The
Cosmic Microwave Background

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The legacy of Edoardo Amaldi
in Science and Society

Roma, 24/Oct/2008

- In 1981 the Physics Department of University of Rome La Sapienza called Francesco Melchiorri as a professor of Astrophysics. Edoardo Amaldi had an important part in this decision.
- Francesco Melchiorri at that time was a CNR researcher, at IROE in Firenze, teaching the class of Observational Astrophysics at the University of Firenze. He was a pioneer of Cosmic Microwave Background research.
- Myself and Silvia Masi were student of his class, fascinated by the possibility to study cosmology in a quantitative way, with direct measurements of the early universe.
- In 1980 we had participated in a balloon flight campaign with launches from Trapani, helping to setup Francesco’s experiment ULISSE: one of the first searches of CMB anisotropy at intermediate angular scales.

- So, when Francesco moved to Rome we followed him.
- For a few months, the experimental activities of the group were hosted in the G23 laboratory. It was a very good period for us.
- The young researchers of Amaldi’s group helped us continuously, and we soon became good friends: Gabriella Castellano, Carlo Cosmelli, Valeria Ferrari, Sergio Frasca, Piero Rapagnani, Fulvio Ricci, had always some new trick to teach or some component to loan.
- Even outside the laboratory we had the opportunity to meet and have fun…
- At that epoch experimental CMB was still at the beginning, but Amaldi had a strong opinion in favour of it, probably forecasting its future growth, and supported Francesco in many ways, despite of the exotic appearence of CMB research.

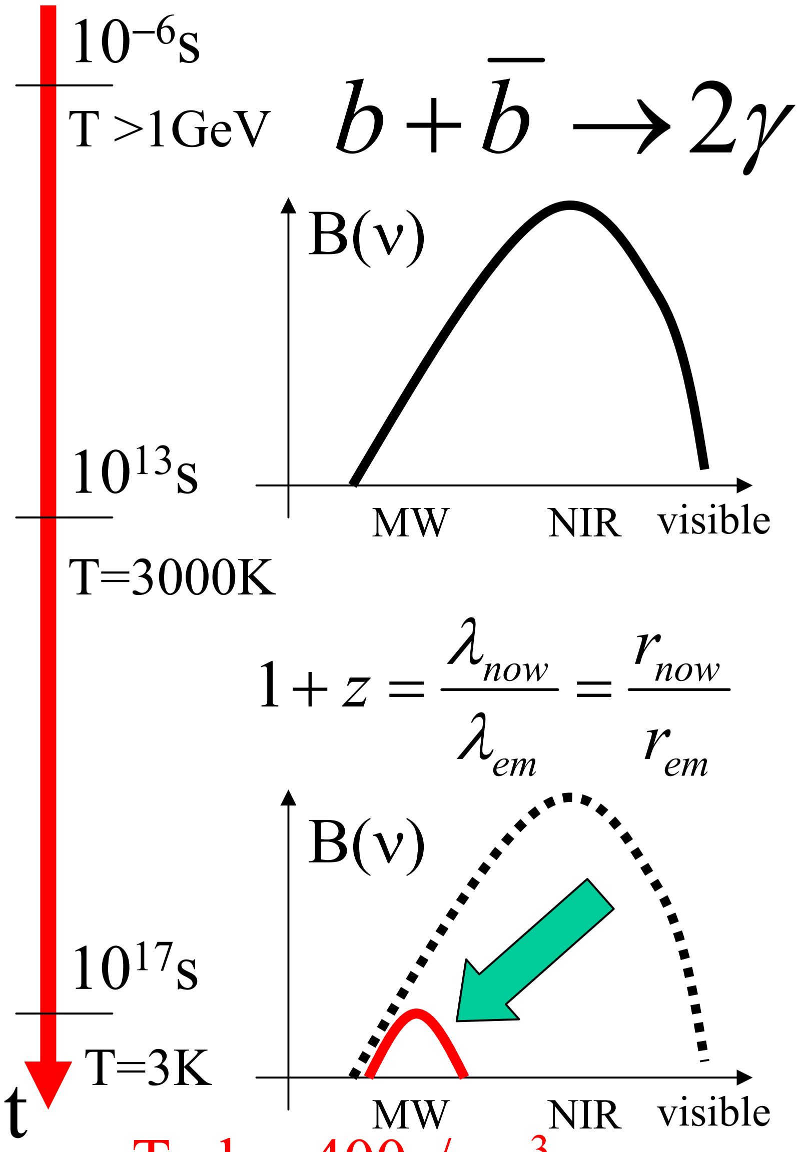
1984

1988

1992

What is the CMB

According to modern cosmology:



$$b+\bar{b}\rightarrow 2\gamma$$

$$1+z=\frac{\lambda_{now}}{\lambda_{em}}=\frac{r_{now}}{r_{em}}$$

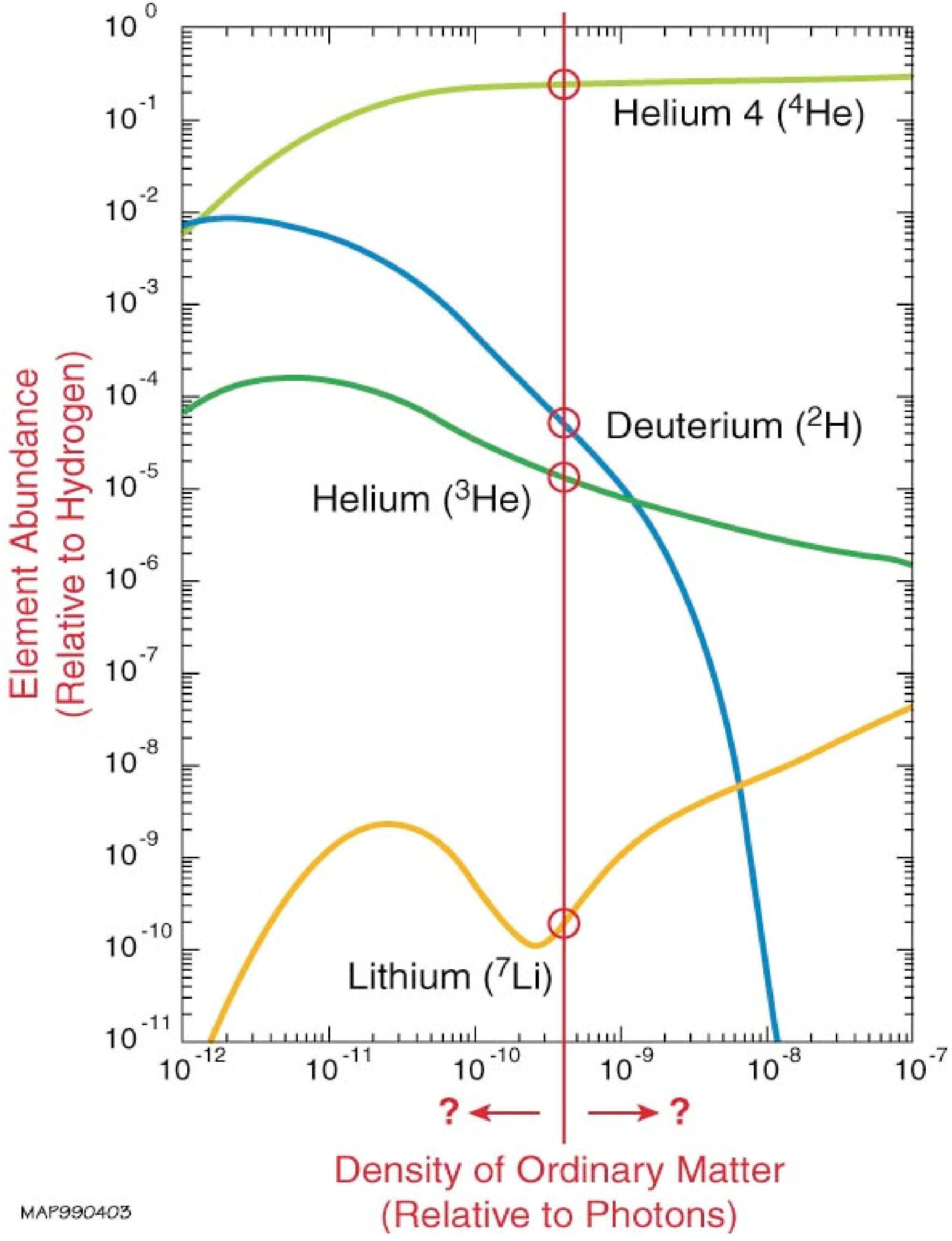
Today $400\gamma/\text{cm}^3$

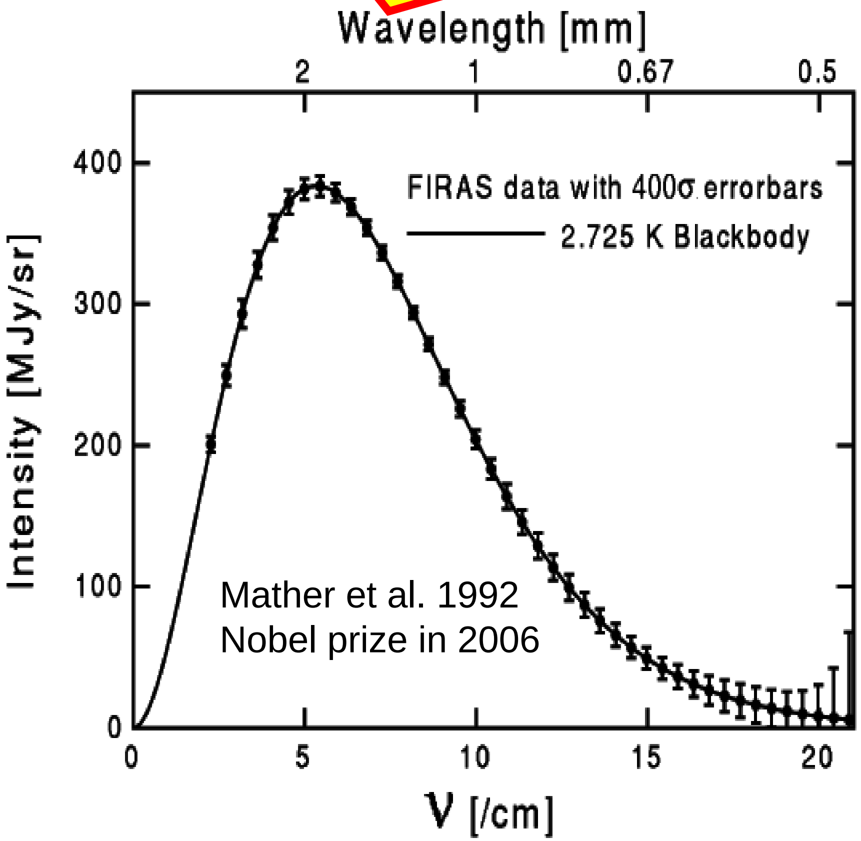
An abundant background of photons filling the Universe.

- **Generated** in the very early universe, less than 4 μs after the Big Bang ($10^9\gamma$ for each baryon) from a small $b-\bar{b}$ asymmetry
- **Thermalized** in the primeval fireball (in the first 380000 years after the big bang) by repeated scattering against free electrons
- **Redshifted** to microwave frequencies (z_{CMB}=1100) **and diluted** in the subsequent 14 Gyrs of expansion of the Universe

Primeval Fireball

Evidence
for an early
hot phase

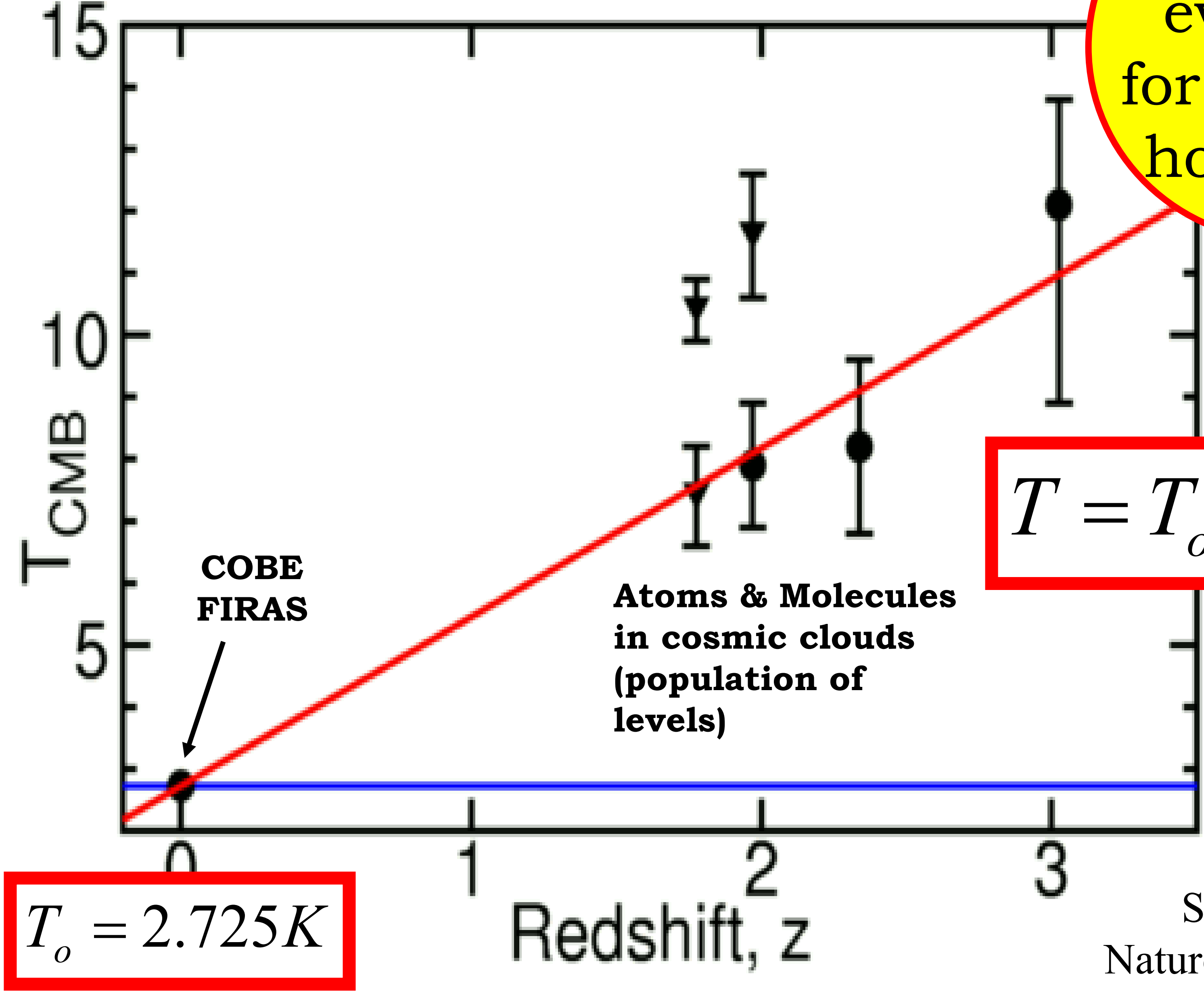




Mather et al. 1992
Nobel prize in 2006

$$\boxed{T_o = 2.725K}$$

Primeval Fireball



Additional evidence for an early hot phase

COBE FIRAS

Atoms & Molecules in cosmic clouds (population of levels)

$$T = T_o(1+z)$$

$$T_o = 2.725K$$

Srinand et al.
Nature 408 931 (2000)

T_ν vs T_γ

- Neutrinos have lost contact with the plasma slightly before annihilation of electrons and positrons, when the temperature of the cosmic plasma was of the order of the electron mass.
- So neutrinos do not inherit any of the associated energy. The photons, instead, do, and are therefore hotter than the neutrinos.
- Imposing that the total entropy density $s = \frac{\rho + p}{T}$ scales as a^{-3}, it can be shown that

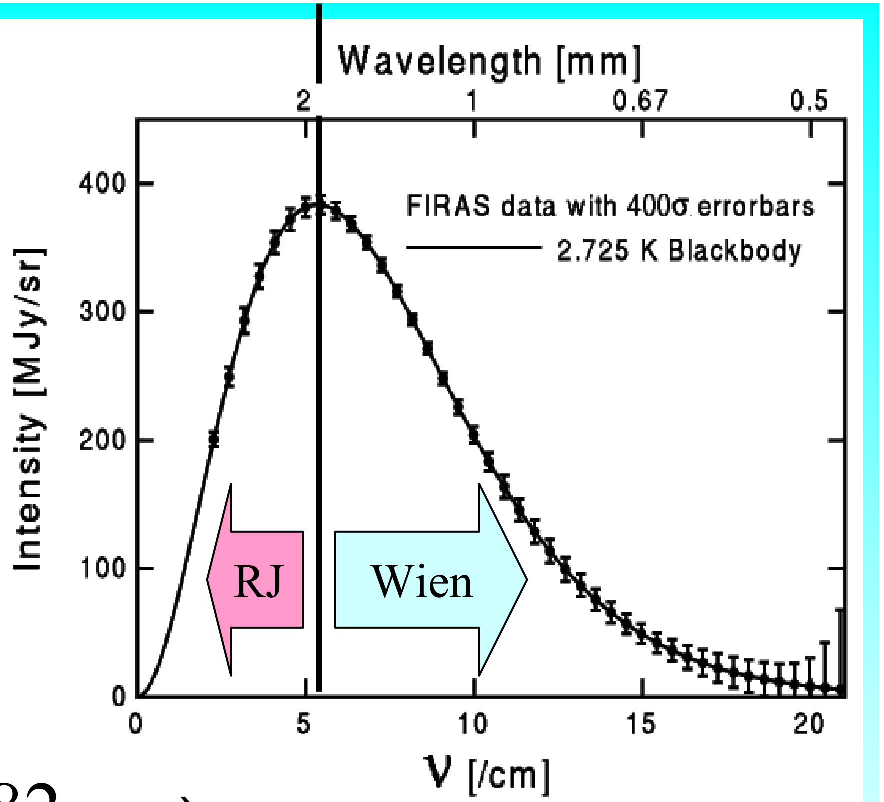
$$\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{\frac{1}{3}} \quad \rightarrow \quad \boxed{T_\nu = 1.94K}$$

- **The CMB :**

$$\boxed{B(\nu,T)=\frac{2h}{c^2}\frac{\nu^3}{e^x-1}}$$

$$T_{CMB}=2.725K$$

$$x_{CMB}=\frac{h\nu}{kT_{CMB}}\cong\frac{\nu}{56\;GHz}$$



$$1-e^{-x_{\max}}=\frac{x_{\max}}{3}\quad\Rightarrow x_{\max}=2.82\quad\Rightarrow$$

$$\nu_{\max}=159\;GHz\quad(\sigma_{\max}=5.31\,cm^{-1})$$

$$B(\nu,T)=\frac{\lambda}{\nu}B(\lambda,T)\quad\Rightarrow\quad\lambda_{\max}=1.06\;mm$$

- $E(\gamma_{CMB}) < 1$ meV

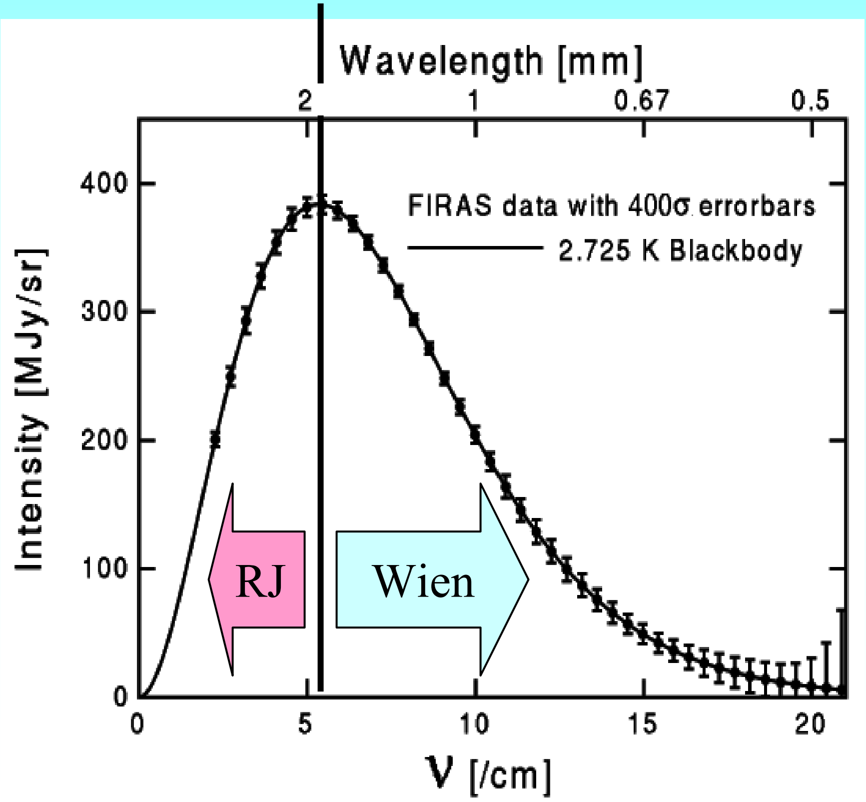
- **How to detect it ?**

$$\nu << \nu_{\max} = 160\, GHz \quad \Rightarrow \quad \text{coherent detectors}$$

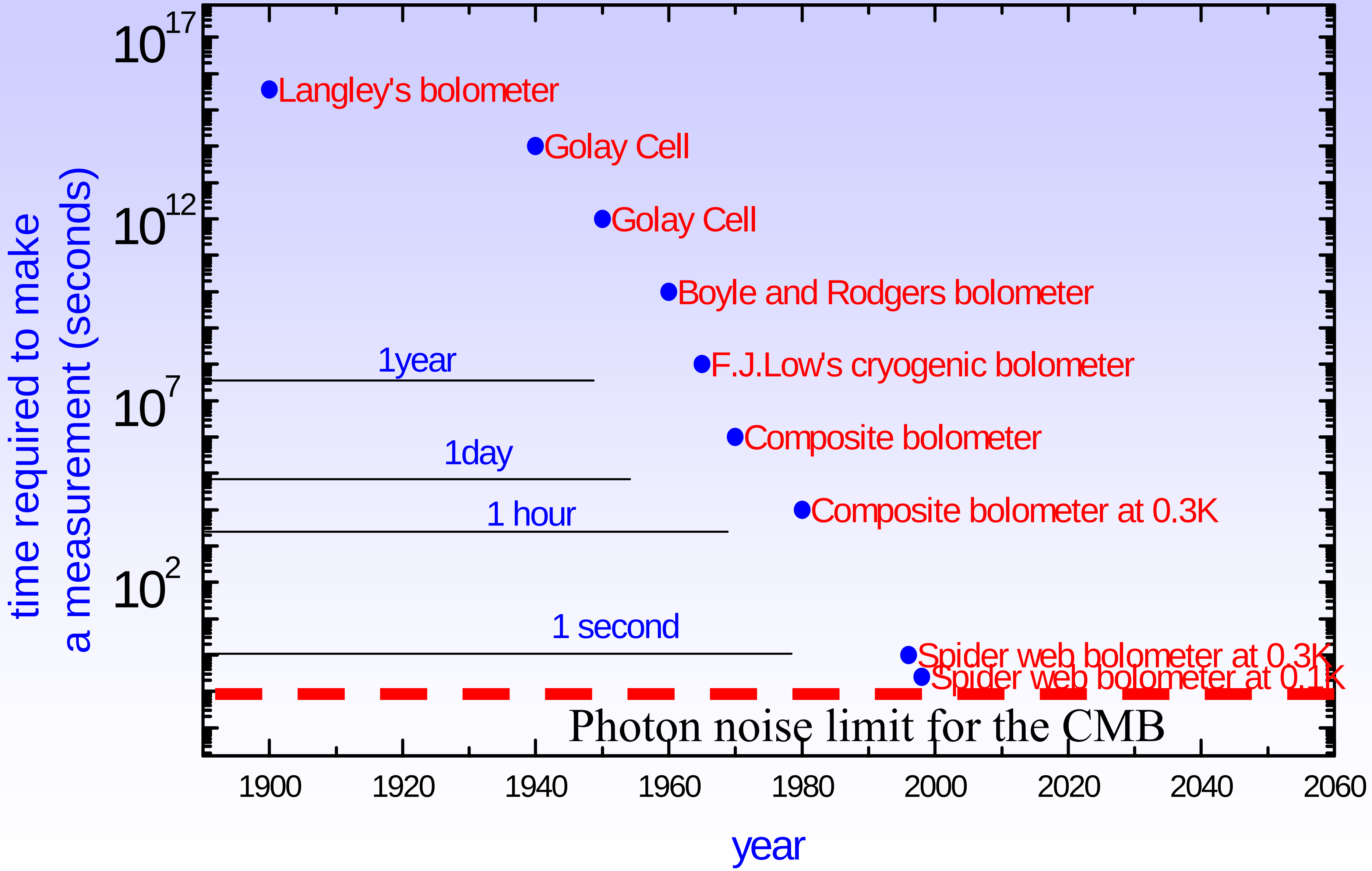
$$\nu >> \nu_{\max} = 160\, GHz \quad \Rightarrow \quad \text{bolometers}$$

$$\nu \quad \approx \nu_{\max} = 160\, GHz \quad \Rightarrow \quad ???$$

- Only thermal detectors (bolometers) can reach a noise lower than the intrinsic noise of the CMB which is the natural limit for measurements of images of the CMB)



Development of thermal detectors for far IR and mm-waves



Radiation Noise

- Thermal radiation (like the CMB) has also wave interference noise: the correct statistics is Bose-Einstein.

$$\langle N \rangle = \frac{g}{e^{(E-\mu)/kT} - 1} \quad ; \quad \langle \Delta N^2 \rangle = T \left. \frac{d\langle N \rangle}{d\mu} \right|_{T,V}$$

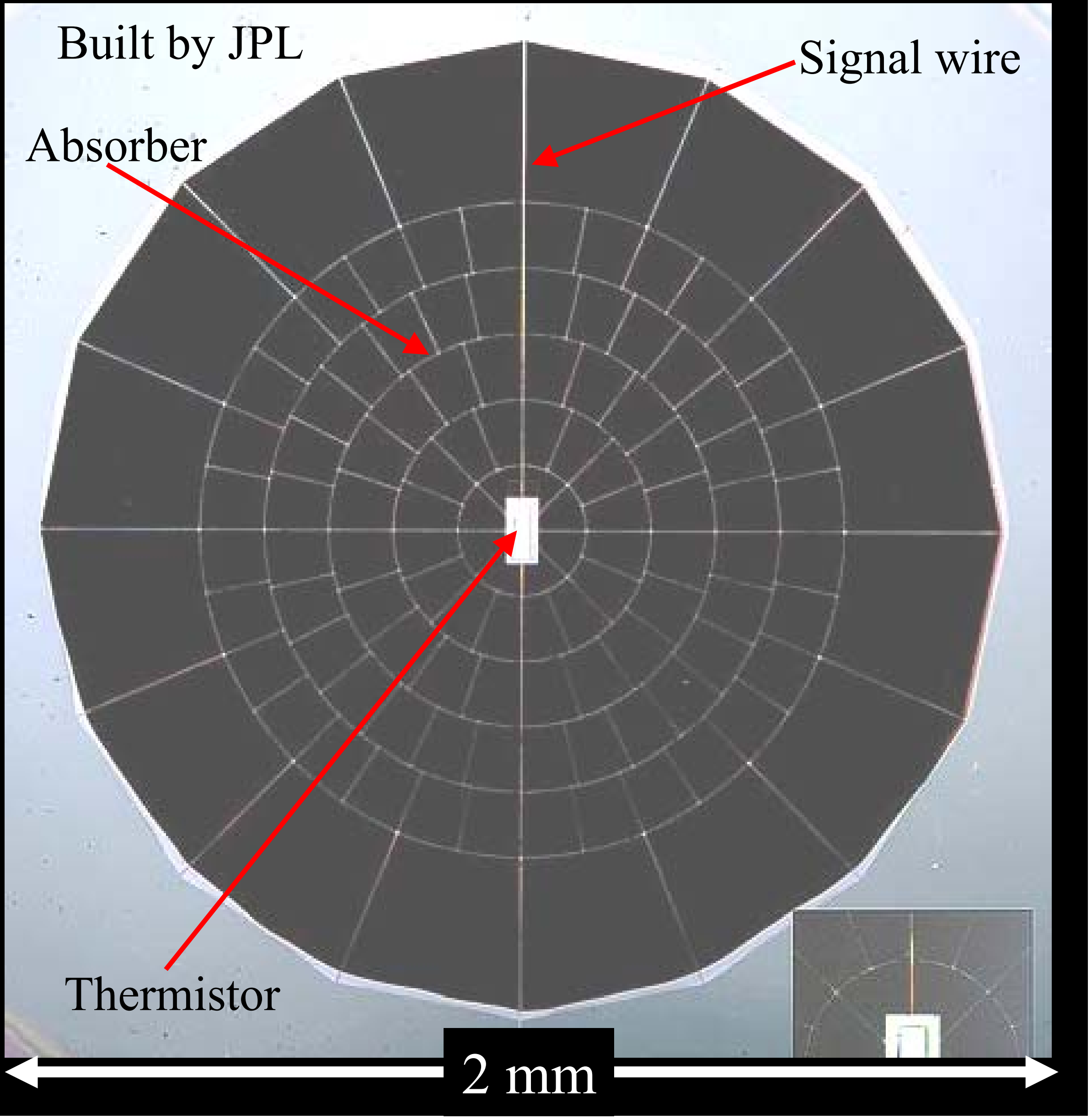
$$\Rightarrow \boxed{\langle \Delta N^2 \rangle = \langle N \rangle + \frac{\langle N \rangle^2}{g}}$$

Poisson noise

Wave interference noise

Spider-Web Bolometers

- The absorber is micro machined as a web of metallized Si_3N_4 wires, 2 μm thick, with 0.1 mm pitch.
- This is a good absorber for mm-wave photons and features a very low cross section for cosmic rays. Also, the heat capacity is reduced by a large factor with respect to the solid absorber.
- NEP ~ 2 10^{-17} W/$Hz^{0.5}$ is achieved @0.3K
- 150μK_{CMB} in 1 s
- Mauskopf *et al.* Appl.Opt. **36**, 765-771, (1997)



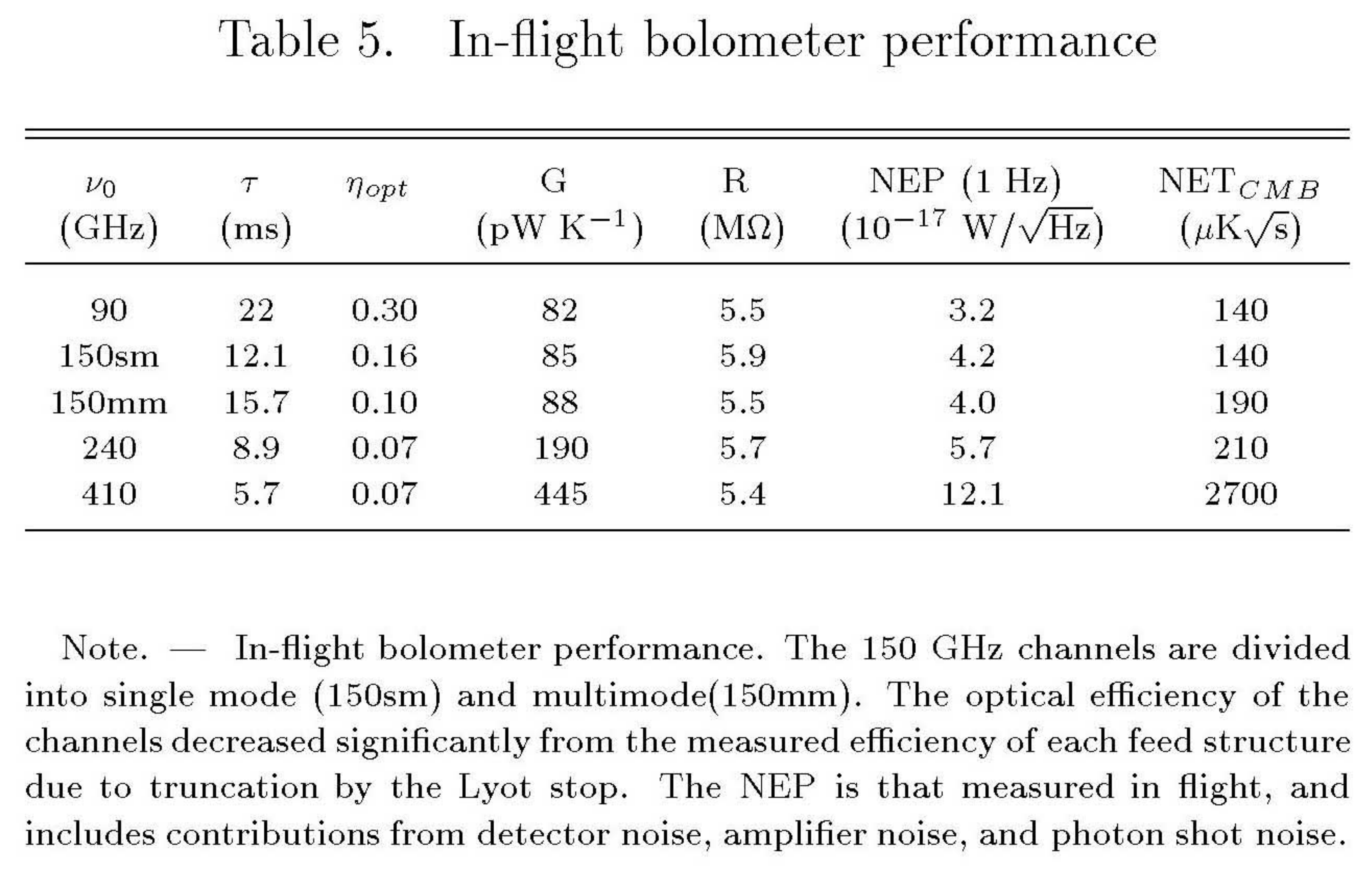


Table 5. In-flight bolometer performance

ν_0 (GHz)	τ (ms)	η_{opt}	G (pW K^{-1})	R (MΩ)	NEP (1 Hz) (10^{-17} $W/\sqrt{Hz}$)	NET_{CMB} ($\mu K\sqrt{s}$)
90	22	0.30	82	5.5	3.2	140
150sm	12.1	0.16	85	5.9	4.2	140
150mm	15.7	0.10	88	5.5	4.0	190
240	8.9	0.07	190	5.7	5.7	210
410	5.7	0.07	445	5.4	12.1	2700

Note. — In-flight bolometer performance. The 150 GHz channels are divided into single mode (150sm) and multimode(150mm). The optical efficiency of the channels decreased significantly from the measured efficiency of each feed structure due to truncation by the Lyot stop. The NEP is that measured in flight, and includes contributions from detector noise, amplifier noise, and photon shot noise.

Crill et al., 2003 – BOOMERanG 1998 bolometers, 300 mK
The same kind of bolometer is used now in Planck @100mK

Bolometers in Planck – High Frequency Instrument

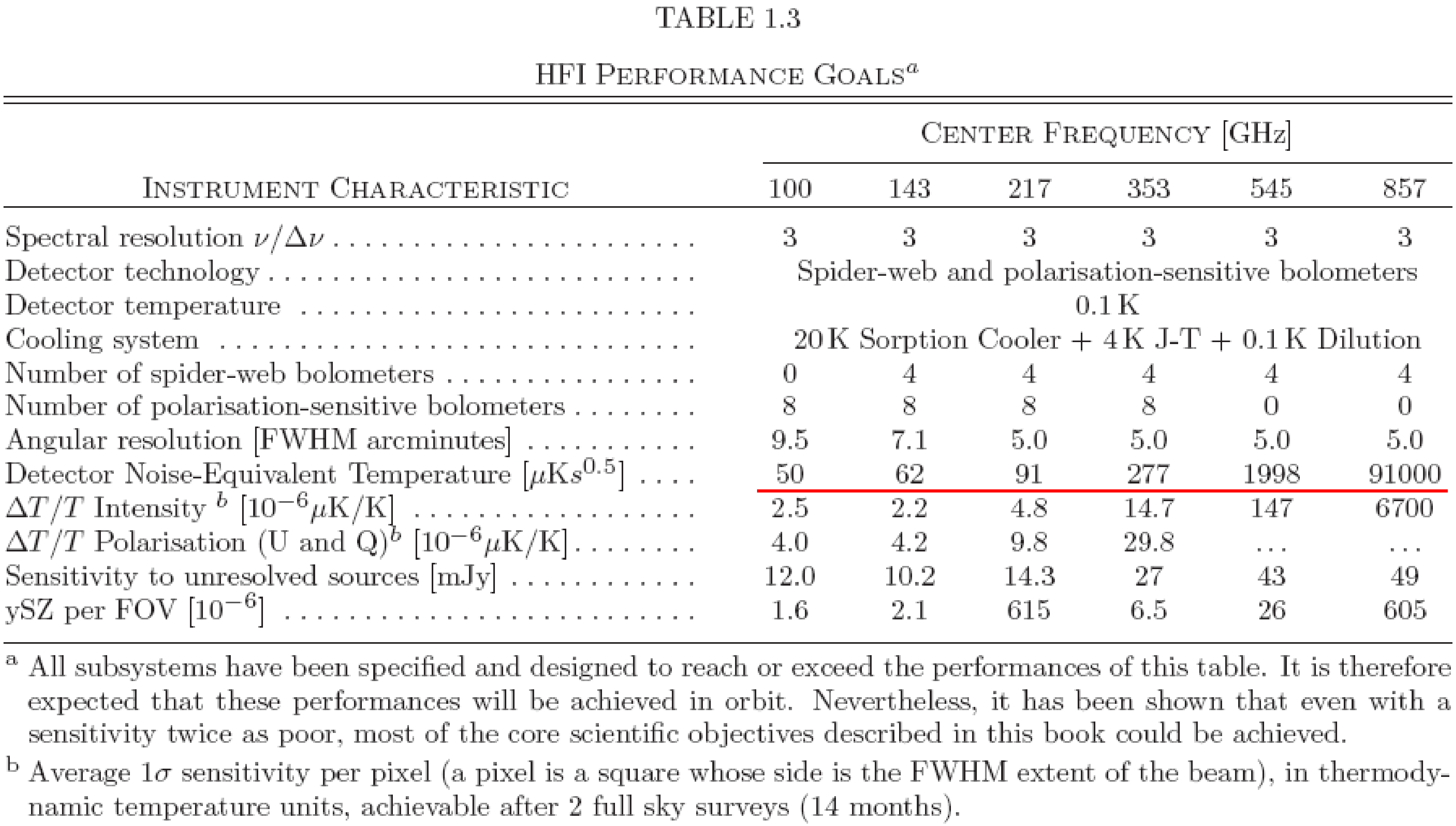


TABLE 1.3

HFI PERFORMANCE GOALS[a]

INSTRUMENT CHARACTERISTIC	CENTER FREQUENCY [GHz] 100	143	217	353	545	857
Spectral resolution $\nu/\Delta\nu$	3	3	3	3	3	3
Detector technology	Spider-web and polarisation-sensitive bolometers					
Detector temperature	0.1 K					
Cooling system	20 K Sorption Cooler + 4 K J-T + 0.1 K Dilution					
Number of spider-web bolometers	0	4	4	4	4	4
Number of polarisation-sensitive bolometers	8	8	8	8	0	0
Angular resolution [FWHM arcminutes]	9.5	7.1	5.0	5.0	5.0	5.0
Detector Noise-Equivalent Temperature $[\mu\mathrm{K}s^{0.5}]$	50	62	91	277	1998	91000
$\Delta T/T$ Intensity [b] $[10^{-6}\mu\mathrm{K/K}]$	2.5	2.2	4.8	14.7	147	6700
$\Delta T/T$ Polarisation (U and Q)[b] $[10^{-6}\mu\mathrm{K/K}]$	4.0	4.2	9.8	29.8	...	...
Sensitivity to unresolved sources [mJy]	12.0	10.2	14.3	27	43	49
ySZ per FOV $[10^{-6}]$	1.6	2.1	615	6.5	26	605

[a] All subsystems have been specified and designed to reach or exceed the performances of this table. It is therefore expected that these performances will be achieved in orbit. Nevertheless, it has been shown that even with a sensitivity twice as poor, most of the core scientific objectives described in this book could be achieved.

[b] Average 1σ sensitivity per pixel (a pixel is a square whose side is the FWHM extent of the beam), in thermodynamic temperature units, achievable after 2 full sky surveys (14 months).

Most of these sensitivity limits are dominated by radiation noise, and have been achieved in the latest calibration run of Planck-HFI.

Why such a sensitivity ?

- To measure the anisotropy of the CMB (maps of the early universe), due to protostructures and oscillations in the primeval plasma
- To measure the Polarization of the CMB, due to Thomson scattering of CMB photons at the last scattering surface and related to scalar and tensor perturbations of the primeval plasma
- All this to infer cosmological parameters and test the standard cosmological model.

CMB anisotropy

- Different physical effects, all related to $\delta\rho/\rho$, produce CMB Temperature fluctuations:

$$\boxed{\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\varphi}{c^2} + \frac{1}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} - \frac{\vec{\mathrm{v}}}{c}\cdot\vec{n}}$$

Sachs-Wolfe (gravitational redshift)

Photon density fluctuations

Doppler effect from velocity fields

- Scales larger than the horizon are basically frozen in the pre-recombination era.
- If the power spectrum of density fluctuations P(k) is scale-invariant (P(k)=Ak), a characteristic power spectrum of $\delta T/T$ is produced at large scales: $c_\ell \approx 1/\left[\ell(\ell+1)\right]$
- This has been detected in 1992 by COBE DMR

- Photons coming out of an overdensity loose some energy due to the gravitational potential gradient they have to climb (gravitational redshift):

$$\frac{\delta T}{T} = \frac{\delta \nu}{\nu} = \frac{\delta \Phi}{c^2}$$

- However, the same overdensity also produces a time delay, so these photons effetively come from an earlier epoch with respect to surrounding ones:

$$\frac{\delta t}{t} = \frac{\delta \Phi}{c^2}$$

- During matter domination

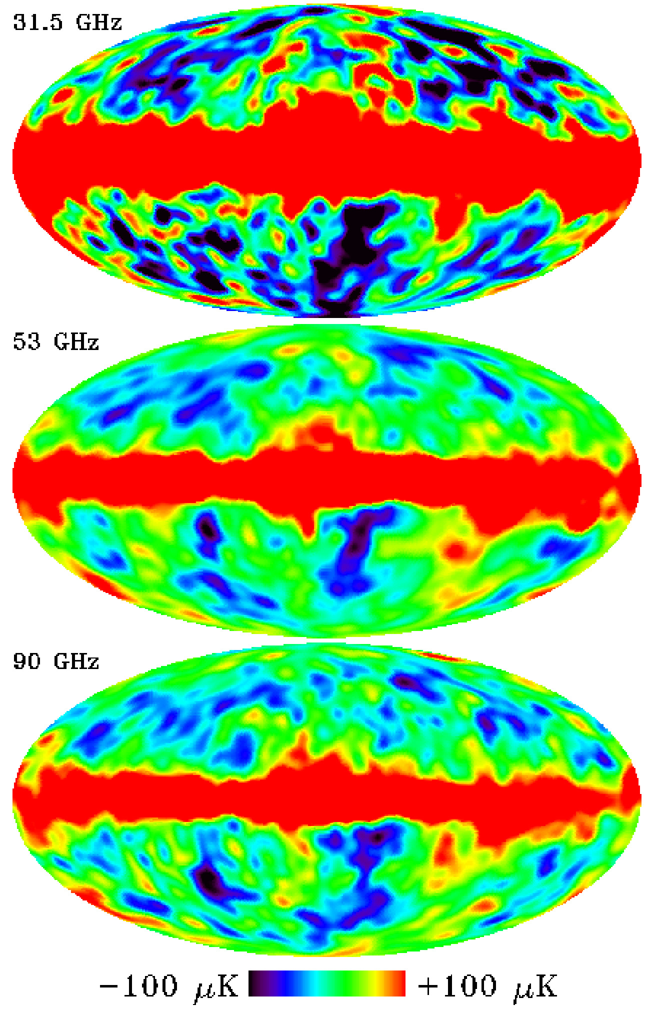
$$a \propto t^{2/3} \quad ; \quad T \propto 1/a \quad \rightarrow \quad \frac{\delta T}{T} = -\frac{\delta a}{a} = -\frac{2}{3}\frac{\delta t}{t} = -\frac{2}{3}\frac{\delta \Phi}{c^2}$$

- The sum of the two effects is called the Sachs-Wolfe (1967) effect, dominant at large angular scales

$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta \Phi}{c^2}$$

Large-Scale Anisotropy

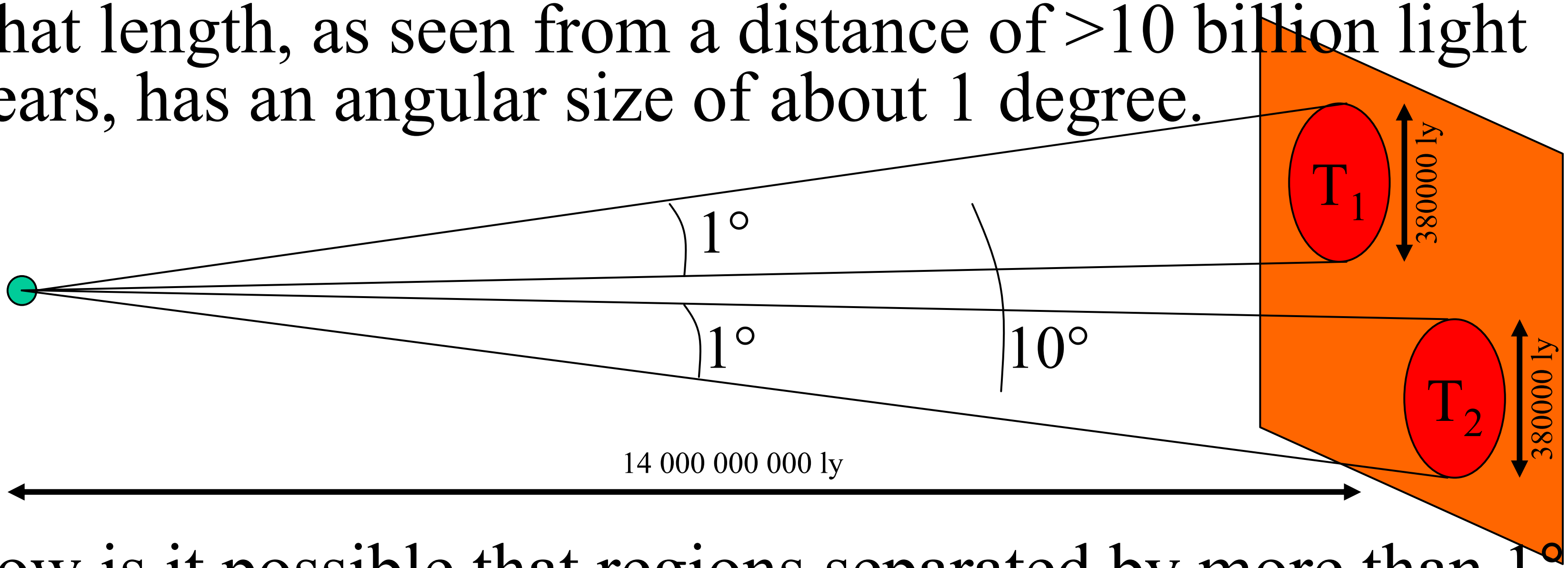
- 1992: COBE-DMR detects the small (10ppm) large-scale anisotropy of the CMB.
- The measured spectrum requires a scale invariant P(k) (n=1)
- Its incredible smoothness requires an inflationary process happening in the first split second after the Big Bang.



G. Smoot et al. 1992, Nobel Pize in 2006

Horizons

- At recombination (t=380000 years), only regions of the Universe closer than 380000 light years have had the possibility (enough time) to interact.
- That length, as seen from a distance of >10 billion light years, has an angular size of about 1 degree.



- How is it possible that regions separated by more than 1° are seen in the COBE map to have the same temperature, within 1 part in 10000 ? They could not interact in all the history of the Universe, from the Big Bang to recombination ! (the “Paradox of Horizons”)

Inflation ?

- At recombination, the causal horizon ct subtends an angle of about 1°.
- In the original Hot Big Bang scenario, regions separated by more than 1° are not causally connected, and have not been causally connected before.
- They are, however, highly isotropic. How can this be ?
- Idea: an ultrafast **inflation** of space, happening at around the grand-unification energy, can separate regions that had been in causal contact before. All the sky we can see today has been in causal contact in a microscopic region before inflation.
- Can we test inflation experimentally ?

Inflation ?

- Inflation is a predictive theory:

  1. Any initial curvature is flattened by the huge expansion: we expect a Euclidean universe.
  2. Adiabatic, gaussian density perturbations are produced from quantum fluctuations. This is the physical origin for density fluctuation.
  3. The power spectrum of scalar perturbations is approximately scale invariant, $P(k)=Ak^n$ with n slightly less than 1.
  4. Tensor perturbations produce a background of gravitational waves, inducing a characteristic polarization pattern in the CMB

- 1,2,3 can be tested measuring CMB anisotropy
- 4 can be tested measuring CMB polarization

CMB anisotropy

- Different physical effects, all related to $\delta\rho/\rho$, produce CMB Temperature fluctuations:

$$\boxed{\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\varphi}{c^2} + \frac{1}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} - \frac{\vec{\mathrm{v}}}{c}\cdot\vec{n}}$$

Sachs-Wolfe (gravitational redshift)	Photon density fluctuations	Doppler effect from velocity fields

- Scales larger than the horizon are basically frozen in the pre-recombination era. Flat power spectrum of $\delta T/T$ at large scales.
- Scales smaller than the horizon undergo acoustic oscillations from horizon-crossing to recombination. Acoustic peaks in the power spectrum of $\delta T/T$ at sub-degree scales.

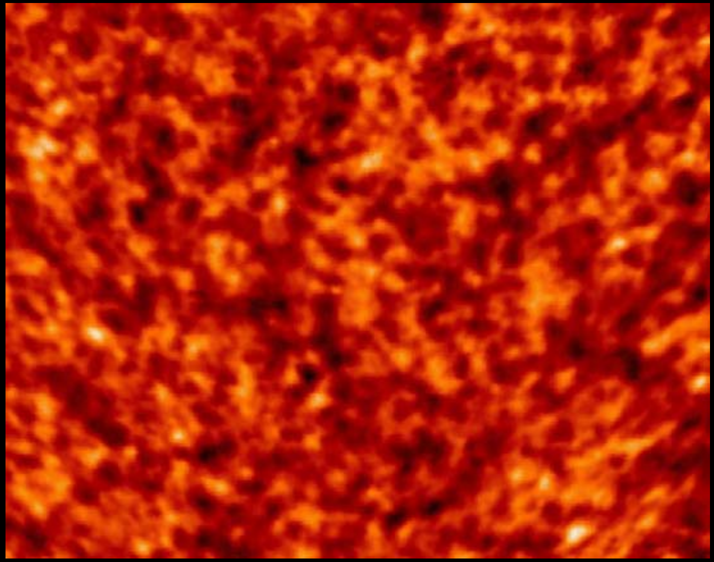
How does the image of the early universe form ?

Physics
of the
Primeval
fireball and
very early
universe

Geometry
of
space

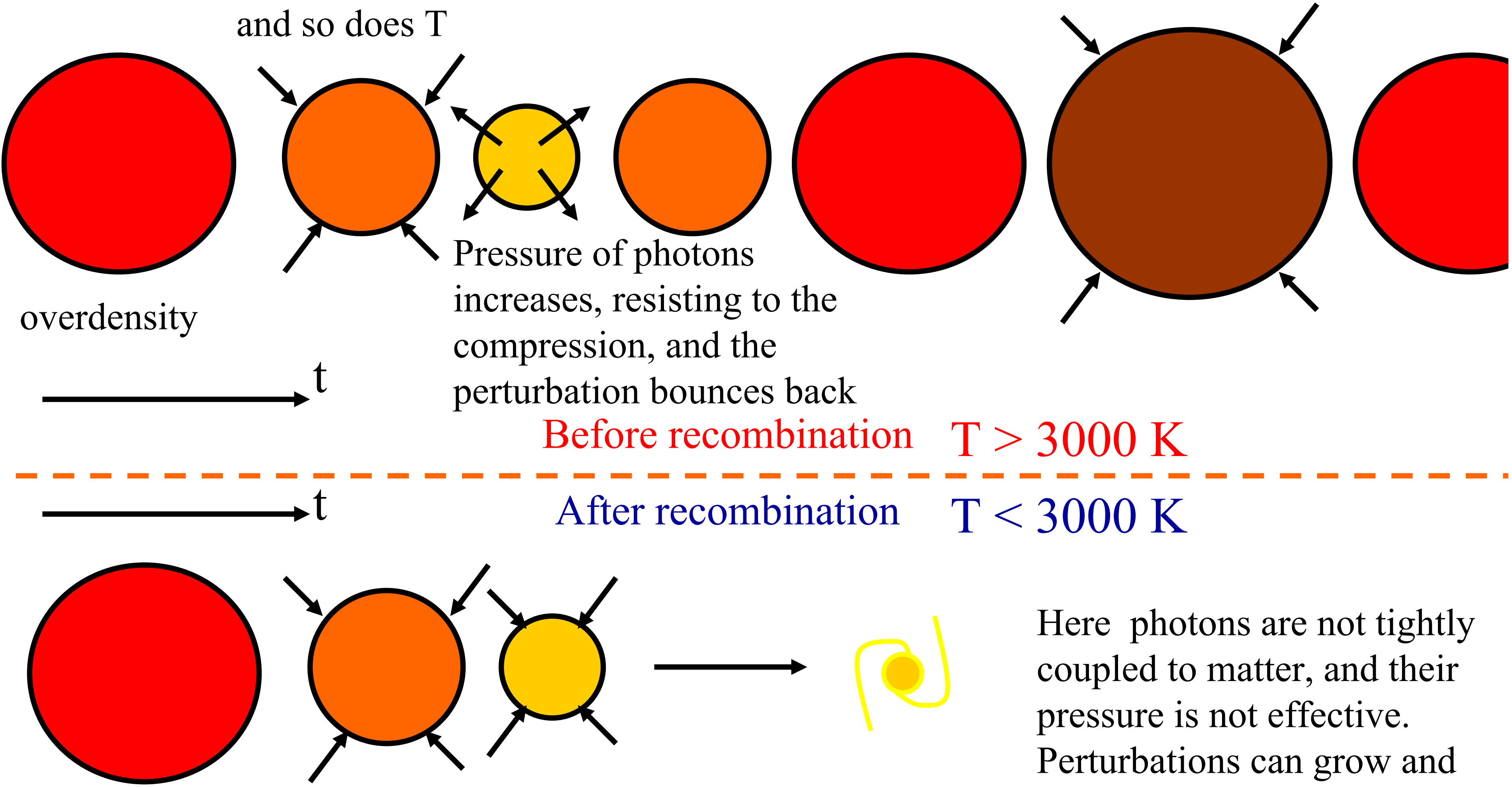
Here, now

14 billion light years



The BOOMERanG map of the last scattering surface

Density perturbations ($\Delta\rho/\rho$) were **oscillating** in the primeval plasma (as a result of the opposite effects of gravity and photon pressure).



Due to gravity, $\Delta\rho/\rho$ increases, and so does T

Pressure of photons increases, resisting to the compression, and the perturbation bounces back

T is reduced enough that gravity wins again

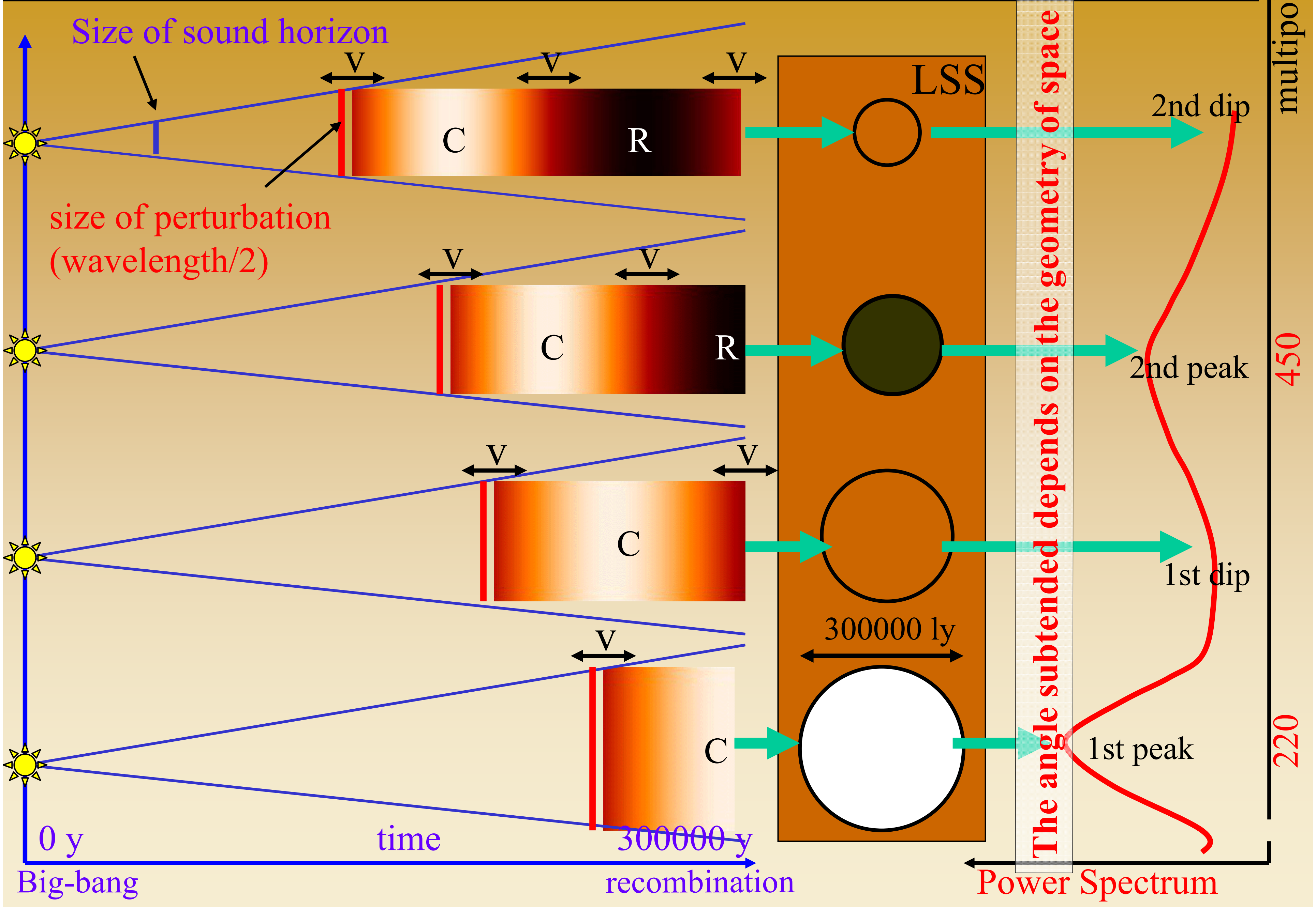
Before recombination $T > 3000$ K

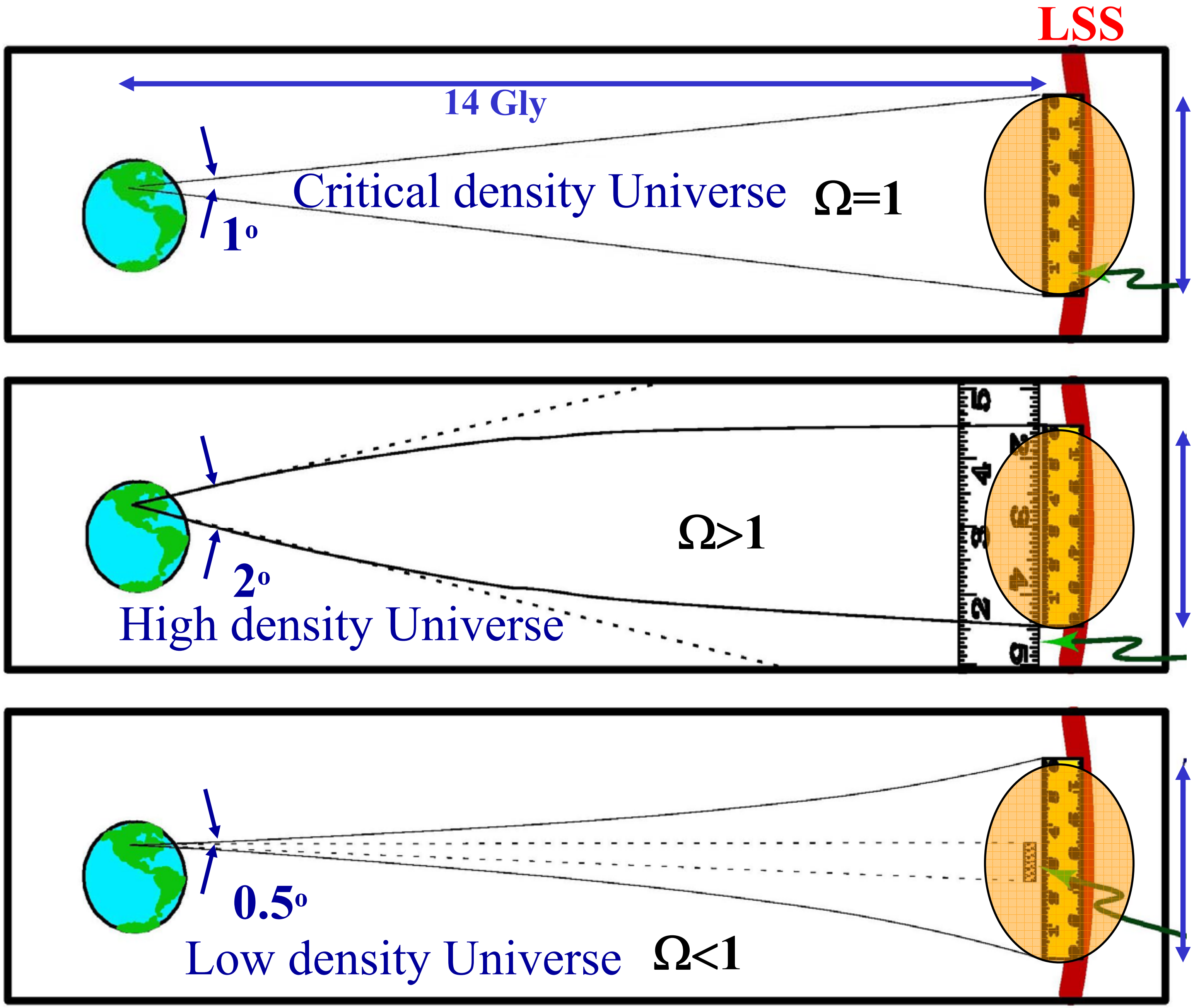
After recombination $T < 3000$ K

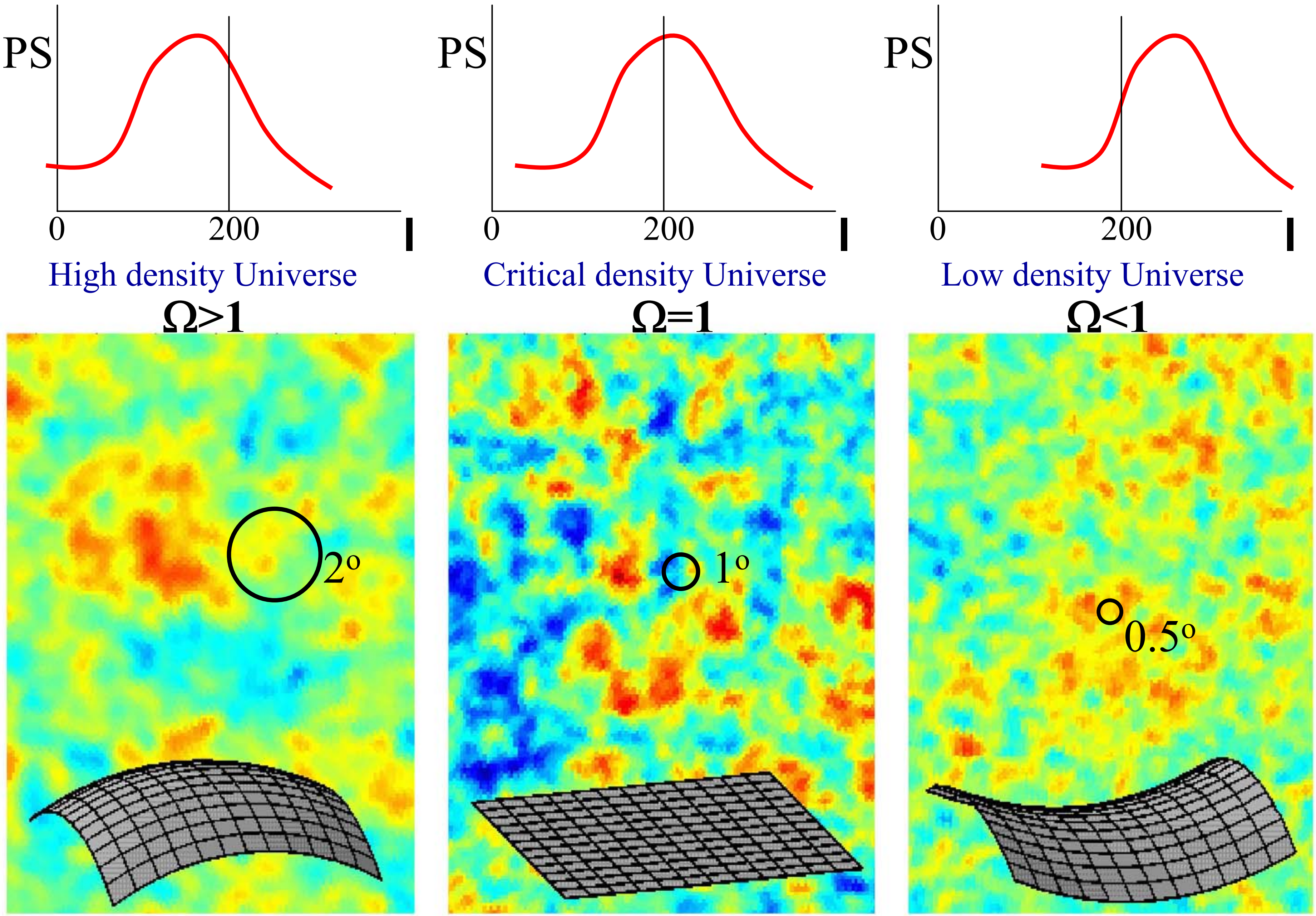
Here photons are not tightly coupled to matter, and their pressure is not effective. Perturbations can grow and form Galaxies.

After recombination, density perturbation can **grow** and create the hierarchy of structures we see in the nearby Universe.

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.




LSS
14 Gly
Critical density Universe
Ω=1
1°
horizon
Ω>1
2°
High density Universe
horizon
0.5°
Low density Universe
Ω<1
horizon

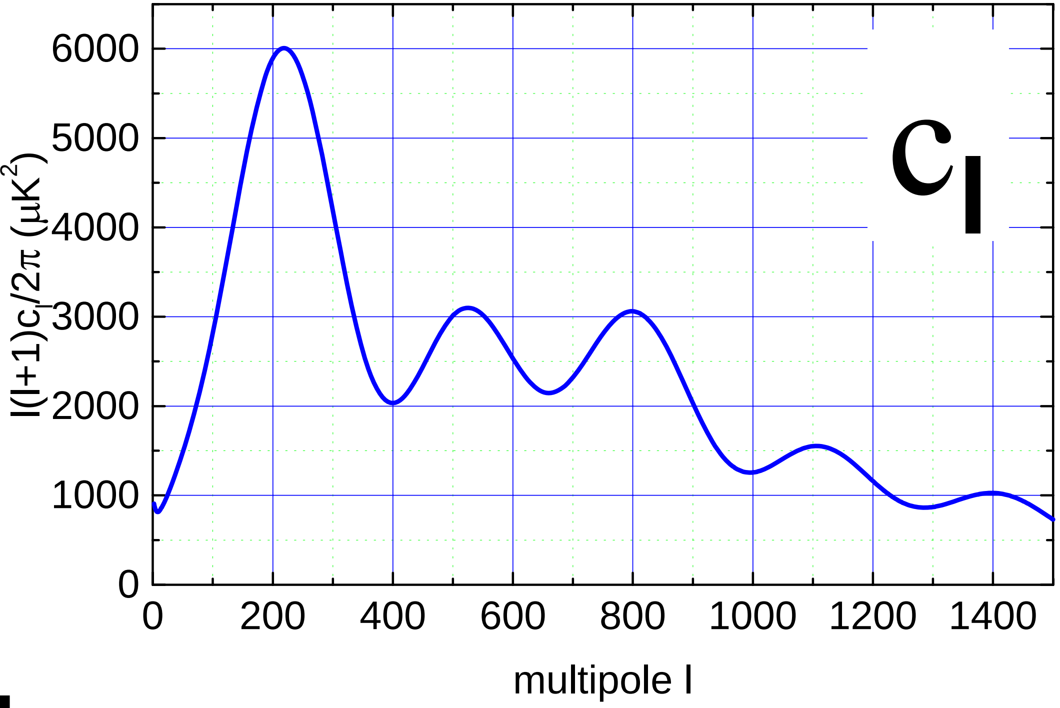

PS
0
200
l
High density Universe
Ω>1
2°
PS
0
200
l
Critical density Universe
Ω=1
1°
PS
0
200
l
Low density Universe
Ω<1
0.5°

Expected power spectrum:

$$\Delta T(\theta,\varphi)=\sum_{\ell,m} a_{\ell m} Y_{\ell}^{m}(\theta,\varphi)$$

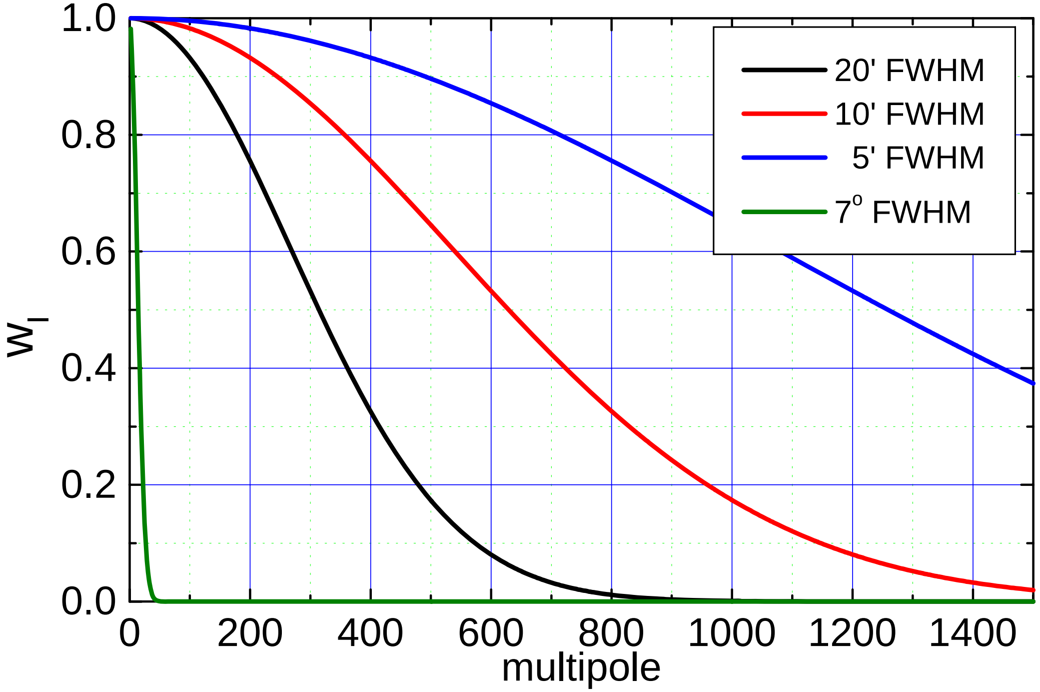
$$c_{\ell} = \left\langle a_{\ell m}^{2} \right\rangle$$

$$\left\langle \Delta T^{2} \right\rangle = \frac{1}{4\pi}\sum_{\ell} (2\ell+1)c_{\ell}$$



An instrument with finite angular resolution is not sensitive to the smallest scales (highest multipoles). For a gaussian beam with s.d. σ:

$$w_{\ell}^{LP} = e^{-\ell(\ell+1)\sigma^{2}}$$

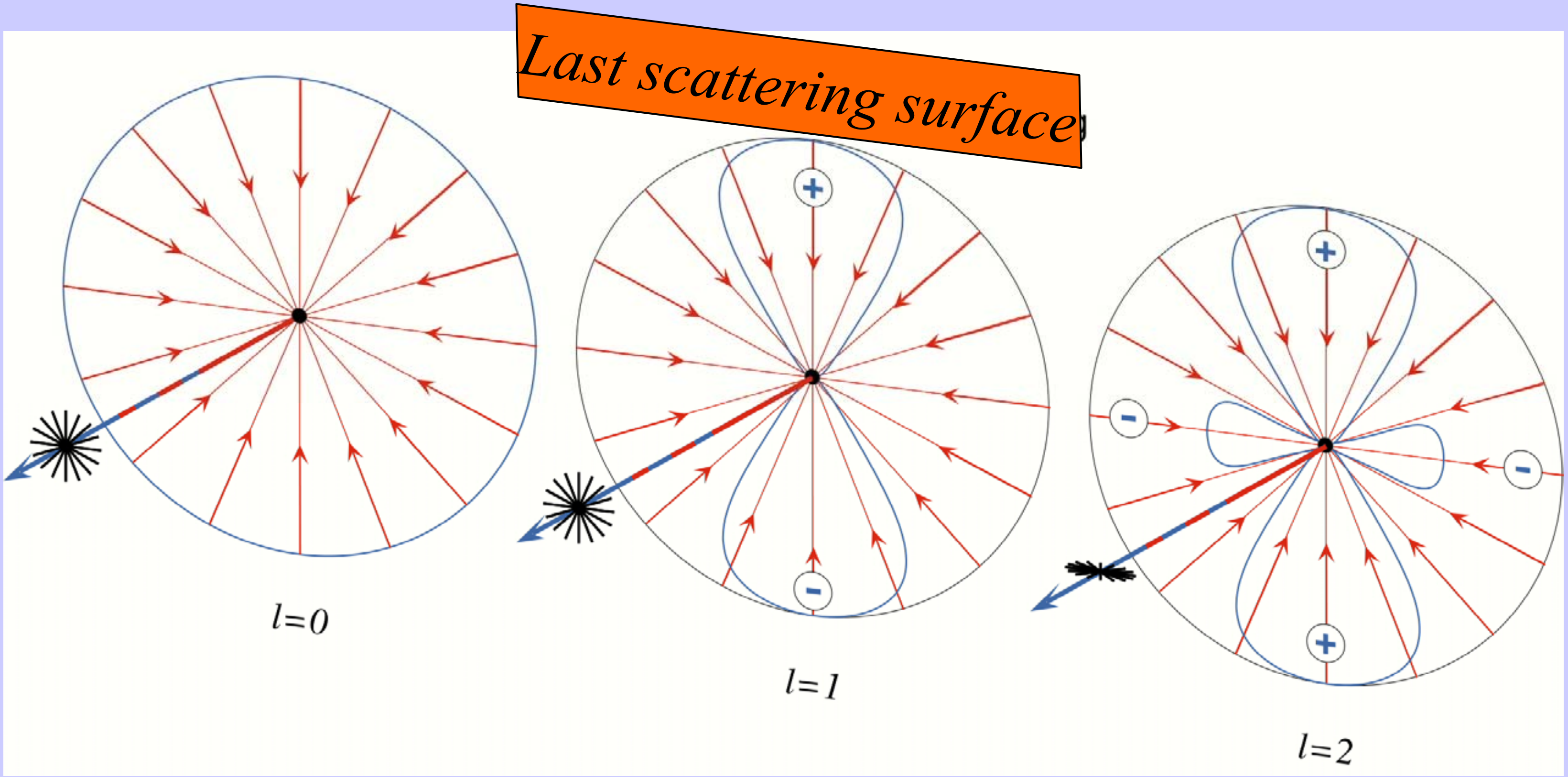


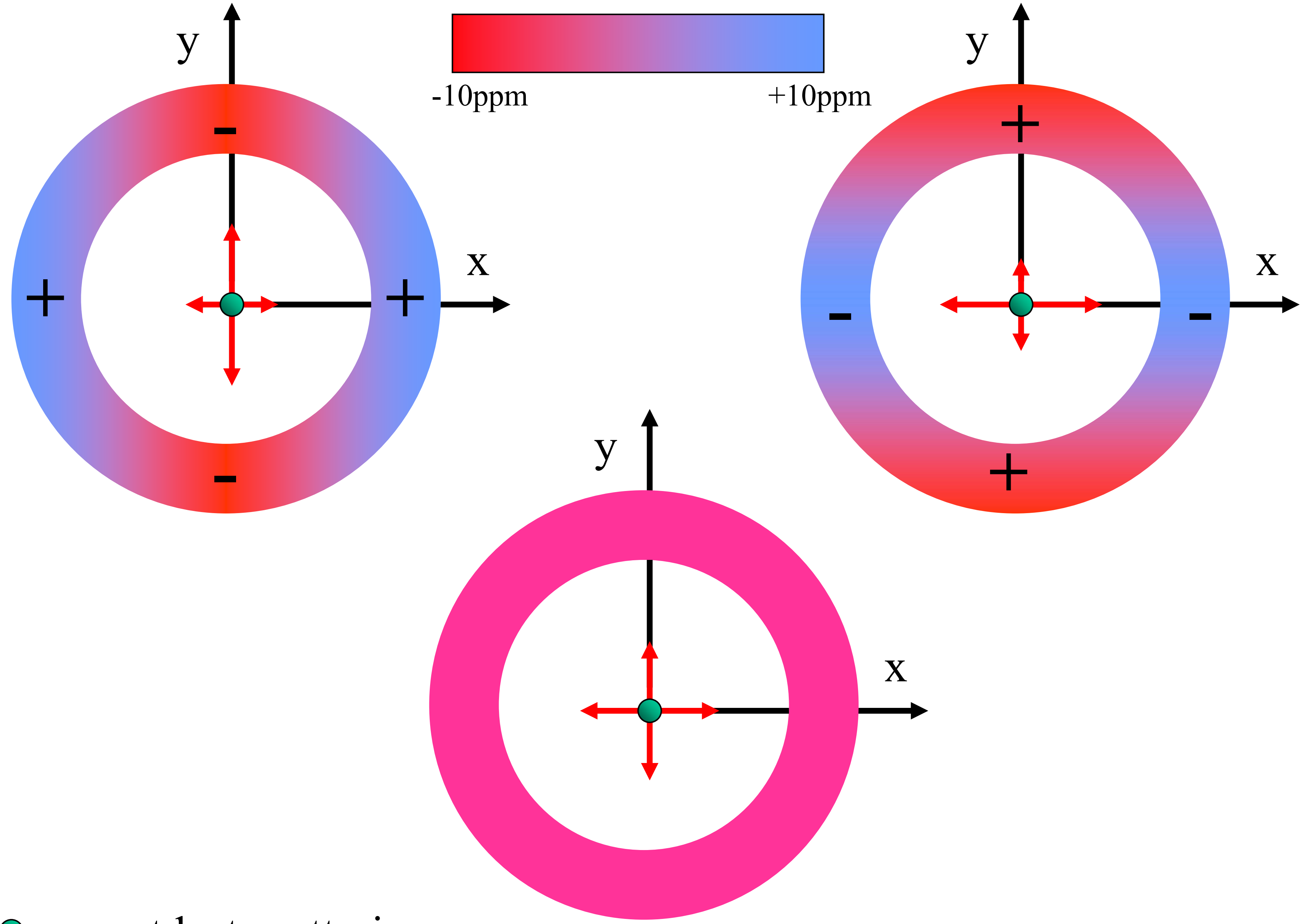
Did Inflation really happen ?

- **We do not know**. Inflation has not been proven yet. It is, however, a mechanism able to produce primordial fluctuations with the right characteristics.
- Four of the basic predictions of inflation have been proven:
  - existence of super-horizon fluctuations
  - gaussianity of the fluctuations
  - flatness of the universe
  - scale invariance of the density perturbations
- One more remains to be proved: the stochastic background of gravitational waves produced during the inflation phase.
- **CMB can help** in this – see below.

CMB polarization

- CMB radiation is Thomson scattered at recombination.
- If the local distribution of incoming radiation in the rest frame of the electron has a *quadrupole moment*, the scattered radiation acquires some degree of linear polarization.





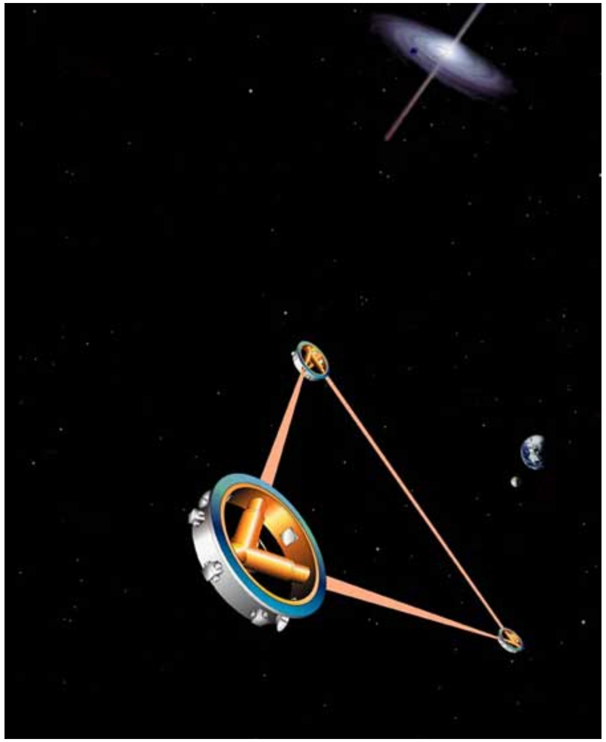
● = e^- at last scattering

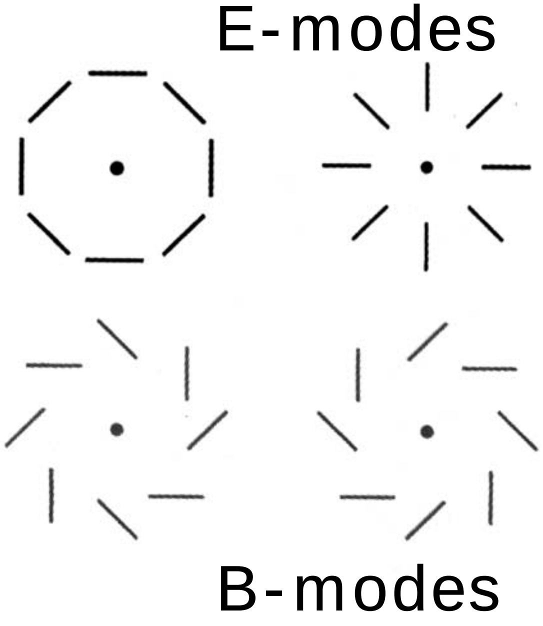
If inflation really happened...

- It stretched geometry of space to nearly Euclidean ← OK
- It produced a nearly scale invariant spectrum of density fluctuations ← OK
- It produced a stochastic background of gravitational waves. ← ?

Quadrupole from P.G.W.

- If inflation really happened:
  - ✓ It stretched geometry of space to nearly Euclidean
  - ✓ It produced a nearly scale invariant spectrum of gaussian density fluctuations
  - ✓ It produced a stochastic background of gravitational waves: Primordial G.W. The background is so faint that even LISA will not be able to measure it.
- Tensor perturbations also produce quadrupole anisotropy. They generate irrotational (E-modes) **and rotational (B-modes) components** in the CMB polarization field.
- Since B-modes are not produced by scalar fluctuations, they represent a signature of inflation.





B-modes from P.G.W.

- The amplitude of this effect is very small, but depends on the Energy scale of inflation. In fact the amplitude of tensor modes normalized to the scalar ones is:

$$\left(\frac{T}{S}\right)^{1/4} \equiv \left(\frac{C_2^{GW}}{C_2^{Scalar}}\right)^{1/4} \cong \frac{V^{1/4}}{3.7\times10^{16}\,\mathrm{GeV}}$$

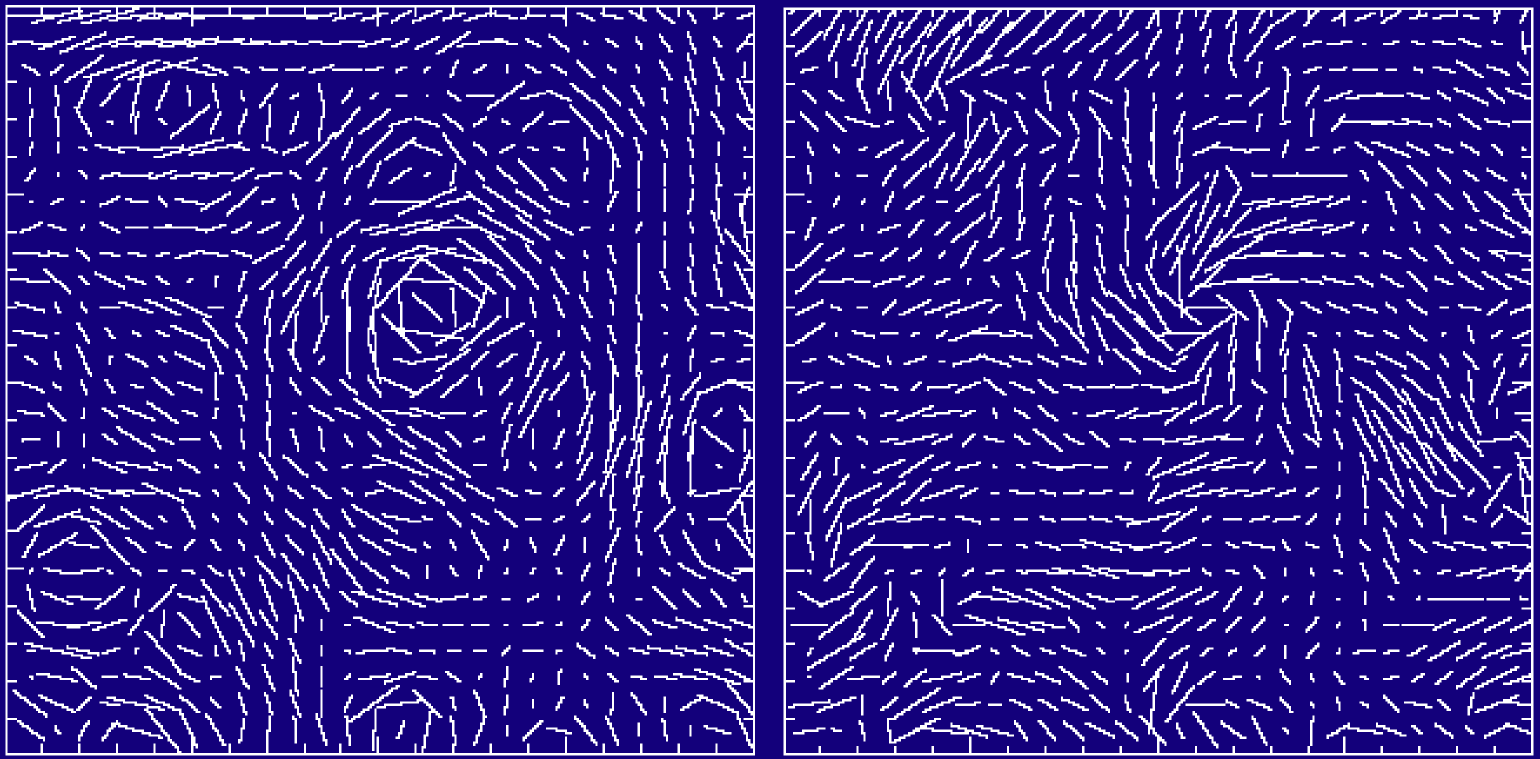
← Inflation potential

- and

$$\sqrt{\frac{\ell(\ell+1)}{2\pi}c_{\ell\max}^{B}} \cong 0.1\mu K\left[\frac{V^{1/4}}{2\times10^{16}\,\mathrm{GeV}}\right]$$

- There are theoretical arguments to expect that the energy scale of inflation is close to the scale of GUT i.e. around 10^{16} GeV.
- The current upper limit on anisotropy at large scales gives $T/S<0.5$ (at 2σ)
- A competing effect is lensing of E-modes, which is important at large multipoles.

Pure E(left) & B(right)



Can you spot the difference ??!!

E-modes & B-modes

Spin-2 quantity

Spin-2 basis

$$(Q \pm iU)(\vec{n}) = \sum_{\ell,m} \left(a^{E}_{\ell m} \pm i a^{B}_{\ell m} \right) {}_{\pm 2}Y_{\ell m}(\vec{n})$$

- From the measurements of the Stokes Parameters $\boldsymbol{Q}$ and $\boldsymbol{U}$ of the linear polarization field we can recover both irrotational and rotational a_{lm} by means of modified Legendre transforms:

E-modes produced by scalar and tensor perturbations

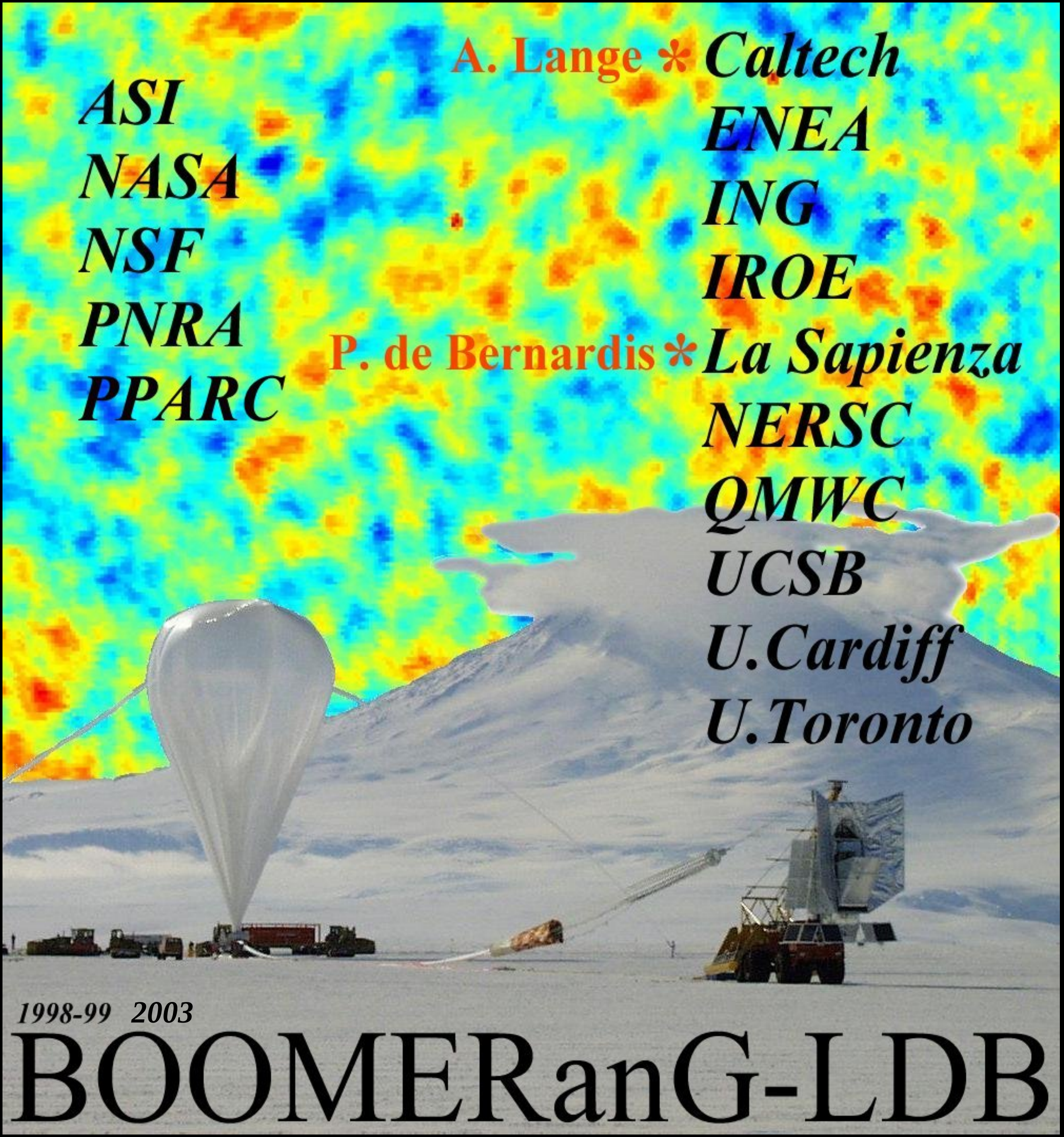
$$a^{E}_{\ell m} = \frac{1}{2} \int d\Omega W(\vec{n}) \left[(Q + iU)(\vec{n})_{+2} Y_{\ell m}(\vec{n}) + (Q - iU)(\vec{n})_{-2} Y_{\ell m}(\vec{n}) \right]$$

B-modes produced **only** by tensor perturbations

$$a^{B}_{\ell m} = \frac{1}{2i} \int d\Omega W(\vec{n}) \left[(Q + iU)(\vec{n})_{+2} Y_{\ell m}(\vec{n}) - (Q - iU)(\vec{n})_{-2} Y_{\ell m}(\vec{n}) \right]$$

The signal is extremely weak

- Nobody really knows how to detect this.
  - Pathfinder experiments are needed
- Whatever smart, ambitious experiment we design to detect the B-modes:
  - It needs to be extremely sensitive
  - It needs an extremely careful control of systematic effects
  - It needs careful control of foregrounds
  - It will need independent experiments with orthogonal systematics.
- There is still a long way to go: ...



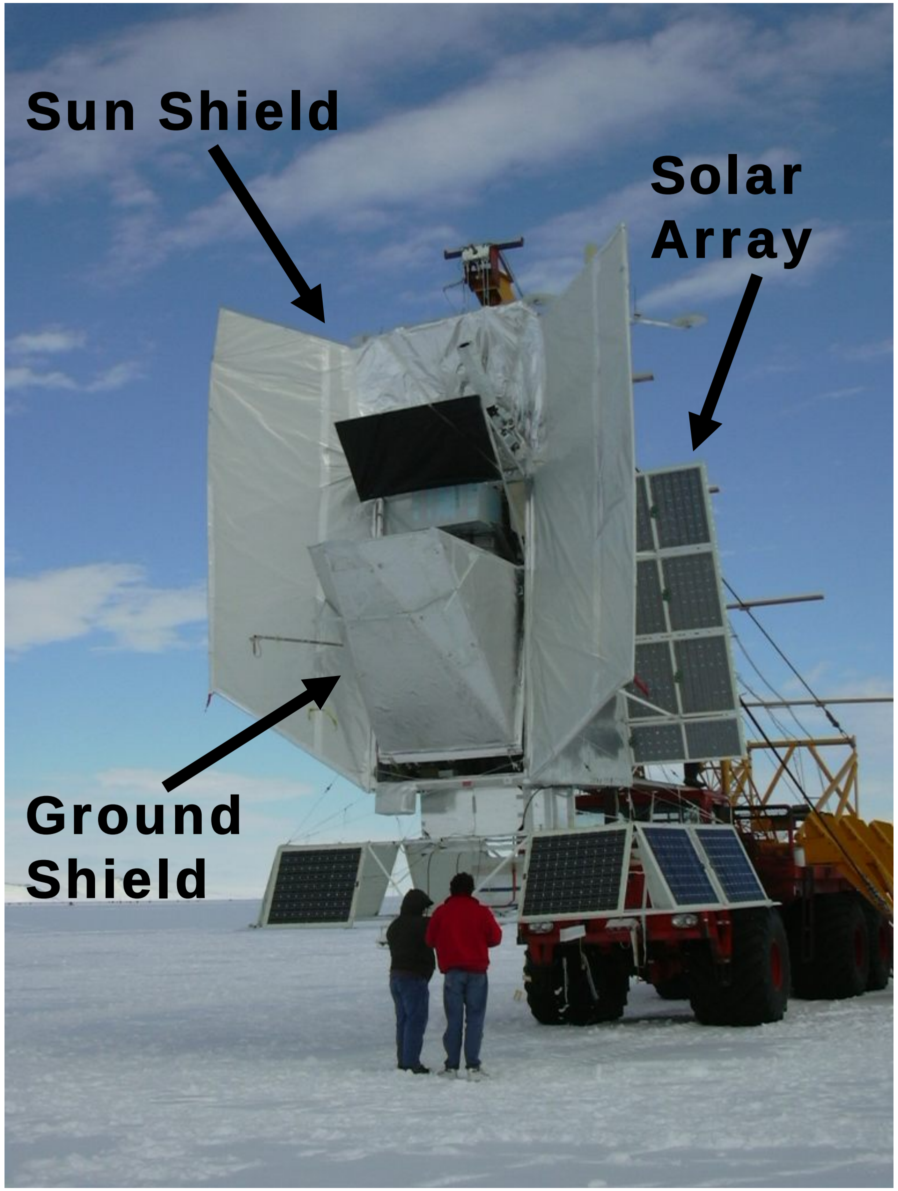
BOOMERanG-LDB

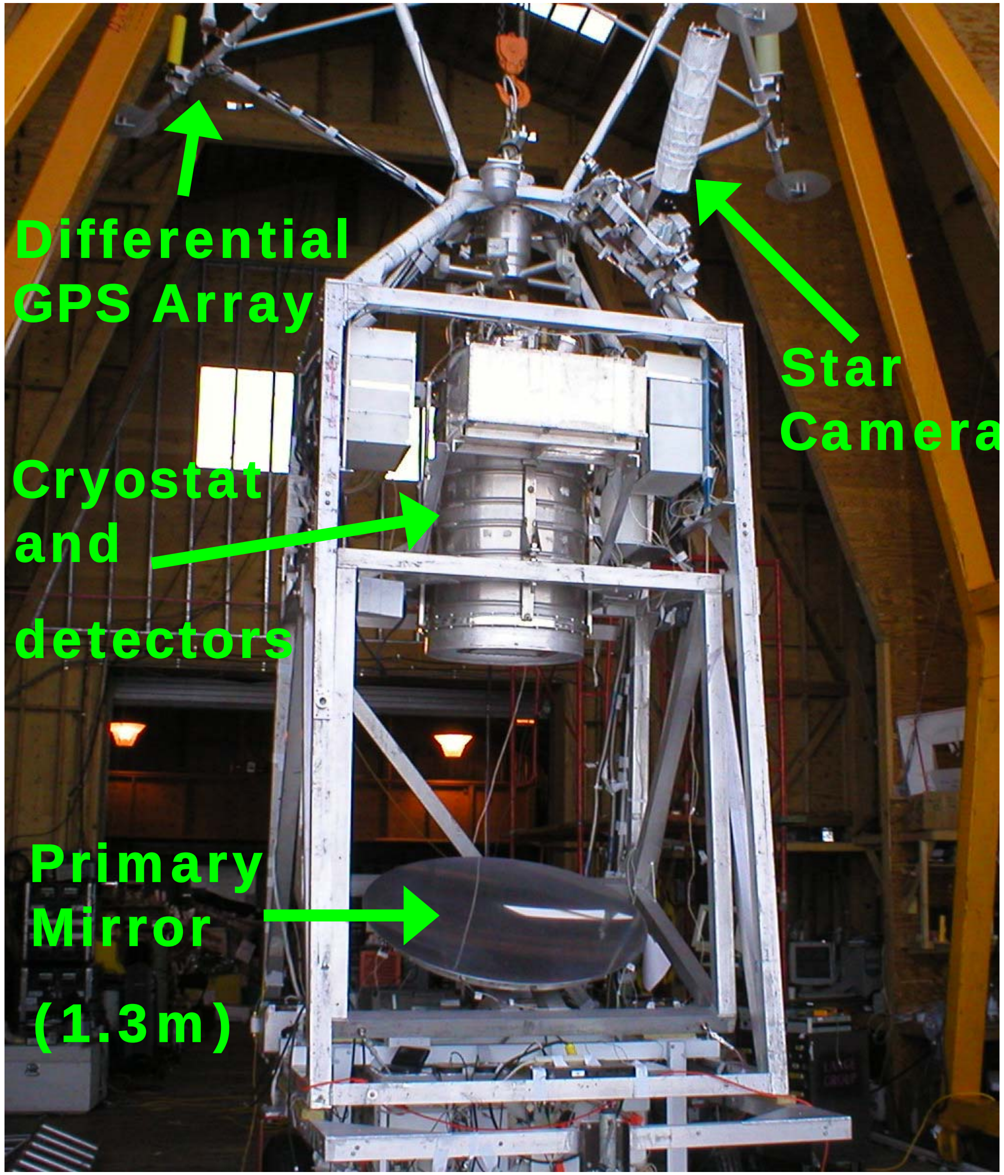
1998-99 **2003**

ASI
NASA
NSF
PNRA
PPARC

A. Lange * ***Caltech***
ENEA
ING
IROE
P. de Bernardis * ***La Sapienza***
NERSC
QMWC
UCSB
U.Cardiff
U.Toronto

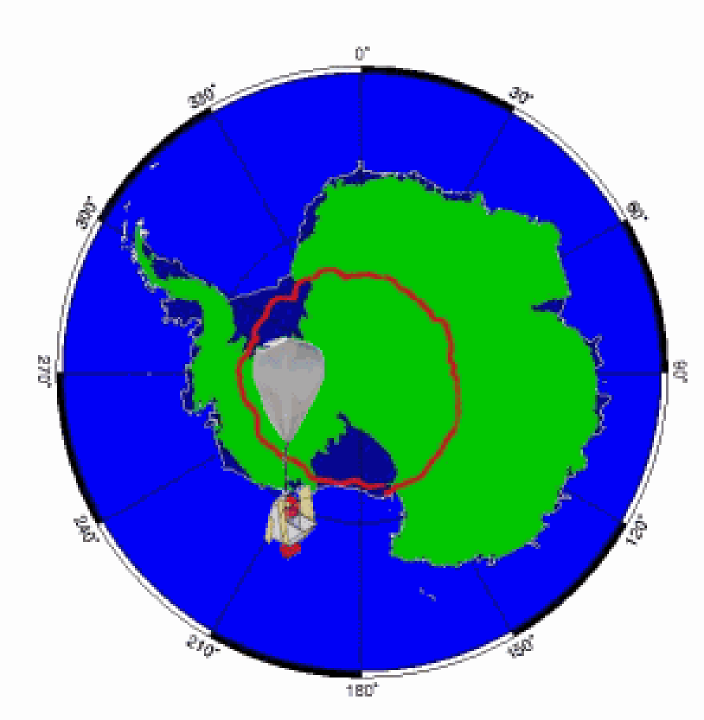
the BOOMERanG ballon-borne telescope



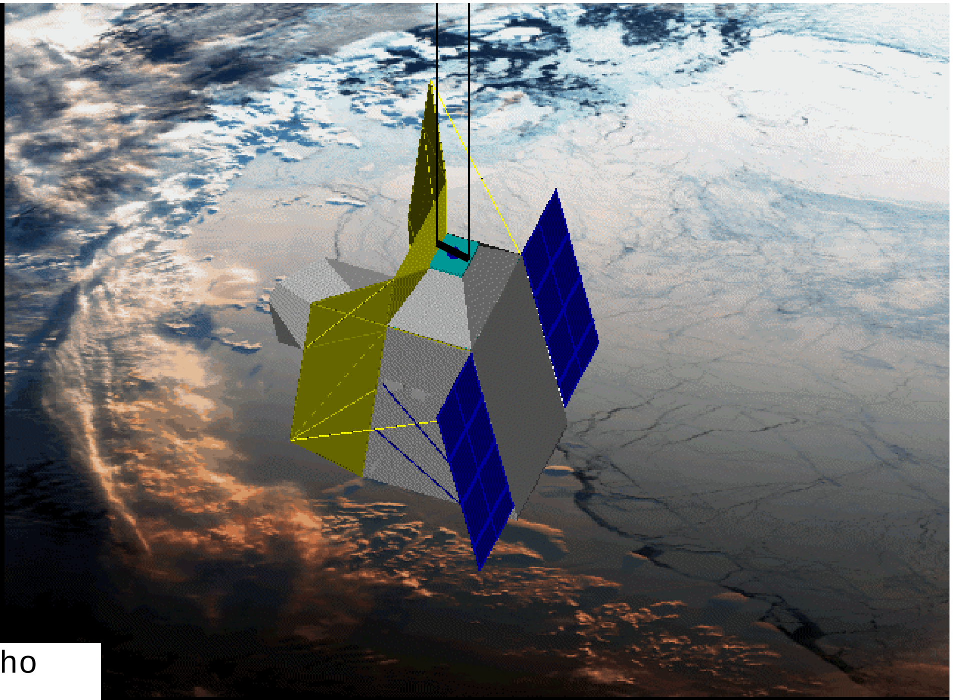


Sensitive at 90, 150, 240, 410 GHz

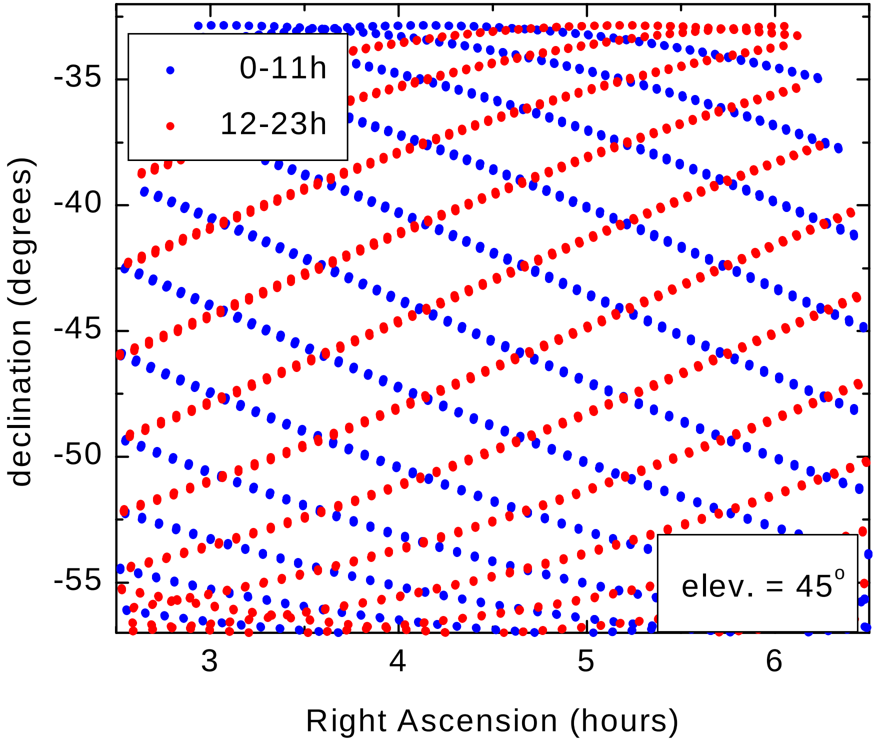
- The instrument is flown above the Earth atmosphere, at an altitude of 37 km, by means of a stratospheric balloon.
- Long duration flights (LDB, 1-3 weeks) are performad by NASA-NSBF over Antarctica
- BOOMERanG has been flown LDB two times:
- From Dec.28, **1998** to Jan.8, 1999, for CMB anisotropy measurements
- In **2003**, from Jan.6 to Jan.20, for CMB polarization measurements (B2K).



- The image of the sky is obtained by slowly scanning the full payload in azimuth (±30°) at constant elevation

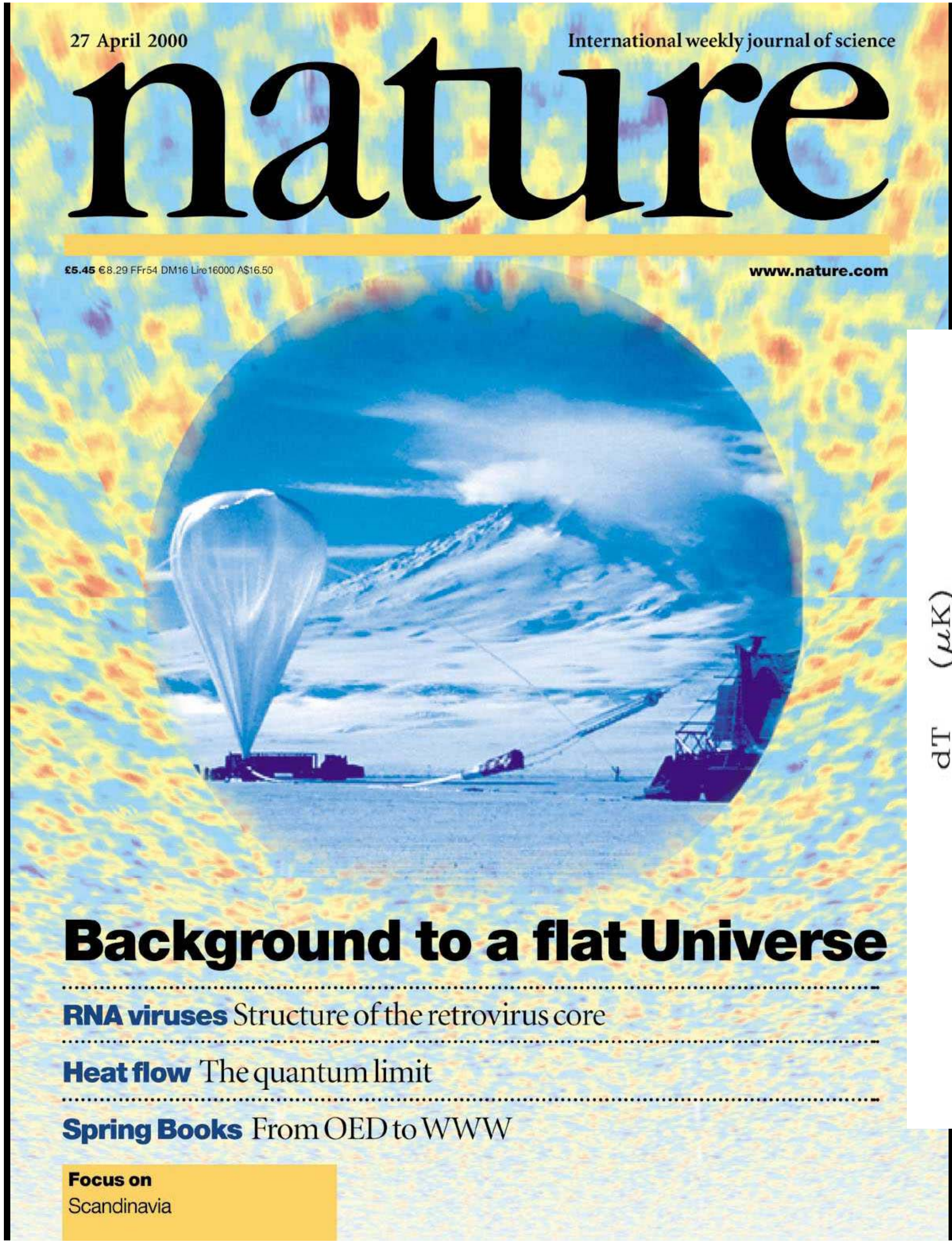


crosslink in BOOMERanG LDB scans (1 scan/hour sho



- The scan center constantly tracks the azimuth of the lowest foreground region
- Every day we obtain a fully crosslinked map.
- This is the key for an accurate map of the sky

First evidence (2000) from BOOMERanG



27 April 2000

International weekly journal of science

nature

£5.45 €8.29 FFr54 DM16 Lire16000 A$16.50

www.nature.com

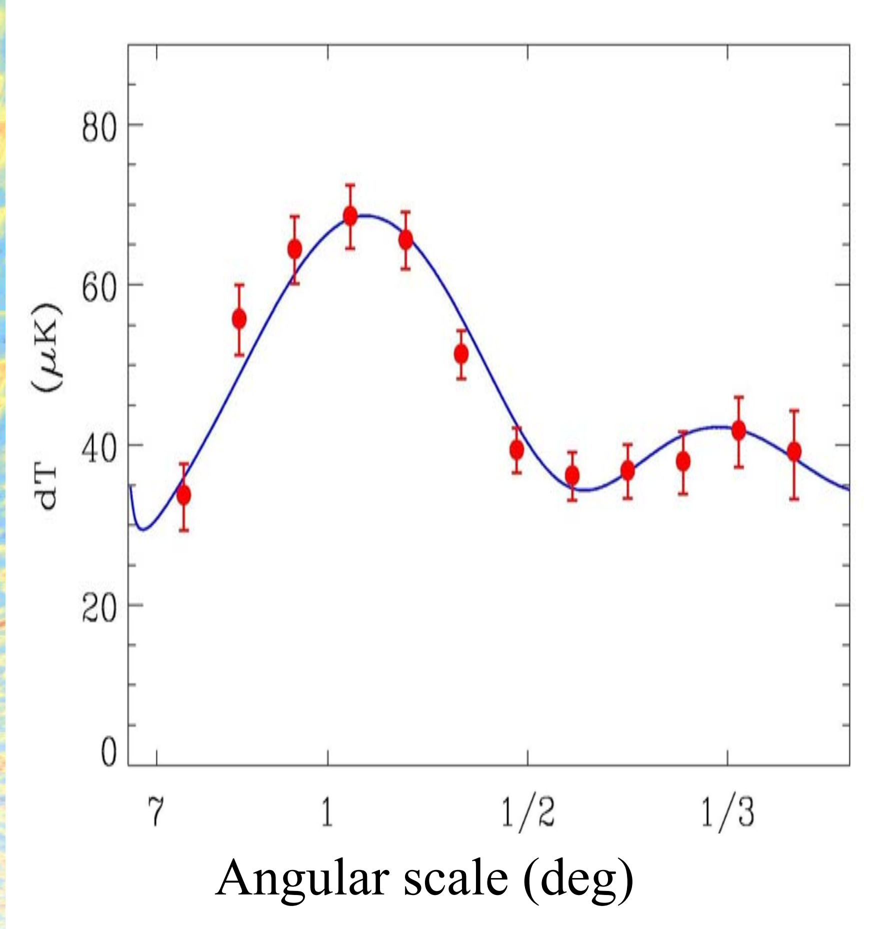
Background to a flat Universe

RNA viruses Structure of the retrovirus core

Heat flow The quantum limit

Spring Books From OED to WWW

Focus on
Scandinavia



THE ASTROPHYSICAL JOURNAL, 564:559–566, 2002 January 10

MULTIPLE PEAKS IN THE ANGULAR POWER SPECTRUM OF THE COSMIC MICROWAVE BACKGROUND: SIGNIFICANCE AND CONSEQUENCES FOR COSMOLOGY

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Received 2001 May 18; accepted 2001 September 11

ABSTRACT

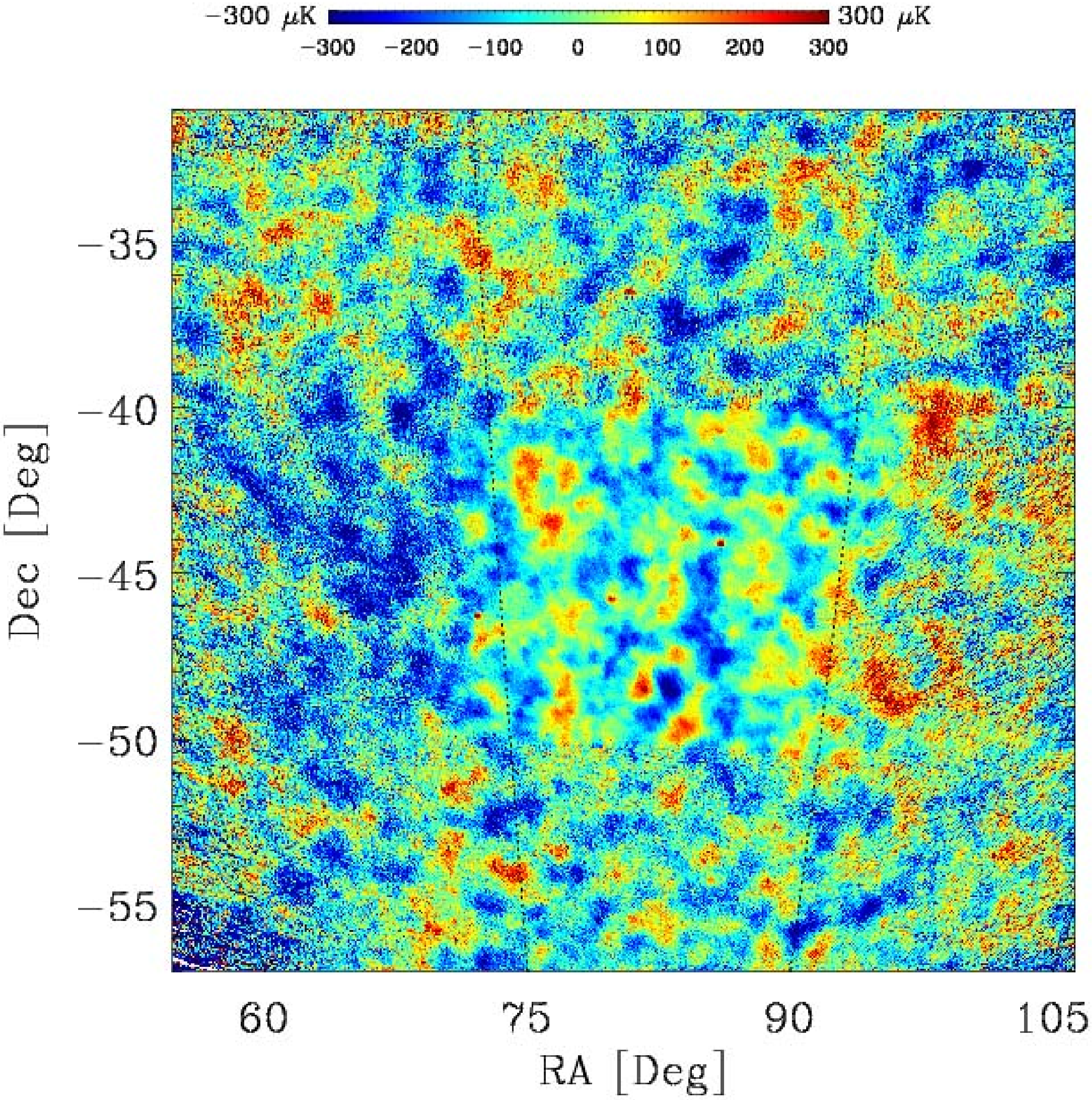
Three peaks and two dips have been detected in the power spectrum of the cosmic microwave background by the BOOMERANG experiment, at $l = (213^{+10}_{-13})$, (541^{+20}_{-32}), (845^{+12}_{-25}) and $l = (416^{+22}_{-12})$, (750^{+20}_{-750}), respectively. Using model-independent analyses, we find that all five features are statistically significant, and we measure their location and amplitude. These are consistent with the adiabatic inflationary model. We also calculate the mean and variance of the peak and dip locations and amplitudes in a large seven-dimensional parameter space of such models, which gives good agreement with the model-independent estimates. We forecast where the next few peaks and dips should be found if the basic paradigm is correct. We test the robustness of our results by comparing Bayesian marginalization techniques on this space with likelihood maximization techniques applied to a second seven-dimensional cosmological parameter space, using an independent computational pipeline, and find excellent agreement: $\Omega_{\rm tot} = 1.02^{+0.05}_{-0.06}$ versus 1.04 ± 0.05, $\Omega_b h^2 = 0.022^{+0.004}_{-0.003}$ versus $0.019^{+0.005}_{-0.004}$, and $n_s = 0.96^{+0.09}_{-0.08}$ versus 0.90 ± 0.08. The determination of the best fit by the maximization procedure effectively ignores nonzero optical depth of reionization $\tau_C > 0$, and the difference in primordial spectral index n_s between the two methods is thus a consequence of the strong correlation of n_s with the τ_C.

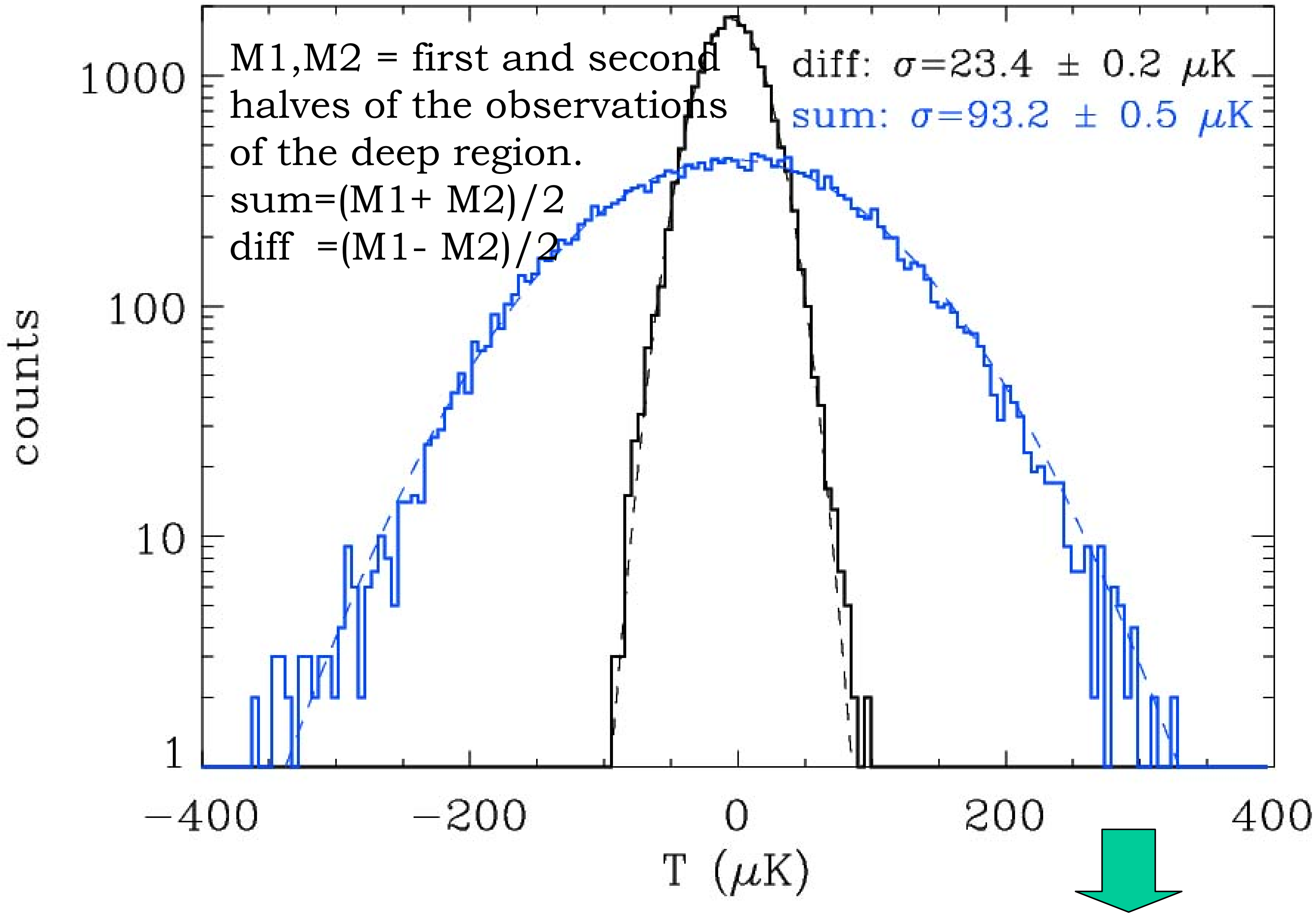
Subject headings: cosmic microwave background — cosmological parameters —
cosmology: observations

145 GHz
T map

(Masi et al., 2005)

the deepest CMB map ever



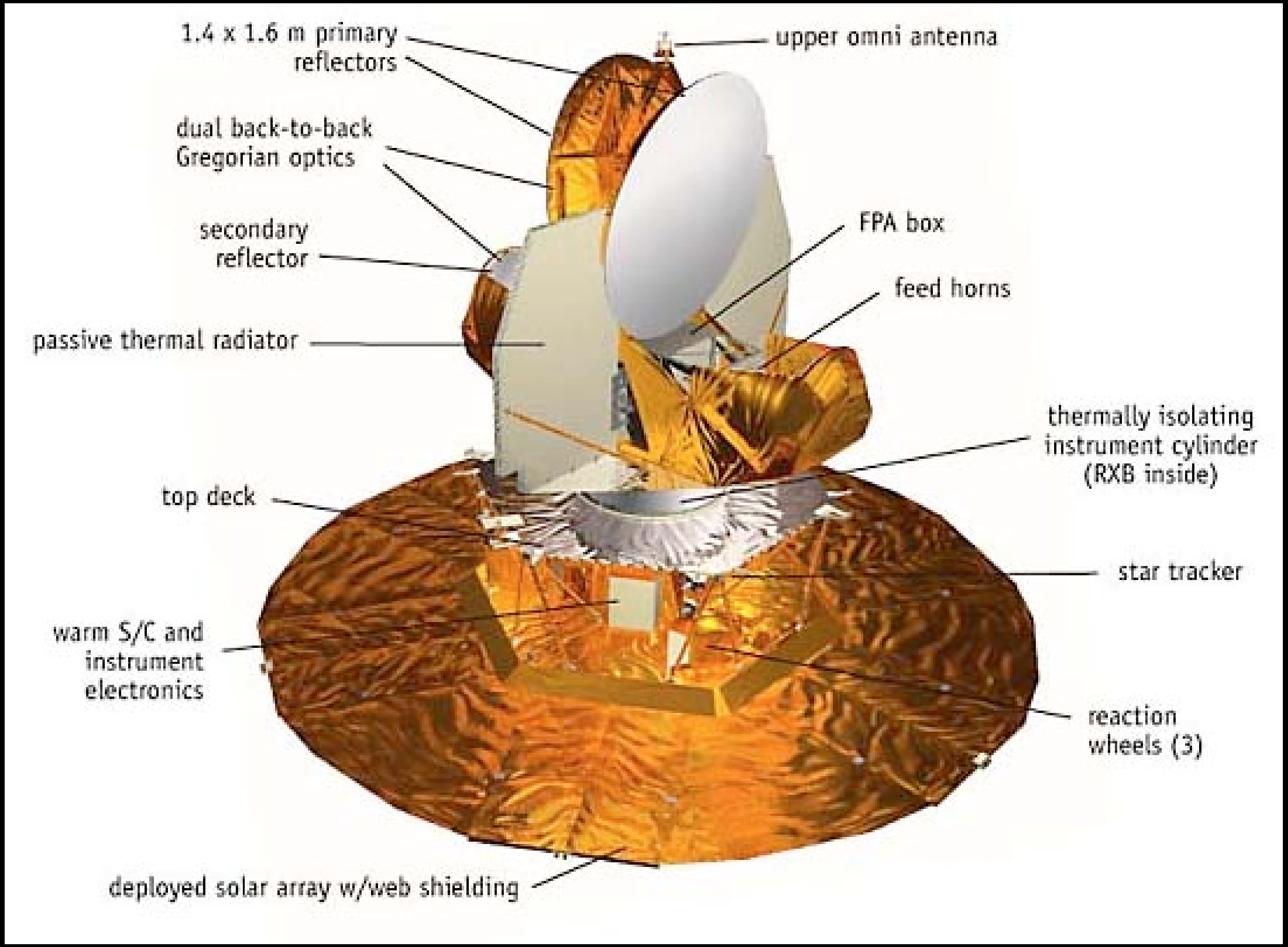


- In the deep survey the S/N is high.
- The fluctuations are gaussian.

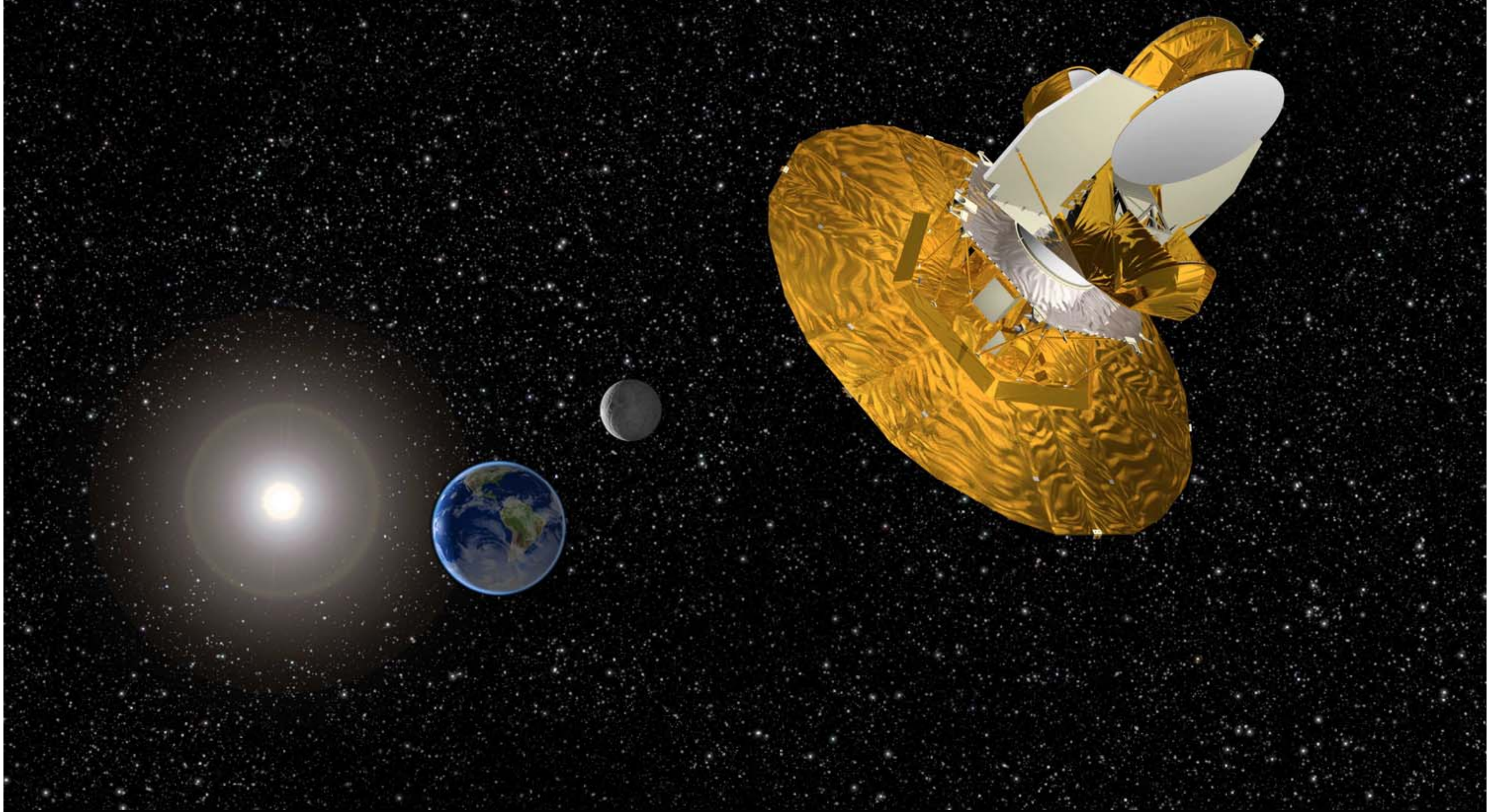
ΔT_{rms} = (90.2±2.3) μK

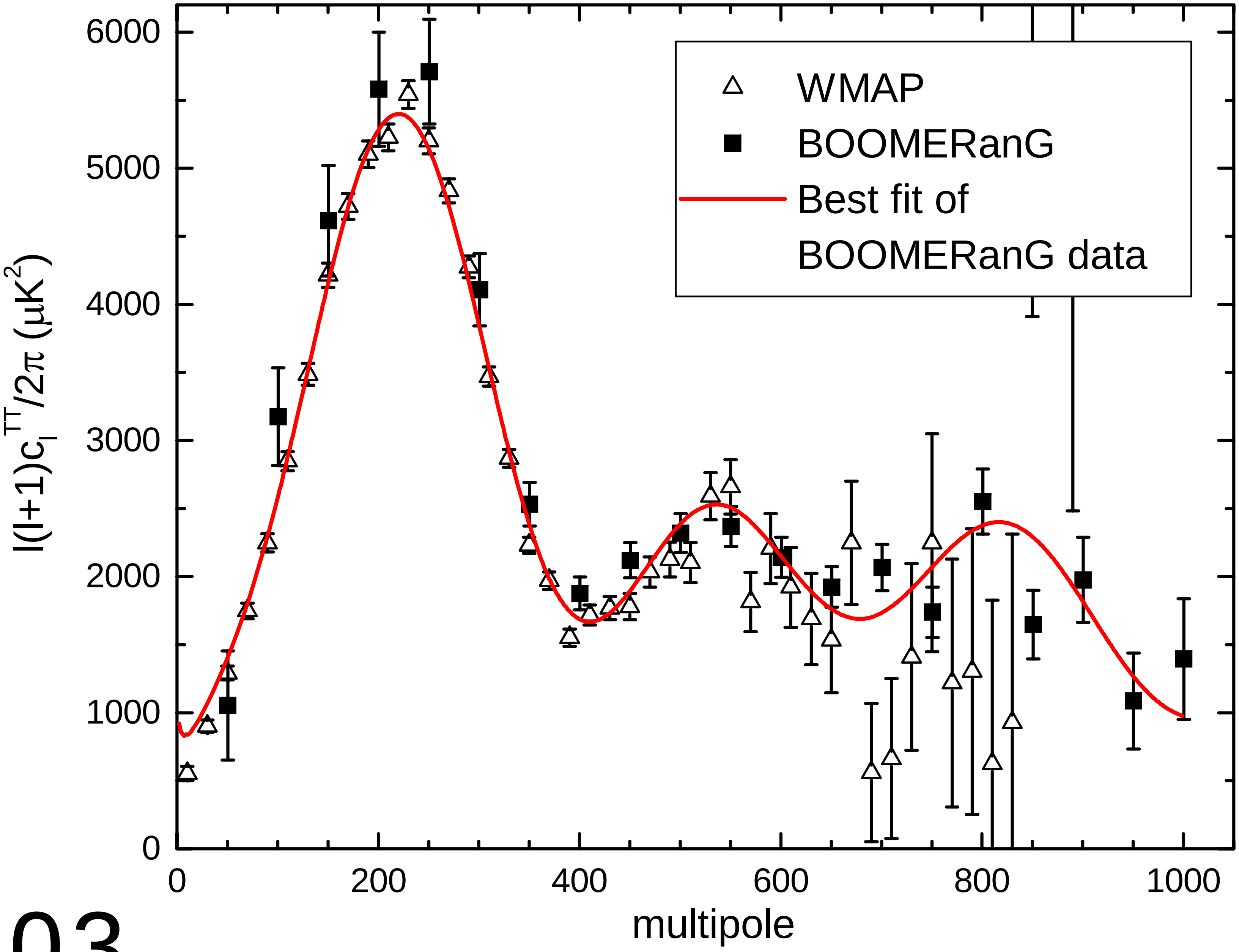
WMAP (2002)

Wilkinson Microwave Anisotropy Probe

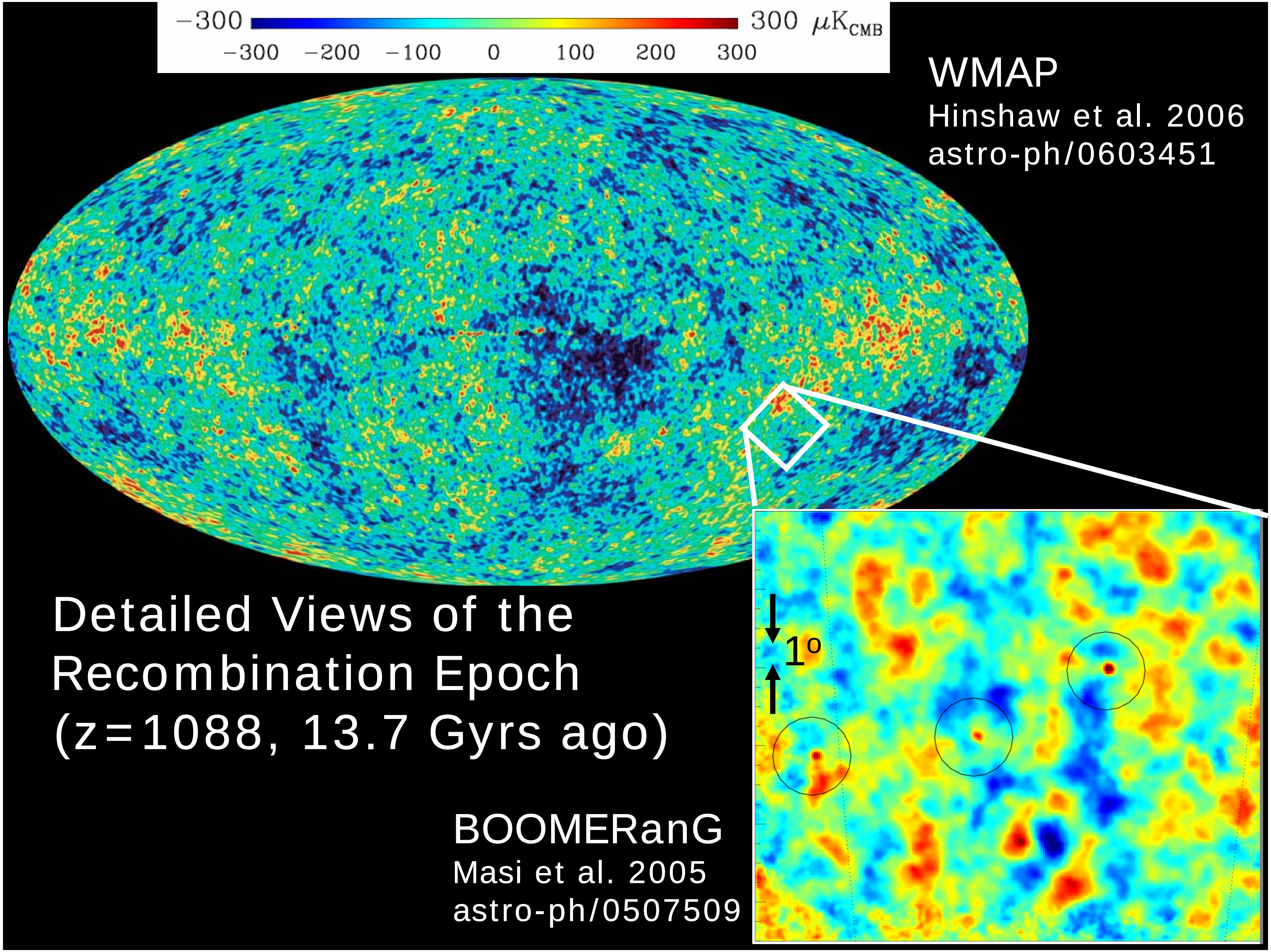


WMAP in L_2 : sun, earth, moon are all well behind the solar shield.




WMAP
BOOMERanG
Best fit of BOOMERanG data
$l(l+1)c_l^{TT}/2\pi$ (μK^2)
0
1000
2000
3000
4000
5000
6000
0
200
400
600
800
1000
multipole

2003



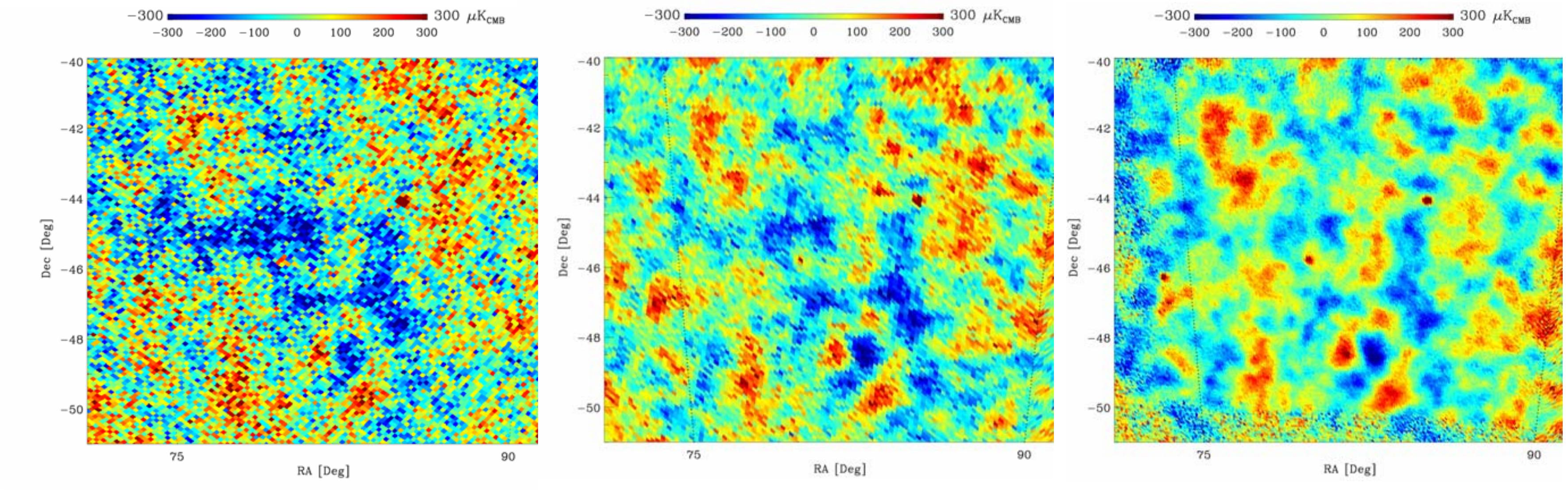
WMAP

Hinshaw et al. 2006
astro-ph/0603451

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

BOOMERanG

Masi et al. 2005
astro-ph/0507509



WMAP 3 years
23-94 GHz

BOOMERanG-98
145 GHz

BOOMERanG-03
145 GHz

The consistency of the maps from three *independent* experiments, working at very different frequencies and with very different mesurement methods, is the best evidence that the faint structure observed

- *is not due to instrumental artifacts*
- *has exactly the spectrum of CMB anisotropy, so it is not due to foreground emission*
- The comparison also shows the *extreme sensitivity of cryogenic bolometers* operated at balloon altitude (the B03 map is the result of 5 days of observation)

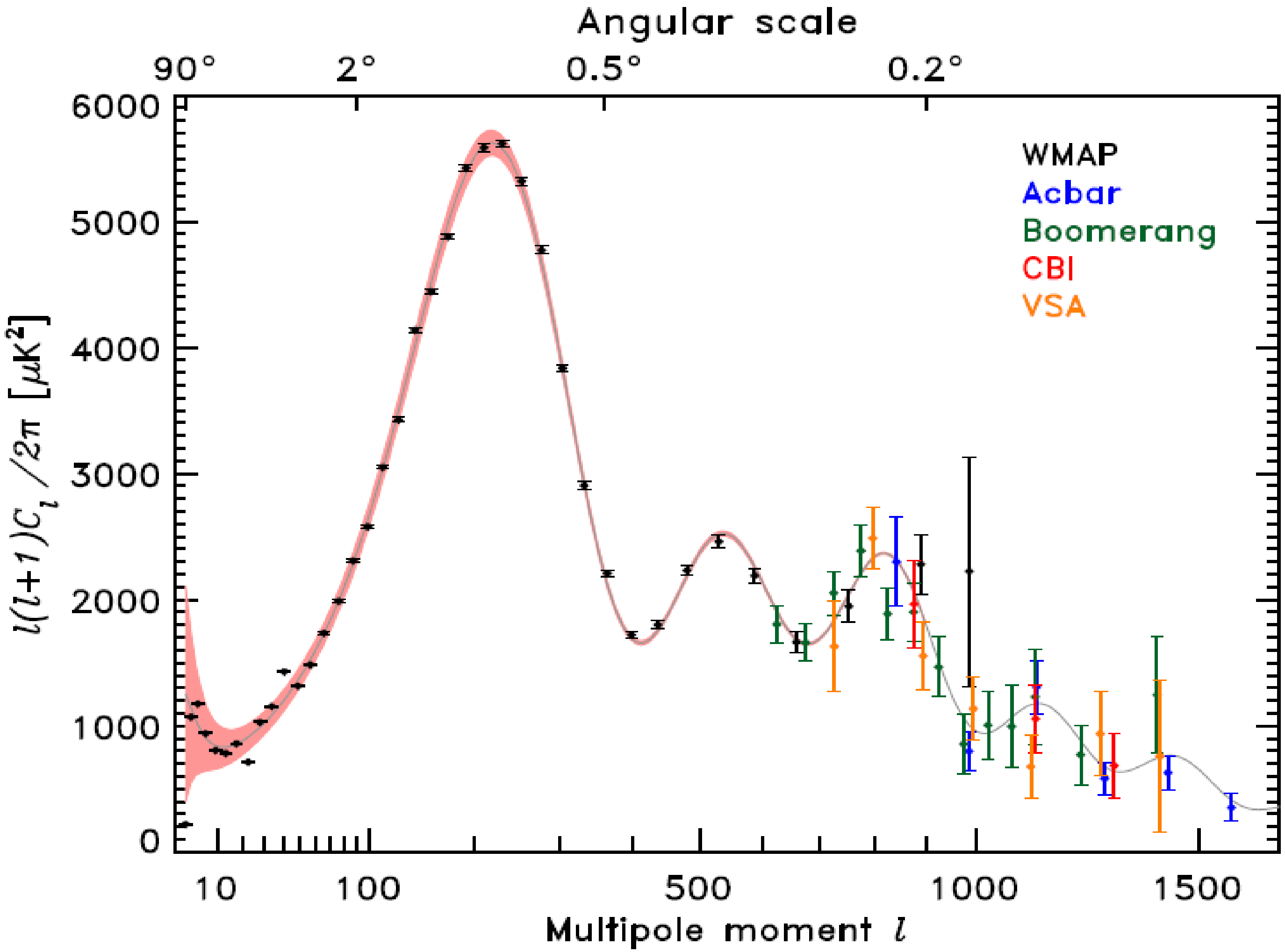


Fig. 18.— The *WMAP* three-year power spectrum (in black) compared to other recent measurements of the CMB angular power spectrum, including Boomerang (Jones et al. 2005), Acbar (Kuo et al. 2004), CBI (Readhead et al. 2004), and VSA (Dickinson et al. 2004). For clarity, the $l < 600$ data from Boomerang 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. d sensitivity on sub-degree scales, the *WMAP* data are becoming an increasingly important rce for high-resolution experiments.

2006

Hinshaw et al. 2006

- The second LDB flight of BOOMERanG was devoted to CMB polarization measurements
- Was motivated by the desire to measure polarization :
  - at 145 GHz (higher ν wrt WMAP, DASI, CBI etc.)
  - with bolometers (vs. coherent amplifiers of WMAP, DASI, CBI etc.)
  - controlling the dominant foreground (dust) by means of simultaneous observations at higher frequencies (245, 345 GHz)
  - in one of the best sky regions (foreground-wise)
  - in a multipoles range where the polarization signal can be higher than the foreground signal.

Universita' di Roma, La Sapienza:
P. de Bernardis, G. De Troia, A. Iacoangeli, **S. Masi**, A. Melchiorri, L. Nati, F. Nati, F. Piacentini, G. Polenta, S. Ricciardi, P. Santini, M. Veneziani

Case Western Reserve University:
J. Ruhl, T. Kisner, E. Torbet, T. Montroy

Caltech/JPL:
A. Lange, J. Bock, W. Jones, V. Hristov

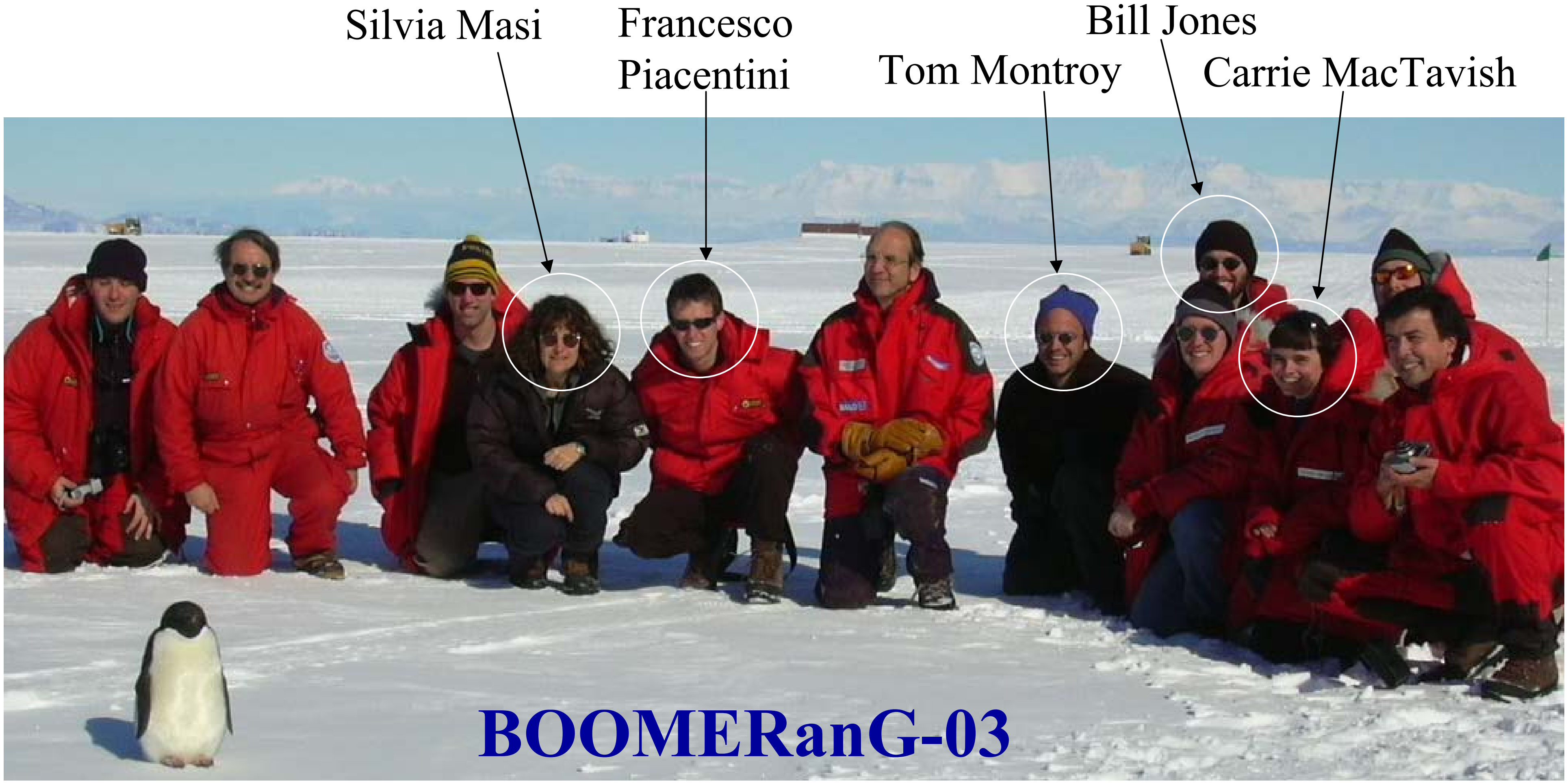
University of Toronto:
B. Netterfield, C. MacTavish, E. Pascale

Cardiff University: P. Ade, **P. Mauskopf**
IFAC-CNR: A. Boscaleri
INGV: G. Romeo, G. di Stefano
IPAC: B. Crill, E. Hivon
CITA: D. Bond, S. Prunet, D. Pogosyan
LBNL, UC Berkeley: J. Borrill
Imperial College: A. Jaffe, C. Contaldi
U. Penn.: M. Tegmark, A. de Oliveira-Costa
Universita' di Roma, Tor Vergata: N. Vittorio, G. de Gasperis, P. Natoli, P. Cabella

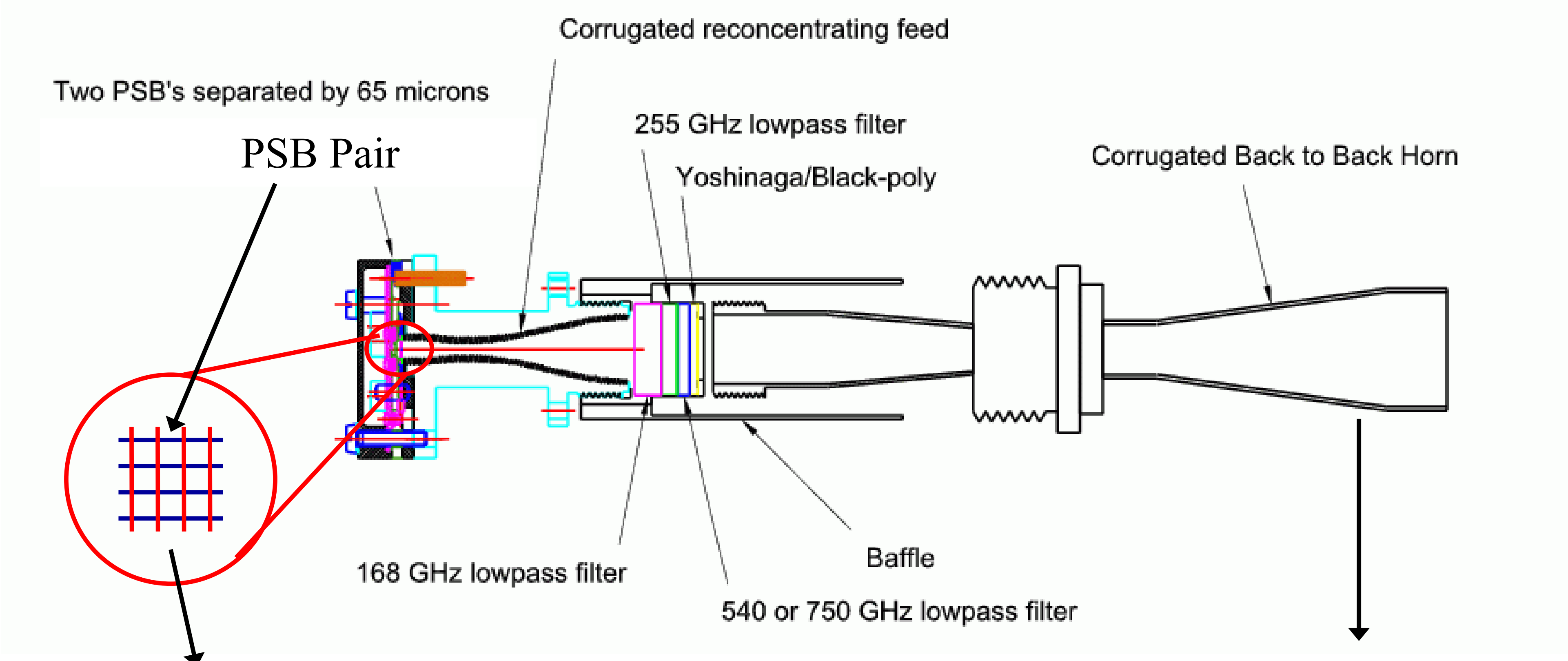
BOOMERanG-03

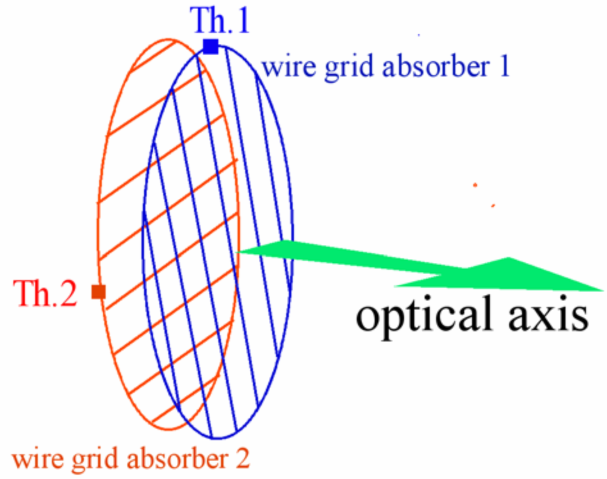
First release of
data: July 2005
Five papers:

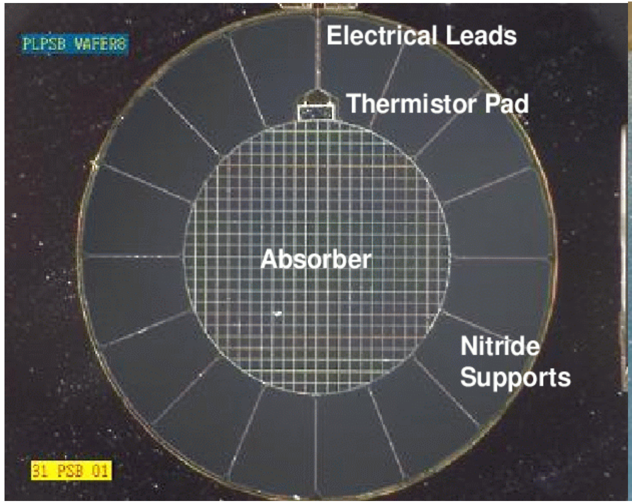
- Masi et al. astro-ph/0507509 : instrument & maps
- Jones et al. astro-ph/0507494 : <TT>
- Piacentini et al. astro-ph/0507507 : <TE>
- Montroy et al. astro-ph/0507514 : <EE>
- MacTavish et al. astro-ph/0507503 : cosmological parameters



PSB devices & feed optics (Caltech + JPL)







06/01/2003

From Page et al. 2006

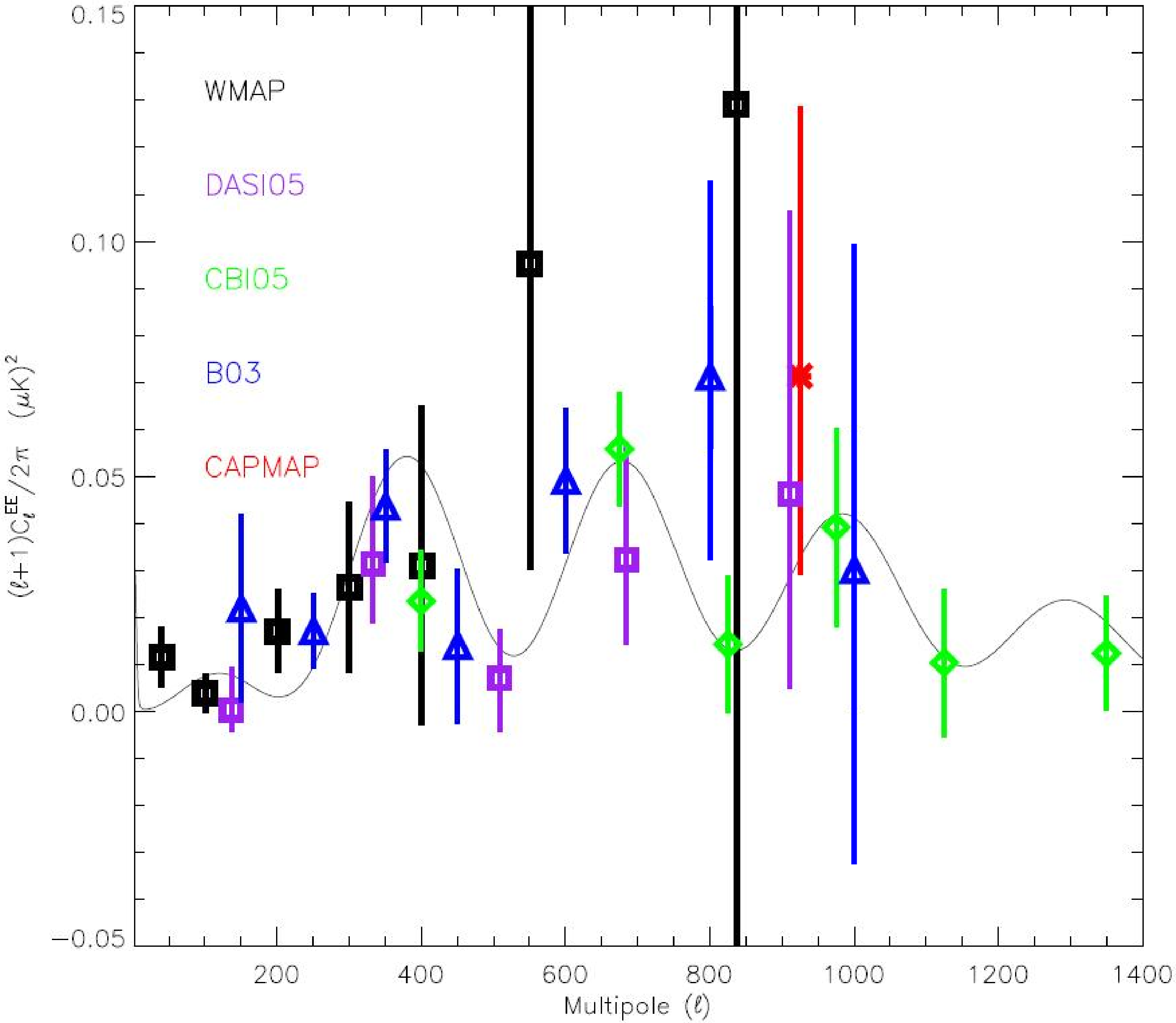
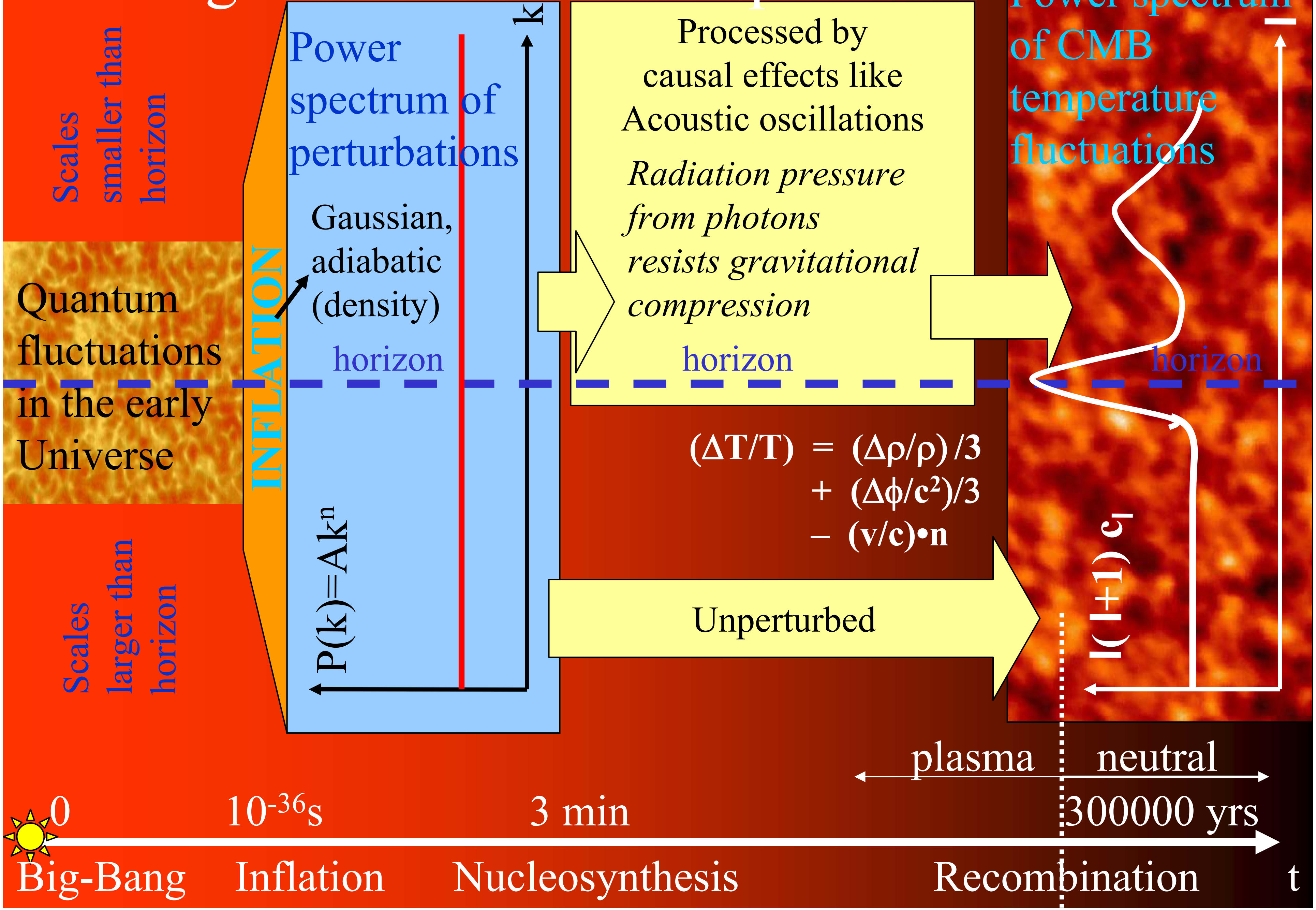


FIG. 22.— The EE spectrum at $\ell > 40$ for all measurements of the CMB polarization. The curve is the best fit EE spectrum. Note that the y axis has only one power of ℓ. The black boxes are the *WMAP* data; the triangles are the BOOMERanG data; the squares are the DASI data; the diamonds are the CBI data; and the asterisk is the CAPMAP data. The *WMAP* data are the QVW combination. For the first point, the cleaned value is used. For other values, the raw values are used. The data are given in Table 8

Paradigm of CMB anisotropies



Scales smaller than horizon

Quantum fluctuations in the early Universe

Scales larger than horizon

INFLATION

Power spectrum of perturbations

Gaussian, adiabatic (density)

horizon

k

$P(k)=Ak^n$

Processed by causal effects like Acoustic oscillations

Radiation pressure from photons resists gravitational compression

horizon

$$(\Delta T/T) = (\Delta\rho/\rho)/3 + (\Delta\phi/c^2)/3 - (v/c)\bullet n$$

Unperturbed

Power spectrum of CMB temperature fluctuations

horizon

$l(l+1)\,c_l$

l

plasma neutral

0 10^{-36}s 3 min 300000 yrs

Big-Bang Inflation Nucleosynthesis Recombination t

Cosmological Parameters

Assume an adiabatic inflationary model, and compare with same weak prior on 0.5<h<0.9

WMAP

(100% of the sky, <1% gain calibration, <1% beam, multipole coverage 2-700)

Bennett et al. 2003

- $\Omega_o = 1.02 \underline{+} 0.02$
- $n_s = 0.99 \underline{+} 0.04$ *
- $\Omega_b h^2 = 0.022 \underline{+} 0.001$
- $\Omega_m h^2 = 0.14 \underline{+} 0.02$
- $T = 13.7 \underline{+} 0.2$ Gyr
- $\tau_{rec} = 0.166 \underline{+} 0.076$

BOOMERanG

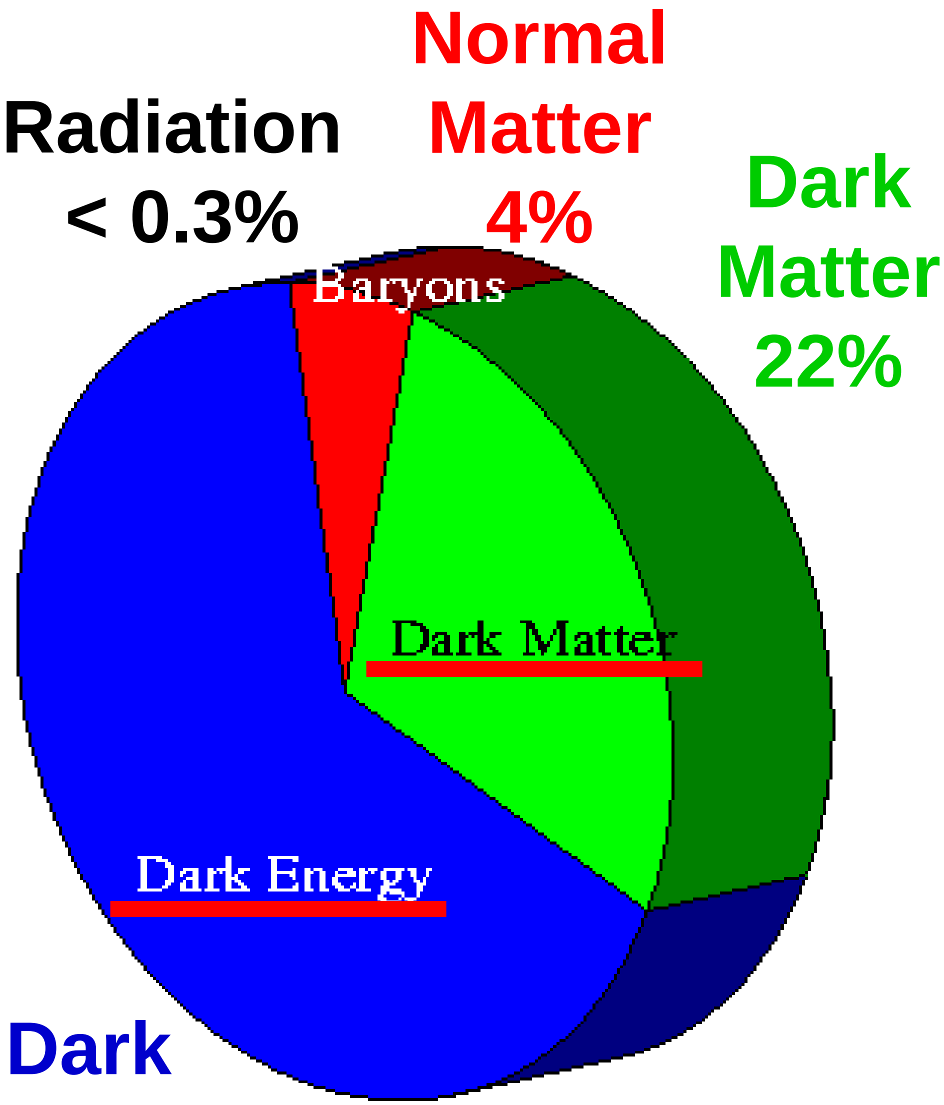
(4% of the sky, 10% gain calibration, 10% beam, multipole coverage 50-1000)

Ruhl et al. astro-ph/0212229

- $\Omega_o = 1.03 \underline{+} 0.05$
- $n_s = 1.02 \underline{+} 0.07$
- $\Omega_b h^2 = 0.023 \underline{+} 0.003$
- $\Omega_m h^2 = 0.14 \underline{+} 0.04$
- $T = 14.5 \underline{+} 1.5$ Gyr
- $\tau_{rec} = ?$

- There is a minimalist model with only 6 free parameters (H_o, Ω_o, Ω_b, Ω_Λ, n, A) describing very well the angular power spectrum of the CMB, but also other measurements:
  - The spectrum of the CMB
  - The abundances of primordial light elements
  - The expansion of the Universe
  - The fluxes of high redshift SN1a “candles”
  - The large-scale distribution of galaxies and Ly-α clouds
  - The polarization of the CMB …. Etc …
- So a question could be: “ are we done with cosmology ?...”
- Not at all. The “model” is still not satisfactory, since it requires “dark matter”, “dark energy”, and also an “inflation phase” in the very early universe, and there is no evidence from non-cosmological physics for these three components.
- As a CMB experimentalist, I would rather try to answer two different questions:
  - **are there open issues in CMB anisotropy measurements ?**
  - **are there critical CMB observations still to be done ?**

INFLATION


Radiation
< 0.3%
Normal
Matter
4%
Dark
Matter
22%
Baryons
Dark Matter
Dark Energy
Dark
Energy
74%

- There is a minimalist model with only 6 free parameters (H_o, Ω_o, Ω_b, Ω_Λ, n, A) describing very well the angular power spectrum of the CMB, but also other measurements:
  - The spectrum of the CMB
  - The abundances of primordial light elements
  - The expansion of the Universe
  - The fluxes of high redshift SN1a "candles"
  - The large-scale distribution of galaxies and Ly-α clouds
  - The polarization of the CMB …. Etc …
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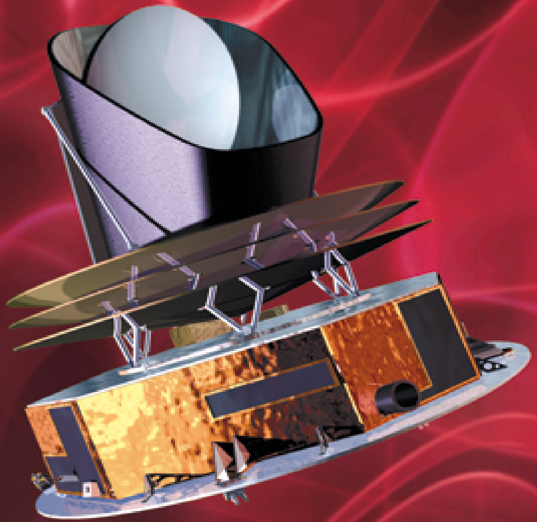
- As a CMB experimentalist, I would rather try to answer two different questions:
  - **are there open issues in CMB anisotropy measurements ?**
  - **are there critical CMB observations still to be done ?**

YES !



esa

PLANCK

Looking back to the dawn of time
Un regard vers l'aube du temps

http://sci.esa.int/planck

PLANCK

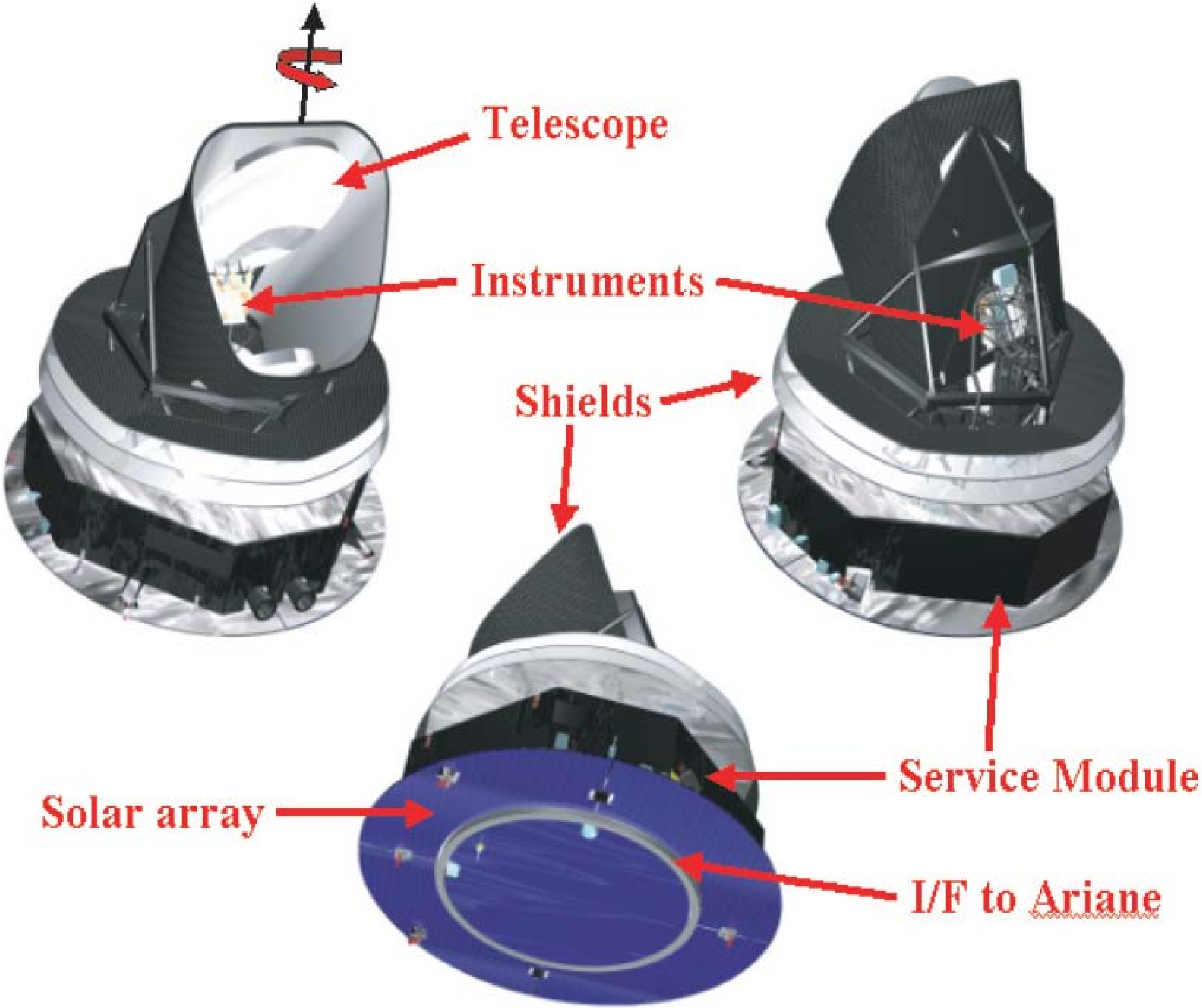
ESA mission to map the Cosmic Microwave Background

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

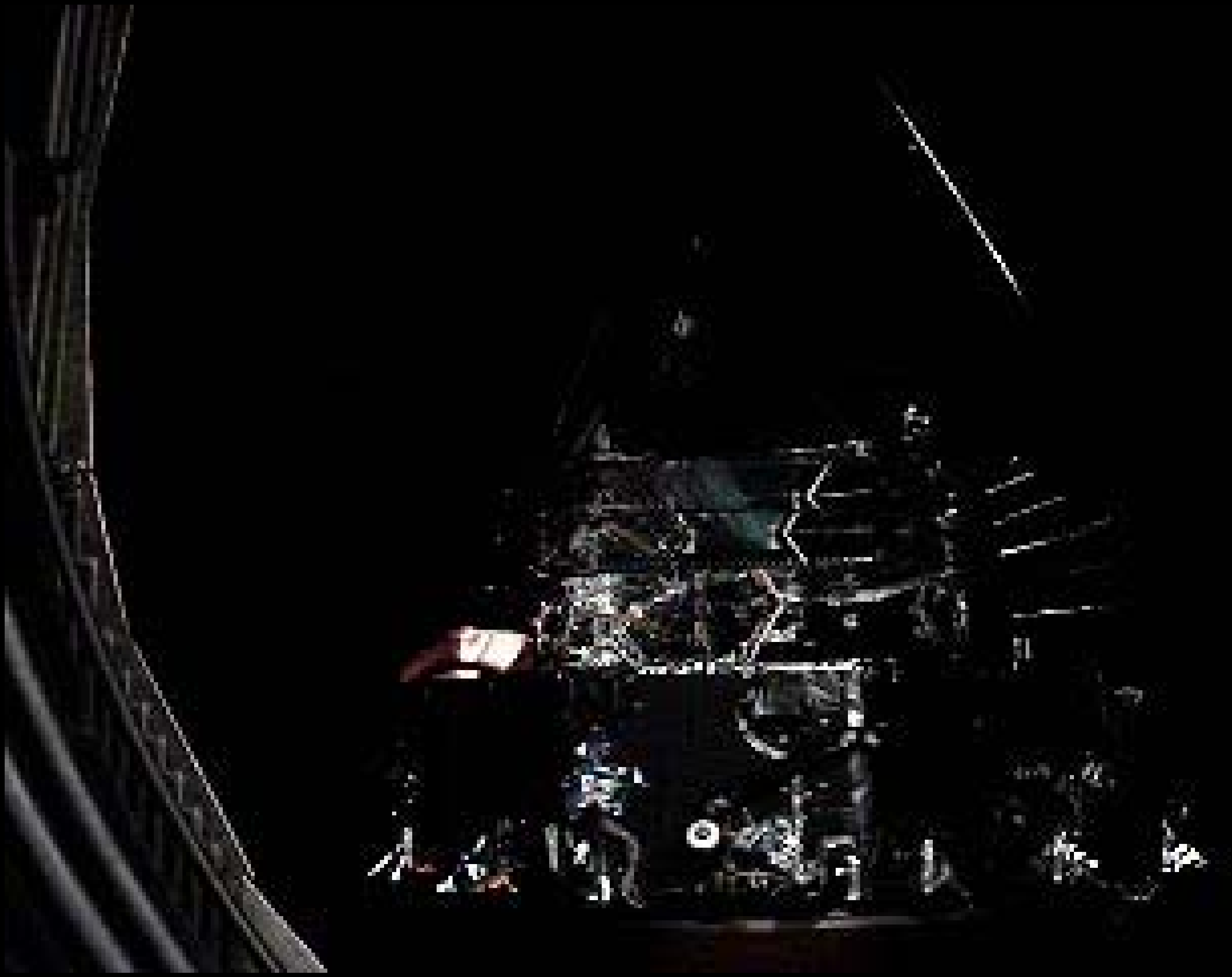
- high instrument sensitivity ($\Delta T/T \sim 10^{-6}$)
- high resolution (≈5 arcmin)
- wide frequency coverage (25 GHz-950 GHz)
- high control of systematics

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)

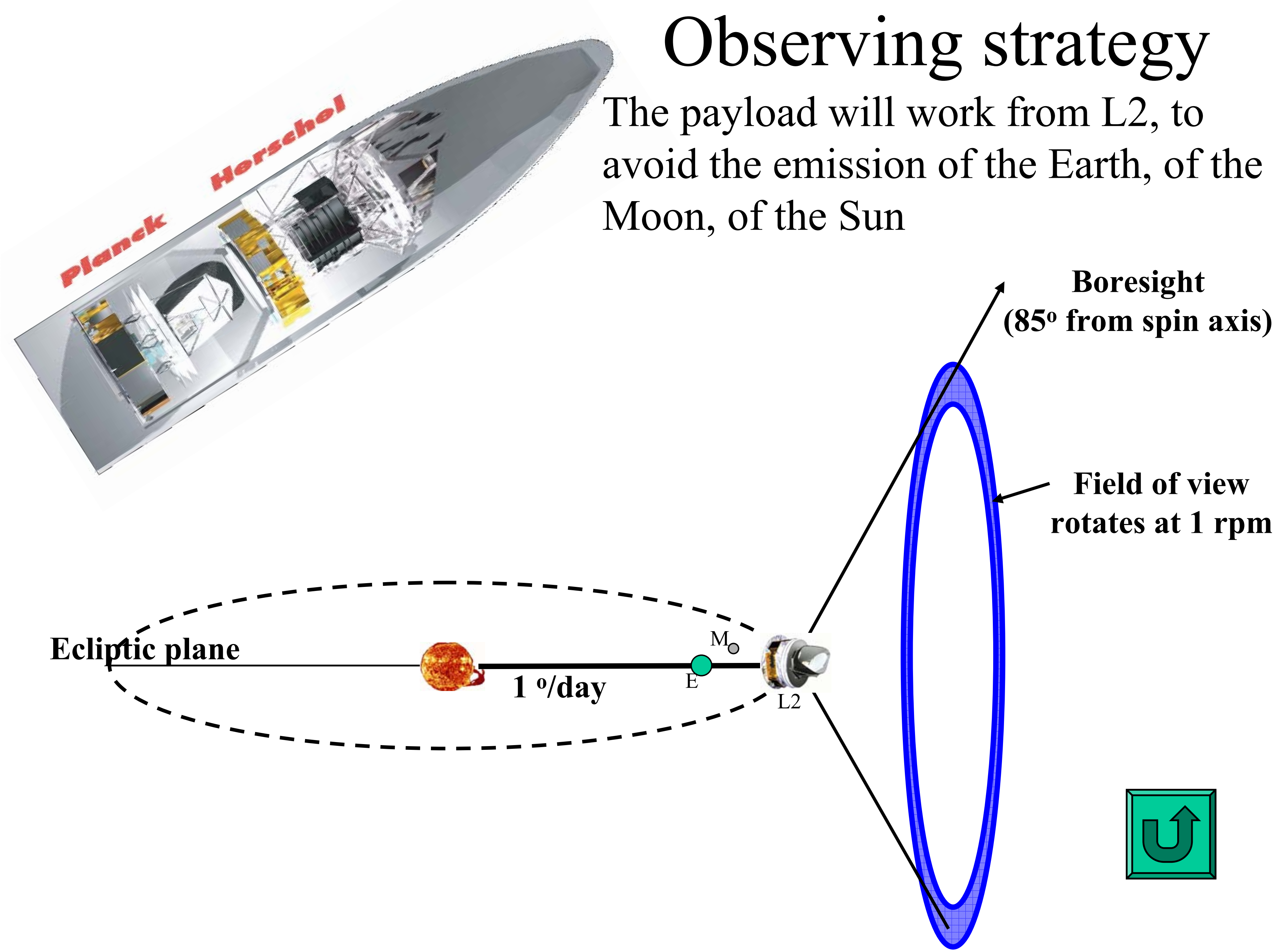

Telescope
Instruments
Shields
Service Module
Solar array
I/F to Ariane

Planck rotated in the thermal-vacuum chamber of ESA (real video, not a simulation !)



Observing strategy

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



Boresight (85° from spin axis)

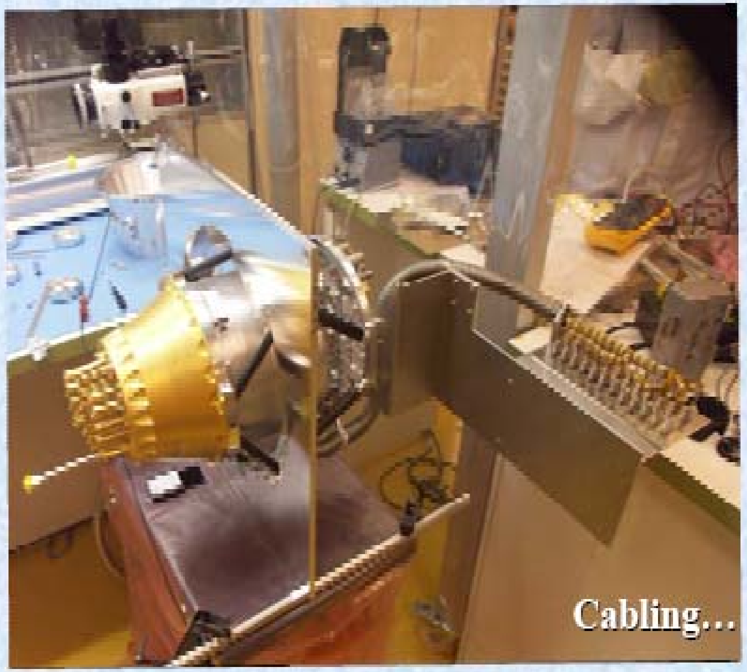
Field of view rotates at 1 rpm

Ecliptic plane

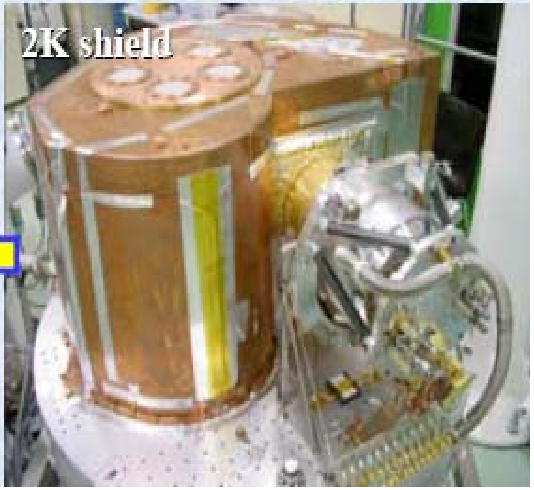
1 °/day

CQM integration & calibration @ IAS

(CQM = Cryogenic Qualification Model)


Cabling…

2K platform


2K shield

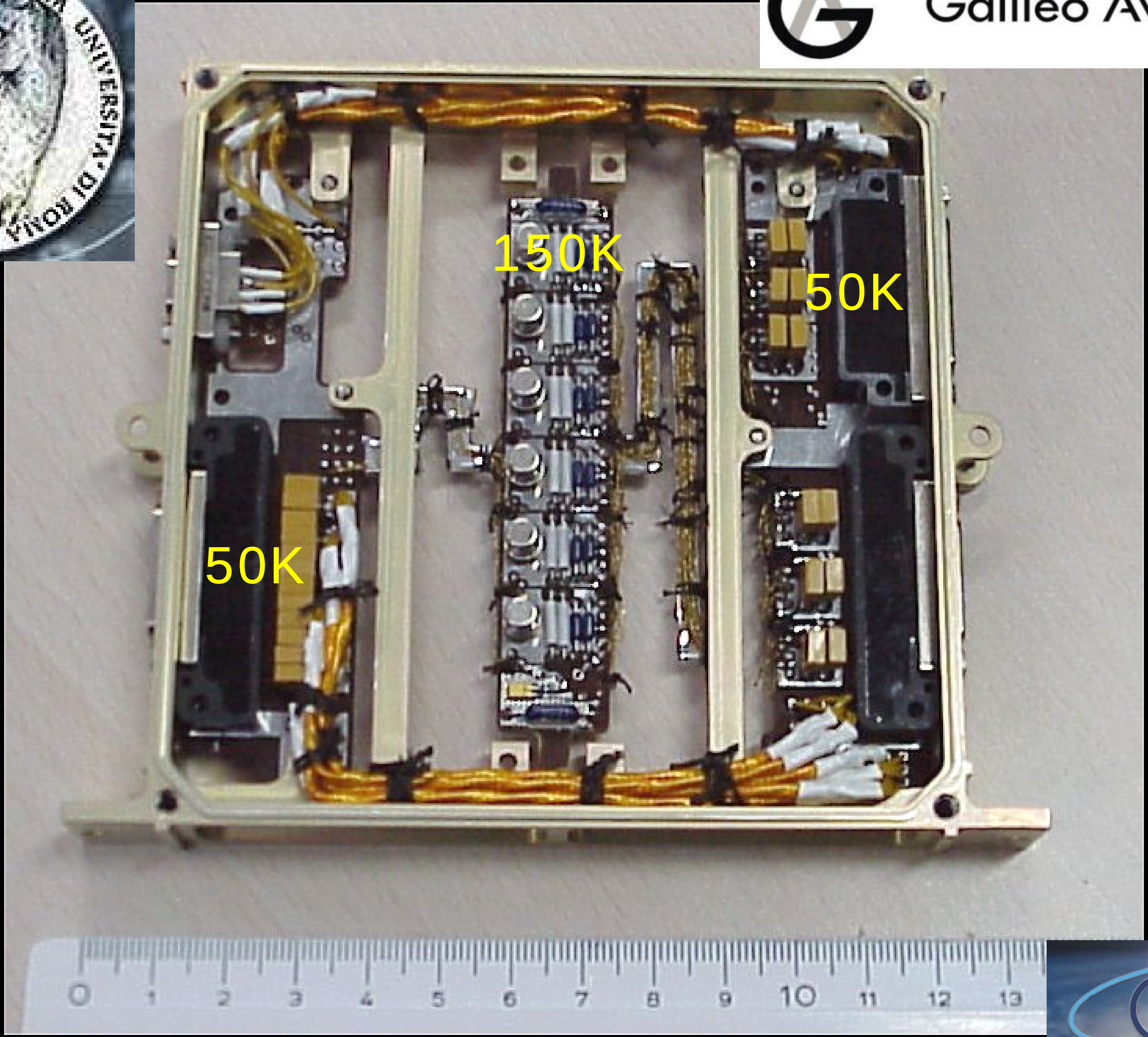

20K shield


In ops,
Nov 2004

- And the full cryogenic qualification model has been vibration and thermal tested.

DIPARTIMENTO DI FISICA UNIVERSITA' DI ROMA "LA SAPIENZA"

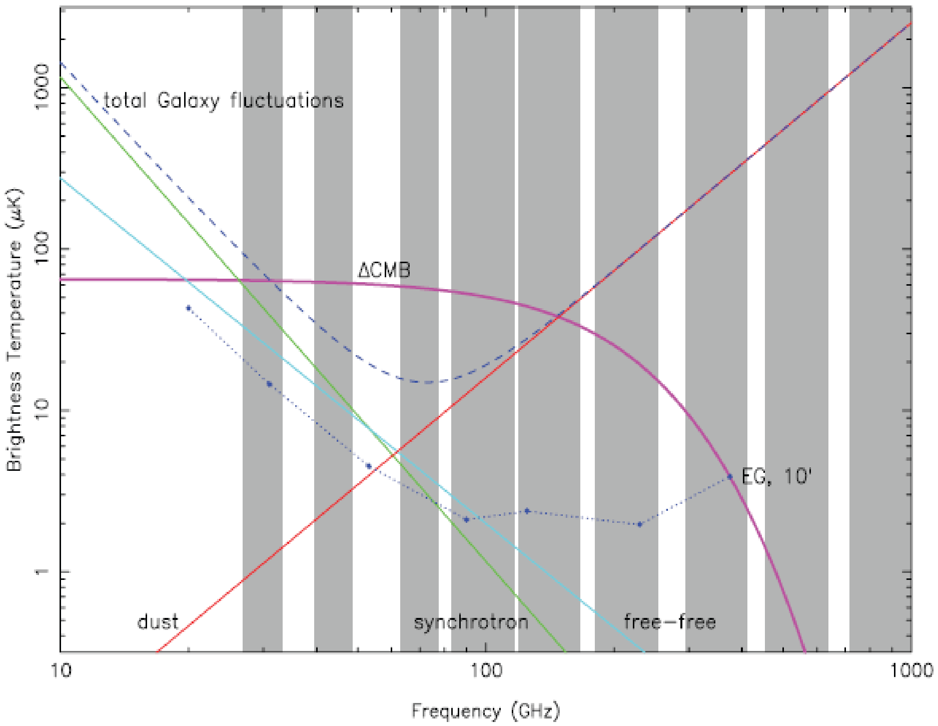
Galileo Avionica



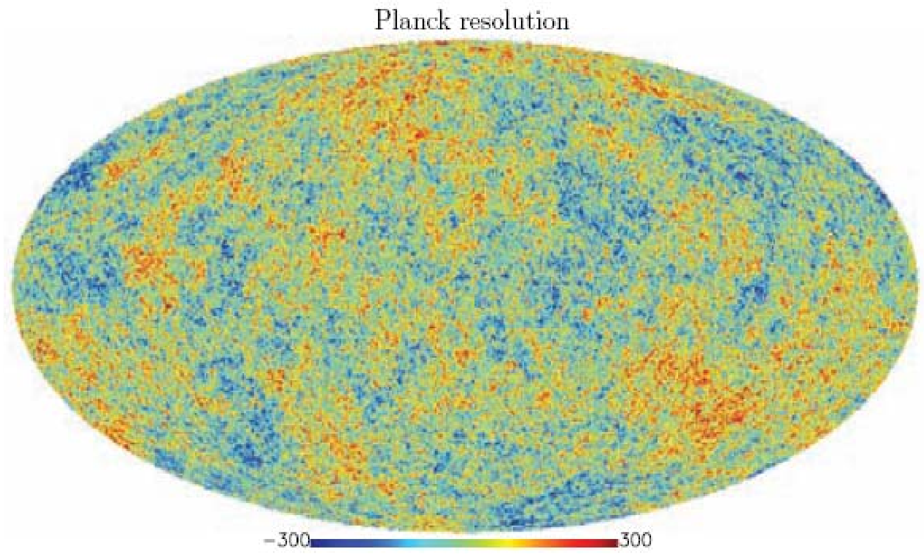
agenzia spaziale italiana

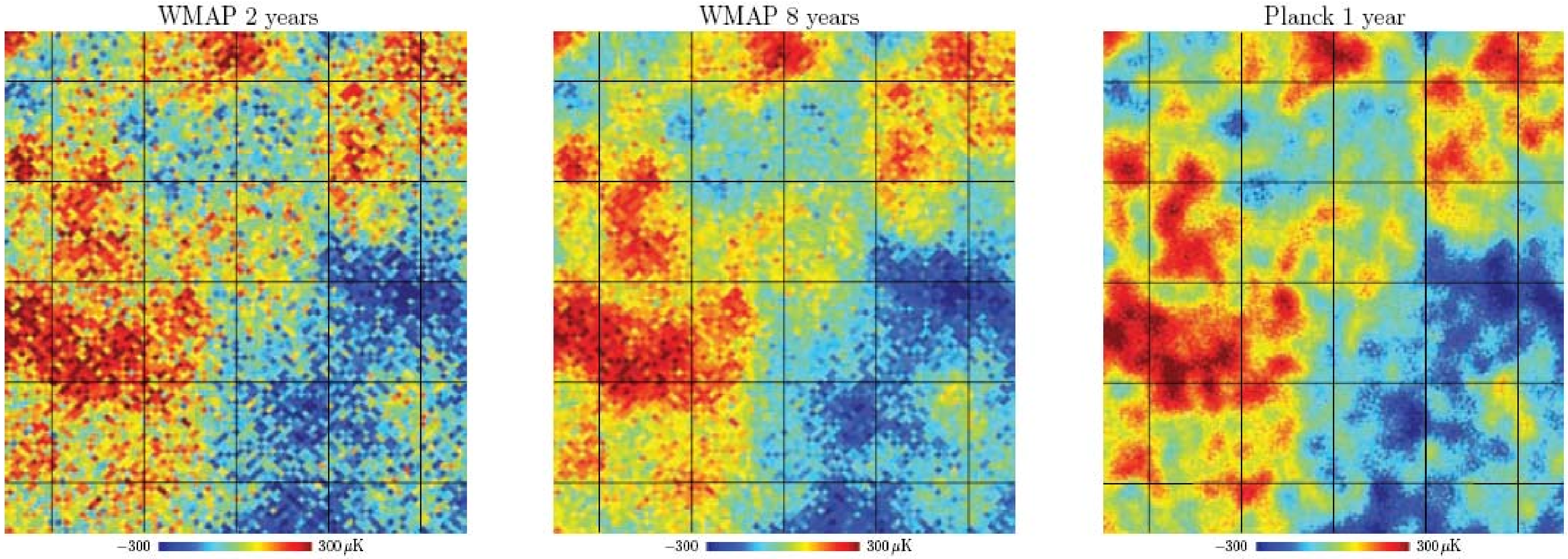
So we can expect in 2 years from now :

- 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



Planck resolution





WMAP 2 years

WMAP 8 years

Planck 1 year

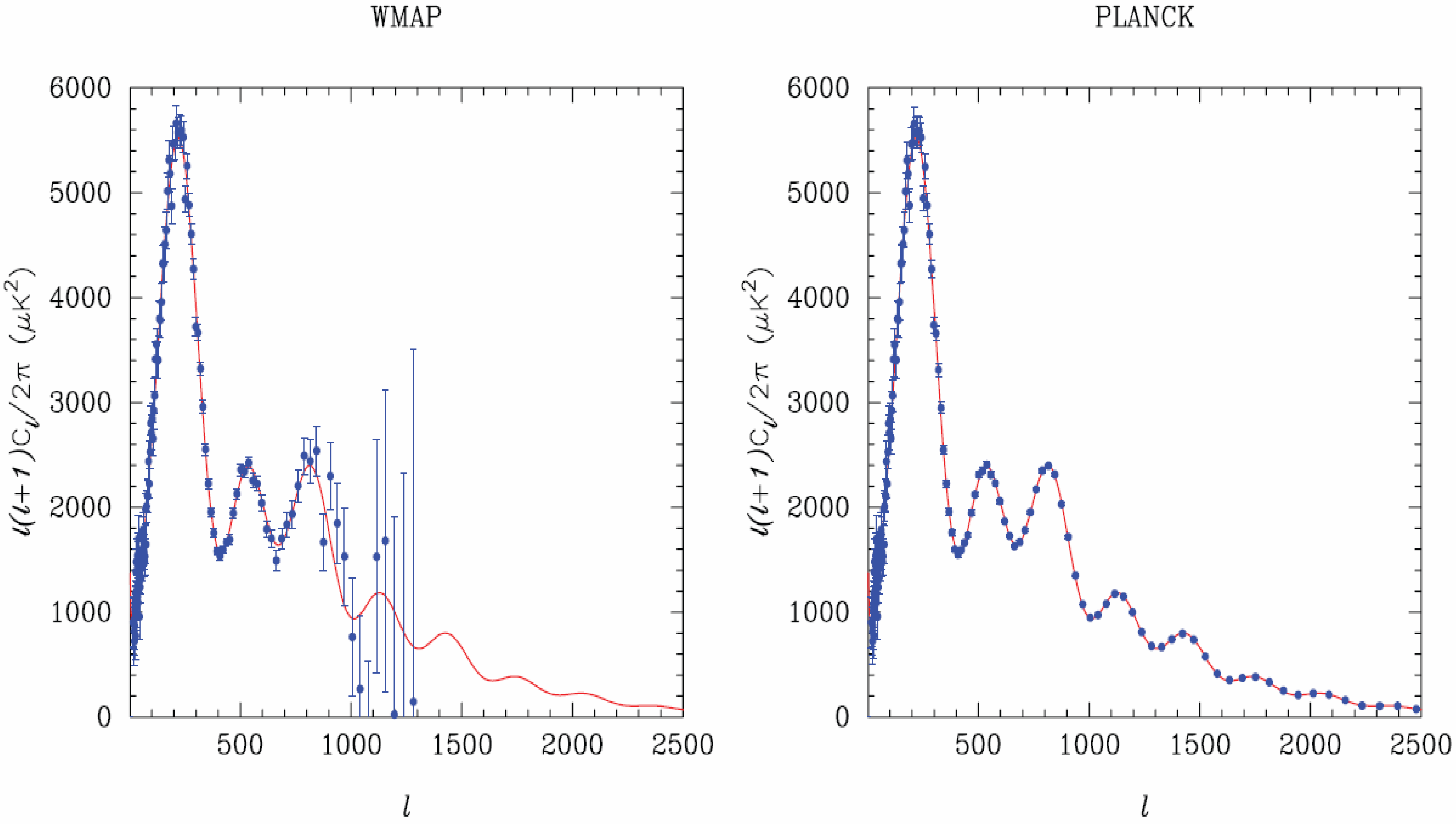


FIG 2.8.—The left panel shows a realisation of the CMB power spectrum of the concordance ΛCDM model (red line) after 4 years of *WMAP* observations. The right panel shows the same realisation observed with the sensitivity and angular resolution of *Planck*.

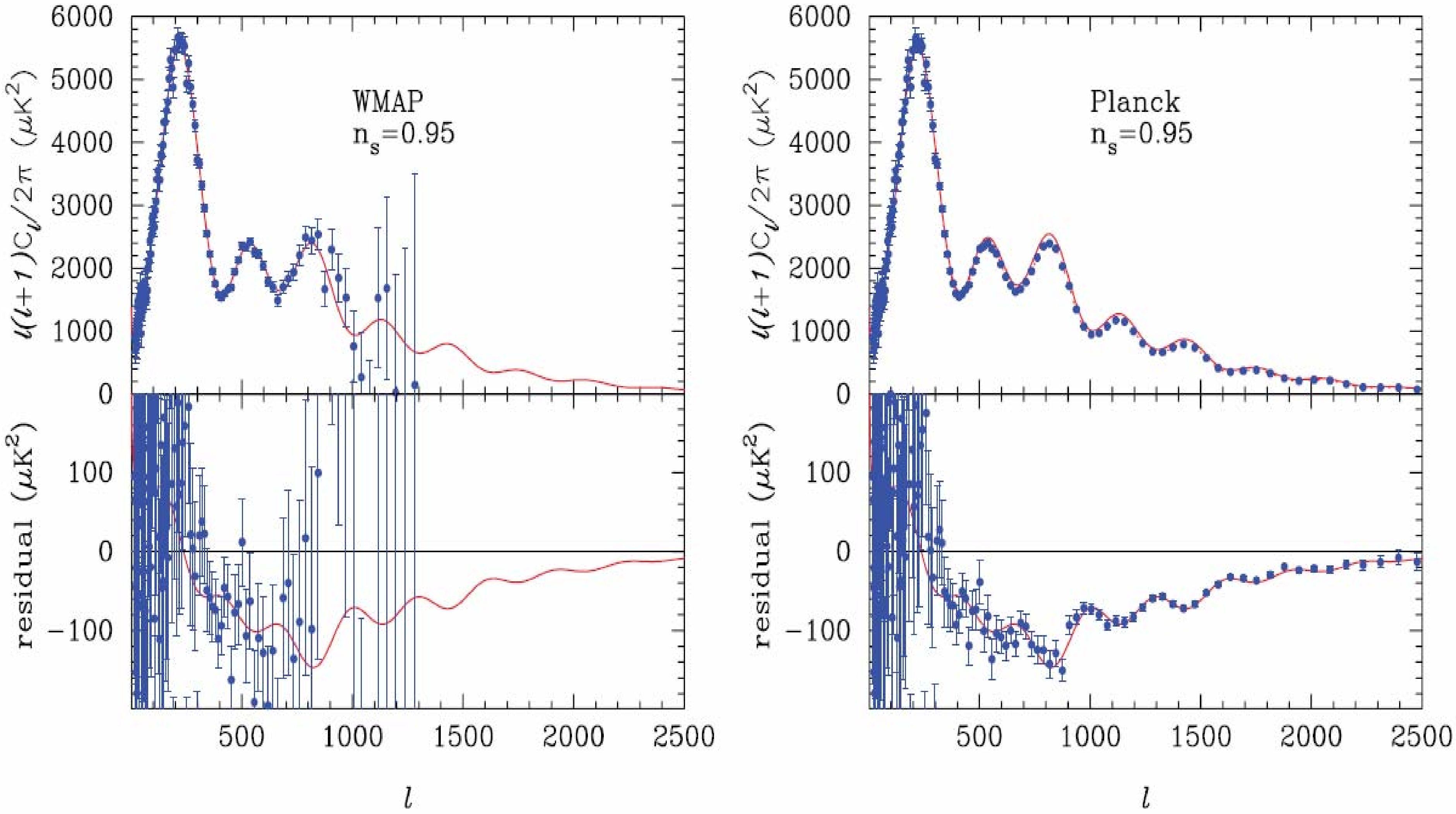


FIG 2.11.—The solid lines in the upper panels of these figures show the power spectrum of the concordance ΛCDM model with an exactly scale invariant power spectrum, $n_S = 1$. The points, on the other hand, have been generated from a model with $n_S = 0.95$ but otherwise identical parameters. The lower 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.

Planck and Neutrinos

- Neutrinos affect the power spectra TT, TE, EE
- Free-streaming neutrinos suppress the amplitude of matter fluctuations at wavenumbers $k>0.03(m_\nu/eV)\Omega_m^{1/2}$ Mpc^{-1}. This effect can be seen combining matter surveys (SDSS, 2dF etc.) with CMB anisotropy. Current data constrain $m_\nu<0.7eV$.
- Planck data will improve this bound safely down to 0.2eV.
- Through gravitational lensing, CMB measurements are also sensitive to the matter power spectrum at intermediate redshifts, thus adding sensitivity to the effects of neutrinos on matter fluctuations.
- The effective number of neutrinos ($N_\nu=3.04$ at the epoch of Big Bang Nucleosynthesis) can be constrained since it produces a slight shift in the position of the doppler peaks.
- With Planck the measured spectra will constrain N_ν with $\Delta N_\nu=0.24$.

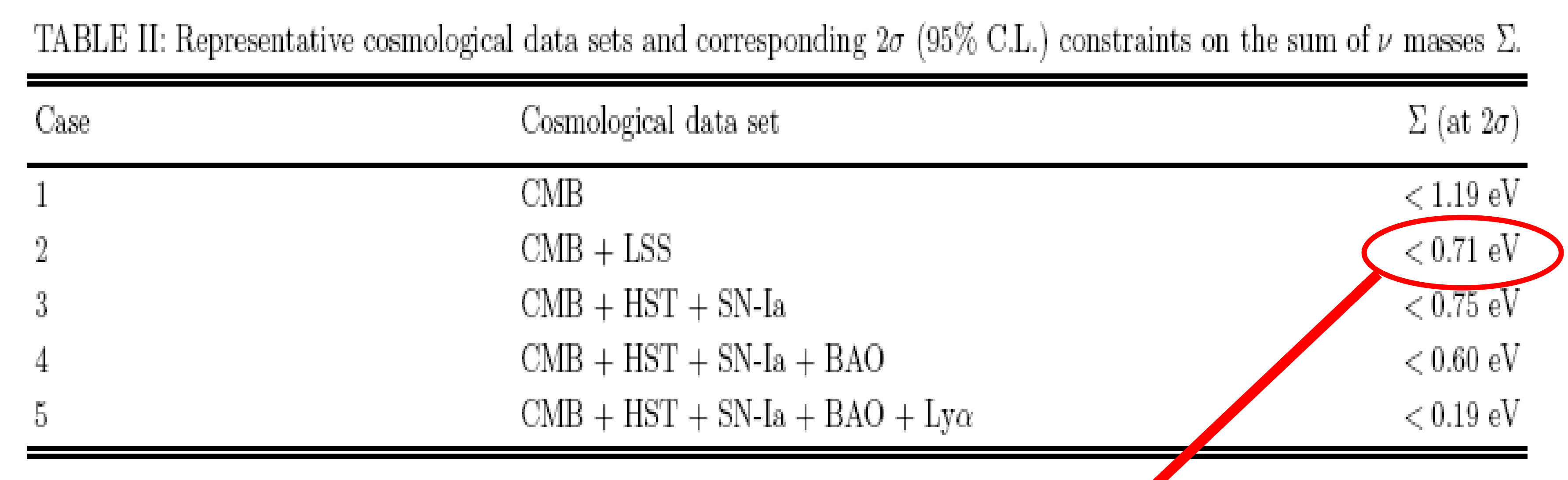


TABLE II: Representative cosmological data sets and corresponding 2σ (95% C.L.) constraints on the sum of ν masses Σ.

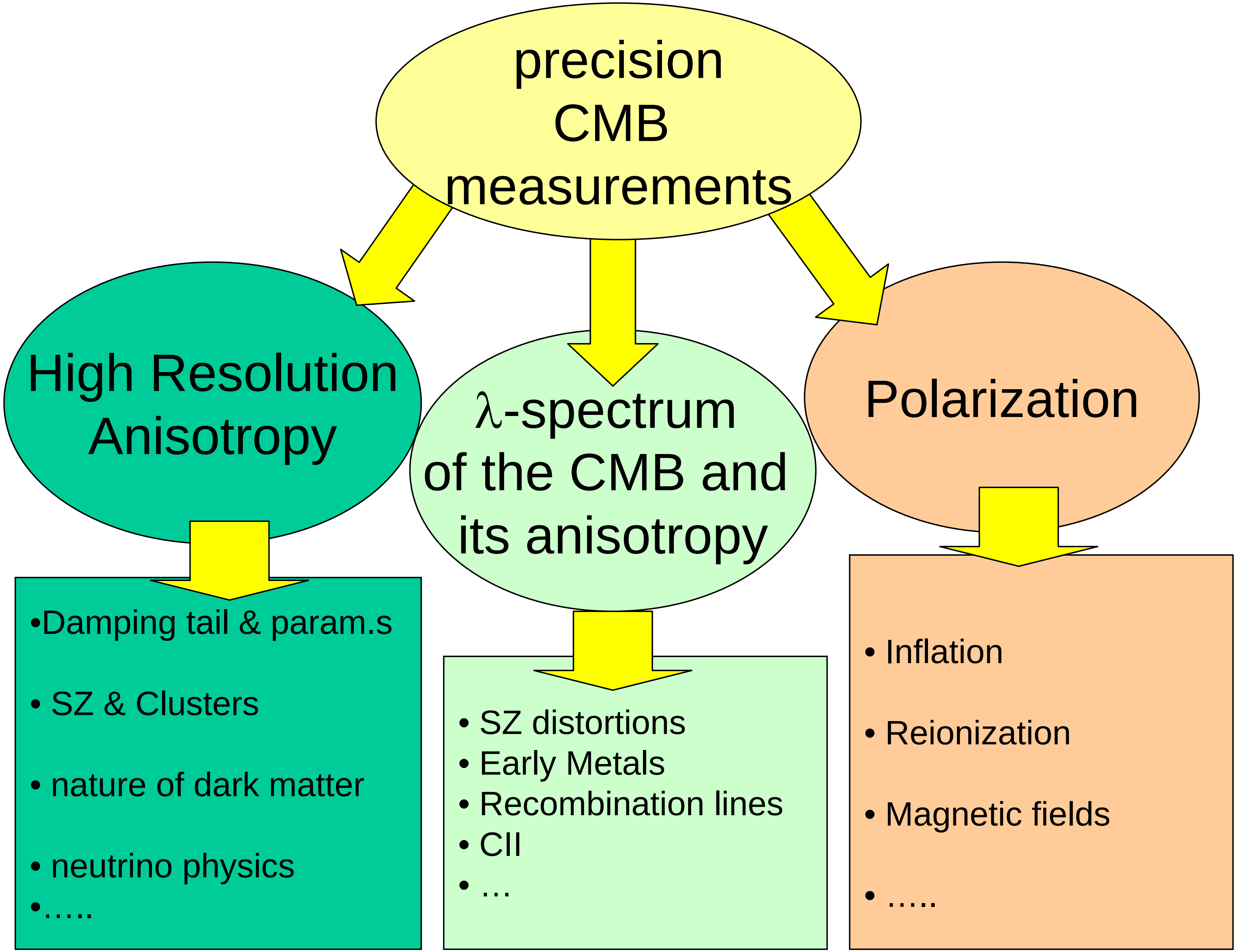
Case	Cosmological data set	Σ (at 2σ)
1	CMB	< 1.19 eV
2	CMB + LSS	< 0.71 eV
3	CMB + HST + SN-Ia	< 0.75 eV
4	CMB + HST + SN-Ia + BAO	< 0.60 eV
5	CMB + HST + SN-Ia + BAO + Lyα	< 0.19 eV

From Fogli et al. 2008, Astro-ph/0805.2517

With Planck : < 0.2 eV

After Planck

- Planck will do many things but will not do:
  - Measurement of B-Modes (gravitational waves from inflation)
  - Measurements at high angular resolution
  - Deep surveys of clusters and superclusters of galaxies



precision CMB measurements

High Resolution Anisotropy

- Damping tail & param.s
- SZ & Clusters
- nature of dark matter
- neutrino physics
- …..

λ-spectrum of the CMB and its anisotropy

- SZ distortions
- Early Metals
- Recombination lines
- CII
- …

Polarization

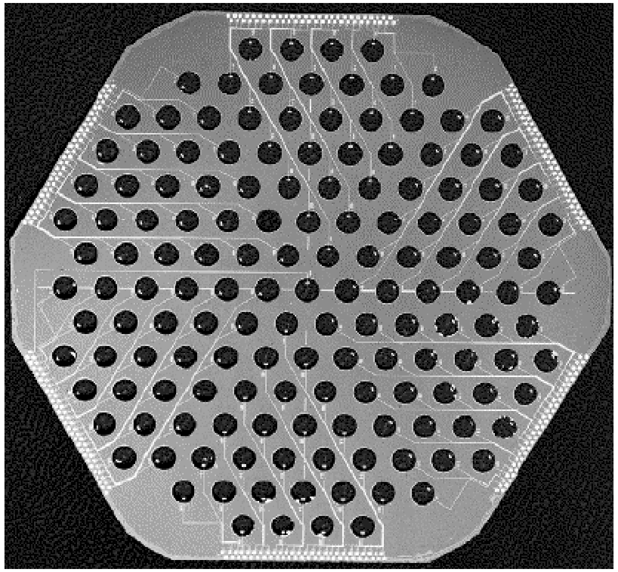
- Inflation
- Reionization
- Magnetic fields
- …..

After Planck: CMB arrays

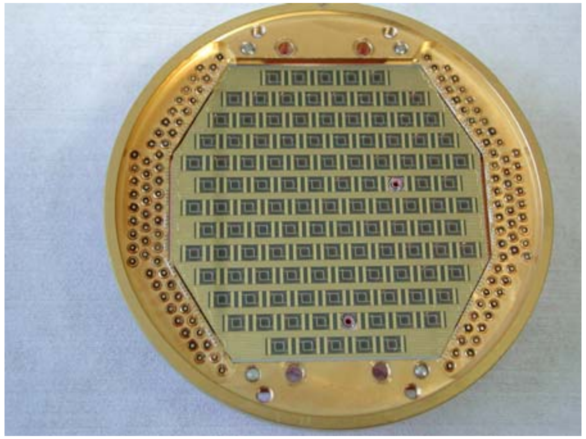
- Once we get to the photon noise limit, the only way to improve the measurement is to improve the mapping speed, i.e. to produce large detector arrays.
- The most important characteristic of future CMB detectors, in addition to be CMB noise limited, is the possibility to ***replicate detectors in large arrays*** at a reasonable cost.
- Suitable detection methods:
  - TES bolometers arrays
  - Direct detection and KIDs arrays

Bolometer Arrays

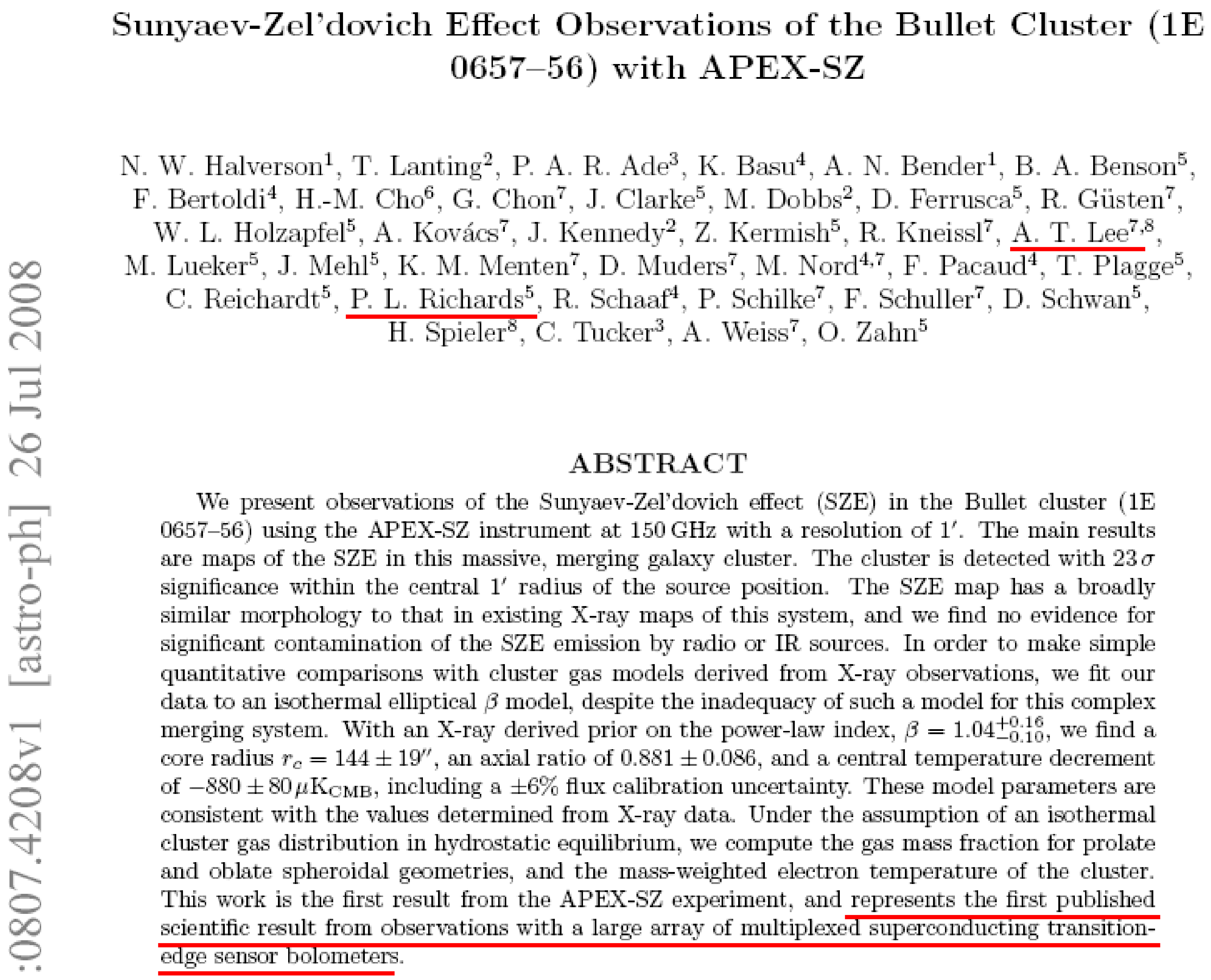
- Once bolometers reach BLIP conditions (CMB BLIP), the mapping speed can only be increased by creating large bolometer arrays.
- BOLOCAM and MAMBO are examples of large arrays with hybrid components (Si wafer + Ge sensors)
- Techniques to build fully litographed arrays for the CMB are being developed.
- TES offer the natural sensors. (A. Lee, D. Benford, A. Golding, F. Gatti ...)



Bolocam Wafer (CSO)



MAMBO (MPIfR for IRAM)



Sunyaev-Zel'dovich Effect Observations of the Bullet Cluster (1E 0657–56) with APEX-SZ

N. W. Halverson[1], T. Lanting[2], P. A. R. Ade[3], K. Basu[4], A. N. Bender[1], B. A. Benson[5], F. Bertoldi[4], H.-M. Cho[6], G. Chon[7], J. Clarke[5], M. Dobbs[2], D. Ferrusca[5], R. Güsten[7], W. L. Holzapfel[5], A. Kovács[7], J. Kennedy[2], Z. Kermish[5], R. Kneissl[7], A. T. Lee[7,8], M. Lueker[5], J. Mehl[5], K. M. Menten[7], D. Muders[7], M. Nord[4,7], F. Pacaud[4], T. Plagge[5], C. Reichardt[5], P. L. Richards[5], R. Schaaf[4], P. Schilke[7], F. Schuller[7], D. Schwan[5], H. Spieler[8], C. Tucker[3], A. Weiss[7], O. Zahn[5]

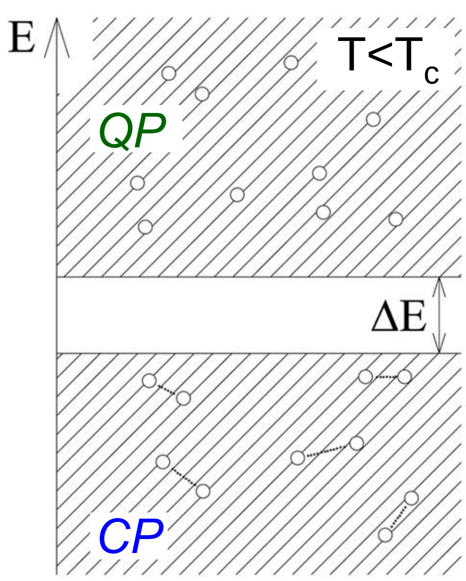
:0807.4208v1 [astro-ph] 26 Jul 2008

ABSTRACT

We present observations of the Sunyaev-Zel'dovich effect (SZE) in the Bullet cluster (1E 0657–56) using the APEX-SZ instrument at 150 GHz with a resolution of $1'$. The main results are maps of the SZE in this massive, merging galaxy cluster. The cluster is detected with $23\,\sigma$ significance within the central $1'$ radius of the source position. The SZE map has a broadly similar morphology to that in existing X-ray maps of this system, and we find no evidence for significant contamination of the SZE emission by radio or IR sources. In order to make simple quantitative comparisons with cluster gas models derived from X-ray observations, we fit our data to an isothermal elliptical β model, despite the inadequacy of such a model for this complex merging system. With an X-ray derived prior on the power-law index, $\beta = 1.04^{+0.16}_{-0.10}$, we find a core radius $r_c = 144 \pm 19''$, an axial ratio of 0.881 ± 0.086, and a central temperature decrement of $-880 \pm 80\,\mu\mathrm{K_{CMB}}$, including a ±6% flux calibration uncertainty. These model parameters are consistent with the values determined from X-ray data. Under the assumption of an isothermal cluster gas distribution in hydrostatic equilibrium, we compute the gas mass fraction for prolate and oblate spheroidal geometries, and the mass-weighted electron temperature of the cluster. This work is the first result from the APEX-SZ experiment, and represents the first published scientific result from observations with a large array of multiplexed superconducting transition-edge sensor bolometers.

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: $Z_s = R_s + i\Omega L_s$

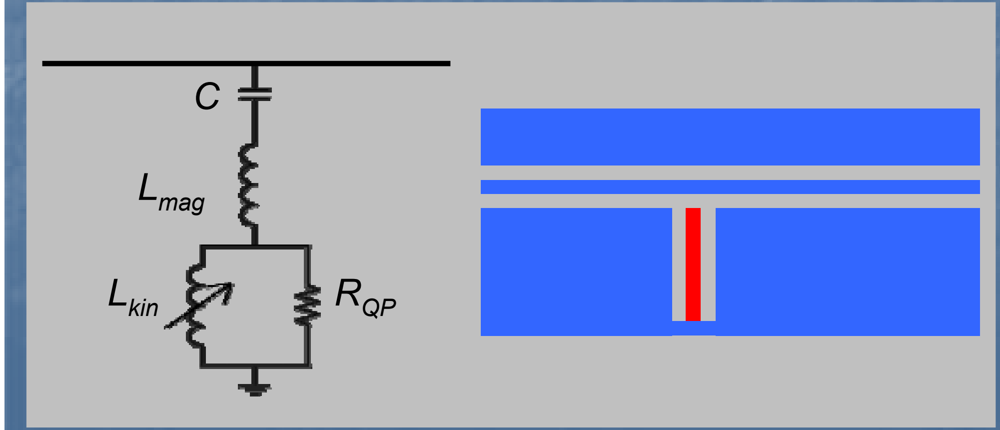
CP

Quasi-Particles $L_{magn} + L_{kin}$

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

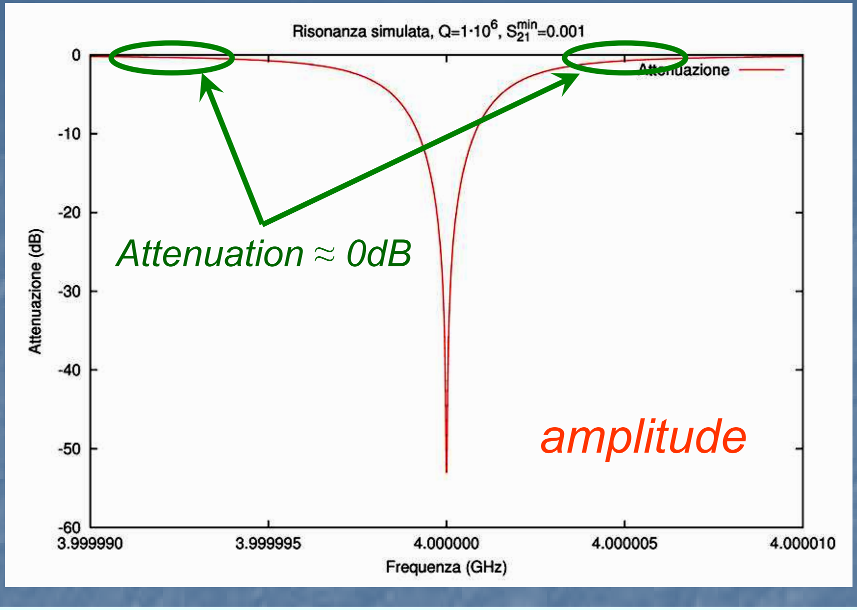
depends on the density of CPs, n_{CP}:

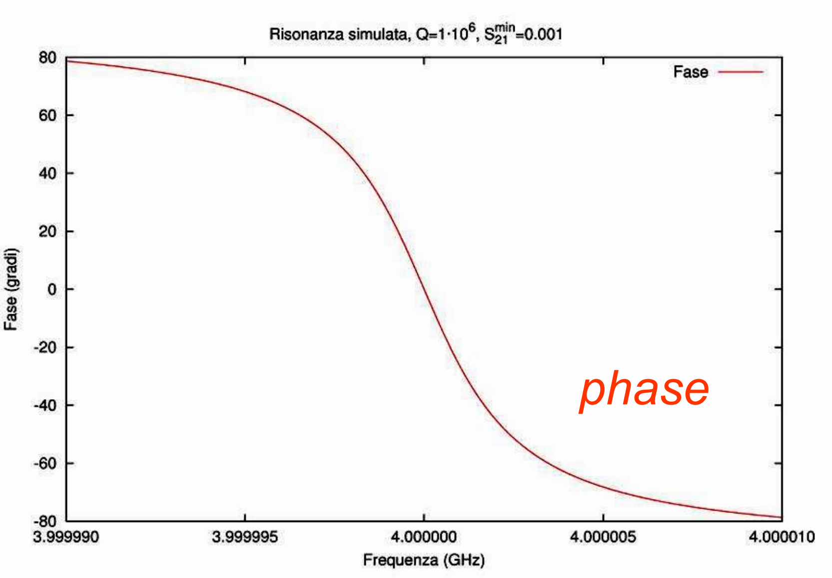
n_{CP} ↑ L_{kin} ↓



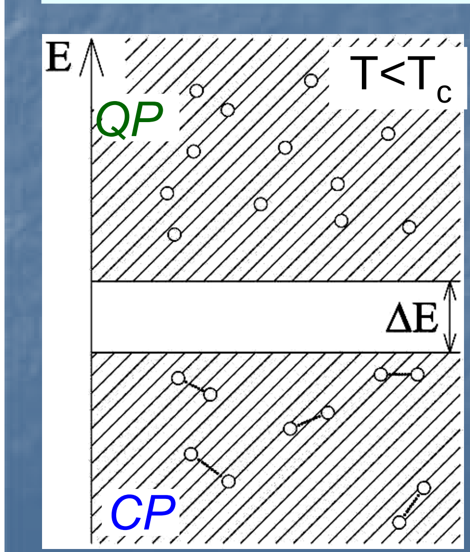
The value of L_{kin} can be measured by capacitively coupling a strip of superconductor to a feed line. One thus gets an *LC* resonator with ***very high Q values.***

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

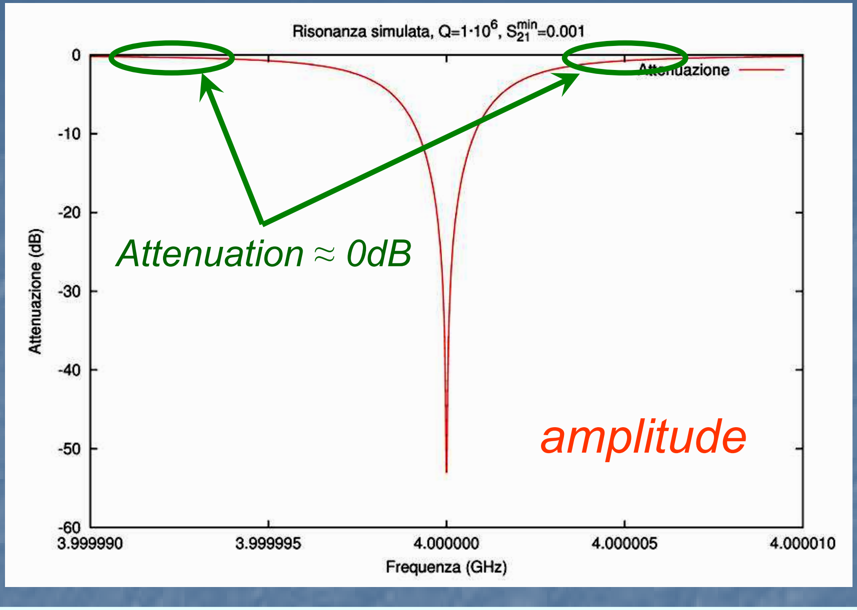


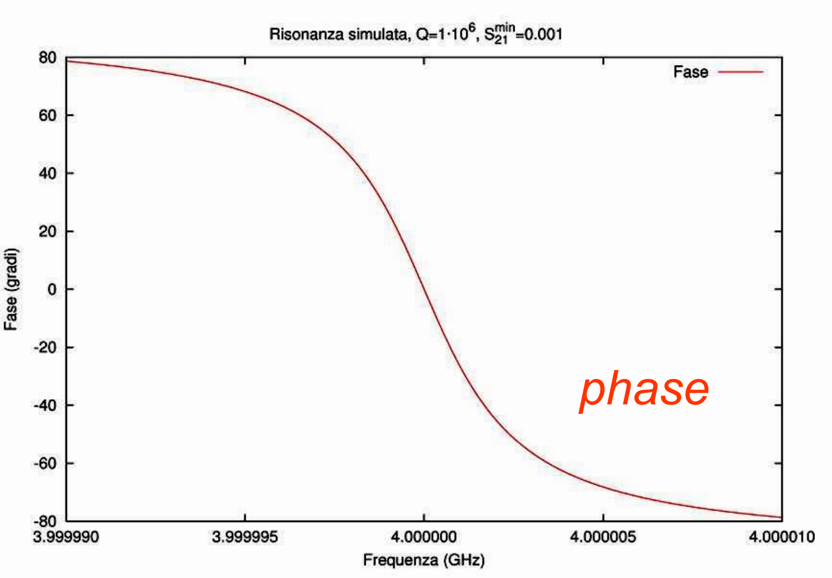


Which are the effects of incoming radiation?



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





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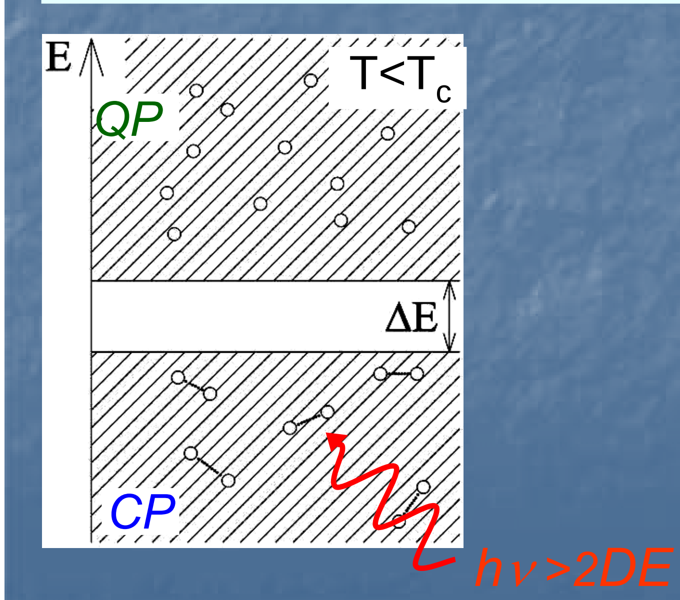
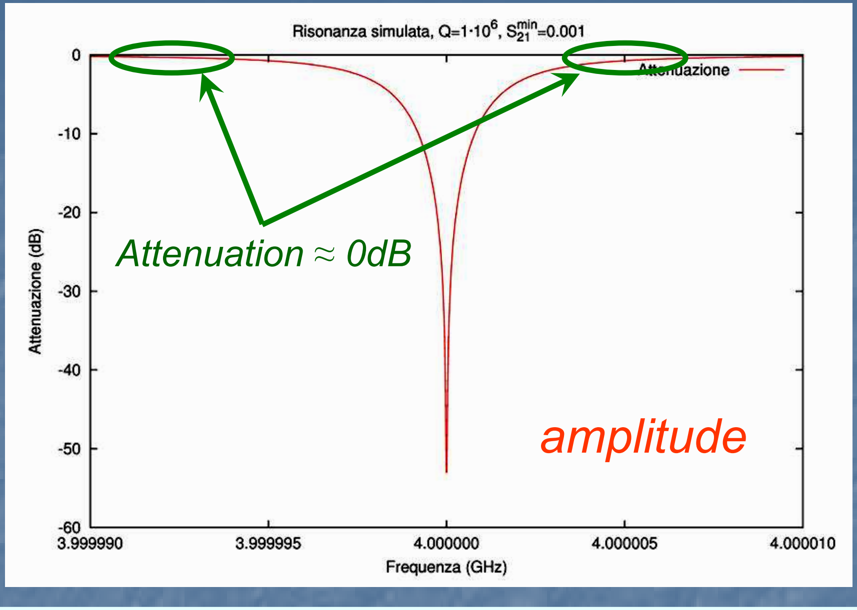


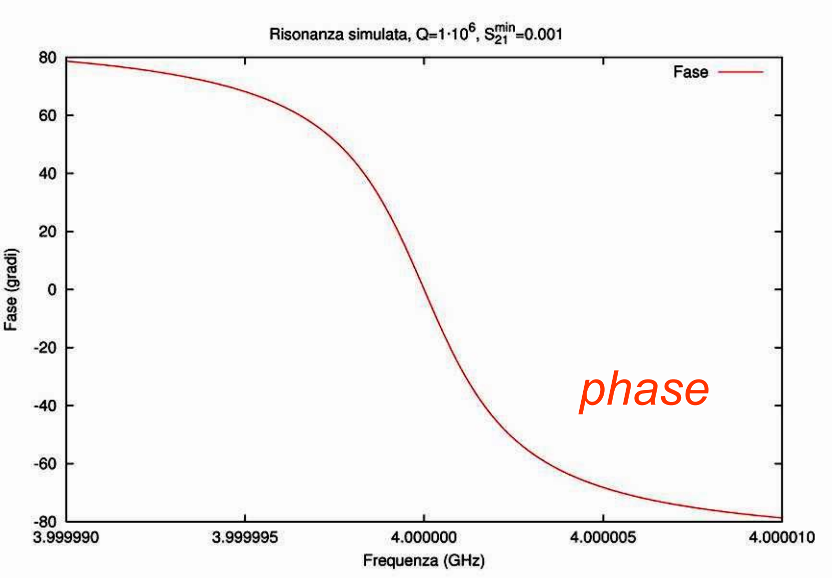
Claudia Giordano

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



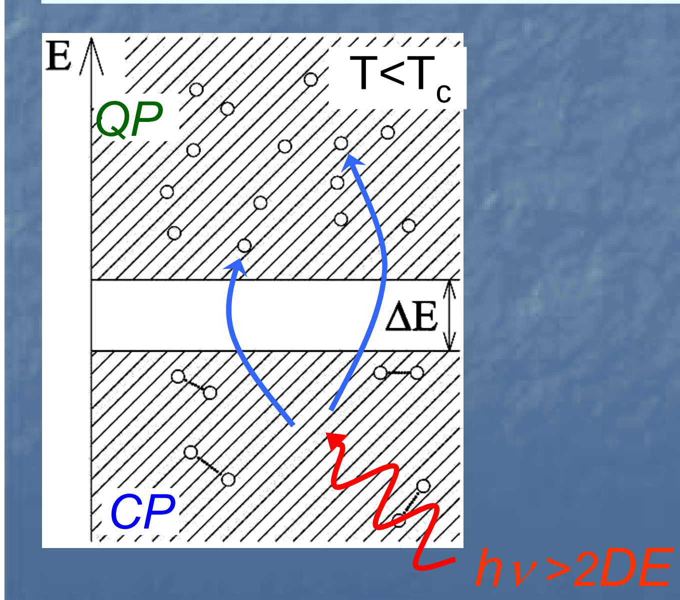
Attenuation ≈ 0dB

amplitude



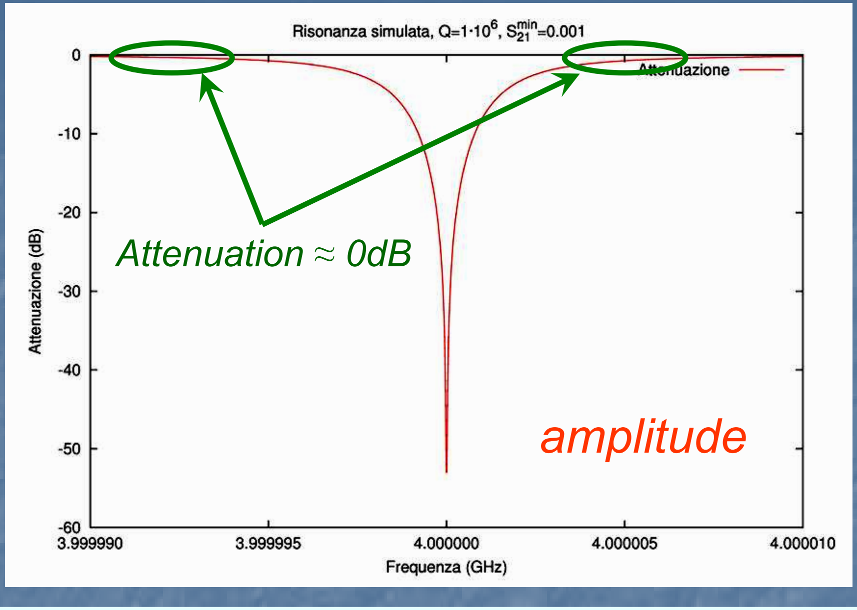
phase

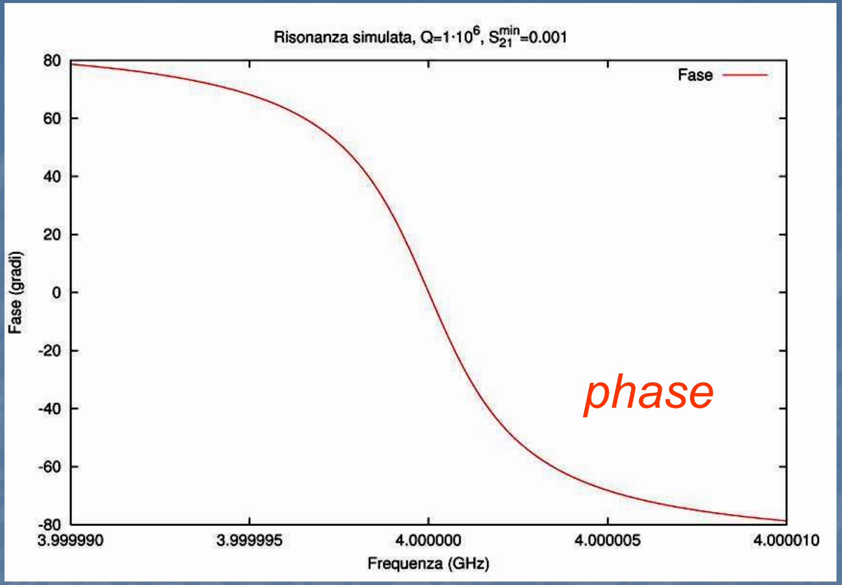
Which are the effects of incoming radiation?



Claudia Giordano

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





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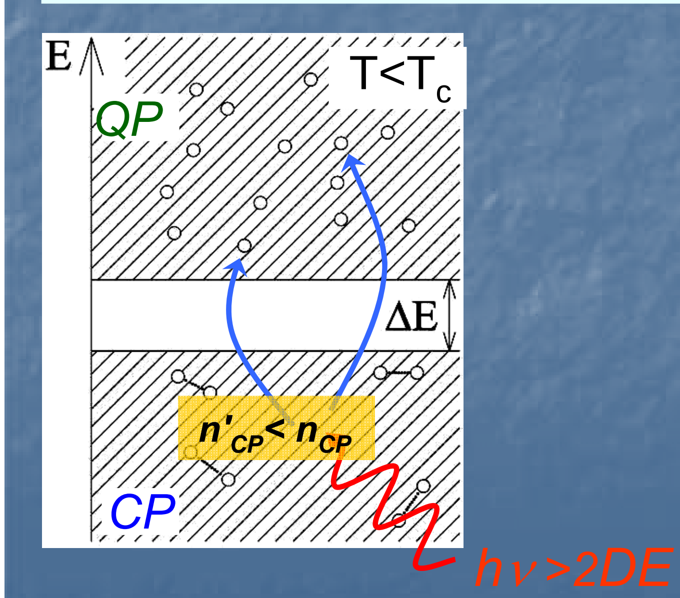

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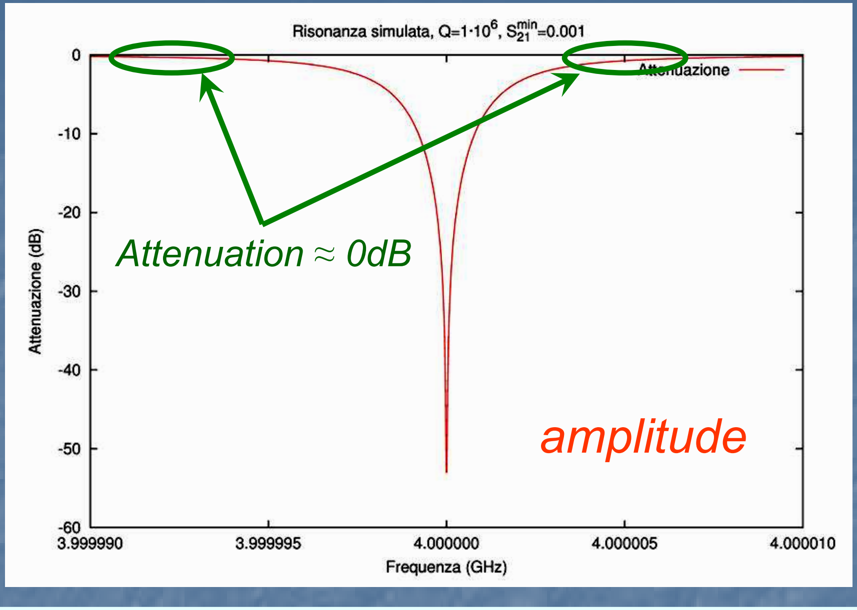

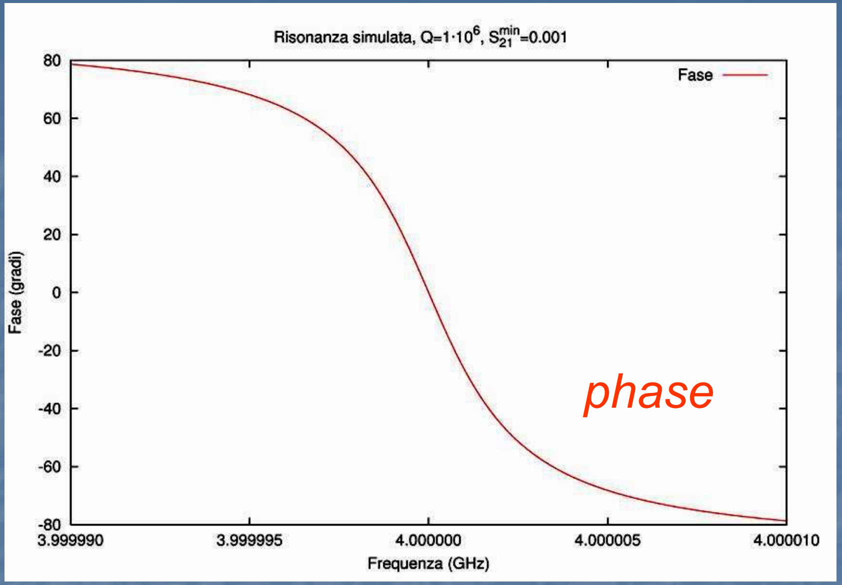

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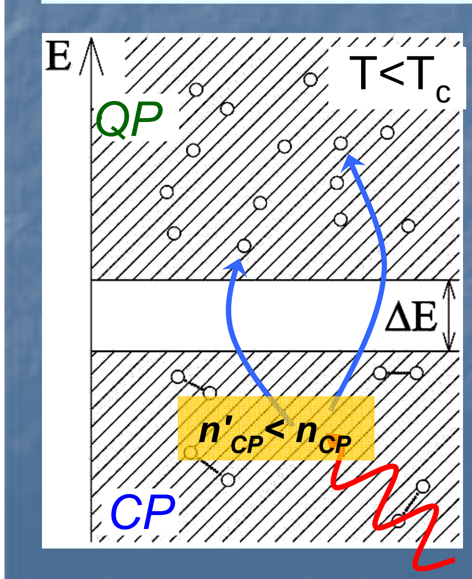

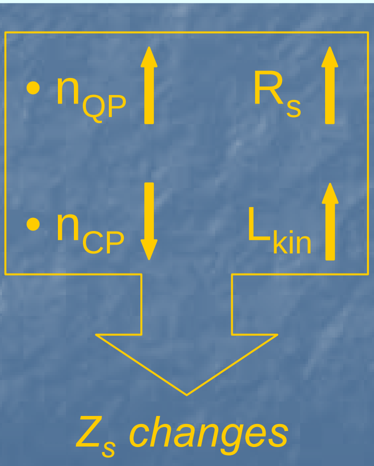

- n_{QP} ↑ R_s ↑
- n_{CP} ↓ L_{kin} ↑

Z_s changes

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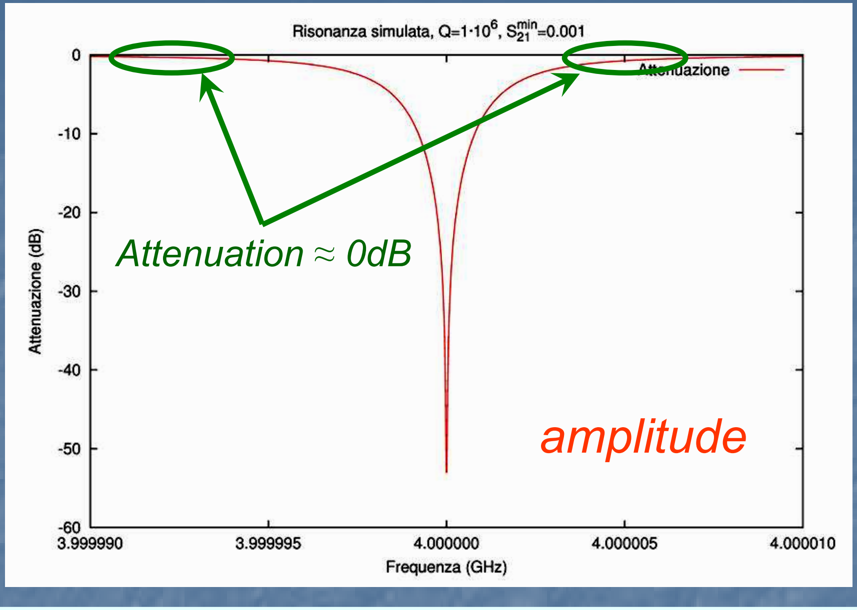
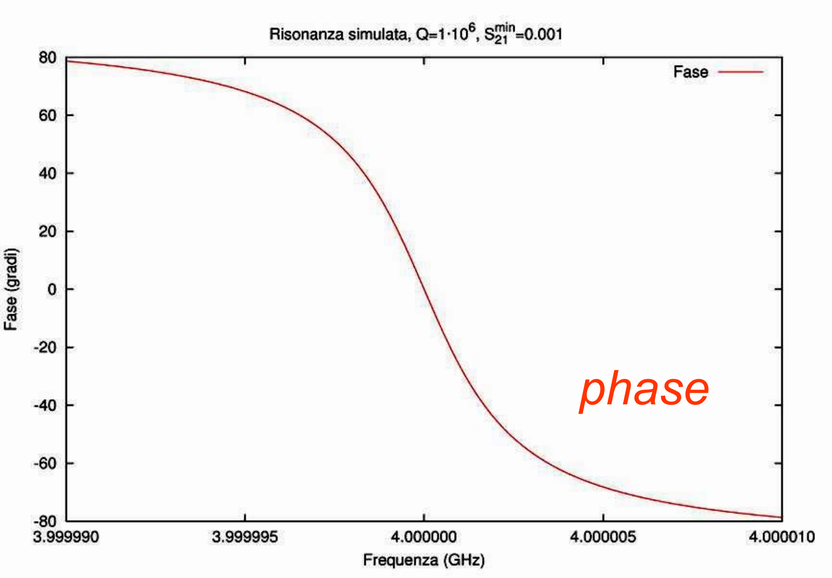
Effect of a signal transmitted through the feed line past the resonator:





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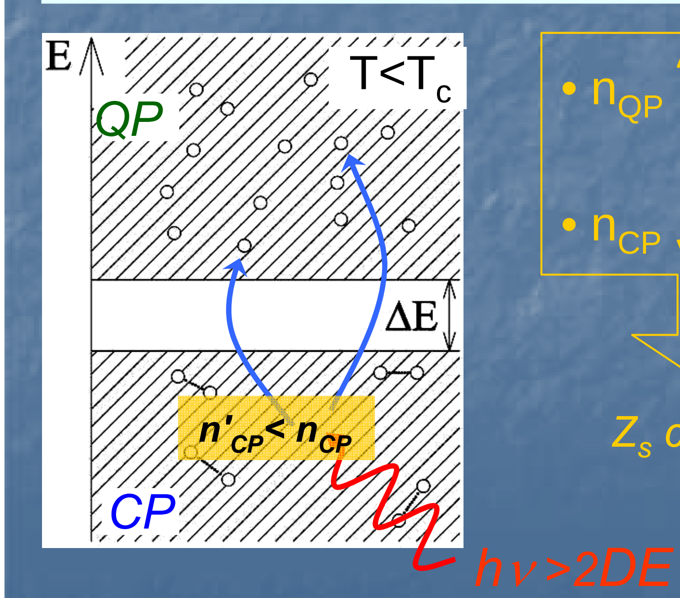

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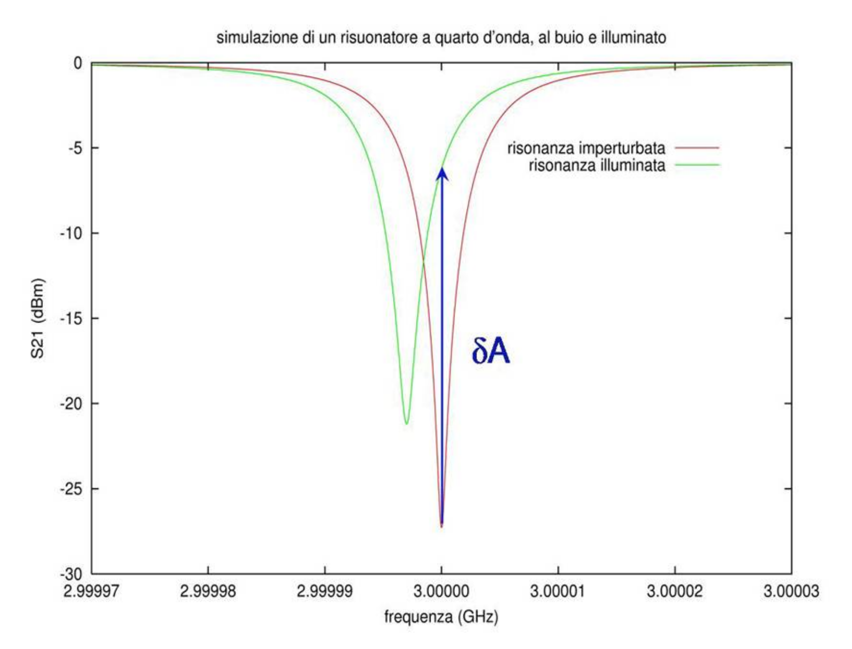
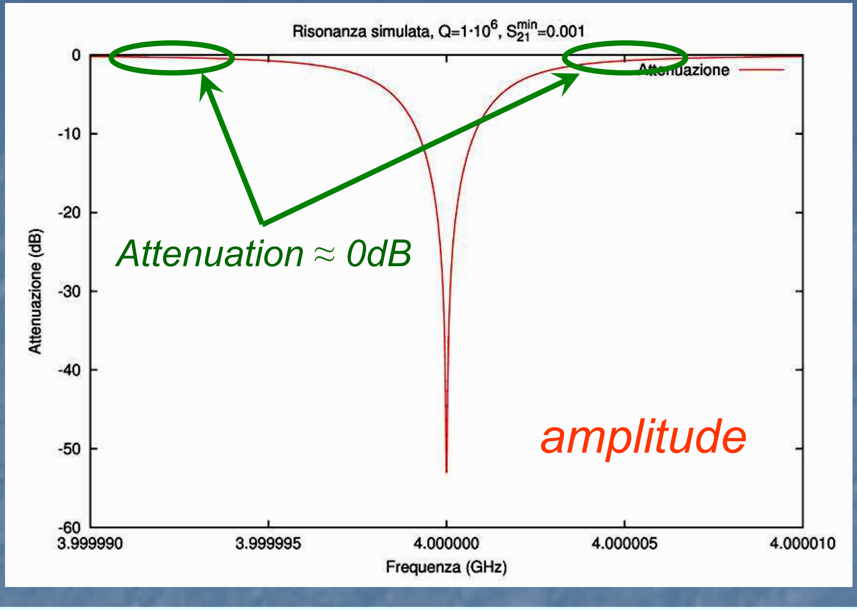
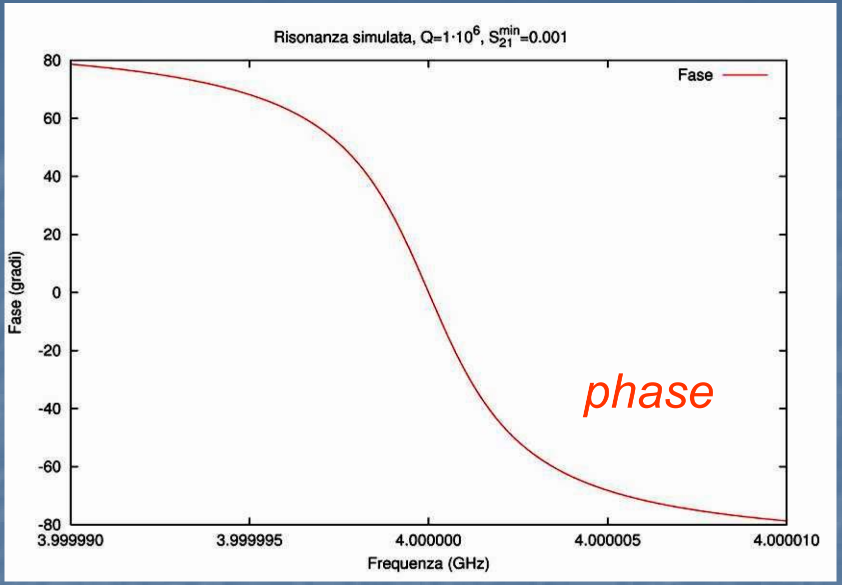
Z_s changes



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





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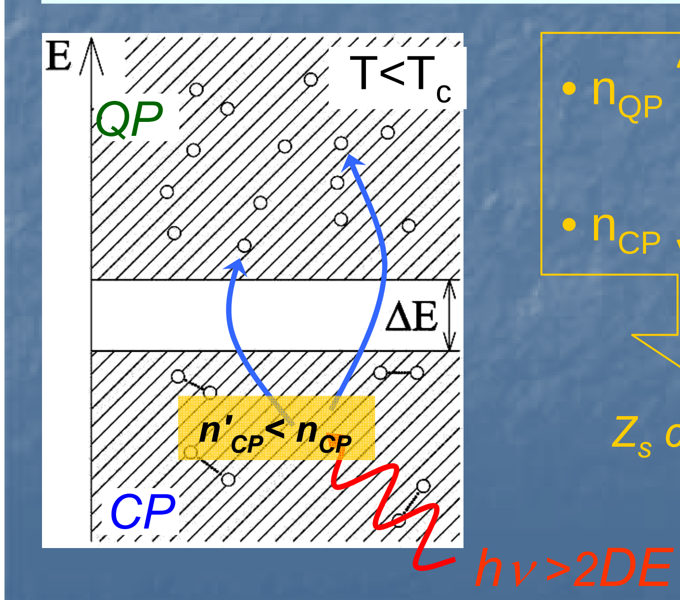

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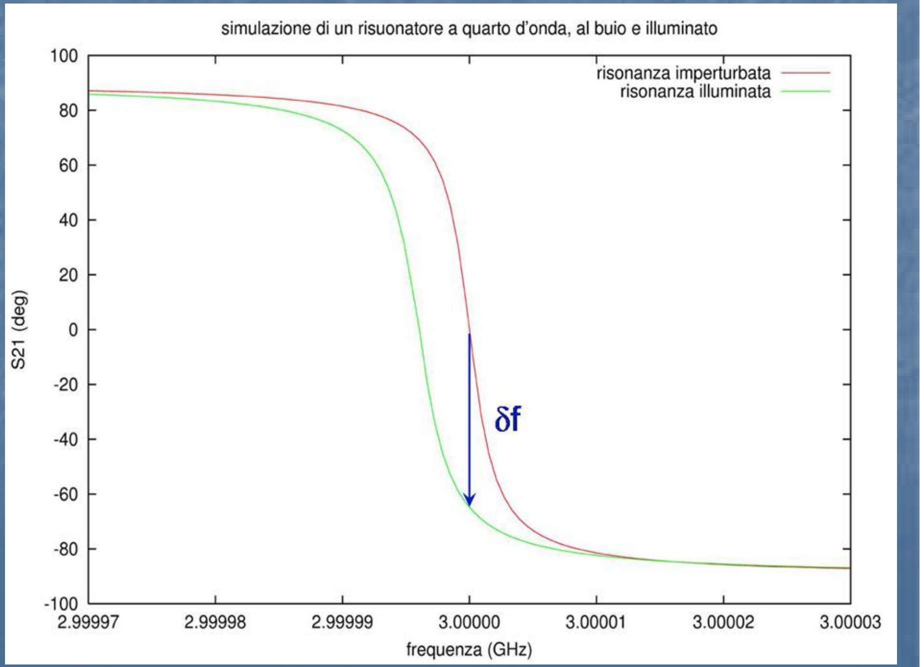
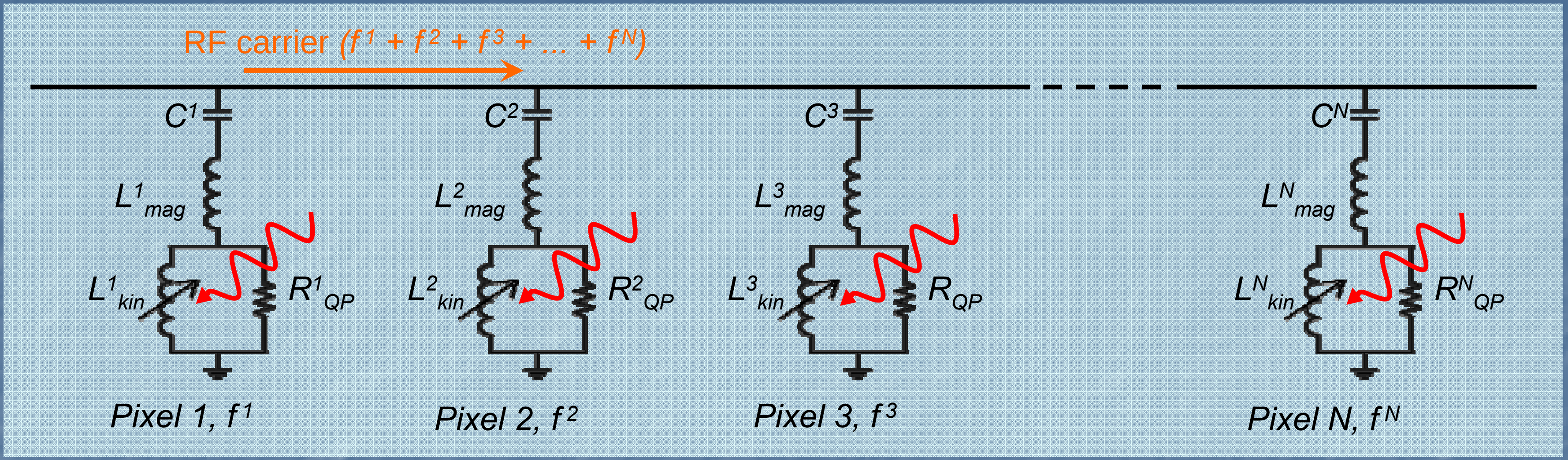
Z_s changes



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.

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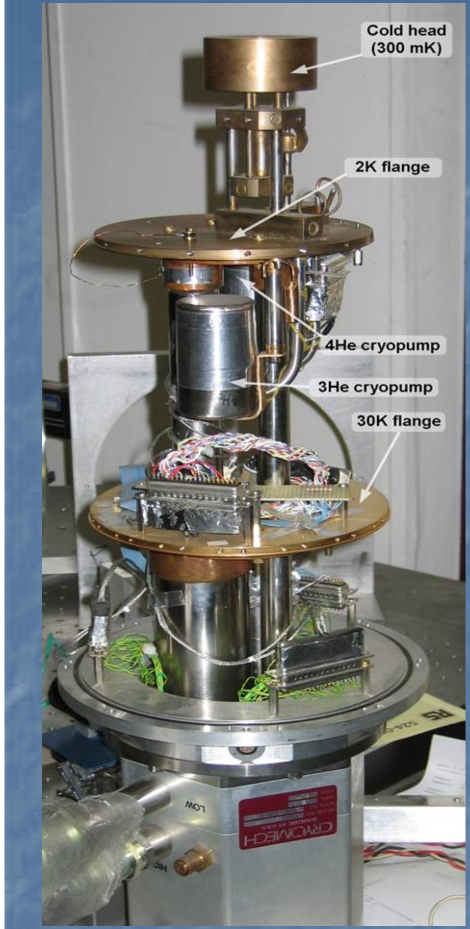
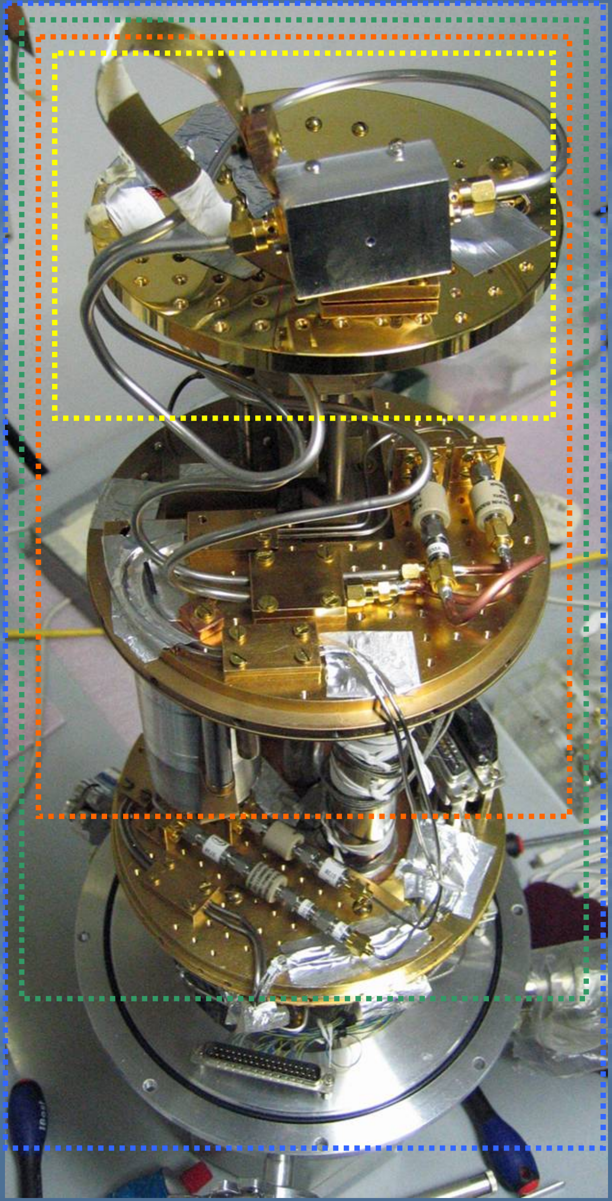
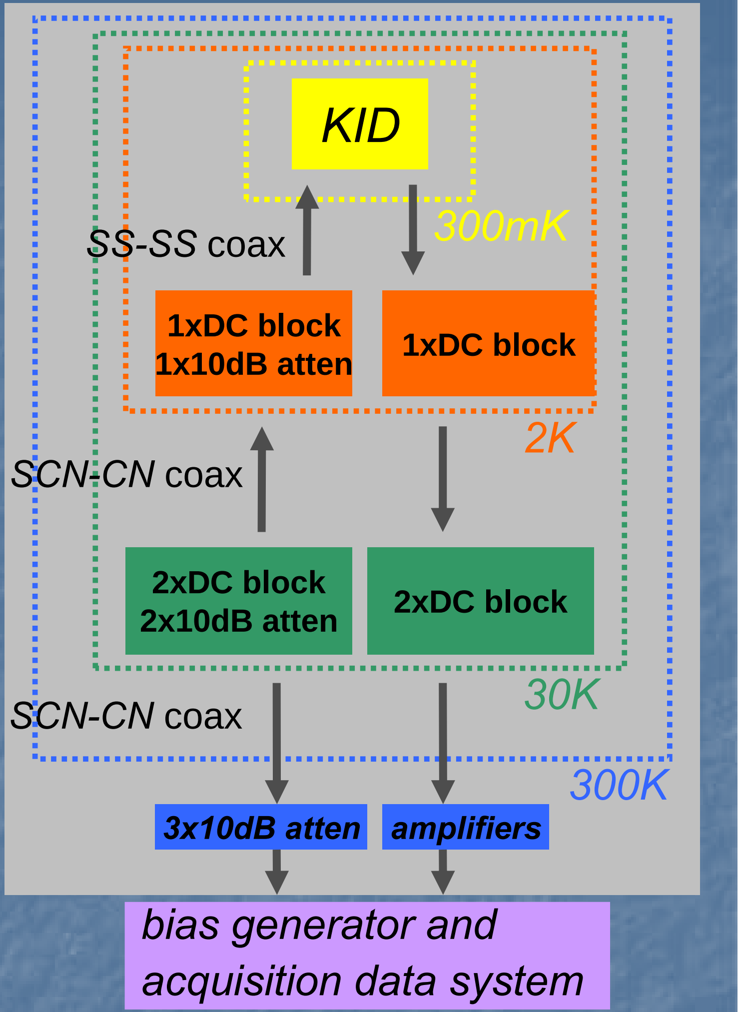
KIDs testbench: RIC esperiment (INFN gruppo V)



Cryostat modified to have RF ports





KID

300mK

SS-SS coax

1xDC block 1x10dB atten

1xDC block

2K

SCN-CN coax

2xDC block 2x10dB atten

2xDC block

30K

SCN-CN coax

300K

3x10dB atten

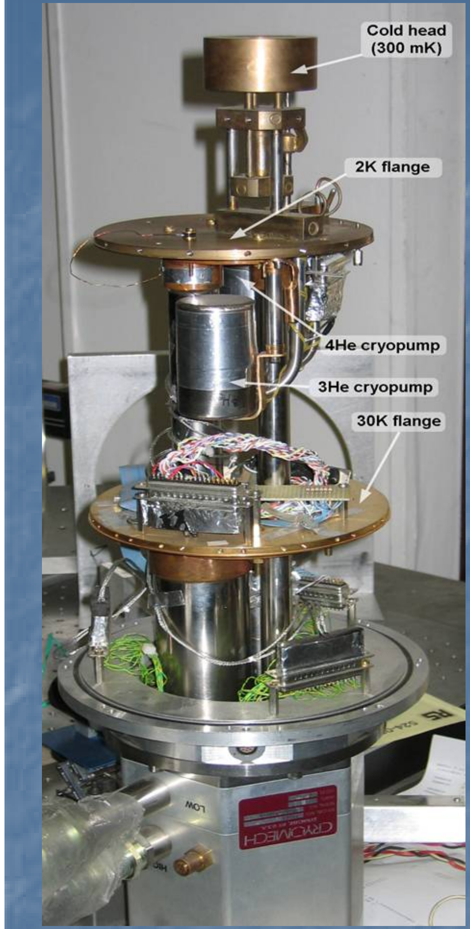
amplifiers

bias generator and acquisition data system

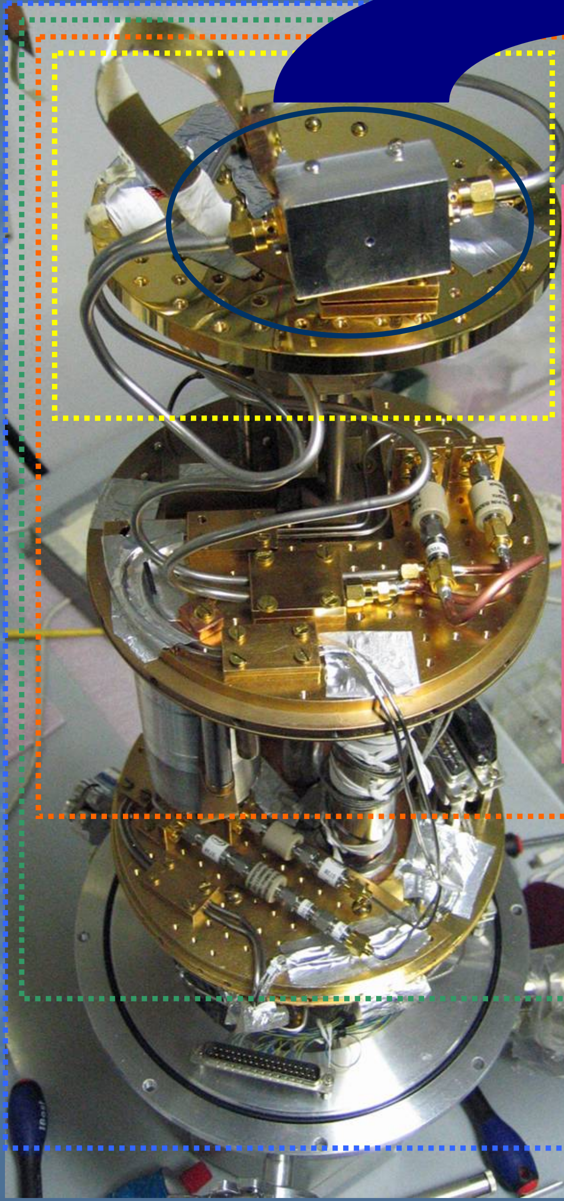
VNA : slower, easier, can give information on the sanity of the whole circuit. Ideal for the first runs.

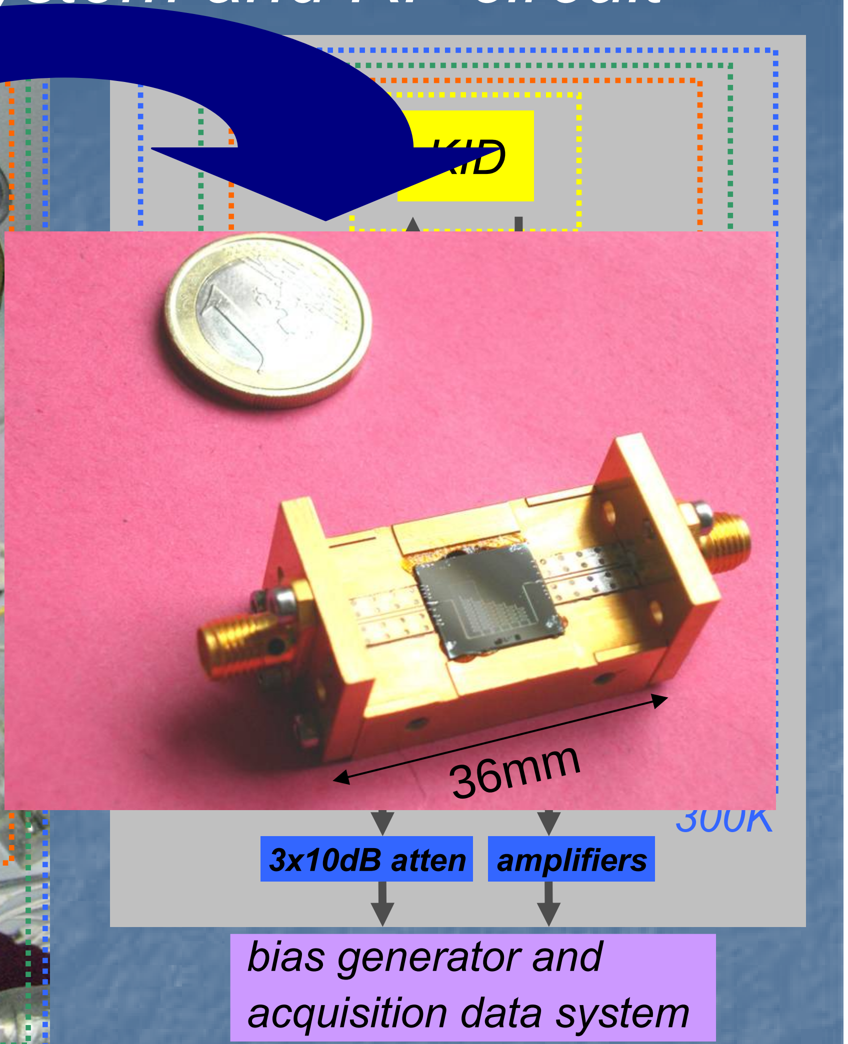
IQ mixers: faster, essential to measure noise, QP lifetime... Need fast acquisition system

KIDs testbench: cryogenic system and RF circuit



Cryostat modified to have RF ports





bias generator and acquisition data system

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

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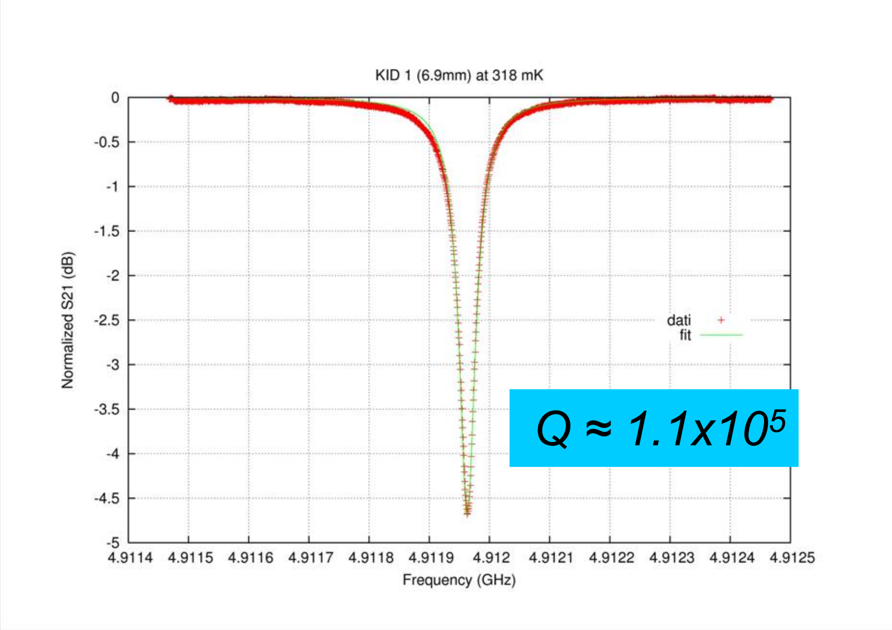
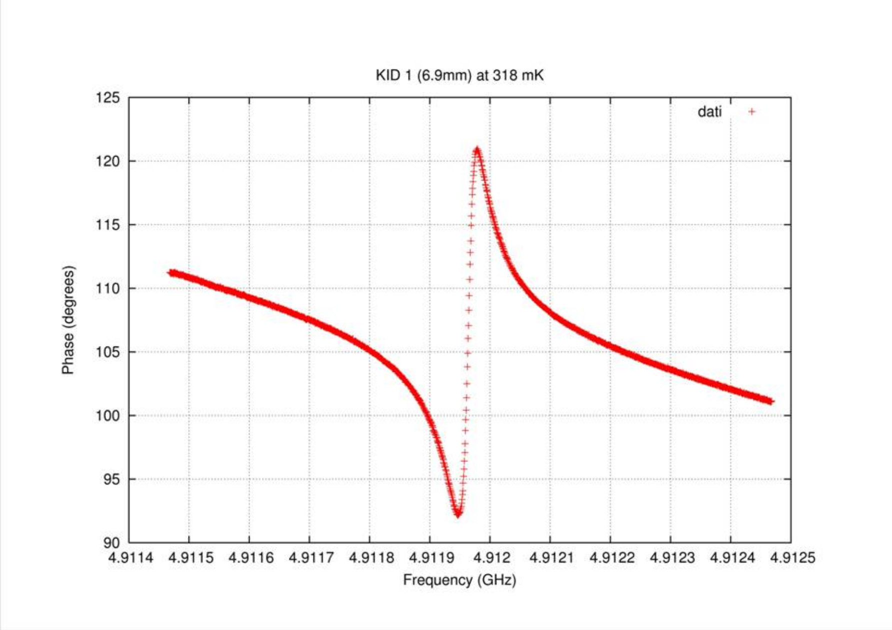
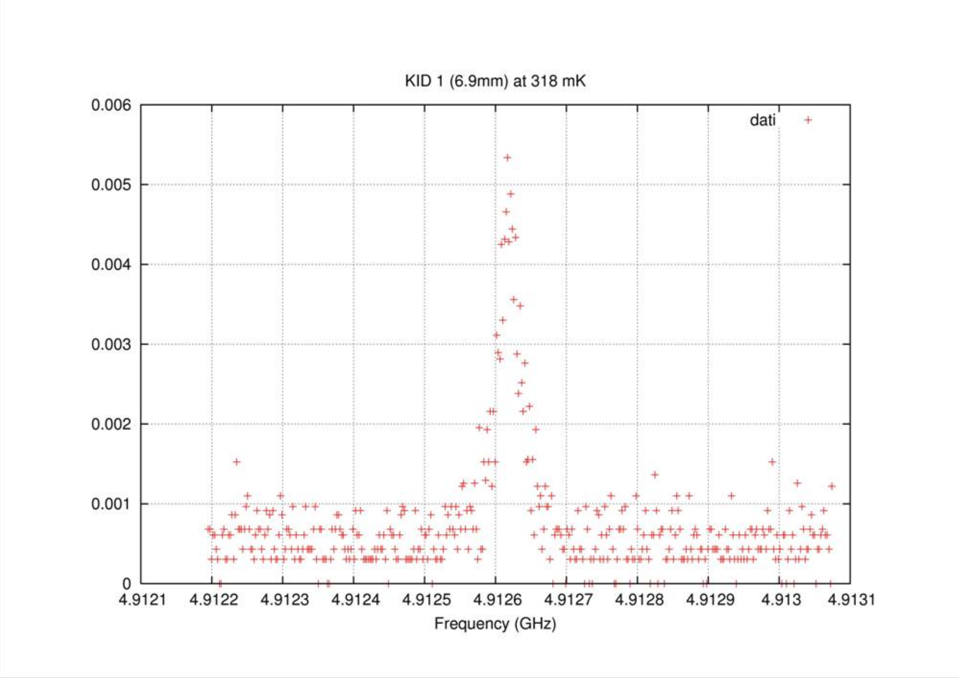
Measurements:



$Q \approx 1.1x10^5$

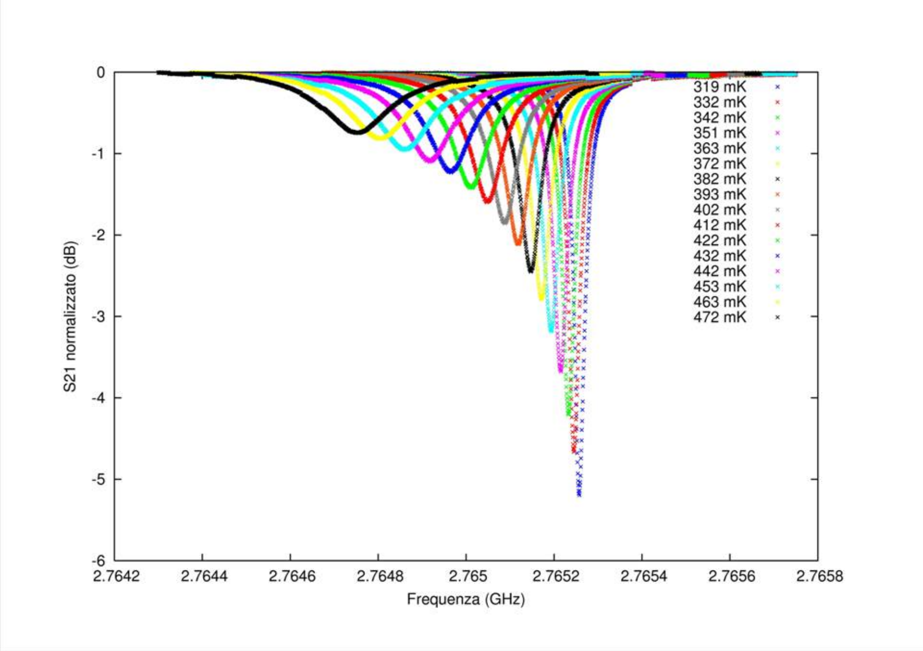


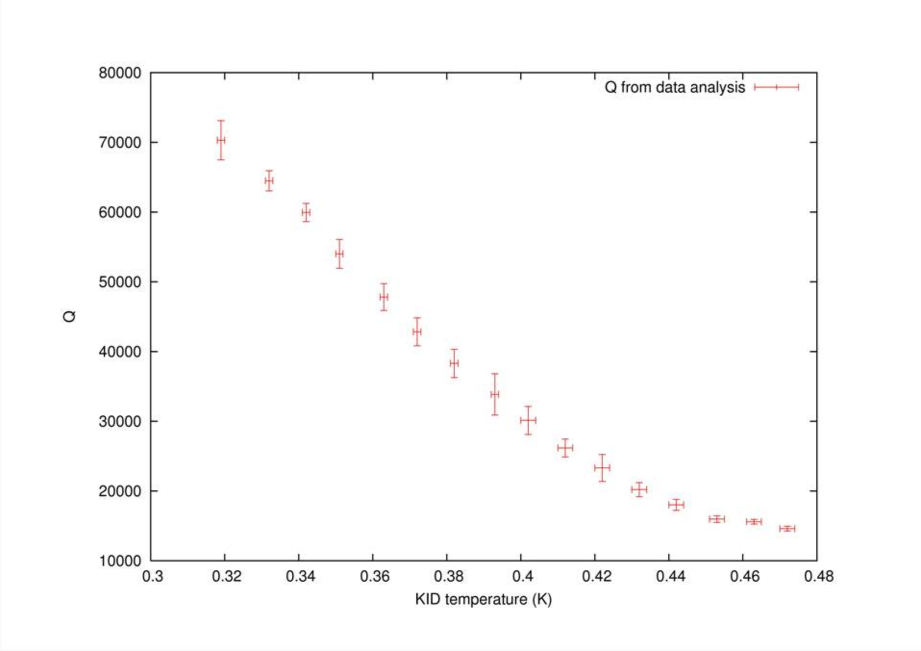


F$_{reso}$ (GHz)	2.76526±0.00002	2.83595±0.00002	2.89025±0.00002
Q	(7.0±0.1)x10^4	(8.0±0.2)x10^4	(14.0±1.1)x10^4
F$_{reso}$ (GHz)	3.29813±0.00002	3.94470±0.00002	4.91196±0.00002
Q	(14.4±0.4)x10^3	(7.2±0.1)x10^4	(11.0±0.3)x10^4

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

Variation of f_0 and Q with temperature:





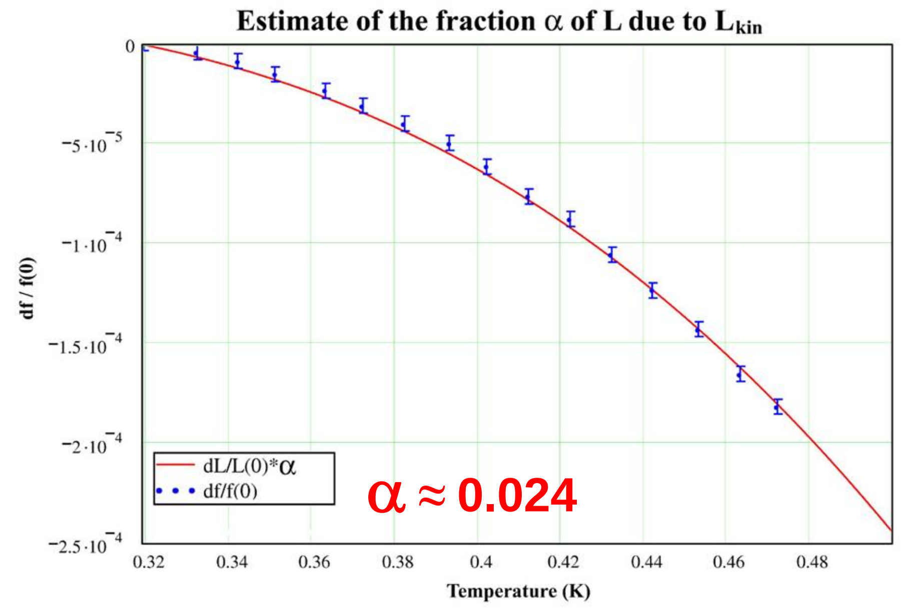
$$f_{reso} \propto \frac{1}{\sqrt{L_{TOT}(T)}}$$

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

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

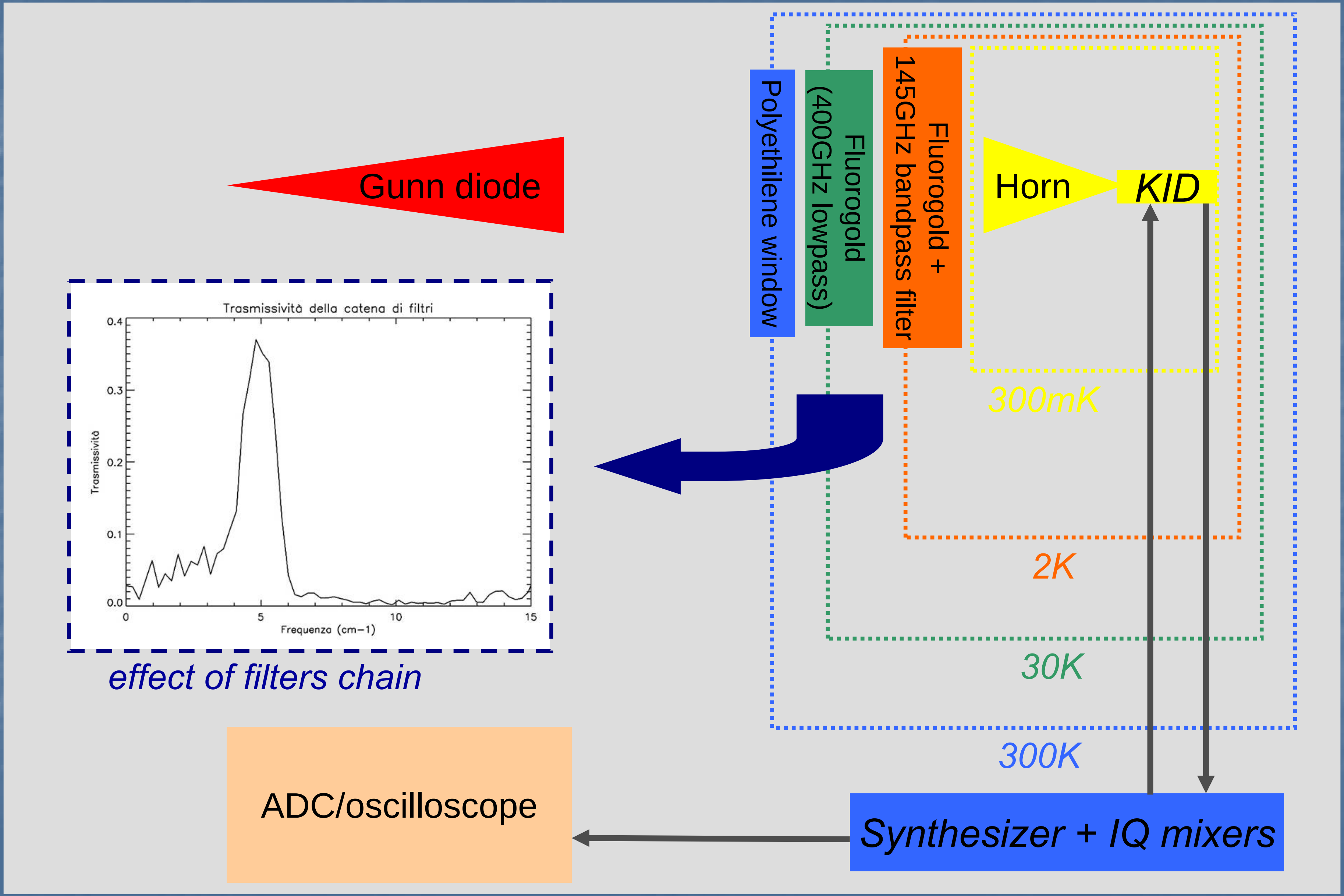
$$\frac{\delta f_{reso}(T)}{f_{reso}(0)} = -\frac{1}{2}\frac{\delta L_{TOT}(T)}{L_{TOT}(0)}$$

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


Estimate of the fraction α of L due to L_{kin}

$\alpha \approx 0.024$

System modified for optical measurements on Aluminum chip:



Gunn diode

Polyethilene window

Fluorogold (400GHz lowpass)

Fluorogold + 145GHz bandpass filter

Horn

KID

300mK

2K

30K

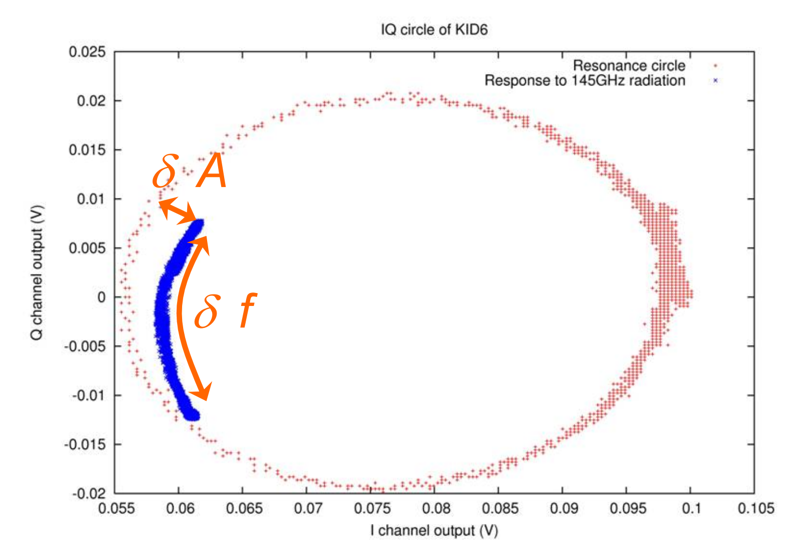
300K

Synthesizer + IQ mixers

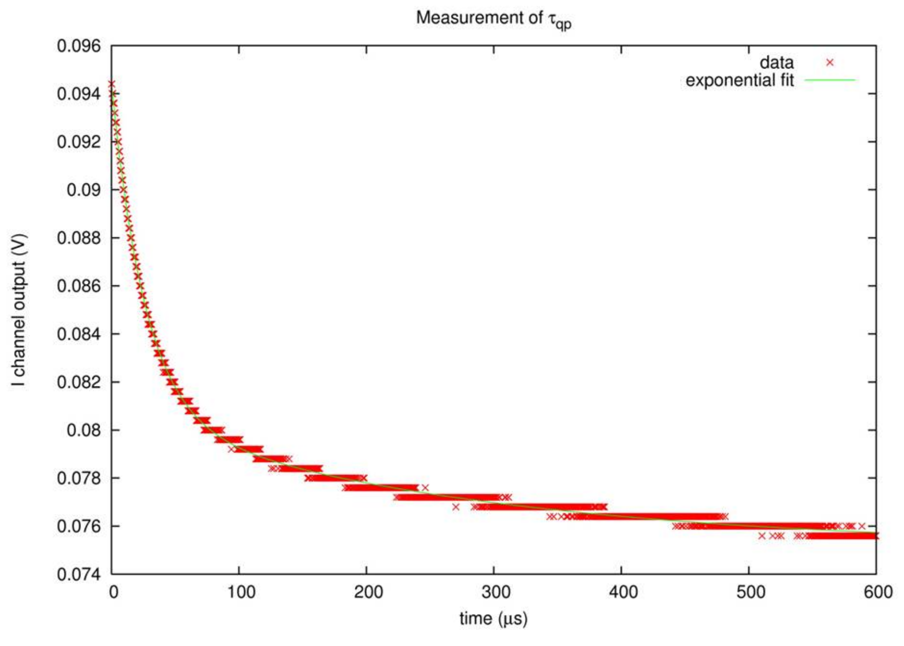
ADC/oscilloscope

effect of filters chain

We have seen light!



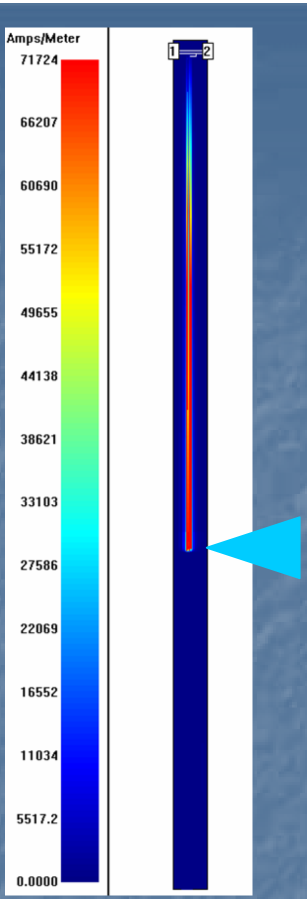
Typical IQ resonant circle, T=318mK. The blue line represents the response to radiation.



Recombination lifetime of photon excited QPs:

$\tau_{QP} \approx 26\mu s$

Coupling to radiation: an open point



First aluminum chip is not optimized for coupling to radiation

◆ *Distributed element KIDs:* response depends on where the photon hits the sensor → needs some sort of antenna

Antenna coupling can however introduce a significant loss of efficiency, therefore a direct absorption method can be considered.

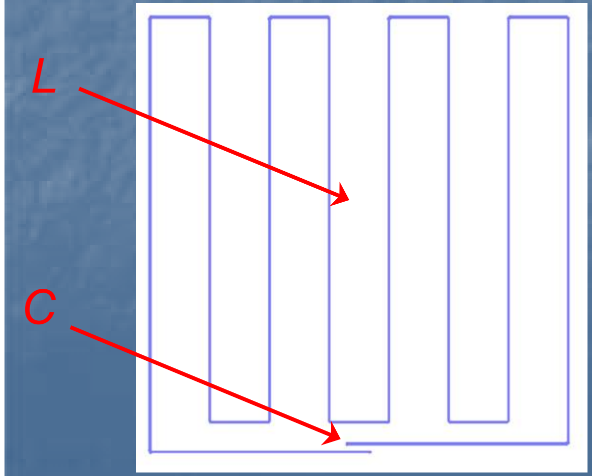
◆ *Lumped element KIDs:* no current variation along its length

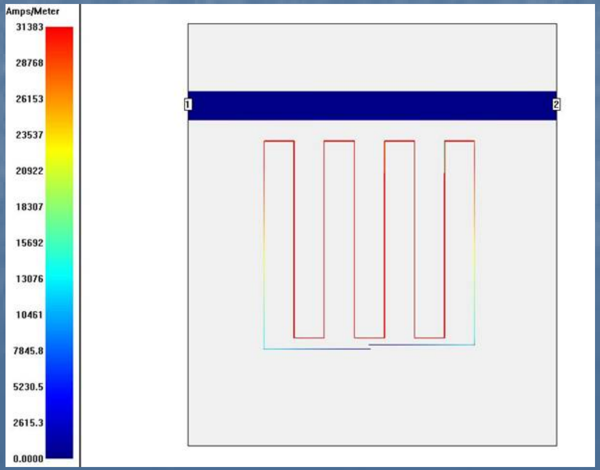
lumped resonance frequency

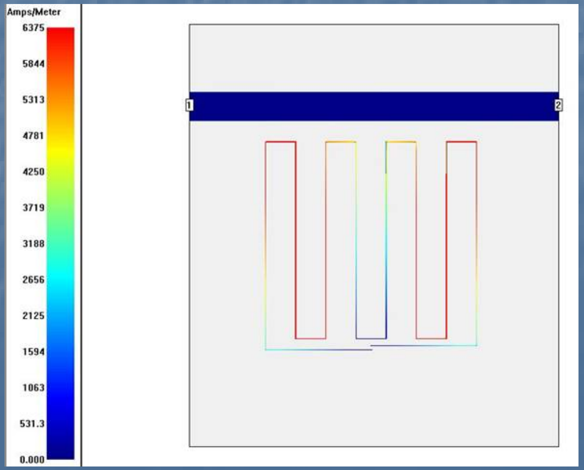
f_{LR}=3.965GHz

distributed resonance frequency

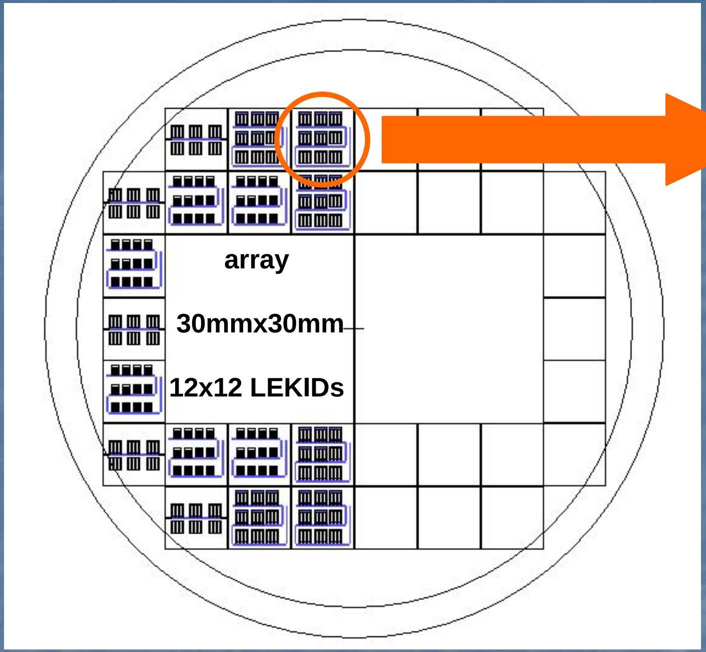
f_{DR}=7.317GHz (>>f_{LR})

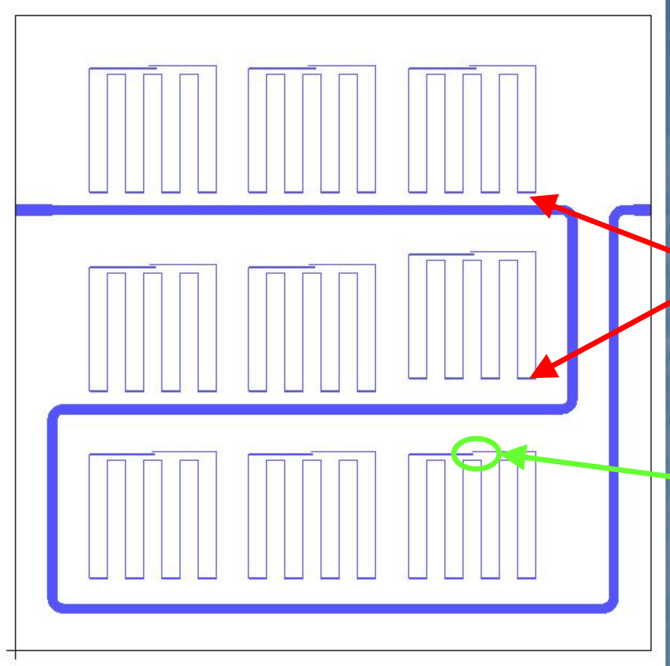






We are preparing a mask layout for different types of mm-wave LEKIDs to be fabricated in Trento and tested in Rome





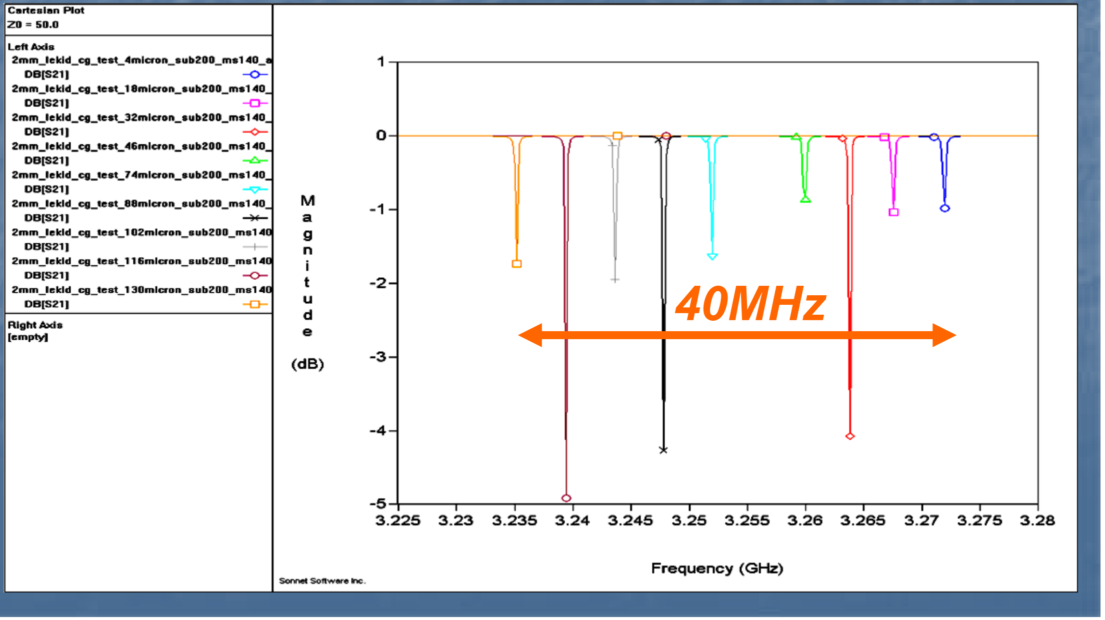
9 resonators, varying:

- the mutual inductance coupling (distance from feedline)
- the resonating frequency (capacitor)

test chip splittings:

- optical frequencies: 1.25mm and 2mm (pixel dimensions)
- CPW vs microstrip
- linewidth 2micron/4micron

The chips that will be fabricated have been simulated and show the feasibility of the multiplexing scheme

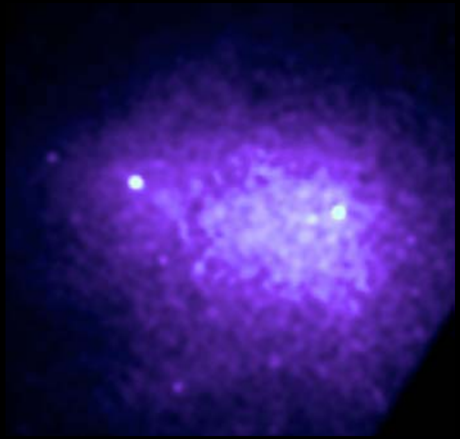


KIDs

- Extremely promising technology for CMB detectors (Al resonators):
  - Cost of a single detector about the same as array
  - Intrinsically multiplexable
  - Wide band (LEKIDs)
- Still in development phase, but growing fast.
- Several groups are pursuing this: e.g. Zmuidinas (Caltech), Mauskopf (Cardiff), Margesin (RIC INFN collaboration), Monfardini (Grenoble) …

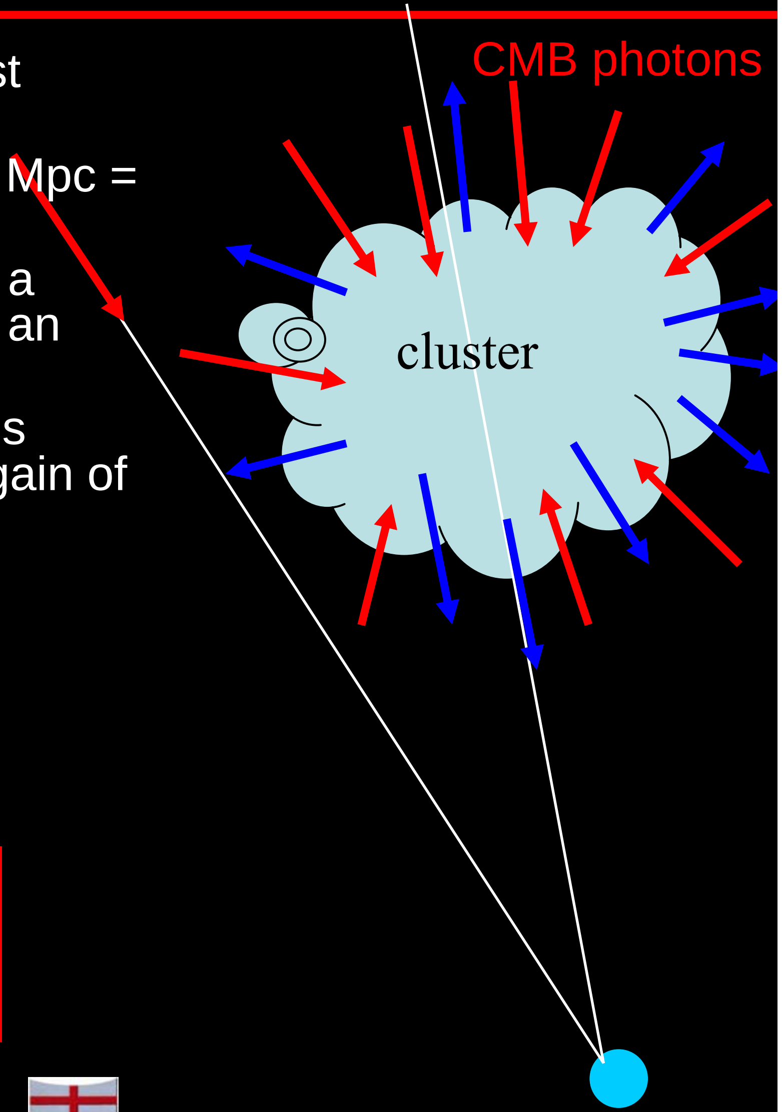
Hot Plasma in Clusters of galaxies

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: $\tau = n\sigma \mathbf{l}$ where $\mathbf{l}$ = a few Mpc = 10^{25} cm, $n < 10^{-3}$ cm^{-3} , $\sigma = 6.65 \times 10^{-25}$ cm^2
- So $\tau = n\sigma \mathbf{l} < 0.01$: 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

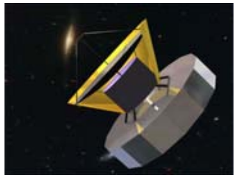
$$\boxed{\frac{\Delta\nu}{\nu} = \frac{kT_e}{m_e c^2} \approx \frac{5keV}{500keV} = 0.01}$$

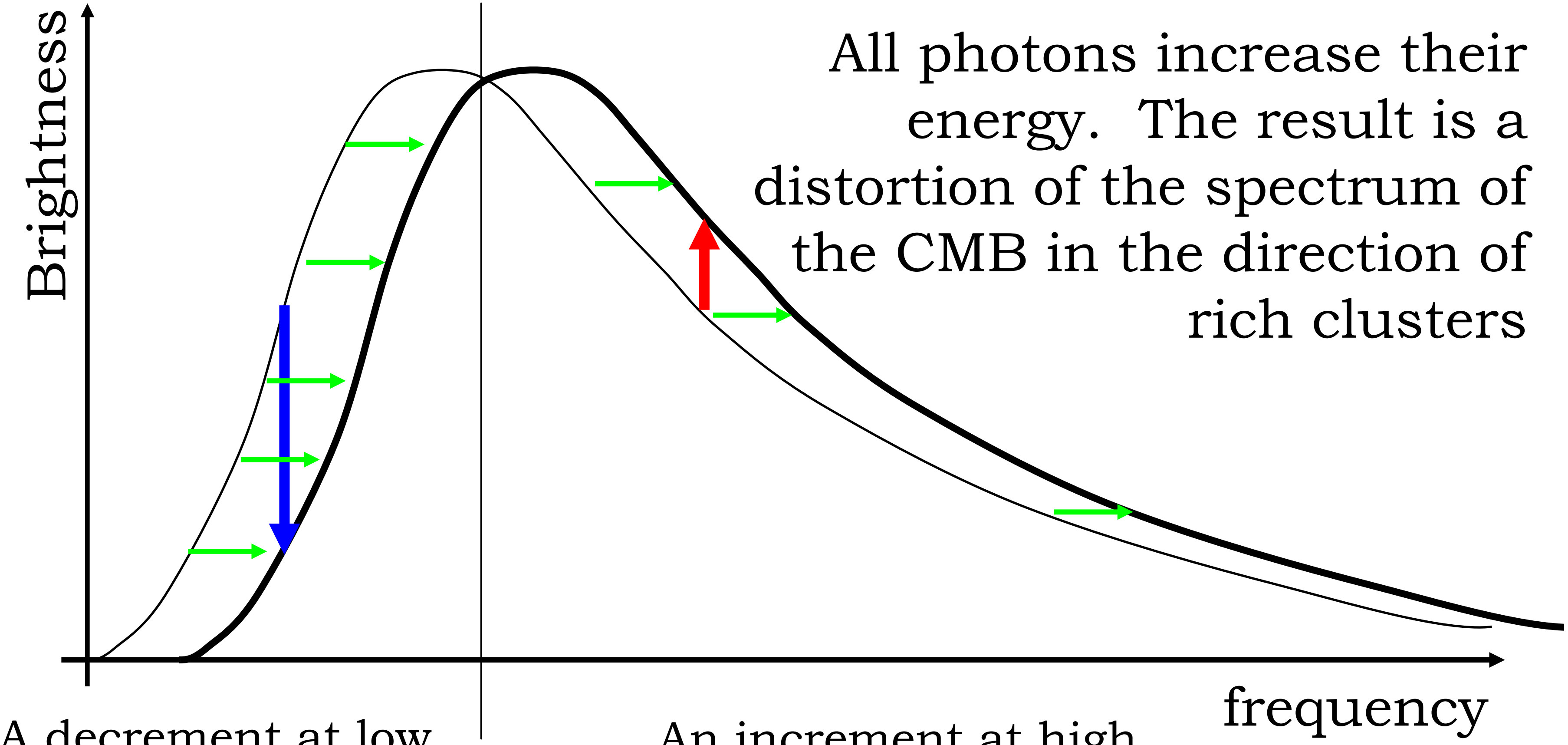
- The resulting CMB temperature anisotropy is

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

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

Sunyaev-Zeldovich Effect



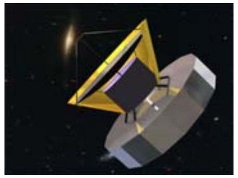


All photons increase their energy. The result is a distortion of the spectrum of the CMB in the direction of rich clusters

A decrement at low frequencies
(<217GHz)

An increment at high frequencies
(> 217GHz)

The Sunyaev-Zeldovich Effect



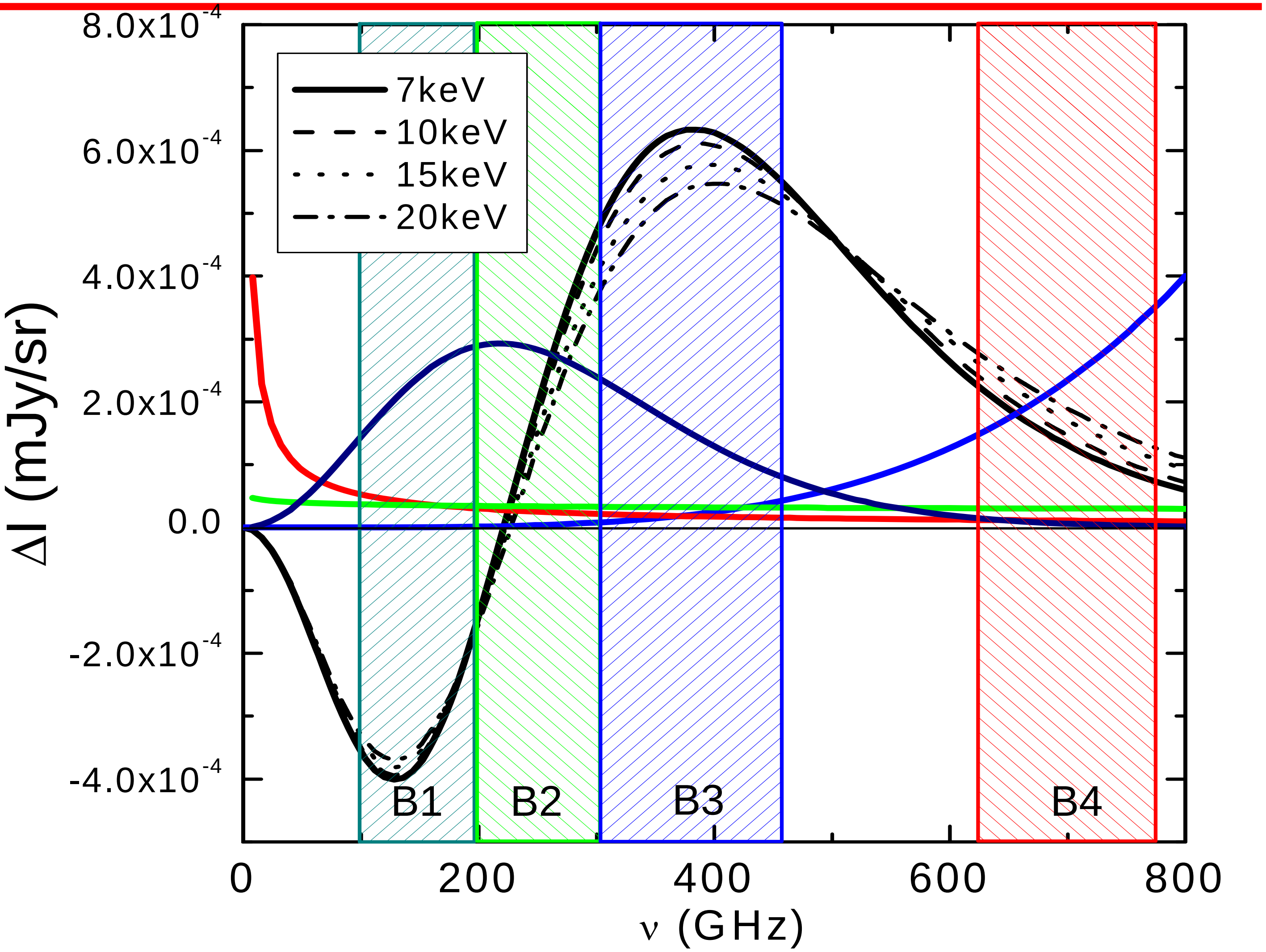
S-Z

Dust

Synchrotron

Free-free

CMB



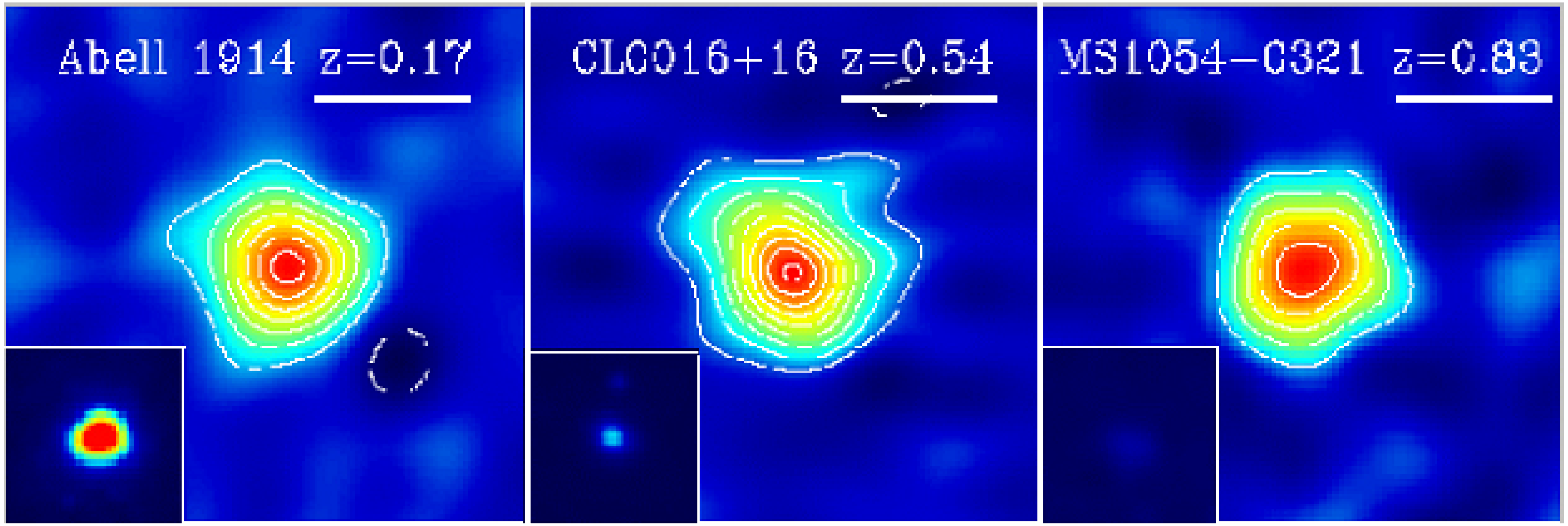
Spectral coverage of SAGACE

▨

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

The Sunyaev-Zeldovich Effect

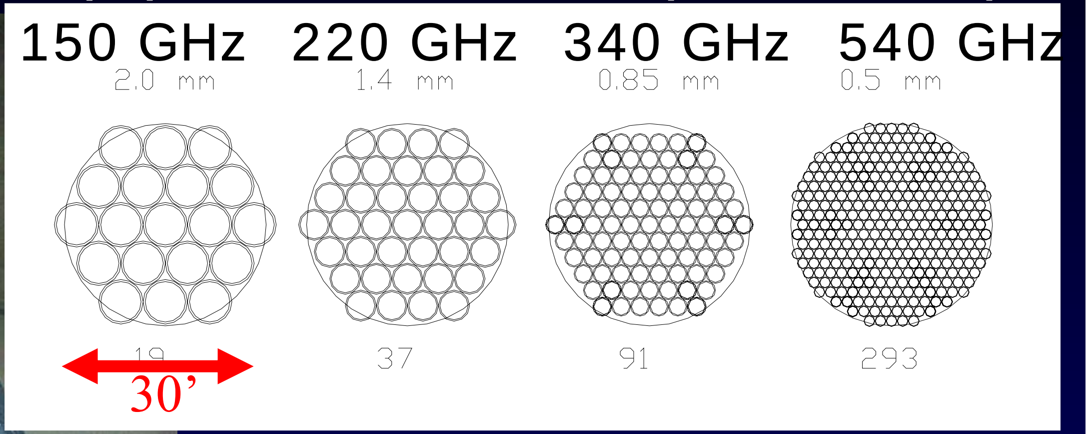
- The S-Z Effect does not depend on the distance (redshift) of the cluster, and depends linearly on the density of the gas
- X-ray brightness decreases significantly with distance and gas density (depends on the square of the density).

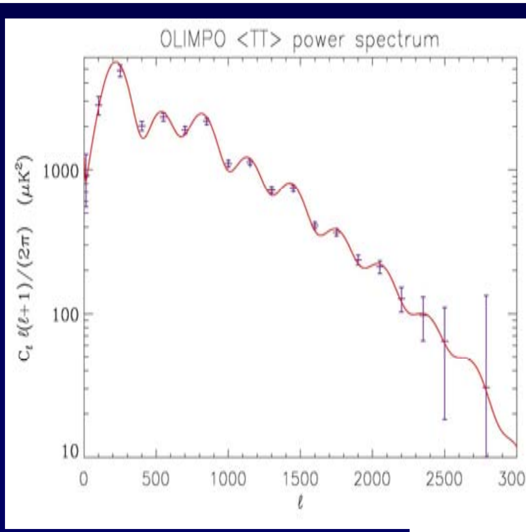


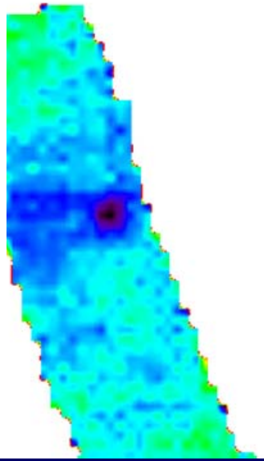
X-ray **S-Z** **X-ray** **S-Z** **X-ray** **S-Z**

OLIMPO (PI Silvia Masi, Roma)

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



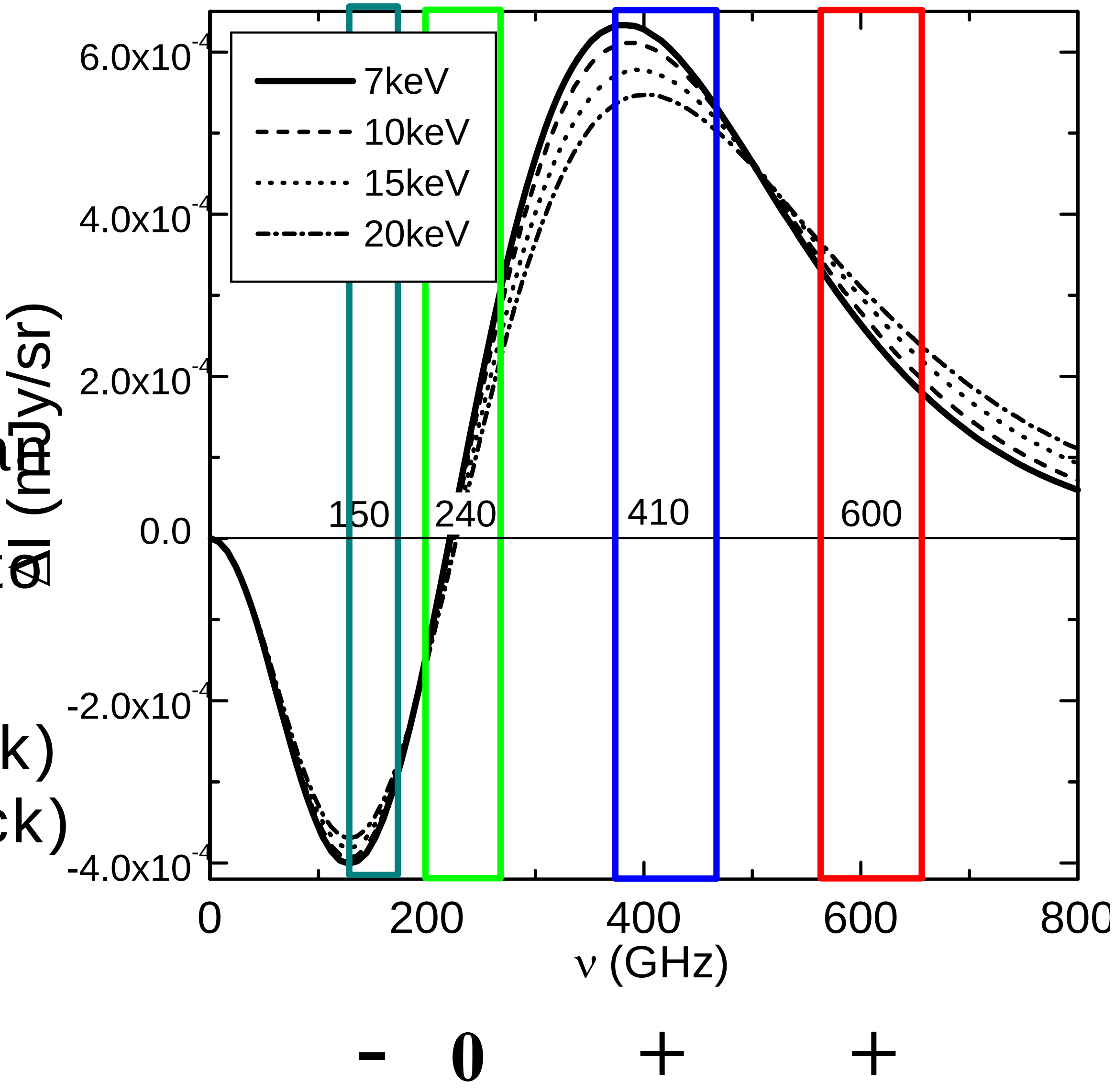




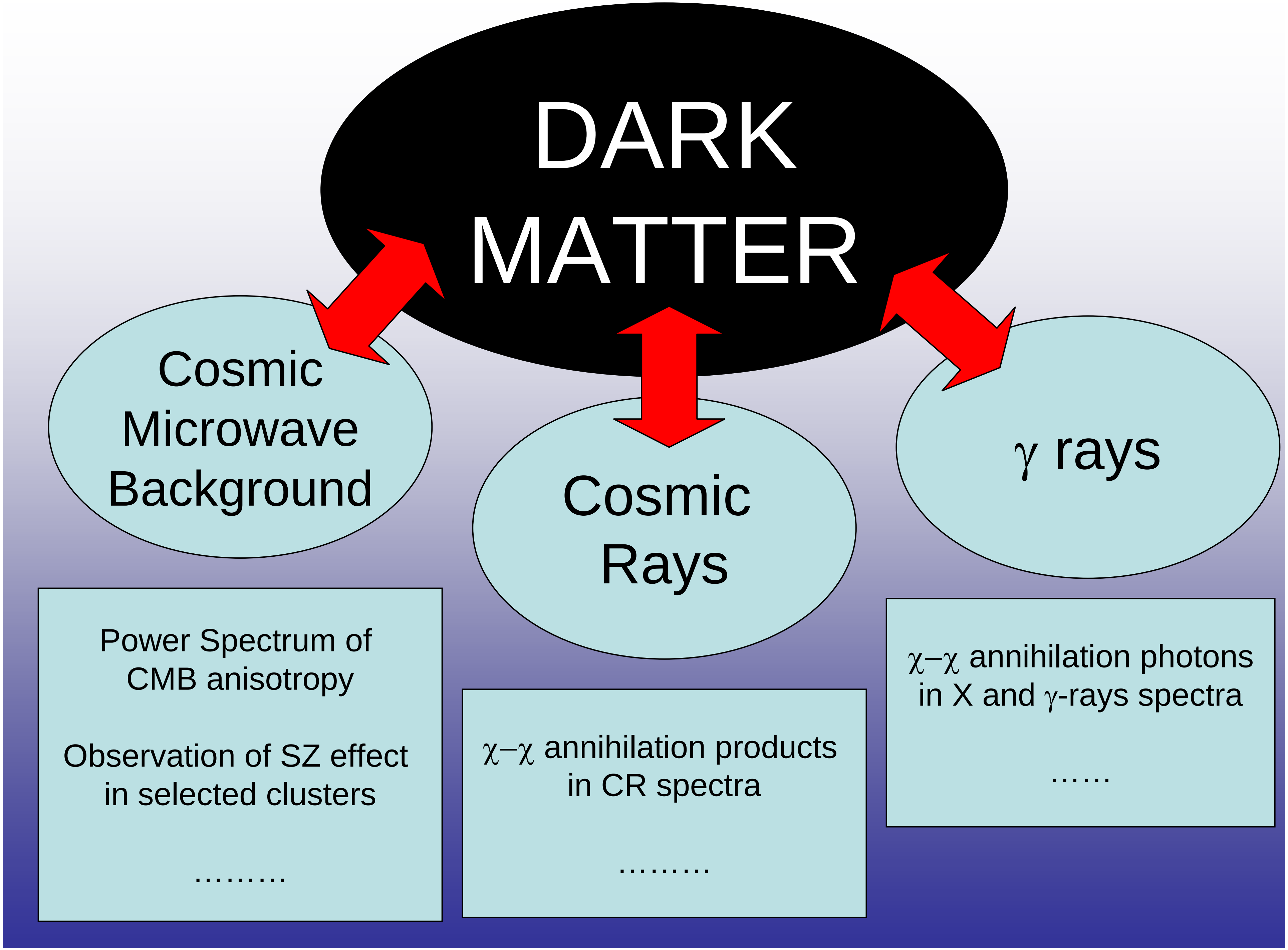
Uniqueness of OLIMPO

- 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

………

$\chi-\chi$ annihilation products in CR spectra

………

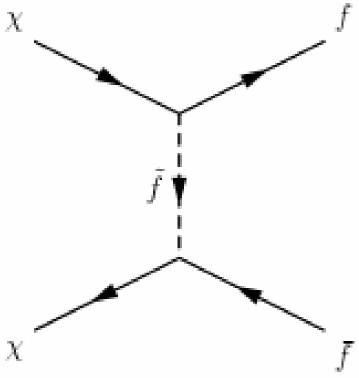
$\chi-\chi$ annihilation photons in X and γ-rays spectra

……

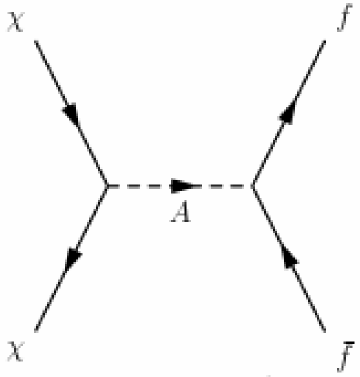
What is Dark Matter ?

- **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

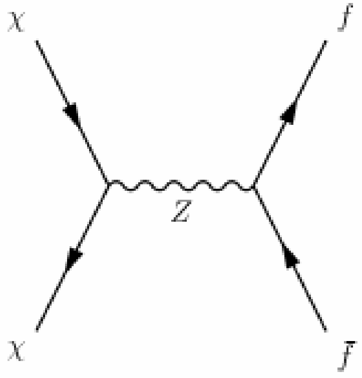


$$\propto \frac{m_\chi \cdot m_f}{m_{\tilde{f}}^2}$$

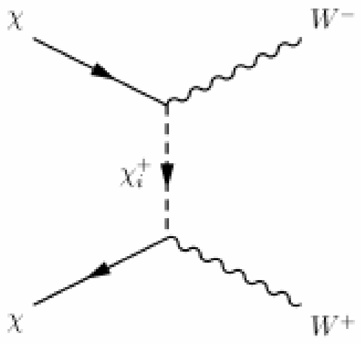


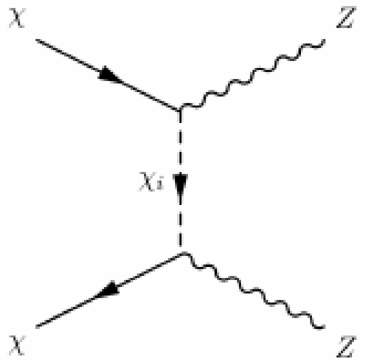
$$\propto \frac{\tan\beta \cdot m_{f_d}}{m_W} \left(\frac{m_\chi}{m_A}\right)^2 N_1 N_{3(4)}$$

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



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

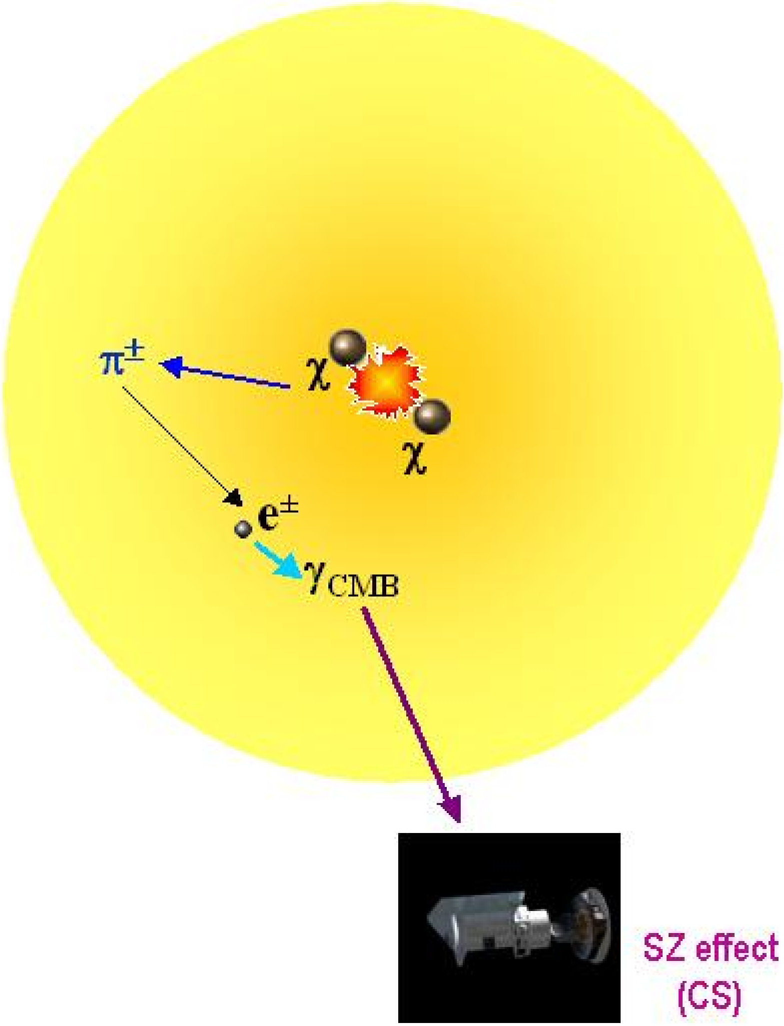




$$\propto \frac{1}{1+(m_{\chi_i^+}/m_\chi)^2-(m_W/m_\chi)^2}$$

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

SZ effect from $\chi\chi$ annihilation



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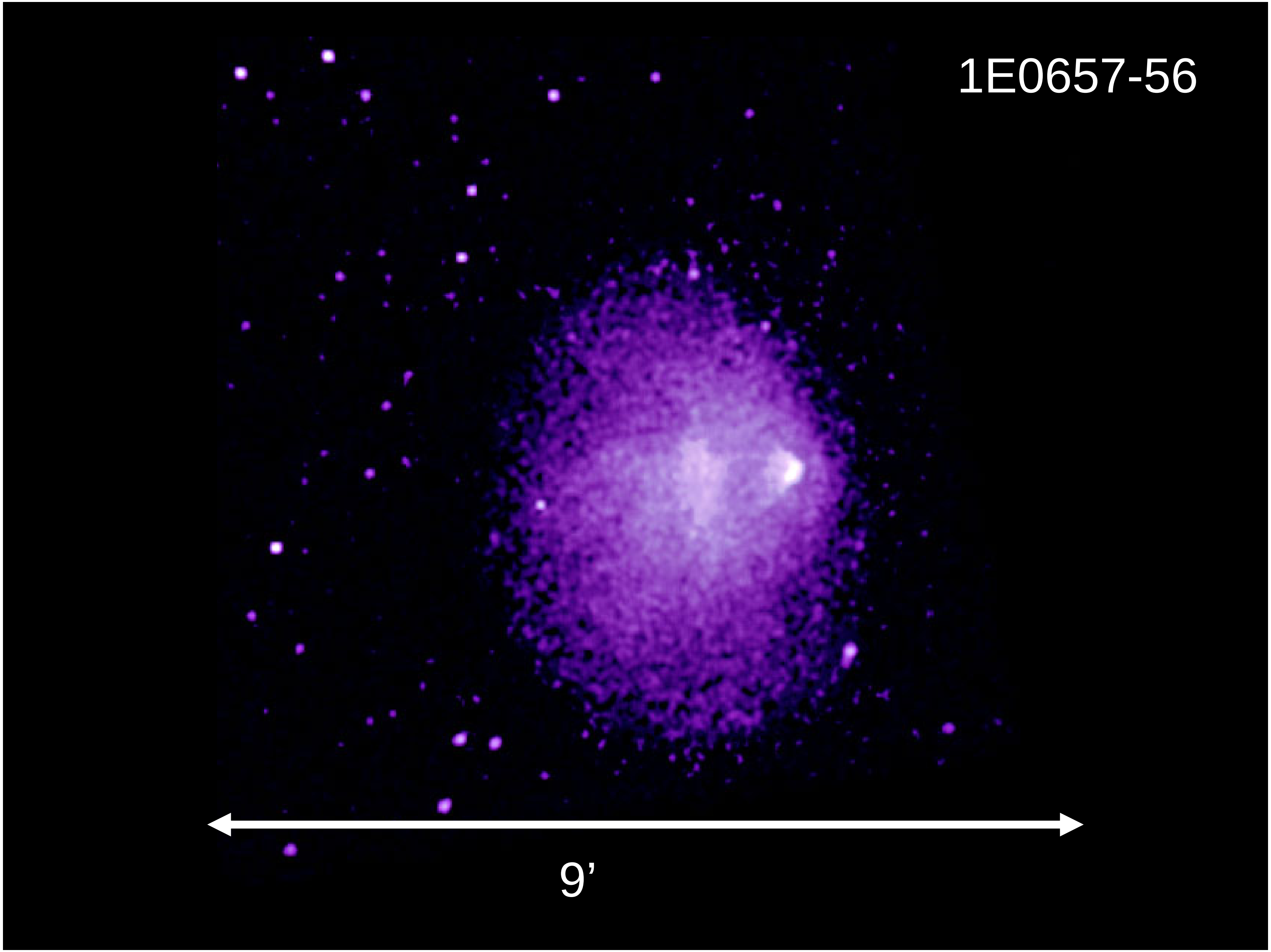
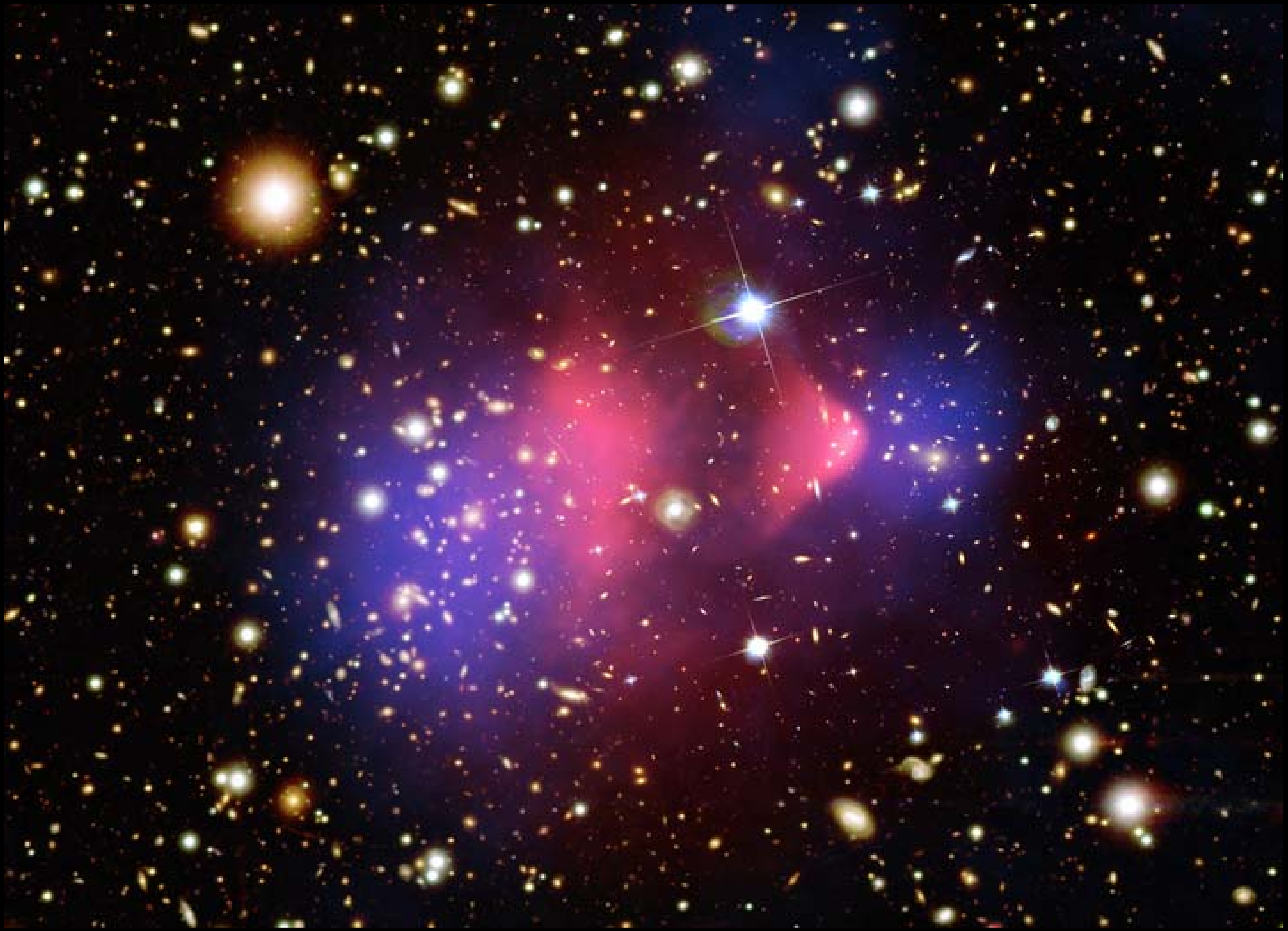
- Annihilation of Neutralinos would produce fluxes of
  - Neutral and charged pions
  - Secondary electrons protons
  - Neutrinos
  - etc.
- They produce various effects
- One of them is the SZ from the charged component (see Colafrancesco, 2004)
- Subdominant with respect to SZE from the gas.
- We need clusters where Dark Matter and Baryonic Matter are separated.

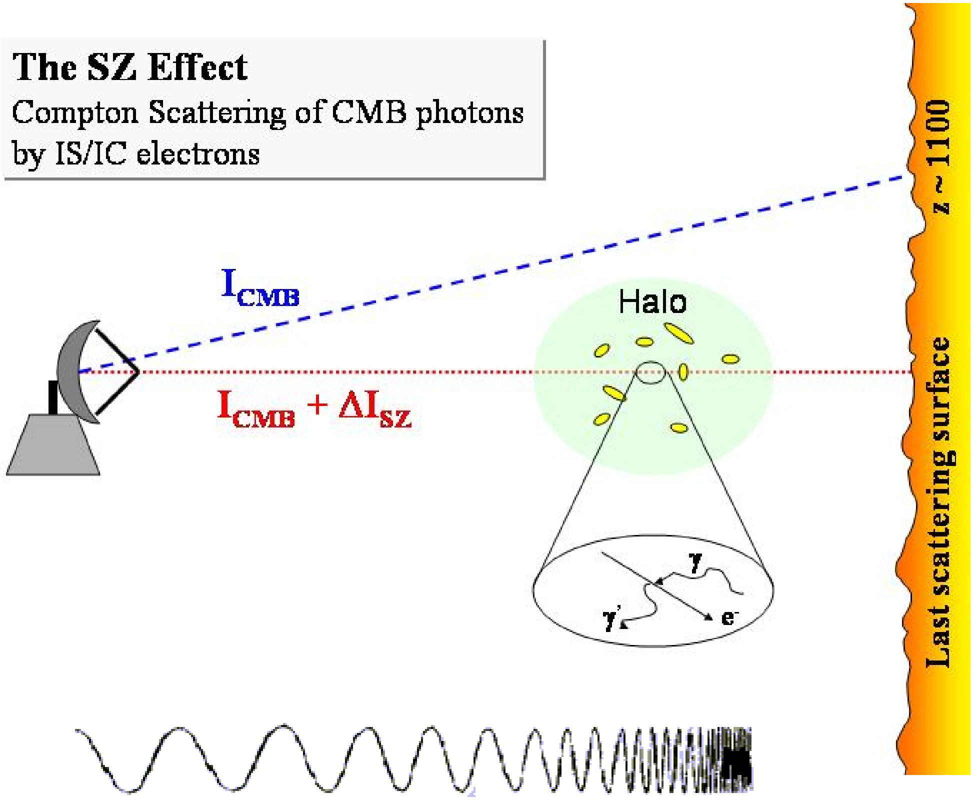

1E0657-56
9’

1E0657-56

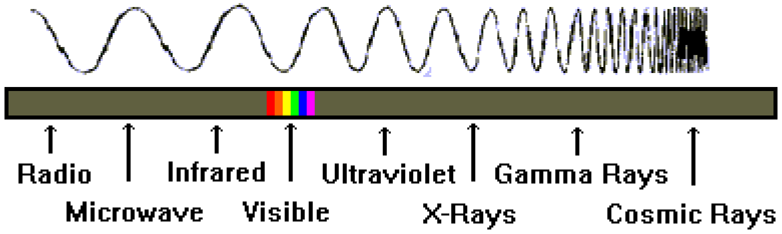


SZ effect from DM

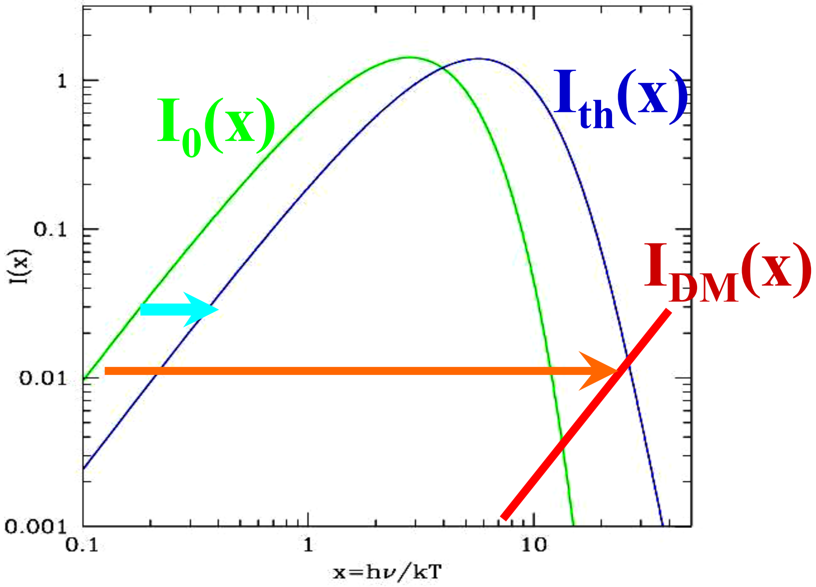
[Colafrancesco 2004 , A&A, 422, L23]



The SZ Effect
Compton Scattering of CMB photons
by IS/IC electrons



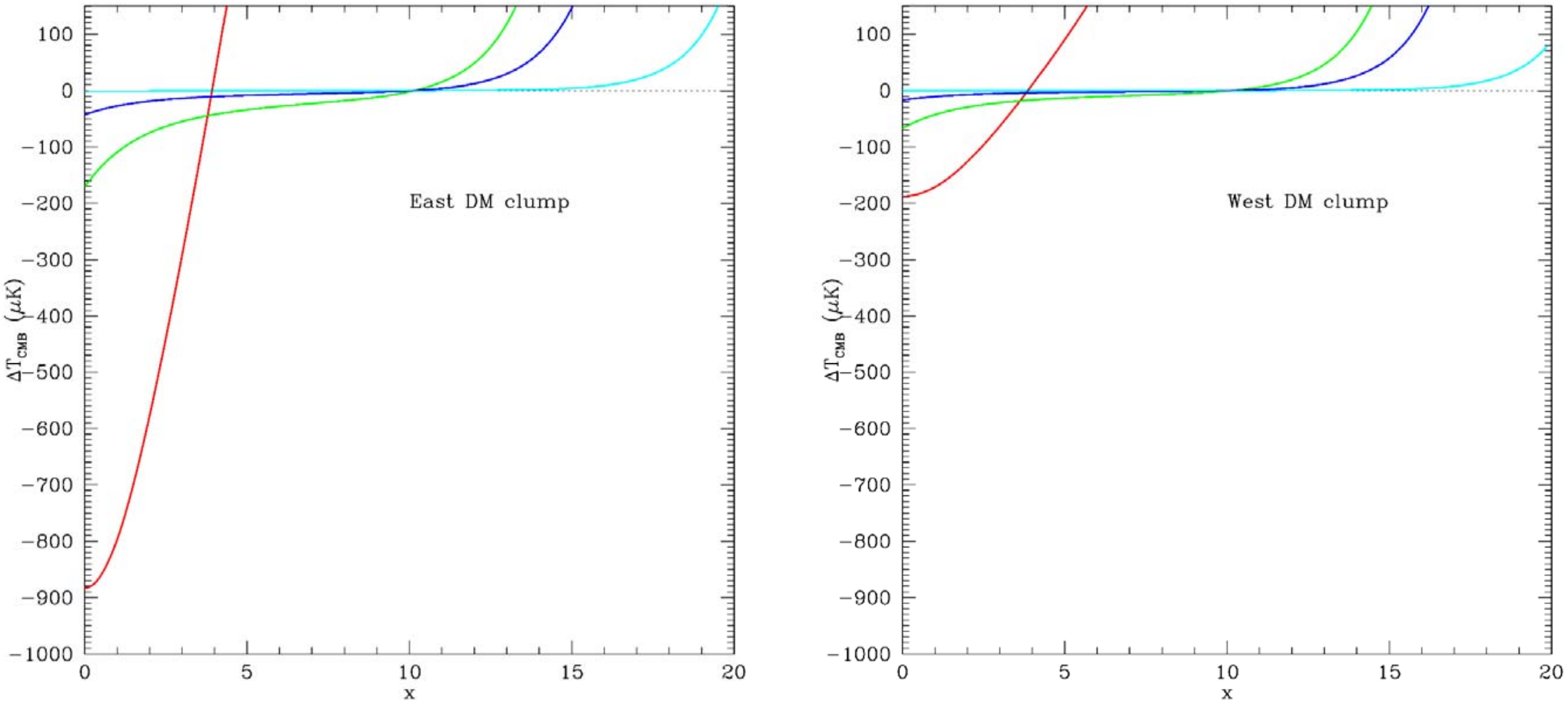
$$\Delta I(x) = I(x) - I_0(x)$$



thermal e⁻ $\quad \frac{\nu'}{\nu} = \frac{4}{3}$

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

SZ effect at clump centres



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

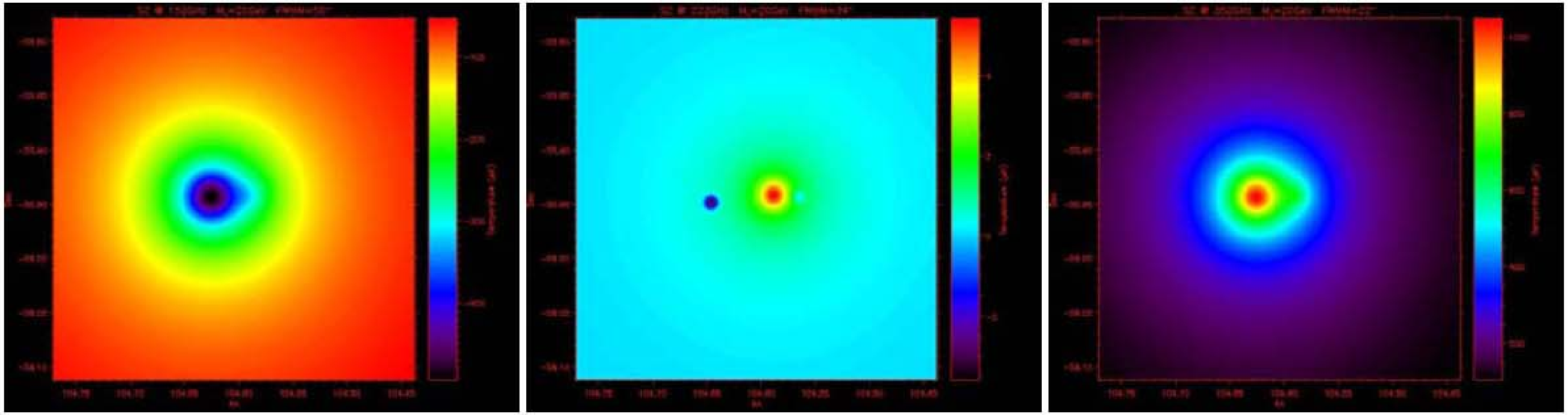
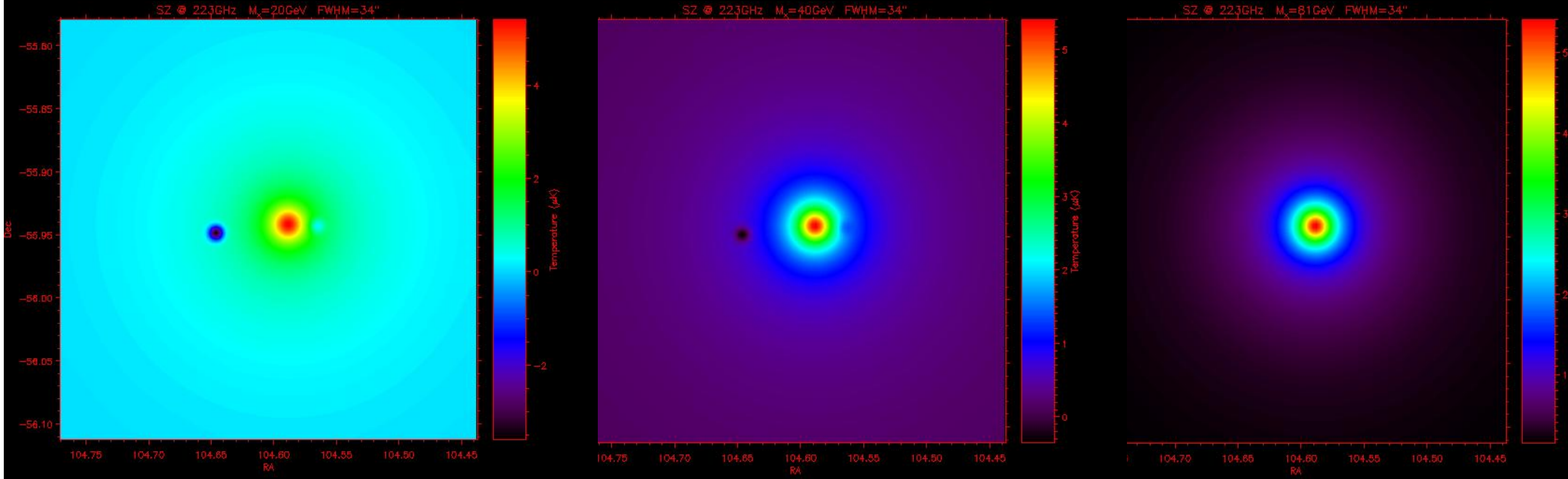


Fig. 2. The simulated SZ maps of the cluster 1ES0657-556 as observable with the SPT telescope at three frequencies: $\nu = 150$ GHz (left panel), $\nu = 223$ GHz (mid panel), $\nu = 350$ GHz (right panel). A neutralino mass of $M_\chi = 20$ GeV has been adopted here. Note that choosing the frequency 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



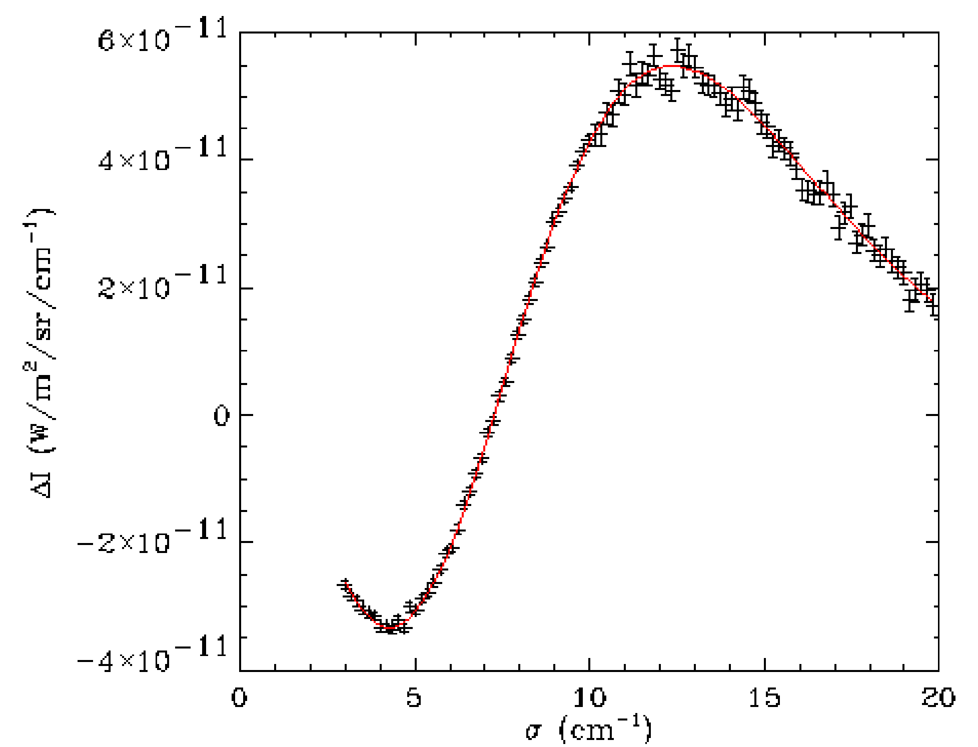
The SZE from the hot gas disappears at $x_{0,th}$ (~ 220-223 GHz) while the SZ_{DM} expected at the locations of the two DM clumps remains negative and with an amplitude and spectrum which depend on M_χ.

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

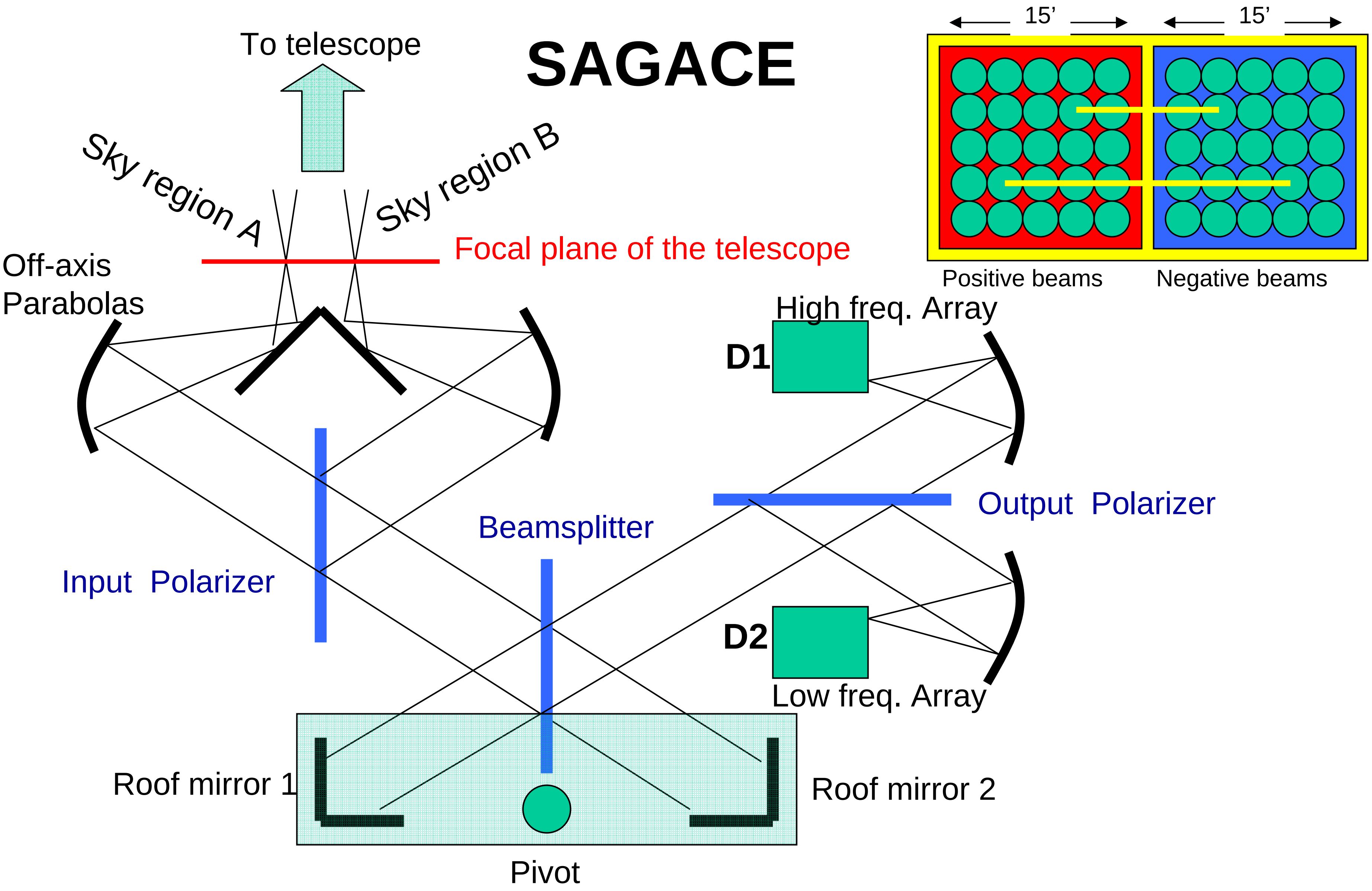
SAGACE

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



SAGACE

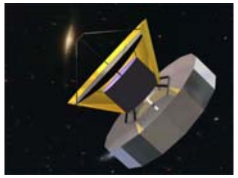


A possible spectrometer: Differential Martin Puplett Interferometer :
Each detector measures the difference of spectra from two sky regions

A differential spectrometer

- The detectors measure the difference in the spectra of two contiguous regions of the sky.
- With this configuration
  - The background produced by the mirror, the instrument, the CMB, most of the foregrounds is the same on both beams and is canceled
  - This is the only way to measure anisotropy at a level of 10^{-5} without requiring unfeasible dynamical ranges.
  - The sidelobes are similar in the two beams: a cheap earth orbit (elliptical) can be considered in place of L2, fitting the small mission requirement.

Cosmology and Astrophysics with SAGACE

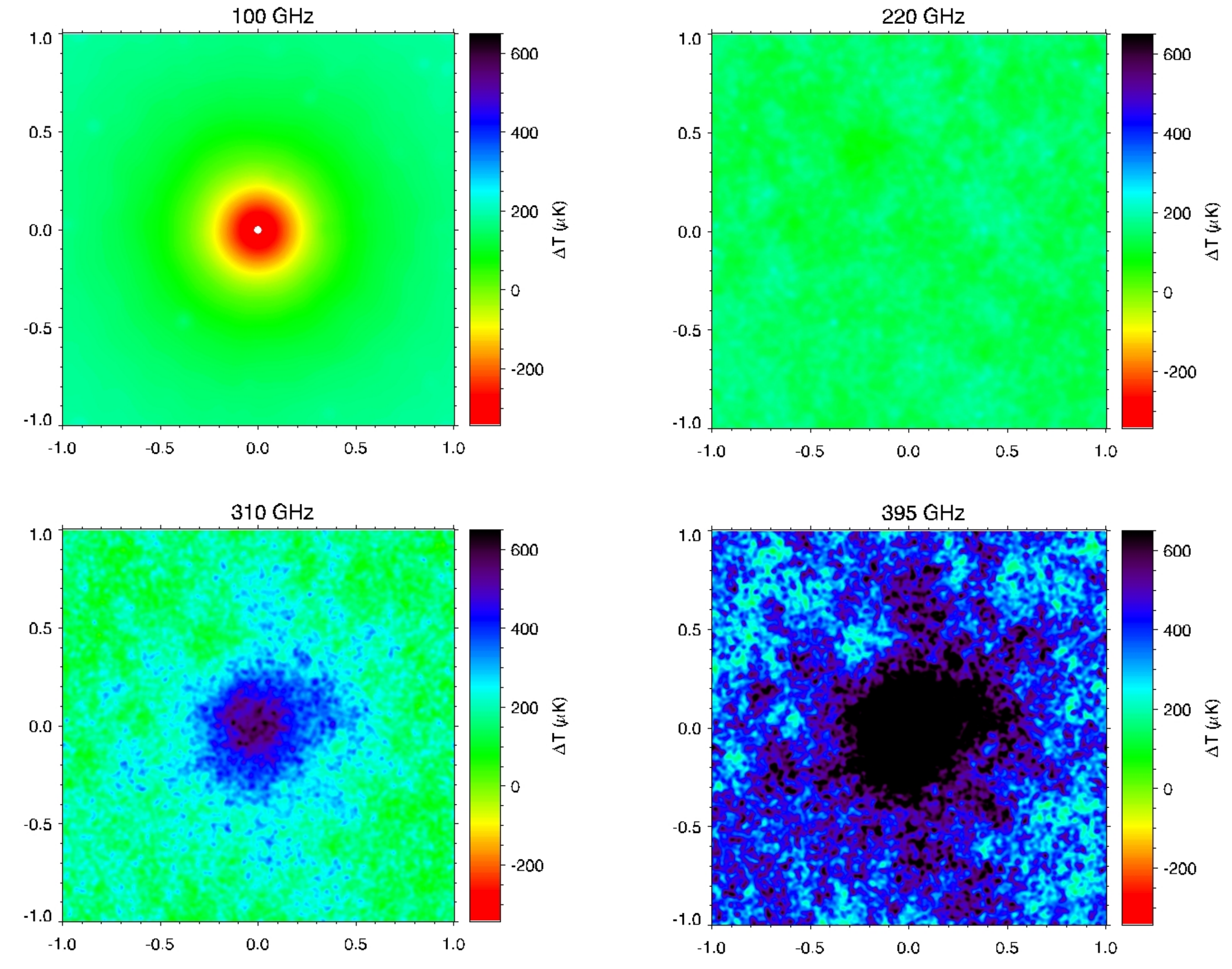


- Science Goals for SAGACE
  - Get ***mm/submm spectra*** of a large number of **Clusters of Galaxies** via the Sunyaev-Zeldovich effect (SZE), and *spectral maps* of nearby ones
    - To study the formation of structures in the Universe
    - To study dark matter and dark energy [n(z)]
    - To study cosmic evolution [Ho, T_{CMB}(z)]
  - Get C+ line emission of a large number of galaxies at high redshift
    - To study the formation of **early galaxies** (cosmic middle ages) and their evolution (cosmic SFR, atoms, molecules)
  - **AGNs** at high redshift: featureless spectrs. Get mm/sub-mm precise photometry of a very large number of them.
    - To study the physical processes happening in AGNs
    - To study the statistics of different classes of AGNs
    - To study AGNs as a foreground for ultrsensitive measurements of the CMB

KAYSER ITALIA SAPIENZA UNIVERSITÀ DI ROMA UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

Confusion from extragalactic sources ?

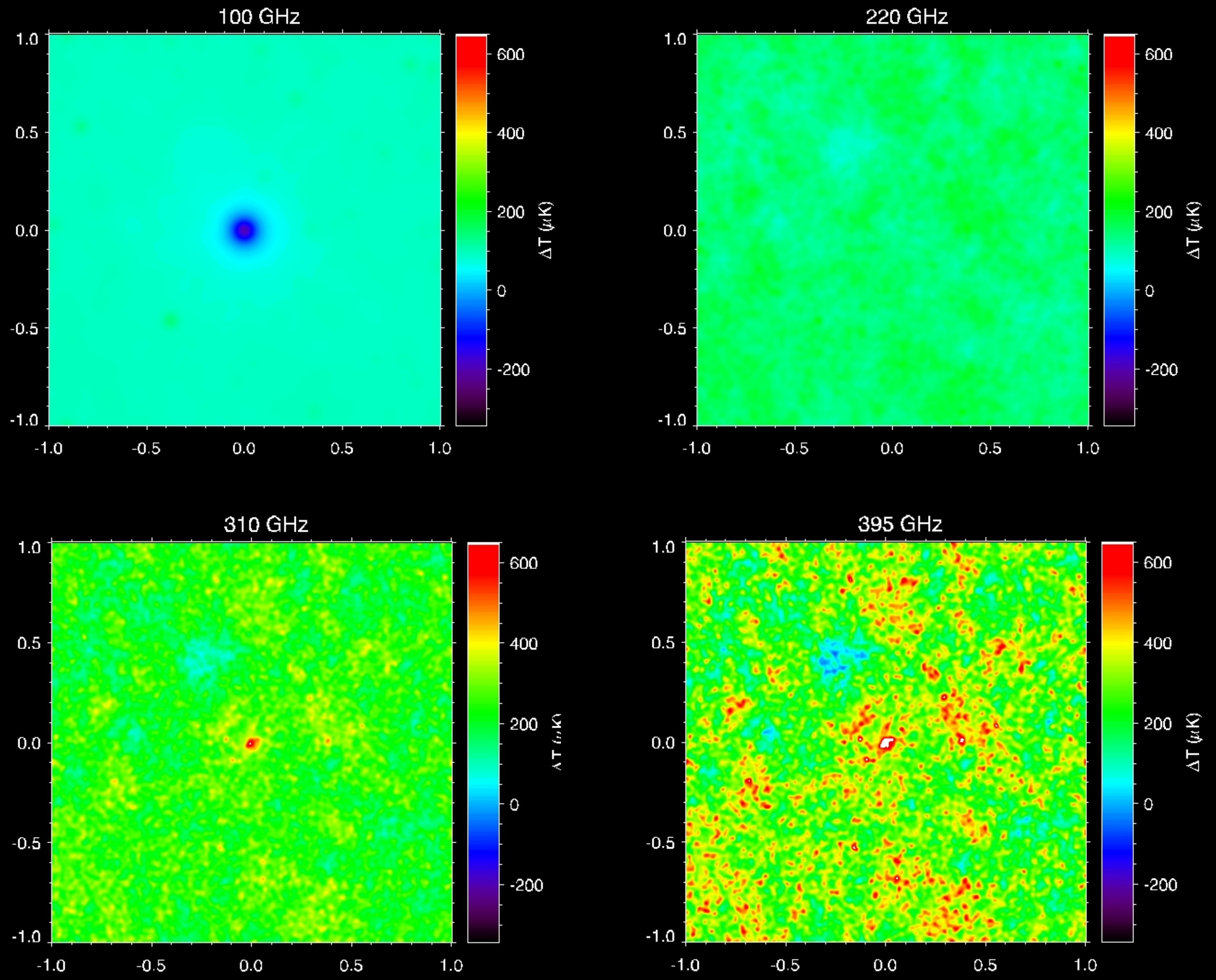
Large cluster (Coma-like)



Confusion simulations by the Padova/Trieste group

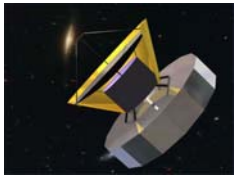
Confusion from extragalactic sources ?

Small cluster (1.2' core diameter)

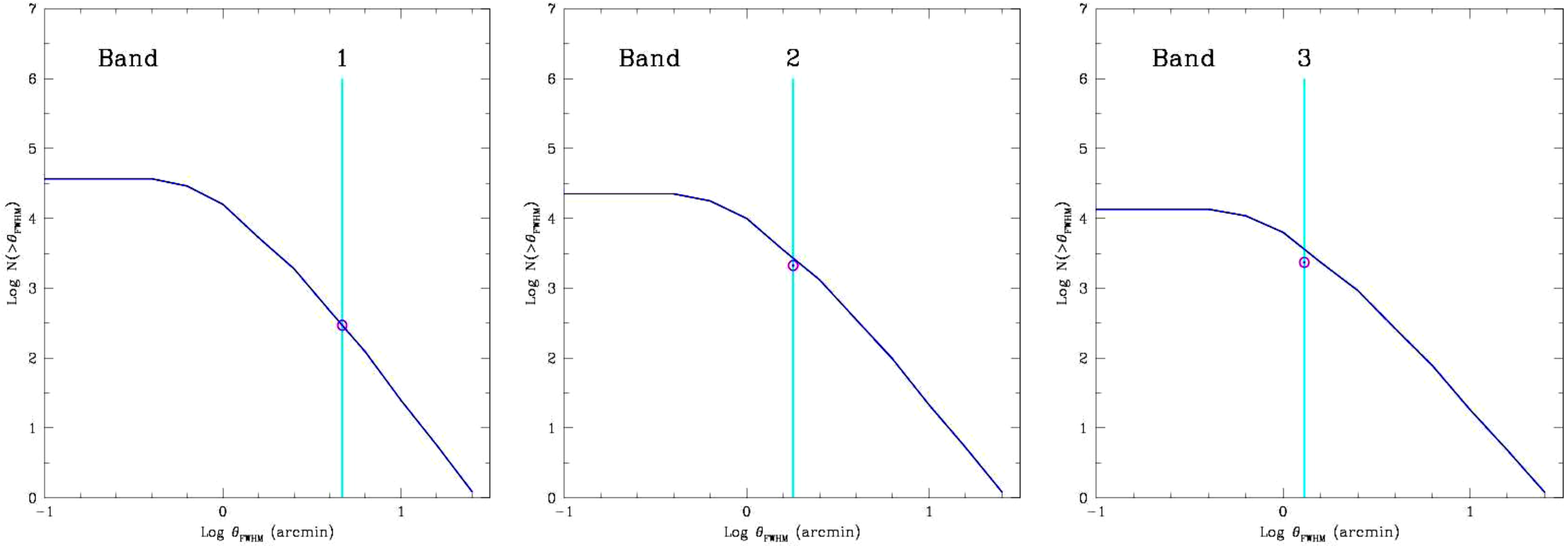


Confusion simulations by the Padova/Trieste group

S-Z Clusters survey



- Q: How many clusters can we detect with a small mission ?

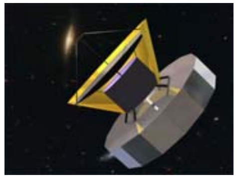


- A: thousands, with an angular resolution better than a few arcmin and the limiting flux is around 20 mJ !

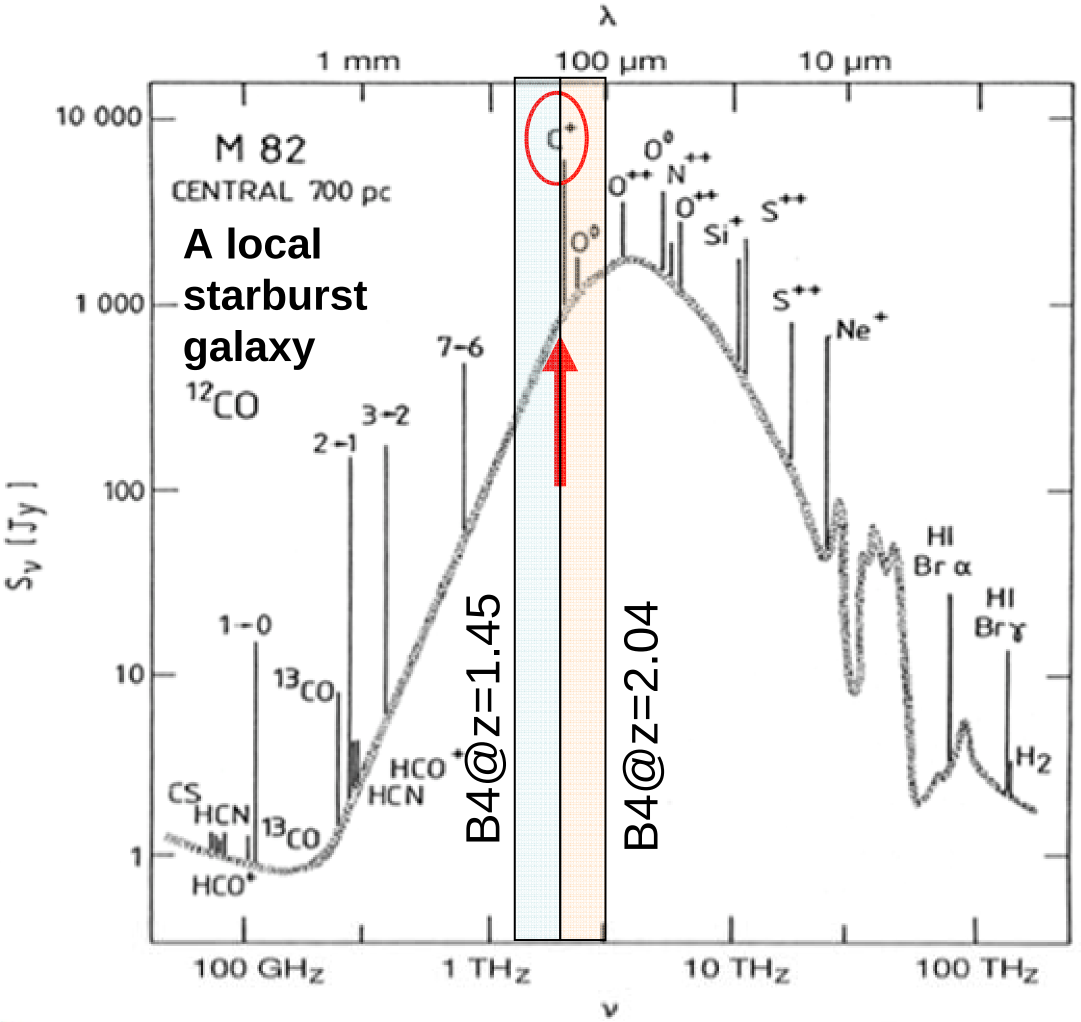
Analysis by S. Colafrancesco

KAYSER ITALIA
SAPIENZA UNIVERSITÀ DI ROMA
UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

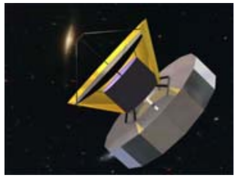
C+ lines in high redshift galaxies



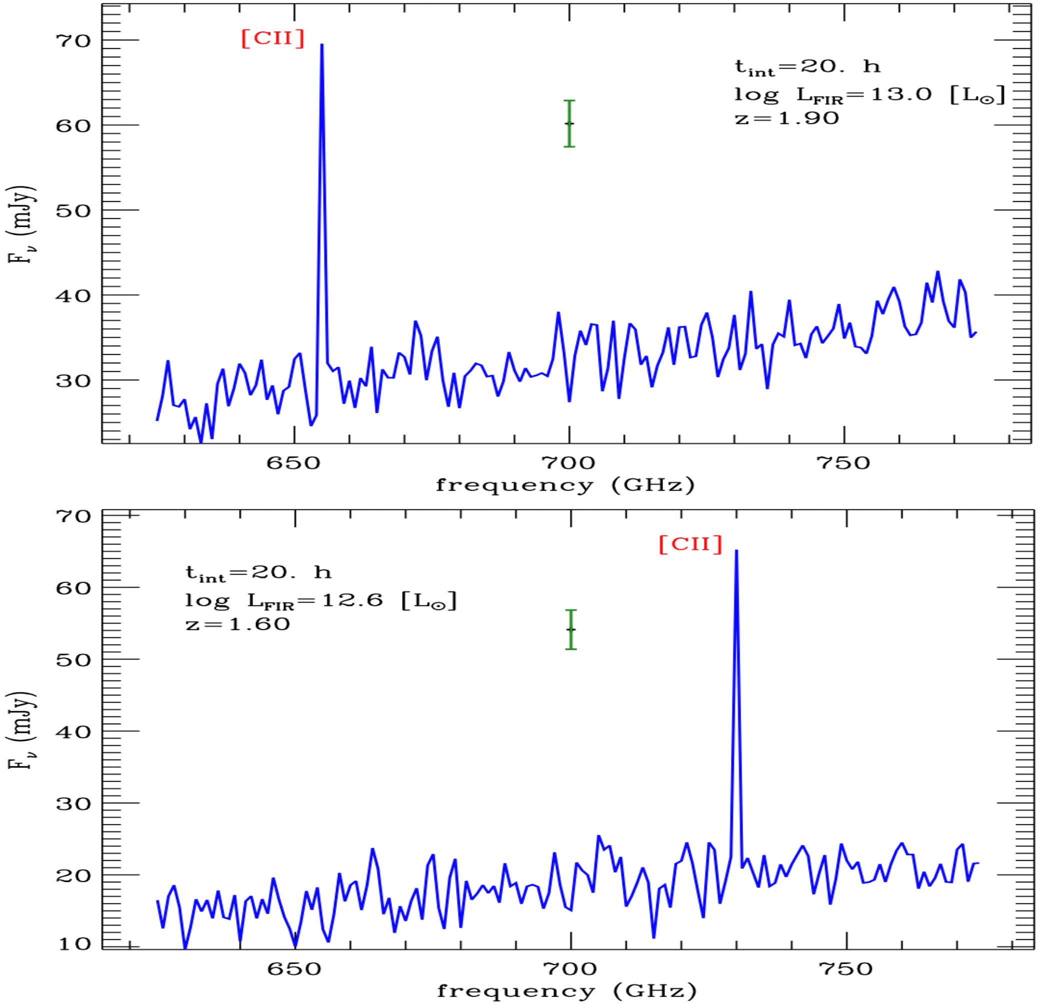
- Band B4 in SAGACE has been optimized to be sensitive to the C+ line produced by galaxies in the “redshift desert “ z=1.4-2, where strong optical lines are not visible.
- For this reason SAGACE will be a unique tool to complement optical redshift surveys, population and evolution studies.



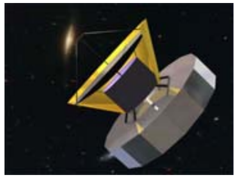
C+ lines in high redshift galaxies



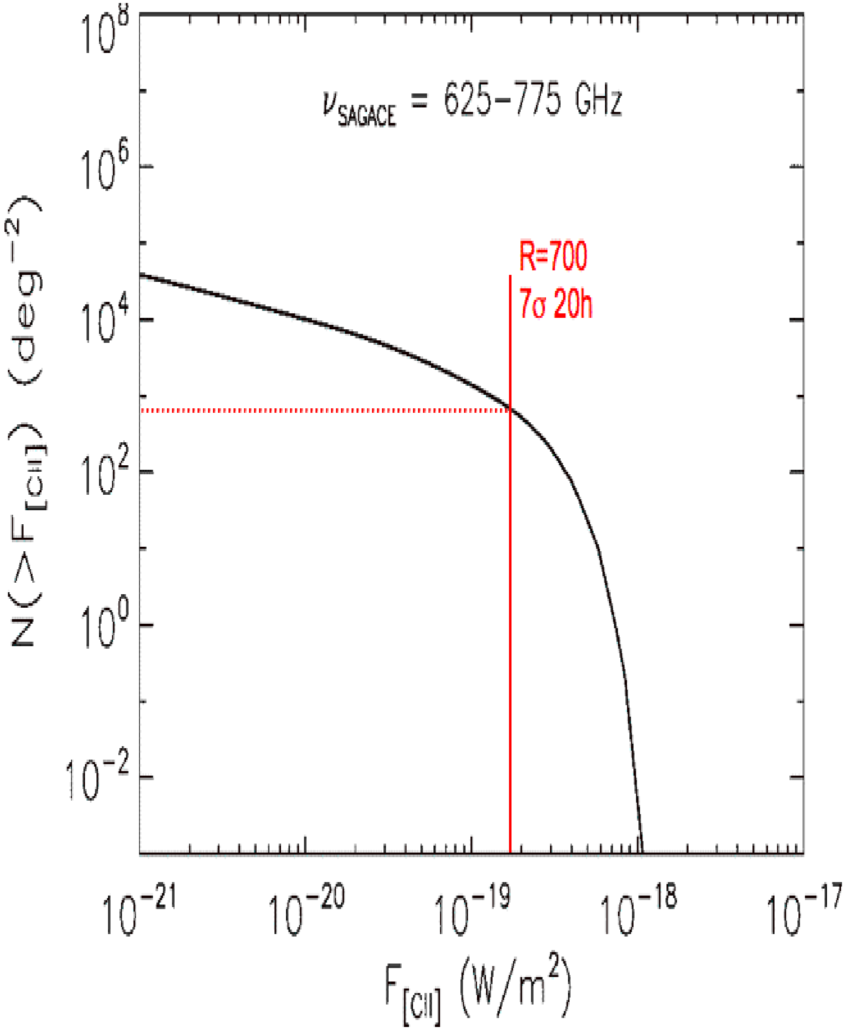
- Simulated spectra of high-z sources (L_{FIR} = 5 10^{12} - 10^{13} $L_{\odot}$) observed with SAGACE through a deep integration of 20 hours.
- The [CII] line is clearly detected with a significance higher than 10σ.
- The green bar indicates the noise level.
- Note that also the continuum is detected in both sources with high significance.



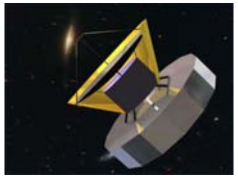
C+ lines in high redshift galaxies

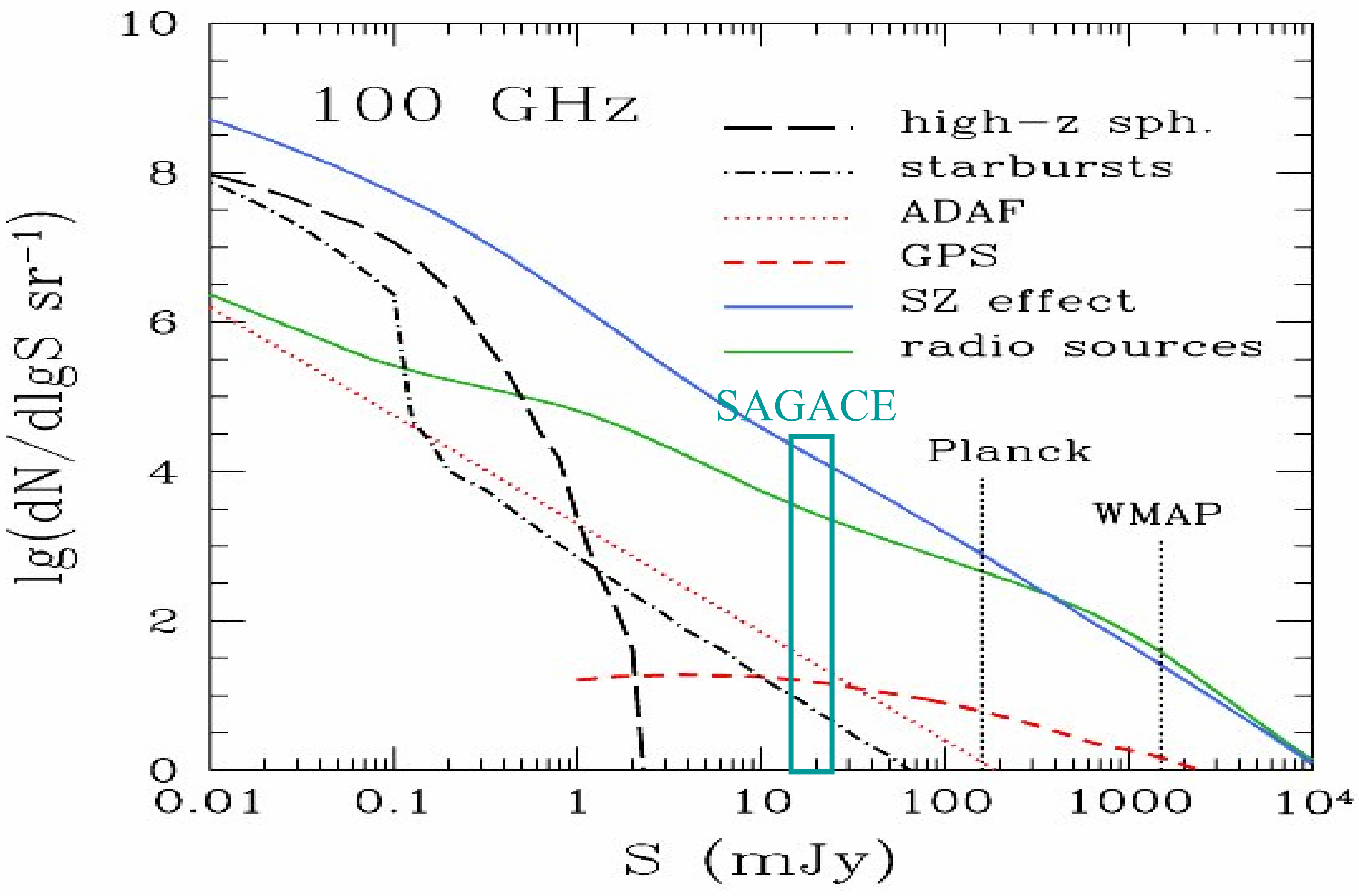


- Cumulative counts of galaxies with [CII] and CO line fluxes above a given flux in the band 625-775 GHz (the highest frequency band of SAGACE).
- The red line shows the expected 7σ detection limit of SAGACE at high resolution (R(700GHz) = 700) and with an integration time of 20 hours.
- Since the FOV is 0.25 sq.deg, in 20*(10/0.25) h = 1 month SAGACE can measure the redshift of a sample of about 1000 early galaxies, in the redshift desert !



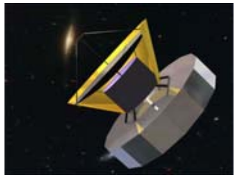
A photometric survey with SAGACE

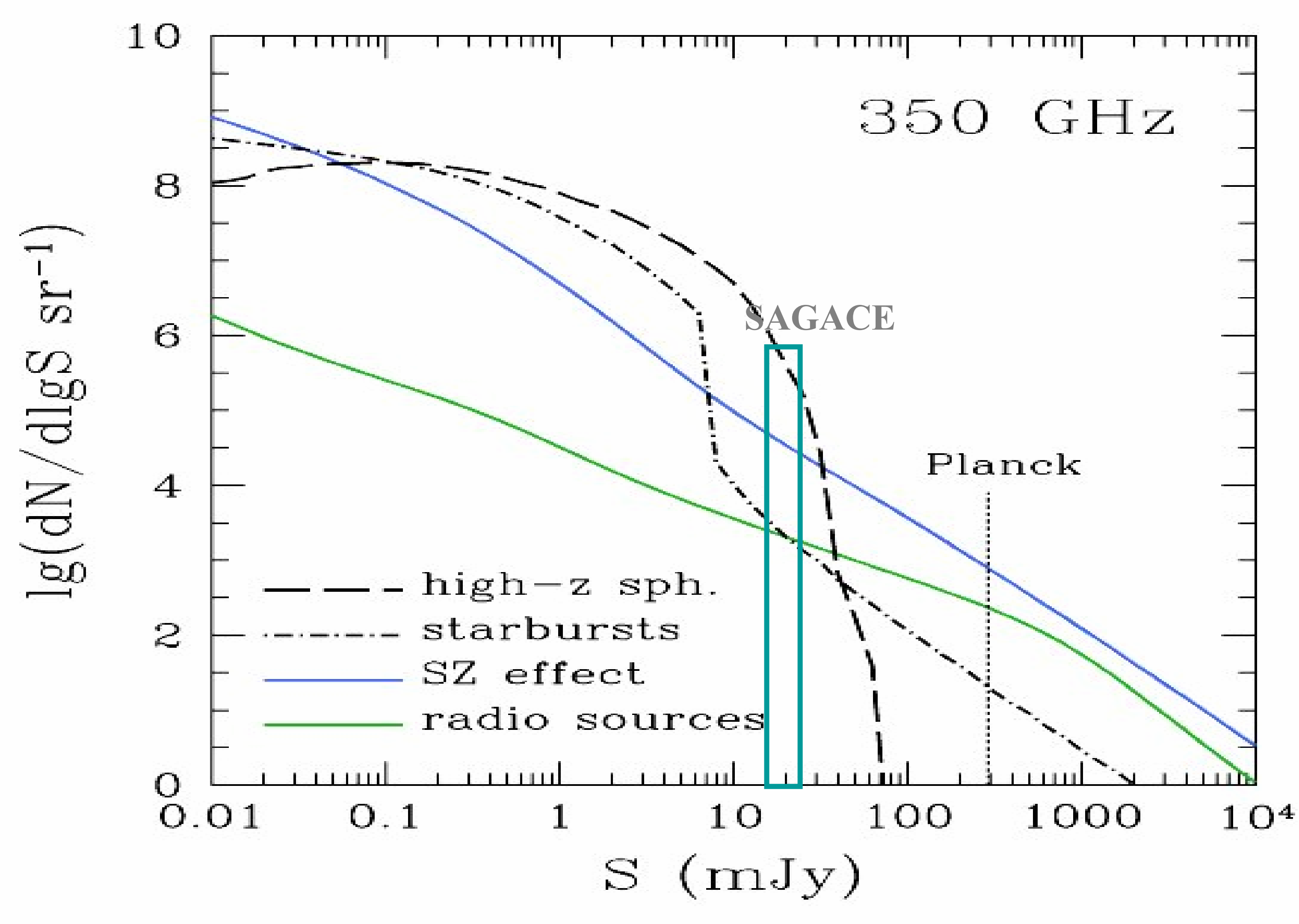




Simulations by G. De Zotti

A photometric survey with SAGACE





Simulations by G. De Zotti

CMB Polarization and B-Modes

- Polarization measurements do not constrain parameters better than anisotropy measurements, yet.
- Most of the weight in the results above is in Temperature power spectra.
- If we want to constrain better the cosmological model, and finally detect B-modes, and we need to improve in three ways:

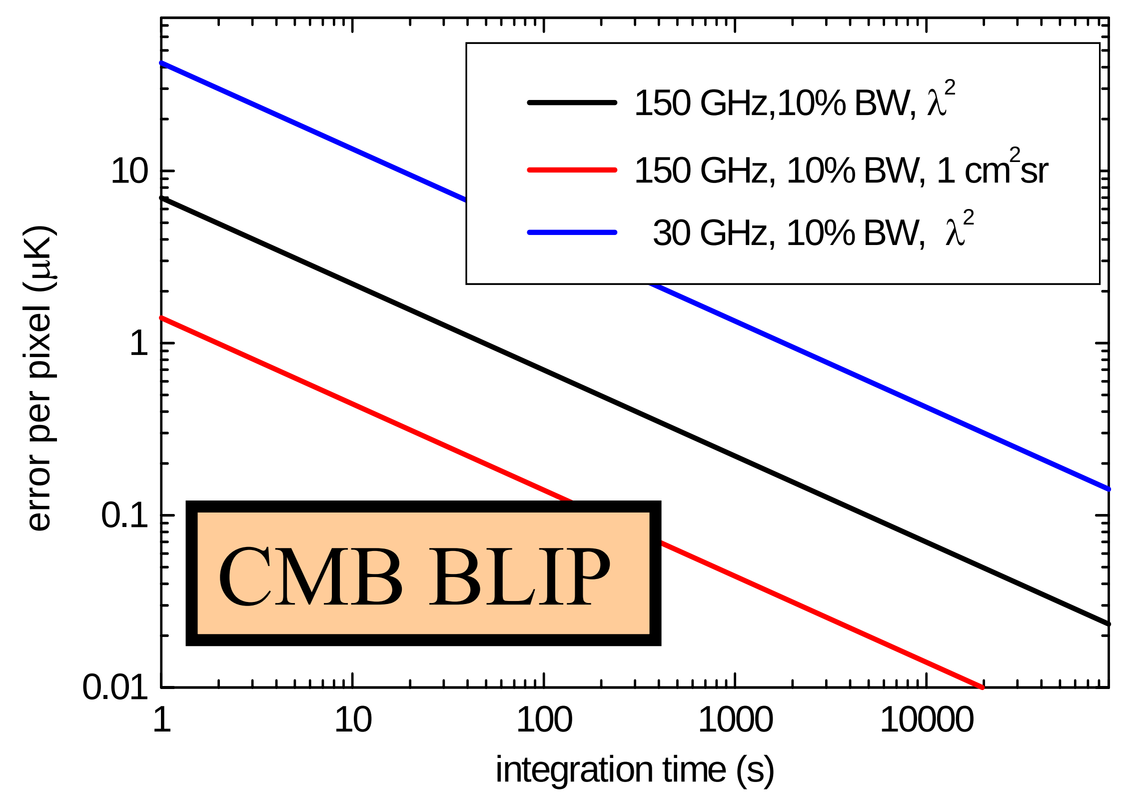
1. Sensitivity
2. Control of systematics
3. Knowledge of foregrounds

Sensitivity

- B03 has shown that Polarization Sensitive Bolometers work well for CMB polarization measurements.
- Their sensitivity is close to be photon-noise-limited. In Planck-HFI the same bolometers will be cooled a factor 3 more and will be limited only by quantum fluctuations of the CMB itself. It is useless to improve the detector noise below the photon noise limit.

A post-Planck mission

- Planck will or will not detect Inflationary B-Modes (depending on amplitude, foregrounds, systematics... and if they are really there).
- In a diffraction limited 150 GHz survey, CMB BLIP gives 1 μK in 1 min of integration. But we need to observe 10^5 pixels !



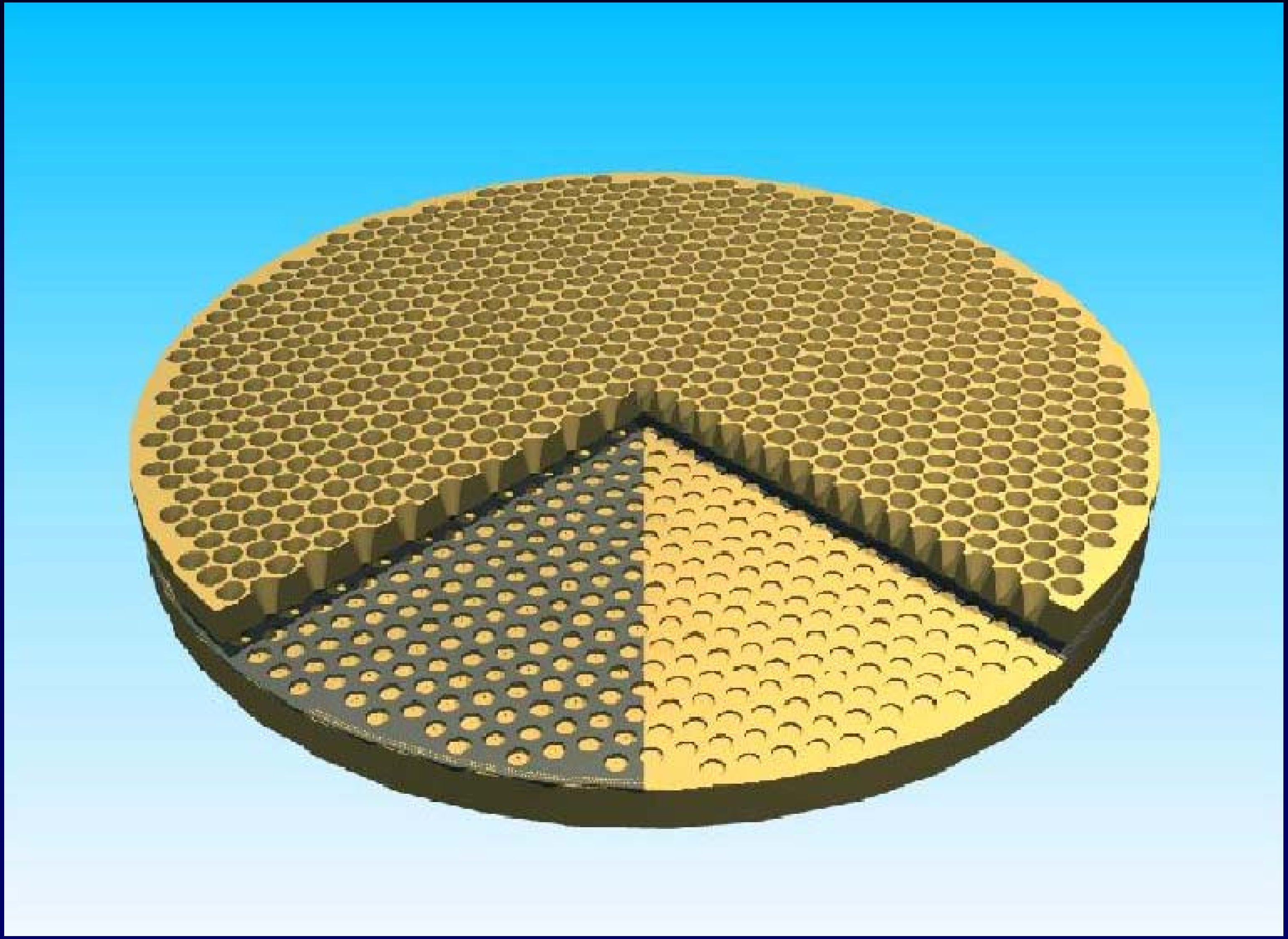
- We need to increase the mapping speed using more detectors than in the Planck focal plane.

Sensitivity

- At variance with interferometers, Bolometer technology is easily scalable, and the throughput can be larger than λ^2.
- Focal planes hosting thousands of bolometers are being developed already.

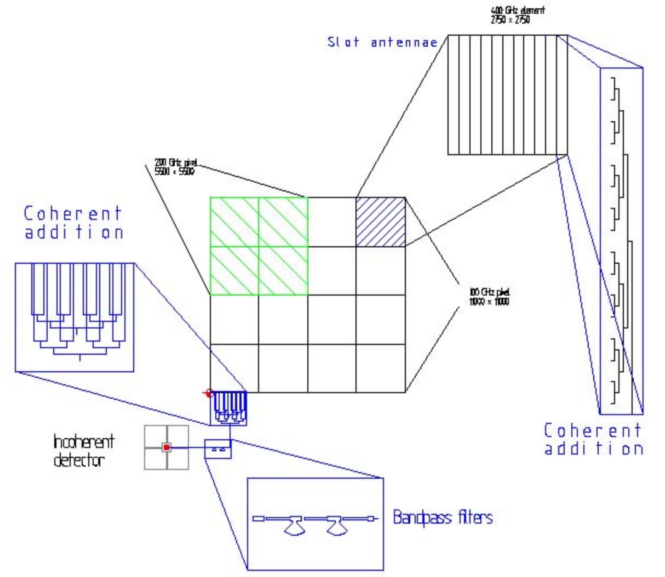
Large Bolometer Arrays

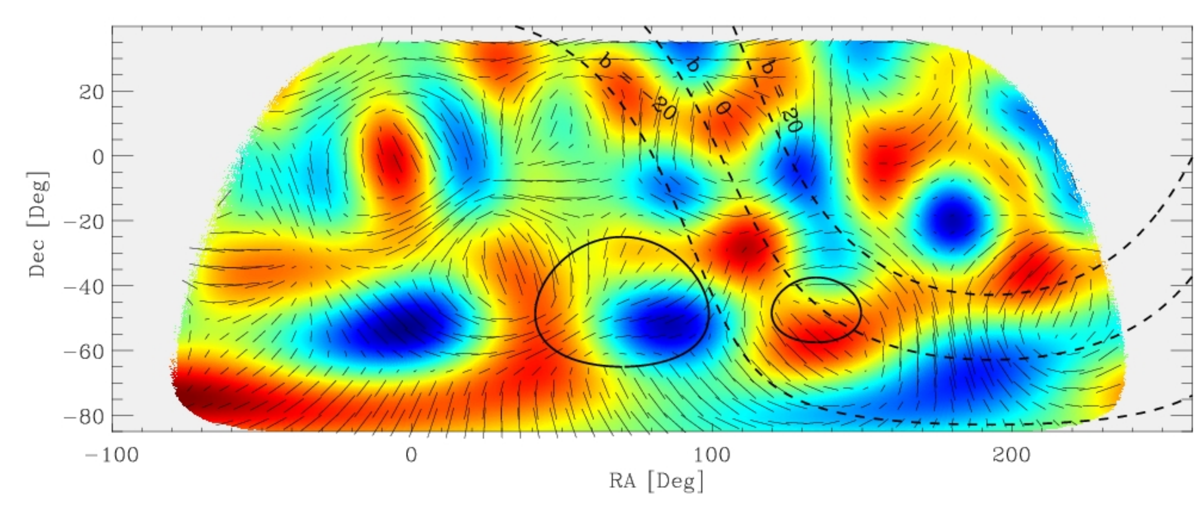
- > 1000 TES bolometers for the South Pole Telescope devoted to SZ (Adrian Lee, Berkeley)

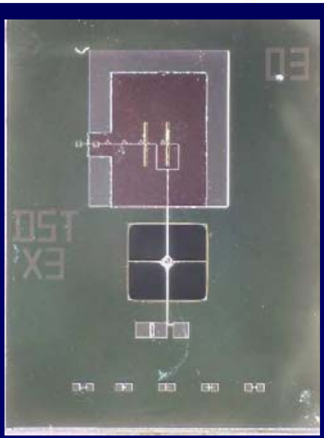


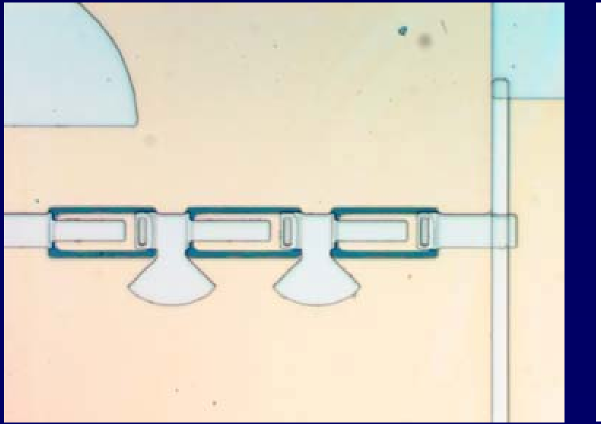
Large Bolometer Arrays

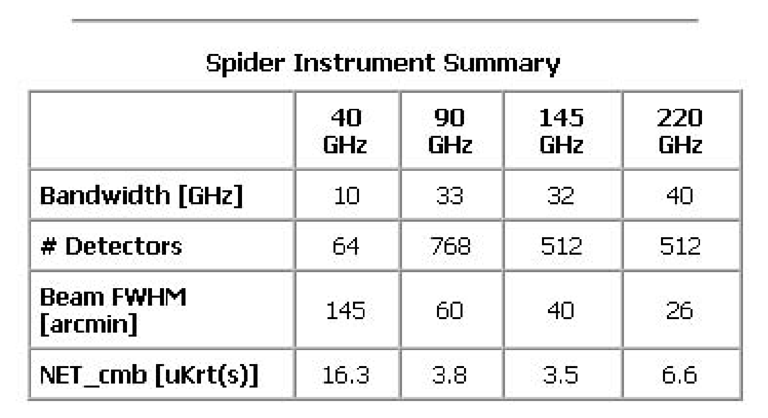
- > 1000 TES bolometers for SPIDER a proposed spinning polarimeter on a LDB (Andrew Lange, Caltech) devoted to large scale CMB polarization









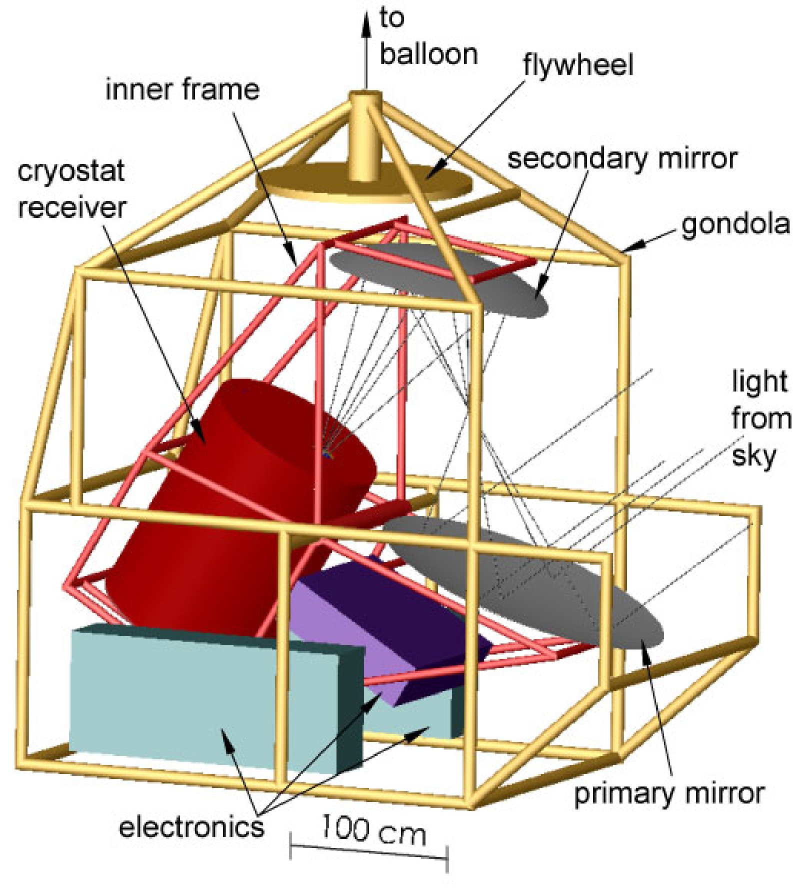


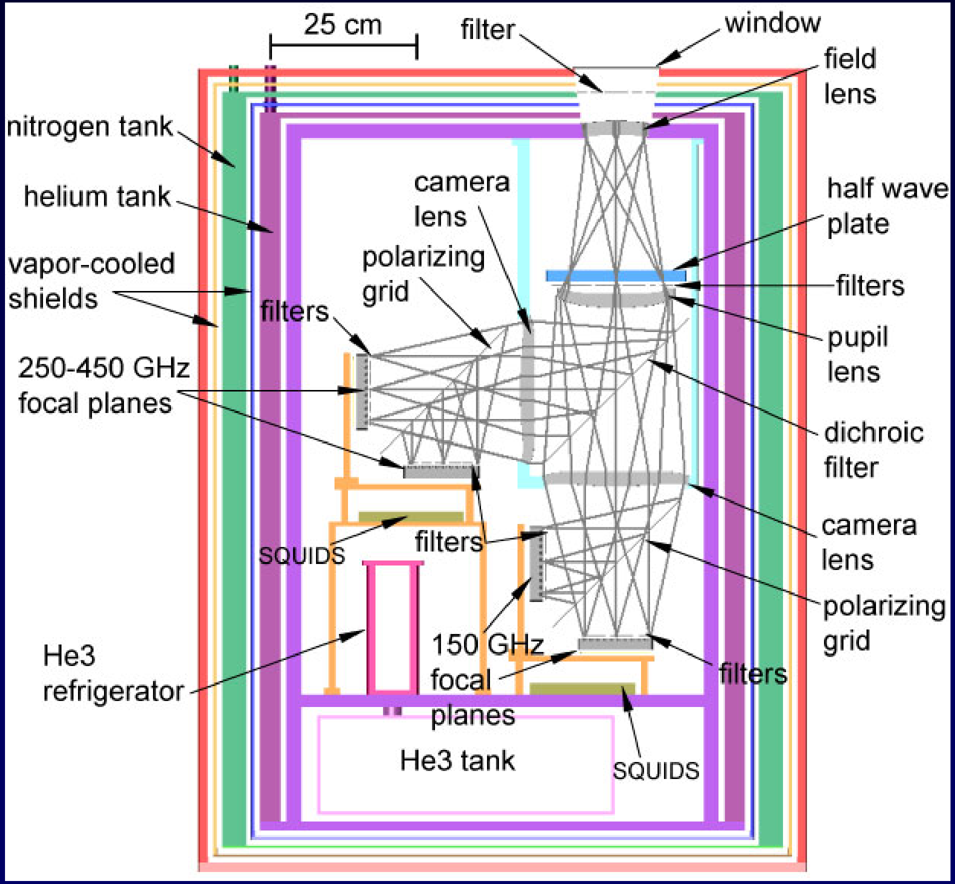
Spider Instrument Summary

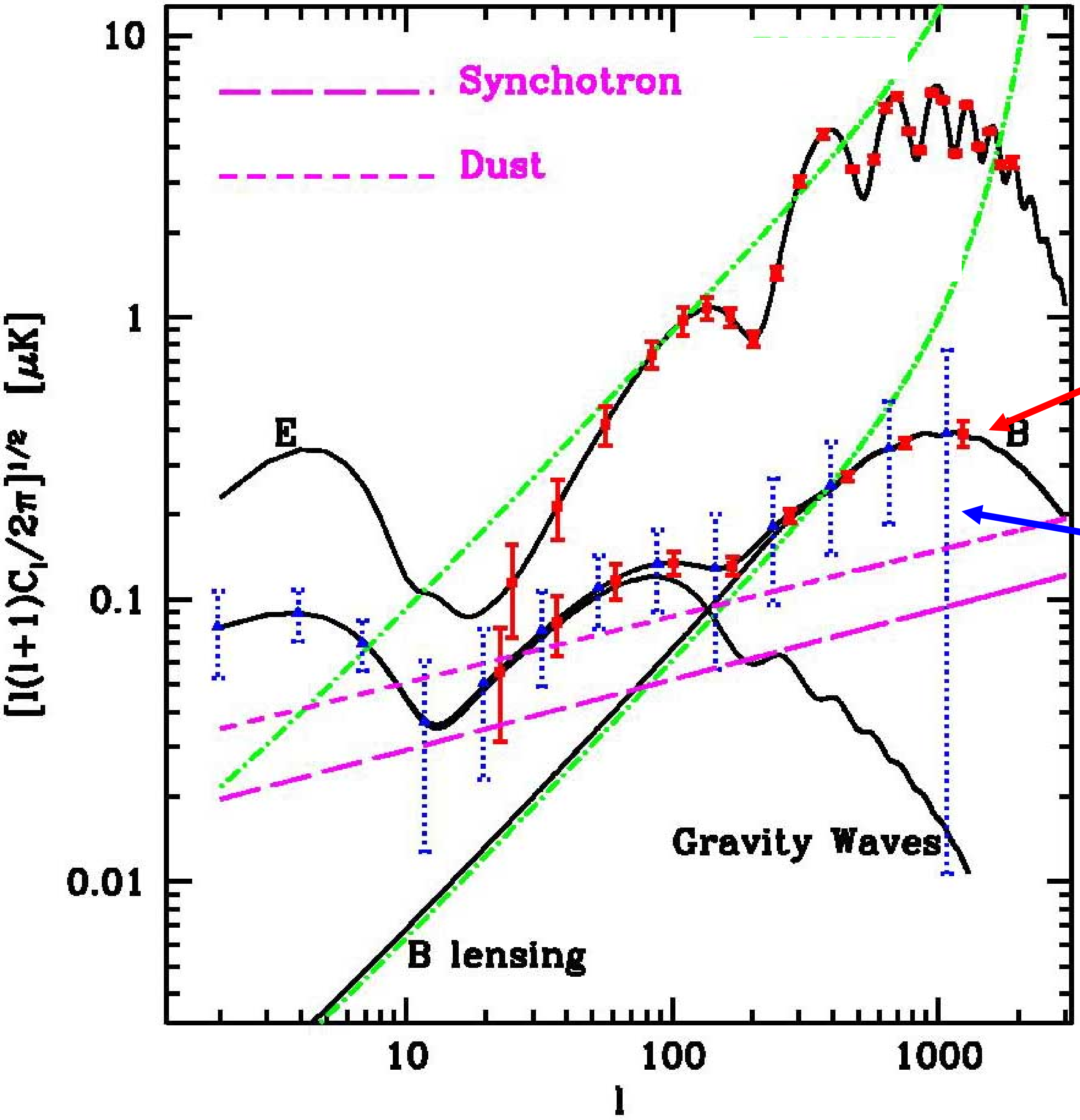
	40 GHz	90 GHz	145 GHz	220 GHz
Bandwidth [GHz]	10	33	32	40
# Detectors	64	768	512	512
Beam FWHM [arcmin]	145	60	40	26
NET_cmb [uKrt(s)]	16.3	3.8	3.5	6.6

Large Bolometer Arrays

- >1000 TES bolometers for the EBEX CMB polarization balloon telescope (Shaul Hanany, Minneapolis)







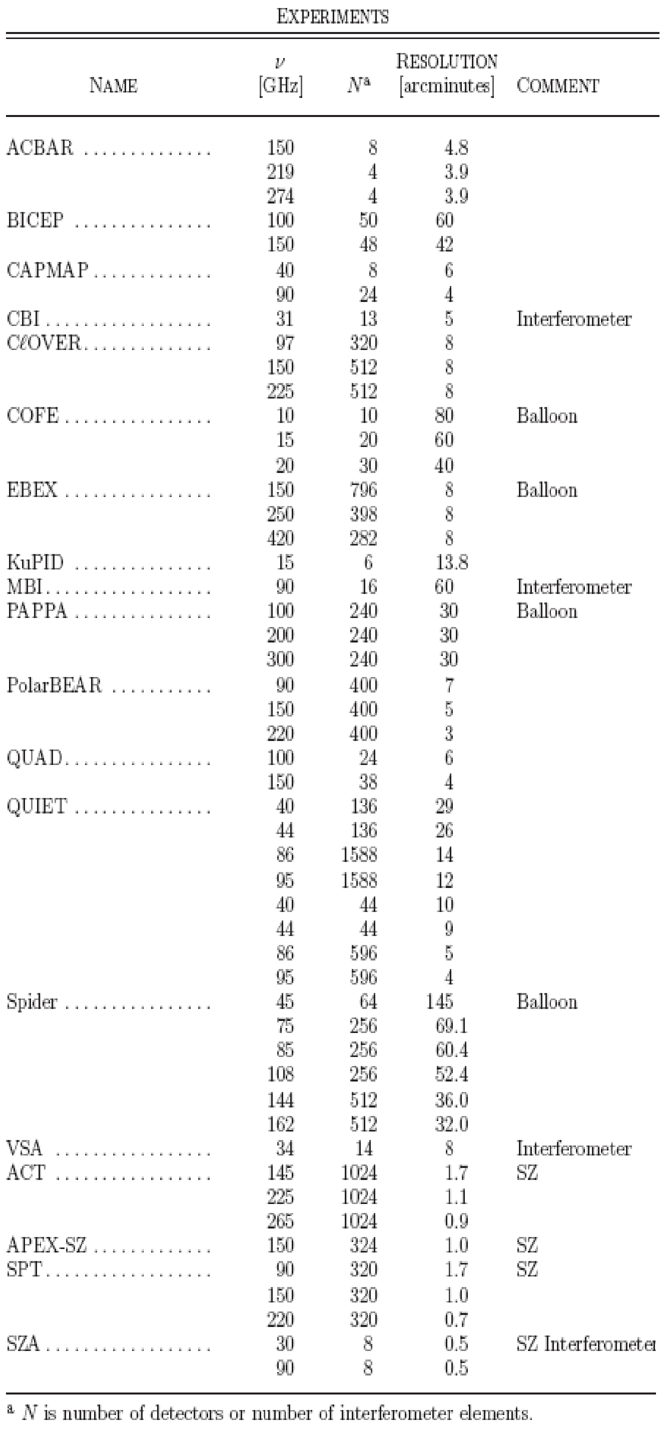
Bolom.
Array

Planck

From the EBEX proposal

Control of Systematic Effects

- B03 has shown that systematic effects can be controlled by a combination of
  - Multifrequency capabilities
  - Scan variation
  - Polariziation angle redundancy
  - Variations of observing conditions
  - Accurate pre-flight and in-flight calibration
- This was OK at the level of sensitivity of B03 (i.e. 3σ detection of E-modes, 4 μK rms).
- Nobody knows how to control systematics for a B-modes experiment (<0.1 μK rms).
- The only way is to experiment !
- Calibration sources must be found and characterized.
- Balloon and Antarctica experiments are necessary to test the technique/methodology before to start the design of a B-modes space mission.



EXPERIMENTS

NAME	ν [GHz]	N[a]	RESOLUTION [arcminutes]	COMMENT
ACBAR	150	8	4.8	
	219	4	3.9	
	274	4	3.9	
BICEP	100	50	60	
	150	48	42	
CAPMAP	40	8	6	
	90	24	4	
CBI	31	13	5	Interferometer
CℓOVER	97	320	8	
	150	512	8	
	225	512	8	
COFE	10	10	80	Balloon
	15	20	60	
	20	30	40	
EBEX	150	796	8	Balloon
	250	398	8	
	420	282	8	
KuPID	15	6	13.8	
MBI	90	16	60	Interferometer
PAPPA	100	240	30	Balloon
	200	240	30	
	300	240	30	
PolarBEAR	90	400	7	
	150	400	5	
	220	400	3	
QUAD	100	24	6	
	150	38	4	
QUIET	40	136	29	
	44	136	26	
	86	1588	14	
	95	1588	12	
	40	44	10	
	44	44	9	
	86	596	5	
	95	596	4	
Spider	45	64	145	Balloon
	75	256	69.1	
	85	256	60.4	
	108	256	52.4	
	144	512	36.0	
	162	512	32.0	
VSA	34	14	8	Interferometer
ACT	145	1024	1.7	SZ
	225	1024	1.1	
	265	1024	0.9	
APEX-SZ	150	324	1.0	SZ
SPT	90	320	1.7	SZ
	150	320	1.0	
	220	320	0.7	
SZA	30	8	0.5	SZ Interferometer
	90	8	0.5	

---

[a] N is number of detectors or number of interferometer elements.

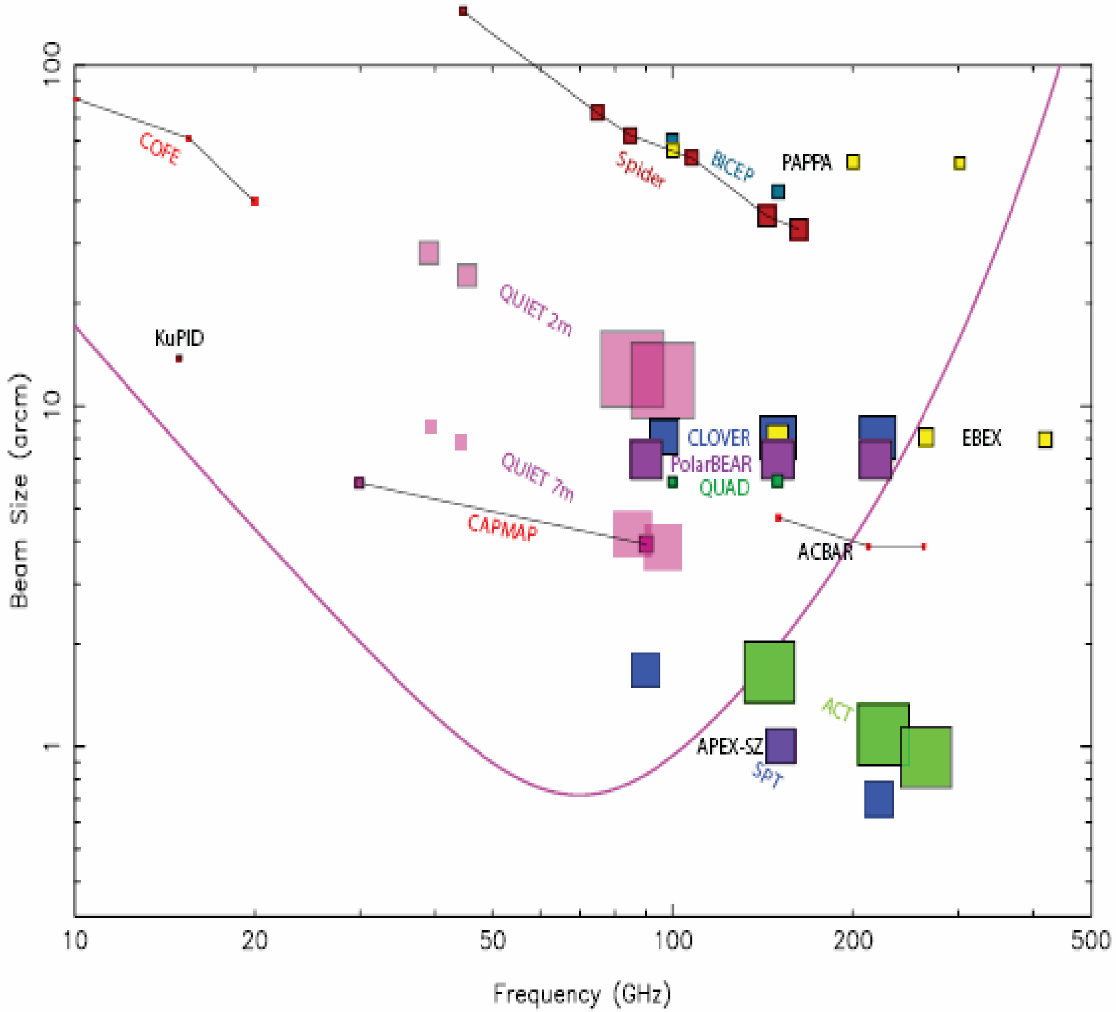
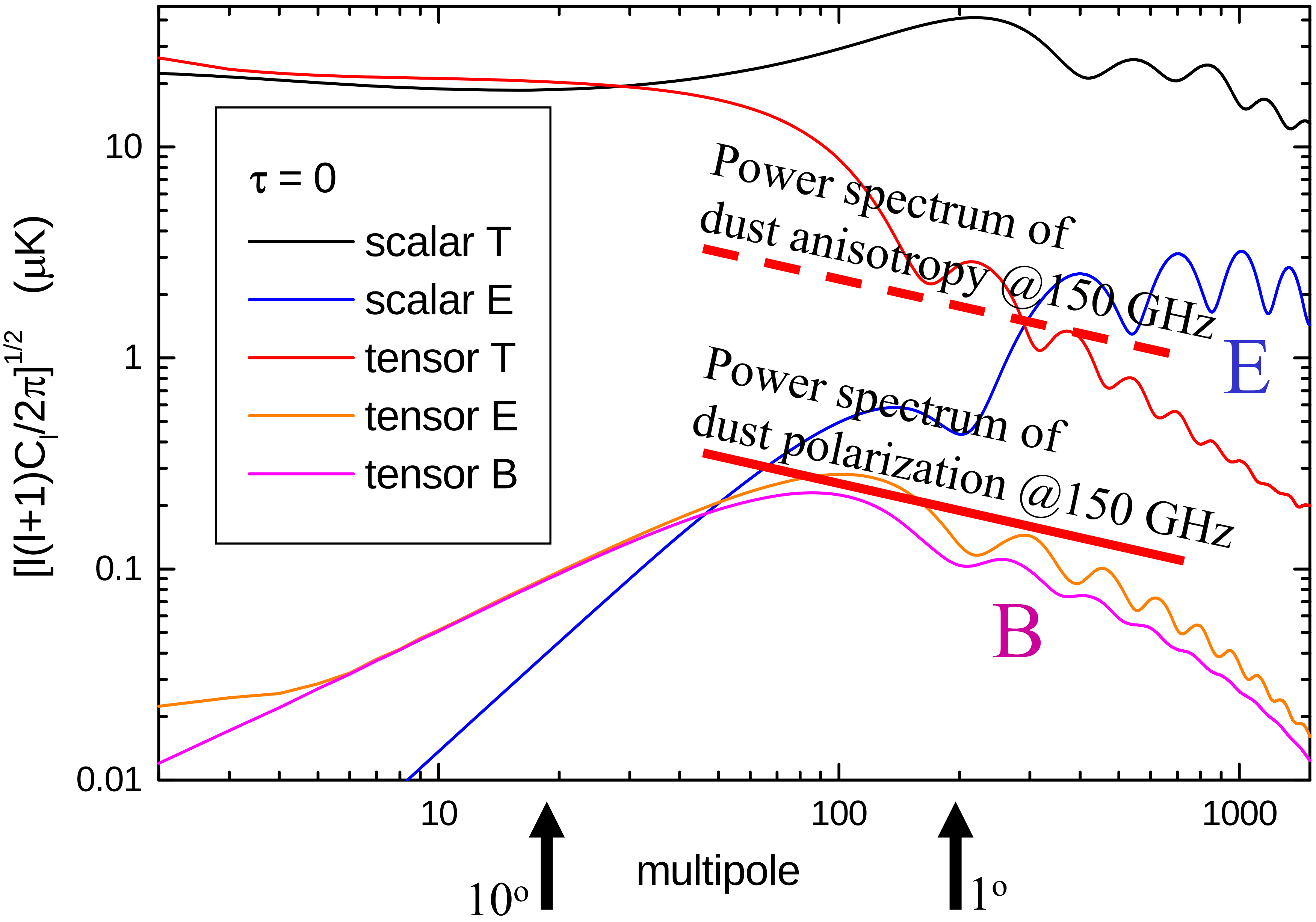


Figure 3: A sampling of suborbital experiments underway or planned. The area of the square is proportional to the number of detectors × integration time, where time = 1 year for ground experiments, and 20 days × 5 for balloon experiments. The factor of 5 for balloon experiments accounts roughly for the sensitivity advantage of bolometers above the atmosphere. No additional adjustments for sensitivity have been attempted, nor has any account been taken of planned sky coverage, etc. All frequency bands of the same experiment

From
C. Lawrence, PoS (CMB2006) 012

Control of Foregrounds

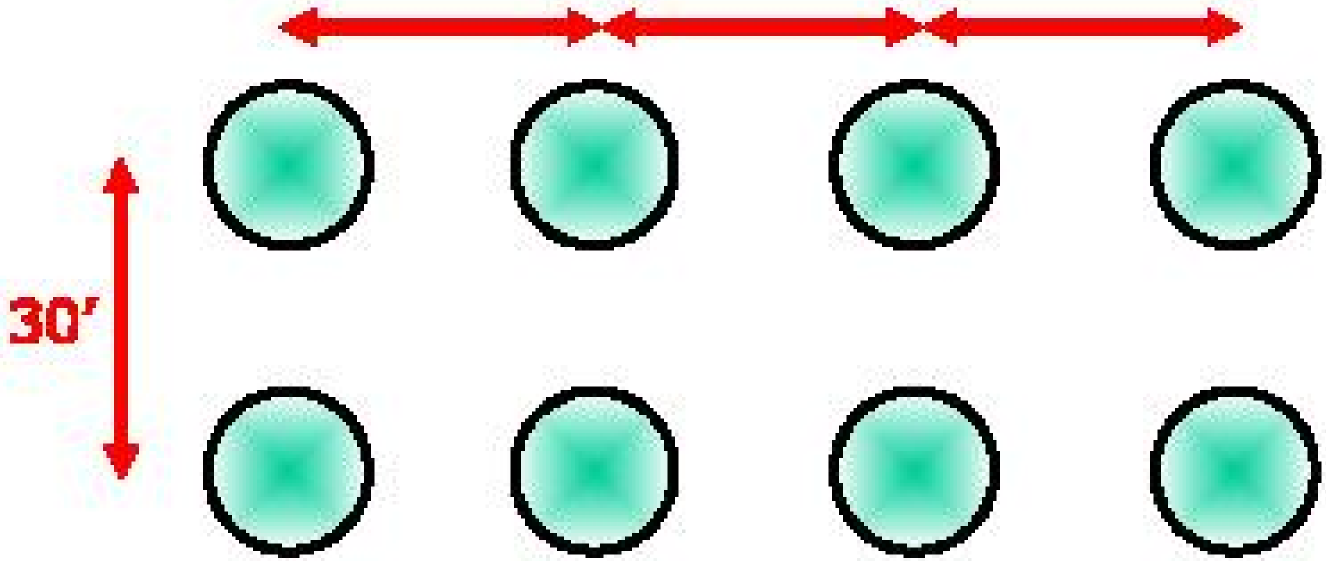
- Diffuse Dust emission is polarized at 10% in the plane of the Galaxy. See **astro-ph/0306222** “First Detection of Polarization of the Submillimetre Diffuse Galactic Dust Emission by Archeops”.
- Its polarization will have both E-modes and B-modes.
- We know that **at 150 GHz** at high latitudes the PS of dust emission is about 1% of the PS of CMB anisotropy (Masi et al. **Ap.J. 553,** L93-L96, 2001)
- So **we naively expect B-modes from dust polarization PS at a level of 10^{-4} of the anisotropy**.
- This is an important foreground for B-modes of CMB, whose level is also about 10^{-4} of anisotropy !
- These are only rough estimates. We know very little about the configuration and distribution of the magnetic fields aligning the dust grains.


τ = 0
scalar T
scalar E
tensor T
tensor E
tensor B
Power spectrum of dust anisotropy @150 GHz
Power spectrum of dust polarization @150 GHz
E
B
[l(l+1)C$_l$/2π]$^{1/2}$ (μK)
10
1
0.1
0.01
10
100
1000
multipole
10°
1°

BOOMERanG-FG

- We plan to re-fly B03 with an upgraded forcal plane, to go after foreground cirrus dust polarization.
- This information is **essential** for all the planned B-modes experiments (e.g. BICEP, Dome-C etc.) and is very difficult to measure from ground.
- The BOOMERanG optics can host an array of >100 PSB at >350 GHz.

BOOMERanG-03

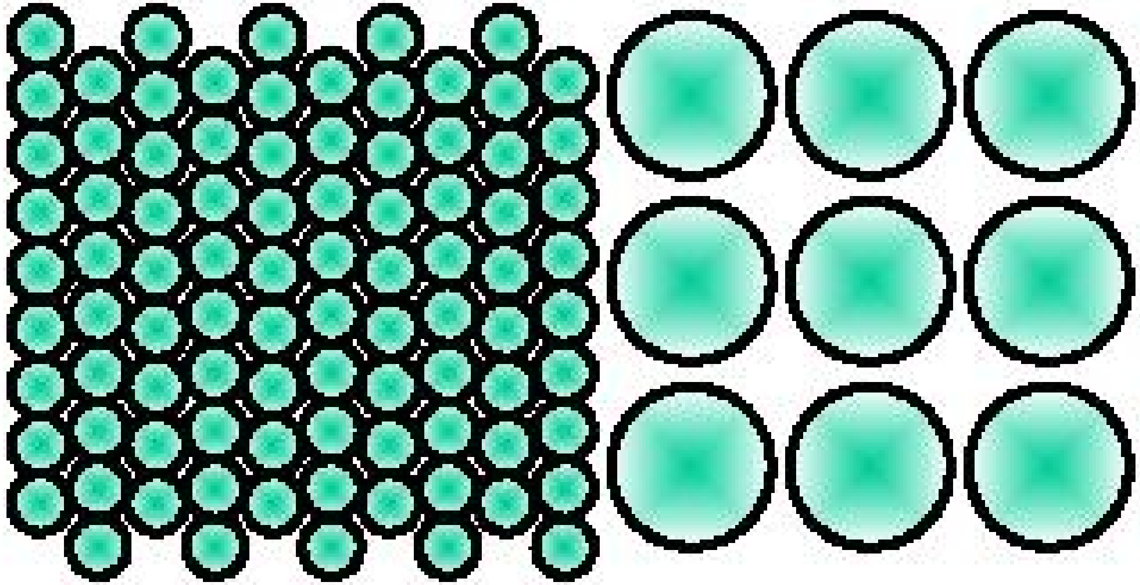


140 GHz
PSB

240 GHz
340 GHz

BOOMERanG-FG

340 GHz
PSB



140 GHz
PSB

Frequency range complementary to PILOT
(higher f. J.F. Bernard, Toulouse)

A post-Planck mission

- A post-Planck mission, with a large array of sensitive polarized detectors, is needed to detect B-modes **and** constrain inflationary parameters (energy scale, r, n_T, $V(\phi)$ ...)
  - NASA – Beyond Einstein : Inflation Probe
  - ESA - Cosmic Vision : B-Pol

- Meanwhile, laboratory, ground-based, and balloon-borne experiments are necessary develop the needed technology

B-Pol

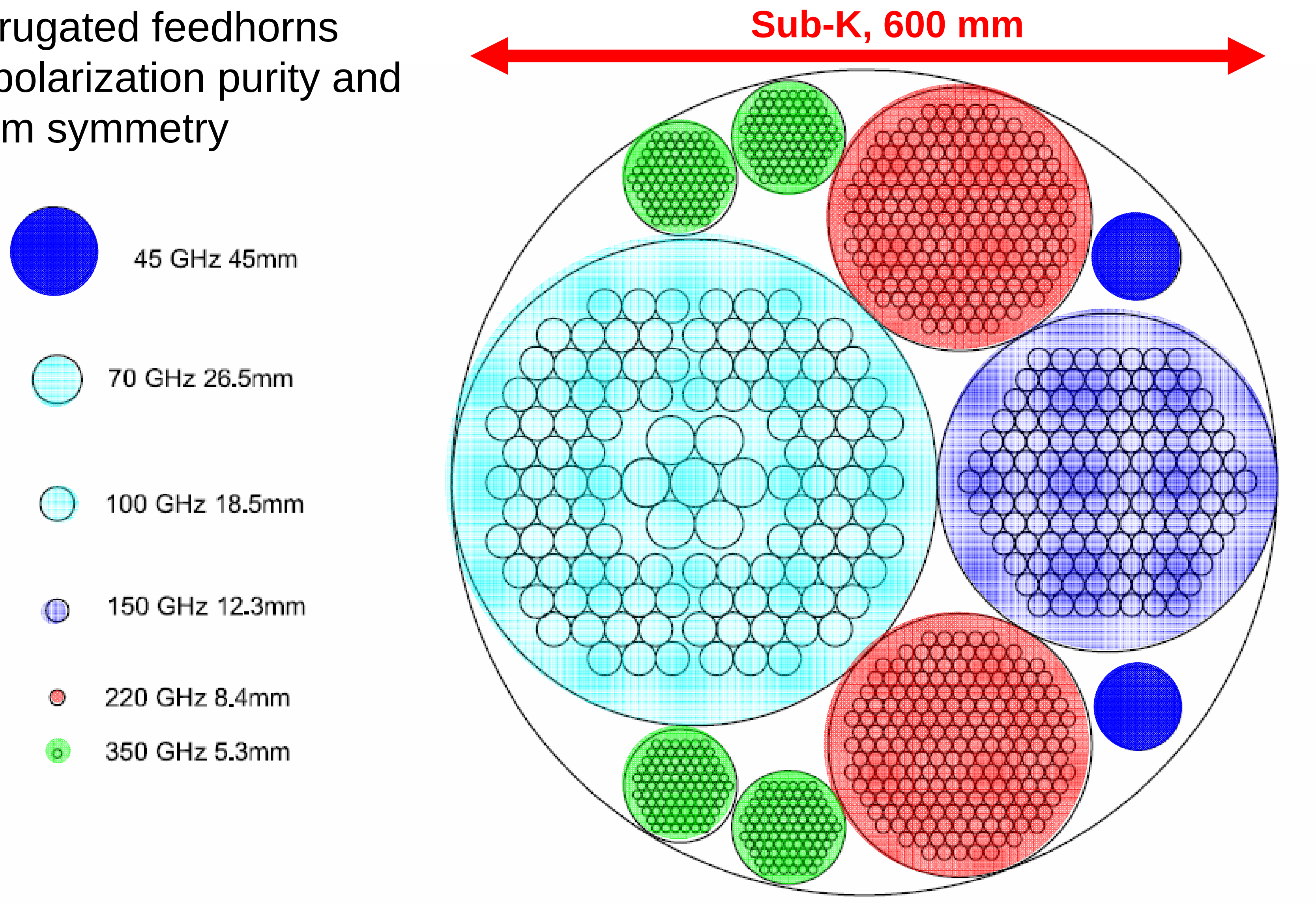
(www.b-pol.org)

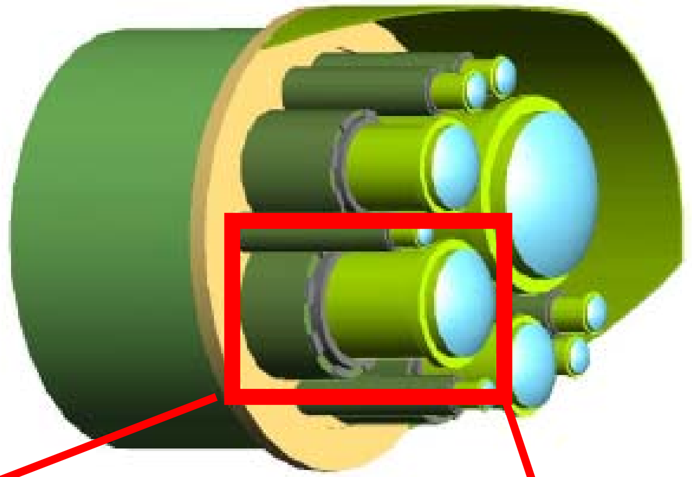
- European proposal recently submitted to ESA (Cosmic Vision).
- ESA encourages the development of technology and resubmission for next round
- Detector Arrays development activities (KIDs in Rome, TES in Oxford, Genova etc.)
- A balloon-borne payload being developed with ASI (B-B-Pol).

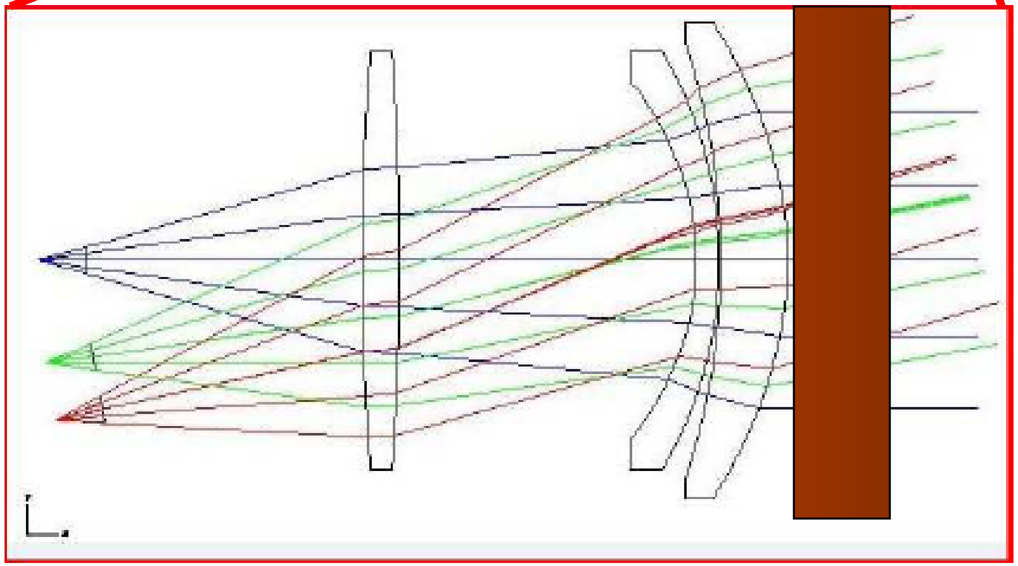
Sensitivity and frequency coverage: the focal plane

- Baseline technology: TES bolometers arrays

Corrugated feedhorns
for polarization purity and
beam symmetry



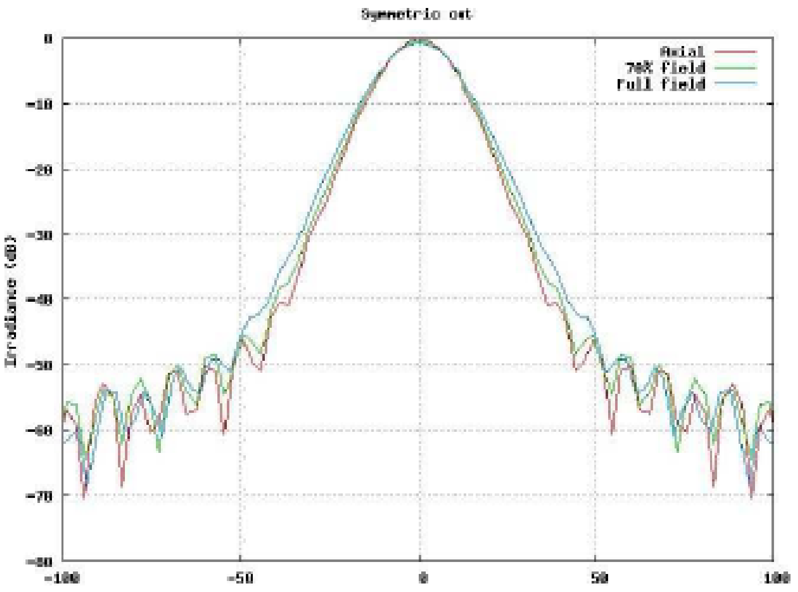


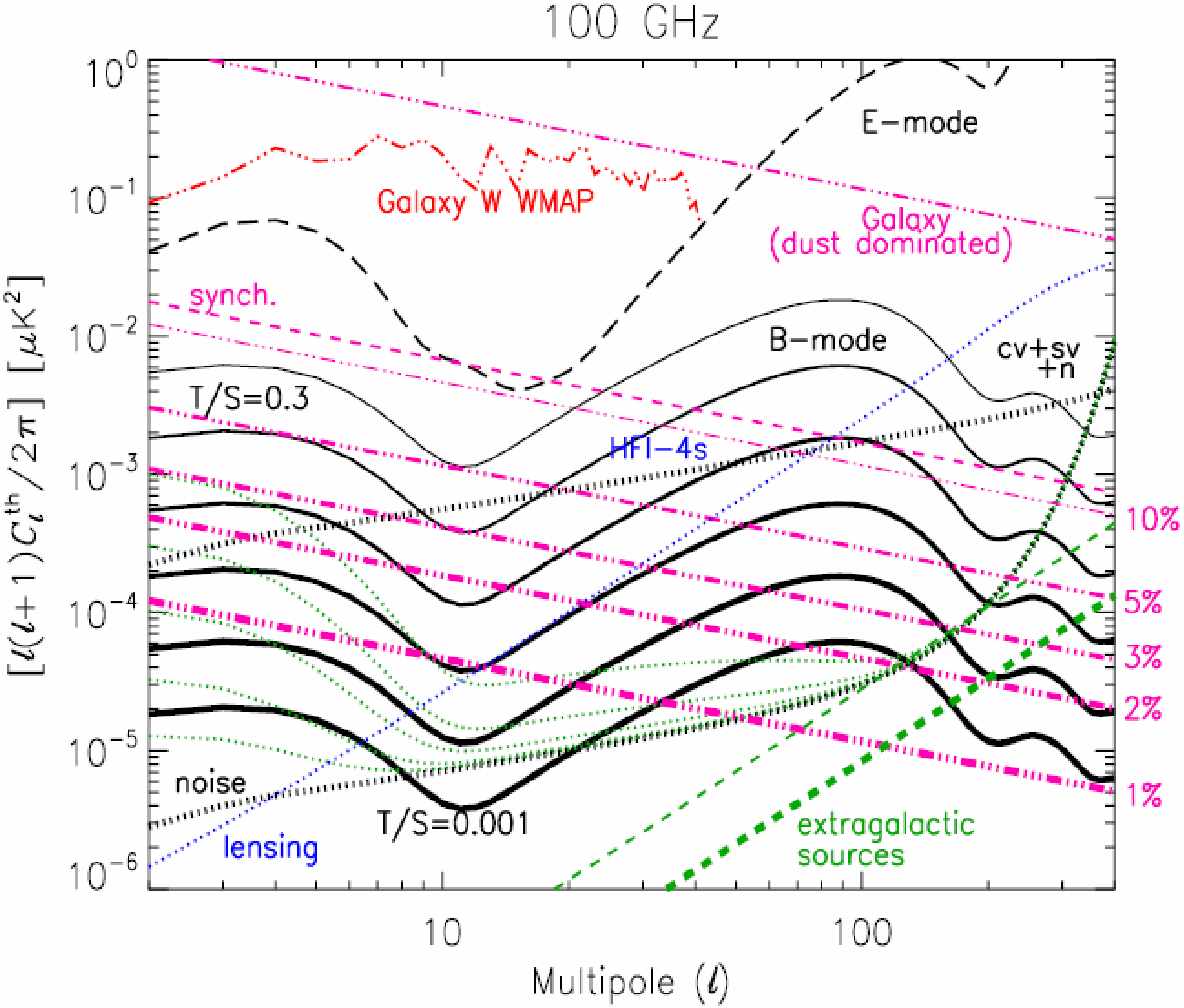


Optical system:

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

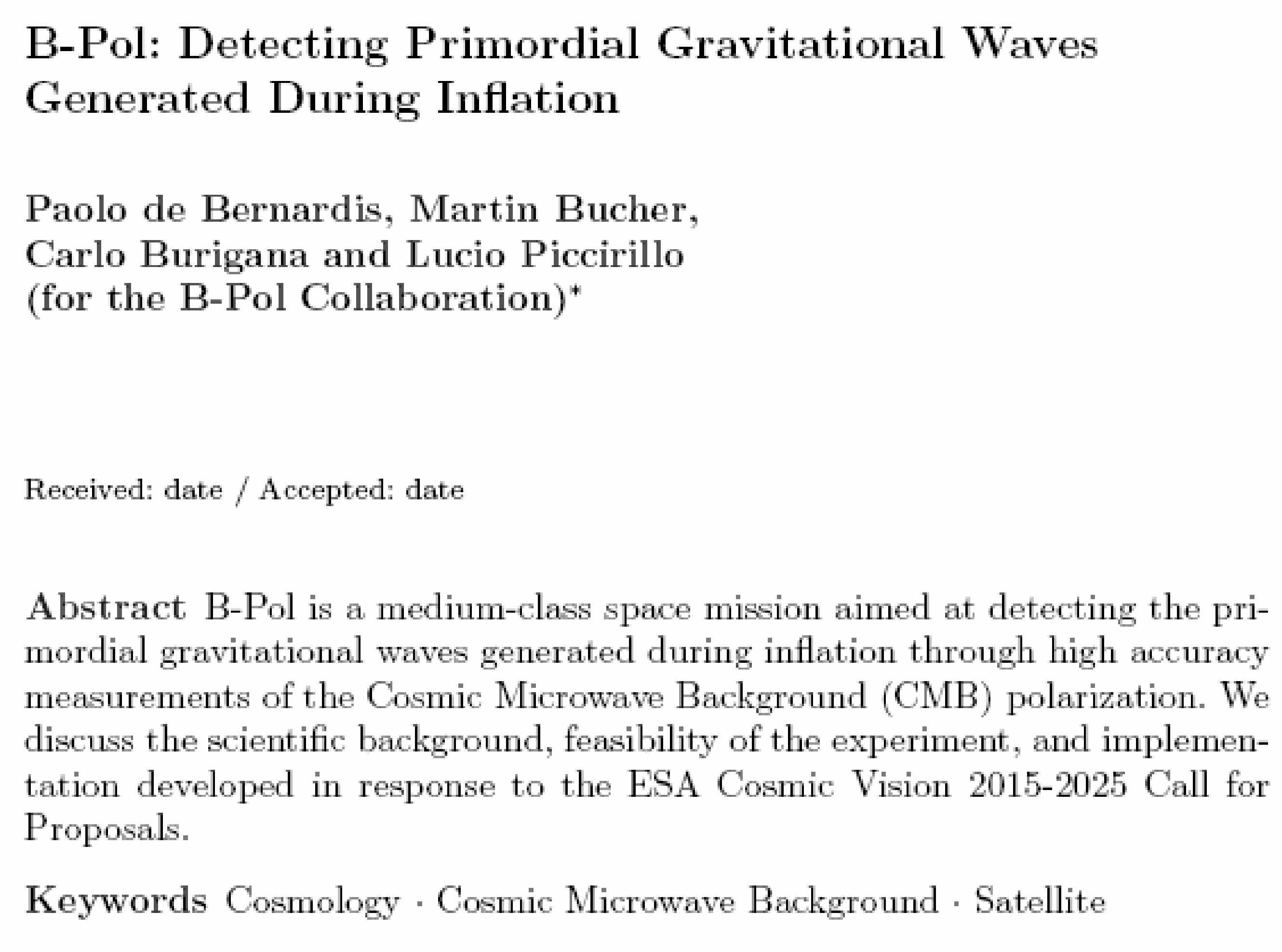
Possible solution: modified telecentric telescope




100 GHz
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$[\ell(\ell+1)C_\ell^{th}/2\pi]$ $[\mu K^2]$
10
100
Multipole (ℓ)
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

For more information visit www.b-pol.org

And see 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

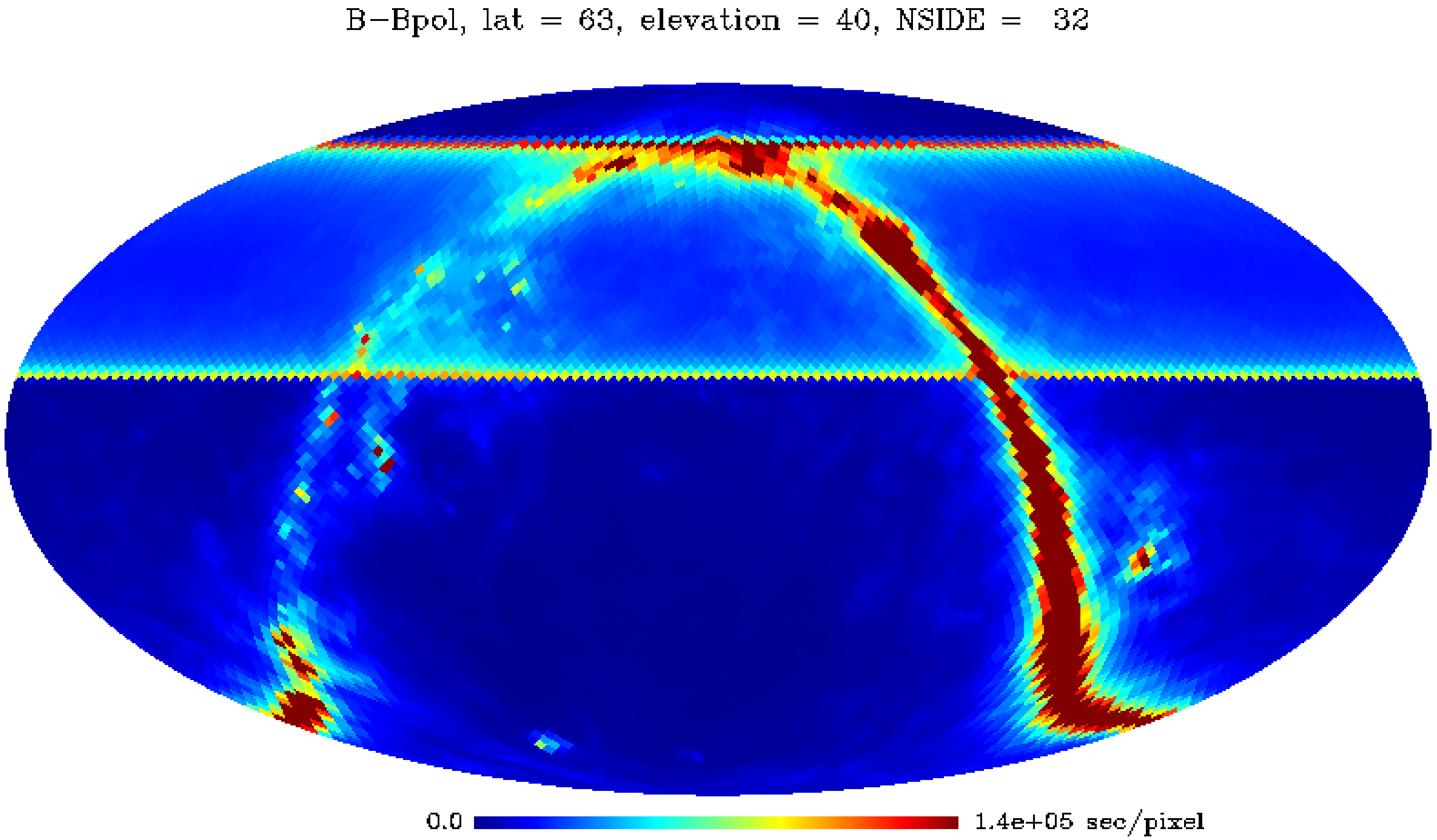
B-B-Pol: The Balloon Option

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

Worksheet Sensitivity

150 GHz band				
FWHM =	2	deg =	0.034904	rad
Tcmb =	2.735	K		
sigma =	**5**	**cm-1**		
Delta_sigma =	2	cm-1		
x=	2.63			
xex/ex-1 =	2.83			
B =	2.32945E-11	W/cm2/sr		
Efficiency =	0.4			
Omega =	0.00096	srad		
wl =	0.2	cm		
N_modes =	10			
AOmega =	0.4	cm2sr		
Diam =	23.07	cm		
BKG_det =	3.72712E-12	W		
To =	0.3	K		
NEP(Aomega = 0.1 cm2sr, sigma=5 cm-1) =			1.00E-17	W/sqrt(Hz cm-1)
NEP(Aomega, sigma=5 cm-1) =			2.00E-17	W/sqrt(Hz cm-1)
NEP(Aomega, sigma=5 cm-1, dsigma) =			2.83E-17	W/sqrt(Hz)
NEP(eff) =	1.79E-17	W/sqrt(Hz)		
G =	8.28248E-11	W/K		
NEP_i =	2.5356E-17	W/sqrt(Hz)		
NEP_tot =	3.10311E-17			
NET_cmb =	8.03E-06	K/sqrt(Hz) =	**8.03**	**uK/sqrt(Hz)**
dimension of absorber =	0.064	cm2		
diameter of absorber =	0.285	cm		
lens f/#	2			
lens f =	46.14	cm		
theta =	0.24	rad		
omega_det =	0.19	srad		
Diam_det =	1.65	cm		
Diam Array =	11.54	cm		

220 GHz band				
FWHM =	2	deg =	0.034904	rad
Tcmb =	2.735	K		
sigma =	**7.5**	**cm-1**		
Delta_sigma =	3	cm-1		
x=	3.95			
xex/ex-1 =	4.02			
B =	2.99537E-11	W/cm2/sr		
Efficiency =	0.4			
Omega =	0.00096	srad		
wl =	0.133333333	cm		
N_modes =	20			
AOmega =	0.355555556	cm2sr		
Diam =	21.75	cm		
BKG_det =	4.26008E-12	W		
To =	0.3	K		
NEP(Aomega = 0.1 cm2sr, sigma=7 cm-1) =			1.60E-17	W/sqrt(Hz cm-1)
NEP(Aomega, sigma=7 cm-1) =			3.02E-17	W/sqrt(Hz cm-1)
NEP(Aomega, sigma=7 cm-1, dsigma) =			5.23E-17	W/sqrt(Hz)
NEP(eff) =	3.30E-17	W/sqrt(Hz)		
G =	9.46685E-11	W/K		
NEP_i =	2.71084E-17	W/sqrt(Hz)		
NEP_tot =	4.27449E-17			
NET_cmb =	6.82E-06	K/sqrt(Hz) =	**6.82**	**uK/sqrt(Hz)**
dimension of absorber =	0.057	cm2		
diameter of absorber =	0.268	cm		
lens f/#	2			
lens f =	43.50	cm		
theta =	0.24	rad		
omega_det =	0.19	srad		
Diam_det =	1.55	cm		
Diam Array =	10.88	cm		

Worksheet Performance

$$\sigma_{pix}^2 = NET^2 \frac{1}{T_{pix}}$$

$$T_{pix} = \frac{T}{N_{pix}}$$

$$N_{pix} = \frac{4\pi f}{\Omega_{pix}}$$

$$\sigma_{pix}^2 = NET^2 \frac{4\pi f}{TN\Omega_{pix}}$$

$$N_\ell = NET^2 \frac{4\pi f}{TN}$$

$$\Delta C_\ell = \sqrt{\frac{2}{(2l+1)f}} \left(C_\ell + N_\ell / B_\ell^2 \right)$$

With $r = 0.01$ the reionization peak is

$$\ell(\ell+1)C_\ell/(2\pi) = 2 \times 10^{-4} \mu K^2$$

at $\ell = 6$

To be Cosmic Variance Dominated, we need

$$N_\ell < C_\ell$$

thus

$$NET^2 \frac{4\pi f}{TN} < 2 \times 10^{-4}(2\pi)/(\ell(\ell+1))\mu K^2$$

We need

$$N > \frac{NET^2 4\pi f}{T2 \times 10^{-4}(2\pi)/(\ell(\ell+1))}$$

In case of Polarization , we must use

$$NET_P = \sqrt{2} \times NET = \sqrt{2} \times 10\mu K/\sqrt{Hz}$$

$$N > \frac{NET^2 4\pi f}{T 2 \times 10^{-4}(2\pi)/(\ell(\ell+1))}$$

In case of Polarization , we must use

$$NET_P = \sqrt{2} \times NET = \sqrt{2} \times 10 \mu K/\sqrt{Hz}$$

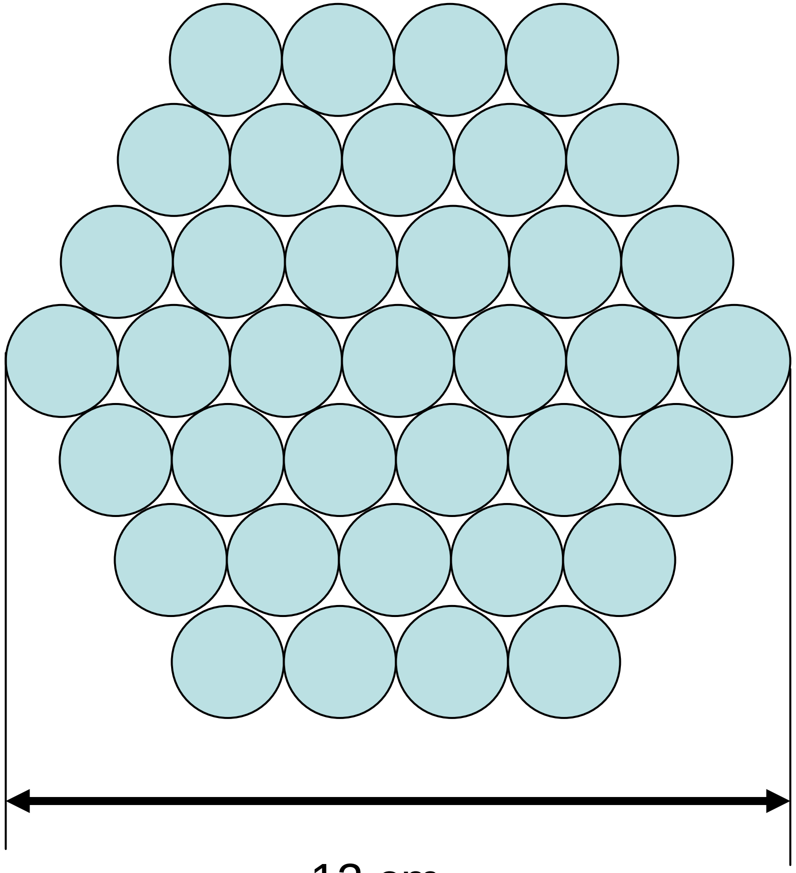
$$f = 0.2$$

$$\ell = 6$$

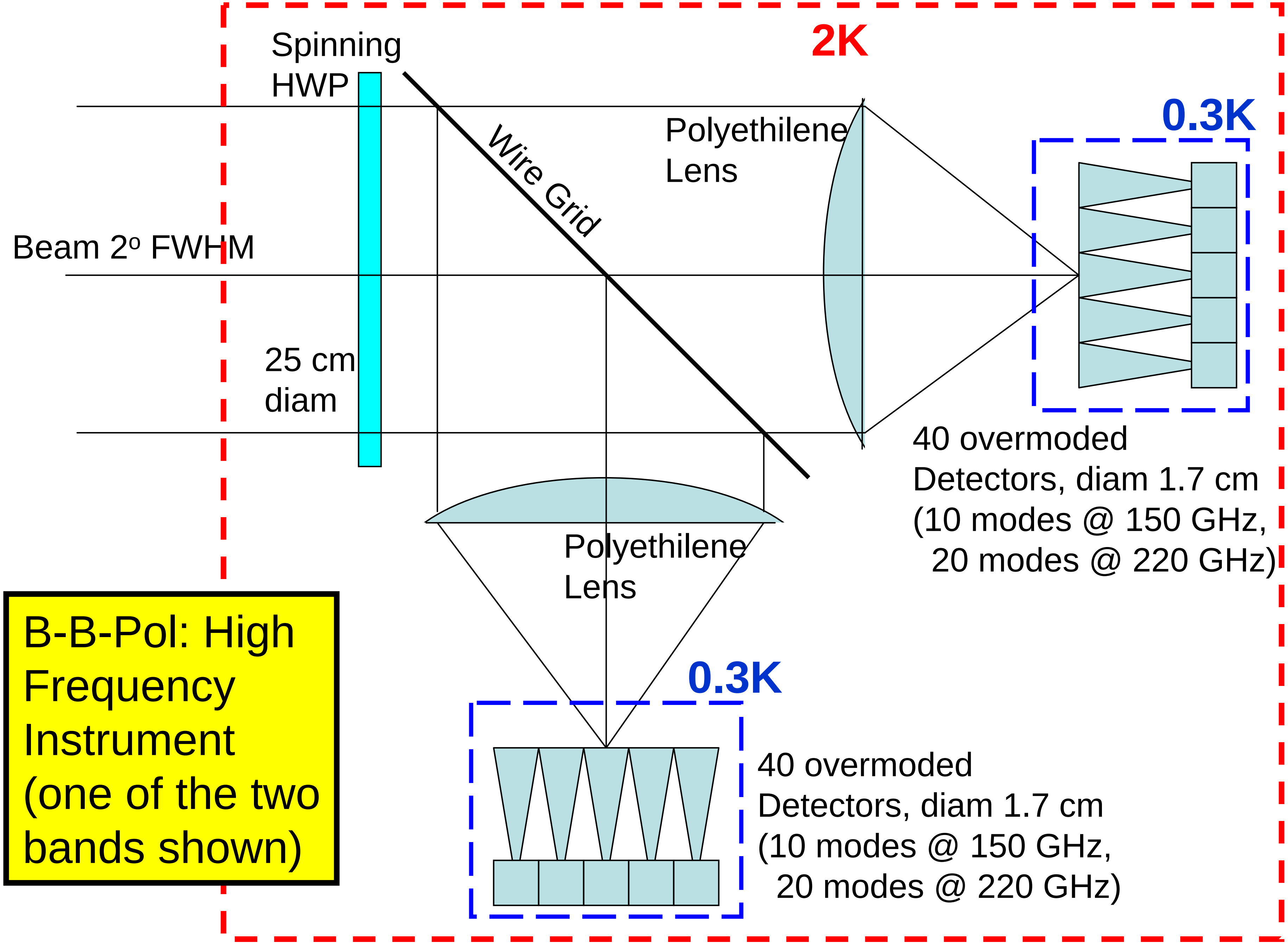
$$T = 14 days$$

$$N > 35$$

37 overmoded detectors



B-B-Pol: High Frequency Instrument (one of the two bands shown)



2K

Spinning HWP

Wire Grid

Polyethilene Lens

0.3K

Beam 2^{o} 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: A spinner in the polar night

- Can provide extremely competitive measurements of CMB polarization at large angular scales.
- Is complementary to NASA's SPIDER and EBEX
- Will qualify, producing great science results, the required technology, in view of next Cosmic Vision call.
- Will exploit the unique ASI-ARR capability to launch long duration balloons in the polar night

CMB research is not over….
Stay tuned !