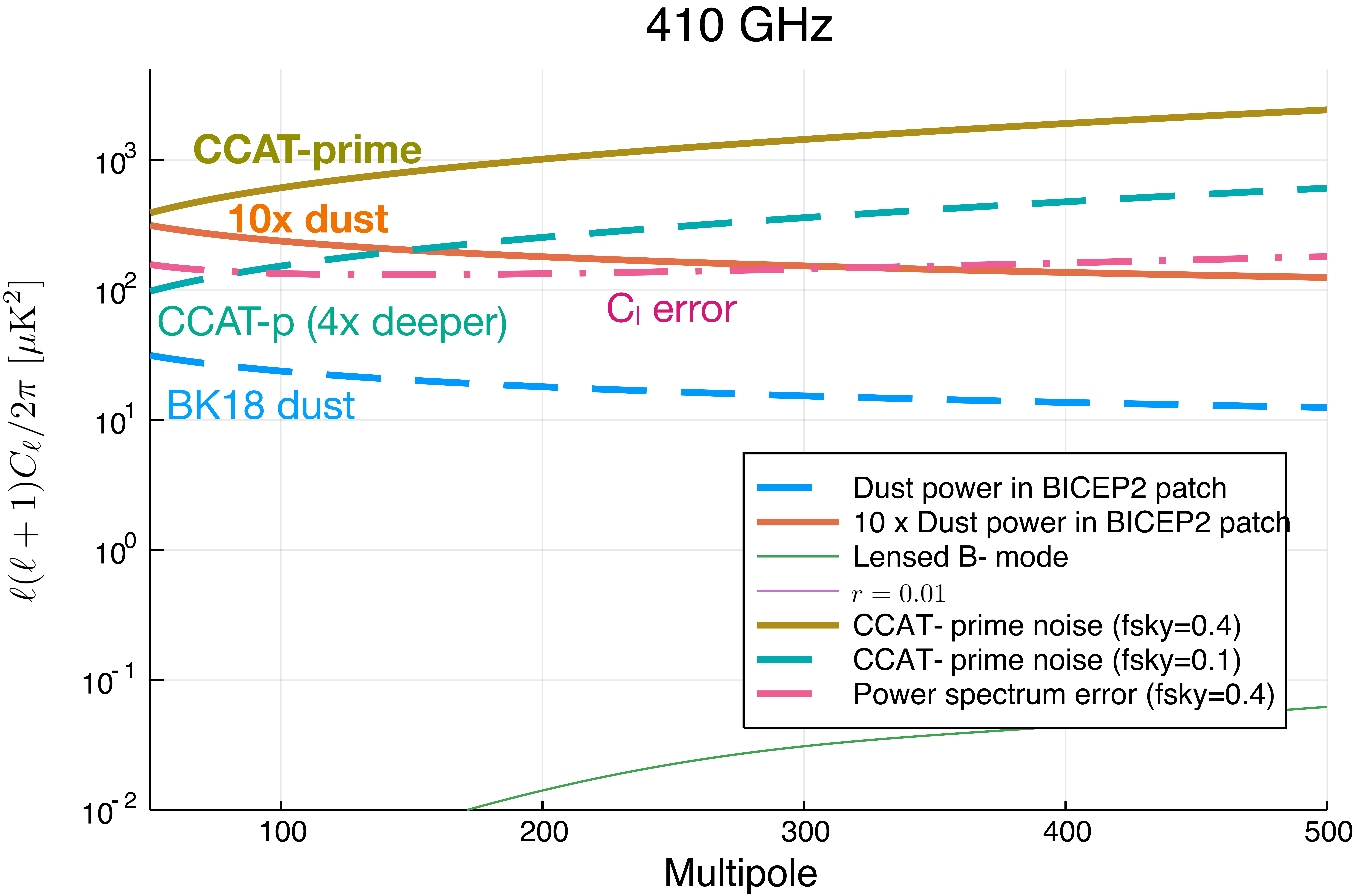
$$\mathrm{Var}(C_\ell^{BB}) = \frac{2(C_\ell^{BB,d} + N_\ell/b_\ell^2)^2}{(2\ell+1)f_{\mathrm{sky}}}$$

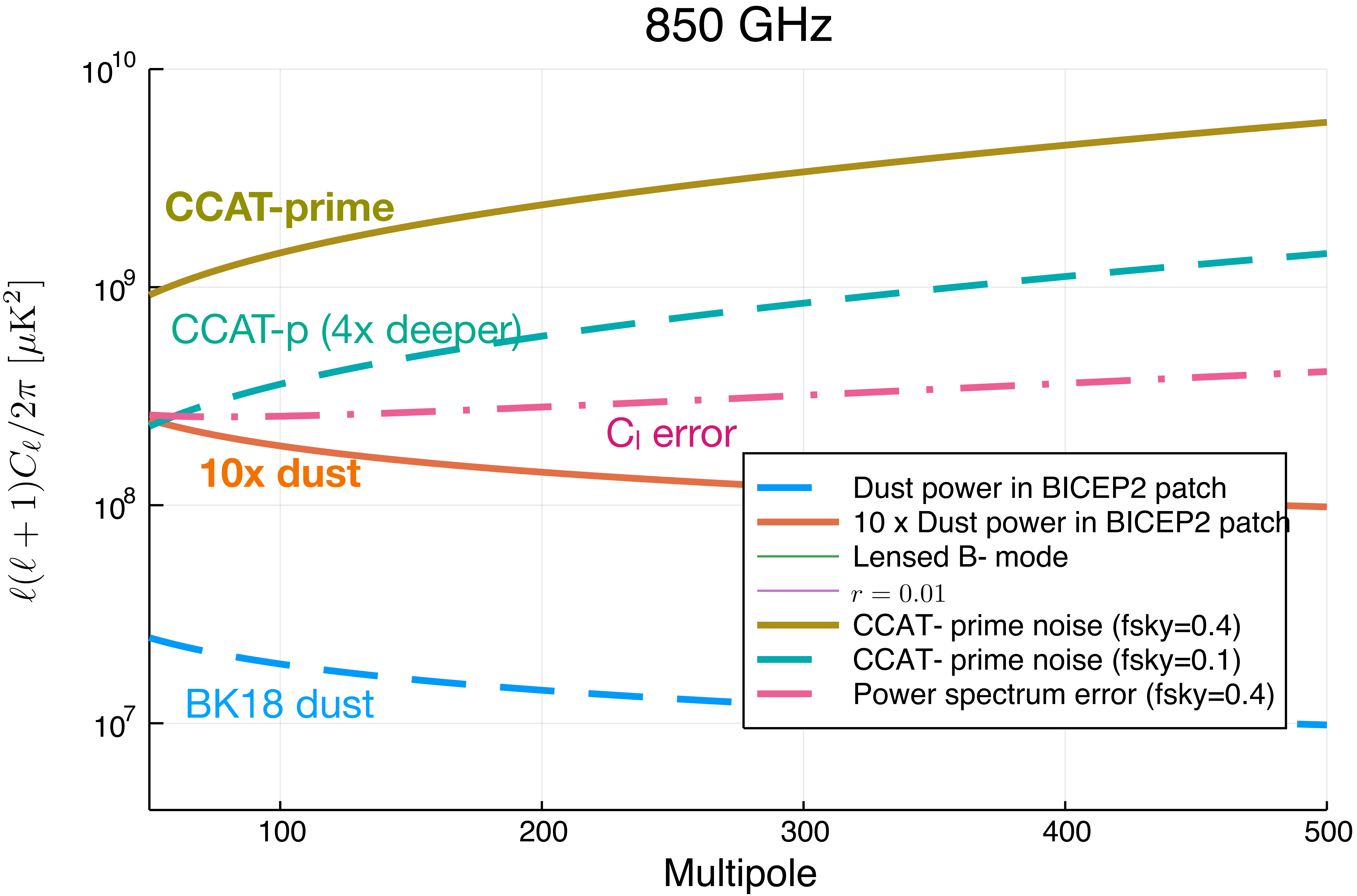
- CMB is ignored because it is small


225 GHz
SO-LAT
CCAT-prime
10x dust
CCAT-p (4x deeper)
BK18 dust
SO-SAT
lensed B-mode
r=0.01
Dust power in BICEP2 patch
10 x Dust power in BICEP2 patch
Lensed B- mode
$r = 0.01$
CCAT- prime noise (fsky=0.4)
CCAT- prime noise (fsky=0.1)
SO LAT noise
SO SAT noise
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
100
200
300
400
500
Multipole


280 GHz
SO-LAT
CCAT-prime
10x dust
CCAT-p (4x deeper)
BK18 dust
SO-SAT
lensed B-mode
r=0.01
Dust power in BICEP2 patch
10 x Dust power in BICEP2 patch
Lensed B- mode
$r = 0.01$
CCAT- prime noise (fsky=0.4)
CCAT- prime noise (fsky=0.1)
SO LAT noise
SO SAT noise
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
100
200
300
400
500
Multipole
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$


350 GHz
CCAT-prime
10x dust
CCAT-p (4x deeper)
C_l error
BK18 dust
Dust power in BICEP2 patch
10 x Dust power in BICEP2 patch
Lensed B- mode
$r = 0.01$
CCAT- prime noise (fsky=0.4)
CCAT- prime noise (fsky=0.1)
Power spectrum error (fsky=0.4)
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
10^2
10^1
10^0
10^{-1}
10^{-2}
100
200
300
400
500
Multipole


410 GHz
CCAT-prime
10x dust
C_l error
CCAT-p (4x deeper)
BK18 dust
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
100
200
300
400
500
Multipole
Dust power in BICEP2 patch
10 x Dust power in BICEP2 patch
Lensed B- mode
$r = 0.01$
CCAT- prime noise (fsky=0.4)
CCAT- prime noise (fsky=0.1)
Power spectrum error (fsky=0.4)


850 GHz
10^{10}
10^9
10^8
10^7
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
100
200
300
400
500
Multipole
CCAT-prime
CCAT-p (4x deeper)
C$_l$ error
10x dust
BK18 dust
Dust power in BICEP2 patch
10 x Dust power in BICEP2 patch
Lensed B- mode
$r = 0.01$
CCAT- prime noise (fsky=0.4)
CCAT- prime noise (fsky=0.1)
Power spectrum error (fsky=0.4)

Estimating dust parameters (β_d, T_d)

- In principle we should calculate the expected uncertainty on the tensor-to-scalar ratio, r.
  - This requires more work…

- As a start, let me calculate the expected uncertainties on the dust parameters and see how adding CCAT-prime improves the constraints

  1. Vary β_d only

  2. Vary T_d only

  3. Vary both β_d and T_d

Method

- Simple χ^2, assuming uniform spectral parameters (which is fine because we want to see the **relative** improvement, rather than the absolute values)

$$\chi^2(\beta_d, T_d) = \sum_{\nu} \sum_{i}^{N_{\rm pix}} [m_i(\nu) - d_i(\nu, \beta_d, T_d)](N^{-1})_{ij}[m_j(\nu) - d_j(\nu, \beta_d, T_d)]$$

- Fisher matrix is

$$\left(\frac{\nu}{353}\right)^{\beta_d+1} \frac{\exp(h \cdot 353/k_B T_d) - 1}{\exp(h\nu/k_B T_d) - 1}$$

$$F_{ij} = \frac{1}{2}\frac{\partial^2 \chi^2}{\partial \theta_i \theta_j} = f_{\rm sky} \sum_{\nu} \frac{\partial \ln \boxed{f_\nu}}{\partial \theta_i} \frac{\partial \ln f_\nu}{\partial \theta_j} \sum_{\ell=2}^{\ell_{\rm max}} (2\ell+1) \frac{C_\ell^{BB,d}(\nu) b_\ell^2(\nu)}{N_\ell(\nu)}$$

Vary β_d only (ν >= 225 GHz)

l_{max}=100

- SO-SAT only (f_{sky}=0.1)
    - 225, 280 GHz
    - Err(β_d) = 0.0222
- CCAT-prime only (f_{sky}=0.4)
    - 225, 280, 350, 410, 850 GHz
    - Err(β_d) = 0.0579
- SO-SAT 225, 280 GHz + CCAT-prime 350, 410, 850 GHz
    - Err(β_d) = 0.0217; thus, CCAT-prime adds very little

Vary T_d only (ν >= 225 GHz)

l_{max}=100

- SO-SAT only (f_{sky}=0.1)
  - 225, 280 GHz
  - Err(T_d) = 1.00 K
- CCAT-prime only (f_{sky}=0.4)
  - 225, 280, 350, 410, 850 GHz
  - Err(T_d) = 1.74 K
- SO-SAT 225, 280 GHz + CCAT-prime 350, 410, 850 GHz
  - Err(T_d) = 0.906 K; thus, CCAT-prime improves the temperature by 10%

Vary β_d and T_d (ν >= 225 GHz)

l_{max}=100

- SO-SAT only (f_{sky}=0.1)
  - 225, 280 GHz
  - Err(β_d) = 0.595, Err(T_d) = 26.8 K
- CCAT-prime only (f_{sky}=0.4)
  - 225, 280, 350, 410, 850 GHz
  - Err(β_d) = 0.151, Err(T_d) = 4.54 K
- SO-SAT 225, 280 GHz + CCAT-prime 350, 410, 850 GHz
  - Err(β_d) = 0.0913, Err(T_d) = 3.81 K; thus, adding CCAT-prime is crucial

Importance of 850 GHz to break degeneracy

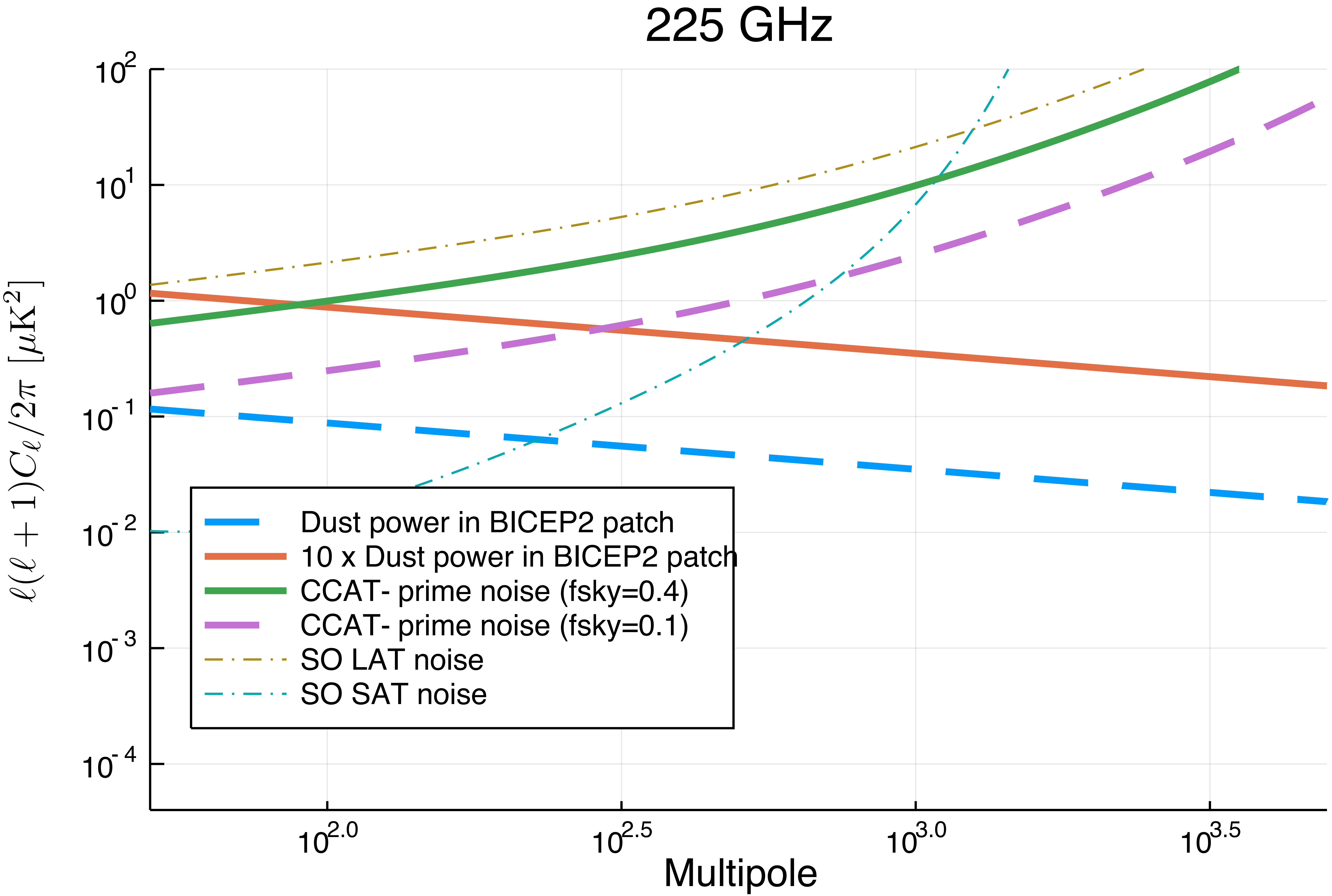
l_{max}=100

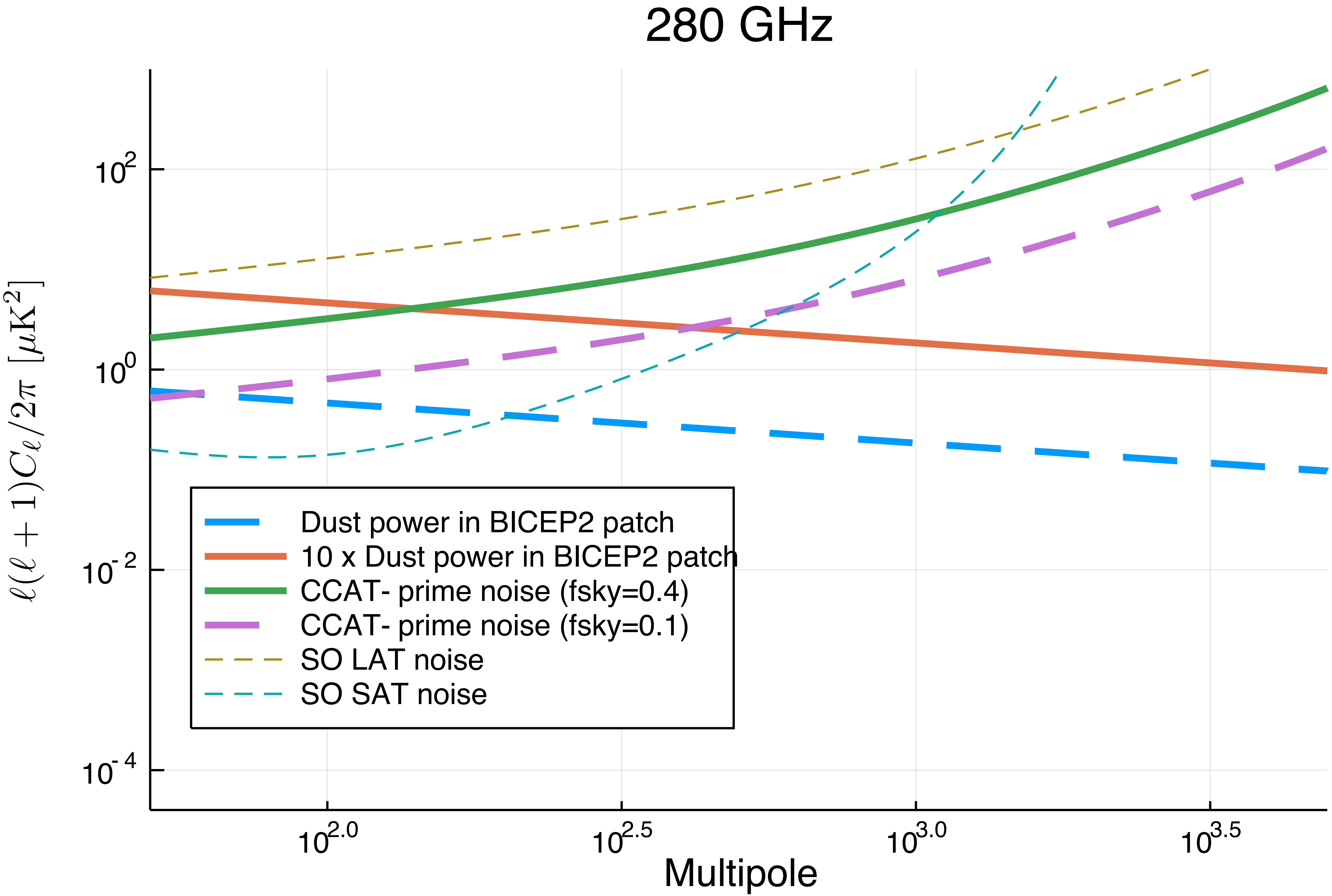
- SO-SAT 225, 280 GHz + CCAT-prime 350, 410, 850 GHz
  - Err(β_d) = 0.0913, Err(T_d) = 3.81 K

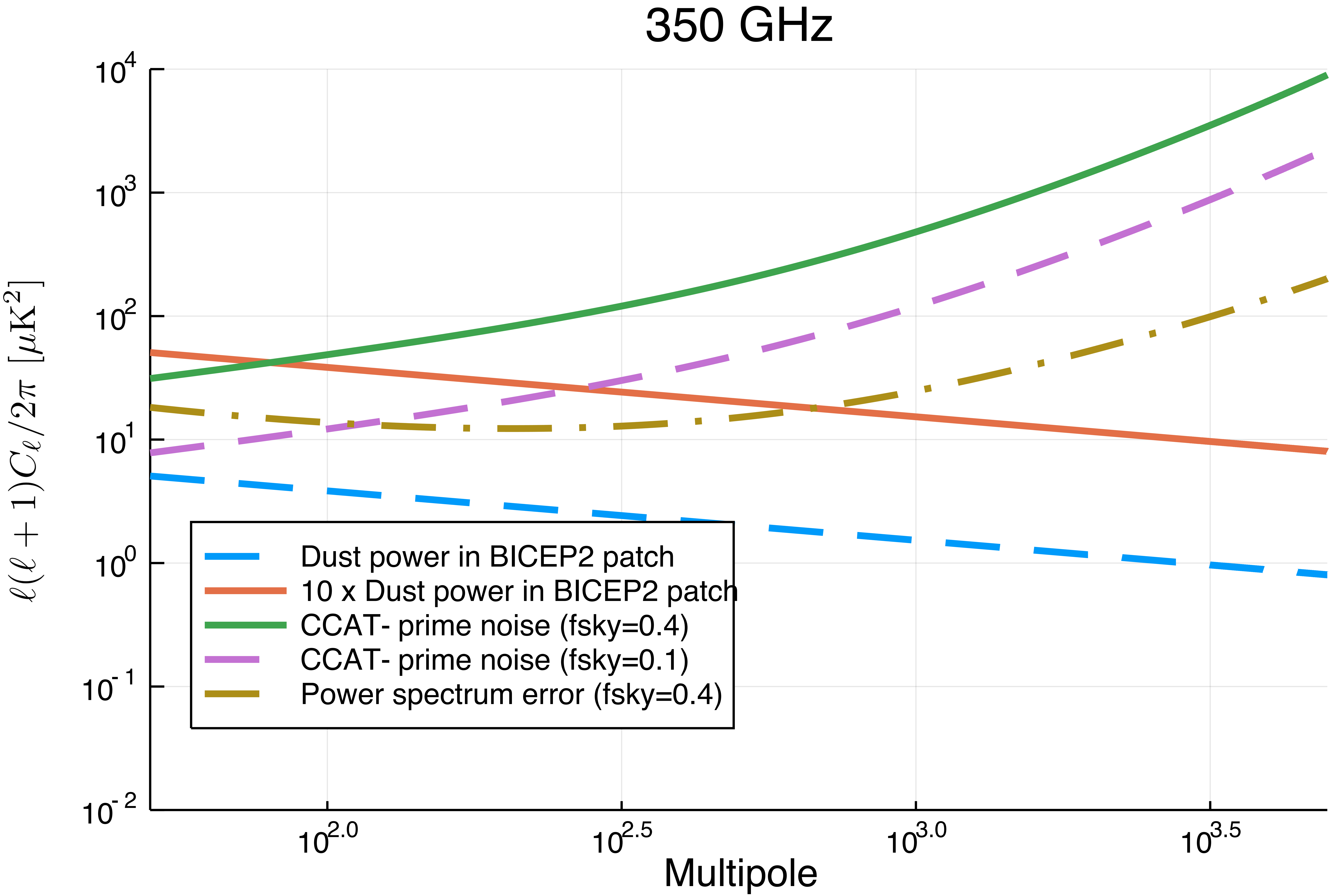
- Remove 350 GHz, keep 410 and 850 GHz
  - Err(β_d) = 0.0914, Err(T_d) = 3.81 K
- Remove 410 GHz, keep 350 and 850 GHz
  - Err(β_d) = 0.0915, Err(T_d) = 3.82 K
- Remove 850 GHz, keep 350 and 410 GHz
  - **Err(β_d) = 0.504, Err(T_d) = 22.69 K**

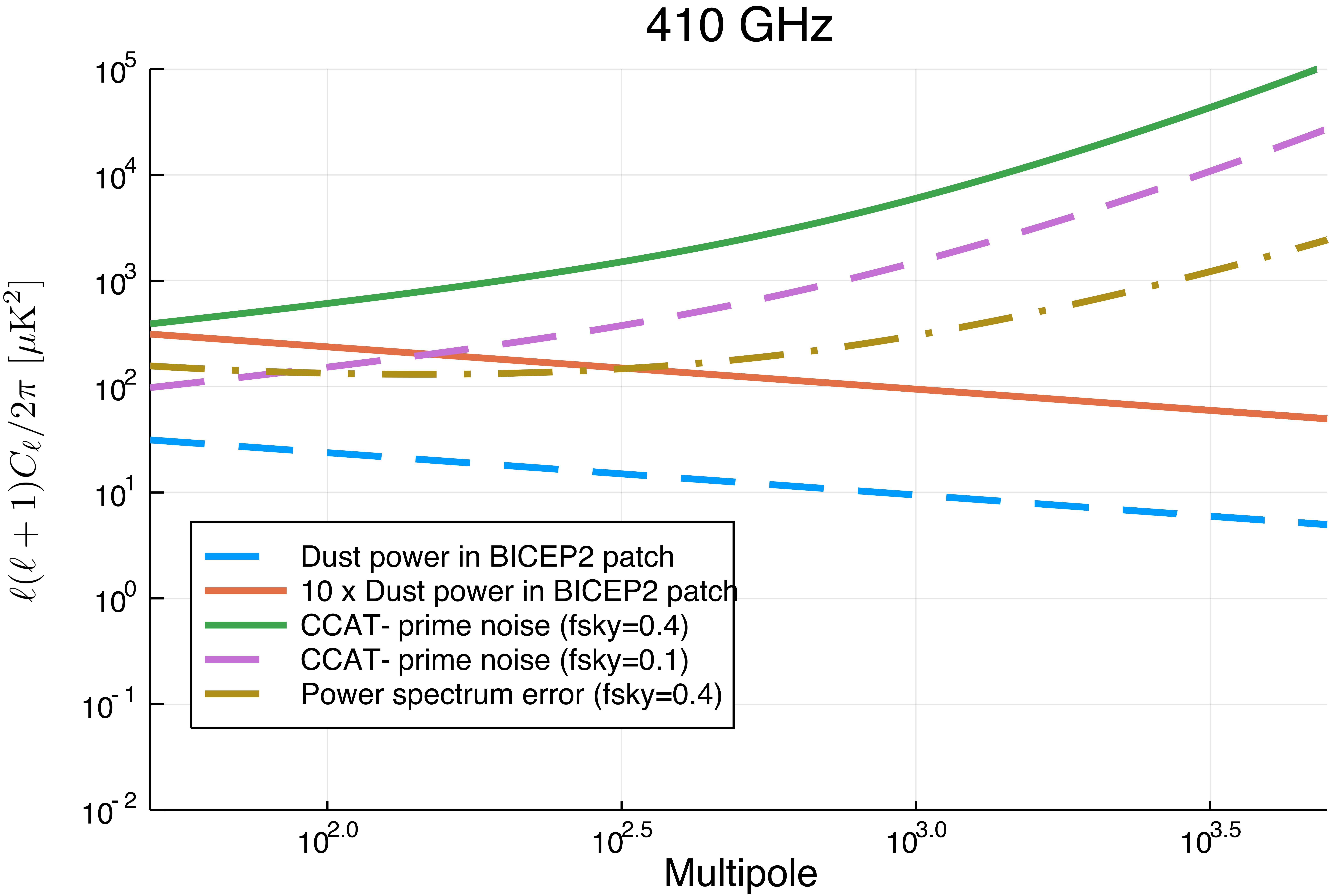
β_d-T_d degeneracy is broken by 850 GHz

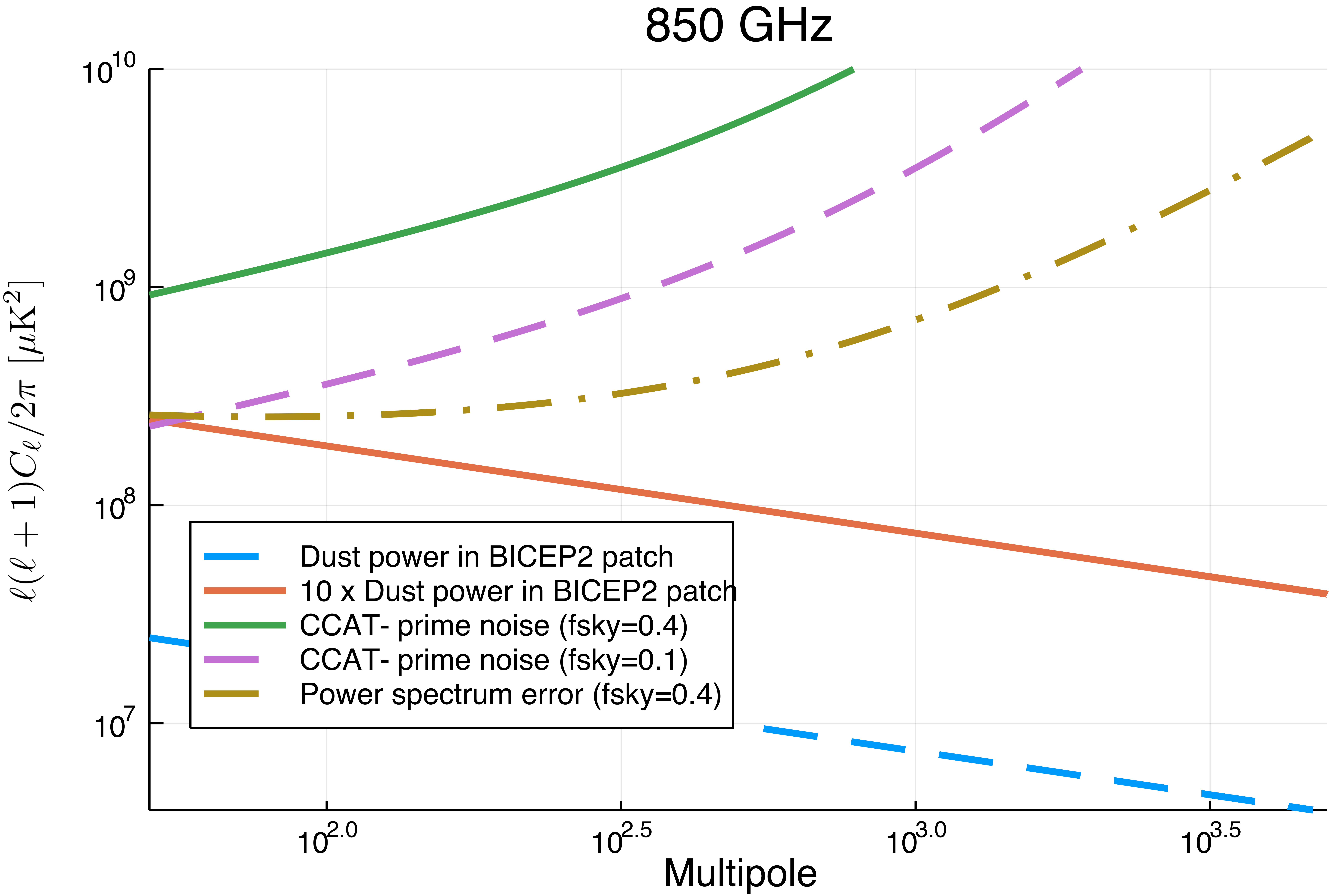
Going to larger l_{max}…


225 GHz
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$10^{2.0}$
$10^{2.5}$
$10^{3.0}$
$10^{3.5}$
Multipole
Dust power in BICEP2 patch
10 x Dust power in BICEP2 patch
CCAT- prime noise (fsky=0.4)
CCAT- prime noise (fsky=0.1)
SO LAT noise
SO SAT noise


280 GHz
$\ell(\ell+1)C_\ell/2\pi$ [μK^2]
10^2
10^0
10^{-2}
10^{-4}
$10^{2.0}$
$10^{2.5}$
$10^{3.0}$
$10^{3.5}$
Multipole
Dust power in BICEP2 patch
10 x Dust power in BICEP2 patch
CCAT- prime noise (fsky=0.4)
CCAT- prime noise (fsky=0.1)
SO LAT noise
SO SAT noise


350 GHz
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
$10^{2.0}$
$10^{2.5}$
$10^{3.0}$
$10^{3.5}$
Multipole
Dust power in BICEP2 patch
10 x Dust power in BICEP2 patch
CCAT- prime noise (fsky=0.4)
CCAT- prime noise (fsky=0.1)
Power spectrum error (fsky=0.4)


410 GHz
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
$10^{2.0}$
$10^{2.5}$
$10^{3.0}$
$10^{3.5}$
Multipole
Dust power in BICEP2 patch
10 x Dust power in BICEP2 patch
CCAT- prime noise (fsky=0.4)
CCAT- prime noise (fsky=0.1)
Power spectrum error (fsky=0.4)


850 GHz
10^{10}
10^{9}
10^{8}
10^{7}
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
$10^{2.0}$
$10^{2.5}$
$10^{3.0}$
$10^{3.5}$
Multipole
Dust power in BICEP2 patch
10 x Dust power in BICEP2 patch
CCAT- prime noise (fsky=0.4)
CCAT- prime noise (fsky=0.1)
Power spectrum error (fsky=0.4)

Summary of results

Caveat: Uniform dust SED parameters!

l_{max}	**CCAT-prime 225, 280, 350, 410, 850 GHz**	**SO-SAT: 225, 280 + CCAT-p: 350, 410, 850 GHz**	**SO-SAT + CCAT-prime with l_{knee} = 350**
100	Err(βd) = 0.151 Err(Td) = 4.54K	0.091 3.81 K	0.065 2.48 K
500	Err(βd) = 0.073 Err(Td) = 2.20K	0.047 1.87 K	0.036 1.34 K
1000	Err(βd) = 0.058 Err(Td) = 1.74K	0.039 1.51 K	0.032 1.15 K
5000	Err(βd) = 0.043 Err(Td) = 1.27K	0.032 1.14 K	0.029 0.96 K

- Perhaps, a better strategy for CCAT-p to help SO-SAT is **not** to clean SAT maps by CCAT-p maps on degree scales directly, but to gain knowledge of dust SED parameters (incl. spatial variations) and use them as priors

Conclusion

- Despite that we do not have HWP and the data are affected by 1/f, CCAT-prime should be able to measure the dust power spectrum on degree angular scales
- CCAT-prime has a potential to improve the primordial B-mode polarisation measurement of SO-SAT by measuring dust parameters better
- Next step: What does this mean for the tensor-to-scalar ratio (r)?
  - SO is not using parametric foreground removal, so they do not have to measure dust parameters. So, impacts on r would probably be less drastic than the previous slide
  - In any case, we should repeat the SO analysis with CCAT-prime!