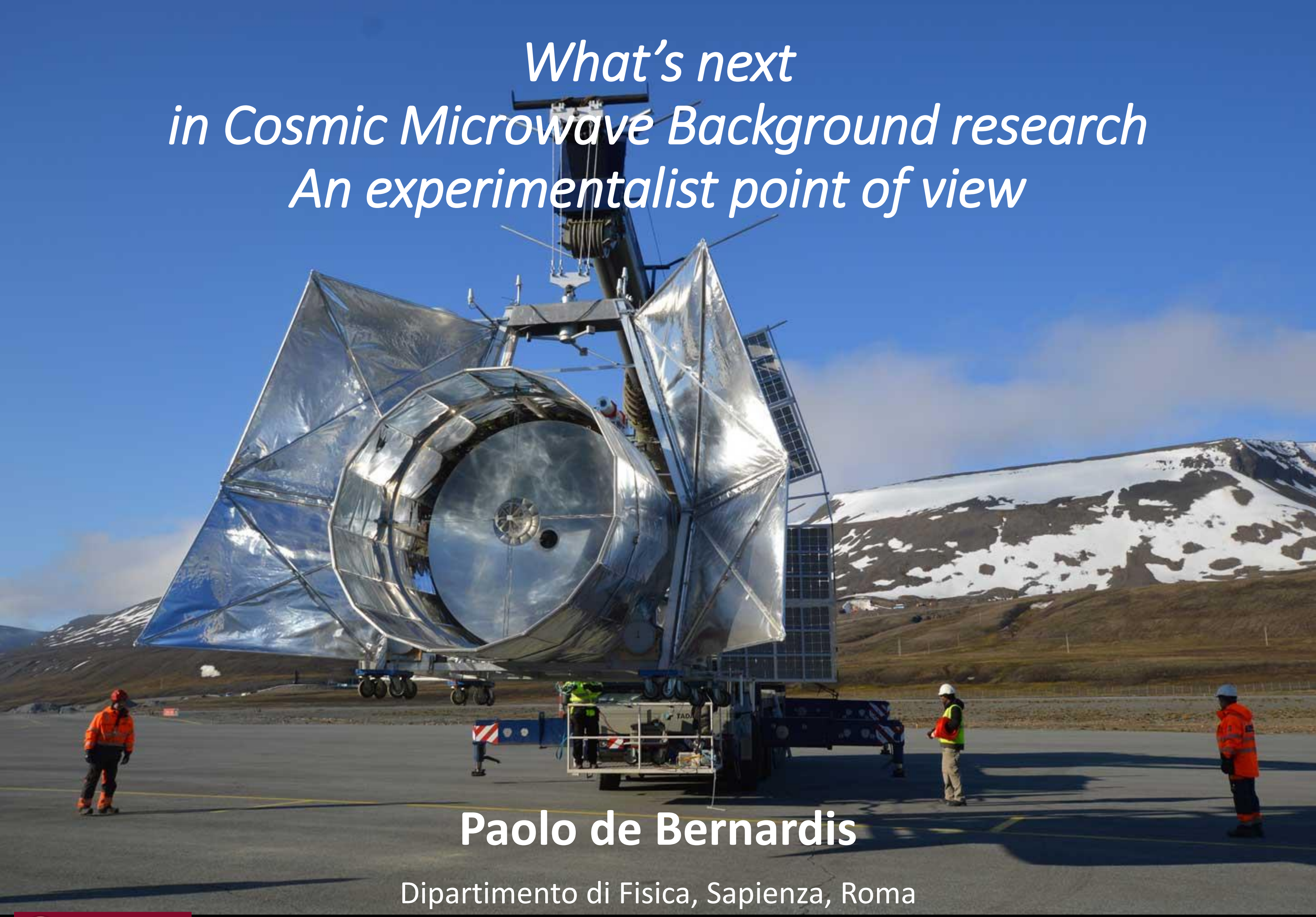

What's next in Cosmic Microwave Background research An experimentalist point of view

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Dipartimento di Fisica, Sapienza, Roma

"MG15", Sapienza, Rome, July 6, 2018

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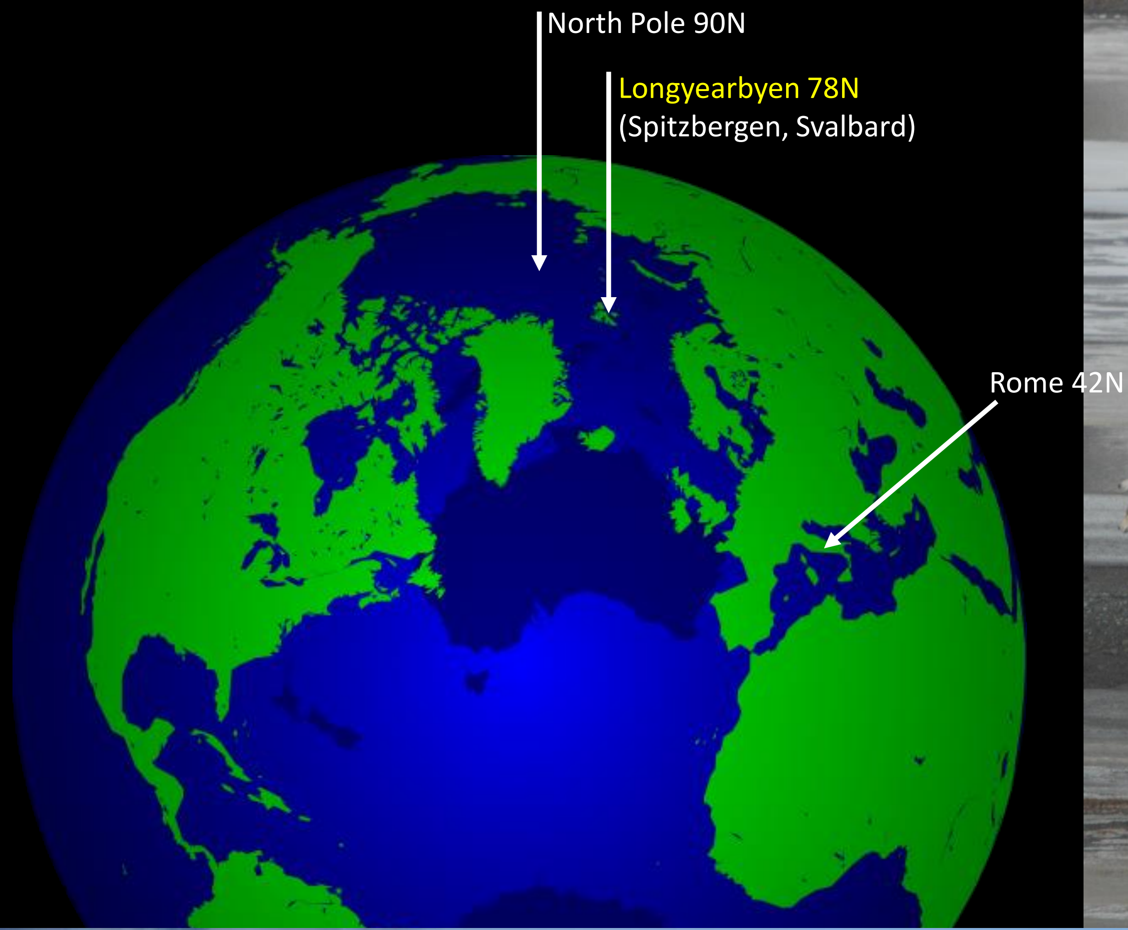
Sorry for not being with you !



Two main Cosmic Microwave Background observables, widely discussed in parallel sessions CM2, CM3, CM4, CM5

- B-mode polarization: produced by inflation and LSS. < 0.1 μK signal (cfr 2.73K CMB);
- linearly polarized, in an overwhelming background of Galactic polarized emission and CMB E-modes
- We don't have a firm theoretical prediction of the level of B-modes, but convincing arguments point to $r > 0.001$
- Spectral distortions (deviation of CMB from the Planck curve): produced in several ways in the early (earlier than recombination) and late (structure formation) universe
  - Isotropic
  - Anisotropic
- Low level distortions ($\Delta I/I_{isotropic} <= 10^{-6}$) embedded in overwhelming foregrounds… but firm predictions for their amplitude do exist (see e.g. Chluba & Sunyaev 2012)

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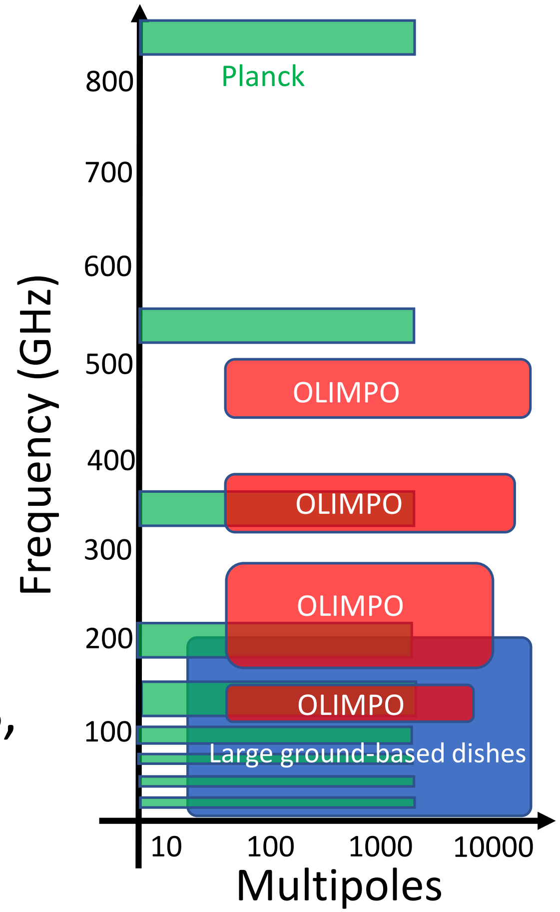
OLIMPO

PI: Silvia Masi

OLIMPO collaboration: see (http://planck.roma1.infn.it/olimpo/collaboration.html)

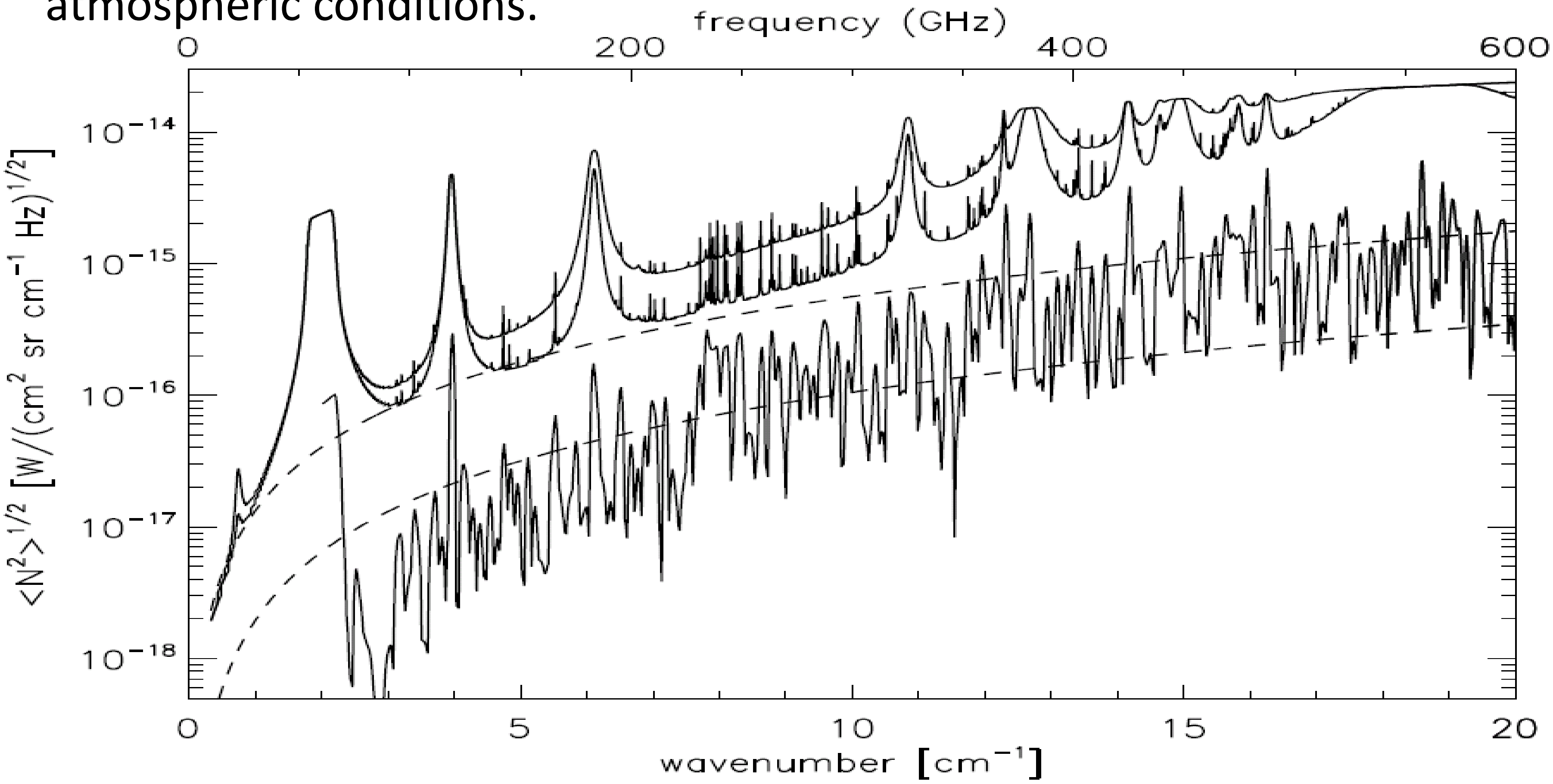
What is OLIMPO and why is it relevant here

- OLIMPO is a large ballon-borne telescope (2.6m aperture), with a differential Fourier transform spectrometer and cryogenic detector arrays covering the frequency range 120 – 480 GHz in 4 wide bands.
- OLIMPO will carry-out two measurements:
  - Spectroscopic Measurement of the SZ effect in a number (order 40) of selected clusters, with angular resolution around 1'-2' (similar to ground-based 140 GHz surveys) and wide frequency coverage, not easily achievable from the ground.
  - Spectroscopic survey of a blank sky patch, to measure the frequency dependance of the anisotropy of the mm-wave sky (mainly CMB, CIB, ISD) in frequency/multipoles range still unexplored. These are important foregrounds for anisotropic spectral distortion measurements.
- OLIMPO is propedeutic to more sensitive space-borne instruments, targeting fluctuating spectral distortions.



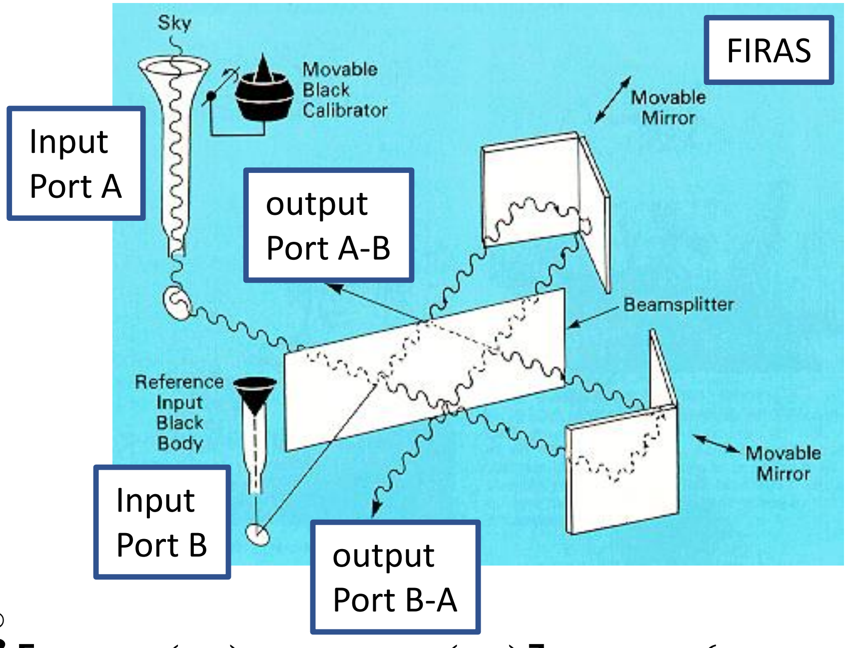
OLIMPO performance

- The sensitivity of OLIMPO detector arrays is limited by photon noise from the warm optical system and the residual atmosphere at 38 km altitude.
- The latter is dominated by oxygen and ozone lines, and is almost 100 times lower than in the best grond-based sites.
- Roughly speaking, at f>200 GHz 1 day of observation on the balloon is equivalent to 100 days of observation on the ground in outstanding atmospheric conditions.



OLIMPO measurement approach

- The Fourier Transform Spectrometer of OLIMPO is a Martin-Pupplett instrument, with two input ports (as in FIRAS and PIXIE).
- This instrument is intrinsically differential, and measures the spectrum of the difference in brightness at the two input ports.

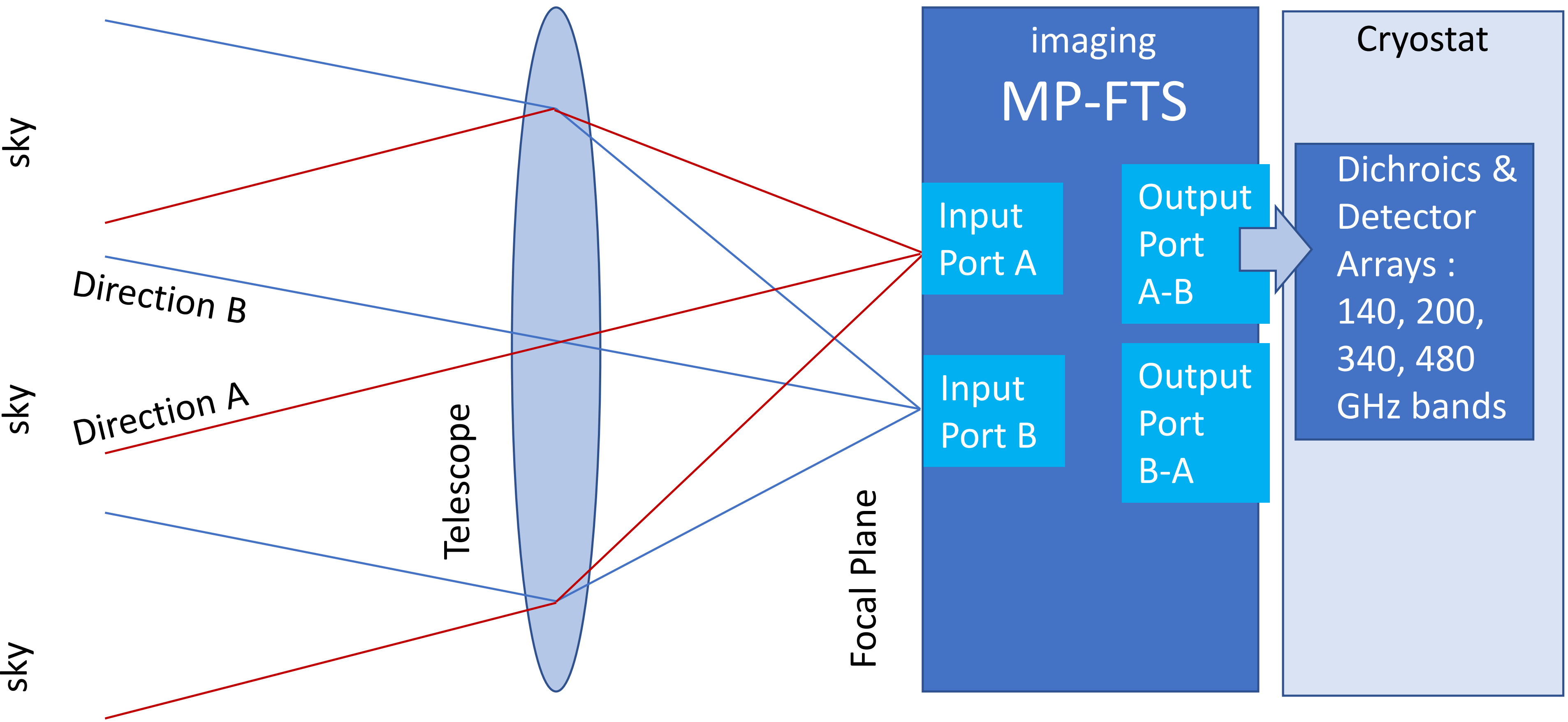


$$I_{SKY}(x) = C\int_0^\infty [S_{SKY}(\sigma) - S_{REF}(\sigma)] rt(\sigma)\{1+\cos[4\pi\sigma x]\} d\sigma$$

$$I_{CAL}(x) = C\int_0^\infty [S_{CAL}(\sigma) - S_{REF}(\sigma)] rt(\sigma)\{1+\cos[4\pi\sigma x]\} d\sigma$$

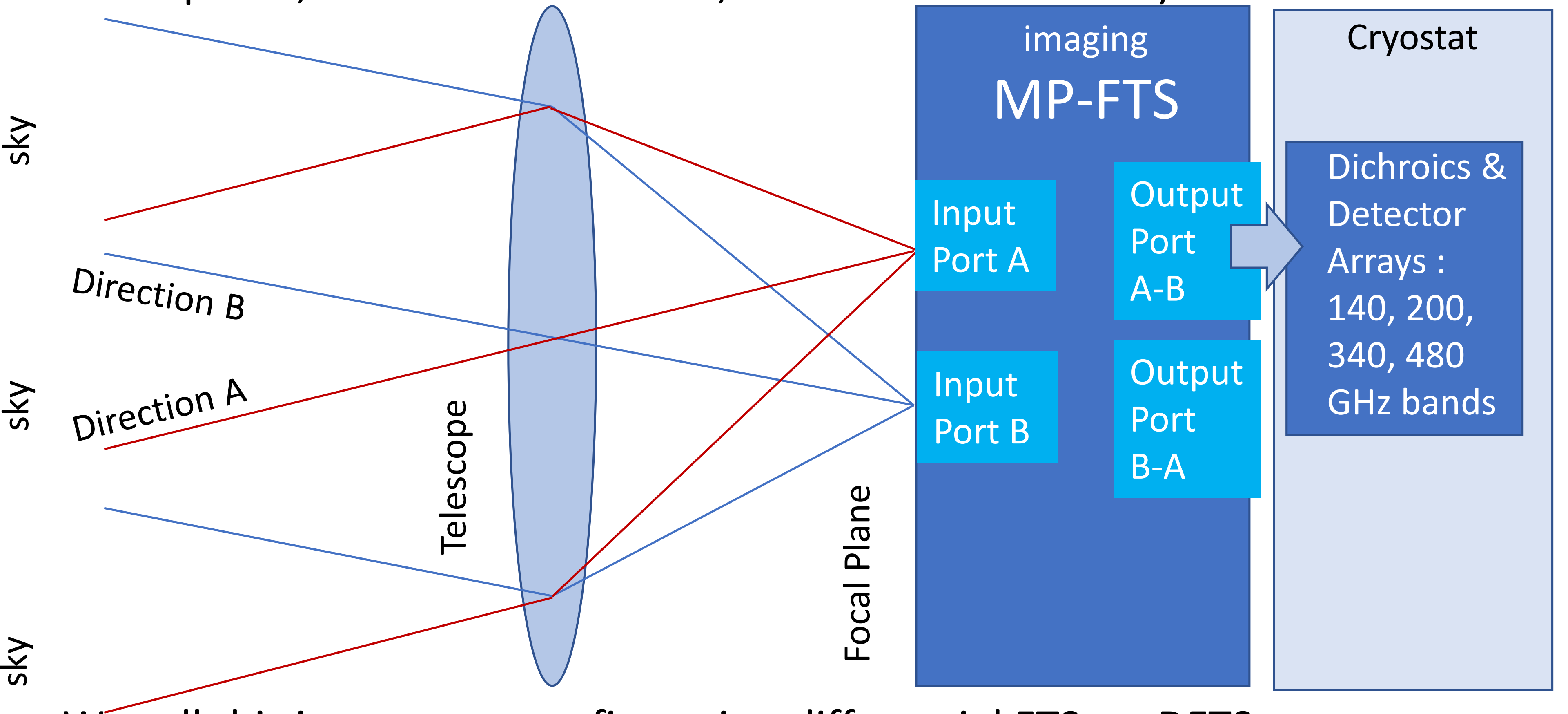
OLIMPO measurement approach

- Instead of comparing the sky brightness (port A) to a cold reference blackbody (port B), as in FIRAS, here the two ports are located in different positions of the telescope focal plane, i.e. *they look at different directions in the sky*.



OLIMPO measurement approach

- If the telescope is pointed so that
  - port A looks at the center of a galaxy cluster and
  - port B looks at a blank sky reference position outside the cluster,
- the instrument will measure the classical negative-zero-positive brightness difference due to the Sunyaev-Zeldovich effect, rejecting with high accuracy the common mode signal (i.e. the isotropic CMB, residual atmosphere, instrument emission, electronics offset etc.).



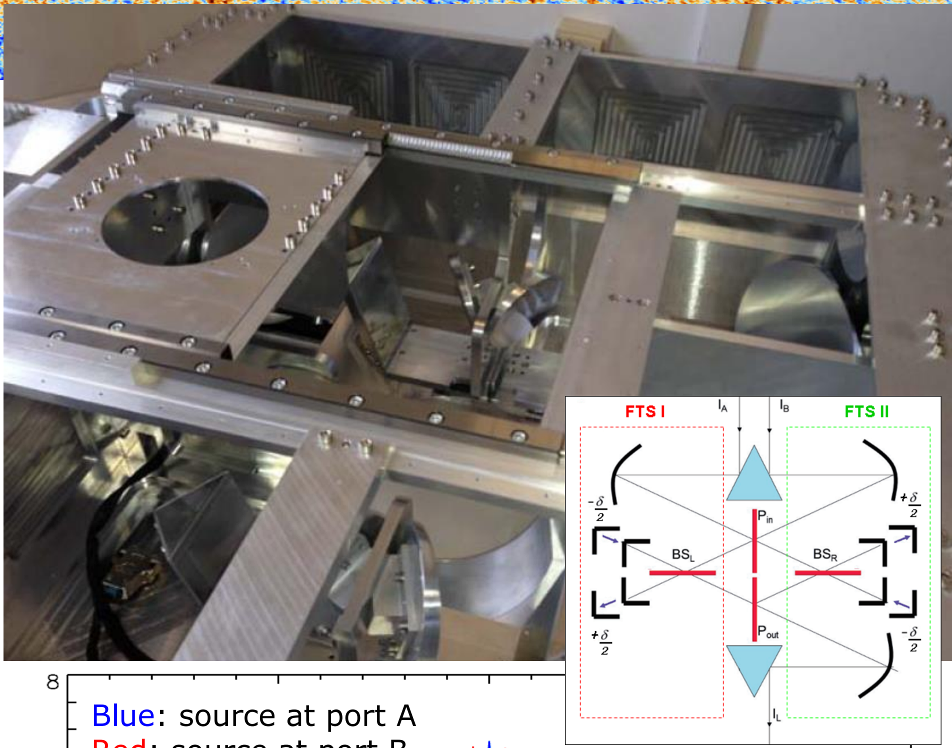
- We call this instrument configuration differential FTS, or DFTS.

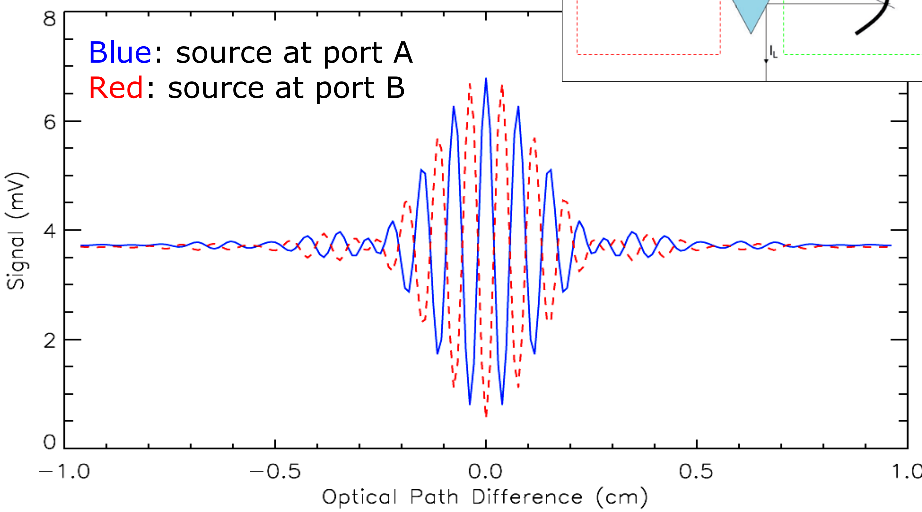
OLIMPO

Rear side: complex HW

OLIMPO: DFTS

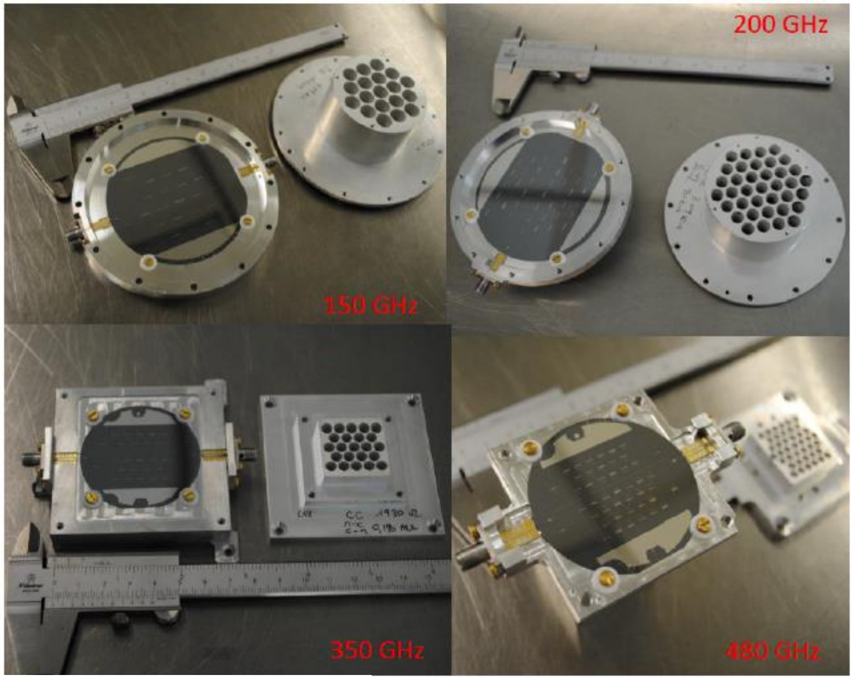
- OLIMPO uses an imaging Differential Fourier Transform Spectrometer (**DFTS**, see Schillaci et al. A&A **565**, A125 (2014))
- The instrument is able to measure the **difference in brightness** between the two input ports, which are placed in different locations in the focal plane of the telescope.
- This instrument has an excellent rejection of the common mode signal, allowing to measure the spectrum of small signals (like the SZ) embedded in an overwhelming background (from the CMB, the residual atmosphere, and the instrument, see D'Alessandro et al. App.Opt. **54**, 9269-9276 (2015))

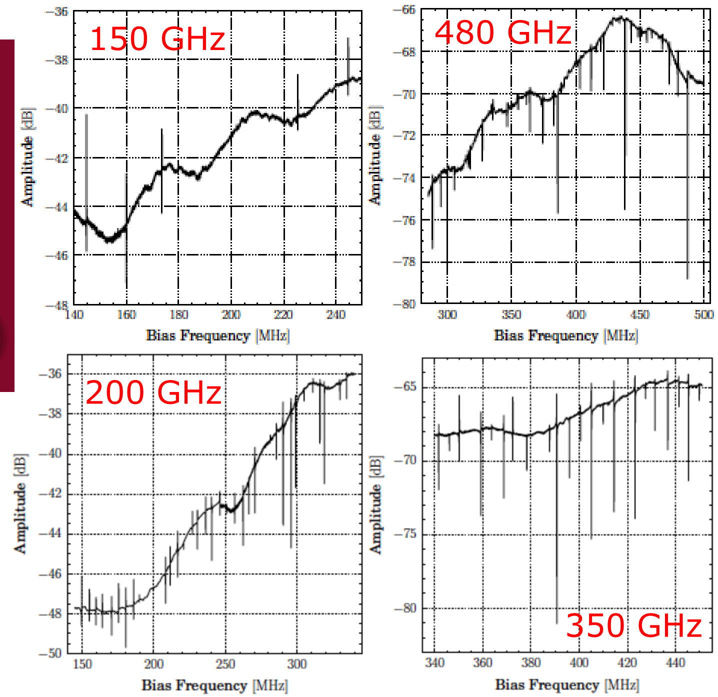


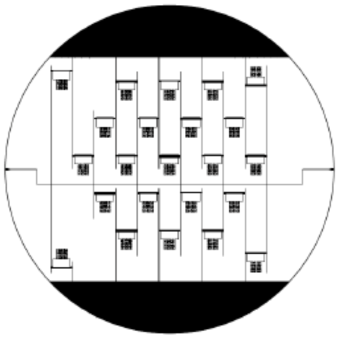


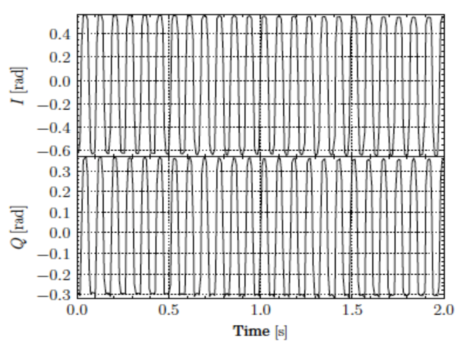
OLIMPO: Detectors

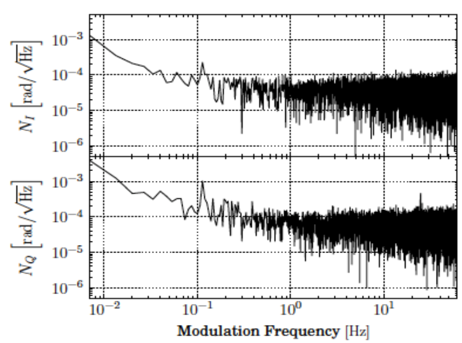
- OLIMPO uses Kinetic Inductance Detecotors









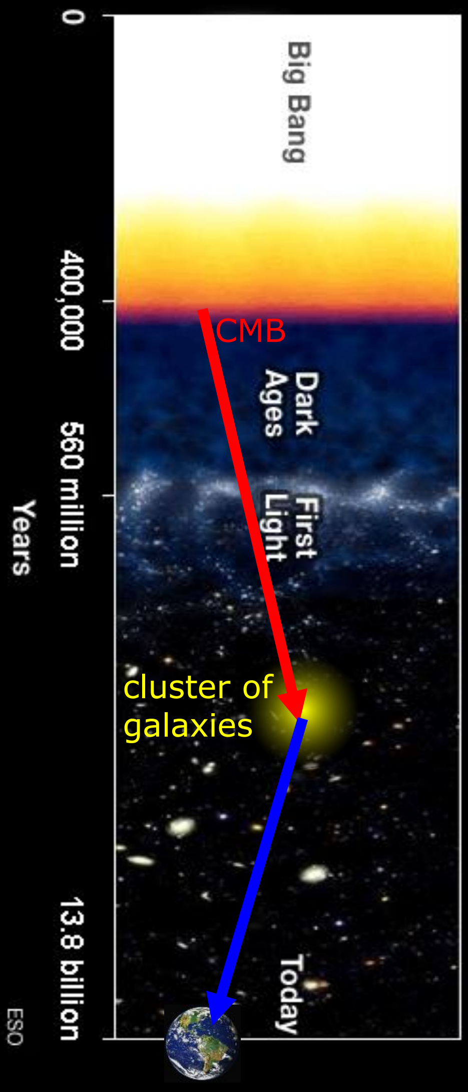


Channel	NET_{RJ} $[mK/\sqrt{Hz}]$
150 GHz	0.180
200 GHz	0.145
350 GHz	0.288
480 GHz	0.433

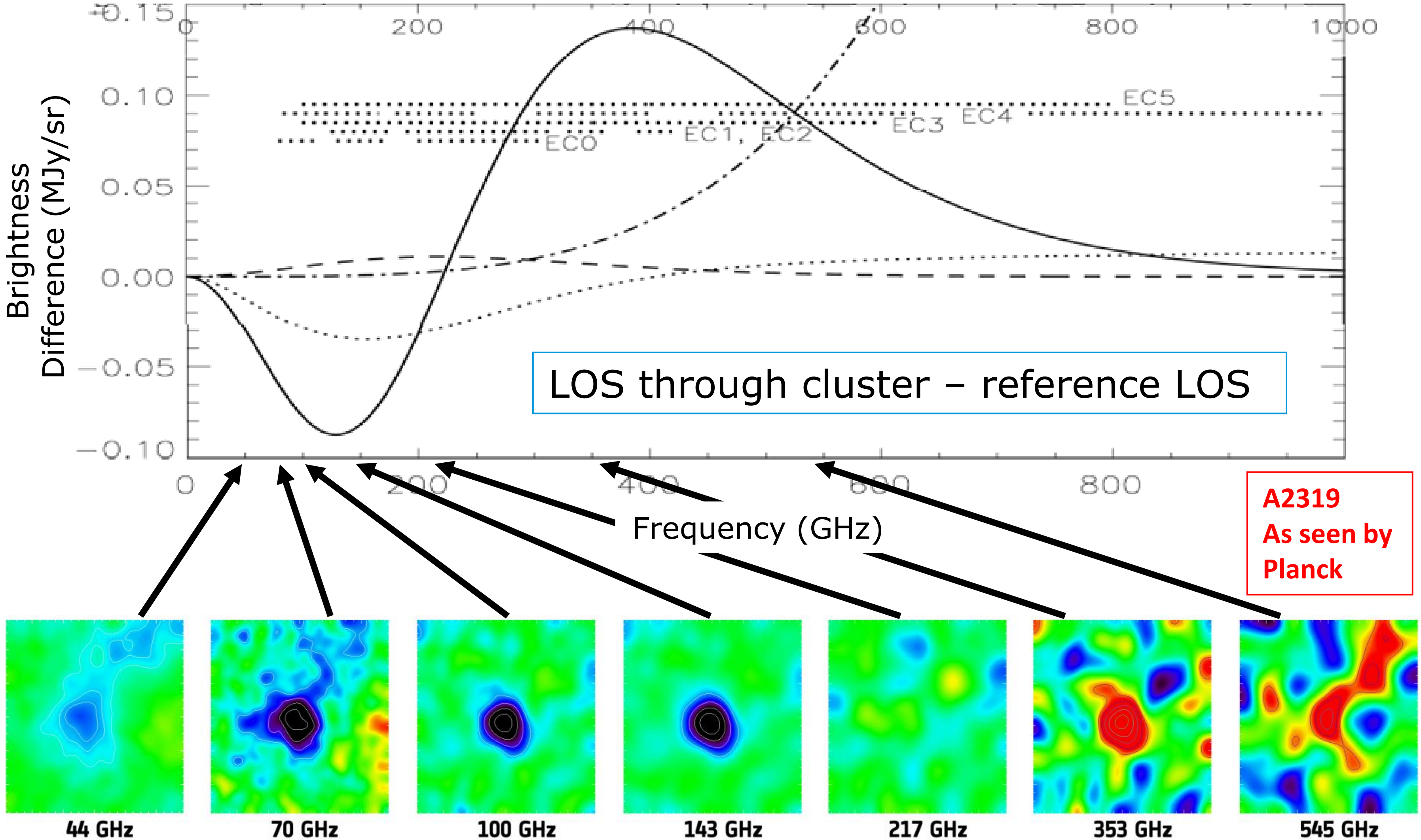
typical NET

OLIMPO & Sunyaev-Zeldovich Effect

- The hot gas filling the volume of clusters of galaxies scatters CMB photons.
- It is an **Inverse Compton** scattering, where CMB photons acquire energy from charged scatterers.
- The spectrum of the CMB is perturbed with a very distinct spectral signature, allowing efficient separation from other signals from the same direction
- The amplitude of the signal is of the order of $\Delta T/T = 10^{-4}$; it is proportional to the **density** of the ionized gas, and **does not depend on the distance** of the cluster.
- The **OLIMPO** balloon-borne mission is aimed at accurate **spectroscopic** measurements of the SZ.

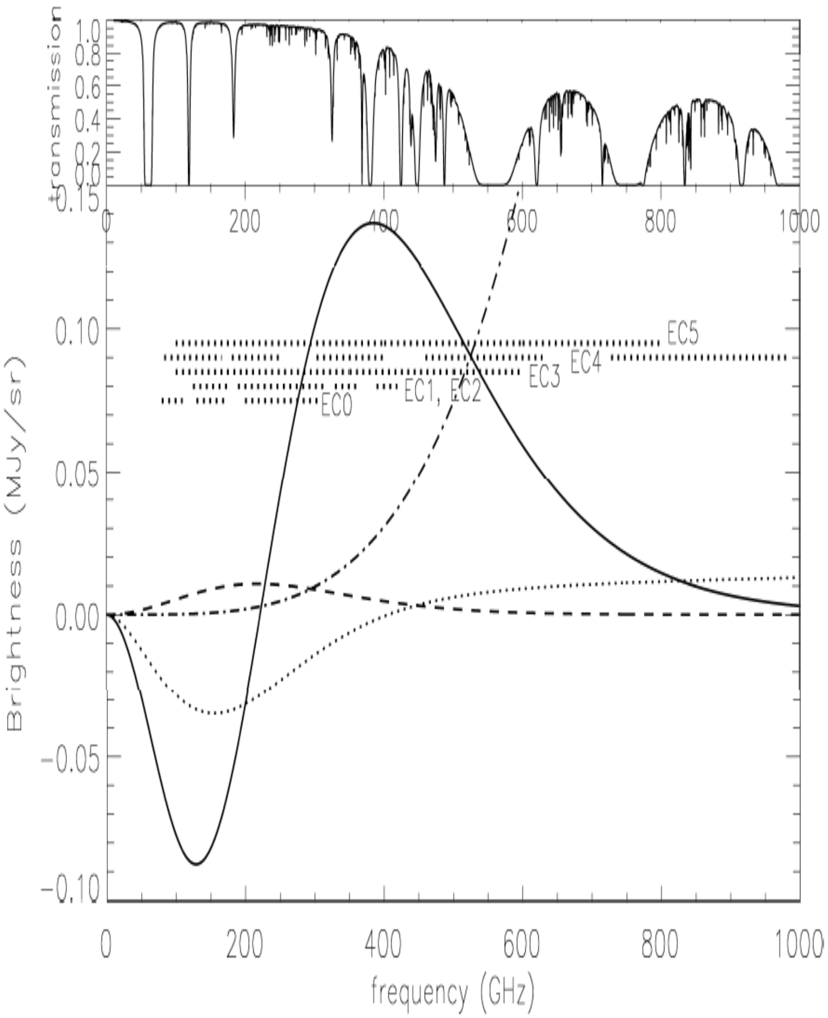


Sunyaev-Zeldovich Effect



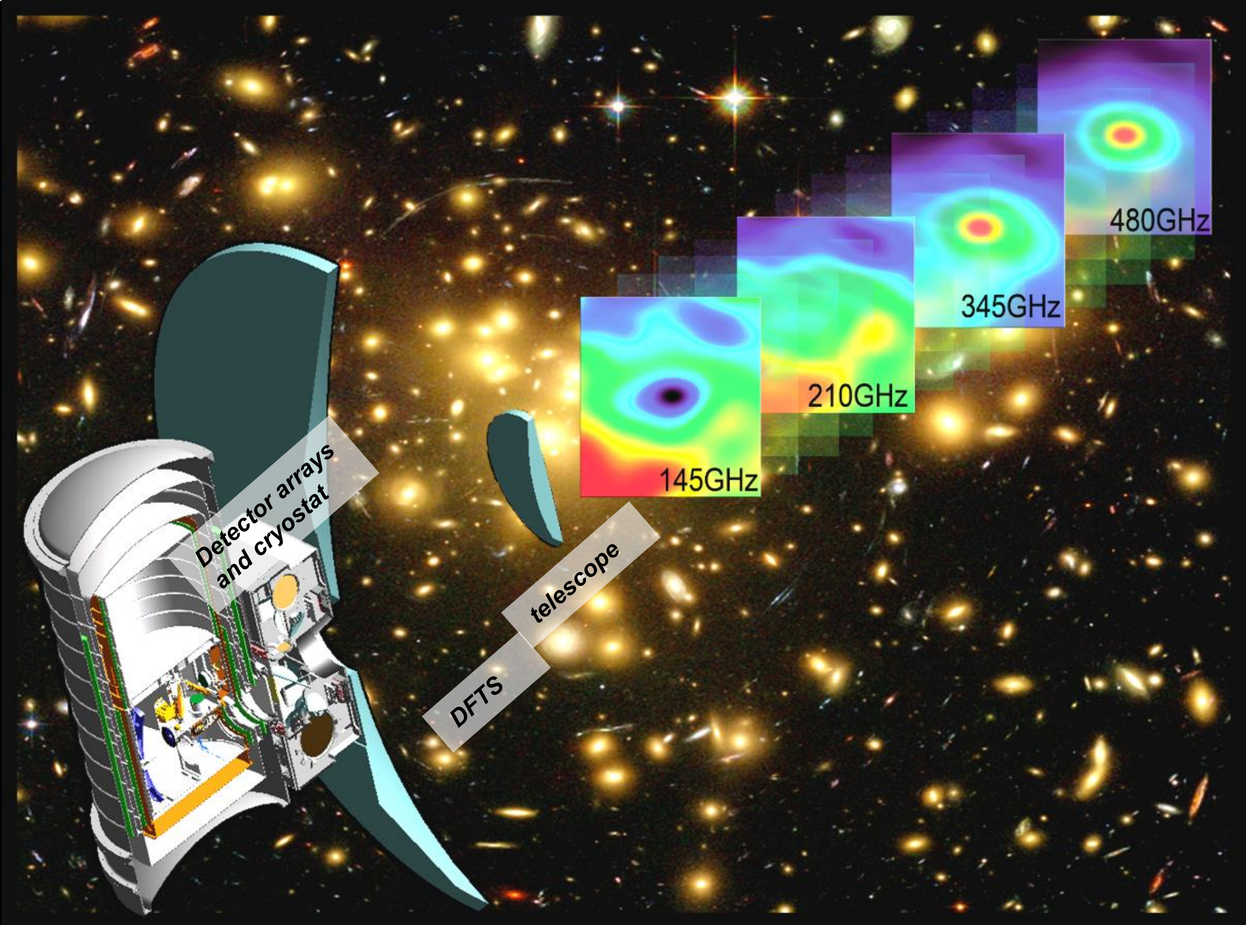
Spectral measurements of CMB anisotropy and SZ

- A **spectral** measurement of CMB anisotropy, which can be done only from space or (partially) from the stratosphere, can:
- Vastly improve the **accuracy**, allowing efficient, unbiased separation of the CMB and SZ components from all other components in the same LOS (see **A&A 538 A86 2012**).
- Produce **unique science** like:
  - The study of patchy reionization
  - Unbiased estimates of cluster parameters and SZ clusters catalogues
  - Temperature profiles of clusters, including the periphery
  - Study of low-density ionized regions (e.g. filaments of the LSS)
  - Accurate $T_{CMB}(z)$ measurements



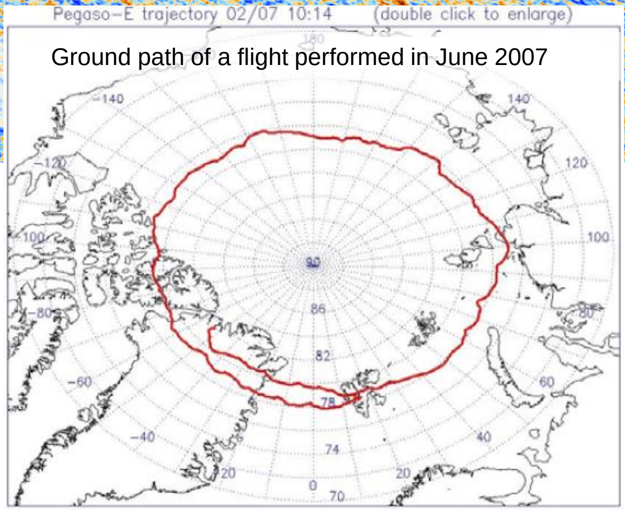
OLIMPO

- The OLIMPO experiment is a first attempt at spectroscopic measurements of CMB anisotropy.
- see http://planck.roma1.infn.it/olimpo for a collaboration list and full details on the mission
- Photon-noise limited detectors
- Spectroscopic resolution: 1.8 GHz within 4 bands centered @ 140, 210, 345, 480 GHz



At high frequency, OLIMPO has the same angular resolution as the ground-based large telescopes used for SZ surveys @140 GHz.

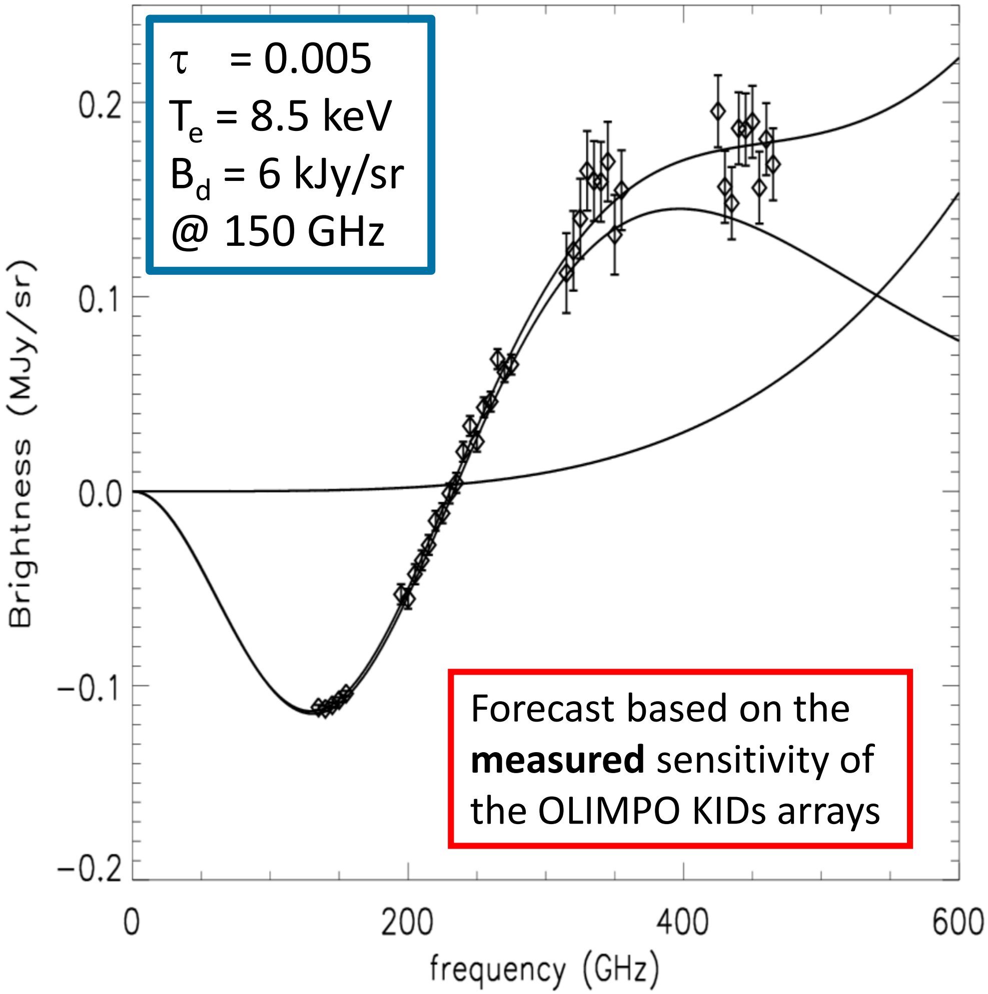
Long-duration flights in the Arctic



- The Longyearbyen (Svalbard) launch site offers circumpolar flights, in both summer and winter (see Mem. S. A. It., 79, 792-798 (2008), ESA SP-700 (2011), Proc. of the I.A.U., 8, 208-213 (2013)).
- CMB experiments can access most of the northern sky in a single flight,
  - within a cold and very stable environment
  - Accumulating more than 10 days of integration at float (>38 km altitude).
- ASI is organizing the forthcoming OLIMPO flight campaign.

Launch of a heavy-lift balloon from the Longyearbyen airport (Svalbard 78°N).

OLIMPO: Expected performance



- In a FTS the spectral resolution can be changed (changing the path of the moving mirror). Mind the noise per bin, however: it is proportional to the inverse of the spectral bin-width. In the case of OLIMPO, with a spectrometer at 250K, photon noise is important.
- 1.8 GHz resolution: About 110 independent spectral bins, within optimized bands.
- 5 GHz resolution: 40 independent spectral bins, within the same bands (see figure).

Products: For a single flight:

- high accuracy multi(40)frequency maps of selected sky regions (2^ox2^o tiles, 2' FWHM resolution) centered on ~20 clusters and 20 blank-sky regions;
- one deep blank sky survey of > 100 square degrees.

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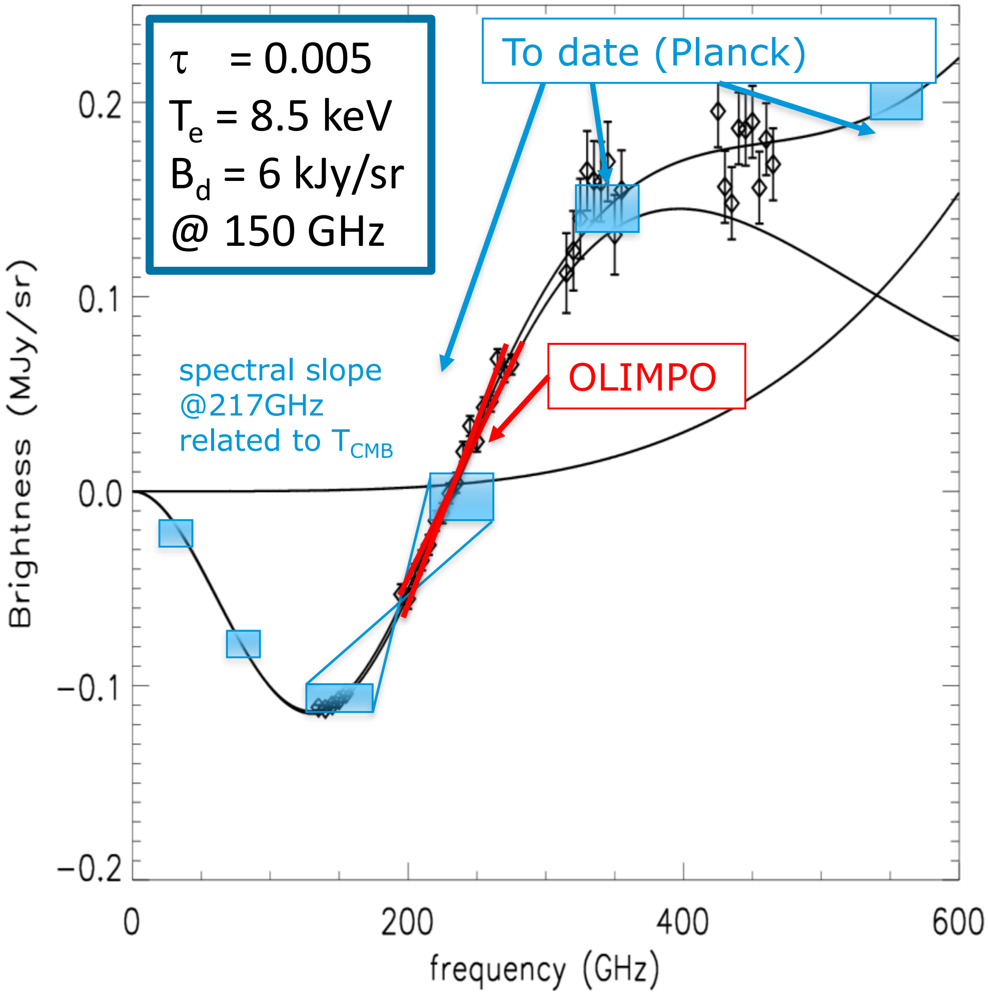
OLIMPO: Expected performance



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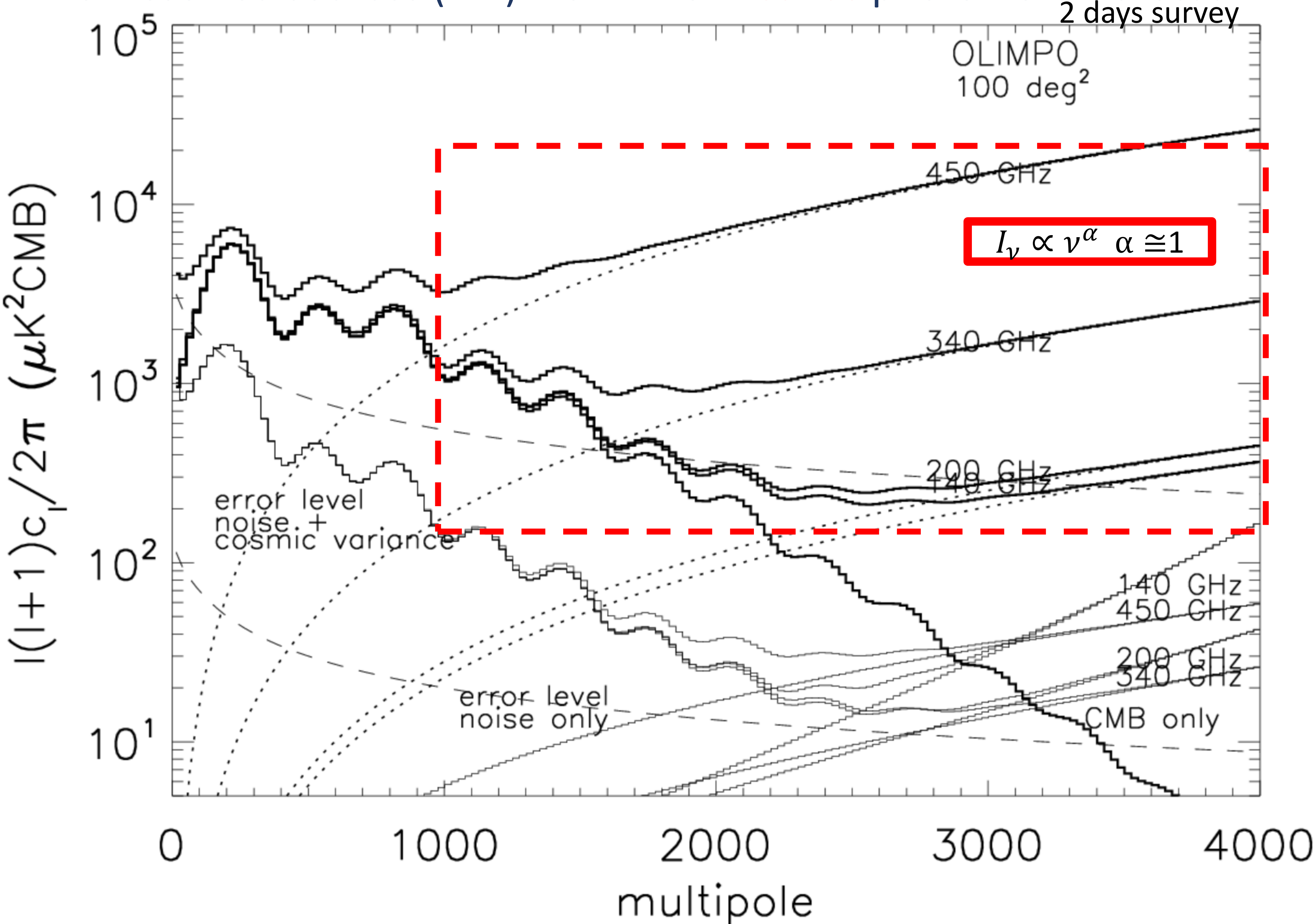
Blank-sky spectral-spatial anisotropy with OLIMPO

- In addition to spectroscopic measurements of the SZ in clusters, OLIMPO will carry-out a blank sky survey, mapping say 100 square degrees while taking spectra.
- The measured power spectra are dominated by regular CMB anisotropy + anisotropy in the cosmic infrared background. The former is well known, the latter is poorly known at high multipoles (say > 1500).
- Spectral distortions due to fluctuating diffuse SZ are sub-dominant but within reach TBC.

Unresolved sources (CIB) – OLIMPO 4-bands photometer forecast



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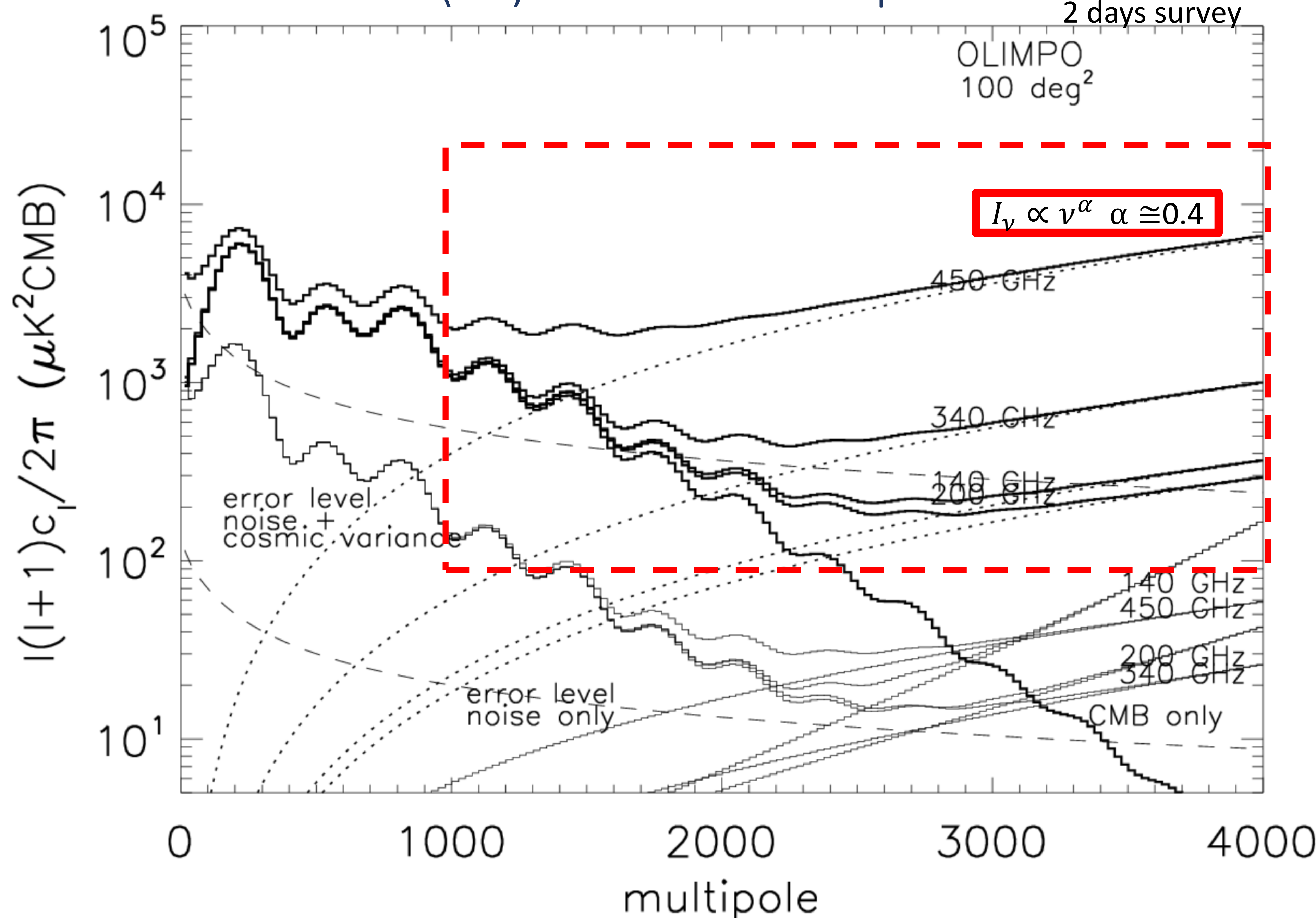
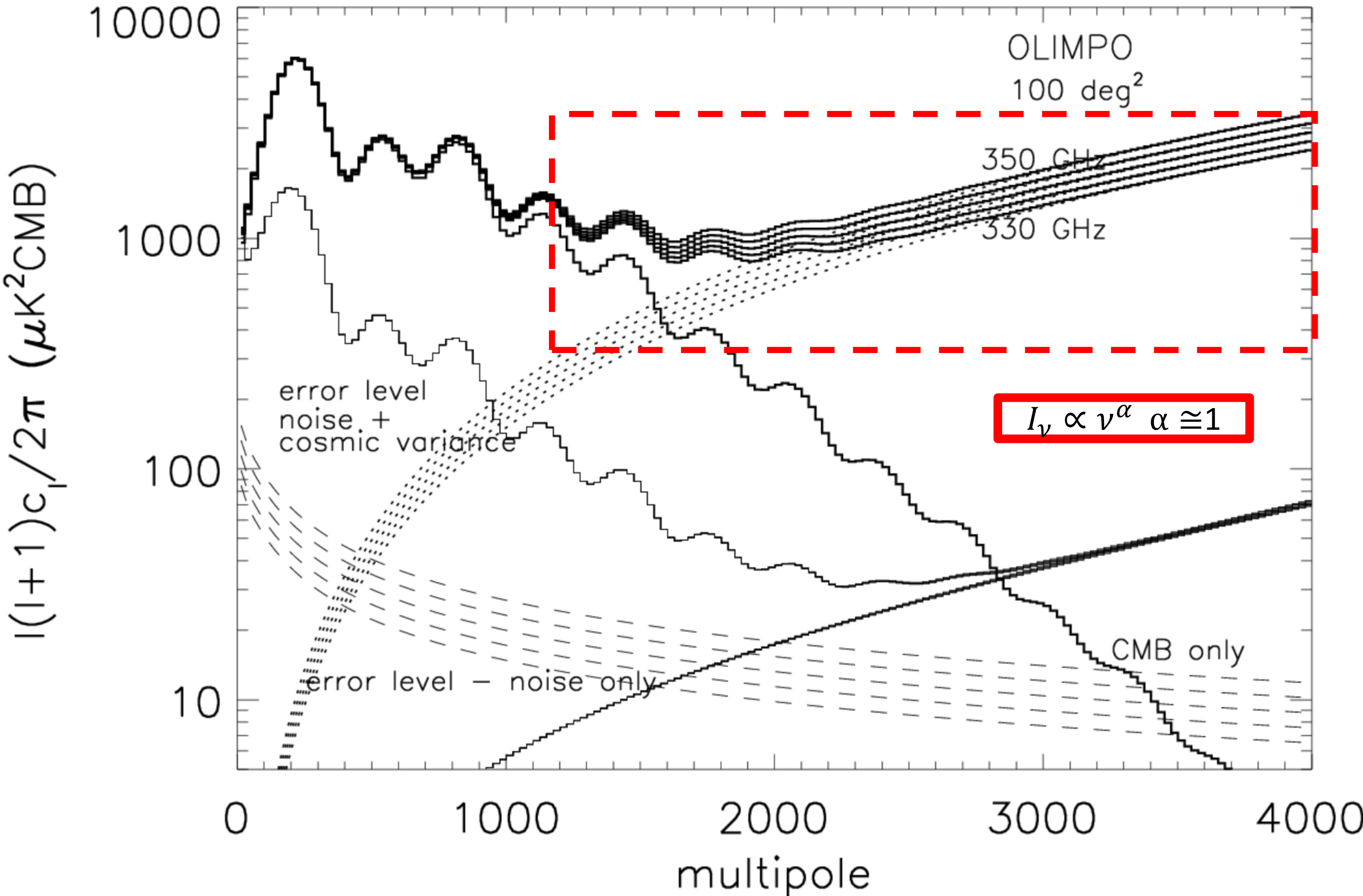


Unresolved sources (CIB) – OLIMPO spectrometry within band 3

4 days survey



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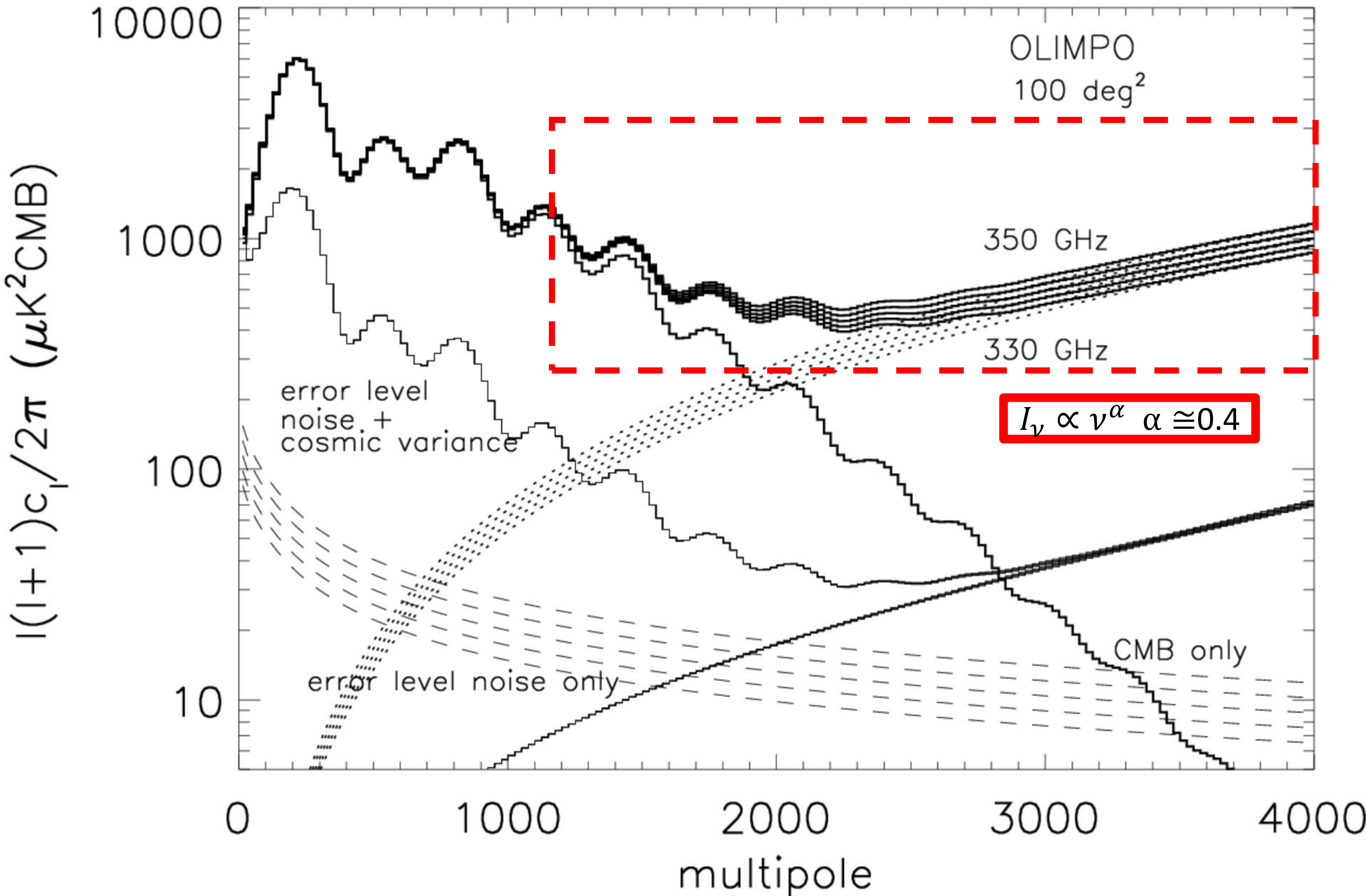

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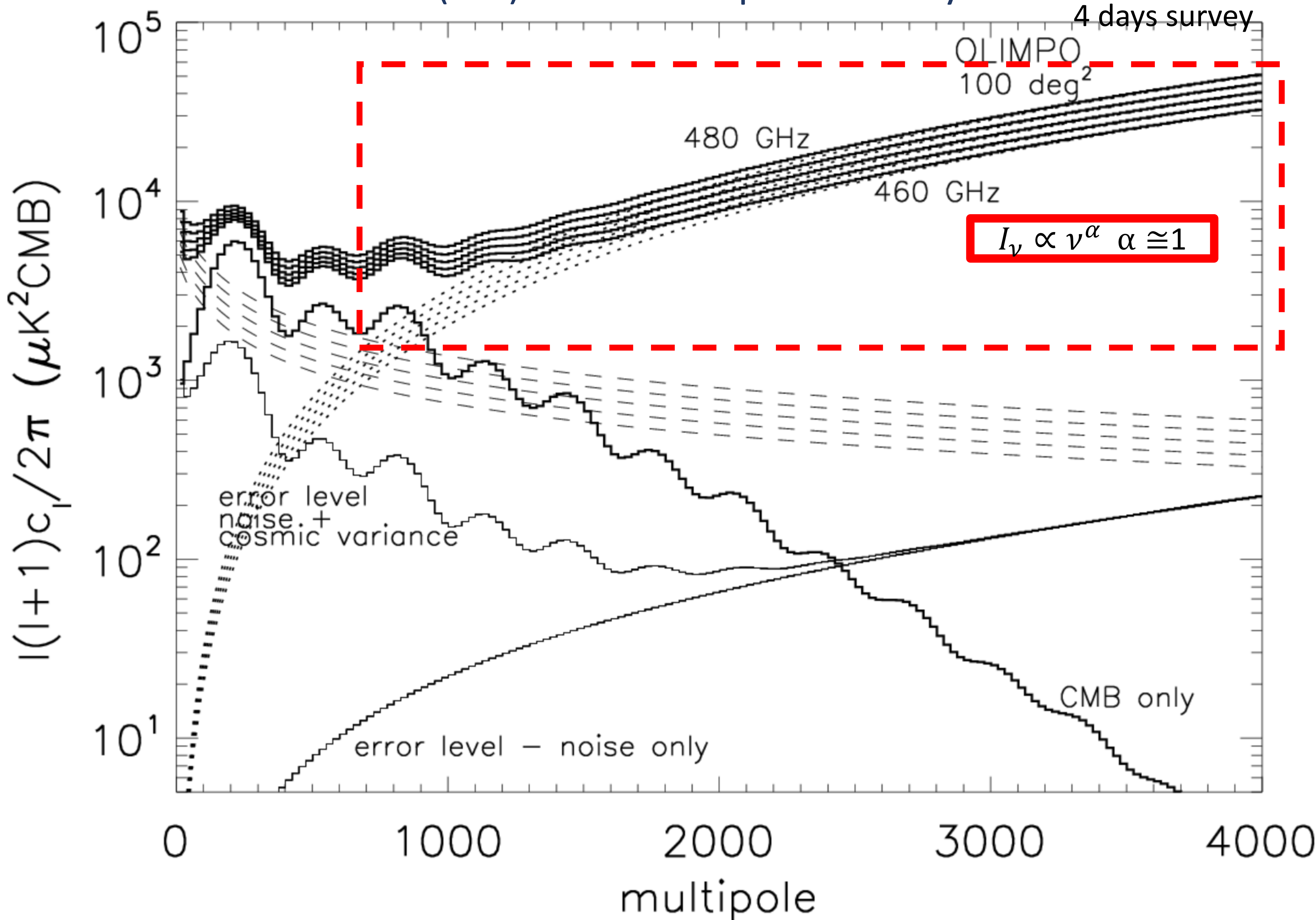

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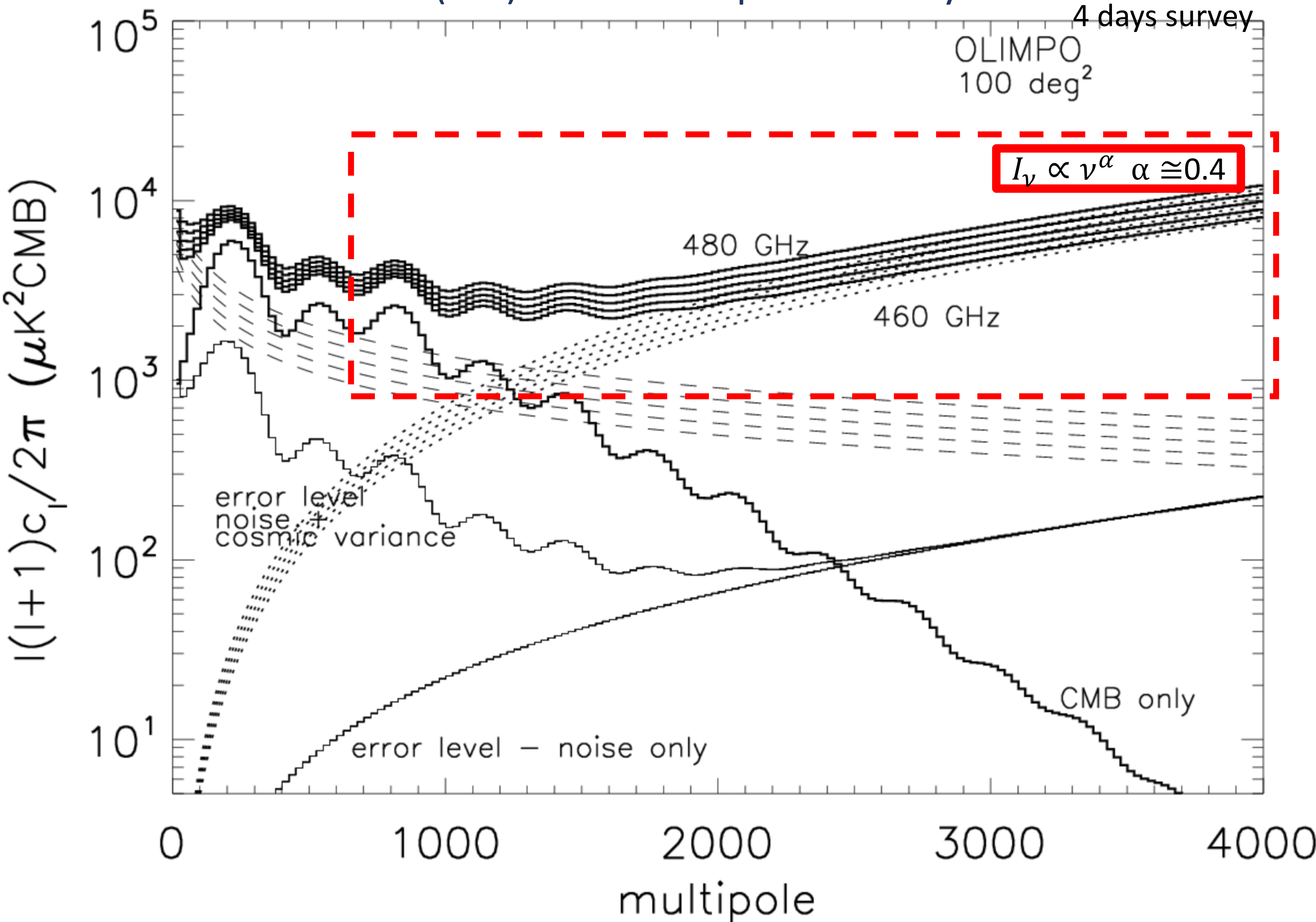
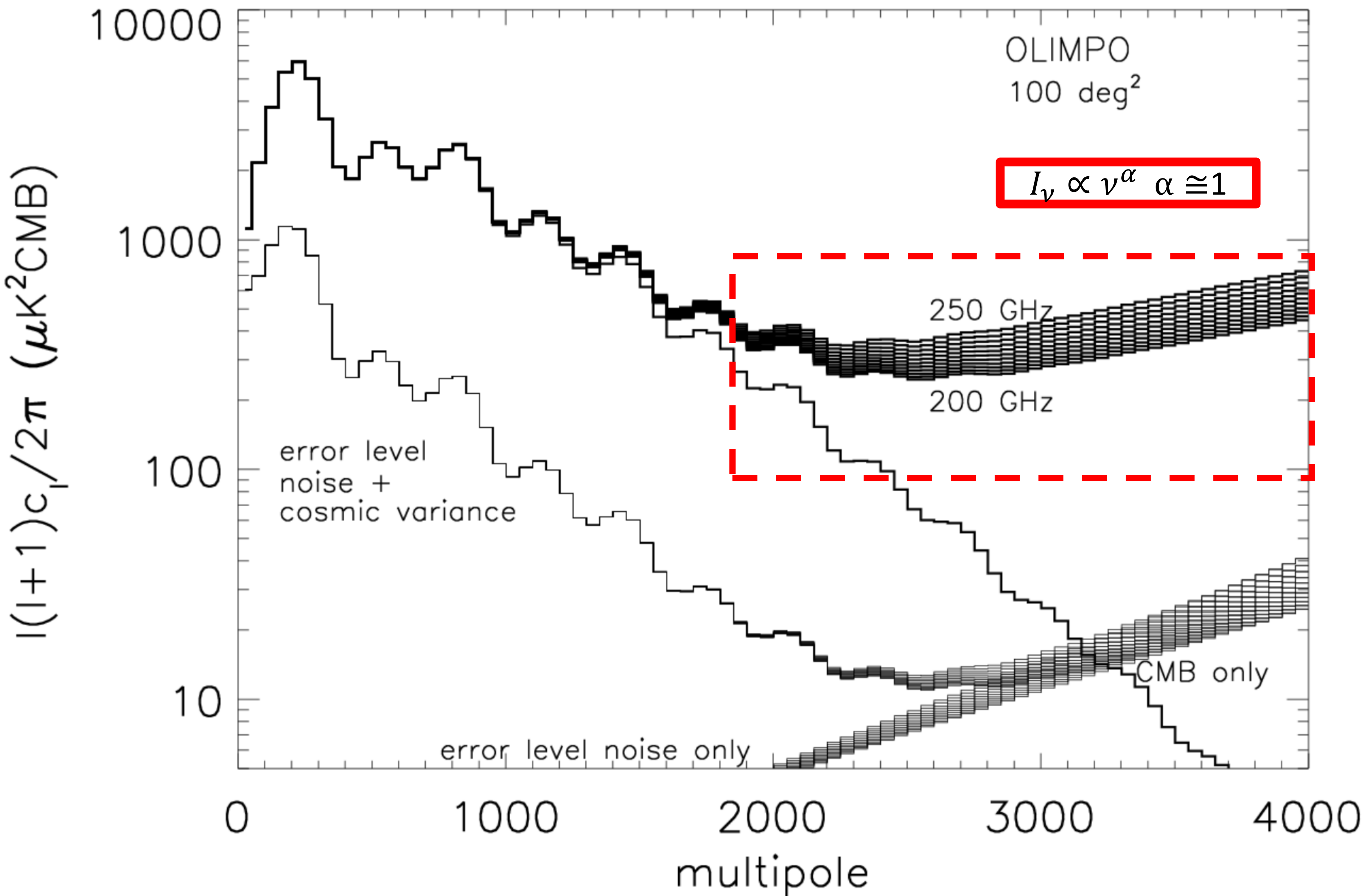


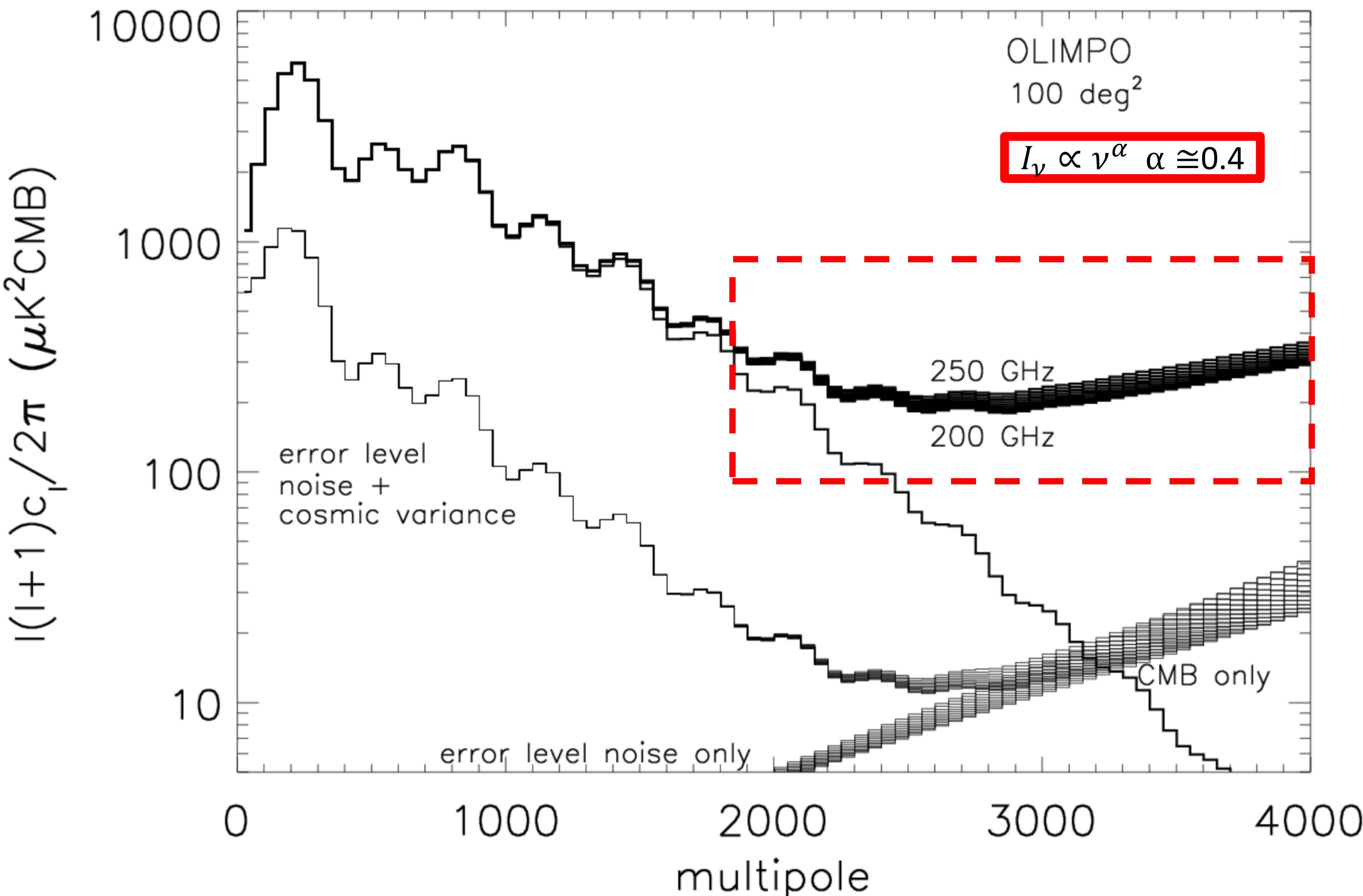
Unresolved sources (CIB) – OLIMPO spectrometry within band 2

4 days survey



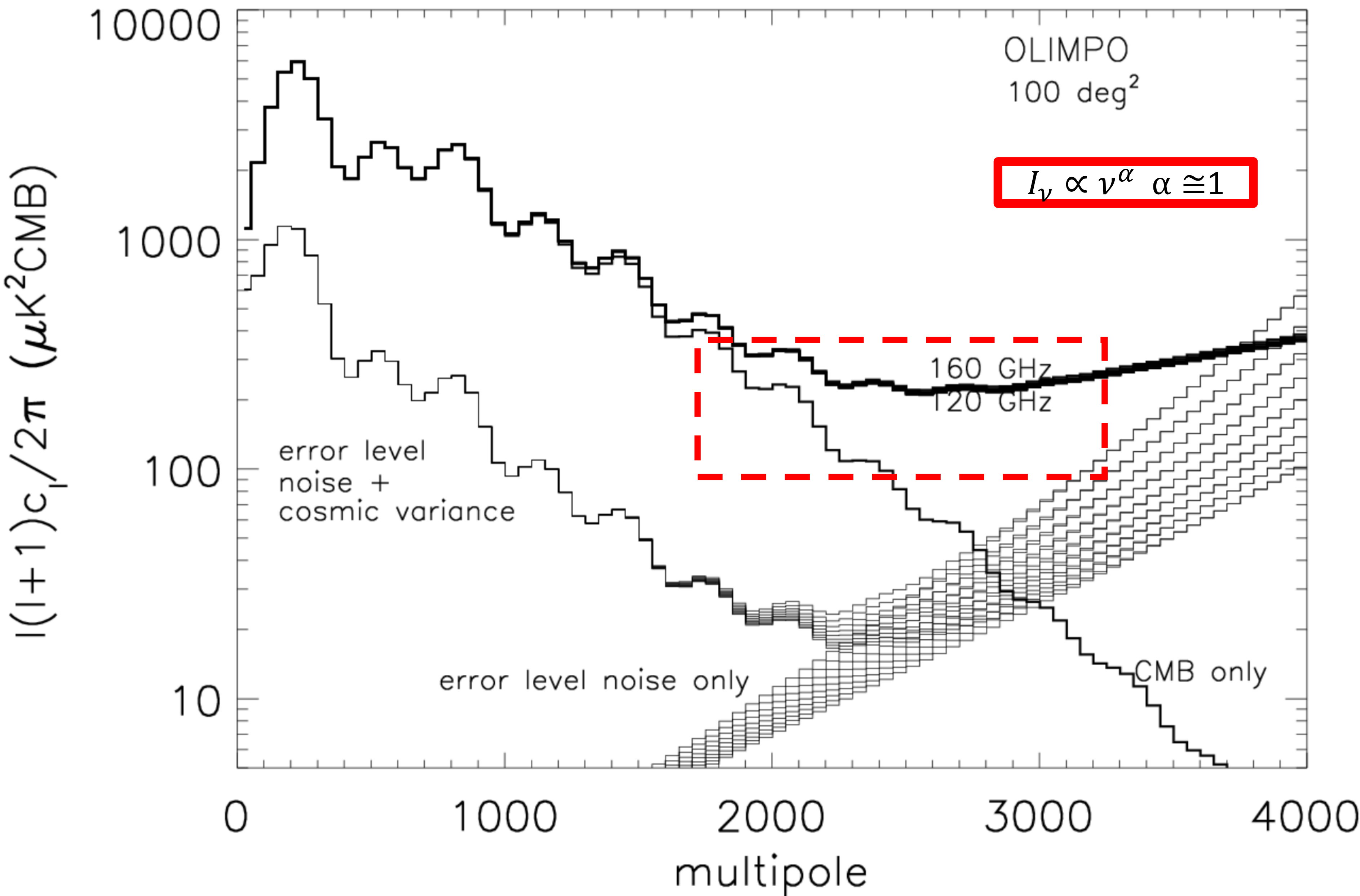
Unresolved sources (CIB) – OLIMPO spectrometry within band 2

4 days survey



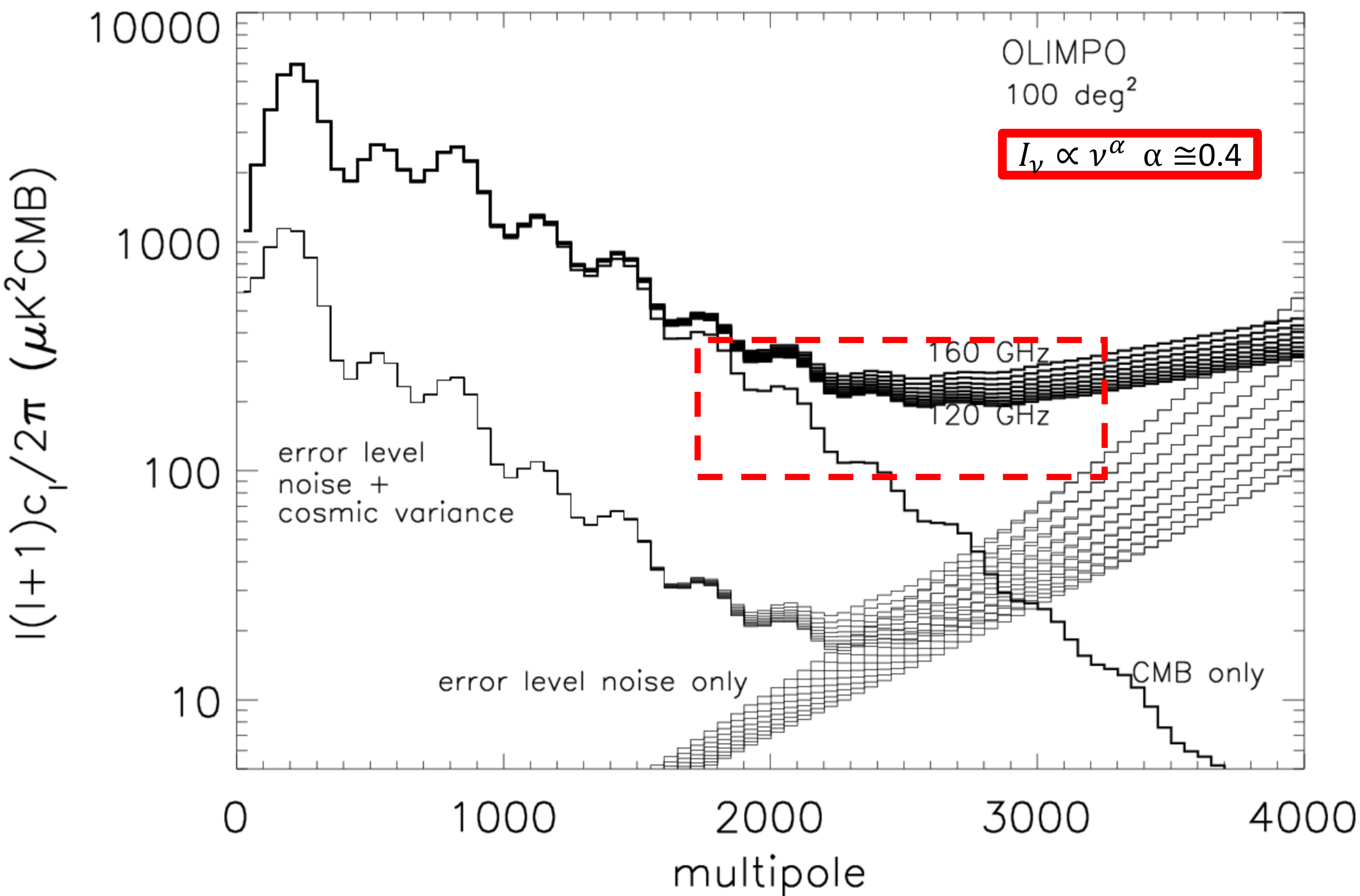
Unresolved sources (CIB) – OLIMPO spectrometry within band 1

4 days survey



Unresolved sources (CIB) – OLIMPO spectrometry within band 1

4 days survey

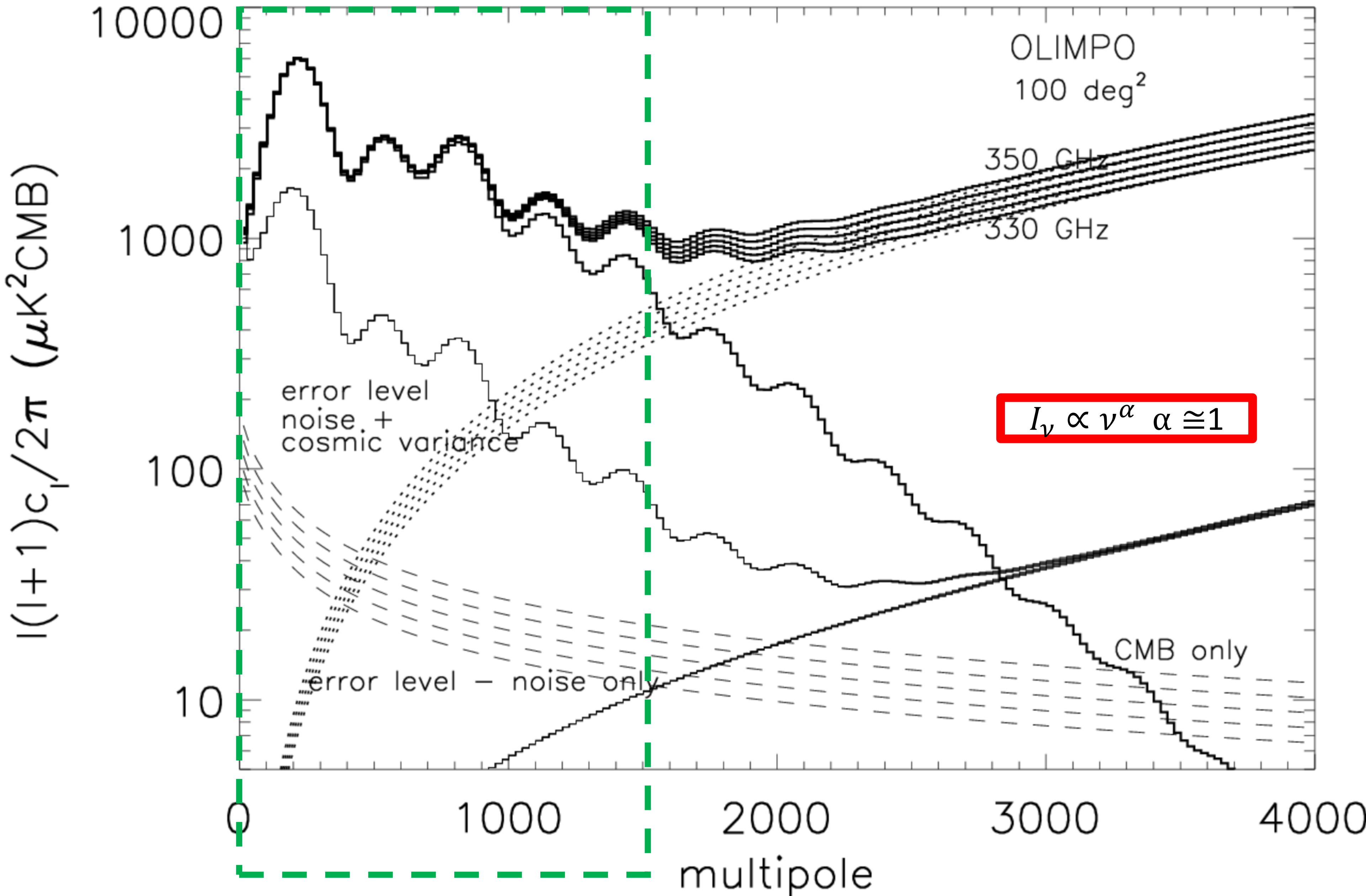


Spectral distortions of CMB anisotropy

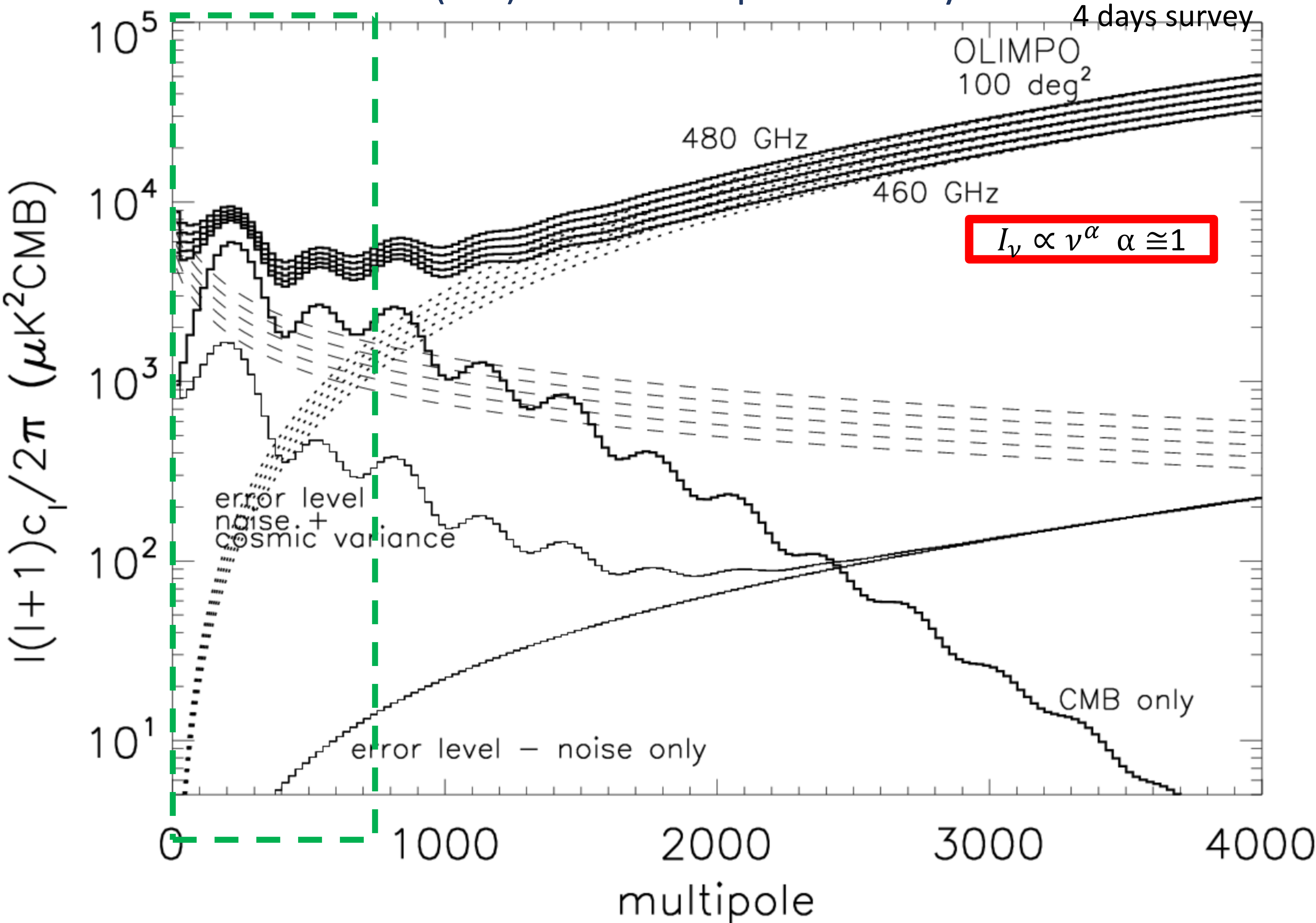
- Even in the low-multipole range, which is cosmic-variance dominated, there is important information to retrieve.
- Slightly frequency-dependent CMB anisotropy is expected e.g. due to Rayleigh scattering effects.
- Moreover, fluctuations in diffuse *y* produce frequency dependent CMB anisotropy.
- Neglecting cosmic variance and asking ourselves which is the wavelength dependance of the anisotropy for the observed sky patch, the OLIMPO blank-sky survey has a very high SNR.
- Galactic CO emission (115 GHz, 230 GHz, 345 GHz, 460 GHz) is readily excluded by neglecting the corresponding frequency bins (and mapped, using them, if one is interested)

Unresolved sources (CIB) – OLIMPO spectrometry within band 3

4 days survey

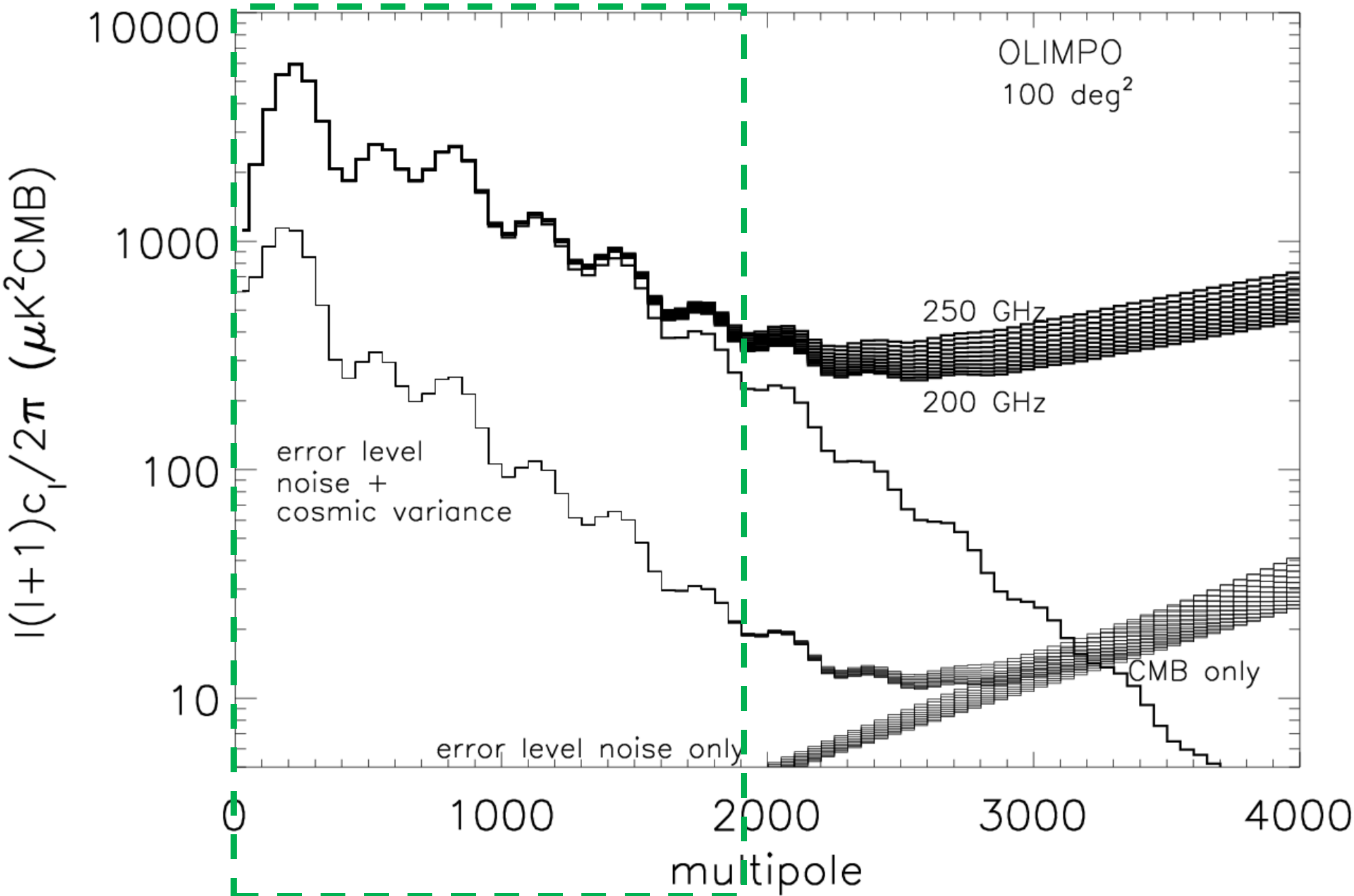


Unresolved sources (CIB) – OLIMPO spectrometry within band 4



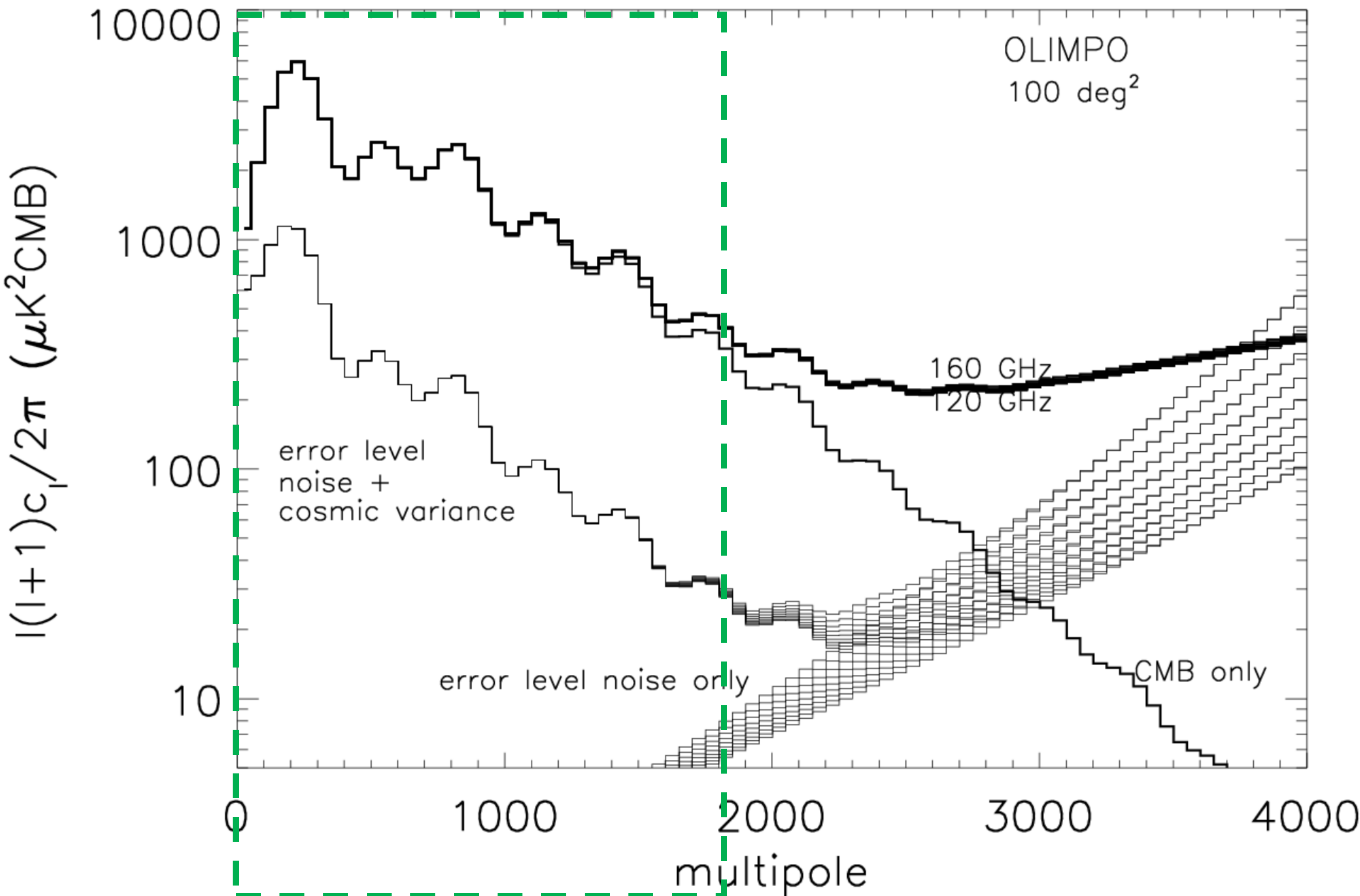
Unresolved sources (CIB) – OLIMPO spectrometry within band 2

4 days survey



Unresolved sources (CIB) – OLIMPO spectrometry within band 1

4 days survey

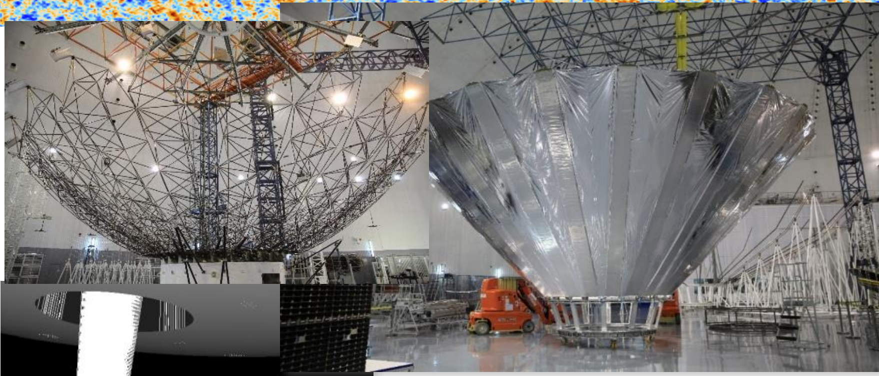


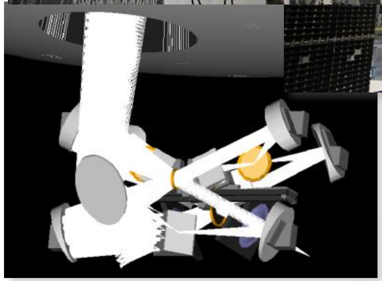
OLIMPO is an experimental challenge

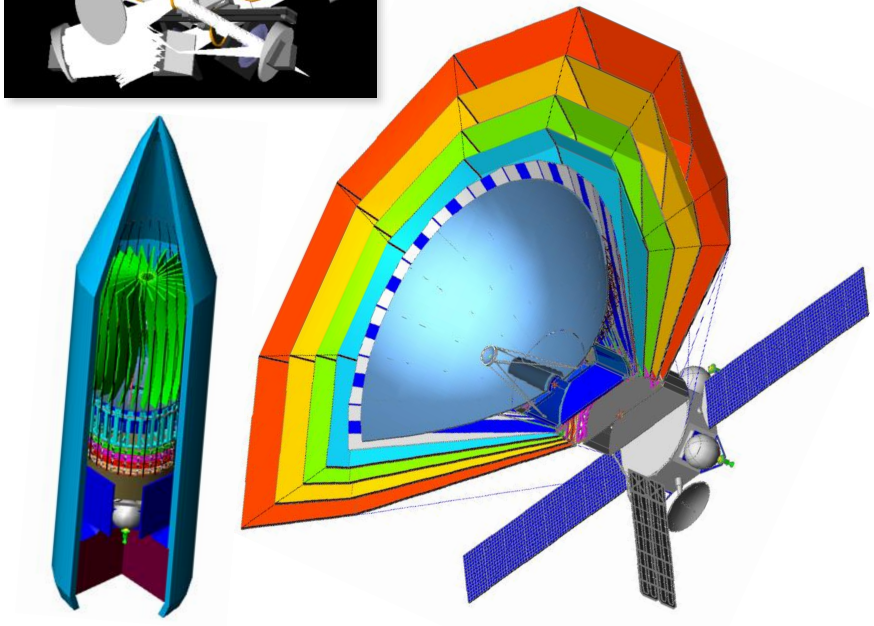
- OLIMPO is mainly a demonstrator of the DFTS technique.
- The main experimental challenges for this first implementation are
  - Kinetic Inductance Detectors (used for the first time on a balloon)
  - Instrumental offsets due to misalignment in the FTS
  - Common-mode rejection performance (see D'Alessandro et al. 2017)
  - Calibration (use differential dipole and planets)
  - …
- If succesfull, the differential FTS approach can be upgraded in several ways:
  - Using a ultra-long duration flight to boost the integration time
  - Using larger detector arrays with a higher throughput telescope
  - Using a cold FTS to reduce the background on the detectors
  - Going in space with a larger, cold telescope (like Millimetron)

OLIMPO as a precursor of forthcoming space-missions

- OLIMPO is extending BLAST observations at low frequencies
- Is a demonstrator of new detectors, to be used in forthcoming missions (PRISM etc.)
- Will demonstrate the power of polar ballooning in the northern hemisphere for CMB missions
- The DFTS Methodology has been used in space (COBE-FIRAS, missions for remote sensing), and will be used again (PIXIE, PRISM, Millimetron)
- >20% of fhe focal plane of **Millimetron** (a ROSCOSMOS mission) is available for a cryogenic version of the OLIMPO DFTS (ASI phase-A study).







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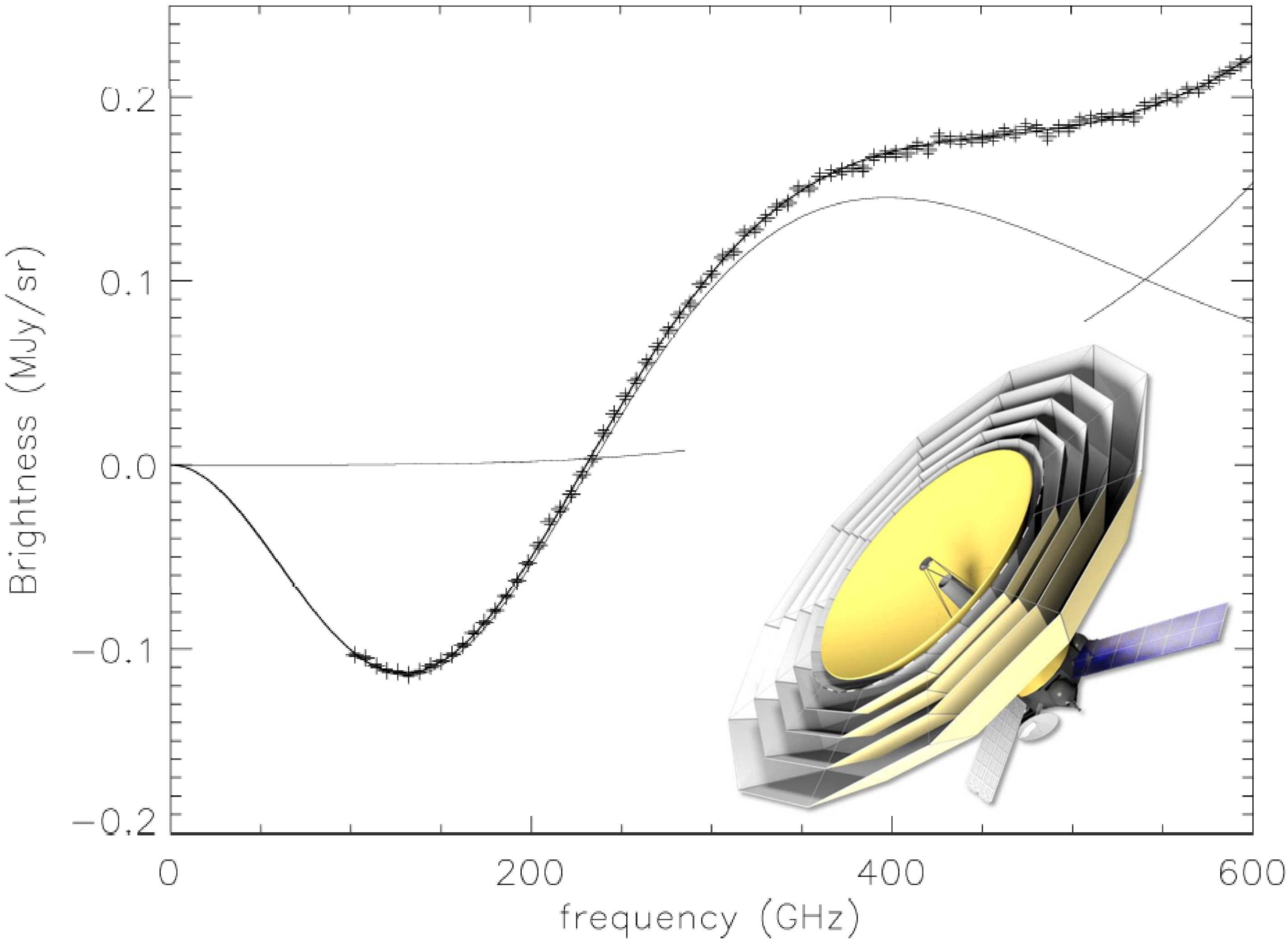
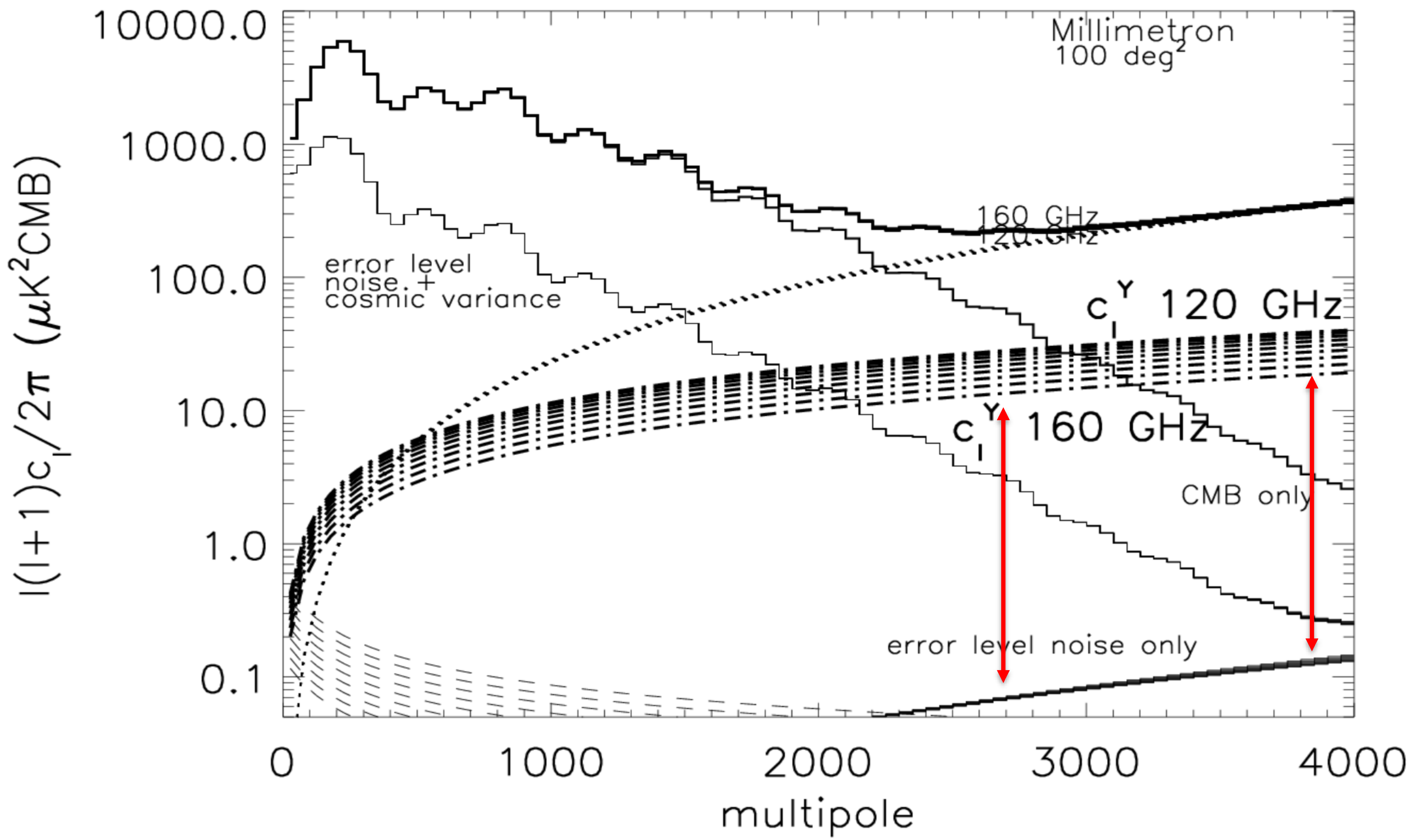
Millimetron DFTS

3 hours of observations of a rich cluster with a DFTS on **Millimetron,** using a photon-noise limited detector in the cold environment of L2, with a 10m telescope cooled to <10K. (see A&A 538 A86 2012)

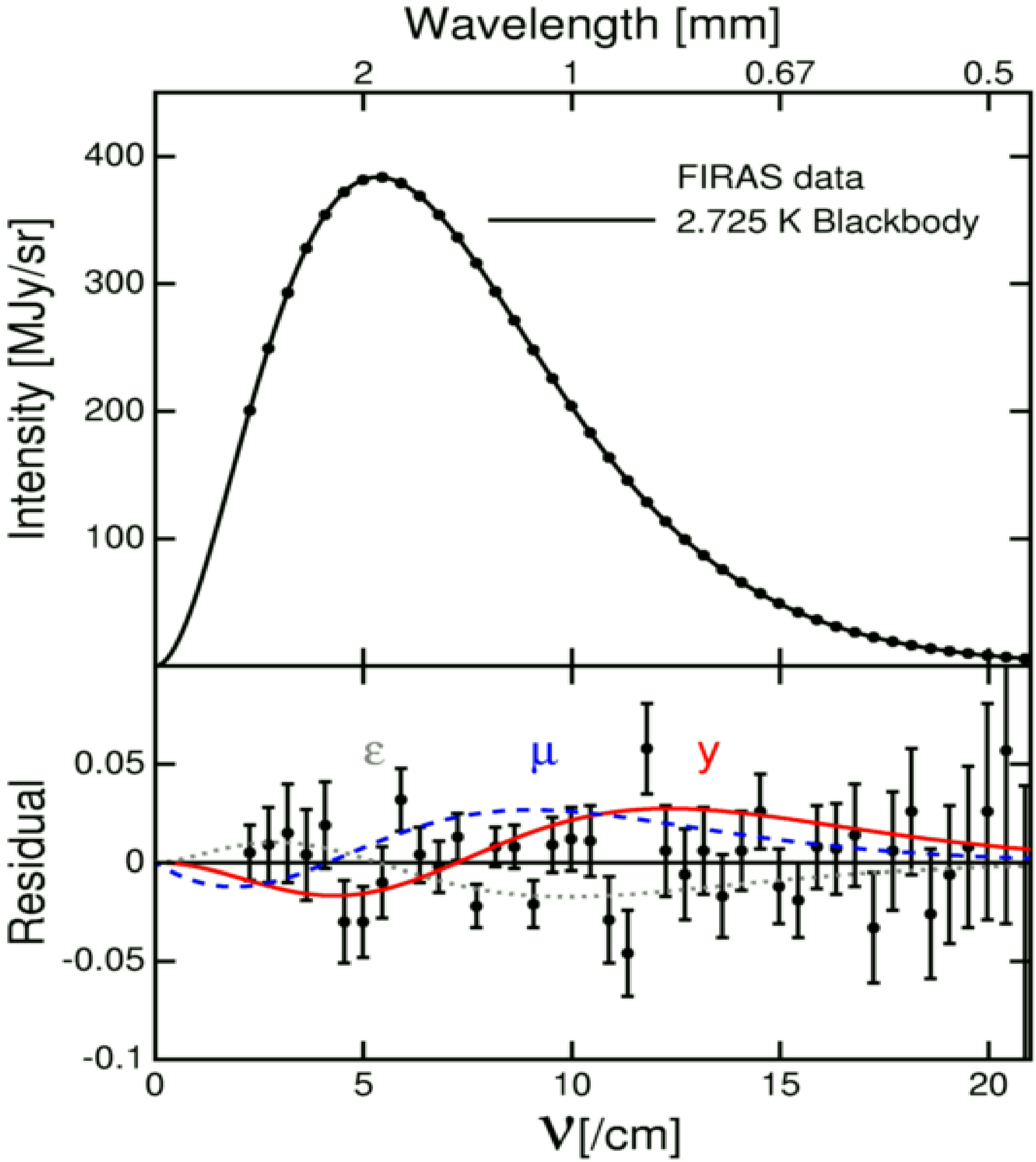


Millimetron DFTS



A survey of a blank sky region would produce accurate power spectra at a large number of frequencies … and access to diffuse Y distortions with unprecedented accuracy.

Isotropic Spectral Distortions



Depending on the physical process, the expected spectral distortions have a different shape (ε, μ, y)
See e.g.: **The evolution of CMB spectral distortions in the early Universe**
J. Chluba
R. A. Sunyaev
MNRAS (2012) 419 1294

No distortions have been observed to-date (may be not ? See Bowman et al. Nature 2018).

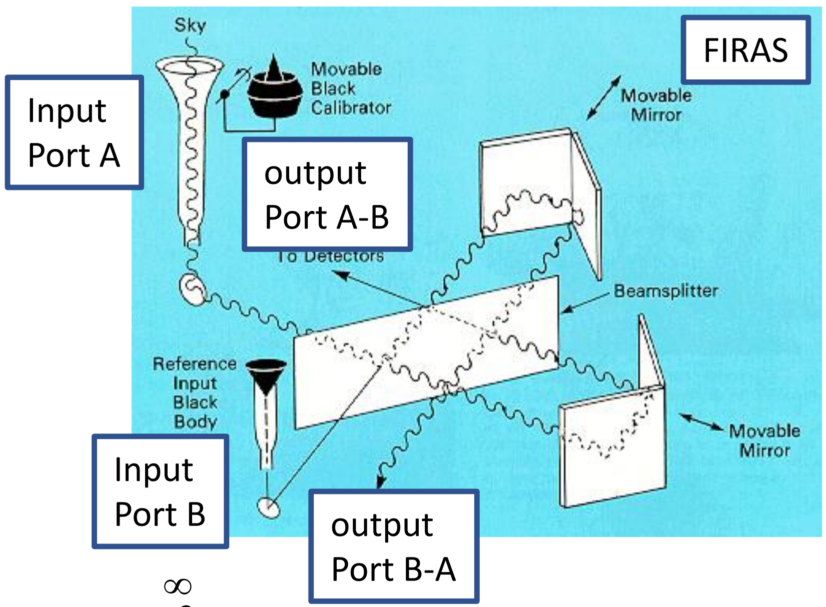
Current upper limits are at a level of 0.01% of the peak brightness of the CMB (COBE – FIRAS), Mather et al. (1990) Ap.J.L. 354 37

The observable is small, compared to … everything.

- Great scientific importance of measuring spectral distortions in the CMB – Cosmology and Fundamental Physics.
- Distortion signals are *guaranteed to exist*, but are *very small* compared to
  - detector noise,
  - instrument emission,
  - atmospheric emission and fluctuations,
  - foregrounds,
  - the CMB itself.
- Intelligent measurement methods required. Experimentalists way behind theorists. Final measurement certainly to be carried out from space (see PIXIE, PRISM, now PRISTINE, etc …).
- Here focus on a *pathfinder* experiment, ground-based, which does not target at the smallest distortions, but tries to exploit at best existing, relatively cheap opportunities.

Absolute measurement approach

- The Martin-Pupplett Fourier Transform Spectrometer used un FIRAS and PIXIE has two input ports.
- The instrument is intrinsically differential, measuring the spectrum of the difference in brightness at the two input ports. Normally one port looks at the sly, the other onbe at an internal reference blackbody

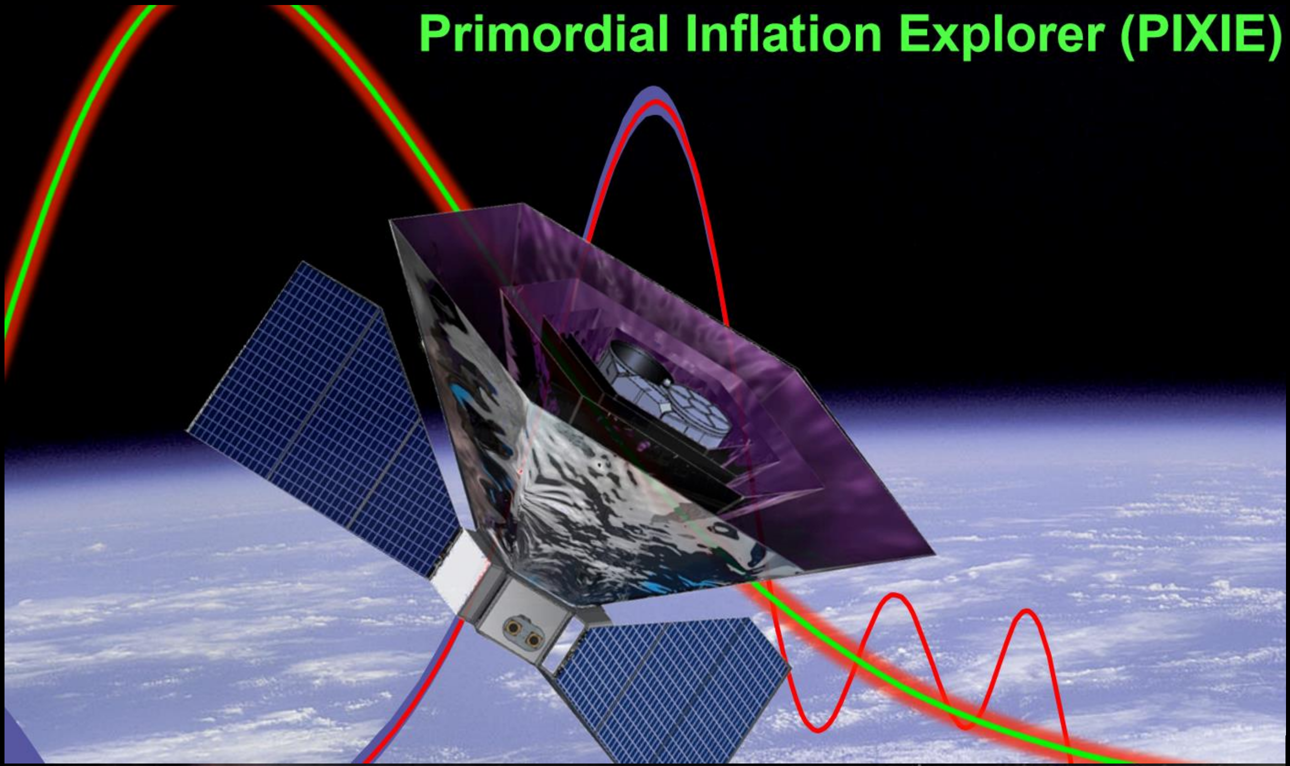


Sky measurement

$$I_{SKY}(x) = C\int_0^\infty [S_{SKY}(\sigma) - S_{REF}(\sigma)] rt(\sigma)\{1+\cos[4\pi\sigma x]\} d\sigma$$

Calibration measurement

$$I_{CAL}(x) = C\int_0^\infty [S_{CAL}(\sigma) - S_{REF}(\sigma)] rt(\sigma)\{1+\cos[4\pi\sigma x]\} d\sigma$$



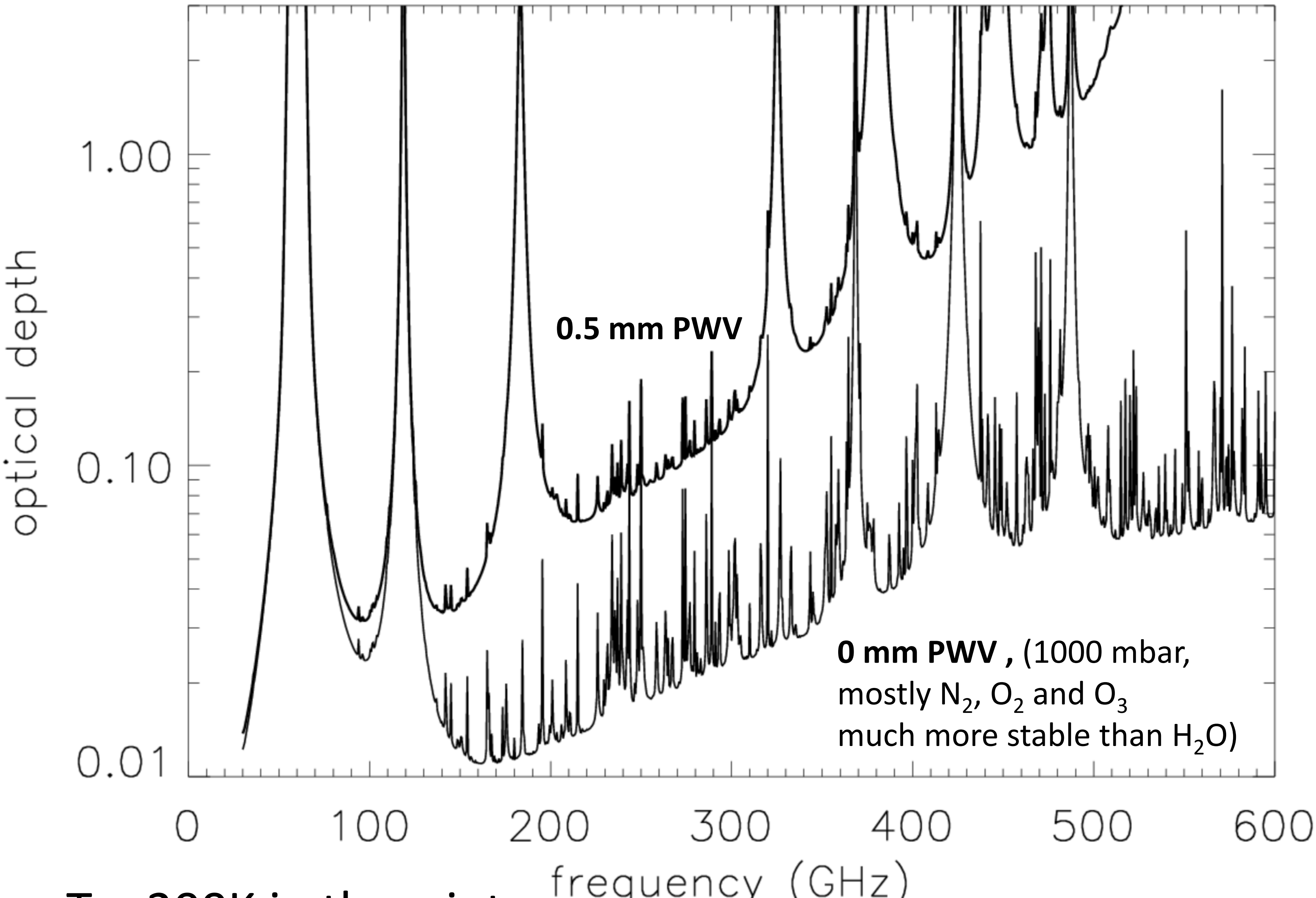
Satellite measurements can sample the CMB spectrum over the entire range 0-600 GHz.
PIXIE !!!
(*https://asd.gsfc.nasa.gov/pixie/*).

Ground based measurements are surely limited to frequencies in the atmospheric transmission windows.

If a ground-based measurement can be attempted from the ground, the site should be the high Antarctic Plateau (e.g. Dome-C or Soith Pole).

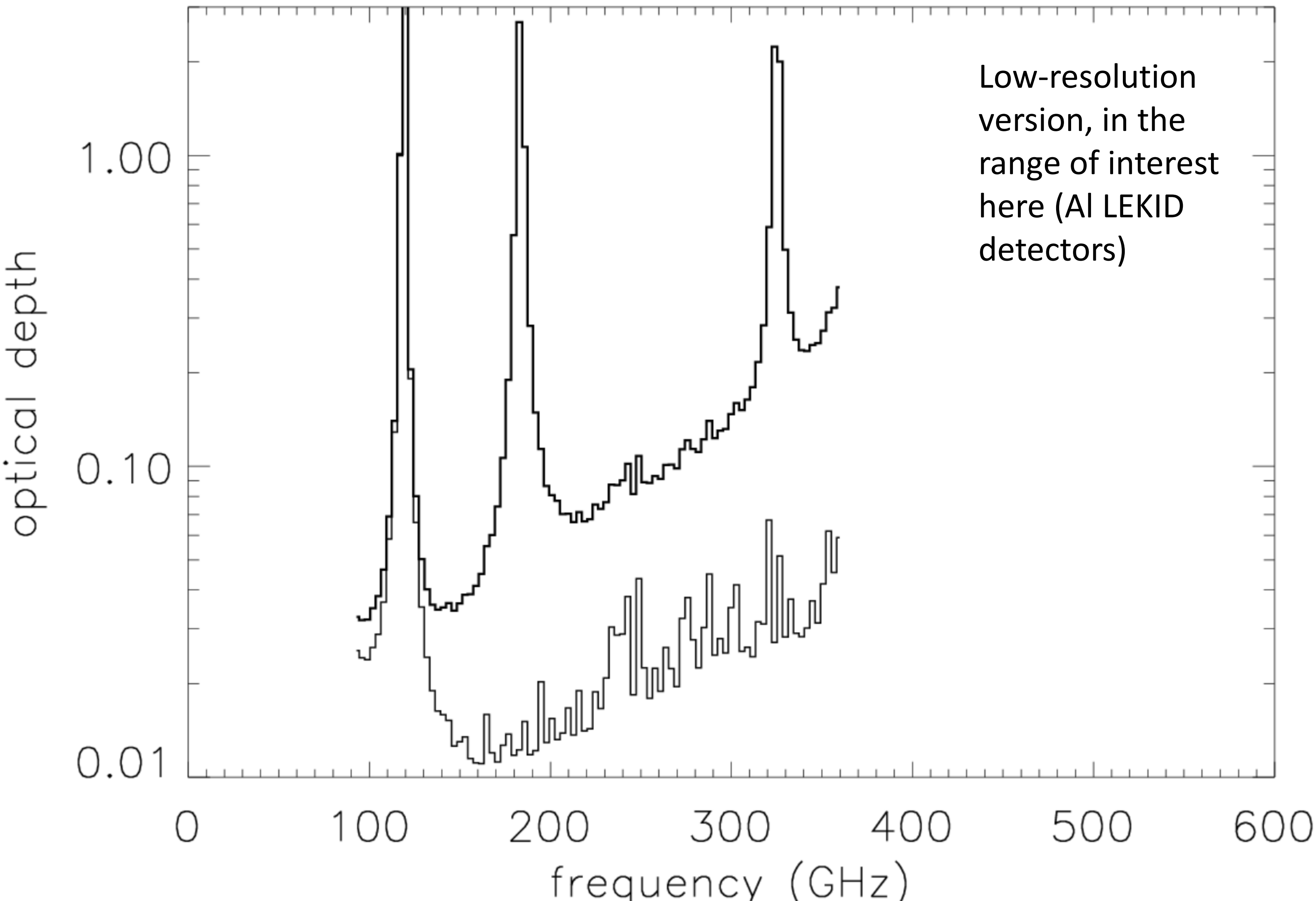
COSMO (COSmological Monopole Observer) targets this observable from Dome-C

Why Dome-C : optical depth of the atmosphere (credits : AM code)



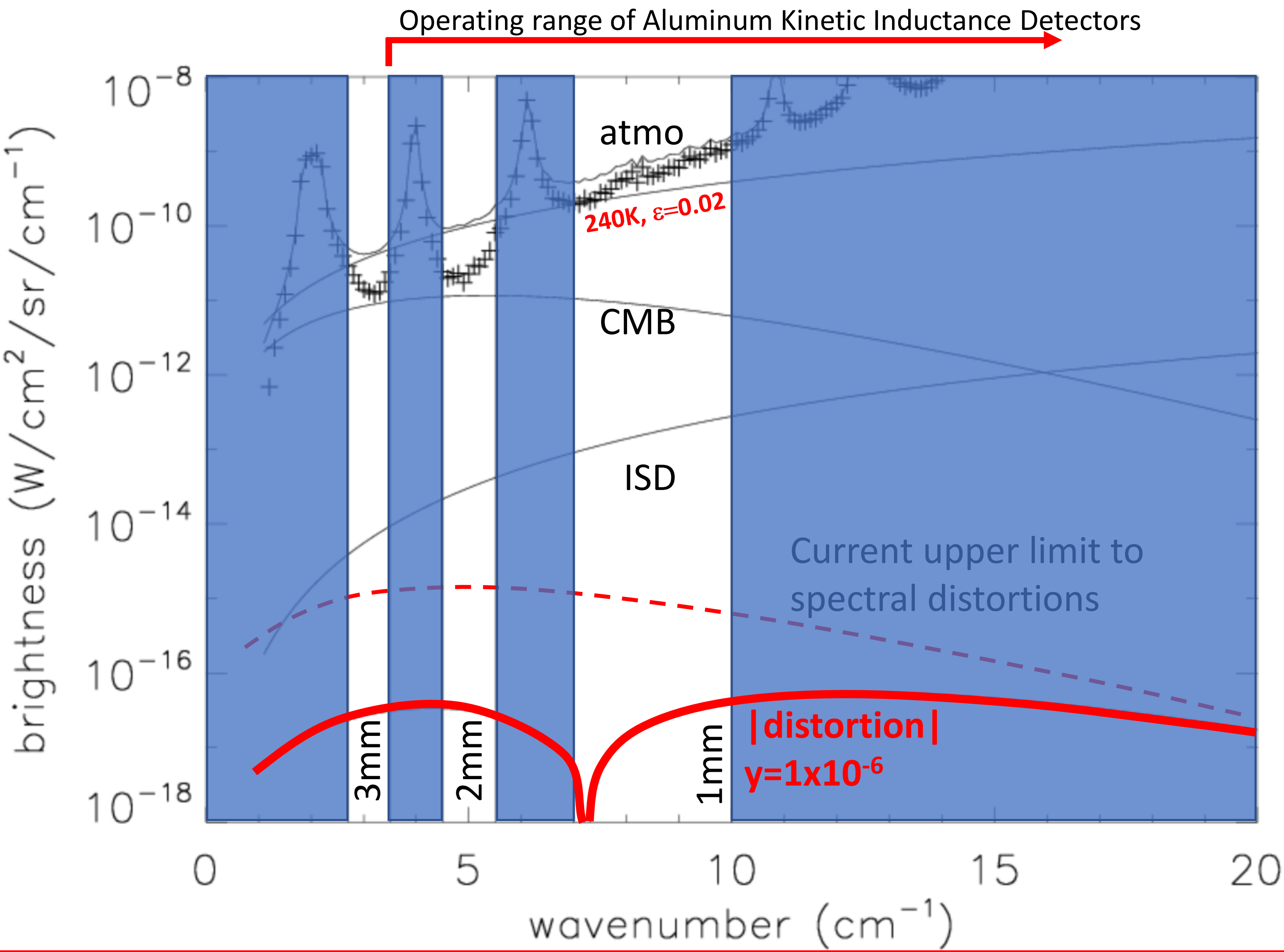
+ <T>=200K in the winter

Why Dome-C : optical depth of the atmosphere (credits : AM code)



Low-resolution version, in the range of interest here (Al LEKID detectors)

+ <T>=200K in the winter



Consider the 2 mm and 1 mm atmospheric windows, which are very transparent (low emission) and where Aluminum KIDs work efficiently. Simulate measurements, mask lines, and attempt spectral template fitting for y, since it has a characteristic shape:

$$\text{meas} = \text{atmo} + \text{CMB} + \text{ISD} + \text{distor}(y=10^{-6}) - B_{ref}\,(300\text{K}, \varepsilon=0.02) + \text{noise (BLIP)}$$

a NAIVE SIMULATION of the measurement performance is encouraging :

meas(ν) = atmo(ν) + CMB(ν) + ISD(ν) + distor($y=10^{-6}$,ν) - B_{ref} (300K, ν, ε=0.02) + noise (BLIP)
meas(ν) = atmo(ν) + CMB(ν) + ISD(ν) + distor($y=10^{-6}$,ν) - B_{ref} (1.65K,ν) + noise (BLIP)

Spectral template fitting procedure to detect spectral distortion:

fit(ν) = A*atmo(ν) + B*CMB(ν) + C*B_{ref} (1.65K,ν) + D*ISD(ν) + E*distor($y=10^{-6}$,ν)

HP: No 1/f (fast scan, see below)
Perfect knowledge of the spectral shape of atmospheric brightness (atmo(ν))

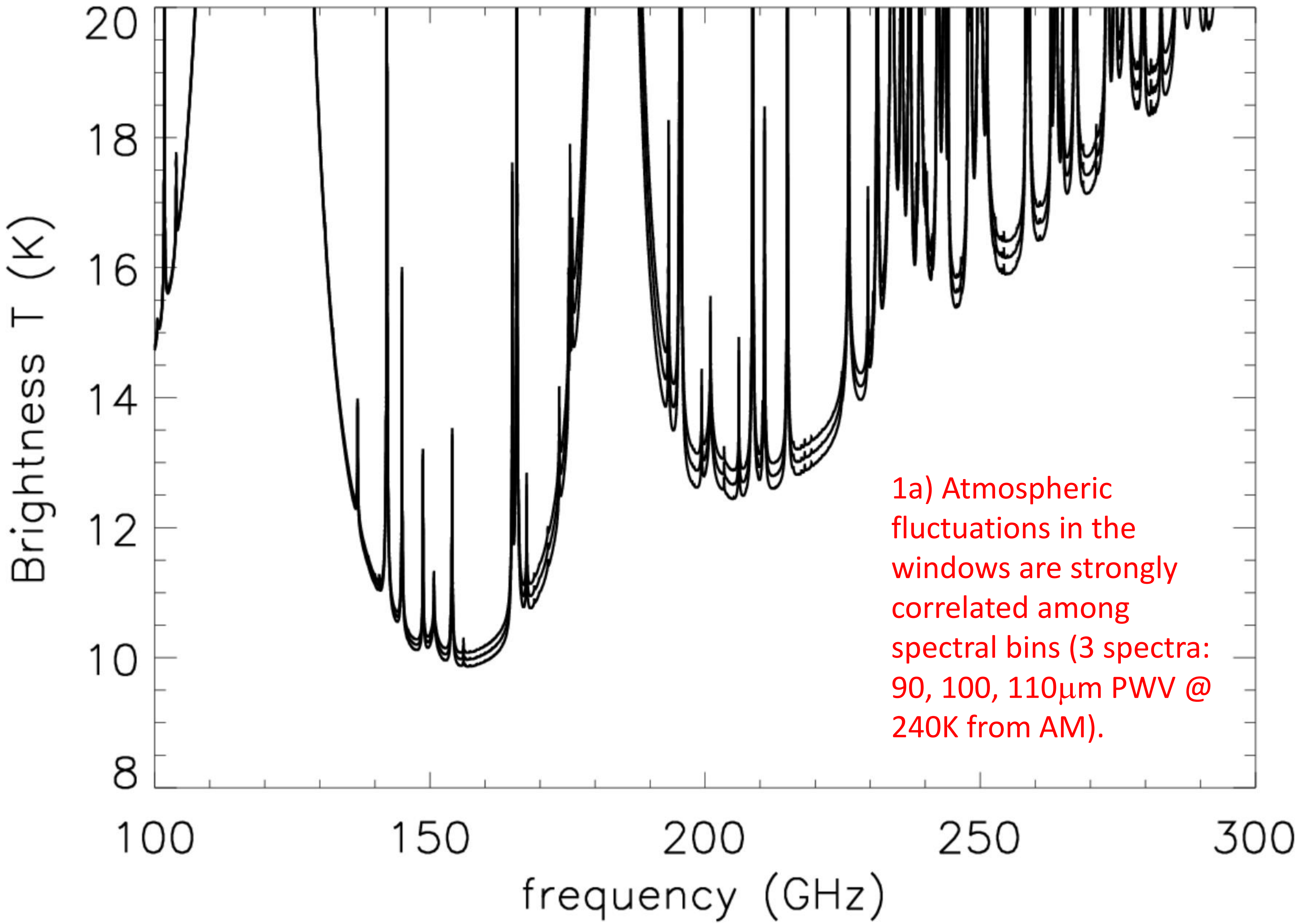
y parameter = 1.00e-06

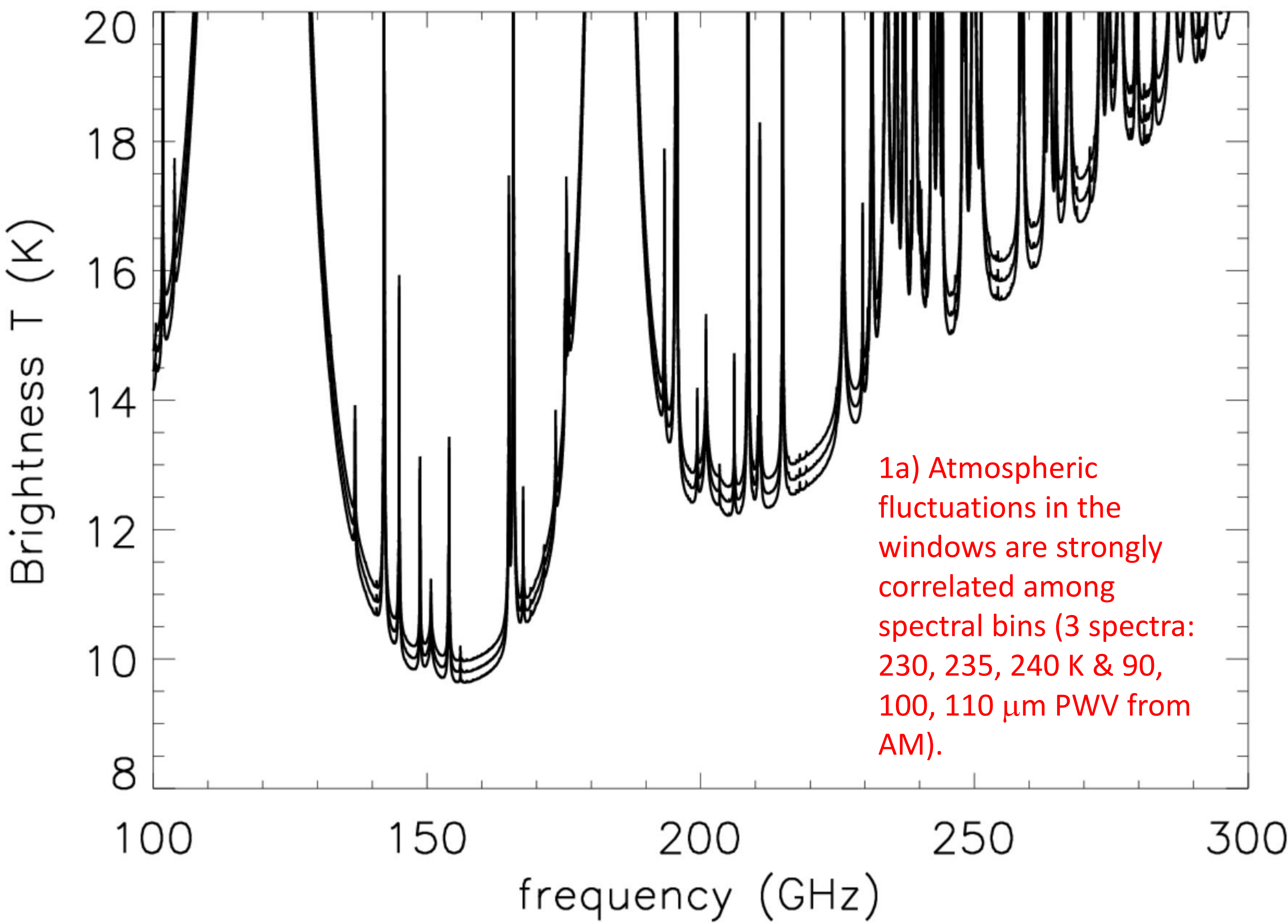
NEP = 1.50e-16 W/sqrt(Hz)
integration time for each spectrum = 3600 s
photon noise per resolution bin (1 spectrum) = 1.52e-17 W/cm2/sr/cm-1
number of spectra simulated = 10001
corresponding to 416 days of observation
fractional atmospheric fluctuations = **1.00e-04** rms, correlated among spectral bins
(e.g. PWV fluctuation, see below)

# of used spectral bins 40
A= atmos/model = 1.0000007 +/- 1.0019570e-006
B= cmb/model = 1.0000023 +/- 1.1284262e-006
C= refe/model = -0.99999581 +/- 2.1003349e-006
D= dust/model = 1.0000142 +/- 8.5398778e-006
E= DSZ/model = **1.21** +/- **0.11**
offset = -2.8e-017 +/- 1.4e-017

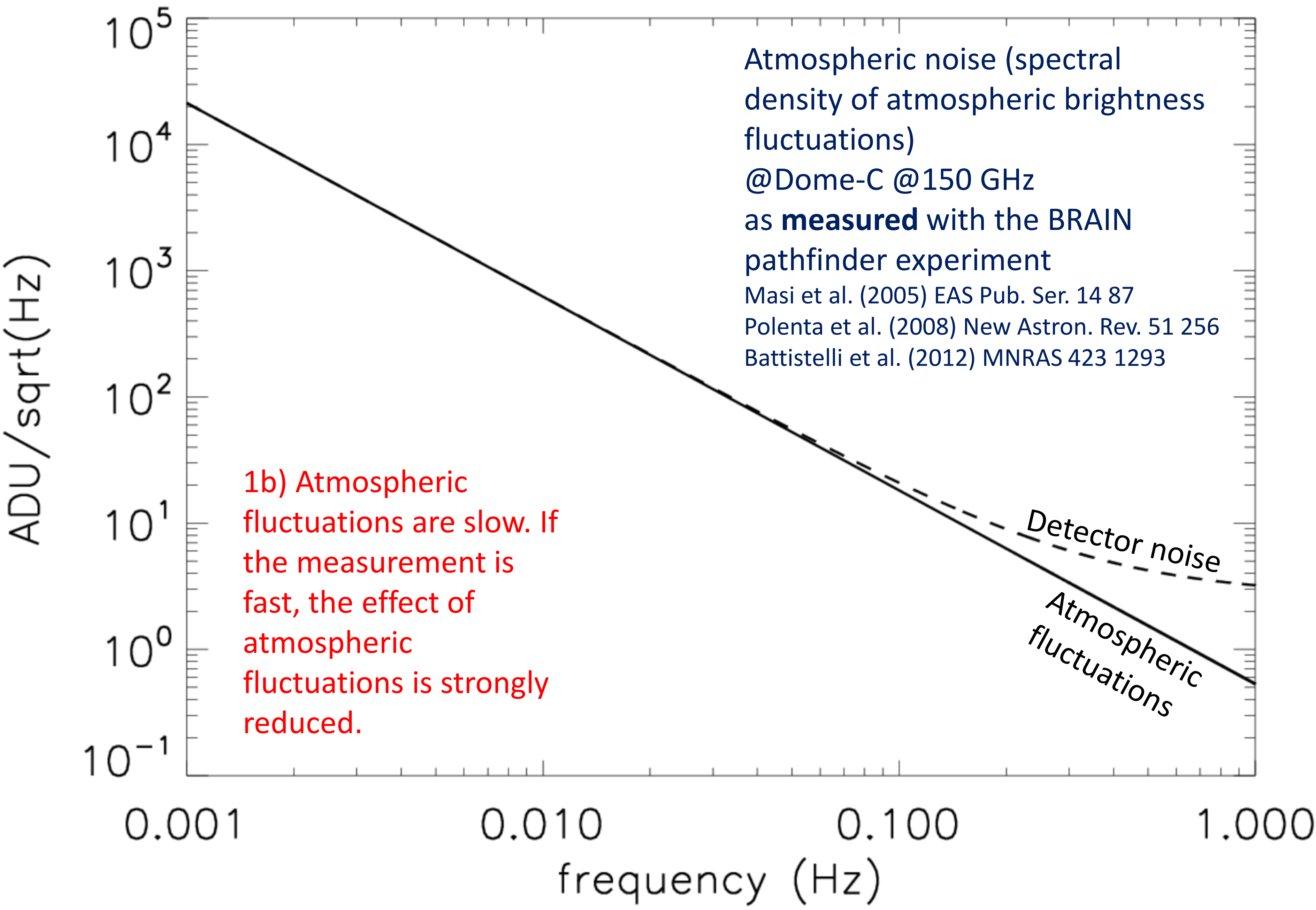
The amplitude of the y distortion is retreived to 10% accuracy. However:

1. Assumed fractional fluctuations correlated, and very small. Is this reasonable ?
2. Perfect knowledge of the spectrum of the atmosphere is impossible. Any deviation from reality in the model will be interpreted as a spectral distortion. Can we find a way to actually *measure* the atmospheric contribution ?


20
18
16
14
12
10
8
Brightness T (K)
100
150
200
250
300
frequency (GHz)
1a) Atmospheric fluctuations in the windows are strongly correlated among spectral bins (3 spectra: 90, 100, 110μm PWV @ 240K from AM).



20
18
16
14
12
10
8
Brightness T (K)
100
150
200
250
300
frequency (GHz)
1a) Atmospheric fluctuations in the windows are strongly correlated among spectral bins (3 spectra: 230, 235, 240 K & 90, 100, 110 μm PWV from AM).



Atmospheric noise (spectral density of atmospheric brightness fluctuations)
@Dome-C @150 GHz
as **measured** with the BRAIN pathfinder experiment
Masi et al. (2005) EAS Pub. Ser. 14 87
Polenta et al. (2008) New Astron. Rev. 51 256
Battistelli et al. (2012) MNRAS 423 1293
1b) Atmospheric fluctuations are slow. If the measurement is fast, the effect of atmospheric fluctuations is strongly reduced.
Detector noise
Atmospheric fluctuations
ADU/sqrt(Hz)
frequency (Hz)
0.001
0.010
0.100
1.000
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}

COSMO : coping with the atmosphere

- We have to measure and subtract atmospheric emission, and we have to do it very quick.
- Recipe to mitigate the problem:

1. Work from a high altitude, cold and dry site (Dome-C, Antarctica) to minimize the problem
2. Measure the specific spectral brightness of atmospheric emission while measuring the brightness of the sky, modulating the optical depth
3. Use fast, sensitive detectors, and fast modulators.

COSMO sky/atmosphere scan strategy

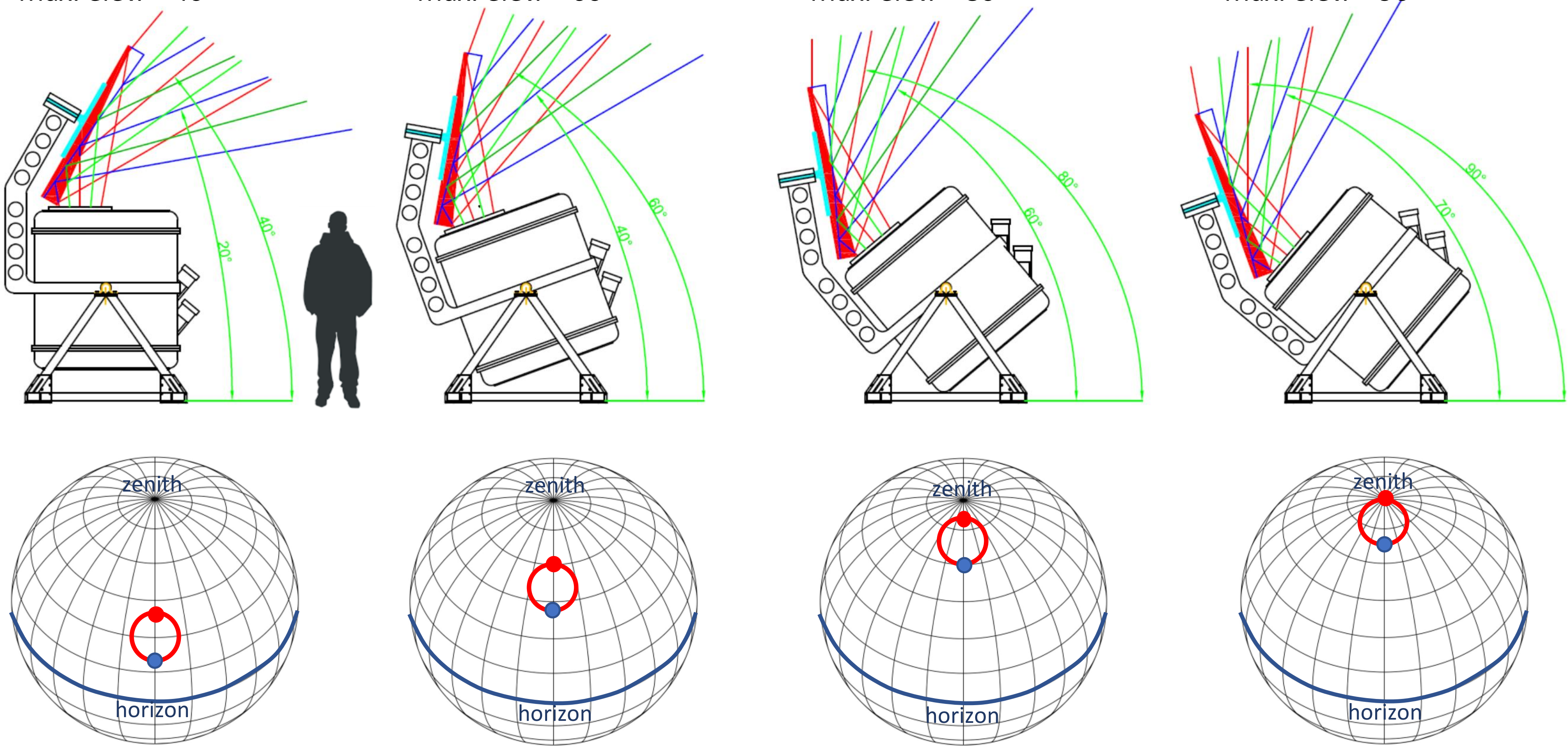
Oversized (1.6m diameter), spinning flat mirror, 10° wedge (red/blue)
To scan circles (D=5°-20°) in the sky modulating atmospheric emission.
Center elevation ranges between 30° and 80° depending on cryostat tilt.

Cryostat tilt = 0°
PT tilt = 40°
Min. elev. = 20°
Max. elev. = 40°

Cryostat tilt = 20°
PT tilt = 20°
Min. elev. = 40°
Max. elev. = 60°

Cryostat tilt = 40°
PT tilt = 0°
Min. elev. = 60°
Max. elev. = 80°

Cryostat tilt = 50°
PT tilt = -10°
Min. elev. = 70°
Max. elev. = 90°



COSMO measurement timing

Exploits the availability of fast detectors (Kinetic Inductance Detectors - KIDs) and the know how of racing cars to beat atmospheric noise

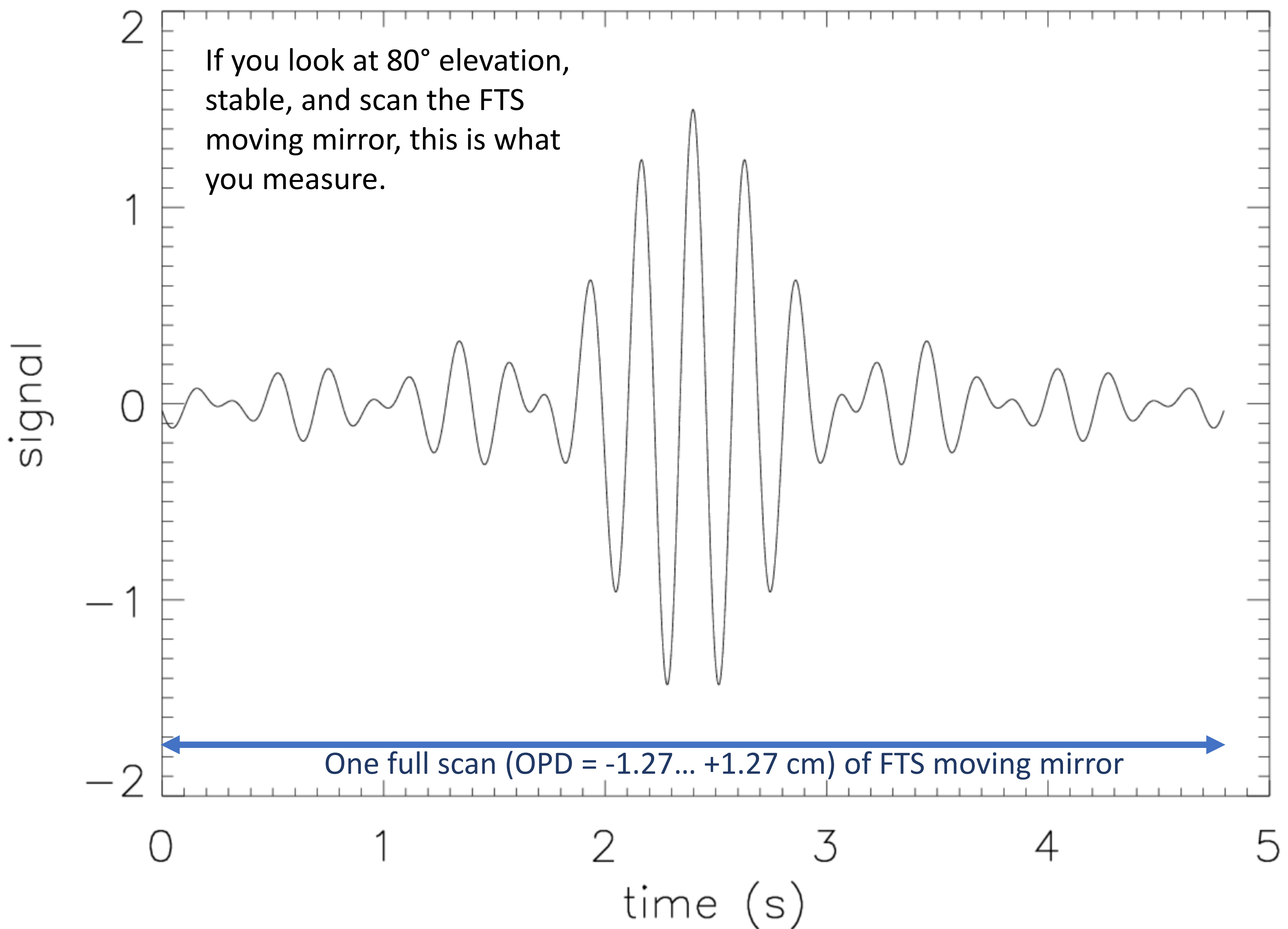
detector performance		
detector time constant	**5.00E-05**	**s**
5 time constants	2.50E-04	s
NET	100	uK/sqrt(Hz)
noise per sample	6.3	mK

interferogram scan fast		
maximum wavenumber (Nyquist)	20	cm-1
sampling step	0.0125	cm
resolution	6	GHz
resolution	0.200	cm-1
number of frequency samples	100	
number of samples in double-sided interferogram	256	
time to complete an interferogram	0.064	s
interferograms per second	15.6	
mirror scan mechanism period	0.13	s
sky scan slow		
circle radius	5	deg
circle length	31.4	deg
beam size	0.5	deg
number of samples per circle (3 per beam)	188	
time per beam	0.192	s
time for 2 sky dips (downwards + upwards)	36.19	s
wedge mirror rotation rate	1.66	rpm
sky stability required for	18.10	s

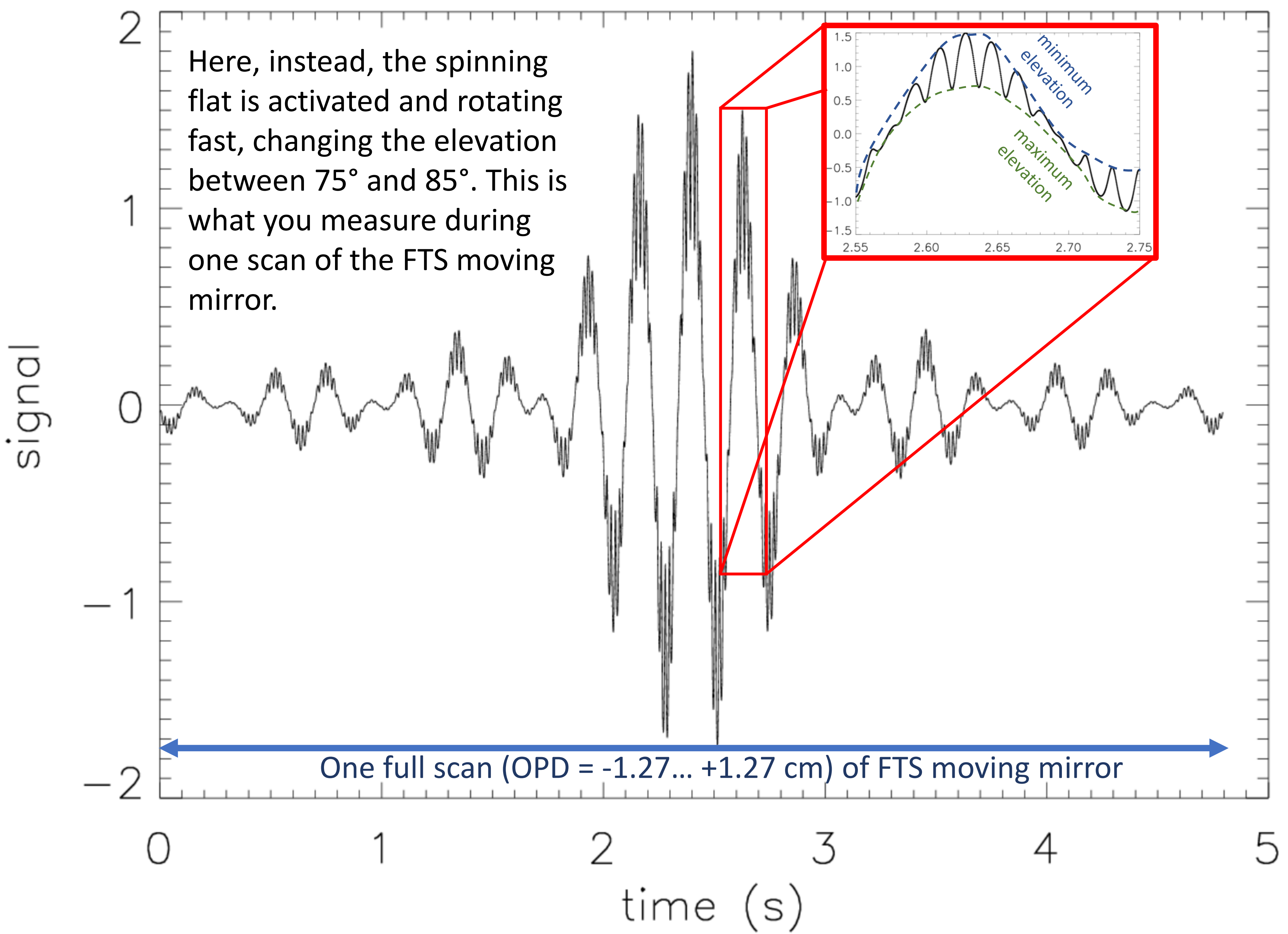
- This configuration requires a fast cryogenic mirror scanning mechanism
- High dissipation in the cryo system

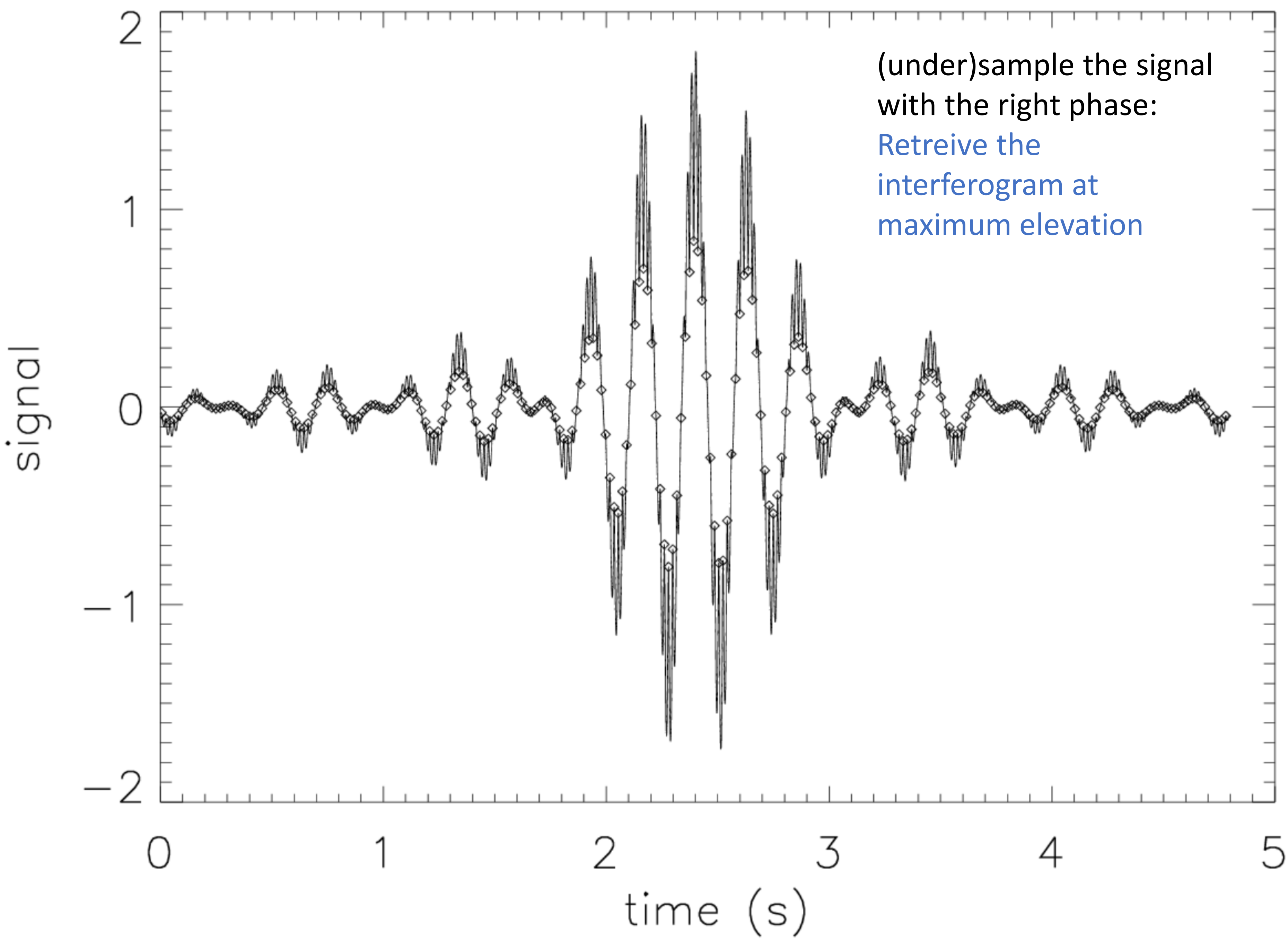
sky scan fast		
circle radius	5	deg
circle length	31.4	deg
beam size	1	deg
number of samples per circle (3 per beam)	94	
time per beam	2.50E-04	s
time for 2 sky dips (downwards + upwards)	2.36E-02	s
wedge mirror rotation rate	2546	rpm
interferogram scan slow		
maximum wavenumber (Nyquist)	20	cm-1
sampling step	0.0125	cm
resolution	6	GHz
resolution	0.200	cm-1
number of frequency samples	100	
number of samples in double-sided interferogram	256	
time to complete an interferogram	6.032	s
interferograms per second	0.2	
mirror scan mechanism period	12.06	s
sky stability required for	**6.03**	**s**

- This configuration requires a fast room-temperature mirror rotation device
- Not impossible.

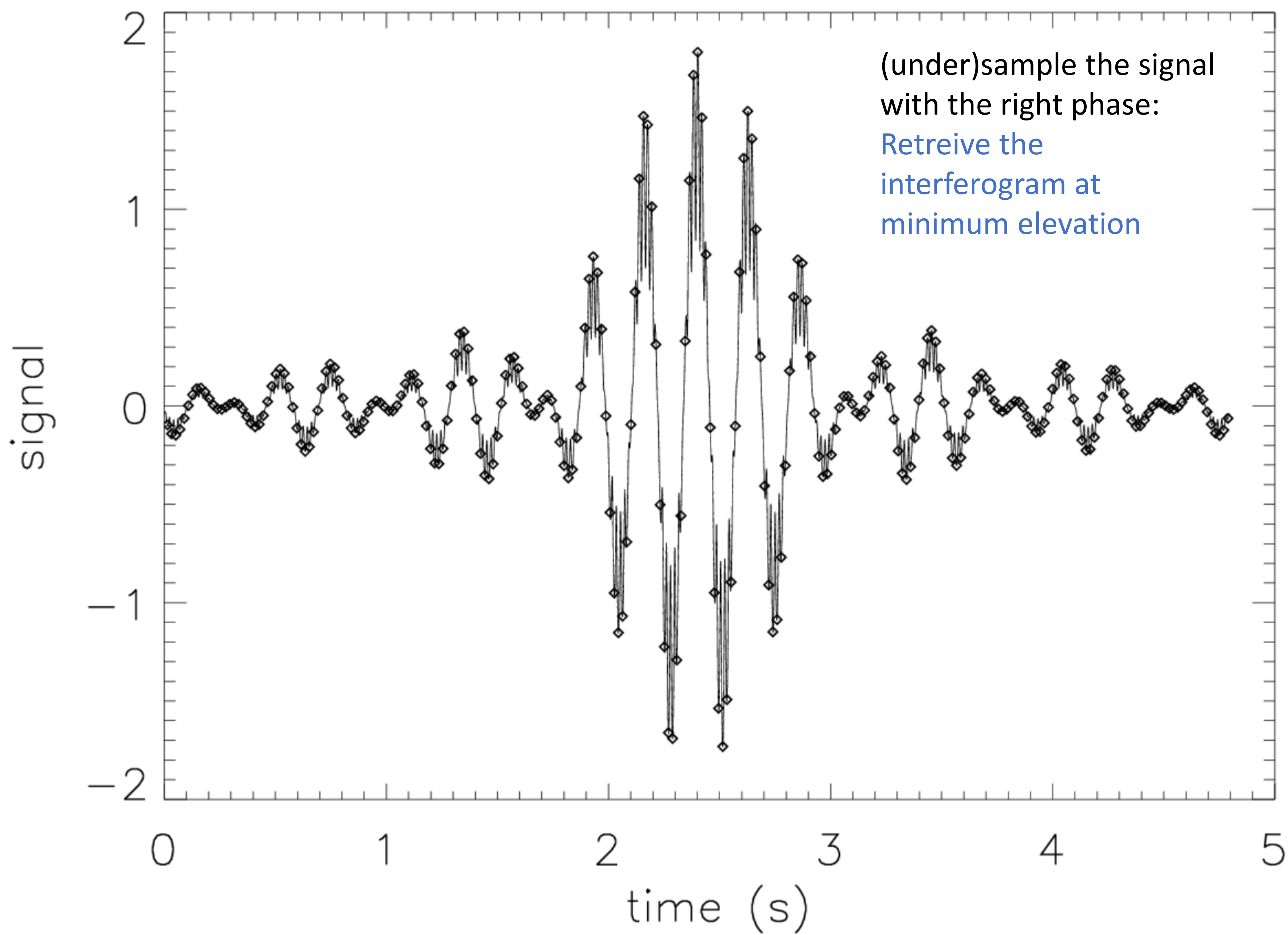


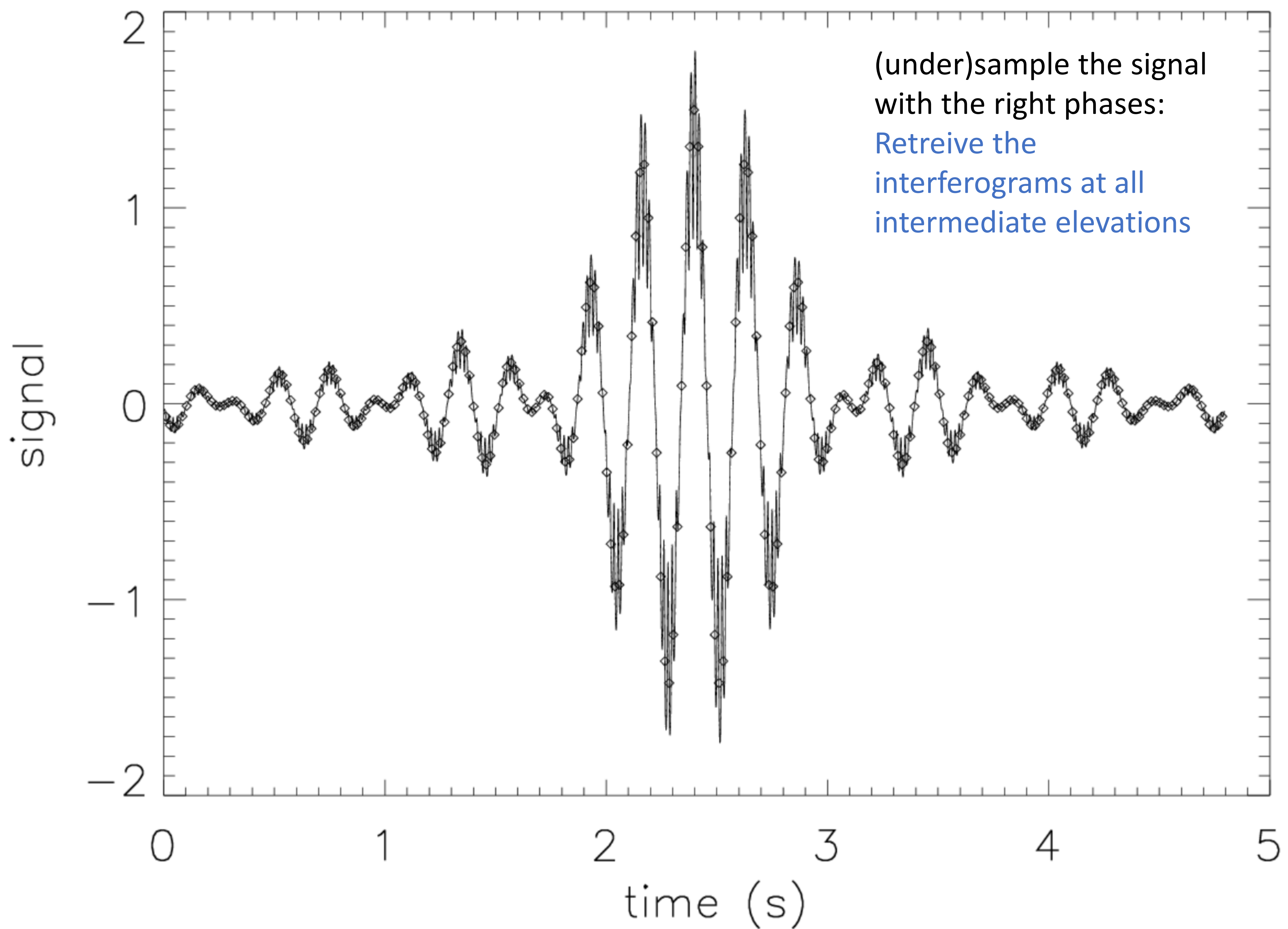
If you look at 80° elevation, stable, and scan the FTS moving mirror, this is what you measure.
One full scan (OPD = -1.27… +1.27 cm) of FTS moving mirror
signal
time (s)
2
1
0
−1
−2
0
1
2
3
4
5

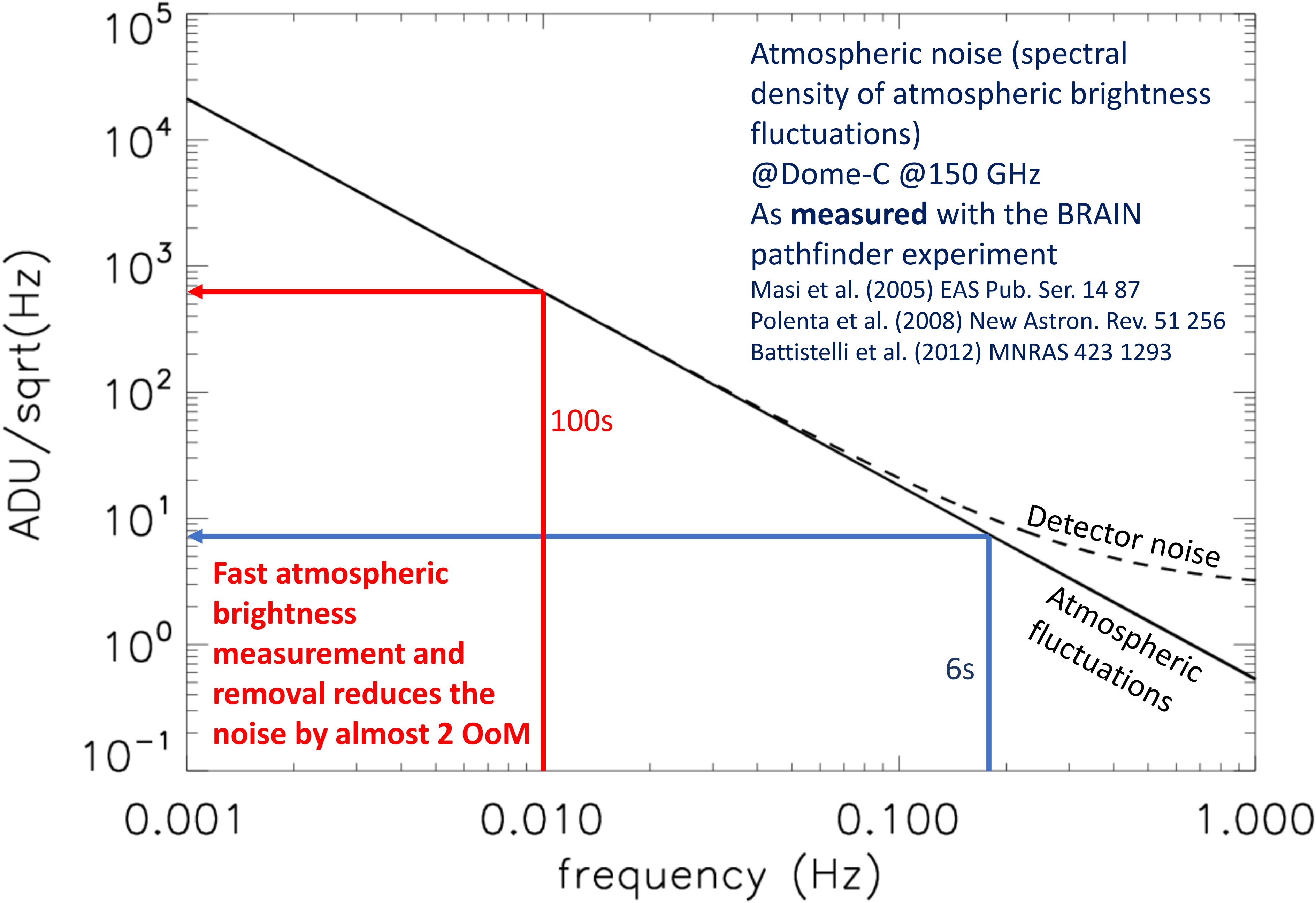

Here, instead, the spinning flat is activated and rotating fast, changing the elevation between 75° and 85°. This is what you measure during one scan of the FTS moving mirror.
minimum elevation
maximum elevation
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
2.55
2.60
2.65
2.70
2.75
One full scan (OPD = -1.27… +1.27 cm) of FTS moving mirror
2
1
0
−1
−2
signal
0
1
2
3
4
5
time (s)



(under)sample the signal
with the right phase:
Retreive the
interferogram at
maximum elevation
signal
time (s)
2
1
0
−1
−2
0
1
2
3
4
5


(under)sample the signal
with the right phase:
Retreive the
interferogram at
minimum elevation
signal
time (s)
2
1
0
−1
−2
0
1
2
3
4
5


(under)sample the signal
with the right phases:
Retreive the
interferograms at all
intermediate elevations
signal
time (s)
2
1
0
−1
−2
0
1
2
3
4
5



Atmospheric noise (spectral density of atmospheric brightness fluctuations)
@Dome-C @150 GHz
As **measured** with the BRAIN pathfinder experiment
Masi et al. (2005) EAS Pub. Ser. 14 87
Polenta et al. (2008) New Astron. Rev. 51 256
Battistelli et al. (2012) MNRAS 423 1293
100s
6s
Detector noise
Atmospheric fluctuations
Fast atmospheric brightness measurement and removal reduces the noise by almost 2 OoM
ADU/sqrt(Hz)
frequency (Hz)
0.001
0.010
0.100
1.000

Another naive simulation

- Retreive all the interferograms at all different elevations, and Fourier transform them to obtain the measurements of the specific spectral brightness at all elevations. This is a very fast *sky-dip* measurement.
- The atmospheric contribution depends on the optical depth and on the temperature profile.
- For a naive single isothermal layer, the measured brightness at elevation ***e*** is

$$B(\nu, e) = B(T_{atm}, \nu)\left(1 - e^{-\tau(\nu,e)}\right) + B_{sky} e^{-\tau(\nu,e)} - B(T_{ref}, \nu).$$

- which can be rewritten $B(\nu, e) = a(\nu)x(\nu, e) + b(\nu)$
- where

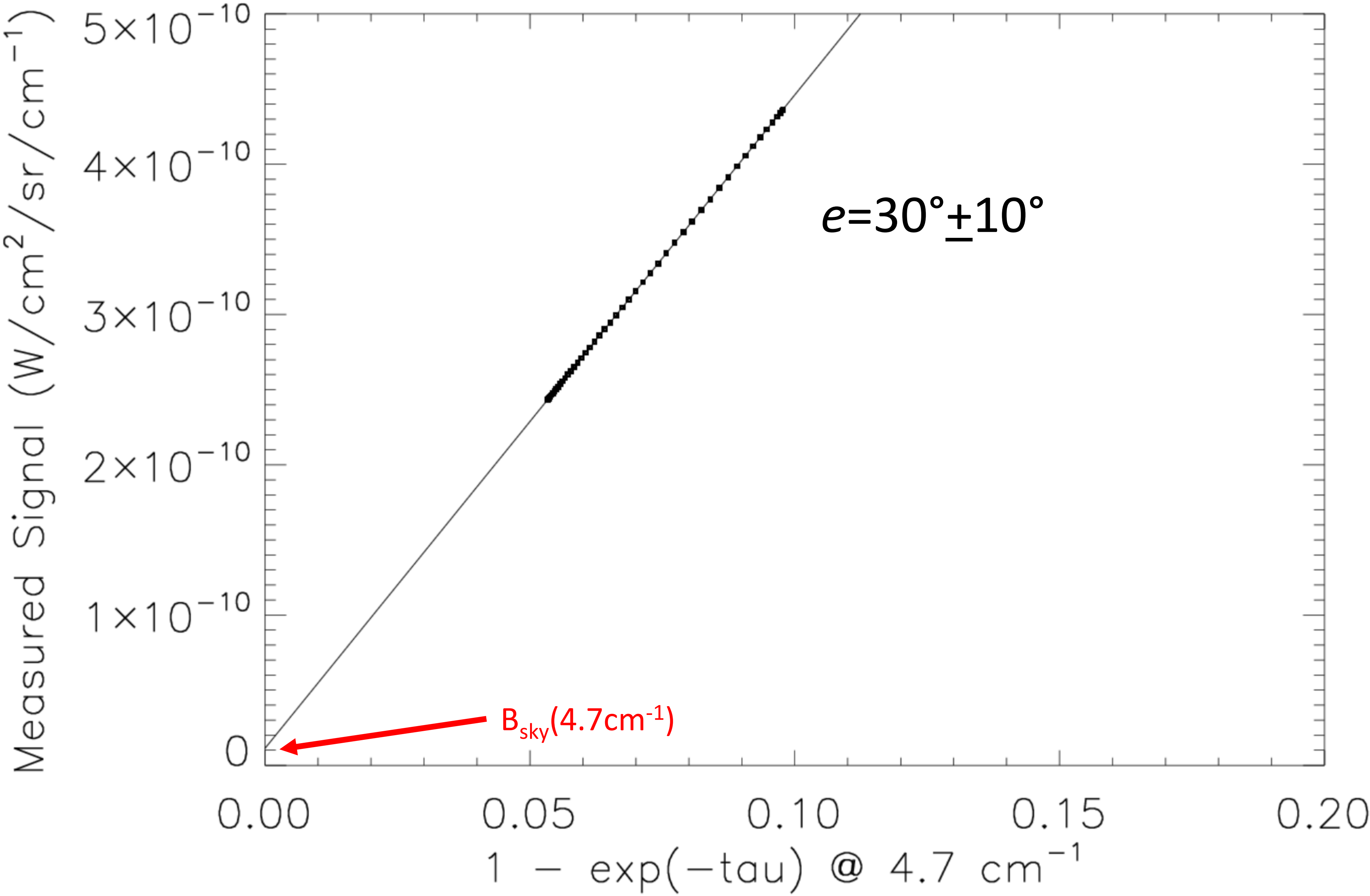
$$x = 1 - \exp(-\tau_z(\nu)/\cos(e))$$

$$B_{sky}(\nu) - B(T_{ref}, \nu) = a(\nu)$$

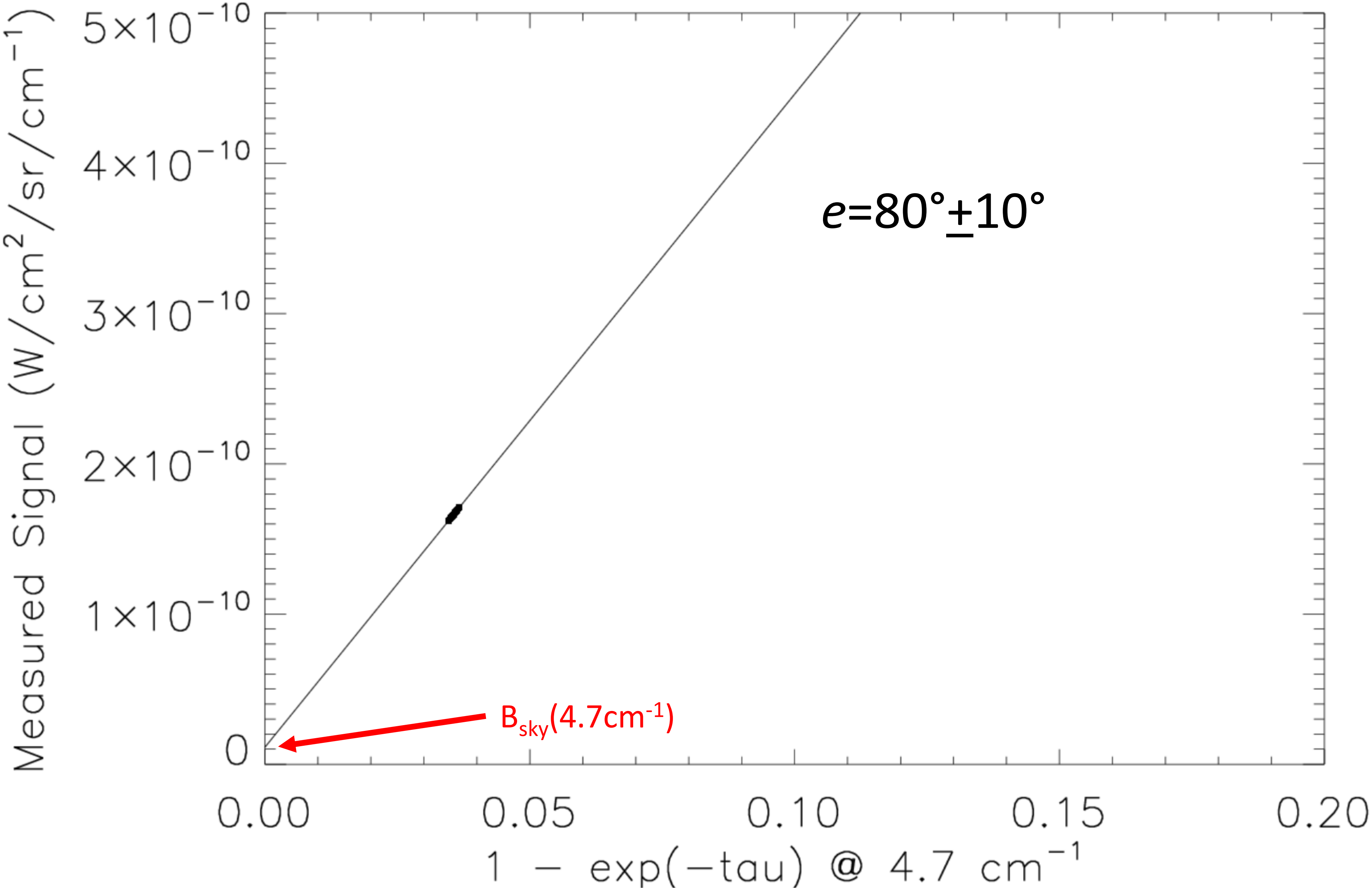
$$B(T_{atm}, \nu) = b(\nu) + a(\nu)$$

- So, for each frequency, a simple linear fit will provide the measurement of the sky brightness, with atmospheric emission removed.
- Since the length of the data record used for this procedure is very short (few seconds) slowly fluctuating atmospheric emission is continuously removed.
- The SNR of this determination will be low, but many measurements can be stacked to gain SNR for the monopole of sky emission.

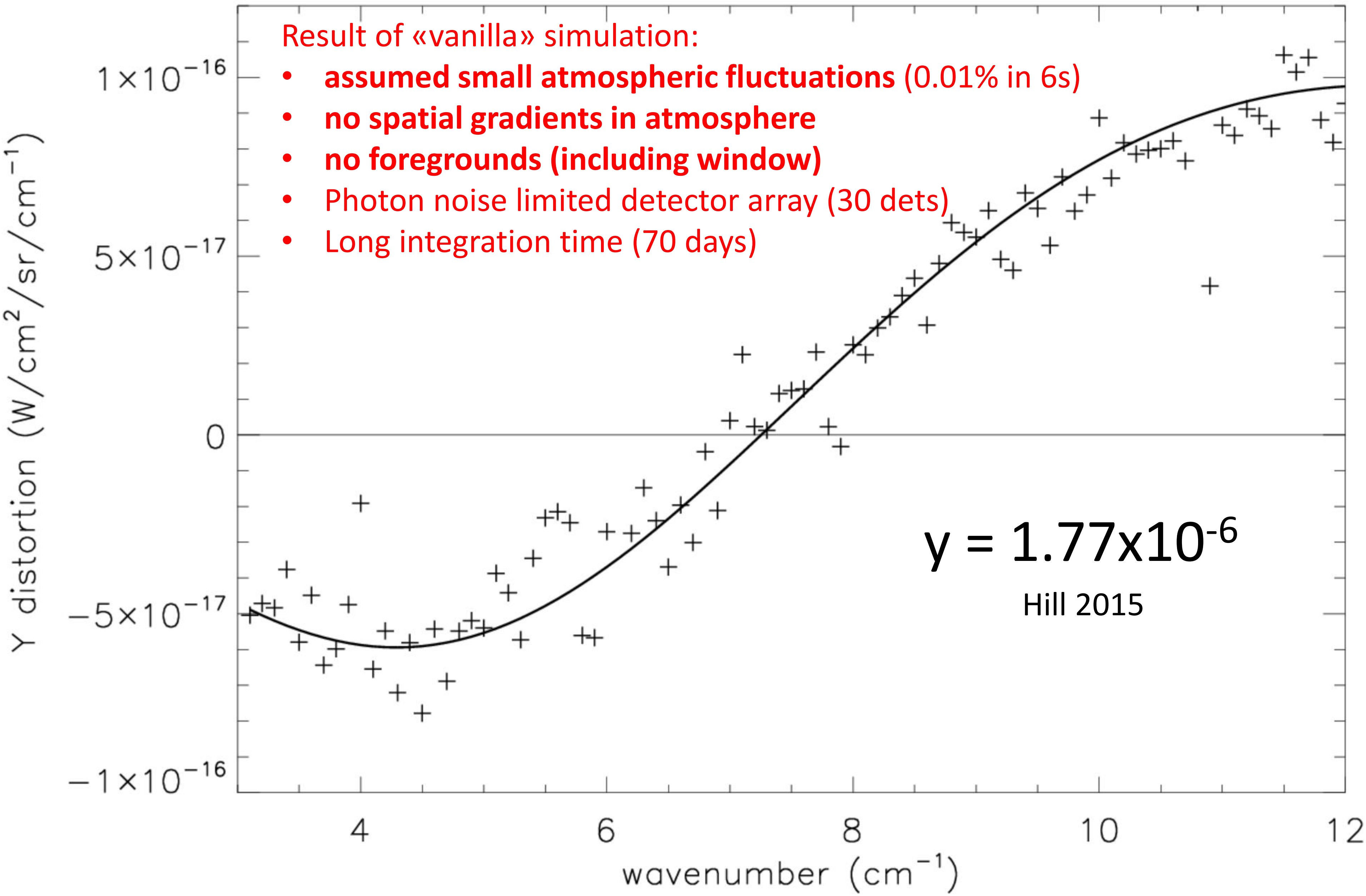
COSMO sky / atmosphere scan simulations



COSMO sky / atmosphere scan simulations



COSMO sky / atmosphere scan simulations

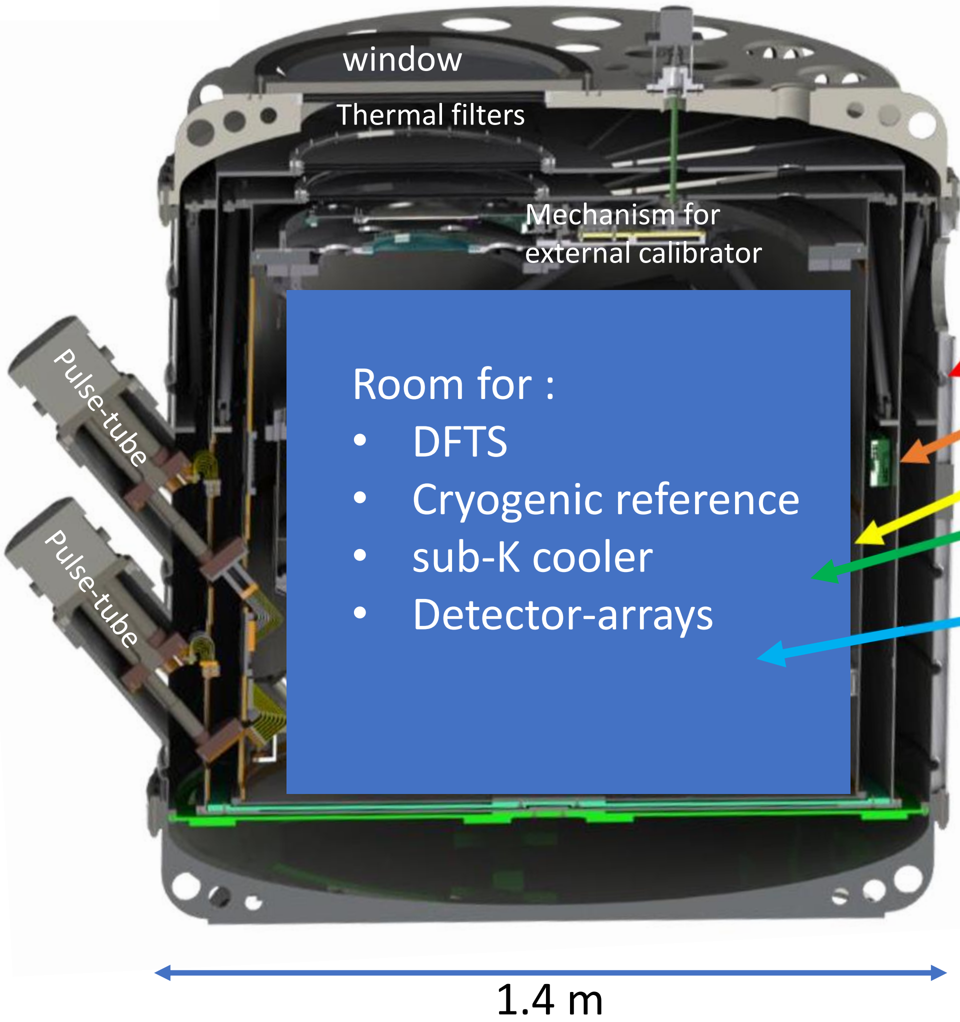


COSMO implementation

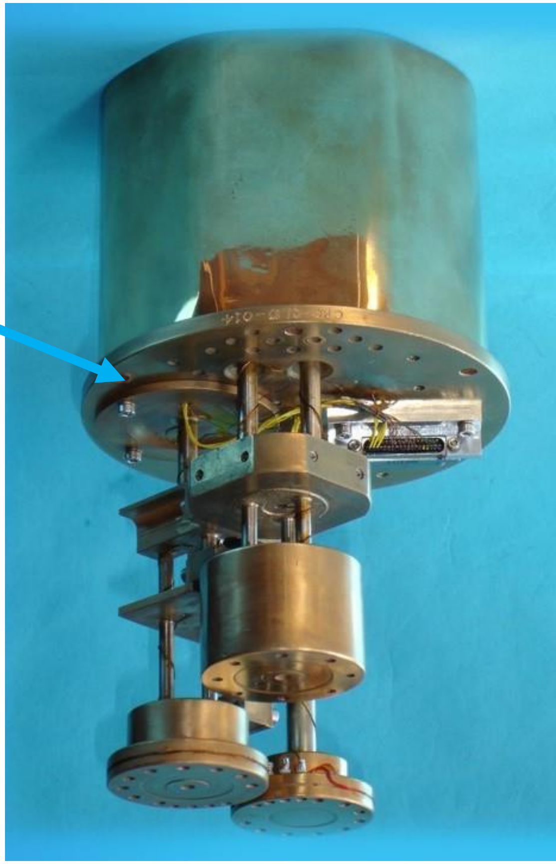
- As of today, still moving from *concept* into *instrument design*
- However:
  - PNRA proposal funded to provide cryogeinc system, optics, and logistic support for the Concordia base (PI Silvia Masi, partner institutions UniMI (Mennella), UniMIB (Zannoni))
  - PNRA proposal funded to support development of KID detector arrays and coupling optics (PI Elia Battistelli, partner institutions CNR-IFN (Castellano), UniMI, UniMIB)
  - PRIN proposal being finalized to support development of optical design and construction of the cryogenic interferometer (PI P. de Bernardis, partners CNR-IFN (Cibella), UniMI, UniMIB)
  - Additional partner Cardiff University
- International interest expressed from other international institutions … the experiment is gaining momentum.

COSMO continuous cryogenics

- Main cryostat based on pulse-tube coolers (3K, 0.9W each) + sub-K cooler (0.25K)
- Stays cold as long as there is power for the two pulse tubes
- Large window (50 cm dia)
- Large 3K volume (500 l)



- «^{10}He» 0.25K fridge from Chase Cryogenics
- To cool the detector arrays



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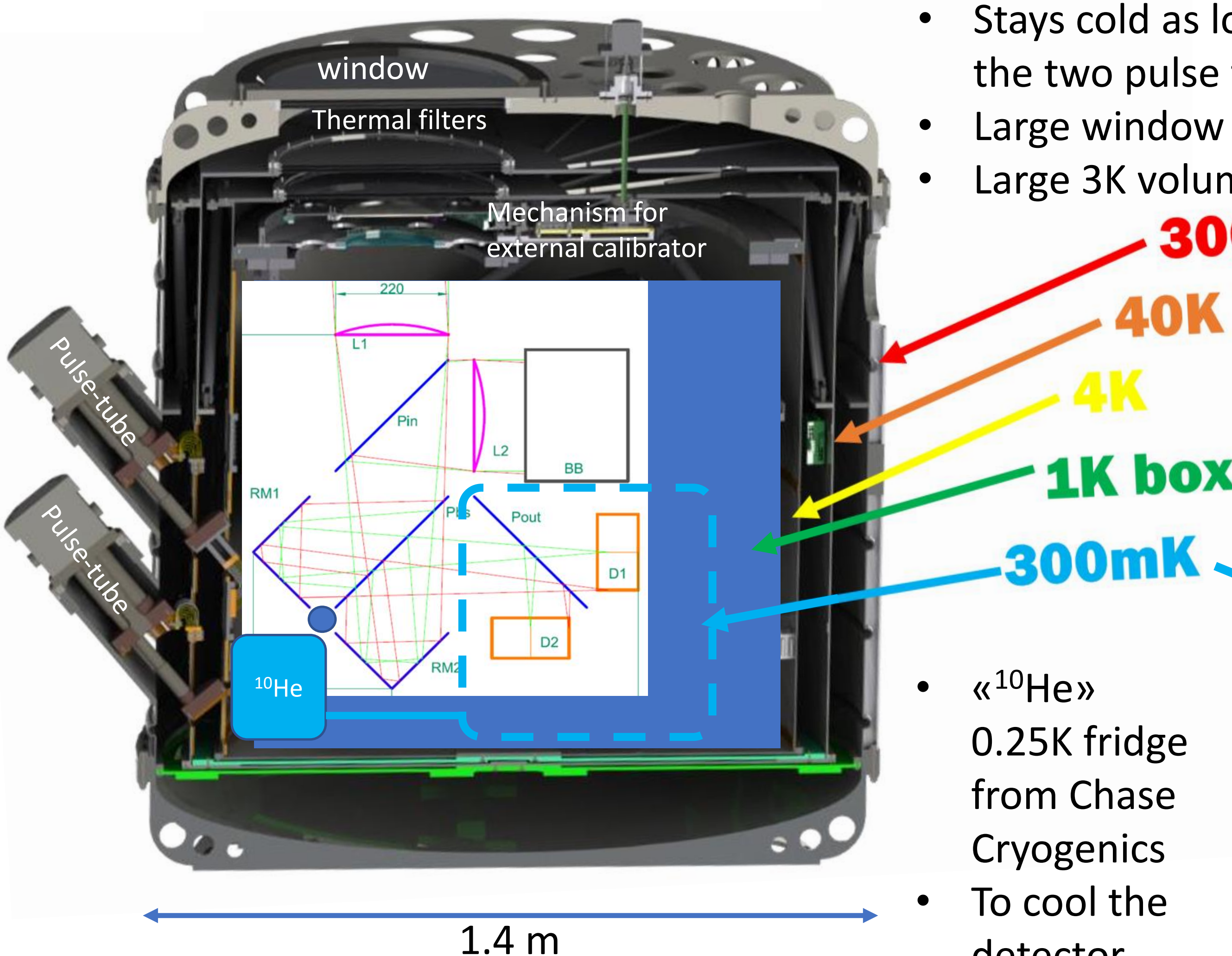

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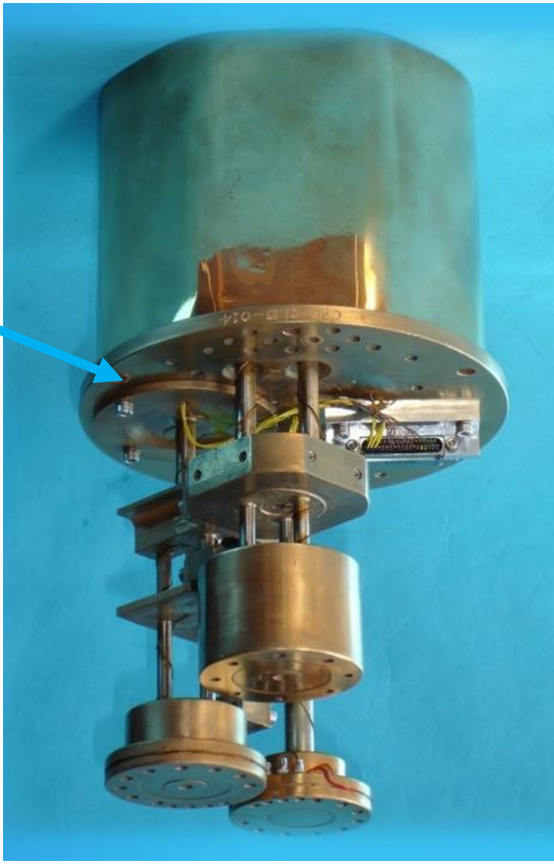
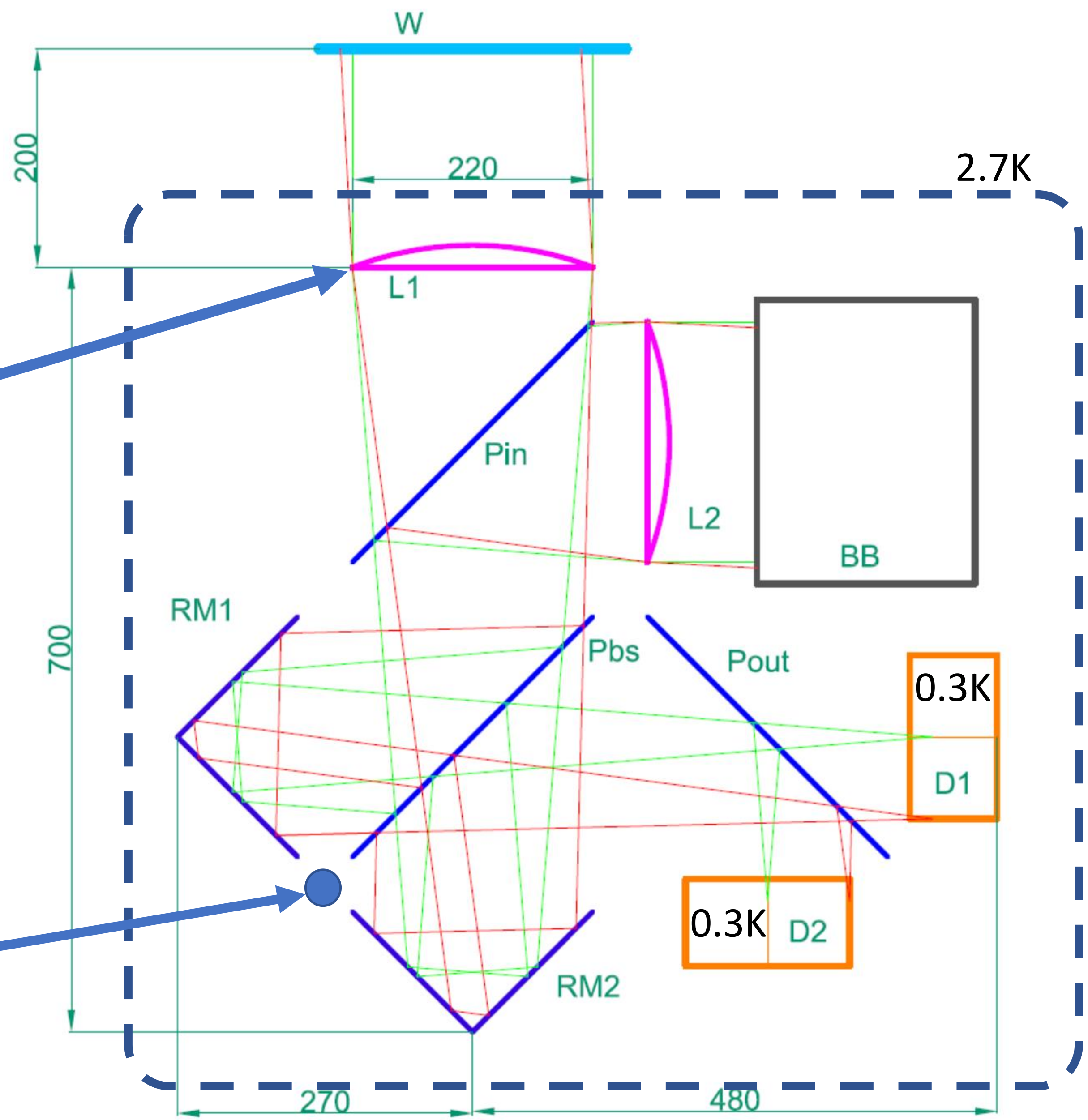


COSMO instrument basic design



200 mm aperture
1.4m focal length
15 mm aperture dets
0.9° FWHM

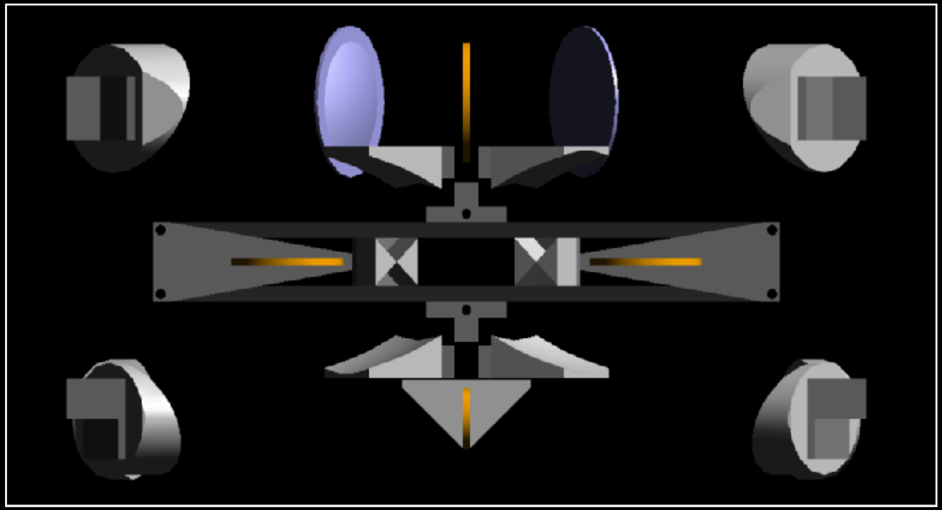
Pivot for double
pendulum design

COSMO continuous cryogenics

COSMO continuous cryogenics

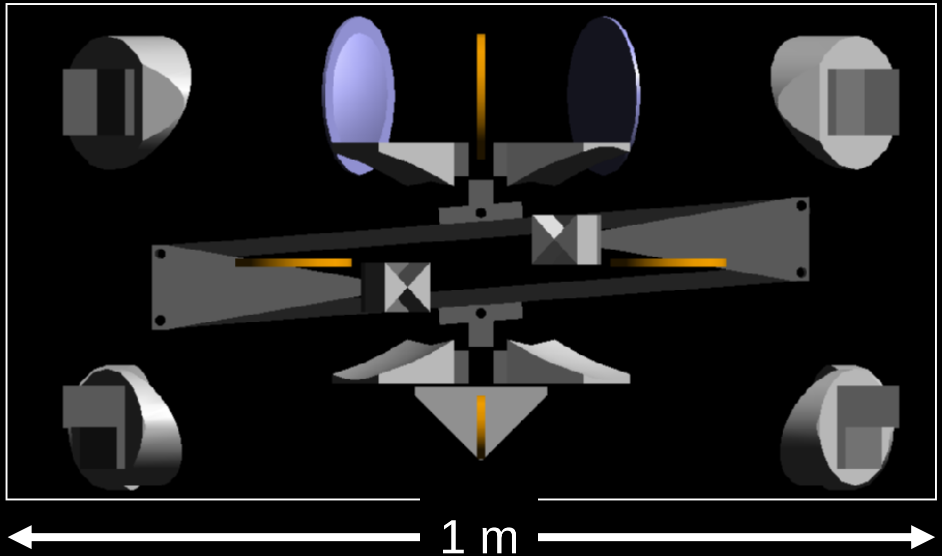
WP3200: Cryogenic operation of a double pendulum

From the *Millimetron* study



Non abbiamo un criostato così grande !

Serve un dimostratore più piccolo, con la stessa inerzia e le stesse costanti elastiche.



WP3200: Cryogenic operation of a double pendulum

From the *Millimetron* study

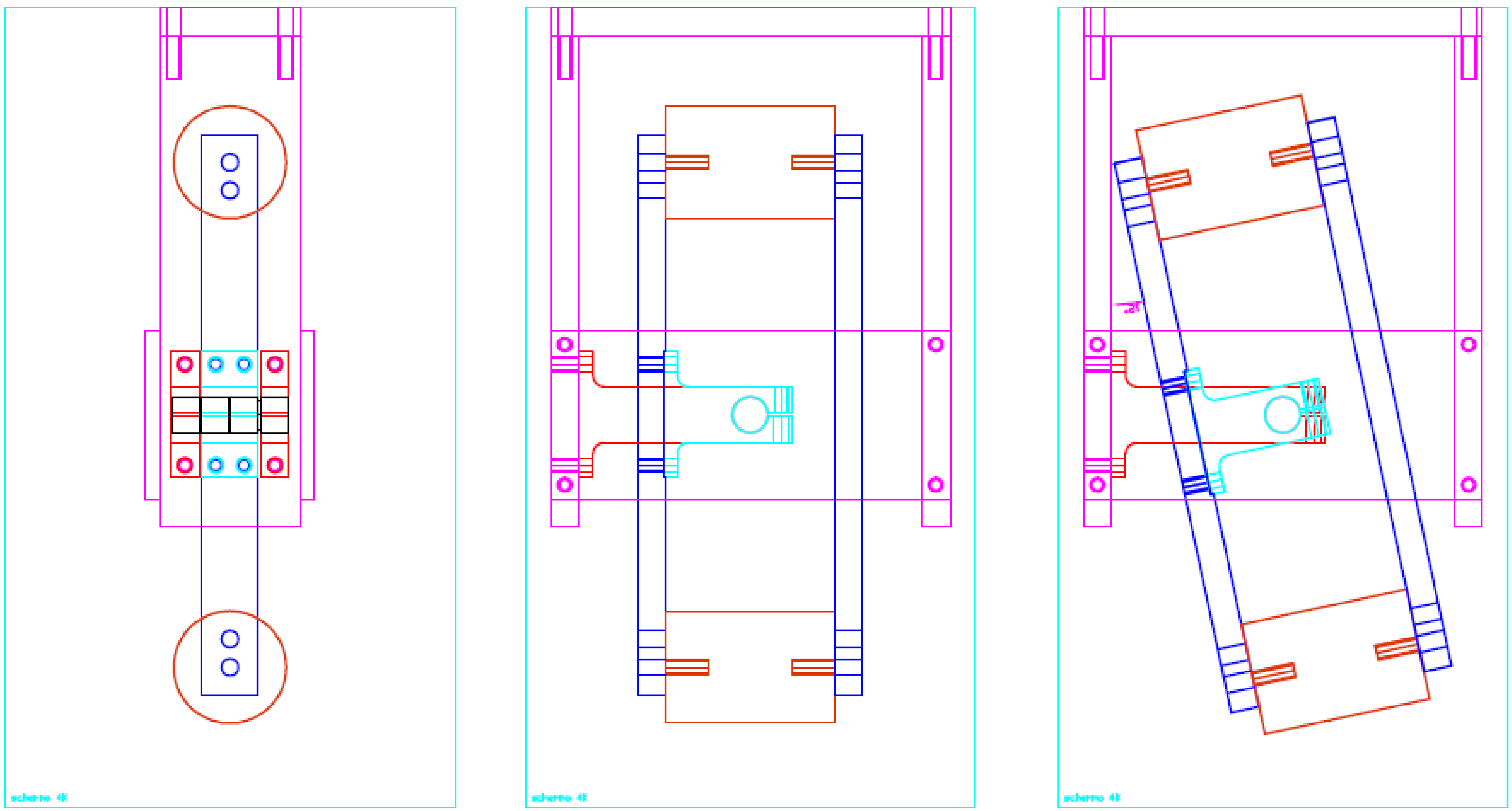
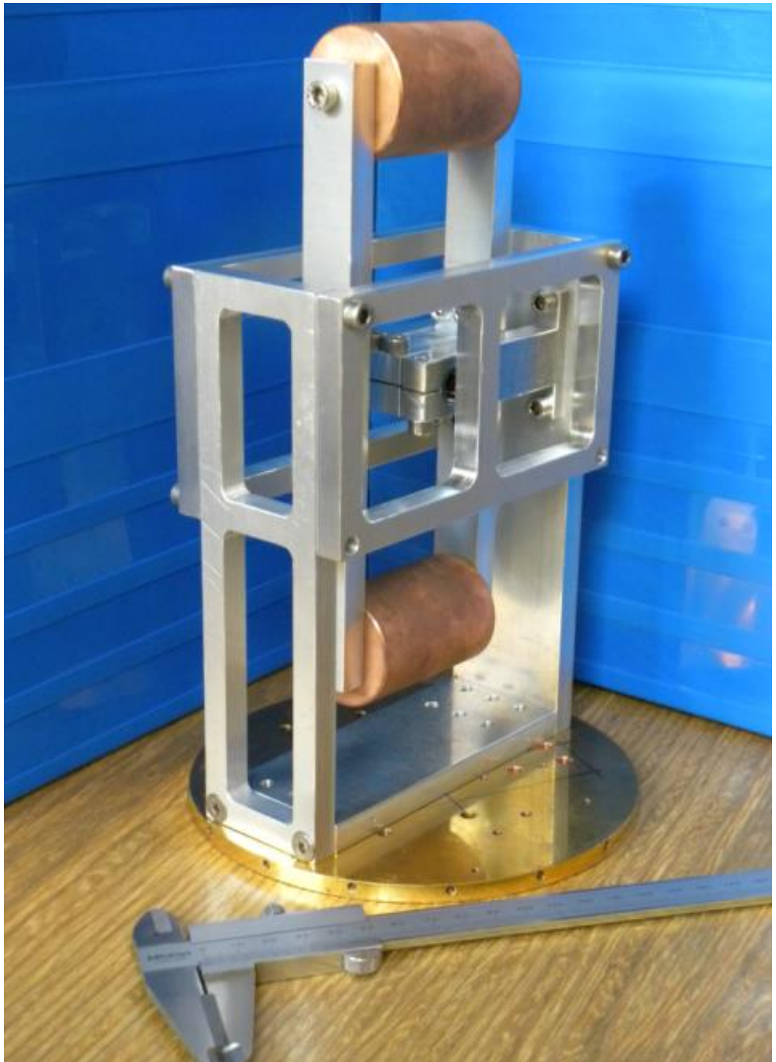


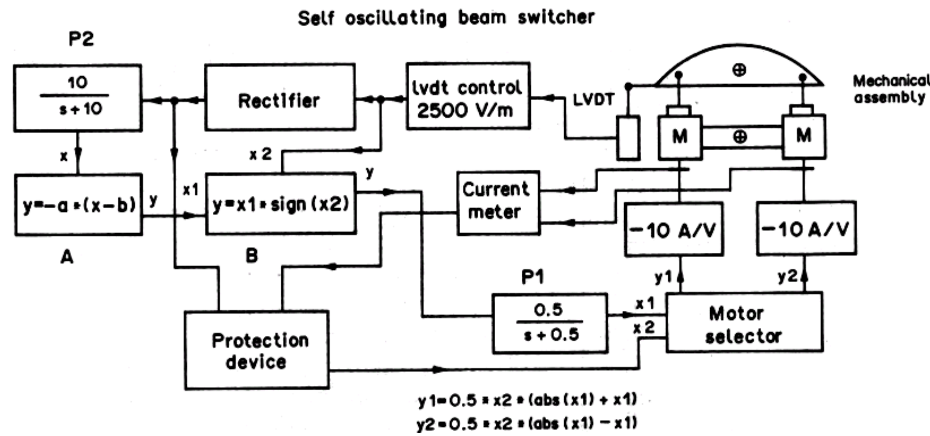
Figura 14: *disegno meccanico del dimostratore alloggiato all' interno dello stadio freddo del criostato (in colore ciano nel disegno, ha un diametro di 160 mm e una altezza di 285 mm). Il disegno è in scala. I due cilindri in rame sono rappresentativi, per massa e inerzia, degli specchi a tetto.*

WP3200: Cryogenic operation of a double pendulum

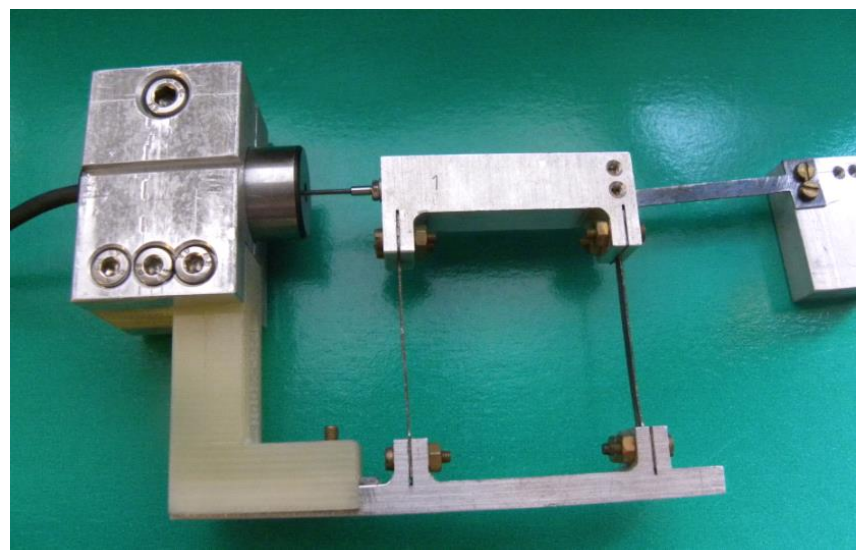
From the *Millimetron* study



Il dimostratore



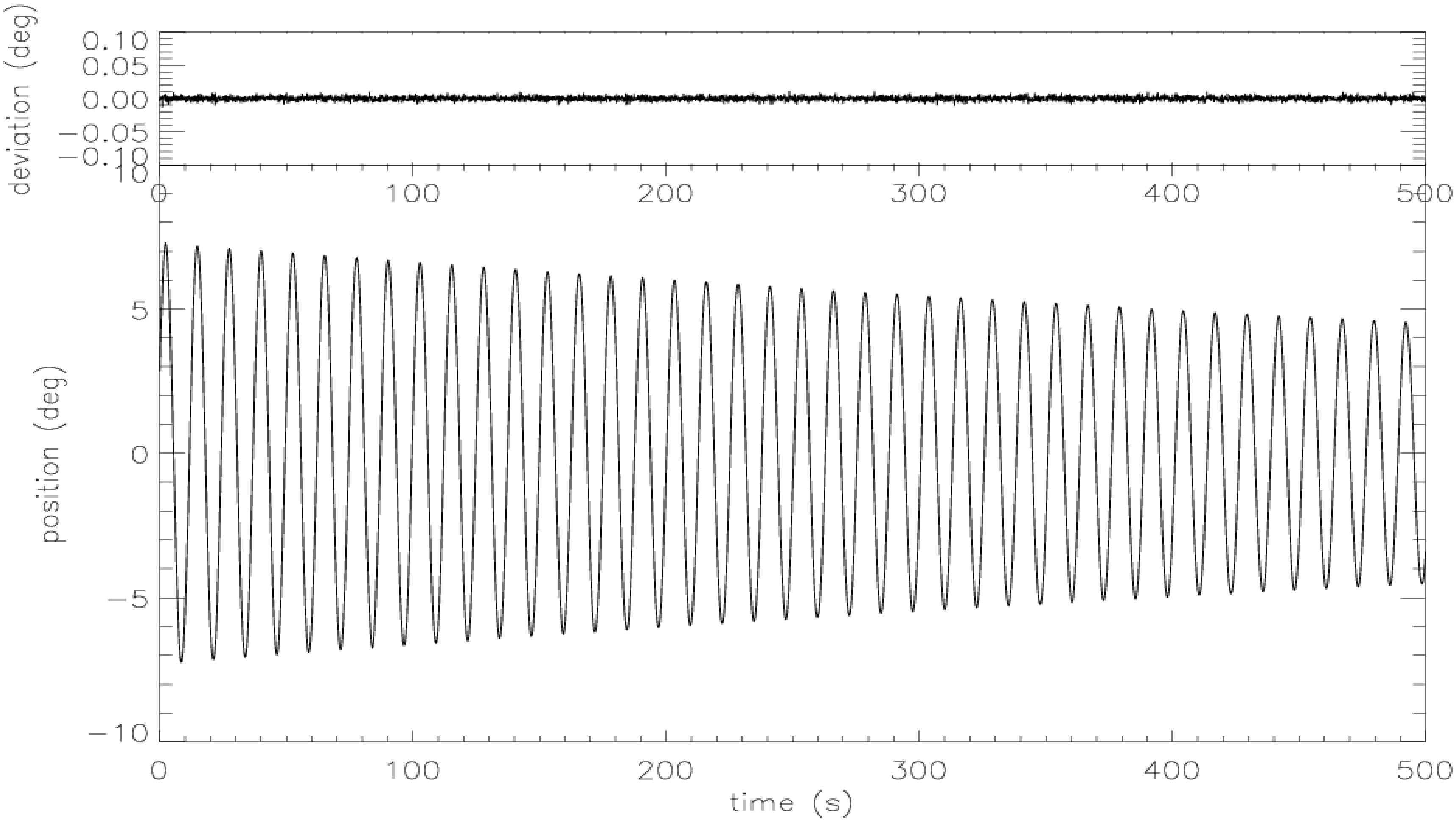
Schema a blocchi elettronica di controllo



LVDT con dispositivo elastico di linearizzazione del moto

WP3200: Cryogenic operation of a double pendulum

From the *Millimetron* study



Oscillazione libera del simulatore. Il tempo di decadimento ($t_{1/2}$ = 17.3 min) permette di stimare la potenza necessaria a mantenere l' oscillazione.
Che risulta **inferiore a 6 μW**.

WP3200: Cryogenic operation of a double pendulum

From the *Millimetron* study

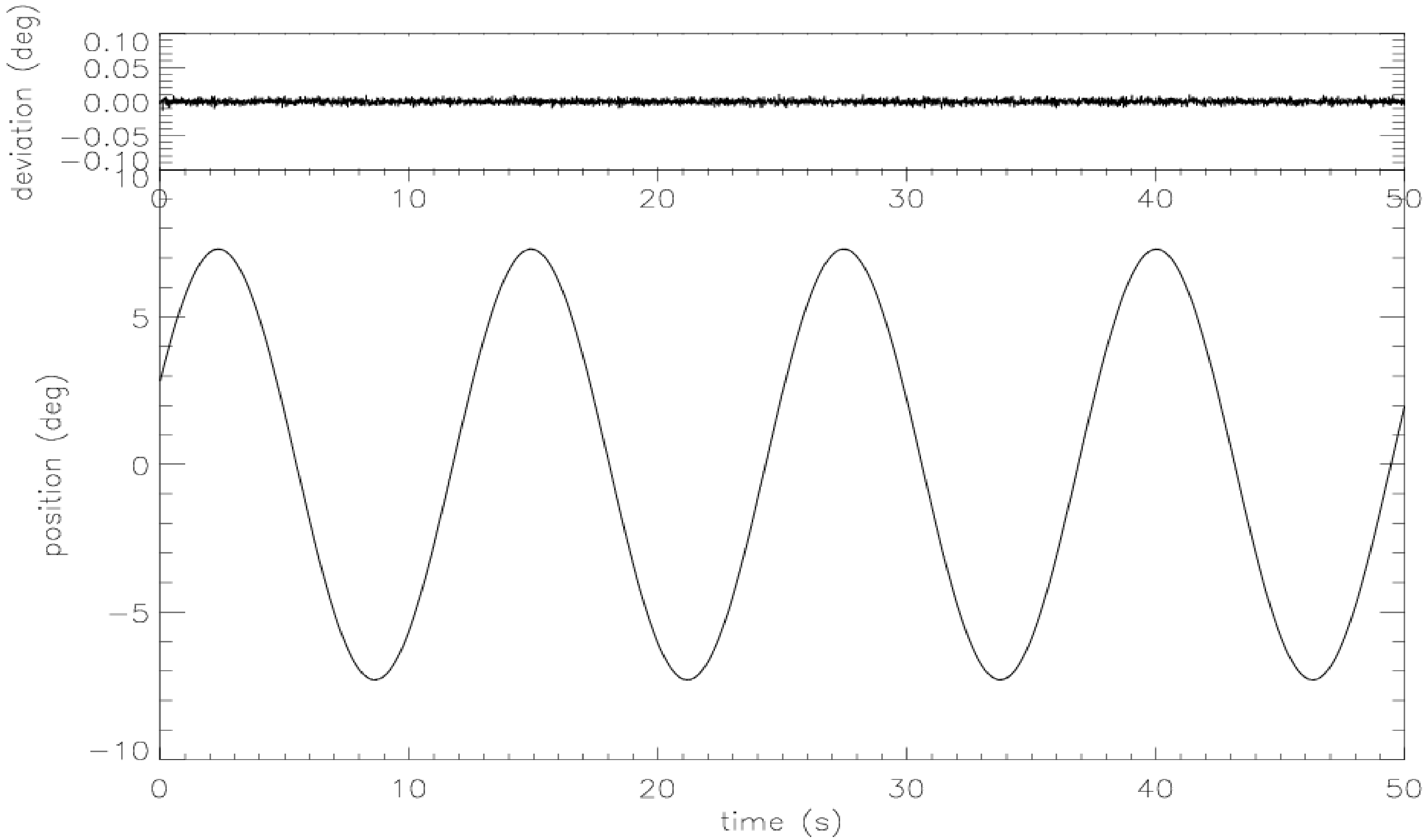
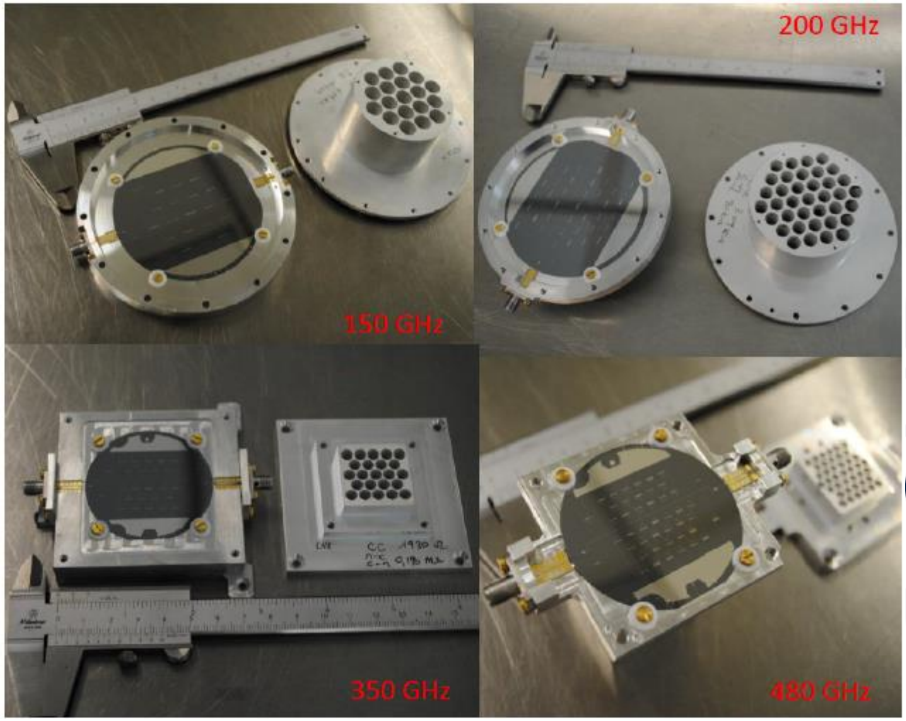
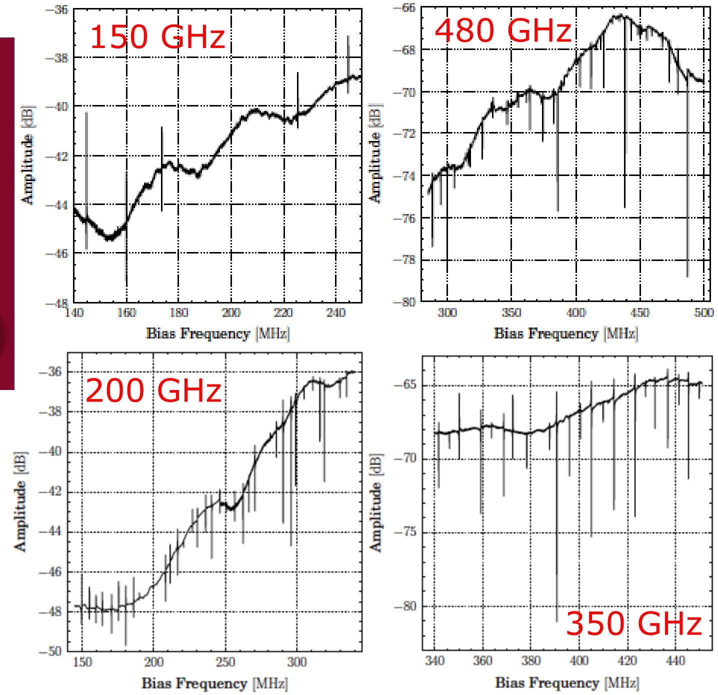
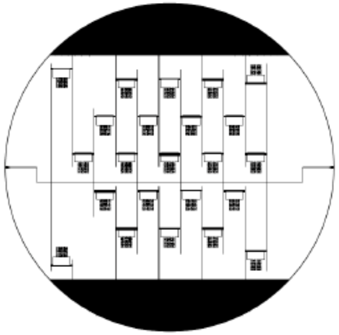


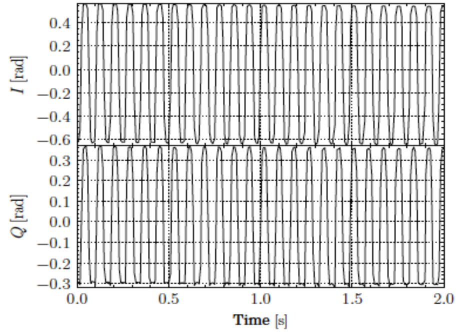
Figura 18: *tipica misura di oscillazione controllata del dimostratore, ottenuta dall' uscita demodulata dell' LVDT. Nel pannello in alto, differenza tra oscillazione misurata e oscillazione sinusoidale, consistente con il rumore di lettura.*

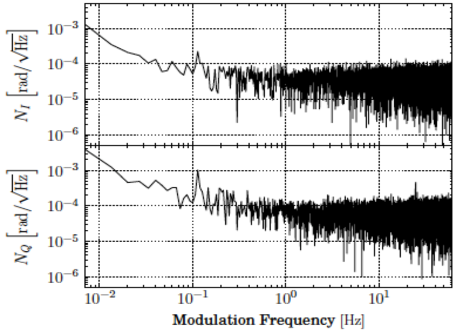
Kinetic Inductance Detectors









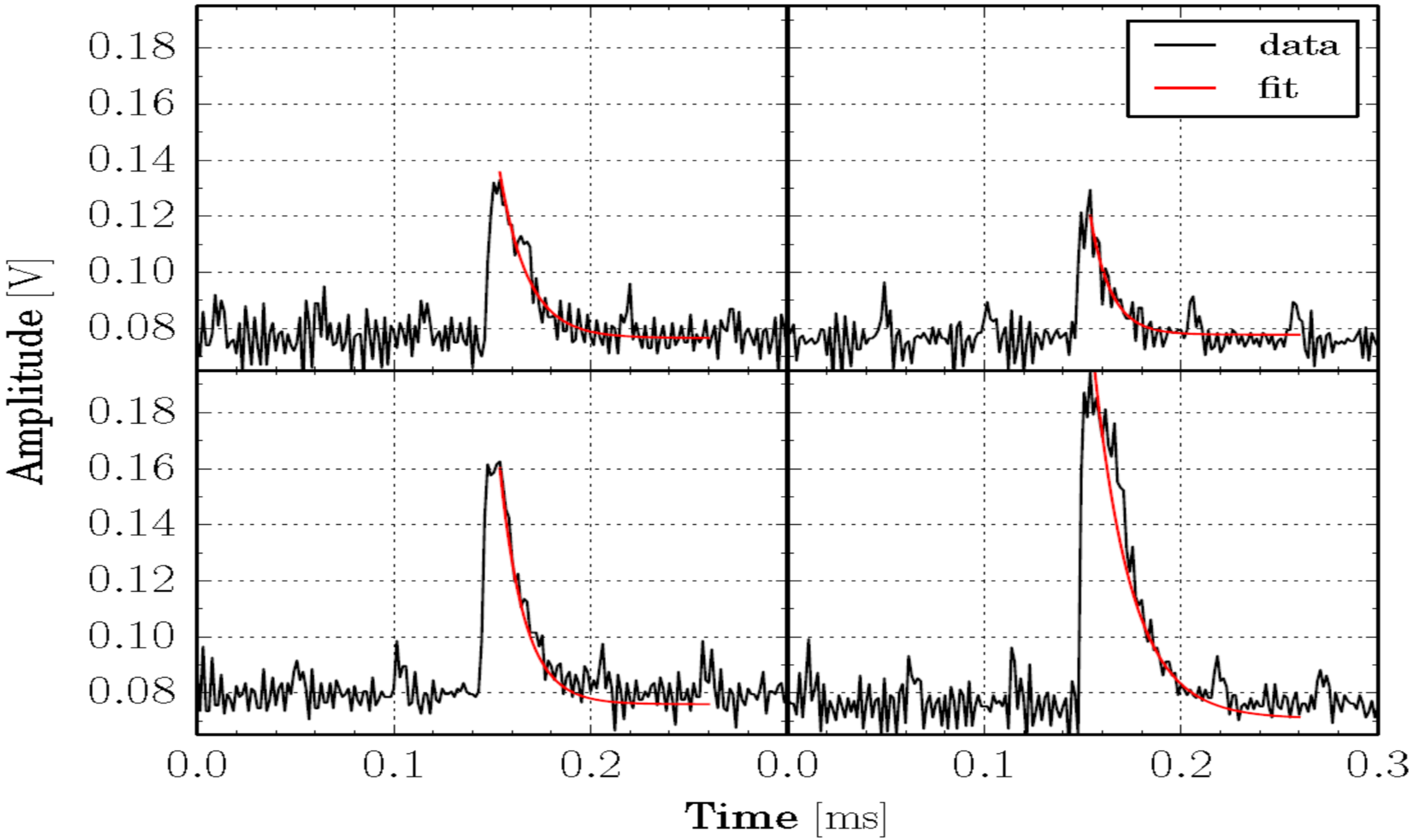


Channel	NET_{RJ} $[mK/\sqrt{Hz}]$
150 GHz	0.180
200 GHz	0.145
350 GHz	0.288
480 GHz	0.433

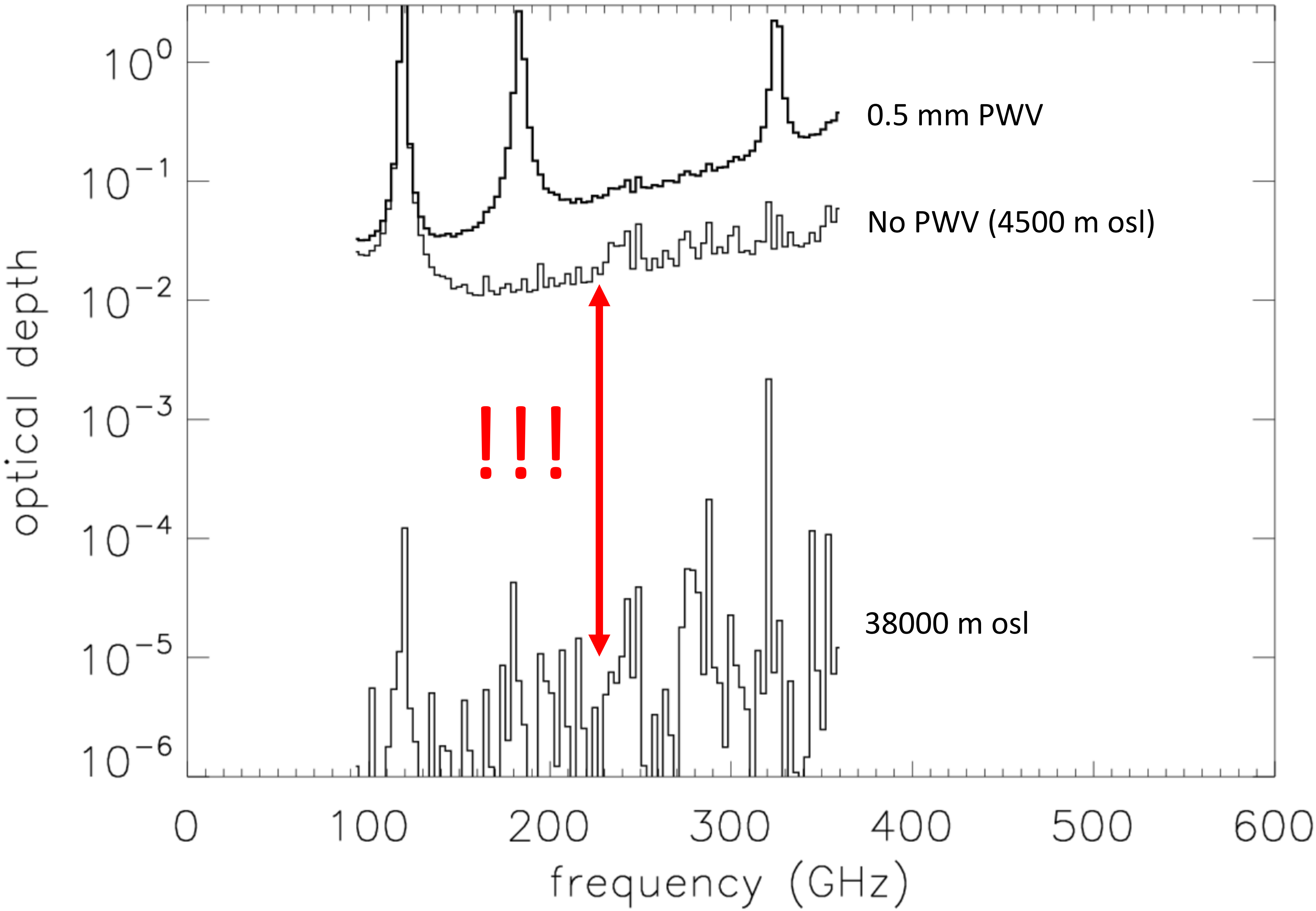
typical NET

From Silvia Masi - OLIMPO

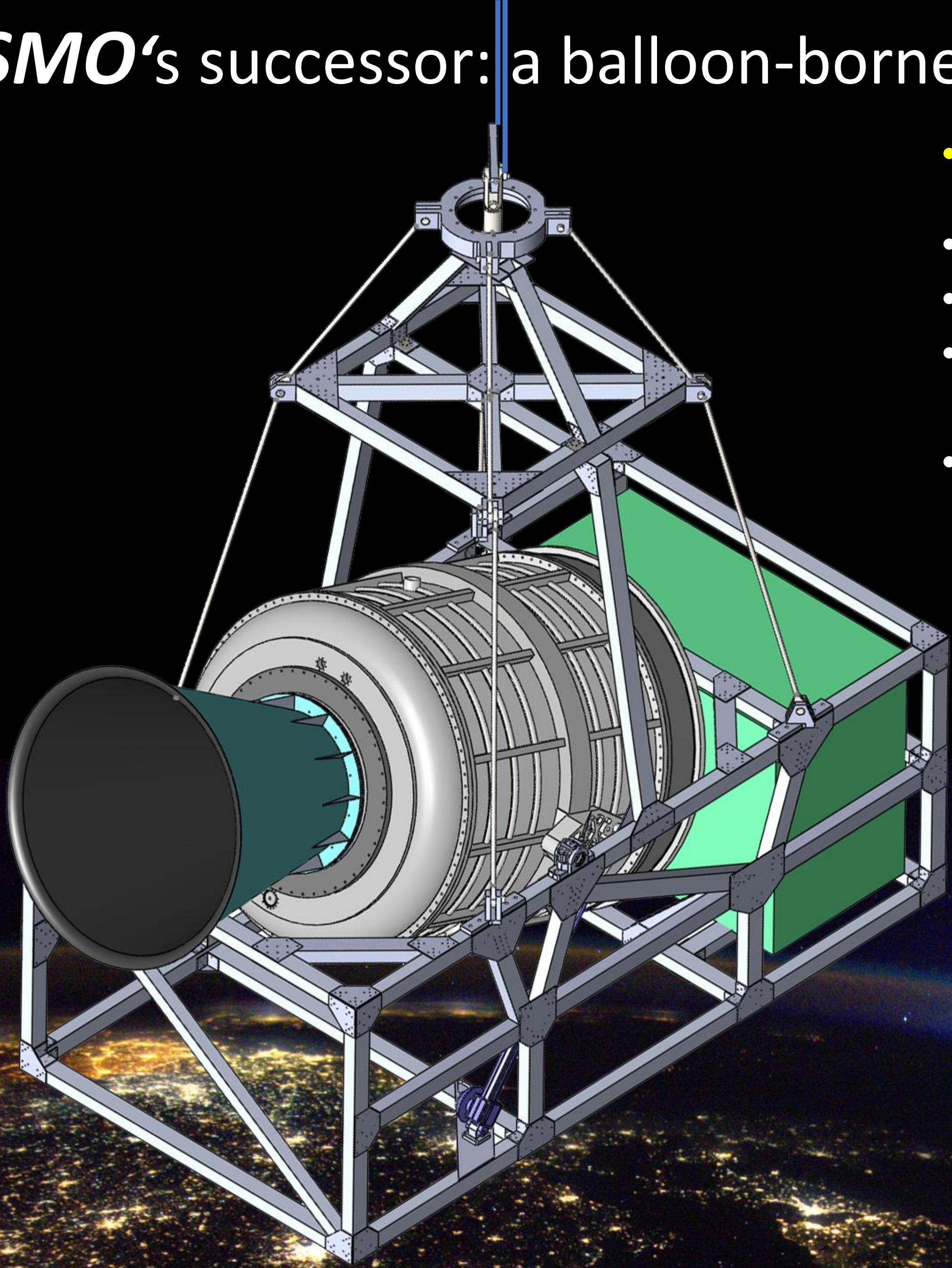
Cosmic rays events in OLIMPO KIDs



COSMO‘s successor: a balloon-borne (ULDB) instrument ?



COSMO's successor: a balloon-borne instrument ?



- **LSPE** LDB payload
  http://planck.roma1.infn.it/LSPE
- Works in the polar night
- Suitable cryogenic system
- Possible to add (slower ?) modulator, if needed
- Might gain a factor 10.

In summary

- A giant effort worldwide to uncover the last secrets of the CMB !
- Large programs targeting for B-mode polarization
- Increased interest in Spectral Distortions
- OLIMPO and COSMO are among a number of near-term medium-size exploratory experiments, in preparation of larger efforts.
- A lot of work to do ….