Balloons

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Sapienza – Rome

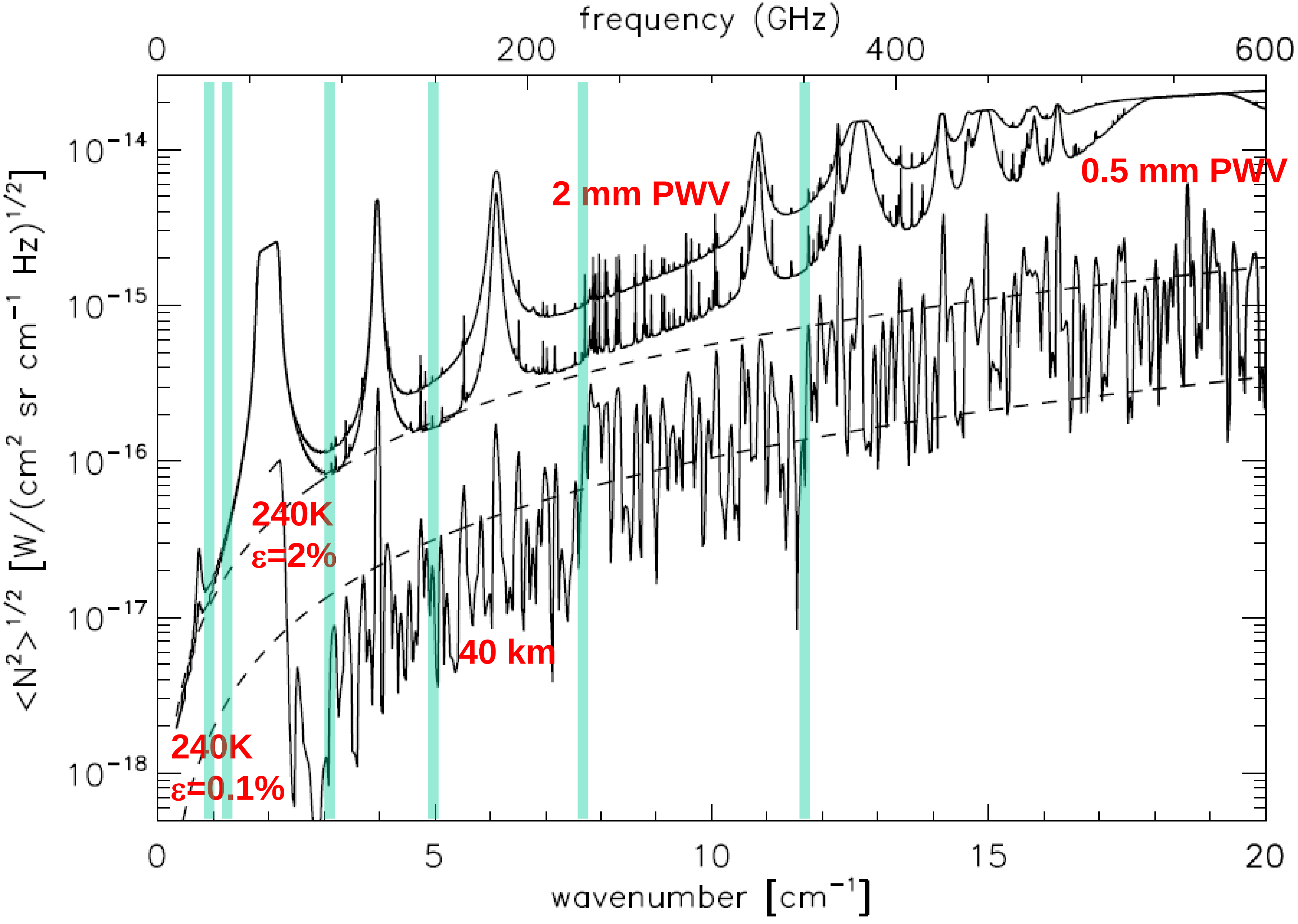
Towards the European Coordination of the CMB programme
Villa Finaly, Firenze, 6th -8th Septemeber, 2017

https://indico.in2p3.fr/event/14661/

Stratospheric Balloons:

- Near-space carriers able to:
  - Reach 40 km (3 mbar)
  - Stay there for up to 40 days
  - Lift heavy (2 tons) large payloads (larger than what we can reasonably fly on satellites)
  - Cost roughly 1/100 of a satellite mission
  - Allow for recovery and refly of the payload
- Important for the CMB community:
  - **To carry out sensitive observations at high frequency, high resolution, and at the largest angular scales**
  - To qualify instrumentation in preparation of satellites
  - To educate young experimentalists !

Photon noise from the local environment for CMB observations



Future balloon borne CMB experiments
Worked Sensitivity Example: Ground-based

GROUND BASED MEASUREMENT

telescope aperture diameter (m)	4.5	integration time (days)	730
T CMB (K)	2.725	time efficiency	0.5
T atmo (K)	240		

Channel center f (GHz)	**33**	**44**	**90**	**145**	**220**	**270**	**340**	**480**
wavenumber (cm-1)	1.10	1.47	3.00	4.84	7.34	9.01	11.34	16.01
Channel center wavelength (mm)	9.09	6.82	3.33	2.07	1.36	1.11	0.88	0.63
fractional bandwidth	0.20	0.20	0.20	0.20	0.20	0.10	0.10	0.10
bandwidth (GHz)	6.60	8.80	18.00	29.00	44.00	27.00	34.00	48.00
throughput (m2 sr)	82.6E-6	46.5E-6	11.1E-6	4.3E-6	1.9E-6	1.2E-6	778.5E-9	390.6E-9
Airy disk diameter (first zero, arcmin)	8.5	6.4	3.1	1.9	1.3	1.0	0.8	0.6
Edge taper (dB)	-23	-23	-23	-23	-23	-23	-23	-23
Spill-over (assuming Gaussian beam)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Pure Gaussian beam FWHM (arcmin)	8.5	6.4	3.1	1.9	1.3	1.0	0.8	0.6
Beam FWHM (arcmin)	9.2	6.9	3.4	2.1	1.4	1.1	0.9	0.6
detector efficiency	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
x_CMB	0.58	0.77	1.59	2.55	3.87	4.76	5.99	8.45
background (CMB only, W)	184.7E-15	221.2E-15	279.1E-15	237.1E-15	137.2E-15	42.3E-15	19.4E-15	3.3E-15
shot noise (W/sqrt(Hz))	2.8E-18	3.6E-18	5.8E-18	6.7E-18	6.3E-18	3.9E-18	3.0E-18	1.4E-18
total NEP (W/sqrt(Hz)	5.7E-18	7.2E-18	11.5E-18	13.5E-18	12.6E-18	7.8E-18	5.9E-18	2.9E-18
NET (uK_CMB/sqrt(Hz))	63	61	56	56	63	104	138	283
x_atm	0.007	0.009	0.018	0.029	0.044	0.054	0.068	0.096
T_b (K) 4500 m OSL	2.3	8.3	5.3	5.8	9.7	14.5	28	117
Transmission 4500 m OSL	0.99	0.96	0.98	0.98	0.96	0.95	0.81	0.47
background (atmo only, W)	210.8E-15	1.0E-12	1.3E-12	2.3E-12	5.8E-12	5.3E-12	12.8E-12	74.5E-12
shot noise (W/sqrt(Hz))	3.0E-18	7.7E-18	12.5E-18	21.0E-18	41.1E-18	43.5E-18	75.8E-18	217.3E-18
NET (uK_CMB/sqrt(Hz))	34	69	62	89	215	615	2187	45394
NET_GND (uK_CMB/sqrt(Hz)) no turbulence	**72**	**92**	**84**	**105**	**224**	**624**	**2191**	**45394**
Number of detectors	10	30	150	400	200	200	200	200
Survey sensitivity (uK arcmin)	**9.8**	**5.4**	**1.1**	**0.5**	**1.0**	**2.3**	**6.4**	**94.6**

Future balloon borne CMB experiments
Worked Sensitivity Example: Balloon-borne

BALLON-BORNE MEASUREMENT

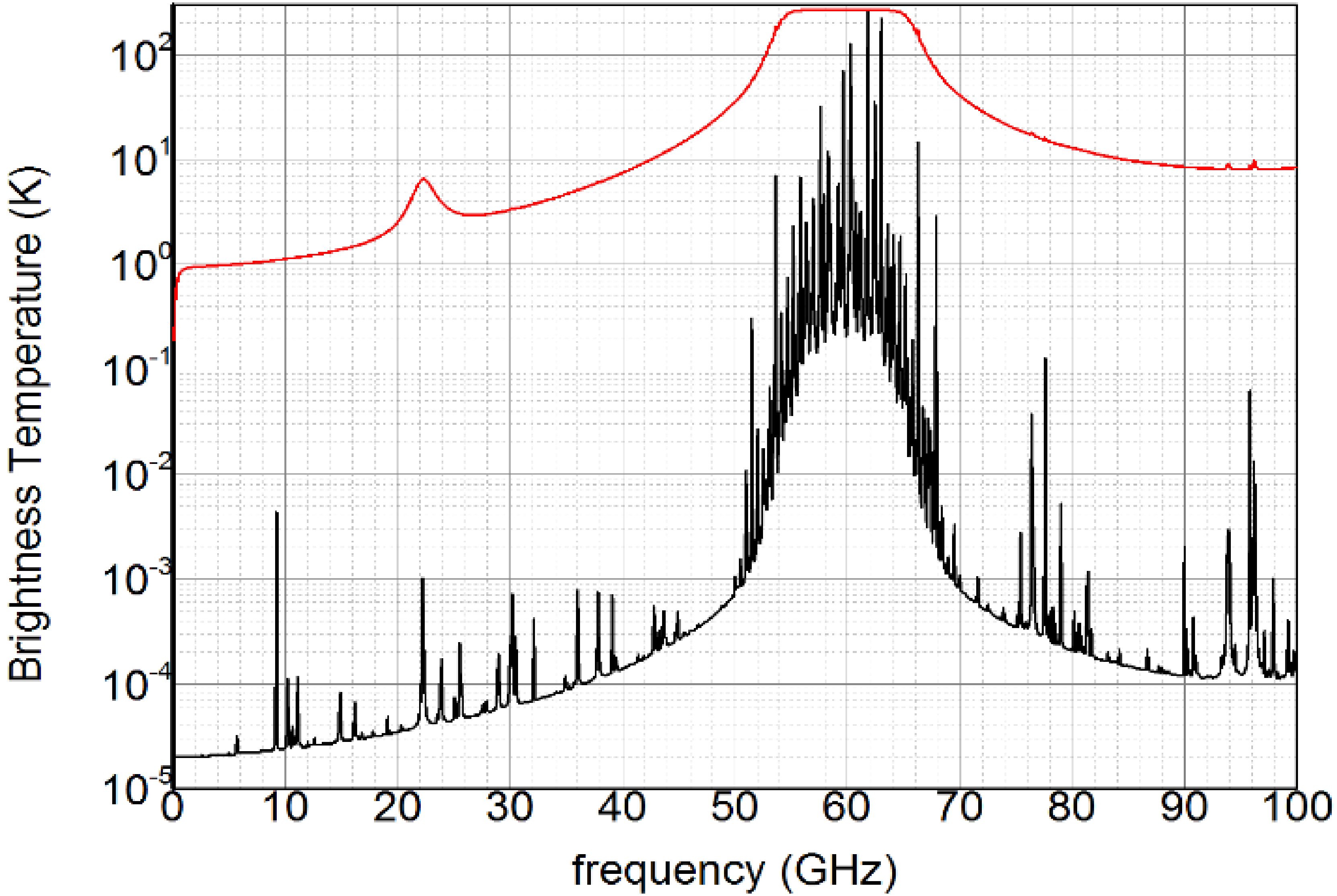
telescope aperture diameter (m)	4.5	integration time (days)	120
T CMB (K)	2.725	time efficiency	0.9
T atmo (K)	240		

Channel center f (GHz)	**33**	**44**	**90**	**145**	**220**	**270**	**340**	**480**
wavenumber (cm-1)	1.10	1.47	3.00	4.84	7.34	9.01	11.34	16.01
Channel center wavelength (mm)	9.09	6.82	3.33	2.07	1.36	1.11	0.88	0.63
fractional bandwidth	0.20	0.20	0.20	0.20	0.20	0.10	0.10	0.10
bandwidth (GHz)	6.60	8.80	18.00	29.00	44.00	27.00	34.00	48.00
throughput (m2 sr)	82.6E-6	46.5E-6	11.1E-6	4.3E-6	1.9E-6	1.2E-6	778.5E-9	390.6E-9
Airy disk diameter (first zero, arcmin)	8.5	6.4	3.1	1.9	1.3	1.0	0.8	0.6
Edge taper (dB)	-23	-23	-23	-23	-23	-23	-23	-23
Spill-over (assuming Gaussian beam)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Pure Gaussian beam FWHM (arcmin)	8.5	6.4	3.1	1.9	1.3	1.0	0.8	0.6
Beam FWHM (arcmin)	9.2	6.9	3.4	2.1	1.4	1.1	0.9	0.6
detector efficiency	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
x_CMB	0.58	0.77	1.59	2.55	3.87	4.76	5.99	8.45
background (CMB only, W)	184.7E-15	221.2E-15	279.1E-15	237.1E-15	137.2E-15	42.3E-15	19.4E-15	3.3E-15
shot noise (W/sqrt(Hz))	2.8E-18	3.6E-18	5.8E-18	6.7E-18	6.3E-18	3.9E-18	3.0E-18	1.4E-18
total NEP (W/sqrt(Hz)	5.7E-18	7.2E-18	11.5E-18	13.5E-18	12.6E-18	7.8E-18	5.9E-18	2.9E-18
NET (uK_CMB/sqrt(Hz))	63	61	56	56	63	104	138	283
x_atm	0.007	0.009	0.018	0.029	0.044	0.054	0.068	0.096
T_b (K) 40 km OSL	0.00011	0.00018	0.0002	0.00074	0.00408	0.02408	0.0461	0.4937
background (atmo only, W)	10.1E-18	22.0E-18	49.7E-18	294.6E-18	2.4E-15	8.8E-15	21.1E-15	314.5E-15
shot noise (W/sqrt(Hz))	2.0954E-20	3.572E-20	7.6838E-20	2.375E-19	8.428E-19	1.772E-18	3.077E-18	1.4116E-17
NET (uK_CMB/sqrt(Hz))	0.23	0.31	0.38	0.99	4.23	23.80	71.88	1385.90
NET_balloon (uK_CMB/sqrt(Hz))	**63**	**61**	**56**	**56**	**64**	**107**	**156**	**1415**
Number of detectors	10	30	150	400	200	200	200	200
Survey sensitivity (uK arcmin)	**15.8**	**6.6**	**1.3**	**0.5**	**0.5**	**0.7**	**0.8**	**5.4**

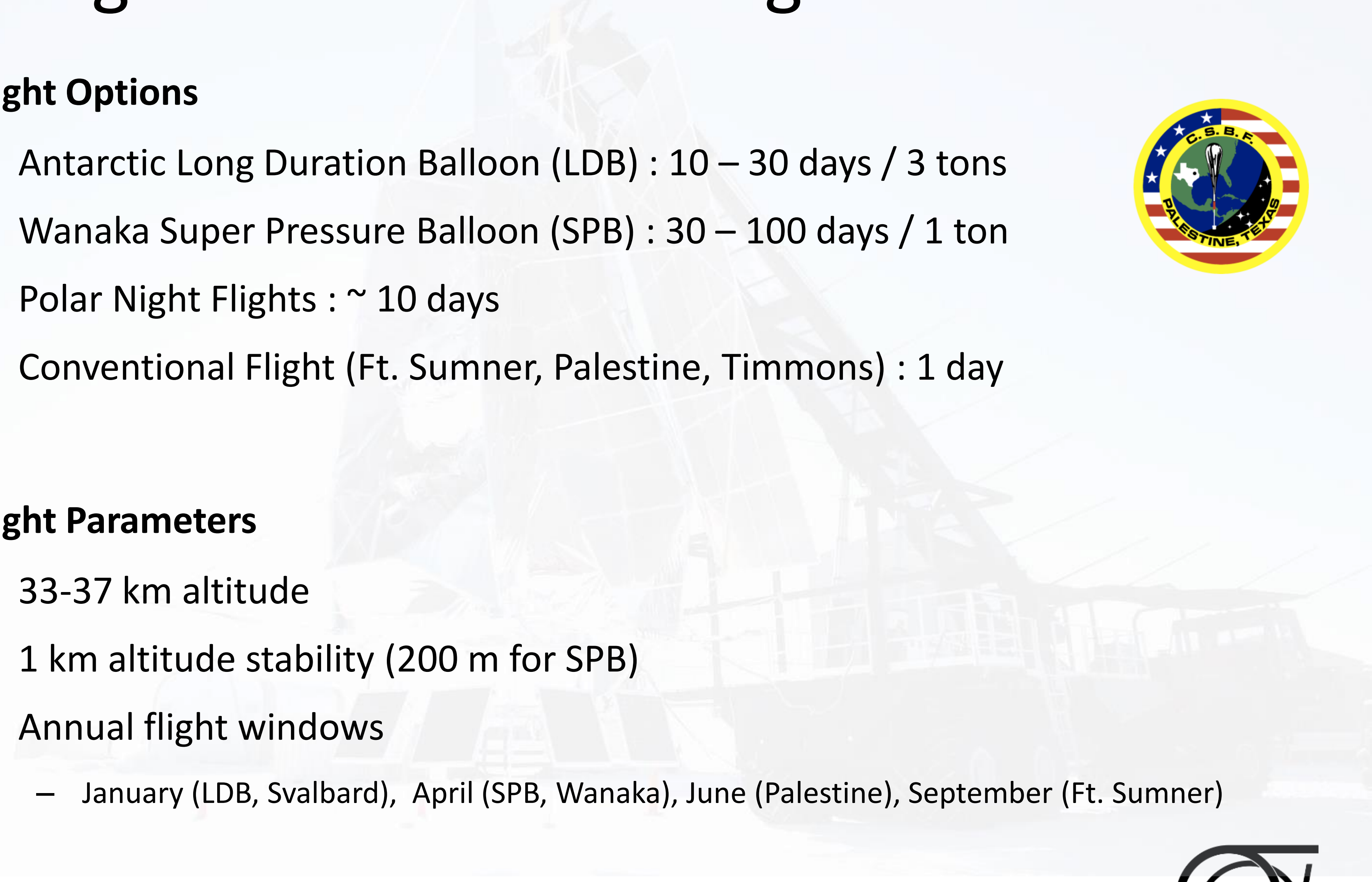
Future balloon borne CMB experiments
Worked Sensitivity Example

- In absolute terms, a large array of photon-noise limited detectors on a ultra-long-duration balloon is able to reach cosmic variance limits at all interesting angular scales.
- The comparison to the theoretical sensitivity of ground-based experiments is interesting because defines the frequency range where the balloon advantage is larger.
- In the absence of atmospheric turbulence:
  - one day of integration on a balloon equals:
    - 12 days of operation on the ground at 220 GHz
    - 34 days of operation on the ground at 270 GHz
    - 198 days of operation on the ground at 340 GHz
    - 1390 days of operation on the ground at 480 GHz
  - At these high frequencies, the advantage of a balloon mission is going to improve if atmospheric turbulence is taken into account.

Future balloon borne CMB experiments
Atmospheric Effects: absolute brightness



Long Duration Ballooning



Flight Options

- Antarctic Long Duration Balloon (LDB) : 10 – 30 days / 3 tons
- Wanaka Super Pressure Balloon (SPB) : 30 – 100 days / 1 ton
- Polar Night Flights : ~ 10 days
- Conventional Flight (Ft. Sumner, Palestine, Timmons) : 1 day

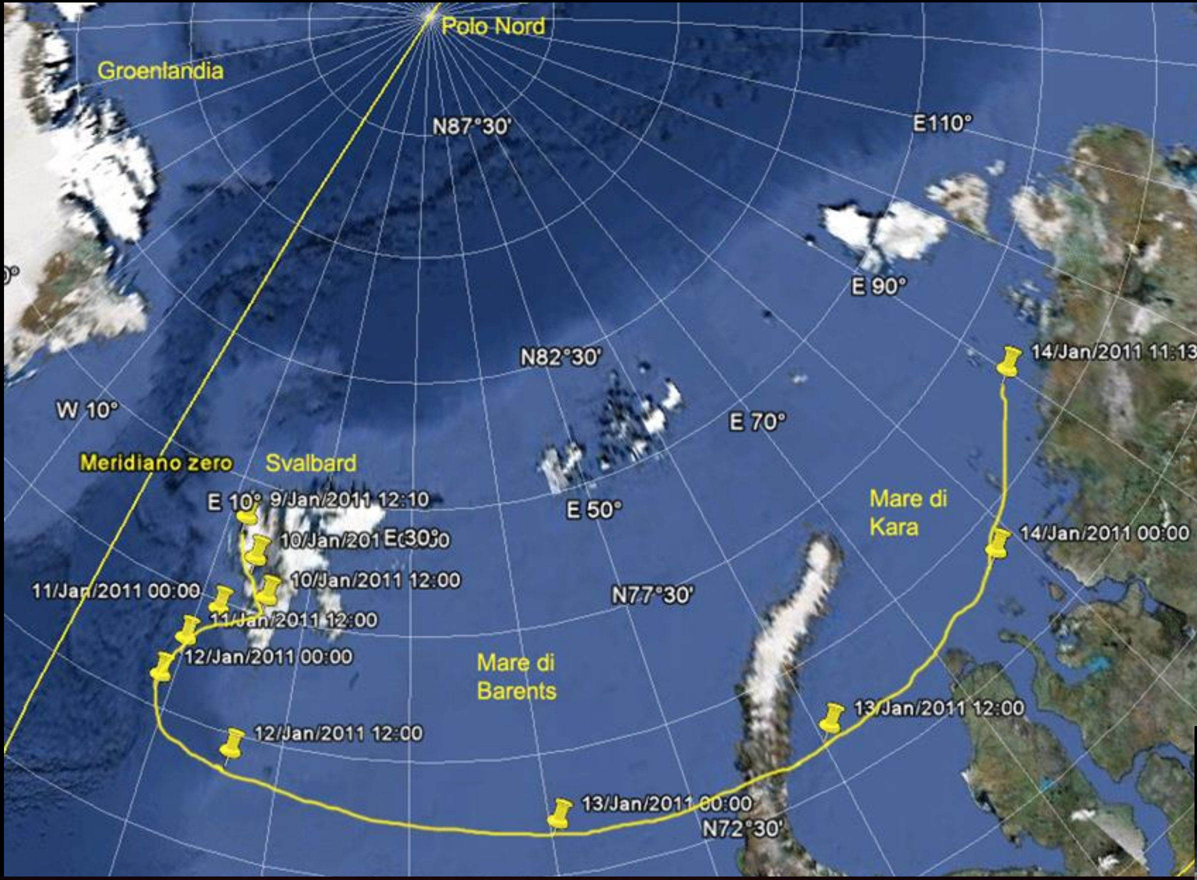
Flight Parameters

- 33-37 km altitude
- 1 km altitude stability (200 m for SPB)
- Annual flight windows
  - January (LDB, Svalbard), April (SPB, Wanaka), June (Palestine), September (Ft. Sumner)

Great progress with super-pressure balloons: COSI payload flown by CSBF in may 2016 for 47 days at altitudes between 33 km and 21 km, with a with a 0.5Mm^3 SPB

https://blogs.nasa.gov/superpressureballoon/

Polar Night Flights



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PROGRAMMA NAZIONALE DI RICERCHE IN ANTARTIDE
ITALIANTARTIDE

STVDIVM VRBIS

Stratospheric Balloons:

Disadvantages:

- Stringent limits on mass, power
- Complexity of automation
- Insane integration schedule
- Narrow, and scarce, flight windows
- Risky recovery

CMB-related science from balloons

(with large advantage wrt ground-based experiments)

- Dust-cleaned polarization & Dust-cleaned inflationary and lensing B-modes
- CMB Polarization at very large angular scales
- Spectral measurements of the SZ
- Spectral measurements of CIB anisotropy
- Precision measurements of CMB spectrum (at selected frequencies)

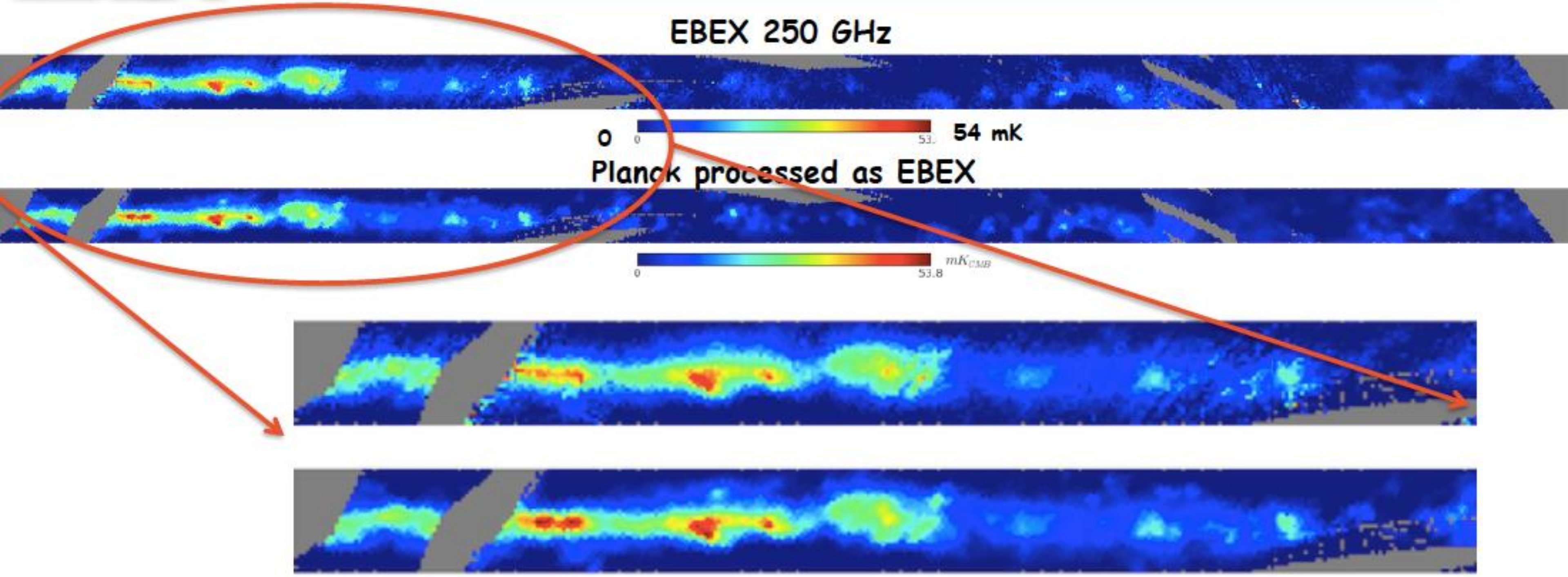
Current / Pending Balloons for CMB-related science

Missions Recently Flown	survey area [sky fraction]	frequencies [GHz]	resolution [arcmin]
EBEX (2012/13)	0.2	150/250/410	8/5/5
Spider (2014/15)	0.1	94/150	42/28
PILOT (2015)	<0.01	1200/545	3

Missions Planned	survey area [sky fraction]	frequencies [GHz]	resolution [arcmin]
Piper (2016)	0.8	200	36
Spider (LDB 2017)	0.1	94-285 (3)	42-15
OLIMPO (N.LDB 2017)	0.01	140-220-340-450	2/4
LSPE (N.LDB 2018)	0.25	44-240 (4)	85-20

Missions in Preparation	survey area [sky fraction]	frequencies [GHz]	resolution [arcmin]
Piper (2017-2020)	0.8	200-600 (4)	36-12
BLAST-TNG	< 0.01	1200, 860, 600	1
EBEX-IDS	0.035	150-360 (7)	8-3
BFORE	0.23	270-600 (3)	4
BSIDE	0.05	600-700	7

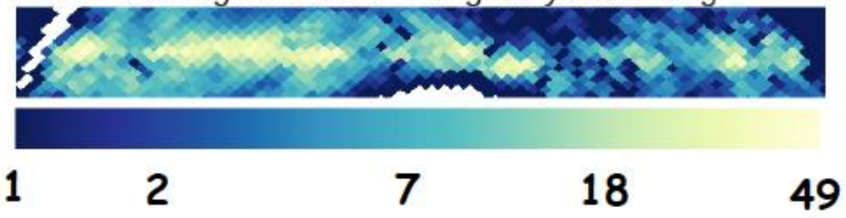
2013 Flight


EBEX 250 GHz

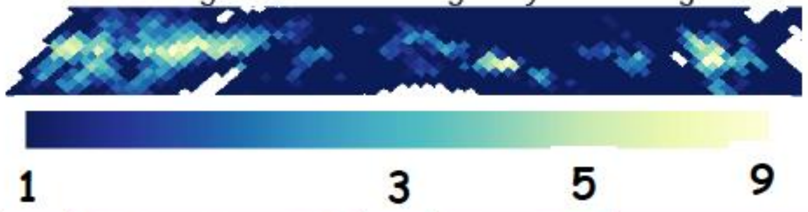
Planck processed as EBEX

Pol Signal to Noise on galaxy at 150 log

Pol Signal to Noise on galaxy at 250 log



Pol Signal to Noise on galaxy at 410 log

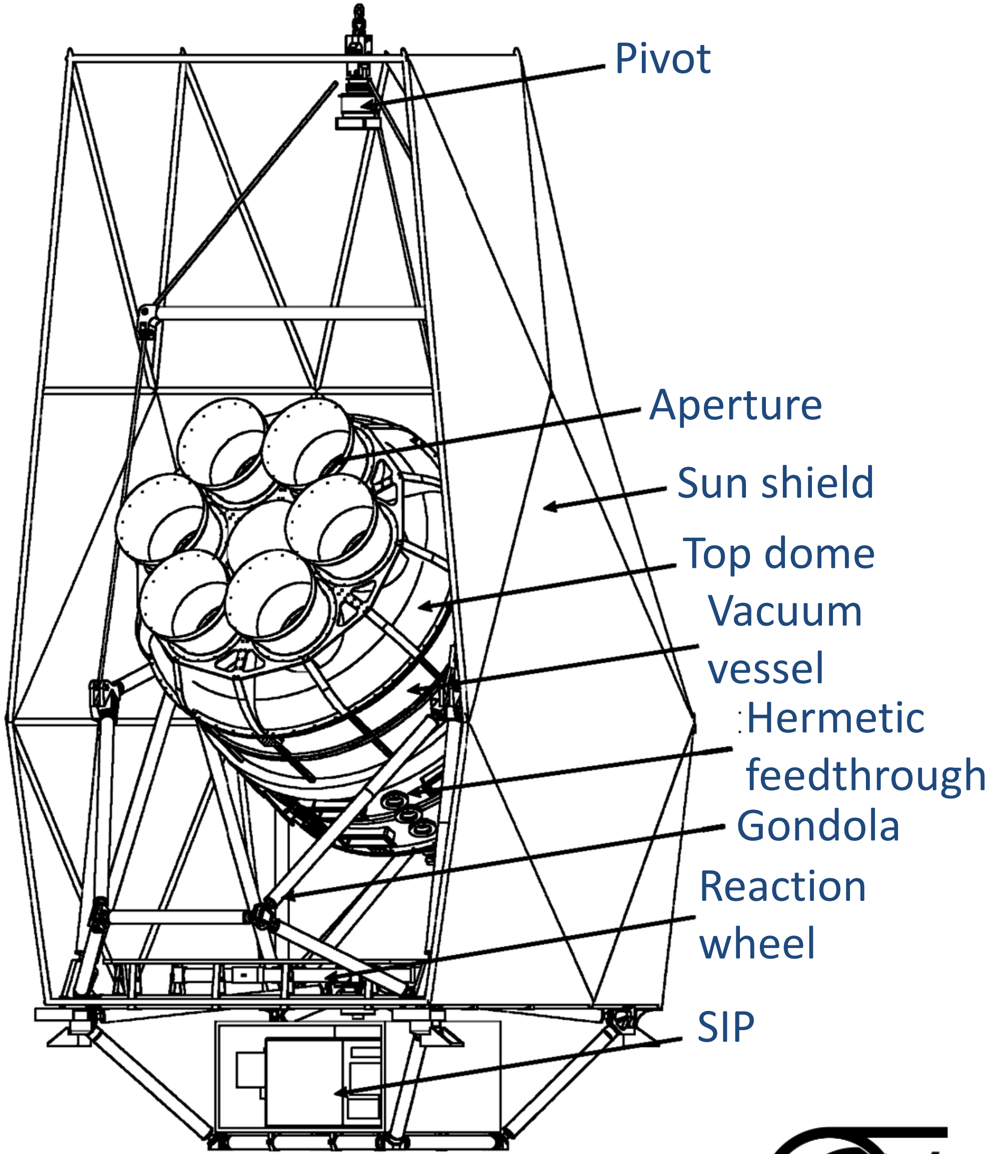


Spider 2015: Overview

Sky coverage	About 10 %
Scan rate (az, sinusoid)	3.6 deg/s at peak
Polarization modulation	Stepped cryogenic HWP
Detector type	Antenna-coupled TES
Multipole range	$10 < \ell < 300$
Observation time	16 days at 36 km
Limits on r[†]	0.03

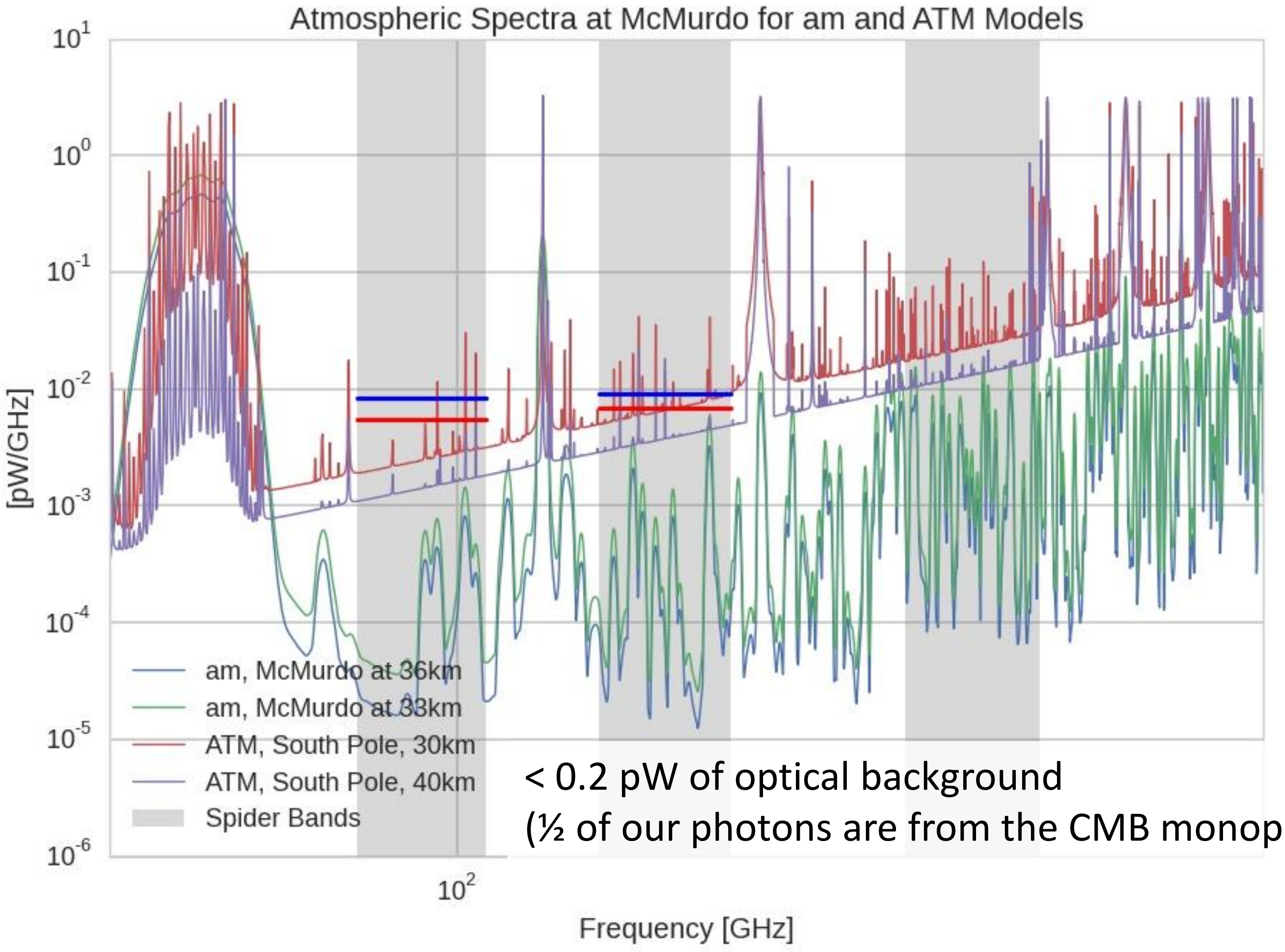
[†] Ignoring all foregrounds, at 99% confidence

	Frequency [GHz]	
	94	150
Telescopes	3	3
Bandwidth [GHz]	22	36
Optical efficiency	30-45%	30-50%
Angular resolution[*] [arcmin]	42	28
Number of detectors[†]	652 (816)	1030 (1488)
Optical background[‡] [pW]	≤ 0.25	≤ 0.35
Instrument NET[†] [μK·rts]	6.5	5.1
[*]FWHM. [†]Only counting those currently used in analysis [‡]Including sleeve, window, and baffle		



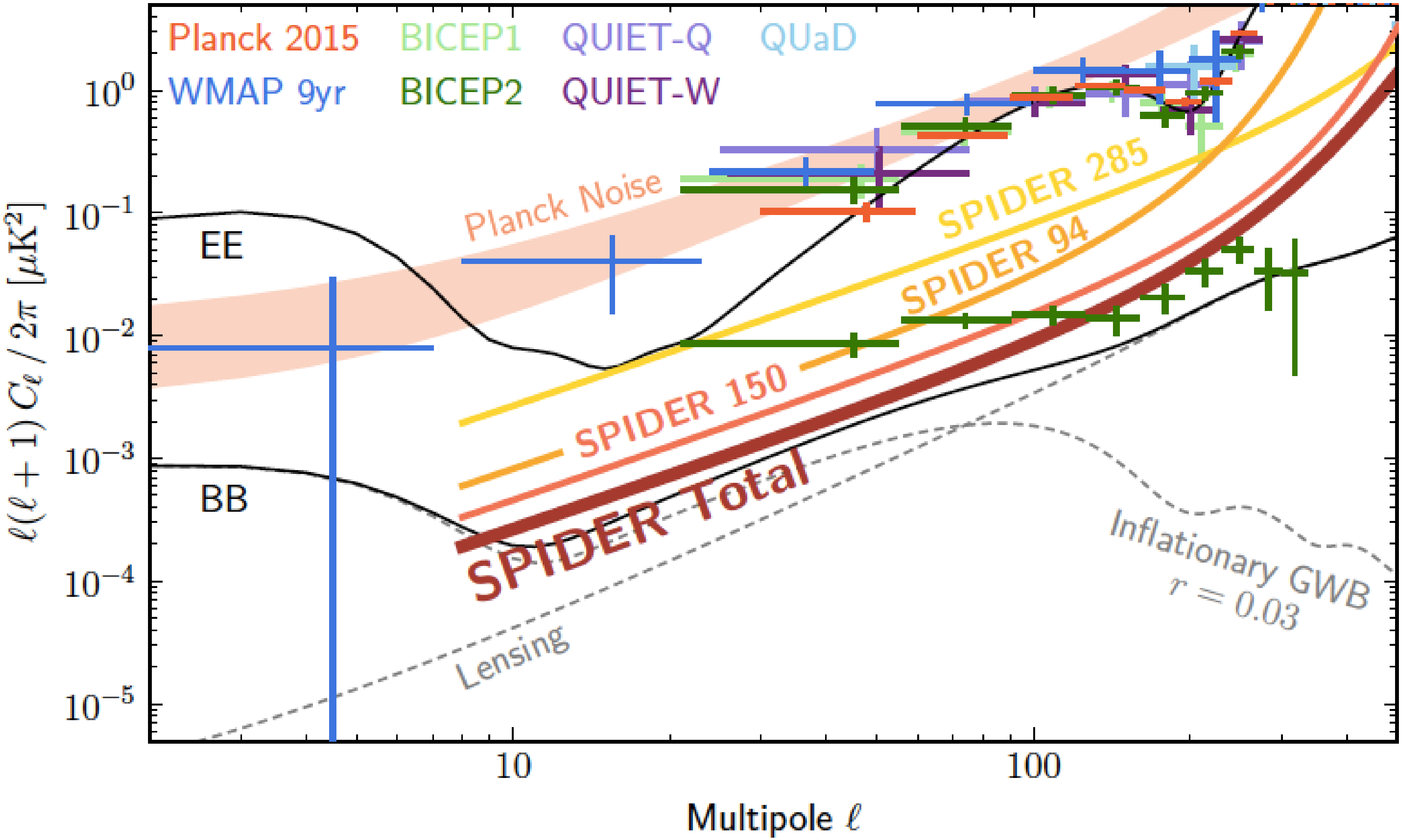
Sub-orbital radiative environment:

radiative backgrounds comparable to that of *Planck* HFI

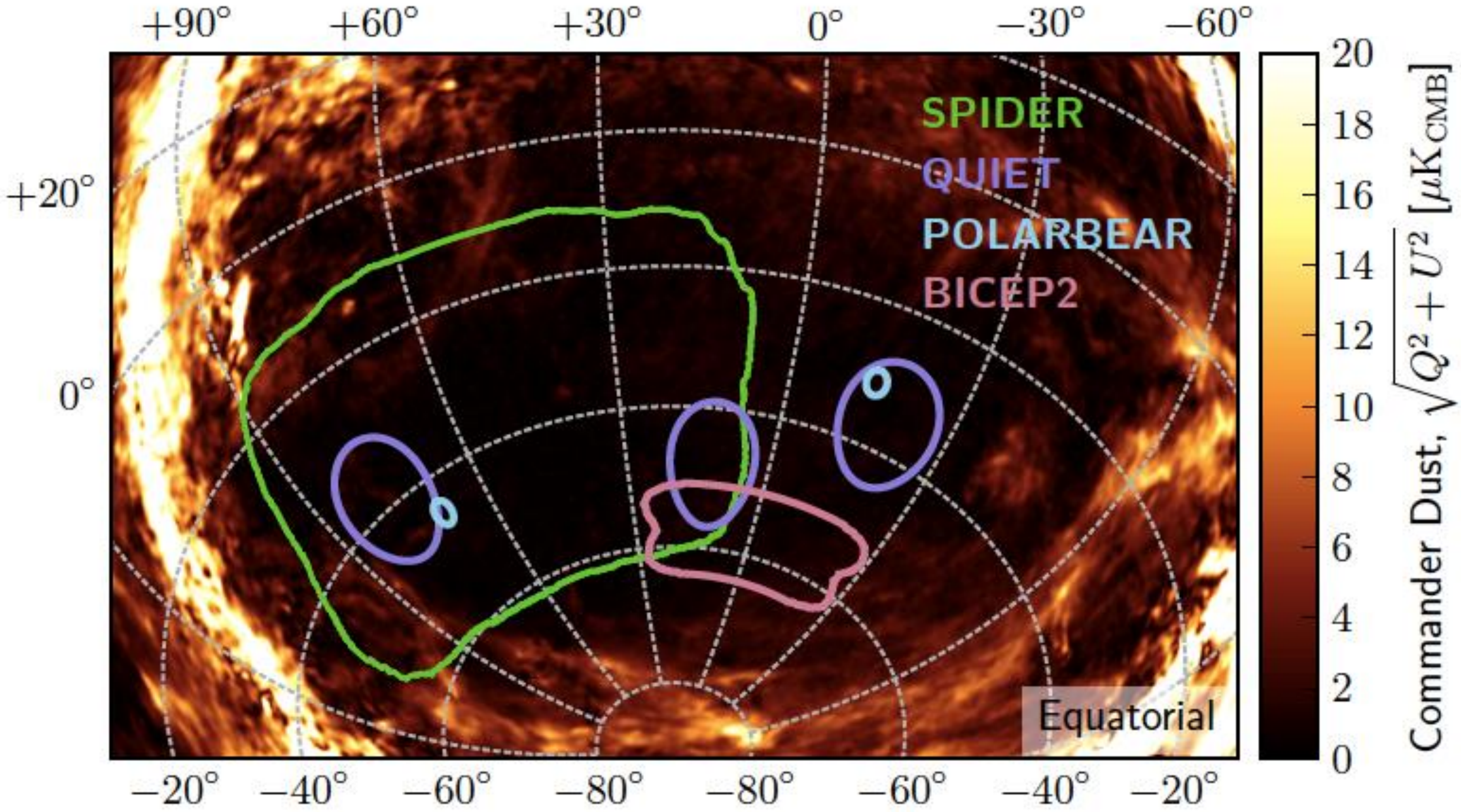


< 0.2 pW of optical background
(½ of our photons are from the CMB monopole!)

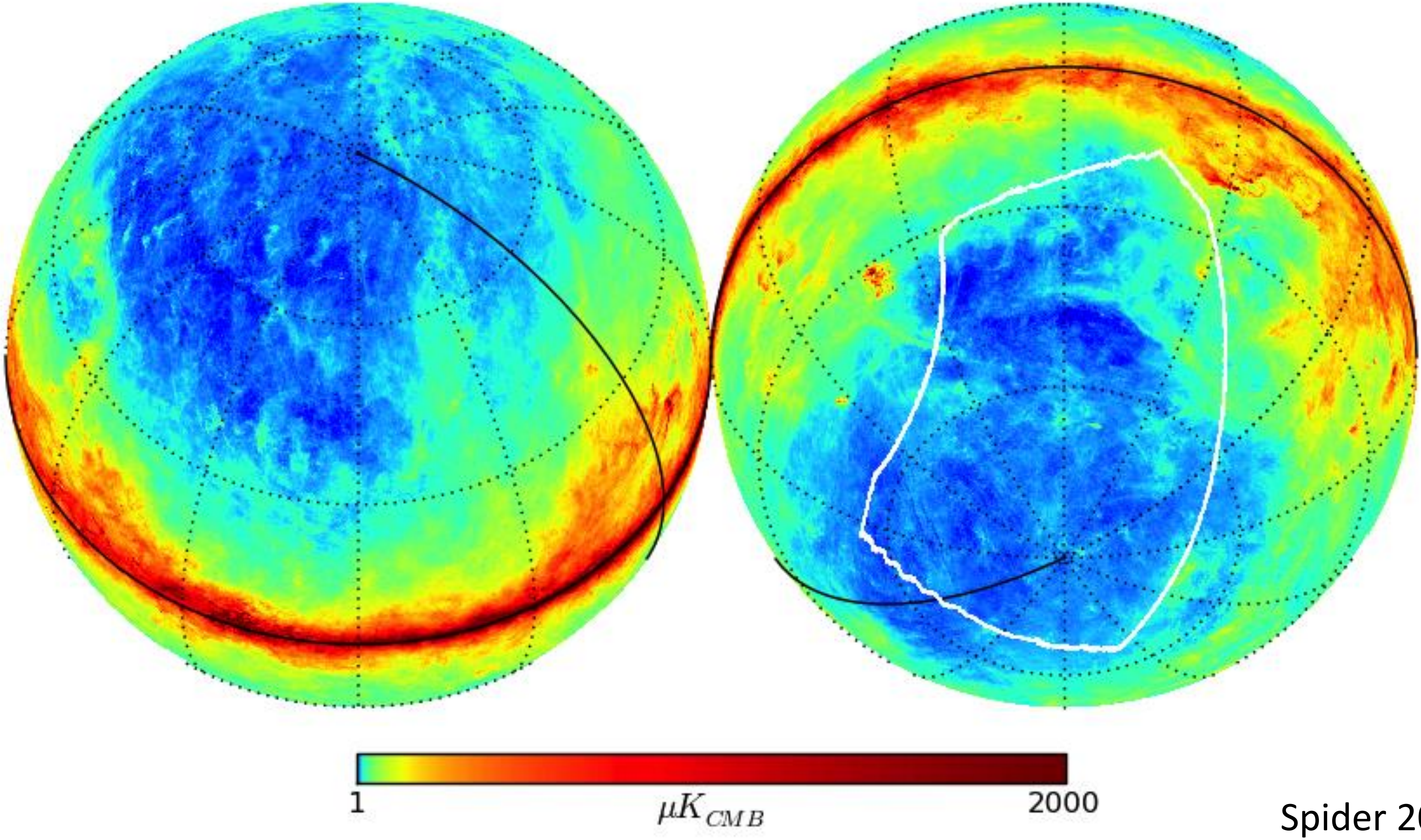
Spider 2015: flight performance



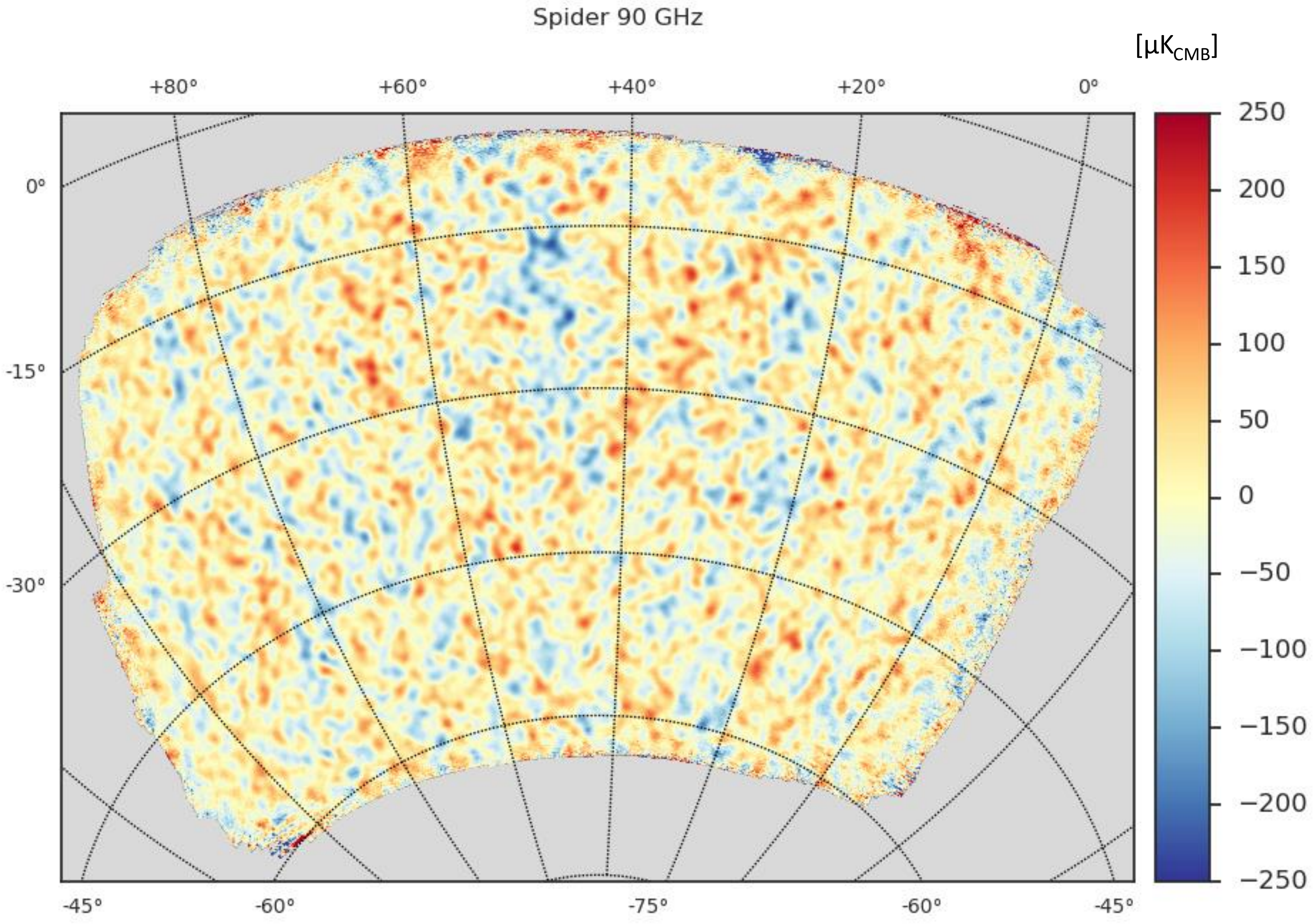
Spider 2015: survey coverage

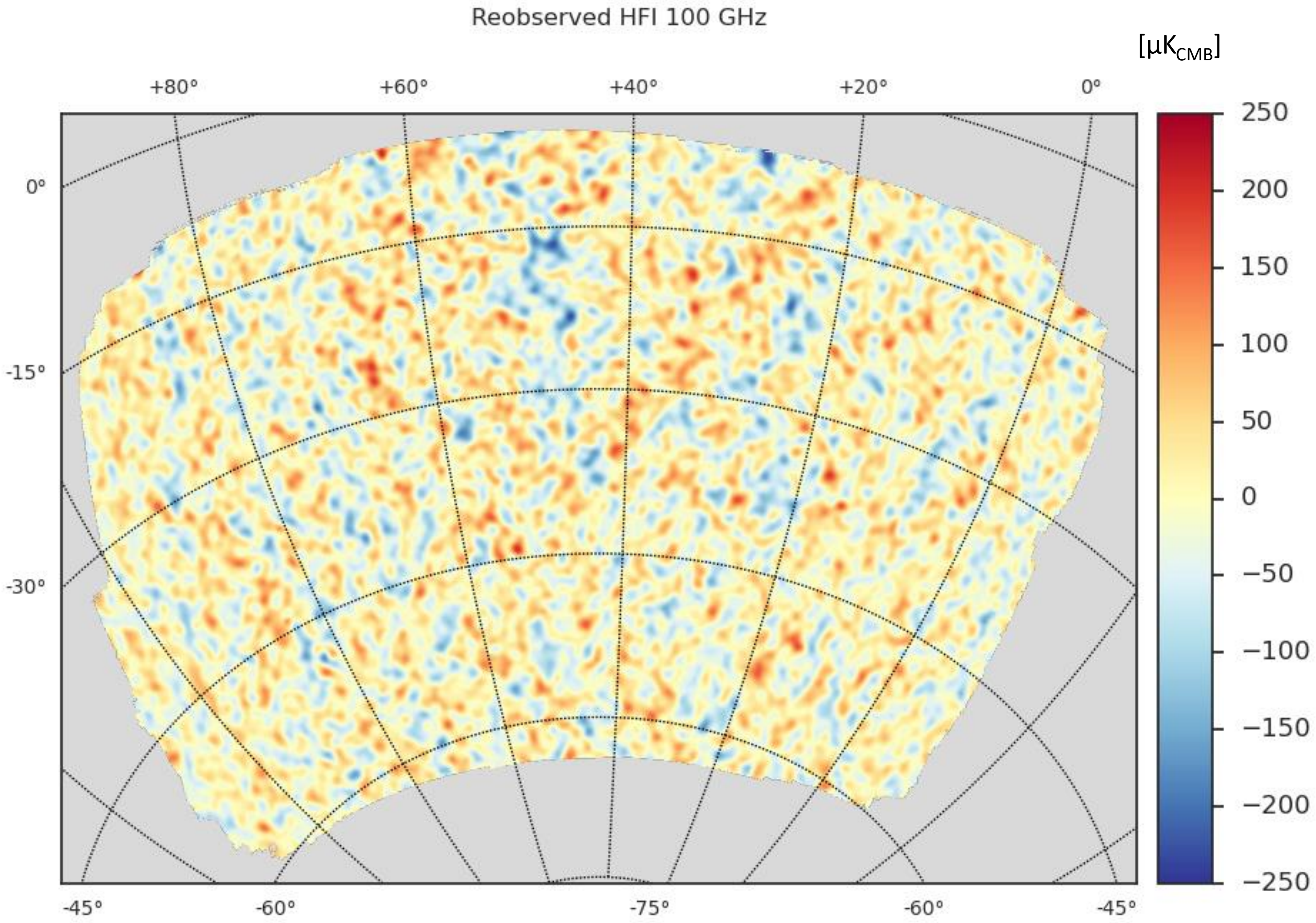


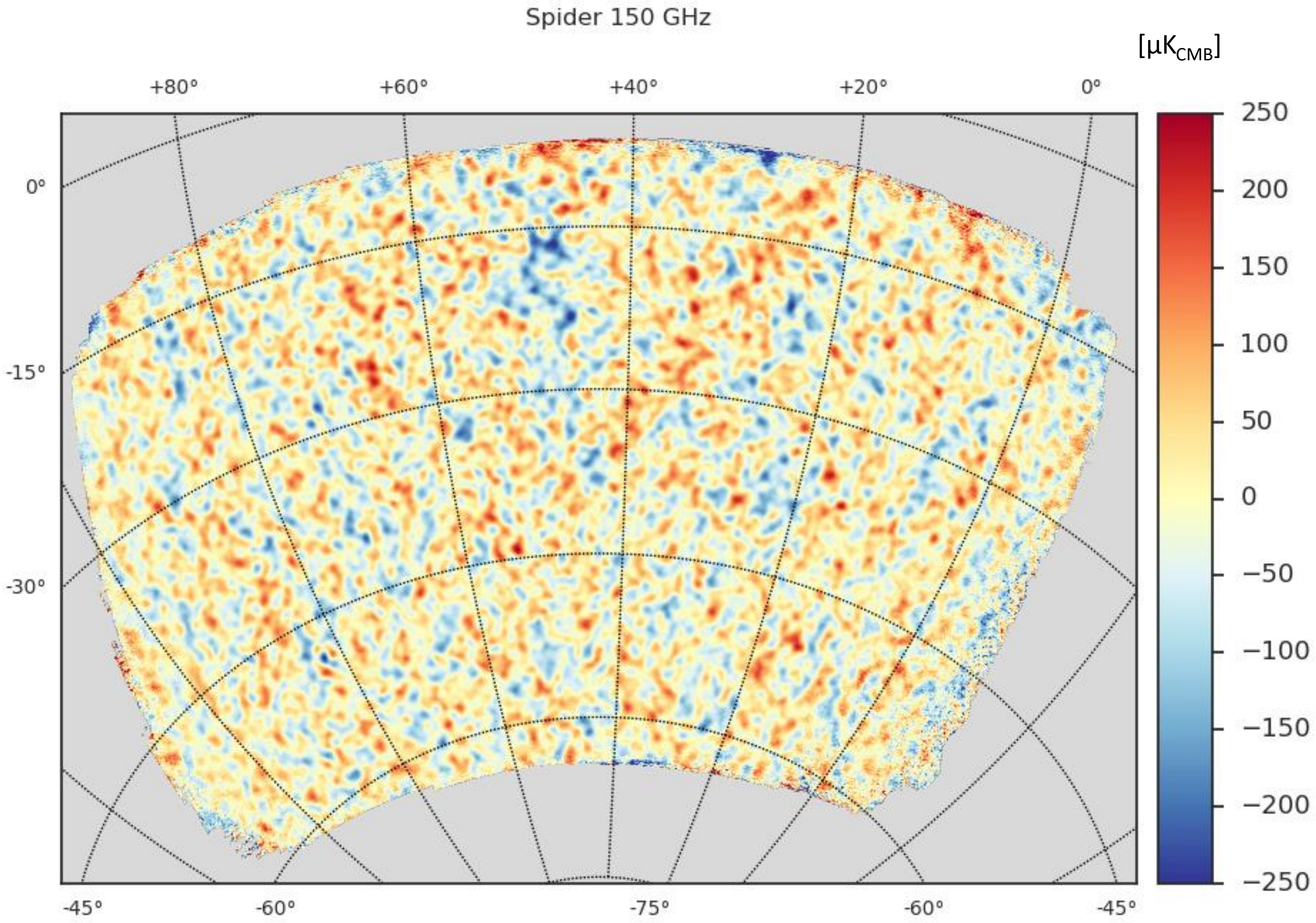
The observational challenge:

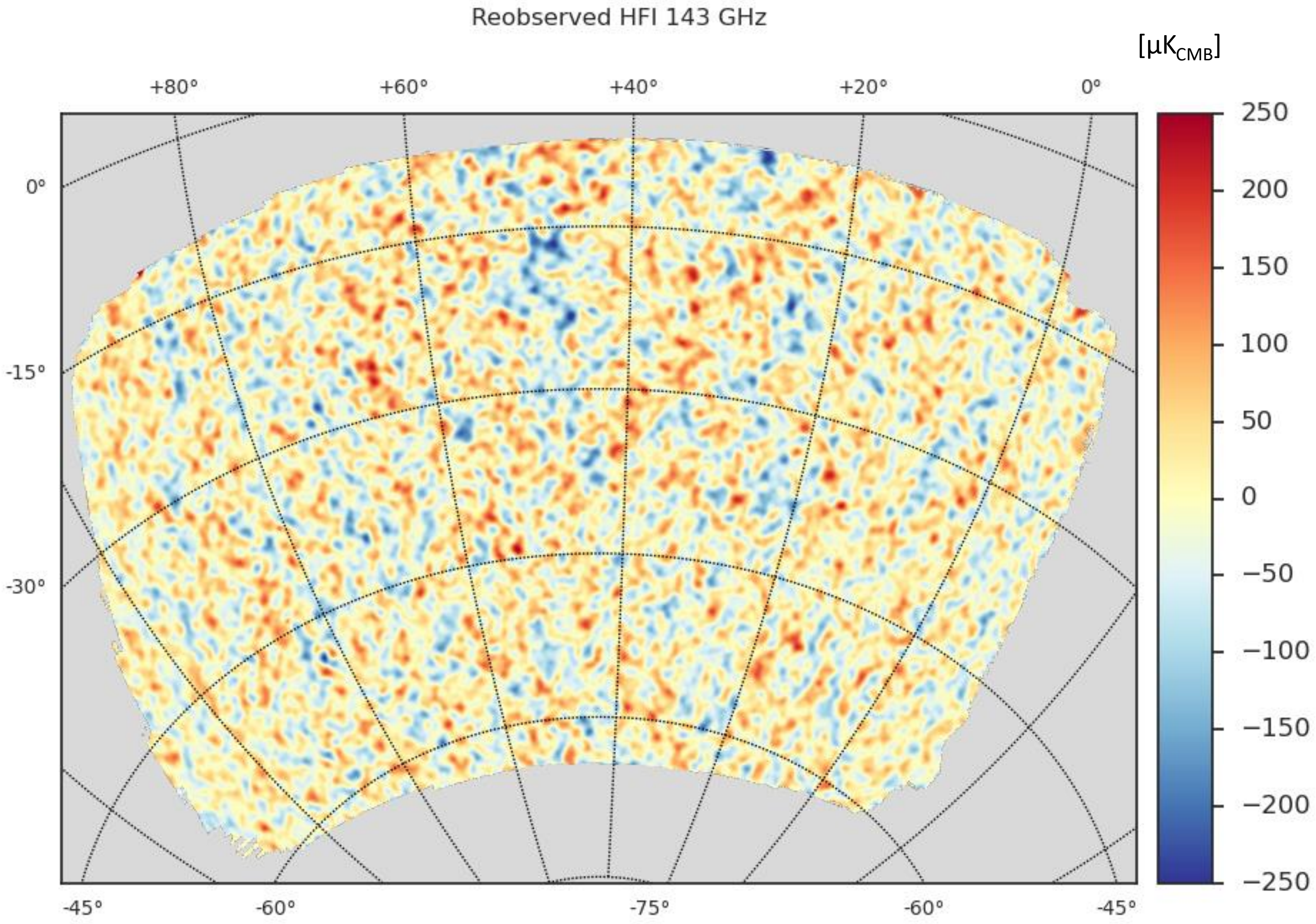


Spider 2015

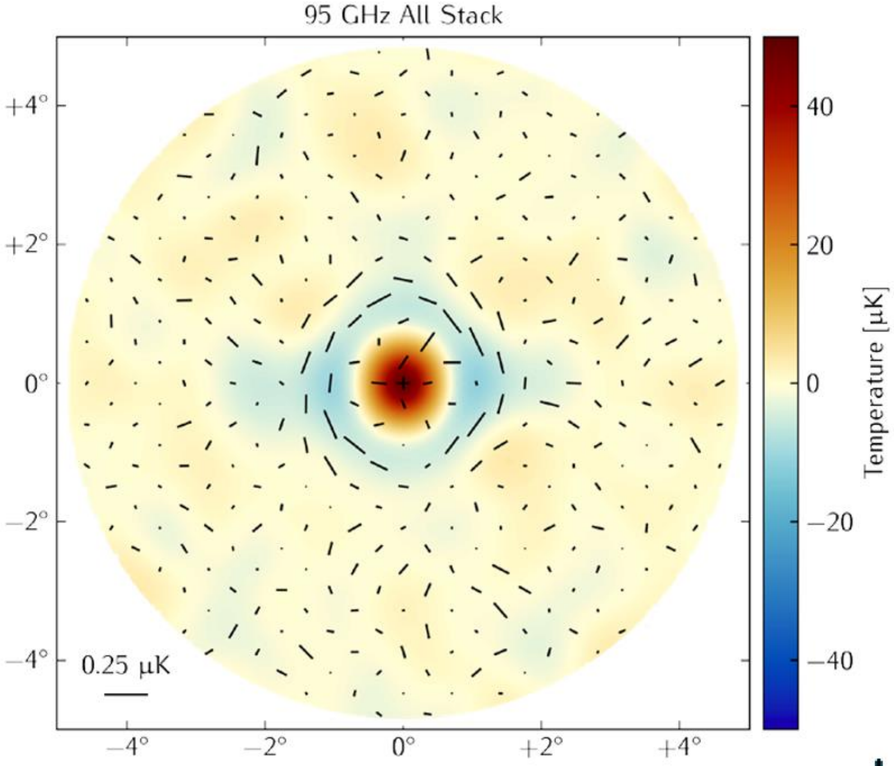

Spider 90 GHz
[μK$_{CMB}$]
+80°
+60°
+40°
+20°
0°
0°
-15°
-30°
-45°
-60°
-75°
-60°
-45°
250
200
150
100
50
0
−50
−100
−150
−200
−250

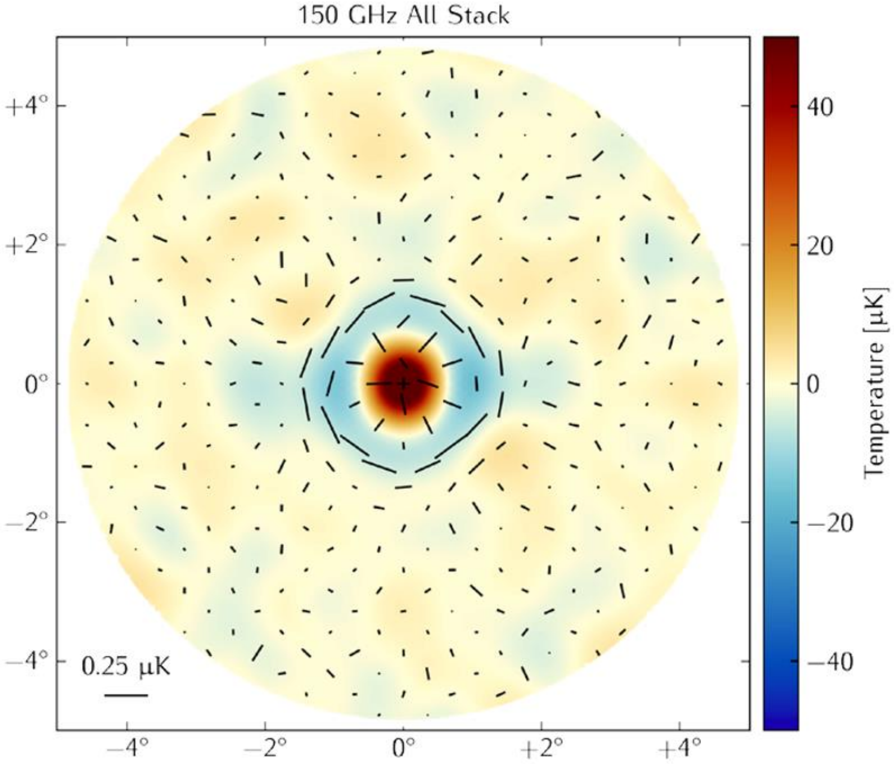

Reobserved HFI 100 GHz
[μK$_{CMB}$]
+80°
+60°
+40°
+20°
0°
0°
-15°
-30°
-45°
-60°
-75°
-60°
-45°
250
200
150
100
50
0
−50
−100
−150
−200
−250


Spider 150 GHz
[μK_{CMB}]
+80°
+60°
+40°
+20°
0°
0°
-15°
-30°
-45°
-60°
-75°
-60°
-45°
250
200
150
100
50
0
−50
−100
−150
−200
−250


Reobserved HFI 143 GHz
[μK$_{CMB}$]
+80°
+60°
+40°
+20°
0°
0°
-15°
-30°
-45°
-60°
-75°
-60°
-45°
250
200
150
100
50
0
−50
−100
−150
−200
−250

Stacking hot spots : SPIDER

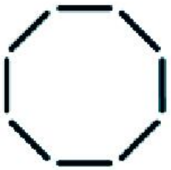




PRELIMINARY

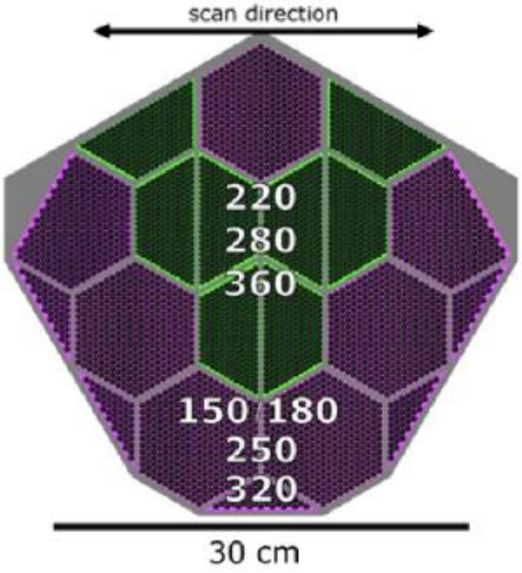
PRELIMINARY

E-modes

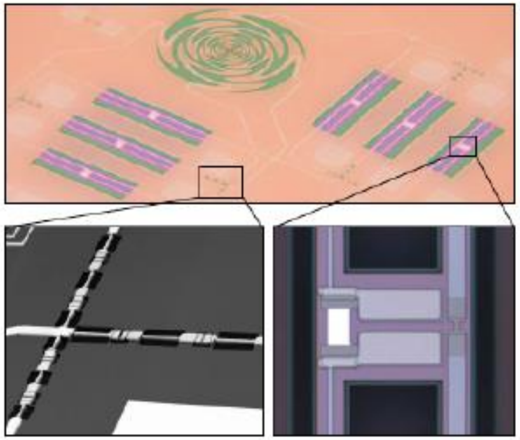


EBEX-IDS

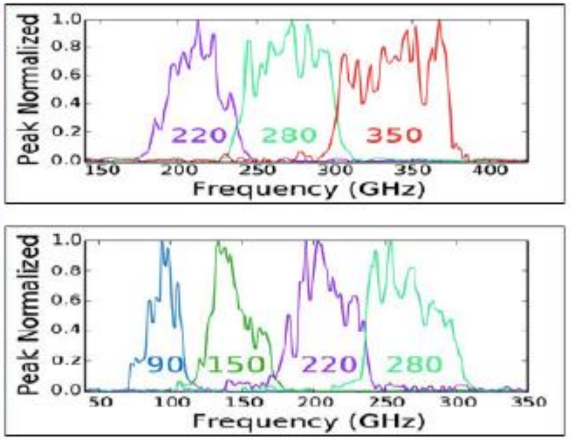
- 7 bands: 150, 180, 220, 250, 280, 320, 360 GHz
- 1500 sq. deg. Co-observe with BICEP/Keck + Simmons Array
- Sinuous Antenna Trichroic Pixels (PB2, SPTPol, LiteBIRD)

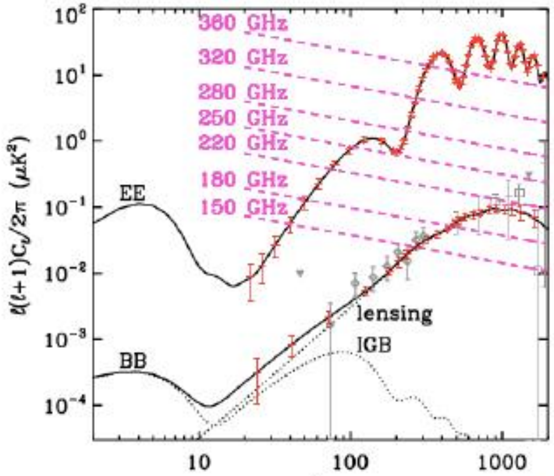


Total of 20562 detectors

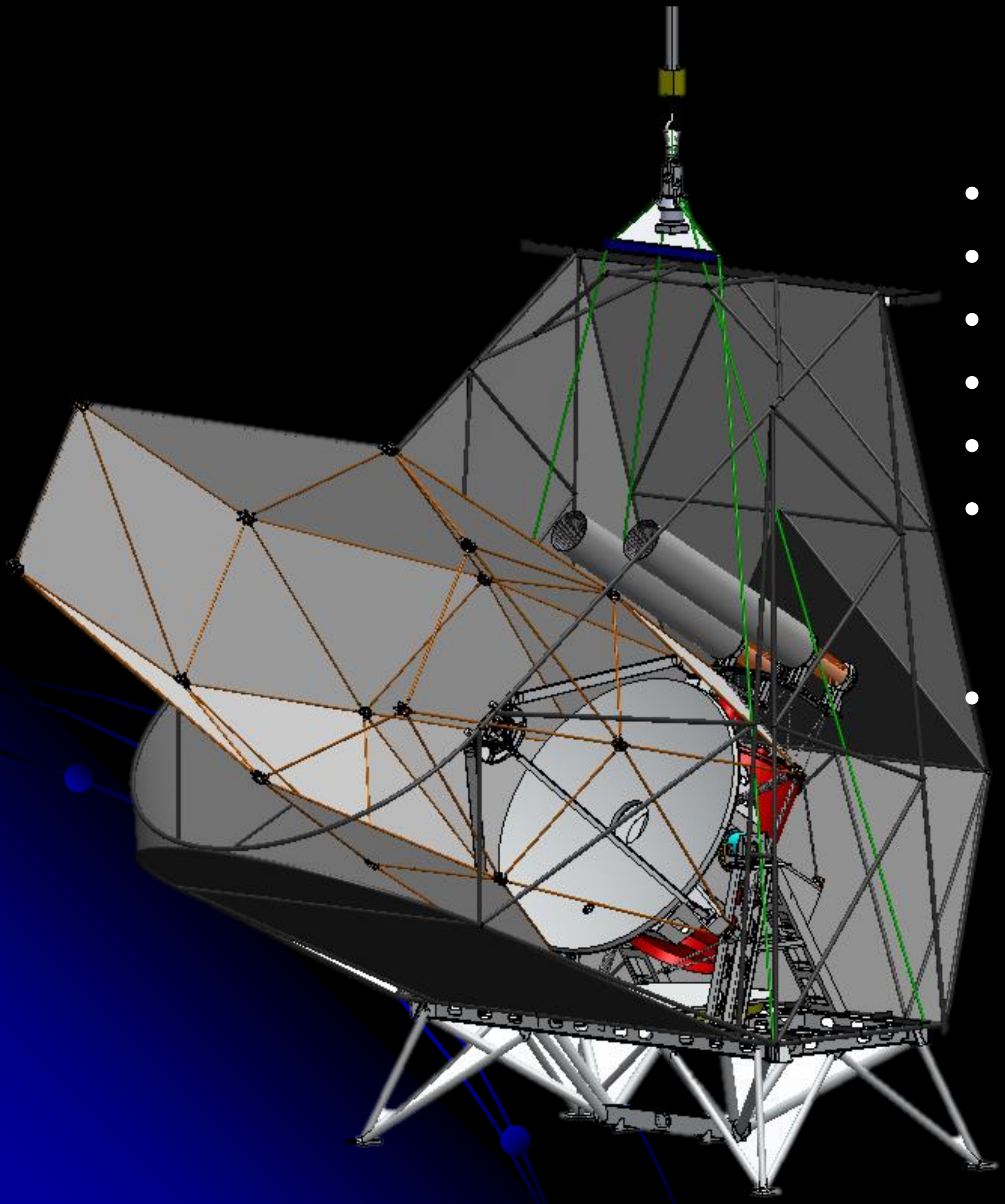


Lee + Westbrook, UCB





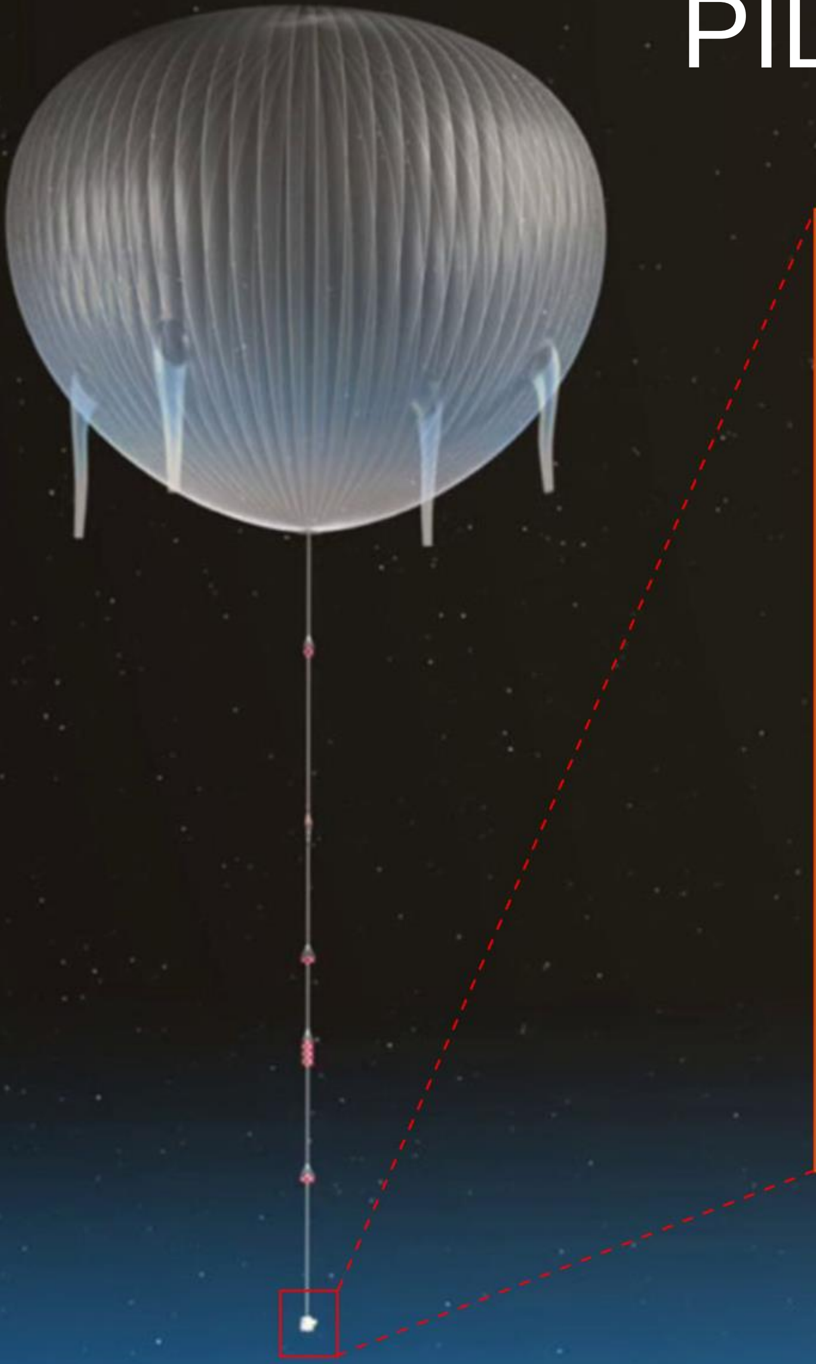
BLAST-TNG

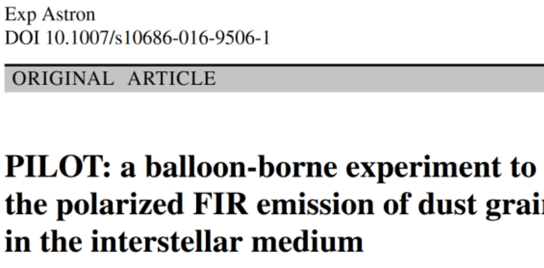


- 2.5 meter Carbon Fiber Mirror
- 2200 Polarized KID detectors
- Three bands: 250, 350, and 500 μm
- 22 arcsec resolution at 250 μm
- 28 day flight!
- 10 times the mapping speed of BLAST-pol

- First flight December 2018 (TBC) with Shared Risk Observing

PILOT





Exp Astron
DOI 10.1007/s10686-016-9506-1

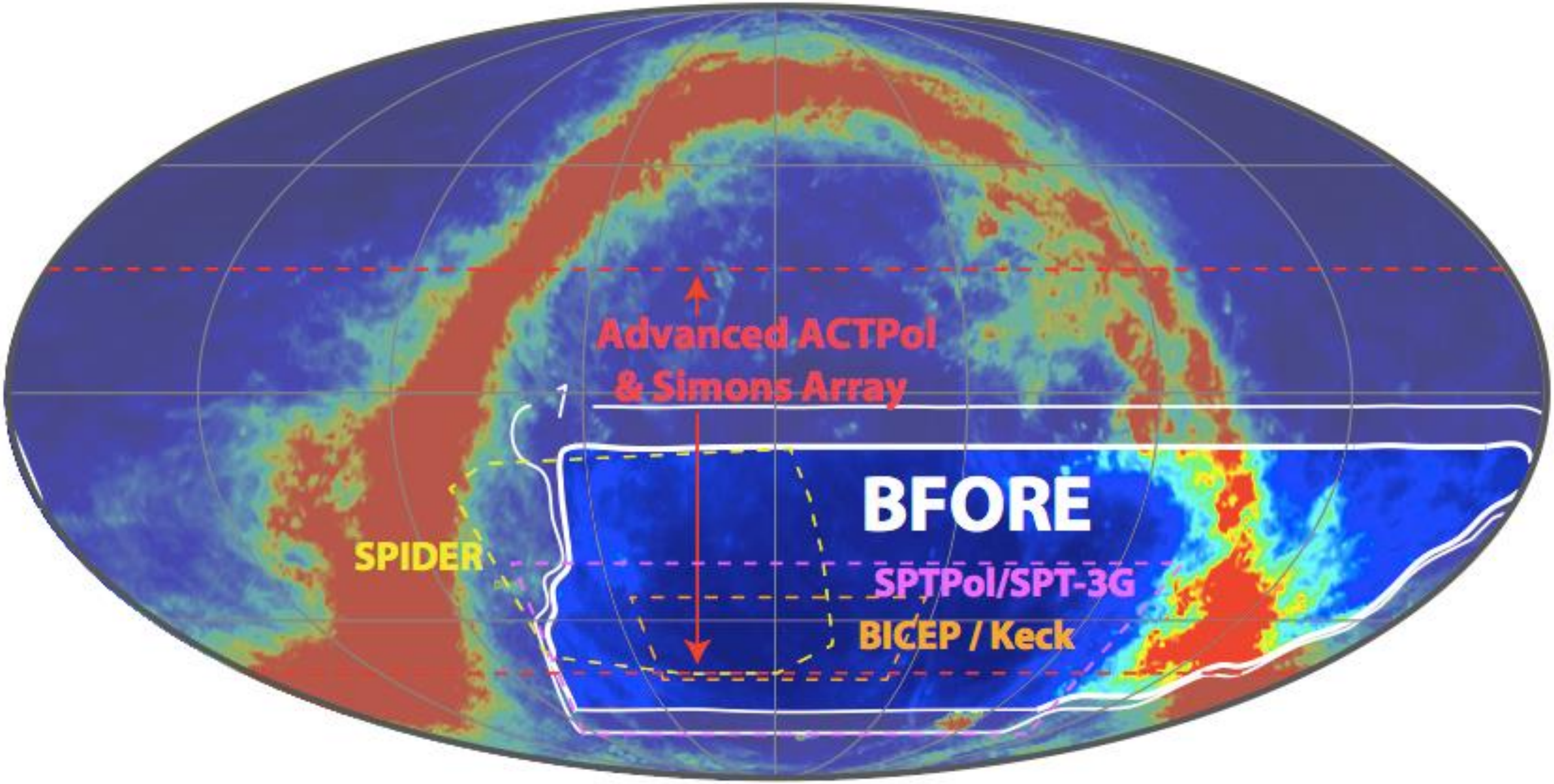
ORIGINAL ARTICLE

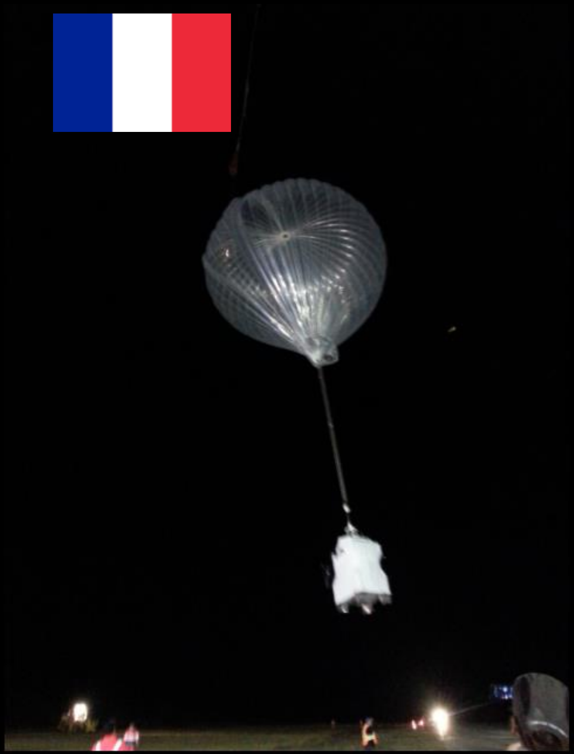
PILOT: a balloon-borne experiment to
the polarized FIR emission of dust grai
in the interstellar medium

Table 1 Key characteristics and performance of the *PILOT* instrument in its nominal configuration. The last lines gives the expected 3σ performance in the two extreme observing modes corresponding to deep ($5^{\square}$/hour) and large ($150^{\square}$/hour) surveys respectively, where the $^{\square}$ symbol stands for square degree. Our estimated polarization sensitivity assumes a dust polarization fraction of 10 %

Primary mirror diameter [mm]	730	
Equivalent focal length [mm]	1800	
Numerical aperture	$F/2.5$	
Detector temperature [mK]	300	
Mapping speed [$^{\square}$/h]	[5-150]	
FOV [°]	1.0 × 0.8	
	SW Band	LW Band
λ_0 [μm]	240	550
ν_0 [GHz]	1250	545
$\Delta\nu/\nu$	0.27	0.31
Tr(dust)	0.025	0.136
beam FWHM [′]	1.9	3.29
Number of Detectors	1024	1024
background [pW/pix]	5.7	4.0
NEP$_{Det}$ [$W/\sqrt{Hz}$]	$2.0\,10^{-16}$	$2.0\,10^{-16}$
NEP$_{Phot}$ [$W/\sqrt{Hz}$]	$9.8\,10^{-17}$	$6.0\,10^{-17}$
NEP$_{Tot}$ [$W/\sqrt{Hz}$]	$2.2\,10^{-16}$	$2.1\,10^{-16}$
Sensitivity (3σ in 3.5′)		
Intensity [MJy/sr]	[0.98-6.28]	[0.33-2.13]
Av [mag]	[0.05-0.30]	[0.12-0.75]
Av polar [mag]	[0.47-2.99]	[1.17-7.48]

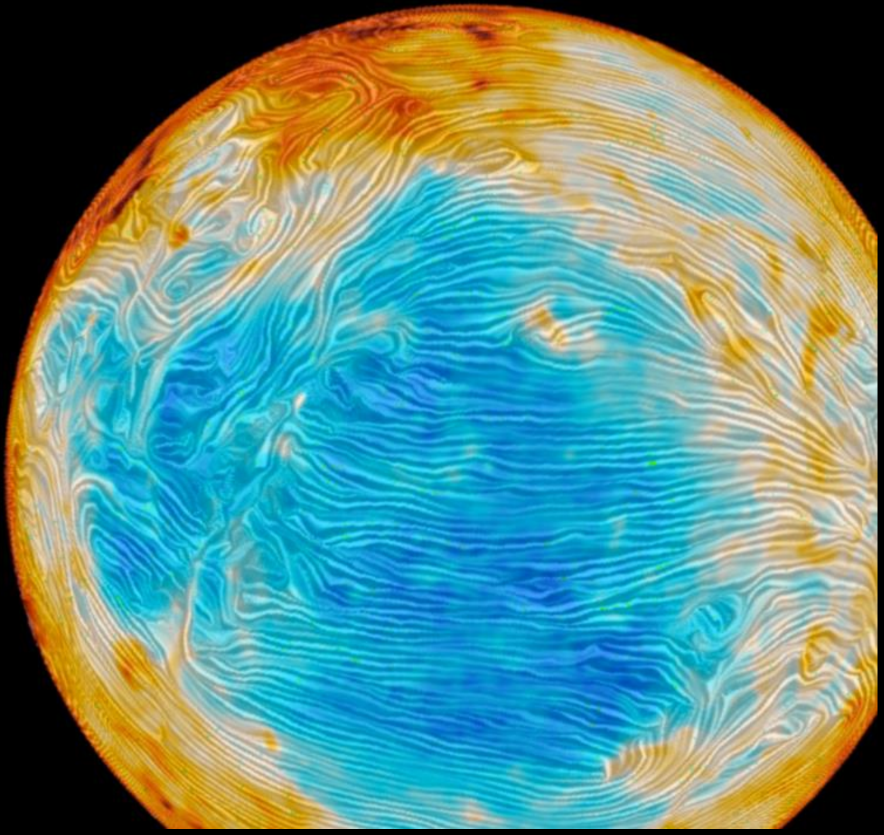
BFORE


Advanced ACTPol
& Simons Array
BFORE
SPIDER
SPTPol/SPT-3G
BICEP / Keck



BSIDE

A balloon project to map dust polarization with the accuracy required to search for primordial B-modes down to a tensor-to-scalar ratio $r = 0.01$



B-SIDE Requirements

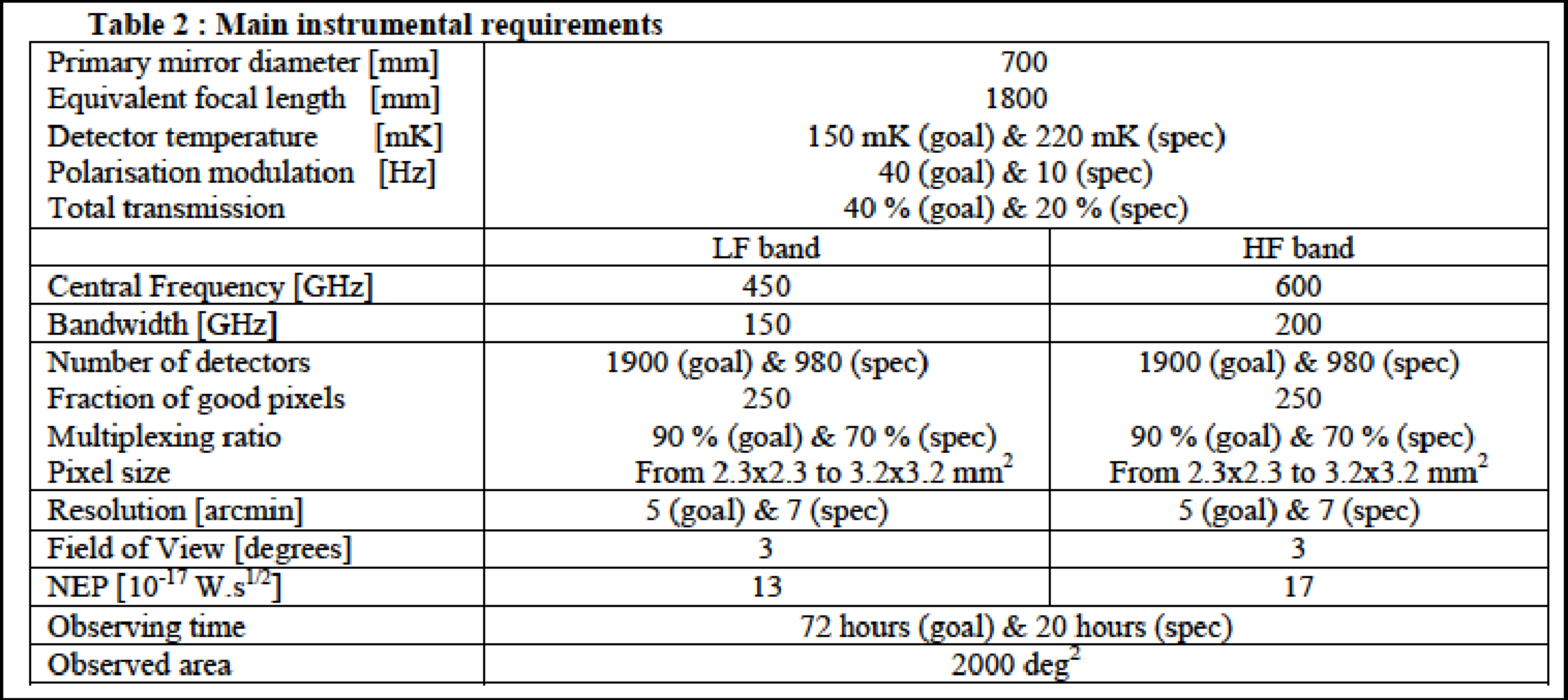


Table 2 : Main instrumental requirements

Primary mirror diameter [mm]	700	
Equivalent focal length [mm]	1800	
Detector temperature [mK]	150 mK (goal) & 220 mK (spec)	
Polarisation modulation [Hz]	40 (goal) & 10 (spec)	
Total transmission	40 % (goal) & 20 % (spec)	
	LF band	HF band
Central Frequency [GHz]	450	600
Bandwidth [GHz]	150	200
Number of detectors	1900 (goal) & 980 (spec)	1900 (goal) & 980 (spec)
Fraction of good pixels	250	250
Multiplexing ratio	90 % (goal) & 70 % (spec)	90 % (goal) & 70 % (spec)
Pixel size	From 2.3x2.3 to 3.2x3.2 mm^2	From 2.3x2.3 to 3.2x3.2 mm^2
Resolution [arcmin]	5 (goal) & 7 (spec)	5 (goal) & 7 (spec)
Field of View [degrees]	3	3
NEP [10^{-17} W.$s^{1/2}$]	13	17
Observing time	72 hours (goal) & 20 hours (spec)	
Observed area	2000 deg^2	

- B-SIDE data to be combined with ground-based observations at 95, 150, 220 GHz and Planck 353 GHz
- We are discussing a joint data analysis with the BICEP/Keck and the Polarbear/Simons array teams

Credit: Ken Ganga

Bside datasheet

OPTICS:
- M1 = 0.8 m
- M2 and M3 at 50K
- FoV = 3 deg
- Angular resolution (540 GHz) ~ 3 arc-min

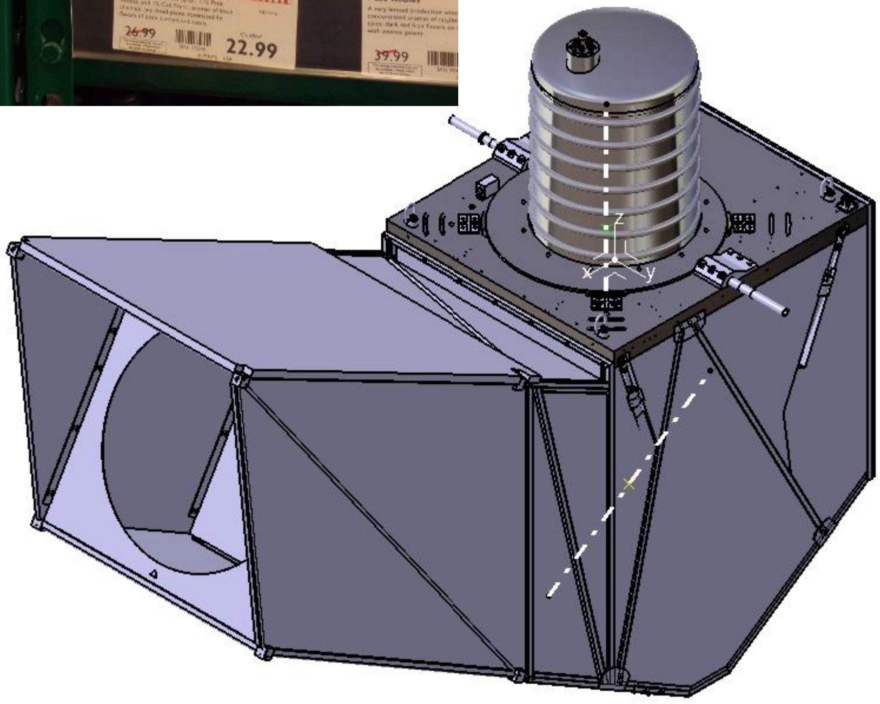
DETECTORS:
- Baseline (2018): 493 x 2 = **986 KID**
- Angular resolution (baseline) **~ 7 arc-min**
- Electronics power consumption < 150 W
- Cryostat cabled for 2000 KID at the beginning
- Angular resolution (2000 KID) ~ 5 arc-min
- Pixels 23 times bigger than PILOT !!
- Roughly 50-100 pW per pixel

  --> **Goal NEP of the order of $2 \cdot 10^{-16}$ W/Hz$^{0.5}$**

BANDS:
- Baseline: single band 450-630 GHz
- PlanB will be compatible with **two bands**,

e.g. Band 1: 450-630 GHz, Band 2: as-you-like
My choice: Band 1: 450-630GHz, Band 2: 390-540GHz

NO NEED TO DECIDE NOW !!!



Paris 05/04/2016

LSPE

the Large-Scale Polarization Explorer

Paolo de Bernardis,
Università La Sapienza, Roma, Italy
for the LSPE collaboration

Peter	Ade	University of Cardiff
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Alessandro	Baldini	INFN Pisa
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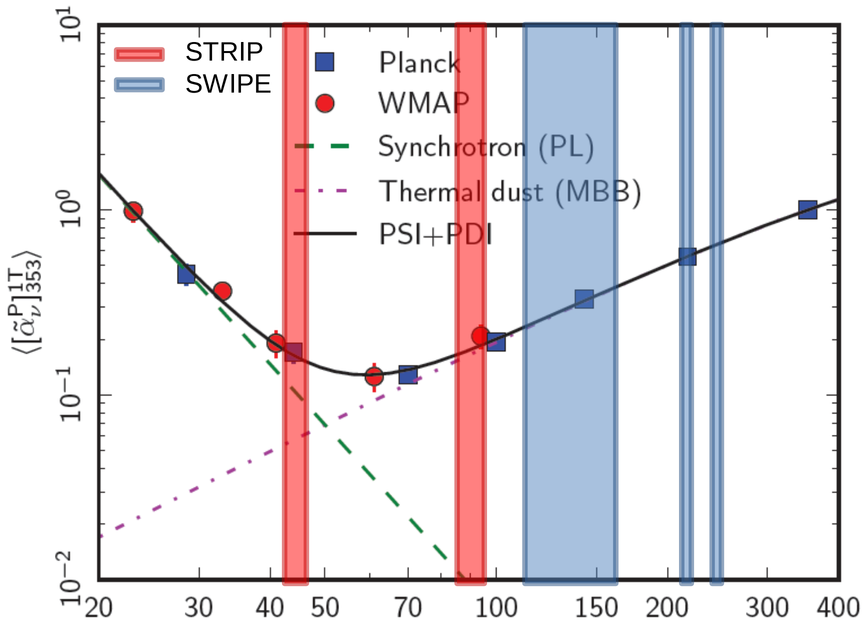
Guido	Zavattini	Università di Ferrara & INFN Ferrara

LSPE in a nutshell

- The Large-Scale Polarization Explorer is :
    - an instrument to measure the polarization of the Cosmic Microwave Background at large angular scales
    - The SWIPE instrument uses *a spinning stratospheric balloon payload* to avoid atmospheric noise, flying *long-duration, in the polar night*
    - uses a *polarization modulator* to achieve high stability
- Frequency coverage: 40 – 250 GHz (5 channels, 2 instruments: STRIP & SWIPE)
- Angular resolution: 1.3° FWHM
- Sky coverage: 20-25% of the sky per flight / year
- Combined sensitivity: 10 μK arcmin per flight
- Current collaboration: Sapienza, UNIMI, UNIMIB, IASFBO-INAF, IFAC-CNR, Uni.Cardiff, Uni.Manchester. INFN-GE, INFN-PI, INFN-RM1, INFN-RM2, INFN-FE
- See astro-ph/1208.0298, 1208.0281, 1208.0164 and forthcoming updates

LSPE : Foreground cleaning strategy



44 GHz
Monitor polarized synchrotron

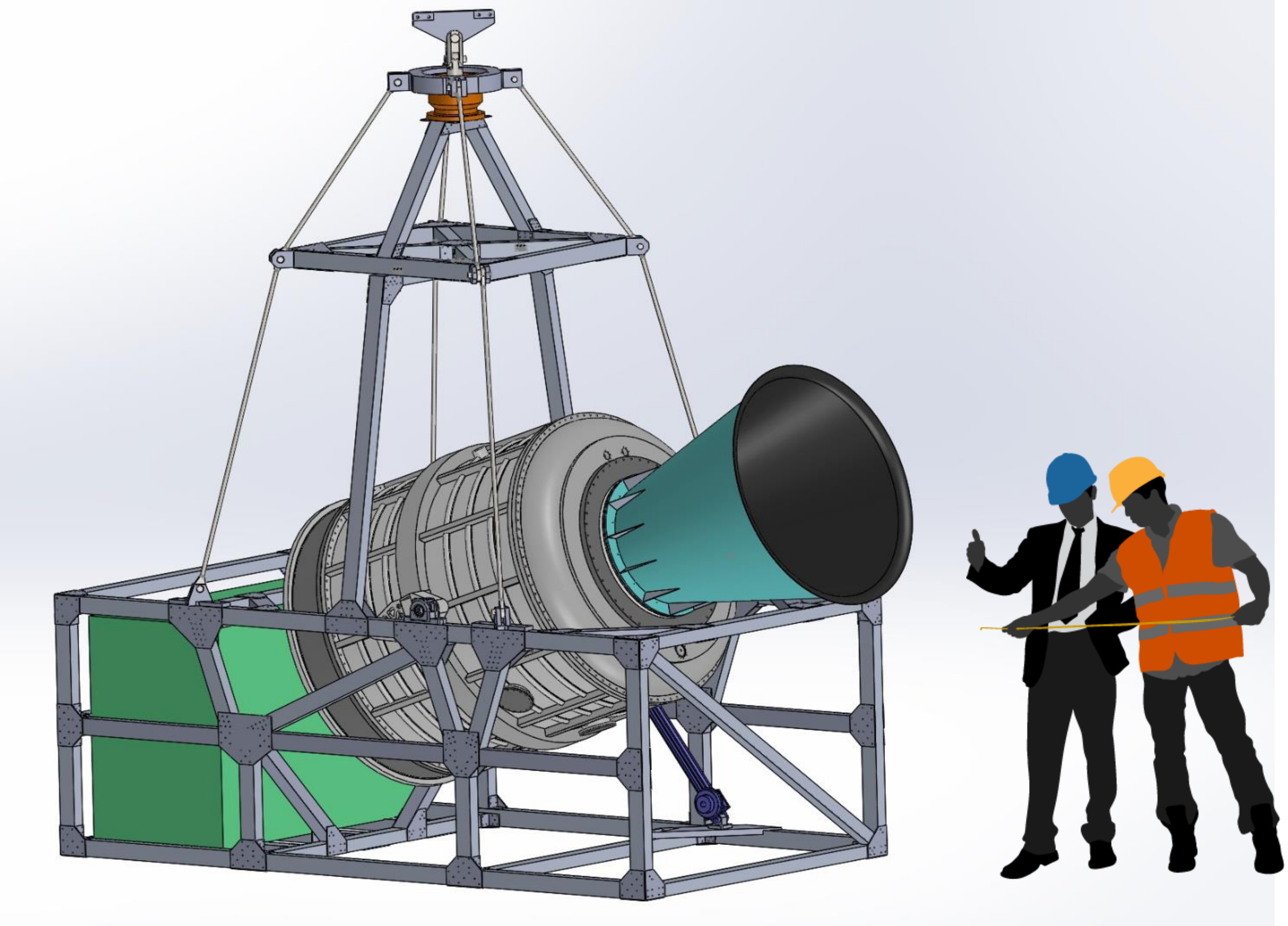
90 + 140 GHz
Main CMB channels

220 + 240 GHz
Monitor level **and slope and rotation** of polarized dust emission

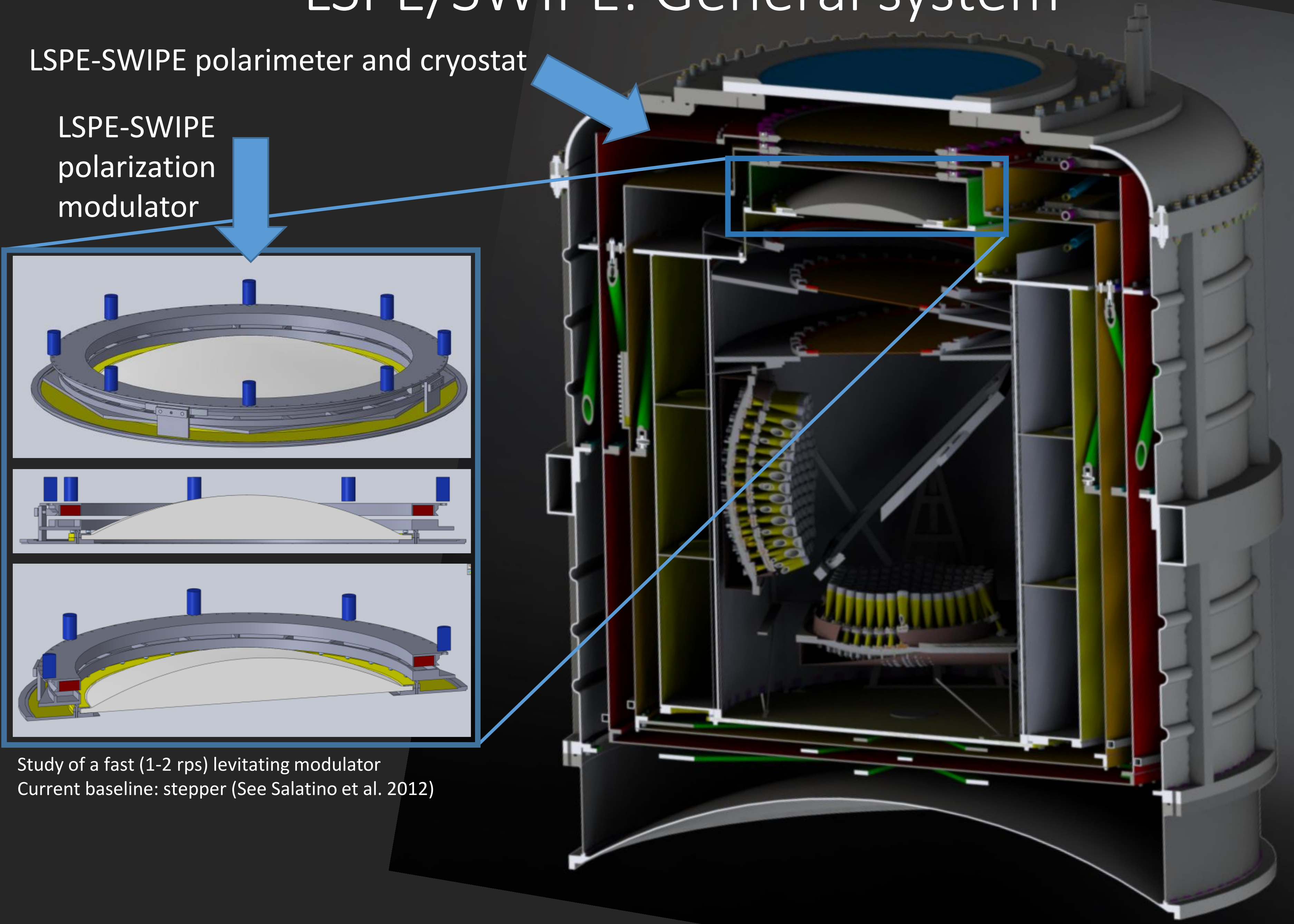
To date extrapolated from 350 GHz only

STRIP polarimeter in Tenerife)

LSPE/SWIPE



LSPE/SWIPE: General system



LSPE-SWIPE polarimeter and cryostat

LSPE-SWIPE
polarization
modulator

Study of a fast (1-2 rps) levitating modulator
Current baseline: stepper (See Salatino et al. 2012)

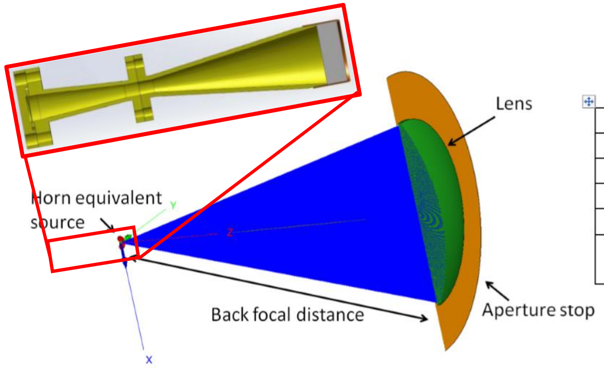
LSPE/SWIPE:
large polarizer and HWP

- Made in Cardiff (G.Pisano P. Ade, C. Tuker)
- Production phase started for polarizer and HWP, thermal filters.

50 cm diameter polarizer – defining principal angle – accurate mearuement of angles.

LSPE/SWIPE: multimode optical system

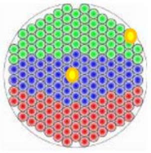
- Whole system multi.mode EM simulation described in: Legg, Lamagna, Coppi, de Bernardis, Giuliani, Gualtieri, Marchetti, Masi, Pisano, Maffei, *Development of the multi-mode horn-lens configuration for the LSPE-SWIPE B-mode experiment* Proc. SPIE 9914, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII, 991414 doi:10.1117/12.2232400

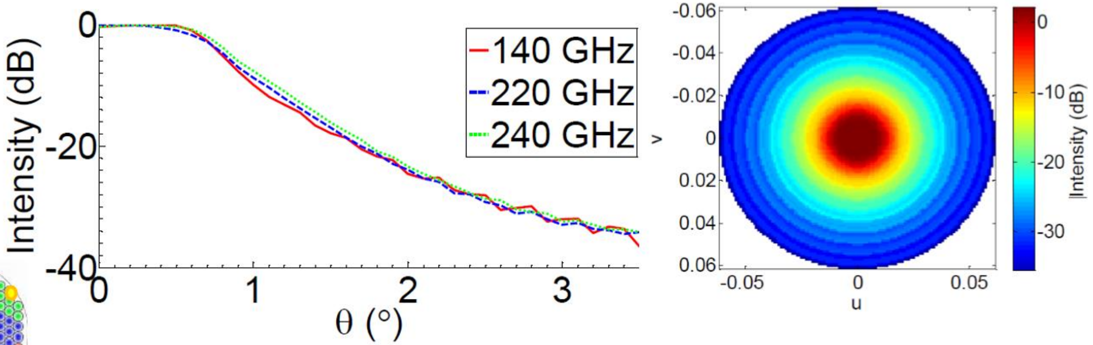


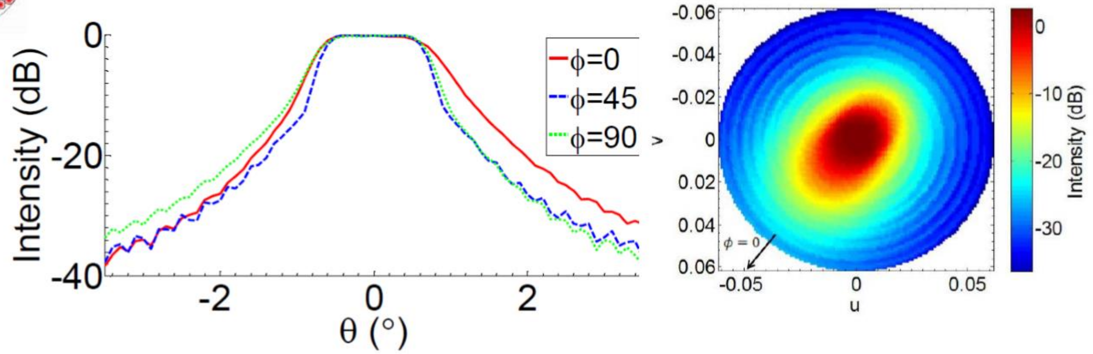
Diameter (mm)	428
Centre thickness (mm)	60
Focal length (mm)	805
Refractive index	1.57
Conic constant	-0.54
Cold stop diameter (mm)	420

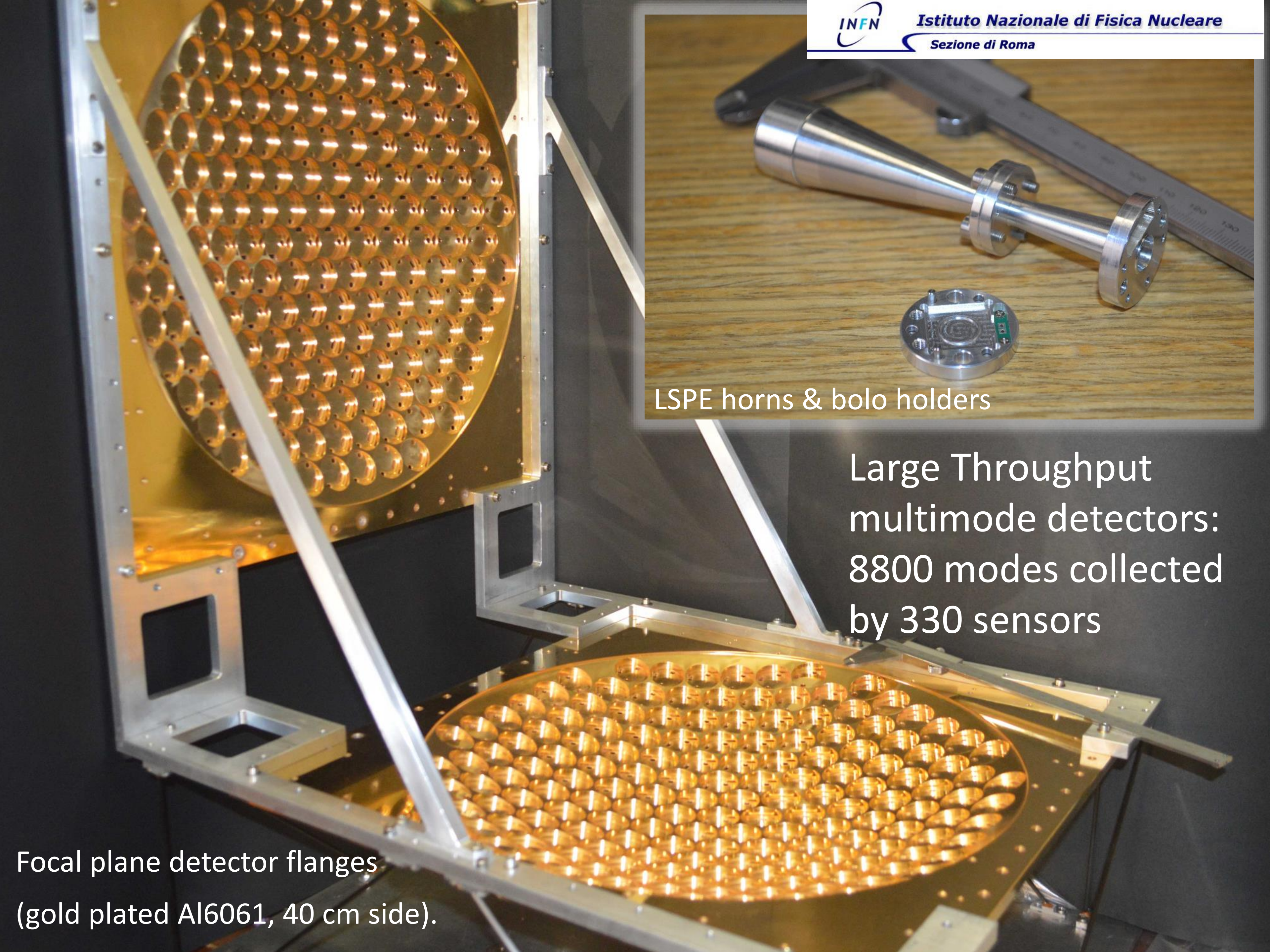
Coupling analysis – small angle beams

L. Lamagna, S. Legg





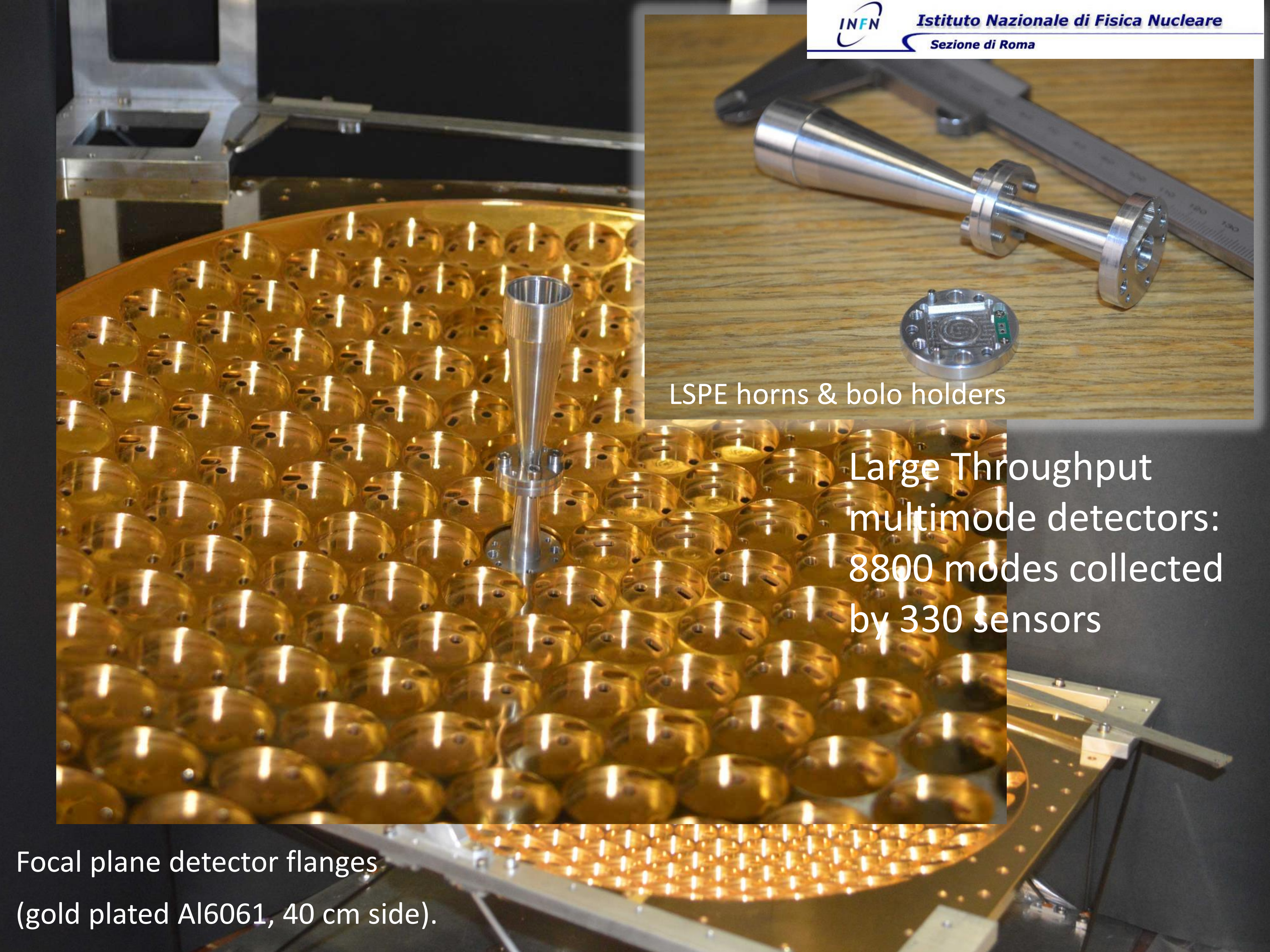




LSPE horns & bolo holders

Large Throughput multimode detectors: 8800 modes collected by 330 sensors

Focal plane detector flanges
(gold plated Al6061, 40 cm side).



LSPE horns & bolo holders

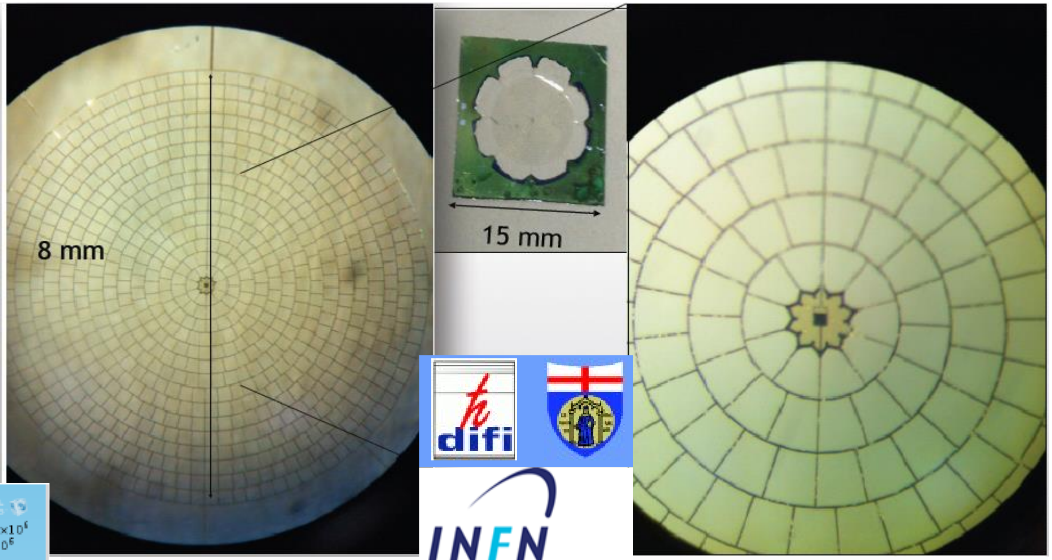
Large Throughput multimode detectors: 8800 modes collected by 330 sensors

Focal plane detector flanges

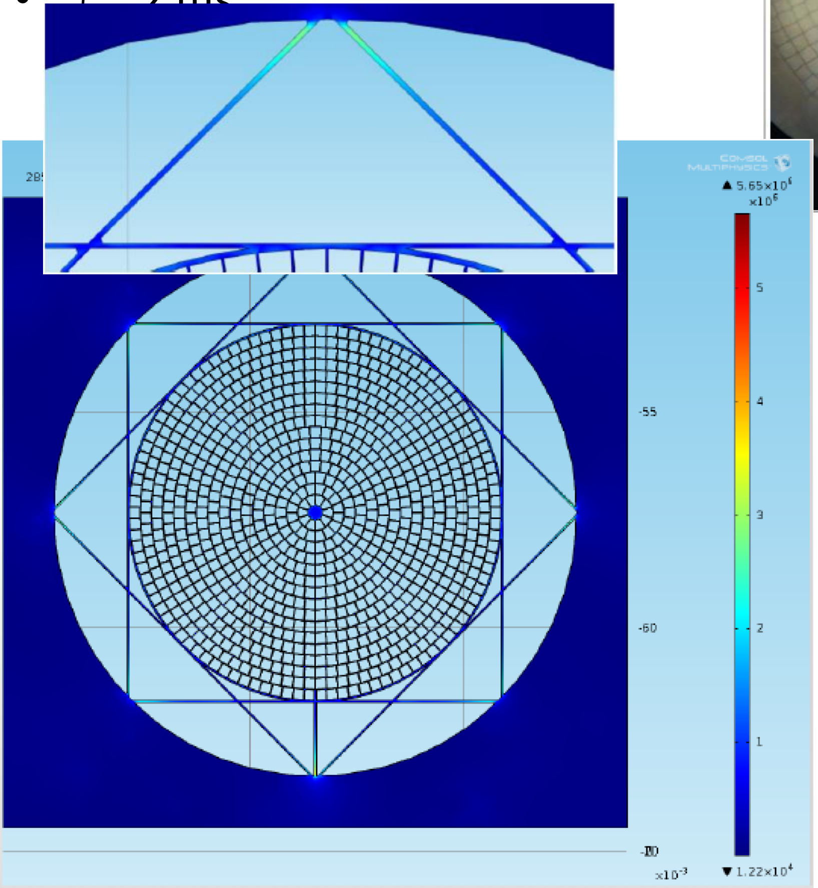
(gold plated Al6061, 40 cm side).

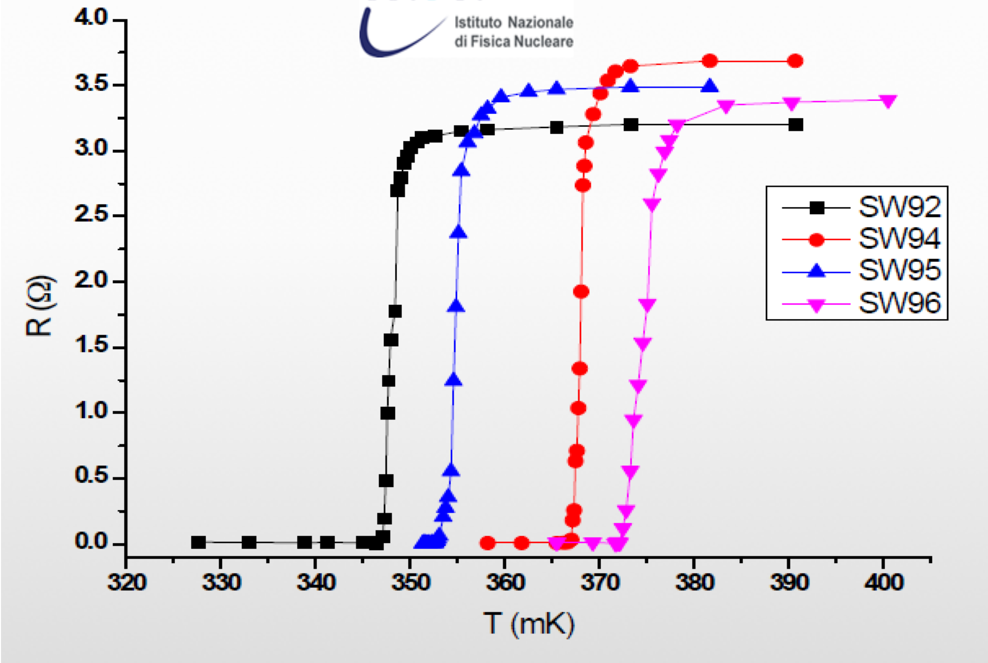
SWIPE - multimode absorbers & TES

- The absorbers are large Si_3N_4 spider-webs (8 mm diameter, multimode)
- Sensors are Ti-Au TES
- Photon noise limited
- τ = 2 ms



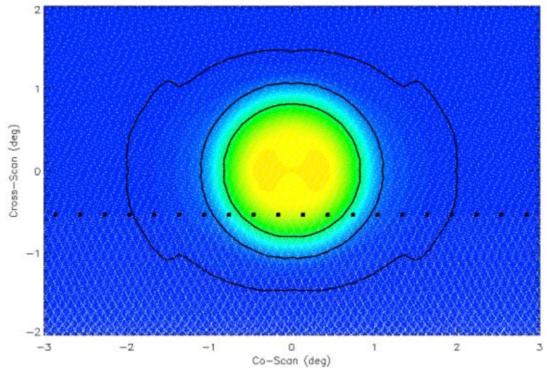
INFN Istituto Nazionale di Fisica Nucleare





Observations and Calibration Plan

- Scanning strategy: payload spin in azimuth, at 3 rpm (18°/s)
- Coverage of the same sky area by the two instruments
- Elevation changes once a day, at the same time for both instruments
- Specific calibration observations of
  - Jupiter (to map the main beam, see figure below, samples = white dots)



  - the Crab nebula and the Moon Limb (to calibrate the main axis of the polarimeters)
  - the Moon can be used to map sidelobes

LSPE coverage for different sets of elevation changes. The first column reports the boresight elevation range in degrees for the two instruments. Second column, the full coverage. Third column, the coverage after masking the galaxy with the WMAP polarization mask.

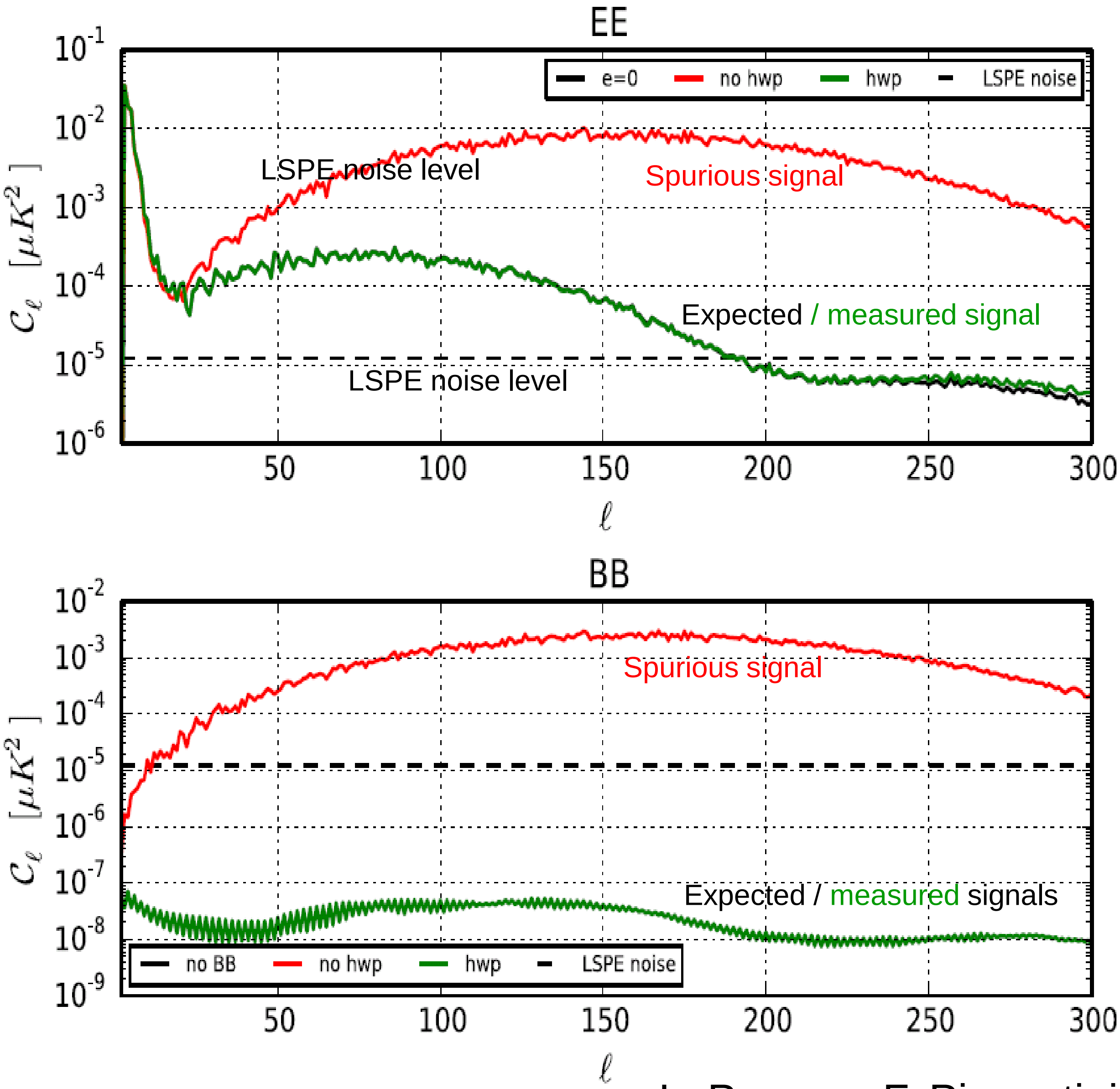
Elevation	**Coverage**	**Unmasked**
SWIPE [30-40]	31%	23%
SWIPE [40-50]	27%	20%
SWIPE 35	24%	19%
SWIPE 45	22%	18%
SWIPE [30-50]	35%	26%
STRIP 45	27%	20%
STRIP 30	33%	24%

		STRIP			SWIPE	
Source	Culmination (deg)	S/N per sample at 44 GHz	S/N per sample at 90 GHz		S/N per sample at 145 GHz	S/N per sample at 245 GHz
Moon	30	37500	200000		700000	2000000
Crab	34	20	18		23	28
~~Mars~~	0	0.30	1.6		5.6	18
Jupiter	27	15	80		275	850
~~Saturn~~	-6	1.4	7		24	70
~~Uranus~~	16	0.05	0.24		0.8	2.5

Sources culmination angle, and expected S/N per sample. Sampling rate is set at 60 Hz. We assume full Moon, as it is when it is observable by LSPE. The Crab flux is based on the free-free spectrum reported in Macías-Pérez, et al. Ap. J., 711, 417 (2010)

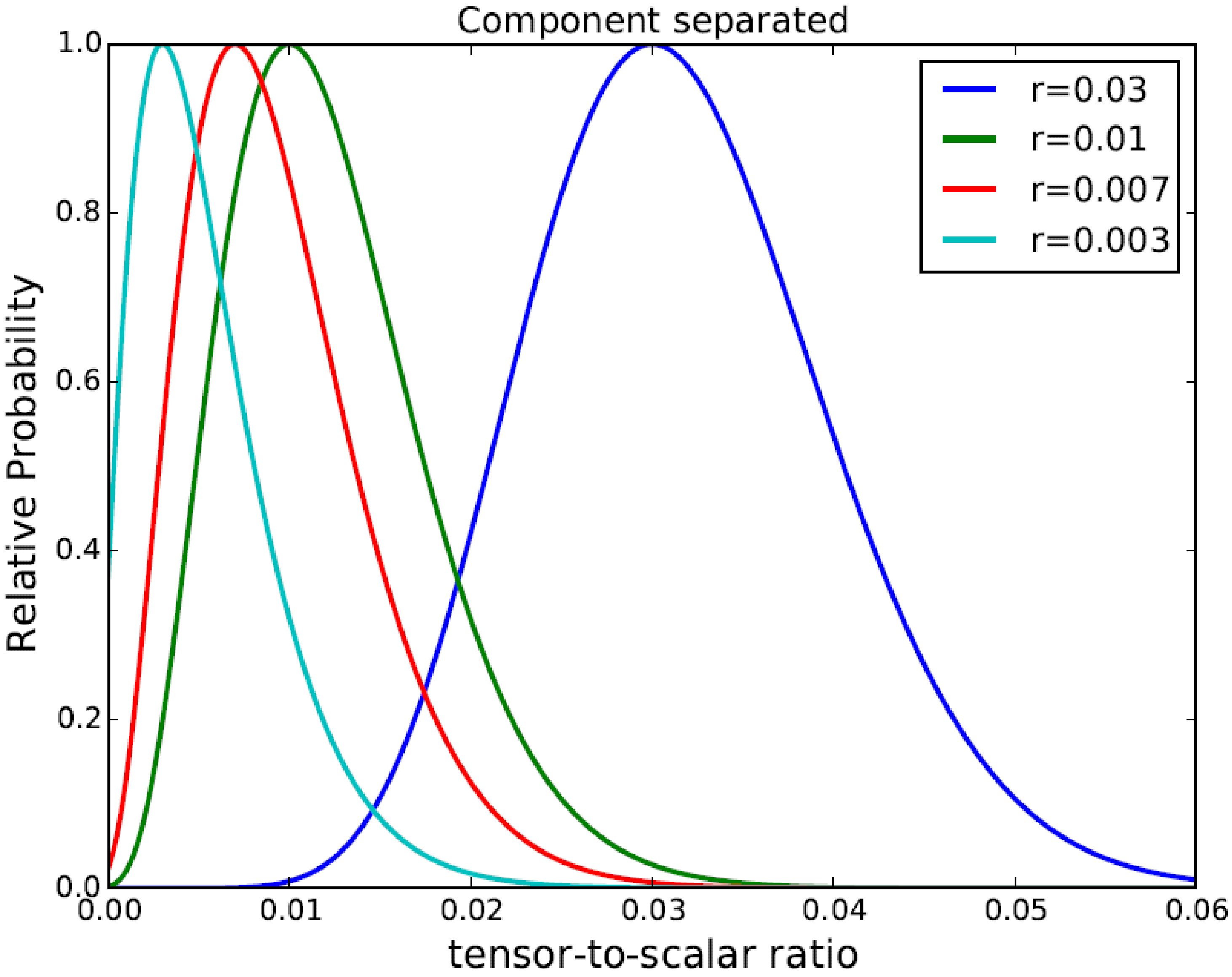
Performance Forecast

- The presence of the HWP allows to fully exploit the sensitivity of LSPE-SWIPE.
- Realistic simulations to assess systematic effects (mainly beam asymmetries) which become irrelevant if the HWP is used.
- The final sensitivity target for *r* is < 0.01



L. Pagano, F. Piacentini

SWIPE Performance Forecast (1^{st} flight)



L. Pagano, F. Piacentini

Current Status

- LSPE is fully funded by ASI and INFN
- STRIP will operate from the ground (Tenerife) covering the same sky as SWIPE
- STRIP and SWIPE in due course of development, consistent with a 1st launch opportunity from Svalbard (78°N) in Winter 2018/19 for SWIPE and start of data taking in 2018 for STRIP.
- Baseline science expected from (one flight + 1 year) is competitive with current gen B-mode experiments – and contributions to polarized foreground science will provide a great complement the CMB science.

OLIMPO

- The OLIMPO experiment is a first attempt at spectroscopic measurements of CMB anisotropy.
- A large balloon-borne telescope with a 4-bands photometric array and a plug-in room temperature spectrometer
- see http://planck.roma1.infn.it/olimpo for a collaborators list and full details on the mission
- **Main scientific targets:**
  - **SZ effect in clusters –> unbiased estimates of cluster parameters**
  - **Spectrum of CMB anisotropy –> anisotropic spectral distortions**

A&A 538, A86 (2012)
DOI: 10.1051/0004-6361/201118062

Astronomy & Astrophysics

Low-resolution spectroscopy of the Sunyaev-Zel'dovich effect and estimates of cluster parameters

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P. Marchegiani[3], S. Masi[1,2], and A. Schillaci[1,2]

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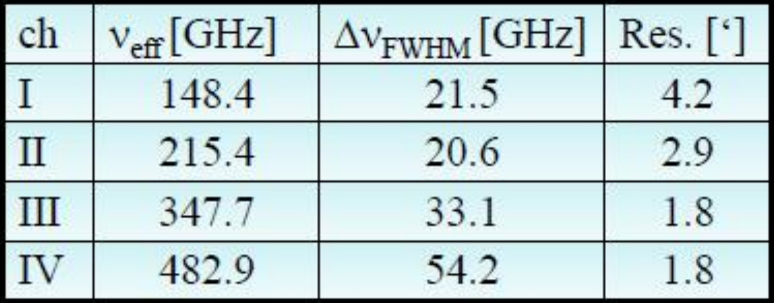
Received 9 September 2011 / Accepted 8 November 2011

ABSTRACT

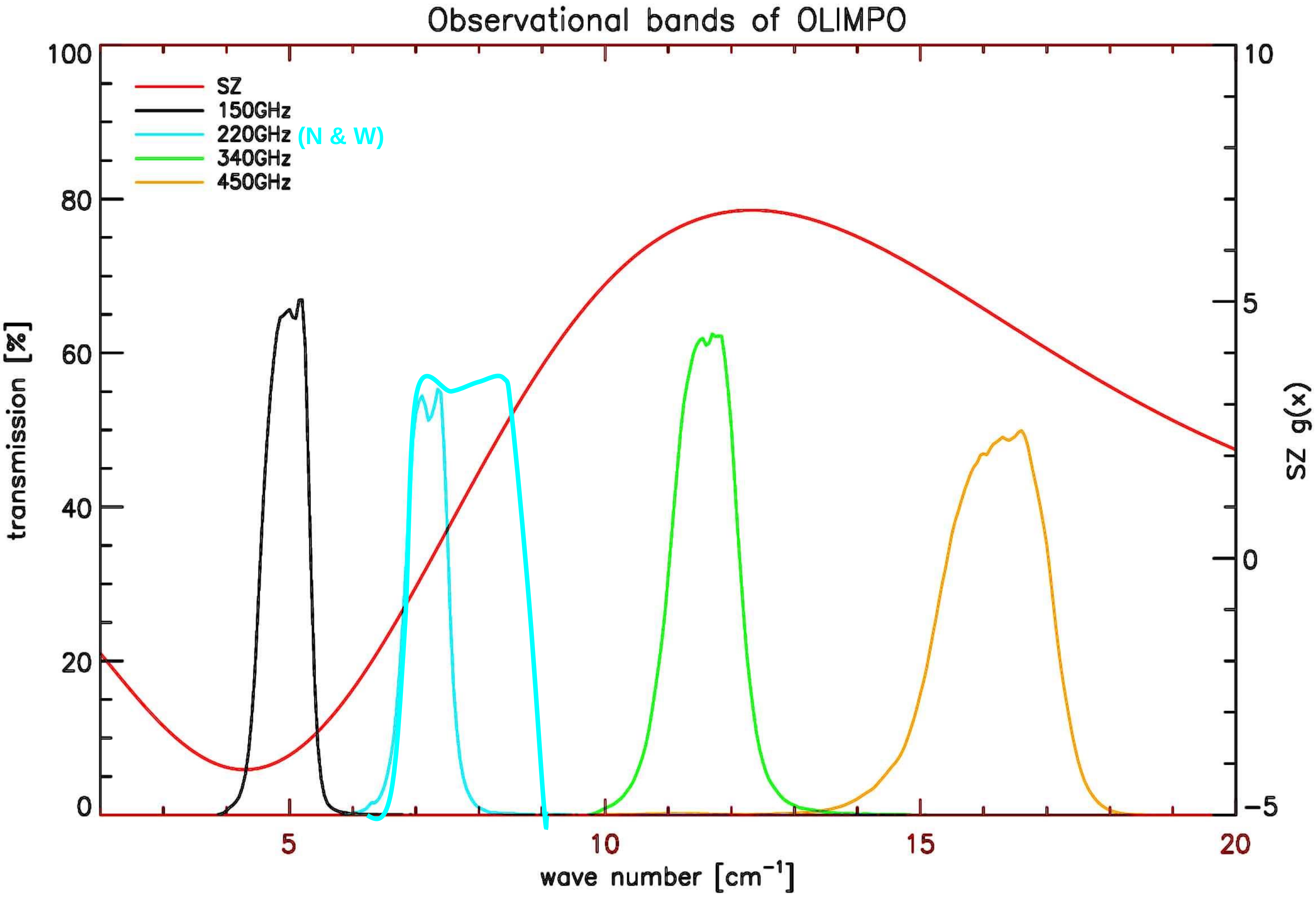
Context. The Sunyaev-Zel'dovich (SZ) effect is a powerful tool for studying clusters of galaxies and cosmology. Large mm-wave telescopes are now routinely detecting and mapping the SZ effect in a number of clusters, measure their comptonisation parameter and use them as probes of the large-scale structure and evolution of the universe.
Aims. We show that estimates of the physical parameters of clusters (optical depth, plasma temperature, peculiar velocity, non-thermal components etc.) obtained from ground-based multi-band SZ photometry can be significantly biased, owing to the reduced frequency coverage, to the degeneracy between the parameters and to the presence of a number of independent components larger than the number of frequencies measured. We demonstrate that low-resolution spectroscopic measurements of the SZ effect that also cover frequencies >270 GHz are effective in removing the degeneracy.
Methods. We used accurate simulations of observations with lines-of-sight through clusters of galaxies with different experimental configurations (4-band photometers, 6-band photometer, multi-range differential spectrometer, full coverage spectrometers) and dif-

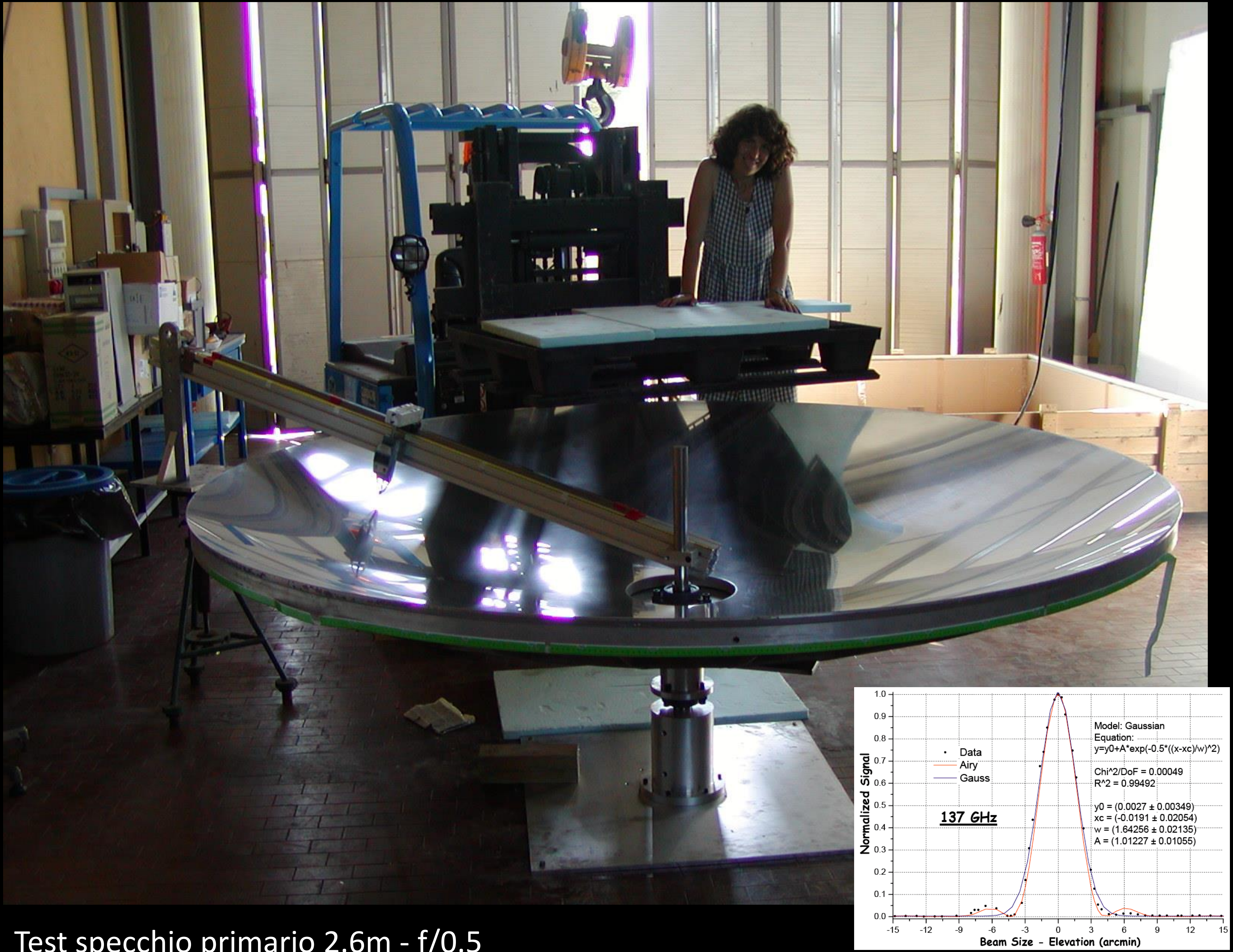
OLIMPO

- Long Duration Balloon experiment for mm & sub-mm astronomy
- Operates from the stratosphere - launch from Svalbard
- Cassegrain telescope, 2.6m aperture
- Multifrequency arrays of bolometers
- Low resolution spectrometer

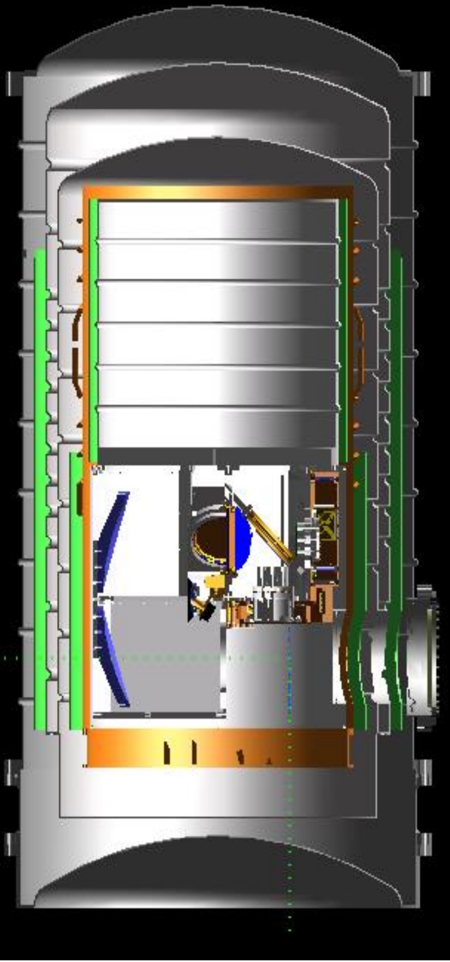


ch	ν_{eff} [GHz]	$\Delta\nu_{FWHM}$ [GHz]	Res. [‘]
I	148.4	21.5	4.2
II	215.4	20.6	2.9
III	347.7	33.1	1.8
IV	482.9	54.2	1.8

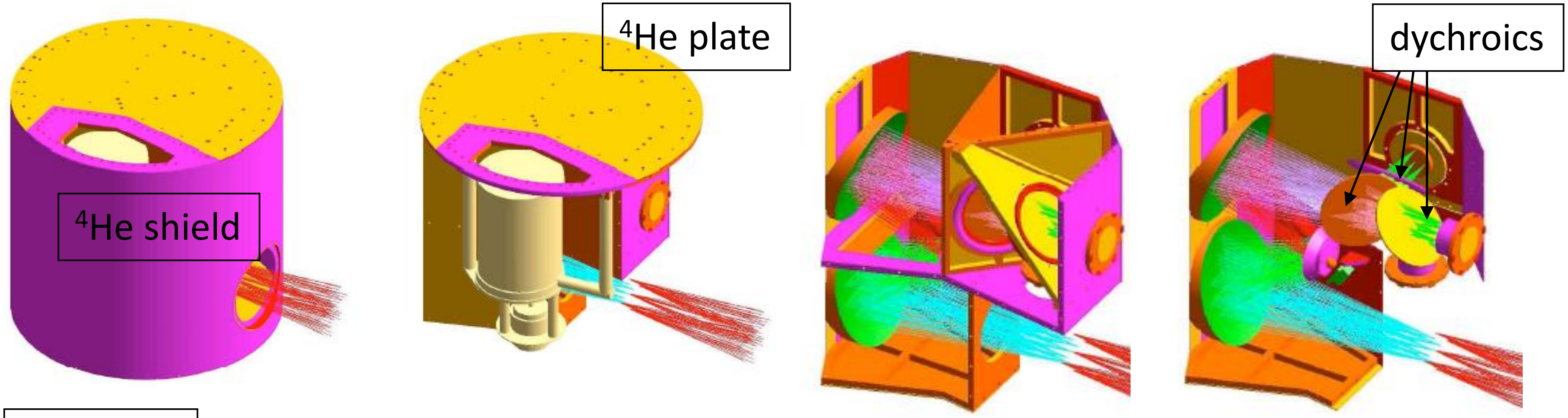


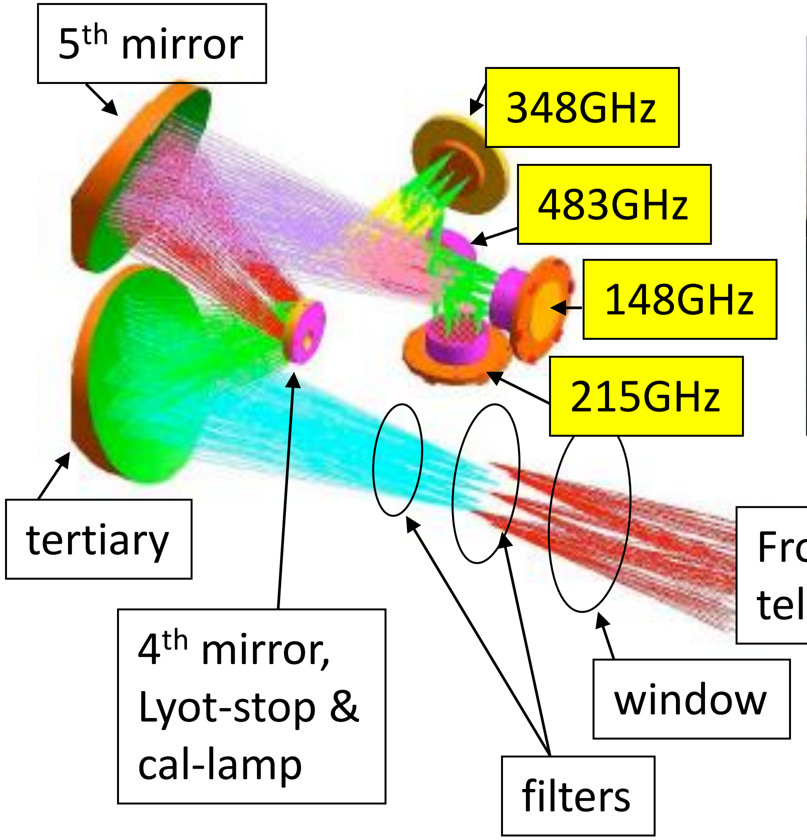


Test specchio primario 2.6m - f/0.5

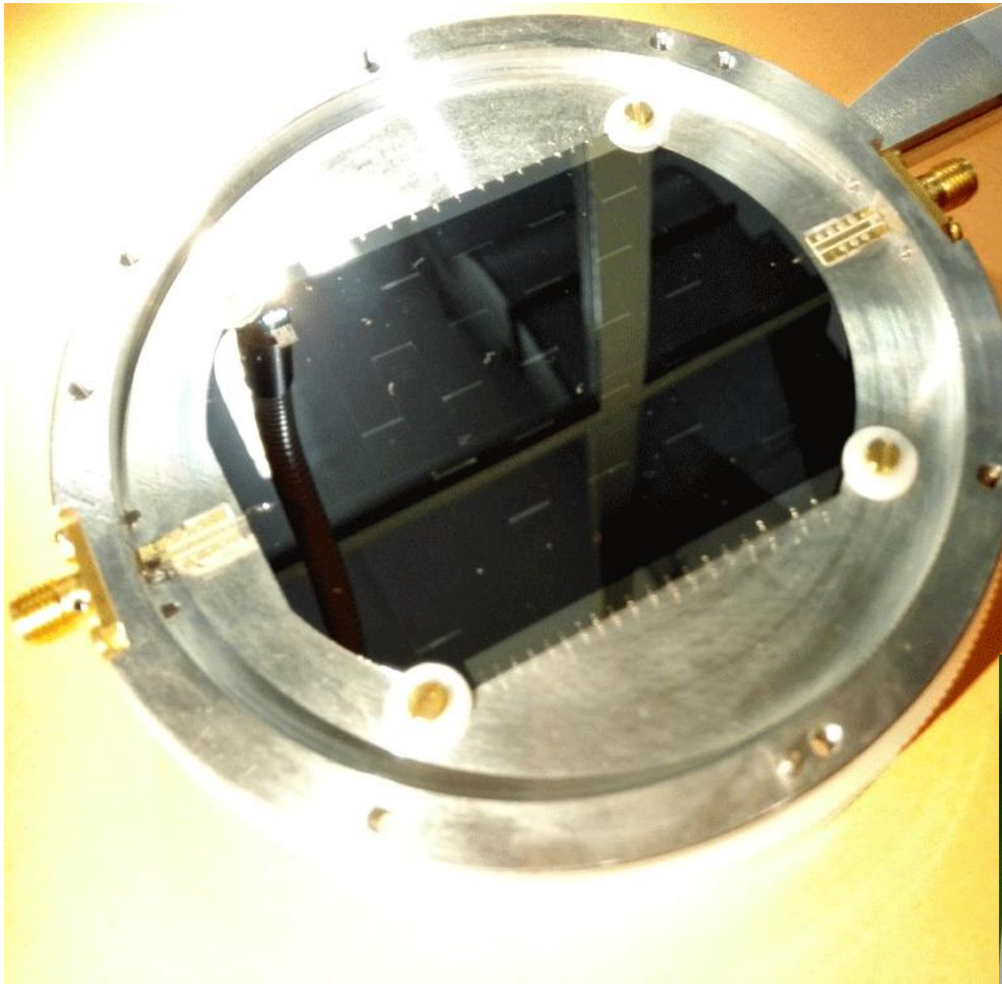


0.3K cryostat (made in Sapienza)
65L superfluid ^{4}He
70L liquid N
40LSTP ^{3}He refrigerator
50L experimental volume
Hold time – 15 days @ 0.3K





OLIMPO: Cold Optics and Arrays

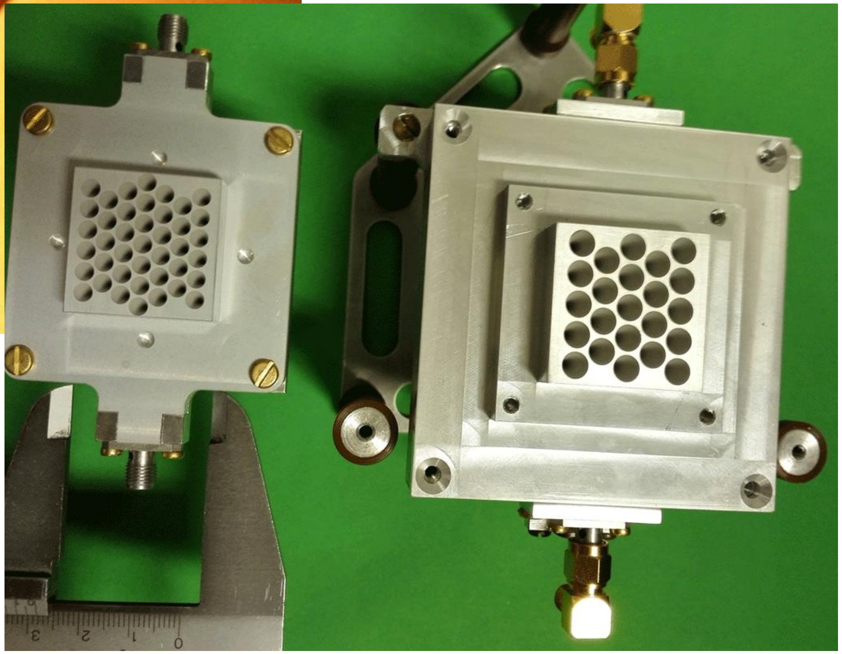


OLIMPO
Kinetic Inductance
Detectors

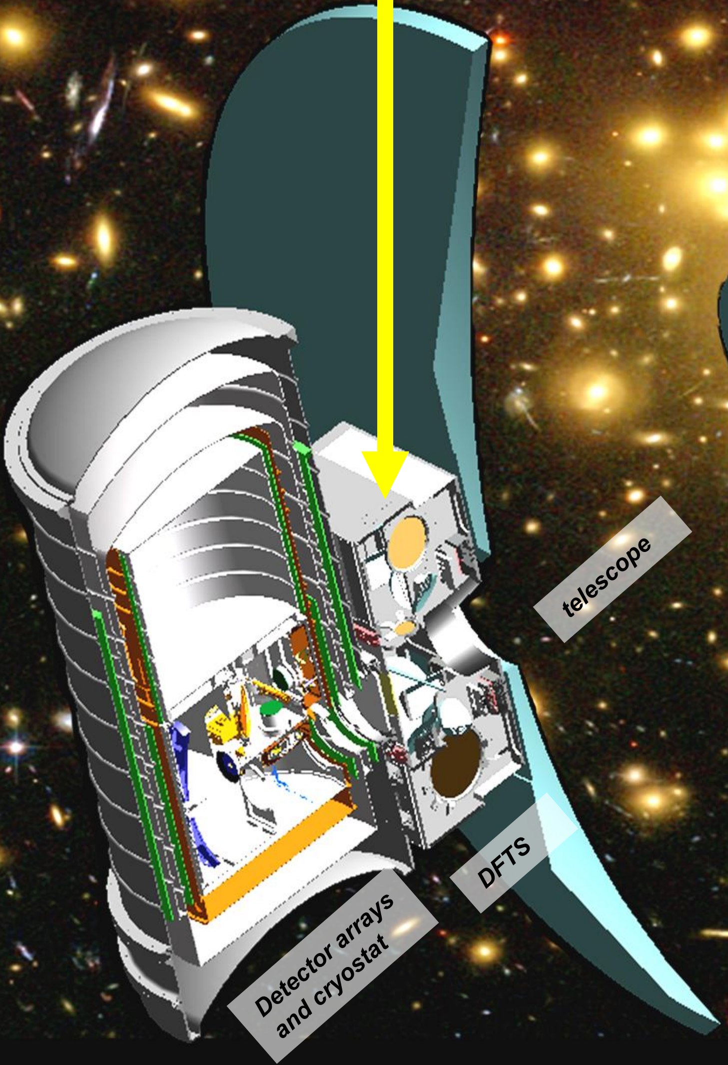
AL LEKIDs @
140, 200, 340, 480 GHz

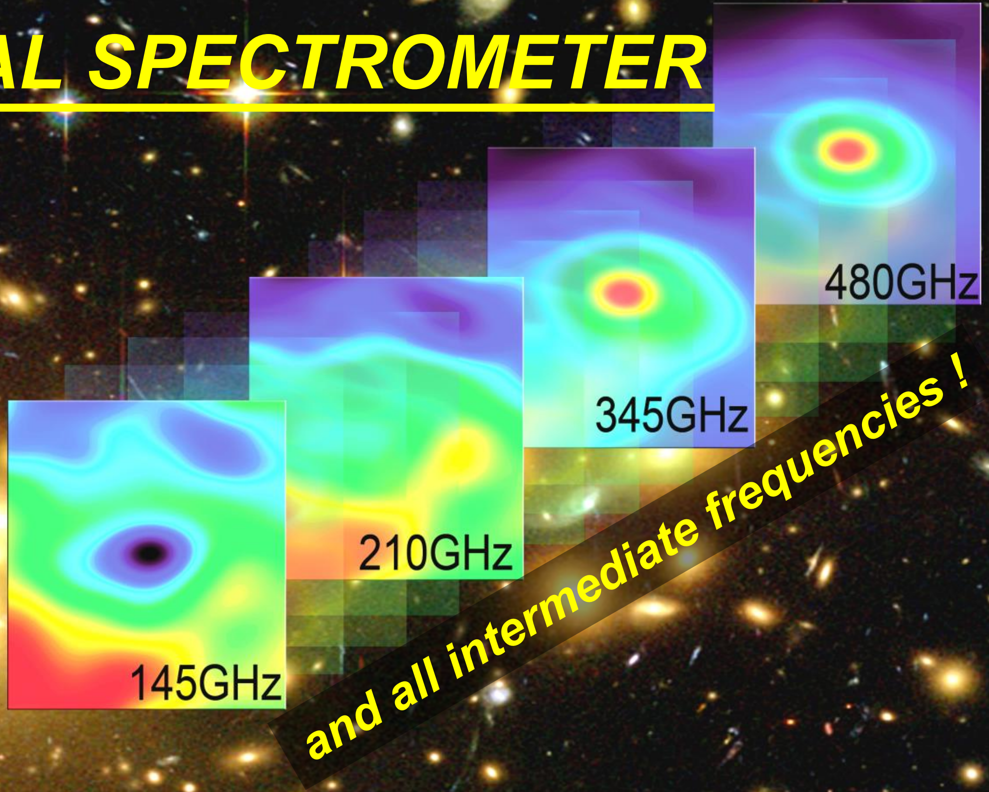
100-600 MHz res.

CNR-IFN + Sapienza



OLIMPO's DIFFERENTIAL SPECTROMETER





A Differential Fourier Transform Spectrometer (DFTS).
Similar to COBE-FIRAS but…
.. rather than measuring the brightness difference between the sky and an internal blackbody, it measures the **brightness difference between two directions in the sky**

- The instrument is based on a double Martin Puplett Interferometer configuration to avoid the loss of half of the signal.
- A wedge mirror splits the sky image in two halves I_a and I_b , used as input signals for both inputs of the two FTS's.
- In the FTSs the beam to be analyzed is split in two halves, and a variable optical path difference is introduced.

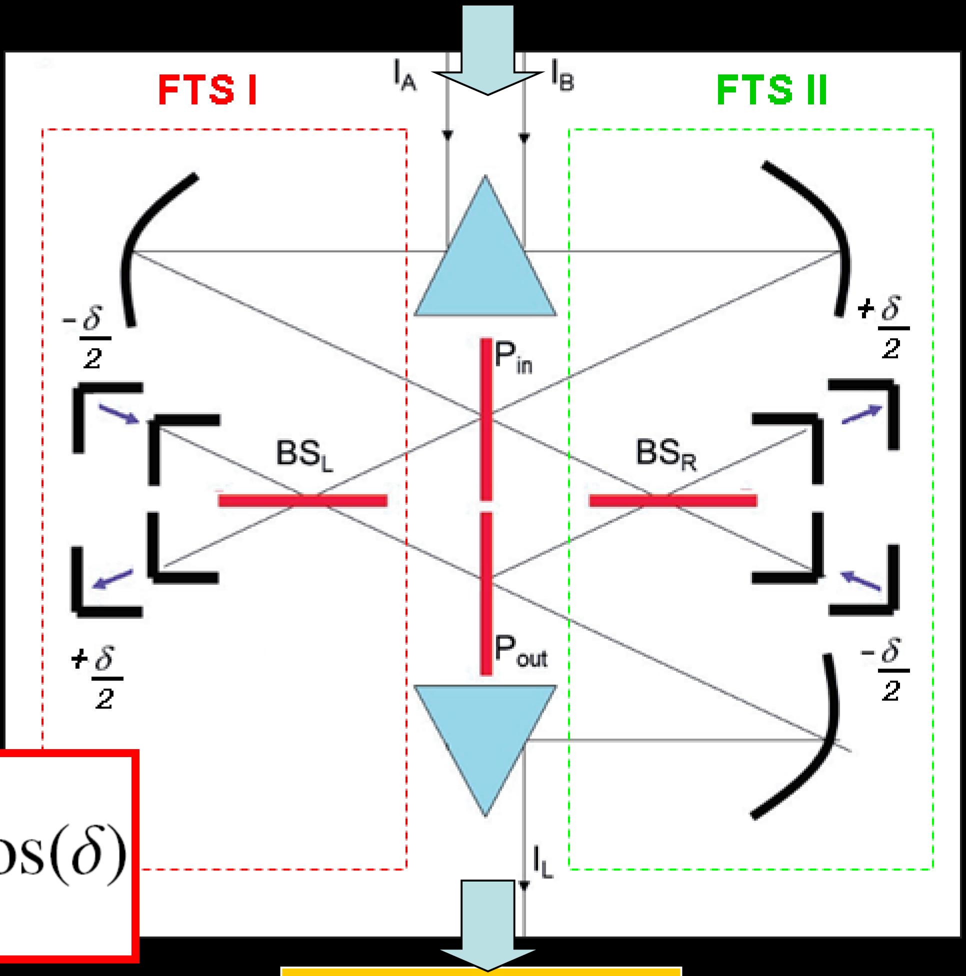
See Schillaci et al. A&A 565, A125, 2014 for a detailed description of the instrument. The output brightness is

$$I_L = \frac{1}{2}(I_a + I_b) + \frac{1}{2}(I_a - I_b)\cos(\delta)$$

δ = variable phase shift, introduced by the variable optical path difference.

Only the *difference* between the two input brightnesses is modulated by the variable optical path difference.

Olimpo Telescope



Olimpo Cryostat

A&A 565, A125 (2014)
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Astronomy & Astrophysics

Efficient differential Fourier-transform spectrometer for precision Sunyaev-Zel'dovich effect measurements

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ABSTRACT

Context. Precision measurements of the Sunyaev-Zel'dovich effect in clusters of galaxies require excellent rejection of common-mode signals and wide frequency coverage.

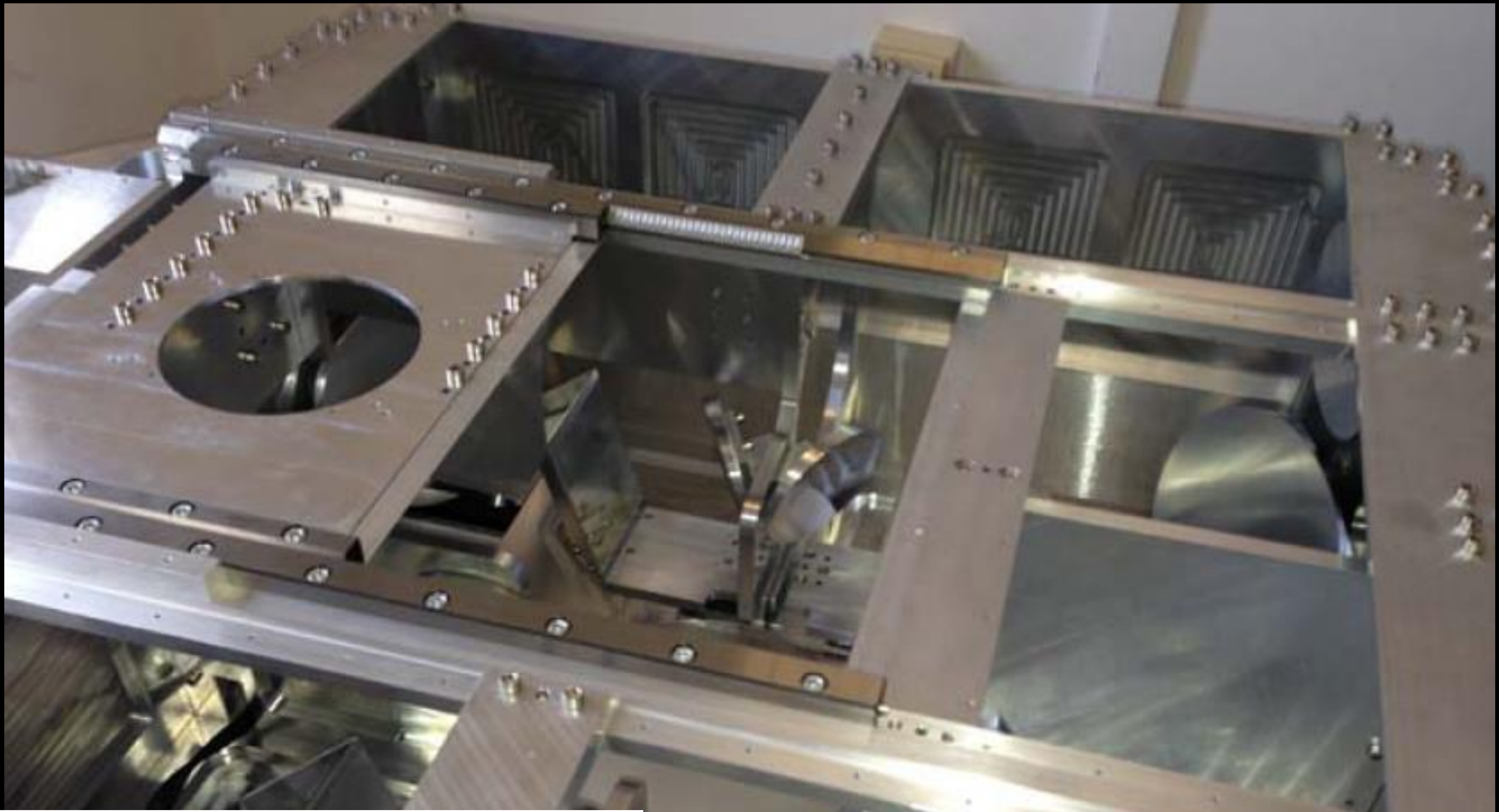
Aims. We describe an imaging, efficient, differential Fourier transform spectrometer (FTS), optimized for measurements of faint brightness gradients at millimeter wavelengths.

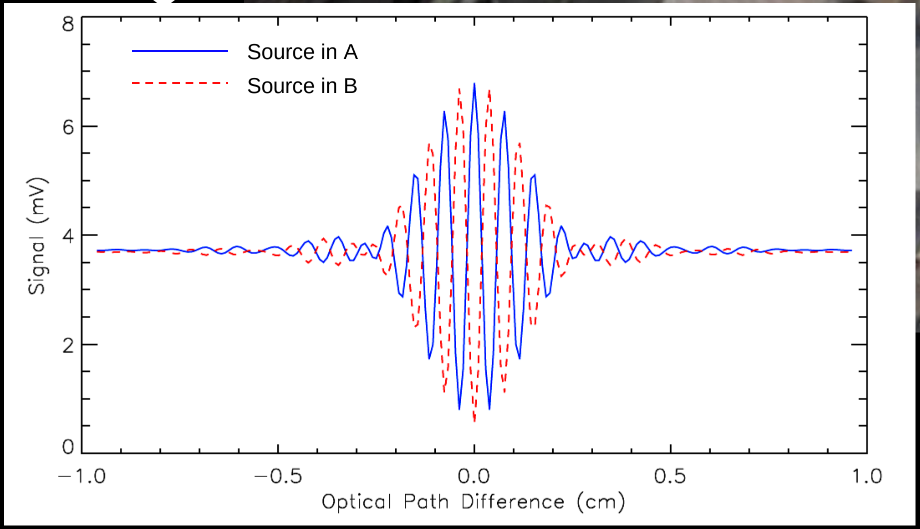
Methods. Our instrument is based on a Martin-Puplett interferometer (MPI) configuration. We combined two MPIs working synchronously to use the whole input power. In our implementation the observed sky field is divided into two halves along the meridian, and each half-field corresponds to one of the two input ports of the MPI. In this way, each detector in the FTS focal planes measures the difference in brightness between two sky pixels, symmetrically located with respect to the meridian. Exploiting the high common-mode rejection of the MPI, we can measure low sky brightness gradients over a high isotropic background.

Results. The instrument works in the range $\sim$1–20 cm^{-1} (30–600 GHz), has a maximum spectral resolution $1/(2\,\mathrm{OPD}) = 0.063$ cm^{-1} (1.9 GHz), and an unvignetted throughput of 2.3 cm^{2}sr. It occupies a volume of $0.7 \times 0.7 \times 0.33$ m^3 and has a weight of 70 kg. This design can be implemented as a cryogenic unit to be used in space, as well as a room-temperature unit working at the focus of suborbital and ground-based mm-wave telescopes. The first in-flight test of the instrument is with the OLIMPO experiment on a stratospheric balloon; a larger implementation is being prepared for the Sardinia radio telescope.

Key words. cosmic background radiation – instrumentation: spectrographs – techniques: spectroscopic – galaxies: clusters: general

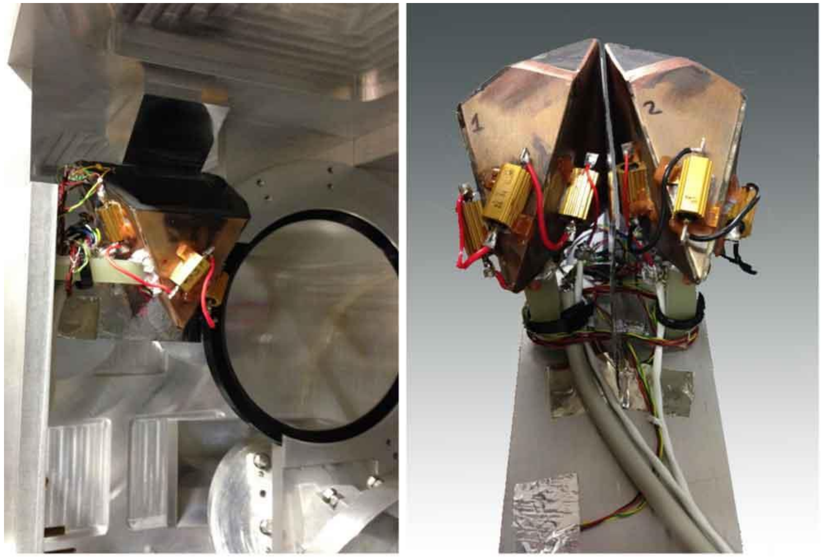
The real thing….
and measured interferograms

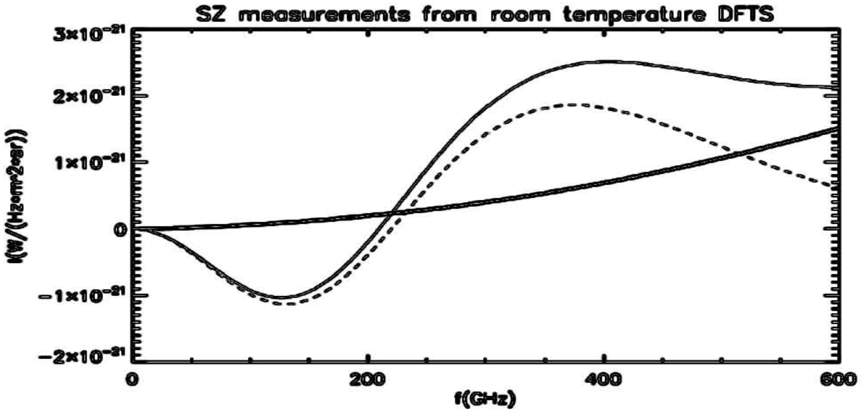


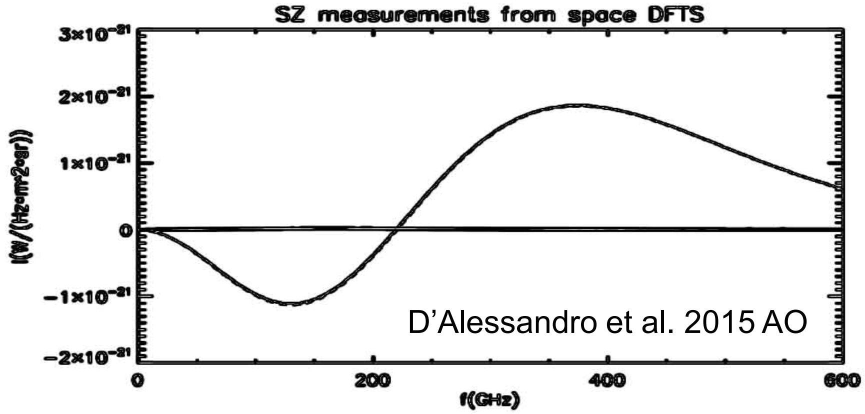


CMRR

- The differential signal (SZ) is much smaller than the common mode, which is CMB + instrument emissivity (a few %) + residual atmosphere.
- We have measured the common-mode rejection ratio of the FTS using custom temperature-controlled blackbody sources at the two entrance ports of the FTS.
- It turns out that the CMRR of our DFTS is <-55dB
- This means that the offset is less than the SZ signal in OLIMPO, and will be much less than the SZ signal in a cryogenic/space implementation.




SZ measurements from room temperature DFTS

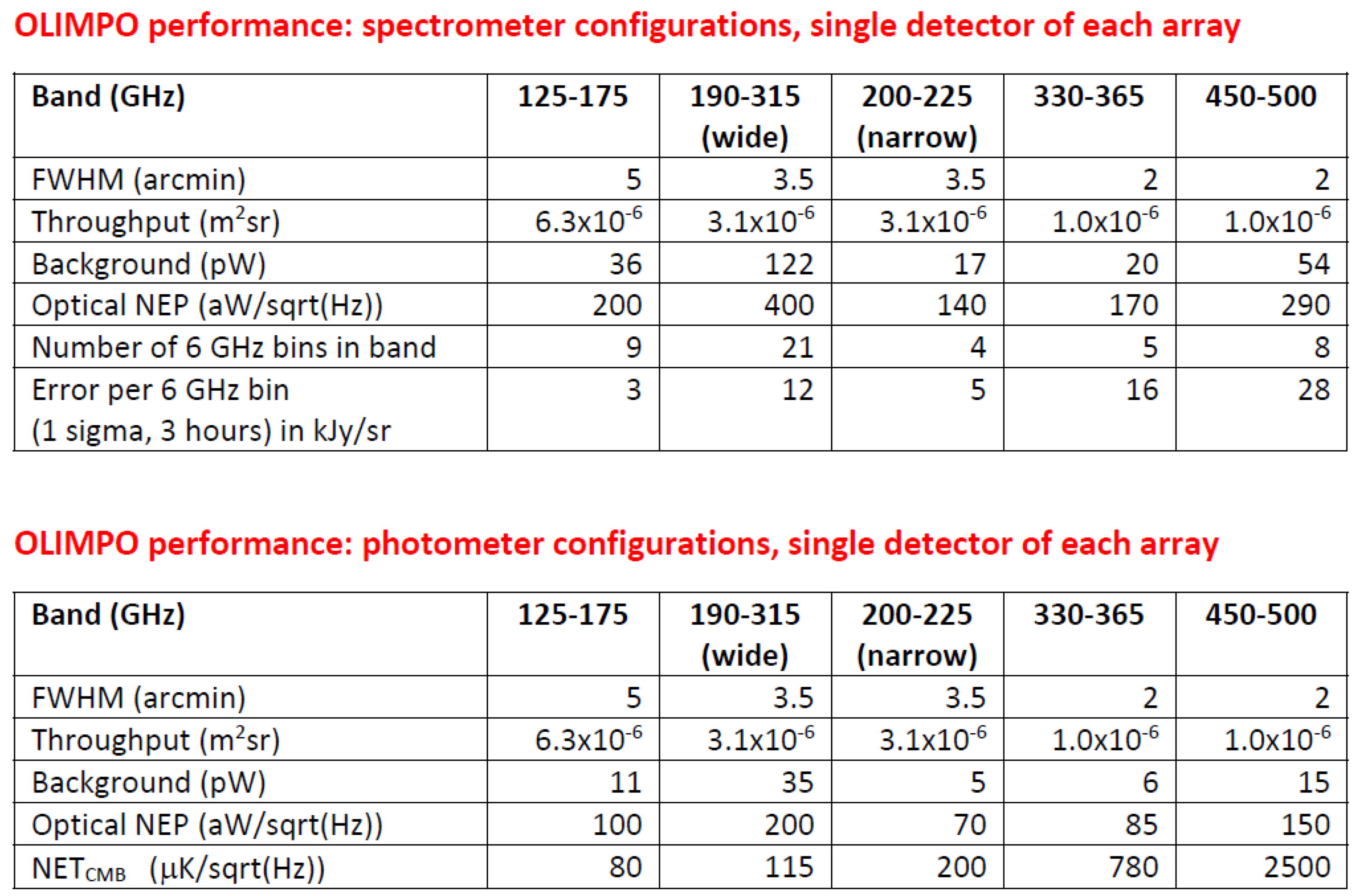

SZ measurements from space DFTS

D’Alessandro et al. 2015 AO

Telescope / primary mirror DFTS cryostat / detectors arrays

Main components of OLIMPO integrated on the payload

Expected performance for OLIMPO (photon noise limited)



OLIMPO performance: spectrometer configurations, single detector of each array

Band (GHz)	**125-175**	**190-315 (wide)**	**200-225 (narrow)**	**330-365**	**450-500**
FWHM (arcmin)	5	3.5	3.5	2	2
Throughput (m^2sr)	6.3×10^{-6}	3.1×10^{-6}	3.1×10^{-6}	1.0×10^{-6}	1.0×10^{-6}
Background (pW)	36	122	17	20	54
Optical NEP (aW/sqrt(Hz))	200	400	140	170	290
Number of 6 GHz bins in band	9	21	4	5	8
Error per 6 GHz bin (1 sigma, 3 hours) in kJy/sr	3	12	5	16	28

OLIMPO performance: photometer configurations, single detector of each array

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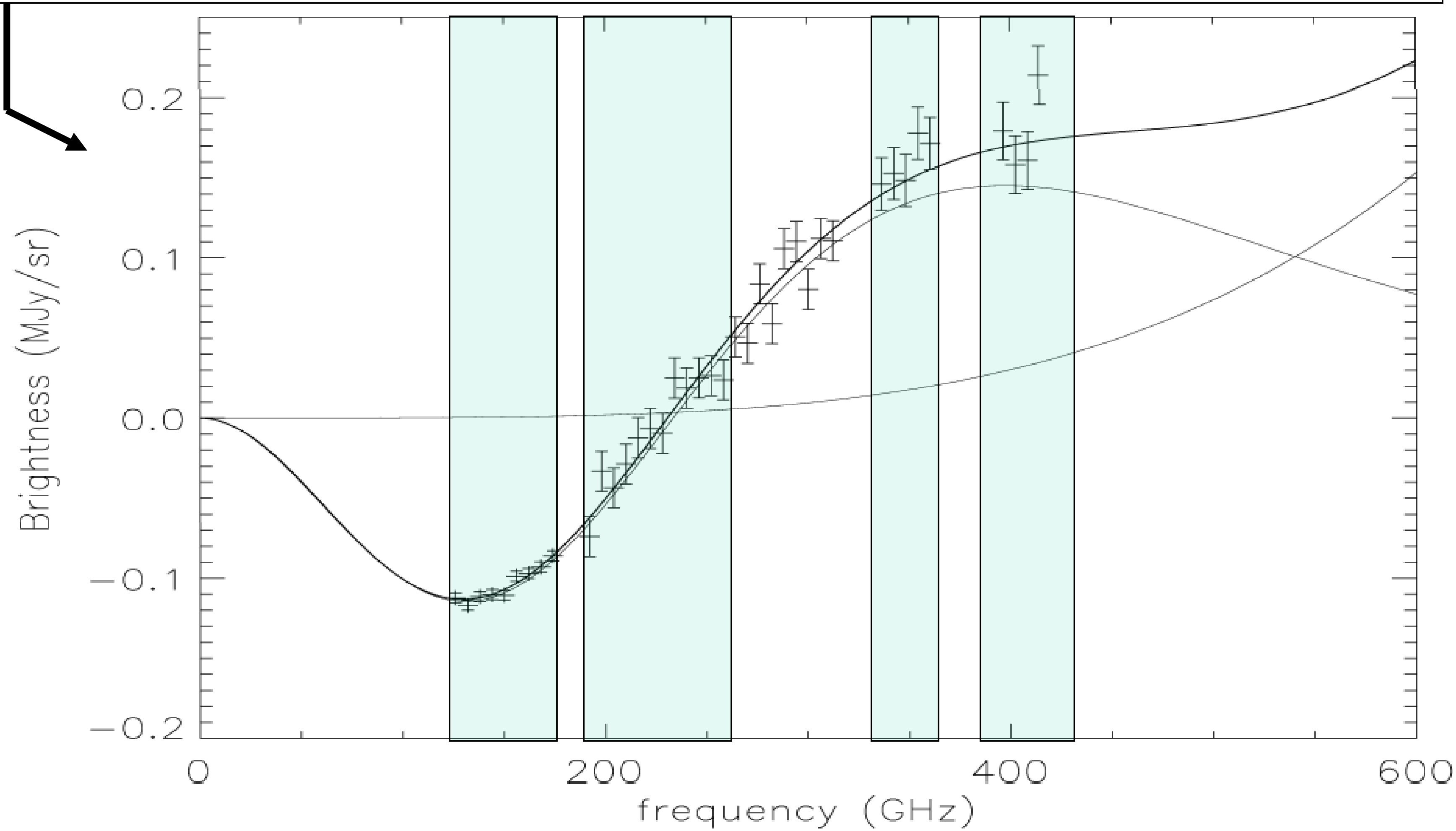
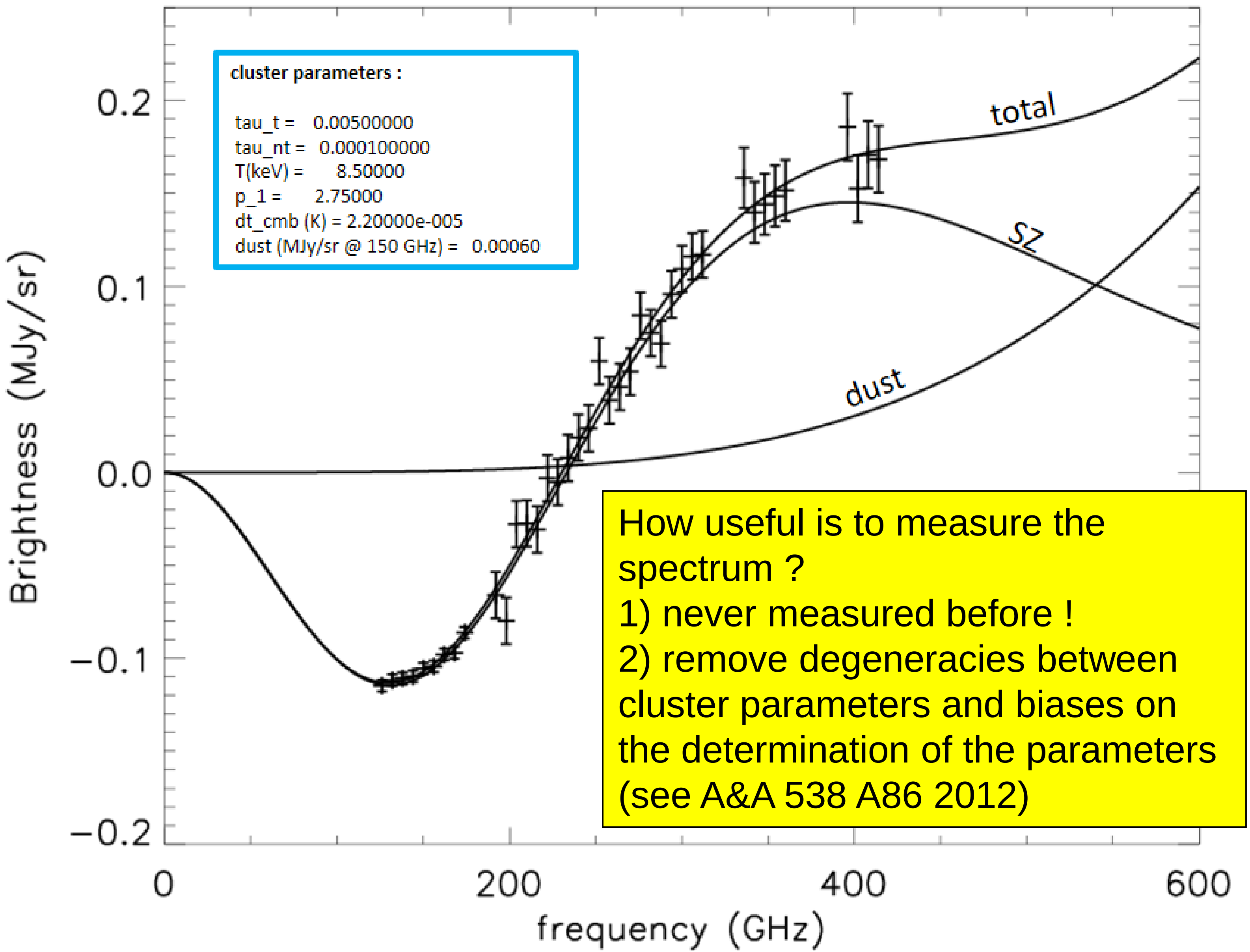
Background (pW)	11	35	5	6	15
Optical NEP (aW/sqrt(Hz))	100	200	70	85	150
NET_{CMB} (μK/sqrt(Hz))	80	115	200	780	2500

In a FTS the spectral resolution can be changed (changing the path of the moving mirror). Mind the noise, 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.
6 GHz resolution: About 34 independent spectral bins, within the same bands.



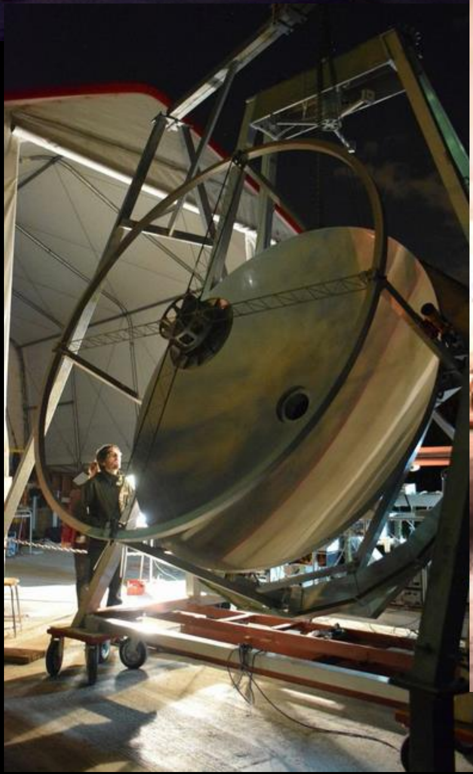


How useful is to measure the spectrum ?

1) never measured before !

2) remove degeneracies between cluster parameters and biases on the determination of the parameters (see A&A 538 A86 2012)

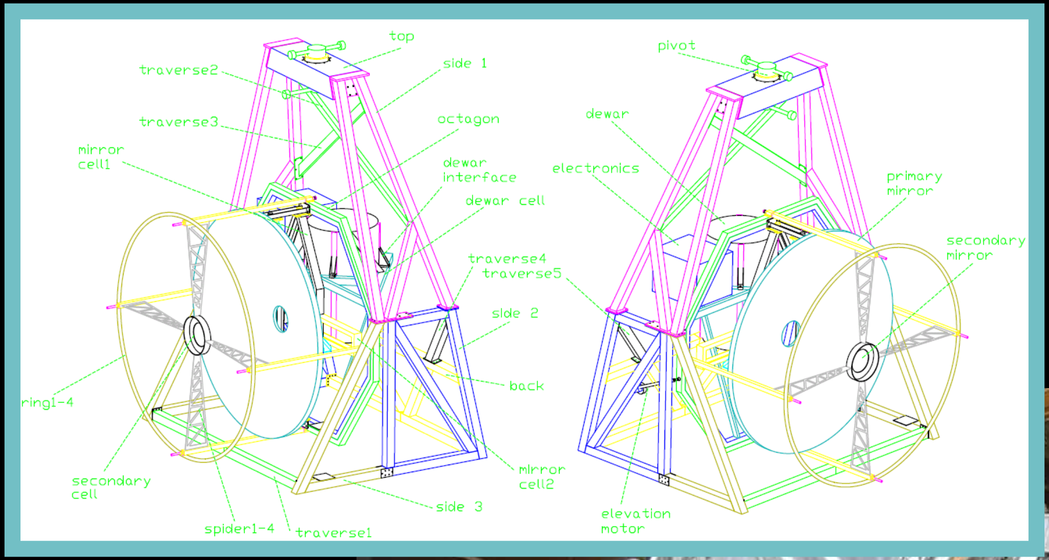




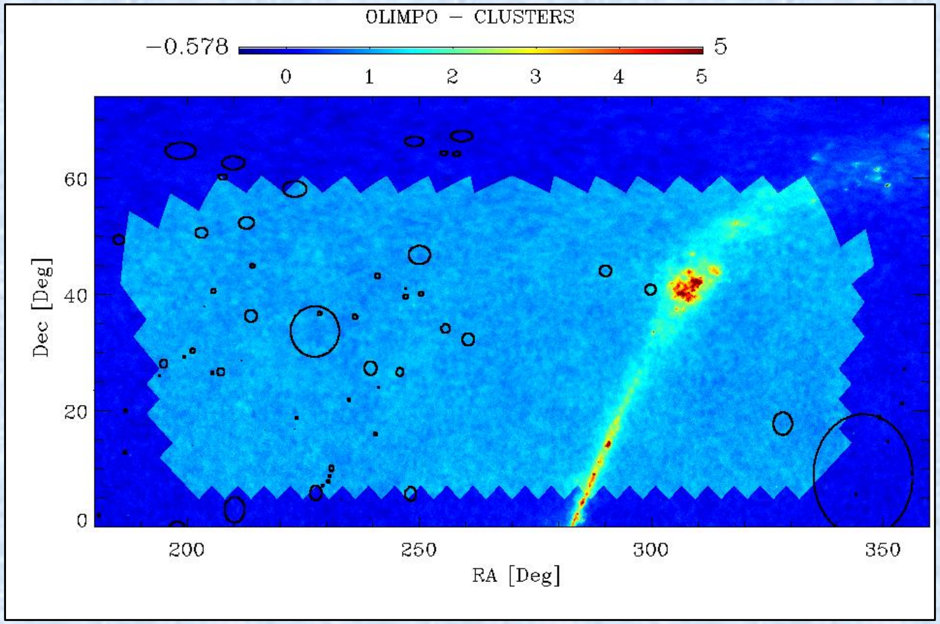

OLIMPO calibration night (Rome, 25/4/2014)
T_{atm}(350GHz)=0.001 !!

The Payload

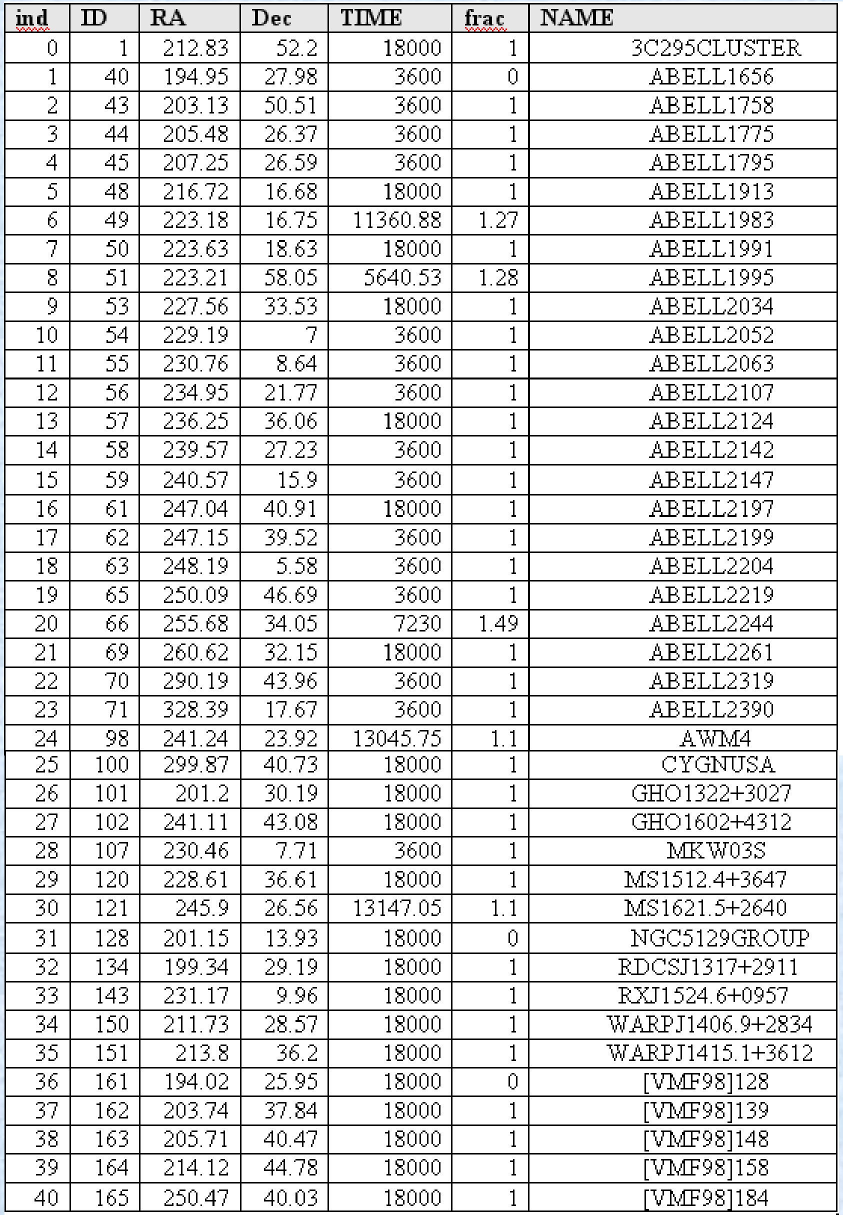
The OLIMPO payload prepared for a long-duration stratospheric flight, at the airport of Longyearbyen (Svalbard) on July 3rd, 2014.



Observation Program



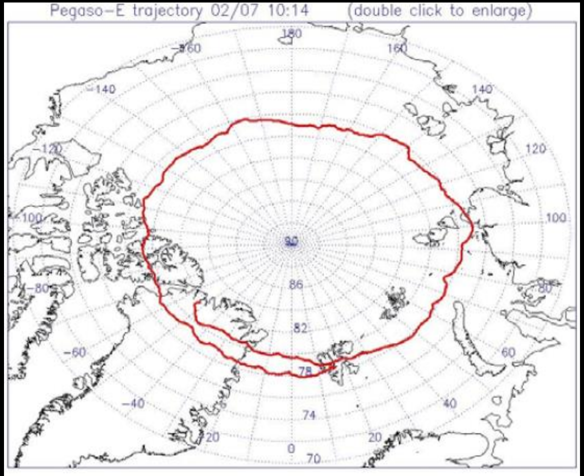
- In a circumpolar summer long duration flight (>200h) we plan to observe 40 selected clusters and to perform a blind deep integration on a clean sky region
- We have optimized the observation plan distributing the integration time among the different targets according to their brightness and diurnal elevation.



ind	ID	RA	Dec	TIME	frac	NAME
0	1	212.83	52.2	18000	1	3C295CLUSTER
1	40	194.95	27.98	3600	0	ABELL1656
2	43	203.13	50.51	3600	1	ABELL1758
3	44	205.48	26.37	3600	1	ABELL1775
4	45	207.25	26.59	3600	1	ABELL1795
5	48	216.72	16.68	18000	1	ABELL1913
6	49	223.18	16.75	11360.88	1.27	ABELL1983
7	50	223.63	18.63	18000	1	ABELL1991
8	51	223.21	58.05	5640.53	1.28	ABELL1995
9	53	227.56	33.53	18000	1	ABELL2034
10	54	229.19	7	3600	1	ABELL2052
11	55	230.76	8.64	3600	1	ABELL2063
12	56	234.95	21.77	3600	1	ABELL2107
13	57	236.25	36.06	18000	1	ABELL2124
14	58	239.57	27.23	3600	1	ABELL2142
15	59	240.57	15.9	3600	1	ABELL2147
16	61	247.04	40.91	18000	1	ABELL2197
17	62	247.15	39.52	3600	1	ABELL2199
18	63	248.19	5.58	3600	1	ABELL2204
19	65	250.09	46.69	3600	1	ABELL2219
20	66	255.68	34.05	7230	1.49	ABELL2244
21	69	260.62	32.15	18000	1	ABELL2261
22	70	290.19	43.96	3600	1	ABELL2319
23	71	328.39	17.67	3600	1	ABELL2390
24	98	241.24	23.92	13045.75	1.1	AWM4
25	100	299.87	40.73	18000	1	CYGNUSA
26	101	201.2	30.19	18000	1	GHO1322+3027
27	102	241.11	43.08	18000	1	GHO1602+4312
28	107	230.46	7.71	3600	1	MKW03S
29	120	228.61	36.61	18000	1	MS1512.4+3647
30	121	245.9	26.56	13147.05	1.1	MS1621.5+2640
31	128	201.15	13.93	18000	0	NGC5129GROUP
32	134	199.34	29.19	18000	1	RDCSJ1317+2911
33	143	231.17	9.96	18000	1	RXJ1524.6+0957
34	150	211.73	28.57	18000	1	WARPJ1406.9+2834
35	151	213.8	36.2	18000	1	WARPJ1415.1+3612
36	161	194.02	25.95	18000	0	[VMF98]128
37	162	203.74	37.84	18000	1	[VMF98]139
38	163	205.71	40.47	18000	1	[VMF98]148
39	164	214.12	44.78	18000	1	[VMF98]158
40	165	250.47	40.03	18000	1	[VMF98]184

Polar flights

- We have flown long duration stratospheric balloons around the North Pole launching from **Longyearbyen** (Svalbard) both in the summer (heavy lift payloads) and in winter (pathfinders) [see Peterzen, S., Masi, S., et al., Mem. S. A. It., 79, 792-798 (2008), and PdB+SM Proc. of the I.A.U., 8, 208-213 (2013)]
- In this way 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).

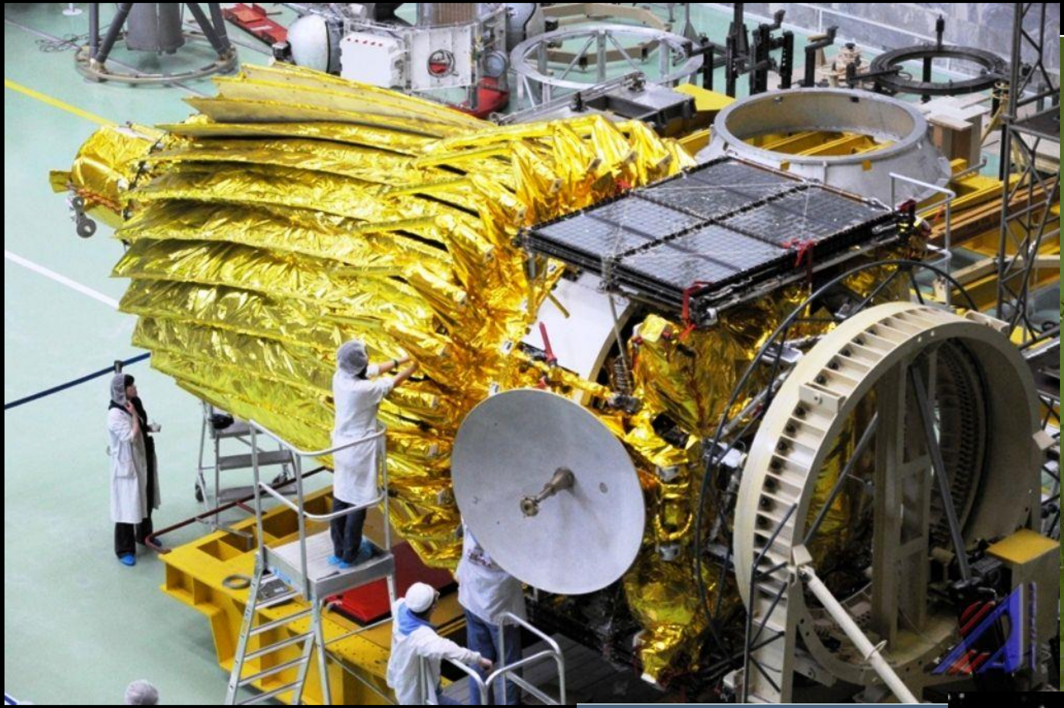


Top: Ground path of a flight performed in June 2007. **Bottom left:** Launch of a heavy-lift balloon from the Longyearbyen airport (Svalbard Islands, latitude 78°N).

- OLIMPO will have its first flight in the Arctic (2016?) and the second one from Antarctica (2018 if recovered well)

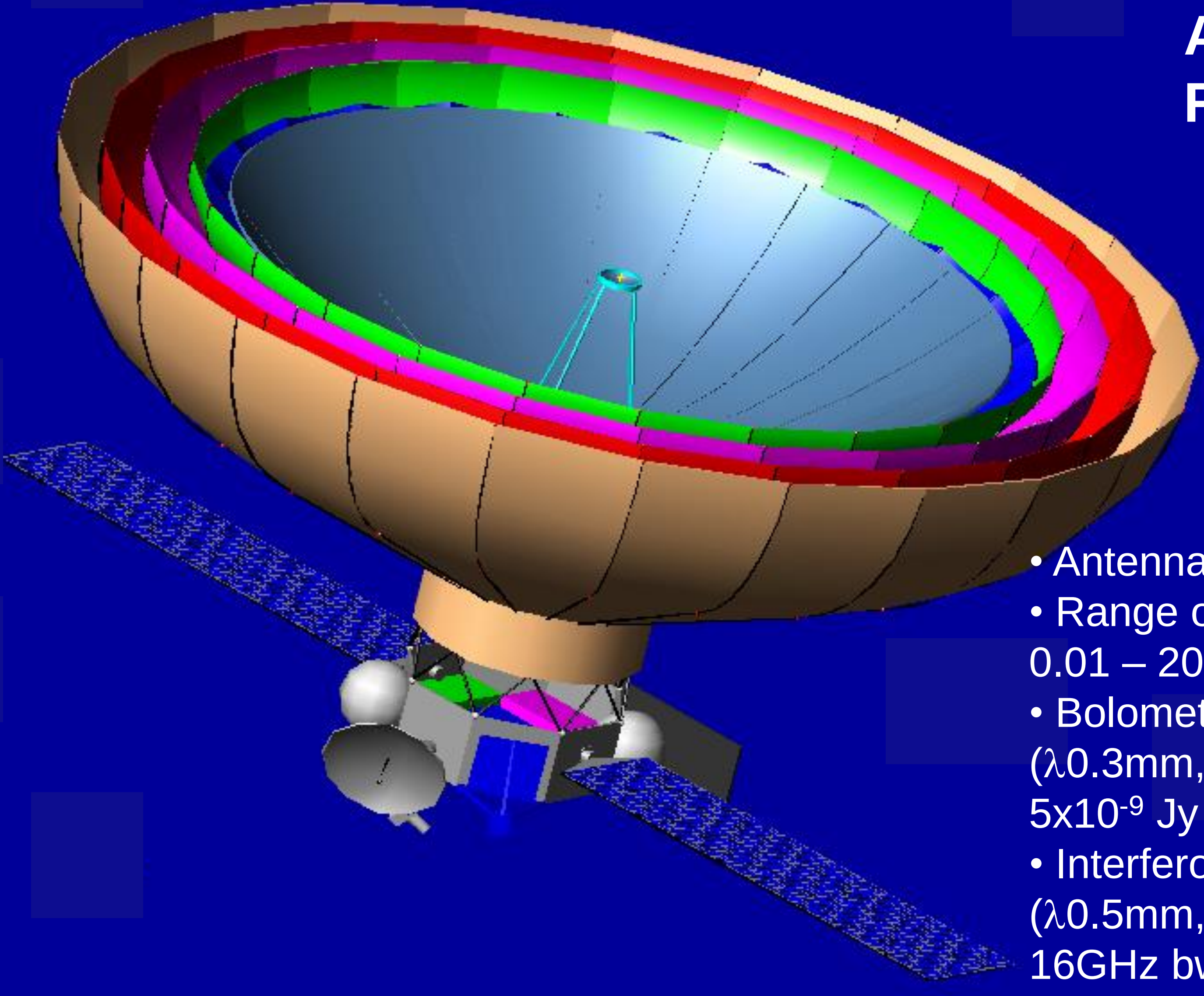
- The OLIMPO spectrometer is the prototype for a similar Differential Fourier Transform Spectrometer to be flown on the Millimetron space mission ….

- So, once again, stratospheric balloons are effectively used as pathfinders for satellite experiments.

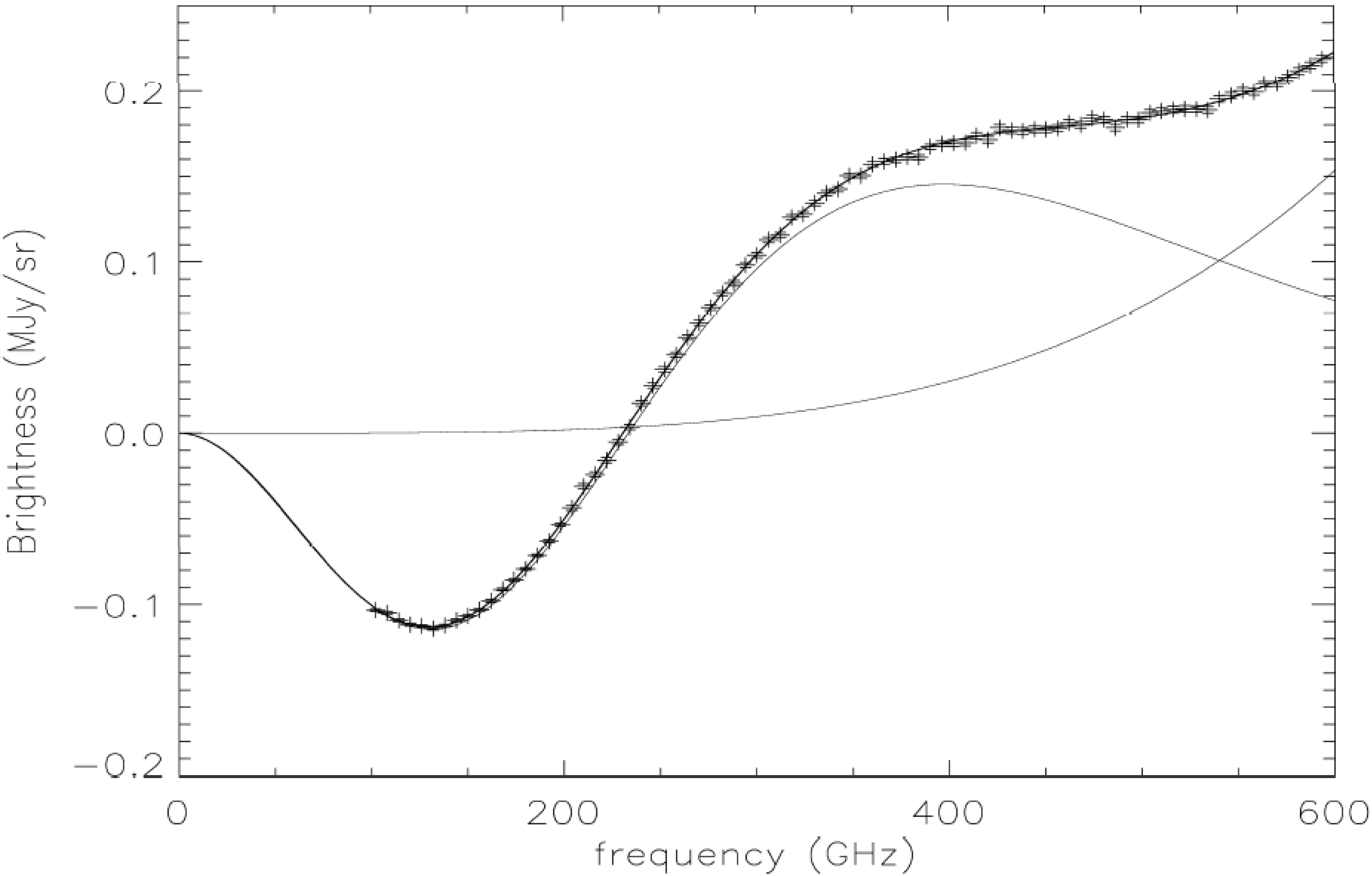


РадиоАстрон

Millimetron
ASC Moscow
ROSCOSMOS



- Antenna diameter: 10 m
- Range of wavelengths: 0.01 – 20 mm
- Bolometric sensitivity (λ0.3mm, 1h integration): 5x10^{-9} Jy
- Interferometry sensitivity (λ0.5mm, 300s integration, 16GHz bw) : 10^{-4} Jy
- Interferometer beam: 10^{-9} arcsec



3 hours of observations of a rich cluster with a DFTS on Millimetron
Absolutely outstanding. USING A PHOTON NOISE LIMITED BOLOMETER IN THE COLD ENVIRONMENT OF L2 WITH A 4K TELESCOPE

Conclusions

- Balloons offer a great deal of opportunities for CMB research.
- They will add reliability to ground based B-modes measurements (waiting for a final space mission, for which they should be used to qualify instruments / detectors / methods)
- Original/new satellite-based science can and should be first implemented using balloon-borne experiments.