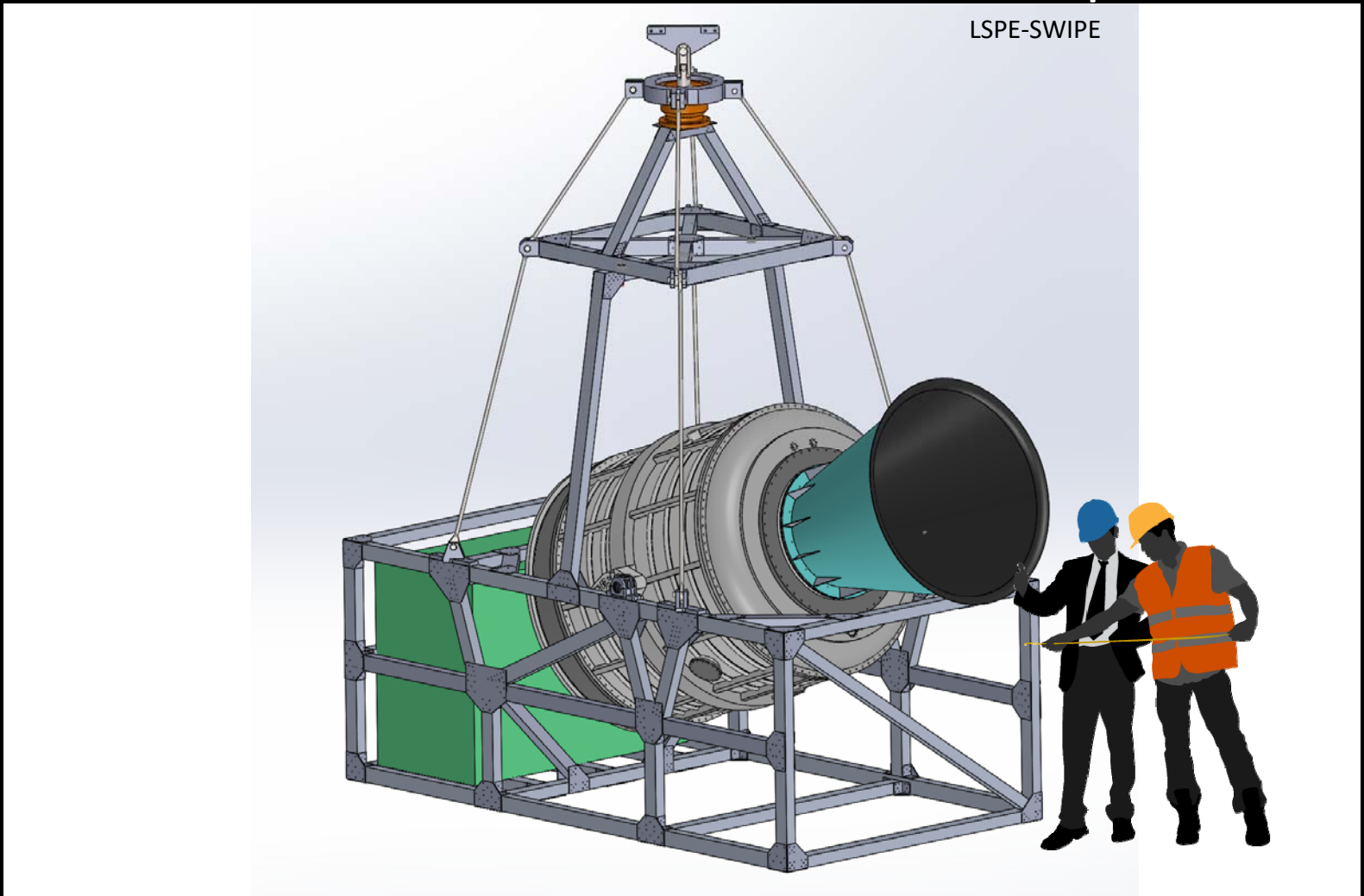
WP 3-6X1: Future balloon-borne CMB experiments



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For the WP3-6X1 team
Bologna, INAF-IAFS - 26/05/2017

Need for new balloon missions

- Planck-HFI detectors and scan stategy were tested by balloon payloads (Archeops, BOOMERanG)
- The same will be needed with CORE, to test:
  - **Operation** of very large arrays in low background conditions at high frequency; their **systematics** (cross-talk, cross-pol, spectral mismatch, …)
  - **Calibration** of very large arrays with real-sky sources
  - Fast scan of the sky for polarization, coverage of largest scales
  - HWP/no HWP systematics
  - Bolometric interferometry vs imager
- In case CORE is not selected:
  - If LiteBIRD goes, balloons are the only way to test high frequency and high multipoles (needed for cleaning lensing effects)
  - If only S4 goes, balloons will be the only way to monitor high frequency foregrounds at the level required for cleaning the CMB polarization survey (and measurements aimed at neutrino masses as well)

Need for new balloon missions

- We do need a 350 GHz polarization survey more sensitive than the Planck one (and higher frequency ones as well).
- That is *impossible* to get from the ground
- We need high-angular resolution for this survey to clean the lensing signal.
- On a balloon payload :
  - Possible to implement 1000x more detectors than Planck
  - 2-5x radiative background
  - 0.1x integration time
  - Integrate only on high latitude clean sky
  - 20x sensitivity possible
  - use polarization modulator (if needed)

Additional need for new balloon missions

- The environment is benign for low-frequency spectral distortions and should be studied for high-frequency spectral distortions.
- The strongest *anisotropic spectral distortions* can be tested with balloon-borne spectrometers :
  - SZ effect (need to cover the entire spectrum with high angular resolution, 3x wrt Planck, match of ground-based 10m class telescopes operating at 140 GHz)
  - CIB fluctuations, CO, C+ line tomography (these are CMB foregrounds, but are very important *per-se* to investigate the cosmological evolution of star formation and dust formation, also a start towards their use for NG)
  - Cosmological distortions detected through dipole distortion
- Techniques must be selected and optimized:
  - Effects of residual atmosphere
  - DFTS systematics
  - Spectrometer on-chip systematics

To be studied here

- Two possible targets for a balloon mission :
  - Polarization at high frequency
    - Study components separation needs
    - Feasibility of very large focal planes for polarization surveys; technology selection
    - Optimization of optical systems
    - Optimization of focal plane distribution of bands
    - HWP/noHWP
    - Feasibility of the related balloon-compatible cryogenics and readout
  - Anisotropic / Absolute spectral distortions
    - Define target distortions (different physics , dipole *vs* higher ℓ)
    - Spectrometer architectures comparison
    - Study effects of residual atmosphere and possible mitigation
    - Calibration strategies (sky vs internal)

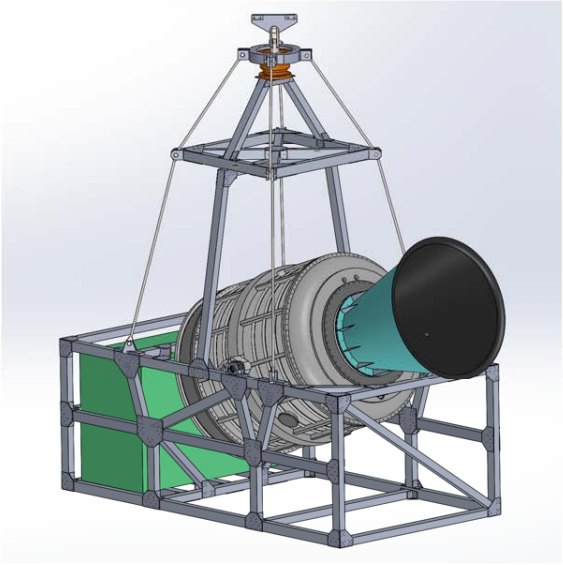
WP3-6X1: Future balloon borne CMB experiments
WP activities, first 6 months:

- Review of ISD polarization models and data
  - Science described in WP1, here focus on relevant cases for balloon-borne observations
- Review of CMB polarization models and data
  - Science described in WP1, here focus on the case of balloon-borne observations
- Review of spectral distortions of the CMB
  - Science described in WP1, here focus on effects relevant for balloon-borne observations
- Simulation of atmospheric effects in polarization and spectral emission/anisotropy
  - Again focus on the stratospheric emission and its fluctuations

WP3-6X1: Future balloon borne CMB experiments
Feasibility study document

Feasibility Study: Next-generation balloon-borne CMB experiments

COSMOS WP3-6X1, coordinated by Paolo de Bernardis, with contributions from Carlo Baccigalupi, Elia Battistelli, Carlo Burigana, Alessandro Buzzelli, Silvia Masi, Francesca Perrotta, Giovanni Signorelli, Franco Spinella, Davide Vaccaro, ...



Design of the LSPE payload

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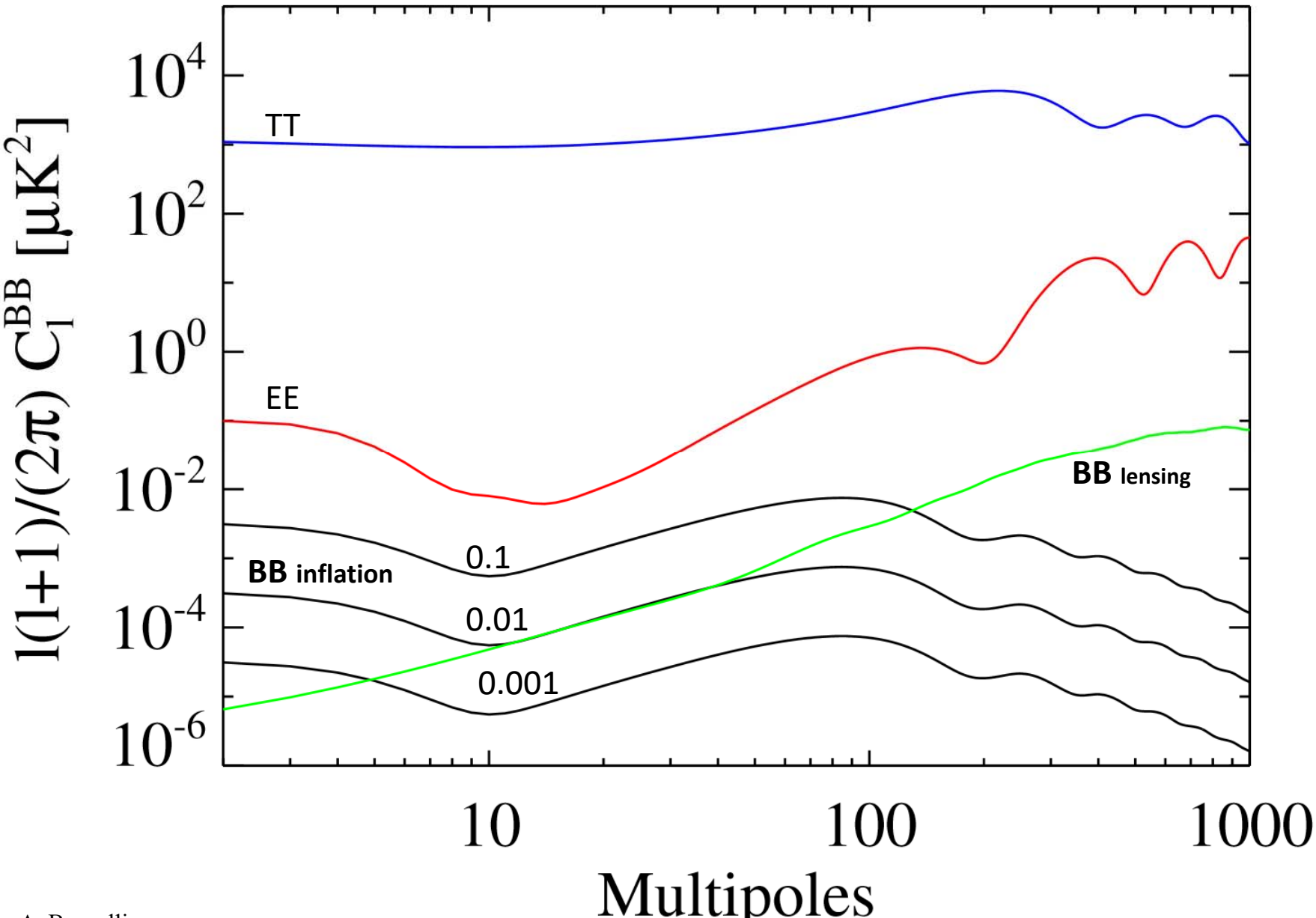
WP3-6X1: Future balloon borne CMB experiments
The CMB polarization Observable



WP3-6X1: Future balloon borne CMB experiments
The CMB polarization Observable: beam effects

Gaussian beam:

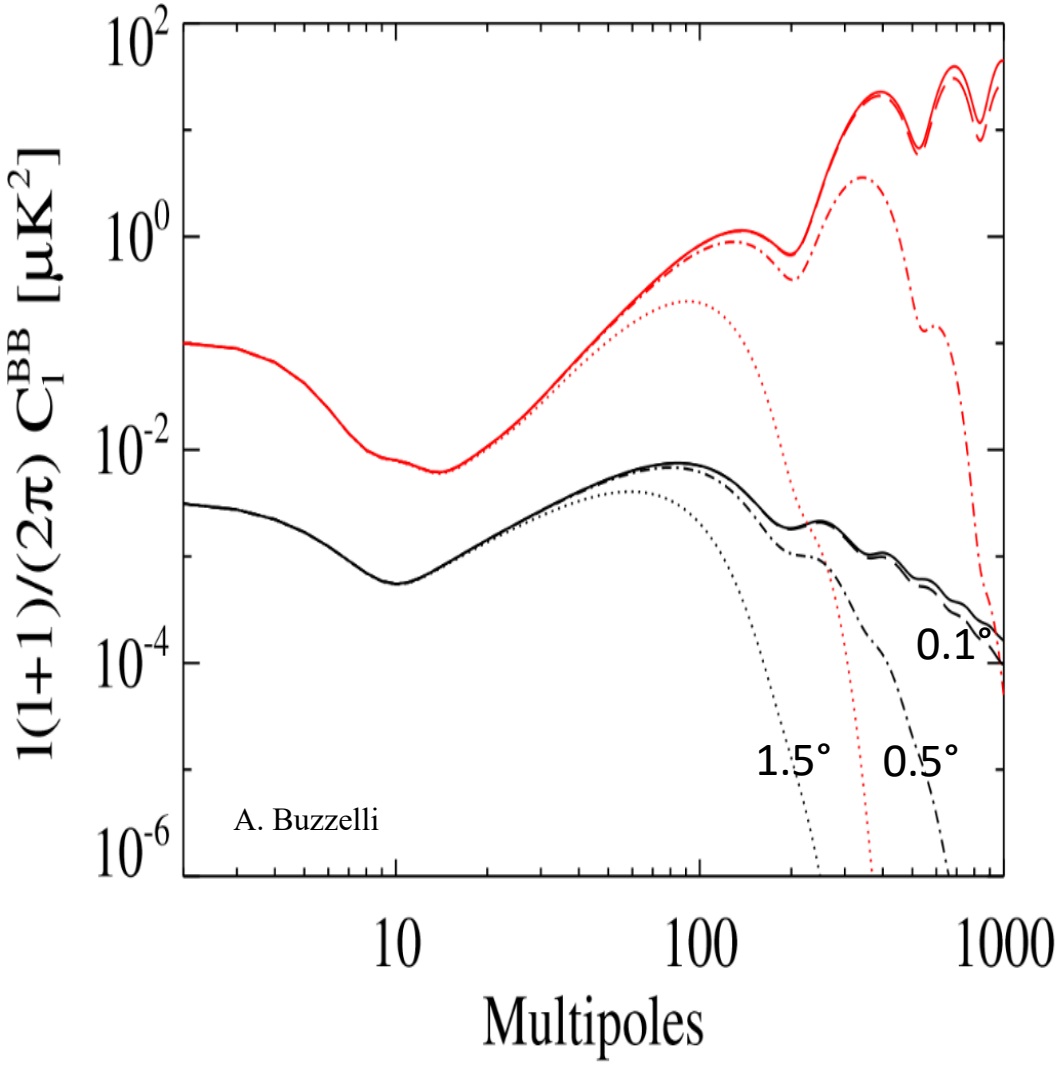
$$\sigma = 0.45\lambda/D$$

$$FWHM = 2\sqrt{\sigma 2 \ln 2}$$

Balloon-borne payloads do not suffer the same severe constraints on the size of the telescope as satellite payloads.

Telescopes up to 2 m diameter have already been flown on balloons (Pronaos by CNES, for example, about 20 years ago),

Perfectly possible to design gondolas accommodating 5m diameter primary mirrors (and the required mount and baffling).

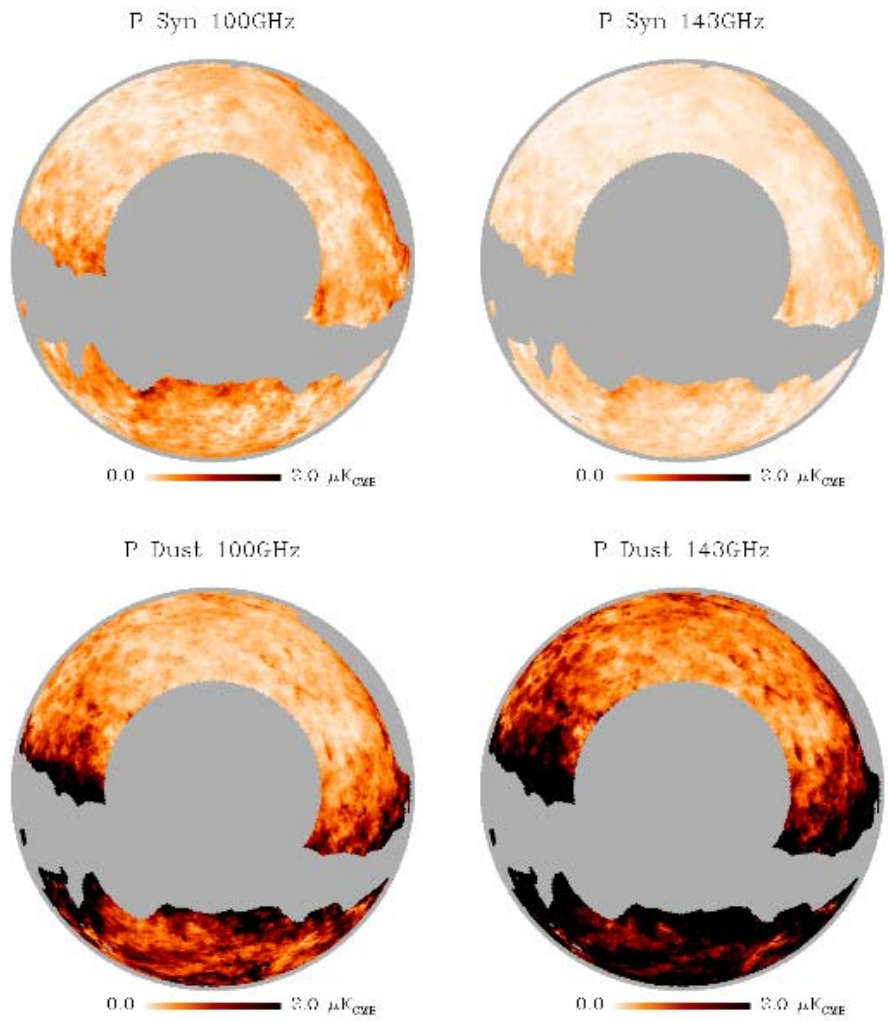


WP3-6X1: Future balloon borne CMB experiments
The CMB polarization Observable: sky coverage effects

- In a single flight a balloon-borne payload cannot observe the entire sky.
- Elevation should be kept constant during sky scans due to residual stratosphere.
- High elevations (balloon pickup) and low elevations (ground pickup) forbidden ($10^o < e < 70^o$)

Two sky scan strategies possible:

- focus on the best patch (say 30° x 30°) with targeted scans
- Spin the payload in azimuth and change elevation (once in many spins) to cover say 360° x 60°, possibly matched to the best sky.



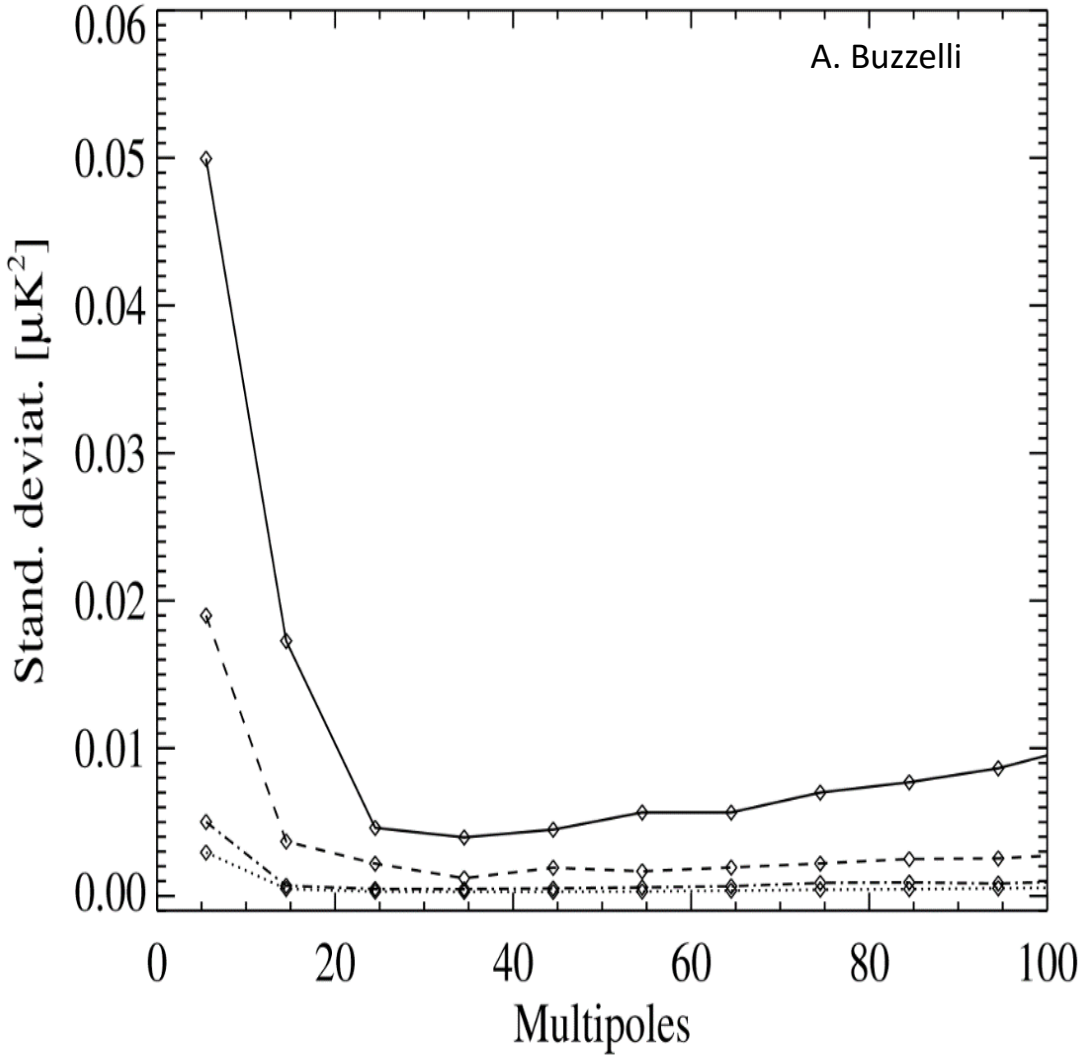
F. Piacentini

WP3-6X1: Future balloon borne CMB experiments
The CMB polarization Observable: sky coverage effects

Comparison of standard deviations on the angular power spectrum BB, due to cosmic/sampling variance related to incomplete sky coverage.

The spectra and their variation have been estimated by an implementation of the MASTER pseudo-C_l method, from 100 CMB-only (r=0.03) Monte-Carlo-simulated maps.

Different observed sky patches have been considered: 30° x 30° (solid line), 360° x 20° (dashed line), 360° x 45° (dashed-dotted line), 360° x 90° (dotted line).

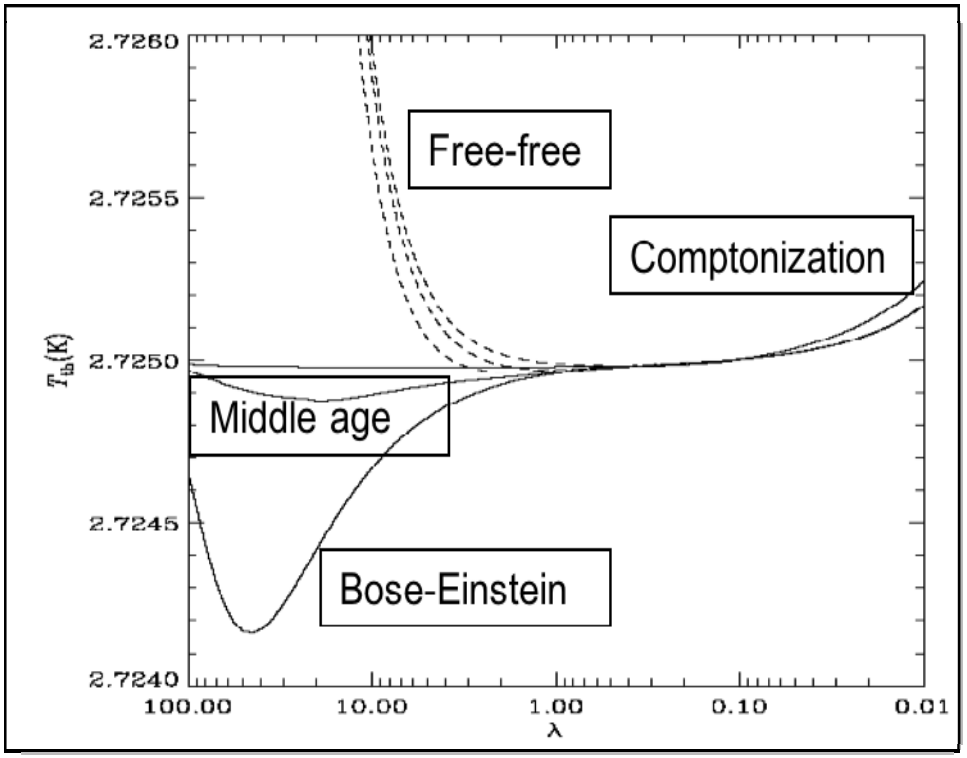


WP3-6X1: Future balloon borne CMB experiments
Systematics for balloon-borne polarimeters

	Systematic effect	Mitigation
Polarization	HWP emission	Low temperature HWP / Sky scan with HWP steady
	Wire grid emission, reflected by HWP	Low temperature WG, antireflection coating on HWP
	Differential transmission of HWP	Sky scan with HWP steady
	Differential reflection of HWP	Sky scan with HWP steady, antireflection coating HWP
	Differential phase shift by HWP	Sky scan with HWP steady, Spectral bandwidth optimization
	Slant incidence of rays on HWP	Scan with HWP steady
	Cross polar leakage	Lab. Calibration
	Absolute polar angles calibration	Lab Calibration / Moon / Crab
	Thermal fluctuations of HWP	Scan with HWP steady, thermal link HWP – cryogen
Optics	Main beam uncertainty	Laboratory calibration / observation of planets
	Main beam ellipticity	Reduced in multimode system; lab. and flight calibration
	Sidelobes pickup of sky signal	Large shields, cold stop
	Sidelobes pickup of Earth and Balloon	Large shields, cold stop
Pointing	Pointing error	ACS Sensors
	Pendulation and atmospheric emission	Not polarized / orthogonal detectors
Detectors	Gain uncertainty	Calibration on anisotropy
	Gain stability	Calibration on anisotropy
	1/f noise	AC bias / T stabilization / continuous rotation of HWP
	Correlated thermal drift	TES
	Non linearities	Compensation on scans
Foregrounds	Polarized emission from ISD	Use high frequency monitors
	Polarized emission from synchrotron	Use low frequency monitors
	Atmosphere	Not polarized / use high frequency monitors

WP3-6X1: Future balloon borne CMB experiments

Spectral distortions of the CMB: the observable



CMB distorted spectra as functions of the wavelength λ (in cm) in the presence of a late energy injection with $\Delta\varepsilon/\varepsilon_i \simeq 4y = 5 \times 10^{-6}$ plus an early/intermediate energy injection with $\Delta\varepsilon/\varepsilon_i = 5 \times 10^{-6}$ occurring at the "time" Comptonization parameter $y_h = 5, 1, 0.01$ (from the bottom to the top; in the figure the cases at $y_h = 5$ – when the relaxation to a Bose-Einstein modified spectrum with a dimensionless chemical potential given, in the limit of small distortions, by $\mu \simeq 1.4\Delta\varepsilon/\varepsilon_i$ is achieved – and at $y_h = 1$ are extremely similar at short wavelengths; solid lines) and plus a free-free distortion with $y_B = 10^{-6}$ (dashes). From Burigana et al. (2004), NAR 48, 1107–1117.

WP3-6X1: Future balloon borne CMB experiments
Spectral distortions of the CMB: the observable

EFFECT	EPOCH / REDSHIFT	MONOPOLE TYPE OF DISTORSION Main (Secondary)	ANISOTROPIES	FAVOURITE FREQUENCY	NOTE: POTENTIAL IMPLICATIONS
Primordial magnetic fields	Continuous, mainly early	Parameter dependent Current upper limits from FIRAS for B ~ 10 nG (y much lower)	Yes (All modes and cross-correlations for stochastic background of PMF)	All	In any case, upper limits on parameters
Cooling by ordinary cooling matter	Continuous, mainly early	$\mu \sim -3\times10^{-9}$ ($y \sim -6\times10^{-10}$)	No	All	
Decaying or annihilating relic particles	Continuous, with z corresponding to t_D Ex.: $z\sim 10^8$-10^9 (e-p) $z\sim 10^4$-10^5 (DM)	Parameter dependent	No (Direct) Yes (Undirect effect)	All spectral shapes strongly dependent on details	In any case, constraints on parameters difficult to achieve with other methods
Topological defects	Early in origin	Parameter dependent	Yes	All	
Black holes evaporation	Continuous, mainly late	Model dependent	Yes	Mainly high and low	

Burigana + Battistelli

WP3-6X1: Future balloon borne CMB experiments

Spectral distortions of the CMB: the observable

EFFECT	EPOCH / REDSHIFT	MONOPOLE TYPE OF DISTORSION Main (Secondary)	ANISOTROPIES	FAVOURITE FREQUENCIES	NOTE: POTENTIAL IMPLICATIONS
Primordial non-Gaussianity	Early in origin	μ T correlations (y T correlations to be better studied)	Yes	All, but likely detectable at high	
Dissipation of acustic peaks	Continuous, mainly early, Bulk at $z \sim 10^6 - 10^5$	Standard $\mu \sim 3\times10^{-9}$ Theoretical upper limit $\mu \sim 10^{-7}$ $y \sim 6\times10^{-10}$	No, but coupled to very small scales perturbations	All	Difficult to detect, but marginally detectable with not too expensive projects although only for models with high small scale power
Cosmological recombination lines	$z \sim 10^3$	10^{-9}	No (?)	All	
Cosmological reionization	Late, continuous (twice?) Bulk at $z < 10$	$y \sim$ some$\times10^{-6}$ (lower limit $> 10^{-7}$) $y_{FF} \sim 10^{-9} - 10^{-7}$ (lower limit 2×10^{-10} at 0.1 GHz; 10^{-9} at 30 GHz)	Yes, and very important	All, but likely more detectable at high for y Low for FF	Great chance of discovery with not too expensive projects Synergies with radio projects for FF (favourite frequencies around few GHz)

Burigana + Battistelli

WP3-6X1: Future balloon borne CMB experiments
Spectral distortions of the CMB: the observable

EFFECT	EPOCH / REDSHIFT	MONOPOLE TYPE OF DISTORSION Main (Secondary)	ANISOTROPIES	FAVOURITE FREQUENCIES	NOTE: POTENTIAL IMPLICATIONS
Diffuse SZ	z < few	$y \sim 10^{-7} - 10^{-6}$	Yes	More prominent at high Complementarity relevant	Related cosmological reionization
Large scale structures shocks	z < few	$y \sim 10^{-6}$	Yes	More prominent at high Complementarity relevant	Related to cosmological reionization
AGN & early star feedback	z ~ few - 10	$y \sim 10^{-6}$	Yes	More prominent at high Complementarity relevant	Likely, main astrophysical sources of cosmological reionization

Burigana + Battistelli

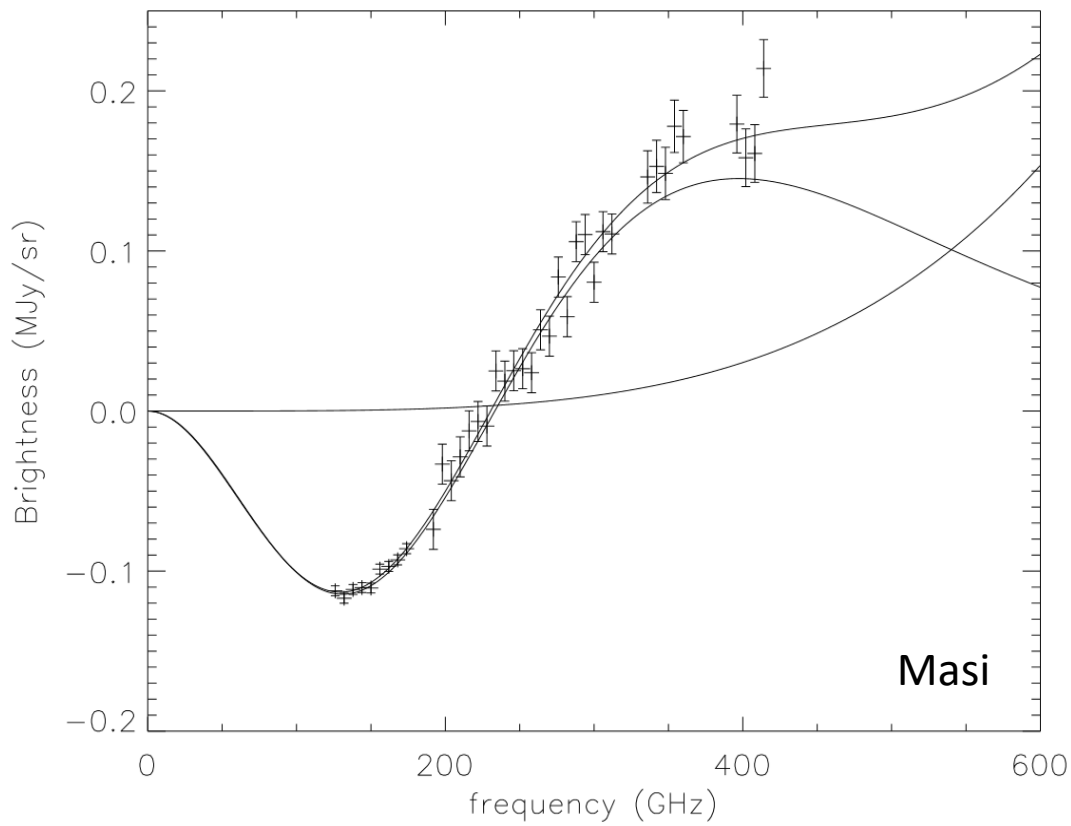
WP3-6X1: Future balloon borne CMB experiments
Spectral distortions of the CMB: instrument approach

- Coherent receiver at low frequency (<75 GHz)
- FTS at high frequency (>75 GHz)
- Always compare to cryogenic reference BB

$$\sigma^2 = \frac{\int_{BW} NEP^2 d\nu}{2\,T}$$

$$\sigma^2 = 0.61\,\frac{\int_{BW} NEP^2 d\nu}{\Delta\nu\,T}$$

Example of calculation for anisotropic spectral distortions (SZ): 3 hours of observation of a y=0.001 cluster with a balloon-borne photon-noise limited spectrometer



WP3-6X1: Future balloon borne CMB experiments

Example of calculation for isotropic spectral distortions and their detectability:

4.5 km altitude

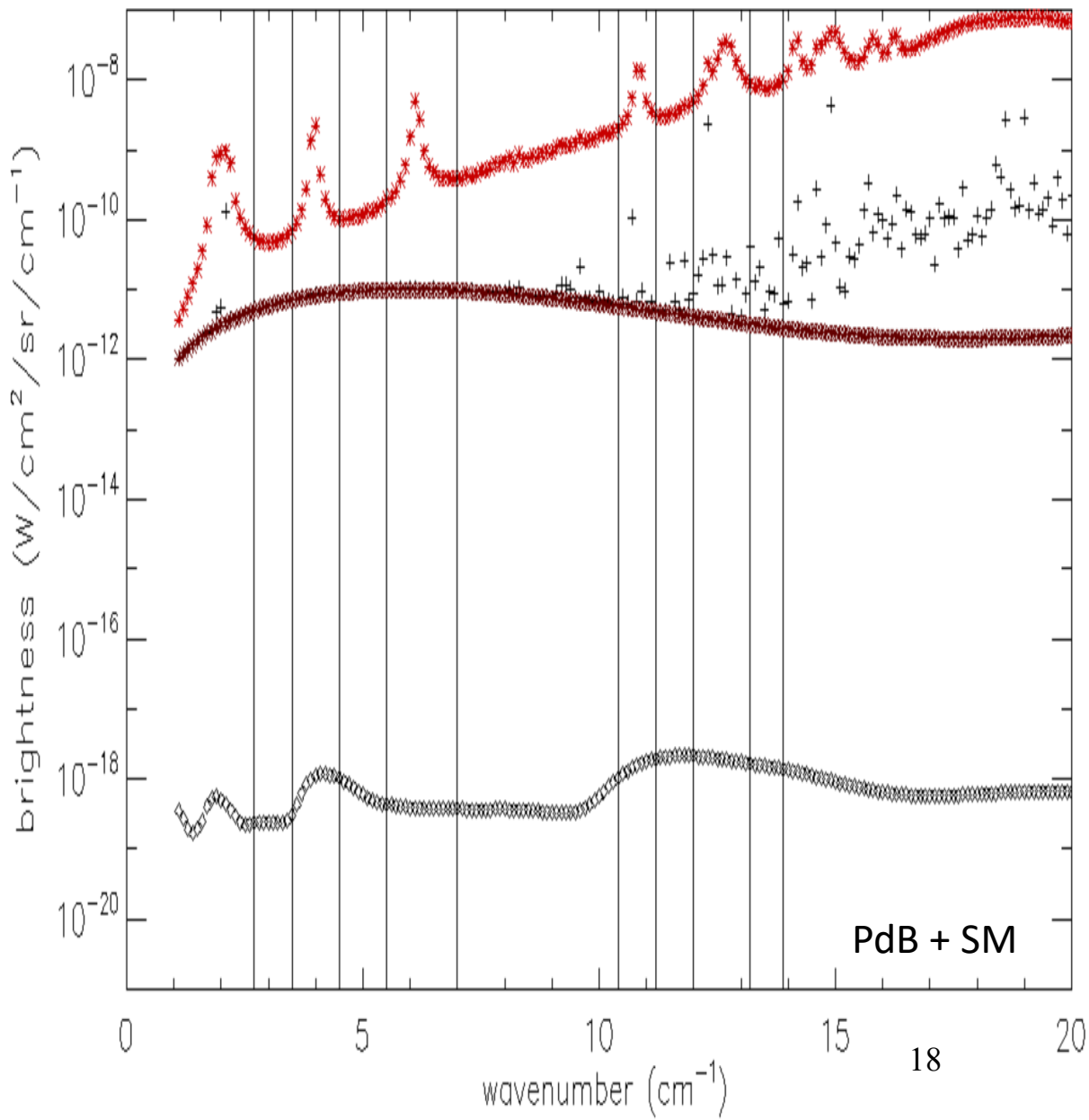
resolution = 2.9997900 GHz
dust normalization = 0.00010000000
NEP = 1.5000000e-016 W/sqrt(Hz)
integration time = 46720.0 days dets
noise per resolution bin = 1.4401668e-020 W/cm2/sr/cm-1
# of used bins 66
# of simulations 101
cmb/model = 0.99999522 +/- 2.1759542e-009
DH/model = 15.356816 +/- 0.0051037992
atmos/model = 1.0000000 +/- 4.9741719e-012
dust/model = 0.99942195 +/- 1.0008435e-007
refe/model = -1.0000230 +/- 6.5021025e-009

45 km altitude

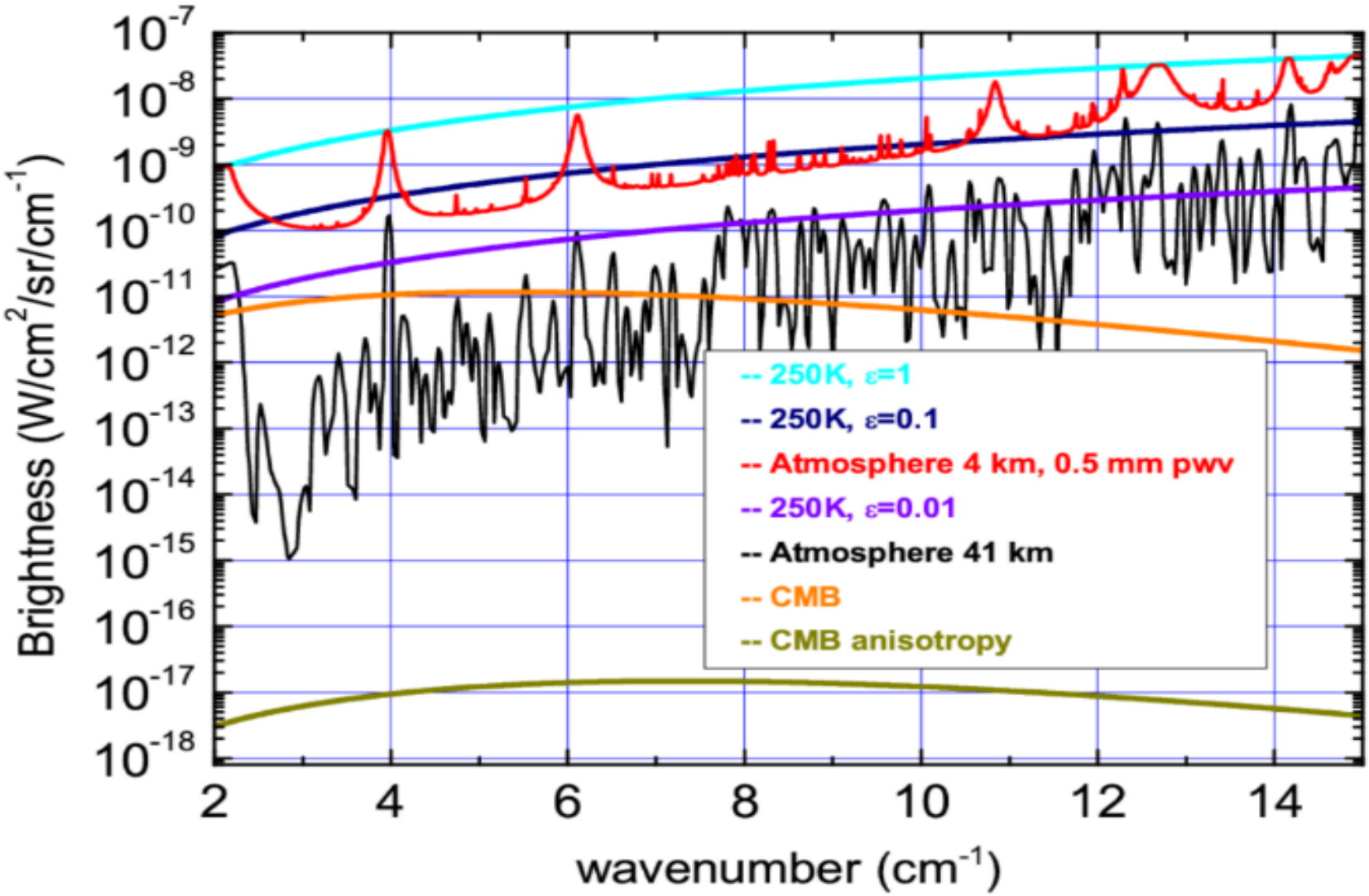
NEP = 1.5000000e-017 W/sqrt(Hz)
integration time = 3840.00 days dets
noise per resolution bin = 5.0234101e-021 W/cm2/sr/cm-1
# of used bins 66
# of simulations 101
cmb/model = 1.00000 +/- 0.000000
DH/model = 1.06983 +/- 0.00150483
atmos/model = 1.00000 +/- 0.000000
dust/model = 1.00000 +/- 4.37440e-008
refe/model = -1.00000 +/- 0.000000

space

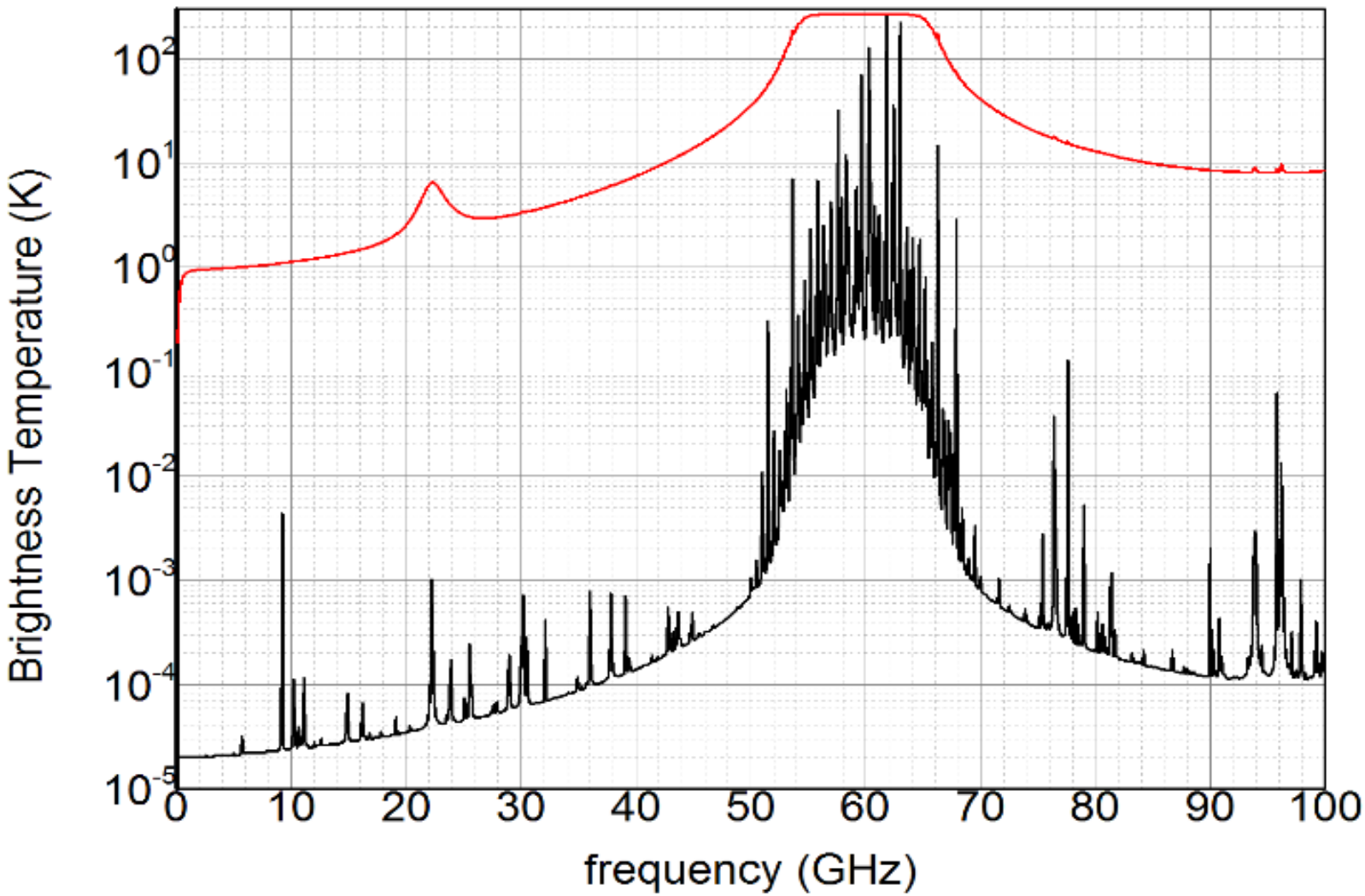
resolution = 2.9997900 GHz
dust normalization = 0.000100000
NEP = 1.5000000e-017 W/sqrt(Hz)
integration time = 46720.0 days dets
noise per resolution bin = 1.4405994e-021 W/cm2/sr/cm-1
# of simulations 101
cmb/model = 1.0000000 +/- 4.6543897e-011
DH/model = 1.0382382 +/- 0.00022717541
dust/model = 1.0000000 +/- 3.6049486e-010
refe/model = -0.99999999 +/- 2.0604789e-010



WP3-6X1: Future balloon borne CMB experiments
Atmospheric Effects: average brightness

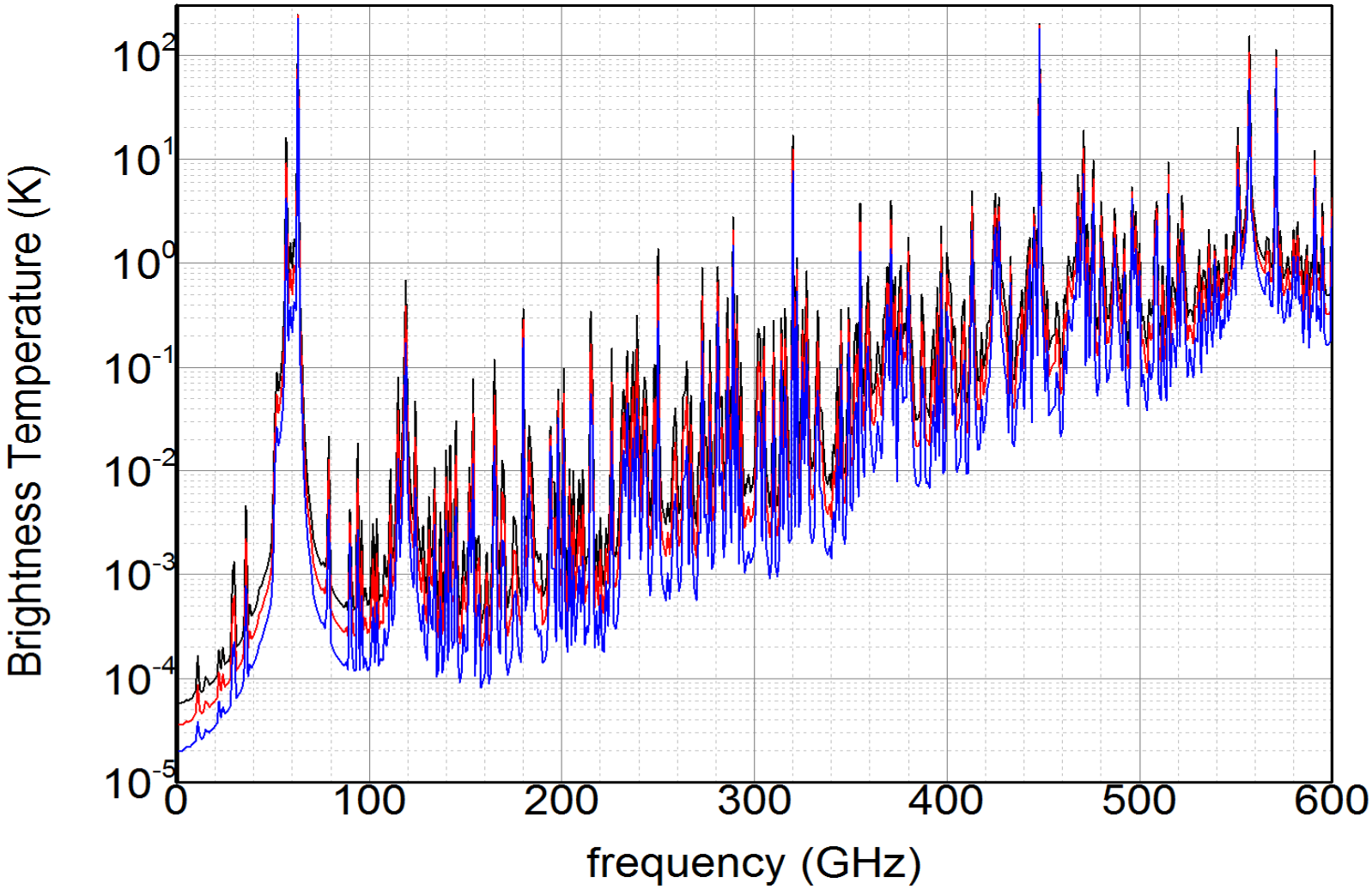


WP3-6X1: Future balloon borne CMB experiments
Atmospheric Effects: average brightness



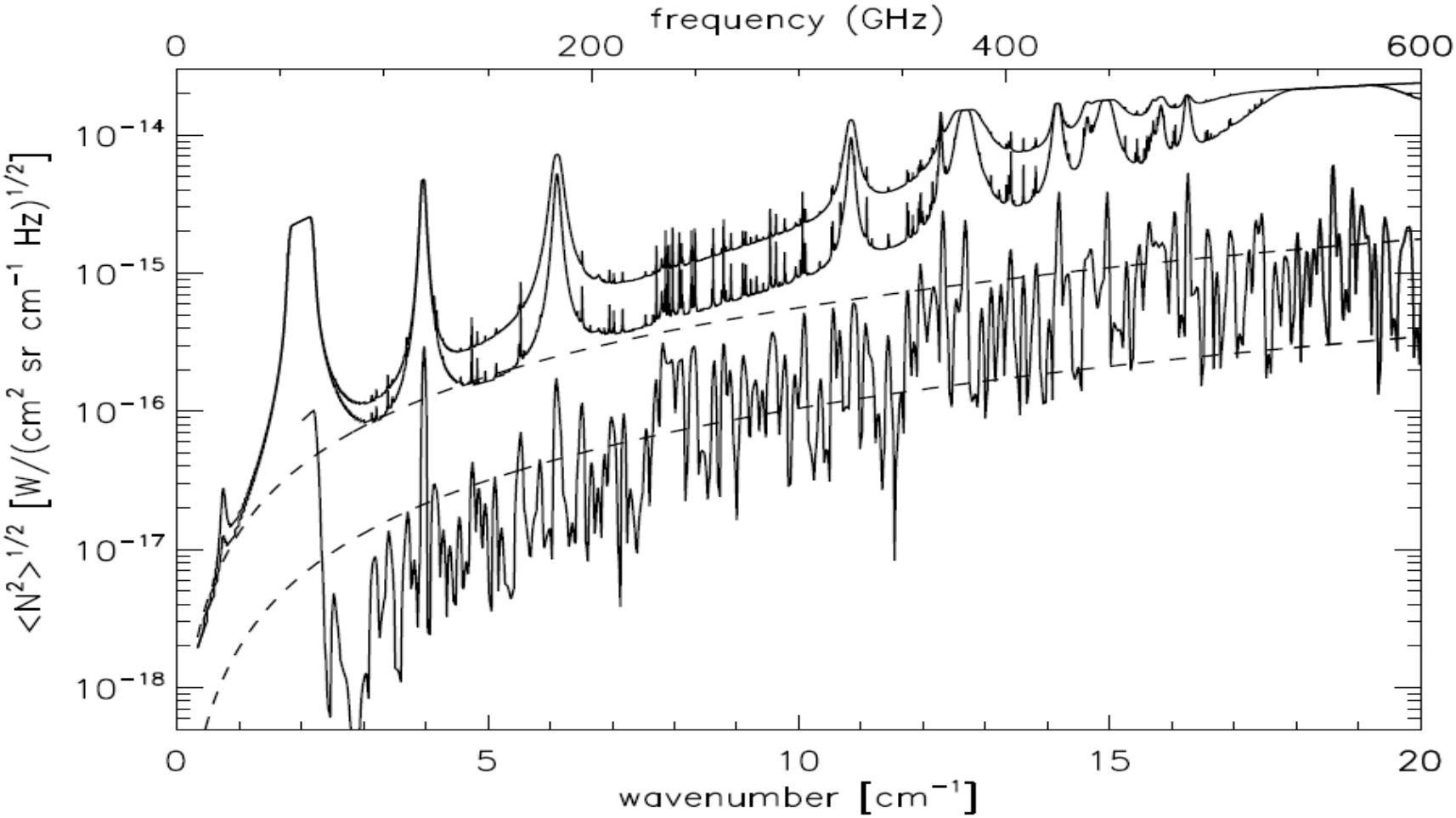
WP3-6X1: Future balloon borne CMB experiments

Atmospheric Effects: variation with altitude



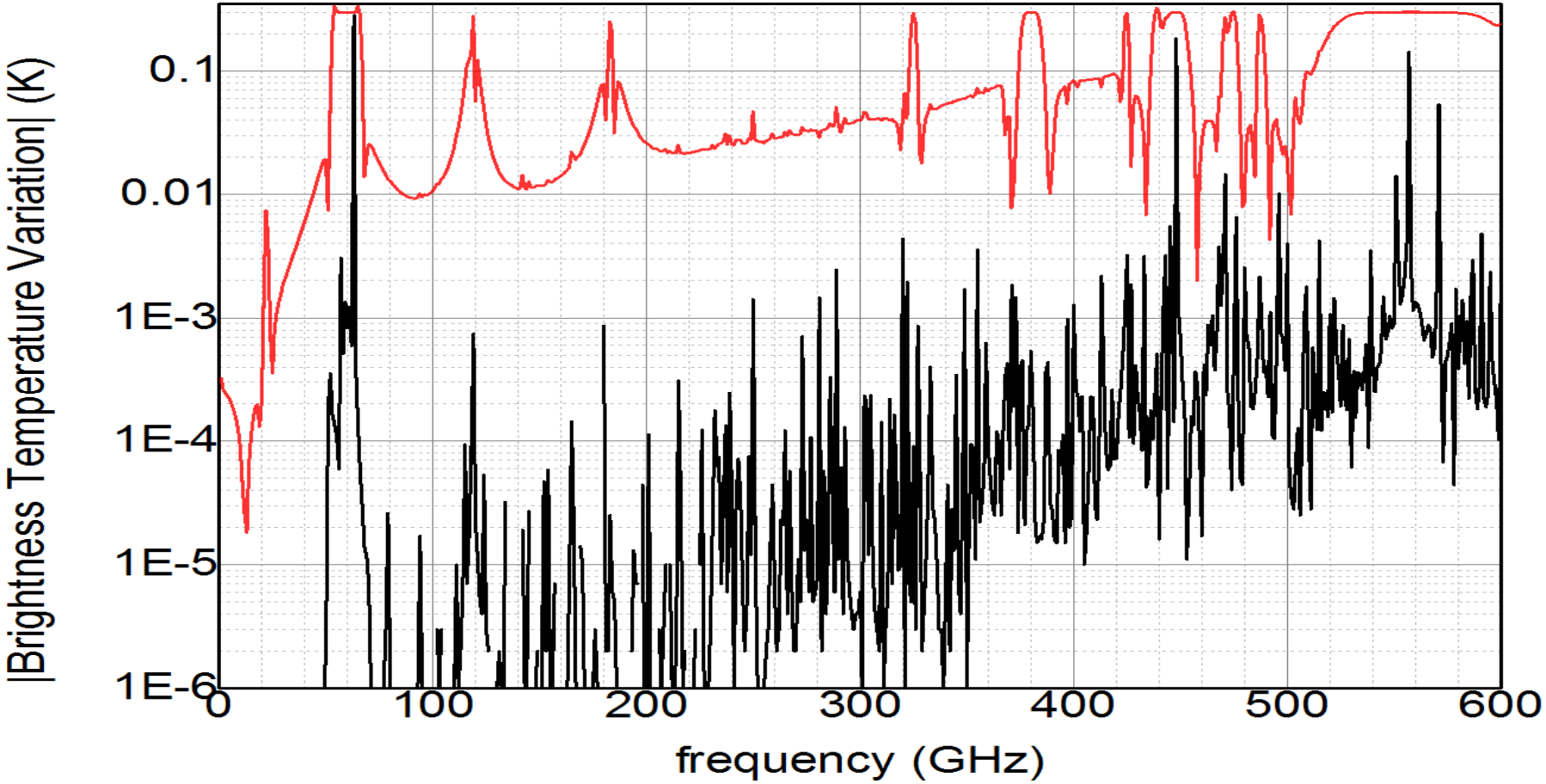
Stratospheric emission at different altitudes for a 45° elevation slant path to space starting at 35km (black), 38 km (red), 45 km (blue) of altitude. In the range of altitudes accessible by stratospheric balloons the brightness of the residual stratosphere does not change very significantly with altitude.

WP3-6X1: Future balloon borne CMB experiments
Atmospheric Effects: photon noise



Atmospheric brightness fluctuations for a ground based site with 2mm PWV (top line), for a ground-based site with 0.5mm PWV (middle line) and for observations on a stratospheric balloon (lower line). Only quantum fluctuations of an otherwise perfectly stable atmosphere have been considered. The dashed lines refer to the fluctuations produced by a 240K thermal emitter with 2% (upper) and 0.1% (lower) emissivity. The integration time required for a given S/N scales as the square of the fluctuation level plotted here.

WP3-6X1: Future balloon borne CMB experiments
Atmospheric Effects: 0.1% ΔT



Absolute value of the brightness fluctuations produced by a 0.1% increase of the thermodynamic temperature of the atmospheric gases. Red: 45° slant path to space starting at 4500m osl. Black: 45° slant path to space starting at balloon altitude (stratospheric balloon).

WP3-6X1: Future balloon borne CMB experiments Foregrounds relevant for stratospheric balloons

- Diffuse Galactic Foregrounds are dominated by thermal dust and synchrotron which, at degree and super-degree angular scale, are comparable or dominant with respect to cosmologically relevant levels of B-modes from cosmological gravitational waves (see section 1, scientific motivations).
- The minimum of the emission, in the few regions where both of them are detected with high confidence, varies substantially in the interval between 60 and 90 GHz, with levels corresponding to a cosmological tensor to scalar ratio comparable of the order of 0.1 (Krachmalnicoff et al., 2016, A&A 588, A65).
- Operating and future B-mode foreground experiments are driven by multi-frequency technology, with robust foreground monitor channels in order to achieve effective subtraction at frequencies corresponding to the foreground minimum. This requires stratospheric balloons to measure dust polarization at high frequency.
- Despite of the vast impact that polarization measurements at 353 GHz by Planck are having, do not provide an high frequency foreground monitor at the required accuracy for efficient subtraction (Planck Intermediate Results, 2016, A&A 586, A133).
- At the same time, recent findings by Planck reveal evidence for multi-component nature of the dust component, resulting in a varying spectral index with frequency and sky location, inducing a de-correlation of the pattern of the dust component at different frequencies. New multi-frequency datasets are necessary in particular at high frequency and in the near future, beginning with those of the LSPE-SWIPE experiment, in order to assess the real complexity of the thermal dust component.
- Next-generation experiments should multiply the high frequency coverage in a way which is studied in the next step of this study.

WP3-6X1: Future balloon borne CMB experiments
Implementation Options

Polarization

- Immediate (?!?) future : LSPE-SWIPE
- Medium term: re-fly LSPE-SWIPE with single-mode detectors (8800) in the focal plane
- Long term: to be studied, depends on the satellite developments (remember, currently only the 30cm telescope of LiteBIRD is likely to fly by 2028).

Spectral Distortions

- Immediate (?!?) future : OLIMPO for anisotropic distortions (SZ at similia)
- Medium term: balloon for isotropic distortion measurement (low-f, high-f, to be studied)
- Long term: to be studied, possible to increase telescope size to 5-6m (great non-gaussianity machine, foregrounds imager, etc etc)