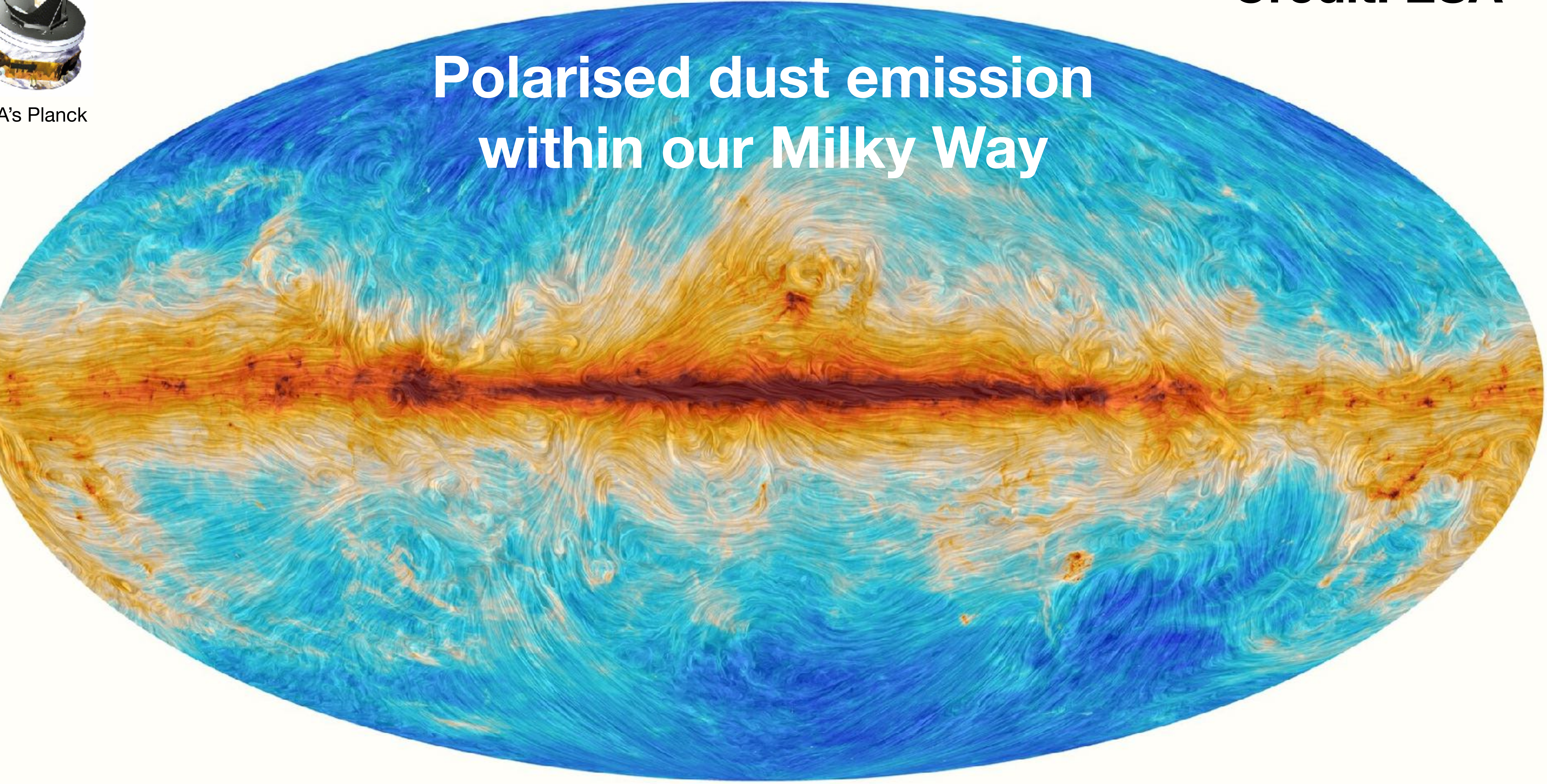
CMB Foregrounds and Gravitational Waves

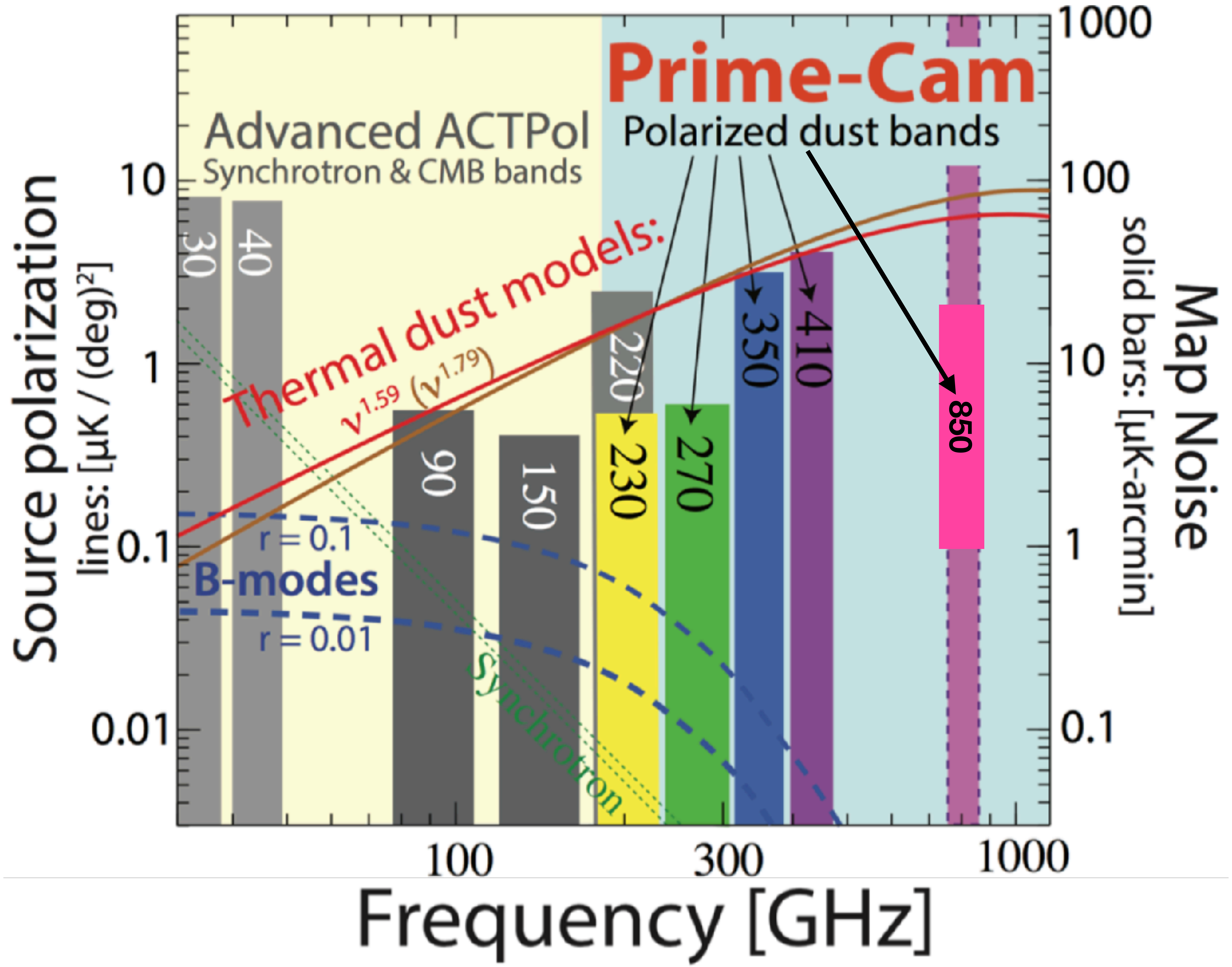
How FYST and SO-SAT can work together to measure the primordial gravitational waves from the early Universe

Eiichiro Komatsu (MPA), CCAT-prime/FYST Collaboration Meeting, April 21, 2021

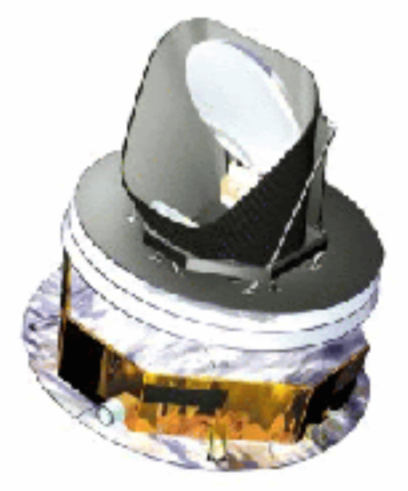
Credit: ESA



Directions of the magnetic field inferred from polarisation of the thermal dust emission in the Milky Way



Prime-Cam
Polarized dust bands
Advanced ACTPol
Synchrotron & CMB bands
Thermal dust models:
$\nu^{1.59}$ ($\nu^{1.79}$)
r = 0.1
B-modes
r = 0.01
Synchrotron
30
40
90
150
220
230
270
350
410
850
Source polarization
lines: [μK / (deg)²]
Map Noise
solid bars: [μK-arcmin]
10
1
0.1
0.01
1000
100
10
1
0.1
100
300
1000
Frequency [GHz]

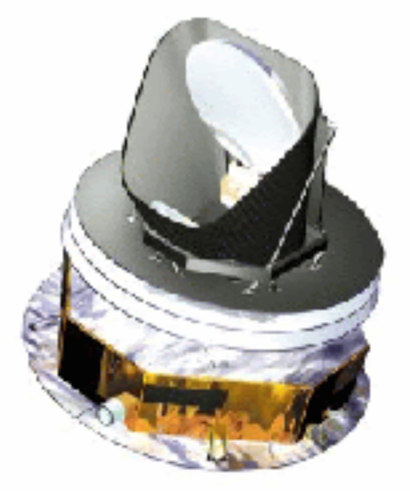


ESA’s Planck

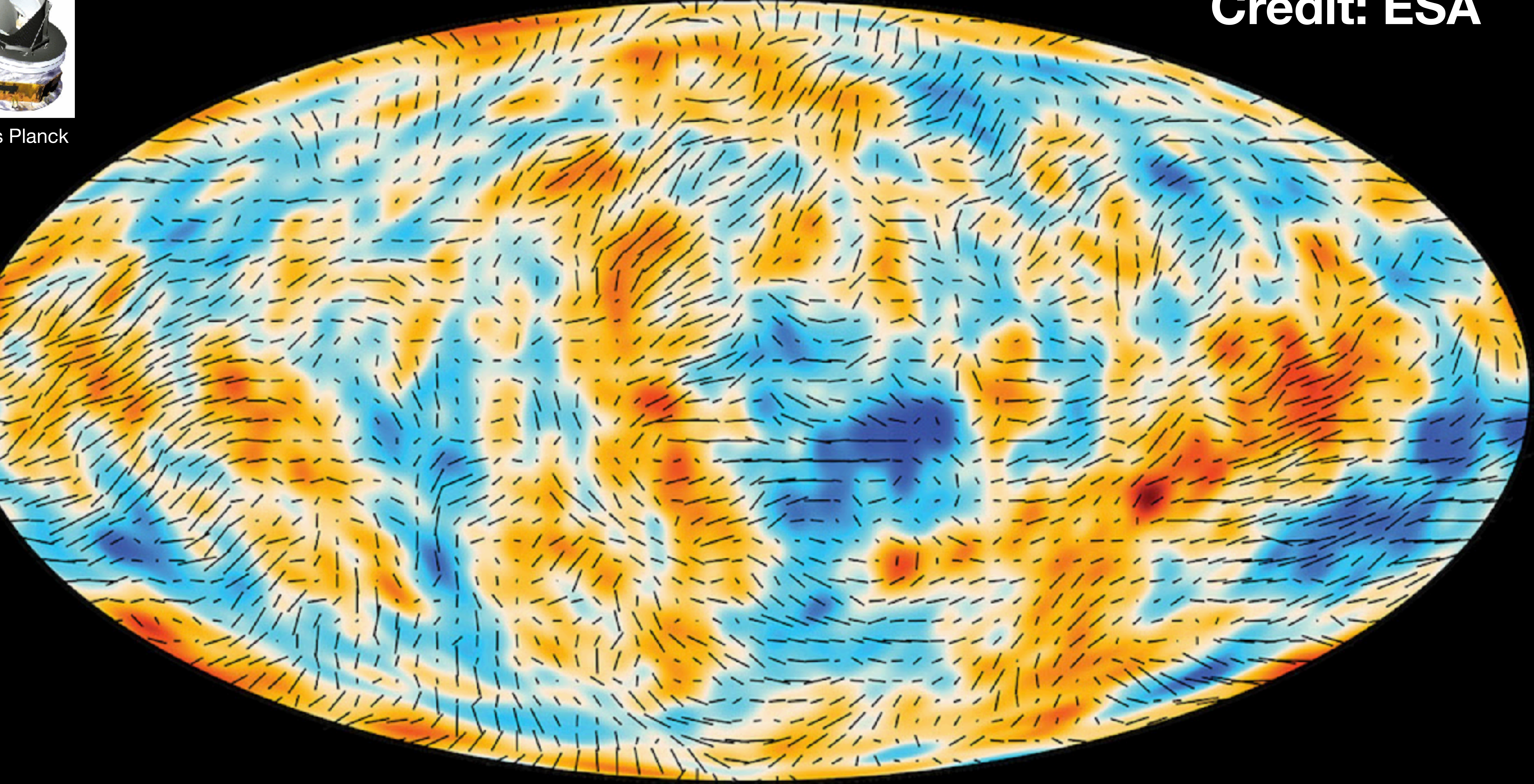
Credit: ESA

Foreground-cleaned Temperature (smoothed)

Emitted 13.8 billions years ago


ESA's Planck

Credit: ESA



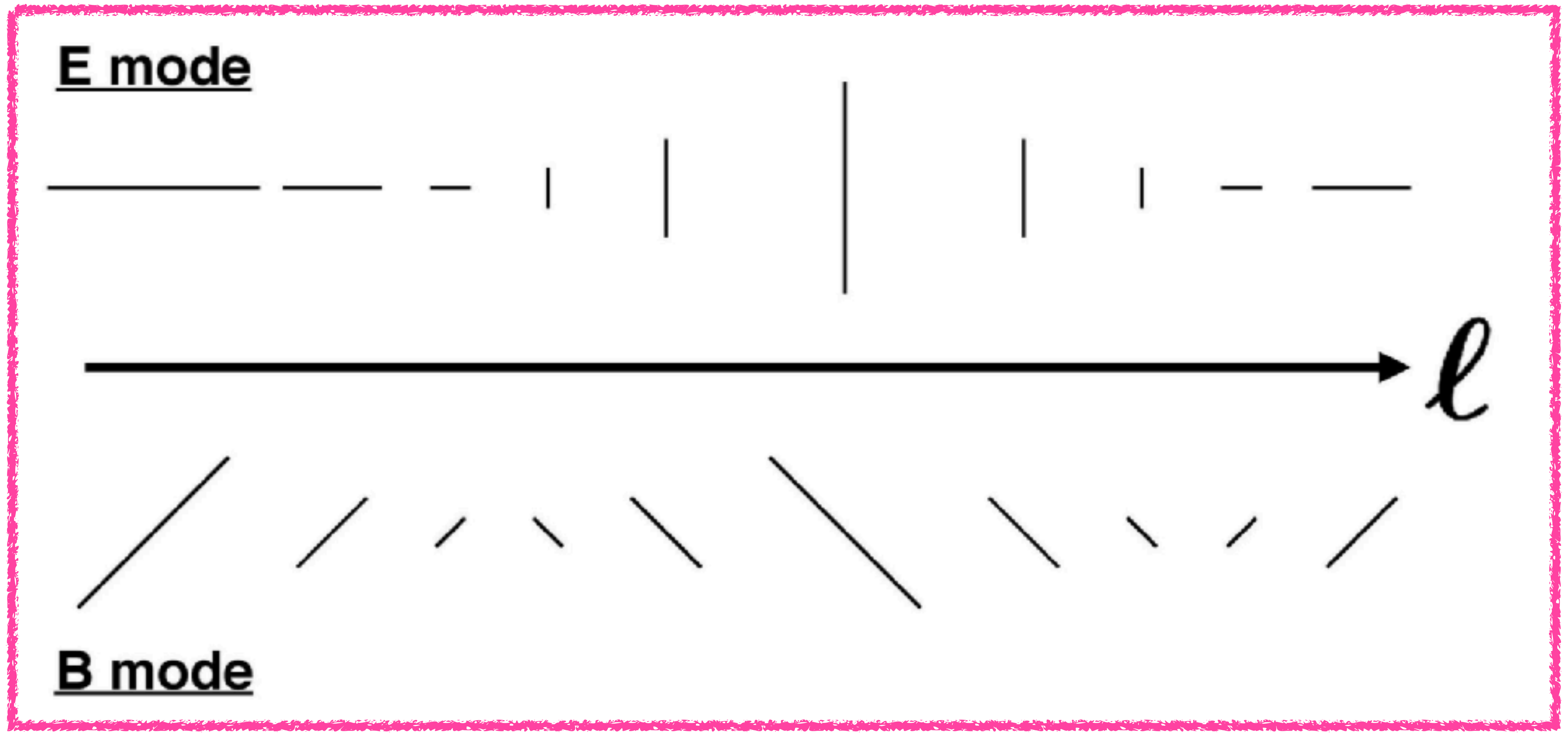
Foreground-cleaned Temperature (smoothed) + Polarisation

Emitted 13.8 billions years ago

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

E- and B-mode decomposition of linear polarisation

Concept defined in Fourier space



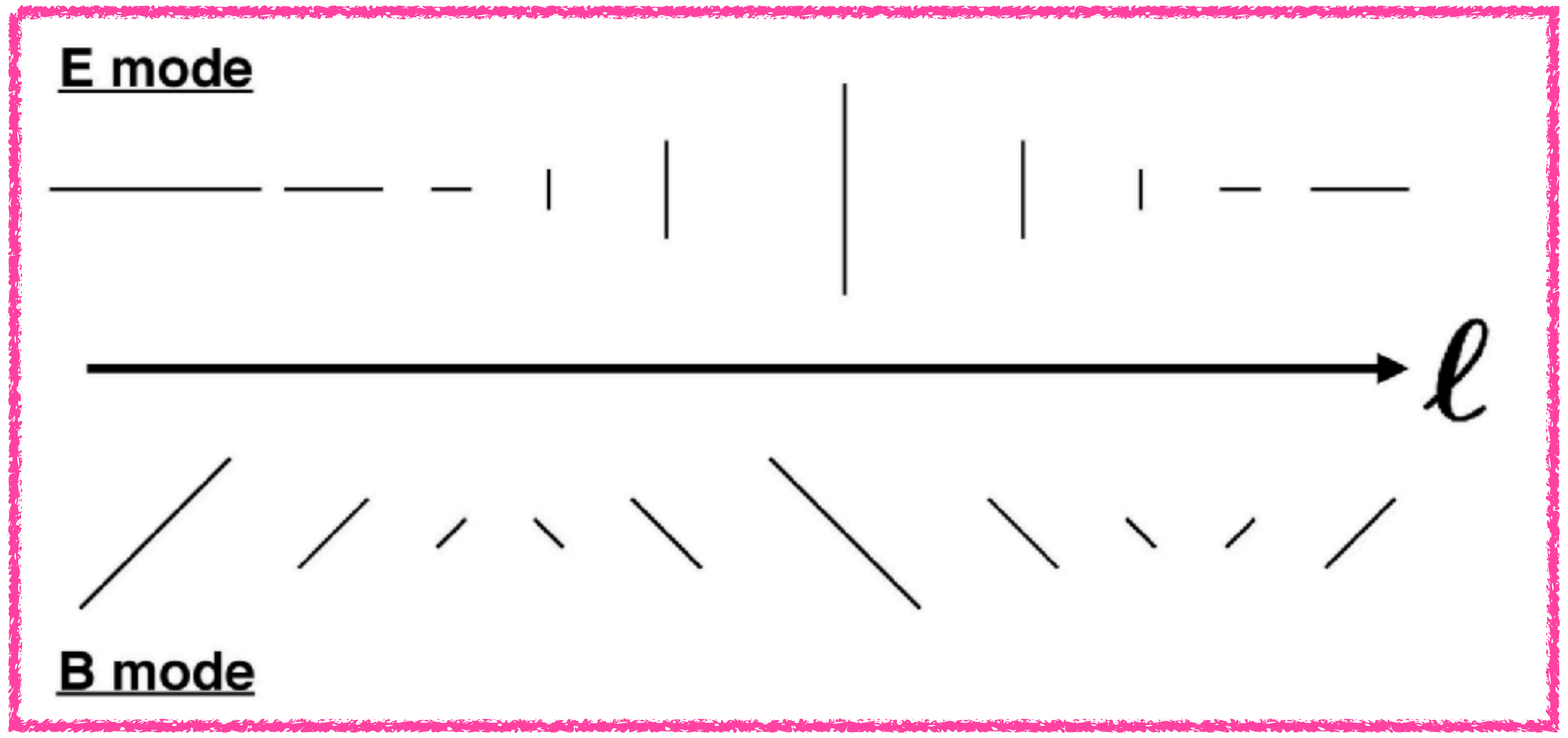
Direction of the Fourier wavenumber vector

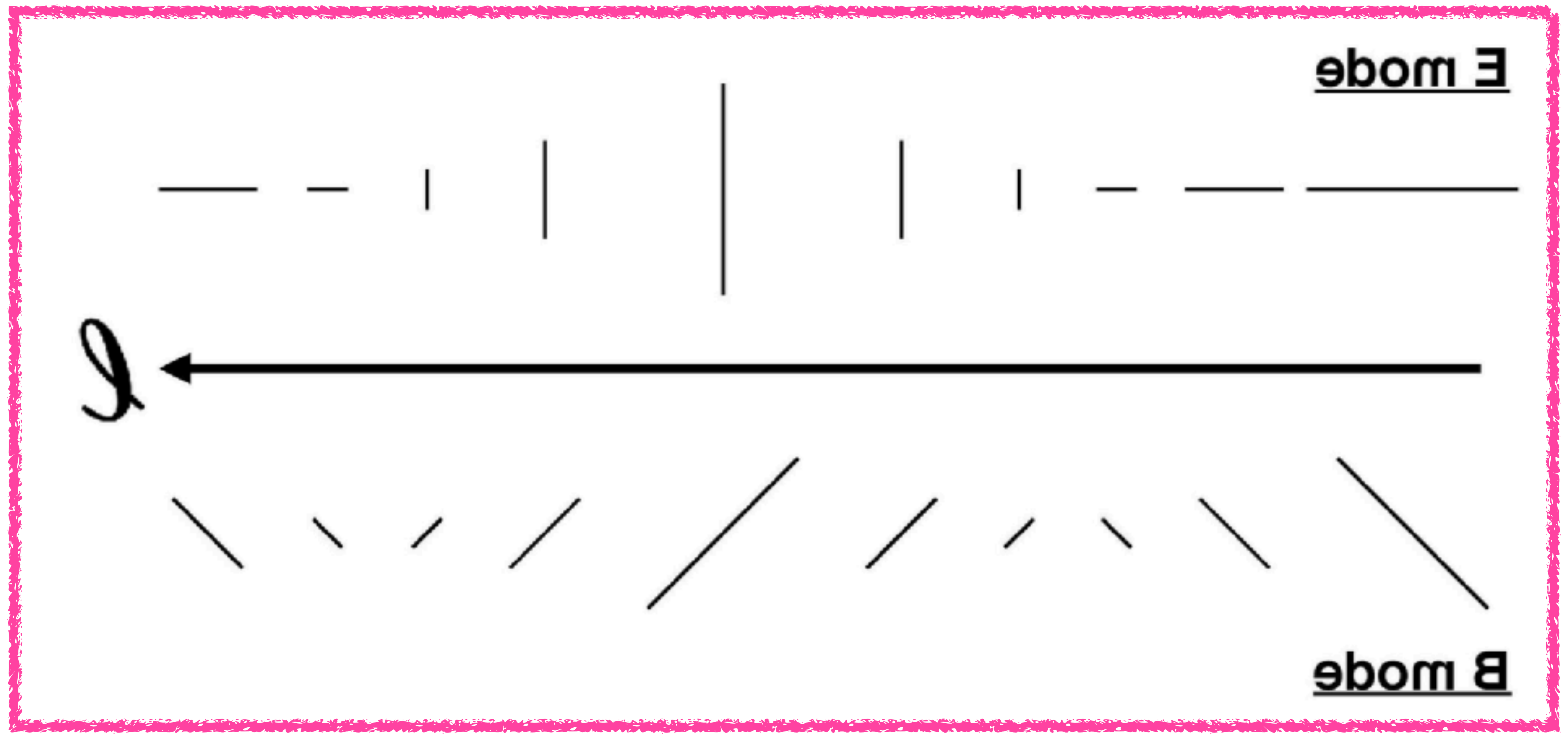
- **E-mode**：Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

Parity Flip

E-mode remains the same, whereas B-mode changes the sign





- Two-point correlation functions invariant under the parity flip are

$$\langle E_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{EE}$$

$$\langle B_{\boldsymbol{\ell}} B^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{BB}$$

$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

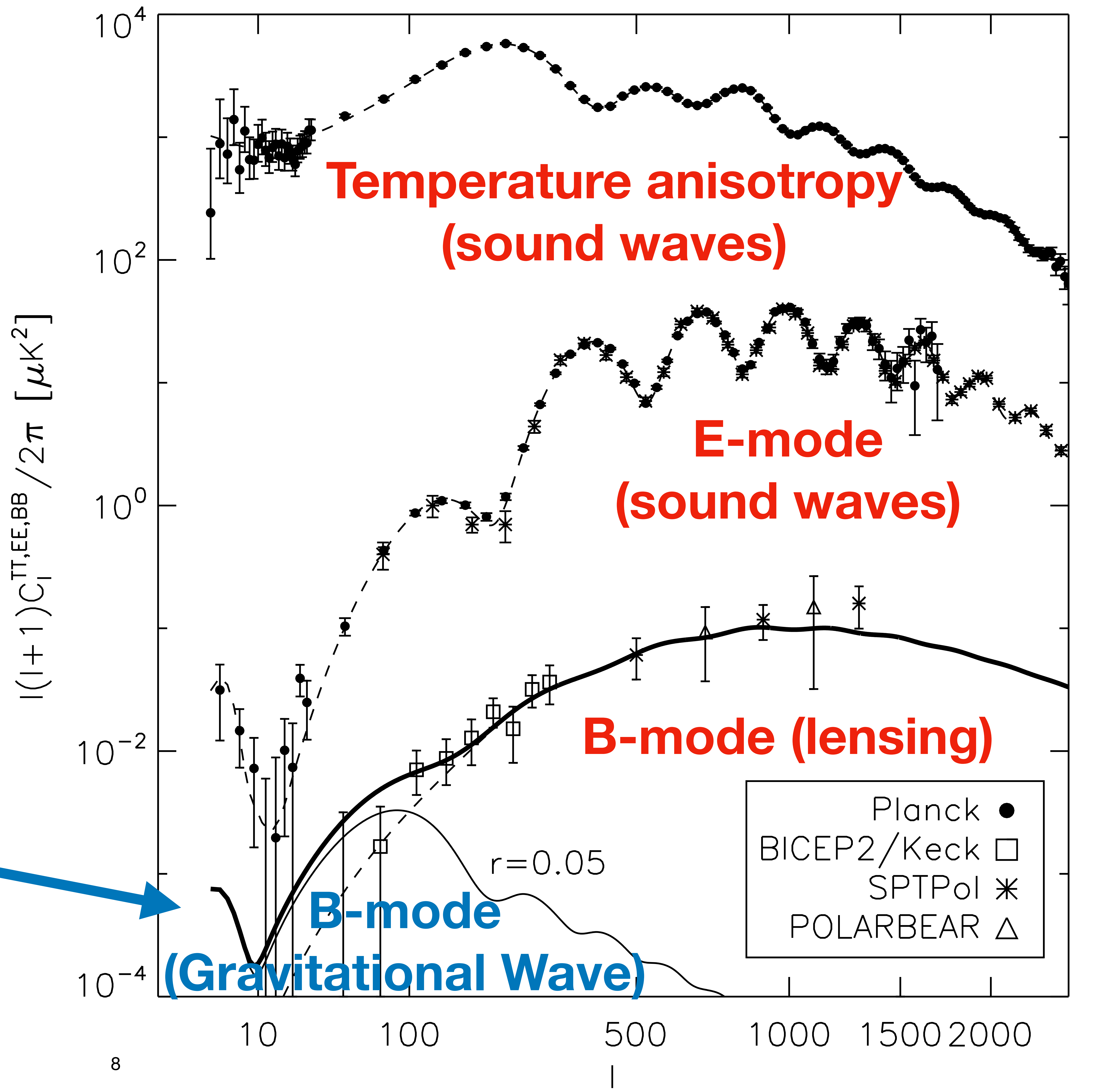
- The other combinations <TB> and <EB> are not invariant under the parity flip.
    - Side Note: We can use these combinations to probe parity-violating physics (e.g., cosmic birefringence)

Power Spectra

A lot have been measured

- The temperature power spectrum and the E- and B-mode polarisation power spectra from the density fluctuations (scalar modes) have been measured well.

- **The next step: B-mode polarisation from the primordial gravitational wave.**



Motivation for the study

Two questions

- We often hear that "*high-frequency data are necessary for removing the polarised Galactic dust emission and cleaning the CMB*". We will have the much-needed high-frequency data from FYST. Then, two questions:
  - **Can the FYST data help remove the polarised Galactic dust emission from other CMB data**, such as Simons Observatory's Small Aperture Telescope (SO-SAT)?
    - Using the highest 3 frequencies (350, 410, 850 GHz) of Prime-Cam.
  - If so, **how/why do the FYST data help?** FYST is not designed to measure polarisation on large (>degree) angular scales relevant to the gravitational wave signal.

Approach: Simulation

Foregrounds, CMB, and noise (white + 1/f)

- We generate realistic realisations of the microwave sky as observed by SO-SAT and FYST. The sky includes: the polarised Galactic **foreground** (synchrotron and dust), **CMB**, and **noise** (white and 1/f).
- The simulation and analysis codes (which together make a “pipeline”) are available in GitHub:

https://github.com/komatsu5147/CleanCMB.jl

CleanCMB

This package contains functions to enable extraction of clean maps of the cosmic microwave background (CMB). Some functions can be used to extract non-CMB astrophysical components as well.

Different algorithms exist for extraction of clean maps of the CMB (as well as of astrophysical components). The package currently supports:

- Internal Linear Combination (ILC) Method
- Parametric Maximum Likelihood Method

See this note for the relationship between them.

Approach: Simulation

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- **Foreground** with spatially-varying SED (generated by "PySM").

```python
import pysm3
import pysm3.units as u
import healpy as hp
import numpy as np
sky = pysm3.Sky(nside=256, preset_strings=["a1", "d1", "f1", "s1"], output_unit="uK_CMB")
nu=[27, 39, 93, 145, 220, 225, 280, 350, 410, 850]
for i in range (0,10):
    map = sky.get_emission(nu[i] * u.GHz)
    map_equ = pysm3.apply_smoothing_and_coord_transform(map, rot=hp.Rotator(coord="GC"))
    # RING format
    hp.write_map("map_equ_{:03d}ghz_r8_uKcmb.fits".format(nu[i]), map_equ, coord="C")
    # NESTED format
    map_nested = hp.reorder(map_equ, r2n=True)
    hp.write_map("map_equ_{:03d}ghz_r8_nested_uKcmb.fits".format(nu[i]), map_nested, coord="C", nest=True)
```

Approach: Simulation

Foregrounds, CMB, and noise (white + 1/f)

- We generate realistic realisations of the microwave sky as observed by SO-SAT and FYST. The sky includes: the polarised Galactic **foreground** (synchrotron and dust), **CMB**, and **noise** (white and 1/f).

- **CMB** is generated as Gaussian random realisations with the power spectra given by the Boltzmann solver “CLASS”.

- **Noise** is generated as Gaussian random realisations with the power spectra given in Choi et al. for FYST and the SO Science Paper for SO-SAT.

    - This generates homogeneous noise. To make it inhomogeneous, we weight noise maps for SO-SAT by the realistic “hits map” of their survey planning.

    - For FYST we assume homogeneous noise over the patch observed by SO-SAT, which is much smaller than that of the FYST Prime-Cam wide survey.

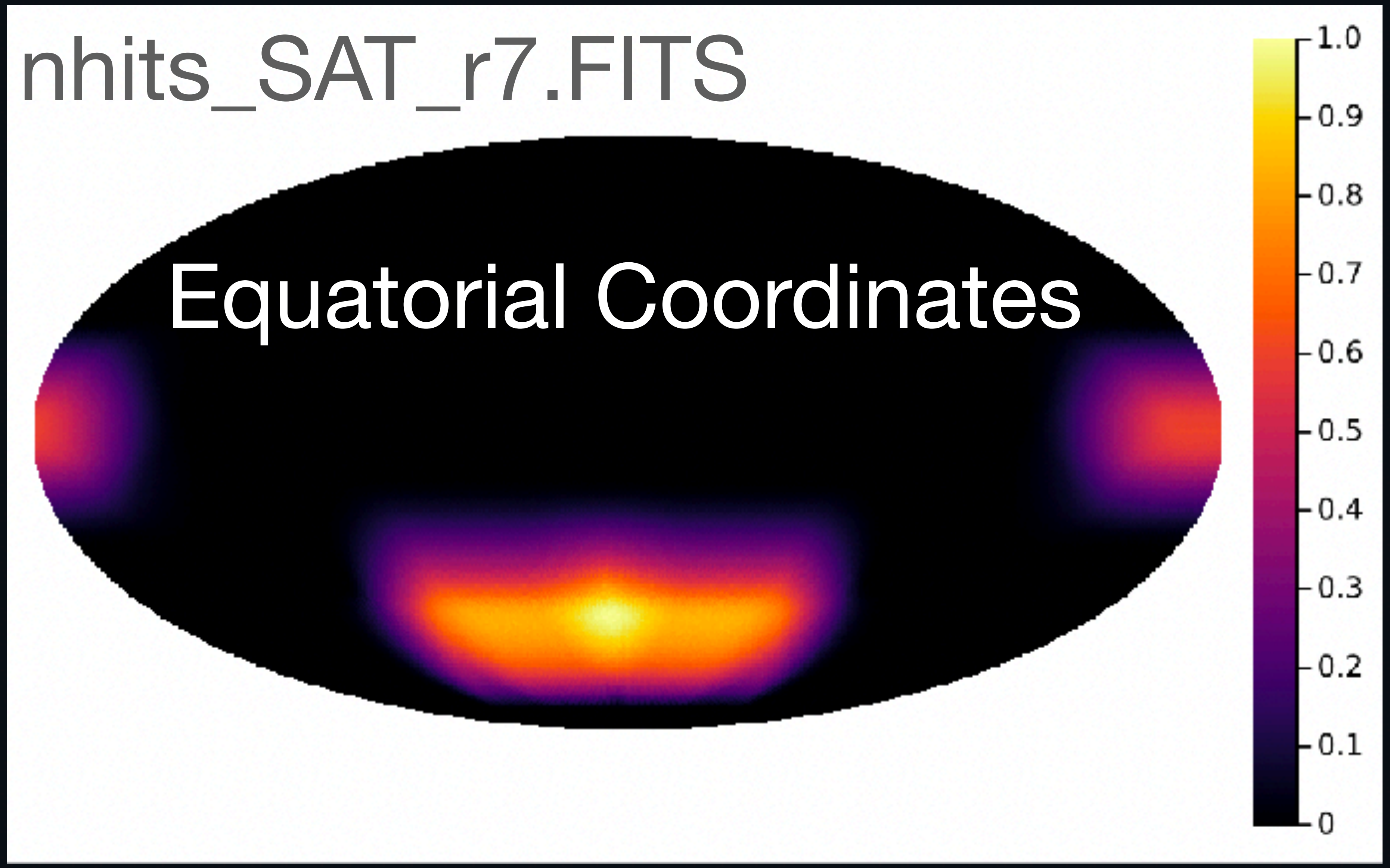
https://github.com/komatsu5147/
CleanCMB.jl/blob/master/examples/
MILCAPipelineSOSATCCATp.jl

```julia
# %% Specification of the experiments
# Reference: Simons Observatory Collaboration, JCAP, 02, 056 (2019), Table 1.
# Reference: CCAT-prime Collaboration, J.Low Temp.Phys., 199, 1089 (2020), Table 1.
ν = [27, 39, 93, 145, 225, 280, 350, 410, 850] # in GHz
nν, nνSO = length(ν), 6
FWHM = [91, 63, 30, 17, 11, 9, 0.58, 0.5, 0.23] # in arcmin
σ = FWHM * π / 10800 / √(8 * log(2)) # in radians
uKarcmin = [35, 21, 2.6, 3.3, 6.3, 16, 105, 372, 5.7e5] # in μK arcmin (for temperature; x√2 for pol)
lknee = [30, 30, 50, 50, 70, 100, 700, 700, 700]
αknee = [-2.4, -2.4, -2.5, -3, -3, -3, -1.4, -1.4, -1.4]
# temperature beam
bTl(ℓ, σb) = exp(-ℓ * (ℓ + 1) * σb^2 / 2)
# polarisation beam, Eq.(5.8) of Ng & Liu, Int.J.Mod.Phys.D, 8, 61 (1999)
bPl(ℓ, σb) = ifelse(ℓ >= 2, exp(-(ℓ * (ℓ + 1) - 4) * σb^2 / 2), 0)

# %% Read in the hits map and calculate weights for inhomogeneous noise
nhitsfile = "data/nhits_SAT_r7.FITS"
nhits = readMapFromFITS(nhitsfile, 1, Float64)
nside = nhits.resolution.nside
nhits /= maximum(nhits)
fsky = mean(nhits)^2 / mean(nhits .^ 2)
K = √(mean(nhits) / fsky)
weight = zeros(12 * nside^2)
for ip = 1:12*nside^2
    if nhits[ip] > 0
        weight[ip] = K / √nhits[ip]
    end
end
```

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

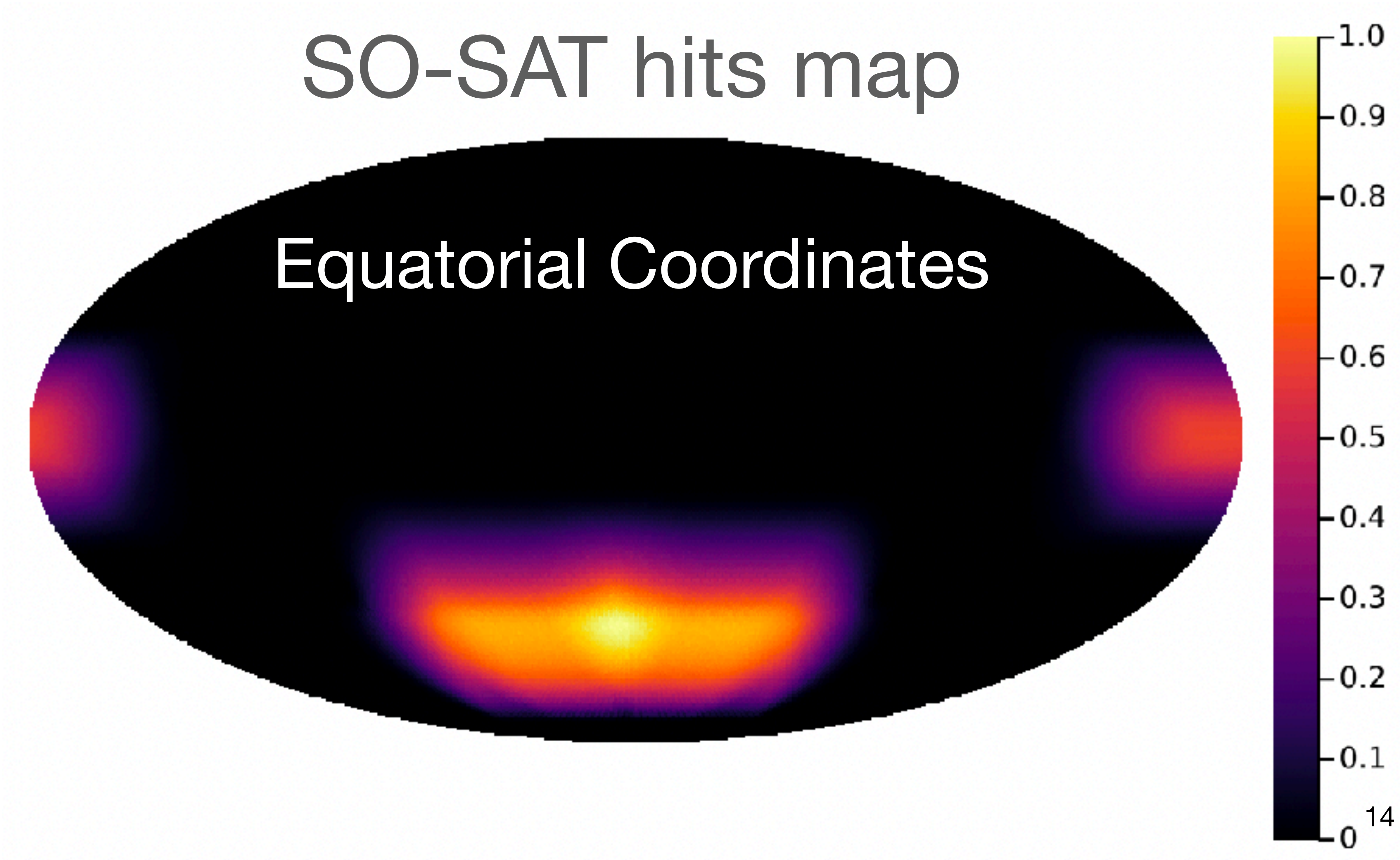
$$N_\ell = N_{\rm red}\left(\frac{\ell}{\ell_{\rm knee}}\right)^{\alpha_{\rm knee}} + N_{\rm white}$$

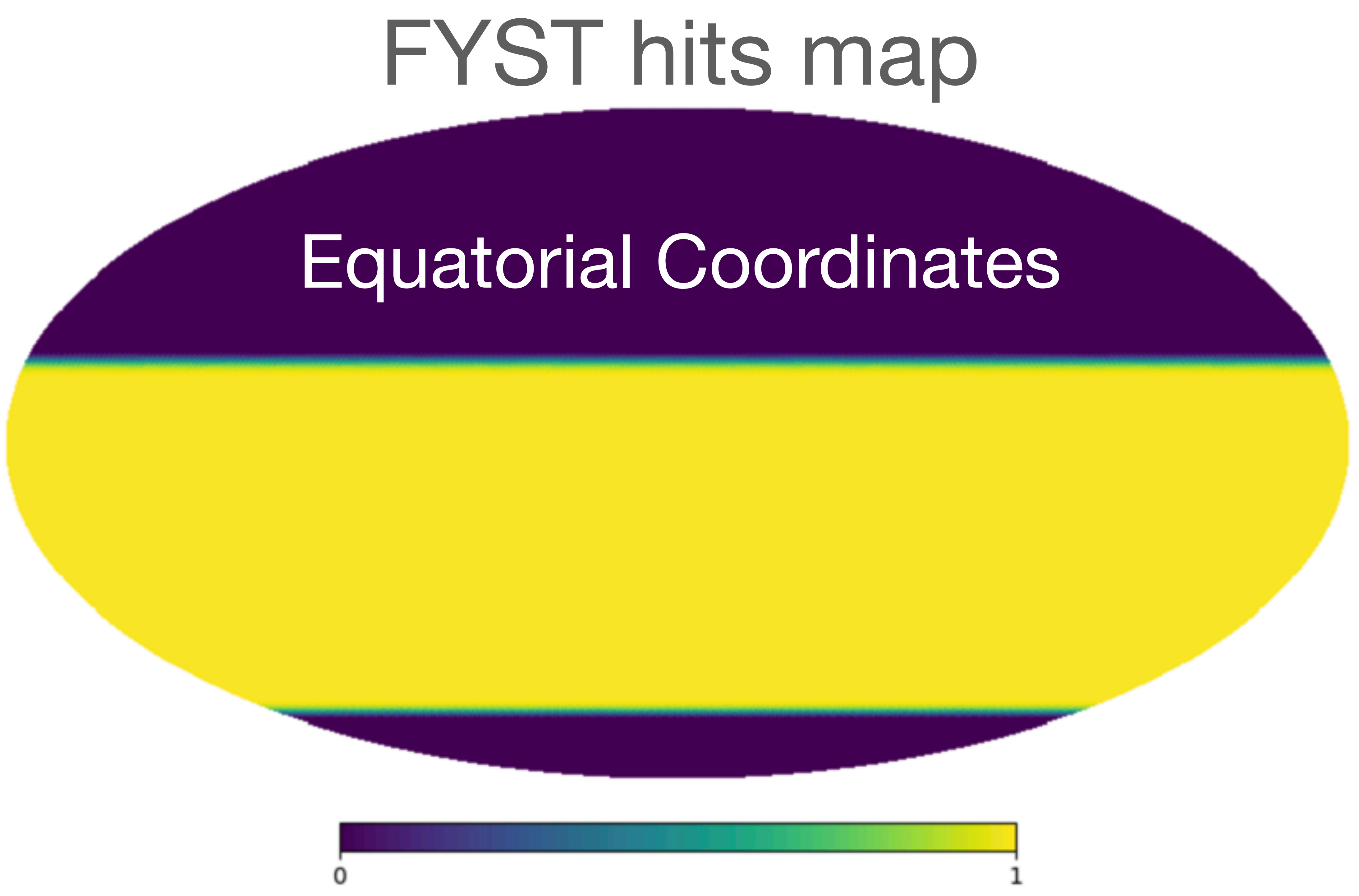


Power spectrum estimation

Using the SO-SAT weights for both SO-SAT and FYST maps

- While the FYST wide survey covers much more area than the SO-SAT survey, we use the same weights for the FYST and SO-SAT data because we can only clean SO-SAT data for the overlapping modes.



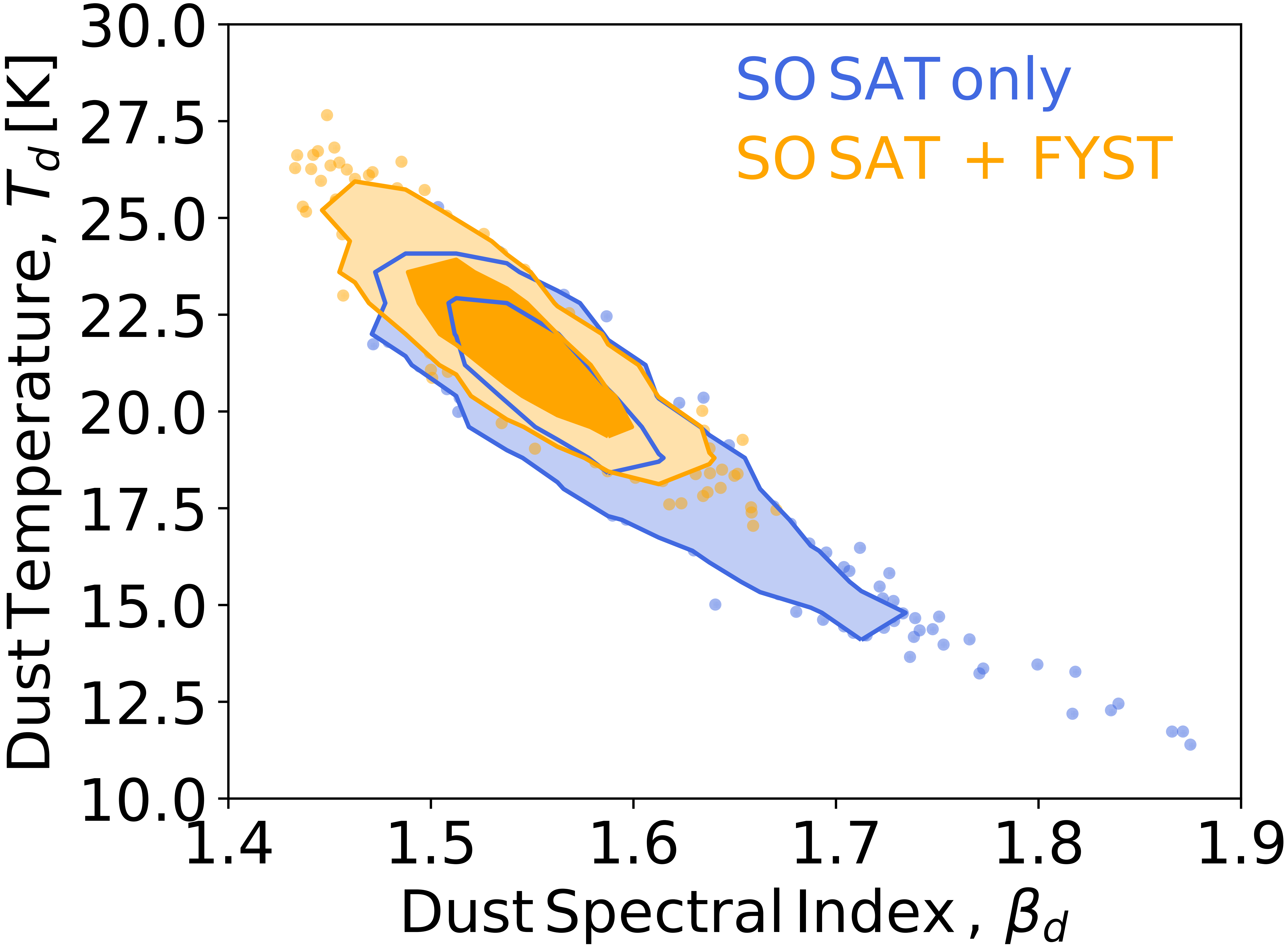


Foreground removal: A hybrid approach

- To remove the foregrounds, we use a (new?) hybrid approach, combining
  - **Parametric method** and
  - **Blind method** (cILC = constrained Internal Linear Combination)
- We first determine three foreground parameters (power-law synchrotron spectral index **β_s**, dust spectral index **β_d**, and dust temperature **T_d**).
  - Assumed to be homogeneous over the SO-SAT patch, although the sky model does contain spatially varying β_s, β_d, and T_d.
  - *Gaussian priors: $\beta_s = -3.0 \pm 0.5$, $\beta_d = 1.6 \pm 0.5$, and $T_d = 19.6 \pm 5$ K.*
- We then use cILC to remove the best-fitting foreground and reduce the remaining foregrounds by minimising variance of the cleaned CMB map.

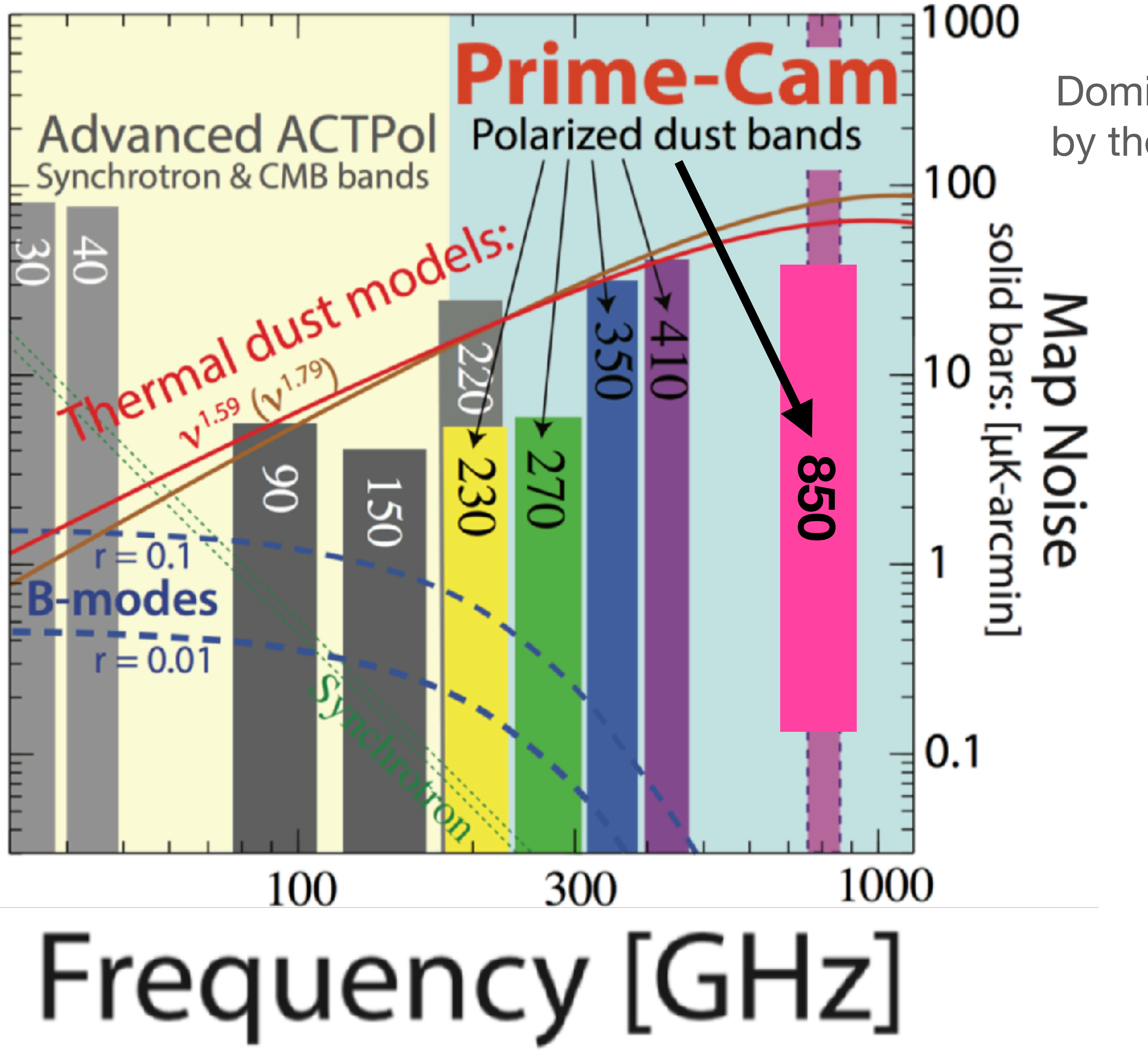
Results: Dusty Parameters

Fig. 6 of Science Paper



- SO-SAT cannot break degeneracy between βd and Td.
    - The constraints are dominated by the prior.
- FYST/Prime-Cam can determine these parameters much more accurately.
    - **850 GHz is the key!**

850 GHz is the key for determining the dusty parameters



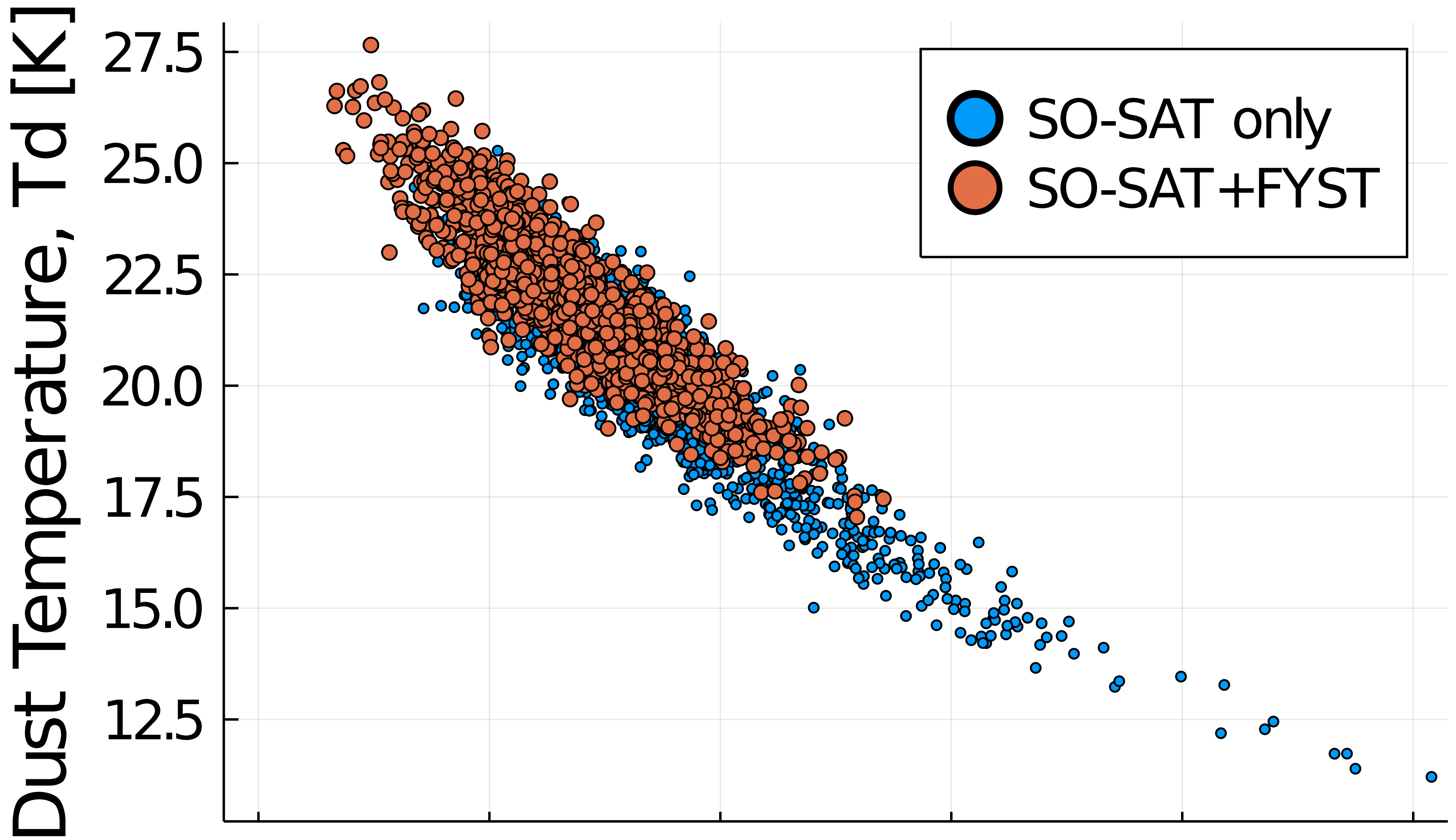
Nominal

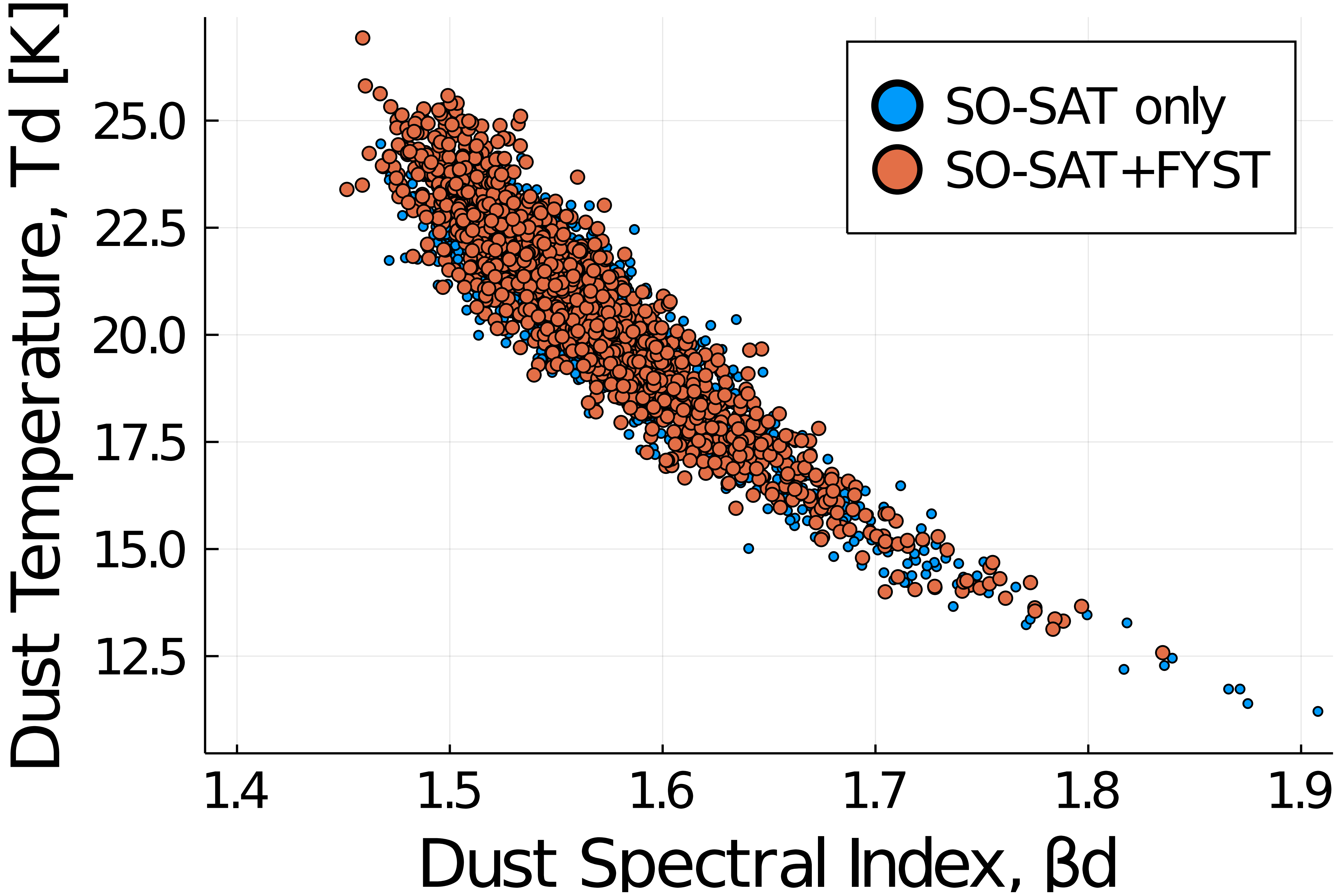
−βd = 1.544 ± 0.038
−Td = 21.86 ± 1.66K

Dominated by the prior

Remove 850GHz

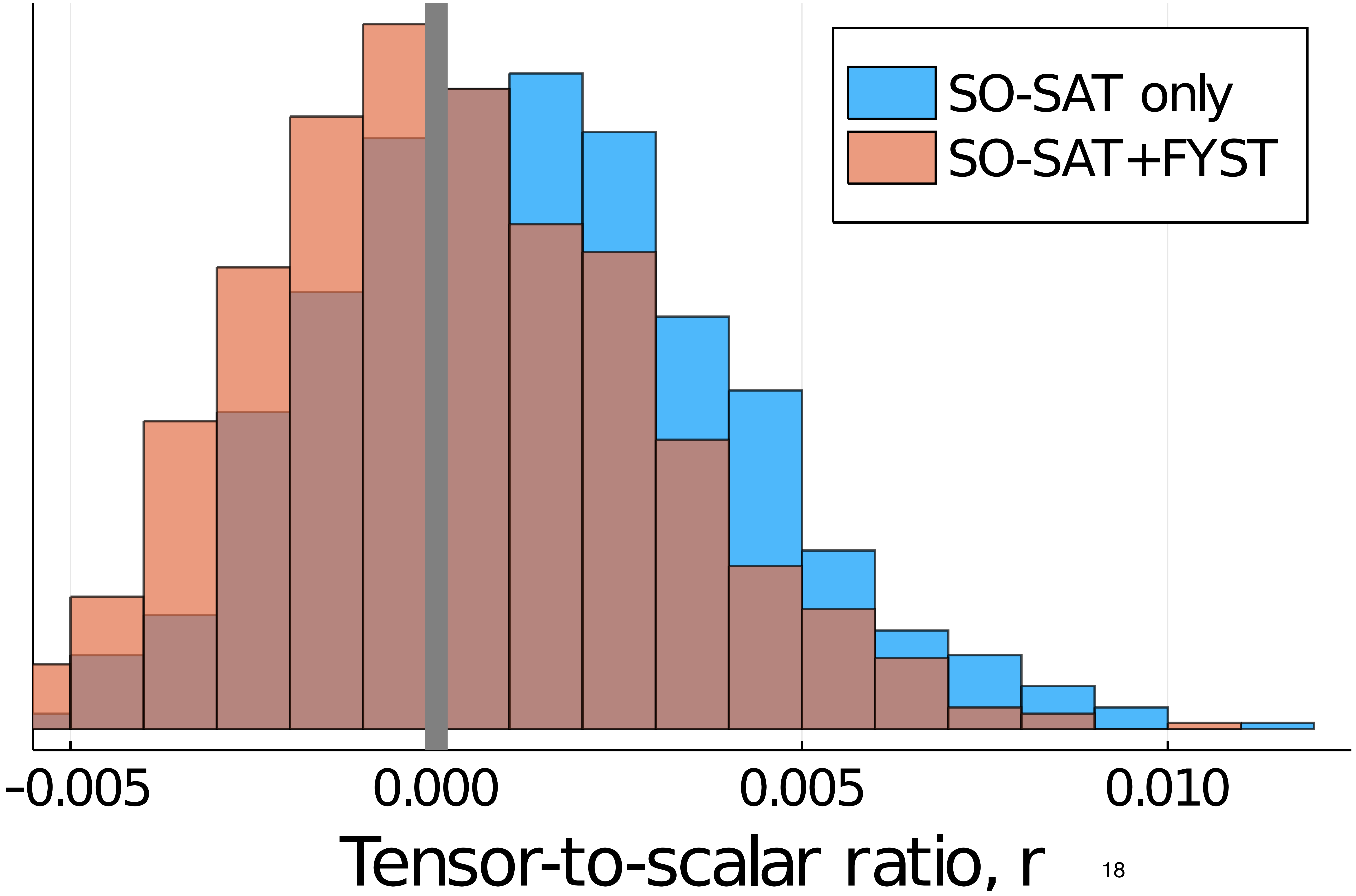
−βd = 1.566 ± 0.054
−Td = 20.56 ± 2.34K





Tensor-to-scalar ratio parameter, r

Fig. 7 of Science Paper



- SO-SAT only
  - $r = (1.30 \pm 2.76) \times 10^{-3}$
  - With 1500 realisations, the error on the mean is 7×10^{-5}. A significant bias is detected, in agreement with the SO forecast paper.
- FYST+SO-SAT
  - $r = (0.19 \pm 2.73) \times 10^{-3}$
  - The bias is largely gone!

Where does the constraint come from?

It isn't just 850 GHz.

- It may be tempting to conclude that the improvement comes primarily from 850 GHz because we can reduce the degeneracy between β_d and T_d.
- This is actually not the case: Addition of **each** of 350, 410, and 850 GHz helps equally well.
- Thus, the improvement comes not only from better determination of β_d and T_d, but also further minimisation of the foreground residual by cILC.
    - In other words, this result depends on the foreground removal method. Our method is not bad at all :) but it could be improved even further. A research project!

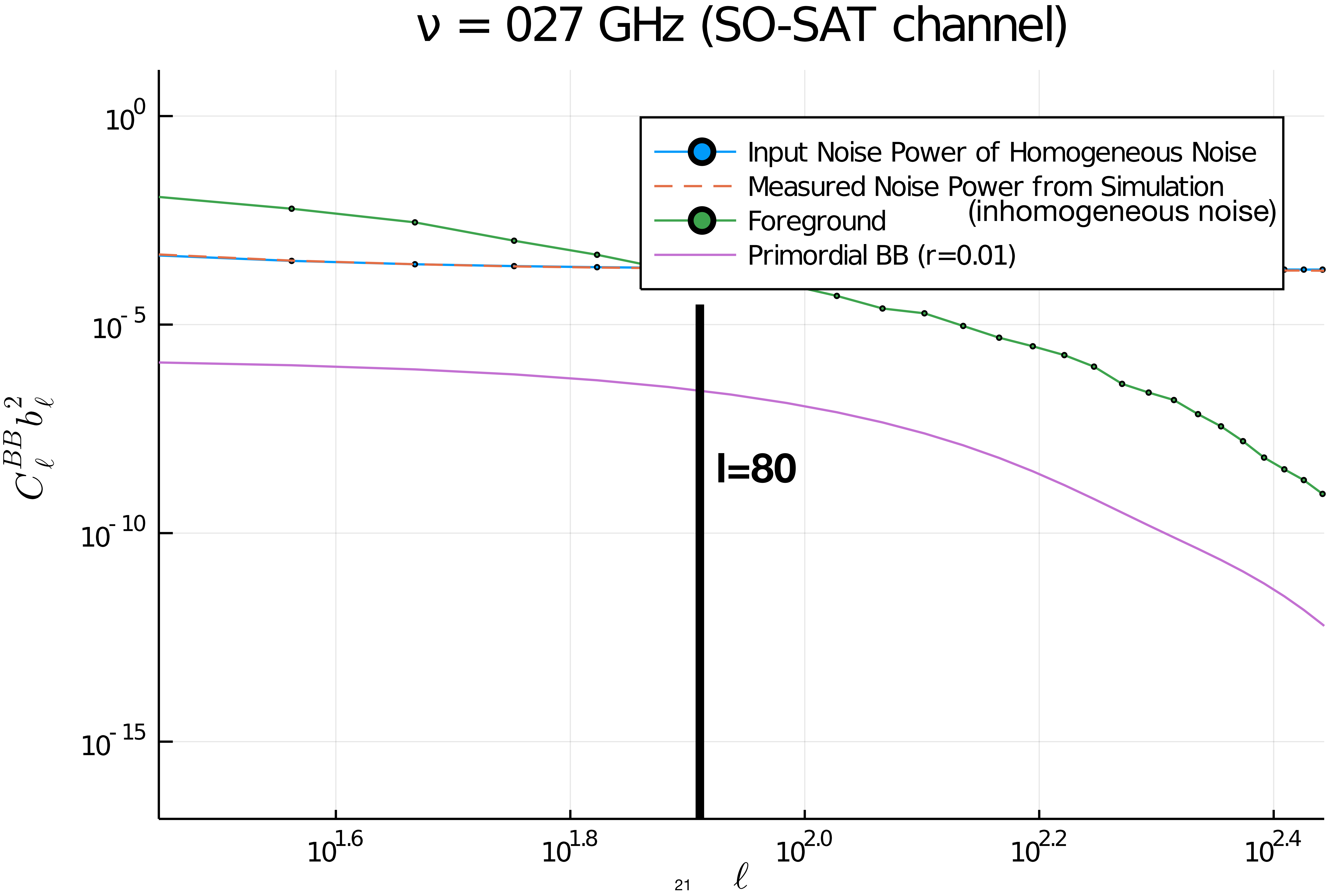
Why does FYST help?

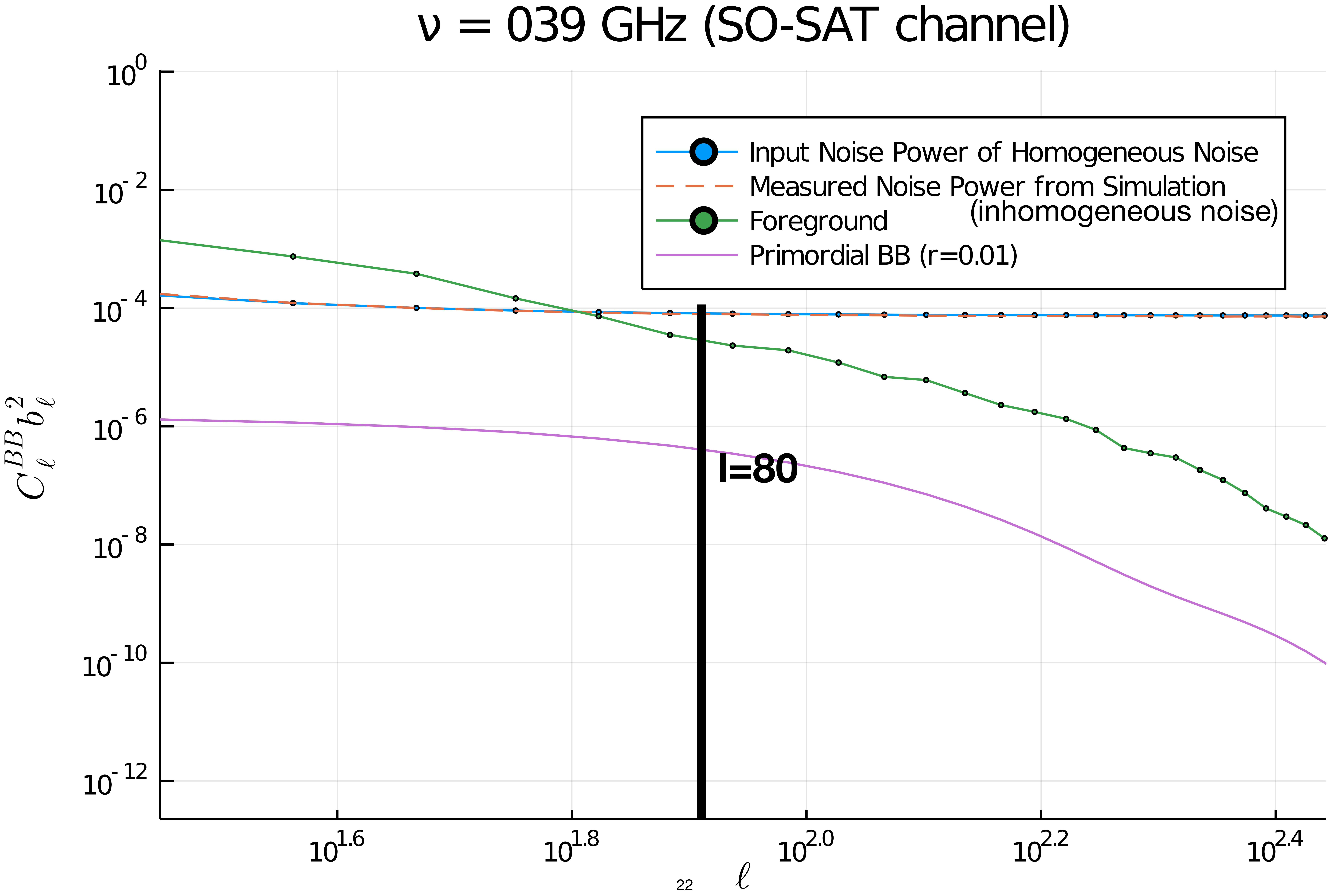
Despite that we do not have a polarisation modulator (HWP)?

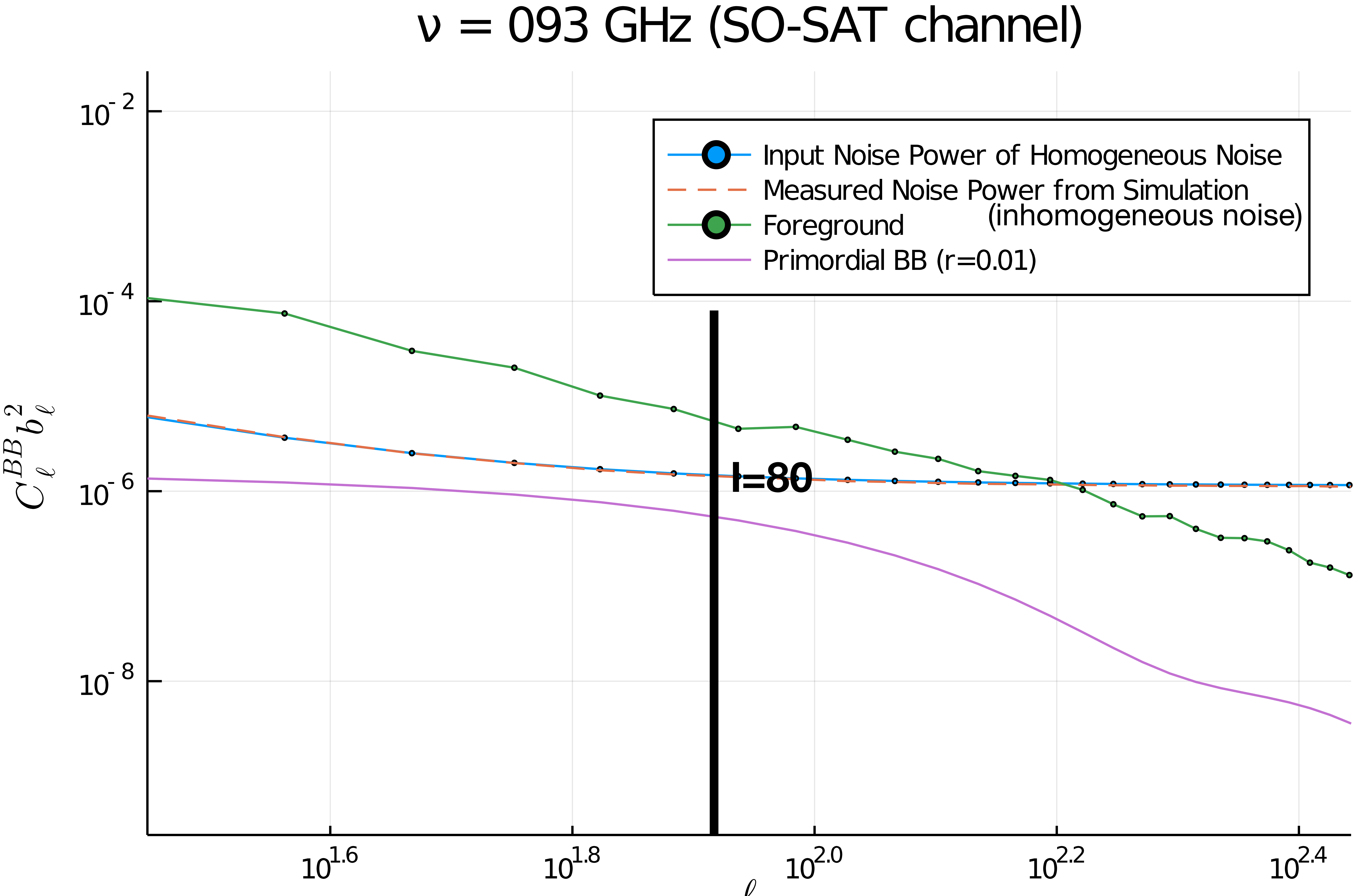
- It would be lovely to have a HWP, but…
  - When the 1/f noise goes like

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

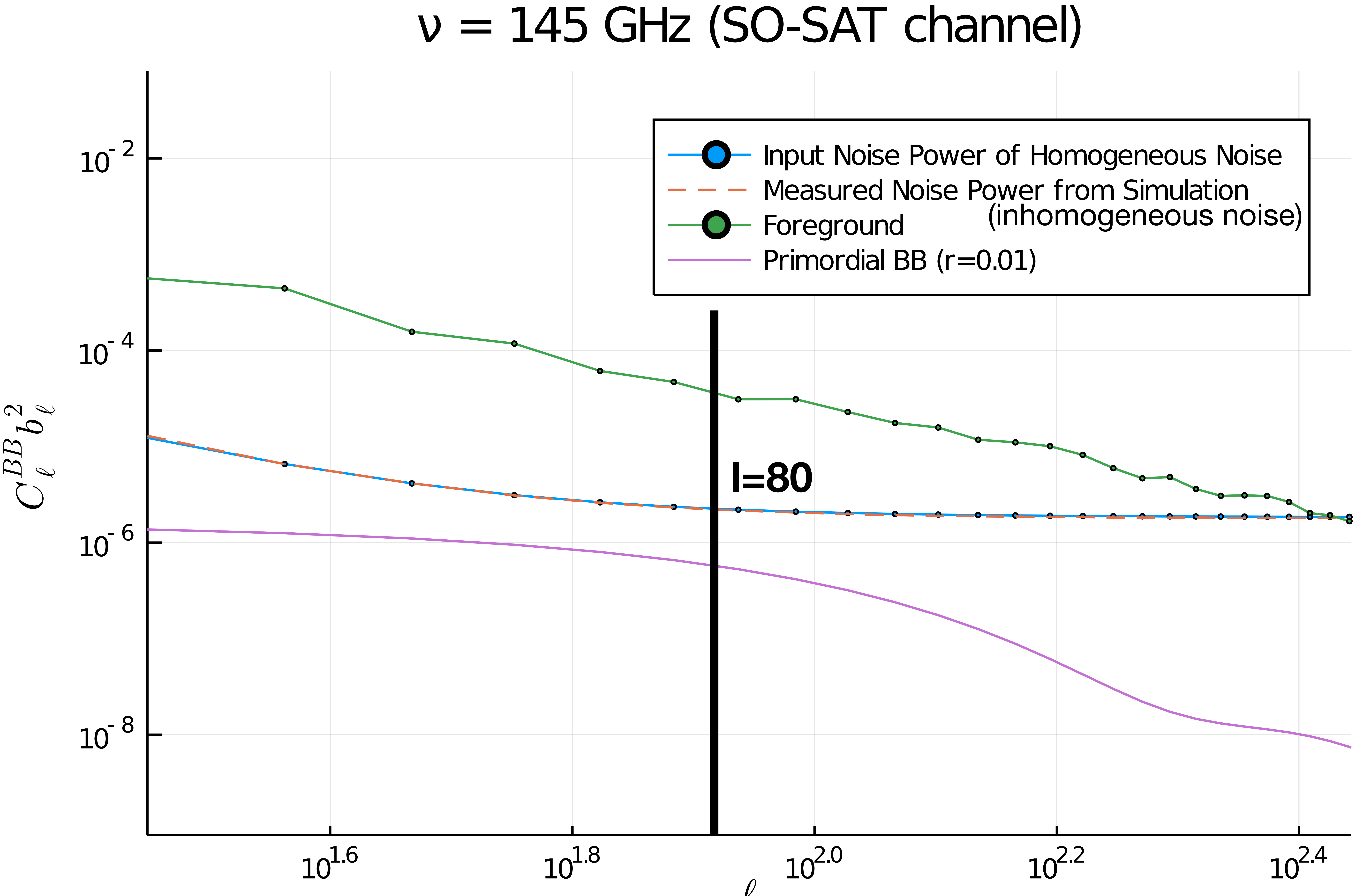
  - The dust power spectrum increase faster than the noise towards low multipoles. This is a (likely) explanation as to why FYST helps.

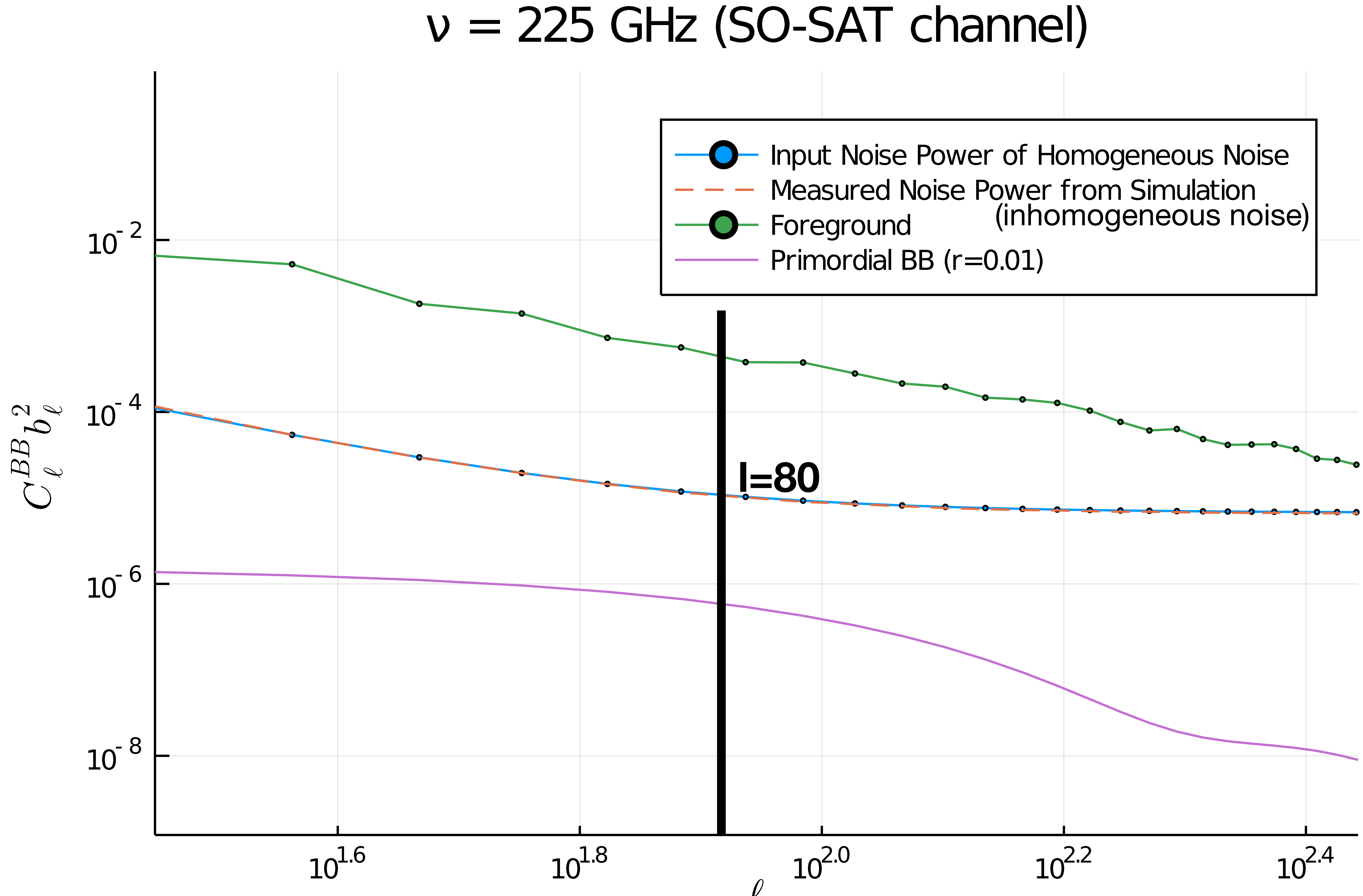

ν = 027 GHz (SO-SAT channel)
Input Noise Power of Homogeneous Noise
Measured Noise Power from Simulation
(inhomogeneous noise)
Foreground
Primordial BB (r=0.01)
l=80
10^{0}
10^{-5}
10^{-10}
10^{-15}
$C_\ell^{BB} b_\ell^2$
$10^{1.6}$
$10^{1.8}$
$10^{2.0}$
$10^{2.2}$
$10^{2.4}$
ℓ

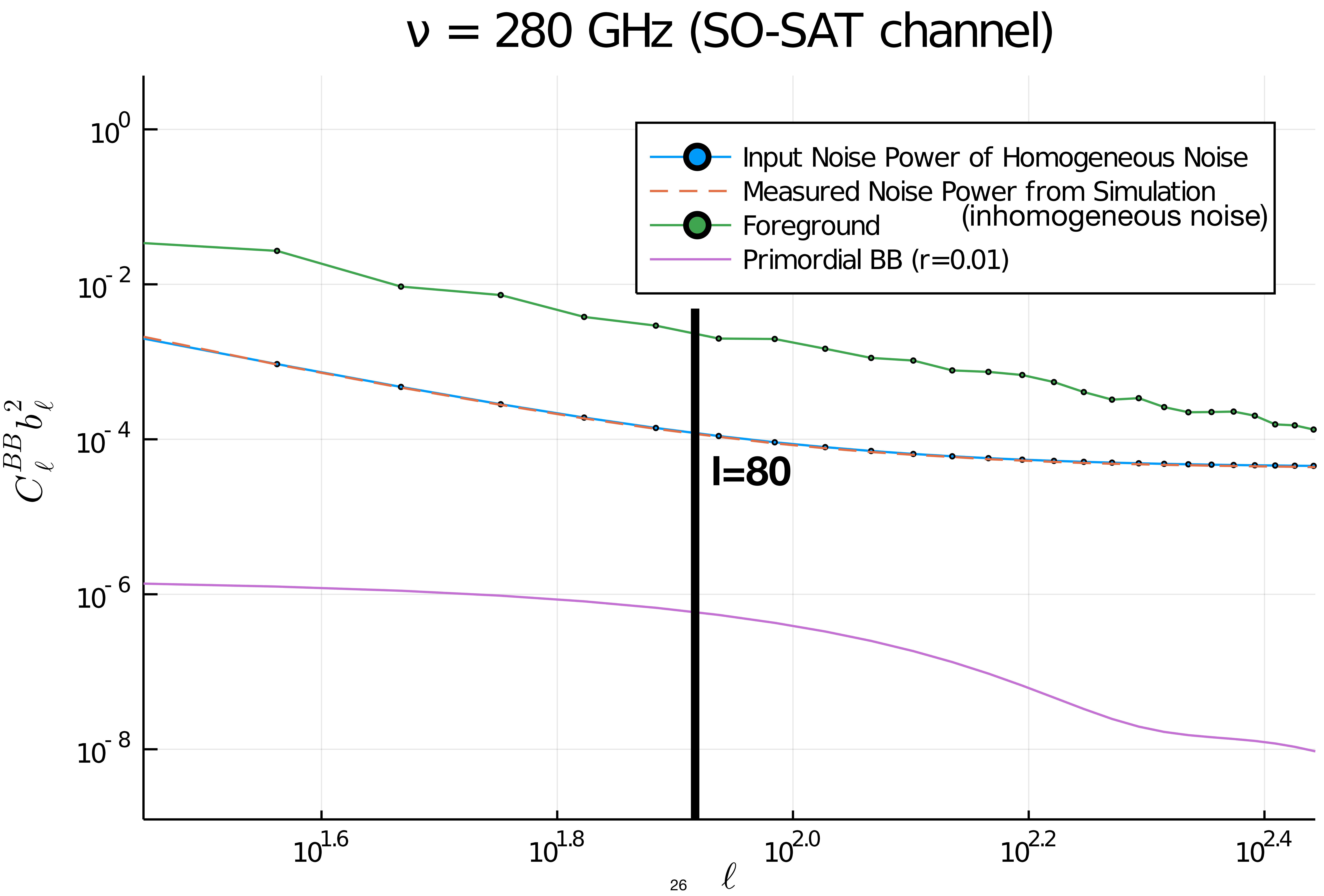

ν = 039 GHz (SO-SAT channel)
Input Noise Power of Homogeneous Noise
Measured Noise Power from Simulation (inhomogeneous noise)
Foreground
Primordial BB (r=0.01)
l=80
$C_\ell^{BB} b_\ell^2$
ℓ
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$10^{1.6}$
$10^{1.8}$
$10^{2.0}$
$10^{2.2}$
$10^{2.4}$



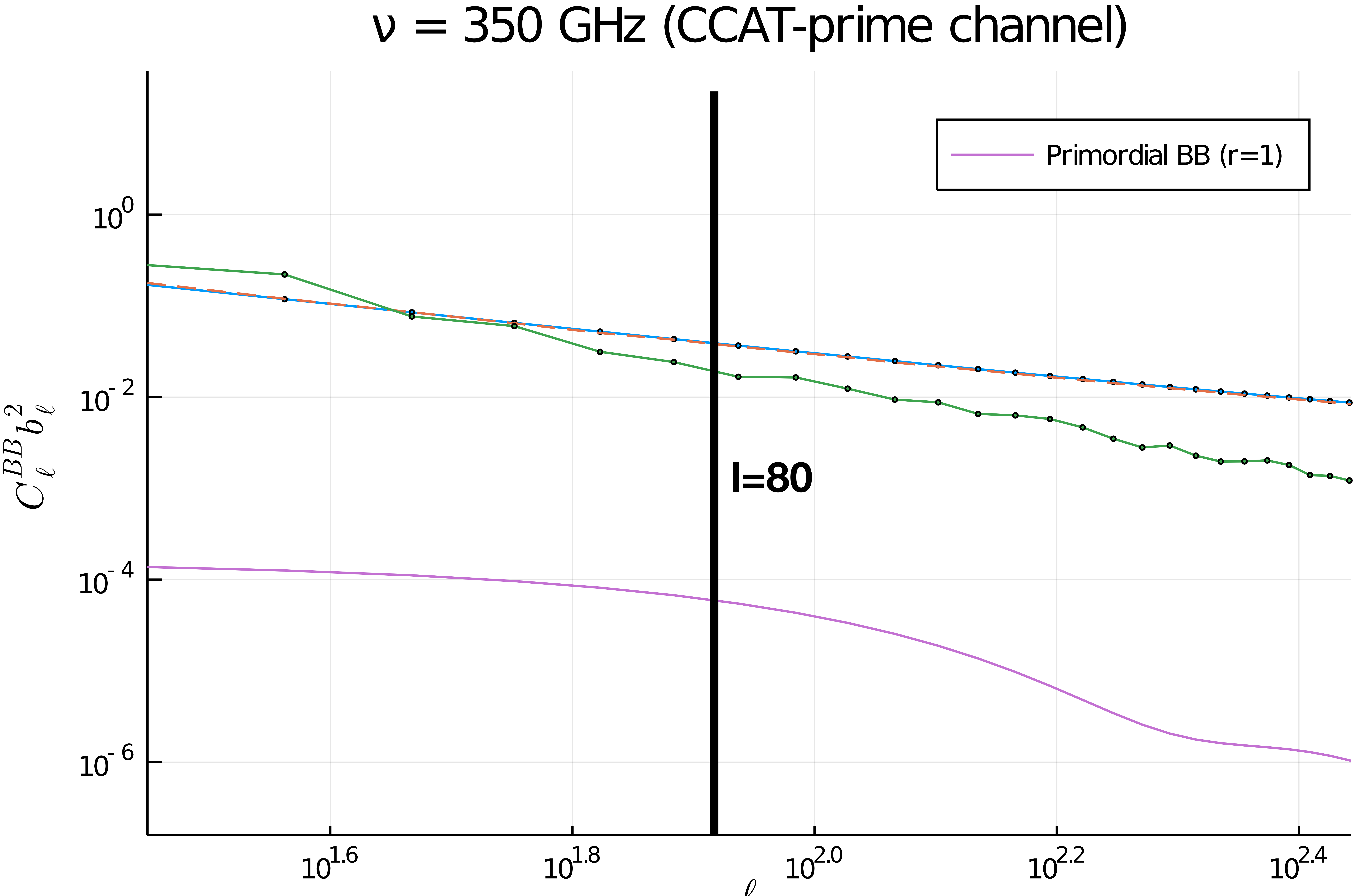
ν = 093 GHz (SO-SAT channel)
Input Noise Power of Homogeneous Noise
Measured Noise Power from Simulation
(inhomogeneous noise)
Foreground
Primordial BB (r=0.01)
l=80
$C_\ell^{BB} b_\ell^2$
ℓ
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$10^{1.6}$
$10^{1.8}$
$10^{2.0}$
$10^{2.2}$
$10^{2.4}$

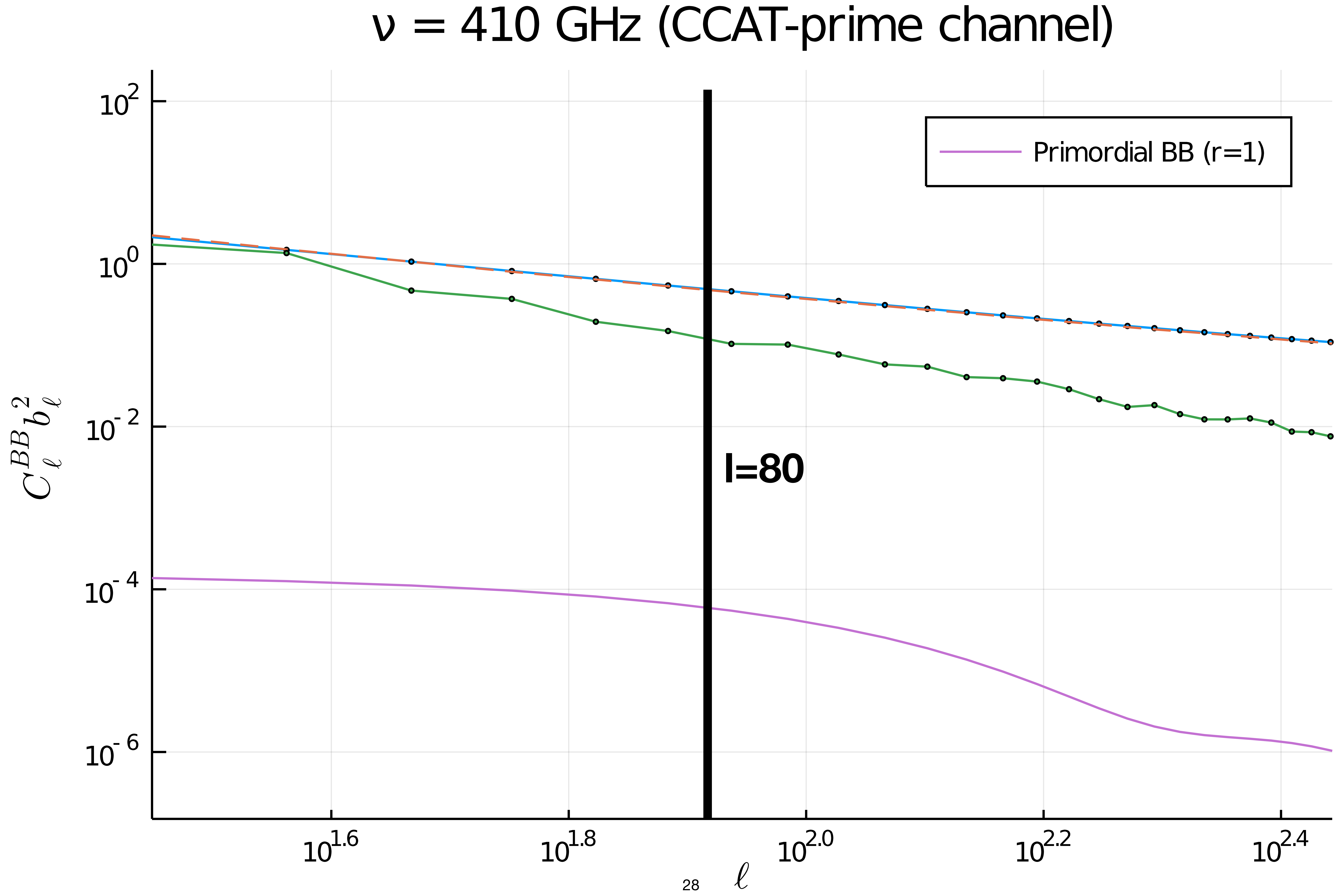

ν = 145 GHz (SO-SAT channel)
Input Noise Power of Homogeneous Noise
Measured Noise Power from Simulation
(inhomogeneous noise)
Foreground
Primordial BB (r=0.01)
l=80
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$C_\ell^{BB} b_\ell^2$
$10^{1.6}$
$10^{1.8}$
$10^{2.0}$
$10^{2.2}$
$10^{2.4}$
ℓ

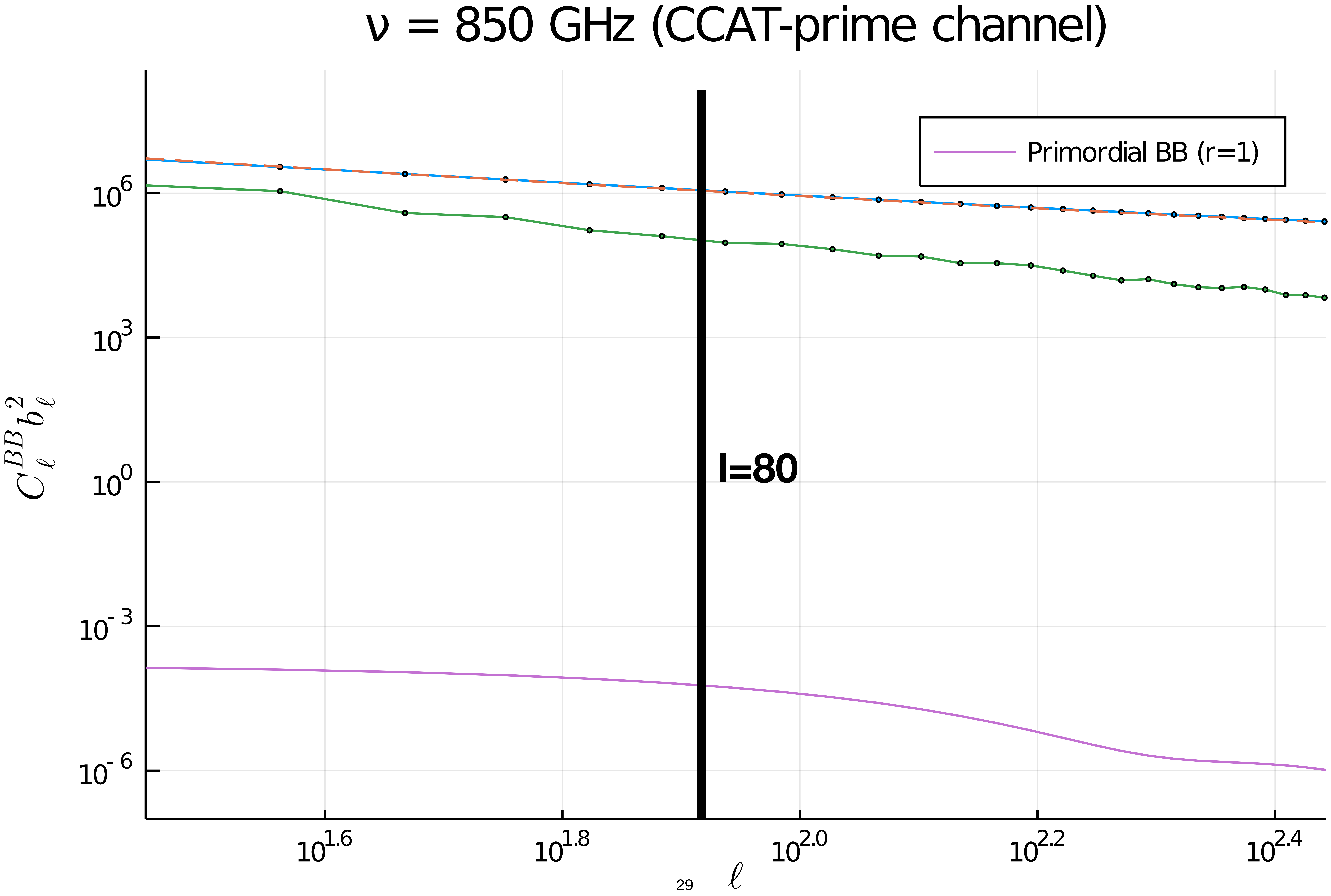

ν = 225 GHz (SO-SAT channel)
Input Noise Power of Homogeneous Noise
Measured Noise Power from Simulation
(inhomogeneous noise)
Foreground
Primordial BB (r=0.01)
l=80
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$C_\ell^{BB} b_\ell^2$
$10^{1.6}$
$10^{1.8}$
$10^{2.0}$
$10^{2.2}$
$10^{2.4}$
ℓ



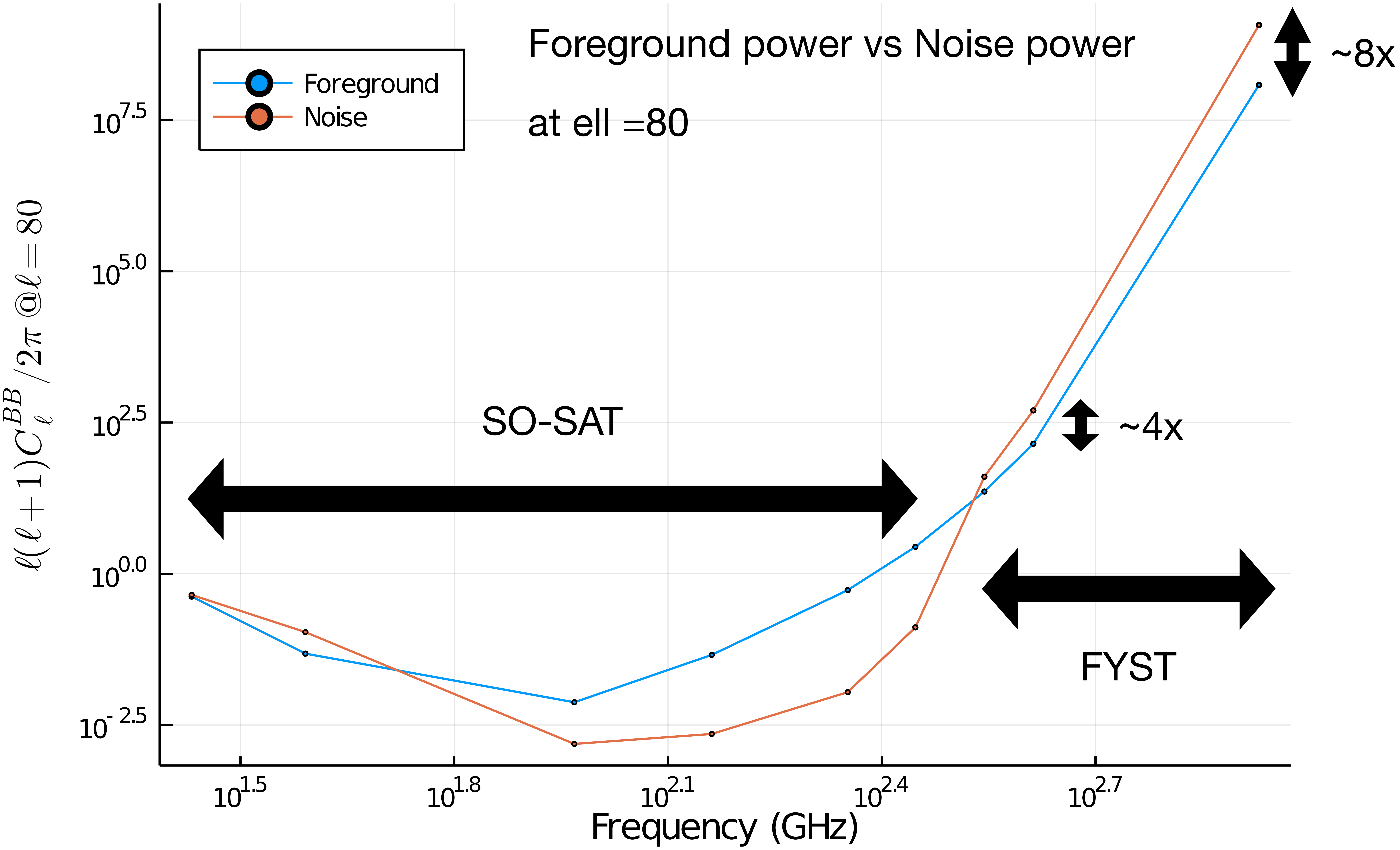
ν = 280 GHz (SO-SAT channel)
Input Noise Power of Homogeneous Noise
Measured Noise Power from Simulation
(inhomogeneous noise)
Foreground
Primordial BB (r=0.01)
l=80
$C_\ell^{BB} b_\ell^2$
ℓ
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$10^{1.6}$
$10^{1.8}$
$10^{2.0}$
$10^{2.2}$
$10^{2.4}$


ν = 350 GHz (CCAT-prime channel)
Primordial BB (r=1)
l=80
$C_\ell^{BB} b_\ell^2$
ℓ
10^{0}
10^{-2}
10^{-4}
10^{-6}
$10^{1.6}$
$10^{1.8}$
$10^{2.0}$
$10^{2.2}$
$10^{2.4}$


ν = 410 GHz (CCAT-prime channel)
Primordial BB (r=1)
l=80
$C_\ell^{BB} b_\ell^2$
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
$10^{1.6}$
$10^{1.8}$
$10^{2.0}$
$10^{2.2}$
$10^{2.4}$
ℓ



ν = 850 GHz (CCAT-prime channel)
Primordial BB (r=1)
l=80
$C_\ell^{BB} b_\ell^2$
10^6
10^3
10^0
10^{-3}
10^{-6}
$10^{1.6}$
$10^{1.8}$
$10^{2.0}$
$10^{2.2}$
$10^{2.4}$
ℓ



Foreground power vs Noise power
at ell =80
Foreground
Noise
~8x
~4x
SO-SAT
FYST
$10^{7.5}$
$10^{5.0}$
$10^{2.5}$
$10^{0.0}$
$10^{-2.5}$
$10^{1.5}$
$10^{1.8}$
$10^{2.1}$
$10^{2.4}$
$10^{2.7}$
Frequency (GHz)
$\ell(\ell+1)C_\ell^{BB}/2\pi\ @\ell=80$

Removing low-ell data

What if our 1/f noise model were completely wrong?

- SO-SAT only: $r = (1.30 \pm 2.76) \times 10^{-3}$
- FYST+SO-SAT nominal: $r = (0.19 \pm 2.73) \times 10^{-3}$

- Removing ell<60: $r = (0.51 \pm 2.77) \times 10^{-3}$
- Removing ell<100: $r = (0.99 \pm 2.80) \times 10^{-3}$

- Improvement is still substantial even when we throw away the low ell data.

Early Science Goals

- The top priority is to examine and understand the atmospheric noise and 1/f performance of instruments on sky.
  - This study enables more realistic forecasts for the improvement in the tensor-to-scalar ratio measurement, and helps coordinate with SO-SAT early on.
- To this end, it would be important to make wide-area measurements during the early science phase.
- Paper(s) on this study will be valuable for CMB-S4.

Summary

The answers to two questions

- **Can the FYST data help remove the polarised Galactic dust emission from other CMB data?**
  - Yes! Even when throwing away low-ell data.
- **How/why do the FYST data help?**
  - Because the dust power spectrum rises faster than ell$^{-1.4}$ noise towards low multipoles.
  - It is not entirely due to better determination of βd and Td. Adding each of 350, 410, and 850 GHz data helps equally. (But this likely depends on the FG removal method.)