COSMO: spectral measurements from Dome C

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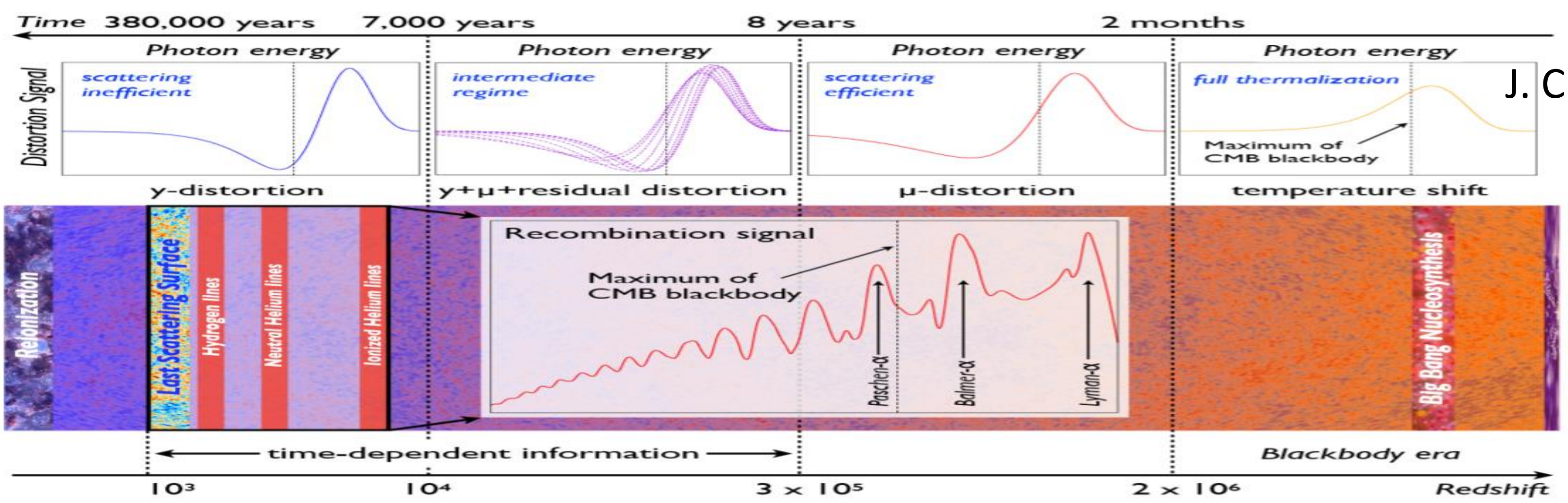
SAPIENZA UNIVERSITÀ DI ROMA CNR IFN Istituto di Fotonica e Nanotecnologie UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

Spectral Distortions of the CMB

- In the primeval fireball, CMB photons are frequently scattered by free electrons, and efficiently thermalized, thus acquiring their blackbody spectrum.
- After recombination, CMB photons do not interact with matter anymore, and the blackbody spectrum is maintained, with its temperature scaling as the inverse of the scale factor.
- The dependences of the number density and the wavelength on the scale factor conspire to maintain a Planck spectrum for CMB photons.
- All this is *very delicate*: if there is any deviation from any of the hypothesis above, the result will be a *spectral distortion*, a deviation from a pure Planck spectrum.

Spectral Distortions of the CMB

- There is a long list of possible physical phenomena disturbing the equilibrium scenario above, leading to small spectral distortions:
  - In the primeval fireball any *energy release/injection* ruins the thermal equilibrium between photons and matter. Possible processes: dissipation of adiabatic modes, primordial black-holes, mater/antimatter annihilation, particles/relics decay, recombination radiation, …
    - If the energy injection is at $z_{inj} > 2x10^6$, thermalization is still efficient, and the result is a shift of the BB temperature without distortions
    - For $5x10^4 < z_{inj} < 2x10^6$, Compton scattering is still efficient, and a μ-type distortion is generated
    - $10^4 < z_{inj} < 5x10^4$ is an intermediate regime with residual y/μ distortions (r-type distortions)
    - For $1100 < z_{inj} < 10^4$ Compton scattering is inefficient, and a y-type distortion is created



J. Chluba

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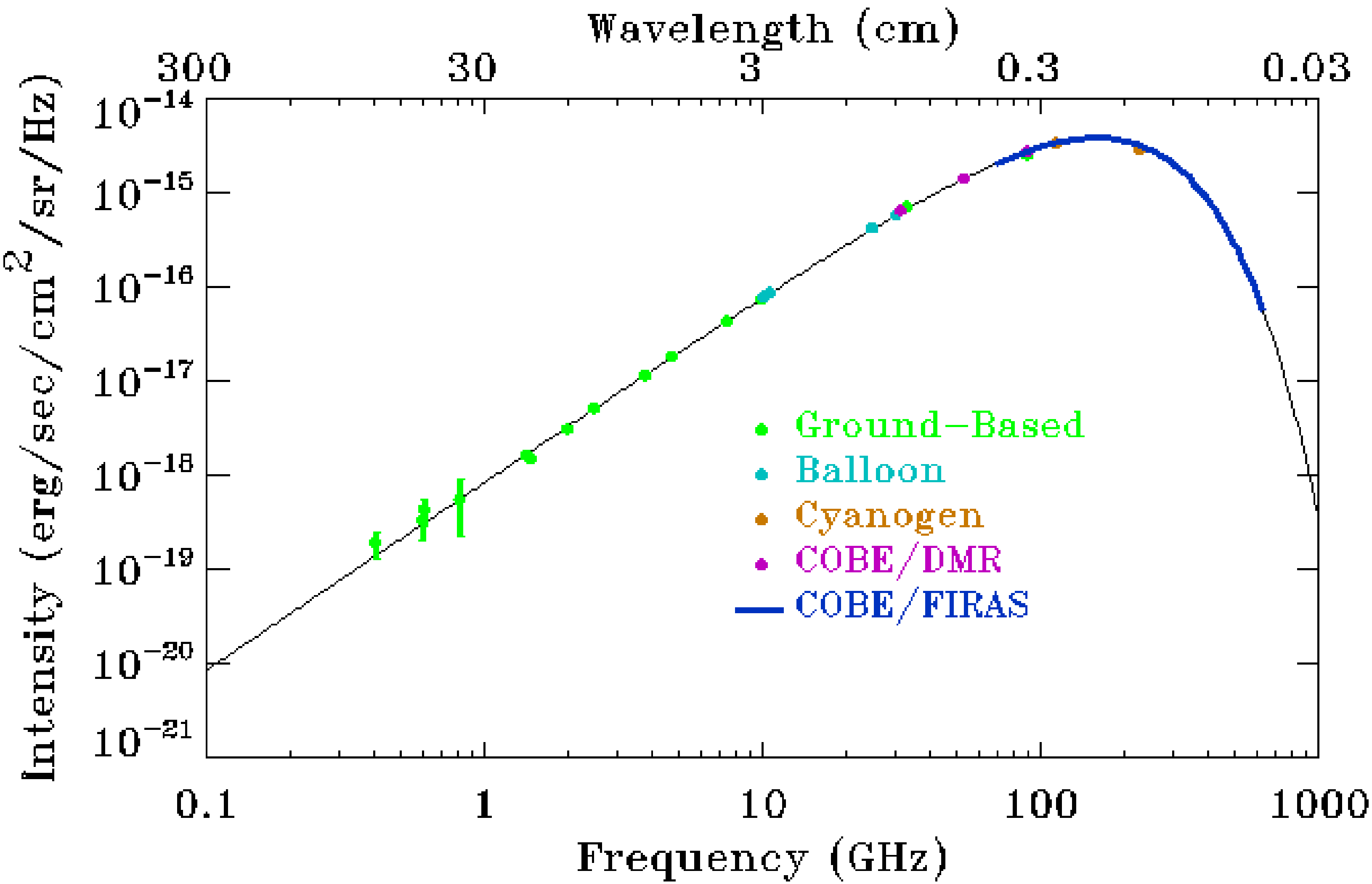
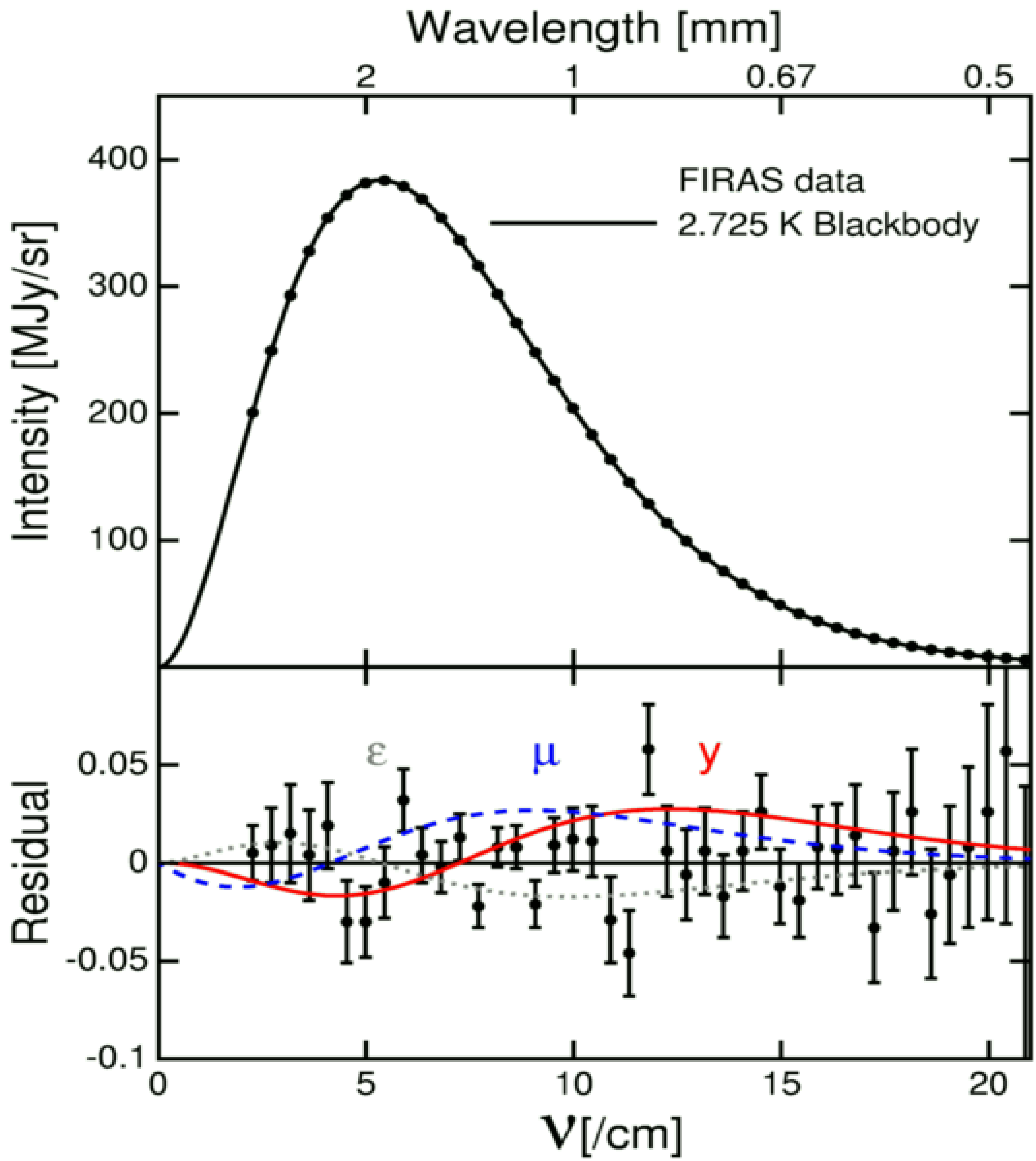
    - For $1100 < z_{inj} < 10^4$ Compton scattering is inefficient, and a y-type distortion is created
  - During recombination, *photon injection* happens due to recombination radiation, producing very low level features-rich spectral distortions
  - After recombination, *thermal Sunyaev Zeldovich effect* in clusters of galaxies and at reionization produce y-type distortions (the largest ones)
  - Interaction with hydrogen atoms (*21 cm line*) also can produce spectral distortions at low frequency
  - ….. Very rich literature ….



Wavelength (cm)
300
30
3
0.3
0.03
Intensity (erg/sec/cm^2/sr/Hz)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
Ground-Based
Balloon
Cyanogen
COBE/DMR
COBE/FIRAS
0.1
1
10
100
1000
Frequency (GHz)



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).

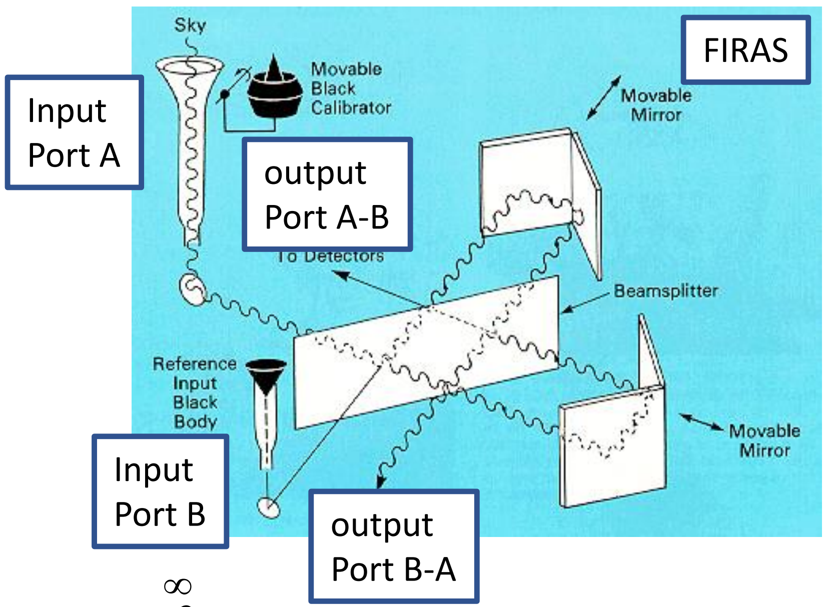
Current upper limits are at a level of 0.01% of the peak brightness of the CMB (COBE – FIRAS), Mather et al. (1990) Ap.J.L. **354** 37, Fixsen et al. (1996) Ap.J. **473** 576

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.
- 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 one at an internal reference blackbody

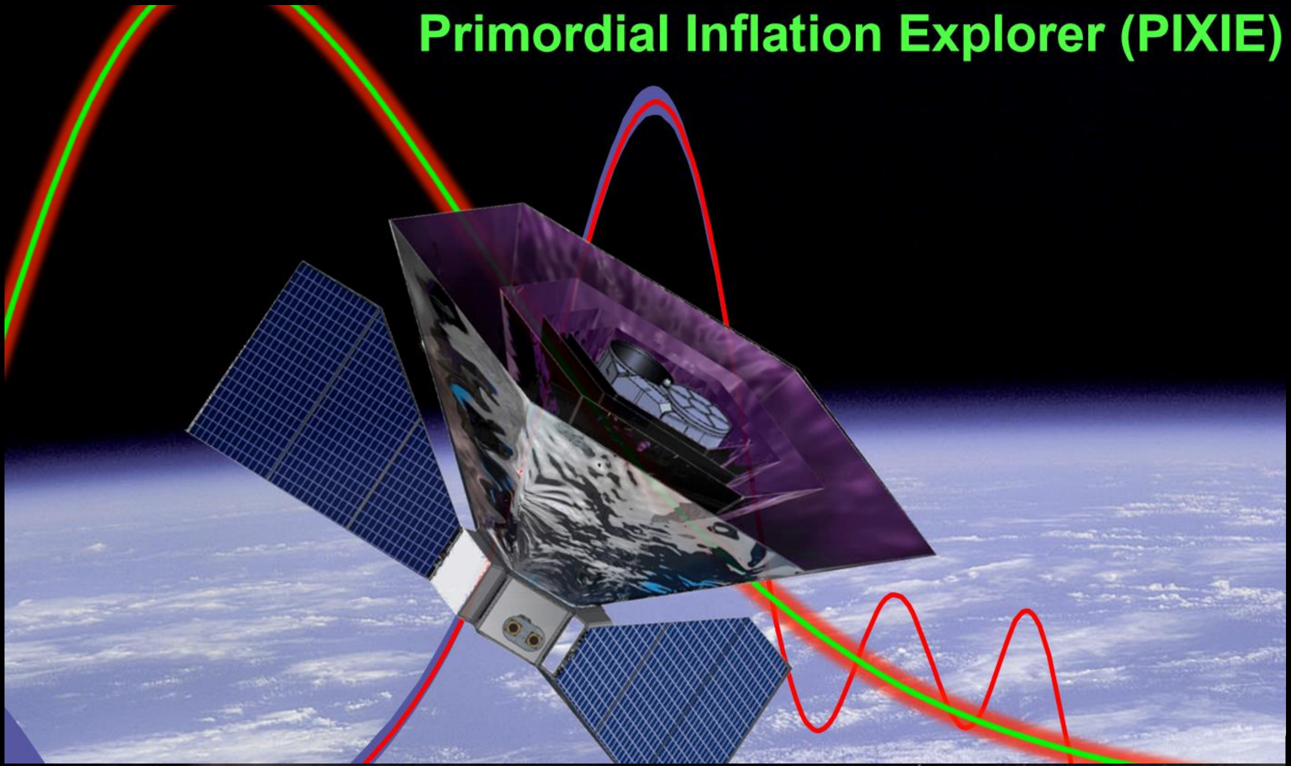


Sky measurement

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

Calibration measurement

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



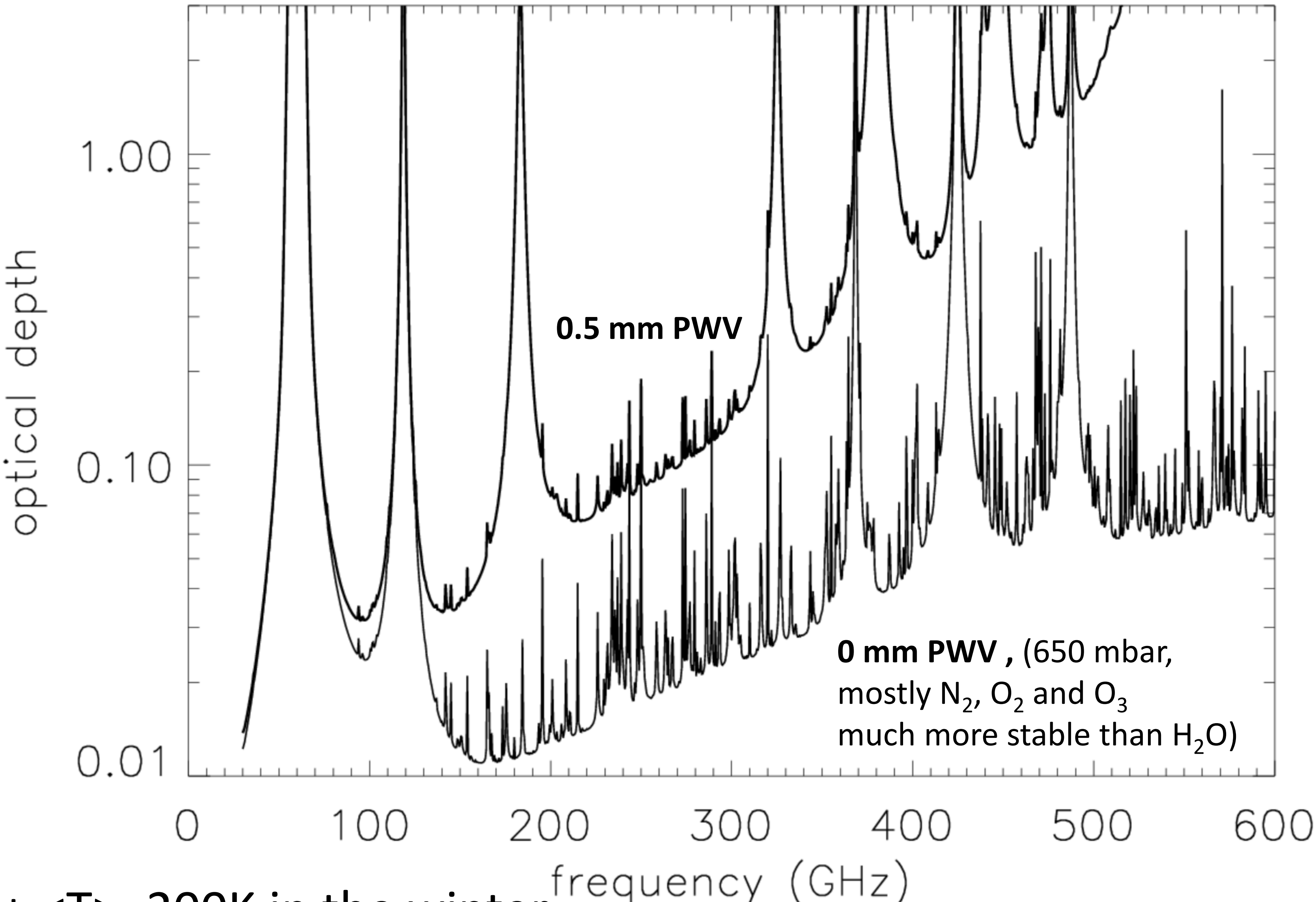
Satellite measurements can sample the CMB spectrum over the entire range 0-600 GHz.
PIXIE !!!
(*https://asd.gsfc.nasa.gov/pixie/*).

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).

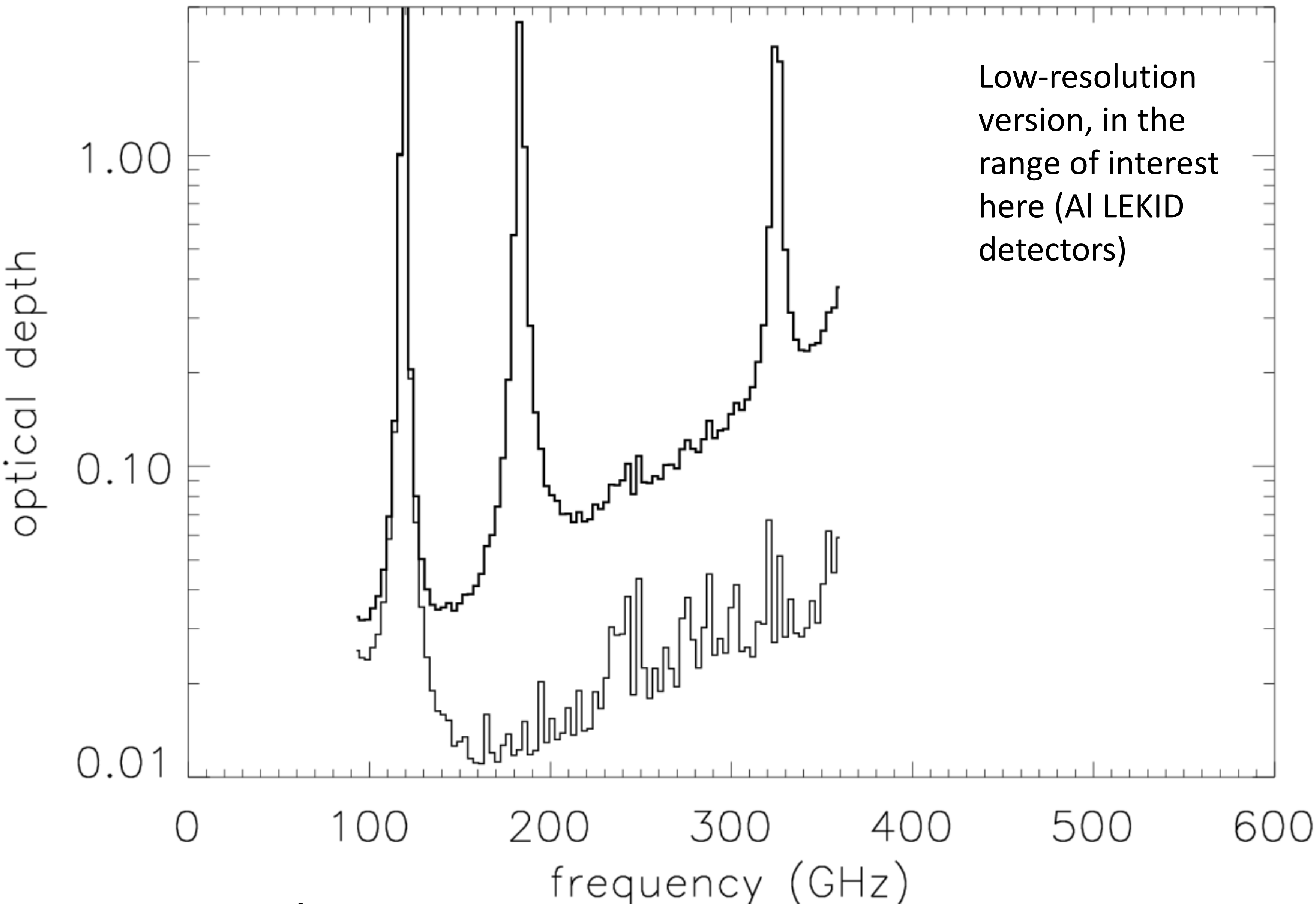
COSMO (COSmological Monopole Observer) targets this observable from Dome-C

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



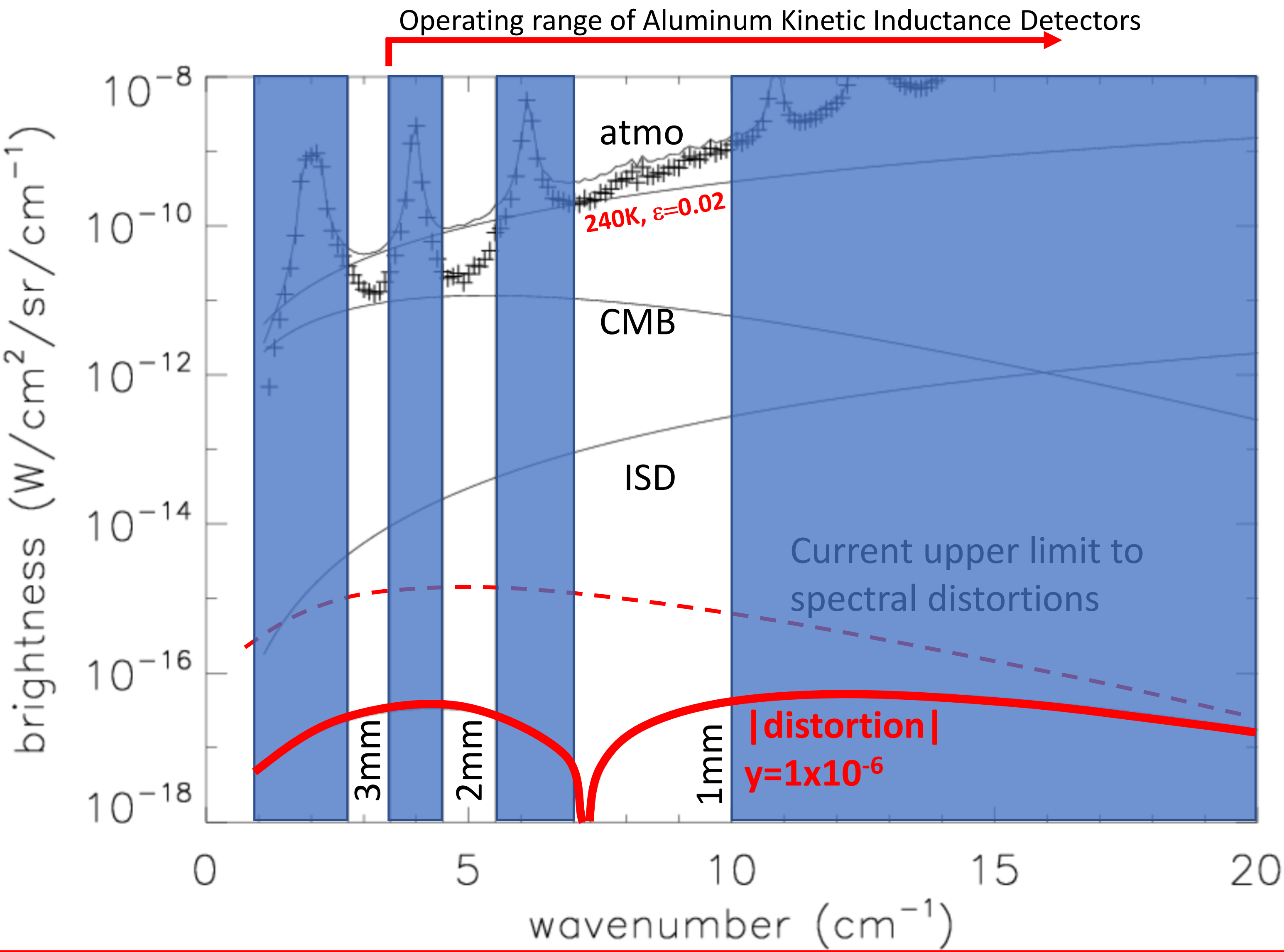
+ <T>=200K in the winter

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



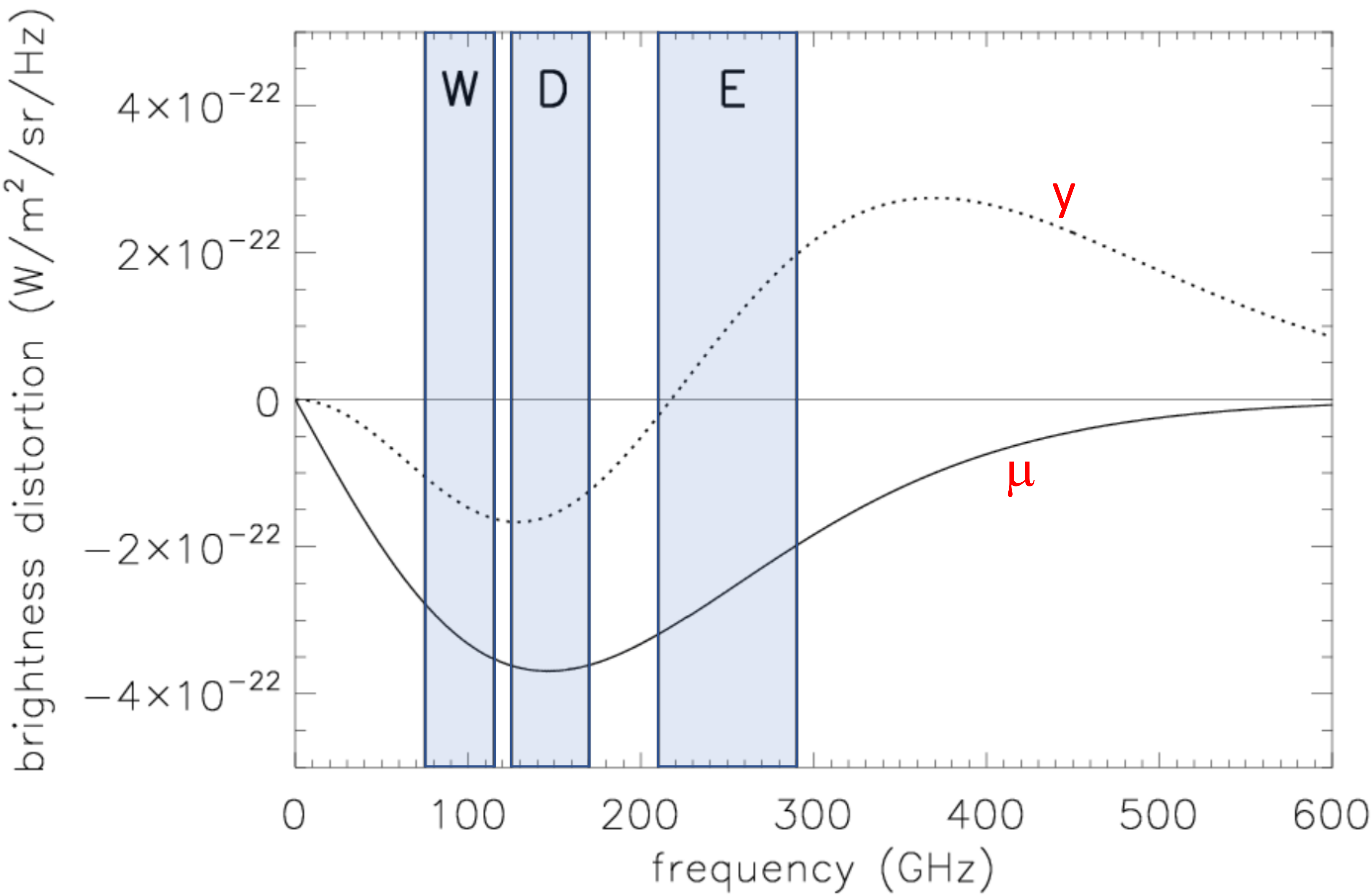
Low-resolution version, in the range of interest here (Al LEKID detectors)

+ <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:

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



W
D
E
y
μ
4×10^-22
2×10^-22
0
−2×10^-22
−4×10^-22
0
100
200
300
400
500
600
frequency (GHz)
brightness distortion (W/m^2/sr/Hz)

a NAIVE SIMULATION of the measurement performance is encouraging :

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

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

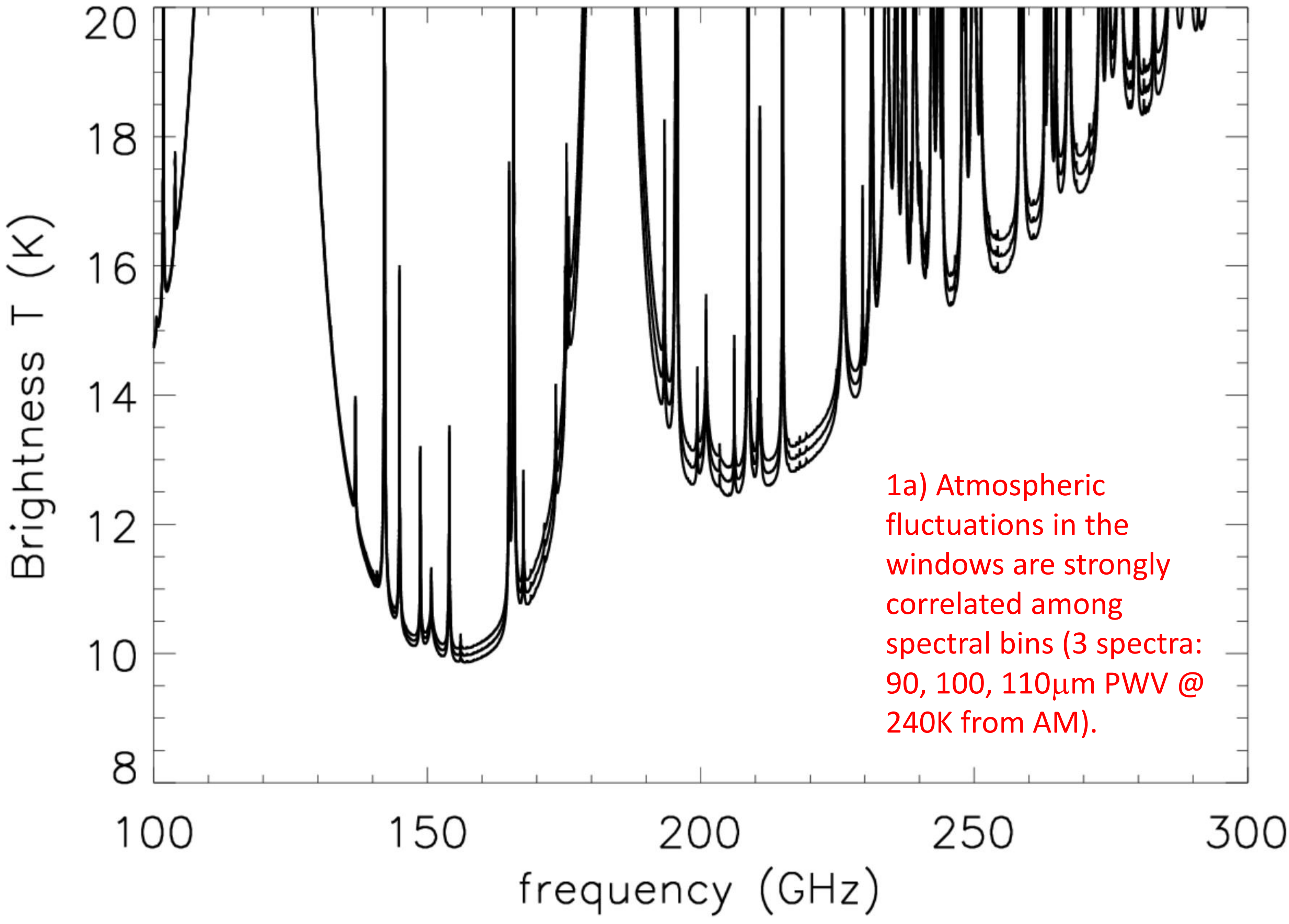
D= dust/model = 1.0000142 +/- 8.5398778e-006

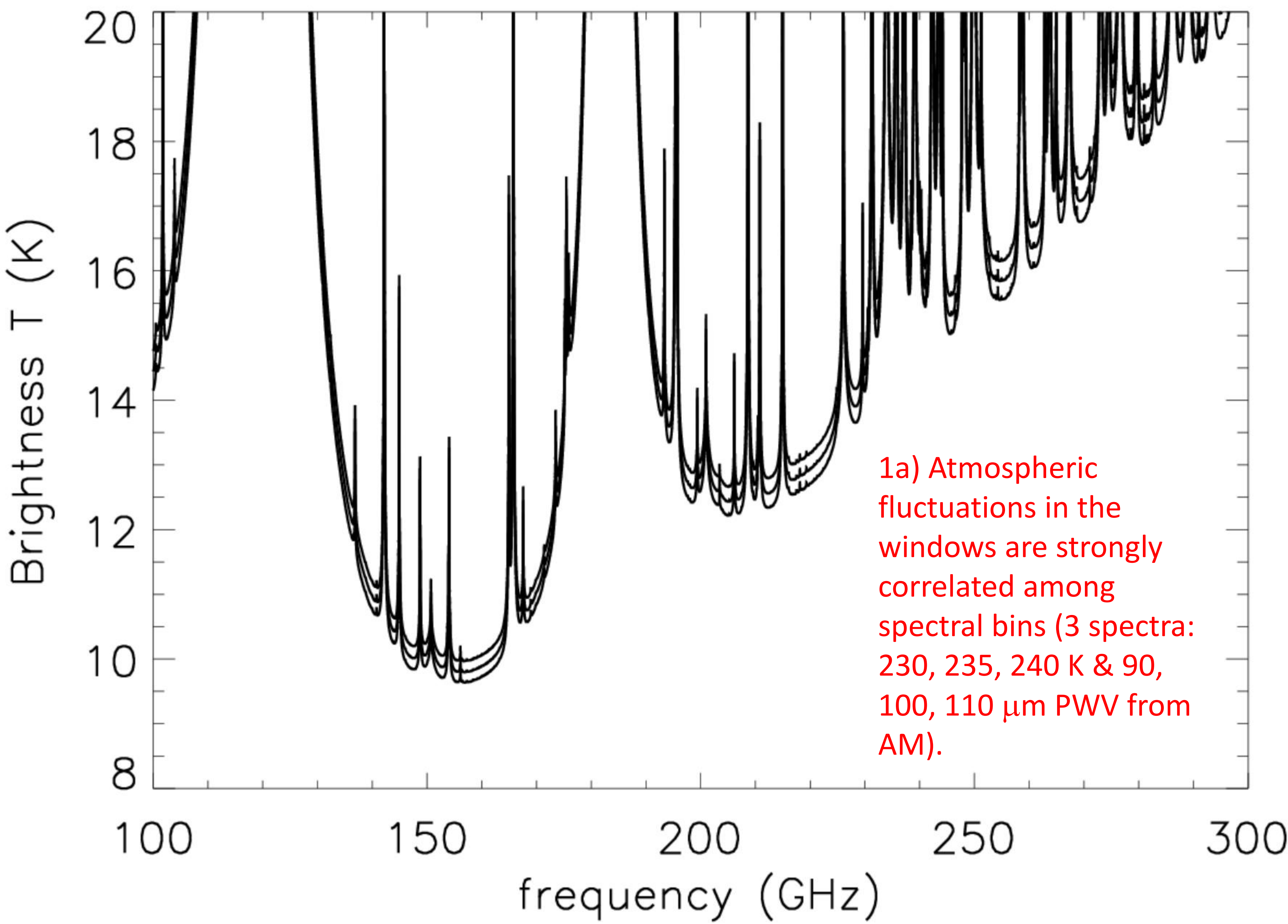
E= DSZ/model = **1.21** +/- **0.11**

offset = -2.8e-017 +/- 1.4e-017

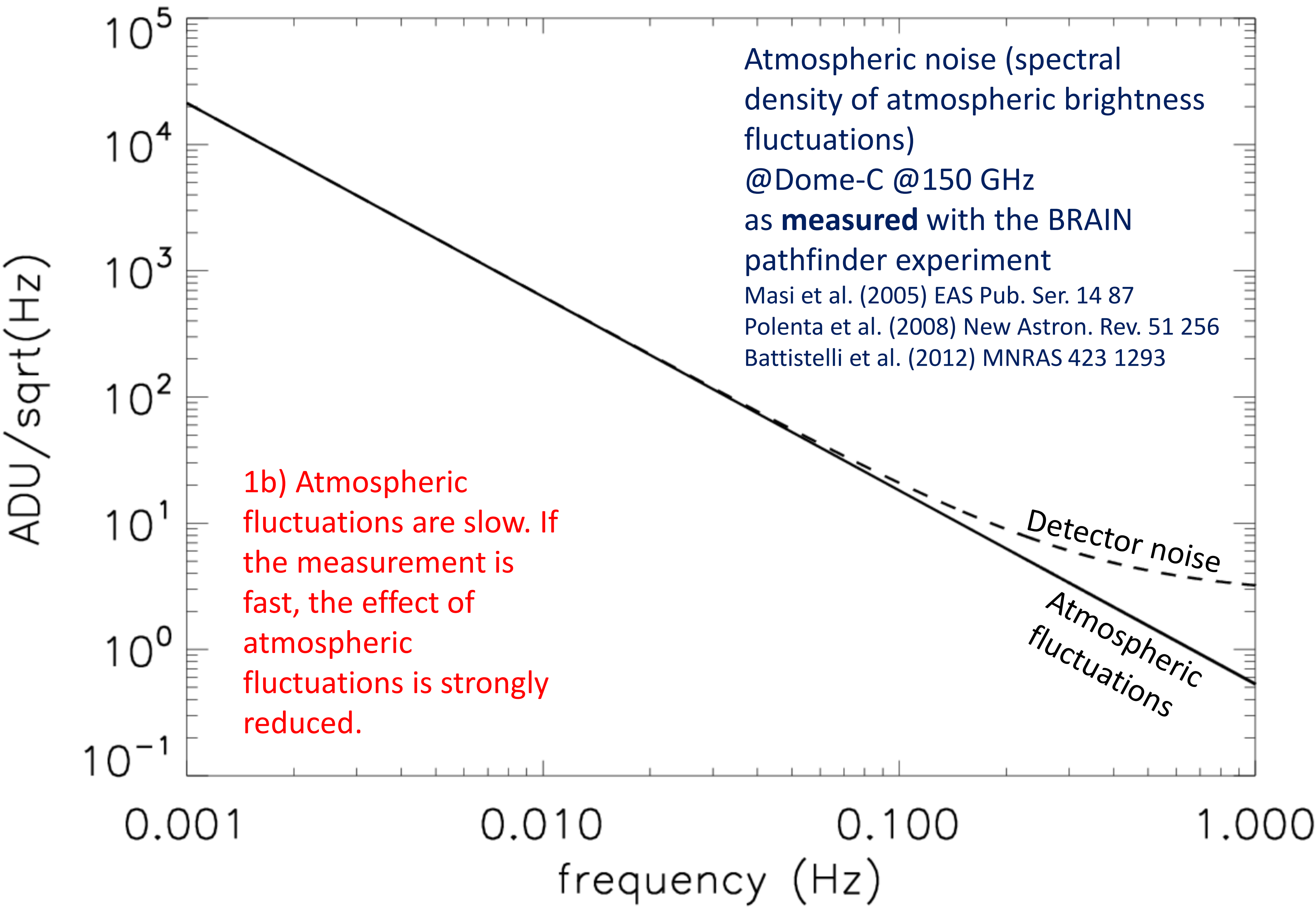
The amplitude of the y distortion is retreived to 10% accuracy. However:

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).



Brightness T (K)
20
18
16
14
12
10
8
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)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
0.001
0.010
0.100
1.000

COSMO : coping with the atmosphere

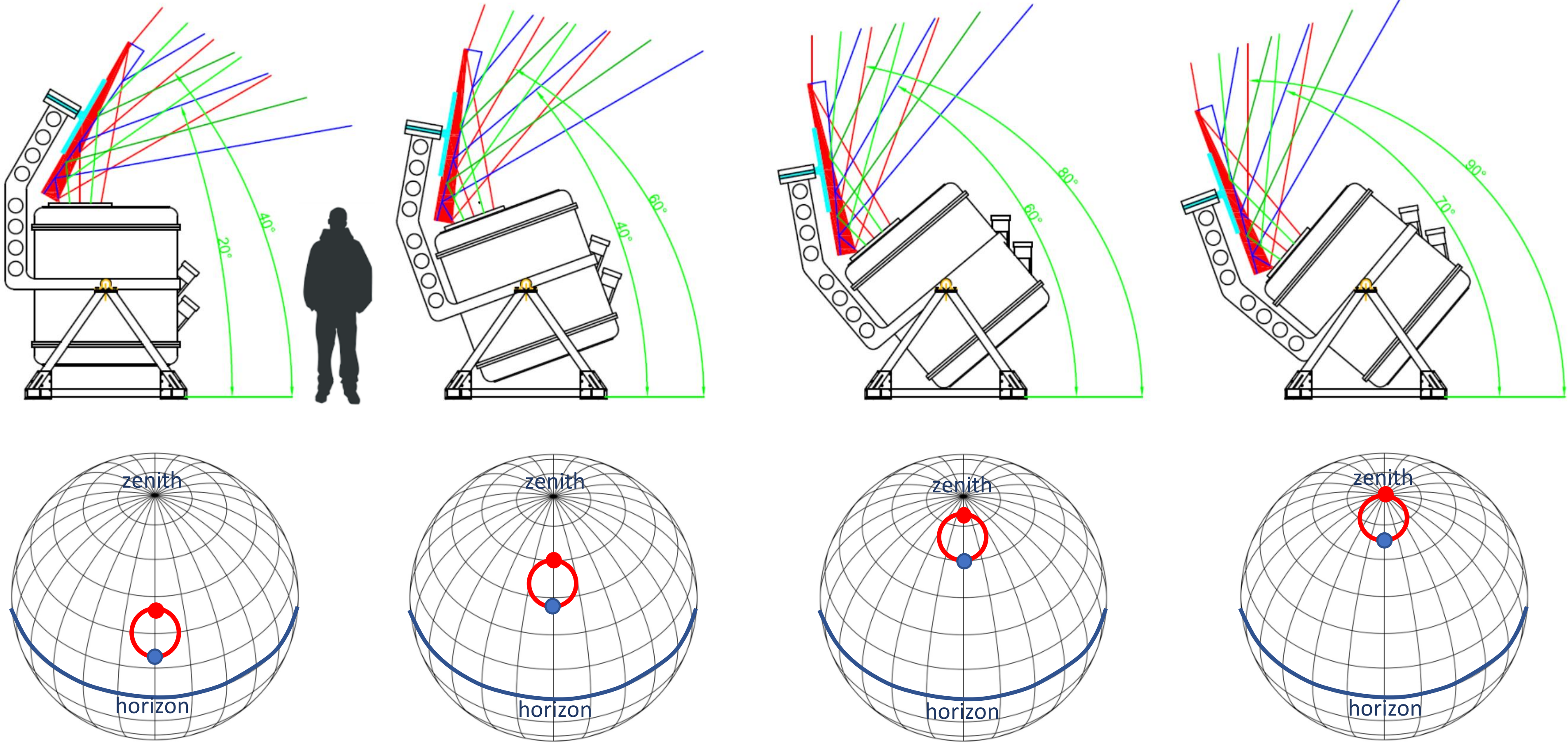
- We have to measure and subtract atmospheric emission, and we have to do it very quick.
- Recipe to mitigate the problem:

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°	Cryostat tilt = 20°	Cryostat tilt = 40°	Cryostat tilt = 50°
PT tilt = 40°	PT tilt = 20°	PT tilt = 0°	PT tilt = -10°
Min. elev. = 20°	Min. elev. = 40°	Min. elev. = 60°	Min. elev. = 70°
Max. elev. = 40°	Max. elev. = 60°	Max. elev. = 80°	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

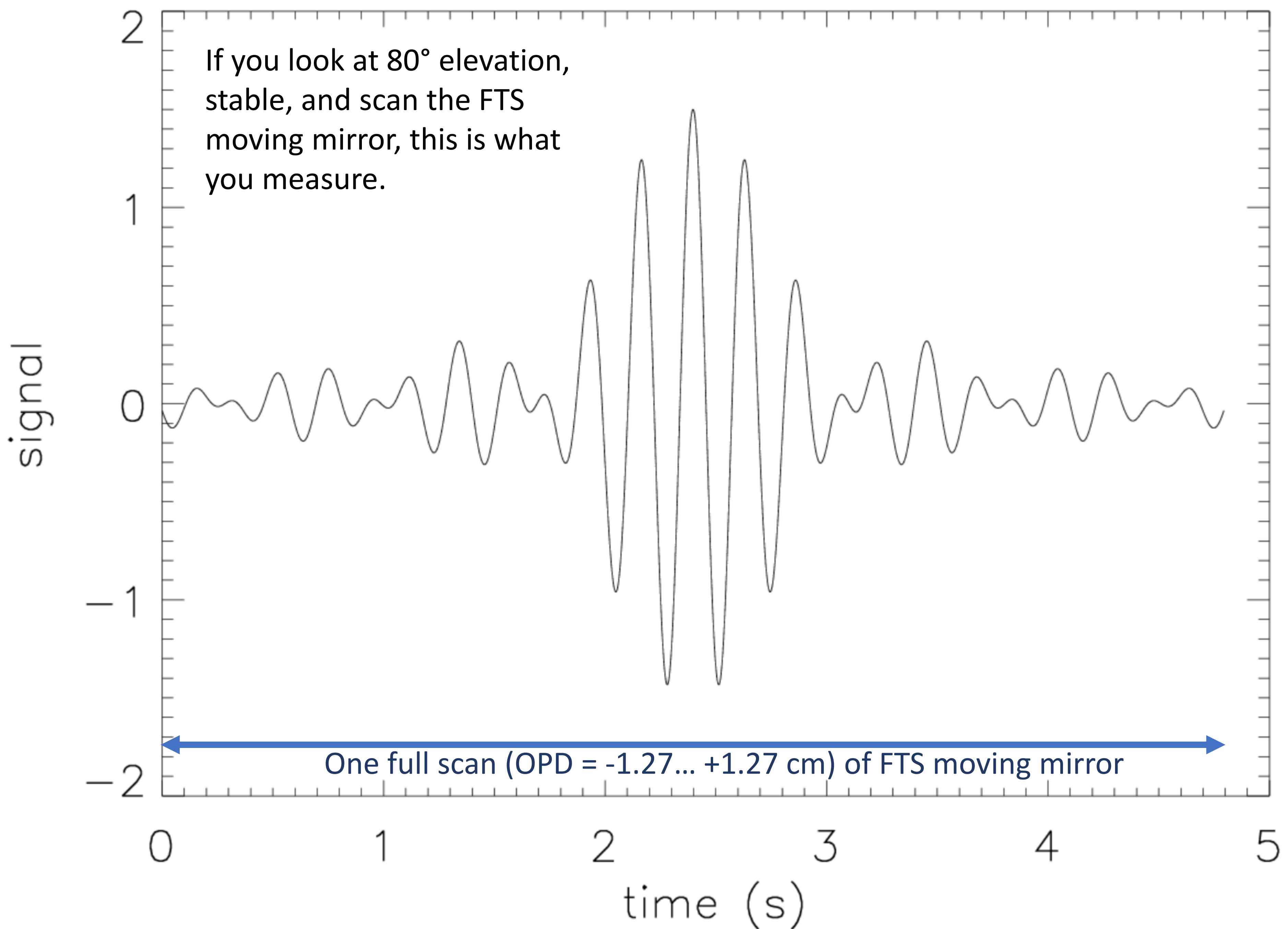
detector performance		
detector time constant	**5.00E-05**	**s**
5 time constants	2.50E-04	s
NET	100	uK/sqrt(Hz)
noise per sample	6.3	mK

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

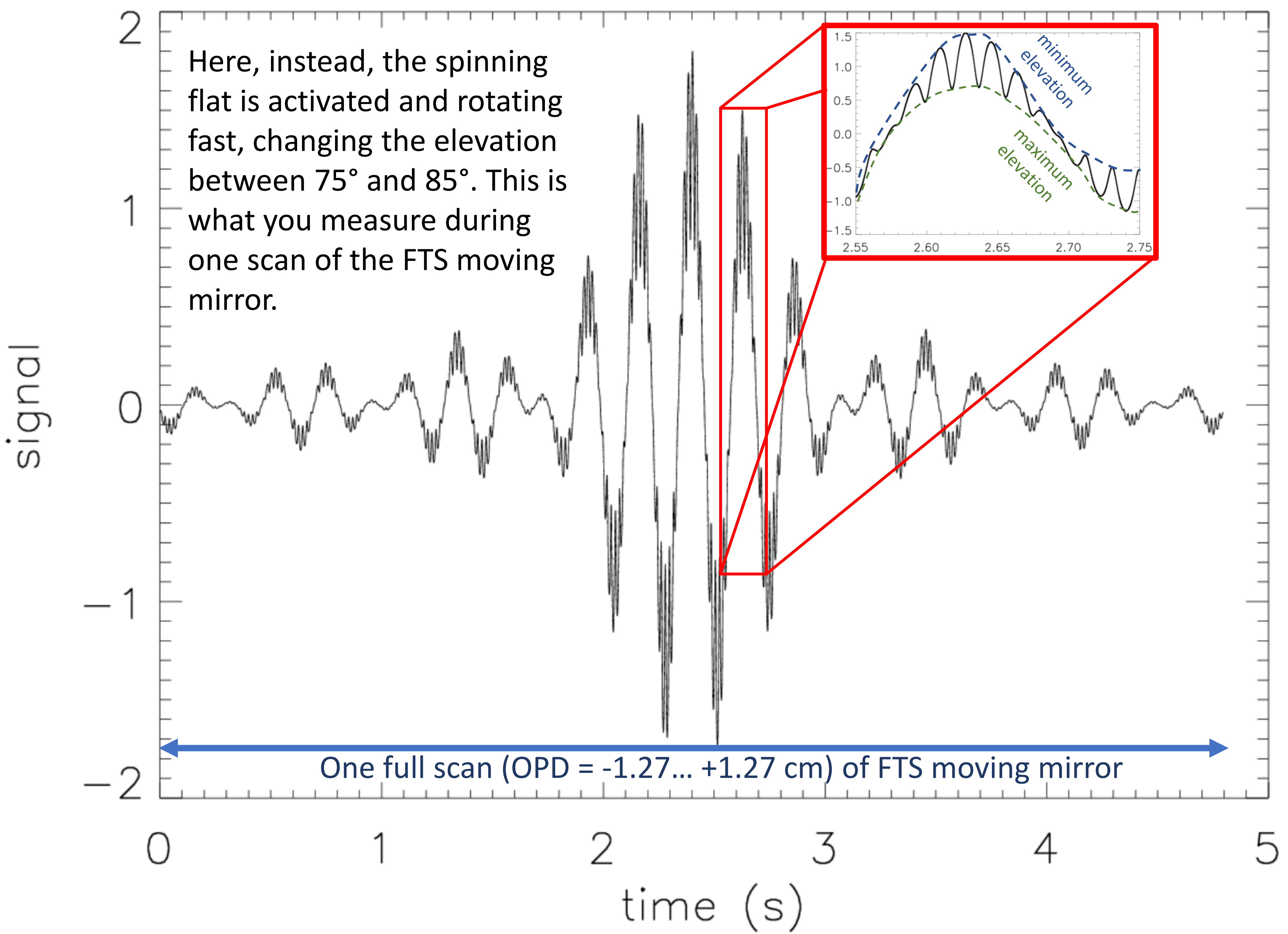
sky scan fast		
circle radius	5	deg
circle length	31.4	deg
beam size	1	deg
number of samples per circle (3 per beam)	94	
time per beam	2.50E-04	s
time for 2 sky dips (downwards + upwards)	2.36E-02	s
wedge mirror rotation rate	2546	rpm
interferogram scan slow		
maximum wavenumber (Nyquist)	20	cm-1
sampling 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 cryogenic mirror scanning mechanism
- High dissipation in the cryo system

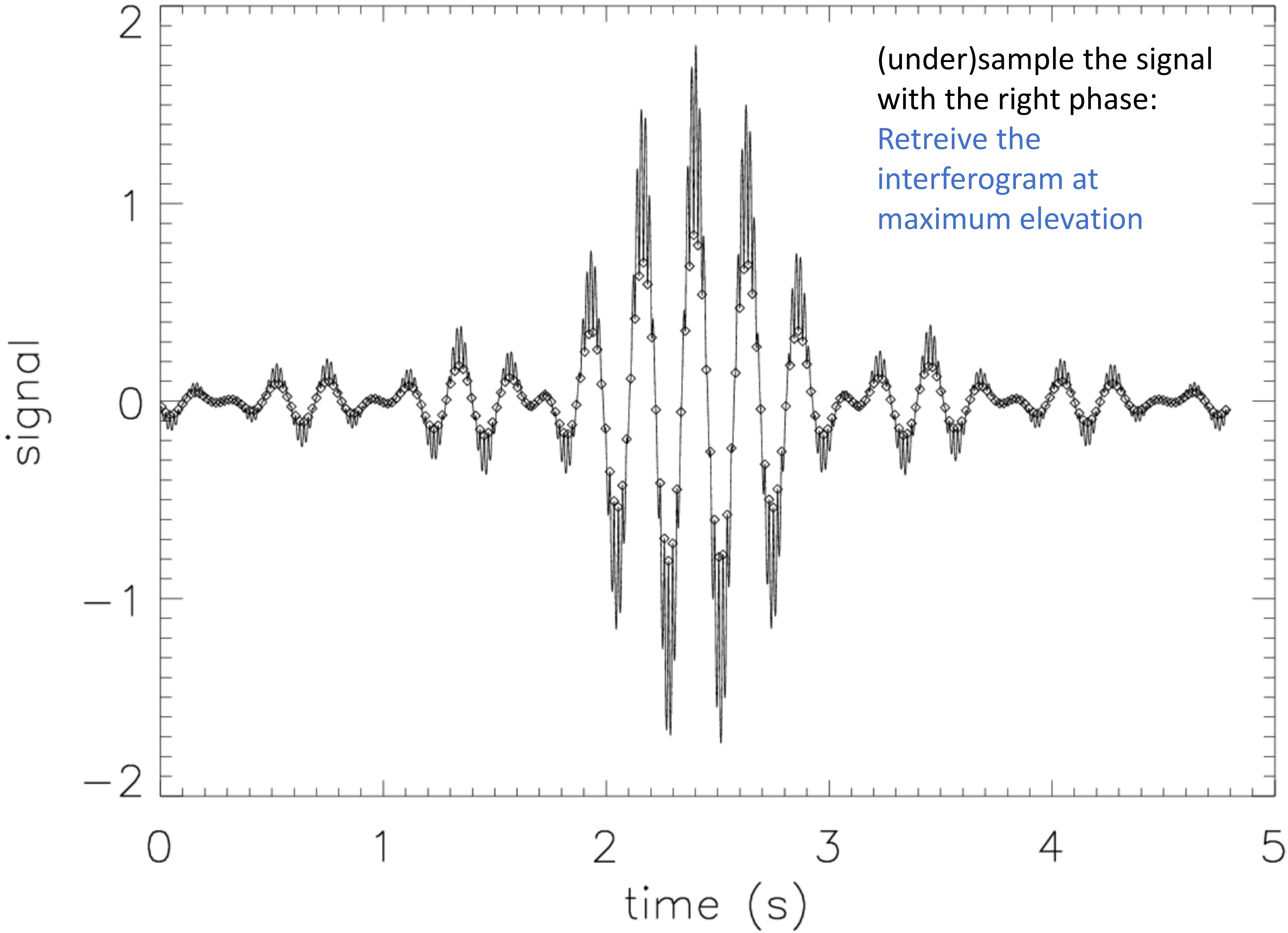
- This configuration requires a fast room-temperature mirror rotation device
- **Not impossible.**



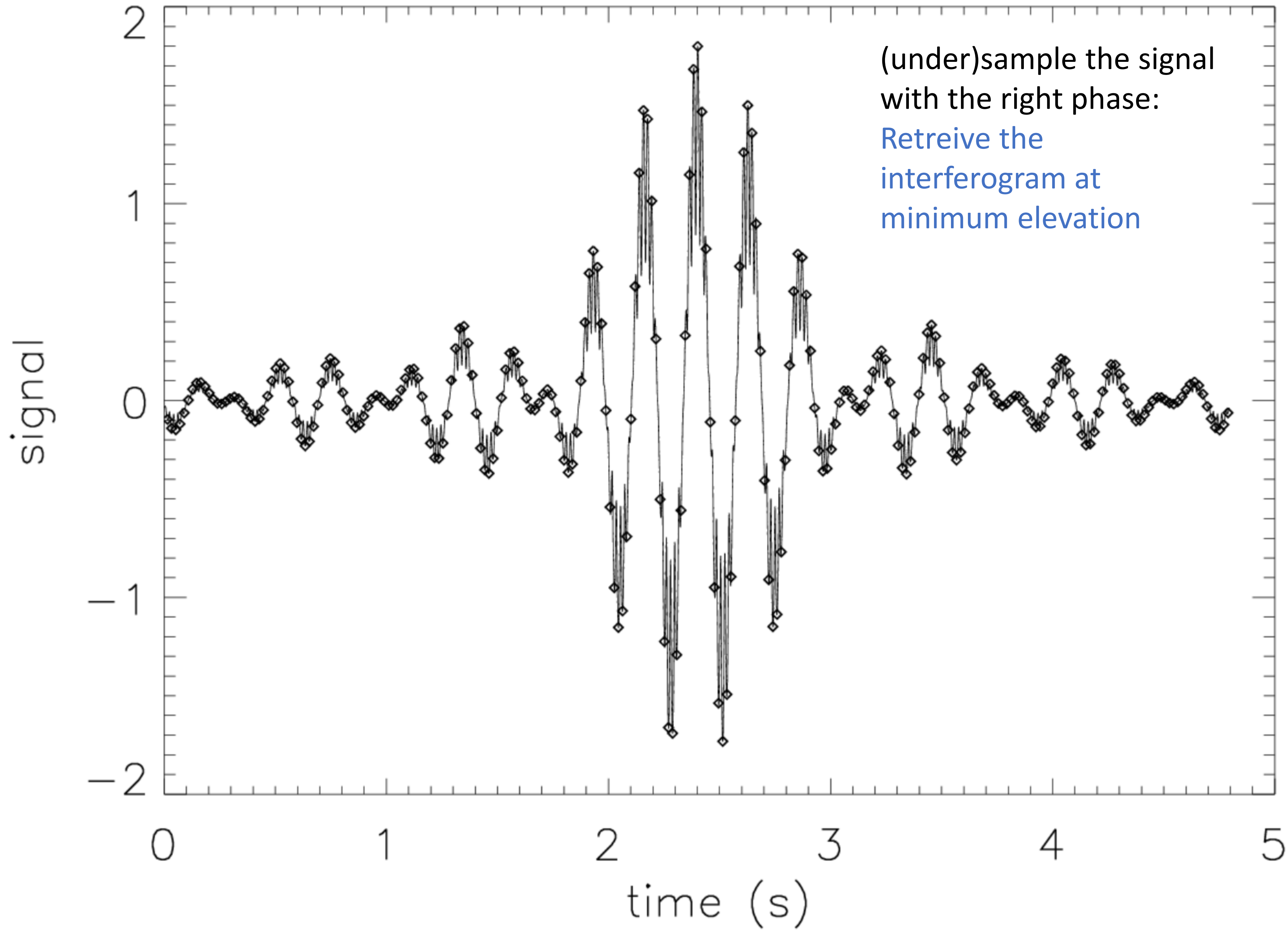
If you look at 80° elevation, stable, and scan the FTS moving mirror, this is what you measure.
One full scan (OPD = -1.27… +1.27 cm) of FTS moving mirror
signal
time (s)
2
1
0
−1
−2
0
1
2
3
4
5

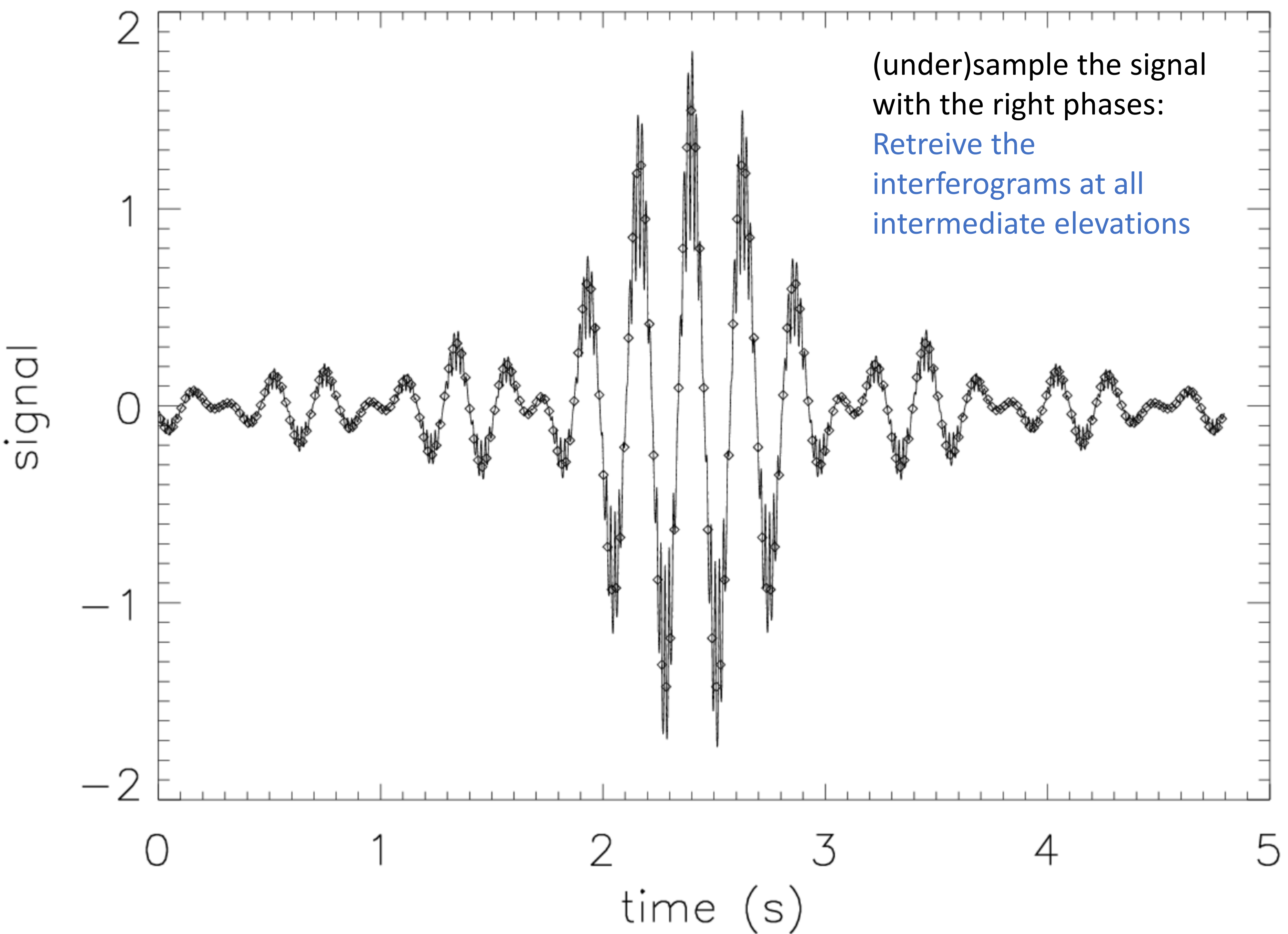


Here, instead, the spinning flat is activated and rotating fast, changing the elevation between 75° and 85°. This is what you measure during one scan of the FTS moving mirror.
minimum elevation
maximum elevation
One full scan (OPD = -1.27… +1.27 cm) of FTS moving mirror
signal
time (s)

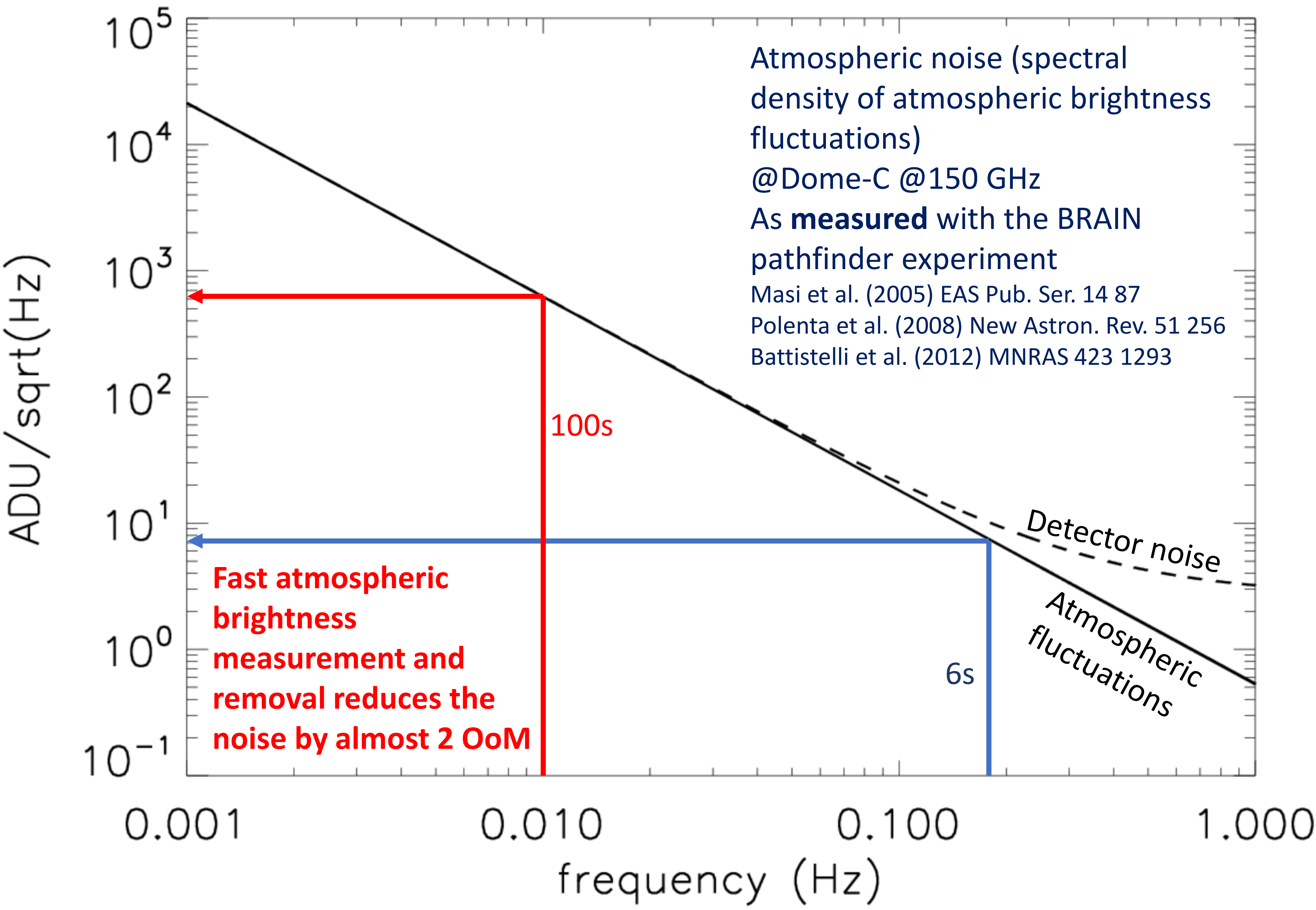


(under)sample the signal with the right phase:
Retreive the interferogram at maximum elevation


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



(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)
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As **measured** with the BRAIN pathfinder experiment
Masi et al. (2005) EAS Pub. Ser. 14 87
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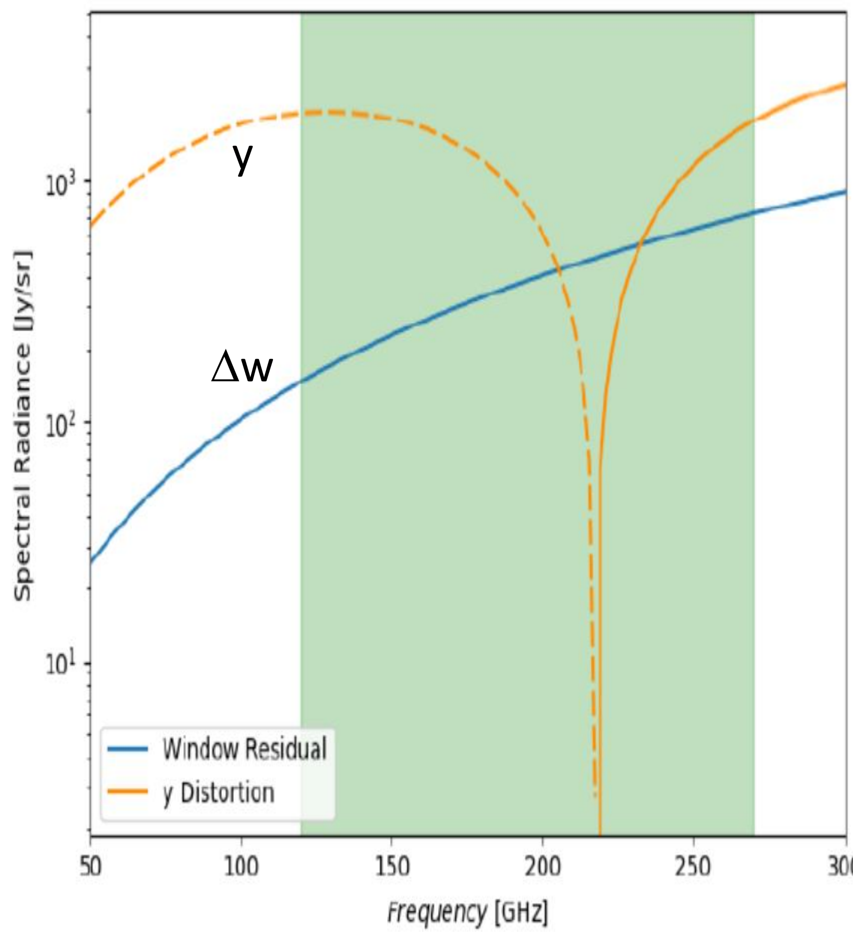
Battistelli et al. (2012) MNRAS 423 1293
100s
6s
Detector noise
Atmospheric fluctuations
Fast atmospheric brightness measurement and removal reduces the noise by almost 2 OoM
ADU/sqrt(Hz)
frequency (Hz)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
0.001
0.010
0.100
1.000

COSMO window emission

- Window (& mirror) common mode emissions must be measured and removed with high accuracy.
- Special calibration procedure based on the comparison of the emission from 1 or 2 windows stacked.
- PhD thesis, Lorenzo Mele
- Preliminary results:



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

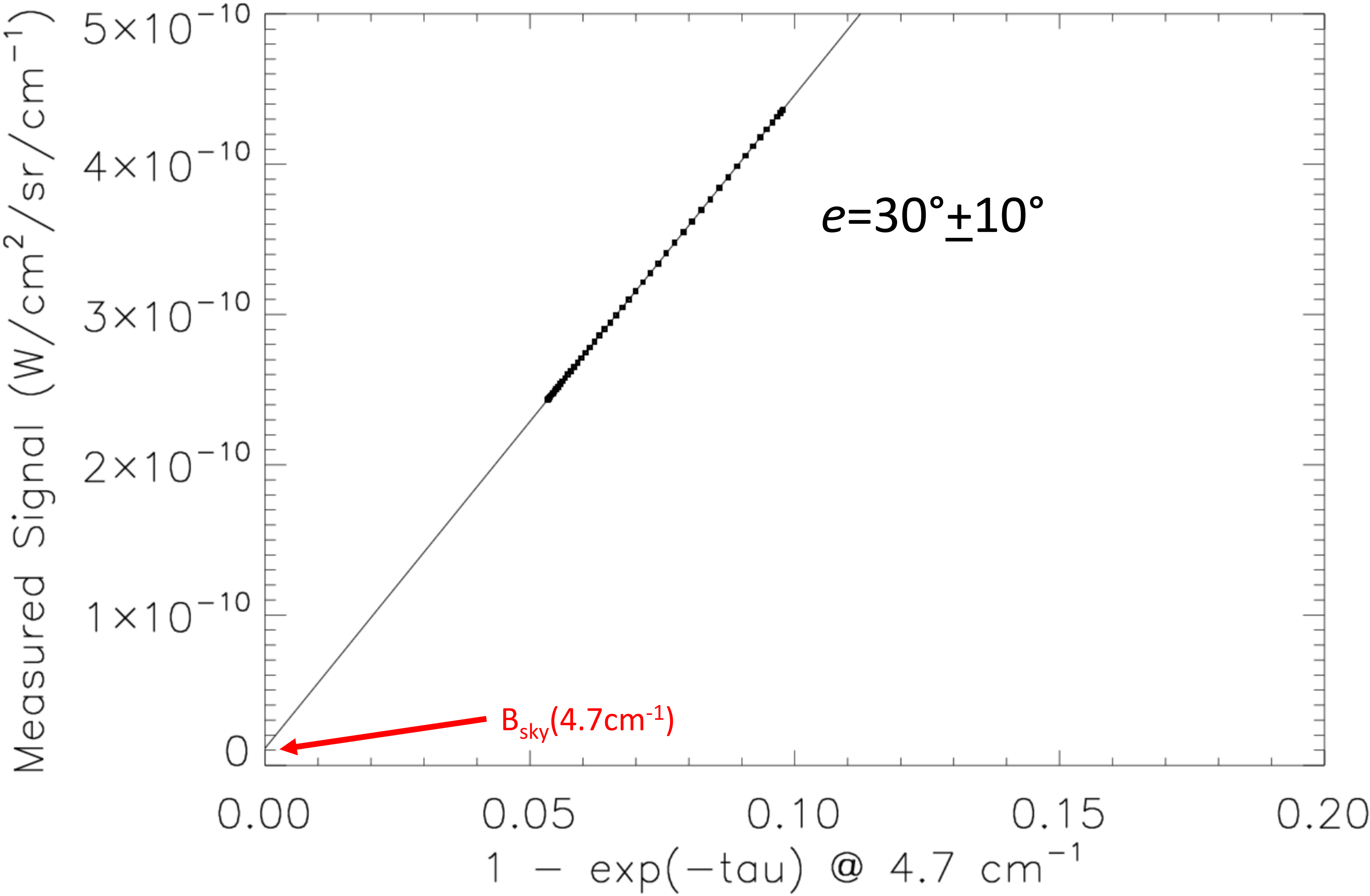
$$x = 1 - \exp(-\tau_z(\nu)/\cos(e))$$

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

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

- 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



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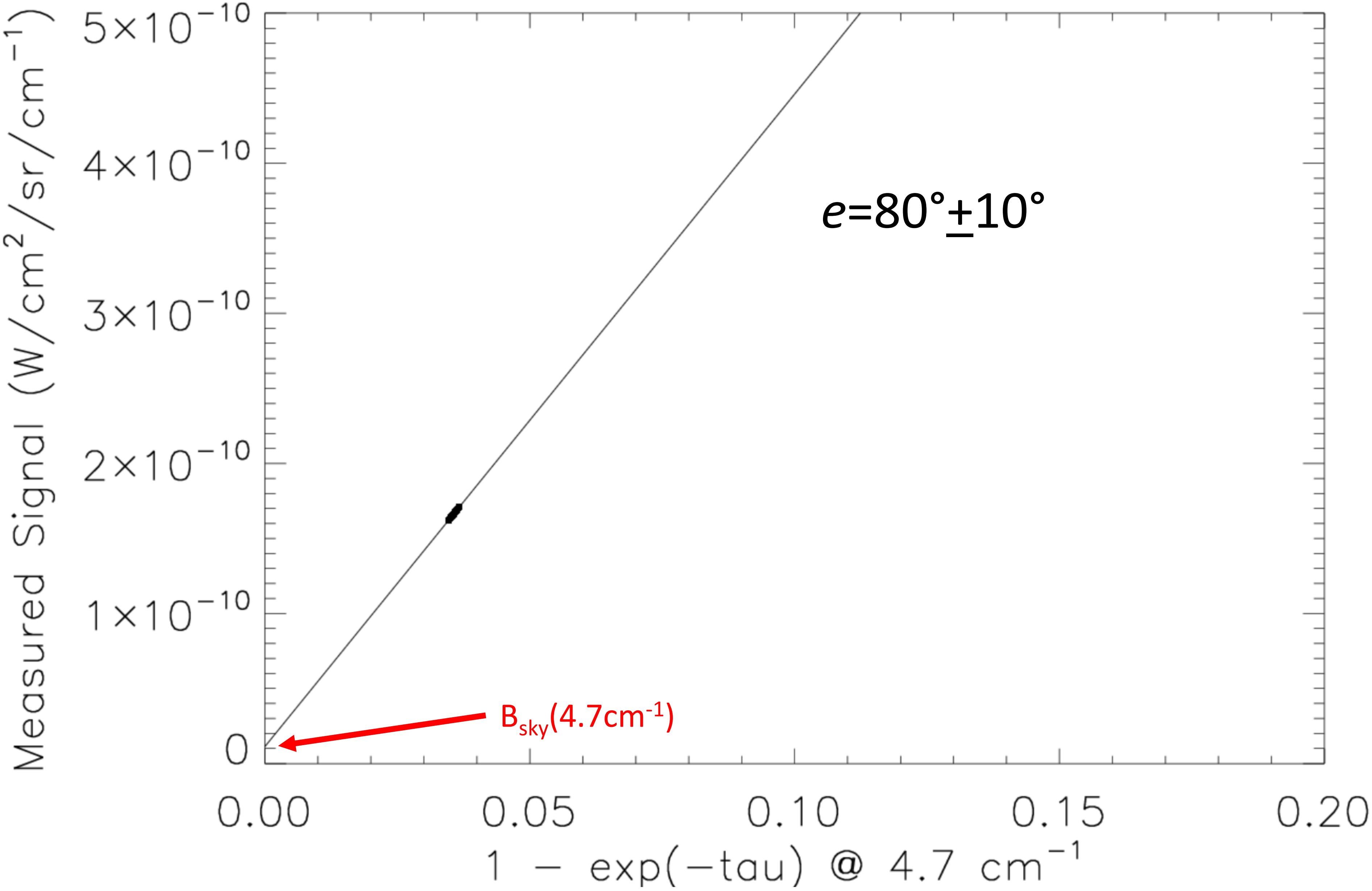
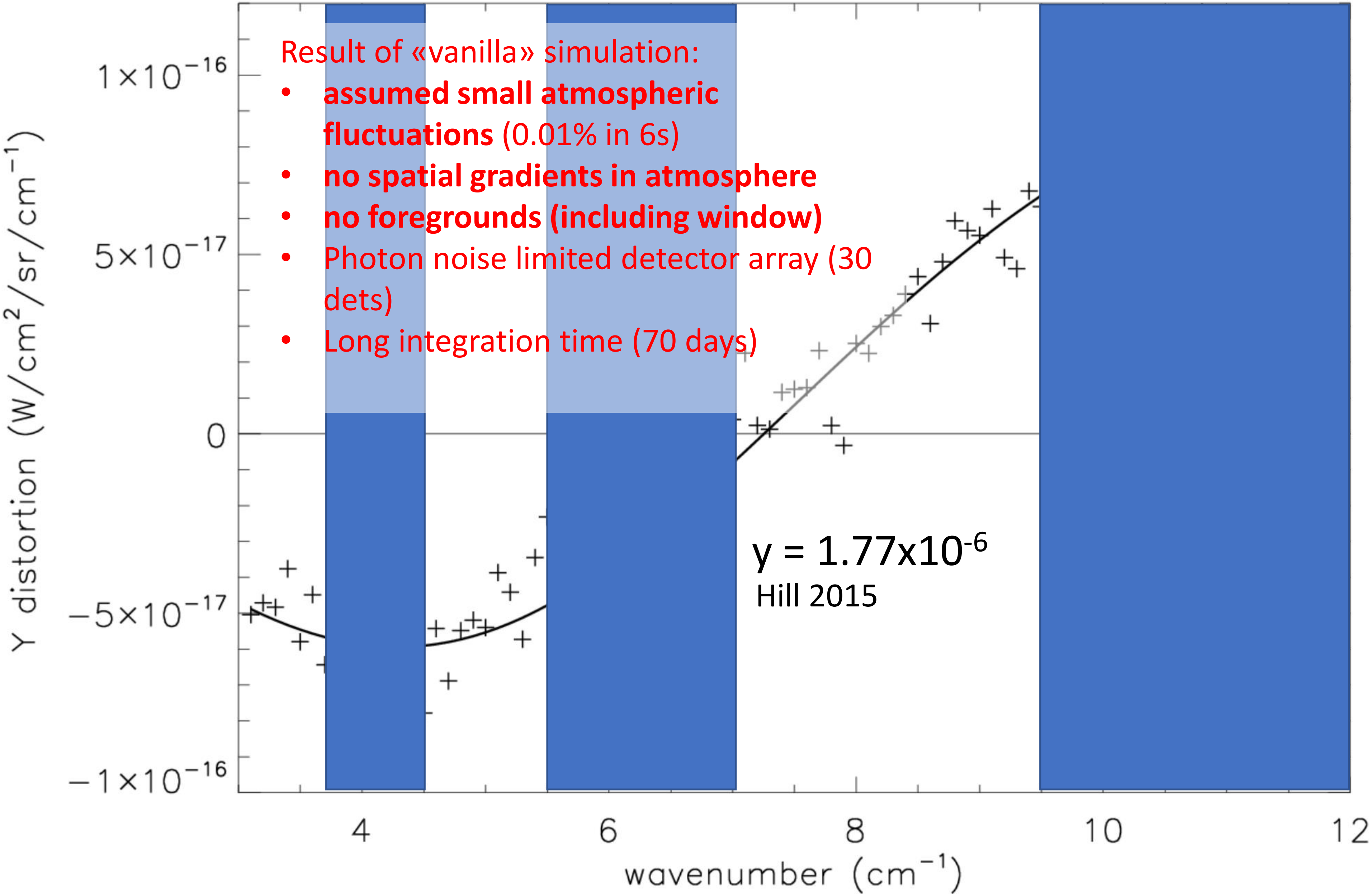


COSMO sky / atmosphere scan simulations



Result of «vanilla» simulation:

- **assumed small atmospheric fluctuations** (0.01% in 6s)
- **no spatial gradients in atmosphere**
- **no foregrounds (including window)**
- Photon noise limited detector array (30 dets)
- Long integration time (70 days)

$y = 1.77\text{x}10^{-6}$

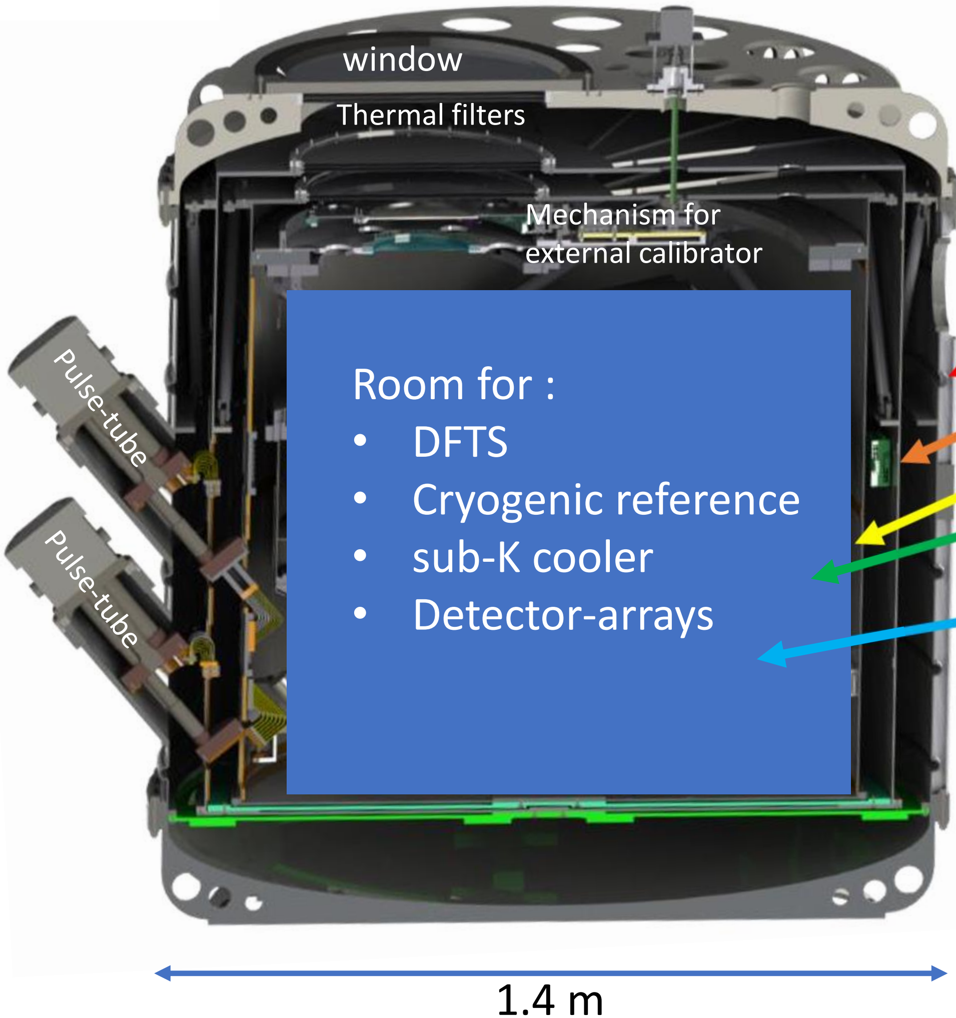
Hill 2015

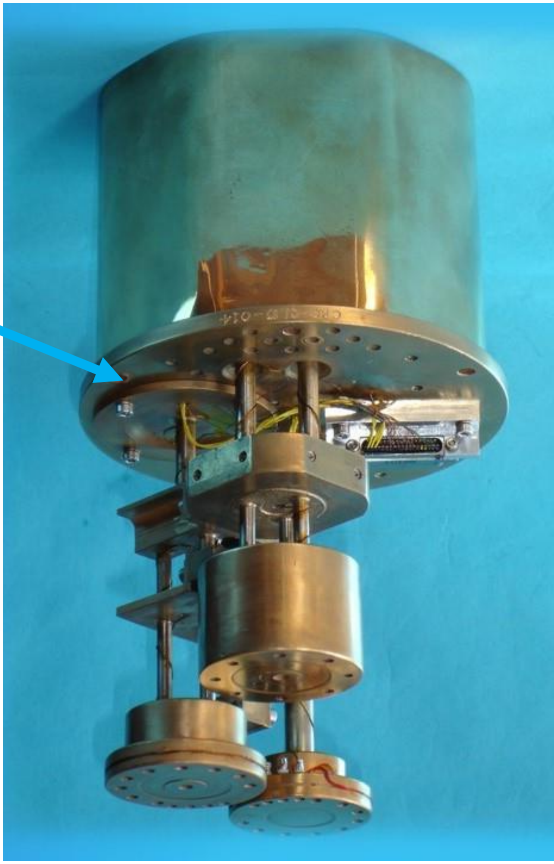
COSMO implementation

- As of today, we are in the *instrument design* phase
  - 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 submitted 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

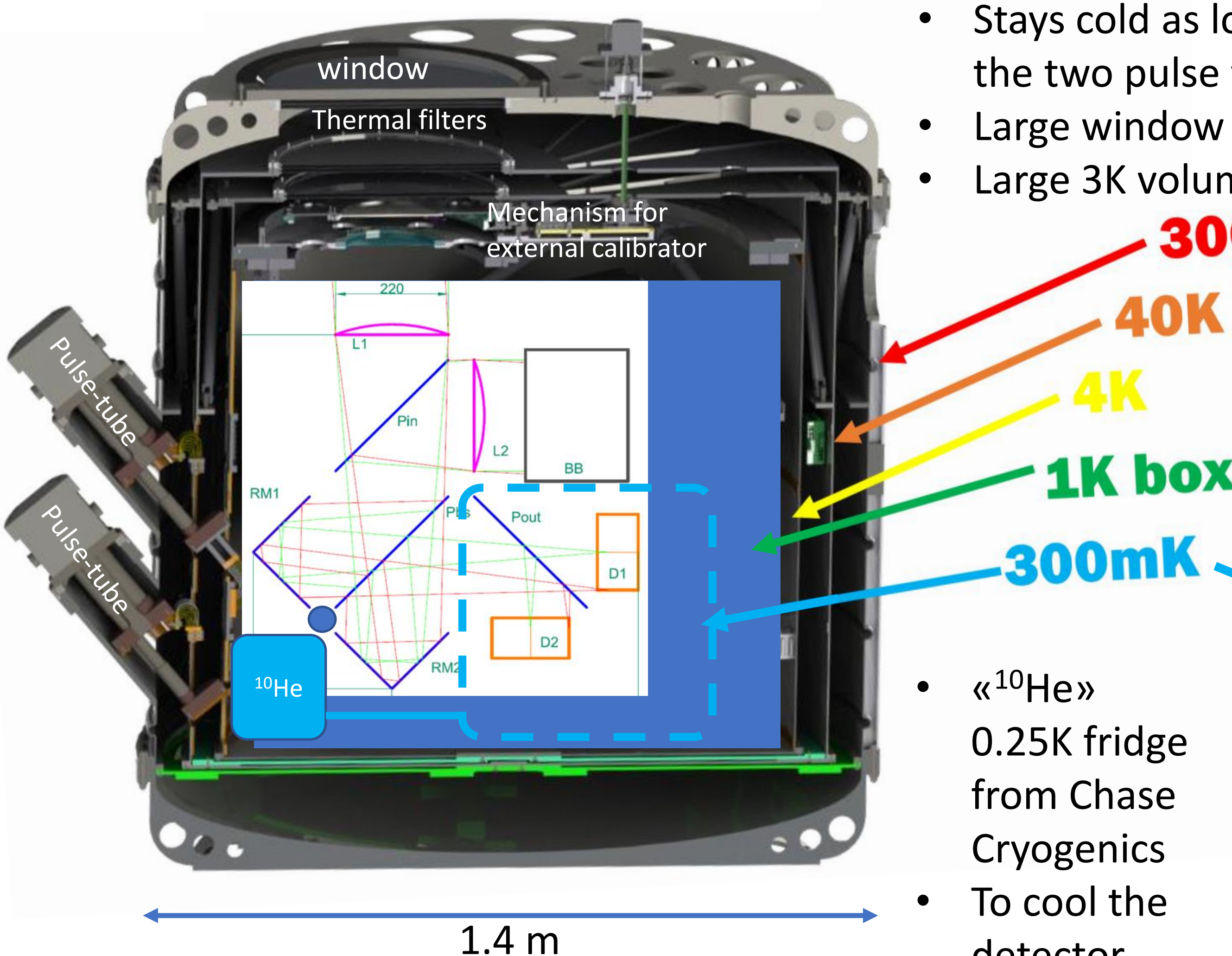
- Main cryostat based on pulse-tube coolers (3K, 0.9W each) + sub-K cooler (0.25K)
- Stays cold as long as there is power for the two pulse tubes
- Large window (50 cm dia)
- Large 3K volume (500 l)





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

COSMO continuous cryogenics



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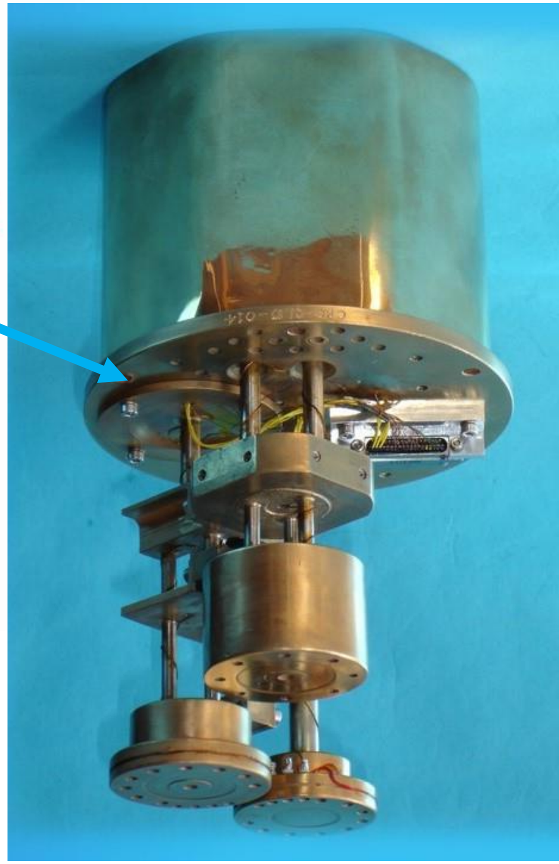
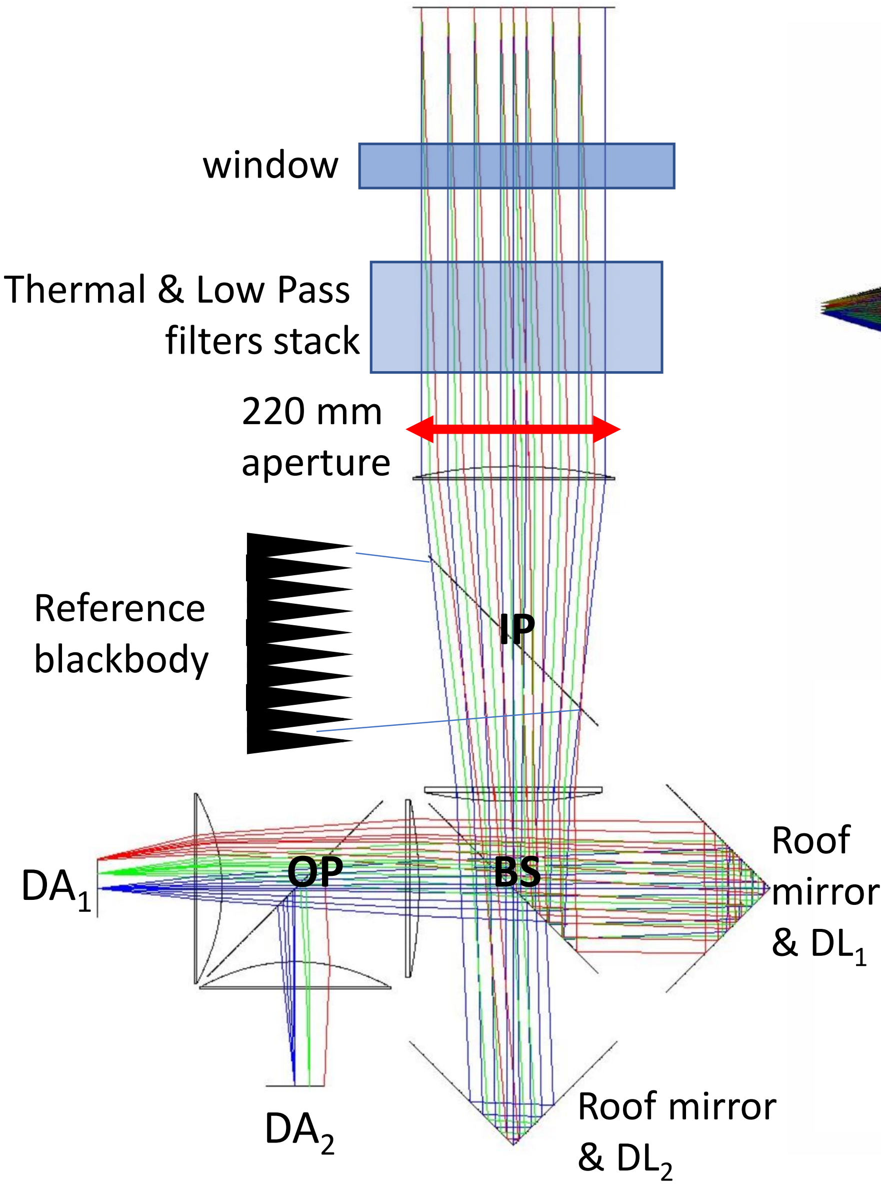
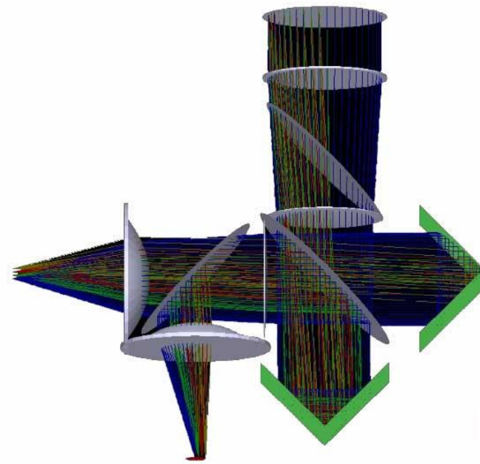


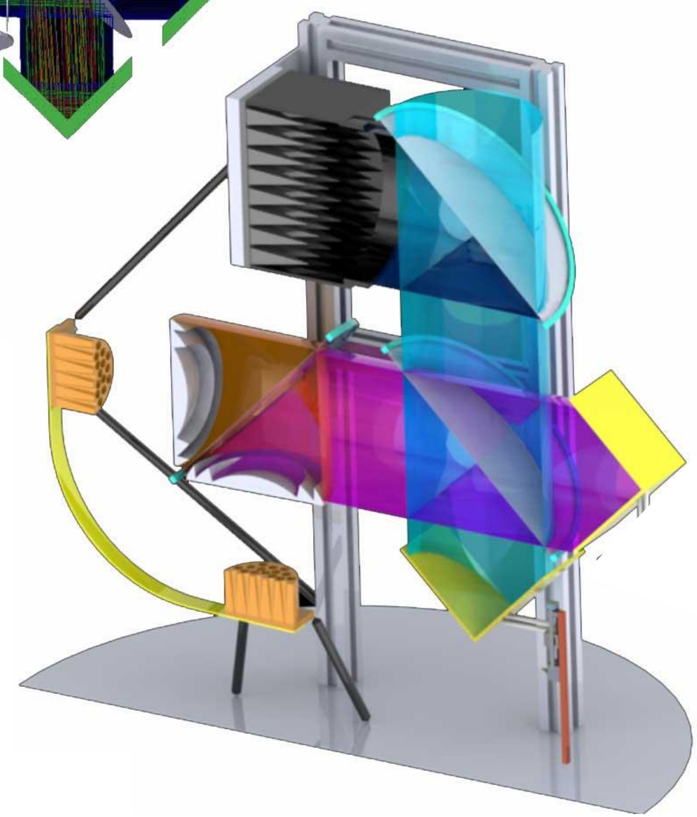
COSMO continuous cryogenics

COSMO continuous cryogenics

COSMO Martin-Puplett interferometer: implementation ideas





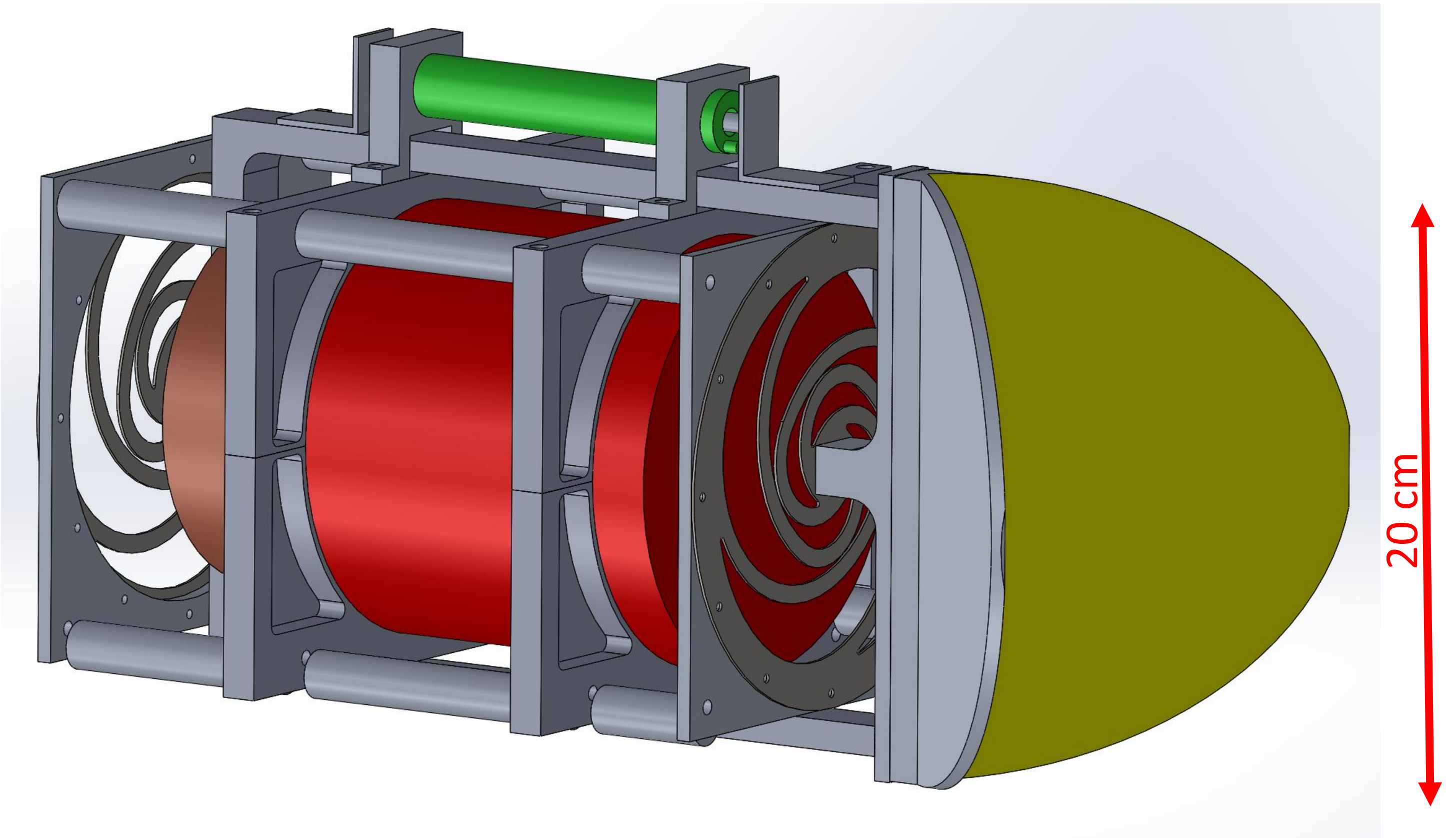


Drawings: G. D’Alessandro

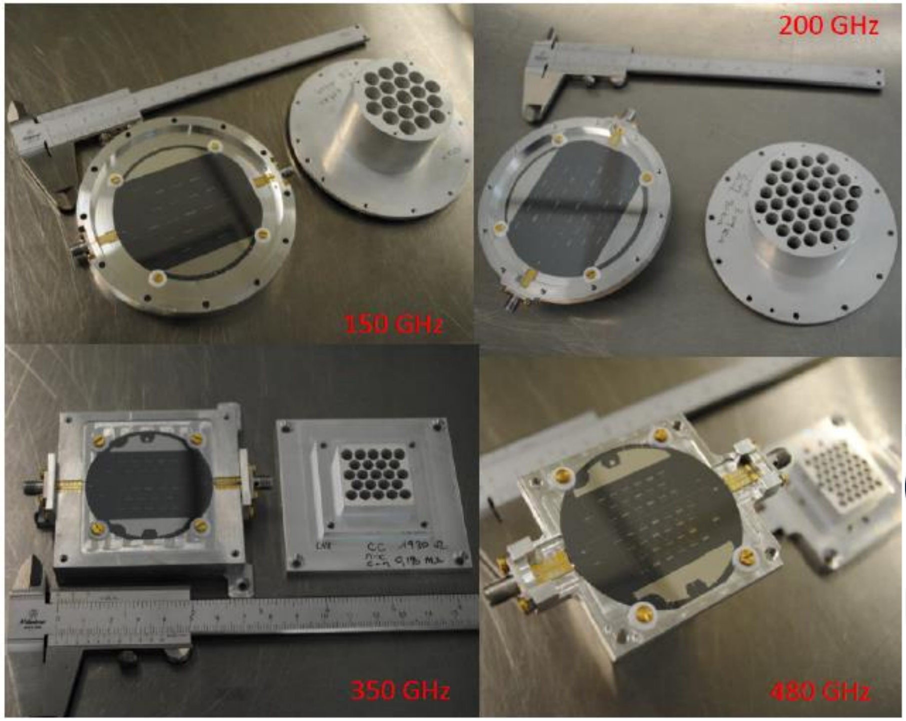
COSMO Martin-Puplett interferometer: implementation ideas

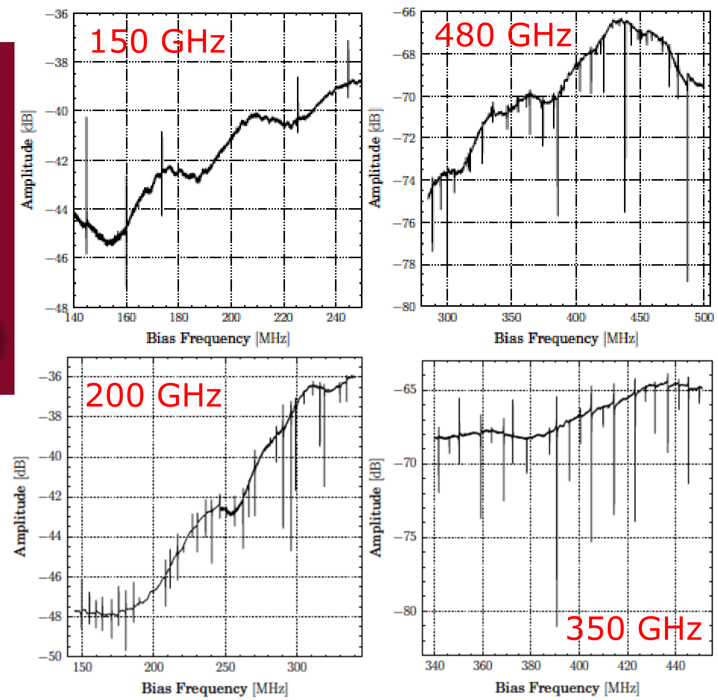
Cryogenic scanning mirror (spectral modulation, slower than sky dip)

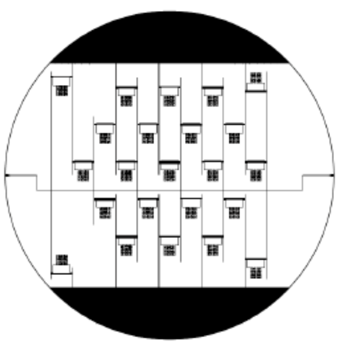
- Max mechnical range = -10 mm … + 40 mm corresponding to max 3.75 GHz resolution
- Max scanning Speed 7 mm/s i.e. one interferogram in 6 s (atmospheric stability)
- Voice coil actuator, low power dissipation on cryogenic system
- LVDT position sensor, 5 μm resolution at maximum speed

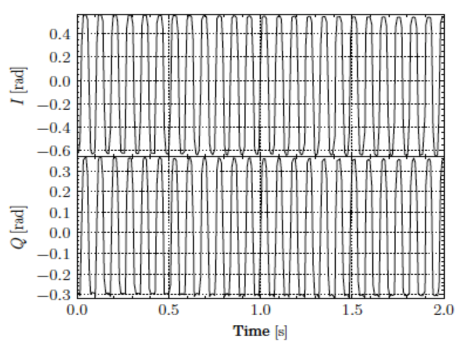


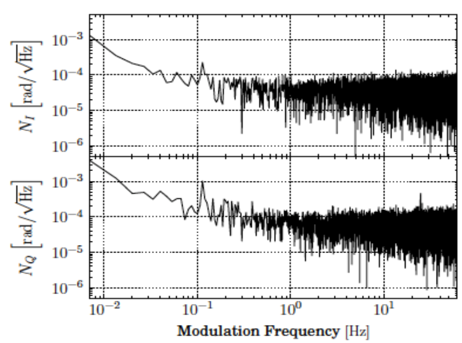
Kinetic Inductance Detectors









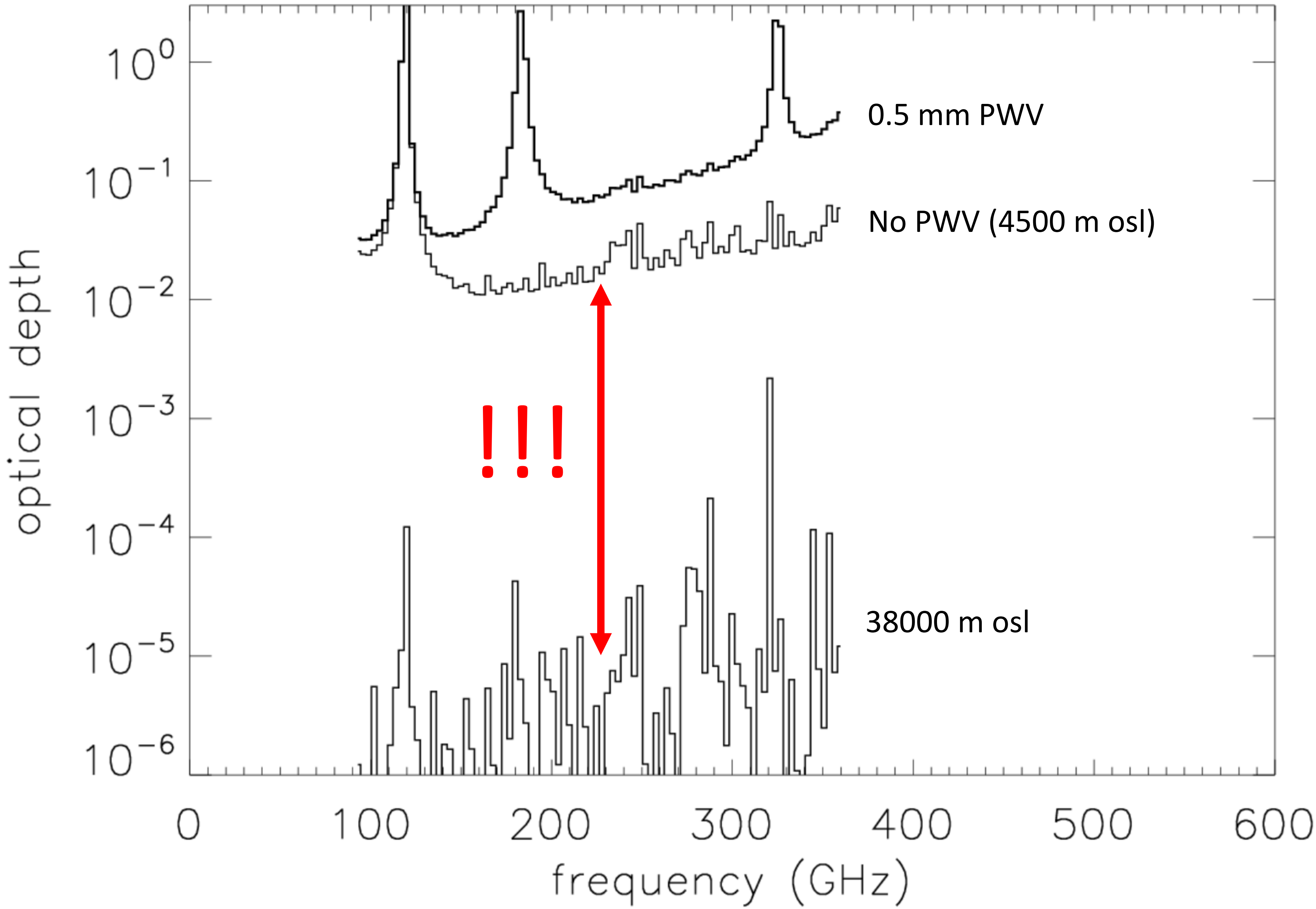


Channel	NET_{RJ} $[mK/\sqrt{Hz}]$
150 GHz	0.180
200 GHz	0.145
350 GHz	0.288
480 GHz	0.433

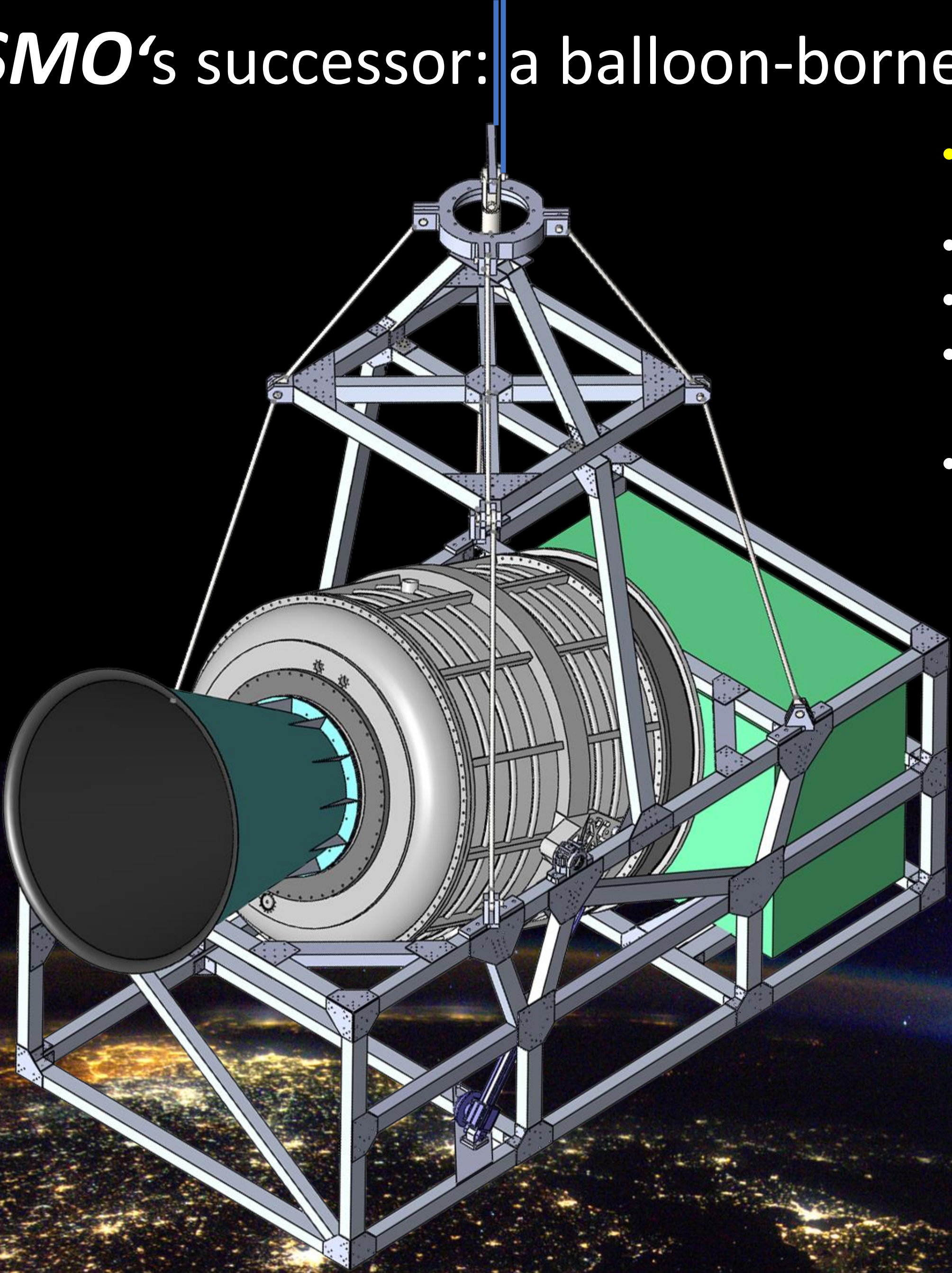
typical NET

See Paiella et al. JCAP (2019) and Masi et al. Submitted to JCAP (2019)

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

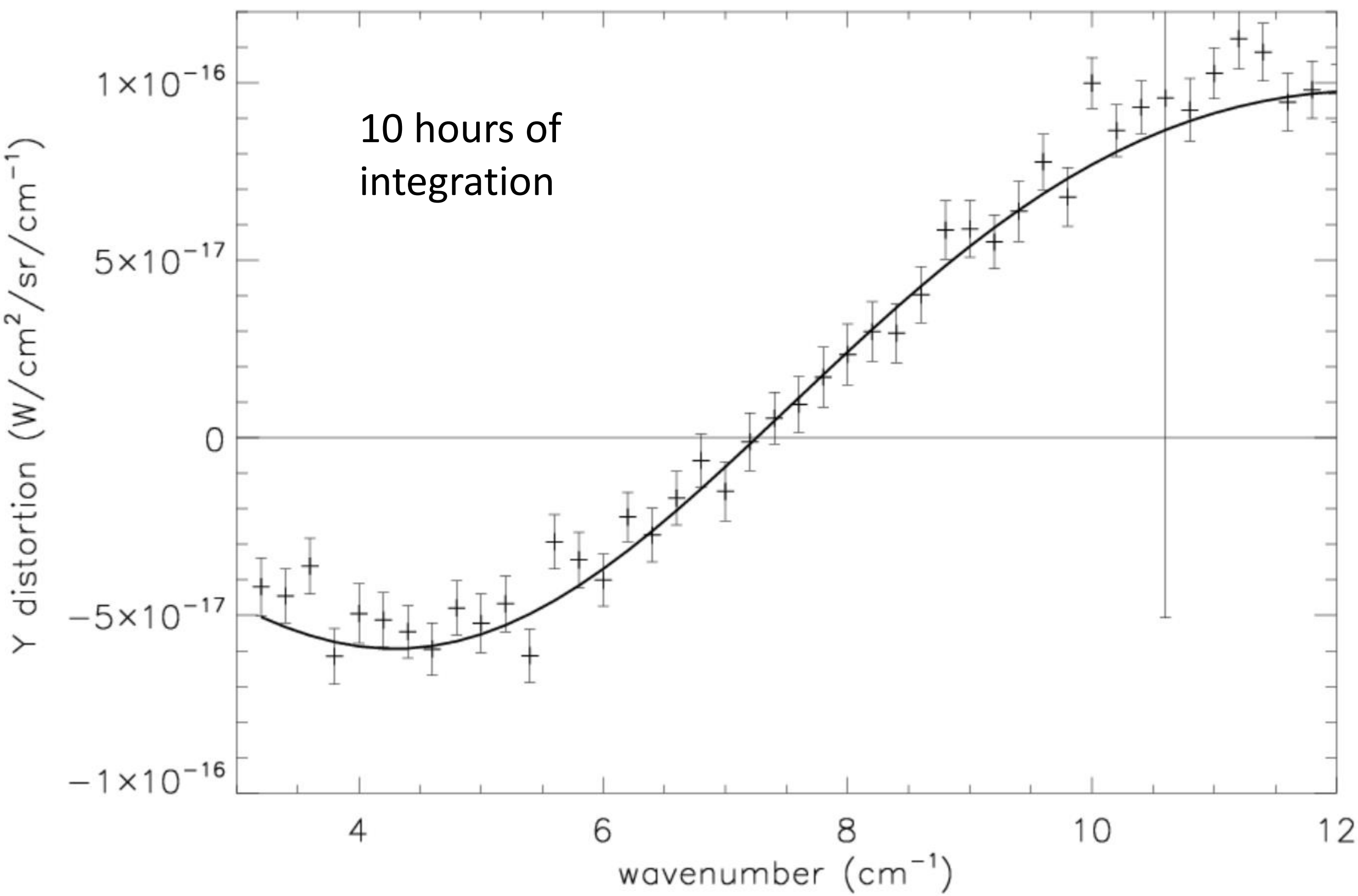


COSMO's successor: a balloon-borne instrument ?



- **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.

COSMO on a balloon:



Conclusions

- COSMO is a first attempt to measure CMB monopole spectral distortions from the ground.
- It beats atmospheric noise and measures atmospheric emission using fast modulation and detectors. If this strategy is effective, the sensitivity is enough to measure the largest spectral distortion, arising from comptonization at recombination.
- It paves the way to more accurate measurements with the same approach, to be carried out on a stratospheric balloon.
- Can (and should) be complemented with low-frequency *monopole* spectral distortion measurements (e.g. TMS in Tenerife and/or evolutions)