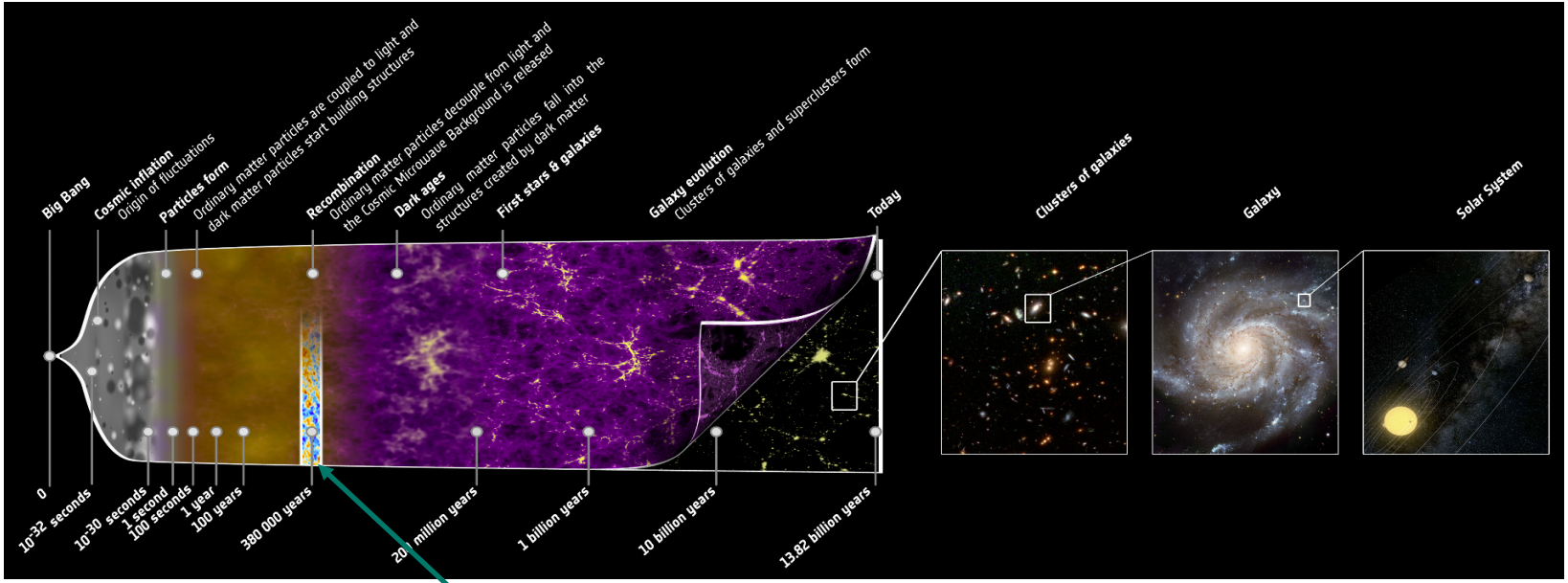
Towards Instruments Measuring Spectral Distortions of the CMB

Xavier COULON
Supervisors:
B. Maffei & N. Aghanim
29/06/2023

A (very) short history of our Universe

~13.8 Gyr



Courtesy of ESA - C. Carreau

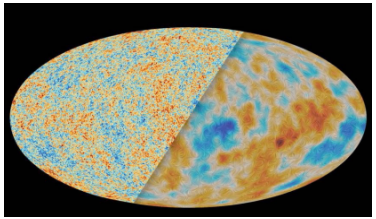
Very hot universe T > 3000K
Opaque Plasma

$T \sim 3000K$ Recombinaison
Universe becomes transparent
Last scattering surface → CMB

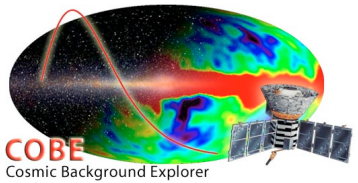
CMB seen today as a perfect blackbody at $T = 2.726K$

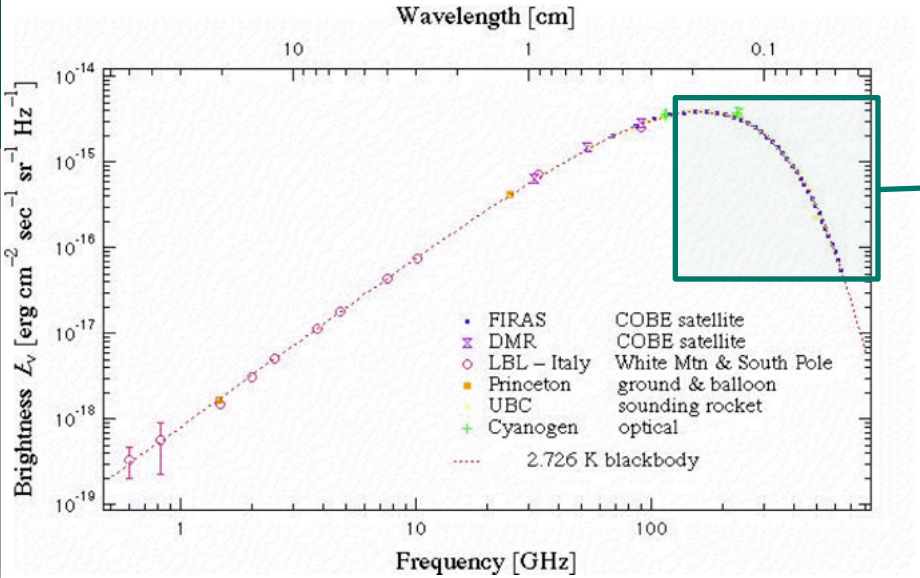
Cosmic Microwave Background

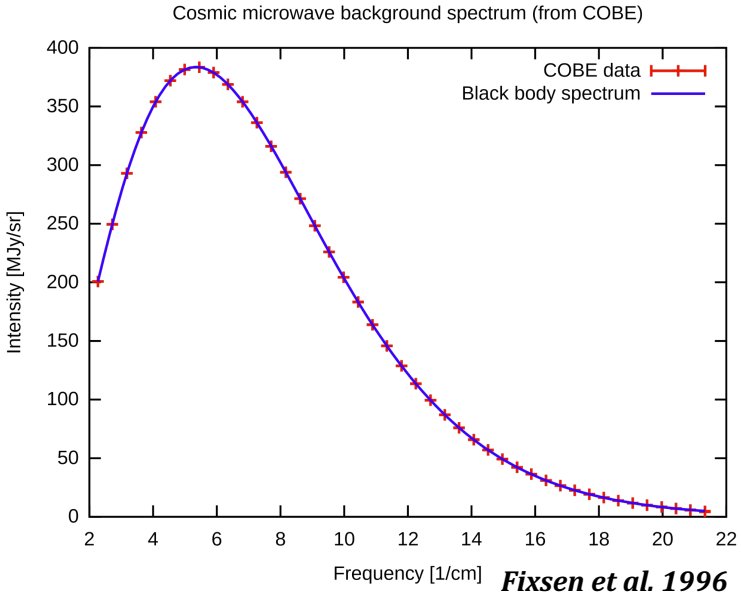
Planck



- Hot **big-bang** scenario
  → CMB with blackbody spectrum





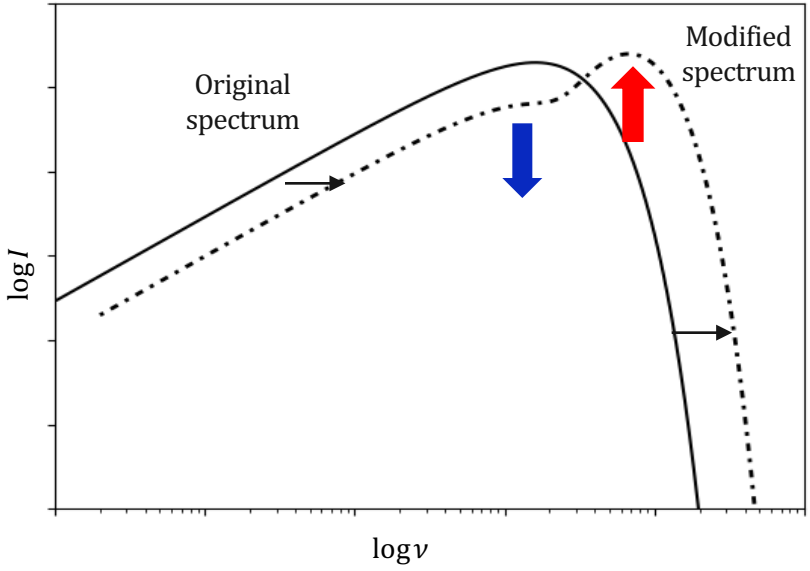


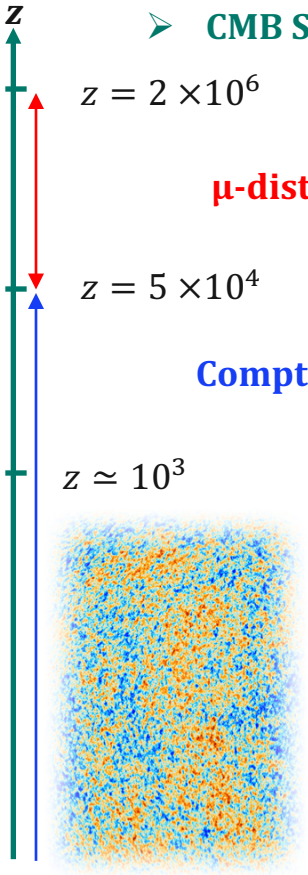
Fixsen et al. 1996

CMB Spectral Distortions

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

Blackbody distortion proportional to energy release





- **CMB Spectral distortions**

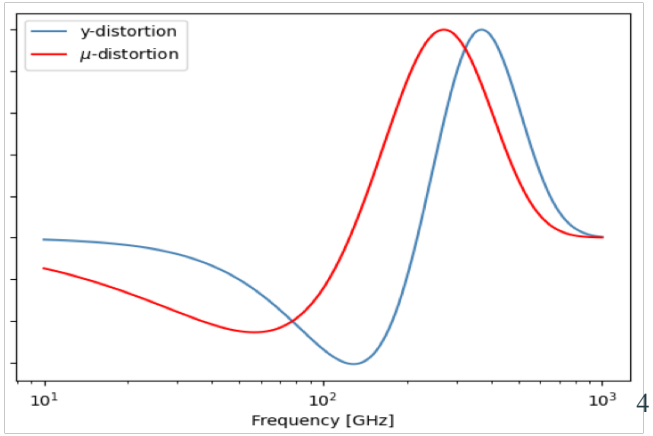
$z = 2 \times 10^6$

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 frequency relevant for CMB spectral distortion measurement

2

Instrumental model considering both photometric and mission parameters

3

- to do forecasts
- to optimisation of the instrument concept
- to study systematic effect

4

Instrument development

Sky model

1

Sky model: Foreground emissions

Foregrounds:

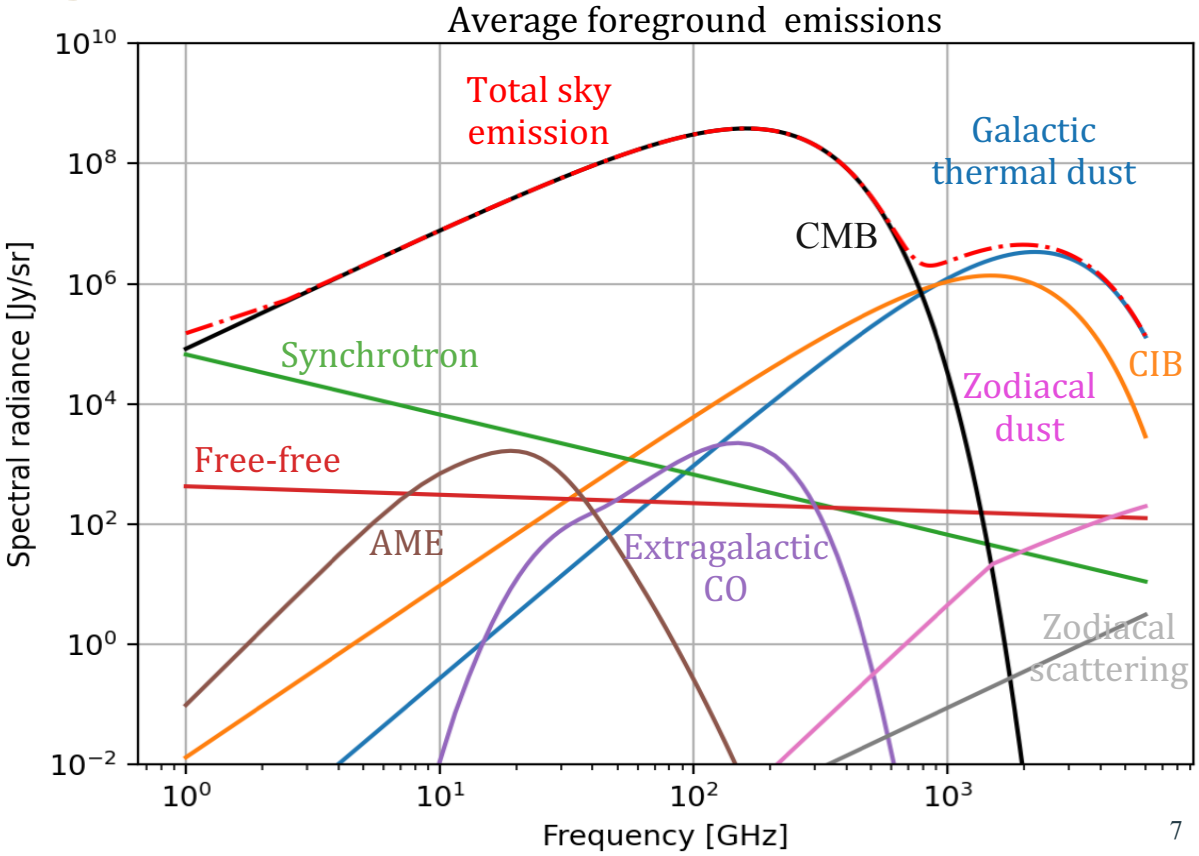
Galactic

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

Extragalactic

- Cosmic Infrared Background (CIB)
- Cumulative CO

Adapetd from Abitbol+ 2017
Planck Collaboration, 2014
Zonca+ 2021 (PySM)

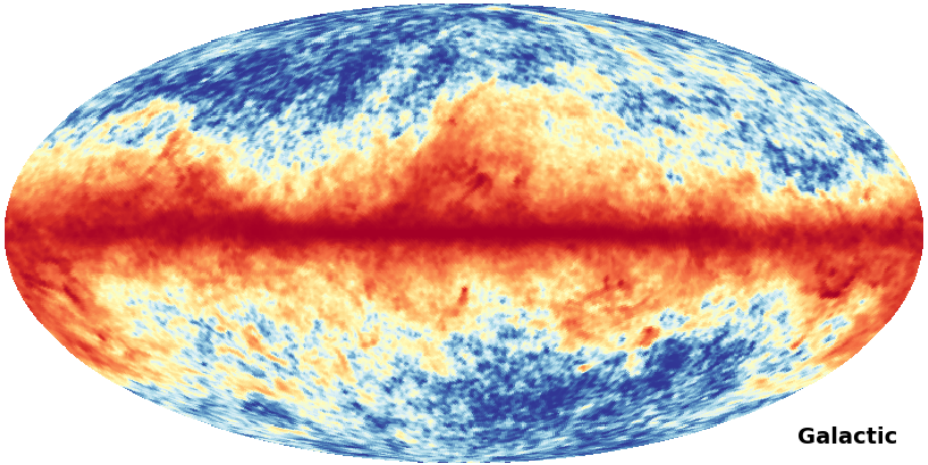


Sky model: spatially varying foregrounds

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

Python Sky Model maps (PySM) :

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



Total Sky emission at 300GHz

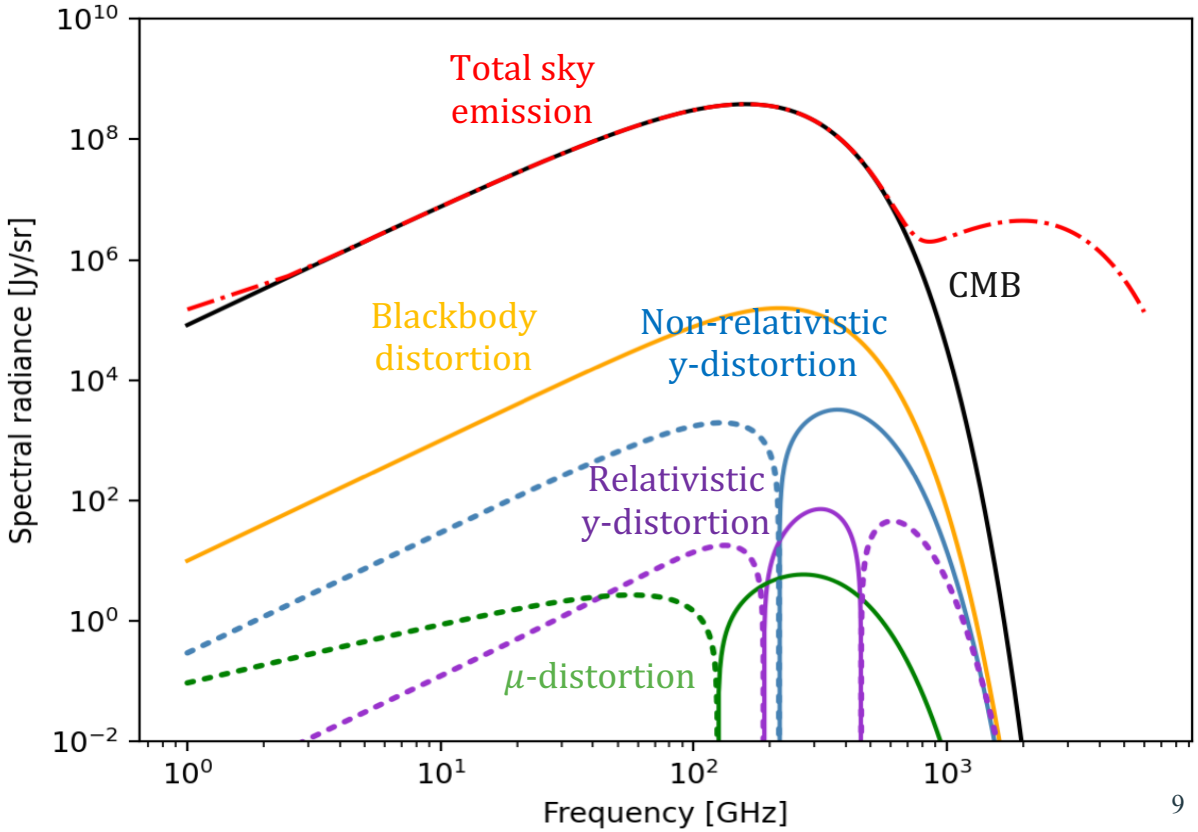
Sky model: CMB spectral distortion

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

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

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

Abitbol+ 2017



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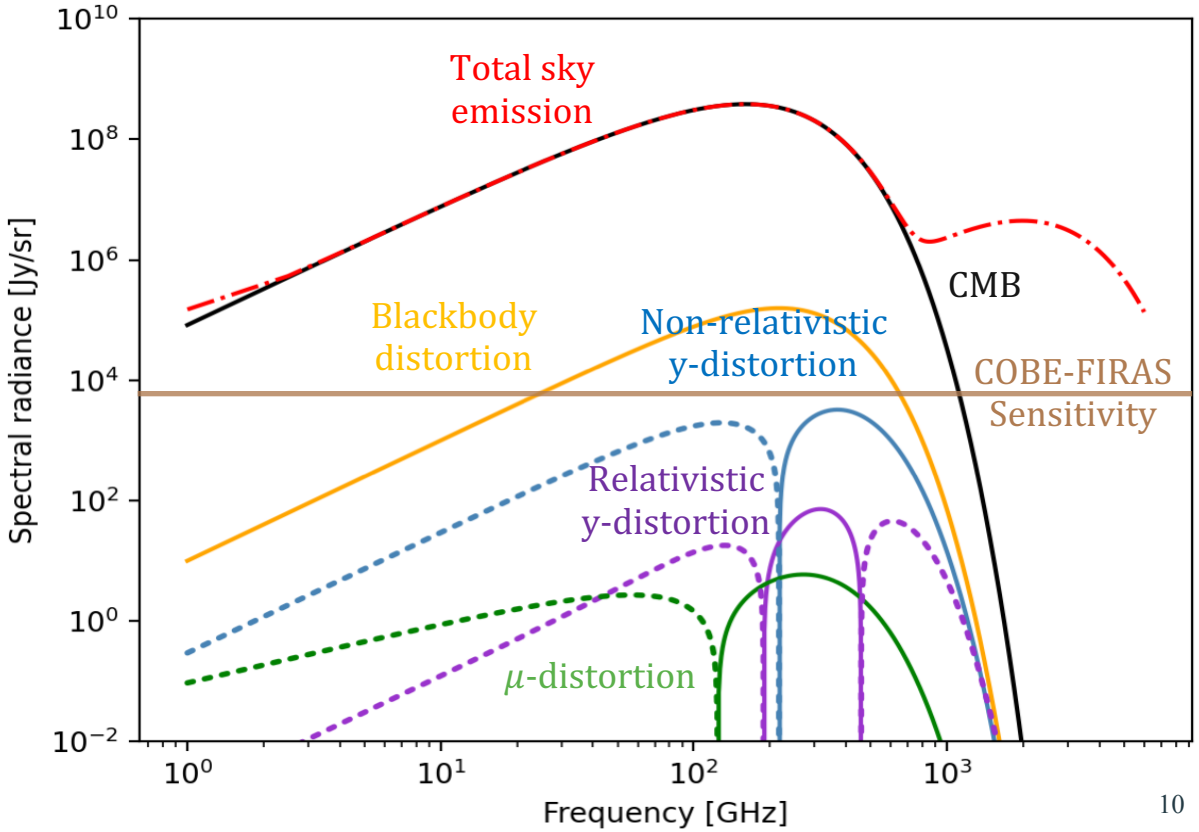
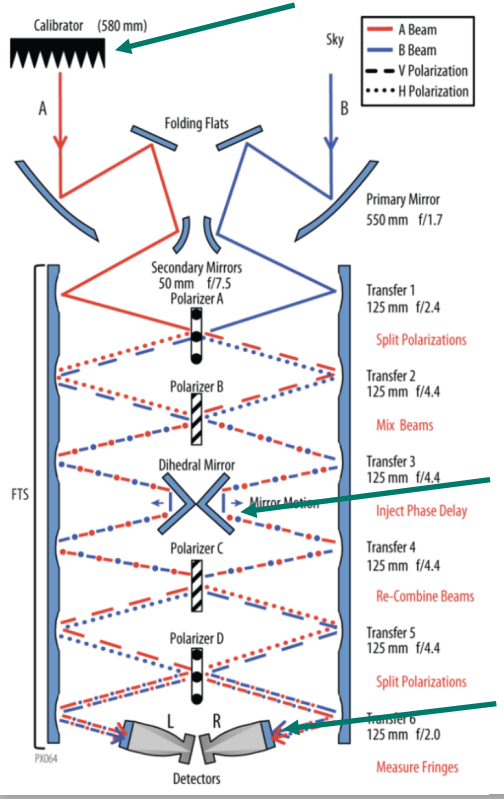


Instrumental model

2

Instrument model: concept

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



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

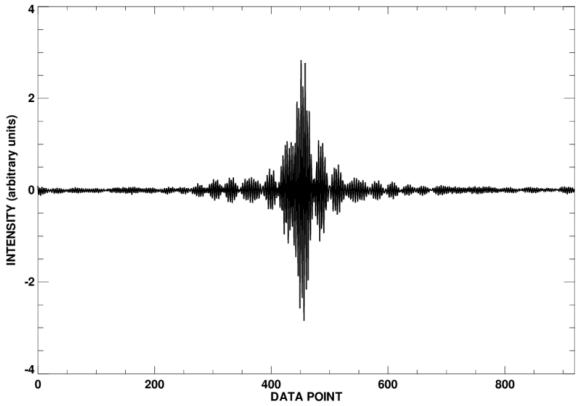
Fourier Transform Spectrometer (FTS)
2 inputs (sky & calibrator)

FTS scanning mirror
for interferogram

Detectors at each
output of the FTS

Differential measurement between
the sky and the calibrator

FTS interferogram

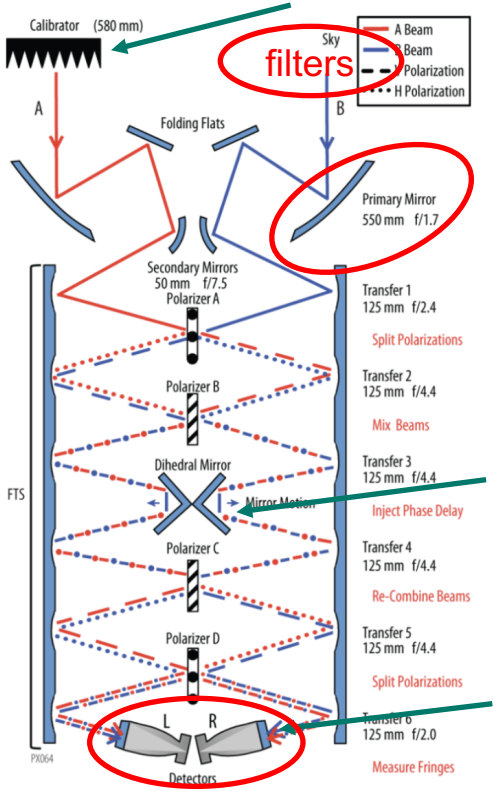


Instrument model: model photometric

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

: optical components modelled in photometric model

+ key mission parameters (duration, scanning strategy,...)



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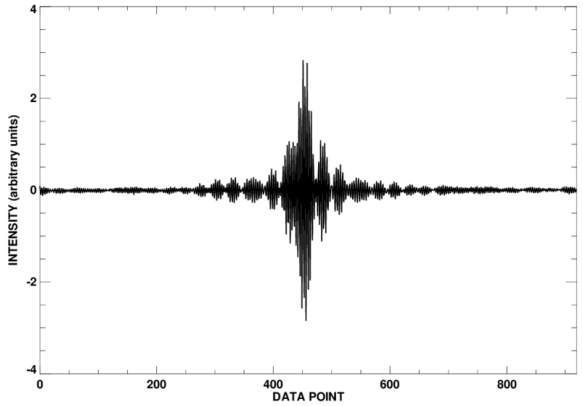

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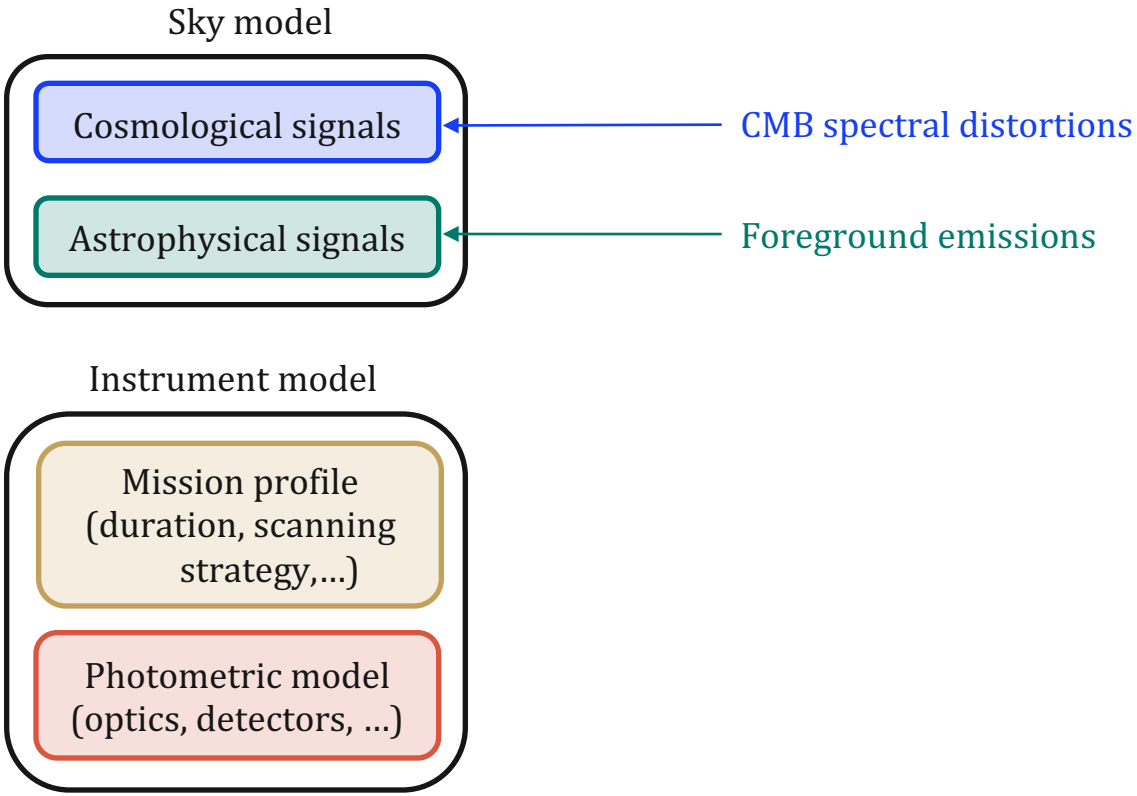
Performance and forecasts

Optimization of the instrument concept



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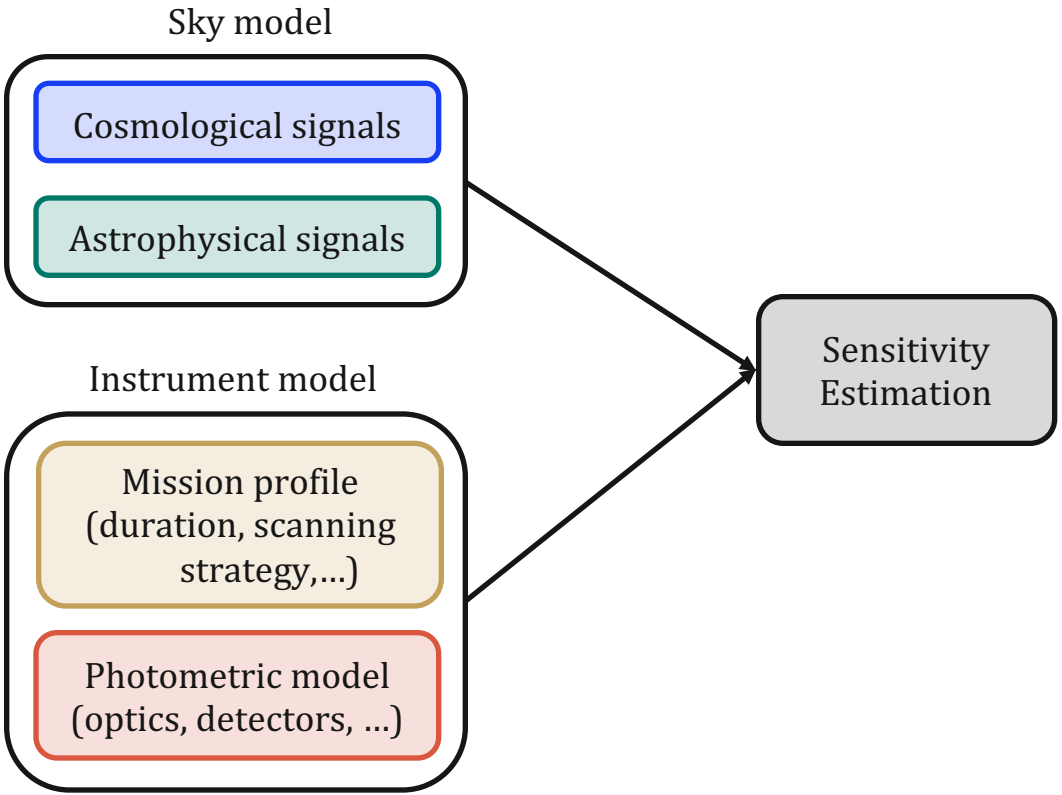
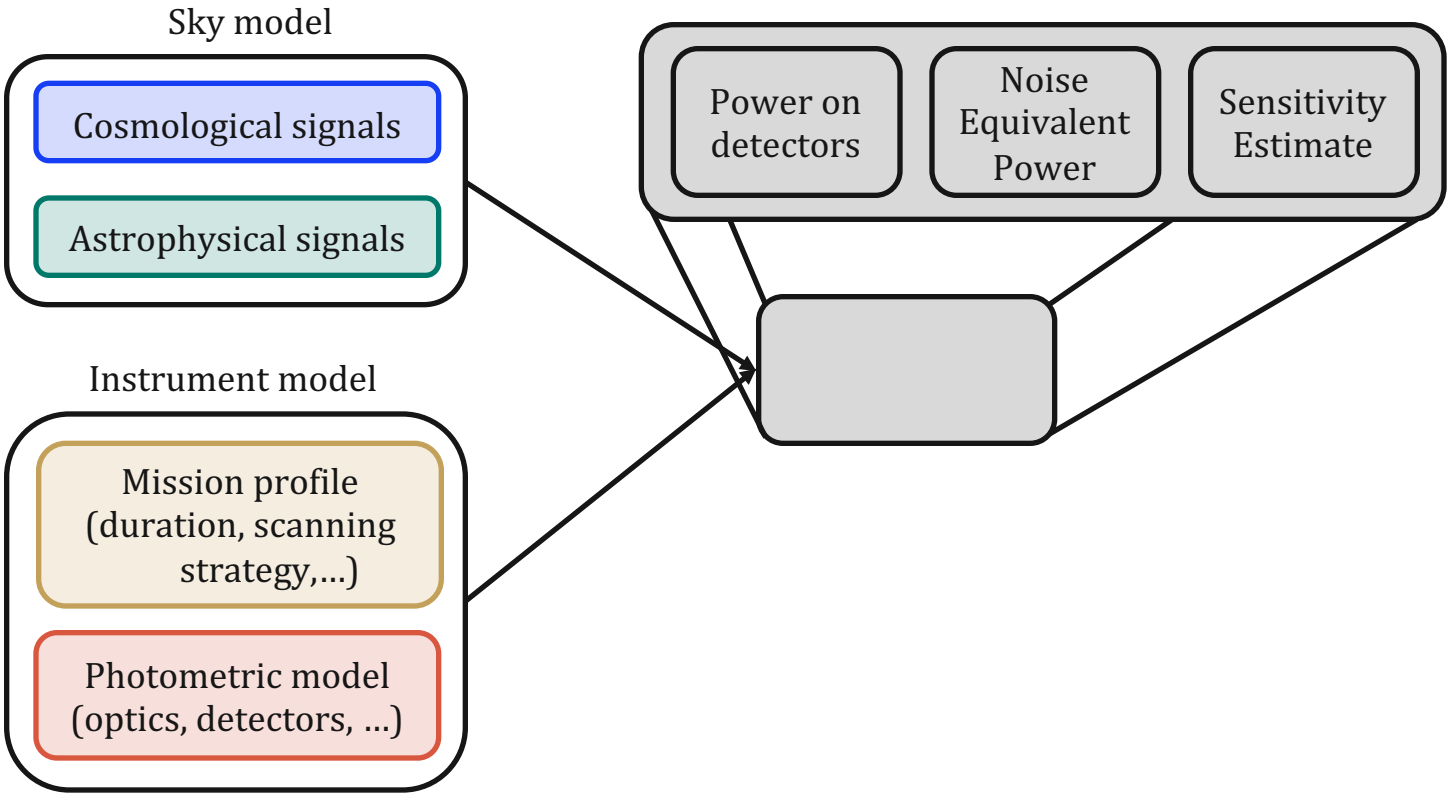


Optimization of the instrument concept



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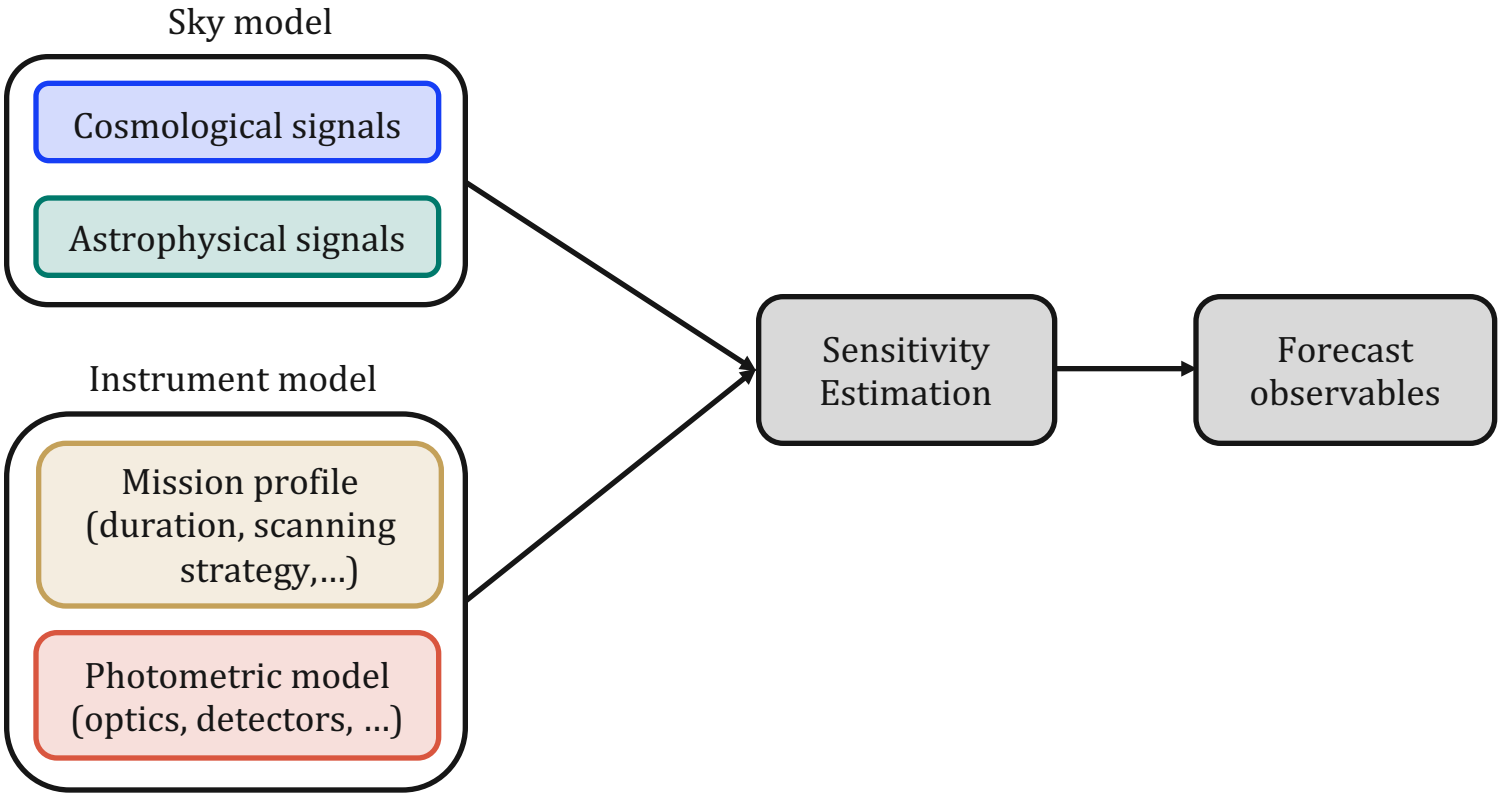

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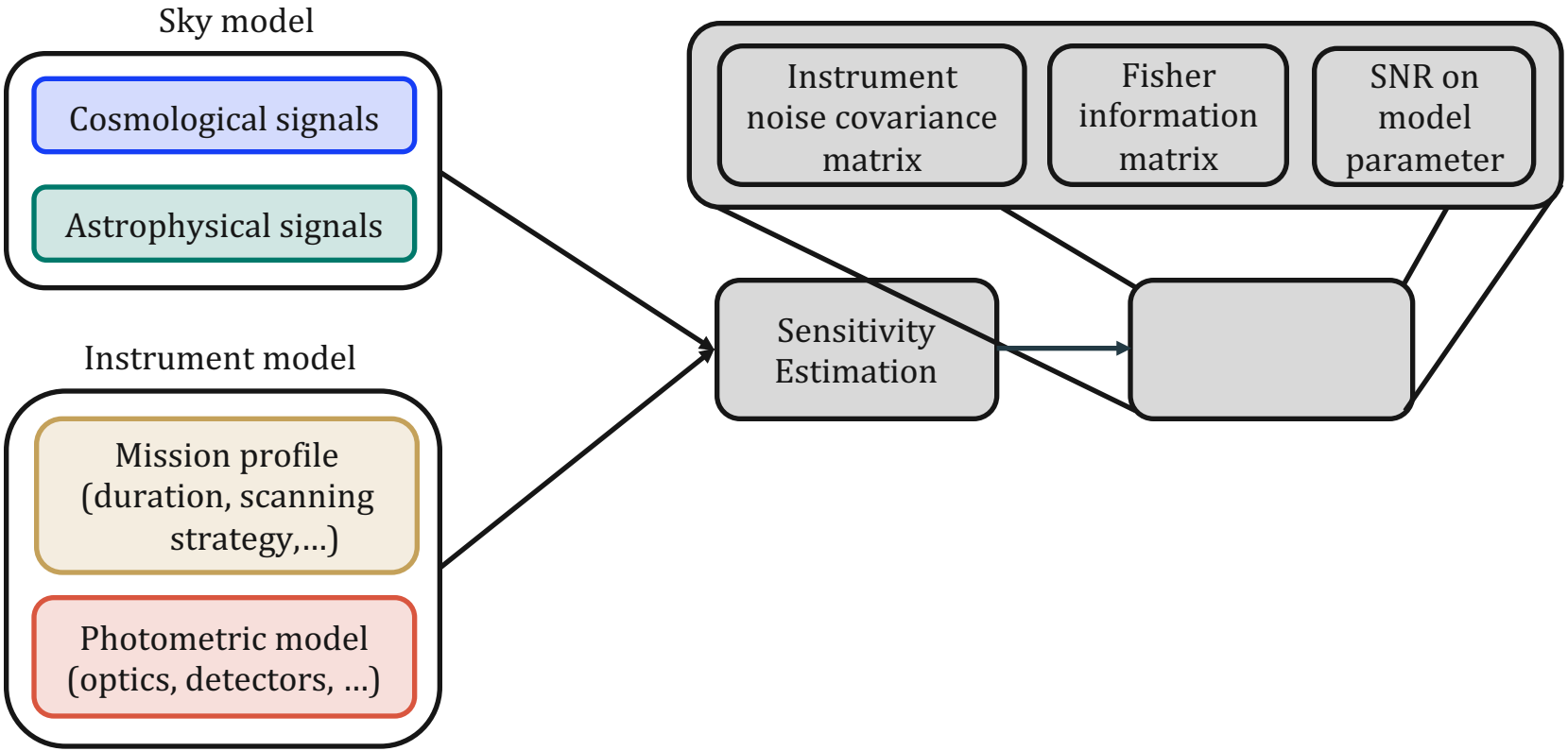

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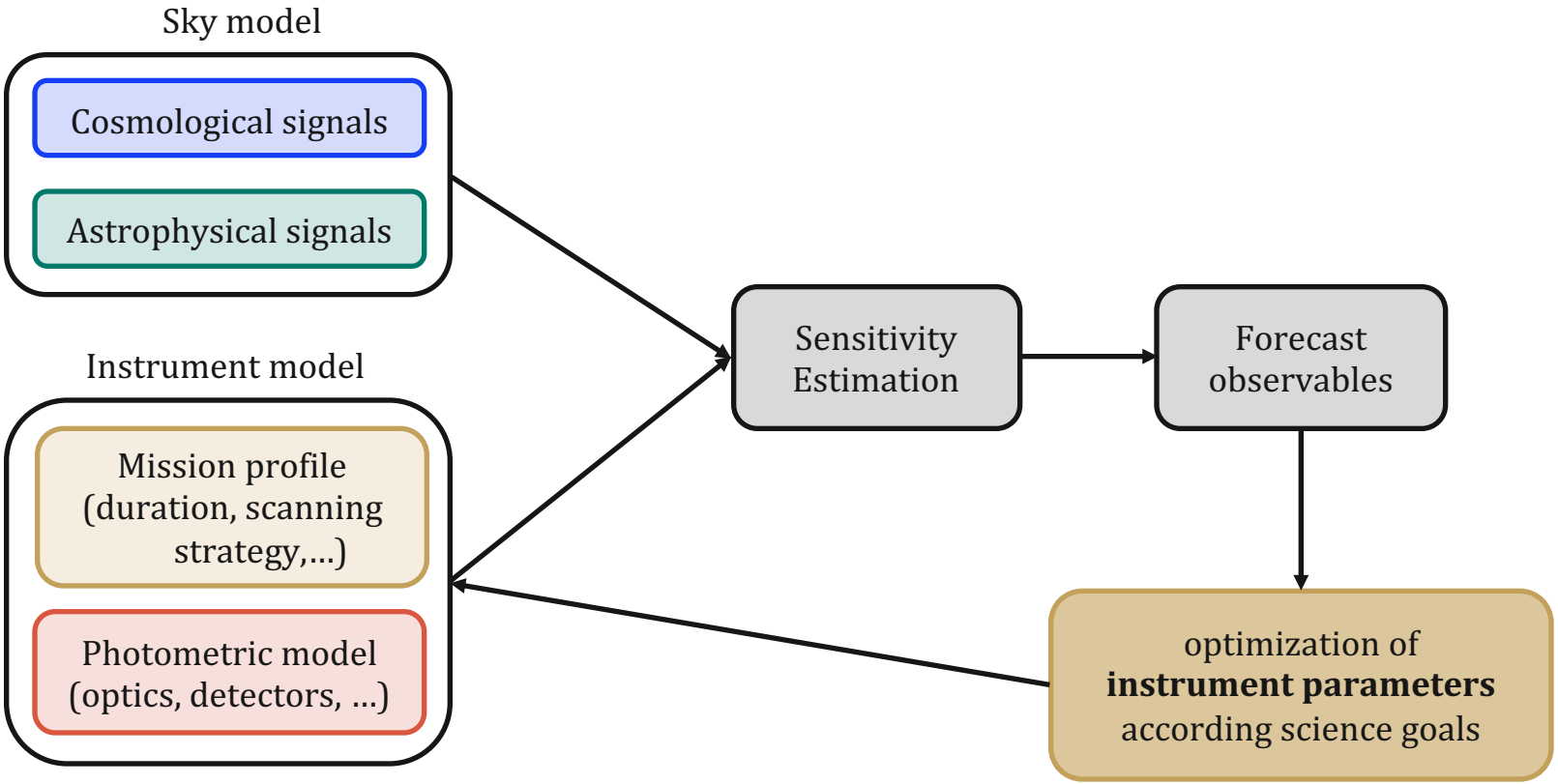

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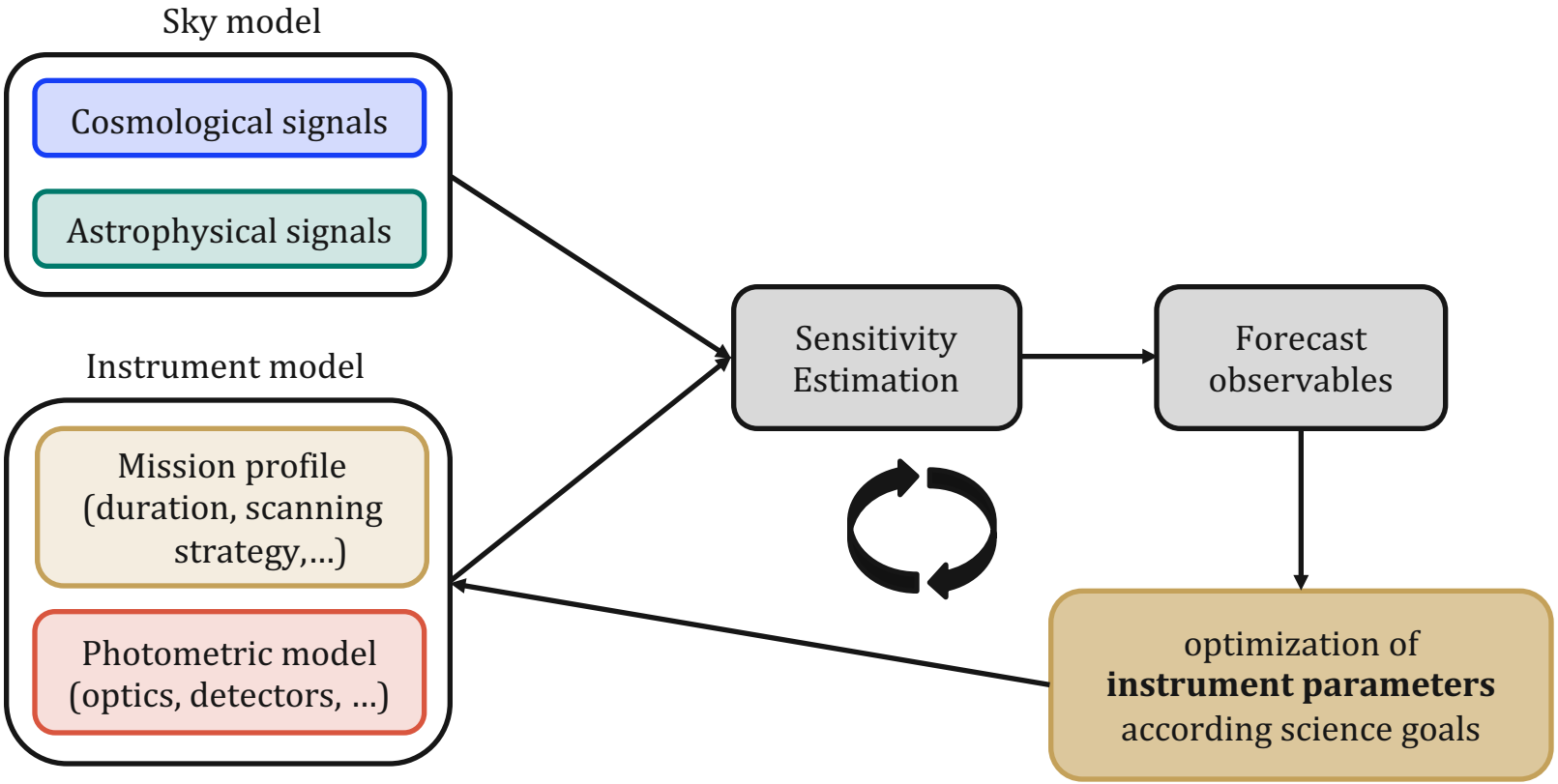
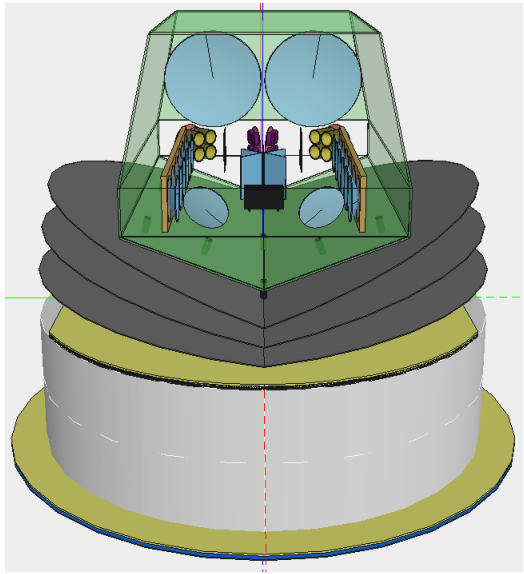


Application cases

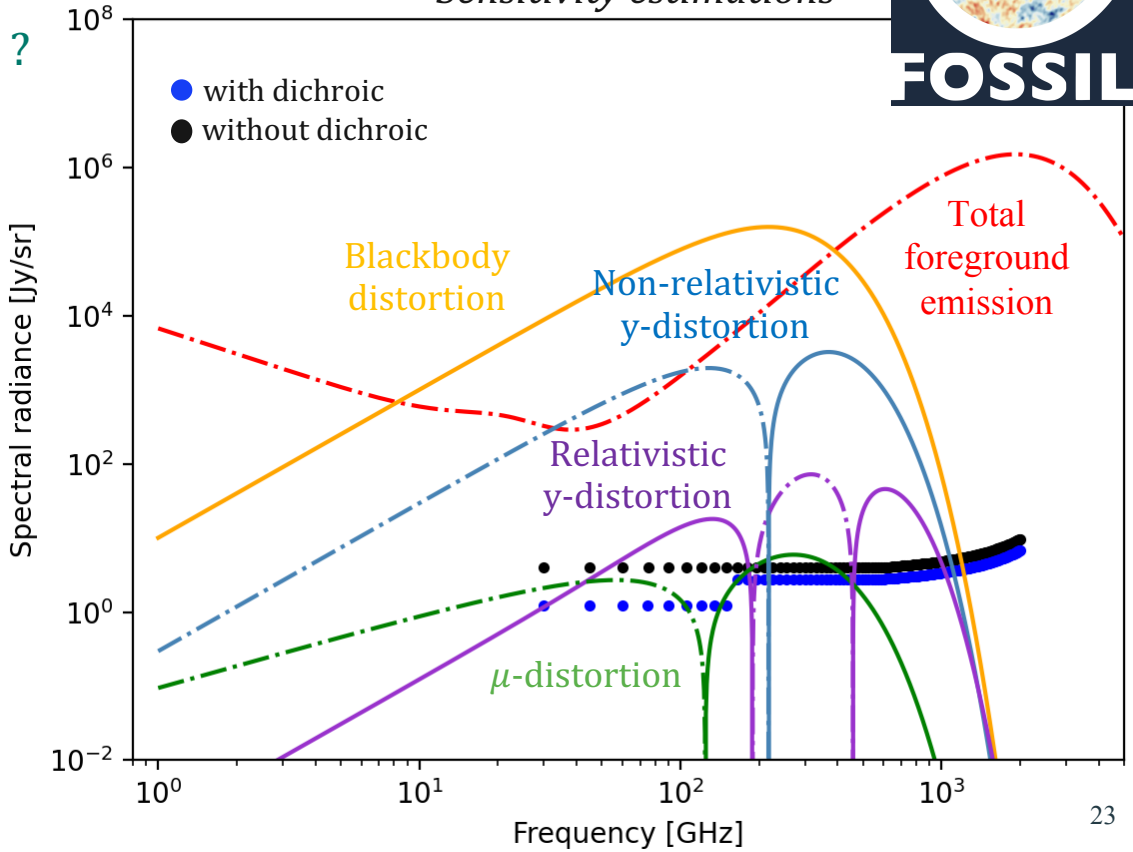
Application case : FOSSIL

What can be done from a space ?
→ answer to ESA M7- call
(N. Aghanim & B. Maffei)



FOSSIL scheme

Sensitivity estimations



Application case : BISOU

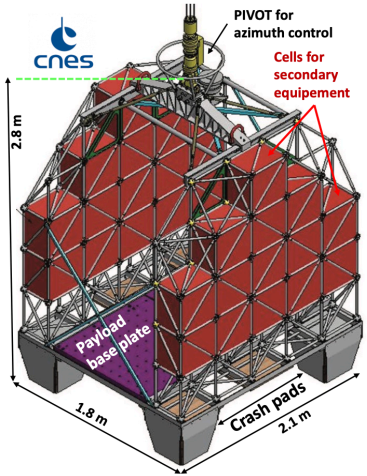
Maffei+ 2021

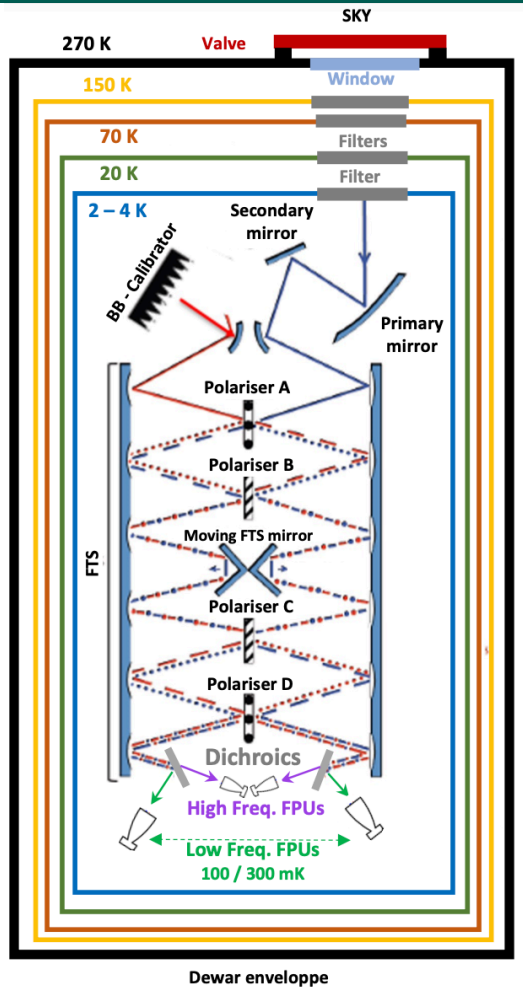
What can be done from a balloon ?
→ CNES phase 0 study

Balloon Interferometer for Spectral Observation of the Universe (B.Maffei)

Balloon constraint:

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



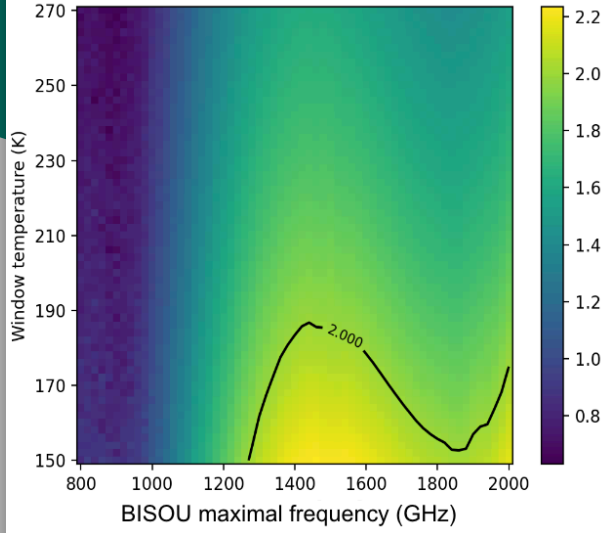


Application case : BISOU

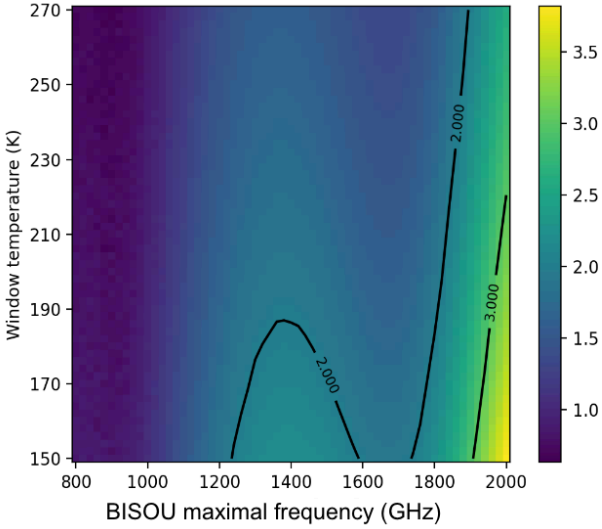
Grid exploration considering: actively cooled window / varying the maximum frequency

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

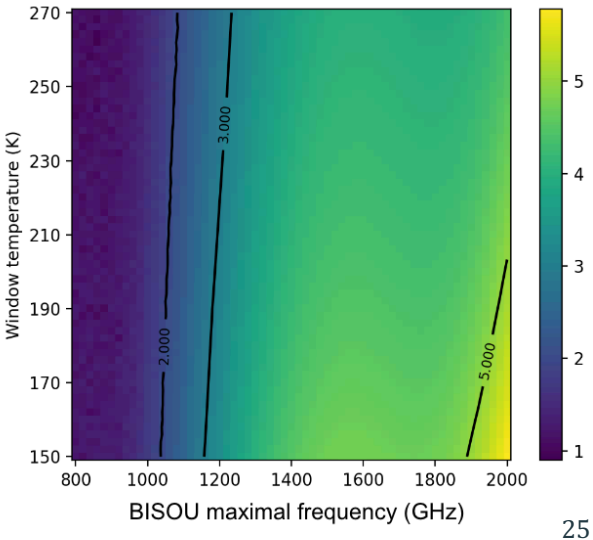
High emissivity window + tapered filtering



Low emissivity window

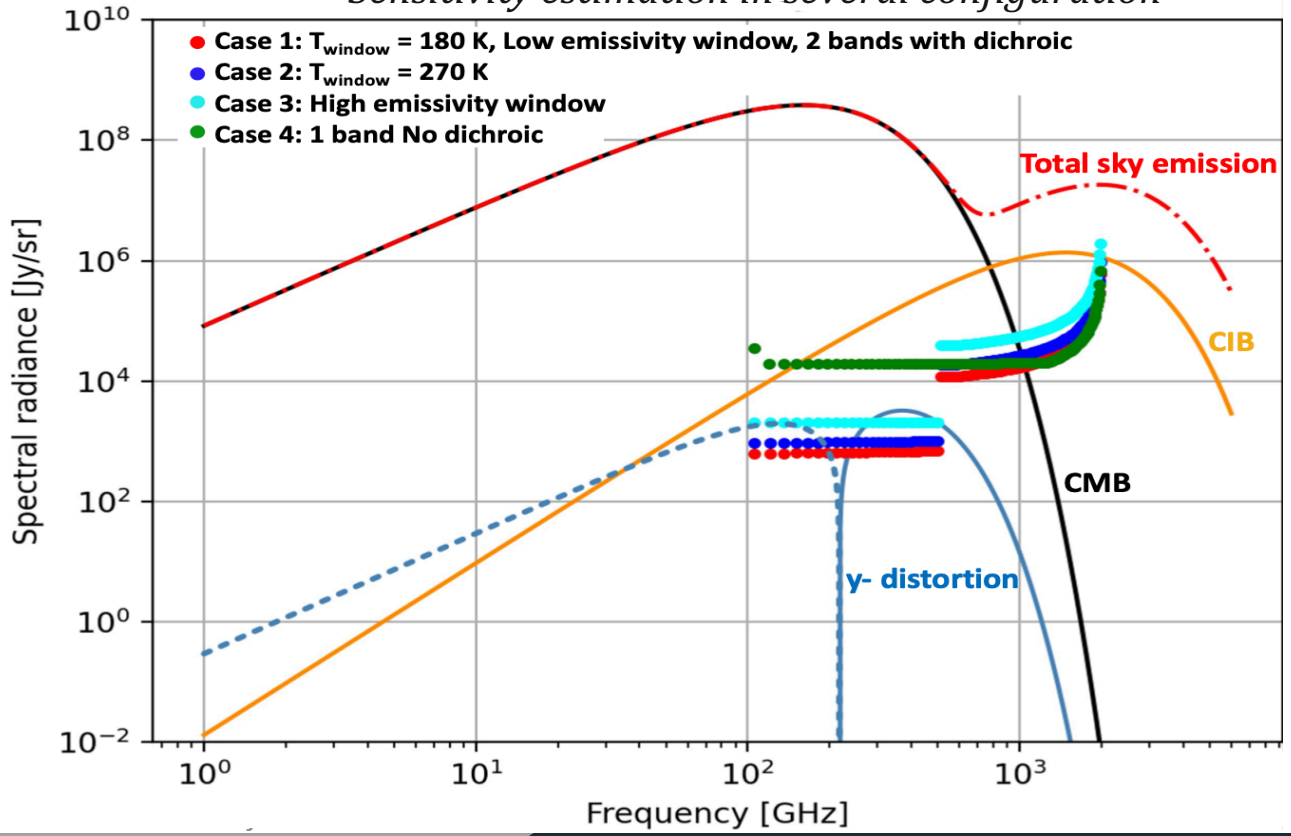


Low emissivity window + dichroic



Application case : BISOU

Sensitivity estimation in several configuration

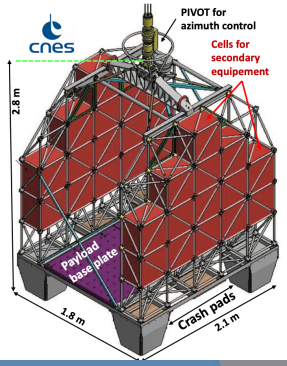


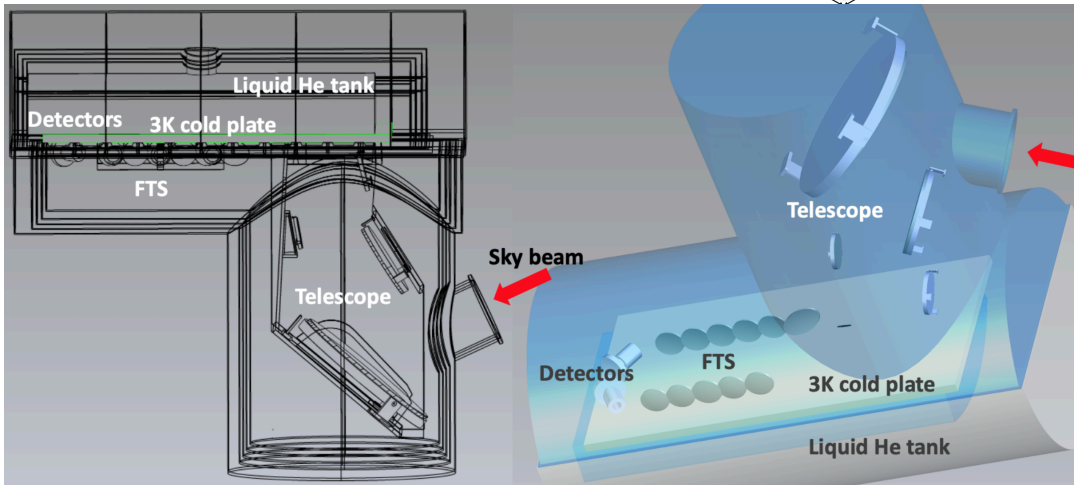
Application case : BISOU

What can be done from a balloon ?

→ CNES phase 0 study

Balloon Interferometer for Spectral Observation of the Universe (BISOU)





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

Application case : Forecasts

Targeting the first measurement of CMB spectral distortions

→ upper limits by COBE/FIRAS

$|y| < 15\times10^{-6}$

$|\mu| < 47\times10^{-6}$

	y	μ	A_{CIB}
BISOU (SNR in σ)	5.6		2.8
FOSSIL (SNR in σ)	186	1	76

→ improvement over COBE/FIRAS

$\times 20$ in balloon configuration

$\times\ few$ 100 in space configuration

Take away

- CMB spectral distortions are a unique probe to access to the full history of the Universe

  → several ground experiment on-going (COSMO, TMS) targeting the first measurement of CMB spectral distortions

- Future large space ESA mission in 2050

  → need a pathfinder to increased the maturity of the instrument concept

  → prepare future generation to work on such project and data

Annexe

Mission context

2019 - CNES SPS:

- "… à long terme, la **mesure des distorsions du spectre du fond diffus** deviendra prioritaire"

2021 – ESA Voyage 2050

- Following 2 white papers:
  - Chluba et al., "New horizons in cosmology with spectral distortions of the cosmic microwave background"
  - Delabrouille et al., "Microwave spectro-polarimetry of matter and radiation across space and time"
- New physical probes of the early Universe and **high precision spectroscopy of CMB** is one of the 3 selected themes for the large missions

2021 – ASTRONET

- identifies spectral distortions as one of the priority probes

Application case : Forecasts

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	y	kT_{eSZ}	μ	A_{CIB}
BISOU (SNR in σ)	5.6			2.8
FOSSIL (SNR in σ)	186	37	1	76
BISOU (n ×FIRAS)	21			
FOSSIL (n ×FIRAS)	~600		~350	

Mission context

COBE-FIRAS measures CMB intensity spectrum:

- sets the only existing limits on spectral distortions in 1992

IAS contribution to proposal:

- **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)

Others project:

- COSMO: ground experiment at Dome C (Antarctic)
- TMS: ground experiment at Teide Observatory (Tenerife)

↳ Large mission horizon 2040-2050

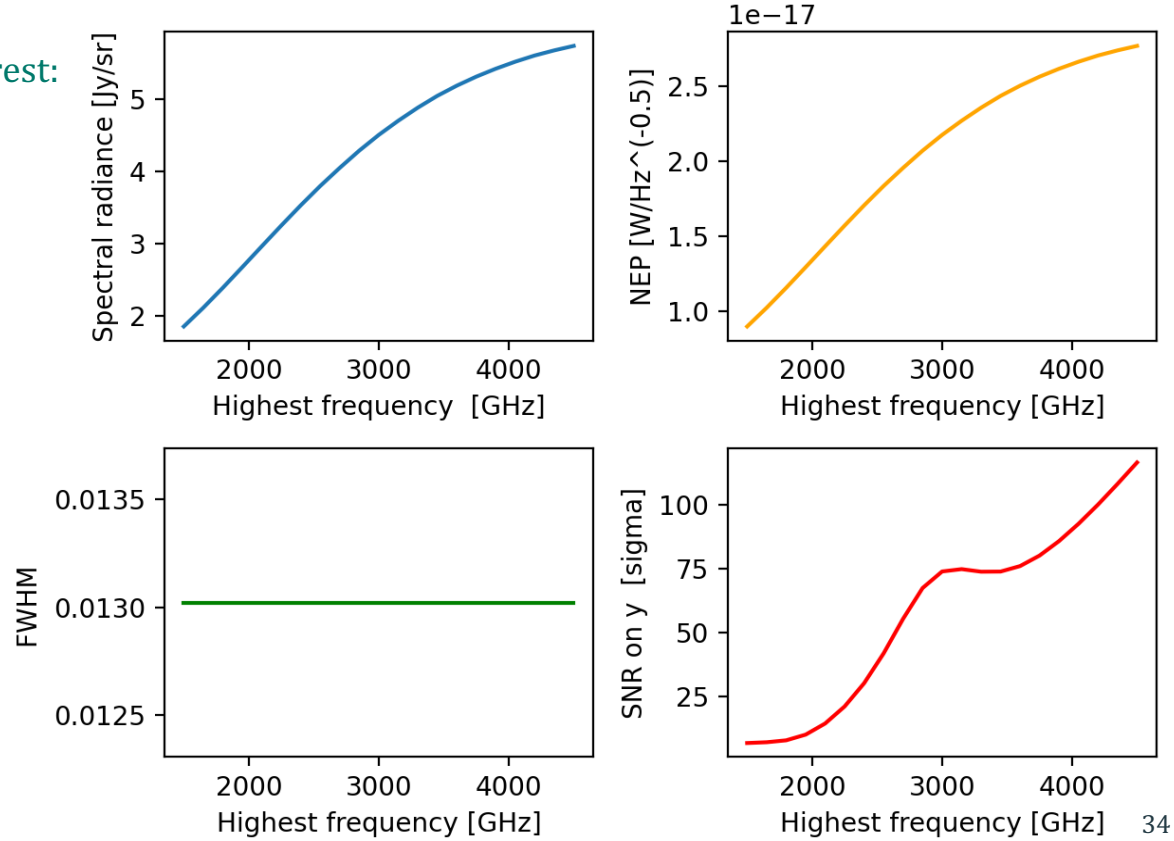
Example of instrument concept optimization

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



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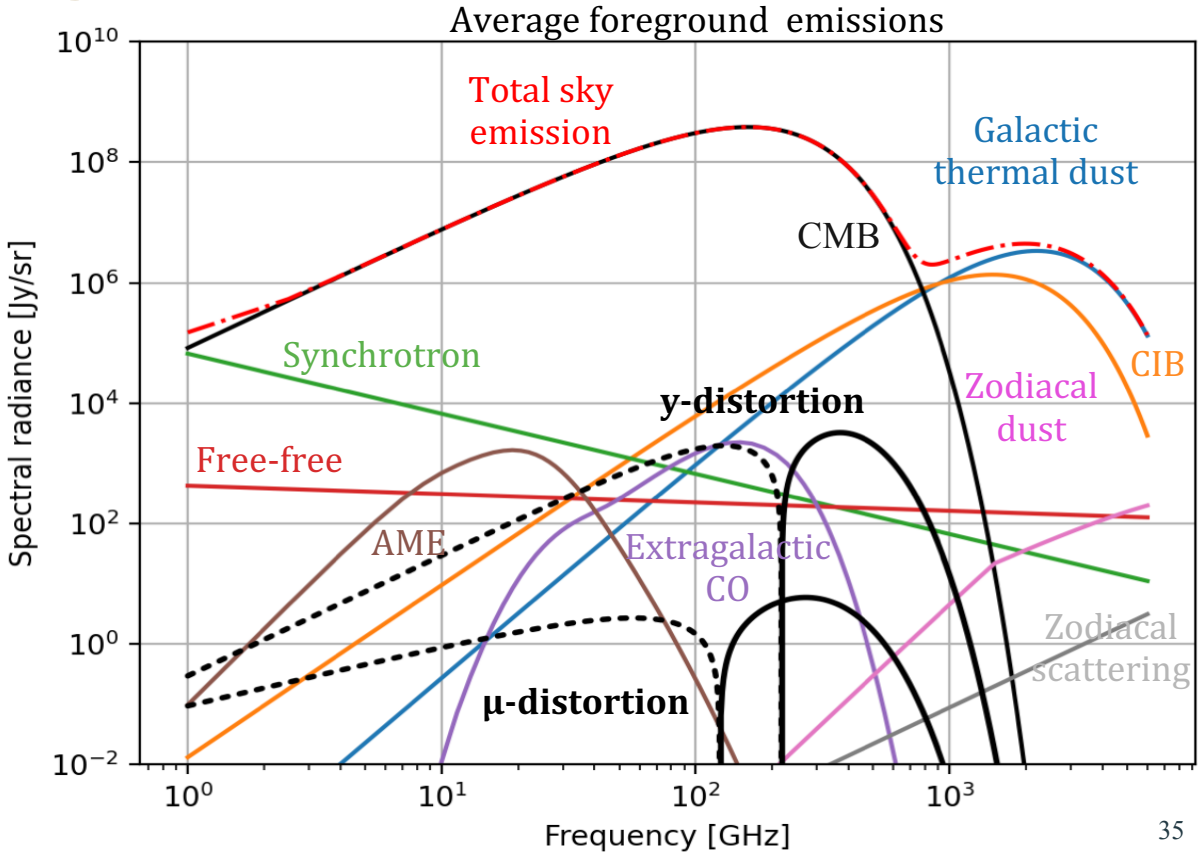

Instrument model: optics model

Each optical elements are define by :

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