CMB-France#7 2025

Optimisation and Forecasting Studies for CMB Spectral Distortion Experiments

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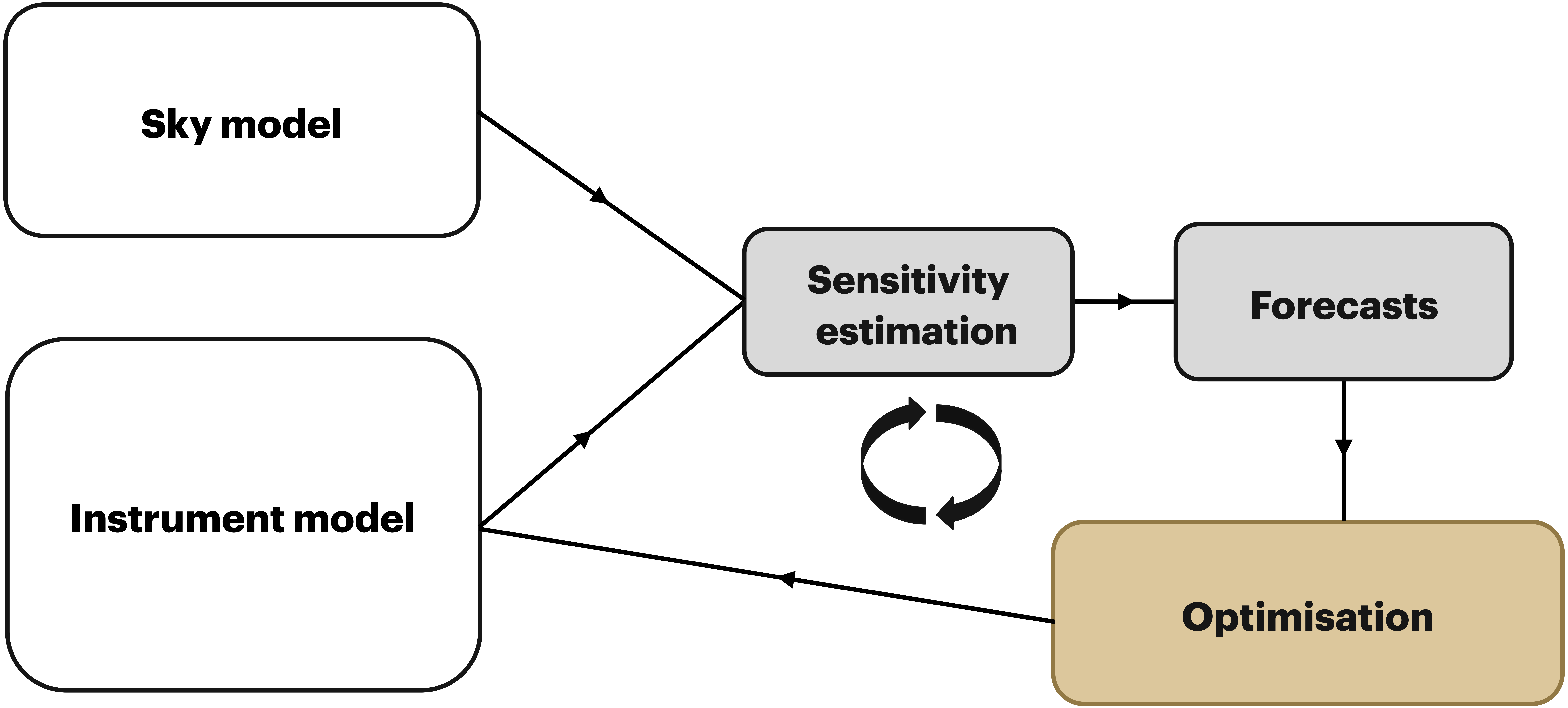
N.AGHANIM

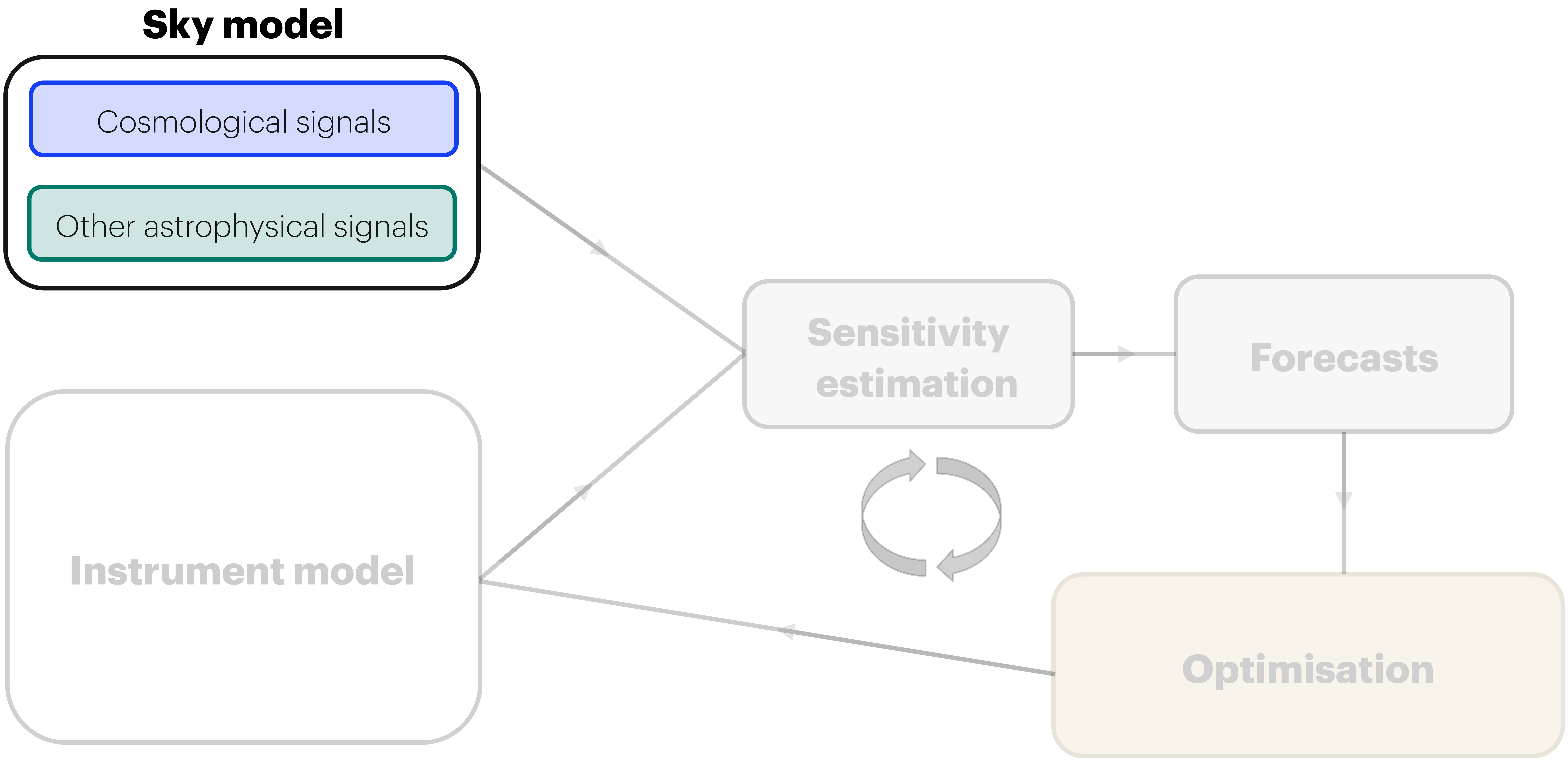
B.MAFFEI

14th of October, 2025

My work - Method



Method - Sky model

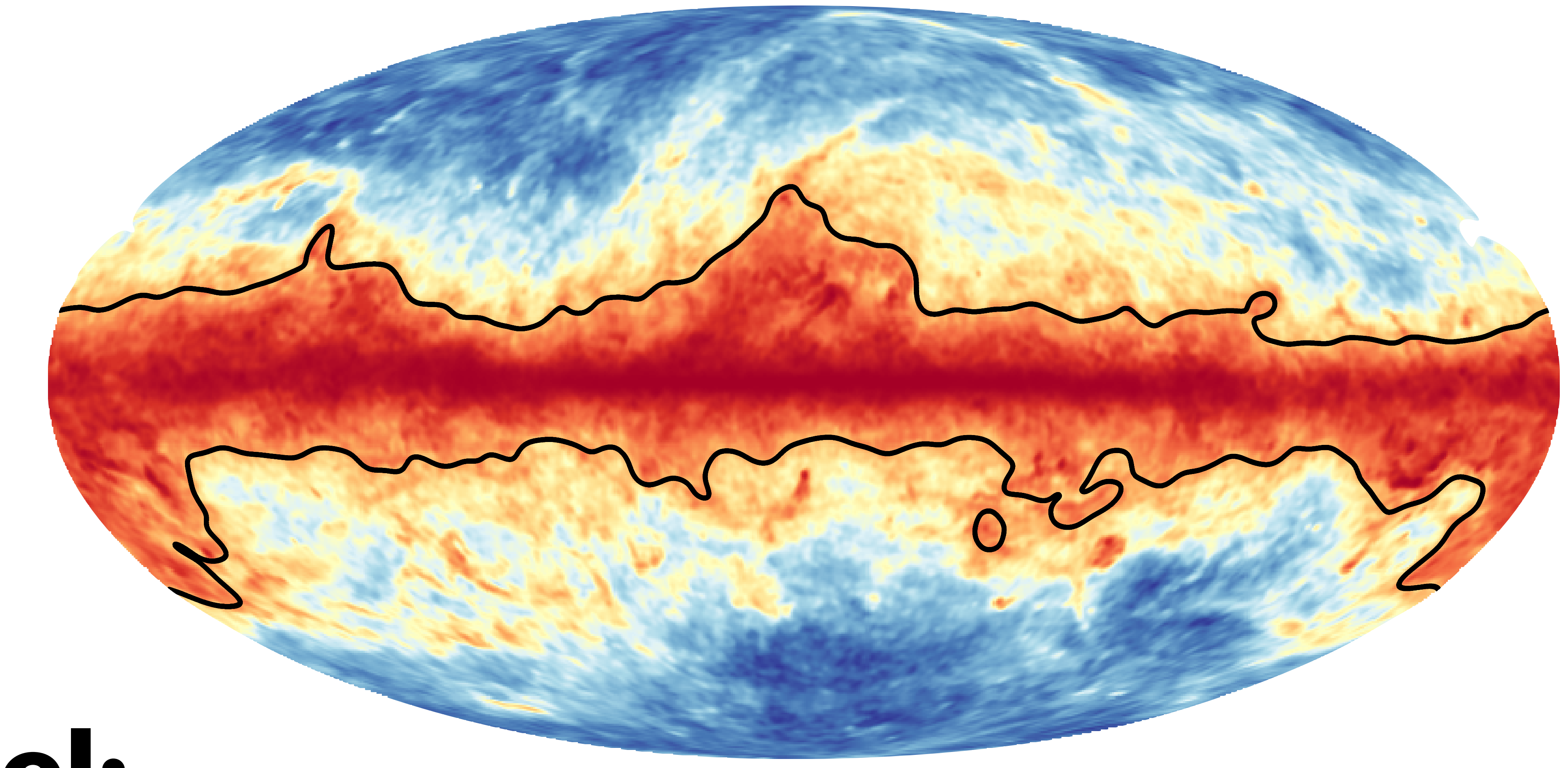


Sky model - State of the art

For CMB spectral distorsions studies/forecasts:

- Average foreground emission over 70% of the sky
  - In particular for missions PIXIE and PRISTINE

Abitbol+2017



More realistic forecasts through a new sky model:

- A more realistic sky model for future experiments (FOSSIL, BISOU)
  - with **spacially varying foregrounds**

Sky model - Sky maps

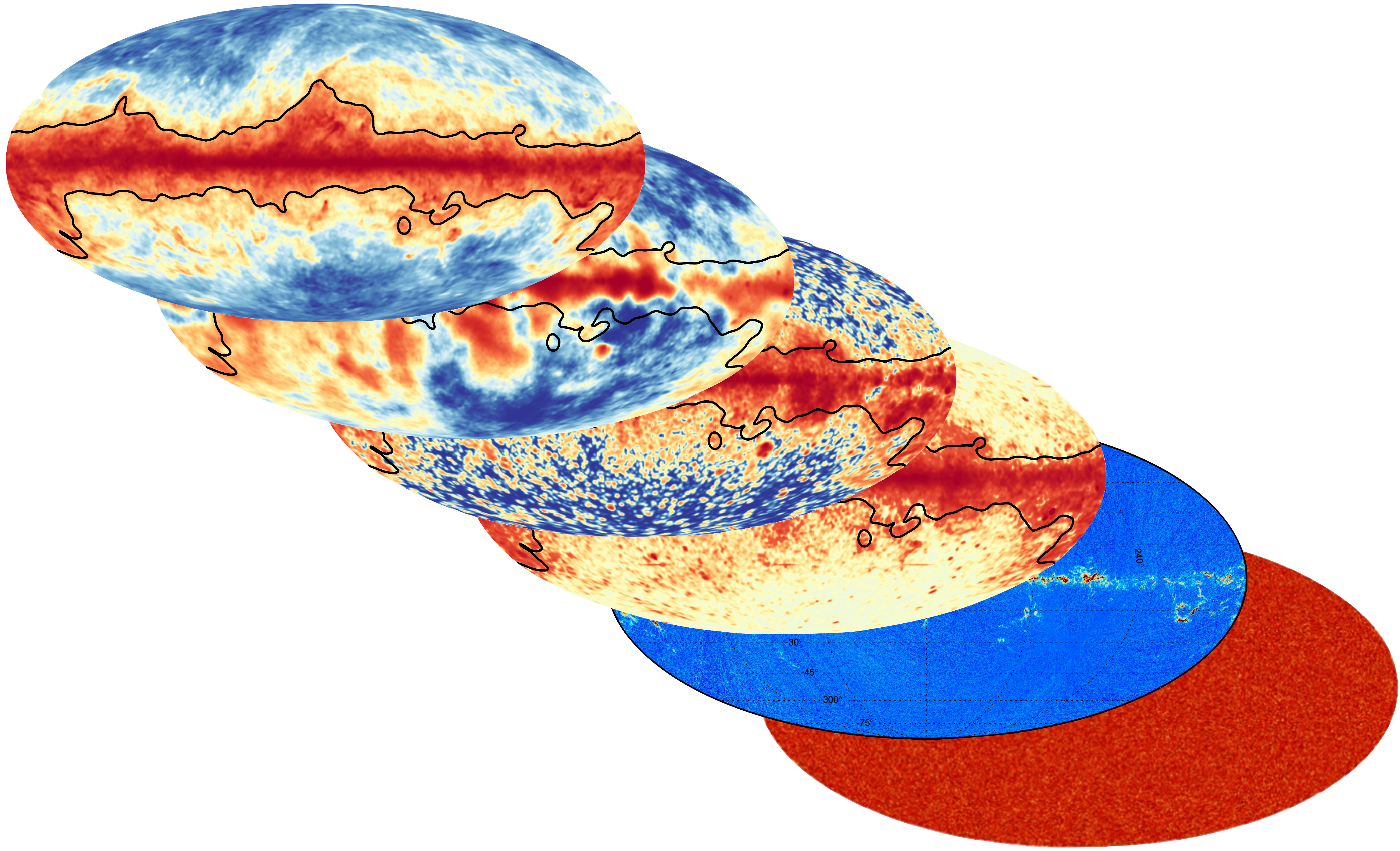
- **Galactic** (PySM3) *Zonca+2012, Thorne+2017*
  - **Thermal dust** ("d1" model)
  - **Synchrotron** ("s1" model)
  - **Free-free** ("f1" model)
  - **Anomalous Microwave Emission (AME)** ("a1" model)

- **CMB** (moment expansion model) *Chluba+2017*
  - **CMB temperature difference**
  - **y-distortion monopole**
  - **Relativistic y-distortion**
  - **μ-distortion monopole**

only **ΛCDM** sources

- **Extragalactic** *PlanckCollab+2014, Mashian+2016*
  - **Cosmic Infrared Background (CIB)** (modified blackbody)
  - **Extragalactic CO lines emission** (Mashian+2016 model)

- **Zodiacal** *PlanckCollab+2014*
  - **Thermal zodiacal dust** (modified blackbody)
  - **Zodiacal scattering** (modified blackbody)



Sky model - Parameters

Foregrounds	Model	Parameters
Galactic dust	Modified blackbody	A_d, T_d, β_d
Synchrotron	Power law	A_s, β_s, C_s
Free-free	Power law	$A_{ff}, \beta_{ff}, C_{ff}$
AME	Power law	$A_1^{ame}, \nu_1, A_2^{ame}$
CIB	Modified blackbody	$A_{cib}, T_{cib}, \beta_{cib}$
Extragalactic CO lines	Template (Mashian+2016)	A_{CO}
Zodiacal dust	Modified blackbody	$\epsilon_{th}(\nu), T_{th}, \beta_{th}$
Zodiacal scattering	Modified blackbody	$\epsilon_{sc}, T_{sc}, \beta_{sc}$

CMB	Model	Parameters
CMB temperature difference	Moment expansion	ΔT_{CMB}
y-distorsion	Moment expansion	y
Relativistic y-distortion	Moment expansion	T_e
μ-distortion	Moment expansion	μ

Moment expansion : decomposition of CMB spectral distortions into a series of moments around a reference spectrum (a blackbody at T_0)

Sky model - Foregrounds

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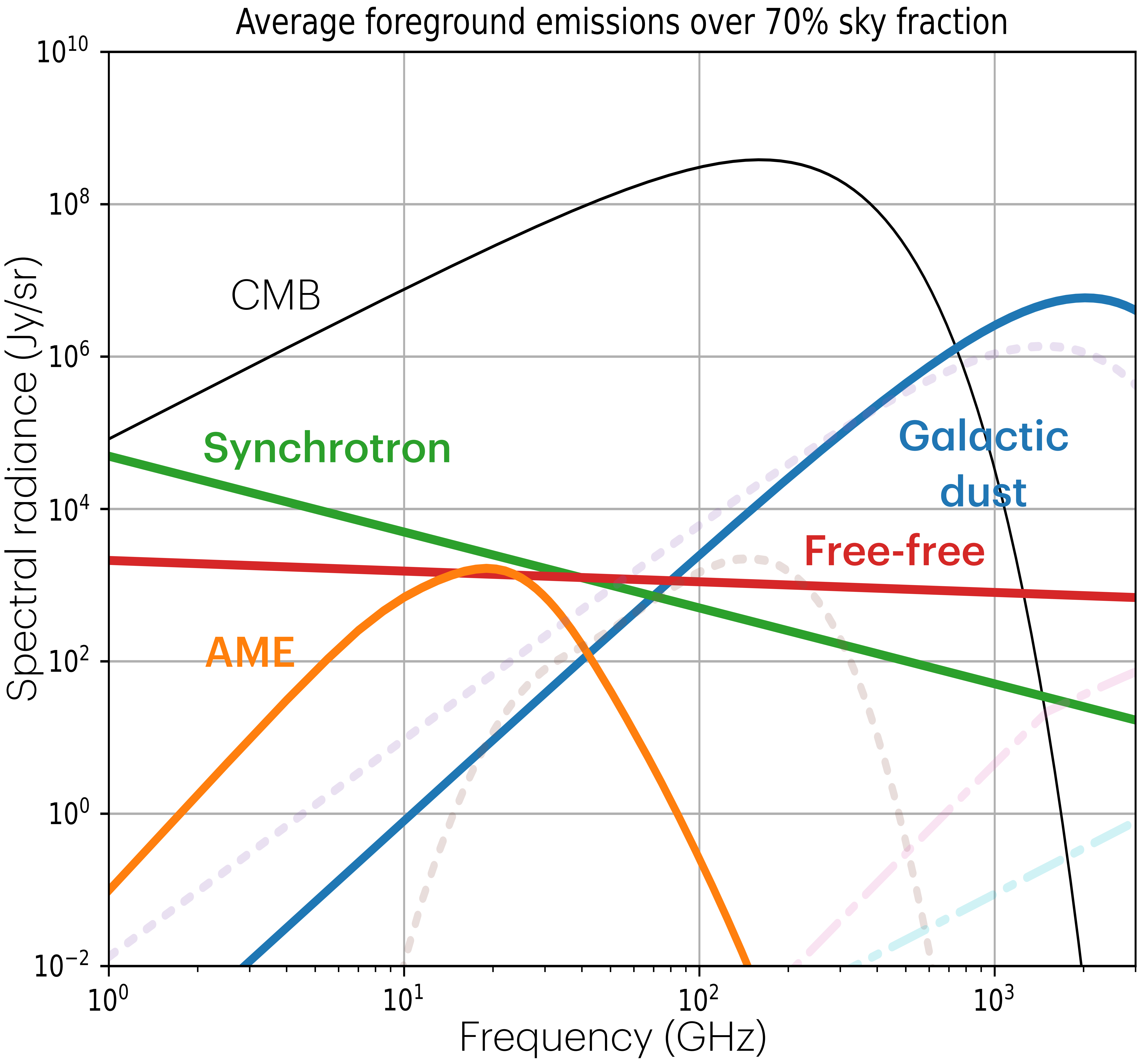
Spatially varying



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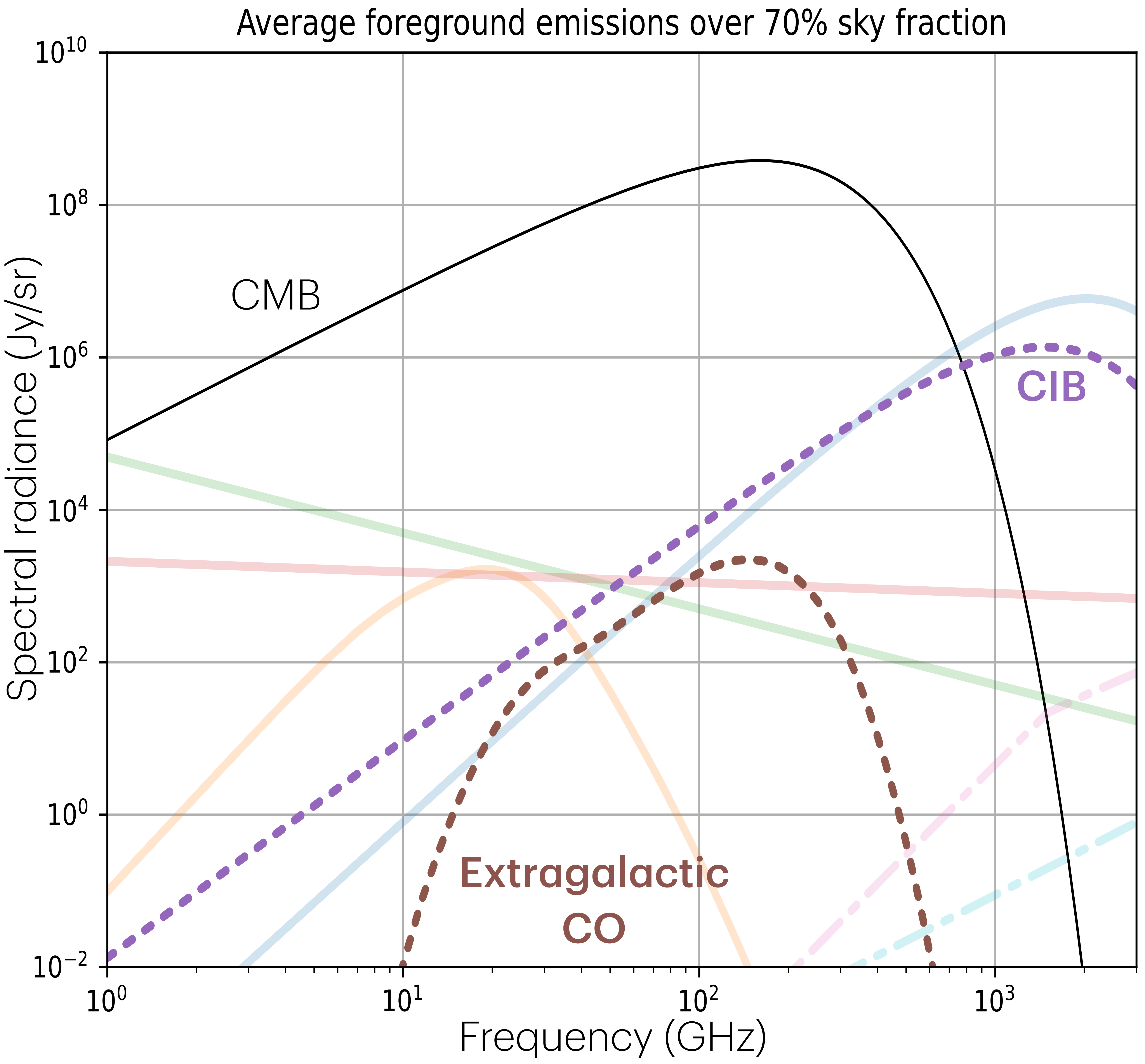
Spatially uniform



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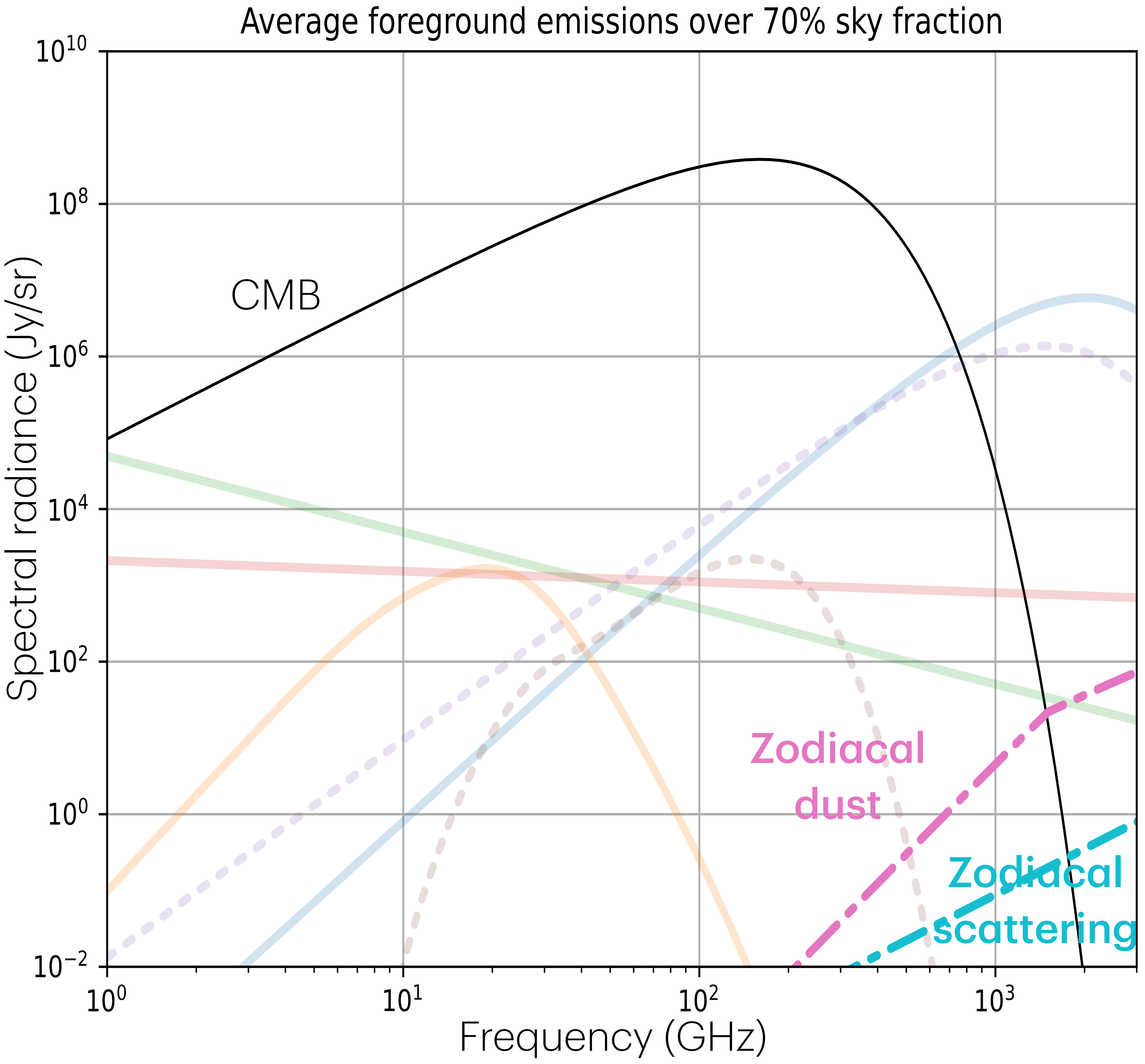
only in $\pm 20^\circ$ from ecliptic



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Spatially varying

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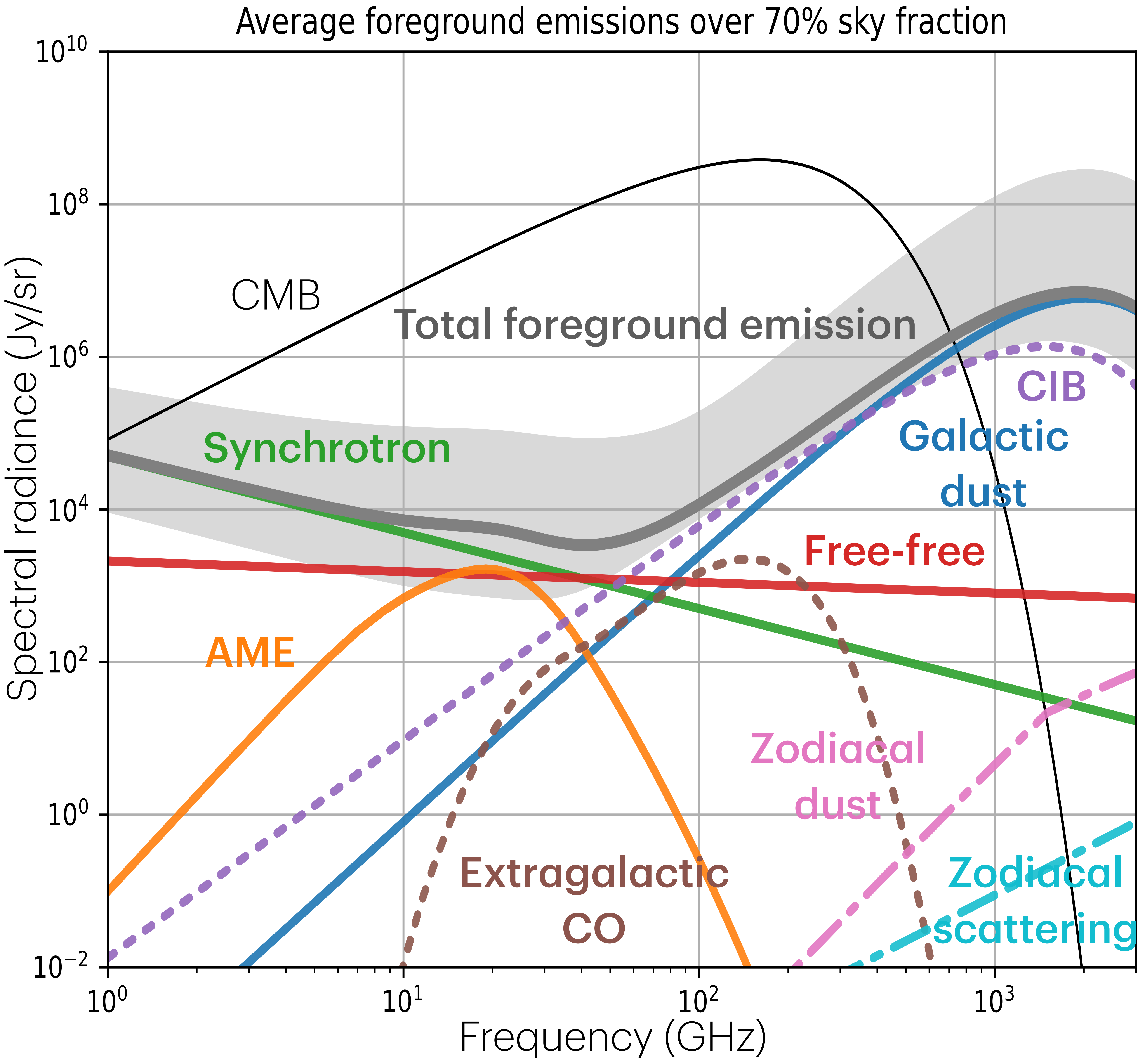
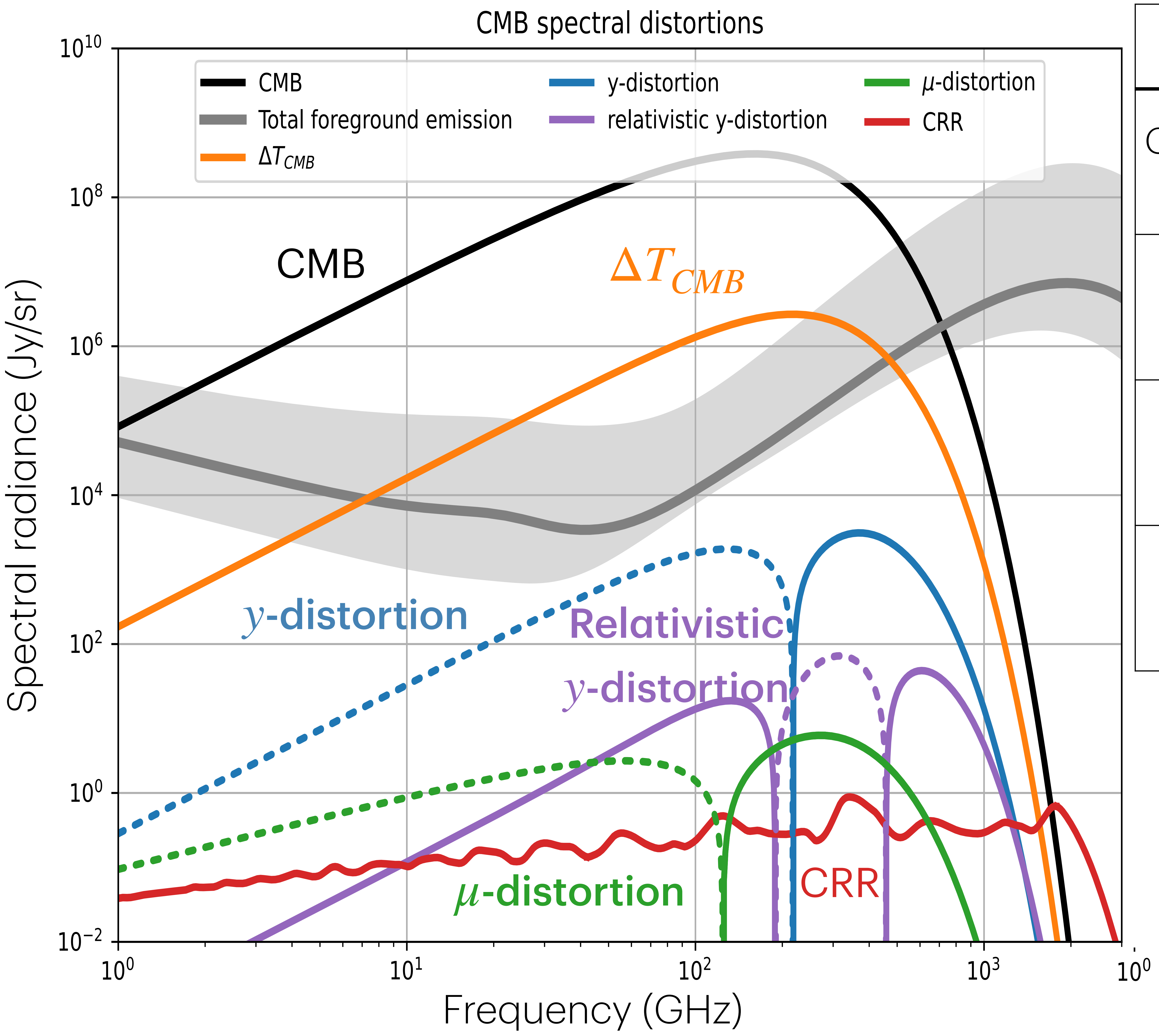


Sky model - CMB spectral distortions



CMB	Model	Parameters
CMB temperature difference	Moment expansion	ΔT_{CMB}
y-distorsion	Moment expansion	y
Relativistic y-distortion	Moment expansion	T_e
μ-distortion	Moment expansion	μ

Cosmological Recombinaison Radiation (CRR) is negleted

Sky model - Parameters

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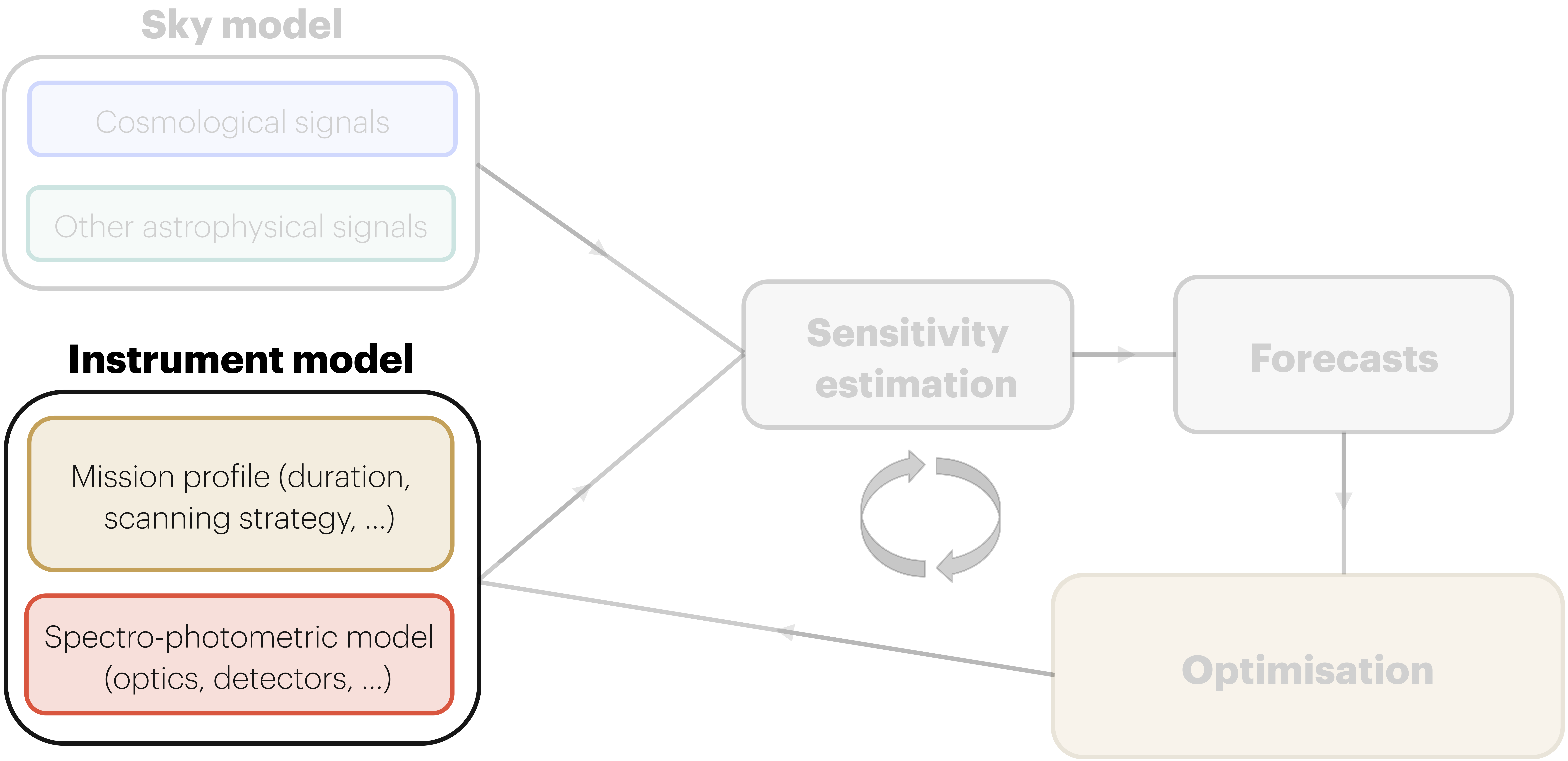
=> 26 parameters

Method - Instrument model



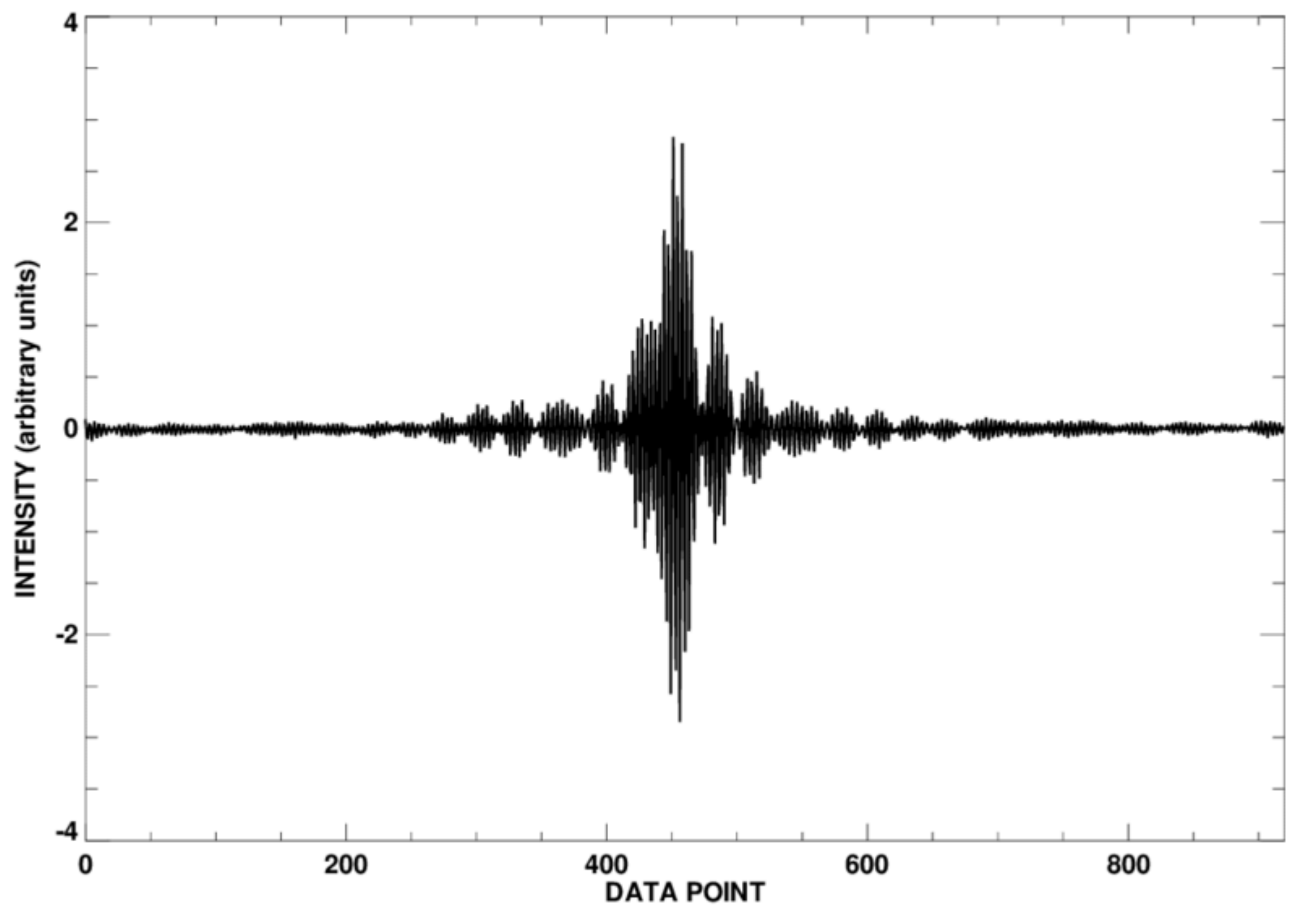
Instrument concept - Fourier Transform Spectrometer (FTS)

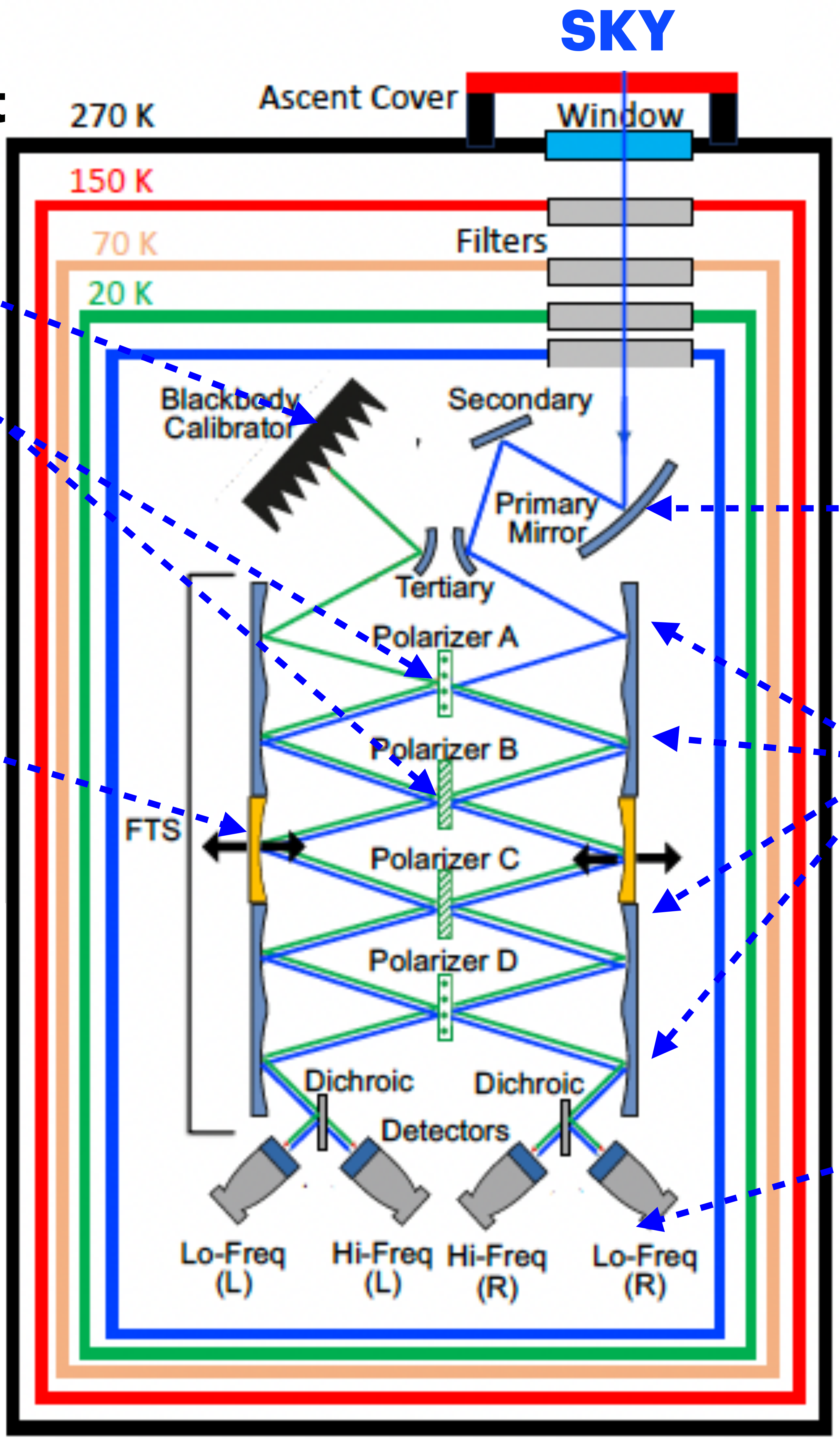
Internal reference at 2.725 K
for **differential measurement**

FTS beam dividers (polarisers)

Also act as beam combiners

FTS scanning mirror
for interferogram





Instrument cooled down to ~3-5 K

- To reduced internal emissions

Detector cooled down to ~100mK

- To be photon noise limited

Telescope
primary

FTS mirrors

Signal proportional to difference with internal reference

$$P_{Lx} = \frac{1}{2}\int (E^2_{x,\mathrm{sky}} + E^2_{y,\mathrm{cal}}) + (E^2_{x,\mathrm{sky}} - E^2_{y,\mathrm{cal}})\cos(4z\omega/c)\,d\omega$$

$$P_{Ly} = \frac{1}{2}\int (E^2_{x,\mathrm{cal}} + E^2_{y,\mathrm{sky}}) - (E^2_{x,\mathrm{cal}} - E^2_{y,\mathrm{sky}})\cos(4z\omega/c)\,d\omega$$

$$P_{Rx} = \frac{1}{2}\int (E^2_{x,\mathrm{cal}} + E^2_{y,\mathrm{sky}}) + (E^2_{x,\mathrm{cal}} - E^2_{y,\mathrm{sky}})\cos(4z\omega/c)\,d\omega$$

$$P_{Ry} = \frac{1}{2}\int (E^2_{x,\mathrm{sky}} + E^2_{y,\mathrm{cal}}) - (E^2_{x,\mathrm{sky}} - E^2_{y,\mathrm{cal}})\cos(4z\omega/c)\,d\omega$$

Multi-moded detectors at
each output of the FTS

Maffei+2024

Instrument model - Main sub-systems

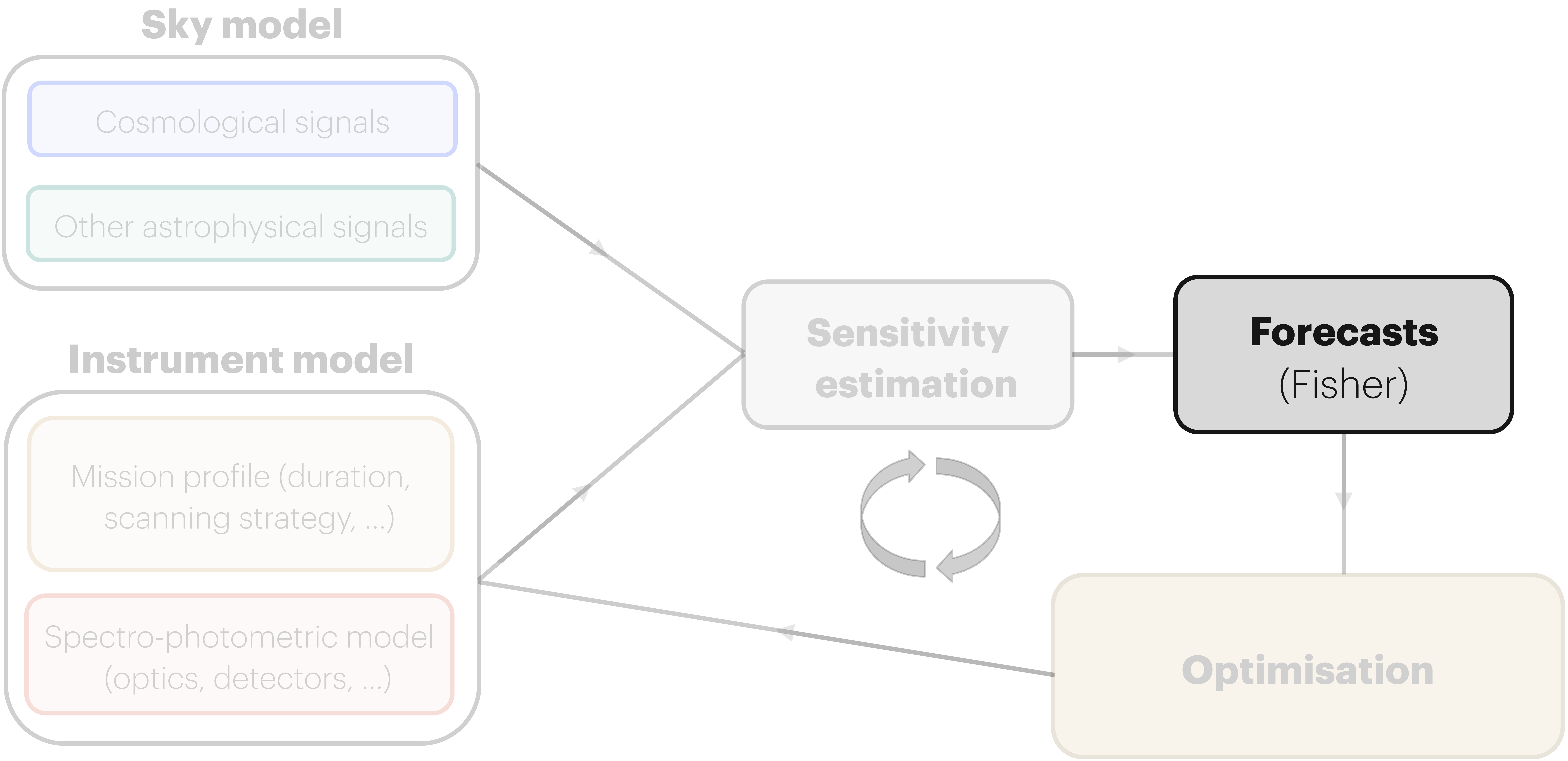
Sub-systems	**FTS**	**Cryogenic Chain**	**Focal Plane Array (FPA)**	**Optics**
Main instrumental constraints	Maximal mirror stroke length	Instrument under vacuum and at ~4 K	Detector time response	Filter bandpass
	Minimum mirror step	Internal emisisons	Detector and feedhorn sizes	Optics transmision
	Mechanism speed	Absolute temperature and temperature stability of the internal reference	Feedhorn–detector coupling	Optics element size
	FTS size	Absolute temperature and temperature stability of all optical elements	Temperature Stability	Primary mirror size
Instrument model parameters	**=> 13 to 61 parameters**			

Instrument model - Parameters

- **Instrument model**
  - **10 parameters**
    - (5-days transatlantic flight)
- **Internal emissions**
  - **3 to 51 parameters** (Modified blackbody)
    - 3 × (number of optical elements considered)

Instrument & mission	Parameters
Minimal frequency	ν_{min}
Maximal frequency	ν_{max}
Splitting frequency	ν_{split}
Spectral resolution	$\Delta\nu$
Detector efficiency	eff_{det}
Number of detectors per FPA	N_{det}
Effective observational time	τ
Number of mode at the minimal freqeucy	N
Primary mirror diameter	A
Line of sight	$\vec{p}$
Number of optical element	K
Transmission of each optical element	$\left(t_k\right)_{1\leq k\leq K}$
Temperature and emissivity of optical element	$\left(\epsilon_k(\nu), T_k\right)_{1\leq k\leq K}$

Method - Fisher Forecasts



Fisher forecasts

- Fisher matrix

$$F_{ij} = \sum_{\nu,\nu'} \frac{\partial(\Delta I)_\nu}{\partial\theta_i} C^{-1}_{\nu\nu'} \frac{\partial(\Delta I)_{\nu'}}{\partial\theta_j}$$

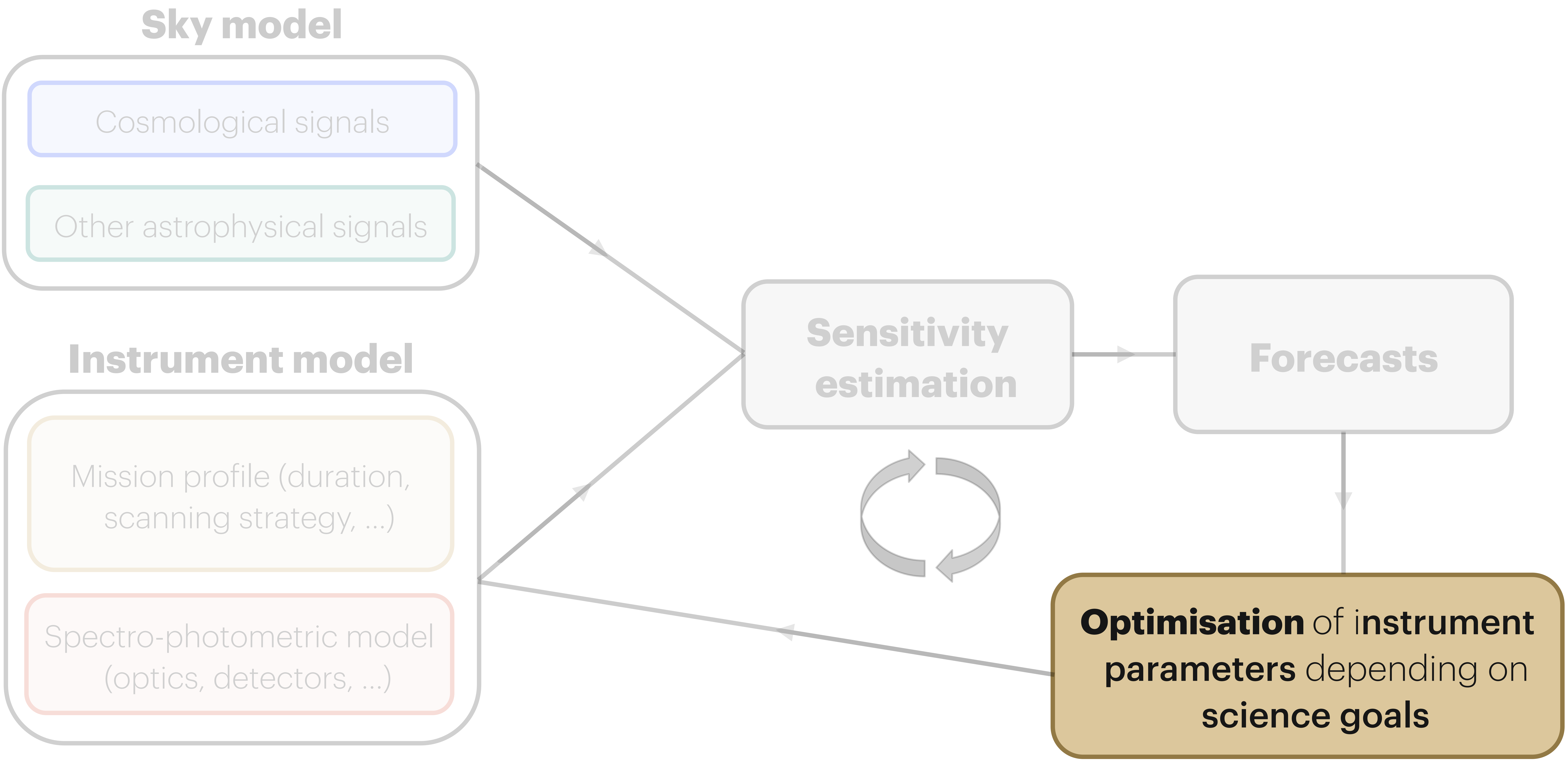
θ_i : CMB and foreground parameters

$C_{\nu\nu'}$: instrument noise covariance matrix

- Assume priors on sky parameters
  - **Gaussian priors** on CMB parameters (4 parameters)
  - **20% uniform priors** on all foregrounds parameters (22 parameters)
  - **Marginalised over all internal emission parameters** (~50 parameters)
    - Assumed to be prefectly known / number of parameters depends on intrumental configuration

=> Signal Noise Ratio (SNR) estimate on sky parameters (in σ)

Method - Optimisation



Applications - BISOU & FOSSIL

Foregrounds	Parameters
Galctic dust	A_d, T_d, β_d
Synchrotron	A_s, β_s, C_s
Free-free	
AME	
CIB	
Extragalactic CO lines	A_{CO}
Zodiacal dust	$\epsilon_{th}(\nu), T_{th}, \beta_{th}$
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CMB	Parameters
CMB	
	TCMB
	y
Relativistic y-distortion	T_e
-distortion	μ

Forecasts are performed on **26 sky parameters**, while the spectro-photometric model parameters are fixed at chosen fiducial values

Foregrounds	Parameters
Minimal frequency	ν_{min}
Maximal frequency	ν_{max}
Splitting frequency	ν_{split}
Spectral resolution	$\Delta\nu$
Detector efficiency	eff_{det}
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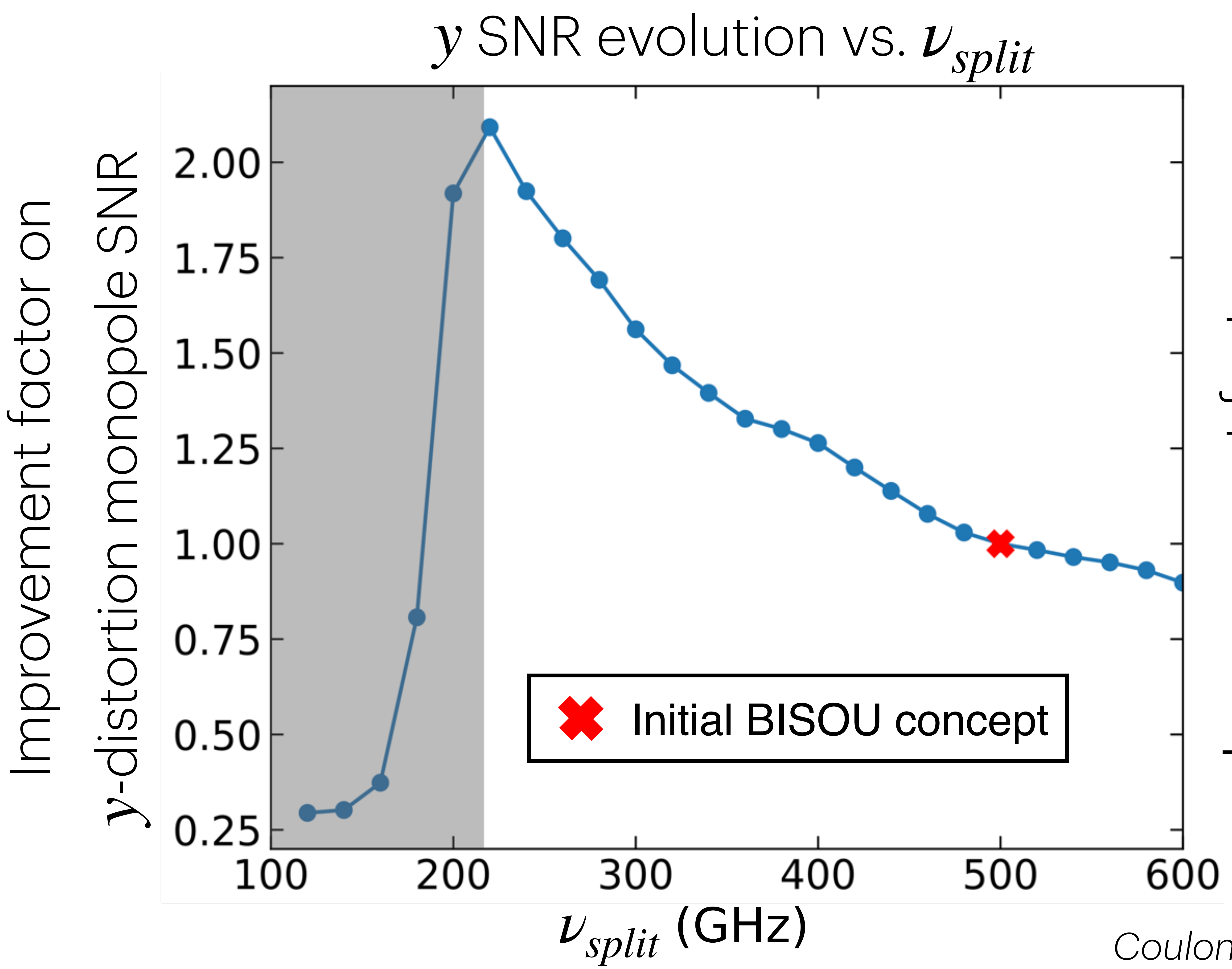
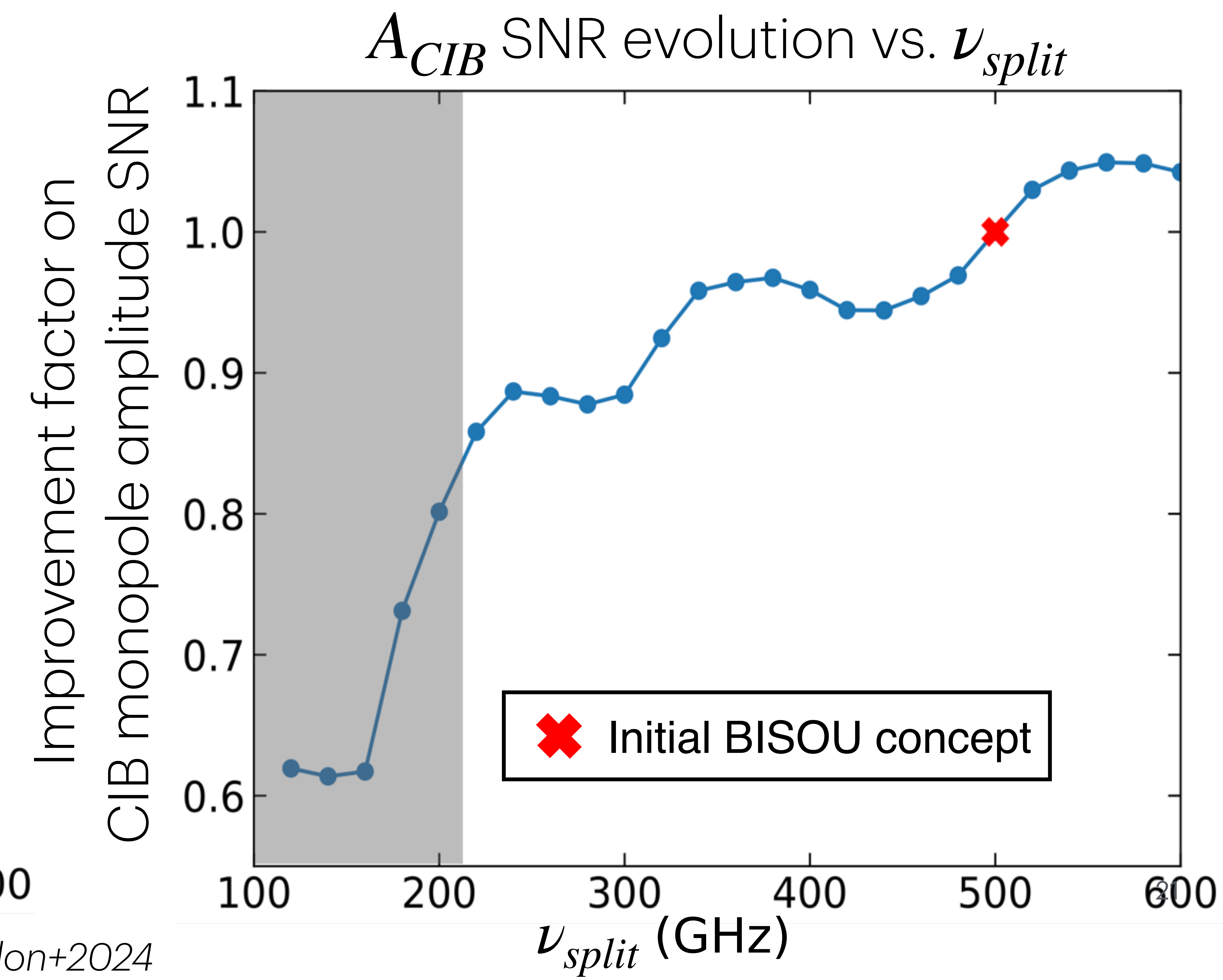
Primary mirror diameter	A
Line of sight	$\vec{p}$

BISOU - Optimisation w.r.t. ν_{split}

- Dichroic
  - **assumed perfect** (no effect other than splitting the observed band in two / no overlap)





Coulon+2024

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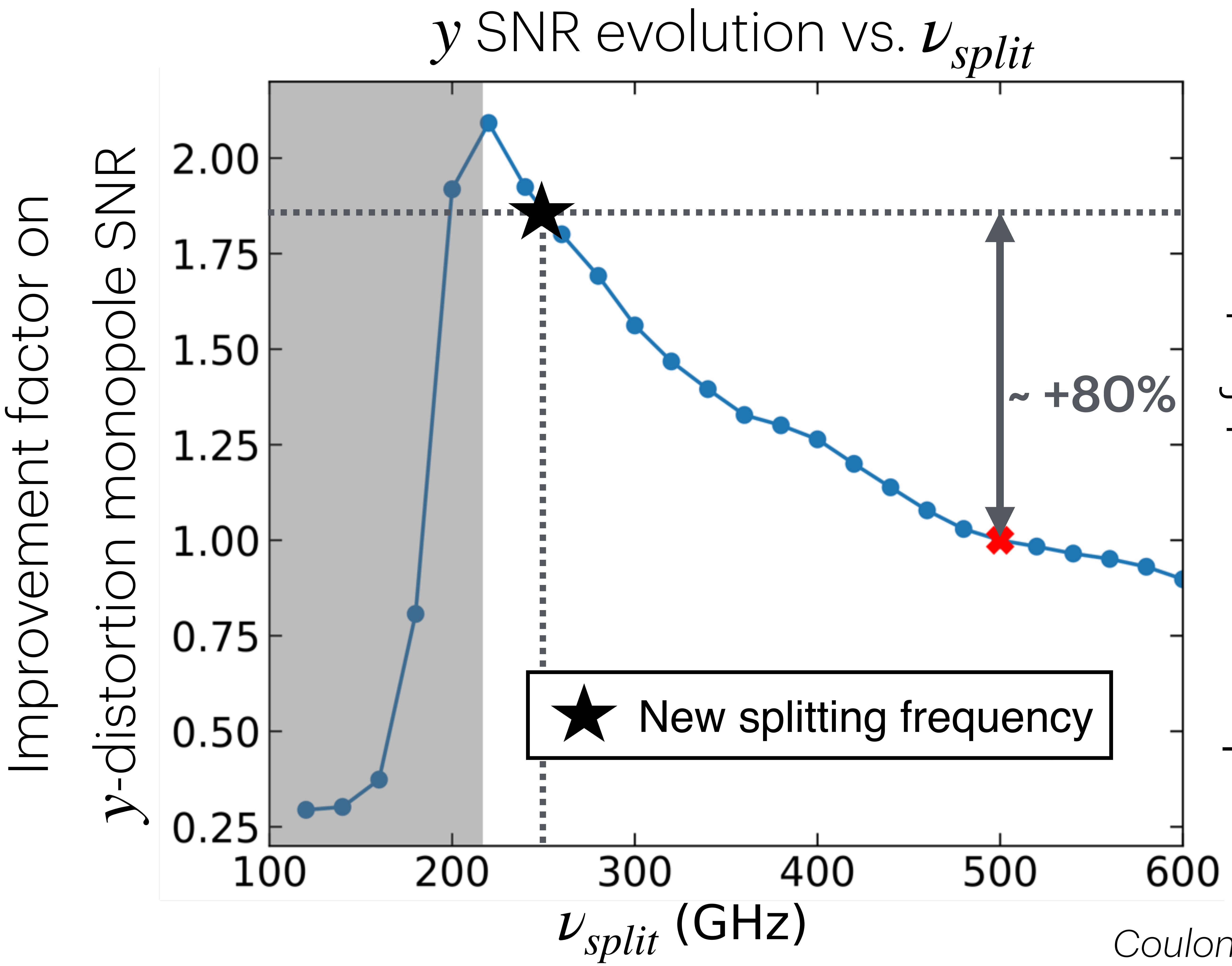
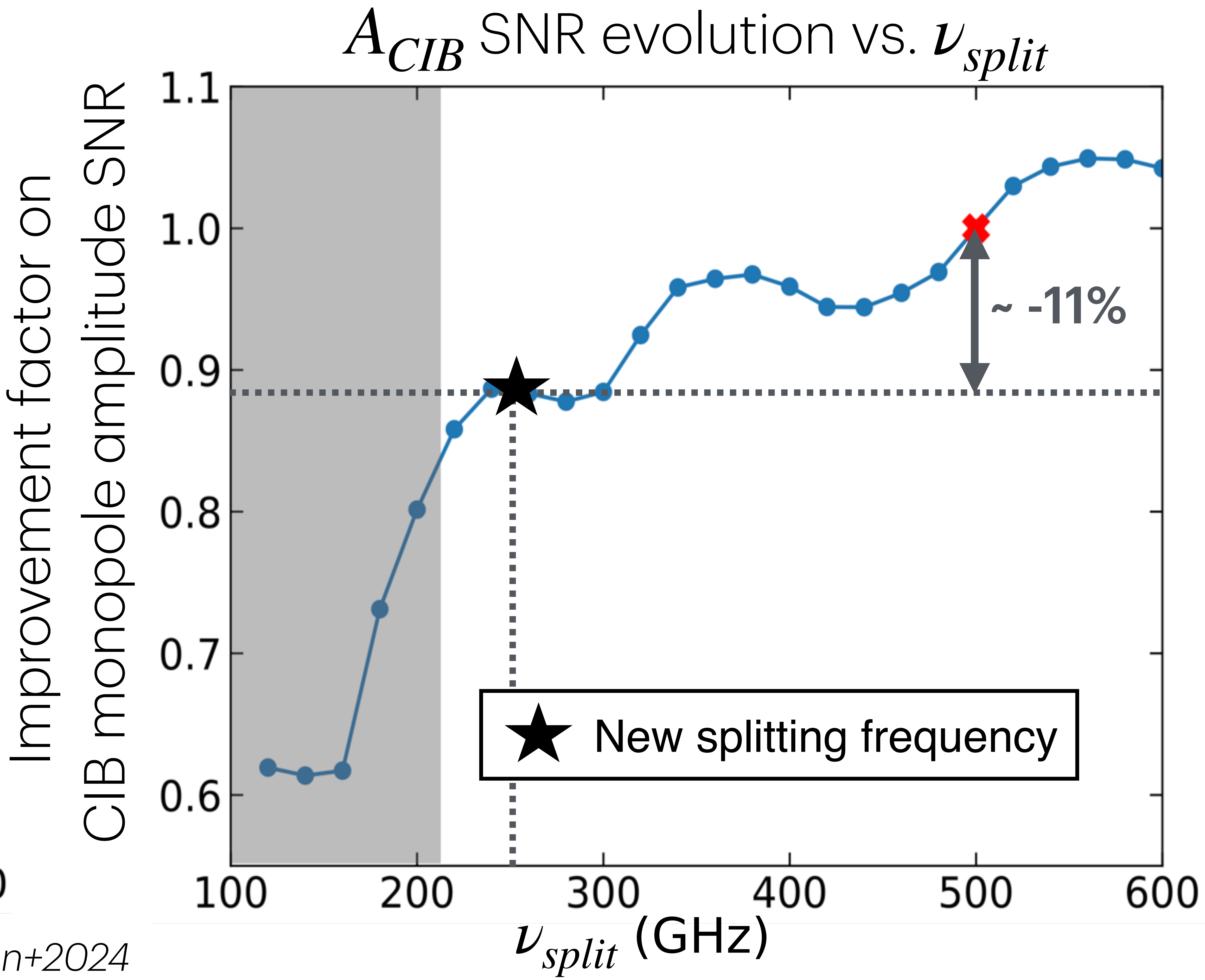
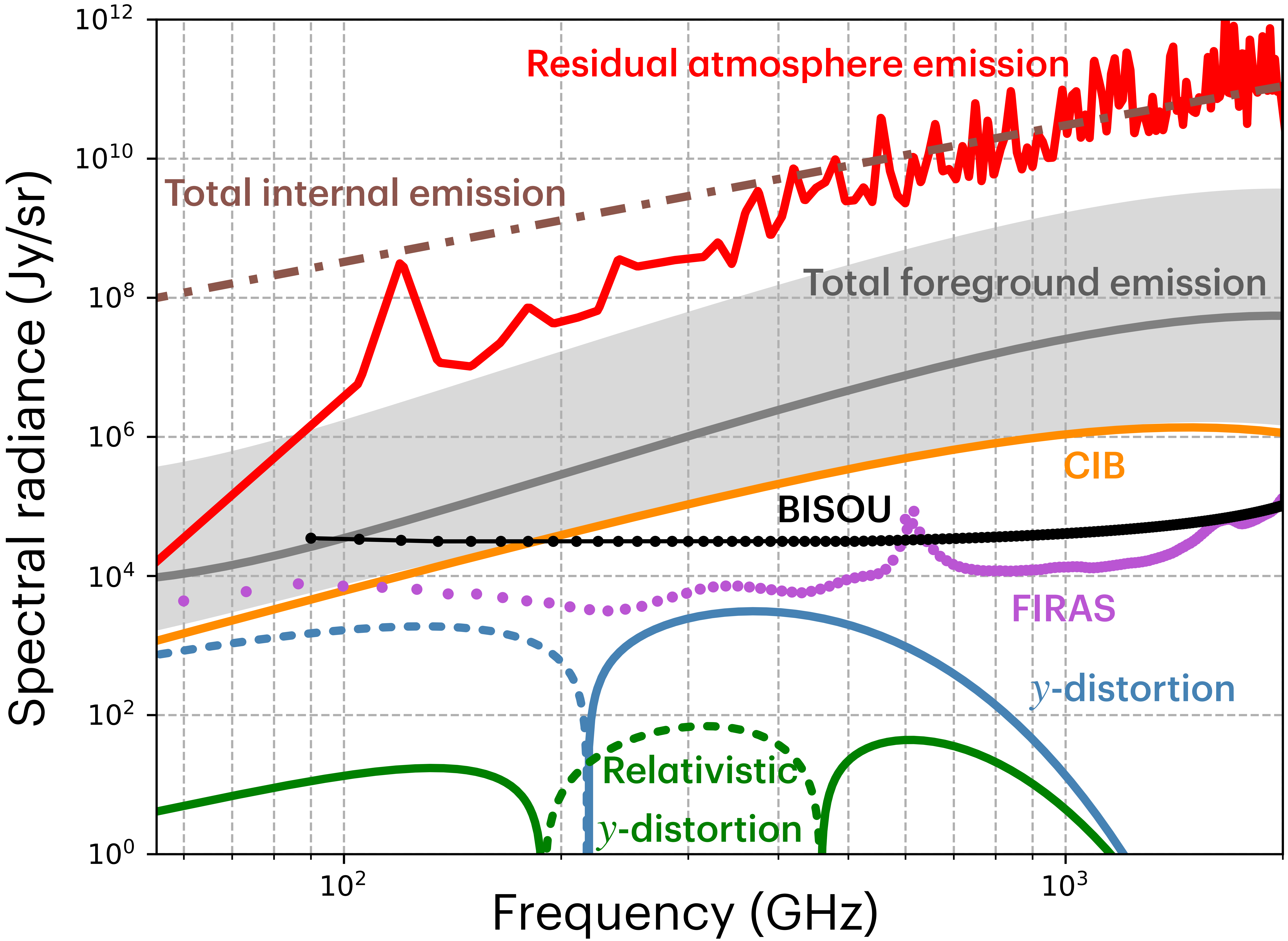




Coulon+2024

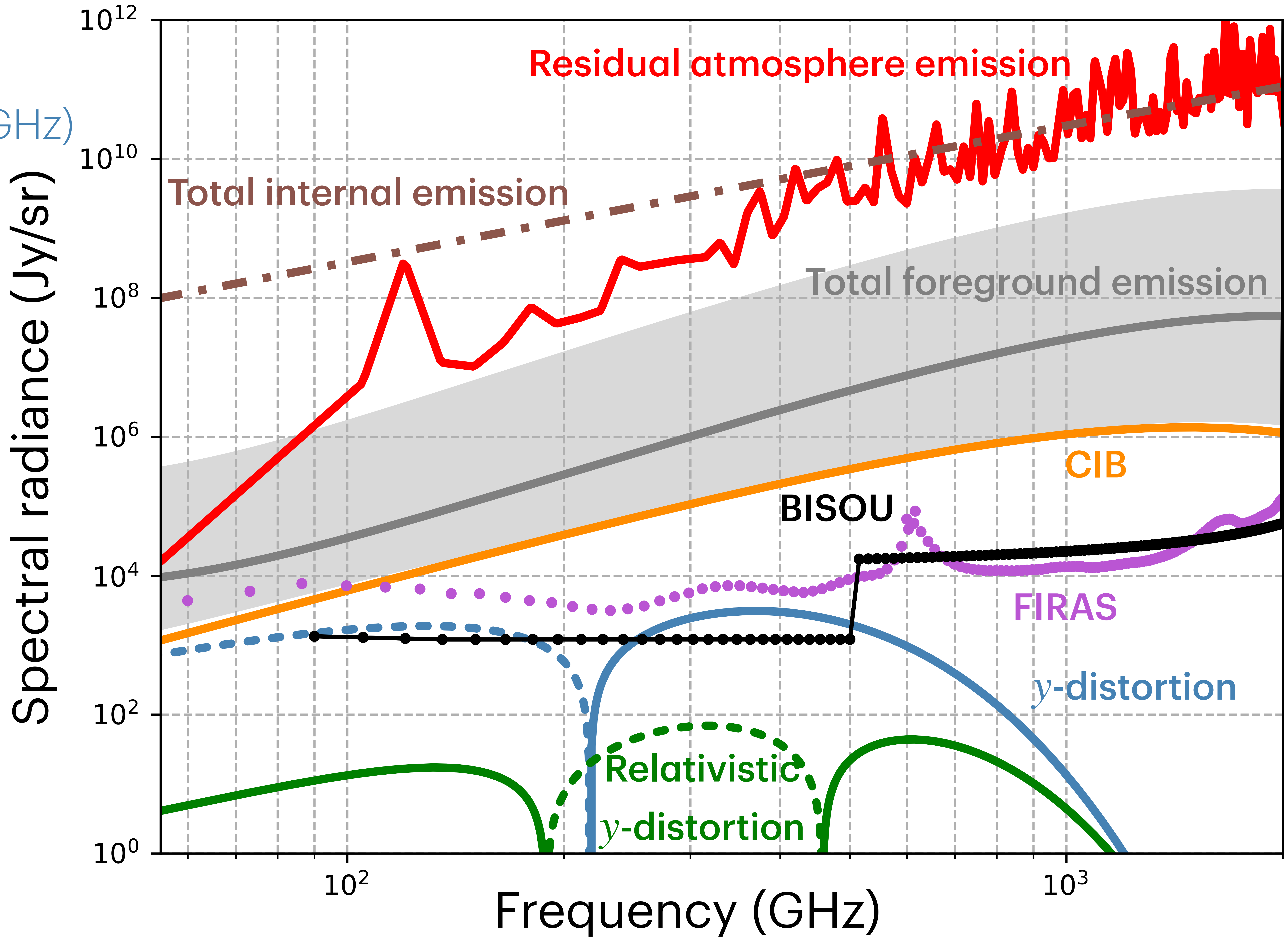
BISOU - Sensitivity w.r.t. ν_{split}

- Impact on sensitivity
  - **No dichroic**



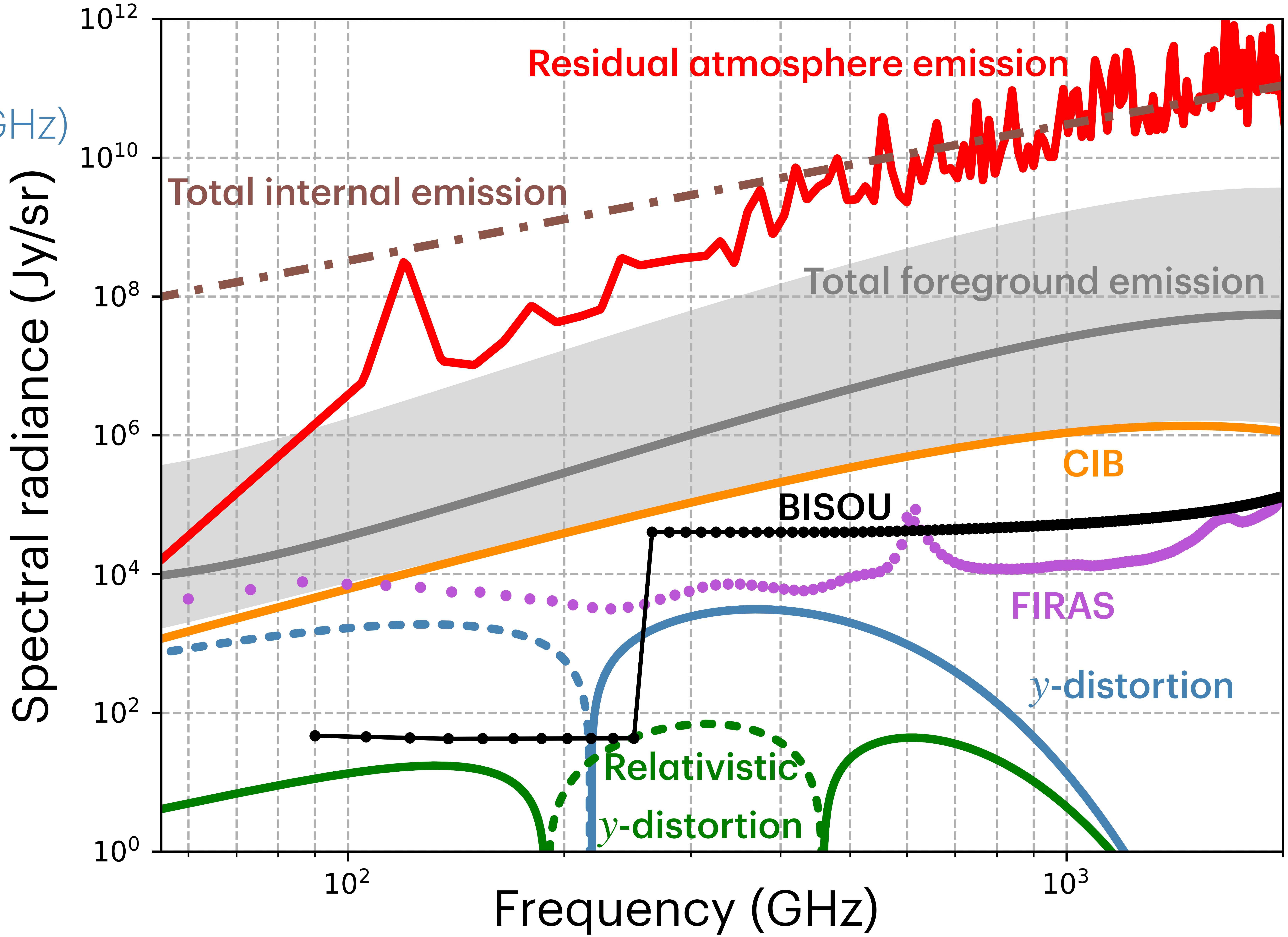
BISOU - Sensitivity w.r.t. ν_{split}

- Impact on sensitivity
  - **Dichroic** (ν_{split} = 500GHz)



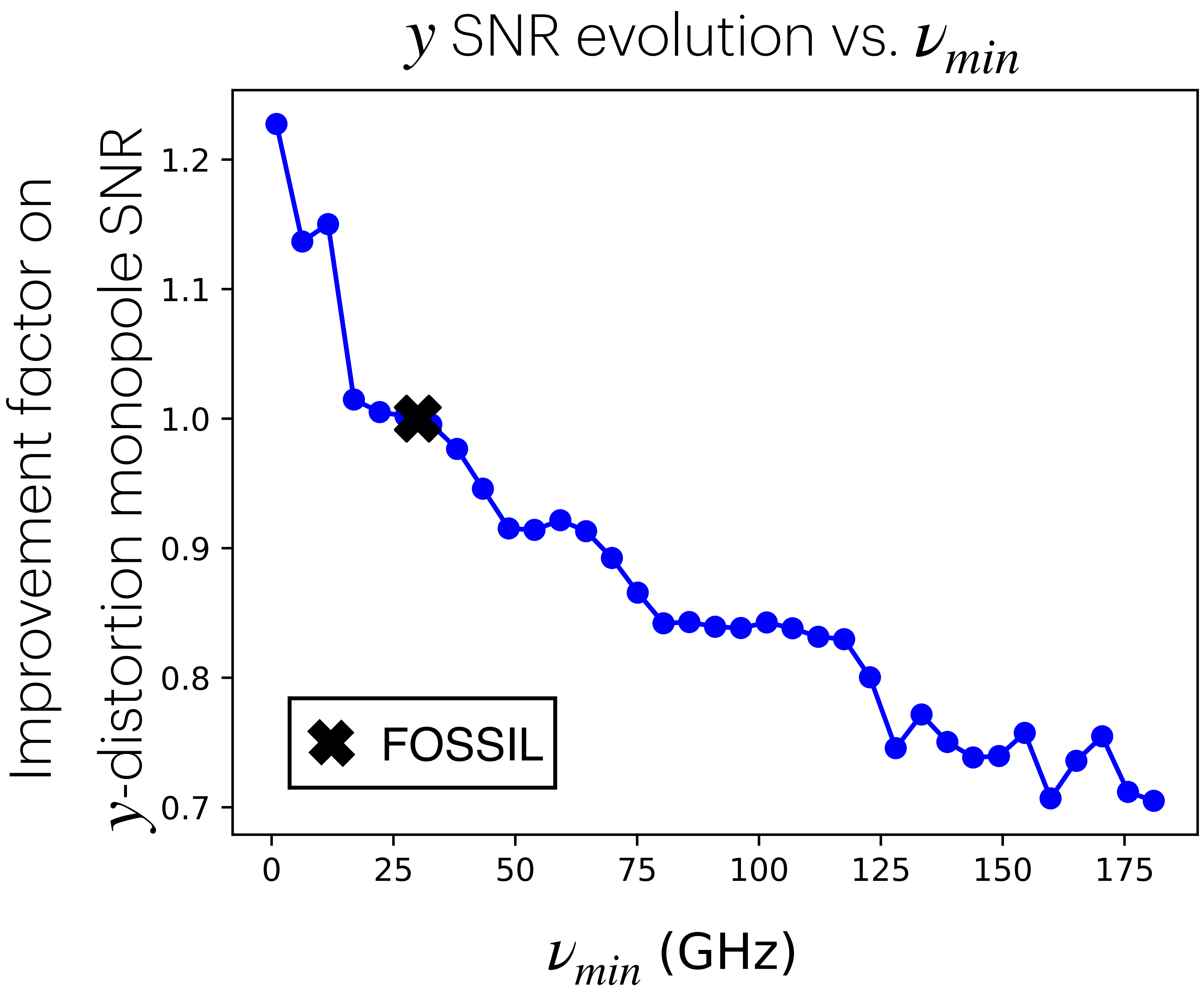
BISOU - Sensitivity w.r.t. ν_{split}

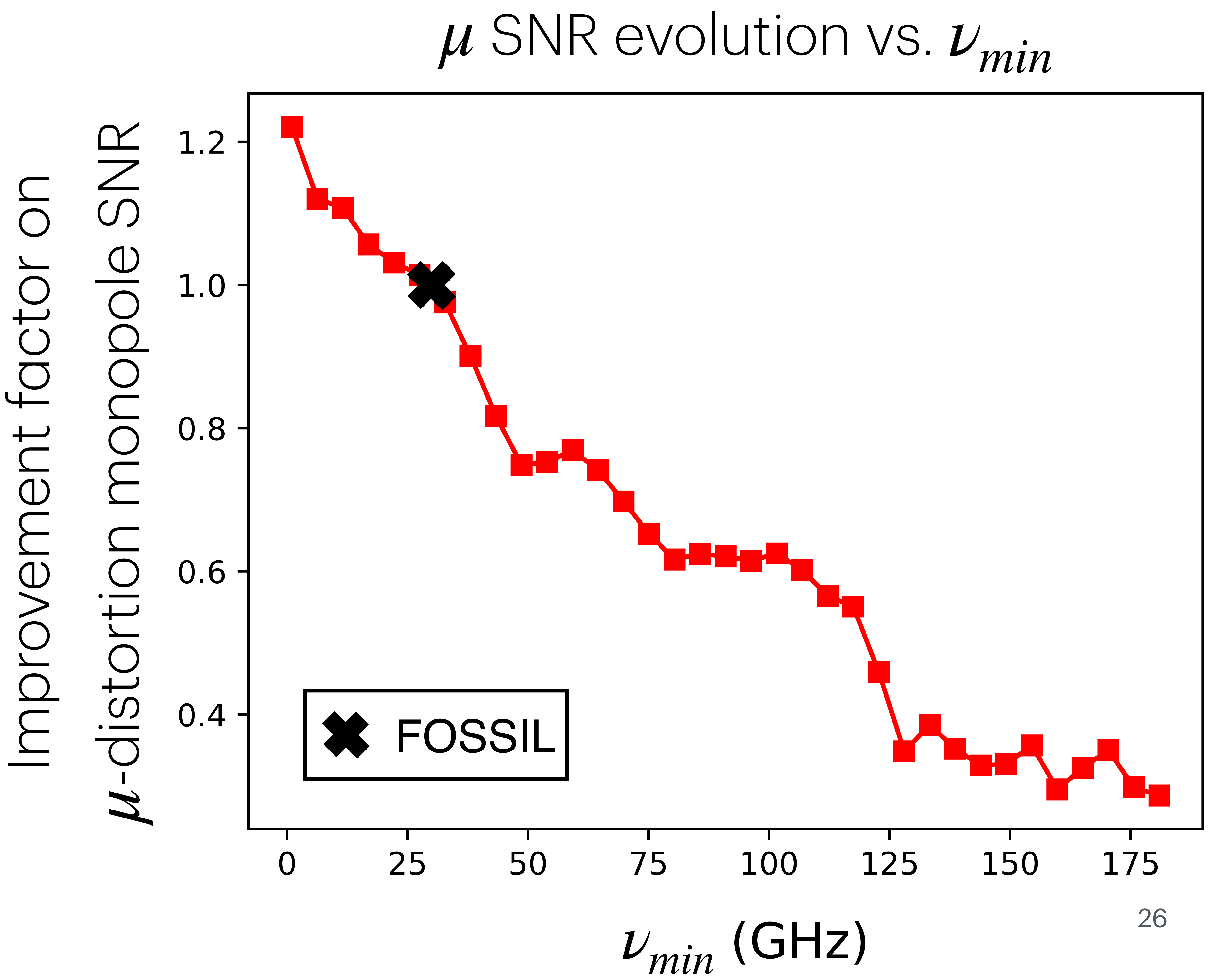
- Impact on sensitivity
  - **Dichroic** (ν_{split} = 250GHz)



FOSSIL - Optimisation w.r.t. ν_{min}

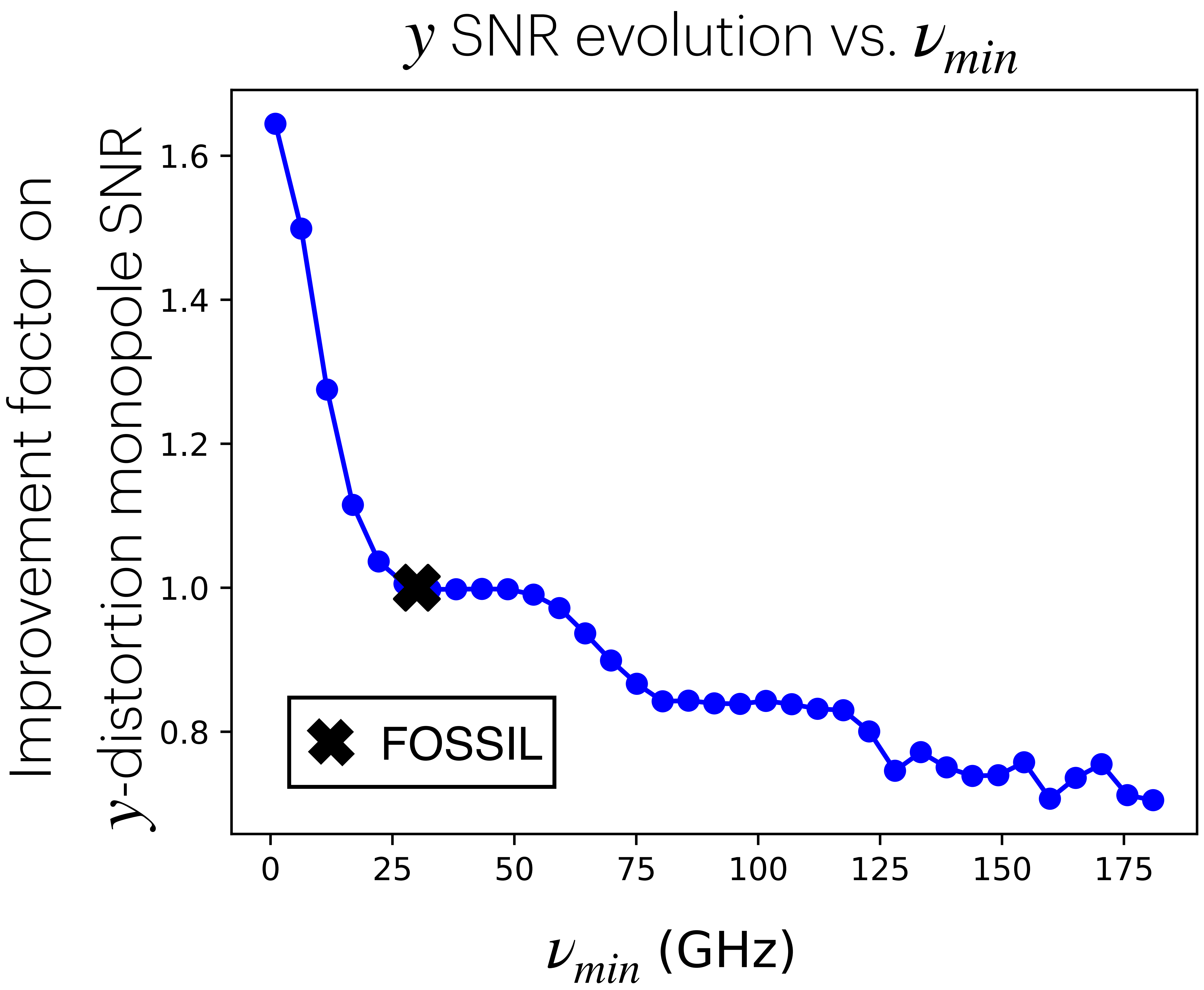
- FOSSIL: ν_{min} = 30GHz

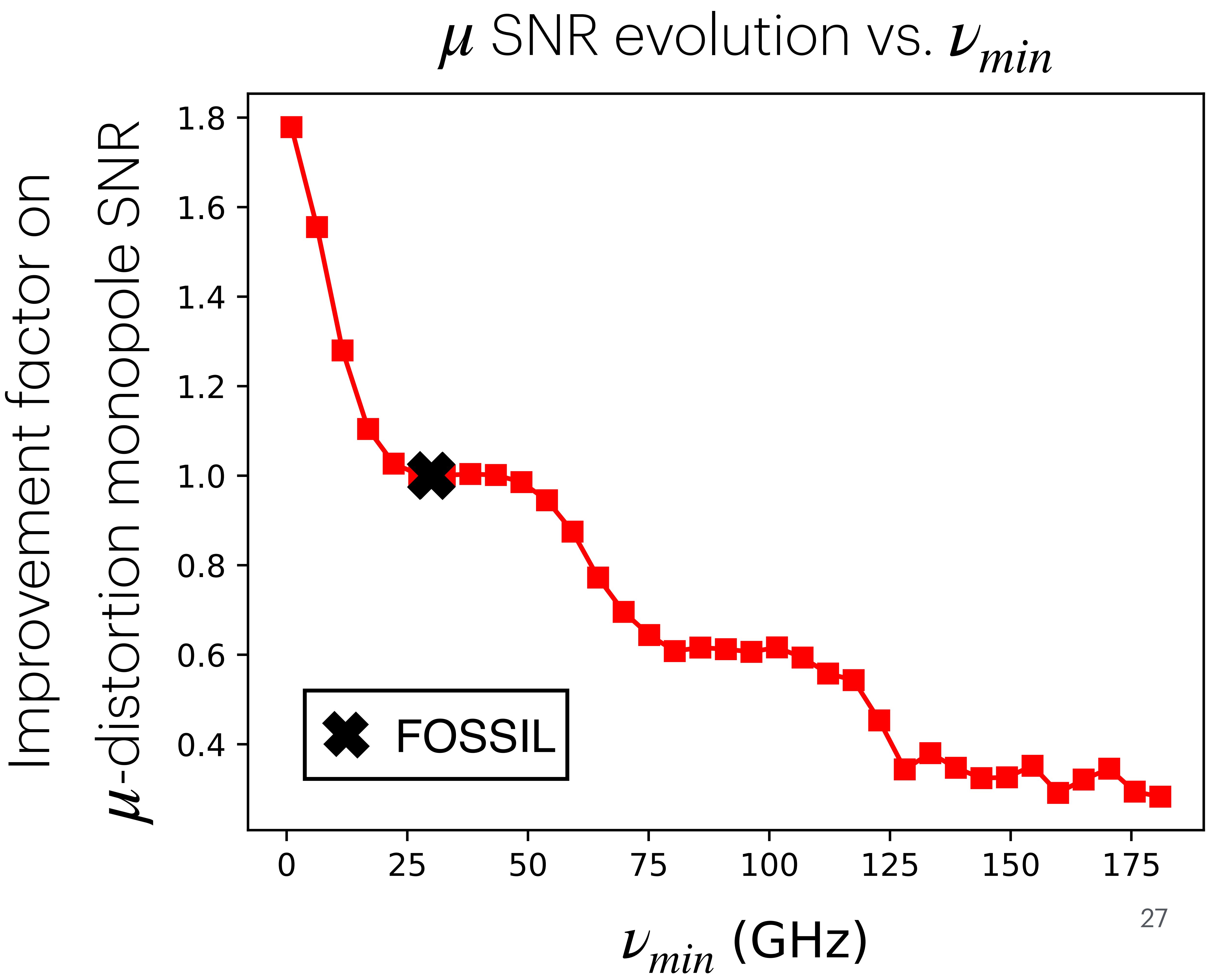




FOSSIL - Optimisation w.r.t. ν_{min}

- **SNR evolution** : depend on sky model / instrument model / assumptions
  - Marginalised over all AME parameters





BISOU & FOSSIL - Forecasts after optimisation

- Assuming 1 detector per focal plane for BISOU and 4 for FOSSIL

- First attempt to account for the emission from the residual atmosphere for BISOU

	SNR on y (in σ)	**SNR on T_e** (in σ)	**SNR on μ** (in σ)	**SNR on A_{CIB}** (in σ)
BISOU	9			6
FOSSIL	2300	148	4	1570

- Improvement over COBE/FIRAS
  - **~ $\times 20$ with BISOU**
  - **~ $\times few100$ with FOSSIL**

Fixsen+2009, Bianchini+2022,

Conclusions

- A realistic model for both sky and instrument has been developed
  - **Spacially varying foregrounds**
  - **Instrument model** (internal emissions, line of sight, etc.)
- Fast running forecasts (timescale ~ seconds)
  - **Can be used for instrument parameters optimisation**

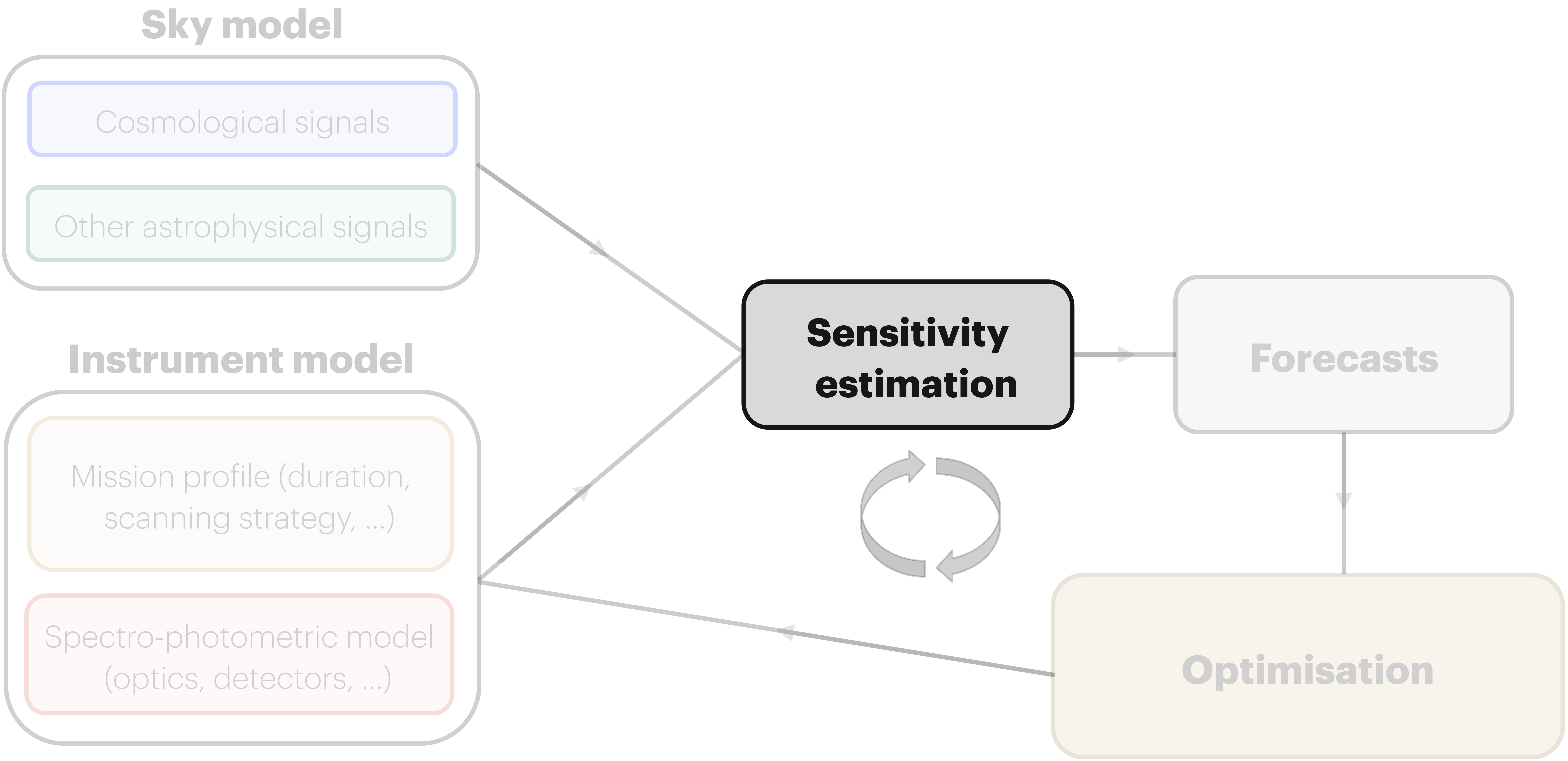
Perspectives:

- Improve sky and instrument model
  - **Spacial variations of extragalactic emissions** (CIB, etc.)
  - **Add systematic effects** (internal reference temperature, etc.)
- Validate Fisher forecasts with MCMC

Thanks you !

Annexes

Method - Sensitivity estimation



Sensitivity estimation

- **Power on detectors** (W/Hz)

$$P_\nu = \frac{1}{2} eff_{det}(\nu) \left[S_{sky} \prod_{k=1}^{K} t_k(\nu) + \sum_{k=1}^{K} \epsilon_k B_\nu(\nu, T_k) \prod_{l=1}^{k-1} t_l(\nu) \right] A\,\Omega(\nu)$$

Sensitivity estimation

- **Power on detectors** (W/Hz)

Effective totale transmission

$$P_\nu = \frac{1}{2} eff_{det}(\nu) \left[S_{sky} \underbrace{\prod_{k=1}^{K} t_k(\nu)}_{= t_{tot}} + \sum_{k=1}^{K} \epsilon_k B_\nu(\nu, T_k) \prod_{l=1}^{k-1} t_l(\nu) \right] A\,\Omega(\nu)$$

Sky signal (CMB + foregrounds)

Internal emissions

Sensitivity estimation

- **Power on detectors** (W/Hz)

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- **NEP** (W.Hz^-1/2)

$$NEP^2_{total} = NEP^2_{photon} = 2 \int_{\nu_{min}}^{\nu_{max}} \left(h\,\nu\,P_\nu + \frac{c^2}{\nu^2 A\Omega} P_\nu^2 \right) d\nu$$

If photon noise limited

Mather+1982, Lamare+1989

Sensitivity estimation

- **Power on detectors** (W/Hz)

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If photon noise limited

Mather+1982, Lamare+1989

- **Sensitivity on sky** (Jy/sr)

$$\delta I_\nu = \frac{NEP_{total}}{A\Omega\,\Delta\nu\,(eff_{det} \times t_{tot}) \sqrt{\frac{\tau N_{det}}{2}}}$$

Sky model - Foregrounds

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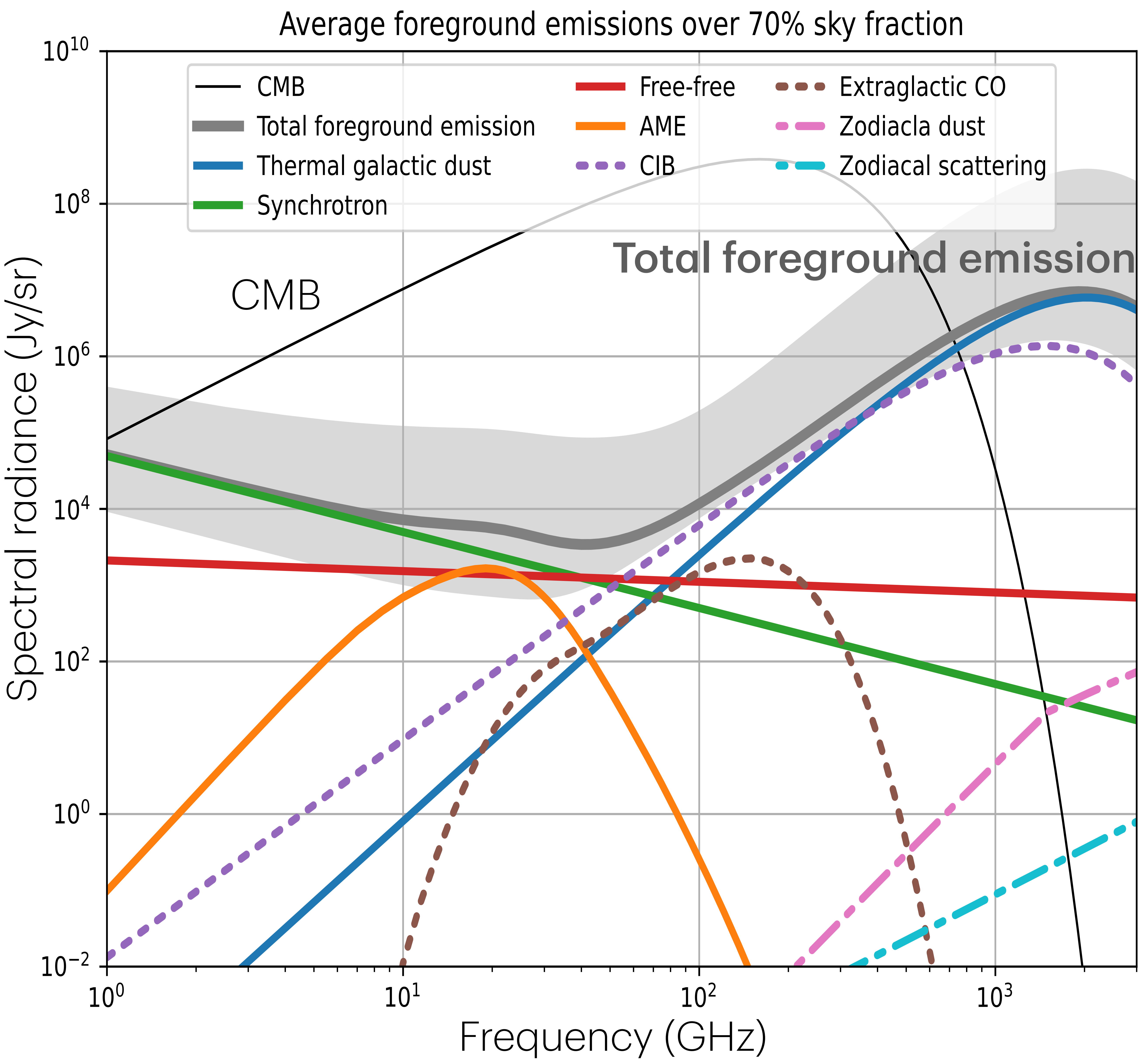
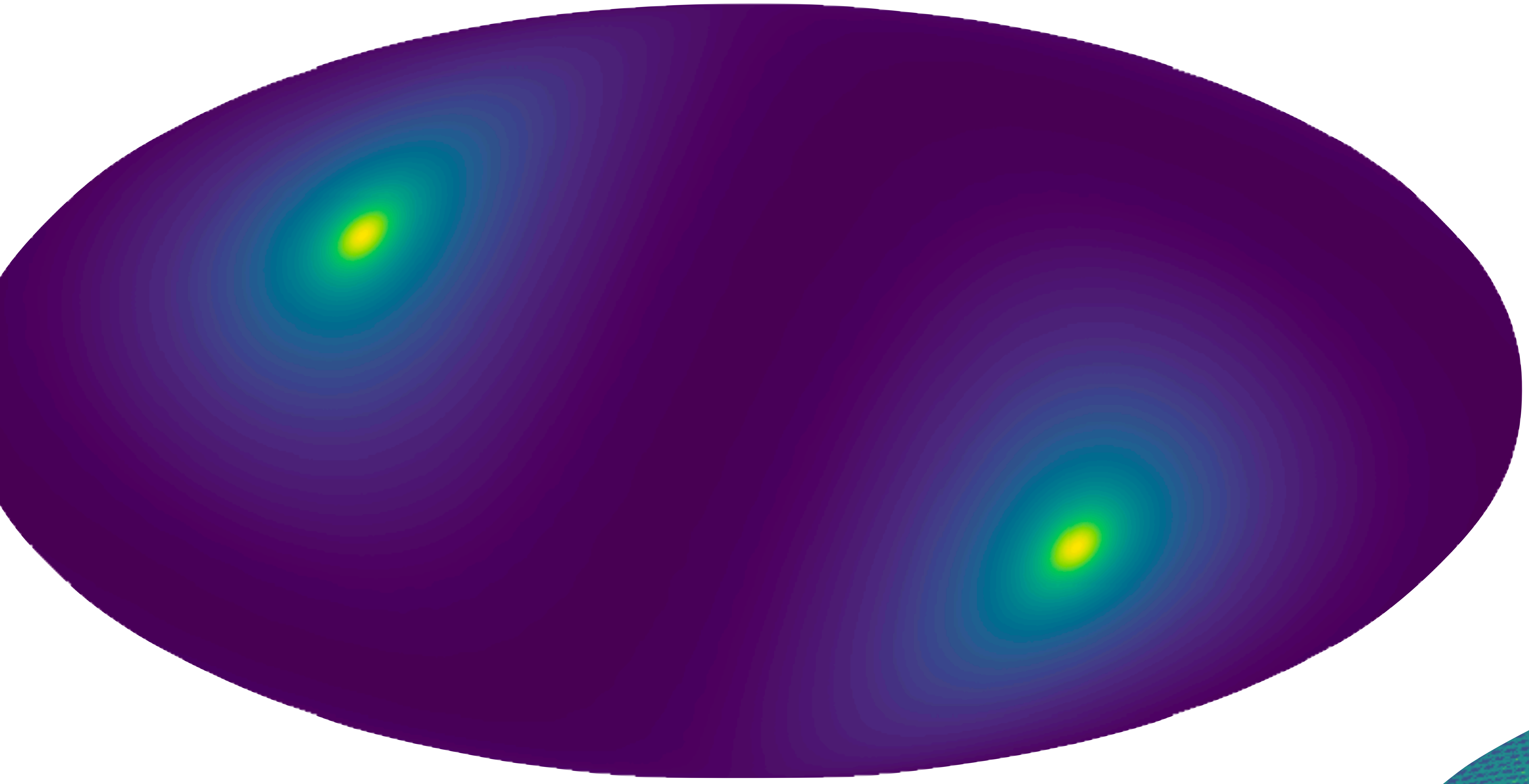
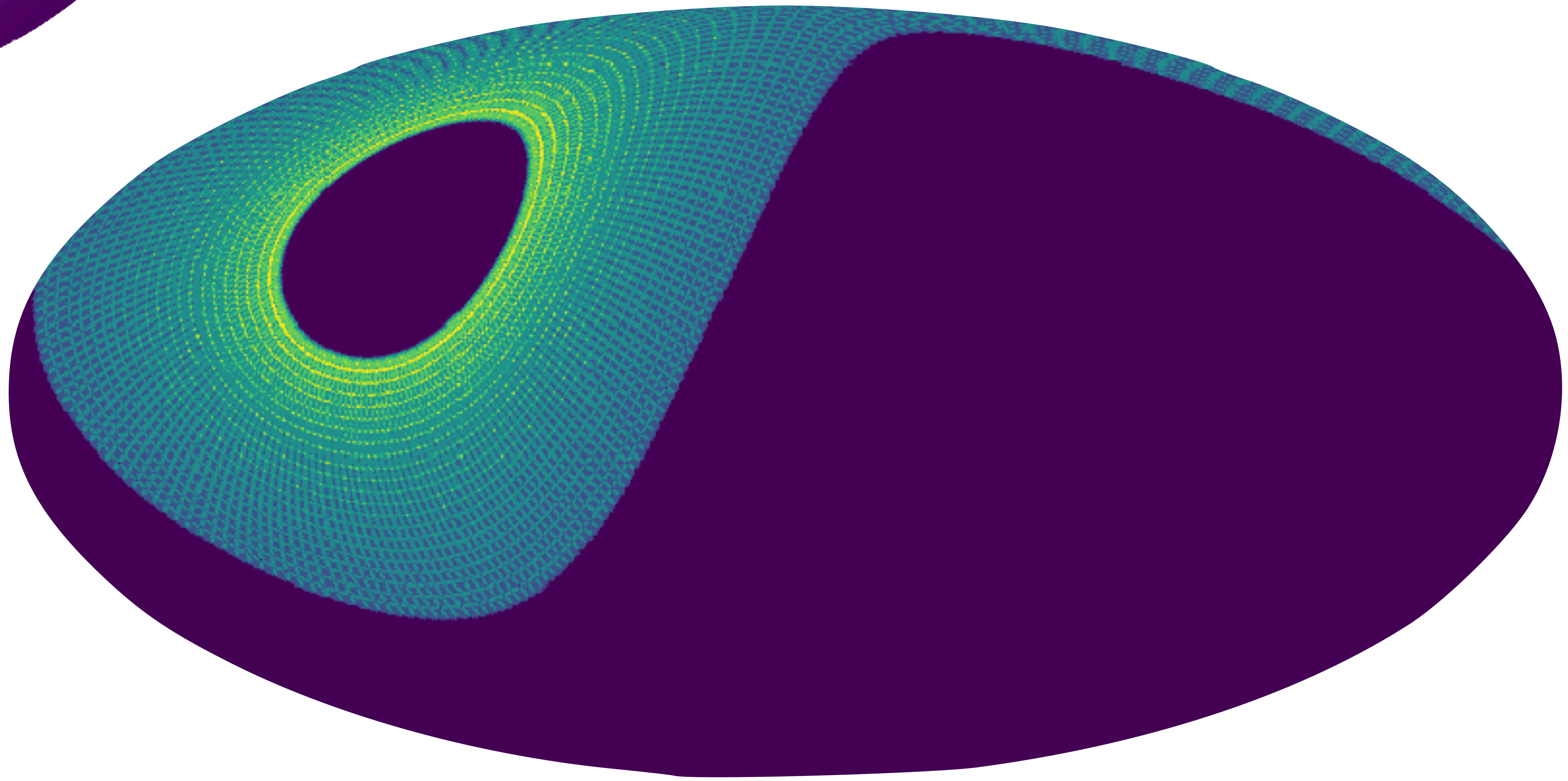


Hitmap





BISOU: Flight plan

- So far CNES is mainly performing relatively short flights
    - About 35 hours
    - **First sucessful trans-Atlantic flight in June 2024**

BISOU base fligth: 5 days trans-Atlantic flight

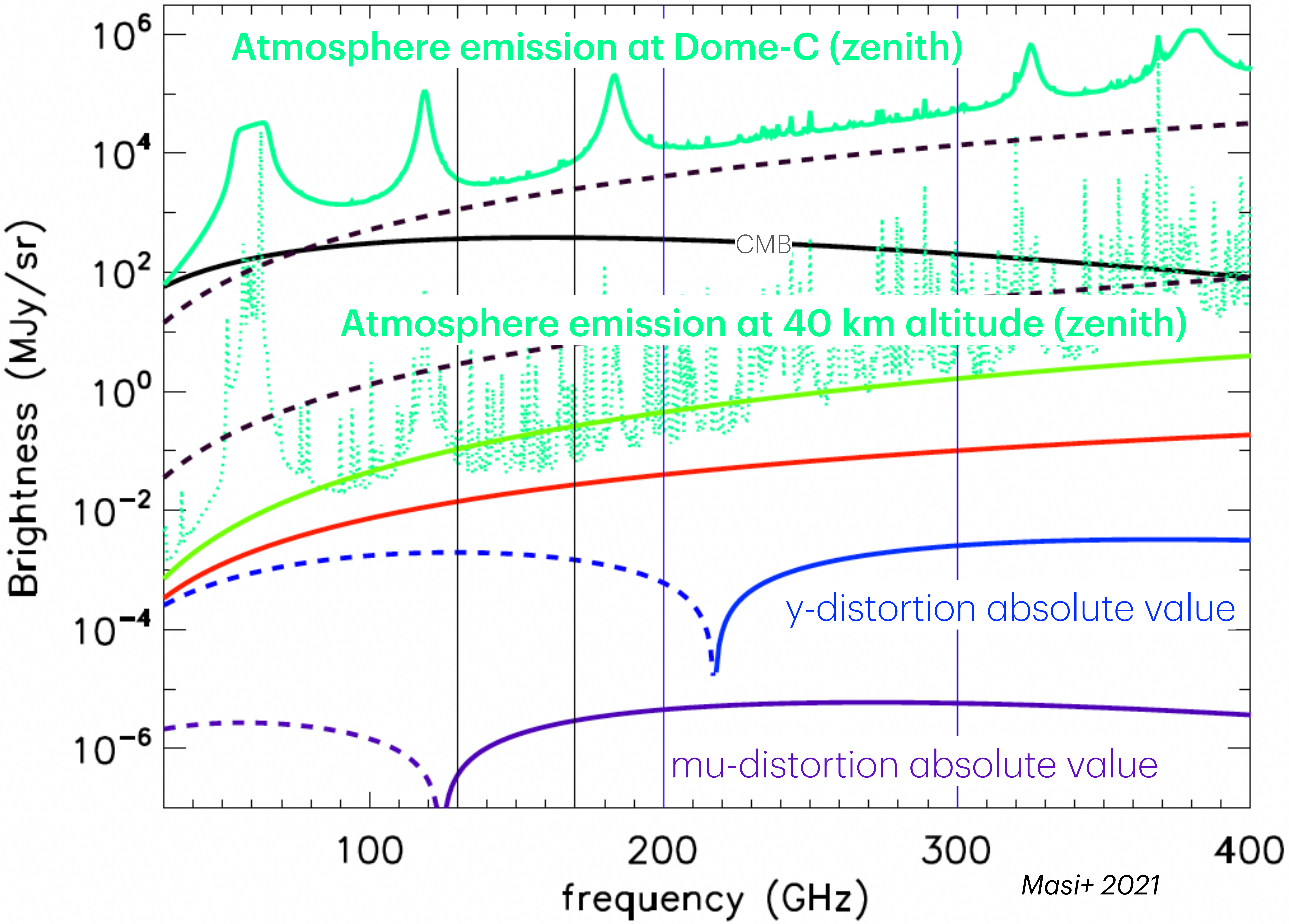
- Summer flight => day flight

Residual atmosphere

Some remaining points:

- Residual atmosphere
  - mitigation
  - modeling
  - modulation

- Systematics need to be analyse and forecast

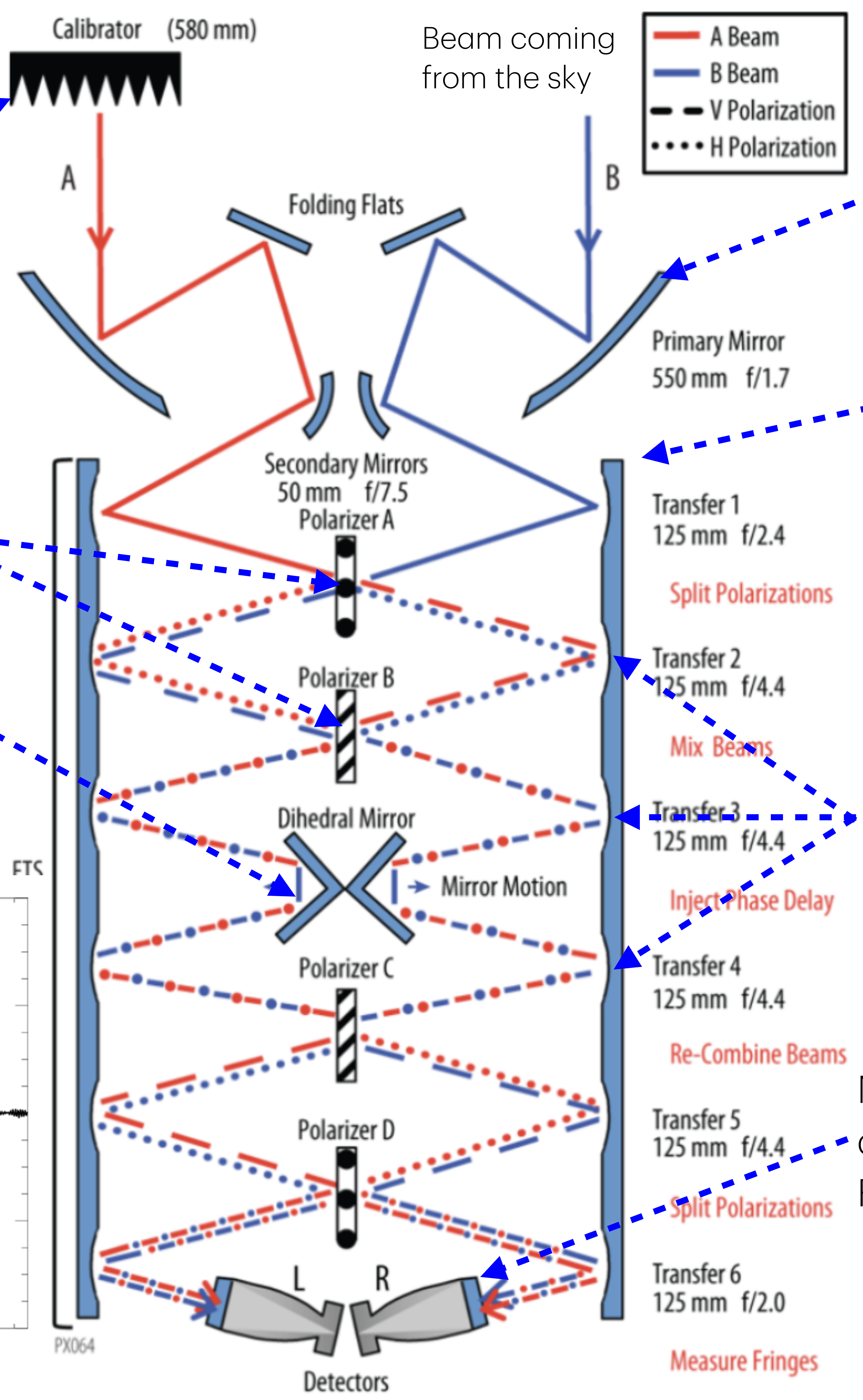


Masi+ 2021

Original instrument concept

Calibrator at 2.7 K
(reference for differential
measurement)

Beam coming
from the sky



PIXIE original concept

Kogut+ 2011

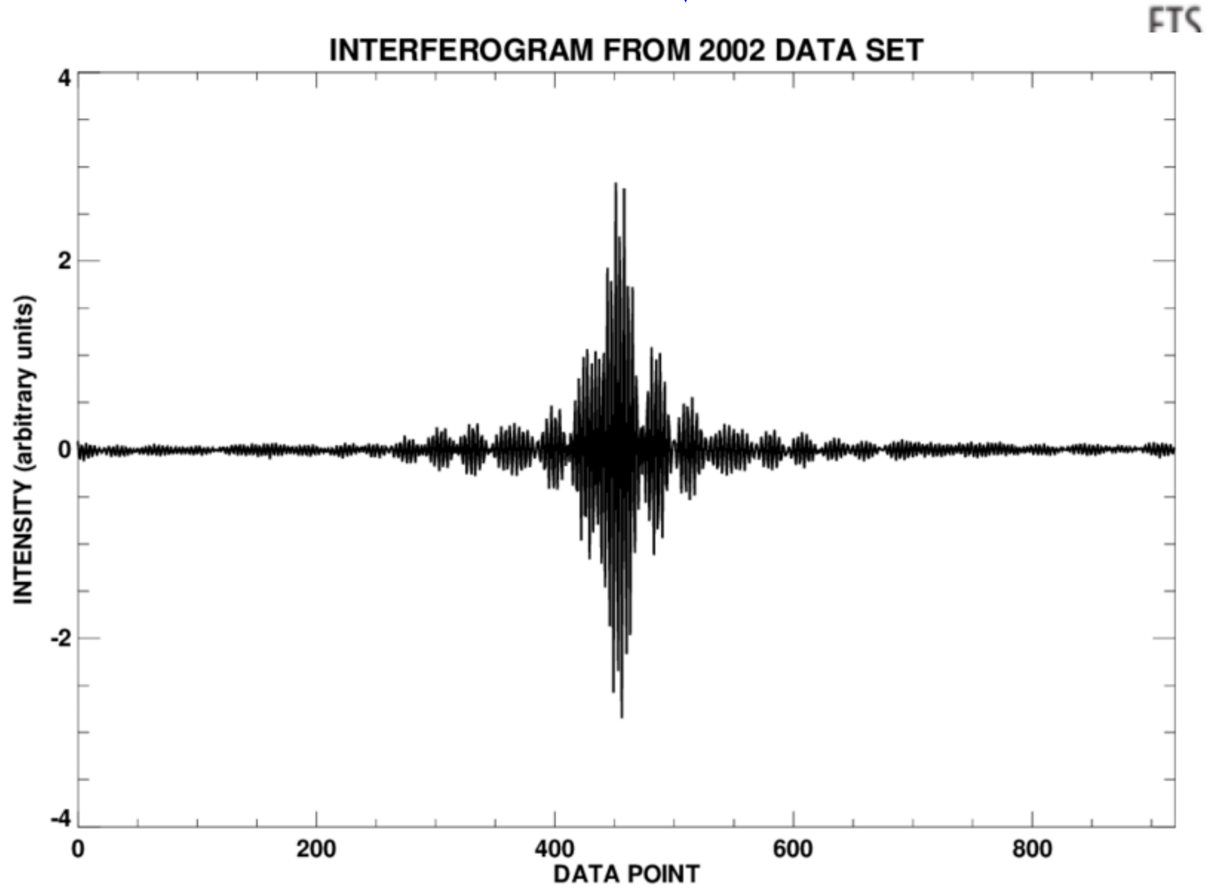
Telescope primary setting the
spatial resolution
(in conj with feed/detectors)

FTS

FTS beam dividers (polarisers
at different angles)

Also act as beam combiners

FTS scanning mirror
for interferogram



FTS mirrors

Signal proportional to difference with blackbody calibrator

$$P_{Lx} = \frac{1}{2}\int (E^2_{x,\rm sky} + E^2_{y,\rm cal}) + (E^2_{x,\rm sky} - E^2_{y,\rm cal})\cos(4z\omega/c)\; d\omega$$

$$P_{Ly} = \frac{1}{2}\int (E^2_{x,\rm cal} + E^2_{y,\rm sky}) - (E^2_{x,\rm cal} - E^2_{y,\rm sky})\cos(4z\omega/c)\; d\omega$$

$$P_{Rx} = \frac{1}{2}\int (E^2_{x,\rm cal} + E^2_{y,\rm sky}) + (E^2_{x,\rm cal} - E^2_{y,\rm sky})\cos(4z\omega/c)\; d\omega$$

$$P_{Ry} = \frac{1}{2}\int (E^2_{x,\rm sky} + E^2_{y,\rm cal}) - (E^2_{x,\rm sky} - E^2_{y,\rm cal})\cos(4z\omega/c)\; d\omega$$

Multi-moded detectors
at each output of the
FTS

Instrument cooled down to ~3 K

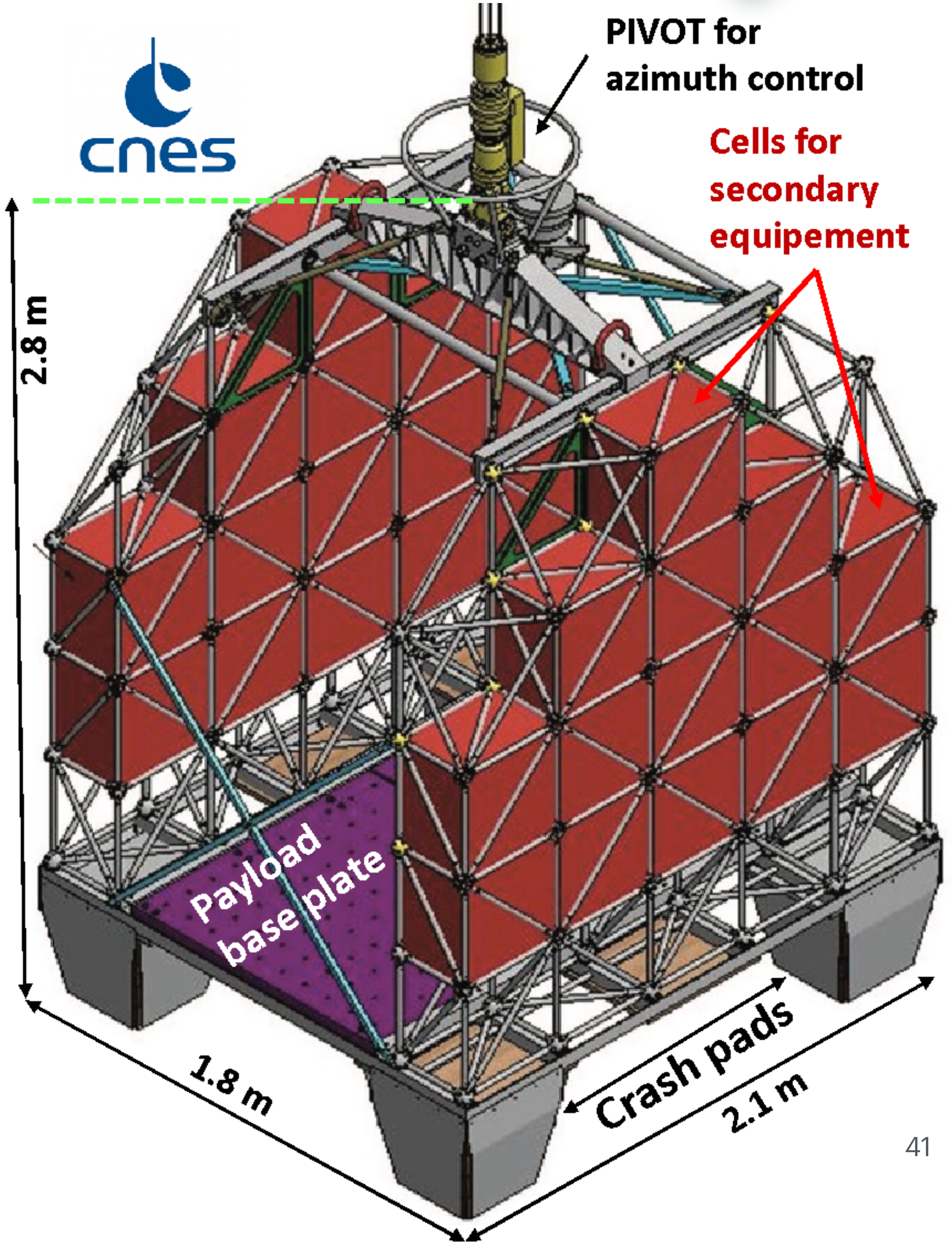
- To reduced internal emission

Detector cooled down to ~100mK

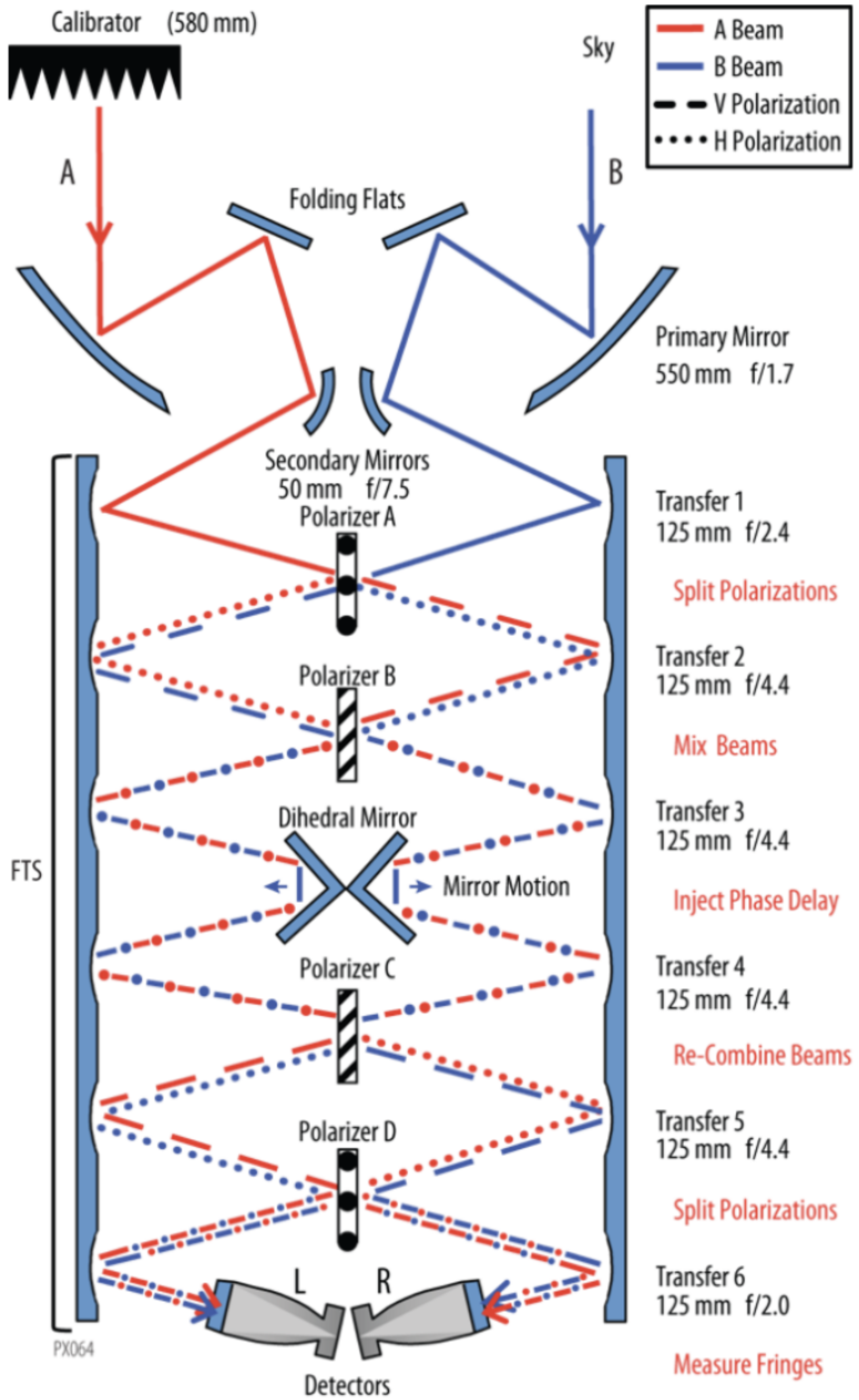
- To be photon noise limited

Balloon constraints

- Mass and size limit
- Limited observation time
  - See later
- Line of sight
  - Minimum 20 deg angle of sight from zenith (balloon above)
- Additional components
  - Cryostat window and filters
  - Higher photon noise
- CryoChain
  - No cryocoolers → Cryogens (Liquid He)
- Residual atmosphere
  - About 3 mbars at 40 kms altitude



Original instrument concept

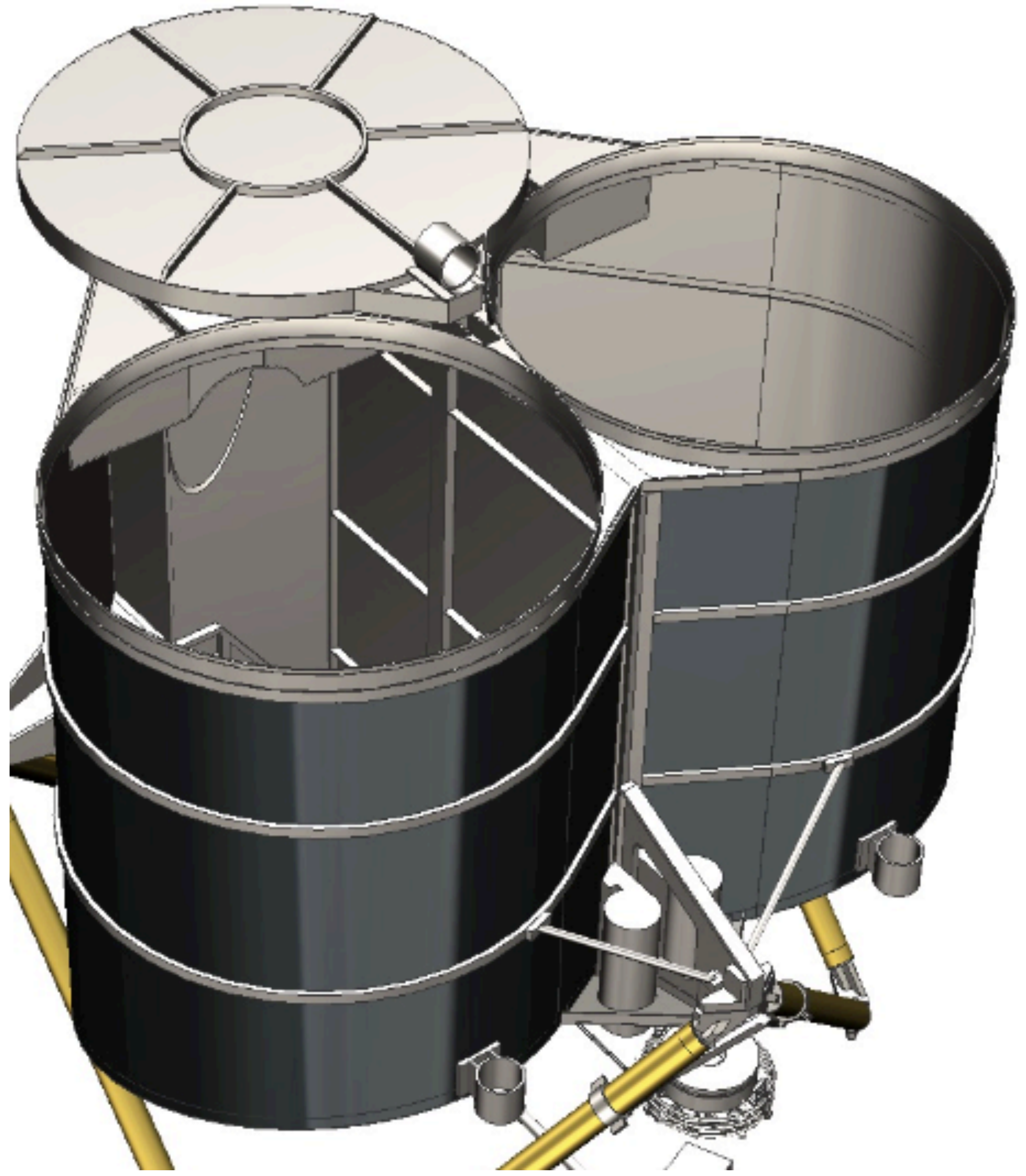


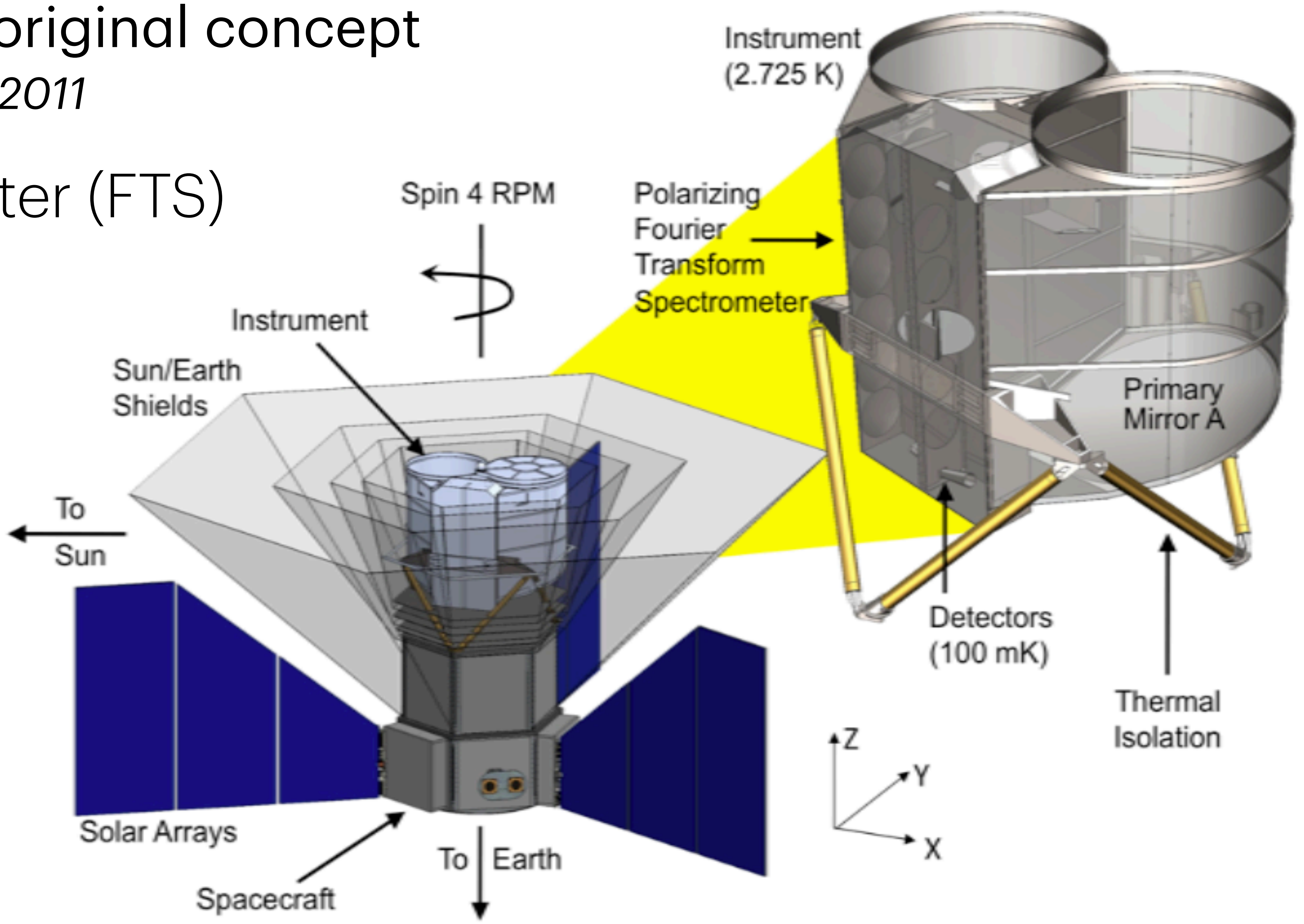
PIXIE original concept

Kogut+ 2011

Fourier **T**ransform **S**pectrometer (FTS) with 2 inputs:

- Sky
- Calibrator





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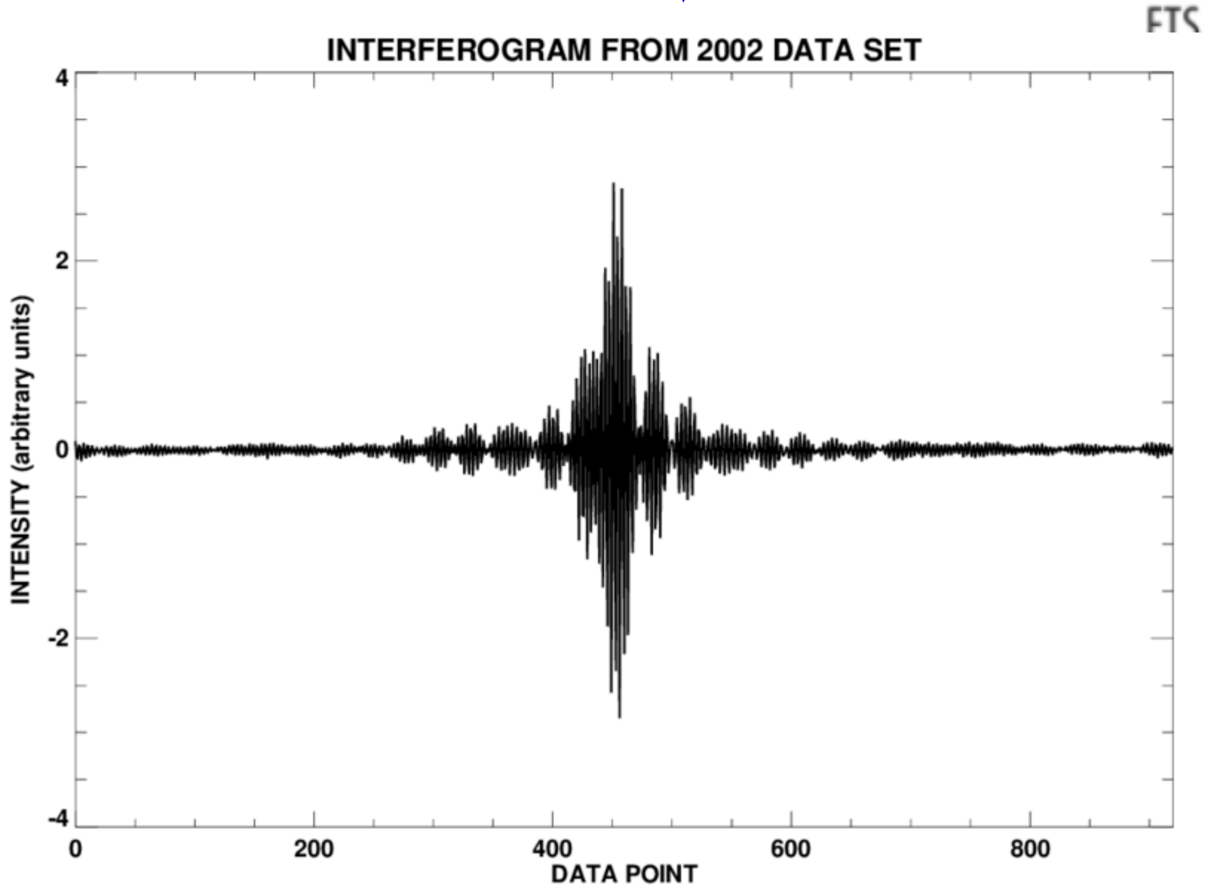
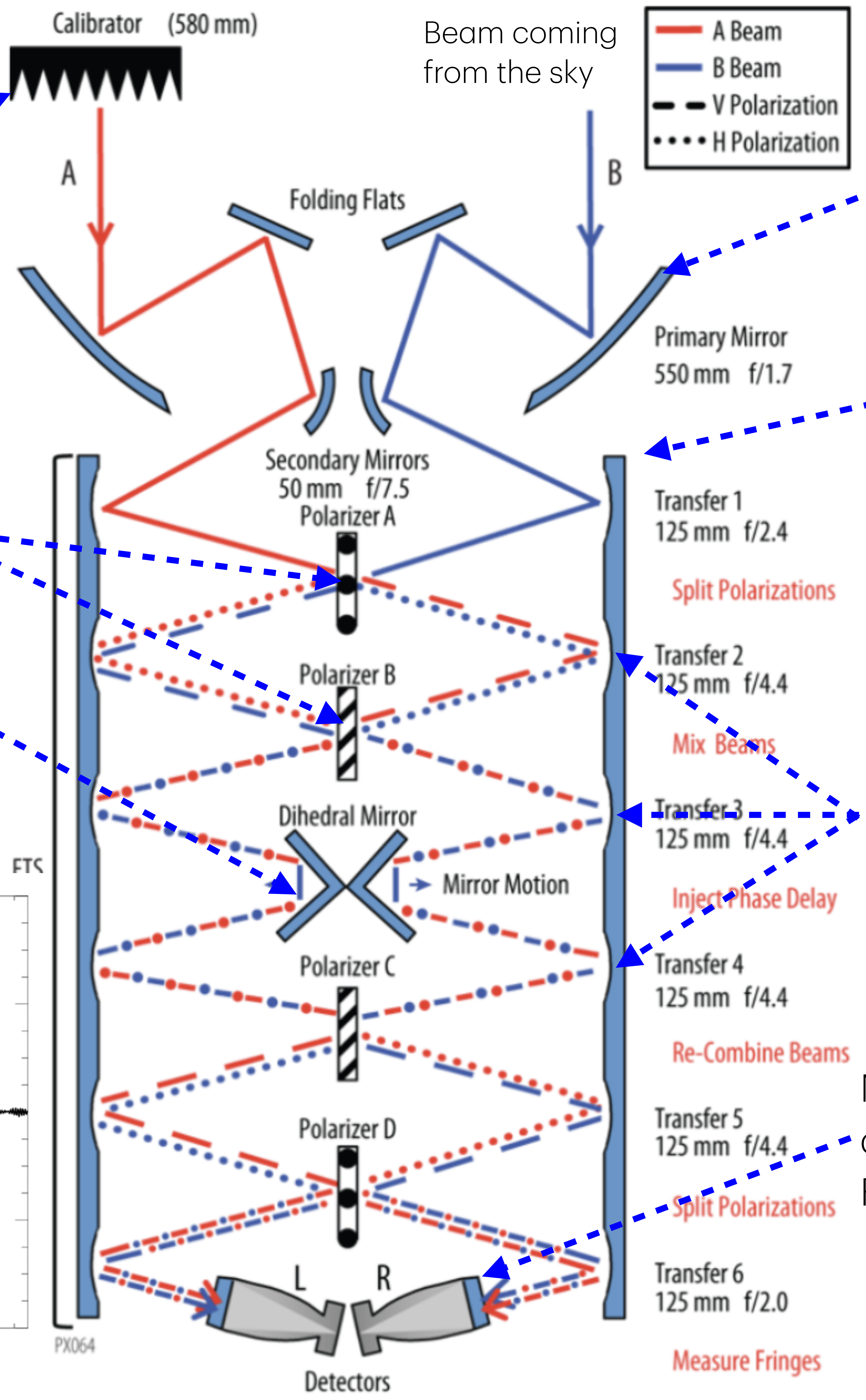
FTS scanning mirror for interferogram





PIXIE original concept

Kogut+ 2011

Telescope primary setting the spatial resolution (in conj with feed/detectors)

FTS

FTS mirrors

Multi-moded detectors at each output of the FTS

Signal proportional to difference with blackbody calibrator

$$P_{Lx} = \frac{1}{2}\int (E^2_{x,\mathrm{sky}} + E^2_{y,\mathrm{cal}}) + (E^2_{x,\mathrm{sky}} - E^2_{y,\mathrm{cal}})\cos(4z\omega/c)\, d\omega$$
$$P_{Ly} = \frac{1}{2}\int (E^2_{x,\mathrm{cal}} + E^2_{y,\mathrm{sky}}) - (E^2_{x,\mathrm{cal}} - E^2_{y,\mathrm{sky}})\cos(4z\omega/c)\, d\omega$$
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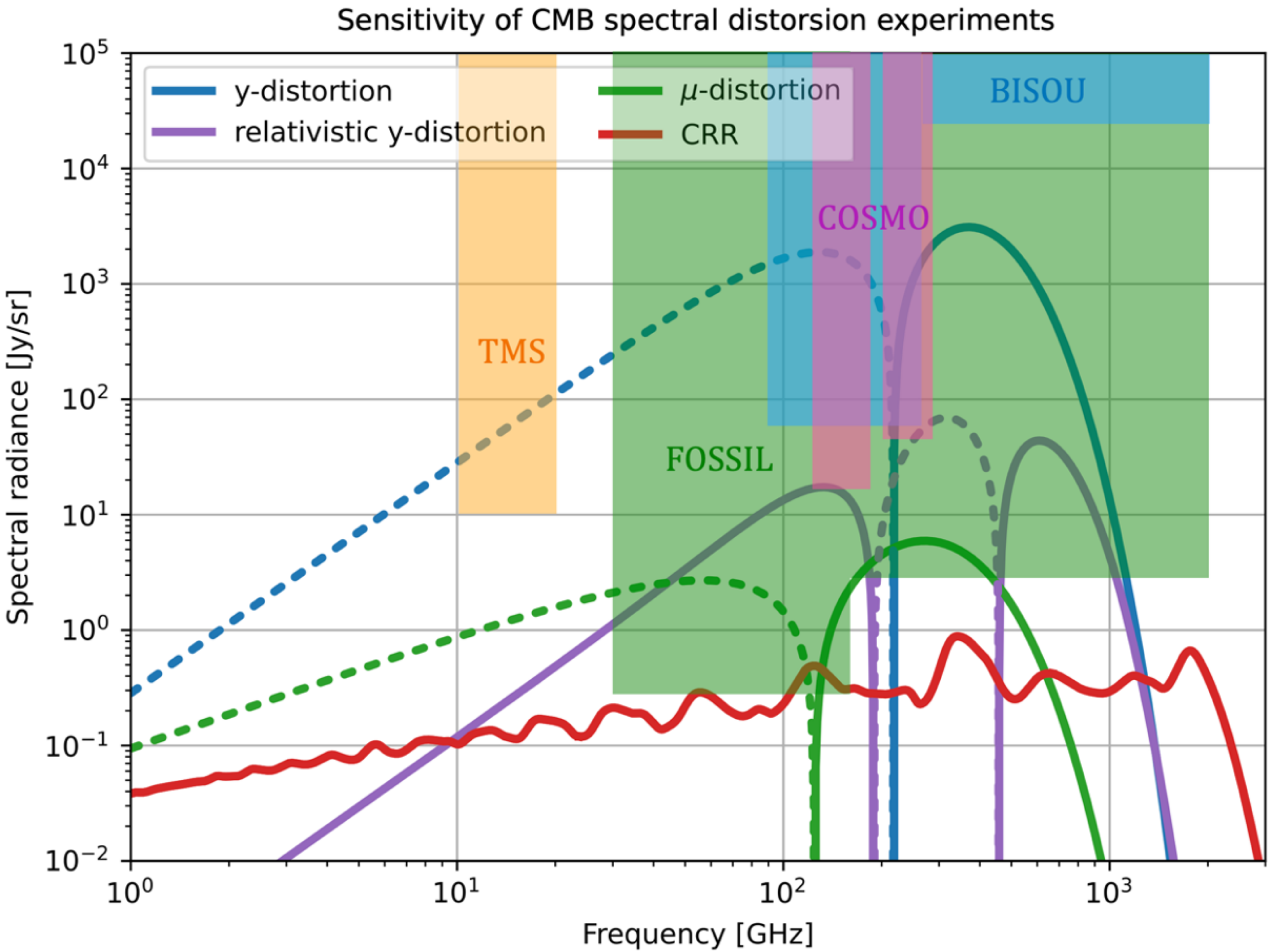
Instrument cooled down to ~3 K

- To reduced internal emission

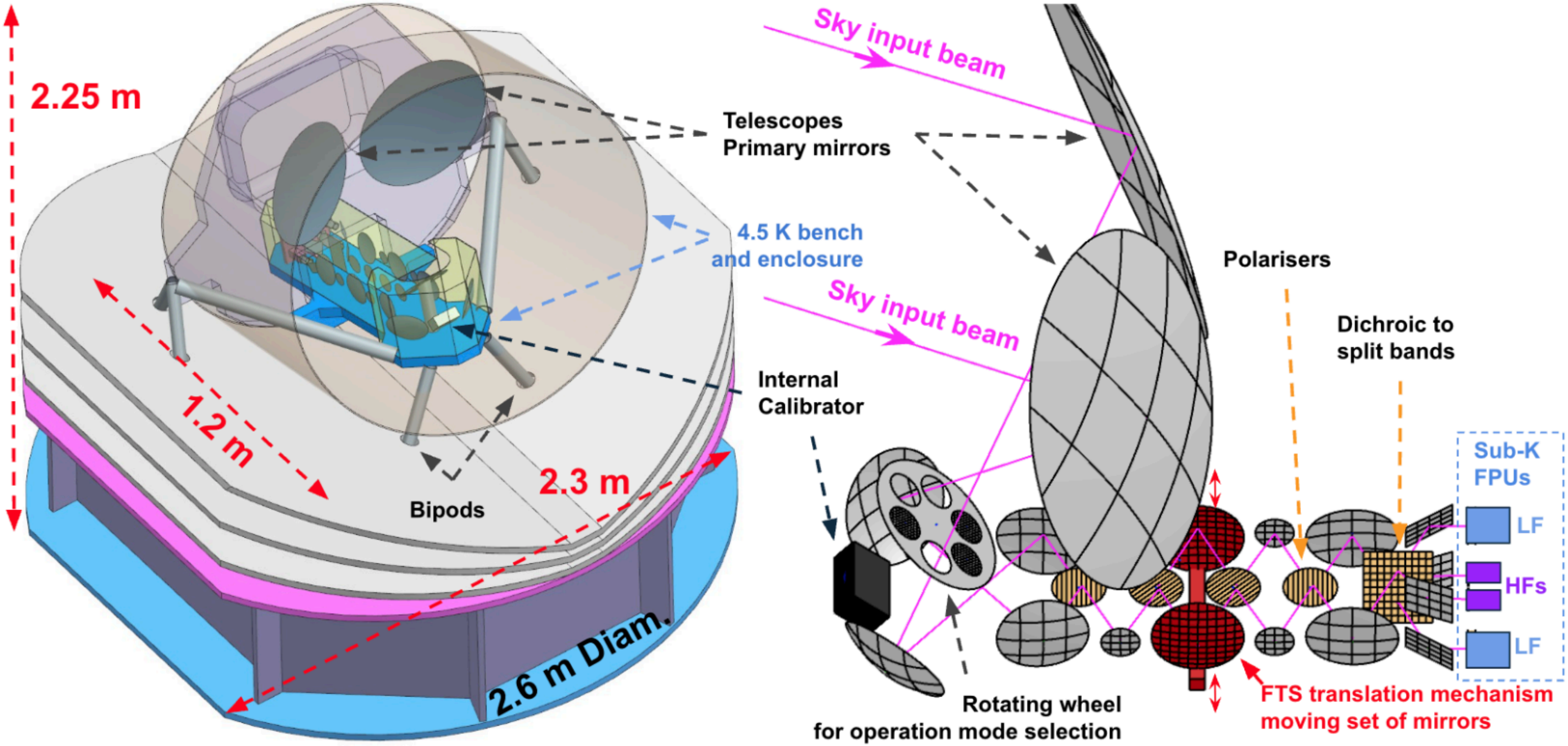
Detector cooled down to ~100mK

- To be photon noise limited

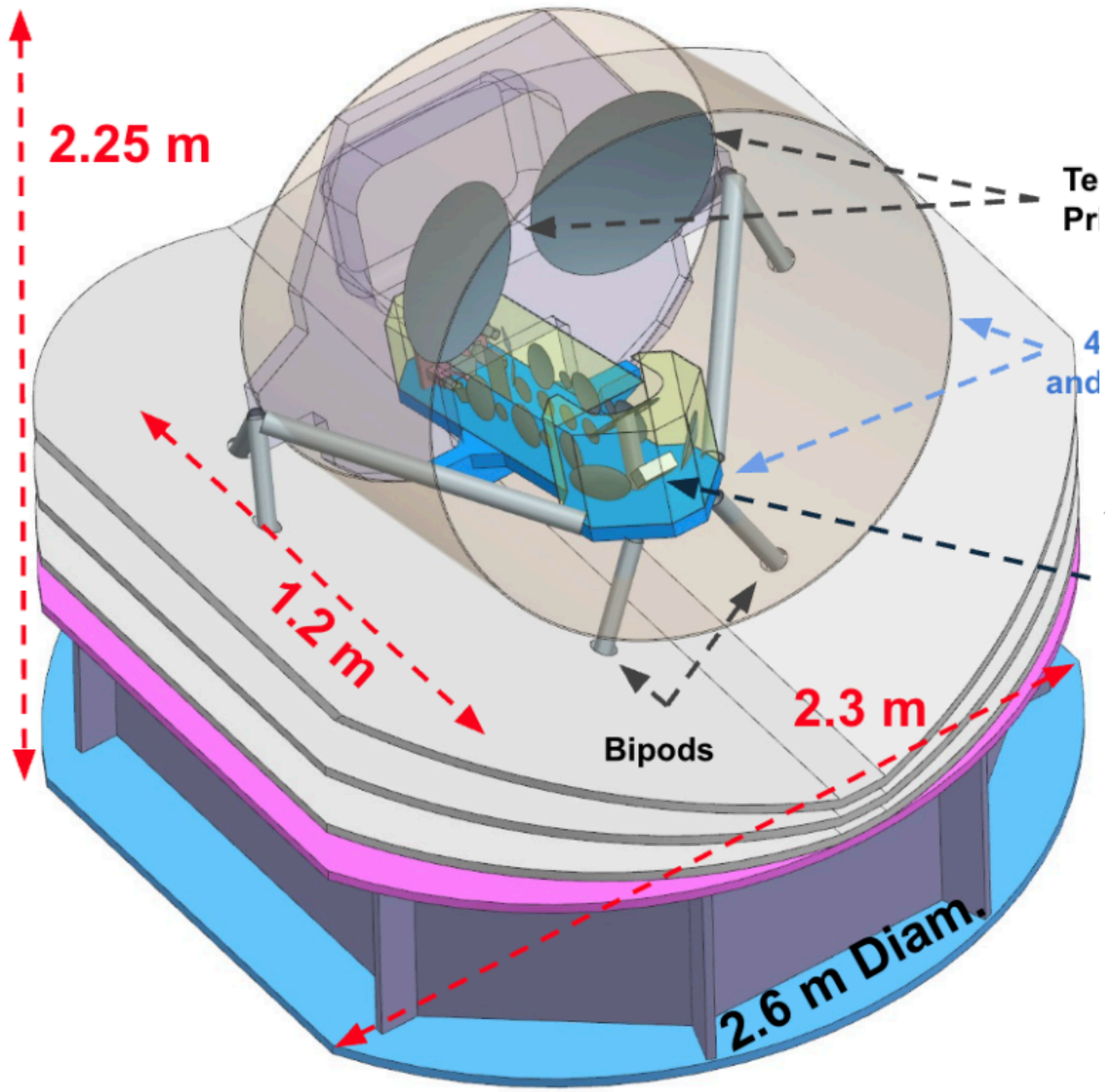
CMB experiments



Evolution: FOSSIL - M8 proposal

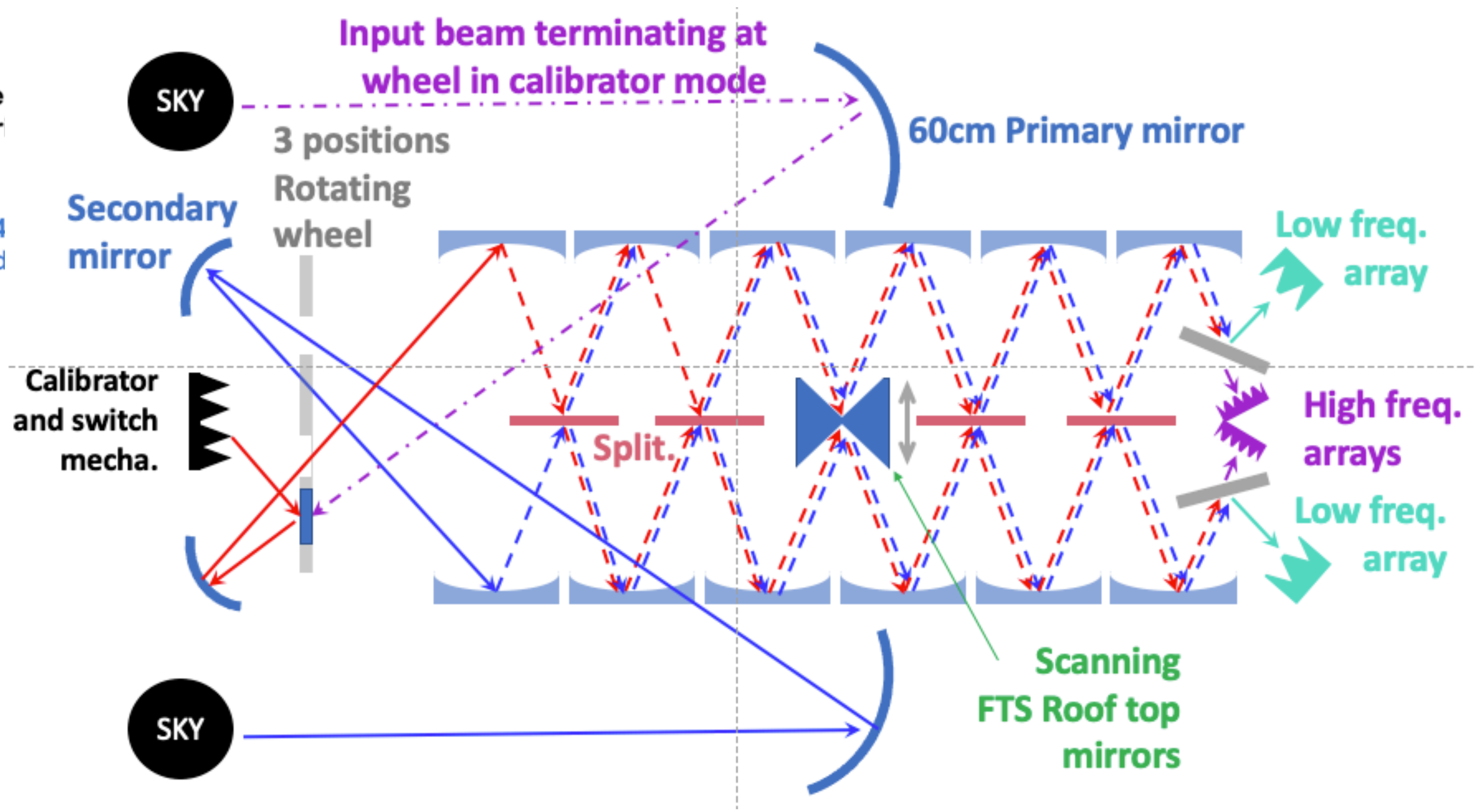


Evolution: FOSSIL



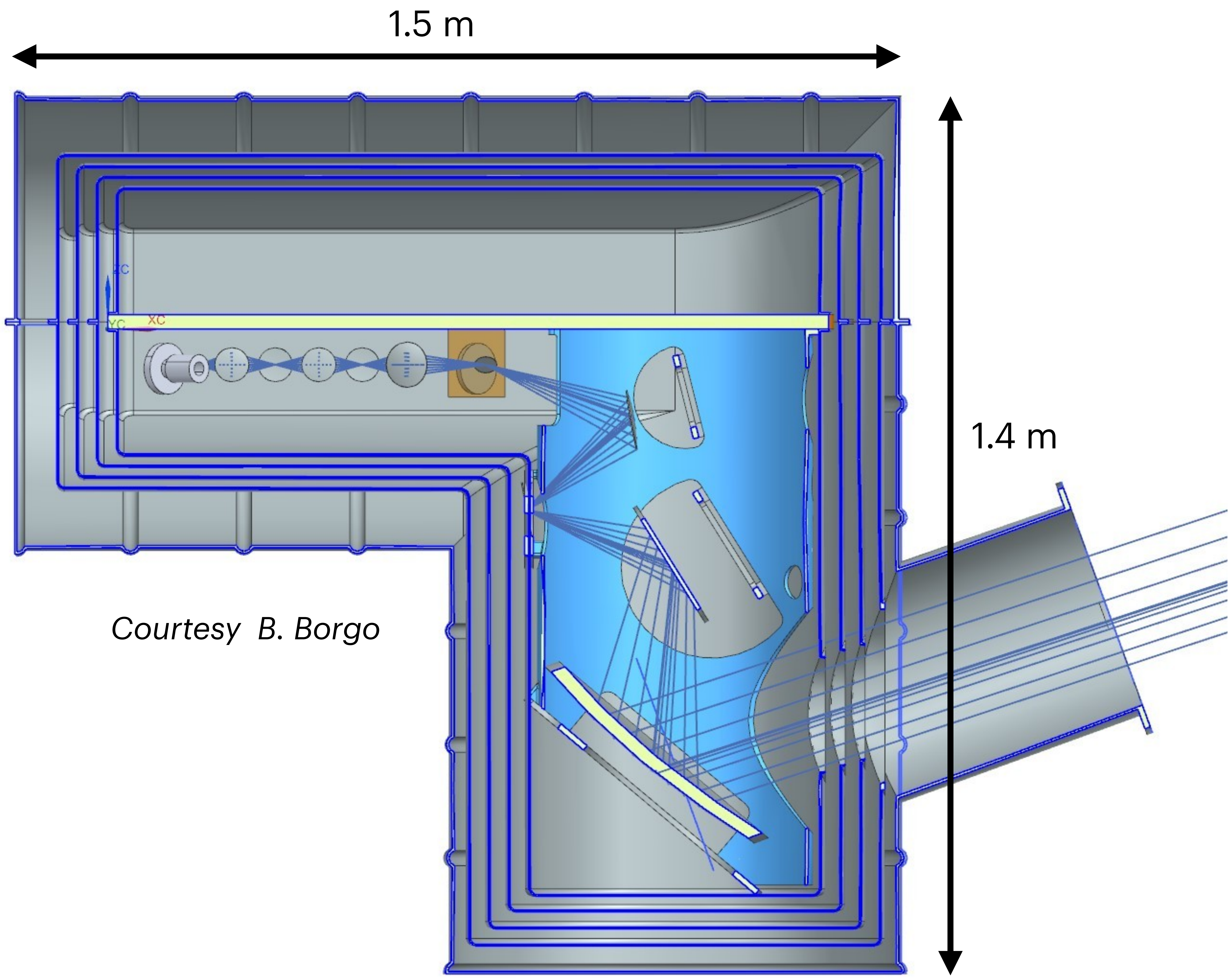
FOSSIL scheme

FOSSIL instrument concept scheme

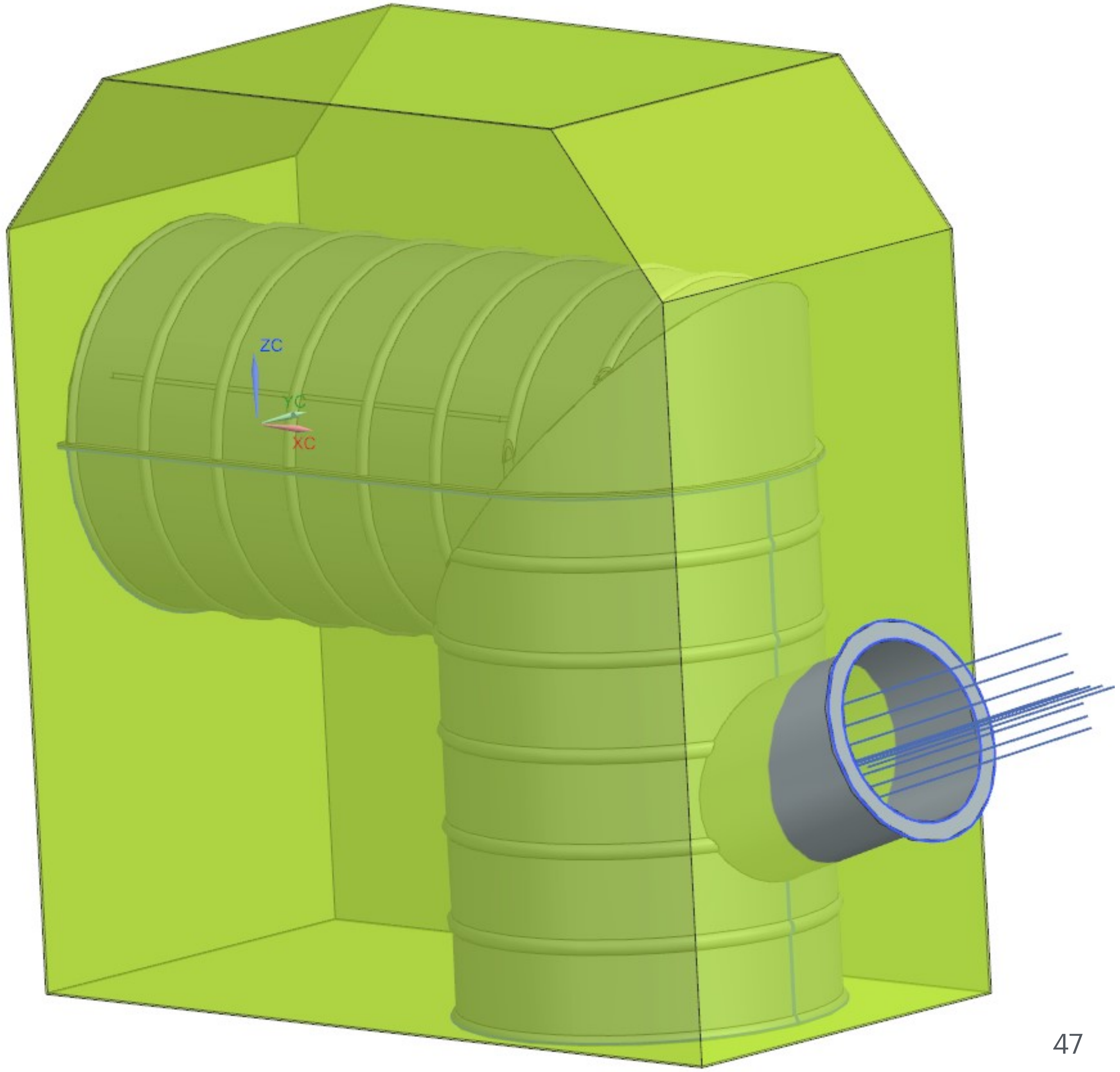


- Internal calibrator
- 2 detections bands (= 4 focal plans)

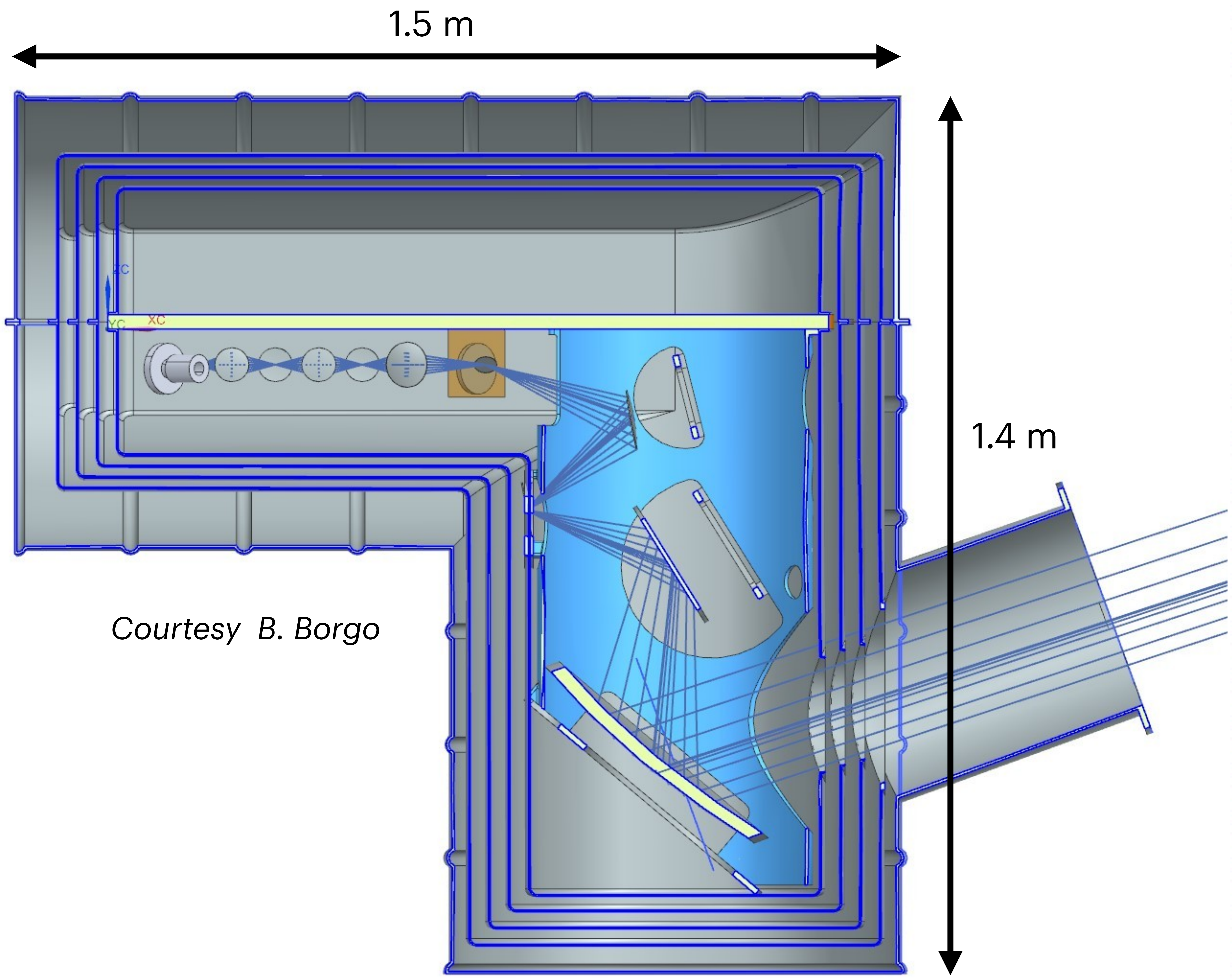
CMB spectral distortion mission : BISOU



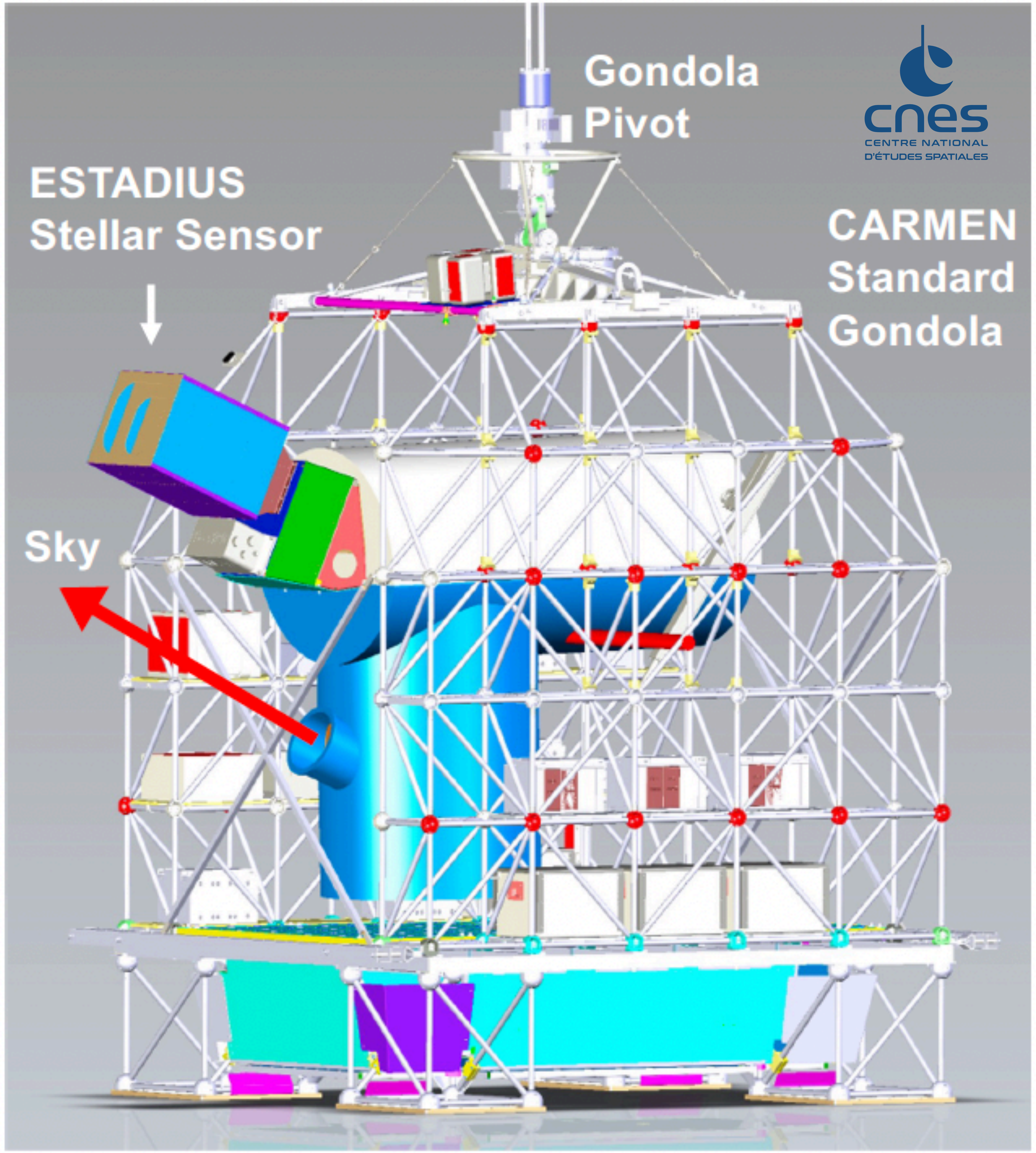
Courtesy B. Borgo



BISOU: Overview

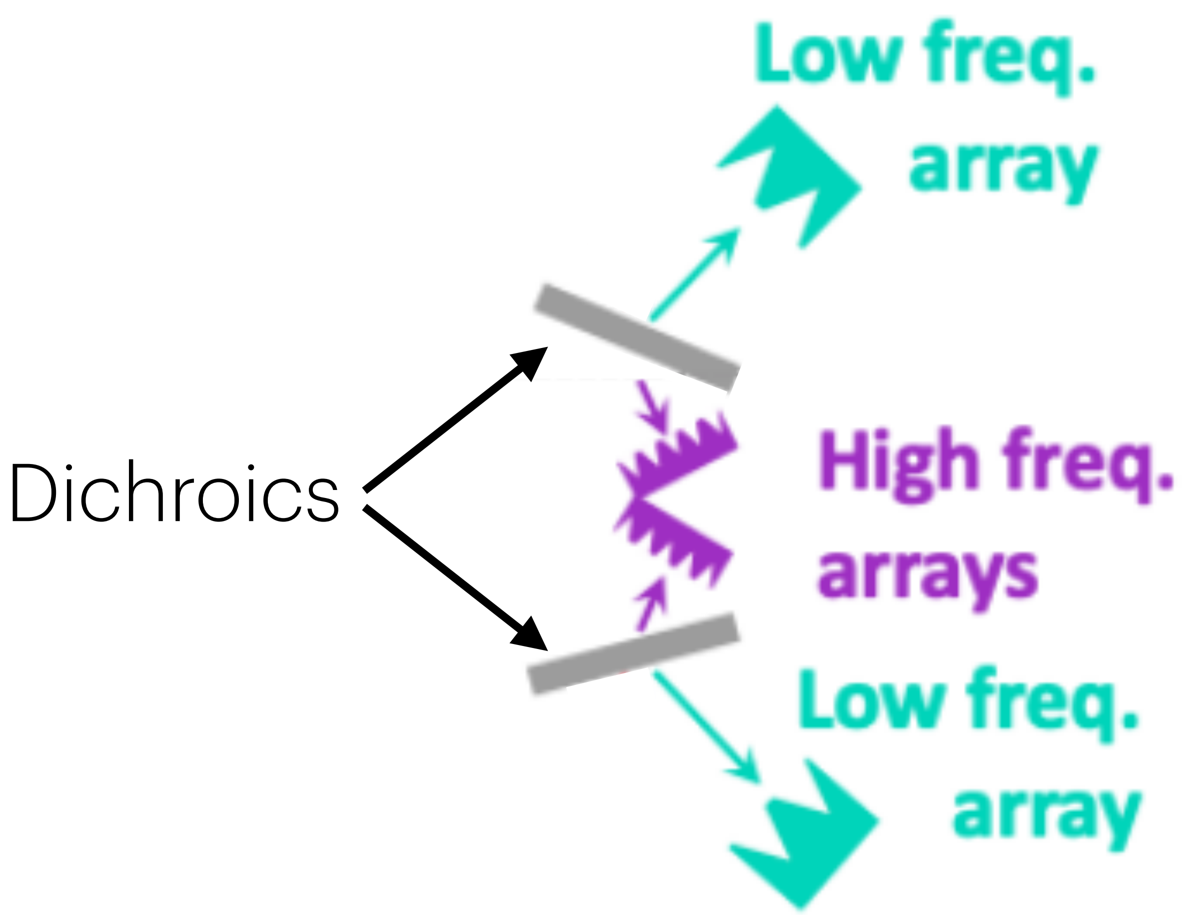


Courtesy B. Borgo



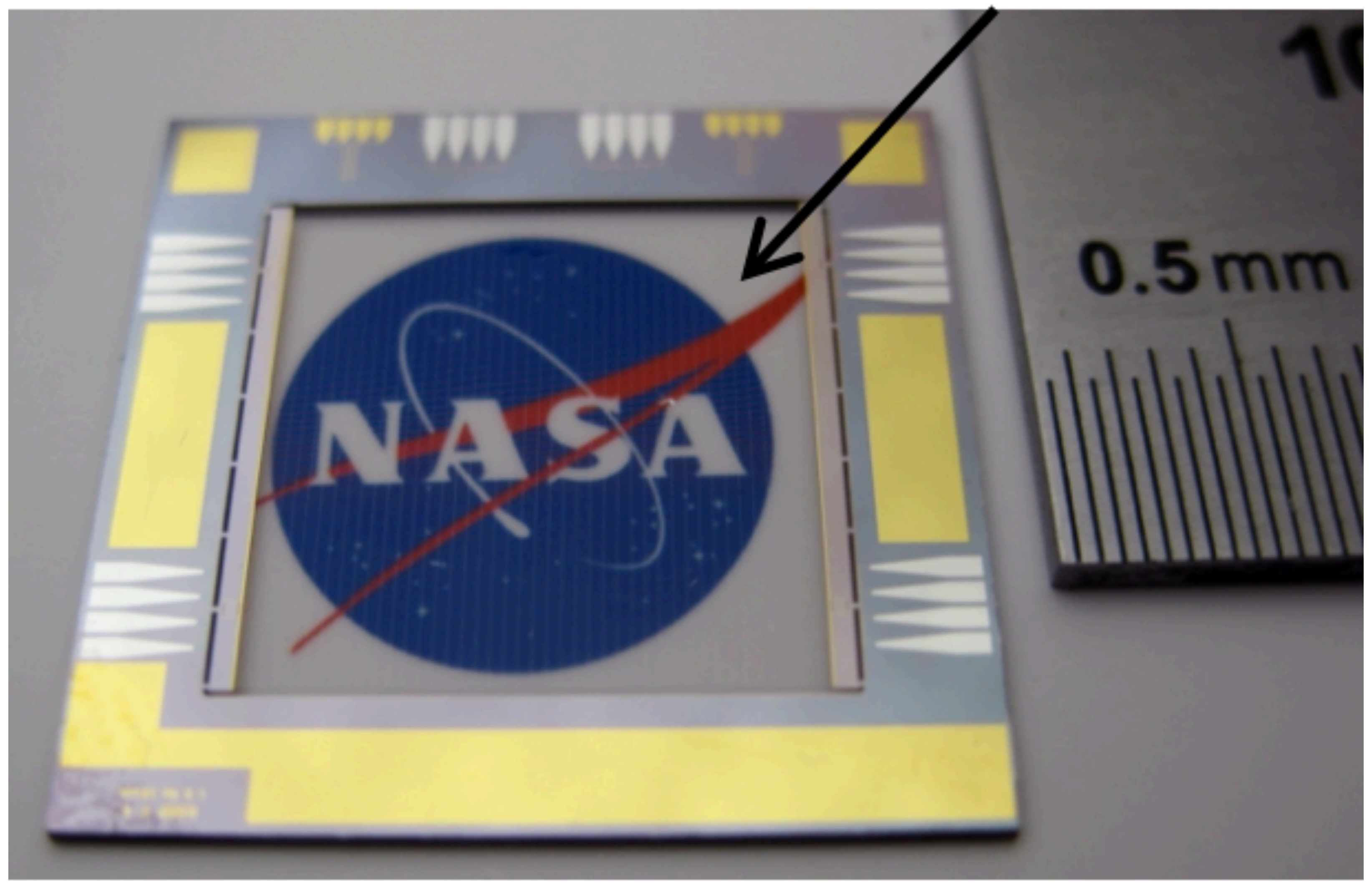
BISOU: Detectors / focal planes

- 4 focal plane units of few detectors each
  - 2 low frequency FPUs (90 – 500 GHz)
  - 2 high frequency FPUs (500 – 2000 GHz)
- Feedhorn coupled detector (baseline)
  - $NEP_{det} < \text{few } 10^{-16}$ W.Hz$^{-0.5}$ enough (high background)



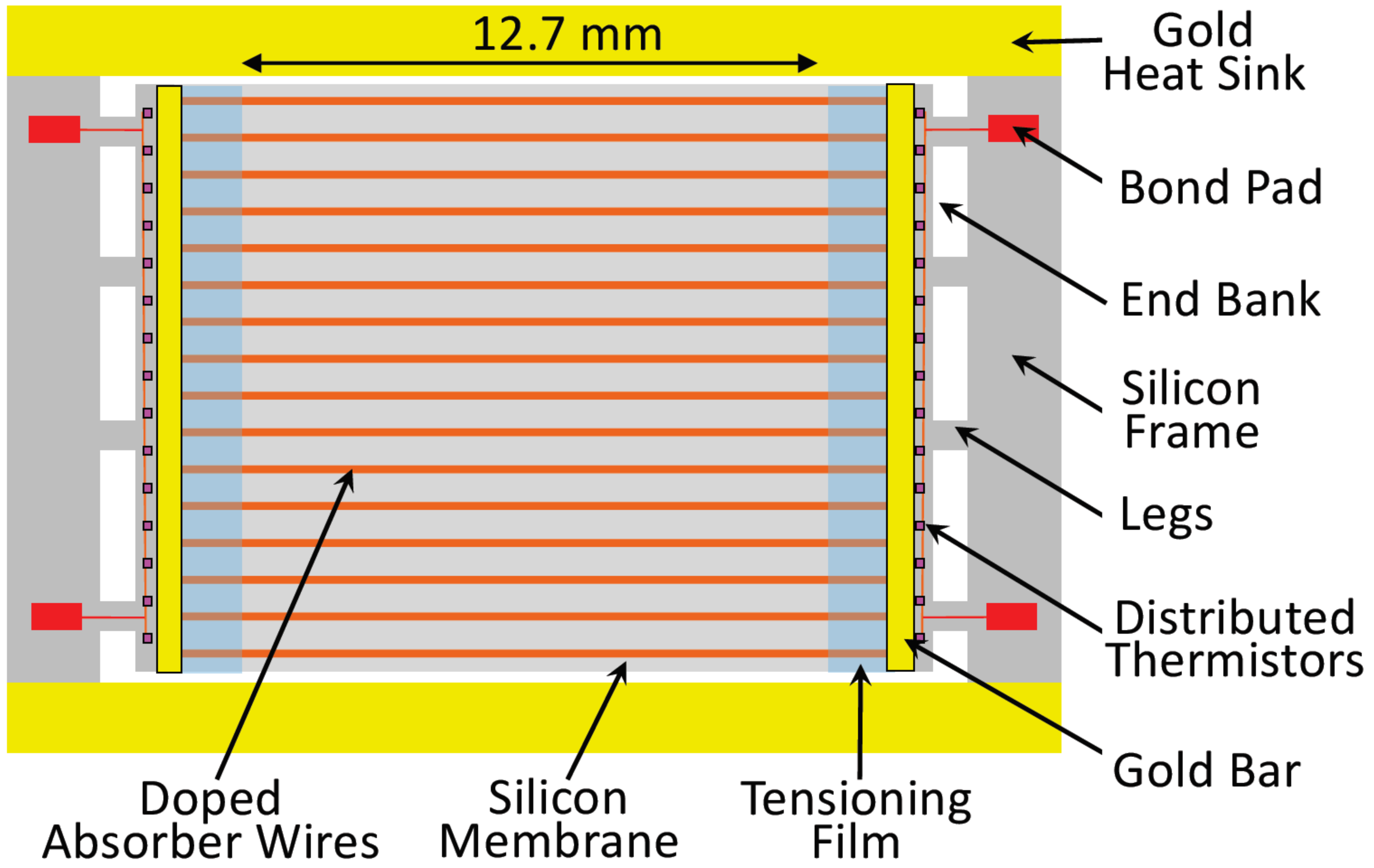
Resistive bolometers developed for PIXIE could be used across the whole frequency range of BISOU *(Kogut et al, 2011)*

30x collecting area as Planck bolometers

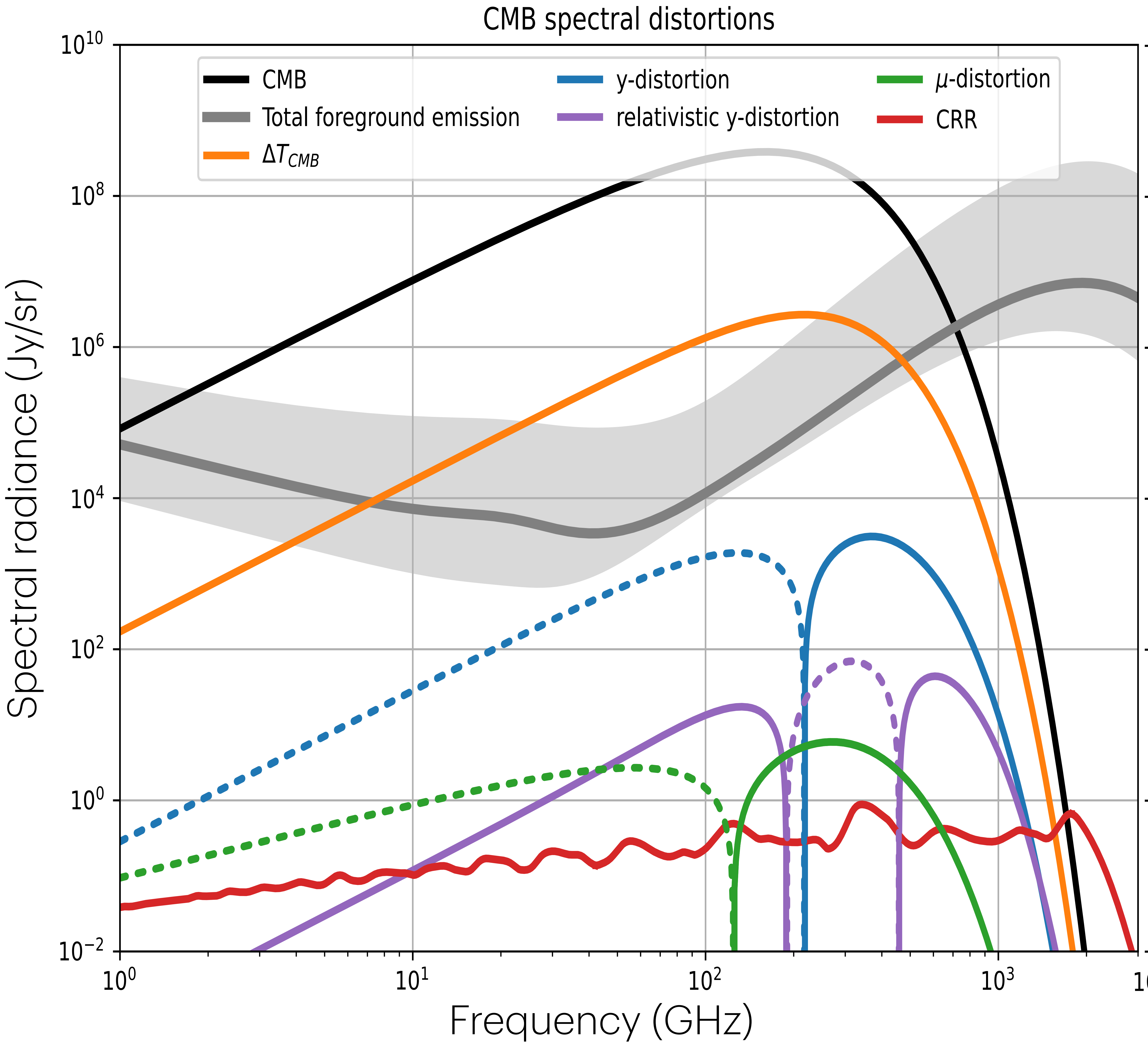


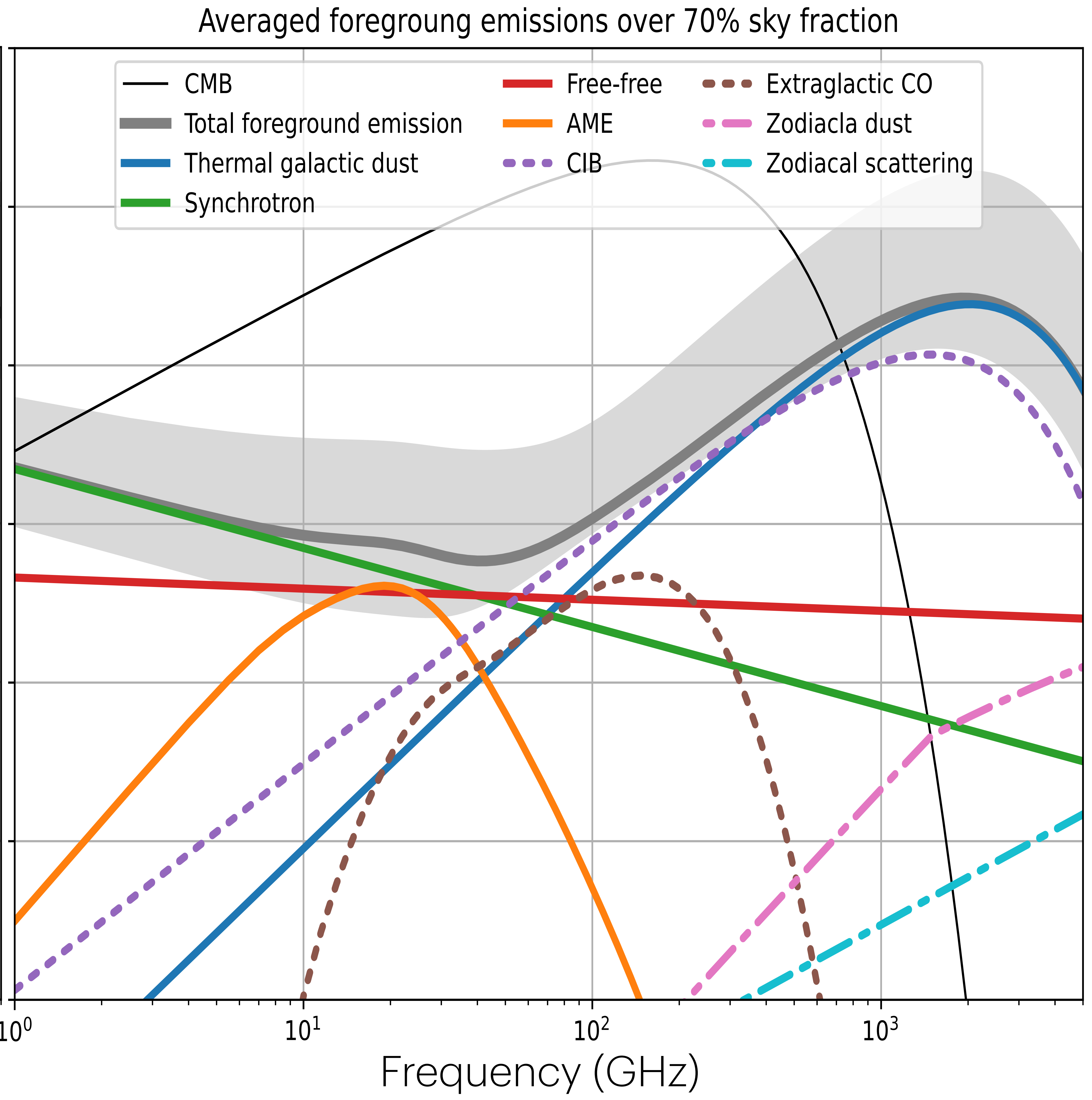
PIXIE polarization-sensitive bolometer

Courtesy A. Kogut



Sky model - Spectra



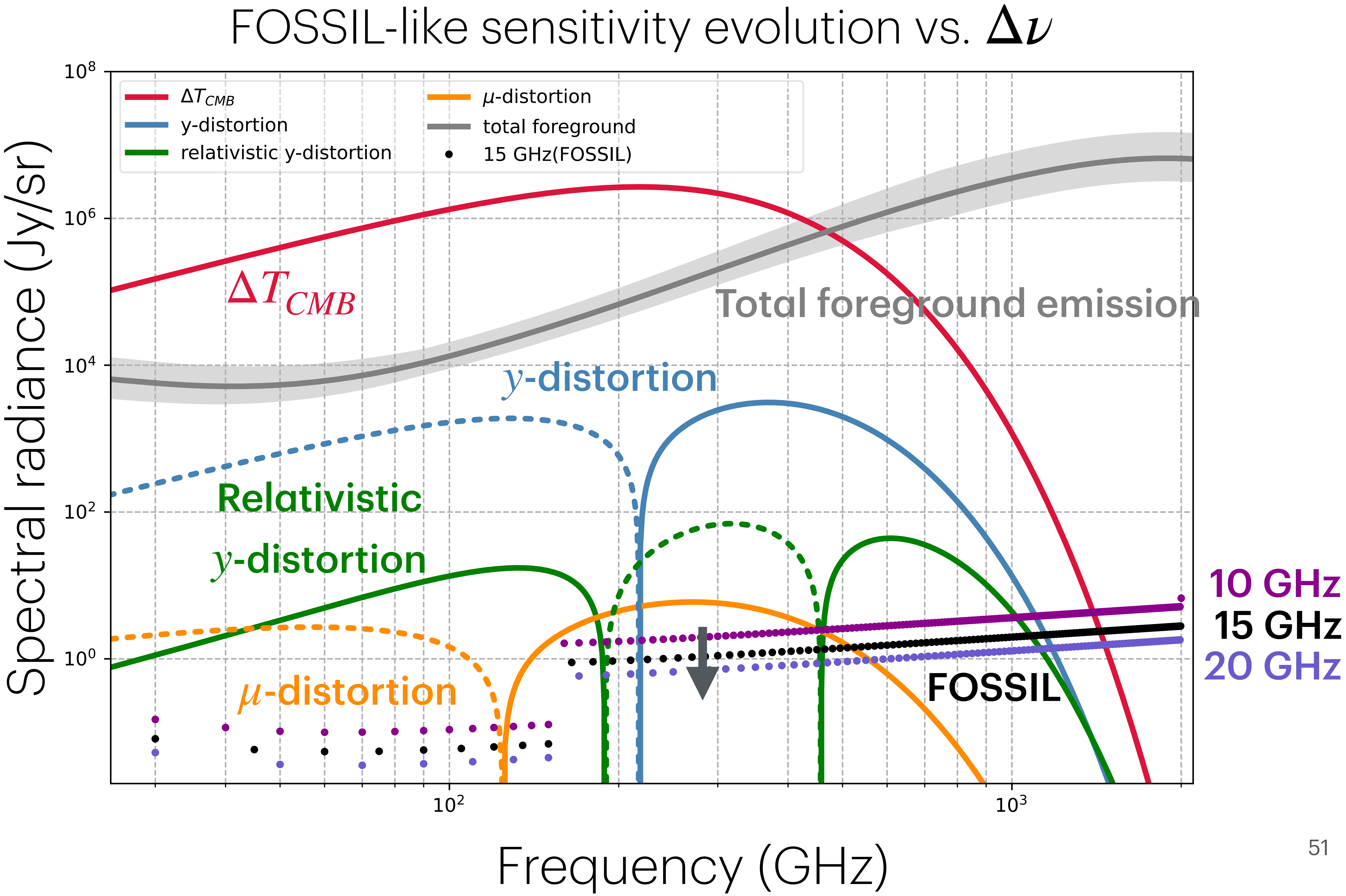


FOSSIL - $\Delta\nu$

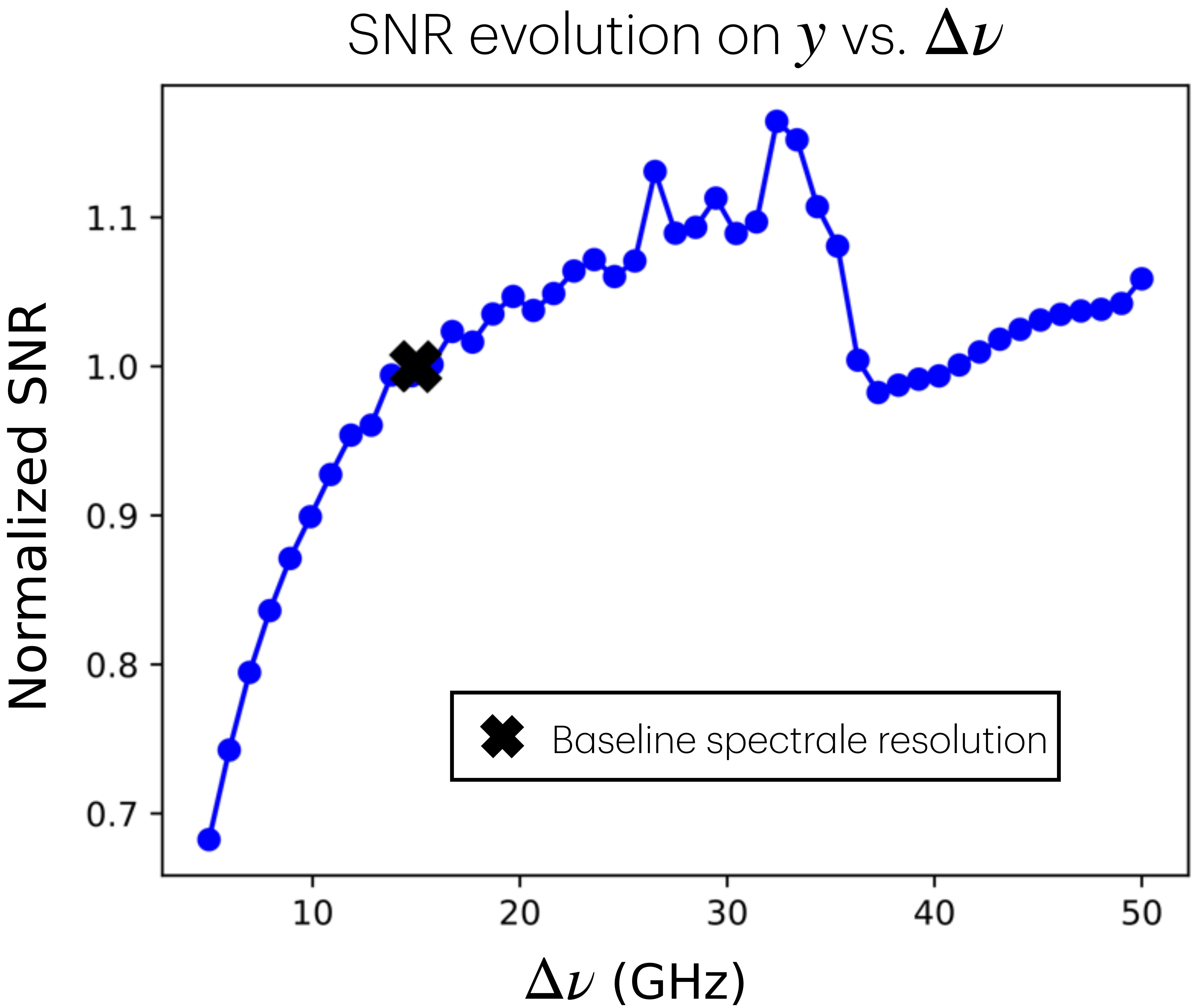
- Impact on sensitivity
  - **Lower spectral resolution**
    - Lower photon noise

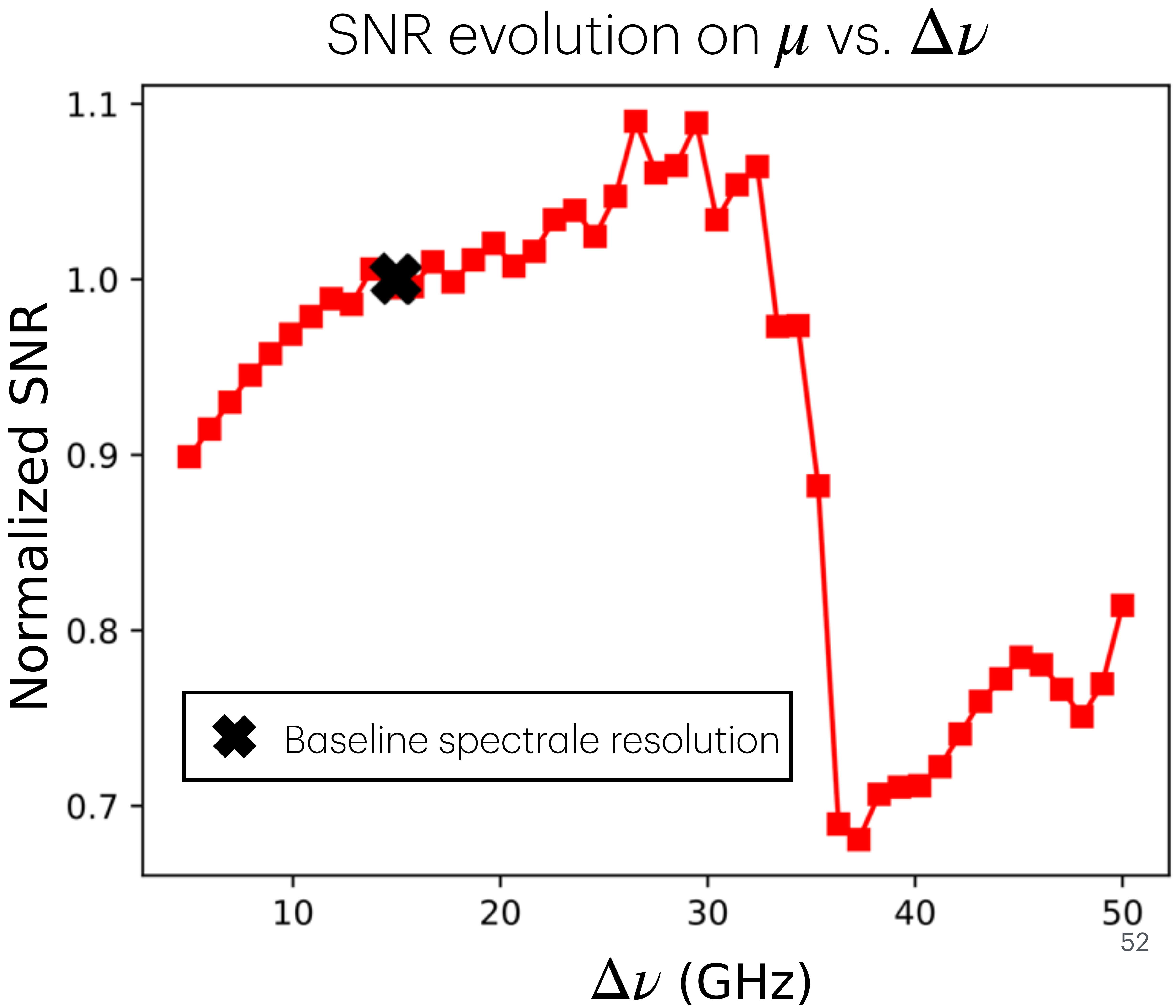
- Sensitivity is not a good performance estimator

- Need to look at forecasts



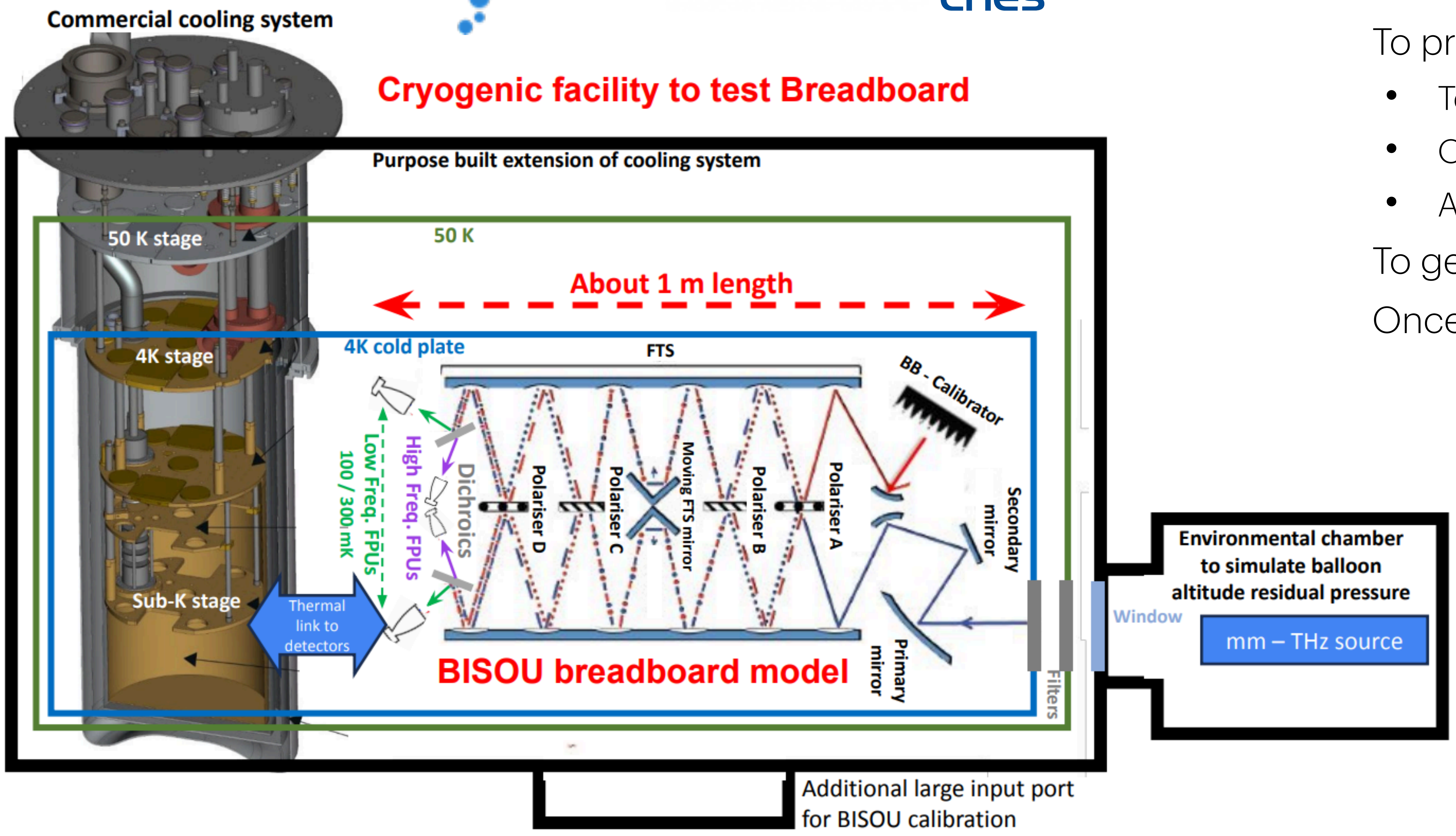
FOSSIL - $\Delta\nu$





Breadboard BISOU

Facility to study the concept of a future CMB spectral distortions project BISOU cryogenic BreadBoard development co-funded by DIM-ORIGINES (Region Ile-de-France) and CNES



Test key components ahead of BISOU final instrument

- Detectors (300 - 100 mK)
- Calibrator

Window / Filters / Dichroics

To test the overall concept on simplified system

To probe systematics

- Temperature variations
- Optics mismatch
- Atmosphere

To get used to specific FTS data and analysis

Once a sub-syst qualified => integration in real instrument

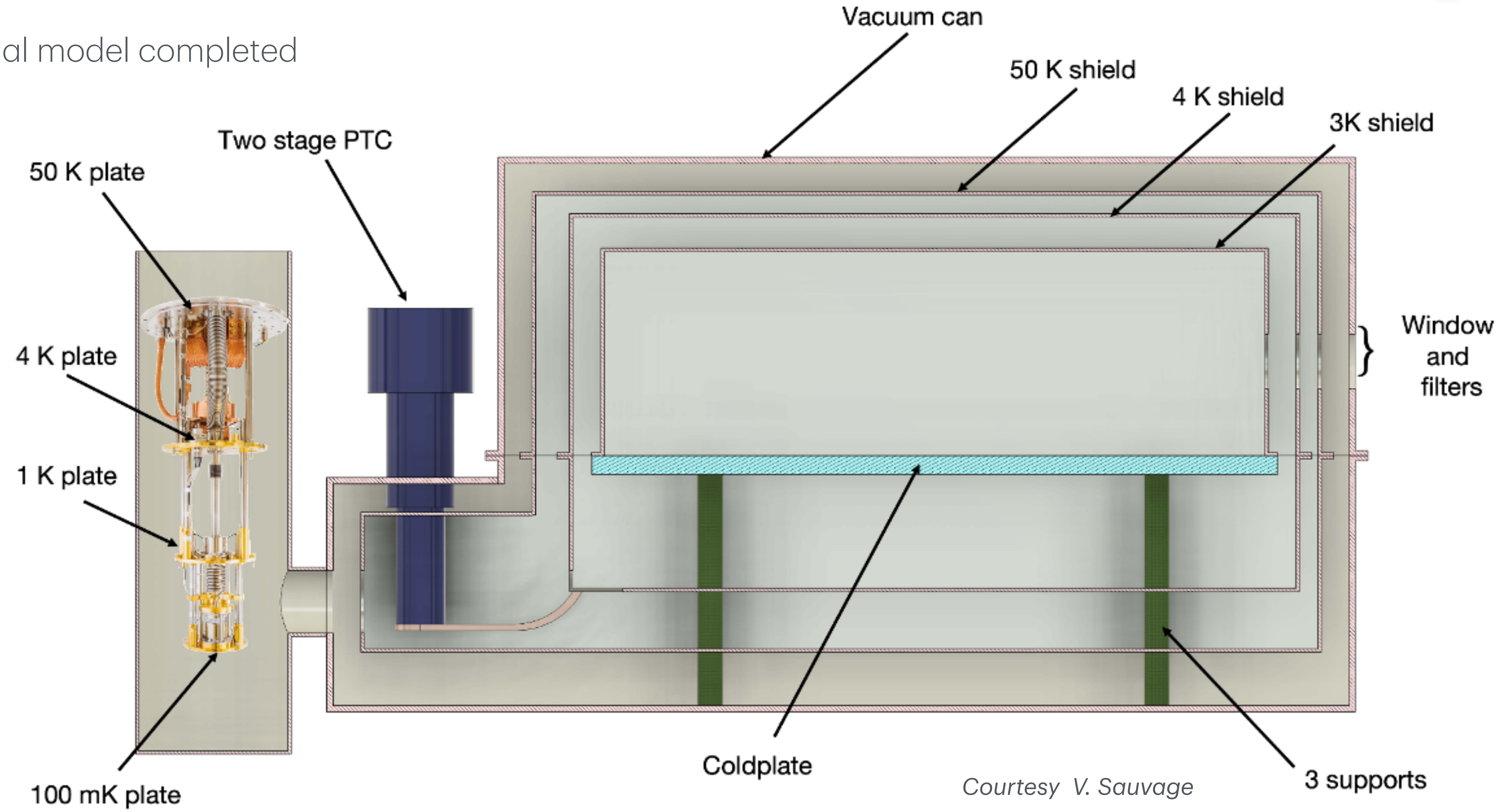
To be re-used as **BISOU calibration facility**

Facility for further development / New tech.

=> future space mission

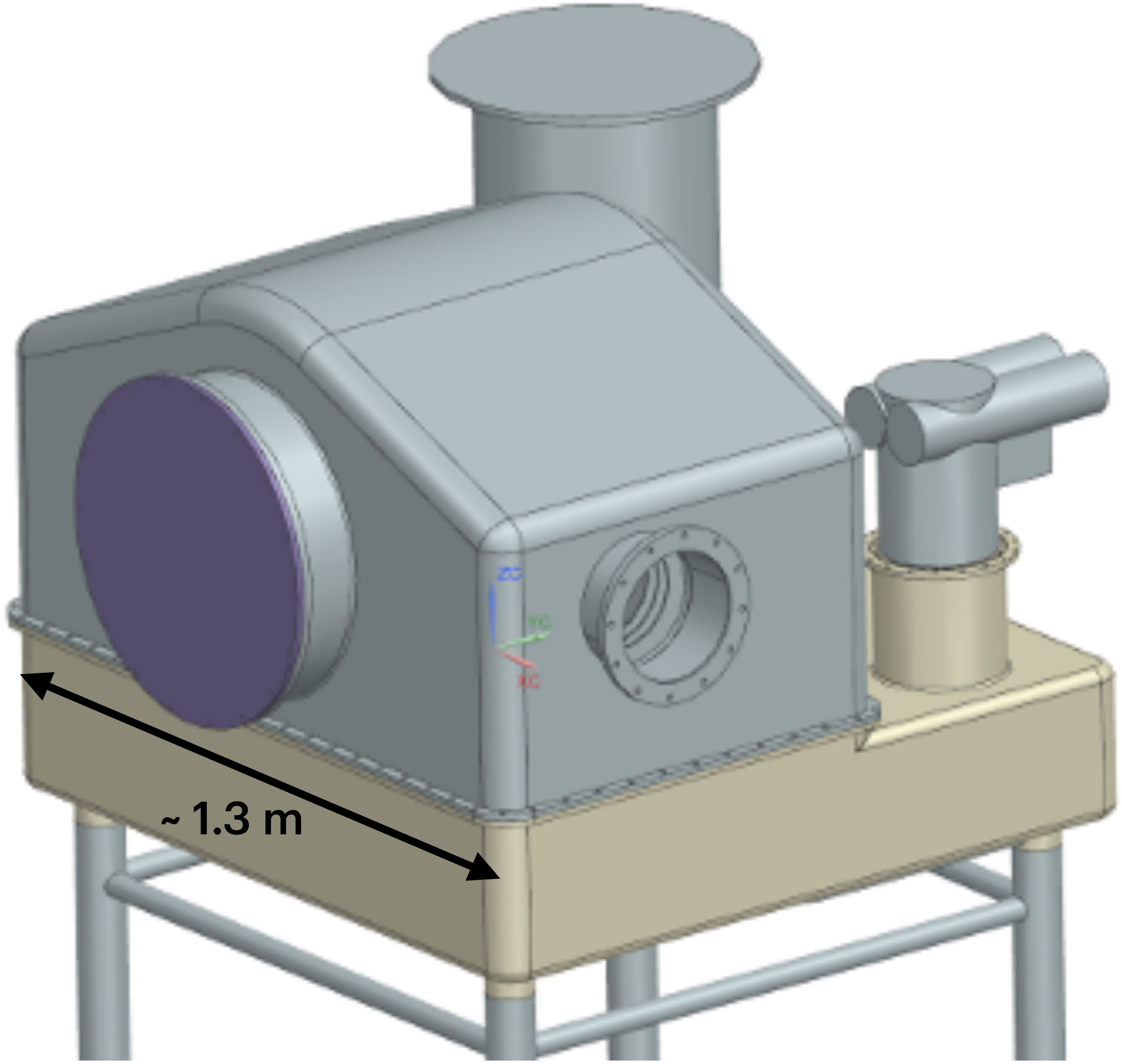
Breadboard BISOU: Overview

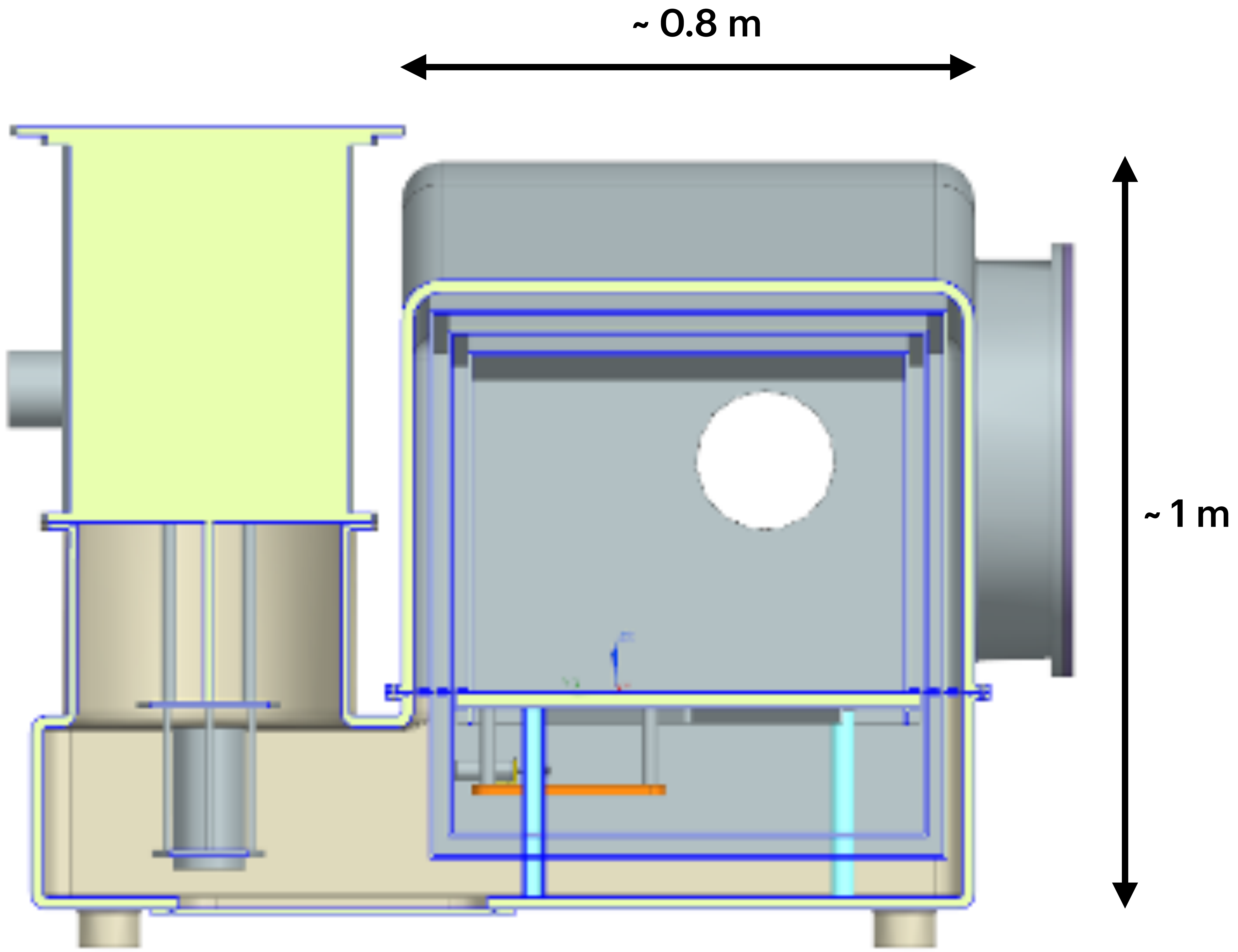
Thermal model completed



Courtesy V. Sauvage

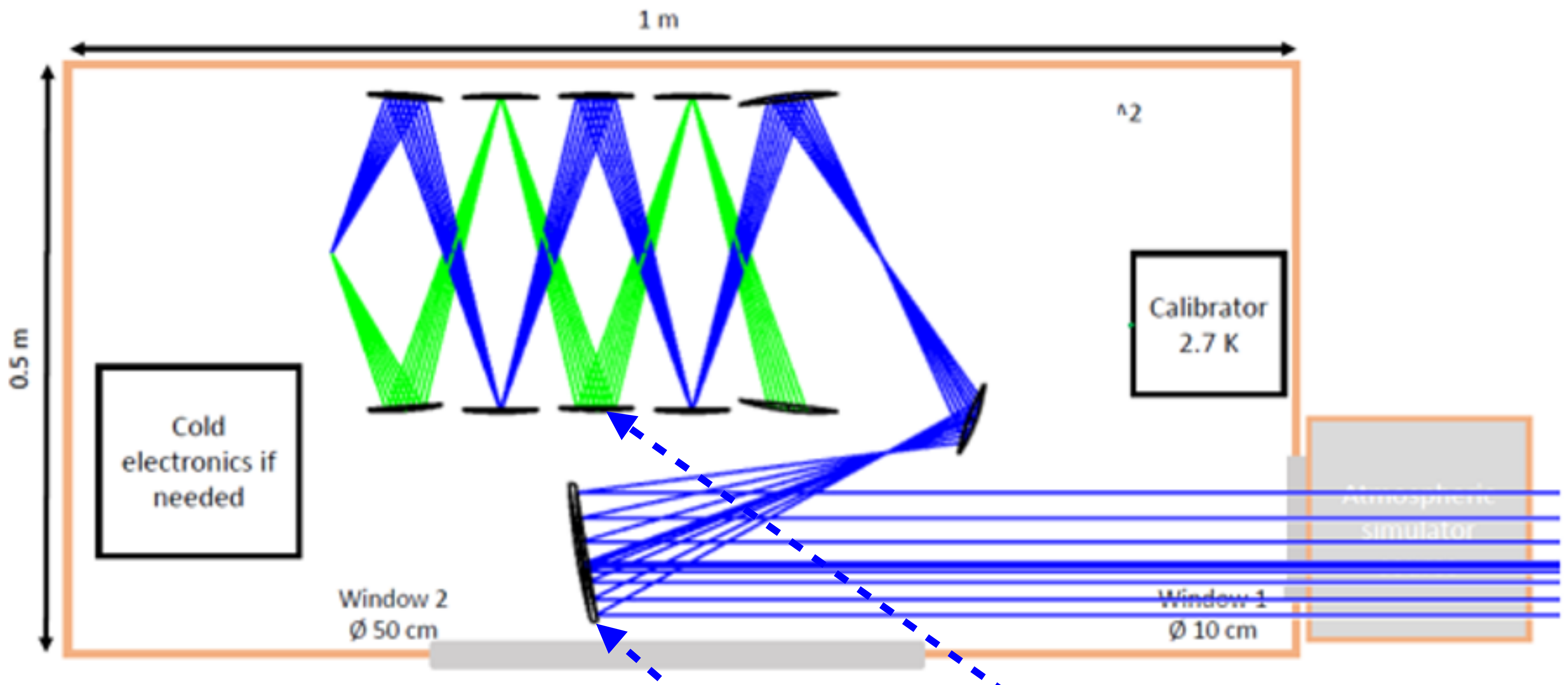
Breadboard BISOU: development



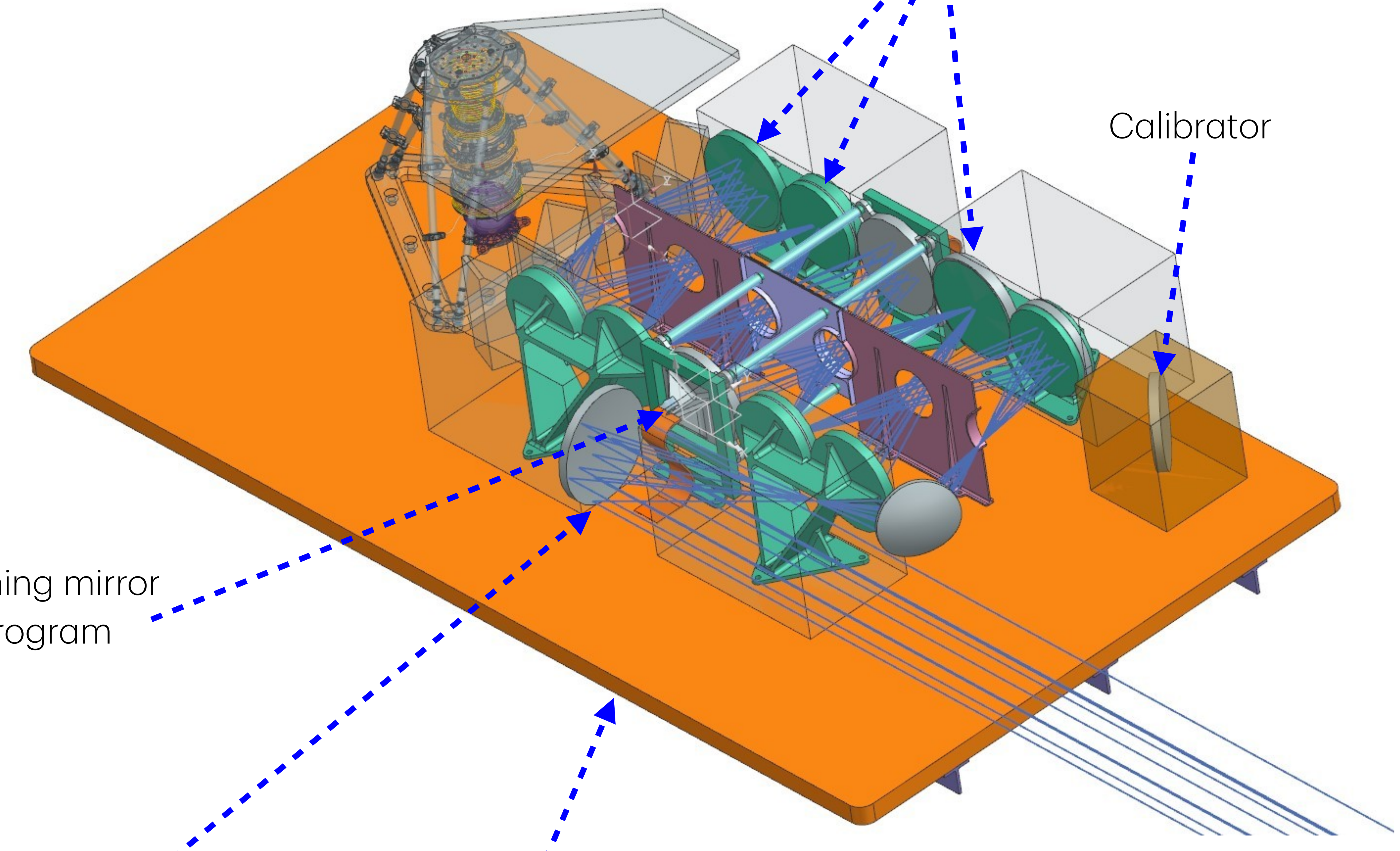


Courtesy B. Borgo

Breadboard BISOU: Coldplate



Optical path sketch



FTS mirrors

Calibrator

FTS scanning mirror for interferogram

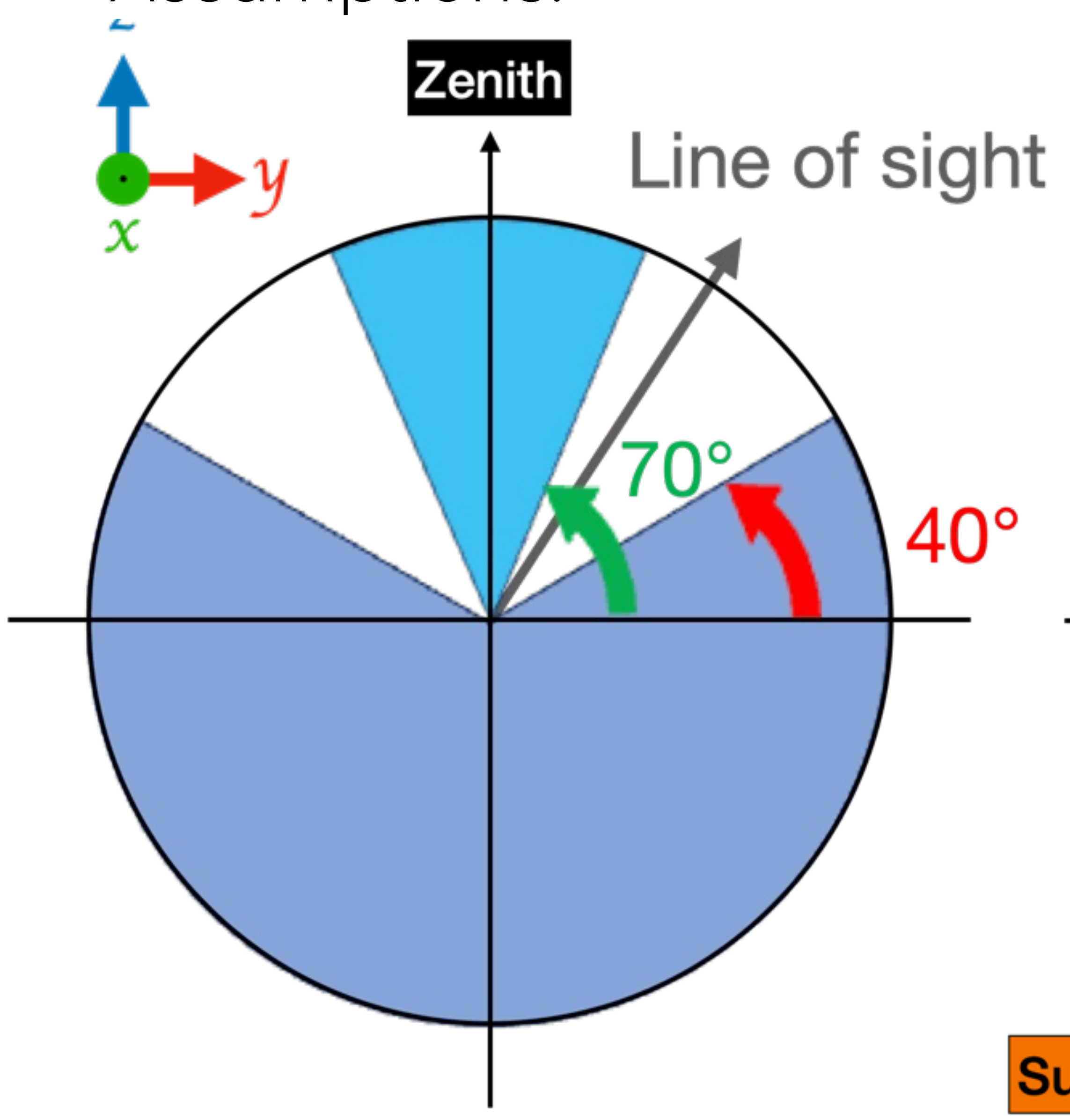
Telescope primary

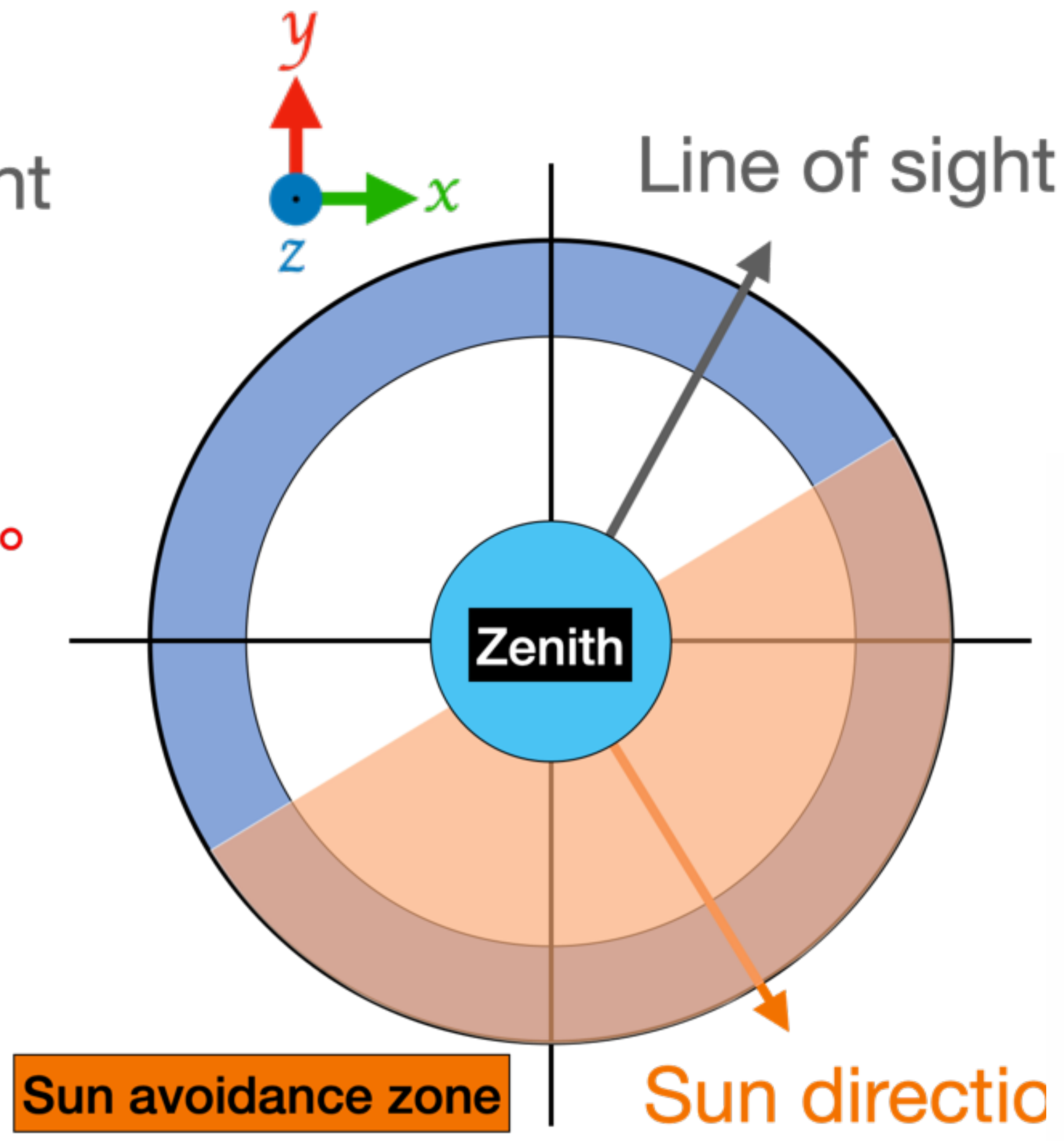
Coldplate

Courtesy B. Borgo

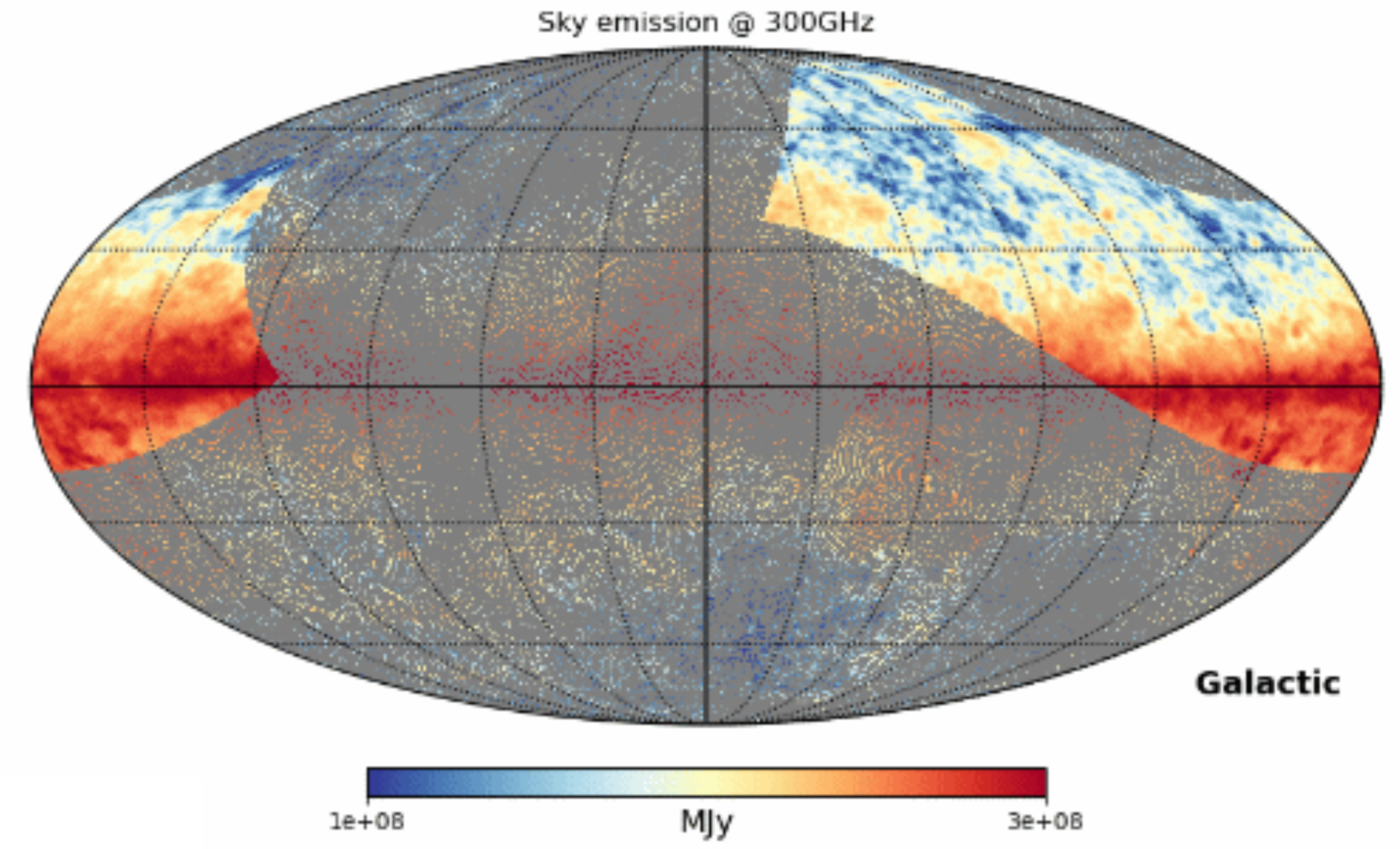
BISOU: Observation strategy

Assumptions:





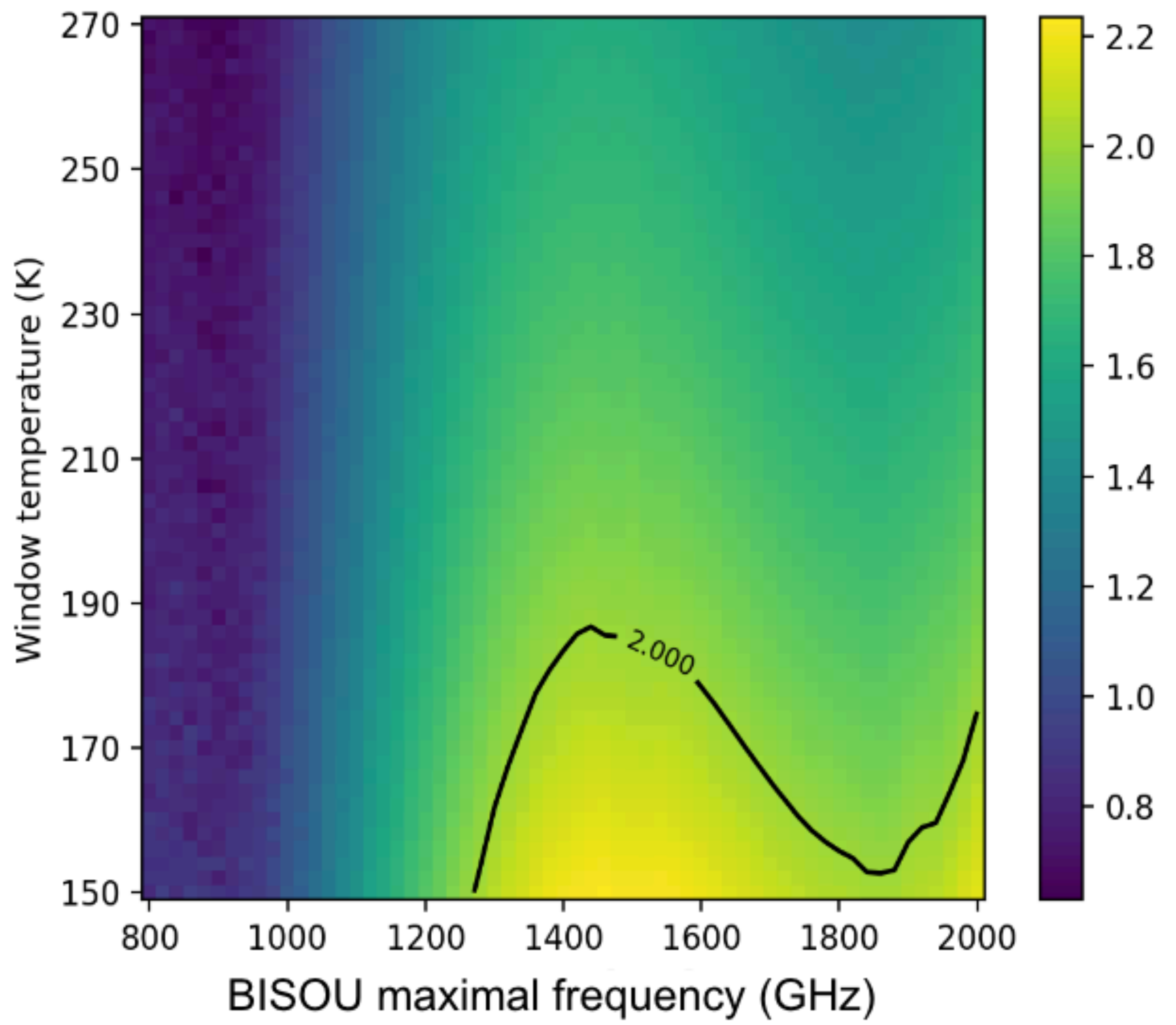
Accessible sky in June 3029 form Kiruna balloon launch site



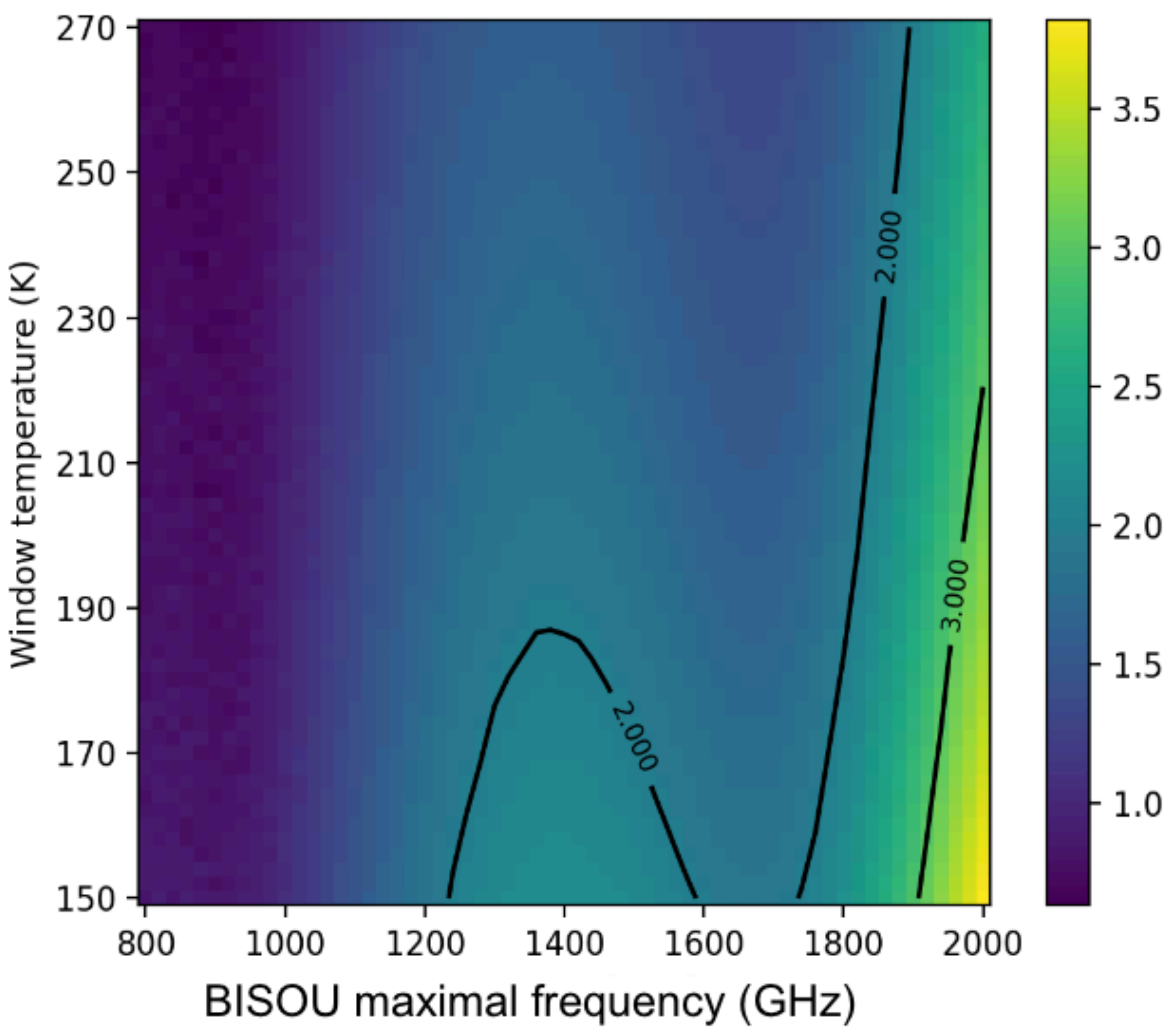
Grid exploration considering: actively cooled window / varying the maximum frequency

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

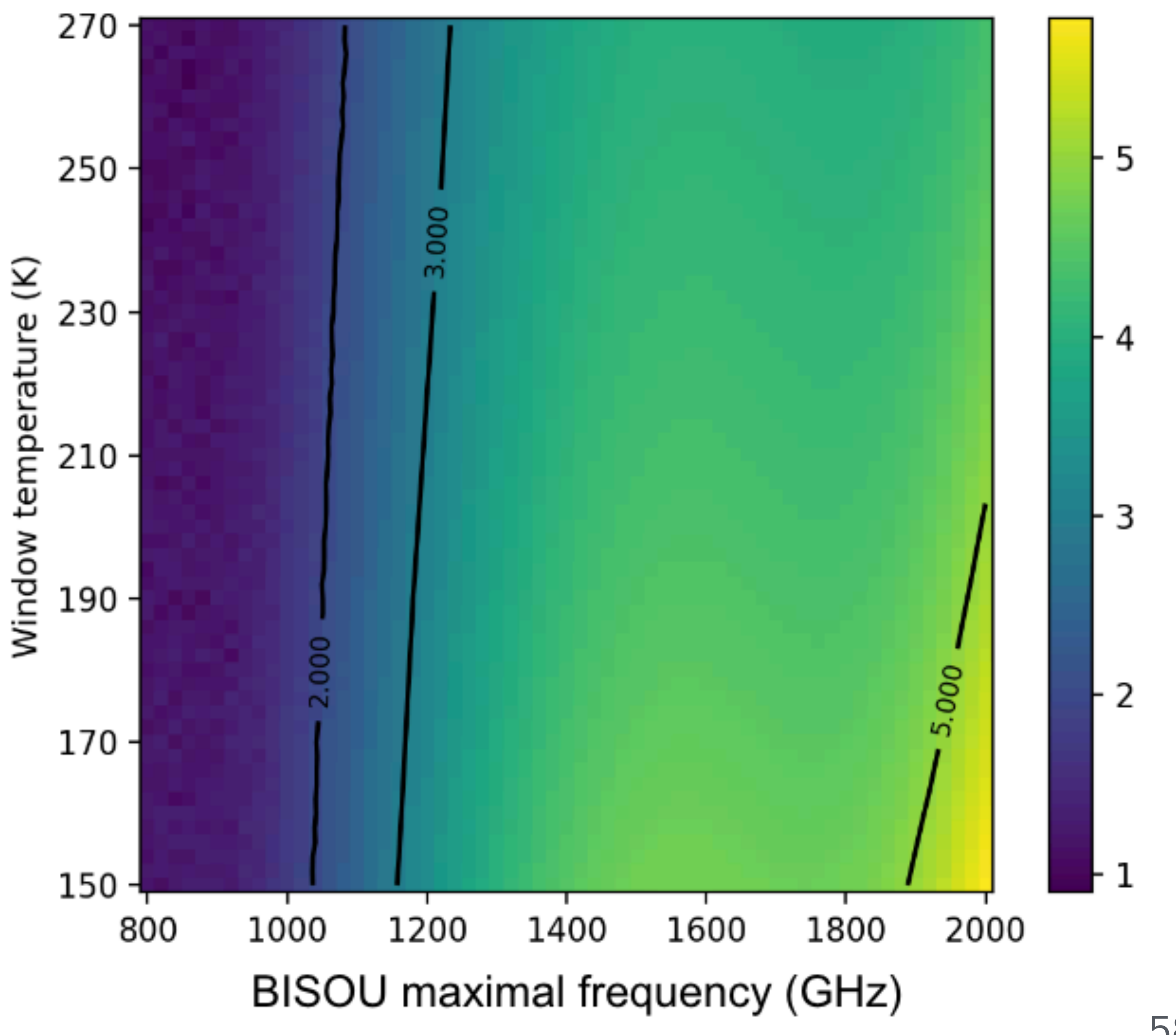
High emissivity window + tapered filtering



Low emissivity window

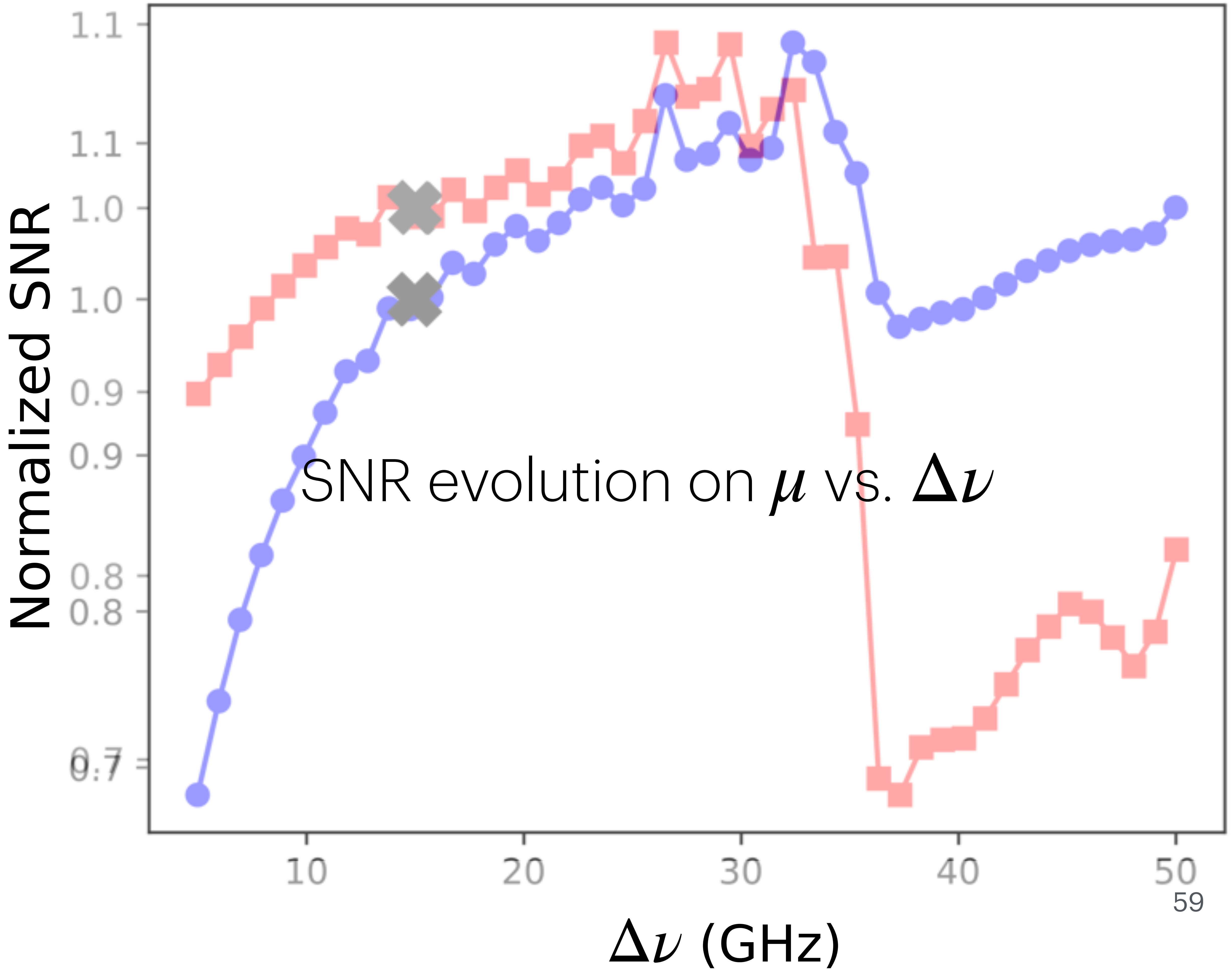


Low emissivity window + dichroic

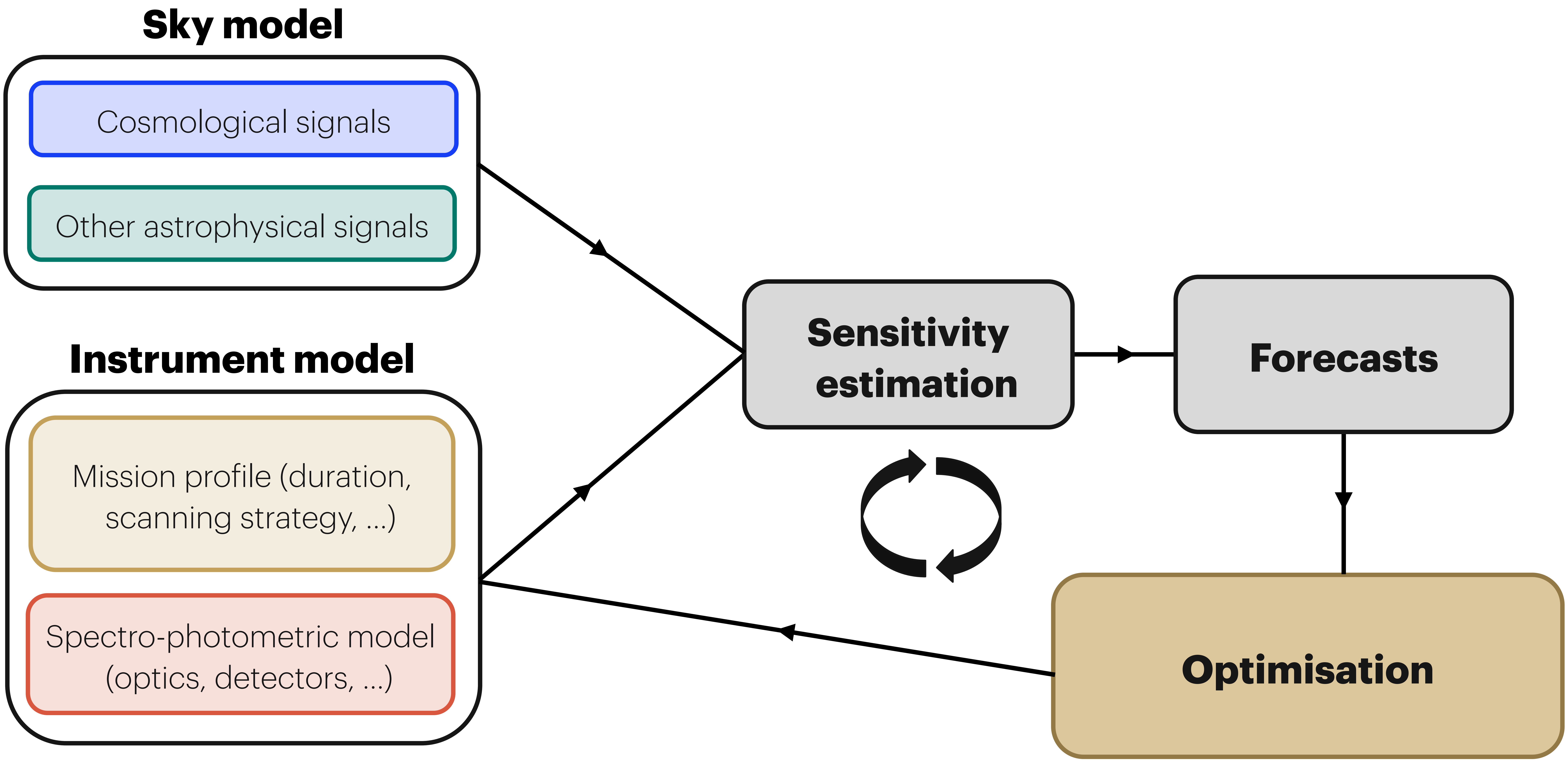


FOSSIL - $\Delta\nu$

- **$\Delta\nu$ = 30 GHz**
  - **SNR gain on y and μ** (~10%)
- **$\Delta\nu$ > 30 GHz**
  - **Drop of SNR on y and μ** (~15% and ~30%)
- **$\Delta\nu$ can be adjusted in flight** (FTS)



Method



Sky model
Cosmological signals
Other astrophysical signals
Instrument model
Mission profile (duration, scanning strategy, ...)
Spectro-photometric model (optics, detectors, ...)
Sensitivity estimation
Forecasts
Optimisation

Sky & Instrument models - Parameters

Foregrounds	Parameters
Galctic dust	A_d, T_d, β_d
Synchrotron	A_s, β_s, C_s
Free-free	$A_{ff}, \beta_{ff}, C_{ff}$
AME	$A_1^{ame}, \nu_1, A_2^{ame}$
CIB	$A_{cib}, T_{cib}, \beta_{cib}$
Extragalactic CO lines	A_{CO}
Zodiacal dust	$\epsilon_{th}(\nu), T_{th}, \beta_{th}$
Zodiacal scattering	$\epsilon_{sc}, T_{sc}, \beta_{sc}$

CMB	Parameters
CMB	
CMB temperature correction	ΔT_{CMB}
y-distorsion	y
Relativistic y-distortion	T_e
-distortion	μ

Instrument & mission	Parameters
Minimal frequency	ν_{min}
Maximal frequency	ν_{max}
Splitting frequency	ν_{split}
Spectral resolution	$\Delta\nu$
Detector efficiency	eff_{det}
Number of detectors per FPA	N_{det}
Effective observational time	τ
Number of optical element	K
Transmission of each optical element	$(t_k)_{1\leq k\leq K}$
Temperature and emissivity of optical element	$(\epsilon_k(\nu), T_k)_{1\leq k\leq K}$
Number of mode at the minimal frrequecy	N
Primary mirror diameter	A
Line of sight	$\vec{p}$