Compton-y distortion: CMB constraints and new prospects with CIB

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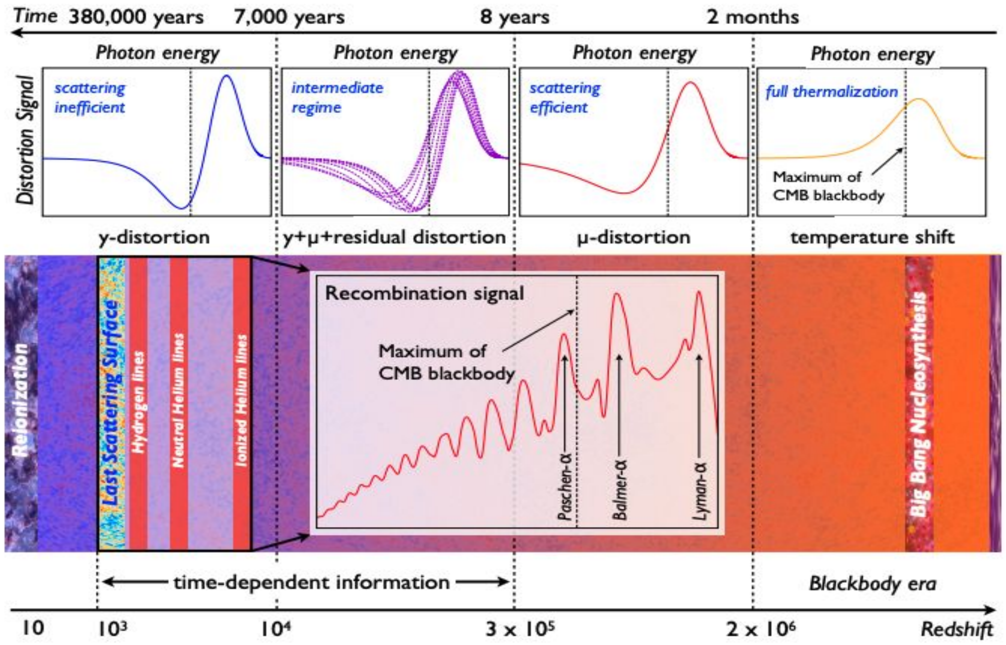
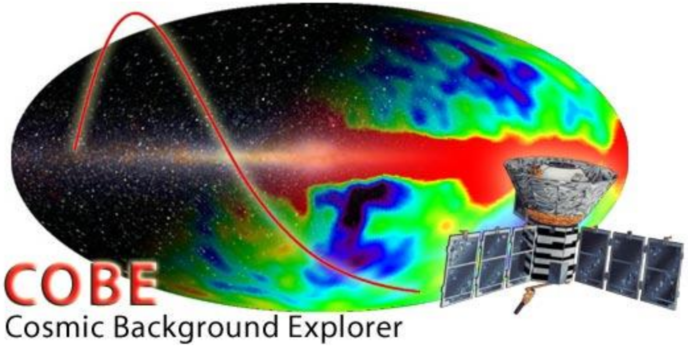
Spectral Distortions

Spectral distortions →
probe the Universe’s **thermal** history

$|\langle y\rangle| < 15 \times 10^{-6}$ and $|\langle \mu\rangle| < 90 \times 10^{-6}$ (Fixsen+1996)
$|\langle \mu\rangle| < 47 \times 10^{-6}$ (Bianchini & Fabbian 2022)



Chluba+2021



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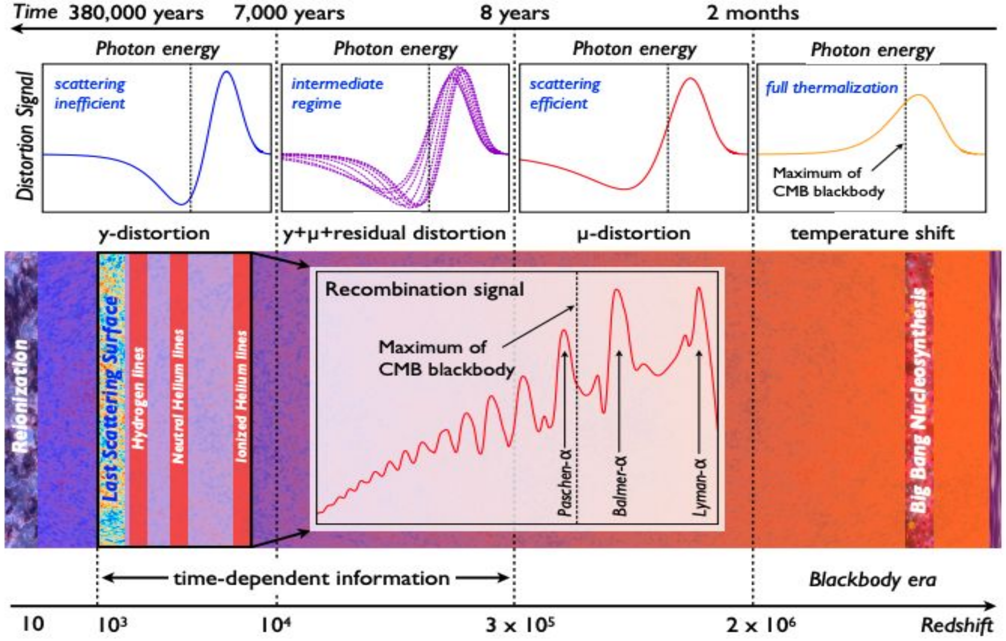
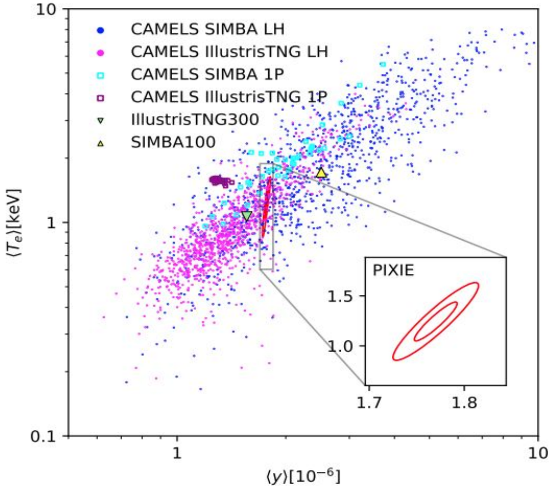


Chluba+2021

y-distortion: total thermal energy
stored in electrons



Thiele+2022

from theory: $y \sim 2 \times 10^{-6}$ (e.g. Hill+2014)

FIRAS Re-Analysis

Main motivation: **validate current forecasting methods** (e.g. PIXIE, Voyage 2050) + **tighten current constraints** on y-distortion (see Bianchini & Fabbian 2022 for pixel-by-pixel μ-distortion analysis)

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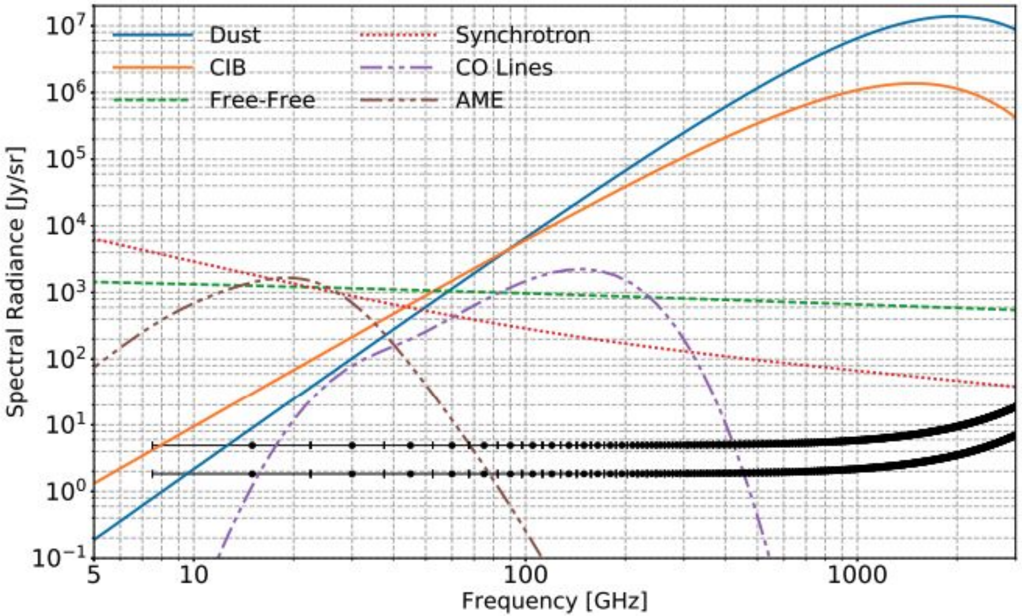
Key ingredients:

1. Sky model:

$$\Delta I_\nu = \underset{\textbf{Tcmb deviation}}{\Delta B_\nu} + \overset{\textbf{y-distortion}}{\Delta I^y_\nu} + \underset{\textbf{foregrounds}}{I^{\rm fg}_\nu}$$



Abitbol+2017

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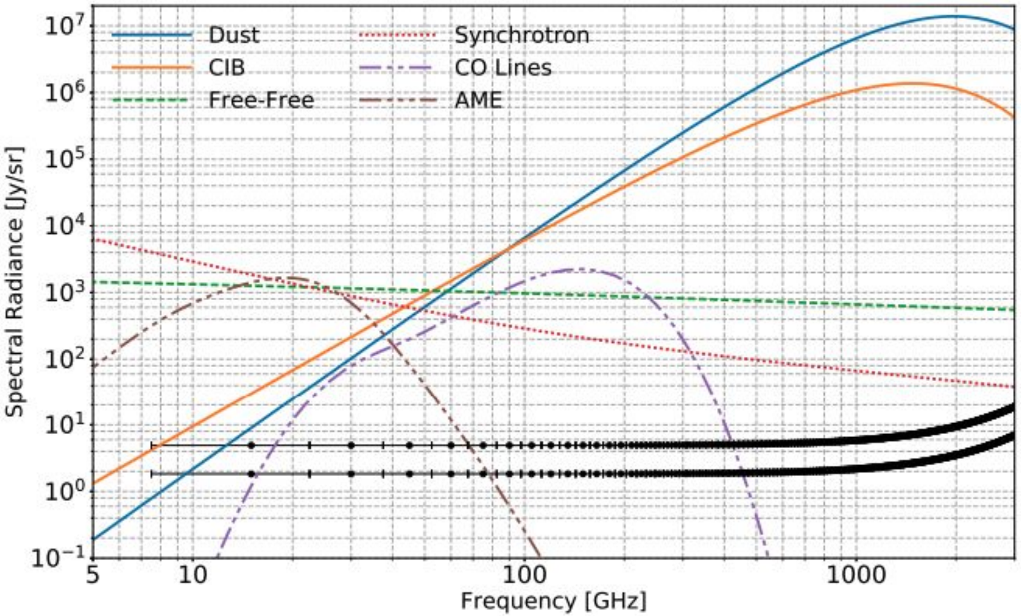
Key ingredients:

1. Sky model:
2. FIRAS Covariance:

$$\begin{aligned} C_{\nu p\nu' p} = {} & C^{\nu\nu'}\left(\delta^{pp'}/Np + \beta^p_k\beta_{p'k} + 0.04^2\right) && \textbf{noise} \\ & + S^{p\nu}S^{p'\nu'}\left(J^\nu J^{\nu'} + G^\nu G^\nu \delta^{\nu\nu'}\right) && \textbf{gain error} \\ & + P^\nu P^{\nu'}\left(U^2\delta^{pp'}/N_p + T^2\right) && \textbf{systematics} \end{aligned}$$



Abitbol+2017

FIRAS Re-Analysis

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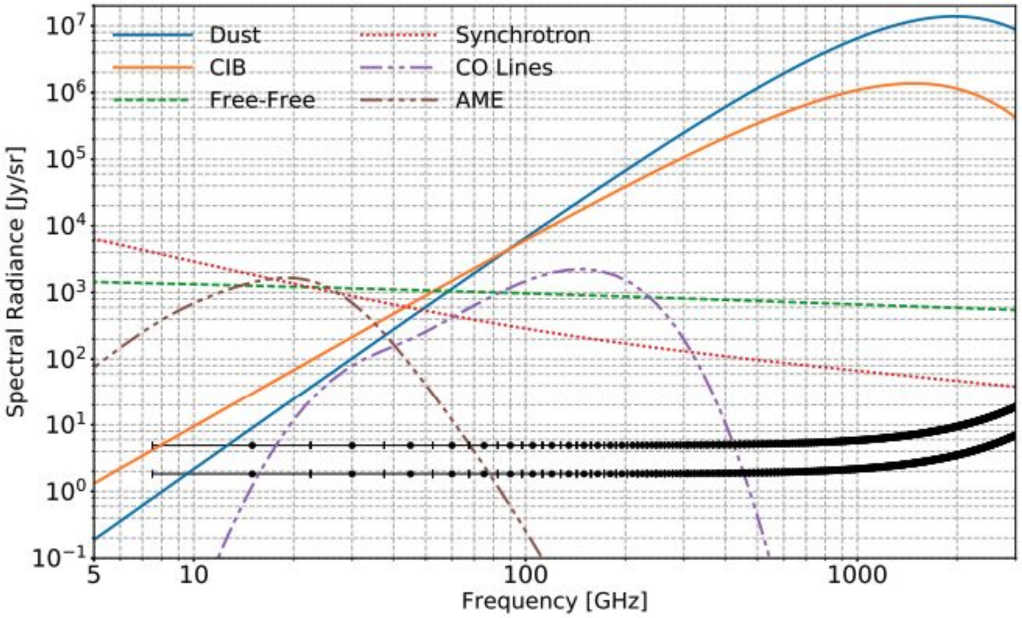
Key ingredients:

1. Sky model:
2. FIRAS Covariance:
3. CMB monopole data:

Low: ~61-650 GHz (43 channels)

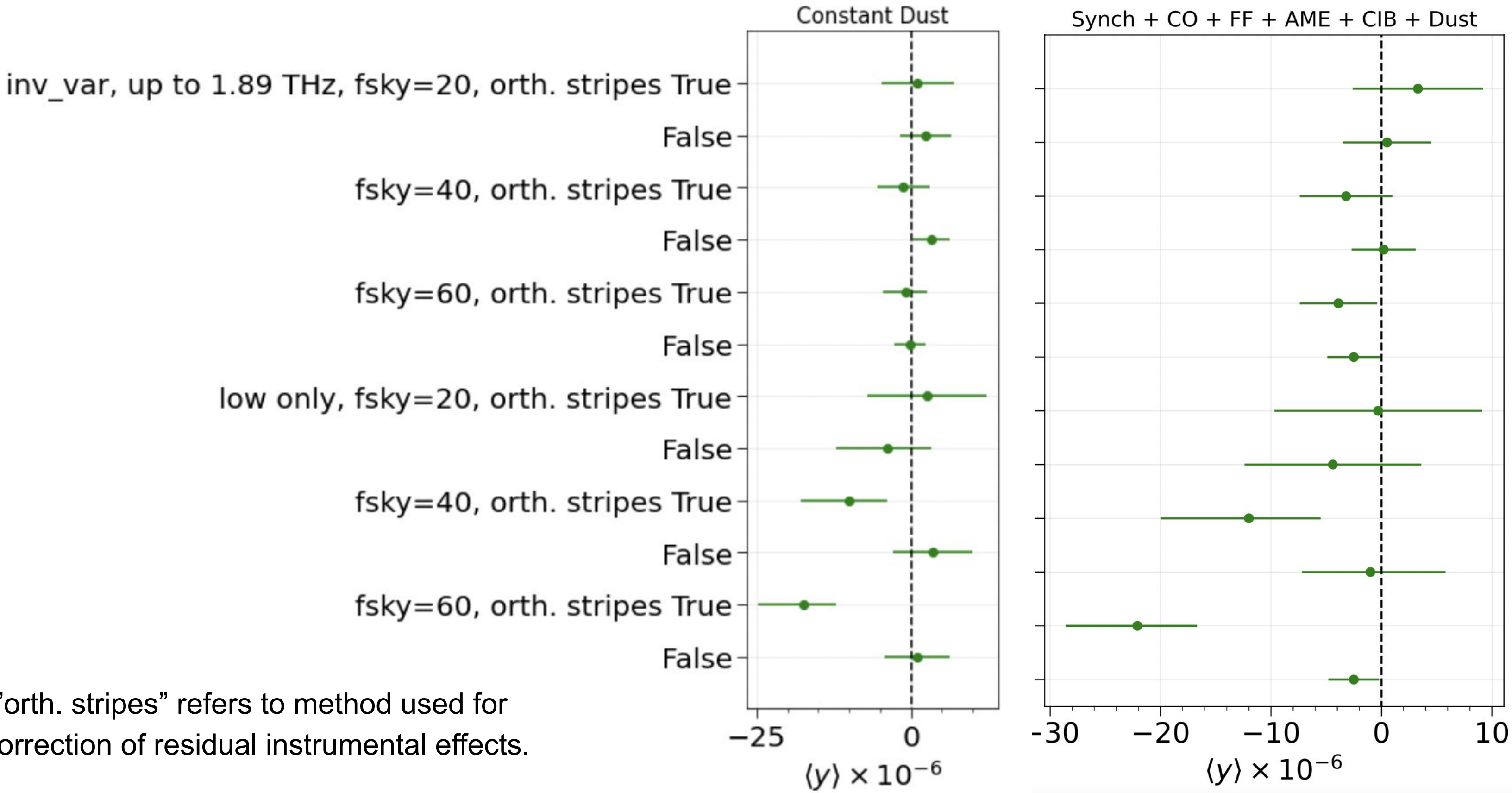
High: ~605-2918 GHz (170 channels)



Abitbol+2017

Mock Data Tests (Preliminary)

sky model: $\Delta_{T,}$ + y + dust



*”orth. stripes” refers to method used for correction of residual instrumental effects.

Results from Data (Preliminary)

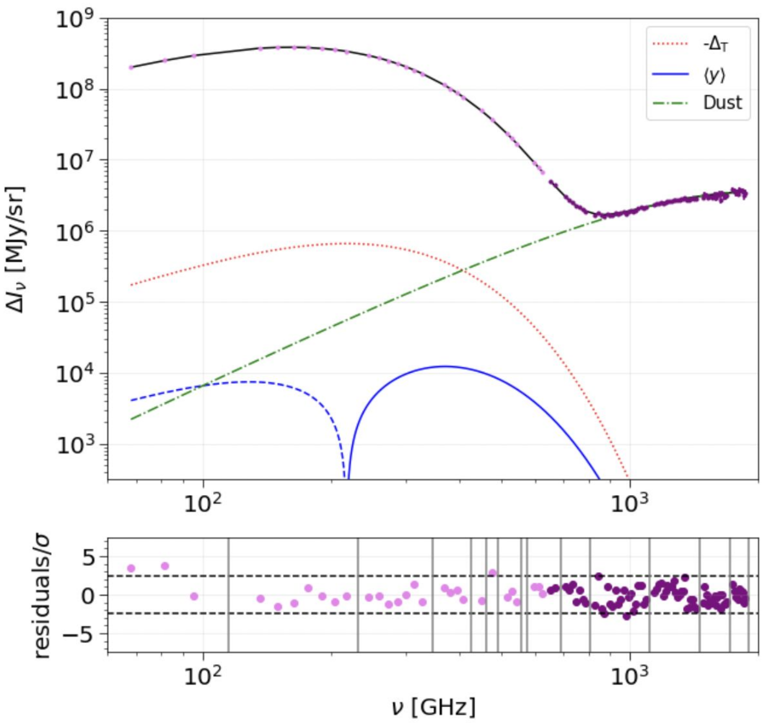
sky model: $\Delta_{T,}$ + y + dust

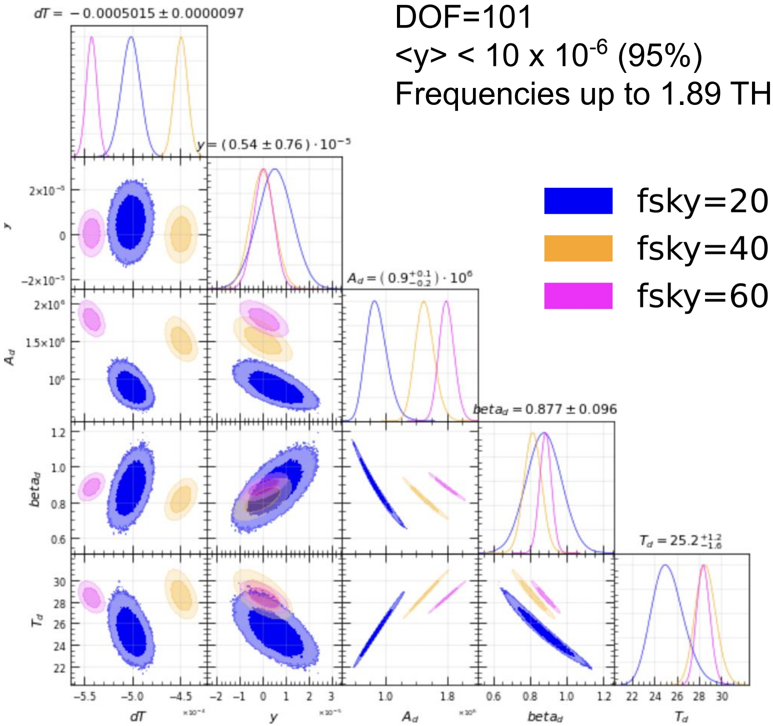
χ^2=156/229/351

DOF=101

<y> < 10 x 10^{-6} (95%)

Frequencies up to 1.89 THz



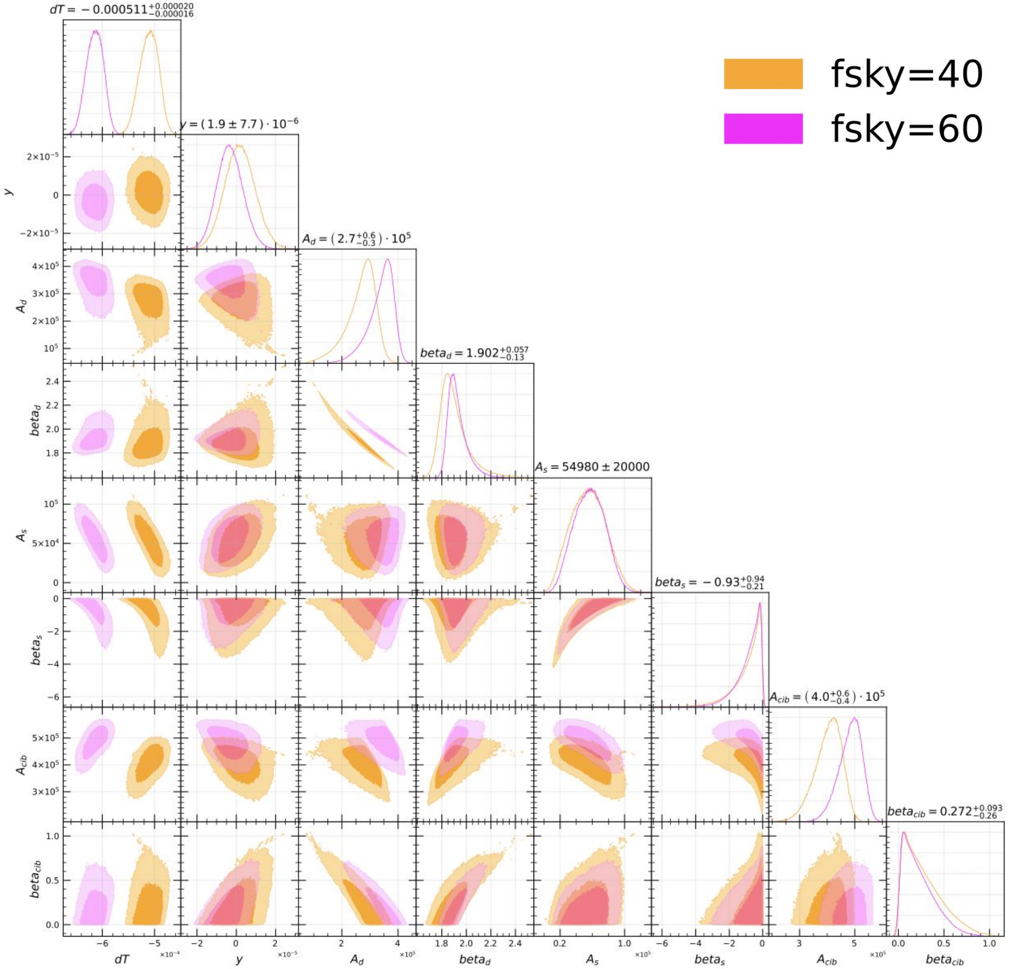


🟦 fsky=20

🟧 fsky=40

🟪 fsky=60

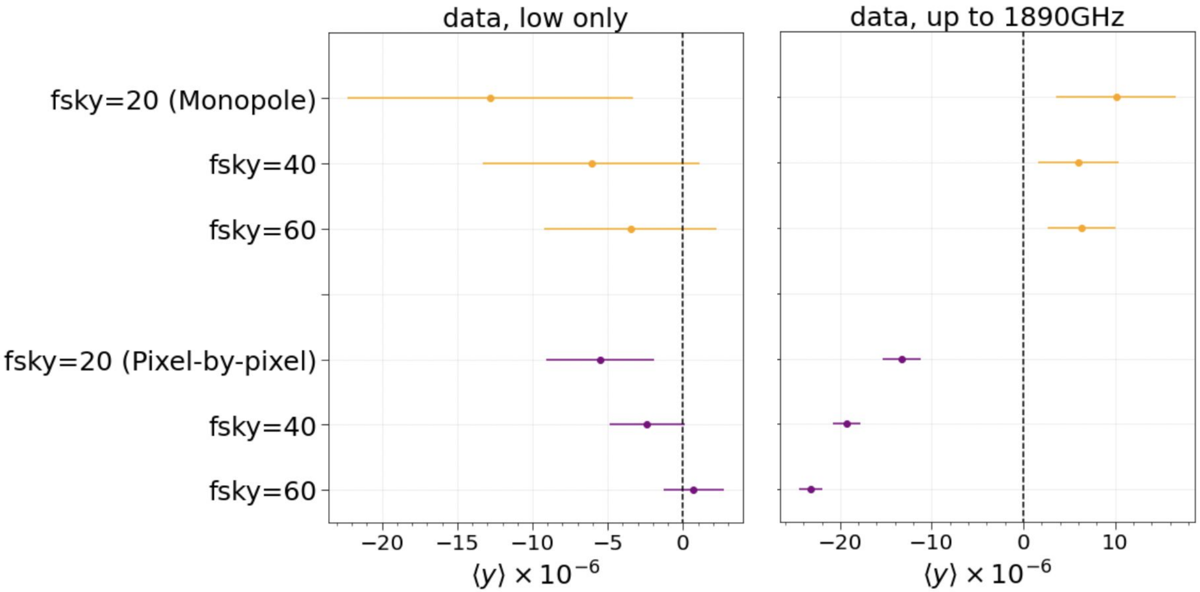
*Note: variability in dT is due to different sky masks

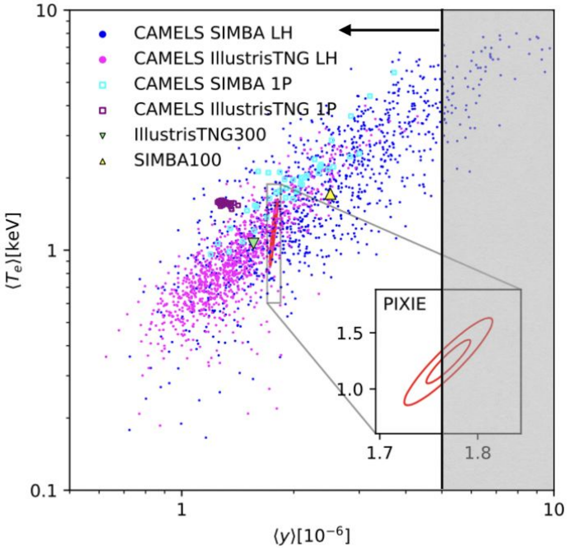


sky model:
$\Delta_{T,}$ + y + dust + synch + cib
(fixed Td & Tcib)

*Note: variability in dT is due to different sky masks

Method and Fisher Forecast Comparison (Preliminary)



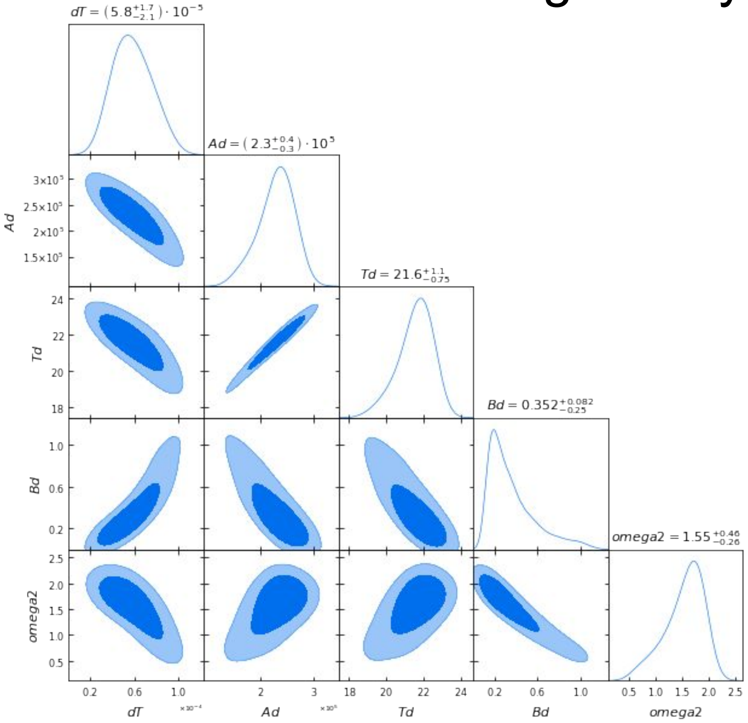


Plot thanks to Giulio & Leander

sky model: $\Delta_{T,}$ + y + dust

up to 1.89 THz , Fisher error (fsky=60) ~ 18 x 10^{-6}
monopole ~ 3.7 x 10^{-6}
pixel-by-pixel ~ 2 x 10^{-6} (low only)

+ consider moment expansion for foregrounds to fit higher sky fractions (in progress)



$\Delta_{\mathrm{T}},\ \langle y\rangle,\ 0 < A_{\mathrm{d}},\ 0 < \beta_{\mathrm{d}} < 3,\ 0 < T_{\mathrm{d}} < 100$	fsky=20	fsky=40	fsky=60
ν_{THz}	1.7	2.6	3.6
$\nu_{1.89\mathrm{THz}}$	1.5	2.3	3.5
$\Delta_{\mathrm{T}},\ \langle y\rangle,\ 0 < A_{\mathrm{d}},\ 0 < \beta_{\mathrm{d}} < 3,\ 0 < T_{\mathrm{d}} < 100, \omega_2, \omega_3$	fsky=20	fsky=40	fsky=60
ν_{THz}	1.5	2.3	3.1
$\nu_{1.89\mathrm{THz}}$	1.3	2.0	3.0

$$\langle I_\nu\rangle = \bar{A}_0 \frac{(\nu/\nu_0)^{\bar{\alpha}}\nu^3}{e^x - 1}\left\{1 + \omega_2 \ln(\nu/\nu_0) + \omega_3 \frac{x e^x}{e^x - 1}\right\}$$

Moment approach from Chluba, Hill & Abitbol 2017

Inverse-Compton scattering of the cosmic infrared background (CIB)

(Sabyr, Hill, & Bolliet 2022, **arXiv:2202.02275)**

CIB:

- ➔ Thermal **dust emission** in **star-forming** galaxies.
- ➔ Generated during **late universe**.

Use halo model prescription from

Sheng+2012, McCarthy & Madhavacheril 2021:

Redshift evolution

$(1+z)^{0.36}$

SED:

Modified blackbody at low ν,

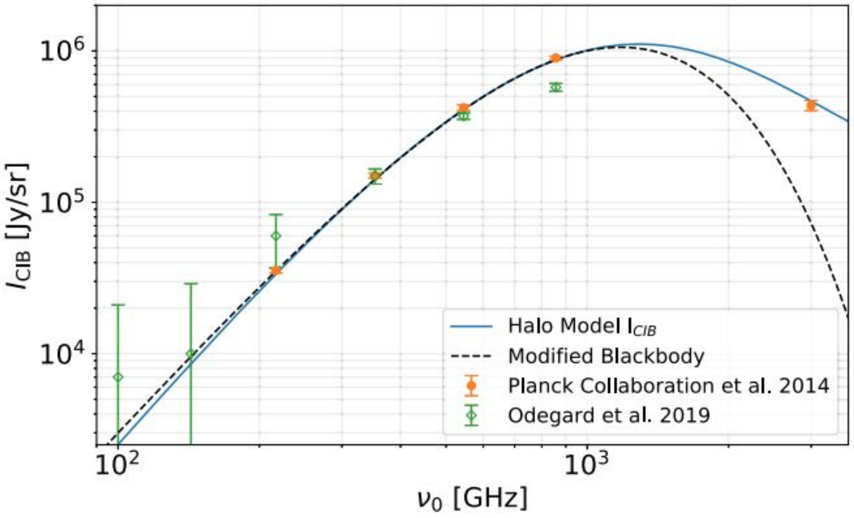
power law at high ν

Galaxy luminosity

$$L_\nu^{\rm gal}(M,z) = L_0 \Phi(z) \Sigma(M) \Theta(\nu, z)$$

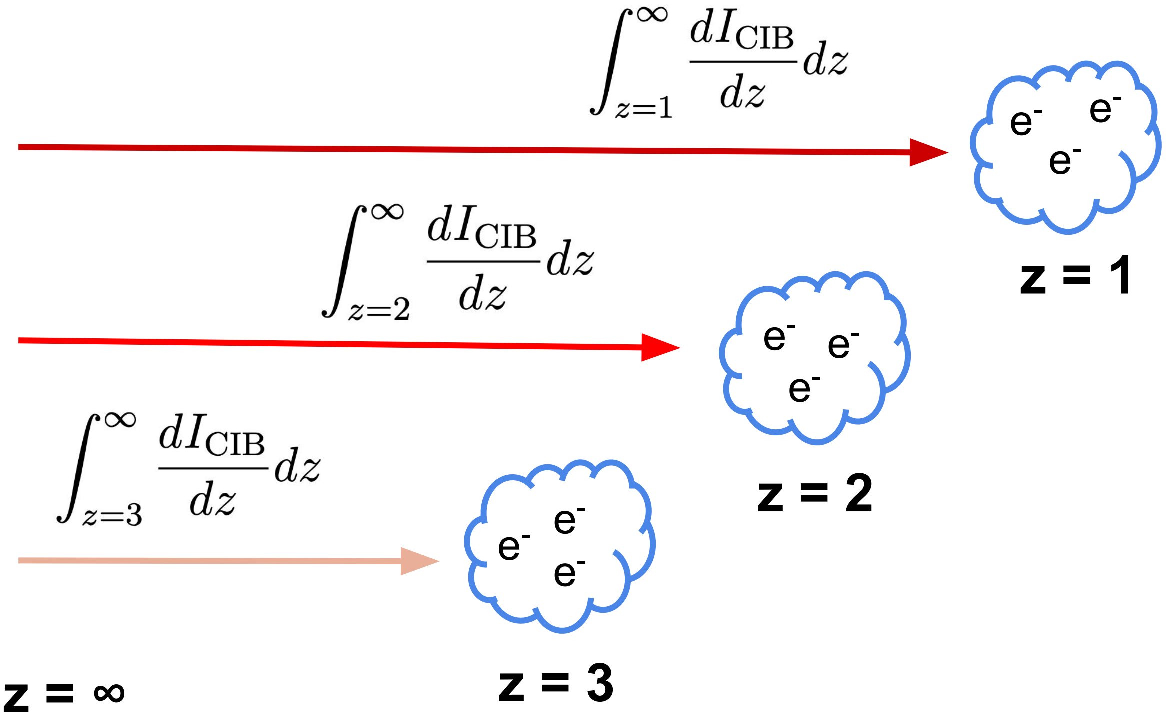
Luminosity-mass relation:

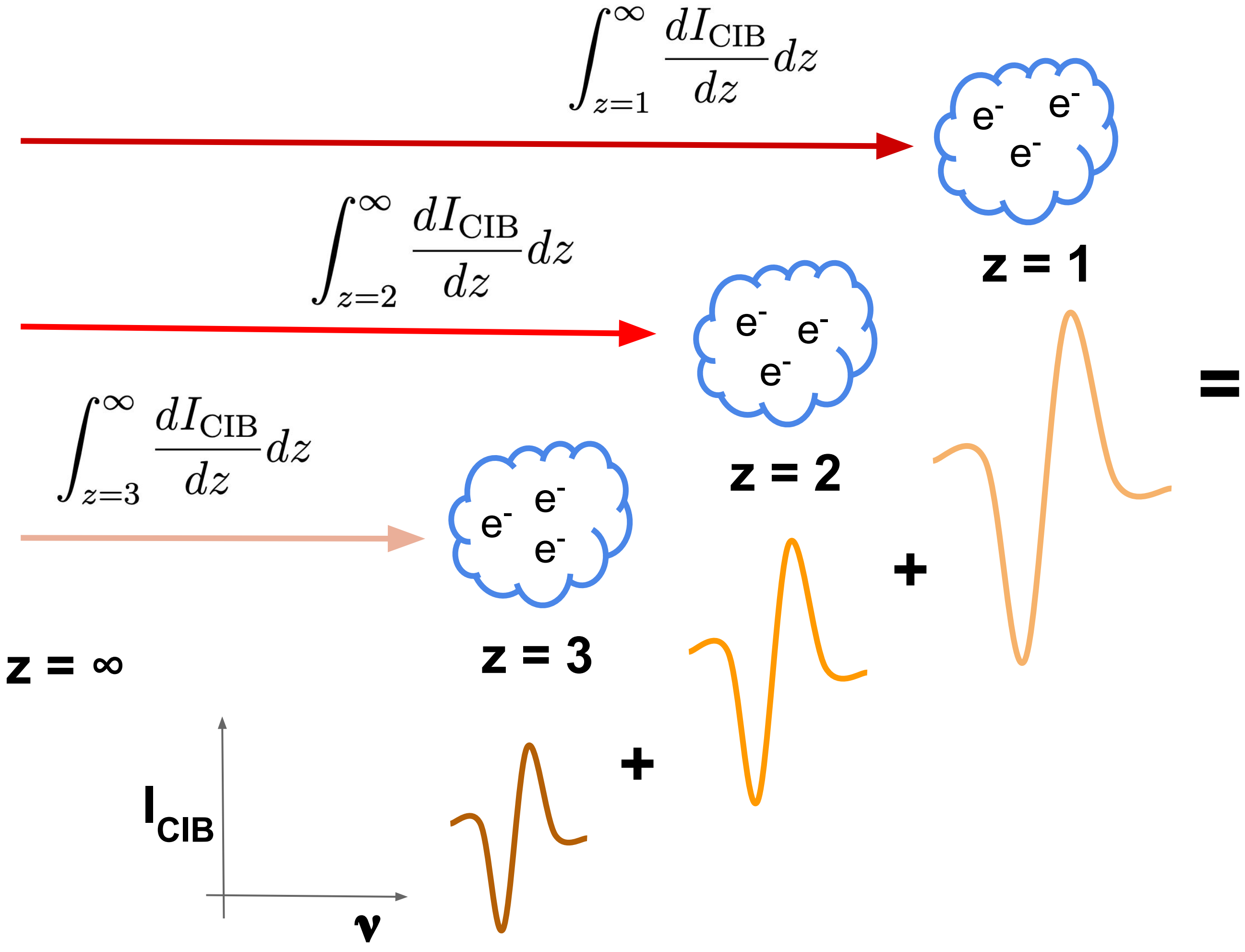
Log-normal distribution



implemented in **class_sz,** https://github.com/borisbolliet/class_sz
https://github.com/CLASS-SZ

Integrate over all halos & redshift to get the monopole

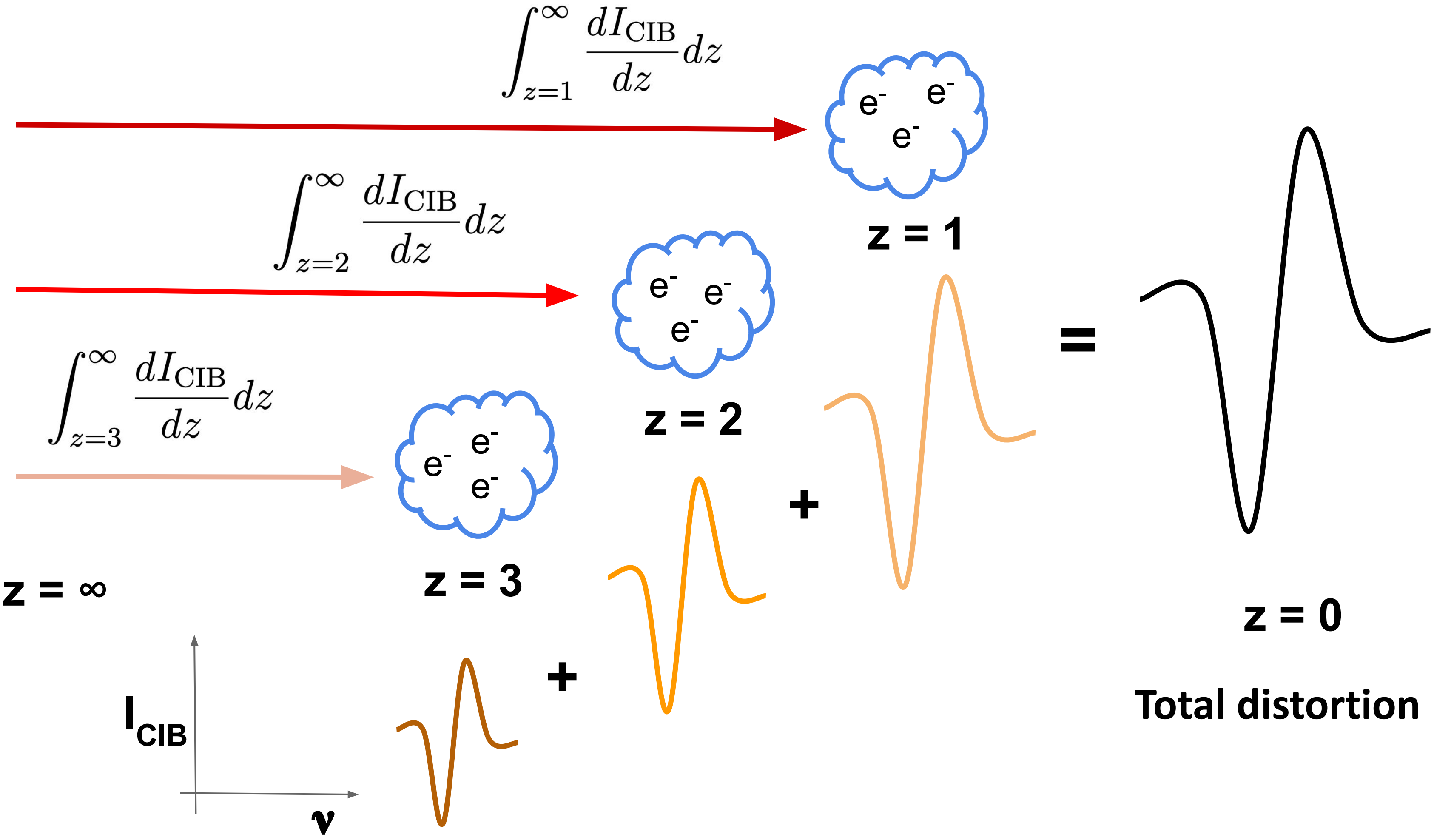

$\int_{z=1}^{\infty} \frac{dI_{\rm CIB}}{dz} dz$
e-
e-
e-
z = 1
$\int_{z=2}^{\infty} \frac{dI_{\rm CIB}}{dz} dz$
e-
e-
e-
z = 2
$\int_{z=3}^{\infty} \frac{dI_{\rm CIB}}{dz} dz$
e-
e-
e-
z = 3
z = ∞

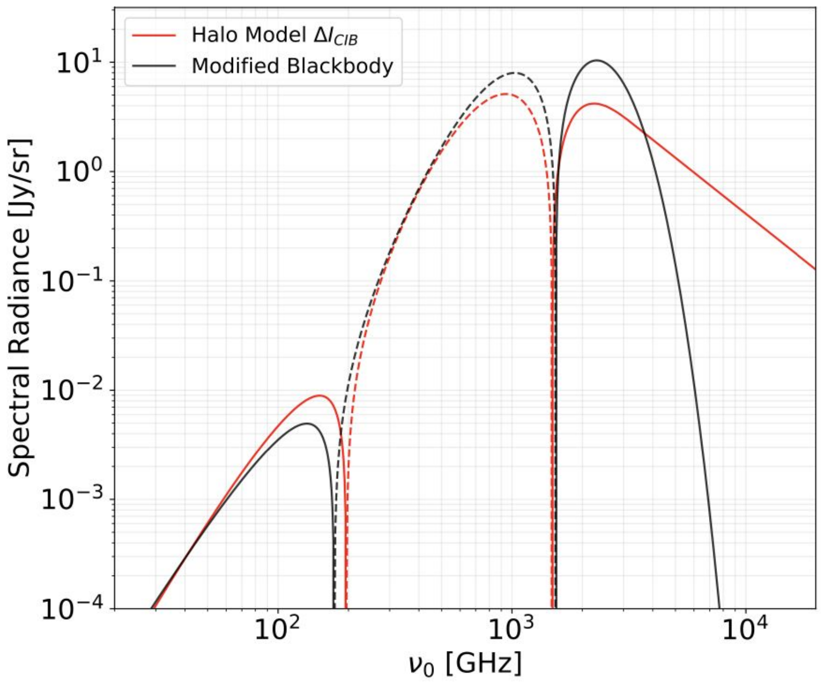


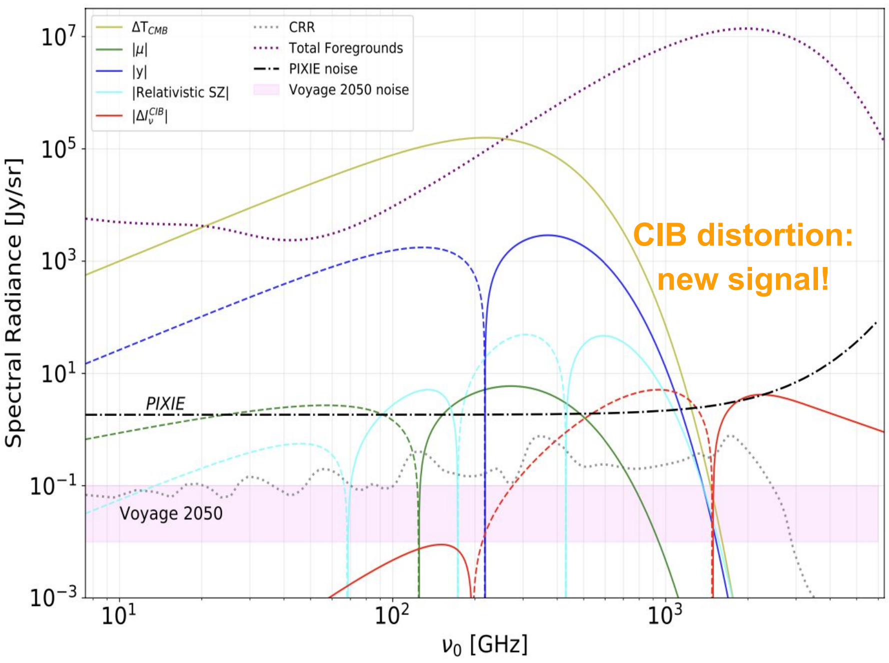
$$\int_{z=1}^{\infty} \frac{dI_{\mathrm{CIB}}}{dz} dz$$

$$\int_{z=2}^{\infty} \frac{dI_{\mathrm{CIB}}}{dz} dz$$

$$\int_{z=3}^{\infty} \frac{dI_{\mathrm{CIB}}}{dz} dz$$


$\int_{z=1}^{\infty} \frac{dI_{\rm CIB}}{dz} dz$
$\int_{z=2}^{\infty} \frac{dI_{\rm CIB}}{dz} dz$
$\int_{z=3}^{\infty} \frac{dI_{\rm CIB}}{dz} dz$
e^-
e^-
e^-
z = 1
z = 2
z = 3
z = ∞
z = 0
+
+
=
$I_{\rm CIB}$
ν
Total distortion





CIB distortion: new signal!

~**4** Jy/sr (-**5** Jy/sr) at **2260** GHz (**940** GHz)

Null frequencies at **196** and **1490** GHz.

Fisher forecast (including all foregrounds):

PIXIE: ~0.1σ

ESA Voyage 2050: ~0.9-4.6σ

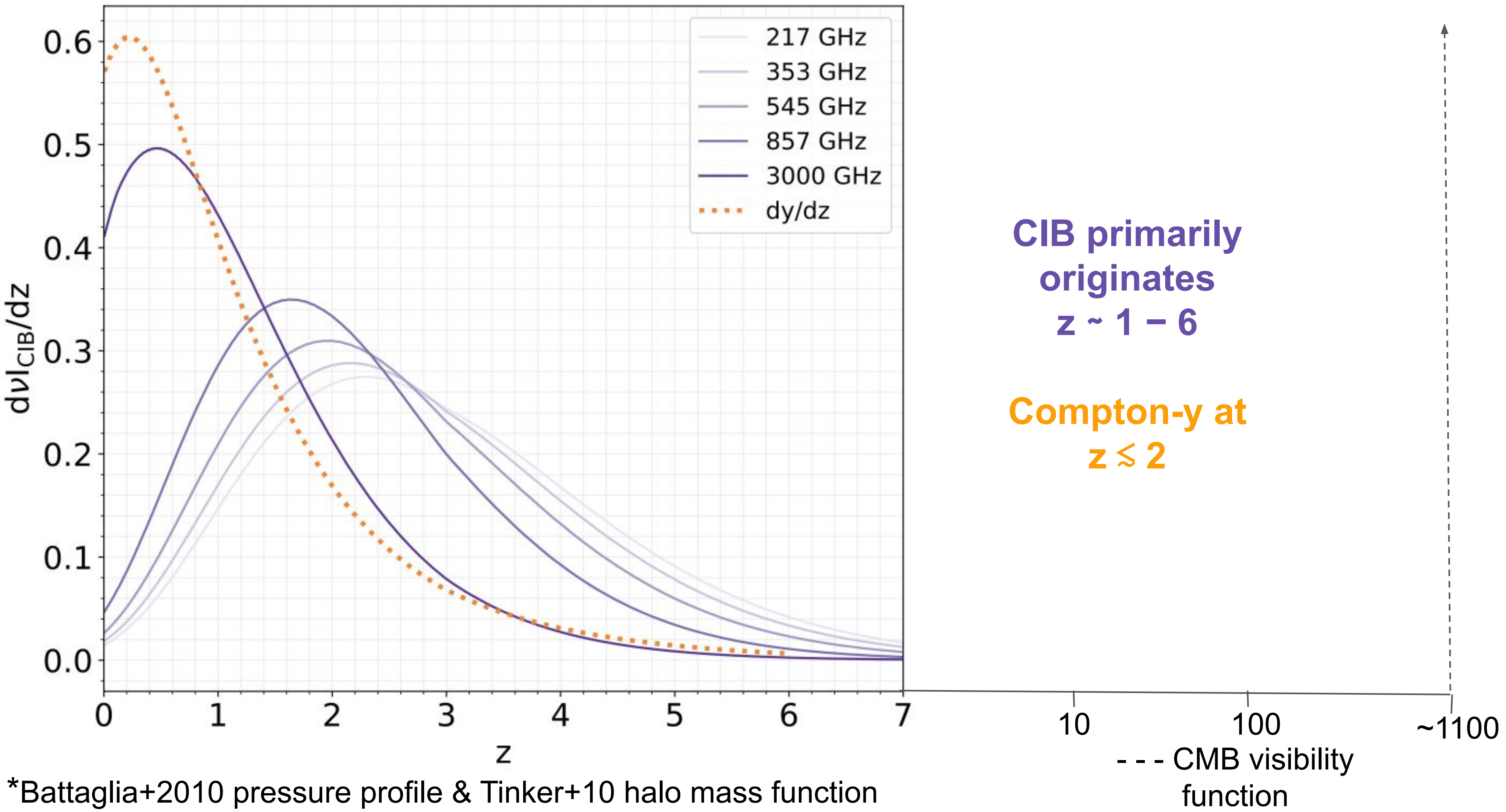
Relativistic & intracluster effects: see **Acharya & Chluba 2022**.

Summary

- ➔ FIRAS re-analysis allows us to asses our **models, analysis techniques,** and **accuracy of forecasts** for future missions and tighten upper bounds by a **factor of ~2-3**.
  - ◆ Noise characterization is crucial to take full advantage of future CMB measurements.
  - ◆ Pixel-by-pixel and monopole methods offer different advantages.

- ➔ Analogue tSZ distortion in the CIB – a **new signal** in the infrared sky and a tool to study the **star formation** history!
  - ◆ Detection with Voyage 2050 is possible but **targeted observations of clusters** & **anisotropy experiments** may provide measurements sooner (e.g. Coma cluster with y ~ 6 x 10^{-4} (Planck+2013); stacking analysis with CCAT-prime + SO)

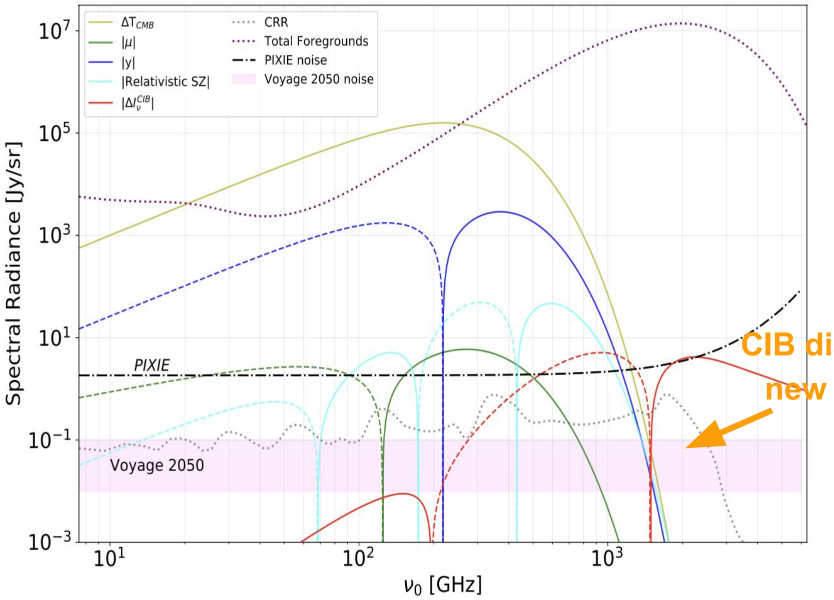
Extra Slides



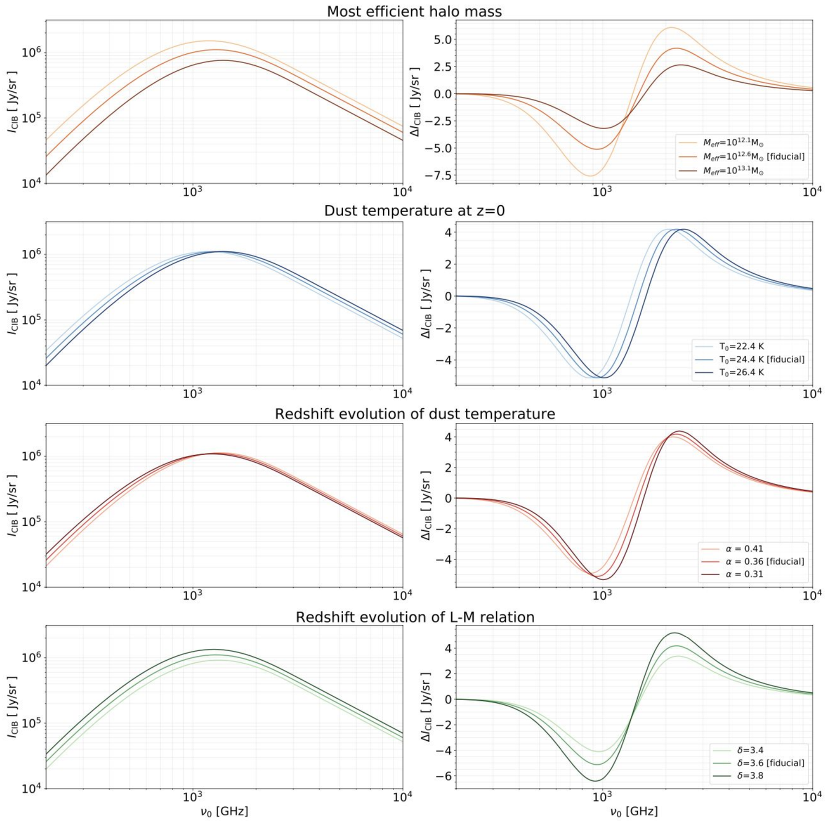
CIB primarily originates $z \sim 1 - 6$

Compton-y at $z \lesssim 2$

*Battaglia+2010 pressure profile & Tinker+10 halo mass function



CIB distortion: new signal!



Distortion’s sensitivity to **halo model parameters**.

CIB alone:
PIXIE: 3.6σ
ESA Voyage 2050: 73-364σ

with all foregrounds:
PIXIE: 0.1σ
ESA Voyage 2050: 0.9-4.6σ

Fisher set-up from **Abitbol+2017** (https://github.com/mabitbol/sd_foregrounds)

Cosmic Infrared Background (CIB)

Integrate over all halos

(comoving emissivity)

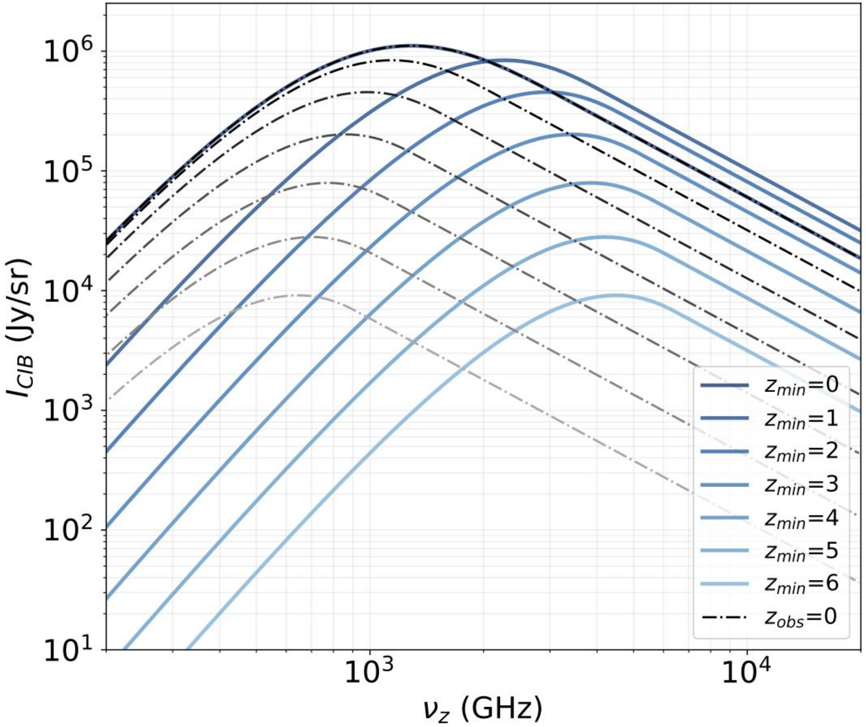
$$\tilde{j}_{\nu_z}(z') = \int_{M_{\min}}^{M_{\max}} \mathrm{d}M \, \frac{\mathrm{d}N}{\mathrm{d}M} \frac{1}{4\pi} \frac{L_{\frac{(1+z')}{(1+z)}\nu_z}(M, z')}{4\pi}$$

Integrate over redshift

(comoving specific intensity)

$$\tilde{I}^{\mathrm{CIB}}_{\nu_z}(z) = \int_{z}^{z_{\max}} \mathrm{d}z' \, \frac{c\tilde{j}_{\nu_z}(z')}{(1+z')H(z')}$$

Implemented in **class_sz,**
https://github.com/borisbolliet/class_sz
https://github.com/CLASS-SZ



Inverse-Compton Scattering

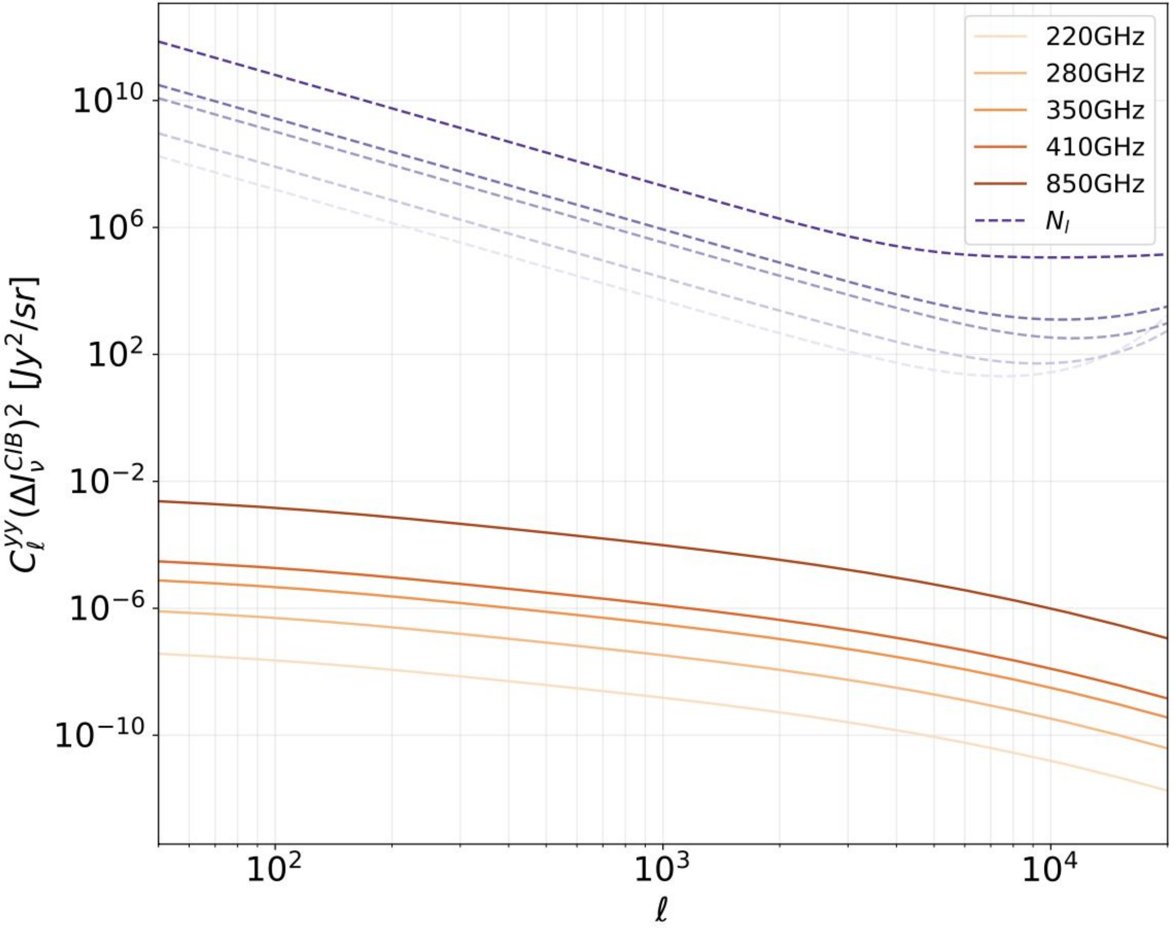
- Use Kompaneets approximation (**Kompaneets 1957**)
  - Non-relativistic, Te >>Tcib and y << 1

Compton-y

$$\Delta N(\nu) \approx \frac{y}{\nu^2}\frac{\partial}{\partial \nu}\left[\nu^4 \frac{\partial N(\nu)}{\partial \nu}\right]$$

photon occupation number

- Calculate differential distortion at each infinitesimal redshift & add up.



220GHz
280GHz
350GHz
410GHz
850GHz
N_l
$C_\ell^{yy}(\Delta I_\nu^{CIB})^2$ $[Jy^2/sr]$
10^{10}
10^{6}
10^{2}
10^{-2}
10^{-6}
10^{-10}
10^{2}
10^{3}
10^{4}
ℓ

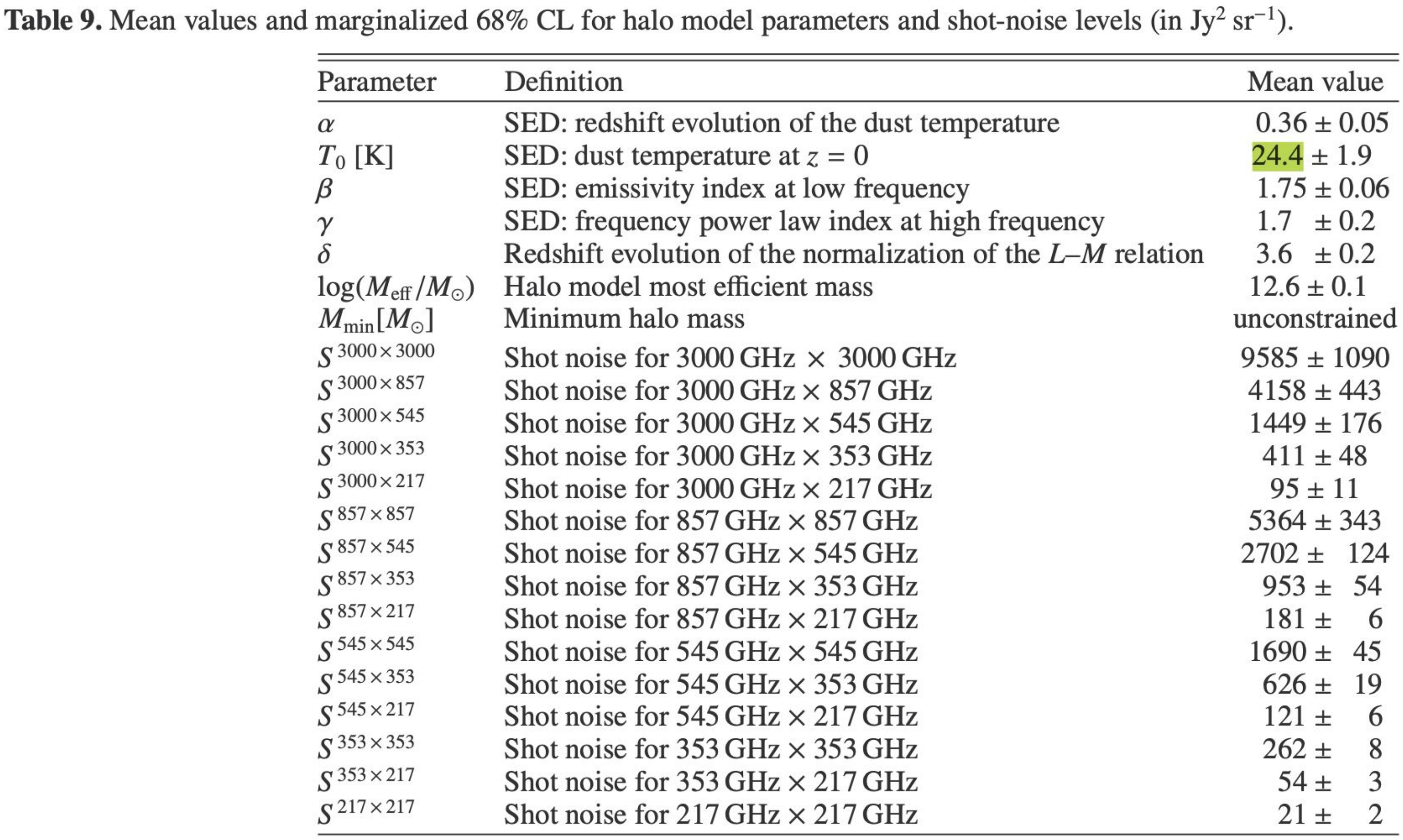
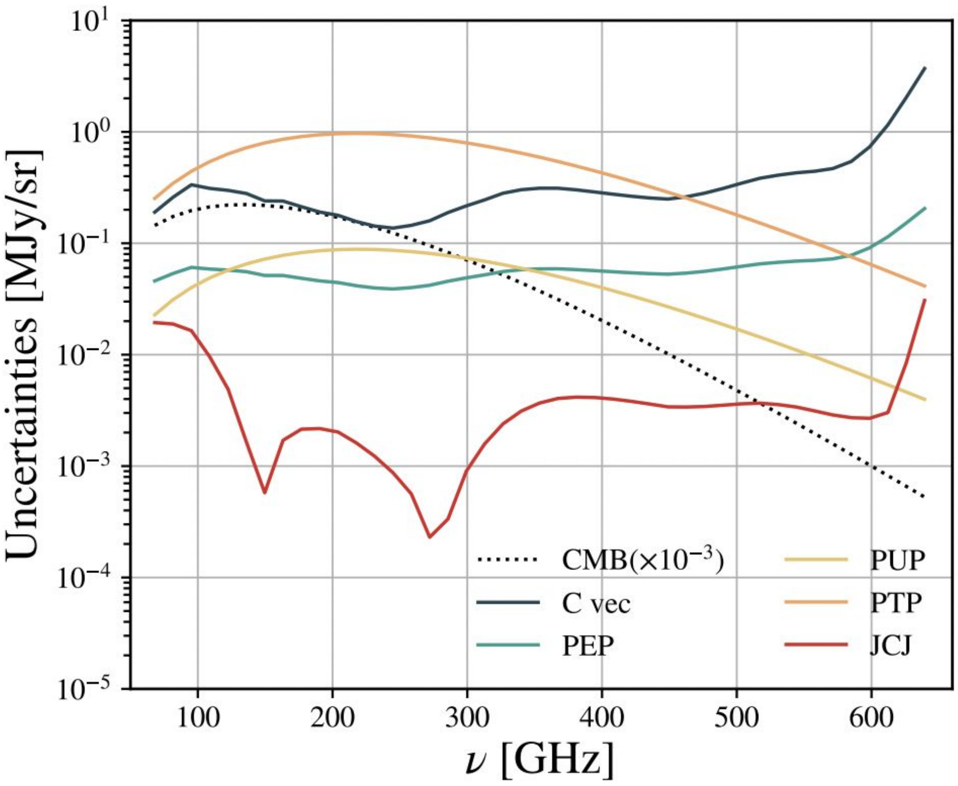


Table 9. Mean values and marginalized 68% CL for halo model parameters and shot-noise levels (in $\mathrm{Jy}^2\,\mathrm{sr}^{-1}$).

Parameter	Definition	Mean value
α	SED: redshift evolution of the dust temperature	0.36 ± 0.05
T_0 [K]	SED: dust temperature at $z = 0$	24.4 ± 1.9
β	SED: emissivity index at low frequency	1.75 ± 0.06
γ	SED: frequency power law index at high frequency	1.7 ± 0.2
δ	Redshift evolution of the normalization of the L–M relation	3.6 ± 0.2
$\log(M_{\mathrm{eff}}/M_\odot)$	Halo model most efficient mass	12.6 ± 0.1
$M_{\mathrm{min}}[M_\odot]$	Minimum halo mass	unconstrained
$S^{3000\times3000}$	Shot noise for 3000 GHz × 3000 GHz	9585 ± 1090
$S^{3000\times857}$	Shot noise for 3000 GHz × 857 GHz	4158 ± 443
$S^{3000\times545}$	Shot noise for 3000 GHz × 545 GHz	1449 ± 176
$S^{3000\times353}$	Shot noise for 3000 GHz × 353 GHz	411 ± 48
$S^{3000\times217}$	Shot noise for 3000 GHz × 217 GHz	95 ± 11
$S^{857\times857}$	Shot noise for 857 GHz × 857 GHz	5364 ± 343
$S^{857\times545}$	Shot noise for 857 GHz × 545 GHz	2702 ± 124
$S^{857\times353}$	Shot noise for 857 GHz × 353 GHz	953 ± 54
$S^{857\times217}$	Shot noise for 857 GHz × 217 GHz	181 ± 6
$S^{545\times545}$	Shot noise for 545 GHz × 545 GHz	1690 ± 45
$S^{545\times353}$	Shot noise for 545 GHz × 353 GHz	626 ± 19
$S^{545\times217}$	Shot noise for 545 GHz × 217 GHz	121 ± 6
$S^{353\times353}$	Shot noise for 353 GHz × 353 GHz	262 ± 8
$S^{353\times217}$	Shot noise for 353 GHz × 217 GHz	54 ± 3
$S^{217\times217}$	Shot noise for 217 GHz × 217 GHz	21 ± 2

Planck+2014



Bianchini & Fabbian 2022