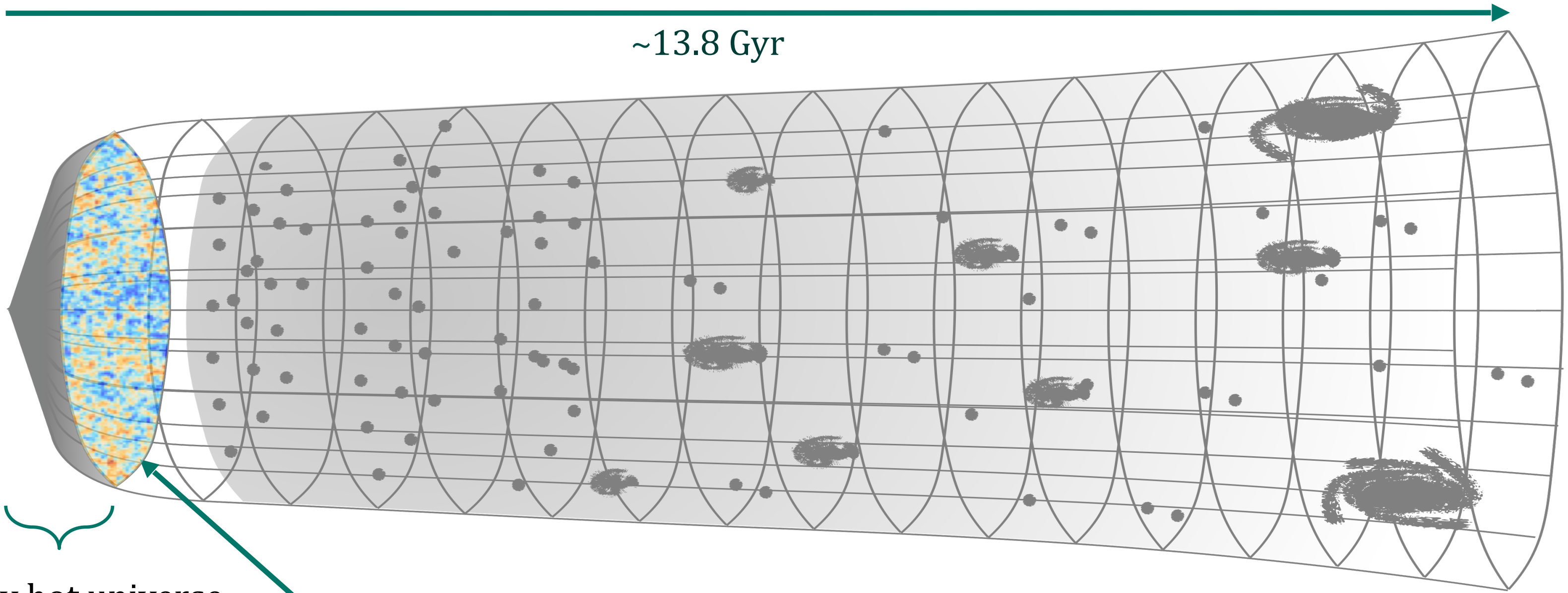
Cosmic Microwave Background Spectral Distortions Measurement Prospects

Xavier COULON

Supervisors: B. Maffei & N. Aghanim

04/12/2023

A (very) short history of our Universe



Courtesy of V.Sauvage

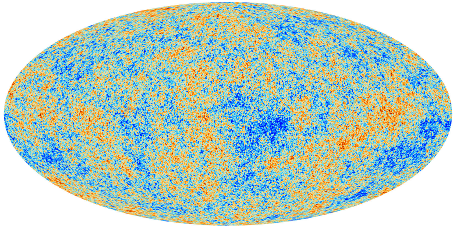
Very hot universe
T > 3000K
Opaque Plasma

T~$3000K$ Recombinaison
Universe becomes transparent
Cosmic **M**icrowave **B**ackground (CMB)

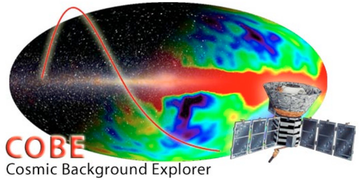
CMB seen today as a perfect blackbody at $T = 2.726K$

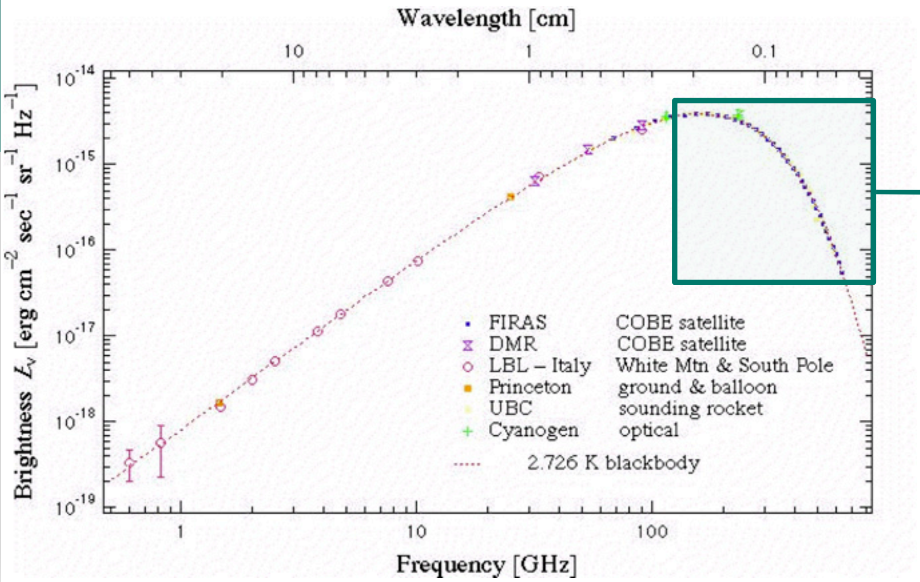
Cosmic Microwave Background

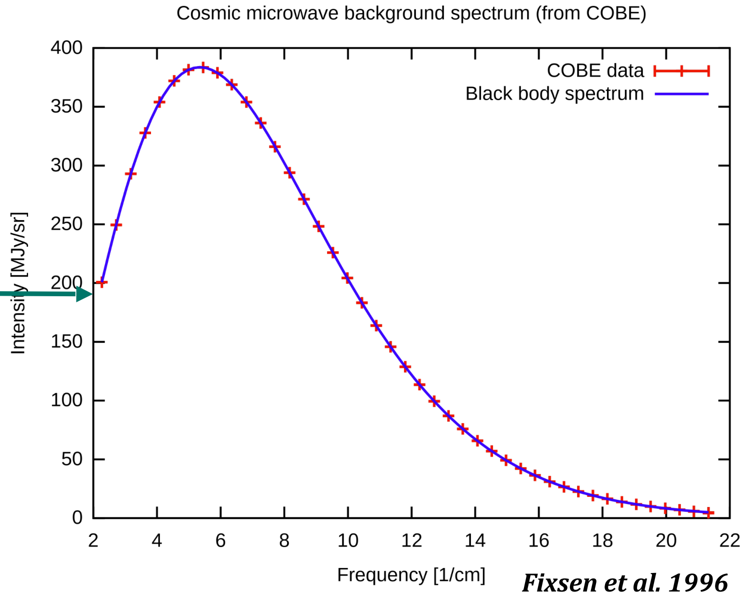
Planck



- ➢ Hot **big-bang** scenario
  → CMB with blackbody spectrum at $T = 2.726K$





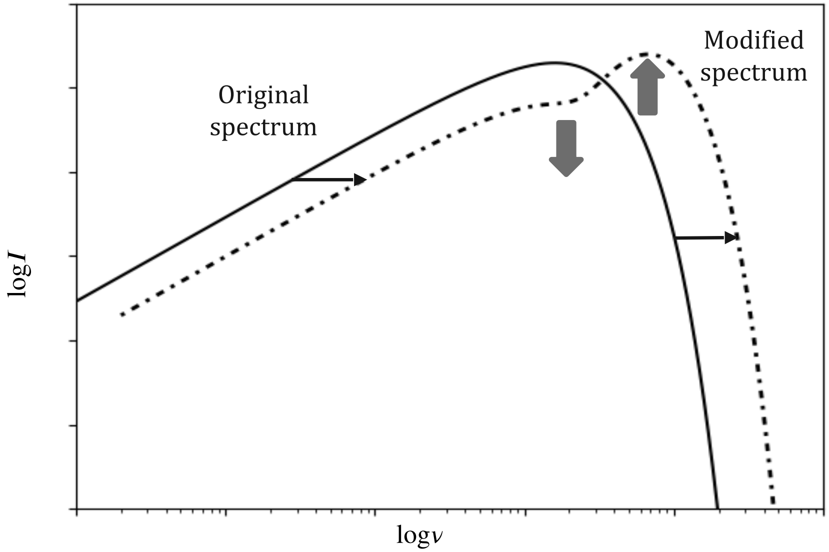


Fixsen et al. 1996

CMB Spectral Distortions

Energy input from inflation to the formation of first stars and galaxies

Blackbody distortion proportional to energy release



z

➢ CMB Spectral distortions

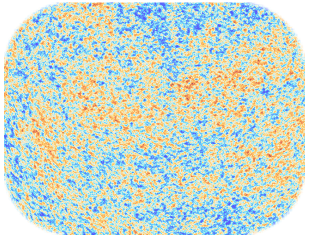
$z = 2 \times 10^6$

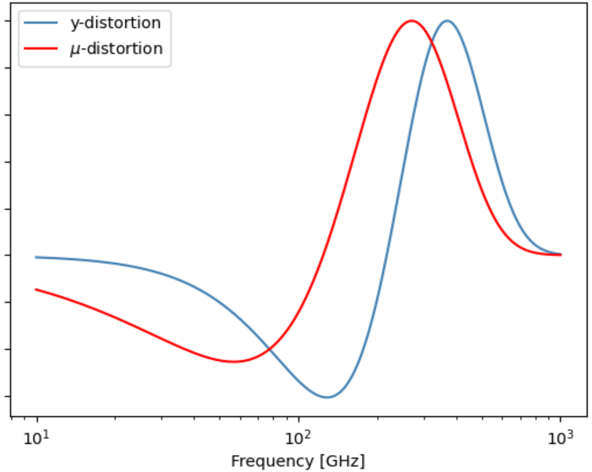
μ-distortion (chemical potential)

$z = 5 \times 10^4$

Compton y-distortion (thermal SZ)

$z \simeq 10^3$





Towards CMB spectral distortion measurement

1

Sky model at frequencies relevant for CMB spectral distortion measurement

2

Instrument model considering both photometric and mission parameters

3

- to perform forecasts
- to optimise the instrument concept
- to study systematic effects

4

Instrument development

Towards CMB spectral distortion measurement

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Sky model

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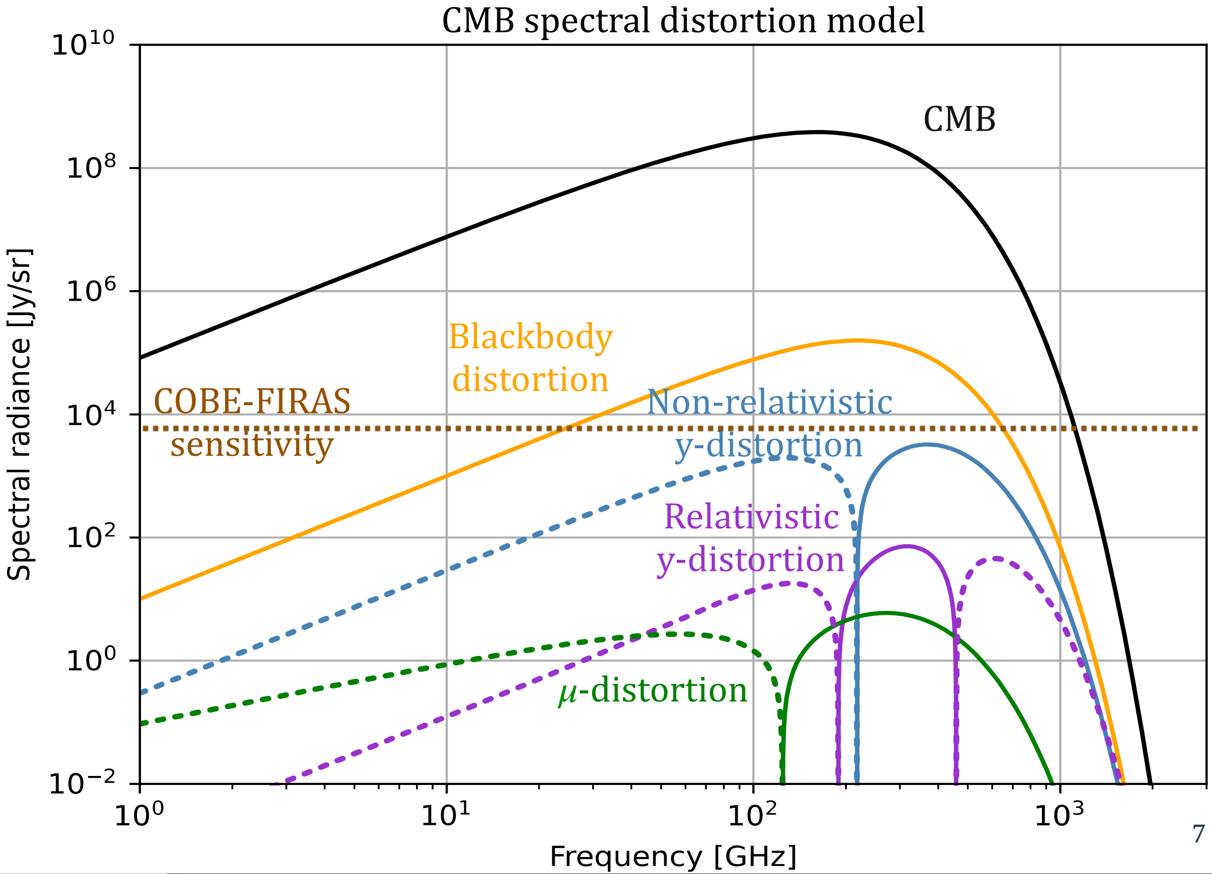
Sky model: CMB spectral distortions

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

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

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

model from Abitbol+ 2017



Sky model: Foreground emissions

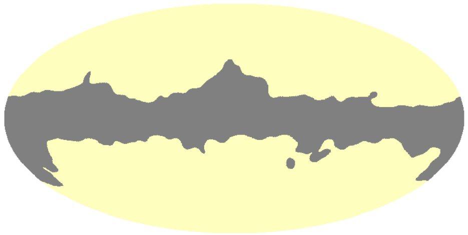
Foregrounds:

Extragalactic

- Cosmic Infrared Background (CIB)
- Cumulative CO

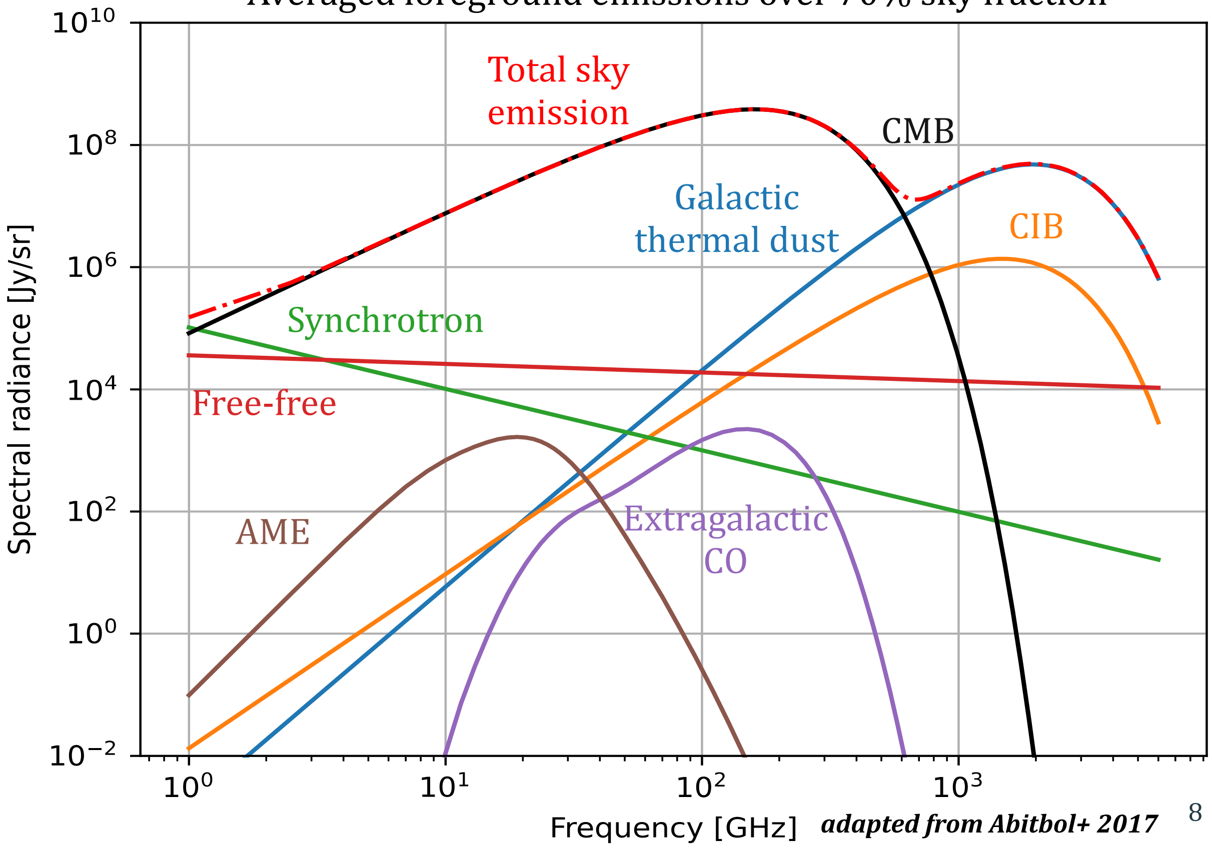
Galactic

- Thermal dust
- Synchrotron
- Free-free
- Anomalous Microwave Emission (AME)
- Zodiacal emissions



uniform sky emissions

Averaged foreground emissions over 70% sky fraction



adapted from Abitbol+ 2017

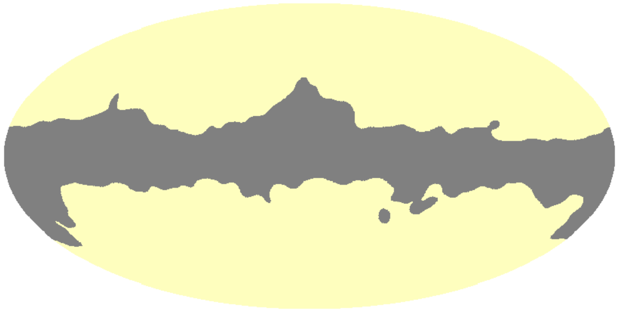
Sky model: spatially varying galactic foregrounds

Improve the sky model by taking into account the spatial dependence of galactic foregrounds :

All foreground emissions are averaged over 70% of the sky (excluding the galactic plane)

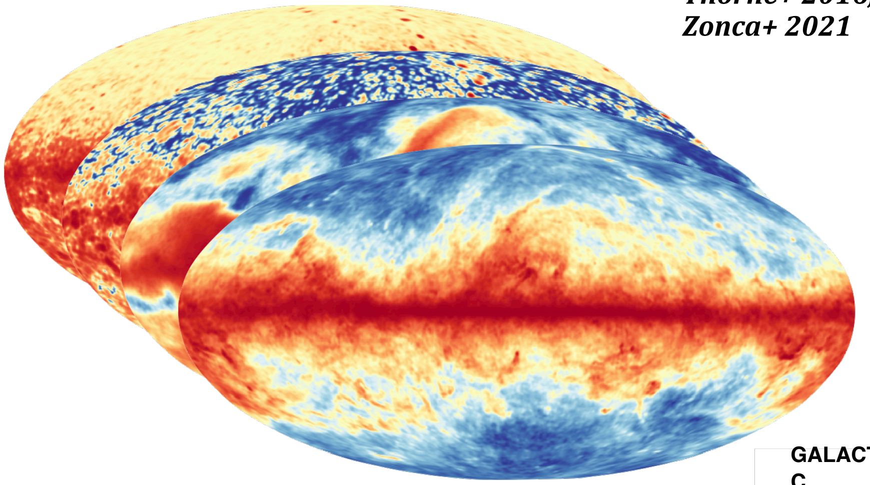
Planck Sky Model maps (PySM) :
- Thermal dust
- Synchrotron
- Free-free
- Anomalous Microwave Emission (AME)

Sky emissions at 300GHz



Sky emissions at 300GHz

Thorne+ 2016, Zonca+ 2021



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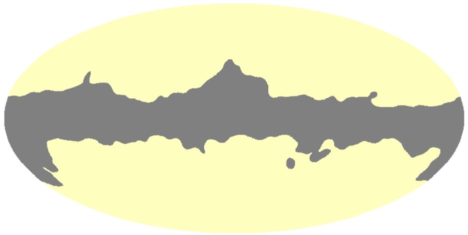
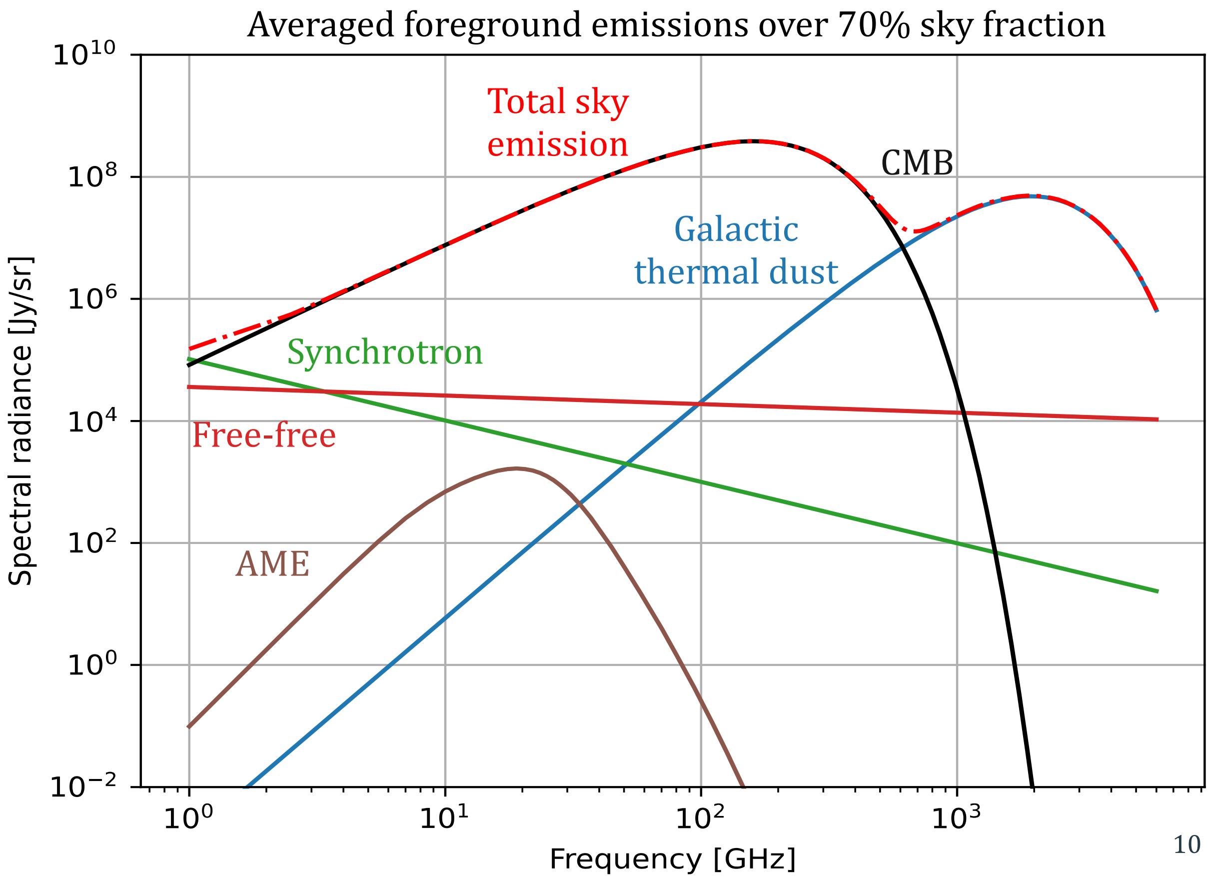


uniform sky emissions



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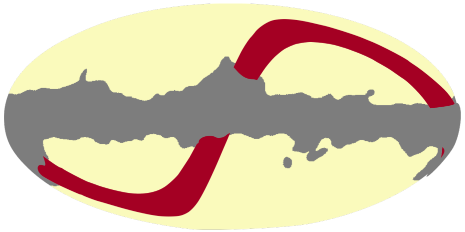

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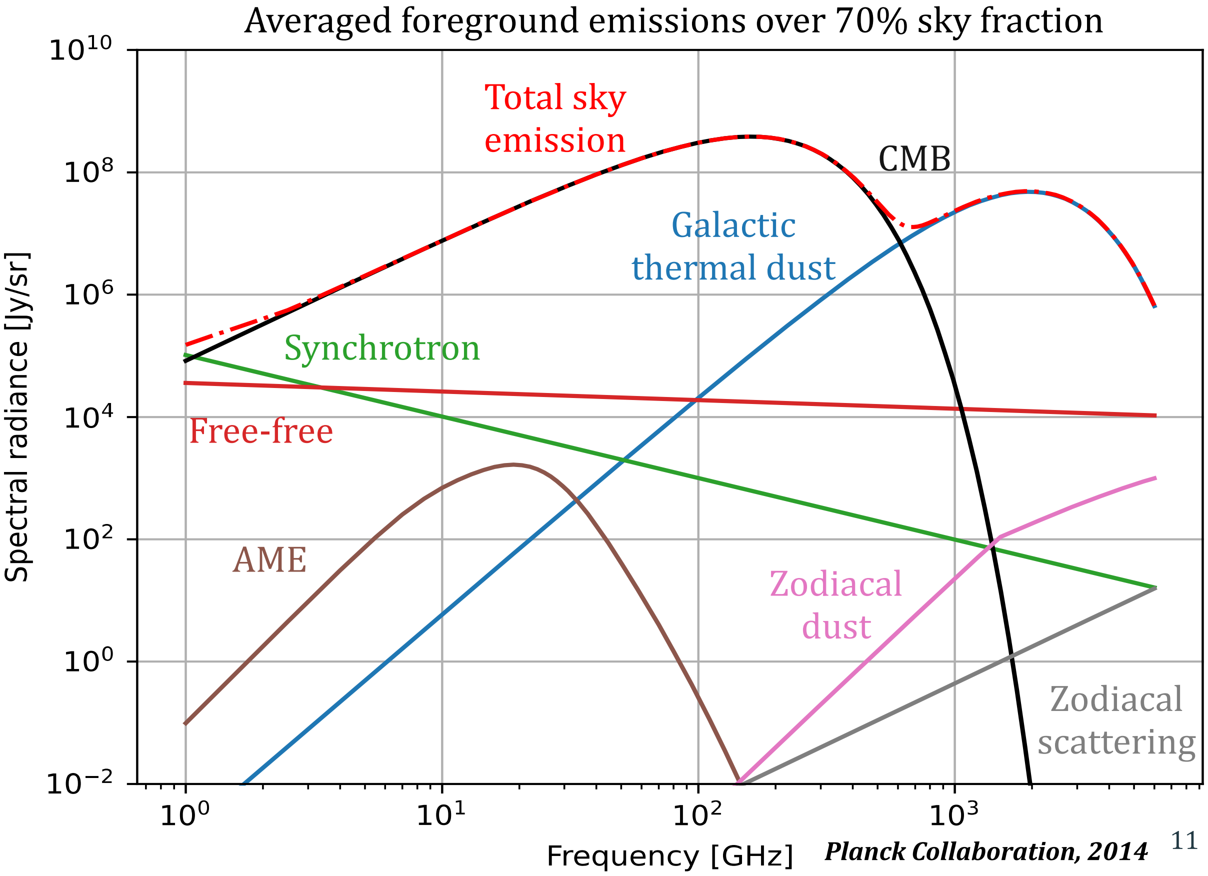

Planck Collaboration, 2014

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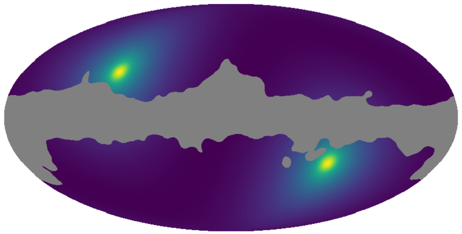

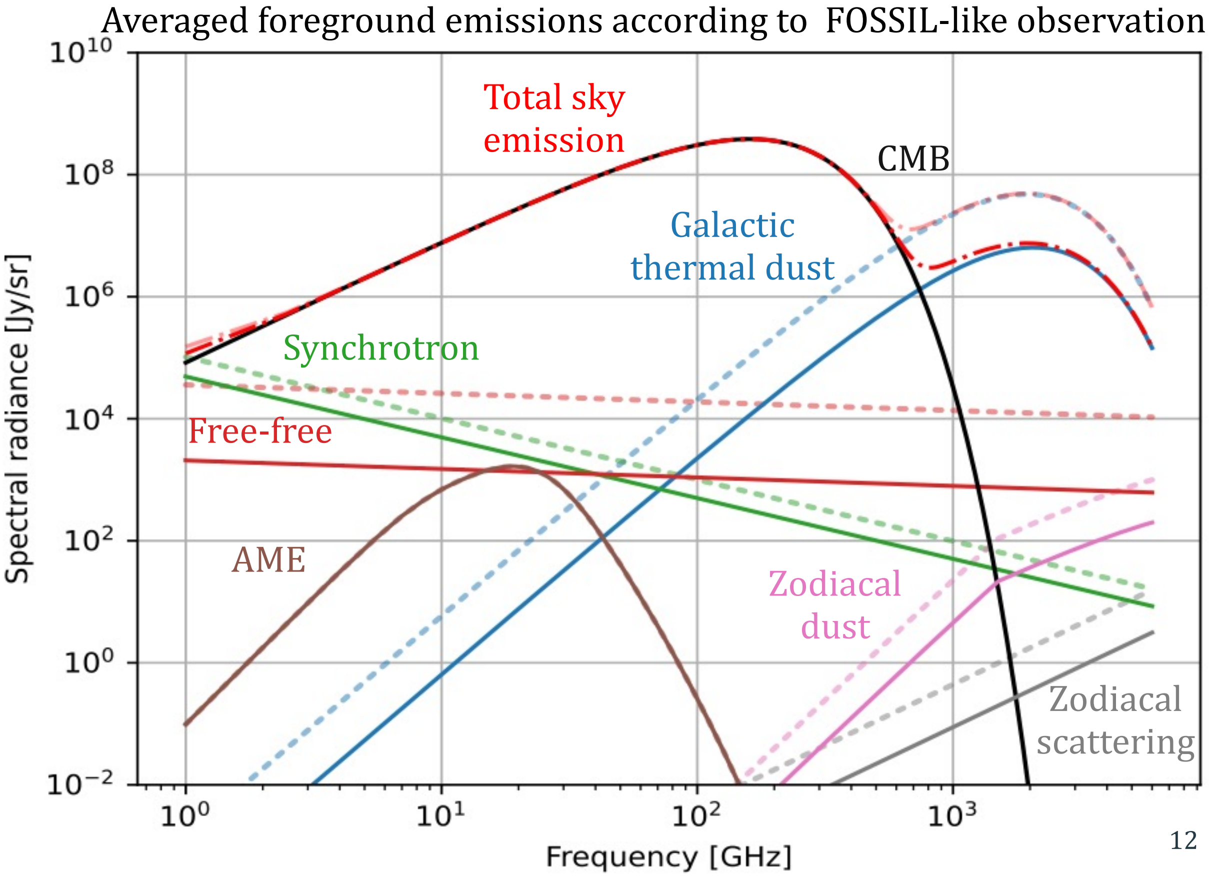

Towards CMB spectral distortion measurement

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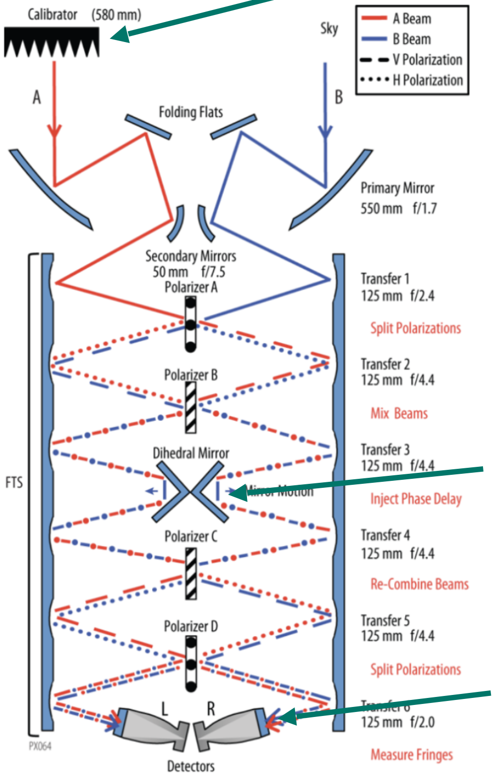
Instrument development

Instrument model: concept

Calibrator = blackbody at 2.7K
(reference for differential measurement)



PIXIE original concept
(*A. Kogut et al. 2011*)

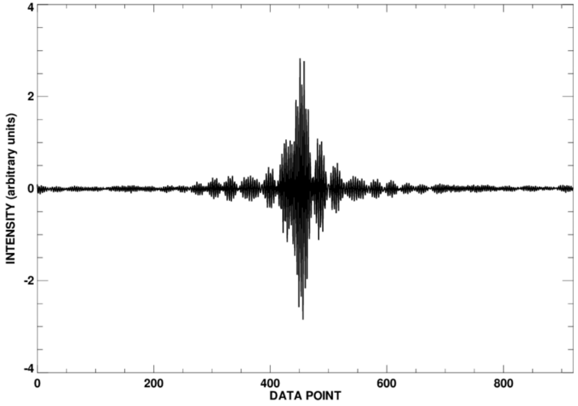
Fourier Transform Spectrometer (FTS)
2 inputs (sky & calibrator)

FTS scanning mirror
for interferogram

Detectors at each
output of the FTS

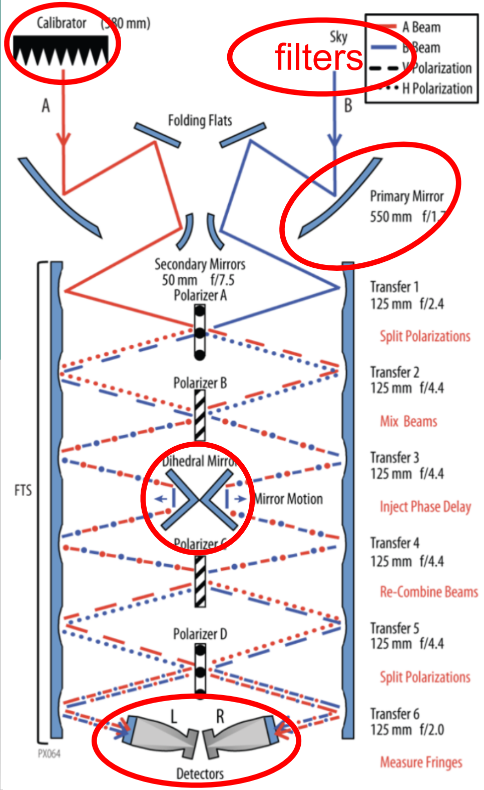
Differential measurement between
the sky and the calibrator

FTS interferogram



Instrument model: photometric model

Calibrator = blackbody at 2.7K
(reference for differential measurement)



: photometric model based on key instrument parameters
+ missions parameters (duration, scanning strategy, etc.)

PIXIE original concept
(A. Kogut et al. 2011)

Fourier Transform Spectrometer (FTS)
2 inputs (sky & calibrator)

FTS interferogram

FTS scanning mirror
for interferogram

Detectors at each
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Differential measurement between
the sky and the calibrator

Towards CMB spectral distortion measurement

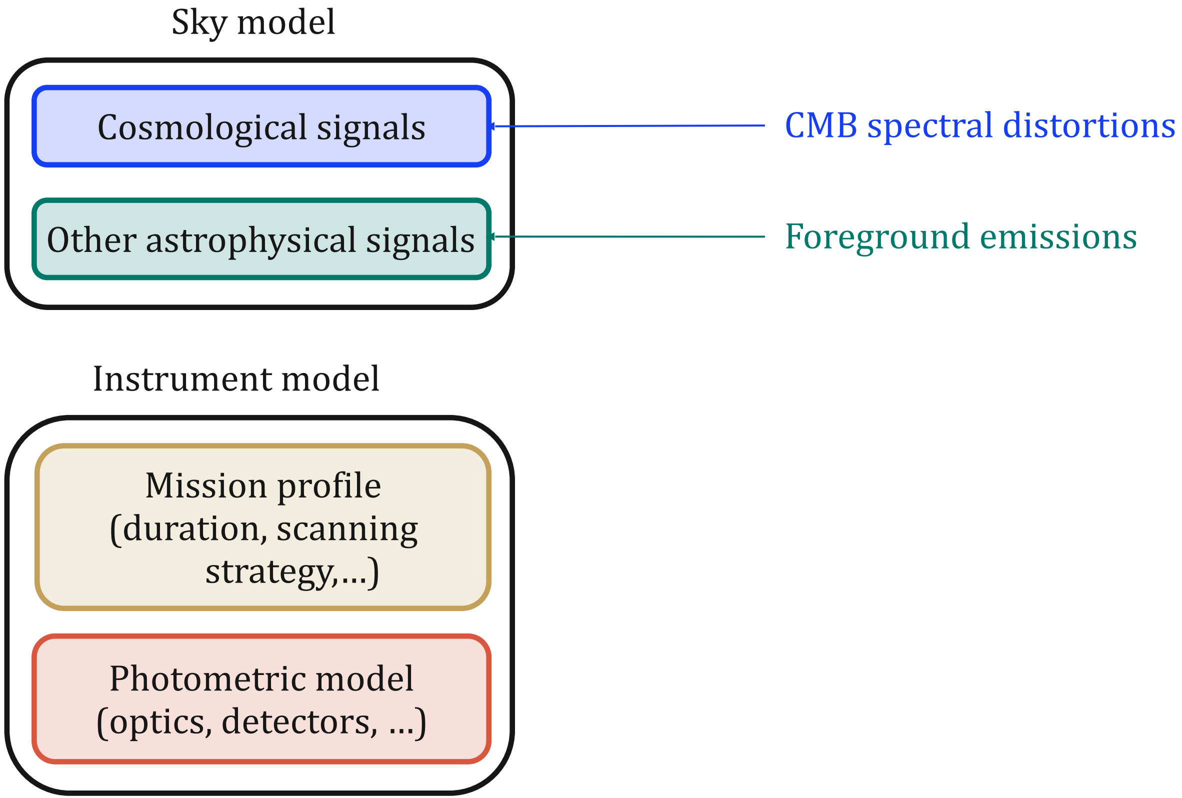
1 Sky model

2 Instrument model

3 Performance and forecasts

4 Instrument development

Optimization of the instrument concept



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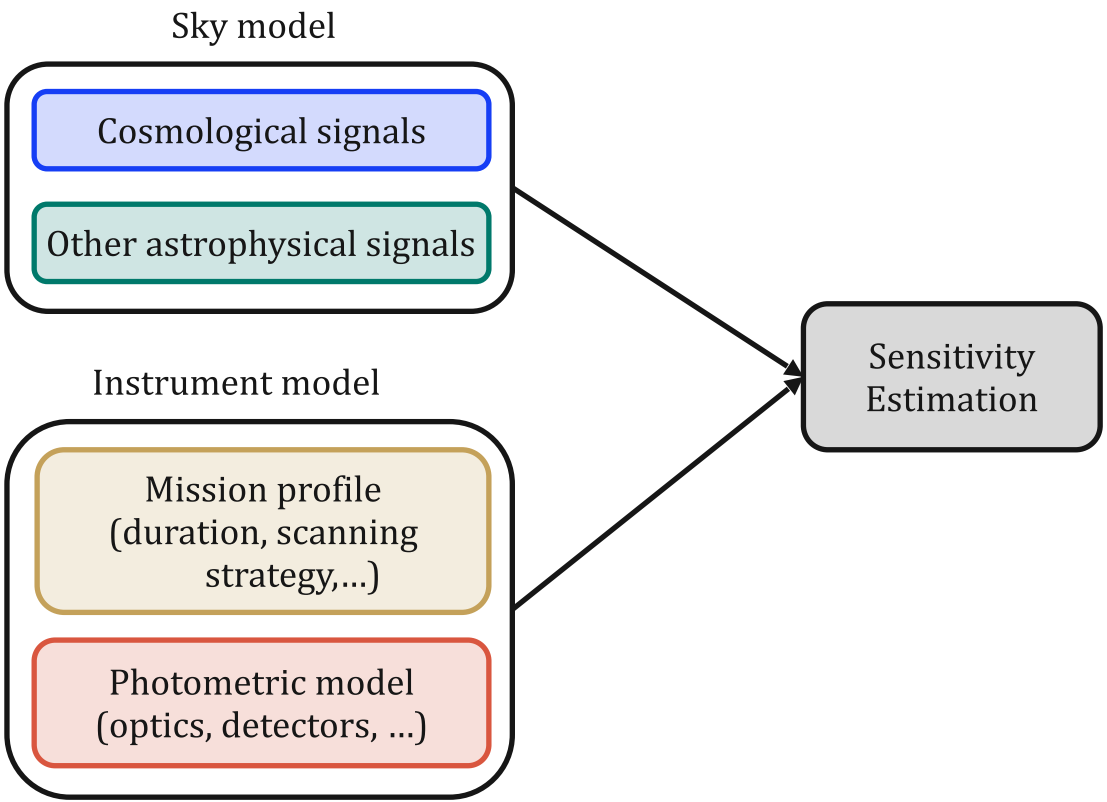

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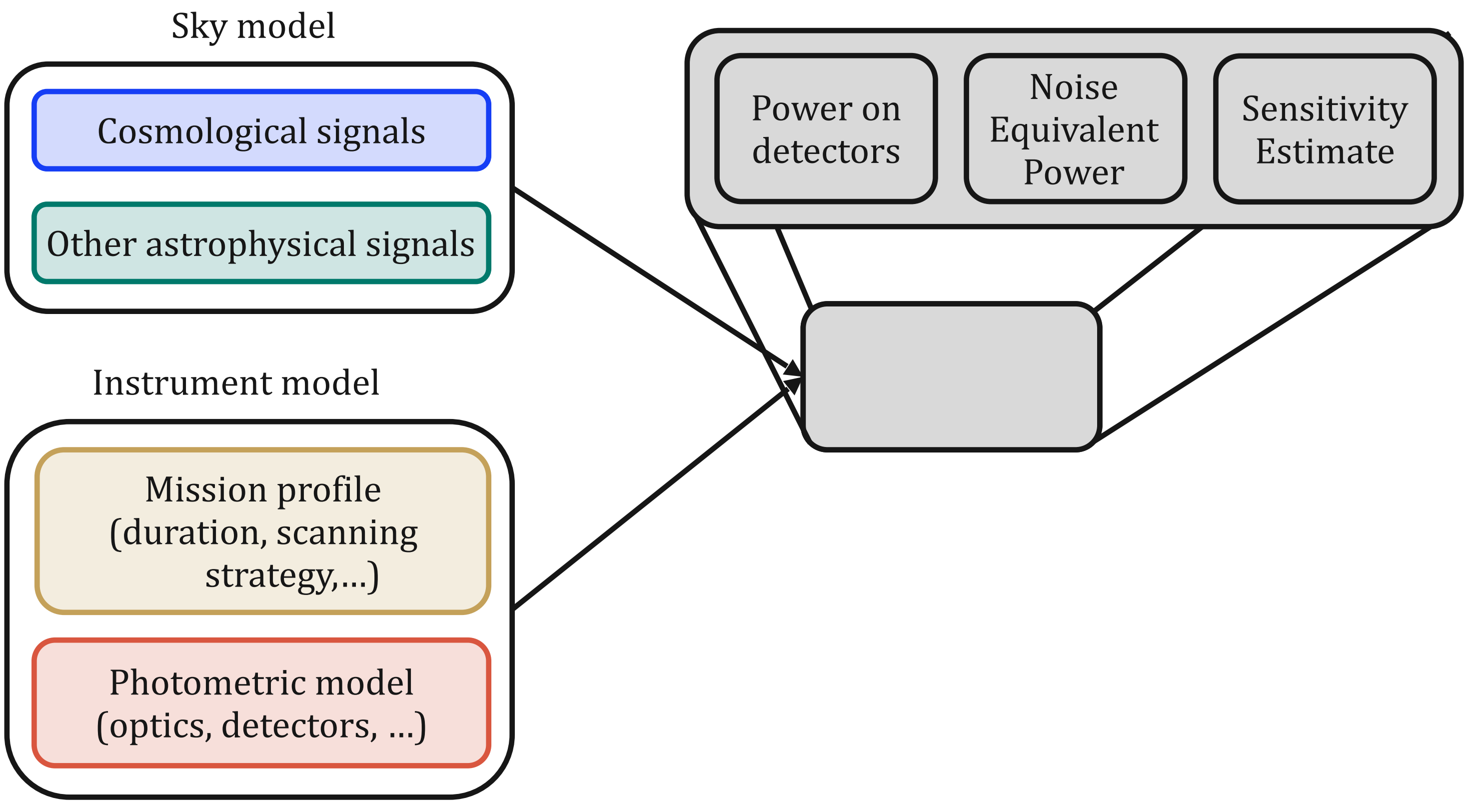

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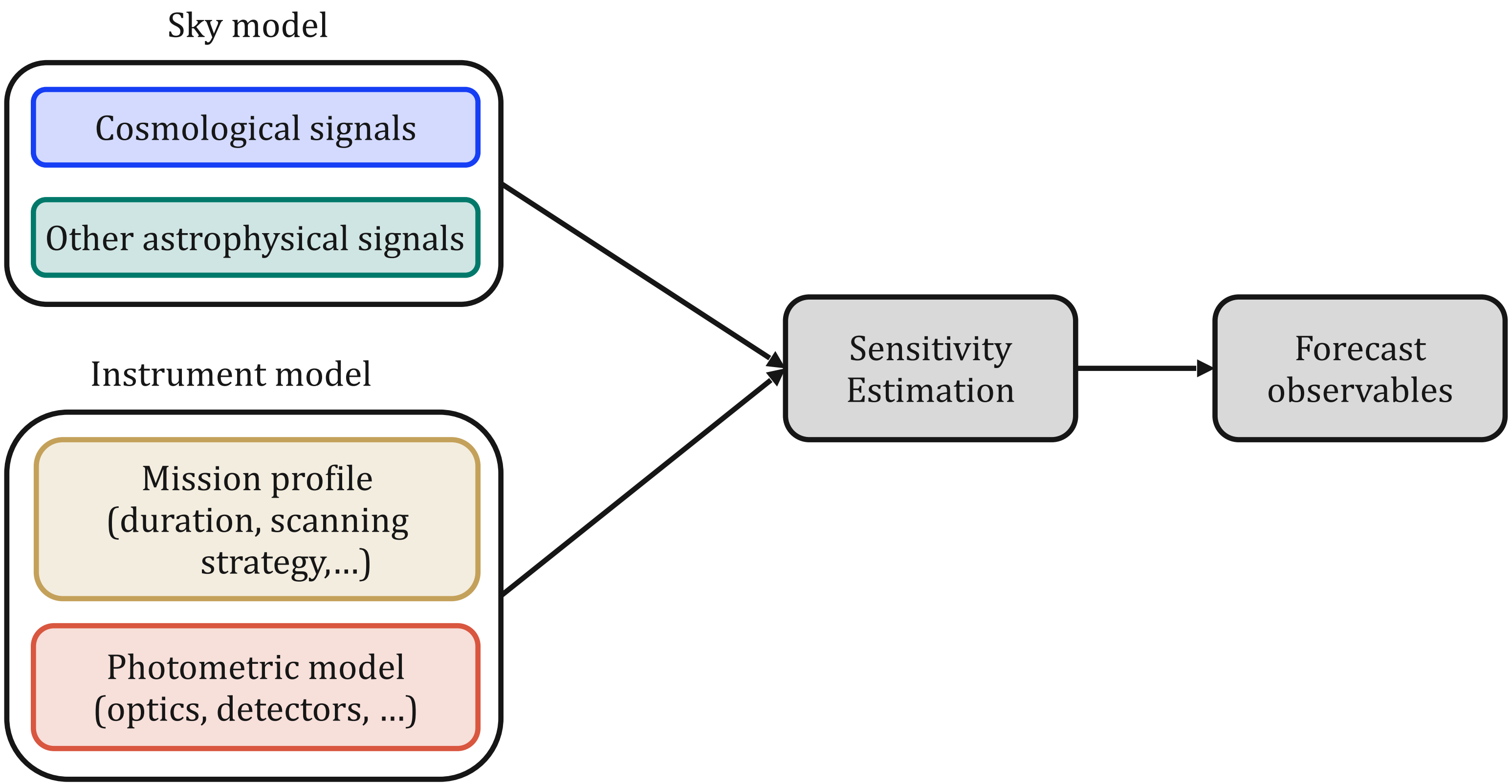

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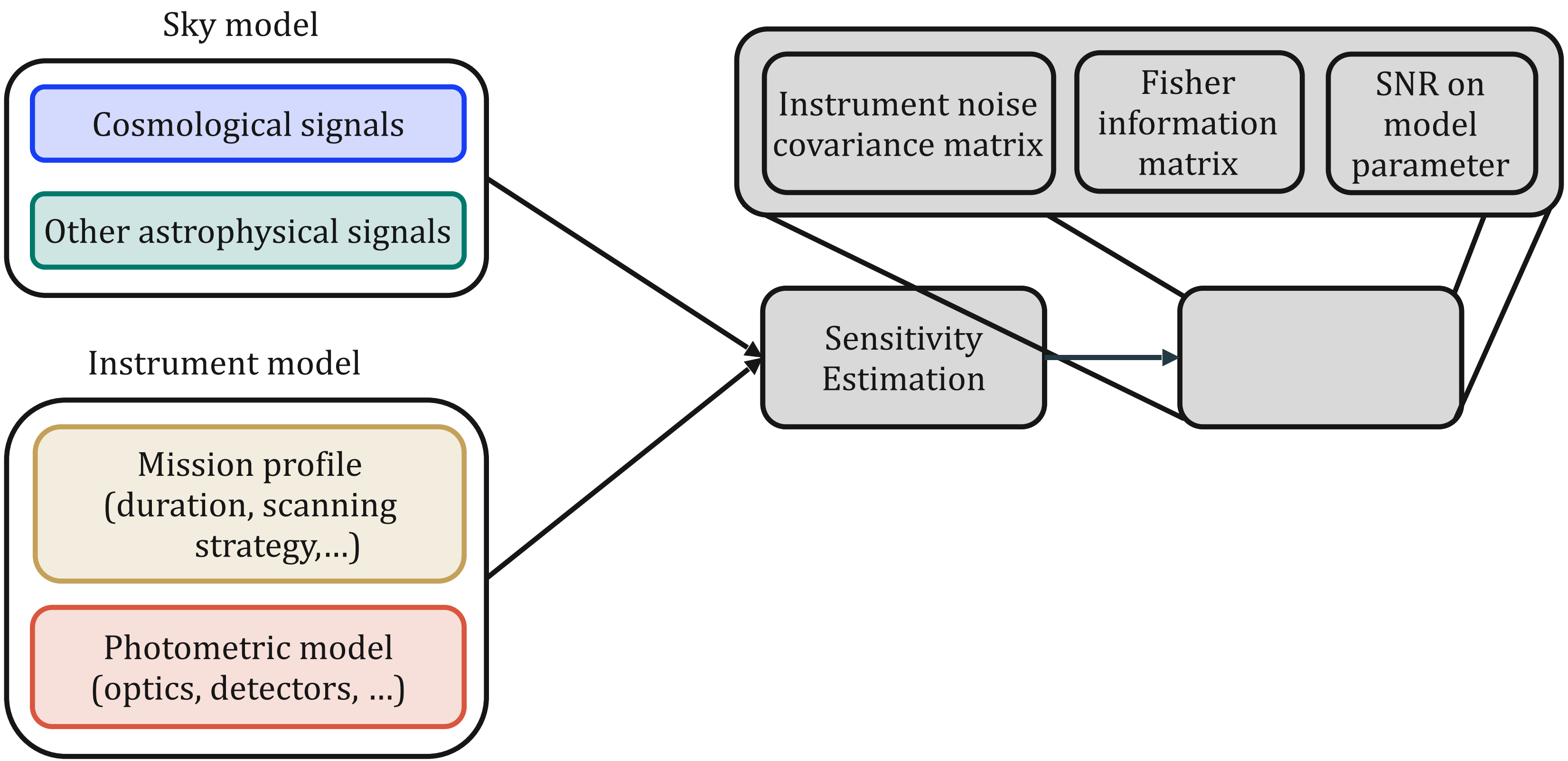

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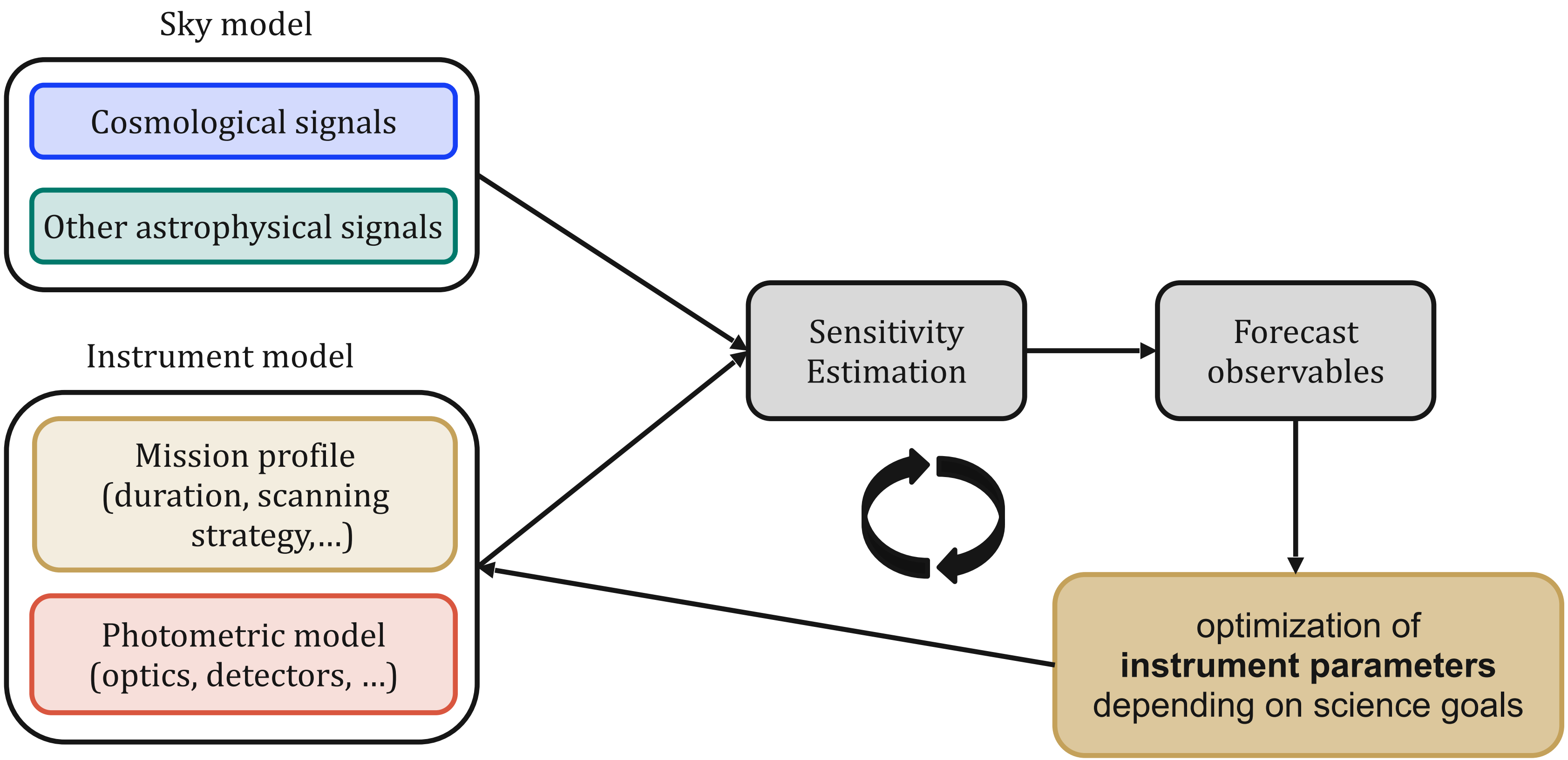


Application case : FOSSIL

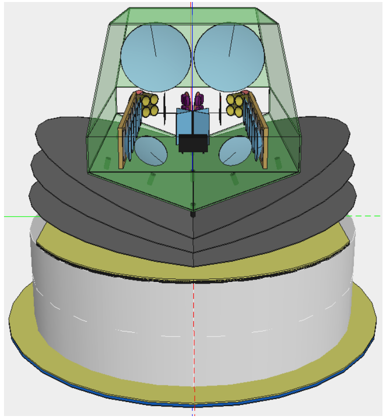
What can be done from space ?

→ space mission proposal to answer ESA M7-call in 2022

https://www.ias.u-psud.fr/en/content/fossil

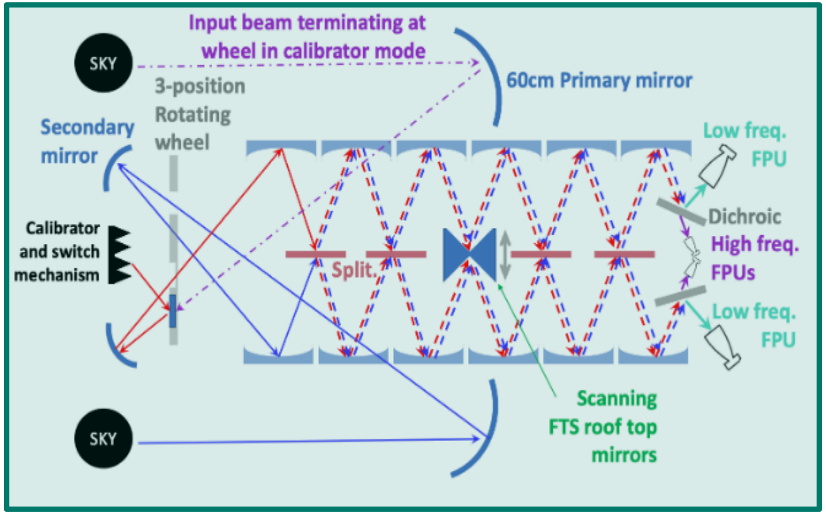
Space mission:

- full sky survey
- cryogenic mission



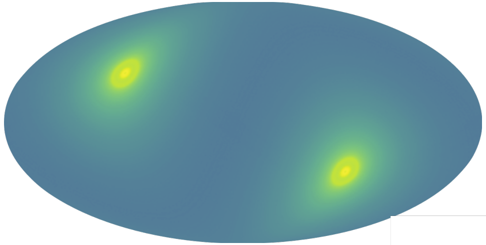
FOSSIL scheme

3K



FOSSIL instrument concept scheme

FOSSIL observation count map



Courtesy of L. Pagano

FTS f**O**r CMB **S**pectral di**S**tort**I**on exp**L**oration (FOSSIL)

Application case : FOSSIL

Assumptions:

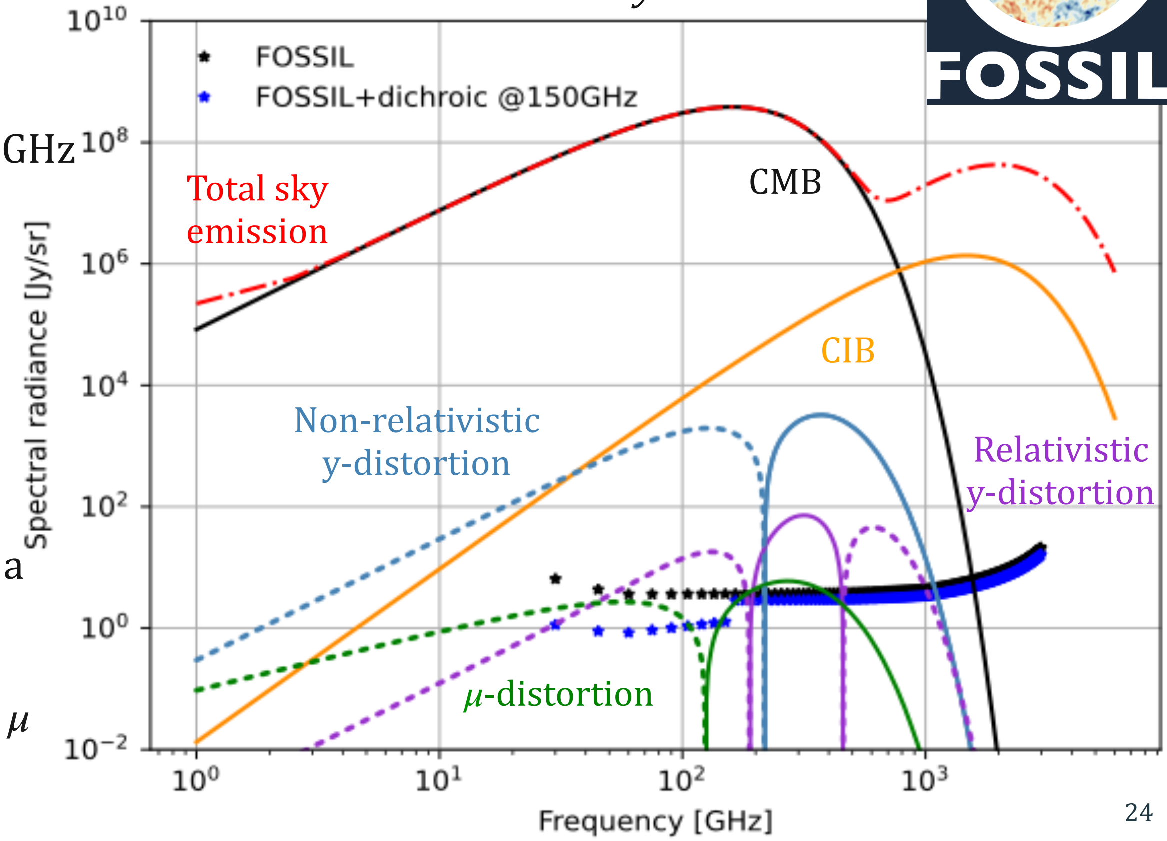
- ν_min =30GHz, ν_max = 2000 GHz
- Δν = 15GHz
- filters with 0.1% emissivity
- 3 years full sky survey
- only 1 detector

Evolution:

splitting the detection band with a dichroic at 150GHz

→ allow to reach 1σ detection on μ

Sensitivity estimates



FOSSIL

Application case : BISOU

What can be done from a balloon ?

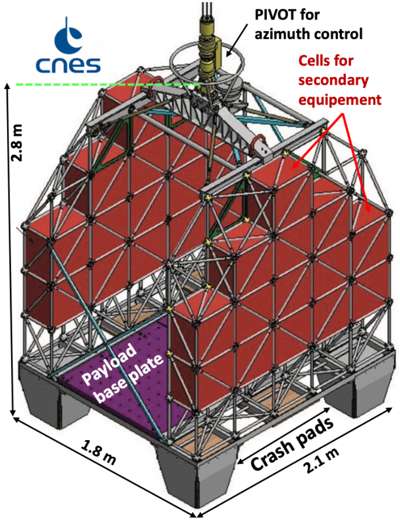
→ end of a successful CNES phase 0 study

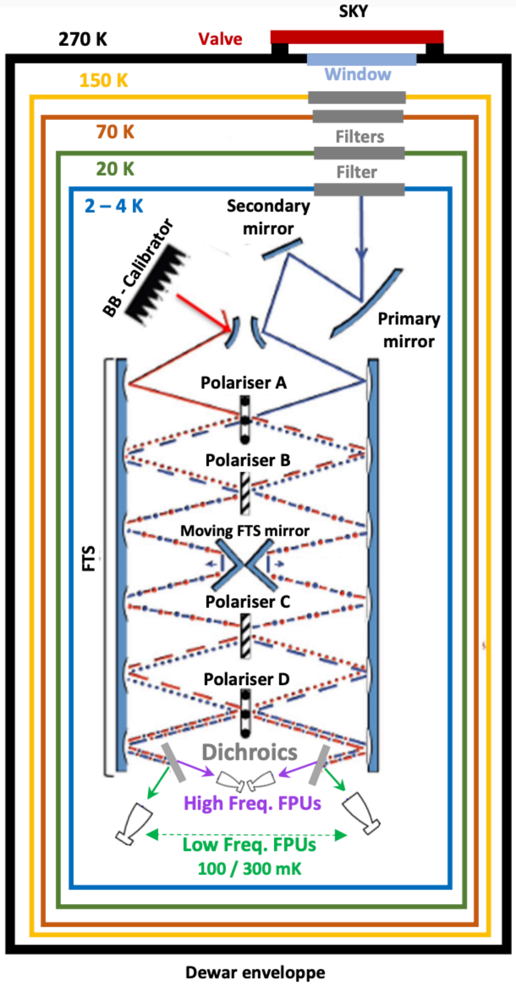
Balloon **I**nterferometer for **S**pectral **O**bservation of the **U**niverse (BISOU)

Maffei+ 2021

Balloon constraint:

- Mass and size limit
- Limited observation time
- Line of sight
- Additional components
- Cryogenic chain
- Residual atmosphere





Application case : BISOU

Main science objective:

- CMB mean temperature, T_{CMB}
- y-distortion monopole, y
- amplitude of CIB monopole

Evolution and trade-offs:

- 250-270K
- whole instrument cold
- thin window (low emissivity)
- one telescope
- raster scan
- need to split detection in 2 sub-bands
- could include more detectors

Forecasts assumptions:

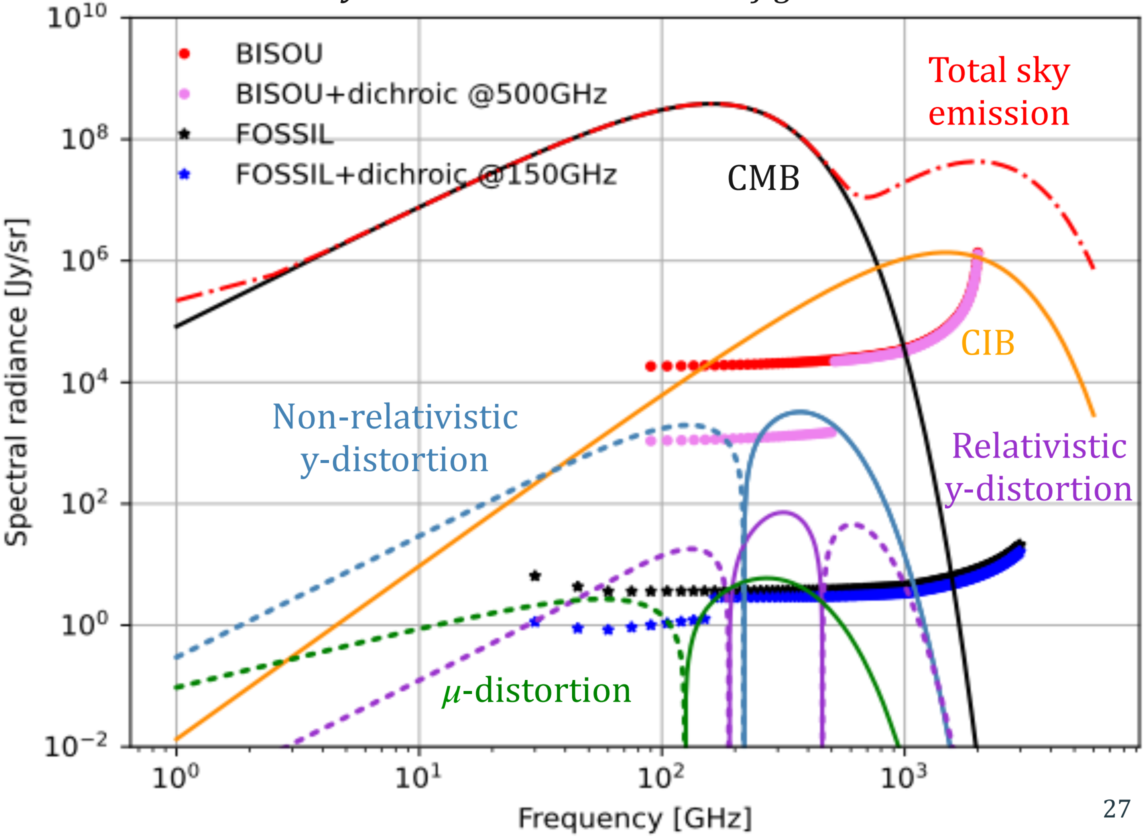
- ν_{min} =90GHz, ν_{max} = 2000 GHz
- $\Delta\nu$ = 15GHz
- filters with 0.1% emissivity
- 5 days flight, 75% obs efficiency
- only 1 detector
- no atmosphere taken into account

Application case : BISOU vs FOSSIL

Main science objective:

- CMB mean temperature, T_{CMB}
- y-distortion monopole, y
- amplitude of CIB monopole
- μ-distortion monopole, μ

Sensitivity estimation in several configuration



Application case : Forecasts

Targeting the first measurement of CMB spectral distortions

→ upper limits by COBE/FIRAS

$$|y| < 15 \times 10^{-6}$$

$$|\mu| < 47 \times 10^{-6}$$

Fixsen et al., 2009, Bianchini et al., 2022

	y	μ	
BISOU (SNR in σ)	5.6		2.8
FOSSIL (SNR in σ)	186	1	76

only 1 detector

→ improvement over COBE/FIRAS

$\times$ 20 in balloon configuration

$\times$ *few* 100 in space configuration

Conclusions and take away

	y	μ	
BISOU (SNR in σ)	5.6		2.8
FOSSIL (SNR in σ)	186	1	76

only 1 detector

- ➢ CMB spectral distortions are powerful probes to access the full thermal Universe history
  - → information beyond the last scattering surface
- ➢ Future large space mission in 2045-2055 (Voyage 2050)
  - → need a pathfinder (hopefully BISOU in 2029)
  - → efforts in foreground and instrument systematics

Annexes

Instrument model: Photometric model

Build photometric model of key elements of the instrument:

→ simplified model with only relevant optical component in the optical path

- primary mirror
- window (only in balloon configuration)
- filters (numbers and temperature change according to configurations)
- dichroic (allow to split detection in 2 sub-bands)
- detectors

Mission context

COBE/FIRAS measures CMB intensity spectrum:

- sets the only existing limits on spectral distortions in 1992

CNES SPS (2019) / **ESA Voyage 2050** (2021) / Astronet (2021)

↳ Large mission horizon 2040-2050

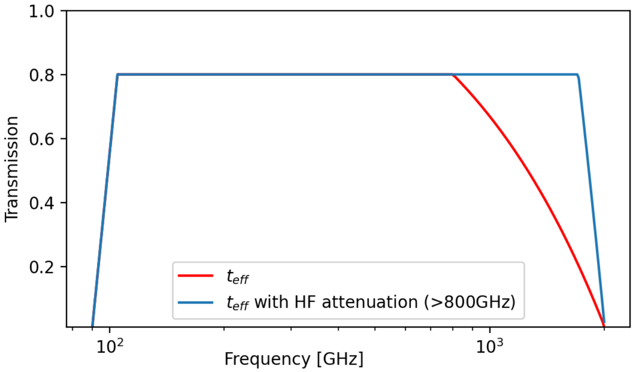
Projects:

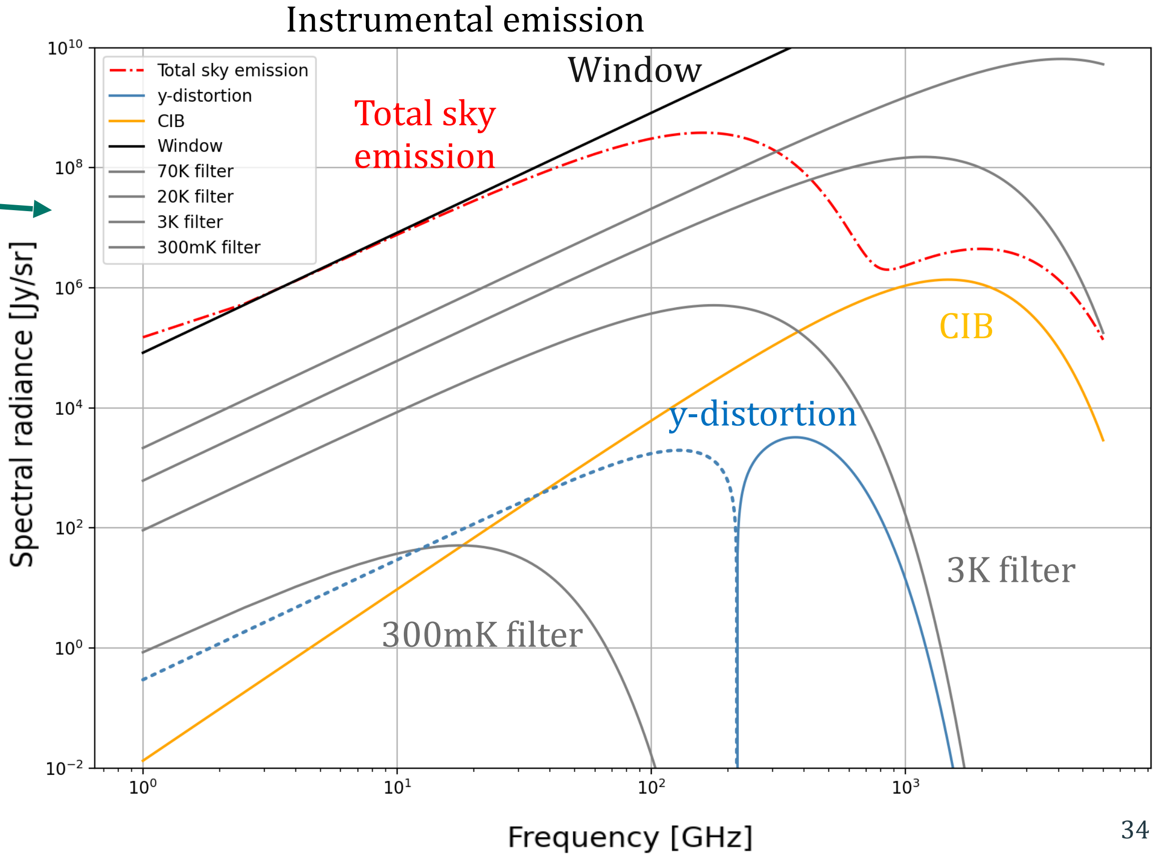
- **PIXIE** (2016): NASA led MIDEx (A. Kogut)
- **PRISTINE** (2018): answer to ESA F1 call (N. Aghanim)
- **FOSSIL** (2022): answer to ESA M7-call (N. Aghanim & B. Maffei)
- **BISOU** (2020 - ...): CNES phase 0 (B.Maffei)
- **COSMO** (???): ground experiment at Dome C (Antarctic)
- **TMS** (???): ground experiment at Teide Observatory (Tenerife)

Instrument model: Photometric model

each optical elements are define by :

- emission (grey body)
- transmission (ideal profile)





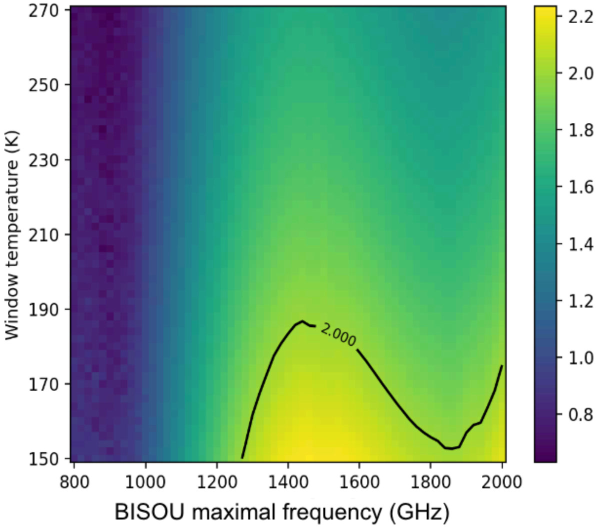
Xavier COULON

Example of instrument concept optimization

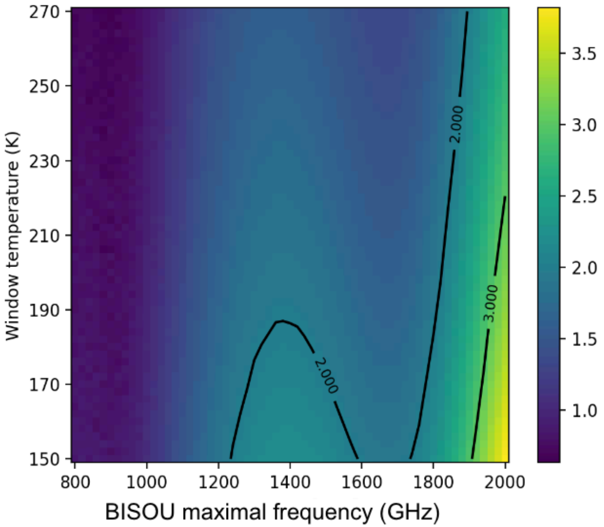
Grid exploration considering: actively cooled window / varying the maximum frequency

SNR of $\boldsymbol{y}$ parameter as a function of the window temperature and maximum frequency

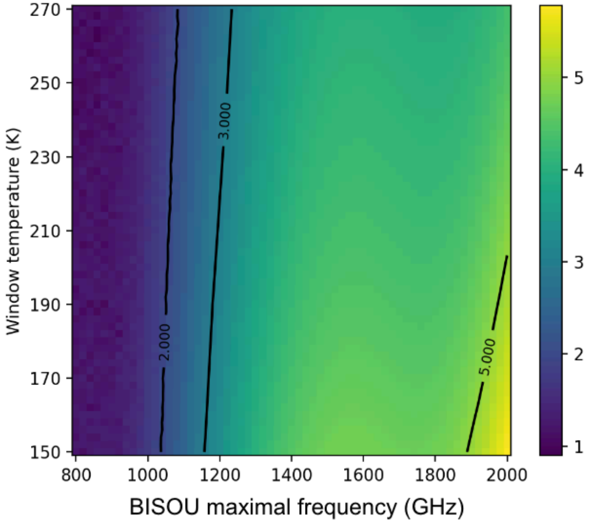
High emissivity window + tapered filtering



Low emissivity window



Low emissivity window + dichroic



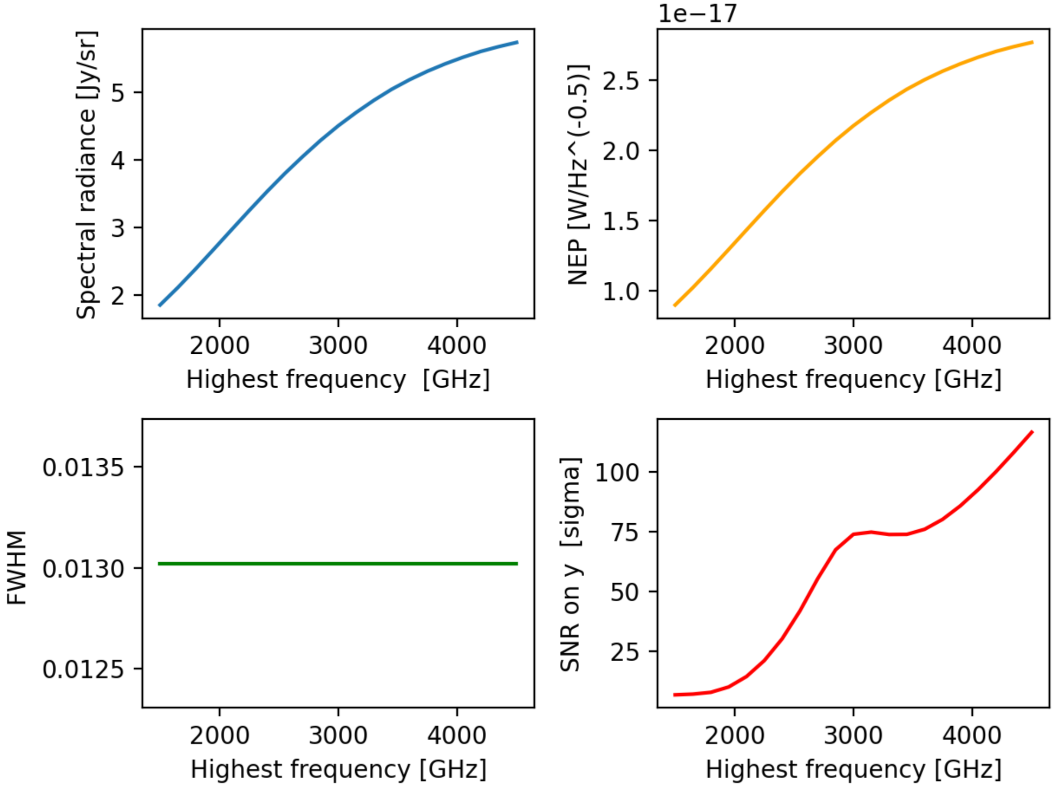
Example of instrument concept optimization

Identifying main parameters of interest:

Evolution according the maximal frequency of the instrument of:

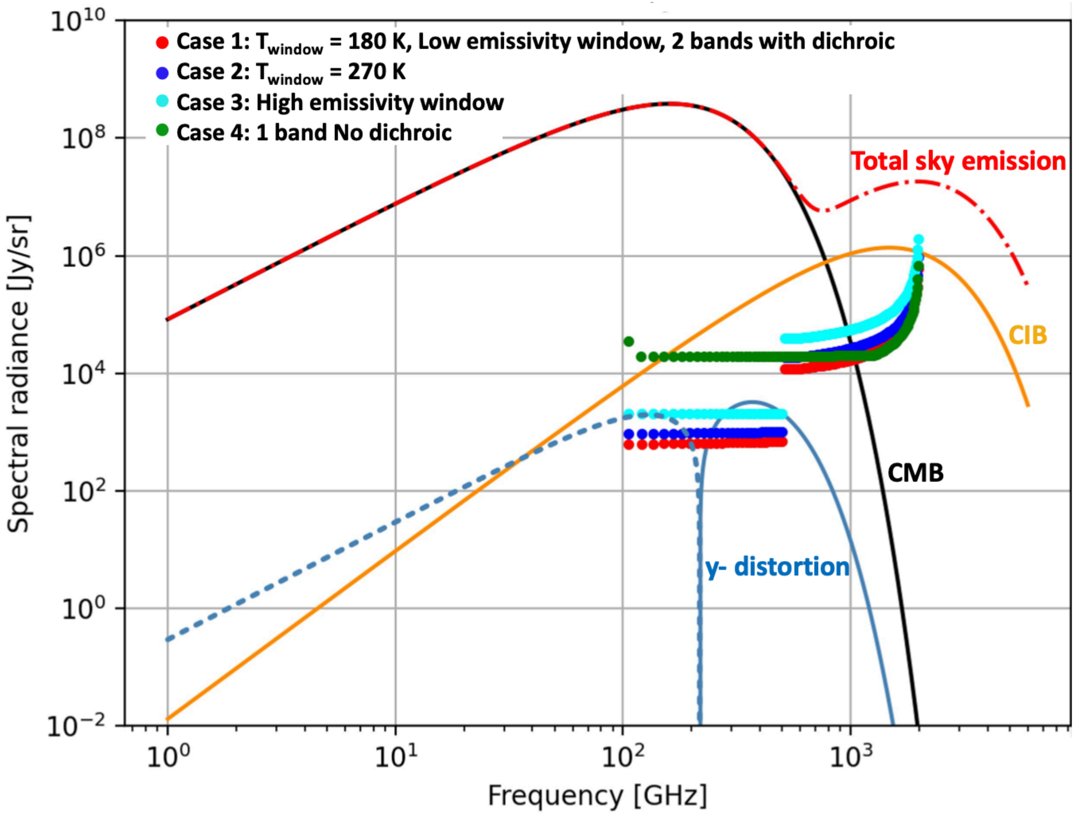
- sensitivity (at 300GHz)
- NEP (at 300GHz)
- FWHM (at 300GHz)
- SNR on *y* parameters

→ adjusting instrument parameters



Application case : BISOU

Sensitivity estimation in several configuration



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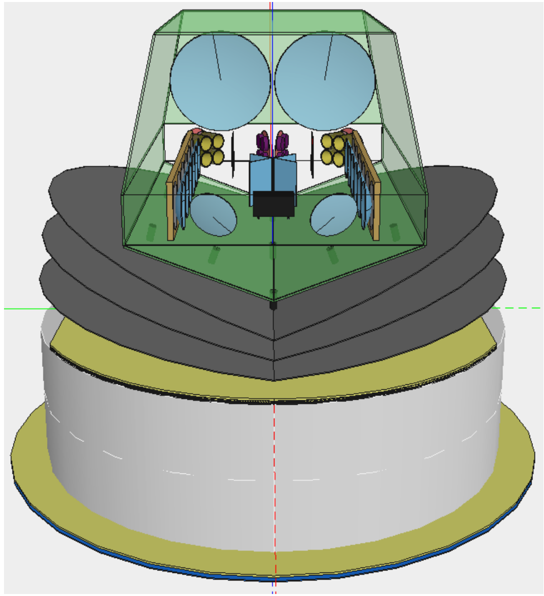
Application case : FOSSIL

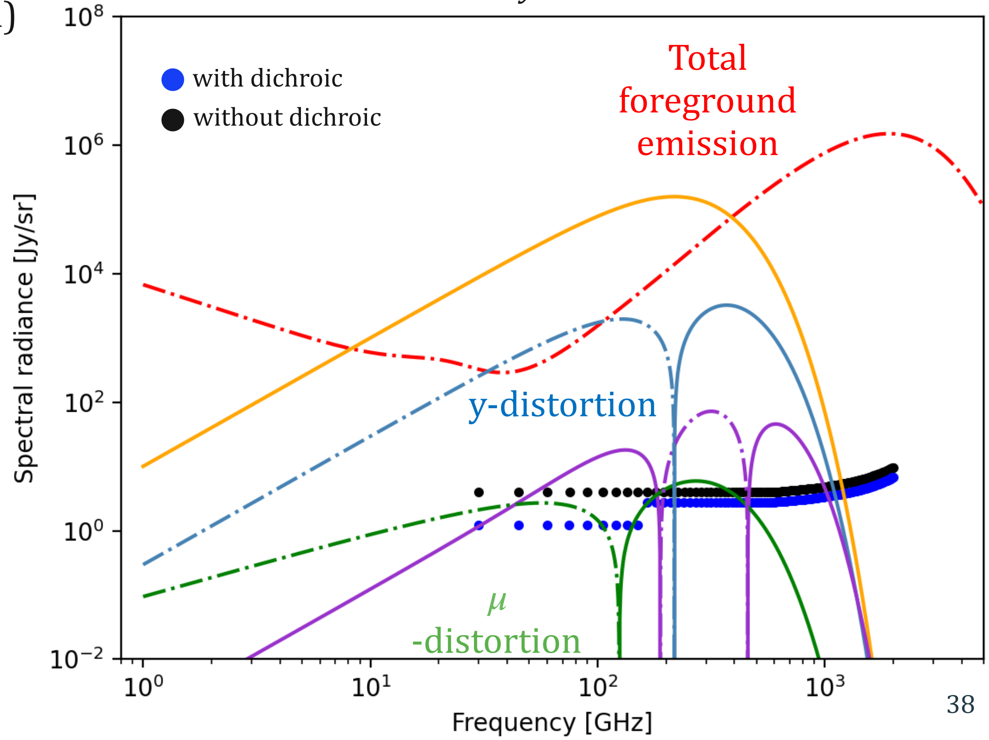
What can be done from a space ?

→ answer to ESA M7-call (N. Aghanim & B. Maffei)



FOSSIL IDM scheme

Sensitivity estimations



4

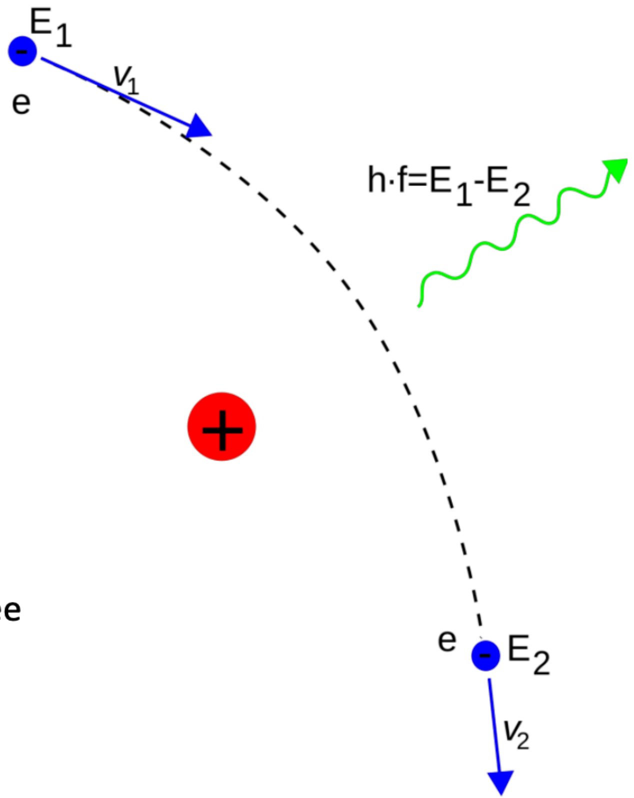
Instrument development

Annexes

Rayonnement continue de freinage ou **Bremsstrahlung**

Rayonnement électromagnétique créer par la décélération d'une particule chargée par une autre particule chargée.

sources : ICM, région HII



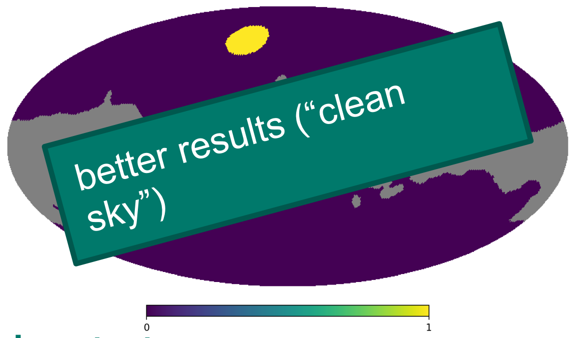
Rayonnement synchrotron

Rayonnement électromagnétique émis par une particule chargée se déplaçant dans un champs magnétique et dont la trajectoire est déviée par ce champ

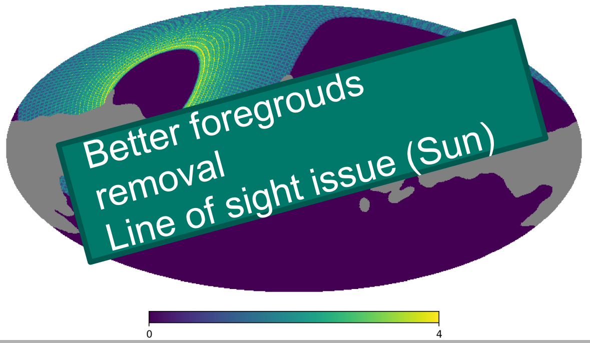
sources : Champs magnétique de la Galaxie, …

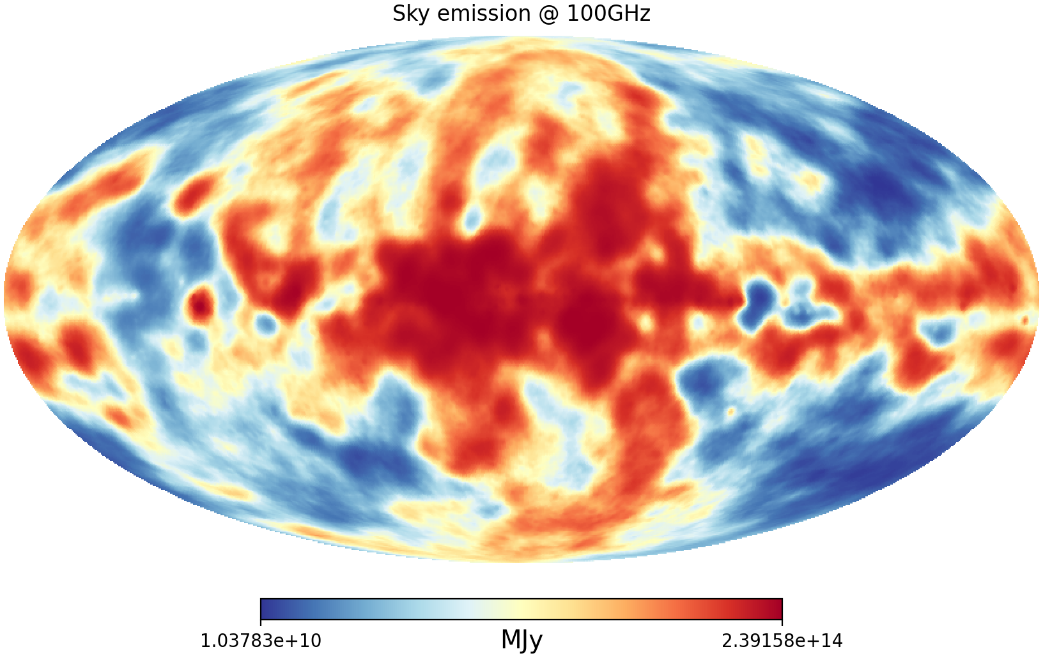
Scanning strategy

- **Raster strategy :**

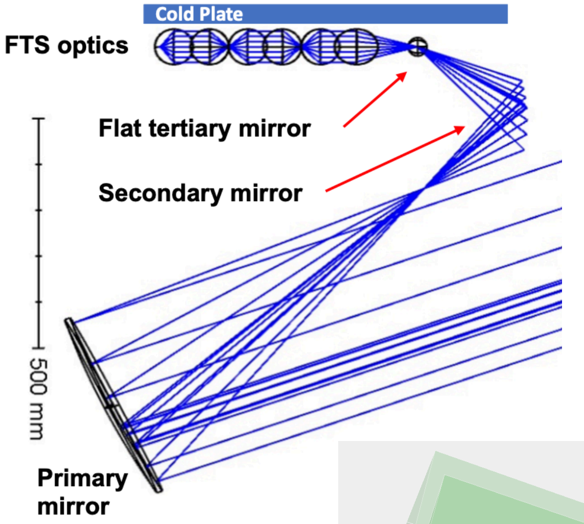


- **Scanning strategy**

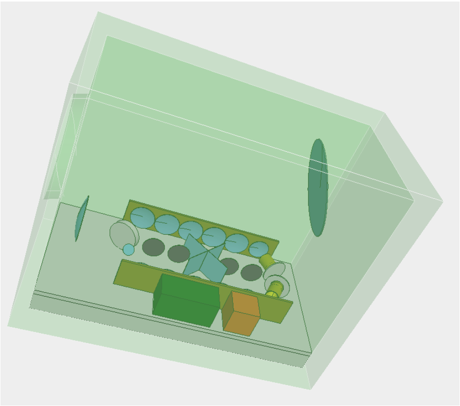




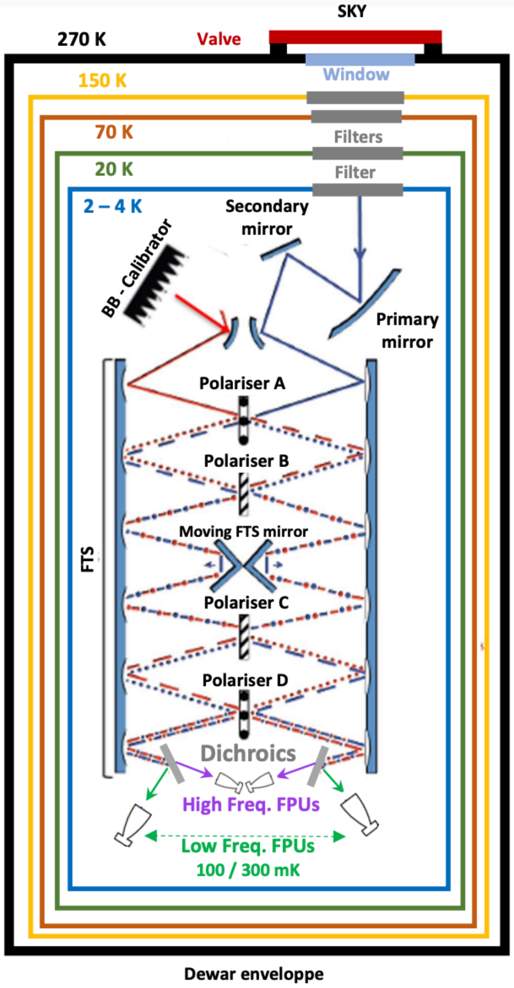
Preliminary scheme



Optical design



IDM scheme



Evolution and trade-offs :

- 250-270K
- whole instrement cold
- thin window

(low emissivity)

- one telescope

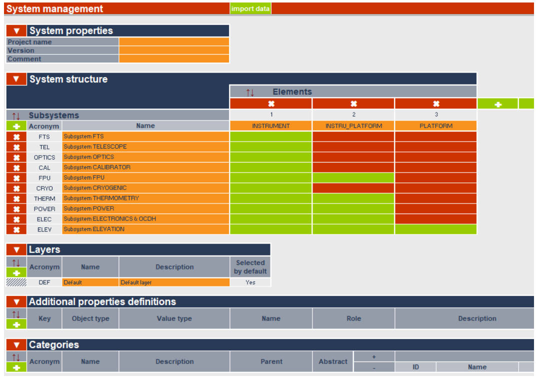
(unbalance optics, effect ?)

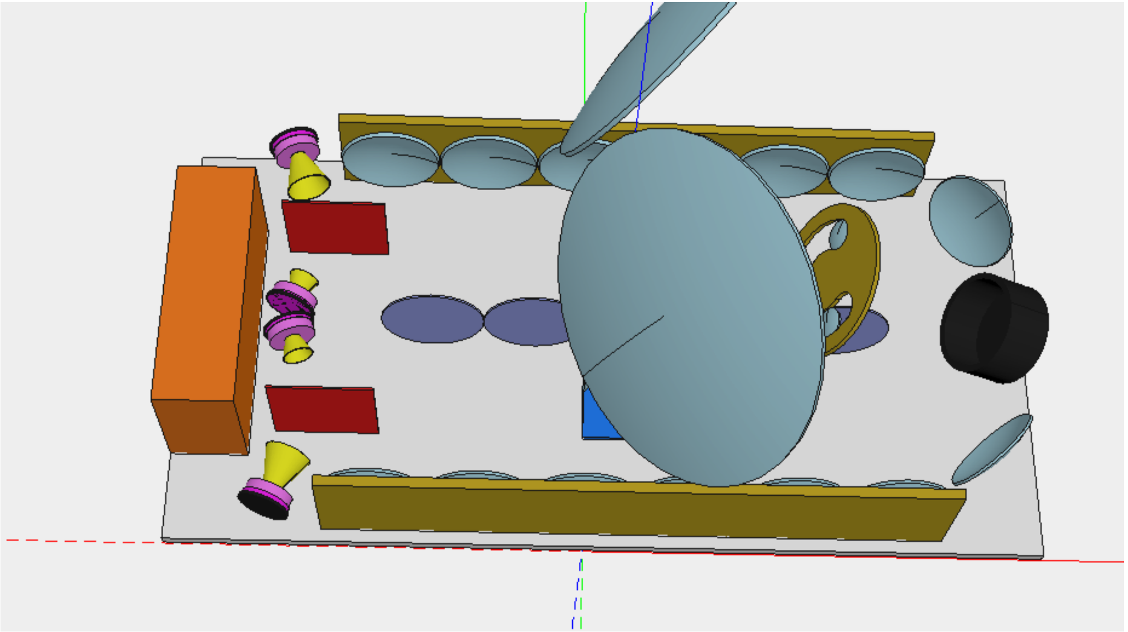
- raster scan
- need to split detection in 2 sub-bands
- could include more detectors

Instrument development: 3D model

IDM-CIC :

- sub-system management
- mass and power budget
- simplified 3D
- parametric model





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Future work

Short term :

- develop code giving accessible sky given time and position for balloon missions
- optimize the observing strategy BISOU end of phase 0 / phase A proposal
  → specifications needed for CNES balloon division
- switch from Fisher to MCMC forecast

Longer term :

- participation R&T window (BISOU)
  → test definition and development / measurement and analysis
- simulate interferogram data from sky and instrument models
  → forecast instrument performance from mock data
  → development of data analysis method base on simulation
- analysis of systematic effects
  → study case BISOU : constraint on pointing accuracy and stability and scanning speed
  → Study beam shape effect
- develop user interface for the sky and instrument simulation code

Mission context

COBE/FIRAS measures CMB intensity spectrum:

- sets the only existing limits on spectral distortions in 1992

CNES SPS (2019) / **ESA Voyage 2050** (2021) / Astronet (2021)

↳ Large ESA mission horizon 2040-2050

Projects:

- **PIXIE** (2016): NASA led MIDEx (A. Kogut)
- **PRISTINE** (2018): answer to ESA F1 call (N. Aghanim)
- **FOSSIL** (2022): answer to ESA M7-call (N. Aghanim & B. Maffei)
- **BISOU** (2020 - ...): CNES phase 0 (B.Maffei)
- **COSMO** : ground experiment at Dome C (Antarctic)
- **TMS** : ground experiment at Teide Observatory (Tenerife)

Foreground modeling

Foregrounds:

Galactic

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

Extragalactic

- Cosmic Infrared Background (CIB)
- Cumulative CO

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

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

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

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

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

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

$$\Delta I_{ZS}(\nu) = \epsilon_{ZS} \frac{2h\nu^3}{(e^{\frac{h\nu}{kT_{ZS}}} - 1)}.$$

CMB spectral distortions

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

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

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

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

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

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

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