LSPE

the Large-Scale Polarization Explorer

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for the LSPE collaboration

Roma 23/09/2015 101° Congresso Nazionale SIF

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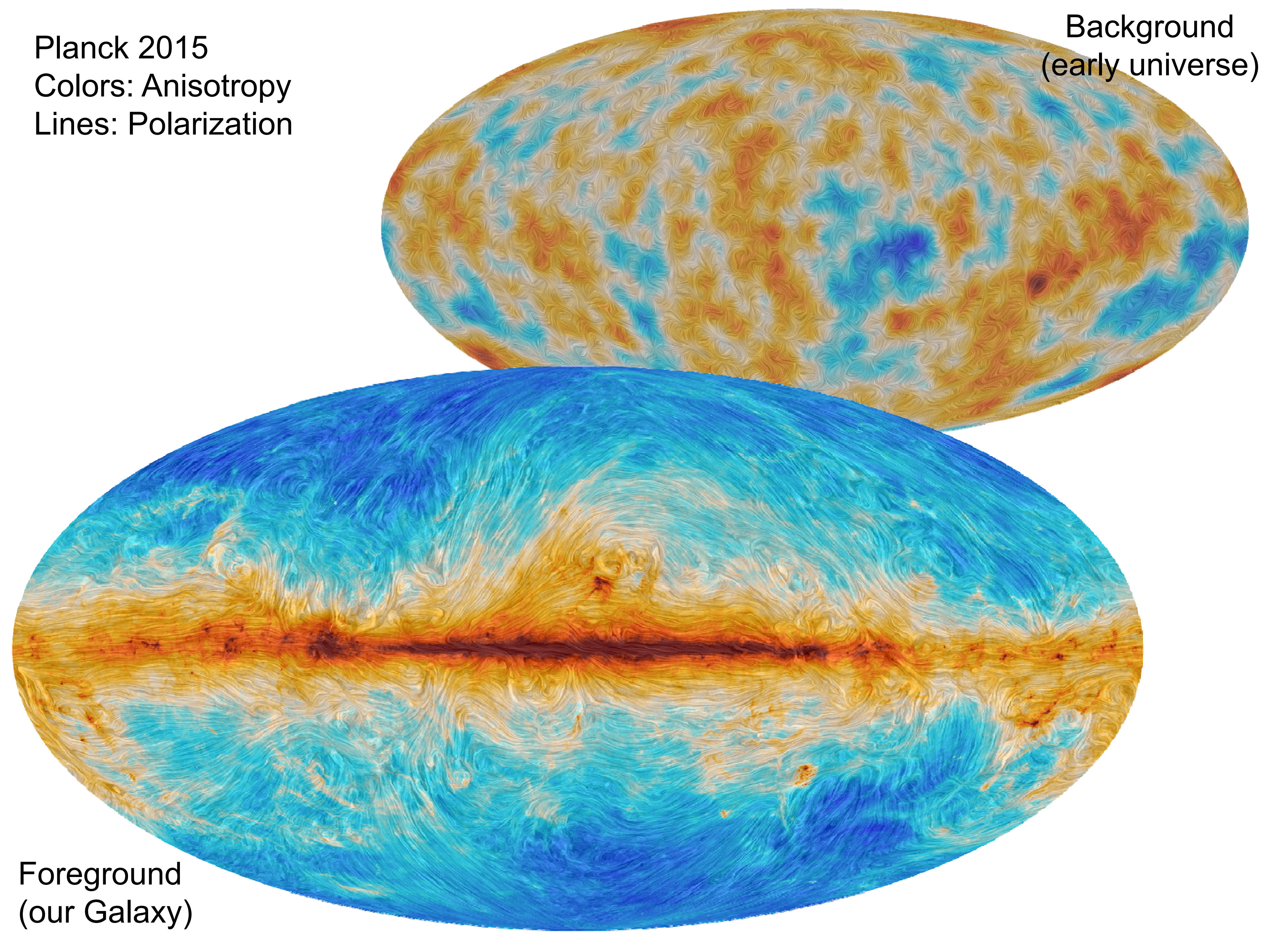
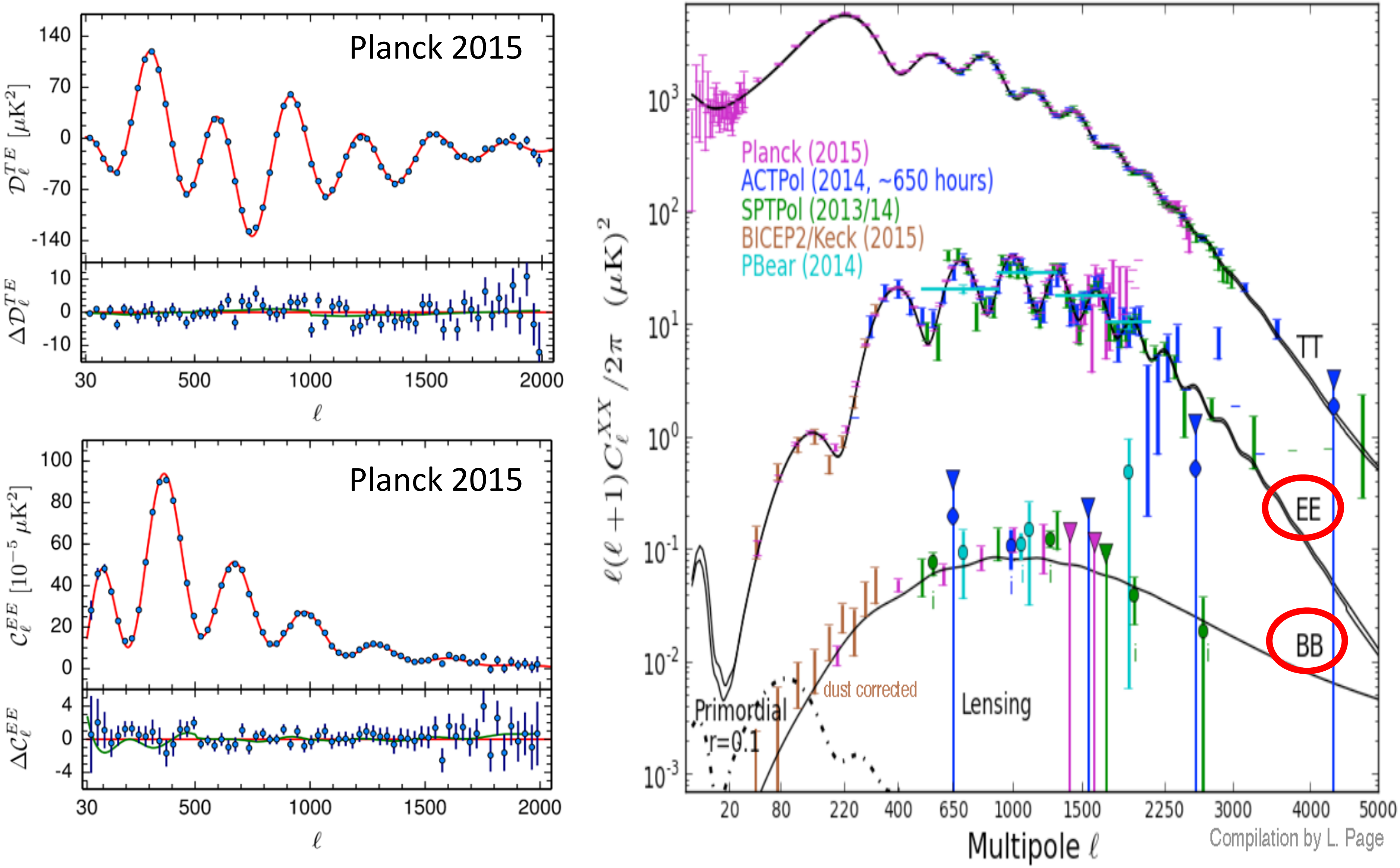
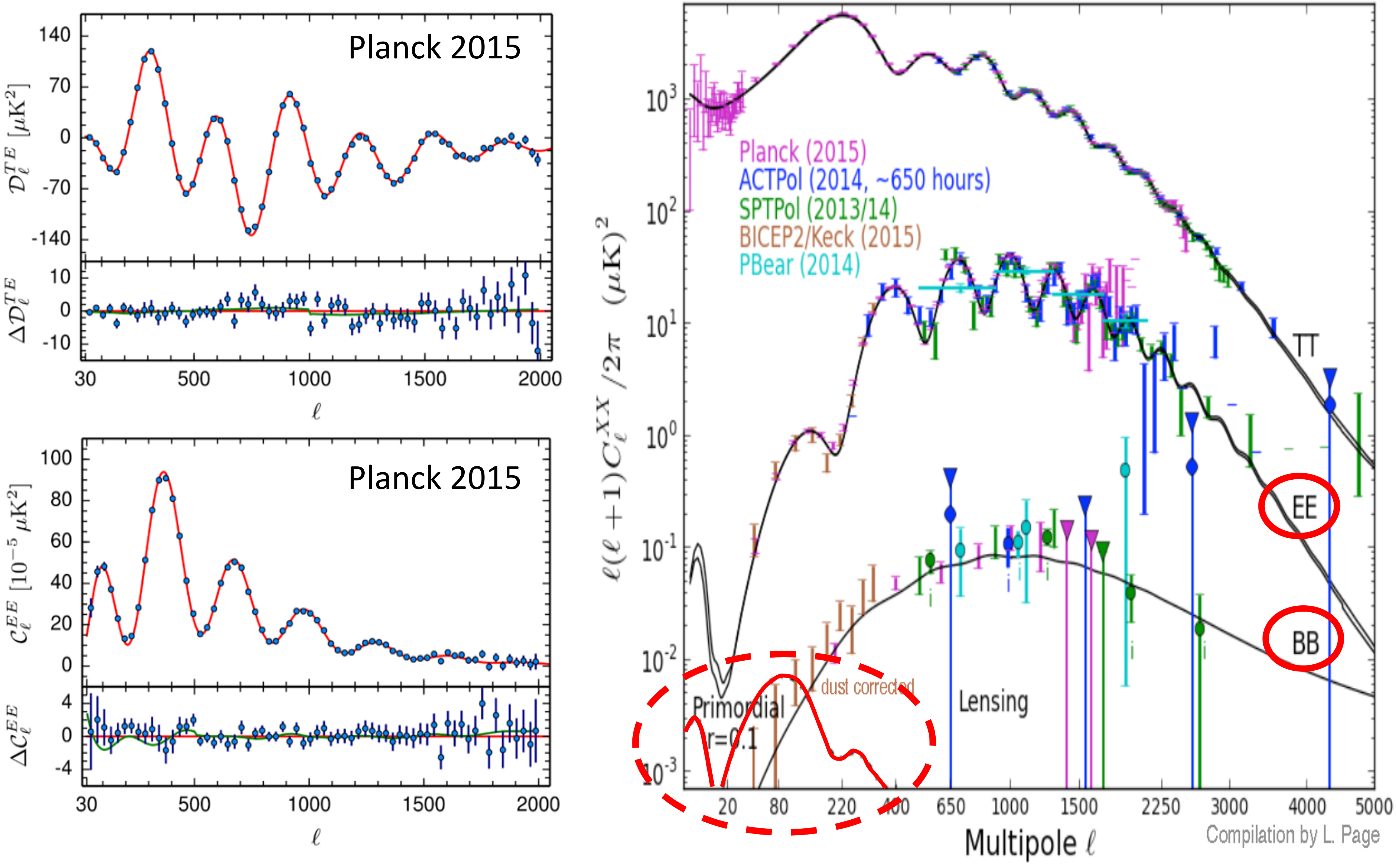


Planck 2015
Colors: Anisotropy
Lines: Polarization
Background
(early universe)
Foreground
(our Galaxy)

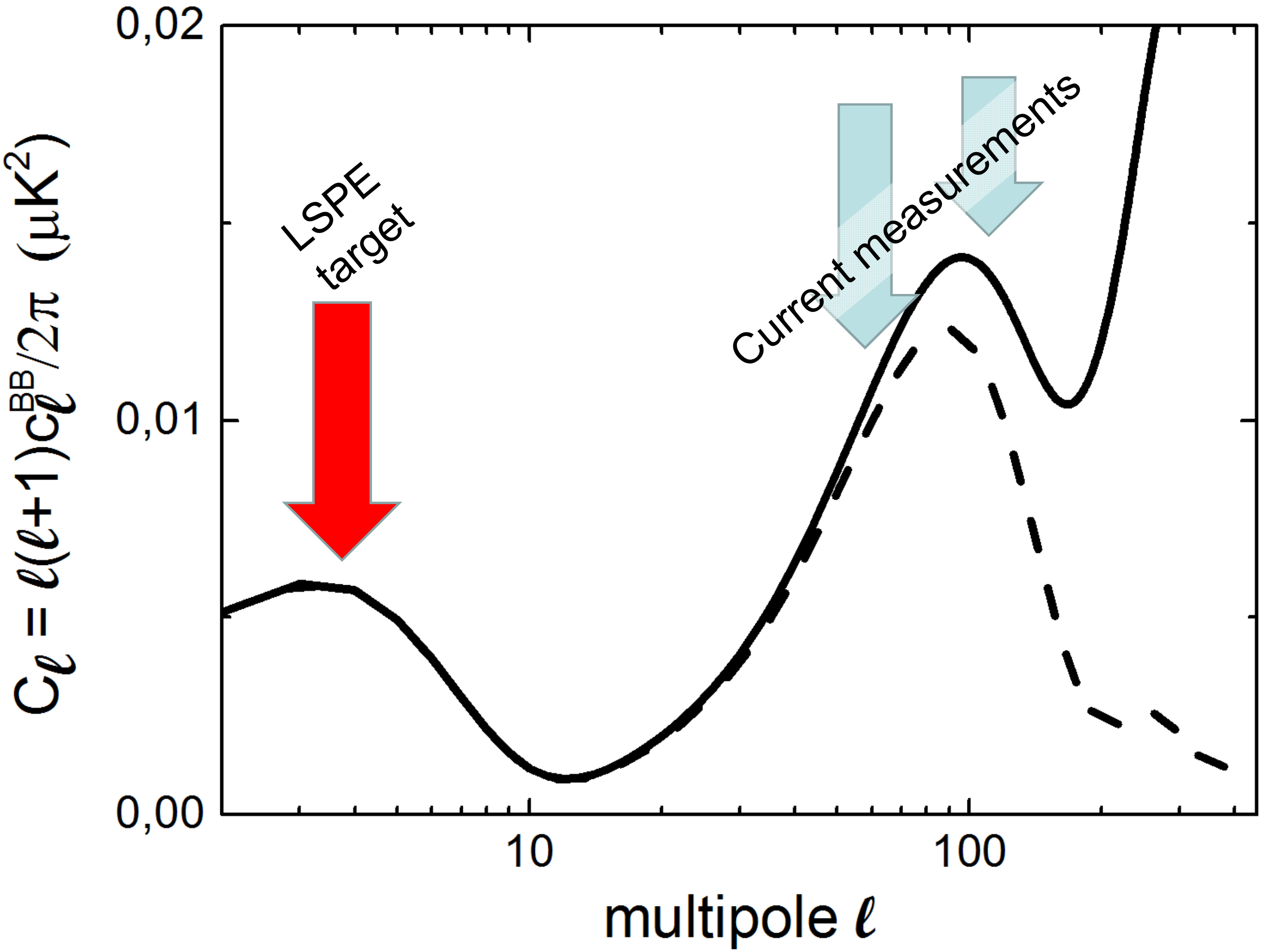
CMB Polarization results at intermediate and small scales



CMB Polarization results at intermediate and small scales



main target : reionization peak



A difficult but important target, to complement measurements of the ℓ=80 peak !

the reionization peak is difficult

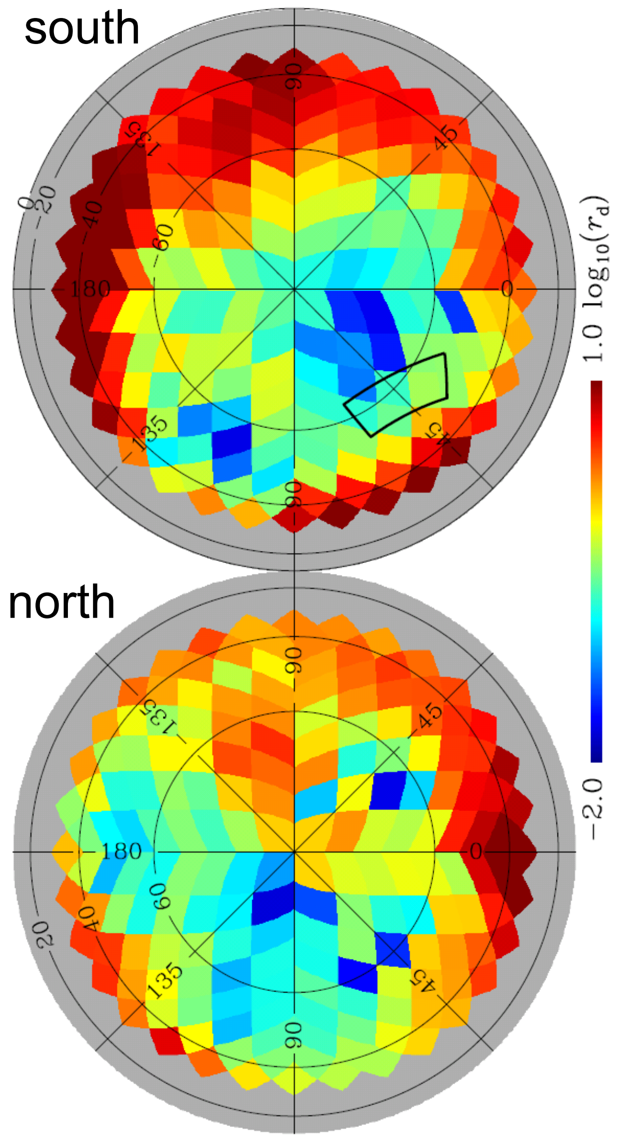
- Large angular scales: wide sky coverage required.
- Foreground contamination is high. From *Planck intermediate results XXX: The angular power spectrum of polarized dust emission at intermediate and high Galactic latitude*
  - Dust B-modes in the best 30% of sky at 350 GHz:

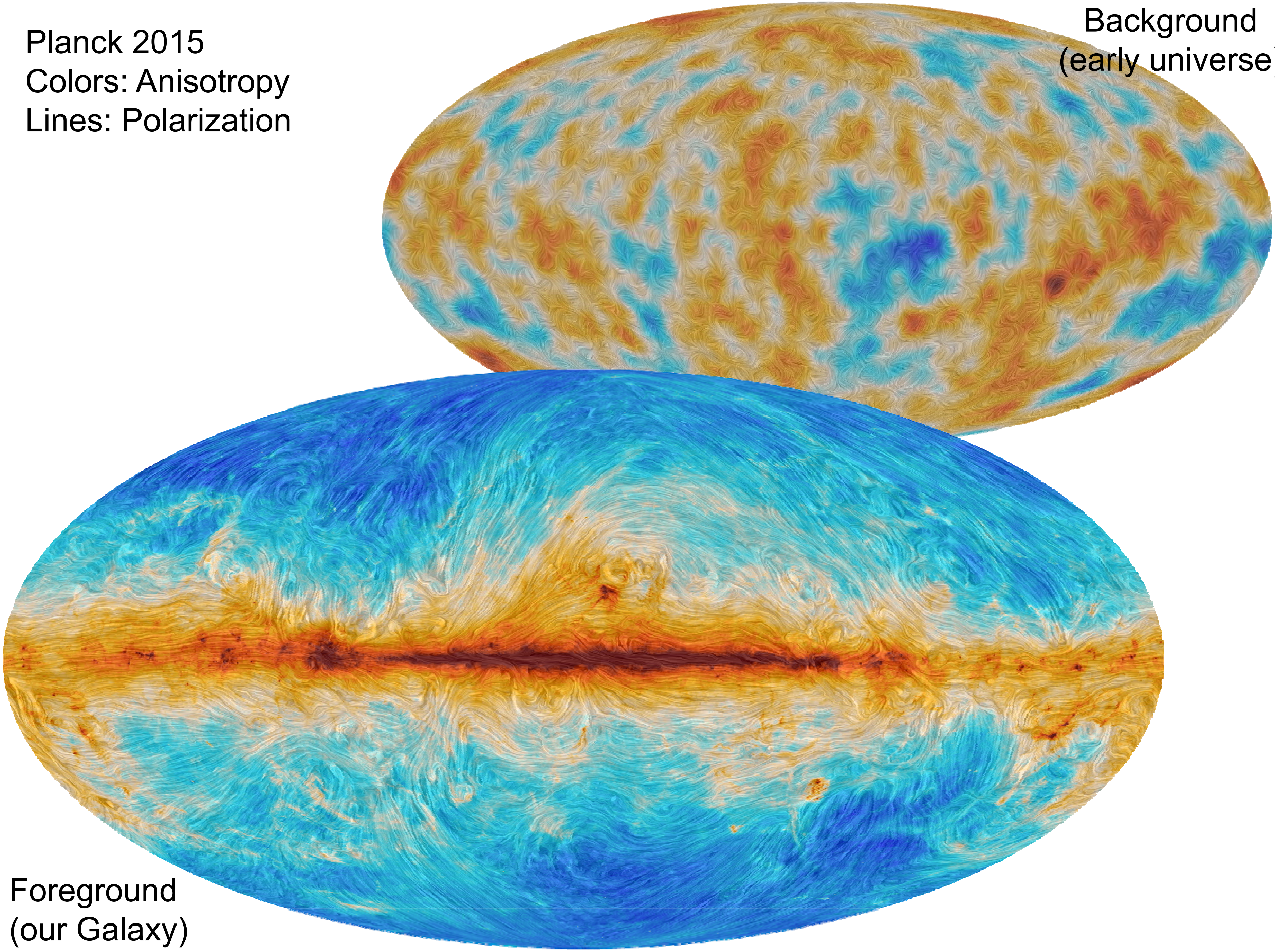
    $$D_\ell = \ell(\ell+1)C_\ell/2\pi$$

    $$D_\ell = 14\mu K^2(\ell/80)^{-0.42}$$

  - Extrapolating to 150 GHz (factor 0.04^2)

    $$D_\ell = 2.2 \cdot 10^{-2}\mu K^2(\ell/80)^{-0.42}$$




Planck 2015
Colors: Anisotropy
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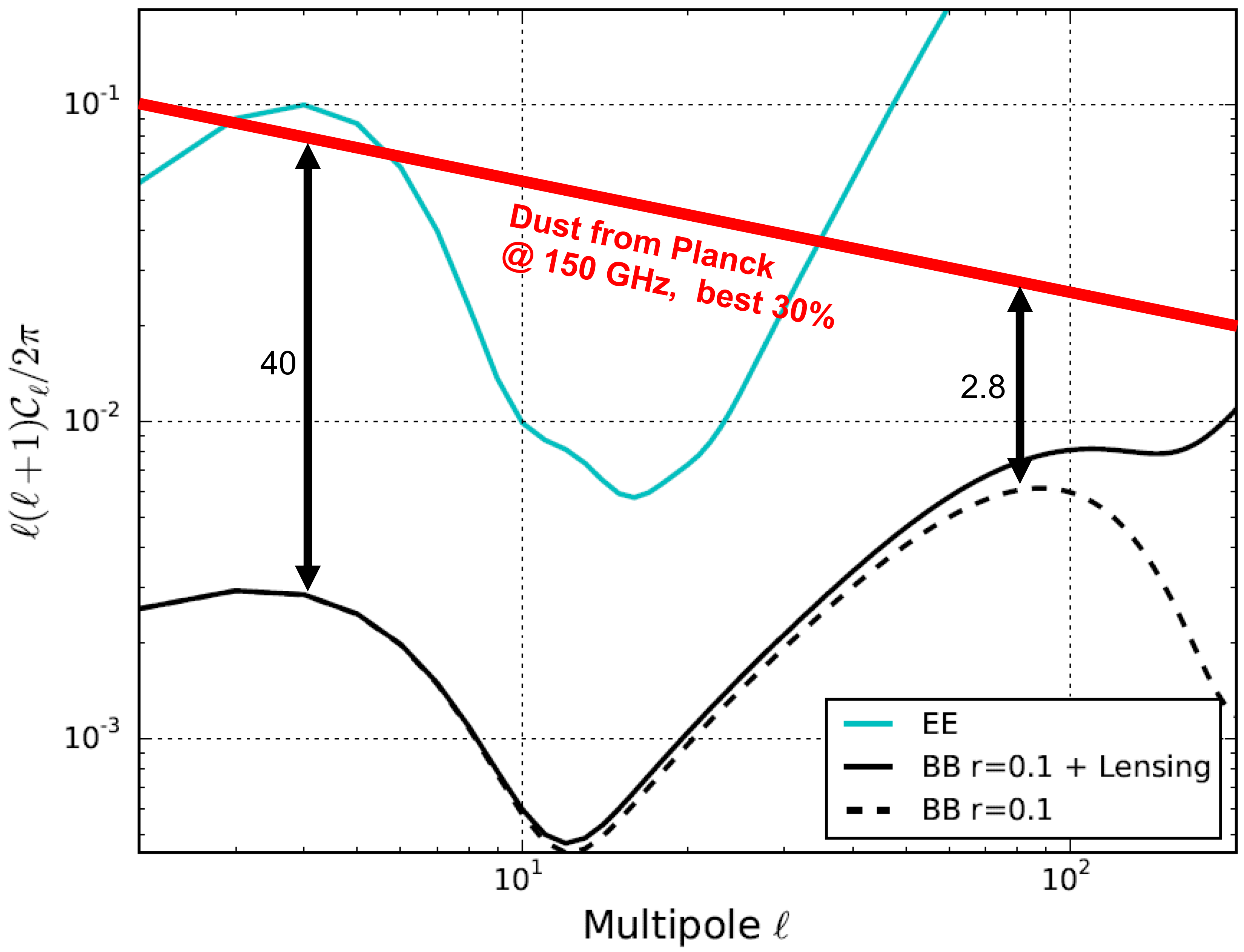
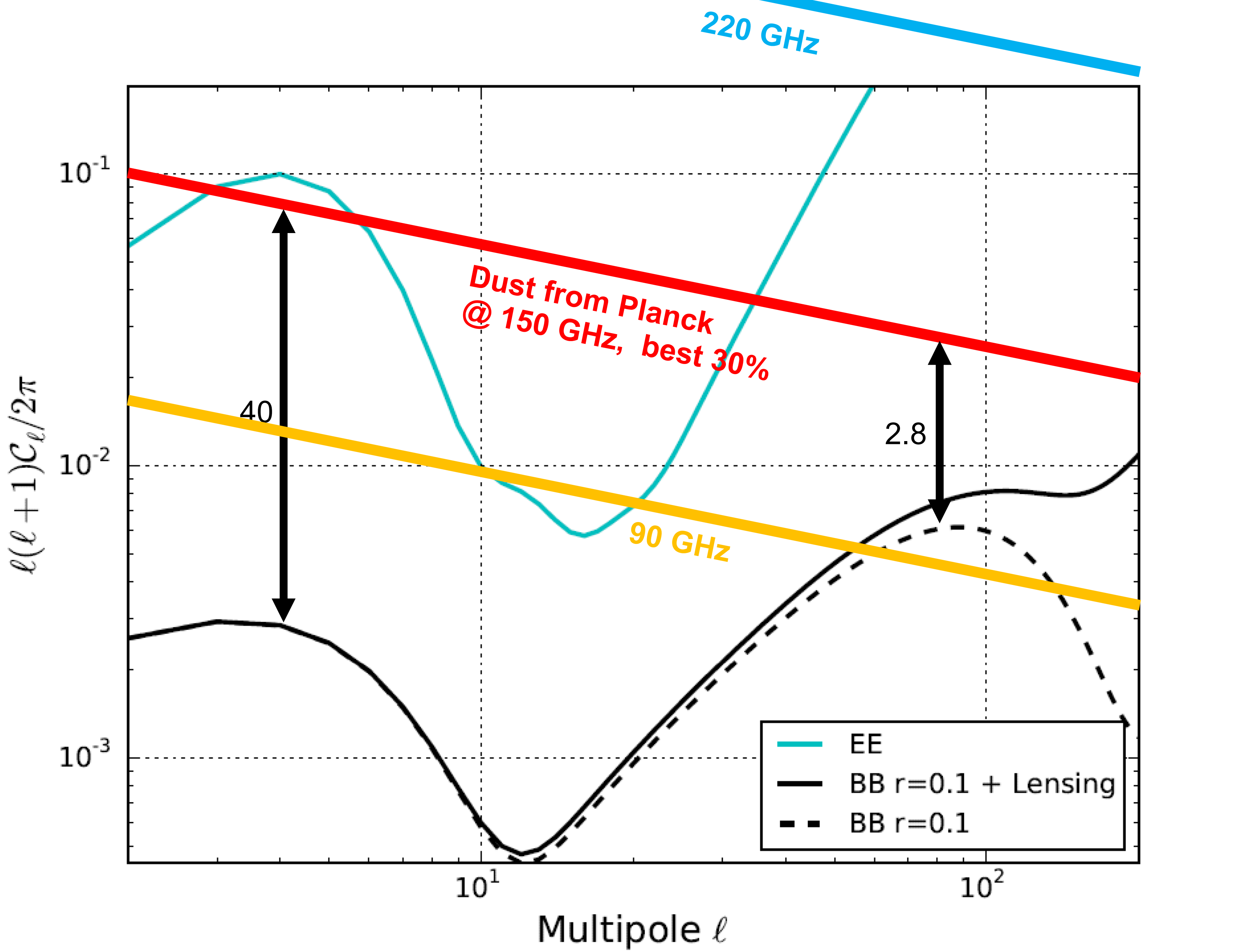
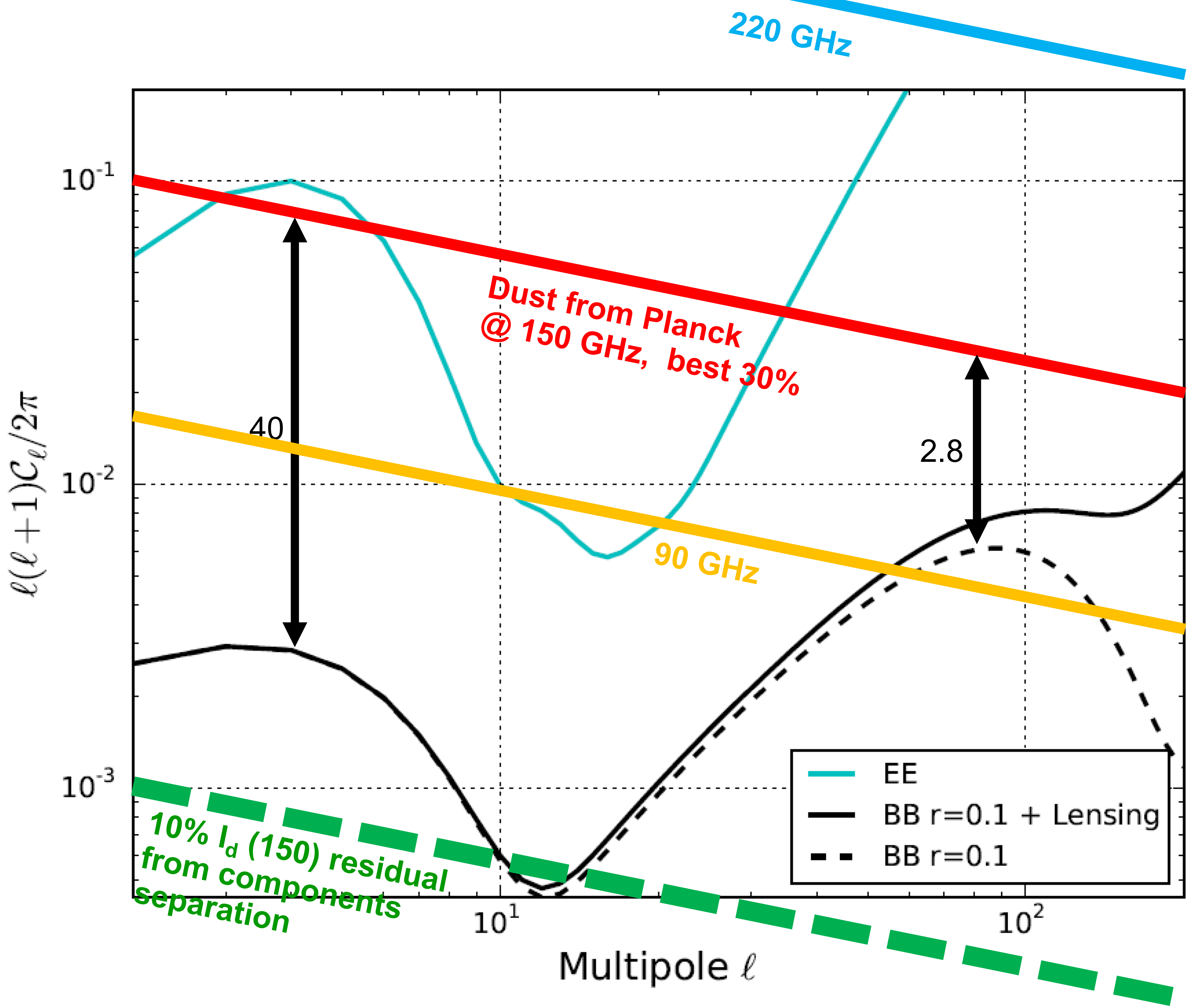


Dust from Planck
@ 150 GHz, best 30%
40
2.8
EE
BB r=0.1 + Lensing
BB r=0.1
10^{-1}
10^{-2}
10^{-3}
10^{1}
10^{2}
Multipole ℓ
$\ell(\ell+1)C_\ell/2\pi$



220 GHz
Dust from Planck
@ 150 GHz, best 30%
40
2.8
90 GHz
EE
BB r=0.1 + Lensing
BB r=0.1
10^{-1}
10^{-2}
10^{-3}
10^{1}
10^{2}
$\ell(\ell+1)\mathcal{C}_\ell/2\pi$
Multipole ℓ

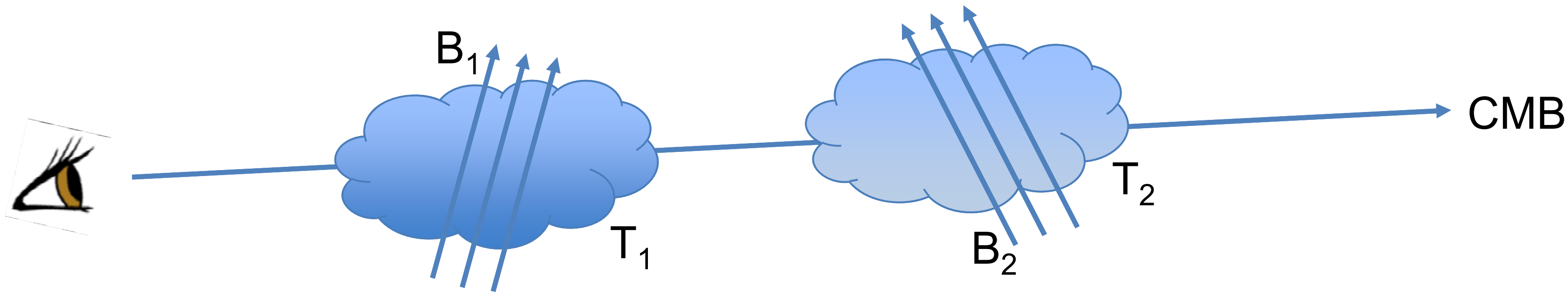


220 GHz
Dust from Planck
@ 150 GHz, best 30%
40
2.8
90 GHz
10% I_d (150) residual
from components
separation
EE
BB r=0.1 + Lensing
BB r=0.1
10^{-1}
10^{-2}
10^{-3}
10^{1}
10^{2}
Multipole ℓ
$\ell(\ell+1)\mathcal{C}_\ell/2\pi$

Experiment Strategy

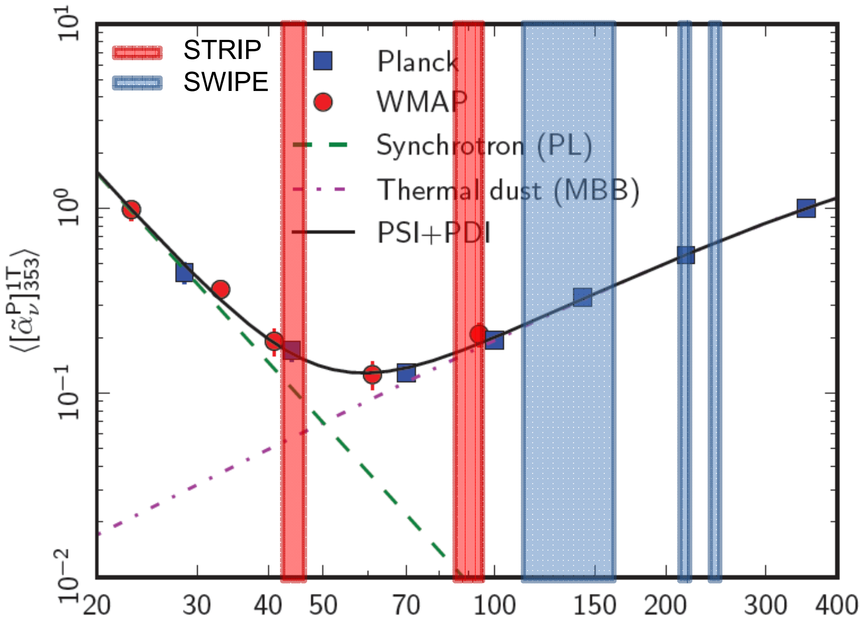
- Large sky coverage and wide frequency coverage call for a space mission. See e.g. COrE+ (just submitted !).
- On a shorter time-scale, experimentation is required to qualify specific instrumentation (optical systems, polarization modulators, detectors …) and methods (sky scan, mapping procedures, polarized foregrounds separation …) and possibly to get detections !
- A *balloon-borne instrument* can
  - avoid atmosperic noise and loading
  - exploit a wide frequency coverage
  - access a large fraction of the sky *during night-time*
  - offer a stable environment *during night-time*
  - reject ground spillover using very large ground-shields

Polarized emission of the ISM



- Often the result of superposition of several clouds along the line of sight
- Different temperature distribution for dust, different magnetic field orientation in different clouds, different electron populations, …
- For example, the *orientation* of linear polarization resulting from the superposition of dust grains differently aligned and with different temperatures changes with frequency.
- For this reason, scalar extrapolation, based on the brightness spectrum alone, is only a zero-order approximation. Has worked to some extent to point-out the presence of ISD emission in BICEP2 data (using 350GHz data from Planck extrapolated to 150GHz, see arXiv:1409.5738). But this is just a rough approximation. For the final mission we need to carry out *precise* corrections.
- Similar arguments apply to synchrotron emission at low frequencies.
- Extrapolation of dust to long wavelengths and of synchrotron to high frequencies is non-trivial, unless you have a number of high and low frequency channels.

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

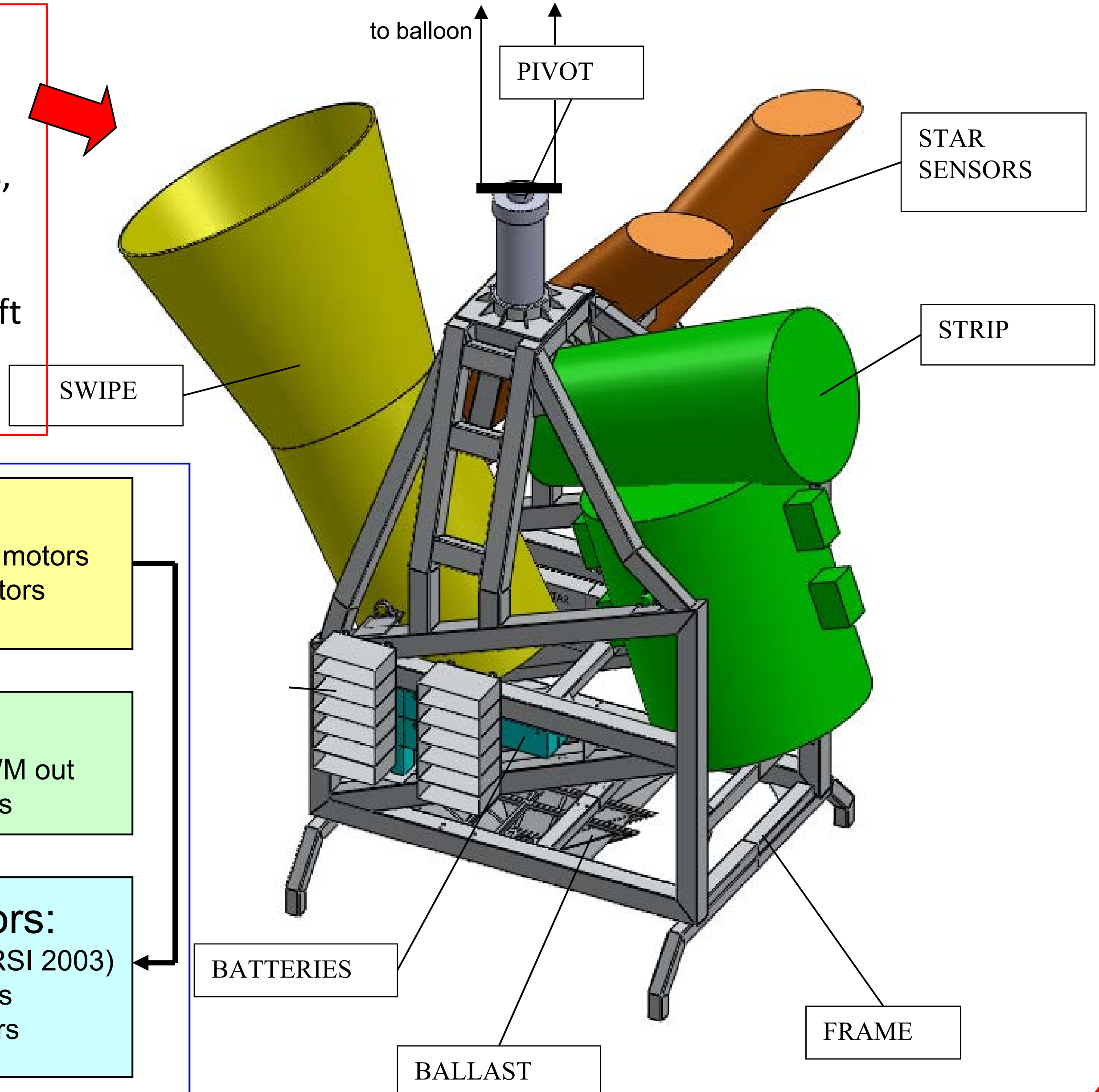
To date extrapolated from 350 GHz only

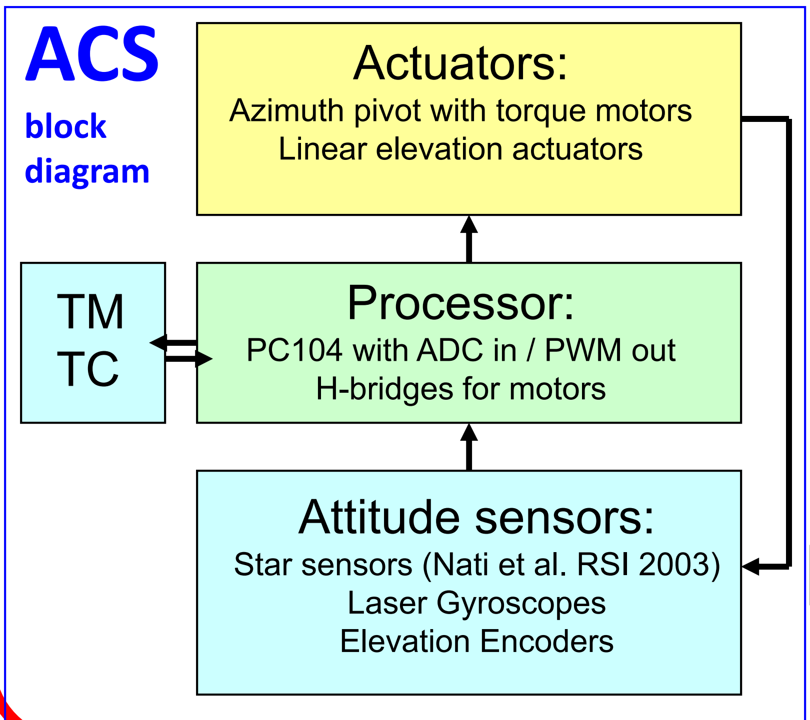
LSPE in a nutshell

- The Large-Scale Polarization Explorer is :
  - an instrument to measure the polarization of the Cosmic Microwave Background at large angular scales
  - using *a spinning stratospheric balloon payload* to avoid atmospheric noise
  - flying *long-duration, in the polar night*
  - using 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
- 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 gondola : frame + pivot + STRIP + SWIPE

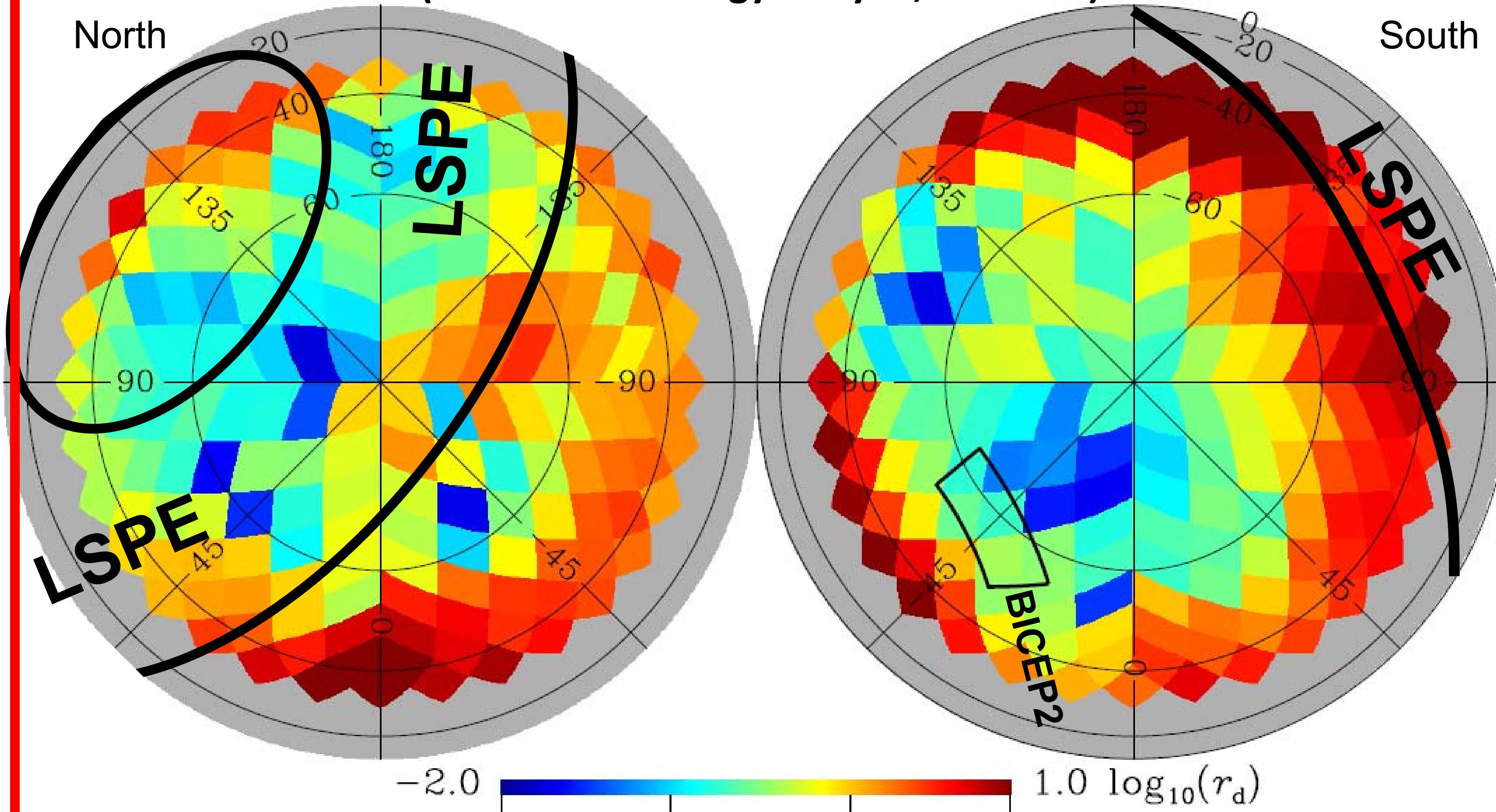
Preliminary sketch of the LSPE experiment, without thermal protections.
The total mass is around 2.5 tons, the overall dimensions are 5.8m(w) x 3.2m(d) x 4.6m (h).
A 800000 m^3 balloon is used to lift the instrument at 37 km of altitude.





Sky coverage of LSPE

(Launch from Longyearbyen, Svalbard)



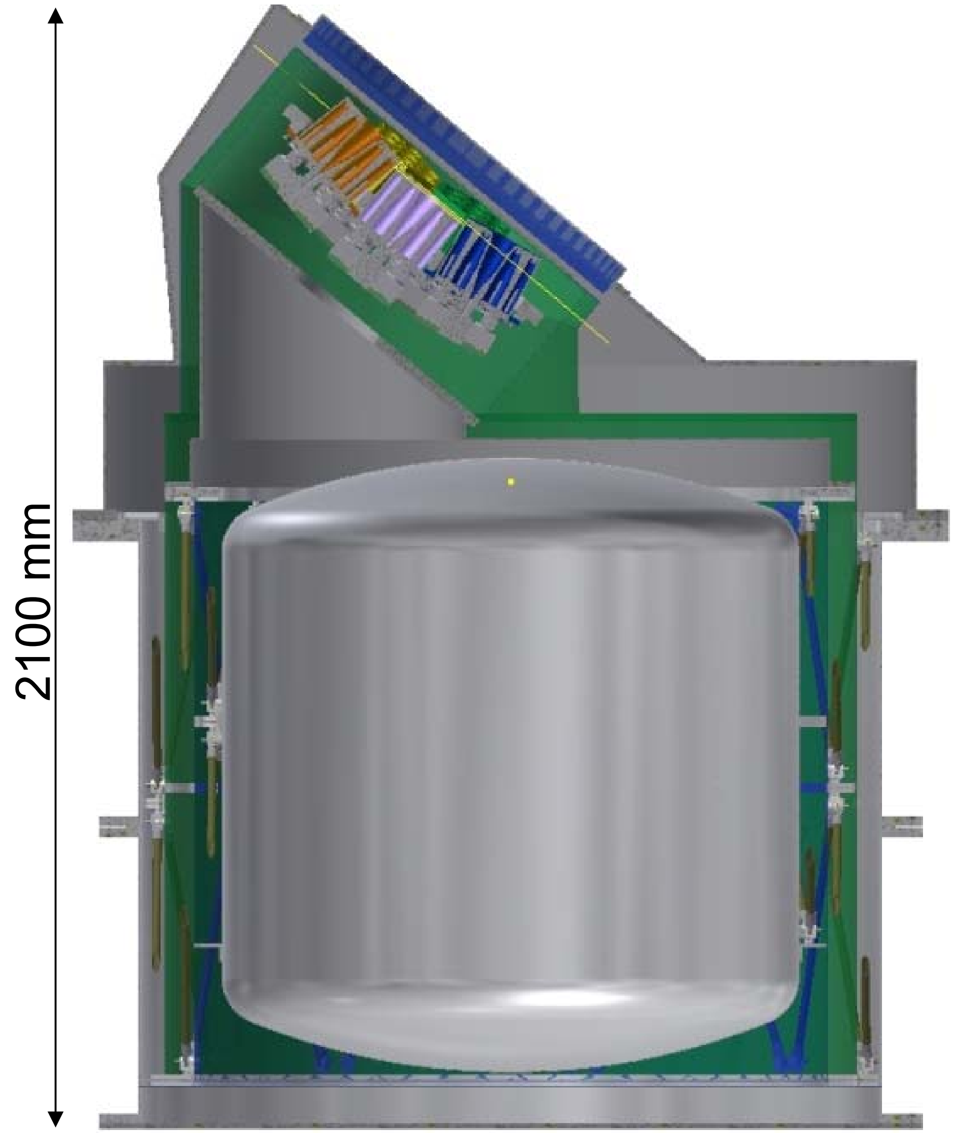
B-modes from dust @140 GHz, as estimated from Planck 343 GHz dust polarization - Planck PIP XXX 1409.5738

The STRIP Instrument

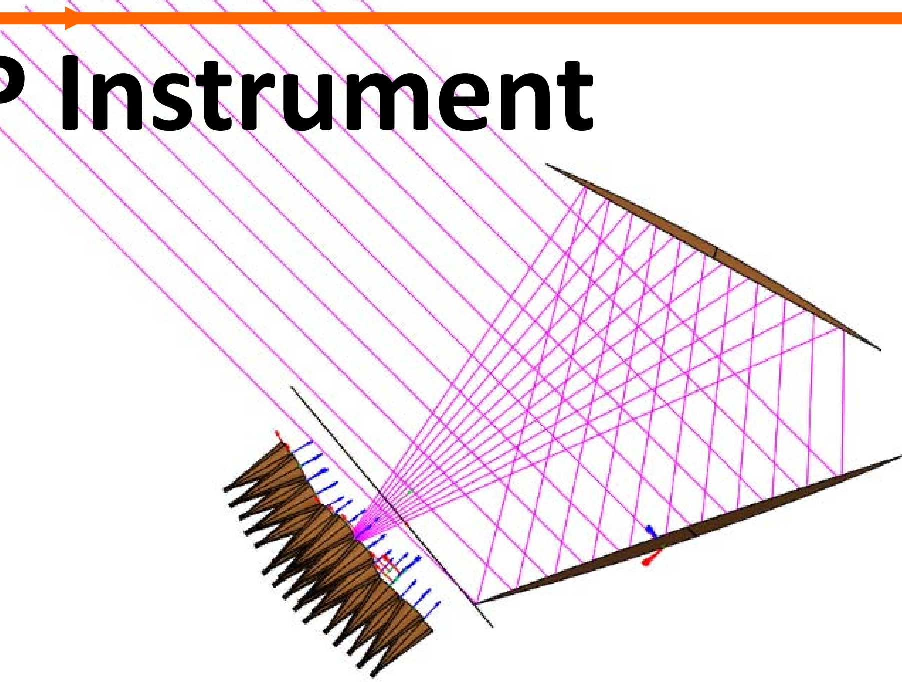
• STRIP is the STRatospheric Italian Polarimeter, aimed at accurate measurements of the low-frequency (44 and 90 GHz) polarized emission, dominated by Galactic synchrotron.

• Its sensitivity at 44 GHz in a single flight is twice better than the final sensitivity of the Planck LFI survey.

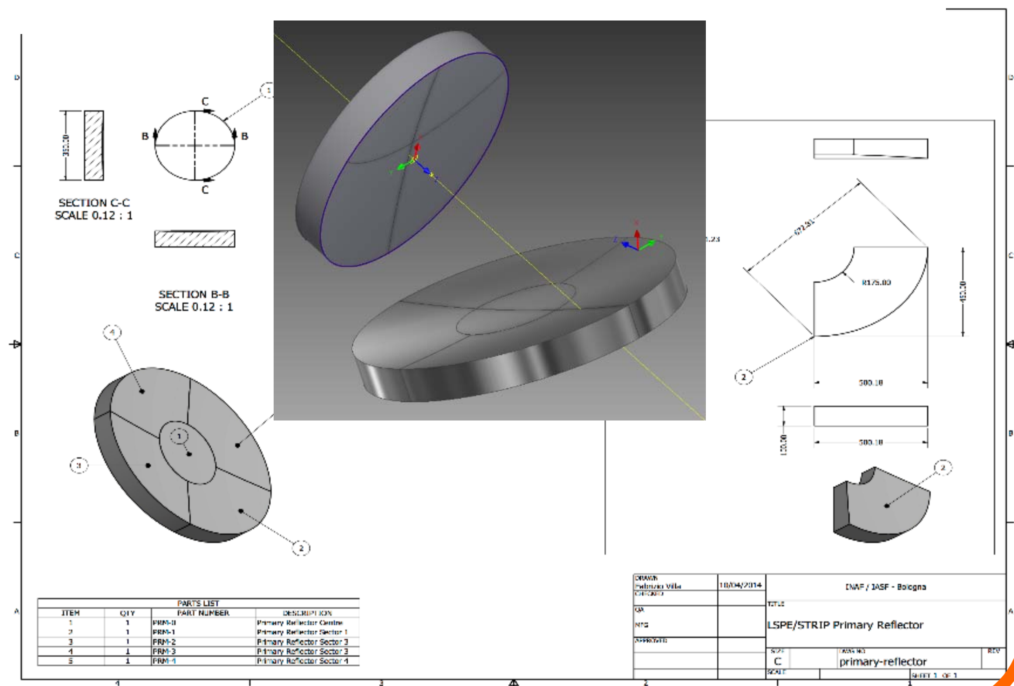
• The correlation radiometers are contained in a large cryostat and cooled at 20K by evaporating ^{4}He.



The STRIP Instrument

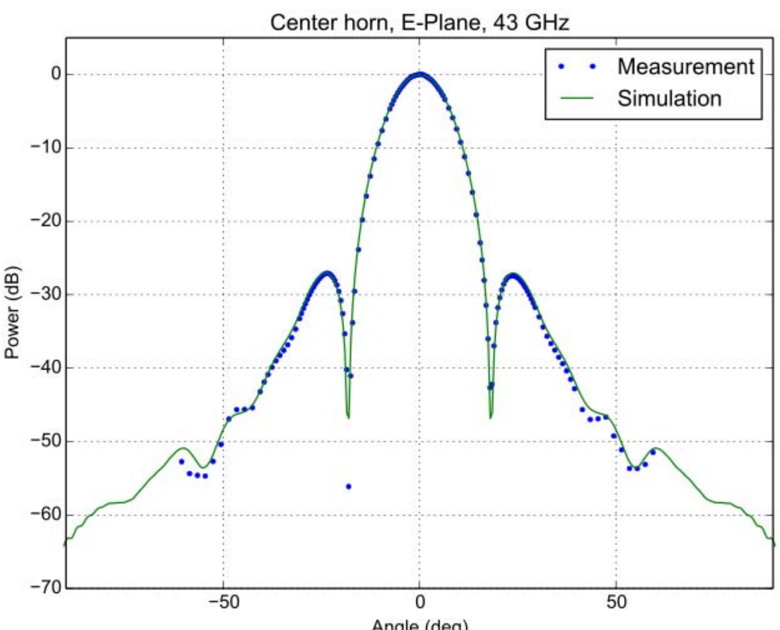


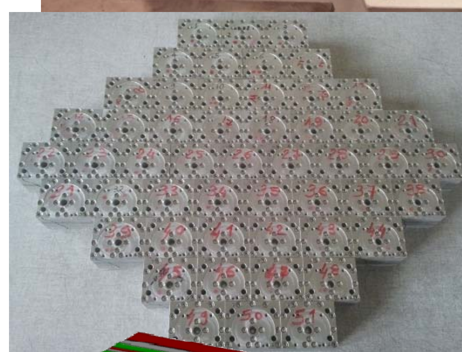
- The beam is defined by a 600 mm aperture side-fed crossed-Dragone telescope, selected for best polarization purity
- Challenging for spillover, stray-light and obscuration
- Modular Primary and secondary mirrors to reduce fabrication costs
- Lightened structure to reduce weight

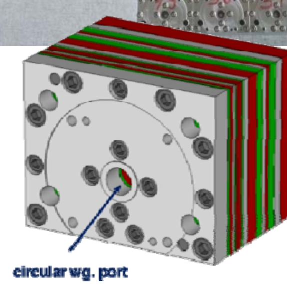


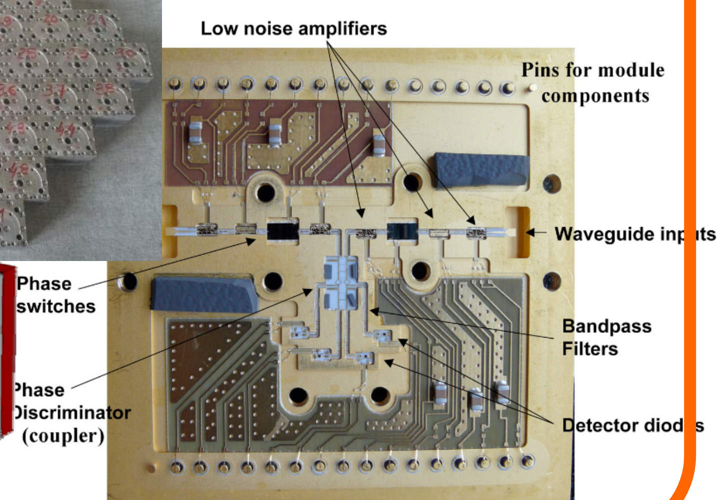
The STRIP Instrument

- In the focal plane, an array of 44 GHz platelet feedhorns (already manufactured) feeds high performance OMTs and LNAs derived from the QUIET exp.
- The measured response of the corrugated feedhorns confirms the expected performance down to -55 dB



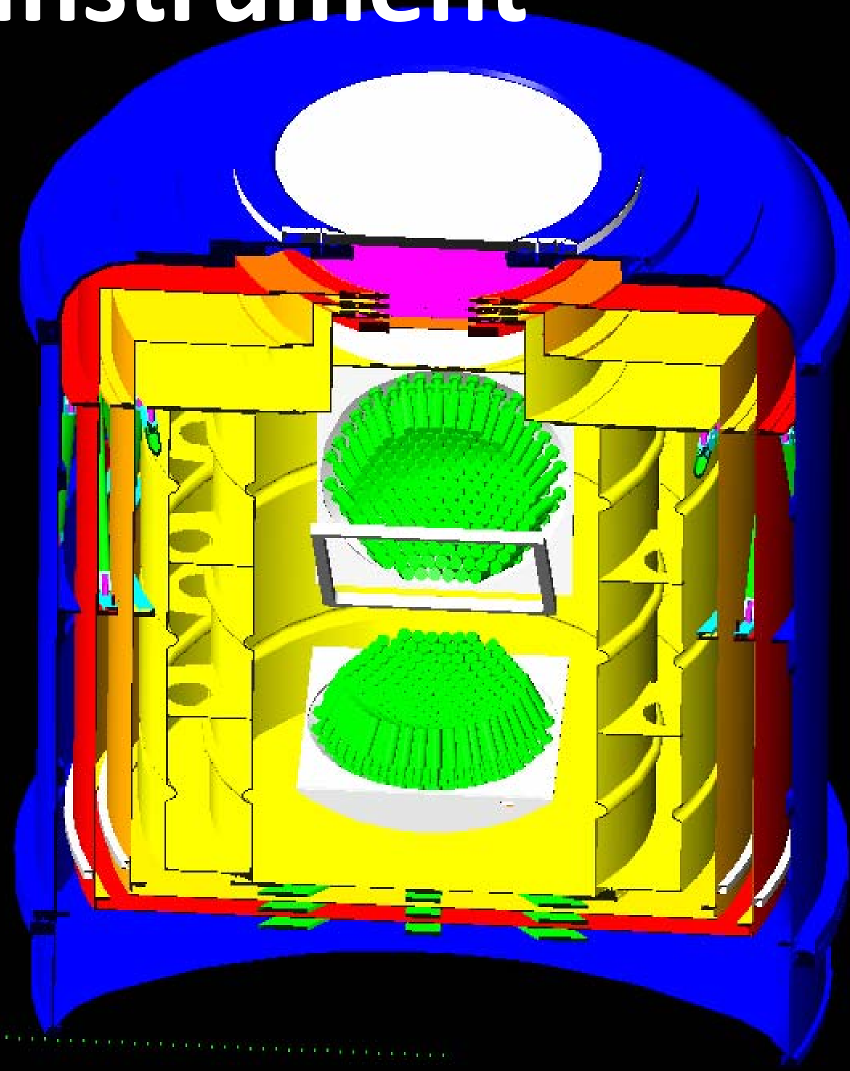




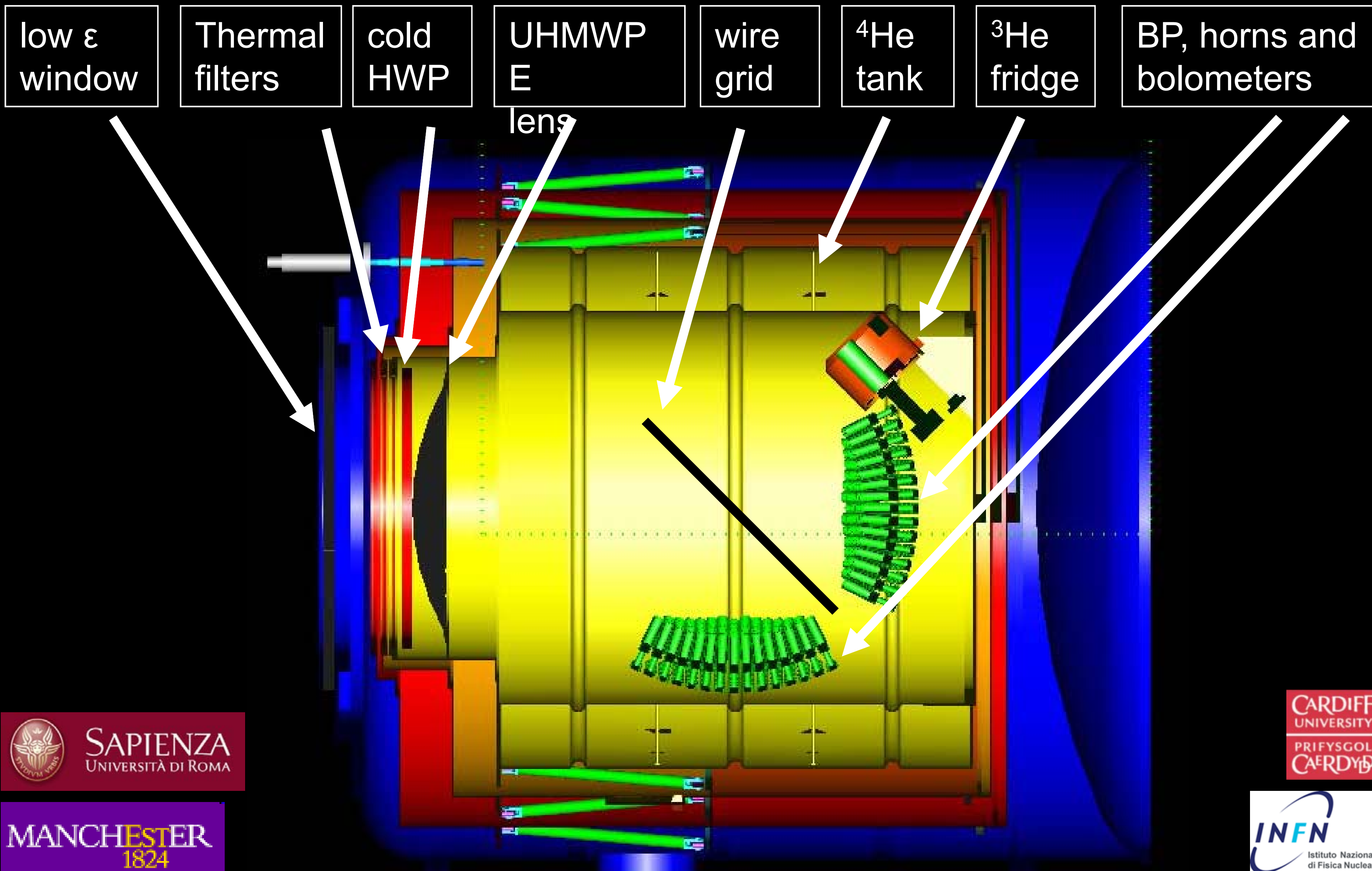


The SWIPE Instrument

- SWIPE is the Short Wavelength Instrument for the Polarization Explorer
- It is a Stokes Polarimeter, based on a simple 50 cm aperture refractive telescope, a cold HWP polarization modulator, a beamsplitting polarizer, and two large focal planes, filled with multimode bolometers at 140, 220, 240 GHz.
- Everything is cooled by a large L^4He cryostat and a ^3He refrigerator, for operation of the bolometers at 0.3K

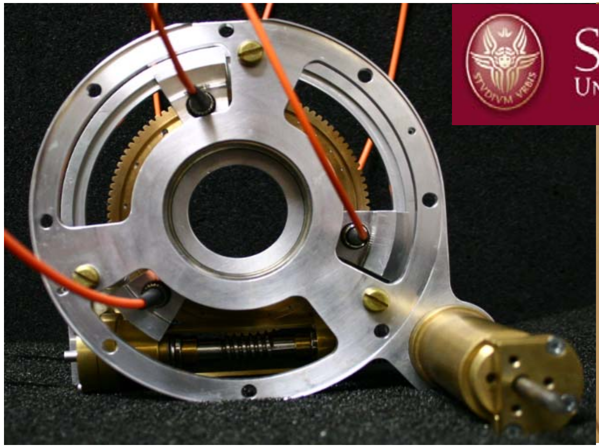


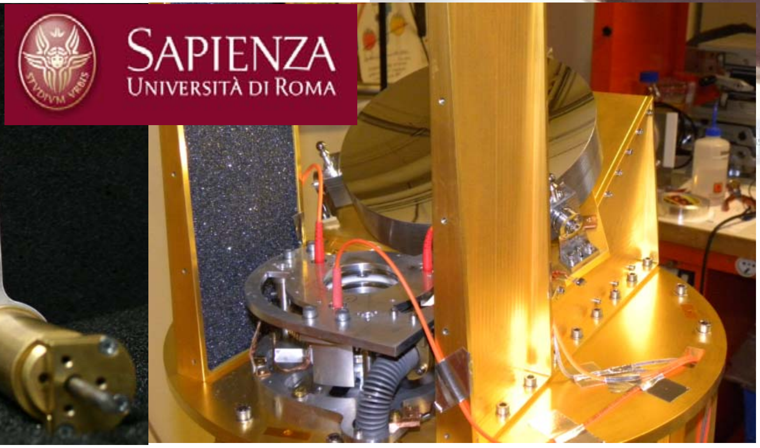
SWIPE: a cryogenic Stokes polarimeter



SWIPE – polarization modulator

- Is a cold (2K), large (50 cm useful dia.), wide band metamaterials HWP, placed immediately behind the window and thermal filters stack.
- HWP characteristics for the ordinary and extraordinary rays are well matched: $(T_o-T_e)/T_o < 0.001$, $X_{pol}<0.01$, over the 100-300 GHz band.
- Its orientation is stepped by 11.25° or 22.5° every few scans.





The cryogenic HWP rotator made for the PILOT experiment. The LSPE one will be based on the same design, and scaled up in dimensions (see Salatino et al. A&A 528 A138 2011)

LSPE - Photolithographic polariser - Period: 20μm , Diameter: 42 cm

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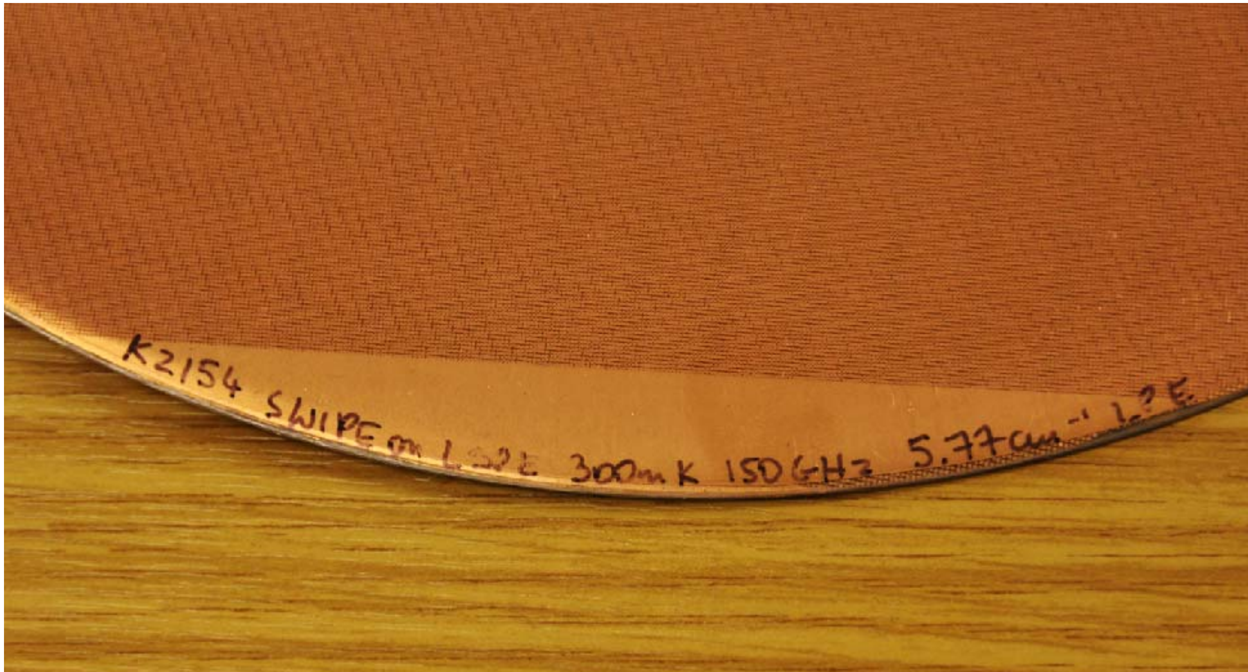
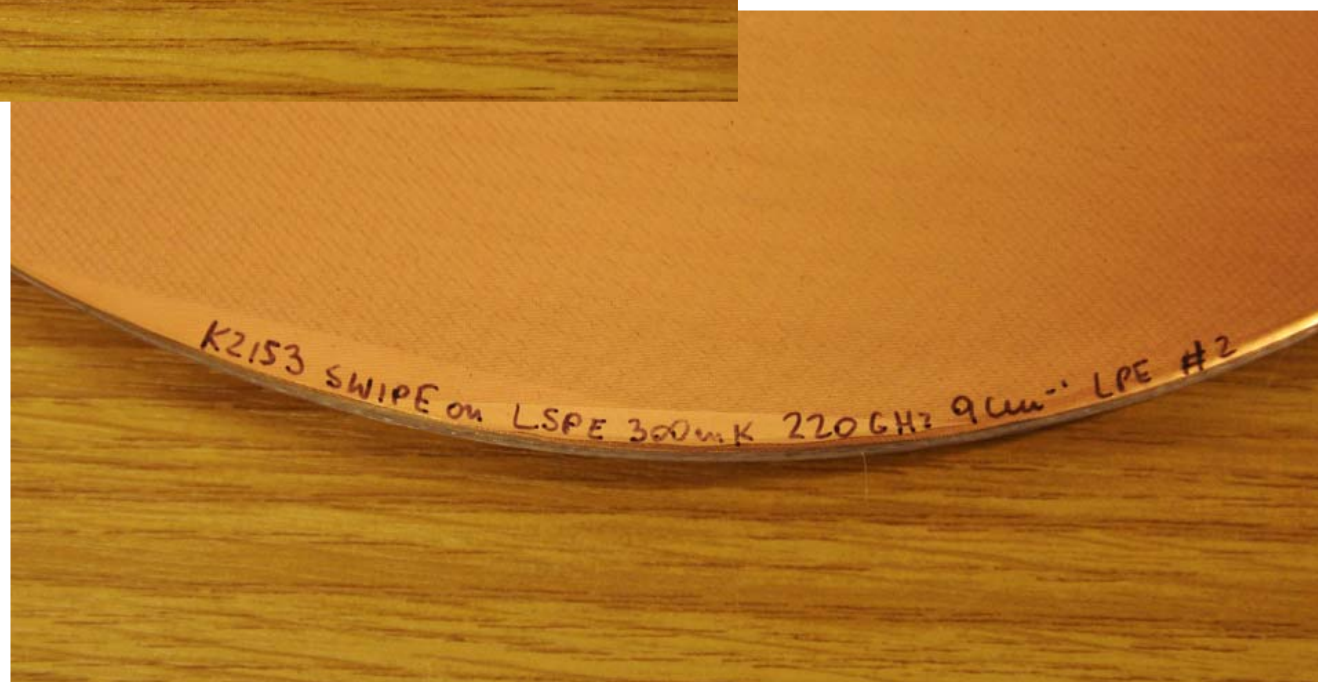
PRIFYSGOL CAERDYDD

LSPE - Mesh Filters - Focal plane band defining Low Pass Edges

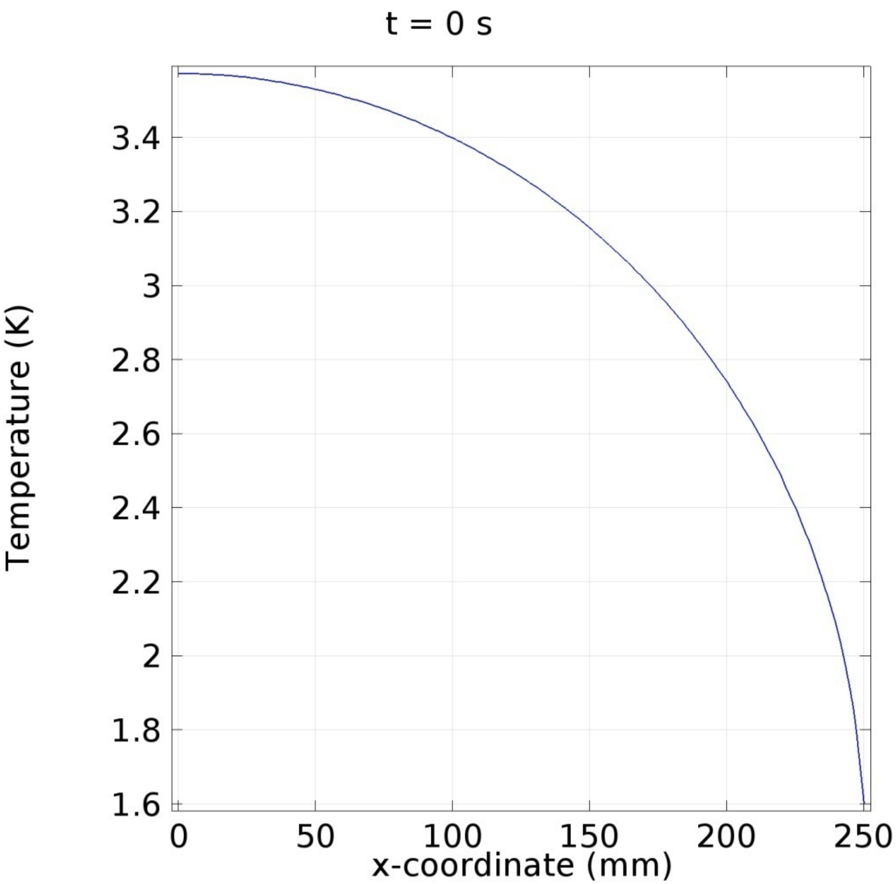
LSPE - Mesh Filters - Focal plane band defining Low Pass Edges

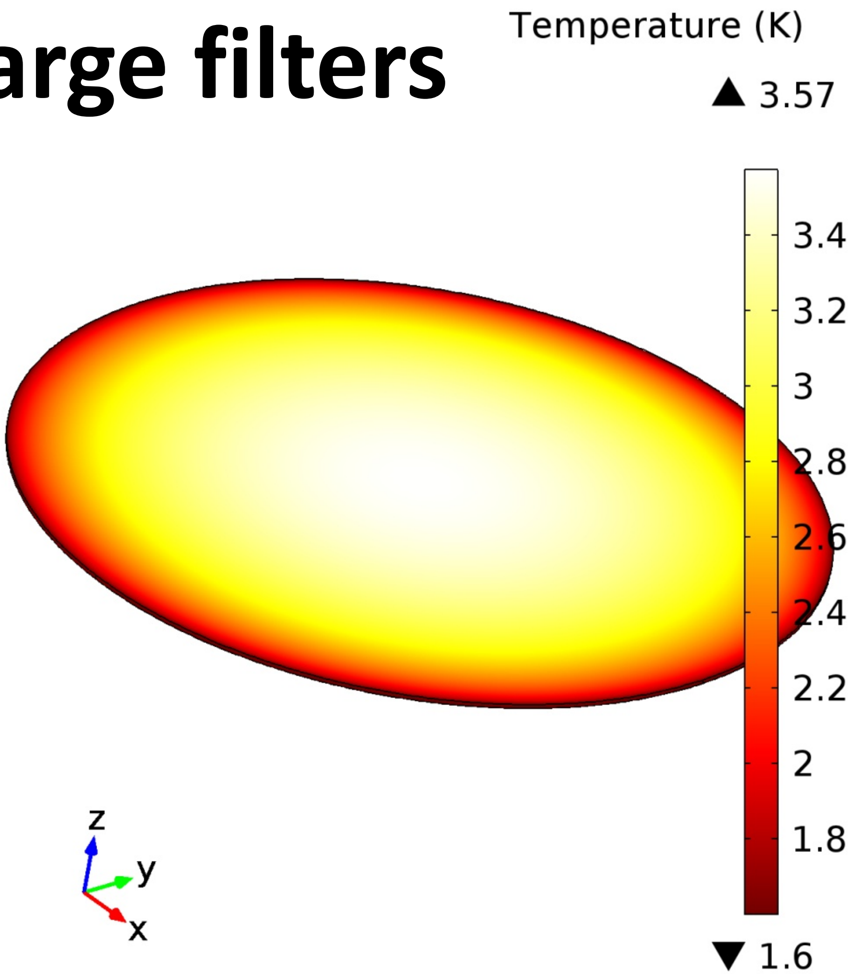




Thermalization of large filters

incoming flux heats the HWP up to 3.57K





This results in a background on the detectors of 0.5, 0.12, 0.12 pW @ 140, 220, 240 GHz : negligible.

M.Salatino

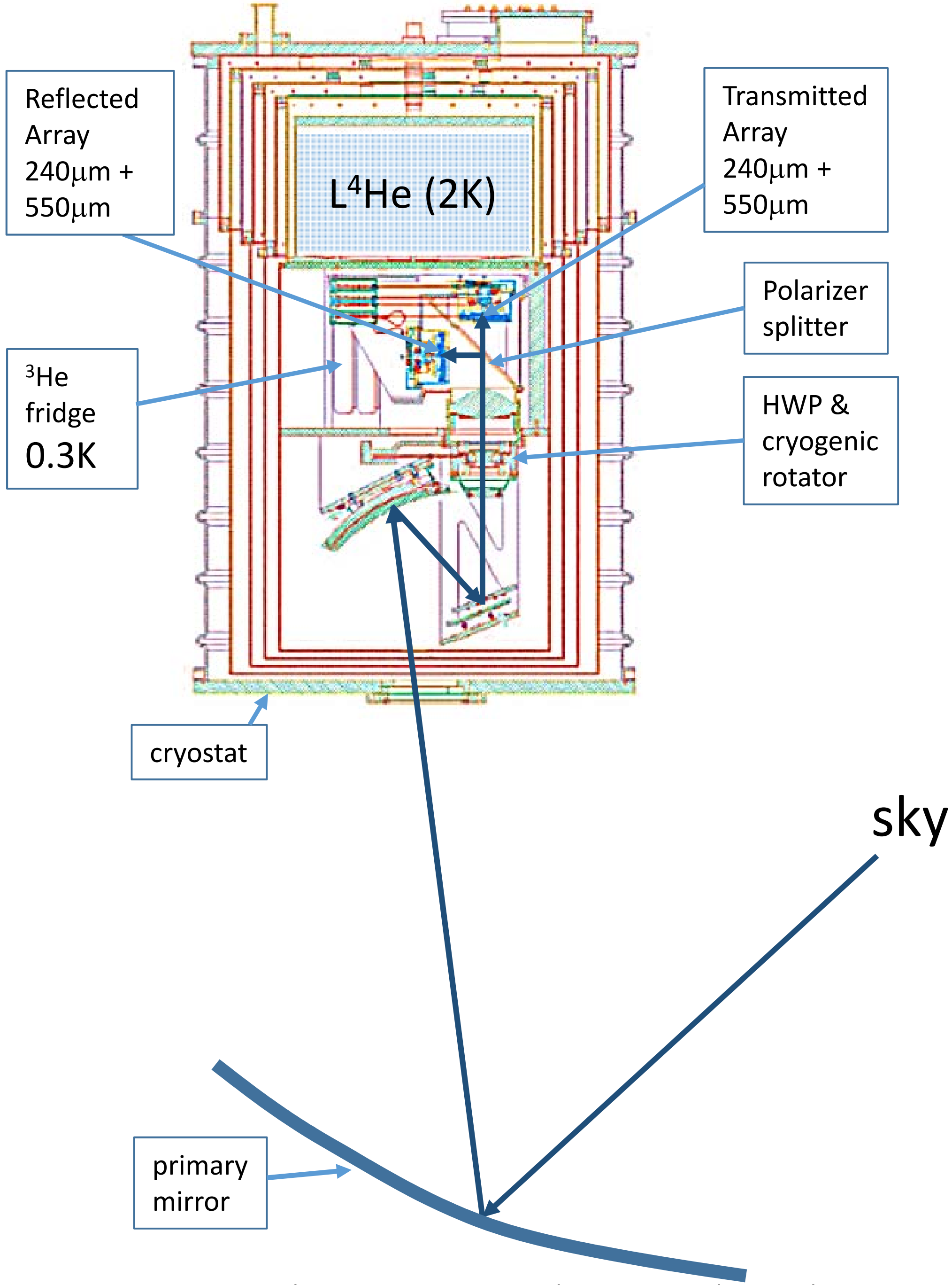
20 sept 2015

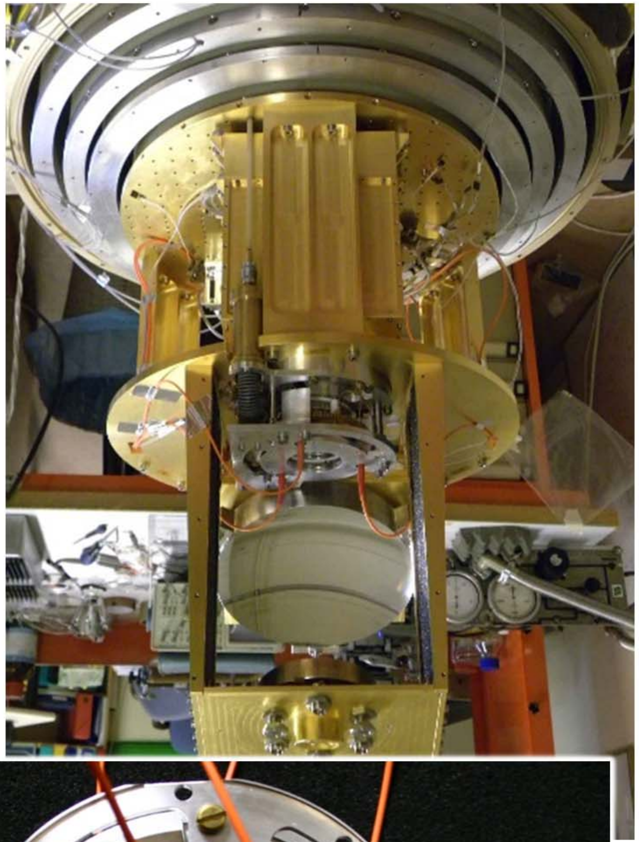
PILOT

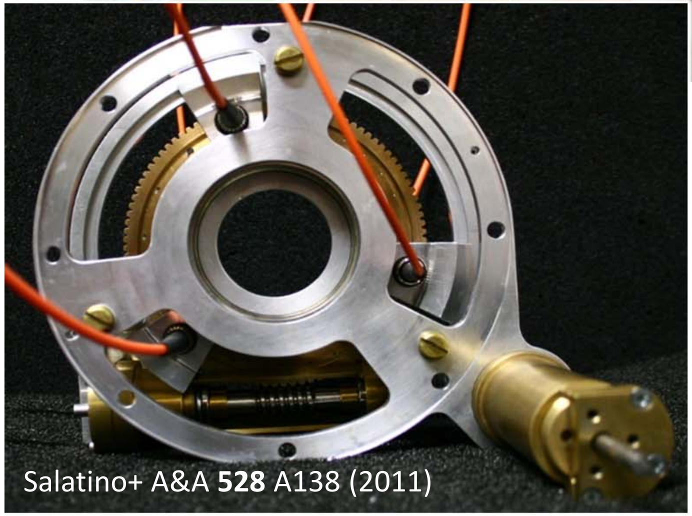
- Measurements of Interstellar Dust Polarization in selected regions of our Galaxy and other targets
- 50 times more sensitive than Planck (!!!)
- 8 arrays of PACS (Herschel) detectors, 256 pixels each, 4 @ 240μm, 4 @ 540μm
- FWHM: 1.4’ @240 μm
- HWP rotator & 4He Cryostat made in Italy (Sapienza)
- Just flown by CNES in Canada !

www.spaceflight.esa.int/pac-symposium2009/proceedings/papers/s7_6engel.pdf

PILOT instrument







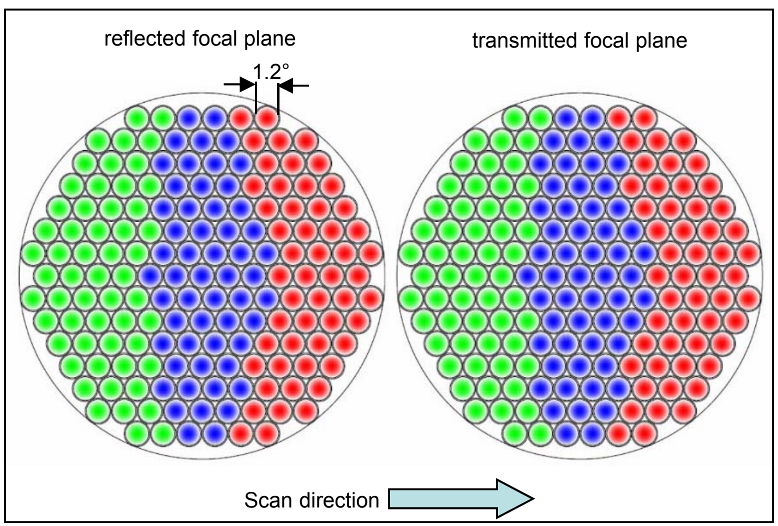
Salatino+ A&A **528** A138 (2011)

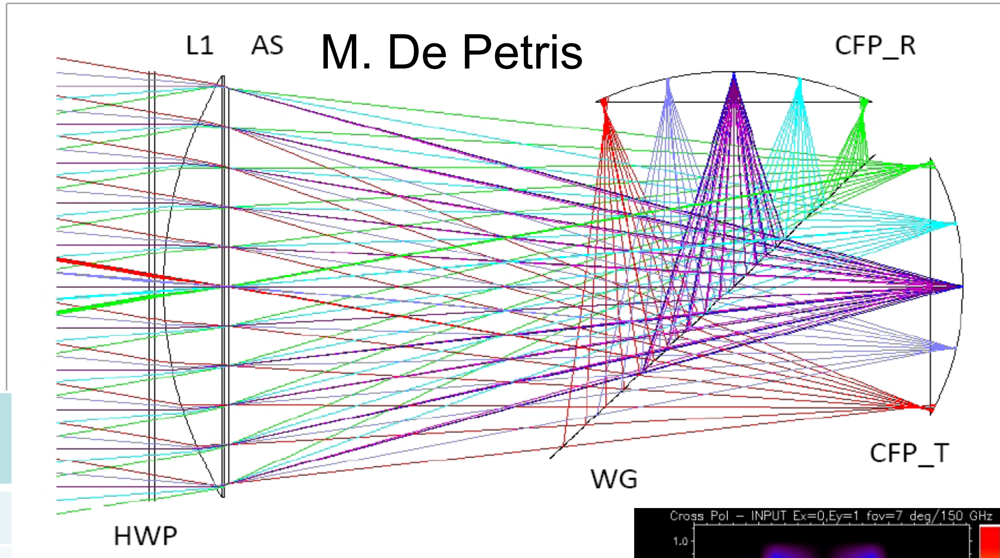
www.spaceflight.esa.int/pac-symposium2009/proceedings/papers/s7_6engel.pdf

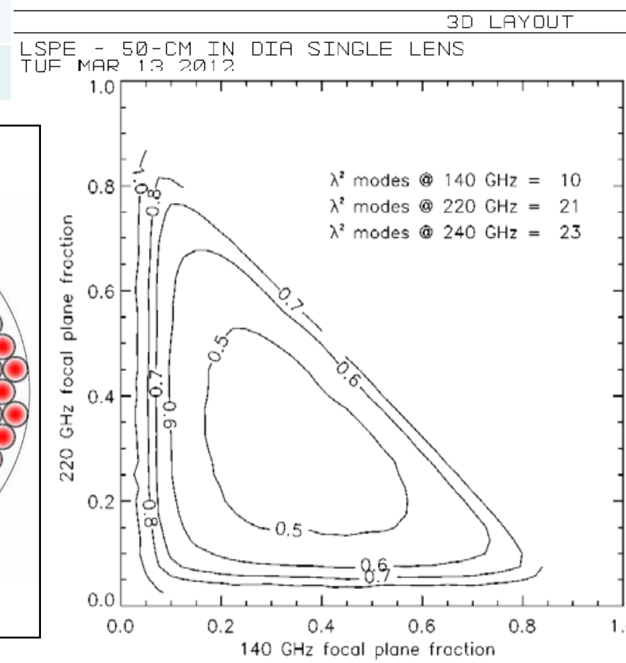
SWIPE – optical system

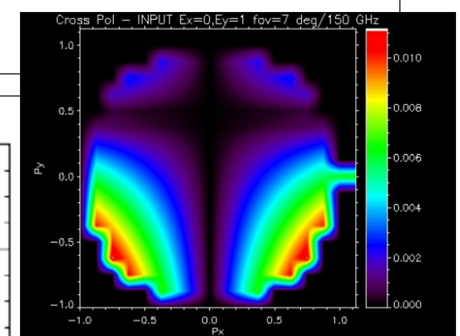
- Single lens UHMWPE @4K, AR coating, D=480, f=800
- Two curved focal planes populated with multimode bolometric detectors, resulting in 1.2°FWHM beams

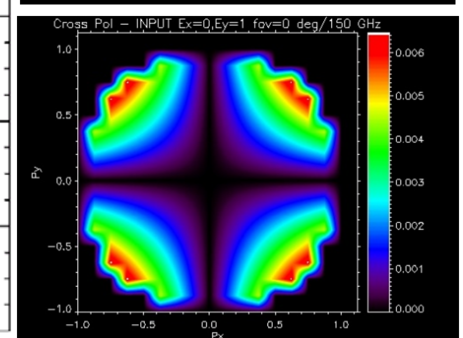
Band (GHz)	Width (%)	Total # detectors	# λ^2 modes
140 GHz	30	110	10
220 GHz	5	110	21
240 GHz	5	110	23





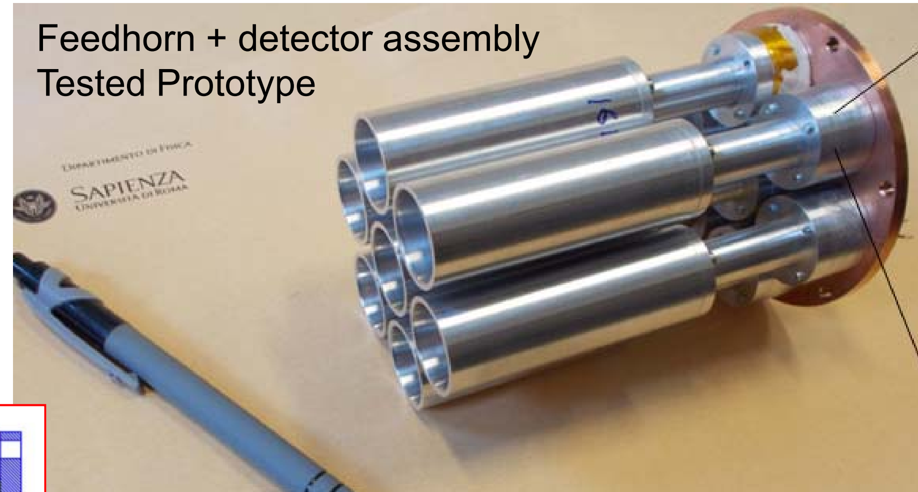


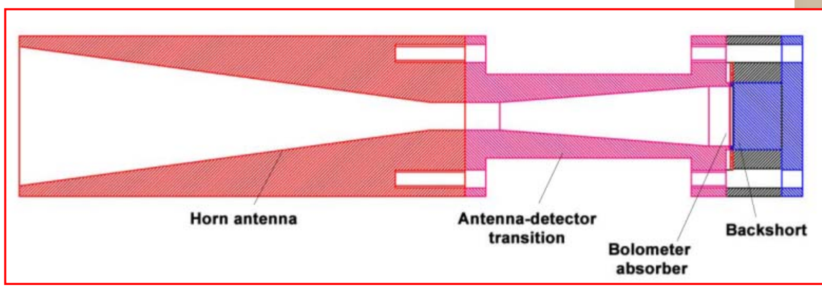


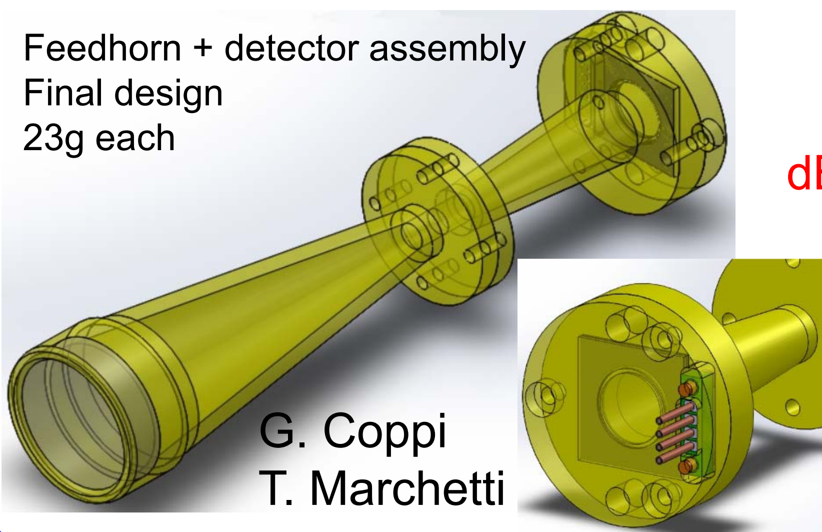


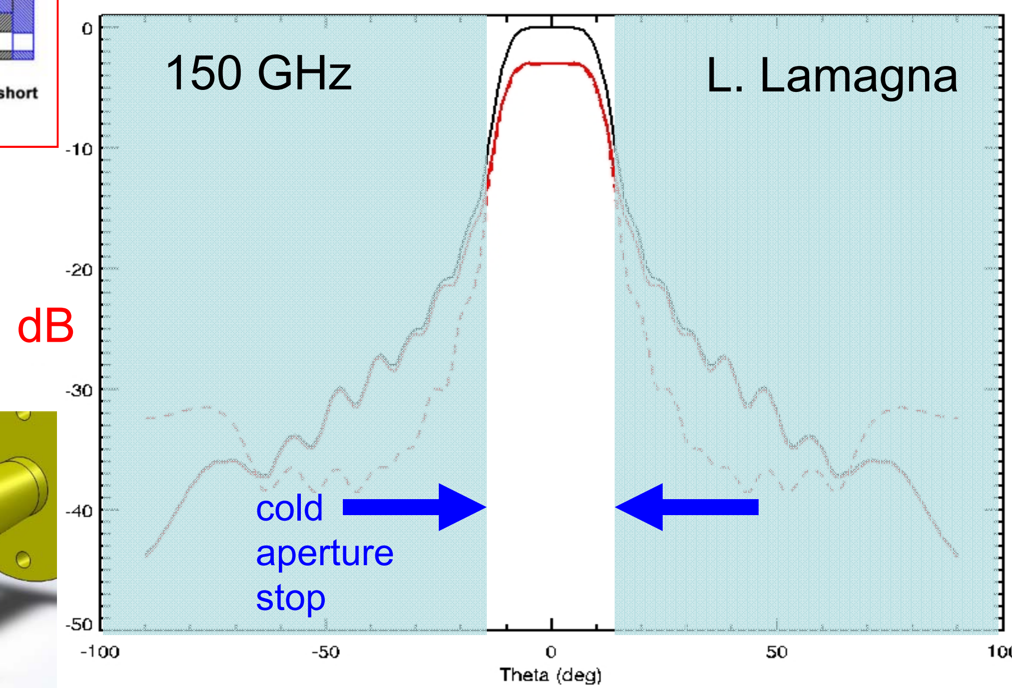
SWIPE – multimode feedhorns

- 20 mm aperture
- High efficiency coupling structure, easy to machine
- Nice top-hat beams
- 10, 21, 23 λ^2 modes @ 140, 220, 240 GHz



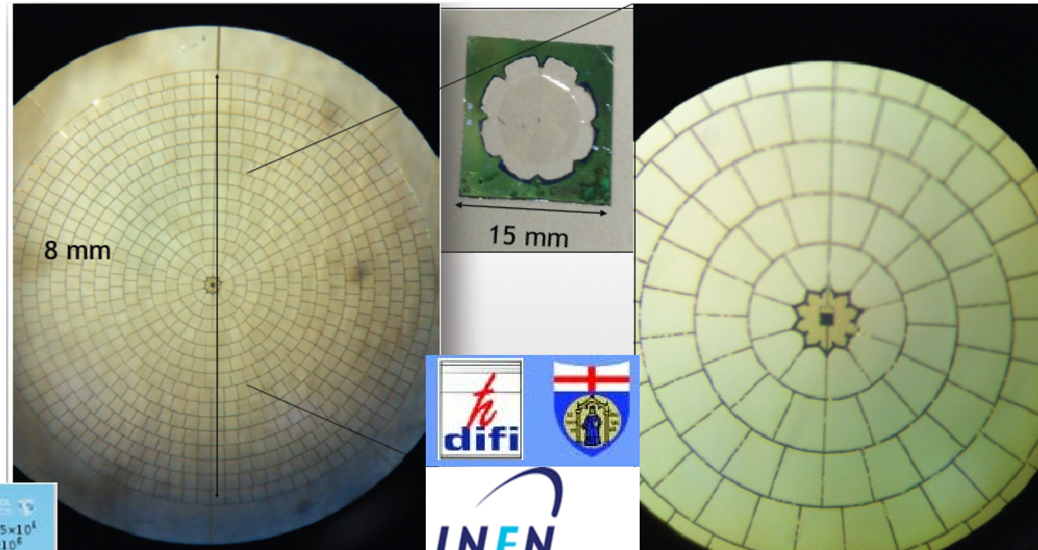


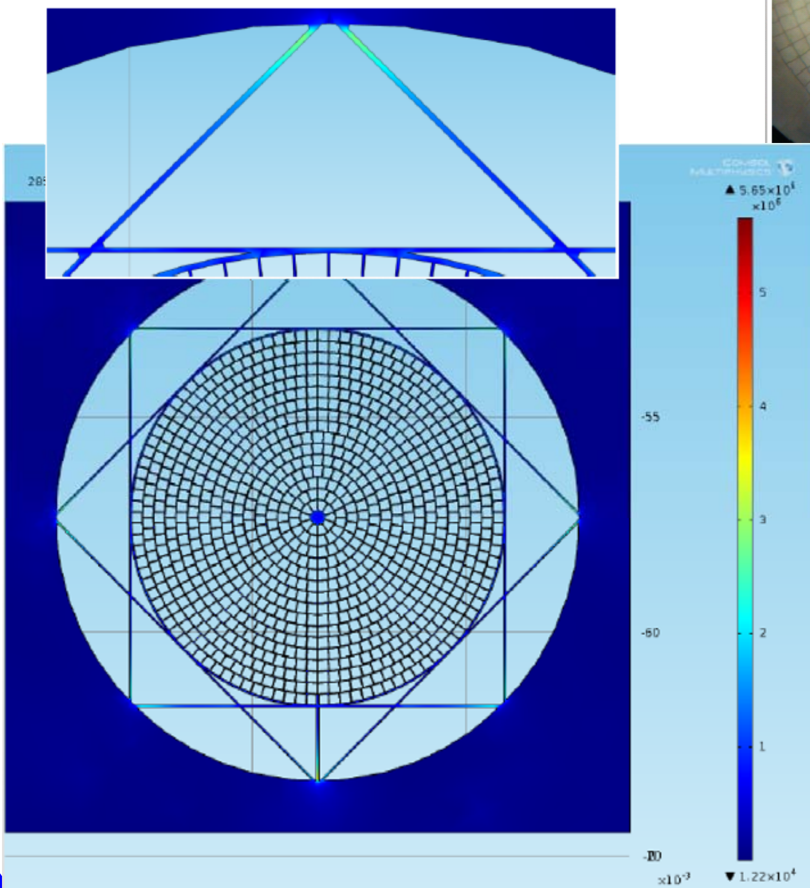


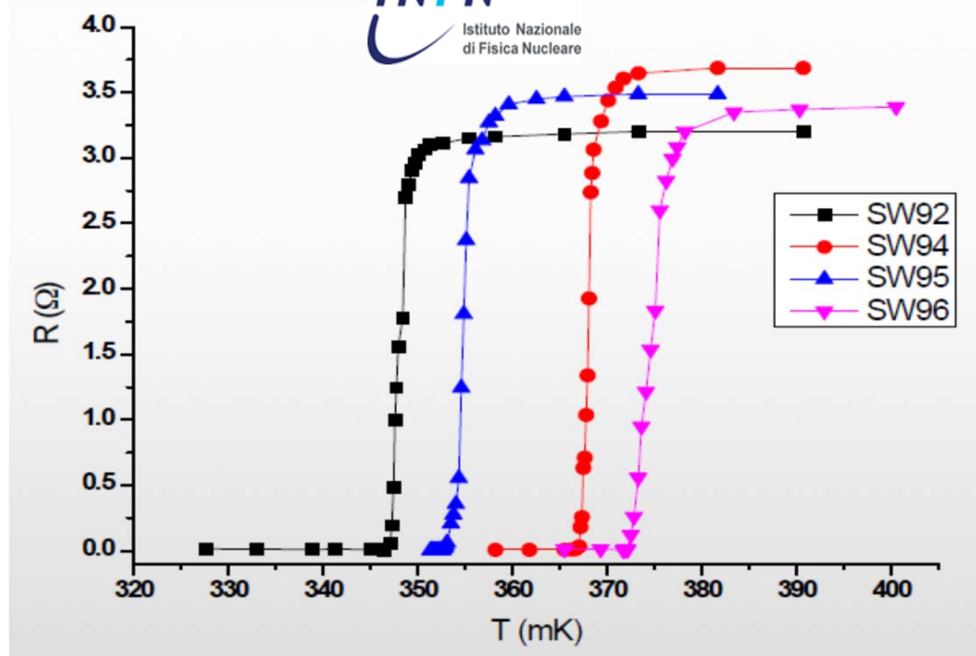


SWIPE - multimode absorbers & TES

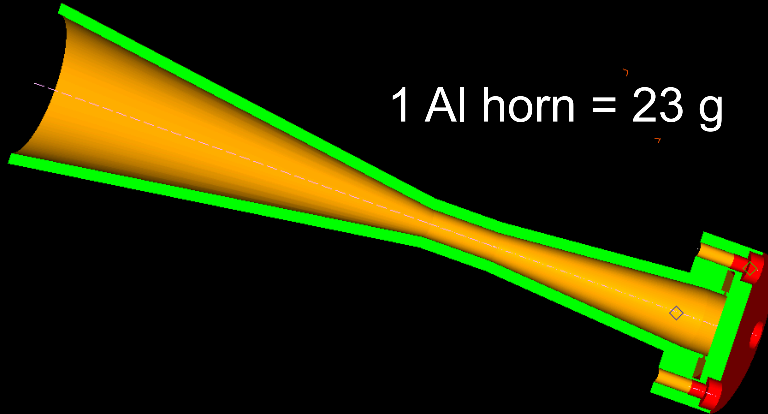
- The absorbers are large Si_3N_4 spider-webs (8 mm diameter, multimode)
- Sensors are Ti-Au TES
- Photon noise limited
- τ = 2 ms

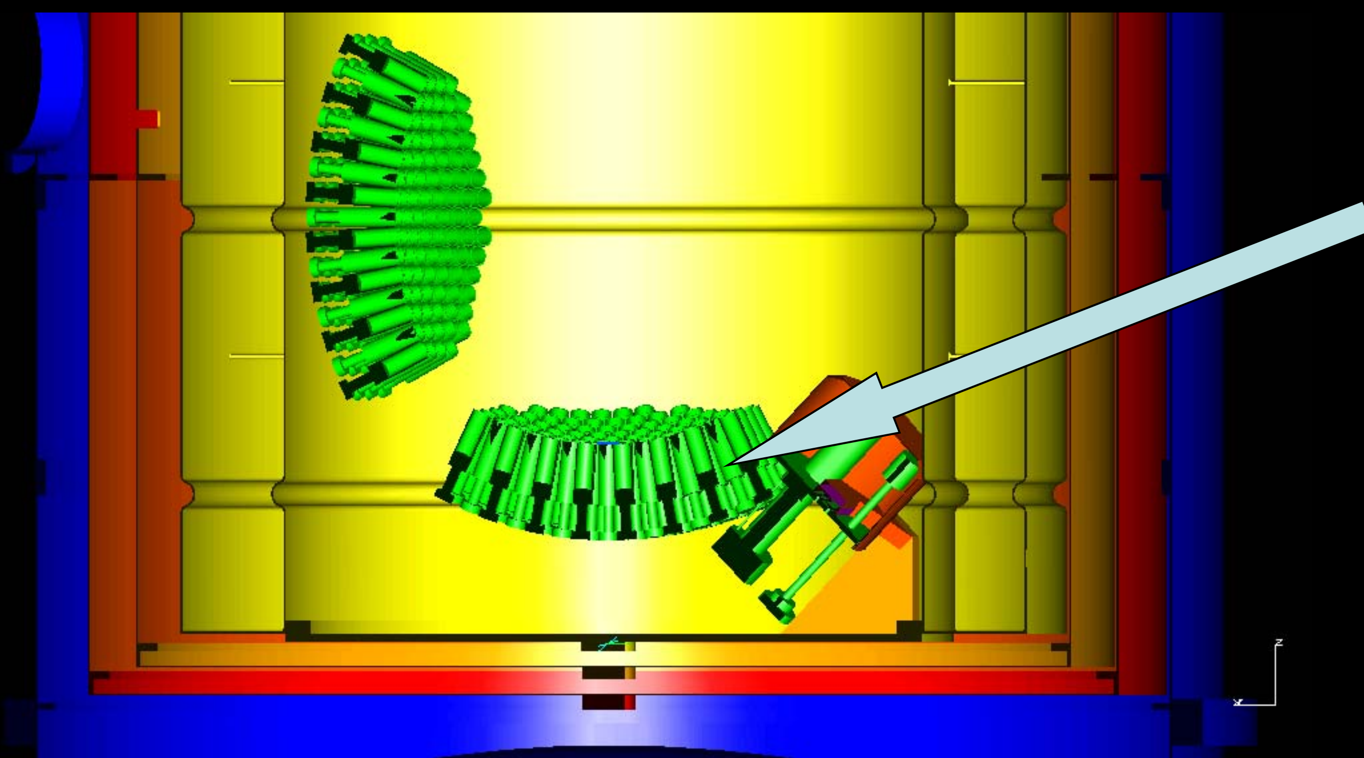






Cryogenic design of LSPE-SWIPE focal planes



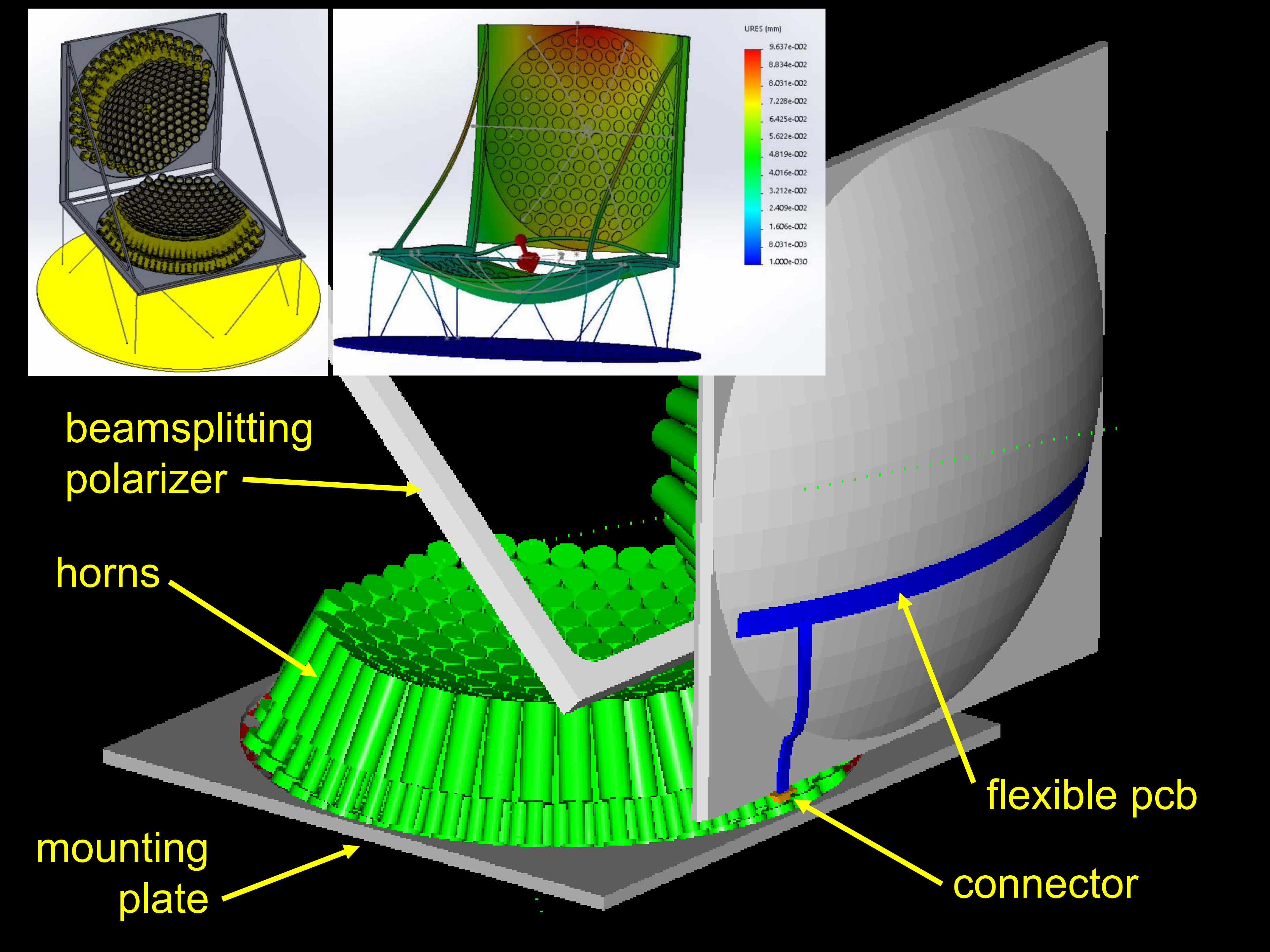


165 Al horns = 3.6 kg

Al mounting plate = 1.6 kg

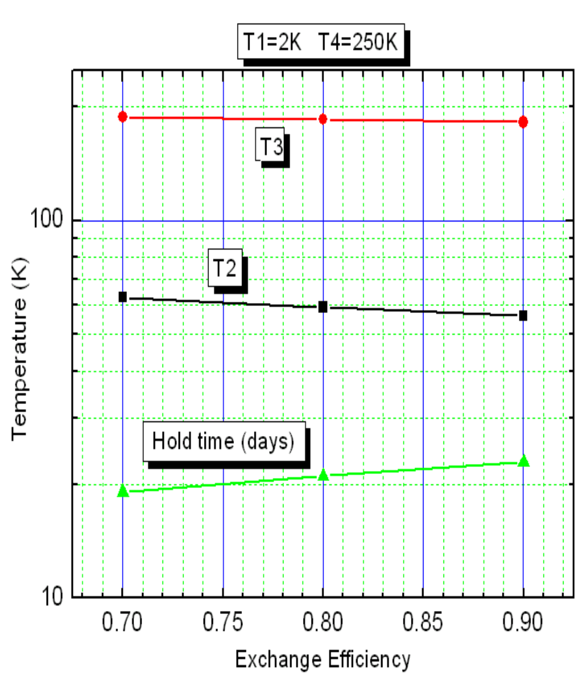
Screws, filters, connectors, cables = 1 kg

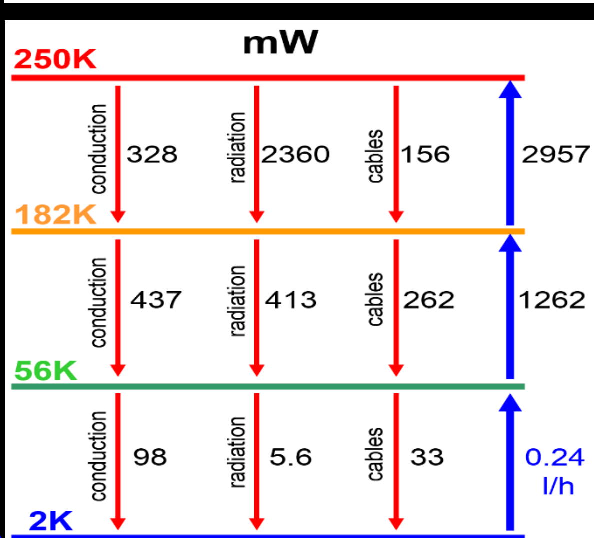
Total suspended mass = 6.3 kg
For 1 focal plane



URES (mm)
9.637e-002
8.834e-002
8.031e-002
7.228e-002
6.425e-002
5.622e-002
4.819e-002
4.016e-002
3.212e-002
2.409e-002
1.606e-002
8.031e-003
1.000e-030
beamsplitting polarizer
horns
mounting plate
flexible pcb
connector

SWIPE - cryostat

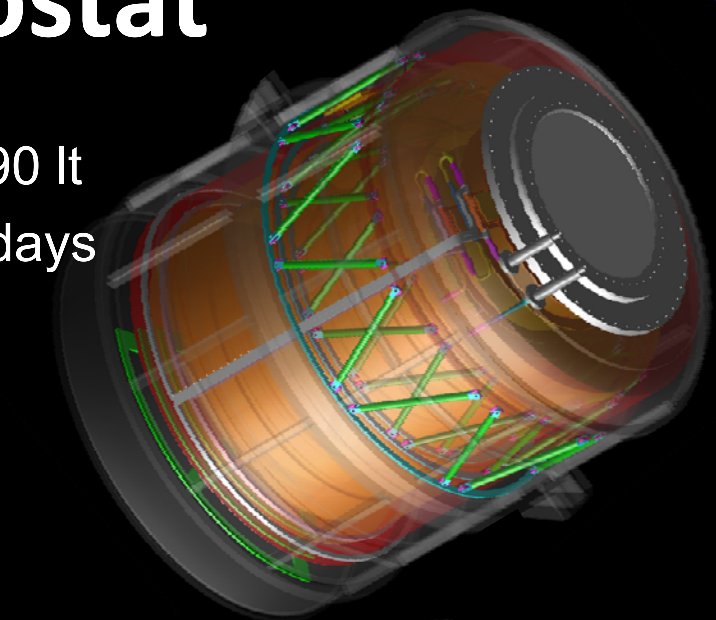


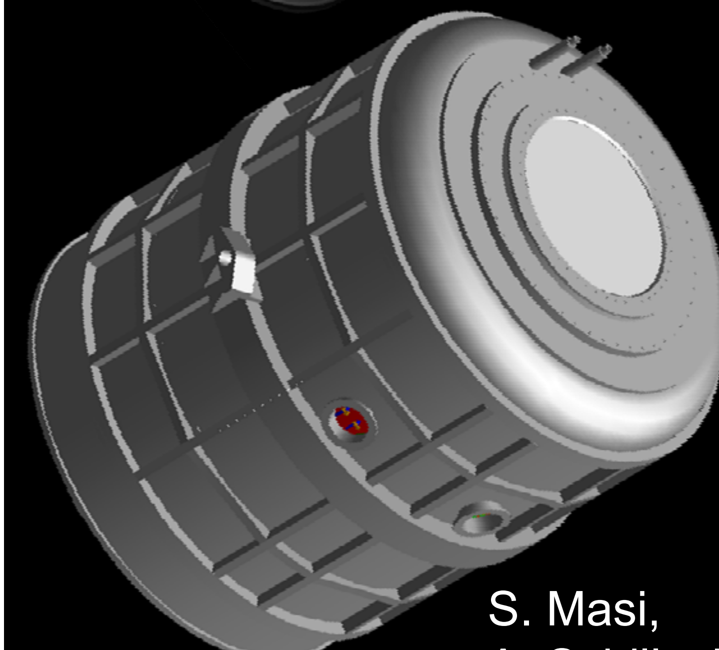


mass = 460 kg

He volume = 0.9 x 290 lt

Hold time = 19 .. 23 days

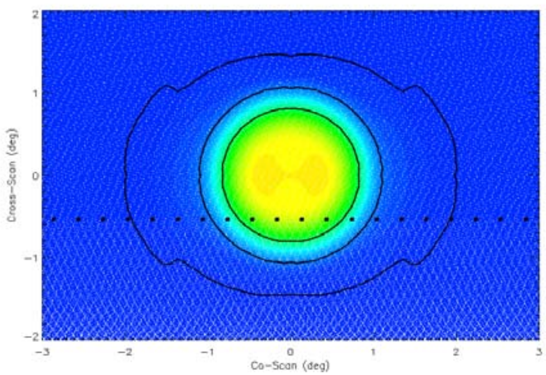




S. Masi,
A. Schillaci

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.

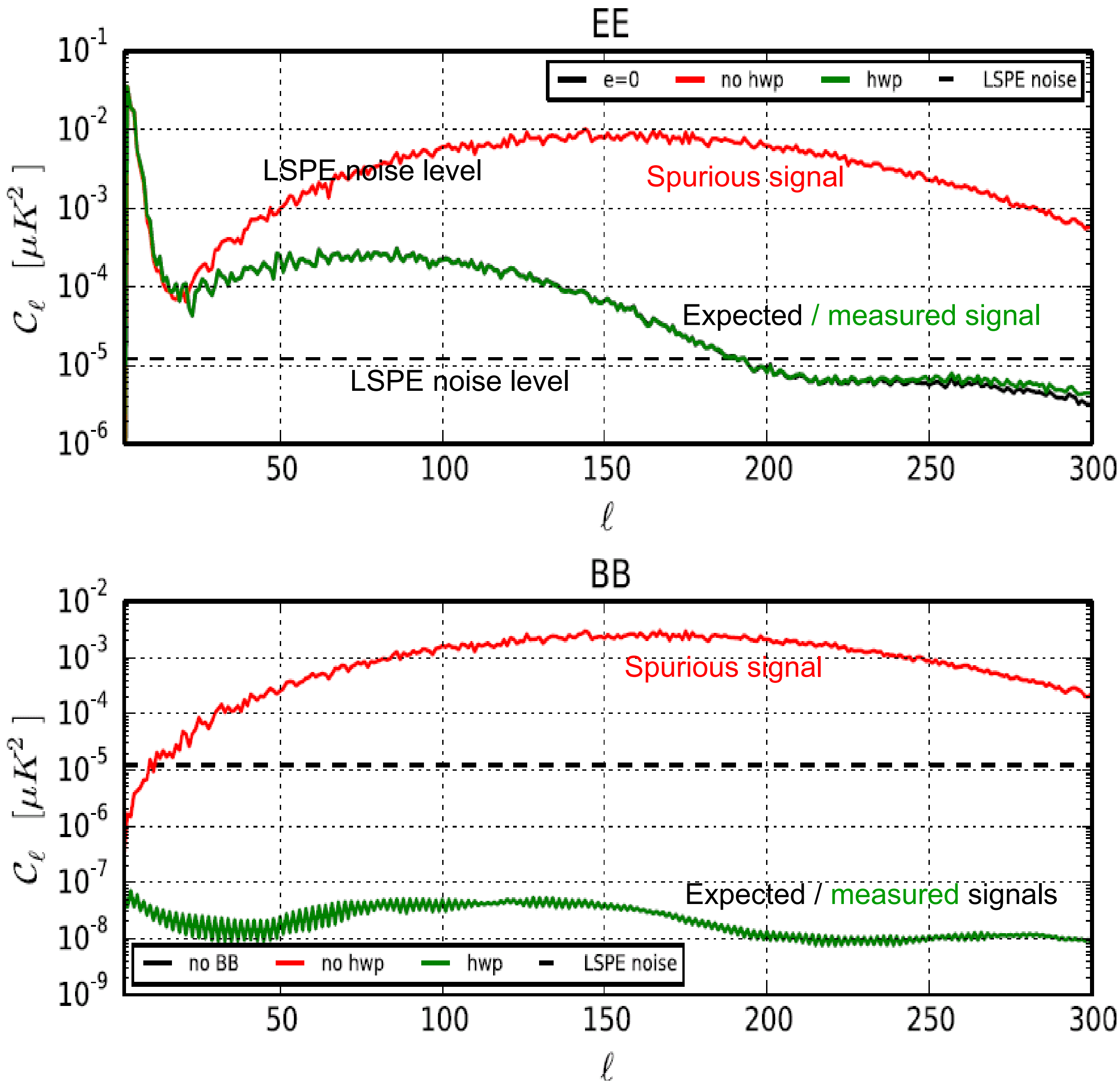
Elevation	Coverage	Unmasked
SWIPE [30-40]	31%	23%
SWIPE [40-50]	27%	20%
SWIPE 35	24%	19%
SWIPE 45	22%	18%
SWIPE [30-50]	35%	26%
STRIP 45	27%	20%
STRIP 30	33%	24%

		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)

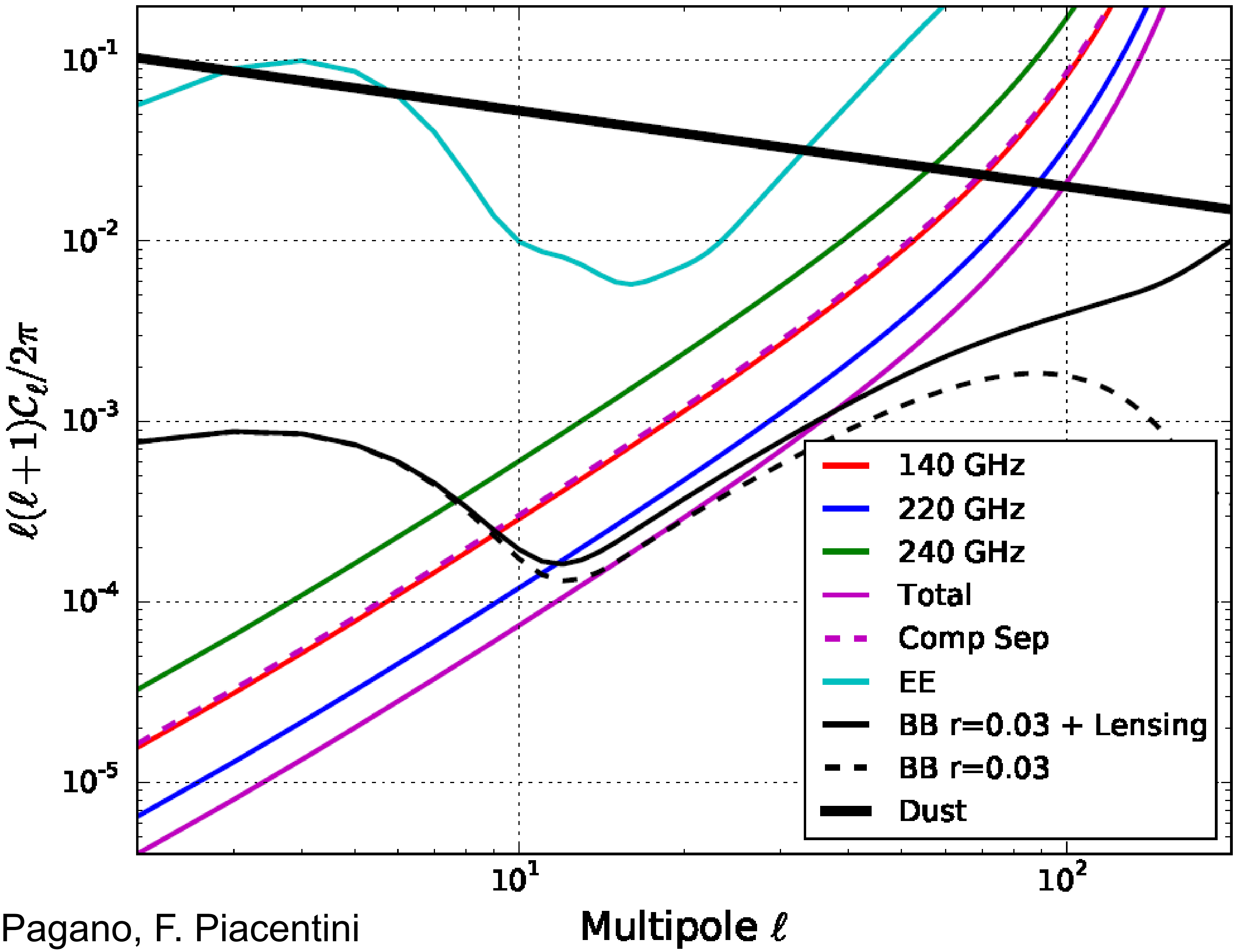
Performance Forecast

- 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 around 0.02



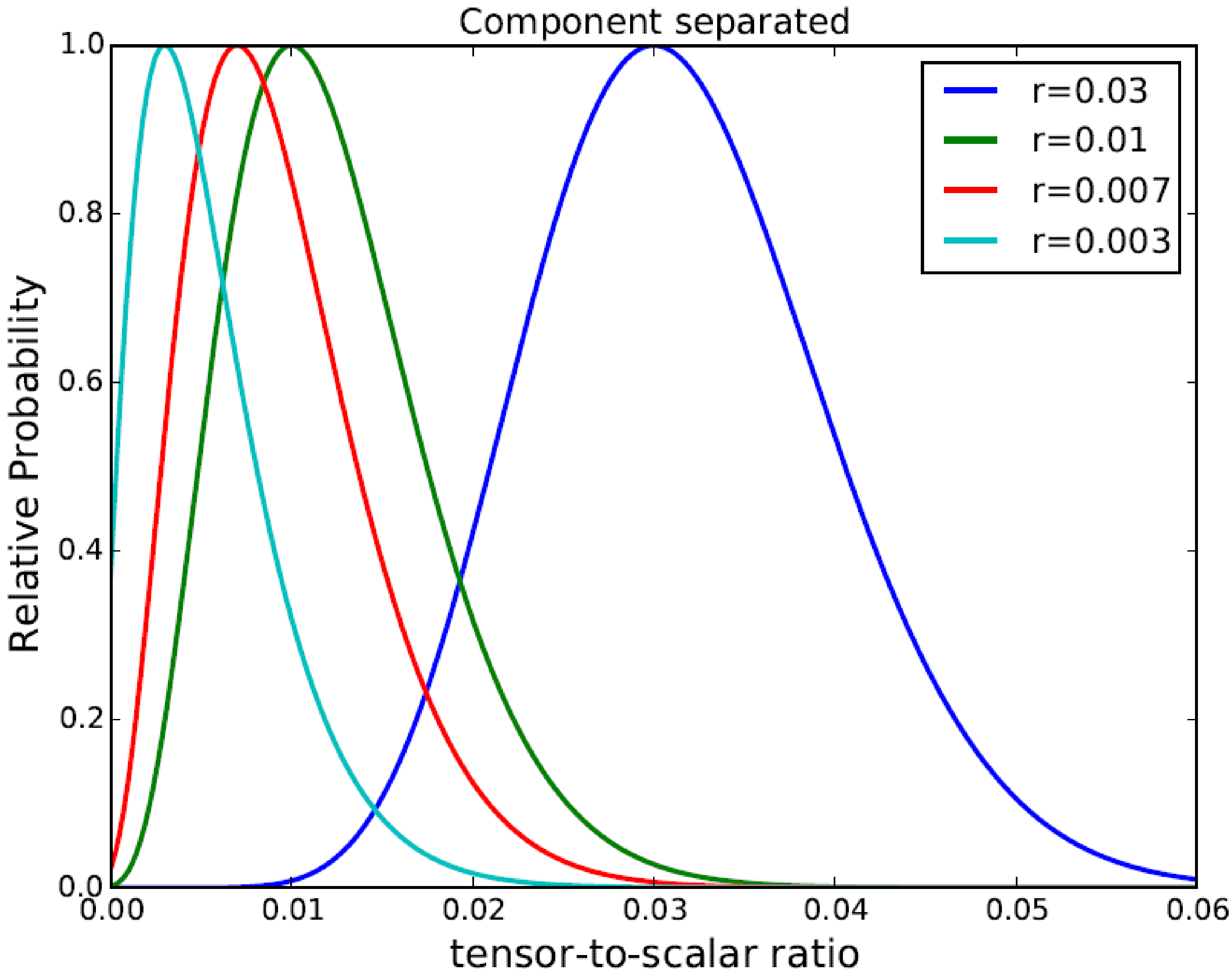
L. Pagano, F. Piacentini

SWIPE Performance Forecast (1st flight)



L. Pagano, F. Piacentini

SWIPE Performance Forecast (1^{st} flight)



L. Pagano, F. Piacentini

Not just inflationary B-modes

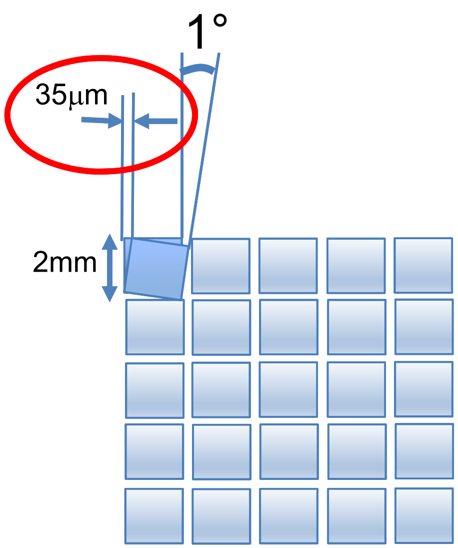
- A very active community is interested to Cosmic Polarization Rotation
- The orientation of polarization appears to be the most stable property of photons.
- However, changes in the polarization angle of photons traveling over cosmological distances are foreseen, for example, if fundamental physical principles, such as the Einstein Equivalence Principle, are violated, or if there is a Faraday rotation.
- A very difficult measurement. Ususally based on non-zero <TB> &<EB>

See presentations/papers at http://www.arcetri.astro.it/cpr/

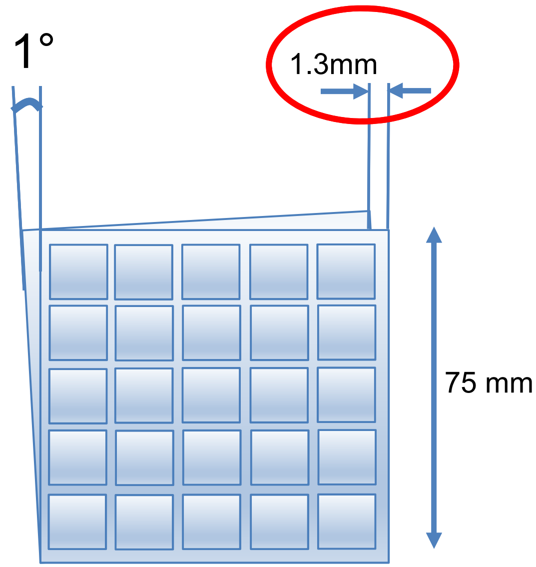
Self-calibration ?

- TB and EB must vanish in the absence of CPR
- Approximate way to proceed: Estimate the rotation of the focal plane θ by computing TB(θ) and find θ^*: TB(θ^*)=0
- Use EB(θ^*) to constrain B modes and CPR
- Iterate to refine θ^* (but will this converge ? May be good enough for B-modes, but not enough for CPR if totally degenerate with angle calibration)
- Having a precise estimate of θ^* from calibration would be much better:
  - No need of dubious iterative processes
  - Two independent spectra to constrain CPR
  - Possibility to calibrate all detectors individually.
- Why is calibrating θ^* so difficult ?

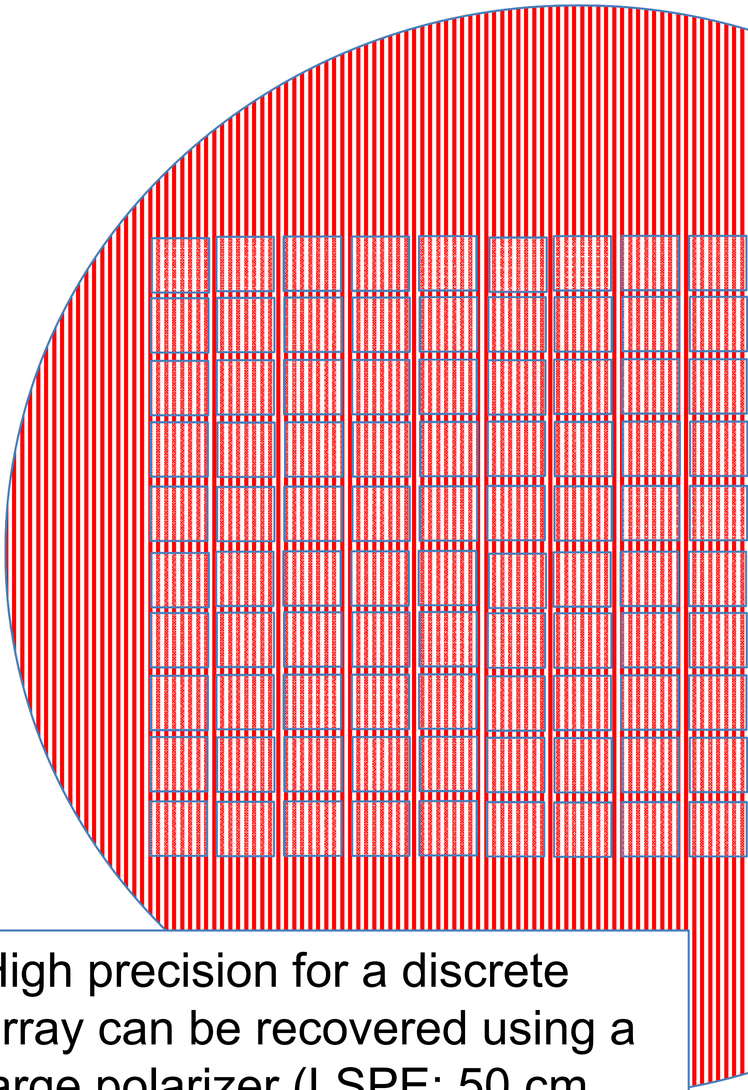
How much is a 1° rotation in practice



In an array of discrete elements (e.g. Planck HFI): difficult to achieve. $\Delta\alpha = O(1°)$



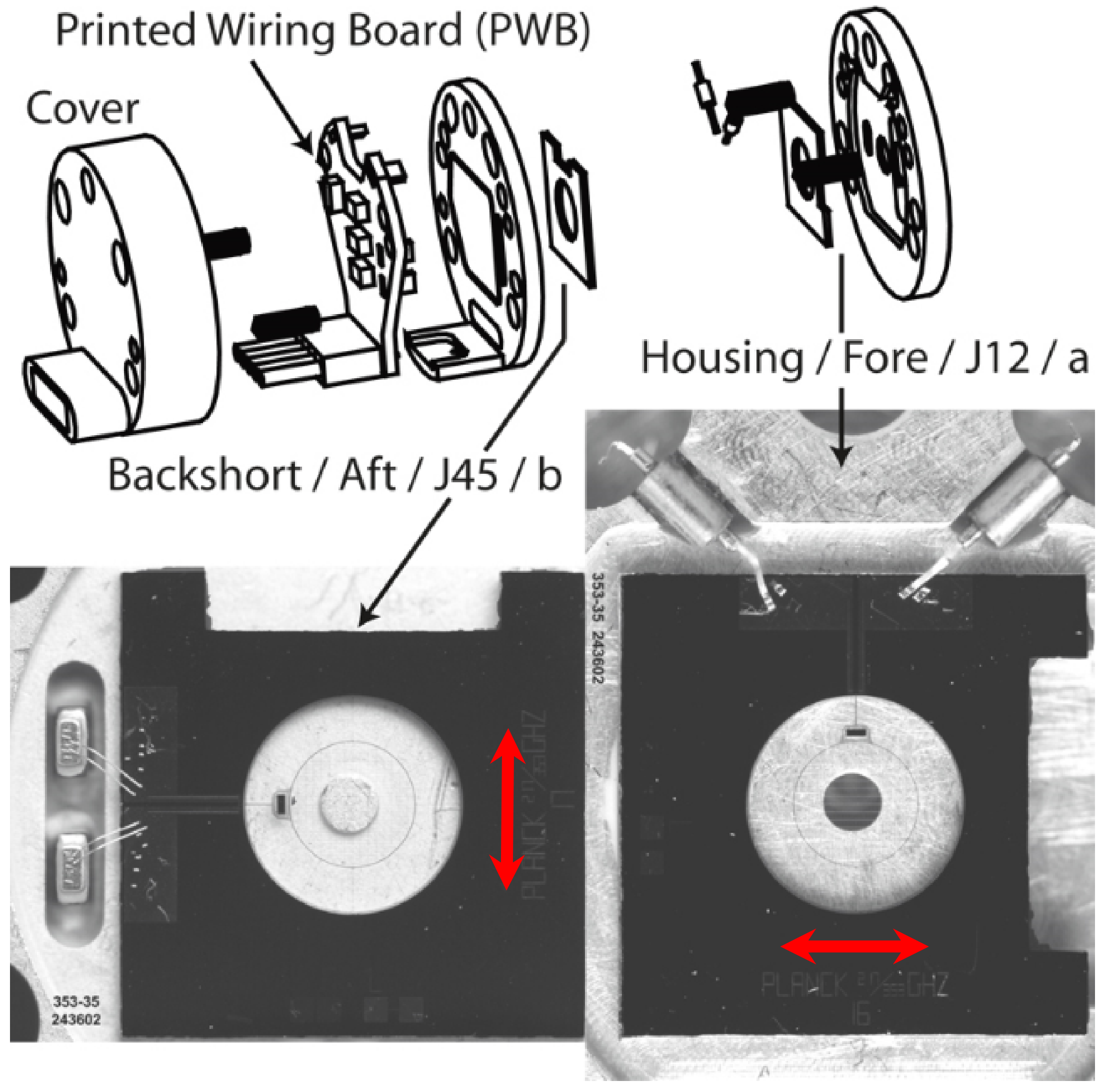
In a photolitographed array – high precision within a tile.
Good precision for the tile : $\Delta\alpha = o(0.1°)$



High precision for a discrete array can be recovered using a large polarizer (LSPE: 50 cm diameter polarizer)

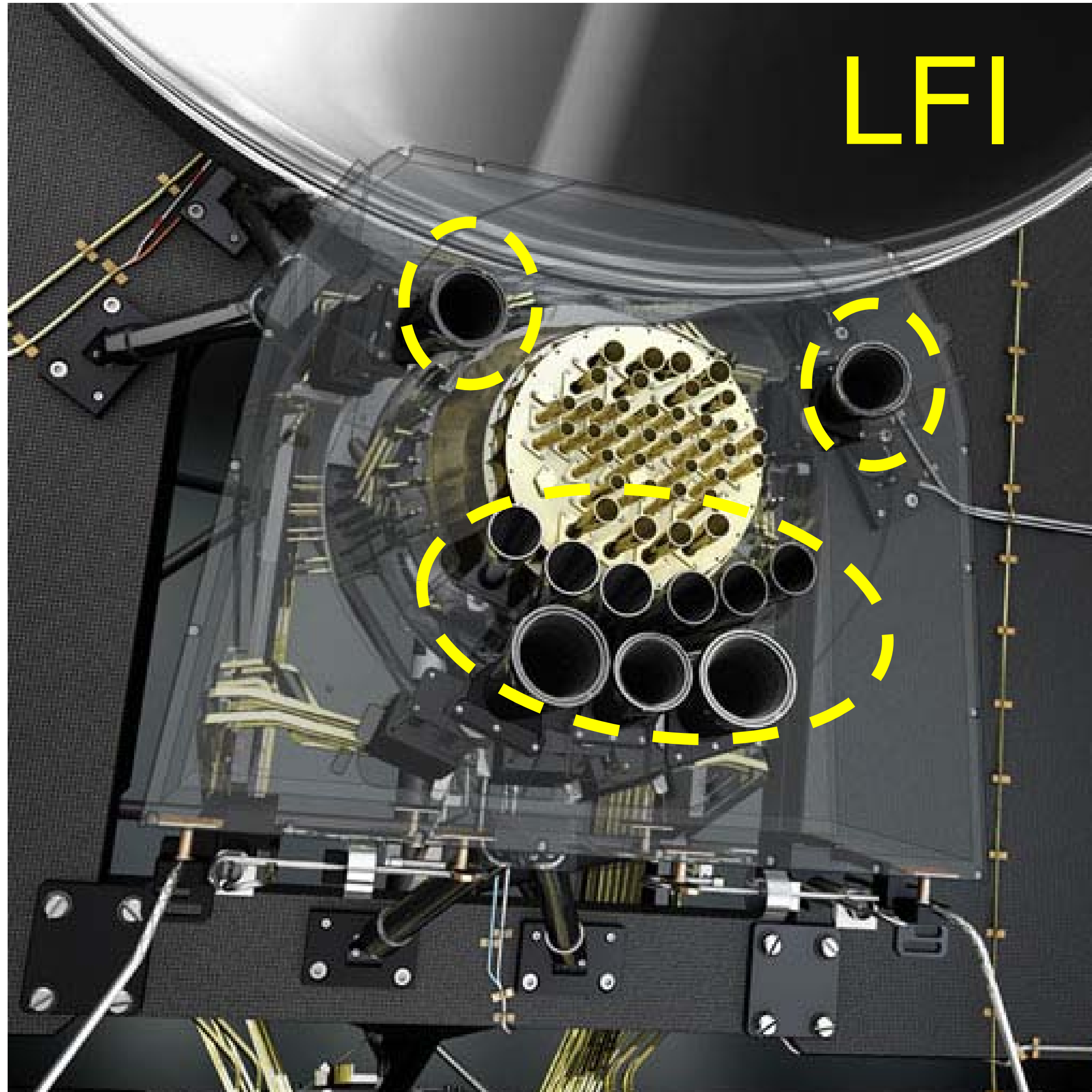
Mechanical Assembly

- Planck HFI: Individual PSBs :
  - Positioning angle error of each wafer in its metal housing of the order of 1°
  - Corresponding to <100μm !
  - arXiv:1502.01587
  - Cannot place polarizer in front.
  - Polarization effects of off-axis telescope can be estimated reliably.



Mechanical Assembly

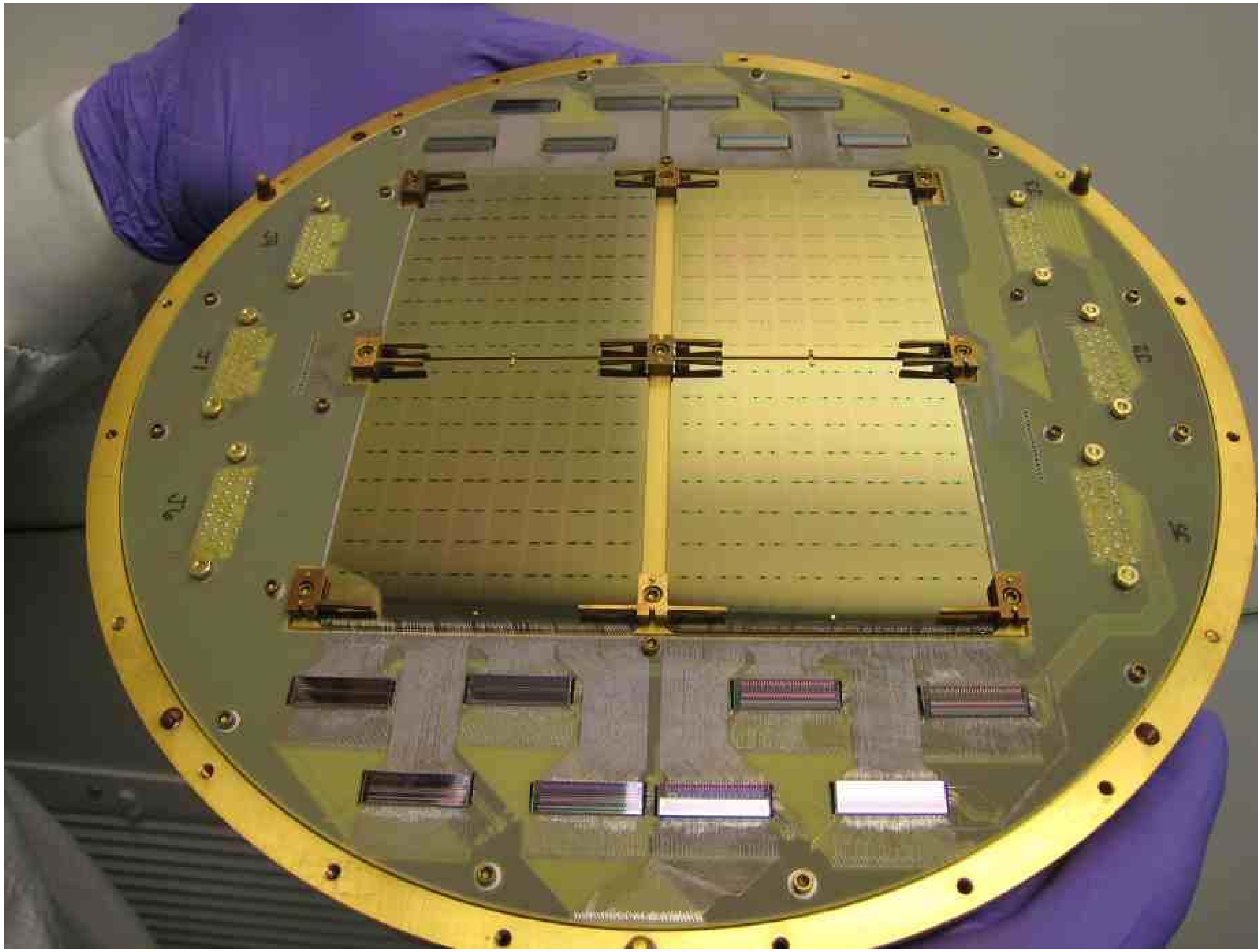
- Planck LFI: Individual horns & OMTs:
  - Positioning angle error of each horn in its metal housing of the order of 0.1°
  - Corresponding to <100μm
  - Cannot place polarizer in front.
  - Polarization effects of off-axis telescope can be estimated reliably.



BICEP: focal plane arrays

Mechanical Assembly

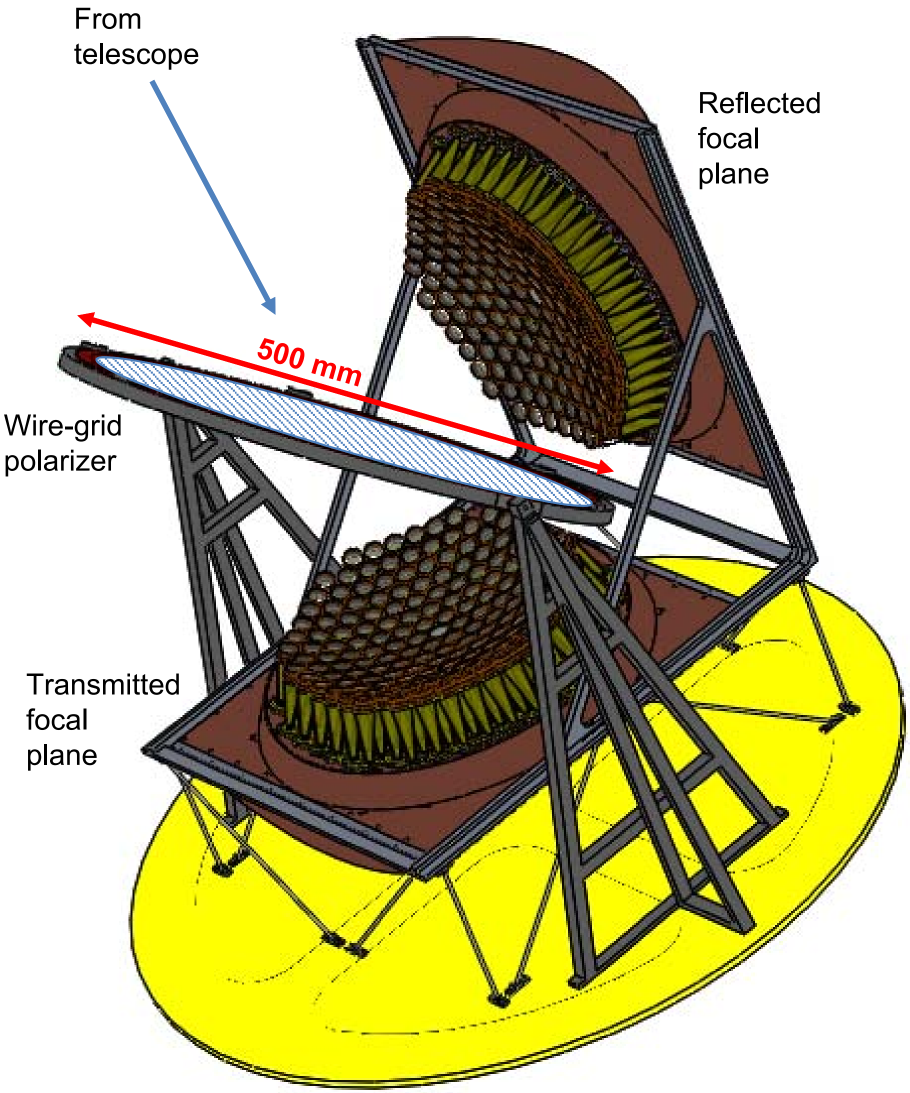
- Positioning angle error of *wafer* in its housing of the order of 0.1°, corresponding to 100μm)
- Polarizer in front not needed.
- Polarization effects of refractive telescope can be computed reliably.
- Ground based calibration of orientation possible with external beam-filling polarized source.



Mechanical Assembly

LSPE: individual multi-mode detectors with large polarizer

- Positioning angle error of *polarizer* in its housing of the order of 0.02°, corresponding to 200μm)
- Ground based calibration of orientation possible with external beam-filling polarized source.

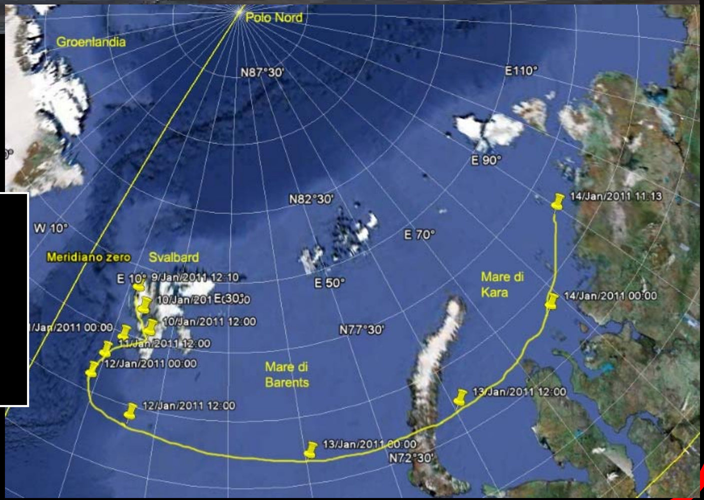


Expected accuracy for LSPE

- Current limits on CPR are of the order of σ_α<1°
- Expected calibration precision for LSPE <0.1°
- Expected performance including instrument noise, from detailed simulations (L. Pagano):
- σ_α = 0.15° (20% of the sky, r, τ, α free, A_s from Planck)

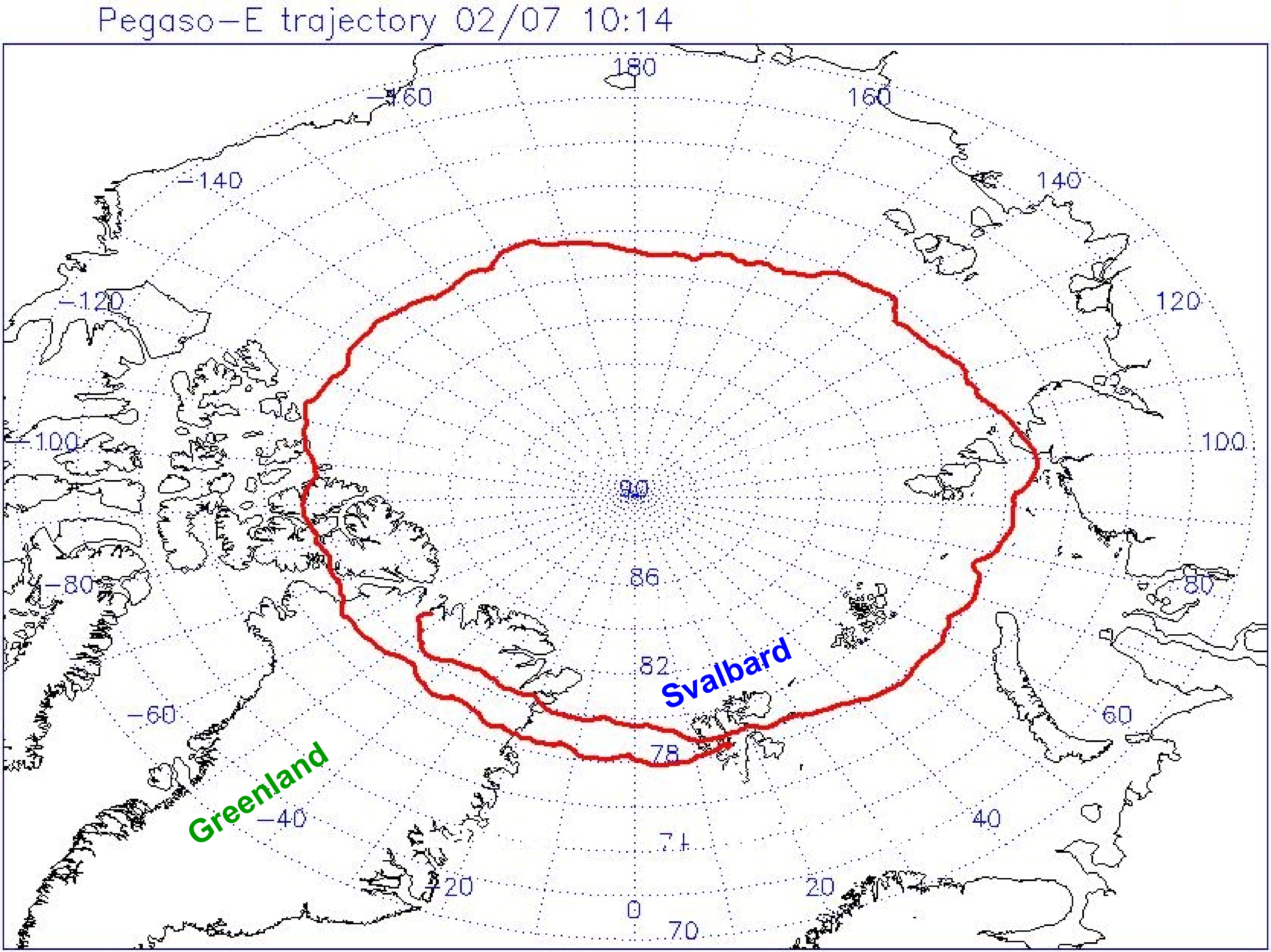
Mission

- The experiment is flown as a stratospheric balloon payload during the polar night, in a long duration flight launched from Longyearbyen (Svalbard). In this way it can access most of the northern sky in a single flight,
  - without contamination from the sun in the sidelobes
  - within a very stable (cold!) environment
  - Accumulating more than 14 days of integration at float (38 km altitude).
- Flight scheduled by ASI for end of 2016

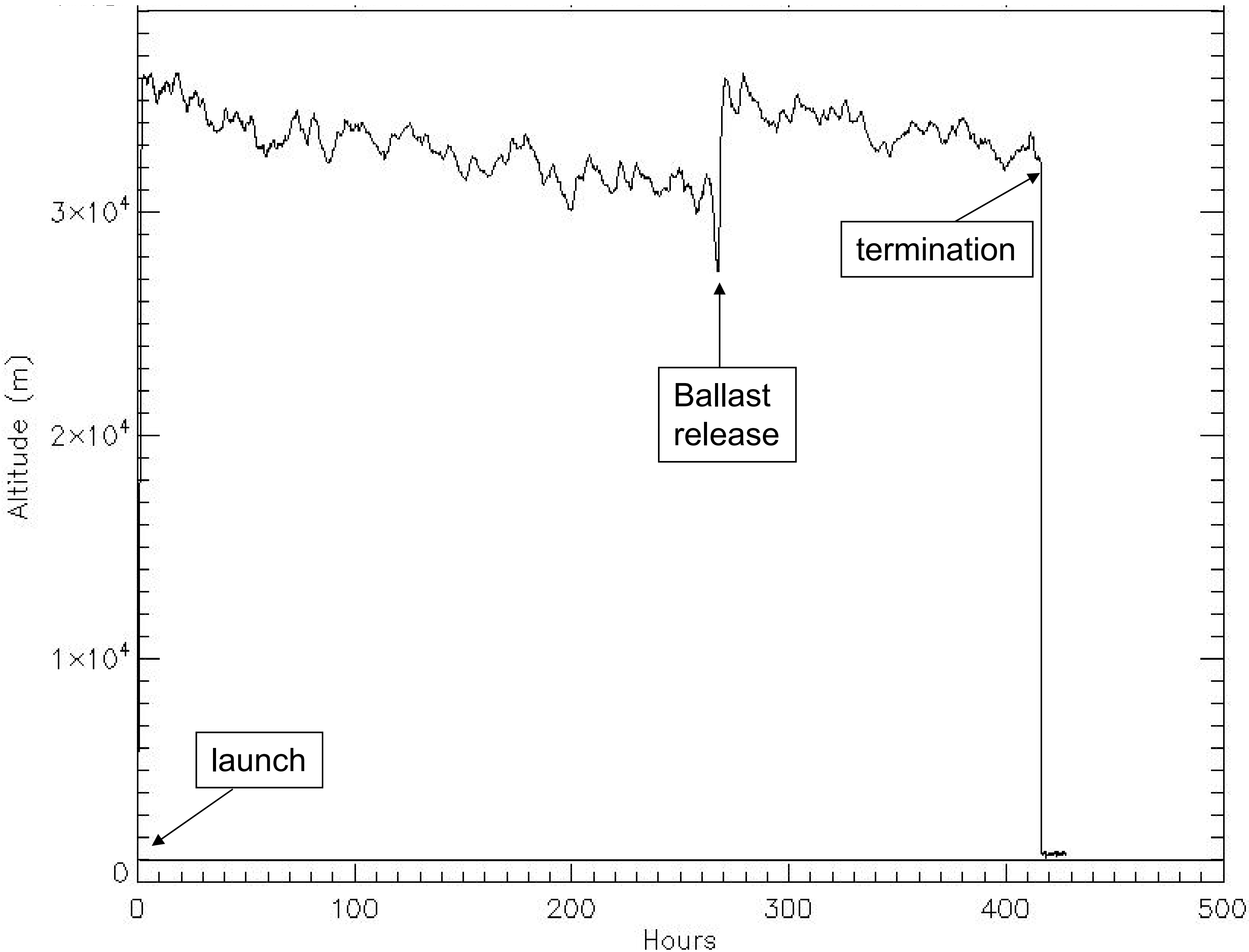


Bottom: Ground path of a small pathfinder test flight performed in January 2011, in the middle of the polar night. The eastward trajectory is evident.. **Top:** Launch of a heavy-lift balloon from the Longyearbyen airport (Svalbard Islands, latitude 78^{o}N).

See Peterzen, S., Masi, S., et al., "Long Duration Balloon flights development ", Mem. S. A. It., 79, 792-798 (2008) for further information on balloon flights from the Svalbard.

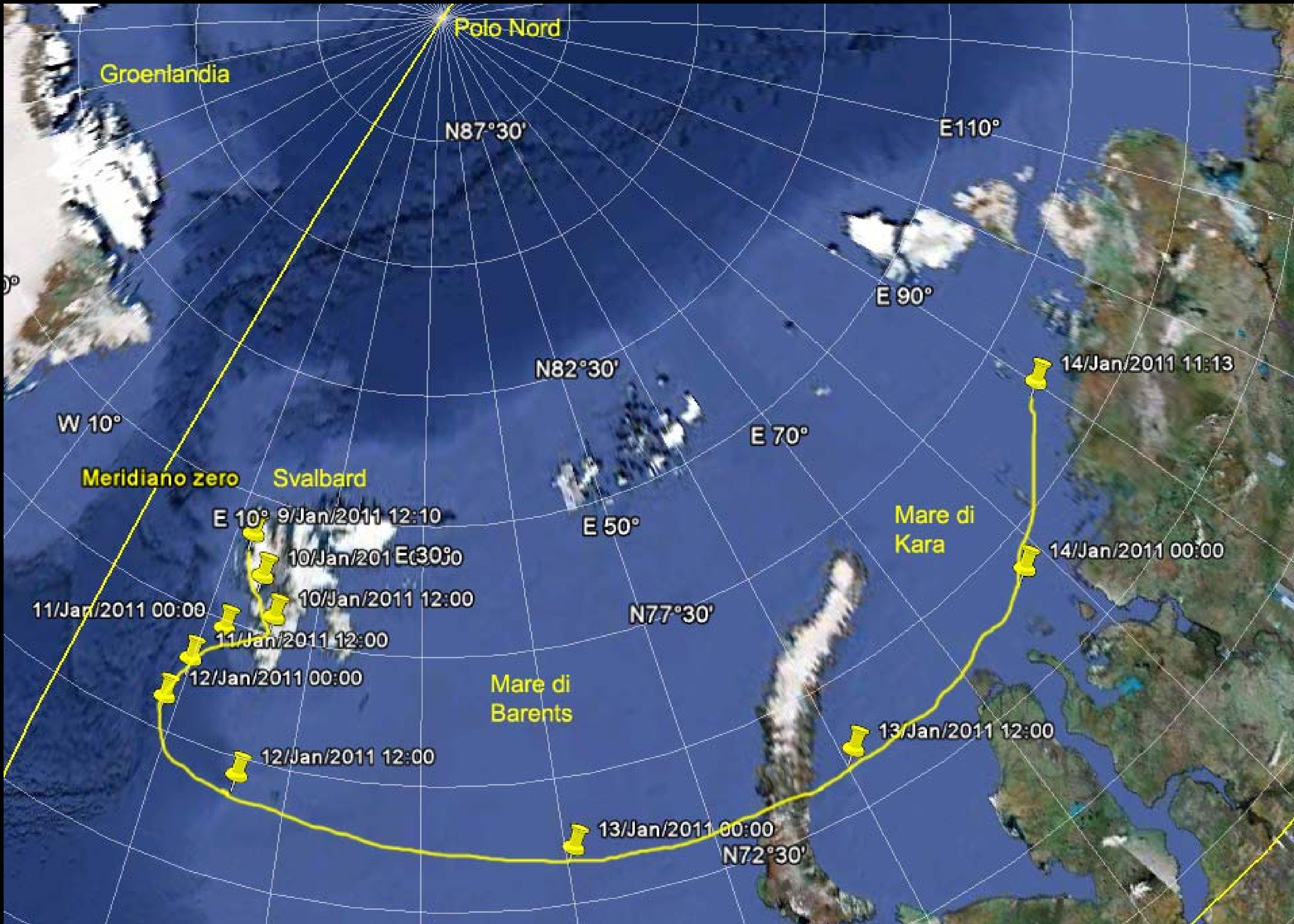

Pegaso-E trajectory 02/07 10:14
180
-160
160
-140
140
-120
120
-100
100
-80
80
-60
60
-40
40
-20
20
0
90
86
82
78
74
70
Svalbard
Greenland

sample flight profile



Night Time Long Duration Stratospheric Balloon Flights

1° LDB launched on Jan. 9°, 2011
From CNR Dirigibile Italia base
With support from ISTAR, AWIPEV
Ny Alesund, Svalbard Islands
5 days at 32 Km, Eastward path
Payload prepared by La Sapienza


Polo Nord
Groenlandia
N87°30'
E110°
E 90°
N82°30'
14/Jan/2011 11:13
W 10°
E 70°
Meridiano zero
Svalbard
E 10°
9/Jan/2011 12:10
E 50°
Mare di
Kara
10/Jan/201
E 30°
14/Jan/2011 00:00
10/Jan/2011 12:00
11/Jan/2011 00:00
N77°30'
11/Jan/2011 12:00
12/Jan/2011 00:00
Mare di
Barents
13/Jan/2011 12:00
12/Jan/2011 12:00
13/Jan/2011 00:00
N72°30'

Current Status

- LSPE is fully funded by the Italian Space Agency (Detector development co-funded by INFN)
- STRIP and SWIPE in due course of development, consistent with a 1st launch opportunity from Svalbard (78°N) in Winter 2016/2017.
- Baseline science expected from one flight is competitive with current gen B-mode experiments – and contributions to pol. foreground science will provide a great complement the CMB science.
- The schedule is tight and there are lots of things still to do…but we'll make it happen.

References

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- P. de Bernardis, et al. *"SWIPE: a bolometric polarimeter for the Large-Scale Polarization Explorer" Proc. SPIE* 8452, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VI, 84523F (October 5, 2012); doi: 10.1117/12.926569; astro-ph/1208.0282 (2012).
- M. Bersanelli, et al. *"A coherent polarimeter array for the Large Scale Polarization Explorer balloon experiment" Proc. SPIE* 8452, Proc. SPIE 8446, Ground-based and Airborne Instrumentation for Astronomy IV, 84467C (24 September 2012); doi: 10.1117/12.925688 ; astro-ph/1208.0164 (2012).
- P. de Bernardis, S. Masi, for the OLIMPO and LSPE teams, "*Precision CMB measurements with long-duration stratospheric balloons: activities in the Arctic*", In Astrophysics from Antarctica - IAU Symposium **288**, Proceedings of the Internatonal Astronomical Union, 8, 208-213 (2013) M. G. Burton, X. Cui & N. F. H. Tothill, eds., Cambridge. doi: 10.1017/S1743921312016894
- Peterzen, S., Masi, S., et al., *"Long Duration Balloon flights development ",* Mem. S. A. It., 79, 792-798 (2008)
- F. Nati, A. Benoit, P. de Bernardis, A. Iacoangeli, S. Masi, D. Yvon, *A fast and reliable star sensor for spinning balloon payloads*, Review of Scientific Instruments, **74**, 4169-4175, (2003)