



# The BISOU optical concept design

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CMB France#7

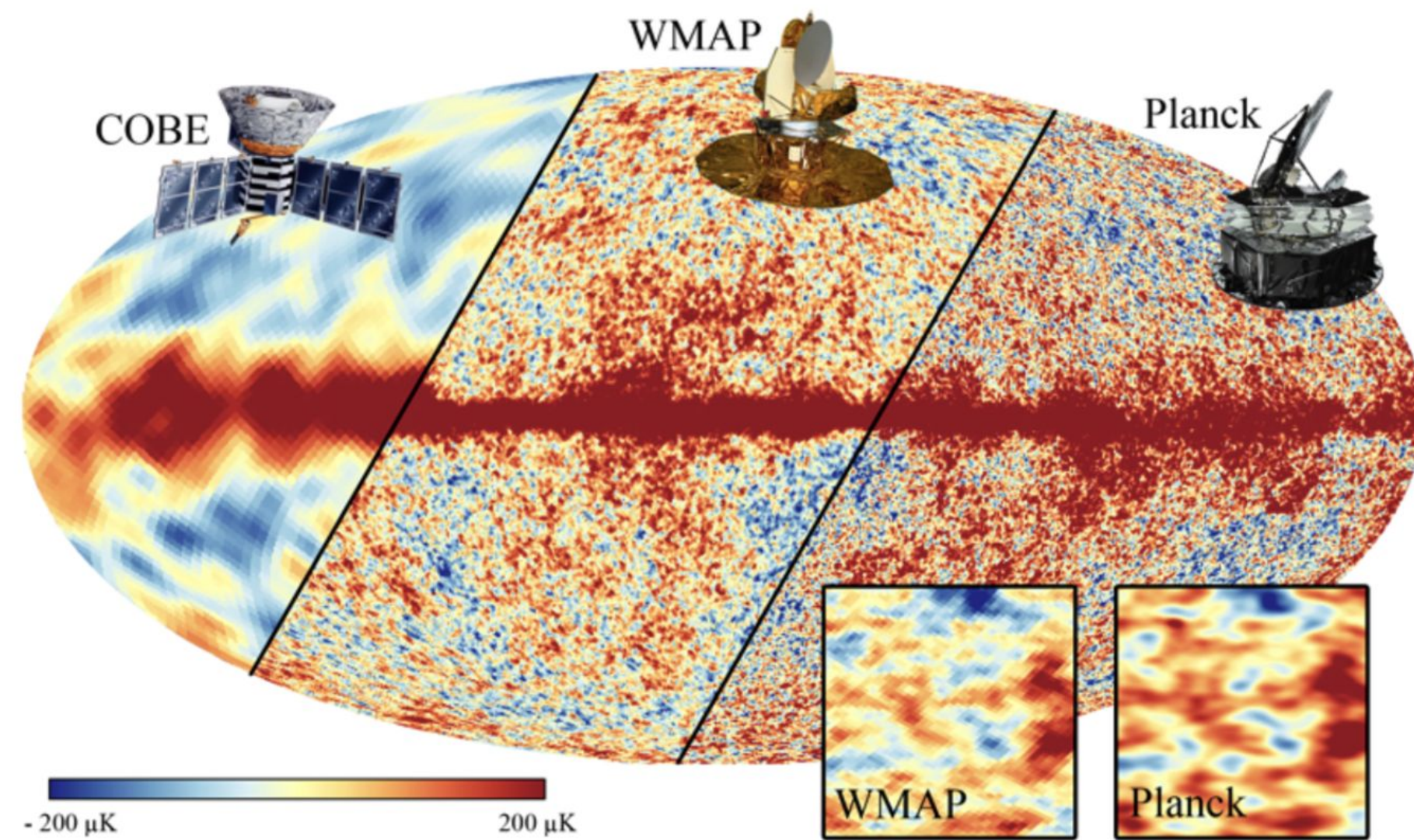
14th October 2025

[morgane.loquet-le-gall@universite-paris-saclay.fr](mailto:morgane.loquet-le-gall@universite-paris-saclay.fr)

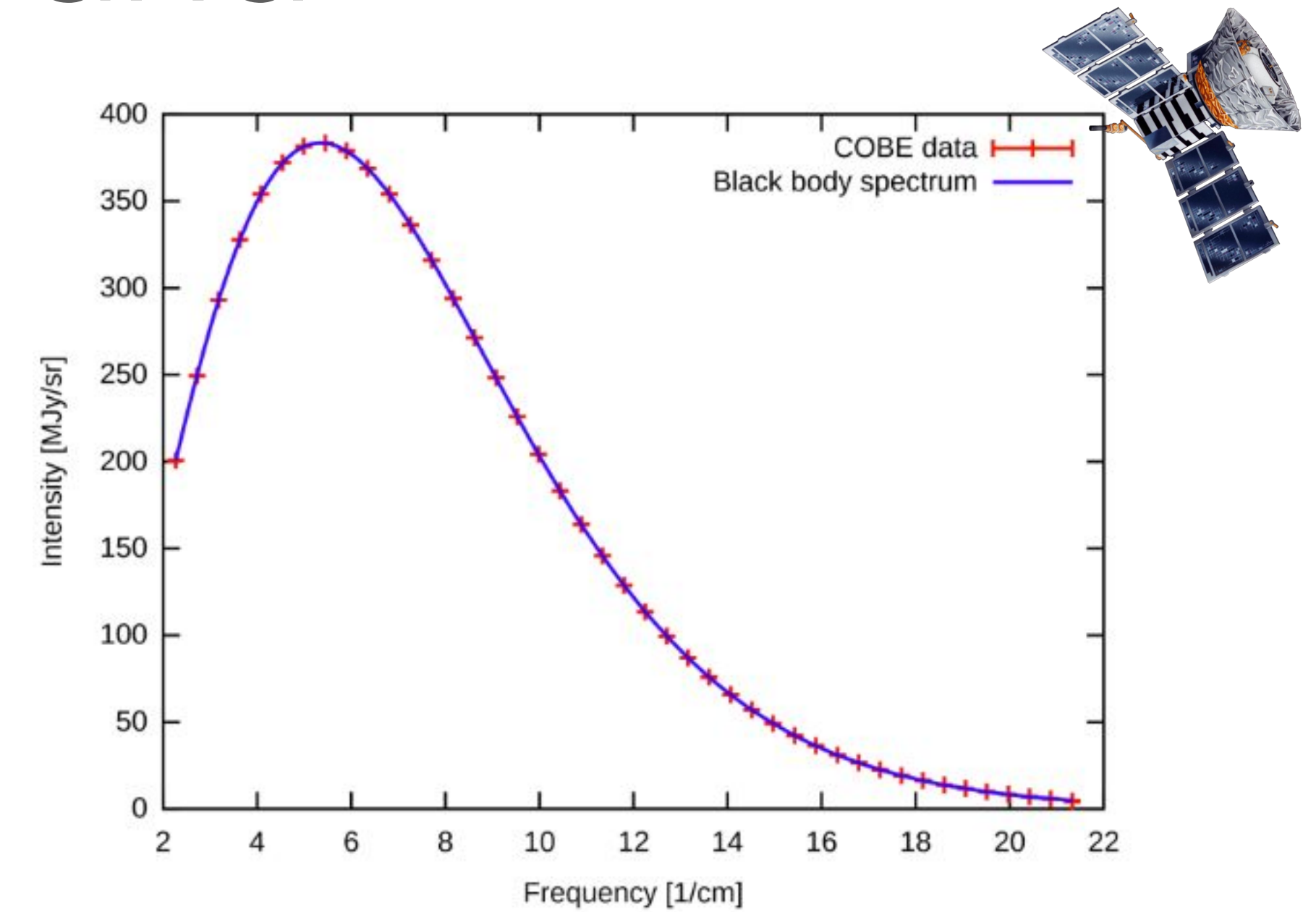




# Cosmic Microwave Background



Comparative CMB maps from COBE, WMAP, and Planck missions

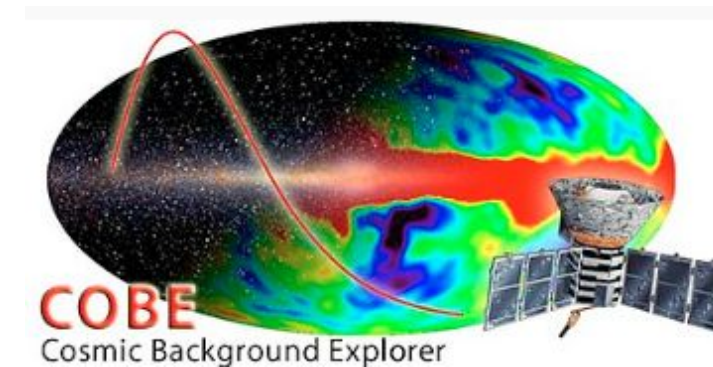


Cosmic Microwave Background Blackbody spectrum by FIRAS (COBE), 1991

## Imaging missions:



## Spectrometric missions:



Proposed missions :

- PIXIE
- PRISTINE
- FOSSIL (M7)

- not selected, due to limited technology readiness.

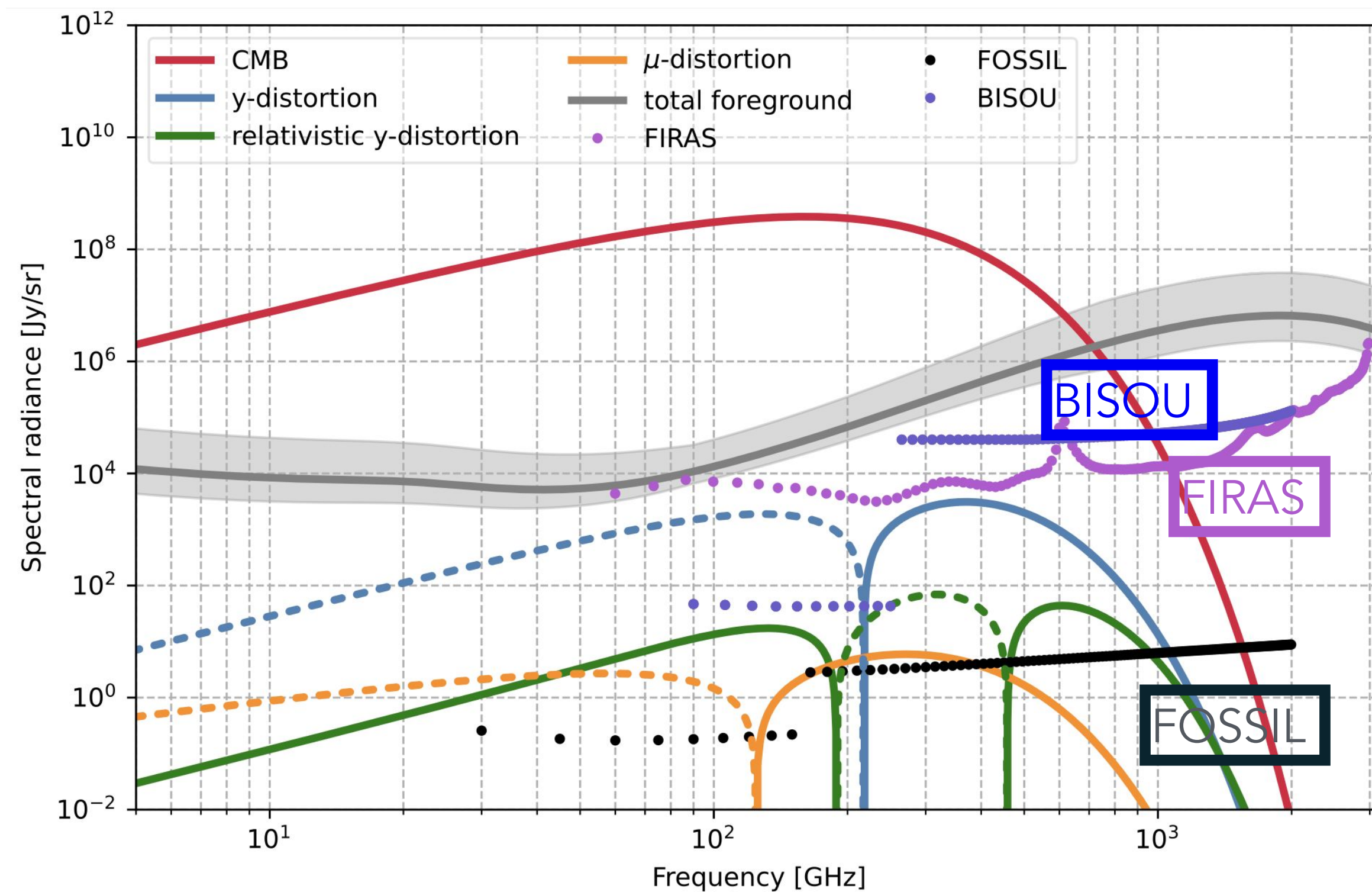


# BISOU: Preparing the future



## Balloon Interferometer for Spectral Observations of the primordial Universe

- Frequency range : 90 GHz - 1.5 THz
- Foregrounds subtraction



Sensitivity to CMB spectral distortions for different projects (X.Coulon)

### BISOU :

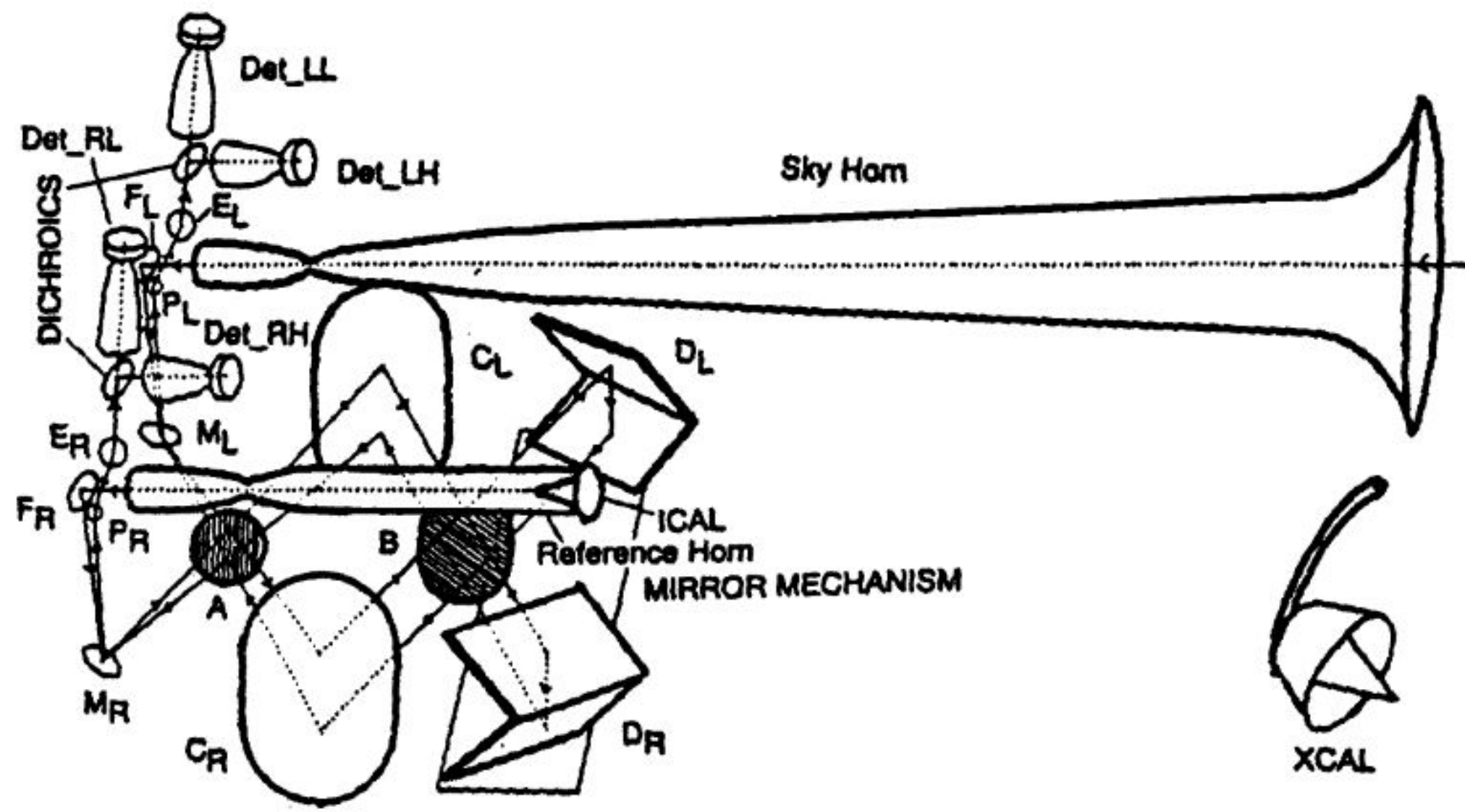
- Pathfinder
- Balloon mission
- To prepare a future space mission
- Systematics effect studies
- First y distortion measurement

# Instrument Concept

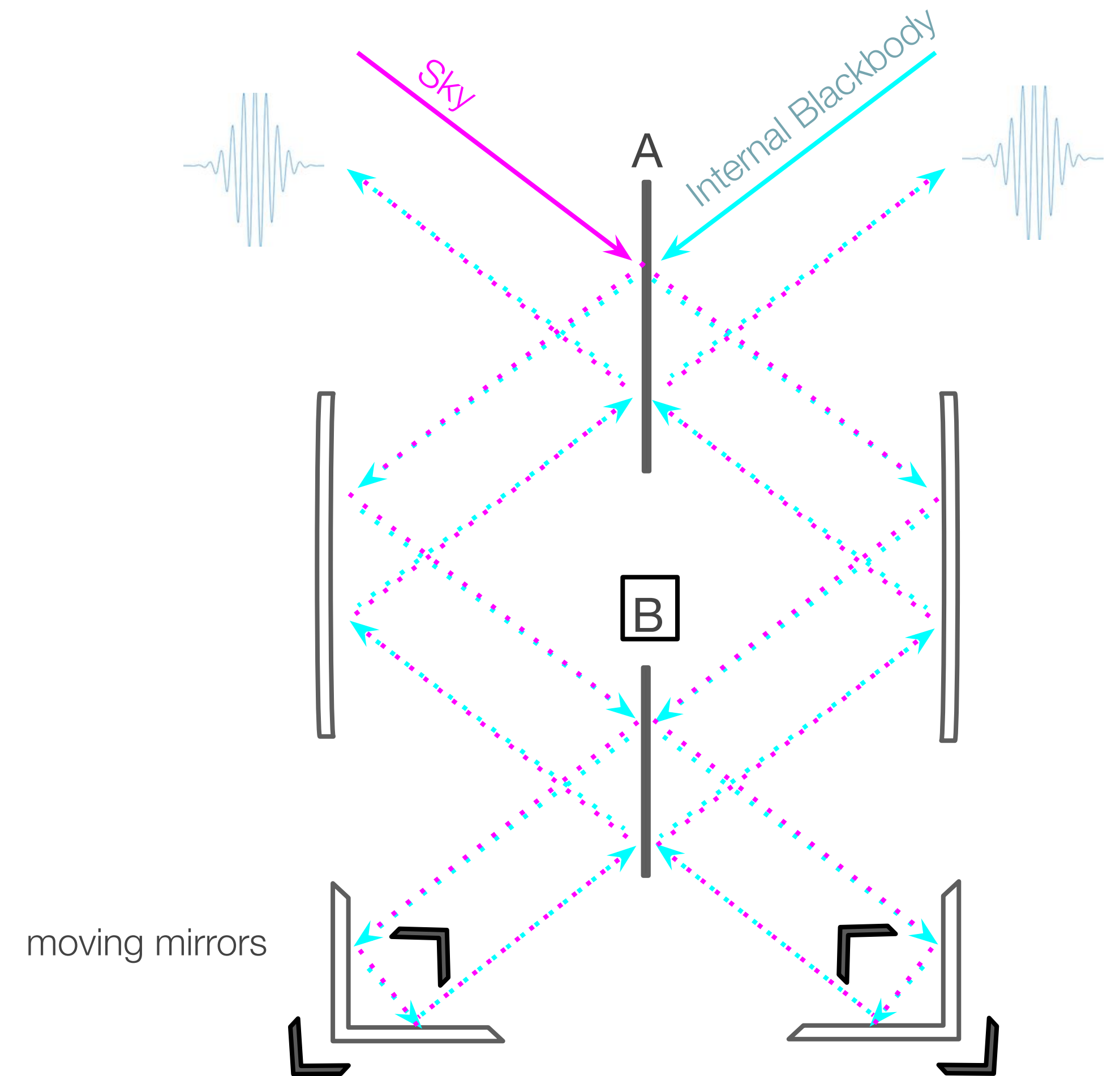
- Measurement over a broad frequency range : 30 GHz - 3 THz

## COBE Far Infrared Absolute Spectrophotometer FIRAS (J. C. Mather et al. 1993)

- Two-beam interferometer: sky signal + internal T°CMB reference
- Path difference introduced with moving mirrors → interferogram
- Beam splitter: mixes the incoming beams.
- Spectrum retrieval via inverse Fourier transform



Optical diagram of the FIRAS instrument



Simplified optical concept of the FIRAS instrument

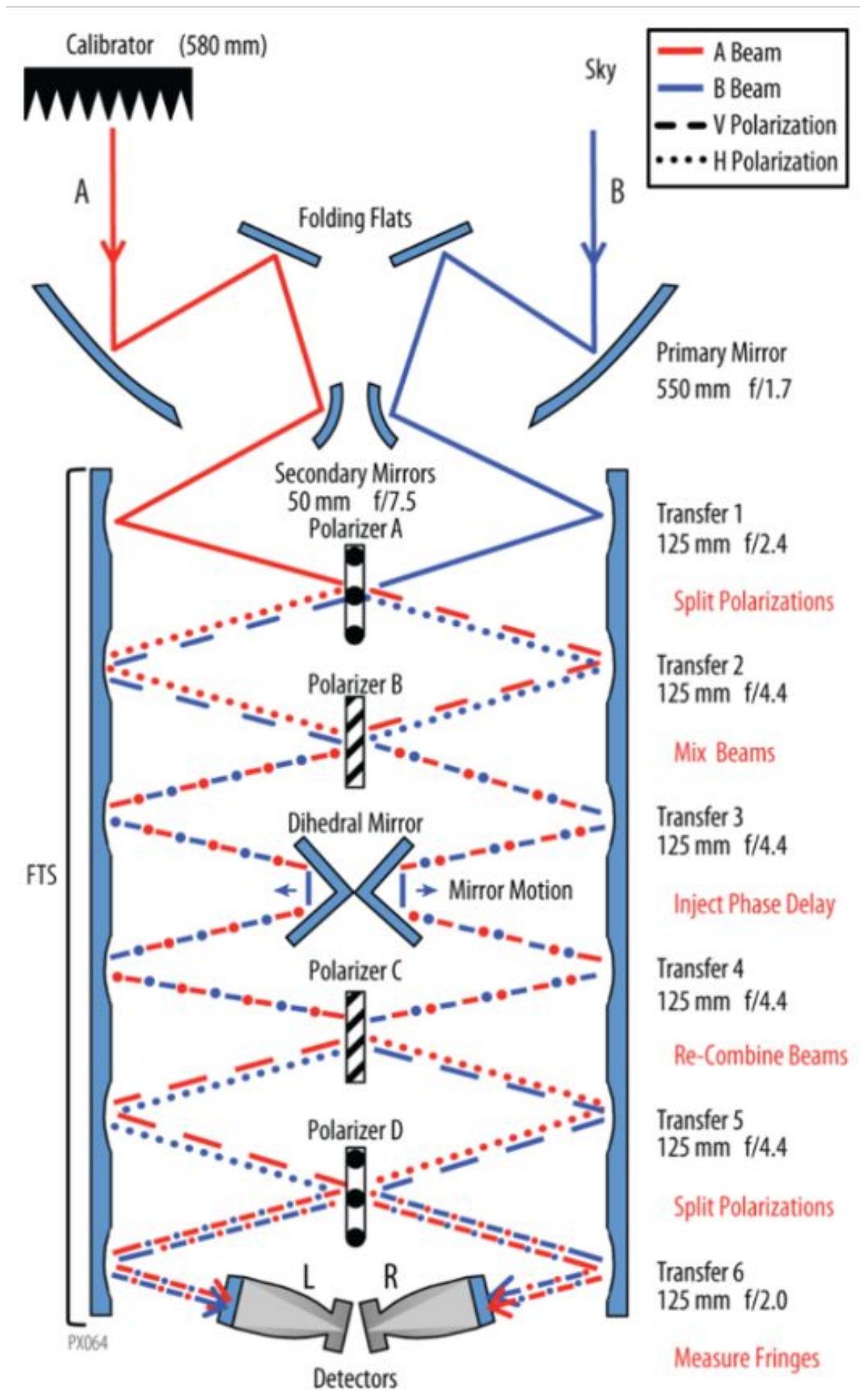


# Instrument Concept

➤ Measurement over a broad frequency range : 30 GHz - 6 THz

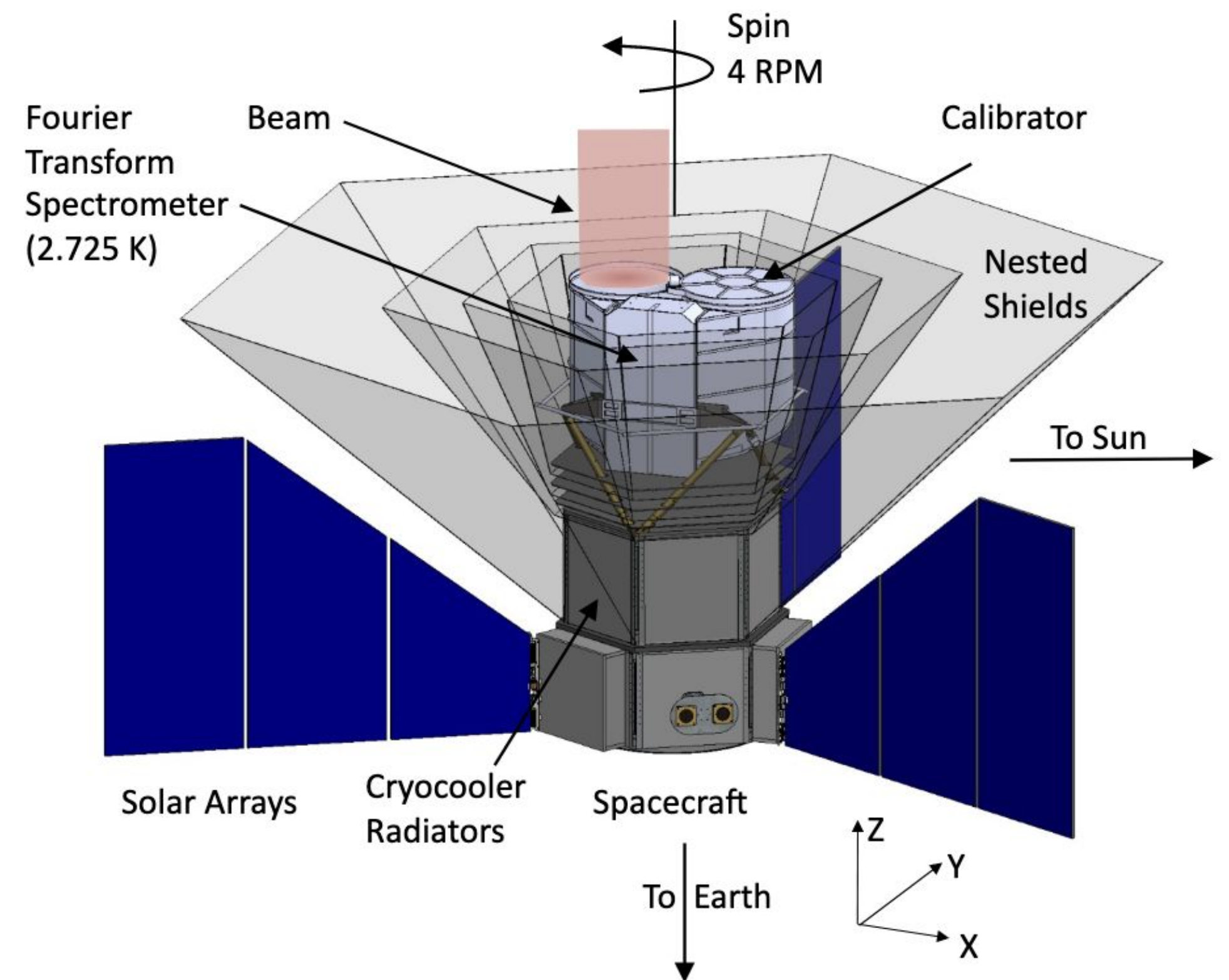
PIXIE original concept (A. Kogut et al. 2011)

Calibrator / Internal  
reference at Tcmb



OPD (optical path  
difference) introduced  
by scanning mirrors

Multi-moded optics



PIXIE observatory and mission concept



# Instrument Concept

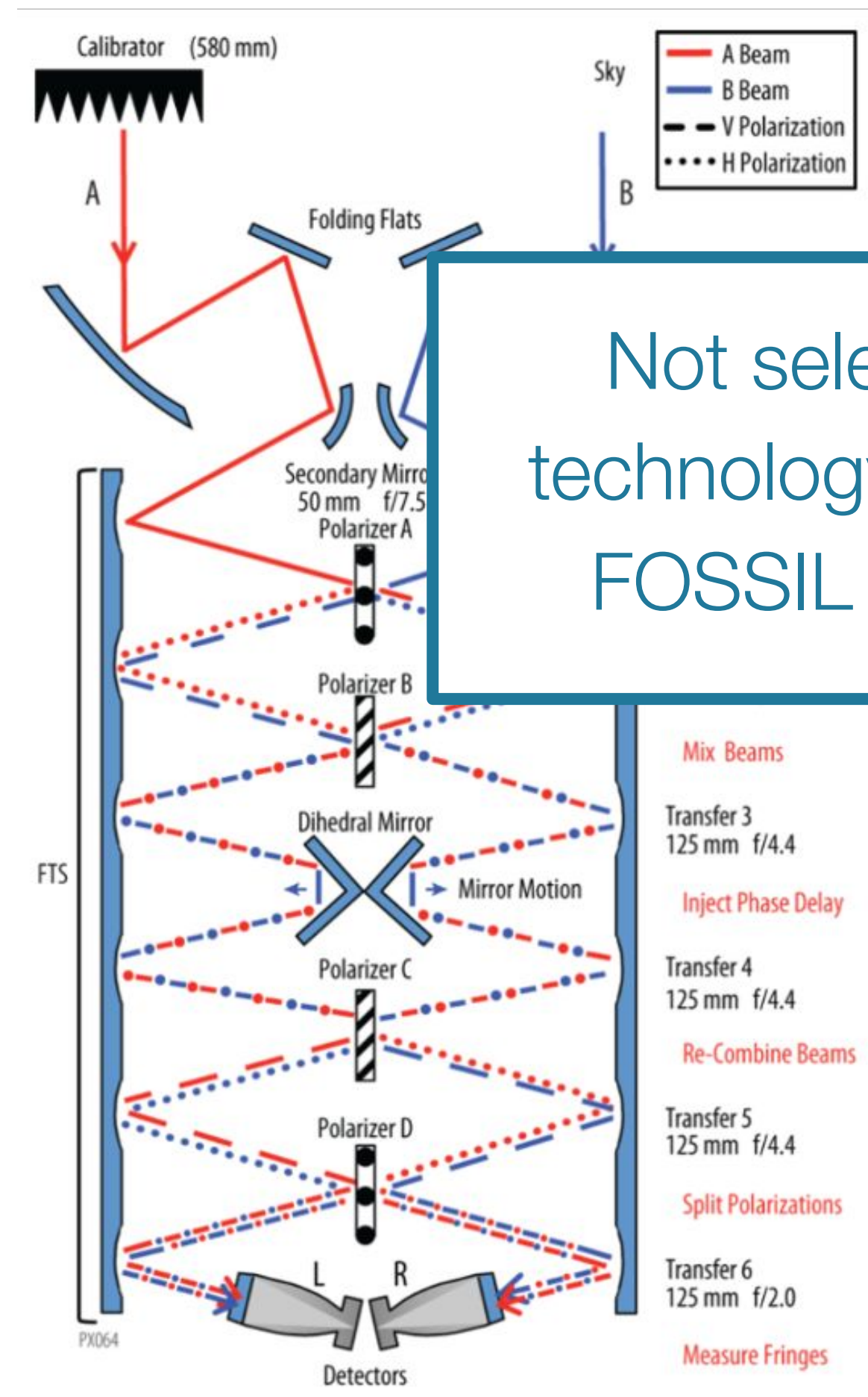
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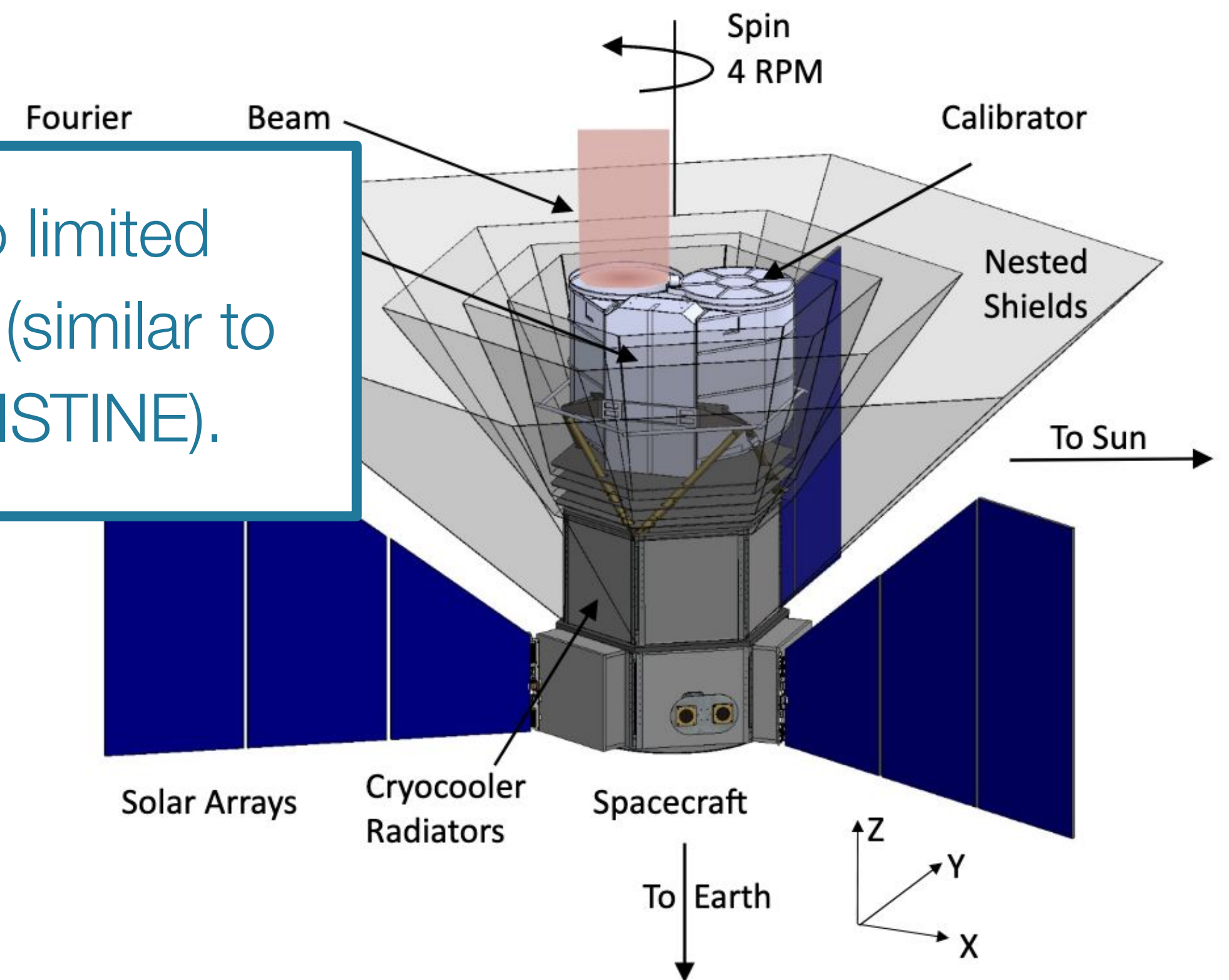
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PIXIE observatory and mission concept



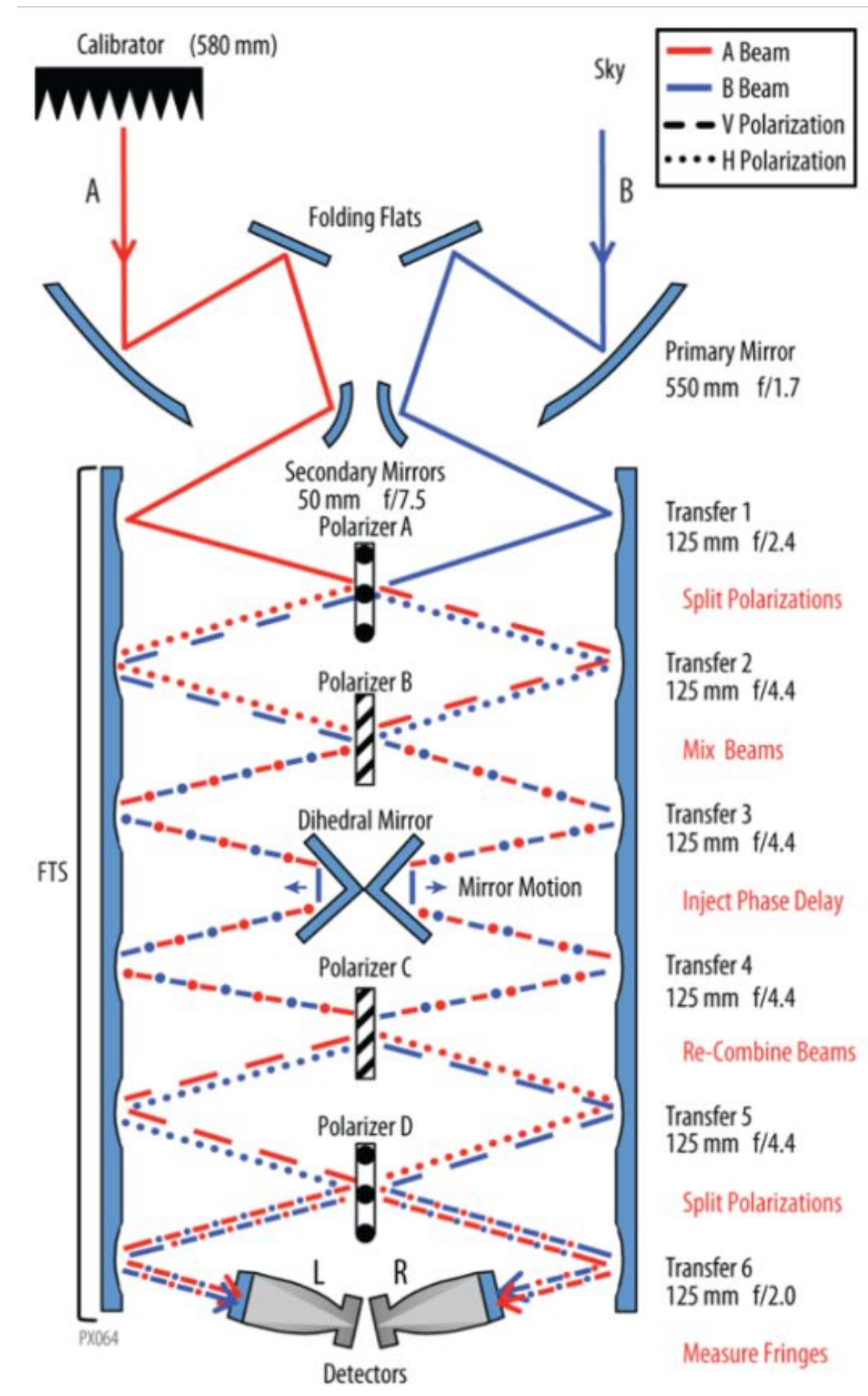
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## BISOU concept

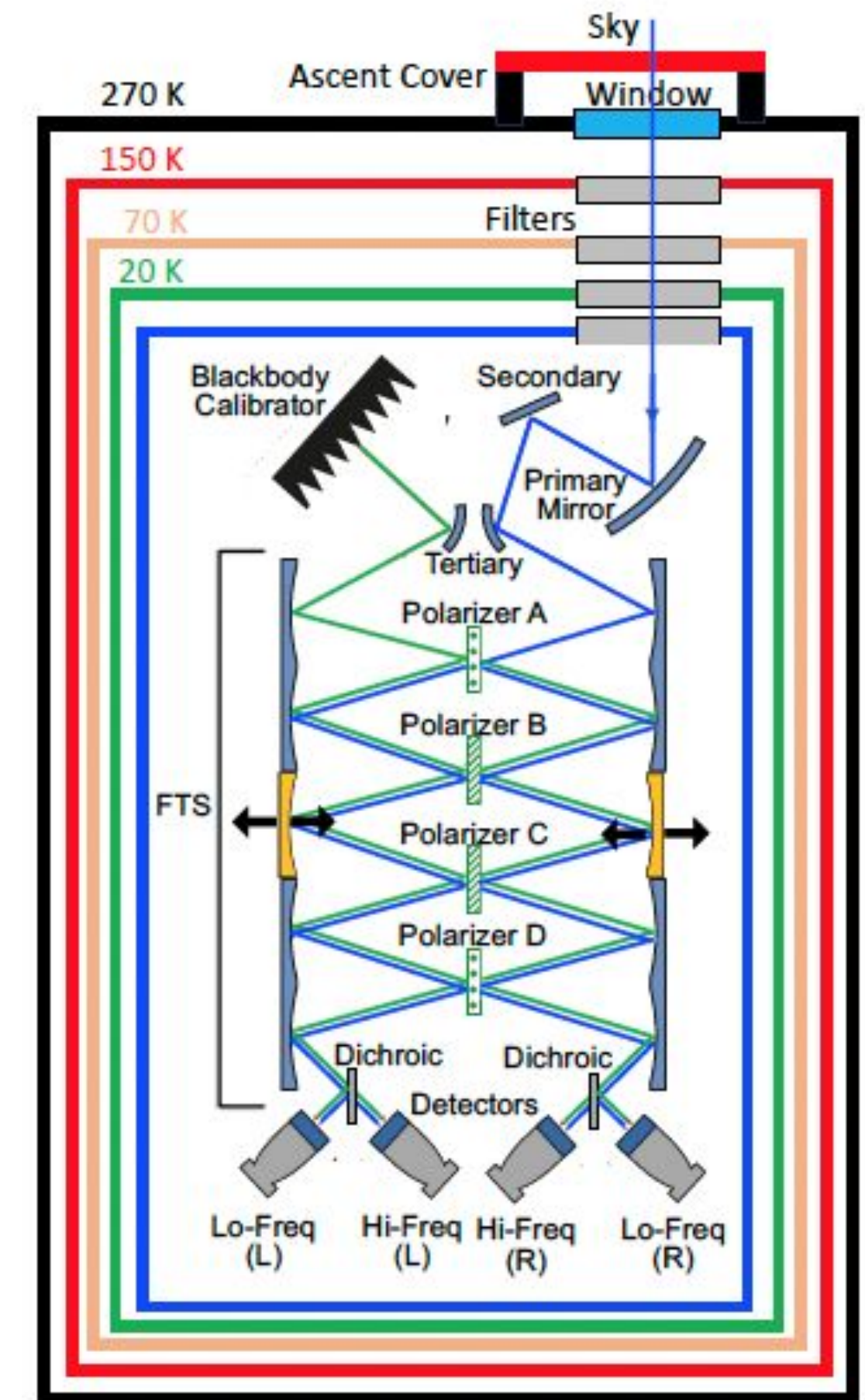
Warmer components

Single telescope (asymmetry)

5 Mirrors in the FTS

2 Sub-bands with Dichroics

- Systematics effects studies





# Instrument Concept

## BISOU concept

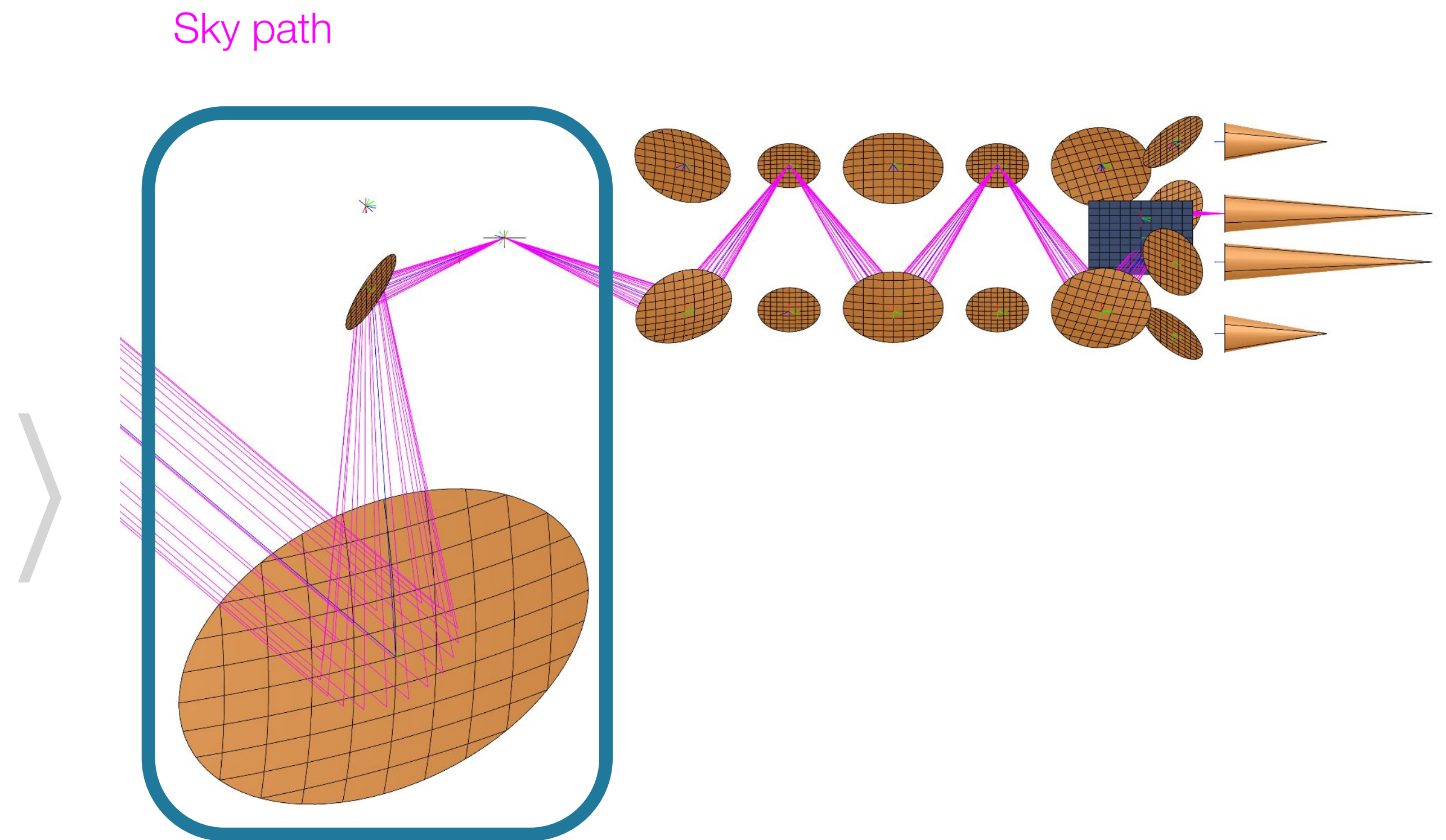
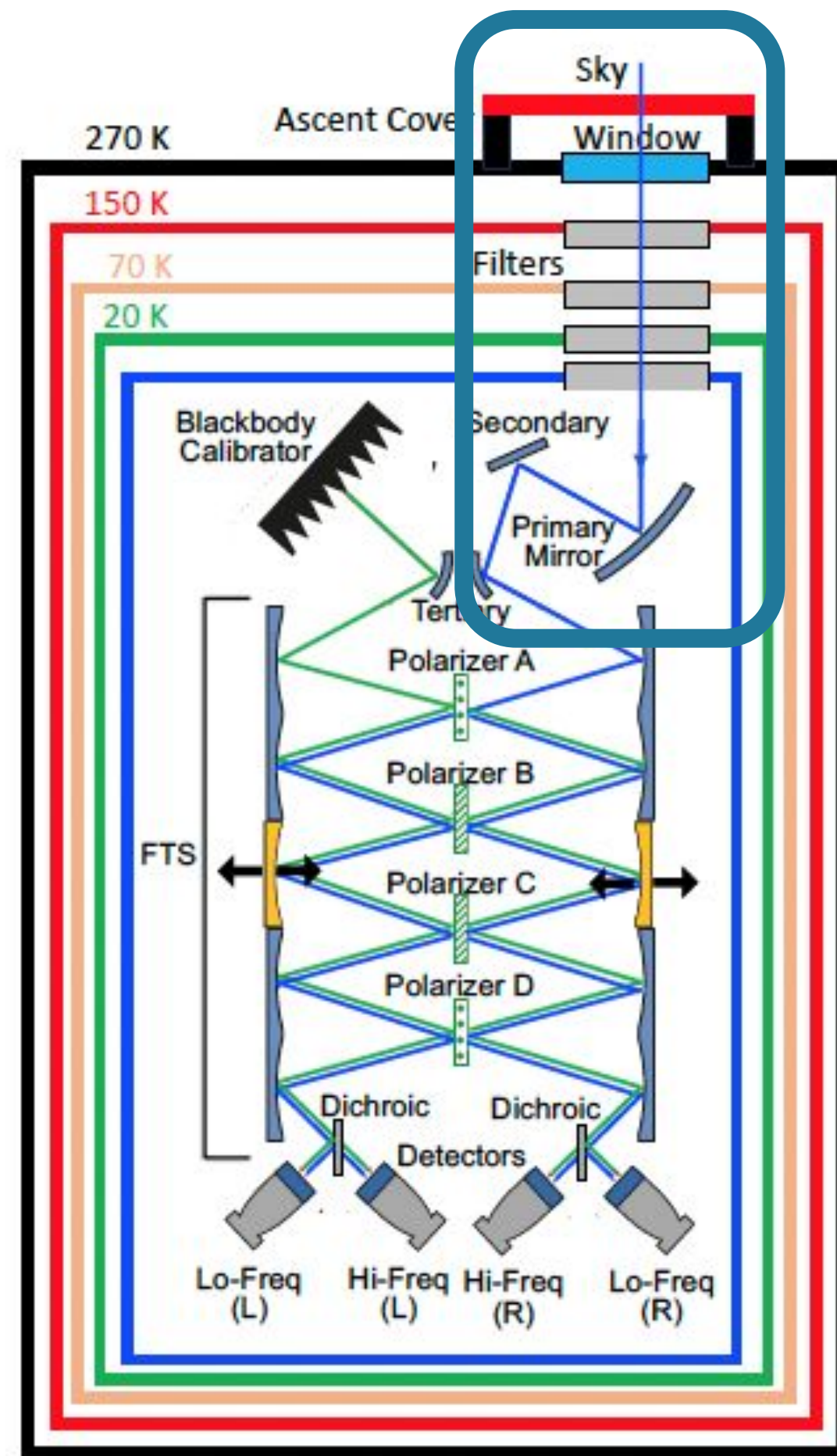
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3D view of the BISOU instrument (Ticra GRASP Software)



# Instrument Concept

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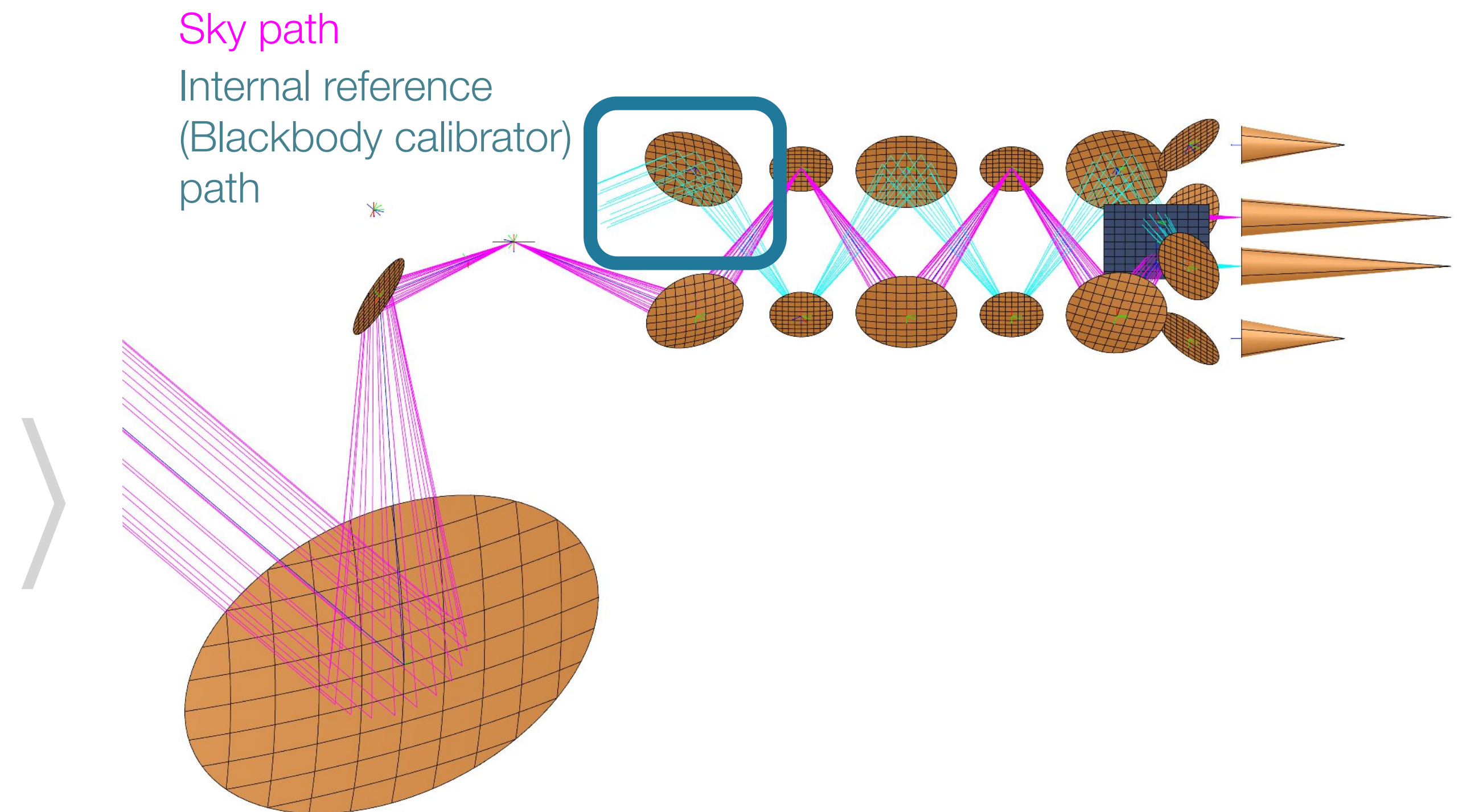
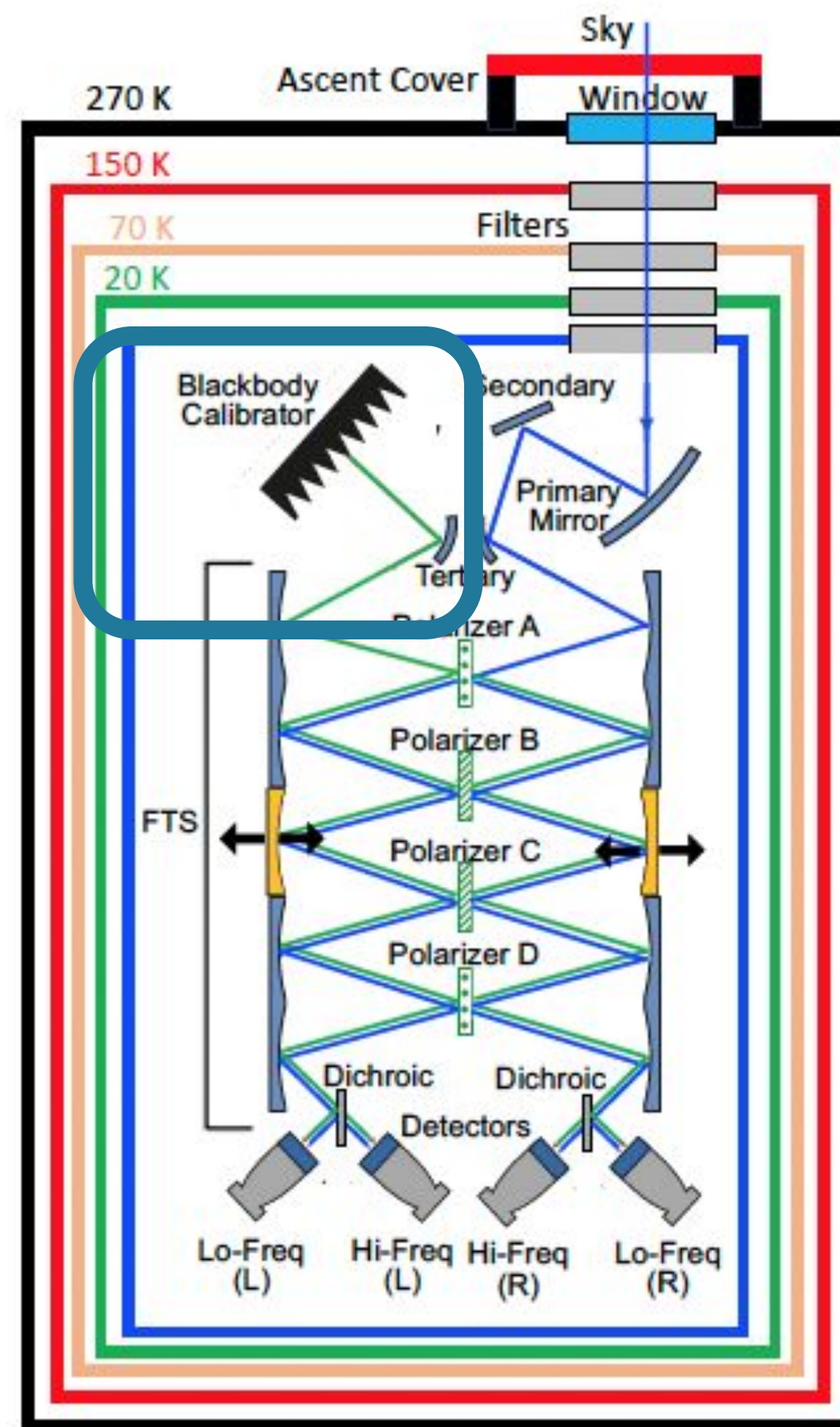
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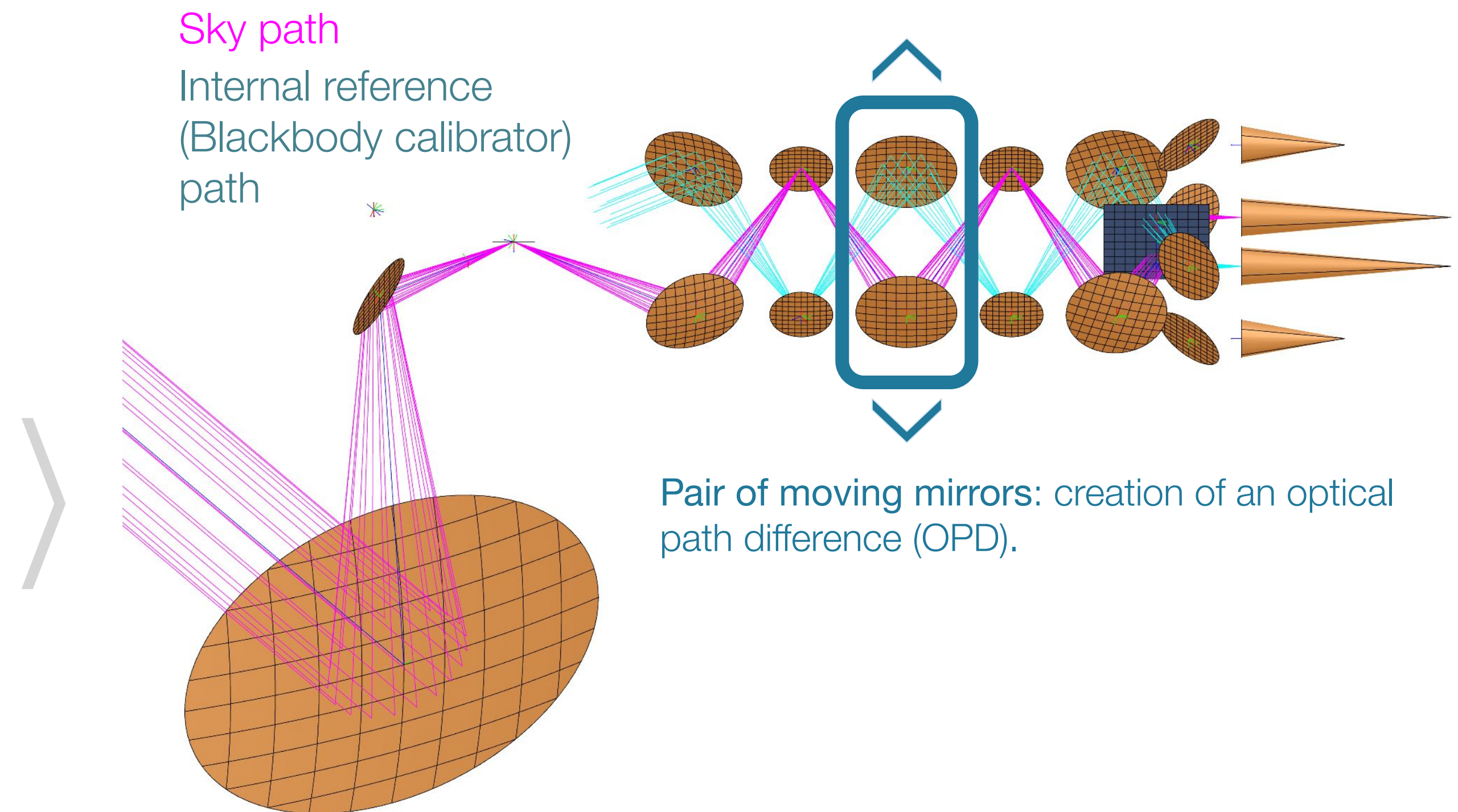
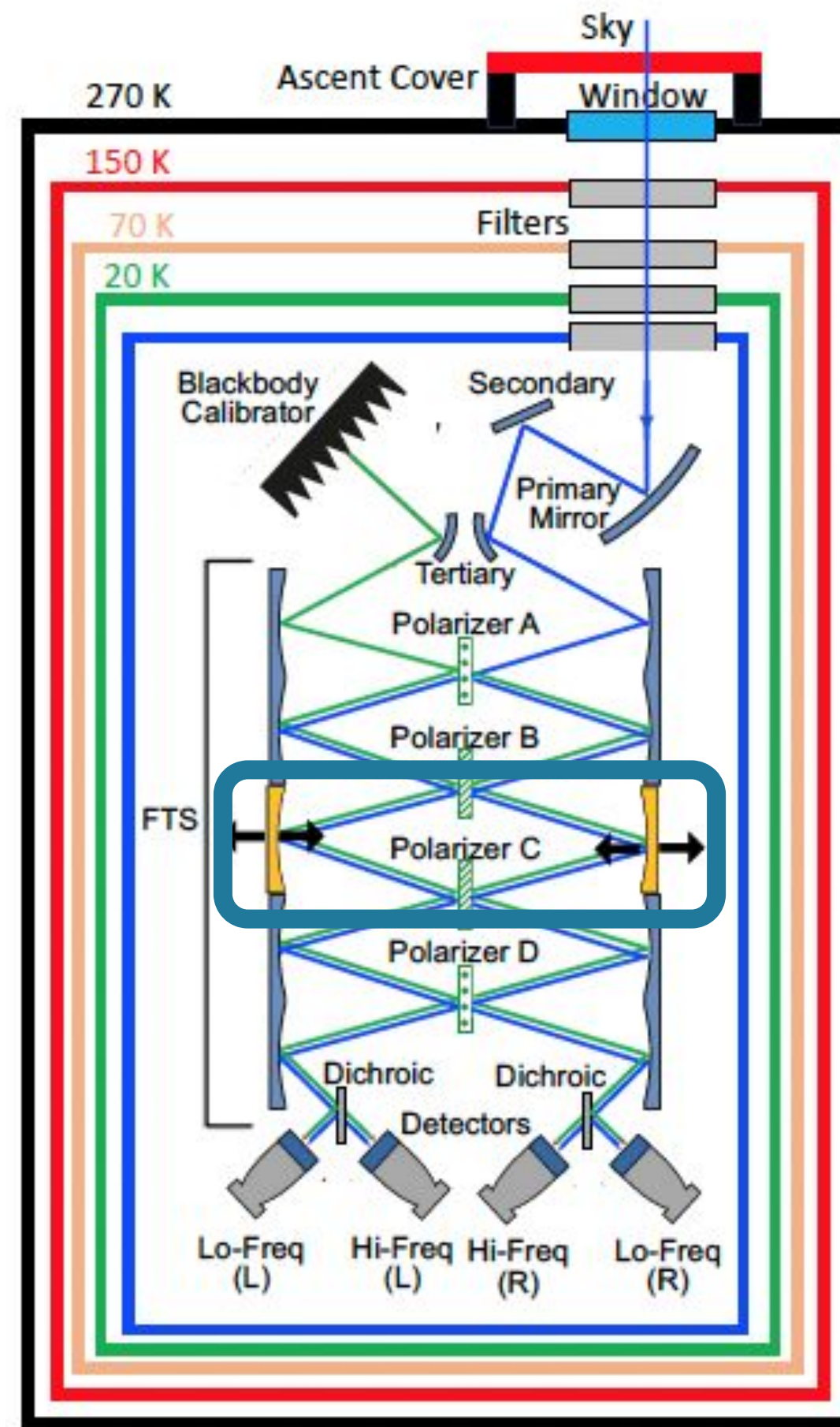
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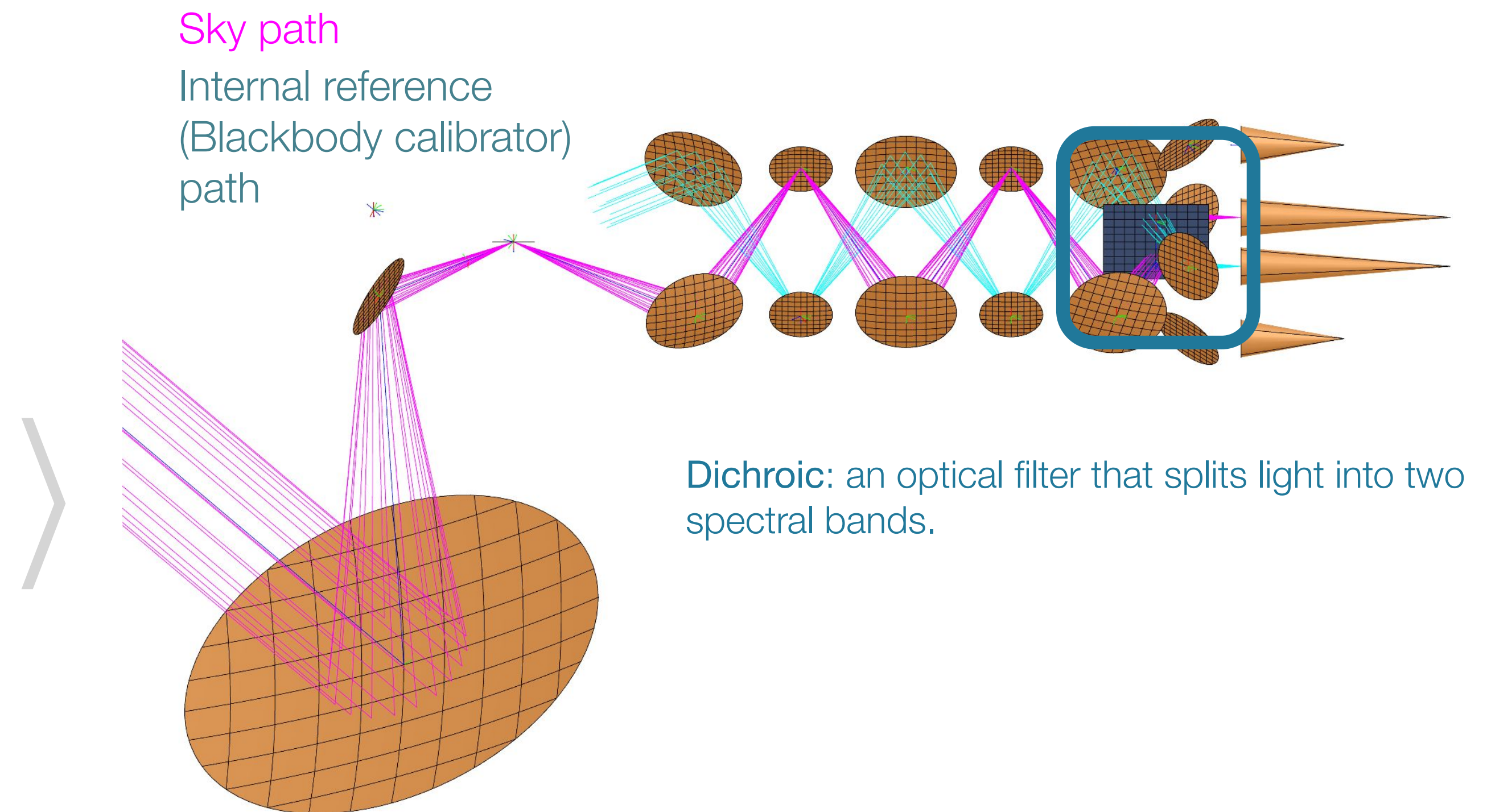
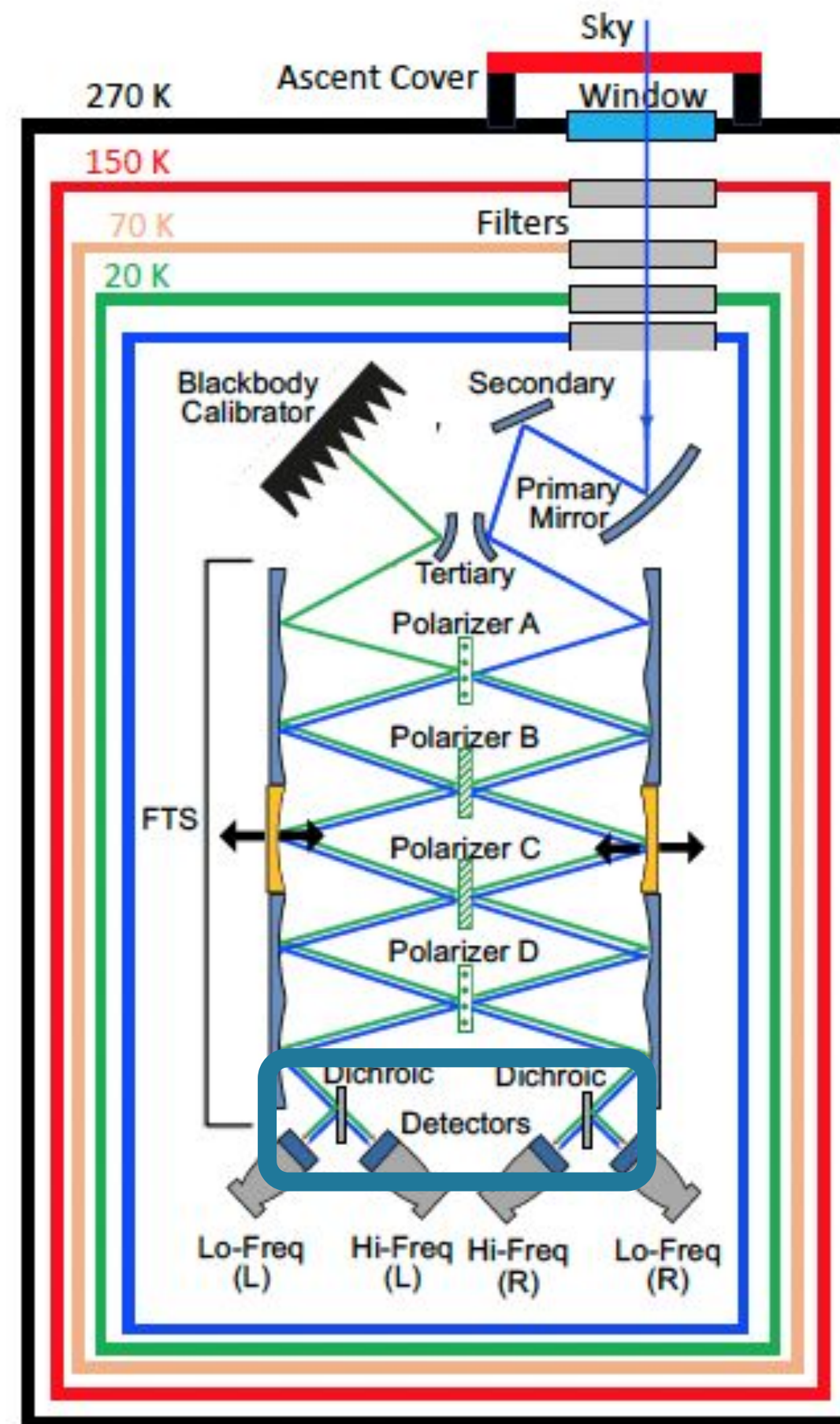
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Sub-bands Dichroics

- Systematics effects studies



Dichroic: an optical filter that splits light into two spectral bands.

3D view of the BISOU instrument (Ticra GRASP Software)



# Instrument Concept

## BISOU concept

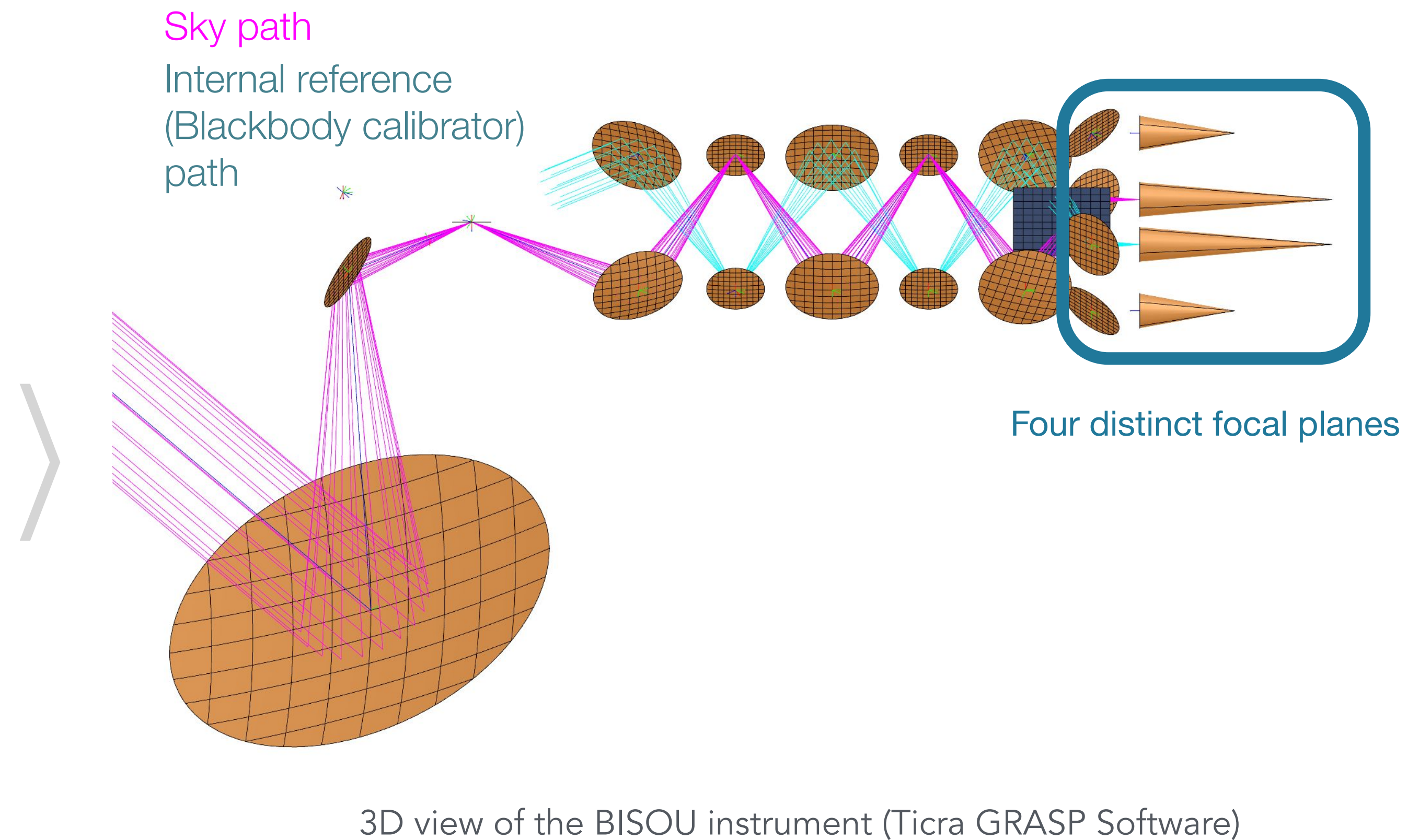
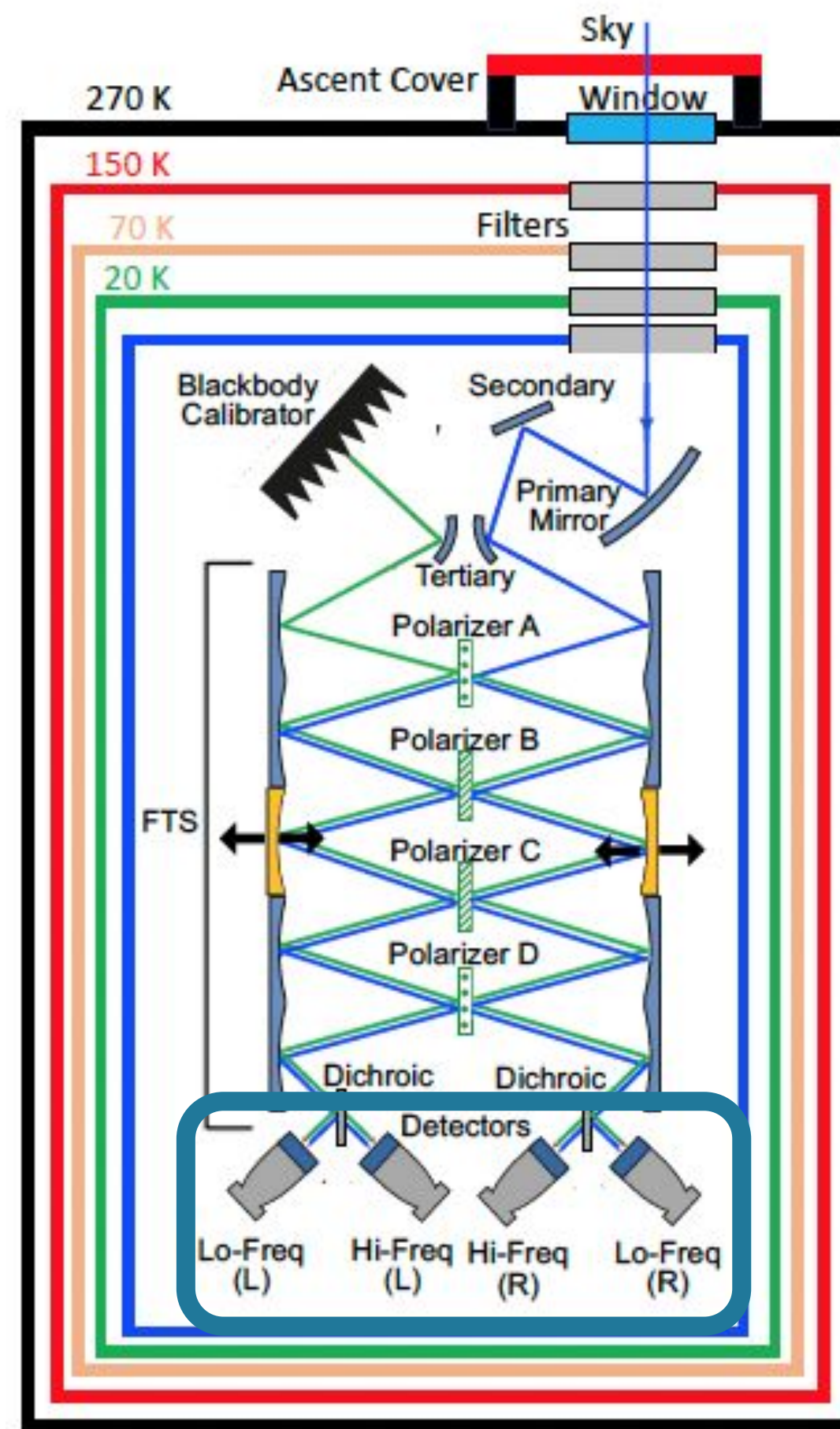
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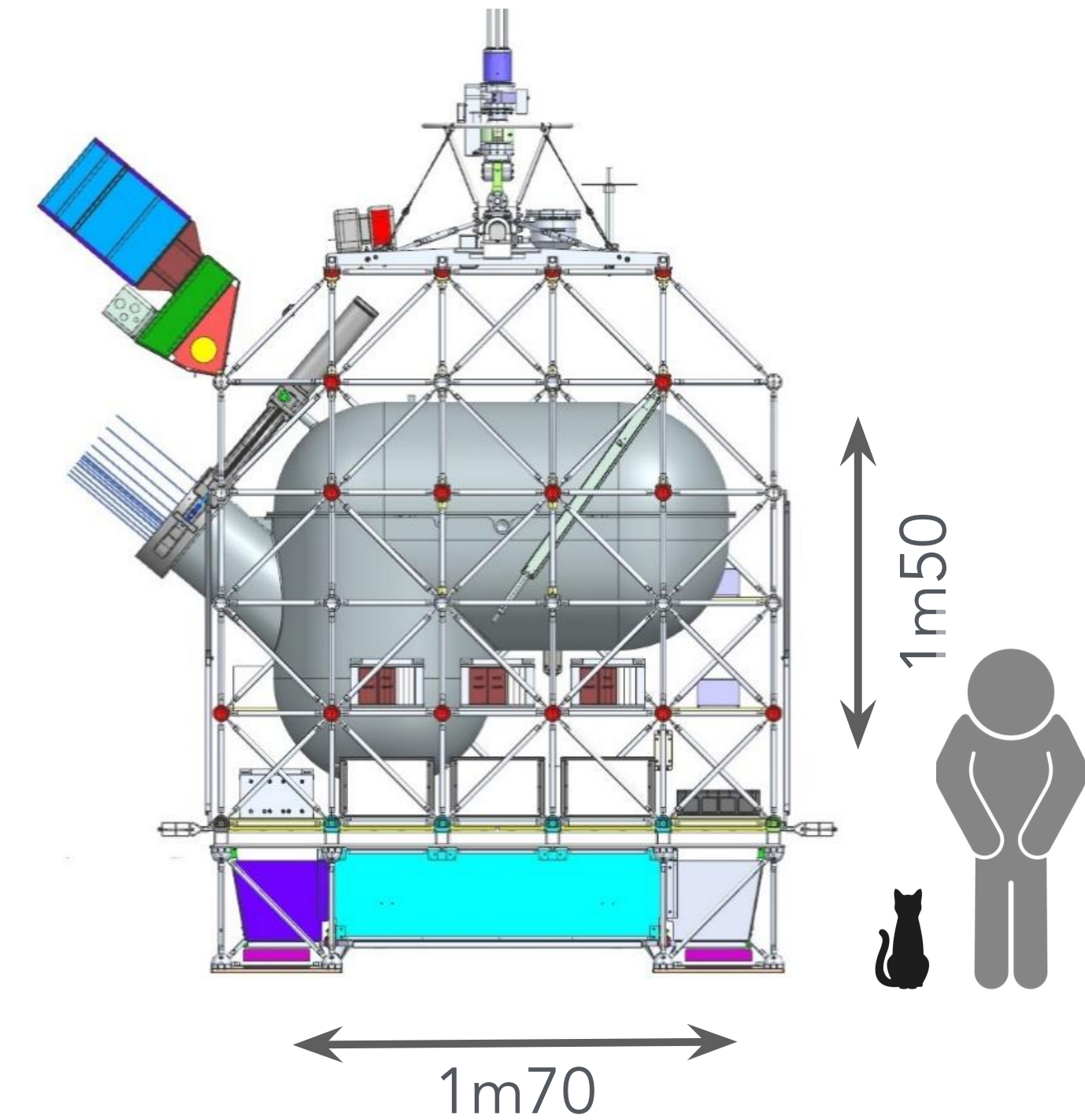
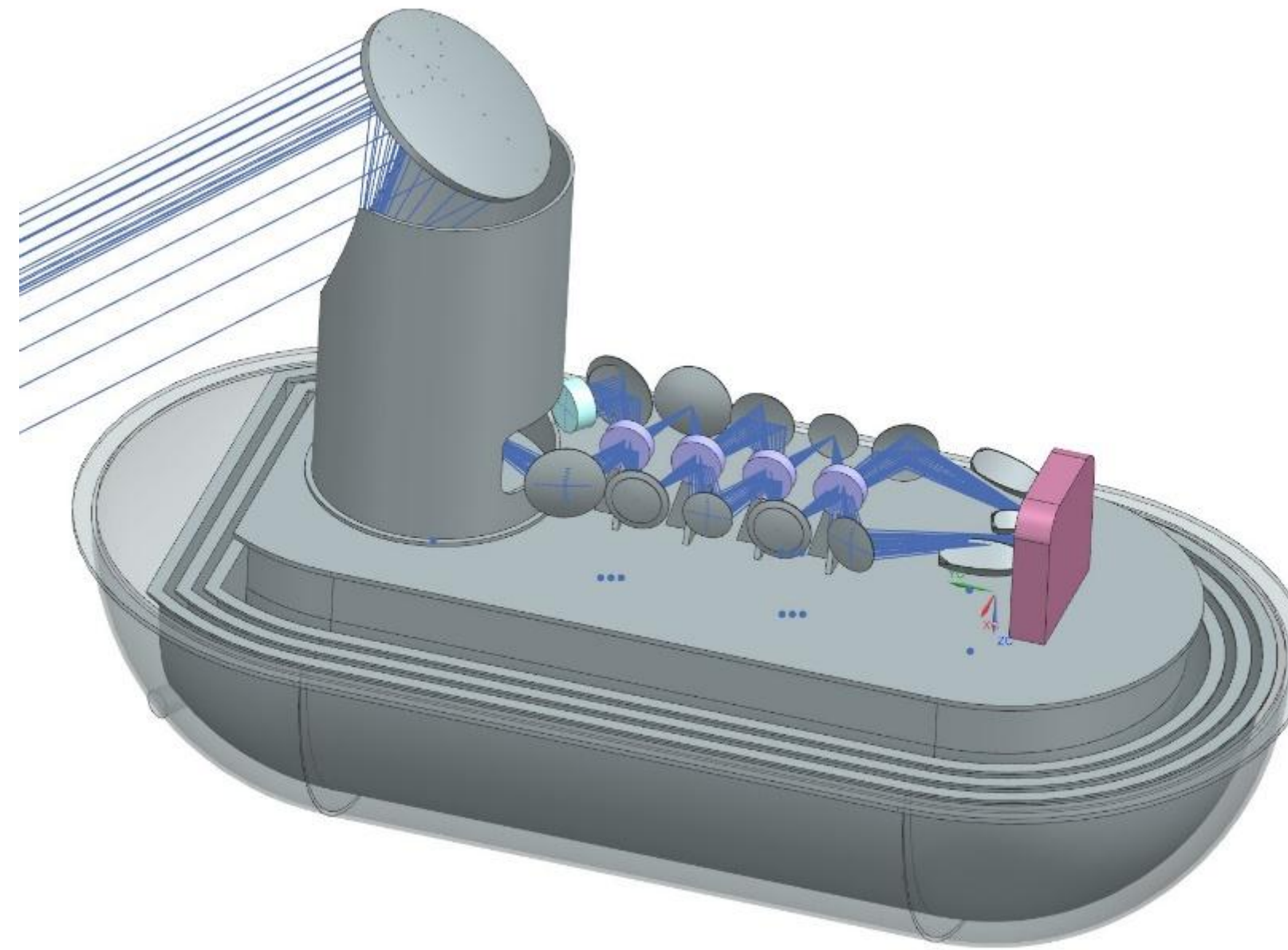
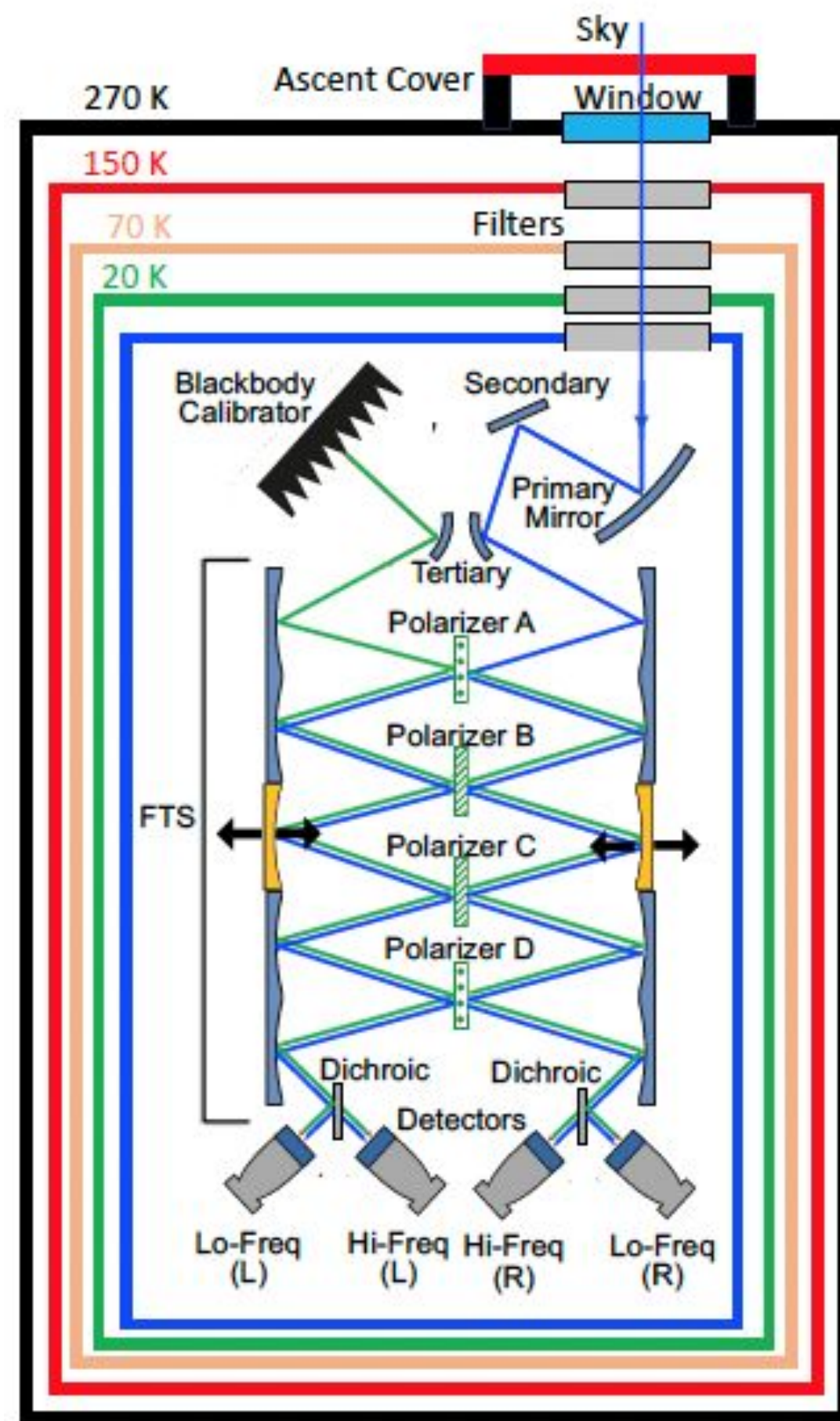
- Systematics effects studies





# Instrument Concept

## BISOU concept



CAD of BISOU in the CNES gondola

### Mission constraints / requirements:

- Mass and volume constraints
- Instrument cooled to  $\sim 2$  K (pumped liquid helium)
- Focal plane cooled to 100 mK / 300 mK

Strong thermo-mechanical constraints

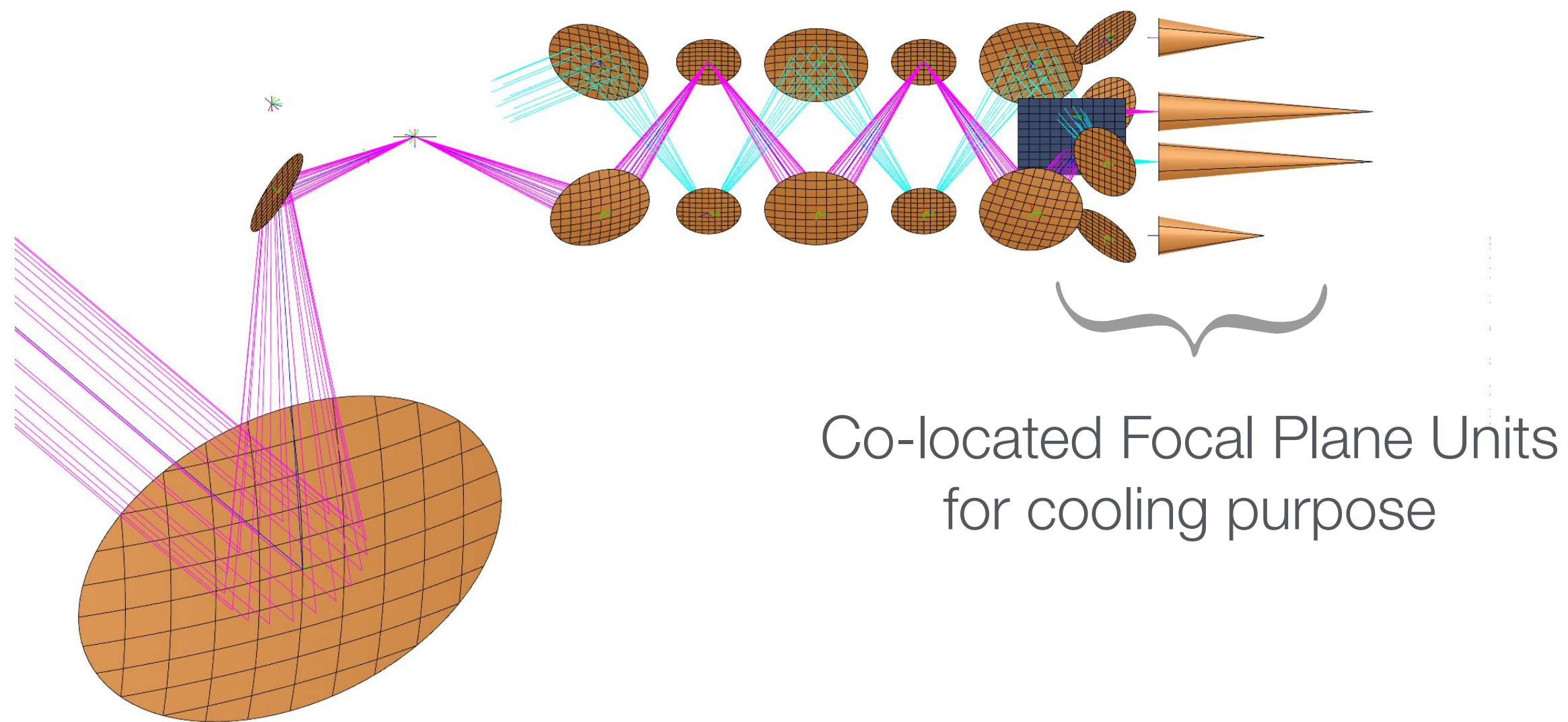


# Instrument Design

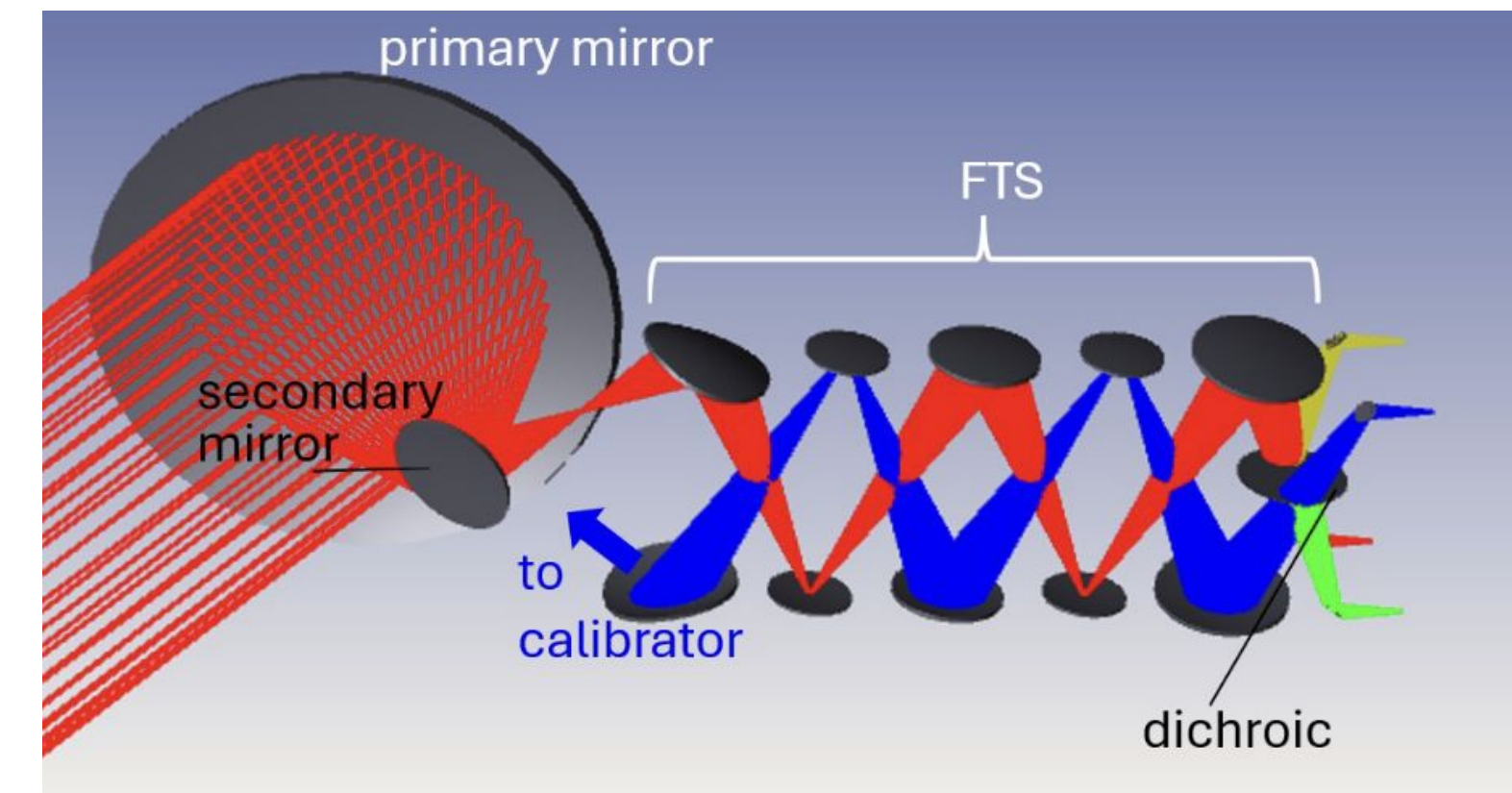
## ➤ Fulfilling Mission Requirements Under Thermo-Mechanical Constraints

### Geometrical optics approach:

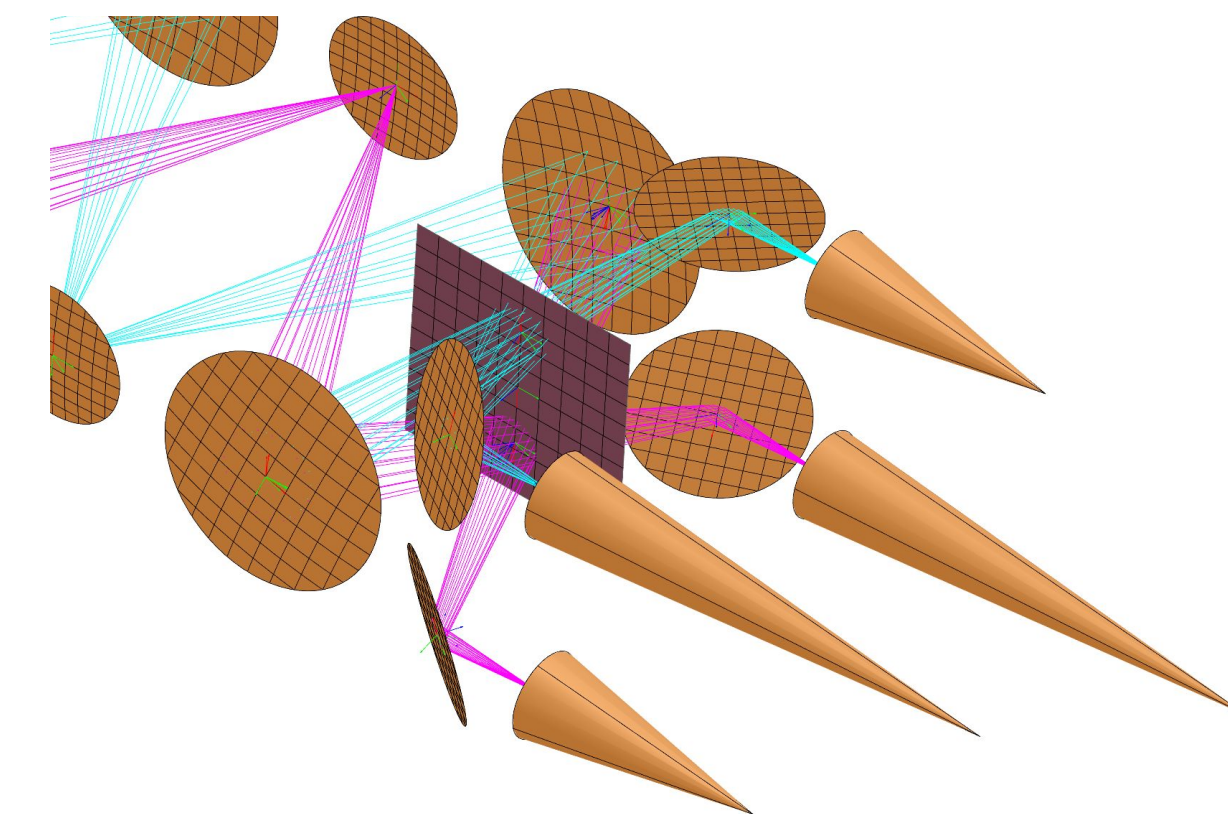
- Light propagation in terms of rays, ignoring wave effects
- Select and place optical components to meet constraints



Ray-tracing simulation of BISOU optics (Tica GRASP software)



Ray-tracing simulation of BISOU optics (Zemax software)  
C. O'Sullivan, Maynooth University



Two Stage focal plane

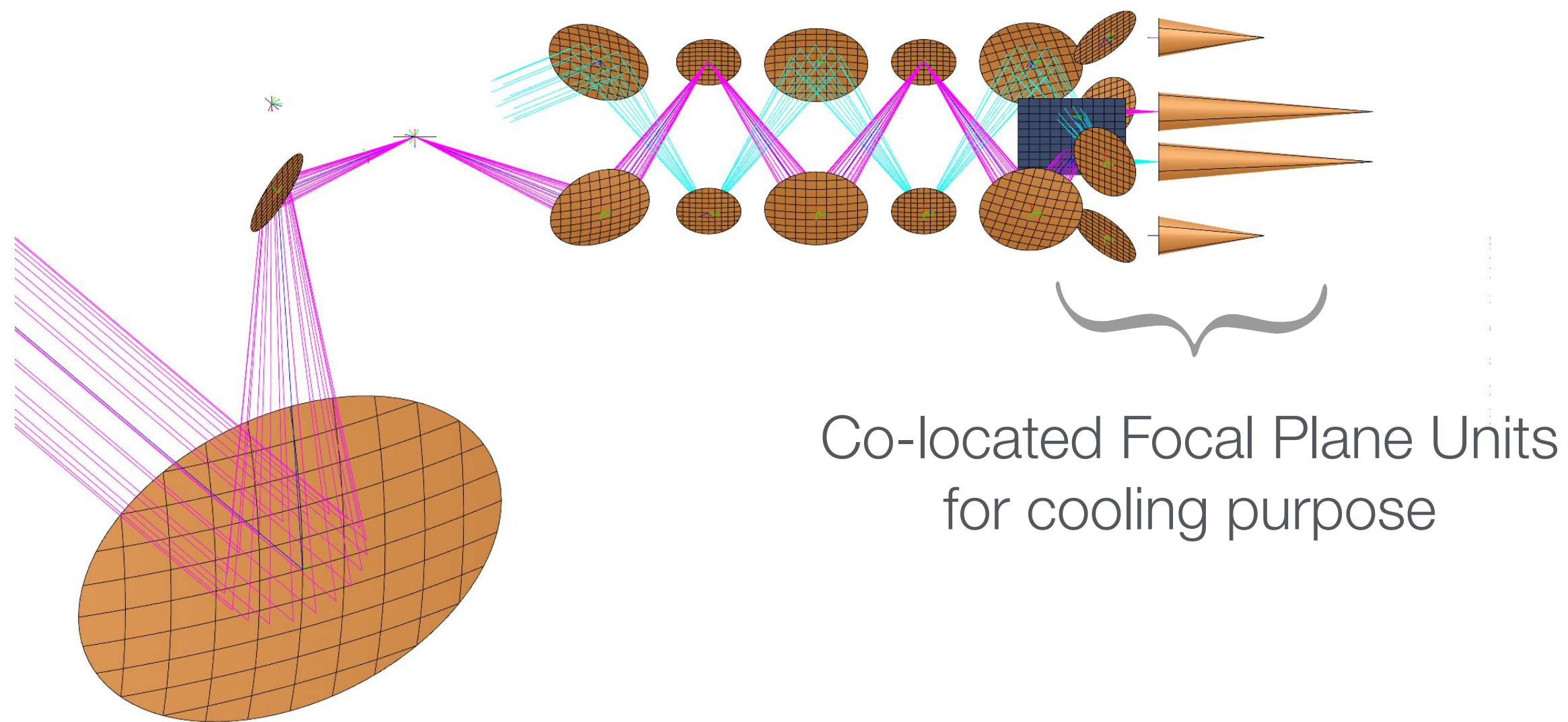


# Instrument Design

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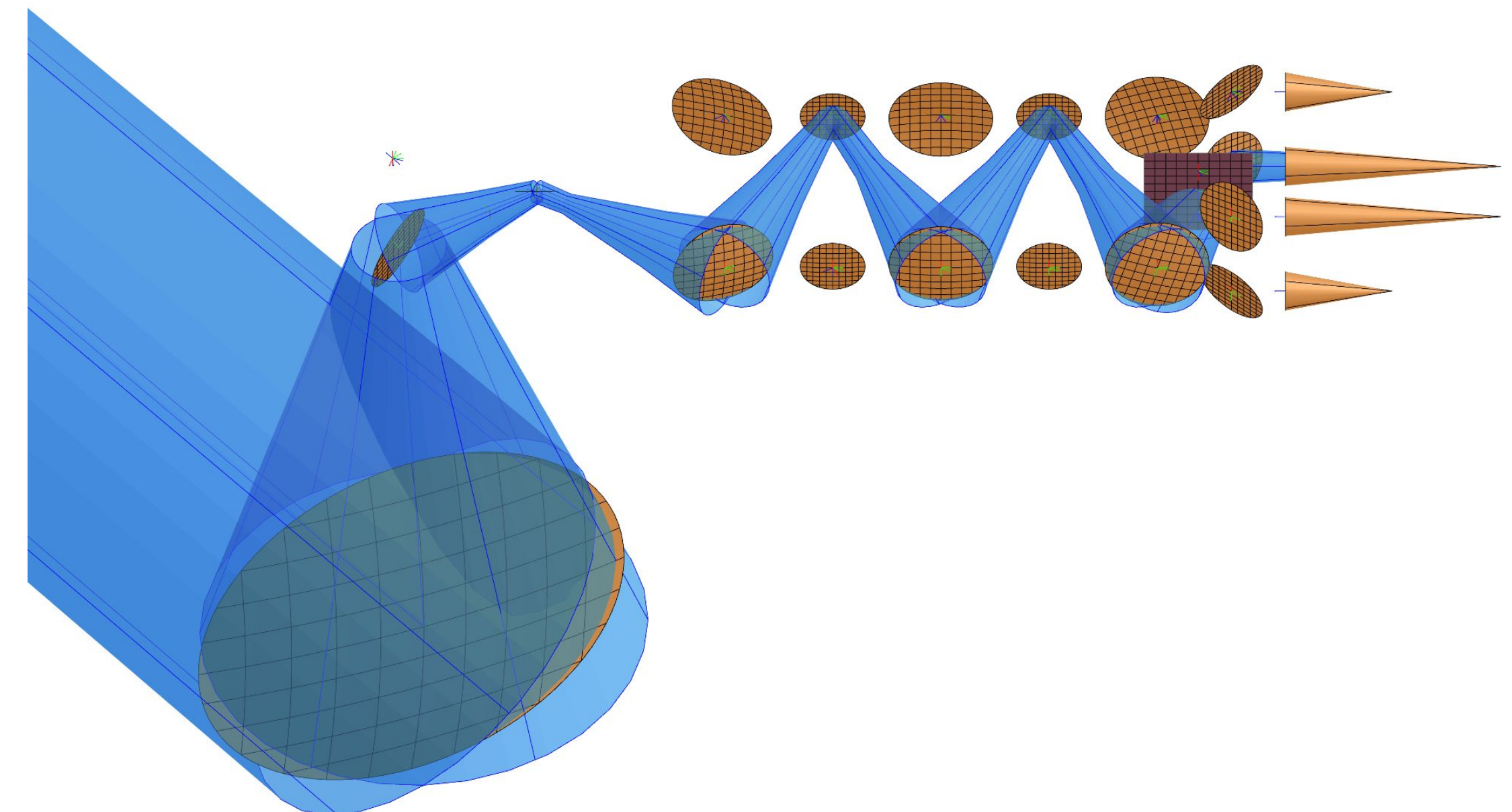
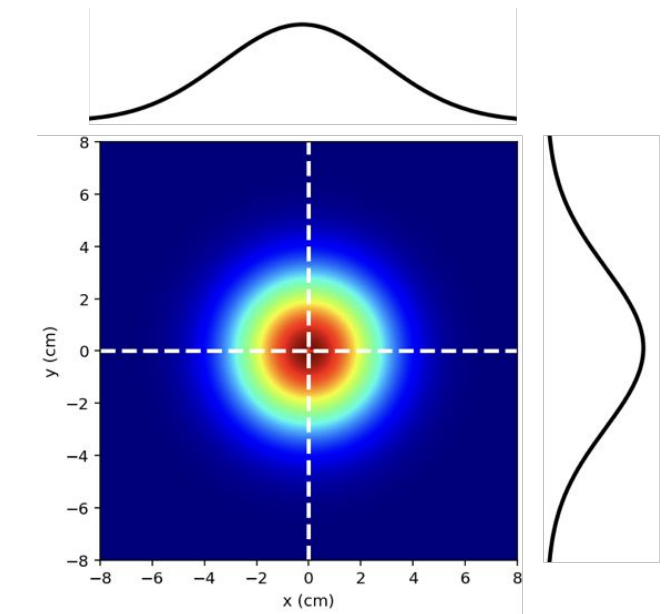
- Light propagation in terms of rays, ignoring wave effects
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Ray-tracing simulation of BISOU optics (Ticra GRASP software)

### Gaussian optics approach:

- Propagation of a Gaussian beam
- Frequency dependent
- Accounts for diffraction effects



Gaussian beam simulation of BISOU optics (Ticra GRASP software)

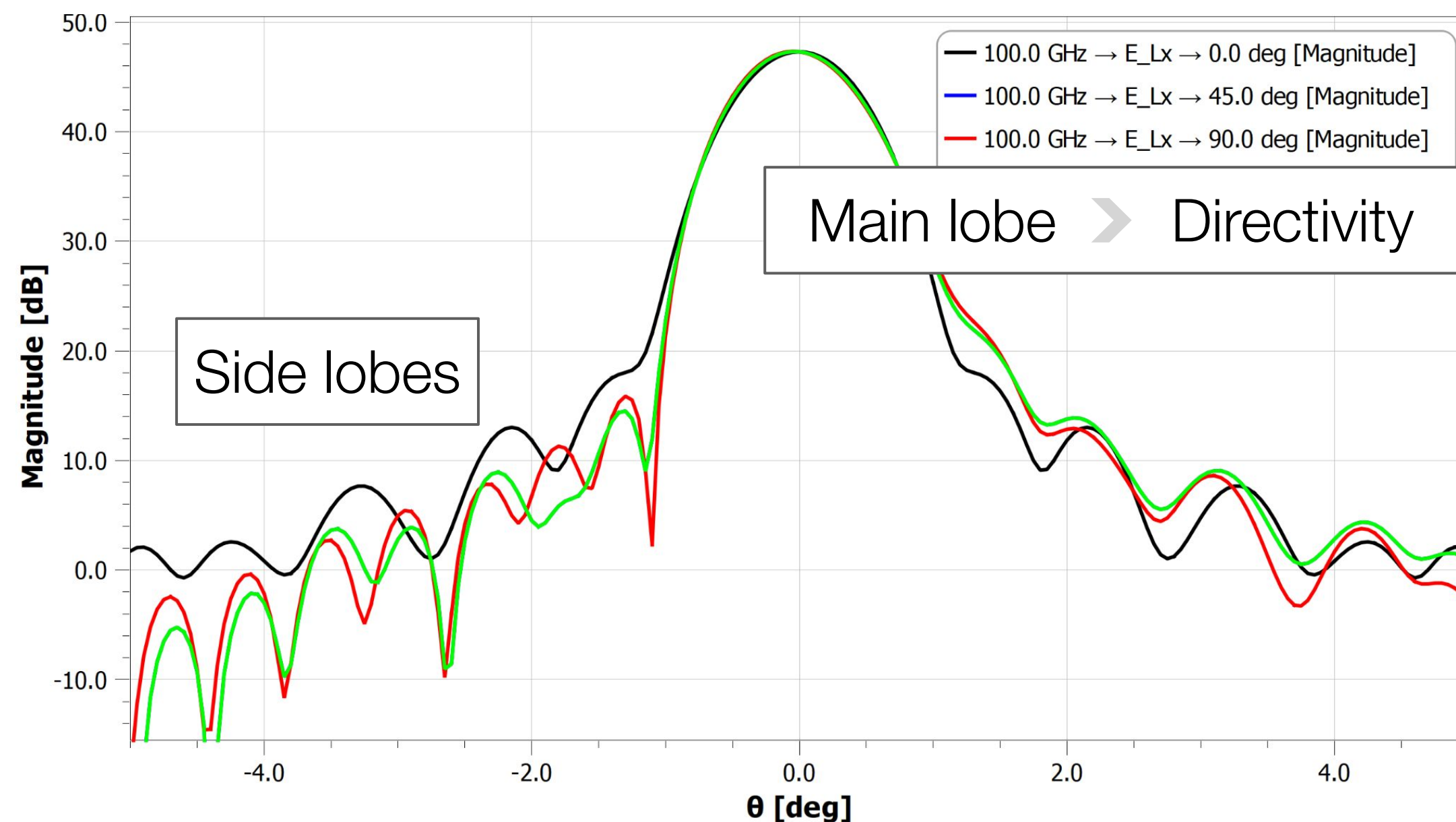


# Simulations

- Once a design appears satisfactory, we proceed to model its performance
  - antenna diagram
  - spillover (power lost on the path from the horn to the sky & signal contamination from surroundings)

## Antenna diagram:

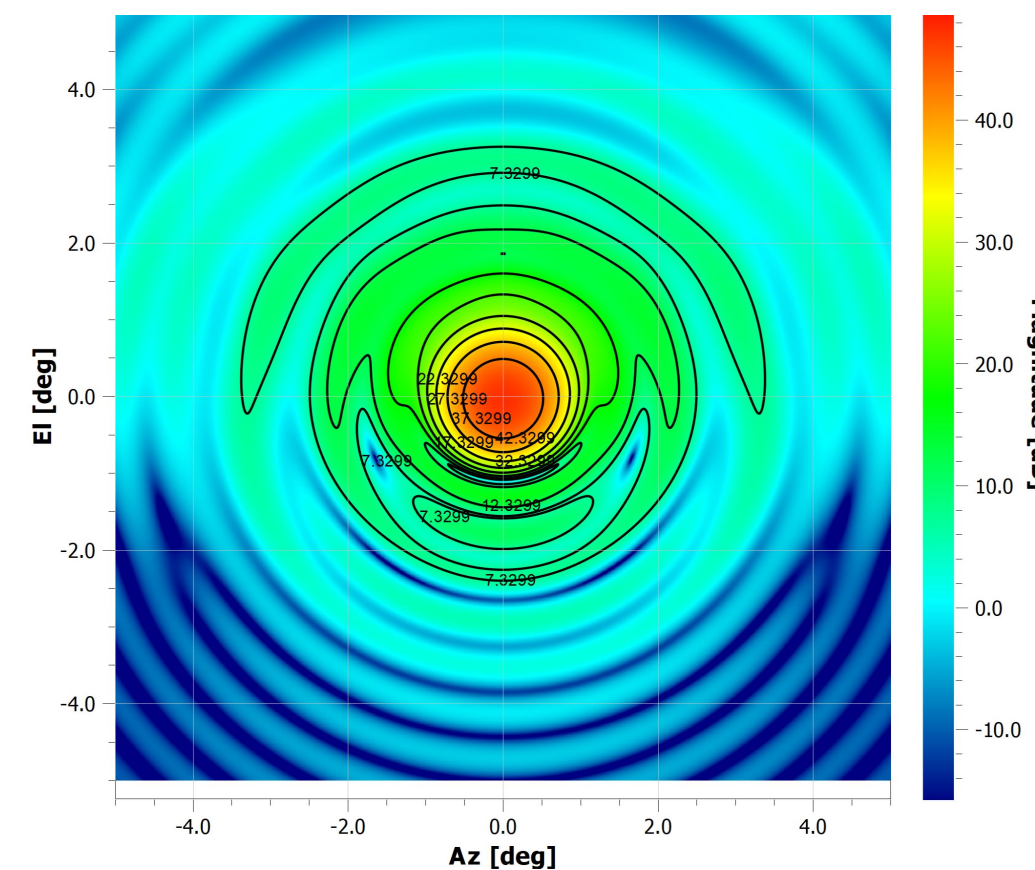
- Graphical representation of an antenna radiation pattern, showing how it emits or receives energy in different directions.



Spherical cut antenna diagram example (Ticra GRASP software)

## Single-mode simulation

- Preliminary design with a single-mode feedhorn
- Multi-mode computation requires significantly higher computational time.



- Multimode beam  $\sim 5^\circ$ , same size at each frequency

Spherical grid antenna diagram example (Ticra GRASP software)

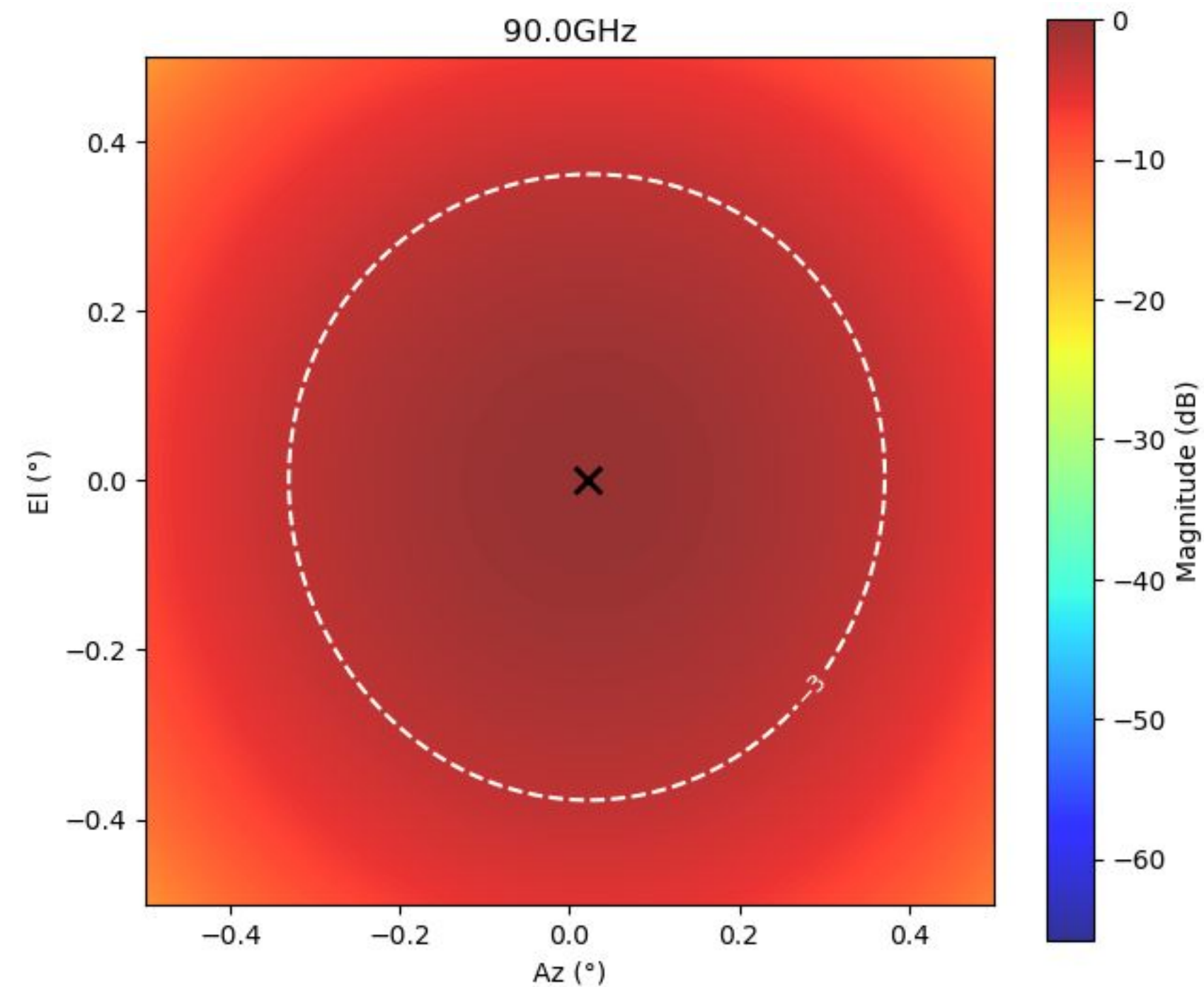
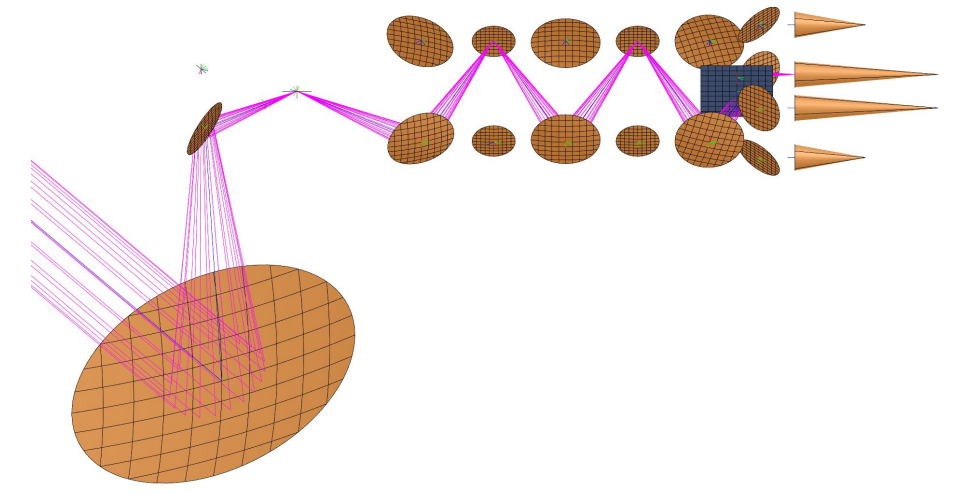


# Simulations

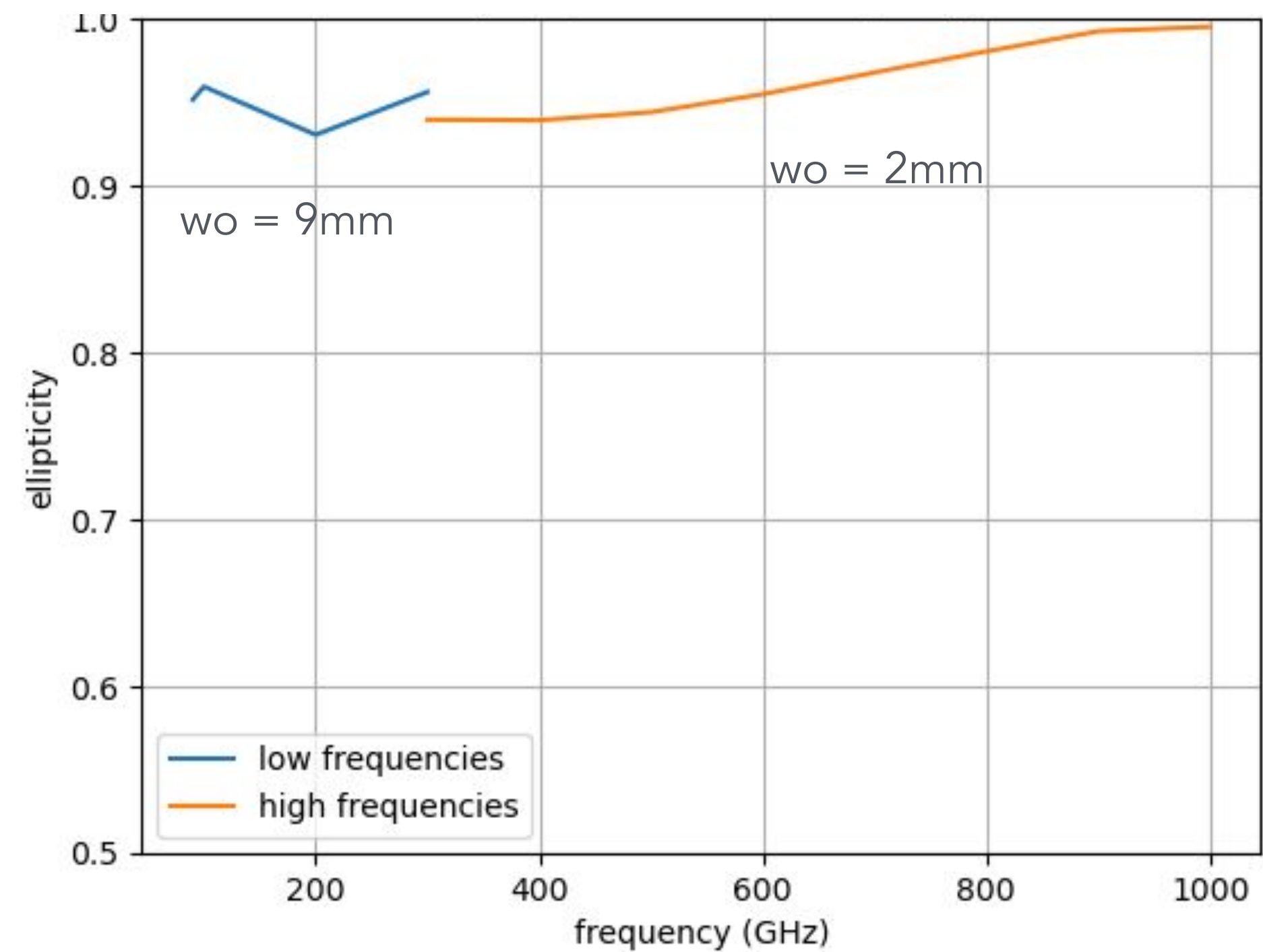
- Single mode gaussian beam modeling from horn to sky for preliminary results

## Ellipticity of the beam

- Evaluates how much the beam is deformed by the optics
- Used to optimize the optical system (e.g., matching the phase center with the telescope focus)



Ellipse fit on the BISO antenna pattern at 90 GHz



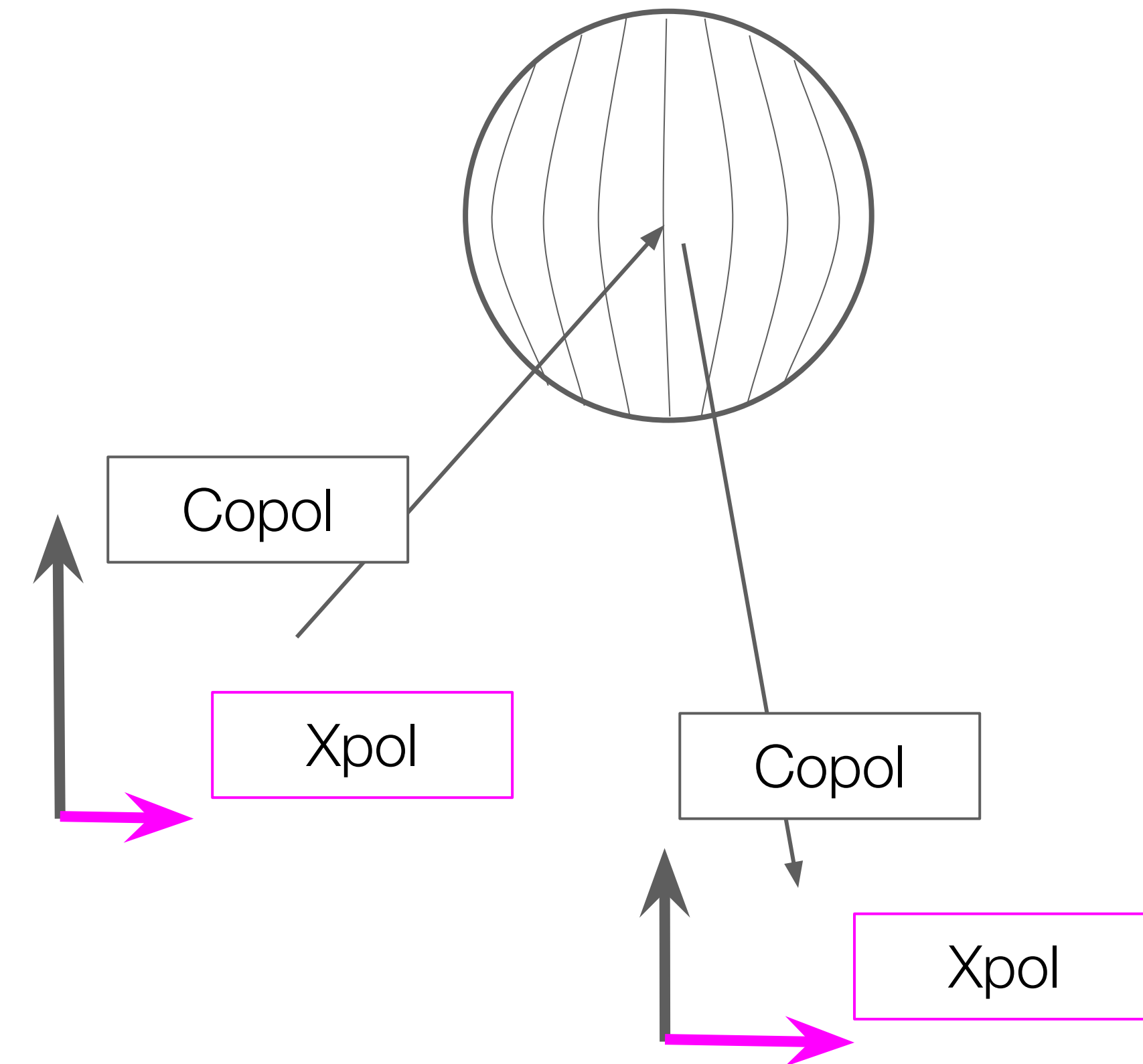
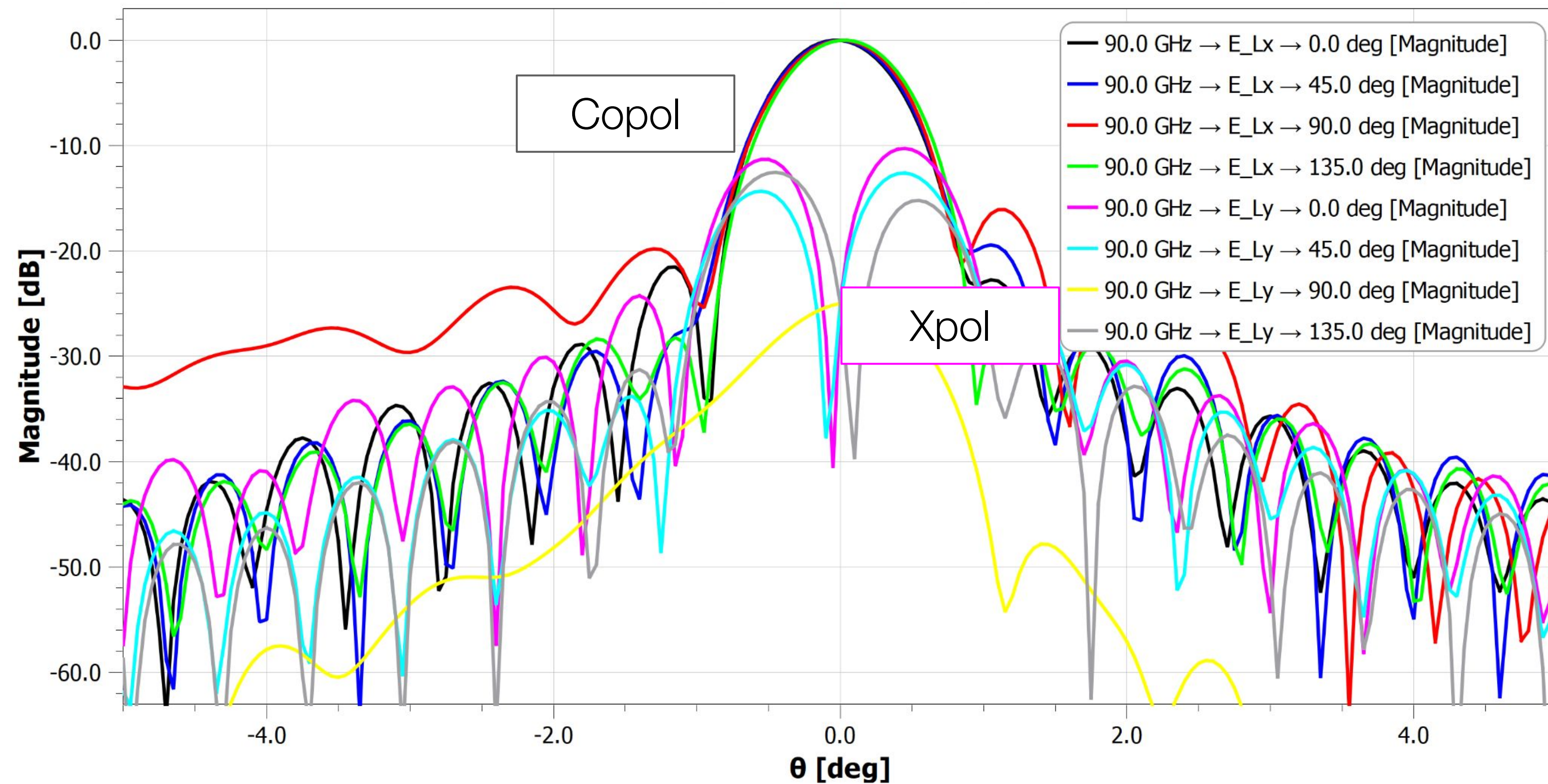
Beam ellipticity of BISO from 90 GHz to 1 THz



# Simulations

➤ Cross-polarization (Xpol): unwanted polarization component orthogonal to the desired one

Antenna diagram representation:



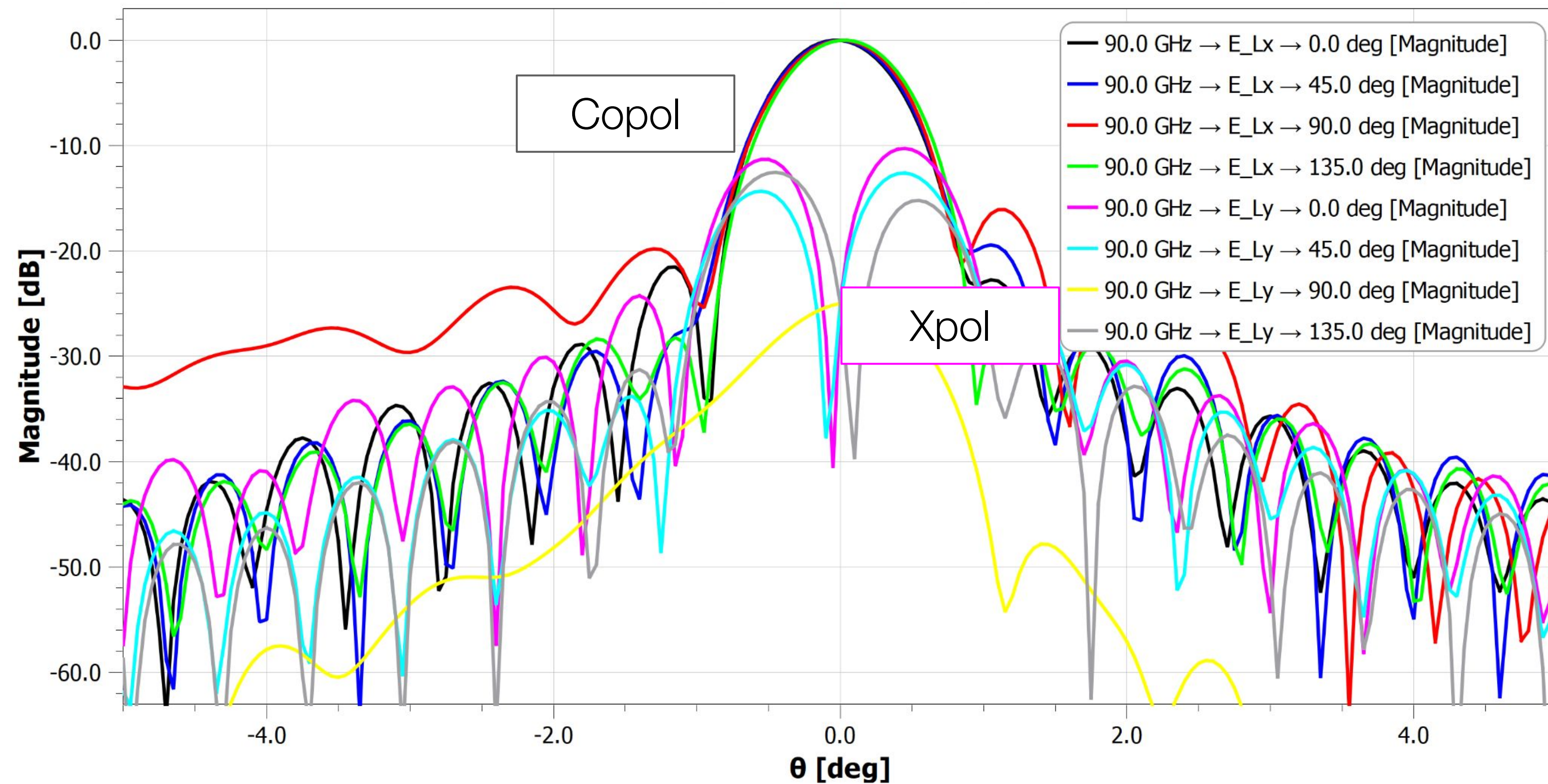
Spherical cut antenna pattern: comparison of Co-polarization and Cross-polarization (TICRA GRASP software) of the BISOU instrument (instrument ver 1)



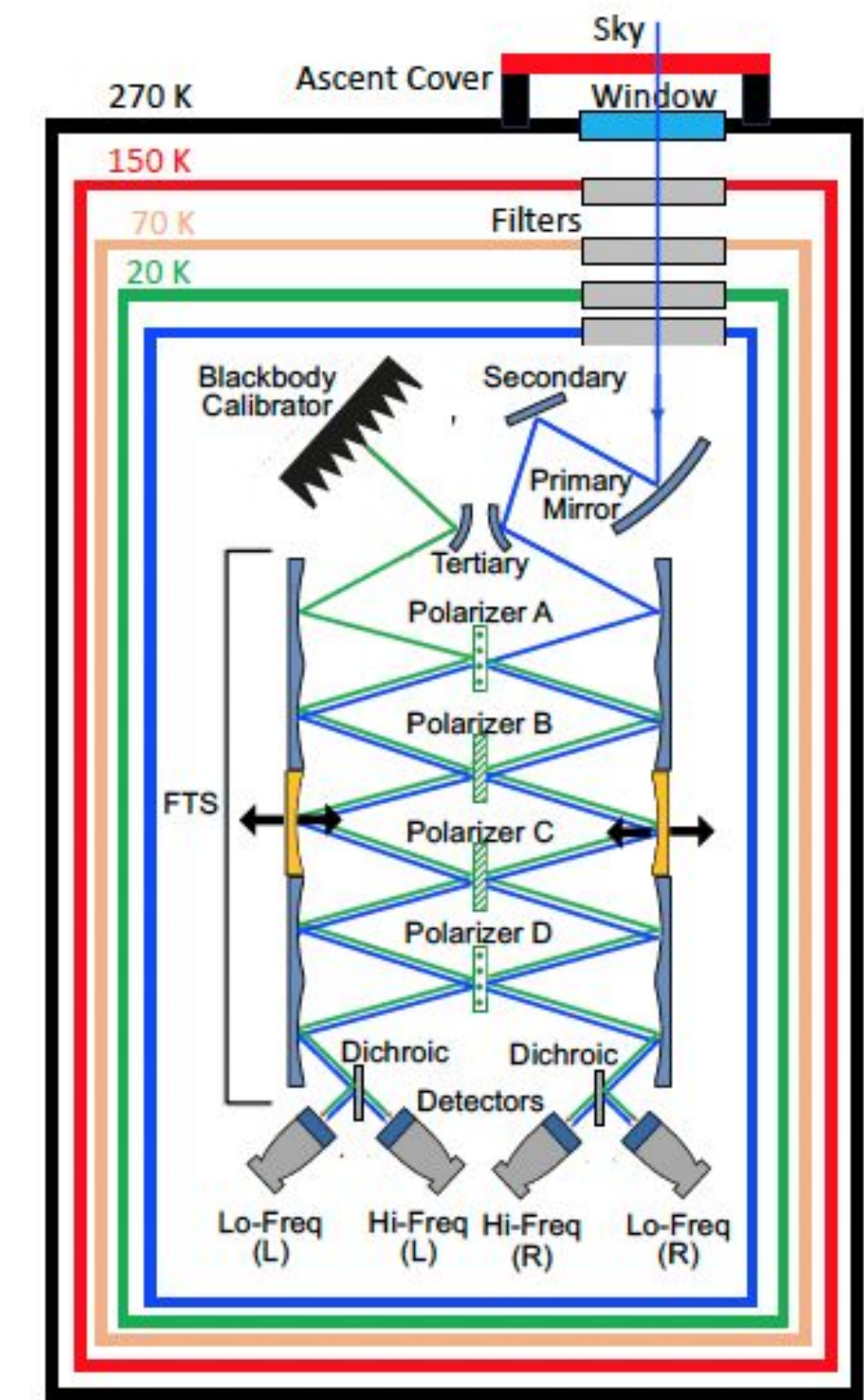
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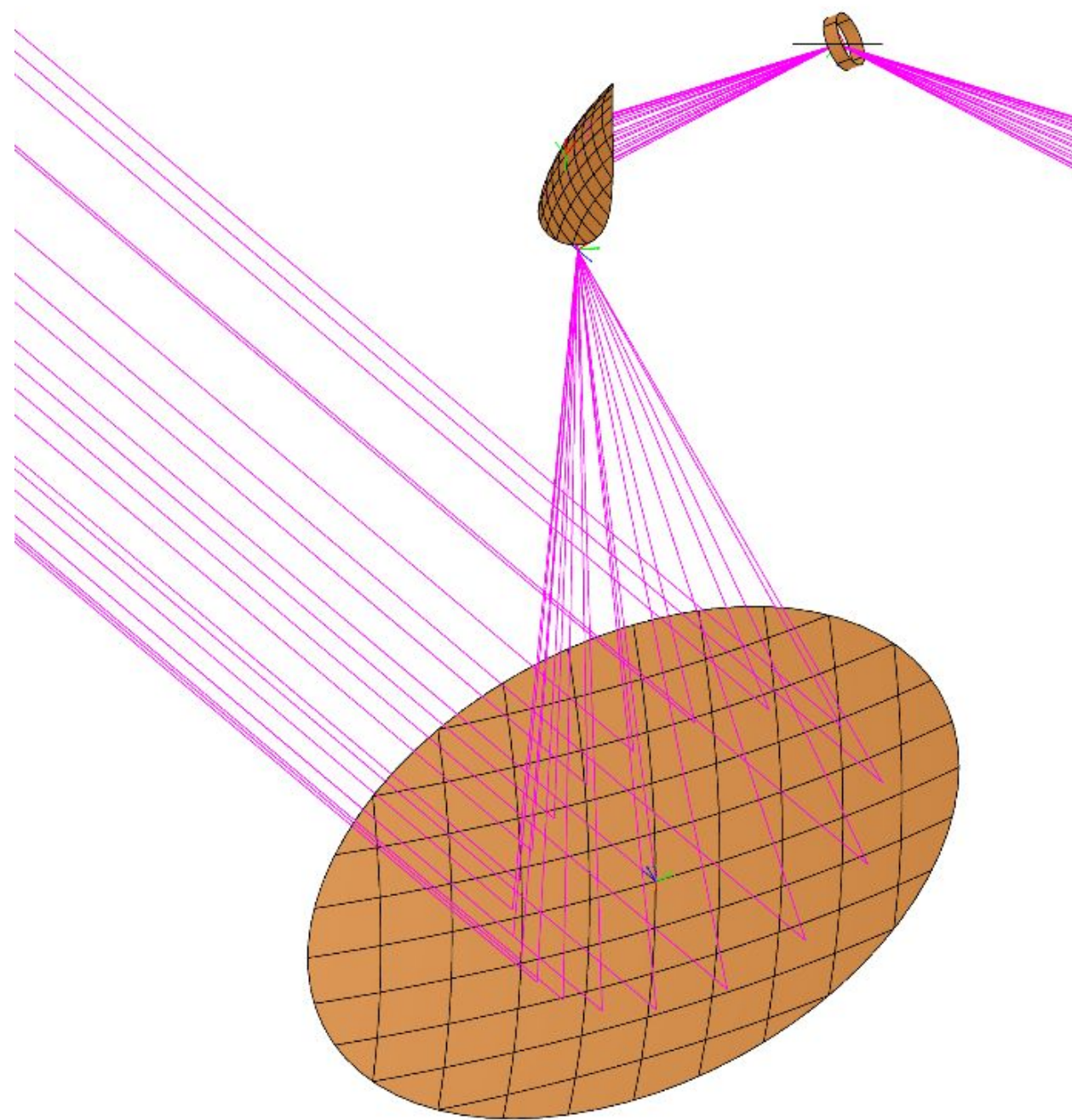
BISOU instrument concept



# Simulations

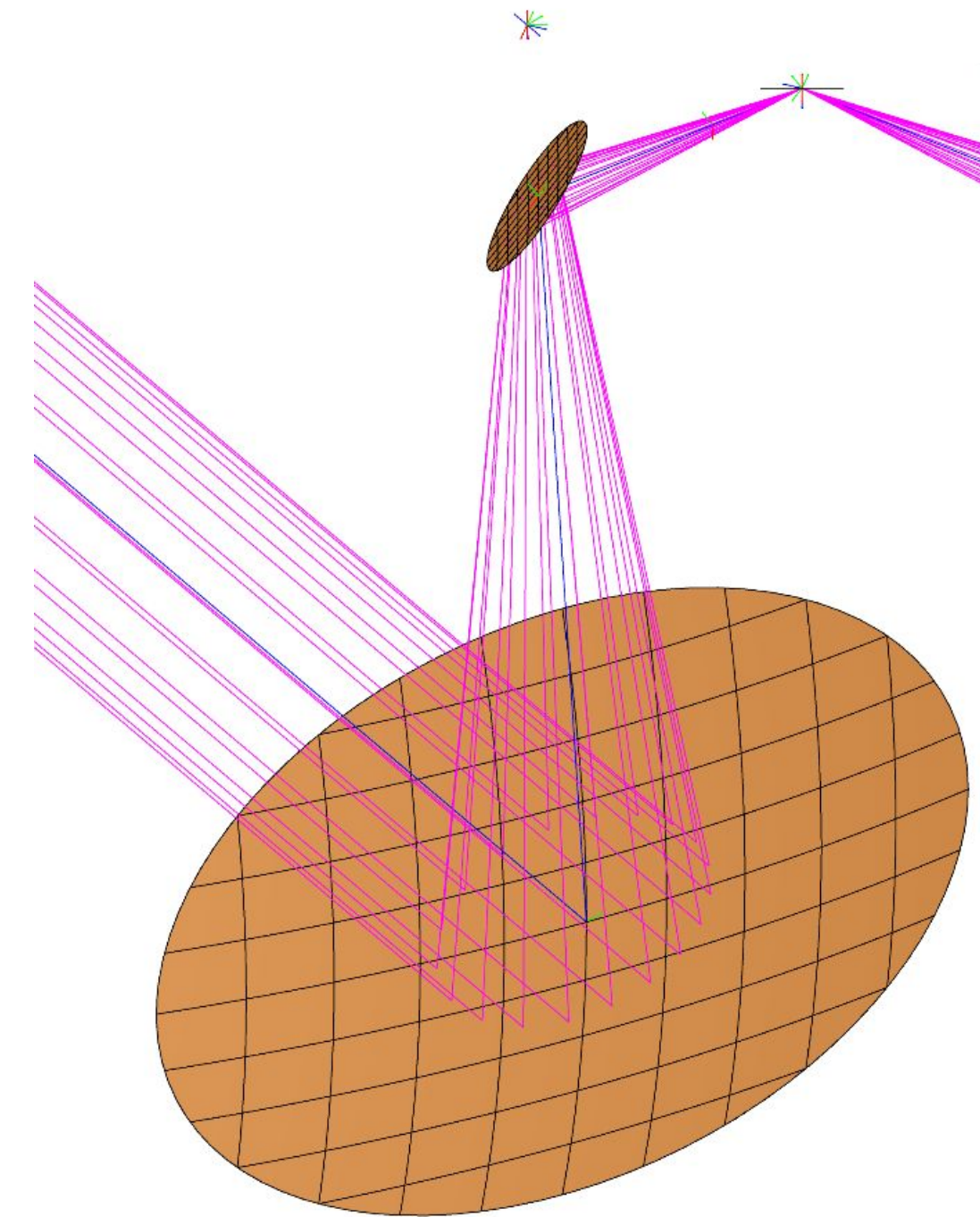
➤ Cross-polarization (Xpol): unwanted polarization component orthogonal to the desired one

Previous telescope design



Off axis telescope with an ellipsoid secondary reflector

Latest telescope design ➤ Mizuguchi-Dragone condition



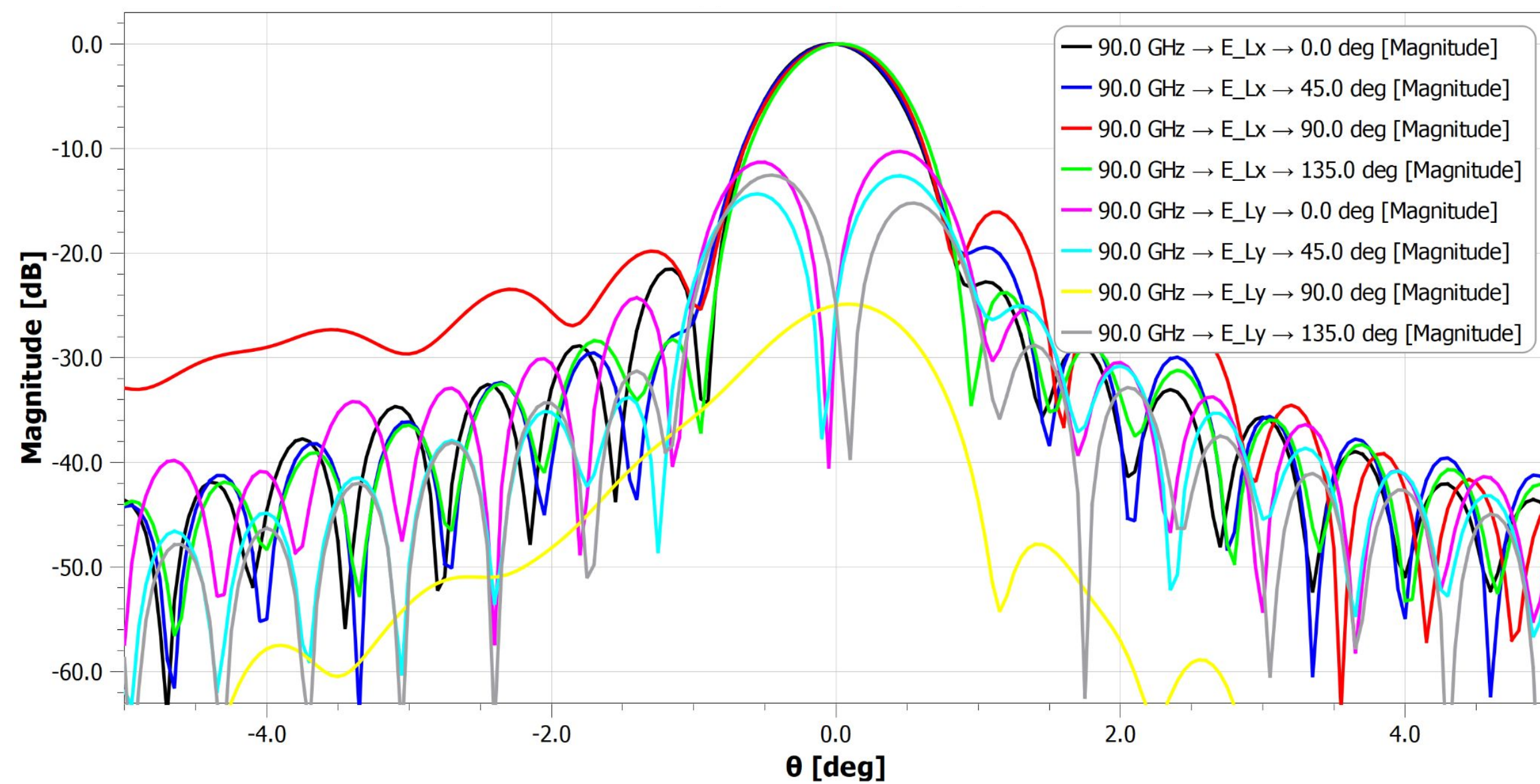
Off axis telescope with an hyperboloid secondary reflector



# Simulations

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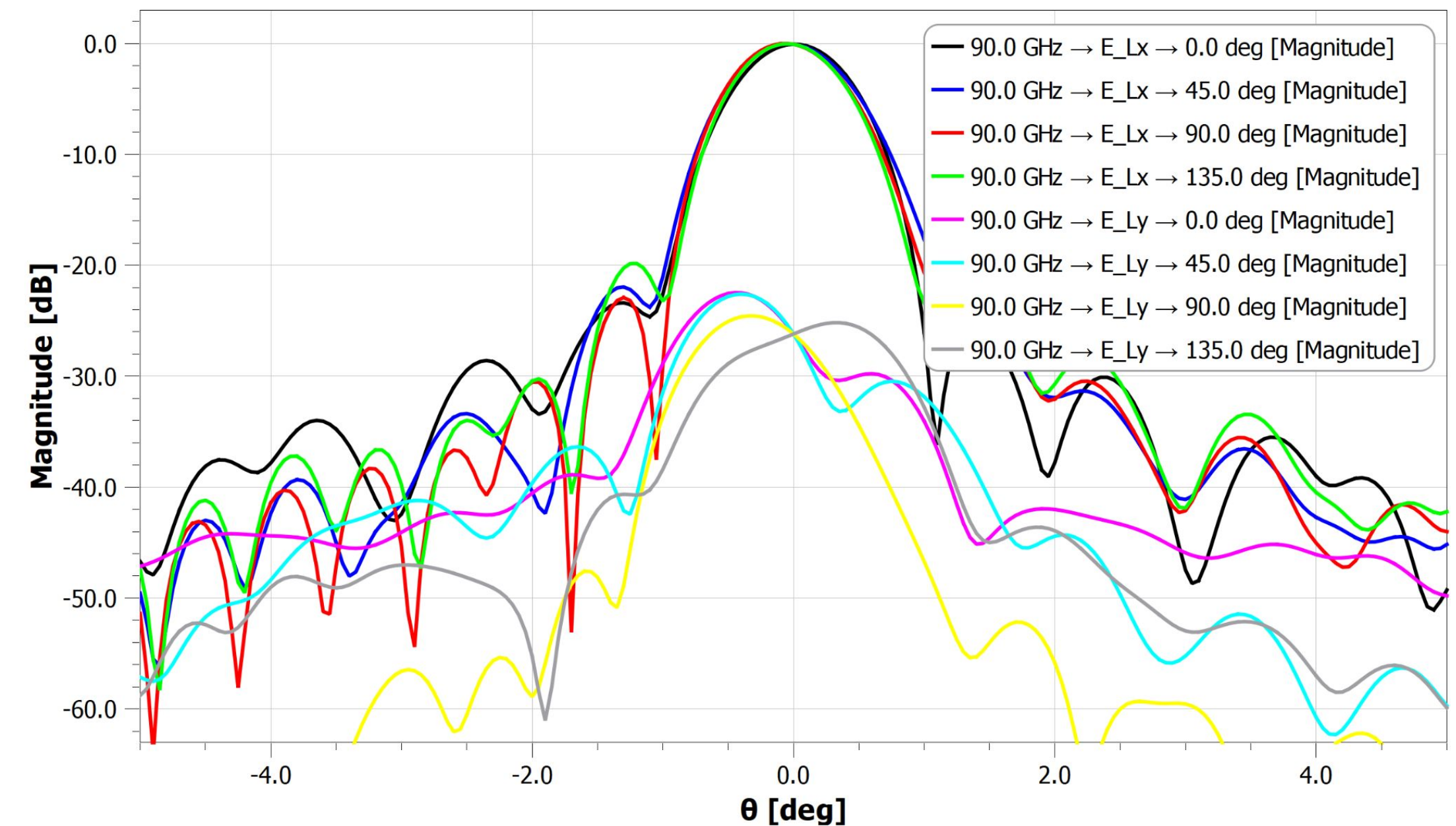
## Instrument with Previous telescope design



Antenna diagram of the instrument with an ellipsoid secondary reflector (90 GHz)

## Instrument with Latest telescope design

➤ Mizuguchi-Dragone condition



Antenna diagram of the instrument with an hyperboloid secondary reflector (90 GHz)



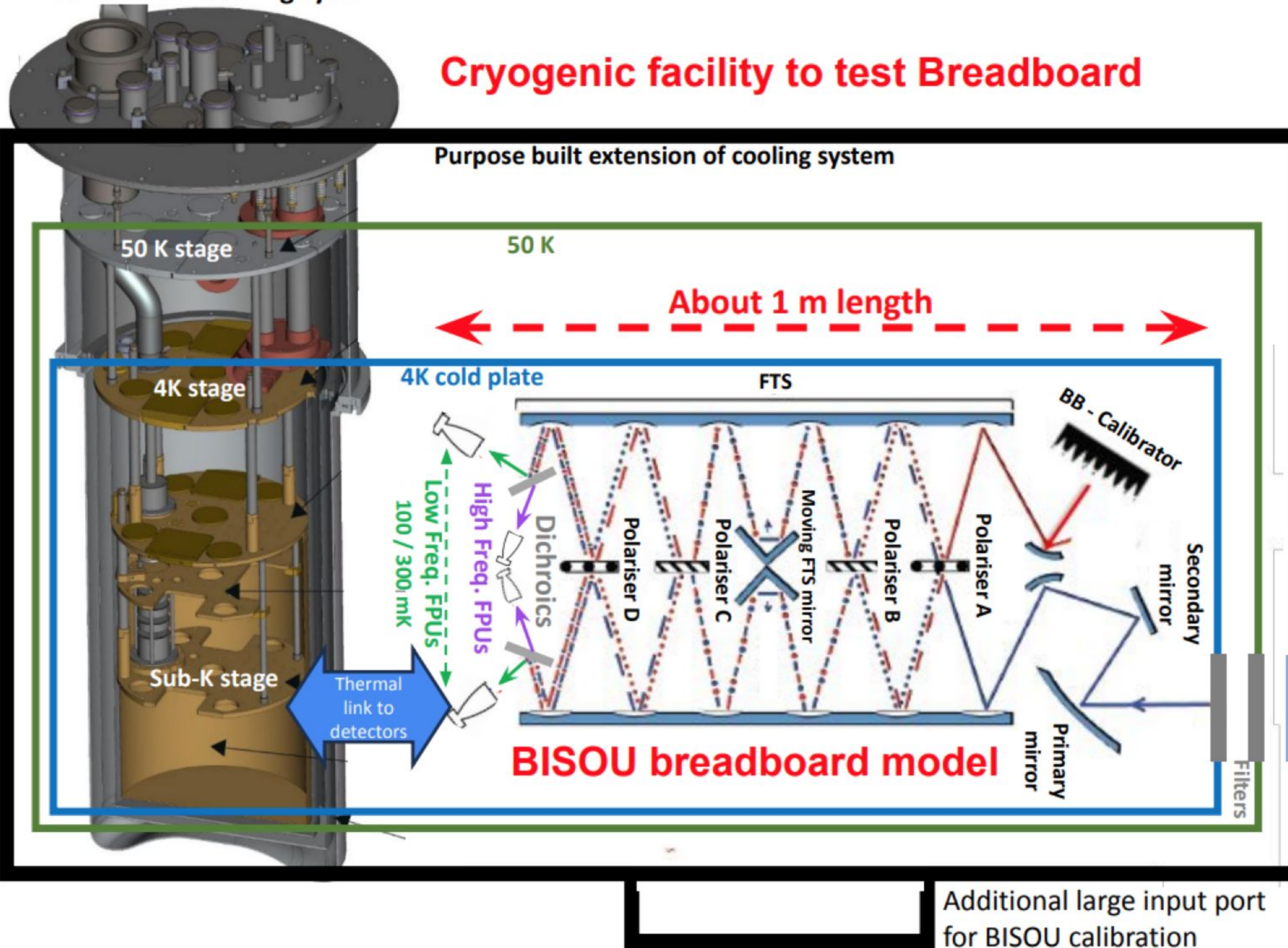
# Breadboard

- Laboratory prototype developed to consolidate the concept and study the systematics ahead of the real BISOU instrument

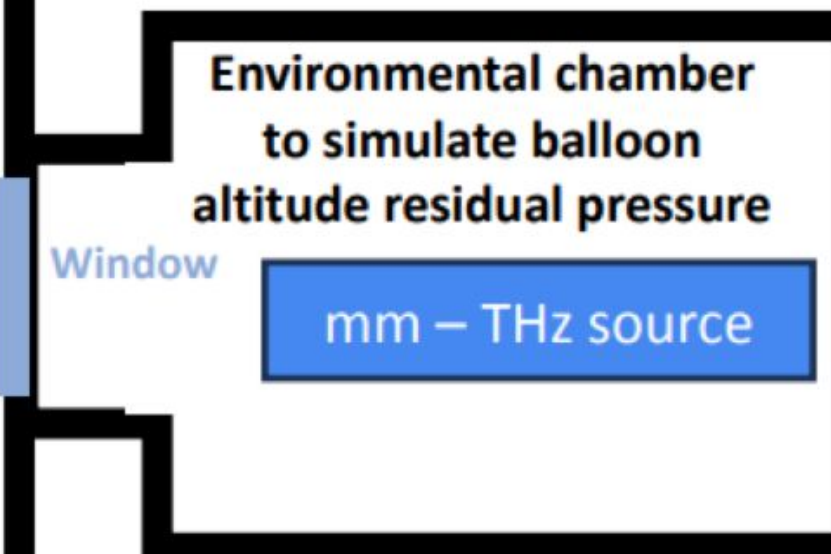
Commercial cooling system

## Cryogenic facility to test Breadboard

Purpose built extension of cooling system



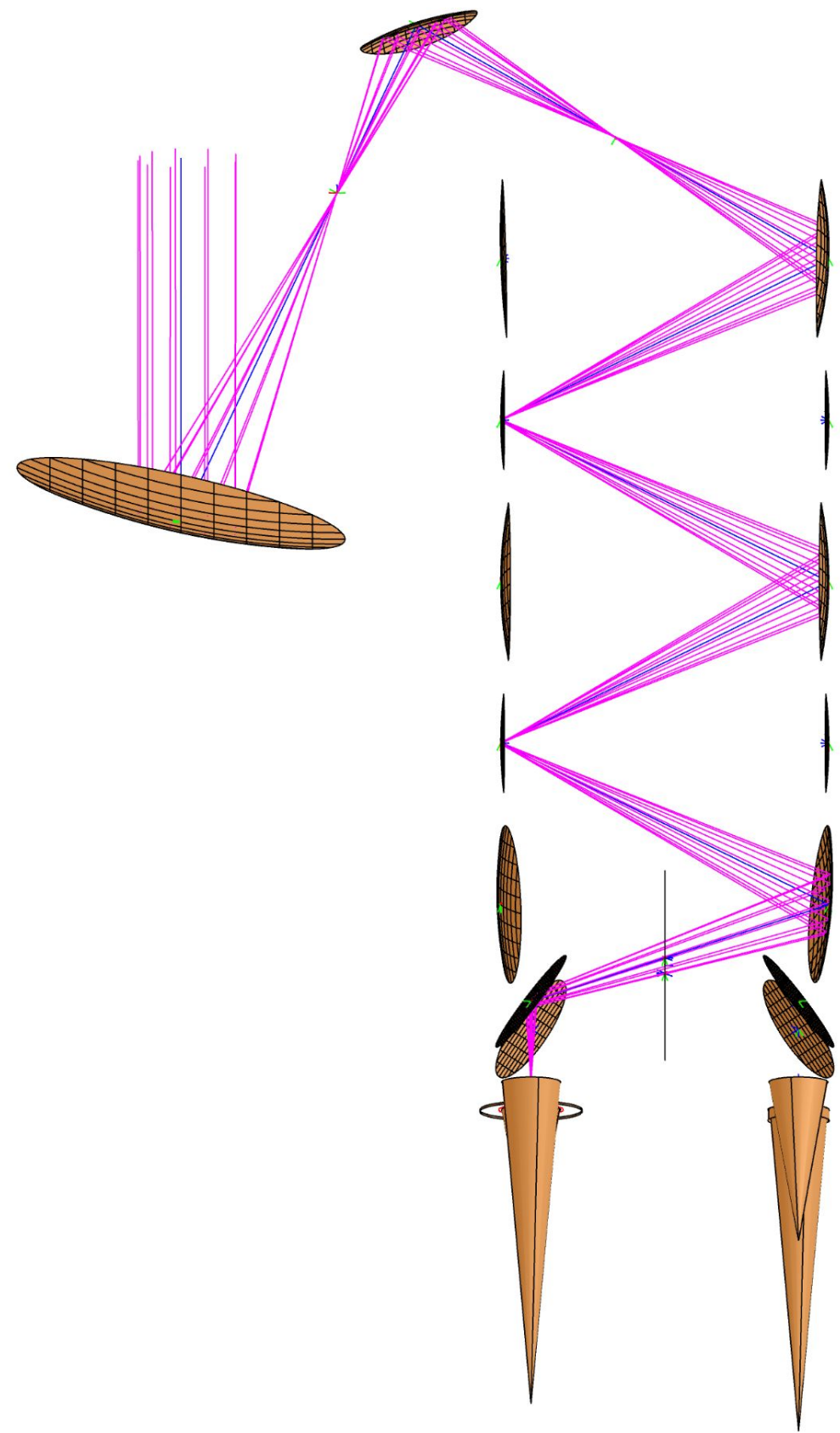
- Test key components ahead of BISOU final instrument
  - Detectors (300 - 100 mK)
  - Calibrator
  - Window / Filters / Dichroics
- To test the overall concept on simplified system
- To probe systematics
  - Temperature variations
  - Optics mismatch
  - Atmosphere
- To get used to specific FTS data and analysis



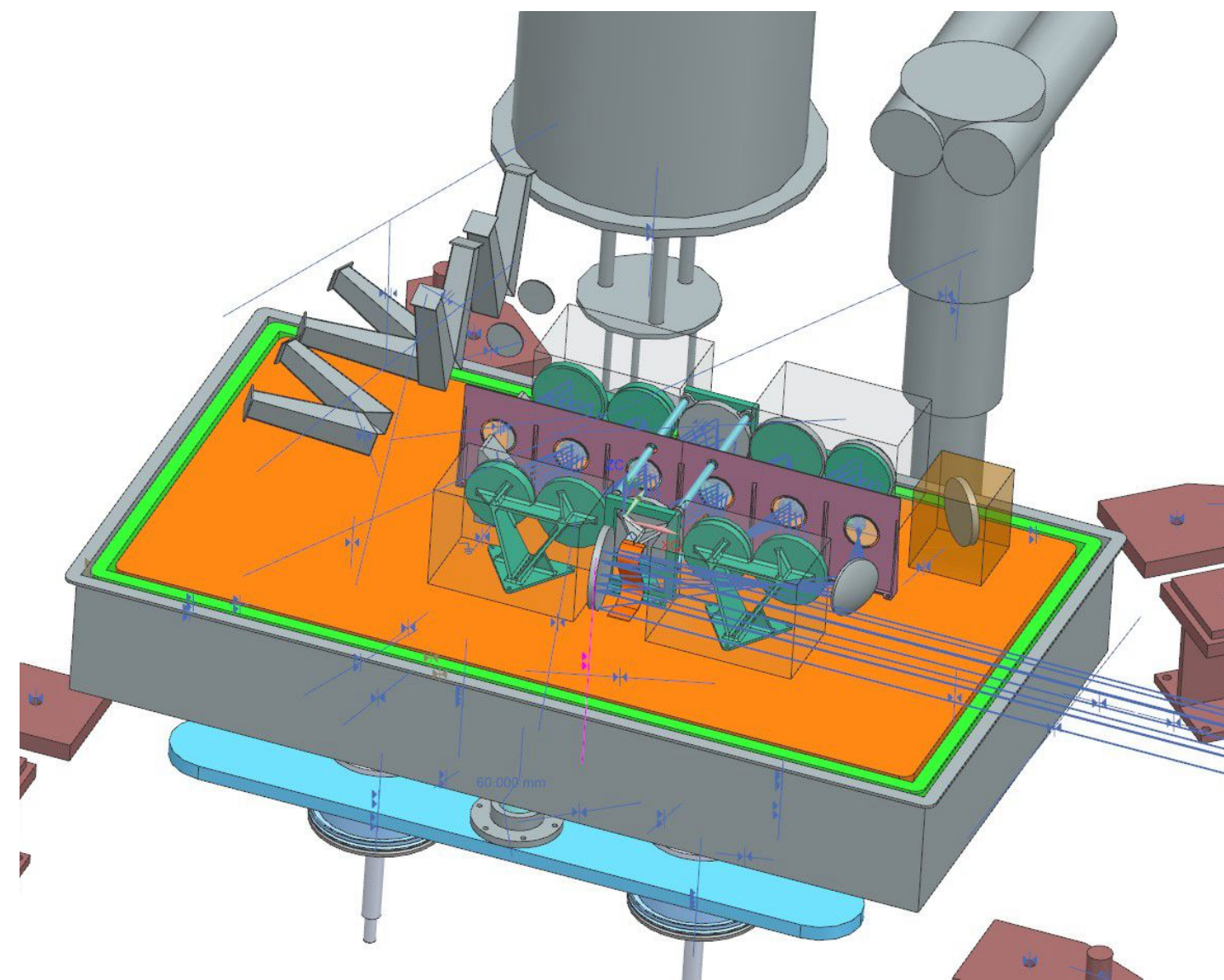


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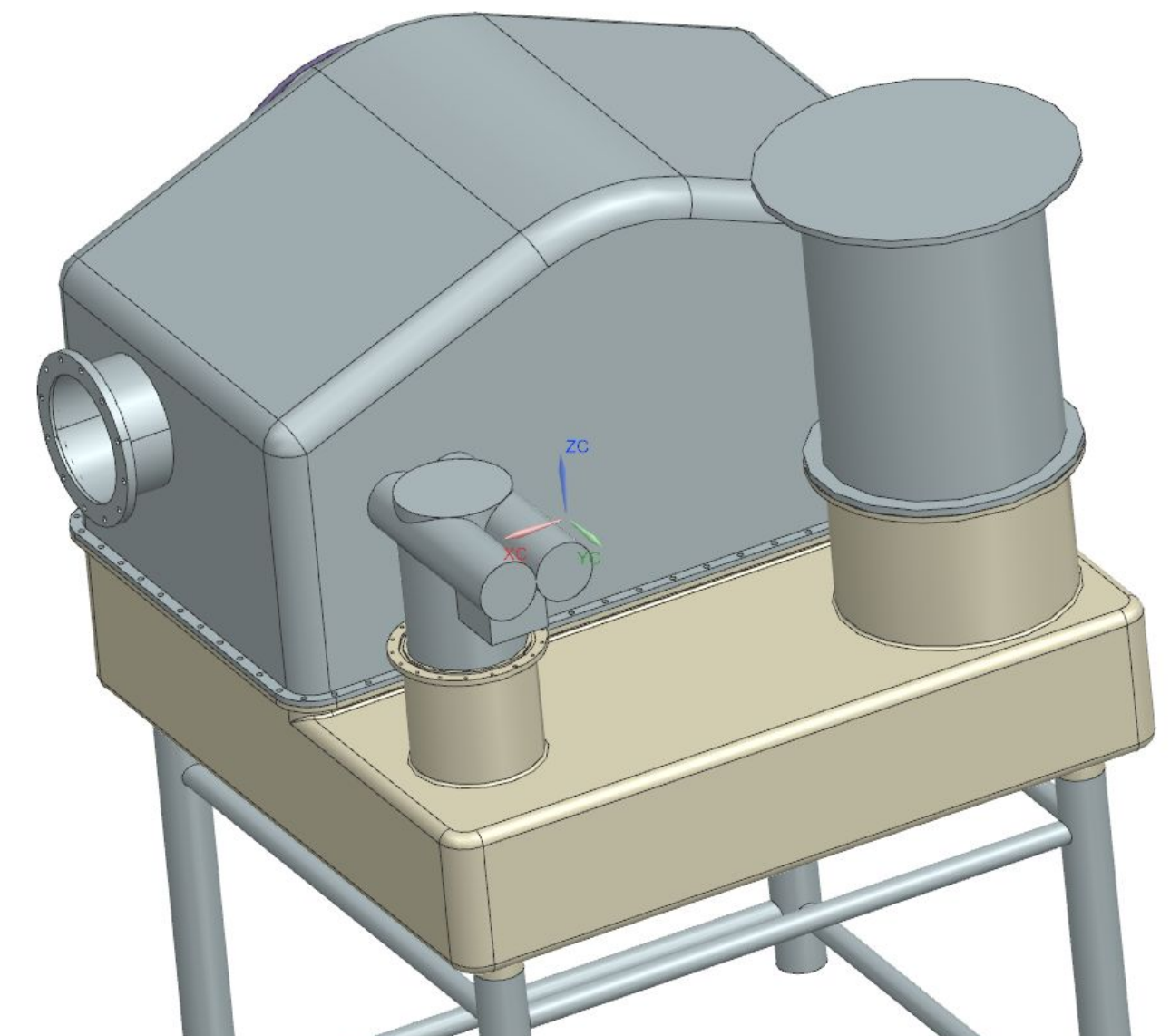
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Ray-tracing simulation of the Breadboard(Ticra GRASP software)



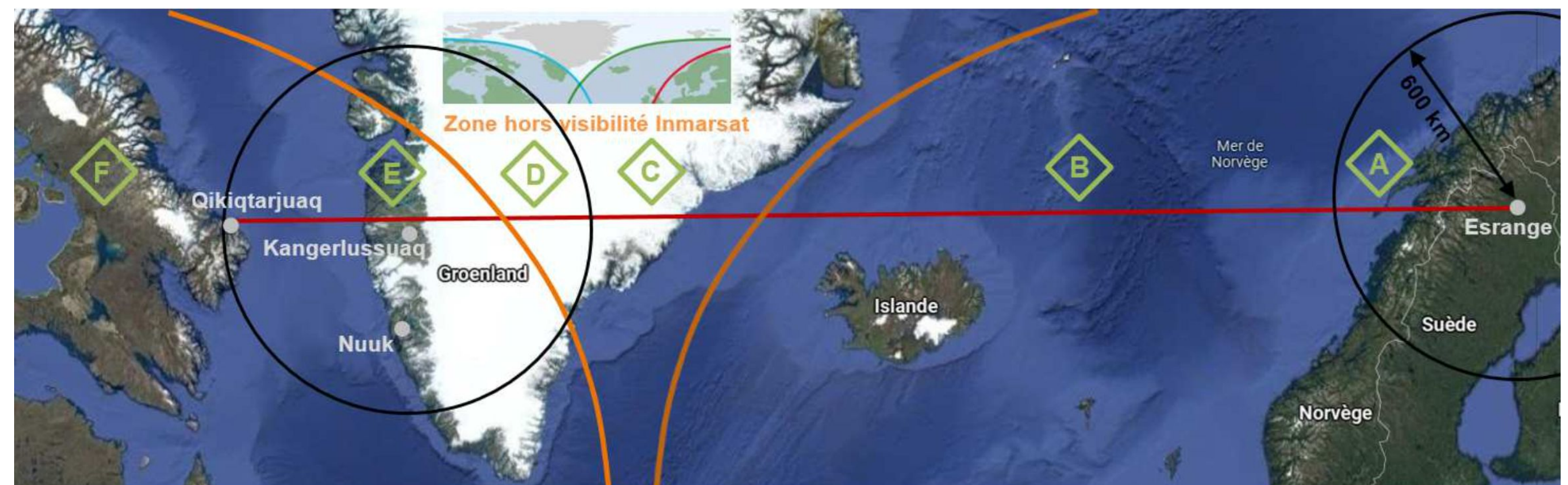
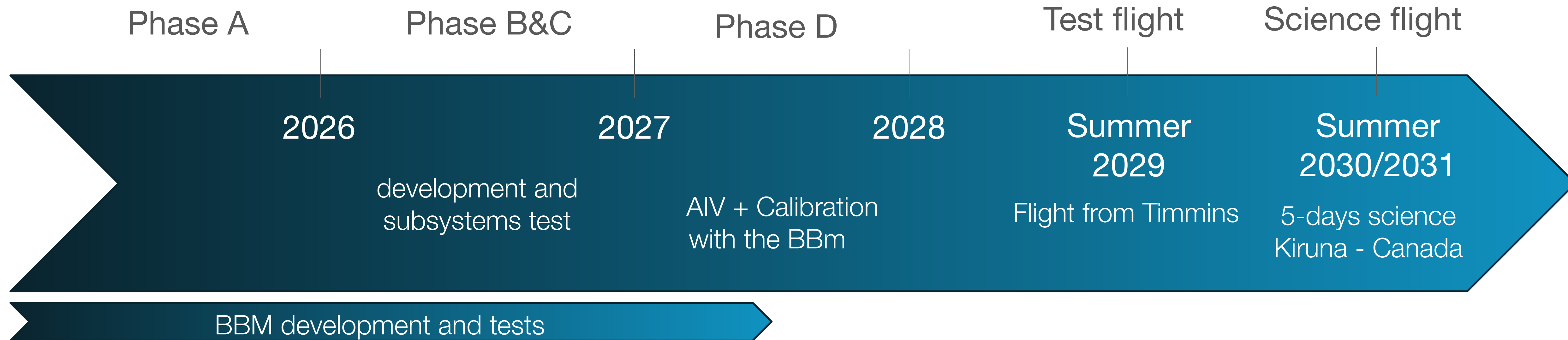
CAD of the Breadboard model





# Time scale

BISOU :



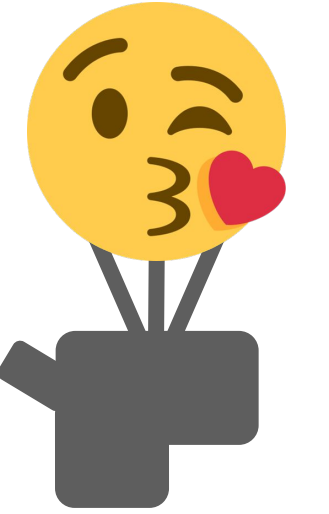
First CNES transatlantic demonstration flight in June 2024





# Conclusions

- The development of BISOU is essential for preparing future space missions dedicated to spectral distortion measurements, such as FOSSIL.
- Phase A is ongoing, with the instrument design becoming more refined.
- Future simulations will include the multimode nature of the optical system.



## References :

- J. C. Mather, D. J. Fixsen, R. A. Shafer, C. Mosier and D. T. Wilkinson, "Calibrator Design for the COBE Far-Infrared Absolute Spectrophotometer (FIRAS)," ApJ, vol. 512, 1999.
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- B. Maffei, et al., "BISOU: A balloon project to measure the CMB spectral distortions," The sixteenth Marcel Grossmann meeting. On recent developments in theoretical and experimental general relativity, astrophysics, and relativistic field theories
- P.F. Goldsmith, P.F., Quasioptical Systems: Gaussian Beam Quasioptical Propagation and Applications, IEEE Press series on microwave technology and techniques, 1998.
- TICRA GRASP, Online at: <https://www.ticra.com/software/grasp>.