CMB spectral distortions from Antarctica with COSMO: performance forecast

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COSMO collaboration: http://cosmo.roma1.infn.it

SAPIENZA
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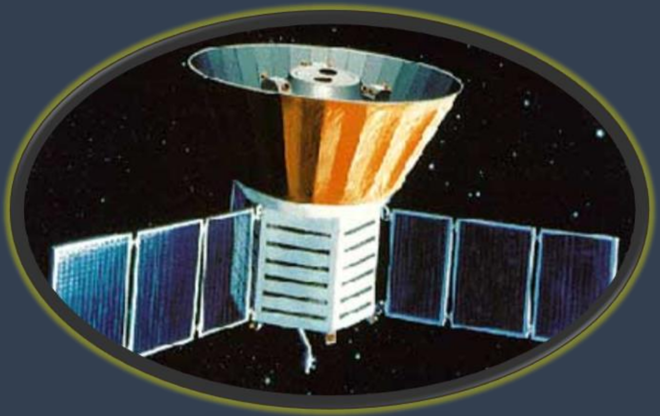
CMB spectral distortions

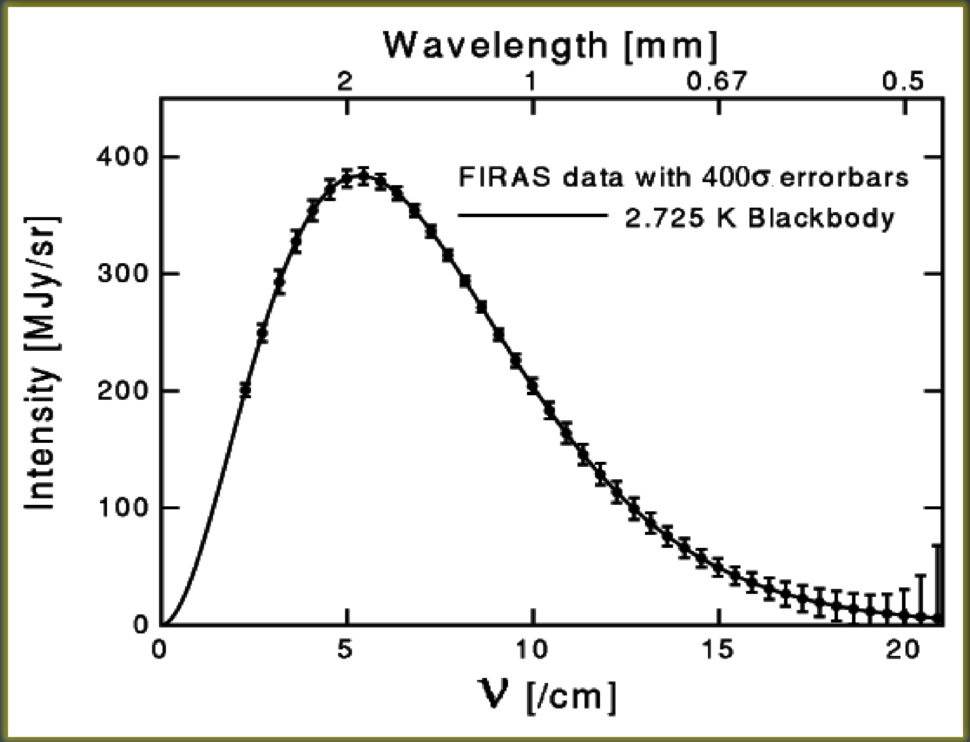
A direct look at the early Universe (at *Recombination* phase, 380000 years after the Big Bang):

- Almost a perfect blackbody at $T = 2.725K$
- Temperature Anisotropies $\Delta T/T = 10^{-5}$

Nobel Prize
in Physics 2006



COsmic Background Explorer (COBE, 1989)
Far InfraRed Absolute Spectrometer (FIRAS)
&
Differential Microwave Radiometer (DMR)

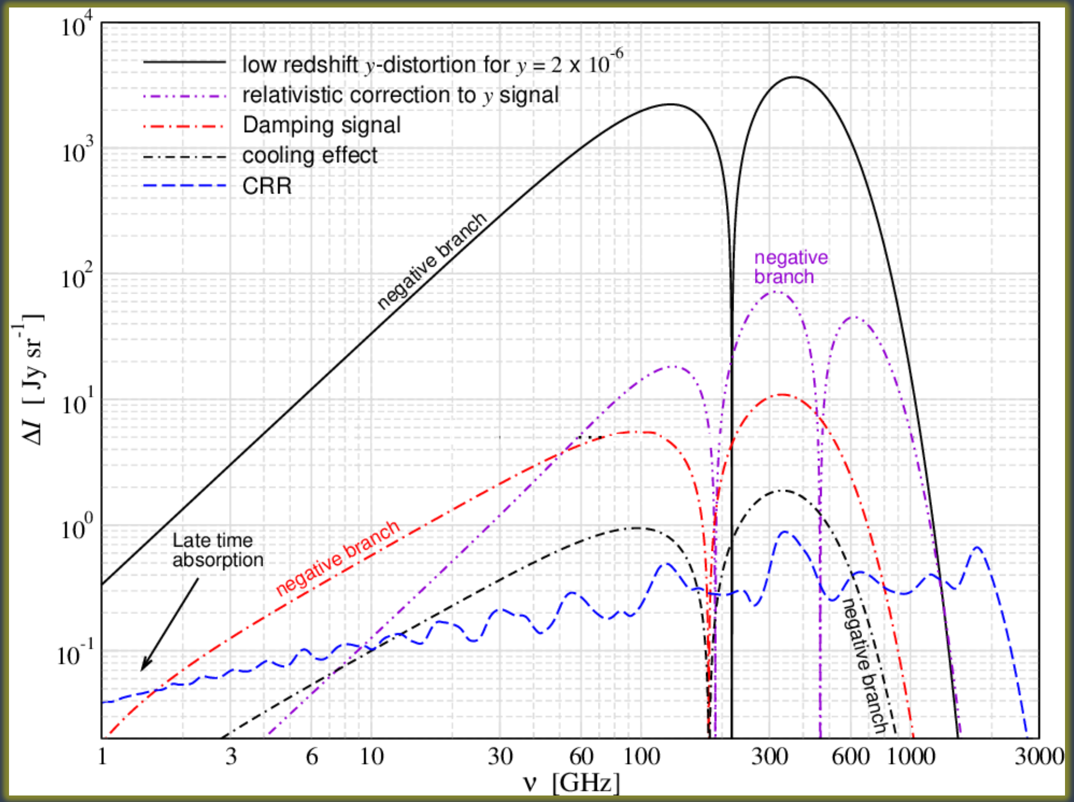


CMB spectral distortions

J. Chluba (2016)

Departures from the blackbody shape are predicted by the standard ΛCDM model (energy injection/ extraction or photon production/ destruction):

- Reionization
- Structure formation shocks
- Adiabatic cooling of baryons
- Damping of small-scale fluctuations
- Sunyeav-Zel'dovich effect (<u>anisotropic</u>)
- Cold dark matter annihilation
- Cosmological recombination radiation
- Particle Decaying



Spectral Distortions carry <u>complementary</u> information about processes in the early-Universe!

But also about <u>fundamental physics</u> !

CMB spectral distortions

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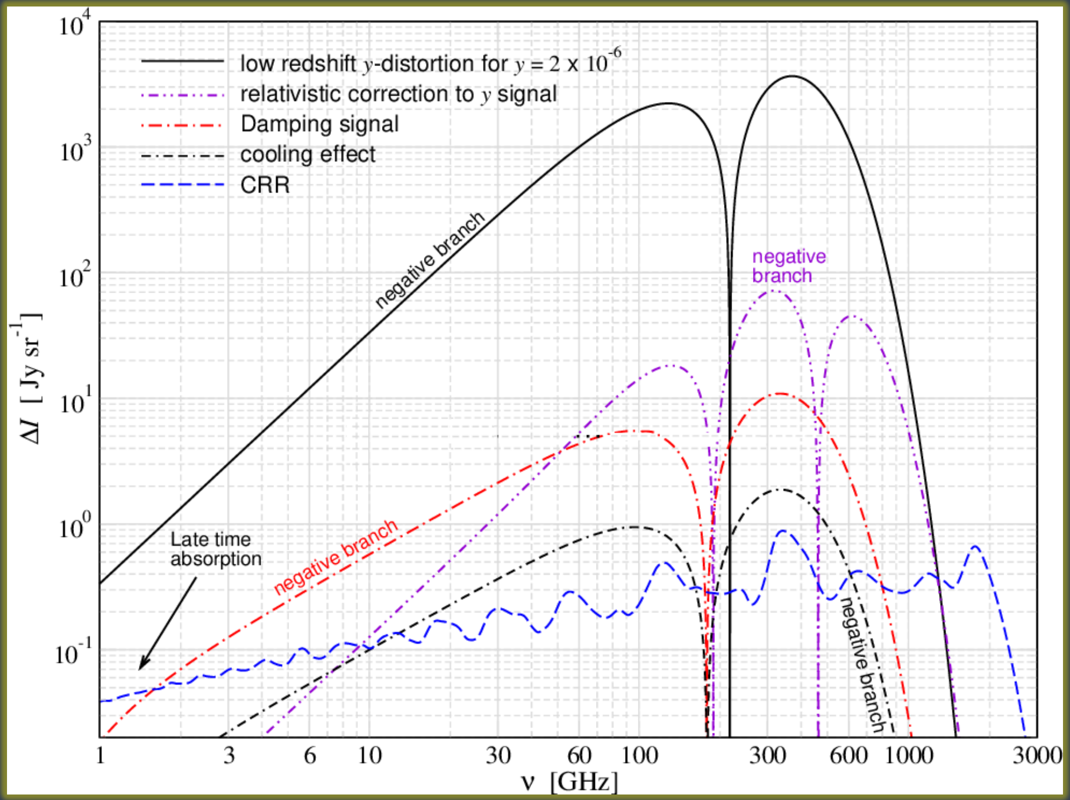

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(J.C. Hill 2015)

$$|y| \sim 1.77 \cdot 10^{-6}$$

$$|\mu| \sim 2 \cdot 10^{-8}$$

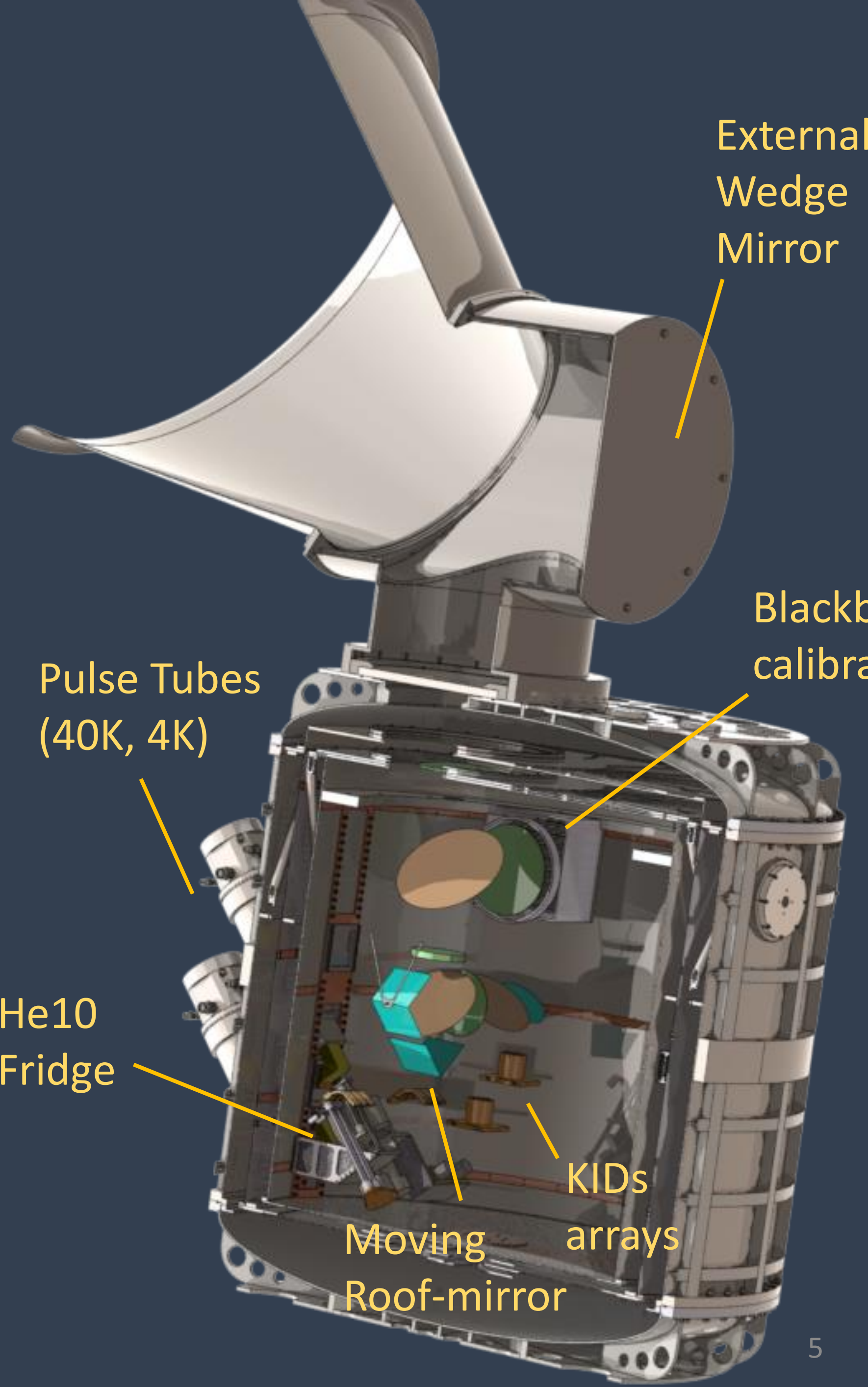
Expected Parameters from ΛCDM

$$|y|, |\mu| < 10^{-5}$$

Current upper-limit (FIRAS 1989!)

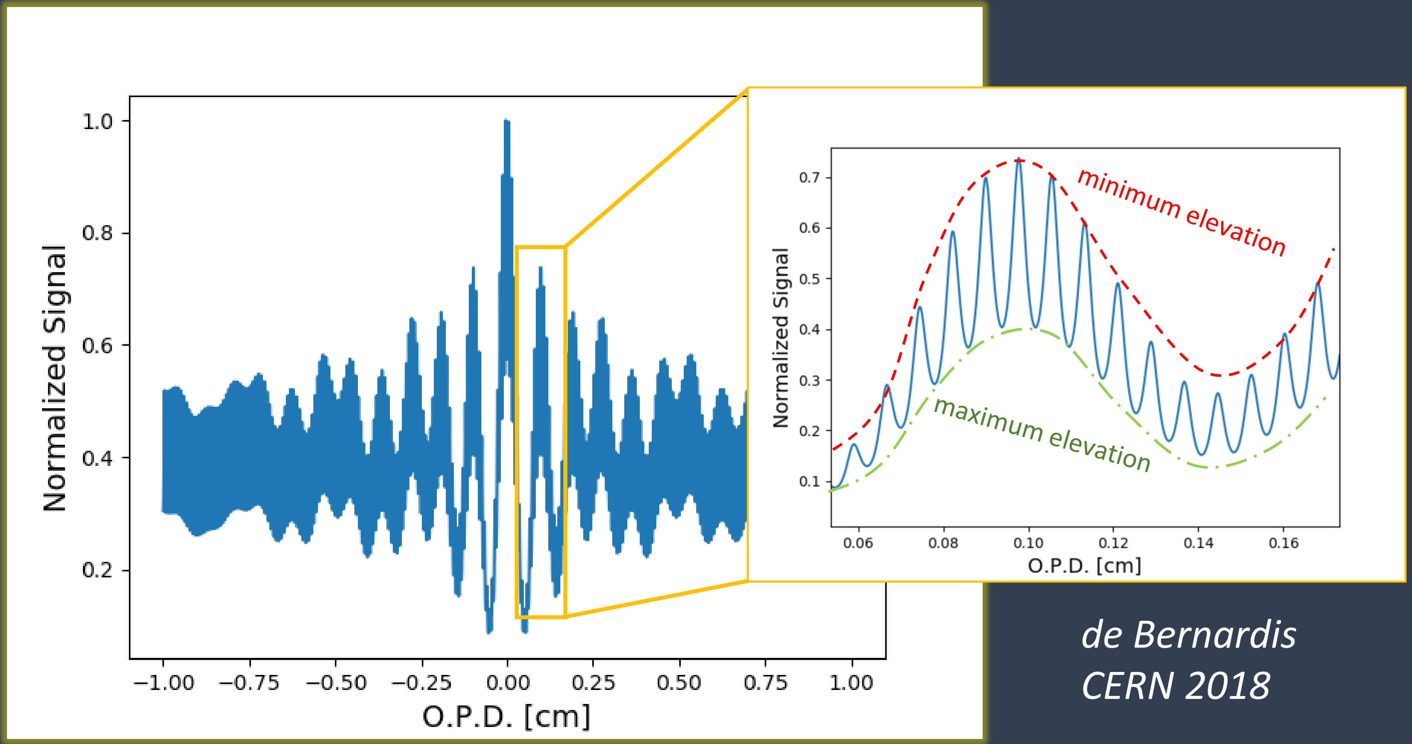
COSMO

- PI: Silvia Masi
- Webpage: http://cosmo.roma1.infn.it/
- Pathfinder experiment to observe the isotropic y-distortions
- Martin-Puplett Interferometer (MPI) to measure the difference between the sky brightness and a reference internal blackbody calibrator
- Two arrays of fast ($\tau = 60\mu s$, NEP=$3.8 \cdot 10^{-17} W/\sqrt{Hz}$) Multi-mode Kinetic Inductance Detectors (KIDs)
- KIDs coupled with the MPI output with multi-mode horn arrays
- Frequency coverage [125-280]GHz - $\Delta\nu \geq 5$GHz
- Fast sky modulation with a rotating wedge-mirror, data collection at different elevations in a single interferogram

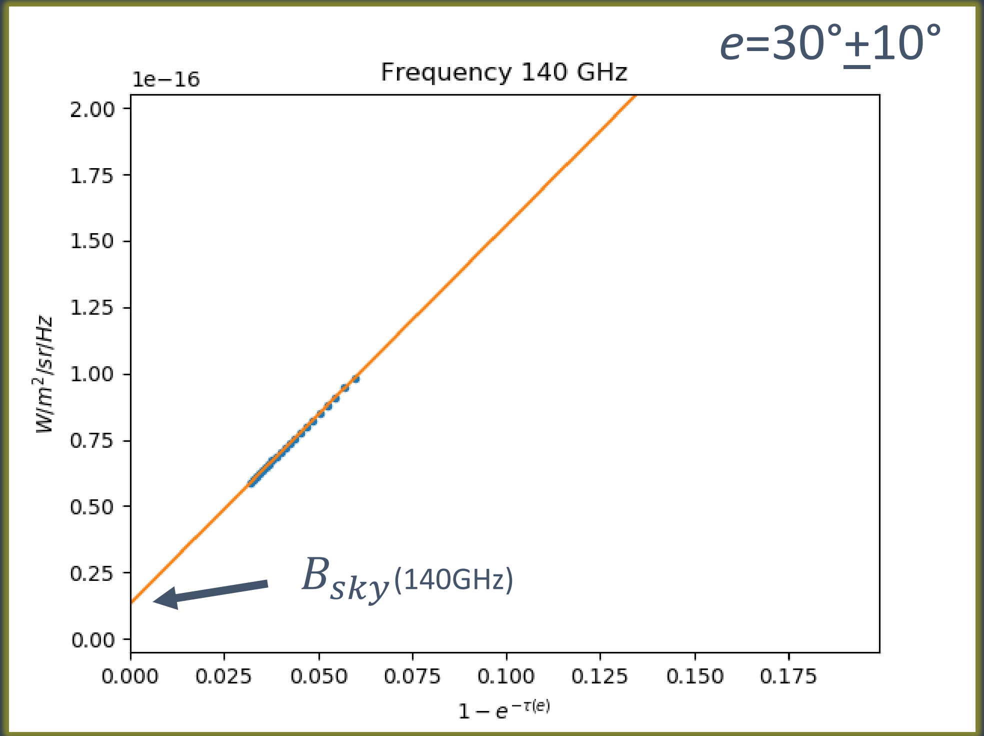


COSMO

The fast spinning wedge (~2500r.p.m.) mirror modulates the elevation
This is what you measure during one scan of the FTS moving mirror

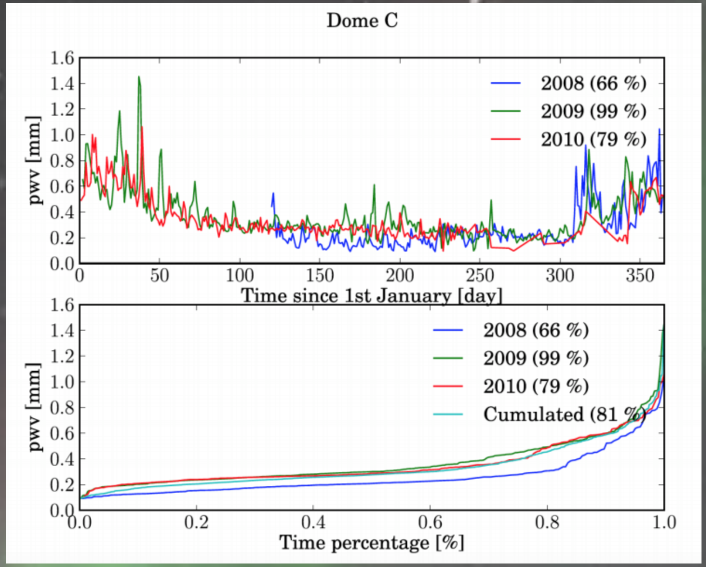


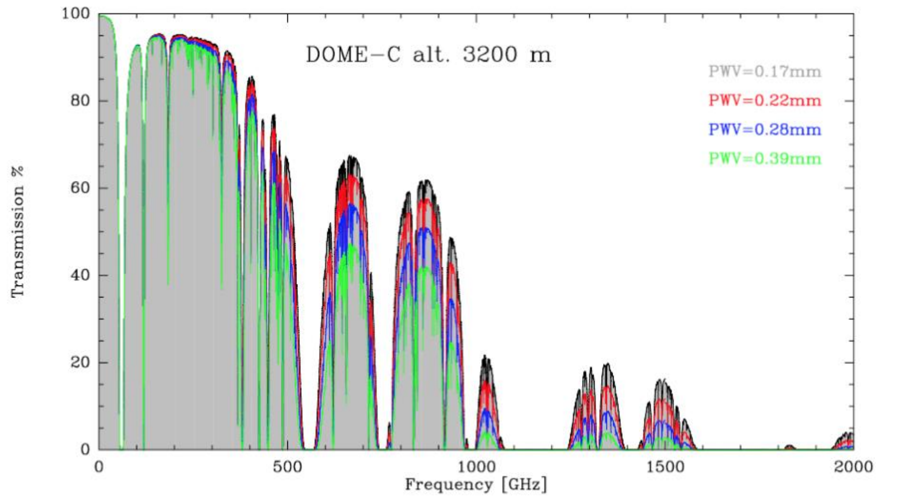
de Bernardis CERN 2018



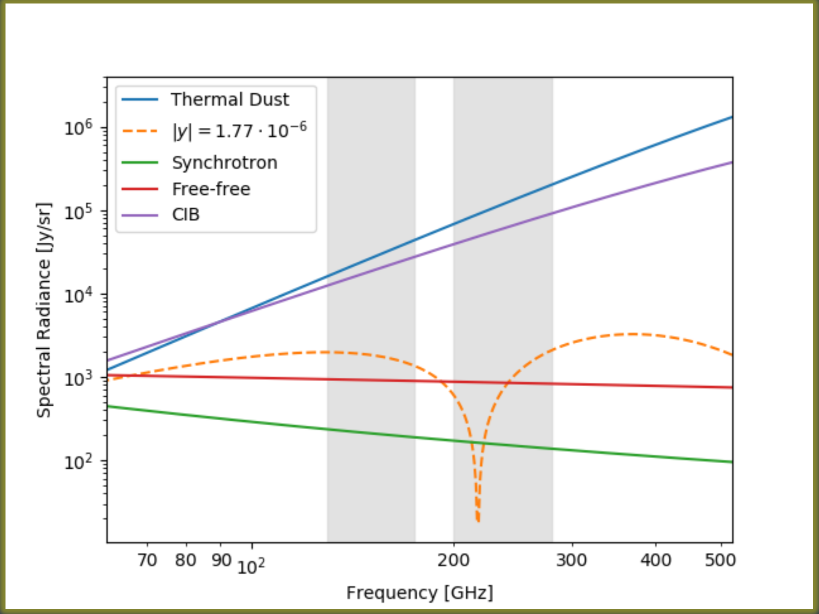
Scanning the sky at different elevations we can interpolate the signal per spectral bin at null air-mass, that is the sky brigthness!

- COSMO will operate from the French-Italian base Concordia in Dome-C (Antarctica) , one of the best logistically supported sites on Earth for CMB measurements
- Water Vapour Content <0.4mm PWV (~75% of the time) and an average of 210μm PVW in the winter season (*Tremblin et al. A&A, 2011*)
- We still have to cope with atmospheric emission and its flucuations
- Fast KIDs detectors and fast elevation scans are required to separate the atmospheric emission from the monopole of the sky brightness





Simulations



Internal Linear Combination (ILC)

- The multi-frequency map can be expressed as: where τ_i^c is the spatial map of the component and s_ν^c is its spectral energy distribution (SED)

- By constructing suitable weights (w) one can solve for the map of each component as:

- The solution is optimized by demanding that the weigths minimize the variance of the reconstructed component map (solved using the method of the Lagrange multipliers), where a represents the SED of the component to be separated and C the covariance matrix of the observed maps

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$$d_{\nu i} = \sum_c s_\nu^c \, \tau_i^c + n_{\nu i}$$

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$$\tau_i^{c_0} = \sum_\nu w_\nu^{c_0} \, d_{\nu i}$$

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$$w_\nu^{c_0} = \frac{a^T C^{-1}}{a^T C^{-1} a}$$

Simulations

- **Constrained-ILC** (c-ILC): By demanding simultaneous constrains on the weights w we conserve the y-distortion signal (a) and eliminate the foregrounds (b_i)

$$\begin{cases} w^T a = 1 \\ w^T b_i = 0 \end{cases}$$

$$d_{\nu i} = \sum_c s_\nu^c \, \tau_i^c + n_{\nu i}$$

Input spatial map

Additive bias from noise and other components

$$\tau_i^{c_0} = \sum_\nu w_\nu^{c_0} \, d_{\nu i} = \boxed{\tau_i^{c_0-input}} + \sum_{c \neq c_0} \boxed{(w_c^T s^c \tau^c} + \boxed{w_c^T n)}$$

- **Moment method**: can be used to model the effect of averaging (along the line of sight, within the beam..) for known fundamental SEDs

$$I_\nu(\hat{n}) = A_{\nu 0}(\hat{n}) s_\nu(\bar{p}) + \sum_i \eta_i(\hat{n}) \, s_\nu^i(\bar{p}) + \sum_{ij} \eta_{ij}(\hat{n}) \, s_\nu^{ij}(\bar{p}) + \sum_{ijk} \eta_{ijk}(\hat{n}) \, s_\nu^{ijk}(\bar{p})$$

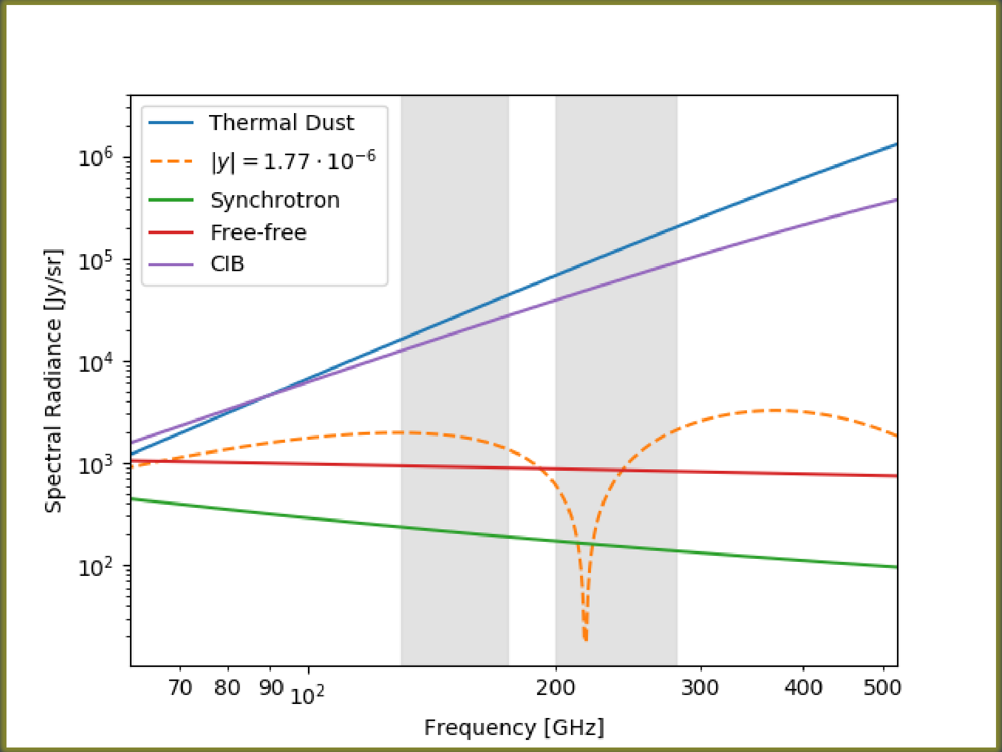
A. Rotti & J. Chluba 2020 (arXiv:2006.02458)

Simulations

Input Maps (nside=64, FWHM=1°, ν=[125,180]GHz+[200,280]GHz, Δν=[5, 10, 15]GHz)

- PySM model of Thermal Dust («d2», emissivity that varies spatially on degree scales)
- PySM model of CMB anisotropies («c1», A lensed CMB realisation made starting from a set of unlensed Cl's generated using CAMB.)
- Isotropic Compton y-map with $y = 1.77 \cdot 10^{-6}$
- Isotropic μ-map with $\mu = 2.0 \cdot 10^{-8}$

- Different sky patches where the (ILC) is indipendentely applied ($el = 60° \pm 5°$)
- Photon noise limited performance (cryostat window, 1% emissivity, $T_w = 240K$, and atmospheric emission, *a.m.* model $PWV = 0.15mm$)



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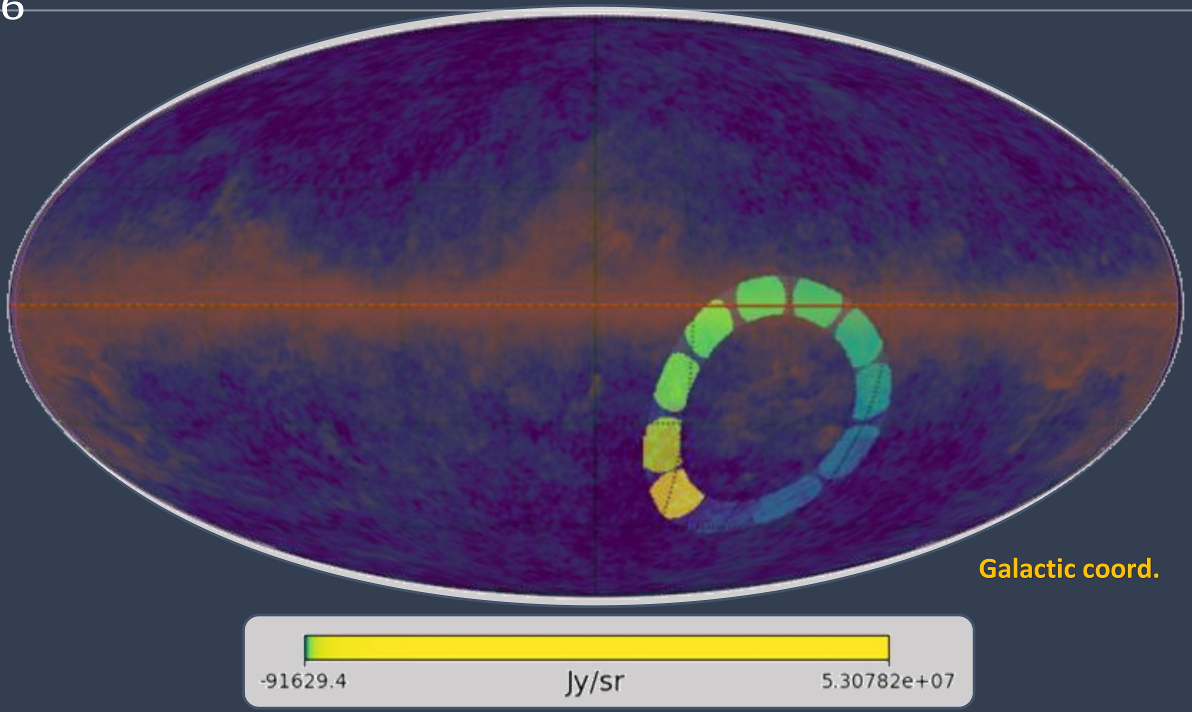
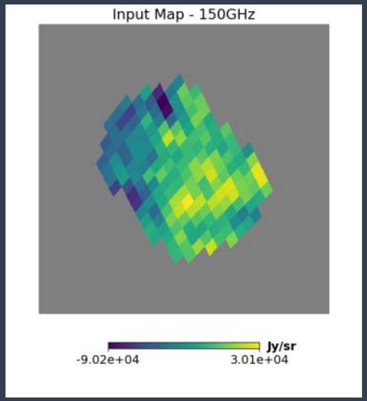
275GHz PySM thermal dust map

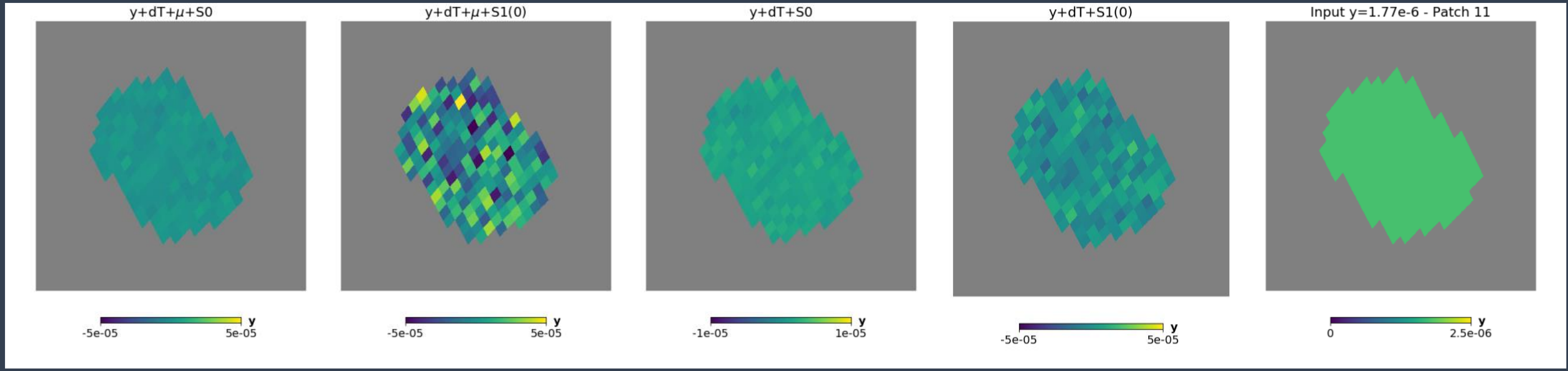


Simulations

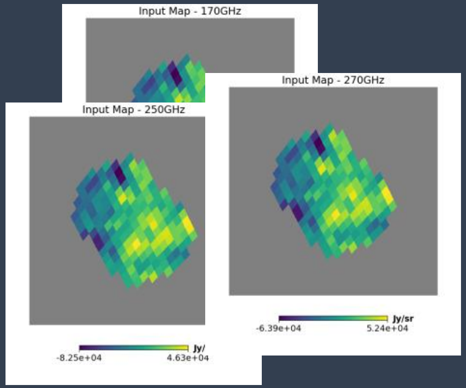
Output Compton-y maps with different combination of the spectral components to be removed

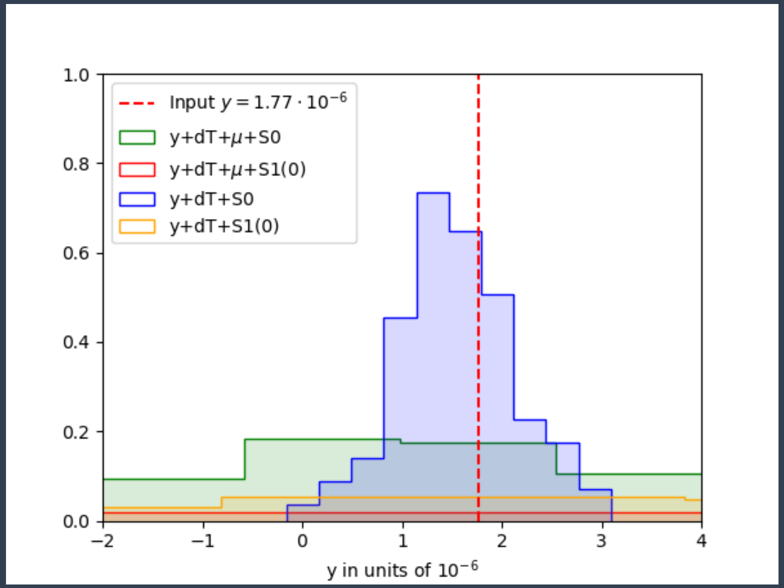


c-ILC

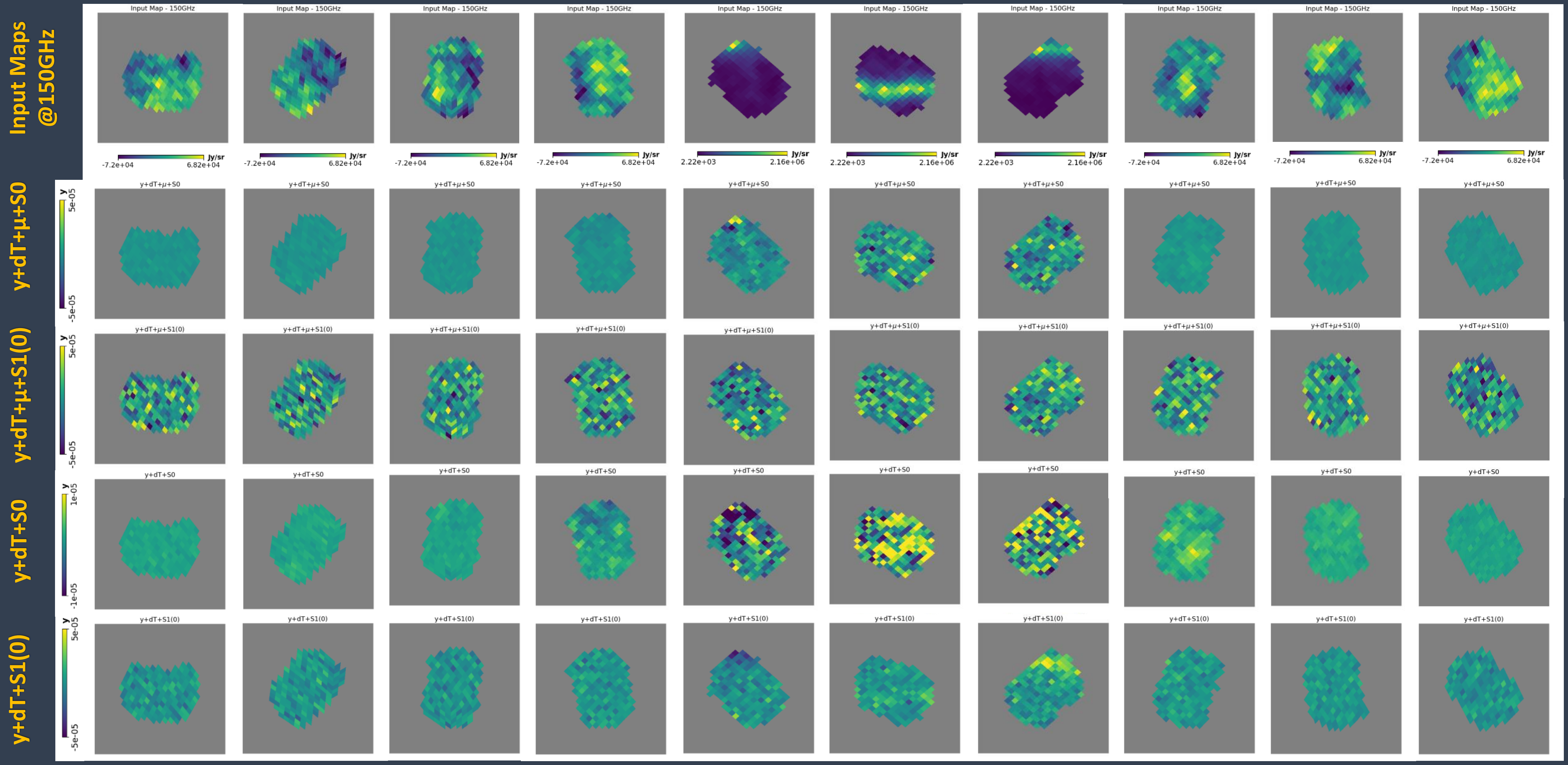


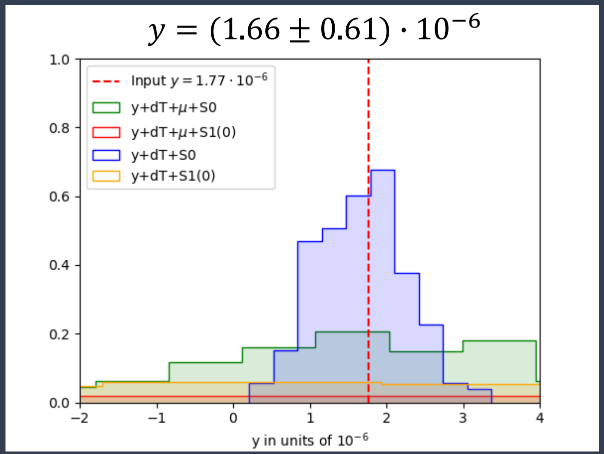
- **Input Multi-Frequency Maps + Noise Realization**

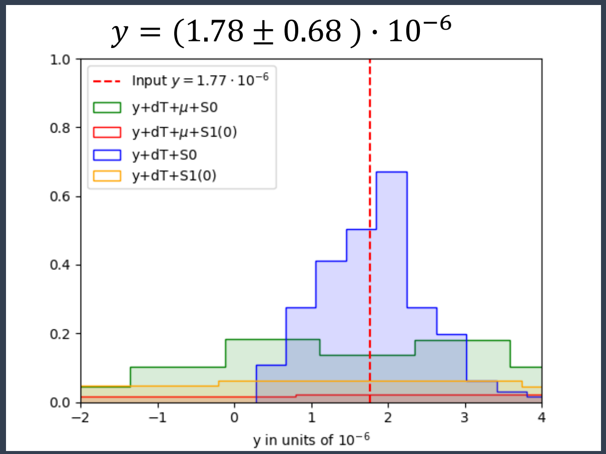


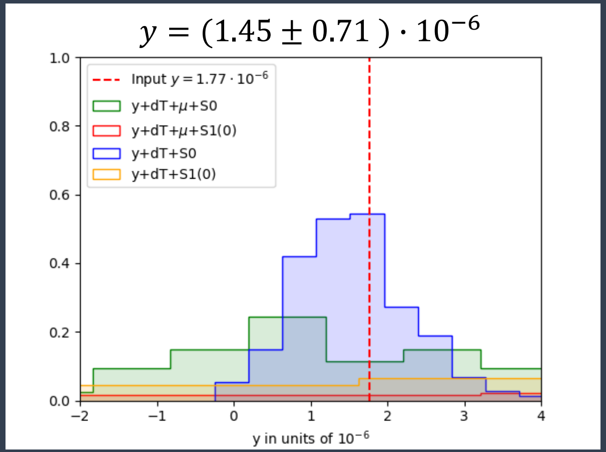


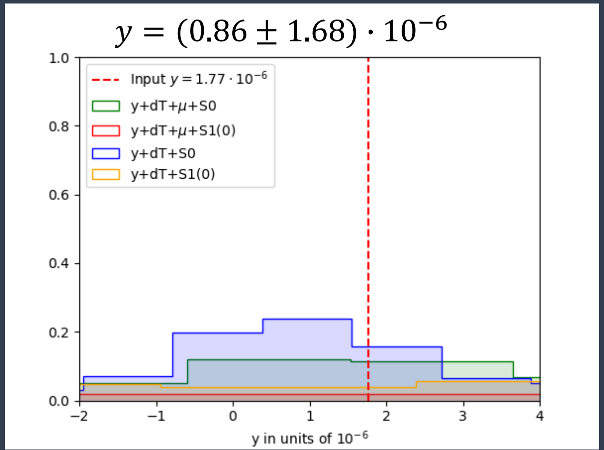
Sky patches

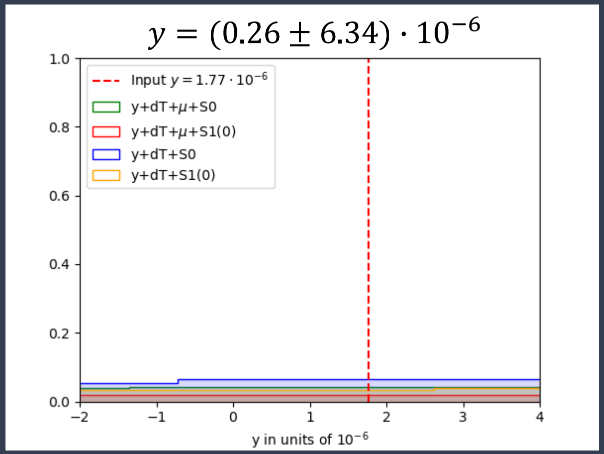

Input Maps @150GHz
y+dT+μ+S0
y+dT+μ+S1(0)
y+dT+S0
y+dT+S1(0)
Input Map - 150GHz
Jy/sr
-7.2e+04
6.82e+04
2.22e+03
2.16e+06
y+dT+μ+S0
y+dT+μ+S1(0)
y+dT+S0
y+dT+S1(0)
5e-05
-5e-05
1e-05
-1e-05

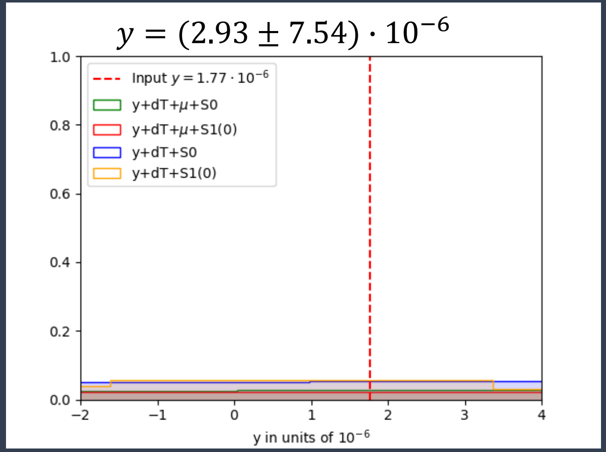


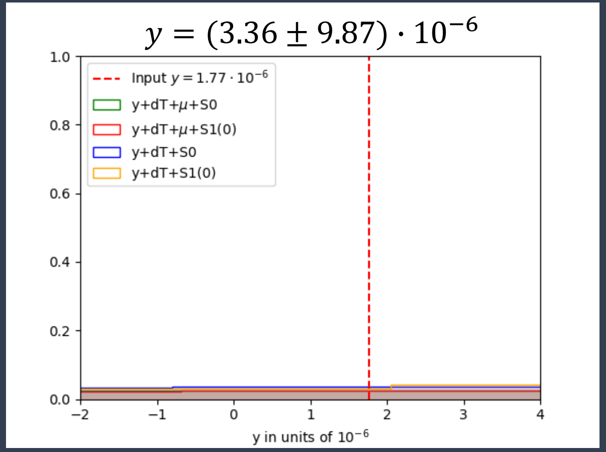


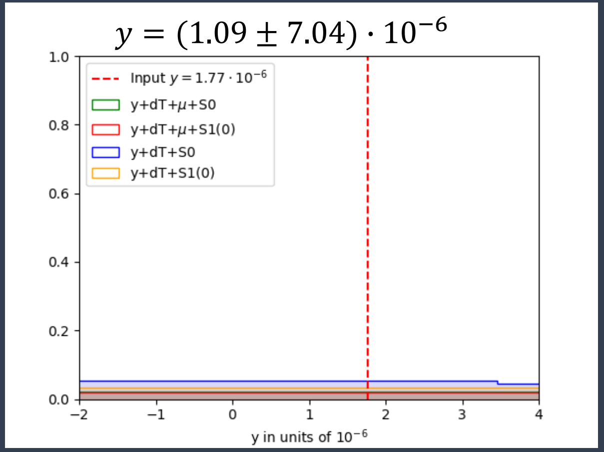


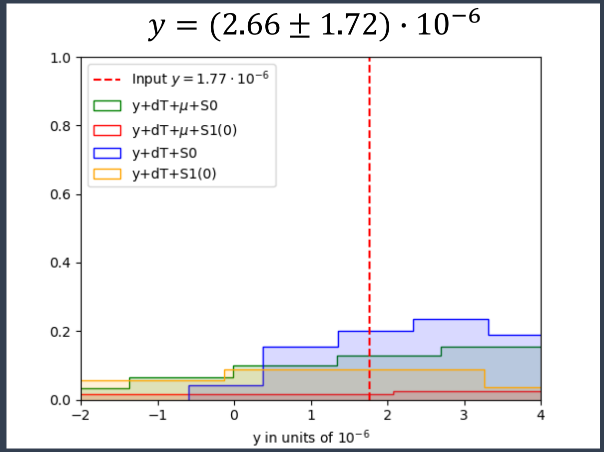


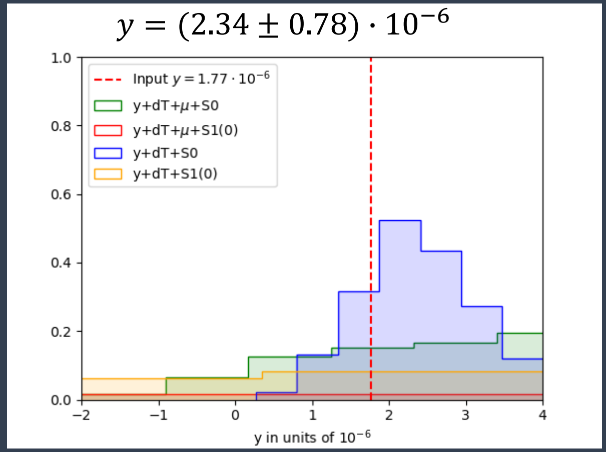


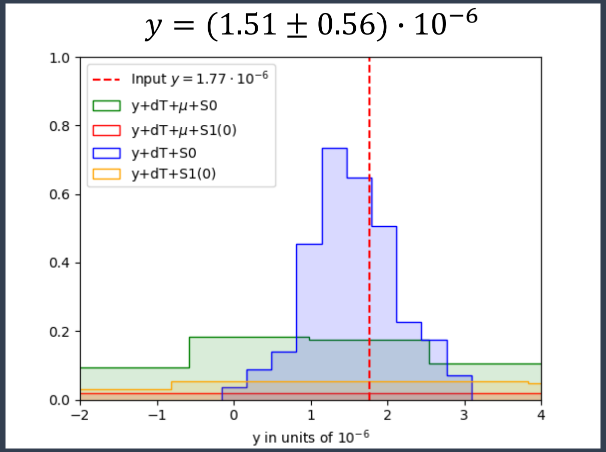












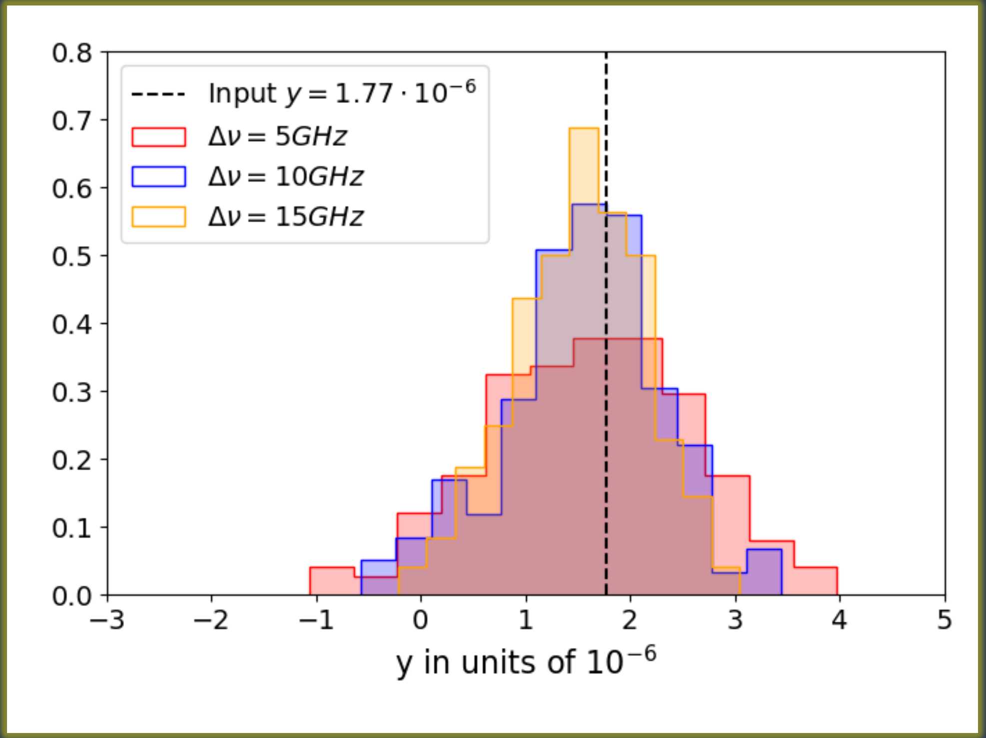
Weighted average over all the sky patches

$$\langle y \rangle_w = (1.73 \pm 0.35) \cdot 10^{-6}$$

Δν=10GHz

Simulations

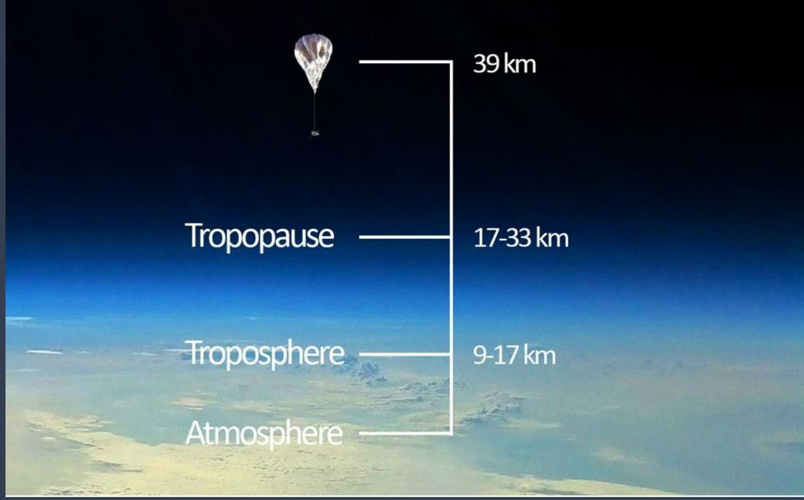
Histograms of output Compton-y maps from (y+dT+S0) solution for sky patch #11 with different spectral resolutions [5, 10, 15]GHz (different noise levels)



Weighted average over all the sky patches with different spectral resolutions

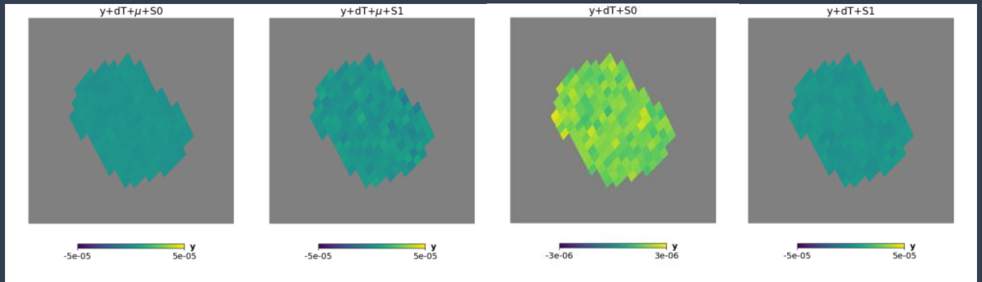
Δν [GHz]	$\langle y \rangle_w \cdot 10^{-6}$	s2n
5	1.87 ± 0.42	4.4
10	1.73 ± 0.35	4.9
15	1.70 ± 0.28	6.2

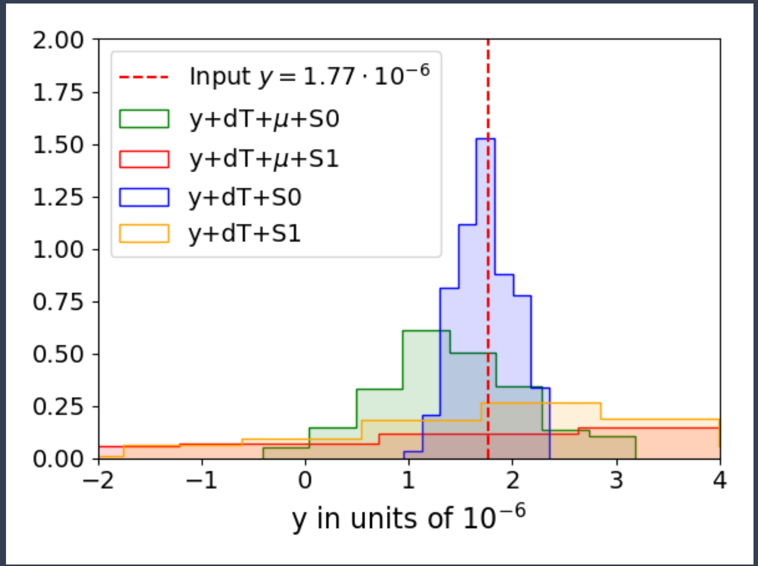
COSMO on a Stratospheric Balloon



- Wider spectral coverage (150, 250, 350, 450 GHz bands)
- Lower atmospheric emission and fluctuations
- Thin low emissivity vacuum window (<0.1%)
- Reduced time for the measurement (~15 days)
- Nowadays longer balloon flights (2-6 months) are achievable

Patch #11





Weighted average over all the sky patches with different spectral resolutions, robust against atmospheric effects

Δν [GHz]	$\langle y \rangle_w \cdot 10^{-6}$	s2n
5	1.76 ± 0.18	9.8
10	1.82 ± 0.14	13.0
15	1.84 ± 0.13	14.1

for a 15-days LDB flight

Conclusions

- ILC methods fit for the quest of isotropic CMB spectral distortions (already used for anisotropic SZ-effect extraction by galaxy clusters ($y \sim 4 \cdot 10^{-5}$)
- Constrained – ILC method is effective for extracting isotropic spectral distortion signals in sky-patches where dust emission is low enough that the 0th order dust SED removal provides satisfactory results → Ground-based COSMO $(1.73 \pm 0.35) \cdot 10^{-6}$ ($\Delta\nu = 10GHz$)
- Full Moment Expansion – ILC method is hard to use given the limited spectral coverage and the expected noise level
- Slow atmospheric fluctuations to be included (small contribution is expected via fast modulation) → inhomogeneities along a line-of-sight, temperature, emissivity, density and PWV fluctuations (developing a model from BRAIN data @150GHz at Dome-C). The balloon-borne version of COSMO will not suffer for these effects
- All the foregrounds need to be included in the problem, some with the inclusion of complex emission mechanisms, as different dust clouds along a line-of-sight (different temperatures and dust population, PySM allows to include a model with 2 different dust populations)

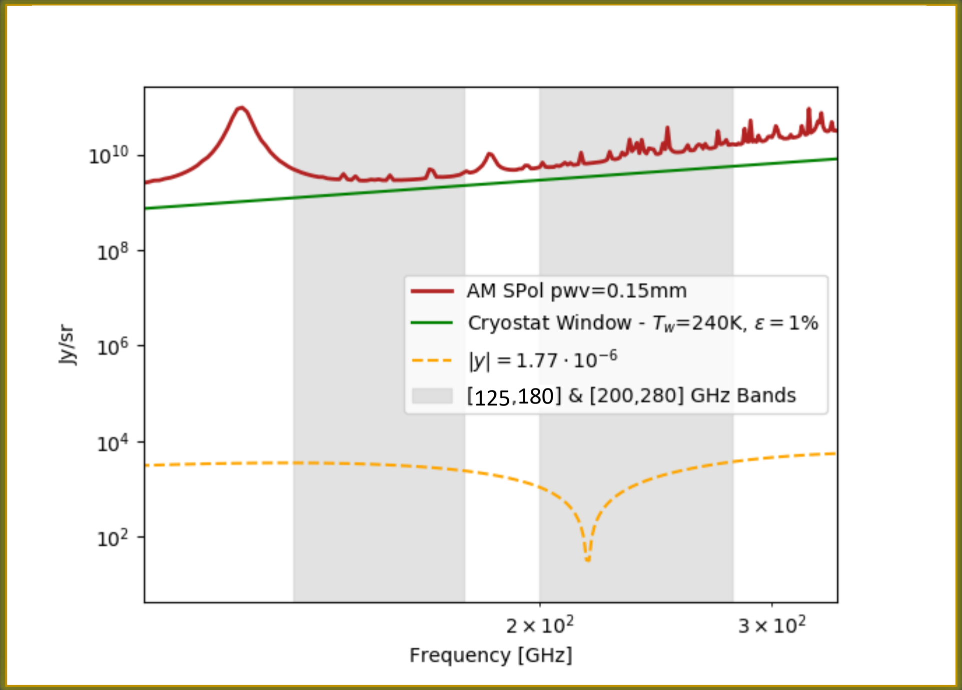
Backup

Noise Estimate

[125,180]GHz & [200,280]GHz

$t = 1\ year$
$\eta = 0.3$
$N_{det} = 9$
$A\Omega = 0.14\ cm^2 sr$
$T_w = 240K,\ \varepsilon_w = 1\%$

Given a gaussian beam with FWHM=1°, each 1° sky-pixel will integrate for $t = 1year/1801$ for a Map scale factor $= 1801 \deg^2$



$$NEP_{ph}^2 = 2\int f_\nu \eta A\Omega I_\nu h\nu \left(1 + \frac{f_\nu \eta c^2 I_\nu}{h\nu^3}\right) d\nu$$

$$NEP_{ph}^{tot} = \sqrt{NEP_{ph-atm}^2 + NEP_{ph-window}^2}$$

$$\sigma_S = 0.61 \frac{NEP_{ph}^{tot}}{\eta A\Omega\ \Delta\nu\sqrt{t}\sqrt{N_{det}}}$$

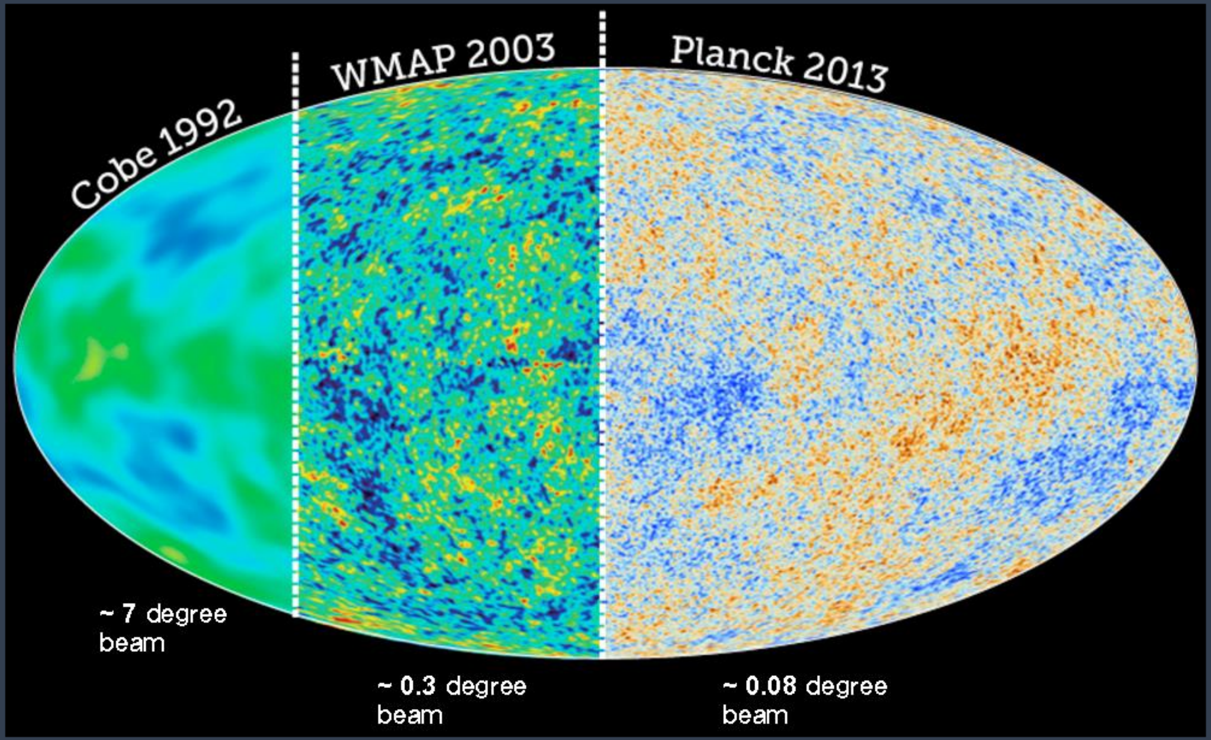
«Low-resolution spectroscopy of the Sunyaev-Zel'dovich effect and estimates of cluster parameters» P. de Bernardis et al. (2012)
(https://www.aanda.org/articles/aa/abs/2012/02/aa18062-11/aa18062-11.html)

A direct look at the early Universe (at *Recombination* phase, 380000 years after the Big Bang):

- Almost a perfect blackbody at $T = 2.725K$
- Temperature Anisotropies $\Delta T/T = 10^{-5}$
- Linearly Polarized $1 - 10\%$

Improvements:

- Sensitivity, Planck is 10 times more sensitive than WMAP
- Angular resolution, Planck angular resolution is 100 times better than COBE
- 9 frequency bands for Planck (30-857)GHz



Jens Chluba 2018

Temperature anisotropies described with the angular power spectrum C_l

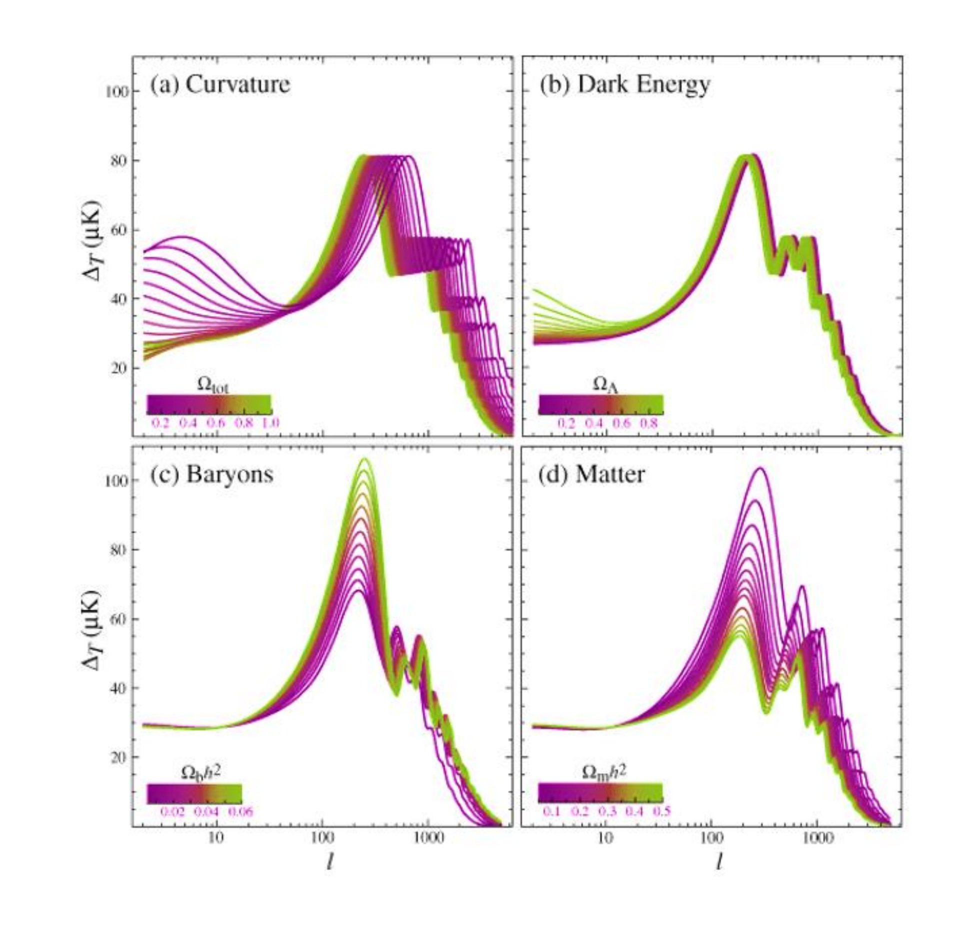
$$\frac{\delta T}{\langle T \rangle} = \sum_{l=0}^{\infty} \sum_{l=-m}^{m} a_{lm} Y_{lm}(\theta, \varphi)$$

$$C_l = \frac{1}{2l+1} \sum_{-l}^{l} |a_{lm}|^2$$

ΛCDM Model

Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042

Planck Collab. 2015



Wayne Hu 2001