Sensitivity modeling to CMB spectral distortions

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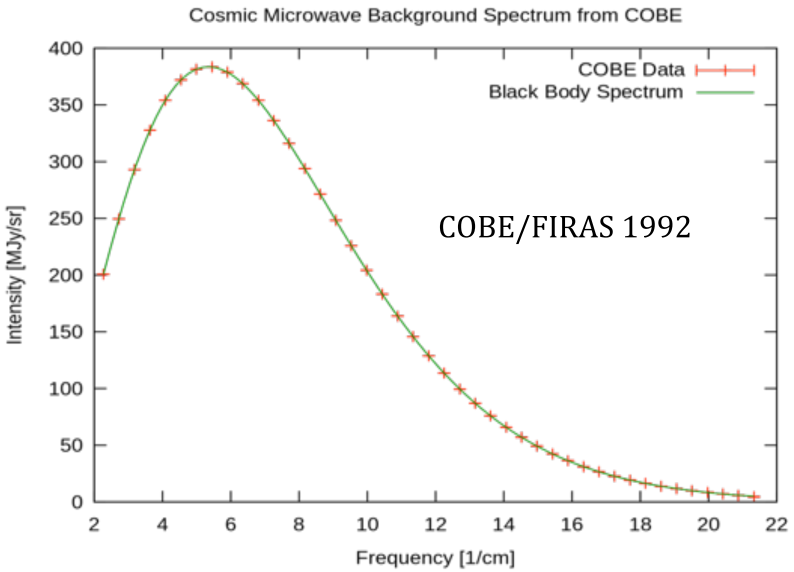
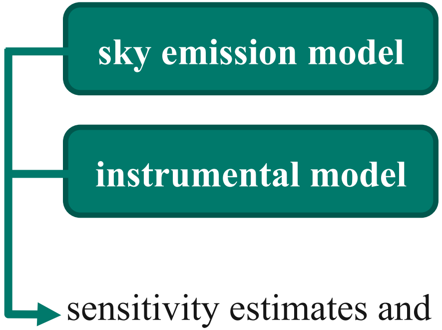
Introduction

Last measurement of CMB spectrum :



COBE/FIRAS 1992

Prepare CMB spectral distortion measurement :



sky emission model

instrumental model

sensitivity estimates and forecast of potential spectral distortion observables.

Sky signal modeling

Adapted from Abitbol et al,2017

Sky average spectral radiance relative to the assumed CMB blackbody :

$$\Delta I_\nu = \Delta B_\nu + \Delta I_\nu^{y} + \Delta I_\nu^{rel-tSZ} + \Delta I_\nu^{\mu} + \Delta I_\nu^{fg}$$

With :

- $\Delta B_\nu = B_\nu(T_{CMB}) - B_\nu(T_0)$ is the deviation of true CMB blackbody spectrum at temperature $T_{CMB} = T_0(1 + \Delta_T)$ from that of a blackbody with temperature $T_0 = 2.726\ K$
- ΔI_ν^{y} is the y-type distortion
- $\Delta I_\nu^{rel-tSZ}$ is the relativistic temperature correction to tSZ distortion
- ΔI_ν^{μ} is the μ-type distortion
- ΔI_ν^{fg} sum of all foreground contributions

Foreground modeling

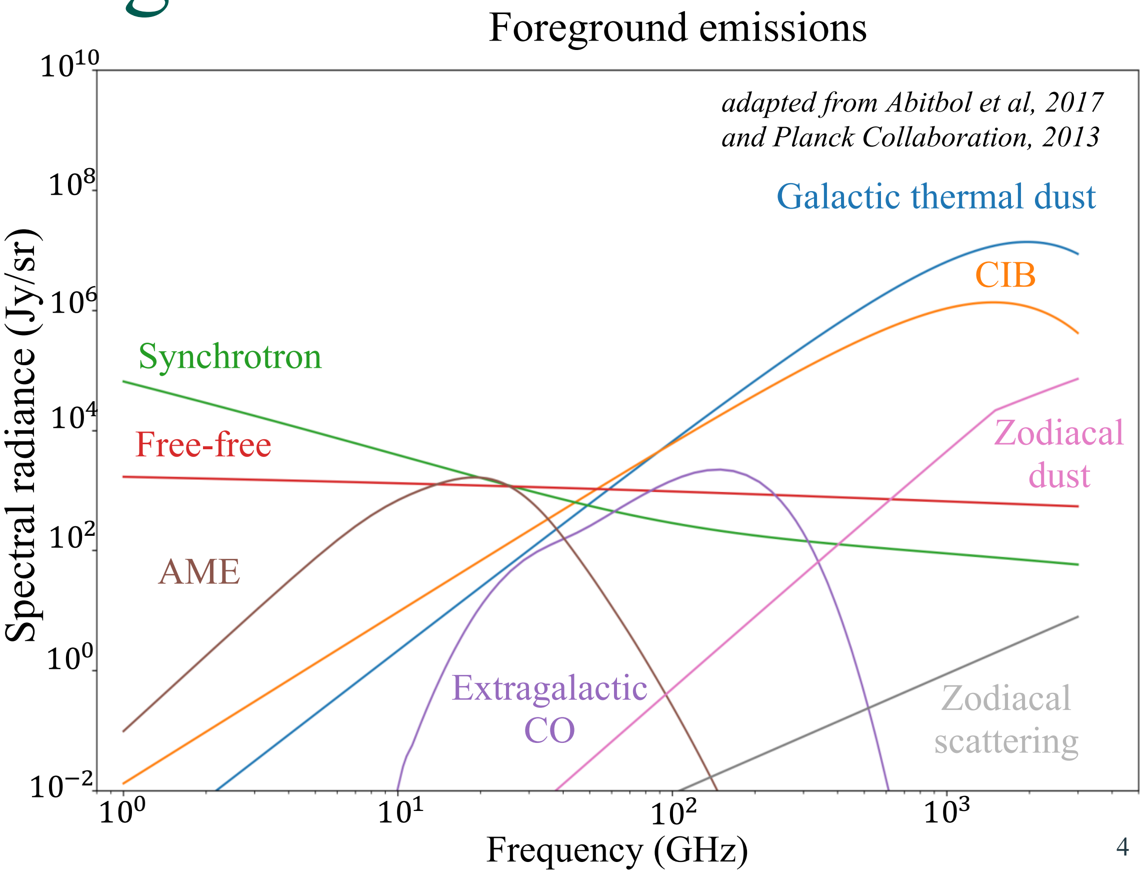
Foregrounds:

Galactic

- Thermal dust
- Synchrotron
- Free-free
- Anomalous Microwave Emission
- Zodiacal emissions

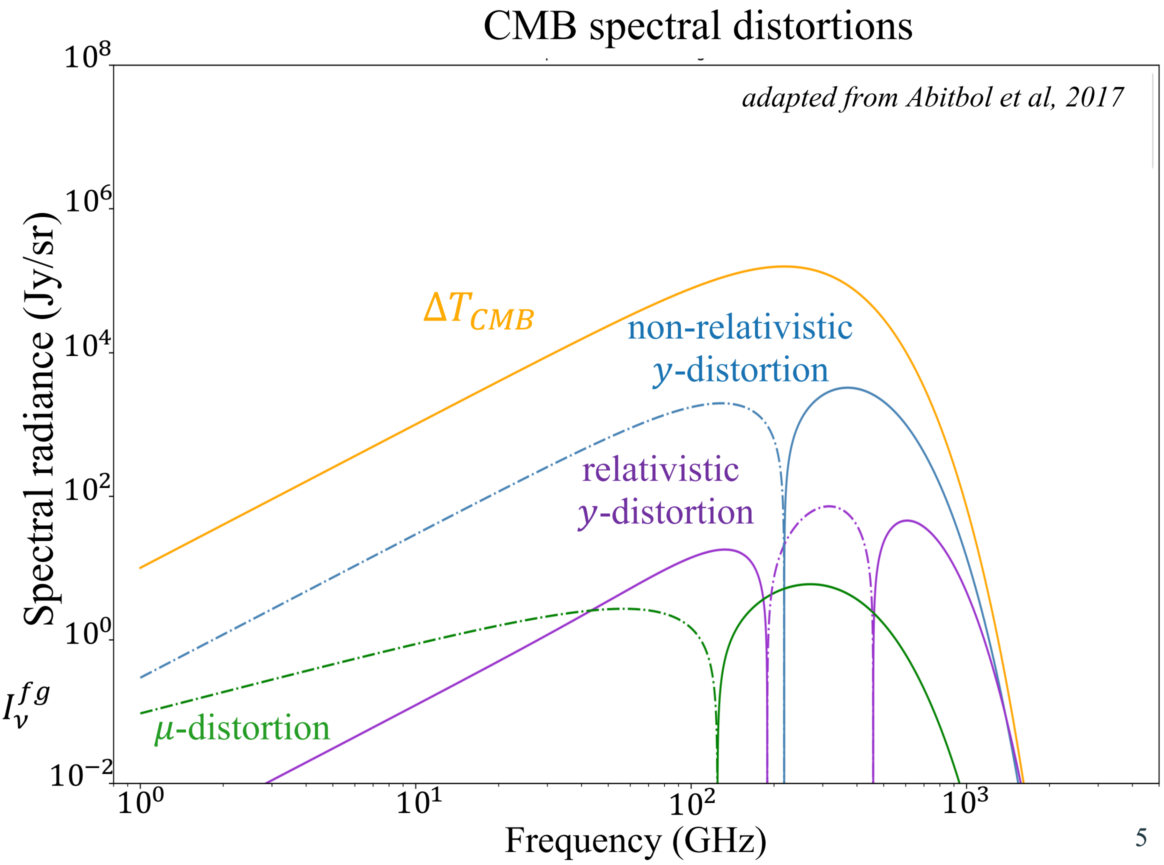
Extragalactic

- Cosmic Infrared Background (CIB)
- Cumulative CO



CMB spectral distortions

- **Blackbody component :**
  $\Delta I_\upsilon / I_\upsilon \sim 10^{-5}$
- ***y*-distortion (thermal SZ) :**
  $\Delta I^y_\upsilon / I_\upsilon \sim 10^{-6}$
- ***μ*-distortion (chemical potential) :**
  $\Delta I^\mu_\upsilon / I_\upsilon \sim 10^{-8}$


CMB spectral distortions

adapted from Abitbol et al, 2017

$$\Delta I_\nu = \Delta B_\nu + \Delta I^y_\nu + \Delta I^{rel-tSZ}_\nu + \Delta I^\mu_\nu + \Delta I^{fg}_\nu$$

Instrument model

Based on PRISTINE/PIXIE/BISOU concept :

- **F**ourier **T**ransform **S**pectrometer (FTS)

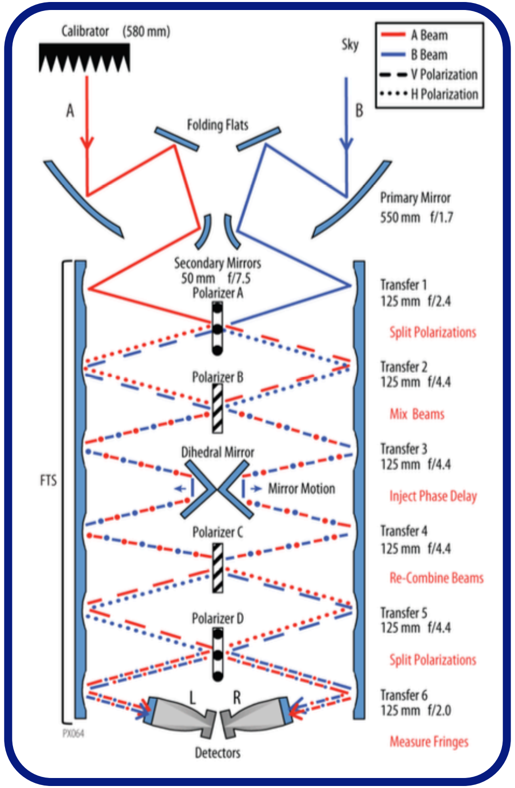
Space / Balloon configuration :

- window, additional filters, atmosphere, …

To sensitivity estimations :

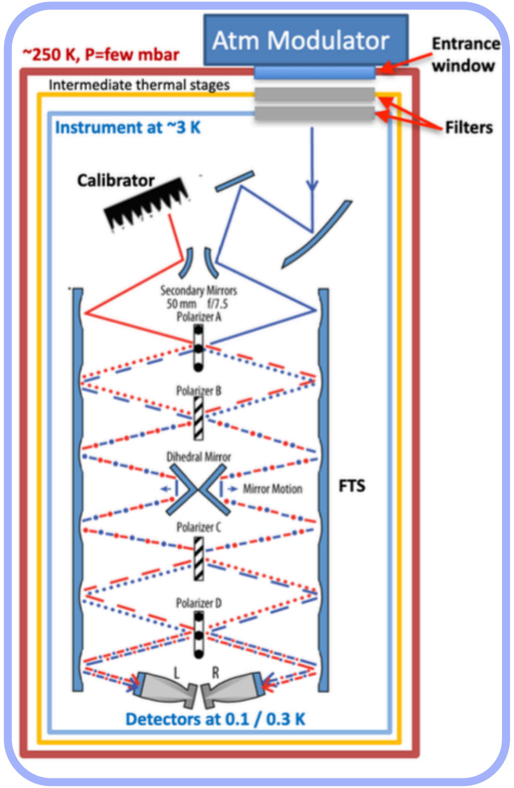
- Sky emission model
- Photometric model
- Power on detector estimation
- Noise Equivalent Power (NEP)
- Sensitivity Estimation

Space configuration



Kogut et al, 2011

Balloon configuration



Photometric model

Generic photometric model : only components in optical path are considered.

Assumptions :
- Balloon configuration
- Components

1 window (270K)

3 filters (70K, 20K, 3K)
- Emissivity

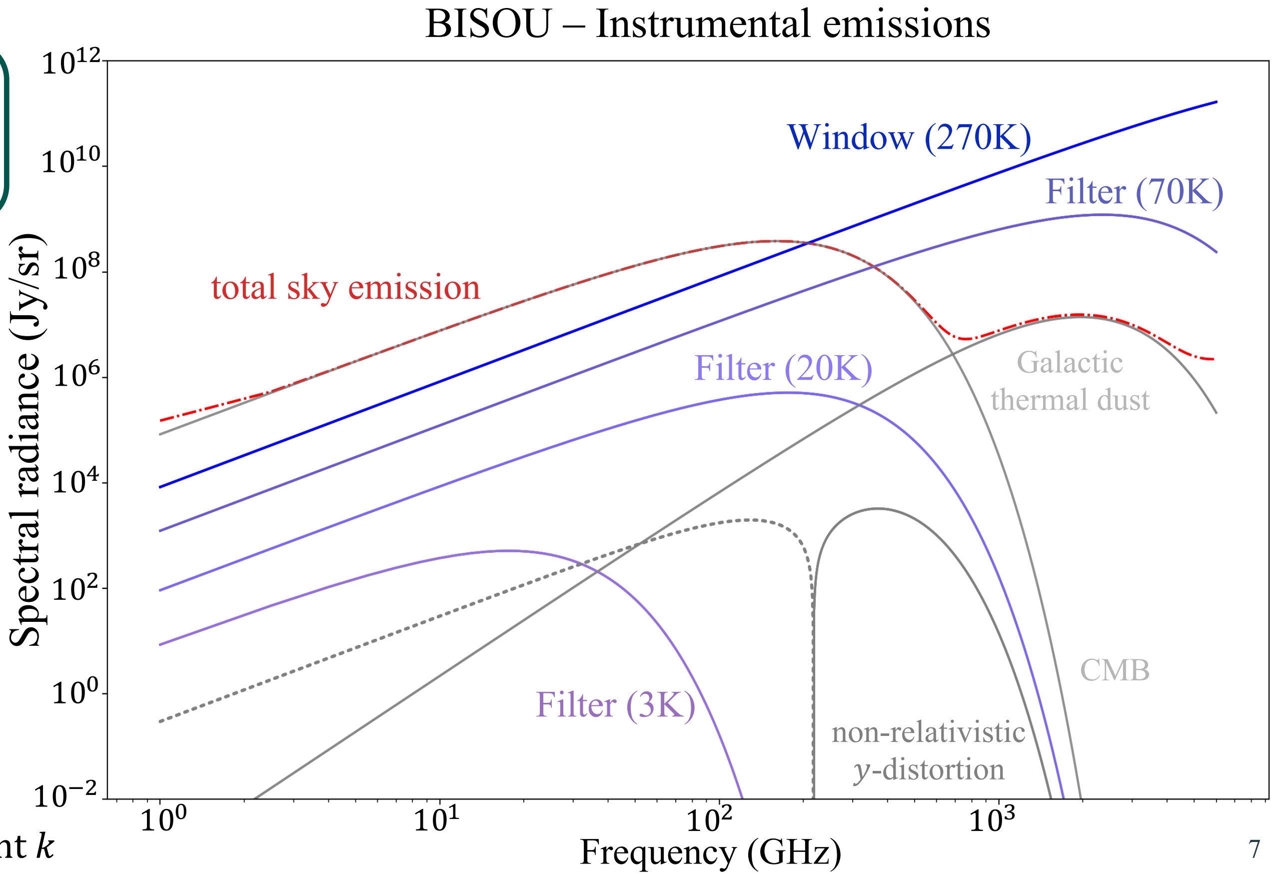
$\sim\mathbf{0.1\%}$ **window emissivity**

$\sim\mathbf{0.1\%}$ **filter emissivity**

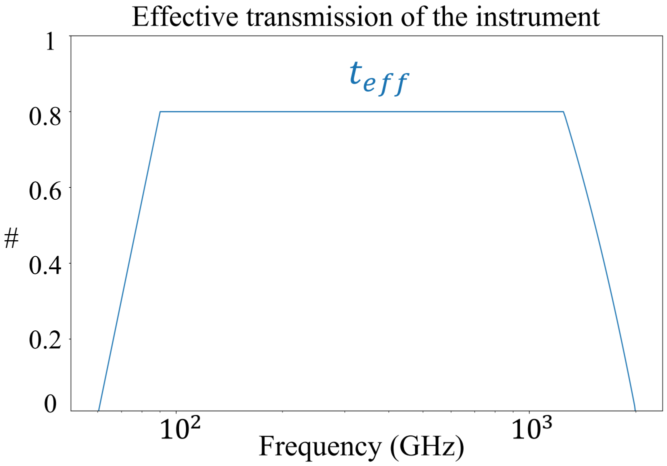
Emission modeled as **grey body** :

$$I_\nu^k = \mathcal{E}_k(\nu, T_k) \times B_\nu(\nu, T_k)$$

$\mathcal{E}_k(\nu, T_k)$, emissivity of component k



Sensitivity Estimation



Detected noise of the frequency ν for a fixed integration time τ :

$$\delta P(\nu) = \frac{NEP_{total}(\nu)}{\sqrt{\tau/2}}$$

Sensitivity estimation :

$$\delta I_\nu(\nu) = \frac{\delta P(\nu)}{A\Omega(\nu)\times\Delta\nu\times eff_{det}\times t_{eff}(\nu))}$$

Parameters :

CMB emission, all foreground emissions and spectral distortions (12-20 parameters)
A, detector area
Ω, detector solid angle
eff_{det}, detector efficiency
$\Delta\nu$, FTS bandwidth
$t_{eff}(\nu) = \prod_{k=1}^{K} t_k(\nu)$, the effective transmission of the instrument
$t_k(\nu)$, transmission of optical component k at frequency ν
K, total number of optical component considered from photometric model.

Sensitivity Estimation – example

Assumptions :

- Space configuration

- Flight / effective observe time

1 year
75% observation time

- Components

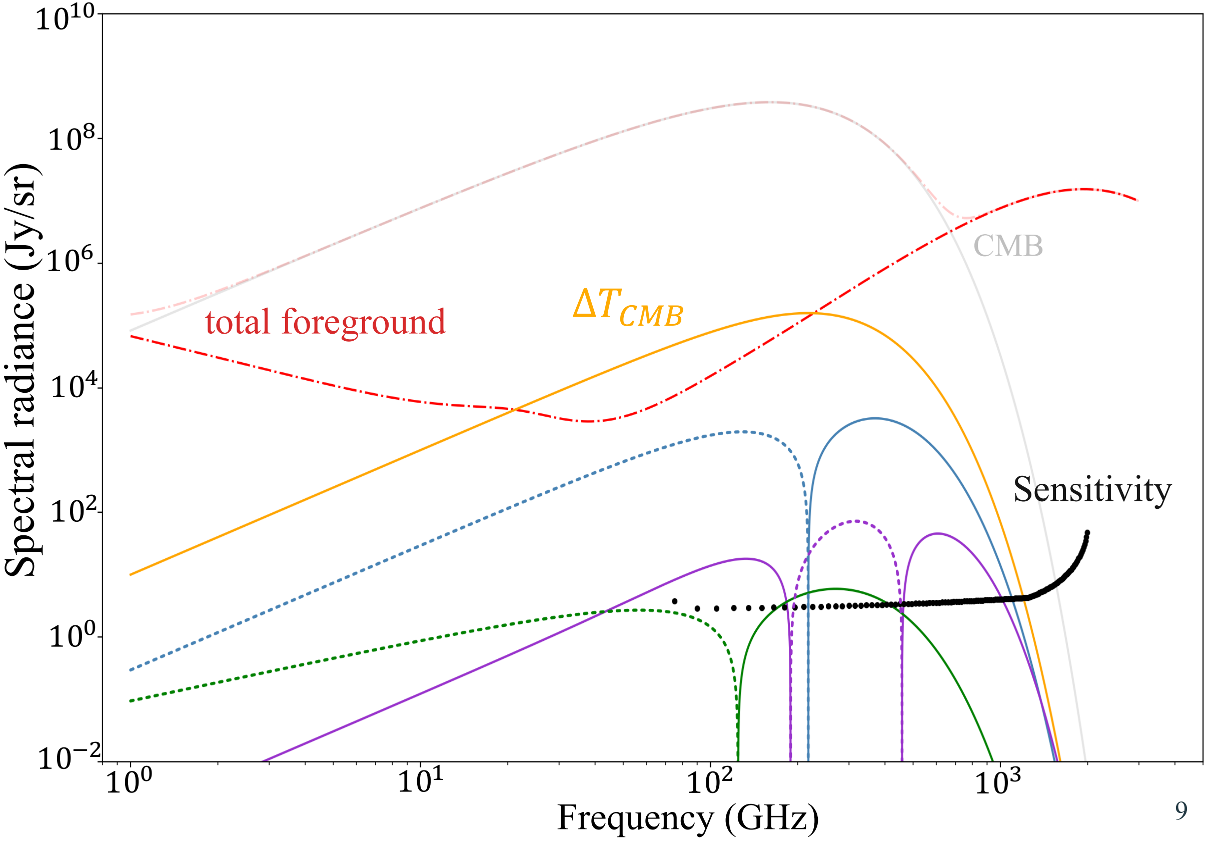
2 filters (3K, 300mK)

- Frequency range

60GHz – 2THz

- Emissivity

$\sim 0.1\%$ filter emissivity



Forecasting and optimization

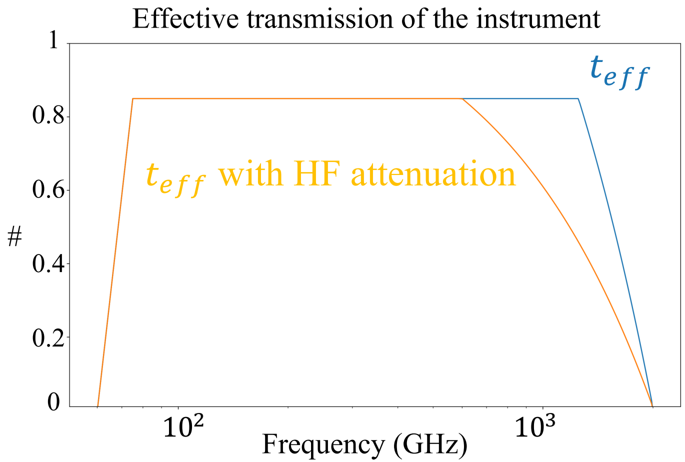
Forecasts with Fisher method

Application on BISOU experiment

Optimizing BISOU instrumental concept to improve SNR forecasts on two sciences goals (y-distortion and CIB)

Improving SNR on y-distortion and CIB parameters :

- reducing window emissivity
- attenuation of high frequencies
- using a dichroic
- lowering window temperature
- reducing maximal frequency of the instrument



Optimization – BISOU experiment

Assumptions :

- No atmosphere

- Flight / effective observe time

5 days
75% observation time

- Components

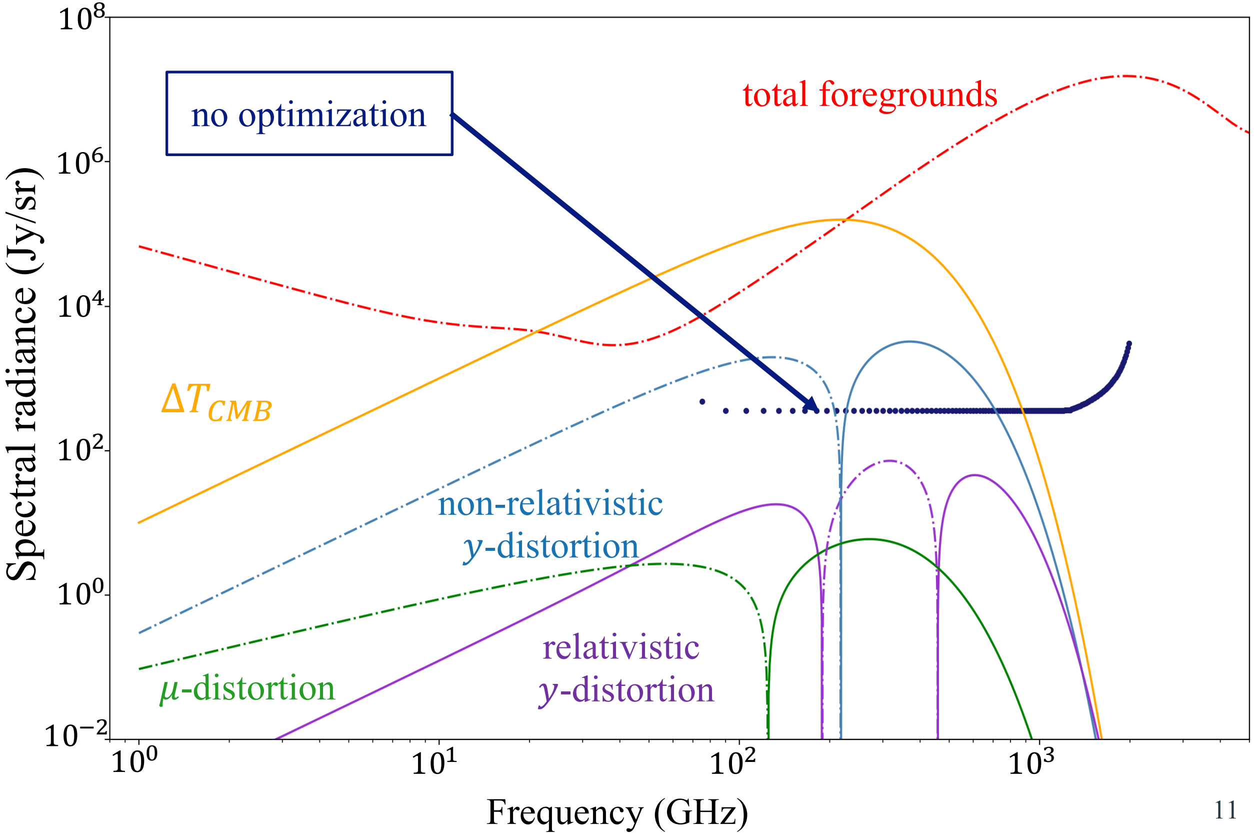
1 window (270K)
4 filters (70K, 20K, 3K, 300mK)

- Frequency range

60GHz – 2THz

- Emissivity

$\sim 0.1\%$ window emissivity
$\sim 0.1\%$ filter emissivity



Optimization – BISOU experiment

Assumptions :

- No atmosphere

- Flight / effective observe time
5 days
75% observation time

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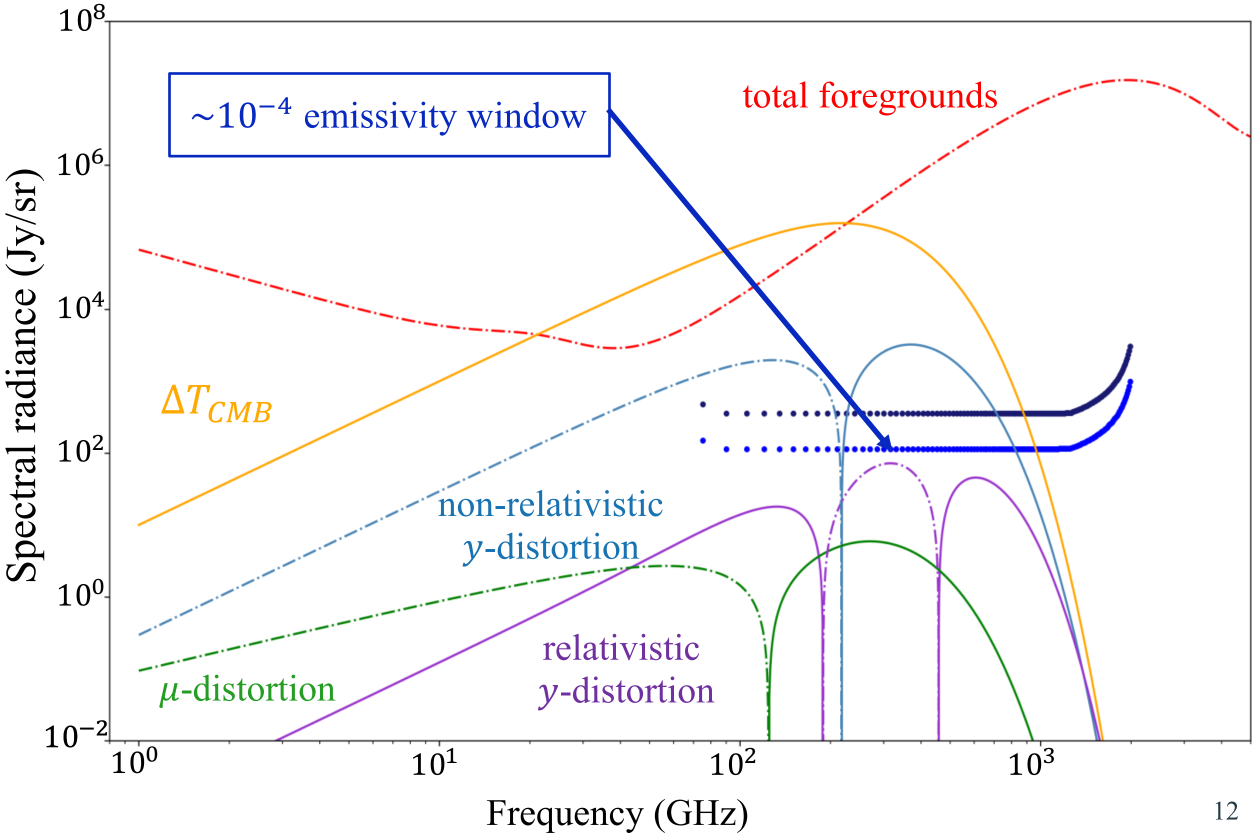

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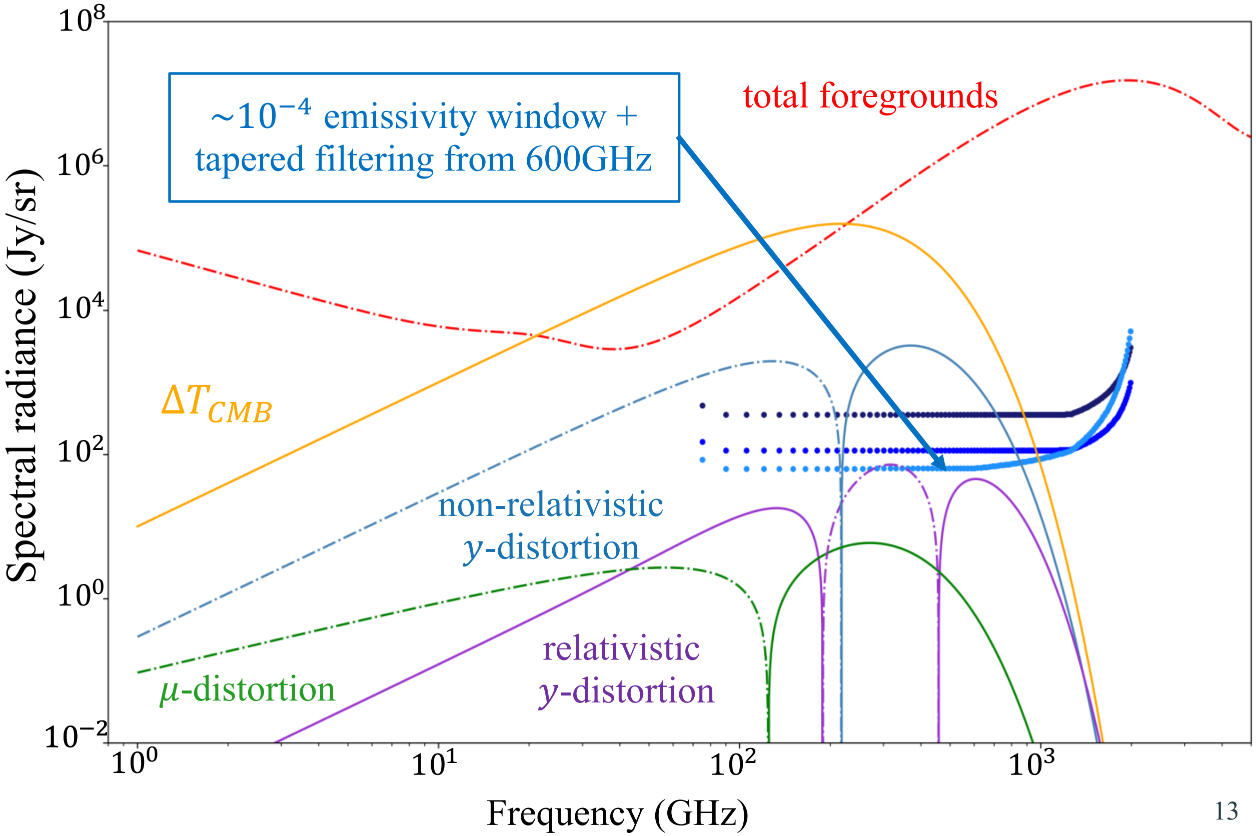

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Assumptions :

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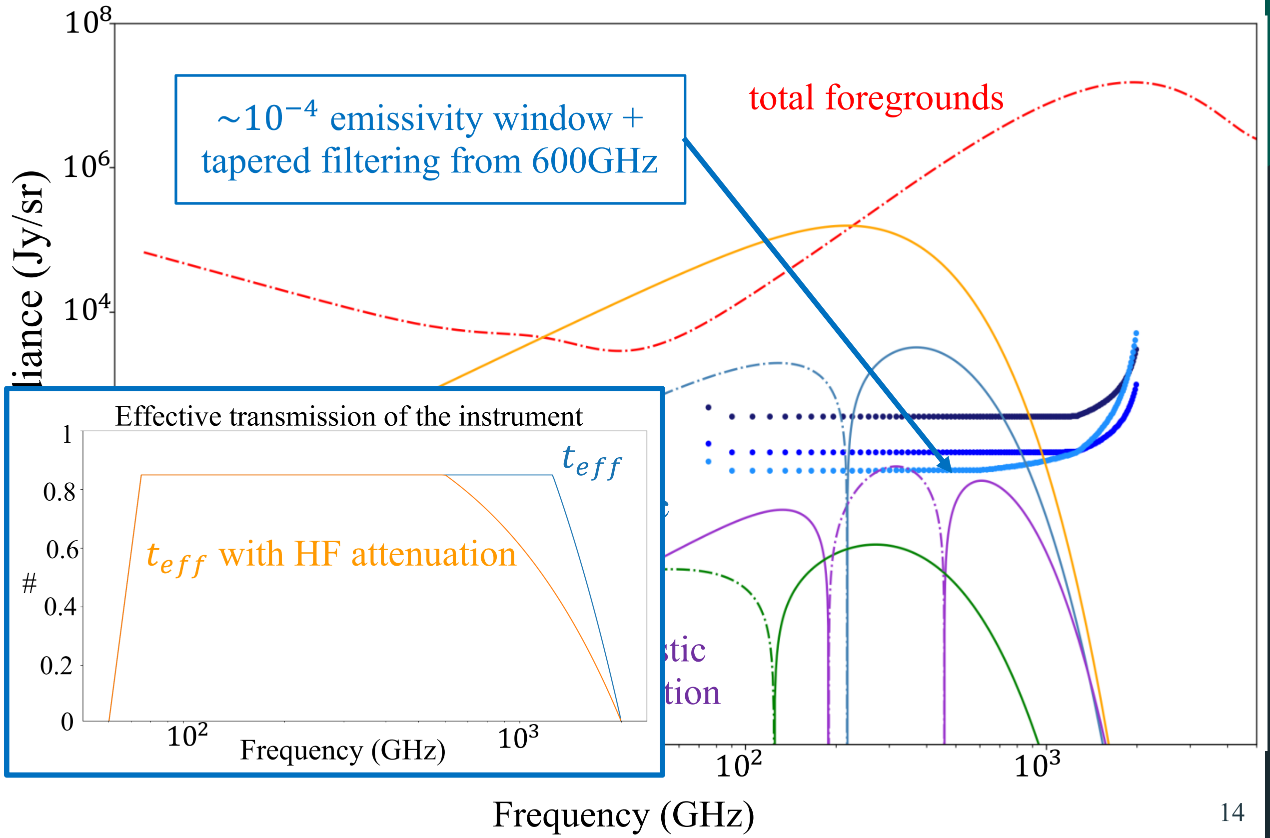

$\sim 10^{-4}$ emissivity window + tapered filtering from 600GHz

Optimization – BISOU experiment

Assumptions :

- No atmosphere

- Flight / effective observe time

5 days
75% observation time

- Components

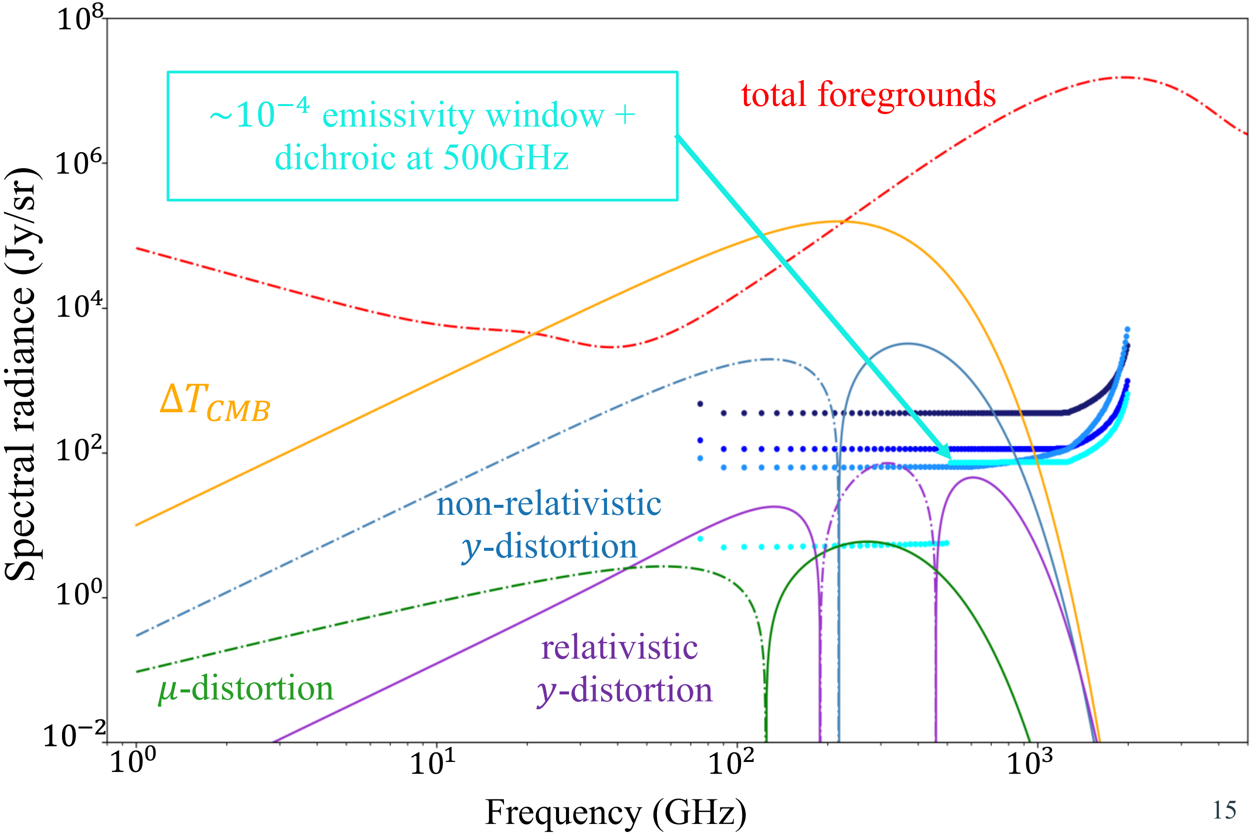
1 window (270K)
4 filters (70K, 20K, 3K, 300mK)

- Frequency range

60GHz – 2THz

- Emissivity

$\sim 0.1\%$ filter emissivity



Optimization – SNR for *y*-distortion

Grid exploration to optimize considering :
- cooling actively the window
- decreasing the maximal frequency

Assumptions :
- No atmosphere
- Flight / effective observe time

5 days

75% observation time
- Components

1 window (270K)

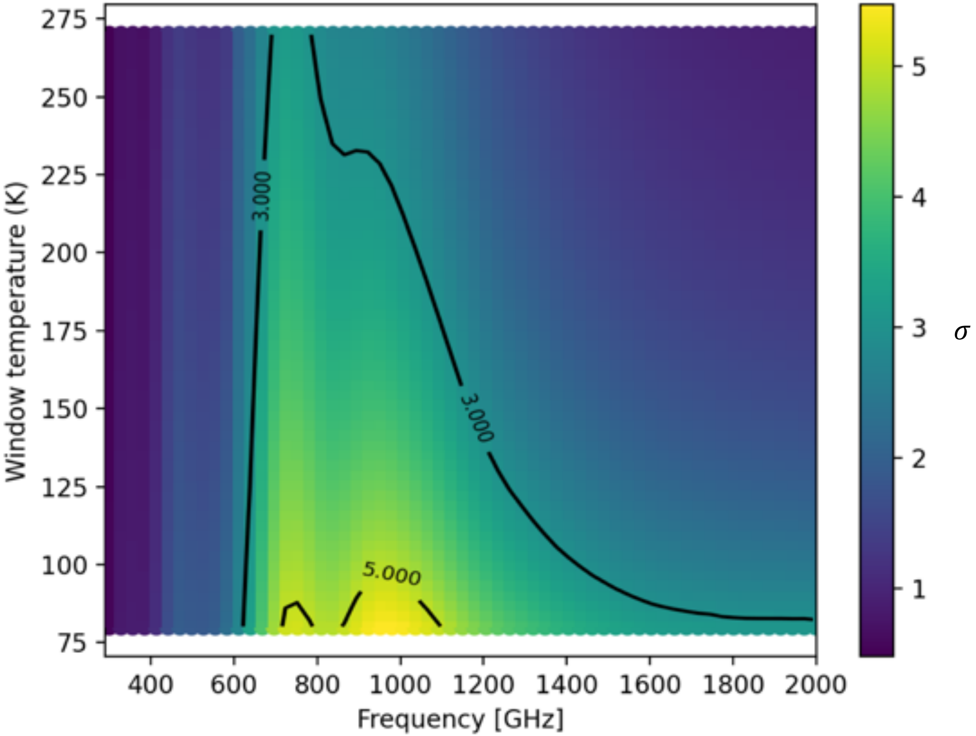
4 filters (70K, 20K, 3K, 300mK)
- Frequency range

60GHz – 2GHz
- Emissivity

~0.1% window emissivity

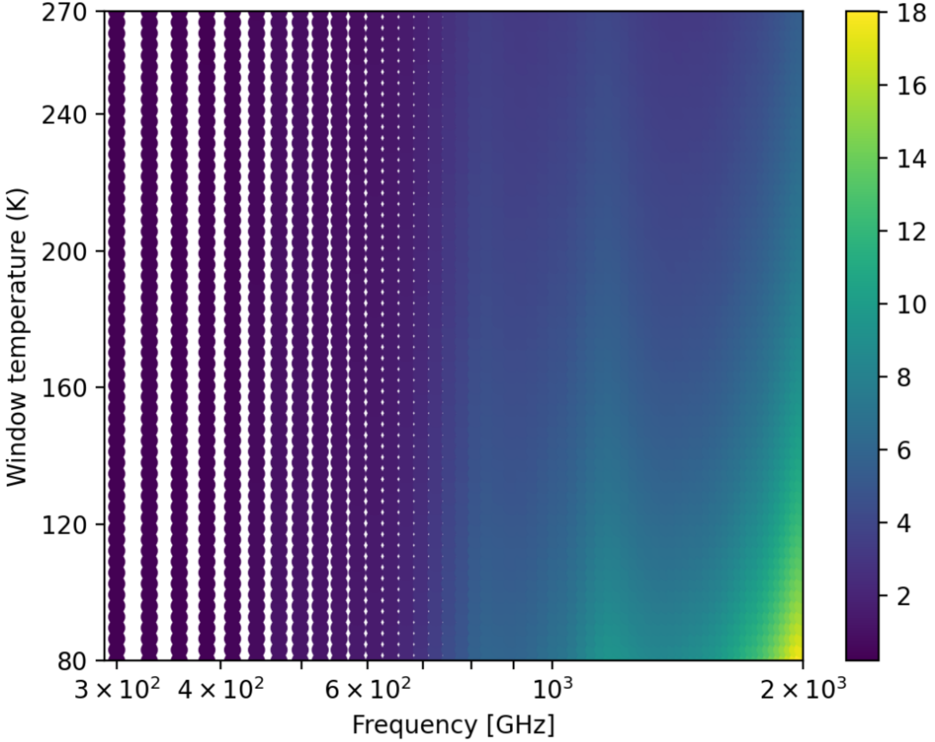
~0.1% filter emissivity

SNR of ***y*** parameter evolution according the **temperature of the window** and **the maximal frequency of the instrument**



Optimization - SNR for CIB

SNR of T_{CIB} parameter evolution according the **temperature of the window** and **the maximal frequency of the instrument**



Assumptions :

- No atmosphere
- Flight / effective observe time

5 days

75% observation time

- Components

1 window (270K)

4 filters (70K, 20K, 3K, 300mK)

- Frequency range

60GHz – 2GHz

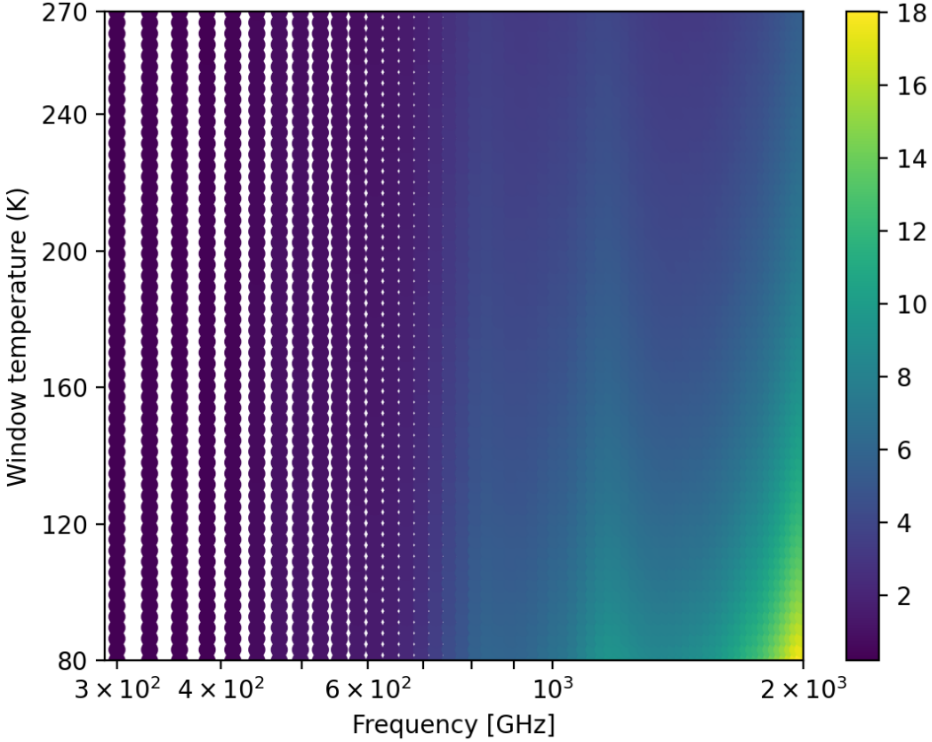
- Emissivity

$\sim 0.1\%$ window emissivity

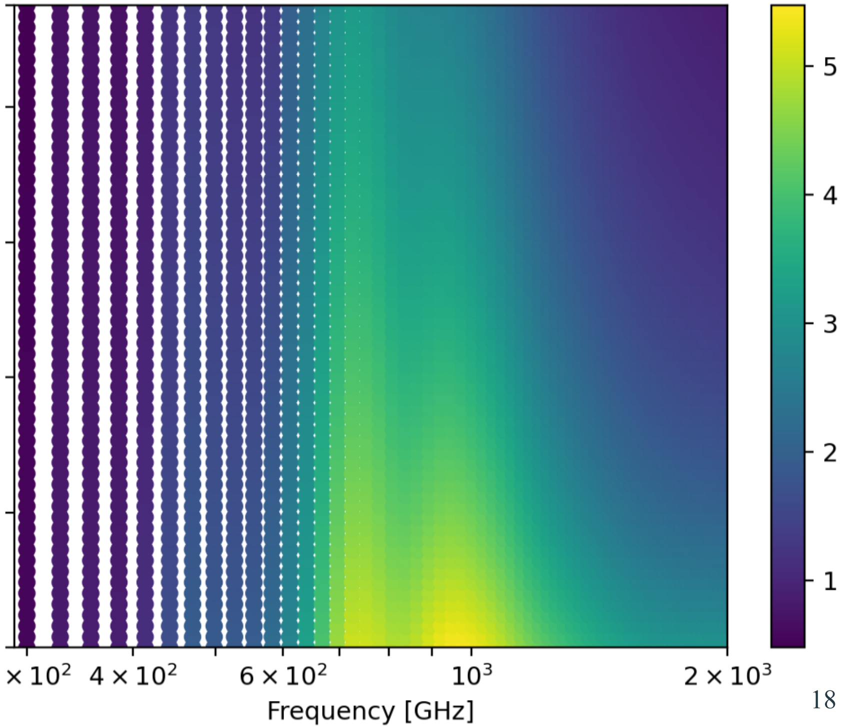
$\sim 0.1\%$ filter emissivity

Optimization - SNR for CIB

SNR of T_{CIB} parameter evolution according the **temperature of the window** and **the maximal frequency of the instrument**



SNR of y parameter evolution



Optimization – SNR estimations

SNR (in σ) of some spectral distortion, dust and CIB parameters for different configurations

SNR (σ)	5 days (75%)	5 days (75%) $T_{window} = 150K$	5 days (75%) $T_{window} = 150K$ $\nu_{max} = 1.2$ THz	5 days (75%) $T_{window} = 150K$ $\nu_{max} = 1.2$ THz dichroic at 500GHz
y_{tot}	1	1.8	3	7
ΔT_{CMB}	6	11	24	49
μ_{amp}	3×10^{-4}	5×10^{-4}	1×10^{-3}	3×10^{-3}
T_{dust}	83	164	87	602
T_{CIB}	5	11	9	18

Optimization – SNR estimations

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$\mathbf{y_{tot}}$	1	1.8	3	7
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$\mathbf{\mu_{amp}}$	3×10^{-4}	5×10^{-4}	1×10^{-3}	3×10^{-3}
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Optimization – SNR estimations

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Optimization – SNR estimations

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Conclusion

Perspectives :

- spatial variation of emissions (foregrounds)
- mission profile (scanning strategy, …)
- atmosphere model
- instrumental model (transmission profile, detector efficiency, …)
- more realistic forecasting (MCMC method)

Thank you for your attention

Annexes

Foreground modeling

Foregrounds:

Galactic

- Thermal dust
- Synchrotron
- Free-free
- Anomalous Microwave Emission
- Zodiacal emissions

Extragalactic

- Cosmic Infrared Background (CIB)
- Cumulative CO

$$\Delta I_D(\nu) = A_D x^{\beta_D} \frac{x^3}{(e^x - 1)},$$

$$\Delta I_{CIB}(\nu) = A_{CIB} x^{\beta_{CIB}} \frac{x^3}{(e^x - 1)}.$$

$$\Delta I_S(\nu) = A_S \left(\frac{\nu}{\nu_0}\right)^{\alpha_S} \left[1 + \frac{1}{2}\omega_S \ln^2\left(\frac{\nu}{\nu_0}\right)\right],$$

$$\nu_{ff} = \nu_{FF}(T_e/10^3 K)^{\frac{3}{2}}$$

$$\Delta I_{FF}(\nu) = A_{FF}\left(1 + \ln\left[1 + \left(\frac{\nu_{ff}}{\nu}\right)^{\frac{\sqrt{3}}{\pi}}\right]\right),$$

$$\Delta I_{ZT}(\nu) = \epsilon(\nu) \frac{2h\nu^3}{\left(e^{\frac{h\nu}{kT_{ZT}}} - 1\right)}. \quad \epsilon(\nu) = \epsilon_{ZT} \times \begin{cases} 1, & \text{if } \nu > 2\text{THz} \\ (\frac{\nu}{\nu_0})^2 & \text{if } \nu < 2\text{THz} \end{cases}, \nu_0 = 2\text{THz} \qquad \Delta I_{ZS}(\nu) = \epsilon_{ZS} \frac{2h\nu^3}{(e^{\frac{h\nu}{kT_{ZS}}} - 1)}.$$

CMB spectral distortions

- **Blackbody component :**
$\Delta I_\upsilon / I_\upsilon \sim 10^{-5}$

- ***y*-distortion (thermal SZ) :**
$\Delta I_\upsilon^{y} / I_\upsilon \sim 10^{-6}$

- ***μ*-distortion (chemical potential) :**
$\Delta I_\upsilon^{\mu} / I_\upsilon \sim 10^{-8}$

$$\Delta I_\nu = \Delta B_\nu + \Delta I_\nu^{y} + \Delta I_\nu^{rel-tSZ} + \Delta I_\nu^{\mu} + \Delta I_\nu^{fg}$$

$$\Delta B_\nu = I_0 \frac{x^4 e^x}{(e^x-1)^2} \Delta_T,$$

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

$$\Delta I_\nu^{y} = I_0 \frac{x^4 e^x}{(e^x-1)^2} \left[\frac{1}{\beta} - \frac{1}{x} \right] \mu,$$

$$\Delta I_\nu^{rel-tSZ} = I_0 \frac{x^4 e^x}{(e^x-1)^2} \left[Y_1(x)\theta_e + Y_2(x)\theta_e^2 + Y_3(x)\theta_e^3 + \left[Y_2(x)\theta_e^2 + 3Y_3(x)\theta_e^3 \right] \omega_2^{eSZ} \right] y,$$

Power on detectors

Estimation of the load on the detector

Signal consider

- S_{sky} CMB emission, all foregrounds +spectral distortions
- Instrument emission of component in optical path
- Total power receive on the detector

$$P = \frac{1}{2} eff_{det} \int_{\nu_{min}}^{\nu_{max}} \left[S_{sky}(\nu) \prod_{k=1}^{K} t_k(\nu) + \sum_{k=1}^{K} (\mathcal{E}_k B_\nu(\nu, T_k) \prod_{l=k+1}^{K} t_k(\nu)) \right] A\Omega(\nu) d\nu$$

A detector area
Ω detector solid angle
eff_{det} detector efficiency
t_k transmission of k-ieme optical component at frequency ν
K total number of optical component considered (from photometric model)

Noise Equivalent Power (NEP)

Estimation of NEP_{photon}

$$NEP_{photon}(\nu_0) = (2h\nu_0 P + \frac{2P^2}{\Delta\nu})^2$$

where ν_0 is the central frequency of the frequency band considered (bandwidth $\Delta\nu$)

We need NEP_{photon} dominant to be background dominated.

Estimation of NEP_{total}

$$NEP_{photon} = \sqrt{NEP_{photon} + NEP_{detector}}$$

with $NEP_{detector}$ value fixed at $NEP_{photon}/\sqrt{2}$

Sensitivity Estimation

Detected noise of the frequency band of central frequency ν_0 for a fixed integration time τ :

$$\delta P(\nu_0) = \frac{NEP_{total}(\nu_0)}{\sqrt{\tau/2}}$$

τ will be deduce from mission profile ad detector parameter :

$$\tau = n_{scan} \times \mathrm{tc}_{det}$$

$n_{scan}$is the number of FTS scan realized and tc_{det} is the time constant of the detectors.
Note that effective observed time t_{obs} is defined as :

$$t_{obs} = n_{sample/scan} \times \tau$$

where $n_{sample/scan}$ is the number of sample during one scan of FTS.
Noise at the detector referred to specific intensity on the sky which give an equivalent of the instrumental concept sensitivity that can be compare to sky emissions :

$$\delta I_\nu(\nu_0) = \frac{\delta P(\nu_0)}{A\Omega(\nu_0)\Delta\nu(eff_{det} \times t_{eff}(\nu_0))}$$

with $t_{eff}(\nu_0) = \prod_{k=1}^{K} t_k(\nu_0)$ is the effective transmission of the instrument at frequency ν_0 and at the observing bandwidth $\Delta\nu$.

CMB spectral distortions

adapted from J.Silk and J.Chulba, 2014

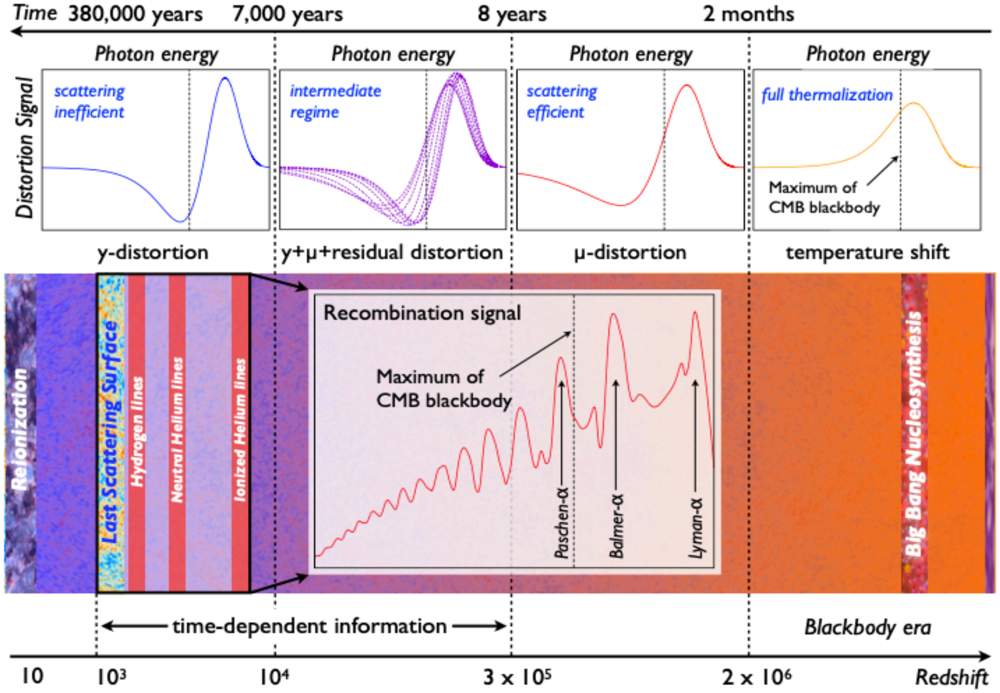
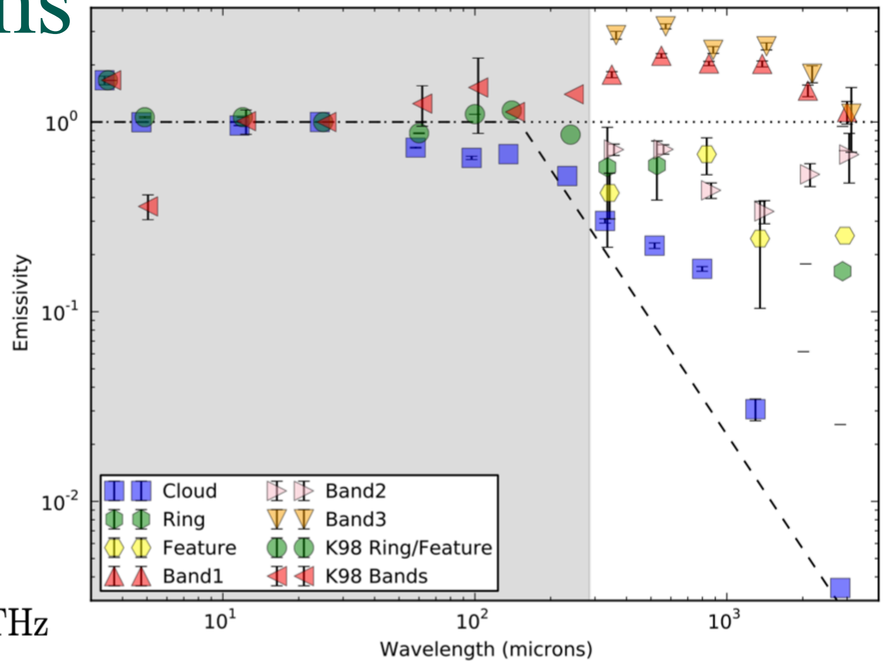


FIG. 1: Evolution of spectral distortions across time. Distortions probe the thermal history over long periods deep into the primordial Universe that are inaccessible by other means. The distortion shape contains valuable epoch-dependent information that allows distinguishing different sources of distortions. Line-emission is created during the cosmological recombination eras leaving a detailed 'fingerprint' of the recombination process. The figure is adapted from [8].

Zodiacal emissions

$$\Delta I_{ZT}(\nu) = \epsilon(\nu)\frac{2h\nu^3}{\left(e^{\frac{h\nu}{kT_{ZT}}} - 1\right)}.$$

$$\epsilon(\nu) = \epsilon_{ZT} \times \begin{cases} 1, & \text{if } \nu > 2\text{THz} \\ \left(\frac{\nu}{\nu_0}\right)^2 & \text{if } \nu < 2\text{THz} \end{cases}, \nu_0 = 2\text{THz}$$



from Planck Collaboration, 2013

FIGURE 3 – Emissivities of components of the K98 zodiacal emission model obtained from Planck/HFI ($\lambda > 250\mu m$) and COBE/DIRBE ($\lambda < 250\mu m$, grey shading ; K98).The dotted line indicates an emissivity of unity at all wavelengths, and the dashed line indicates an emissivity that is unity at wavelengths below $150\mu m$ and proportional to λ^{-2} at longer wavelengths. From Planck Collaboration, 2013 [3]

Model parameters

Sky signal parameters
y_{tot}
kT_{eSZ}
ΔT_{CMB}
μ_{amp}
A_d
β_d
T_d
A_{CIB}
β_{CIB}
T_{CIB}
A_{FF}
A_s
α_s
ω_s
A_{SD}
A_{CO}