From OLIMPO to Millimetron (through SAGACE) CMB spectroscopy (and polarimetry ?)

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On behalf of the
OLIMPO collaboration

Workshop on Microwave Spectral Polarimetry
Paris, APC 11/12/2012

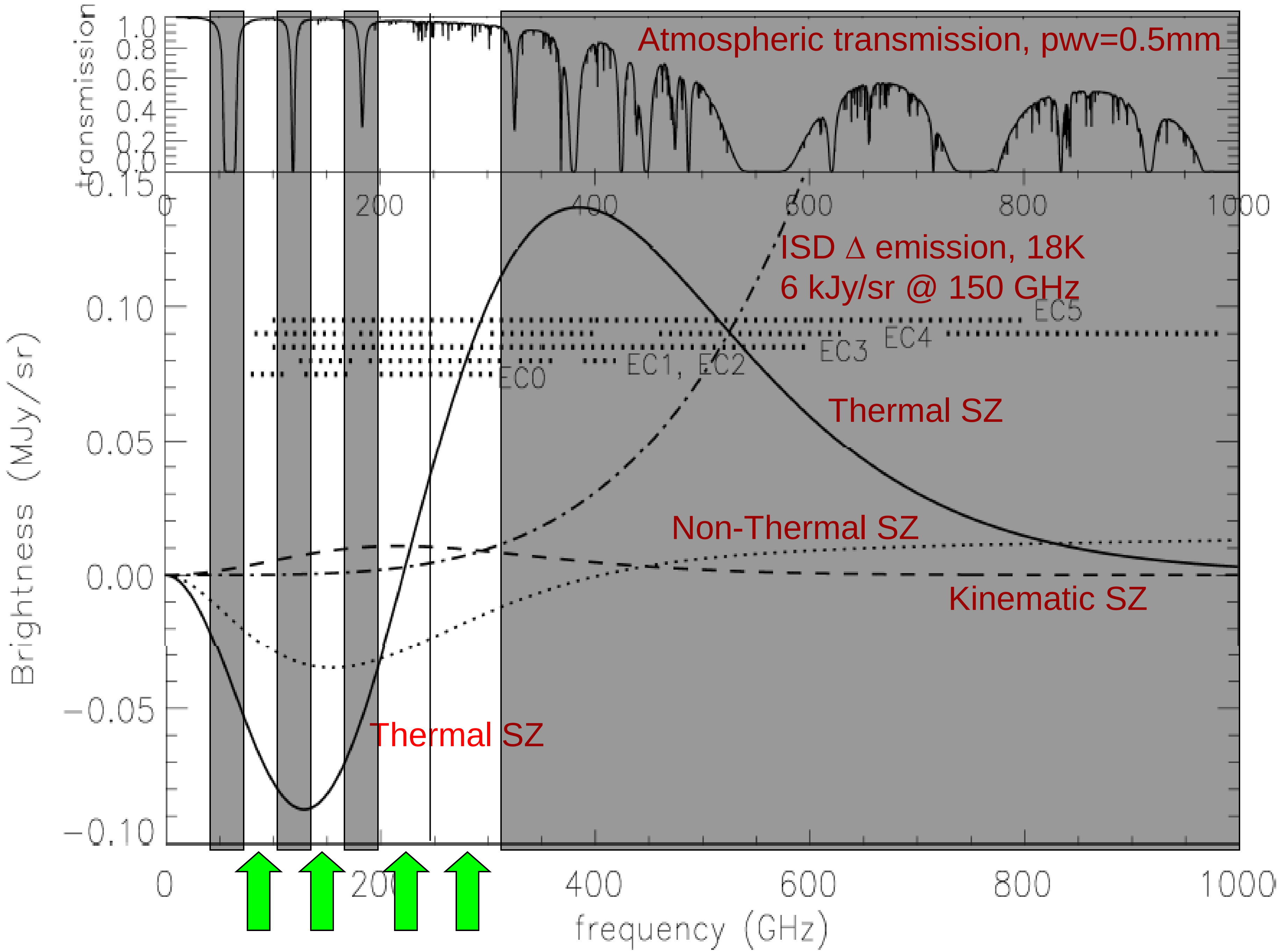
The MPI *Differential* Spectrometer

- A Martin-Puplett interferometer (MPI) measures the *difference* in the spectral brightness at its two input ports, with
  - remarkable common-mode rejection,
  - imaging capabilities,
  - considerable throughput advantage and wider spectral coverage with repect to dispersion spectrometers.
- If at the two input ports you enter the two orthogonal polarizations of the same source, the MPI measures the spectrum of linear polarization (a-la PIXIE astro-ph/1105.2044)
- If at the two input ports you enter the brightnesses coming from two sky directions, the MPI measures the spectrum of anistropy (a-la SAGACE astro-ph/1002.0867)
- I'll report on the second configuration, but the two share several common methods and technologies.
- If there is a significant anisotropy in the spectal distorion of the CMB, then this configuration can measure it very well (see e.g. SZ effect, but also inhomogeneous energy releases in the early universe)
- Moreover, the second configuration can measure linear polarization if a polarization modulator (a rotating HWP) is added at both inputs.

Spectroscopic measurements of the Sunyaev-Zeldovich Effect

- Requirements:
  - Wide spectral coverage
    (in principle <100 to >1000 GHz)
  - Modest spectral resolution ($\lambda/\Delta\lambda$ = 10 to 100)
  - Differential input, high rejection of common mode signal (CMB is common mode and is 2725000 μK, cluster signal is differential and can be as low as 10 μK).
  - Imaging instrument, resolution ad high frequency comparable to SPT 150 GHz (1 arcmin).
  - Wide field of view to image the whole cluster and have a clean reference area to compare
  - Polarimetric capabilities would be a plus (hear Sergio Colafrancesco later)
- A sequence of experiments : OLIMPO (2.6m telescope, balloon), SAGACE (3m telescope, low orbit), and finally Millimetron (10m telescope, L2)

best ground-based photometers: 4 bands



- Photometric observations of the SZ can be significantly biased, when there are less spectral channels than free parameters.
- Components, LOS through a rich cluster:

ThSZ $$\frac{\Delta I_t}{I_{CMB}} = y\frac{x^4 e^x}{(e^x-1)^2}[x\coth(x/2)-4], \quad y = \int_{LOS}\frac{kT_e}{m_e c^2} n_e \sigma_T d\ell,$$

NThSZ p_{min}, Amp

KSZ $$\frac{\Delta I_v}{I_{CMB}} \sim -\tau_t \frac{v_{LOS}}{c}\frac{x e^x}{(e^x-1)}$$

CMB $$\frac{\Delta I_{CMBi}}{I_{CMB}} = \frac{x e^x}{(e^x-1)}\frac{\Delta T}{T}$$

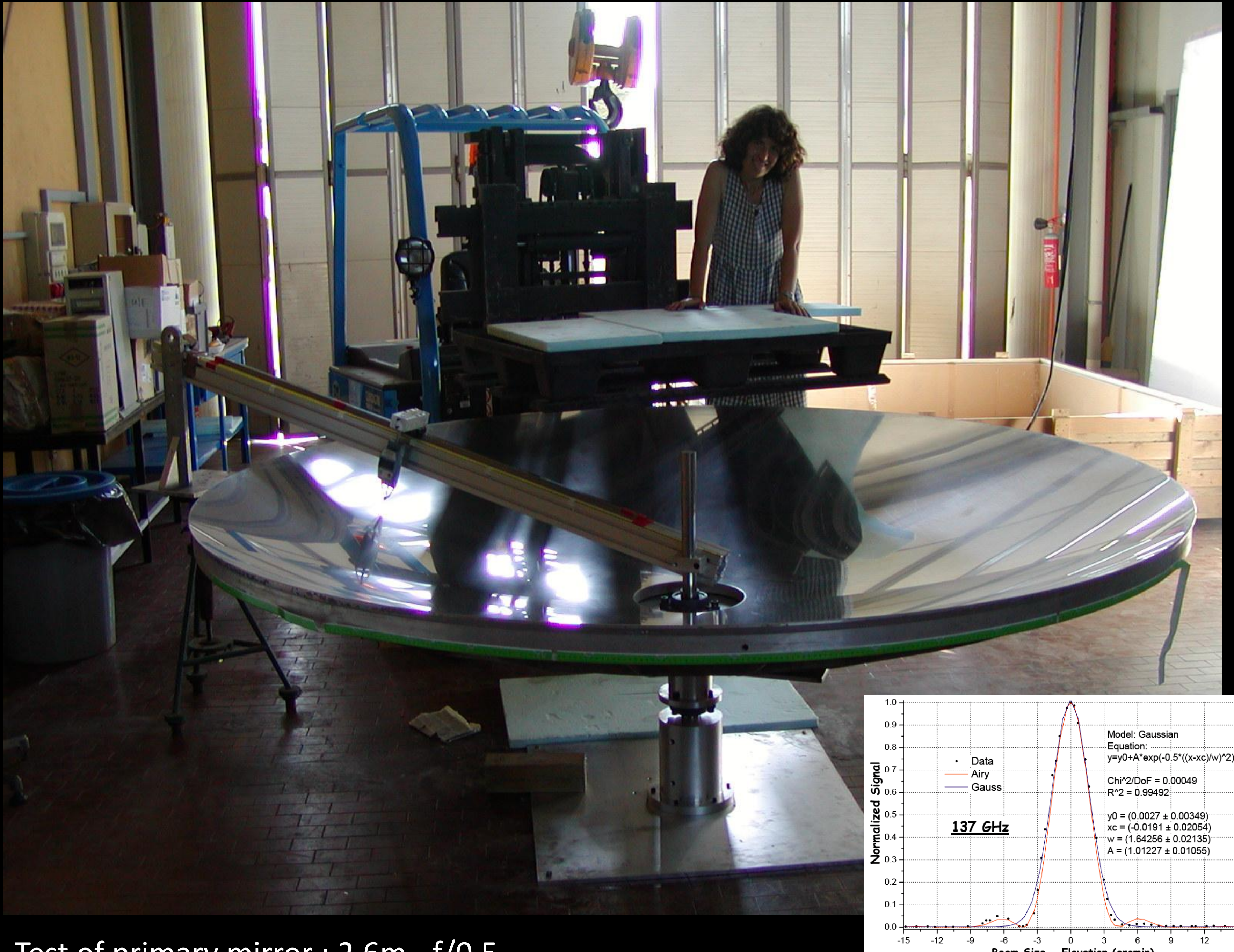
ISD T_d, τ_d ....(β)

At least, 8 independent parameters !

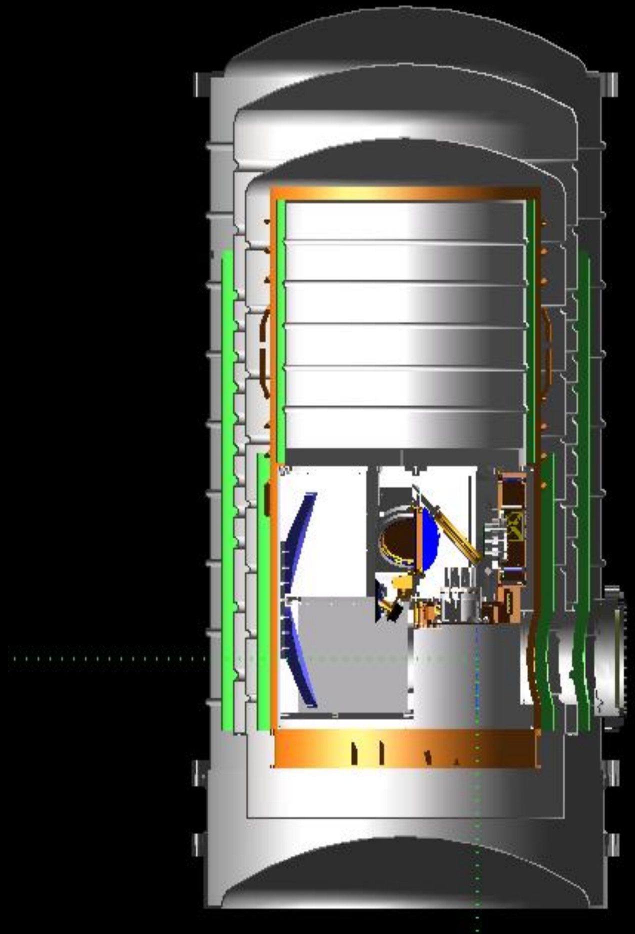
OLIMPO
(PI S. Masi, La Sapienza, Roma)

- Long Duration Balloon experiment for mm and sub-mm astronomy
- Operate from the stratosphere
- Launch from Svalbard
- Cassegrain, 2.6 m primary with scanning capability
- Multi-frequency array of bolometers

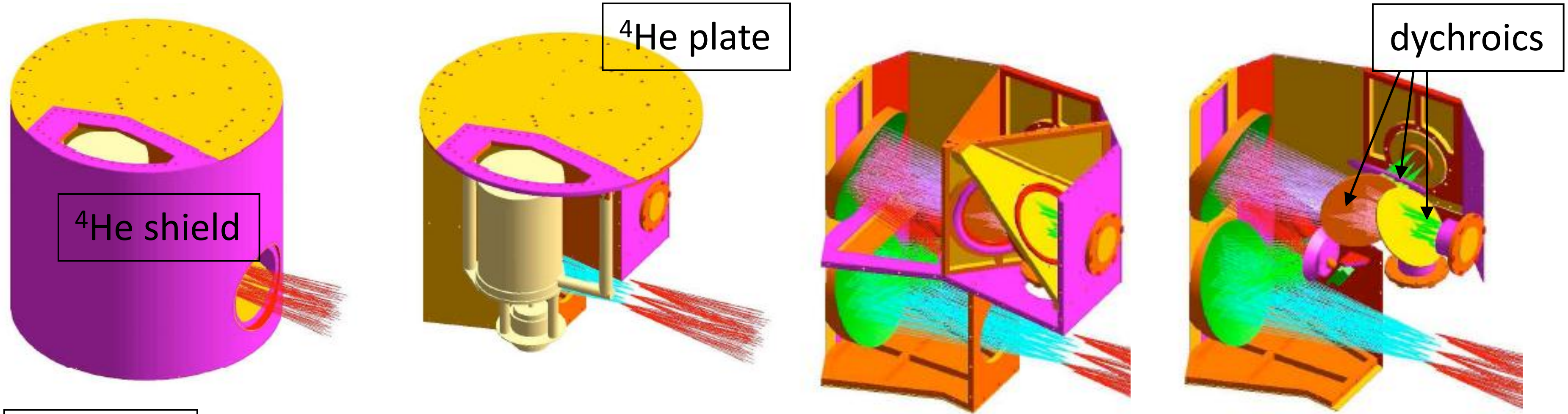
ch	ν_{eff} [GHz]	$\Delta\nu_{FWHM}$ [GHz]	Res. [‘]
I	148.4	21.5	4.2
II	215.4	20.6	2.9
III	347.7	33.1	1.8
IV	482.9	54.2	1.8

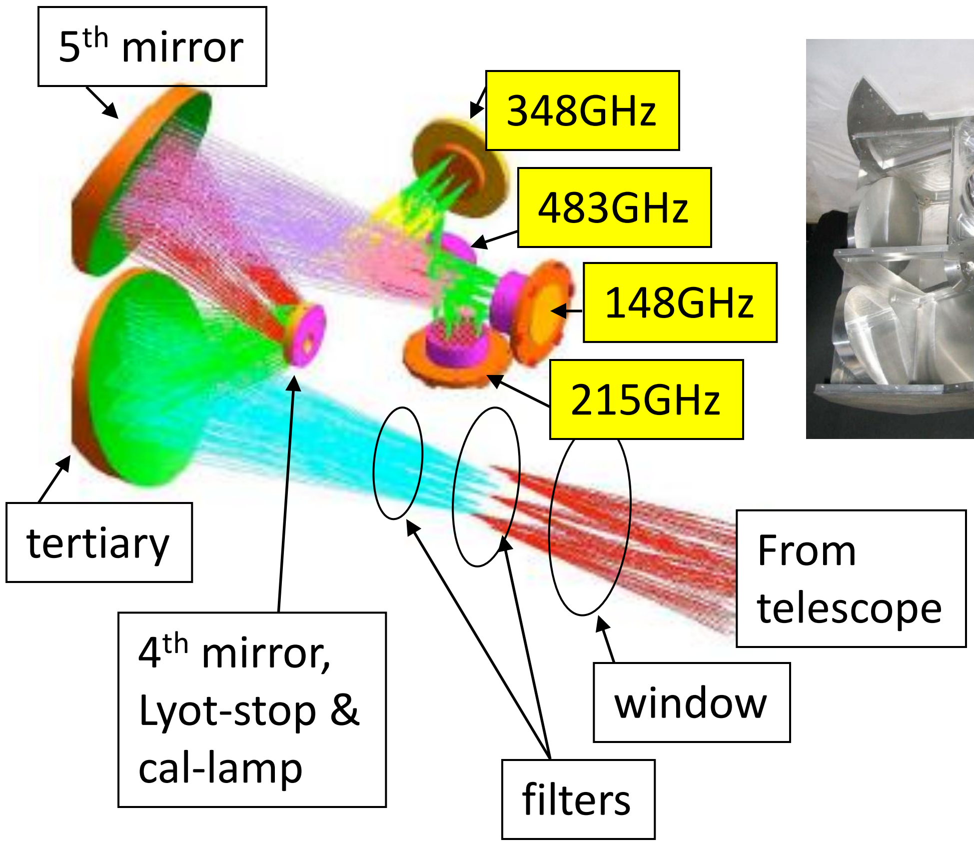


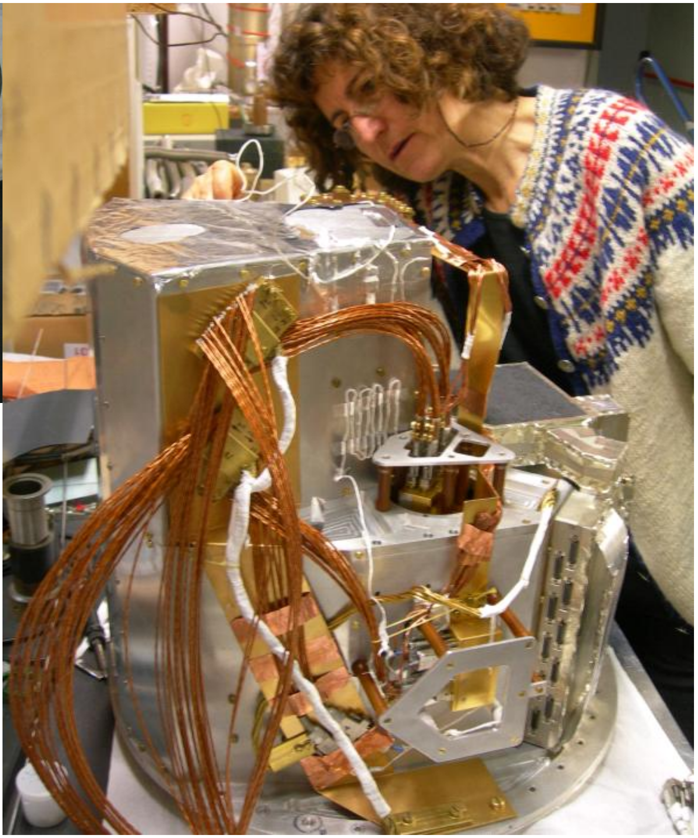
Test of primary mirror : 2.6m - f/0.5



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



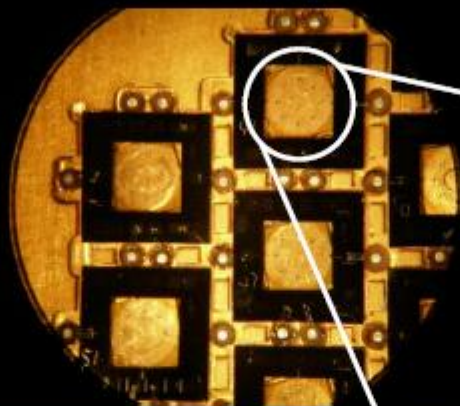


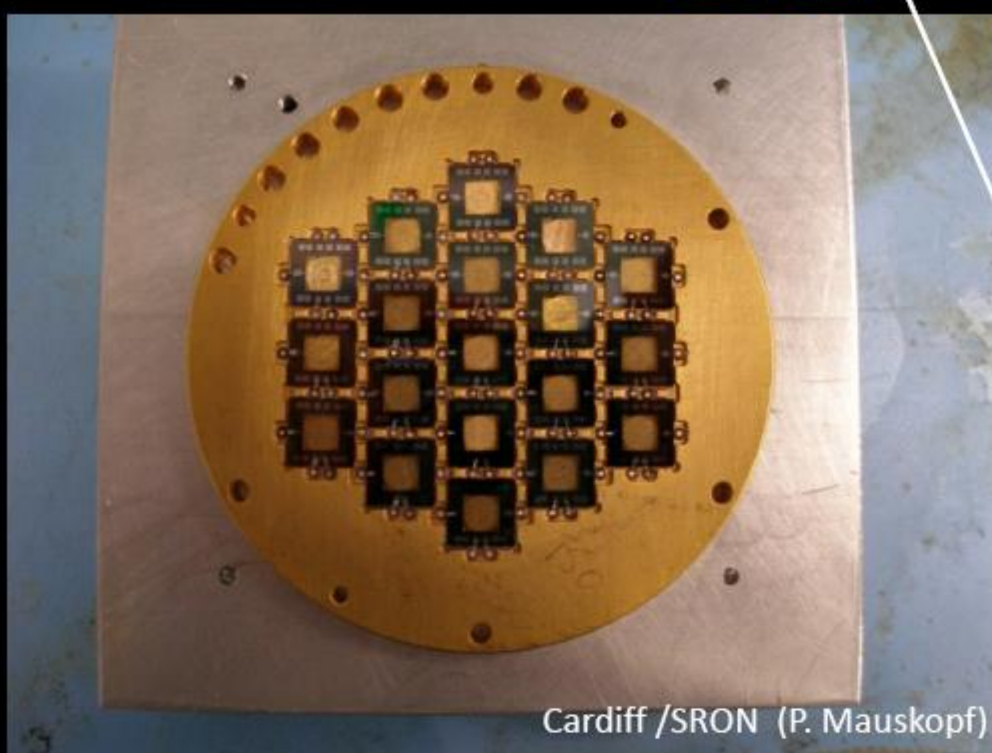


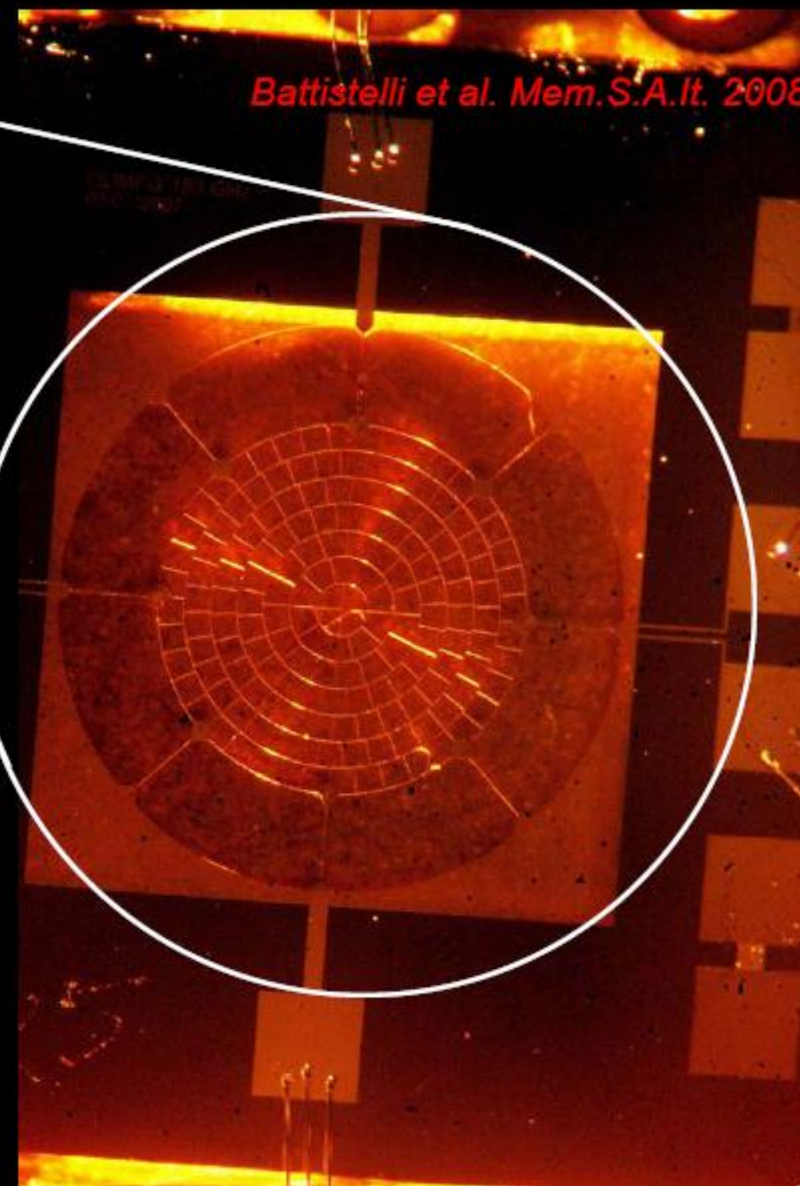
OLIMPO: Cold Optics and Arrays

OLIMPO: Low-frequency arrays (140 GHz & 220 GHz)

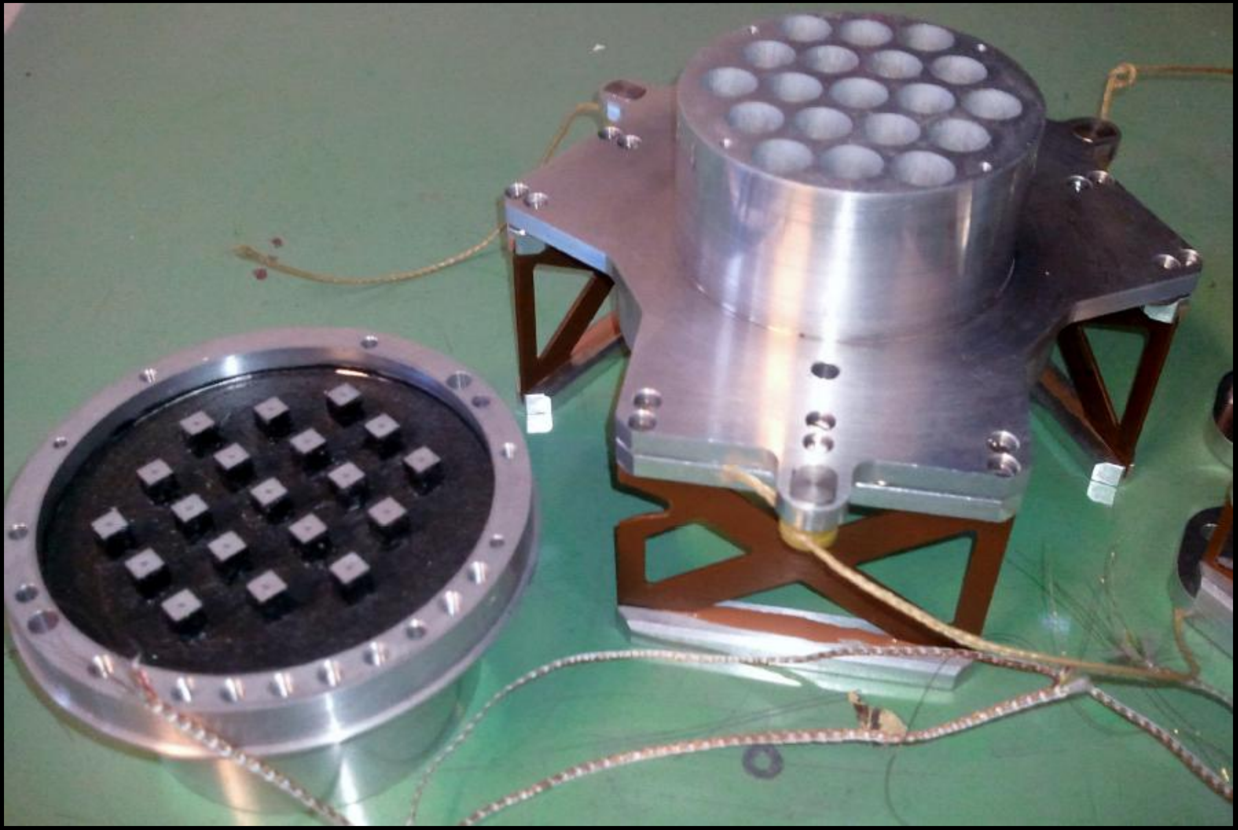
- Wafer: Si_3N_4
- Thermistor: Ti (60nm) + Au (10/20nm)
- Absorber/heater: spiderweb Ti (10nm) + Au (5nm), filling factor 5%





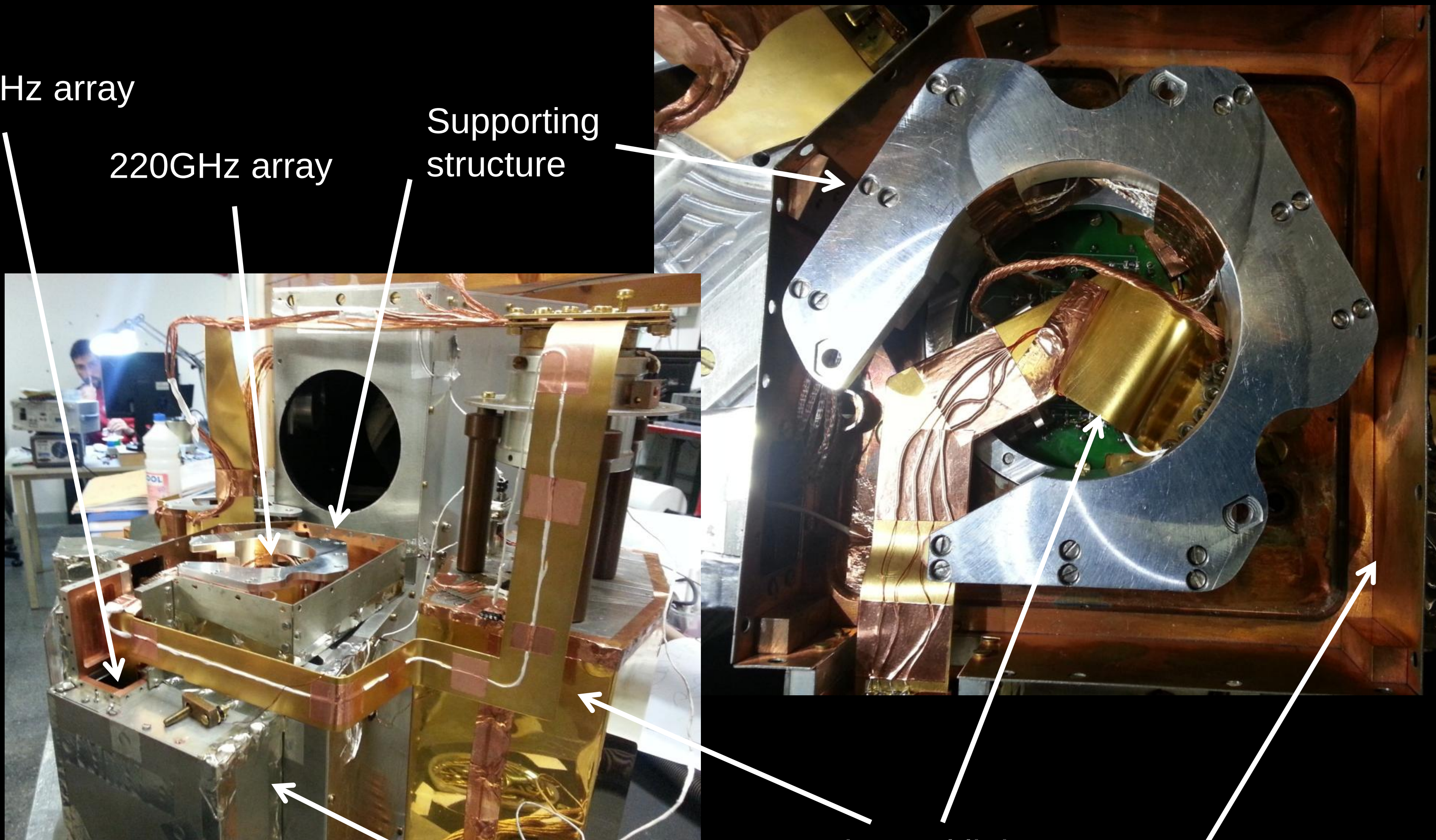


OLIMPO: Low-frequency arrays (140 GHz & 220 GHz)



Cardiff/SRON (P. Mauskopf)

TES in OLIMPO



150GHz array

220GHz array

Supporting structure

Thermal link

Superconducting tinned copper magnetic shield

TES and P_{sat}

$<T_C>=(495 \pm 10)$ mK

$<G>=(1.56 \pm 0.19)\ 10^{-10}$ W/K

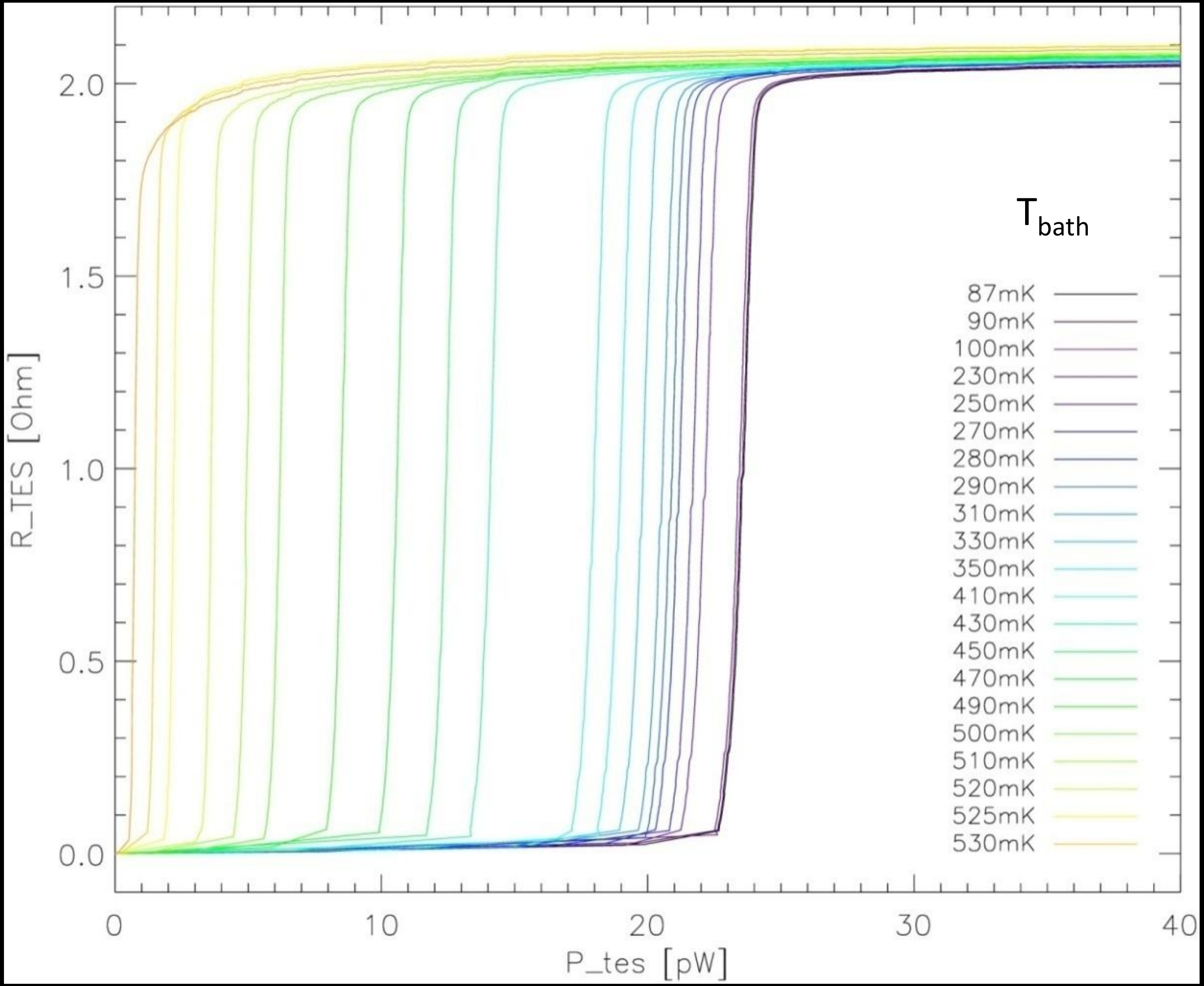
$<NEP>=(3.7 \pm 0.2)\ 10^{-17}$ W/ √Hz

$<R_N>=(2.15 \pm 0.22)$ Ohm

$<P_{SAT}>=(15.5 \pm 1.4)$ pW…
…@ 290-310 mK

- Background MUST be strictly lower than P_{sat}!!!

- We need to account for the additional mirrors and wire grids in the FTS



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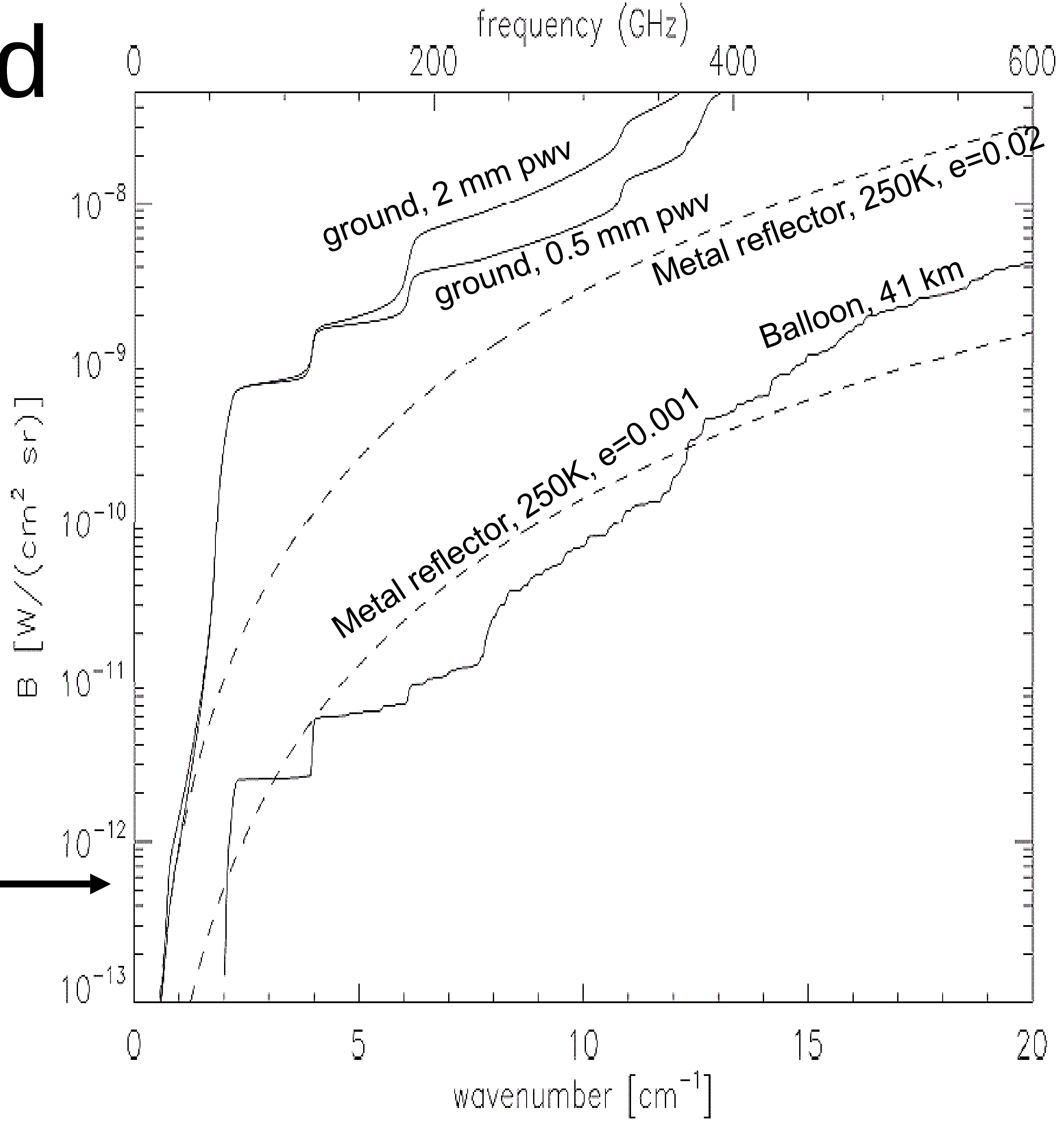
bands

- In a FTS radiation from the whole covered range hits the detector at all times
- This is an advantage in terms of signal, but increases significantly the background.
- In the case of OLIMPO, the spectrometer is a room-temperature plug-in maintaining the same 4-bands and photometer arrays: spectroscopy is achieved within each band.
- The bandwidths cannot be too wide, otherwise the detectors saturate.

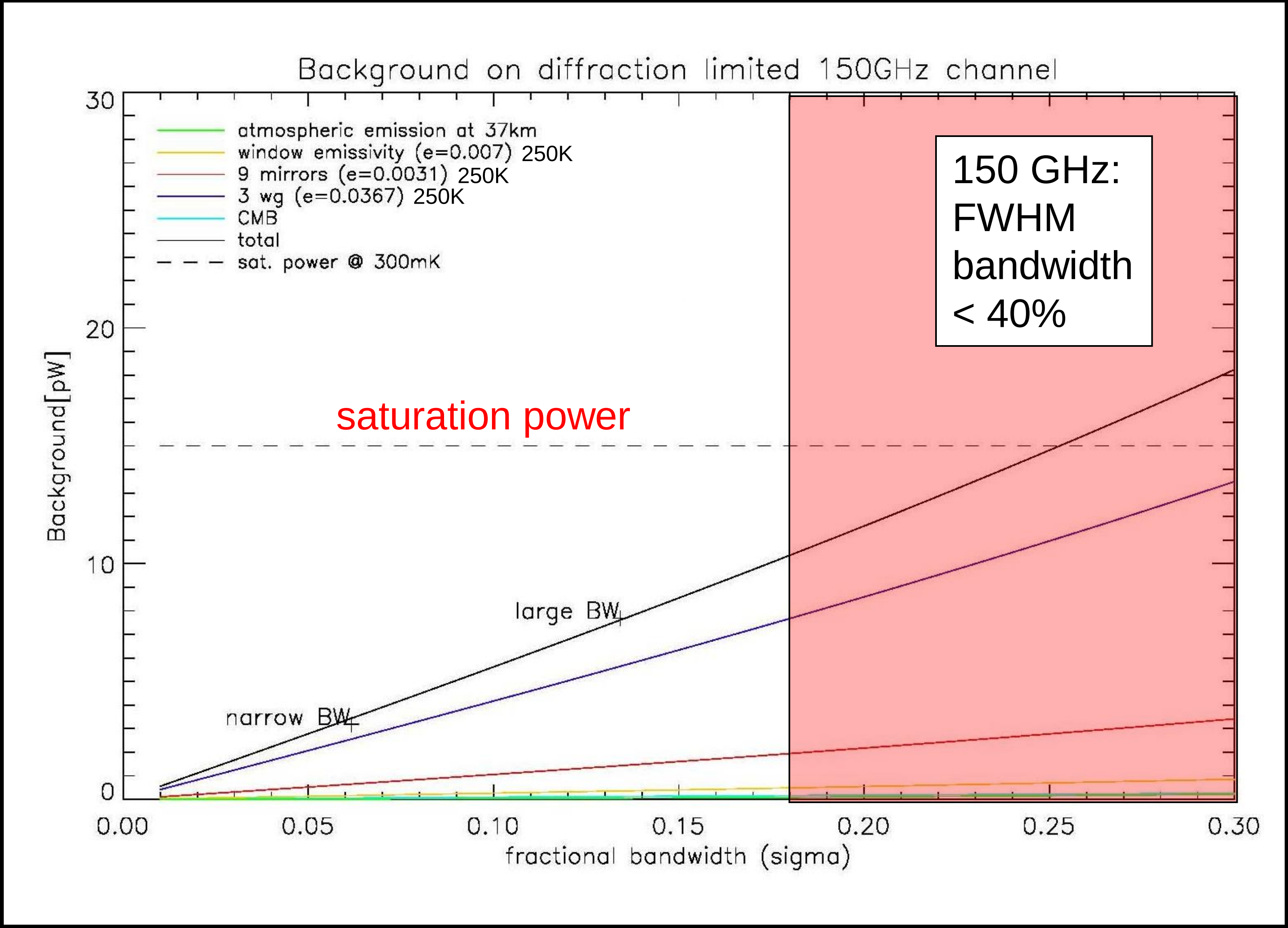
Background

- Dominated by CMB, residual atmosphere, instrument (wire grids).
- Instrument bkg must be lower than CMB+Atm.
- Compare:

$$\int_0^{\nu} B(\nu)\,d\nu$$



Background on the 150GHz TES



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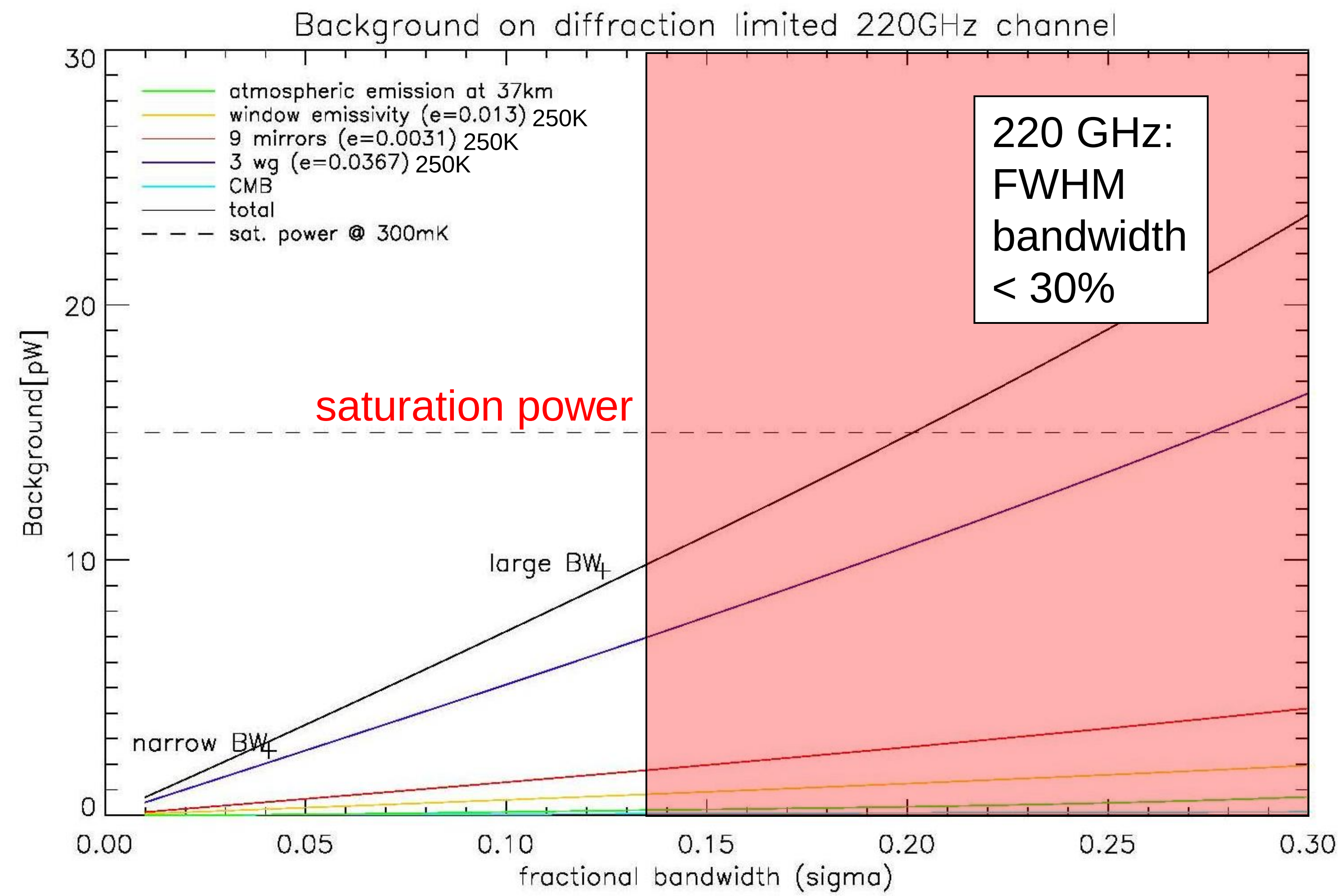
Background on the 220GHz TES



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OLIMPO

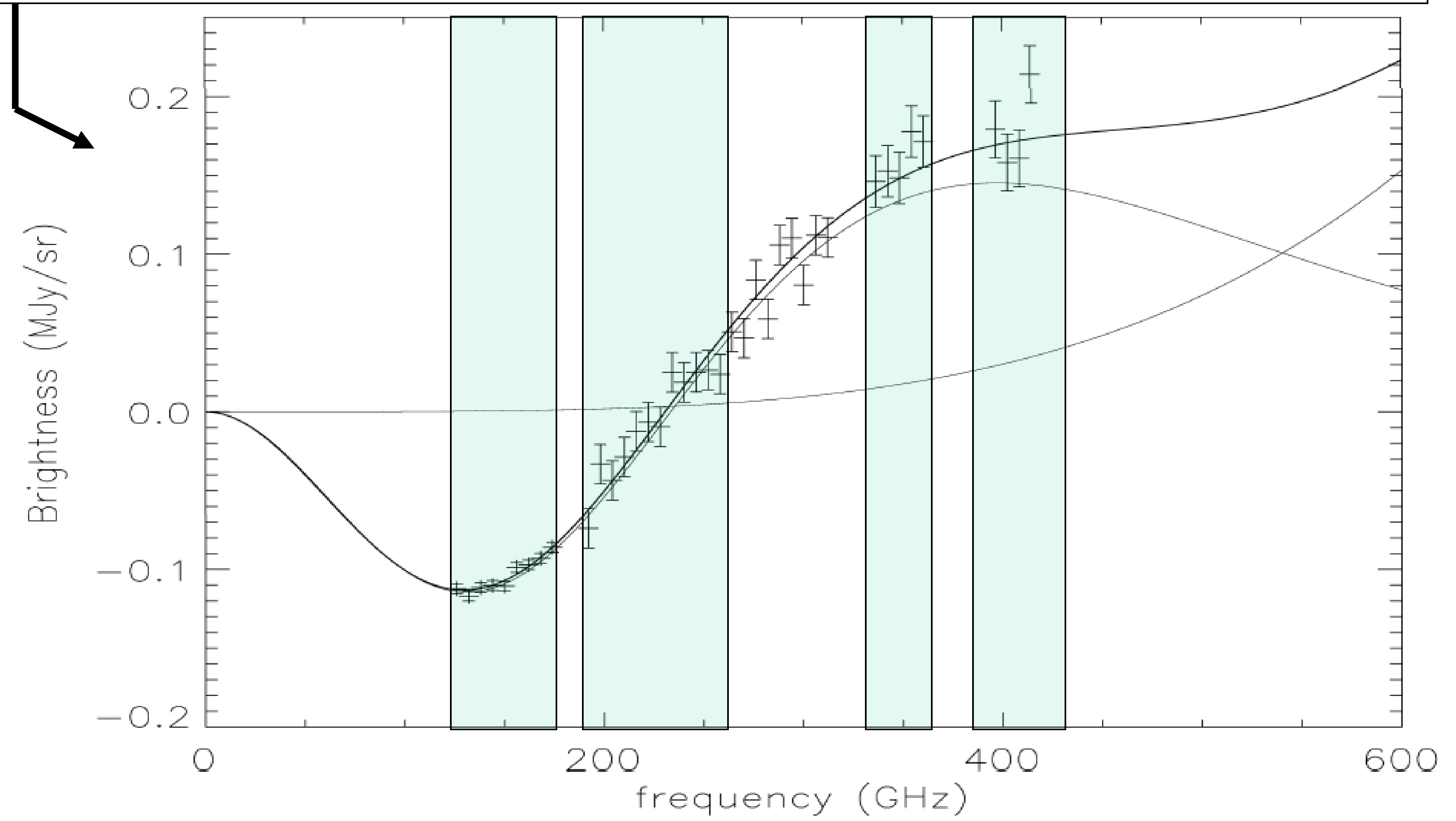
(PI S. Masi, La Sapienza, Roma)

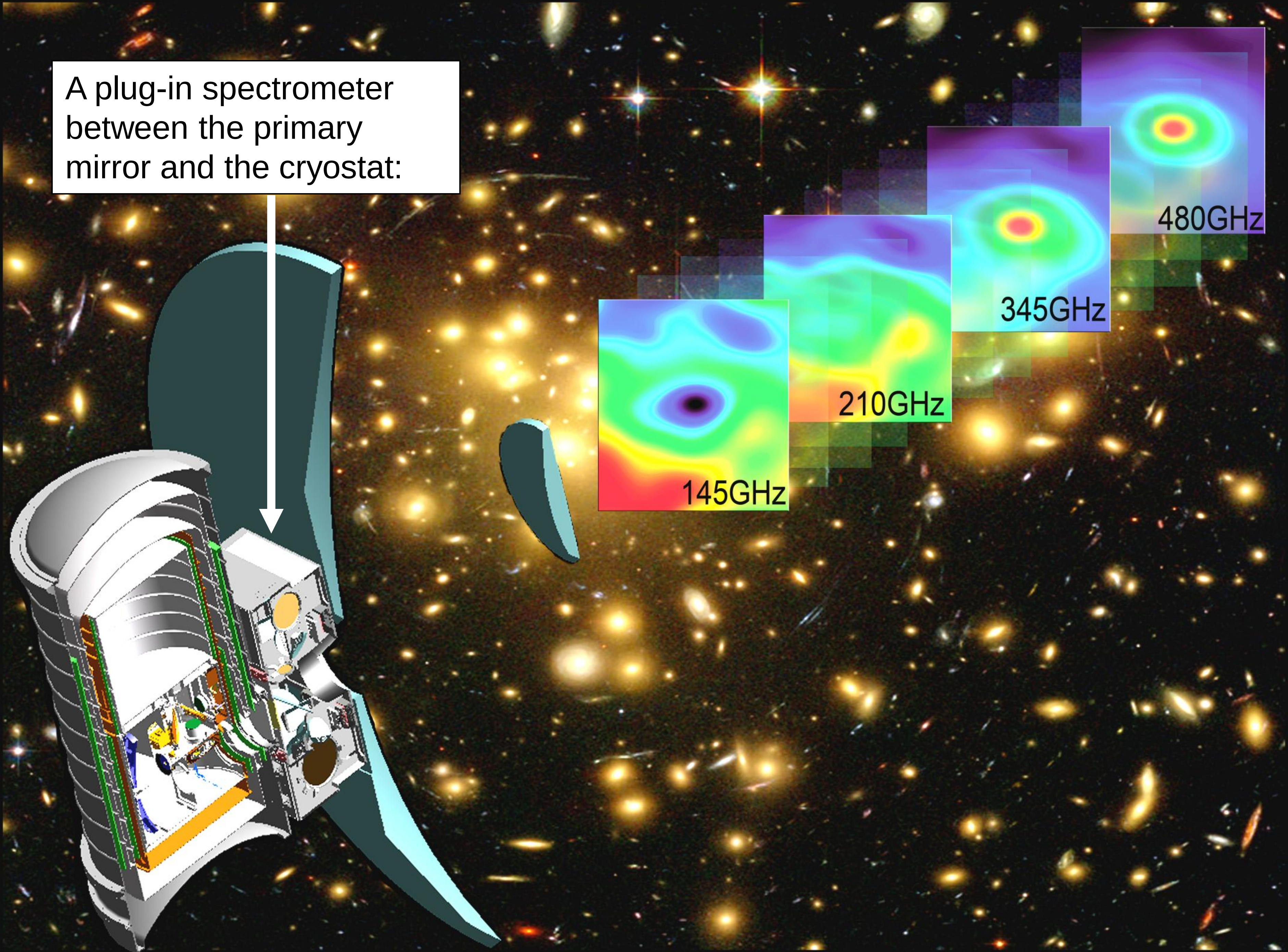
- Long Duration Balloon experiment for mm and sub-mm astronomy
- Operate from the stratosphere
- Launch from Svalbard
- Cassegrain, 2.6 m primary with scanning capability

Optimized filters
(Cardiff, P. Ade, C. Tucker)

ch	ν[GHz]	$\Delta\nu_{FWHM}$[GHz] (6 GHz bins)	Beam FWHM(‘)
I	148.4	60 (10)	4.2
II	215.4	64 (10)	2.9
III	347.7	33 (5)	1.8
IV	482.9	54 (9)	1.8

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.

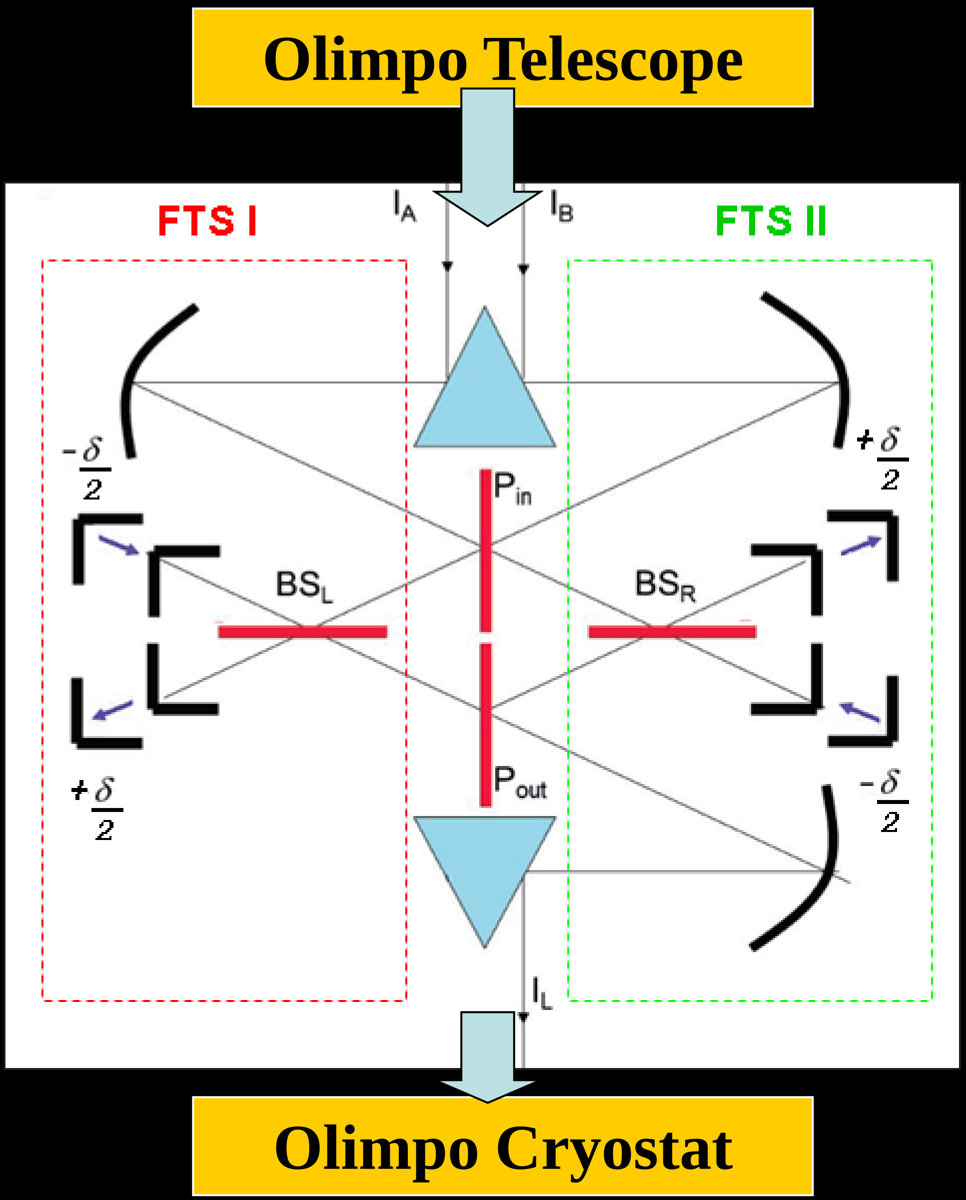




A plug-in spectrometer between the primary mirror and the cryostat:
145GHz
210GHz
345GHz
480GHz

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.



outgoing fields :

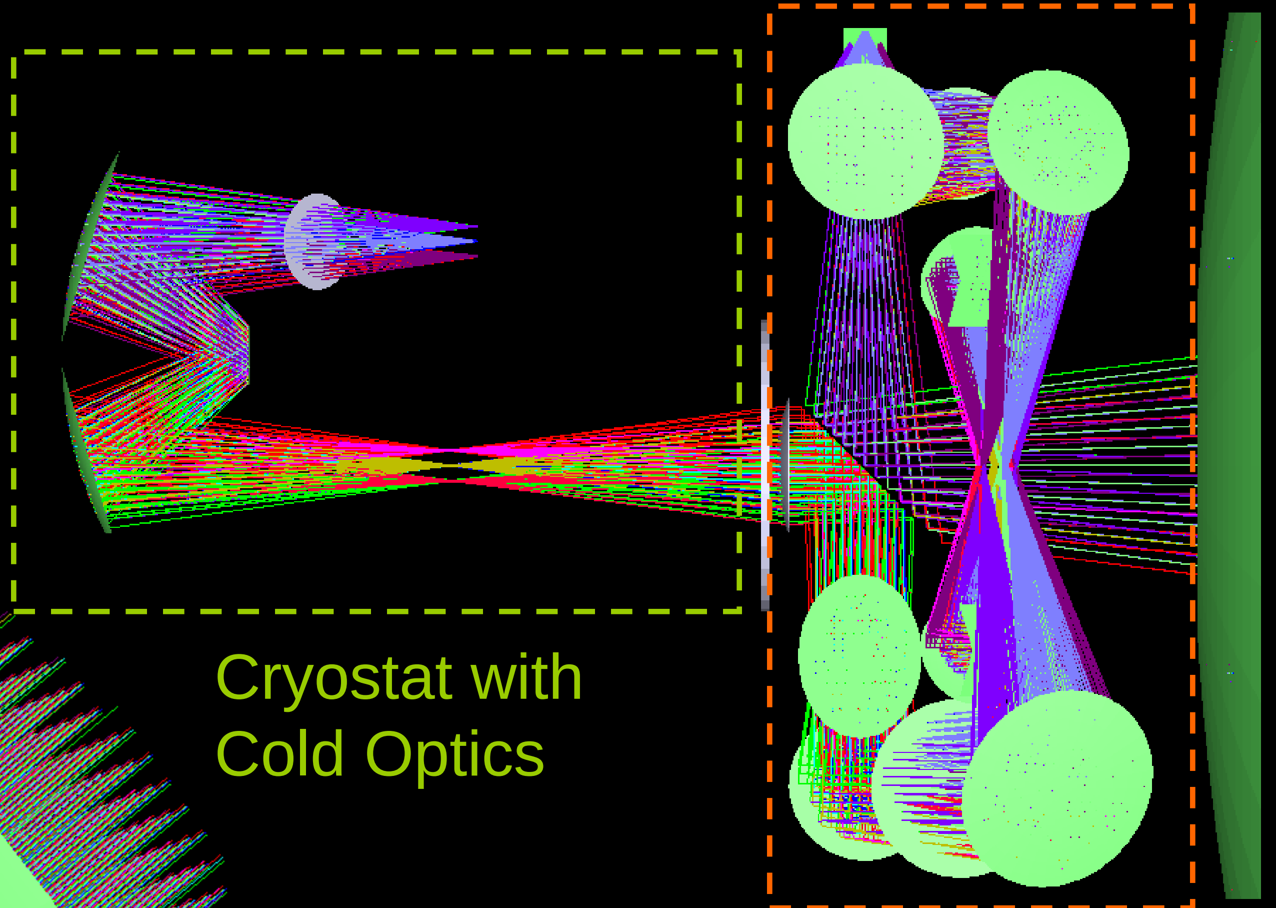
$$E^{FTSII} = \begin{pmatrix} B_x \cos(\delta/2) + i\, A_y \sin(\delta/2) \\ 0 \end{pmatrix}$$

$$E^{FTSI} = \begin{pmatrix} 0 \\ B_y \cos(\delta/2) + i\, A_x \sin(\delta/2) \end{pmatrix}$$

Power at the detector :

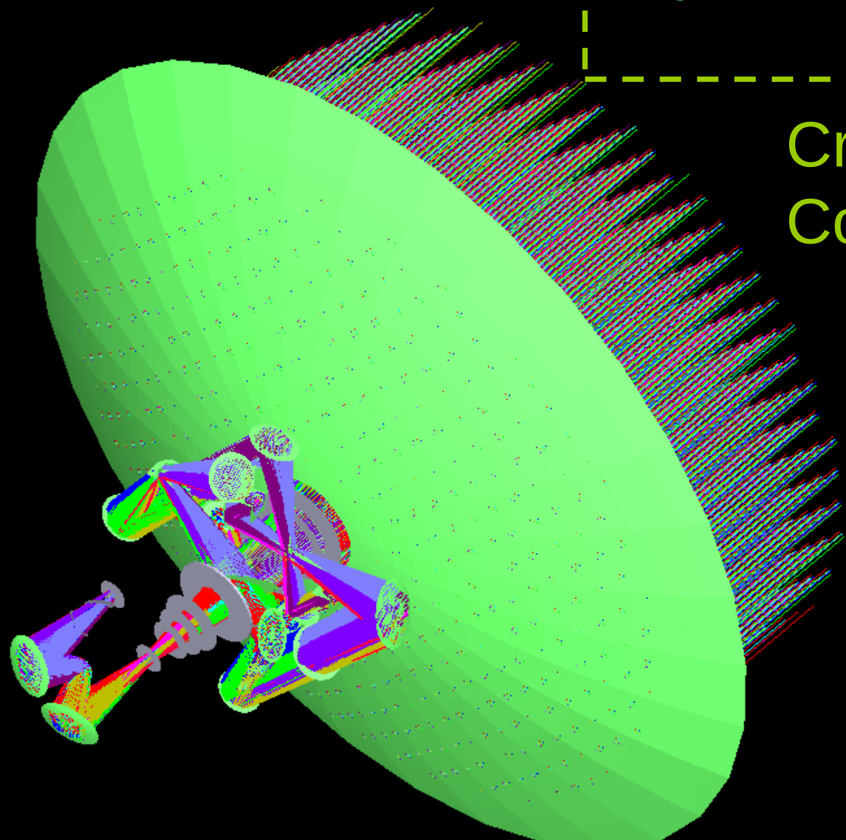
$$I = \langle E_{tot} E_{tot}^{*} \rangle \propto \left[\left(B_x^2 + B_y^2\right) + \left(A_x^2 + A_y^2\right)\right] + \cos\delta \left[\left(B_x^2 + B_y^2\right) - \left(A_x^2 + A_y^2\right)\right]$$

Optical optimization has been performed using ZEMAX^{TM} software optimizing the optical quality in the full FOV of OLIMPO.

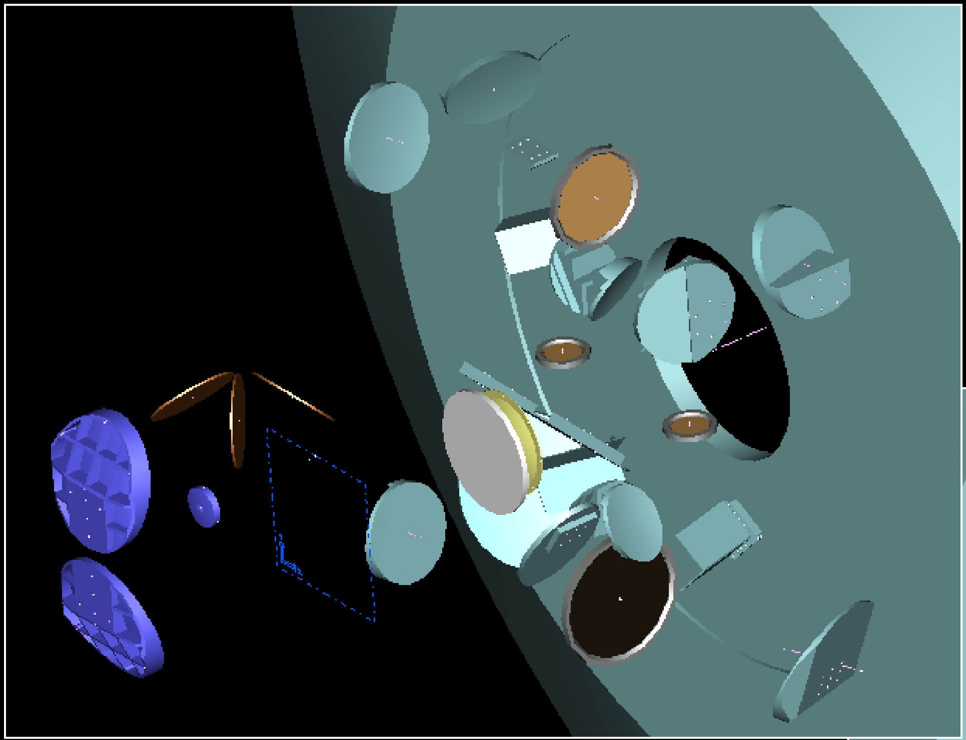


Cryostat with Cold Optics

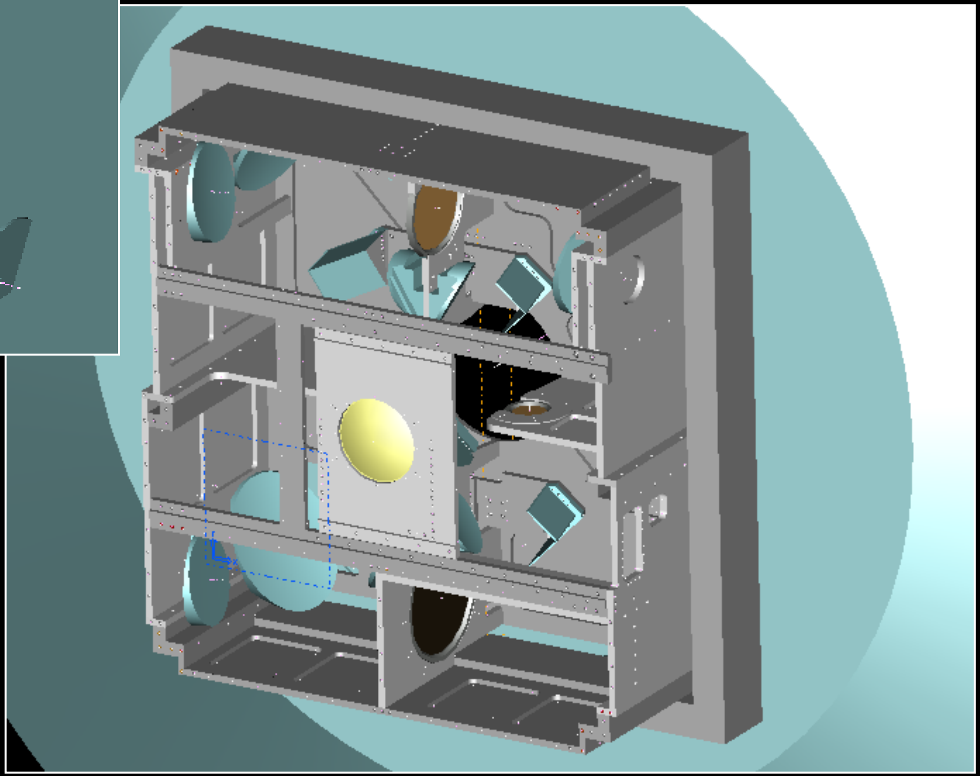
FTS

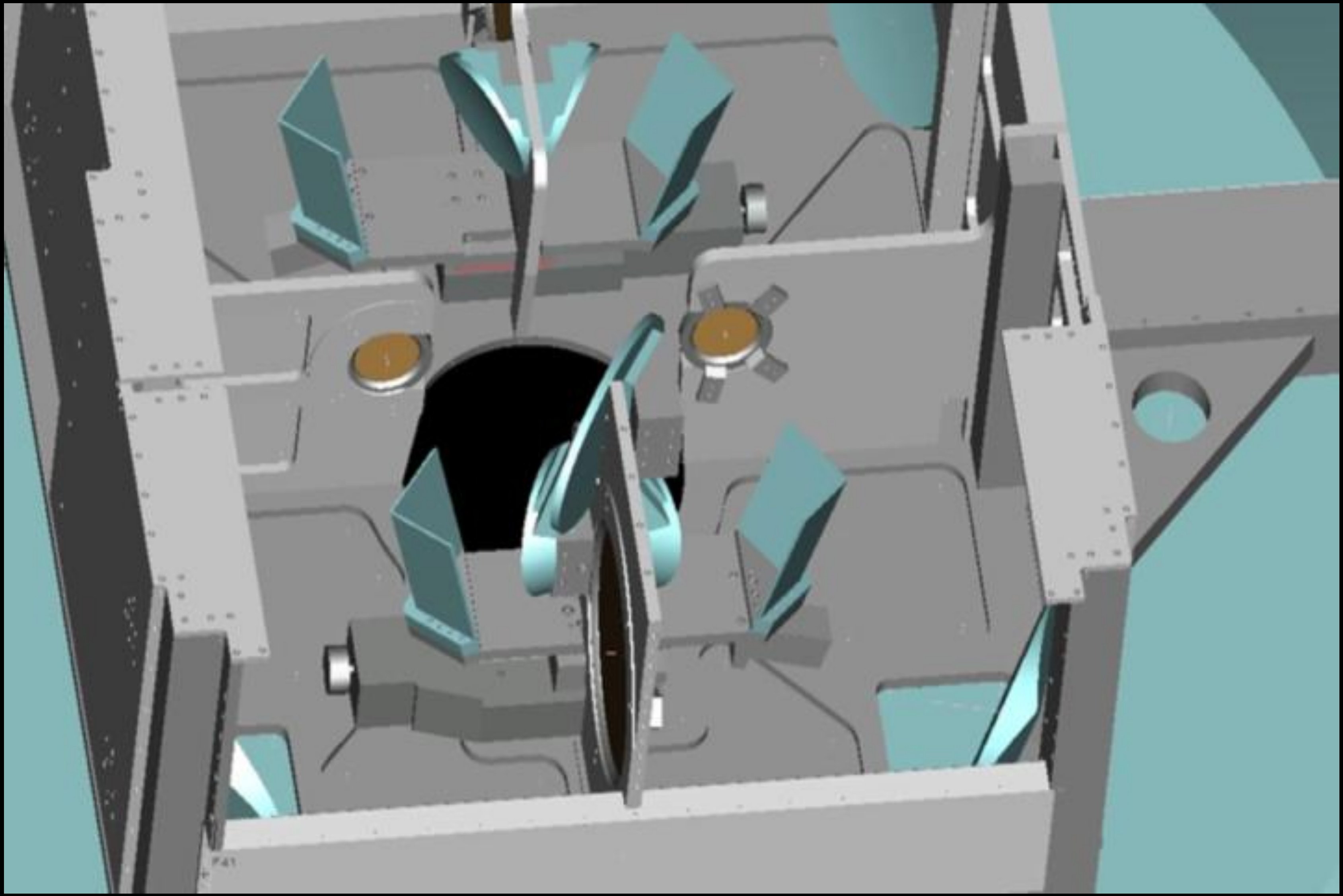


The instrument was designed to fit the available room in between the primary mirror and the cryostat, a 75x75x30 cm^3 box (A.Schillaci)

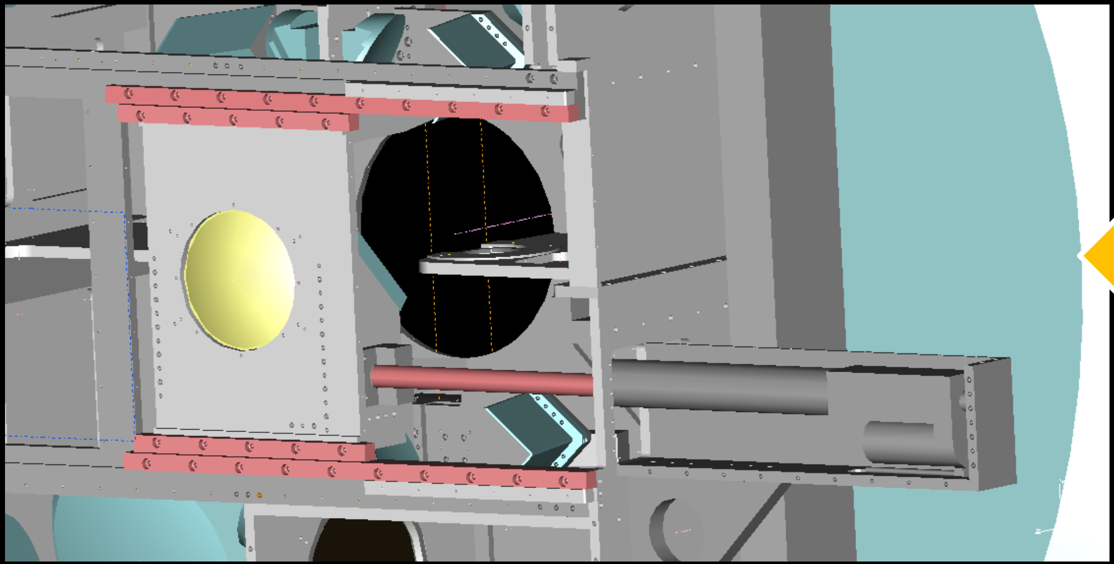


Progettazione 3D con software Ideas NX 11.



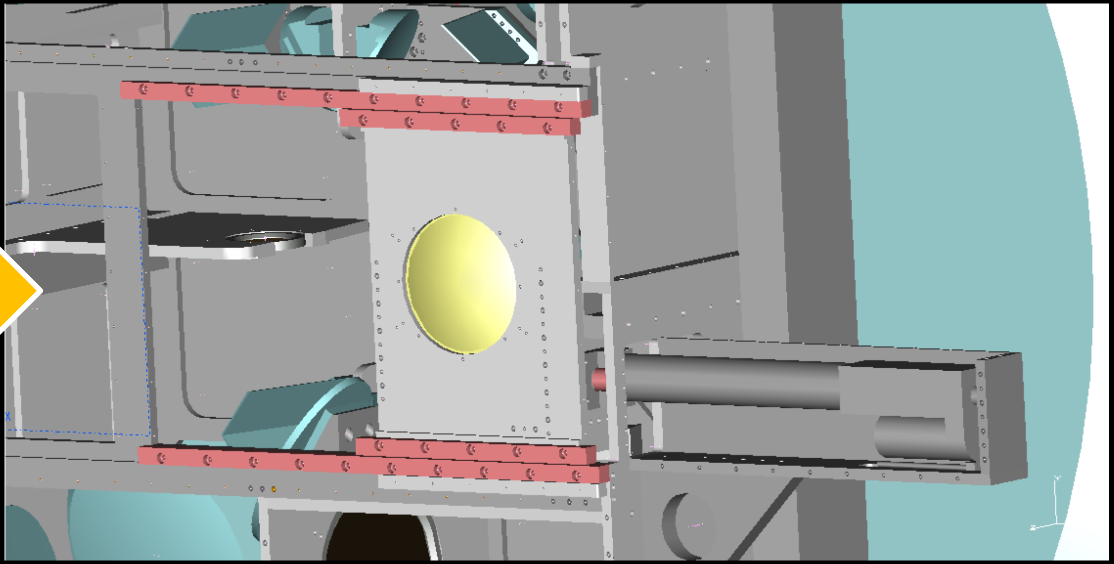


OLIMPO MPI (A. Schillaci et al.)



Spectrometer Mode

Photometer Mode



University of Milano Bicocca

Prof. Massimo Gervasi

Thermal Stress Stabilization cycles for mirrors

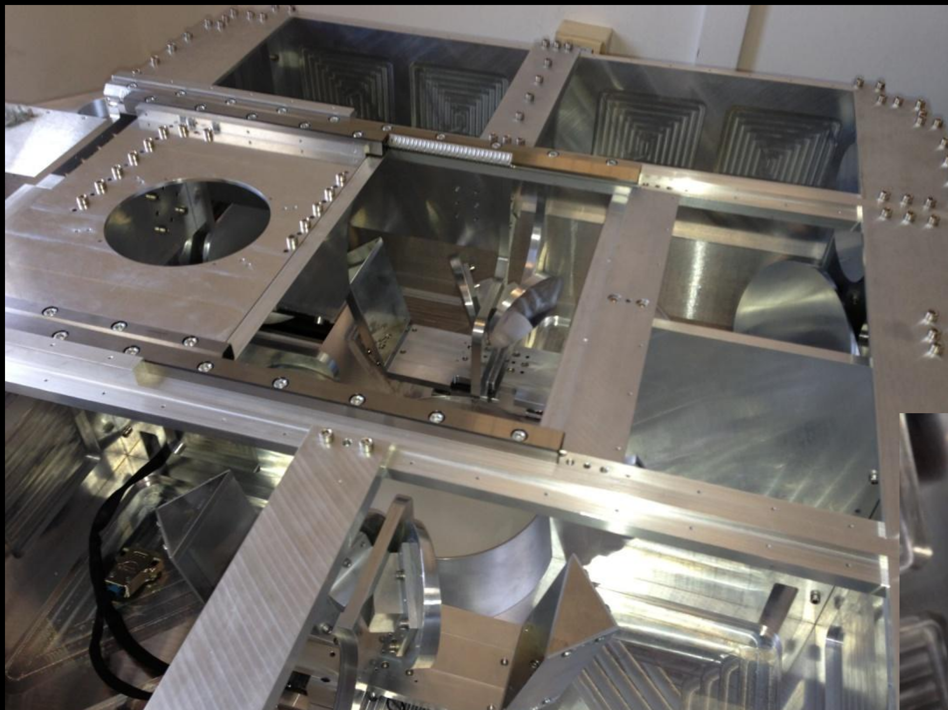
University of Milano Bicocca

Prof. Massimo Gervasi

Università «La Sapienza»
Dipartimento di Fisica

OLIMPO MPI

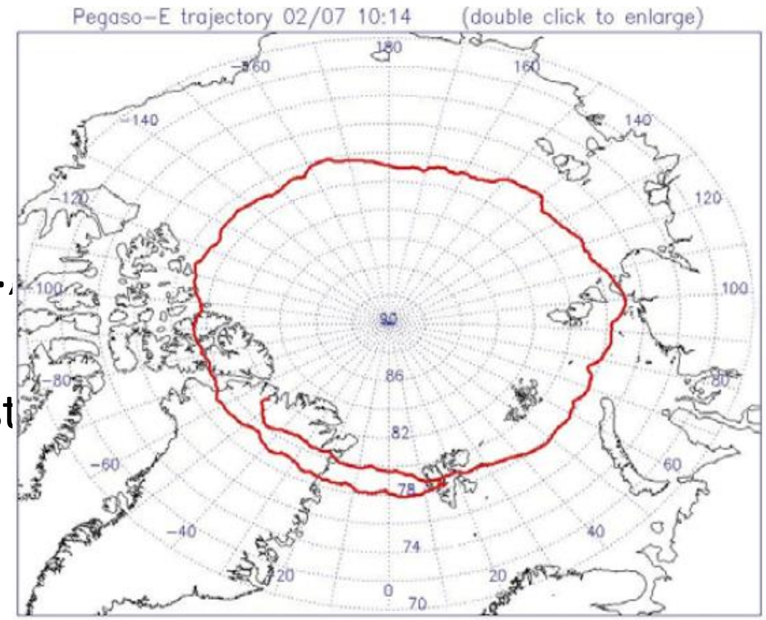
Delay lines and roof mirrors, with tuning movement

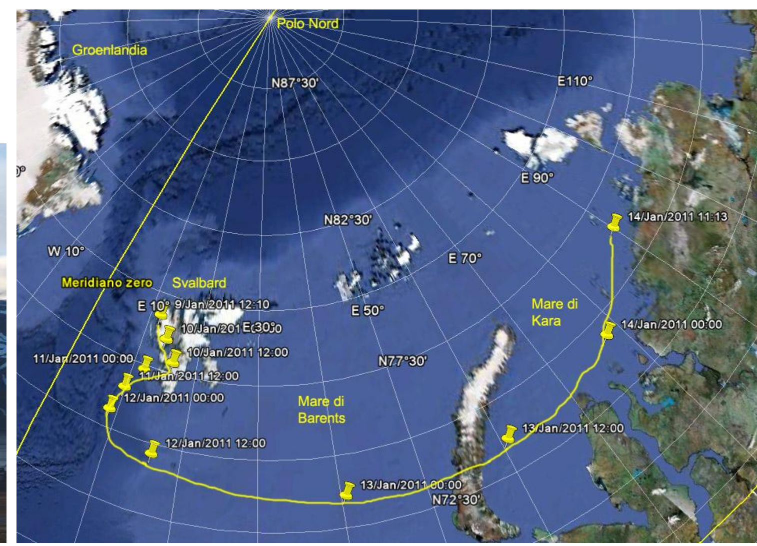


OLIMPO MPI

Polar flights

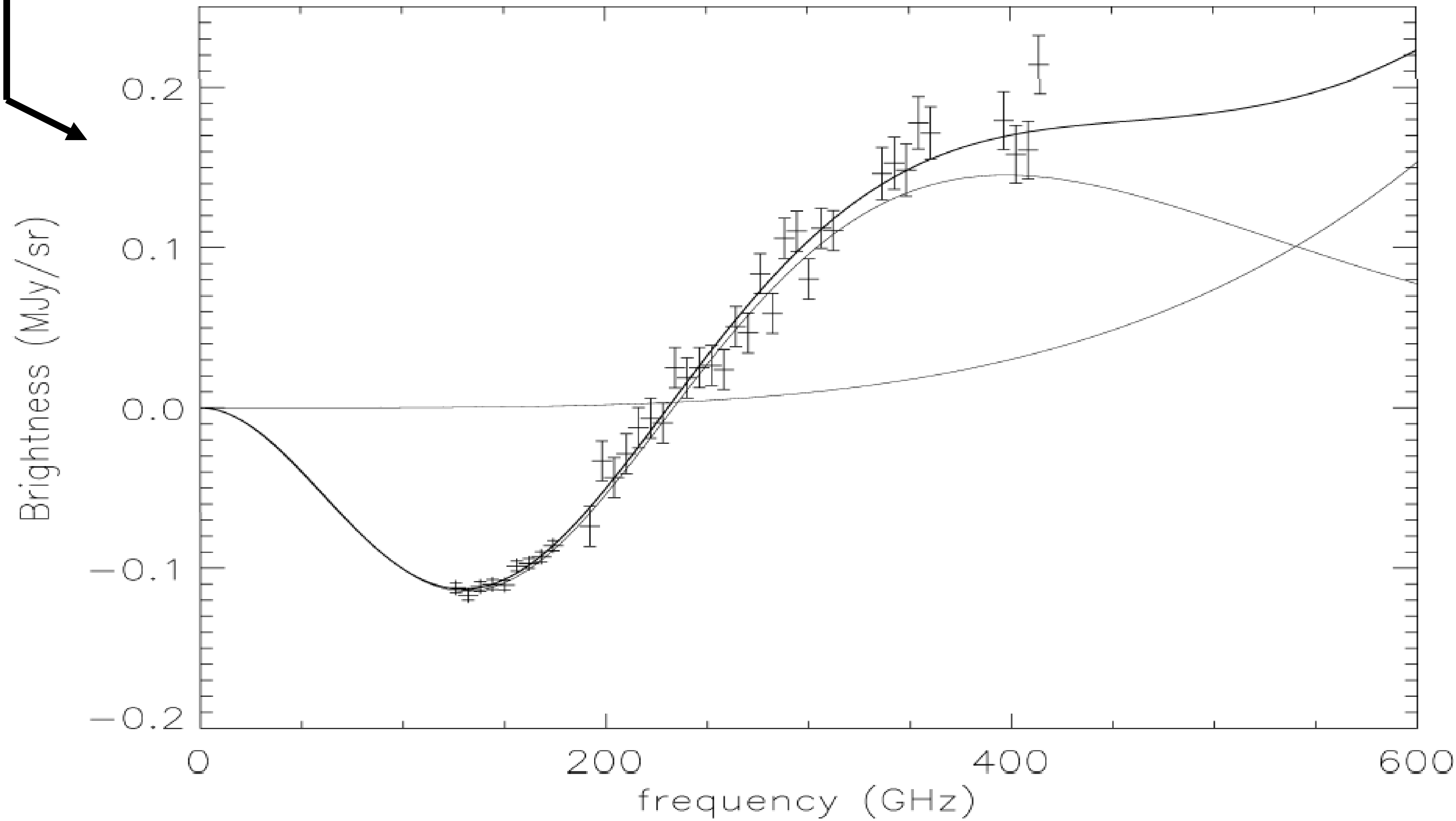
- NASA-CSBF has flown balloons around the south pole for many years.
- We have flown long duration stratospheric balloons around the North Pole launching from **Longyearbyen** (Svalbard) both in the summer (heavy litf payloads) and in winter (pathfinders) [see Peterzen, S., Masi, S., et al., Mem. S. A. It., 79, 792-798 (2008)]
- In this way CMB experiments can access most of the northern sky in a single flight,
  - without contamination from the sun in the sidelobes
  - within a cold and very stable environment
  - Accumulating more than 10 days of integration at float (38 km altitude).

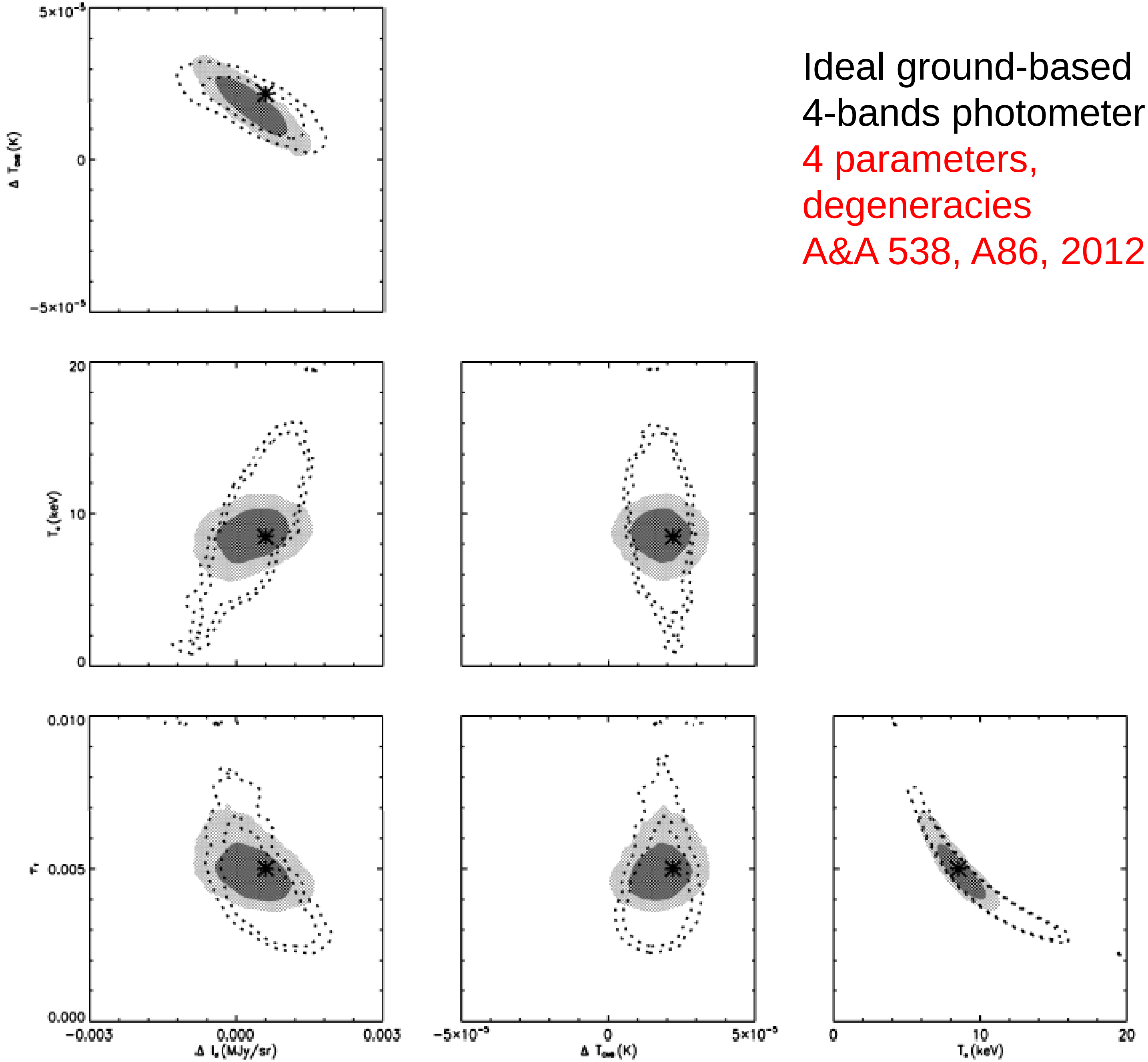




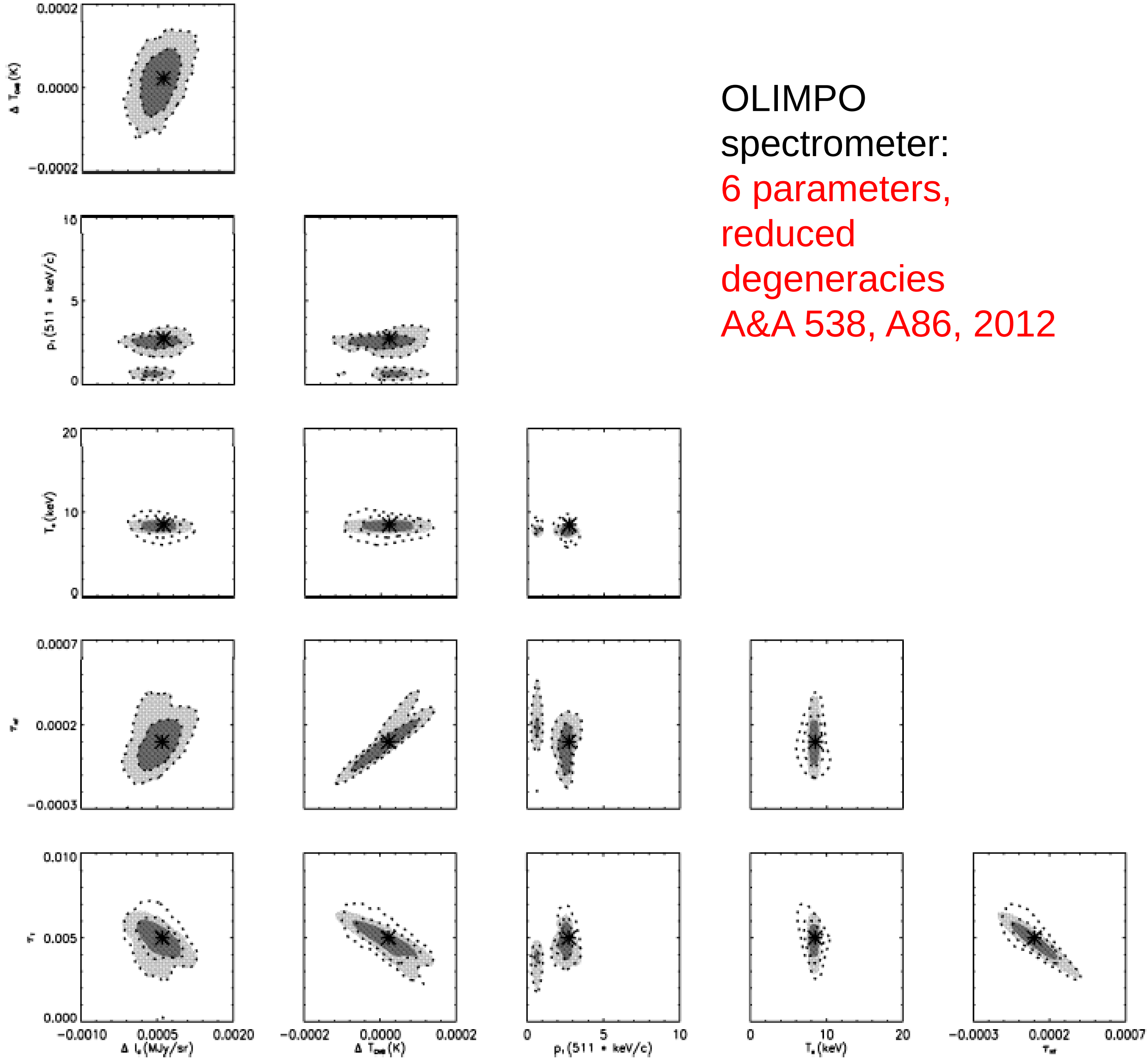
Top: Ground path of a flight performed in June 2007. **Bottom right:** Ground path of a small pathfinder test flight performed in January 2011, in the middle of the polar night. The eastward trajectory is evident. **Bottom left:** Launch of a heavy-lift balloon from the Longyearbyen airport (Svalbard Islands, latitude 78°N).

With these spectral capabilities, it will be possible to complement large telescopes data and to separate efficiently different components of the SZE
(see de Bernardis et al. A&A 538, A86, 2012, and hear Sergio Colafrancesco later).
Additional science:
Hear Chluba, Galli, et al. later.





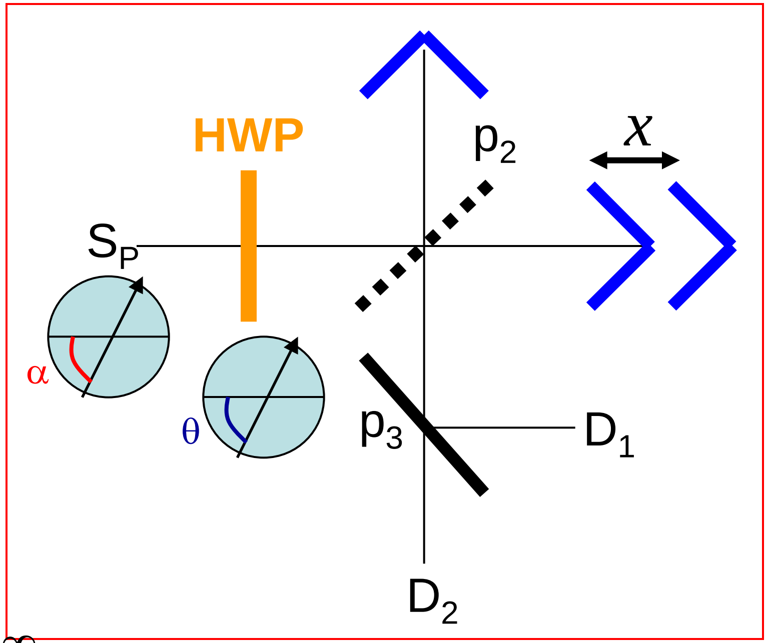
Ideal ground-based
4-bands photometer:
4 parameters,
degeneracies
A&A 538, A86, 2012



OLIMPO
spectrometer:
6 parameters,
reduced
degeneracies
A&A 538, A86, 2012

Polarization sensitive FTS

- First option: Use only one entrance port - remove input polarizer
- Include a spinning broad-band HWP, to rotate the input polarized signal.
- For a linearly polarized input signal S_p the detector signal will be



$$D(x)-\langle D\rangle=\frac{1}{2}\cos(4\theta-2\alpha)\cdot\int_0^{\infty}S_p(\sigma)\cos(4\pi\sigma x)d\sigma$$

Modulation from the HWP

Interferogram from **polarized fraction** of the input spectrum

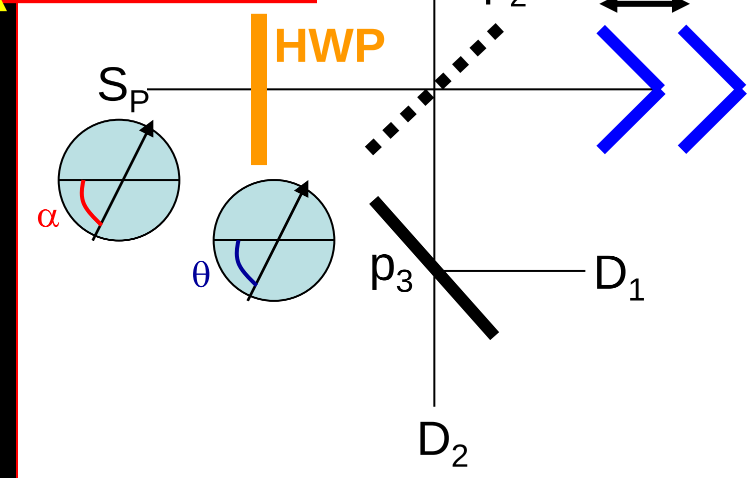
- The unpolarized signal is not modulated, and does not contribute to the interferogram (but contributes to the background)

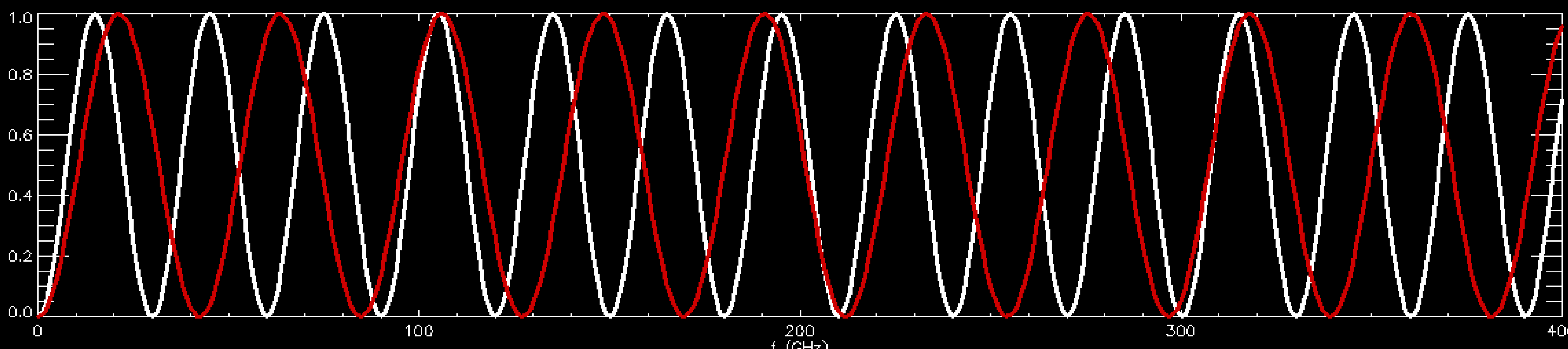
Lock-in demodulation gives spectrum (amplitude) and orientation (phase) of the input polarized signal S_P .

Polarization sensitive FTS

- Main problem: bandwidth of waveplate.
- If the waveplate is a reflective HWP, it is possible to use it at multiples of the first frequency (see COrE approach).
- The performance of an embedded-mesh RHWP at high orders n is currently investigated thoroughly for COrE (see G. Pisano).
- In principle, it is possible to sample different portions of the spectrum using WPs with different d spacing.

$$\nu_n = \frac{2n+1}{4\cos\varphi}\frac{c}{d}$$





----- d = 14.1 mm (COrE

----- d = 5.0 mm

SAGACE

Spectroscopic **A**ctive **G**alaxies **A**nd **C**lusters **E**xplorer

Bagliani D.[1], Bardi A.[2], Battistelli E.[3], Birkinshaw M.[4], Conte A.[3], **de Bernardis P.[3] (P.I.),** De Gregori S.[3], De Petris M.[3], De Zotti G.[5], Donati A.[2], Ferrari L.[1],Franceschini A.[6], Gatti F.[1], Gervasi M.[7], Gonzalez-Nuevo J.[8], Lamagna L.[3], Luzzi G.[3], Maiolino R.[9], Marchegiani P.[3], Mariani A.[2], Masi S.[3], Massardi M.[9], Mauskopf P.[9], Nati L.[3], Nati F.[3], Natoli P.[10], Piacentini F.[3], Polenta G.[3], Porciani M.[2], Savini G.[9], Schillaci A.[3], Spinelli S.[6], Tartari A.[6], Tavanti M.[2], Tortora A.[2], Vaccari M.[5], Vaccarone R.[1], Zannoni M.[6].

(1) Dipartimento di Fisica, Università di Genova, and INFN sez. di Genova
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(4) Department of Physics, University of Bristol, UK
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(7) Dipartimento di Fisica, Università di Milano Bicocca
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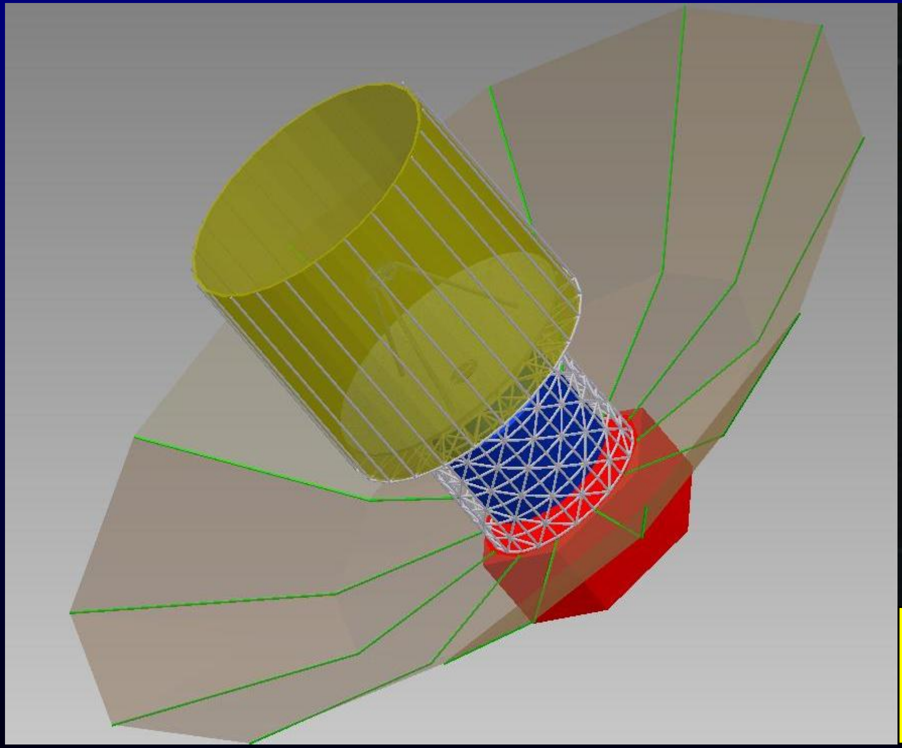
(10) Department of Physics and Astronomy, Cardiff University, UK
(11) Dipartimento di Fisica, Università di Tor Vergata, Roma

All details in astro-ph/1002.0867

SAGACE

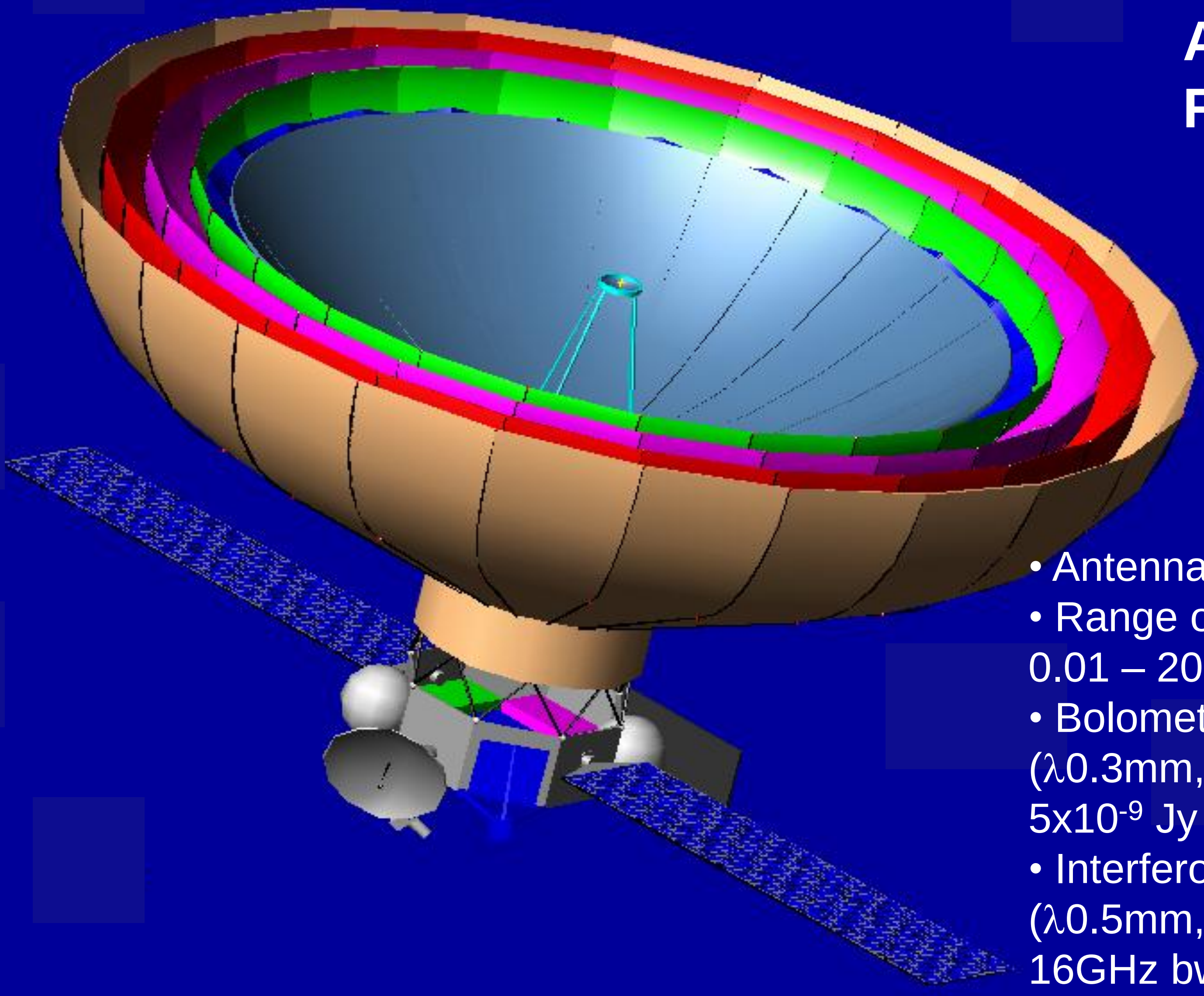
Spectroscopic Active Galaxies And Clusters Explorer

- Selected by ASI for a phase-A study as a small mission in 2008
- Phase-A study completed on october 2008
- 2.6 m telescope + FTS spectrometer on a Soyuz
- Uni. La Sapienza / Uni. Mi. Bicocca / Uni. Genova / Kayser Italiana / ASDC-ASI

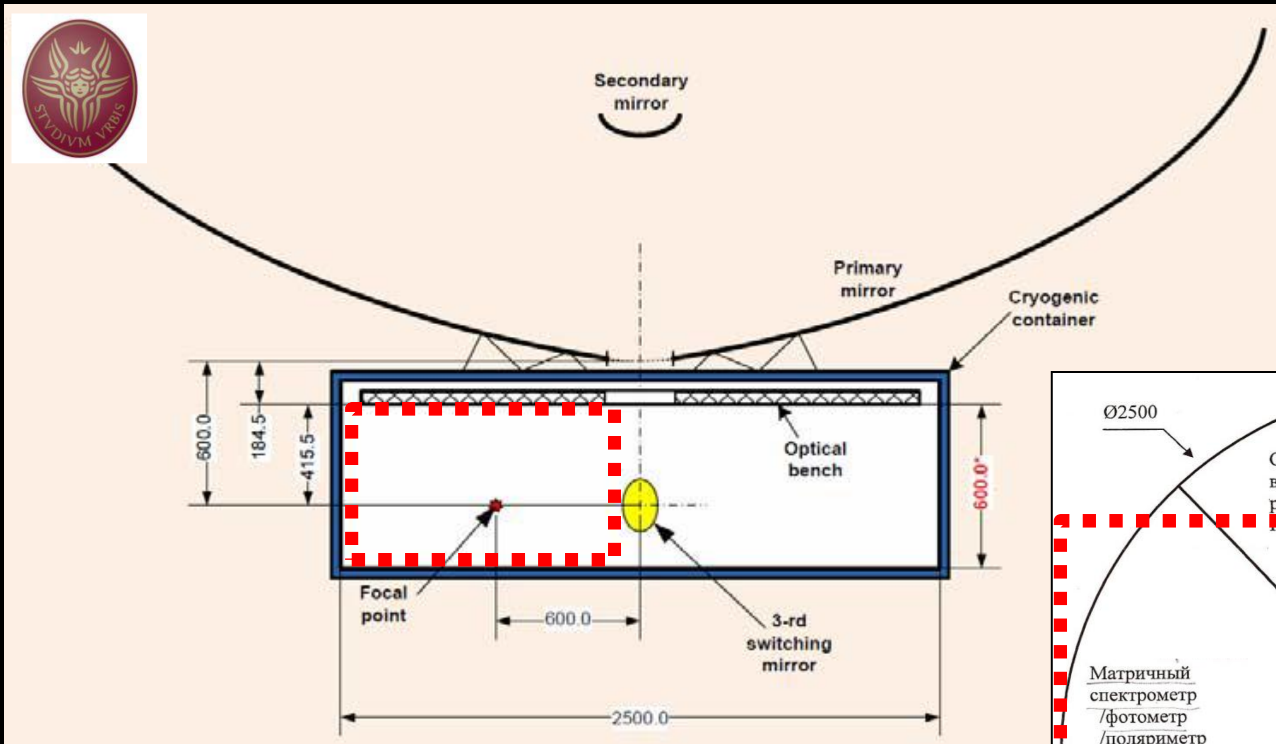


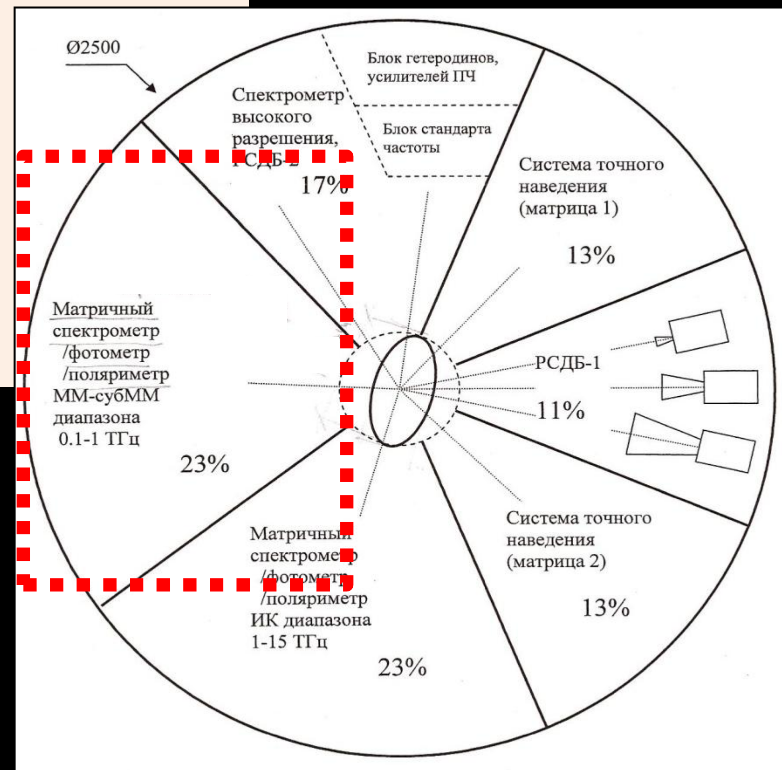
All details in astro-ph/1002.0867

Millimetron
ASC Moscow
ROSCOSMOS



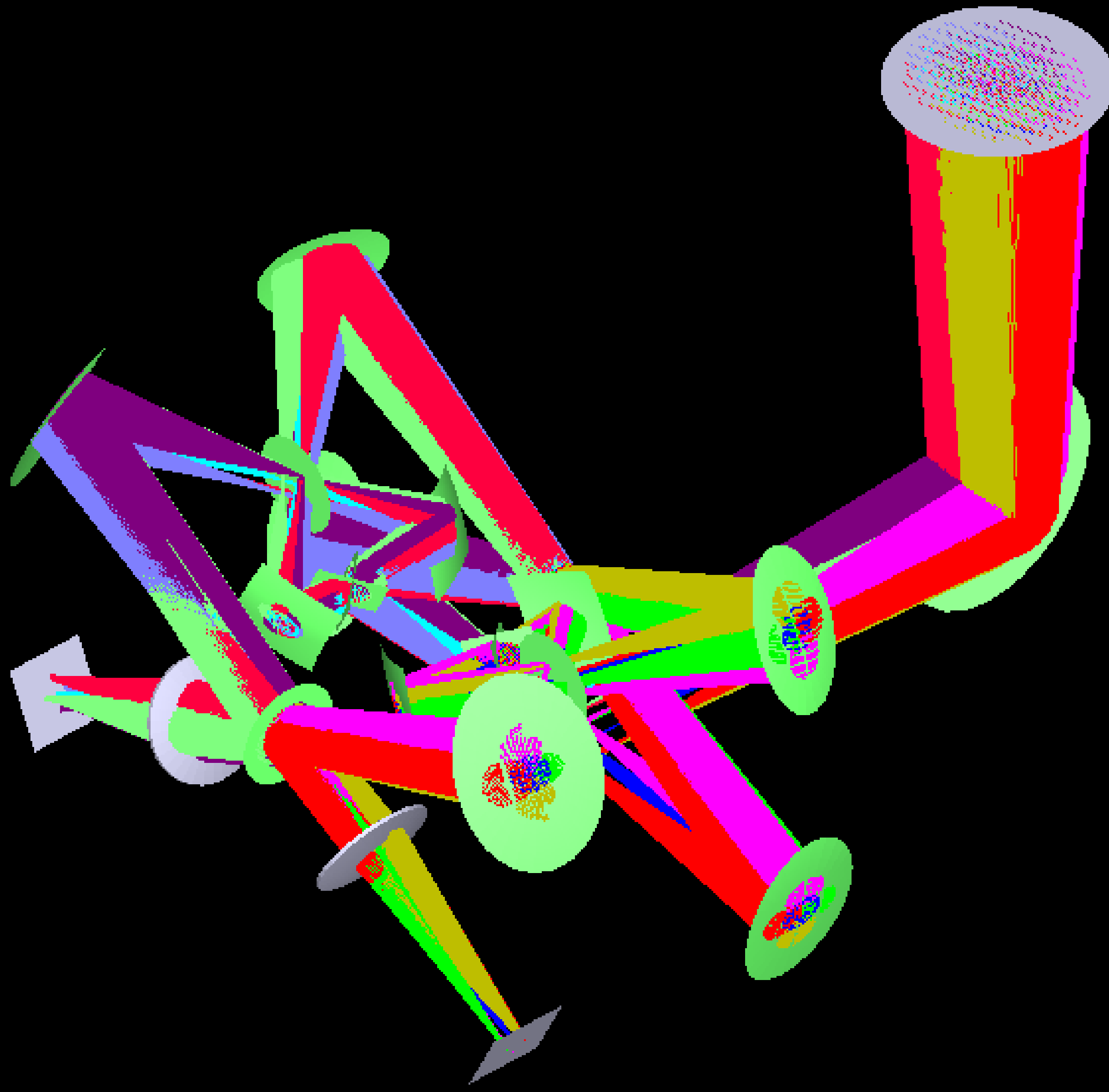
- Antenna diameter: 10 m
- Range of wavelengths: 0.01 – 20 mm
- Bolometric sensitivity (λ0.3mm, 1h integration): $5x10^{-9}$ Jy
- Interferometry sensitivity (λ0.5mm, 300s integration, 16GHz bw) : 10^{-4} Jy
- Interferometer beam: 10^{-9} arcsec





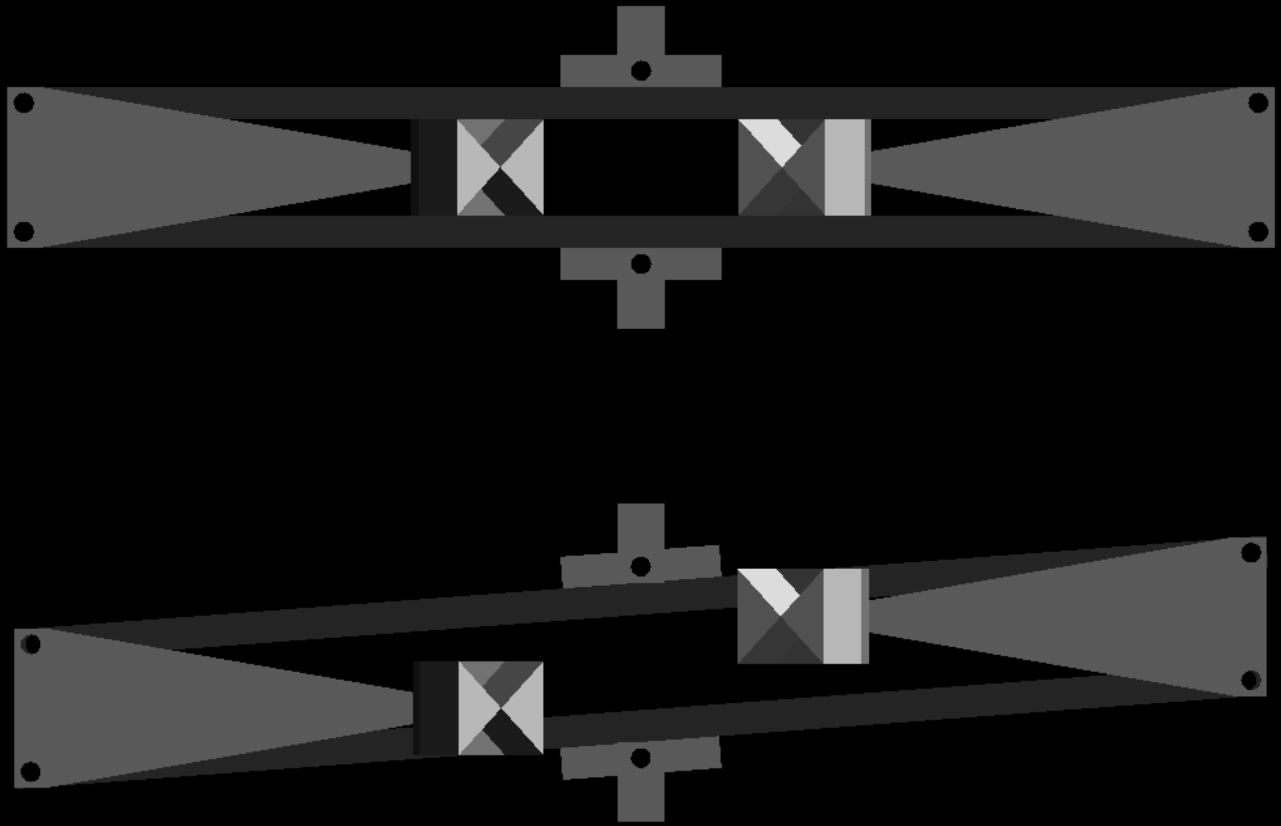
We have been assigned a large sector of the focal plane to insert a low.resolution differential spectrometer.

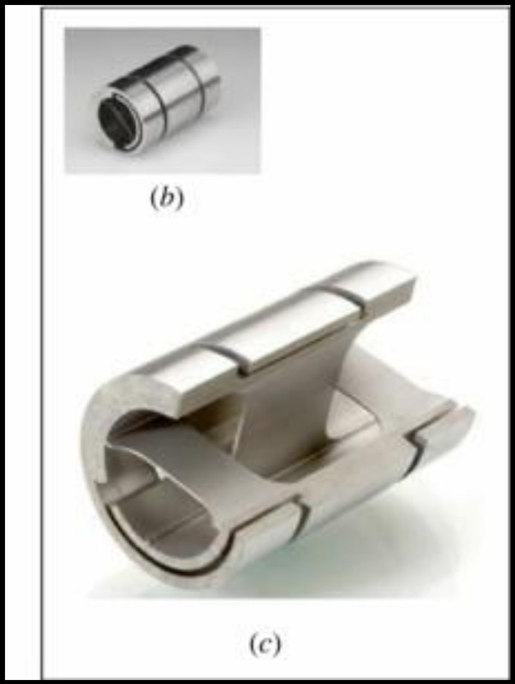
ASI has funded a phase-A study for this instrument.

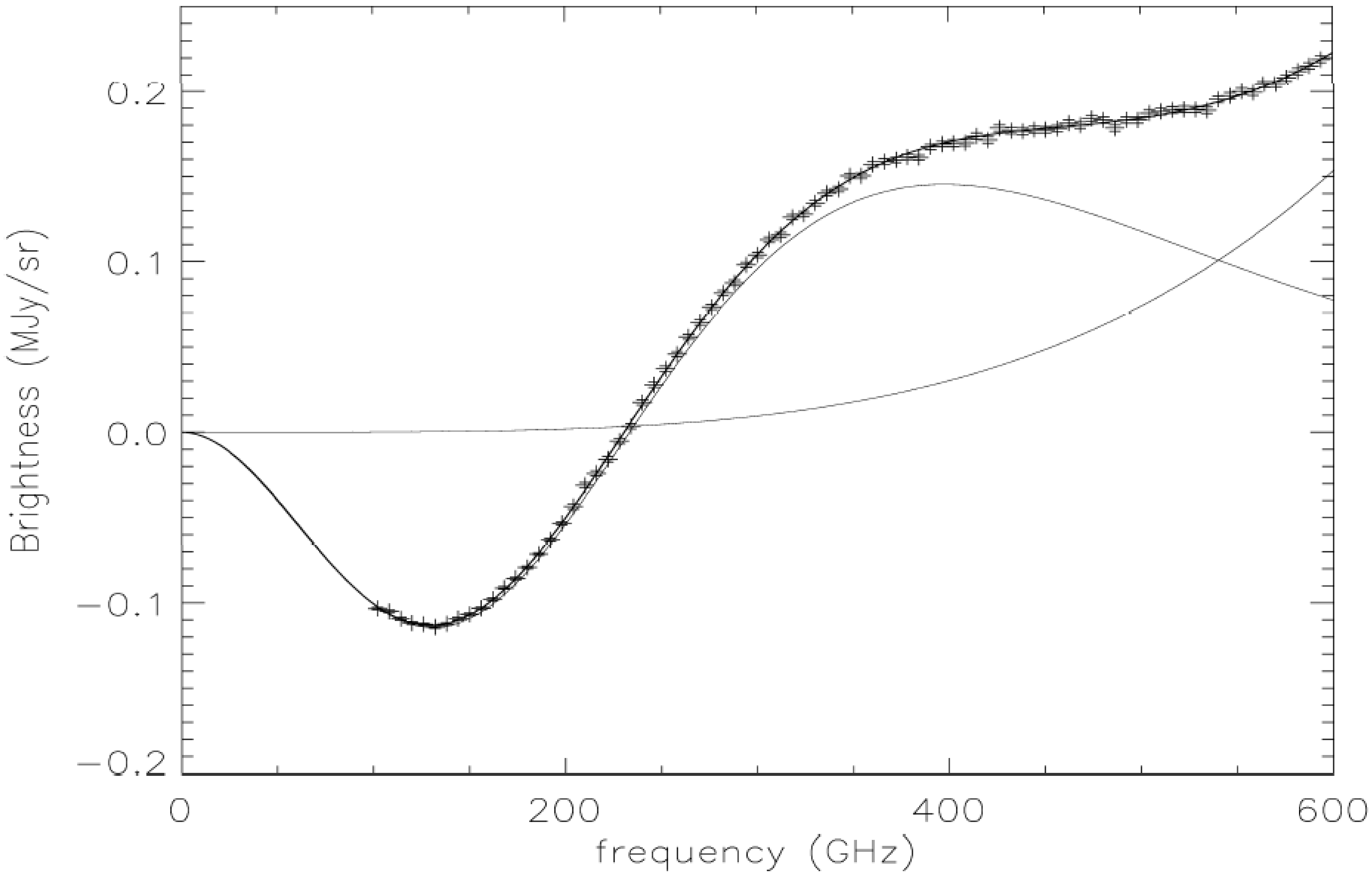


Alessandro Schillaci *21/09/2012*

Oscillating pantograph (negligible dissipation) for the two cryogenic delay lines.





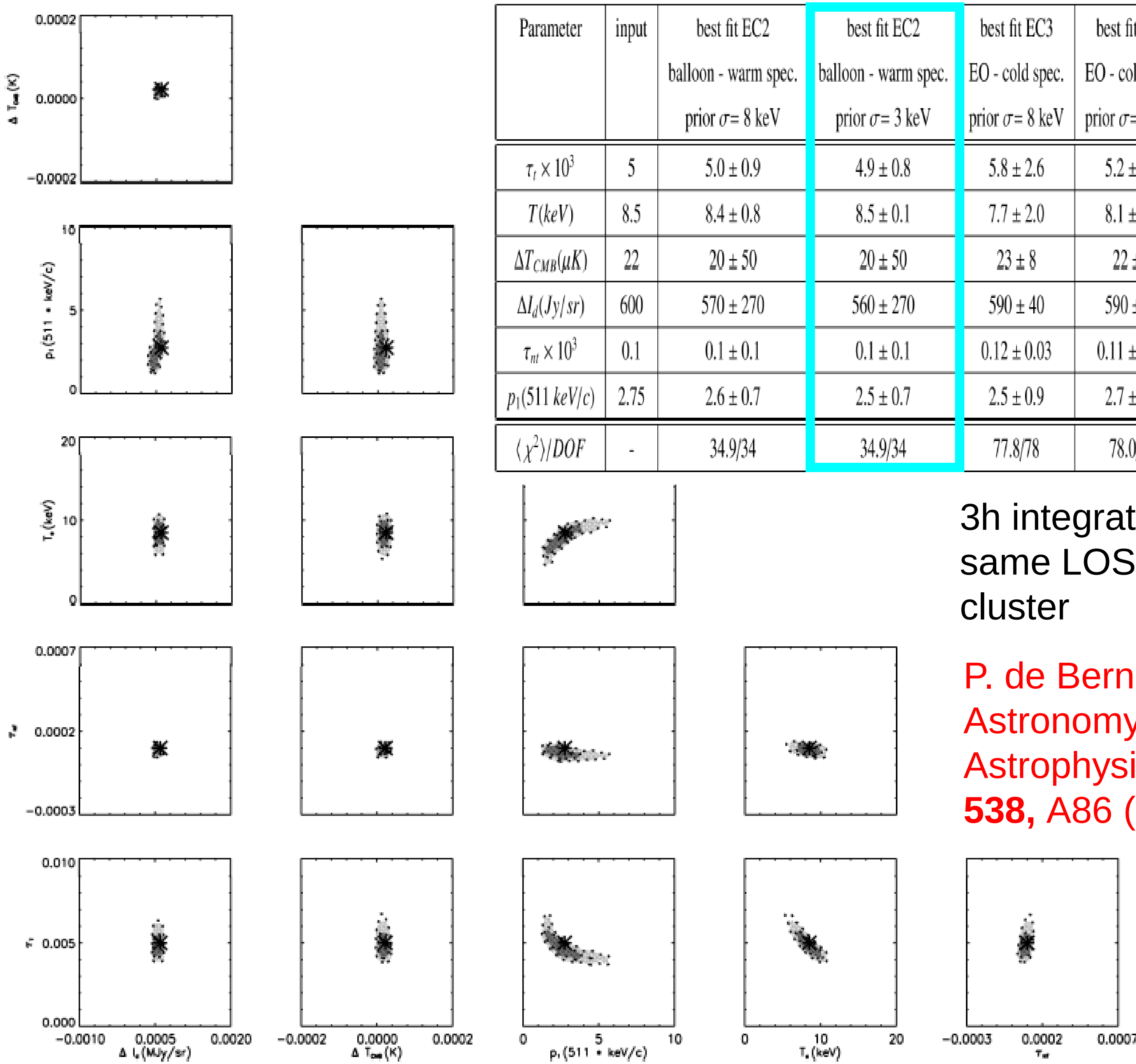


3 hours of observations of a rich cluster with a DFTS on Millimetron
Absolutely outstanding. USING A PHOTON NOISE LIMITED BOLOMETER IN THE COLD ENVIRONMENT OF L2 WITH 4K TELESCOPE

Parameter	input	best fit EC2 balloon - warm spec. prior σ= 8 keV	best fit EC2 balloon - warm spec. prior σ= 3 keV	best fit EC3 EO - cold spec. prior σ= 8 keV	best fit EC3 EO - cold spec. prior σ= 3 keV	best fit EC5 L2 - cold spec. prior σ= 8 keV	best fit EC5 L2 - cold spec. prior σ= 3 keV
$\tau_t \times 10^3$	5	5.0 ± 0.9	4.9 ± 0.8	5.8 ± 2.6	5.2 ± 0.6	5.1 ± 0.6	5.1 ± 0.5
$T(keV)$	8.5	8.4 ± 0.8	8.5 ± 0.1	7.7 ± 2.0	8.1 ± 0.8	8.5 ± 1.2	8.5 ± 1.0
$\Delta T_{CMB}(\mu K)$	22	20 ± 50	20 ± 50	23 ± 8	22 ± 8	22 ± 4	22 ± 4
$\Delta I_d(Jy/sr)$	600	570 ± 270	560 ± 270	590 ± 40	590 ± 40	600 ± 4	600 ± 4
$\tau_{nt} \times 10^3$	0.1	0.1 ± 0.1	0.1 ± 0.1	0.12 ± 0.03	0.11 ± 0.02	0.10 ± 0.01	0.10 ± 0.01
$p_1(511\ keV/c)$	2.75	2.6 ± 0.7	2.5 ± 0.7	2.5 ± 0.9	2.7 ± 1.1	3.0 ± 1.0	2.9 ± 0.9
$\langle \chi^2 \rangle / DOF$	-	34.9/34	34.9/34	77.8/78	78.0/78	110.0/110	110.1/110

3h integration on the same LOS through a rich cluster

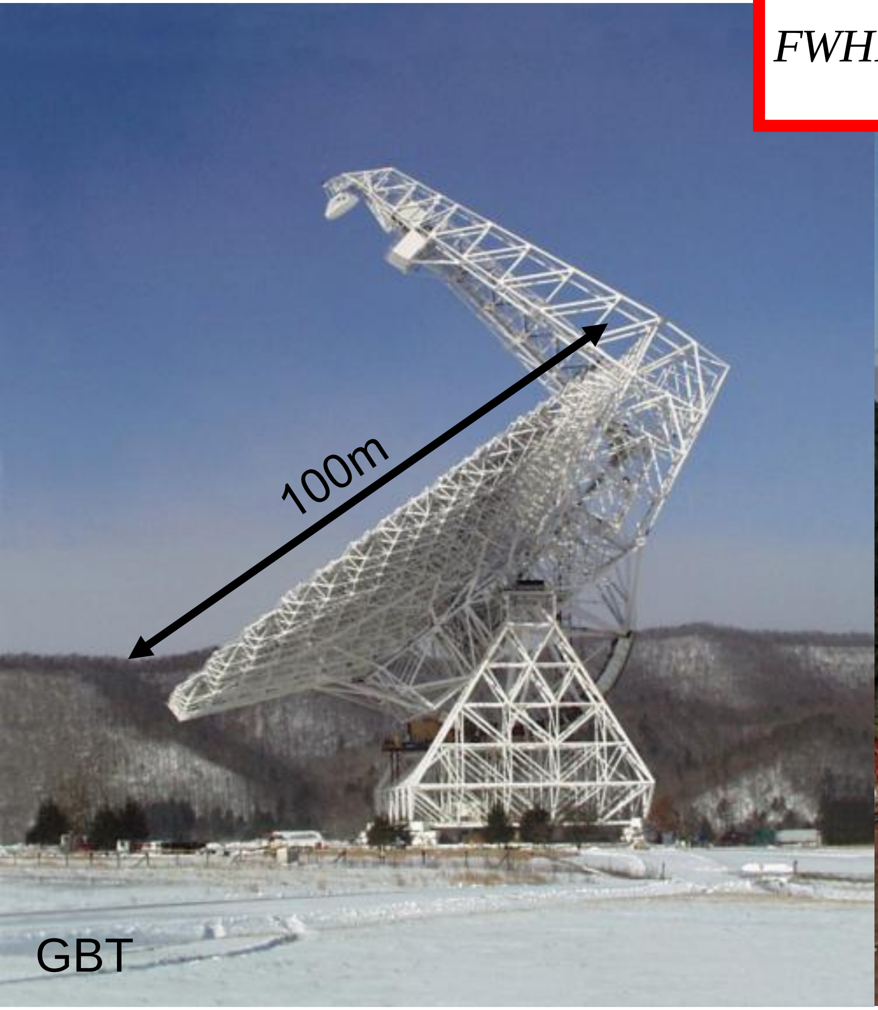
P. de Bernardis, et al., Astronomy and Astrophysics, **538,** A86 (2012)

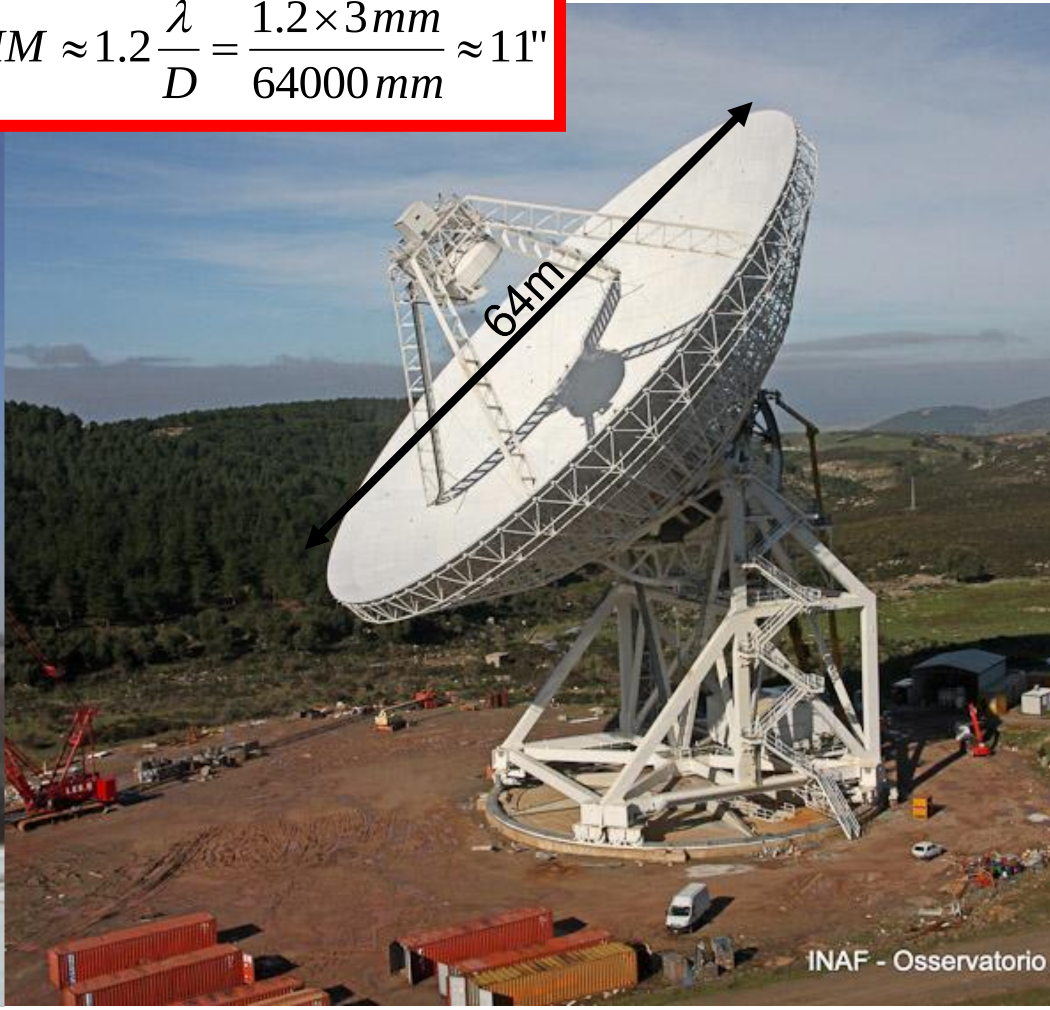


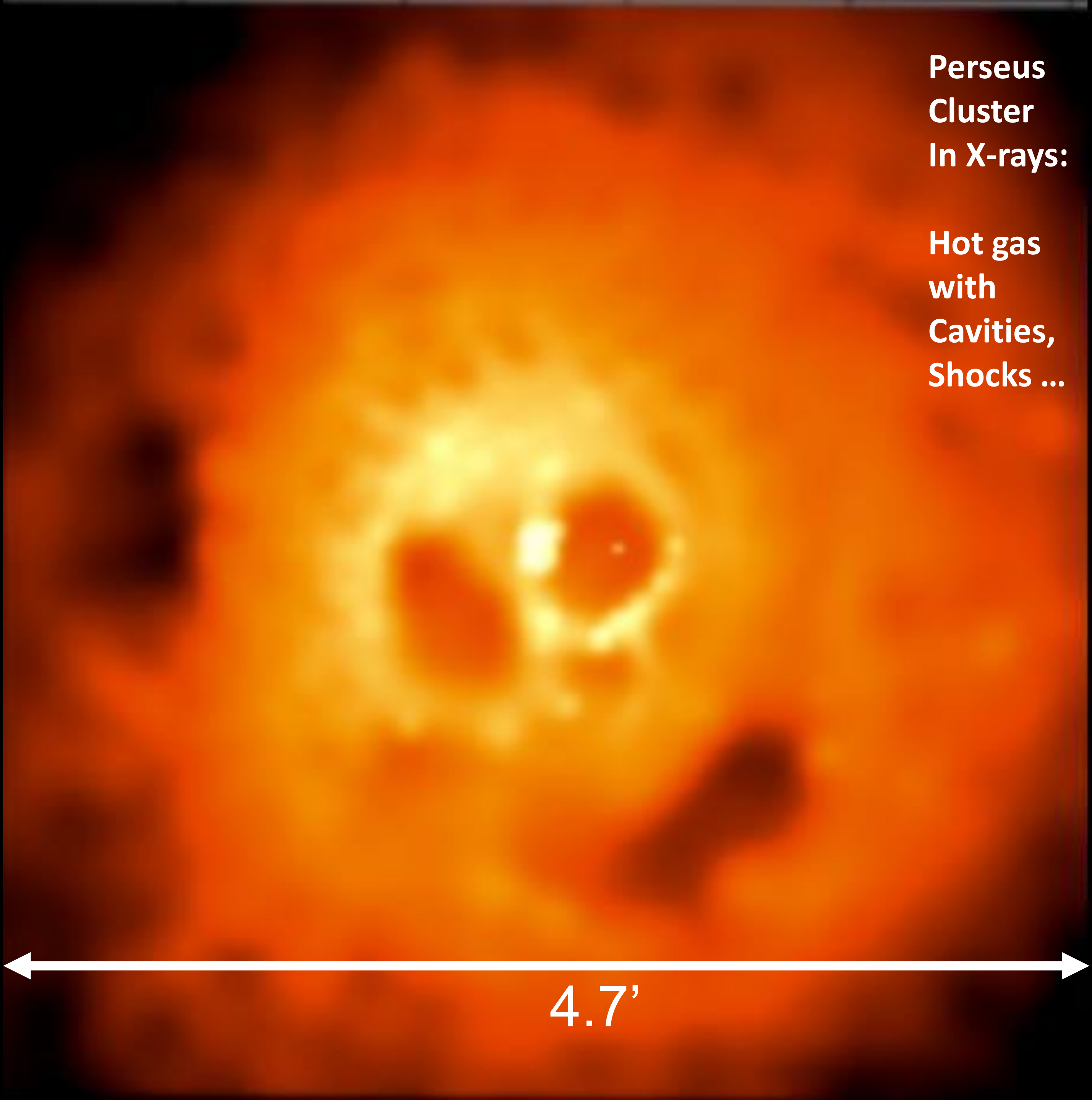
XXXL telescopes & SZ

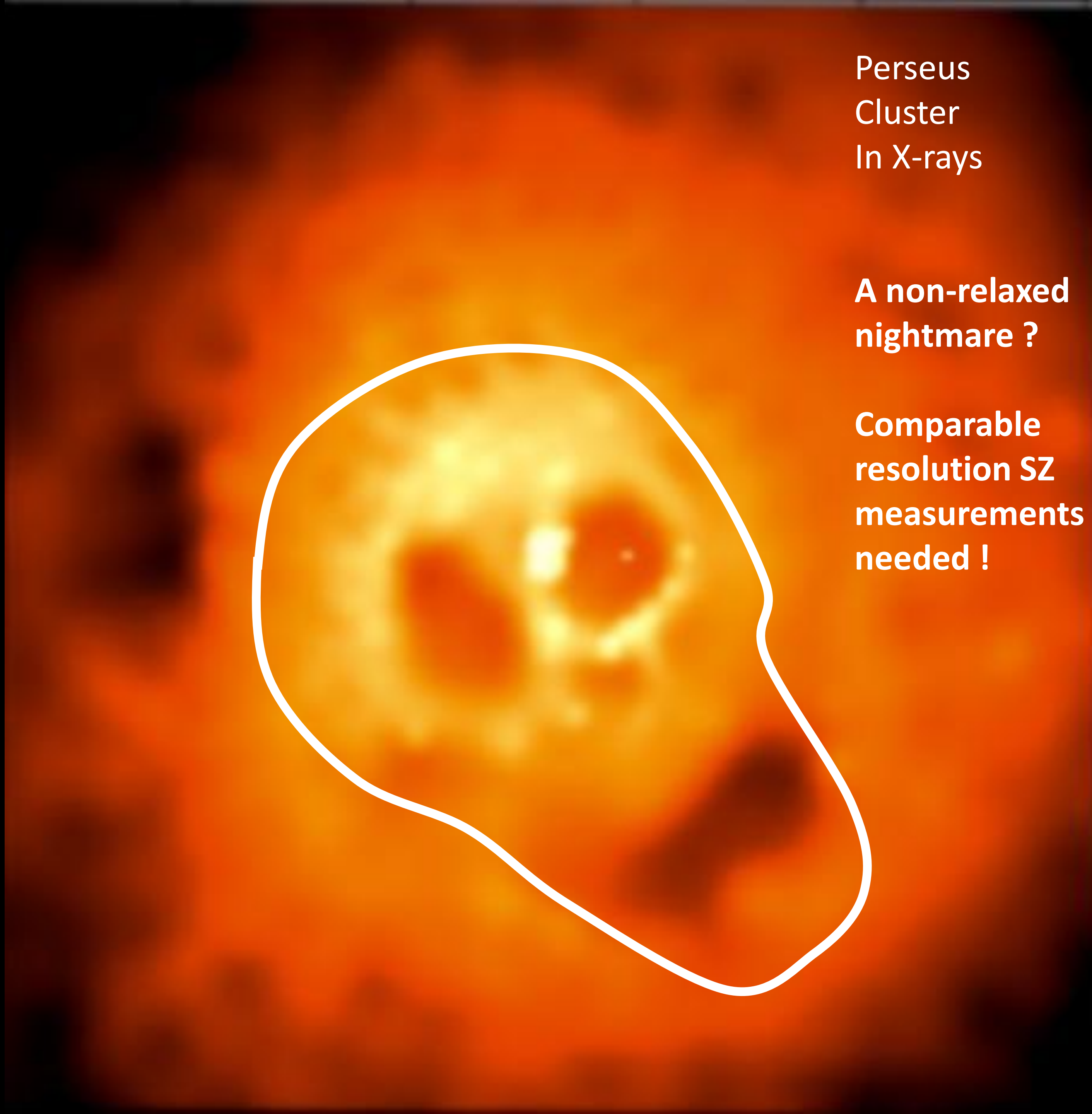
- Very useful to study the internal structure of clusters (shocks, cavities, cooling flows …)
- The 100 m Green Bank Telescope (USA) has a W-band array (Mustang)
- We have the 64m Sardinia Radio Telescope, and we are considering to install a DFTS for the W-band at the focus.

$$FWHM \approx 1.2\frac{\lambda}{D} = \frac{1.2 \times 3\,mm}{64000\,mm} \approx 11''$$






Perseus Cluster In X-rays:
Hot gas with Cavities, Shocks …
4.7’


Perseus
Cluster
In X-rays
A non-relaxed
nightmare ?
Comparable
resolution SZ
measurements
needed !

Conclusions

- Measurements of the SZ are effective and unique to study:
  - Directly ionized matter in the Universe
  - Indirectly: H_o, Ω_Λ ….
- OLIMPO will be the first instrument to host a DFTS.
  - We are on track for a first flight in June 2013
  - We expect to map spectrally 40 clusters in a single long duration flight
  - The sensitivity will be enough to separate reliably the parameters of the cluster (y, τ_t, τ_{NT}, T, v_{pec}) and the foregrounds.
  - Will validate the method in view of SAGACE, Millimetron / SRT
- A DFTS on Millimetron would produce an incredibly rich dataset.
- A DFTS on SRT (W-band) will allow to investigate cluster substructures & lots of additional science (e.g. CO in galaxies in the redshift desert etc …)
- Differential Polarimetry still being investigated, and wide-band HWPs are badly needed.