Cosmologia Osservativa

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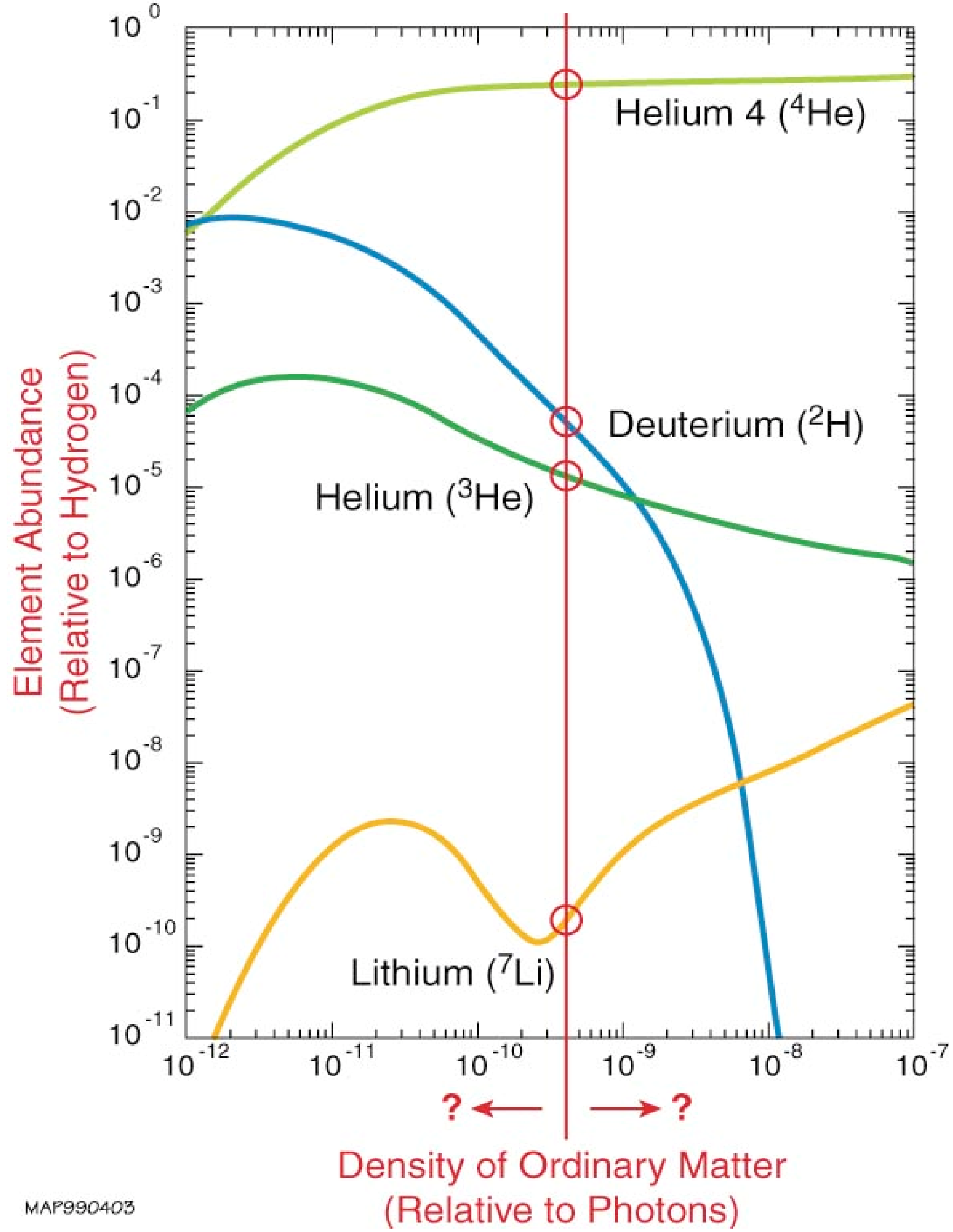
PROSPETTIVE DELLA SEZIONE 2009
Congressino della
Sezione INFN di Roma1

Roma, 07/05/2009

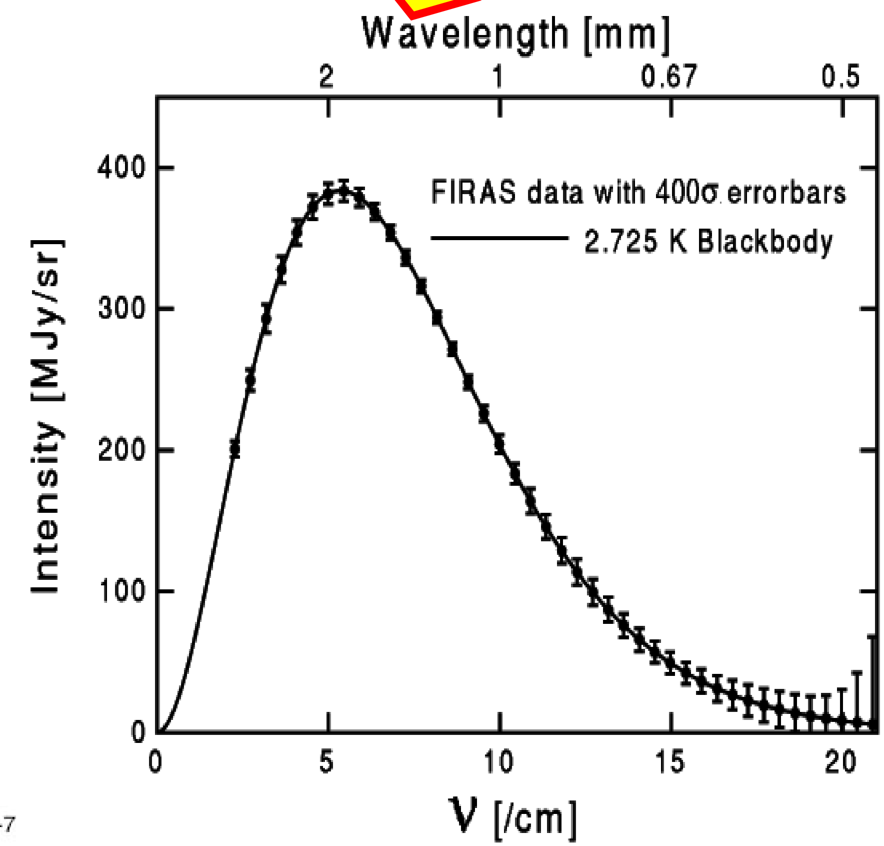
Observables for Cosmology

- Galaxies and their 3D distribution
- Active Galactic Nuclei
- Intergalactic Matter and its distribution
- Primeval Galaxies and their Background
- The Cosmic Microwave Background
- Cosmic Particles
- Primordial Gravitational Waves
- Abundance of elements
- …..

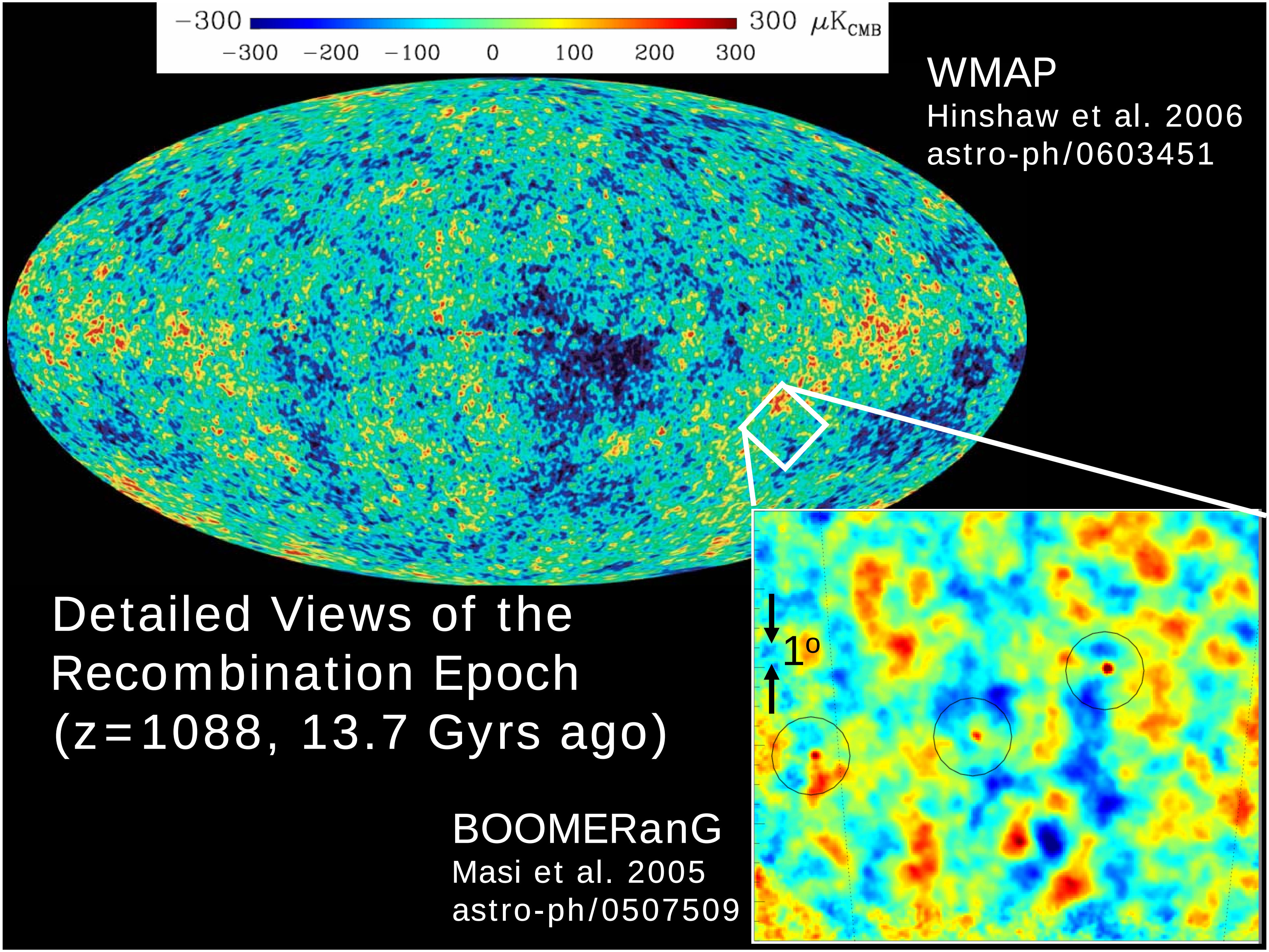
Primeval Fireball



Evidence for an early hot phase



$$T_o = 2.725K$$



Detailed Views of the Recombination Epoch (z=1088, 13.7 Gyrs ago)

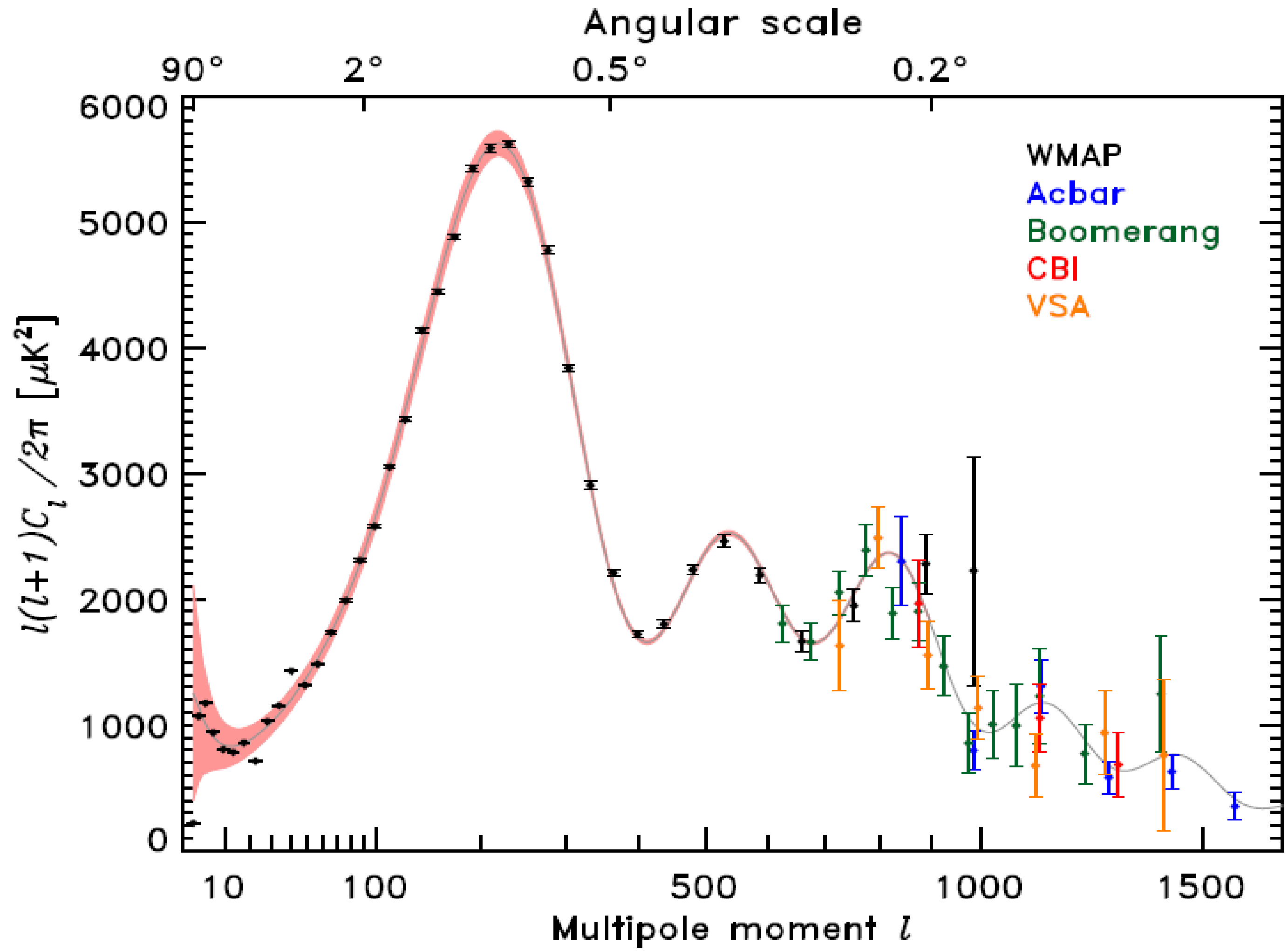
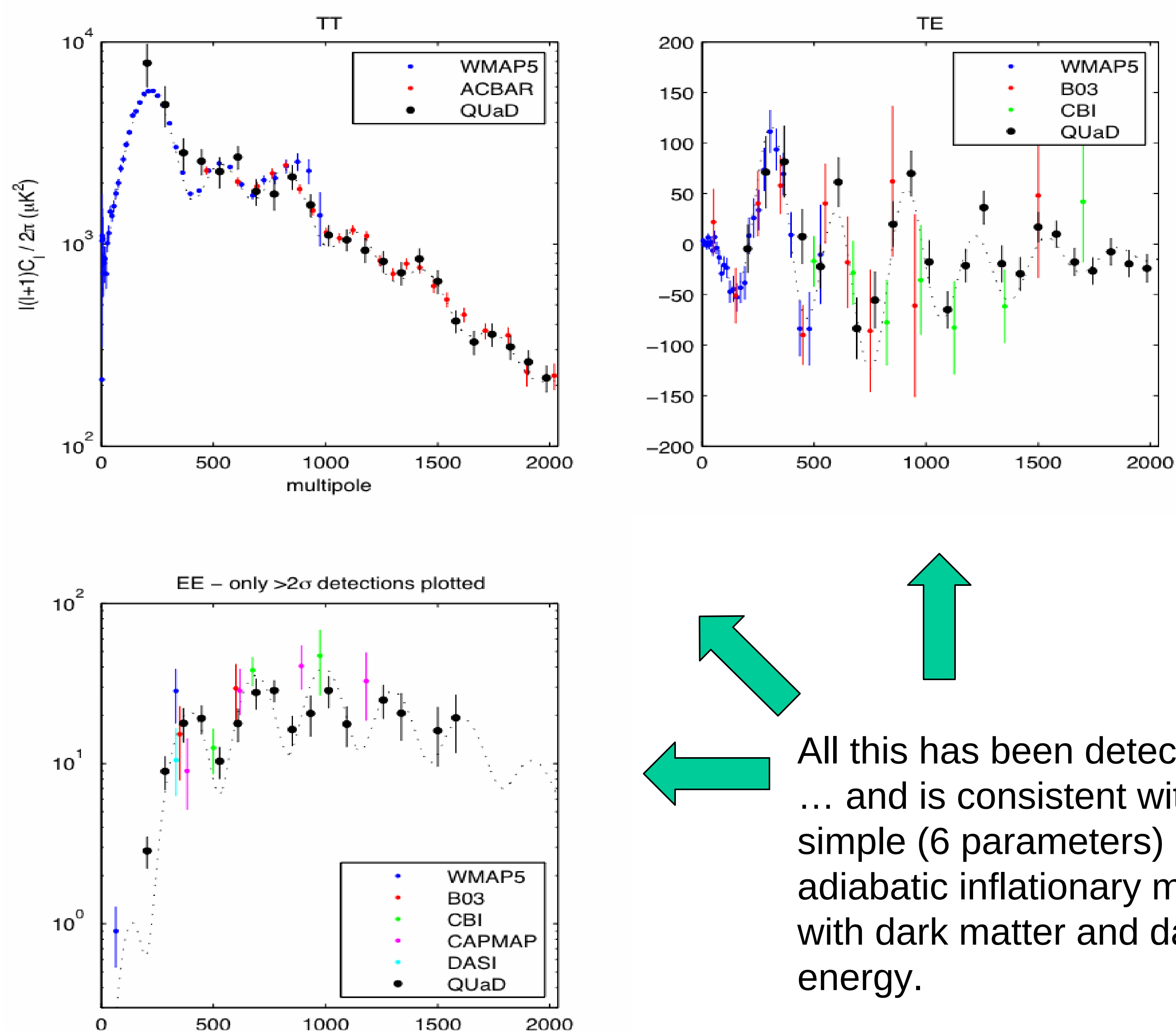


Fig. 18.— The *WMAP* three-year power spectrum (in black) compared to other recent measurements of the CMB angular power spectrum, including Boomerang (Jones et al. 2005), Acbar (Kuo et al. 2004), CBI (Readhead et al. 2004), and VSA (Dickinson et al. 2004). For clarity, the $l < 600$ data from Boomerang and VSA are omitted; as the measurements are consistent with *WMAP*, but with lower weight. These
vely confirm the turnover in the 3rd acoustic peak and probe the onset of Silk damping.
l sensitivity on sub-degree scales, the *WMAP* data are becoming an increasingly important
irce for high-resolution experiments.

2006

Hinshaw et al. 2006



All this has been detected ...
… and is consistent with a simple (6 parameters) adiabatic inflationary model with dark matter and dark energy.

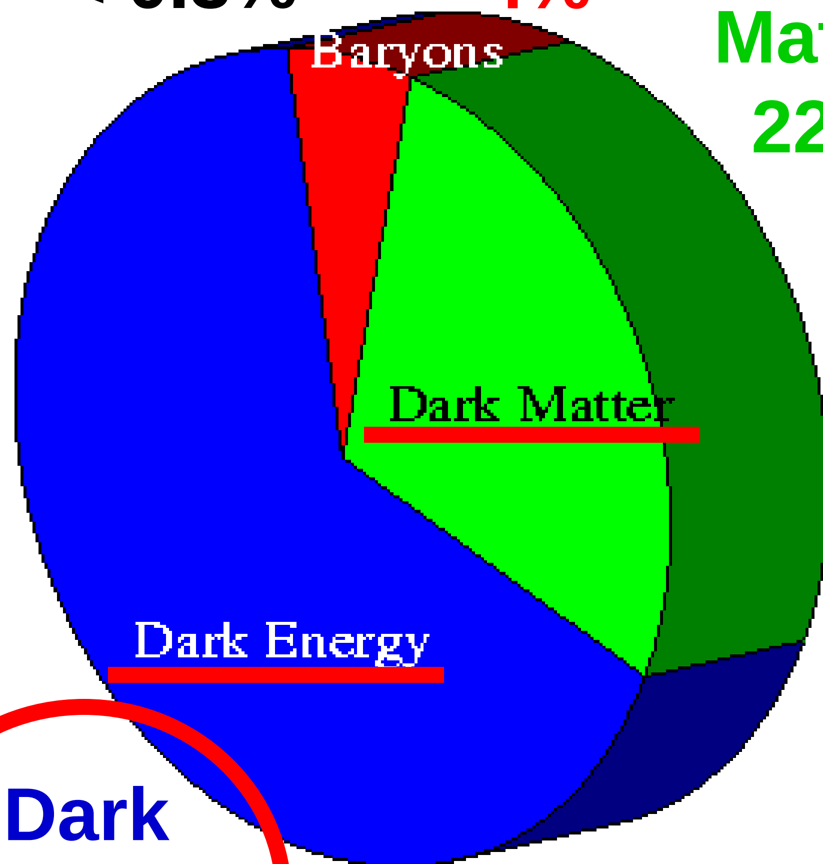
Open Issues :

INFLATION (OOU)

Radiation
< 0.3%

Normal Matter
4%

Dark Matter
22%



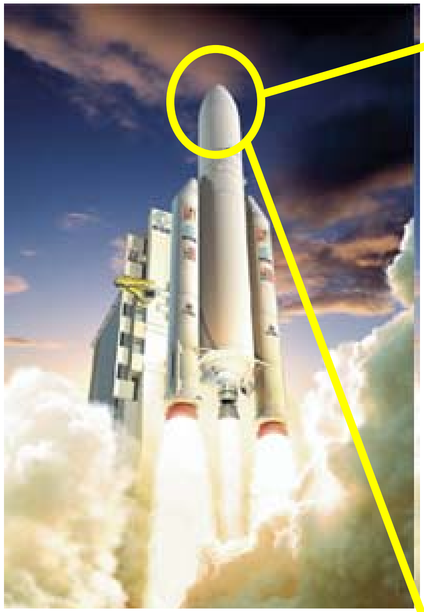
Dark Energy
74%

New, Precision CMB measurements

- Can help in solving all of the previous issues.
- *Polarization* measurements represent the best way to probe the very early universe, and the energy scale of inflation
- *Fine-scale anisotropy* measurements, *possibly with spectral information*, can provide important information on dark matter and dark energy

The Present

7 days to blast-off



Planck-Herschel
Launch
May 14, 2009
15:12 CEST


esa
PLANCK
Looking back to the dawn of time
Un regard vers l'aube du temps
Un satellite per guardare all'alba del tempo
per scoprire com'è fatto l'universo
Info per Roma:
Fernanda Lupinacci
06-49914305
Alba Perrotta
06-49914879
14 MAGGIO 2009
IL LANCIO IN DIRETTA
Inizio ore 14
BOLOGNA
Area della ricerca, via Gobetti 101
MILANO
Dip. di Fisica, UNIMI, Via Celoria 16
ROMA
Dip. di Fisica, Univ. La Sapienza, P.le A. Moro 2
TRIESTE
Oss. Astronomico - Villa Bazzoni, via Bazzoni 2
eventuali variazioni della data di lancio
verranno segnalate sul sito
http://sci.esa.int/planck

PLANCK

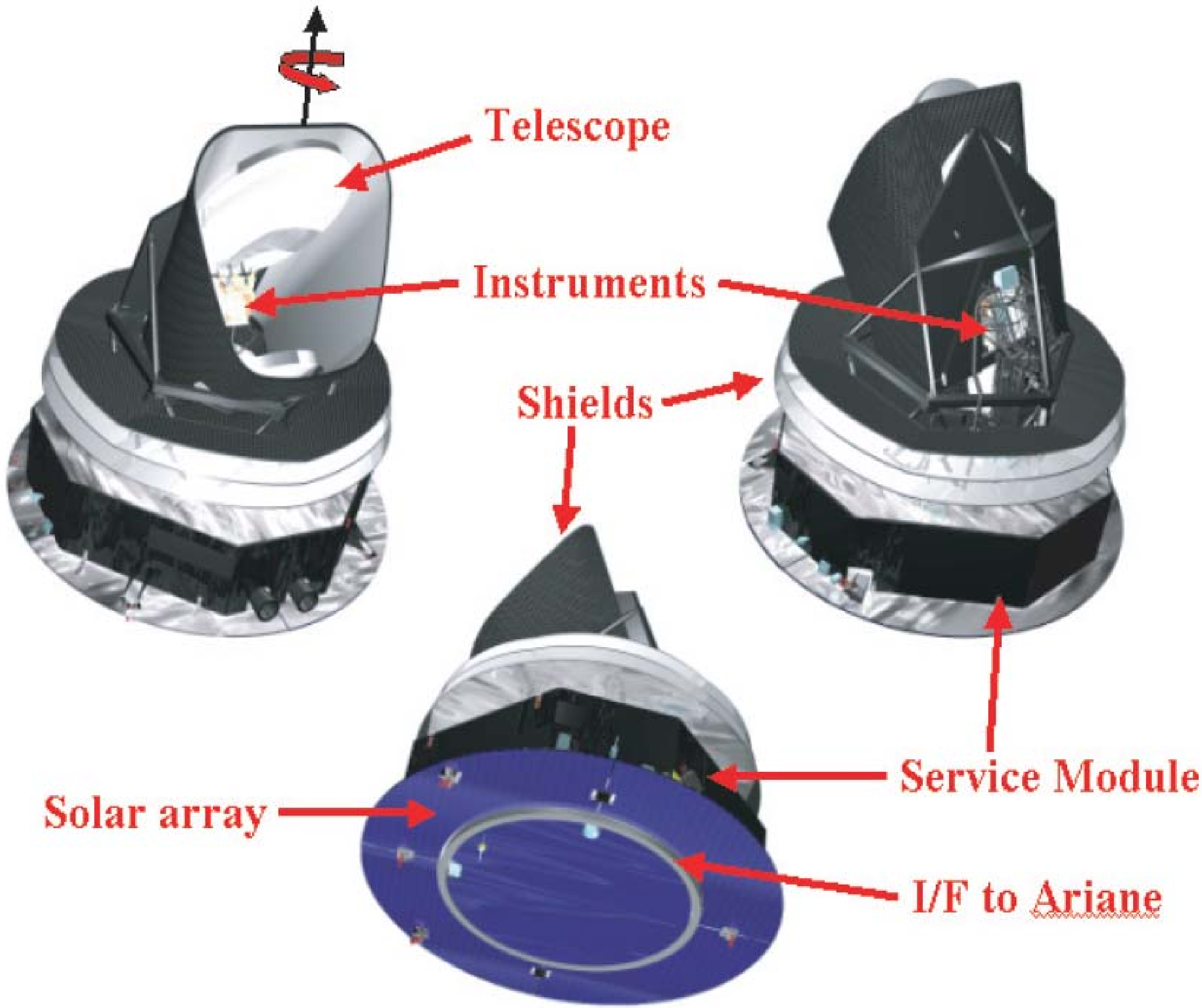
ESA mission to map the Cosmic Microwave Background

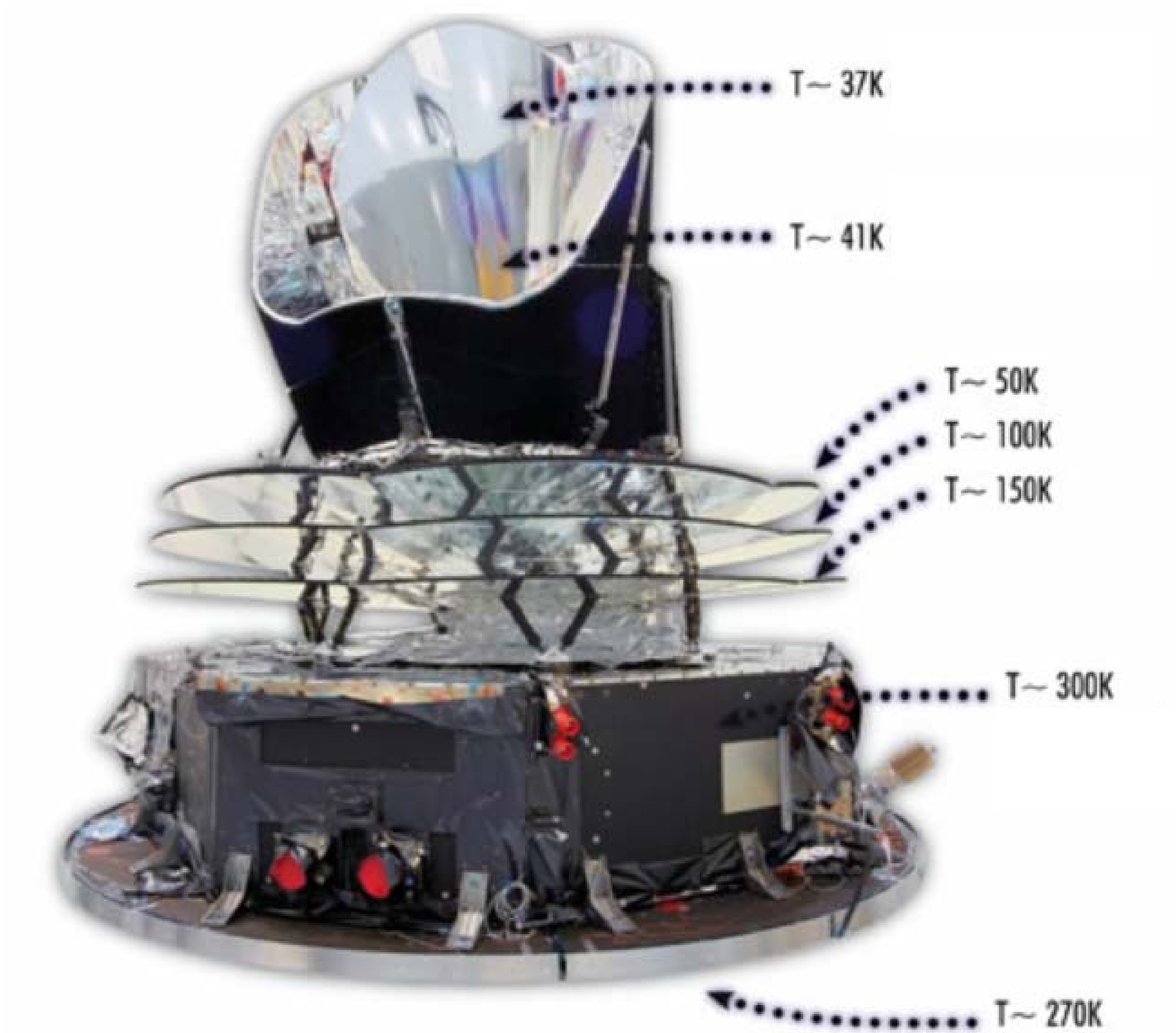
Image of the whole sky at wavelengths near the intensity peak of the CMB radiation, with

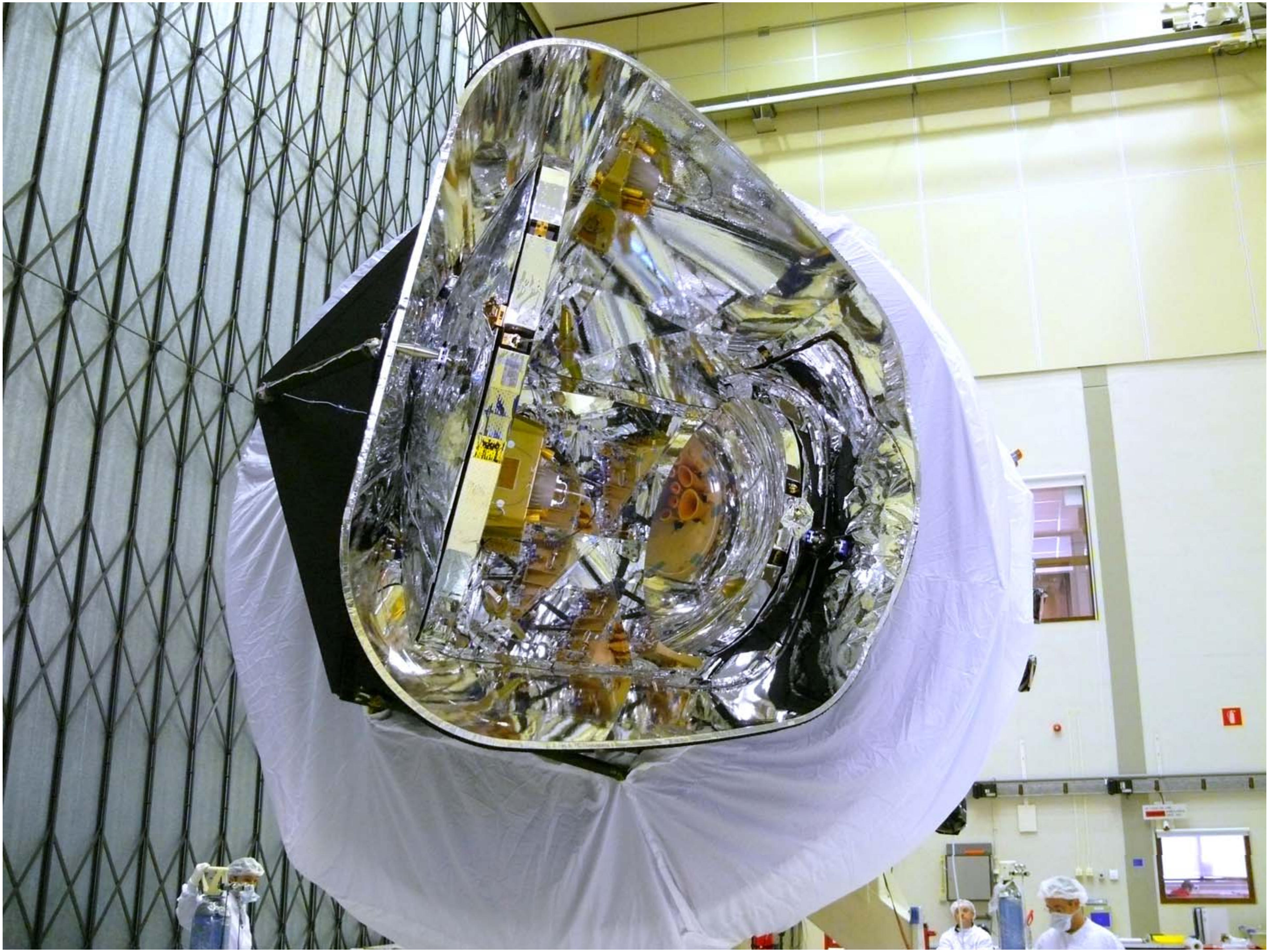
- high instrument sensitivity ($\Delta T/T \sim 10^{-6}$)
- high resolution ($\approx$5 arcmin)
- wide frequency coverage (25 GHz-950 GHz)
- high control of systematics

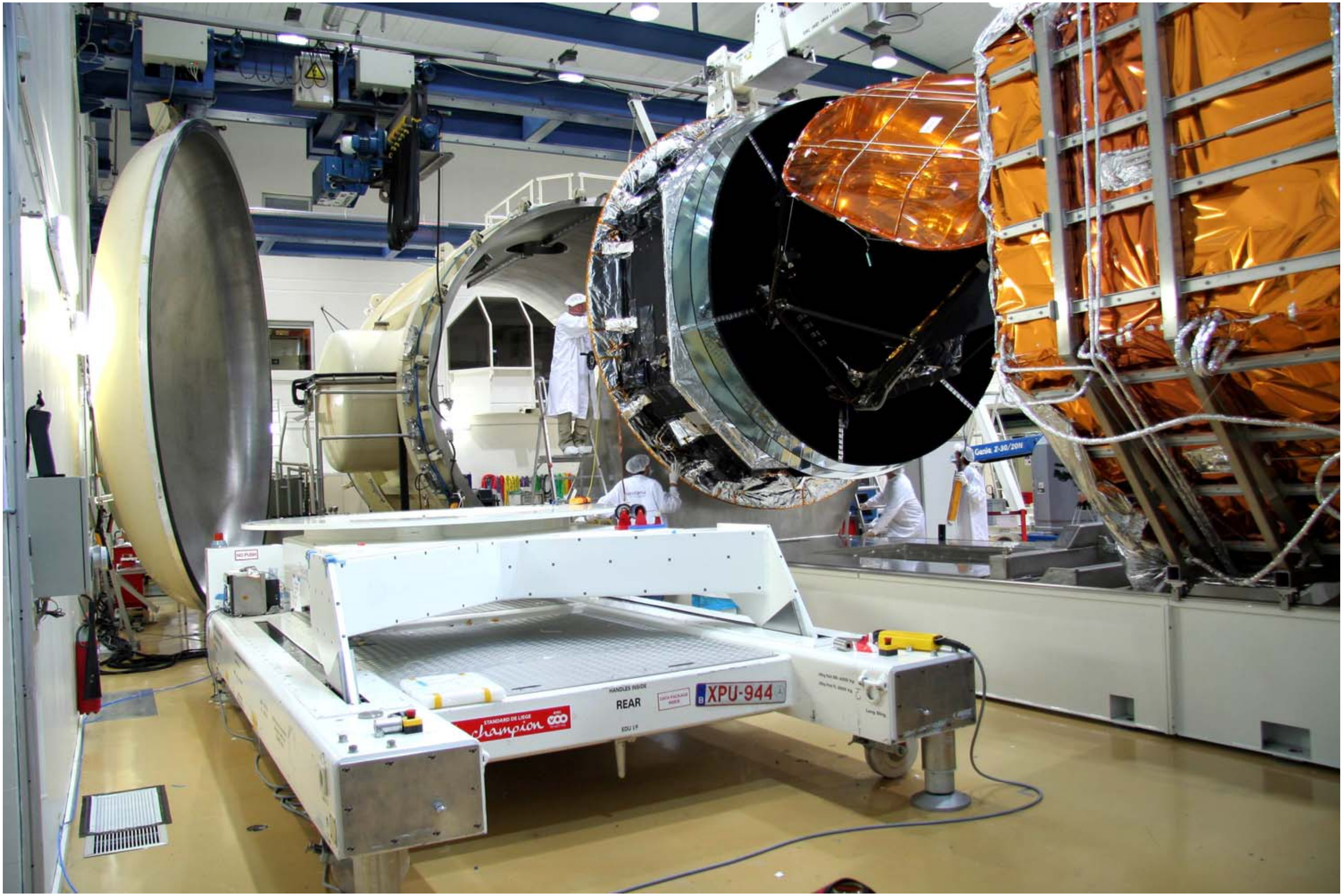
Launch: 2009; payload module: 2 instruments and telescope

- Low Frequency Instrument (LFI, HEMTs)
- High Frequency Instrument (HFI, bolometers)
- Telescope: primary (1.50x1.89 m ellipsoid)


Telescope
Instruments
Shields
Service Module
Solar array
I/F to Ariane

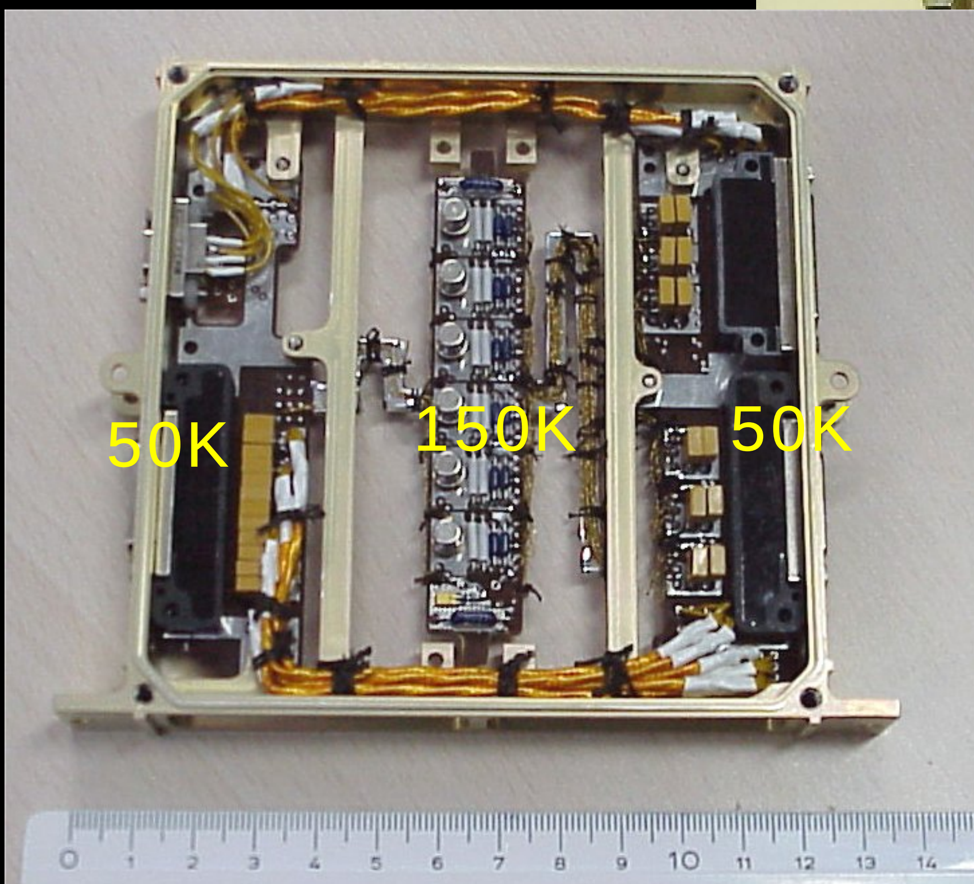

T~ 37K
T~ 41K
T~ 50K
T~ 100K
T~ 150K
T~ 300K
T~ 270K




STANDARD DE LIEGE
champion
HANDLES INSIDE
REAR
XPU-944

Planck-HFI
Cryogenic
Preamplifiers

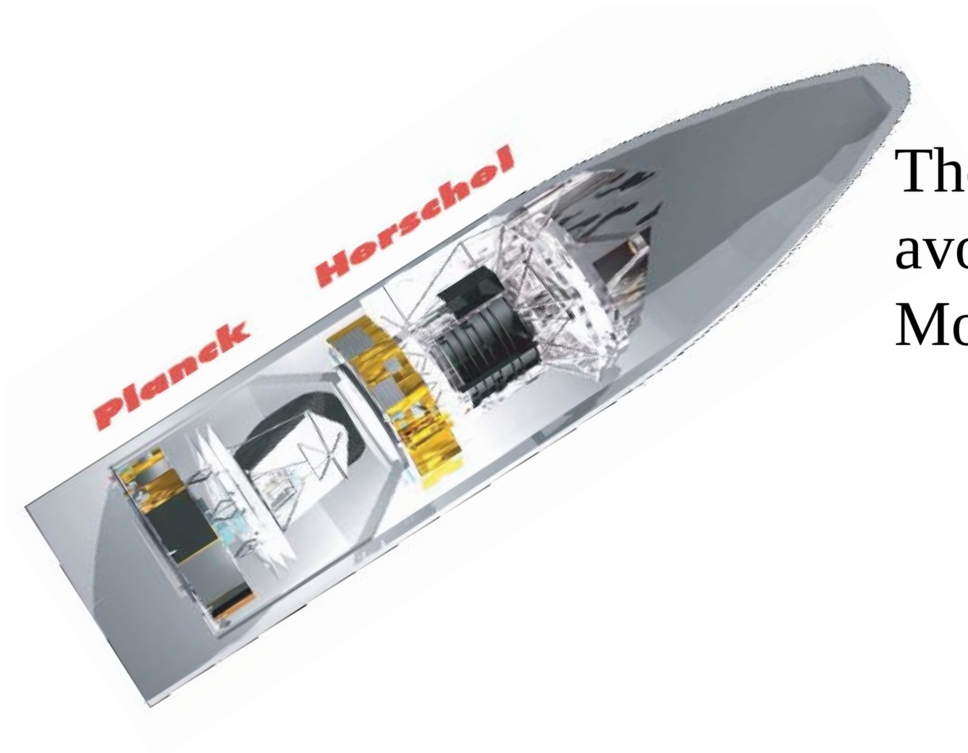
Galileo Avionica



agenzia spaziale
italiana

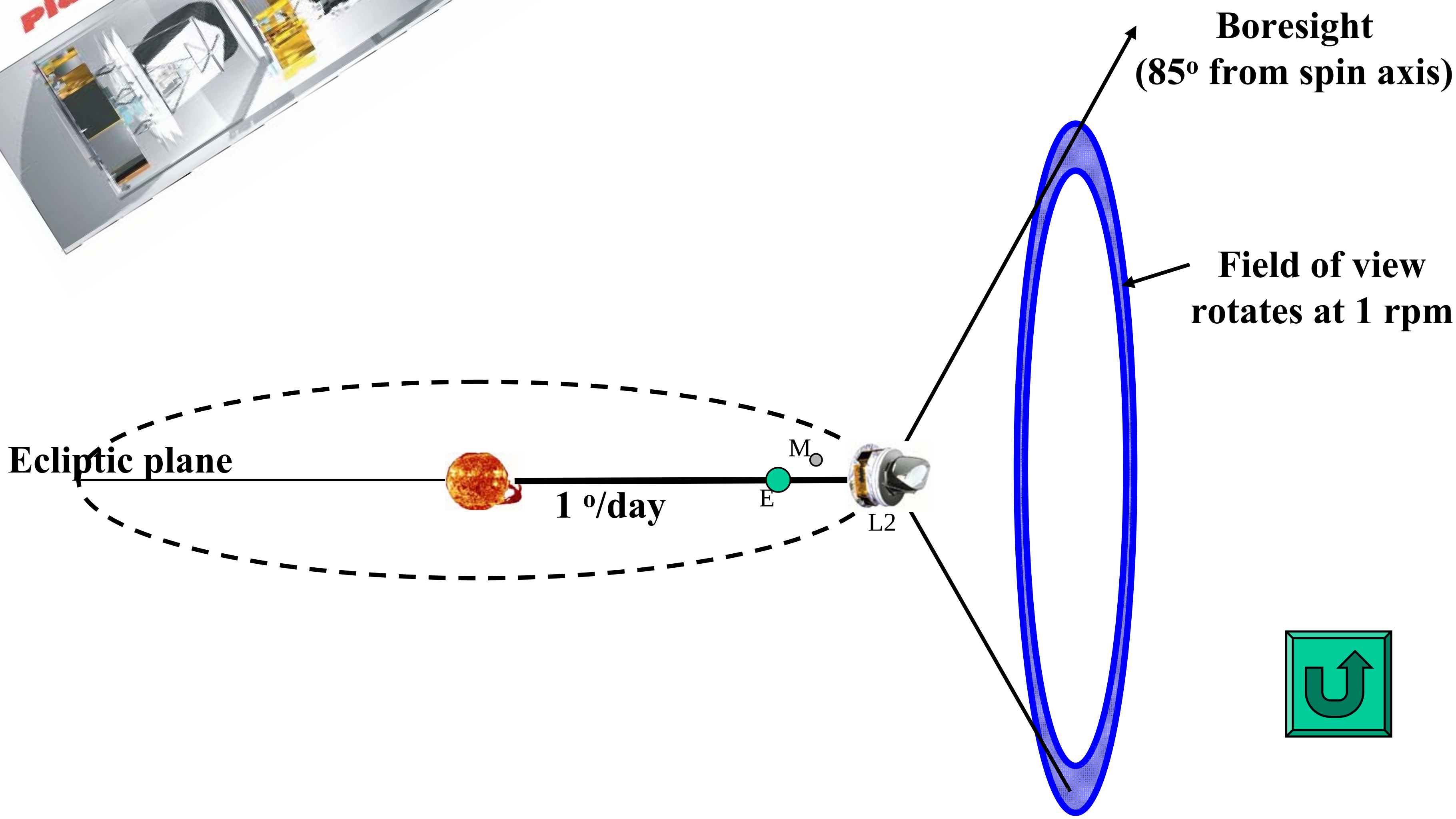

Volga-Dnepr
APCO
PLANCK
TRANSPORT & STORAGE
CONTAINER
esa
SDV

2 months ago …



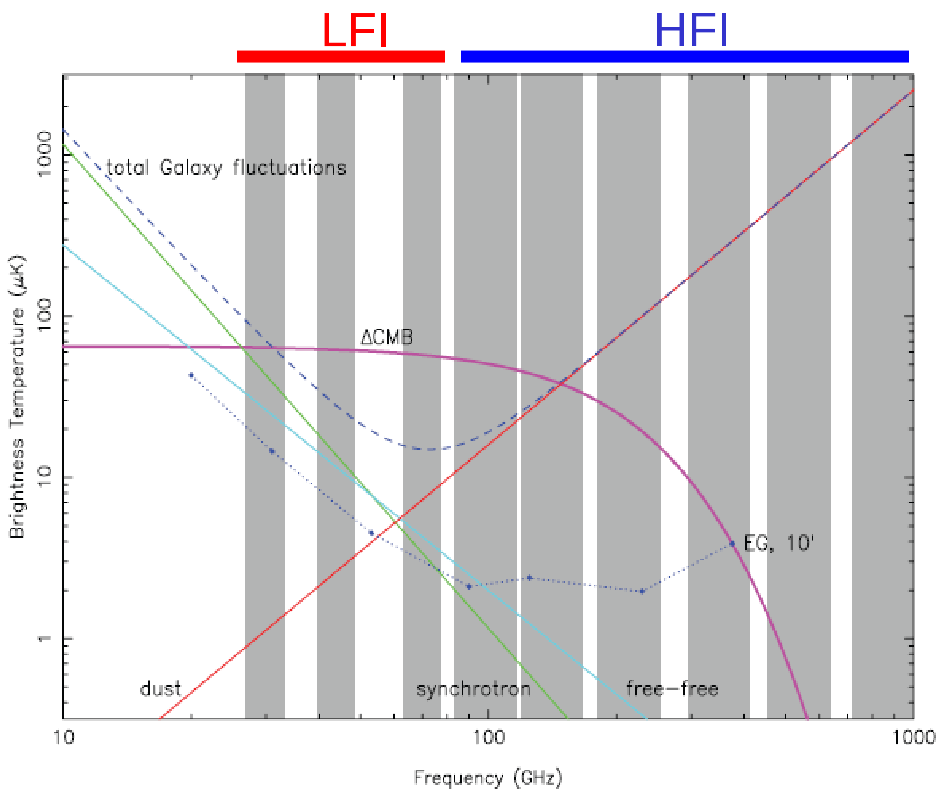
Observing strategy

The payload will work from L2, to avoid the emission of the Earth, of the Moon, of the Sun

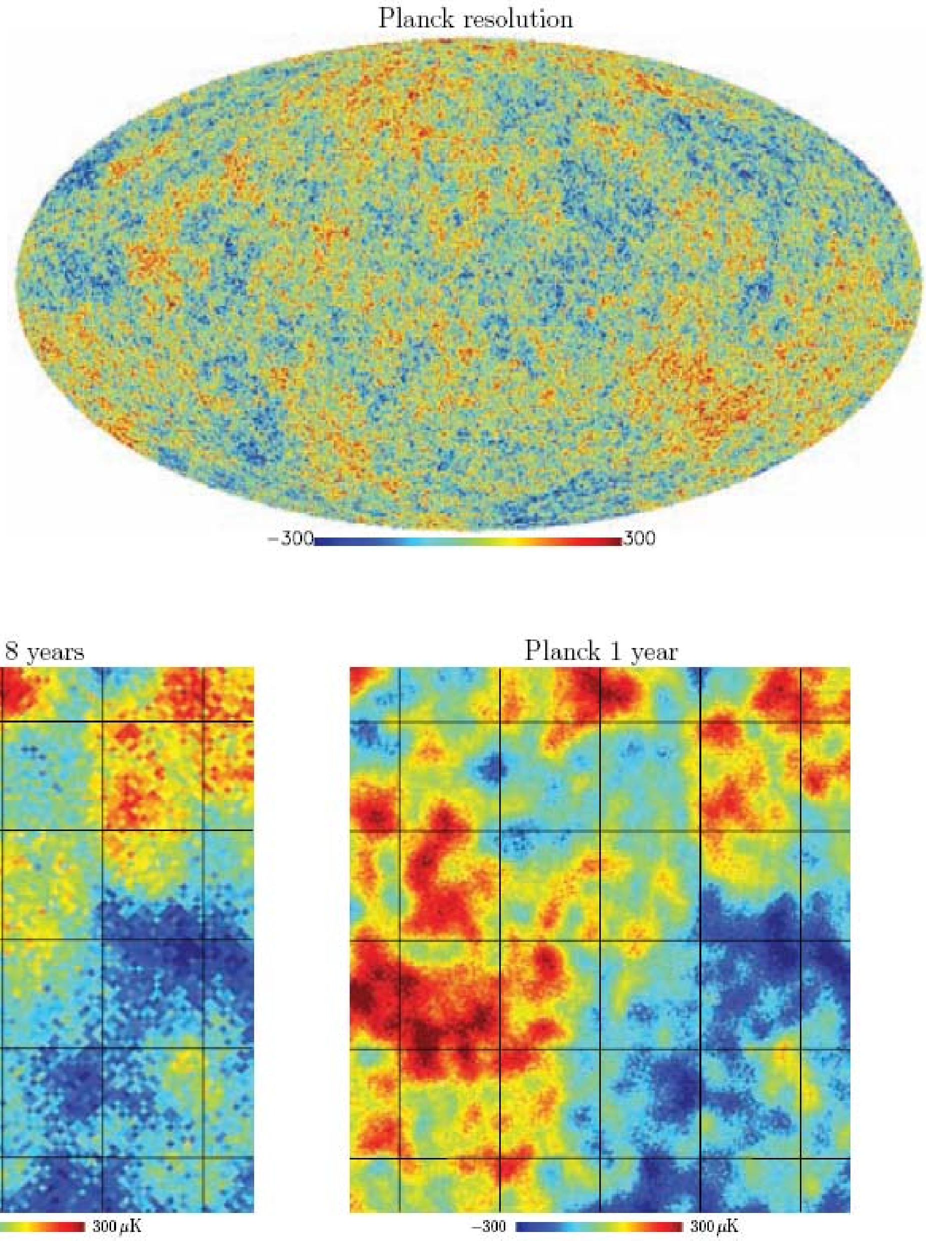


So we can expect in 2 years from now :

- Data from a precisely calibrated instrument operated in the best possible space environment
- Maps covering the full wavelength range and angular resolution of primary CMB anisotropy



The Breakthrough of Planck: spectral coverage, angular resolution, noise



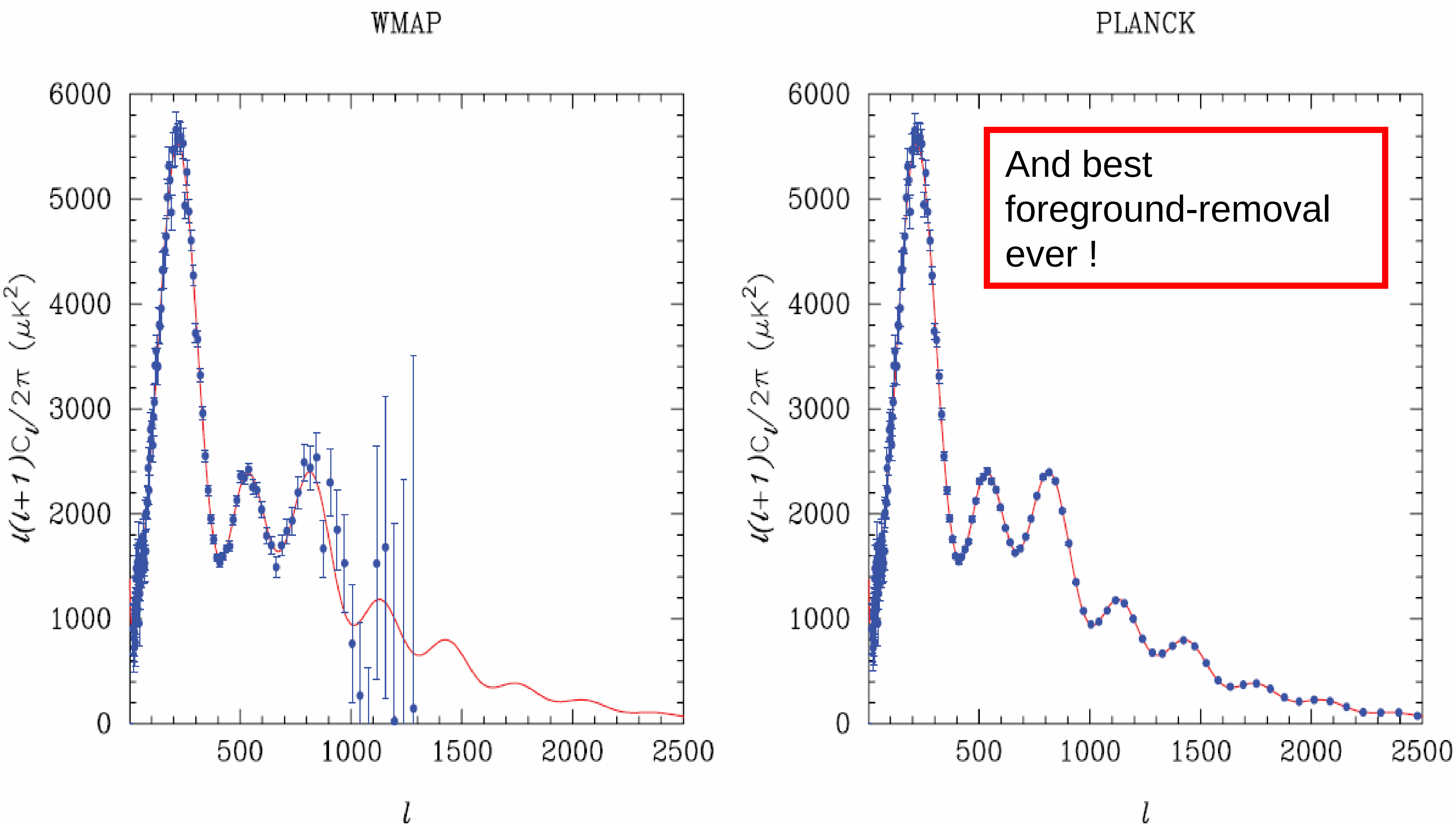


FIG 2.8.—The left panel shows a realisation of the CMB power spectrum of the concordance ΛCDM model (red line) after 4 years of *WMAP* observations. The right panel shows the same realisation observed with the sensitivity and angular resolution of *Planck*.

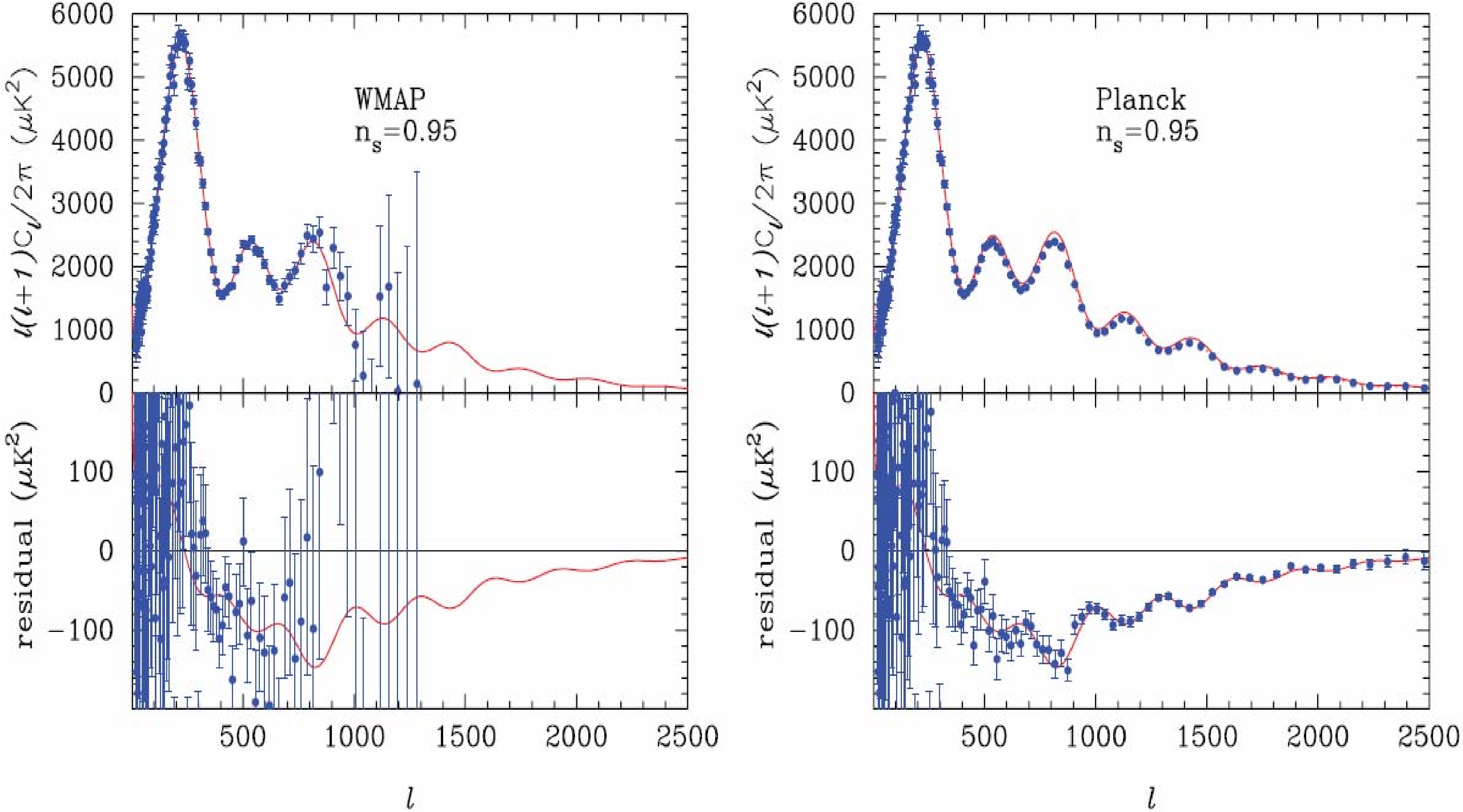


FIG 2.11.—The solid lines in the upper panels of these figures show the power spectrum of the concordance ΛCDM model with an exactly scale invariant power spectrum, $n_S = 1$. The points, on the other hand, have been generated from a model with $n_S = 0.95$ but otherwise identical parameters. The lower panels show the residuals between the points and the $n_S = 1$ model, and the solid lines show the theoretical expectation for these residuals. The left and right plots show simulations for *WMAP* and *Planck*, respectively.

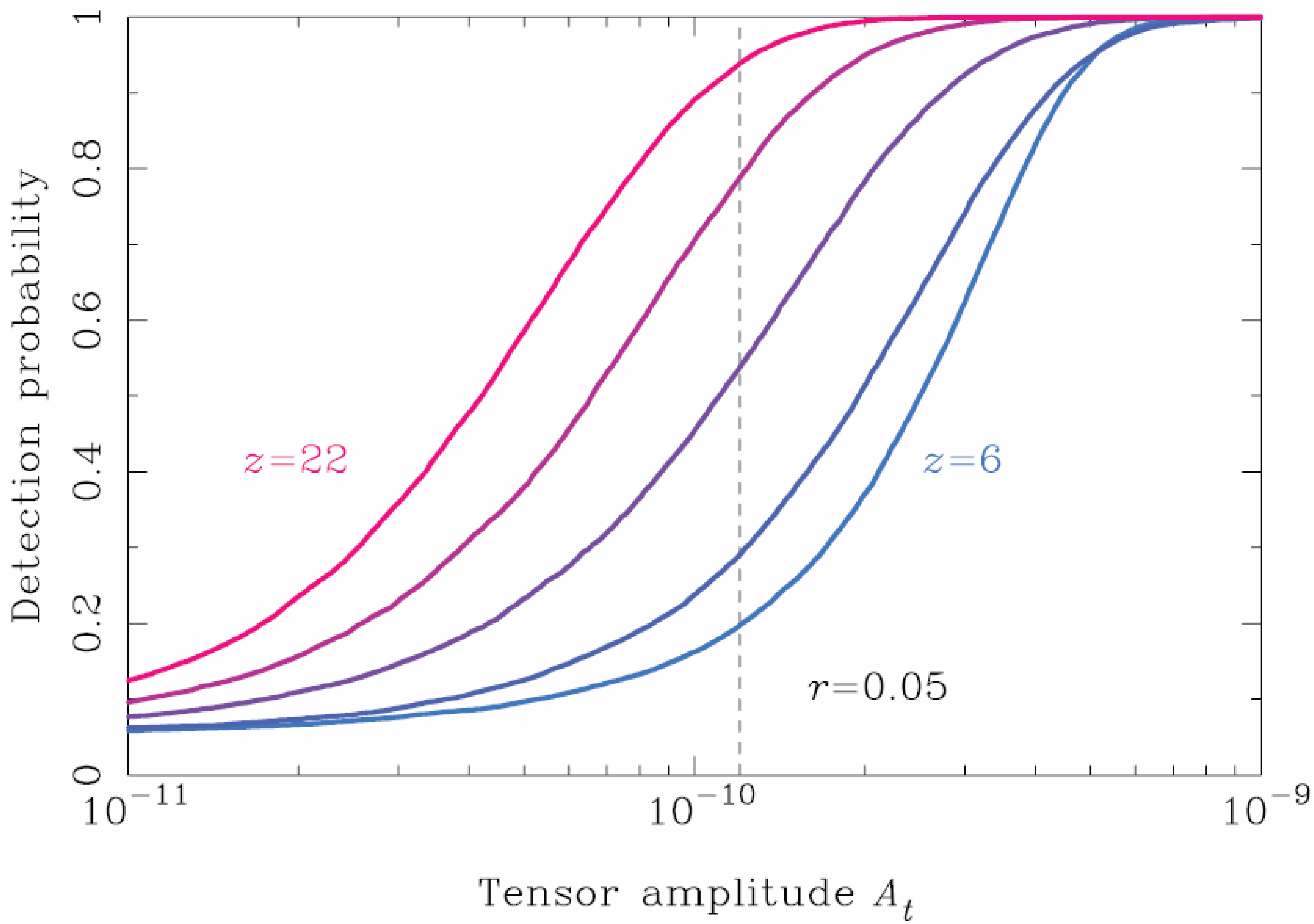
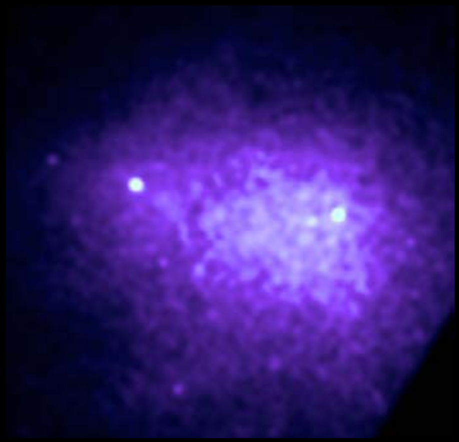


FIG 2.16.—The probability of detecting B-mode polarization at 95% confidence as a function of $A_{\rm T}$, the amplitude of the primordial tensor power spectrum (assumed scale-invariant), for *Planck* observations using 65% of the sky. The curves correspond to different assumed epochs of (instantaneous) reionization: $z = 6$, 10, 14, 18 and 22. The dashed line corresponds to a tensor-to-scalar ratio $r = 0.05$ for the best-fit scalar normalisation, $A_{\rm S} = 2.7 \times 10^{-9}$, from the one-year *WMAP* observations.

Near Future

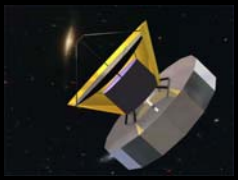
Hot Plasma in Clusters of galaxies

visibile ← **Coma** → X-rays



- X-ray measurements show that there is a hot (>10^7K) ionized and diluted gas filling the intracluster volume between galaxies.
- The baryonic mass of this gas can be more than the baryonic mass in the galaxies of the cluster.

Sunyaev-Zeldovich Effect

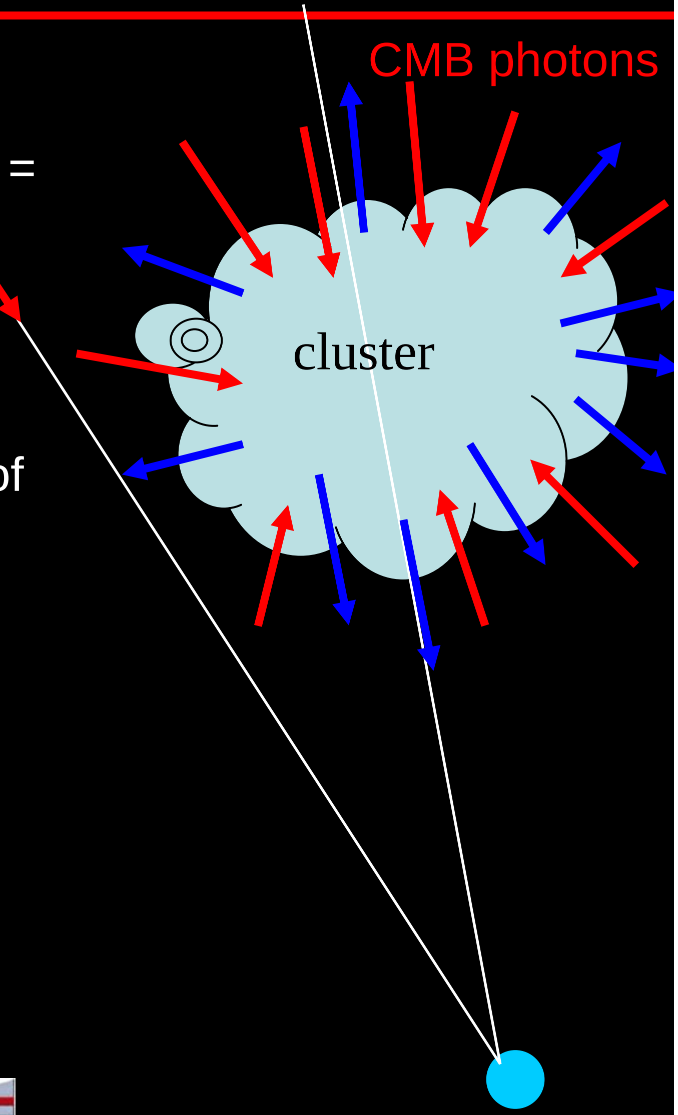


- Inverse Compton Effect for CMB photons against electrons in the hot gas of clusters
- Cluster optical depth: $\tau = n\sigma\ell$ where ℓ = a few Mpc = 10^{25} cm, $n < 10^{-3}$ cm^{-3} , $\sigma = 6.65\times10^{-25}$ cm^2
- So $\tau = n\sigma\ell < 0.01$: there is a 1% likelihood that a CMB photon crossing the cluster is scattered by an electron
- $E_{electron} >> E_{photon}$, so the electron gives part of his energy to the photon. To first order, the energy gain of the photon is

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

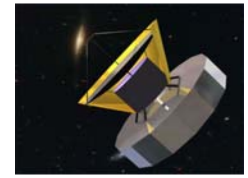
- The resulting CMB temperature anisotropy is

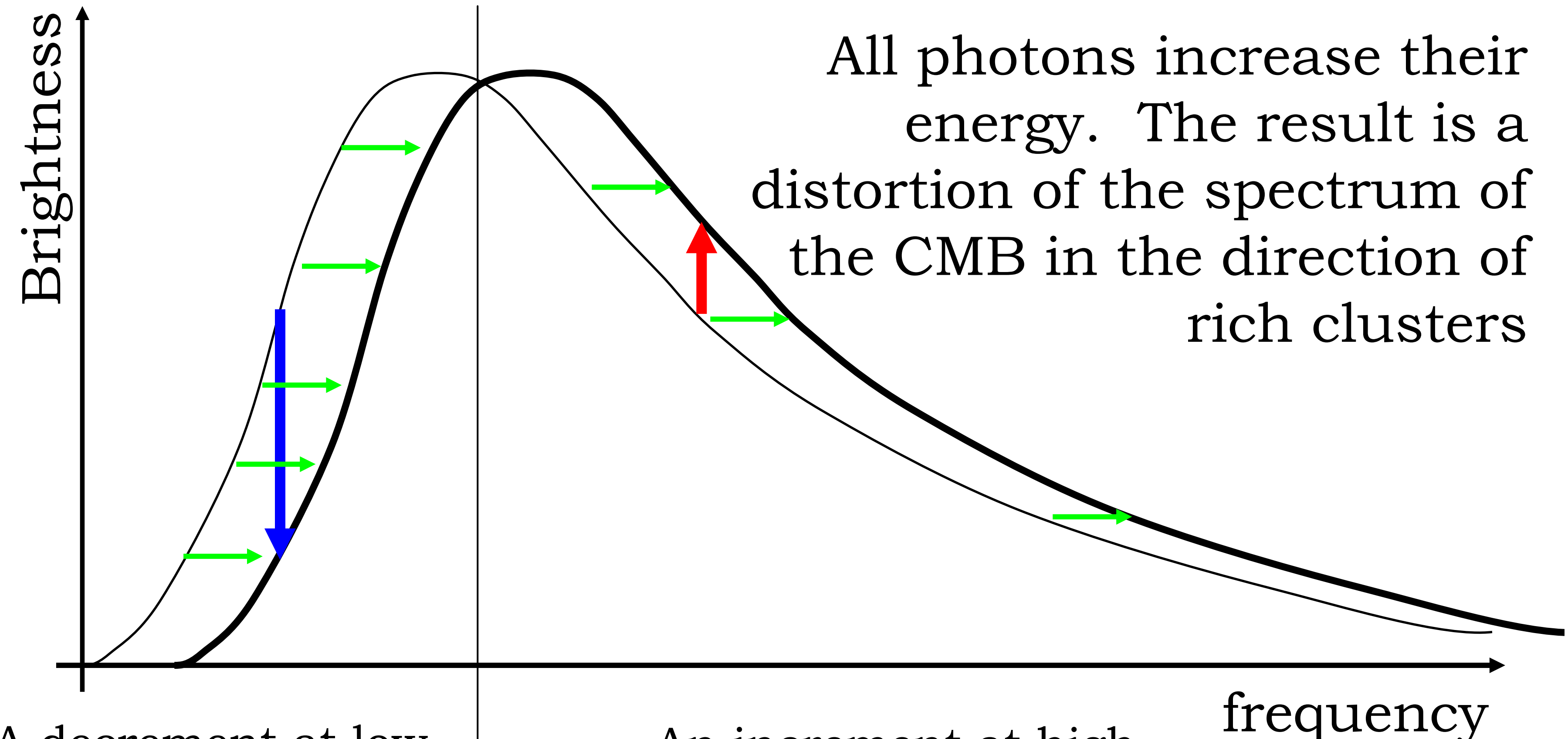
$$\frac{\Delta T}{T} \approx \tau \frac{\Delta\nu}{\nu} \approx 0.01 \times 0.01 = 10^{-4}$$



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

Sunyaev-Zeldovich Effect



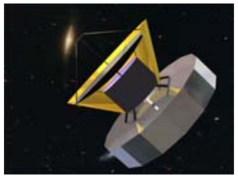


All photons increase their energy. The result is a distortion of the spectrum of the CMB in the direction of rich clusters

A decrement at low frequencies (<217GHz)

An increment at high frequencies (> 217GHz)

The Sunyaev-Zeldovich Effect



S-Z

Dust

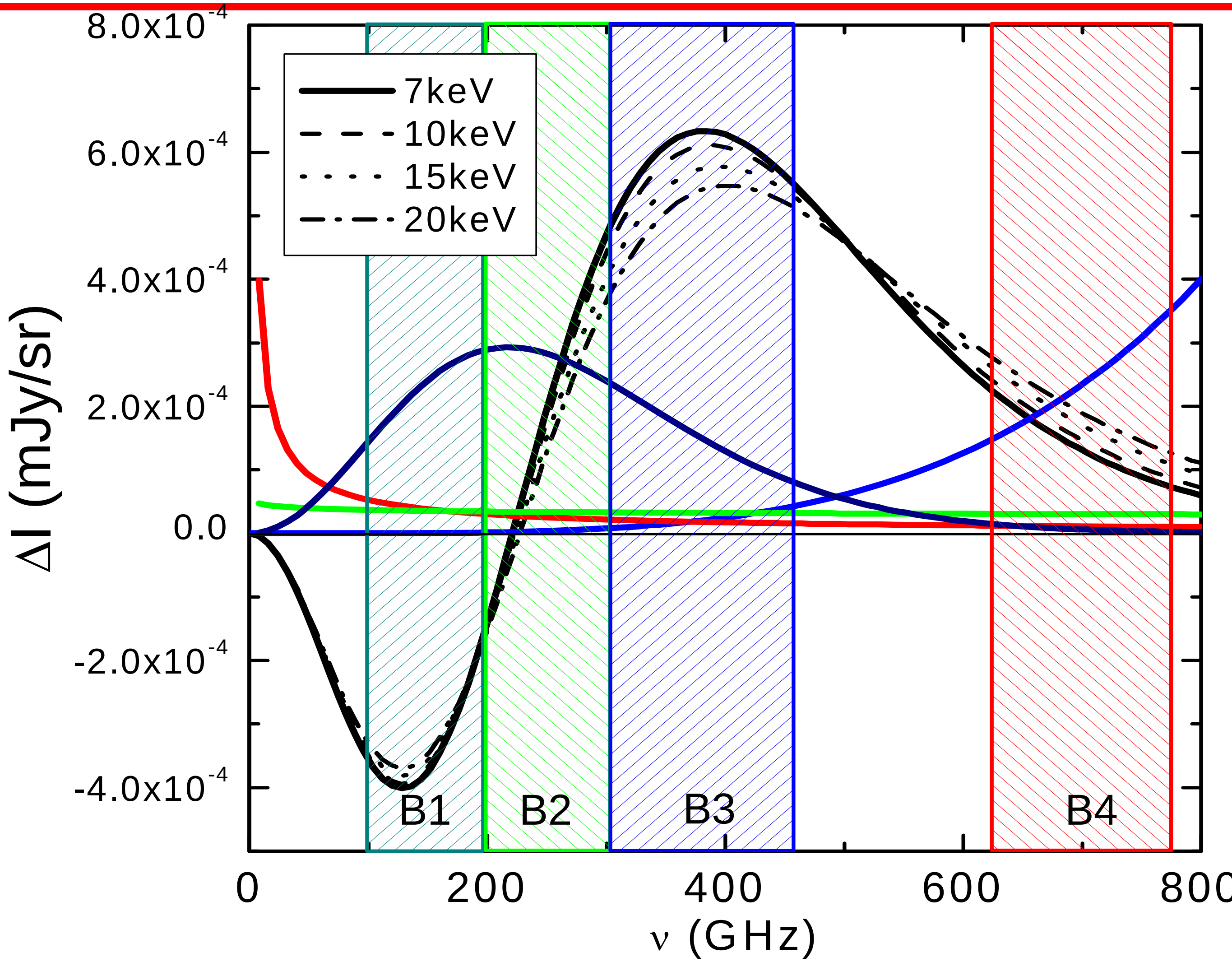
Synchrotron

Free-free

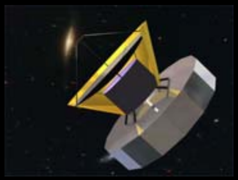
CMB

Spectral coverage of SAGACE

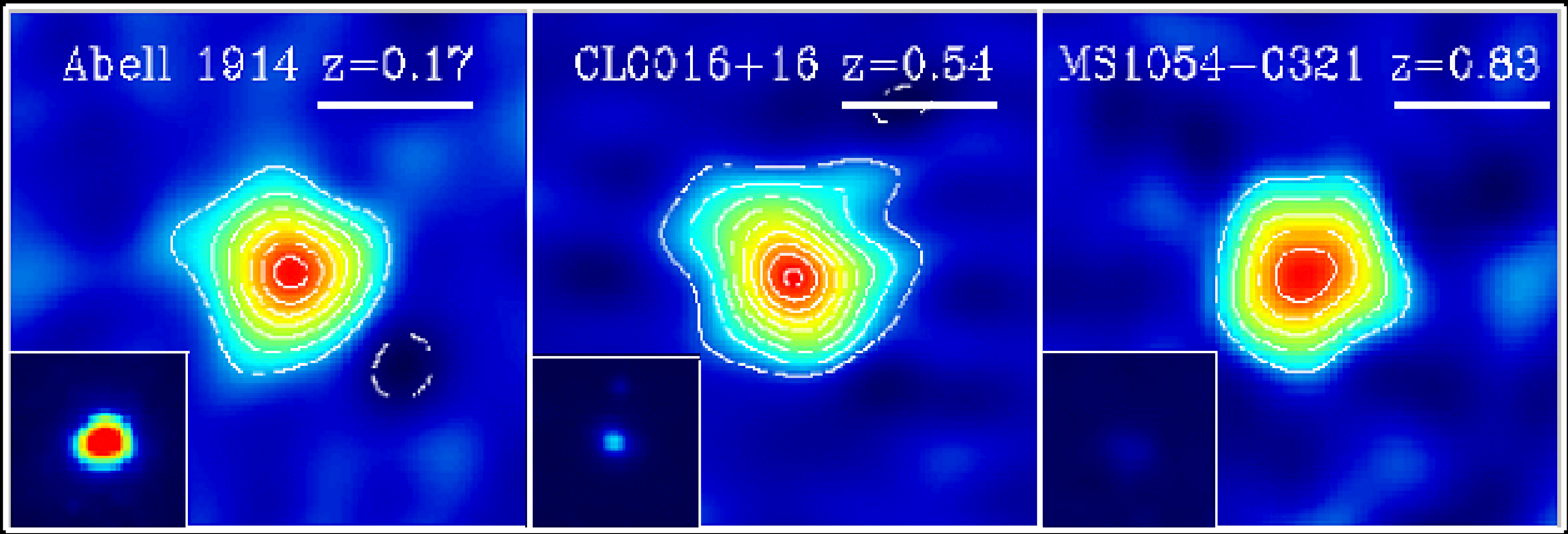
divided in 4 spectral bands B1-B2-B3-B4



The Sunyaev-Zeldovich Effect



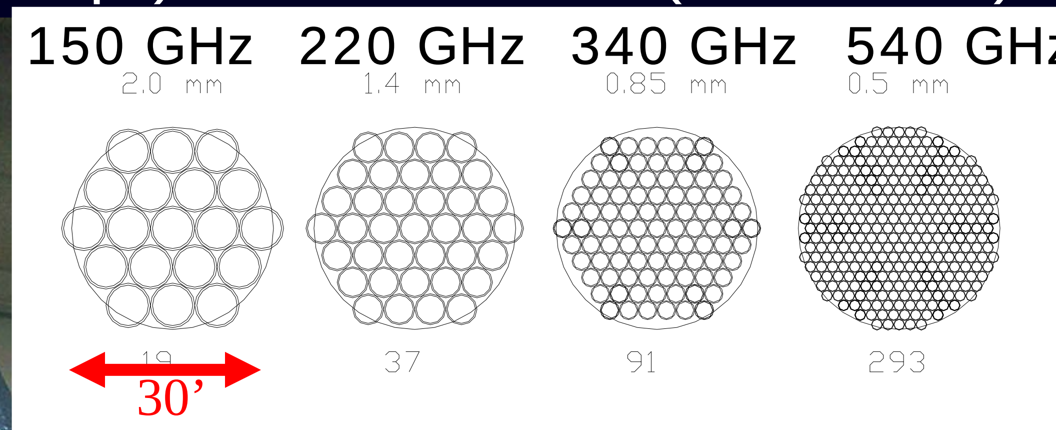
- The S-Z Effect does not depend on the distance (redshift) of the cluster, and depends linearly on the density of the gas
- X-ray brightness decreases significantly with distance and gas density (depends on the square of the density).

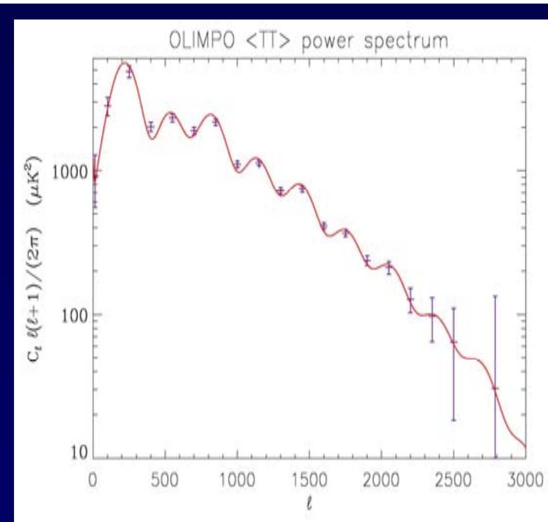


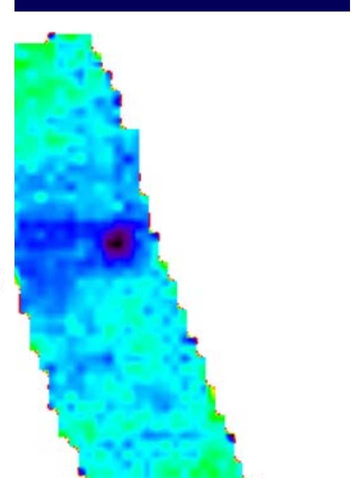
X-ray S-Z X-ray S-Z X-ray S-Z

OLIMPO (PI Silvia Masi, Roma)

- Focal plane can host >400 bolometers
- from Cardiff (P. Mauskopf) and Grenoble (P. Camus)

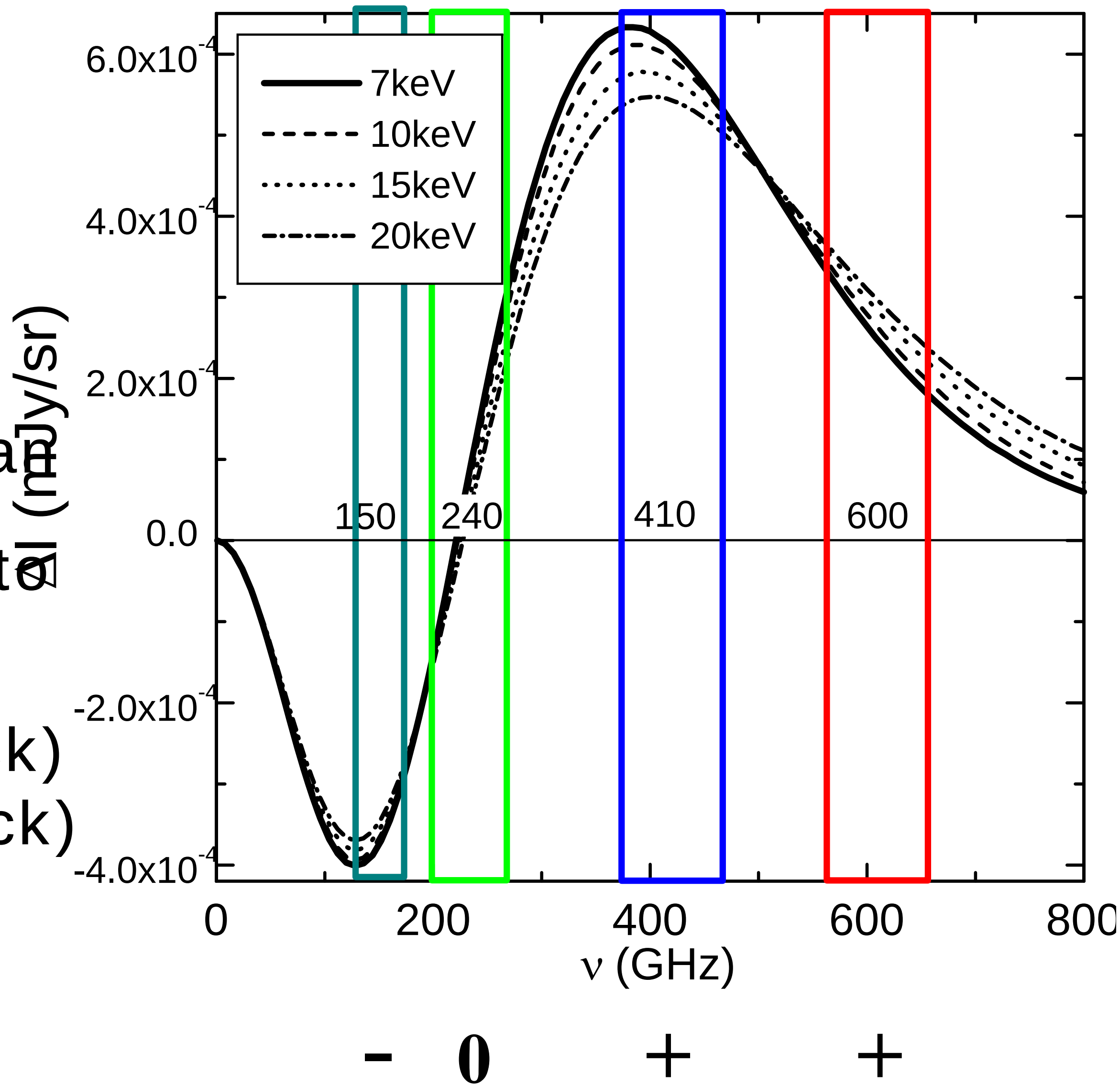




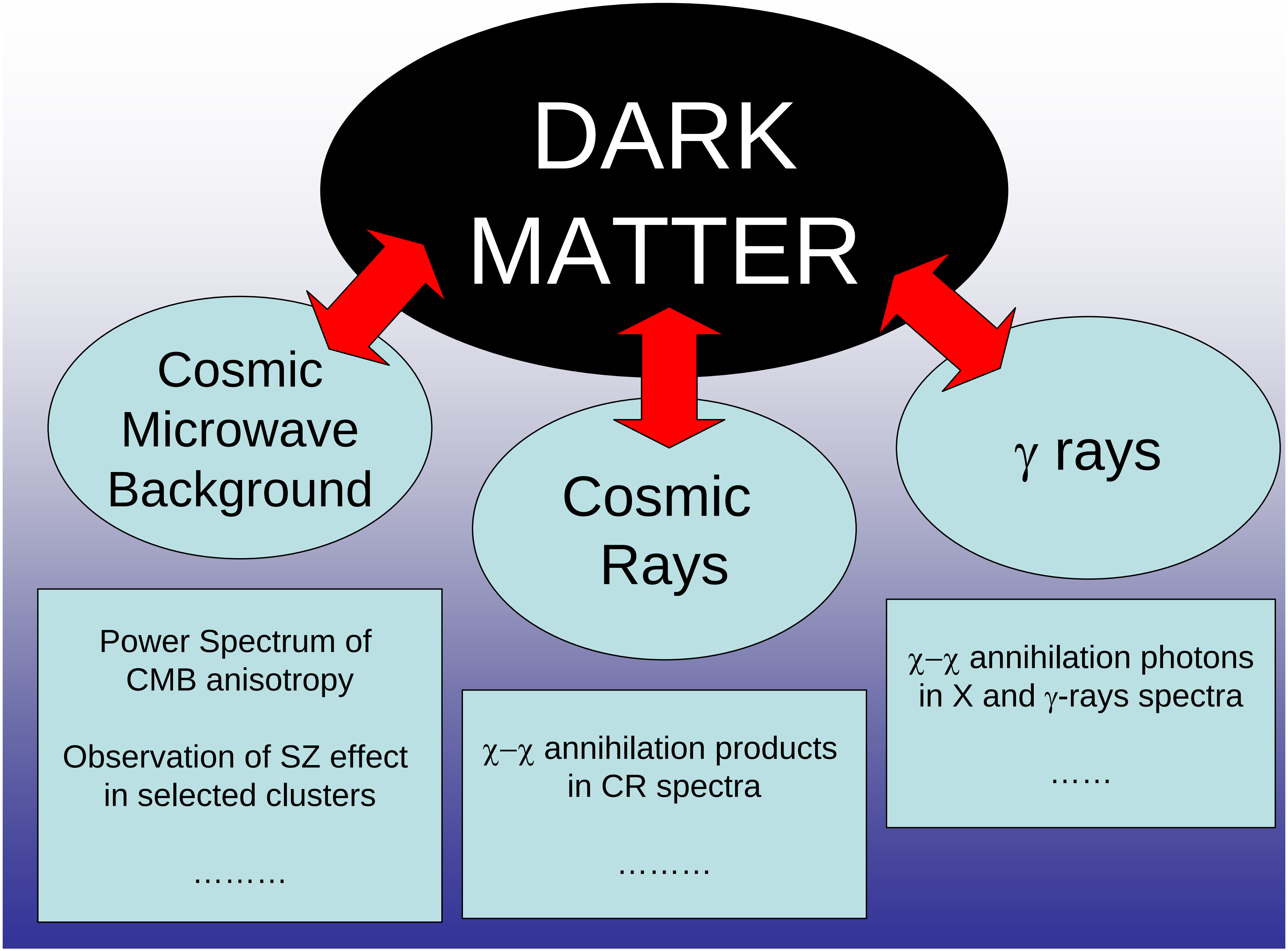


Uniqueness of OLIMPO

- 4 frequency bands simultaneously.
- Optimally sample the spectrum of the SZ effect.
- Opposite signals at 410 GHz and at 150 GHz provide a clear signature of the SZ detection.
- 4 bands allow to clean the signal from dust and CMB, and even to measure T_e
- Resolution: 2x(Planck)
- Detectors: 10x(Planck)
- Integration time per cluster: 10x(Planck) (40 clusters/flight + blind survey)



Flights: 2009 & 2010

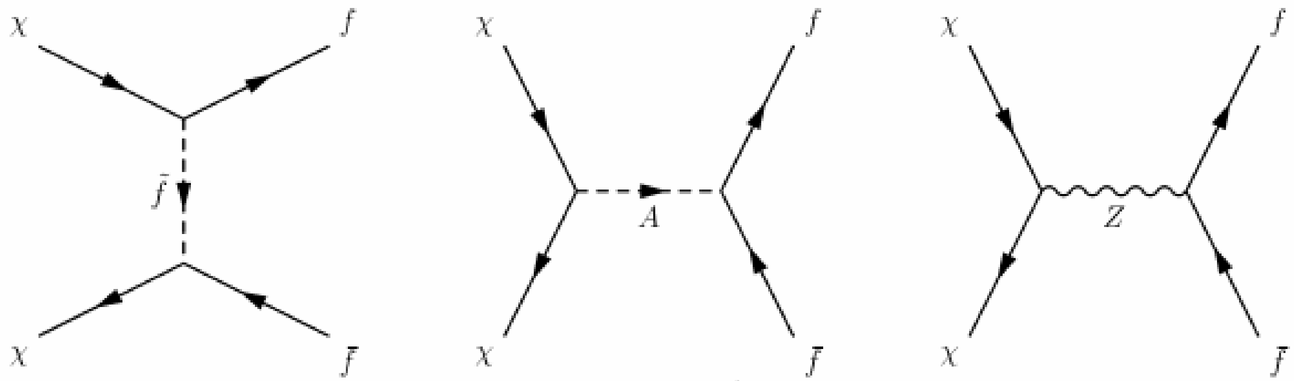


DARK MATTER
Cosmic Microwave Background
Cosmic Rays
γ rays
Power Spectrum of CMB anisotropy
Observation of SZ effect in selected clusters
....
χ−χ annihilation products in CR spectra
....
χ−χ annihilation photons in X and γ-rays spectra
......

What is Dark Matter ?

- **Hp**: Weakly Interacting Supersymmetric Particles (WIMPs)
- Lightest one predicted by SUSY : Neutralino χ
- Could be measured by LHC
- χs tend to cluster in the center of astrophysical structures
- Annihilation of Neutralinos would produce fluxes of
  - Neutral and charged pions
  - Secondary electrons protons
  - Neutrinos
  - etc.
- They produce various effects
- One of them is the SZ from the charged component (see Colafrancesco, 2004)

Dark Matter Annihilation Products

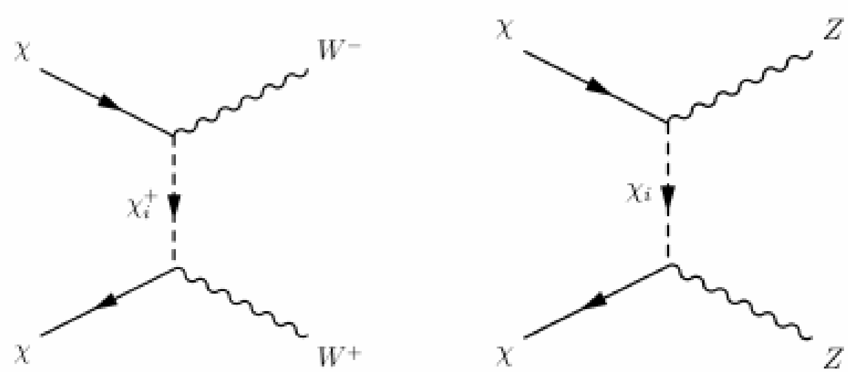


$$\propto \frac{m_\chi \cdot m_f}{m_{\tilde{f}}^2}$$

$$\propto \frac{\tan\beta \cdot m_{f_d}}{m_W}\left(\frac{m_\chi}{m_A}\right)^2 N_1 N_{3(4)}$$

$$\tan\beta \cdot m_{f_d} \leftrightarrow \frac{m_{f_u}}{\tan\beta}$$

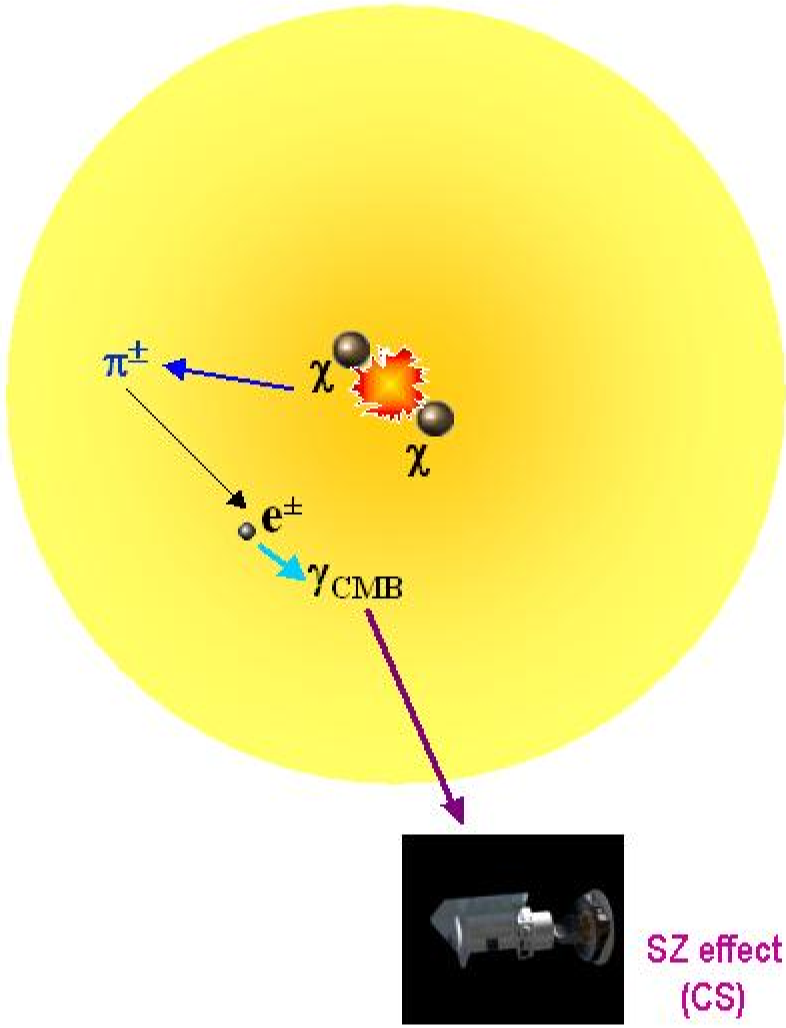
$$\propto \frac{m_f \cdot m_\chi}{m_Z^2} N_{3(4)}^2$$



$$\propto \frac{1}{1+(m_{\chi_i^+}/m_\chi)^2-(m_W/m_\chi)^2}$$

$$(m_{\chi_i^+}, m_W) \leftrightarrow (m_{\chi_i}, m_Z)$$

SZ effect from χχ annihilation



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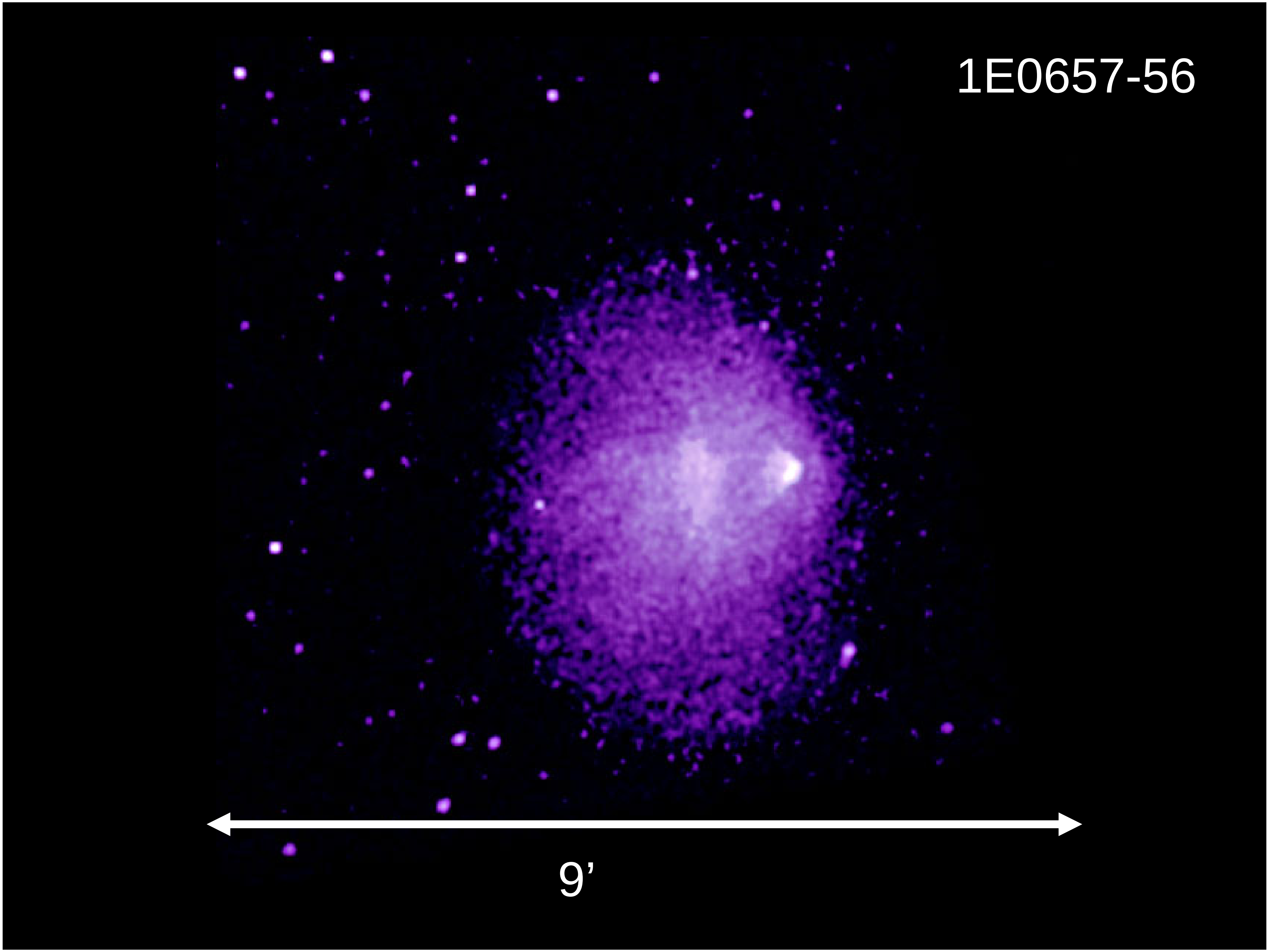
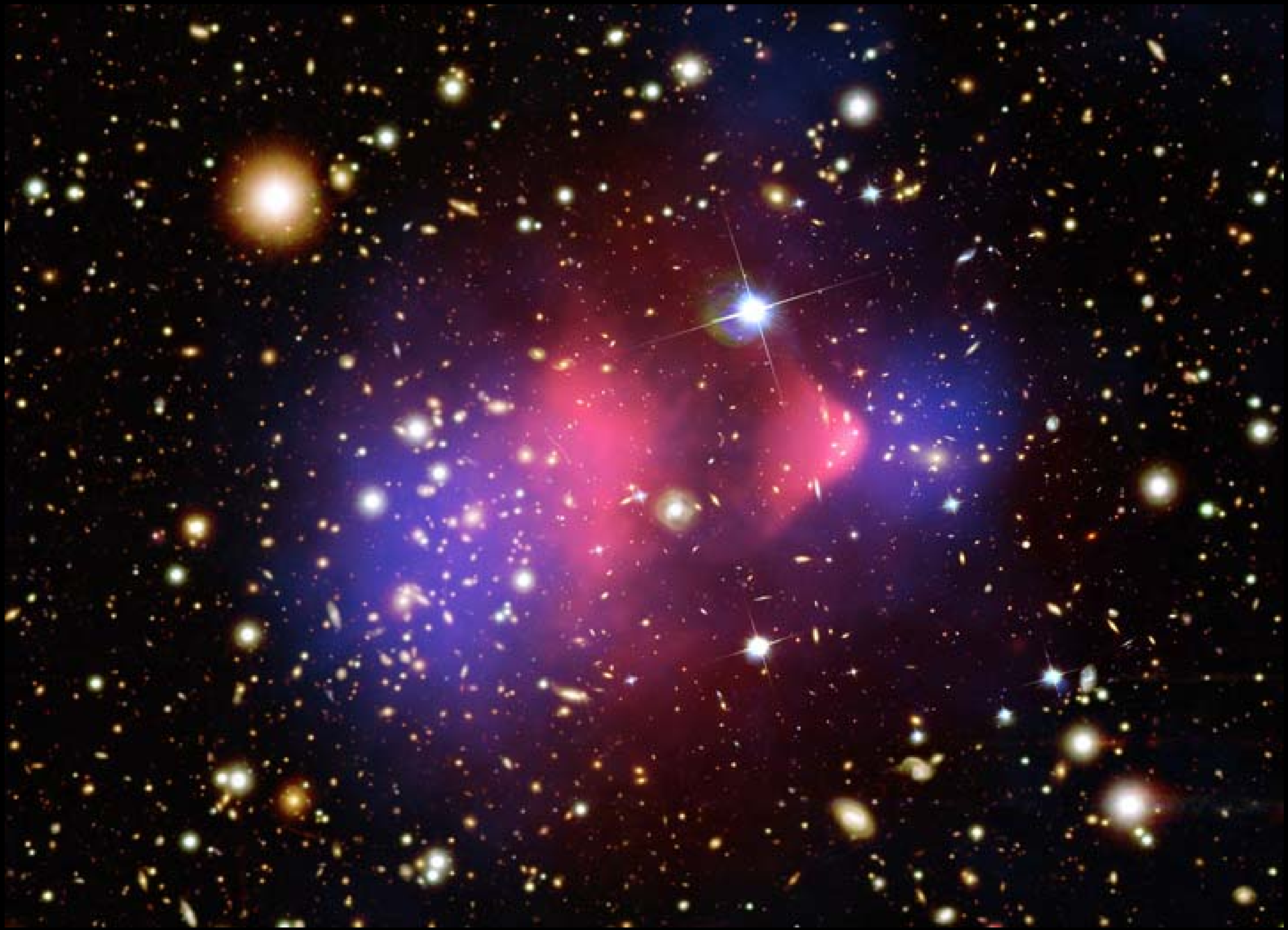
  - etc.
- They produce various effects
- One of them is the SZ from the charged component (see Colafrancesco, 2004)
- Subdominant with respect to SZE from the gas.
- We need clusters where Dark Matter and Baryonic Matter are separated.


1E0657-56
9’

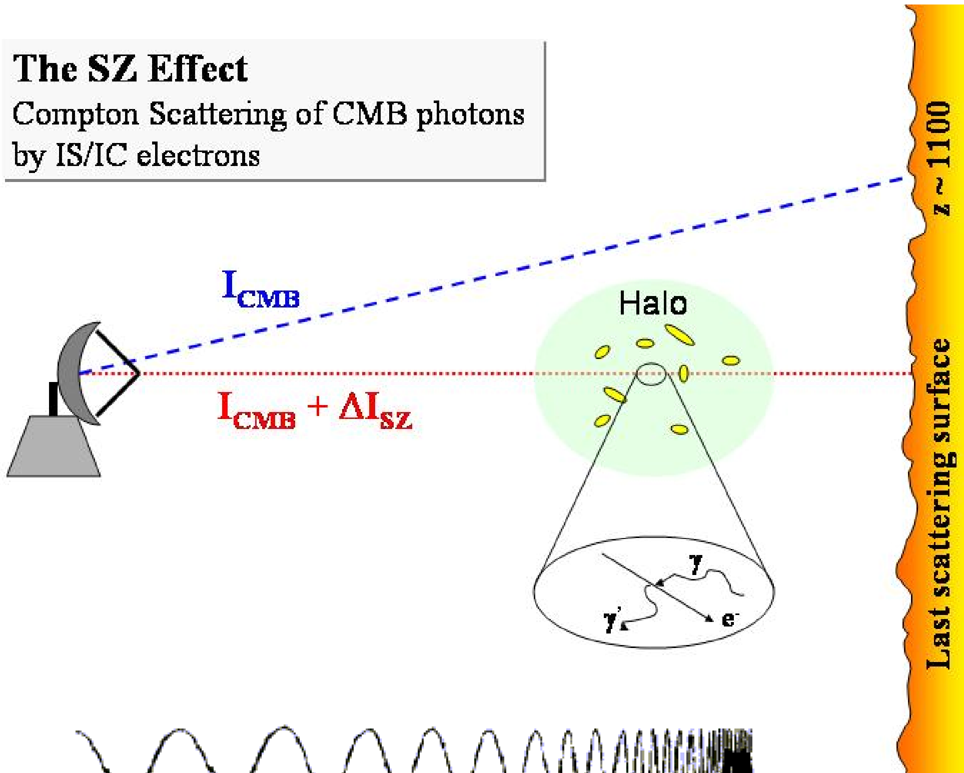
1E0657-56



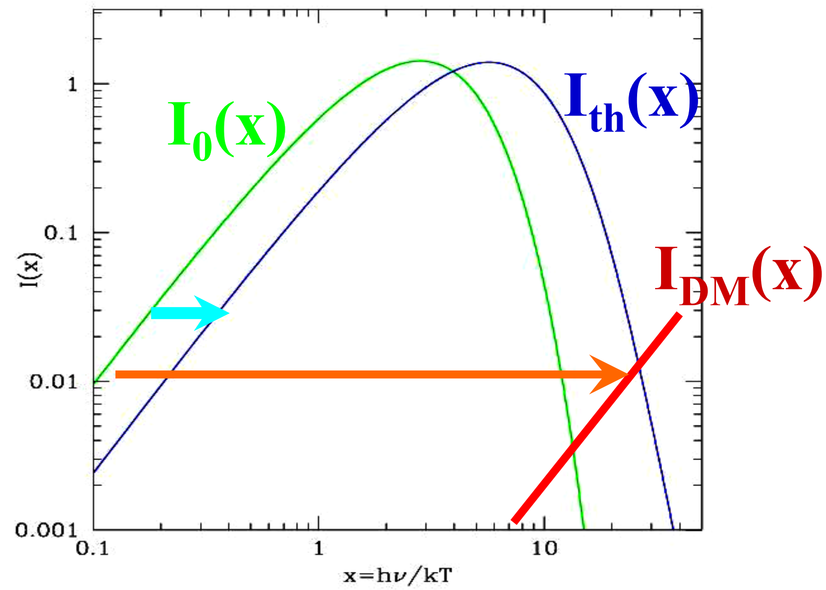
7.5 ’

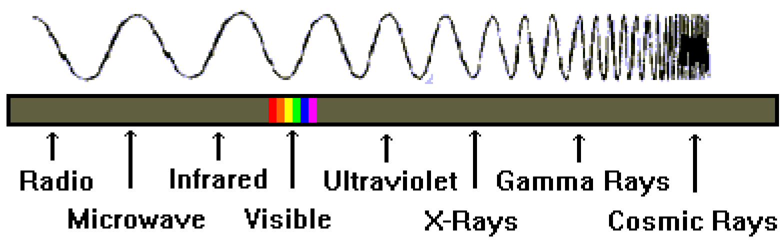
SZ effect from DM

[Colafrancesco 2004 , A&A, 422, L23]



$$\Delta I(x) = I(x) - I_0(x)$$

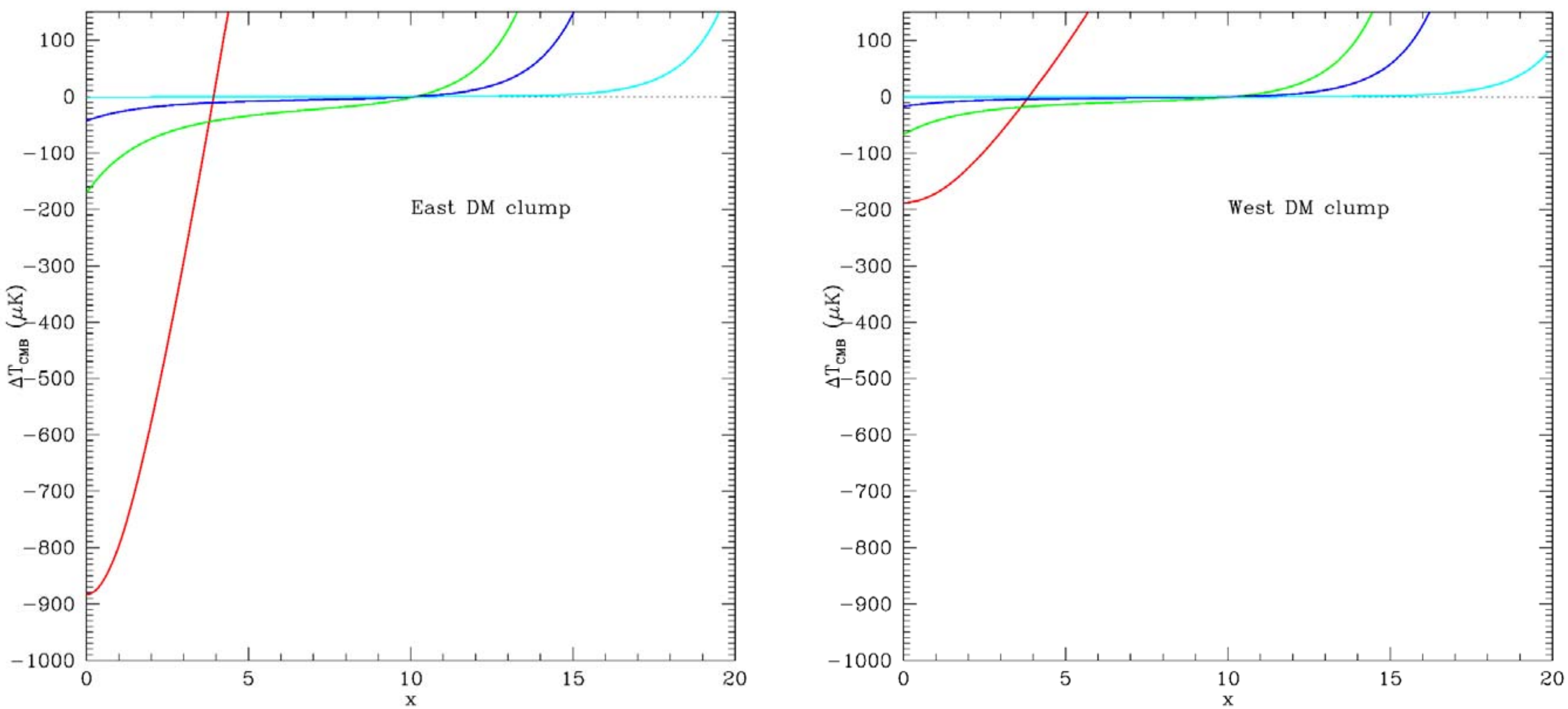




thermal e⁻ $\qquad \dfrac{\nu'}{\nu} = \dfrac{4}{3}$

relativistic e⁻ $\qquad \dfrac{\nu'}{\nu} = \dfrac{4}{3}\gamma^2 - 1$

SZ effect at clump centres



[Colafrancesco, de Bernardis, Masi, Polenta & Ullio 2006]

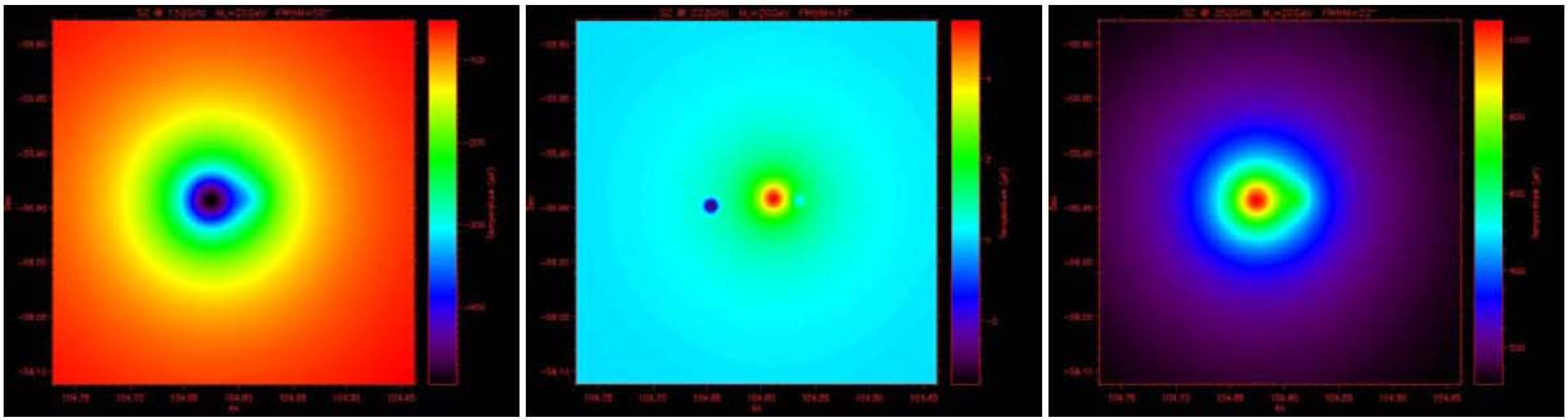
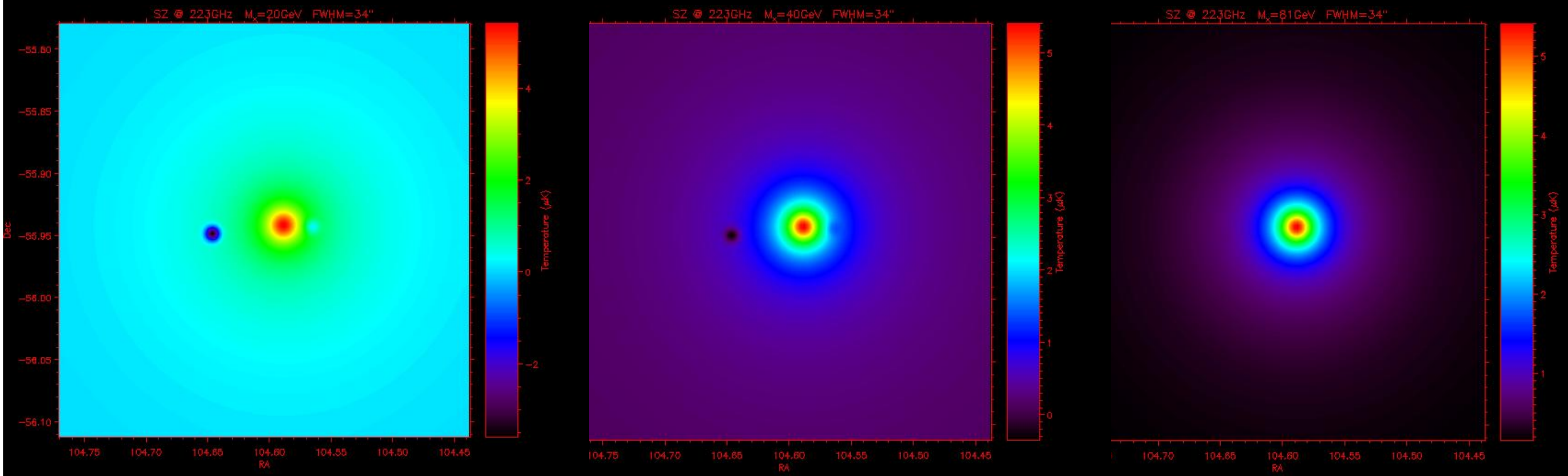


Fig. 2. The simulated SZ maps of the cluster 1ES0657-556 as observable with the SPT telescope at three frequencies: $\nu = 150$ GHz (left panel), $\nu = 223$ GHz (mid panel), $\nu = 350$ GHz (right panel). A neutralino mass of $M_\chi = 20$ GeV has been adopted here. Note that choosing the frequency of 223 GHz where the thermal SZE from the E baryonic clump vanishes maximizes the detectability of the SZ_{DM} effect from the two DM clumps.

[Colafrancesco, de Bernardis, Masi, Polenta & Ullio 2006]

Isolating SZ_{DM} (at 223 GHz)

M_χ = 20 GeV **M_χ = 40 GeV** **M_χ = 80 GeV**



The SZE from the hot gas disappears at $x_{0,th}$ (~ 220-223 GHz) while the SZ_{DM} expected at the locations of the two DM clumps remains negative and with an amplitude and spectrum which depend on M_χ.

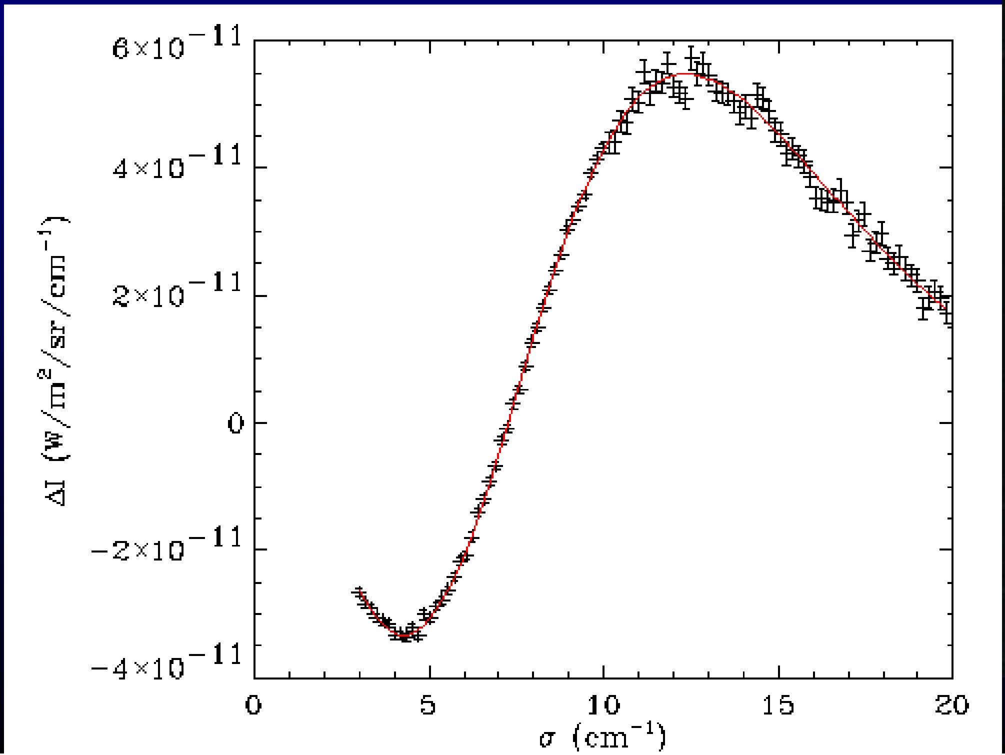
[Colafrancesco, de Bernardis, Masi, Polenta & Ullio 2006]

In a few years (may be)

SAGACE

Spectroscopic Active Galaxies And Clusters Explorer

- The ideal continuation of OLIMPO
- Selected by ASI for a phase-A study as a small mission
- 2.6 m telescope + FTS spectrometer on a Soyuz
- Uni. La Sapienza / Uni. Mi. Bicocca / Uni. Genova / Kayser Italiana / ASDC-ASI



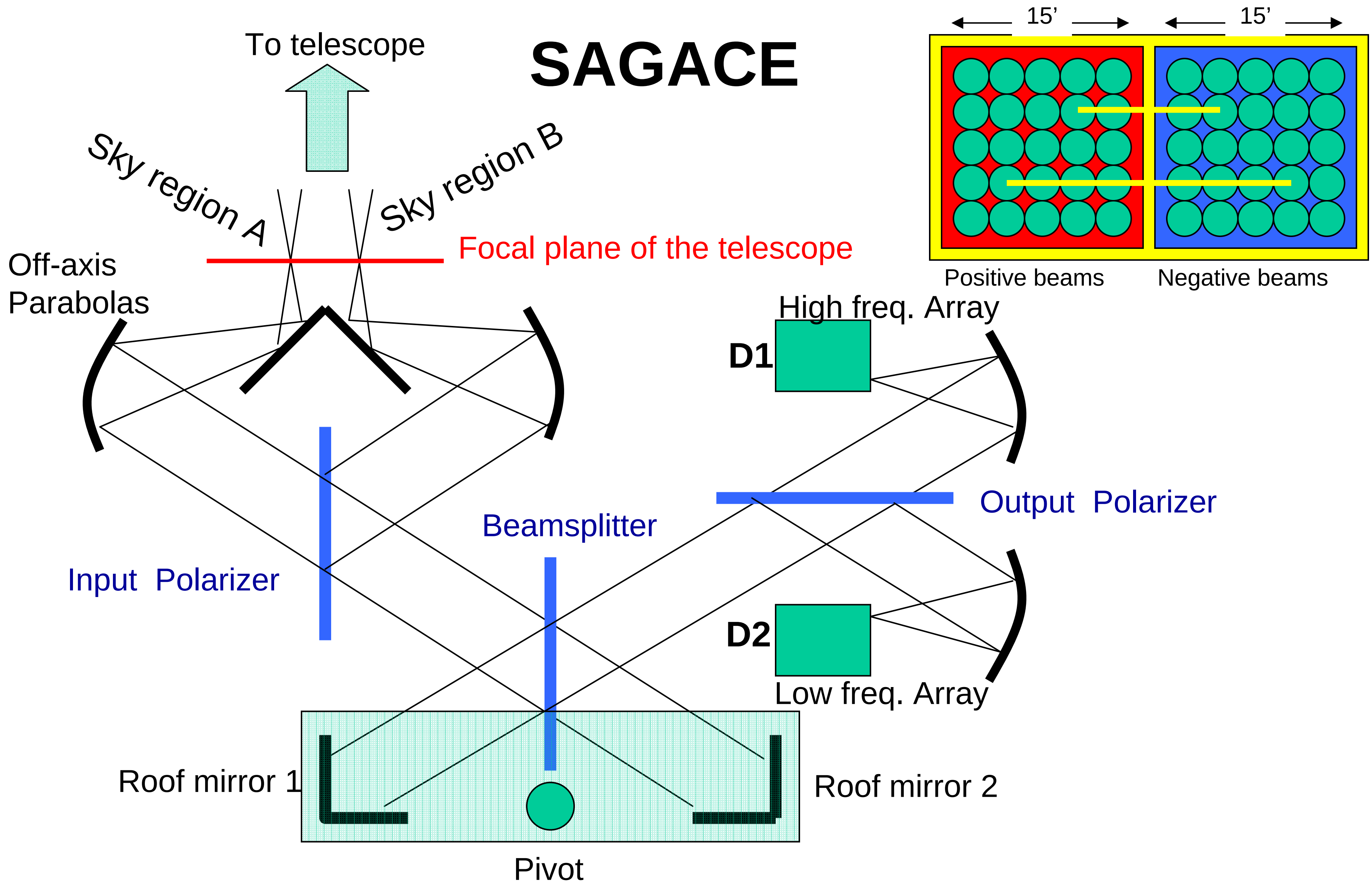
WHAT IS SAGACE ?

We have studied a space-borne spectrometer, coupled to a 3m telescope:

- able to cover the frequency ranges 100-450 and 720-760 GHz;
- with angular resolution ranging from 4.2 to 0.7 arcmin;
- with photon-noise limited sensitivity (~ 1.5 Jy per second of integration for a 1 GHz resolution element, 50 mJy per second for 30 GHz resolution element)

This is a very powerful machine, and has been designed to tackle fundamental unsolved problems related to the cold/active universe.

SAGACE



A possible spectrometer: Differential Martin Puplett Interferometer :
Each detector measures the difference of spectra from two sky regions

In the far future …

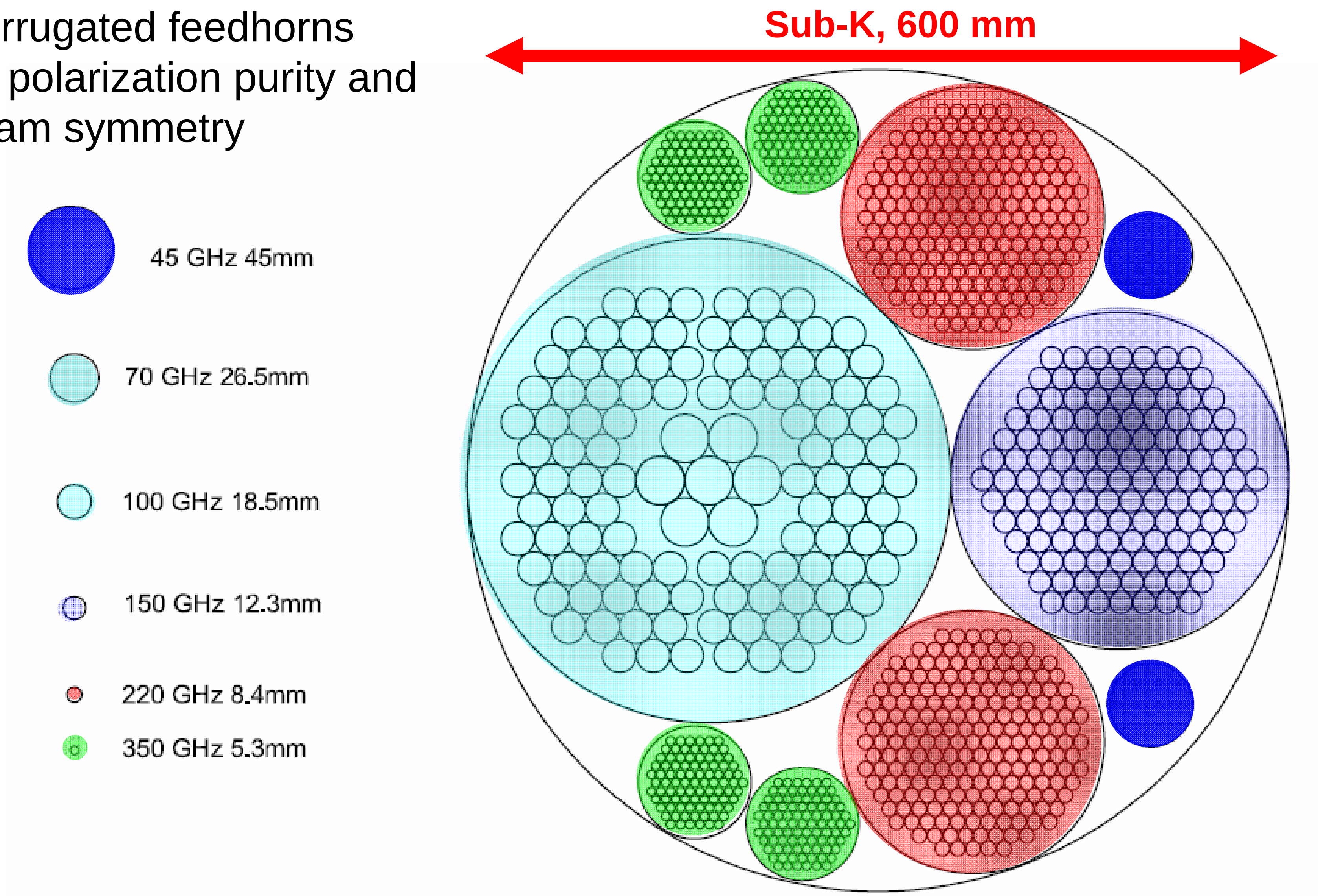
B-Pol
(www.b-pol.org)

- European proposal recently submitted to ESA (Cosmic Vision).
- ESA encourages the development of technology and resubmission for next round
- Detector Arrays development activities (KIDs in Rome, TES in Oxford, Genova etc.)
- A balloon-borne payload being developed with ASI (B-B-Pol).

Sensitivity and frequency coverage: the focal plane

- Baseline technology: TES bolometers arrays

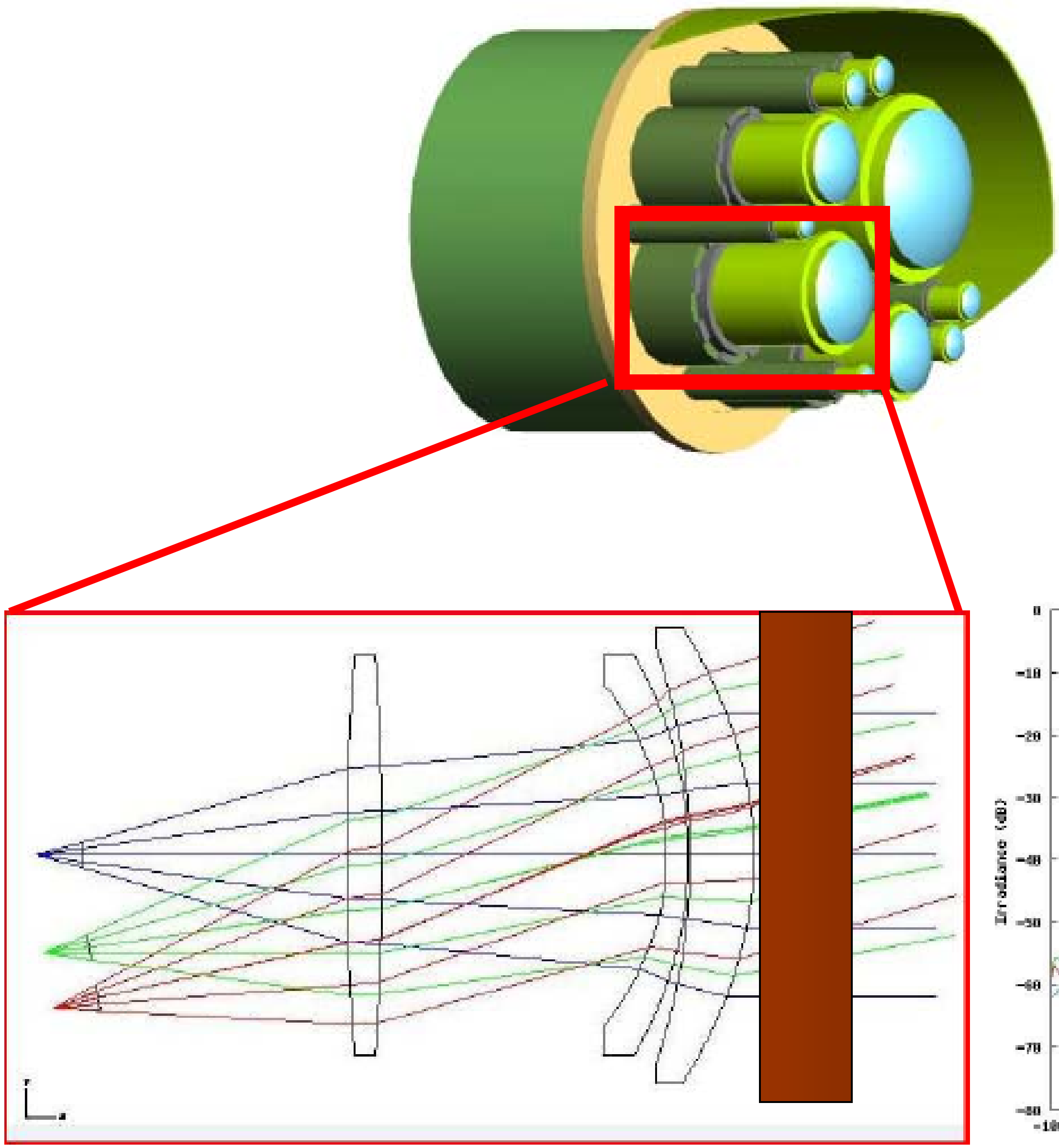
Corrugated feedhorns
for polarization purity and
beam symmetry



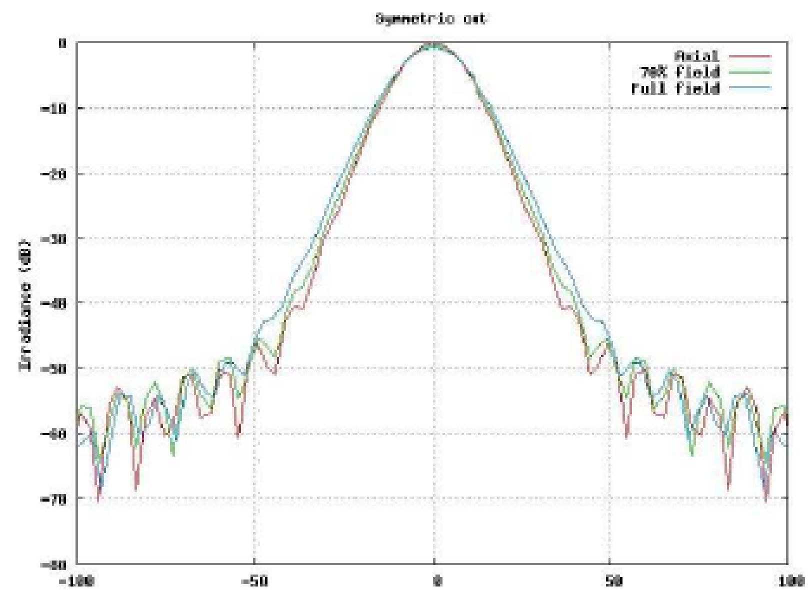
Optical system:

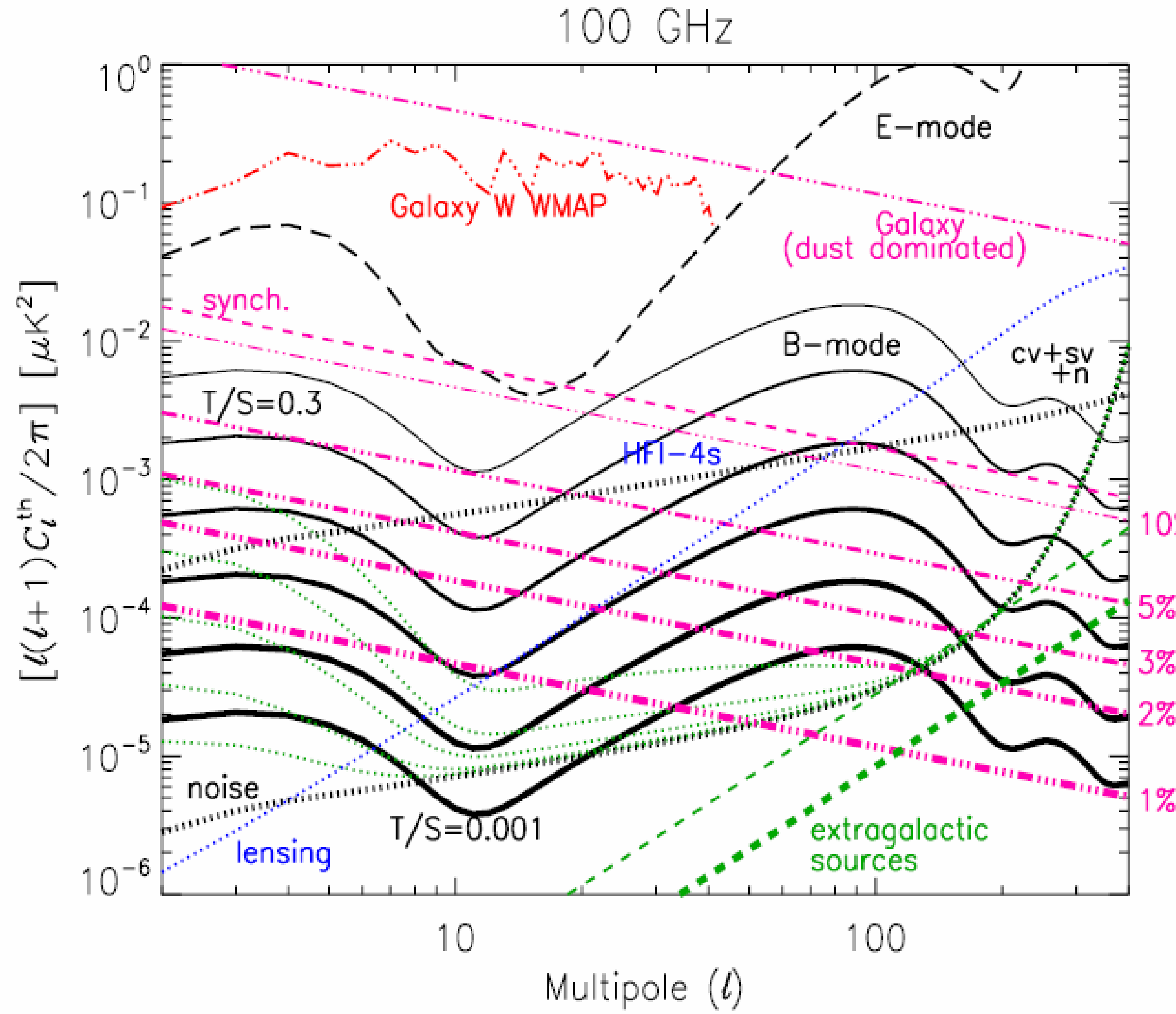
- **Wide field,**
- **low cross-pol,**
- **low emissivity**

Possible solution: modified telecentric telescope



HWP





100 GHz
E−mode
Galaxy W WMAP
Galaxy
(dust dominated)
synch.
B−mode
cv+sv
+n
T/S=0.3
HFI−4s
10%
5%
3%
2%
1%
noise
T/S=0.001
lensing
extragalactic
sources
Multipole (ℓ)
$[\ell(\ell+1)C_\ell^{th}/2\pi]$ [μK^2]

For more information visit www.b-pol.org

And read the paper (astro-ph/0808-1881)

B-Pol: Detecting Primordial Gravitational Waves Generated During Inflation

Paolo de Bernardis, Martin Bucher,
Carlo Burigana and Lucio Piccirillo
(for the B-Pol Collaboration)*

Received: date / Accepted: date

Abstract B-Pol is a medium-class space mission aimed at detecting the primordial gravitational waves generated during inflation through high accuracy measurements of the Cosmic Microwave Background (CMB) polarization. We discuss the scientific background, feasibility of the experiment, and implementation developed in response to the ESA Cosmic Vision 2015-2025 Call for Proposals.

Keywords Cosmology · Cosmic Microwave Background · Satellite

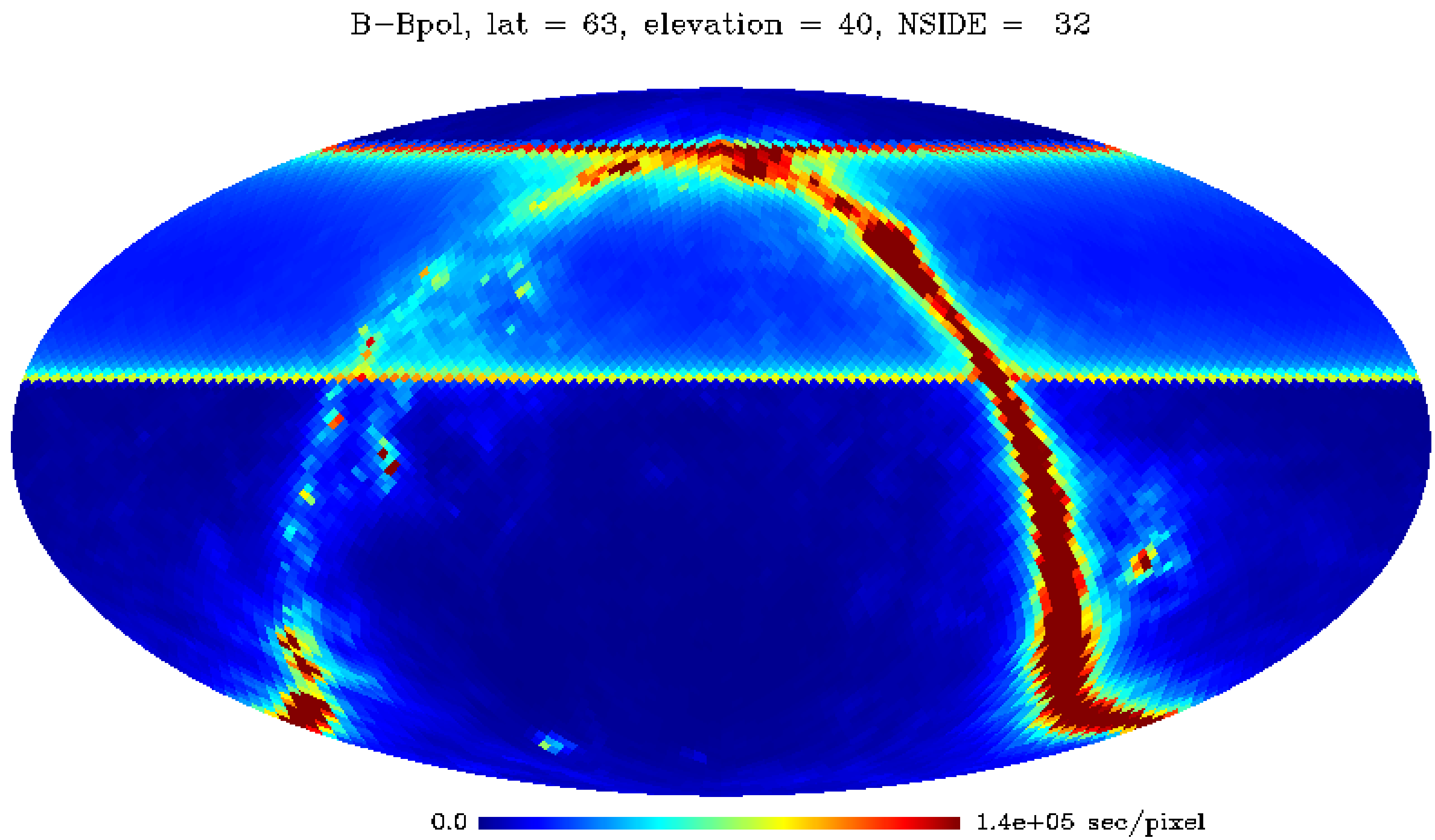
B-B-Pol: The Balloon Option

WHY ?

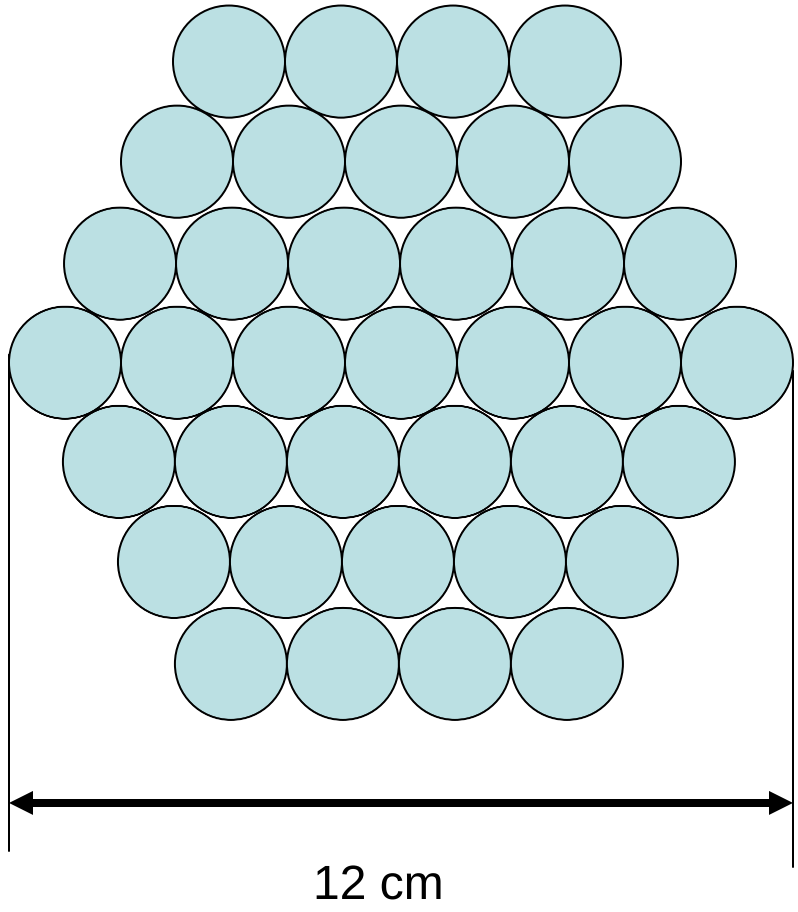
- Get important science (complementary to NASA’s SPIDER, EBEX)
- Validate needed technology, for next round of ESA cosmic vision

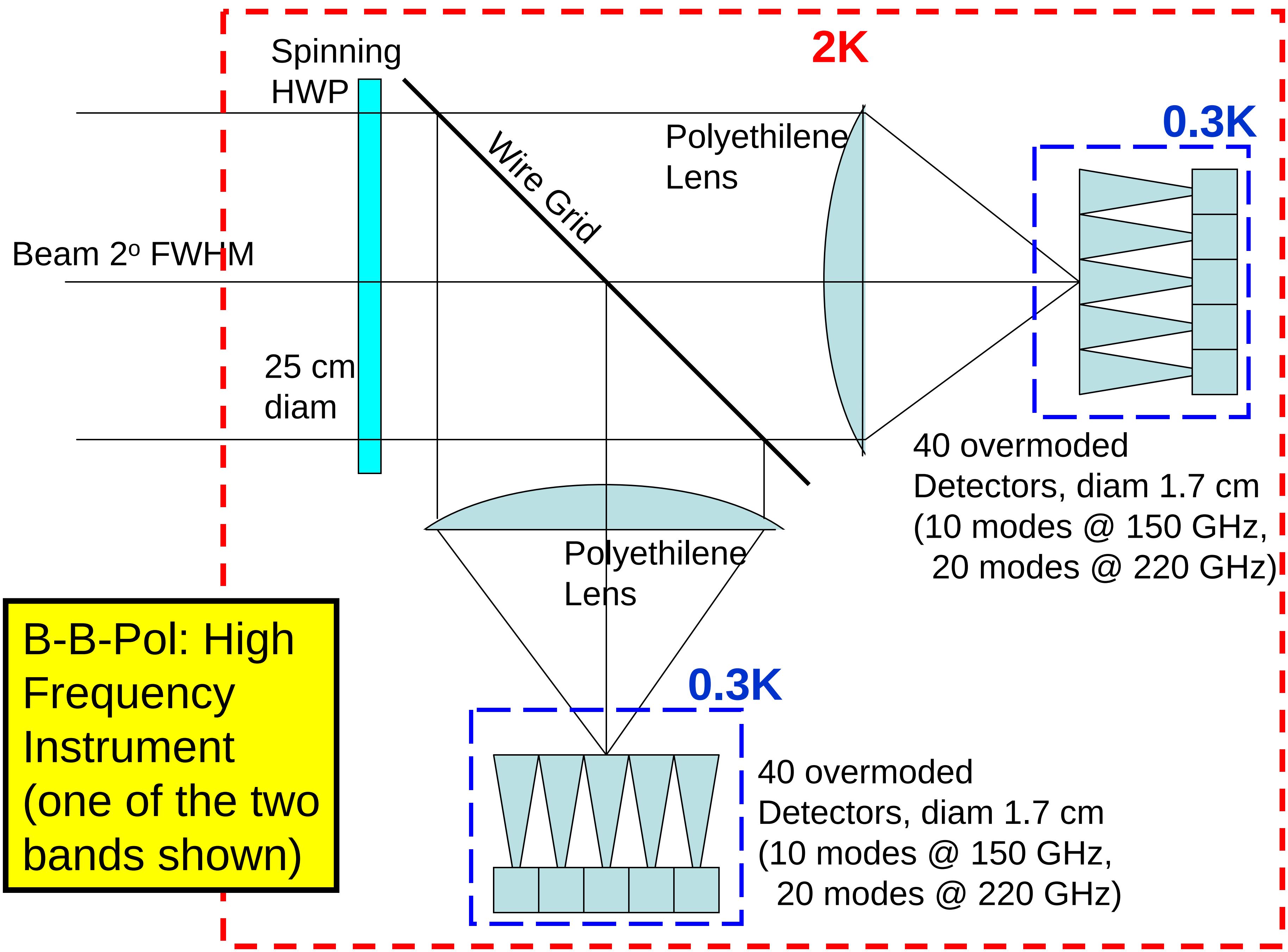
HOW ?

- ASI polar-night flight -> large sky coverage
- Three instruments to cover from 40 to 220 GHz
- Low angular resolution – large scales
- High-Throughput Channels – High sensitivity
- Single-mode channels – Foregrounds
- Large ground shields
- No optics – no spurious polarization


B−Bpol, lat = 63, elevation = 40, NSIDE = 32
0.0
1.4e+05 sec/pixel

37 overmoded detectors




2K
Spinning
HWP
Wire Grid
Polyethilene
Lens
0.3K
Beam 2º FWHM
25 cm
diam
40 overmoded
Detectors, diam 1.7 cm
(10 modes @ 150 GHz,
20 modes @ 220 GHz)
Polyethilene
Lens
0.3K
40 overmoded
Detectors, diam 1.7 cm
(10 modes @ 150 GHz,
20 modes @ 220 GHz)
B-B-Pol: High
Frequency
Instrument
(one of the two
bands shown)

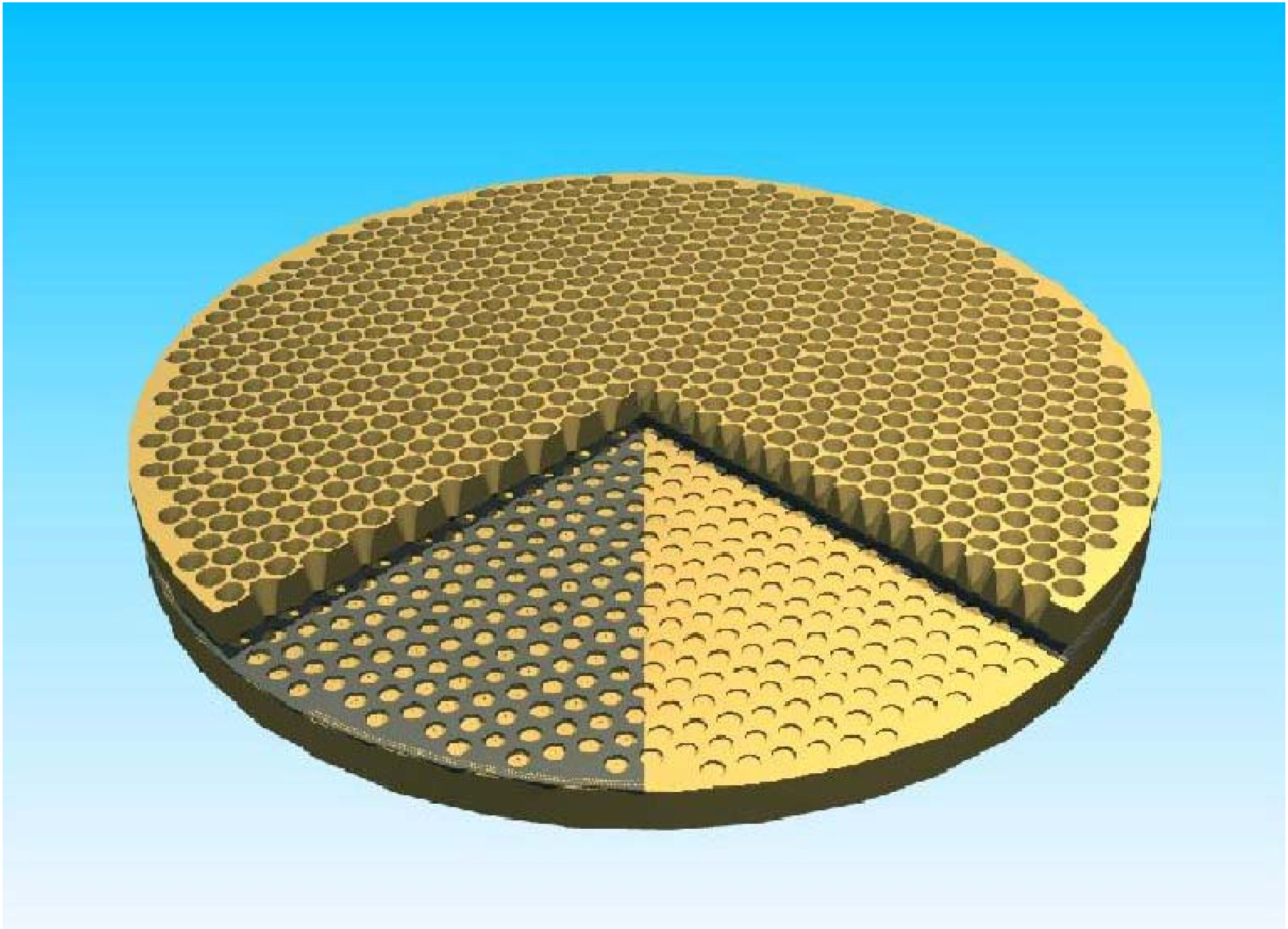
How do we prepare the future ?

Experimental Techniques:

new detectors: KIDs – RIC INFN
new flight opportunities - ASI Svalbard

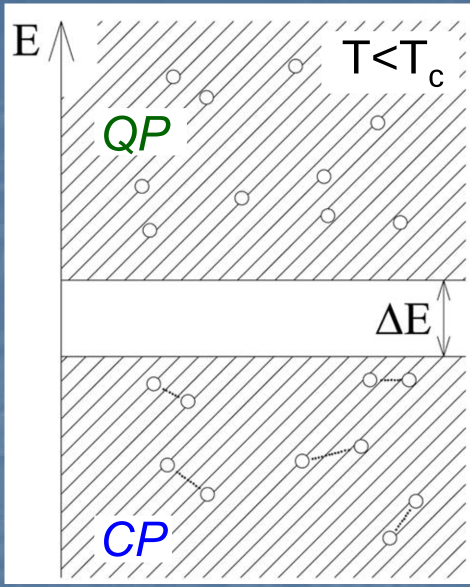
Analysis and Physical Interpretation

methods to constrain cosmology and physics parameters with forthcoming data



A possible solution: Microwave Kinetic Inductance Detectors

Superconductors below a critical temperature T_c have supercurrent carried by pairs of electrons, known as *Cooper Pairs*, bound together by the electron-phonon interaction.



The CPs have zero DC resistance but non zero AC impedance

Complex surface impedance: $Z_s = R_s + i\Omega L_s$

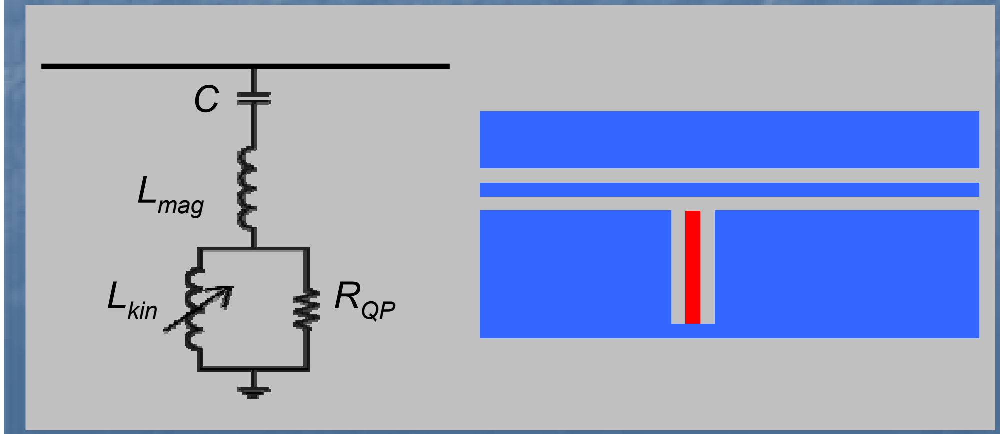
Quasi-Particles (R_s)

CP: $L_{magn} + L_{kin}$

$T \ll T_c \longrightarrow R_s \ll \omega L_s$

L_{kin} depends on the density of CPs, n_{CP}:

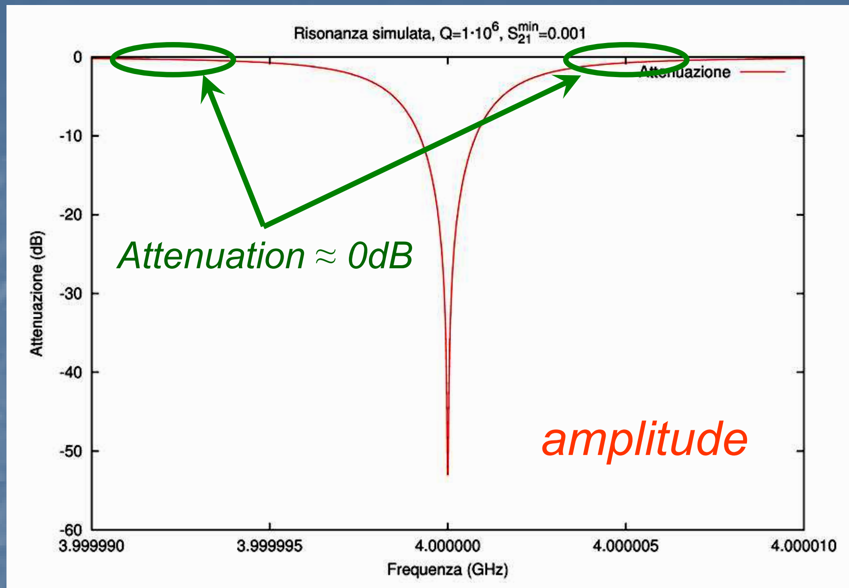
$n_{CP} \uparrow \quad L_{kin} \downarrow$

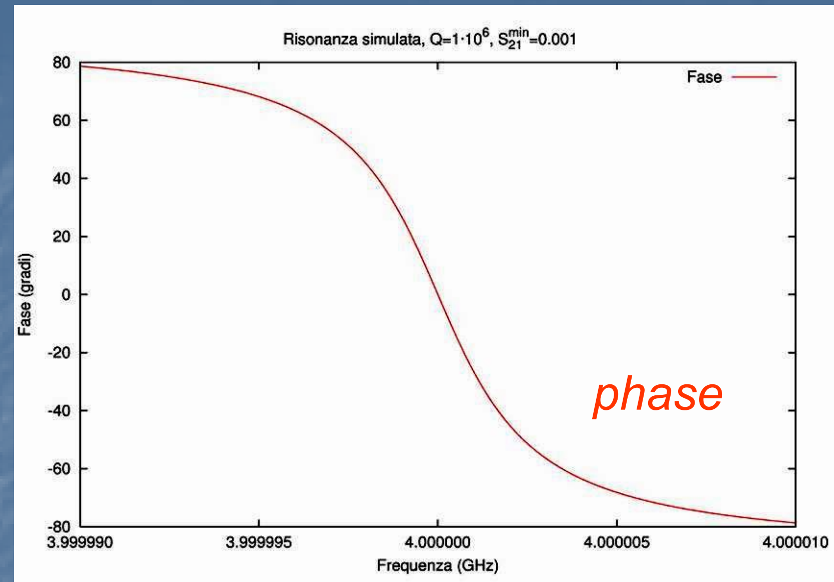


The value of L_{kin} can be measured by capacitively coupling a strip of superconductor to a feed line. One thus gets an *LC* resonator with ***very high Q values.***

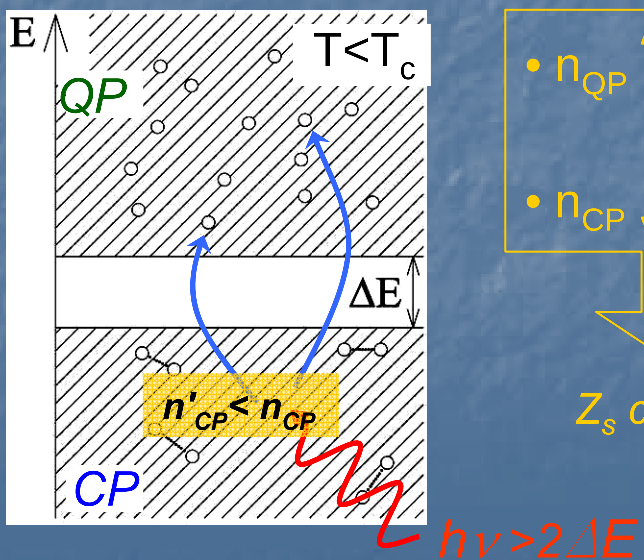
Claudia Giordano + Martino Calvo

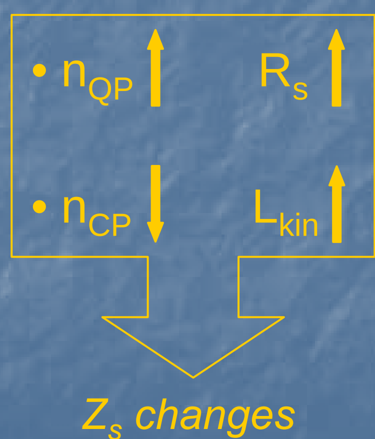
Effect of a signal transmitted through the feed line past the resonator:

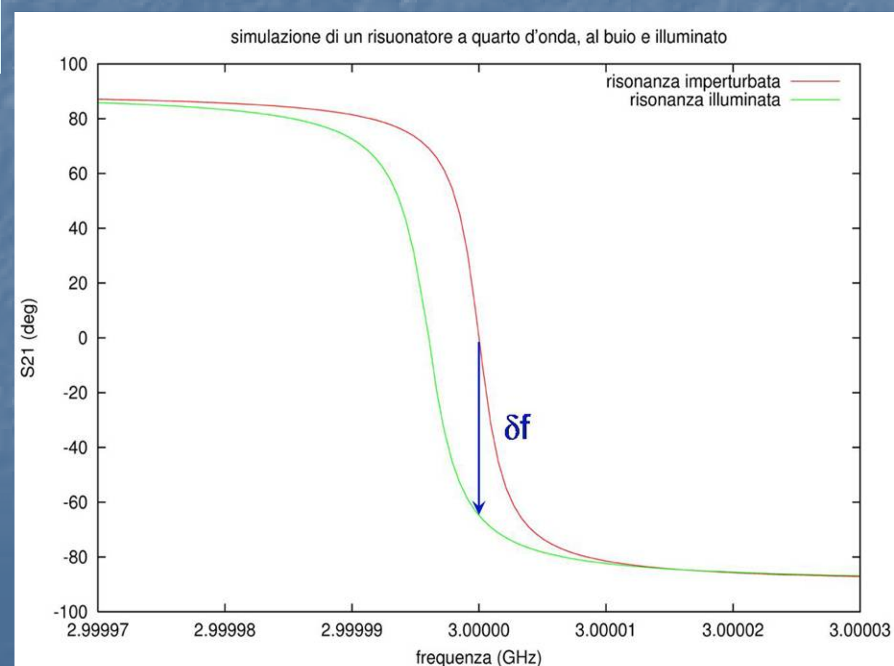




Which are the effects of incoming radiation?

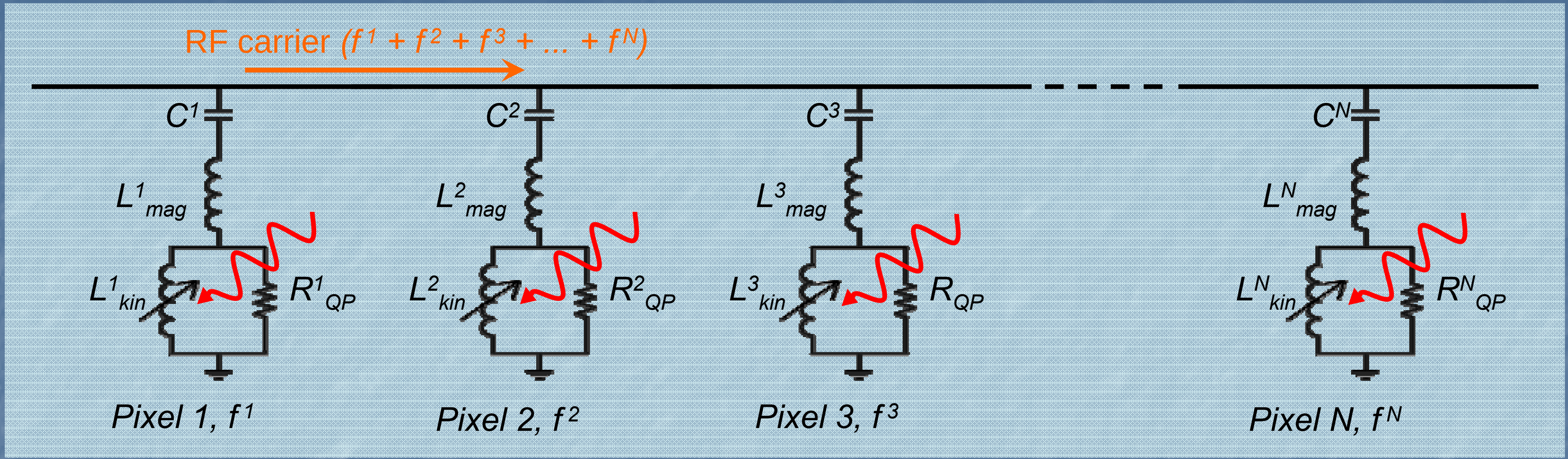






Claudia Giordano + Martino Calvo

The fact that each resonator has no effect even few MHz away from its resonant frequency makes these detectors ideal for *frequency domain multiplexing*:



- order of 10^3-10^4 pixels read with a single coax

➡ ***low thermal load!***

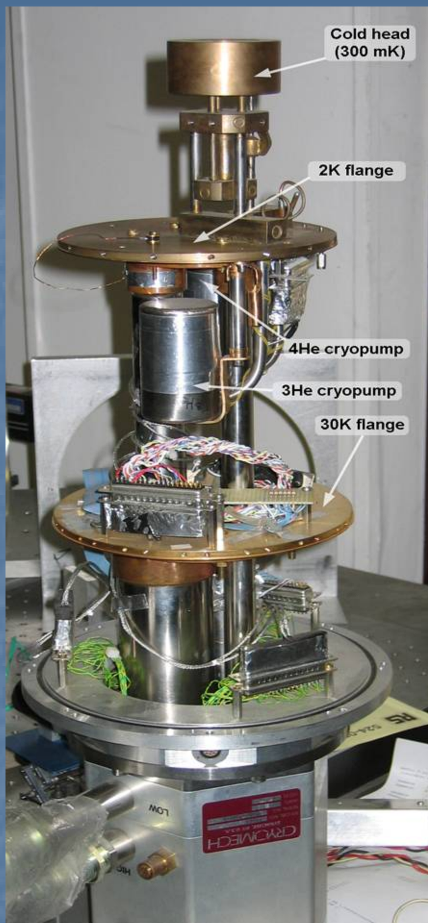
- *Extremely simple cold electronics:* one single amplifier can be used for 10^3-10^4 pixels. The rest of the readout is warm.

- *Very flexible:* different materials and geometries can be chosen to tune detectors to specific needs.

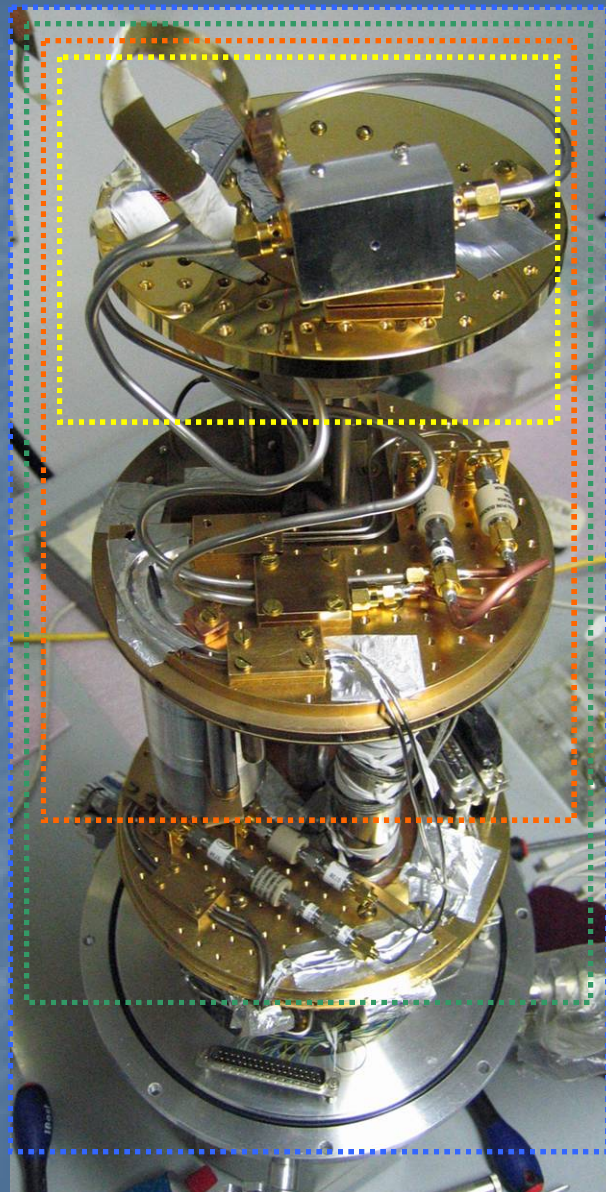
- *Very resistant:* materials are all suitable for satellite and space missions.

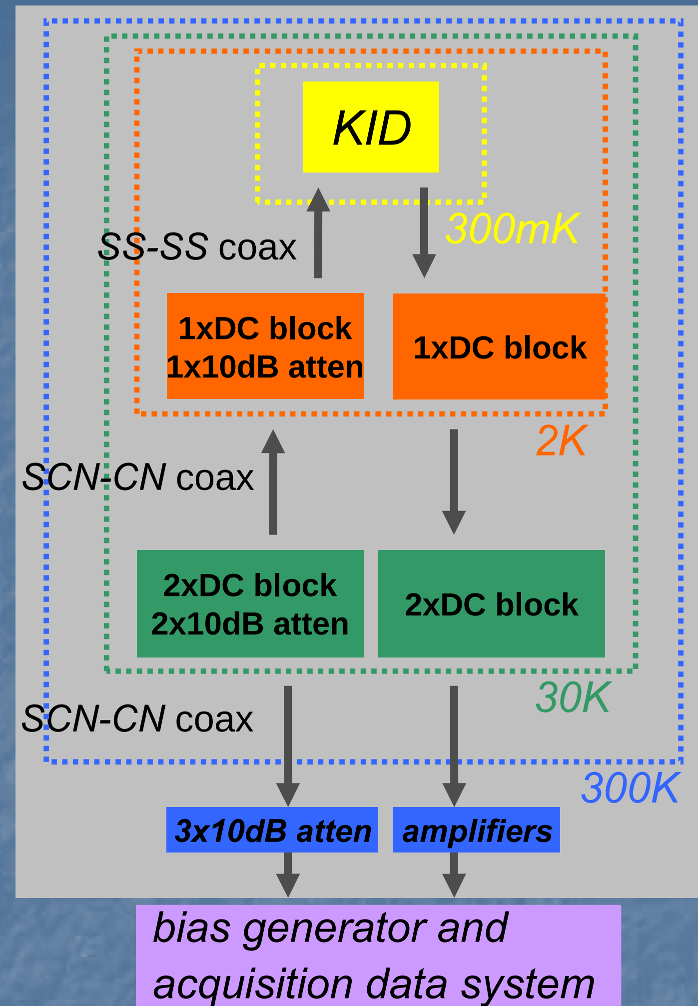
Claudia Giordano + Martino Calvo

KIDs testbench: RIC INFN V



Cryostat modified to have RF ports

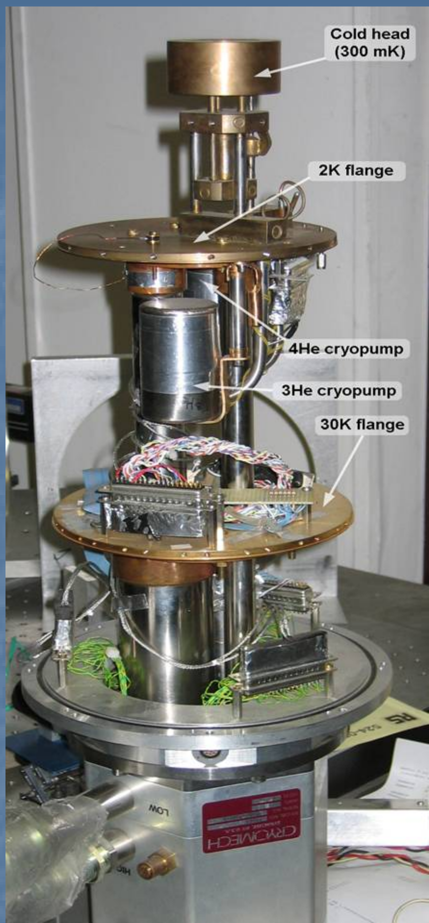




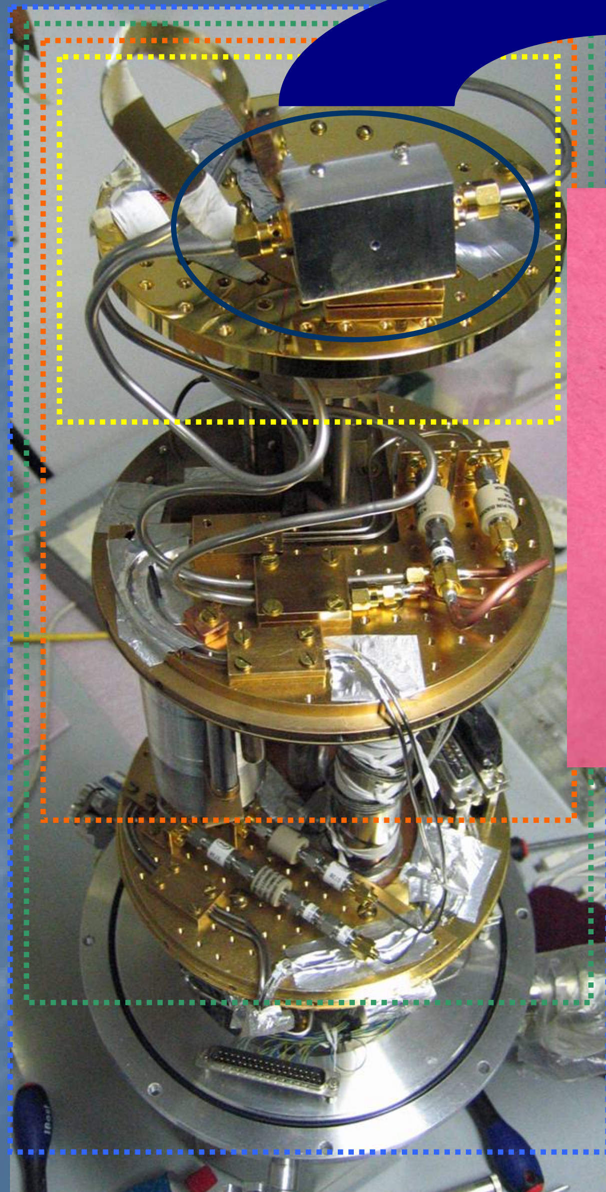
VNA : slower, easier, can give information on the sanity of the whole circuit. Ideal for the first runs.

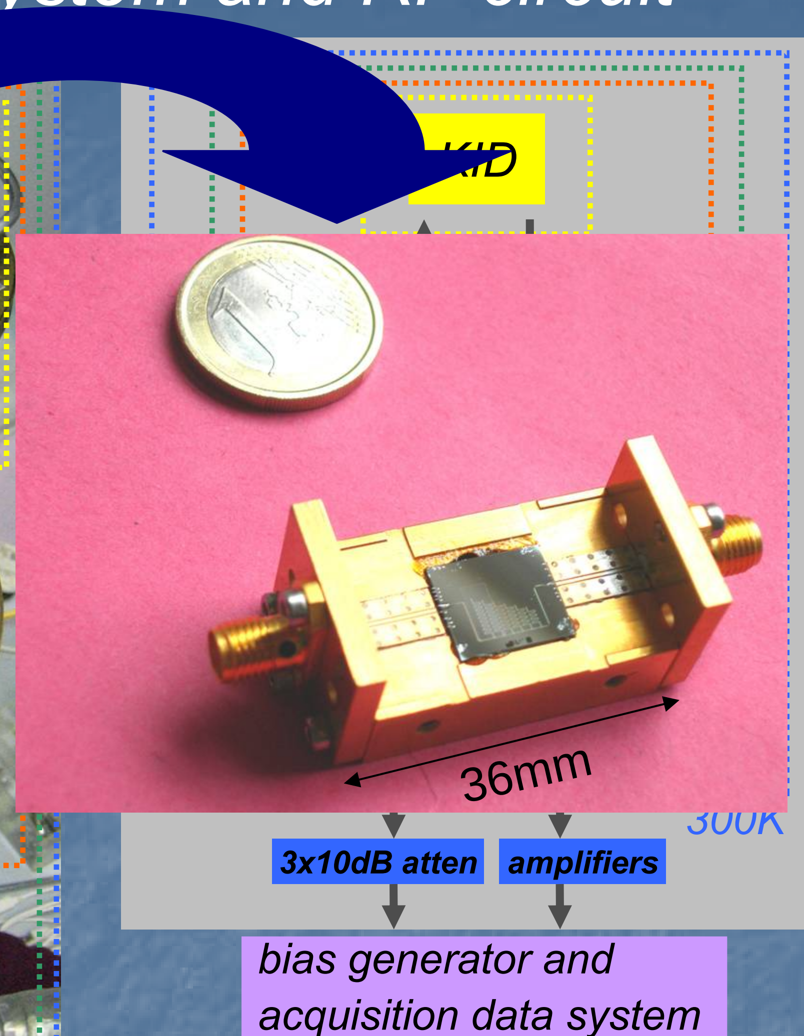
IQ mixers: faster, essential to measure noise, QP lifetime... Need fast acquisition system

KIDs testbench: cryogenic system and RF circuit



Cryostat modified to have RF ports

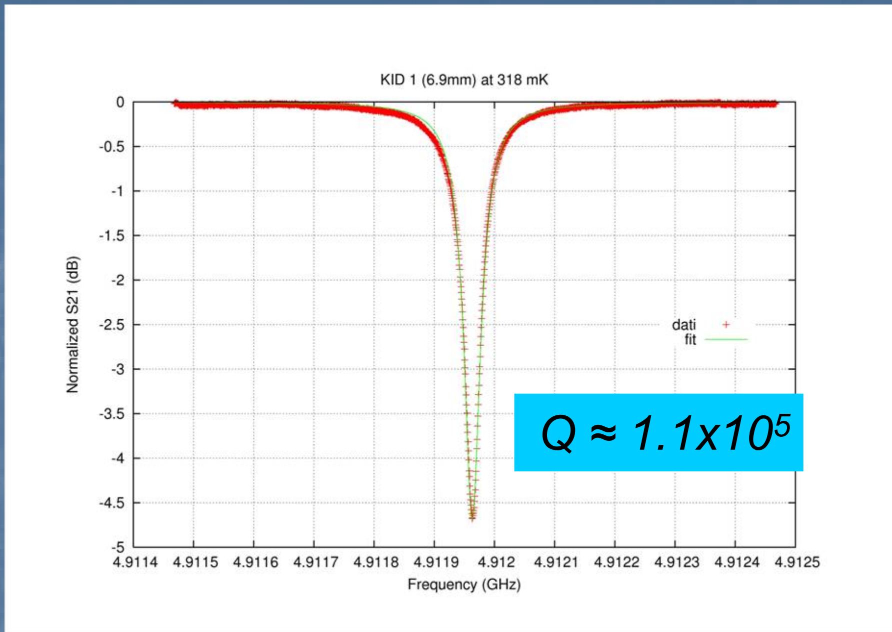


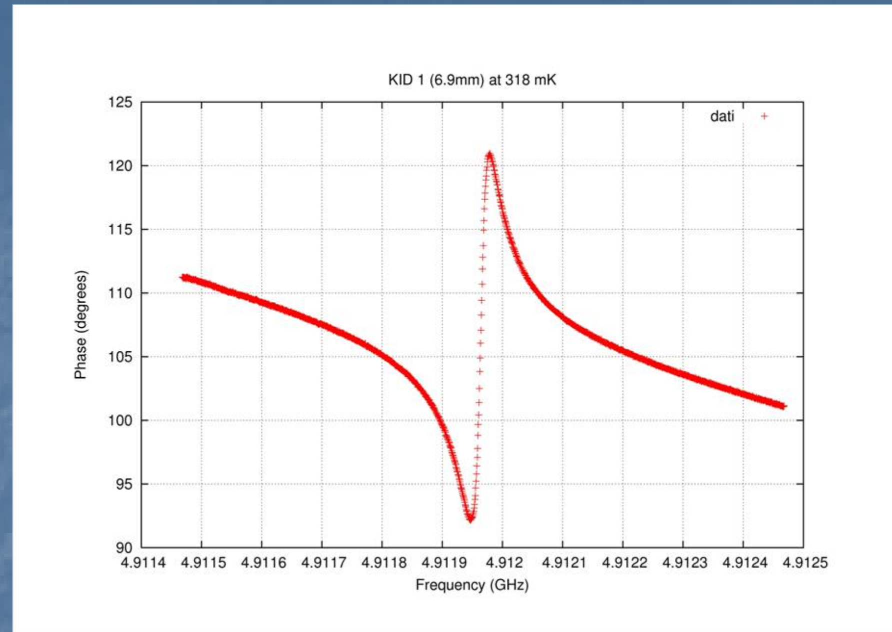


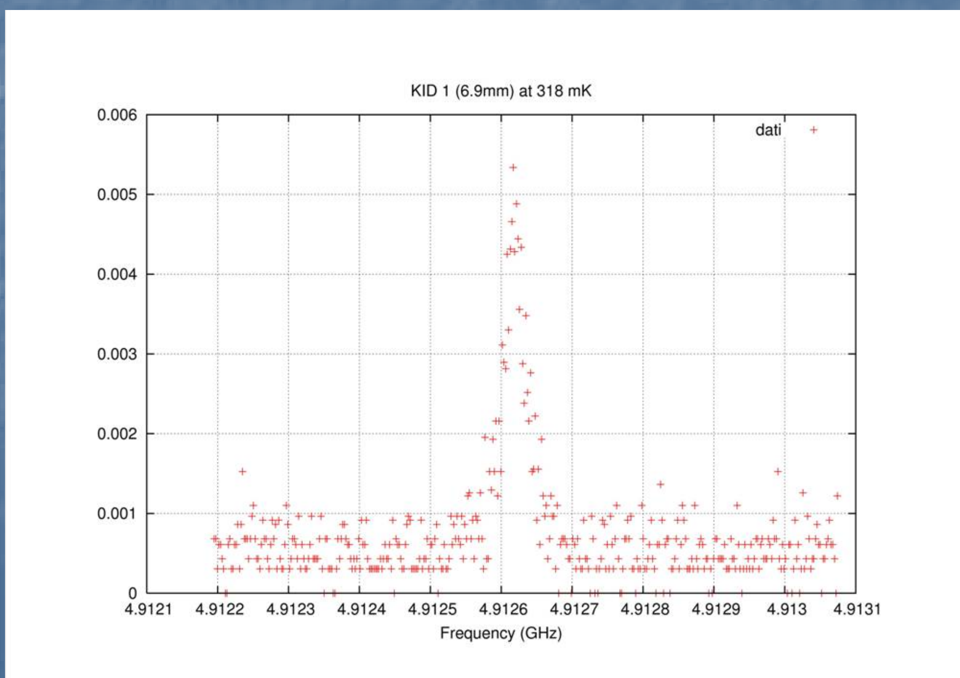
VNA : slower, easier, can give information on the sanity of the whole circuit. Ideal for the first runs.

IQ mixers: faster, essential to measure noise, QP lifetime... Need fast acquisition system

Measurements:



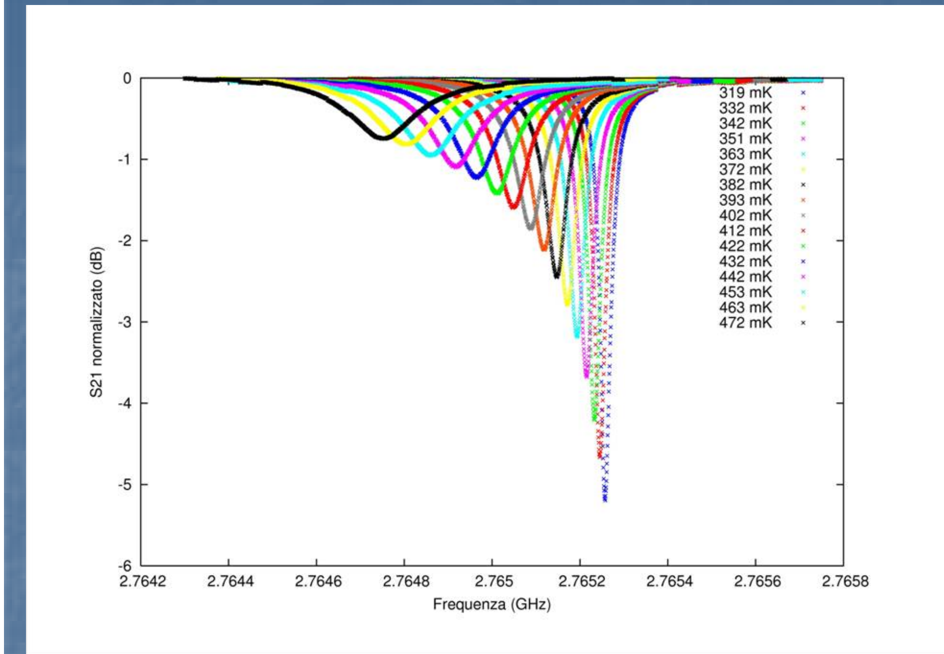


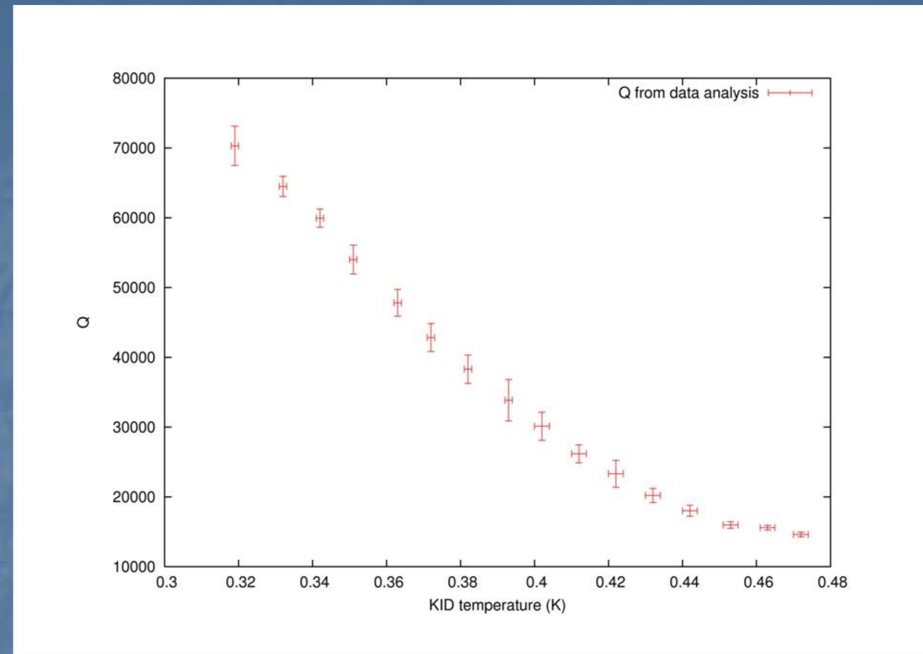


F_{reso} (GHz)	2.76526±0.00002	2.83595±0.00002	2.89025±0.00002
Q	$(7.0\pm0.1)\times10^4$	$(8.0\pm0.2)\times10^4$	$(14.0\pm1.1)\times10^4$
F_{reso} (GHz)	3.29813±0.00002	3.94470±0.00002	4.91196±0.00002
Q	$(14.4\pm0.4)\times10^3$	$(7.2\pm0.1)\times10^4$	$(11.0\pm0.3)\times10^4$

Very high values of Q even at T higher than the ideal one

Variation of f_0 and Q with temperature:





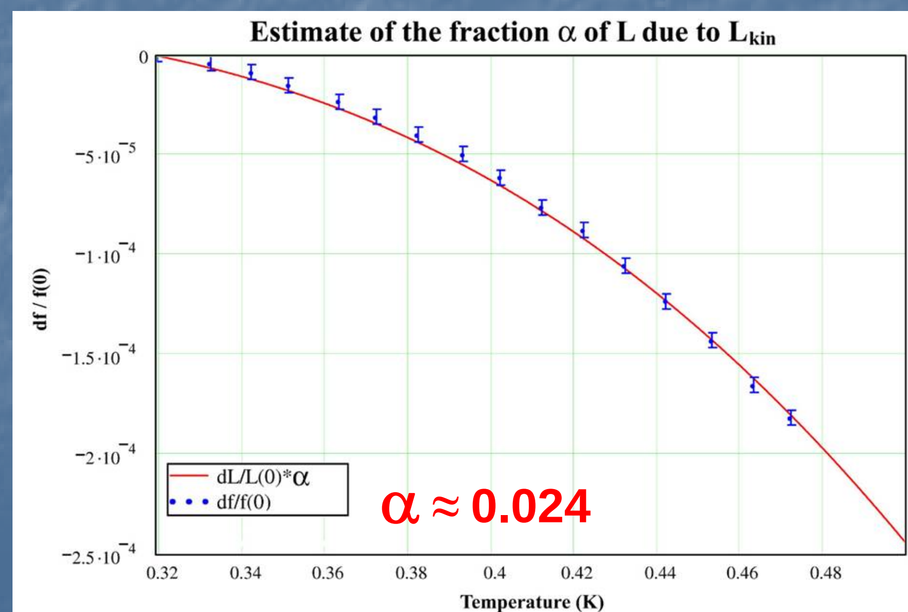
$$f_{reso} \propto \frac{1}{\sqrt{L_{TOT}(T)}}$$

D.C. Mattis and J. Bardeen
Physical Review, July 1958

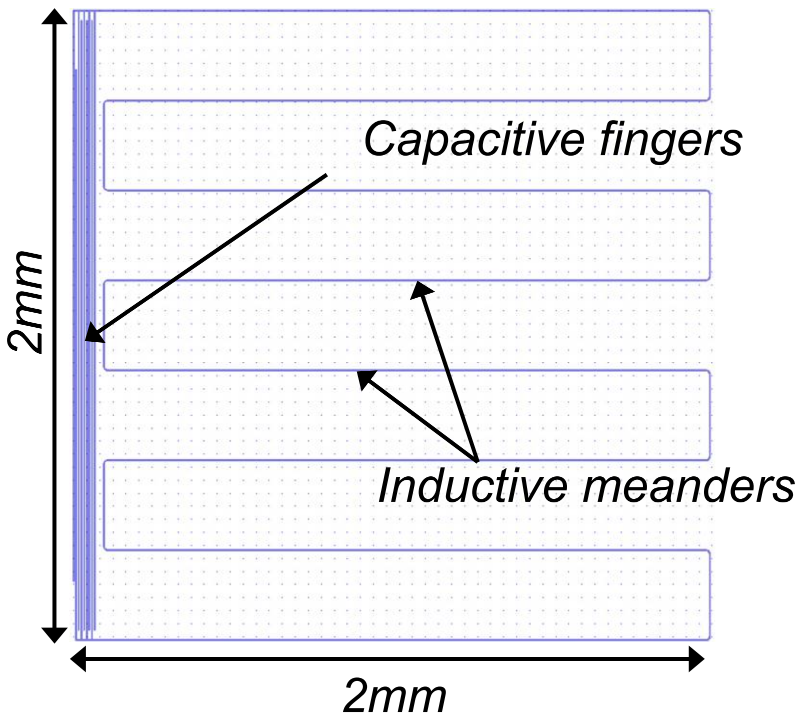
$$\delta f_{reso}(T) \propto -\frac{1}{2}\delta L_{TOT}(T) L_{TOT}(T)^{-3/2}$$

$$\frac{\delta f_{reso}(T)}{f_{reso}(0)} = -\frac{1}{2}\frac{\delta L_{TOT}(T)}{L_{TOT}(0)}$$

$$\alpha = \frac{L_{kin}}{L_{TOT}} \qquad \frac{\delta f_{reso}(T)}{f_{reso}(0)} = -\frac{1}{2}\frac{\alpha \delta L_{kin}(T)}{L_{kin}(0)}$$



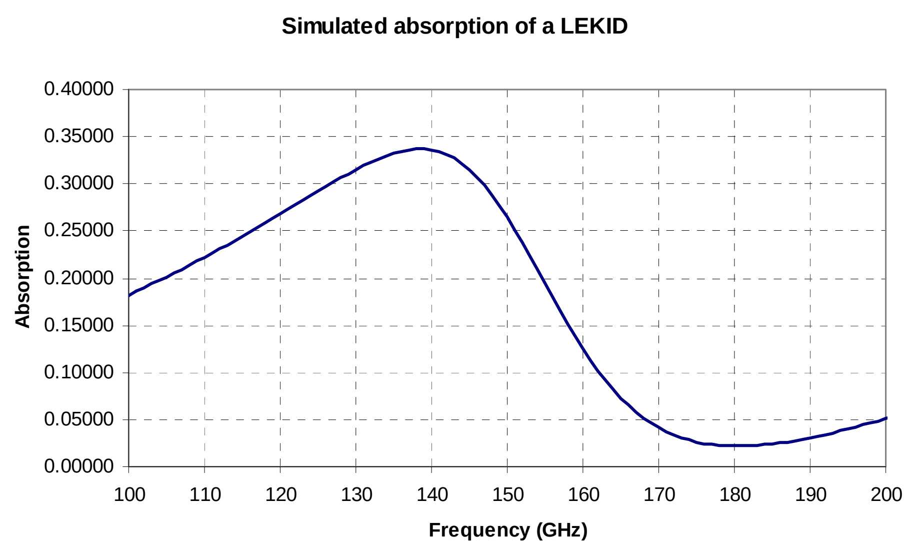
Lumped Elements KID: design and simulations



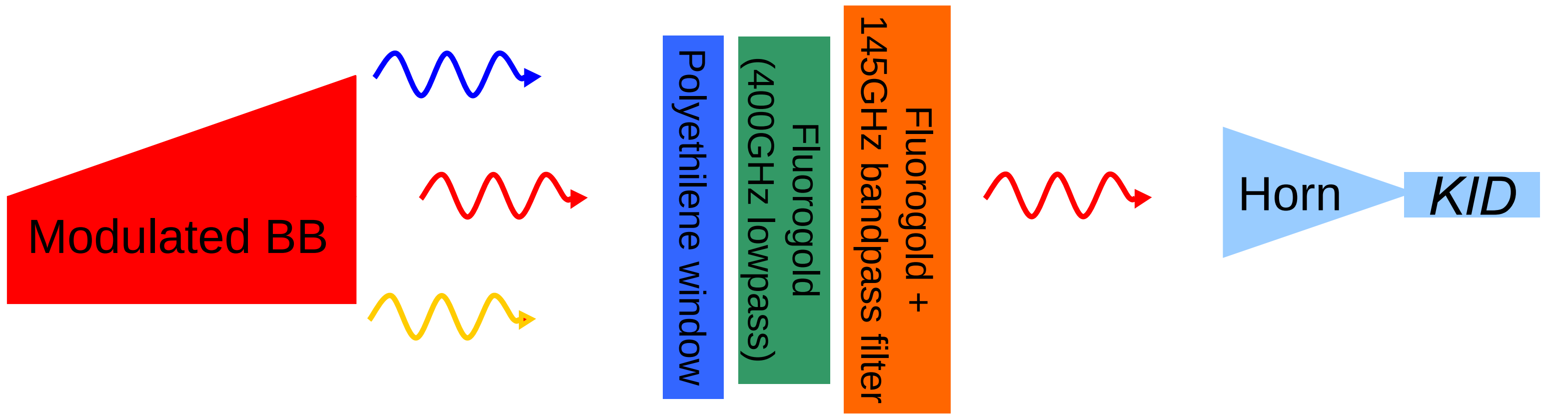
In a LEKID, the resonance is obtained through the effect of lumped inductance and capacitance. The length of the capacitive fingers can be varied to get different values of the resonances, whereas the inductive meanders can be tuned to match the free space impedance

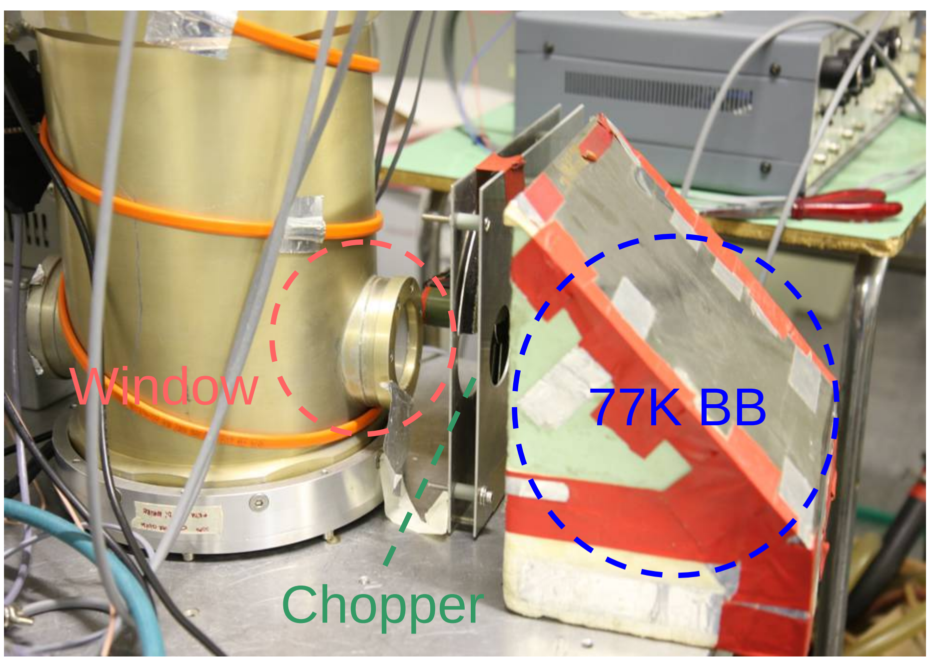
A LEKID is at the same time ***the detector and the absorber!***

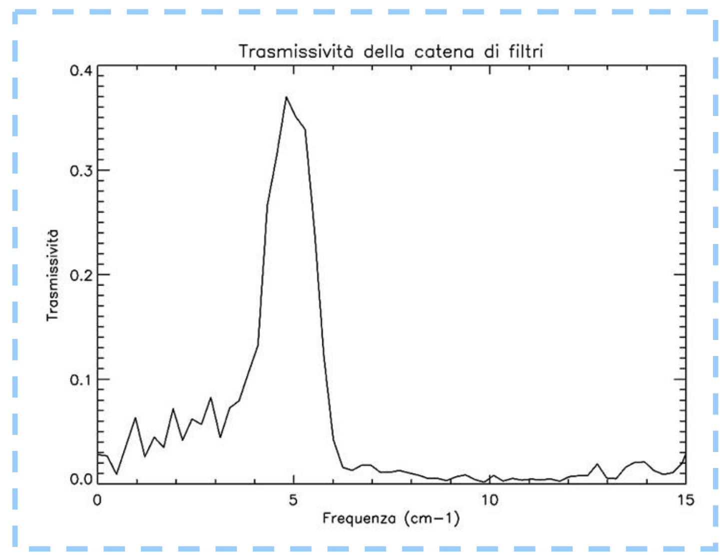
Simulations show the good absorption of the LEKID even when no backshort and no AR coating are used



Optical system setup

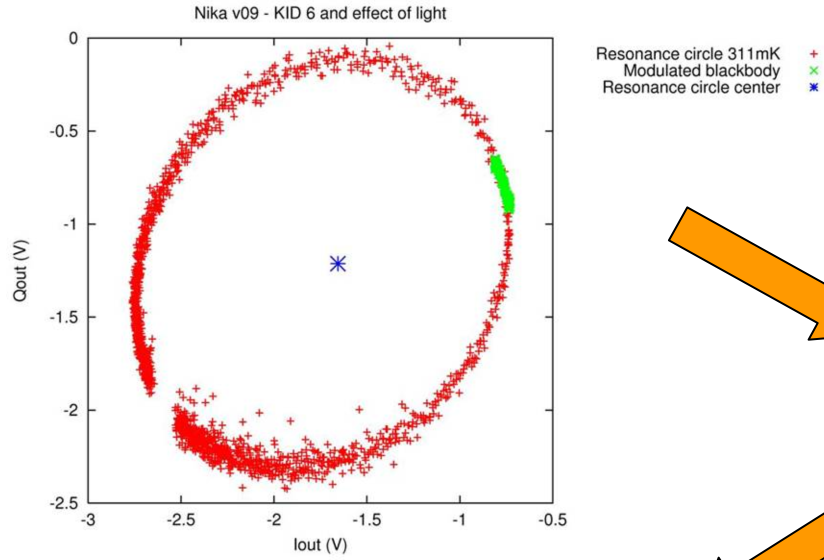




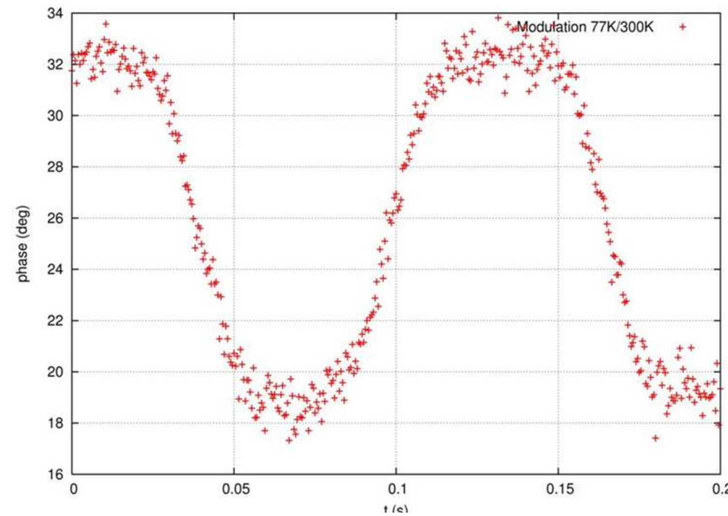


Measurement of 145GHz radiation

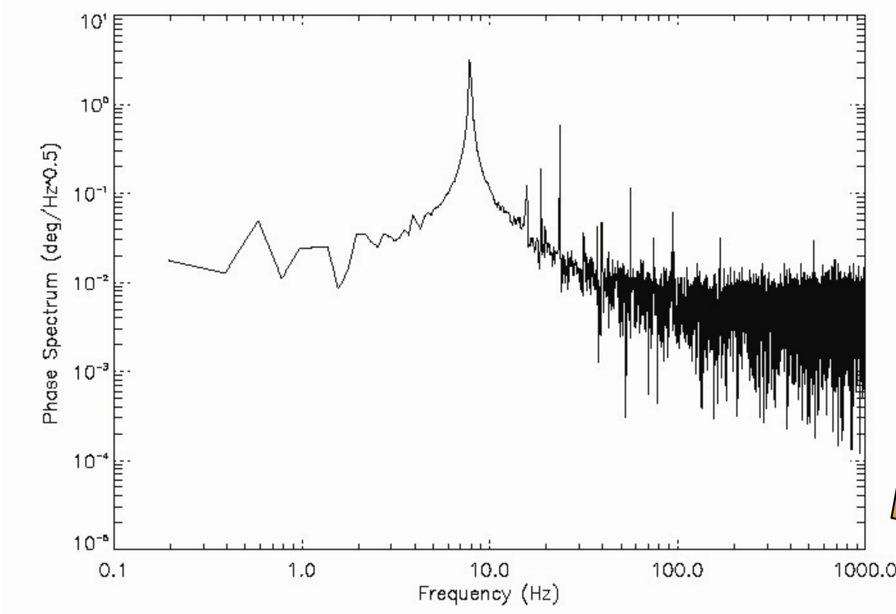
Resonance circle and effect of light



Plot of phase versus time



Phase spectrum



We can get an estimate of the Noise Equivalent Power (*NEP*) by looking at the S/N ratio of the signal and calculating the power absorbed by the KID.

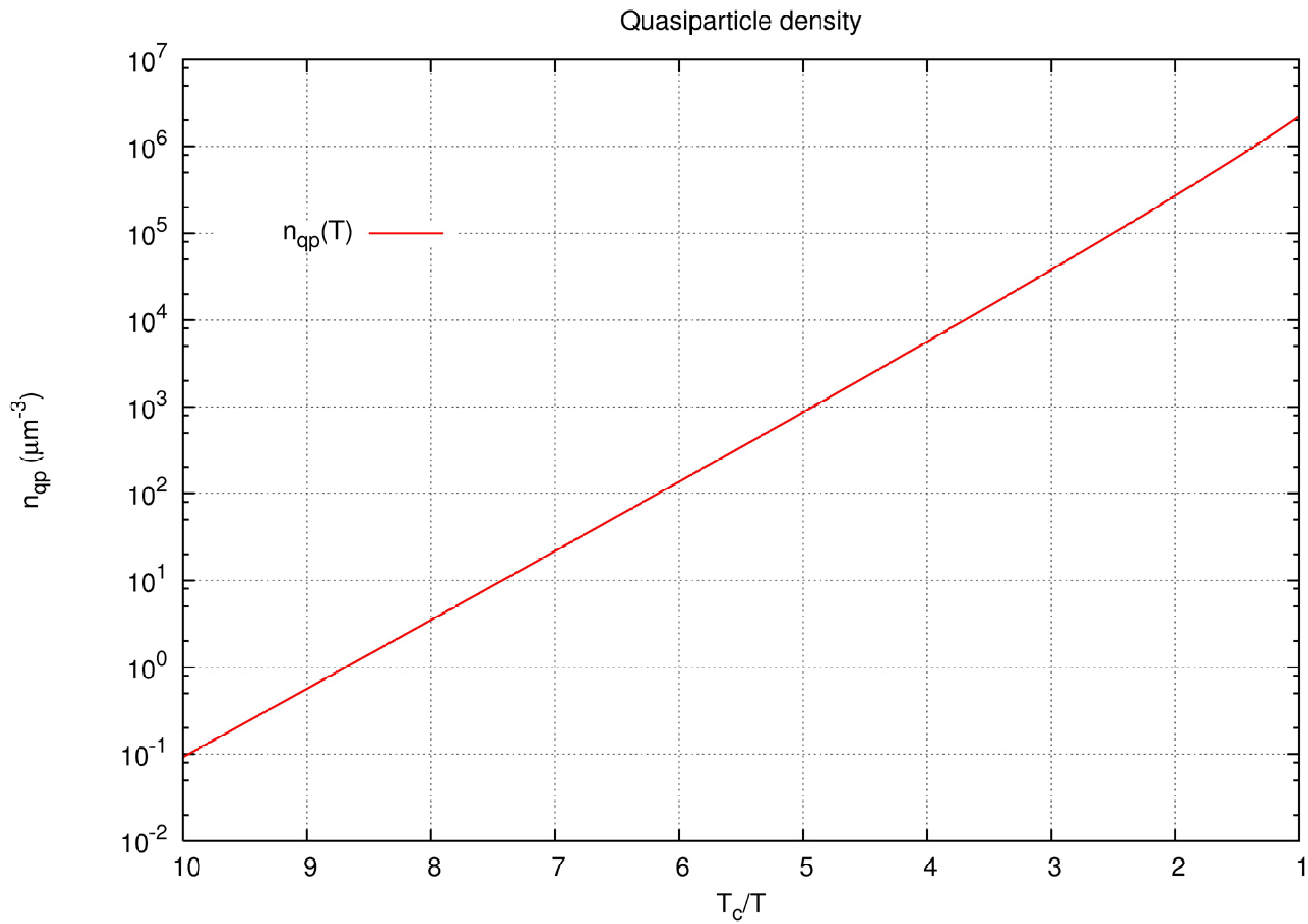
The estimated absorbed power is $P_{abs} \approx 25pW$.

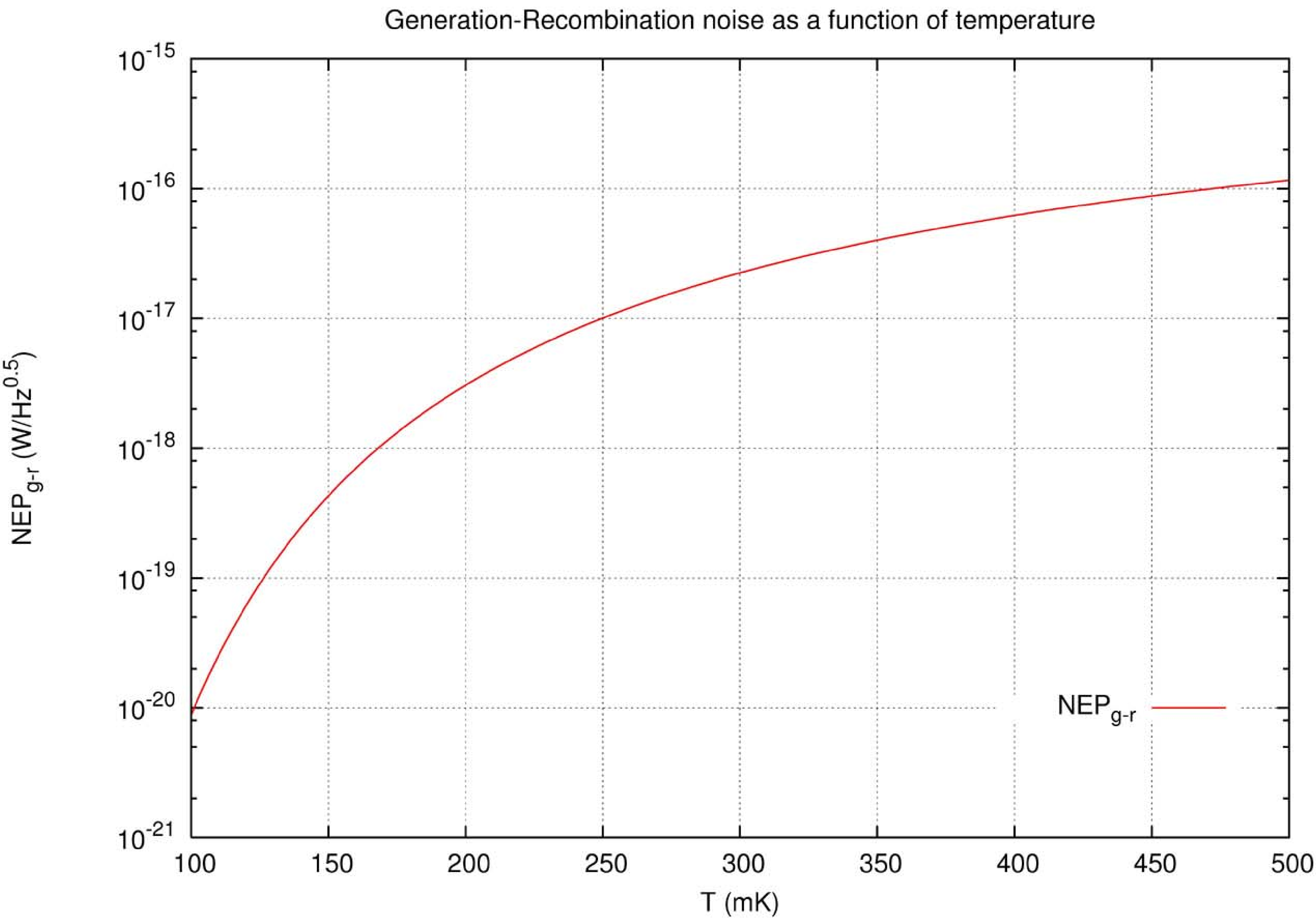
We therefore get a first estimate of the *NEP* at *7Hz* for this detectors:

$$NEP \approx 2 \cdot 10^{-13} W/\sqrt{Hz}$$

Sensitivity Improvements :

• Back-illumination	x 2
• Back-short	x 2
• Quality of Al films	x 10
• Temperature (0.3->0.1K)	> 100 (!)
• Readout Electronics	x 10
• ……	


Quasiparticle density
$n_{qp}(T)$
n_{qp} (μm^{-3})
T_c/T
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10
9
8
7
6
5
4
3
2
1


Generation-Recombination noise as a function of temperature
NEPg-r (W/Hz0.5)
T (mK)
NEPg-r
10-15
10-16
10-17
10-18
10-19
10-20
10-21
100
150
200
250
300
350
400
450
500

Possible Sensitivity Improvements

- Back-illumination x 2 now
- Back-short x 2 now
- Quality of Al films x 10 2 months
- Temperature (0.3->0.1K) > 100 (!) 12 months
- Readout Electronics x 10 12 months
- ……

New cryogenic system (Dilution Refrigerator) ordered.
New readout electronics also ordered.

Cosmological Neutrinos

Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature

$$T_{dec} \approx 1 MeV$$

We then have today a Cosmological Neutrino Background at a temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945 K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

With a density of:

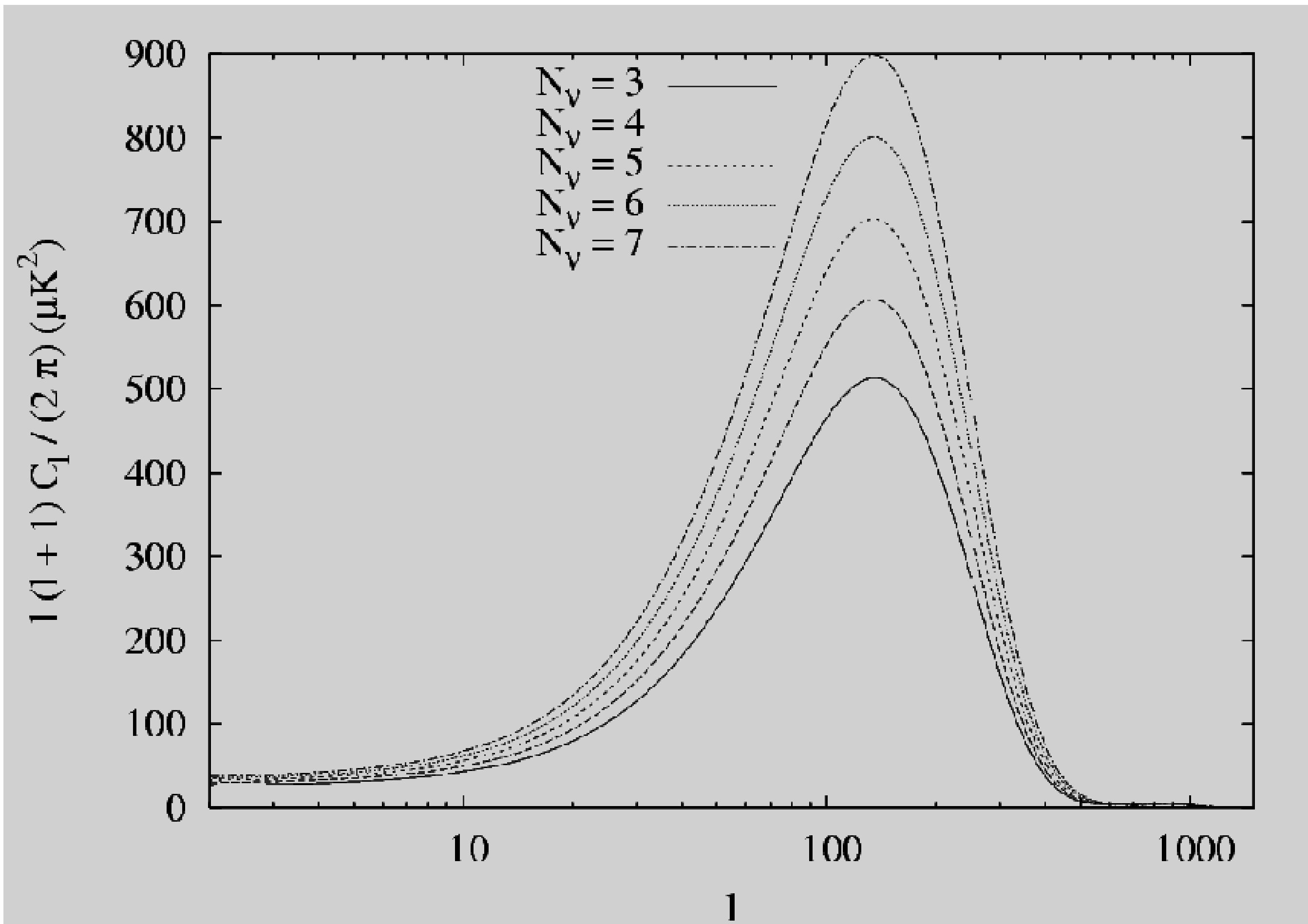
$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

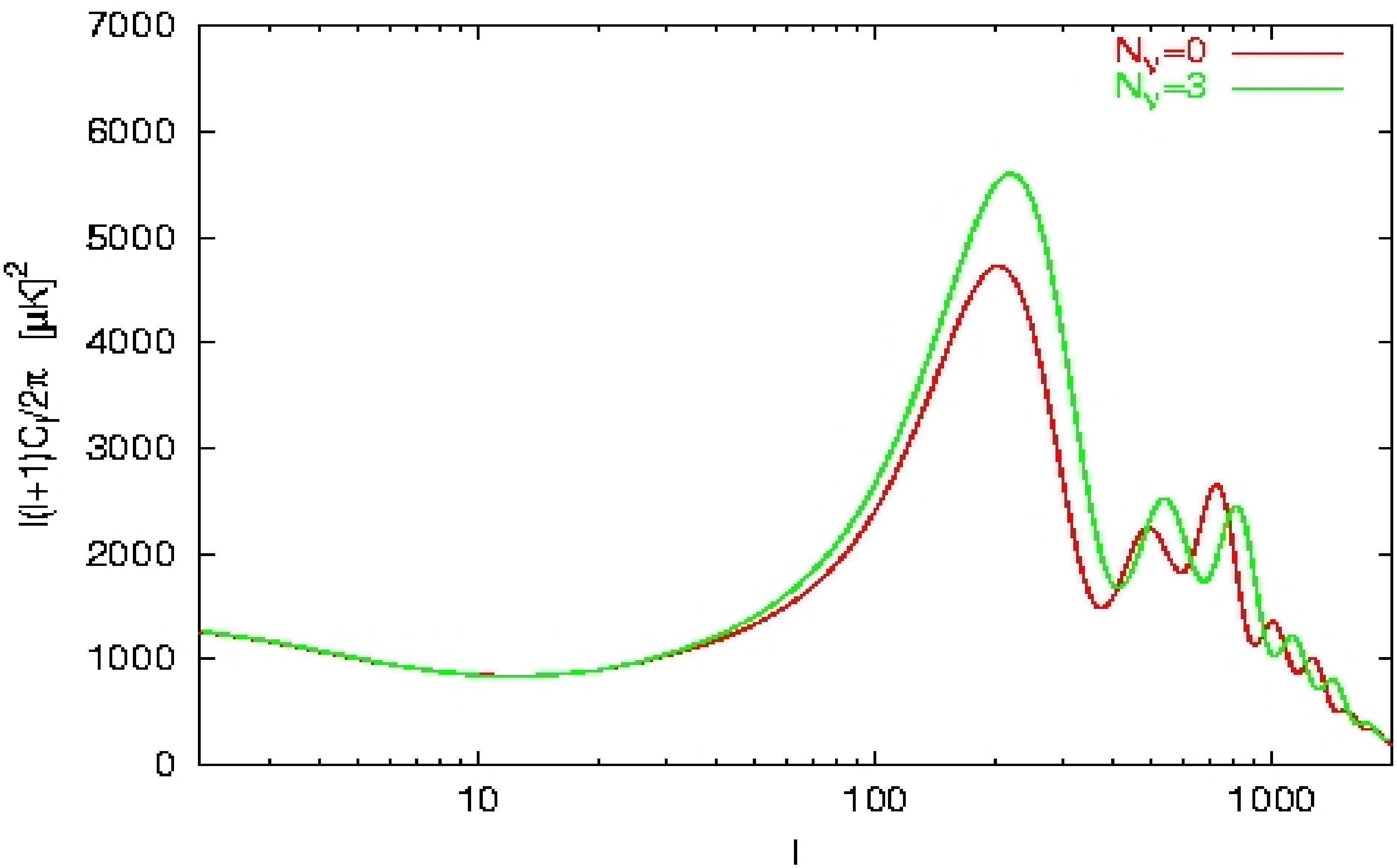
That, for massless neutrinos the total radiation energy density is:

$$\Omega_R = \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_{eff}^\nu\right]\Omega_\gamma$$

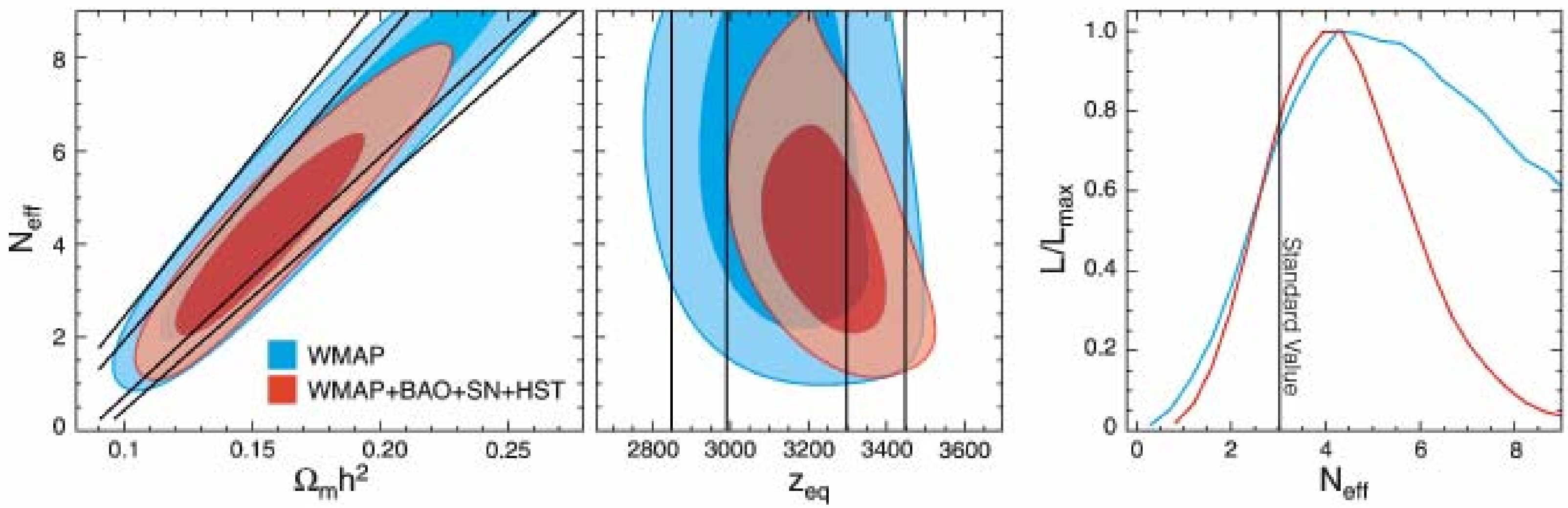
Effect of Radiation in the CMB: Early ISW

Changing the number of neutrinos (assuming them as massless) shifts the epoch of equivalence, increasing the Early ISW:





7000
6000
5000
4000
3000
2000
1000
0
10
100
1000
l
l(l+1)C$_l$/2π [μK]^2
N$_ν$=0
N$_ν$=3



Latest results from WMAP5 $N_{eff}>0$ at 95 % c.l. from CMB DATA alone (Komatsu et al., 2008).

First evidence for a neutrino background from CMB data

Komatsu et al. 2008 WMAP5 paper

(68% and 95% CL), showing a strong degeneracy between $\Omega_m h^2$ and $N_{\rm eff}$. This degeneracy line is given by the equality redshift, $1 + z_{\rm eq} = \Omega_m/\Omega_r = (4.050 \times 10^4)\Omega_m h^2/(1 + 0.2271 N_{\rm eff})$. The thick solid lines show the 68% and 95% limits calculated from the WMAP-only limit on $z_{\rm eq}$: $z_{\rm eq} = 3141^{+154}_{-157}$ (68% CL). The 95% CL contours do not follow the lines below $N_{\rm eff} \sim 1.5$ but close there, which shows a strong evidence for the cosmic neutrino background from its effects on the CMB power spectrum via the neutrino anisotropic stress. The BAO and SN provide an independent constraint on $\Omega_m h^2$, which helps reduce the degeneracy between $N_{\rm eff}$ and $\Omega_m h^2$. (*Middle*) When we transform the horizontal axis of the left panel to $z_{\rm eq}$, we observe no degeneracy. The vertical solid lines show the one-dimensional marginalized 68% and 95% distribution calculated from the WMAP-only limit on $z_{\rm eq}$: $z_{\rm eq} = 3141^{+154}_{-157}$ (68% CL). Therefore, the left panel is simply a rotation of this panel using a relation between $z_{\rm eq}$, $\Omega_m h^2$, and $N_{\rm eff}$. (*Right*) One-dimensional marginalized distribution of $N_{\rm eff}$ from WMAP-only and WMAP+BAO+SN+HST. Note that a gradual decline of the likelihood toward $N_{\rm eff} \gtrsim 6$ for the WMAP-only constraint should not be trusted, as it is affected by the hard prior, $N_{\rm eff} < 10$. The WMAP+BAO+SN+HST constraint is robust. This figure shows that the lower limit on $N_{\rm eff}$ is coming solely from the *WMAP* data. The 68% interval from WMAP+BAO+SN+HST, $N_{\rm eff} = 4.4 \pm 1.5$, is consistent with the standard value, 3.04, which is shown by the vertical line.

The distance information from BAO and SN provides us with an independent constraint on $\Omega_m h^2$, which helps to reduce the degeneracy between $z_{\rm eq}$ and $\Omega_m h^2$.

The anisotropic stress of neutrinos also leaves distinct signatures in the CMB power spectrum, which is not degenerate with $\Omega_m h^2$ (Hu et al. 1995; Bashinsky & Seljak 2004). Trotta & Melchiorri (2005) (see also Melchiorri & Serra 2006) have reported on evidence for the neutrino anisotropic stress at slightly more than 95% CL. They have parametrized the anisotropic stress by the viscosity parameter, $c^2_{\rm vis}$ (Hu 1998), and found $c^2_{\rm vis} > 0.12$ (95% CL). However, they had to combine the *WMAP* 1-year data with the SDSS data to see the evidence for non-zero $c^2_{\rm vis}$.

In Dunkley et al. (2008) we report on the lower limit to $N_{\rm eff}$ solely from the *WMAP* 5-year data. In this paper we shall combine the *WMAP* data with the distance information from BAO and SN as well as Hubble's constant from HST to find the best-fitting value of $N_{\rm eff}$.

6.2.3. *Results*

Figure 18 shows our constraint on $N_{\rm eff}$. The contours in the left panel lie on the expected linear correlation between $\Omega_m h^2$ and $N_{\rm eff}$ given by

$$N_{\rm eff} = 3.04 + 7.44\left(\frac{\Omega_m h^2}{0.1308}\frac{3139}{1+z_{\rm eq}} - 1\right), \qquad (84)$$

which follows from equation (83). (Here, $\Omega_m h^2 = 0.1308$ and $z_{\rm eq} = 3138$ are the maximum likelihood values from the simplest ΛCDM model.) The width of the degeneracy line is given by the accuracy of our determination of $z_{\rm eq}$, which is given by $z_{\rm eq} = 3141^{+154}_{-157}$ (WMAP-only) for this model. Note that the mean value of $z_{\rm eq}$ for the simplest ΛCDM model with $N_{\rm eff} = 3.04$ is $z_{\rm eq} = 3176^{+151}_{-150}$, which is close. This confirms that $z_{\rm eq}$ is one of the fundamental observables, and $N_{\rm eff}$ is merely a secondary parameter that can be derived from $z_{\rm eq}$. The middle panel of Fig. 18 shows this clearly: $z_{\rm eq}$ is determined independently of $N_{\rm eff}$. For each value of $N_{\rm eff}$ along a constant $z_{\rm eq}$ line, there is a corresponding $\Omega_m h^2$ that gives the same value of $z_{\rm eq}$ along the line.

However, the contours do not extend all the way down to $N_{\rm eff} = 0$, although equation (84) predicts that $N_{\rm eff}$ should go to zero when $\Omega_m h^2$ is sufficiently small. This indicates that we are seeing the effect of the neutrino anisotropic stress at a high significance. While we need to repeat the analysis of Trotta & Melchiorri (2005) in order to prove that our finding of $N_{\rm eff} > 0$ comes from the neutrino anisotropic stress, we believe that there is a strong evidence that we see non-zero $N_{\rm eff}$ via the effect of neutrino anisotropic stress, rather than via $z_{\rm eq}$.

While the *WMAP* data alone can give a lower limit on $N_{\rm eff}$ (Dunkley et al. 2008), they cannot give an upper limit owing to the strong degeneracy with $\Omega_m h^2$. Therefore, we use the BAO, SN, and HST data to break the degeneracy. We find $N_{\rm eff} = 4.4 \pm 1.5$ (68%) from WMAP+BAO+SN+HST, which is fully consistent with the standard value, 3.04 (see the right panel of Fig. 18).

7. CONCLUSION

With 5 years of integration, the *WMAP* temperature and polarization data have improved significantly. An improved determination of the third acoustic peak has enabled us to reduce the uncertainty in the amplitude of matter fluctuation, parametrized by σ_8, by a factor of 1.4 from the *WMAP* 3-year result. The E-mode polarization is now detected at 5 standard deviations (c.f., 3.0 standard deviations for the 3-year data; Page et al. 2007), which rules out an instantaneous reionization at $z_{\rm reion} = 6$ at the 3.5σ level. Overall, the *WMAP* 5-year data continue to support the simplest, 6-parameter

NEWS

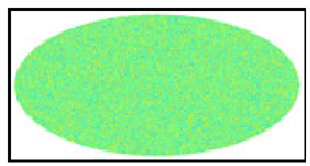
Neutrino ripples spotted in space

Mark Peplow

Universal lumpiness is imprinted in mysterious particles.

Astronomers have spotted a signature of neutrinos created just seconds after the Big Bang.

The find supports current models of the origins of our Universe, and may provide a glimpse of its birth.



This image shows the neutrinos' tiny influence on the cosmic background radiation. Click here to see enlarged picture.

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EXTERNAL LINKS

WMAP

Cosmological Neutrinos

Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature

$$T_{dec} \approx 1MeV$$

We then have today a Cosmological Neutrino Background at a temperature:

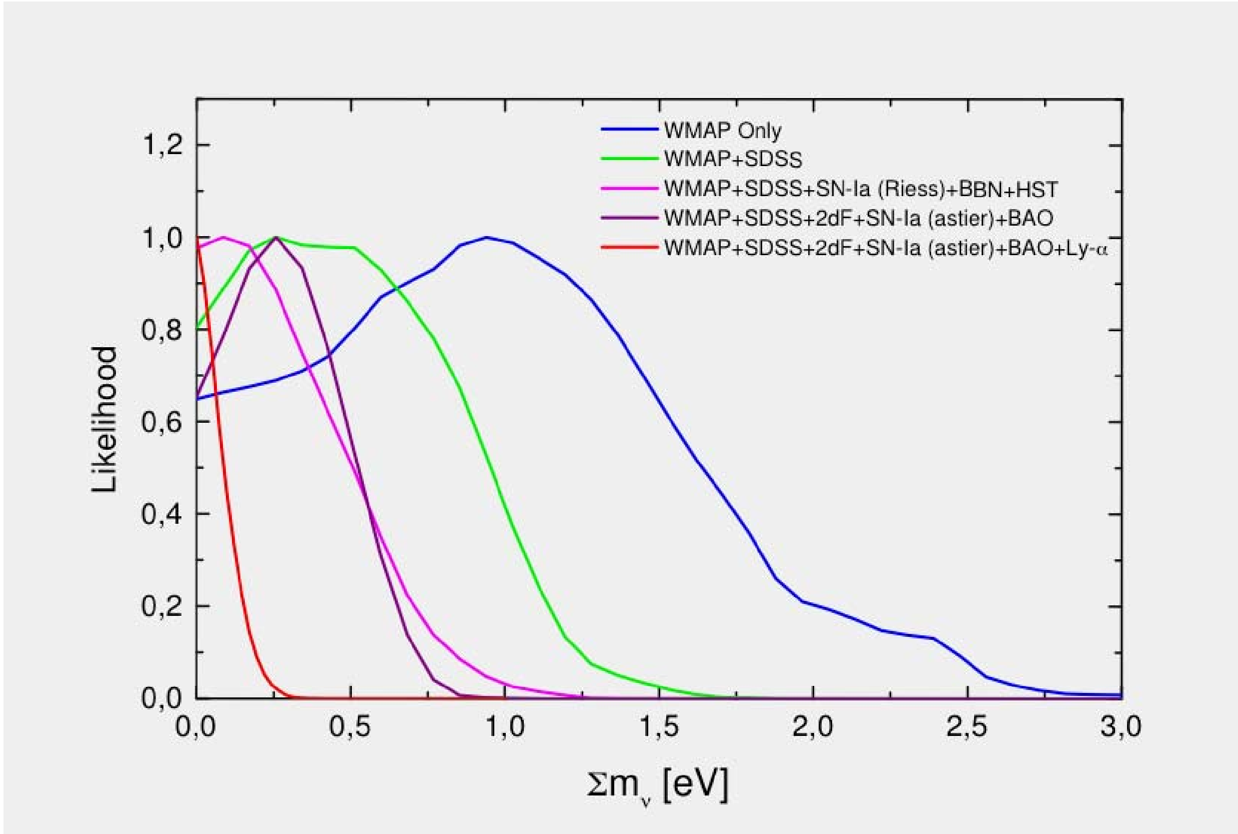
$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

With a density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

That, for a massive neutrino translates in:

$$\Omega_k = \frac{n_{\nu_k,\bar{\nu}_k} m_k}{\rho_c} \approx \frac{1}{h^2}\frac{m_k}{92.5eV} \Rightarrow \Omega_\nu h^2 = \frac{\sum_k m_k}{92.5eV}$$



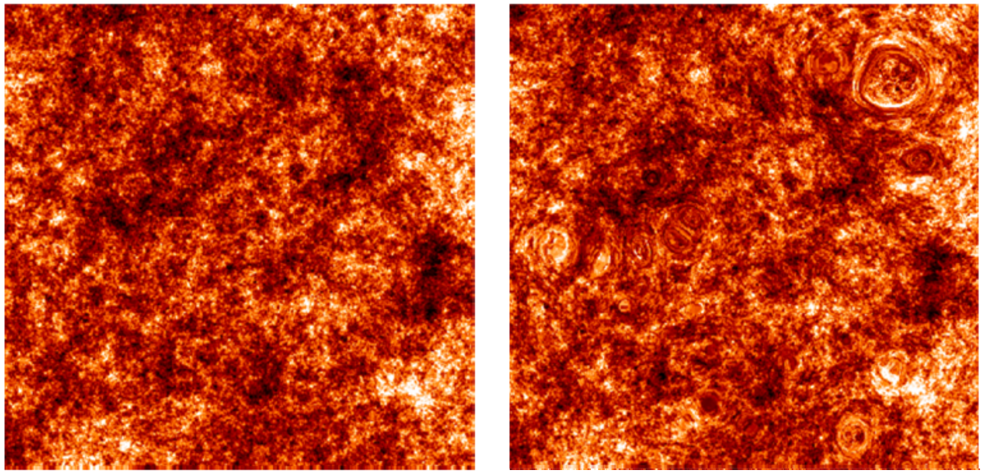
Bounds on Σ for increasingly rich data sets (assuming 3 Active Neutrino model):

Case	Cosmological data set	Σ bound (2σ)
1	WMAP	< 2.3 eV
2	WMAP + SDSS	< 1.2 eV
3	WMAP + SDSS + SN_{Riess} + HST + BBN	< 0.78 eV
4	CMB + LSS + SN_{Astier}	< 0.75 eV
5	CMB + LSS + SN_{Astier} + BAO	< 0.58 eV
6	CMB + LSS + SN_{Astier} + Ly-α	< 0.21 eV
7	CMB + LSS + SN_{Astier} + BAO + Ly-α	< 0.17 eV

Fogli et al., Phys. Rev. D 75, 053001 (2007)

When the luminous source is the CMB, the lensing effect essentially re-maps the temperature field according to :

$$\begin{aligned}\tilde{\Theta}(\boldsymbol{x}) &= \Theta(\boldsymbol{x}') = \Theta(\boldsymbol{x}+\boldsymbol{\alpha}) = \Theta(\boldsymbol{x}+\nabla\psi) \\ &\approx \Theta(\boldsymbol{x}) + \nabla^a\psi(\boldsymbol{x})\nabla_a\Theta(\boldsymbol{x}) + \\ &\quad +\frac{1}{2}\nabla^a\psi(\boldsymbol{x})\nabla^b\psi(\boldsymbol{x})\nabla_a\nabla_b\Theta(\boldsymbol{x}) + \ldots\end{aligned}$$



unlensed **lensed**

95% c.l. limits on neutrino masses from CMB weak lensing (in eV)

Tirspectrum sensitivity

OLIMPO	$0.34\ eV$
Planck + OLIMPO	$0.13\ eV$
2000 detectors)	$0.032\ eV$

E. Calabrese et al.,In preparation

Stay tuned !