Self-consistent CMB secondaries in the FLAMINGO simulations

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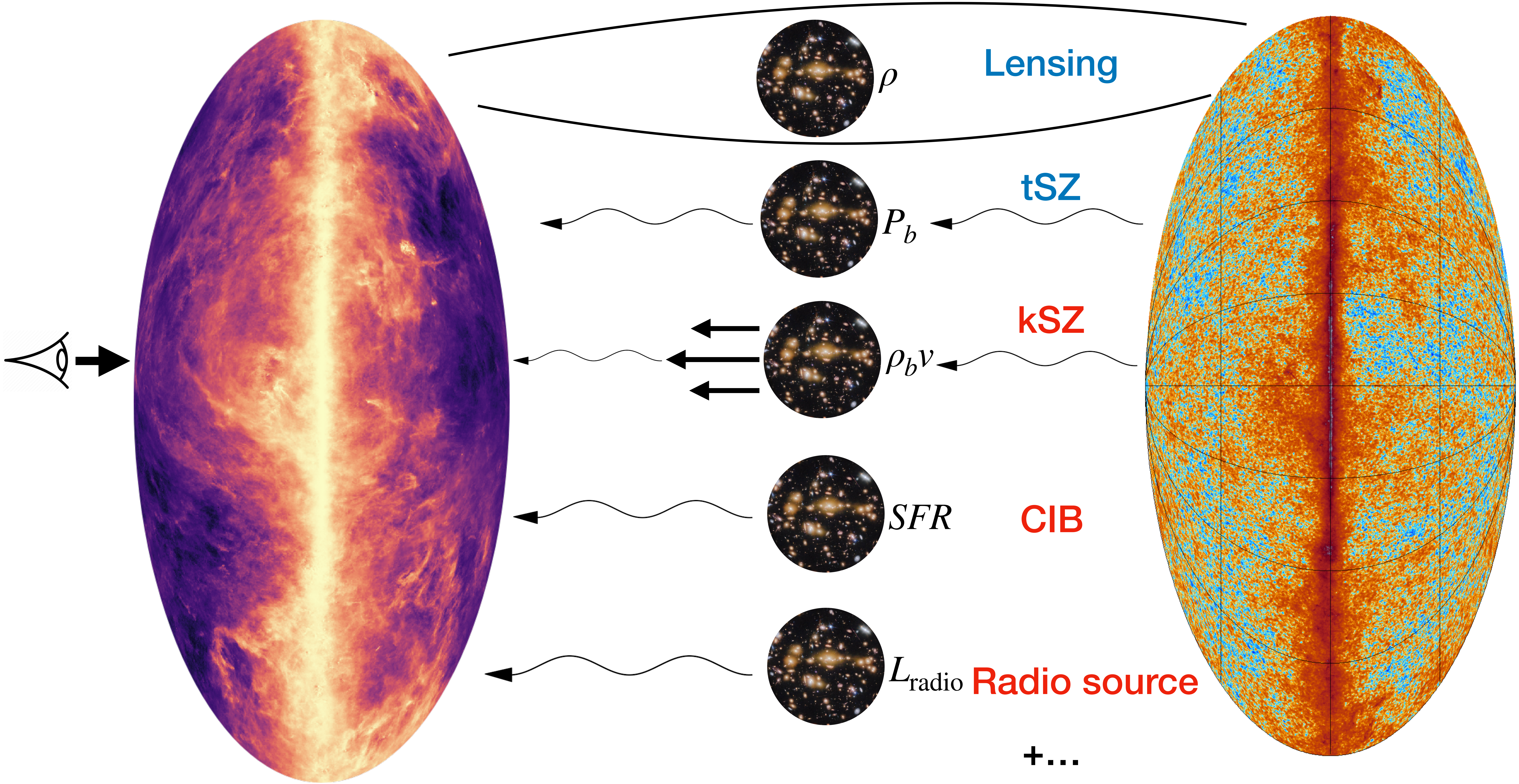
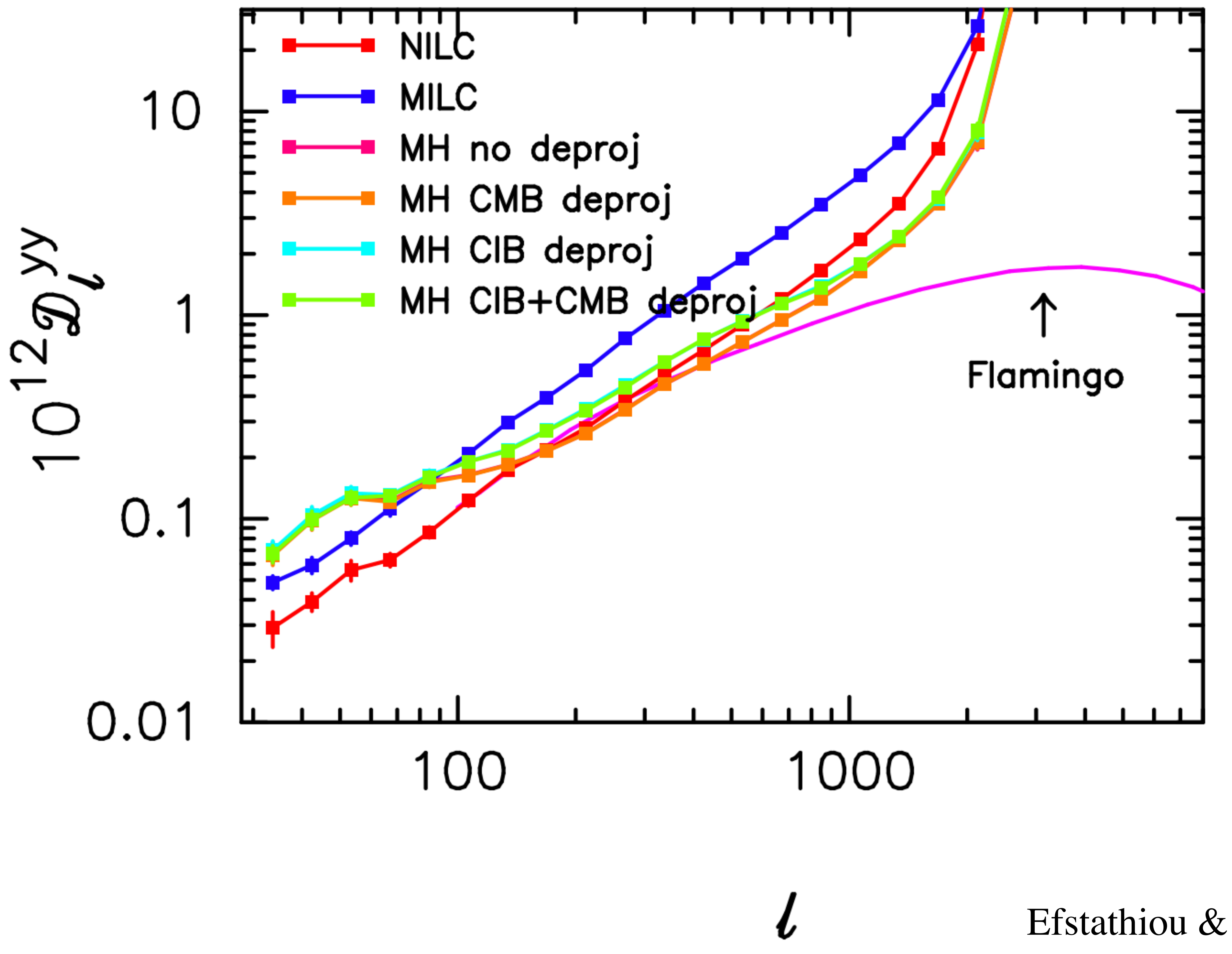
Motivation: primary + secondary effects

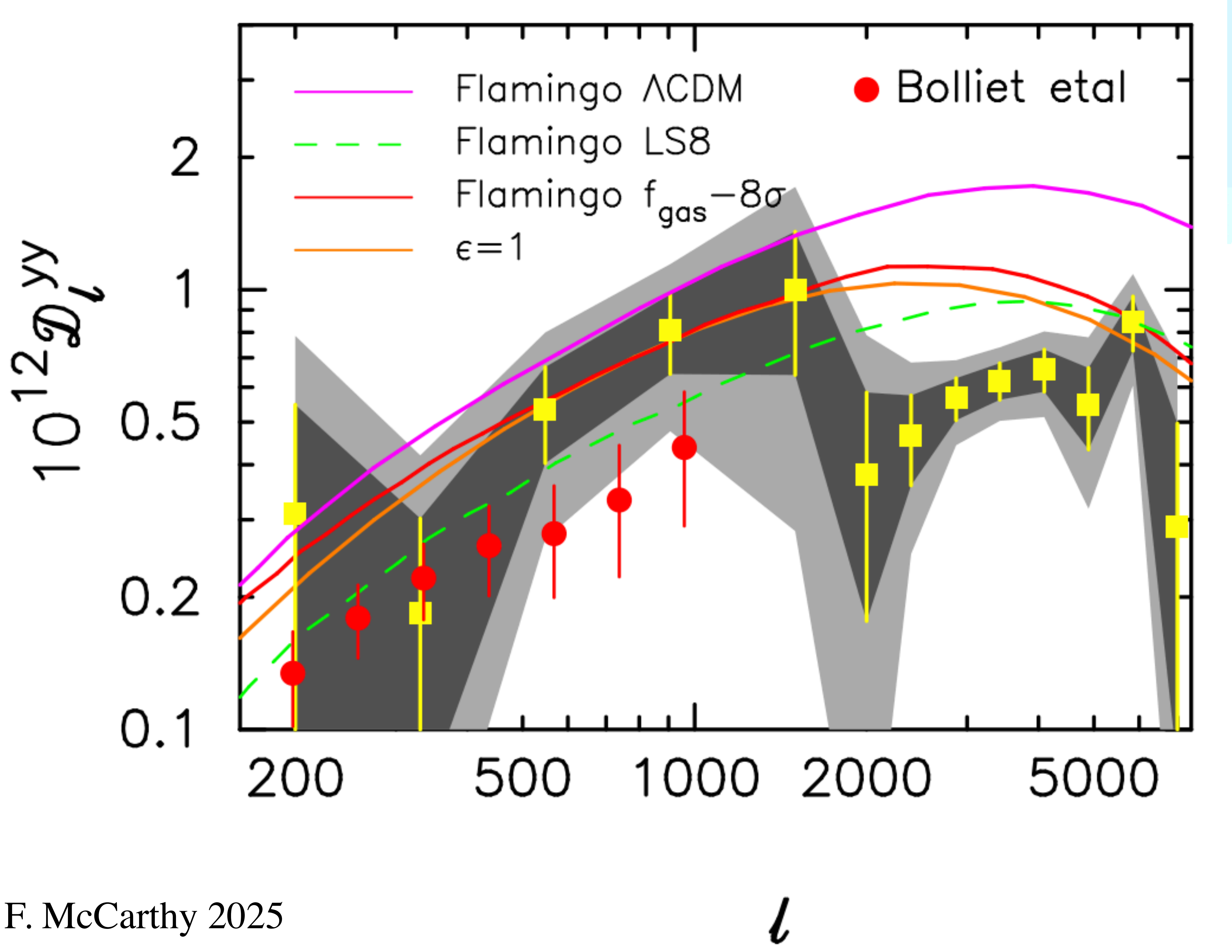


Motivation

- CMB anisotropies contain a wealth information about galaxy formation and cosmology.
- Extracting them can be complicated because of uncertain dependencies of components on spacial scale, frequency, redshift, feedback, etc.——**multi-component CMB simulations are needed!!!**
- **Goal:** create full-sky maps of CMB secondary anisotropies self-consistently:
  - using spatial clustering of different signals from large-volume hydro-dynamical simulations
  - Previous studies (e.g. Sehgal+10, Stein+20 [Websky], Omori24 [AGORA]): rely on halo model-based calculations and/or N-body simulations
  - Allow us to make more realistic comparisons with current observations + forecasts for future CMB data.

Case in point: tSZ power spectrum





Efstathiou & F. McCarthy 2025

Simulation data

The FLAMINGO project:

- Series of gas resolutions from 10^8 to 10^{10} $M_\odot$.
- Fiducial cosmology given by ``Planck+BAO+DES 3×2pt”
- Flagship run: 2.8 Gpc box size with 3×10^{11} particles (5040^3 gas + 5040^3 DM + 2800^3 neutrino)
- Subgrid feedback calibrated against z = 0 GSMF and low-z cluster gas fraction
- 12 model variants: 8 feedback (strong AGN, strong SN, etc.) + 4 cosmology (Planck, LS8, etc.) variations
- Full-sky lightcone particle data for 8 different observers (2 for smaller box size)

Please see Schaye et al. 2023 and online website for more info

CIB modelling

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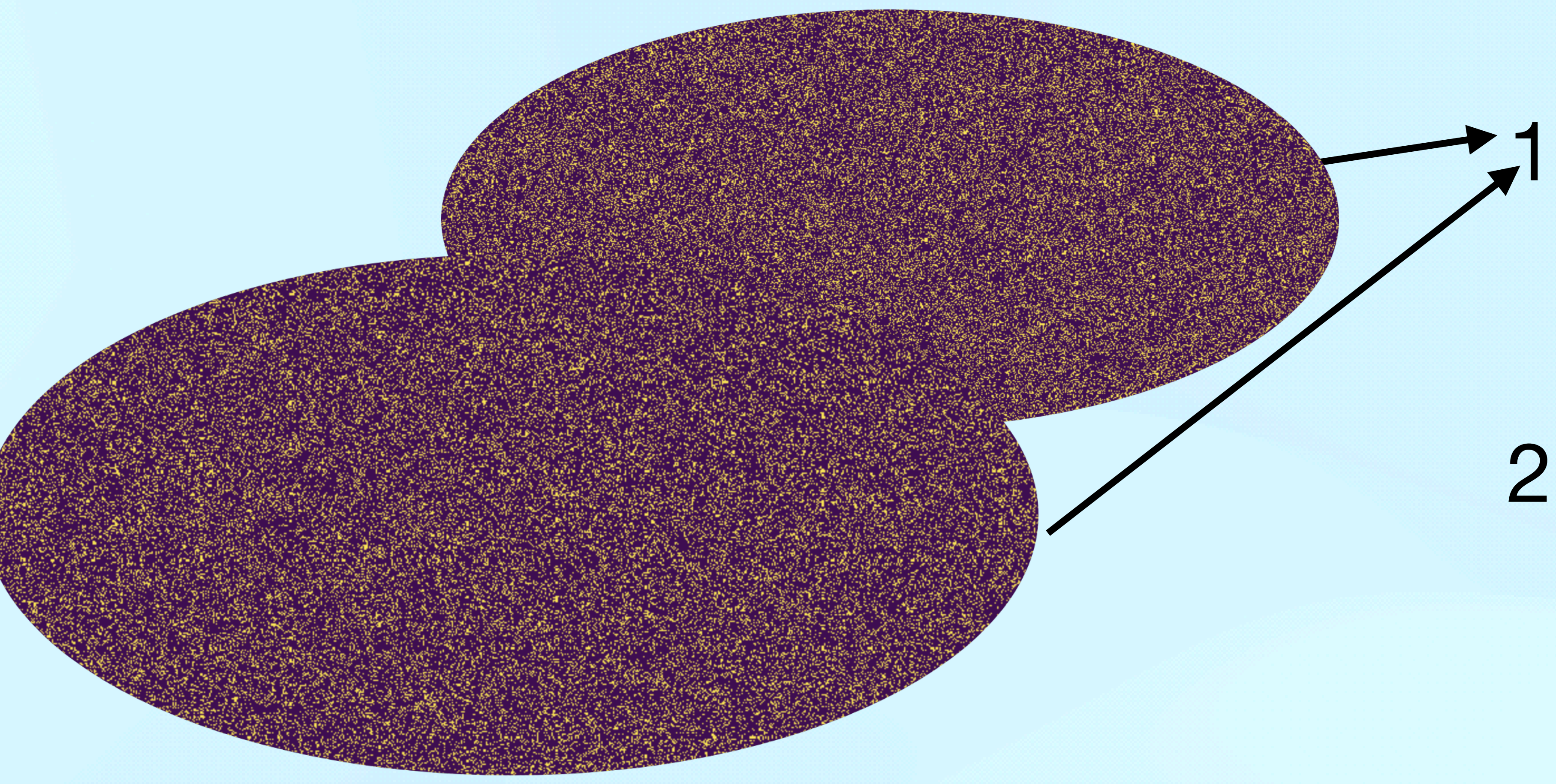

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1. Start from the SFR full-sky map: $\frac{L_{\text{bol}}}{1 \times 10^{N_s} L_\odot} = \frac{\text{SFR}}{1 M_\odot \text{yr}^{-1}}$

2. Convert $L_{\text{IR,bol}}$ to $L_{\text{IR},\nu}$ using the SED: $L_{IR,\nu} = L_{\text{IR,bol}}(\text{SFR}) \frac{\int d\nu \Phi(\nu)\tau(\nu)}{\int d\nu \Phi(\nu)}$,

   with SED $\Phi(\nu)$ modelled as a greybody radiation:

$$\Phi(\nu, z, T_0, \beta_d, \alpha_d) = \left[\exp\left(\frac{h\nu}{kT_{\text{dust}}}\right) - 1\right]^{-1} \nu^{\beta_d+3},$$

   with $T_{\text{dust}} = T_0(1+z)^{\alpha_d}$

3. Compute flux density $S_{\text{IR},\nu}$ per lightcone map: $S_{\text{IR},\nu} = \frac{L_{\text{IR},\nu(1+z)}}{4\pi\chi^2(1+z)}$

4. Compute $S_{\text{IR},\nu}$ power spectrum per lightcone:

$$C_\ell^{i \text{ per lc}} = C_\ell^{S_{\nu,i},\, S_{\nu,i}} + 2\Sigma_{i>j} C_\ell^{S_{\nu,i},\, S_{\nu,j}},$$

   where $C_\ell^{S_{\nu,i},\, S_{\nu,j}}$ accounts for the cross-shell correlation term

5. Stack the ps curves up to z = 4.5, fitted with CIB auto-PS data at 353, 545, 857 GHz from Lenz et al. (2019).

CIB auto- and cross-ps

SED best fit: $T_0 = 35.11 \pm 0.20$, $\beta_d = 1.66 \pm 0.05$

CIB-xxx cross-ps (with other CMB statistics)

kSZ modelling

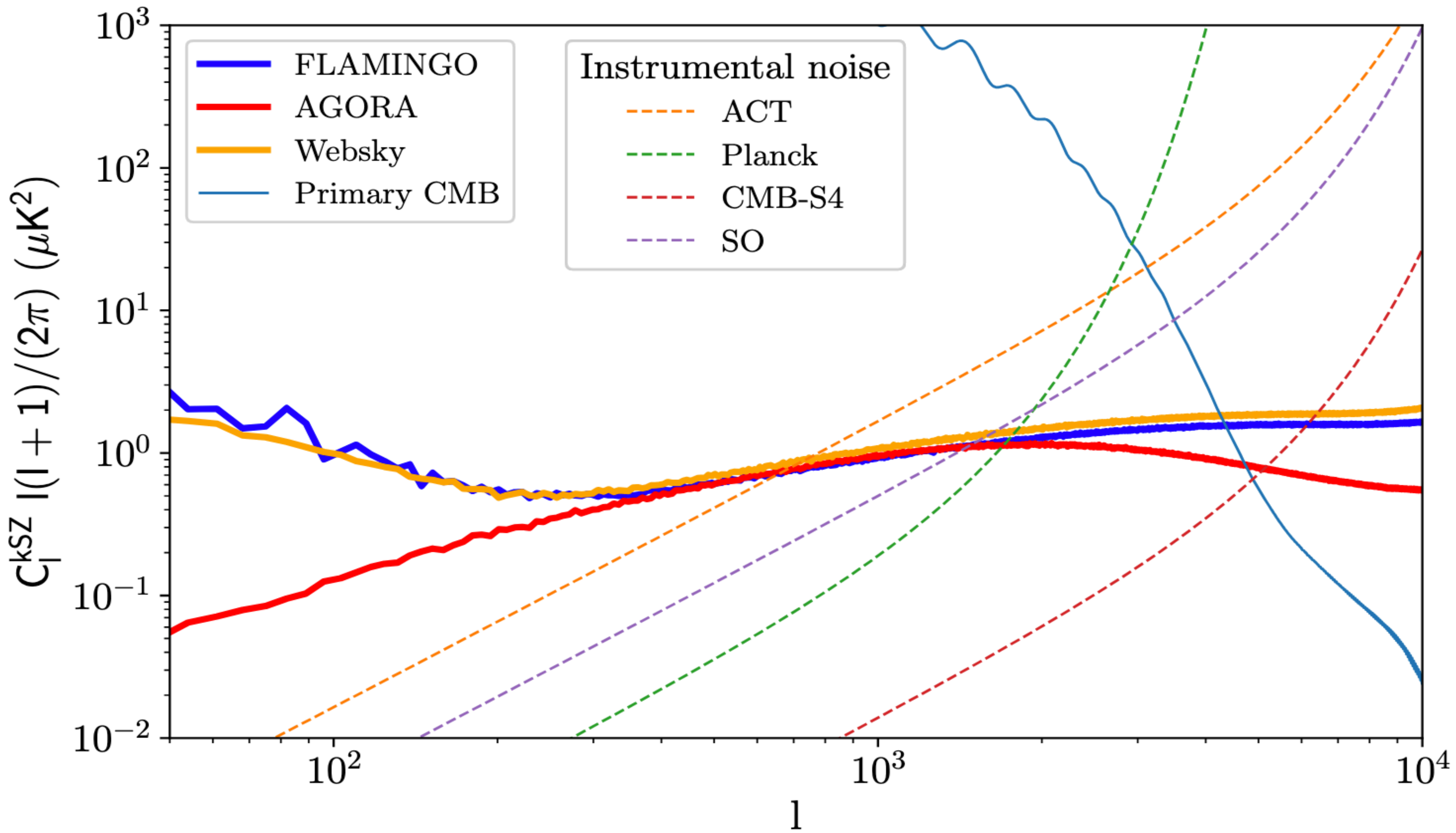
- Straightforward in hydro-sims: for a gas particle in the lightcone, a Doppler B, b, is computed:

$$\Sigma\, b = \Sigma\, \frac{n_\mathrm{e} m_\mathrm{g} \sigma_\mathrm{T} v_\mathrm{r}}{\Omega_\mathrm{pix} d_\mathrm{A}^2 \rho c} \equiv \frac{\sigma_\mathrm{T}}{c} \int n_\mathrm{e} v_\mathrm{r} dl$$

with $m_\mathrm{g}, \rho, v_\mathrm{r}$ are the mass, mass density and radial velocity of a gas particle, Ω_pix is the solid angle of a HEALPix pixel and d_A is the angular diameter distance to the observer.

- Mapping between Doppler B and ΔT_kSZ: $\Delta T_\mathrm{kSZ}/T_\mathrm{CMB} = -b$

kSZ auto-ps



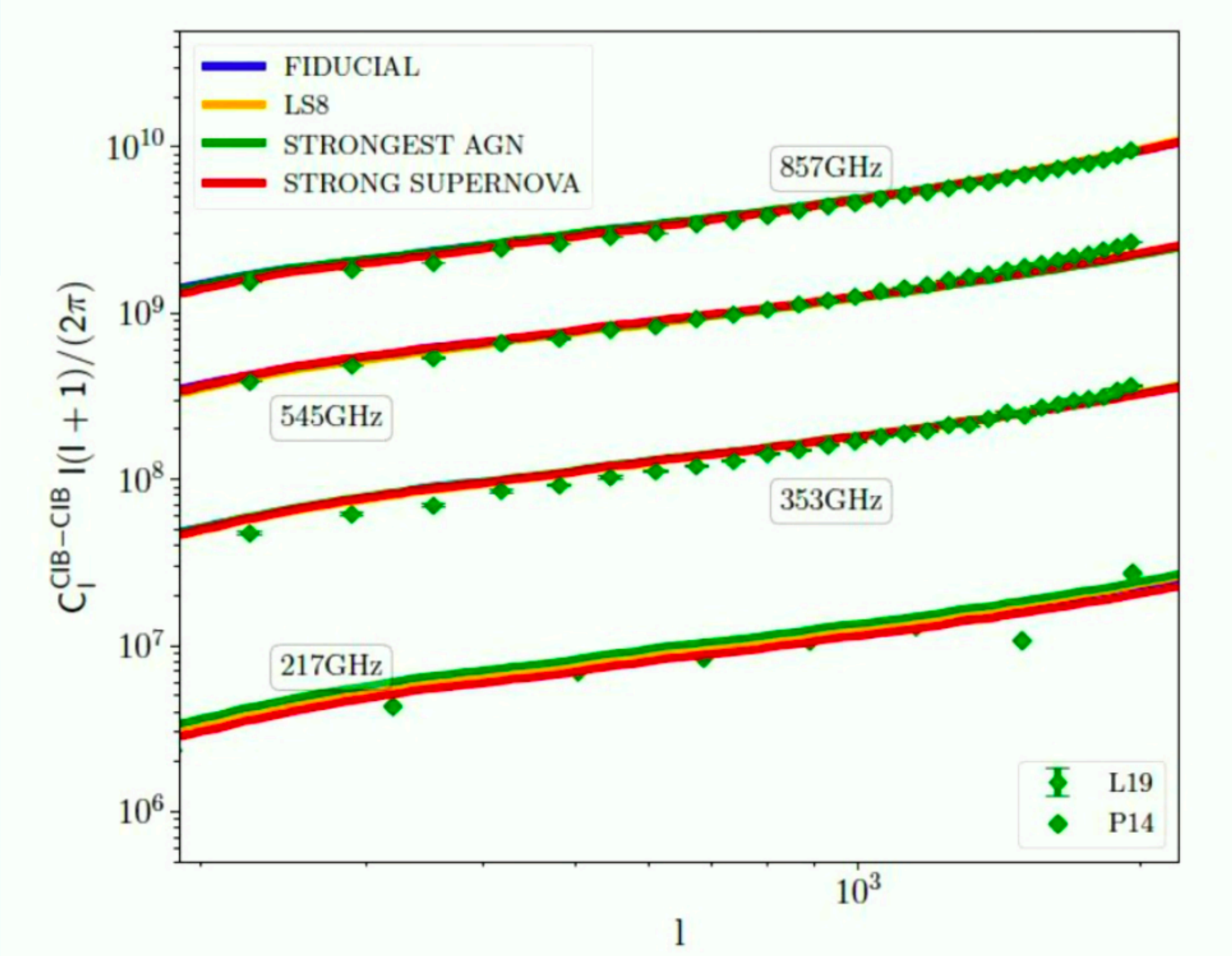
FLAMINGO
AGORA
Websky
Primary CMB
Instrumental noise
ACT
Planck
CMB-S4
SO
$C_l^{kSZ}\ l(l+1)/(2\pi)\ (\mu K^2)$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^2
10^3
10^4
l

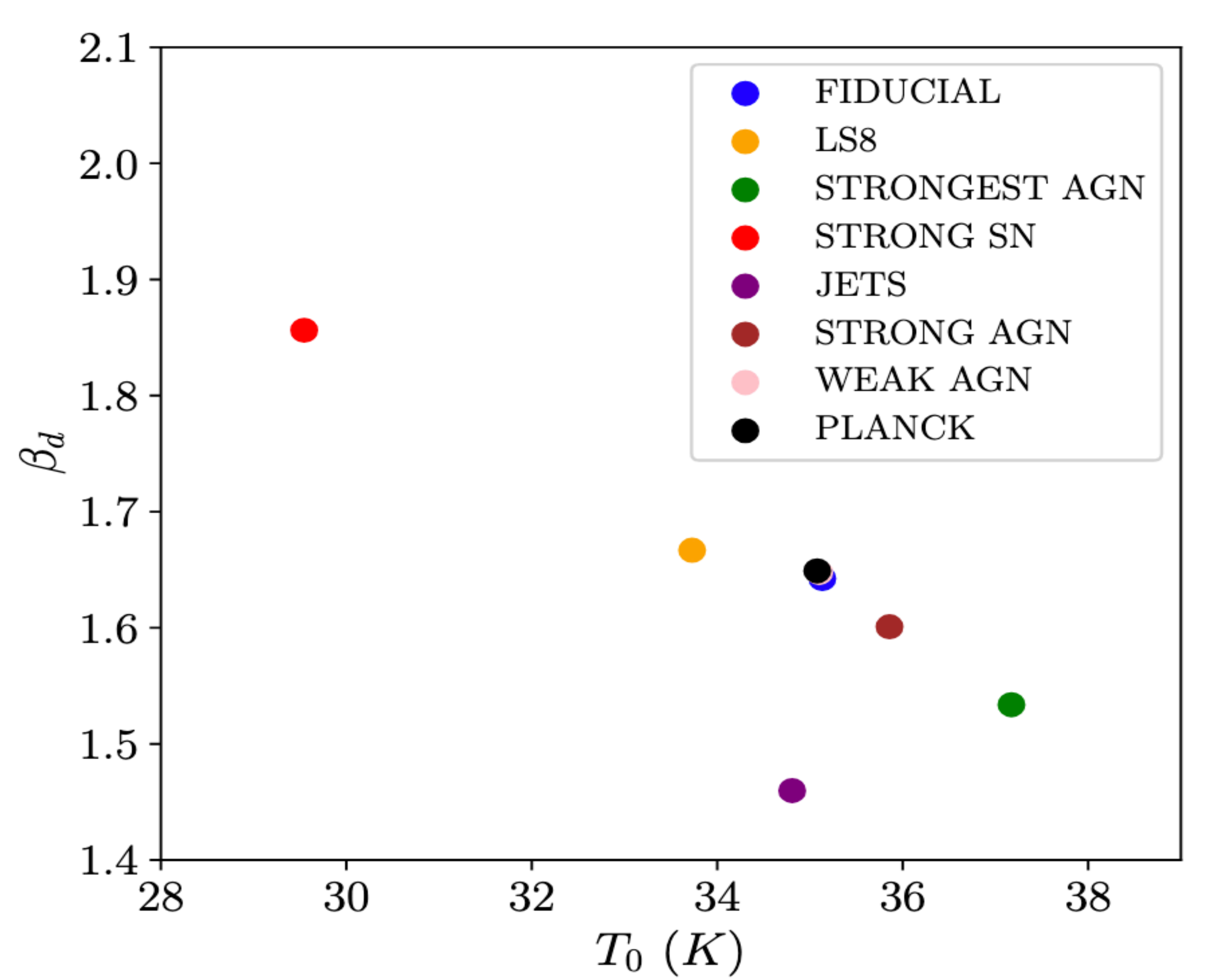
How does feedback affect the CIB and its crosses? ——Case 1: fixing SED parameters

- Fix the best-fit SED parameters fitted from the FIDUCIAL model, then apply them to SFR maps from other model variations.

How does feedback affect the CIB and its crosses? ——Case 2: Varying SED parameters

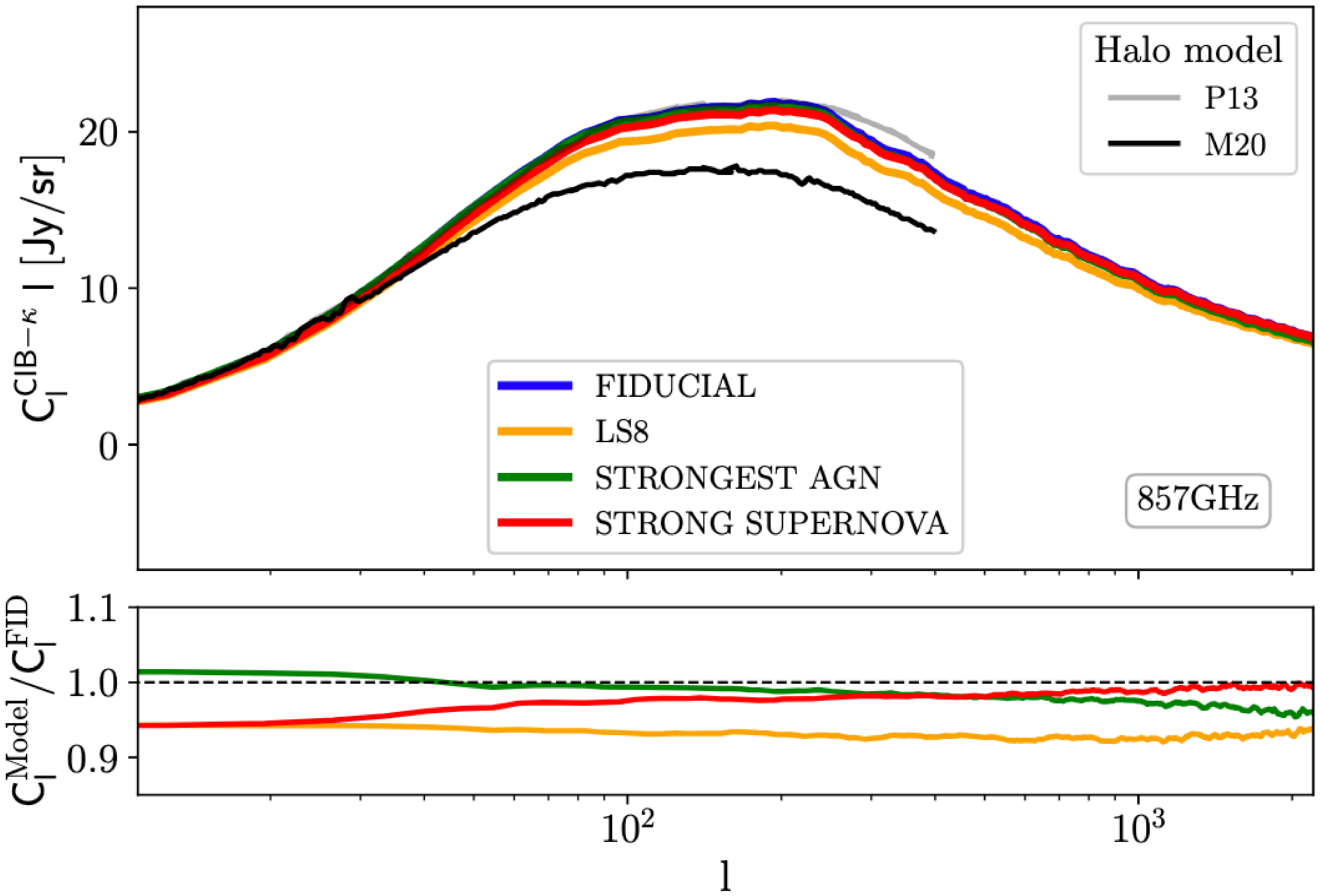
- Use SFR maps from other model variations, refit the predicted CIB statistics to the same set of data

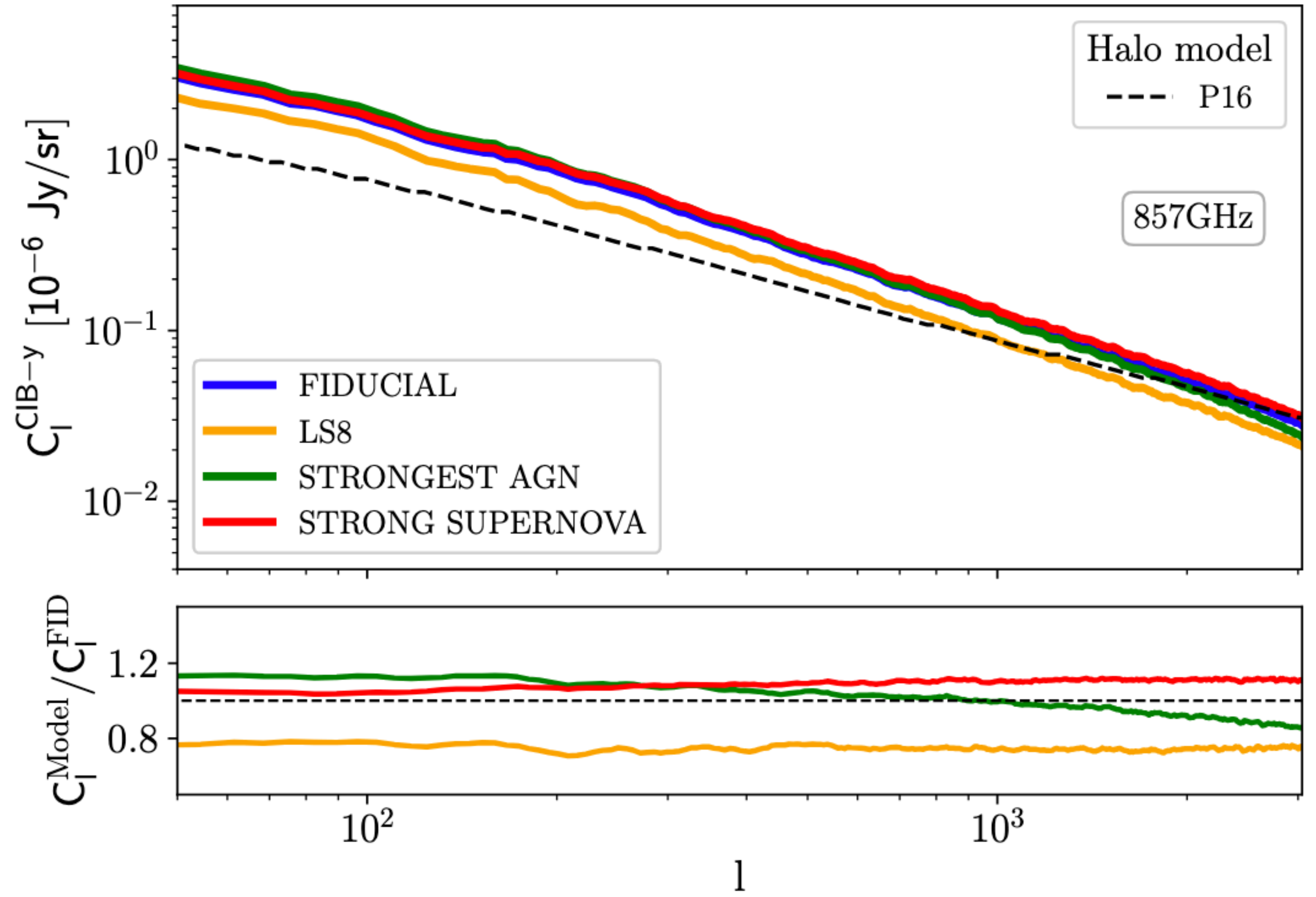




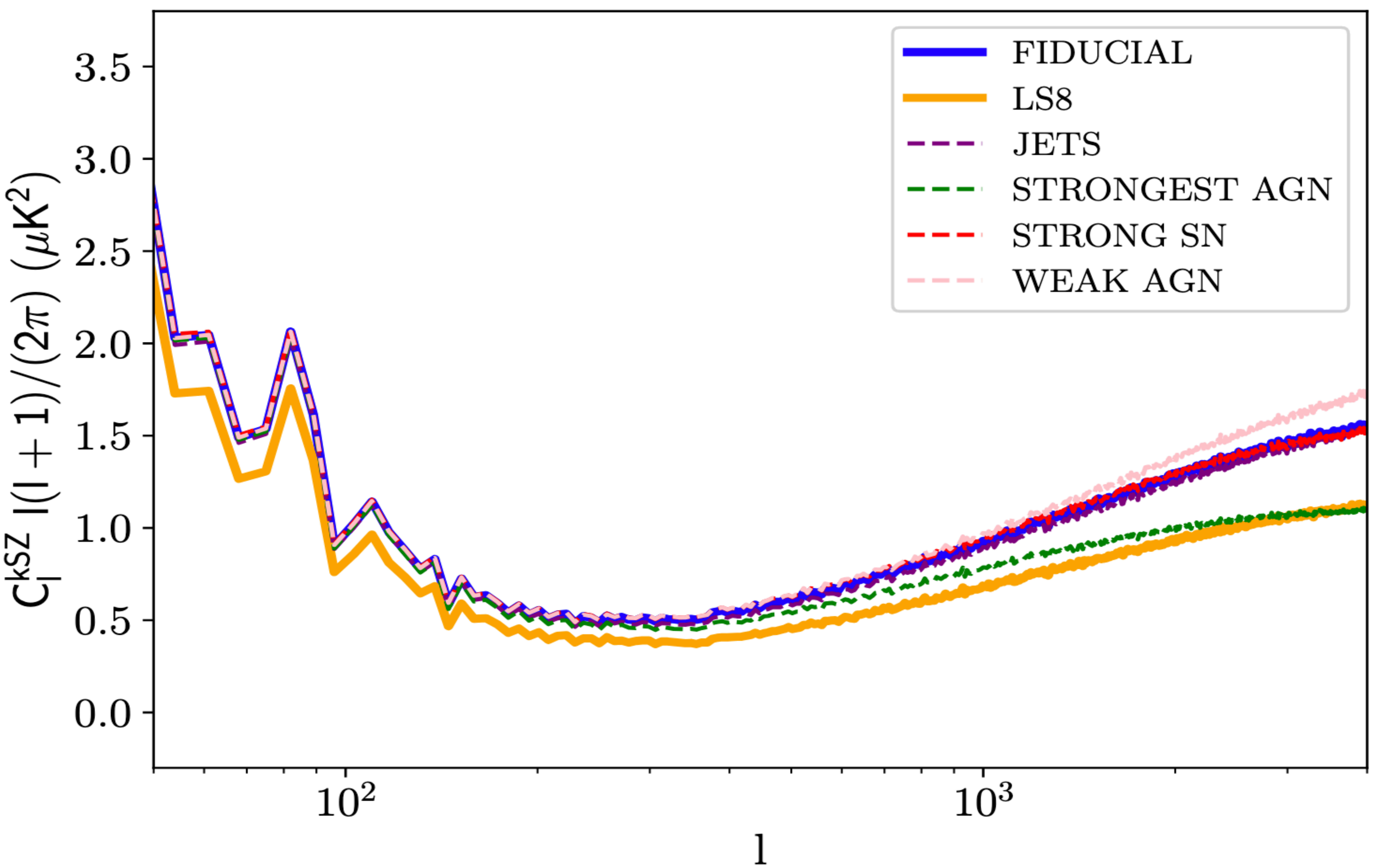
How does feedback affect the CIB and its crosses? ——Case 2: Varying SED parameters

- Although CIB auto-ps are the same across models+uncertainties in the SED, dependence on feedback and cosmology is retained in the cross-power spectra





What does feedback tell us in kSZ?



Radio point source

- For each halo with $M_{\rm subgrid} > 10^7 M_\odot$, re-assigning the L_ν from $L_{\rm bol,radio}$ by abundance-matching to the radio luminosity function measured at 150 MHz from the LOFAR survey, where $L_{\rm bol,radio} = \epsilon_r(1 - \epsilon_f)\dot{M}_{\rm BH}c^2$

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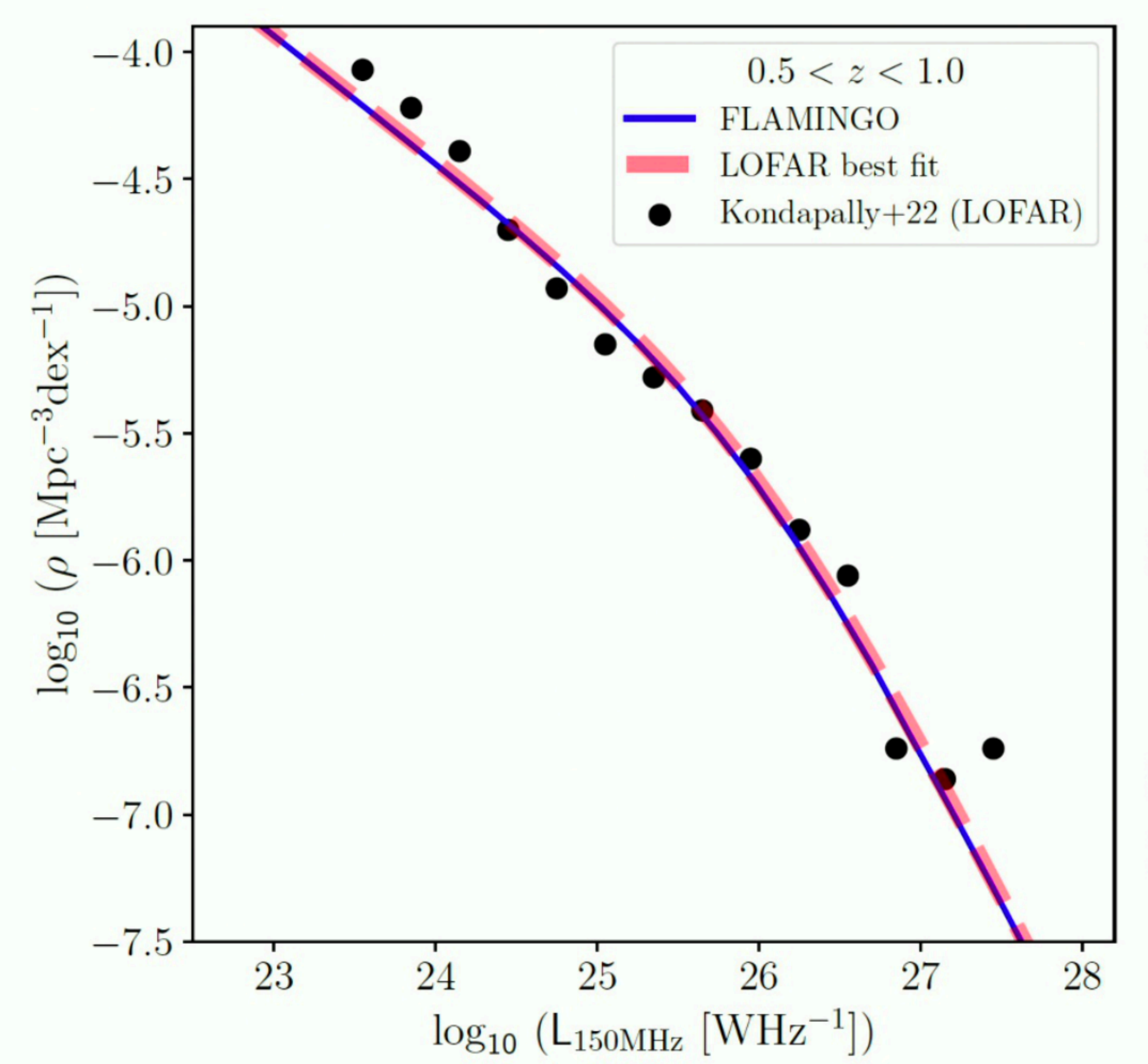

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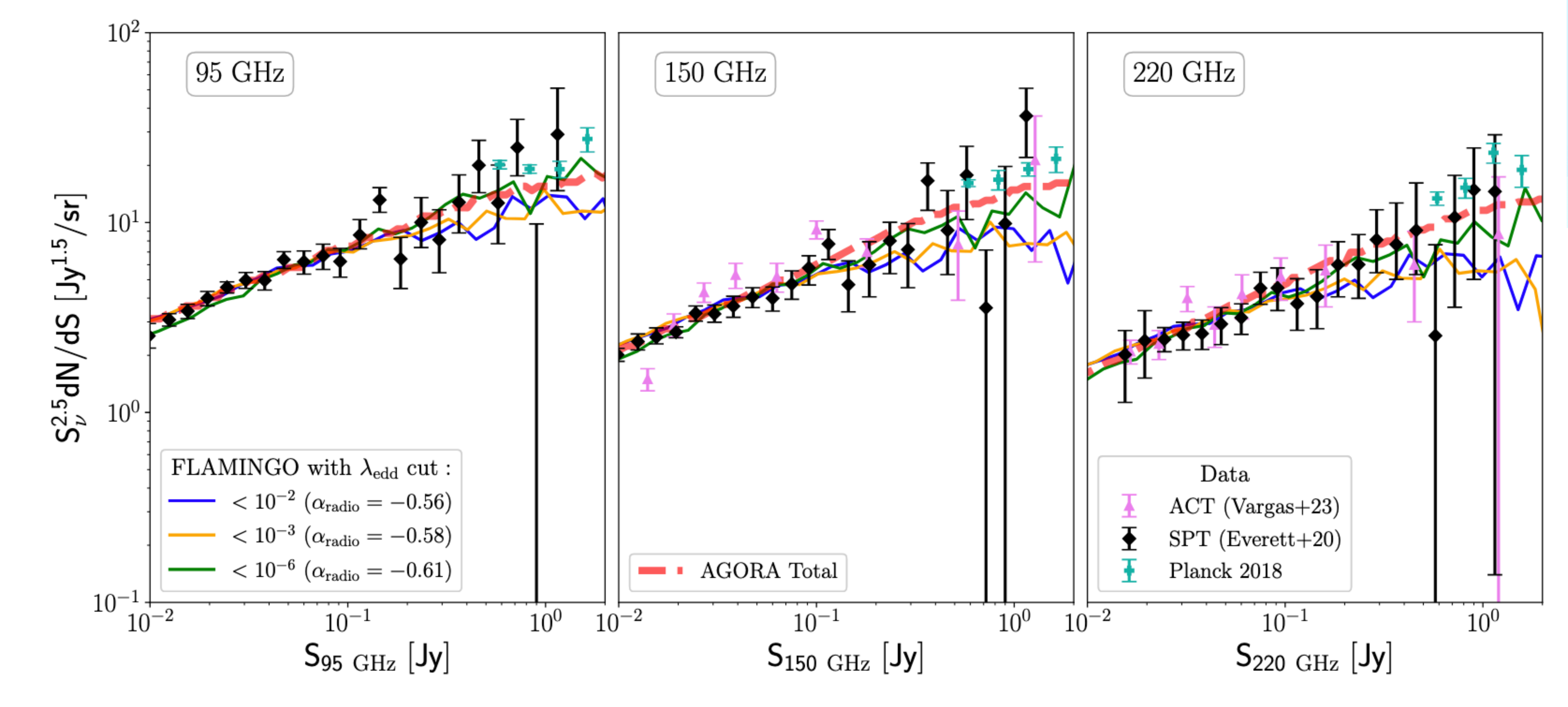
- Extrapolate the source fluxes to other CMB frequencies using $S_\nu = S_{\rm 150\ MHz}\ (\nu/150\ {\rm MHz})^{\alpha_{\rm radio}}$, with $\alpha_{\rm radio}$ determined by the source count curves from SPT survey at 95, 150, and 220 GHz.

- Group samples based on their accretion rate values ($\lambda_{\rm edd} = L_{\rm bol,radio}/L_{\rm edd}$) and examine their correlations with other LSS tracers separately.

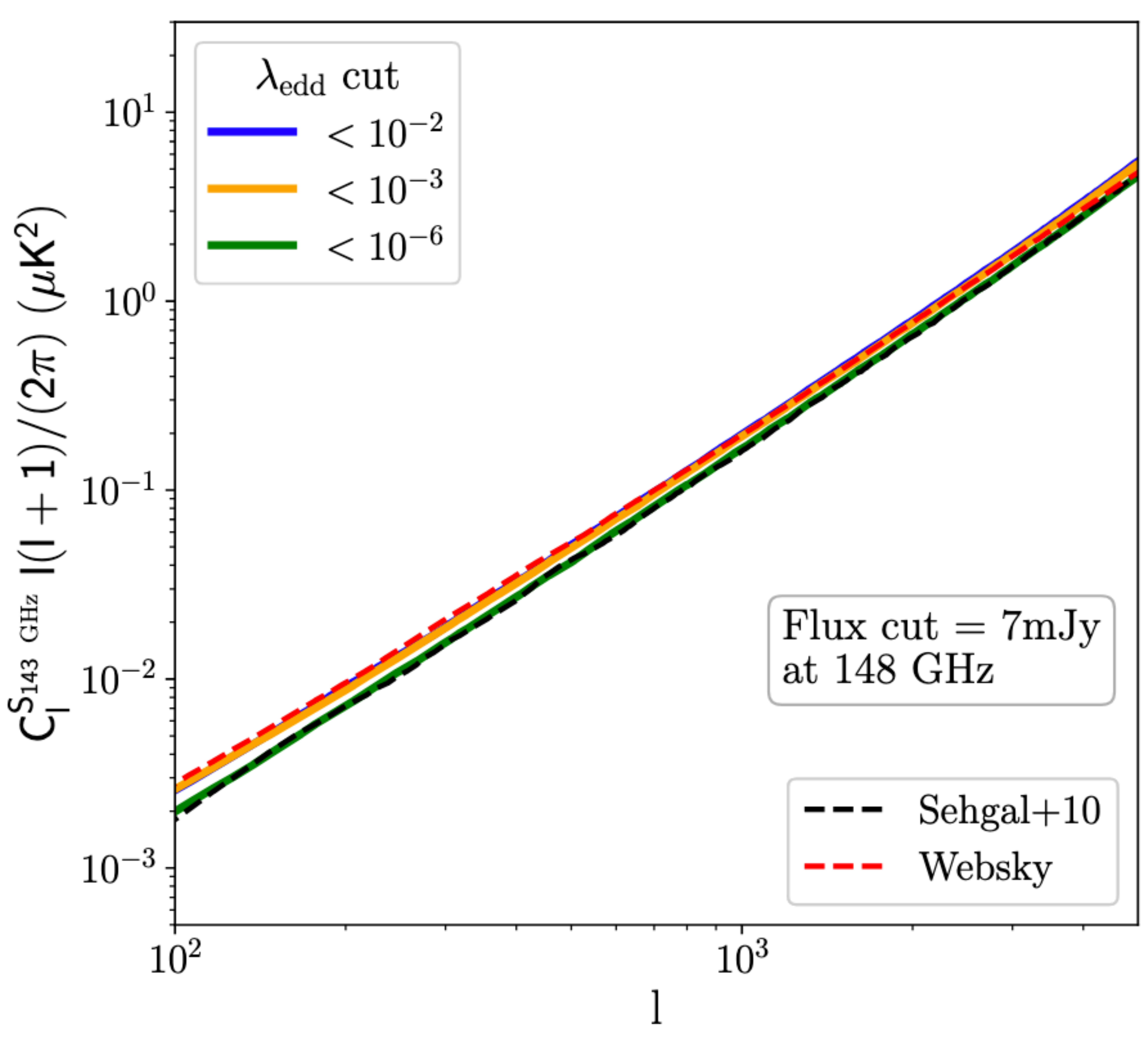
Radio point source

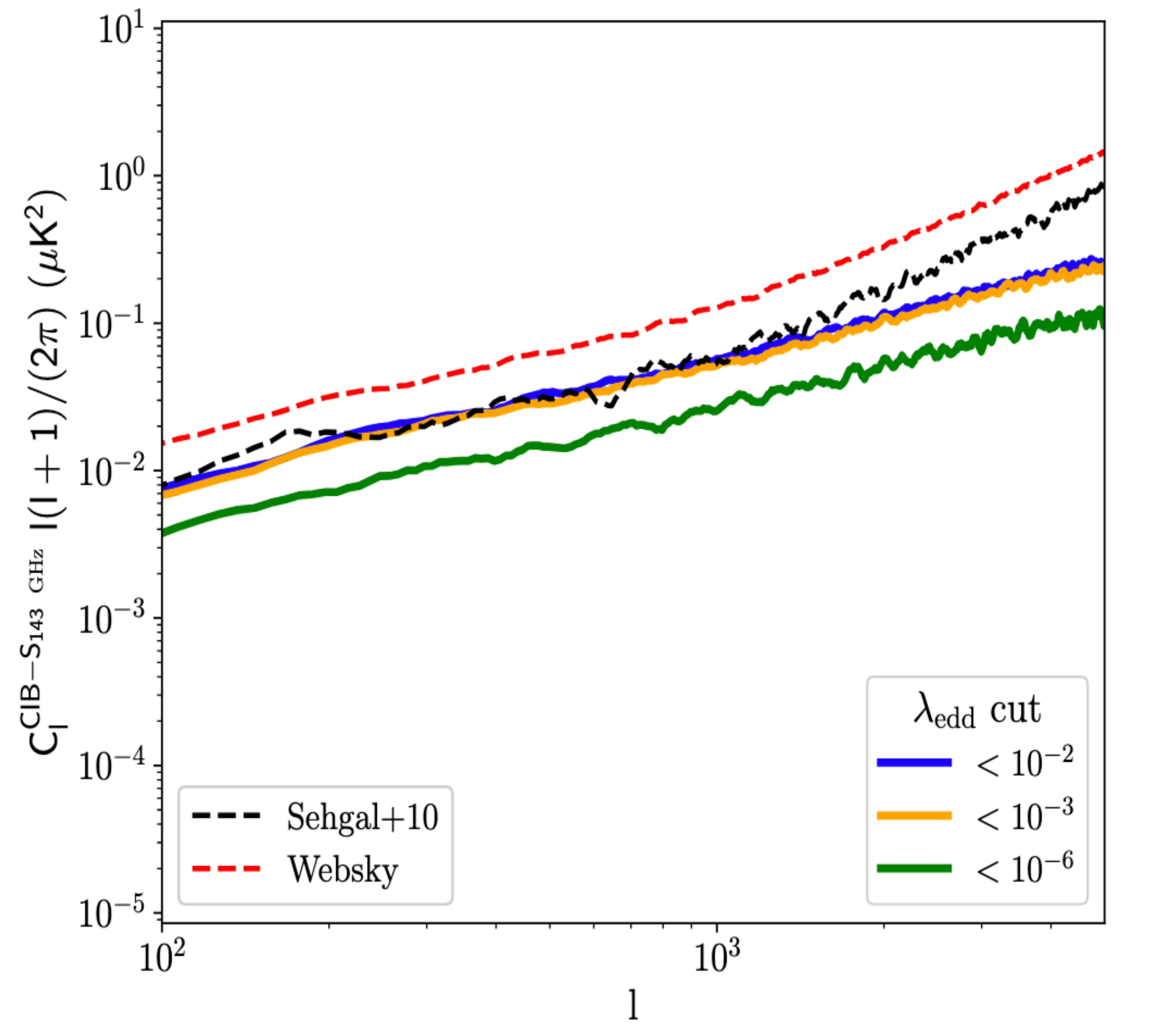
Source number count:



Radio point source

Auto-/cross-power spectrum:





Discussion and Future steps

- We have created a set of CMB secondary anisotropies full-sky maps using the FLAMINGO simulation and its model variants.
- By using the spatial clustering of star-forming galaxies, we have reconstructed relevant CIB statistics. Feedback effects are noticeable in CIB and CIB-LSS power spectrum
- We have constructed reasonable SZ statistics that are comparable to other CMB simulations. SZ statistics also have strong feedback dependencies.
- We have recovered the observed source number count from our simple radio model, and there are non-negligible radio-LSS correlations at low frequencies.
    - A more thorough observational comparison (e.g. with new ACT data, mask construction, with systematics added and apply with real pipelines——planned next step)
    - FRBs and line intensity mapping
    - Relativistic tSZ effect

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