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

Alina Sabyr

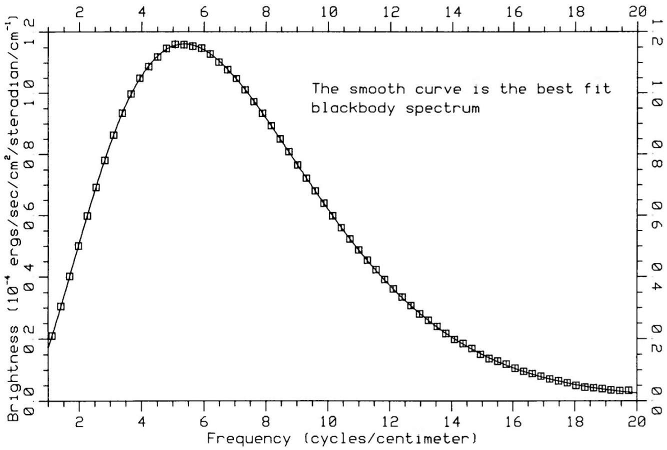
with J. Colin Hill, Giulio Fabbian, Federico Bianchini, Boris Bolliet

Columbia University
in the City of New York

IESC

Spectral Distortions

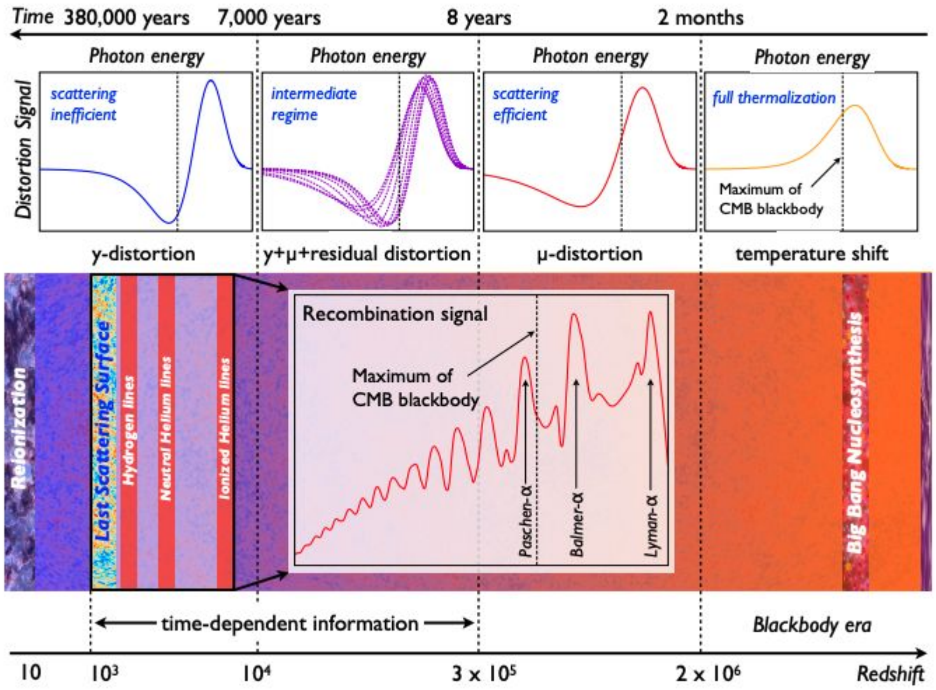
(Quick Review)



Mather+1990

CMB → *almost* a perfect **blackbody**

Spectral distortions →
probe the Universe's **thermal** history
Upper limits:
$|\langle y\rangle| < 15 \times 10^{-6}$ and $|\langle \mu\rangle| < 90 \times 10^{-6}$ (Fixsen+1996)
$|\langle \mu\rangle| < 47 \times 10^{-6}$ (Bianchini & Fabbian 2022)



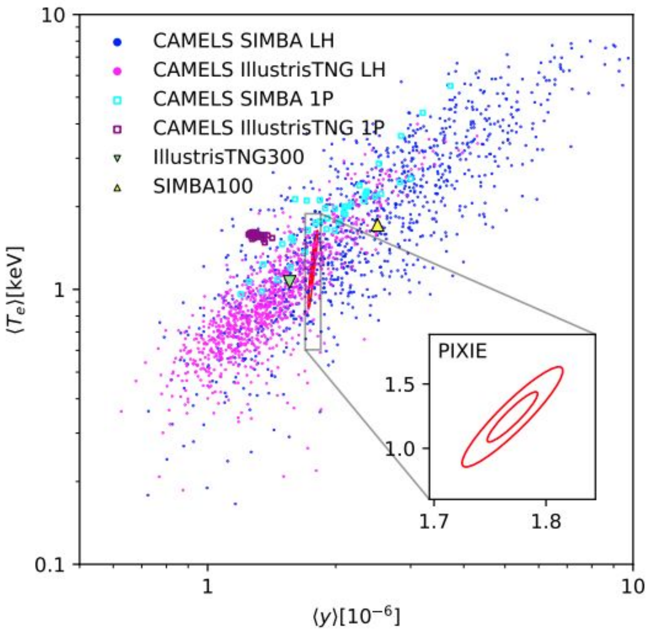
Chluba+2021

Compton-y distortion

- ➔ Known source: thermal Sunyaev-Zel'dovich effect (Sunyaev & Zel’dovich 1980)
- ➔ Primarily sourced by galaxy groups and clusters.
- ➔ Total thermal energy stored in electrons

$$\langle \Delta I_\nu^y \rangle = \langle y \rangle \times I_0 \frac{x^4 e^x}{(e^x - 1)^2} \left[x\coth\left(\frac{\mathrm{x}}{2}\right) - 4 \right]$$

$$\langle y \rangle = \frac{\sigma_\mathrm{T}}{\mathrm{m_e c^2}} \int \frac{\mathrm{d}^2\hat{\mathbf{n}}}{4\pi} \int P_e(\hat{\mathbf{n}}, l) dl$$

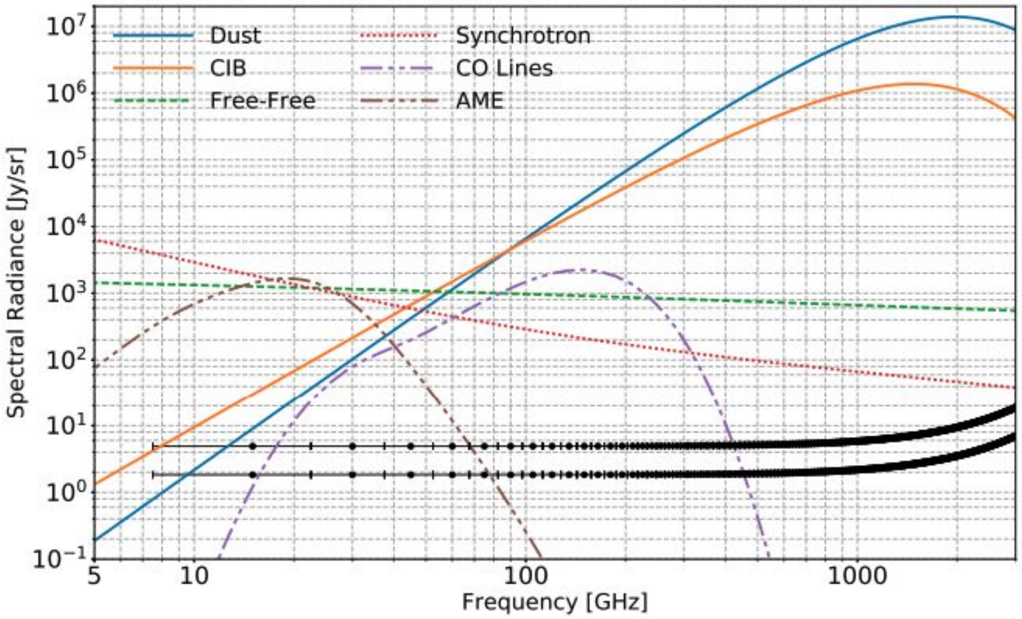


Thiele+2022

FIRAS Re-Analysis

Main motivation: validate current forecasting methods (e.g. PIXIE, Voyage 2050)

(see Bianchini & Fabbian 2022 for pixel-by-pixel μ-distortion analysis)



Abitbol+2017

FIRAS Re-Analysis

Main motivation: validate current forecasting methods (e.g. PIXIE, Voyage 2050)

(see Bianchini & Fabbian 2022 for pixel-by-pixel μ-distortion analysis)

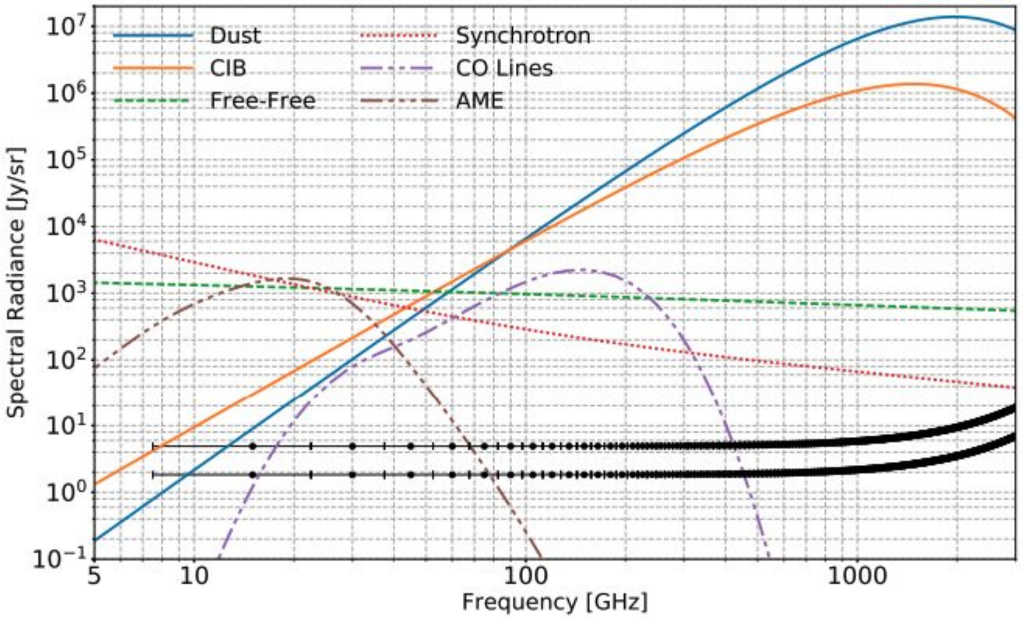
Key ingredients:

1. Sky model:

y-distortion

$$\Delta I_\nu = \Delta B_\nu + \Delta I_\nu^y + I_\nu^{\rm fg}$$

Tcmb deviation　　　foregrounds



Abitbol+2017

FIRAS Re-Analysis

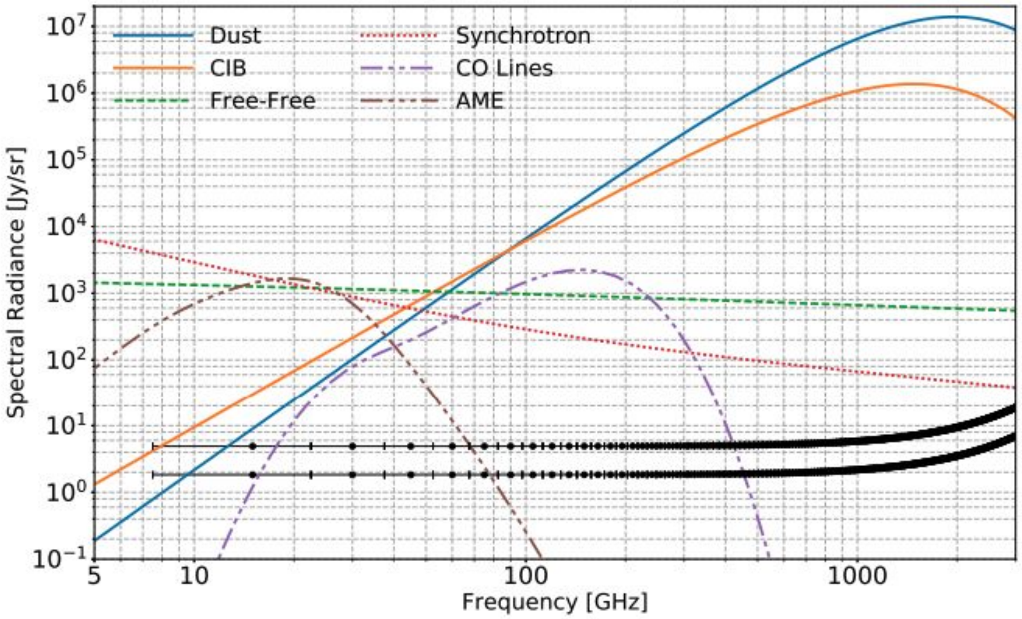
Main motivation: validate current forecasting methods (e.g. PIXIE, Voyage 2050)

(see Bianchini & Fabbian 2022 for pixel-by-pixel μ-distortion analysis)

Key ingredients:

1. Sky model:
2. FIRAS Covariance:

$$C_{\nu p \nu' p} = C^{\nu\nu'}\left(\delta^{pp'}/Np + \beta_k^p \beta_{p'k} + 0.04^2\right) \quad \text{noise}$$
$$+ S^{p\nu} S^{p'\nu'}\left(J^\nu J^{\nu'} + G^\nu G^\nu \delta^{\nu\nu'}\right) \quad \text{gain error}$$
$$+ P^\nu P^{\nu'}\left(U^2 \delta^{pp'}/N_p + T^2\right) \quad \text{systematics}$$



Abitbol+2017

FIRAS Re-Analysis

Main motivation: validate current forecasting methods (e.g. PIXIE, Voyage 2050)

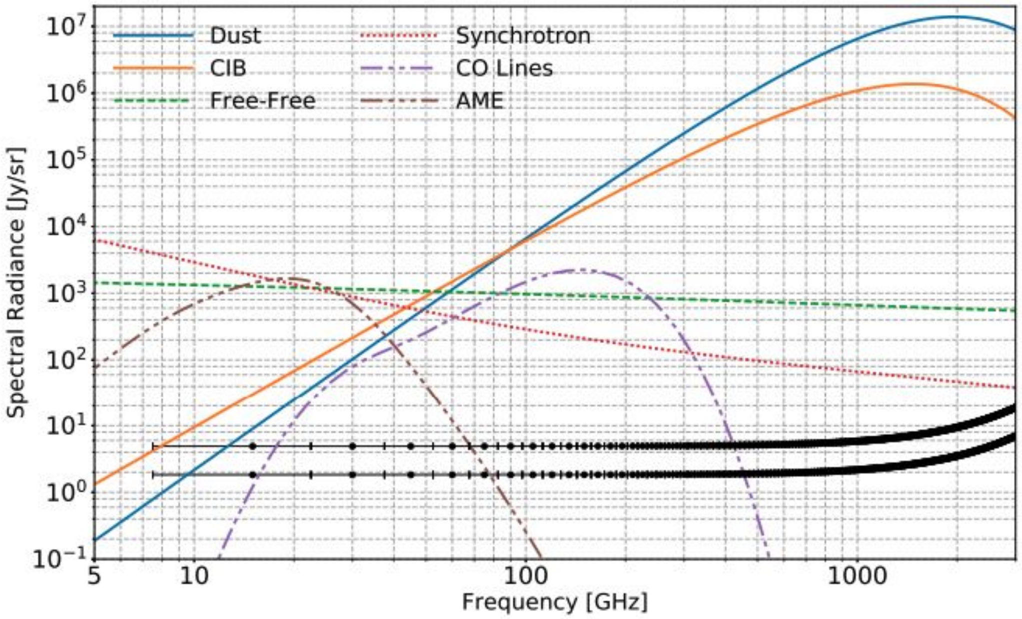
(see Bianchini & Fabbian 2022 for pixel-by-pixel μ-distortion analysis)

Key ingredients:

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

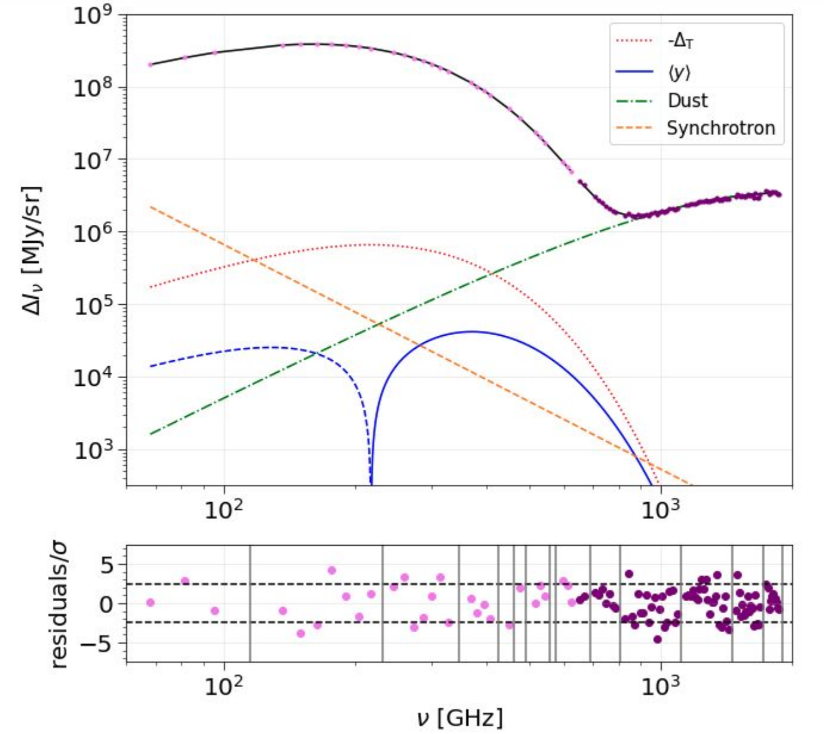
Low: ~61-650 GHz (43 channels)

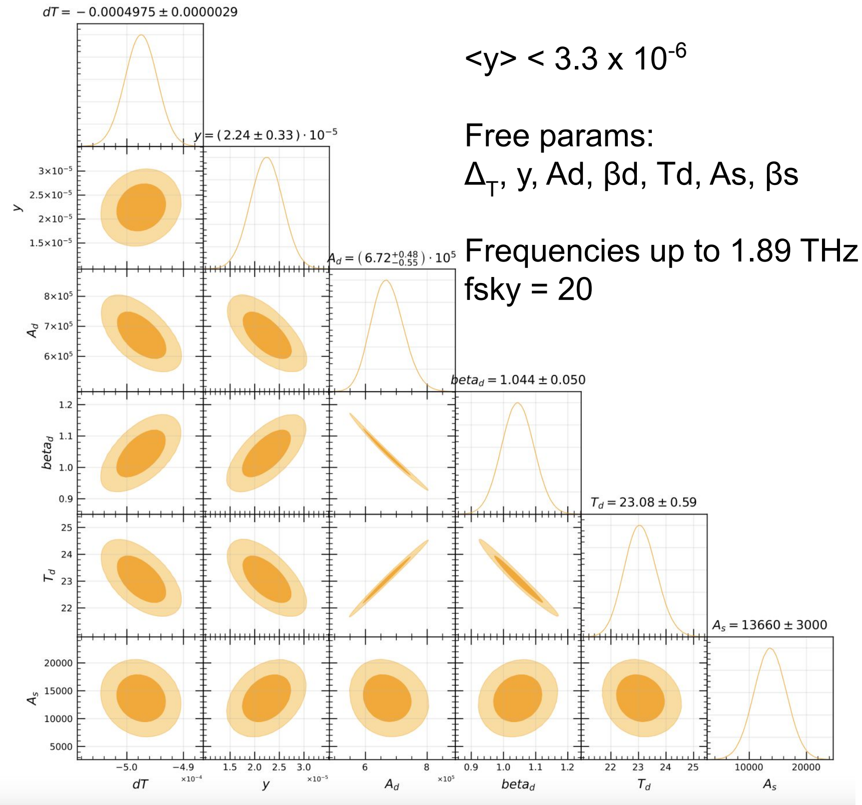
High: ~605-2918 GHz (170 channels)



Abitbol+2017

Preliminary Results from Data





χ^2=378
DOF=100

<y> < 3.3 x 10^{-6}

Free params:
Δ_T, y, Ad, βd, Td, As, βs

Frequencies up to 1.89 THz
fsky = 20

Sampled using *emcee*:*https://github.com/dfm/emcee*;
analyzed with *GetDist*: *https://github.com/cmbant/getdist*

Learning from Mocks

e.g. dust only

Δ_T, $\langle y \rangle$, $\mathrm{A_d} > 0$, $0 < \beta_\mathrm{d} < 3$, $0 < T_\mathrm{d} < 100$	fsky=20	fsky=40	fsky=60
ν_low [37]	1.3	1.1	10.2
ν_THz [63]	1.4	2.0	9.8
$\nu_\mathrm{1.89THz}$ [128]	3.8	1.9	7.1
Δ_T, $\langle y \rangle$, $\mathrm{A_d}$, β_d, T_d, ω_{22}, ω_{23}, ω_{33}			
ν_low [34]	1.2	0.7	1.9
ν_THz [60]	1.3	1.3	3.3
$\nu_\mathrm{1.89THz}$ [125]	1.1	1.7	2.8

Conclusions:

- ❖ Need moment expansion to fit higher sky fractions
- ❖ y-distortion constraints are comparable to fisher forecasts but biased

$$\langle I_\nu^{dust} \rangle = \bar{A}_0 \frac{(\nu/\nu_0)^{\bar{\alpha}} \nu^3}{e^x - 1} \left\{ 1 + \frac{1}{2} \omega_{22}^d ln^2(\nu/\nu_0) + \omega_{23}^d ln(\nu/\nu_0) \frac{x e^x}{e^x - 1} + \frac{1}{2} \omega_{33}^d \frac{x e^x}{e^x - 1} x \coth(x/2) \right\}$$

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:

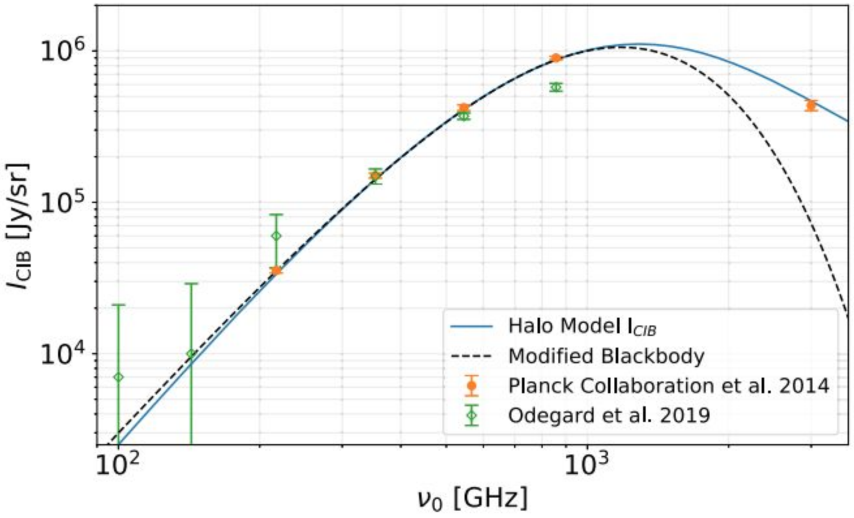
Galaxy luminosity

Redshift evolution $(1+z)^{0.36}$

SED: Modified blackbody at low ν, power law at high ν

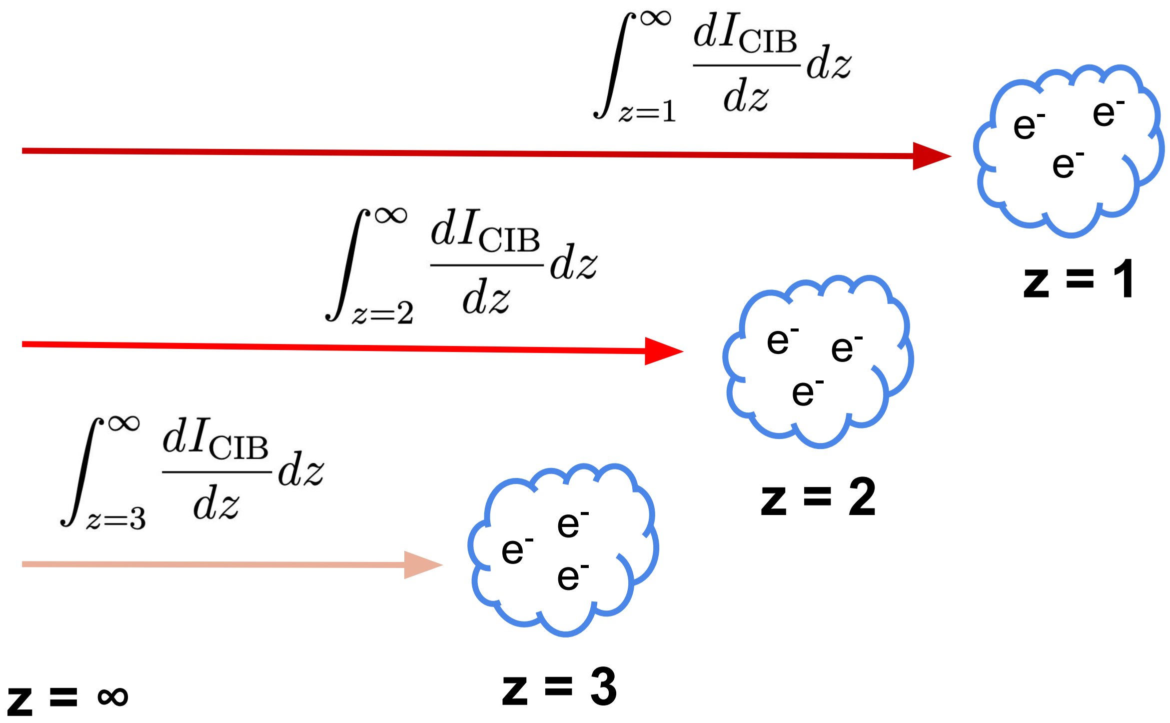
$$L_\nu^{\rm gal}(M,z) = L_0 \Phi(z)\Sigma(M)\Theta(\nu,z)$$

Luminosity-mass relation: Log-normal distribution

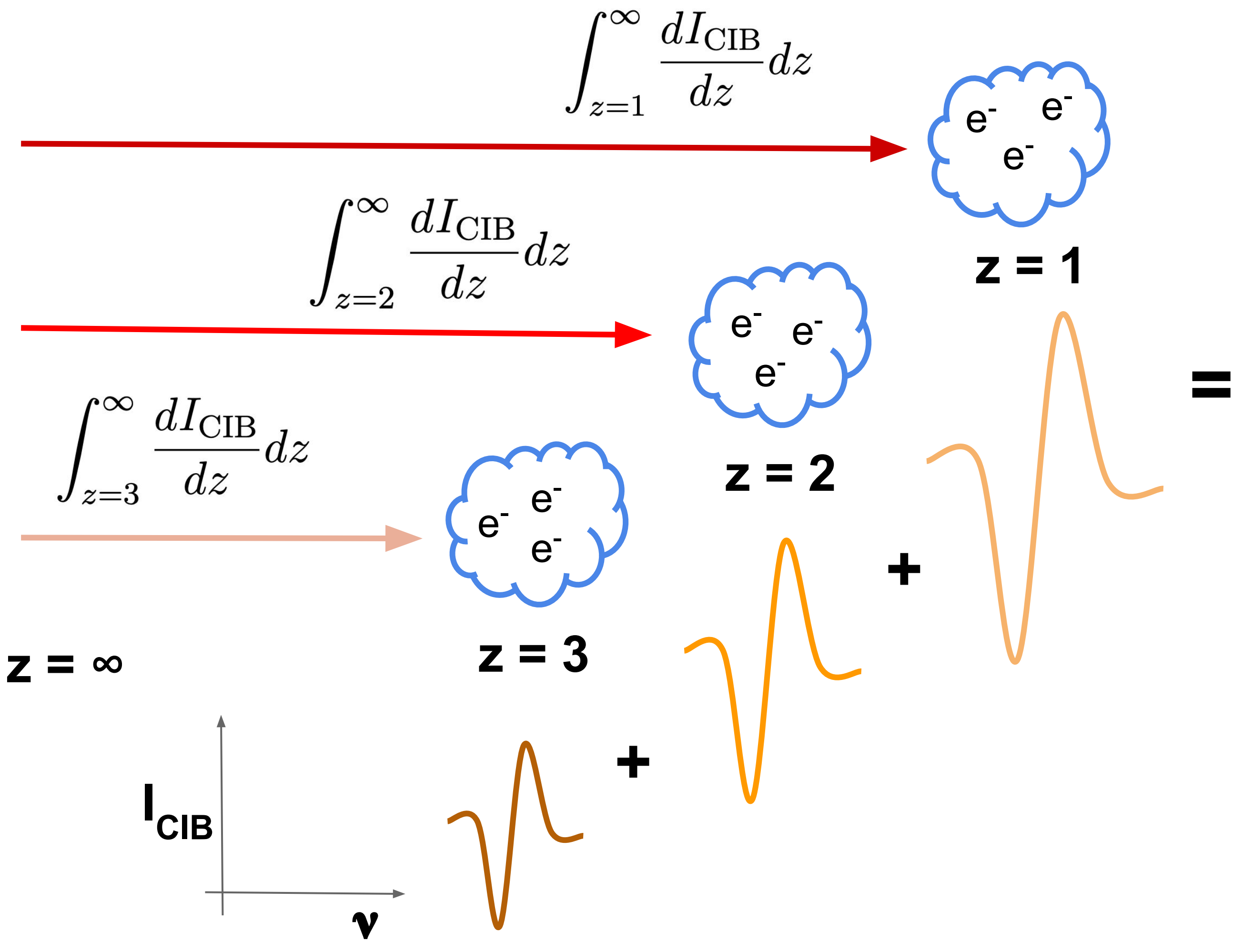


Integrate over all halos & redshift to get the monopole

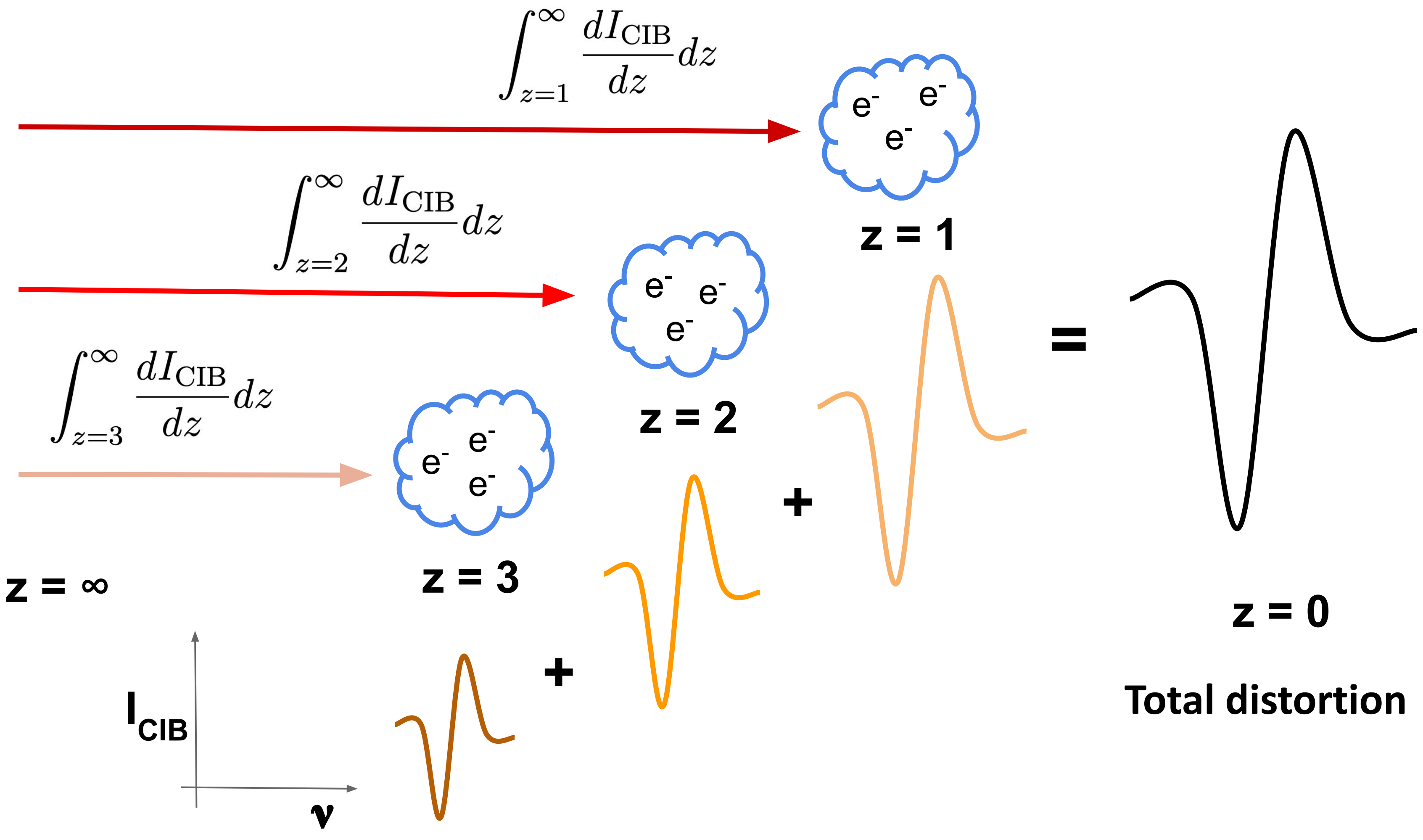
implemented in **class_sz,** https://github.com/borisbolliet/class_sz
https://github.com/CLASS-SZ

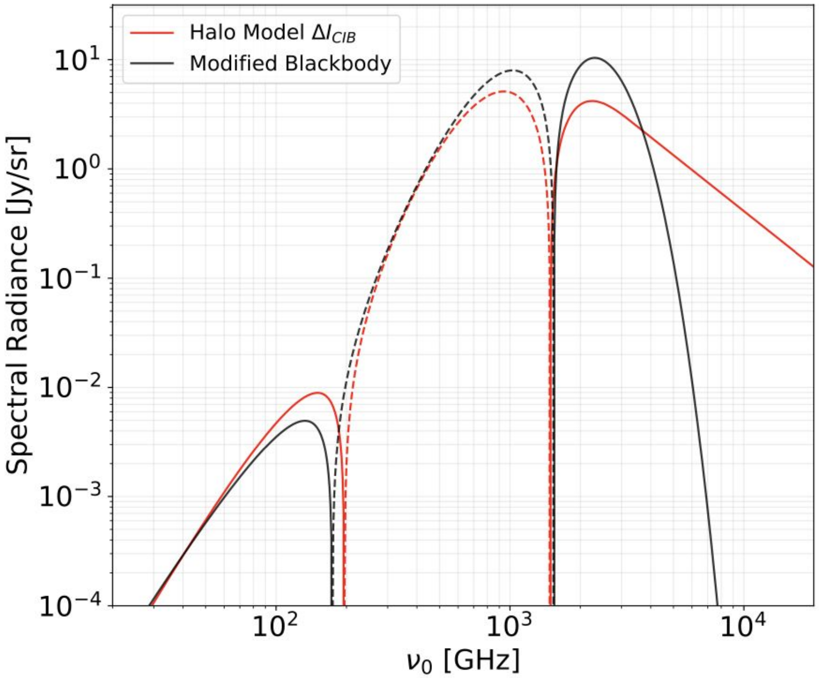


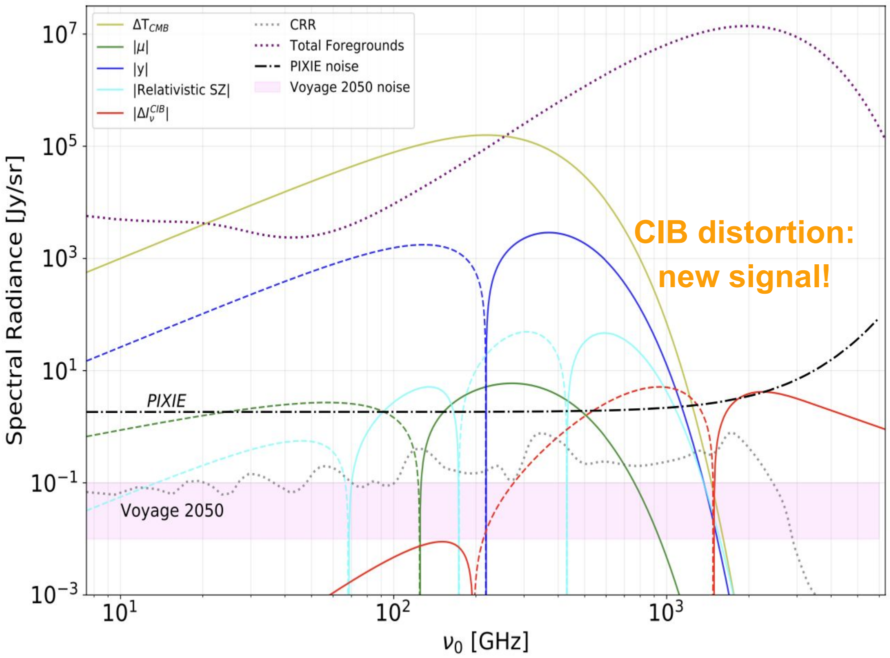
$\int_{z=1}^{\infty} \frac{dI_{\rm CIB}}{dz} dz$
$\int_{z=2}^{\infty} \frac{dI_{\rm CIB}}{dz} dz$
$\int_{z=3}^{\infty} \frac{dI_{\rm CIB}}{dz} dz$
e- e- e-
z = 1
z = 2
z = 3
z = ∞



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


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





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

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

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

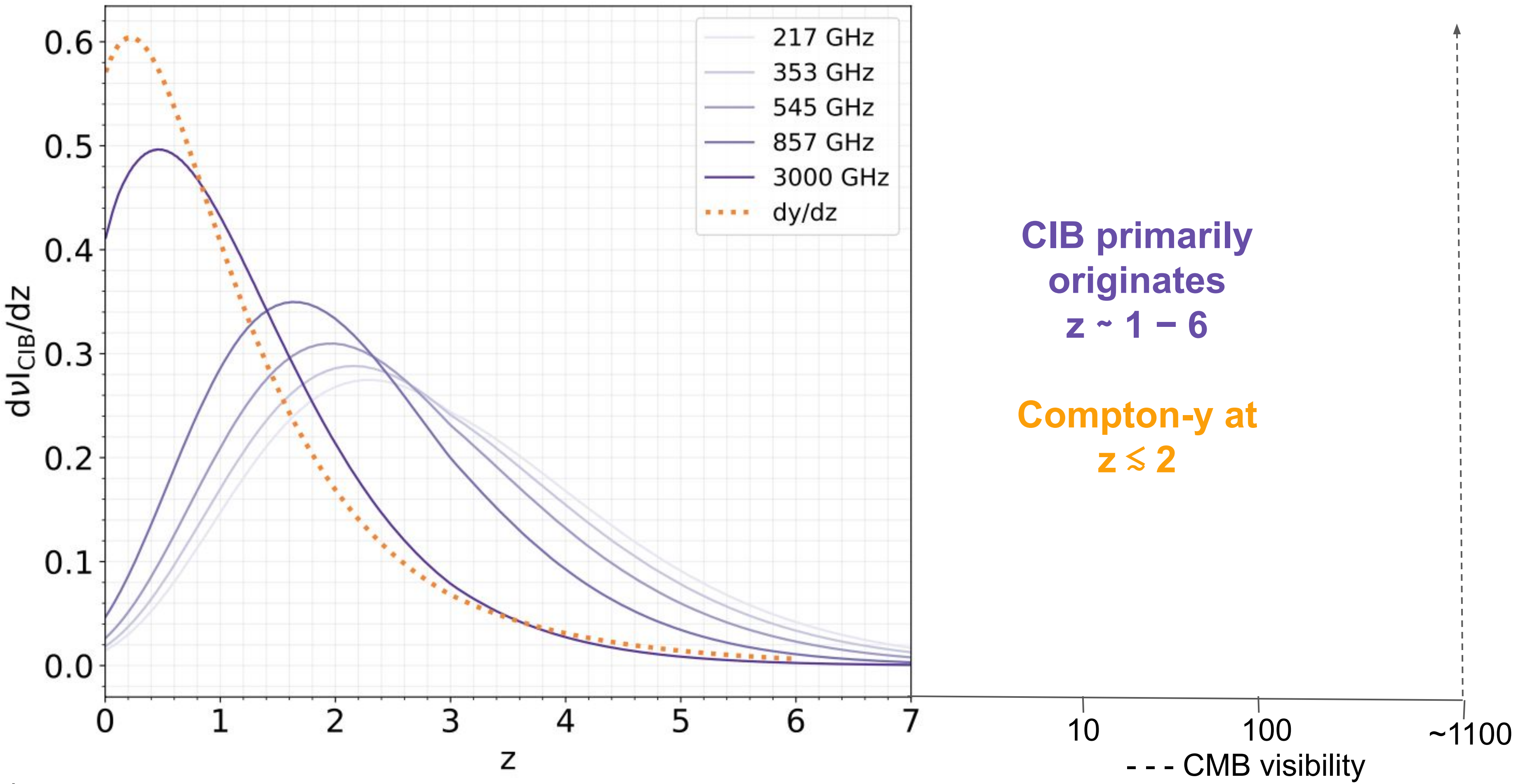
Summary

- ➔ **Compton y-distortion –** unique probe of the thermal energy in electrons – baryonic feedback.

- ➔ FIRAS re-analysis allows us to asses our **models, analysis techniques,** and **accuracy of forecasts** for future missions (+ tighten upper bounds by a factor of ~2-3).

- ➔ 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



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

Cosmic Infrared Background (CIB)

➔ Halo model prescription from **Sheng+2012, McCarthy & Madhavacheril 2021** and parameter fits from **Planck+2014.**

Galaxy luminosity

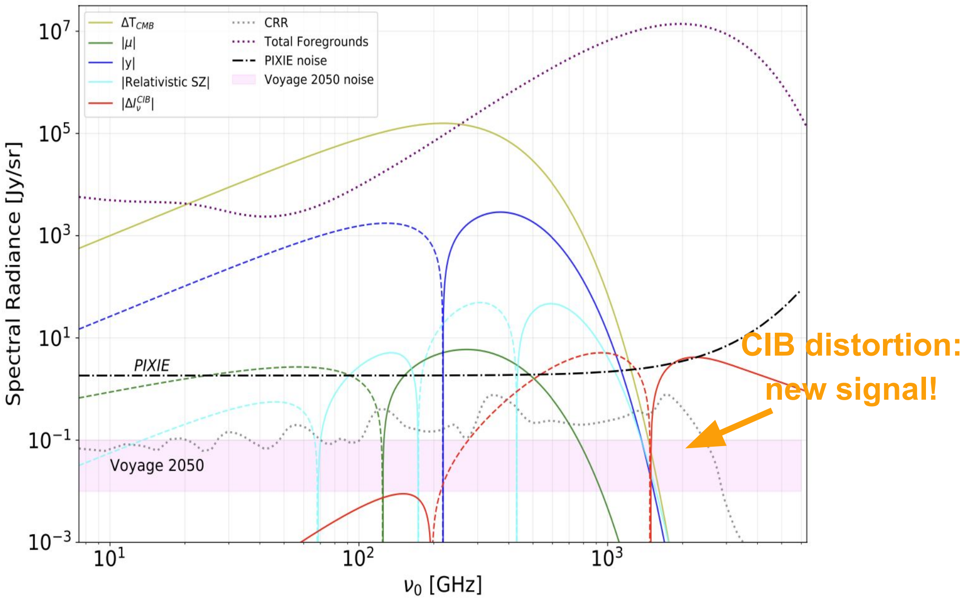
Redshift evolution
$(1+z)^{0.36}$

SED:
Modified blackbody at low ν, power law at high ν

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

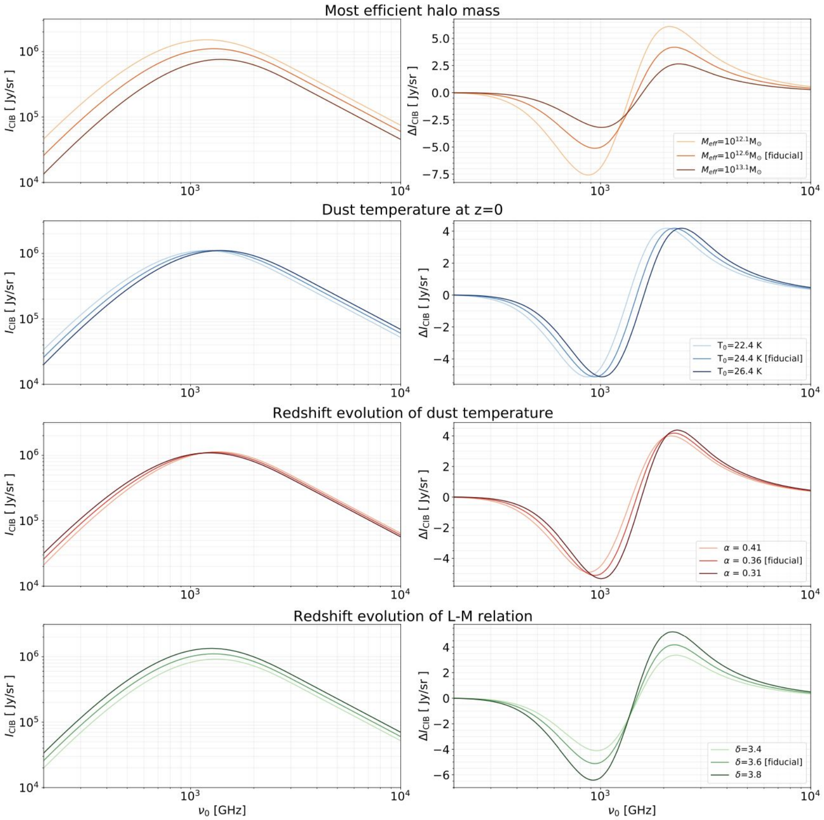
Luminosity-mass relation:
Log-normal distribution

Integrate over all halos & redshift to get the monopole



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

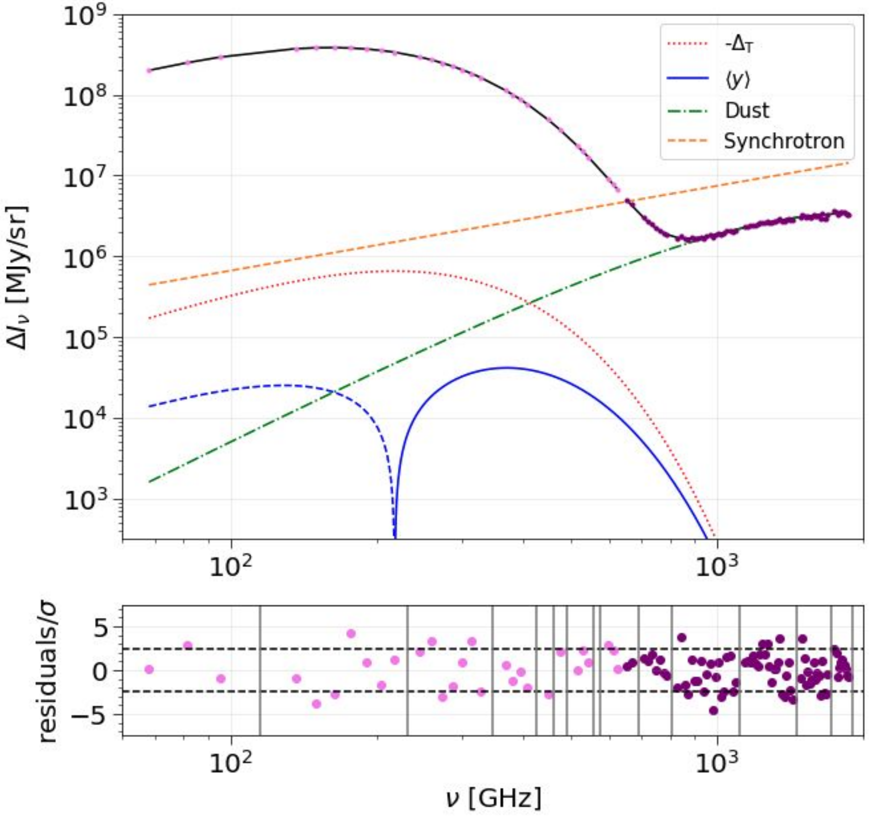
with all foregrounds:
PIXIE: 0.1σ
ESA Voyage 2050: 0.9-4.6σ

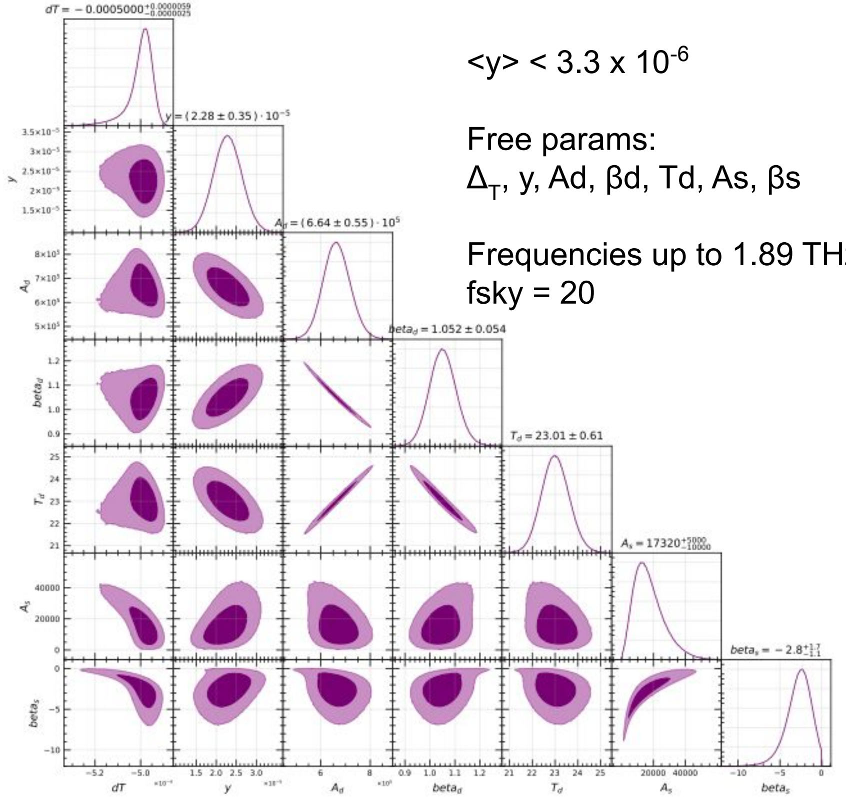


Distortion’s sensitivity to **halo model parameters**.

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

Preliminary Results from Data





χ^2=378
DOF=99

<y> < 3.3 x 10^{-6}

Free params:
Δ_T, y, Ad, βd, Td, As, βs

Frequencies up to 1.89 THz
fsky = 20

Sampled using *emcee:https://github.com/dfm/emcee*;
analyzed with *GetDist: https://github.com/cmbant/getdist*

Cosmic Infrared Background (CIB)

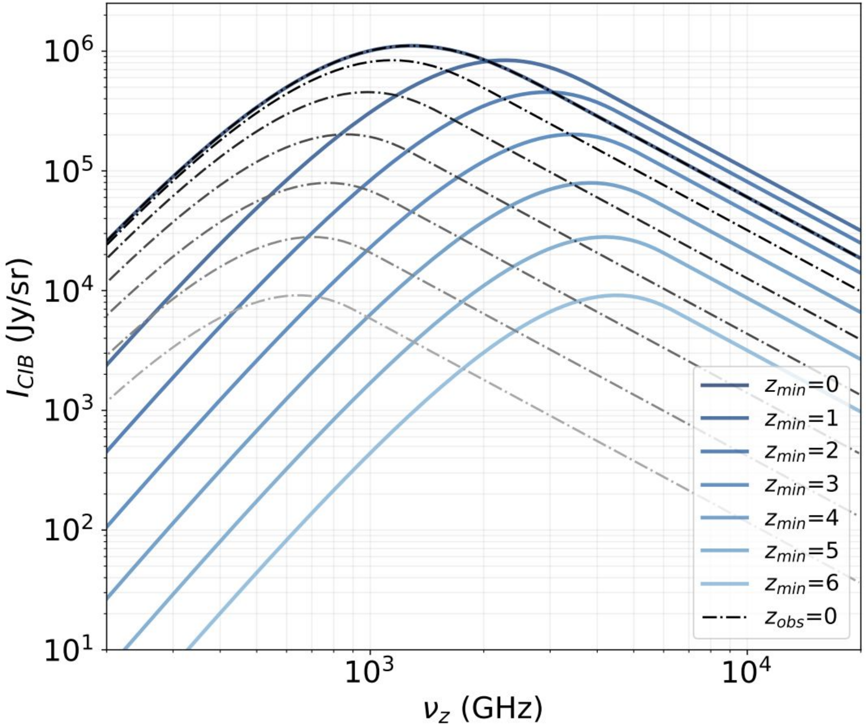
Integrate over all halos
(comoving emissivity)

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

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**)

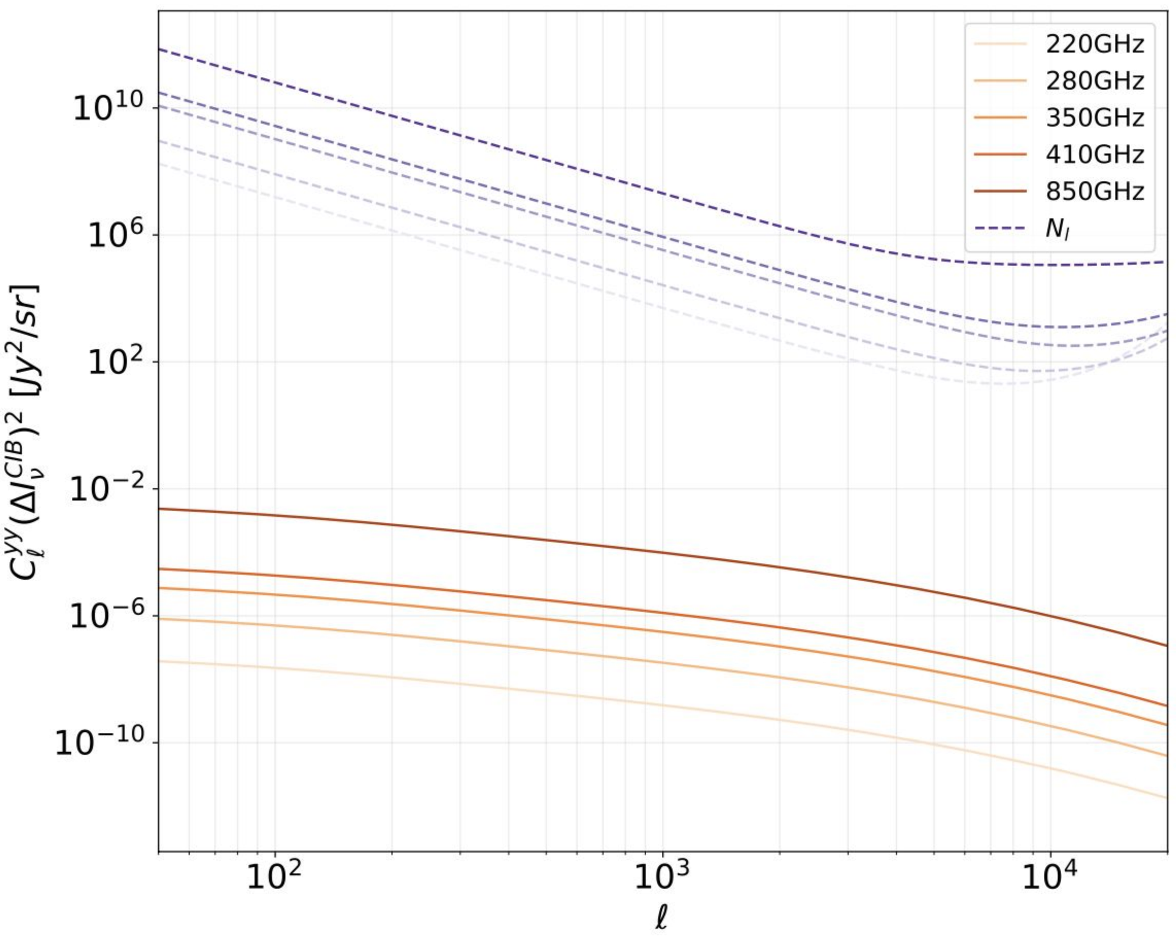
- ◆ Non-relativistic, Te >>Tcib and y << 1

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
10^{10}
10^{6}
10^{2}
10^{-2}
10^{-6}
10^{-10}
$C_\ell^{yy}(\Delta I_\nu^{CIB})^2\ [Jy^2/sr]$
10^2
10^3
10^4
ℓ

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

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
$\log(M_{\rm eff}/M_{\odot})$	Halo model most efficient mass	12.6 ± 0.1
$M_{\rm min}[M_{\odot}]$	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

References