Filling the universe with Light

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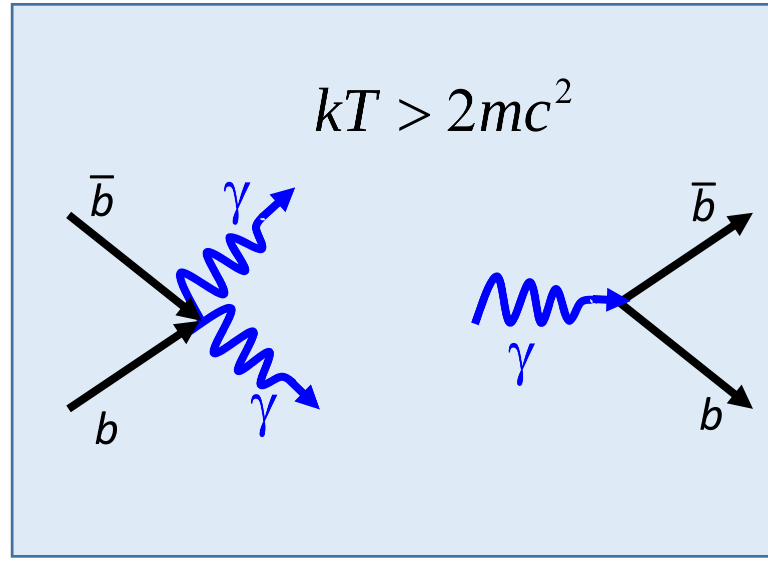
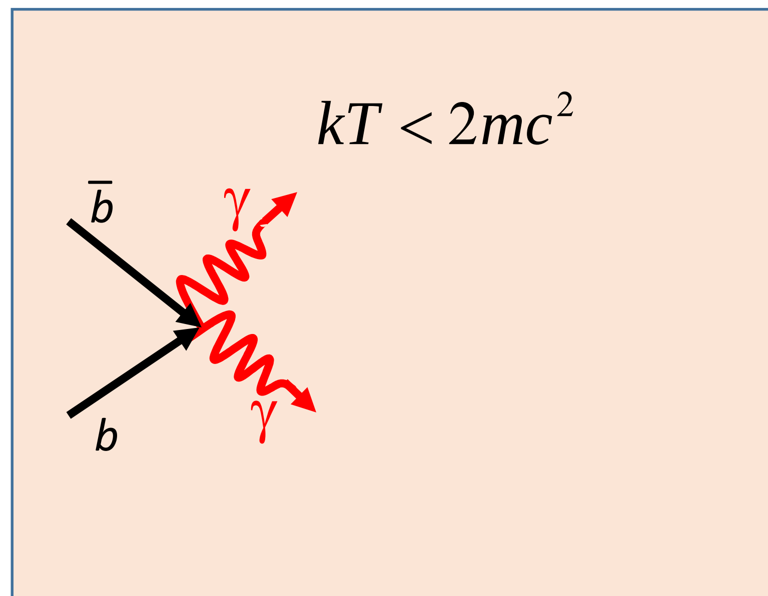
Filling the Universe with Light

- Today, on average, the Universe is a dark place, at least in the visible EM band.
- It was not always this way.
- In the early ionized universe, light dominated the mass-energy density of the Universe.
- The subsequent expansion of the universe diluted and redshifted photons, and the universe became neutral and dark for a long time.
- When the first stars ignited, the universe was flooded with light again and re-ionized.
- In this talk
  - I'll review the history of the first light in the Universe, the CMB.
  - I'll show how the CMB can be used to study the second luminous epoch of the universe, the reionization epoch
  - More in general I'll show how, since the CMB fills the universe, it can be used as a luminous background light to illuminate «from behind» all the structures.

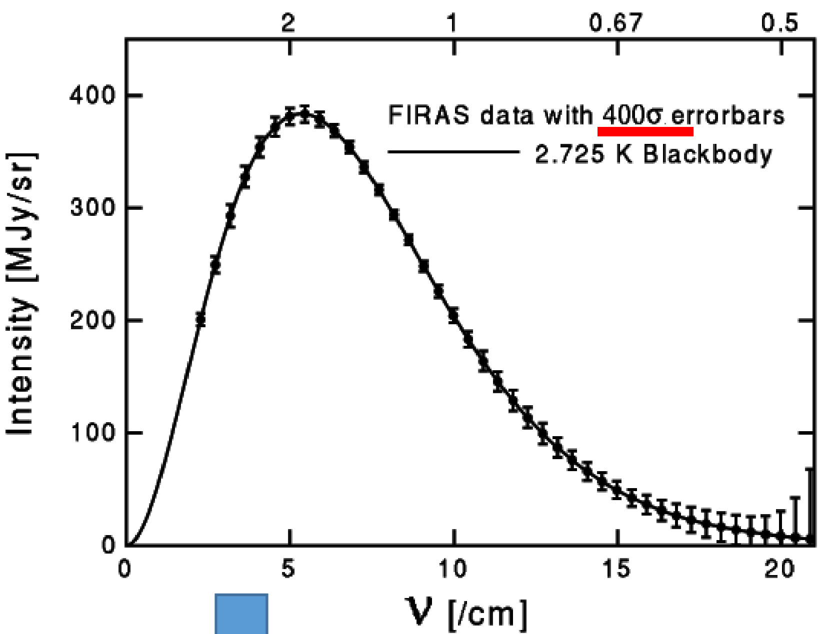
«let there be light» .. and there was light.

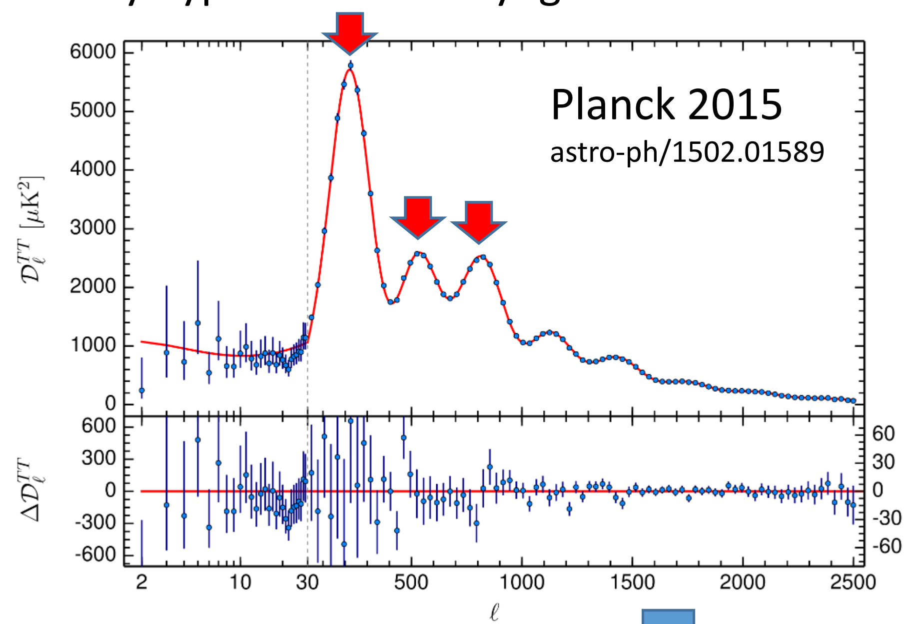
- We live in an expanding universe, started in a big-bang of extreme temperature and density.
- Starting from symmetric contents of matter and antimatter, the processes of annihilation and pairs production generate a background of high energy photons in thermal equilibirium with matter and anti-matter.
- Both processes work until the expansion reduces the energy of photons below the mass of particles.
- Annihilations continue to produce photons, but photons do not produce pairs anymore.
- If physics was perfectly symmetric, this process would produce, after complete annihilation, a universe made only of photons.
- If, instead, there is a **slight asymmetry** favoring matter against anti-matter, the process produces a universe with residual matter, no anti-matter, and a **very high photon-to-baryon ratio**.





- These photons rapidly thermalize in the primeval fireball, producing a cosmic photon background, which redshifts and dilutes with the expansion, and is visible today as the **cosmic microwave background.**
- This blackbody represents the majority of photons in the universe, and their number density can easily be estimated from the measured spectrum.
- Other measurements (including the anisotropy of the CMB, BBN, galaxy counts etc.) allow to estimate the density of baryons.
- In the universe today we do measure a **photon-to-baryon ratio** of the order of **10^9.** This gives remarkable support to the slight asymmetry hypothesis of baryogenesis.





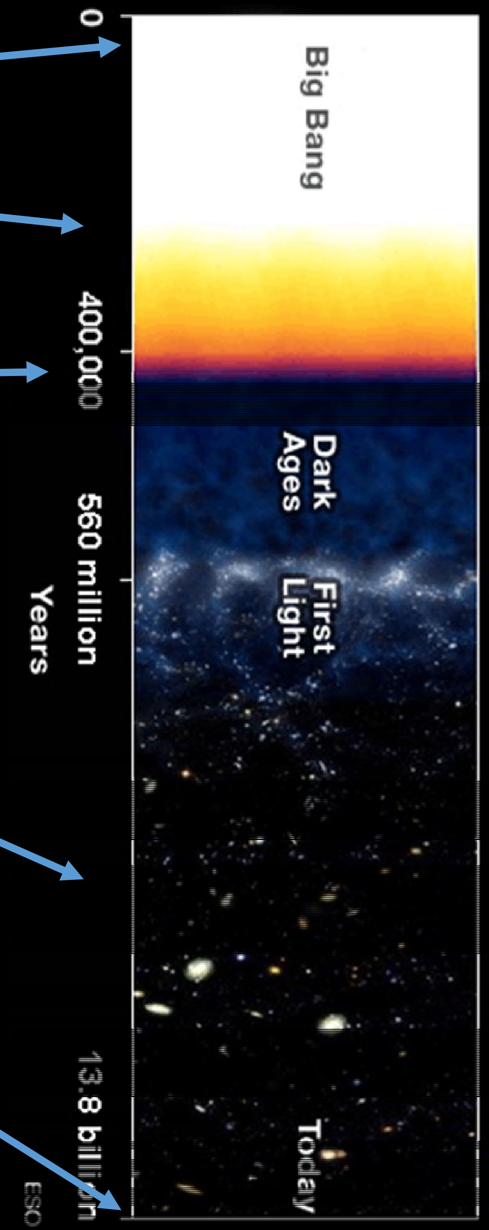
$$n_\gamma = 411\,cm^{-3}$$

$$\frac{n_\gamma}{n_b} = 1.7\times10^9$$

$$n_b \cong \frac{\Omega_b h^2 \rho_c}{m_b} = 2.5\times10^{-7}\,cm^{-3}$$

The long life of CMB photons

- Produced during baryogenesis
- Thermalized in the primeval fireball through repeated Compton/Thomson scattering, the last one at recombination
- A few % of them is scattered again at reionization
- A small fraction of them is scattered again in the hot plasma of clusters of galaxies
- An infinitesimal fraction is collected by CMB telescopes and measured.
- Accurate measurements provide valuable information on all phases of the evolution of the universe.



CMB observables

- Spectrum (specific brightness <I(ν)>) :
  - Measured by COBE-FIRAS
  - Blackbody, T=2.725K
  - Deviations < 0.01% of peak brightness
- Anisotropy (map of the brightness I(θ,ϕ)):
  - Measured full sky, by many experiments, latest is Planck
  - Gaussian, rms around 90 μK
  - Power spectrum c_ℓ consistent with the adiabatic inflationary model for structure formation
- Linear Polarization (maps of Q(θ,ϕ) and U(θ,ϕ)):
  - rms around 3 μK, consistent with anisotropy results
  - Power spectrum of E-modes (irrotational component) measured by several experiments
  - Power spectrum of B-modes (curl component) due to dark matter structures lensing detected
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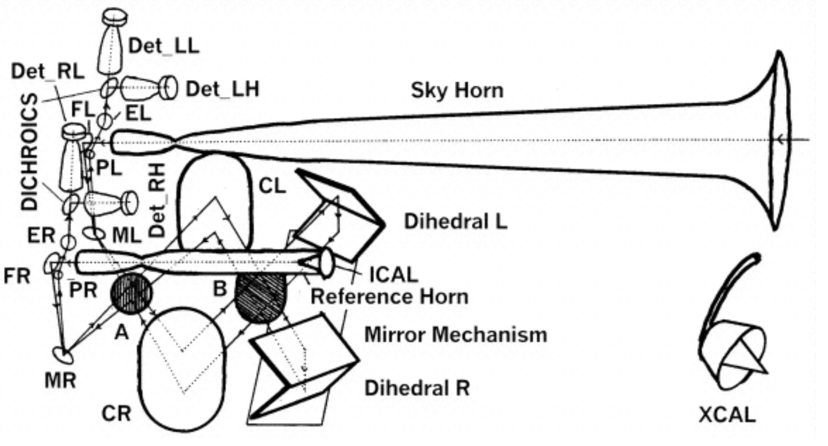
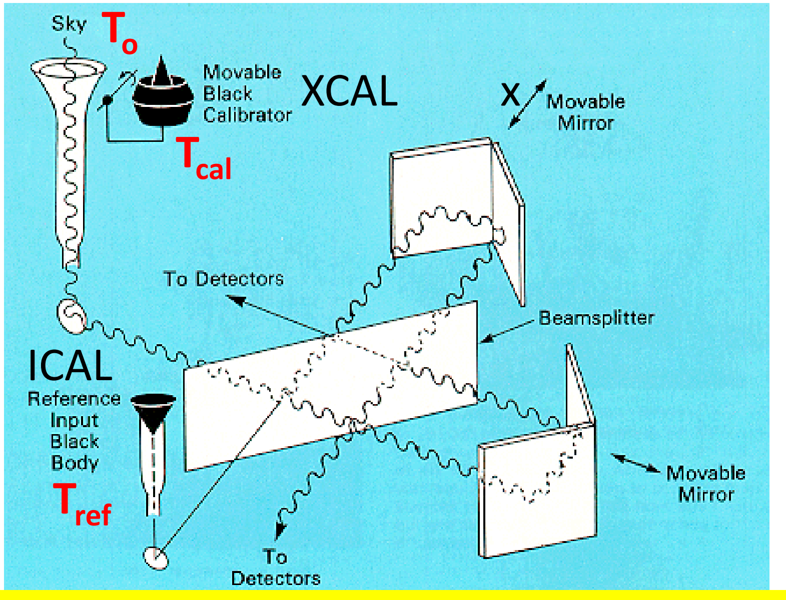
Spectrum: COBE-FIRAS

- COBE-FIRAS was a Martin-Puplett Fourier-Transform Spectrometer with composite bolometers. It was placed in a sun-synchronous 900 km orbit.
- A nulling instrument comparing the specific sky brightness to the brightness of a cryogenic reference blackbody.
- The output was nulled (within detector noise) for T_{ref}=2.725 K.
- The brightness of empty sky is a blackbody at the same temperature: $T_o=T_{ref}$!
- The early universe was in thermal equilibrium, at a temperature $T_o(1+z)$.



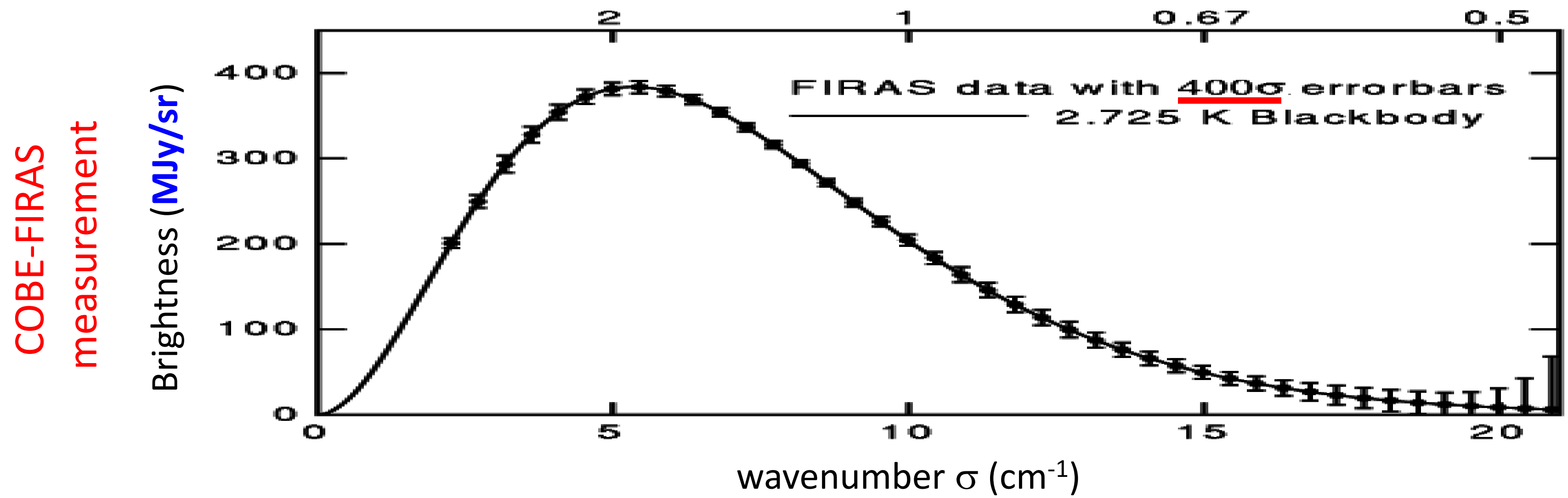


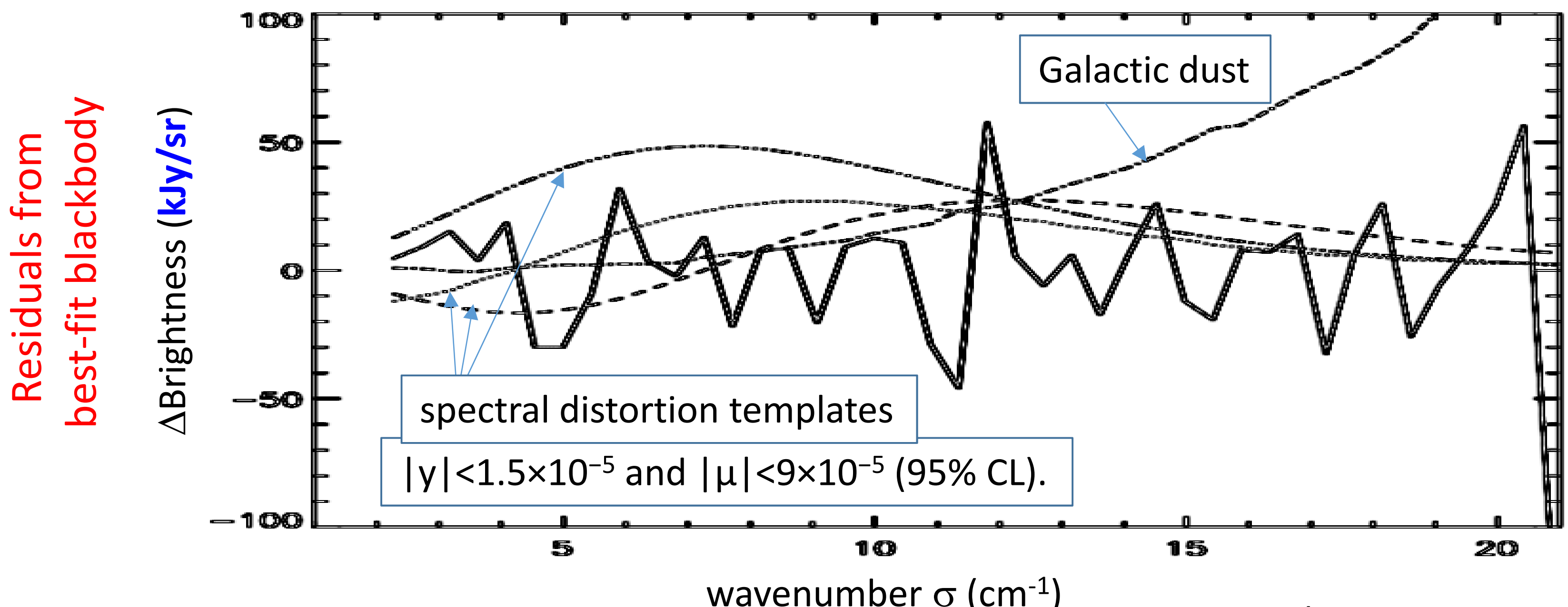
$$I_{SKY}(x)=C\int_0^\infty [S_{SKY}(\sigma)-S_{REF}(\sigma)]rt(\sigma)\{1+\cos[4\pi\sigma x]\}d\sigma$$

$$I_{CAL}(x)=C\int_0^\infty [S_{CAL}(\sigma)-S_{REF}(\sigma)]rt(\sigma)\{1+\cos[4\pi\sigma x]\}d\sigma$$

COBE-FIRAS spectrum of the CMB

Mather et al. Ap.J. , 354, L37 (1990)

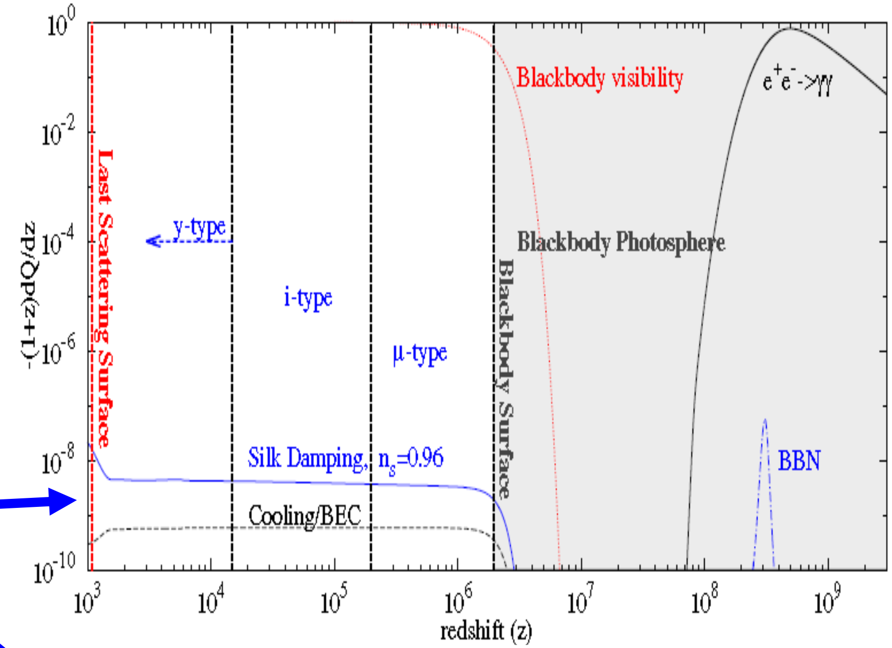


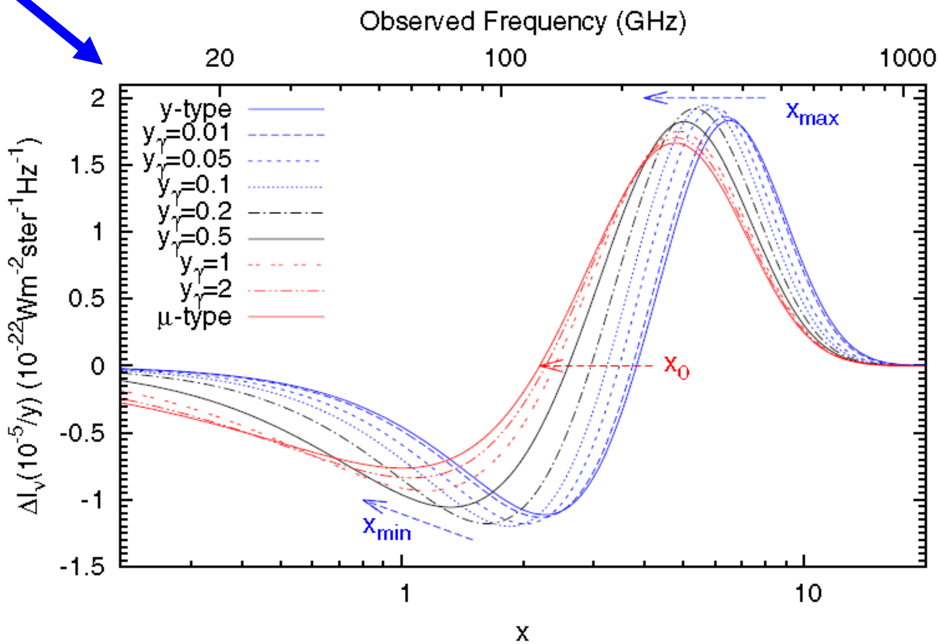


Fixsen et al. Ap.J., 473, 576, (1996)

Early spectral distortions of the CMB

- In the primeval fireball, photons and matter are in thermal equilibirium, with $T_\gamma = T_m$ unless there are processes injecting energy in the medium.
- At redshifts $z > 2\times10^6$ ($T > 0.5$keV) thermalization is so efficient that even a strong energy injection does not produce significant deviations from the blackbody spectrum (e.g. e^+e^- annihilation @T=1MeV, $z = 5\times10^9$).
- At lower redshifts (and T) *y*-type and μ-type distorsions can be generated (see e.g. J. Chluba and R. A. Sunyaev, Mon. Not. R. Astron. Soc. 419 (2012) 1294.)
- Very low level ($10^{-8}/10^{-9}$) distortions are expected due to processes happening in the early universe:
    - Viscosity of the electron-baryon-photon fluid, damping acoustic oscillations at small scales (Silk damping)
    - Adiabatic cooling of matter due to the cosmological expansion
- Additional (and possibly larger) distortions are expected in non-standard scenarios:
    - Annihilation / decay of WIMP dark matter (see e.g. Feng ARAA **48** (2010) 495)
    - Decay of cosmic strings and other topological defects (see e.g. Tashiro et al. Phys. Rev. D 85 (2012) 103522)
    - Evaporating black-holes (see e.g. Tashiro + Sugiyama, Phys. Rev. D 78 (2008) 023004.)





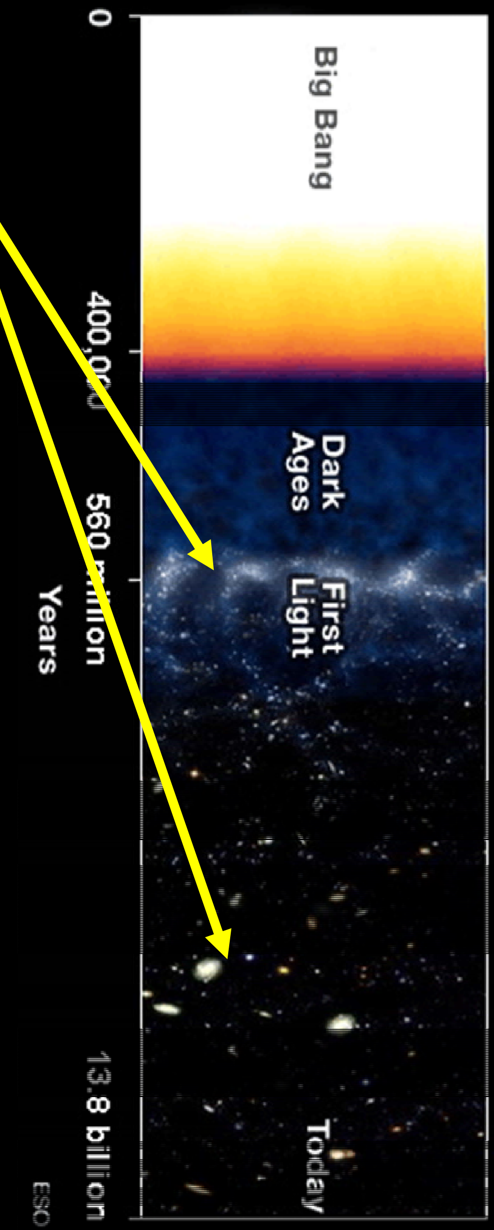
Late spectral distortions of the CMB

- An unavoidable CMB spectral distortion arises from reionization and the WHIM.
- When first generation stars ignite (z=6-20), the universe is flooded with UV photons, ionizing neutral hydrogen (reionization). The plasma heats to $T_e=10^4$K.
- Later structure formation shock-heats the plasma to $10^5\text{K}<T_e<10^7$K, creating the warm-hot intergalactic medium (WHIM).
- The photons of the CMB have a non-negligible likelihood to be scattered by the free electrons of the plasma, via Thomson and inverse Compton scattering.
- The former produces opacity and polarization effects (see later); the latter produces a y-type distortion in the spectrum.

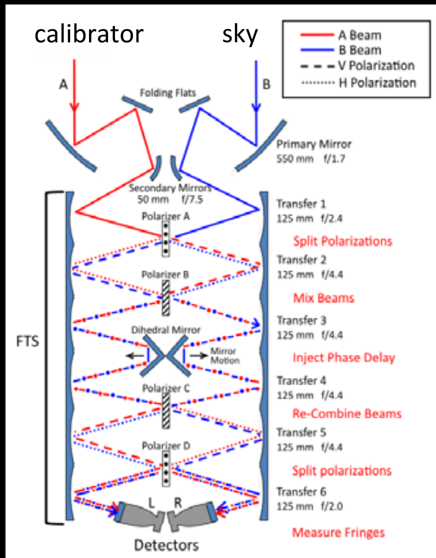
$$y = \int_{LOS} \frac{kT_e}{mc^2} n_e \sigma_{Th} d\ell$$

pressure integral along LOS

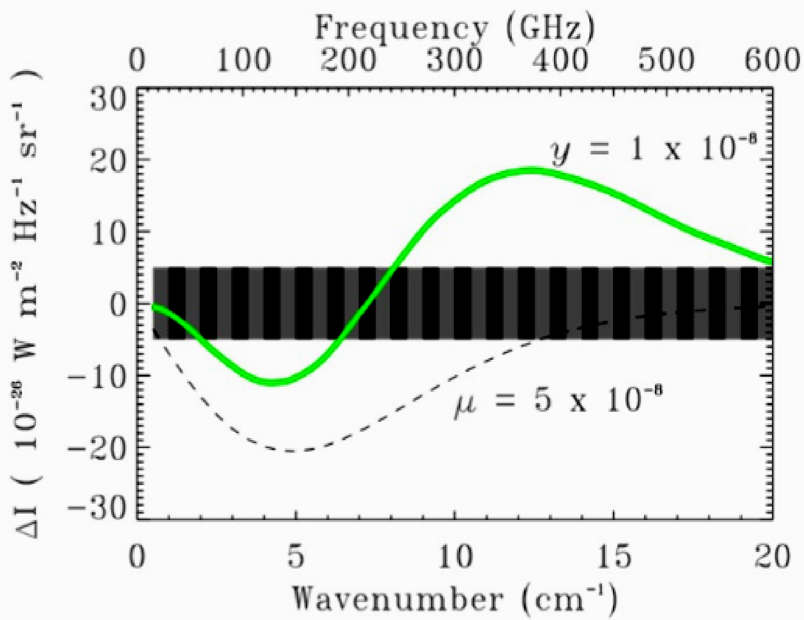
- $y=10^{-7}$ from reionization; $y=10^{-6}$ from the WHIM (see e.g. R. Khatri and R. A. Sunyaev, J. Cosmol. Astropart. Phys. 9 (2012) 16).
- Characteristic spectral shape, detectable with a space mission more sensitive than FIRAS.

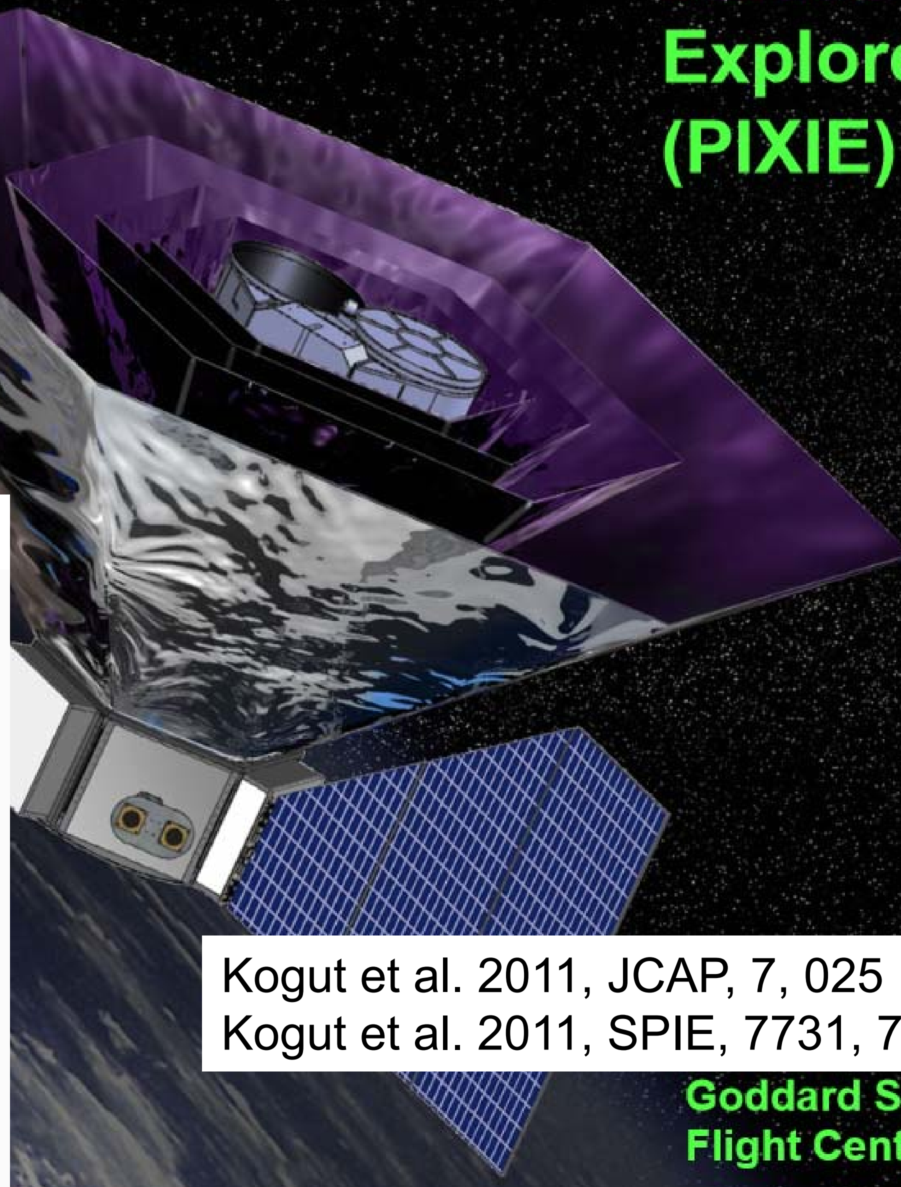


Primordial Inflation Explorer (PIXIE)



- PIXIE limit $y < 5 \times 10^{-9}$
- Distortion must be present at $y \sim 10^{-7}$





Kogut et al. 2011, JCAP, 7, 025
Kogut et al. 2011, SPIE, 7731, 77311S

Goddard Space Flight Center

Studying reionization with the CMB

- Opacity and polarization effects are proportional to the Thomson optical depth:

$$\tau = \int_{LOS} n_e \sigma_{Th} d\ell$$

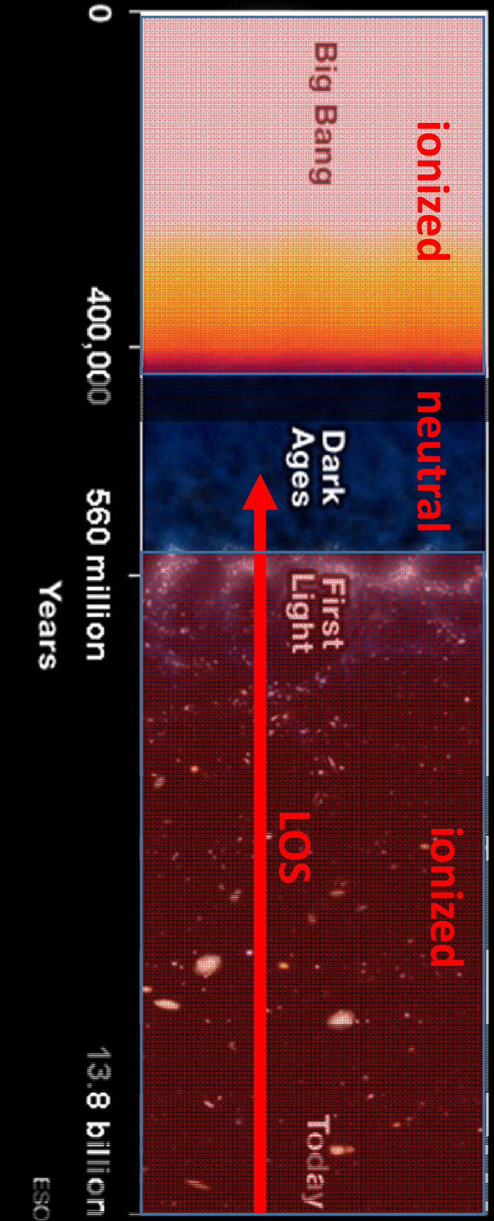
Optical depth along the LOS through reionization

- y-type spectral distortions are proportional to the pressure integral:

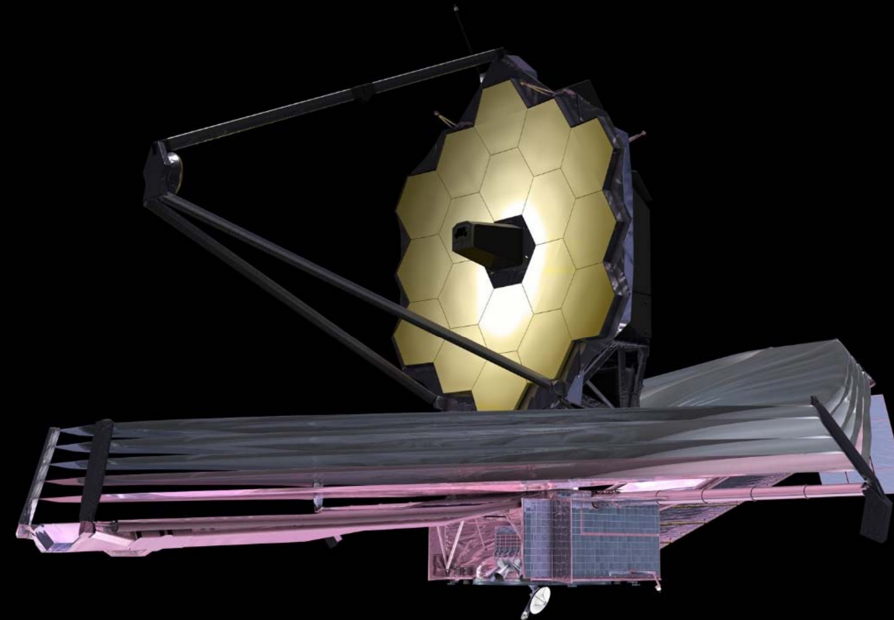
$$y = \int_{LOS} \frac{kT_e}{mc^2} n_e \sigma_{Th} d\ell$$

pressure integral along the LOS through reionization

- Combining the two measurements one can obtain both T_e and n_e, key quantities to constrain the physics of reionization.



JWST will detect and study directly the emission of the first stars



We heard all about this from Antonella Nota on monday.
Here we are focusing on indirect probes of the reionization epoch, using the CMB

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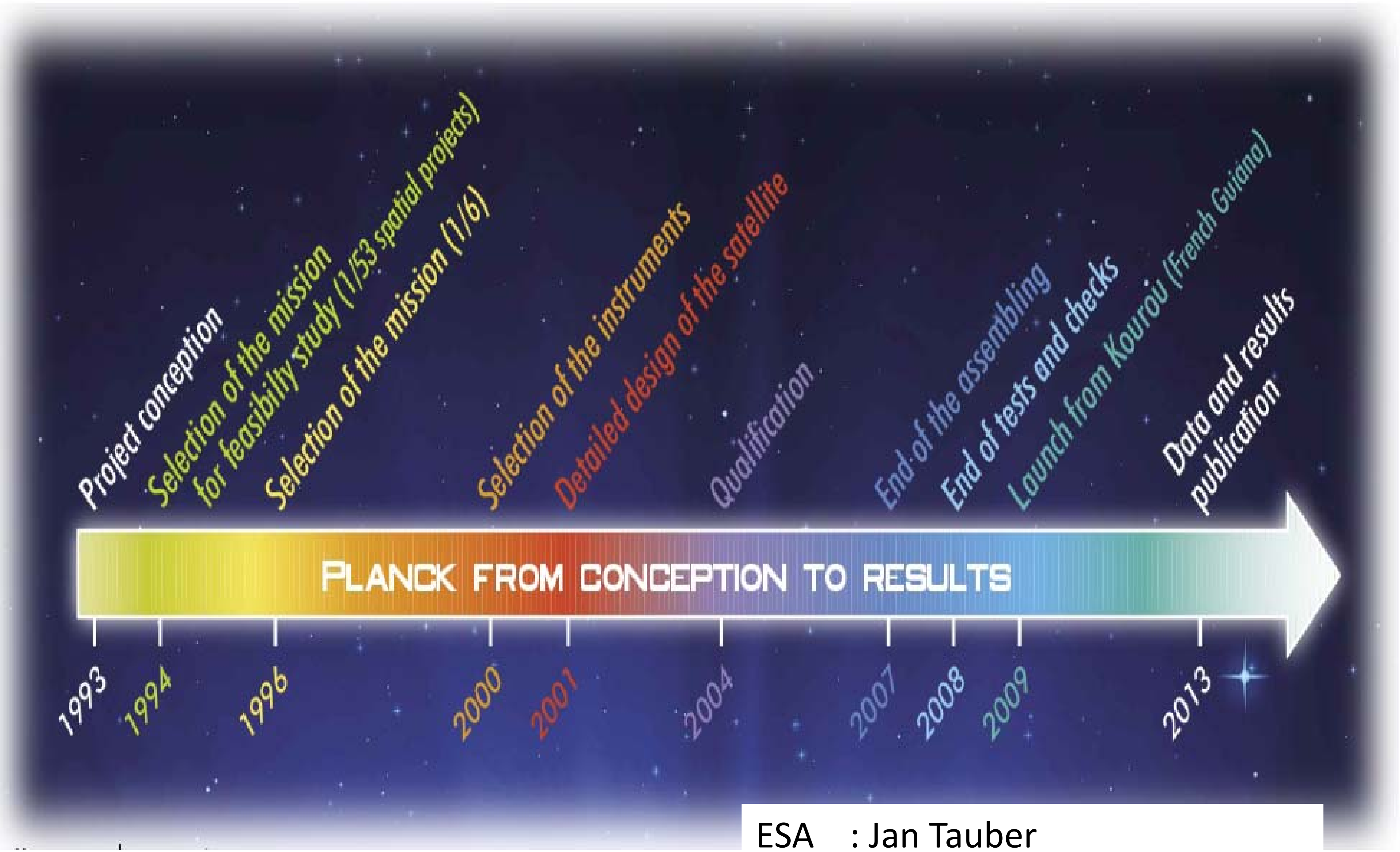
Planck is a very ambitious experiment.

It carries a complex CMB experiment (the state of the art, a few years ago) all the way to L2,

improving the sensitivity wrt WMAP by at least a factor 10,

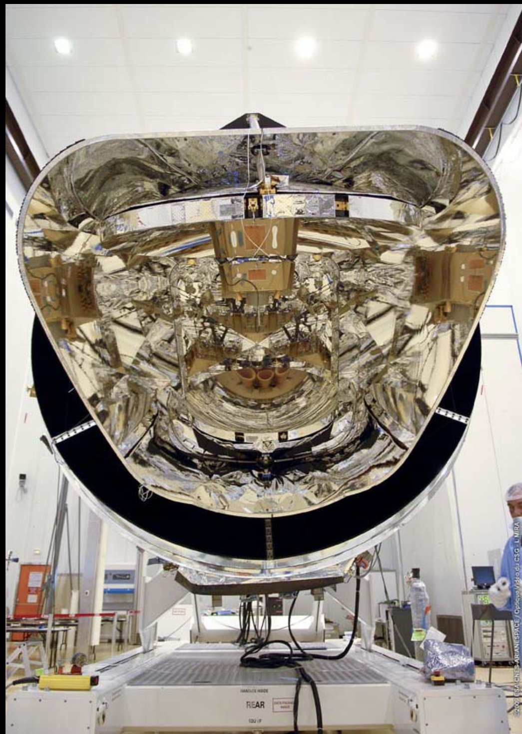
extending the frequency coverage towards high frequencies by a factor about 10



ESA : Jan Tauber
HFI PI : Jean Loup Puget (Paris)
HFI IS : Jean Michel Lamarre (Paris)
LFI PI : Reno Mandolesi (Bologna)
LFI IS : Marco Bersanelli (Milano)

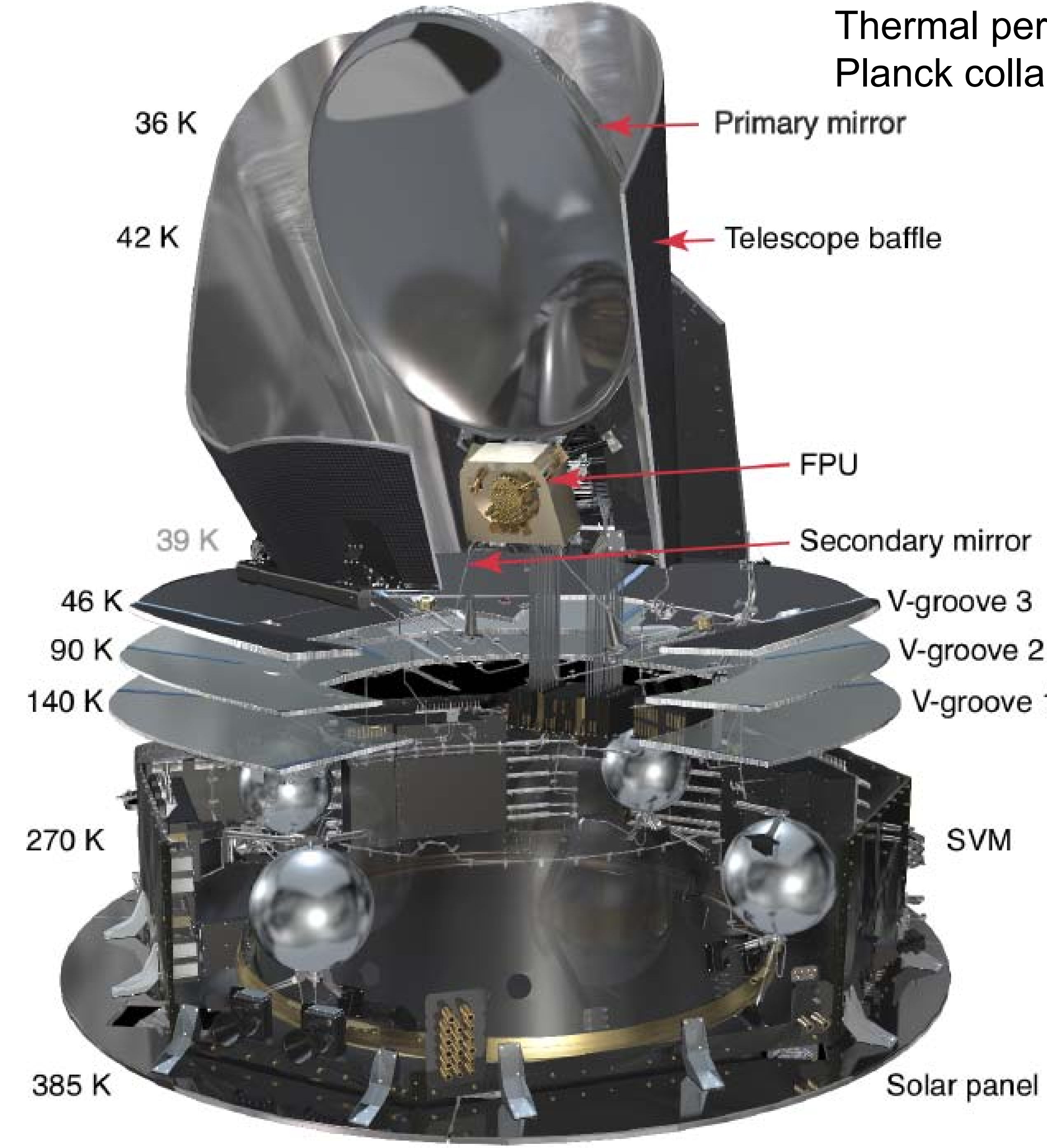
Almost 20 years of hard work of a very large team, coordinated by:

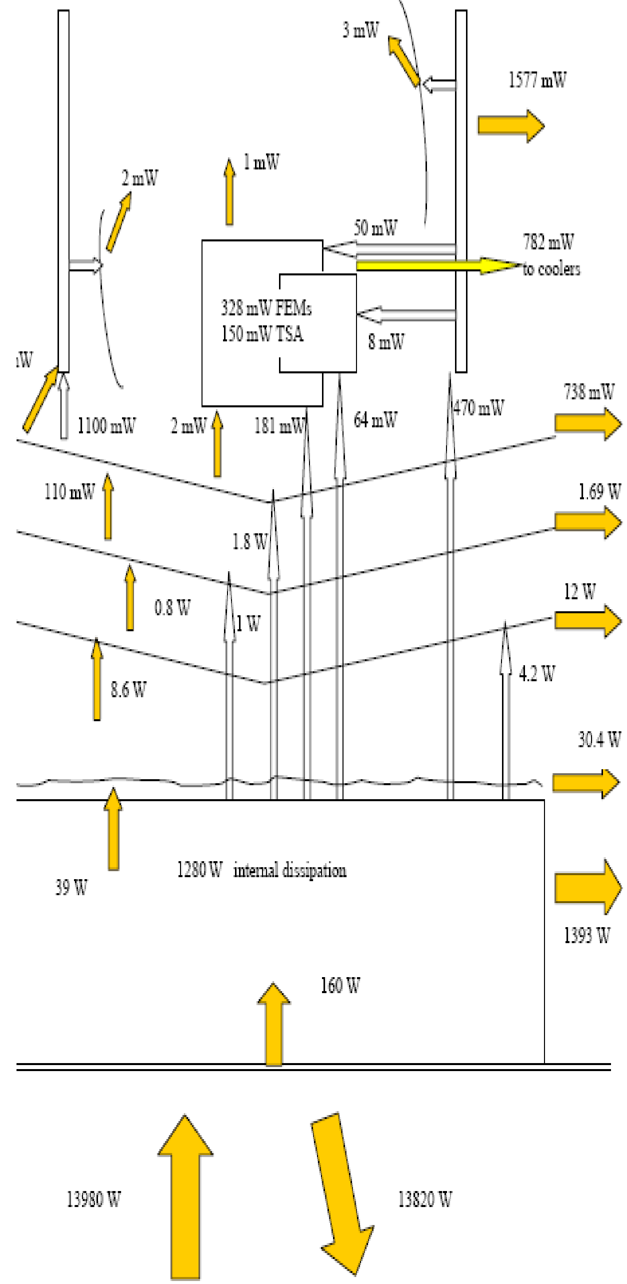
The scientific results that we present today are the product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

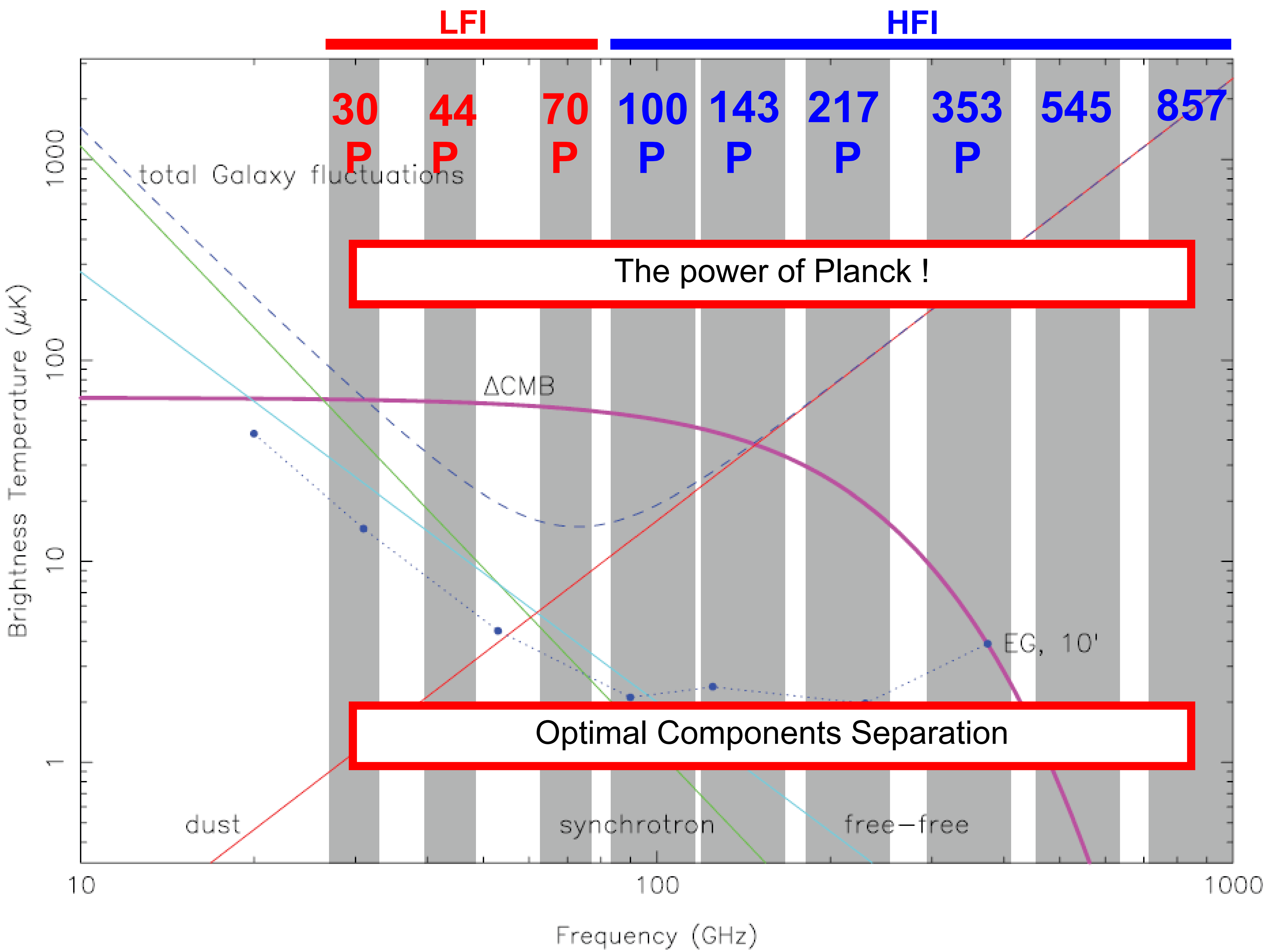


14 / May / 2009

Thermal performance :
Planck collaboration: astro-ph/1101:2023





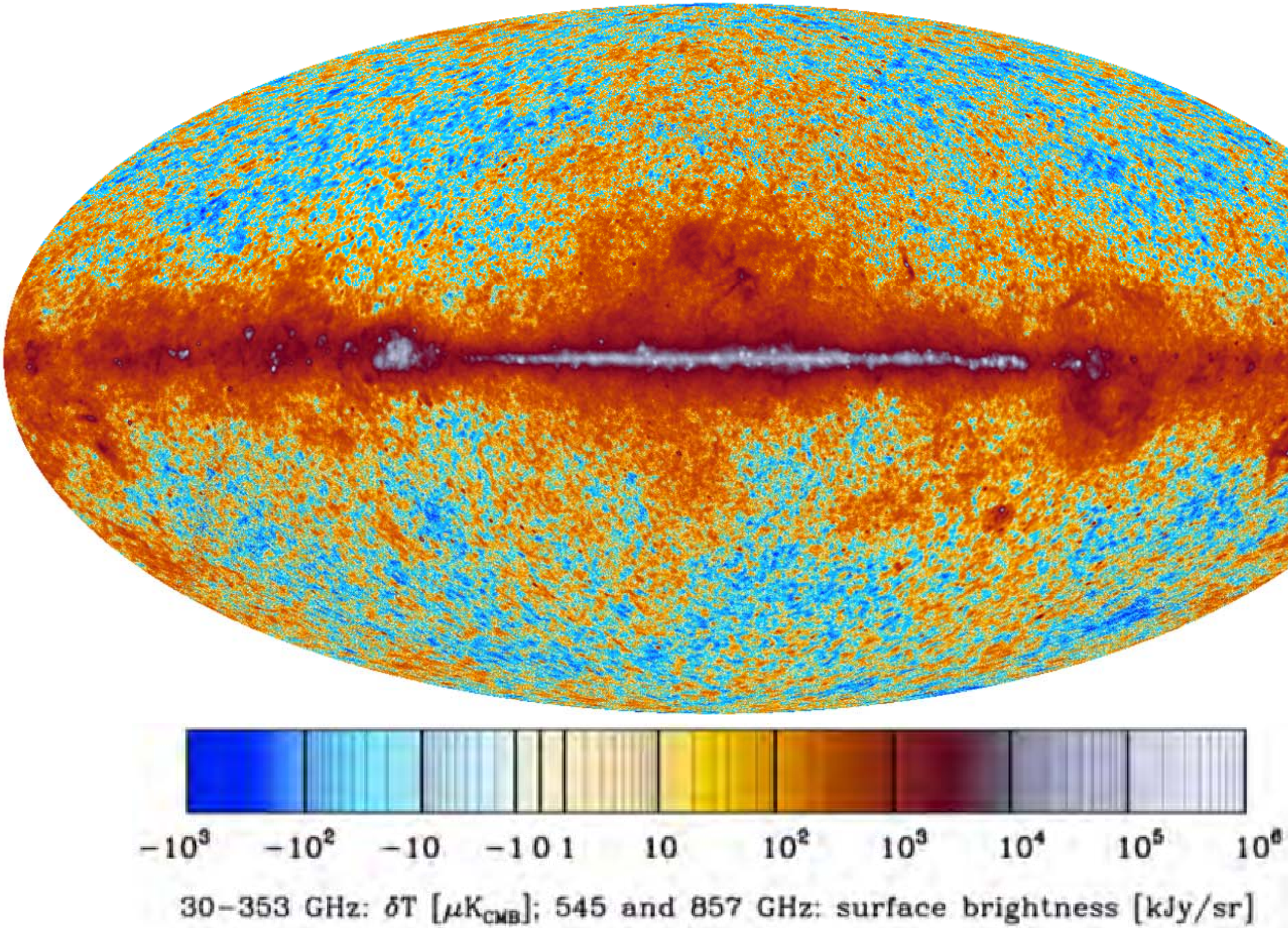


LFI
HFI
30 P
44 P
70 P
100 P
143 P
217 P
353 P
545
857
total Galaxy fluctuations
The power of Planck !
ΔCMB
EG, 10'
Optimal Components Separation
dust
synchrotron
free−free
Brightness Temperature (μK)
1000
100
10
1
10
100
1000
Frequency (GHz)

$6x10^6$ pixels (5')

Planck Legacy Maps

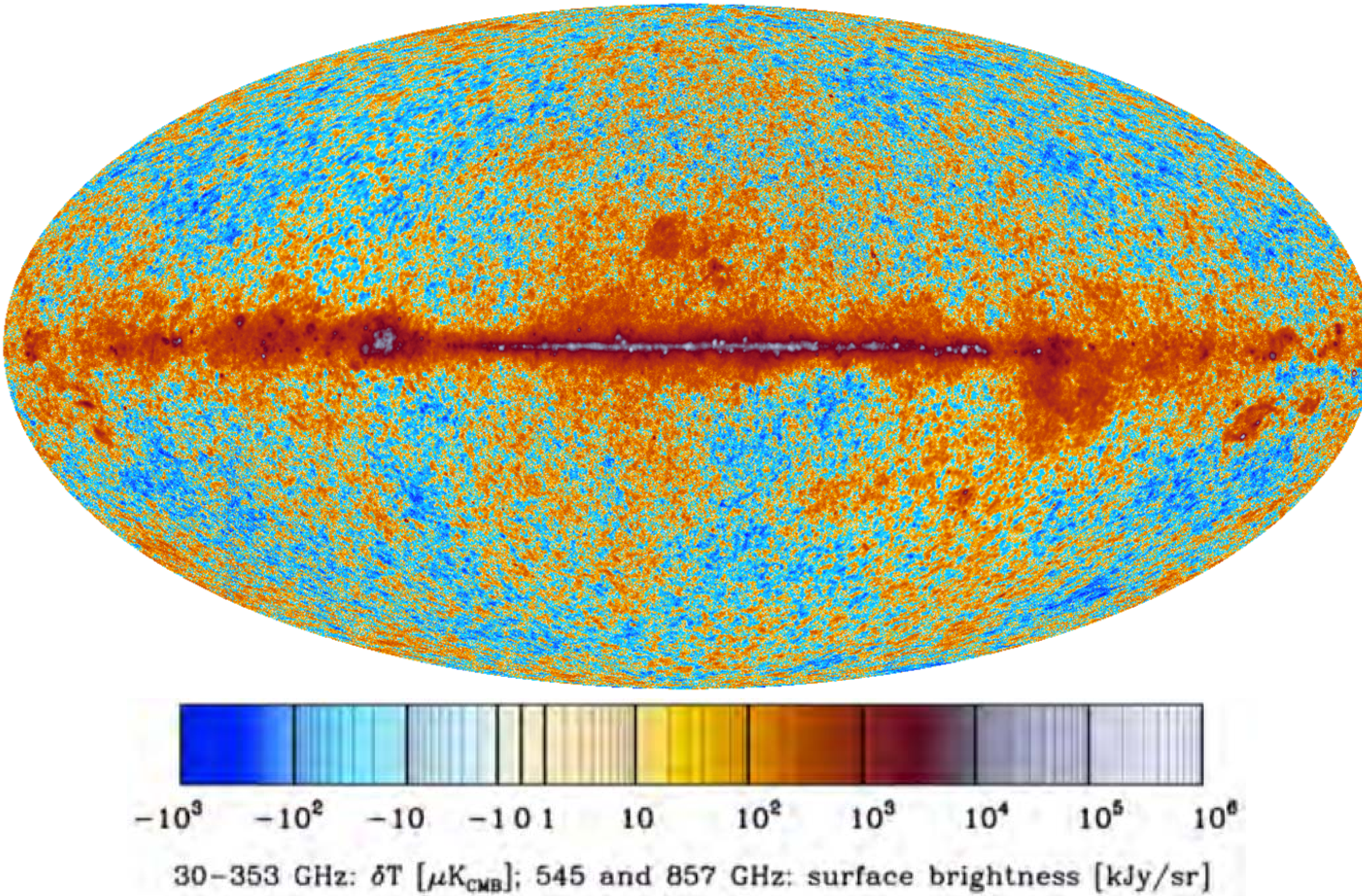
30 GHz



$6x10^6$ pixels (5')

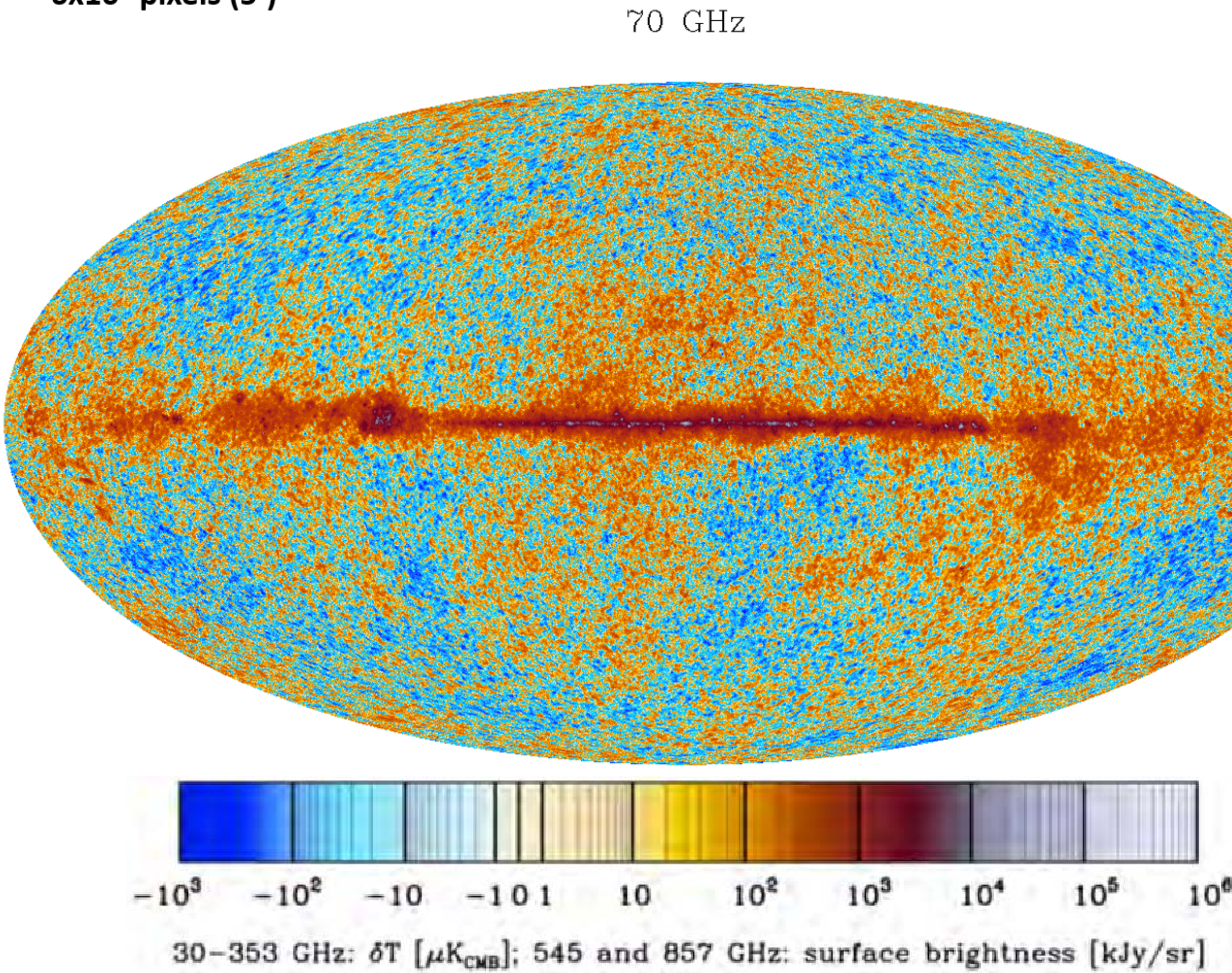
Planck Legacy Maps

44 GHz



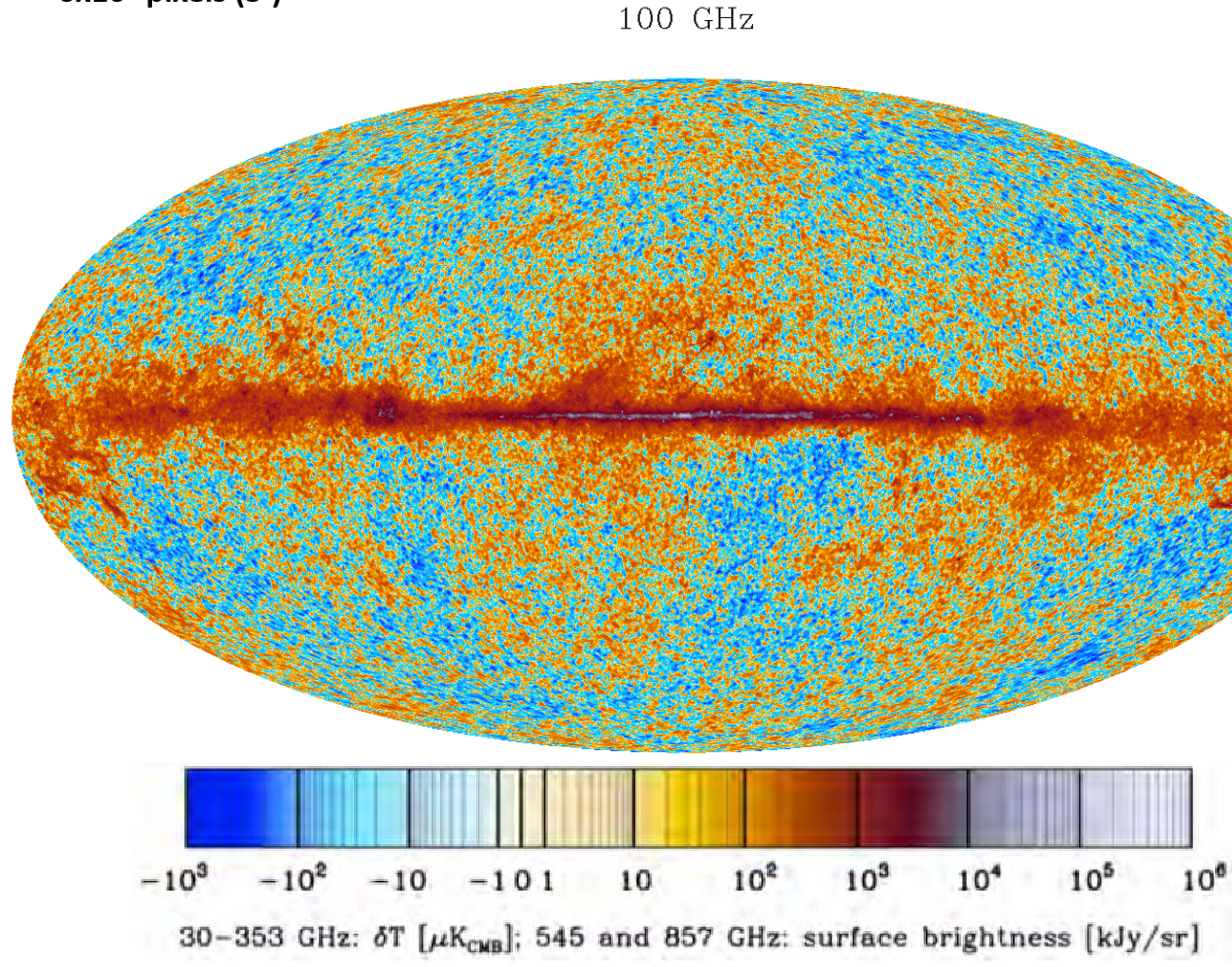
Planck Legacy Maps

$6x10^6$ pixels (5')



Planck Legacy Maps

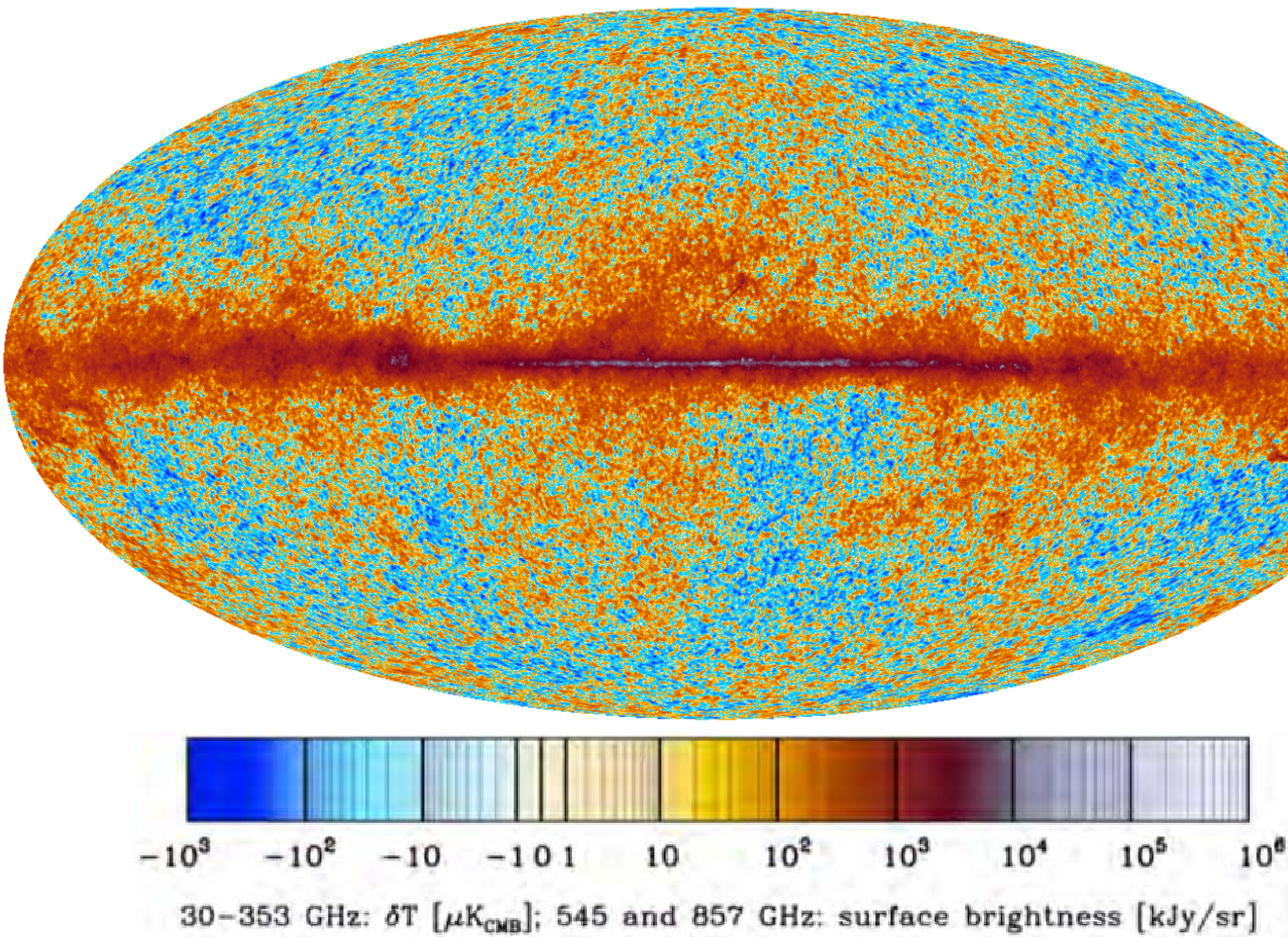
$6x10^6$ pixels (5')



$6x10^6$ pixels (5’)

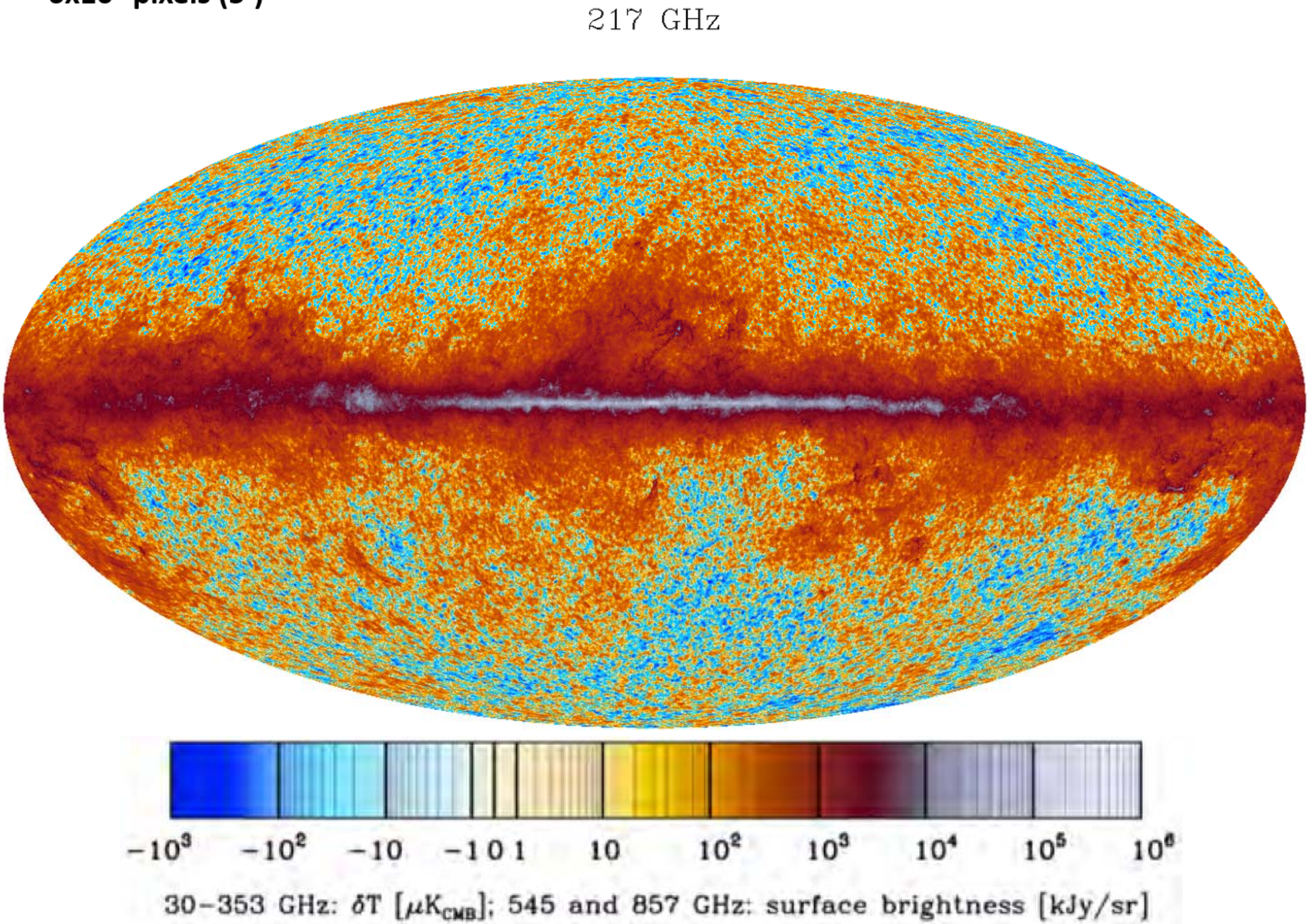
Planck Legacy Maps

143 GHz



6×10^6 pixels (5')

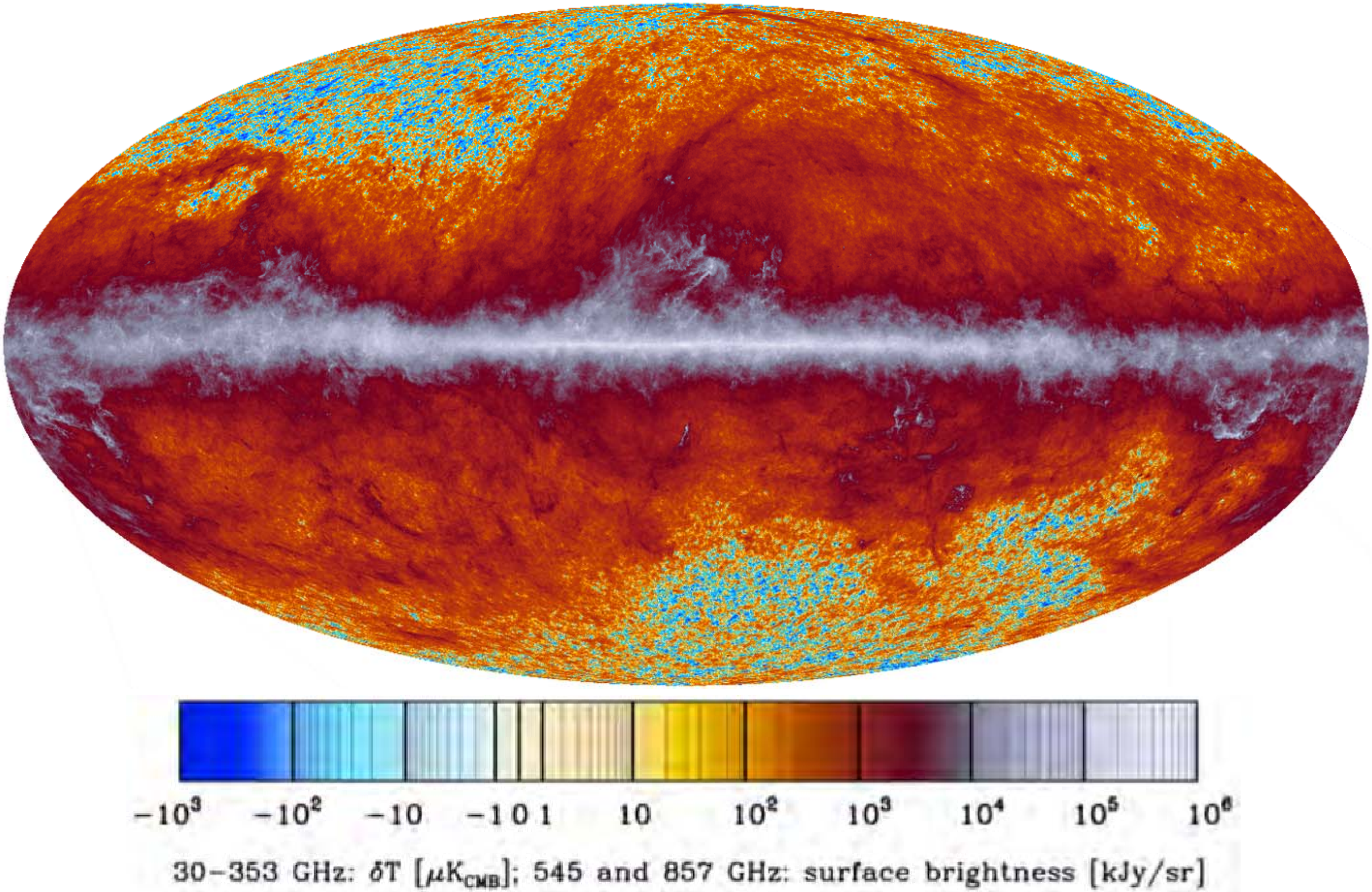
Planck Legacy Maps



Planck Legacy Maps

$6x10^6$ pixels (5')

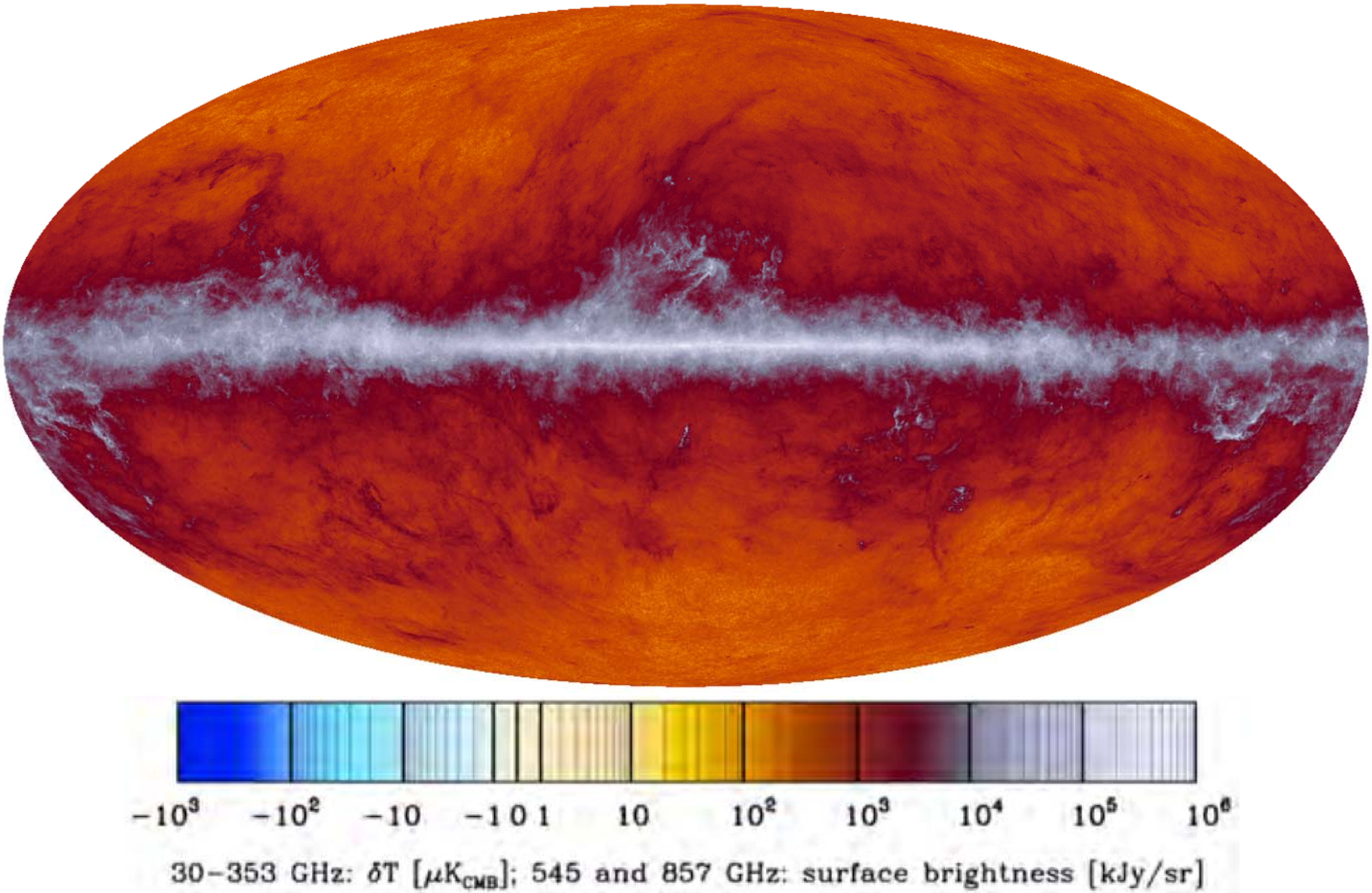
353 GHz



6×10^6 pixels (5')

Planck Legacy Maps

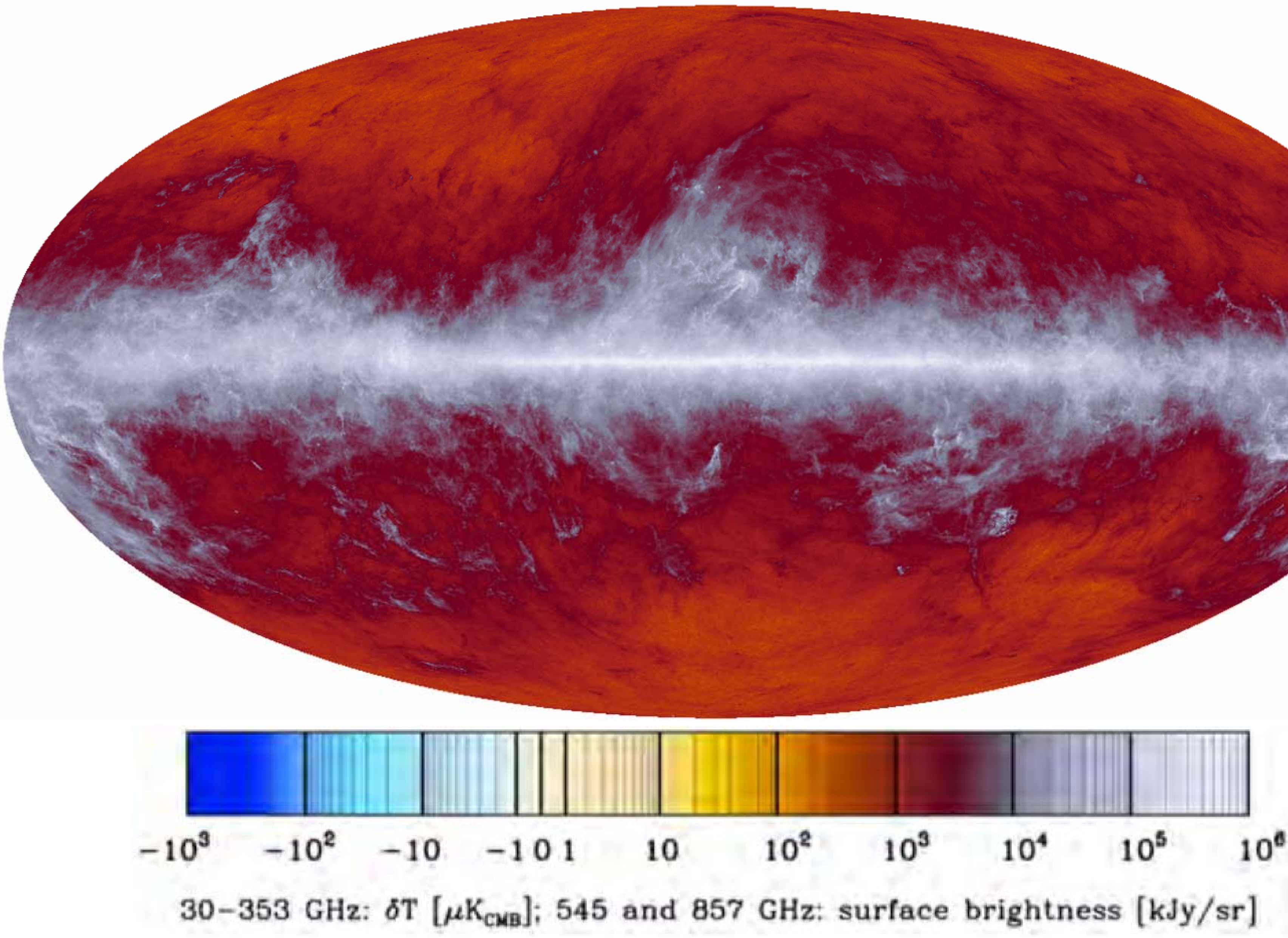
545 GHz



Planck Legacy Maps

857 GHz

$6x10^6$ pixels (5')



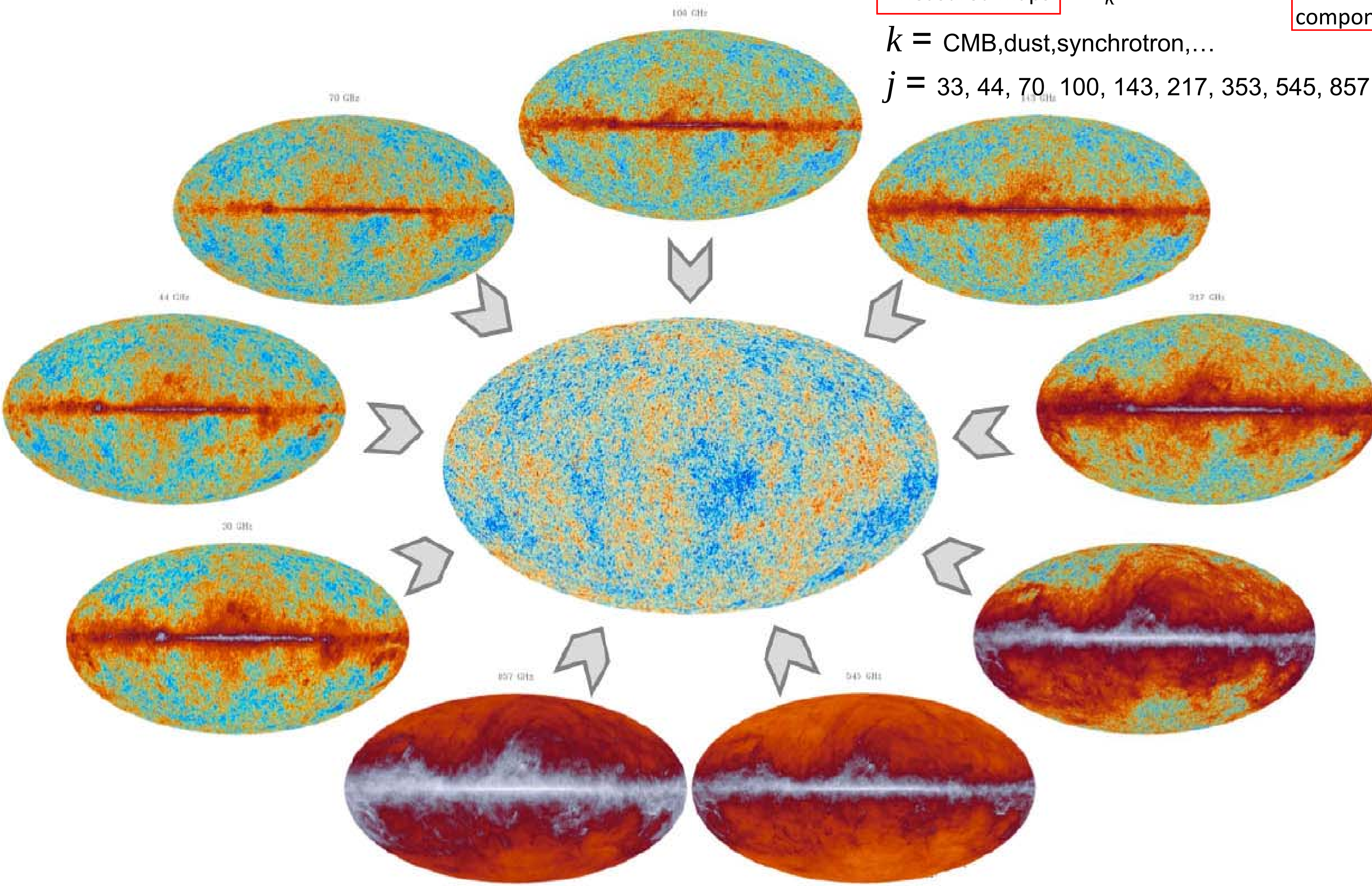
components separation

$$\Delta T(\nu_j,\ell,b) = \sum_k a_k(\nu_j,\ell,b)C_k(\ell,b)$$

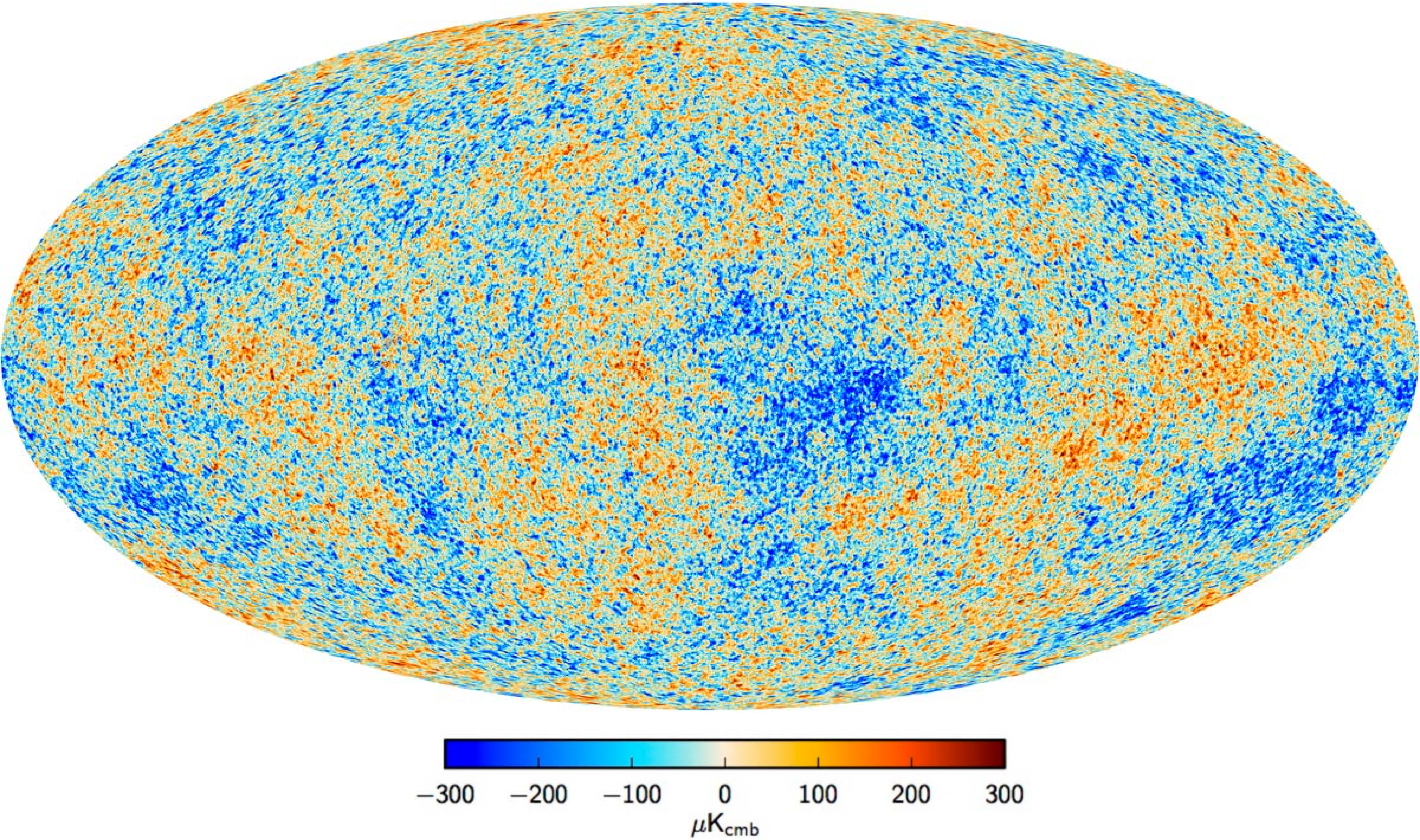
Measured maps — physical components

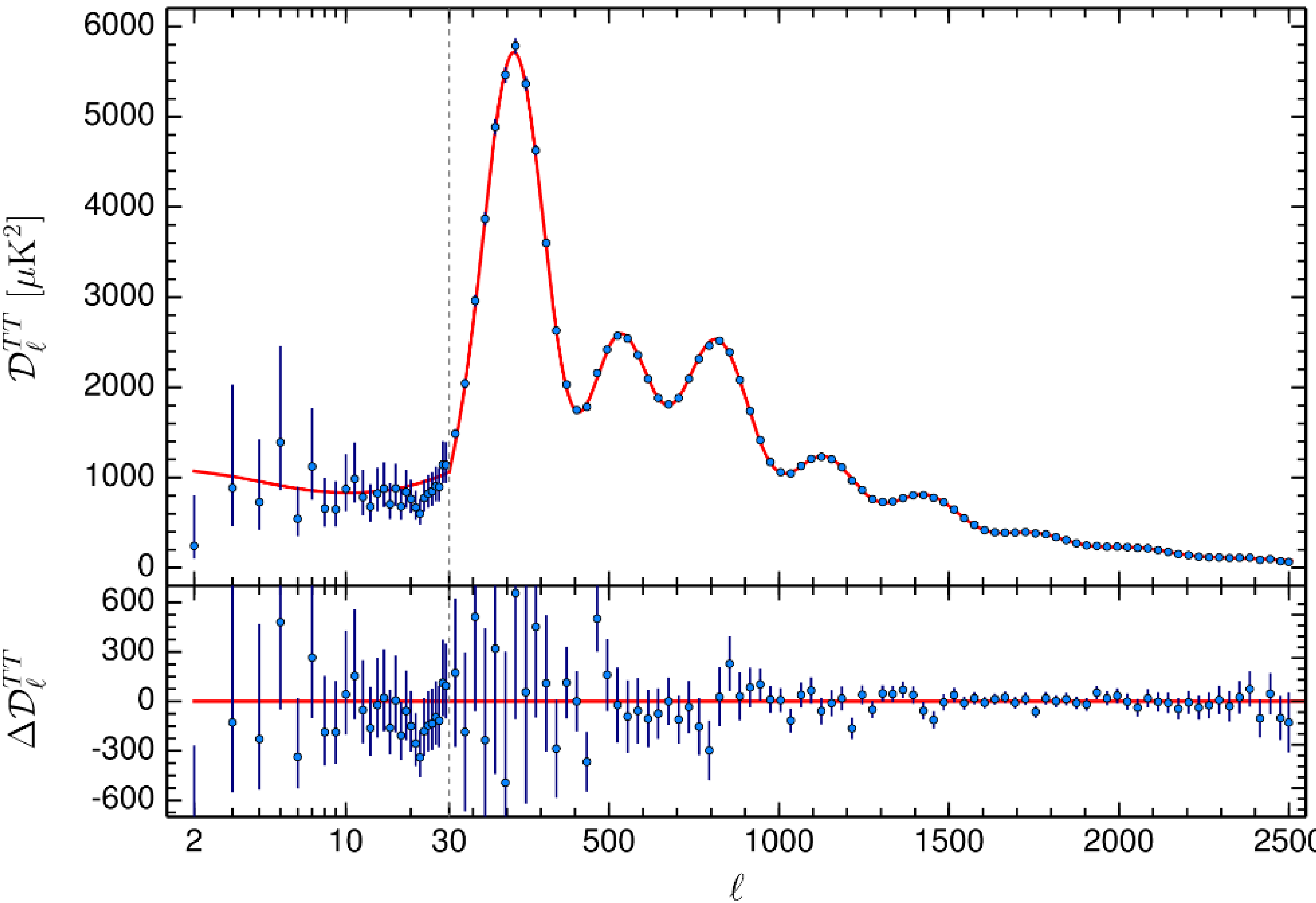
k = CMB,dust,synchrotron,…

j = 33, 44, 70, 100, 143, 217, 353, 545, 857 GHz



The CMB component





6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
60
30
0
-30
-60
$\Delta\mathcal{D}_\ell^{TT}$
2
10
30
500
1000
1500
2000
2500
ℓ

Best fit parameters :

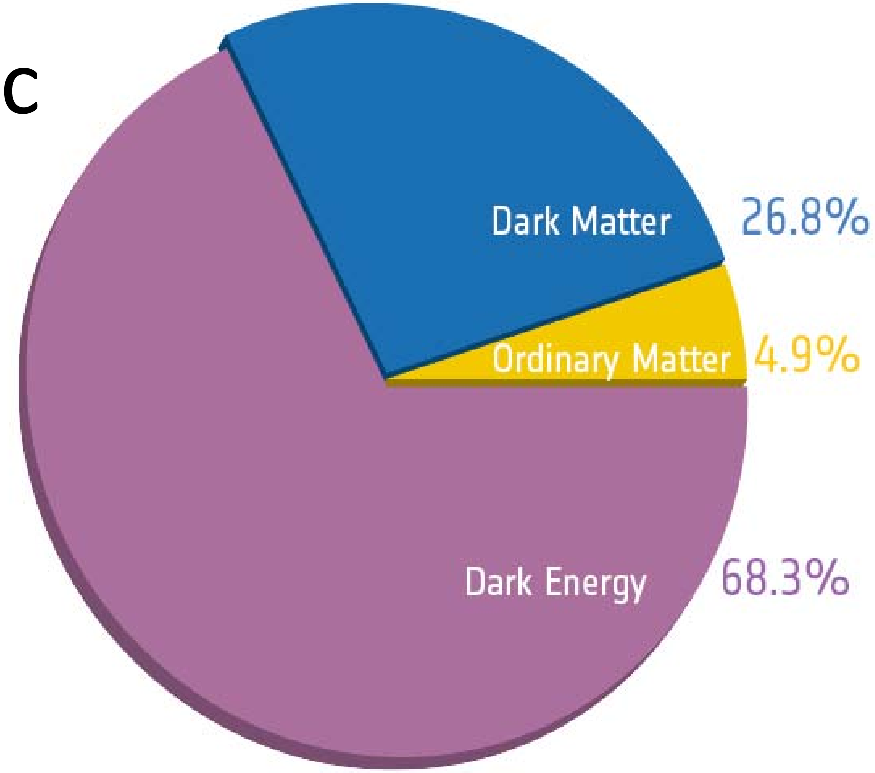
$H_o = (67.3 \pm 1.0)$ km/s/Mpc

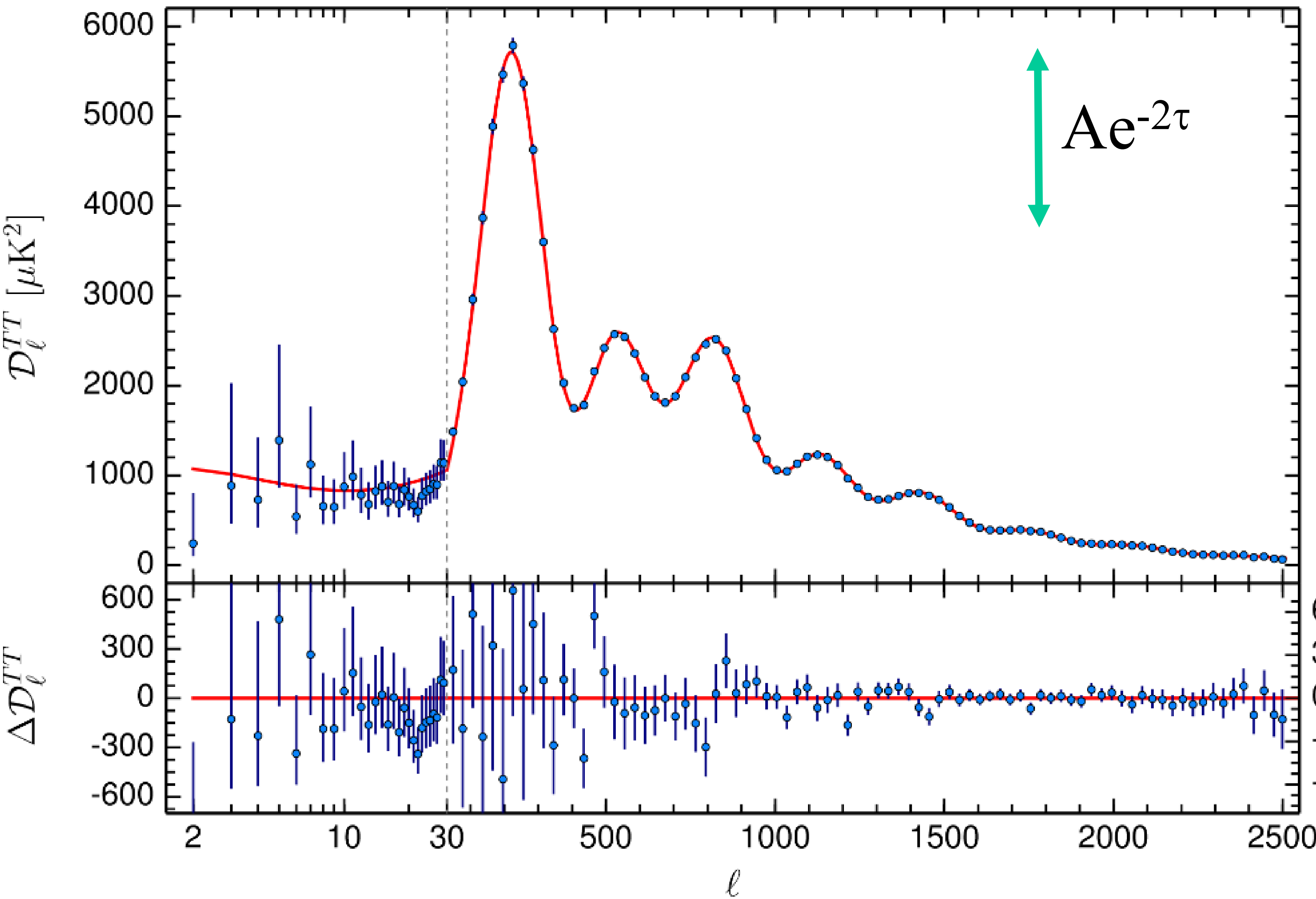
Consistent with low-redshift BAO
and corrected Cepheids data

$n_s=(0.9652 \pm 0.0062)$

Consistent with Inflation

(nearly scale-invariant adiabatic density perturbations,
n_s has to be slightly < 1)





6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
Ae$^{-2\tau}$
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

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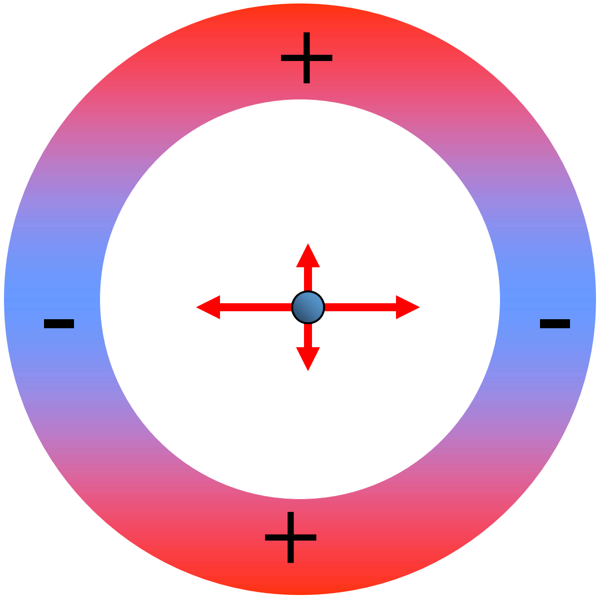
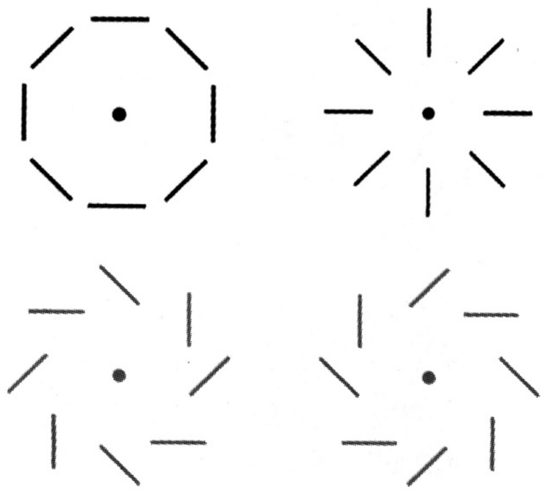
CMB Polarization

- Linear Polarization of CMB photons is produced by Thomson scattering at recombination (z=1100) and at reionization (z=10).

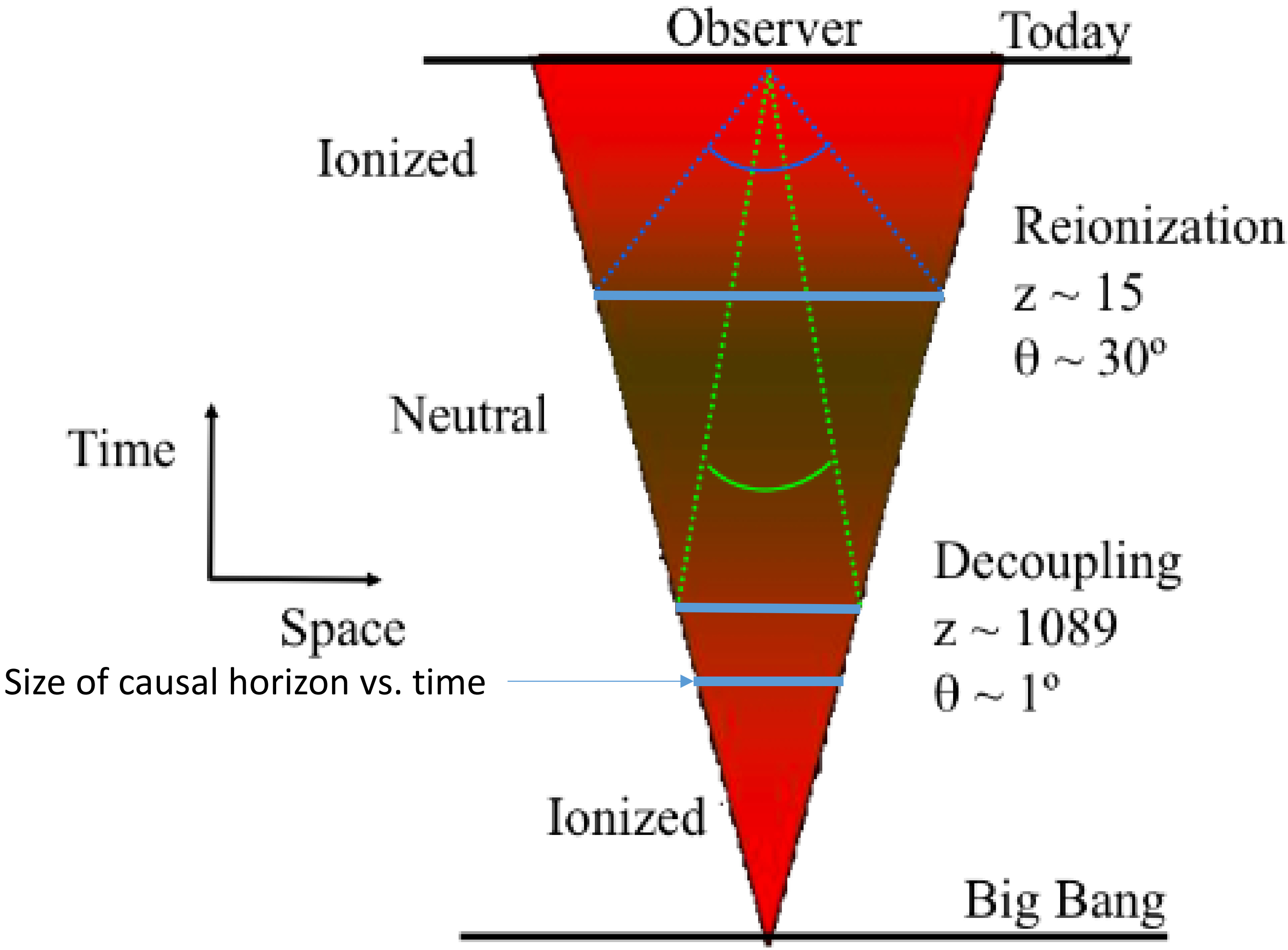


- Scattered photons are polarized only if the incoming radiation has a quadrupole anisotropy. This is induced by:
  - Density perturbations (*scalar* relics of inflation) producing a curl-free field of polarization vectors (**E-modes**)
  - Gravitational waves (*tensor* relics of inflation) producing both curl-free **and curly** field of polarization vectors (**B-modes**)
- There are no other sources for a curly polarization field of the CMB at large angular scales:
- **B-modes at large scales are a clear signature of inflation**.
- Many experiments are trying to measure inflationary B-modes, only upper limits are available to-date.

E-modes

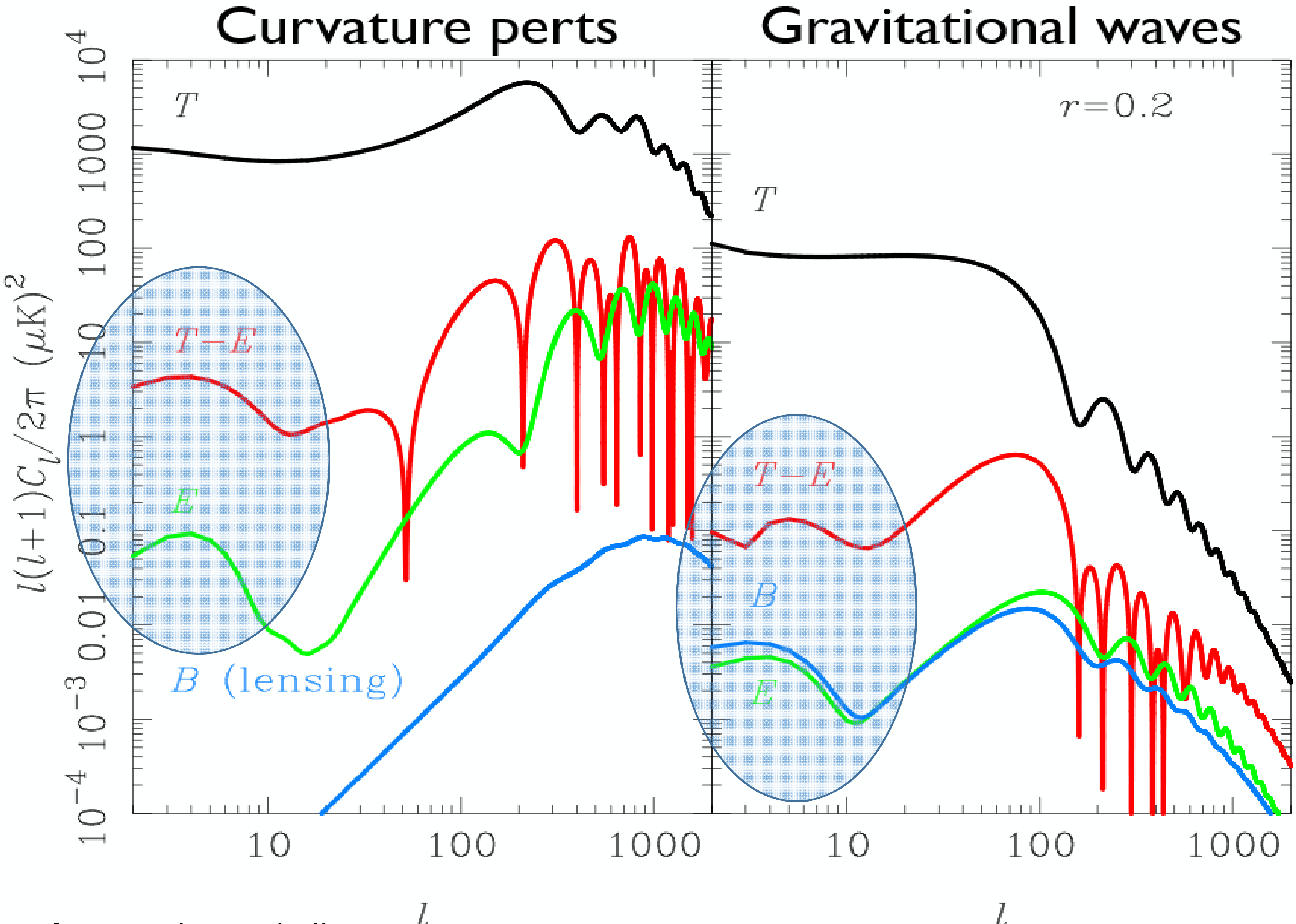


B-modes



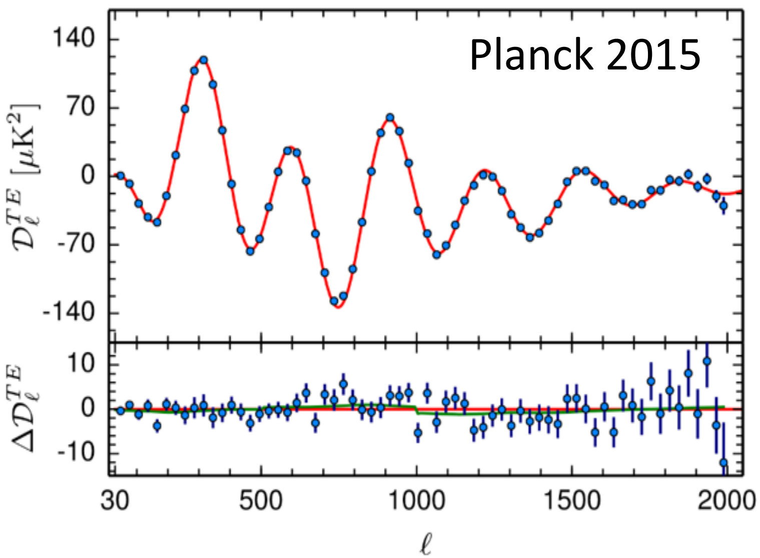
Observer
Today
Ionized
Reionization
z ~ 15
θ ~ 30°
Neutral
Time
Space
Decoupling
z ~ 1089
θ ~ 1°
Size of causal horizon vs. time
Ionized
Big Bang

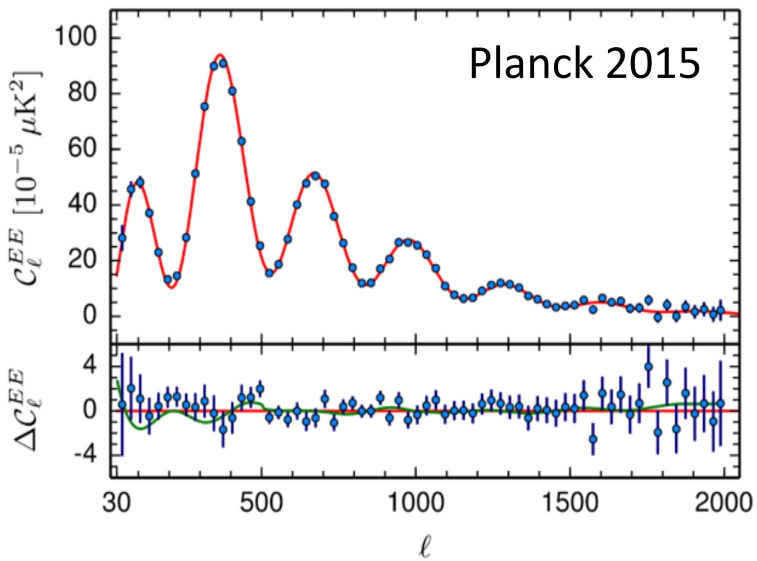
Polarization Spectra

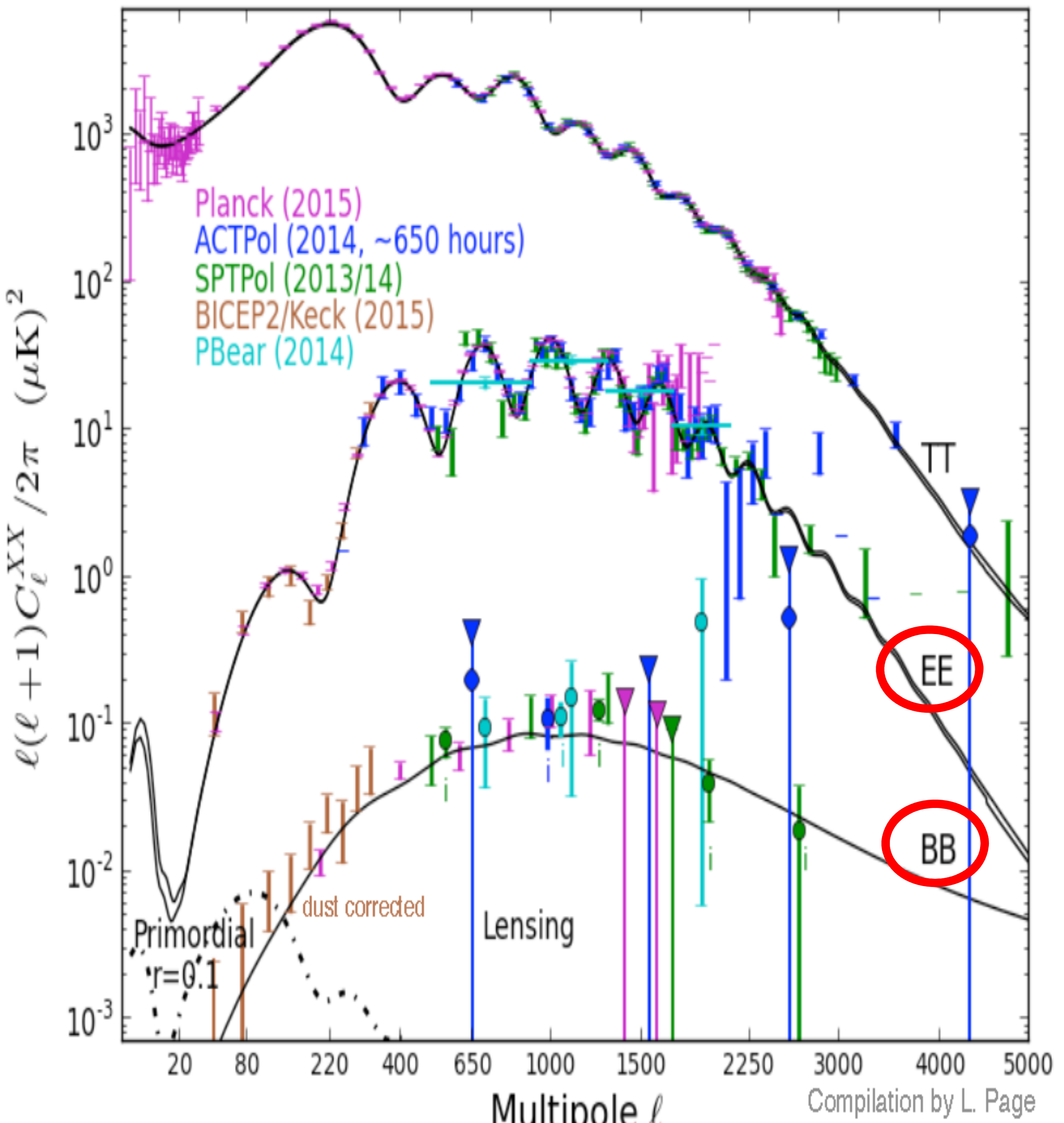


Spectra from Anthony Challinor

CMB Polarization results at intermediate and small scales

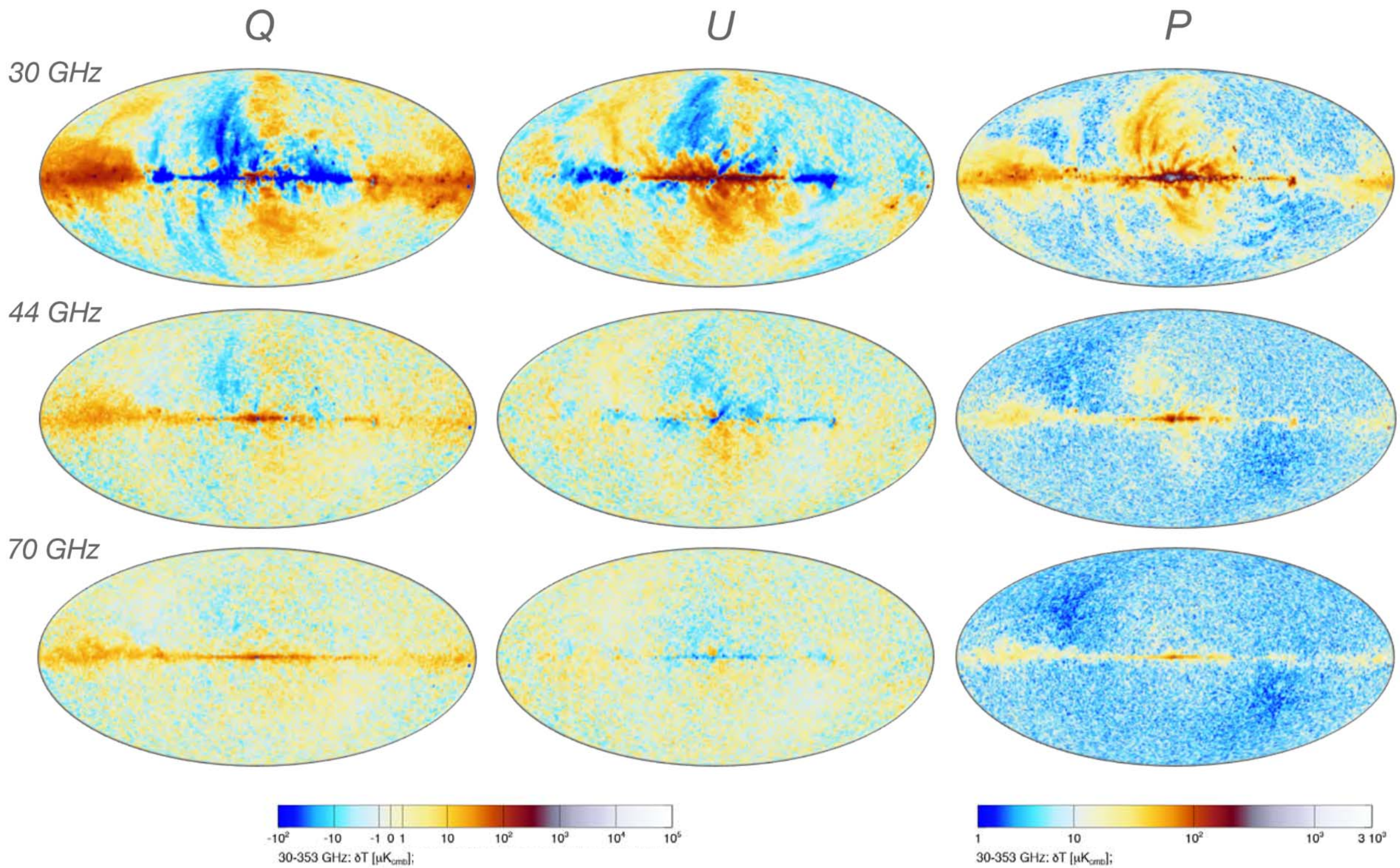




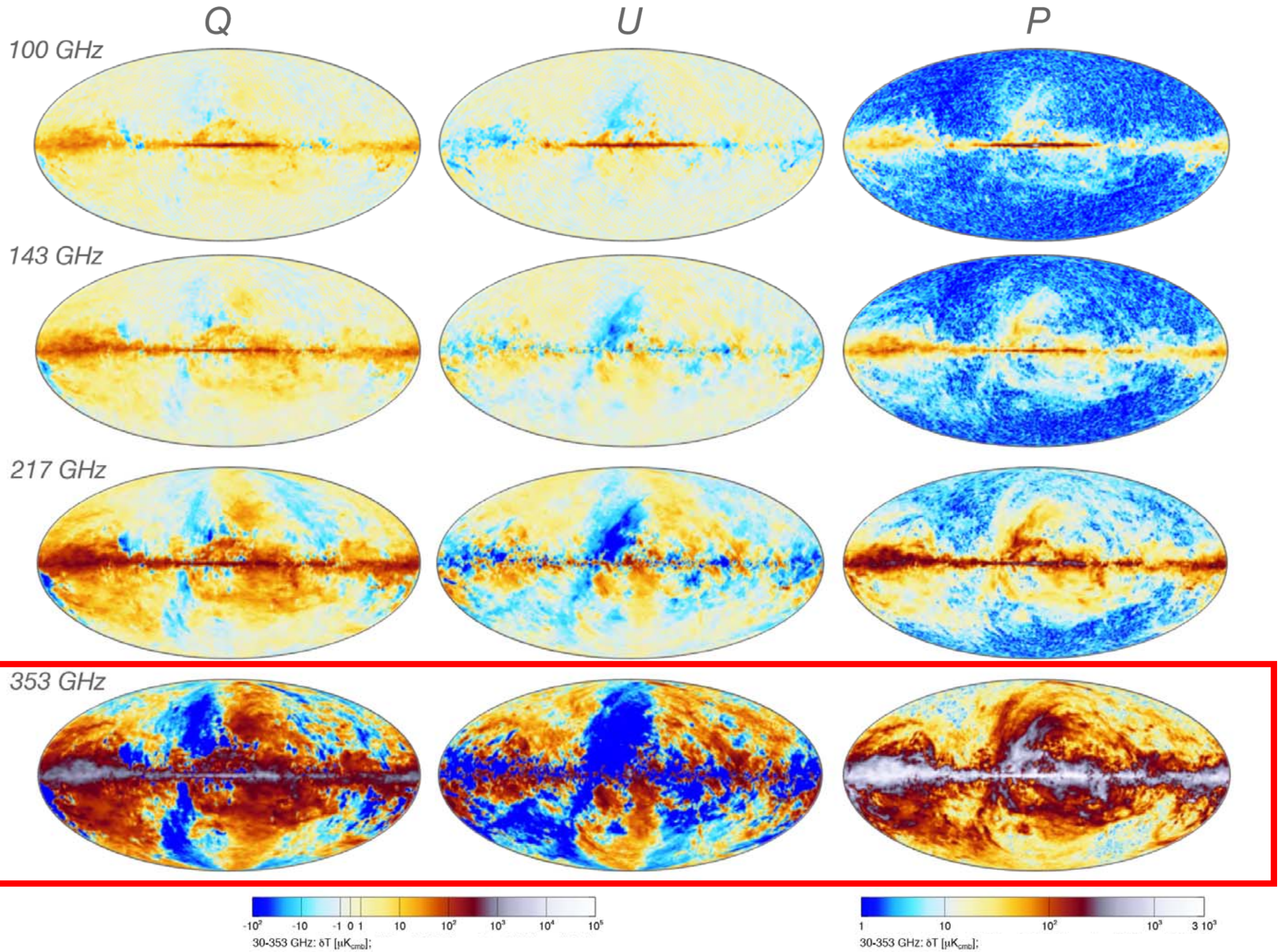


Planck 2015: All-sky polarization measurements. LFI maps

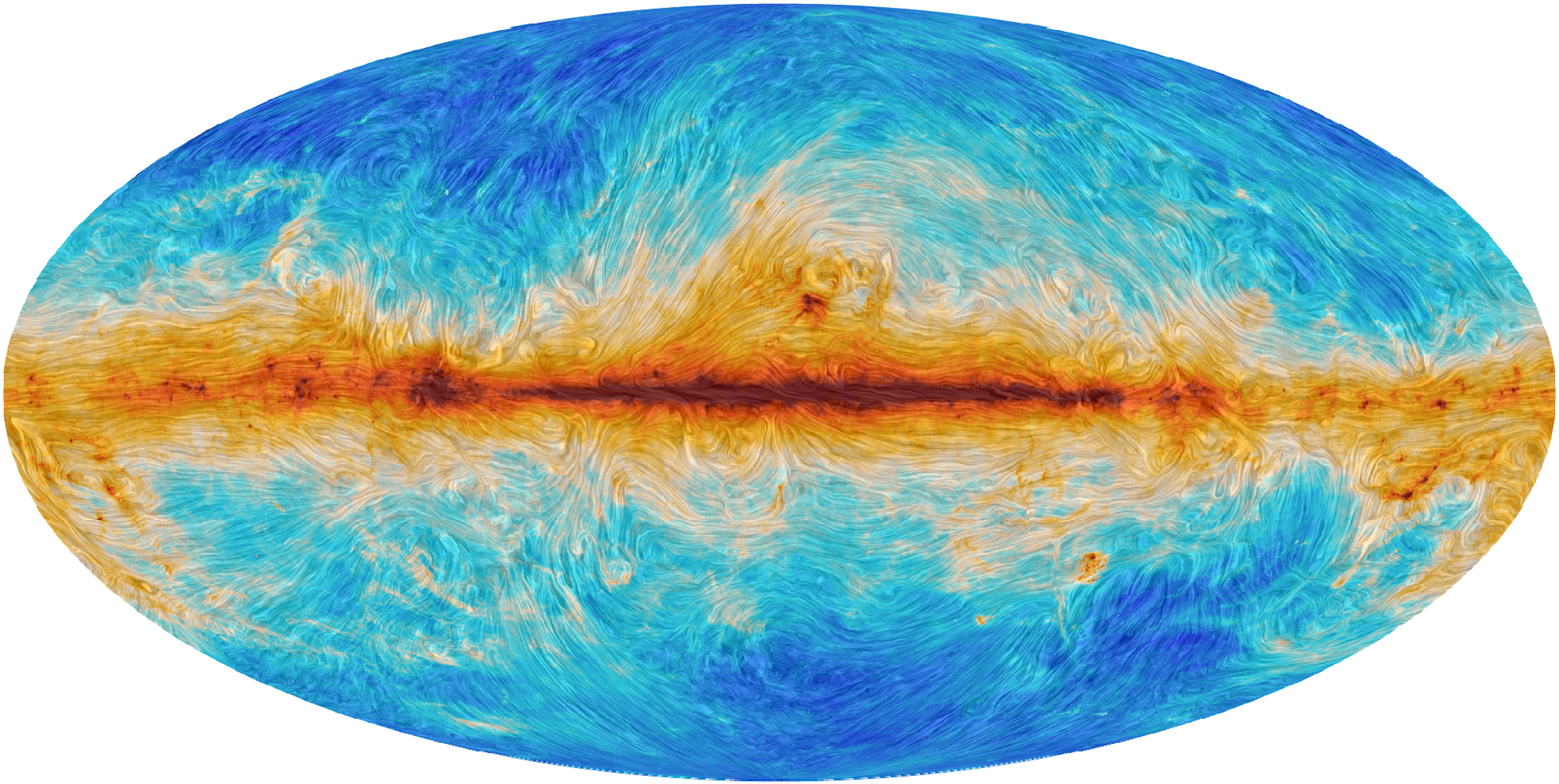
Astro-ph/1502.01582v2

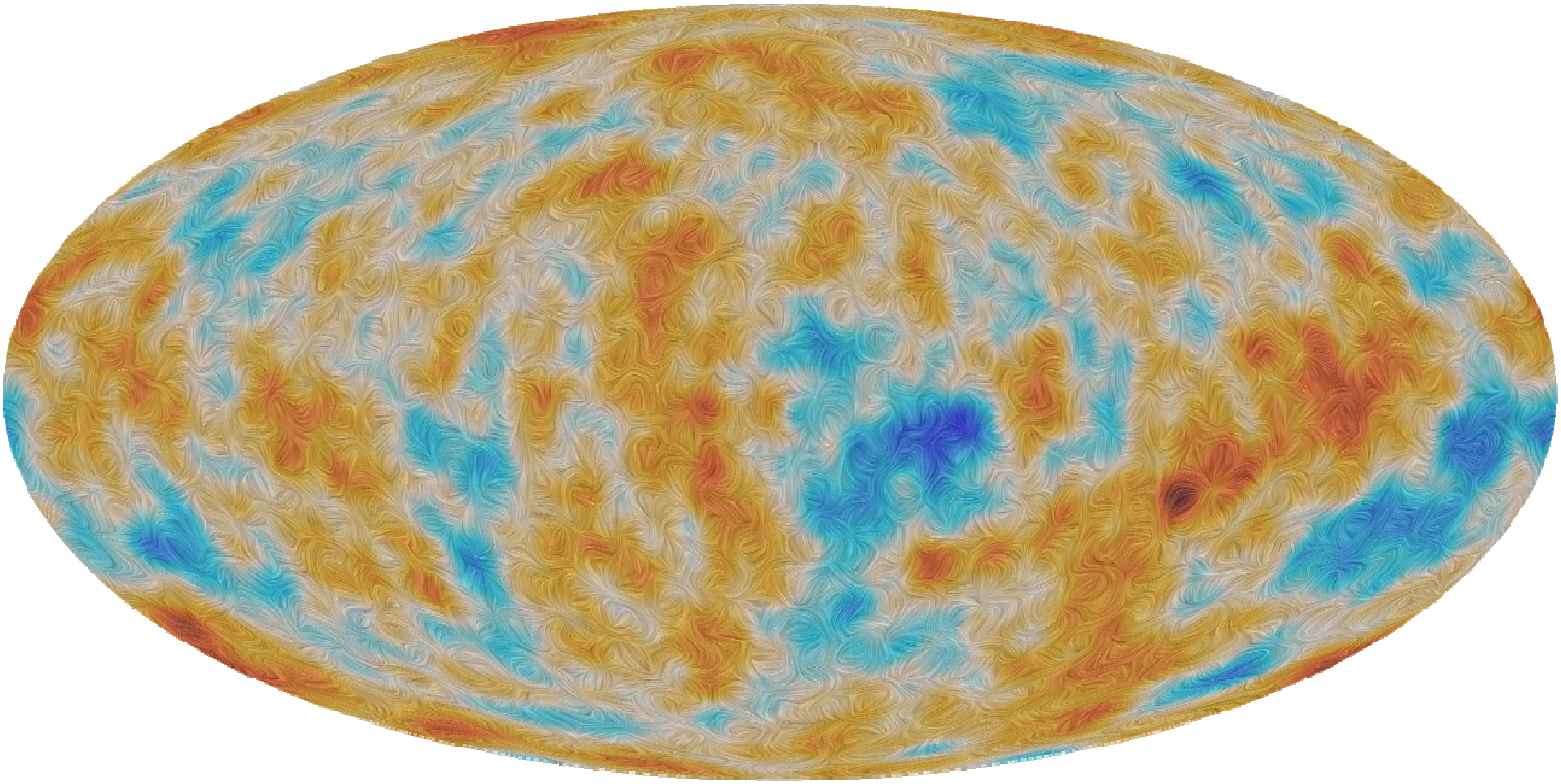


Planck 2015: All-sky polarization measurements. HFI maps



Astro-ph/1502.01582v2





CMB Polarization results at large scales

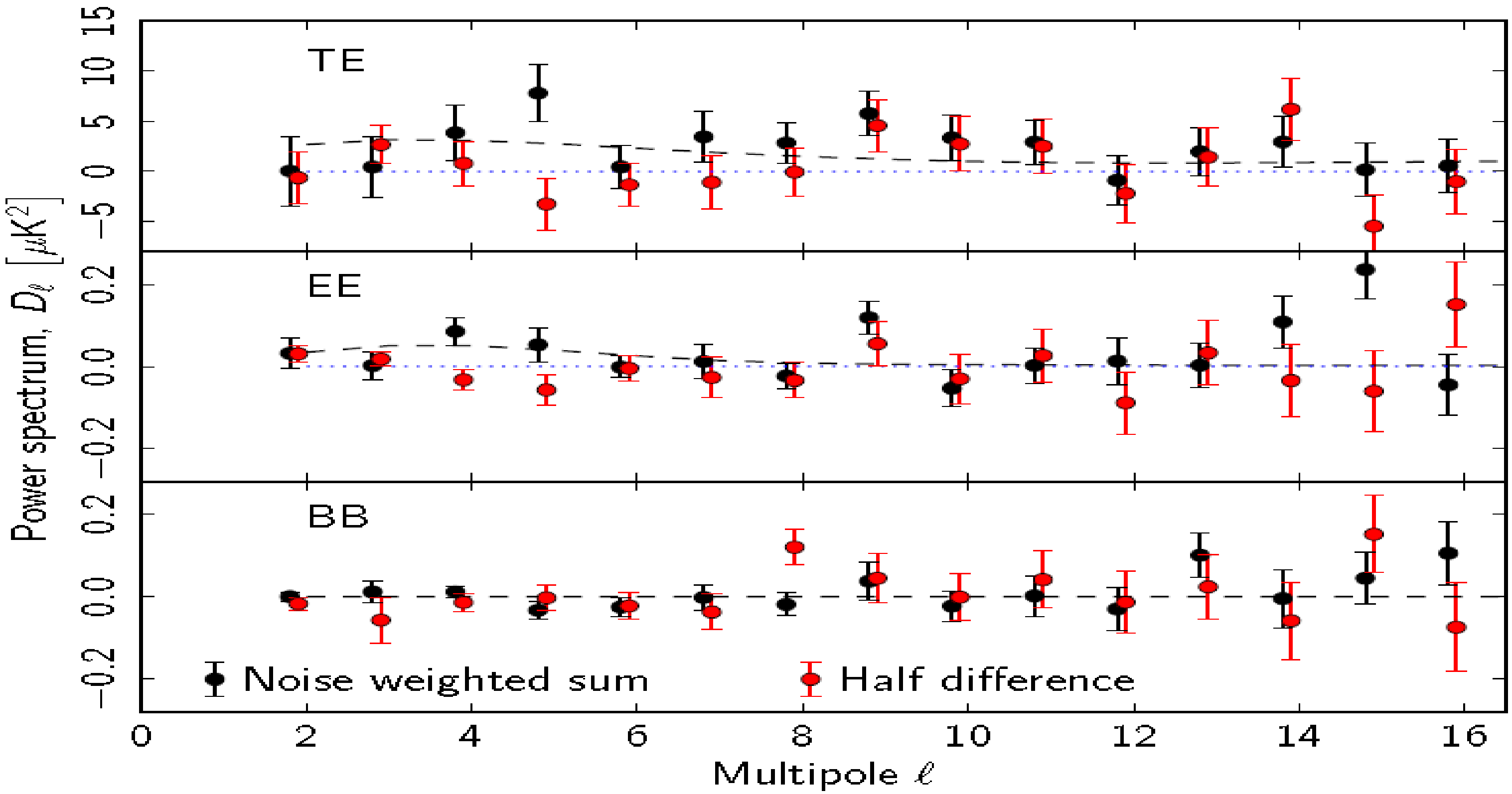


Figure 10. BolPol spectra for the noise-weighted sum (black) and half-difference (red) WMAP and *Planck* combinations. The temperature map employed is always the Commander map described in Sect. 2.2 above. The fiducial model shown has $\tau = 0.065$.

WMAP data have been corrected for polarized dust emission using Planck 353 GHz polarization data. Planck data are from LFI.

Astro-ph/1507.02704

Planck results for reionization optical depth

$$\tau = \int_{LOS} n_e \sigma_{Th} d\ell \quad \rightarrow$$

$$\tau = \frac{c\sigma_{Th}}{H_o} \int_0^{z_{re}} \frac{n_{eo}(z)}{(1+z)\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} dz$$

$$\tau = 0.078^{+0.019}_{-0.019}, \; z_{re} = 9.9^{+1.8}_{-1.6}, \; \textit{Planck}\ \text{TT+lowP}; \quad (17a)$$

$$\tau = 0.070^{+0.024}_{-0.024}, \; z_{re} = 9.0^{+2.5}_{-2.1}, \; \textit{Planck}\ \text{TT+lensing}; \quad (17b)$$

$$\tau = 0.066^{+0.016}_{-0.016}, \; z_{re} = 8.8^{+1.7}_{-1.4}, \; \textit{Planck}\ \text{TT+lowP +lensing}; \quad (17c)$$

$$\tau = 0.067^{+0.016}_{-0.016}, \; z_{re} = 8.9^{+1.7}_{-1.4}, \; \textit{Planck}\ \text{TT+lensing +BAO}; \quad (17d)$$

$$\tau = 0.066^{+0.013}_{-0.013}, \; z_{re} = 8.8^{+1.3}_{-1.2}, \; \textit{Planck}\ \text{TT+lowP +lensing+BAO}. \quad (17e)$$

Astro-ph/1502.01589

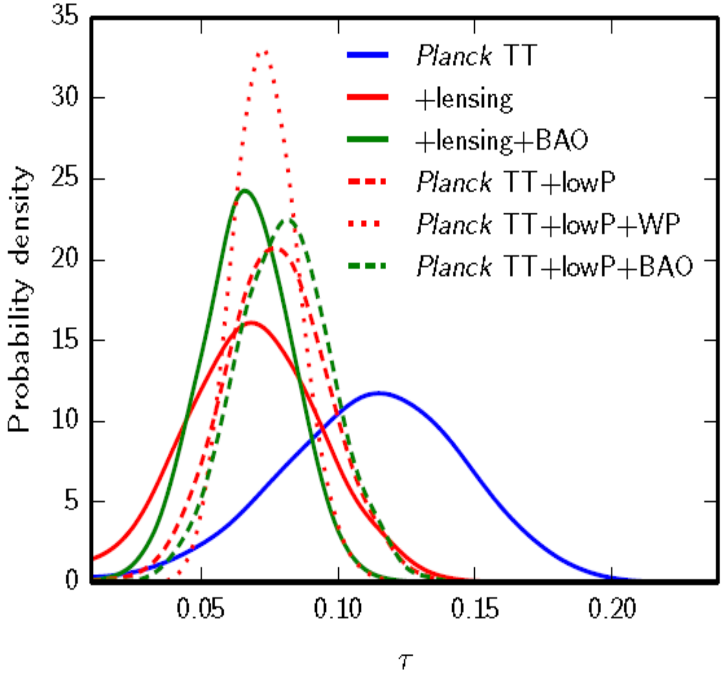


Fig. 8. Marginalized constraints on the reionization optical depth in the base ΛCDM model for various data combinations. Solid lines do not include low multipole polarization; in these cases the optical depth is constrained by *Planck* lensing. The dashed/dotted lines include LFI polarization (+lowP), or the combination of LFI and WMAP polarization cleaned using 353 GHz as a dust template (+lowP+WP).

$$z_{re} = 8.8 \pm^{1.3}_{1.2} \quad \rightarrow \quad t_{re} = (560 \pm^{140}_{80})\,Myr$$

Latest interaction: clusters of galaxies

- Inverse Compton Effect for CMB photons against charged particles in the hot gas of clusters (same as y-type distortion)
- Cluster optical depth: $\tau = n\sigma\ell$

  ℓ = a few Mpc = 10^{25} cm

  $n < 10^{-3}$ cm^{-3}

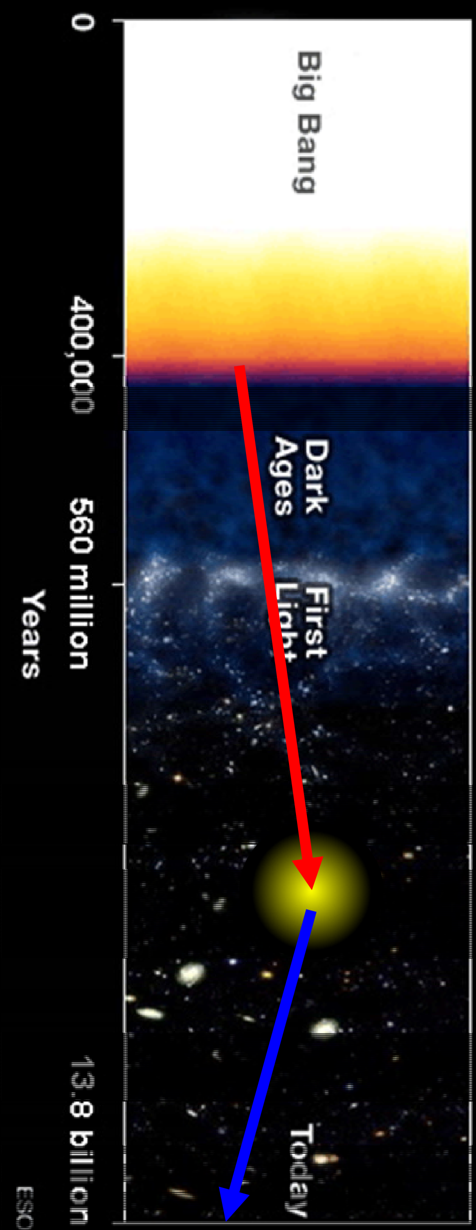
  $\sigma = 6.65\times10^{-25}$ cm^2

- So $\tau = n\sigma\ell < 0.01$: there is a 1% likelihood that a CMB photon crossing the cluster is scattered by an electron
- $E_{electron} >> E_{photon}$, so the electron transfers energy to the photon. To first order, the energy gain of the photon is

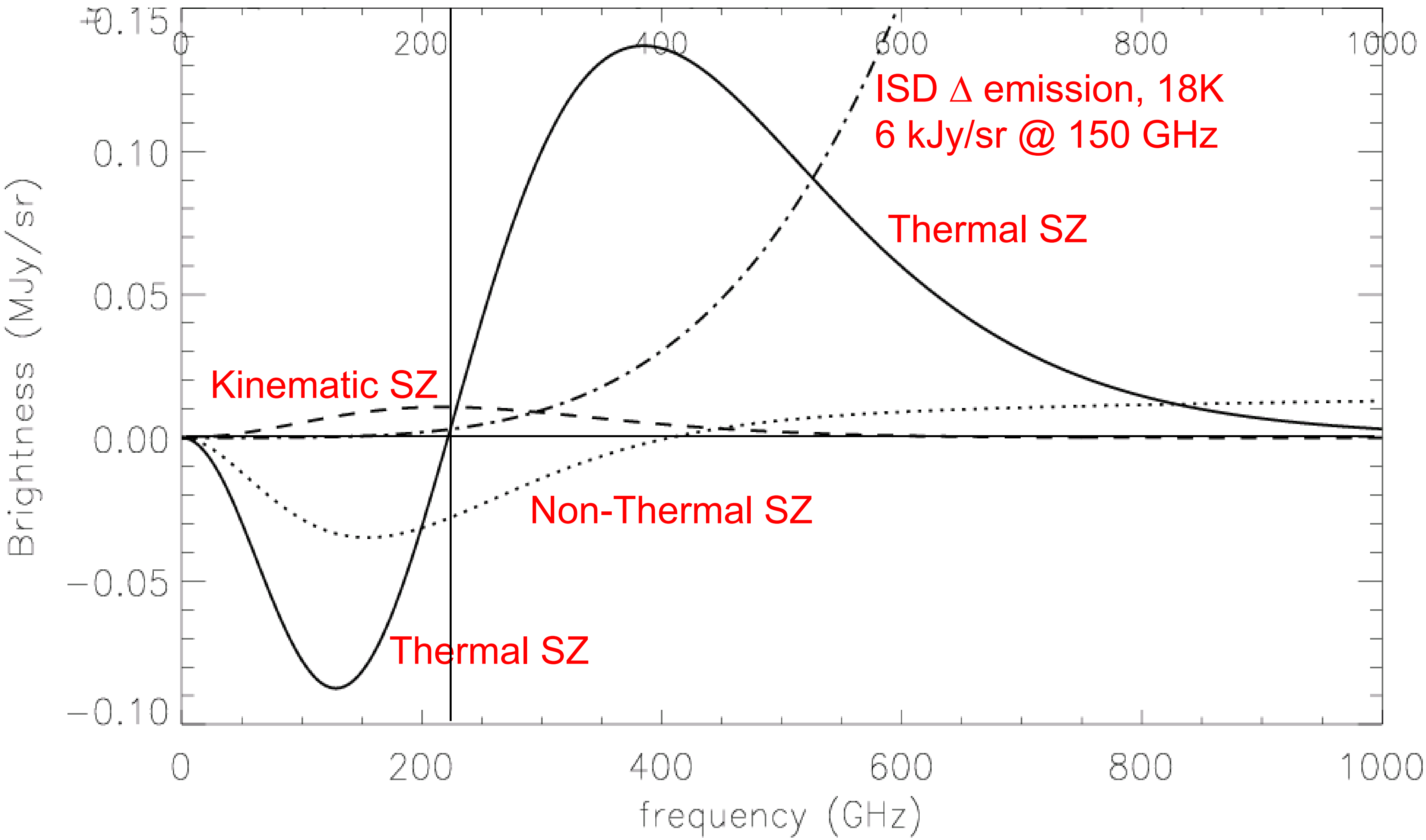
$$\frac{\Delta\nu}{\nu} = \frac{kT_e}{m_e c^2} \approx \frac{5keV}{500keV} = 0.01$$

- The resulting CMB temperature anisotropy is

$$\frac{\Delta T}{T} \approx \tau \frac{\Delta\nu}{\nu} \approx 0.01 \times 0.01 = 10^{-4}$$



Sunyaev R., Zeldovich Y.B., 1972, Comm. Astrophys. Space Phys., 4, 173
Birkinshaw M., 1999, Physics Reports, 310, 97-195

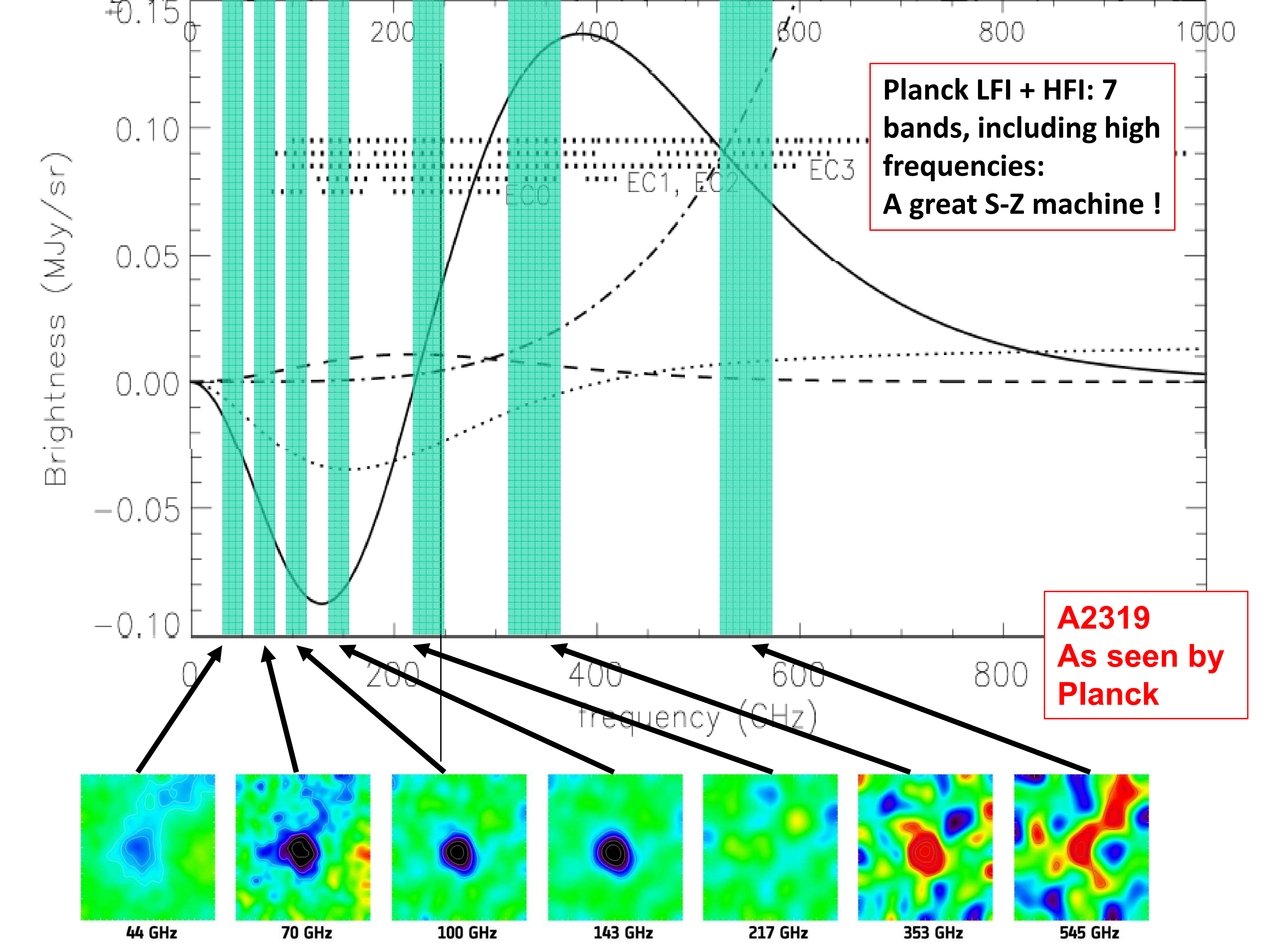


• The SZE can be used in a variety of ways, both as a probe of the physics of the intracluster medium, and as a way to probe the universe by means of distant galaxy clusters.

Sunyaev-Zeldovich Effect

Things you can do with the SZ

- In clusters: combining SZ brightness measurements and X-ray brightness measurements, estimate H_o
- In clusters: measure the density of the gas all the way out, to the periphery (not bright in X rays)
- In clusters: peculiar velocity (kinematic SZ) and bulk flows
- In clusters: Relativistic corrections: Temperature of gas
- In clusters: Non thermal electron populations
- Tracer of the WHIM (in general)
- Probe CMB temperature evolution with z
- Surveys: clusters counts and sz correlation functions as cosmological tools


Planck LFI + HFI: 7 bands, including high frequencies:
A great S-Z machine !
A2319
As seen by Planck
Brightness (MJy/sr)
frequency (GHz)
EC0
EC1, EC2
EC3
0.15
0.10
0.05
0.00
−0.05
−0.10
0
200
400
600
800
1000
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz

components separation:

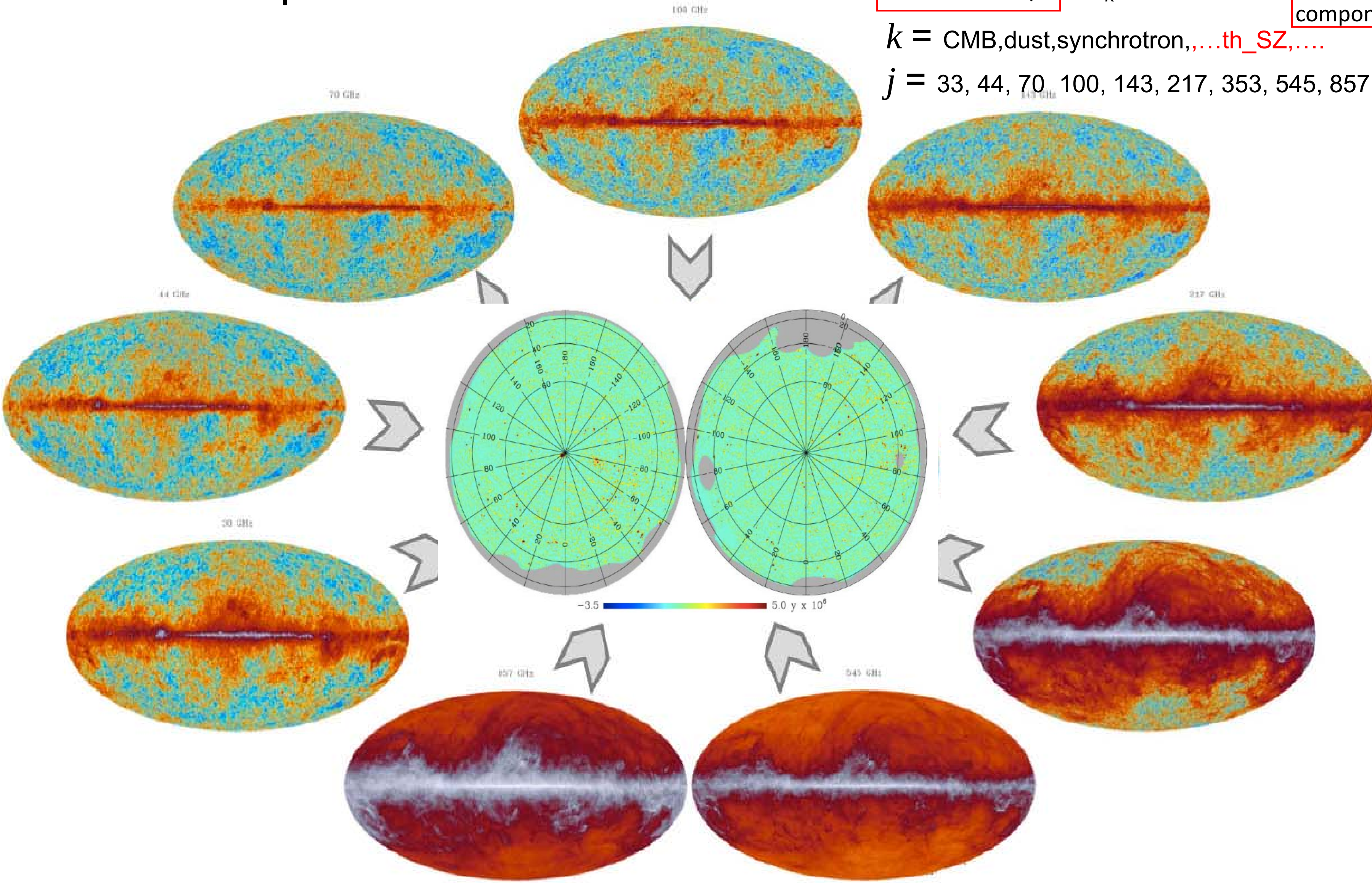
the power of Planck !

$$\Delta T(\nu_j,\ell,b) = \sum_k a_k(\nu_j,\ell,b)\, C_k(\ell,b)$$

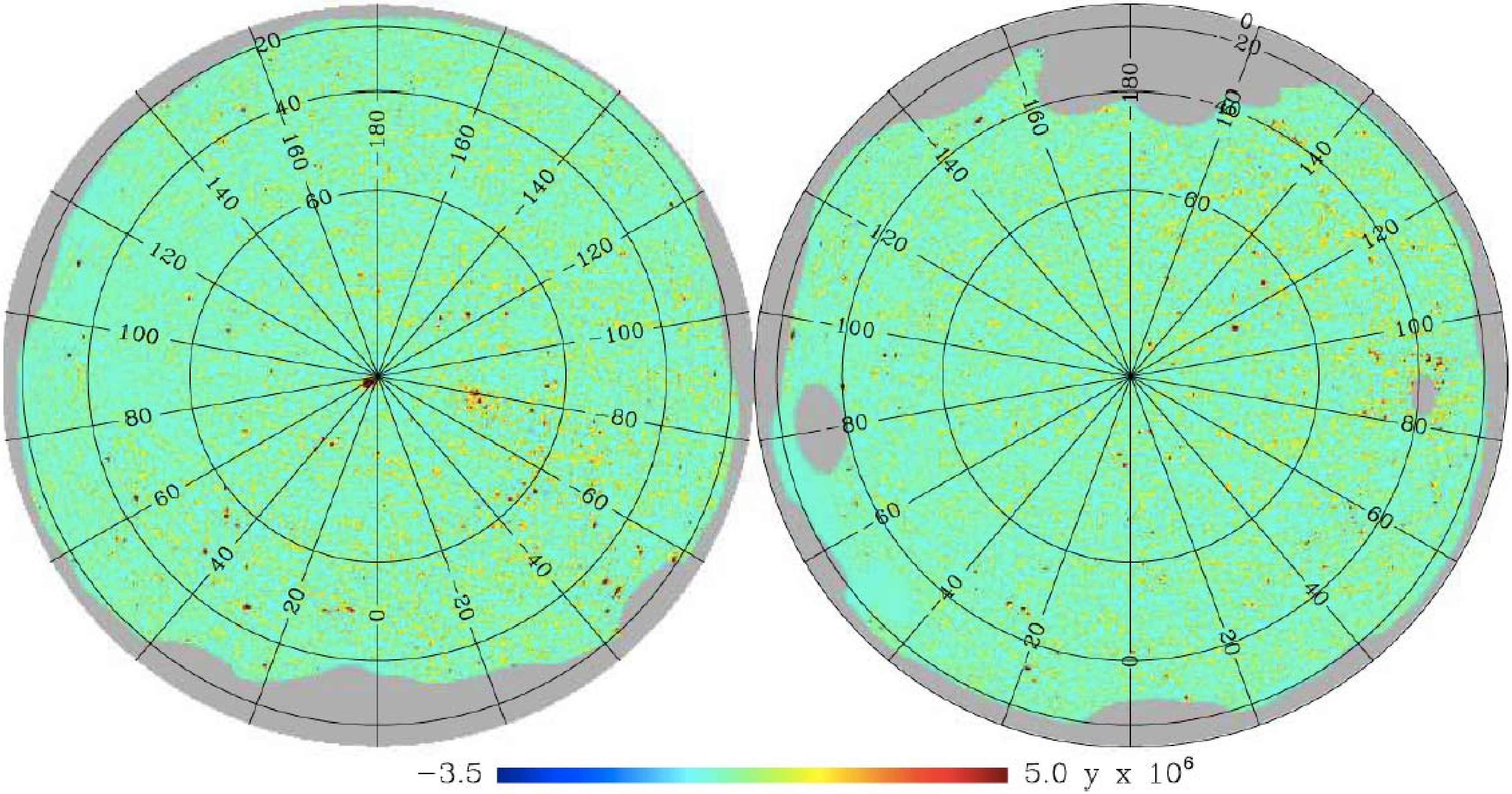
Measured maps — physical components

k = CMB,dust,synchrotron,,….th_SZ,….

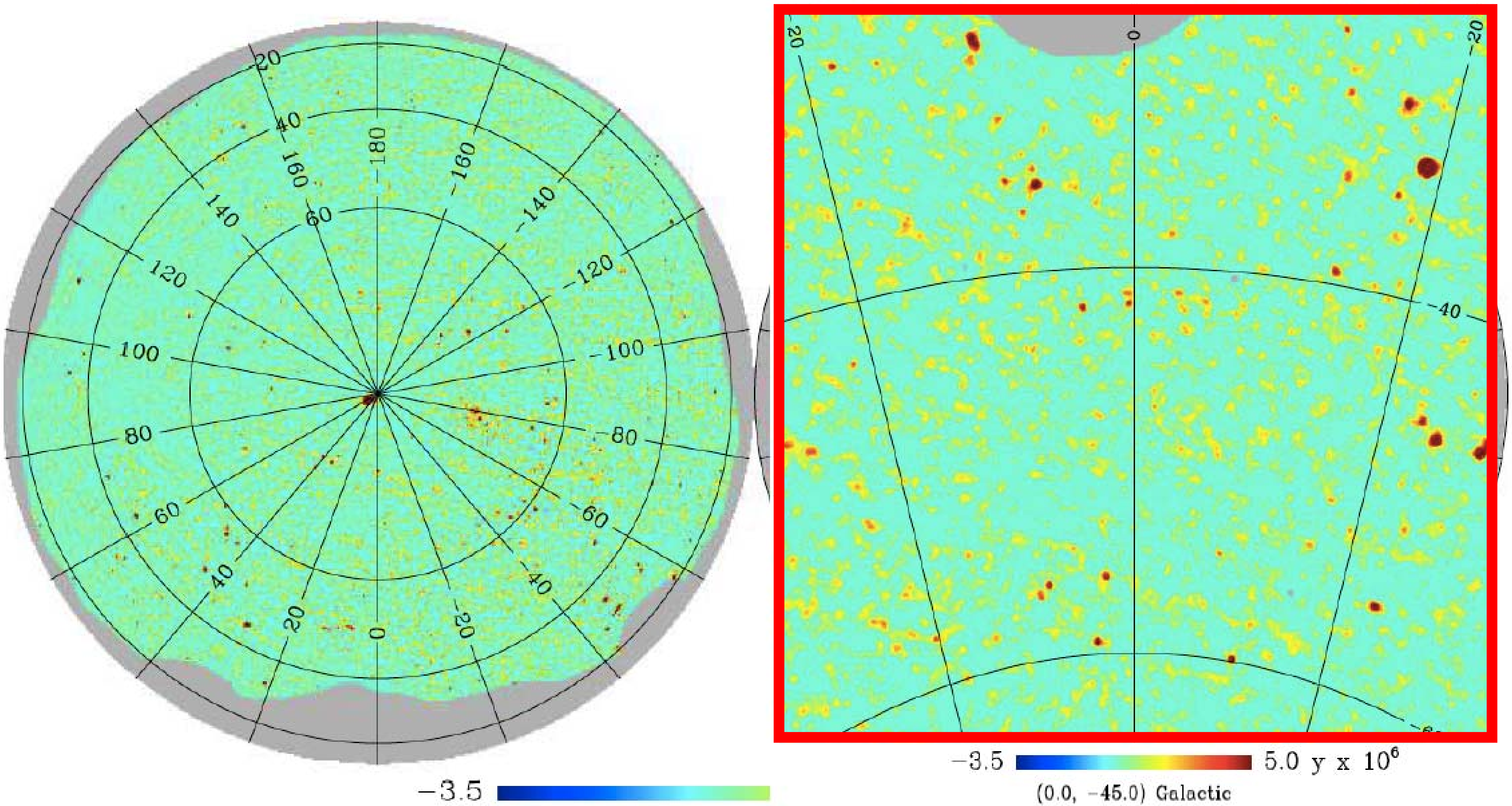
j = 33, 44, 70, 100, 143, 217, 353, 545, 857 GHz



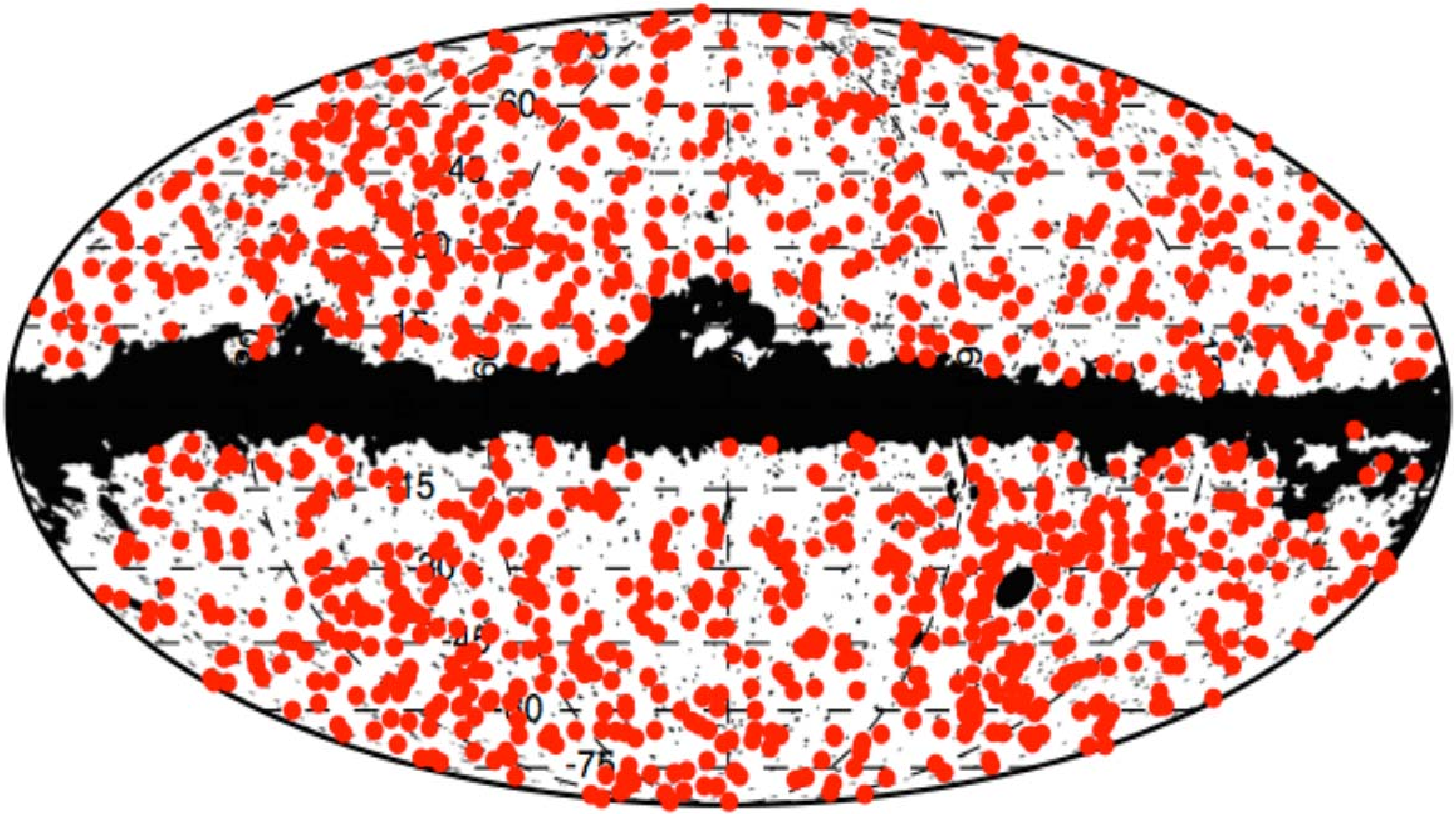
Full-sky map of diffuse SZe (hot baryons)



Full-sky map of diffuse SZe (hot baryons)

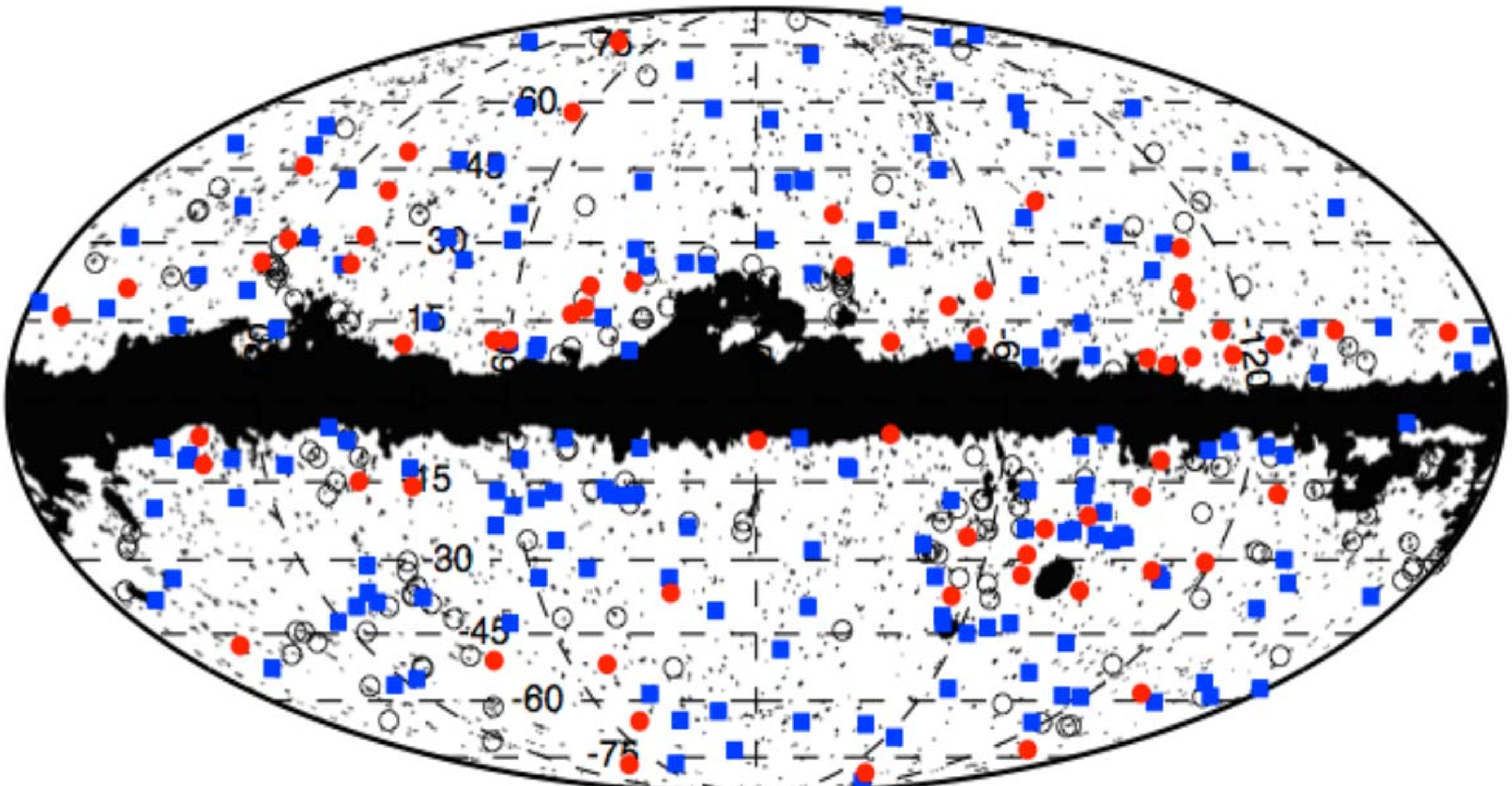


1227 SZ clusters

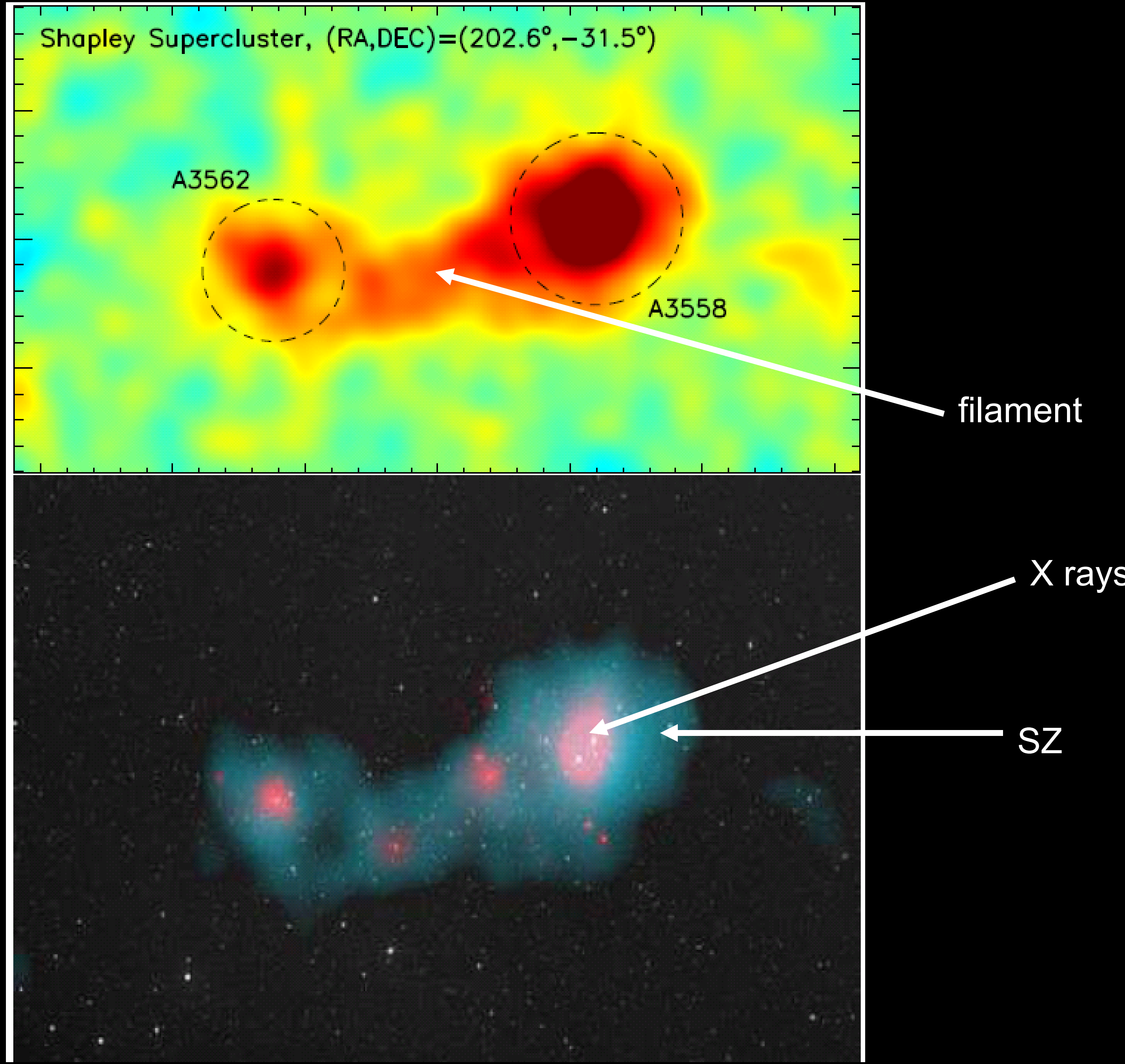


Planck 2013 results. XXIX. Planck catalogue of Sunyaev-Zeldovich sources : arXiv:1303.5089
See also addendum: arxiv:1502.00543

337 brand-new clusters



Filaments of ionized matter !



- Planck measurements, together with SPT, ACT and similar results, represent real milestones in SZ cosmology.

However …

- However,important limitations are still present for both ground-based and space-borne photometric measurements.

- 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 $$T_d, \tau_d \ldots.(\beta)$$

At least, 8 independent parameters.
Even Planck does not have enough channels (!)
Moreover the beam of Planck at high frequency is larger than the beam of SPT & ACT at 150 GHz.

The final solution: **spectroscopic** measurements of the SZ

- Requirements:
  - Wide spectral coverage
    (in principle 100 to 1000 GHz)
  - Modest spectral resolution ($\lambda/\Delta\lambda$ = 20 to 100)
  - Differential input, high rejection of common mode signal (CMB is common mode and is 2750000 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

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

Astronomy & Astrophysics

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

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Received 9 September 2011 / Accepted 8 November 2011

ABSTRACT

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

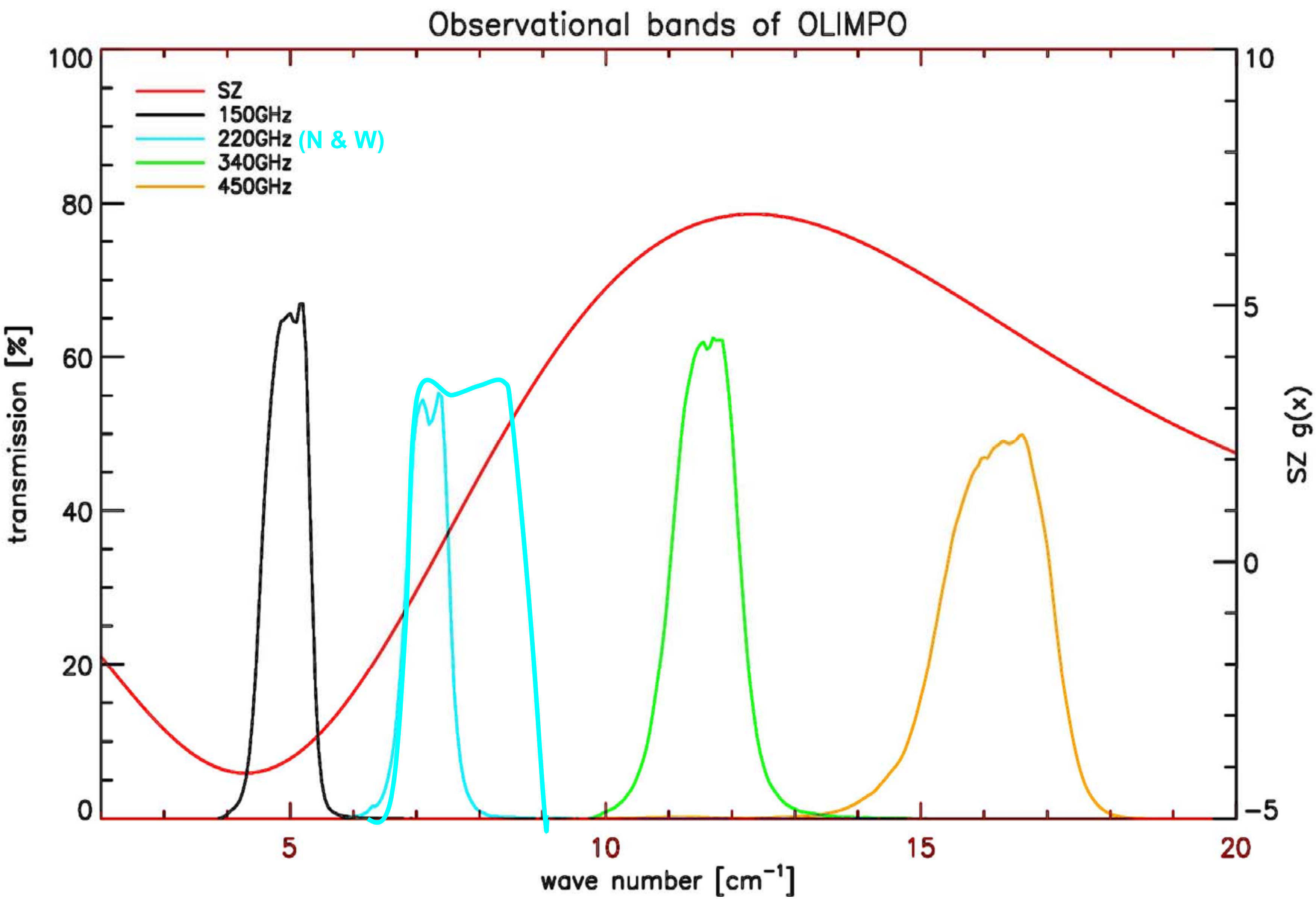
OLIMPO

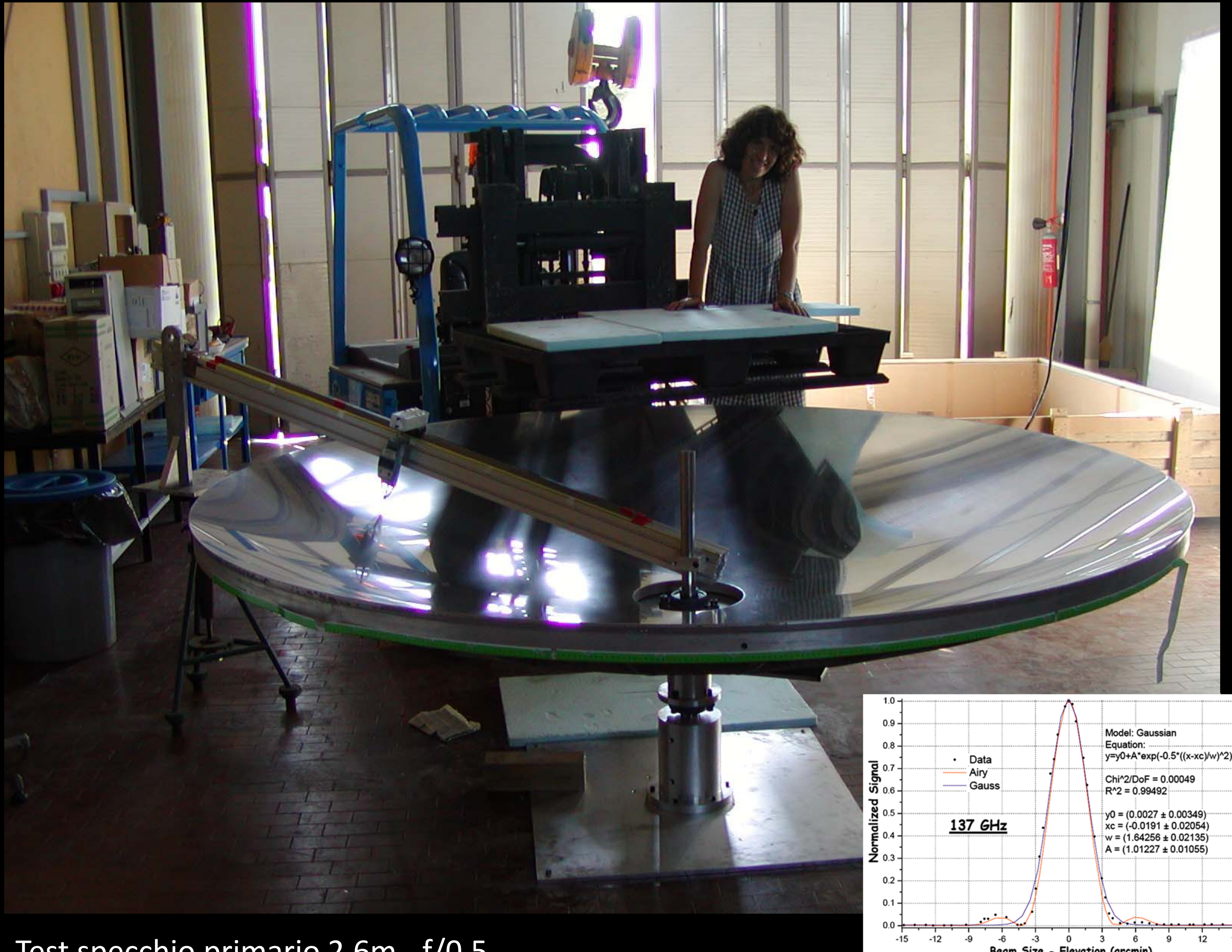
- The OLIMPO experiment is a first attempt at spectroscopic measurements of CMB anisotropy.
- A large balloon-borne telescope with a 4-bands photometric array and a plug-in room temperature spectrometer
- see http://planck.roma1.infn.it/olimpo for a collaborators list and full details on the mission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

OLIMPO

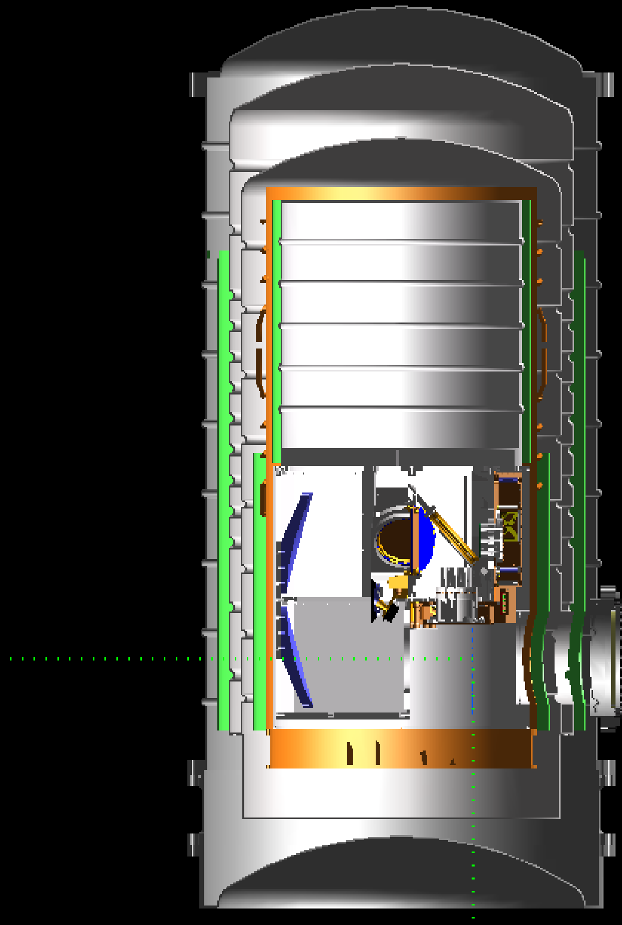
- Long Duration Balloon experiment for mm & sub-mm astronomy
- Operates from the stratosphere - launch from Svalbard
- Cassegrain telescope, 2.6m aperture
- Multifrequency arrays of bolometers
- Low resolution spectrometer

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

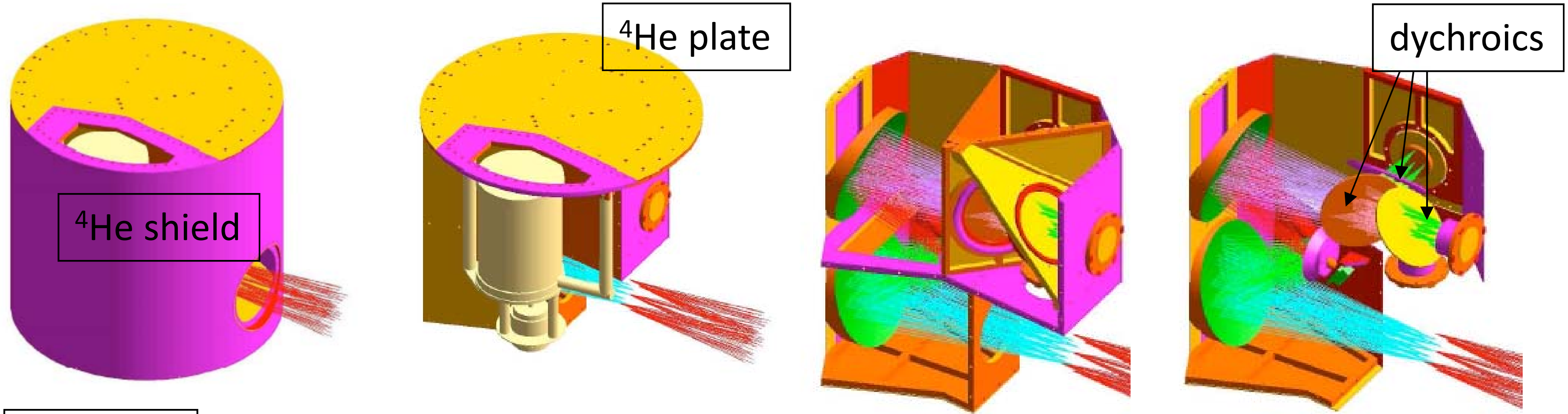

Observational bands of OLIMPO
SZ
150GHz
220GHz (N & W)
340GHz
450GHz
transmission [%]
wave number [cm^{-1}]
SZ g(x)
100
80
60
40
20
0
5
10
15
20
10
5
0
−5

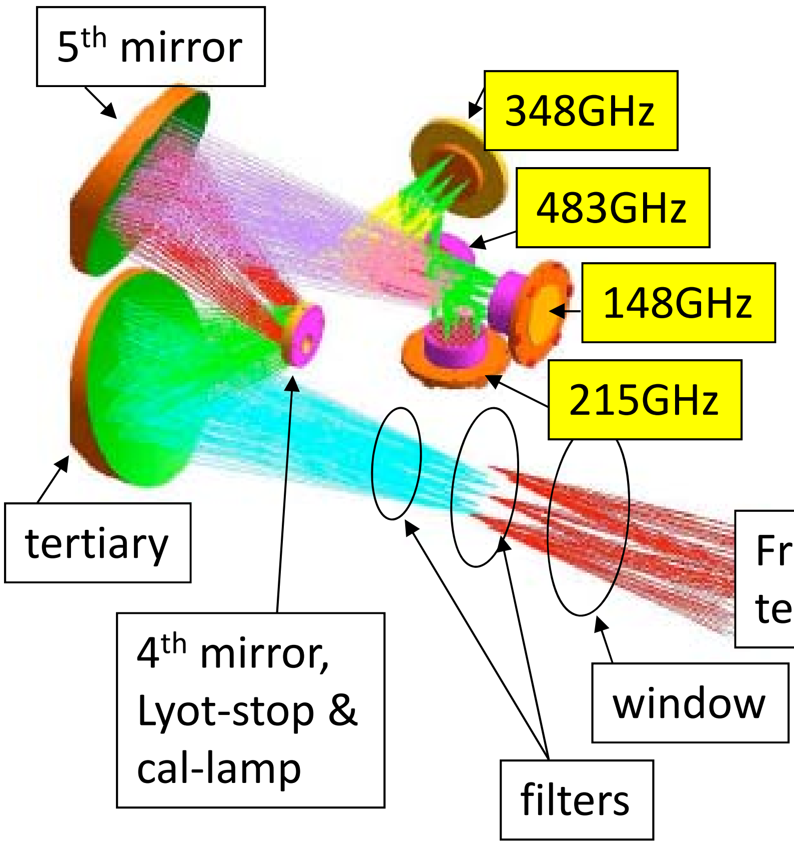


Test specchio primario 2.6m - f/0.5



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

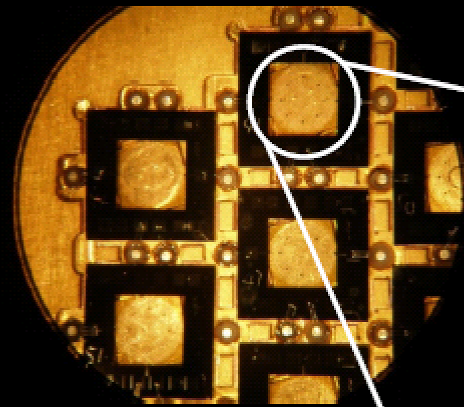


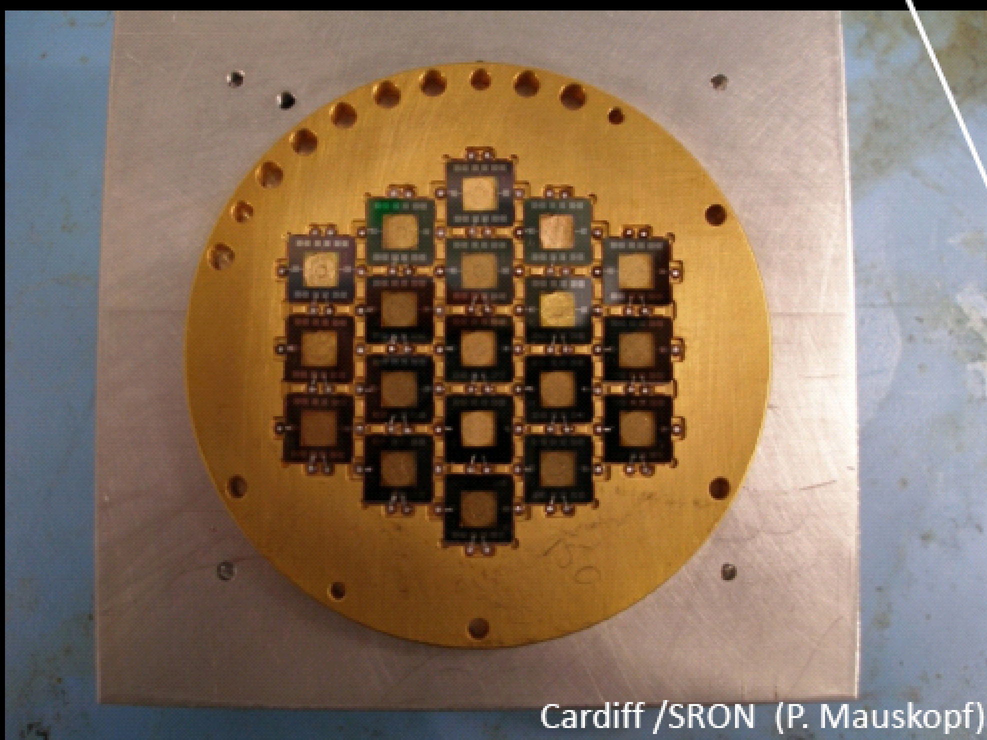


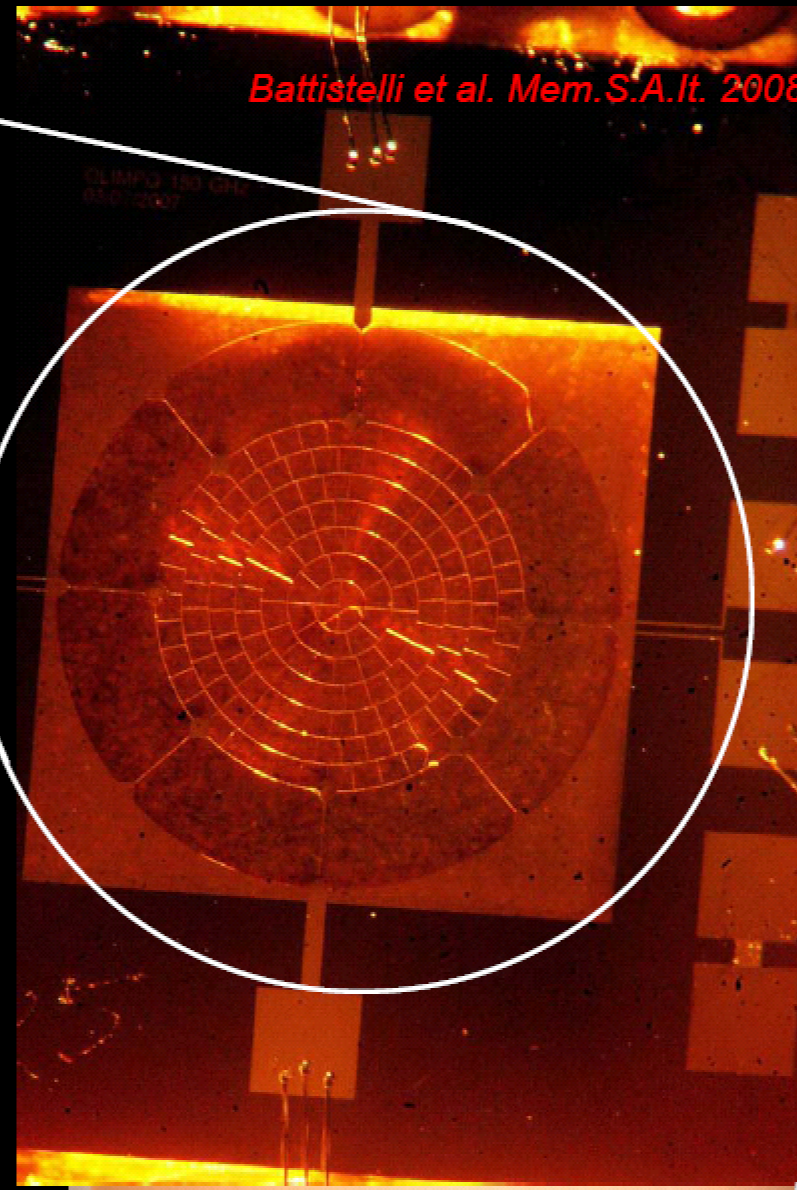
OLIMPO: Cold Optics and Arrays

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

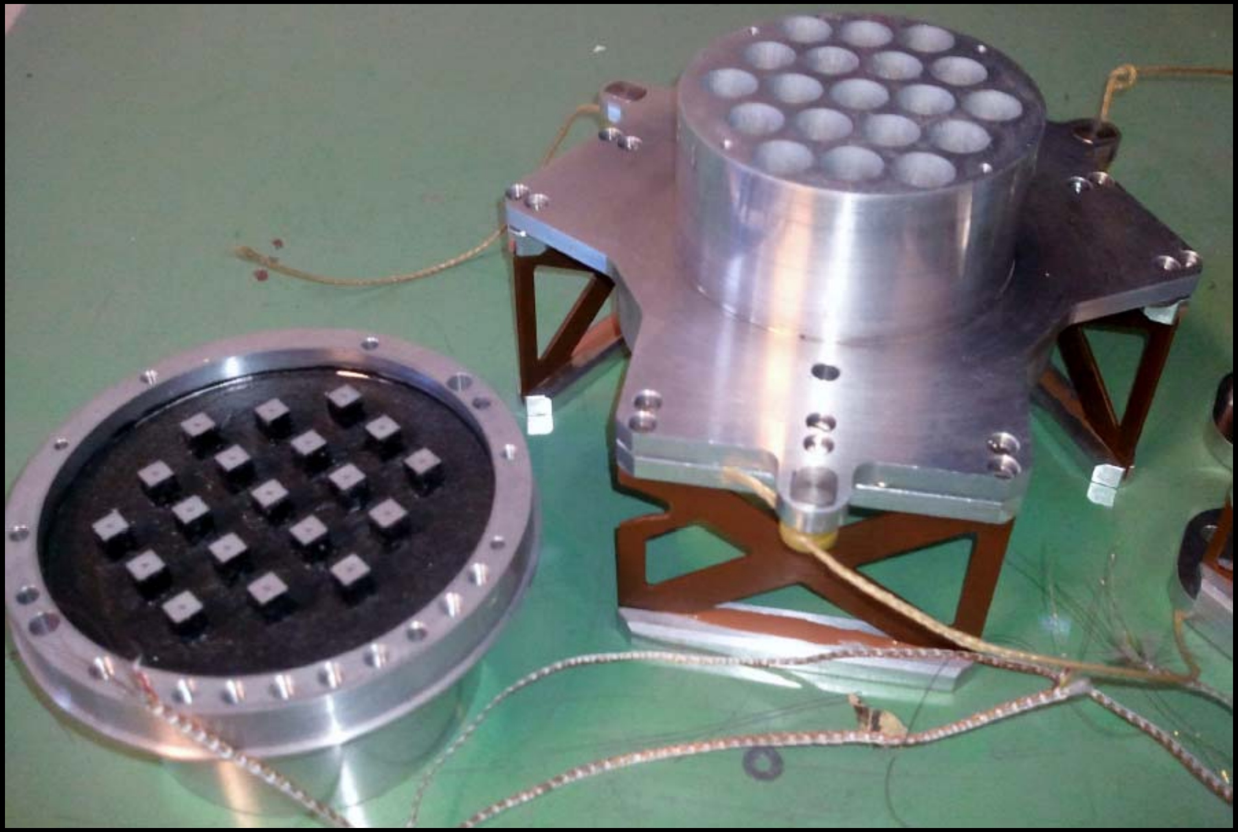
- Wafer: Si_3N_4
- Thermistor: Ti (60nm) + Au (10/20nm)
- Absorber/heater: spiderweb Ti (10nm) + Au (5nm), filling factor 5%



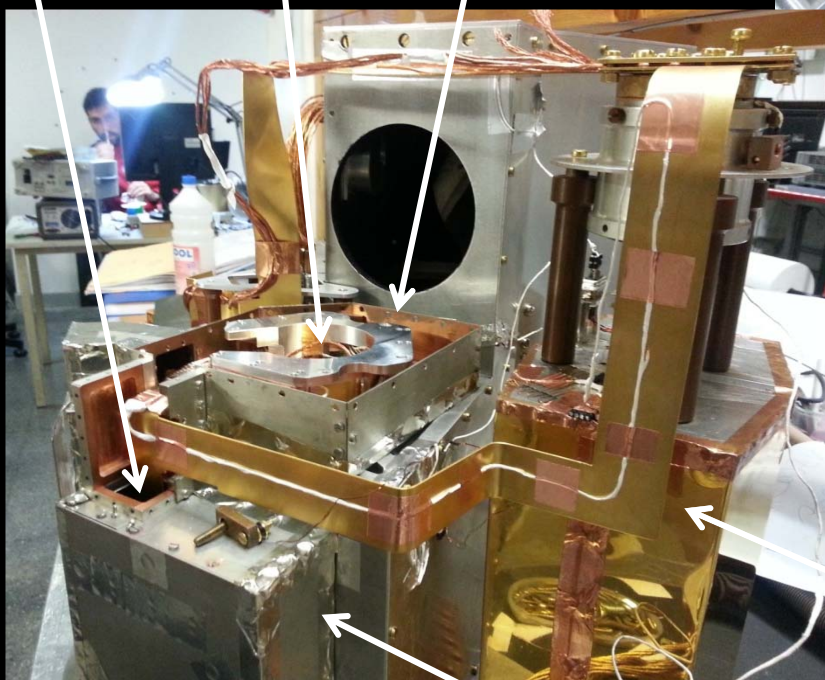
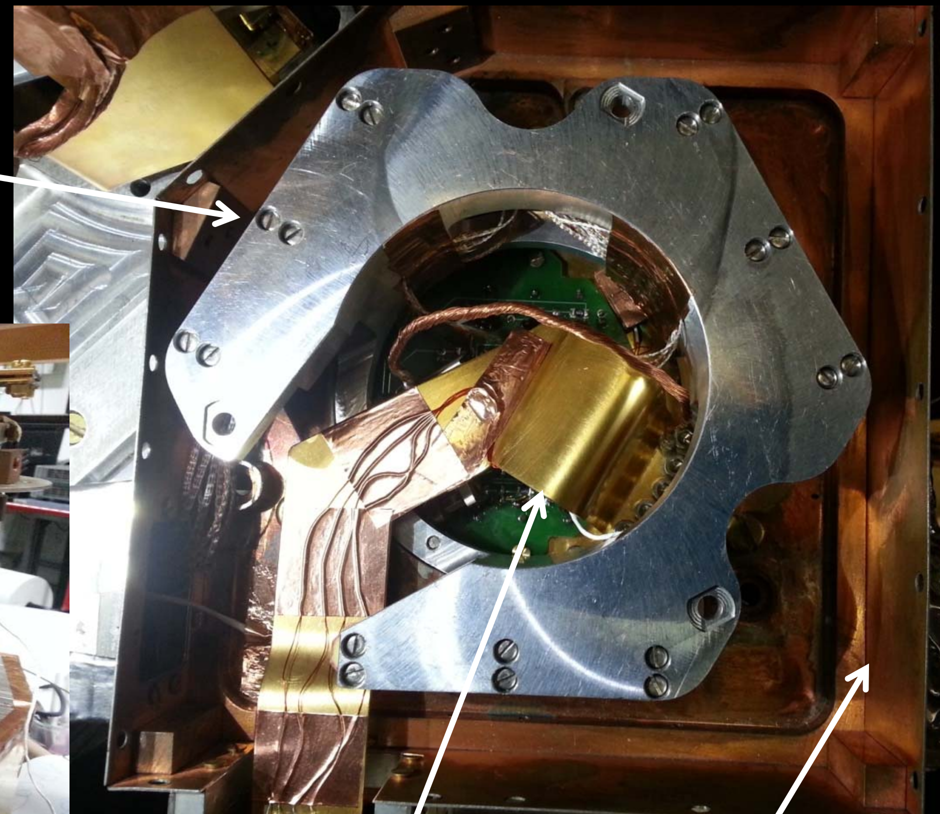




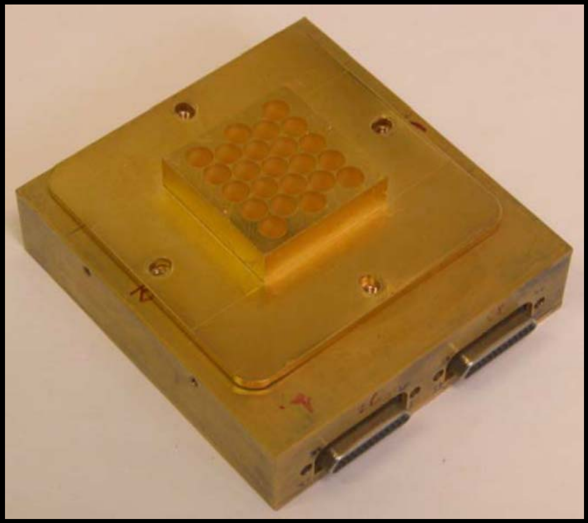
OLIMPO: Low-frequency arrays (140 GHz & 220 GHz)

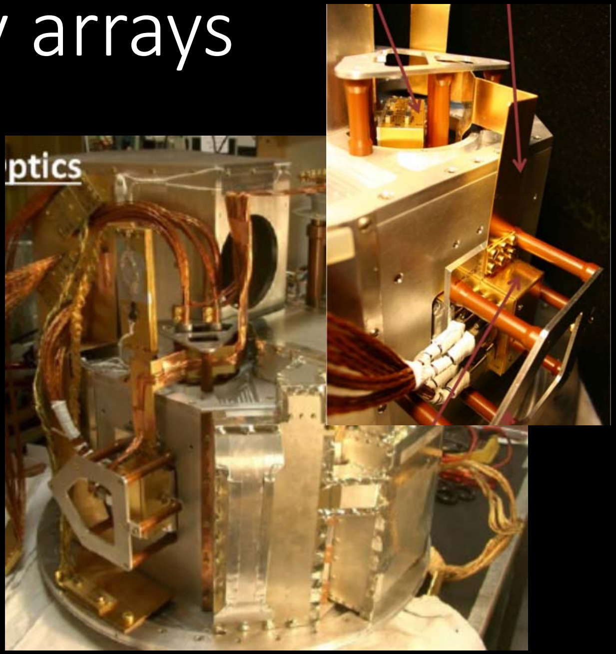


TES in OLIMPO

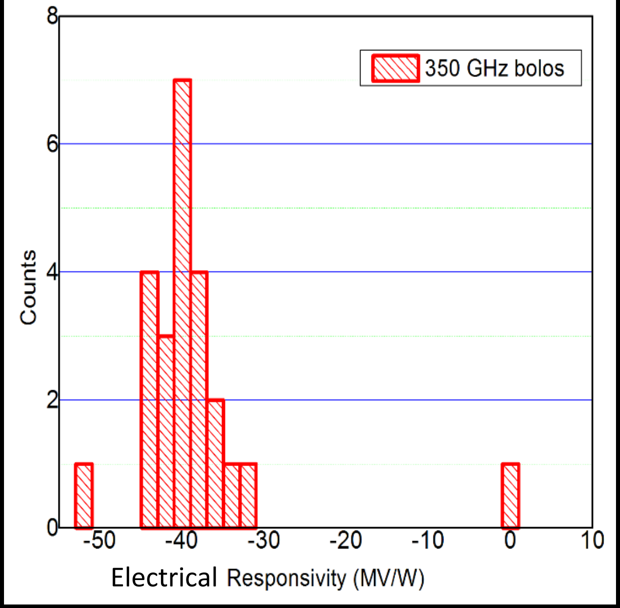



OLIMPO: High-frequency arrays





- Made in Grenoble (Neel institute, P. Camus)
- Si_3N_4 membranes with absorbing Bi layer
- NbSi thermistors (S. Marnieros)
- Bandpass filters matching the 350 GHz and 480 GHz bands (Cardiff)
- JFET readout (a la Planck, made in Sapienza)
- Room temperature biasing/demodulating electronics made in CEA Saclay (D. Yvon)
- Measured optical NEP around a few x 10^{-15} W/$Hz^{1/2}$ with OLIMPO fridge @0.3K and flight background.

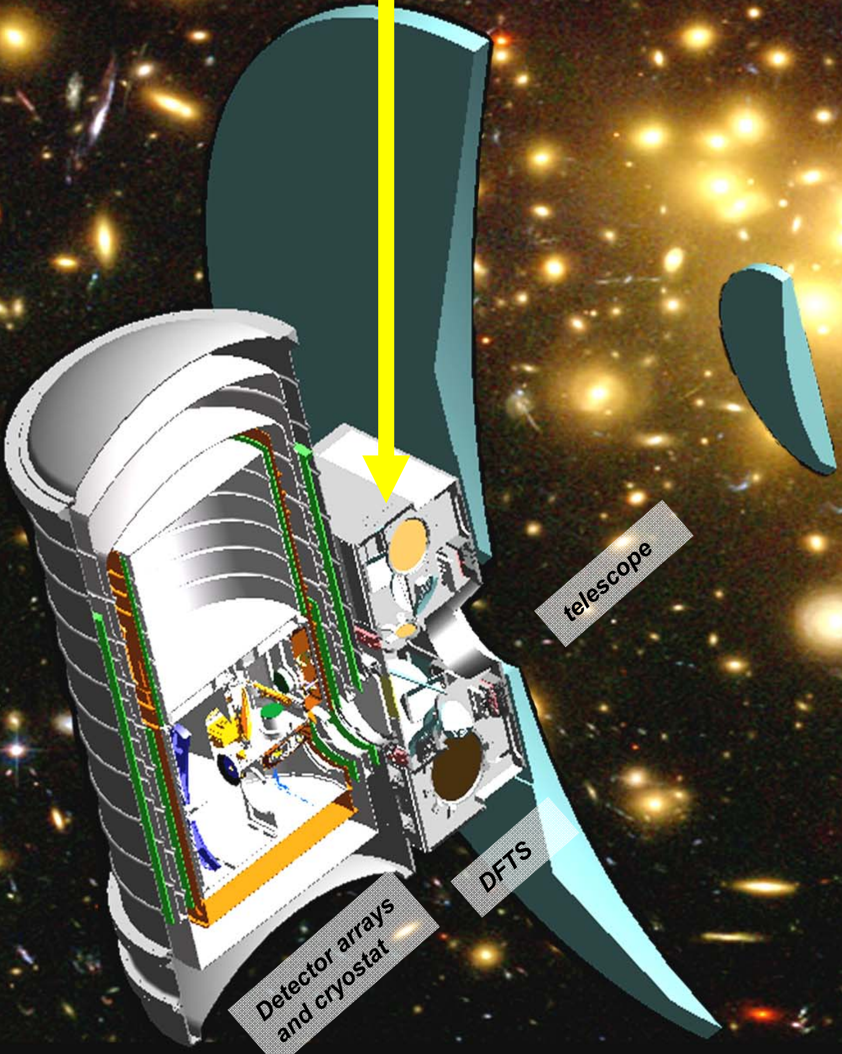


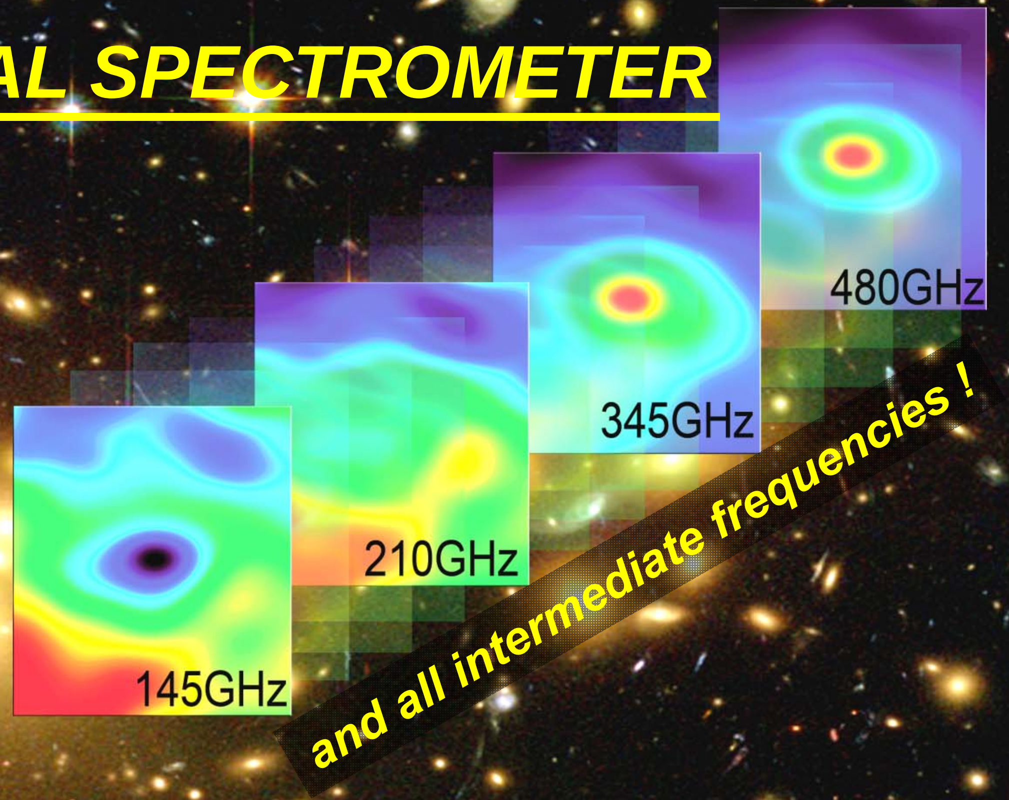
Expected performance for OLIMPO (photon noise limited)

OLIMPO performance: photometer configurations, single detector of each array

Band (GHz)	125-175	190-315 (wide)	200-225 (narrow)	330-365	450-500
FWHM (arcmin)	5	3.5	3.5	2	2
Throughput (m^2sr)	6.3×10^{-6}	3.1×10^{-6}	3.1×10^{-6}	1.0×10^{-6}	1.0×10^{-6}
Background (pW)	11	35	5	6	15
Optical NEP (aW/sqrt(Hz))	100	200	70	85	150
NET_{CMB} (μK/sqrt(Hz))	80	115	200	780	2500

OLIMPO's DIFFERENTIAL SPECTROMETER



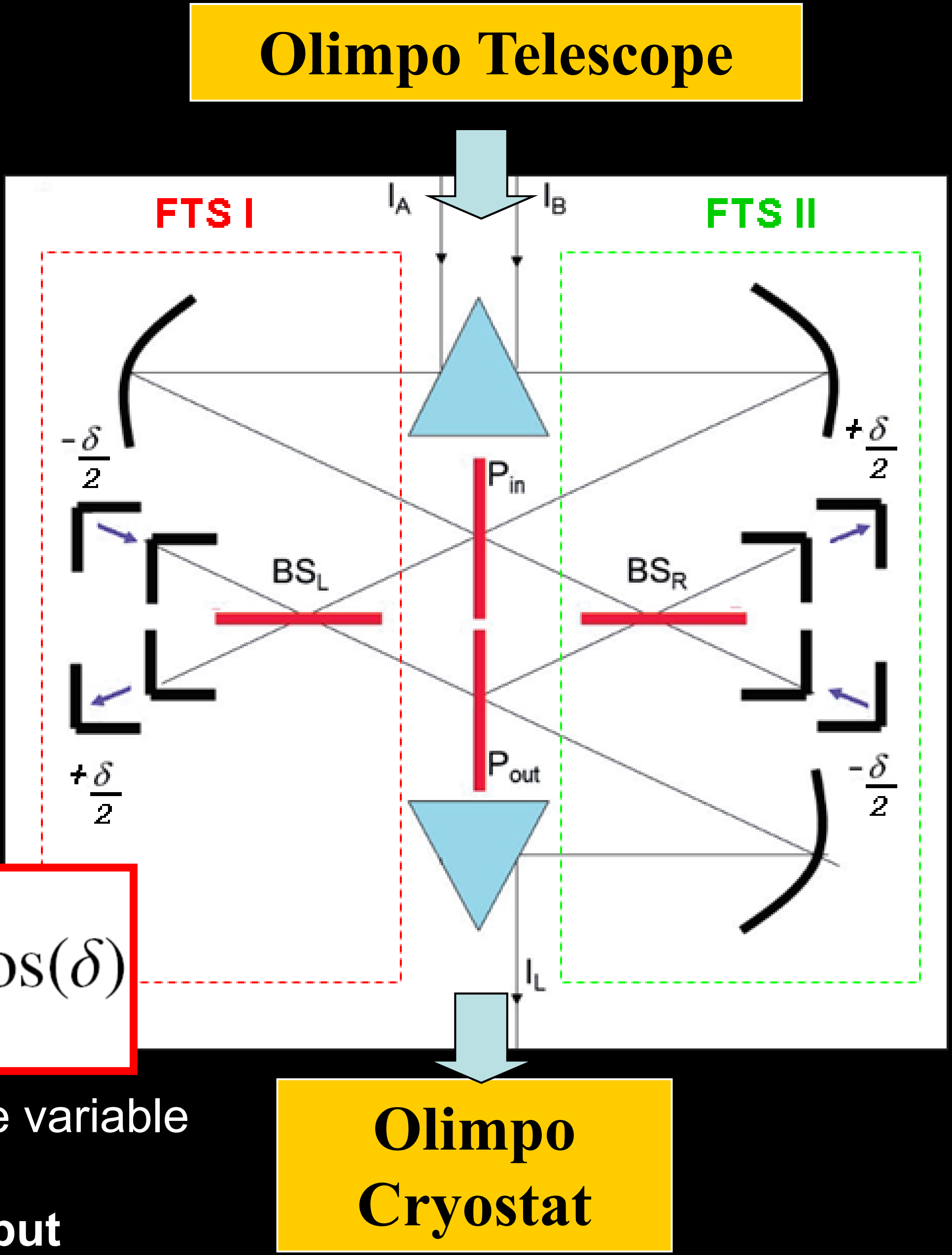


A Differential Fourier Transform Spectrometer (DFTS).

Similar to COBE-FIRAS but…

.. rather than measuring the brightness difference between the sky and an internal blackbody, it measures the **brightness difference between two directions in the sky**

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



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

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

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

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

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DOI: 10.1051/0004-6361/201423631

Astronomy & Astrophysics

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

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[2] Divisão de Astrofísica, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil
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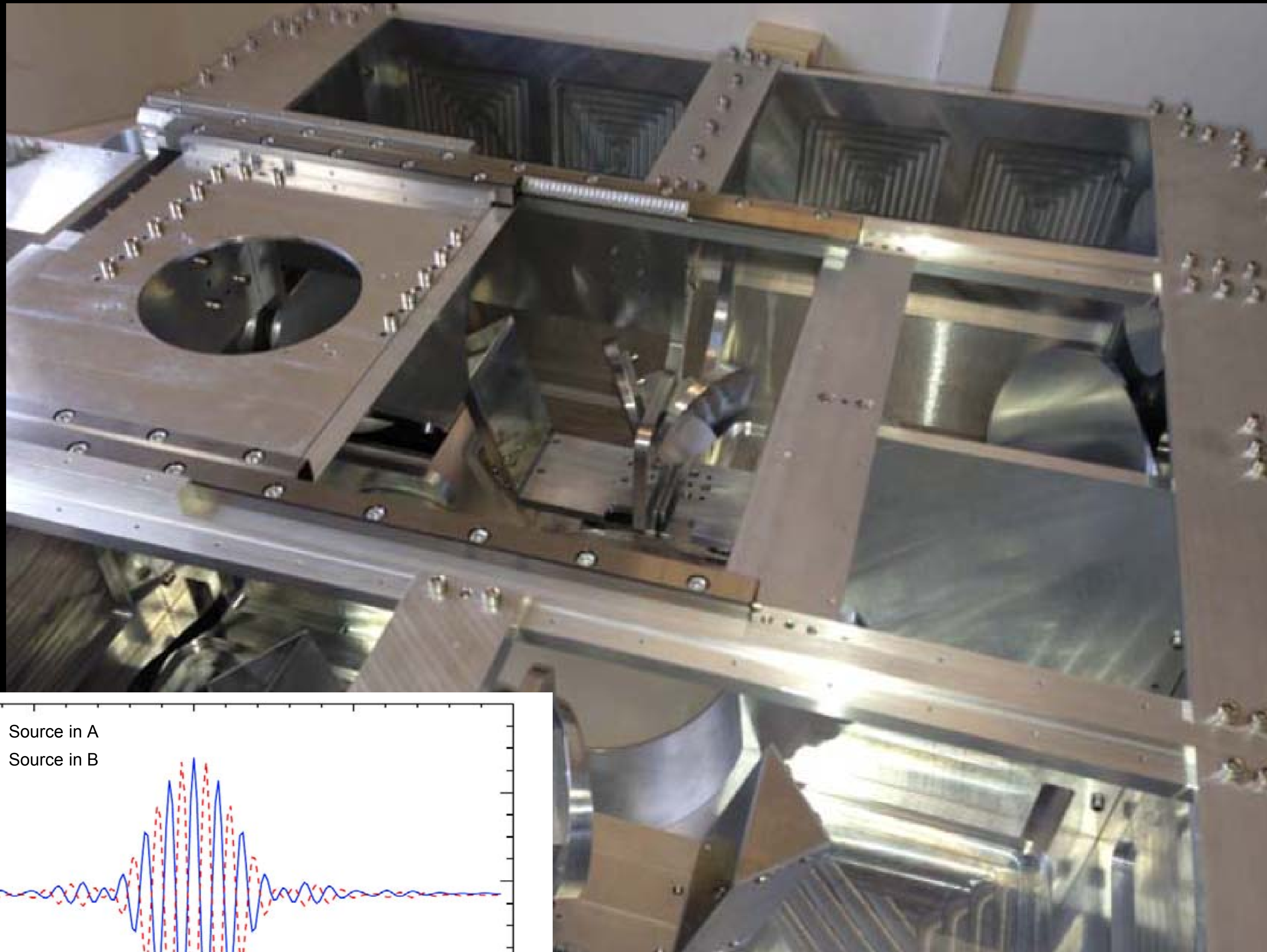
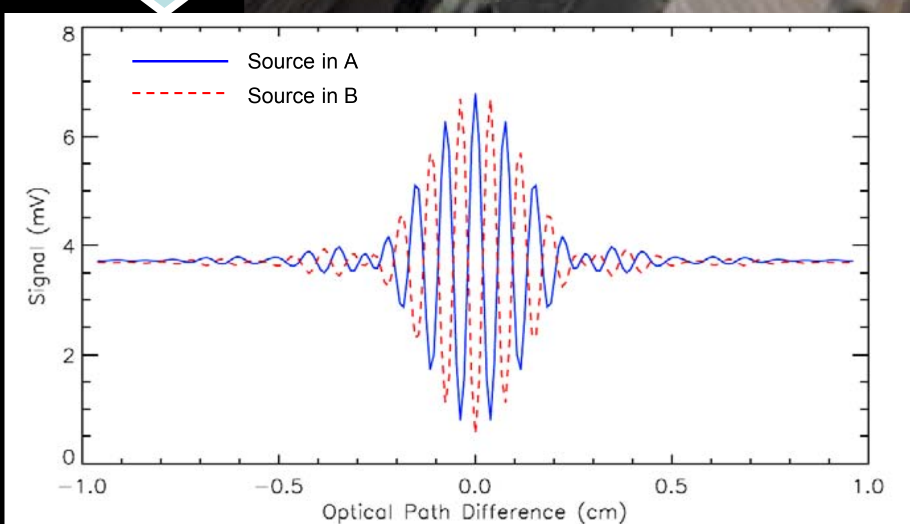
ABSTRACT

Context. Precision measurements of the Sunyaev-Zel'dovich effect in clusters of galaxies require excellent rejection of common-mode signals and wide frequency coverage.
Aims. We describe an imaging, efficient, differential Fourier transform spectrometer (FTS), optimized for measurements of faint brightness gradients at millimeter wavelengths.
Methods. Our instrument is based on a Martin-Puplett interferometer (MPI) configuration. We combined two MPIs working synchronously to use the whole input power. In our implementation the observed sky field is divided into two halves along the meridian, and each half-field corresponds to one of the two input ports of the MPI. In this way, each detector in the FTS focal planes measures the difference in brightness between two sky pixels, symmetrically located with respect to the meridian. Exploiting the high common-mode rejection of the MPI, we can measure low sky brightness gradients over a high isotropic background.
Results. The instrument works in the range ~1–20 cm^{-1} (30–600 GHz), has a maximum spectral resolution 1/(2 OPD) = 0.063 cm^{-1} (1.9 GHz), and an unvignetted throughput of 2.3 cm^2sr. It occupies a volume of $0.7 \times 0.7 \times 0.33$ m^3 and has a weight of 70 kg. This design can be implemented as a cryogenic unit to be used in space, as well as a room-temperature unit working at the focus of suborbital and ground-based mm-wave telescopes. The first in-flight test of the instrument is with the OLIMPO experiment on a stratospheric balloon; a larger implementation is being prepared for the Sardinia radio telescope.

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

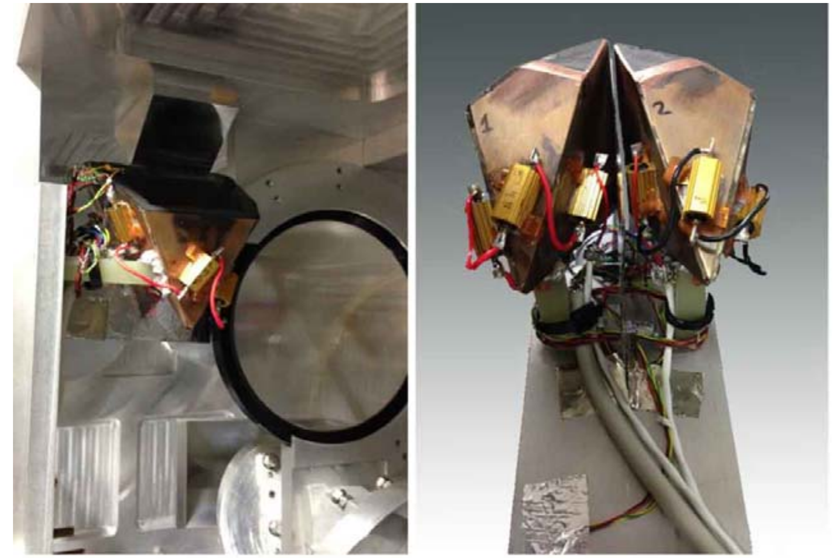
The real thing….
and measured interferograms

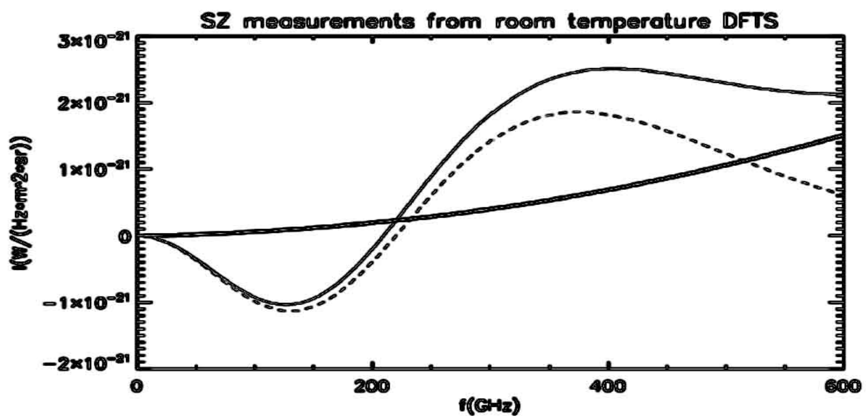


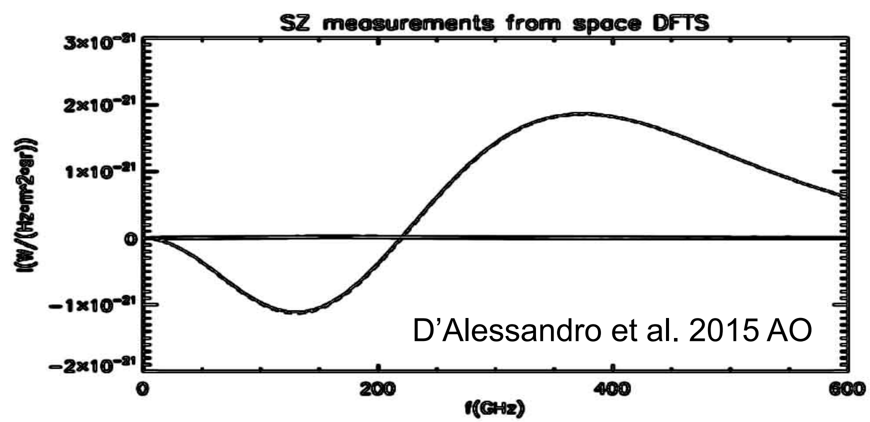


CMRR

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







Telescope / primary mirror DFTS cryostat / detectors arrays

Main components of OLIMPO integrated on the payload

Expected performance for OLIMPO (photon noise limited)

OLIMPO performance: spectrometer configurations, single detector of each array

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

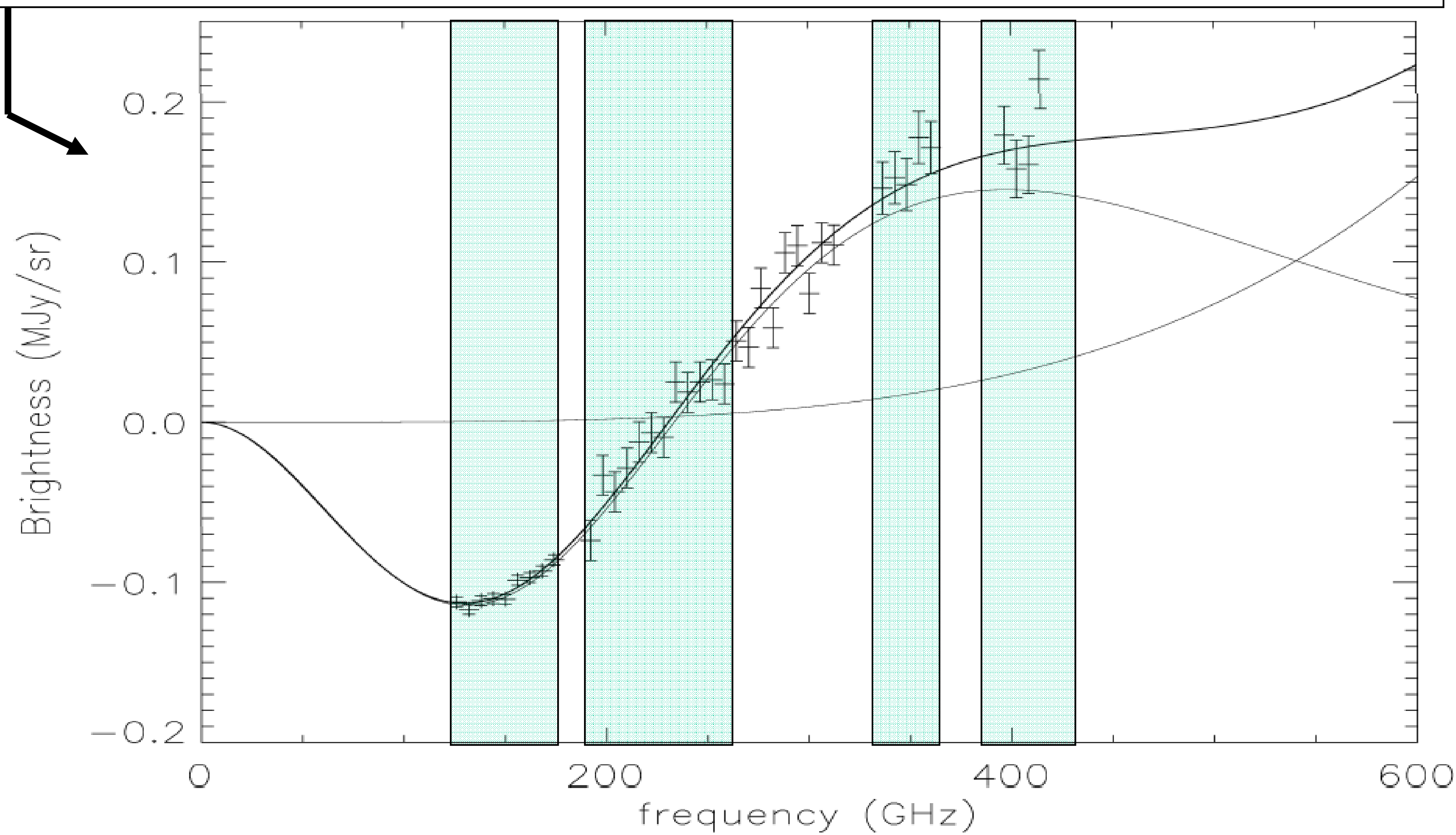
OLIMPO performance: photometer configurations, single detector of each array

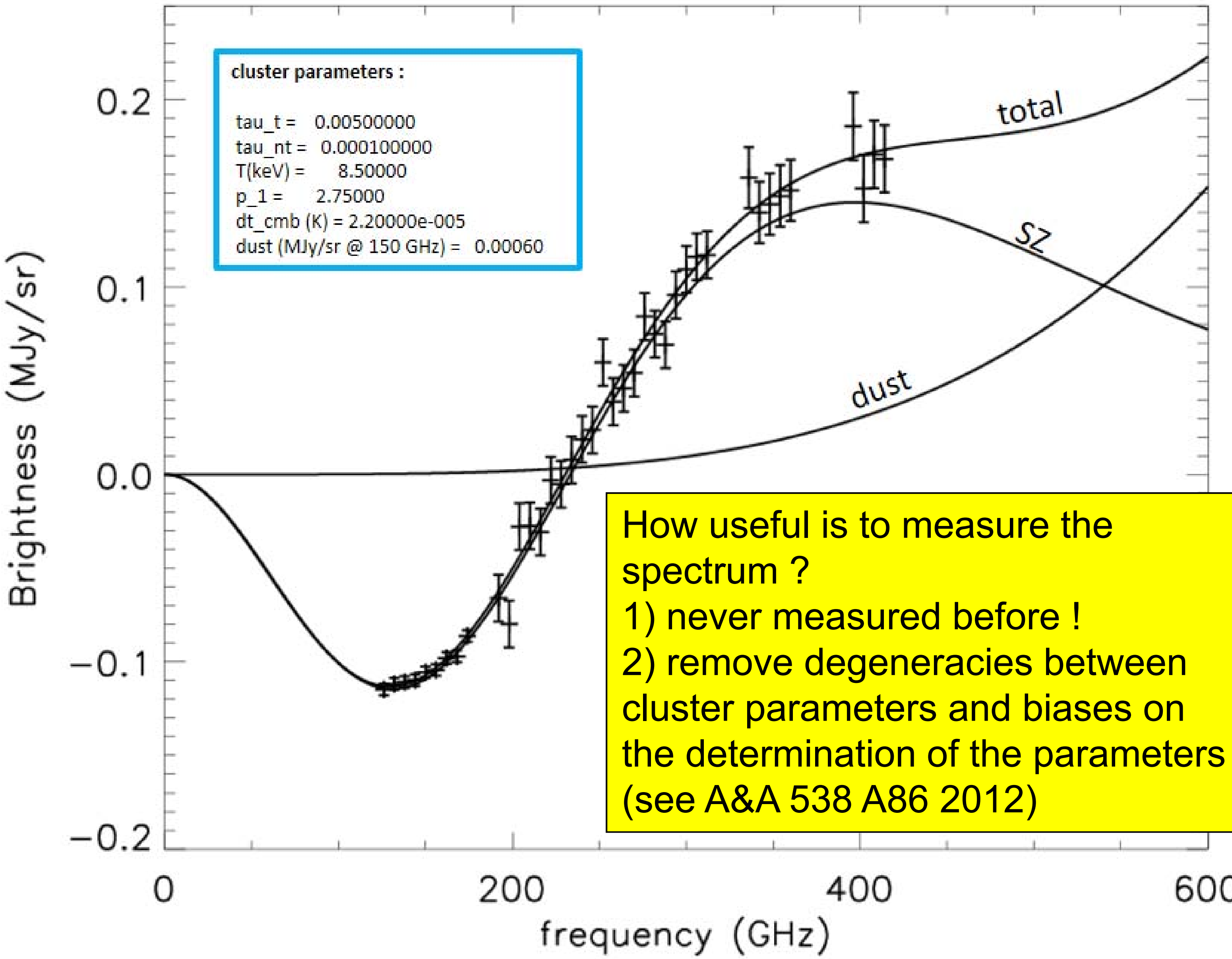
Band (GHz)	125-175	190-315 (wide)	200-225 (narrow)	330-365	450-500
FWHM (arcmin)	5	3.5	3.5	2	2
Throughput (m^2sr)	6.3×10^{-6}	3.1×10^{-6}	3.1×10^{-6}	1.0×10^{-6}	1.0×10^{-6}
Background (pW)	11	35	5	6	15
Optical NEP (aW/sqrt(Hz))	100	200	70	85	150
NET_{CMB} (μK/sqrt(Hz))	80	115	200	780	2500

In a FTS the spectral resolution can be changed (changing the path of the moving mirror). Mind the noise, however: it is proportional to the inverse of the spectral bin-width. In the case of OLIMPO, with a spectrometer at 250K, photon noise is important.

1.8 GHz resolution: About 110 independent spectral bins, within optimized bands.

6 GHz resolution: About 34 independent spectral bins, within the same bands.





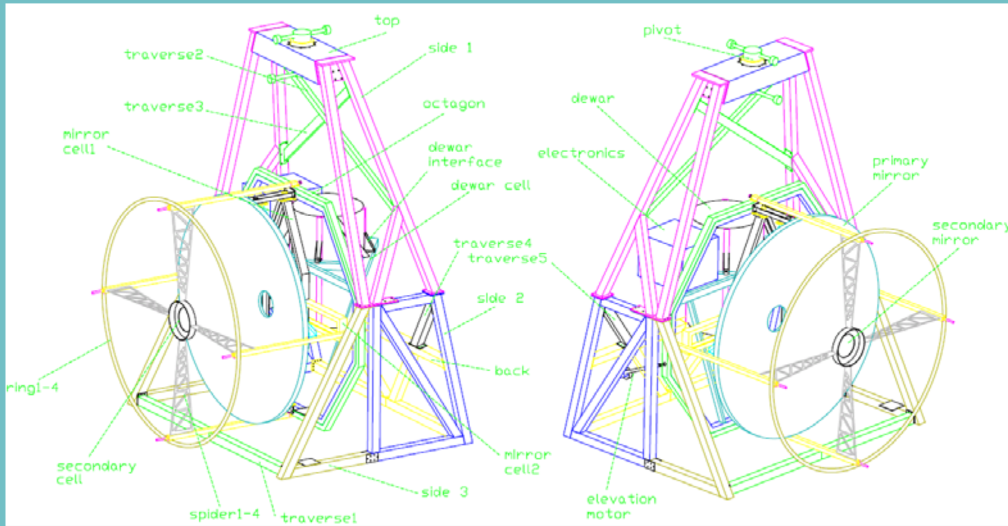
How useful is to measure the spectrum ?

1) never measured before !

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

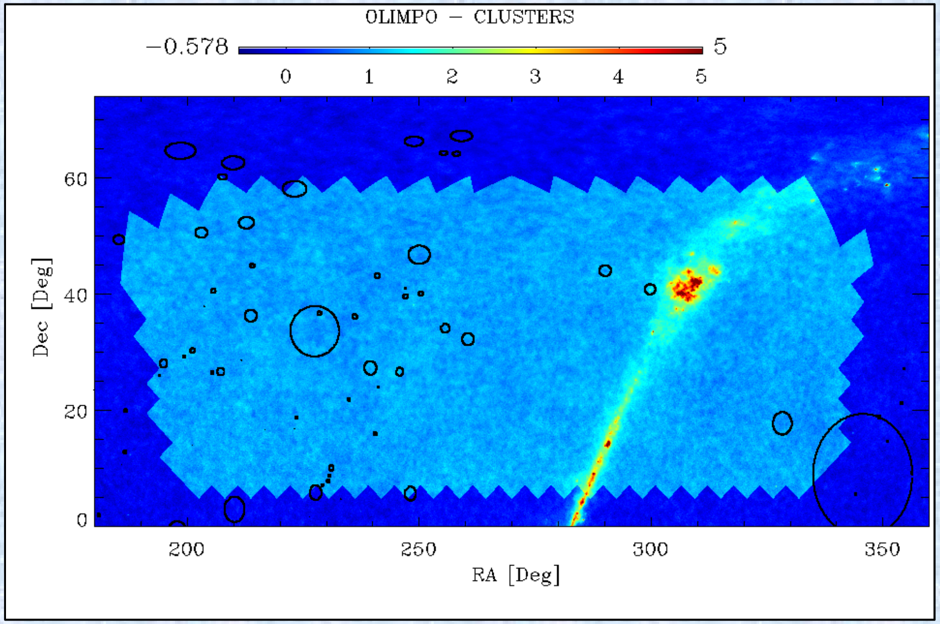
OLIMPO calibration night (Rome, 25/4/2014)
T_{atm}(350GHz)=0.001 !!

The Payload



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

Observation Program



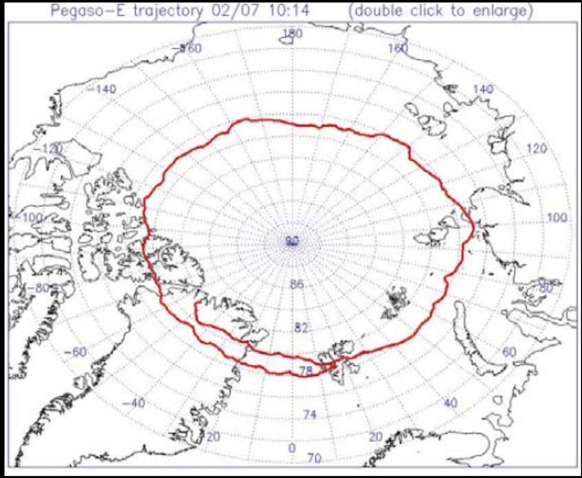
- In a circumpolar summer long duration flight (>200h) we plan to observe 40 selected clusters and to perform a blind deep integration on a clean sky region
- We have optimized the observation plan distributing the integration time among the different targets according to their brightness and diurnal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

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

Polar flights

- We have flown long duration stratospheric balloons around the North Pole launching from **Longyearbyen** (Svalbard) both in the summer (heavy lift payloads) and in winter (pathfinders) [see Peterzen, S., Masi, S., et al., Mem. S. A. It., 79, 792-798 (2008), and PdB+SM Proc. of the I.A.U., 8, 208-213 (2013)]
- In this way CMB experiments can access most of the northern sky in a single flight,
  - within a cold and very stable environment
  - Accumulating more than 10 days of integration at float (38 km altitude).

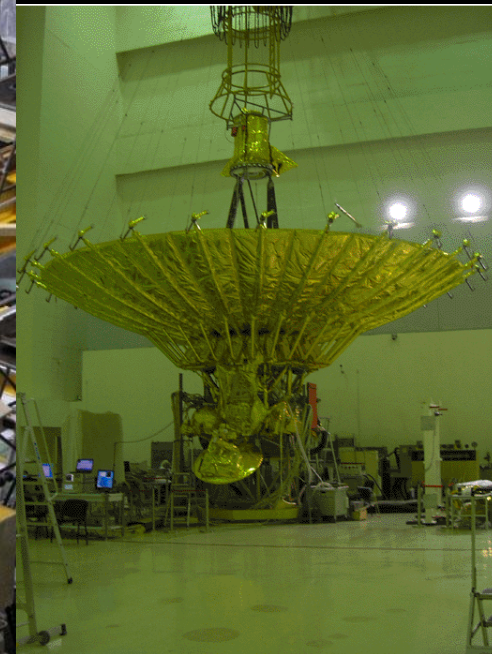
Top: Ground path of a flight performed in June 2007. **Bottom left:** Launch of a heavy-lift balloon from the Longyearbyen airport (Svalbard Islands, latitude 78^{o}N).



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

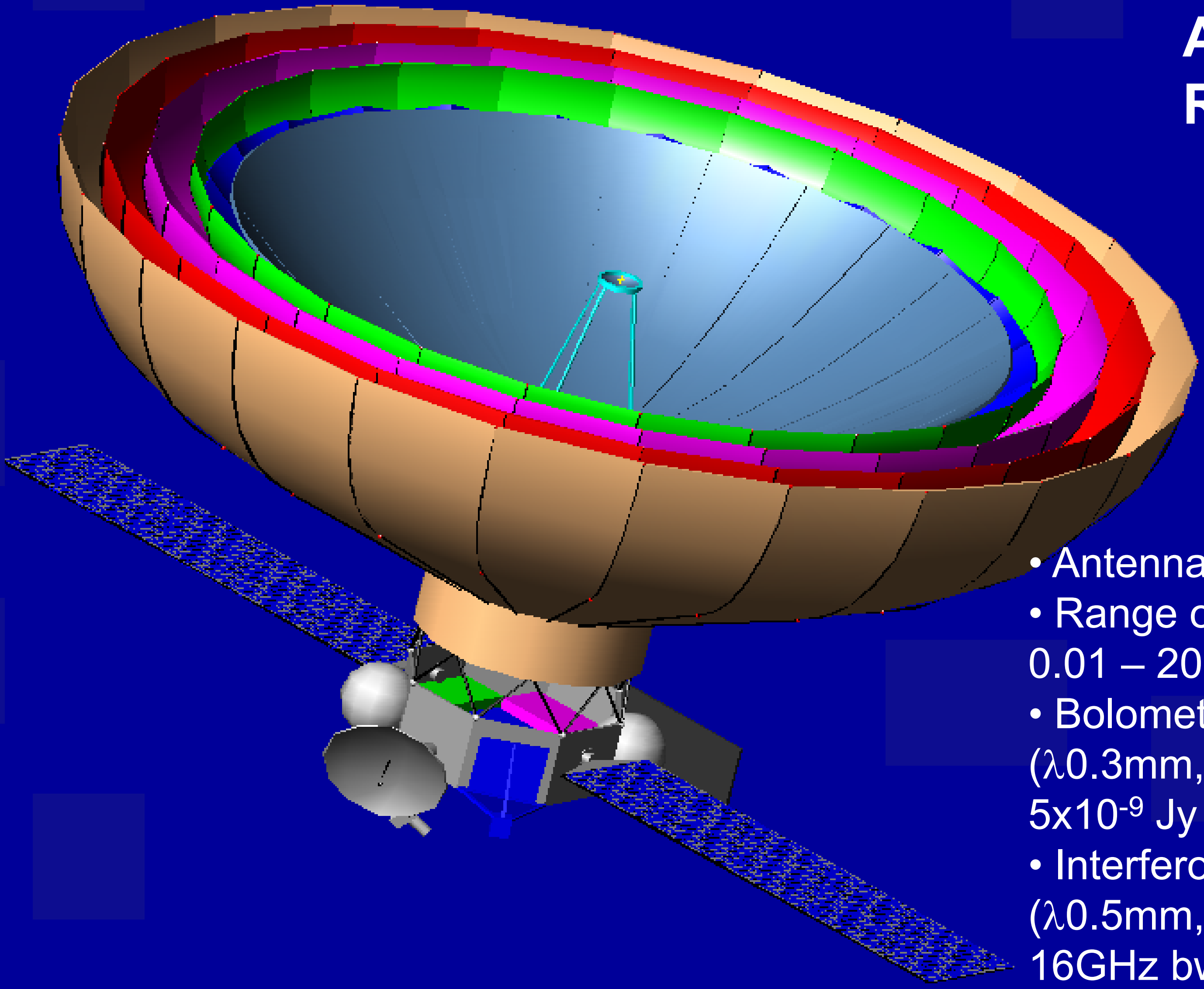
- The OLIMPO spectrometer is the prototype for a similar Differential Fourier Transform Spectrometer to be flown on the Millimetron space mission ….

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

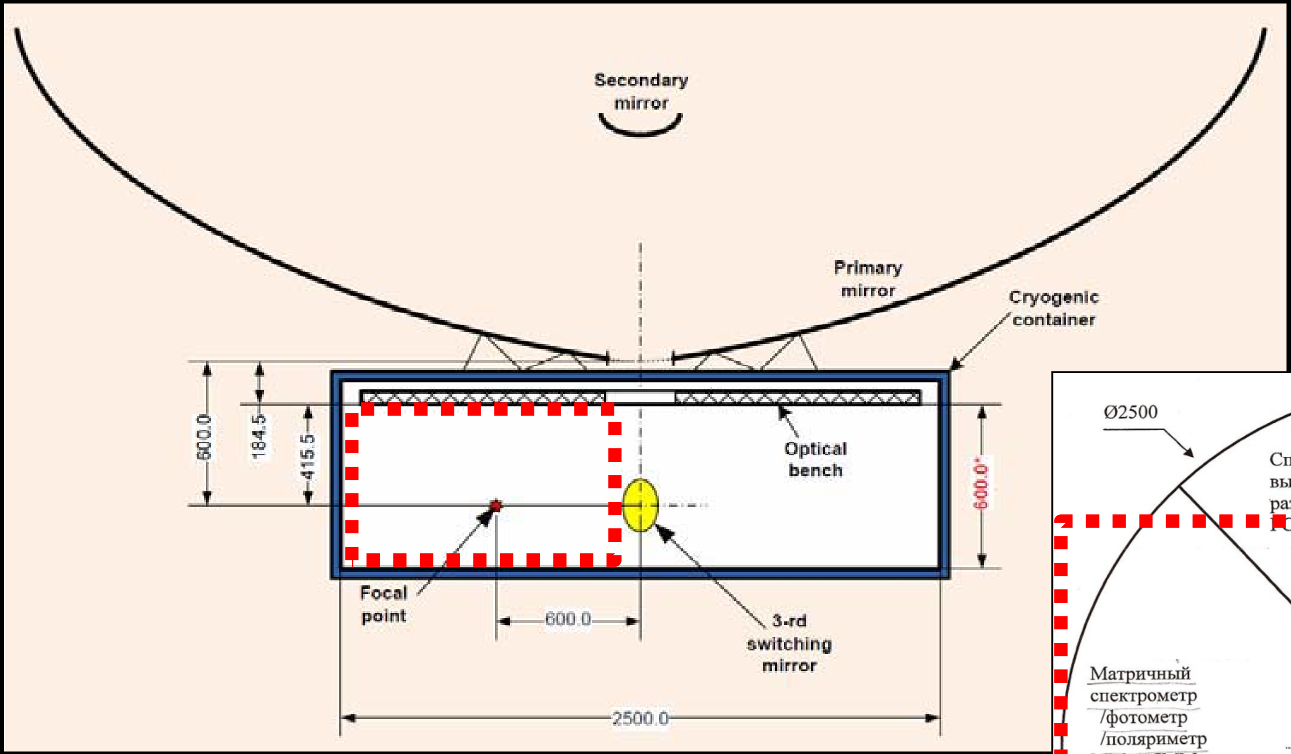


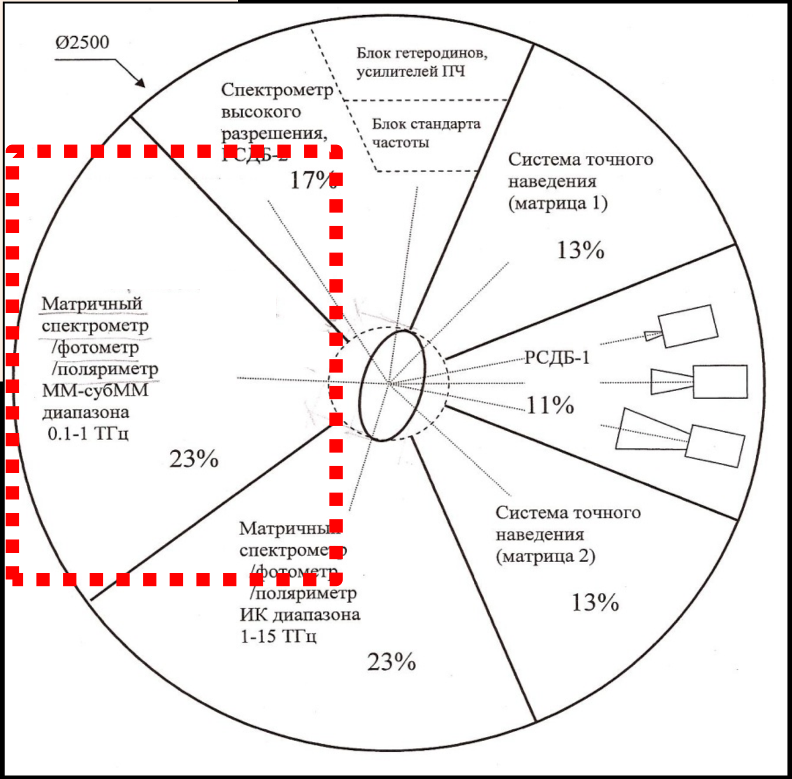
РадиоАстрон

Millimetron
ASC Moscow
ROSCOSMOS

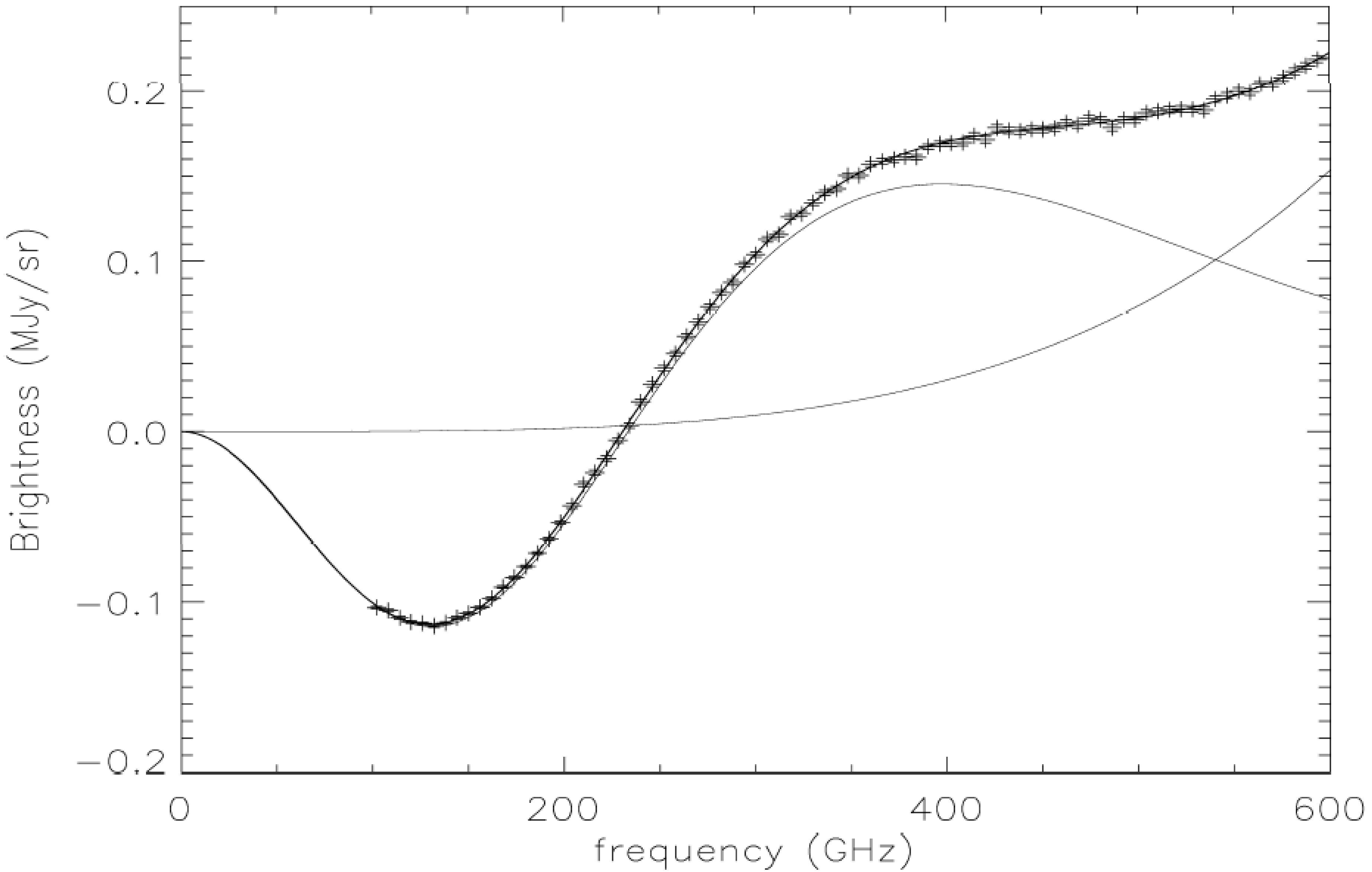


- Antenna diameter: 10 m
- Range of wavelengths: 0.01 – 20 mm
- Bolometric sensitivity (λ0.3mm, 1h integration): 5x10^{-9} Jy
- Interferometry sensitivity (λ0.5mm, 300s integration, 16GHz bw) : 10^{-4} Jy
- Interferometer beam: 10^{-9} arcsec





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



3 hours of observations of a rich cluster with a DFTS on Millimetron

Absolutely outstanding. USING A PHOTON NOISE LIMITED BOLOMETER IN THE COLD ENVIRONMENT OF L2 WITH A 4K TELESCOPE

Conclusions

- CMB photons have a long life and cross basically the entire observable universe before reaching us.
- They filled the universe with light from the first microseconds to 380000 years after the big bang.
- Taking advantage of their interactions, we can use them to study all phases of the evolution of the universe:
  - the very beginning (inflation with B-modes)
  - the primeval fireball (spectral distortions, power spectrum of CMB anisotropy)
  - recombination (polarization)
  - reionization (polarization, spectral distortions)
  - Current large scale structures (SZ effect)
- The OLIMPO experiment will provide the first DFTS spectral measurements of the SZ effect, providing a significant sample of unbiased estimates of cluster parameters.
- After this demonstration, the same instrument concept can be developed for large telescopes, like SRT and Millimetron.

Backup slides

Backup slides

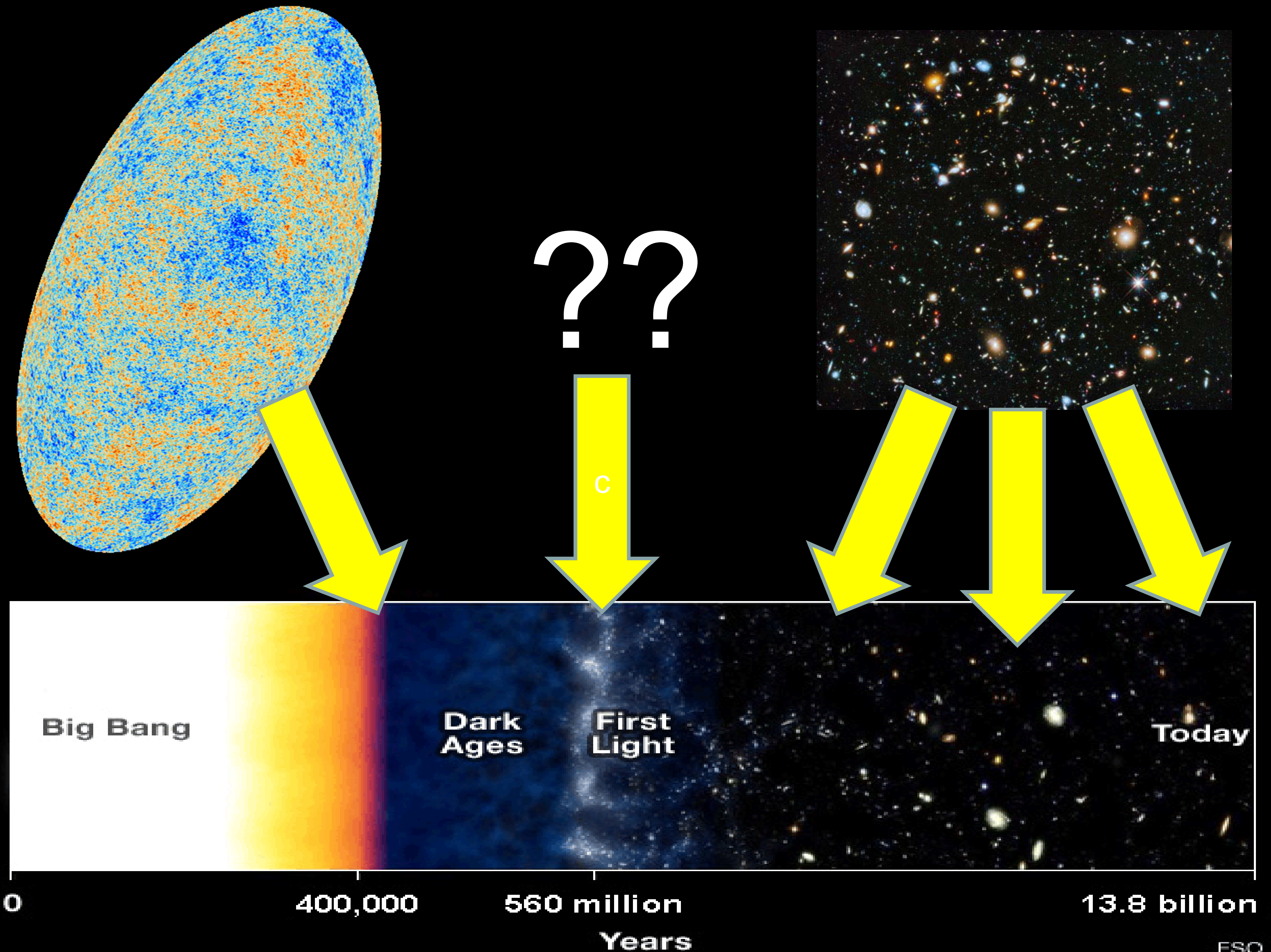
Backup slides

Backup slides

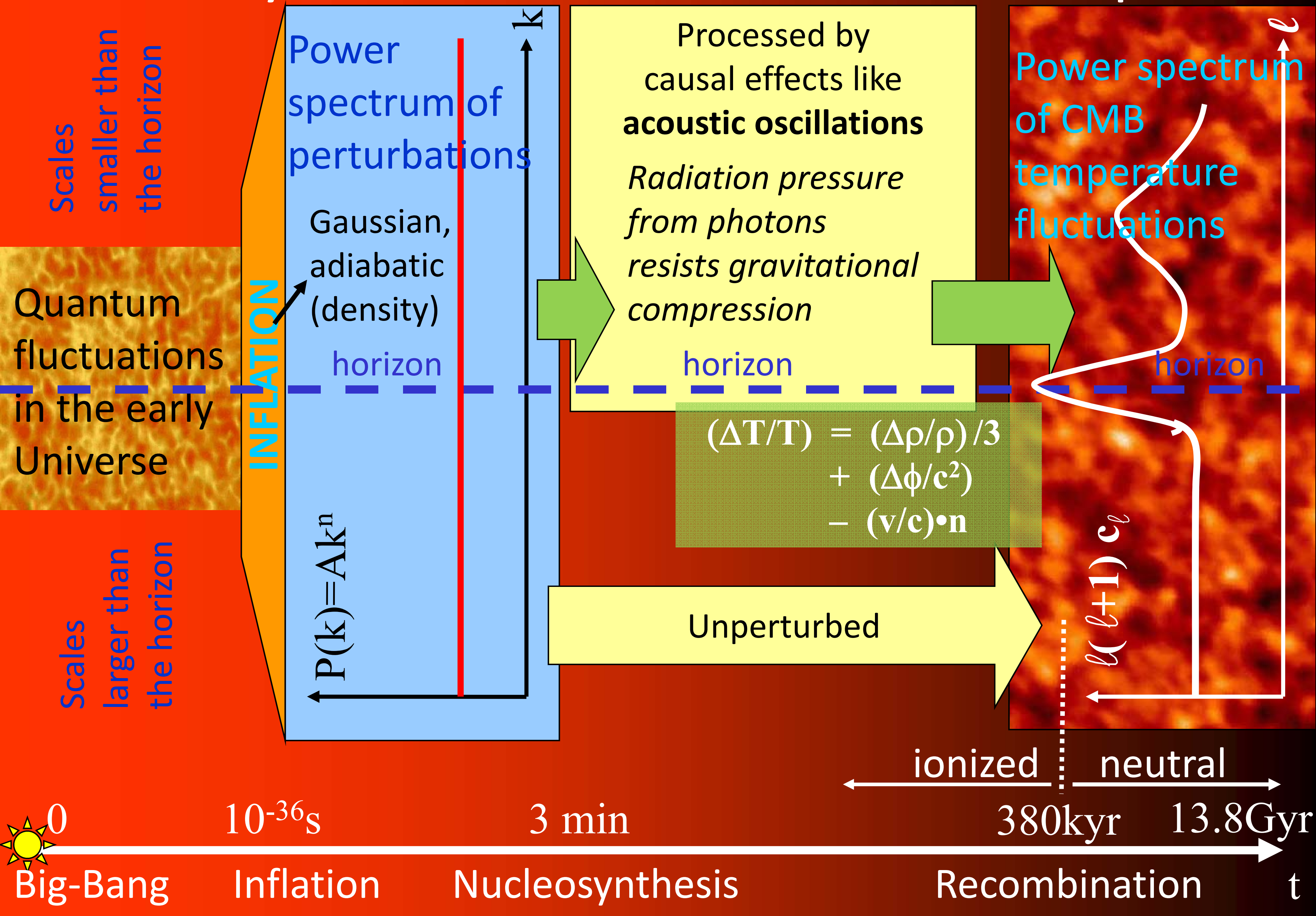
Backup slides

Backup slides

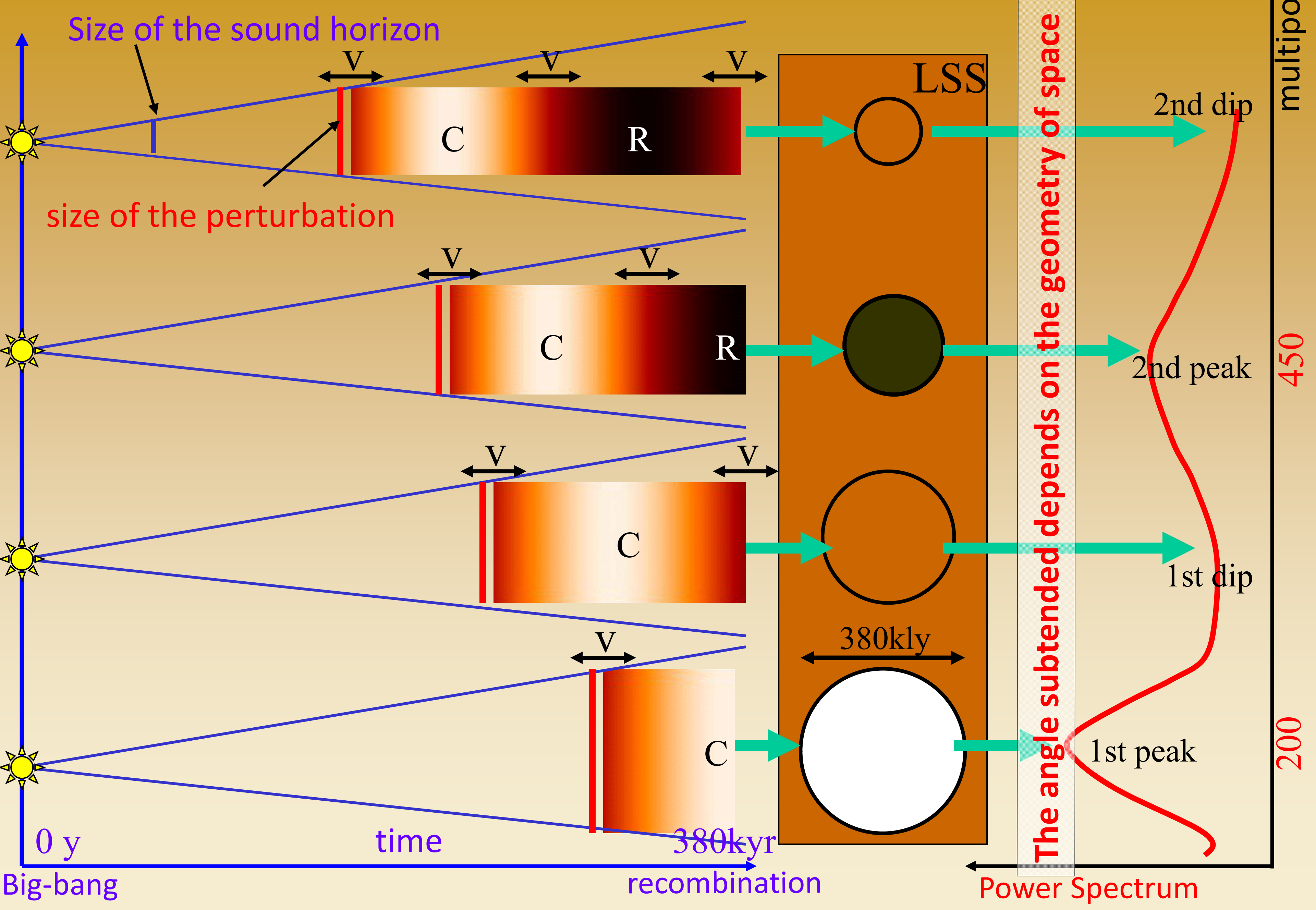
Backup slides


??
c
Big Bang
Dark Ages
First Light
Today
0
400,000
560 million
13.8 billion
Years
ESO

density fluctuations and CMB anisotropies



In the primeval plasma, photons/baryons density perturbations start to oscillate only when the sound horizon becomes larger than their linear size . Small wavelength perturbations oscillate faster than large ones.



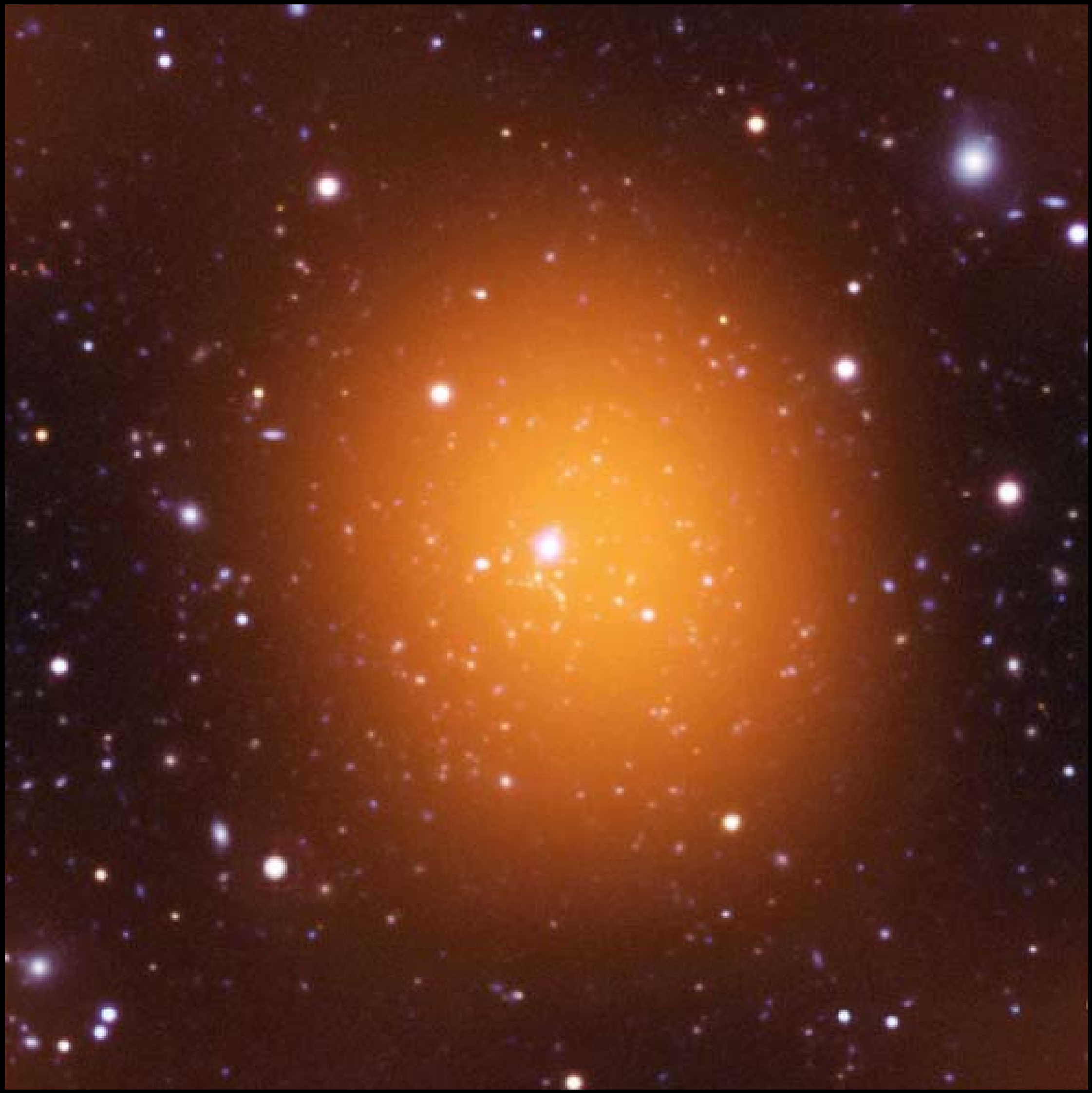
Spectrometer Calibration Procedure

- Frequency calibration – mechanical + CO lines
- Spectral Response calibration
  - In the lab:
    - measure response to cold-NDF reduced beam-filling blackbody sources at different temperatures in the two input ports (and use model for telescope spectral response, if needed)
    - Measure response to 1% emissivity grey-body in one of the two input ports, with cold background and no NDF
    - Measure NDF alone (with/without) in dedicated spectrometer + cold holder setup
  - In flight:
    - confirm response to 1% emissivity beam-filling grey-body in one of the two input ports

- Beam:
  - In the lab:
    - Measure Gunn oscillator in the far-field (>1 km away)
  - In flight:
    - Confirm with planet

Hot ionized gas in clusters

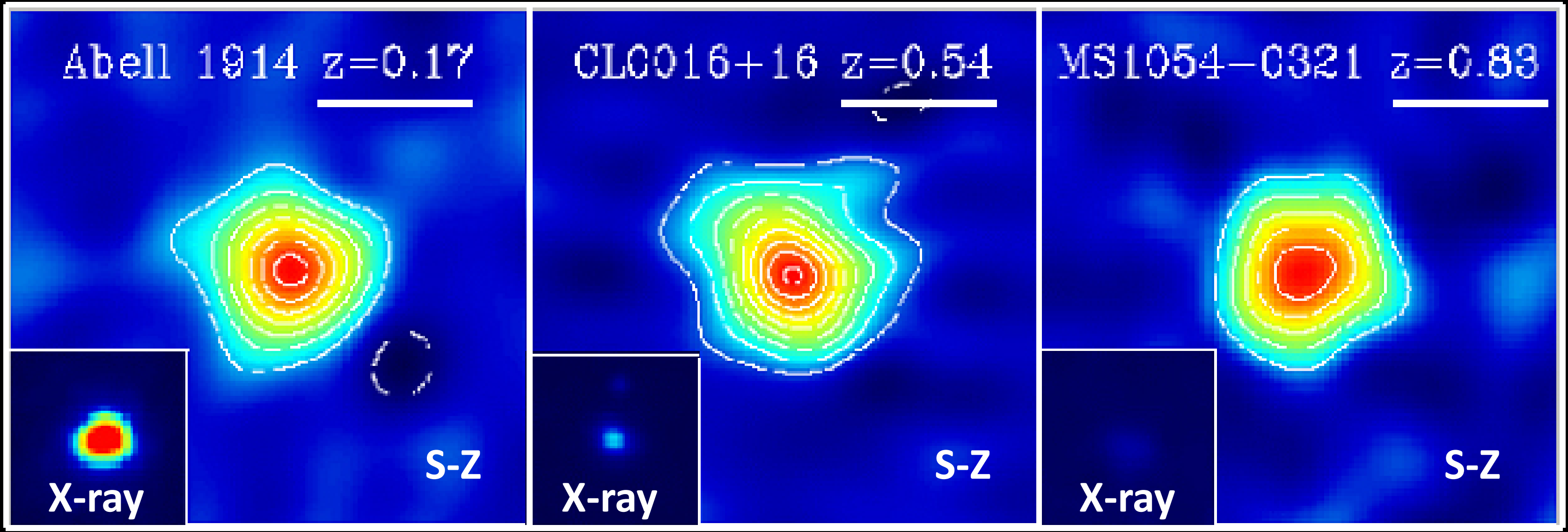
- The potential well of the cluster is so deep that gas falling into the well heated up to millions of K :
- kT ~ 10 keV
- For this reason galaxy clusters are powerful X-ray emitters.
- The same gas scatters CMB photons (inverse Compton, aka Sunyaev-Zeldovich effect).



The center of the Phoenix Cluster, in X-rays, and in visible light

The Sunyaev-Zeldovich Effect

- Being produced by scatterings, the S-Z signal amplitude **does not** depend on the distance (redshift) of the cluster
- Depends **linearly** on the density of the gas
- The X-ray brightness, instead, decreases significantly with distance and gas density (depends on the density squared)



S-Z

- Inverse Compton Effect for CMB photons against charged particles in the hot gas of clusters
- Cluster optical depth: $\tau = n\sigma\ell$

  ℓ = a few Mpc = 10^{25} cm

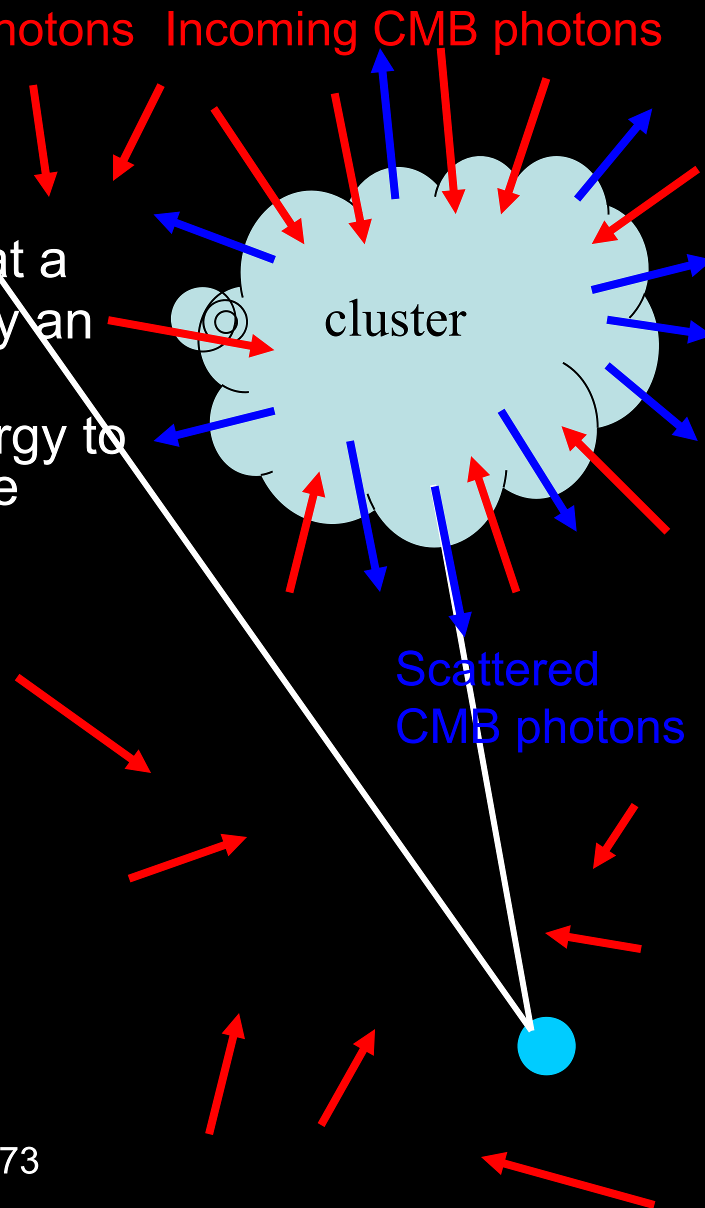
  $n < 10^{-3}$ cm^{-3}

  $\sigma = 6.65\times10^{-25}$ cm^2
- So $\tau = n\sigma\ell < 0.01$: there is a 1% likelihood that a CMB photon crossing the cluster is scattered by an electron
- $E_{electron} >> E_{photon}$, so the electron transfers energy to the photon. To first order, the energy gain of the photon is

$$\frac{\Delta\nu}{\nu} = \frac{kT_e}{m_e c^2} \approx \frac{5keV}{500keV} = 0.01$$

- The resulting CMB temperature anisotropy is

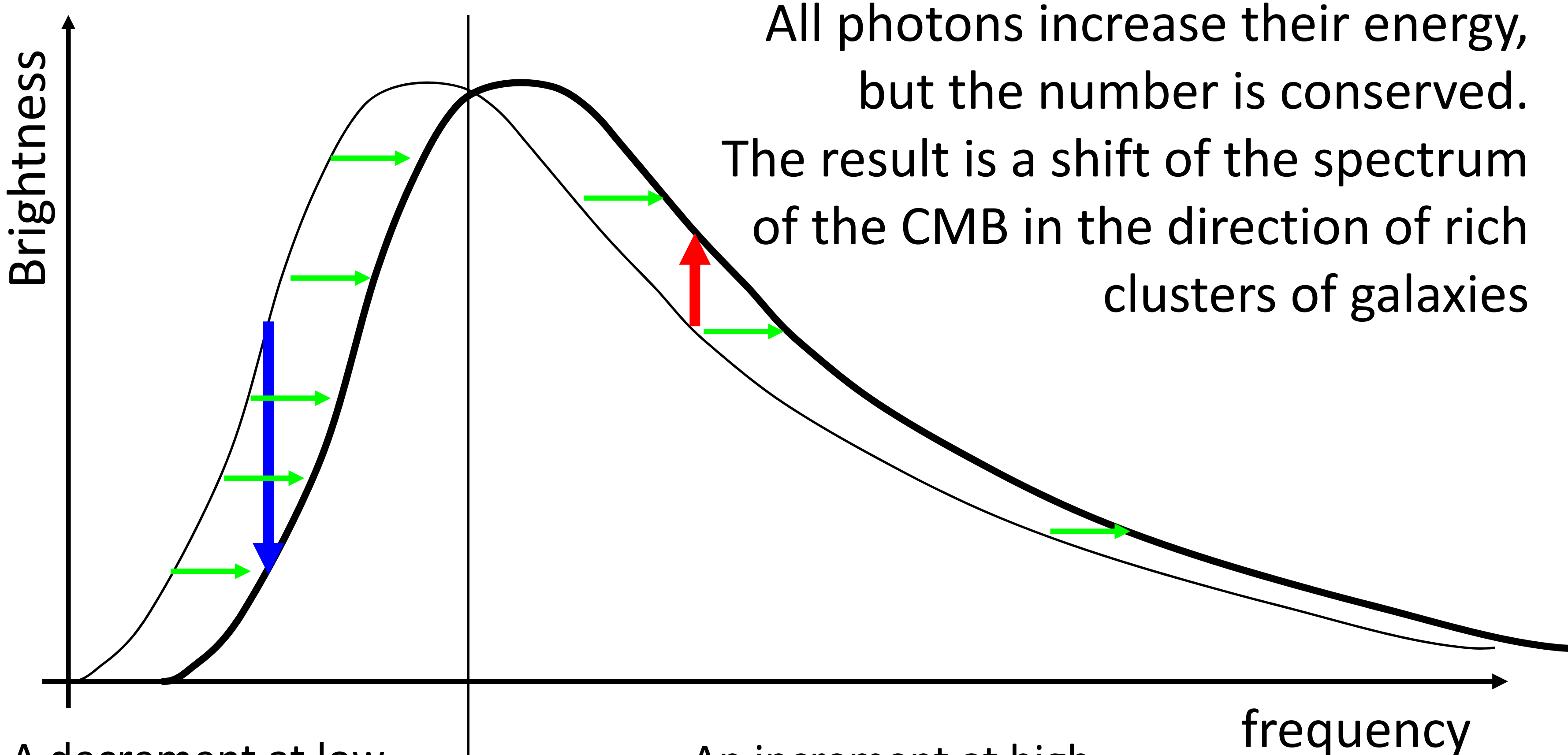
$$\frac{\Delta T}{T} \approx \tau\frac{\Delta\nu}{\nu} \approx 0.01\times0.01 = 10^{-4}$$



Sunyaev R., Zeldovich Y.B., 1972, Comm. Astrophys. Space Phys., 4, 173
Birkinshaw M., 1999, Physics Reports, 310, 97-195

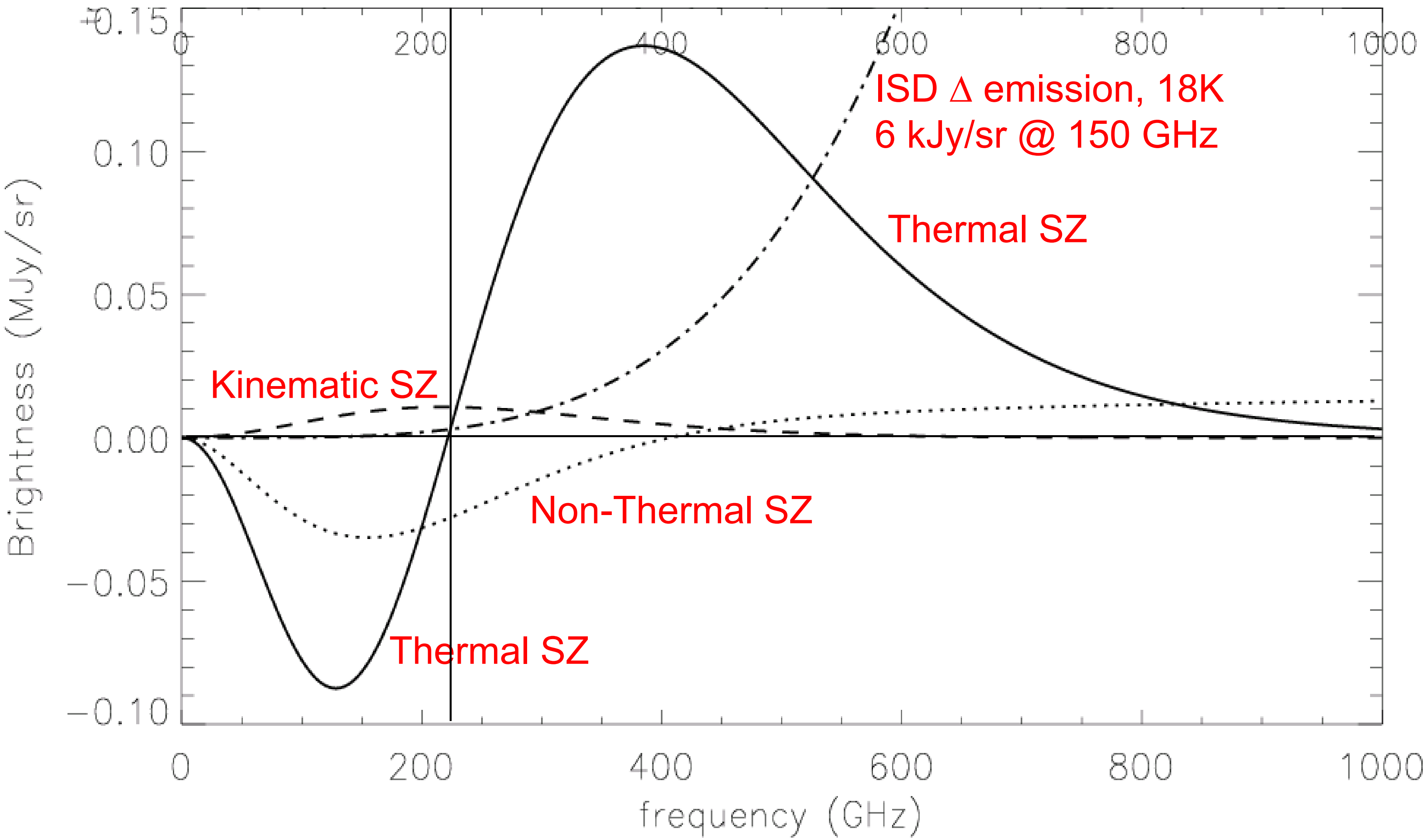
Sunyaev-Zeldovich Effect

All photons increase their energy, but the number is conserved.
The result is a shift of the spectrum of the CMB in the direction of rich clusters of galaxies



A decrement at low frequencies (<217GHz)

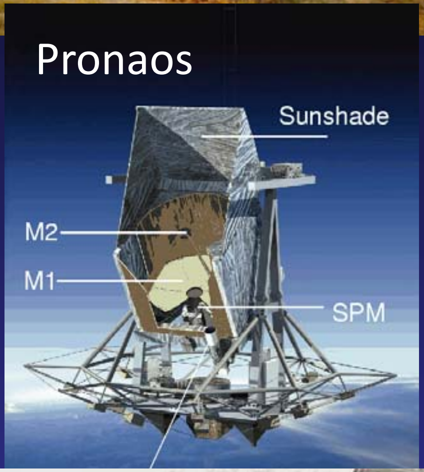
An increment at high frequencies (> 217GHz)

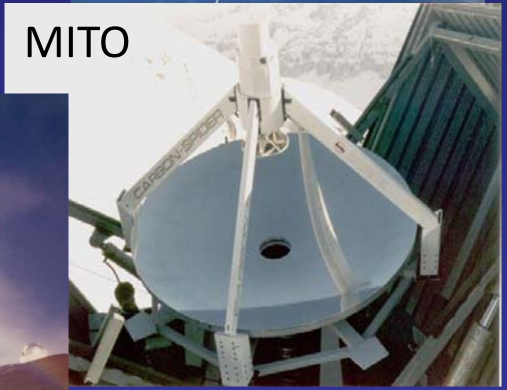


• Here we focus on the detectability of the effect, and on the **optimization of the measurements**.

SZ measurements

- Single-beam radio-telescopes and radio-interferometers (70s)
- Pronaos (balloon, first detection of positive effect)
- Single-beam mm-wave telescopes (MITO@TG, SUZIE@CSO, multiband single-pixel bolometers)
- Targeted observations of rich clusters
- Now: Bolometer Arrays at large telescopes:
  - South Pole Telescope
  - APEX
  - ACT
  - Green Banks (Mustang)
- Systematic blind-surveys of large areas
- WMAP & Planck (satellites, multiband)
- Forthcoming: SZ-Spectrometers

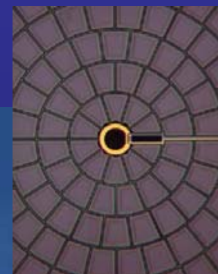


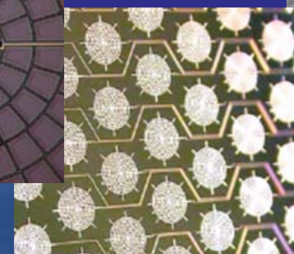


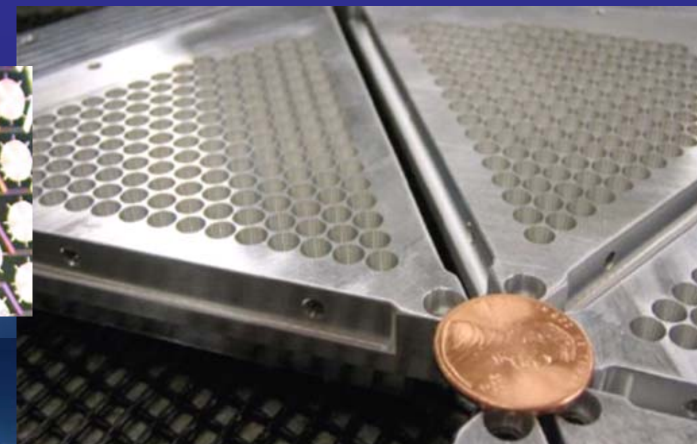
SZ measurements, today

- Large telescopes (10m class)
  - Atacama Cosmology Telescope
  - APEX-SZ
  - South-Pole Telescope

$$FWHM \approx 1.2 \frac{\lambda}{D} = \frac{1.2 \times 2\,mm}{8000\,mm} \approx 1'$$

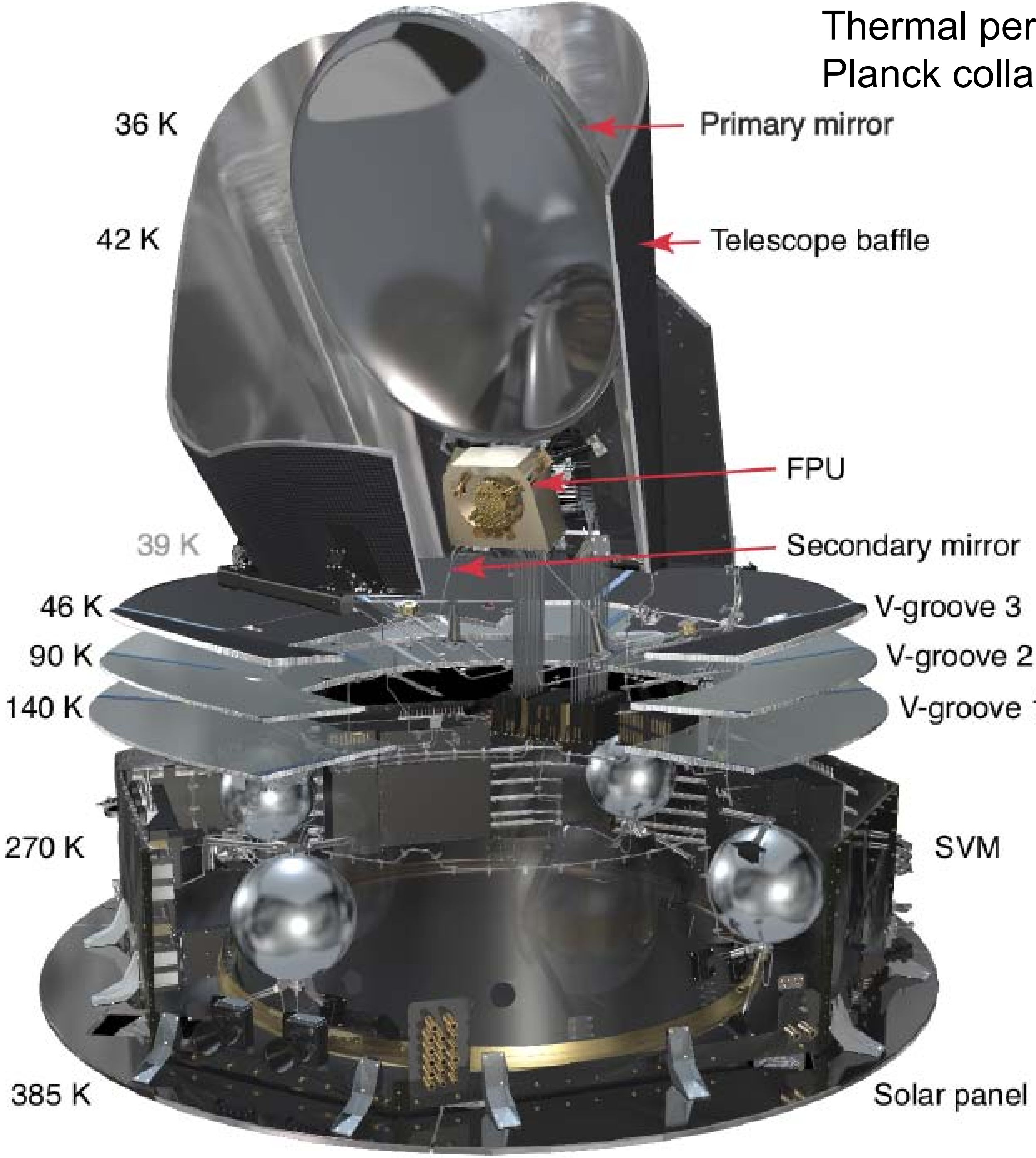


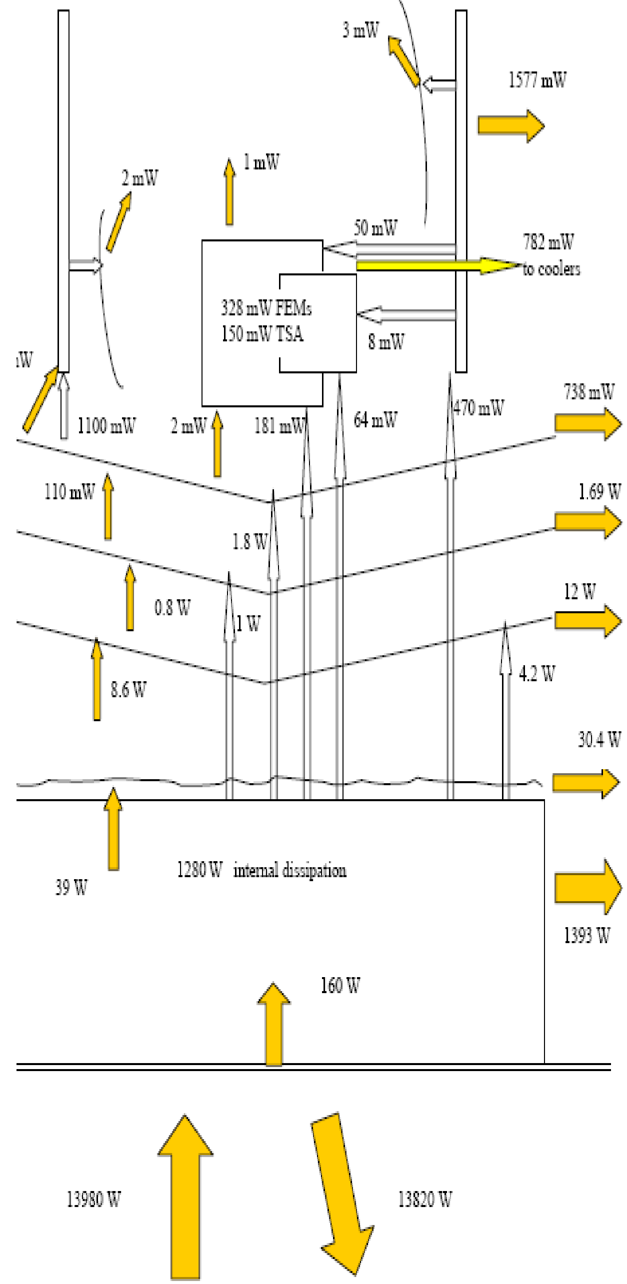


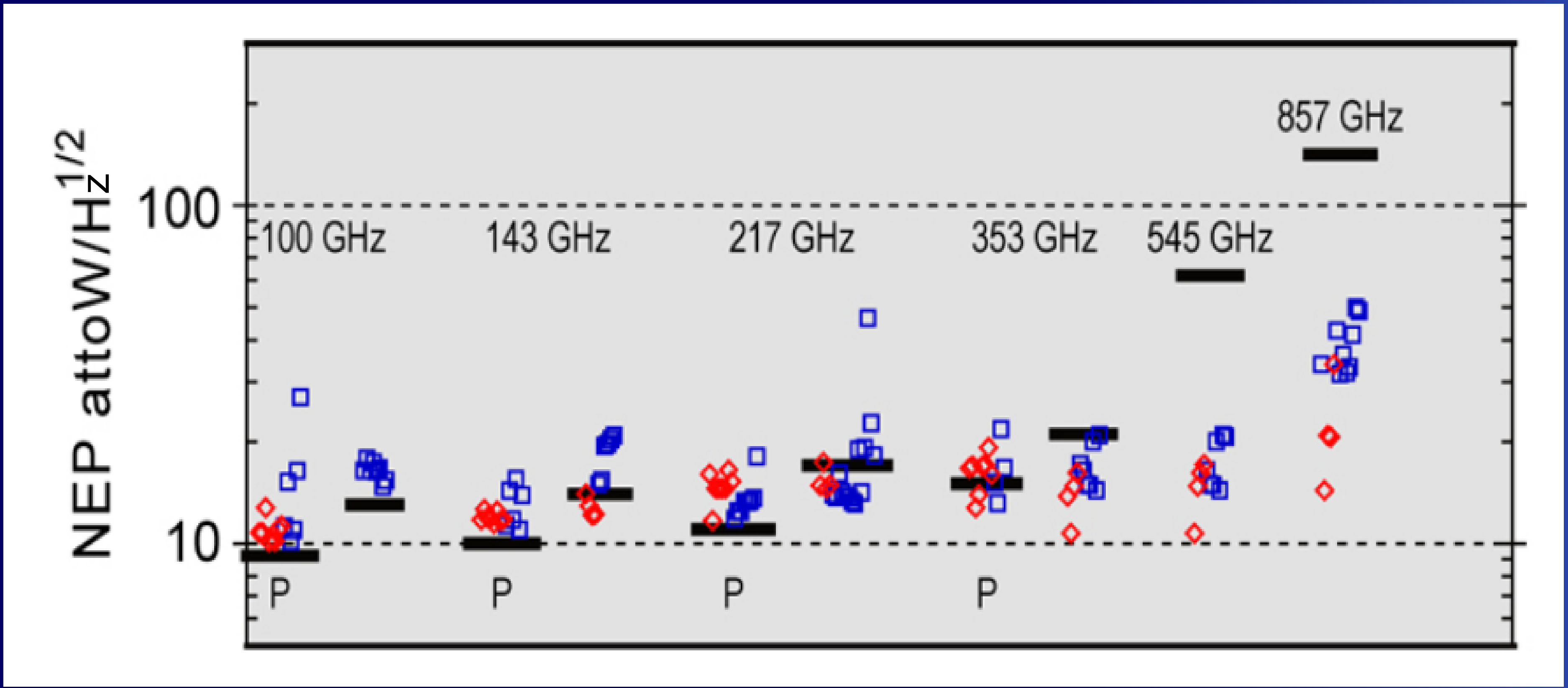


- Arrays of TES Bolometers (cheap to replicate, low power dissipation in the cryostat) – order of 1000 pixels

Thermal performance :
Planck collaboration: astro-ph/1101:2023







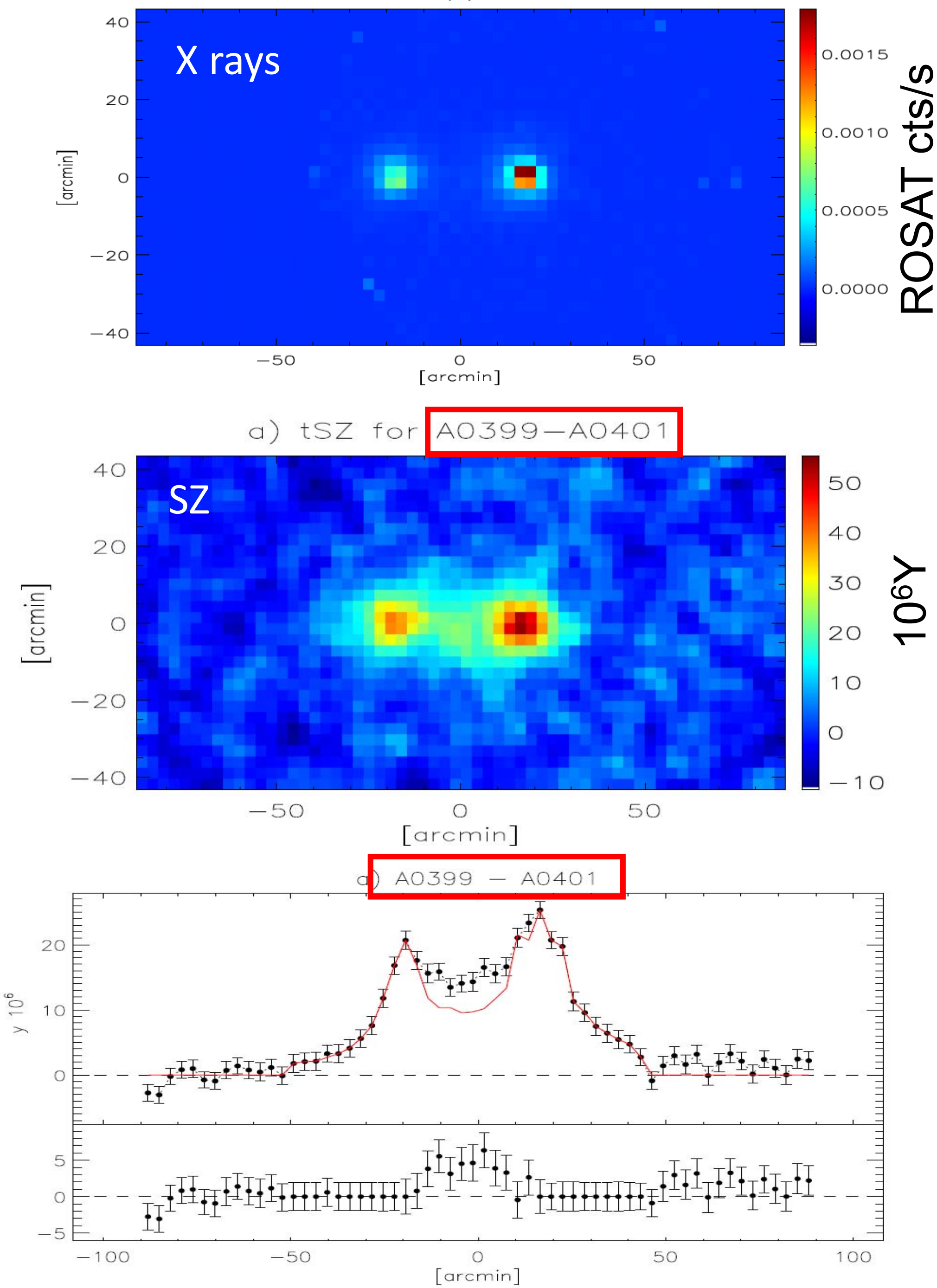
Measured dark noise equivalent power (NEP) of the focal plane detectors, including 6.5 nV / sqrt(Hz) amplifier noise at nominal bias. The open diamond symbols are the NEP for detectors installed in the focal plane. The open square symbols are the NEP of spare bolometers. The thick solid line segments indicate the photon background limit from a 35 K telescope and astrophysical sources in each band for a 30% bandwidth and 30% in band optical efficiency. Unpolarized detectors at 100 GHz were made and delivered but were replaced by polarized detectors. (from Holmes et al. (2008))

NEP_b = 15 aW/Hz$^{1/2}$ -> 70 μK/Hz$^{1/2}$

Total NET (bolo+photon) = 85 μK/Hz$^{1/2}$

Filaments

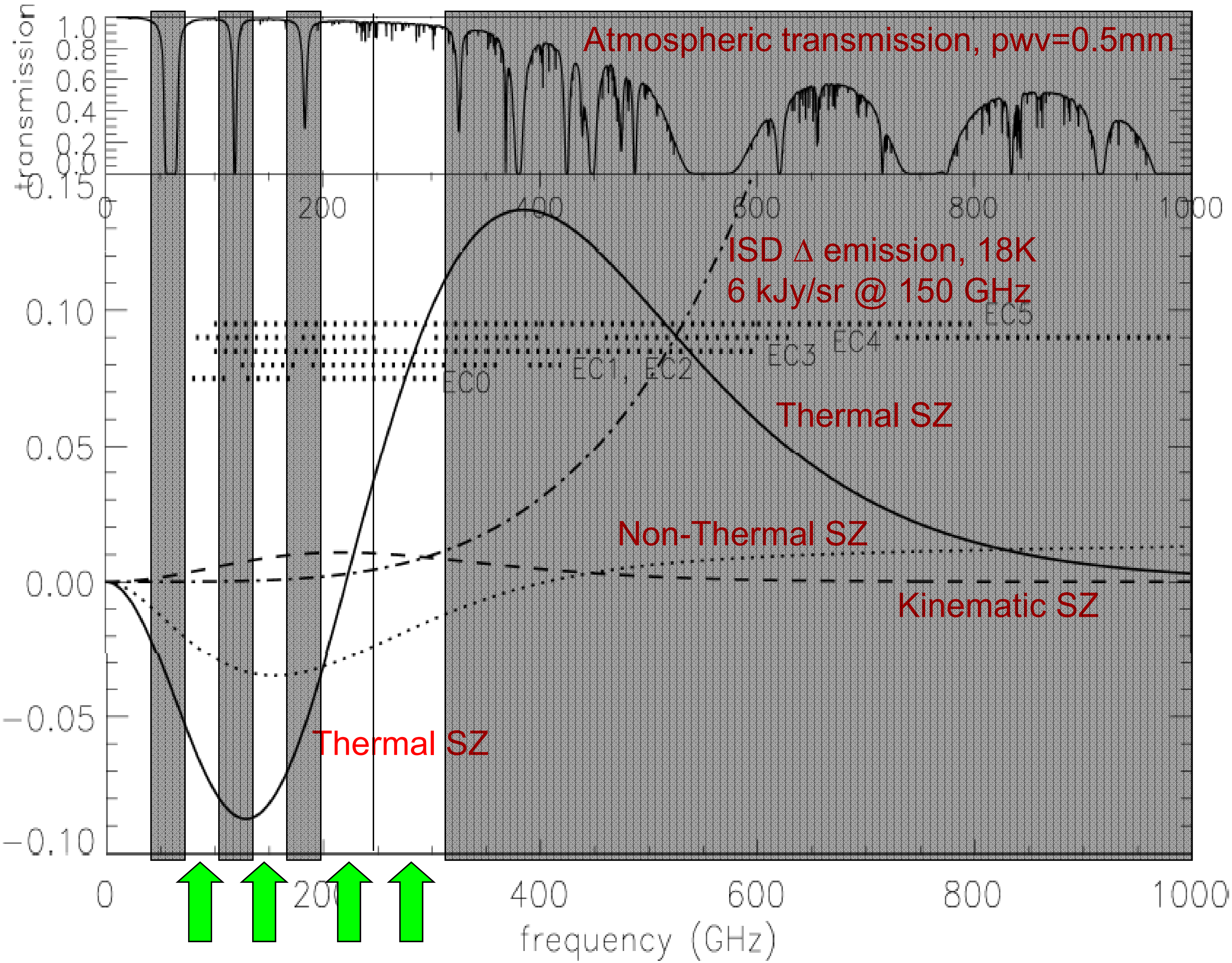
- Half of the baryons known to be present in the universe (from nucleosynthesis estimates) are missing (i.e. have not been detected in emission, nor in absorbtion).
- A possible physical state of baryons escaping detection in the radio, IR, visible, X rays domains, is a ionized medium with low density or warm temperature.
- In principle, this is detectable in the microwaves, because it produces a SZ effect.
- The Planck survey, observing the whole sky, has also observed couples of galaxy clusters, and there is evidence for filaments of gas connecting two of the couples (astro-ph/1208.5911). This is hot gas, probably heated by shocks, but the density is low, so X-ray emission is also very low. It might be one step towards the solution of the missing baryons problem.



Planck results on the SZE

- Planck Collaboration *Planck early results. VIII. The all-sky early Sunyaev-Zeldovich cluster sample* Astronomy and Astrophysics 536, A8 (2011) DOI: 10.1051/0004-6361/201116459
- Planck Collaboration *Planck early results. IX. XMM-Newton follow-up for validation of Planck cluster candidates* Astronomy and Astrophysics 536, A9 (2011) DOI: 10.1051/0004-6361/201116460
- Planck Collaboration *Planck early results. X. Statistical analysis of Sunyaev-Zeldovich scaling relations for X-ray galaxy clusters* Astronomy and Astrophysics 536, A10 (2011) DOI: 10.1051/0004-6361/201116457
- Planck Collaboration *Planck early results. XI. Calibration of the local galaxy cluster Sunyaev-Zeldovich scaling relations* Astronomy and Astrophysics 536, A11 (2011) DOI: 10.1051/0004-6361/201116458
- Planck Collaboration *Planck early results. XII. Cluster Sunyaev-Zeldovich optical scaling relations* Astronomy and Astrophysics 536, A12 (2011) DOI: 10.1051/0004-6361/201116489
- Planck Collaboration *Planck early results. XXVI. Detection with Planck and confirmation by XMM-Newton of PLCK G266.6–27.3, an exceptionally X-ray luminous and massive galaxy cluster at z ~ 1* Astronomy and Astrophysics, 536, A26 (2011); DOI: 10.1051/0004-6361/201117430
- Planck Collaboration *Planck intermediate results. I. Further validation of new Planck clusters with XMM-Newton* Astronomy & Astrophysics, 543, A102 (2012) DOI: 10.1051/0004-6361/201118731
- Planck - AMI Collaborations *Planck Intermediate Results II: Comparison of Sunyaev-Zeldovich measurements from Planck and from the Arcminute Microkelvin Imager for 11 galaxy clusters*, Astronomy and Astrophysics (2013), 550, A128, DOI:10.1051/0004-6361/201219361
- Planck Collaboration *"Planck intermediate results. III. The relation between galaxy cluster mass and Sunyaev-Zeldovich signal"*, Astronomy and Astrophysics (2013), 550, A129, astro-ph/1204.2743, DOI:10.1051/0004-6361/201219398
- Planck Collaboration *"Planck Intermediate Results. IV. The XMM-Newton validation programme for new Planck galaxy clusters"*, Astronomy and Astrophysics (2013), 550, A130, astro-ph/1205.3376, DOI:10.1051/0004-6361/201219519
- Planck Collaboration *"Planck Intermediate Results. V. Pressure profiles of galaxy clusters from the Sunyaev-Zeldovich effect"*, Astronomy and Astrophysics (2013), 550, A131, astro-ph/1207.4061, DOI: 10.1051/0004-6361/201220040
- Planck Collaboration *"Planck intermediate results. VI: The dynamical structure of PLCKG214.6+37.0, a Planck discovered triple system of galaxy clusters"*, Astronomy and Astrophysics (2013), 550, A132, astro-ph/1207.4009, DOI: 10.1051/0004-6361/201220039
- Planck Collaboration *"Planck intermediate results. VIII. Filaments between interacting clusters"*, Astronomy and Astrophysics (2013), 550, A134, astro-ph/1208.5911, DOI: 10.1051/0004-6361/201220194
- Planck Collaboration *"Planck intermediate results. X. Physics of the hot gas in the Coma cluster"*, Astronomy & Astrophysics, 554, A140 (2013) DOI: 10.1051/0004-6361/201220247

best ground-based photometers: 4 bands



The OLIMPO Collaboration

P.A.R. Ade[2], G. Amico[1], E. Battistelli[1], A. Boscaleri[3], A. Coppolecchia[1], P. de Bernardis[1], P. Camus[4], S. Colafrancesco[5], A. Cruciani[1], D'Addabbo[4], G. D'Alessandro[1], S. De Gregori[1], M. De Petris[1], G. Di Stefano[7], M. Gervasi[8], R. Gualtieri[1], K. Irwin[9], L. Lamagna[1], P. Marchegiani[5], S. Masi[1](PI), P. Mauskopf[2], F. Nati[1], L. Pagano[1], C. Paiva Novaes[0] F. Piacentini[1], R. Puddu[1], A.Romano[1], G. Romeo[7], M. Salatino[1], A. Schillaci[1], E. Tommasi[10], C. Tucker[2], D. Yvon[6], A. Wuensche[11], M. Zannoni[8]

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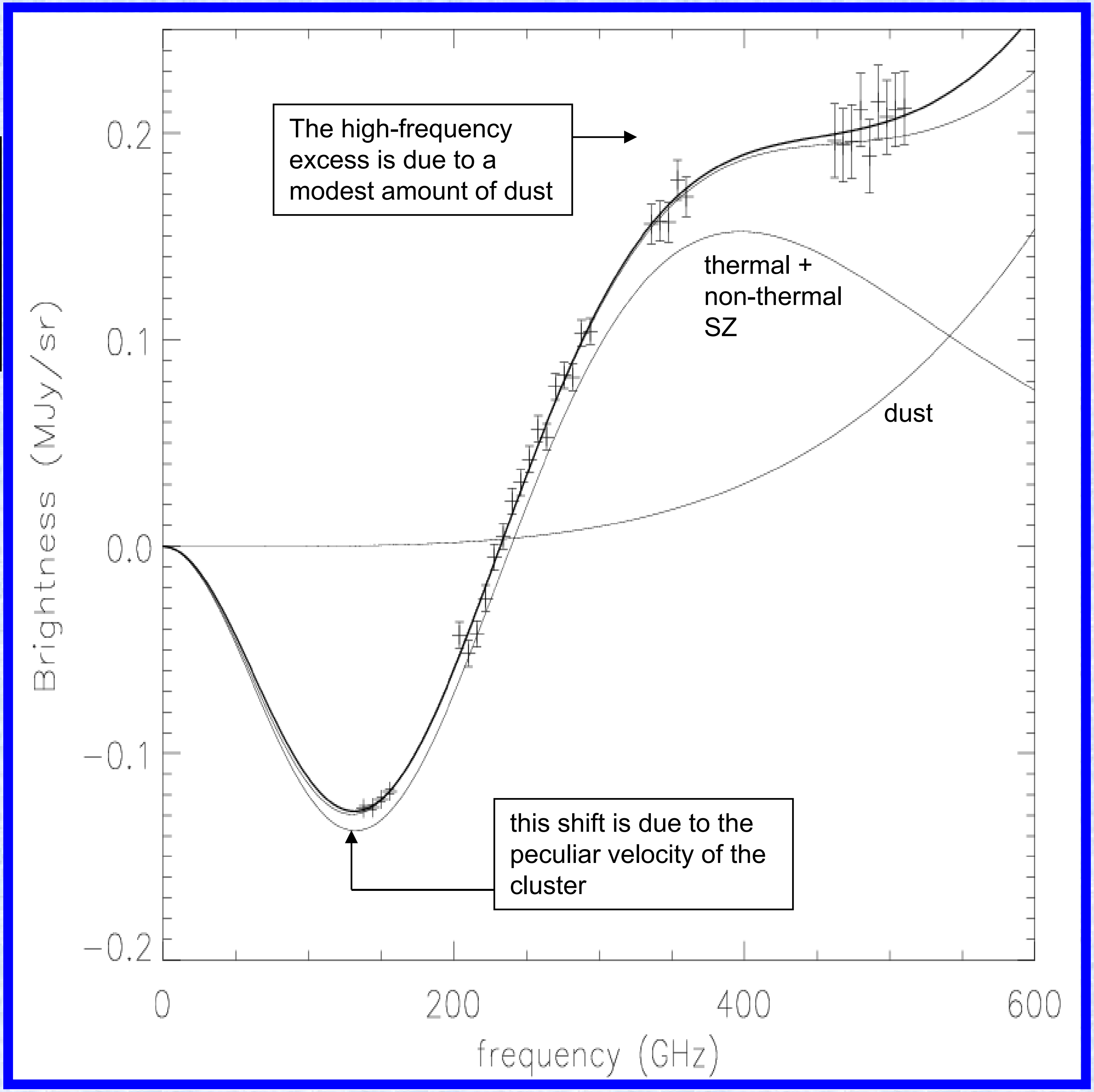
4 : Institut Neel, Grenoble, France
5 : WITS, South Africa
6 : CEA Saclay, France
7 : Istituto Nazionale di Geofisica, Roma, Italy
8 : Dipartimento di Fisica, Università di Milano Bicocca, Italy
9 : NIST Boulder CO. USA
10 : ASI Italy
11 : INPE Brasil

Simulated OLIMPO measurement of a cluster l.o.s. with

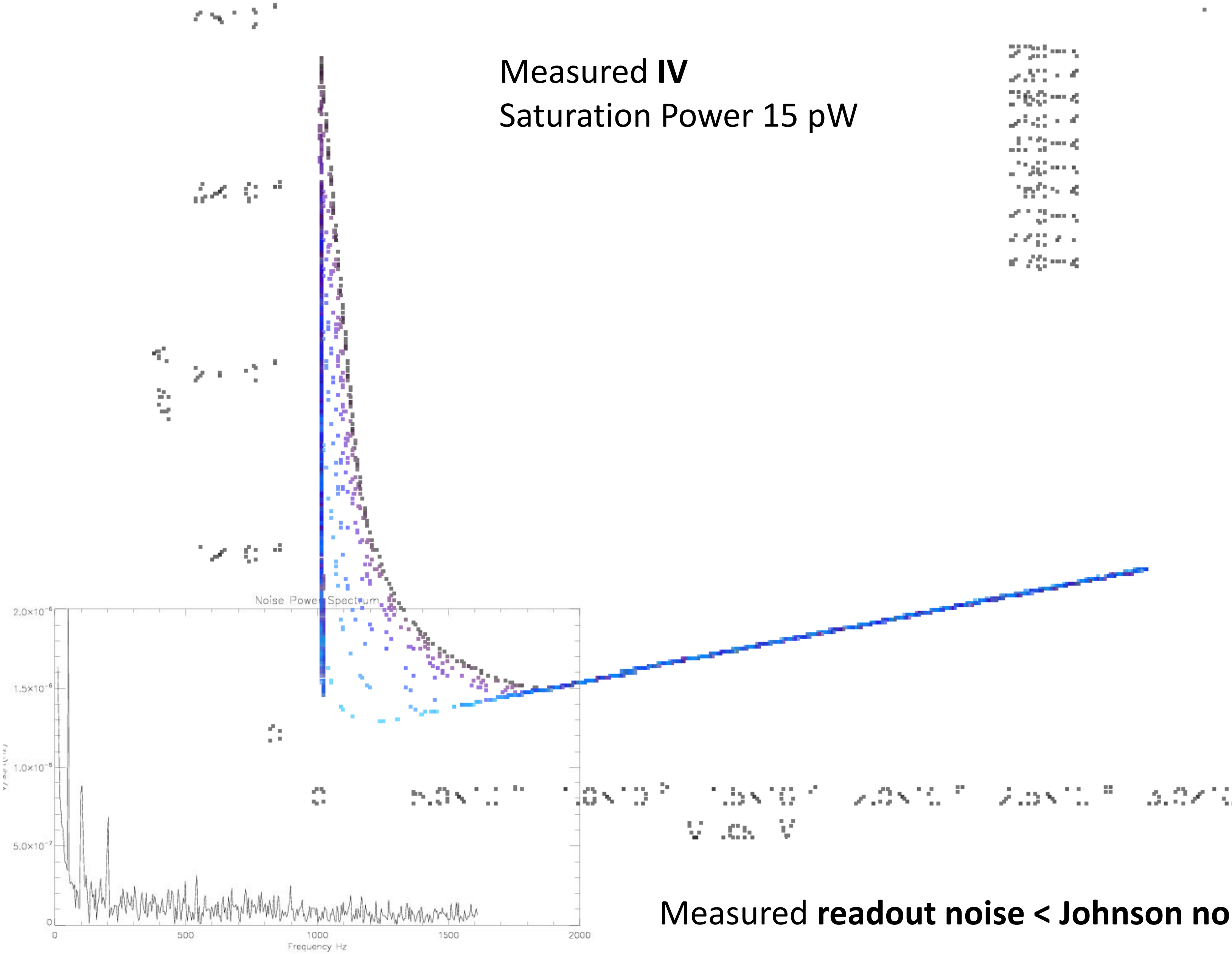
τ_{th}=0.005,
T_e=10 keV,
τ_{nonth}=0.0001,
v_{pec}=500 km/s,
I_{dust}=6kJy/sr@150GHz

The data with the error bars are simulated observations from a single pixel of the OLIMPO-FTS, for an integration time of 3 hours. The two lines through the data points represent the input theory (thin) and the best fit for the plotted data realization (thick). The other thin lines represent thermal plus non-thermal SZE, and dust emission.



Measured **IV**

Saturation Power 15 pW

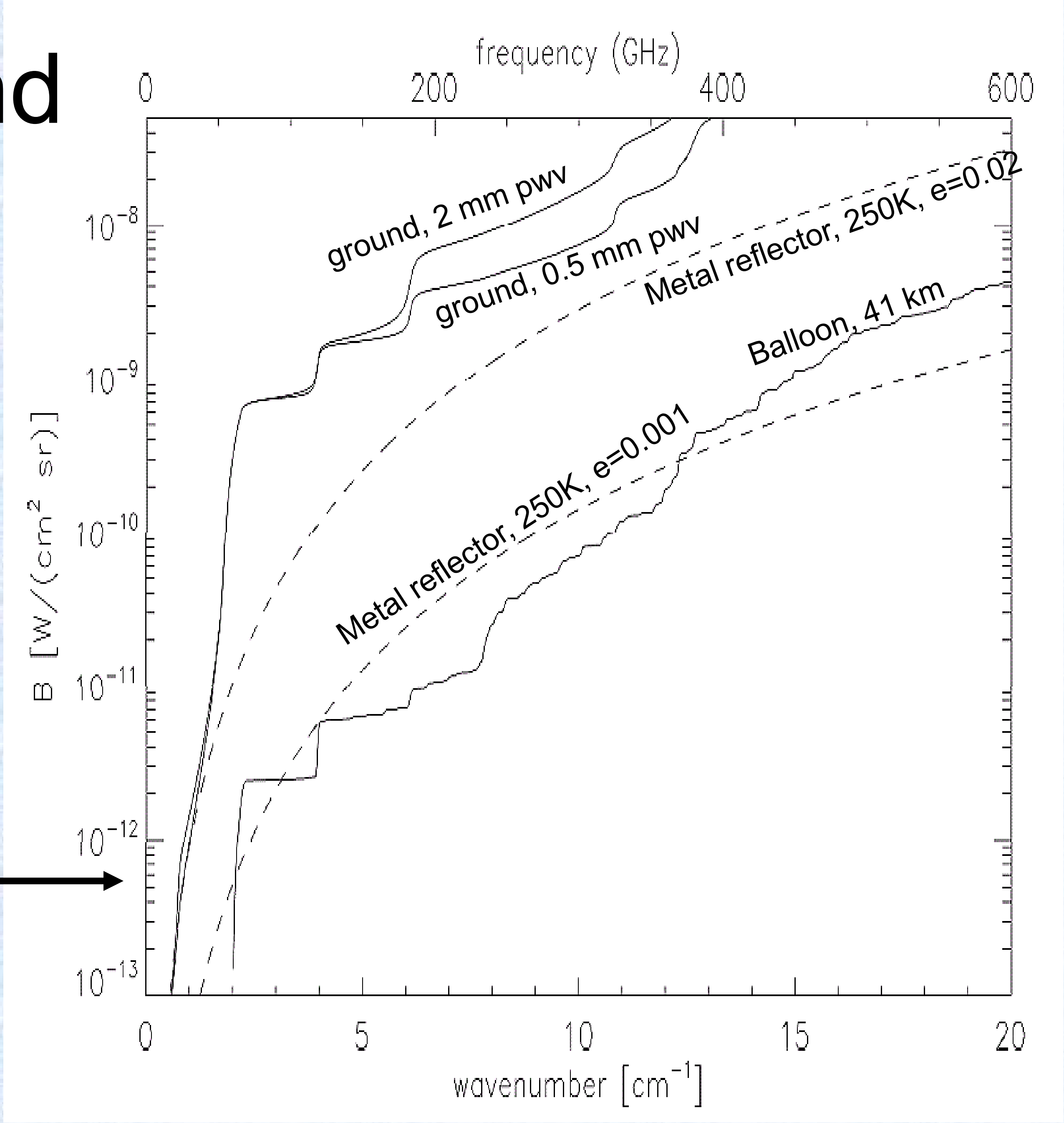


Measured **readout noise < Johnson noise**

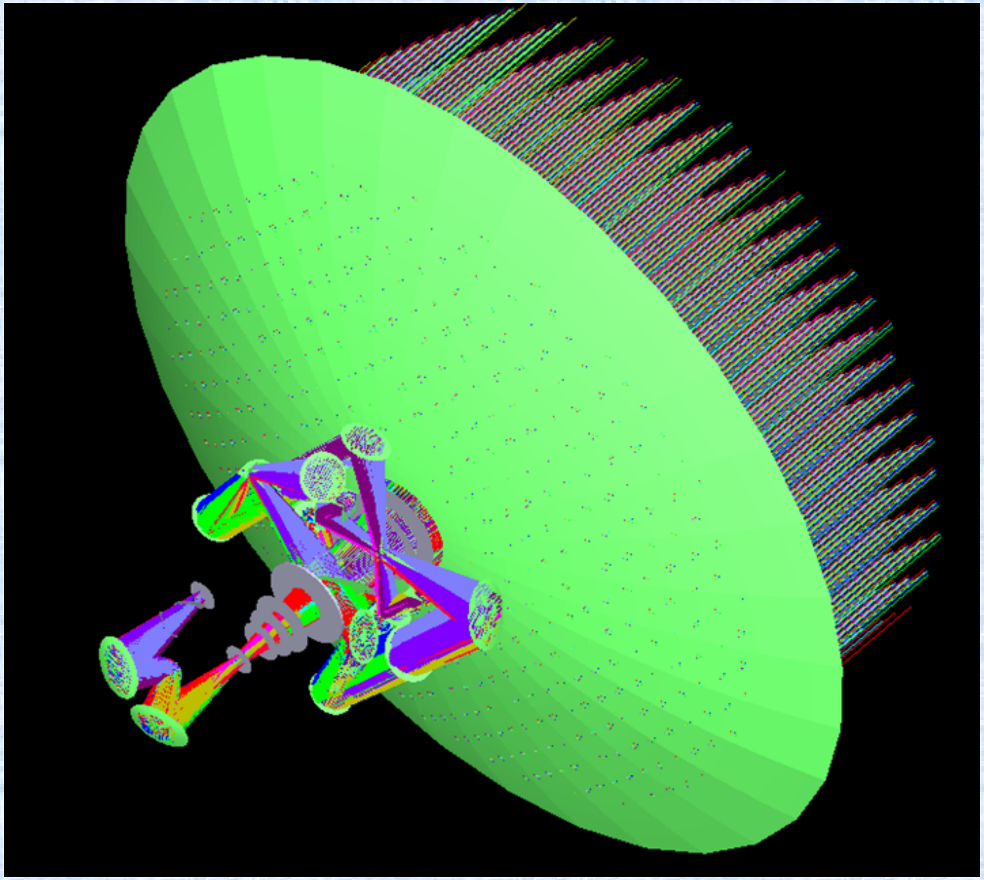
Background

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

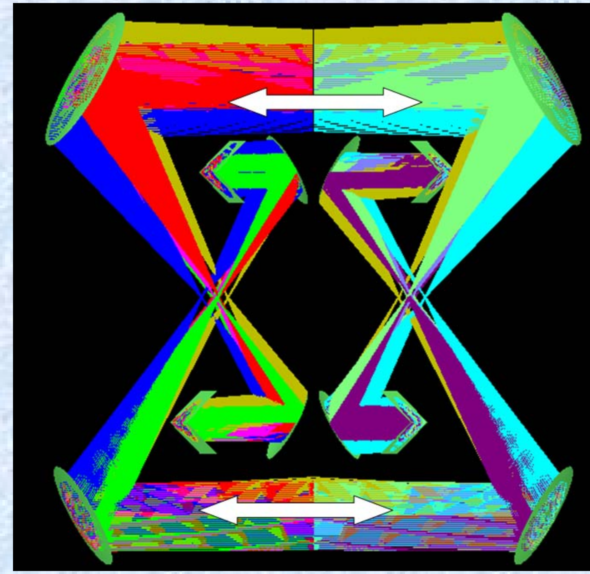
$$\int_0^{\nu} B(\nu)\,d\nu$$



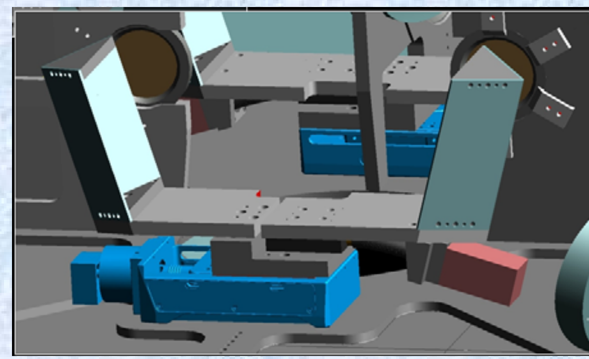
The OLIMPO Martin-Puplett Differential Fourier Transform Spectrometer



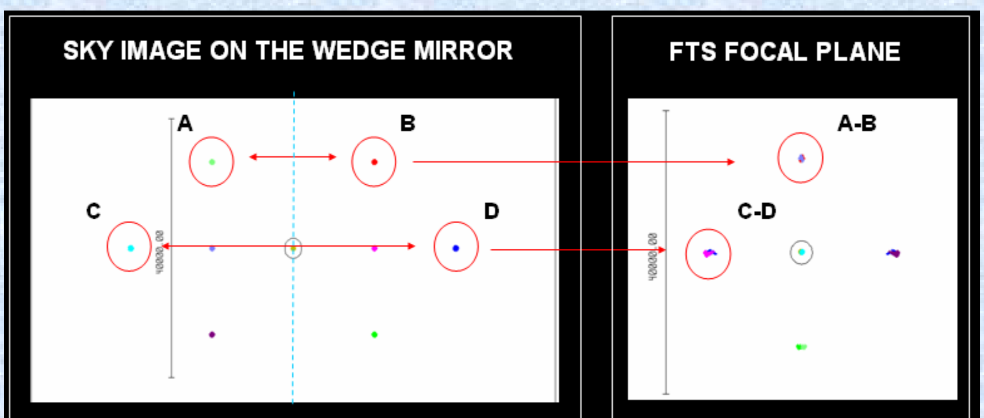
Global design of the optical system



Optical layout of the doublel Martin-Puplett FTS

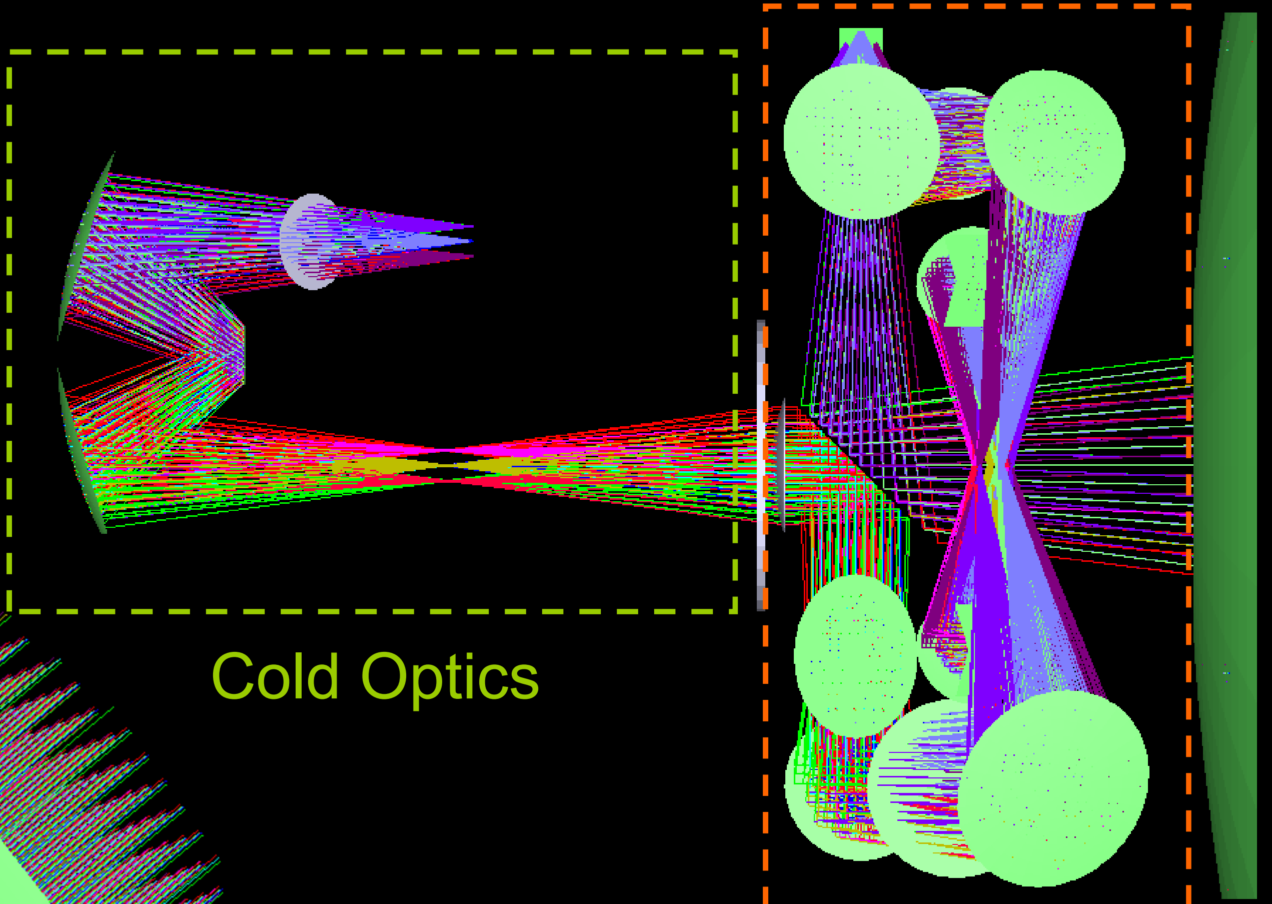


Mechanical arrangement of the translation stages



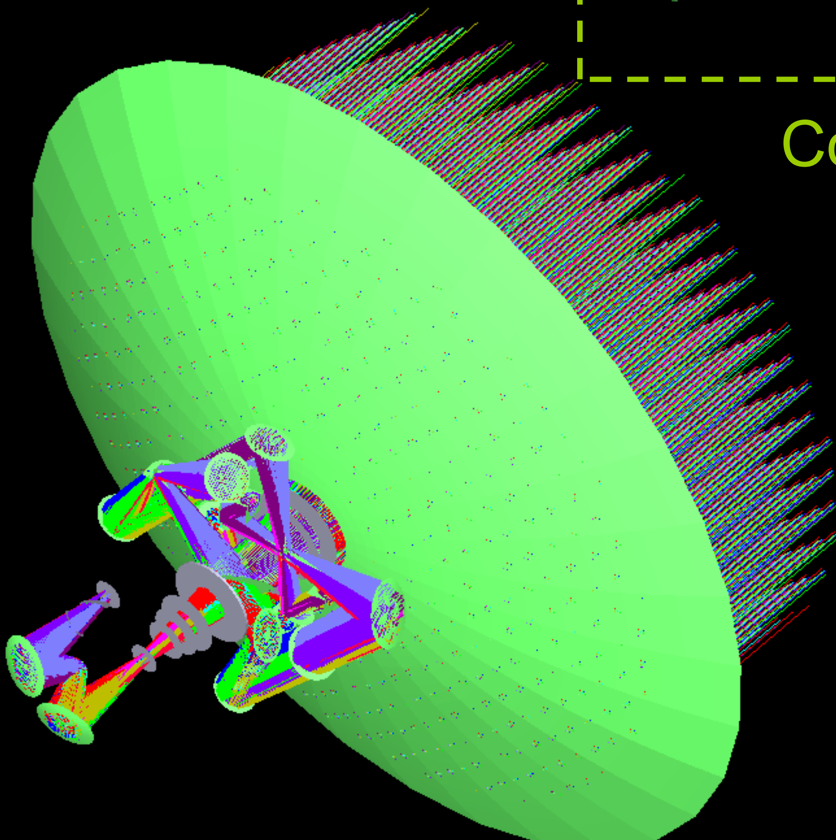
Differential field of view

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



Cold Optics

FTS



The instrument was designed to fit the available room in between the primary mirror and the cryostat, a 75x75x30 cm3 box.(A.Schillaci)

- In the presence of peculiar velocities, non-thermal populations (from AGNs in the cluster), and foreground dust, there are simply too many free parameters to be determined with the observation of a few frequency bands.
- We have carried out detailed simulations of OLIMPO observations in the spectroscopic configuration with an extended 200-300 GHz band.
- The spectroscopic configuration has superior performance in converging to the correct estimate of thermal optical depth and dust parameters, while the photometric configuration, *in the absence of priors*, tends to converge to biased estimates of the parameters.
- See de Bernardis et al. A&A 538 A86 (2012) for details

Input parameters	OLIMPO FTS 3h integ. one detector	• No priors	• Prior T=(10$\pm$3) keV
τ_{th} =50x10^{-4}		τ_{th} =(63$\pm$27)10^{-4}	τ_{th} =(49$\pm$6)10^{-4}
T = 10 keV		T = (9.0$\pm$4.1) keV	T = (9.6$\pm$0.5)keV
τ_{non-th}=1x10^{-4}		τ_{non-th}=(14$\pm$9)10^{-5}	τ_{non-th}=(11$\pm$9)10^{-5}
ΔT_{CMB}=22μK		ΔT_{CMB}=(24$\pm$43)μK	ΔT_{CMB}=(22$\pm$43)μK
$\Delta I_{dust150}$=6 kJy/sr		$\Delta I_{dust150}$=(5.7$\pm$1.6)kJy/sr	$\Delta I_{dust150}$=(5.8$\pm$0.9)kJy/sr

al

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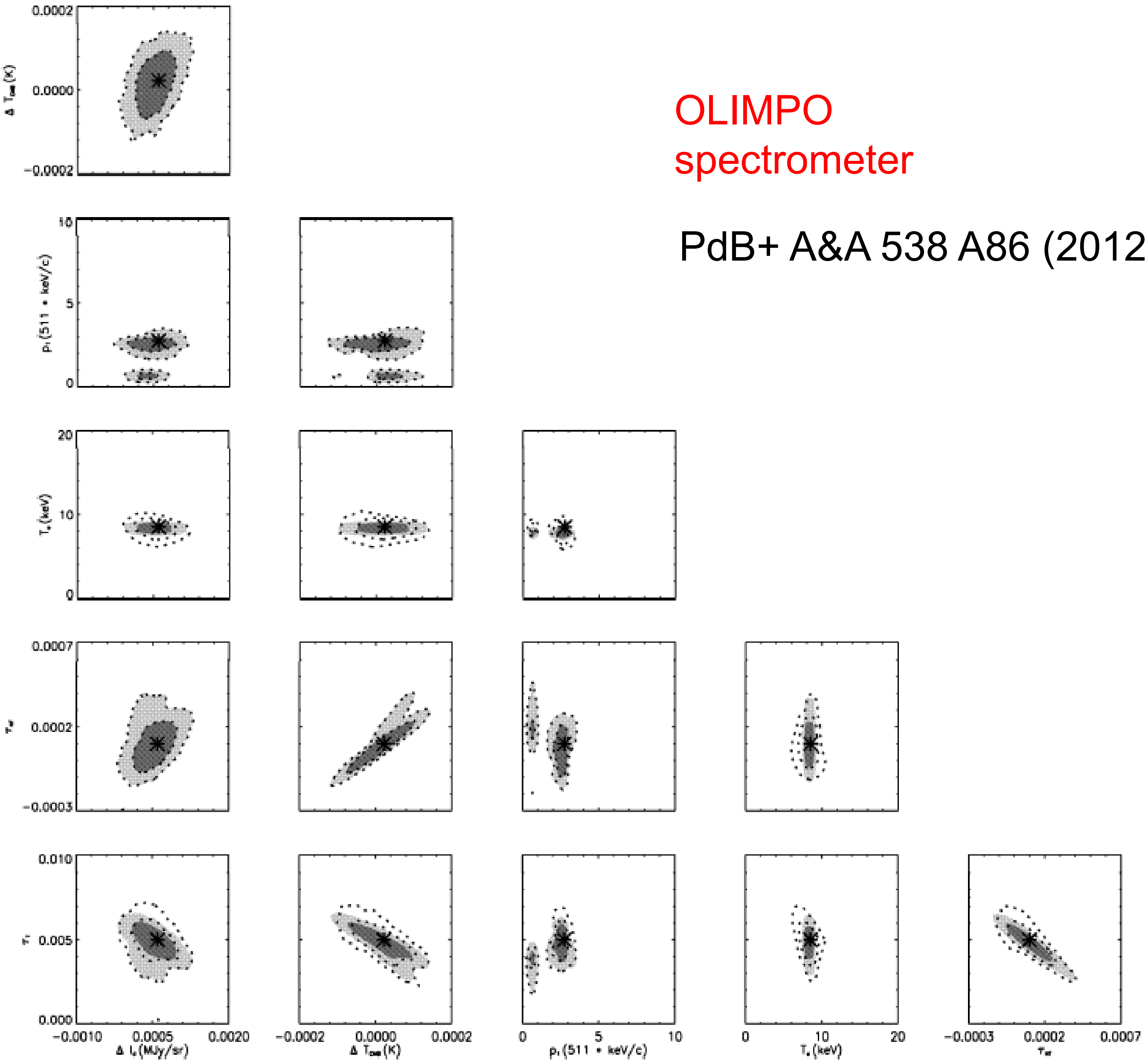
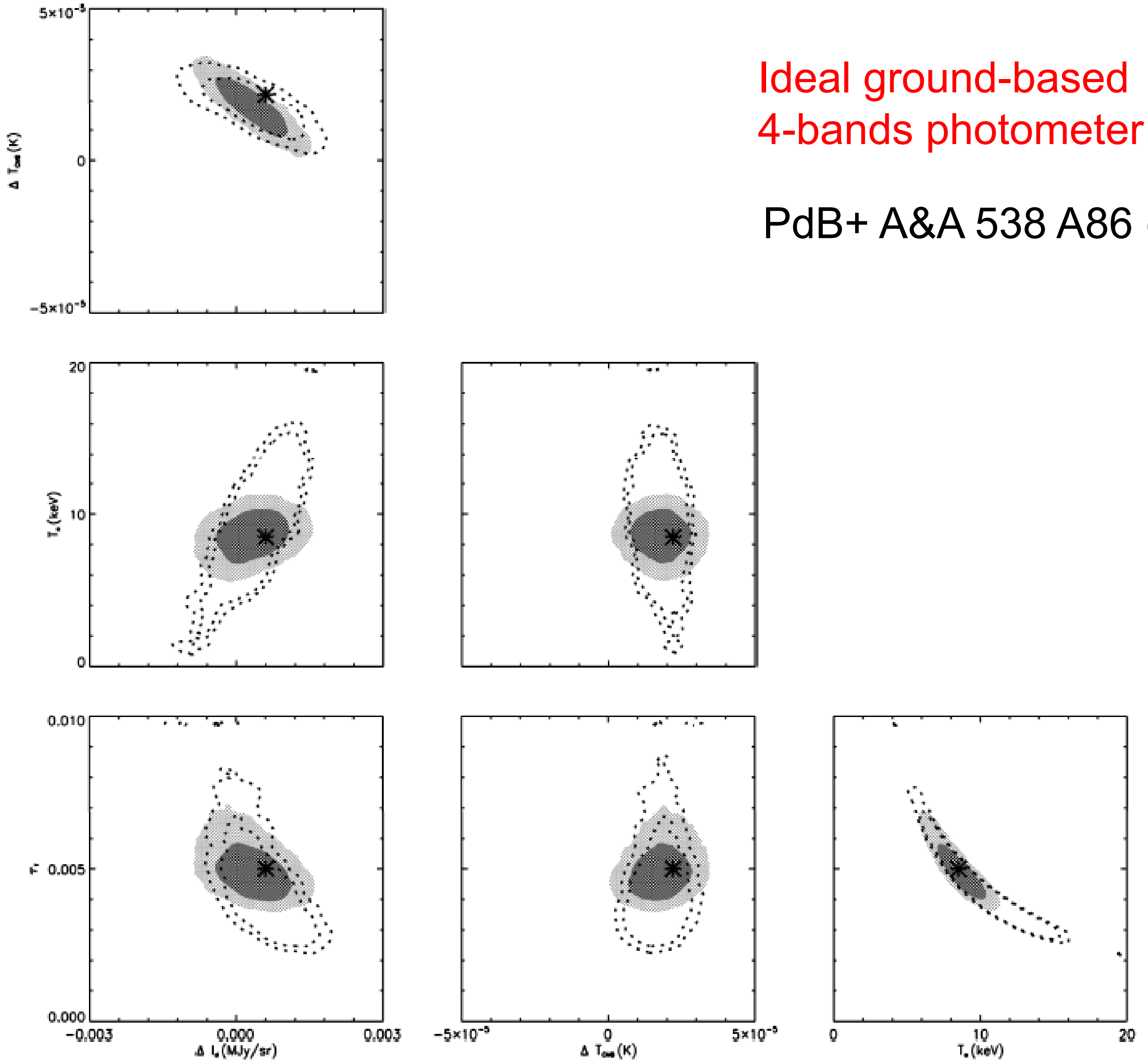


OLIMPO
spectrometer

PdB+ A&A 538 A86 (2012)



Ideal ground-based
4-bands photometer

PdB+ A&A 538 A86 (

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.

TES and P_{sat}

$\langle T_C \rangle = (495 \pm 10)$ mK

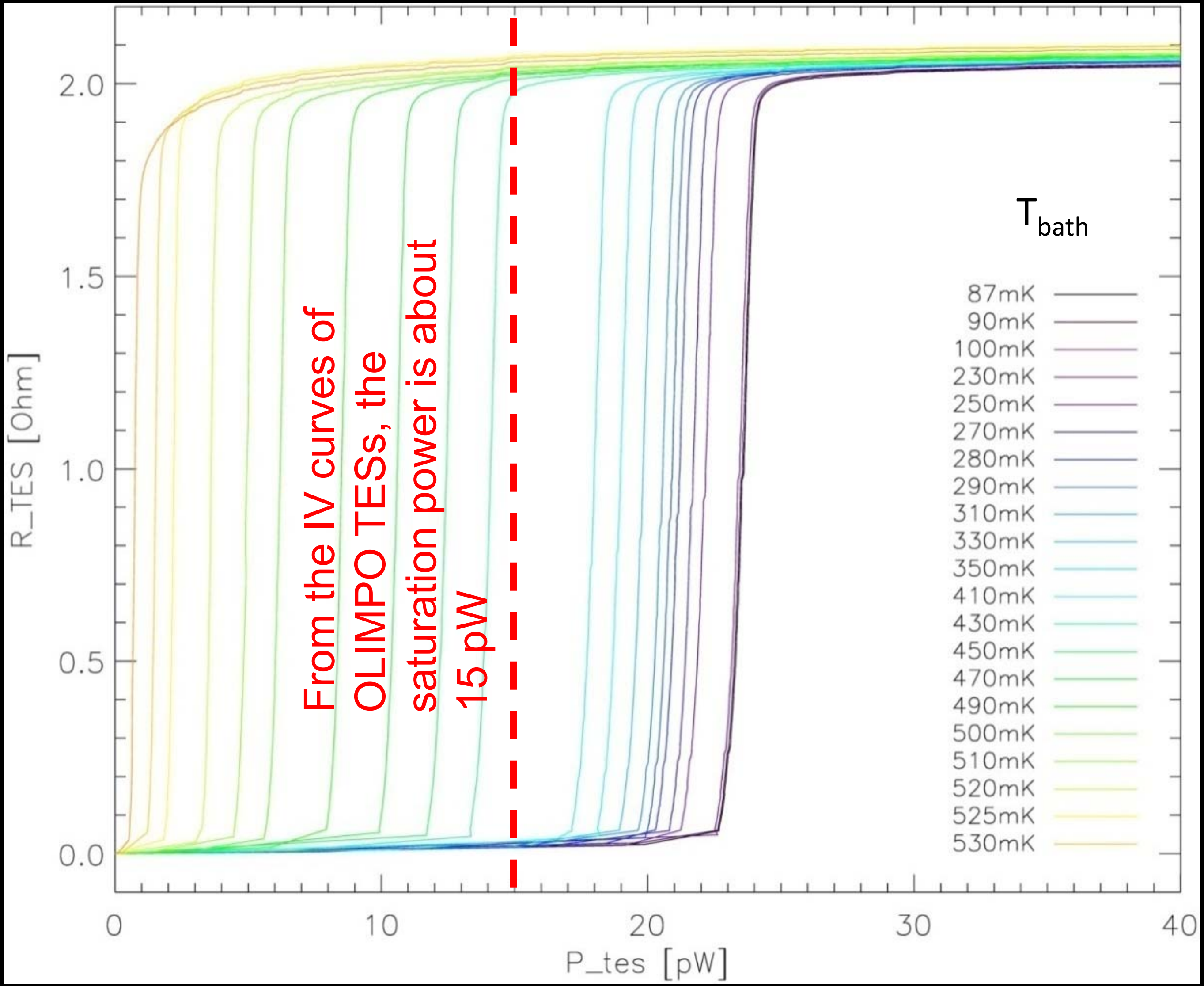
$\langle G \rangle = (1.56 \pm 0.19)\ 10^{-10}$ W/K

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

$\langle R_N \rangle = (2.15 \pm 0.22)$ Ohm

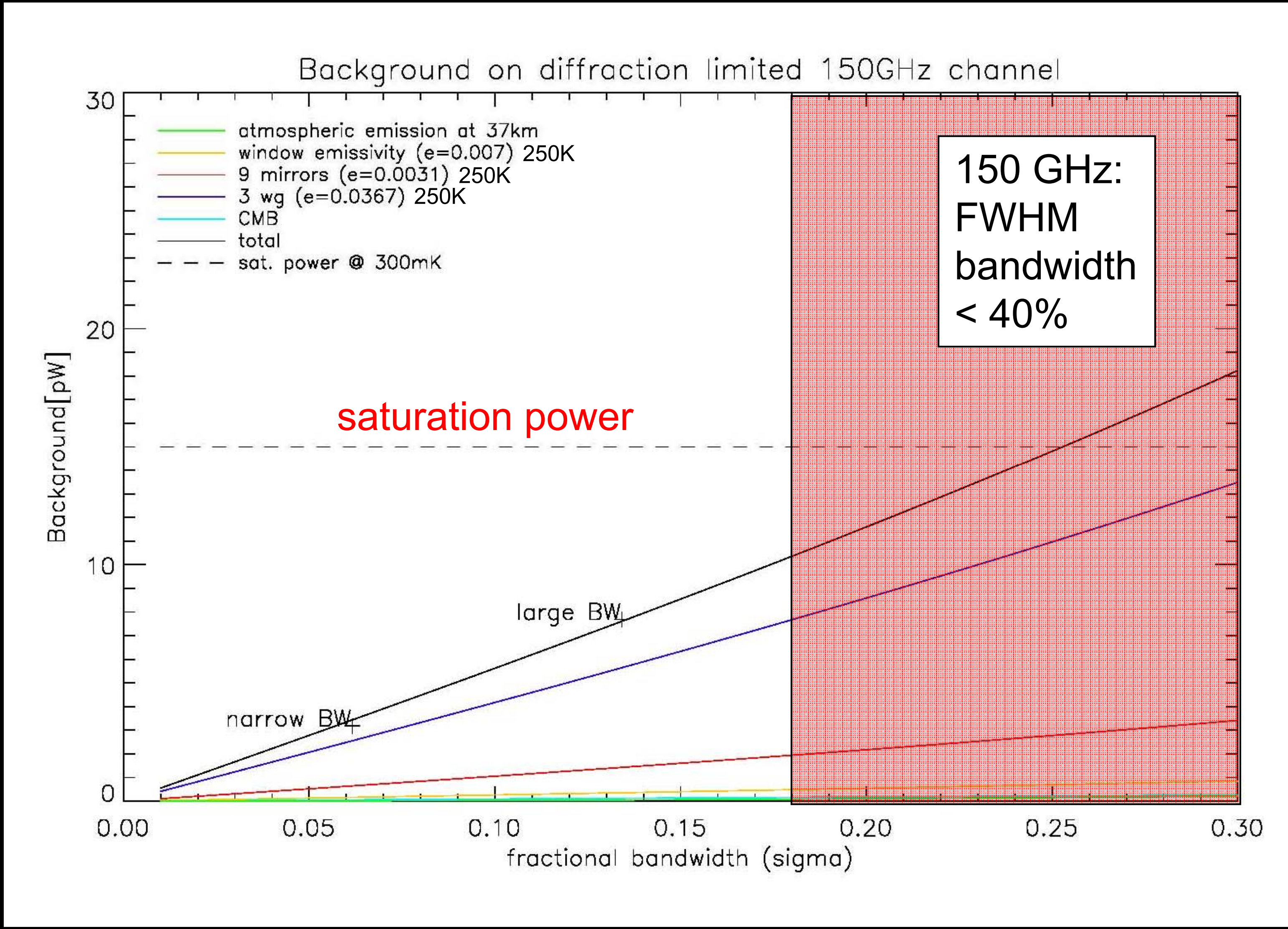
$\langle P_{SAT} \rangle = (15.5 \pm 1.4)$ pW…
…@ 290-310 mK

- Background MUST be strictly lower than P_{sat}!!!
- We need to account for the additional mirrors and wire grids in the FTS



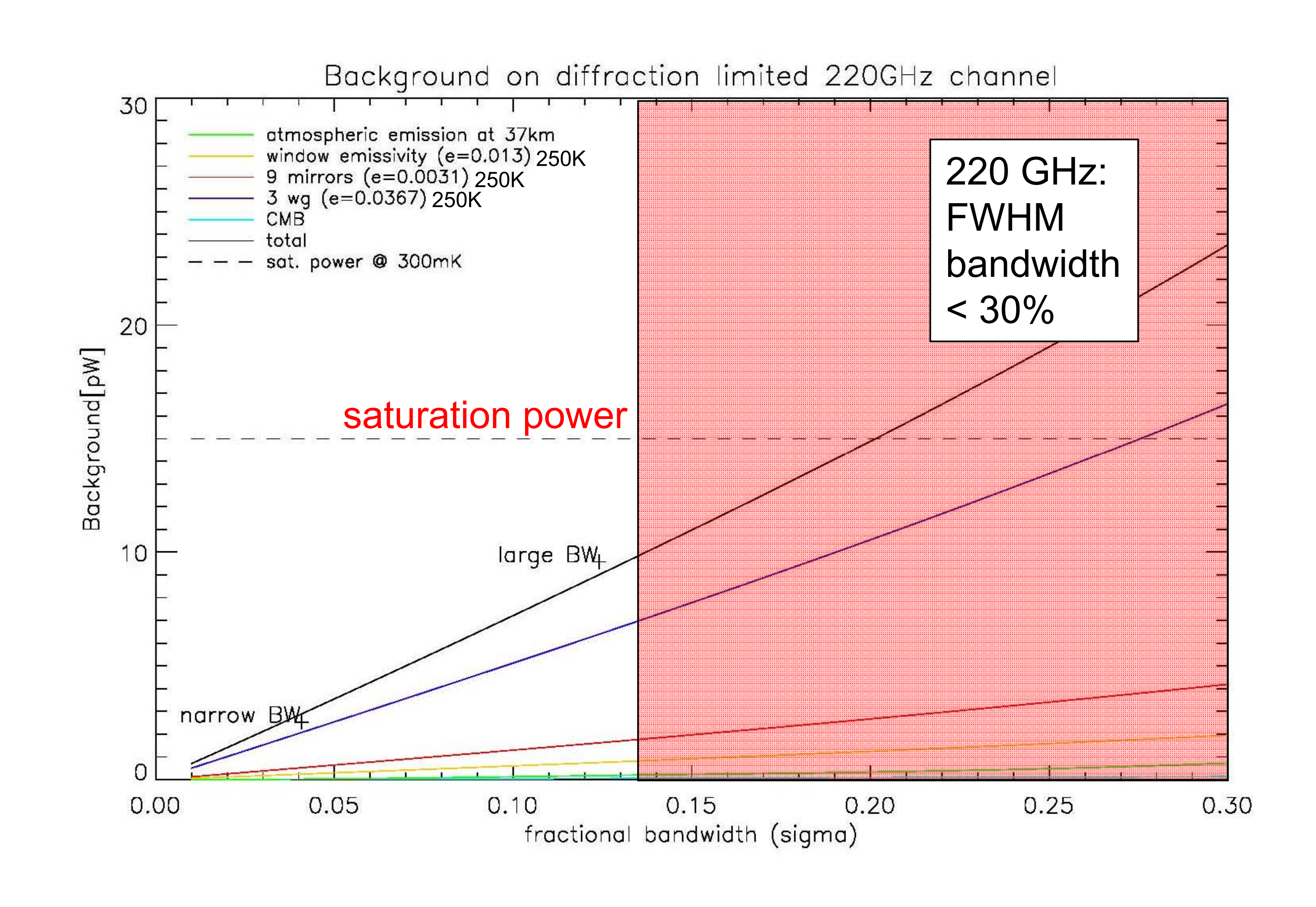
E. Battistelli

Background on the 150GHz TES



E. Battistelli

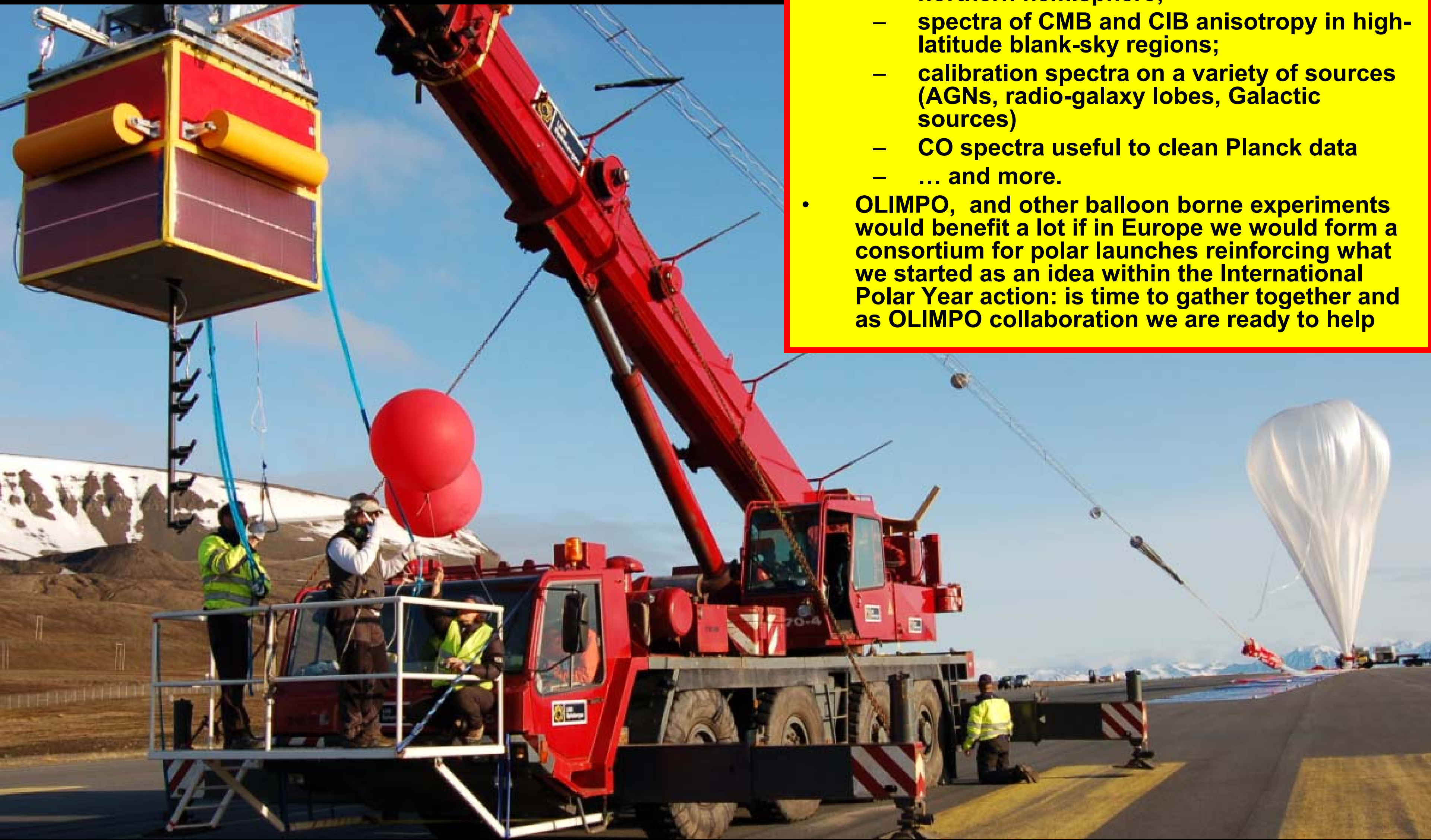
Background on the 220GHz TES



E. Battistelli

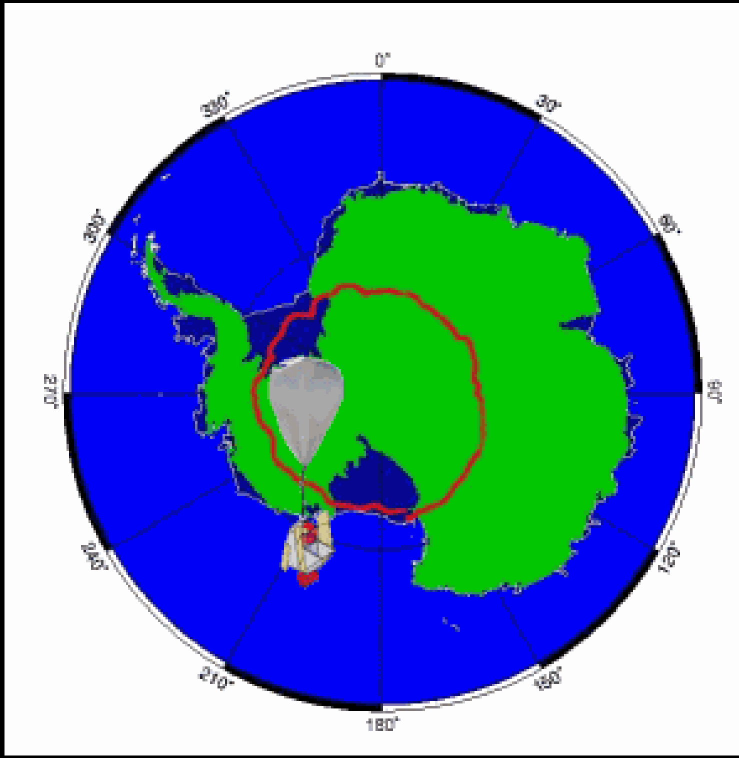
Stay tuned …

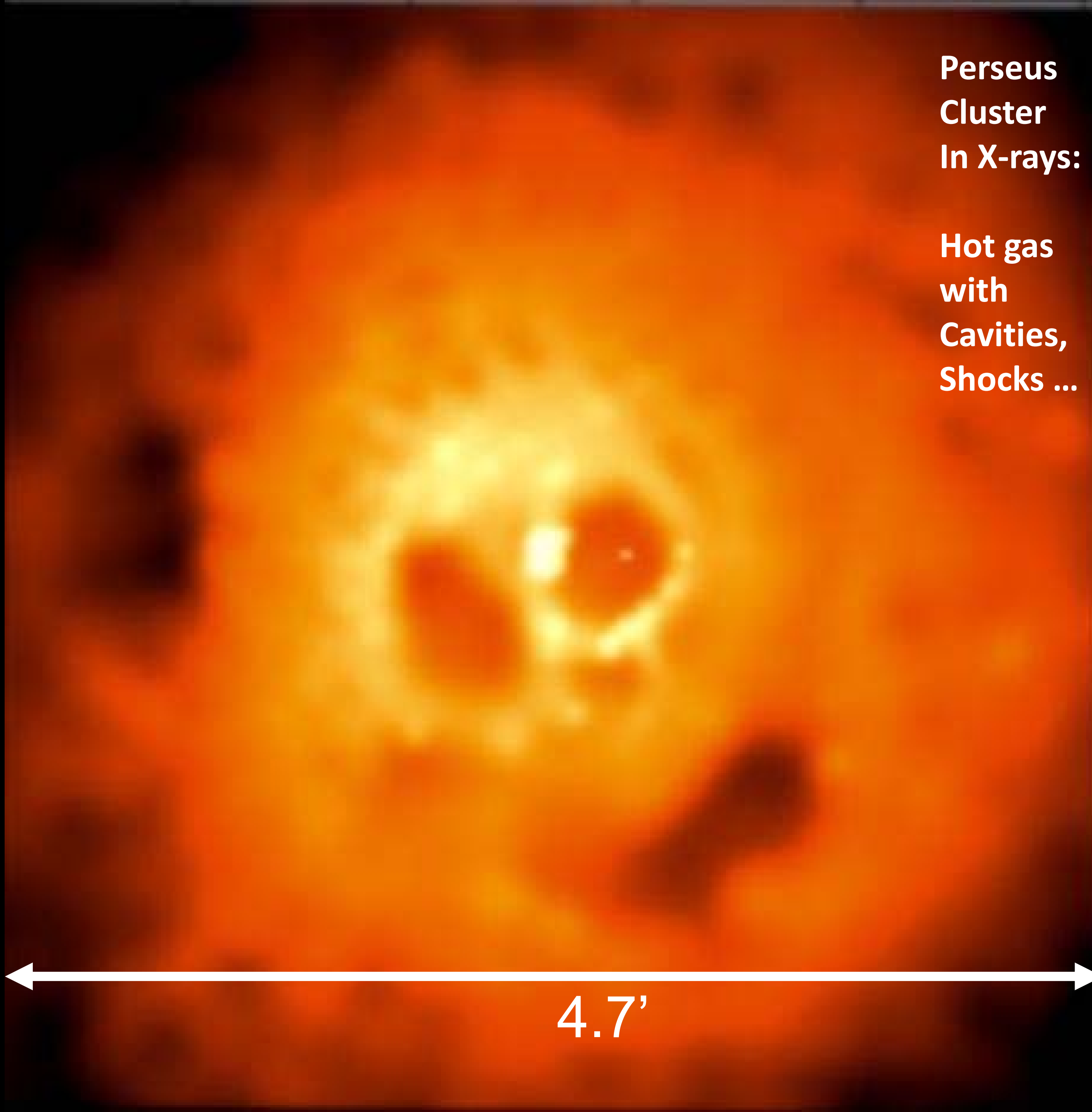
- **OLIMPO will be the first space-based validation of the DFTS approach.**
- **The observation program includes**
  - **spectra of the SZE in tens of clusters in the northern hemisphere;**
  - **spectra of CMB and CIB anisotropy in high-latitude blank-sky regions;**
  - **calibration spectra on a variety of sources (AGNs, radio-galaxy lobes, Galactic sources)**
  - **CO spectra useful to clean Planck data**
  - **… and more.**
- **OLIMPO, and other balloon borne experiments would benefit a lot if in Europe we would form a consortium for polar launches reinforcing what we started as an idea within the International Polar Year action: is time to gather together and as OLIMPO collaboration we are ready to help**



Polar flights

- NASA-CSBF has flown balloons around the south pole for many years, including the very successful BOOMERanG experiments (1998, 2003).

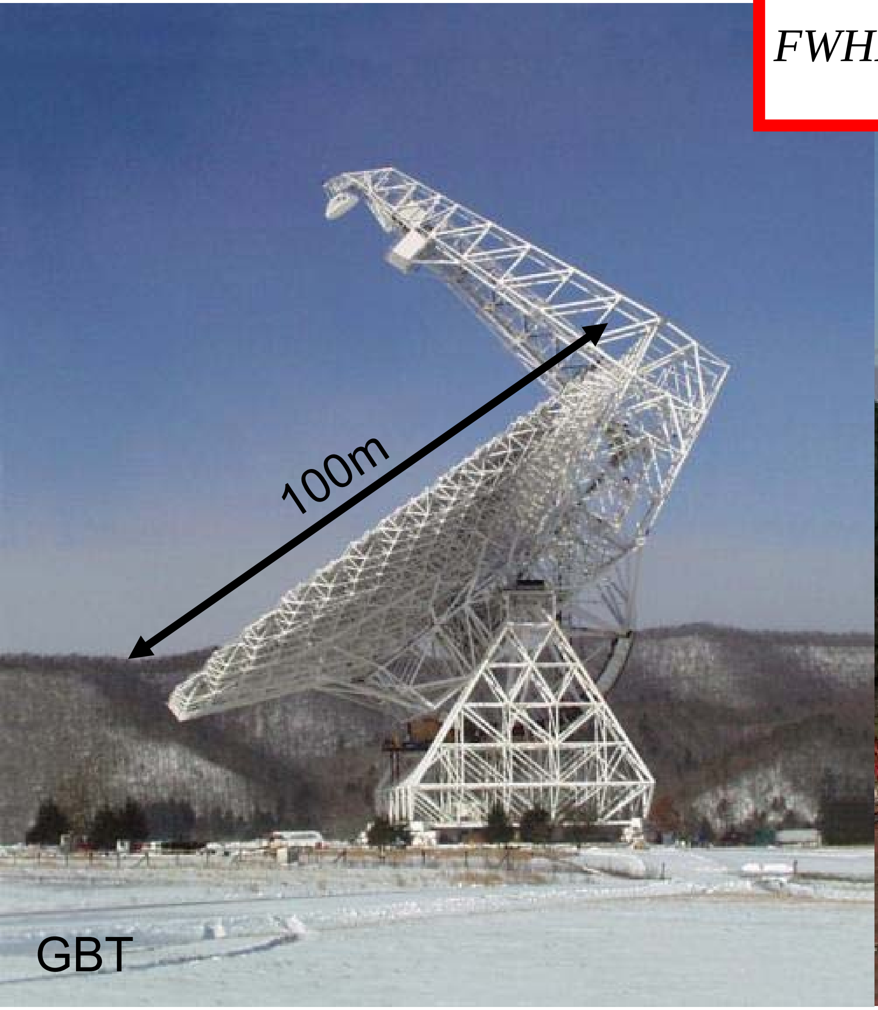


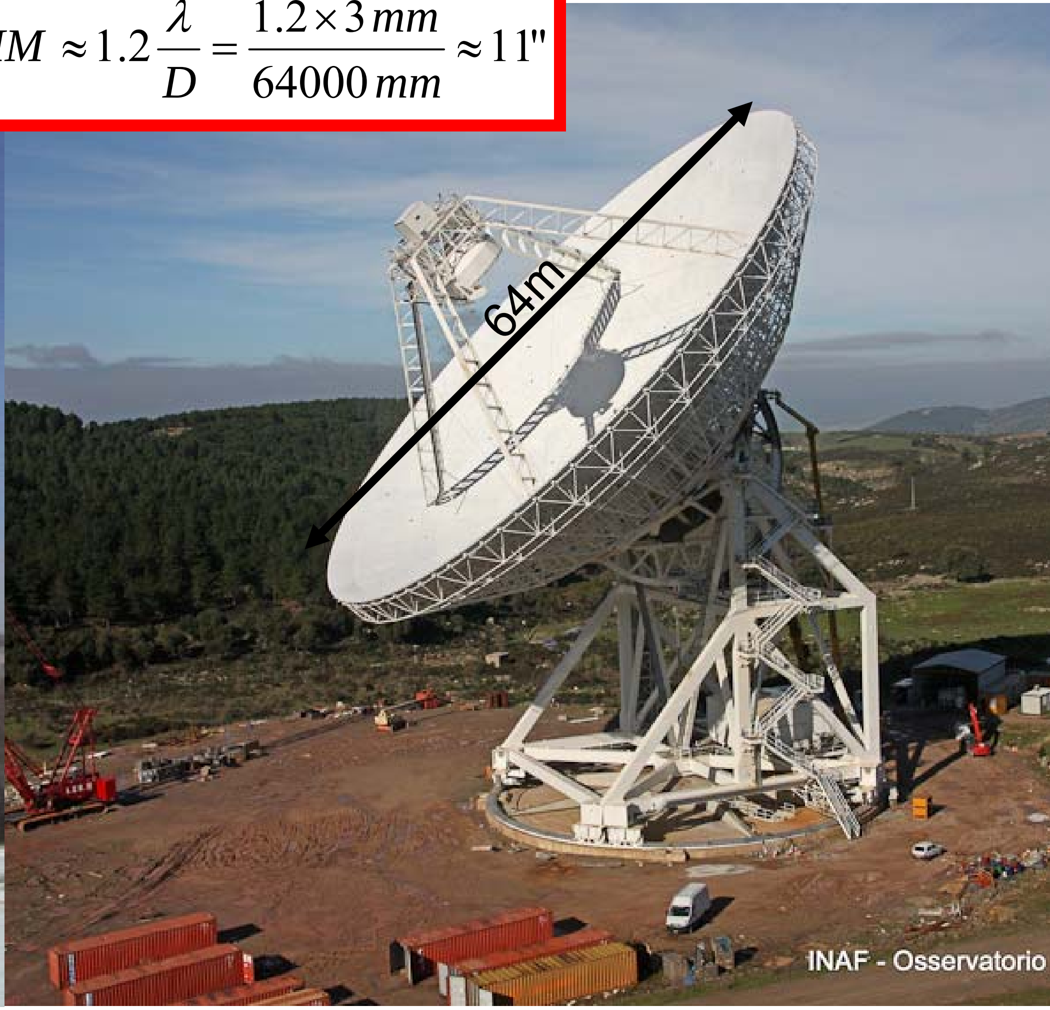

Perseus Cluster In X-rays:
Hot gas with Cavities, Shocks …
4.7’

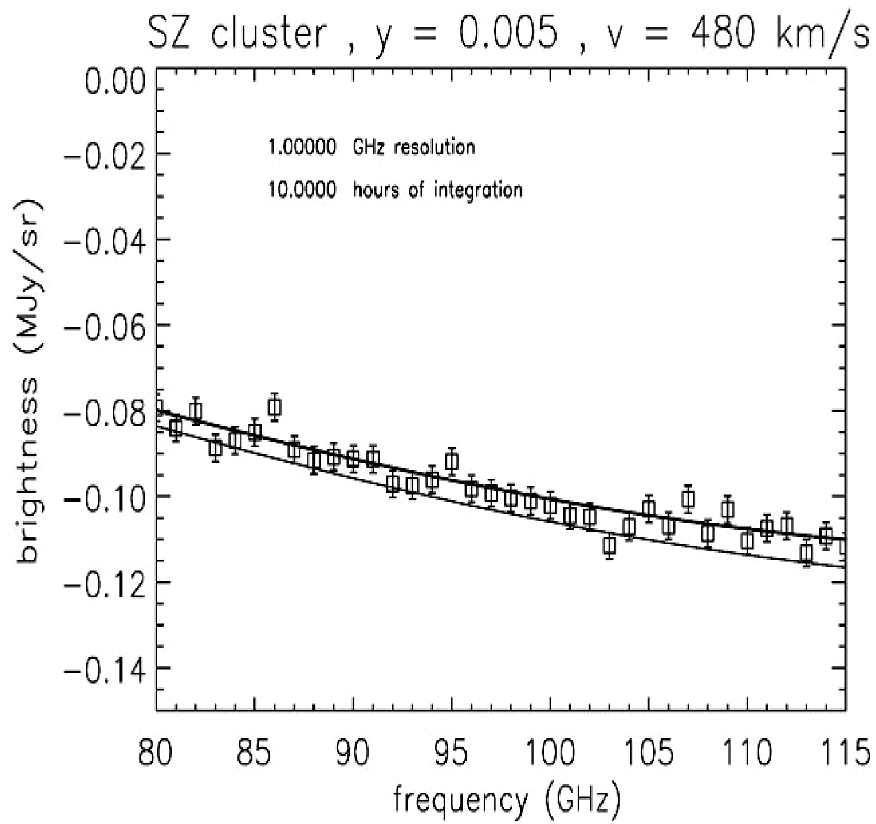
XXXL telescopes & SZ

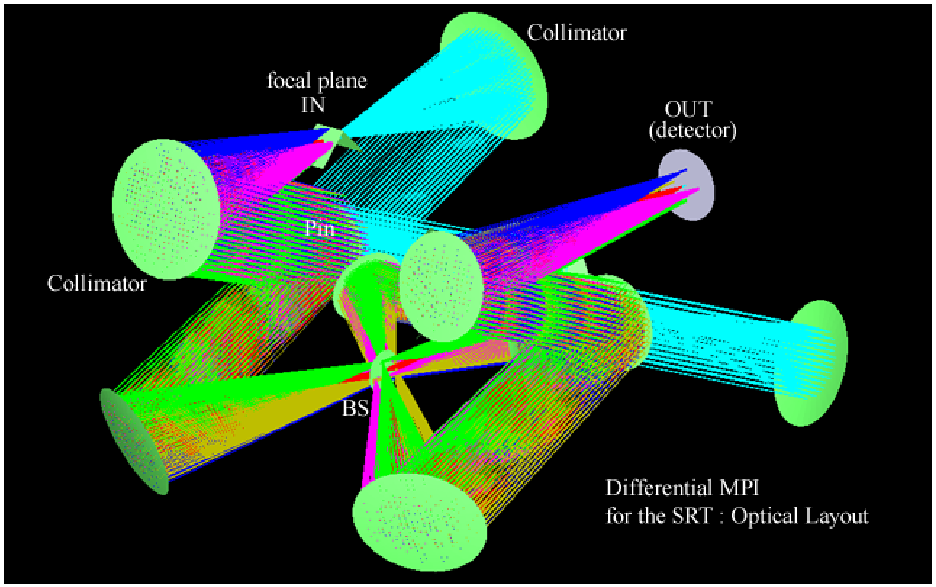
- Very useful to study the internal structure of clusters (shocks, cavities, cooling flows …)
- The 100 m Green Bank Telescope (USA) has a W-band array (Mustang)
- We have the 64m Sardinia Radio Telescope, and we are considering to install a DFTS for the W-band at the focus.

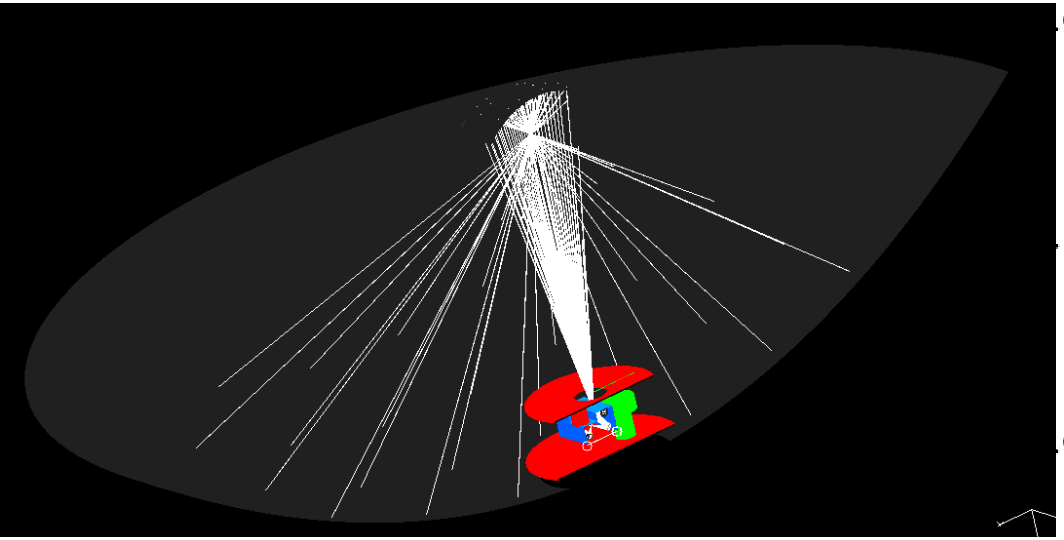
$$FWHM \approx 1.2\frac{\lambda}{D} = \frac{1.2 \times 3\,mm}{64000\,mm} \approx 11''$$

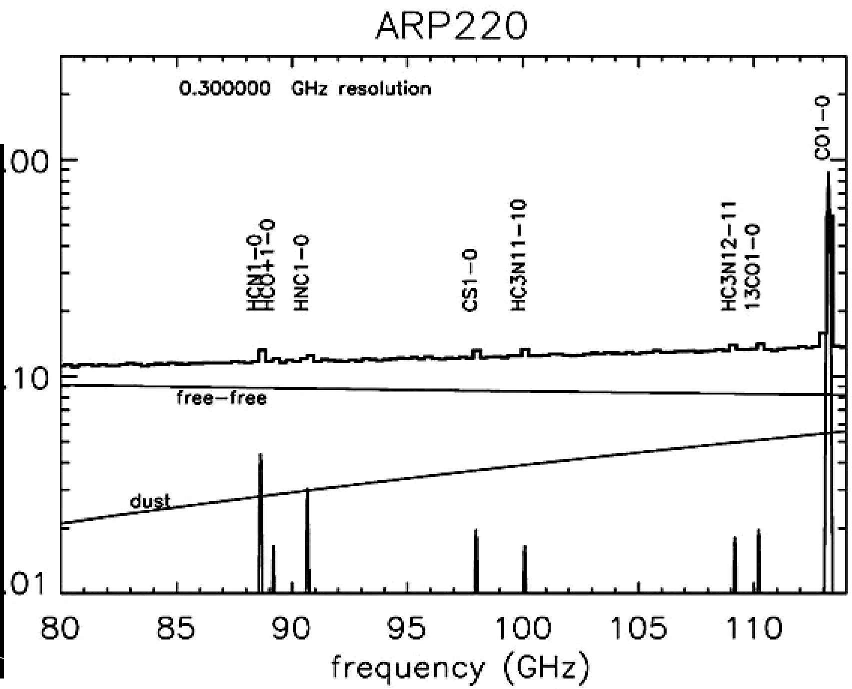


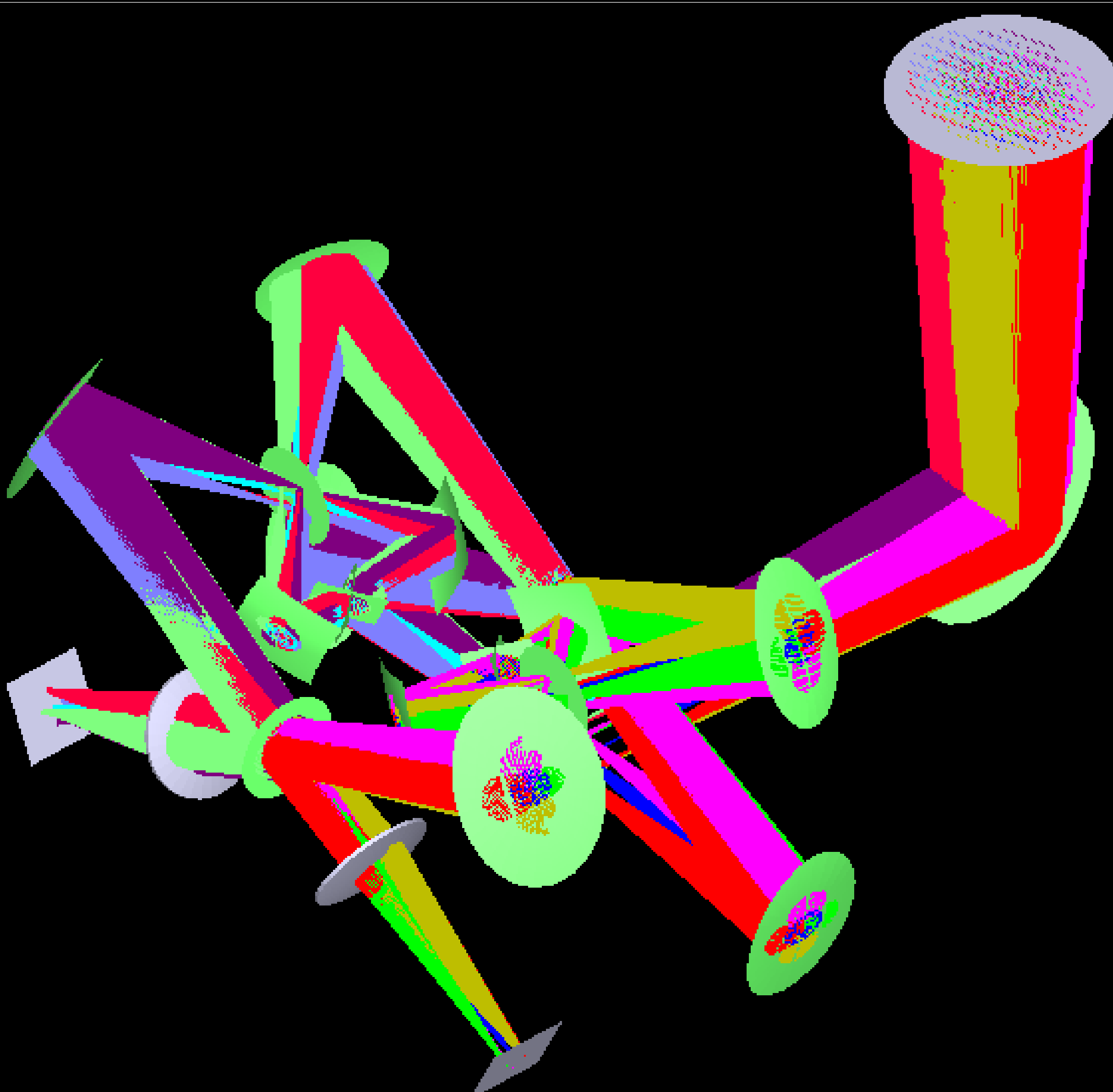



SZ cluster , y = 0.005 , v = 480 km/s
1.00000 GHz resolution
10.0000 hours of integration
brightness (MJy/sr)
0.00
−0.02
−0.04
−0.06
−0.08
−0.10
−0.12
−0.14
80
85
90
95
100
105
110
115
frequency (GHz)

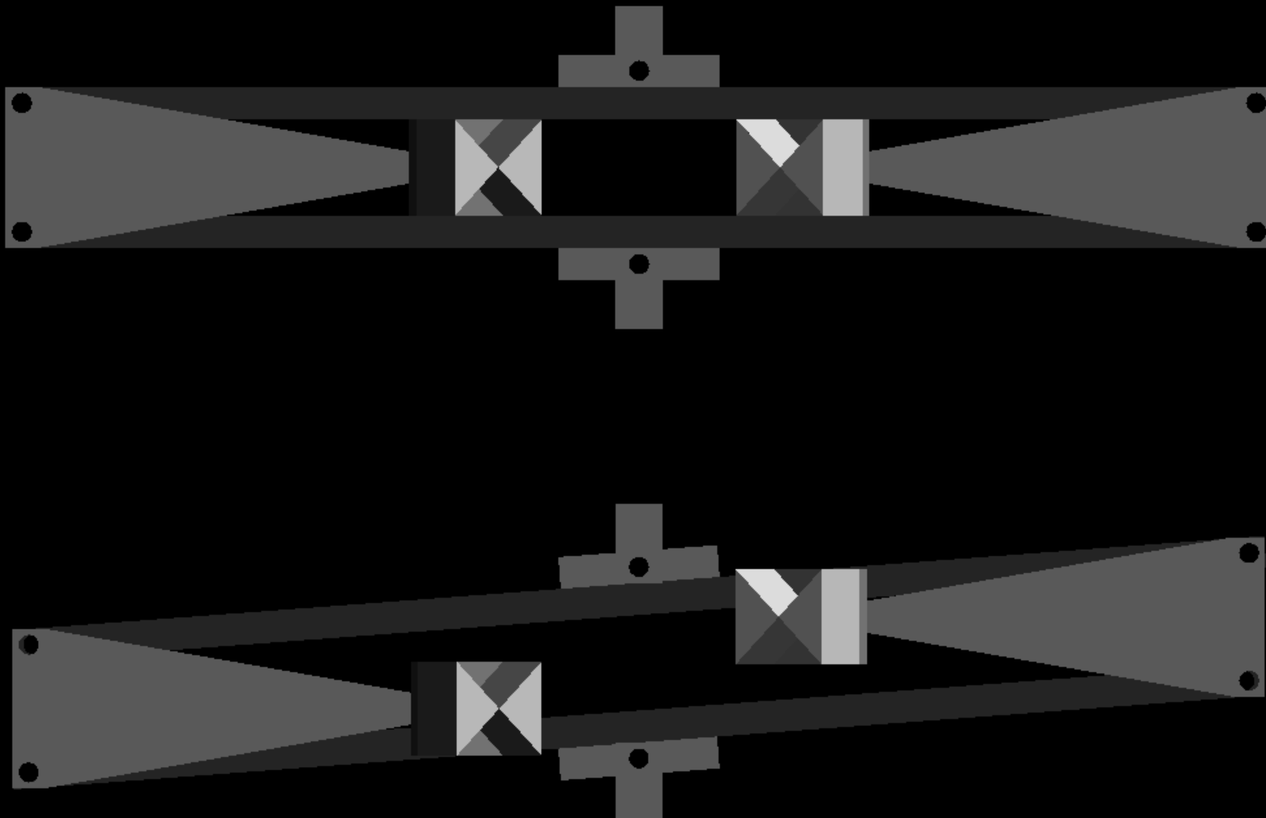

Collimator
focal plane
IN
OUT
(detector)
Pin
Collimator
BS
Differential MPI
for the SRT : Optical Layout

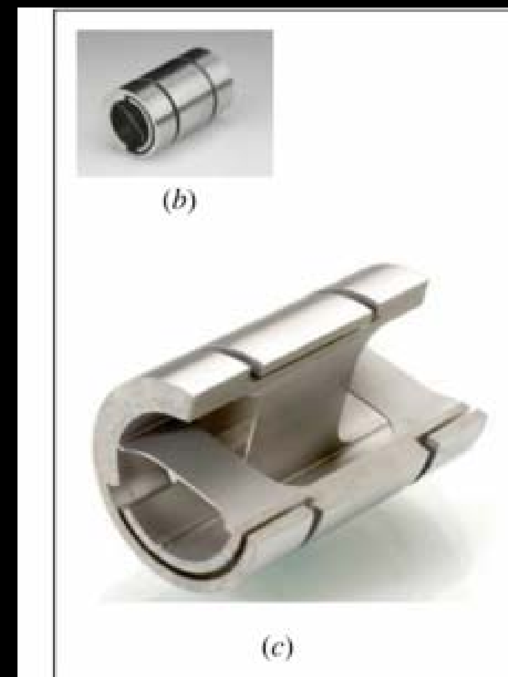



ARP220
0.300000 GHz resolution
CO1−0
HCN1−0
HCO+1−0
HNC1−0
CS1−0
HC3N11−10
HC3N12−11
13CO1−0
free−free
dust
80
85
90
95
100
105
110
frequency (GHz)



Oscillating pantograph (negligible dissipation) for cryogenic delay lines.

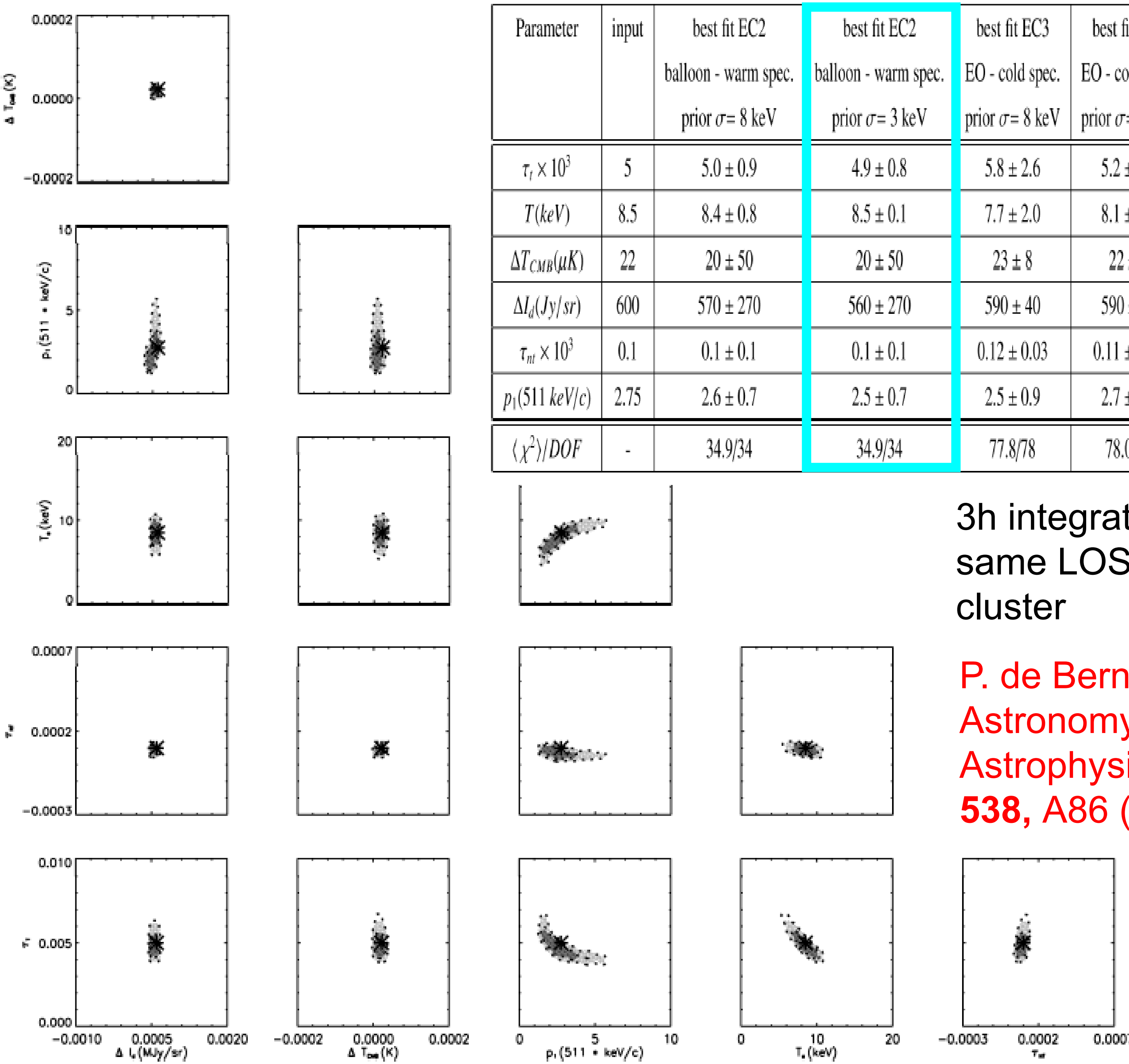




(b)

(c)

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)

$6x10^6$ pixels (5')

Planck Legacy Maps

857 GHz