SZ observables and LSS cross correlations: $C_\ell^{y\kappa_{CMB}}$

Fiona McCarthy

Thanks to many collaborators especially: Boris Bolliet, William Coulton,
Colin Hill *,…….*

see F McCarthy and JC Hill, arXiv:2307.01043 and arXiv:2308.????

FLATIRON INSTITUTE
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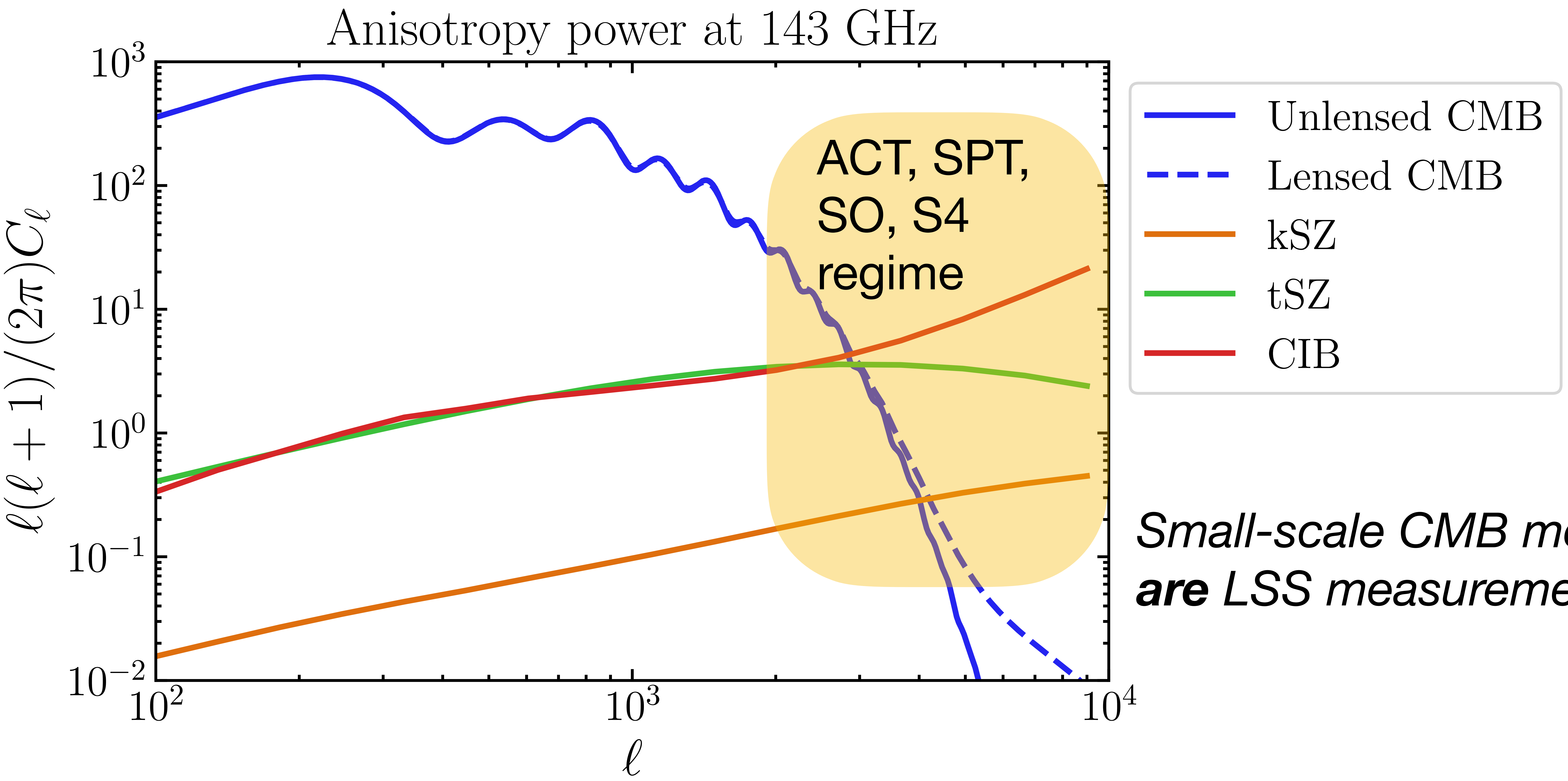
CMBS4 Meeting, 31 July 2023

Anisotropies in the small-scale microwave sky

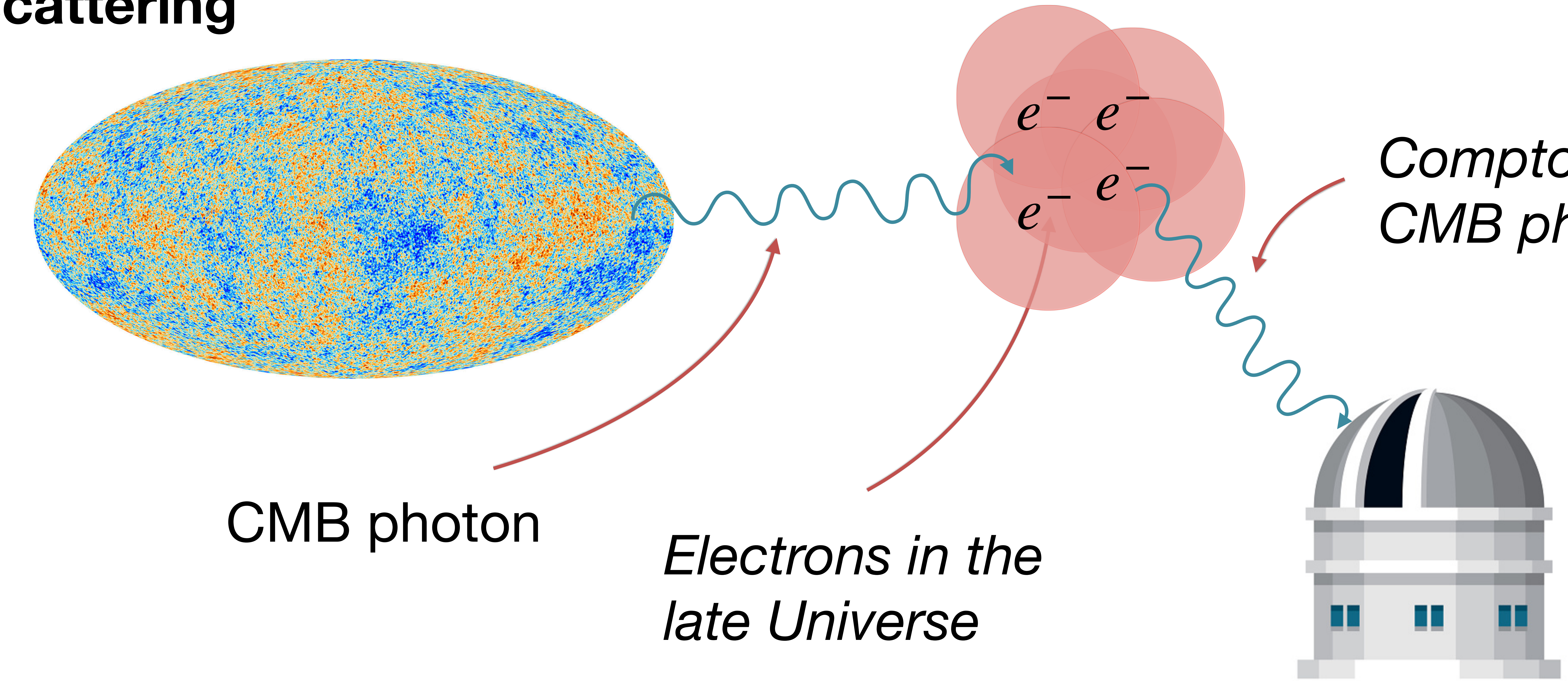


*Small-scale CMB measurements **are** LSS measurements*

All foreground signals calculated with CLASS-SZ *, halomodel/Boltzmann code by Boris Bolliet et al*

The Sunyaev—Zel’dovich effect: the CMB “lighting up” the electrons

- We can use the CMB light to “see” late-Universe electrons through **Compton scattering**



Compton-scattered CMB photon

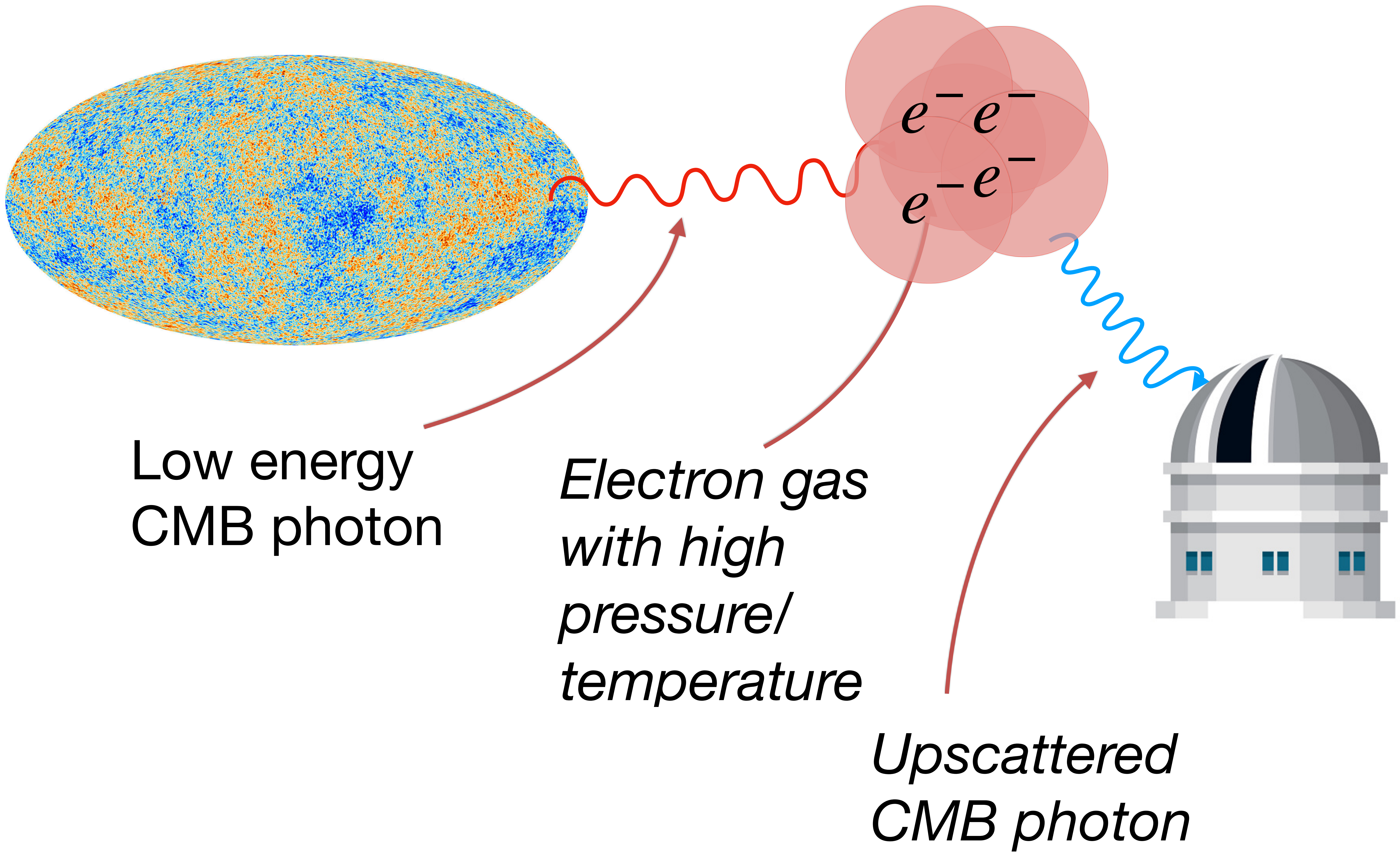
CMB photon

Electrons in the late Universe

- This has several effects in different regimes, in particular **thermal** SZ and **kinetic** SZ

The **thermal** SZ effect: high-energy electrons

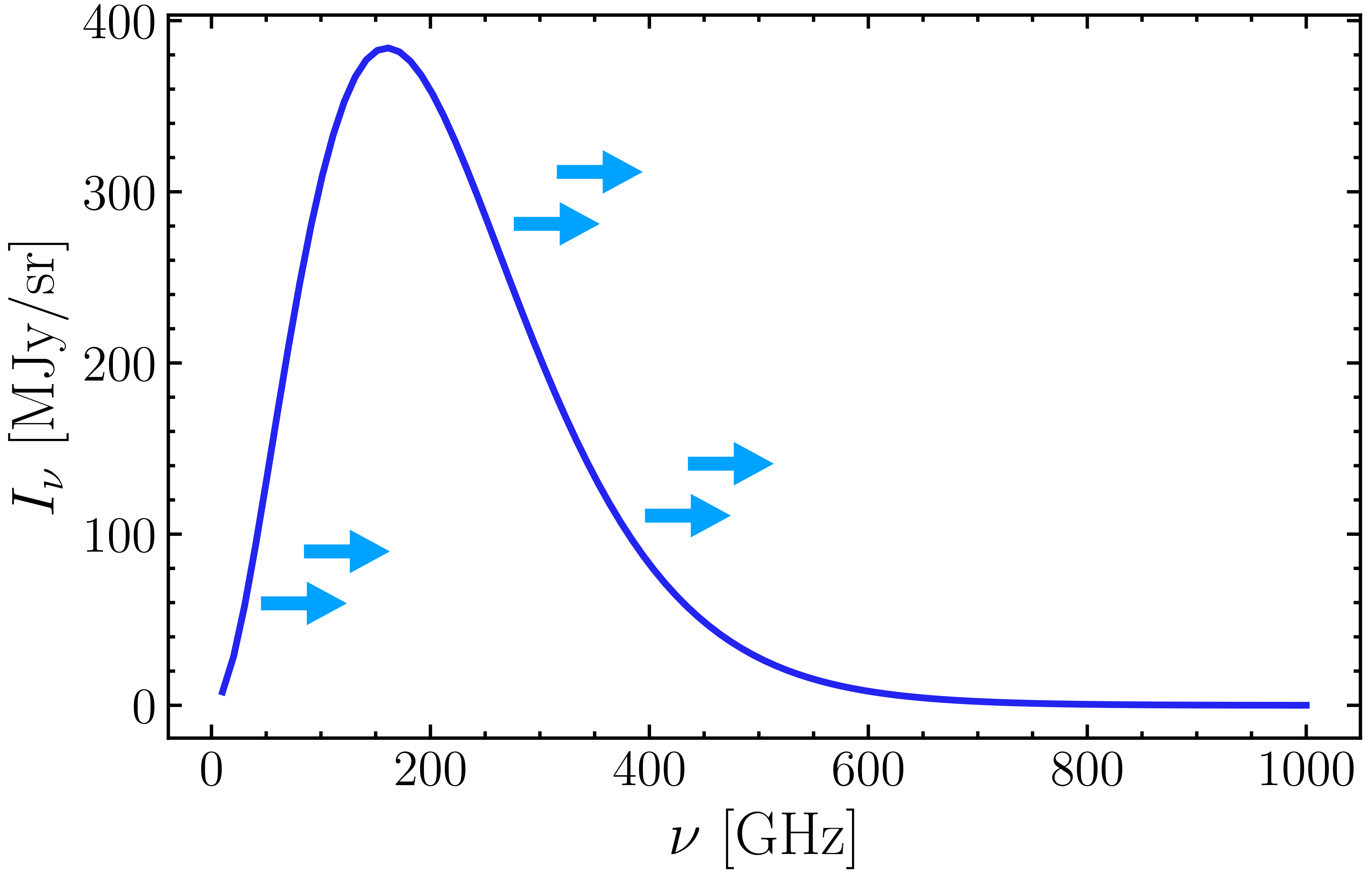
- When the electron has **high energy** it **transfers some to the photon**
- **Changes the CMB frequency spectrum**



Low energy
CMB photon

Electron gas with high pressure/ temperature

Upscattered CMB photon



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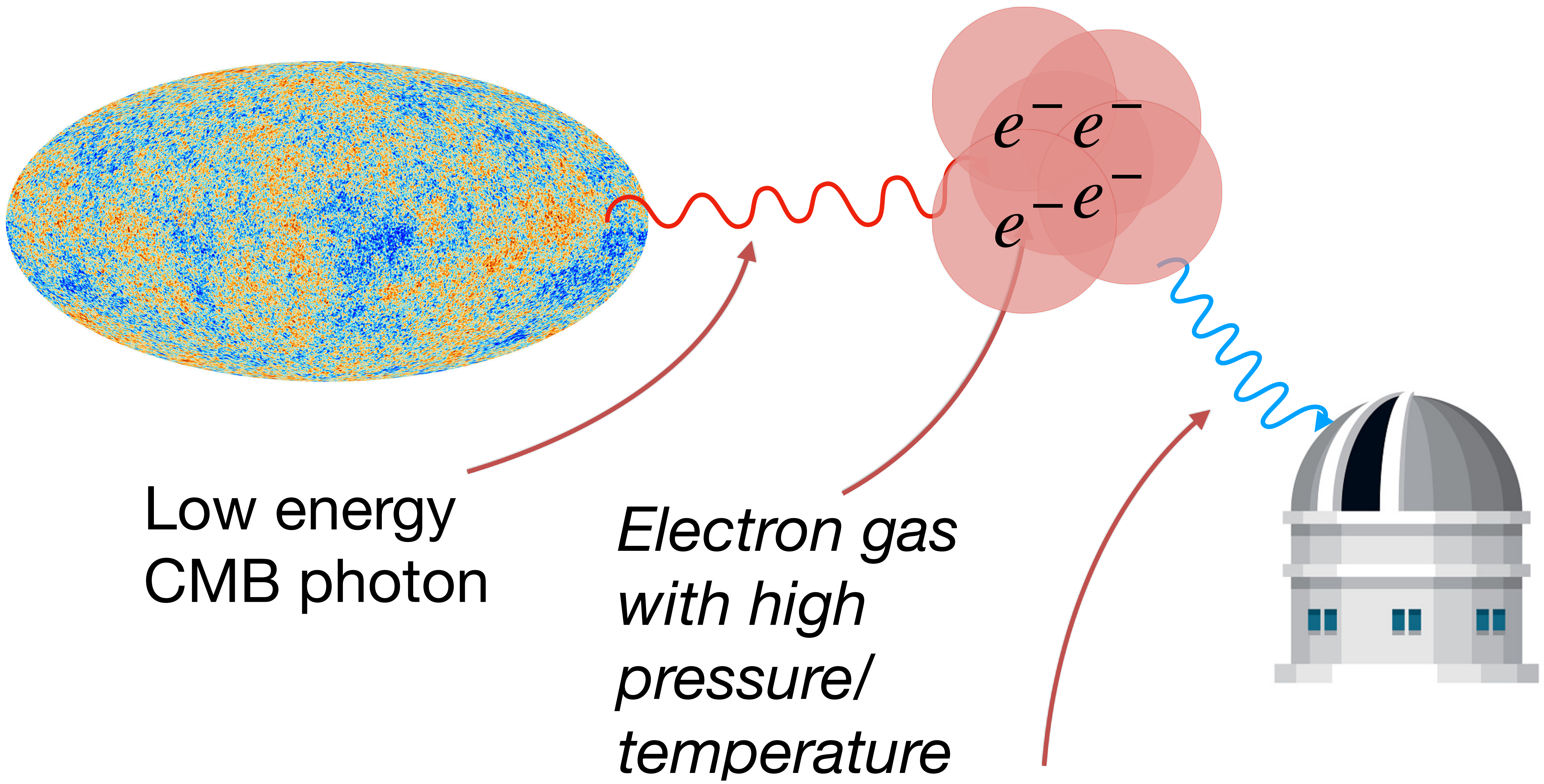

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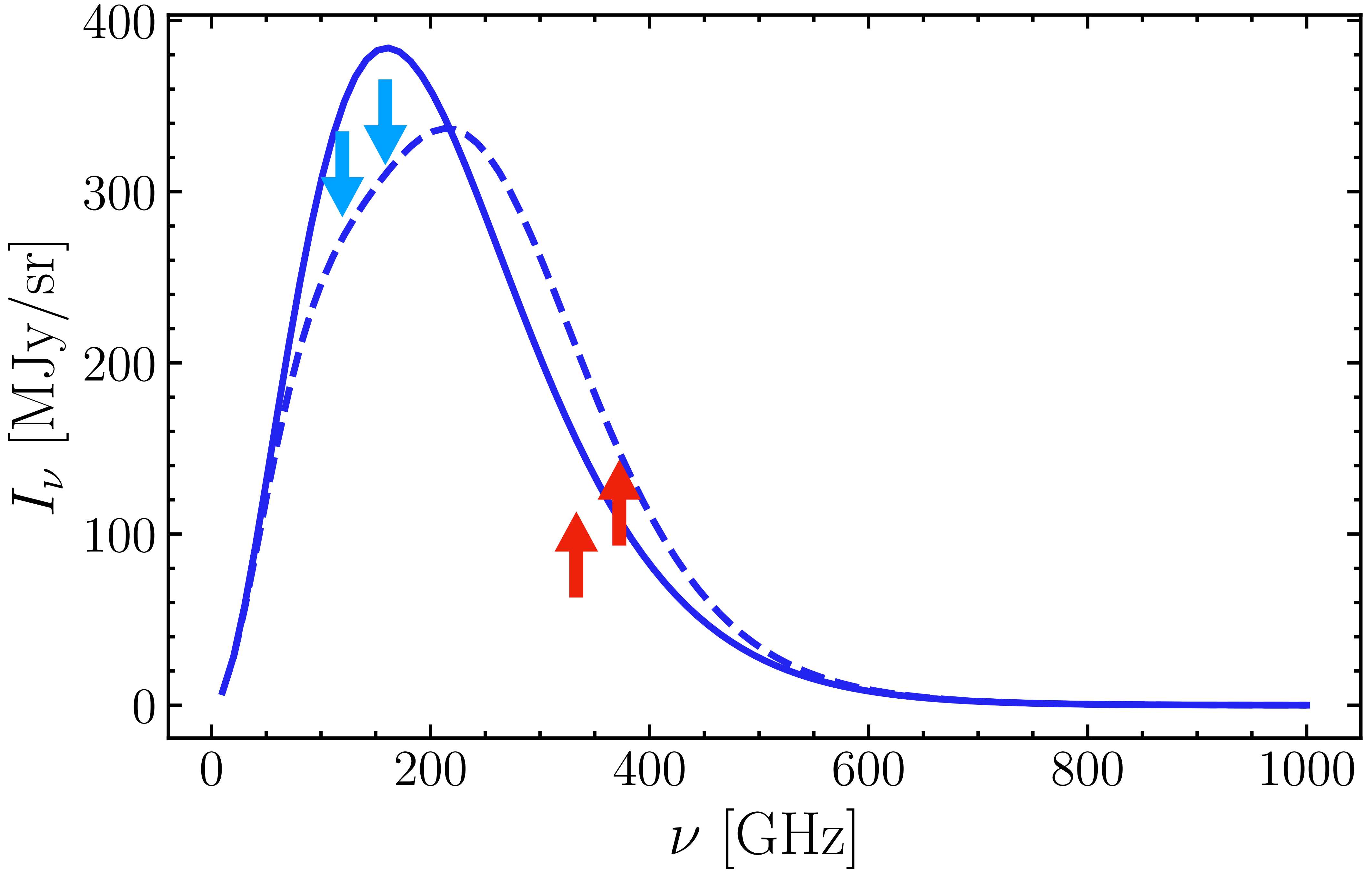

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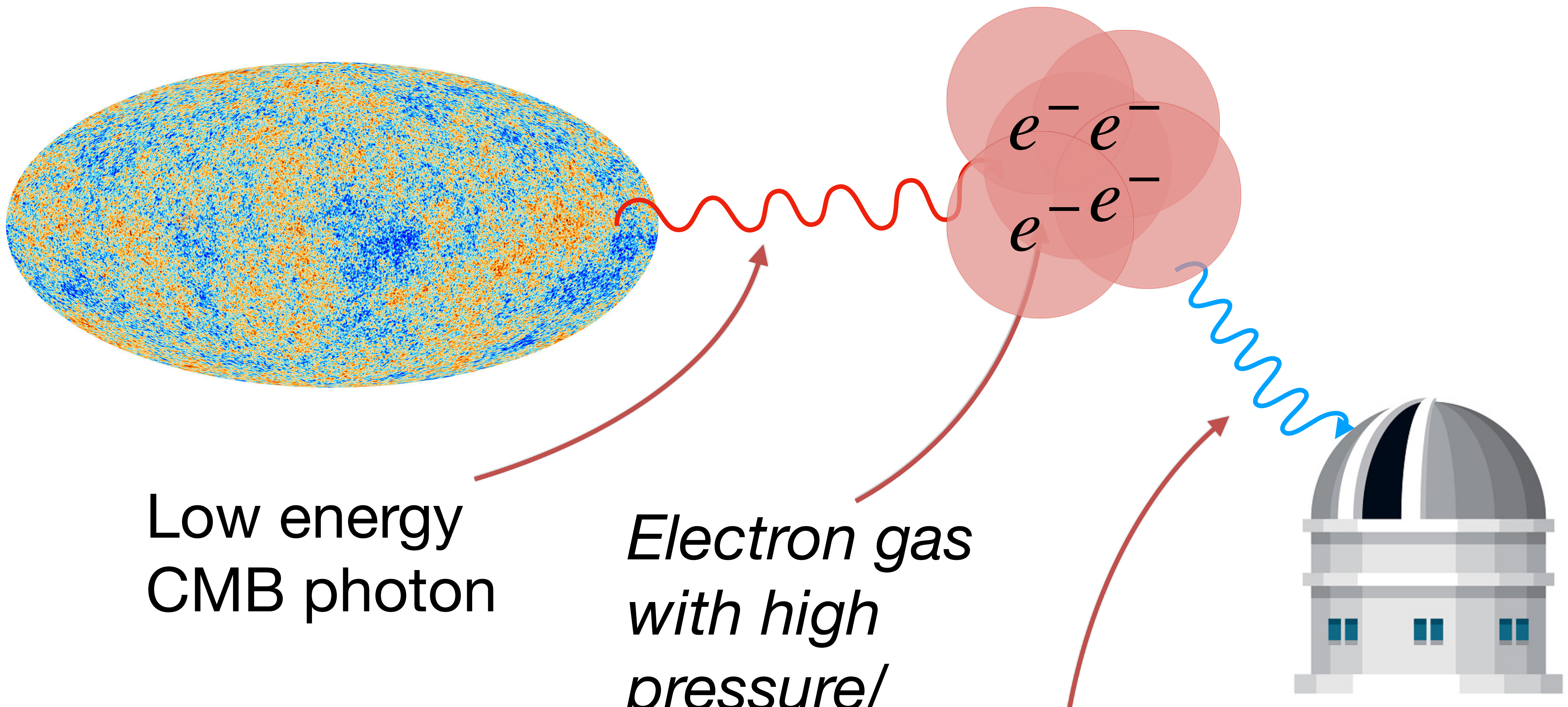

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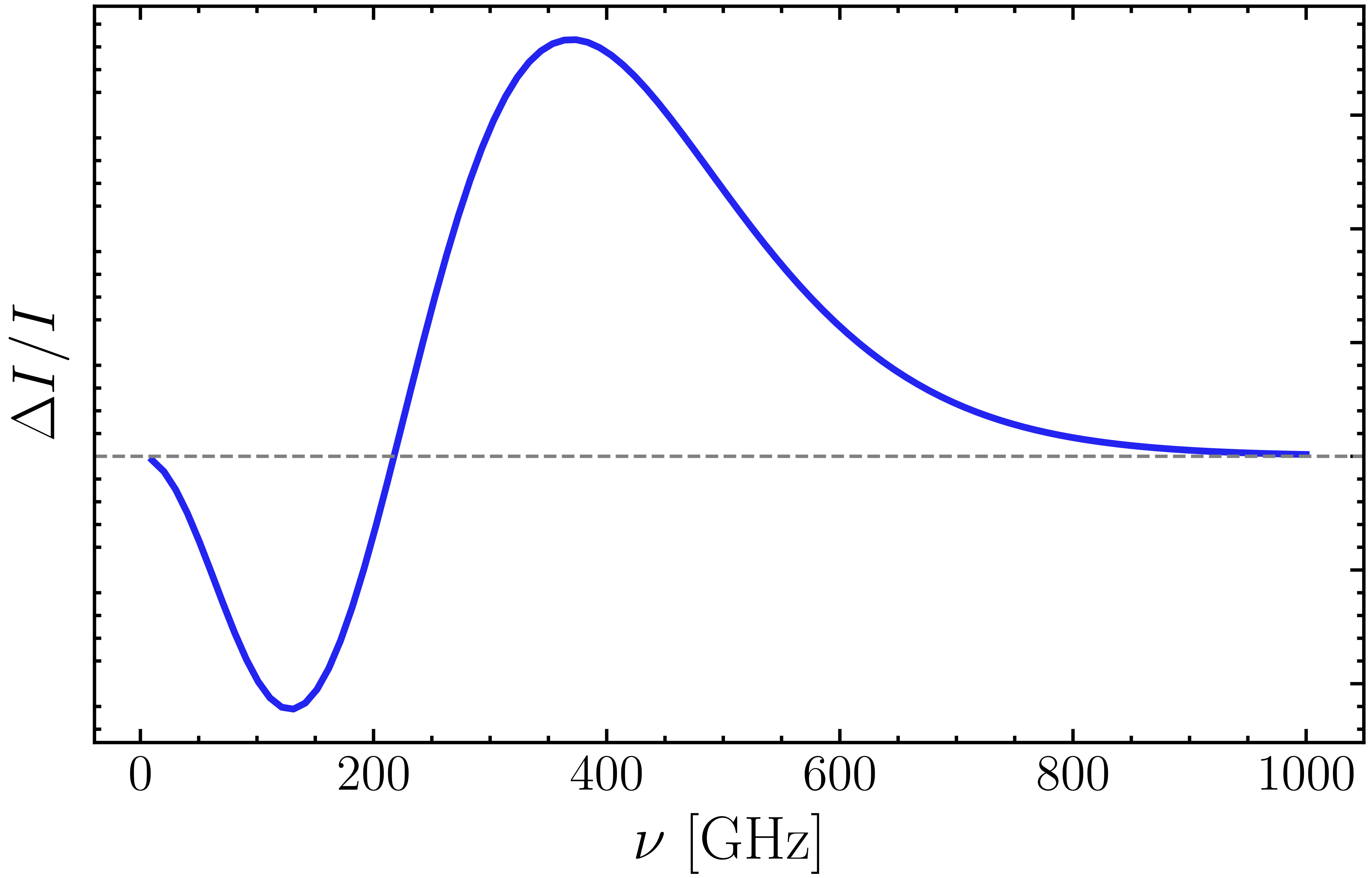
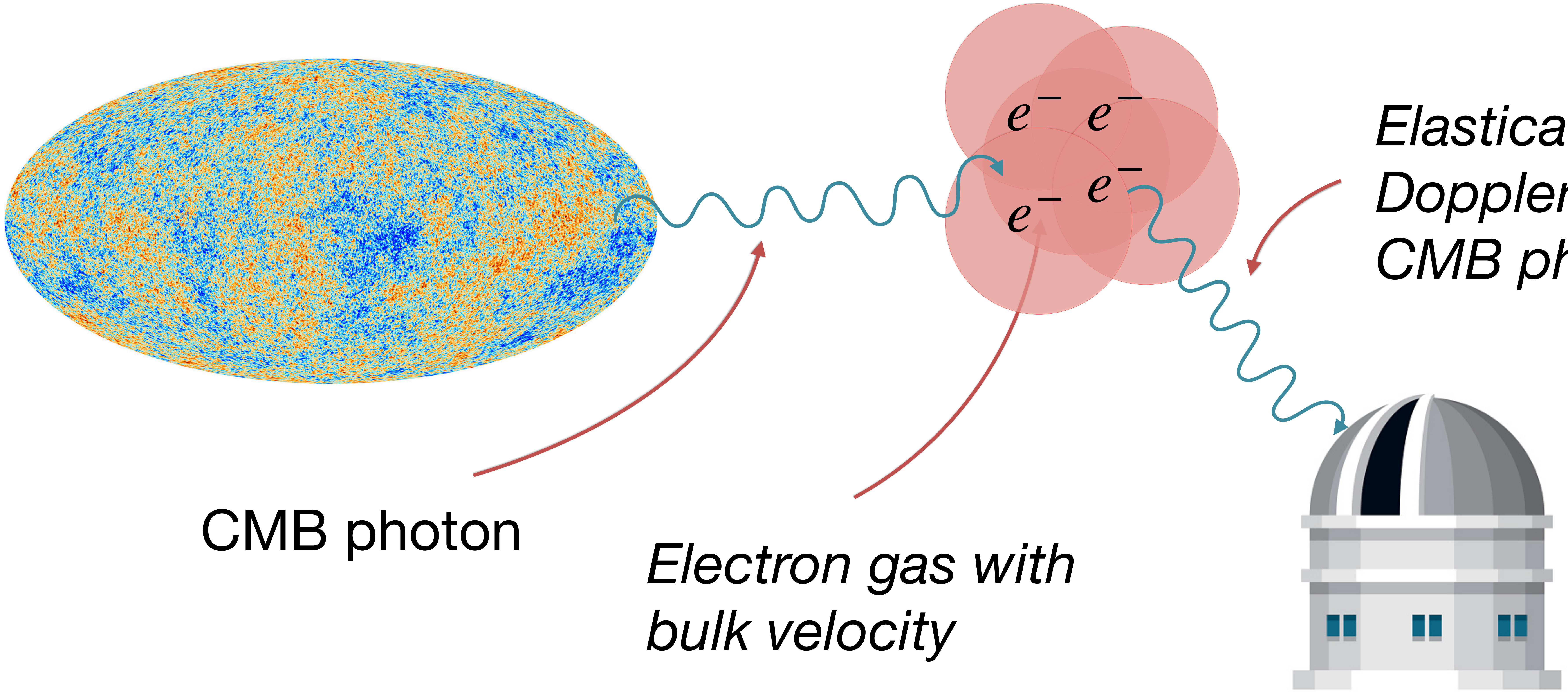


$$\frac{\Delta T}{T} = x\coth\left(\frac{x}{2}\right) - 4 \qquad x \equiv \frac{h\nu}{k_B T_{CMB}}$$

The **kinetic** SZ effect: electrons with velocity

- The low-energy **Thomson scattering** limit of Compton scattering. This is **elastic** -> **no CMB frequency distortion**
- Sensitive to the **CMB dipole the electrons observe** (this is dominated by their velocity)



Elastically scattered Doppler-boosted CMB photon

CMB photon

Electron gas with bulk velocity

Science from SZ 1) Feedback

tSZ: $\frac{\Delta T}{T} = g_\nu y(\hat{n}) \quad y(\hat{n}) = \frac{\sigma_T}{m_e c^2} \int d\chi a(\chi) P_e(\chi, \hat{n})$

kSZ: $\frac{\Delta T}{T} = -\sigma_T \int d\chi a(\chi) v_{||} n_e(\chi)$

Astrophysics

- The SZ effects are sensitive to **electrons in different environments.** We can use kSZ to **map all the electrons directly** and tSZ to **map the hot gas,** directly constraining AGN feedback.

Astrophysics -> Cosmology

- **Baryonic processes** are a major source of uncertainty in modelling the **matter power spectrum**. Getting a handle on baryons will allow us to **use matter probes to smaller scales for cosmology.**

*See talk by **Aleksandra Kusiak** on Wednesday*

Science from SZ 2) Cosmology

tSZ: $\frac{\Delta T}{T} = g_\nu y(\hat{n}) \quad y(\hat{n}) = \frac{\sigma_T}{m_e c^2} \int d\chi a(\chi) P_e(\chi, \hat{n})$

kSZ: $\frac{\Delta T}{T} = -\sigma_T \int d\chi a(\chi) v_{||} n_e(\chi)$

tSZ

- The tSZ effect is sourced in the **most massive clusters** ($P \sim \propto M^{5/3}$)and probes the **tail of the halo mass function** -> constraints on Ω_m, σ_8

See talks by ***Lindsay Bleem, Inigo Zubeldia, Chun-Hao To*** *on Wednesday*

kSZ

- The **velocity dependence** of kSZ allows us to measure P(k) on large scales and constrain primordial physics

See talk by ***Matthew Johnson*** *on Wednesday*

tSZ and kSZ: isolation, separation, probes

- We separate components with **multifrequency measurements**
- We can **isolate the tSZ with the unique frequency spectrum** $\frac{\Delta T}{T} = g_{\nu} y(\hat{n})$
- We **cannot separate kSZ from the background CMB with frequency measurements.** Previous detections come from LSS cross correlations: **stacking**, bispsectra (<kSZ^2-LSS>), targeted observations…
- Probes of the tSZ: cluster counts, power spectrum, 1-point PDF, cross power spectra C_{ℓ}^{yLSS},…
- Probes of the kSZ: power spectrum, stacking projected-fields estimator $C_{\ell}^{kSZ^2LSS}$, kSZ tomography, higher point statistics…

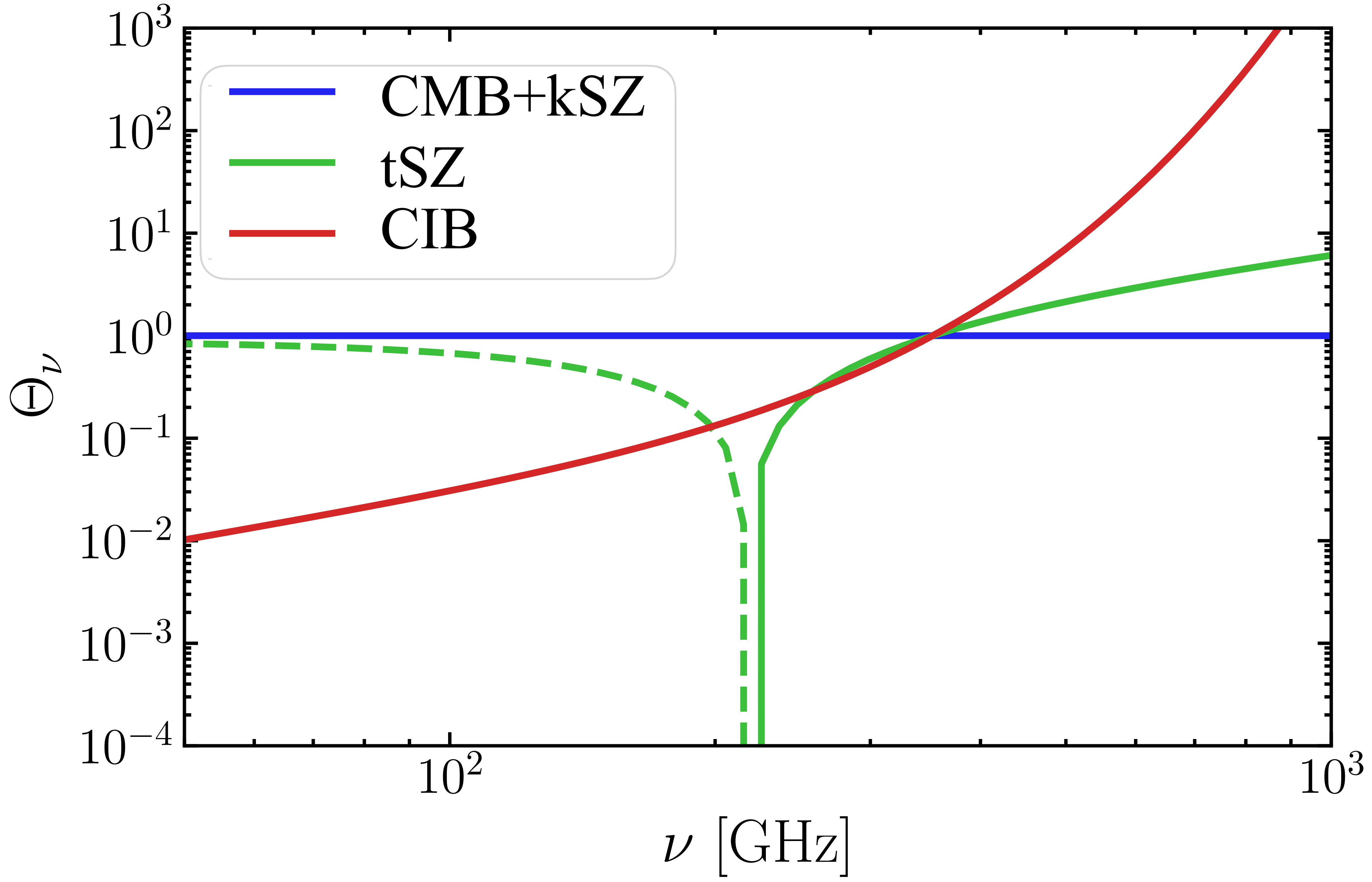
Frequency-based component separation: ILC

$$T(\nu, \hat{n}) = T^{CMB}(\hat{n}) + T^{kSZ}(\hat{n}) + g_\nu y(\hat{n}) + T^{FG}(\nu, \hat{n}) + N(\nu, \hat{n})$$

ILC is a linear combination:

$$\hat{T}^{CMB+kSZ}(\hat{n}) = \sum_\nu c_\nu T_\nu(\hat{n}) \text{ where } \sum_\nu c_\nu = 1$$

$$\hat{y}(\hat{n}) = \sum_\nu c_\nu T_\nu(\hat{n}) \text{ where } \sum_\nu g_\nu c_\nu = 1$$



$$c_\nu = \left[\left(A_\nu^T C^{-1} A_\nu\right)^{-1}\right]_{\nu\nu'} \left[A_\nu^T \left(C^{-1}\right)\right]_{\nu'}$$

with
- $A_\nu = 1$ for CMB+kSZ
- $A_\nu = g_\nu$ for tSZ

where $C_{\nu\nu'} = \langle T_\nu T'_\nu \rangle - \langle T_\nu \rangle \langle T_{\nu'} \rangle$

*See talk by **William Coulton** on Wednesday for ILC maps from ACT!!*

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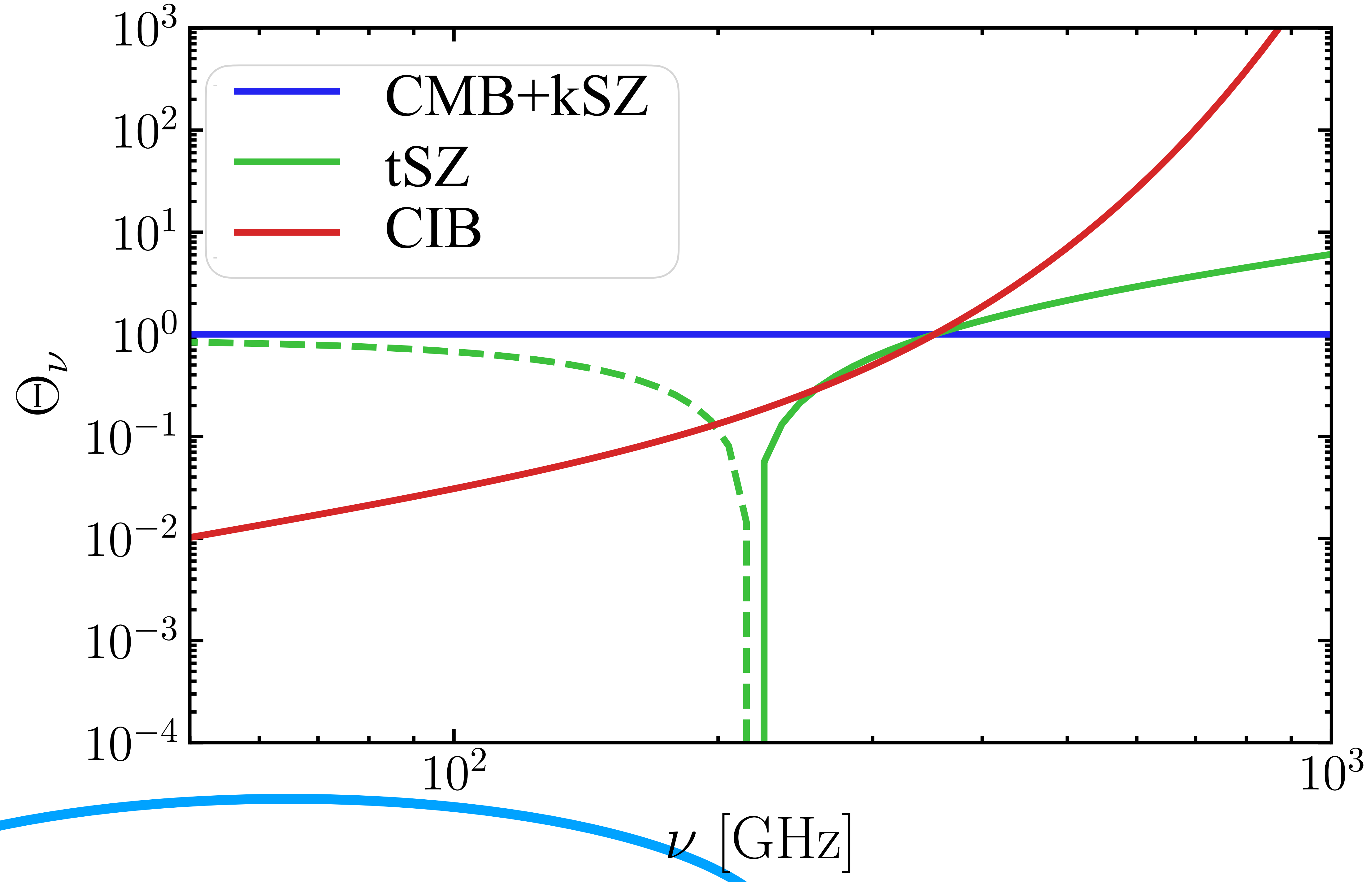

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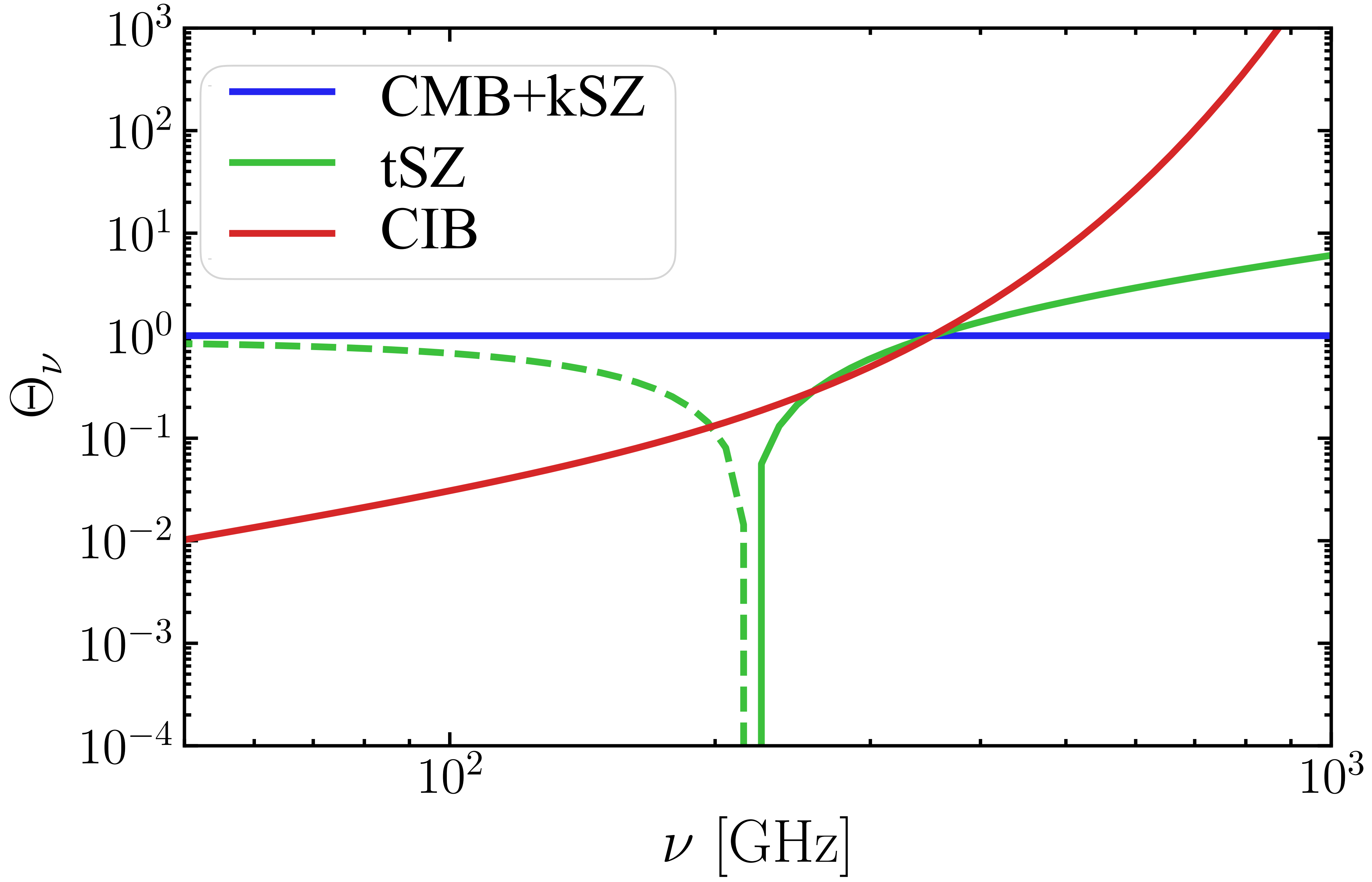

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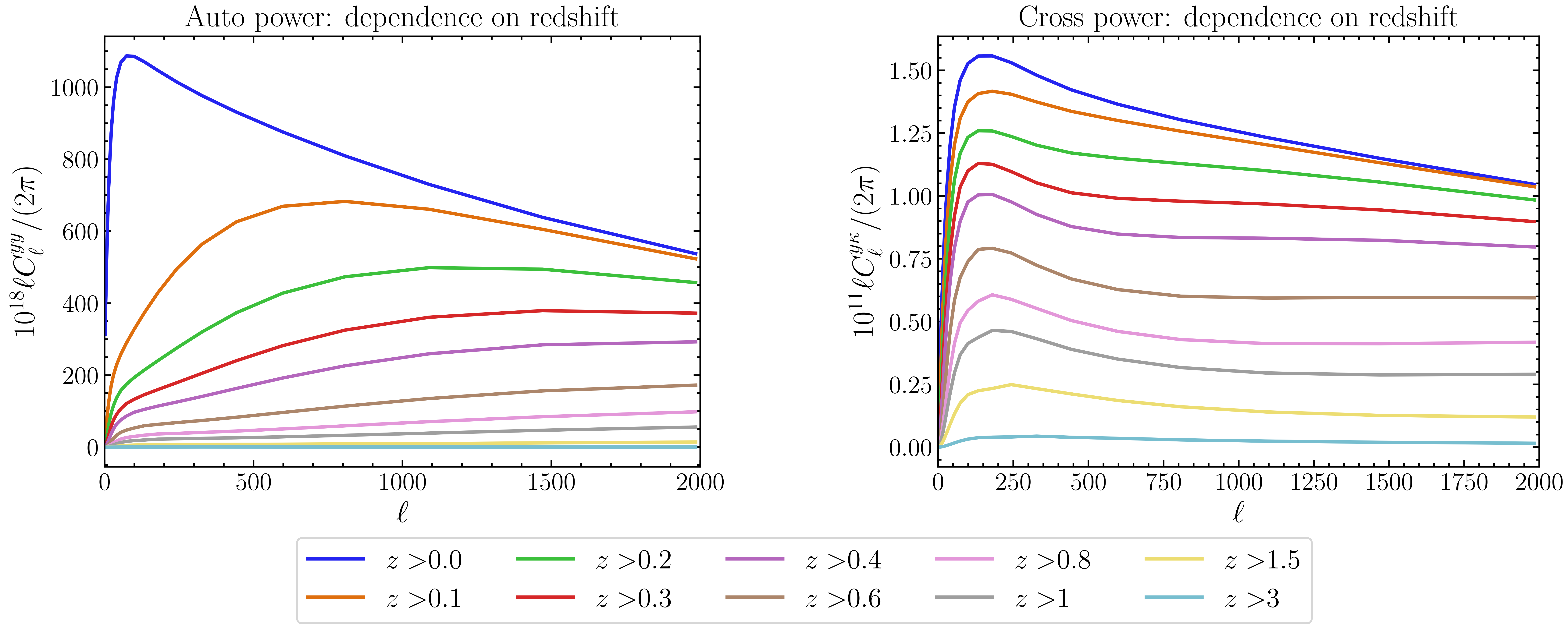
Cross correlation example: tSZ cross CMB lensing

- Cross correlations give us access to new regimes of the signal. What **redshifts** contribute most?



Auto power: dependence on redshift

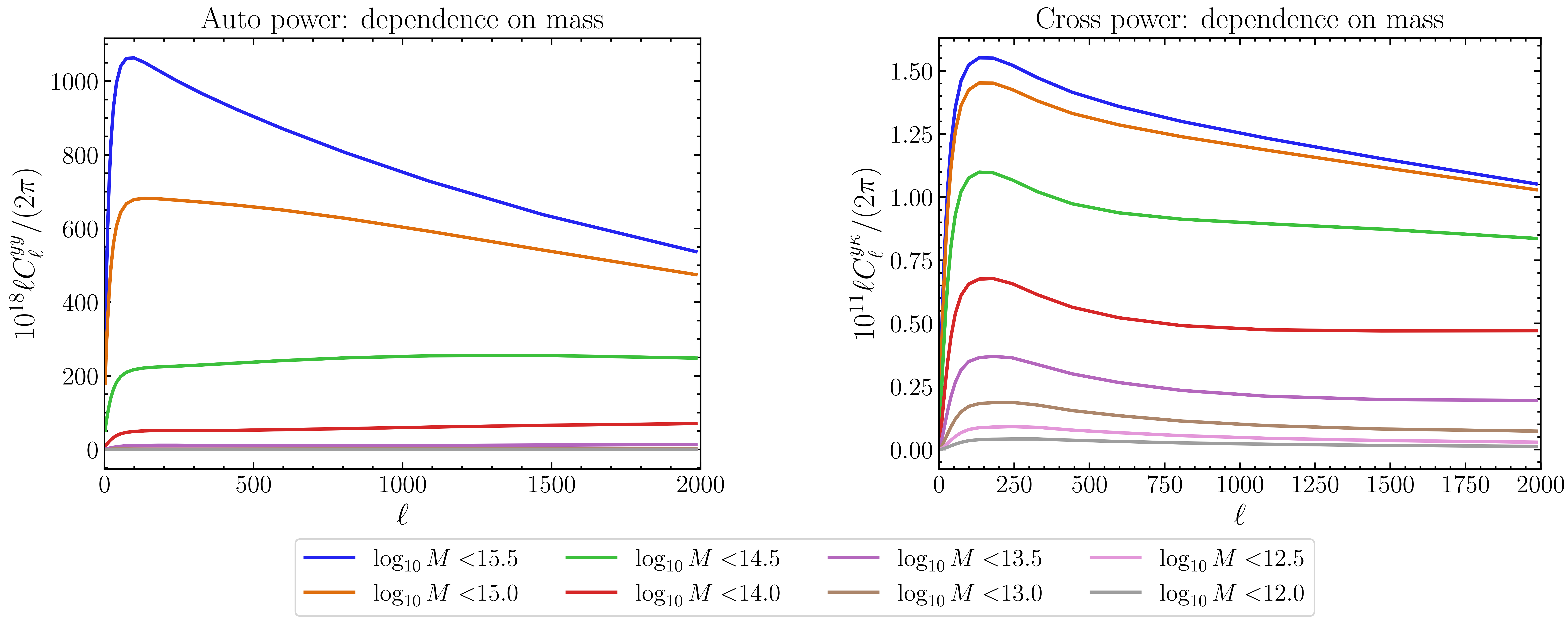
Cross power: dependence on redshift

- We probe a **higher redshift regime** than *y* alone

FMcC and Colin Hill, to appear

Cross correlation example: tSZ cross CMB lensing

- All halo model calculations involve an integral over halo masses. What **masses** contribute most?

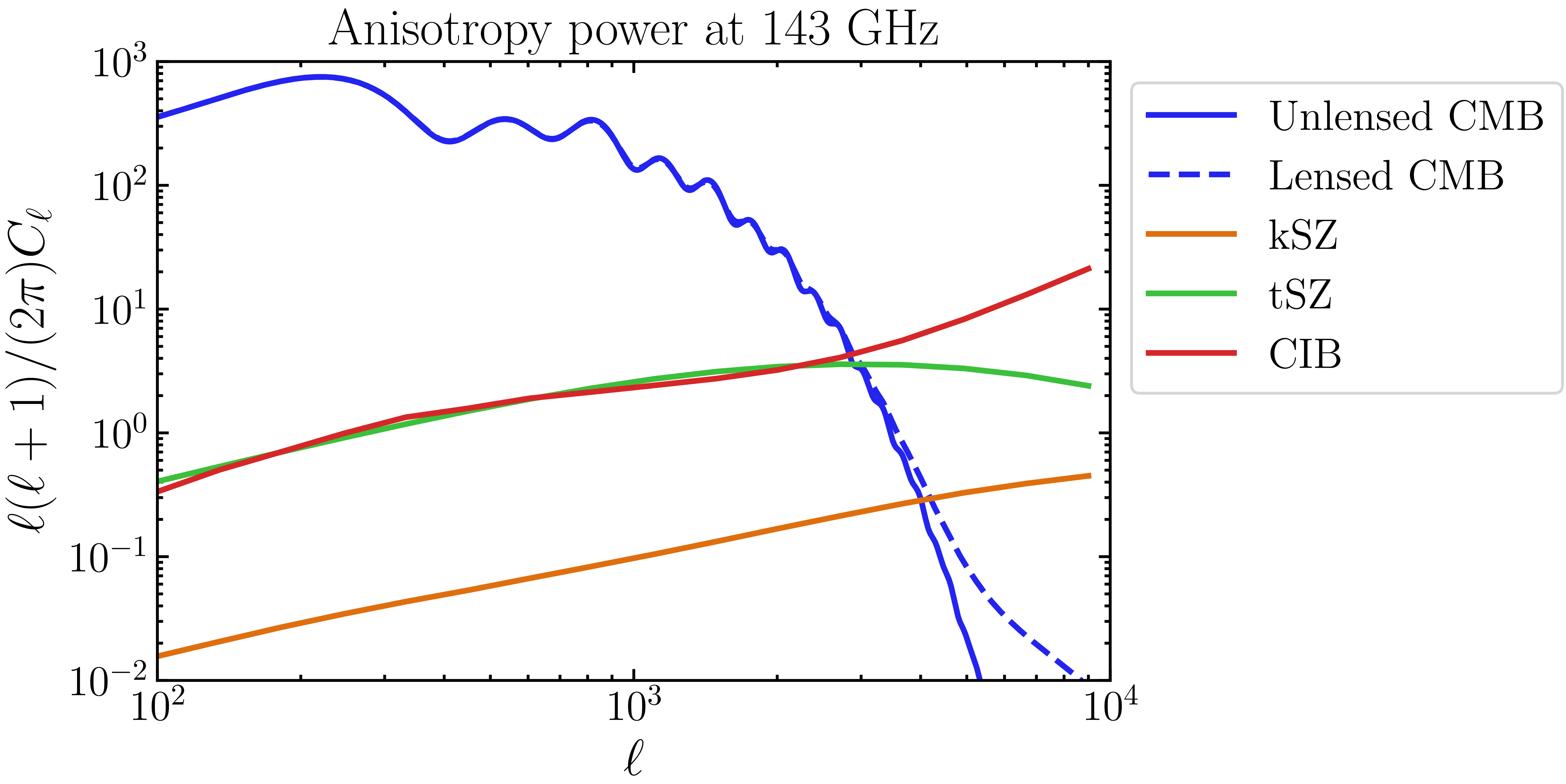


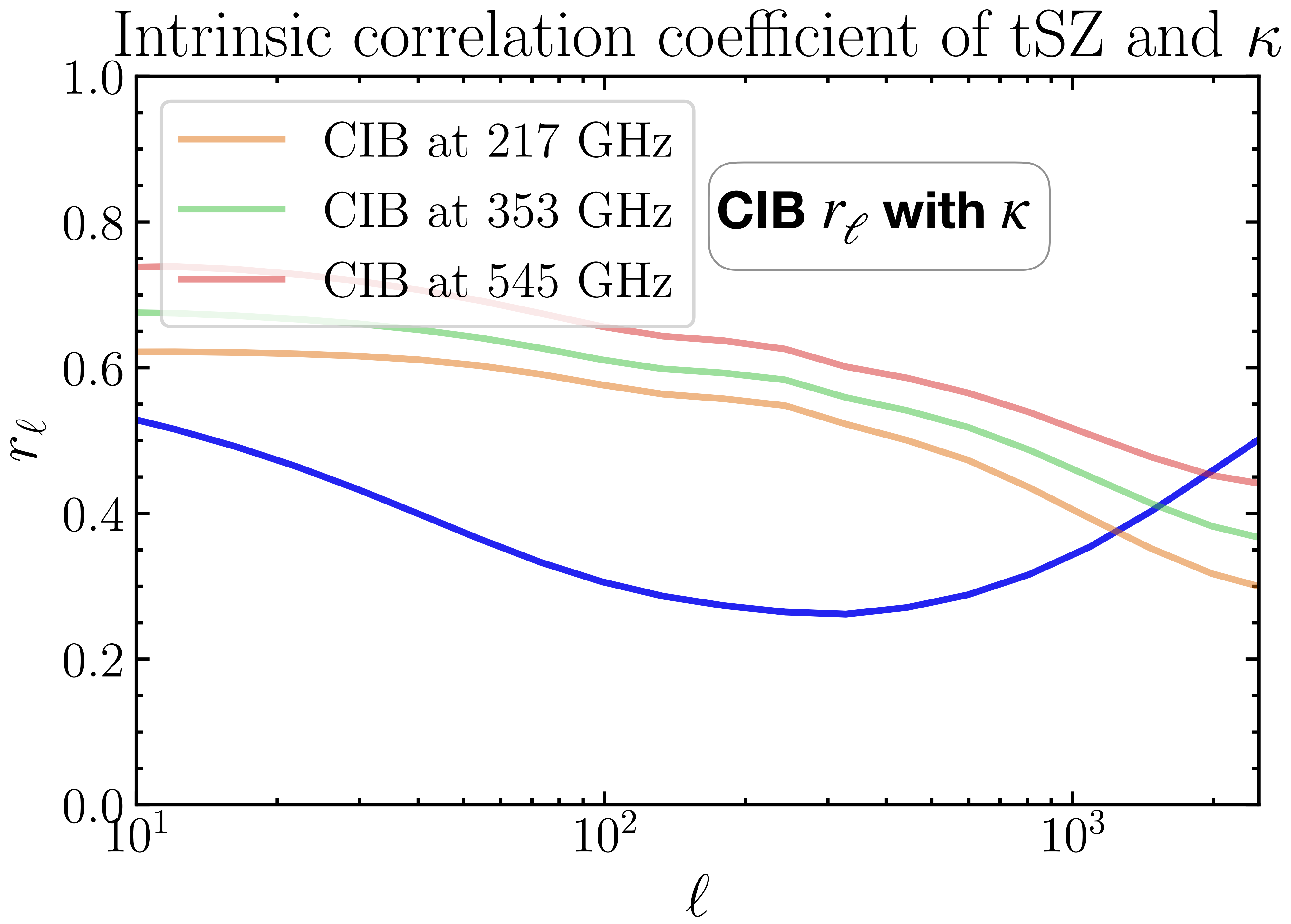
- We probe a **lower mass regime** than *y* alone

FMcC and Colin Hill, to appear

Challenges for cross-correlations: foreground cleaning

- Other foregrounds (the **CIB, radio sources**) appear in our measurements and are **also correlated with LSS**. **These can bias the measurement**

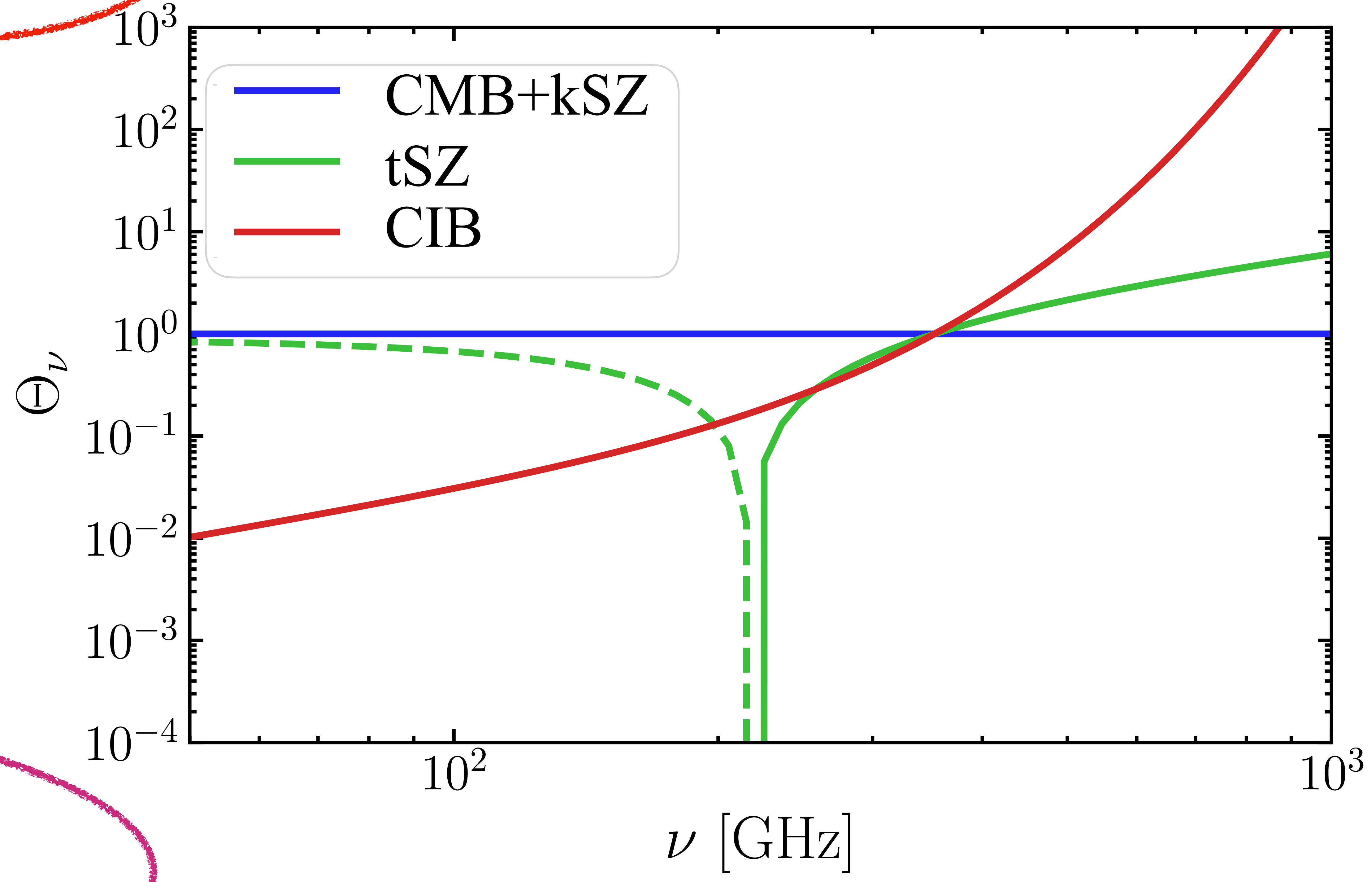




CIB r_ℓ with κ

Frequency-based foreground removal: constrained ILC

$$T(\nu, \hat{n}) = T^{CMB}(\hat{n}) + T^{kSZ}(\hat{n}) + g_\nu y(\hat{n}) + T^{FG}(\nu, \hat{n}) + N(\nu, \hat{n})$$



ILC is a linear combination:

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$$c_\nu = \left[\left(g_\nu^T C^{-1} g_\nu \right)^{-1} \right]_{\nu\nu'} \left[g_\nu^T \left(C^{-1} \right) \right]_{\nu'}$$

where $C_{\nu\nu'} = \langle T_\nu T'_\nu \rangle - \langle T_\nu \rangle \langle T_{\nu'} \rangle$

See talk by ***William Coulton*** *on Wednesday for ILC maps from ACT!!*

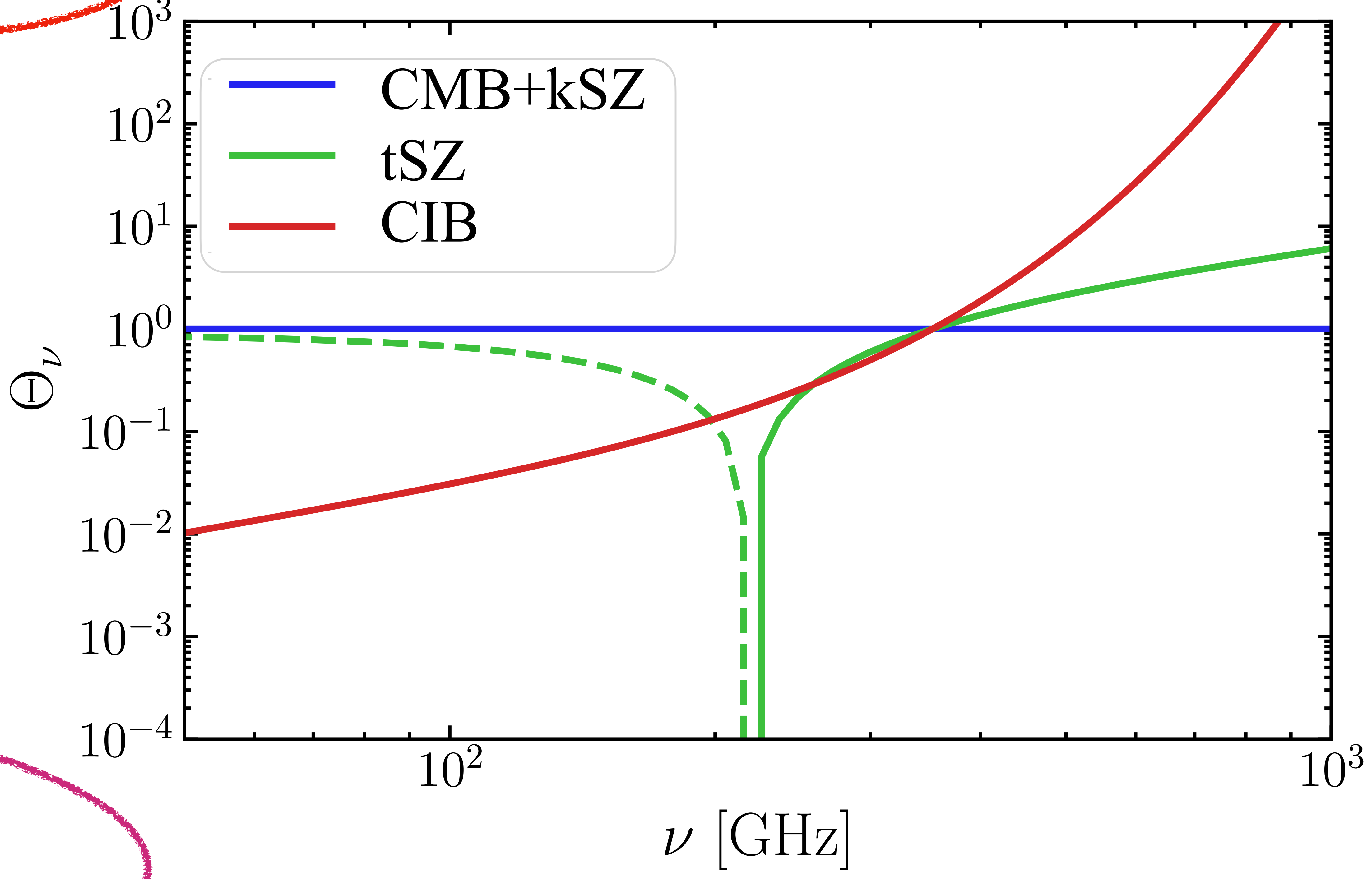
Frequency-based foreground removal: constrained ILC

$$T(\nu, \hat{n}) = T^{CMB}(\hat{n}) + T^{kSZ}(\hat{n}) + g_\nu y(\hat{n}) + \Theta_\nu^{FG} A^{FG}(\hat{n}) + N(\nu, \hat{n})$$

Constrained ILC is a linear combination:

$$\hat{y}(\hat{n}) = \sum_\nu c_\nu T_\nu(\hat{n}) \text{ where } \sum_\nu g_\nu c_\nu = 1 \text{ and}$$

$$\sum_\nu \Theta_\nu^{FG} c_\nu = 0$$



$$c_i = \frac{\left(\Theta_k^{FG}\left(C^{-1}\right)_{kl}\Theta_l^{FG}\right)^{-1}\left(C^{-1}\right)_{ij} g_j - \left(g_k\left(C^{-1}\right)_{kl}\Theta_l^{FG}\right)^{-1}\left(C^{-1}\right)_{ij}\Theta_j^{FG}}{\left(g_k\left(C^{-1}\right)_{kl} g_l\right)\left(\Theta_m^{FG}\left(C^{-1}\right)_{mn}\Theta_n^{FG}\right) - \left(g_k\left(C^{-1}\right)_{kl}\Theta_l^{FG}\right)^2}$$

where $C_{\nu\nu'} = \langle T_\nu T'_\nu \rangle - \langle T_\nu \rangle \langle T_{\nu'} \rangle$

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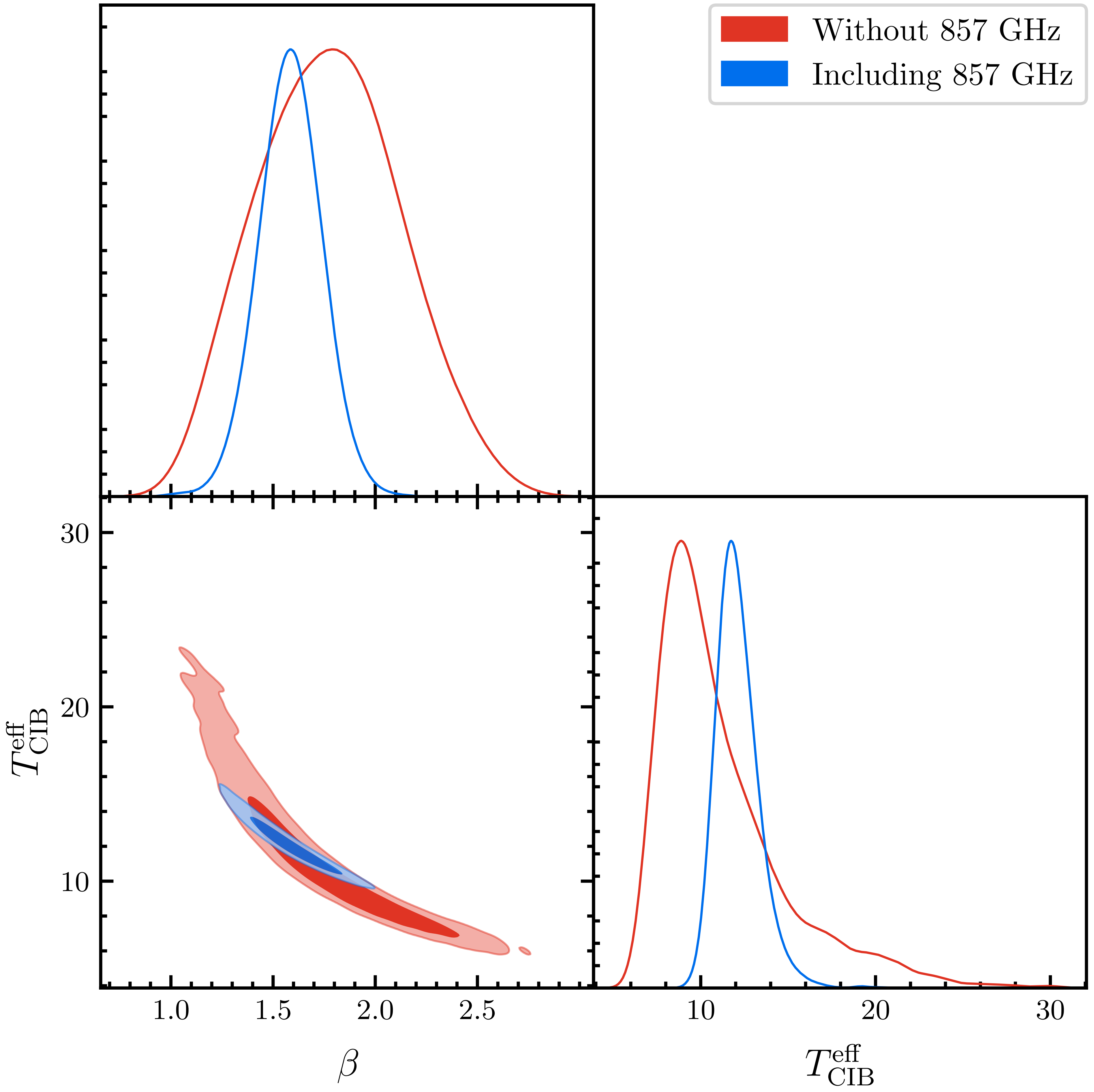
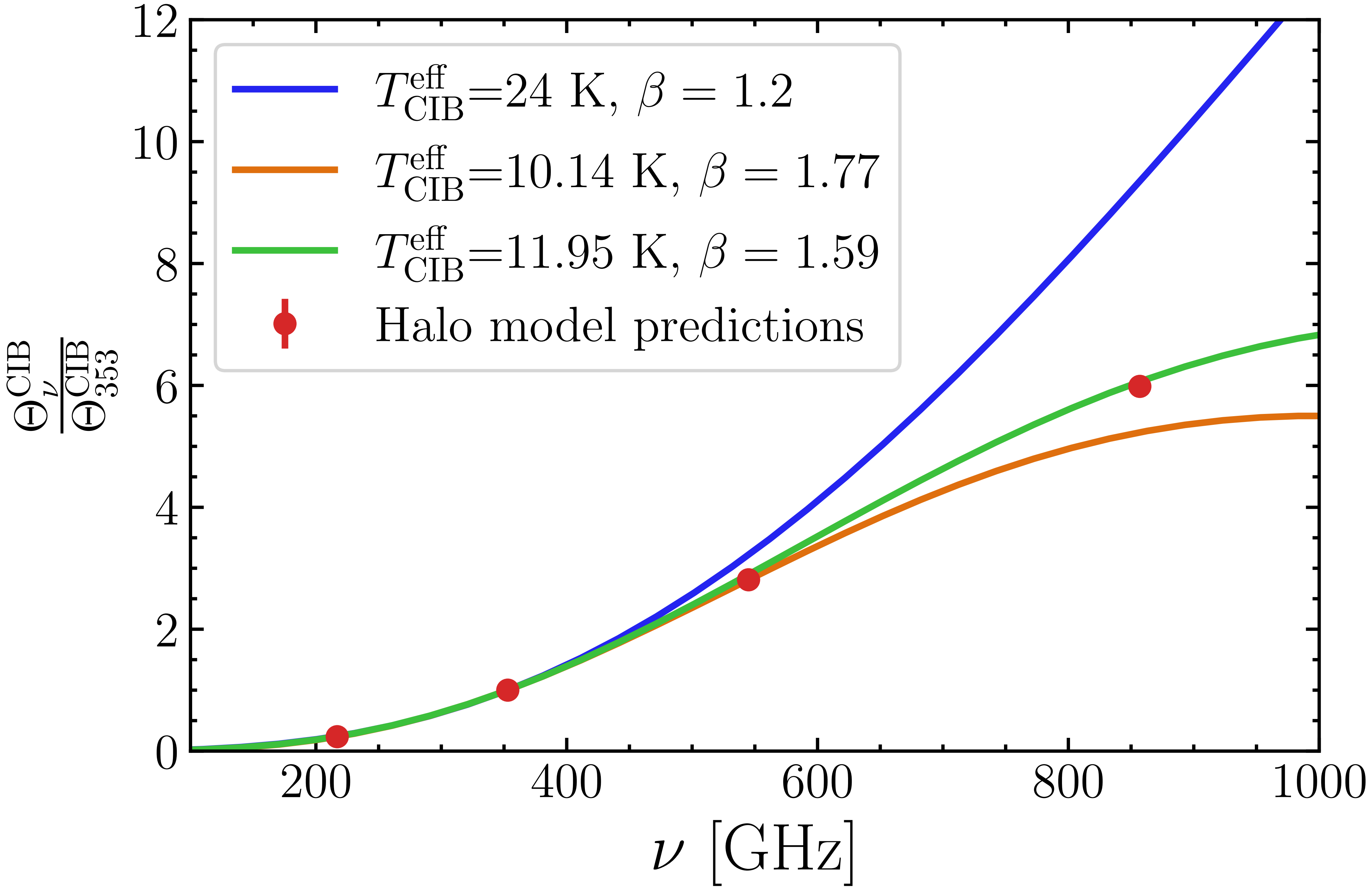
CIB frequency dependence

$$\boxed{\Theta_\nu = \nu^\beta B_\nu(T_d, \nu)}$$

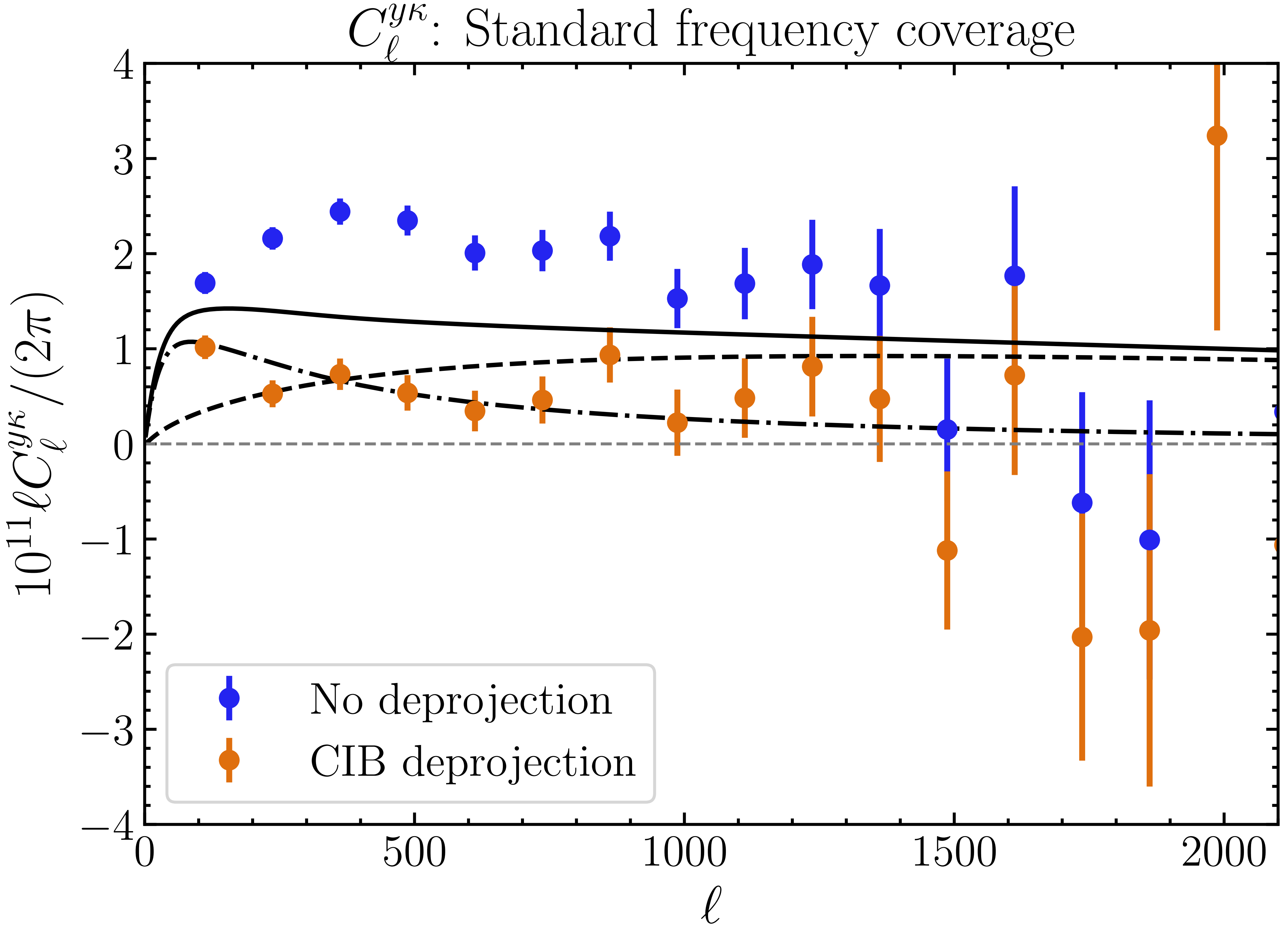


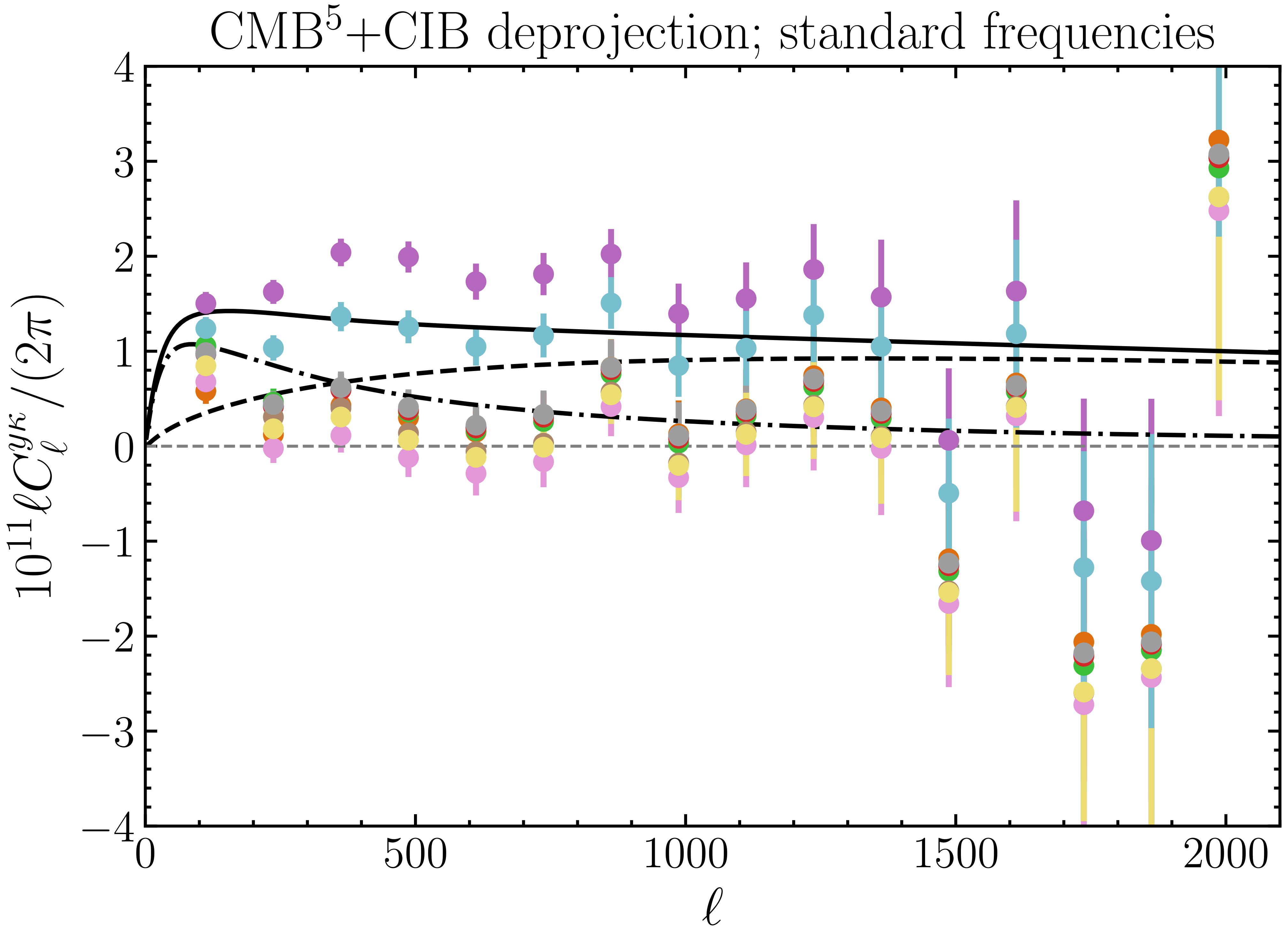


*Fitting to CIB **monopole** predictions from Planck 2013 XXX (CIB halo model)*

CIB x κ: a huge bias to tSZ x κ

- Deprojecting CIB has a huge effect on the signal



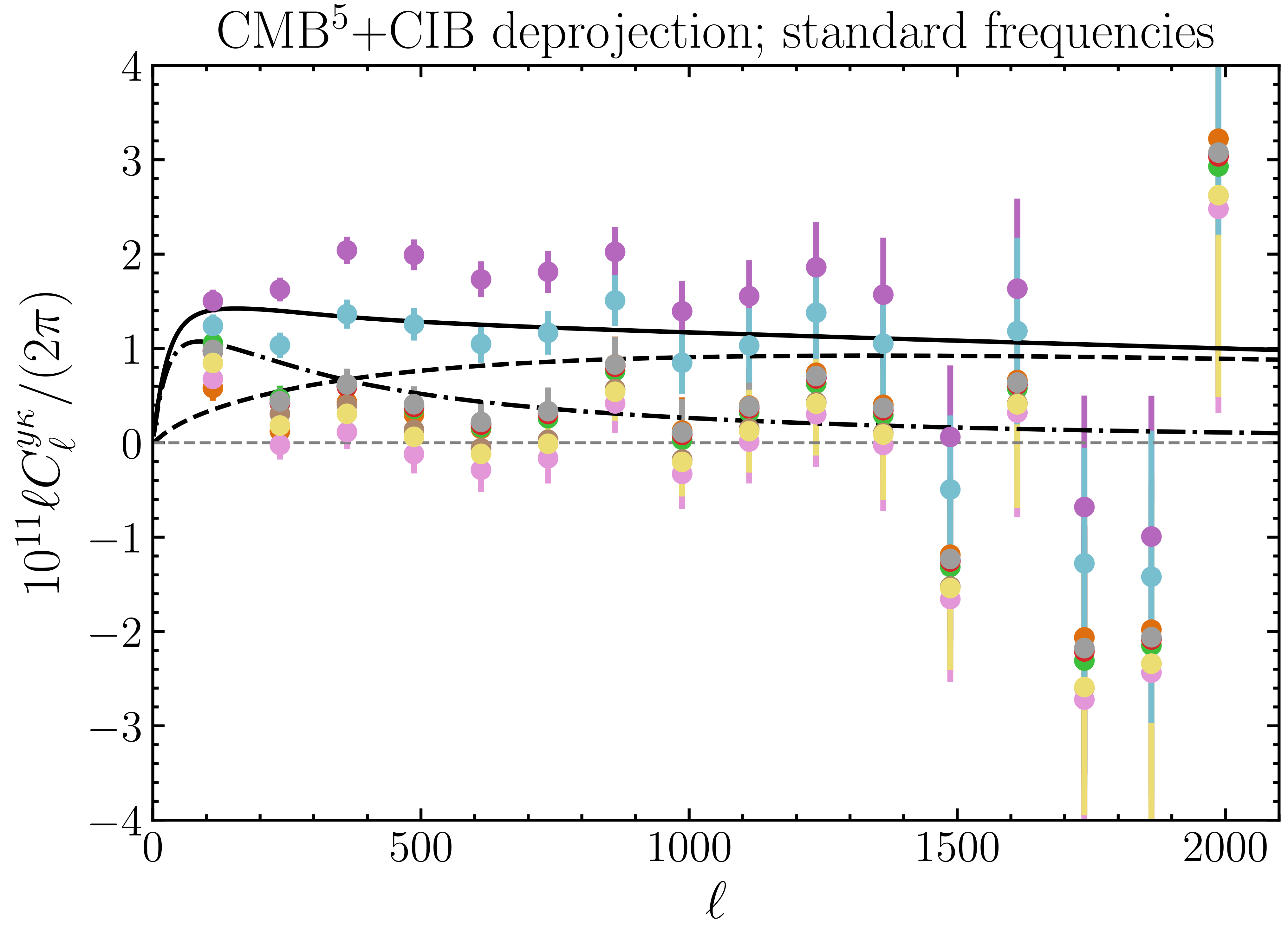


- It is critical to get this removal right! **Points are not stable to reasonable variations in CIB SED**

F McC and JC Hill, in prep

Variations to CIB SED model

- Datapoints are **not stable** to reasonable variation of the parameters
- Solution: **Taylor expand** the SED and deproject **moments**
- This allows for **incorrect parameters** as well as **deviations from exact modified black body** *[Chluba et al 2017]*


CMB^5+CIB deprojection; standard frequencies

$$\Theta_\nu(\beta, T_d) = \nu^\beta B_\nu(T_d, \nu)$$

$$\Theta_\nu(\beta, T_d) = \nu_0^\beta B_\nu(T_{d0}, \nu) + \boxed{\frac{\partial\Theta}{\partial\beta}(\beta - \beta_0)} + \boxed{\frac{\partial\Theta}{\partial T_d}(T_d - T_{d0})}$$

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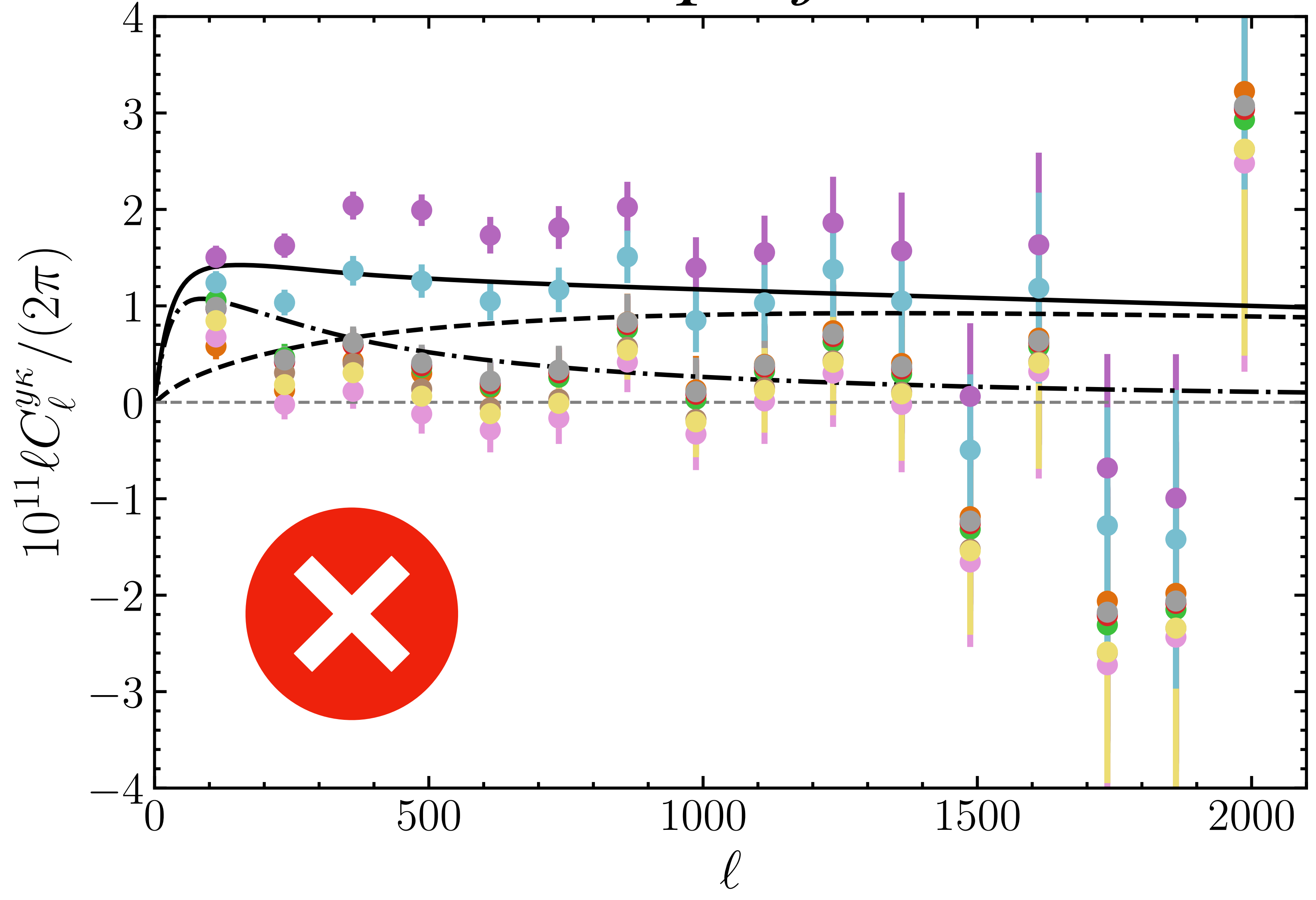
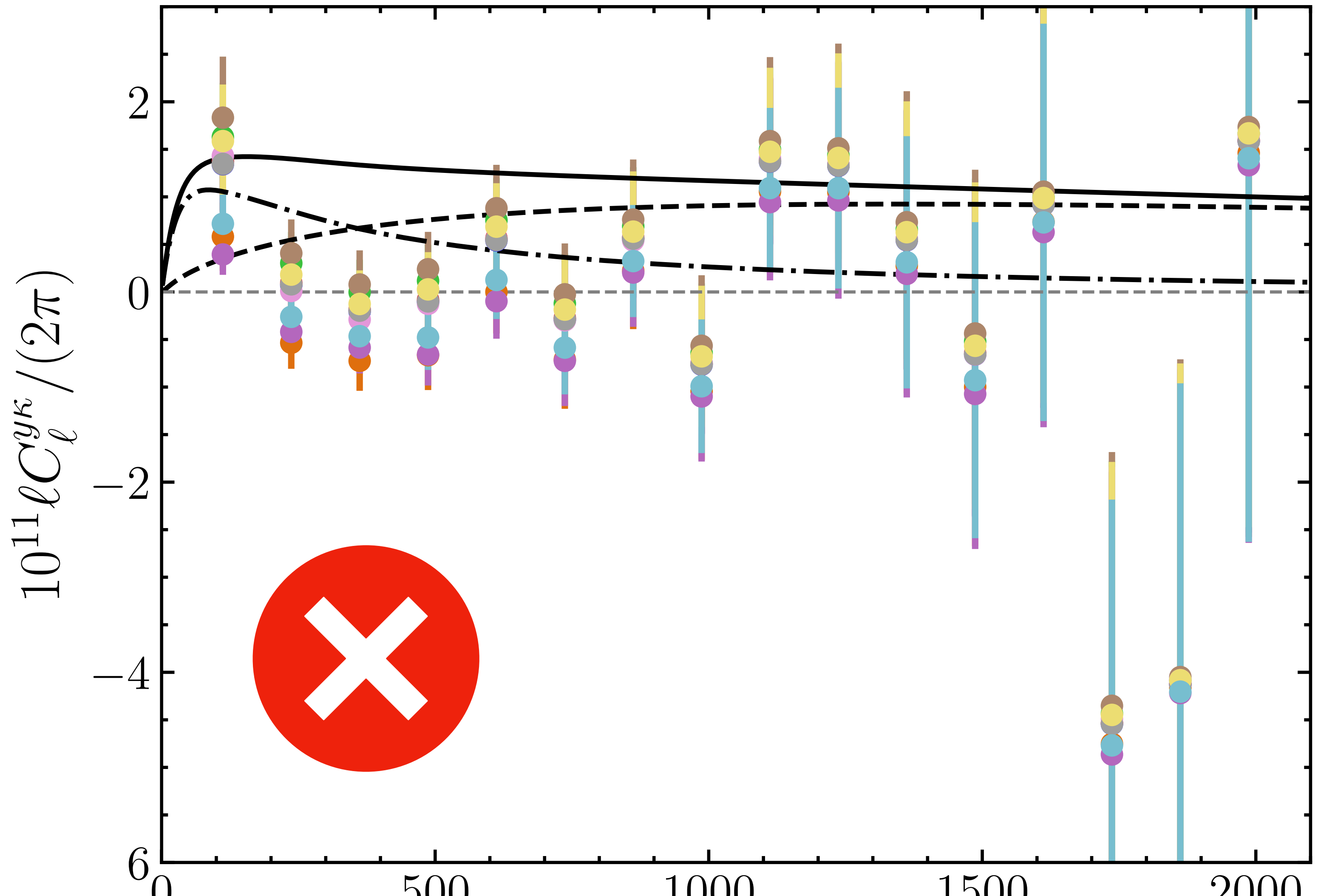
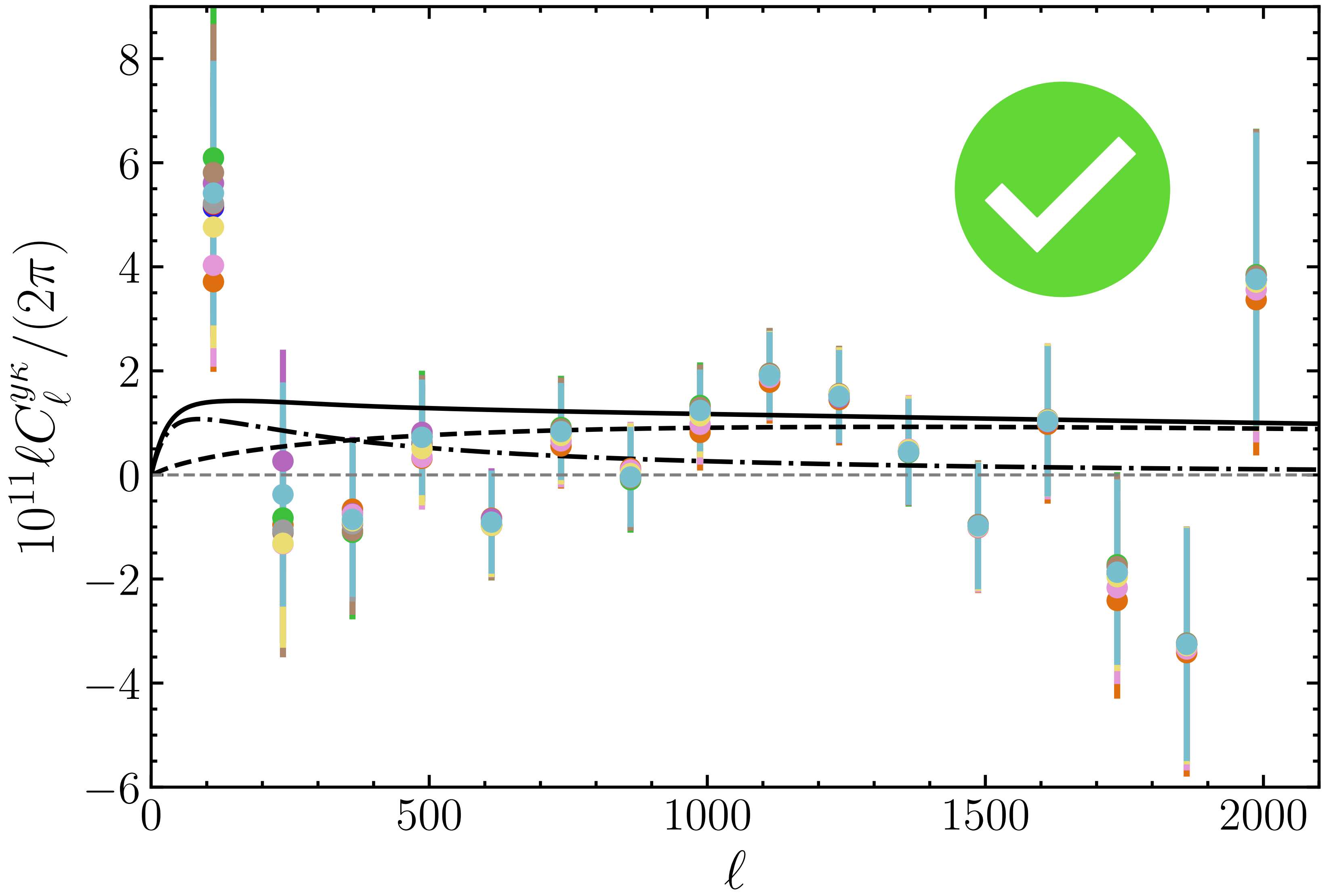
CIB deprojection



CIB $+\delta\beta$ deprojection



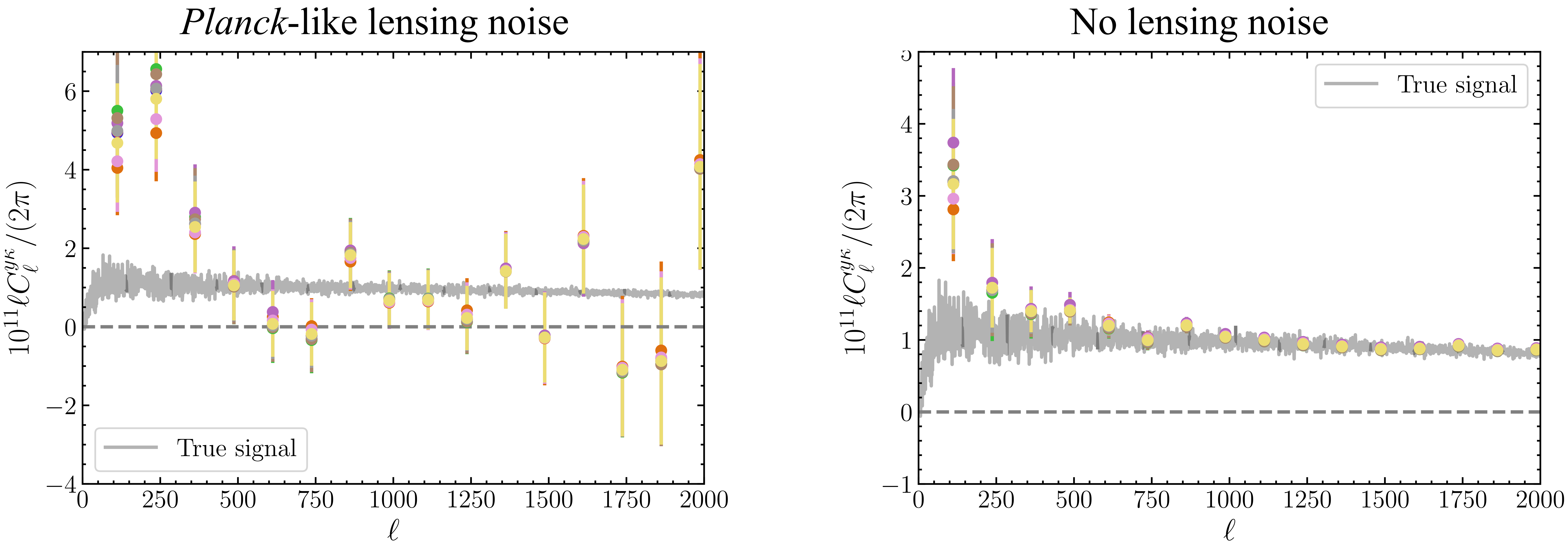
CIB $+\delta\beta+\delta T_d$ deprojection



F McC and JC Hill, in prep

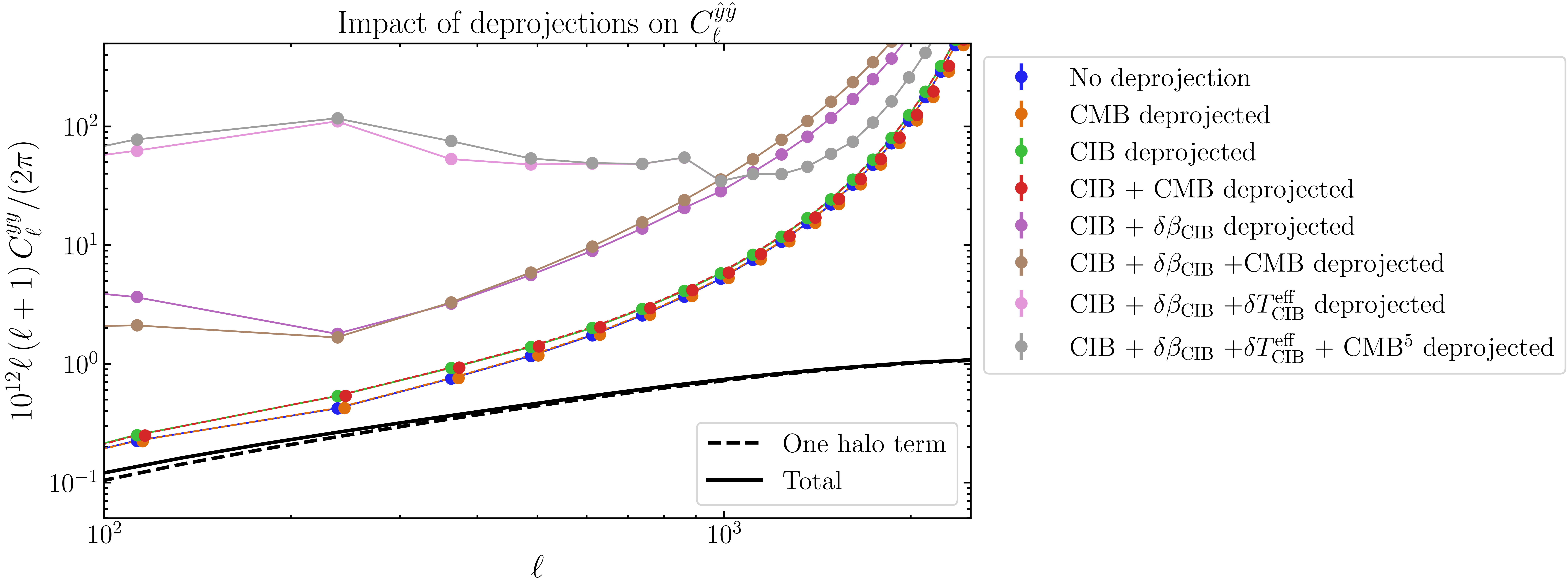
Validation on simulations

- We have validated our pipeline on complex *mm* sky simulations (websky+pysm)



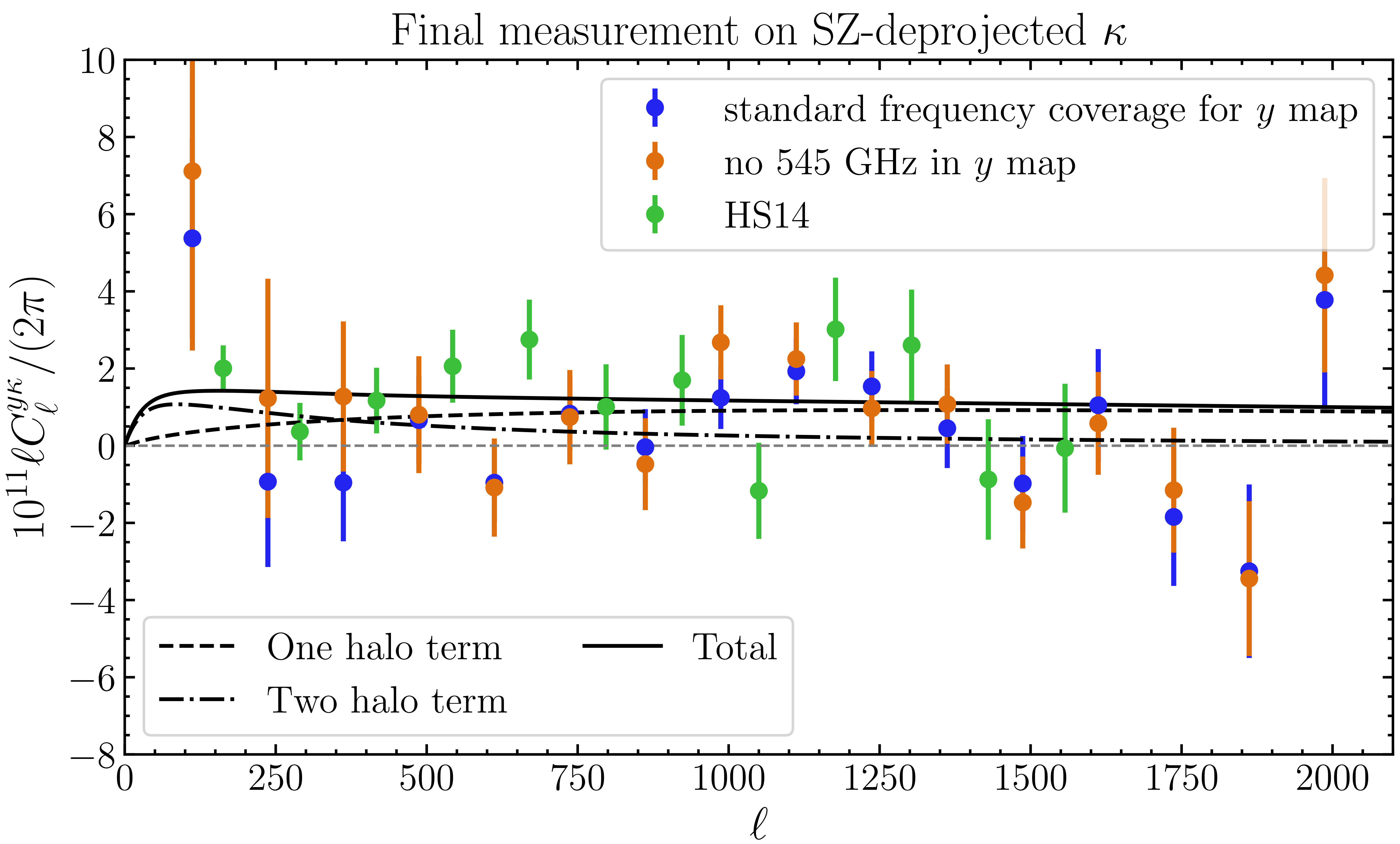
F McC and JC Hill, in prep

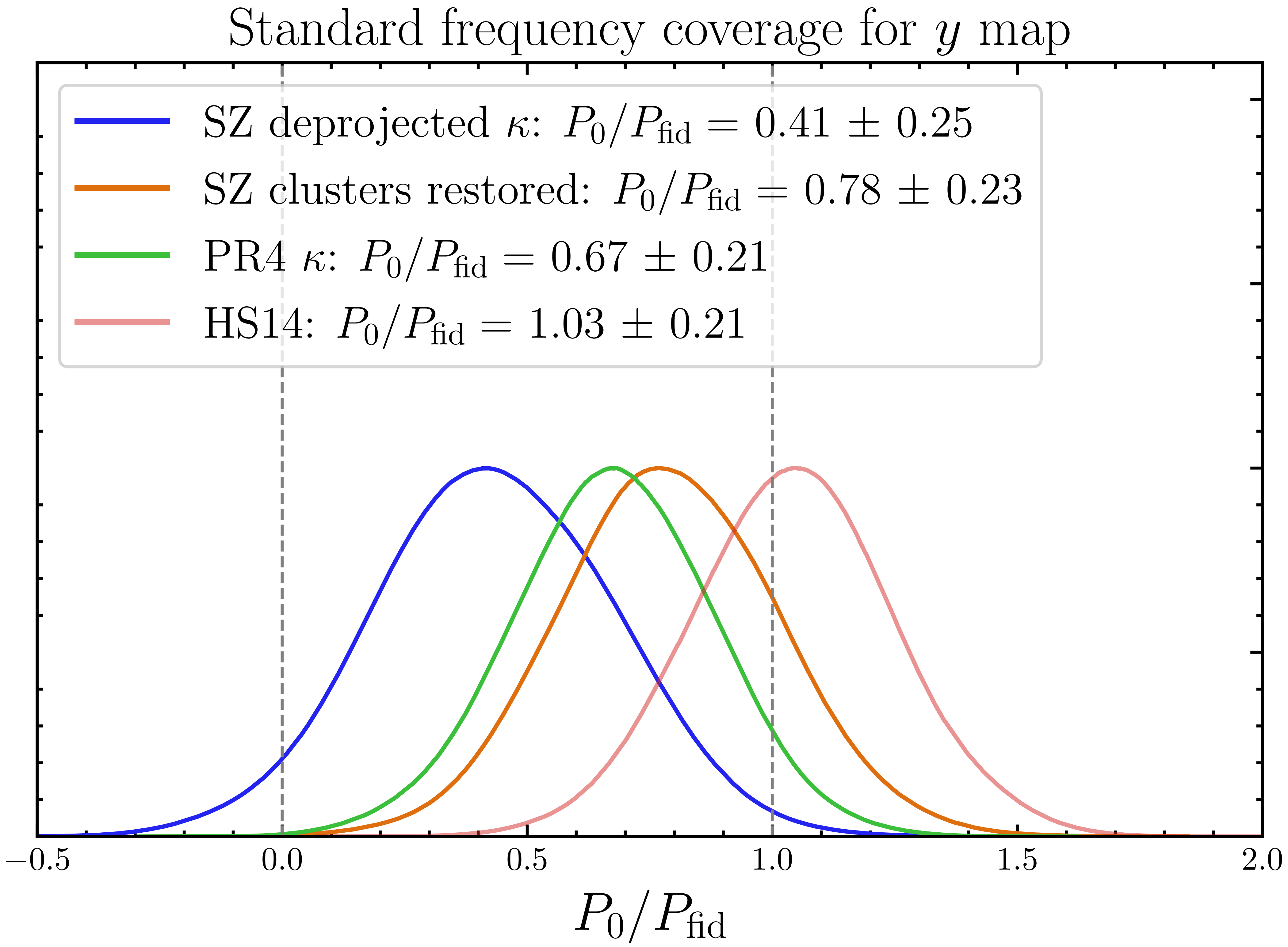
Moment deprojection: increase in variance



F McC and JC Hill, arXiv:2307.01043

Final constraints on tSZ models



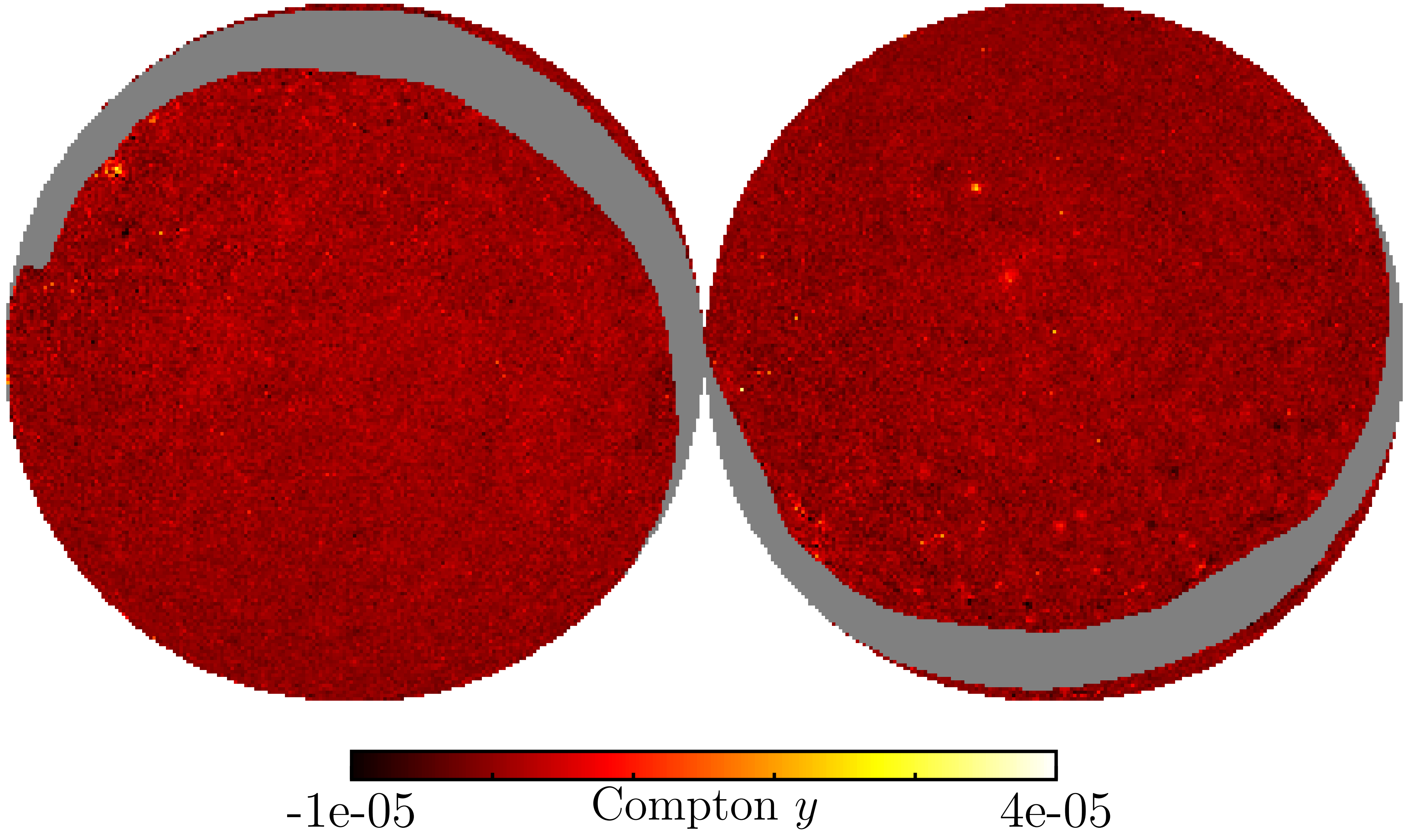


- Moment approach allows us to make a **robust measurement with no CIB contamination**
- Hints of a lower-than-expected SZ signal at high *z* -> strong feedback?

F McC and JC Hill, in prep

New tool for ILC on data and simulations: pyilc

- Introduced in **arXiv:2307.01043** (FMcC & **Colin Hill**) github.com/jcolinhill/pyilc
- **Flexible**, **user-friendly** implementation of **needlet ILC in python**
- You provide **healpix maps** and characterize them (frequency info, etc…)
- It calculates the needlet ILC estimation of a specified component (**tSZ**, **CMB+kSZ**, μ -distortion, **CIB** (as modified black body), **CIB first moments**), **radio sources** (easy to add your own!)
- Useful for data and also **propagating foregrounds in simulations**
- We have used this to make lots of **CIB-deprojected y maps** with ***Planck* data**, which are **public**



Conclusion

- The S4 era will bring extremely high signal-to-noise measurements of SZ observables on small scales
- These will be interpreted with LSS to put constraints on **cosmology and baryon feedback**
- In this regime **other foreground biases will be large and must be mitigated,** often **sacrificing signal-to-noise**
- We illustrate this with our CIB-mitigation for *Planck* tSZ-κ measurement (also relevant for **all** tSZ-lss measurements)
- New tool for component separation: **pyilc**