From BOOMERanG to B-Pol

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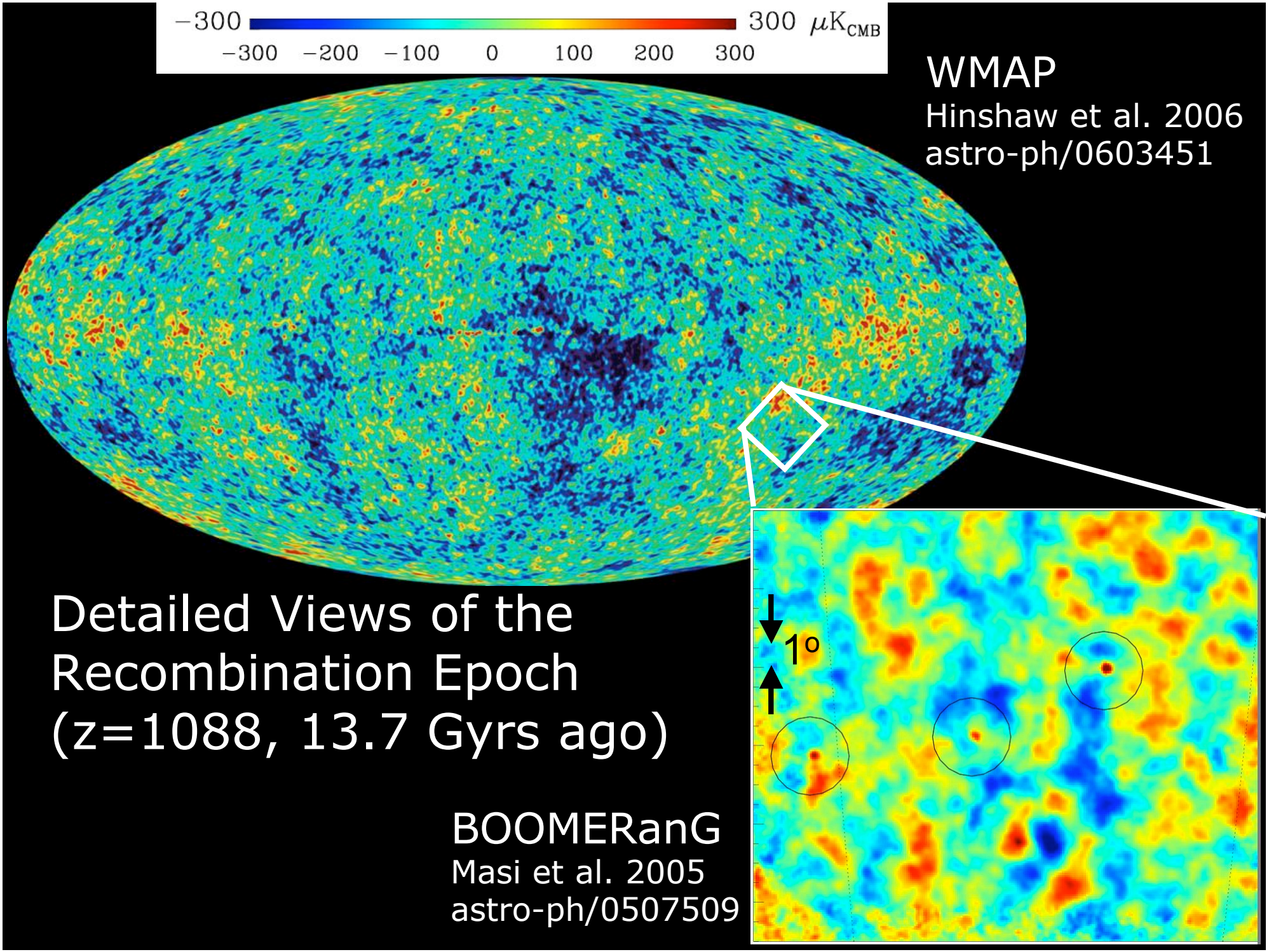
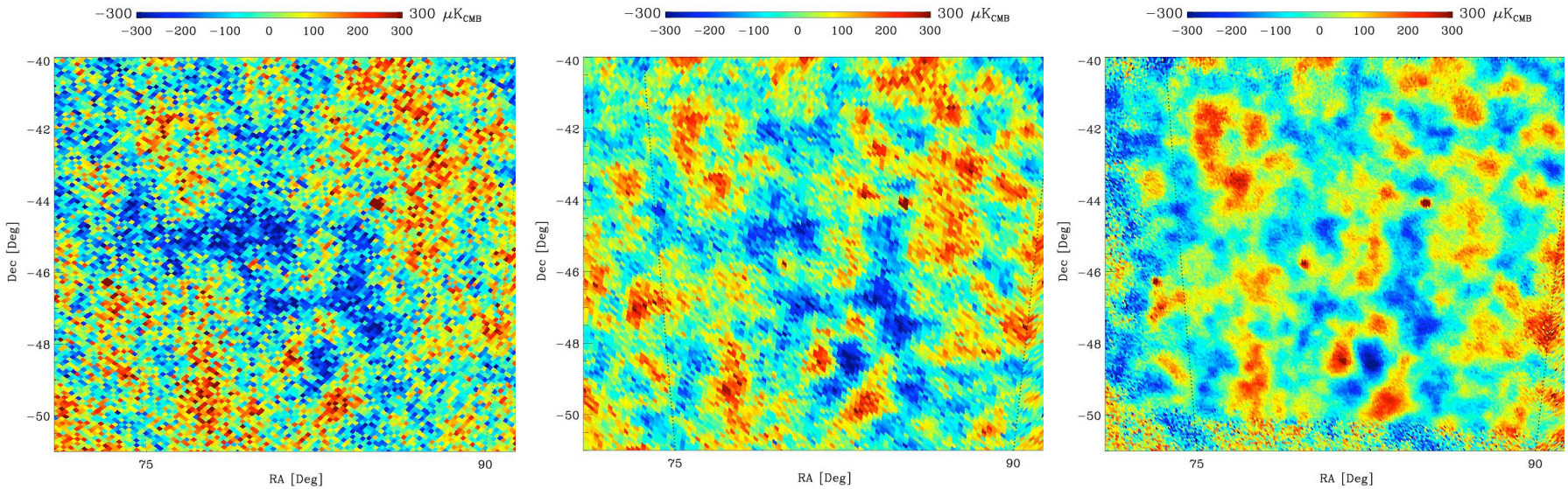
A Century of Cosmology
Venezia, S.Servolo 31/08/2007

contents

- CMB experiments: state of the art
  - Anisotropy
  - Polarization
- Open problems : how to attack them with CMB
- Enabling technologies
- High angular resolution CMB anisotropy
- The spectrum of CMB anisotropy
- The polarization of the CMB


−300
300 μK_CMB
−300 −200 −100 0 100 200 300
WMAP
Hinshaw et al. 2006
astro-ph/0603451
Detailed Views of the
Recombination Epoch
(z=1088, 13.7 Gyrs ago)
1°
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)

- This means that we have a reliable snapshot of density inhomogeneities at recombination, i.e. of the early conditions of the process of structure formation.

- Also, through observations of the irrotational component of the linear polarization of the CMB, we start to have significant information about the velocity fields at recombination.

Angular power spectrum: C_l

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

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

Cosmological Parameters: Ω_o, $\Omega_b h^2$, n, Ω_Λ, H_o, A, τ, ….

The current adiabatic inflationary scenario

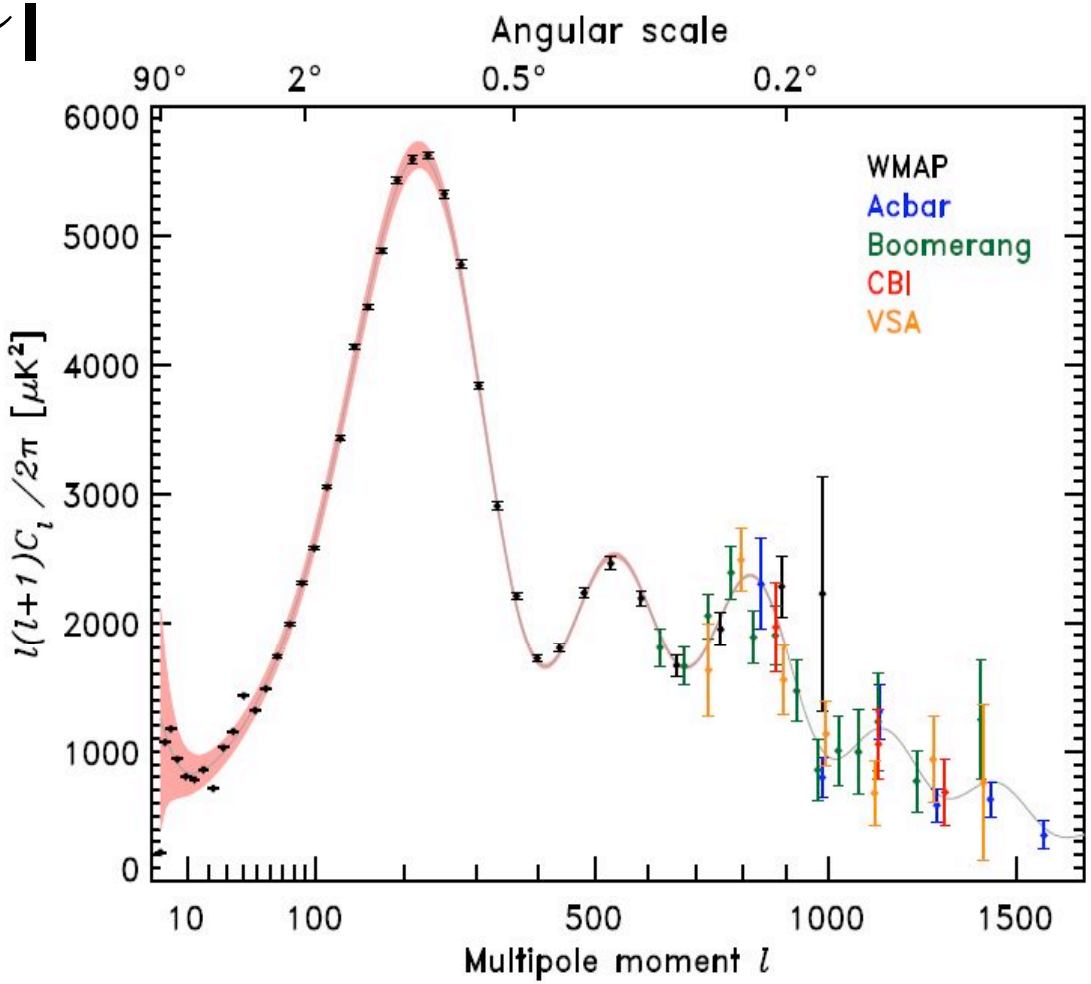
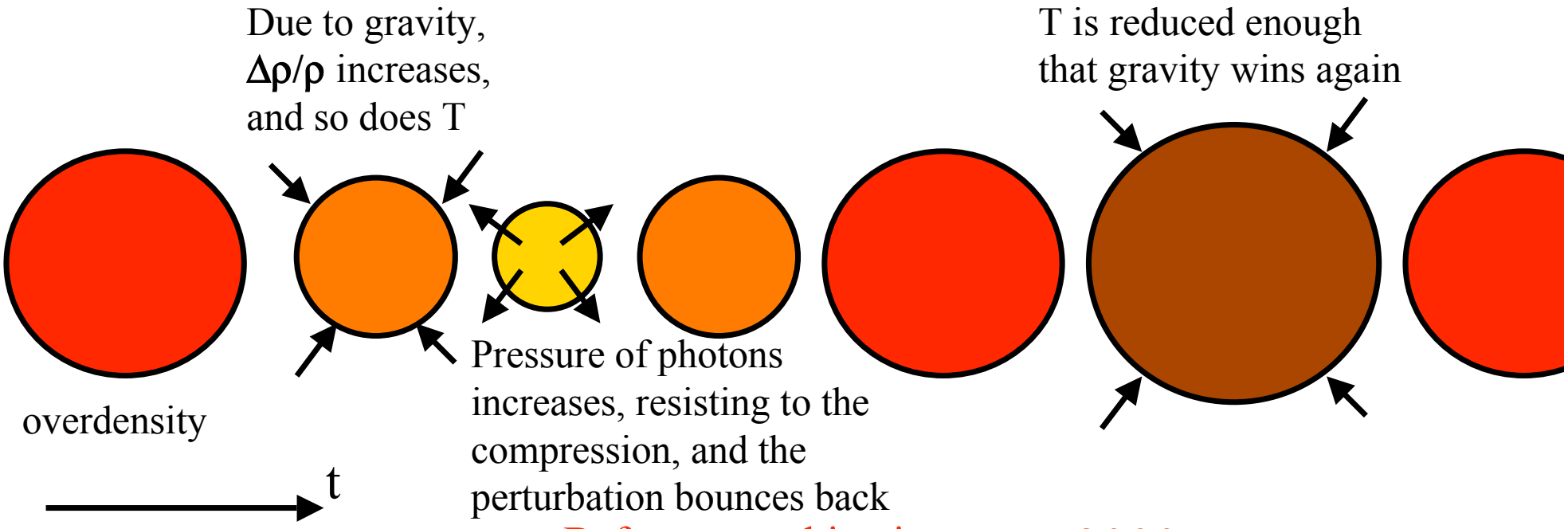
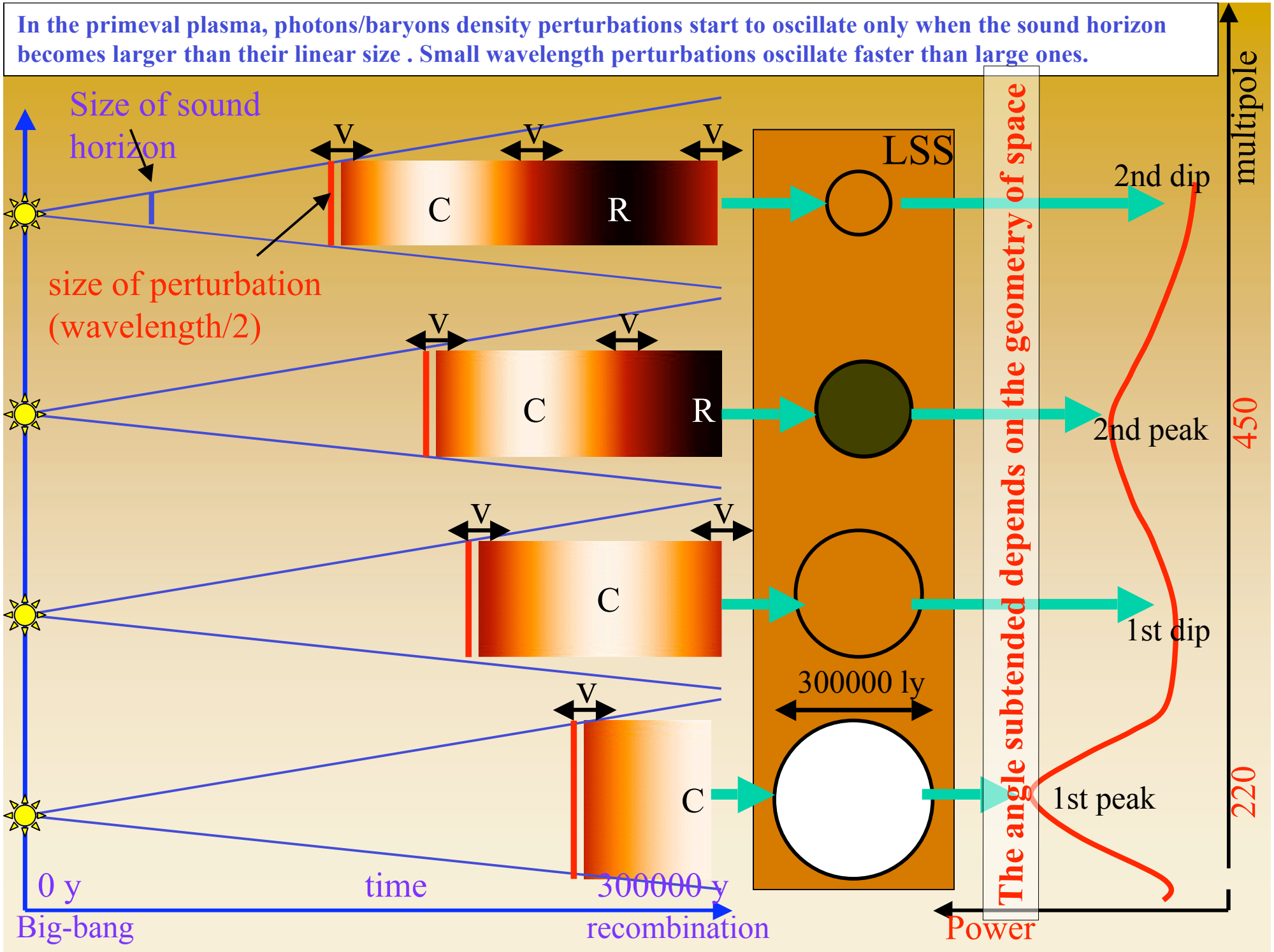


Fig. 18.— The *WMAP* three-year power spectrum (in black) compared to other recent measurements of the CMB angular power spectrum, including Boomerang (Jones et al. 2005), Acbar (Kuo et al. 2004), CBI (Readhead et al. 2004), and VSA (Dickinson et al. 2004). For clarity, the $l < 600$ data from Boomerang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

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



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.
Size of sound horizon
size of perturbation (wavelength/2)
V
C
R
LSS
300000 ly
The angle subtended depends on the geometry of space
2nd dip
2nd peak
1st dip
1st peak
multipole
450
220
0 y
time
300000 y
Big-bang
recombination
Power

Angular power spectrum: C_l

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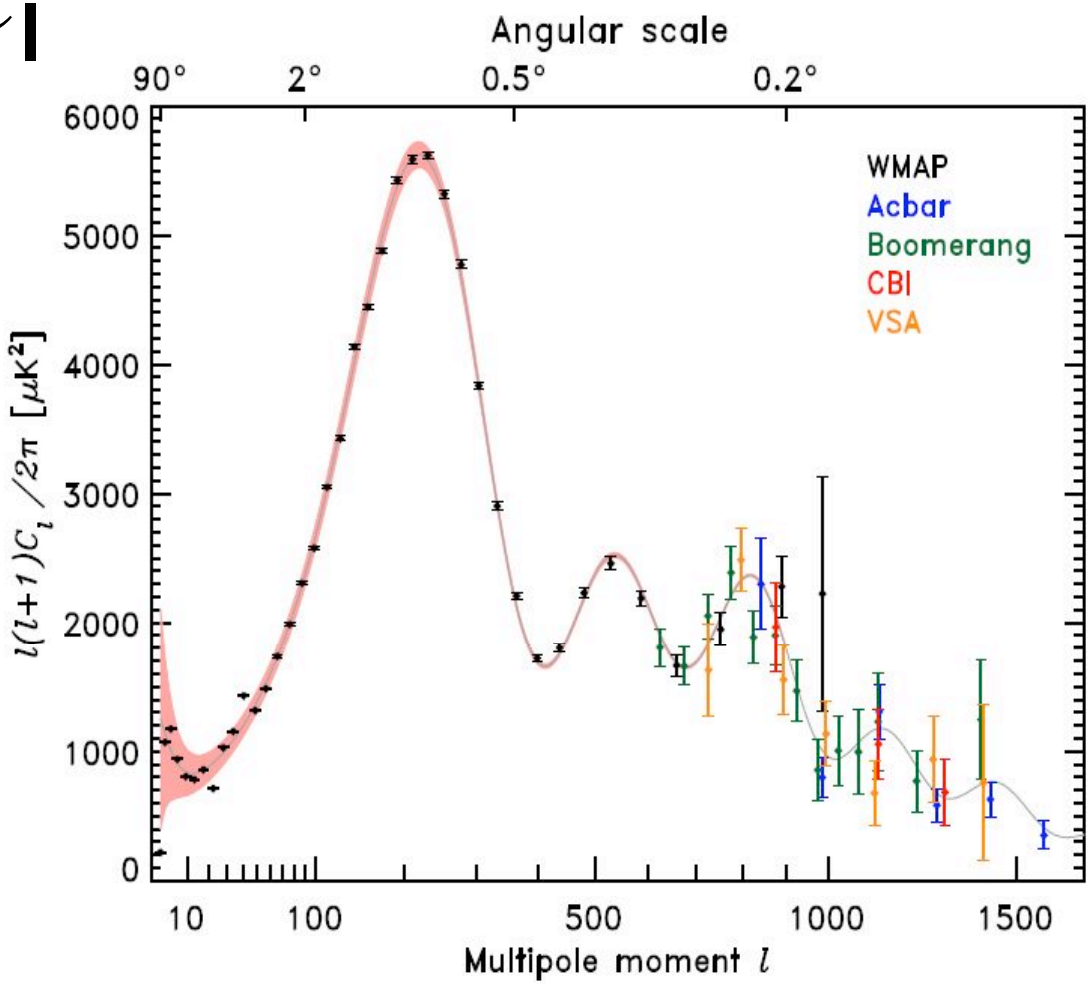

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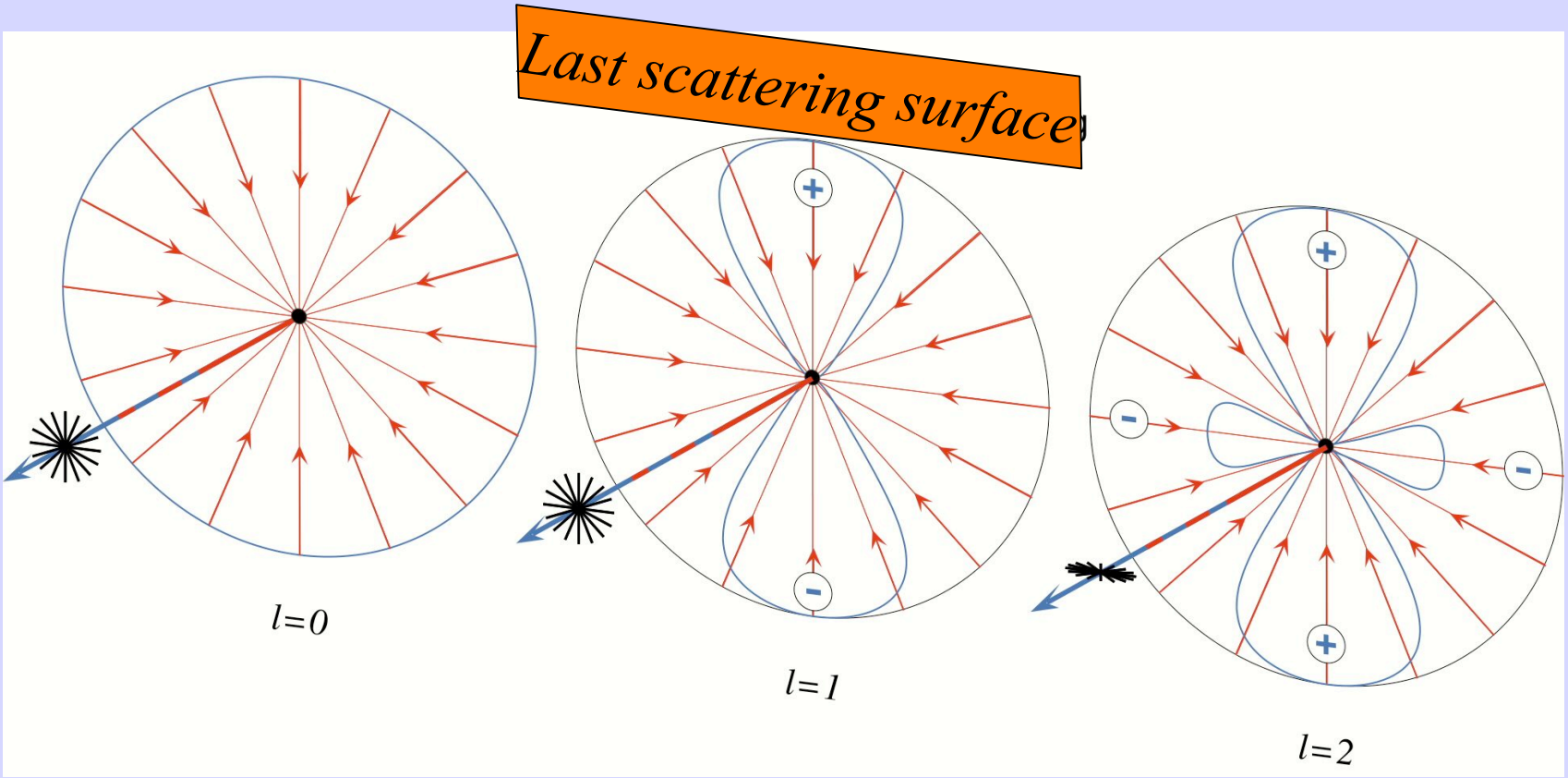
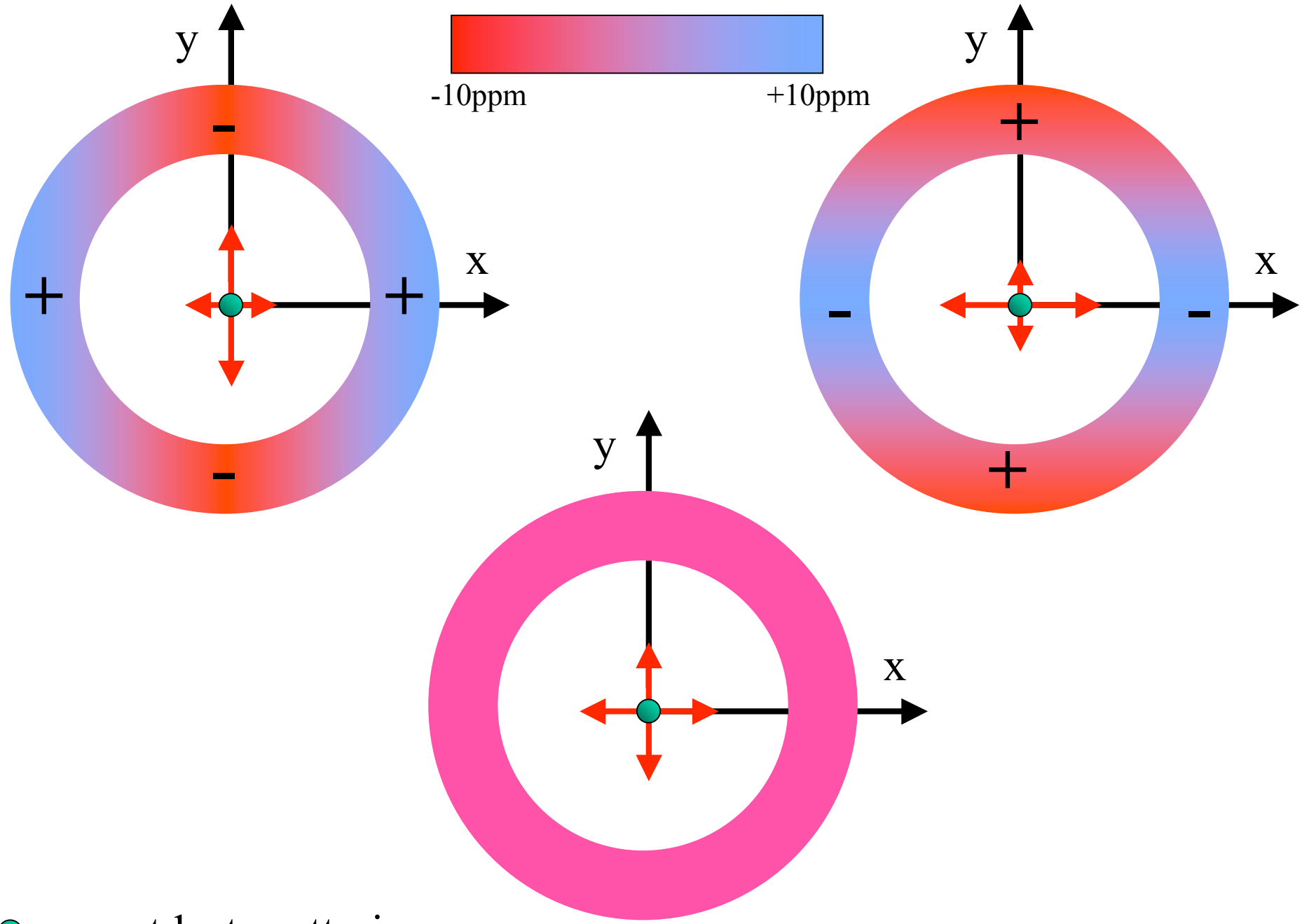
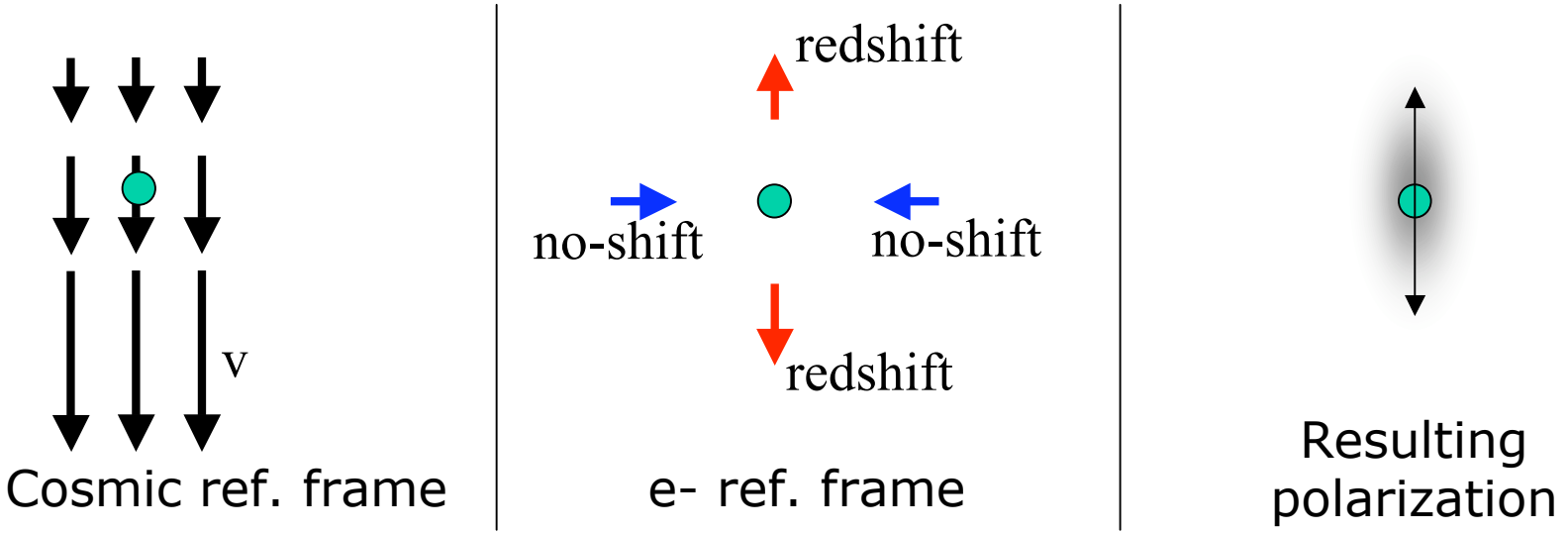
CMB polarization

- 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.

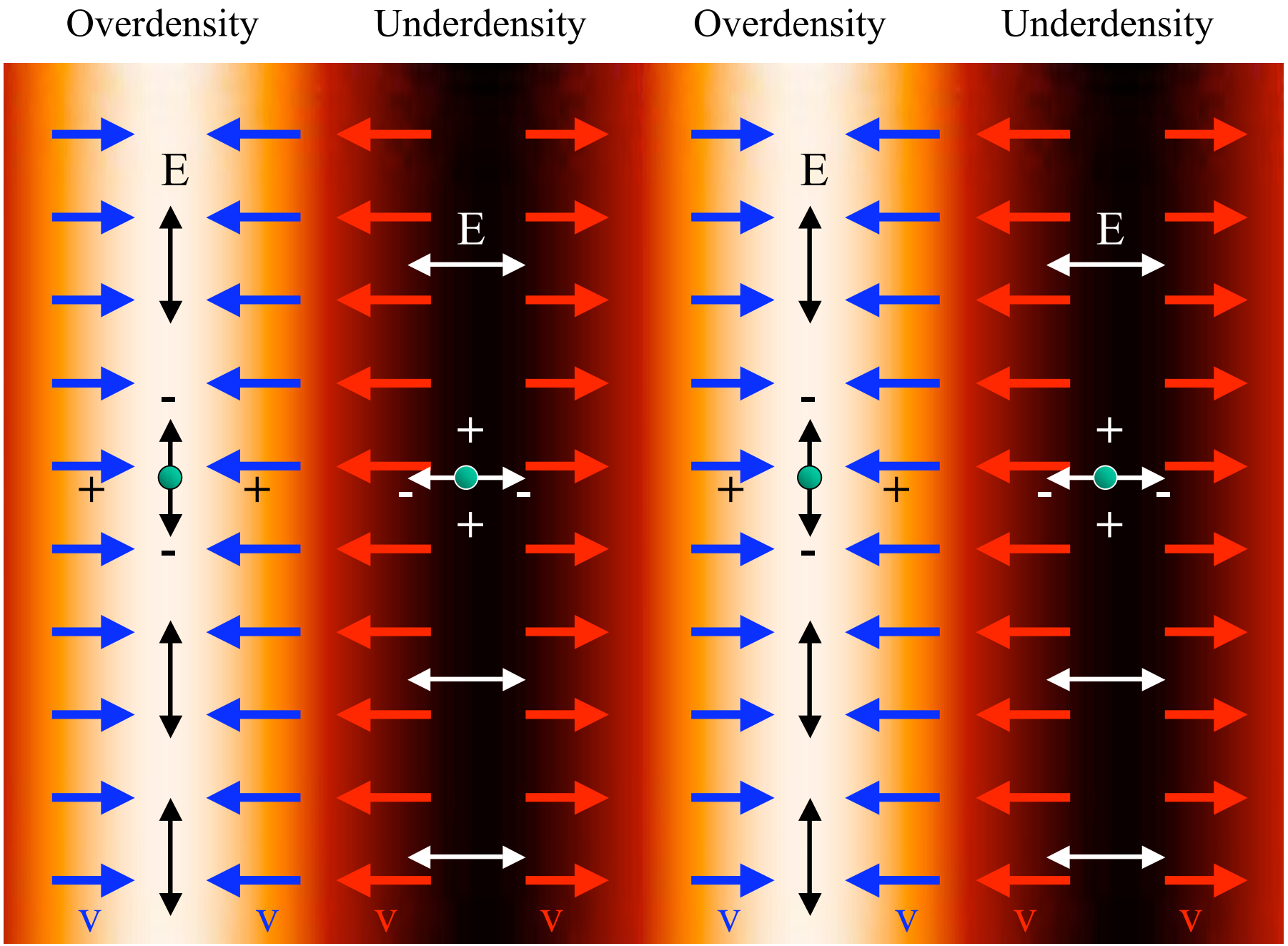



y
x
-10ppm
+10ppm
y
x
y
x
= e- at last scattering

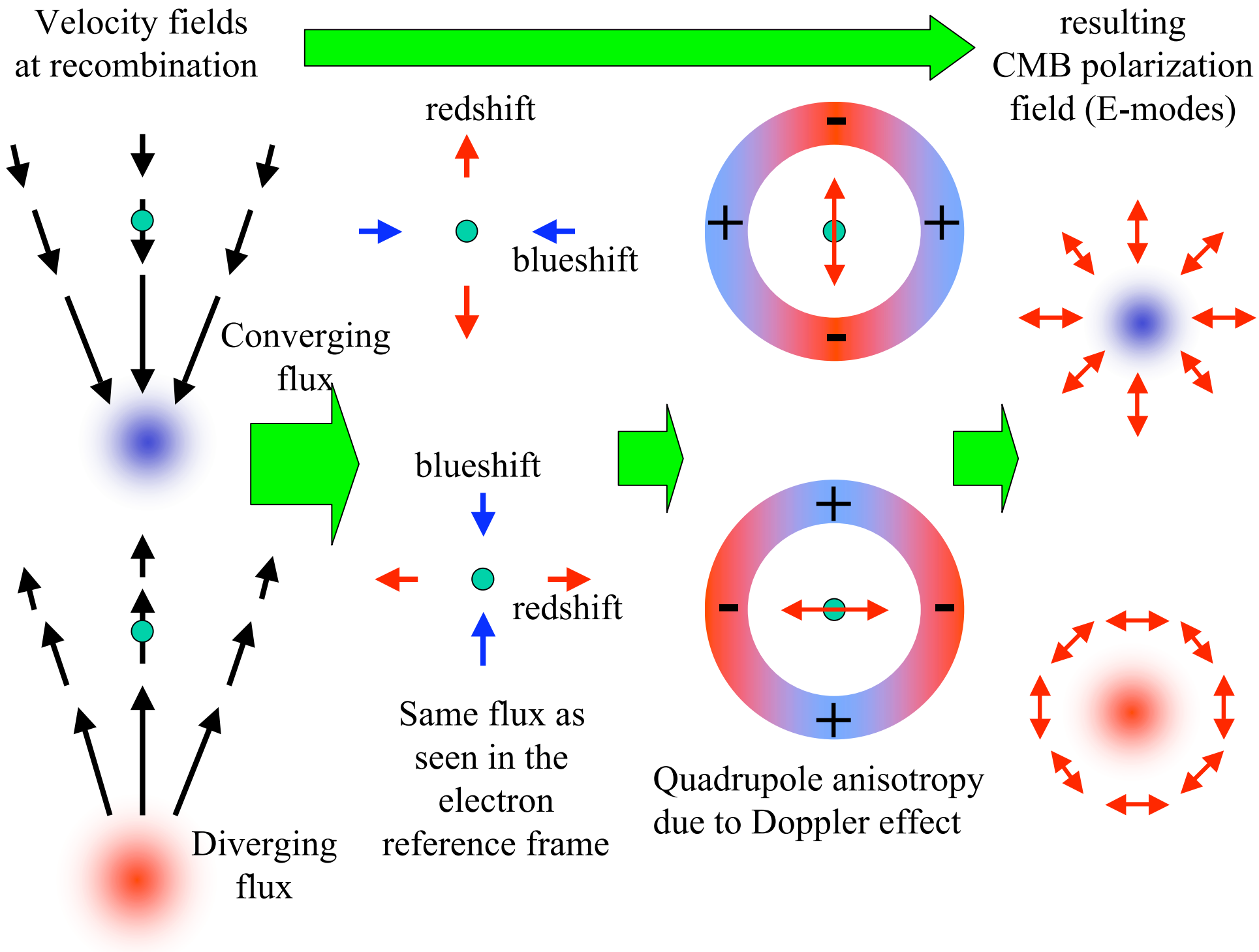
- There are two sources of quadrupole anisotropy at the last scattering:
- **1-Velocity gradients** in the cosmic fluid at recombination produce a **quadrupole** in the rest-frame of the scattering electron.



- This component of the CMB polarization field is called **E** component, or **gradient component**.
- We expect correlations between the CMB anisotropy (T) and the E-modes of the polarization field.



E-modes in the polarization pattern


Velocity fields
at recombination
resulting
CMB polarization
field (E-modes)
redshift
blueshift
Converging
flux
blueshift
redshift
Same flux as
seen in the
electron
reference frame
Diverging
flux
Quadrupole anisotropy
due to Doppler effect

- E-modes are irrotational
- E modes are related to velocities, while T is related mainly to density
- We expect a power spectrum of the E-modes, <EE>, with maxima and mimina in quadrature with the anisotropy power spectrum <TT>.

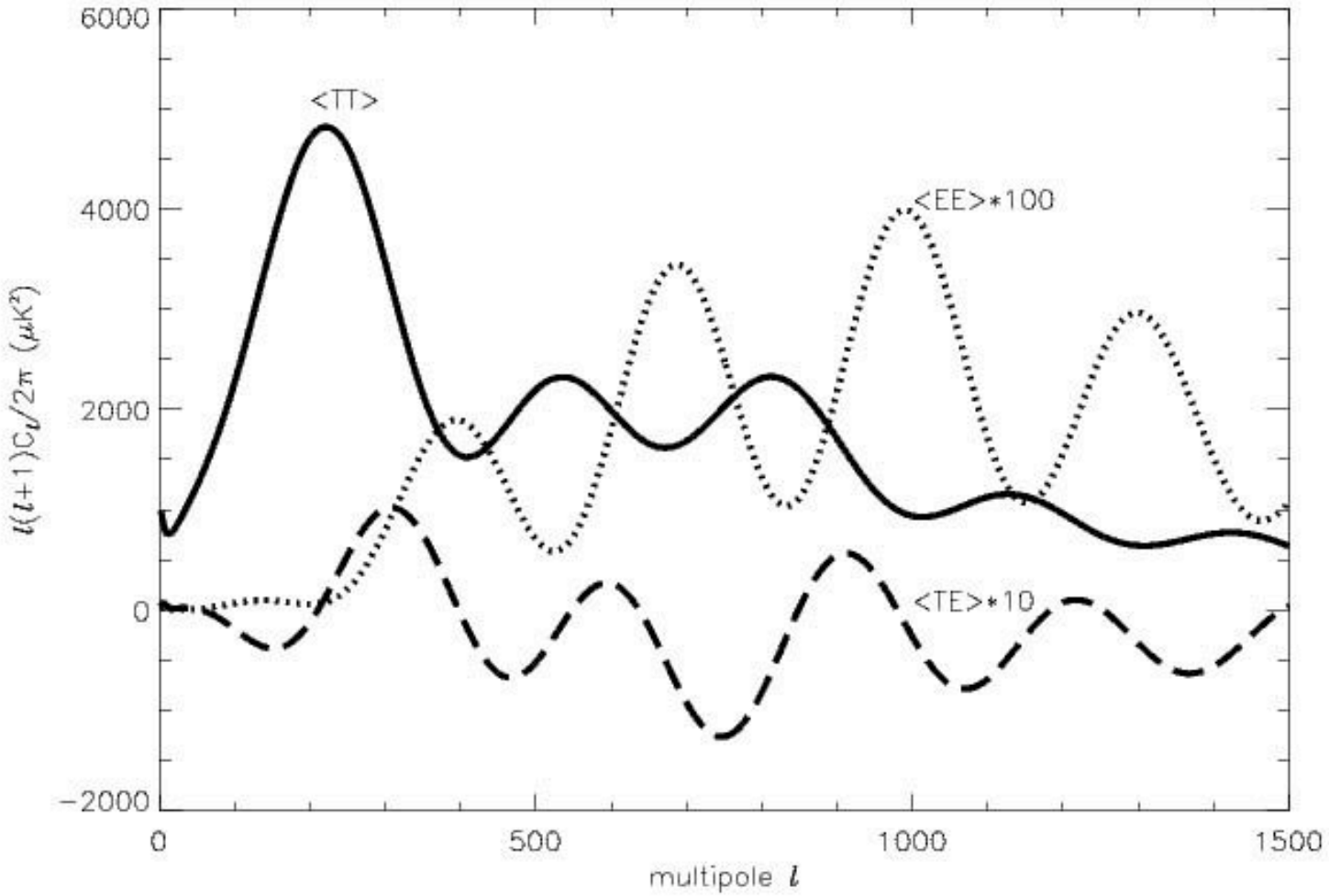


Figure 1.7: Estimated power spectra for the cosmological parameters: $\Omega_b = 0.05$, $\Omega_{cdm} = 0.3$, $\Omega_\Lambda = 0.65$, $\Omega_\nu = 0$, $H_0 = 65$ km/s/Mpc, $\tau = 0.17$. The temperature power spectrum, $\langle TT \rangle = C_\ell^T$, the E-modes power spectrum $\langle EE \rangle = C_\ell^E$ multiplied by a factor 100 to make it visible and the cross power spectrum between temperature and polarization, $\langle TE \rangle = C_\ell^{TE}$ multiplied by a factor 10. The spectra are computed using the publicly available code CMBFAST (http://www.cmbfast.org),

Interest of detecting E-modes (1):

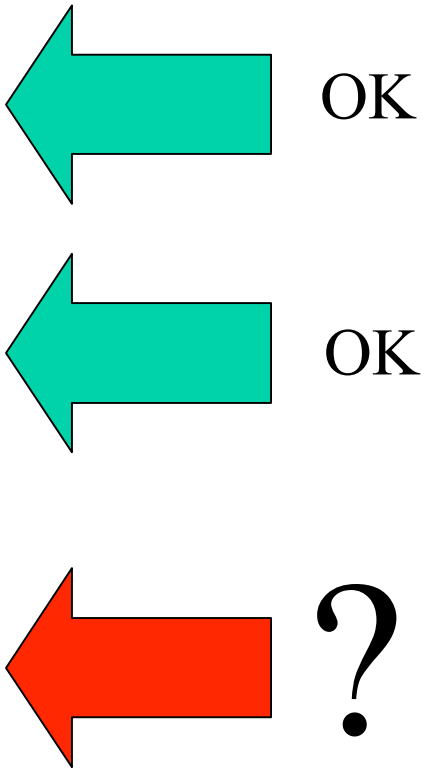
- In all the cosmological parameters analysis an *adiabatic* type of fluctuations is assumed (because simple and predicted by the simplest inflation models)
- If **other types of fluctuations** are considered (for example isocurvature ones) the determination of cosmological parameters becomes much less precise.
- Precision can be recovered by studying independent observables, like the **polarization** of the CMB.
- See e.g. Bucher et al., astro-ph/0012141

Interest of detecting E-modes (2)

- The universe gets reionized when the first stars form.
- The **polarization** of the CMB at **large angular scales** is heavily affected by reionization.
- It is a way to measure the redshift of reionization, between z=5 and 20, complementary to work based on the Gunn-Peterson effect (see e.g. Becker et al. (2001) and Djorgovski et al. (2001).)

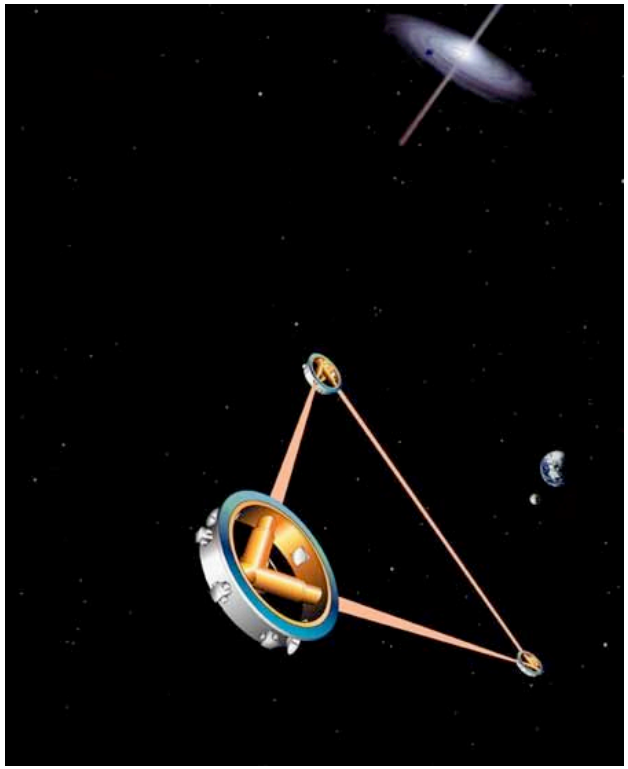
If inflation really happened…

- It stretched geometry of space to nearly Euclidean
- It produced a nearly scale invariant spectrum of density fluctuations
- It produced a stochastic background of gravitational waves, i.e. another source of quadrupole anisotropy at recombination.

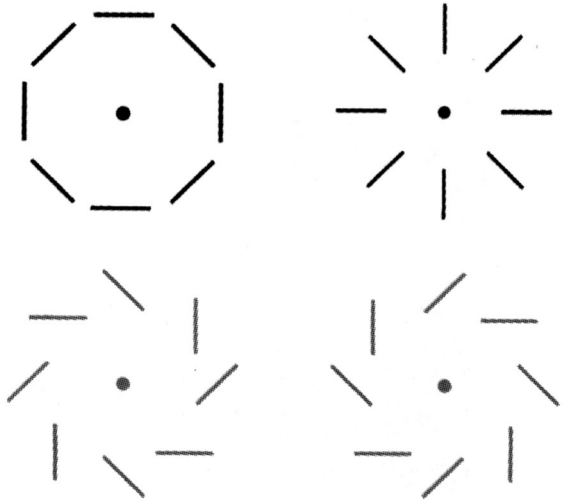


Quadrupole from P.G.W.

- 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.



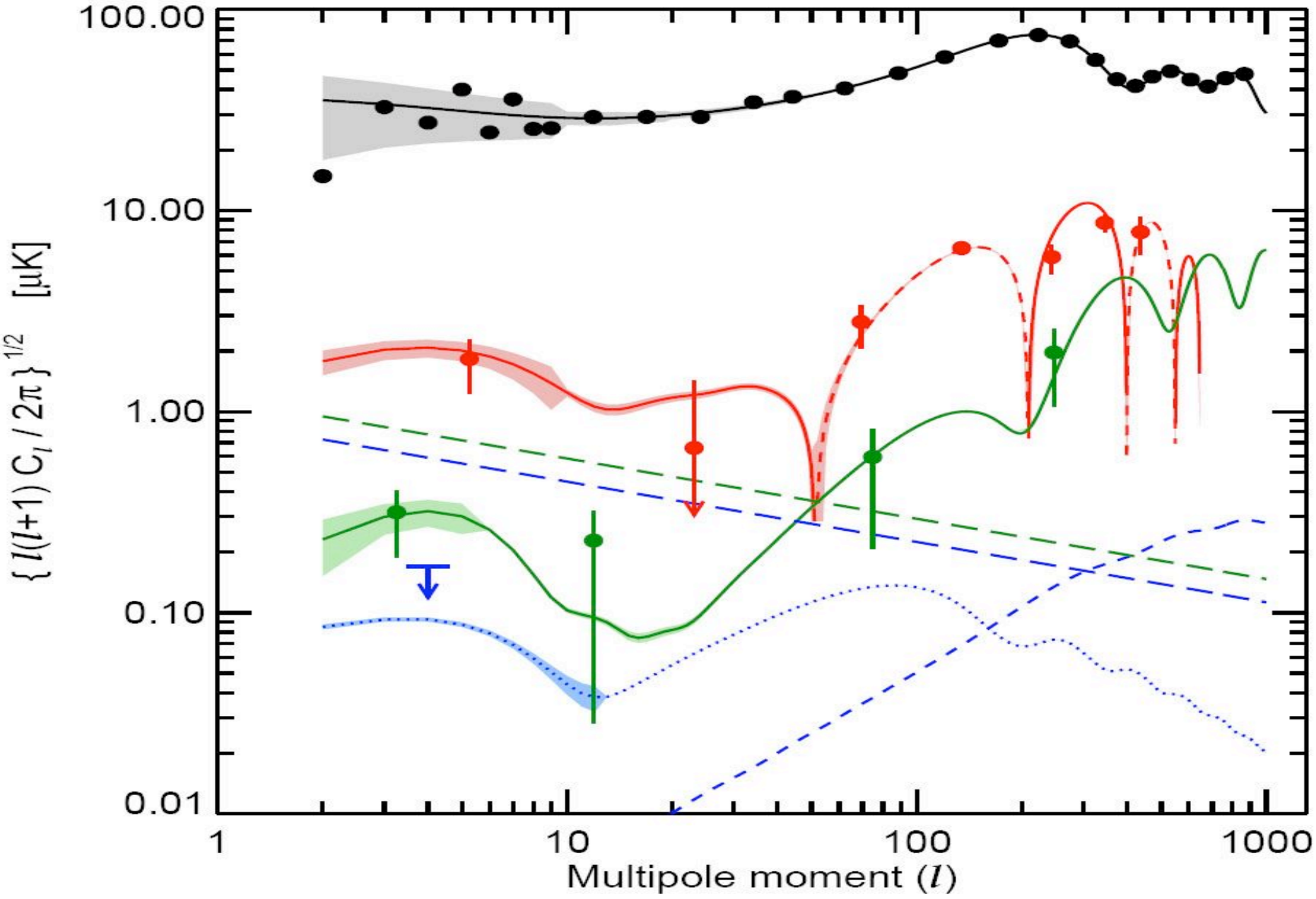
E-modes



B-modes

The signal is extremely weak (<100 nK !!!)

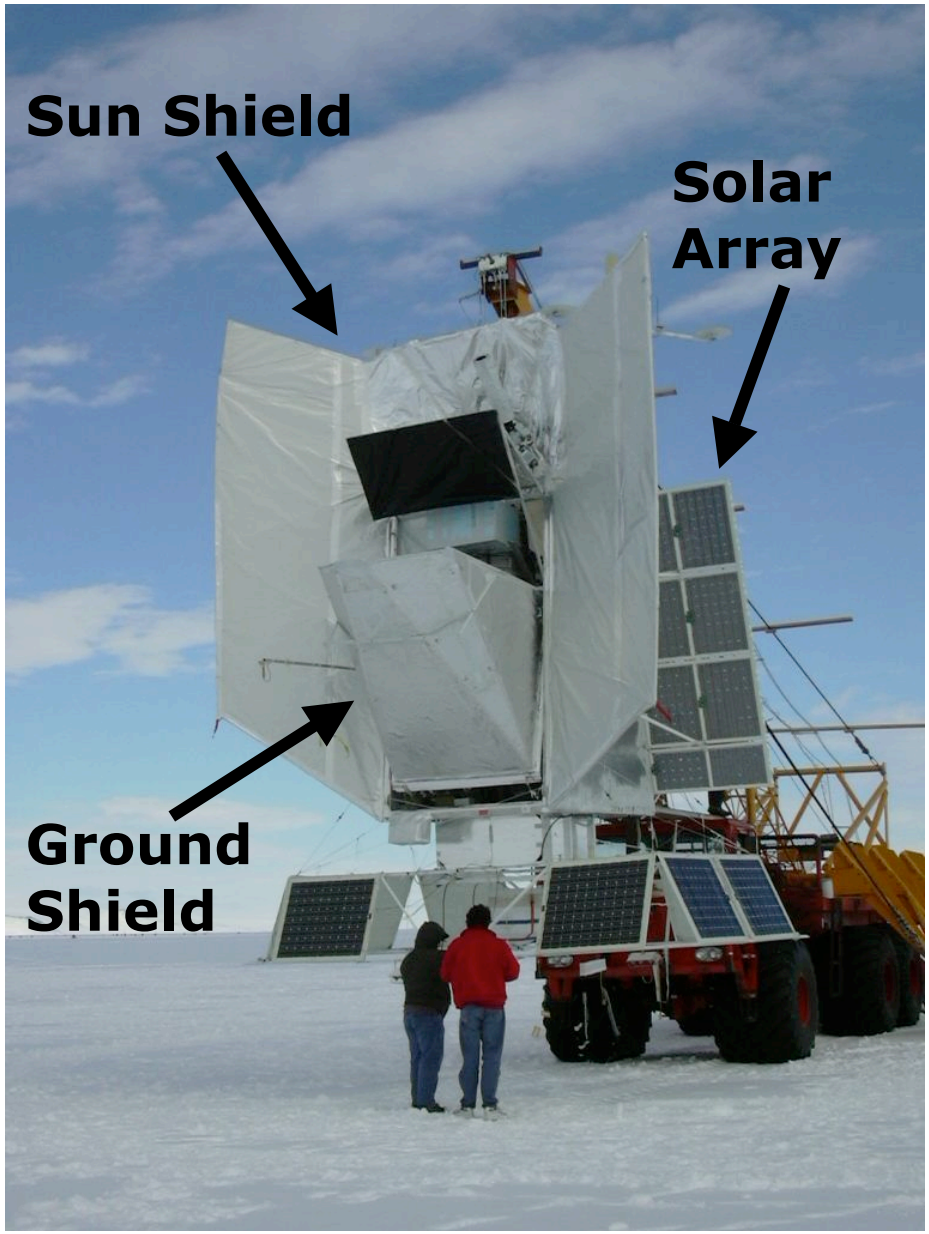
- Nobody really knows how to detect this.
  - Pathfinder experiments are needed
- Whatever smart, ambitious experiment we design to detect the B-modes:
  - It needs to be extremely sensitive
  - It needs an extremely careful control of systematic effects
  - It needs careful control of foregrounds
 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

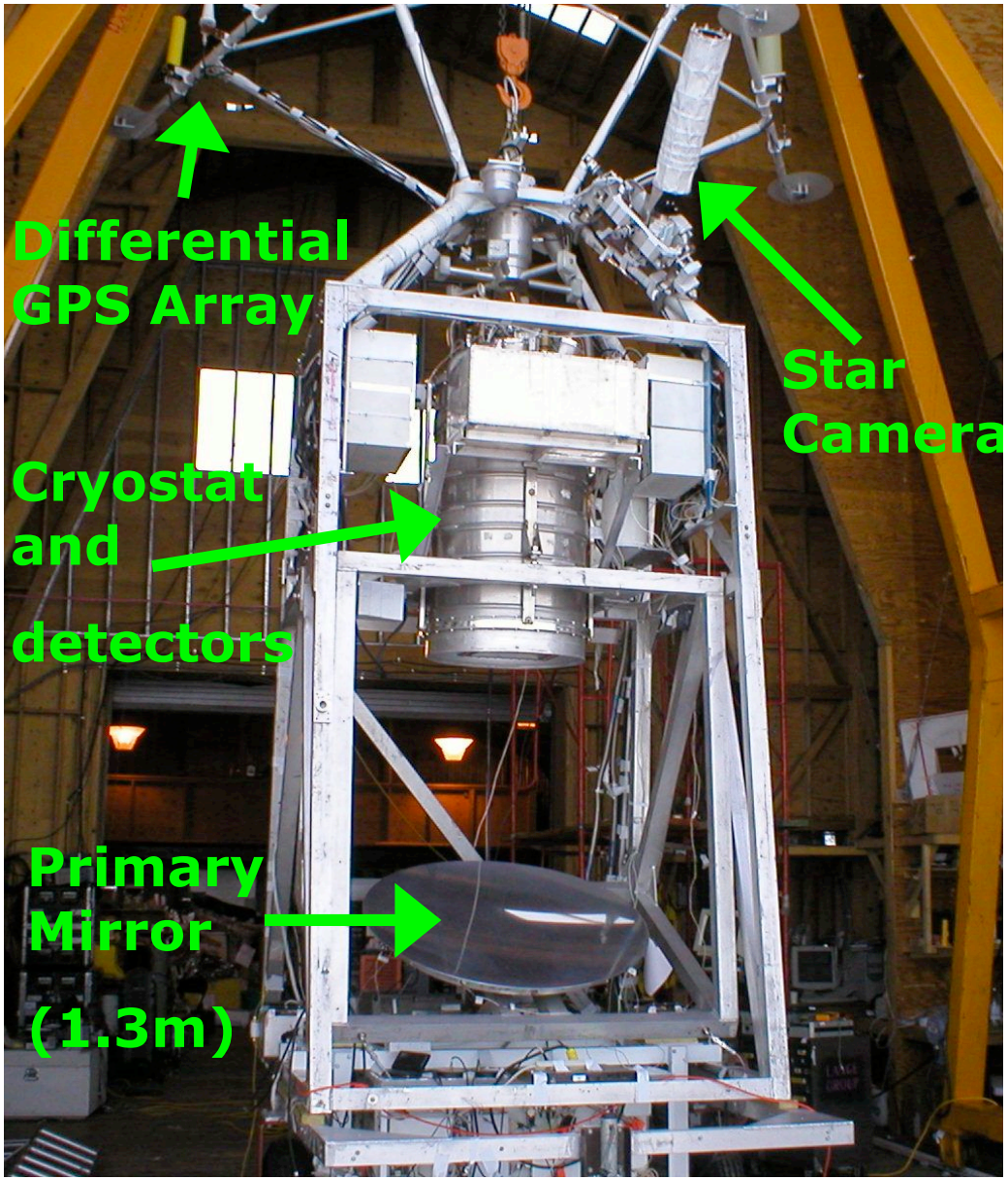


- Page et al., 2006, WMAP 3 years

- CMB polarization was first detected by DASI and then by several other experiments:

the BOOMERanG balloon-borne telescope

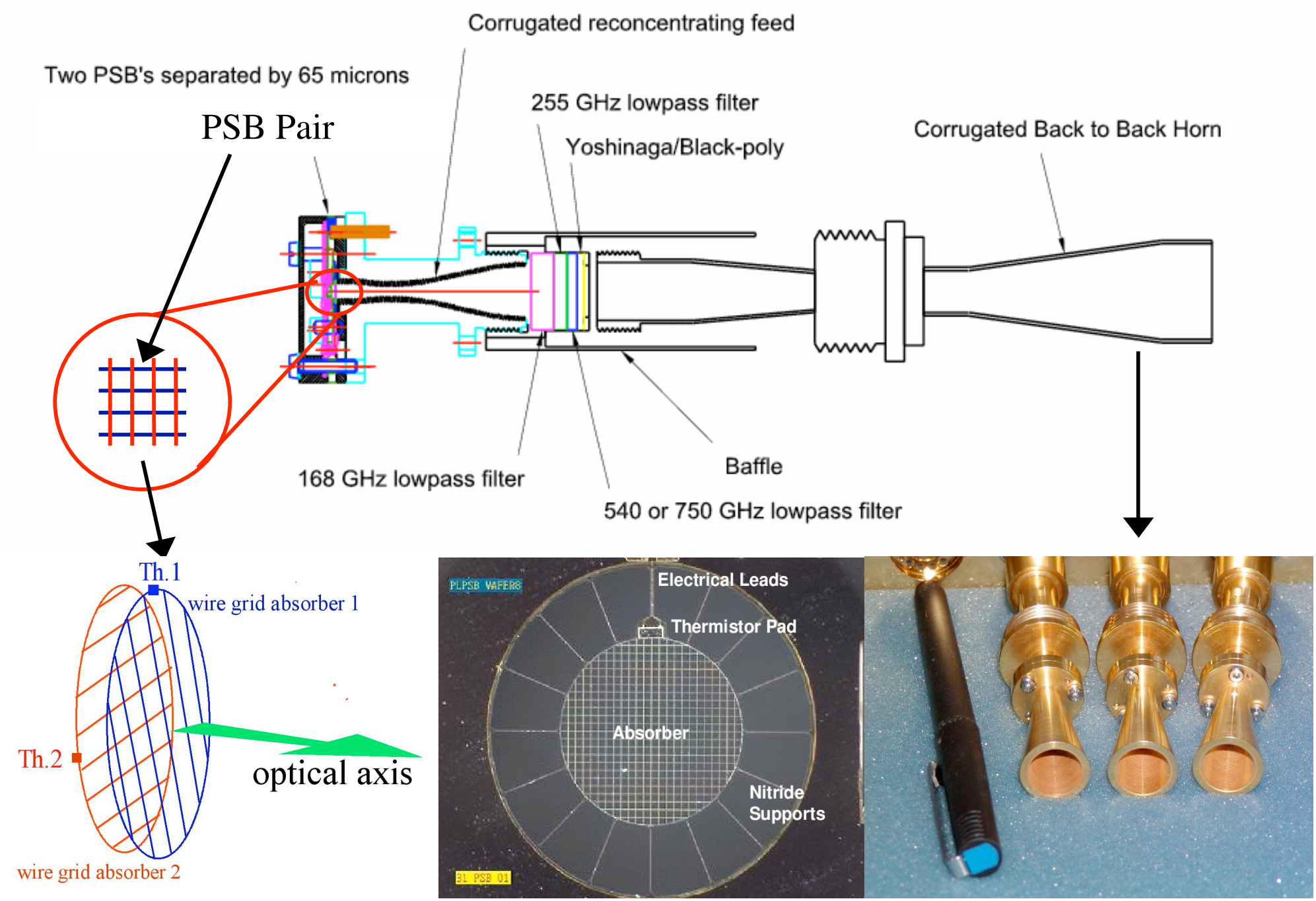




B03 Sensitive at 145, 245, 345 GHz

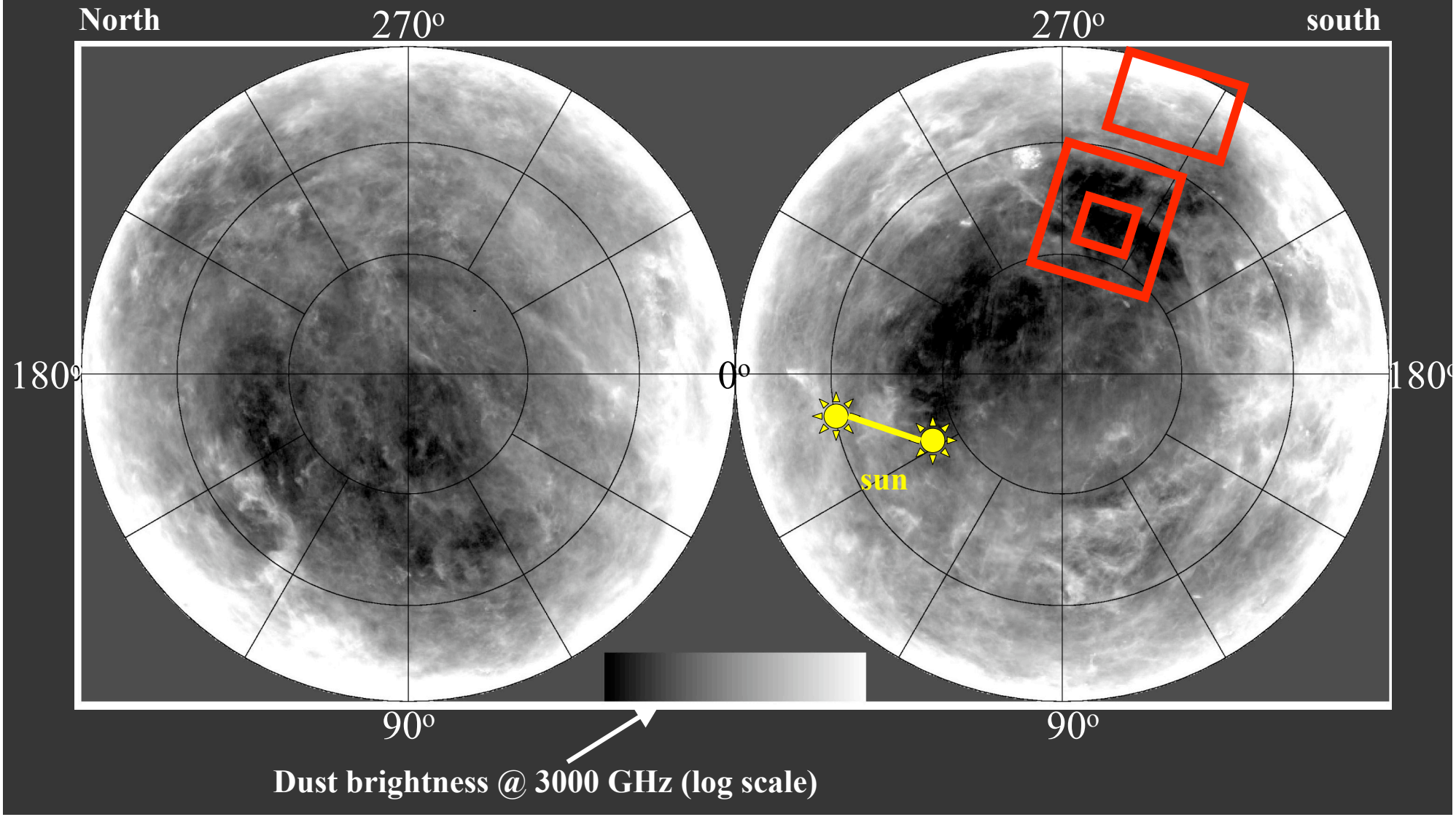
- The focal plane : all you see is cooled at 270 mK

PSB devices & feed optics (Caltech + JPL)

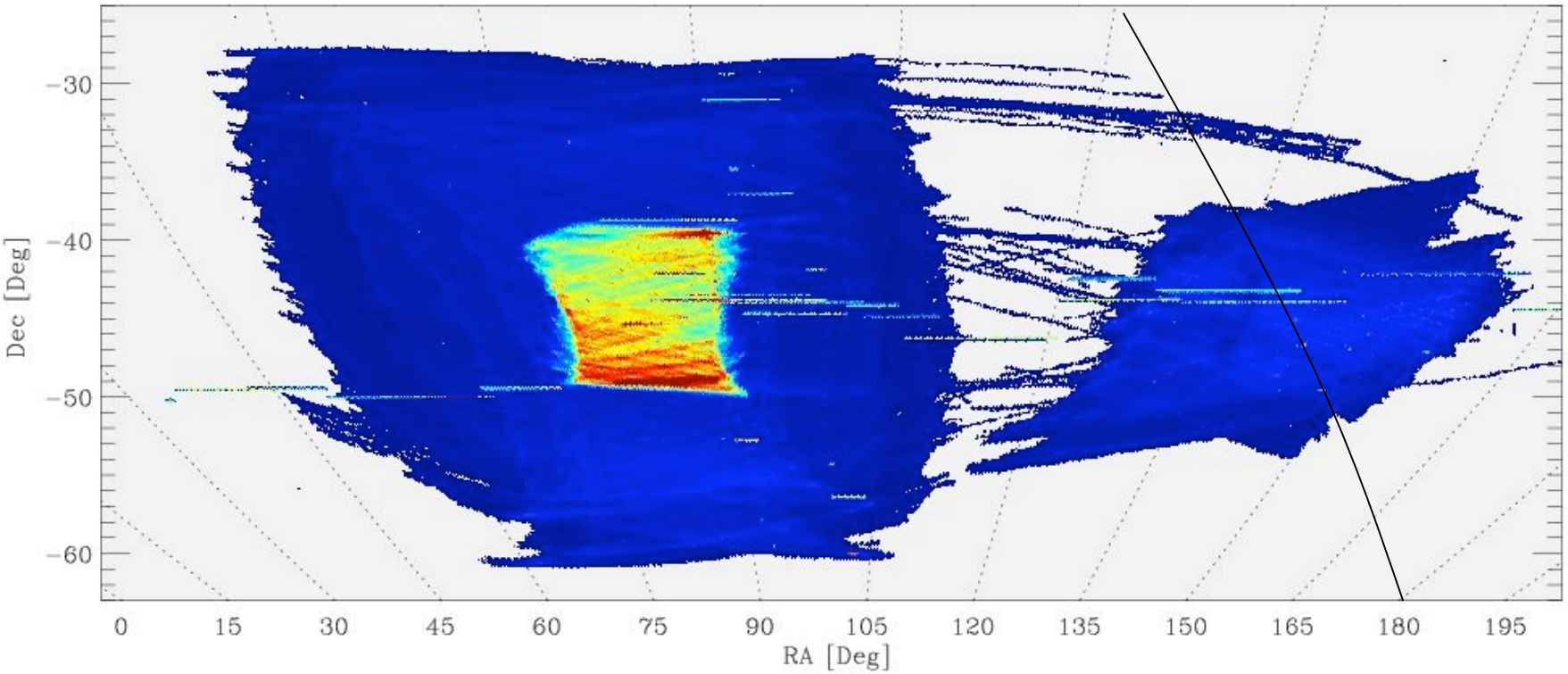



06/01/2003

We have selected one of the lowest dust regions in the sky, which is opposite to the sun during the Antarctic summer



Survey Strategy

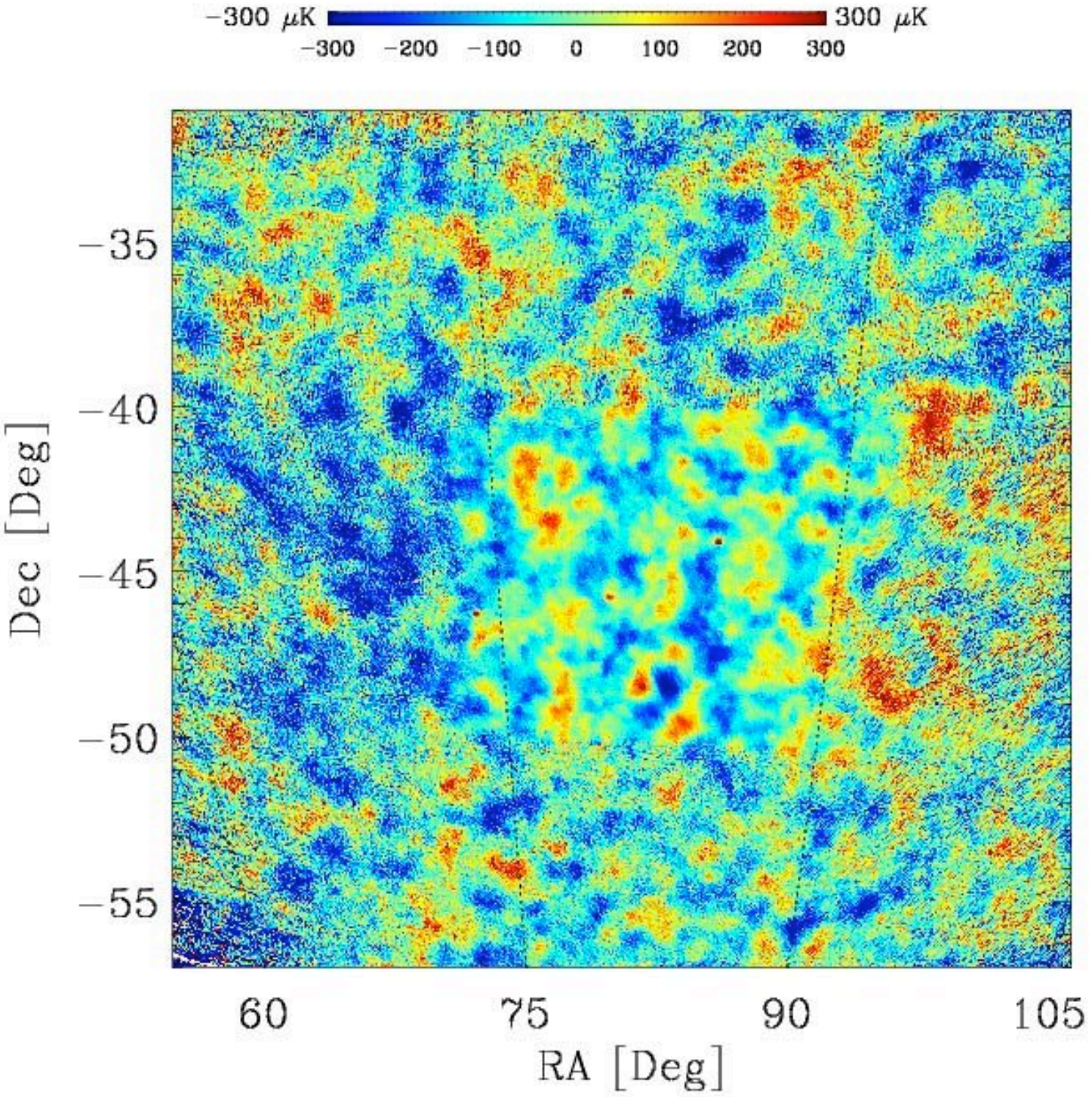


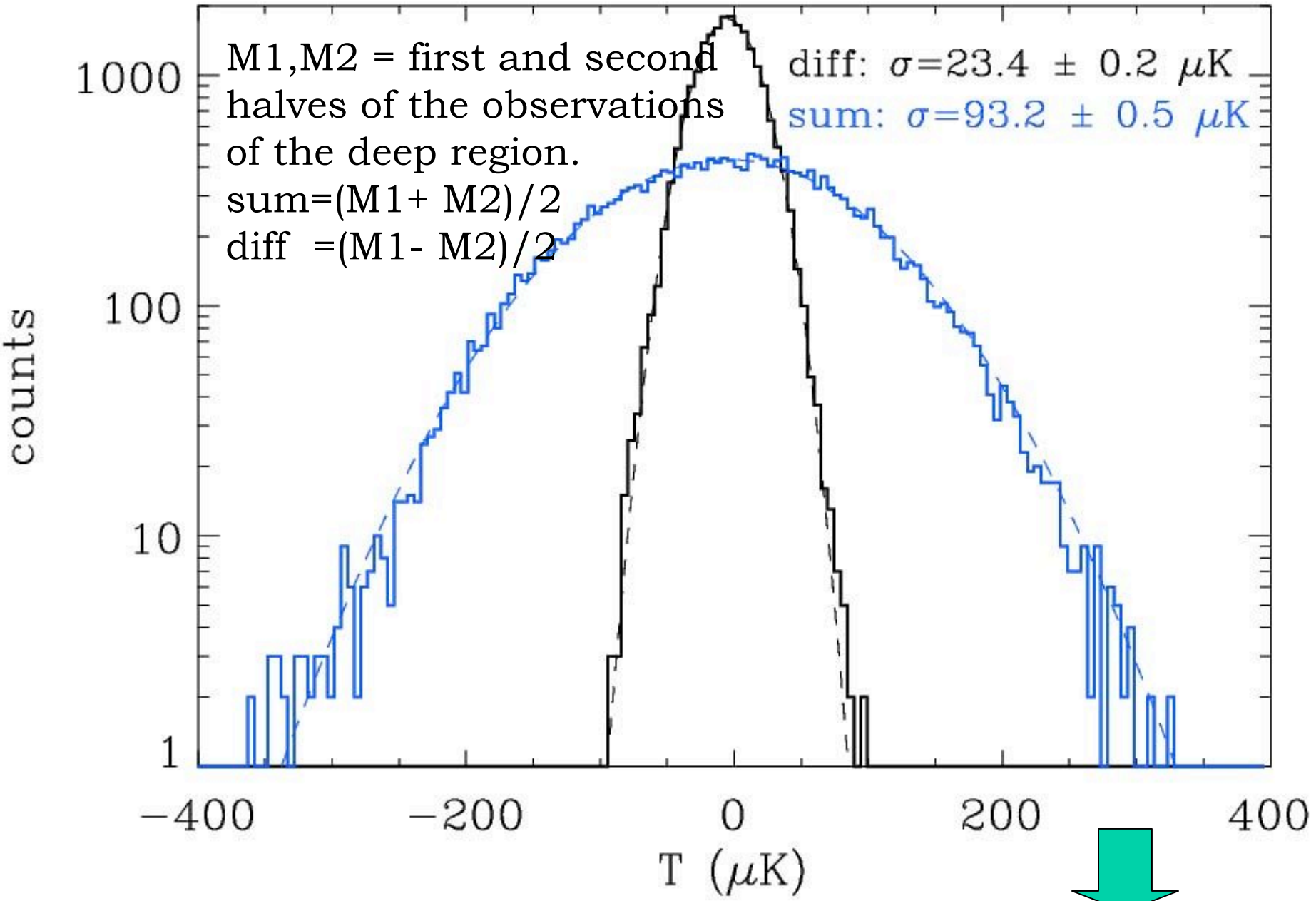
Region	Size (sq deg)	Goal	Time per 7’ pixel (for each detector)
Deep CMB	115	<EE>	60 sec
Shallow CMB	1130	<TE> and <TT>	3.3 sec
Galactic Plane	390	Polarized Foregrounds	4.7 sec

145 GHz T map

(Masi et al., 2005)

the deepest CMB map ever



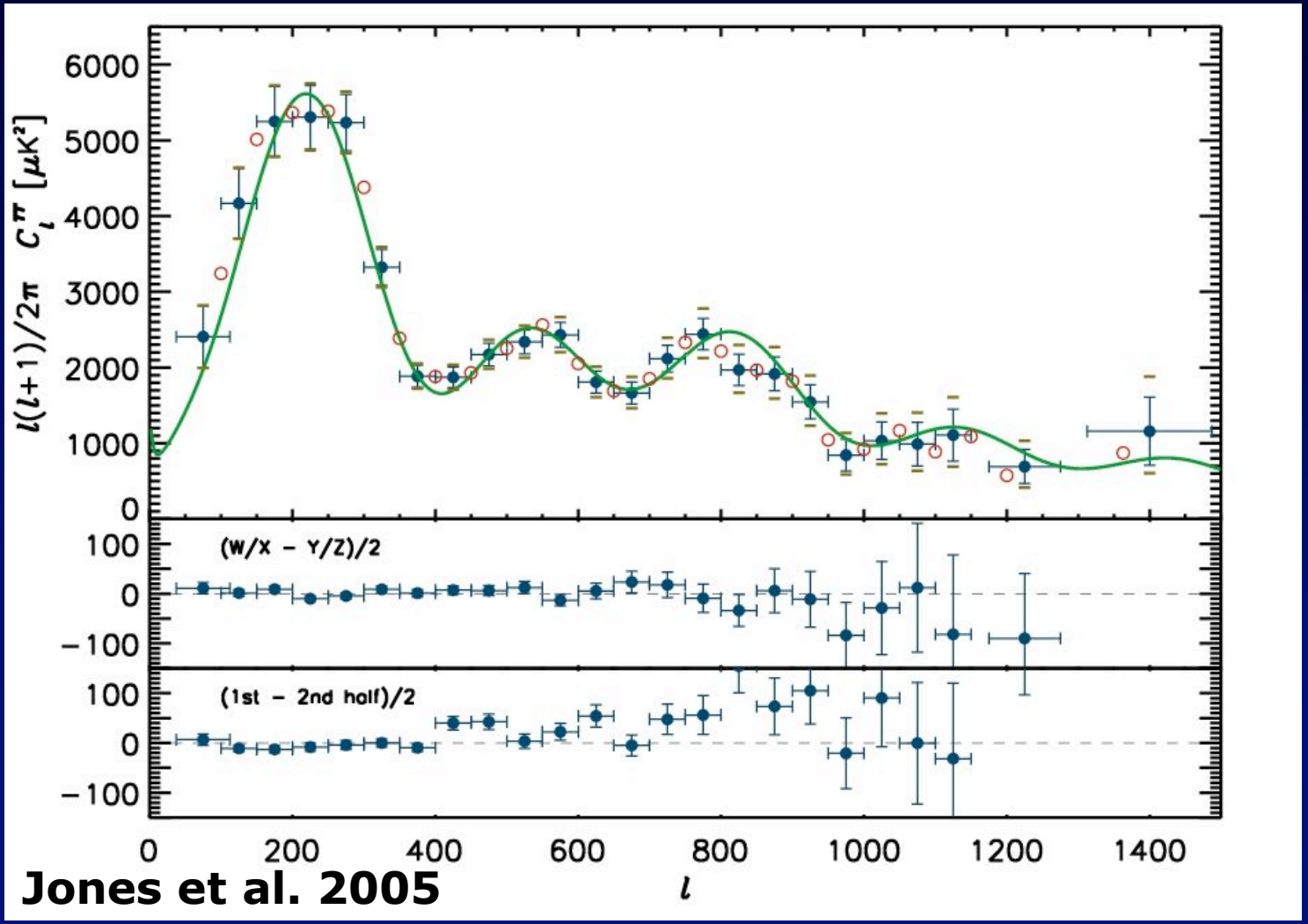


- In the deep survey the S/N is high.
- The fluctuations are gaussian.

$\Delta T_{rms} = (90.2 \pm 2.3)\ \mu K$

B03 TT Power Spectrum

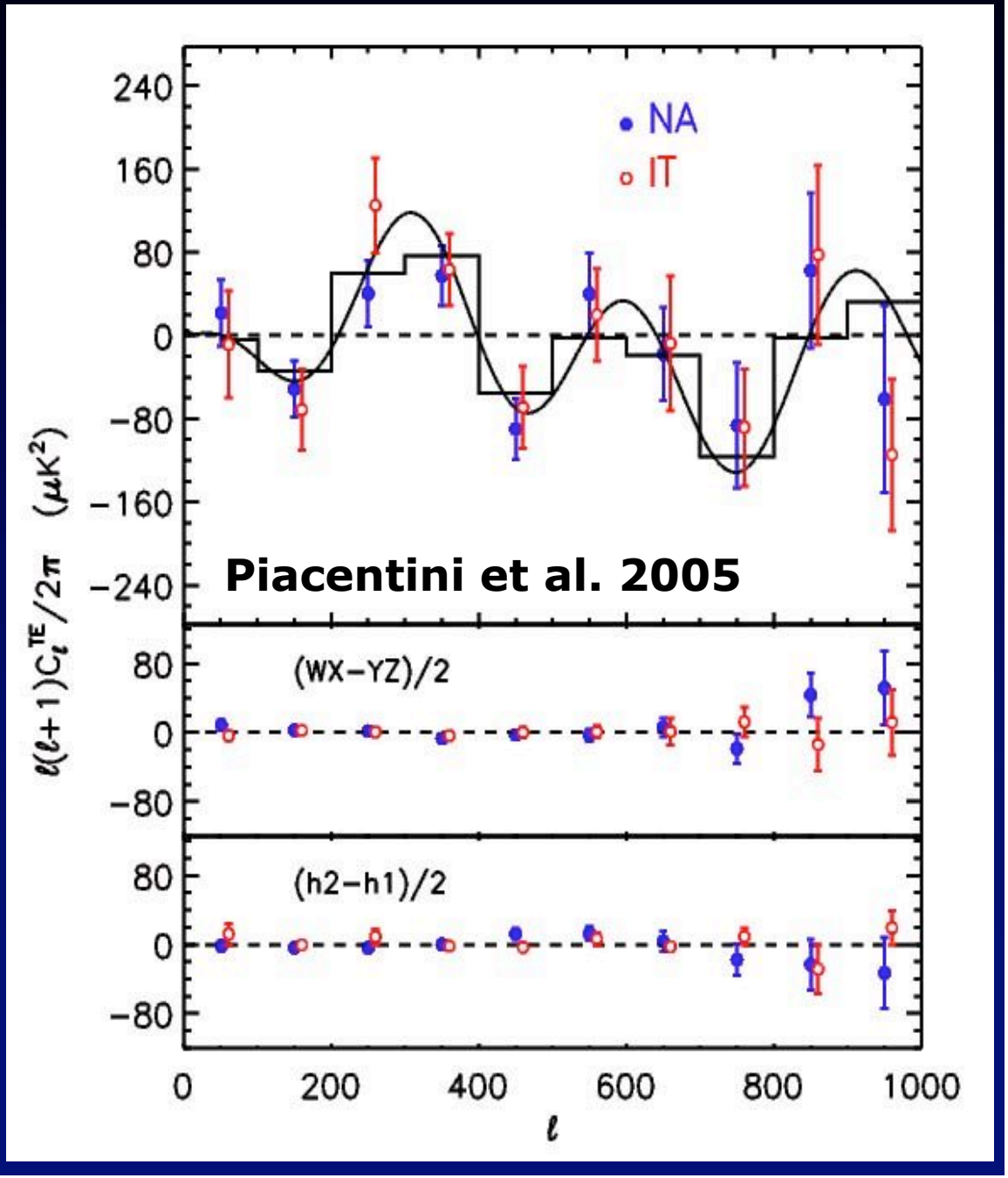
- Detection of anisotropy signals all the way up to **l**=1500
- Time and detector jacknife tests OK
- Systematic effects negligible wrt noise & cosmic variance



Jones et al. 2005

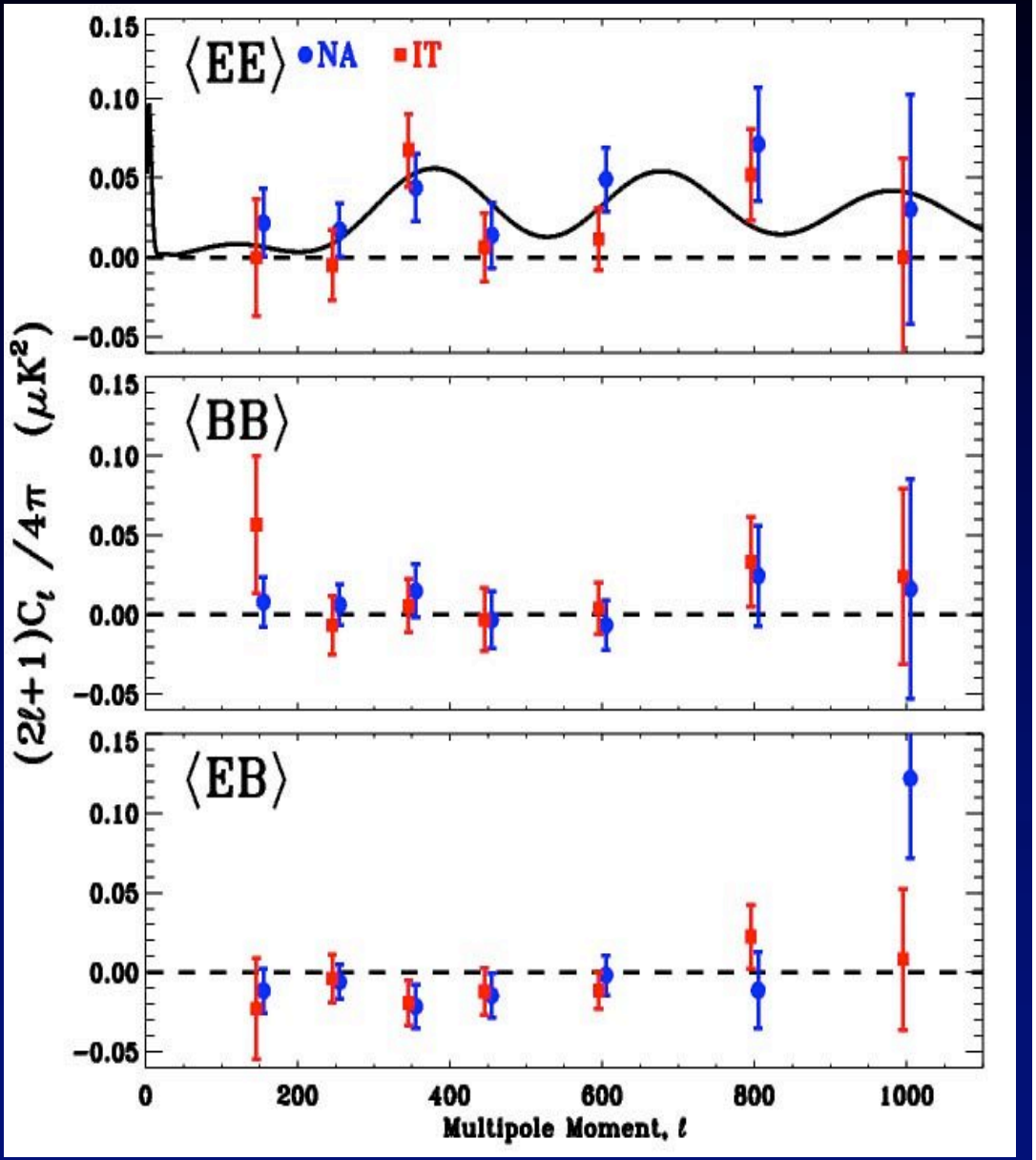
TE from BOOMERanG 03 (140 GHz)

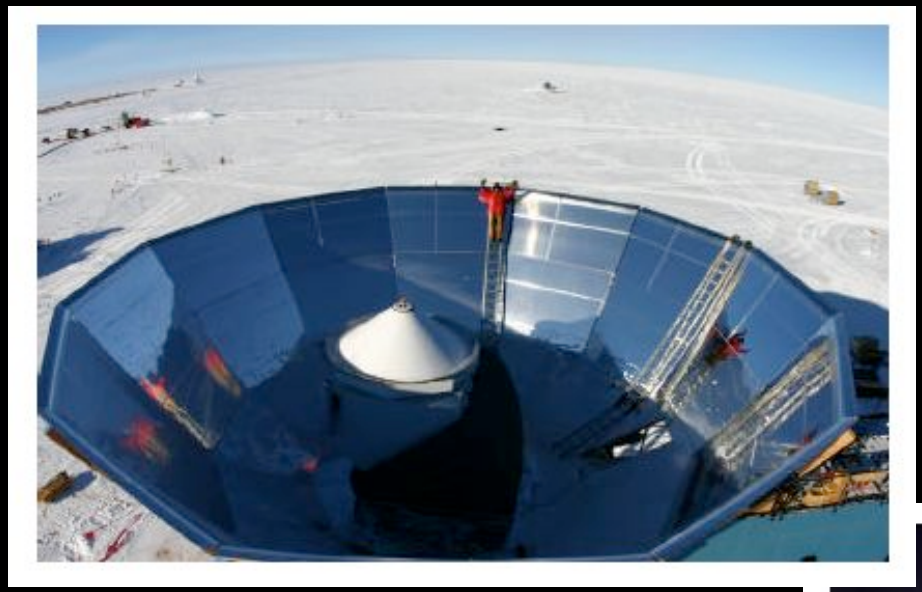
- Small signal, but detection evident (3.5σ)
- NA and IT results consistent
- Error bars dominated by cosmic variance
- Time and detectors jacknife OK, i.e. systematics negligible
- Data consistent with TT best fit model



EE from BOOMERanG-03 (140 GHz)

- Signal extremely small, but detection evident for EE (non zero at 4.8σ).
- No detection for BB nor for EB
- Time and detectors jacknife OK, i.e. systematics negligible
- Data consistent with TT best fit model
- Error bars dominated by detector noise.





QUAD

The QUaD Collaboration

- Stanford University
- U. of Wales, Cardiff
- Caltech
- JPL
- U. of Chicago
- N.U.I Maynooth
- U. of Edinburgh
- Collège de France

QUAD: astro-ph/0705.2359

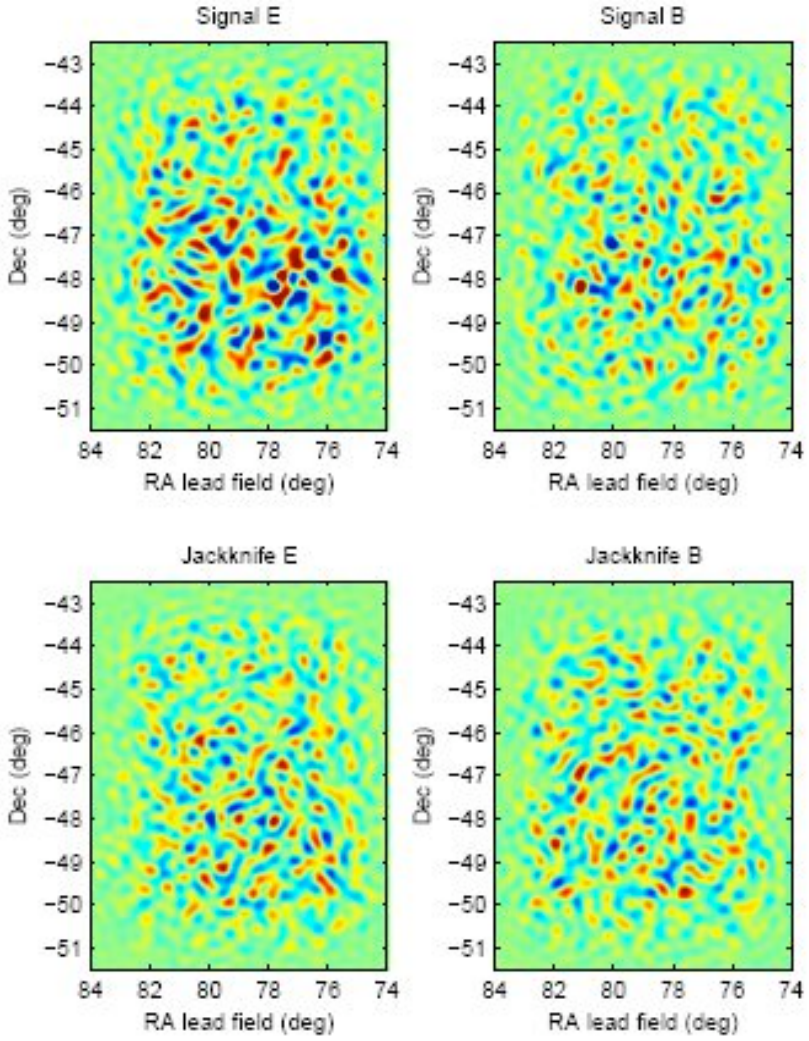
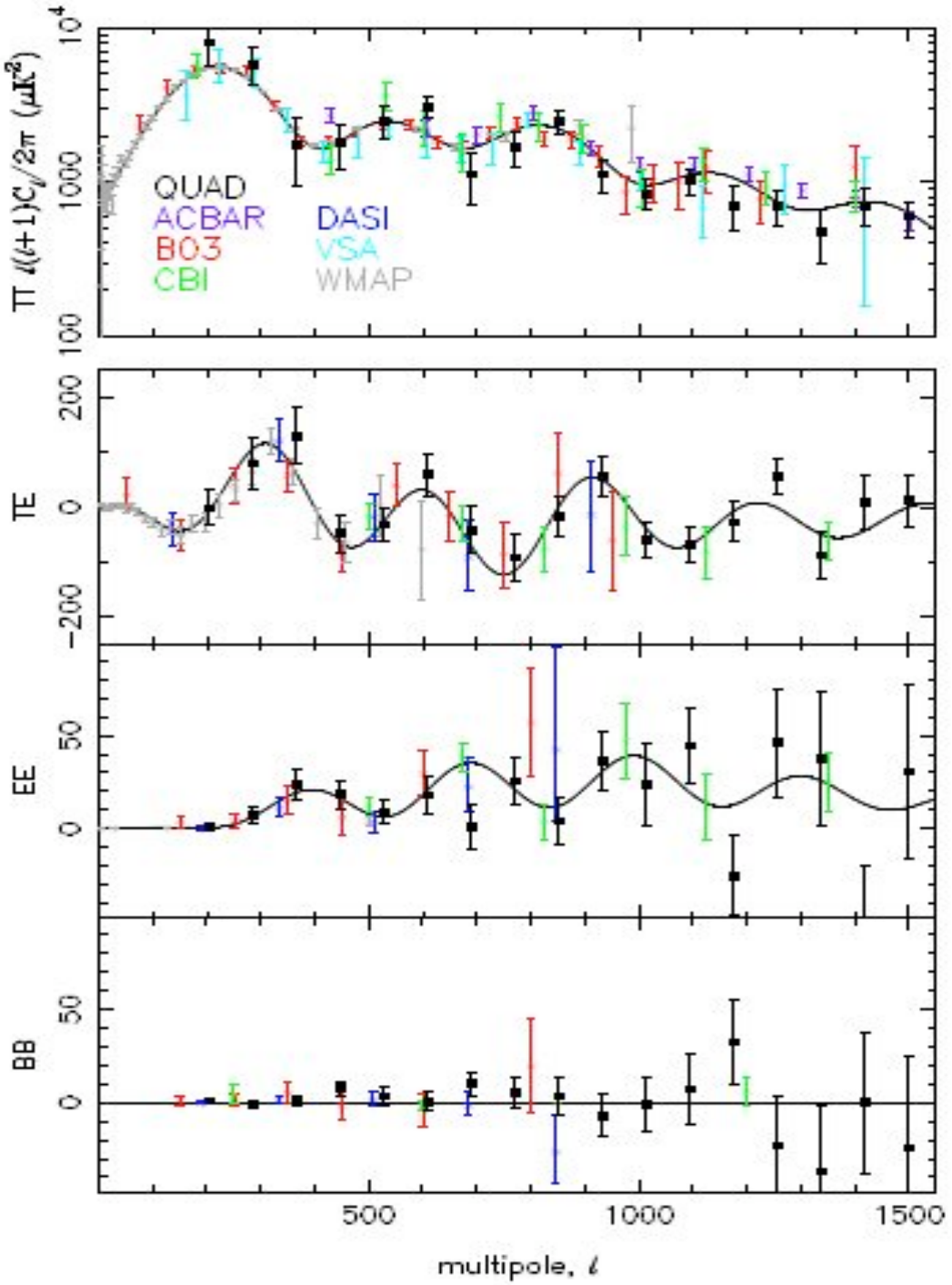


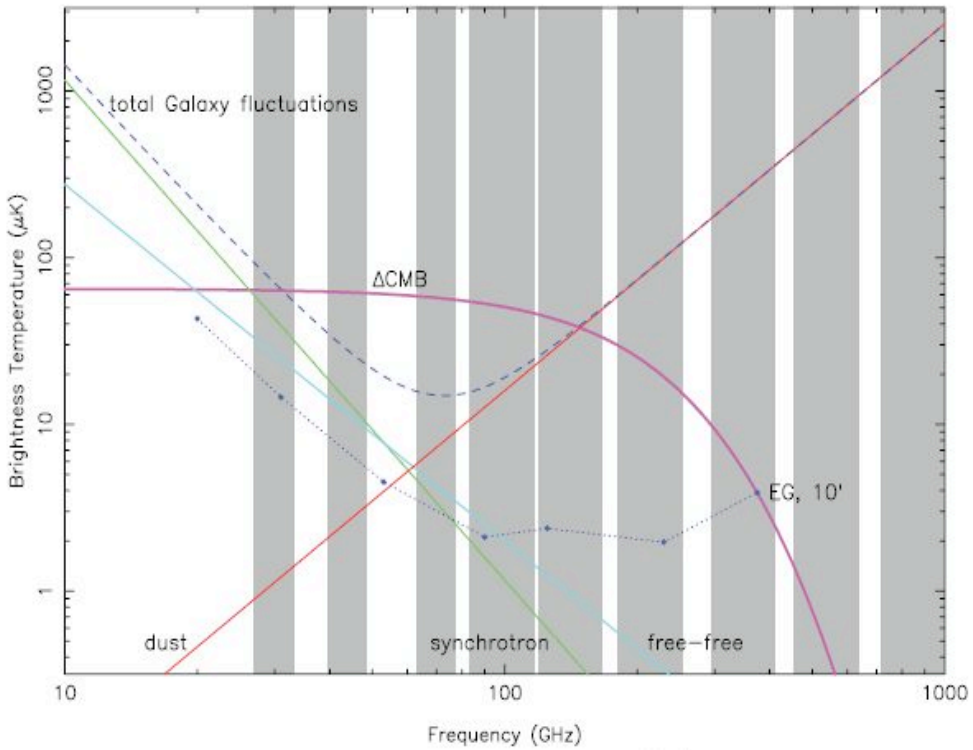
FIG. 1.— QUaD first season field differenced polarization maps decomposed into E and B-modes, and filtered to include only the angular scale range $200 < \ell < 1000$. The top row shows the result for signal (non-jackknife) maps, while the bottom row is for the "deck" jackknife (see text). This plot shows 150 GHz maps and the color scale is $\pm 30\,\mu\mathrm{K}^2$ in all cases.



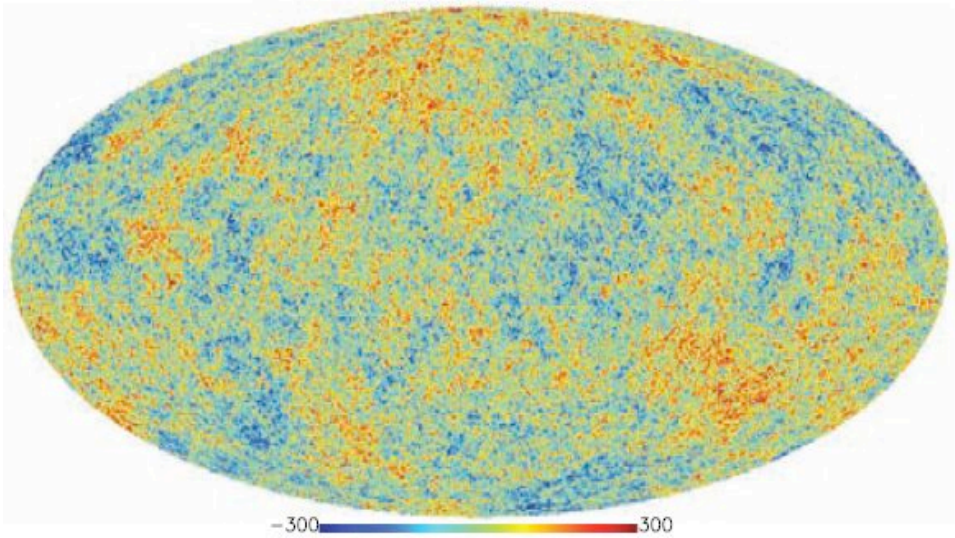
Polarization summary

- CMB polarization is really there (several consistent detections by independent experiments)
- The measured amplitude of the E-modes is consistent with the expectation from the model best-fitting CMB anisotropy data.
- The accuracy is not great yet, and the polarization data do not add much to our knowledge of cosmological parameters.
- Main exception: the optical depth of reionization.
- B-modes not detected yet.

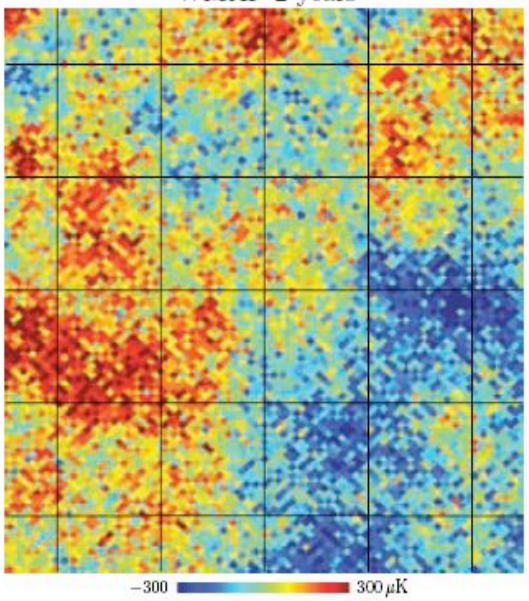

esa
PLANCK
Looking back to the dawn of time
Un regard vers l'aube du temps
http://sci.esa.int/planck



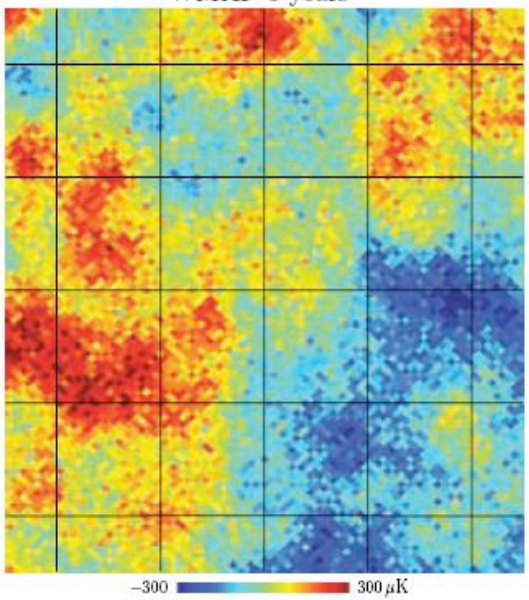
Planck resolution



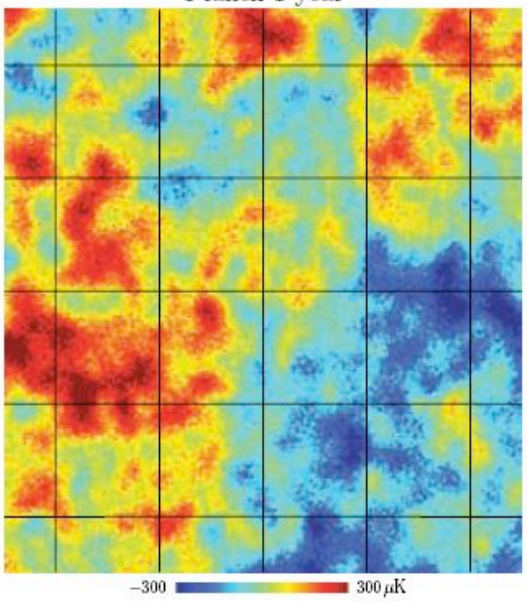
WMAP 2 years



WMAP 8 years



Planck 1 year



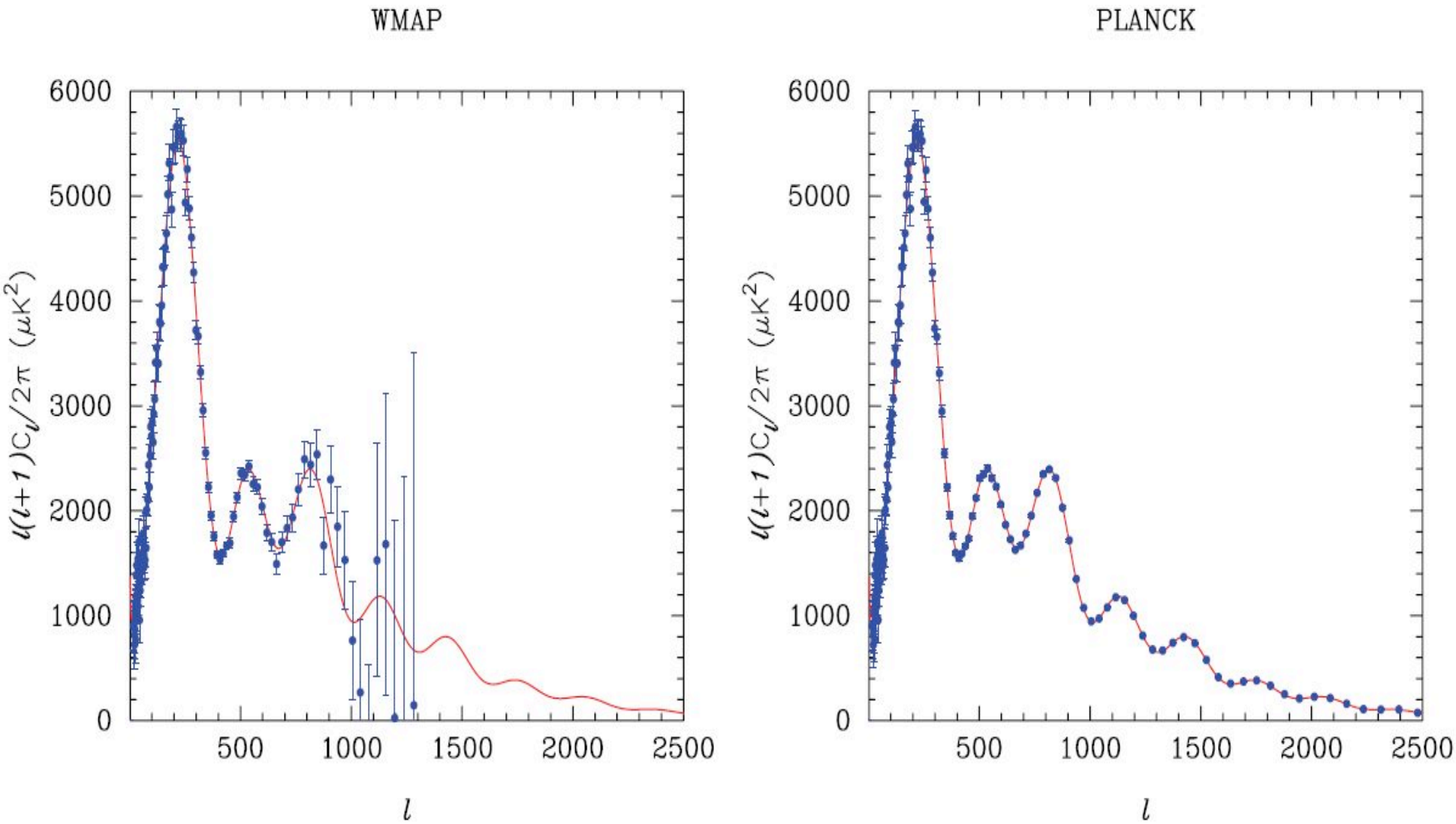


FIG 2.8.—The left panel shows a realisation of the CMB power spectrum of the concordance ΛCDM model (red line) after 4 years of *WMAP* observations. The right panel shows the same realisation observed with the sensitivity and angular resolution of *Planck*.

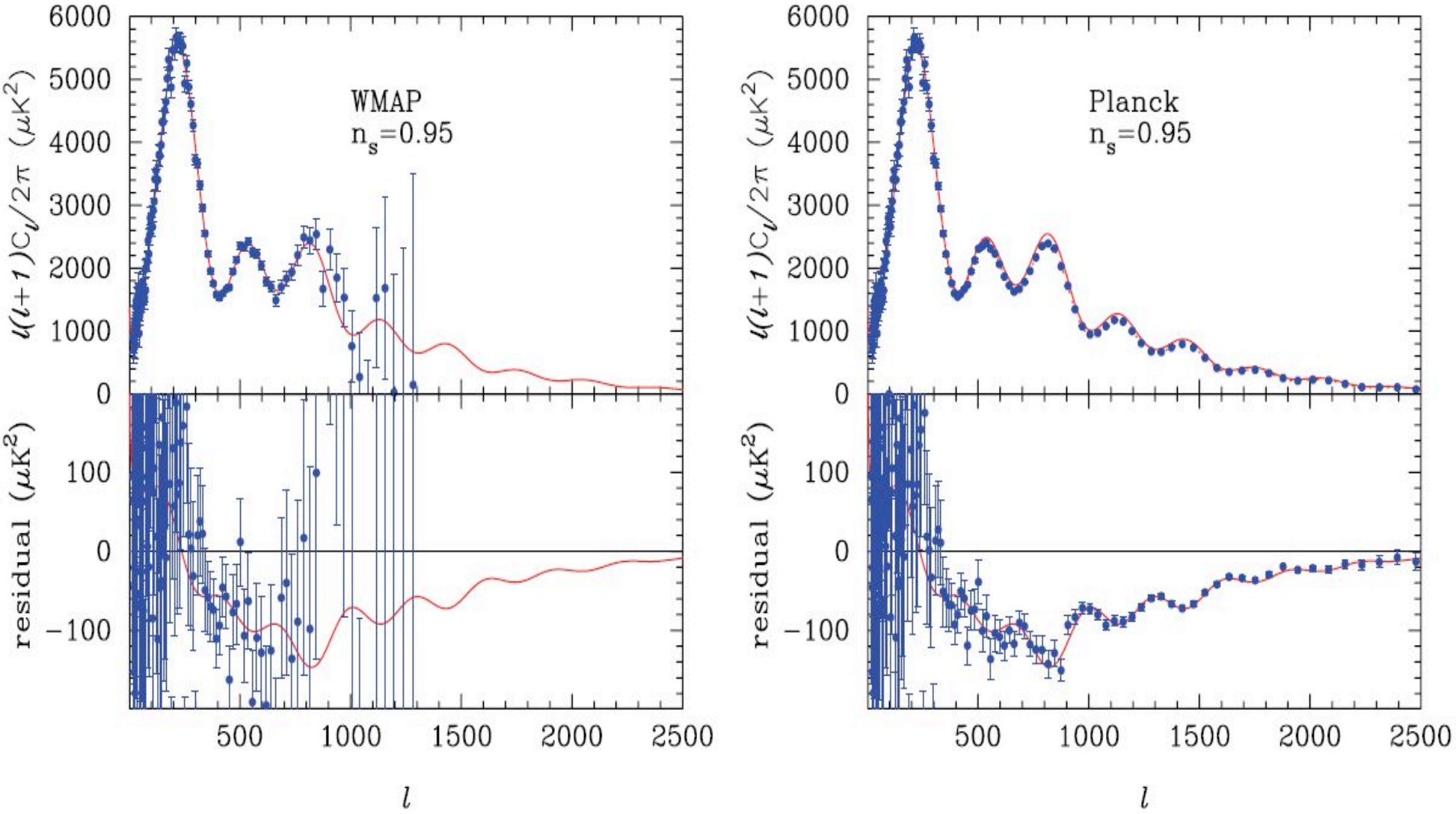
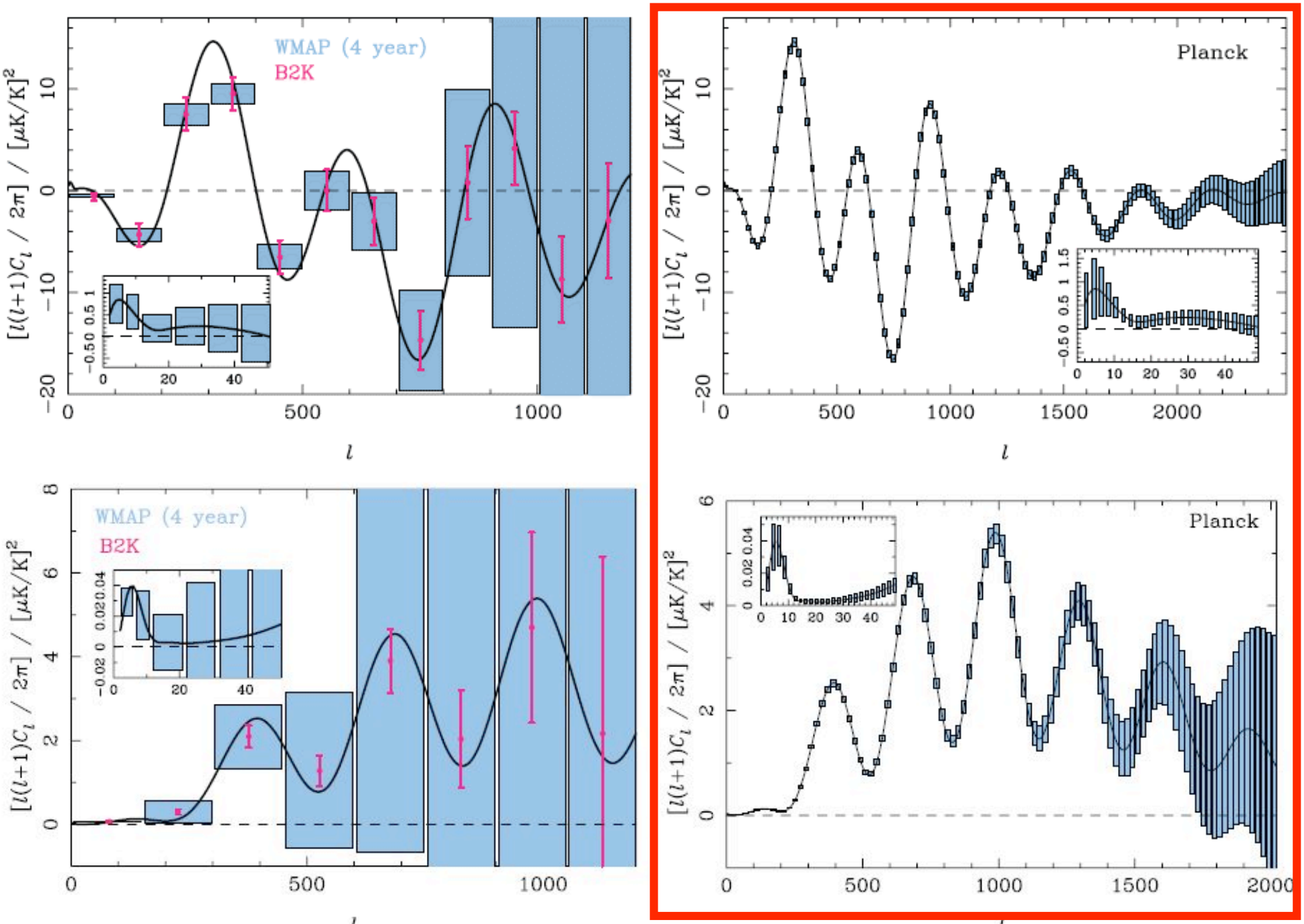
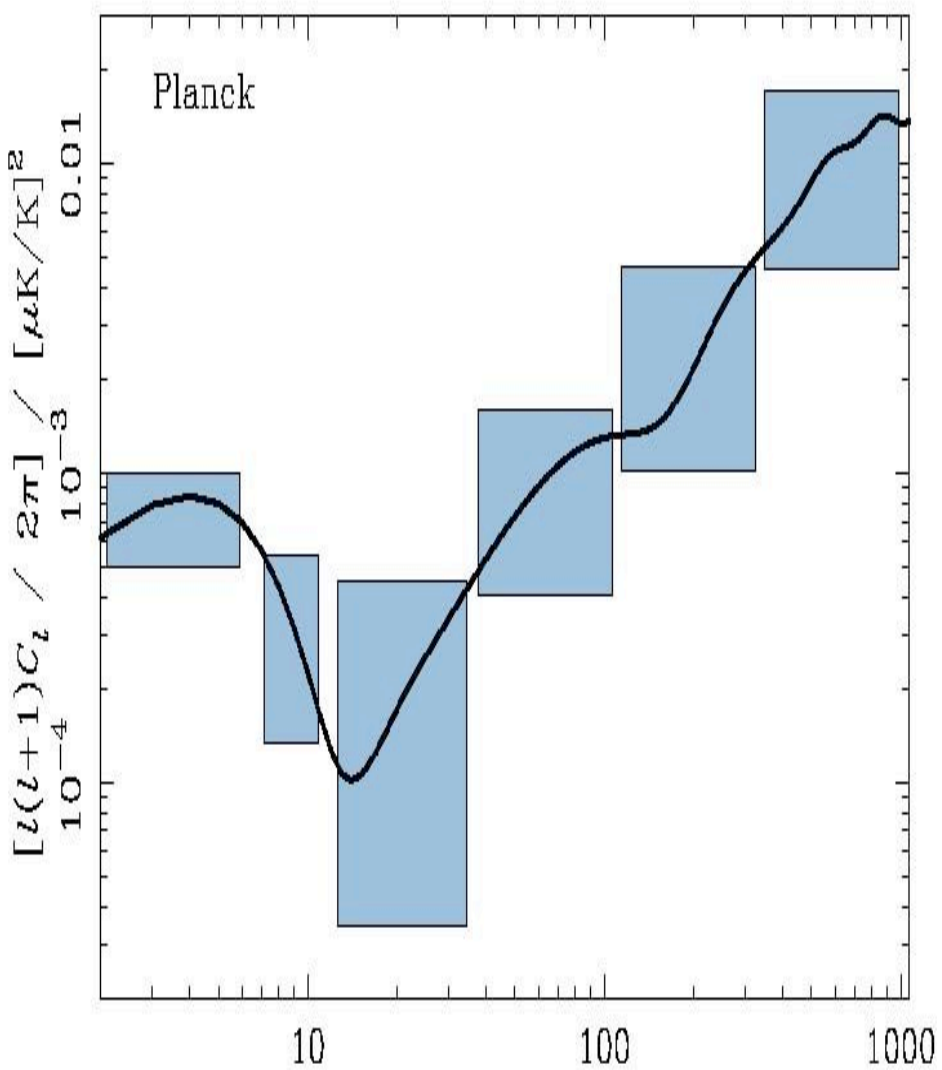
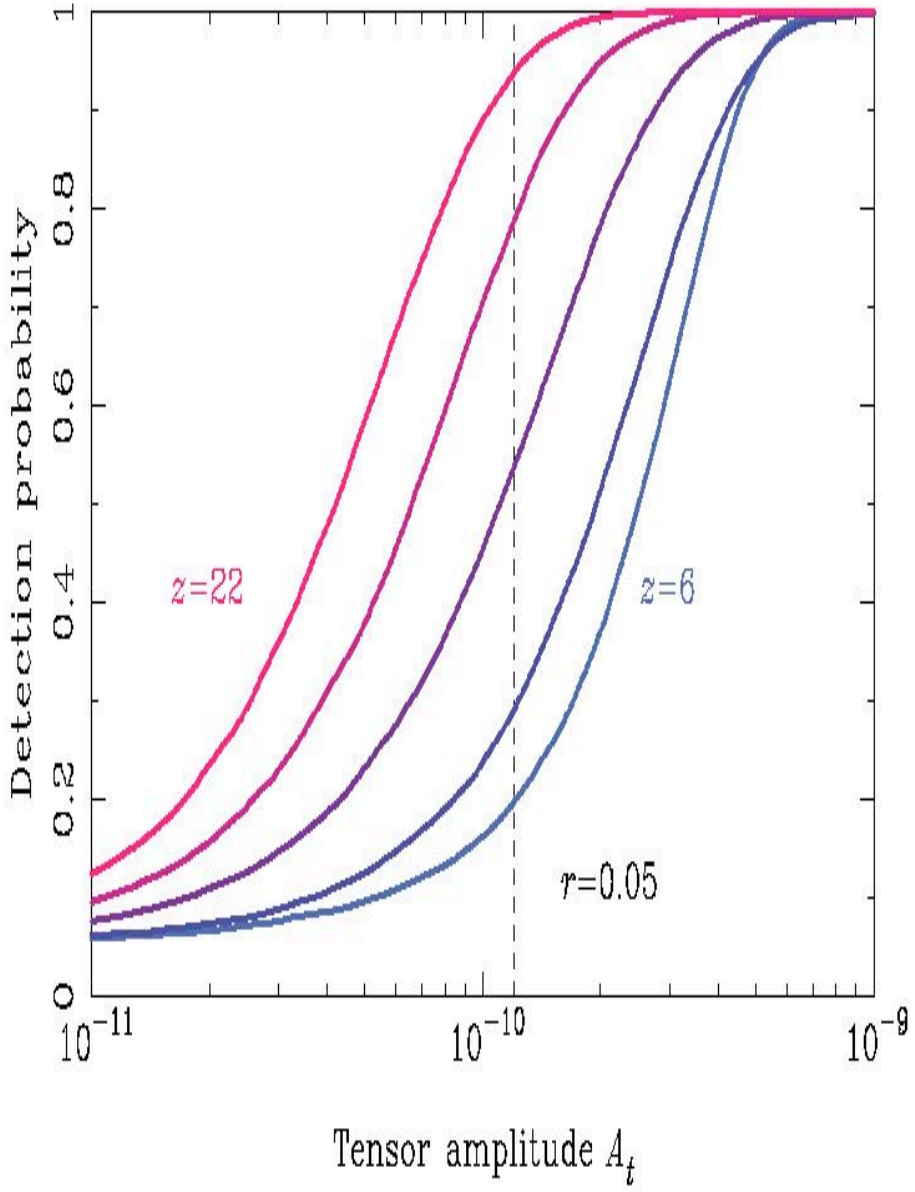


FIG 2.11.—The solid lines in the upper panels of these figures show the power spectrum of the concordance ΛCDM model with an exactly scale invariant power spectrum, $n_S = 1$. The points, on the other hand, have been generated from a model with $n_S = 0.95$ but otherwise identical parameters. The lower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



E-modes, as will be observed by Planck





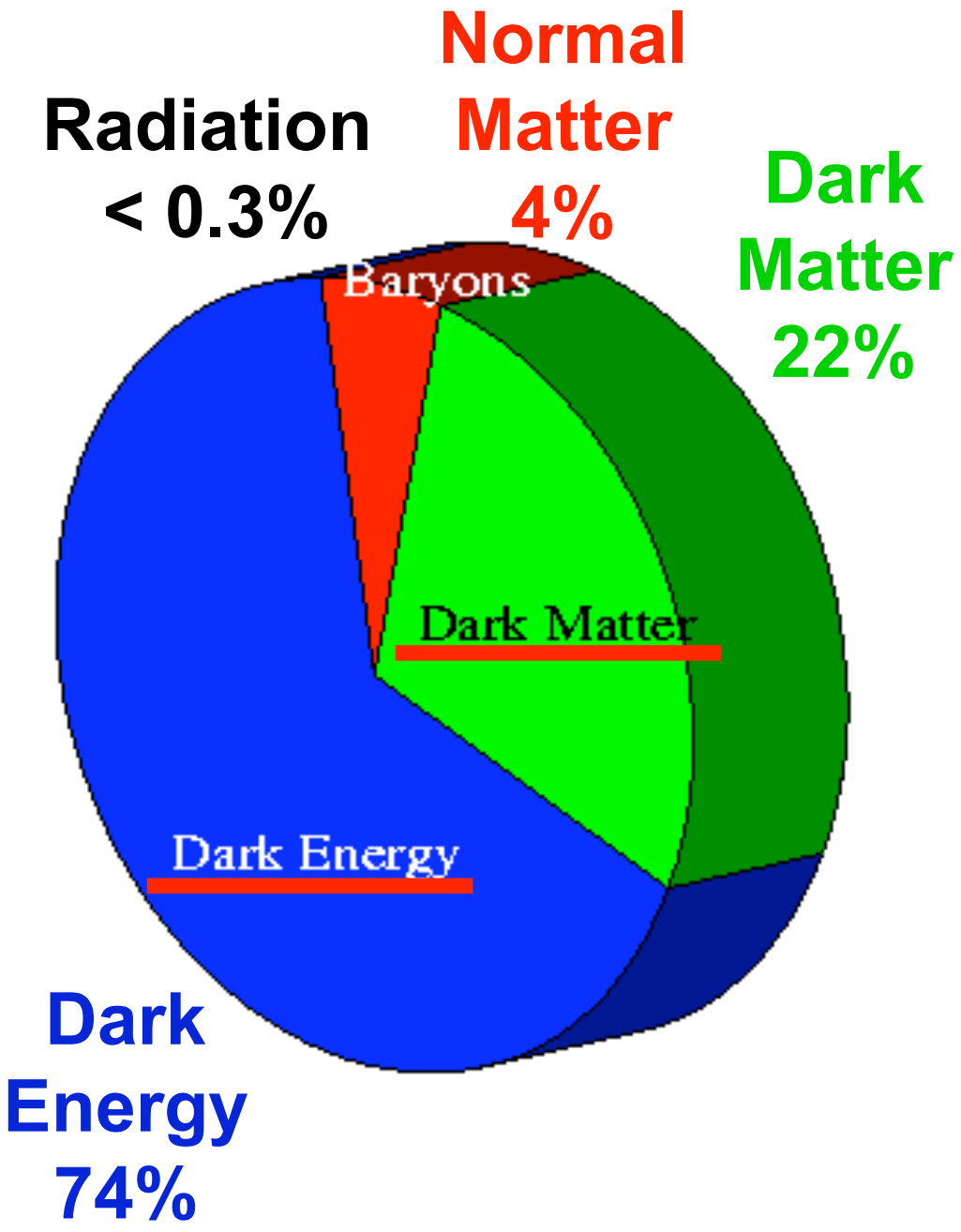
B-modes, as might be observed by Planck

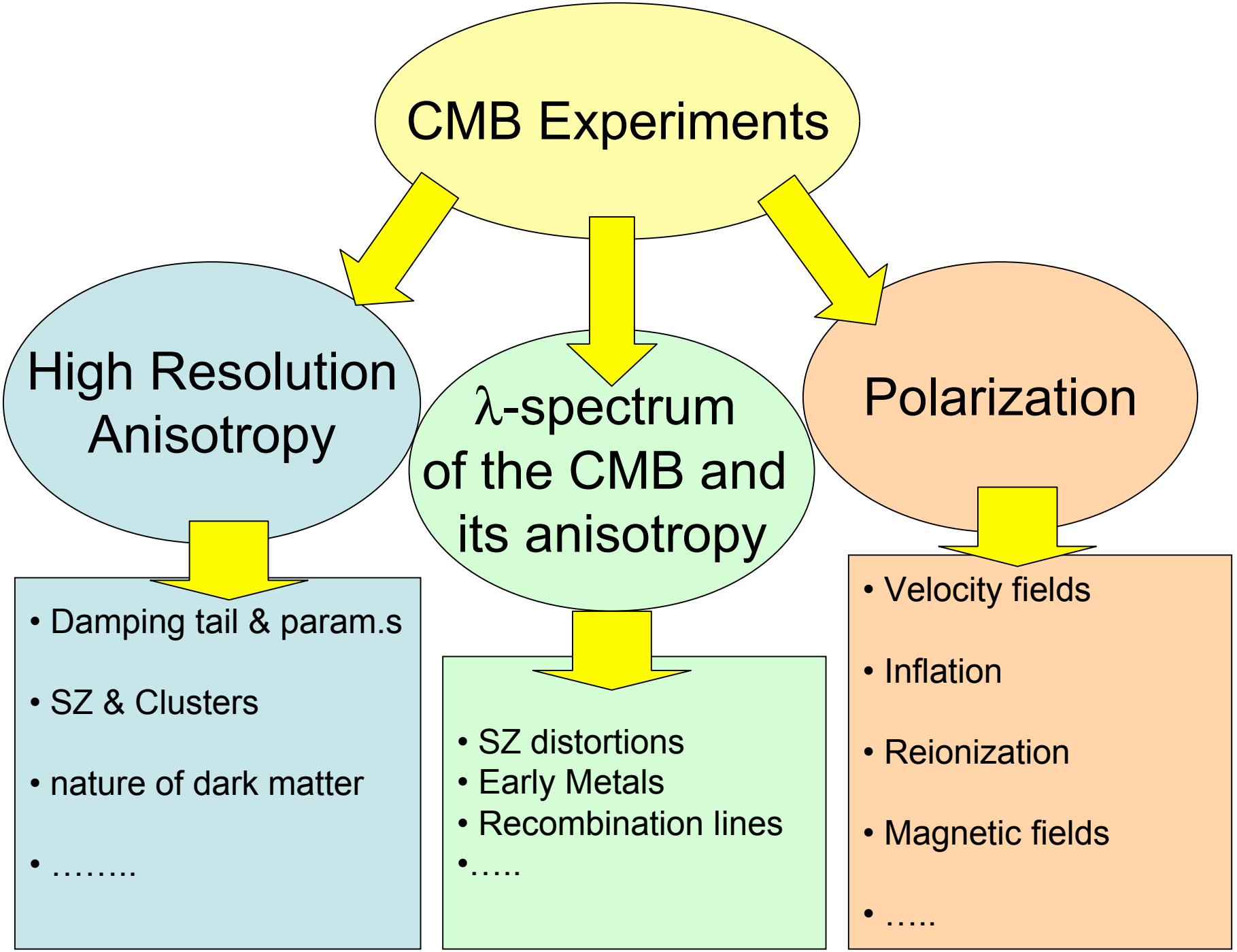
contents

- CMB experiments: state of the art
- Open problems : how to attack them with CMB
- Enabling technologies
- High angular resolution CMB anisotropy
- The spectrum of CMB anisotropy
- The polarization of CMB

- Given all this,
  - Which are the big questions ?
  - Where are we going with new CMB experiments / techniques to answer these questions ?

INFLATION


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


CMB Experiments
High Resolution Anisotropy
λ-spectrum of the CMB and its anisotropy
Polarization
• Damping tail & param.s
• SZ & Clusters
• nature of dark matter
• ……..
• SZ distortions
• Early Metals
• Recombination lines
•…..
• Velocity fields
• Inflation
• Reionization
• Magnetic fields
• …..

contents

- CMB experiments: state of the art
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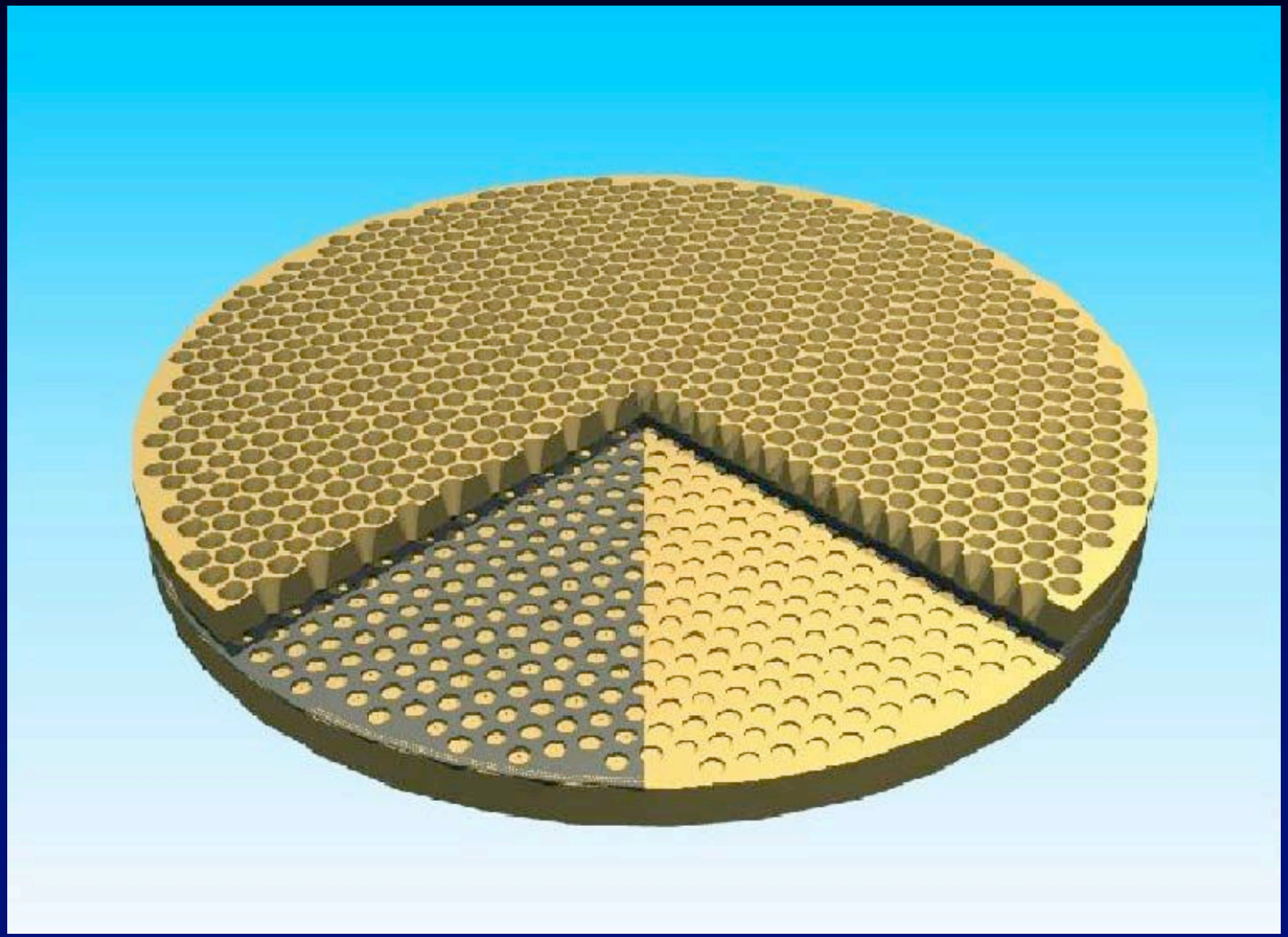
Improvement in sensitivity

- Anisotropy signals: 80 μK rms
- E-Polarization: 3 μK rms
- B-Polarization: < 0.1 μK rms
- Recombination lines < 0.05 μK
- CMB anisotropy detectors are close to be limited by the photon noise of the CMB (e.g. the bolometers in the CMB channels of Planck-HFI will be in CMB BLIP)
- In these conditions, the only way to improve the efficiency of an experiment, is to multiply the number of detectors in the focal plane, to improve the mapping speed.
-  need for large format arrays

Large Bolometer Arrays

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

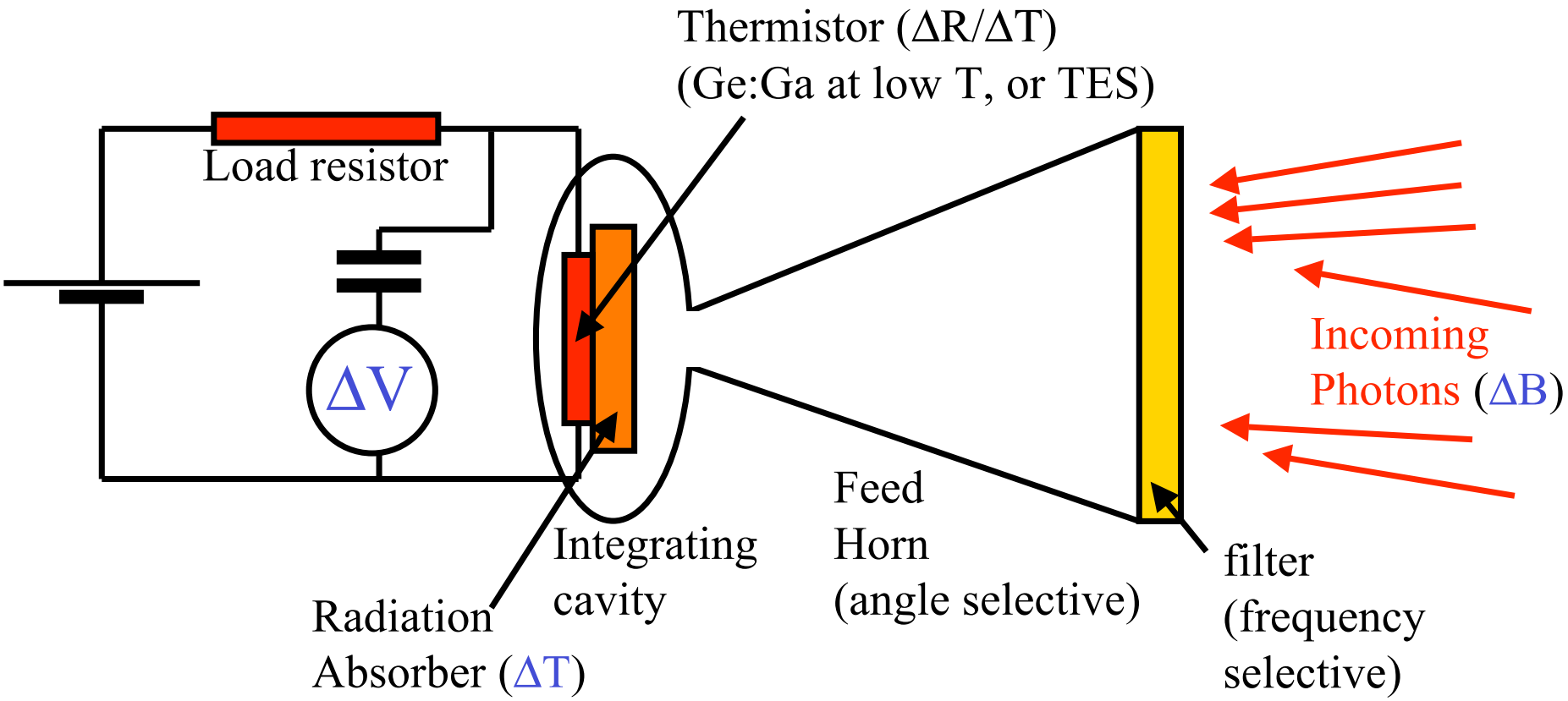


Competing technologies

- CMB brightness peak: 159 GHz
  - High frequency for coherent detectors (antenna + amplifier + rectifier) work at 20 K
  - Low frequency for thermal detectors (absorber + thermistor) work at 0.3-0.1 K
- Search for a **scalable** technology (replicate the sensor in an array with several thousand elements) a big step forward with respect to current technology.
- Radiometers on-a-chip (MMICs, hear about QUIET)
- TES (transition edge superconductor sensors)
- KIDs (kinetic inductance detectors)
- CEBs (cold electrons bolometers)

Cryogenic Bolometers

- The most sensitive broad band detectors for FIR & mm-waves.



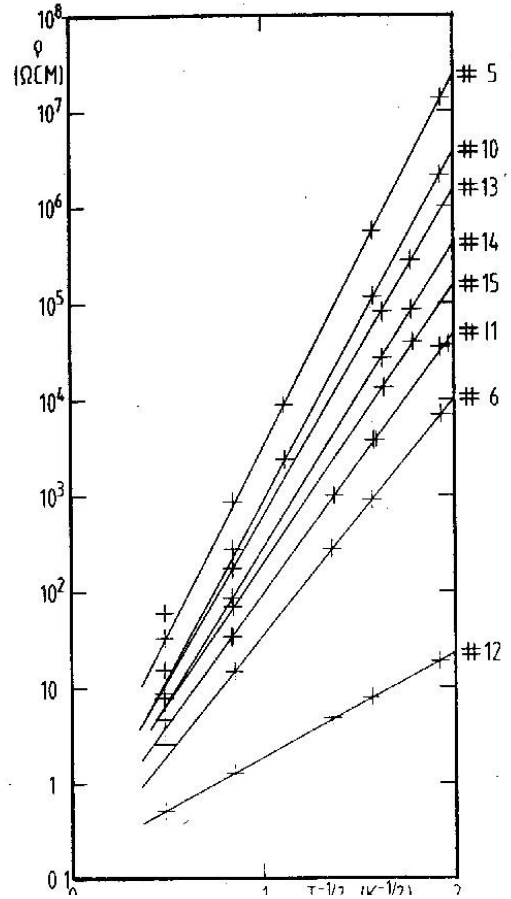
- Fundamental noise sources are Johnson noise in the thermistor ($<\Delta V^2> = 4kTR\Delta f$), temperature fluctuations in the thermistor ($<\Delta W^2> = 4kGT^2\Delta f$), background radiation noise (T_{bkg}^5) need to reduce the temperature of the detector and the radiative background.

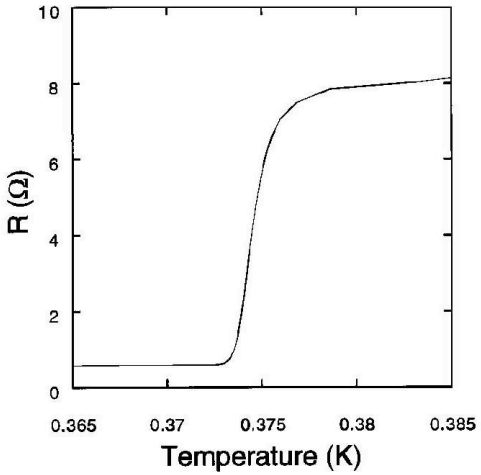
Cryogenic Bolometers

$$\alpha = \frac{1}{R(T)}\frac{dR(T)}{dT}$$

$$\Re = \frac{i\alpha R}{G_{eff}\sqrt{1+\tau^2\omega^2}}$$

- A large α is important for high responsivity.
- Ge thermistors: $\frac{\alpha}{T} \approx -10K^{-1}$
- Superconducting transition edge thermistors: $\frac{\alpha}{T} \approx 1000K^{-1}$

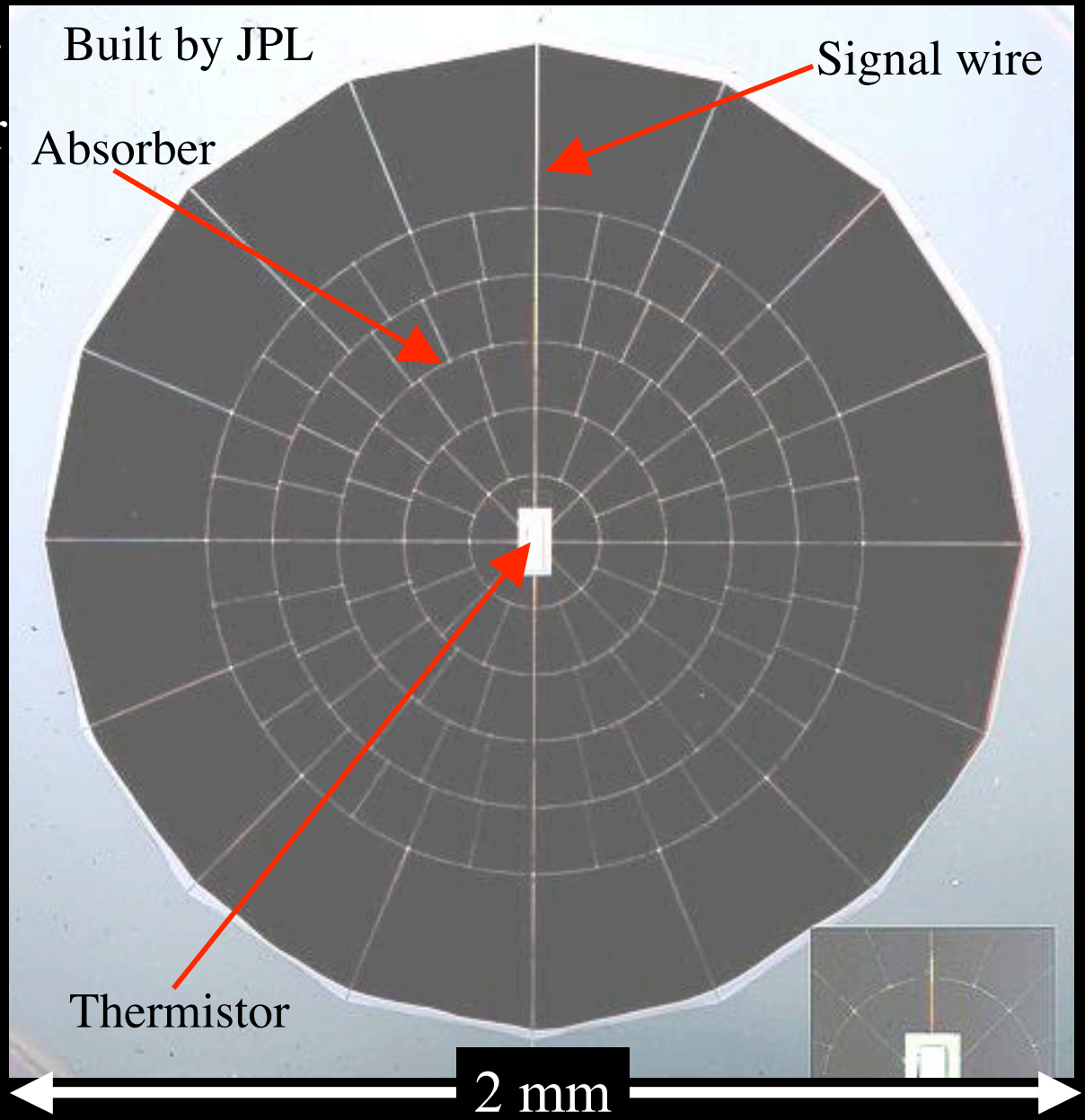




S.F. Lee et al. Appl.Opt. **37** 3391 (1998)

Spider-Web Bolometers

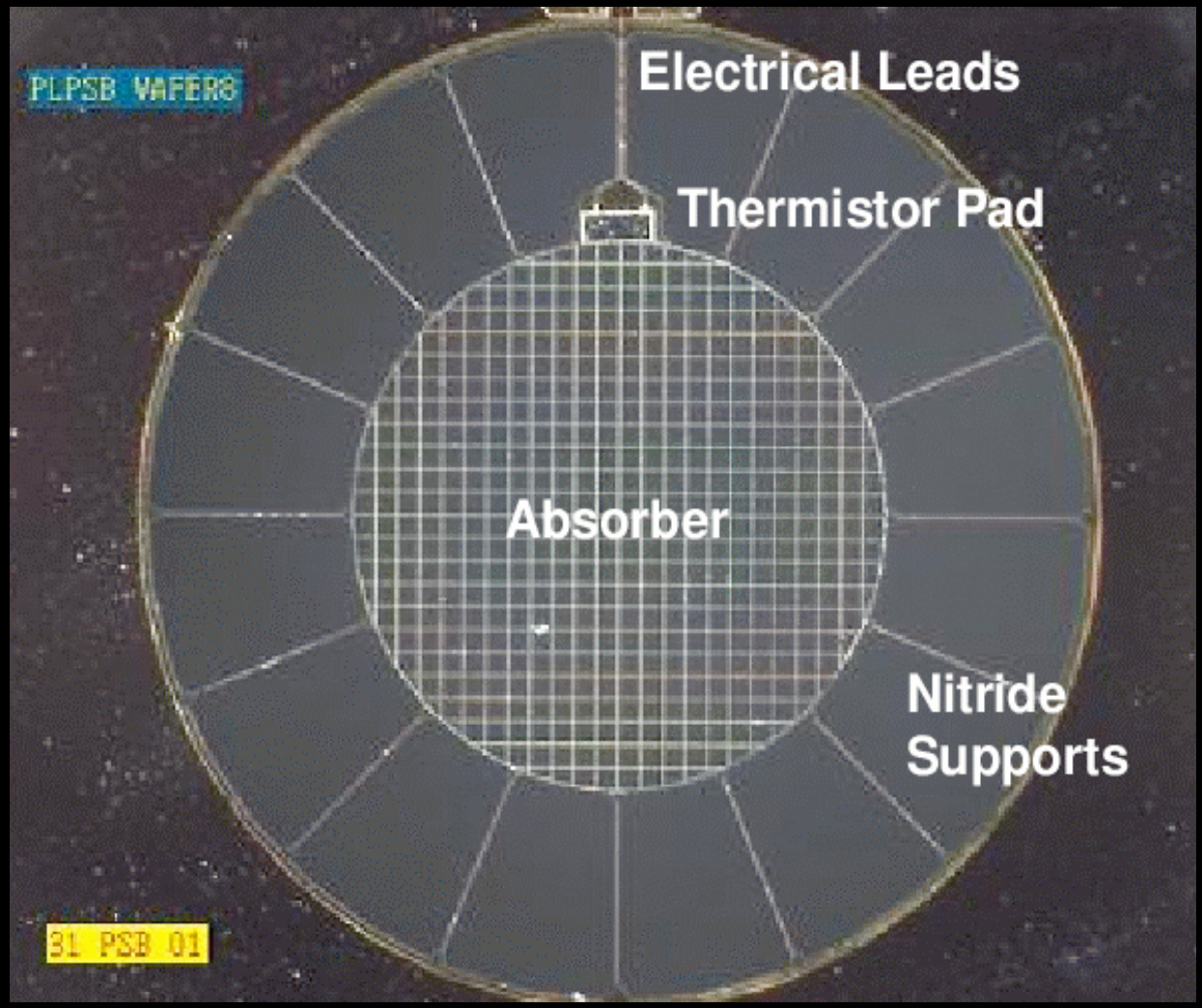
- The absorber is micro machined as a web of metallized Si_3N_4 wires, 2 μm thick, with 0.1 mm pitch.
- This is a good absorber for mm-wave photons and features a very low cross section for cosmic rays. Also, the heat capacity is reduced by a large factor with respect to the solid absorber.
- NEP ~ 2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



Polarization-sensitive version

3 μm thick wire grids, Separated by 60 μm, in the same groove of a circular corrugated waveguide

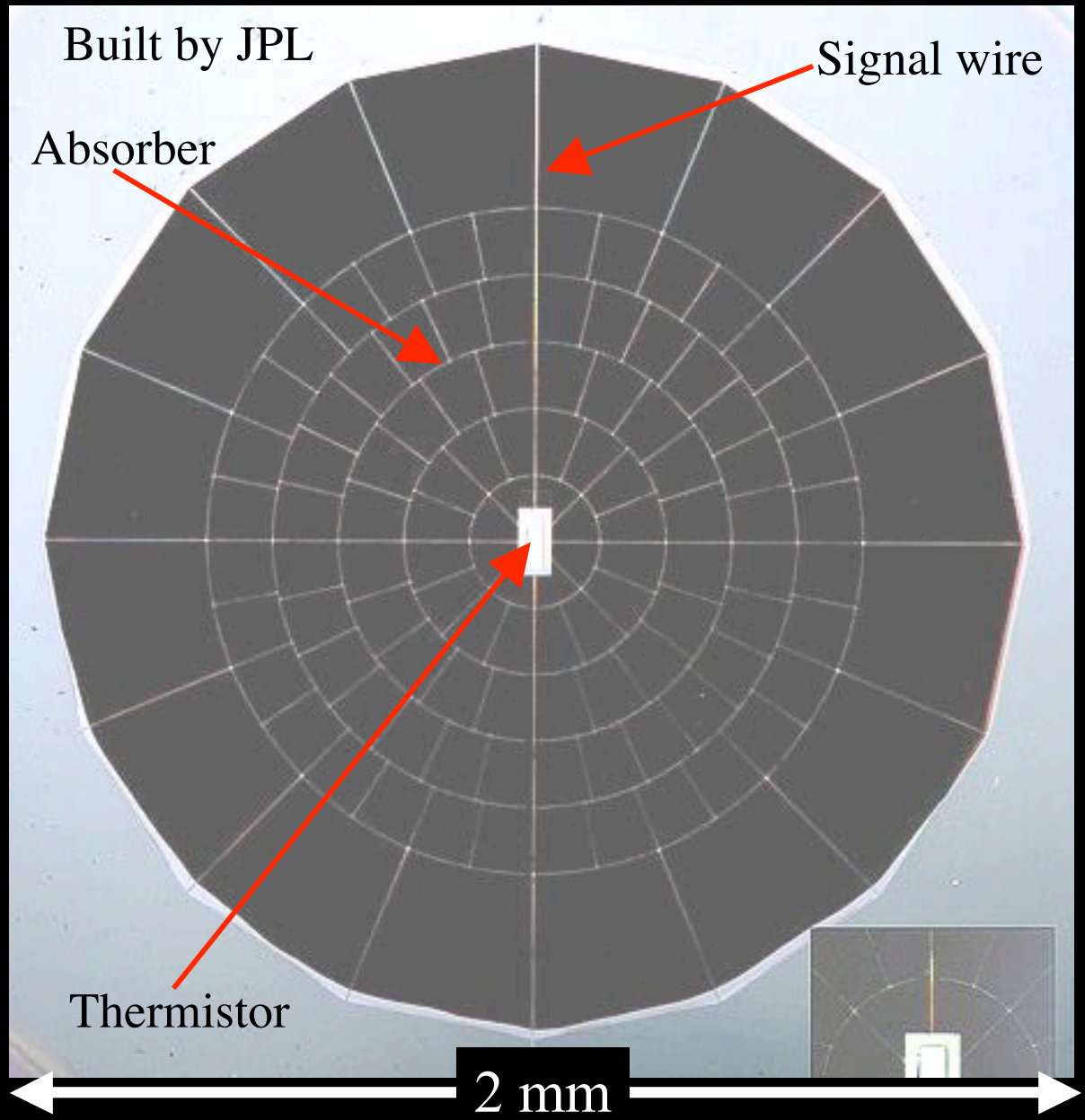
Planck-HFI



Bill Jones et al. Astro-ph/0209132

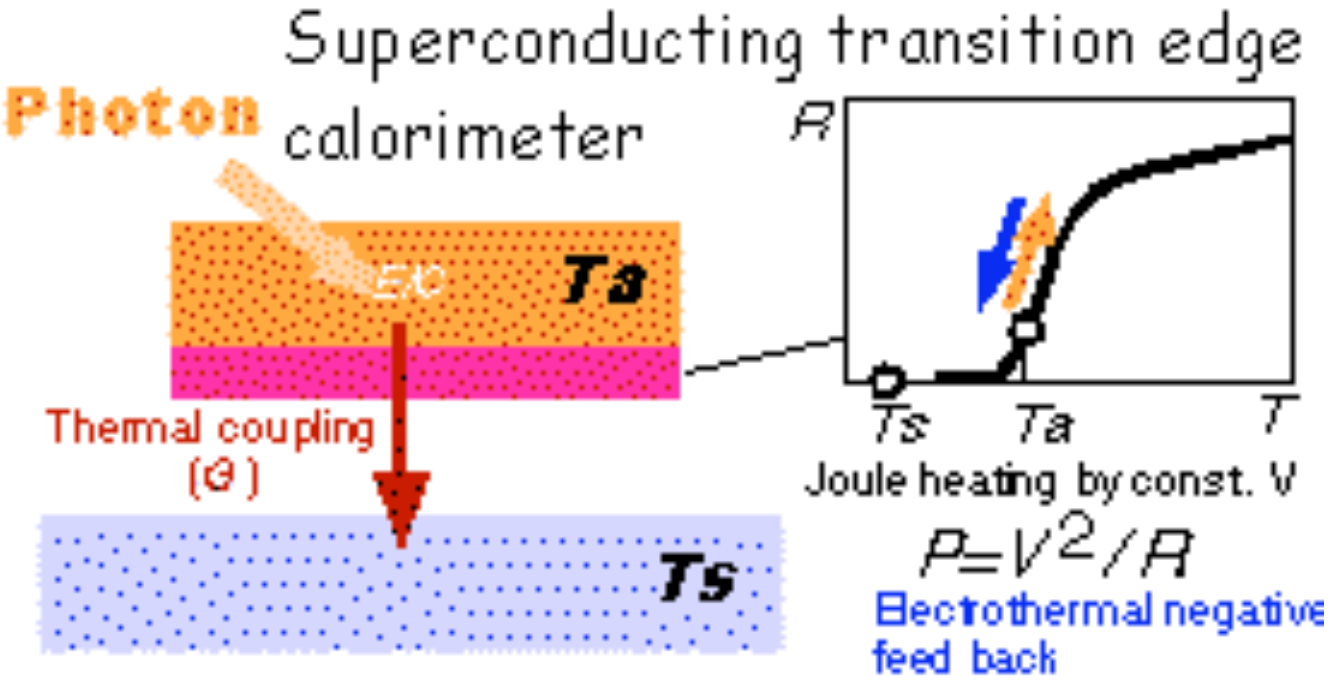
Spider-Web Bolometers

- Used in BOOMERanG, MAXIMA, ARCHEOPS, ACBAR, Planck-HFI, …
- and, in array form, in BOLOCAM (140 pixels)
- This is a composite system: the thermistor (Ge) is glued on the absorber (Si).
- Assembly basically by hand (and critical). Yeld around 70% (see e.g. BOLOCAM).
- Not suitable for thousands of elements.

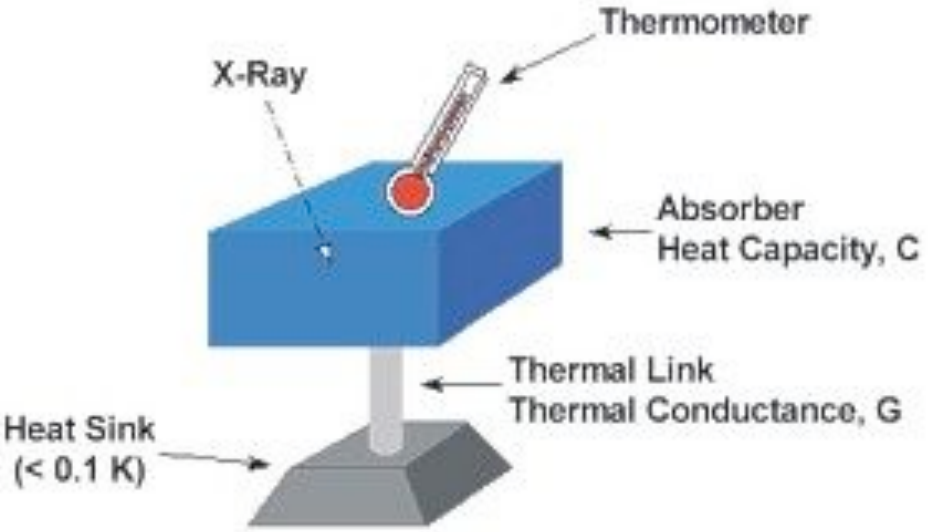


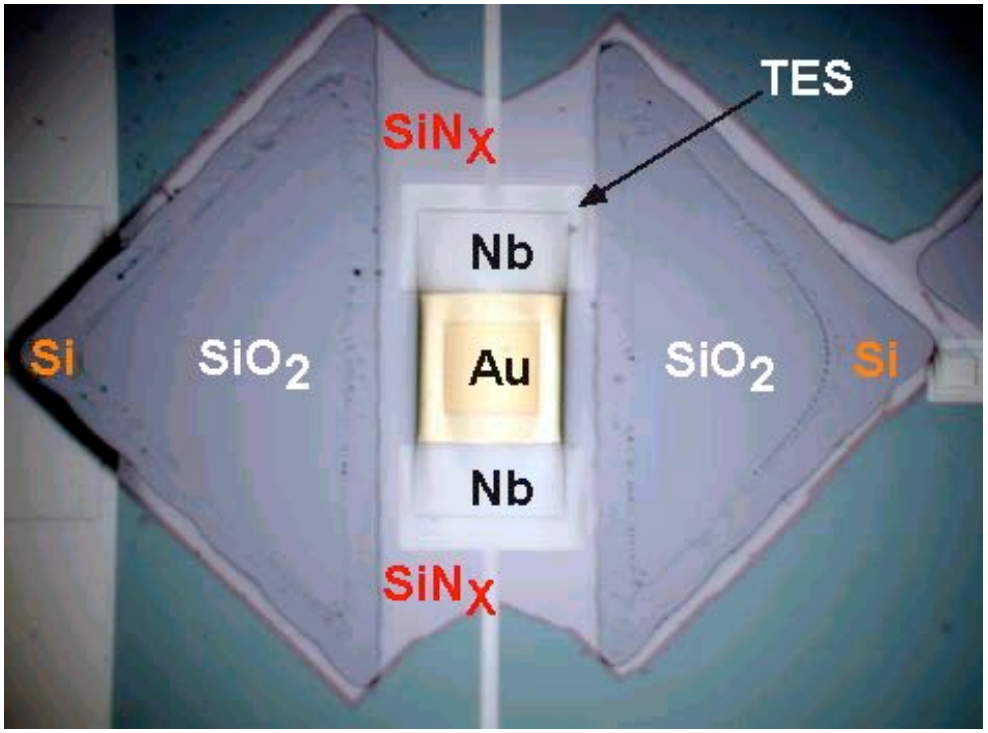
Transition Edge Sensors

- TES can be evaporated on the Si substrate.
- This makes automated construction possible, even if through a very complex process (9-10 masks, and very different materials: Si, Si Nitride, Au, Nb, …)
- Low impedance of the TES implies
  - Low microphonics
  - Voltage-biased autocalibrated detectors (responsivity 1/V in the extreme electrothermal feedback limit EETFL)
  - Improvement in time constant (in EETFL)
- but requires
  - Low impedance amplifier (SQUID amperometer almost ideal)
  - Extremely careful magnetic shielding



Baseline detectors for CMB missions and for X-ray spectroscopy missions



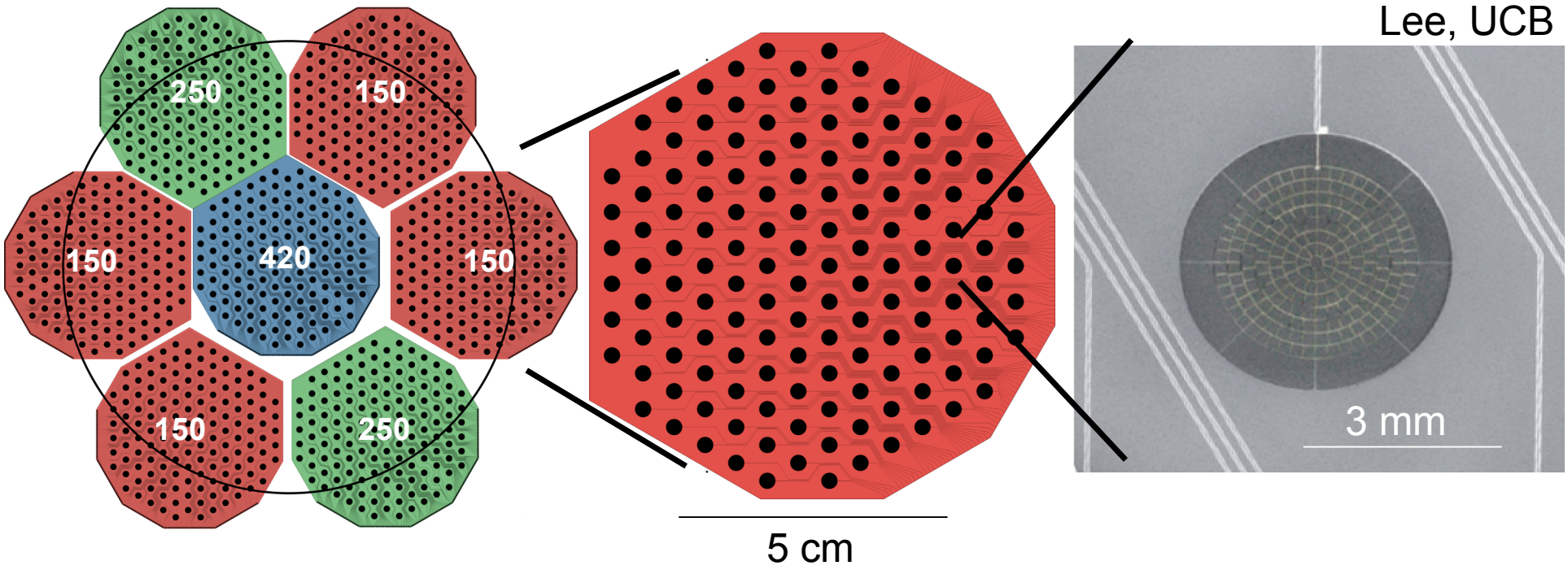


EBEX Focal Plane

738 element array

141 element hexagon

Single TES

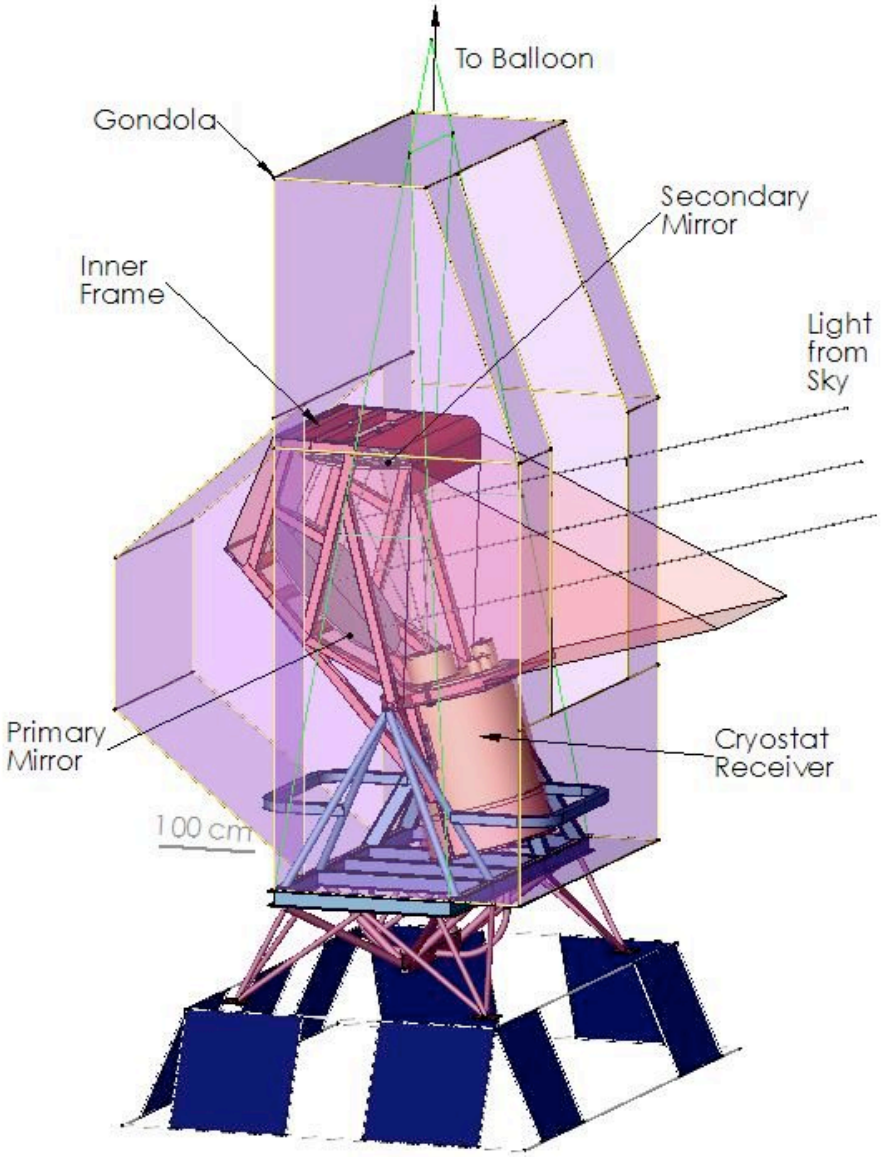


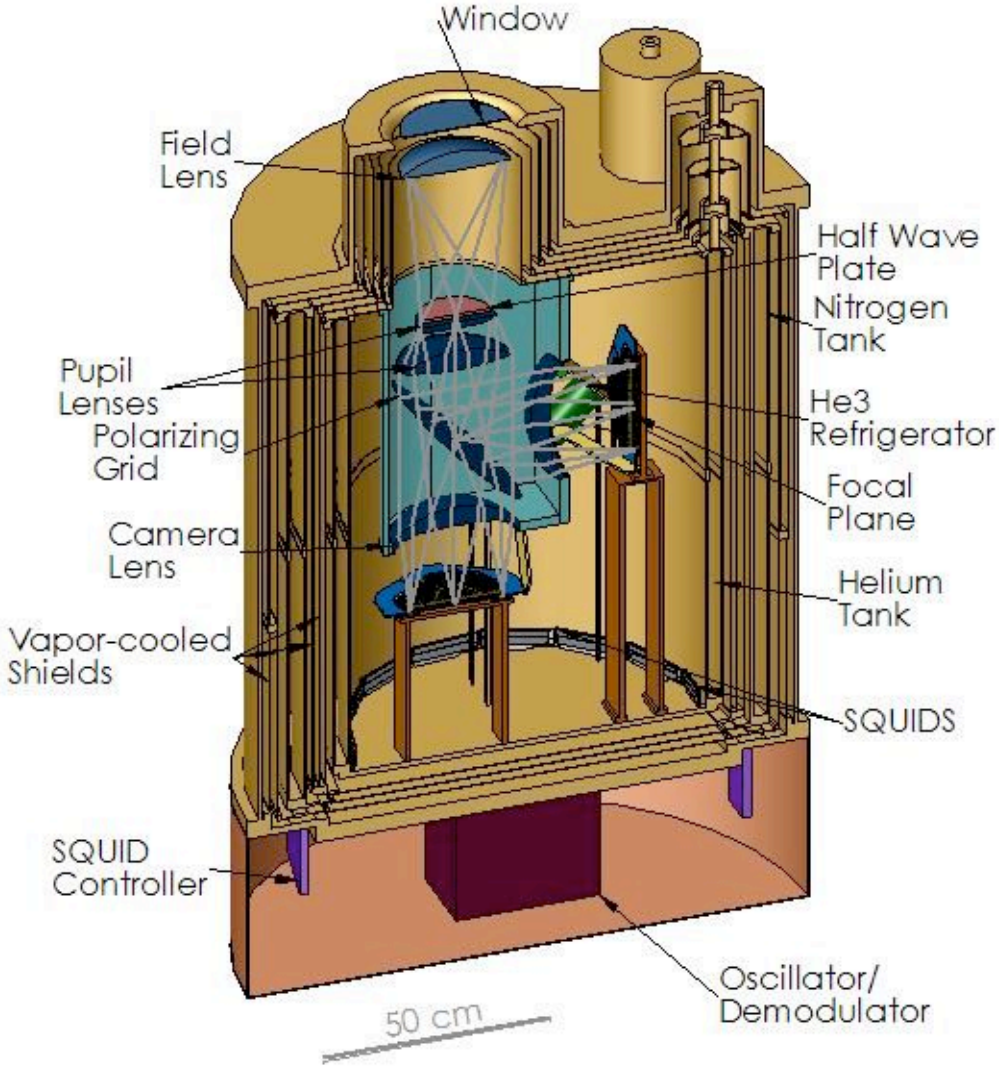
- Total of 1476 detectors
- Maintained at 0.27 K
- 3 frequency bands/focal plane

- G=15-30 pWatt/K
- NEP = 1.4e-17 (150 GHz)
- NEQ = 156 μK*rt(sec) (150 GHz)
- $\tau = 3$ msec,

Slide: Hanany

EBEX Design





Slide: Hanany

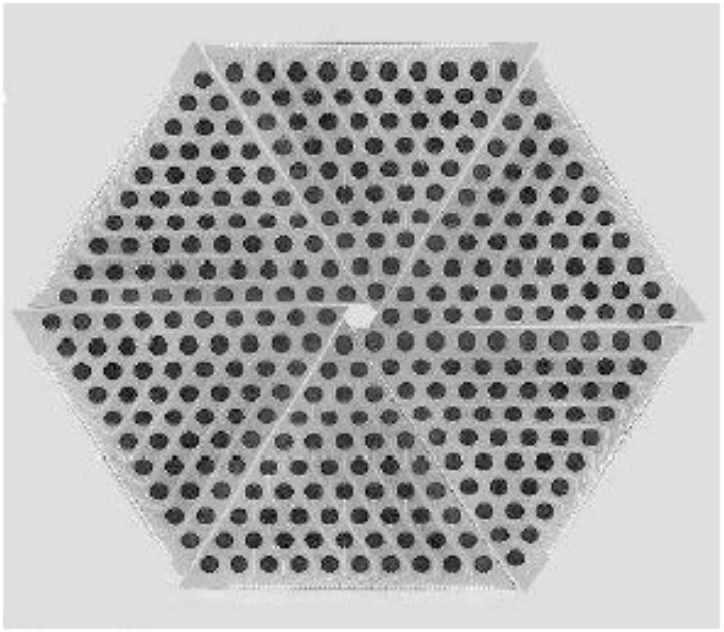


Figure 4. Montage image of a single 55-element TES spider bolometer wedge to show how an array of six identical wedges would look. The complete prototype array will have 330 bolometers and be 12 cm in diameter.

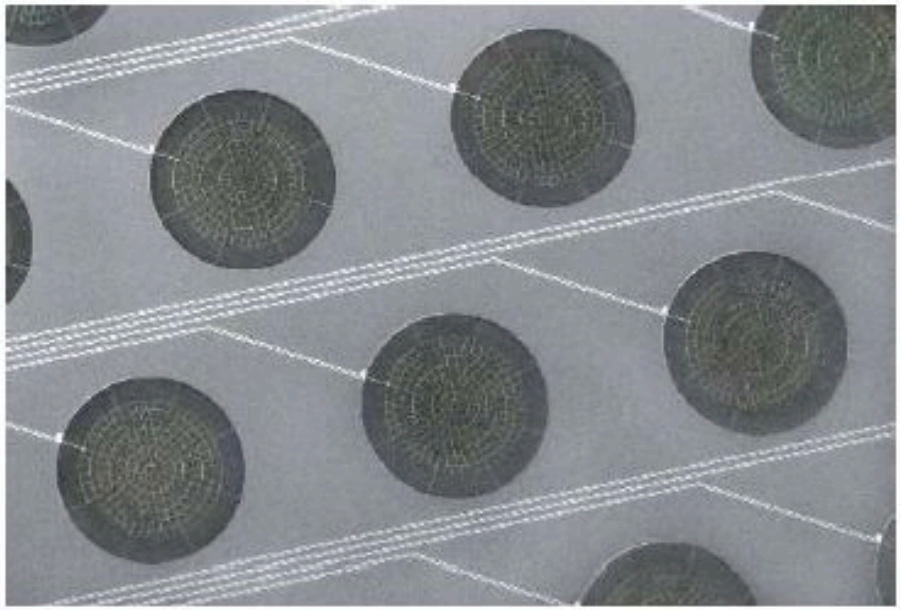


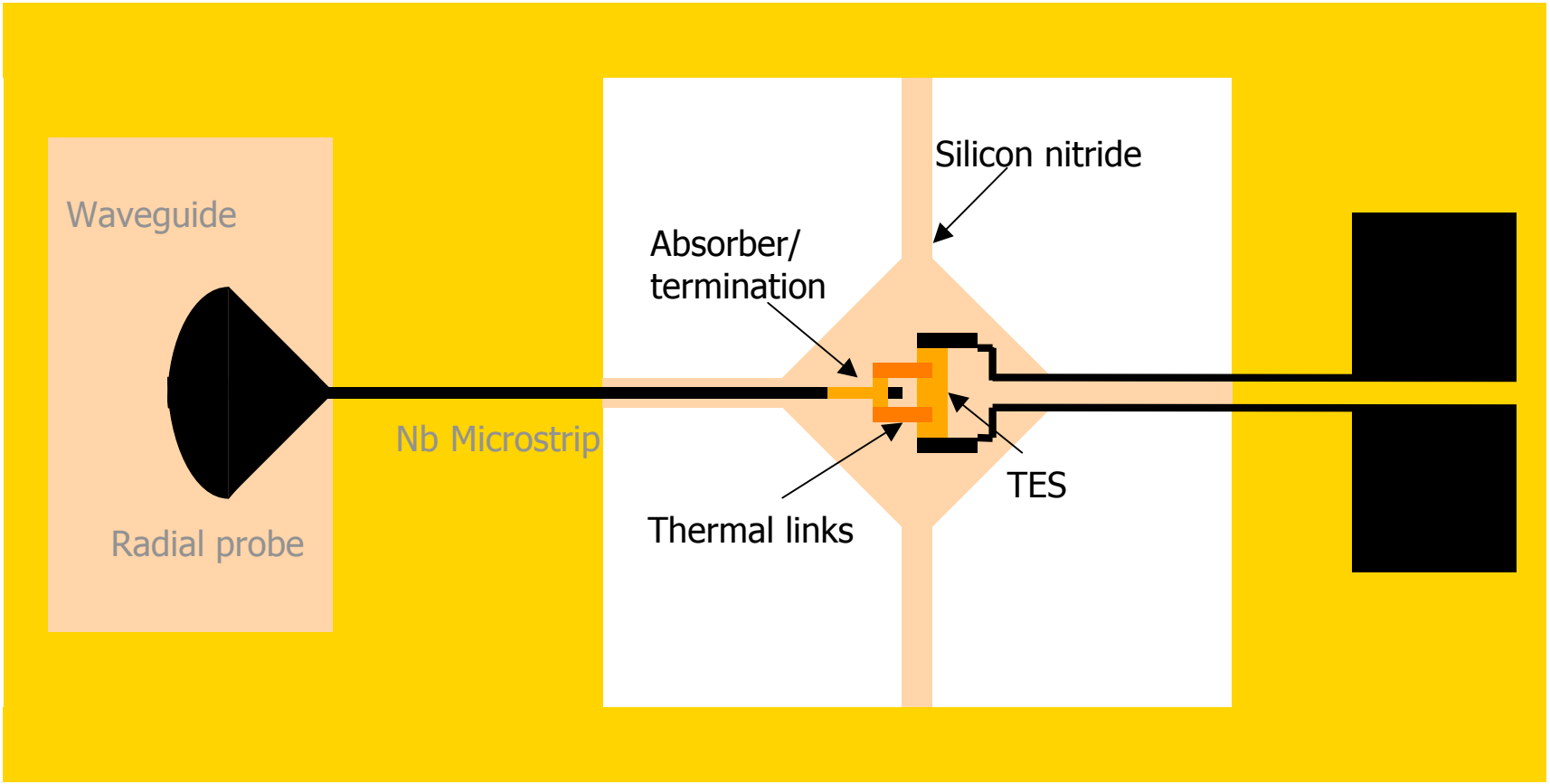
Figure 5. Close up of a 55 element bolometer wedge. The sensors are constructed with an Al/Ti proximity effect sandwich. Webs are metalized with gold for microwave absorption. Suspended spider-web absorbers are fabricated from 1 μm thick silicon nitride. The membrane is released from the front side using a gaseous xenon diflouride etch. Bolometers are 5 mm diameter with 0.5 mm long legs. Wiring layer is superconducting aluminum. This array was fabricated in the U.C. Berkeley microfabrication facility.

ν_0 (GHz)	$\Delta\nu$ (GHz)	T	P_o (pW)	G (pW/K)	NET_{RJ} ($\mu K\sqrt{s}$)	NET_{CMB} ($\mu K\sqrt{s}$)	θ_{fwhm} (arcmin)	NEFD (mJy $\sqrt{s}$)
95	24	0.964	8.1	2×10^{-10}	221	278	1.58	14.6
150	38	0.982	10.8	2×10^{-10}	150	259	1.00	9.9
219	35	0.969	11.0	2×10^{-10}	184	551	0.69	12.2
274	67	0.950	24.5	4×10^{-10}	159	774	0.56	10.5

SPT: Ruhl et al. Astro-ph/0411122

PROTOTYPE SINGLE PIXEL - 150 GHz (Mauskopf)

Schematic:



Similar to JPL design, Hunt, et al., 2002 but with waveguide coupled antenna

- TES arrays are being prepared for

– South Pole Telescope – APEX (Atacama) – ACT (Atacama) – IRAM 30m dish (Pico Veleta) – PolarBear (White Mountain)	Large Dishes
– EBEX – SPIDER – OLIMPO	Balloons

– …..

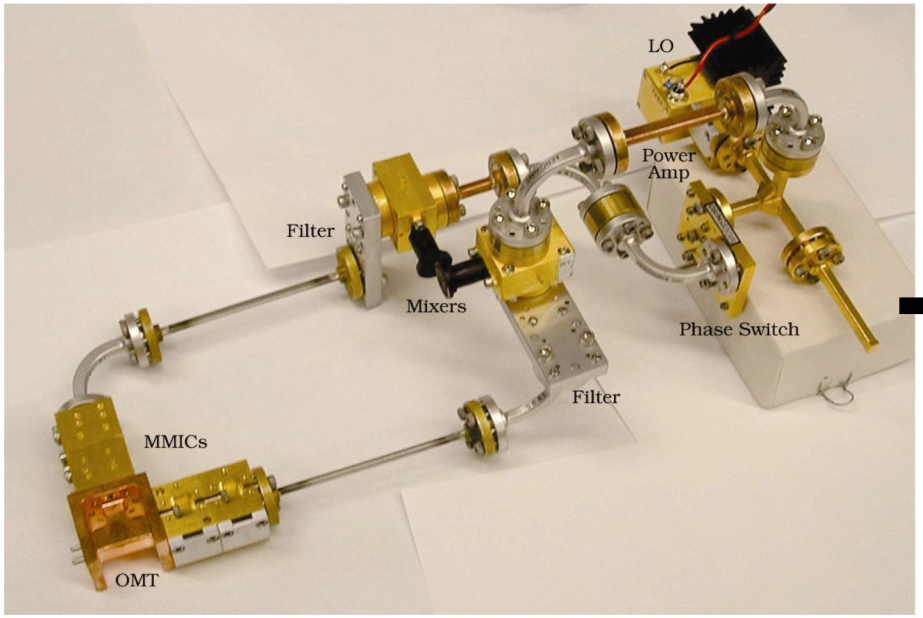
- The readout system for TESs requires SQUIDs and is very complex.

- KIDs (see e.g. Zmuidzinas, Caltech) represent a good alternative because are intrinsically multiplexable

- Cold electron bolometers (e.g. Kuzmin, Chalmers) represent a good alternative because the readout system is much simpler

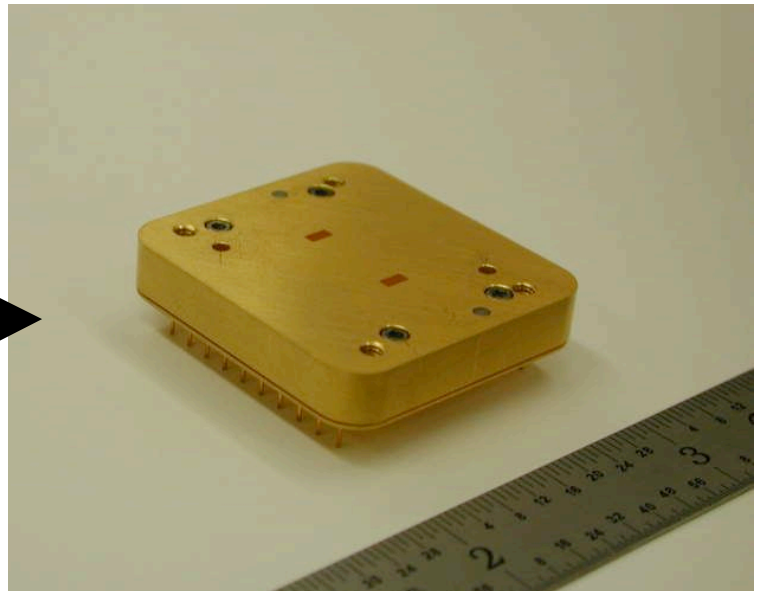
Breakthrough in MMIC Packaging makes arrays of coherent receiver possible

CAPMAP 90 GHz Polarimeter



X-Y Polarizer

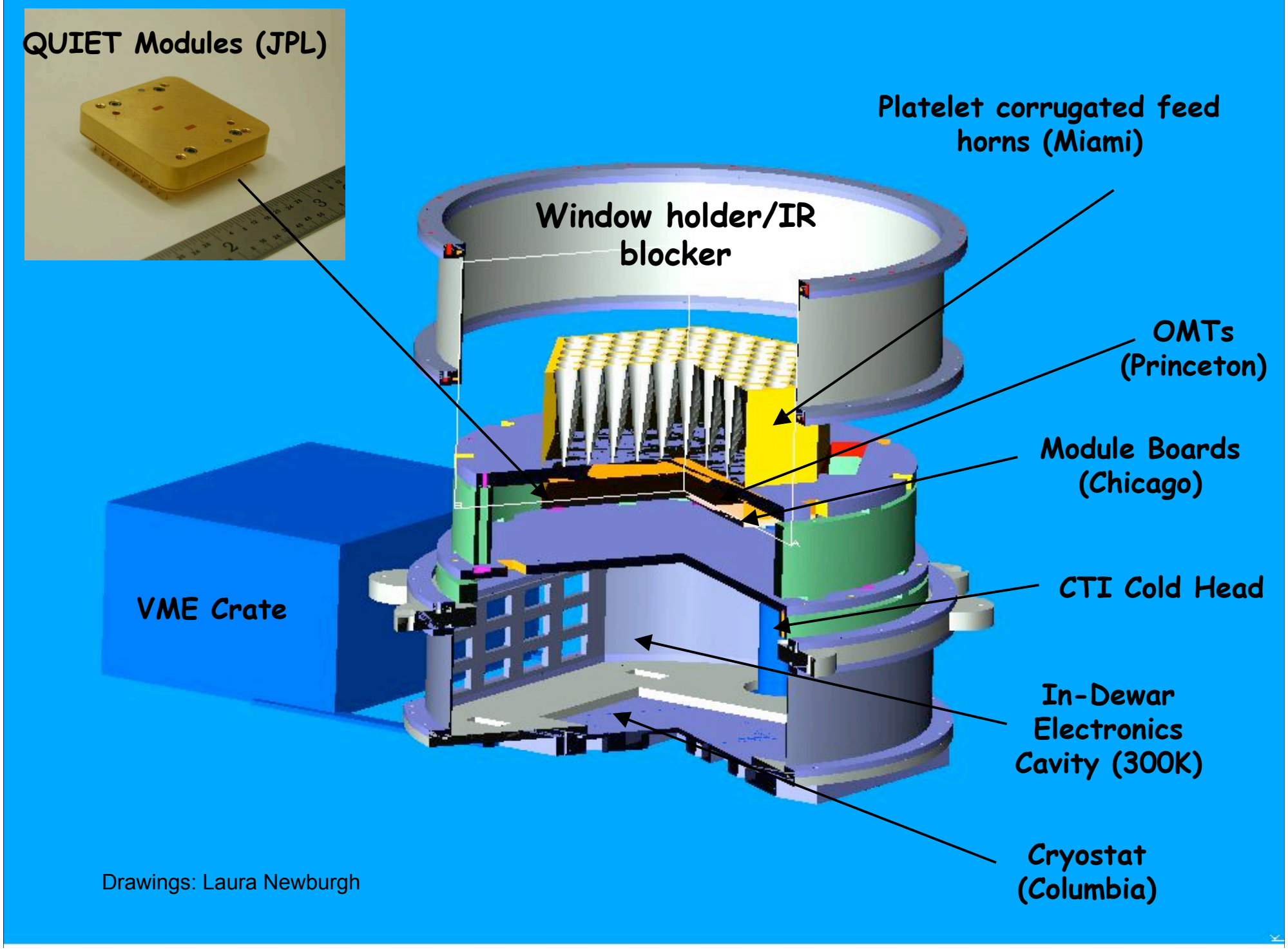
QUIET Polarimeter IC



~ $40K and 50 physicist-hours for checking, characterizing, etc

~ $500 and automated assembly and test, completely scalable

Slide: Todd Gaier


QUIET Modules (JPL)
Platelet corrugated feed horns (Miami)
Window holder/IR blocker
OMTs (Princeton)
Module Boards (Chicago)
VME Crate
CTI Cold Head
In-Dewar Electronics Cavity (300K)
Cryostat (Columbia)
Drawings: Laura Newburgh

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High Angular Resolution CMB (with spectral capabilities)

- Damping tail (parameters)
- Sunyaev-Zeldovich effect (clusters and narue of dark matter)
- Ostriker Vishniac effect (reionization)
- Metals during reionization
- ….

S-Z

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

  l = a few Mpc = 10^{25} cm

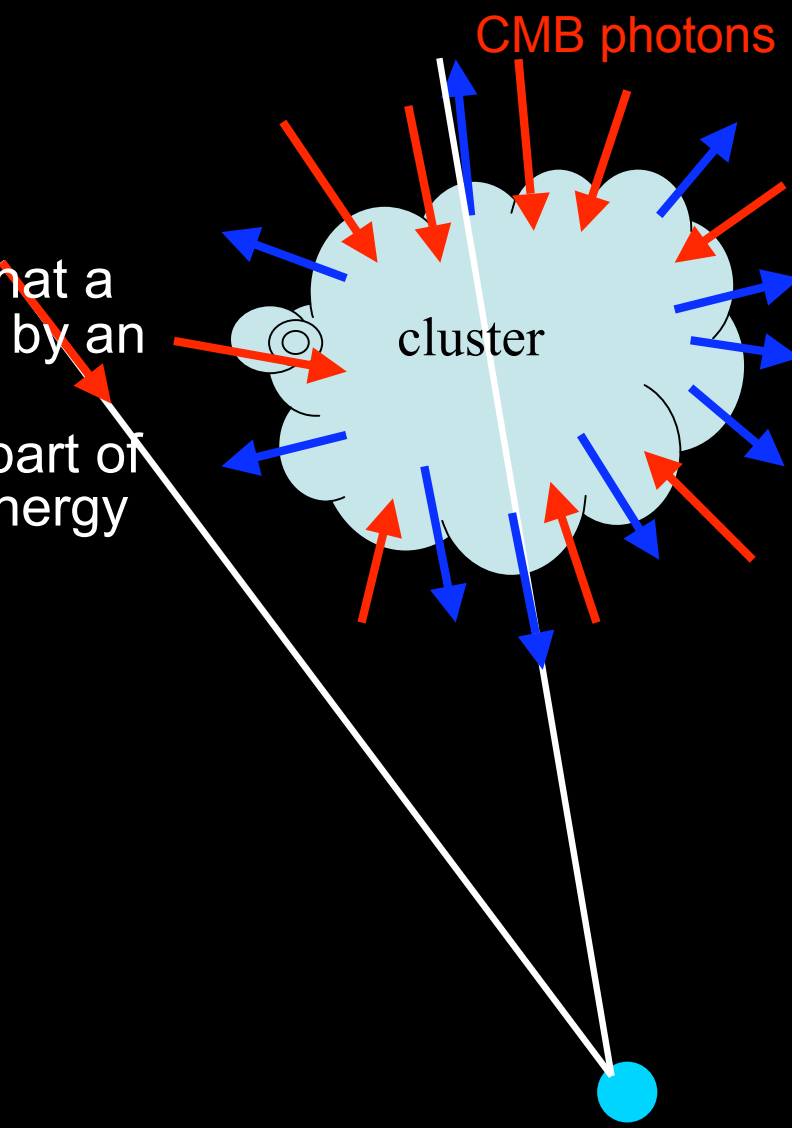
  $n < 10^{-3}$ cm^{-3}

  $\sigma = 6.65 \times 10^{-25}$ cm^2
- So $\tau = n\sigma l < 0.01$: there is a 1% likelihood that a CMB photon crossing the cluster is scattered by an electron
- Eelectron >> Ephoton, so the electron gives part of his energy to the photon. To first order, the energy gain of the photon is

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

- The resulting CMB temperature anisotropy is

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



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

S-Z

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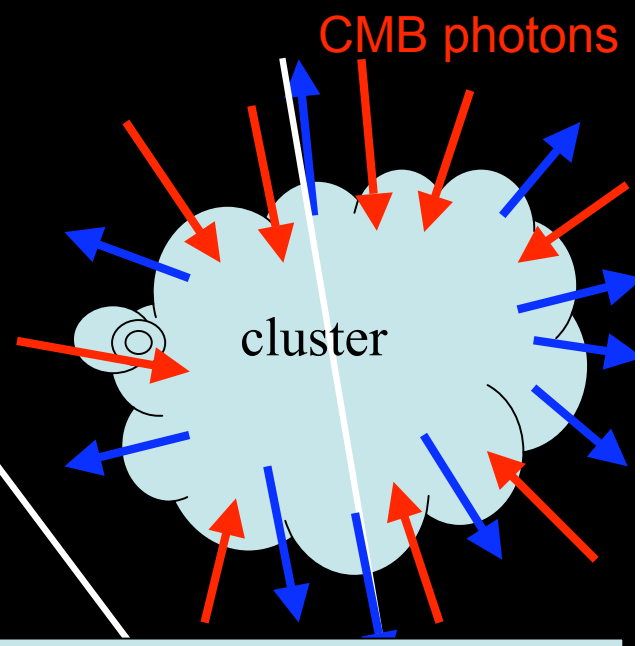
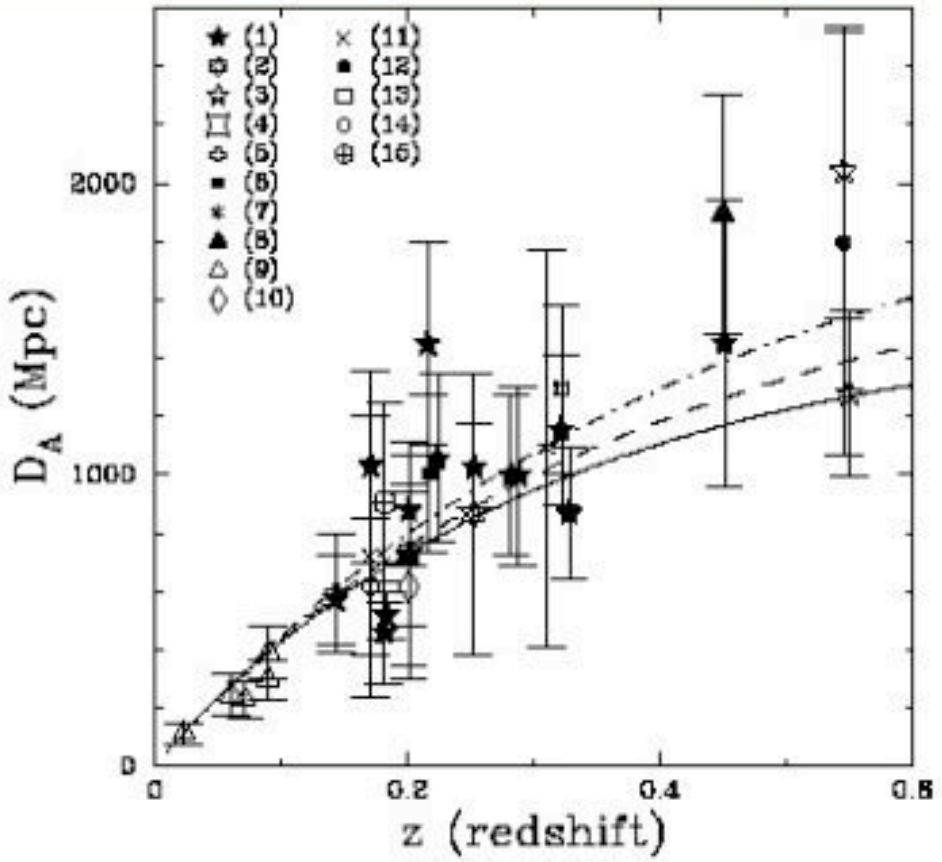


The ΔT does not depend on the distance of the cluster !

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

Carlstrom et al 2001, IAP mtg proceedings

current status of angular diameter distance determinations



H_o

Λ

Figure 11: SZE determined distances versus redshift. Also plotted is the theoretical angular diameter distance relation for three different cosmologies, assuming $H_0 = 60$ km s^{-1} Mpc^{-1}. References: (1) [97], (2) [75], (3) [87], (4) [85], (5) [90], (6) [98], (7) [77], (8) [91], (9) [99,70,59], (10) [100], (11) [101], (12) [102], (13) [76], (14) [103], and (15) [58].

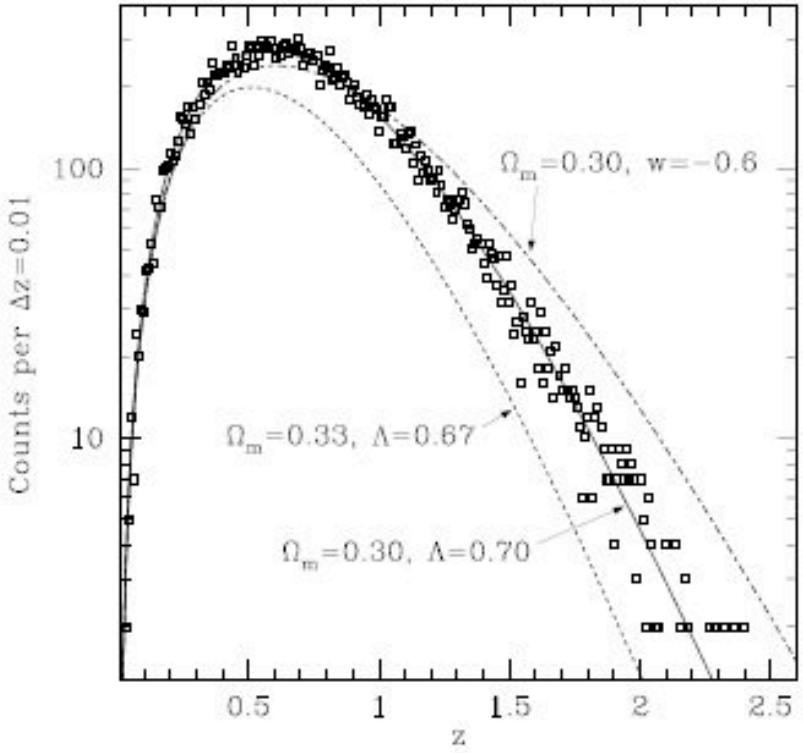


Figure 11. An illustration of the effect of cosmology on the expected number of SZE detected galaxy clusters as a function of redshift. The data points are appropriate for a 4000 square degree SPT survey with idealized sensitivity. The data points and the line passing through them were generated assuming a canonical $\Omega_M = 0.3, \Omega_\Lambda = 0.7, \sigma_8 = 1$ cosmology. The other two lines show the large effect in the expected cluster counts due to slight changes in the cosmology. The value of σ_8 was adjusted to give the same normalization for the local cluster abundance in each model. The bottom curve is for a model with more matter and correspondingly less dark energy. The top curve at shows the effect of only a change in the equation of state of the dark energy in the canonical model. (Figure courtesy of G. Holder)

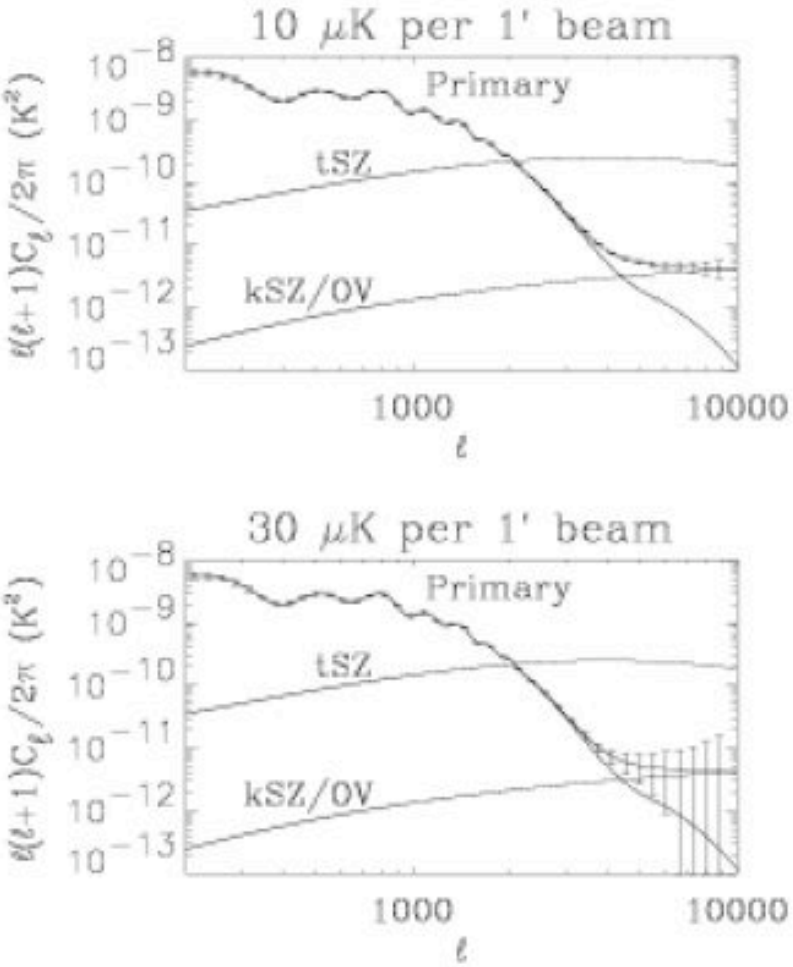
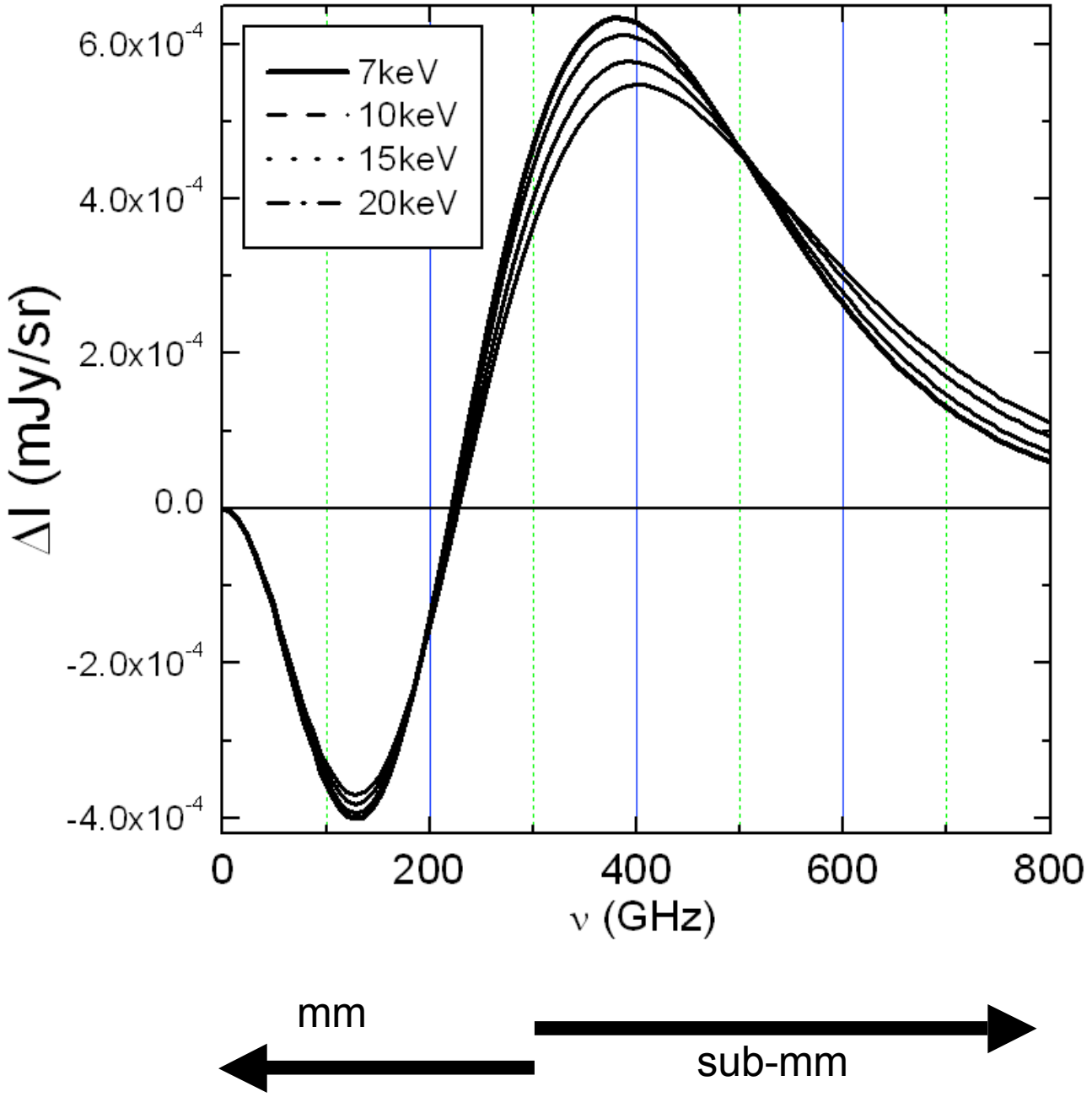
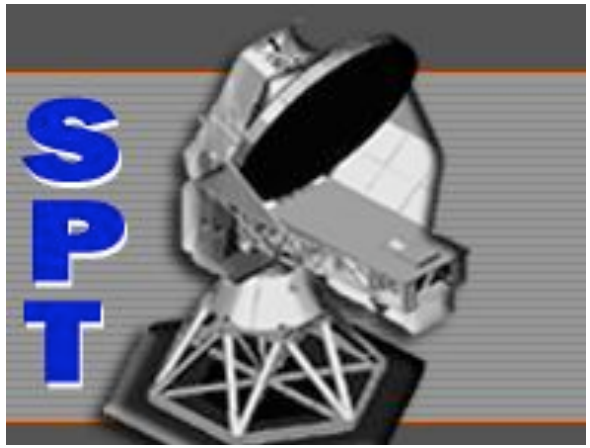


Figure 12. An illustration of the potential of the SPT to measure fine-scale CMB anisotropy. The two panels show statistical errors on the high-ℓ CMB power spectrum from 500 deg^2 of sky measured at two different levels of noise per 1′ beam. Both panels assume perfect subtraction of the thermal SZE signal and other astrophysical contaminants; achieving the required accuracy in this subtraction will be a significant challenge. (Spectra courtesy of W. Hu.)


7keV
10keV
15keV
20keV
6.0x10-4
4.0x10-4
2.0x10-4
0.0
-2.0x10-4
-4.0x10-4
ΔI (mJy/sr)
0
200
400
600
800
ν (GHz)
mm
sub-mm



10 m diameter, f/07 primary
90-270 GHz
arcmin resolution
1000 detectors

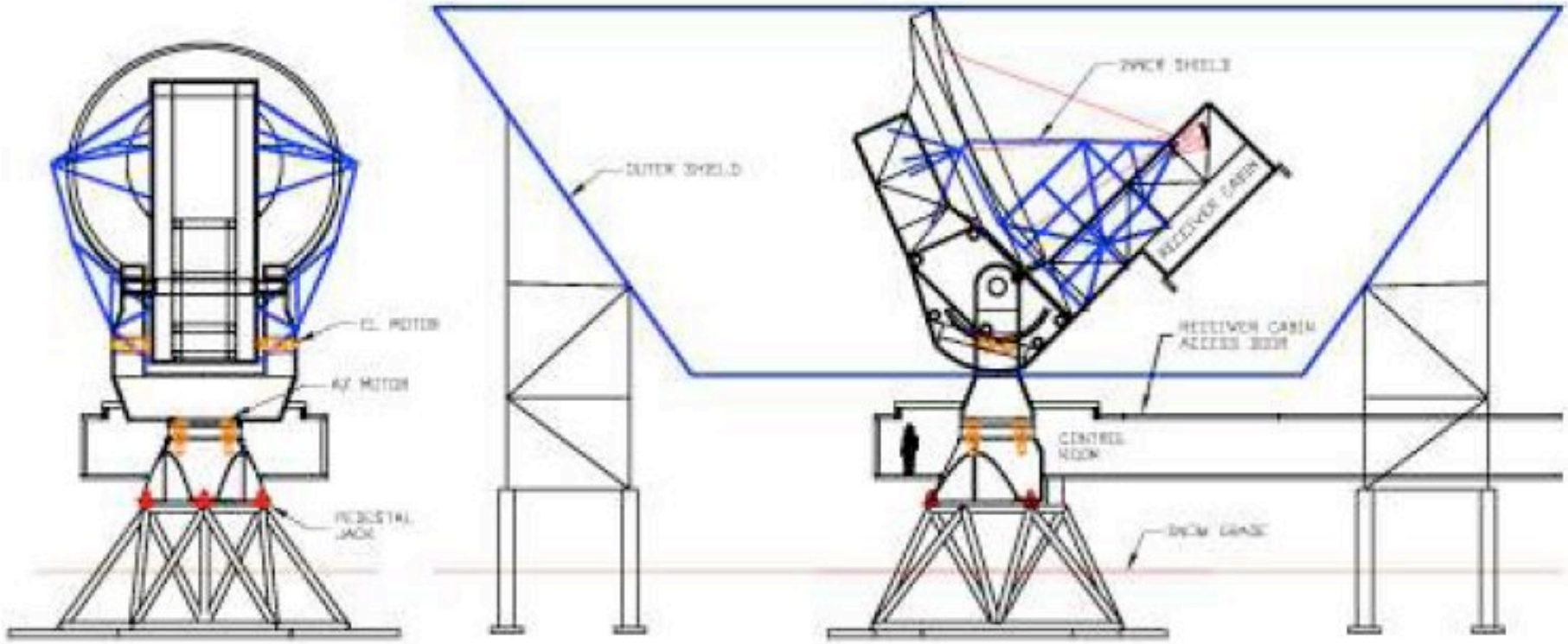
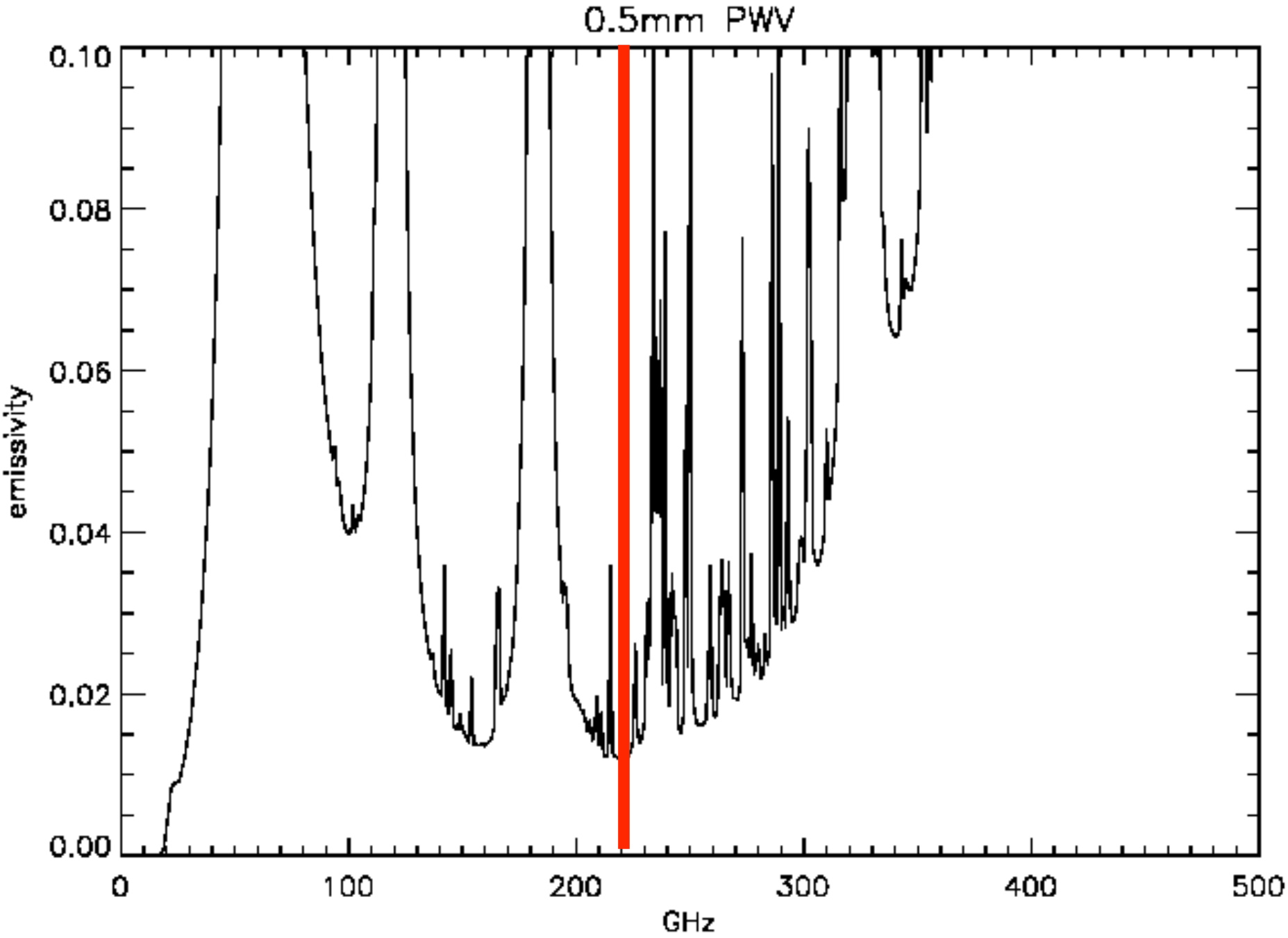


Figure 1. (Left) rear view of the SPT at elevation 0°, and (right) side view at elevation 45° with the outer ground shield.

SPT: Ruhl et al. Astro-ph/0411122


0.5mm PWV
0.10
0.08
0.06
0.04
0.02
0.00
emissivity
0
100
200
300
400
500
GHz

(http://oberon.roma1.infn.it/olimpo)

OLIMPO

An arcmin-resolution survey of the sky at mm and sub-mm wavelengths

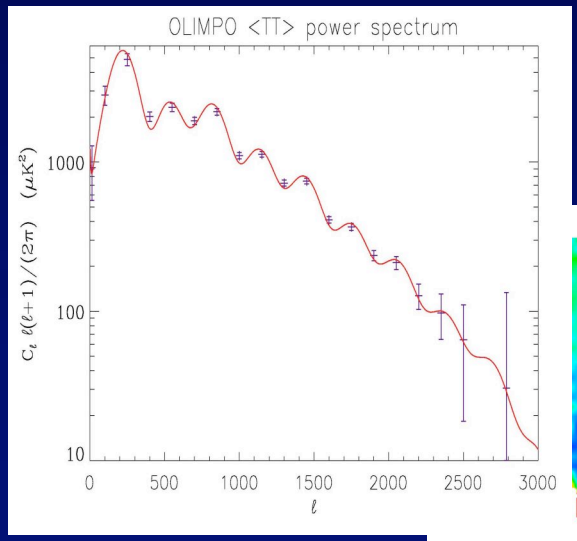
Silvia Masi
Dipartimento di Fisica
La Sapienza, Roma

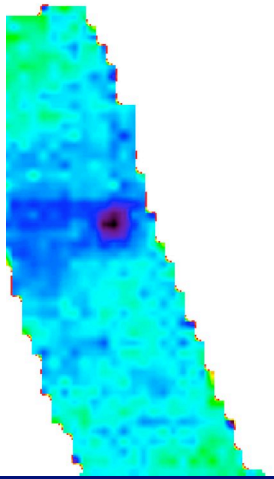
and

the OLIMPO team

Large Bolometer Arrays

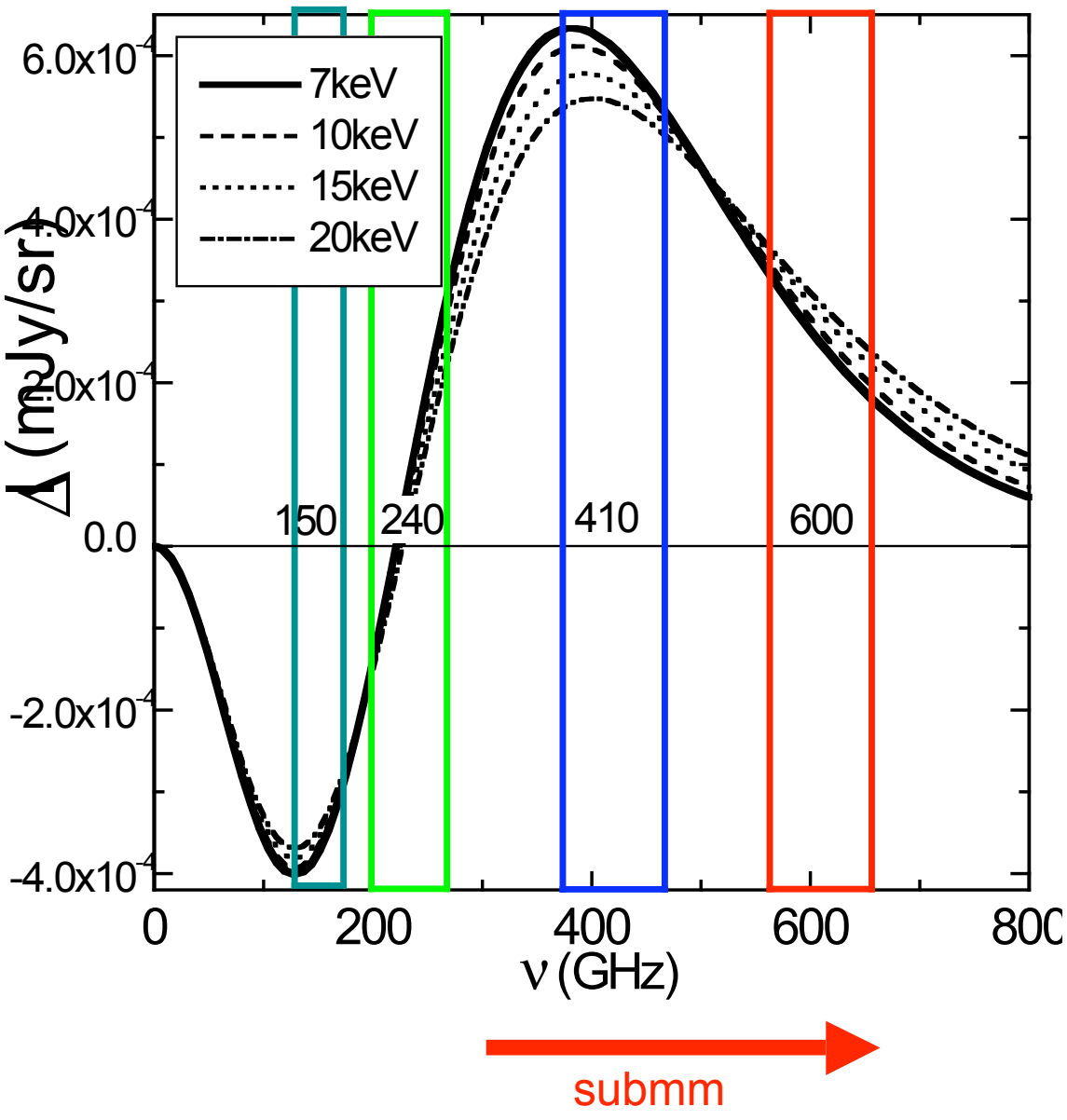
- >400 TES bolometers for the OLIMPO balloon telescope devoted to SZ and CMB anisotropy (Silvia Masi, Roma)





The uniqueness of OLIMPO

- OLIMPO measures in 4 frequency bands simultaneously. These bands optimally sample the spectrum of the SZ effect.
- This allows us to clean the signal from any dust and CMB contamination, and even to measure T_e by means of the relativistic corrections.



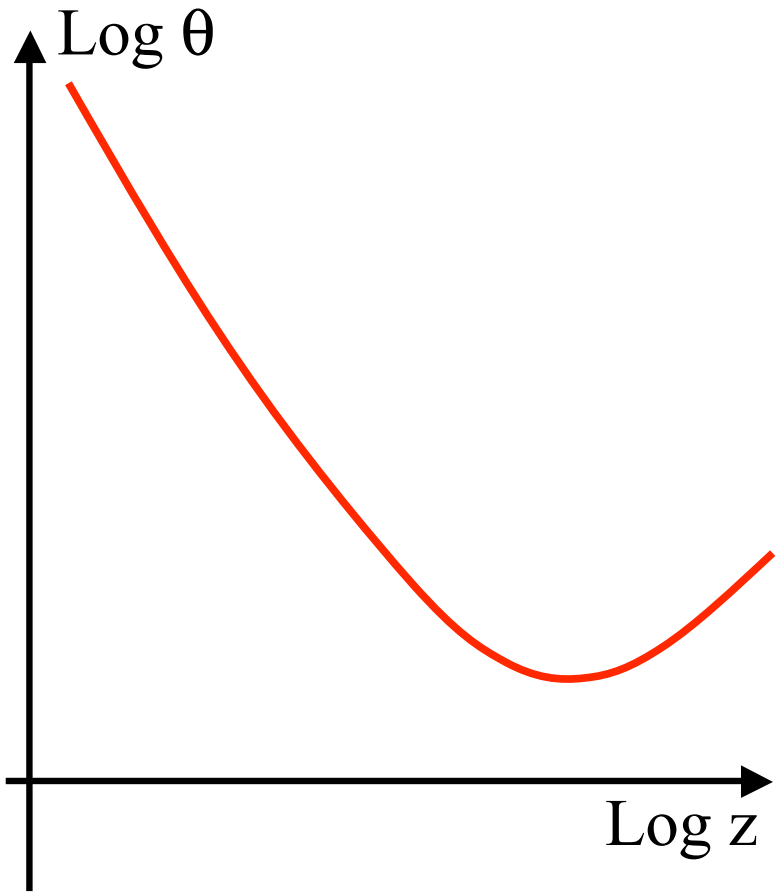
Detailed simulations show that:

- For a
  - $Y=10^{-5}$ cluster,
  - in a dust optical depth of 10^{-5} @ 1 mm,
  - In presence of a 100 μK CMB anisotropy
- In 2 hours of integration over 1 square degree of sky centered on the cluster
  - Y can be determined to $\pm 10^{-6}$,
  - ΔT_{CMB} can be measured to $\pm$10μK
  - T_e can be measured to $\pm$3keV
- OLIMPO WILL MAP 40 OF THESE CLUSTERS, IN A SINGLE, LONG DURATION, POLAR FLIGHT

Angular Diameter Distance

$$D_A = \frac{1}{(1+z)} \frac{c}{H_o} \int_{\frac{1}{(1+z)}}^{1} \frac{d\hat{a}}{\hat{a}^2 [\Omega_{Ro}\hat{a}^{-4} + \Omega_{Mo}\hat{a}^{-3} + \Omega_{\Lambda} + (1-\Omega_o)\hat{a}^{-2}]^{1/2}}$$

- For a 1 Mpc structure, the minimum angular size is 3.8 arcmin
- @ z of the order of 1

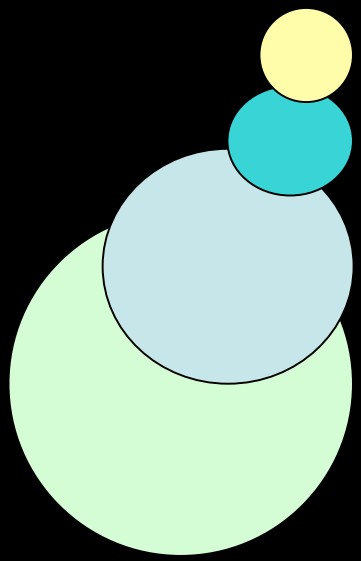


Dynamically Relaxed Clusters

X-ray Images (Chandra)

D = 1 GLy 3.5 GLy 6.7 GLy

OLIMPO

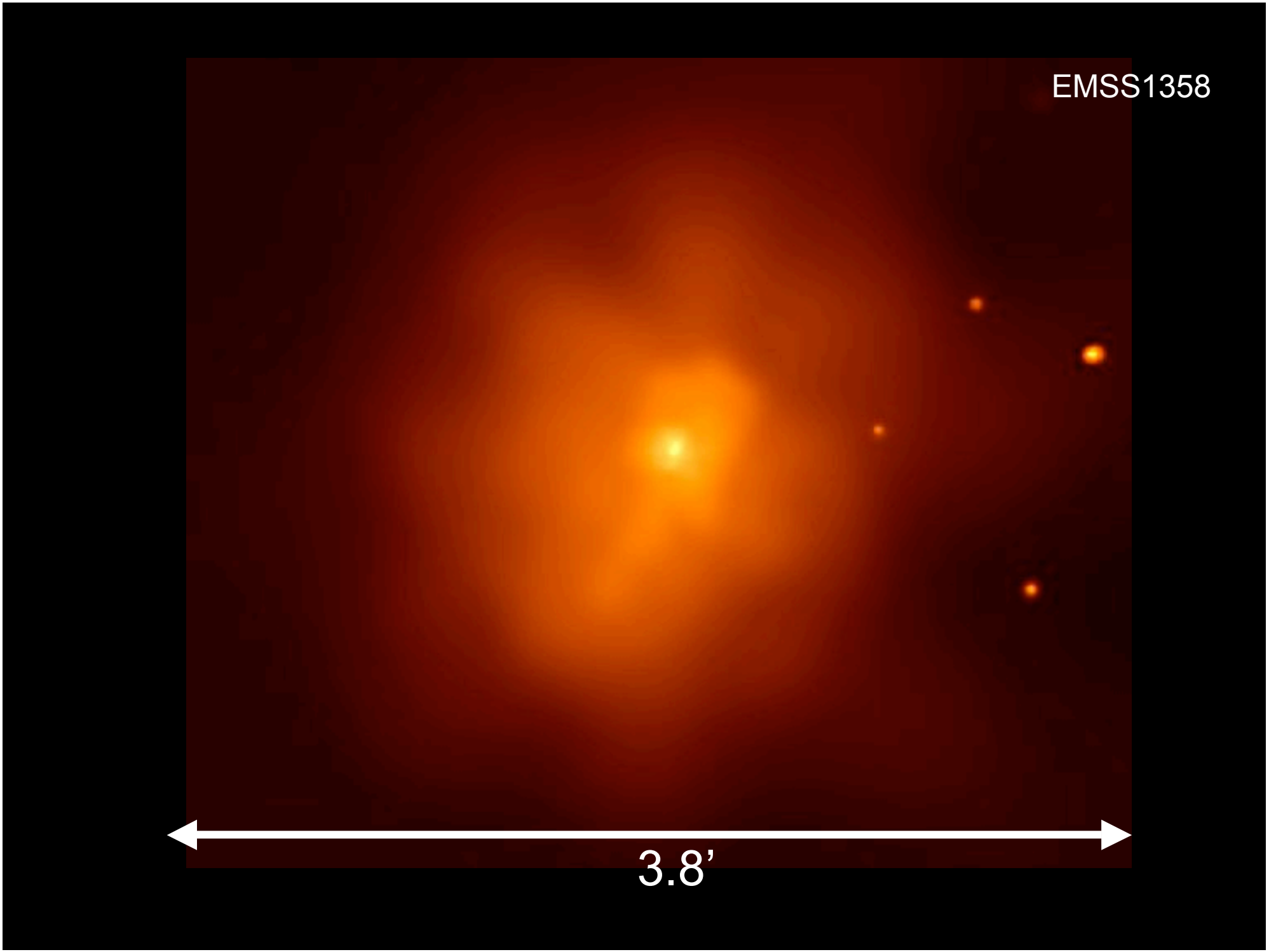


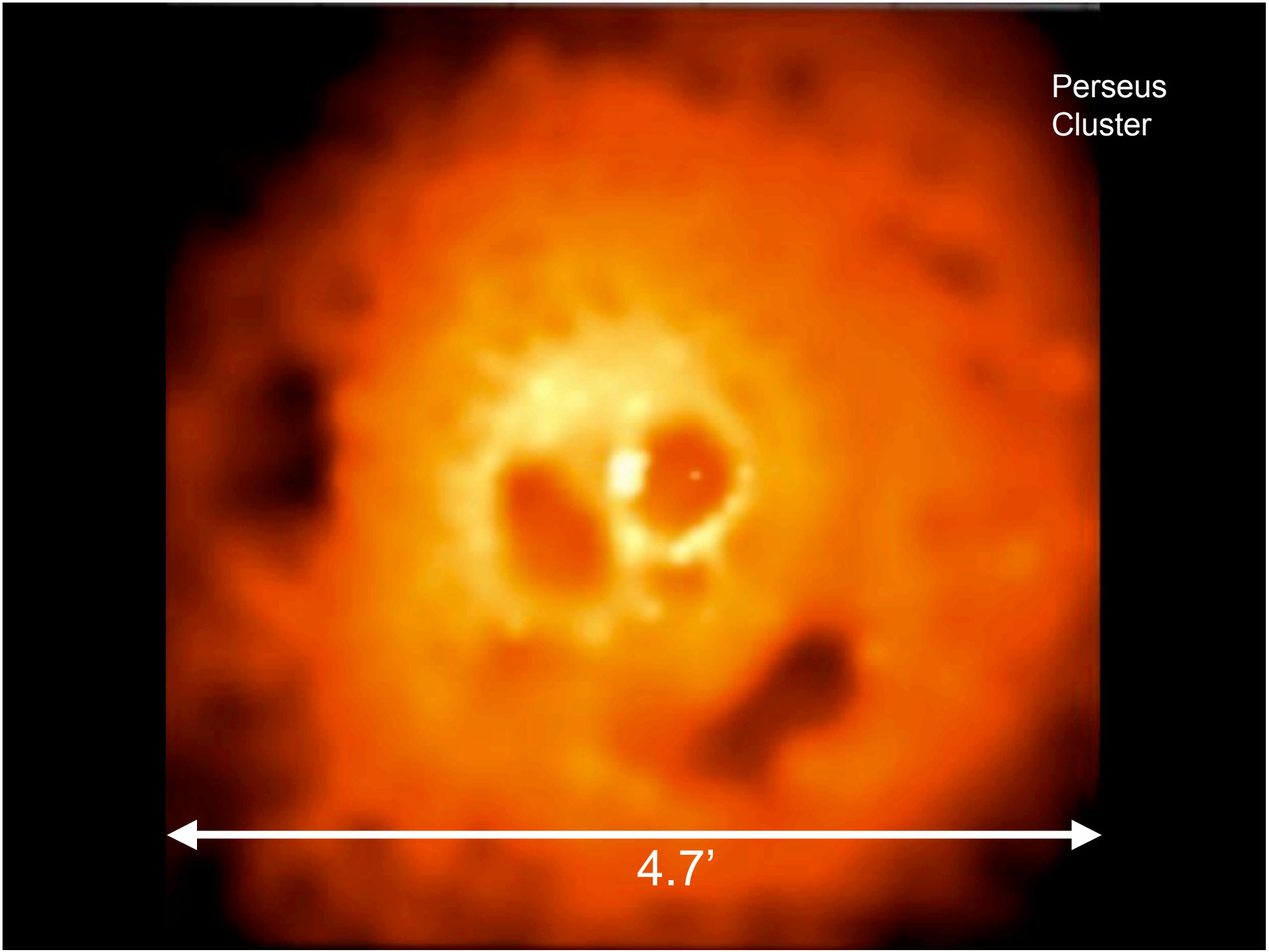
0.9’ FWHM beam (λ = 0.54 mm D = 2600 mm)

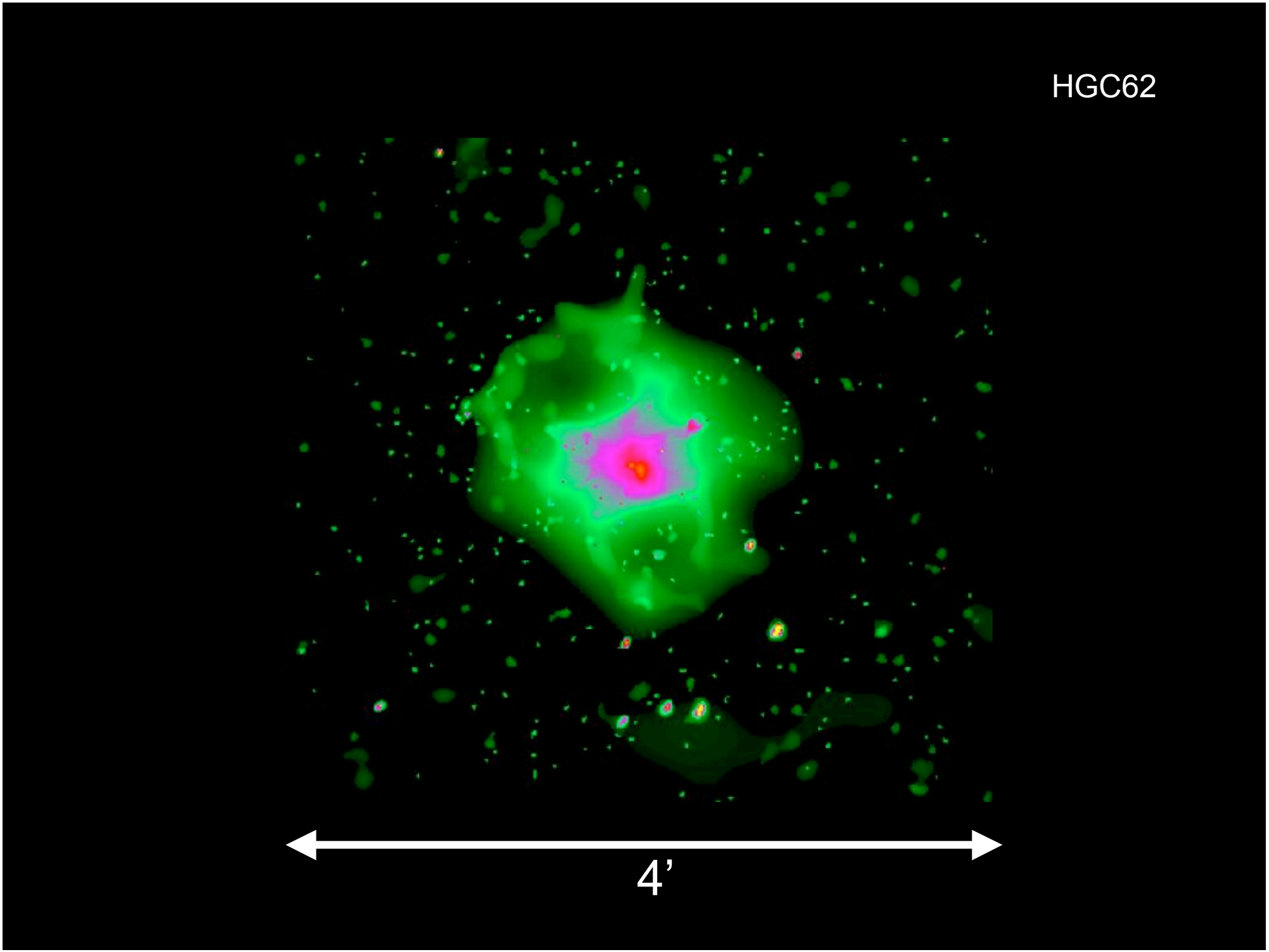
1.1’ FWHM beam (λ = 0.73 mm D = 2600 mm)

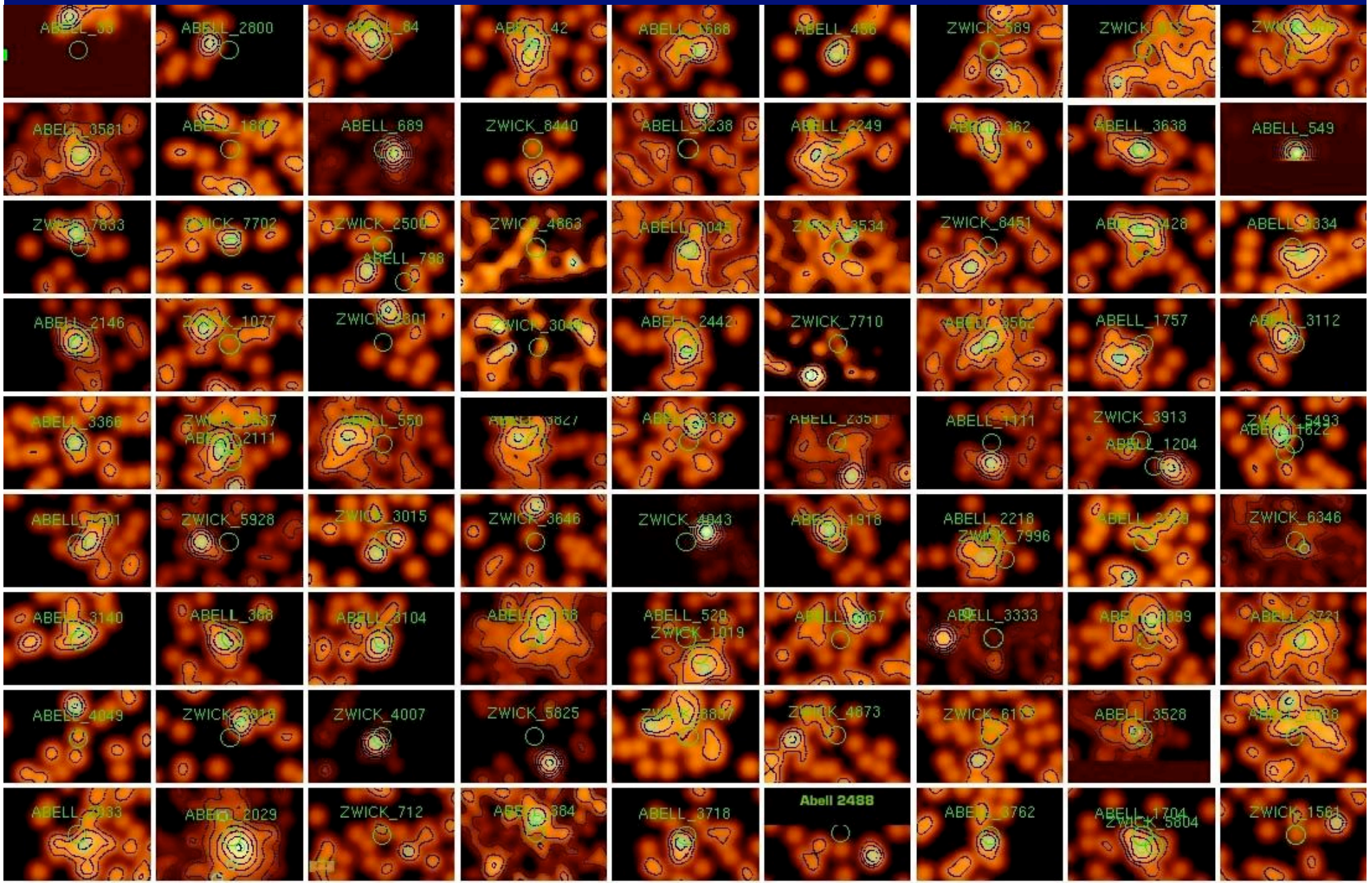
2.2’ FWHM beam (λ = 1.4 mm D = 2600 mm)

3.1’ FWHM beam (λ = 2.0 mm D = 2600 mm)


EMSS1358
3.8’


Perseus
Cluster
4.7’


HGC62
4’


ABELL_2800
ABELL_689
ZWICK_8440
ABELL_549
ZWICK_7702
ZWICK_2500
ABELL_798
ZWICK_8451
ABELL_2146
ZWICK_7710
ABELL_1757
ABELL_3366
ZWICK_3913
ABELL_1204
ZWICK_5928
ZWICK_6346
ABELL_368
ABELL_4049
ZWICK_4007
ZWICK_5825
ABELL_3528
ABELL_2029
ZWICK_712
ABELL_3718
Abell 2488
ZWICK_5804

- A driver for an even larger telescope !!!
- Other driver : (astro-ph/0309005)

Highlights of Astronomy
ASP Conference Series, Vol. 13, 2003
O. Engvold & M.G. Burton

The Case for a 30m Diameter Submillimeter Telescope on the Antarctic Plateau

Antony A. Stark

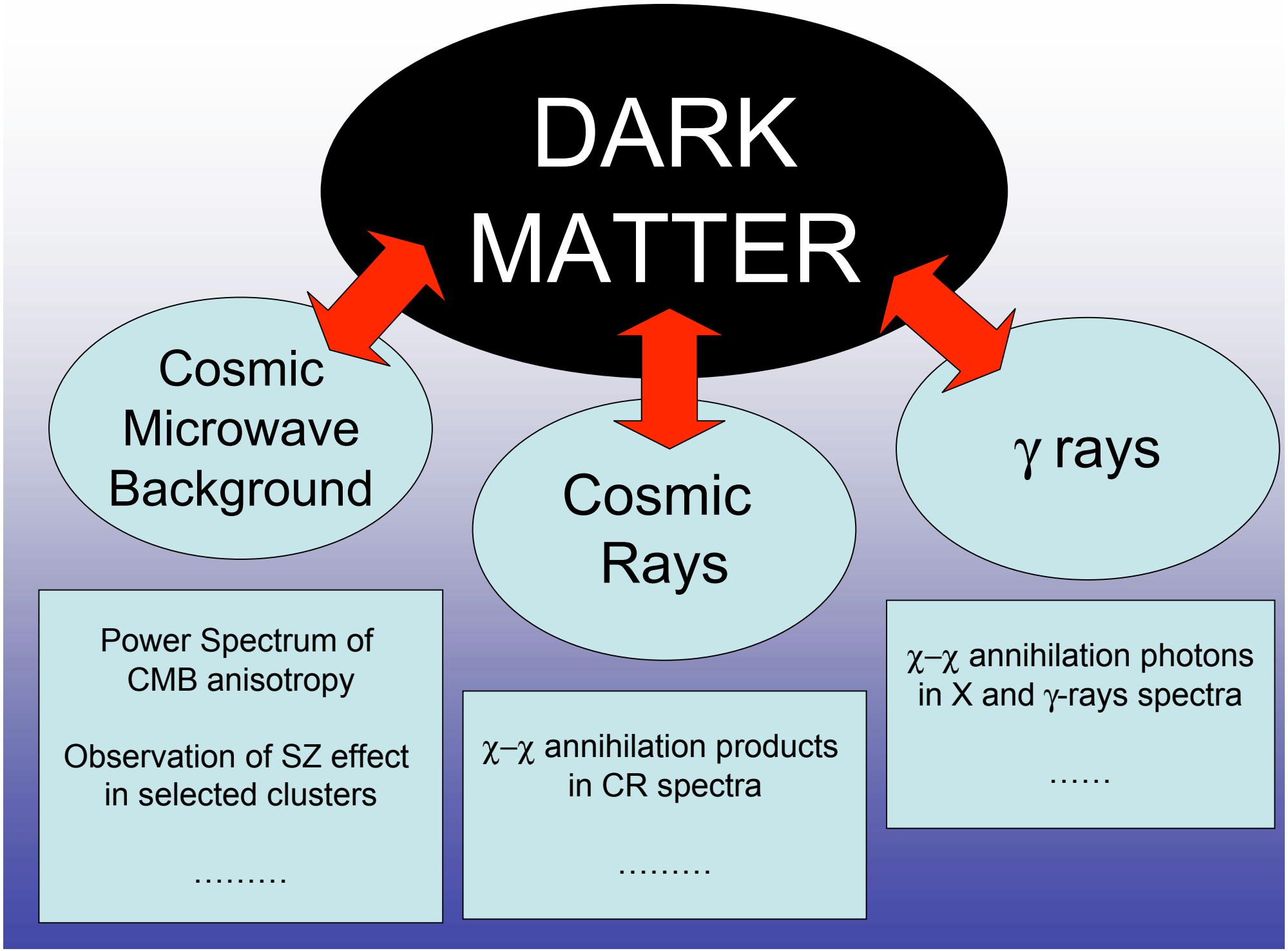
Smithsonian Astrophysical Observatory, 60 Garden St. MS 12, Cambridge, MA 02138 USA

Abstract. A large single-dish submillimeter-wave telescope equipped with a focal plane array containing $\sim 10^4$ bolometers and costing about \$120M could locate most protogalaxies in the southern sky within a year of operation.

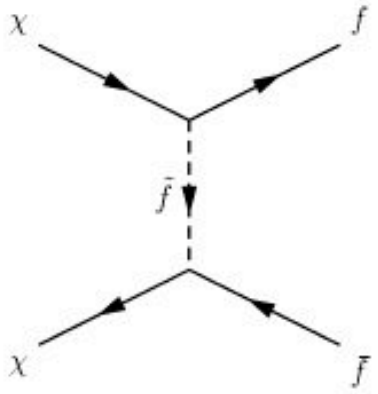
May be for dome-C or dome-A ?

- Third driver : Study of the nature of dark matter

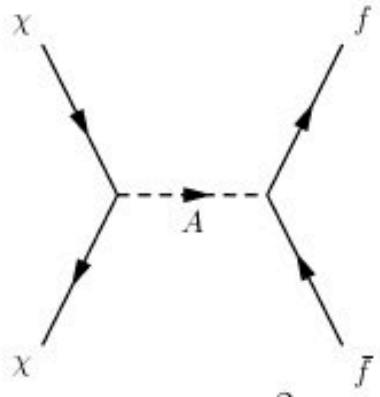

Dome-C Antarctica (France + Italy)


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

Dark Matter Annihilation Products

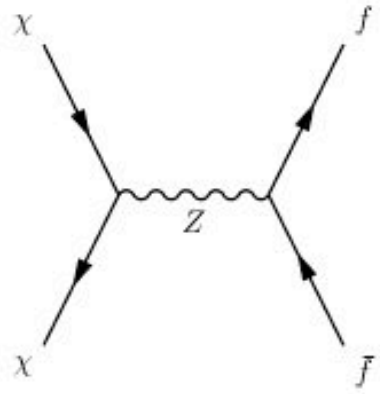


$$\propto \frac{m_\chi \cdot m_f}{m_{\tilde{f}}^2}$$

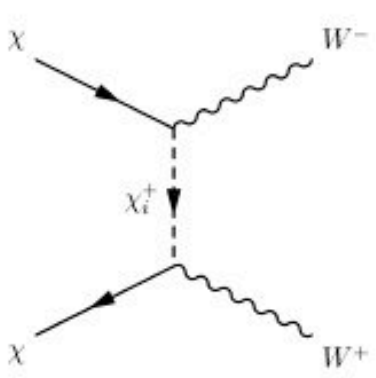


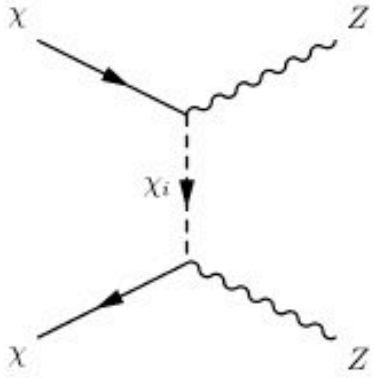
$$\propto \frac{\tan\beta \cdot m_{f_d}}{m_W}\left(\frac{m_\chi}{m_A}\right)^2 N_1 N_{3(4)}$$

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



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





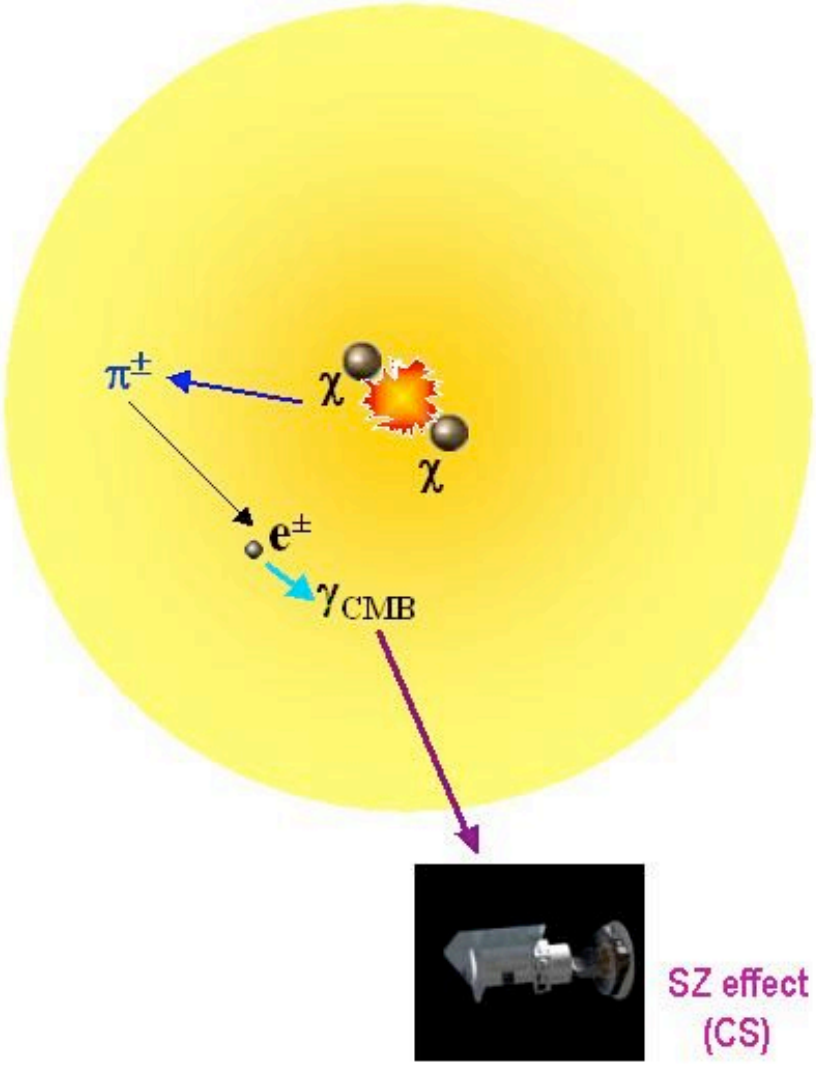
$$\propto \frac{1}{1+(m_{\chi_i^+}/m_\chi)^2-(m_W/m_\chi)^2}$$

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

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)

SZ effect from $\chi\chi$ annihilation



What is Dark Matter ?

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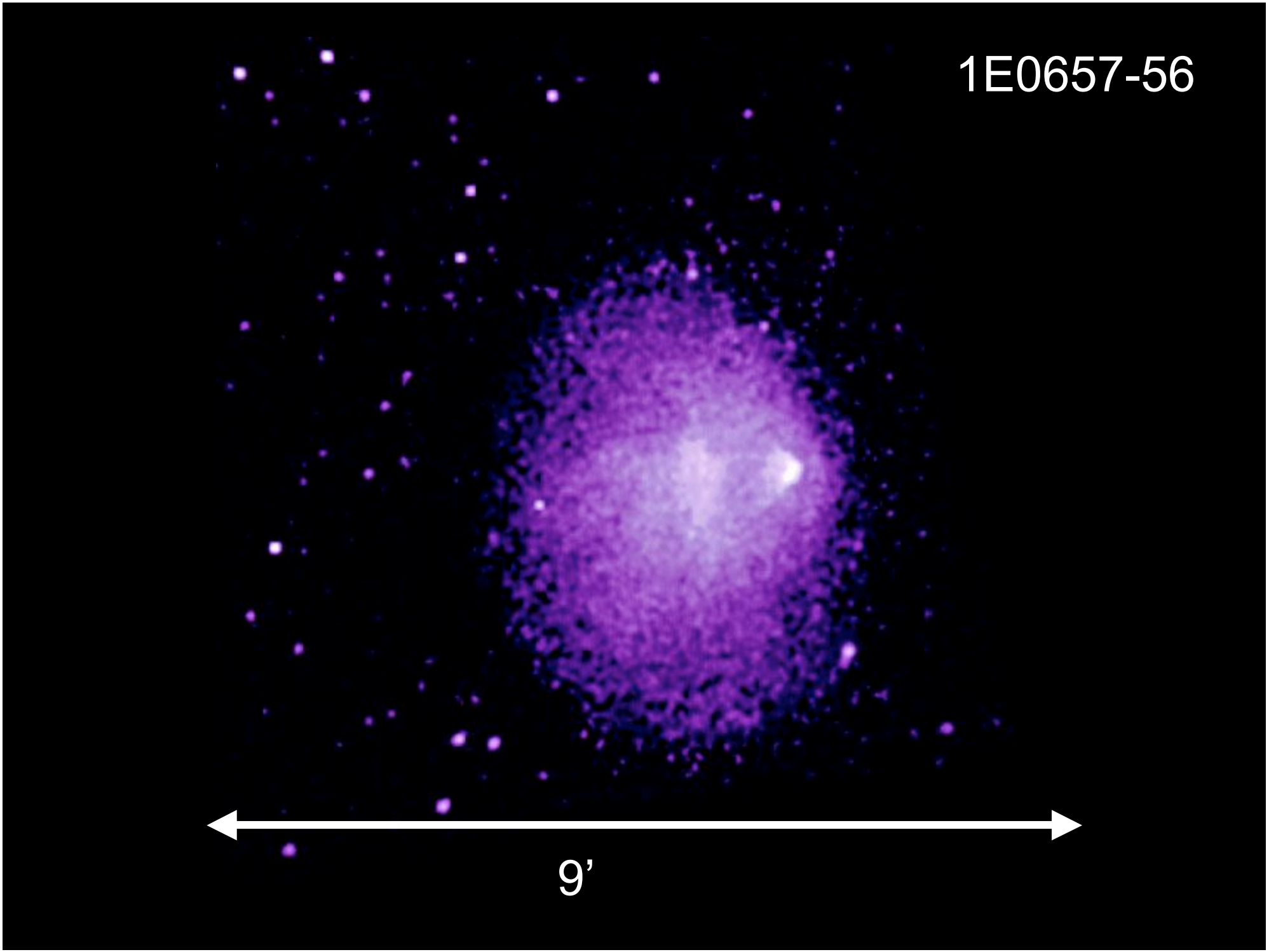
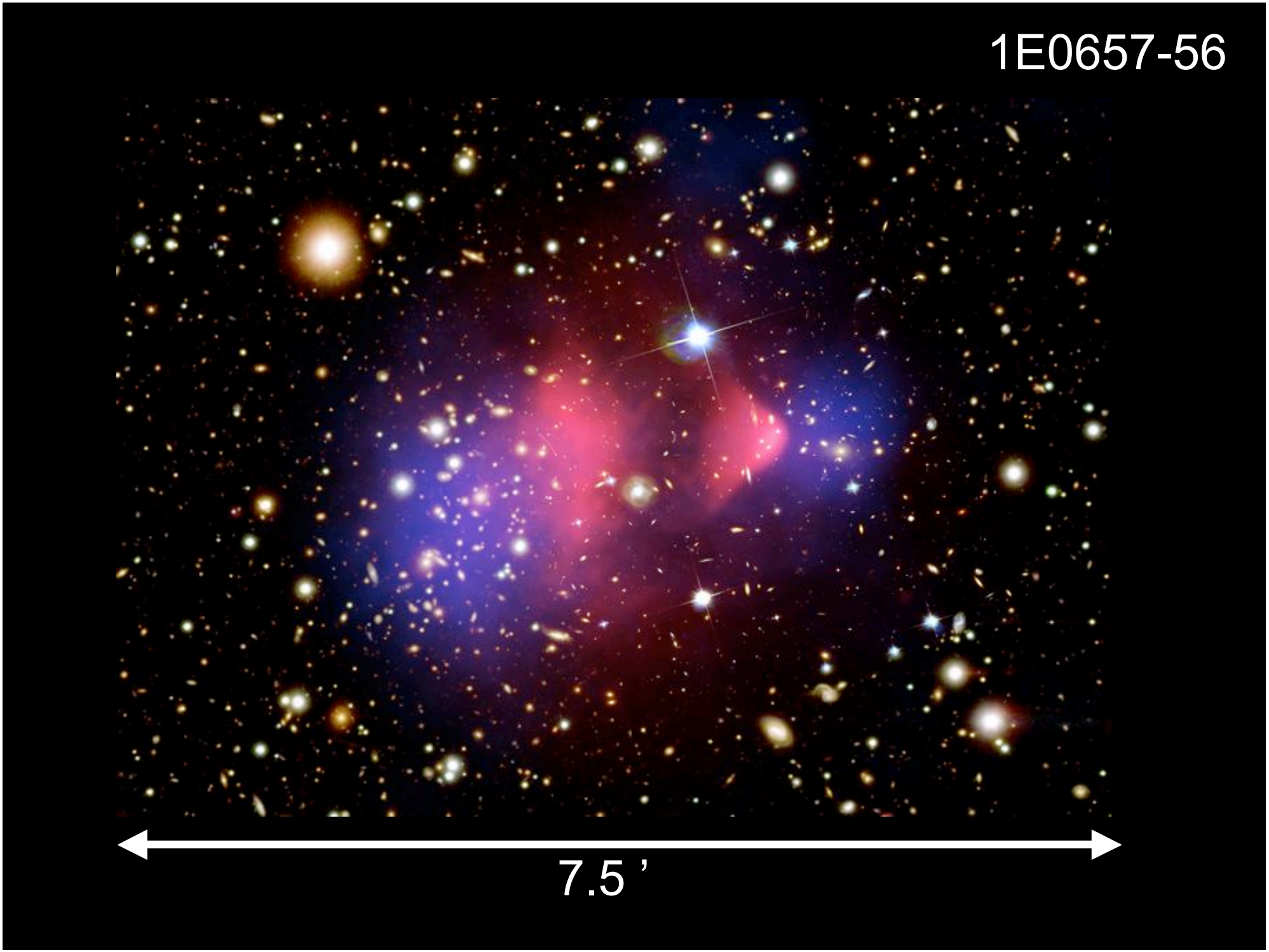
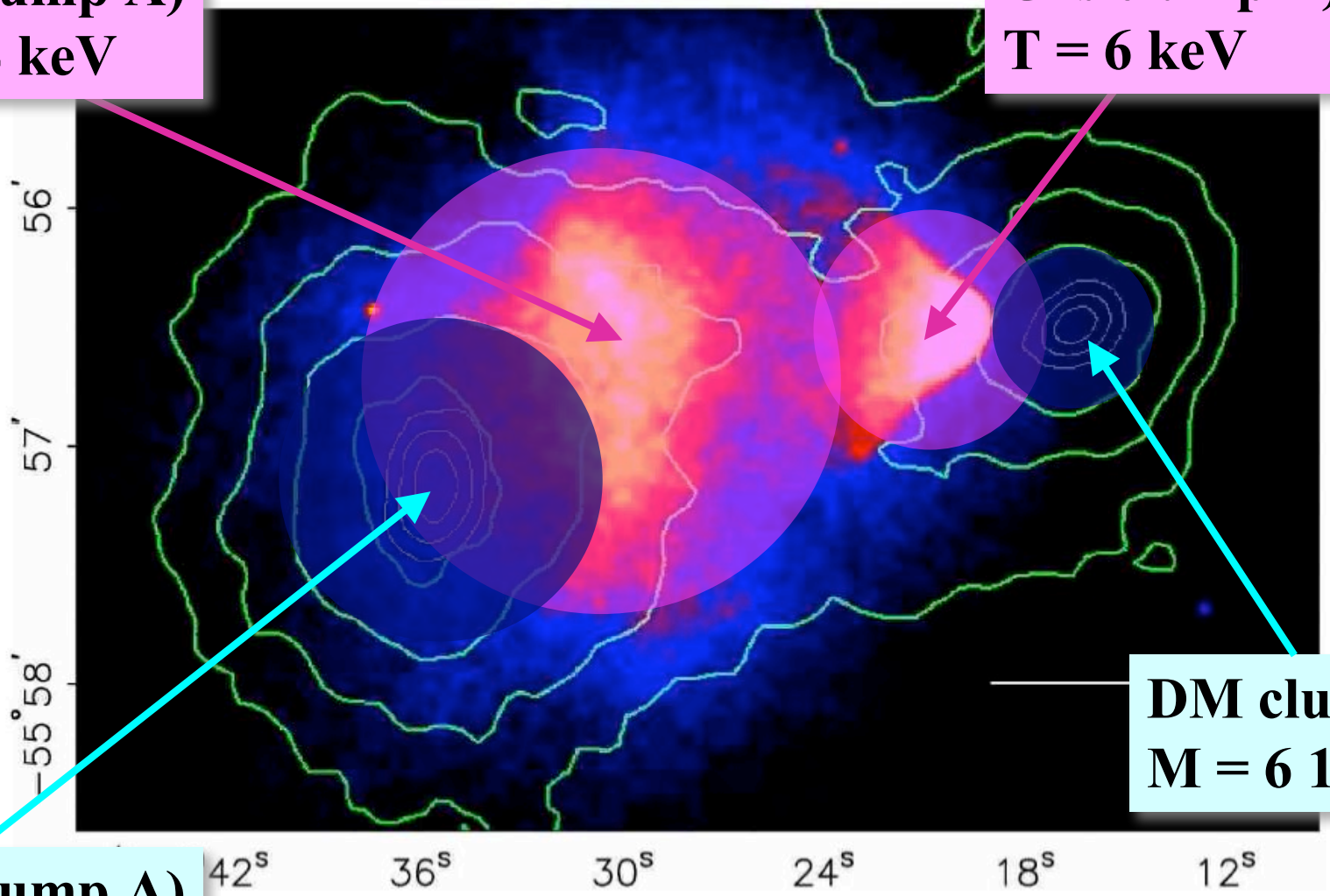
  - Neutrinos
  - etc.
- They produce various effects
- One of them is the SZ from the charged component (see Colafrancesco, 2004)
- Subdominant with respect to SZE from the gas.
- We need clusters where Dark Matter and Baryonic Matter are separated.


1E0657-56
9’


1E0657-56
7.5 ’

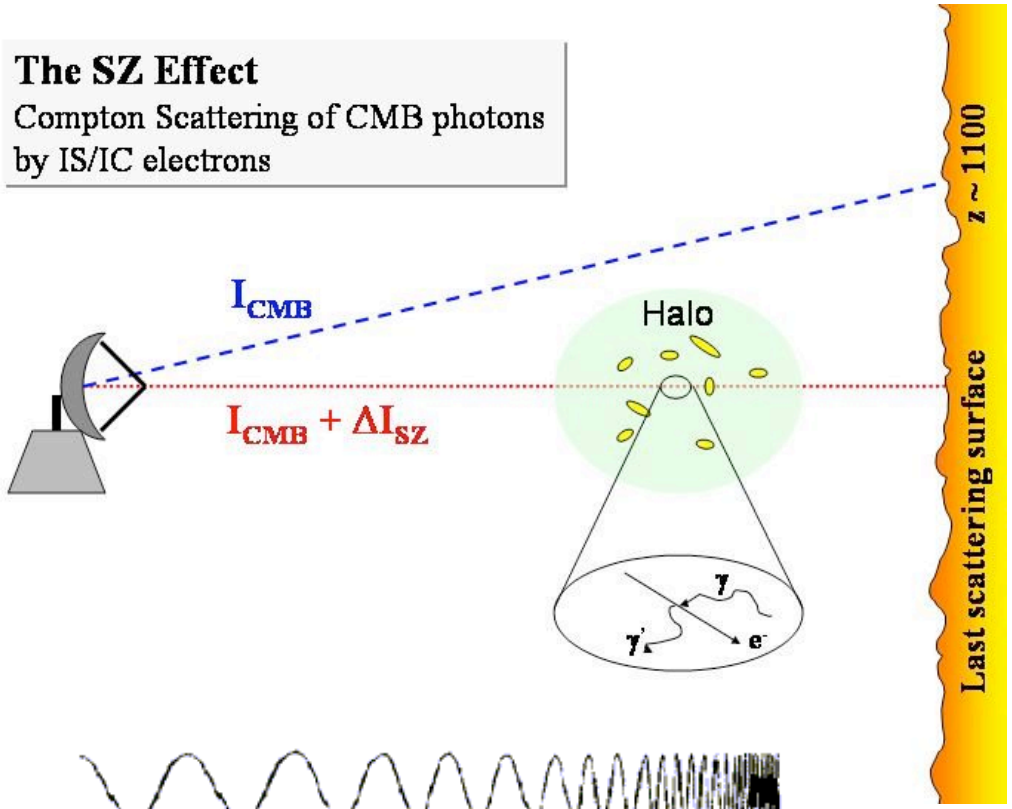
1ES0657-556: DM + thermal gas



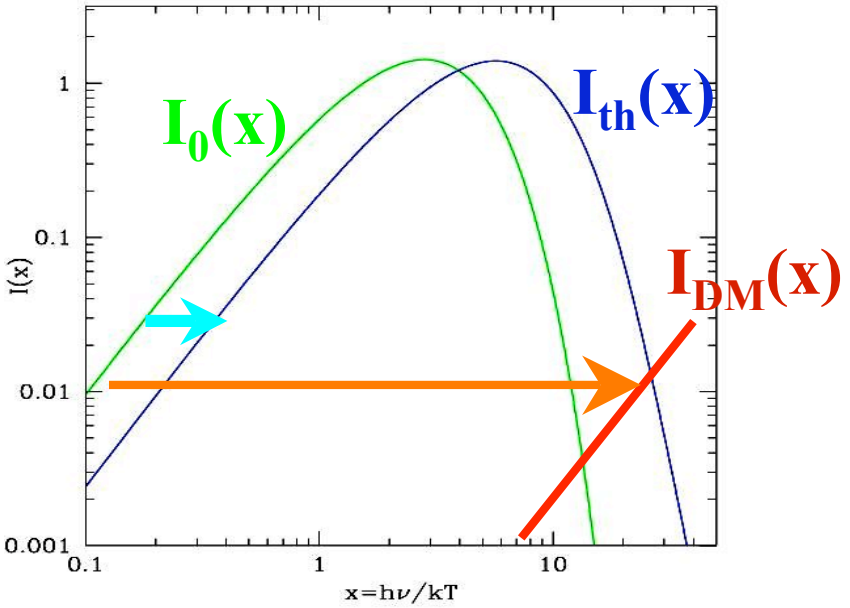
[Clowe et al. 2006, and refs. therein]

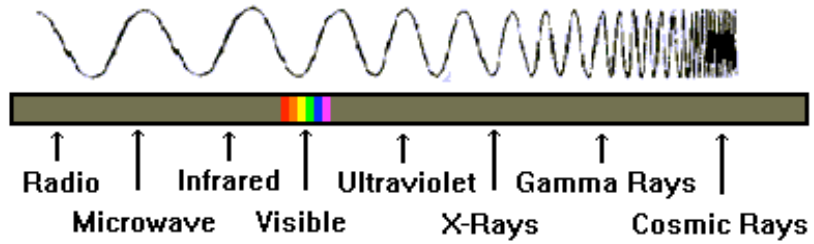
SZ effect from DM

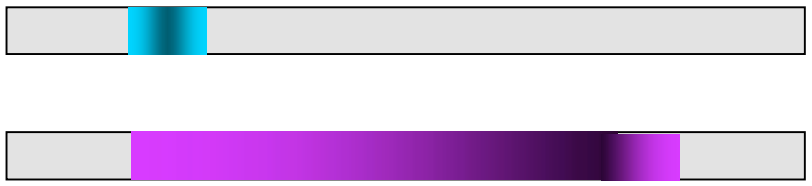
[Colafrancesco 2004 , A&A, 422, L23]



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



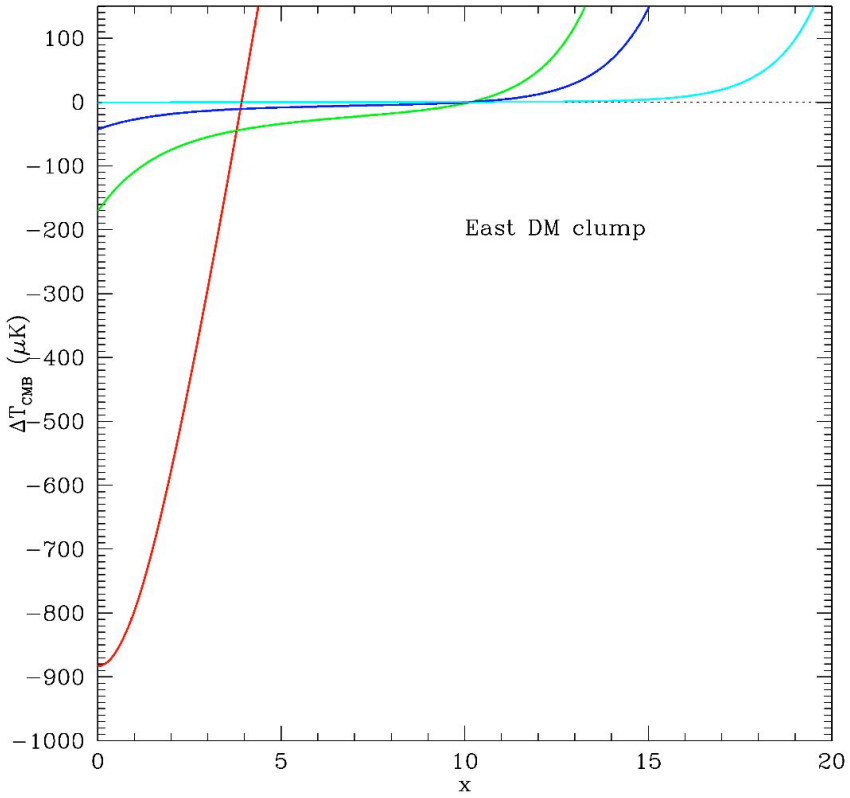


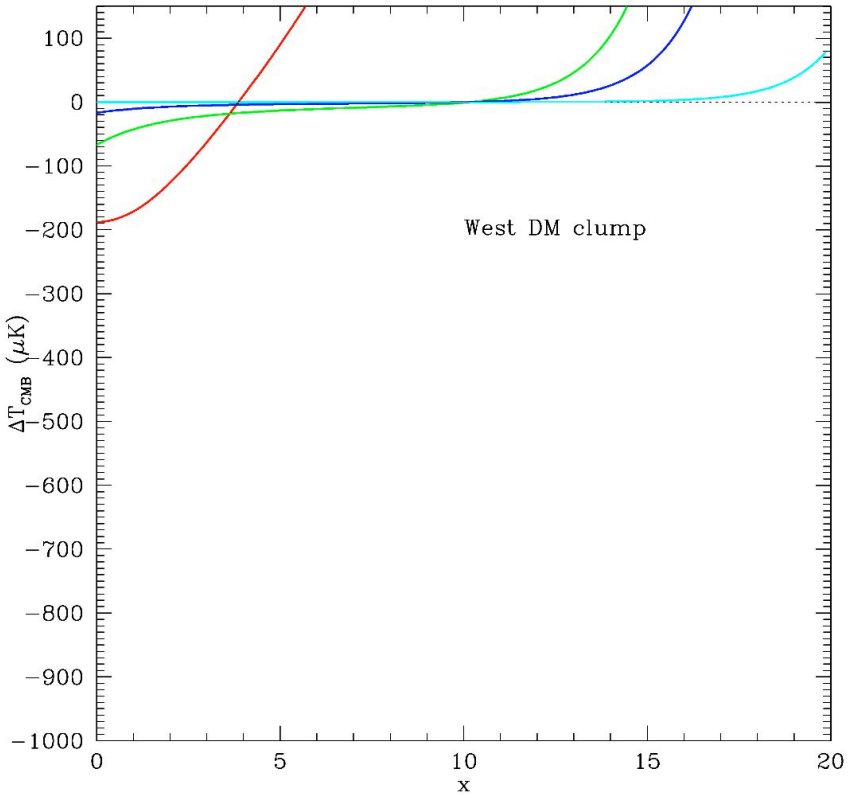


thermal e⁻ $\quad \frac{\nu'}{\nu} = \frac{4}{3}$

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

SZ effect at clump centres





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

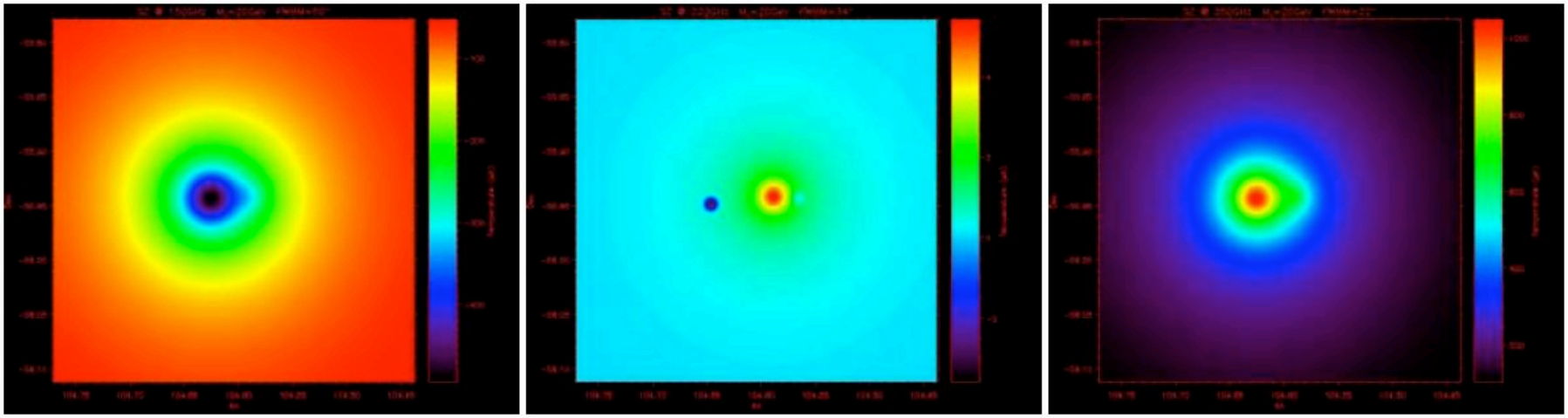
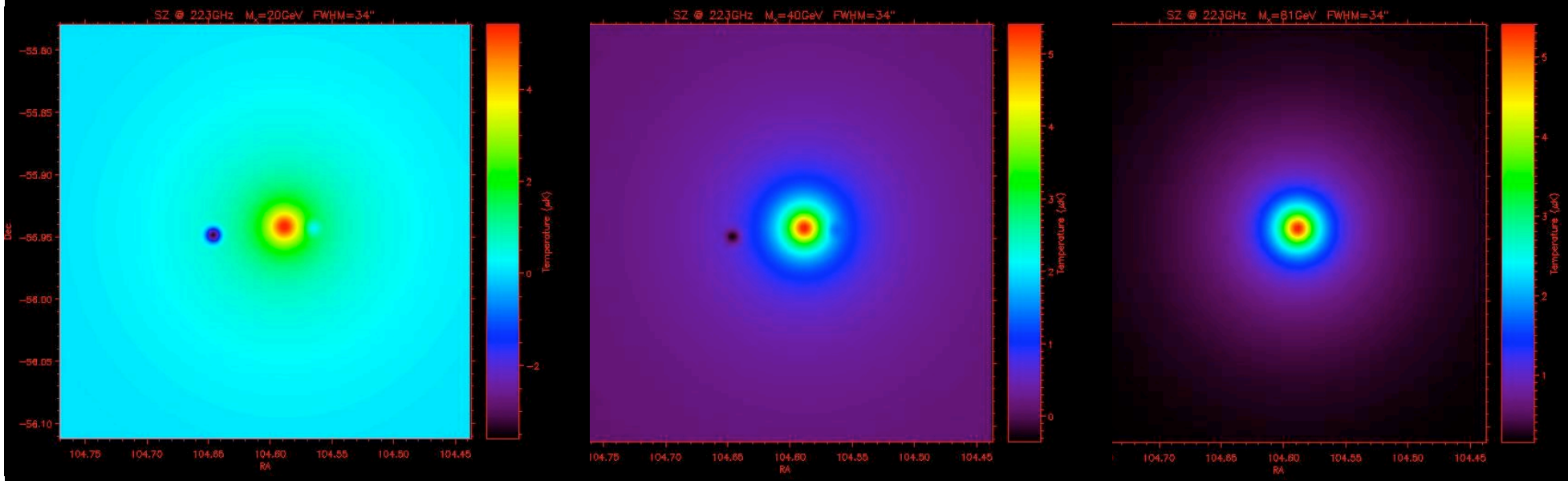


Fig. 2. The simulated SZ maps of the cluster 1ES0657-556 as observable with the SPT telescope at three frequencies: $\nu = 150$ GHz (left panel), $\nu = 223$ GHz (mid panel), $\nu = 350$ GHz (right panel). A neutralino mass of $M_\chi = 20$ GeV has been adopted here. Note that choosing the frequency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

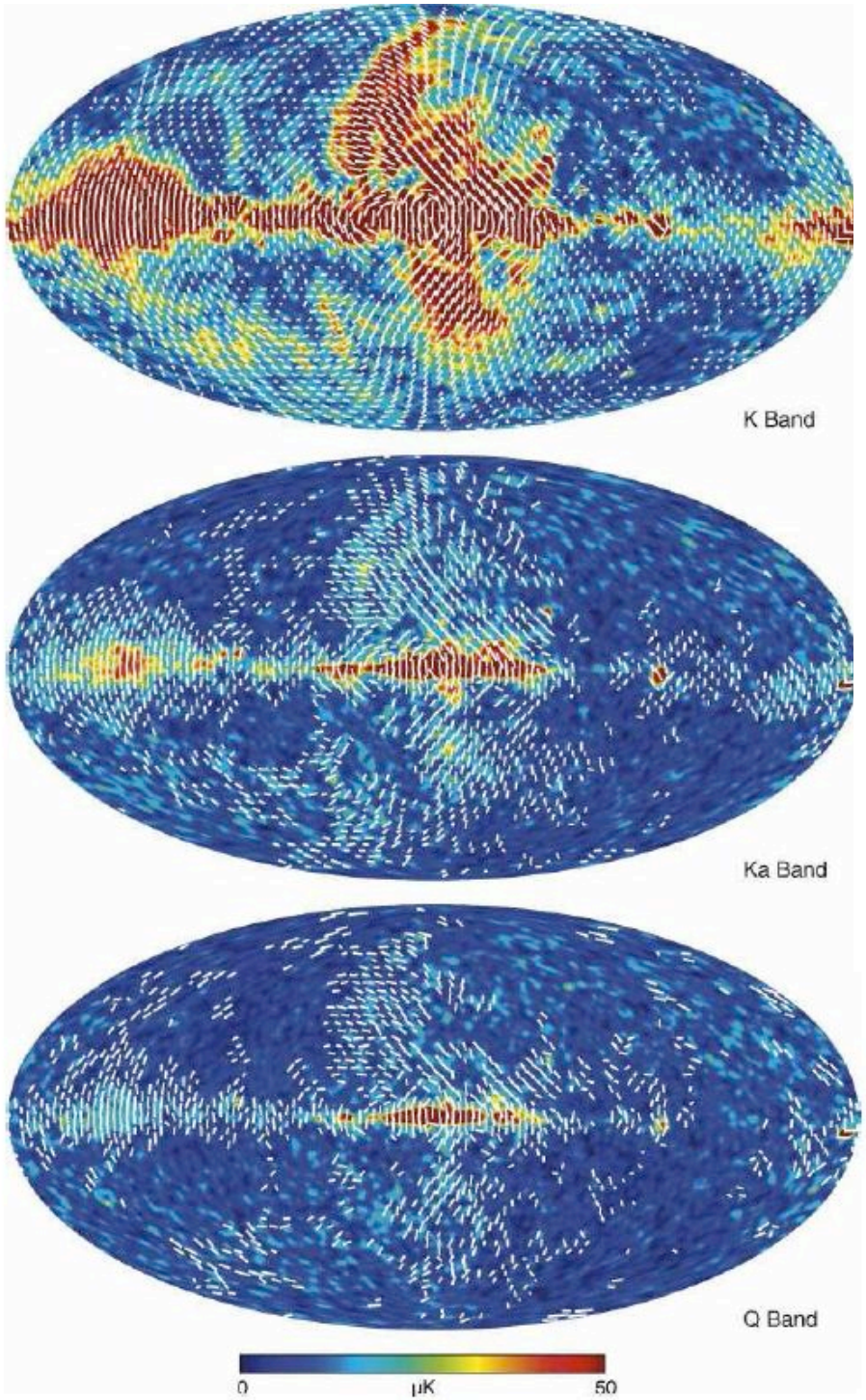


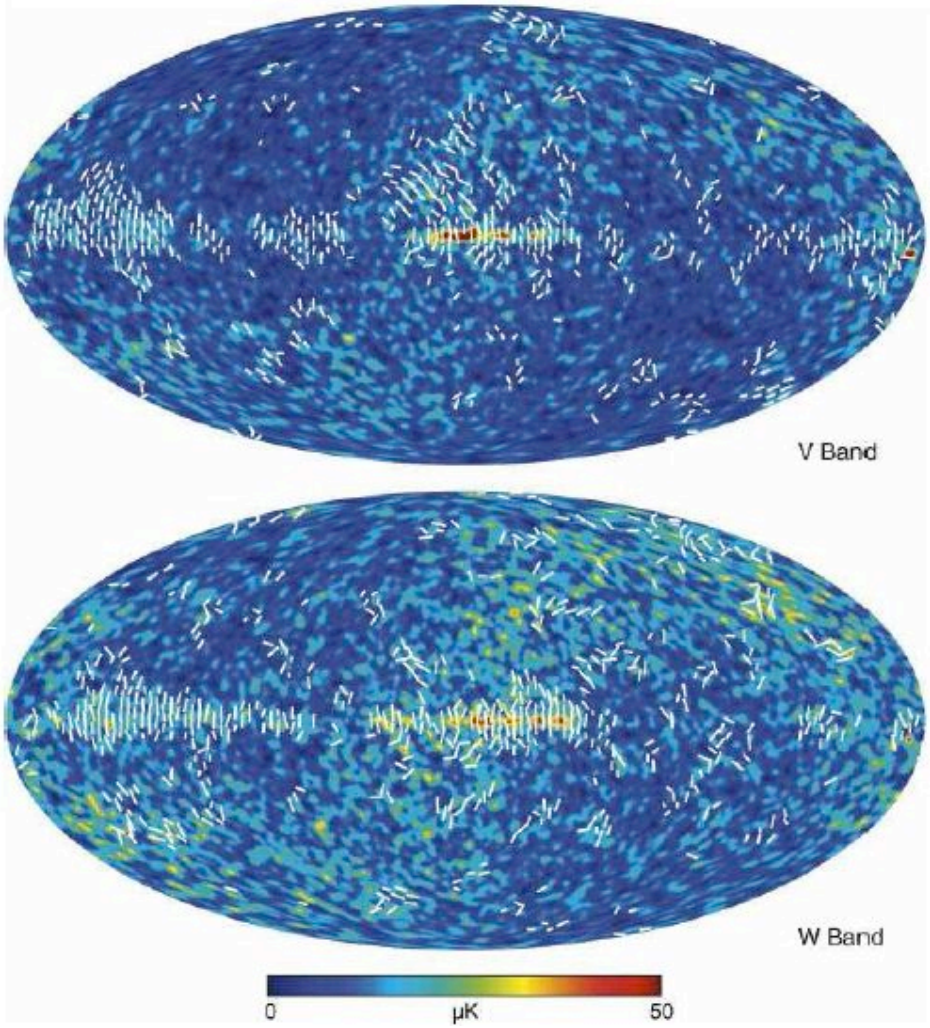
The SZE from the hot gas disappears at $x_{0,th}$ (~ 220-223 GHz) while the SZ_{DM} expected at the locations of the two DM clumps remains negative and with an amplitude and spectrum which depend on M_χ.

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

contents

- CMB experiments: state of the art
- Open problems : how to attack them with CMB
- Enabling technologies
- High angular resolution CMB anisotropy
- The spectrum of CMB anisotropy
- The polarization of CMB





Large-scale Polarization maps from W-MAP 3 years. The detected polarization is mainly due to foregrounds.

- One approach:
  - Focus on the cleanest region of the sky,
  - use extremely sensitive detectors,
  - use frequencies where foreground polarization is lower

- BICEP, QUAD, … (taking data)
- QUIET, ClOVER, BRAIN, EBEX, … (funded, will take data in the near future)
- BOOMERanG (polarized foregrounds, funded)

BICEP: A Large Angular Scale CMB Polarimeter

Brian G. Keating[a], Peter A. Ade[b], James J. Bock[c], Eric Hivon[d],
William L. Holzapfel[e], Andrew E. Lange[a], Hien Nguyen[b], Ki Won Yoon[a]

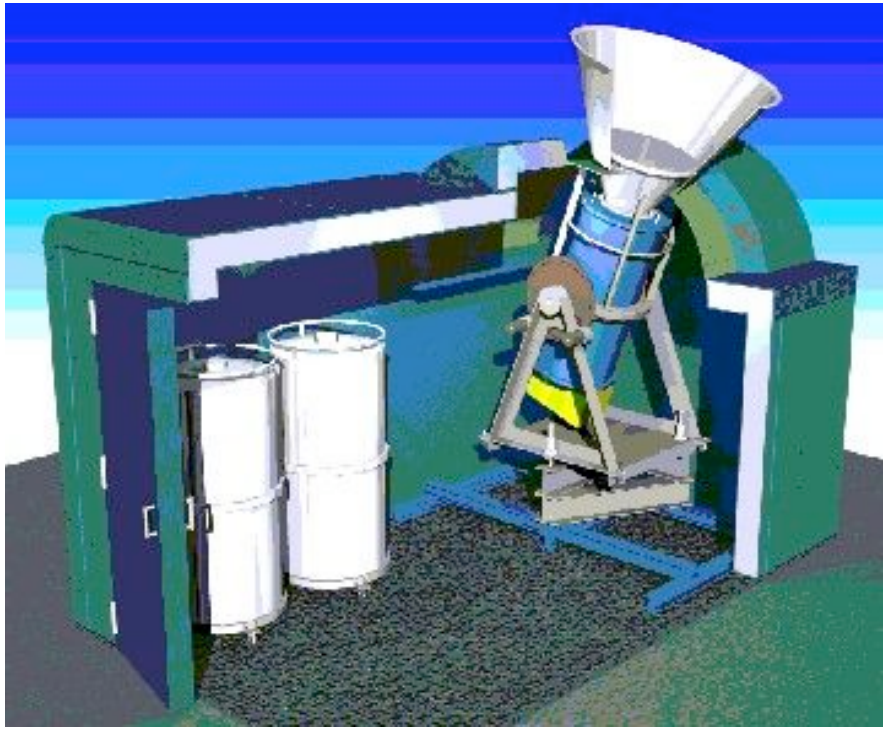
[a]California Institute of Technology, Mail Code 59-33, Pasadena, CA, 91125
[b]Dept. of Physics, Cardiff University, Cardiff CF243YB, Wales, UK.
[c]Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109
[d]IPAC, Mail Code 100-22, Pasadena, CA 91125
[e]Dept. of Physics, University of California at Berkeley, Berkeley, CA, 94720

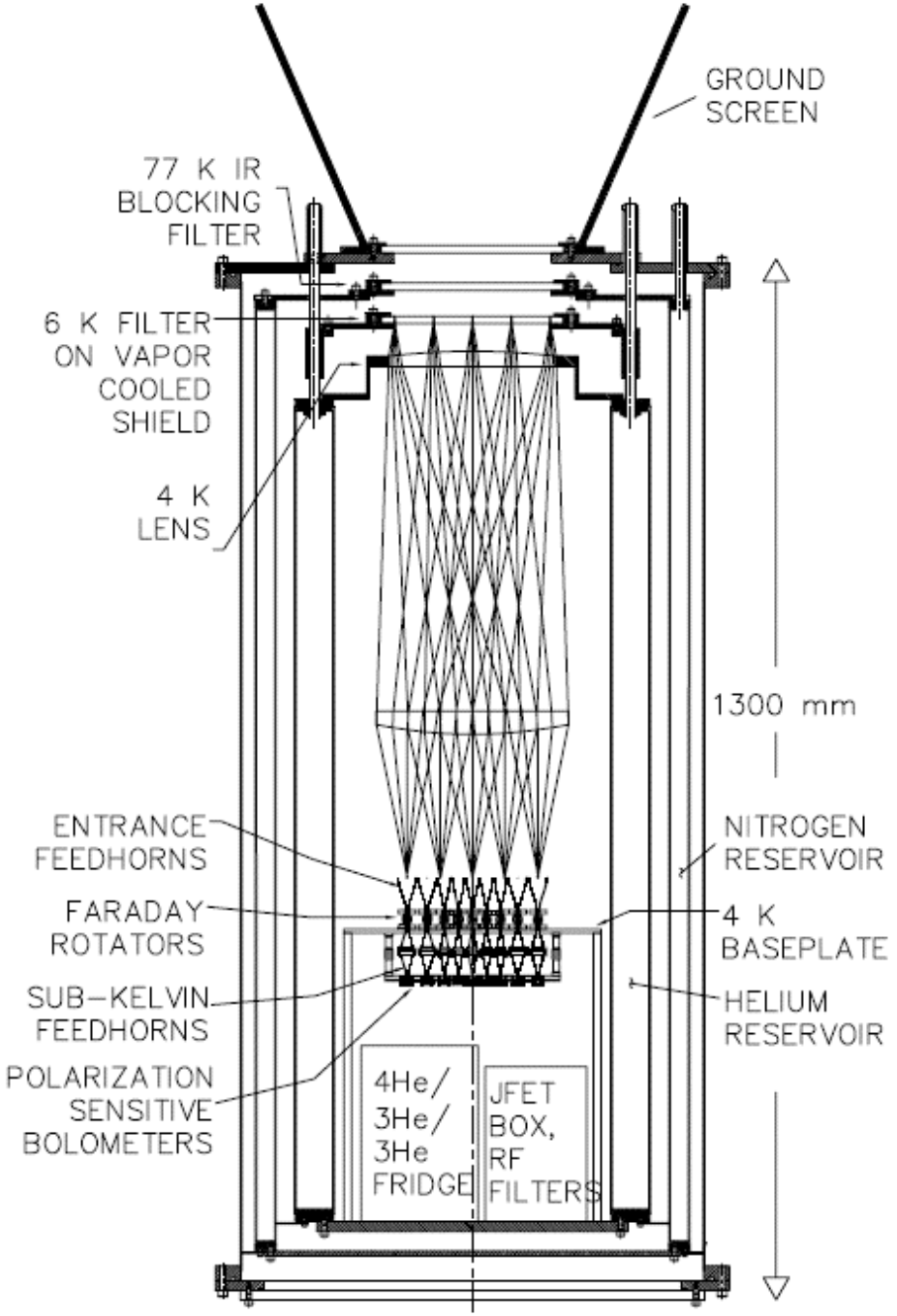
ABSTRACT

We describe the design and expected performance of BICEP, a millimeter wave receiver designed to measure the polarization of the cosmic microwave background. BICEP uses an array of polarization sensitive bolometers operating at 100 and 150 GHz to measure polarized signals over a 20° field of view with $\sim 1°$ resolution. BICEP is designed with particular attention to systematic effects which can potentially degrade the polarimetric fidelity of the observations. BICEP is optimized to detect the faint signature of a primordial gravitational wave background which is a generic prediction of inflationary cosmologies.

Keywords: polarization sensitive bolometers, cosmic microwave background – instrumentation, gravitational wave detection

From the Caltech(Lange) web site





Taking data now from South Pole.

Polarization sensitive detectors from Caltech/JPL

Main goal: detailed measurement of CMB polarization spectra (E-modes)

Background Radiation Interferometer

BRAIN

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD
Astronomy + Instrumentation Group

UNIVERSITÀ DEGLI STUDI DI ROMA LA SAPIENZA

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

IAS orsay

COLLÈGE DE FRANCE 1530

l'Observatoire de Paris

Orthogonal Technique: combines
- Sensitivity of bolometers
- Cleaninless of interferometers
- Excellence of Dome-C site

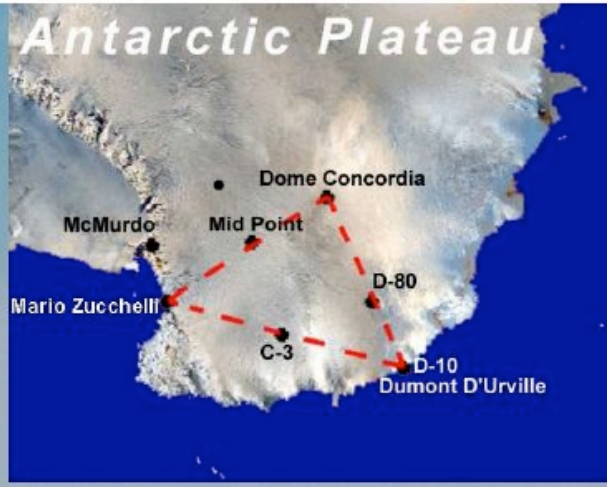
Pathfinder experiment installed in summer campaigns. The site is excellent.

WWW.CESR.FR

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE
CESR
UNIVERSITE PAUL SABATIER
TOULOUSE - FRANCE

Dome-C Concordia Station

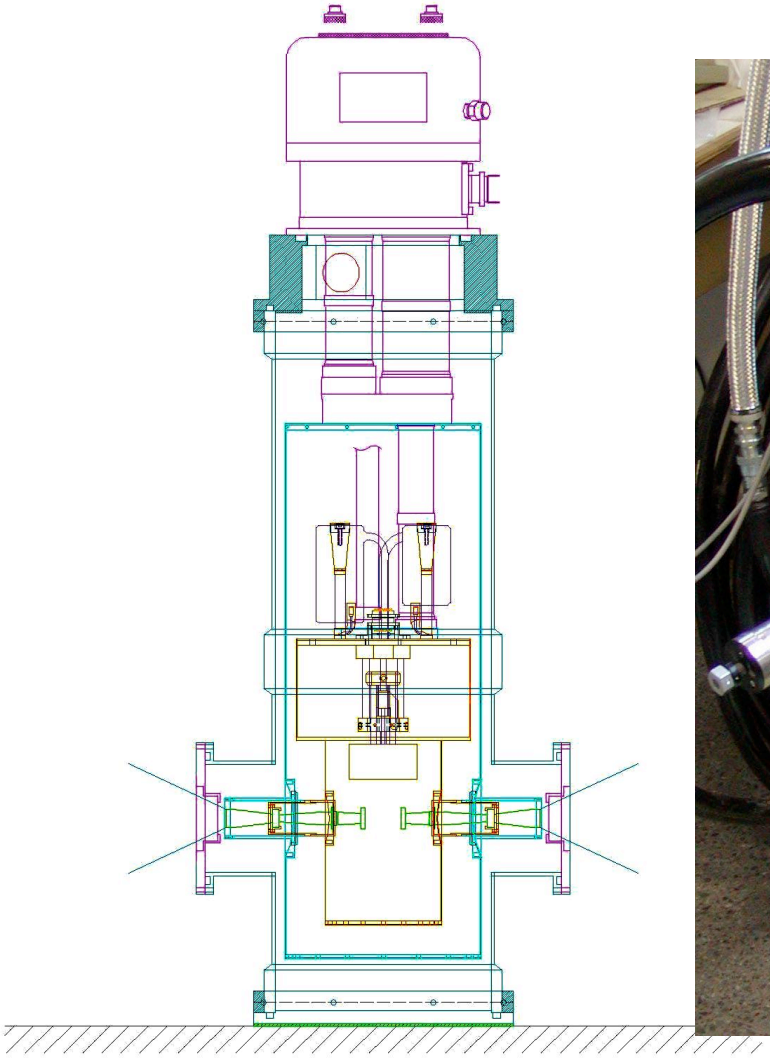
Lat: 75° 06' S Lon: 123° 23' E
Altitude 3230m osl
Main air temperature -50.8 °C
Typical monthly average air temperature in summer -30 °C
Typical monthly average air temperature in winter -60 °C
Mean wind speed 2.8 m/s 5.4 knots
Mean air pressure 645 hPa
Yearly precipitation range (snow) 2-10 cm



BRAIN site

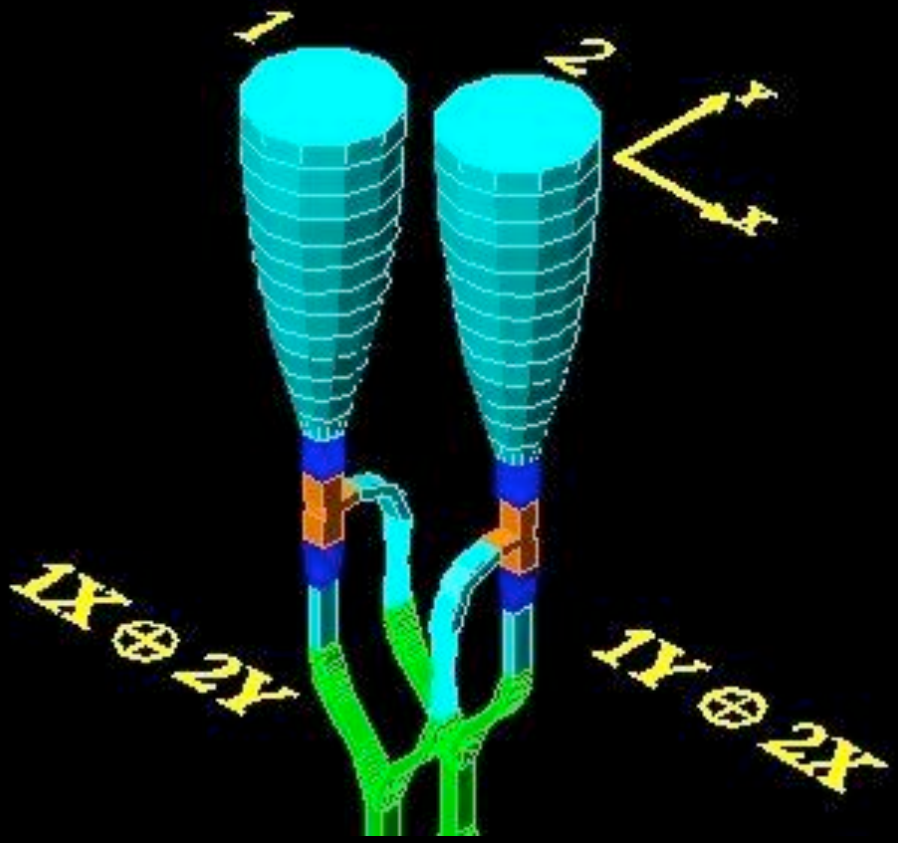
Is Dome-C the best site for B-modes measurements?

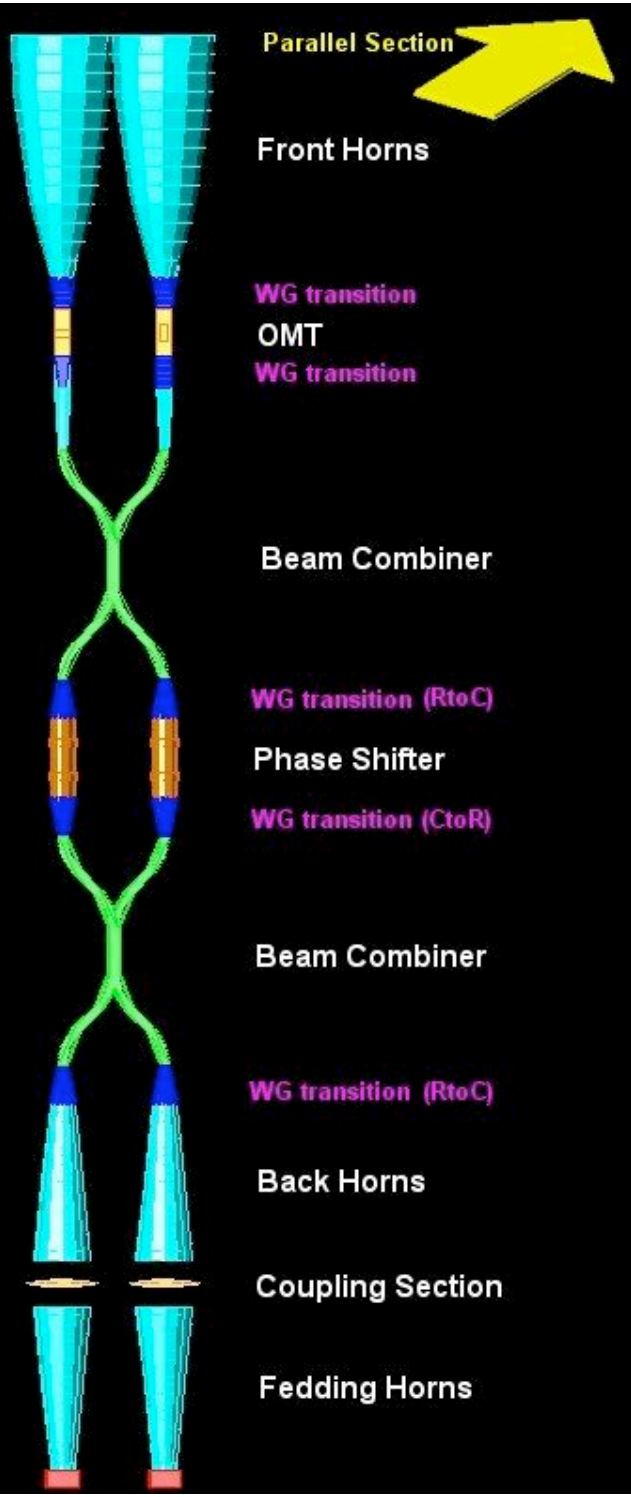
- We have already validated on-site (Dome-C) a technique to operate cryogenic detectors without having to use cryogenic liquids.
- Pulse-tube + 3He fridge (0.3 K).



Bolometric Interferometer

Single Baseline





Working principle of ideal Brain components:

90°Hyb *PhSh* *90°Hyb* *OMT*

$$\left[\frac{1}{\sqrt{2}}\cdot\begin{pmatrix}1 & 1i\\ 1i & 1\end{pmatrix}\right]\cdot\begin{pmatrix}e^{1i\cdot f} & 0\\ 0 & e^{1i\cdot g}\end{pmatrix}\cdot\left[\frac{1}{\sqrt{2}}\cdot\begin{pmatrix}1 & 1i\\ 1i & 1\end{pmatrix}\right]\cdot\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}\cdot\begin{pmatrix}E_{1X}\\ E_{2Y}\cdot e^{1i\cdot d}\end{pmatrix}$$

$$\begin{pmatrix}E_{1Y}\\ E_{2X}\cdot e^{1i\cdot d}\end{pmatrix}$$

$\varphi = f - g$ (dps – differential phase shift)

i.e. the field at the first detector is:

$$D_1 = \frac{E_{1x}}{2}\left(e^{i\varphi}-1\right)+i\frac{E_{2y}e^{id}}{2}\left(e^{i\varphi}+1\right)$$

And the power $P_i = D_i^* D_i$ using Stokes parameters is:

$$P_1 = \frac{1}{2}\left(I - Q\cdot\cos\varphi + U\cdot\sin\varphi\right)$$

$$P_2 = \frac{1}{2}\left(I + Q\cdot\cos\varphi - U\cdot\sin\varphi\right)$$

Likewise:

$$P_2 - P_1 = Q\cdot\cos\varphi - U\cdot\sin\varphi$$

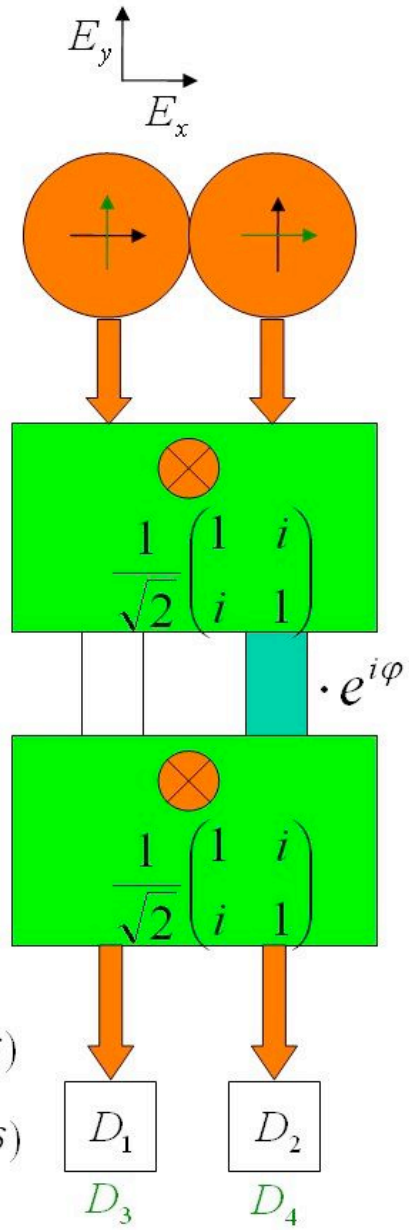
If interferometer fringe pattern δ is introduced, V contribution arises:

$$P_1 = \frac{1}{2}\left(I - Q\cdot\cos\varphi + U\cdot\sin\varphi\cdot\cos\delta - V\cdot\sin\varphi\cdot\sin\delta\right)$$

$$P_4 = \frac{1}{2}\left(I + Q\cdot\cos\varphi - U\cdot\sin\varphi\cdot\cos\delta - V\cdot\sin\varphi\cdot\sin\delta\right)$$

$$P_4 - P_1 = Q\cdot\cos\varphi - U\cdot\sin\varphi\cdot\cos\delta$$

Other two detectors (3 & 4) to combine with (1 & 2) to eliminate V signal and isolate Q and U



Brain meeting presentation G.Savini

BRAIN idea:

Frequencies: 90GHz, 150GHz

2x256 horns

2x512 detectors

expected sensitivity per pixel: 1μK

angular resolution: 1°

cryogenic: Sumitomo Pulse Tube Cooler + 3He-4He fridge

remote control using INMARSAT telemetry system

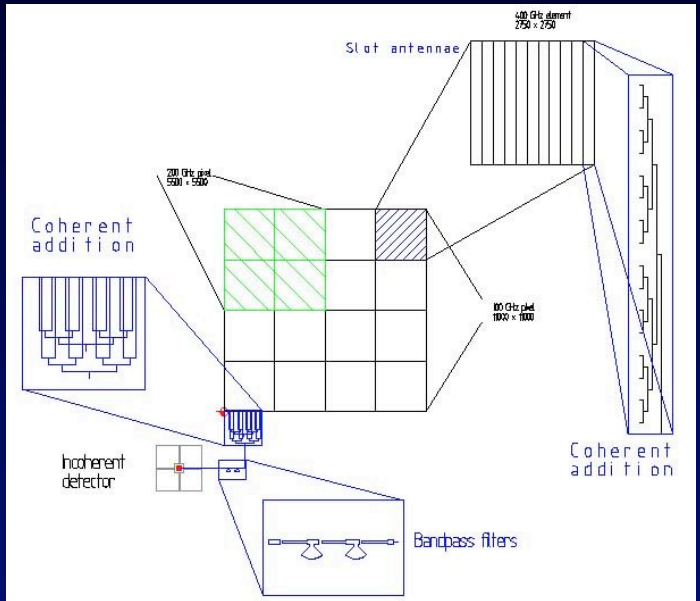
A full study of the instrument is in progress!

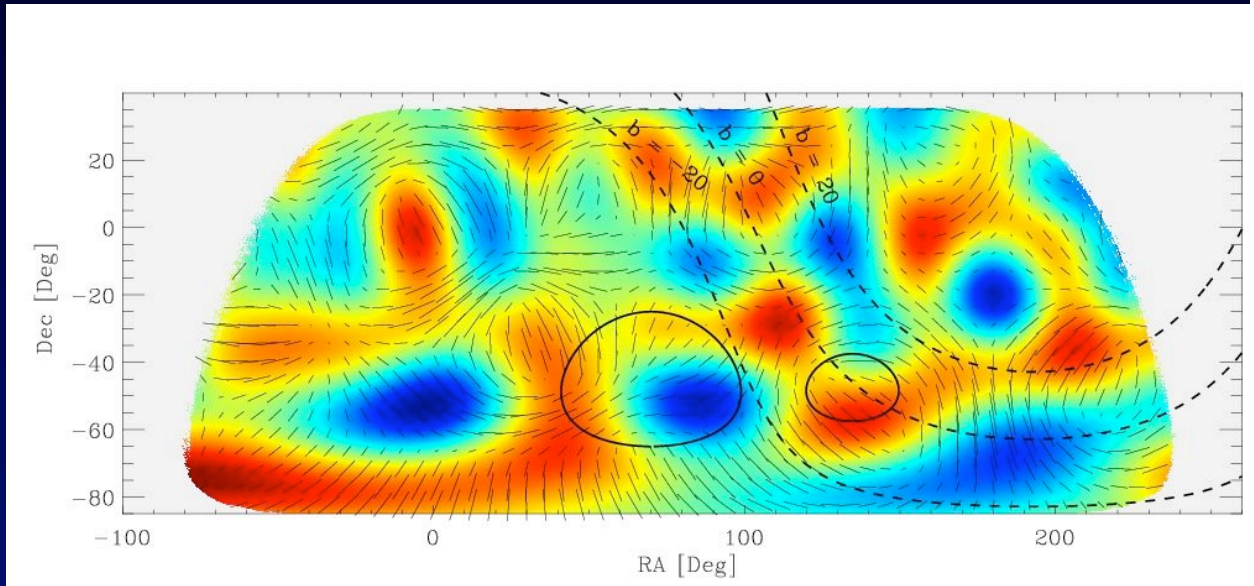
- Another approach:
  - Full sky survey with extremely high precision and wide frequency coverage
  - Go to space

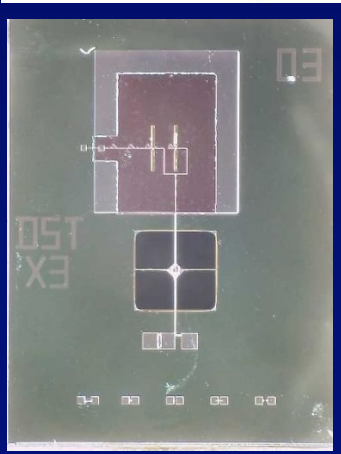
- SPIDER (balloon),
- NASA Beyond Einstein (3 satellite studies)
- BB-Pol (balloon)
- ESA Cosmic Vision (1 satellite study, B-Pol)

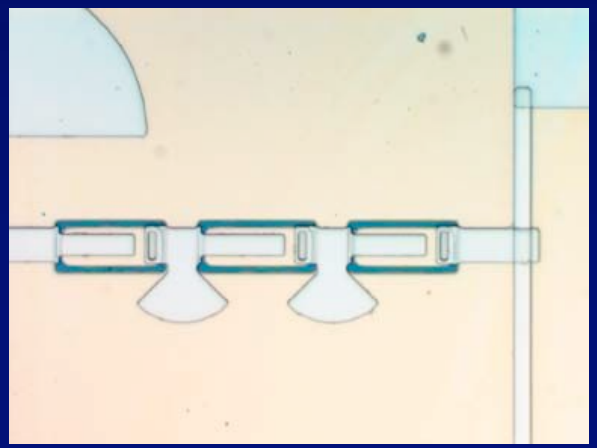
Large Bolometer Arrays

- > 1000 TES bolometers for SPIDER a proposed spinning polarimeter on an **ULDB** (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

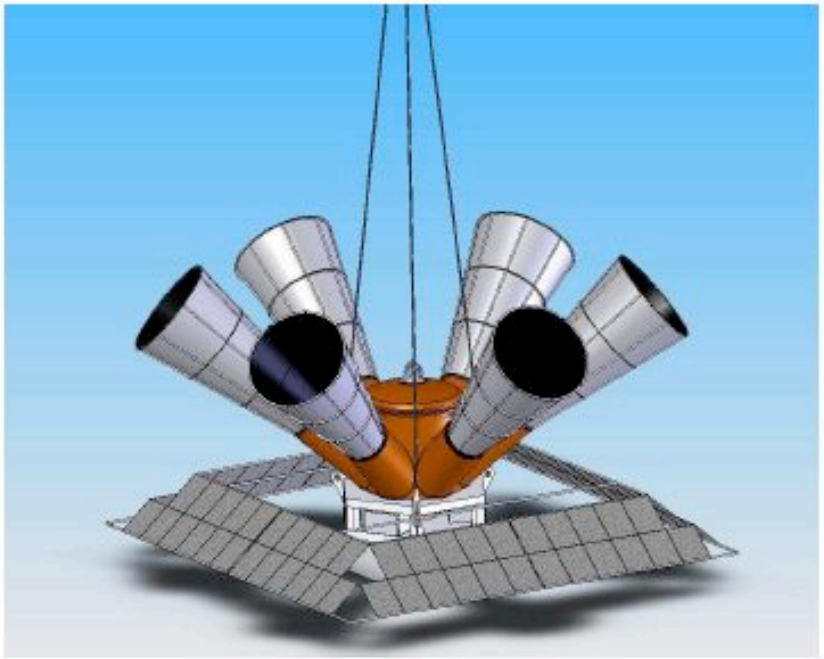


Figure 1: The *SPIDER* payload is designed to obtain maximum sky coverage from a twenty to thirty day mid-latitude balloon flight around the world. The experiment will map out roughly 50% of the sky observing only at night.

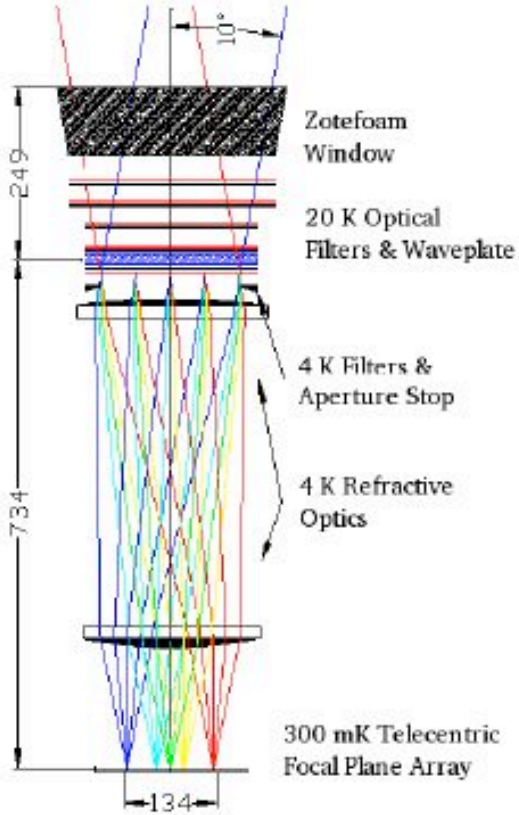
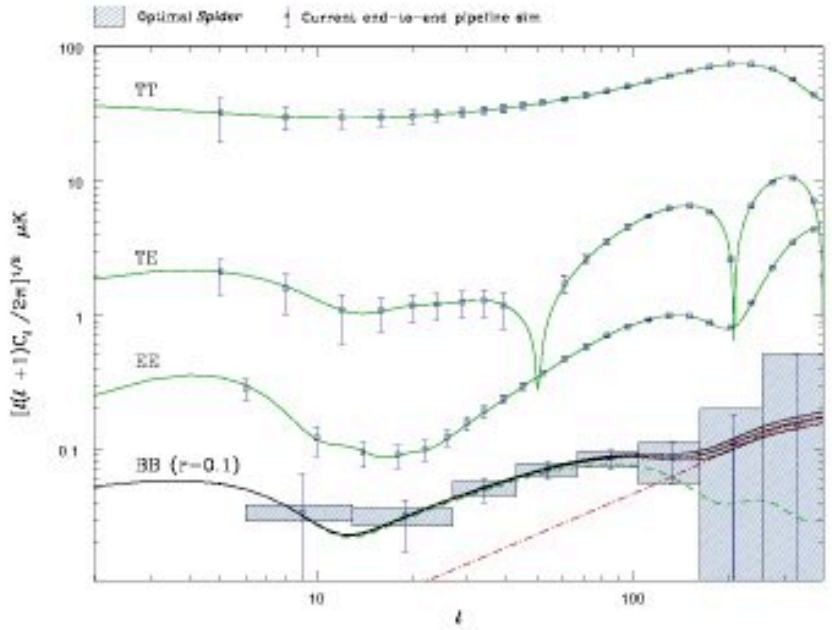
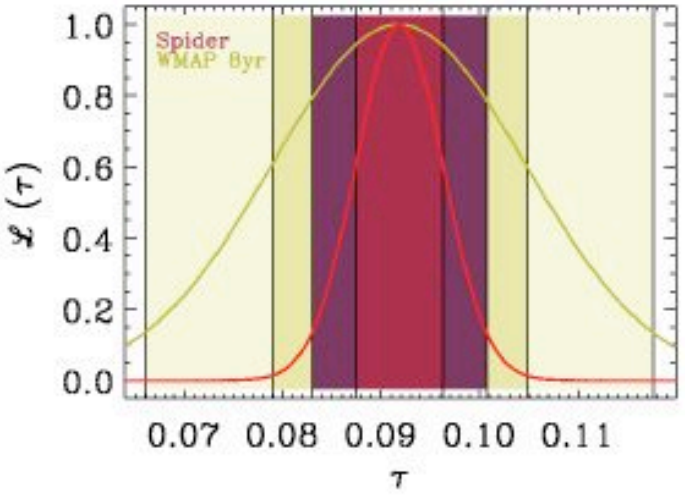


Figure 2: The *SPIDER* optics are based on the BICEP design. SPIDER will incorporate a rotating half-wave plate to modulate incoming polarization signal.

SPIDER: from MacTavish et al., PoS(CMB2006)071





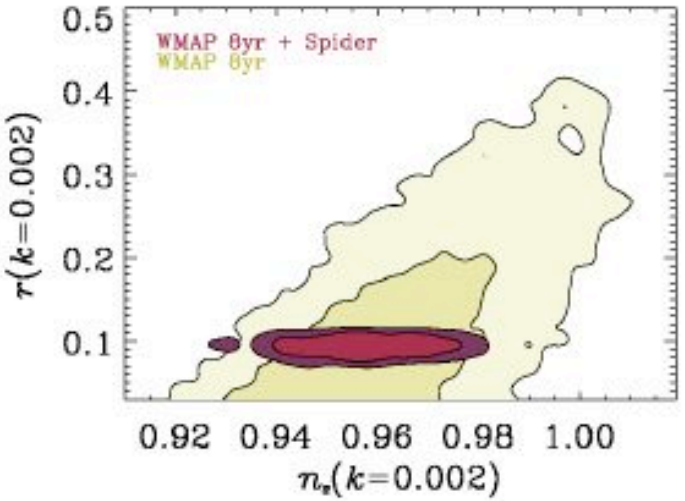
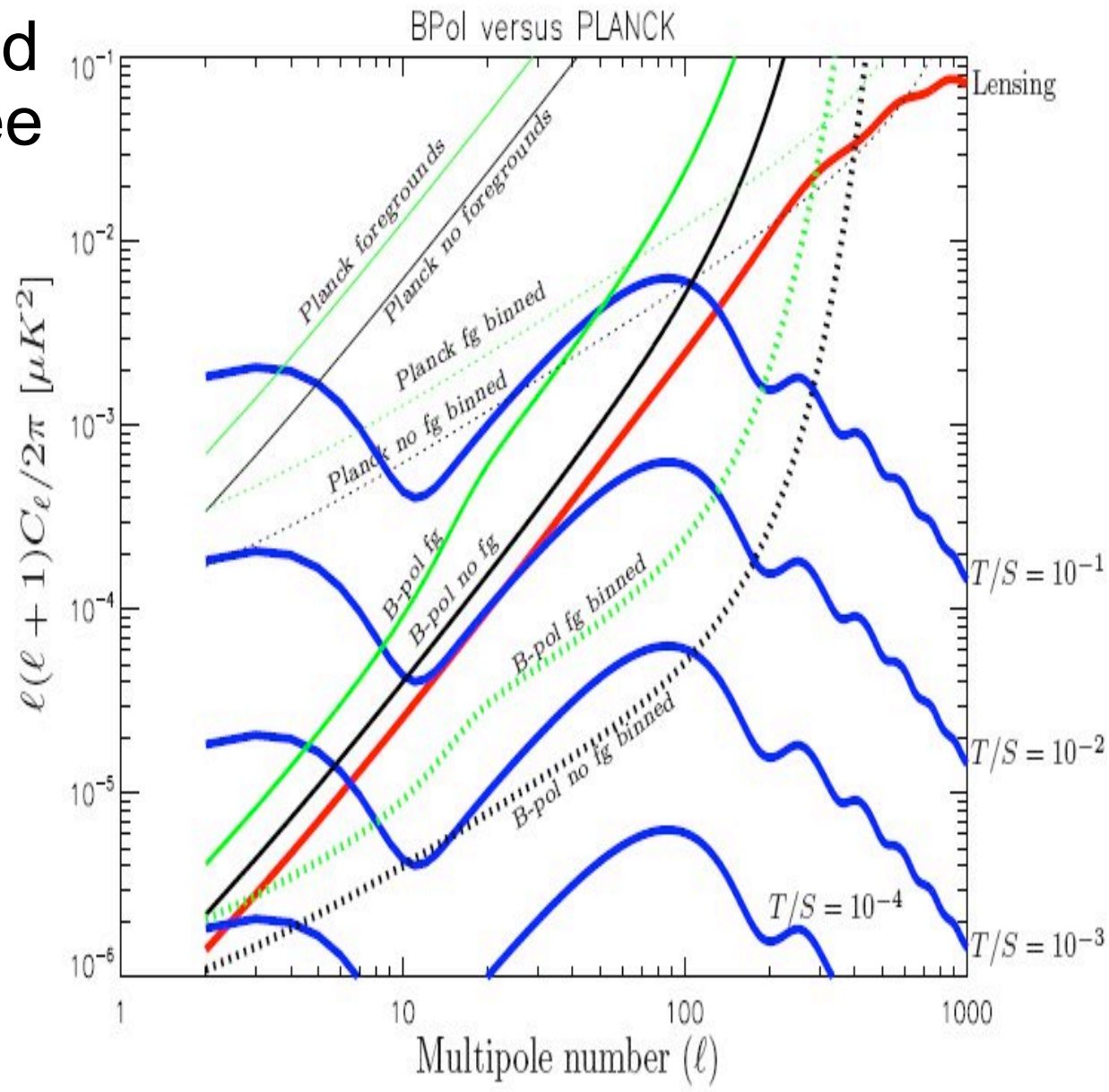


Figure 5: Top left panel: *SPIDER* sensitivity. Data points and errors are derived from end-to-end realizations of a simulated *SPIDER* balloon flight. Minimal modifications to the existing pipeline will result in an improved accuracy of the low multipole BB: the errors will approach the analytical errors (blue boxes) which are fully optimal with respect to the leakage of EE into BB. Top right panel: One-dimensional constraints on τ. Bottom right panel: Two dimensional constraints in the $n_s - r$ plane.

B-Pol

- A mission to study CMB polarization with unprecedented accuracy, at degree angular scales
- Proposed in the framework of ESA Cosmic Vision 2015-2025
- International team (Europe, Canada, USA)
- Able to detect B-modes for T/S down to 10^{-3}



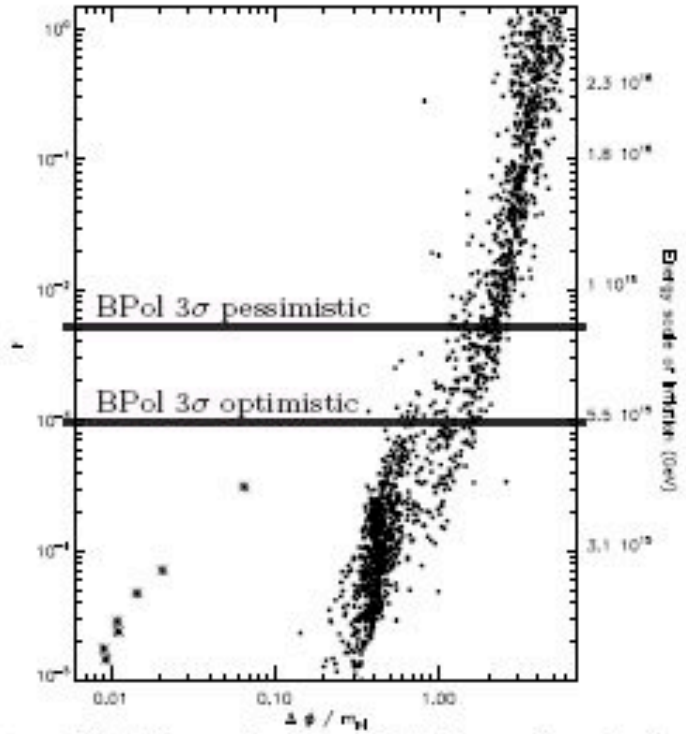


Figure 2: The evolution of ϕ for various inflation models with respect to the energy scale. Dots represent single-field models, which find good agreement with the relation in the text. The crosses represent hybrid models, and due to the sharp features in the potentials of such models, they do not obey the same relation. We show two scenarios for what BPOL will accomplish, one with an optimistic and another with a pessimistic projection for the degree to which foregrounds can be removed. We observe that a large range of models will be ruled out, or discovered, by BPol. Figure produced by L. Verde, following closely the method of W. Kinney et al., Phys. Rev. D74, 023502 (2006) (astro-ph/0605338).

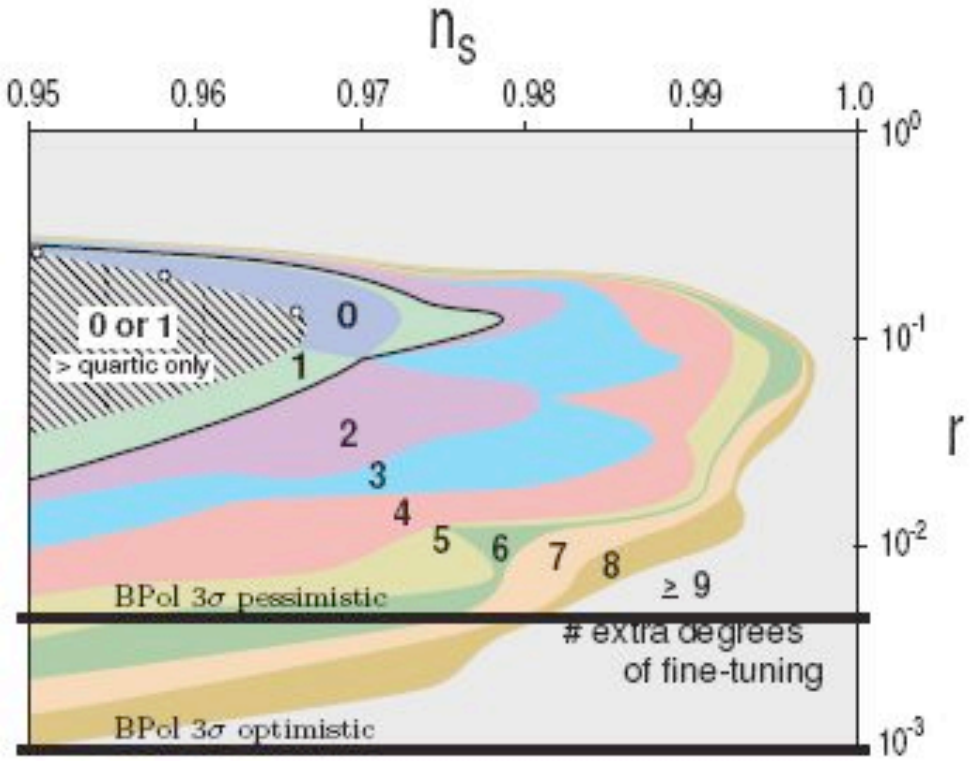
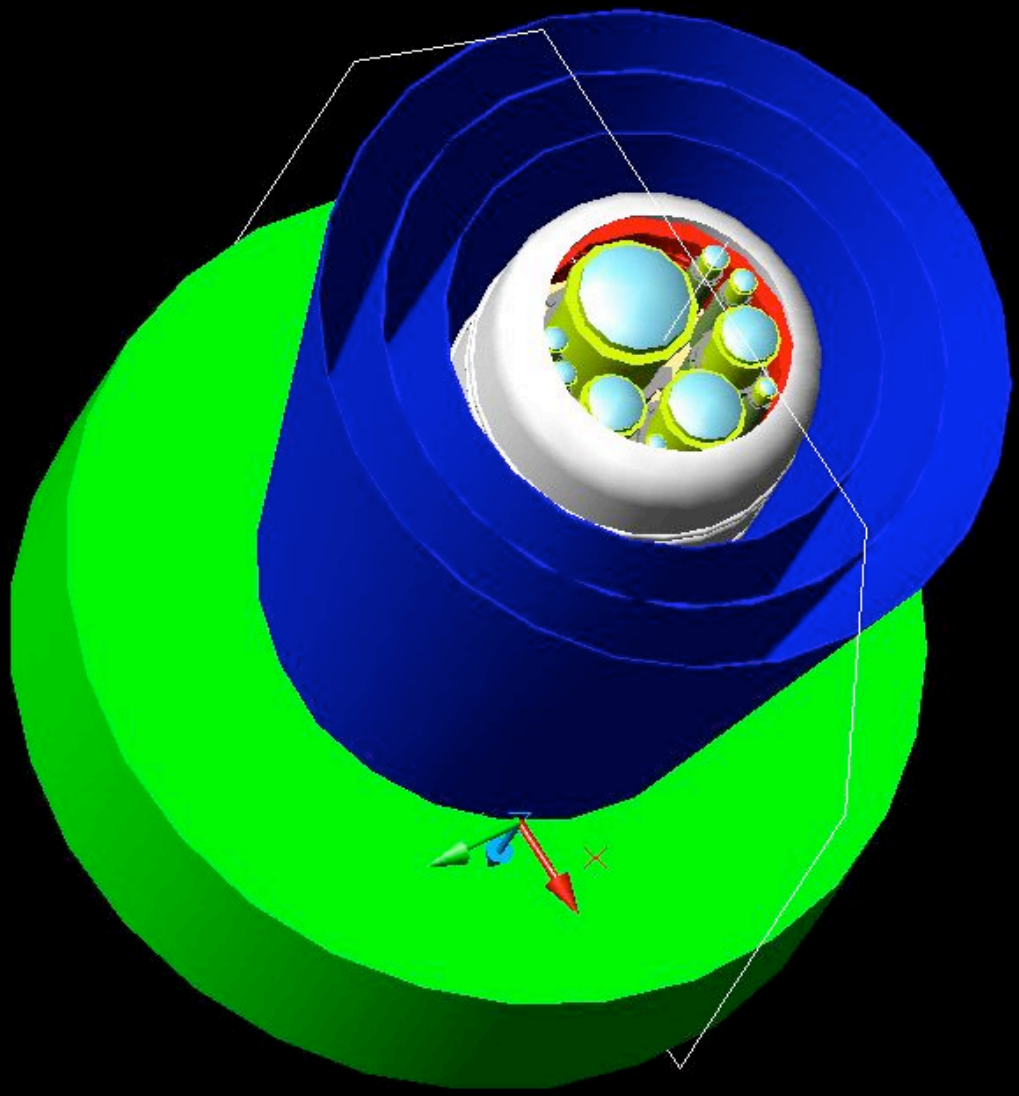


Figure 3: The predictions of general polynomial potentials of increasing order consistent with current observations as a function of degree of 'fine tuning'. This analysis indicates that the most 'natural' potential give values of T/S well within the range of B-Pol. Reprinted from L. Boyle, P.J. Steinhardt and N. Turok, Phys. Rev. Lett. 96, 111301 (2006) (astro-ph/0507455).

B-Pol : how can we get there

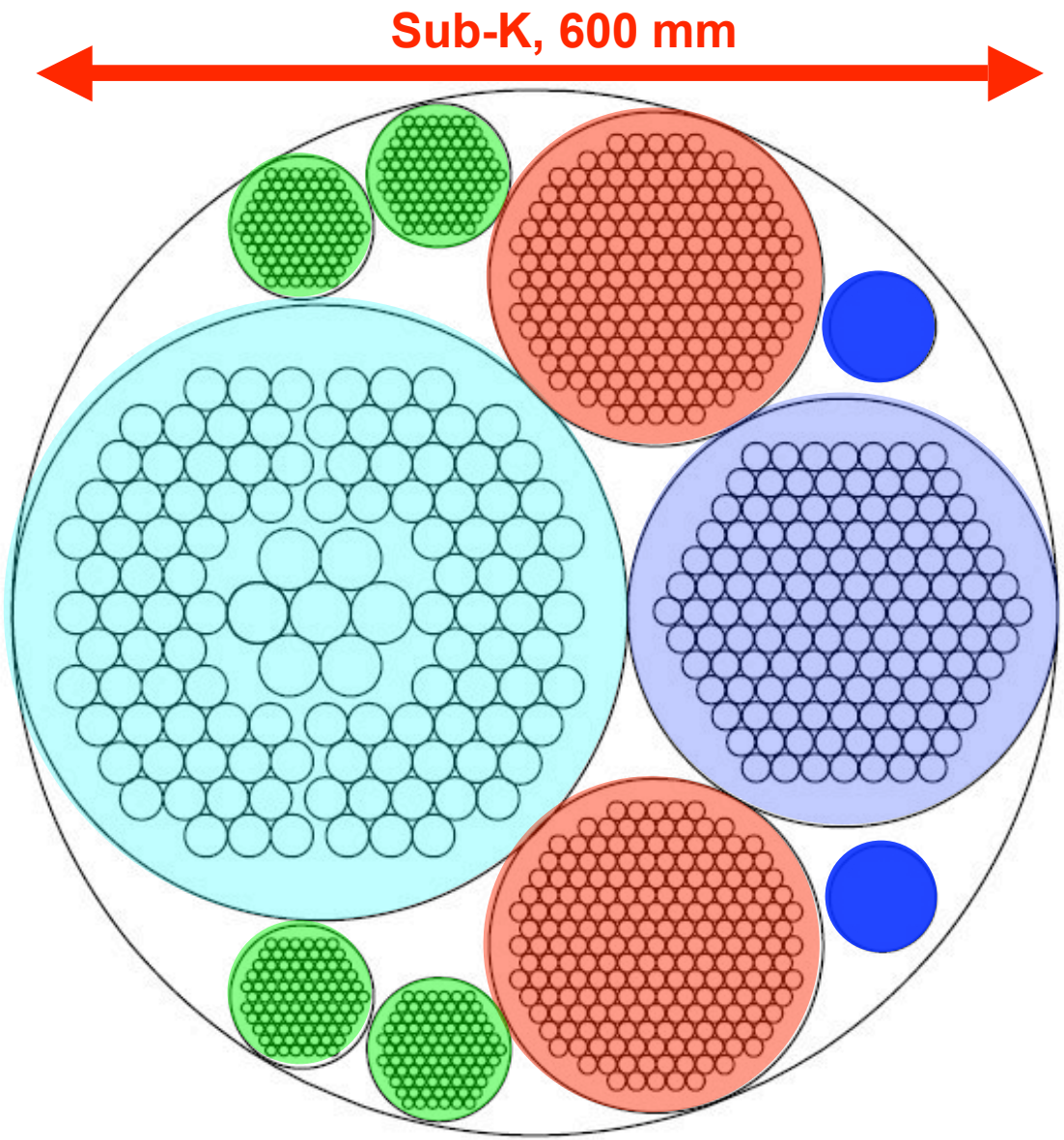
- Soyuz to L2 *(sidelobes)*
- 70, 100, 140, 240, 340 GHz *(separatio of foregrounds)*
- Total 2012 bolometers with 1006 feedhorns *(sensitivity, polarization purity)*
- Internal polarization modulators *(systematics)*
- Fast sky scan *(systematics)*

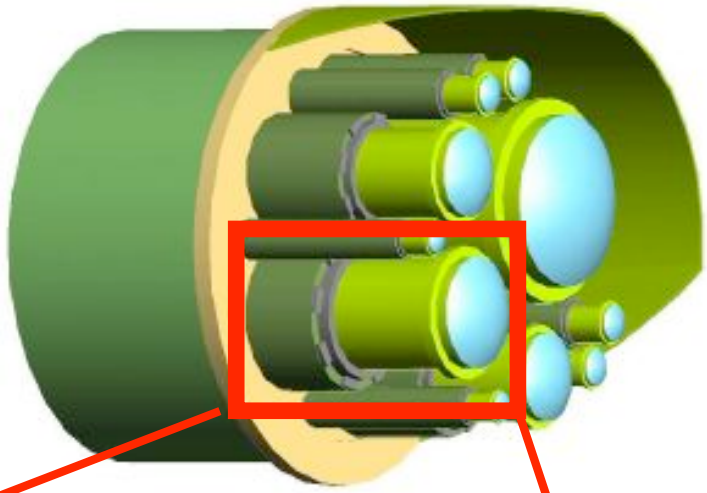


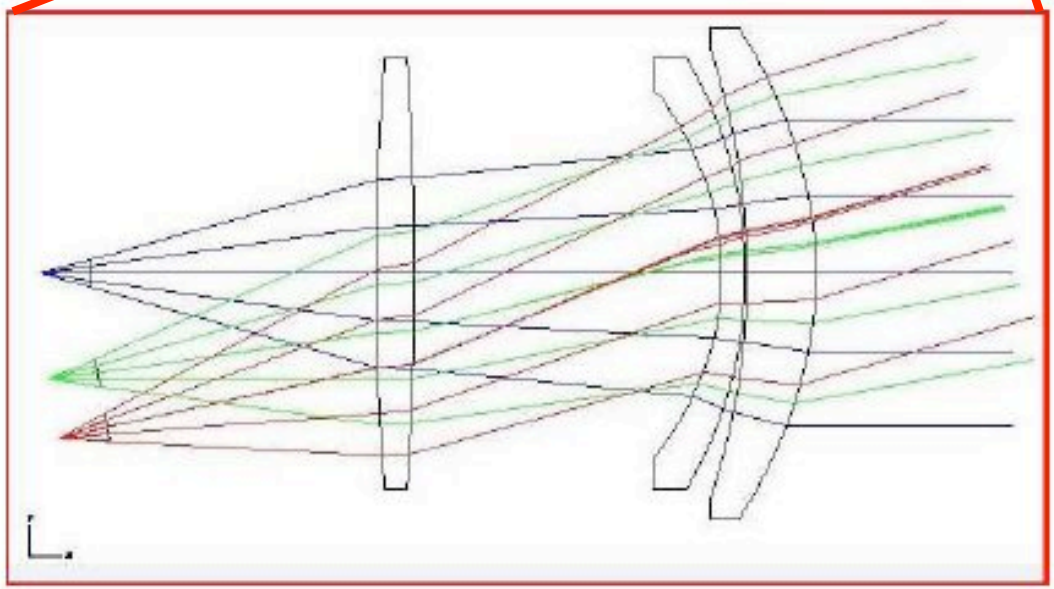
Sensitivity and frequency coverage: the focal plane

- Baseline technology: TES bolometers arrays

Corrugated feedhorns for polarization purity and beam symmetry



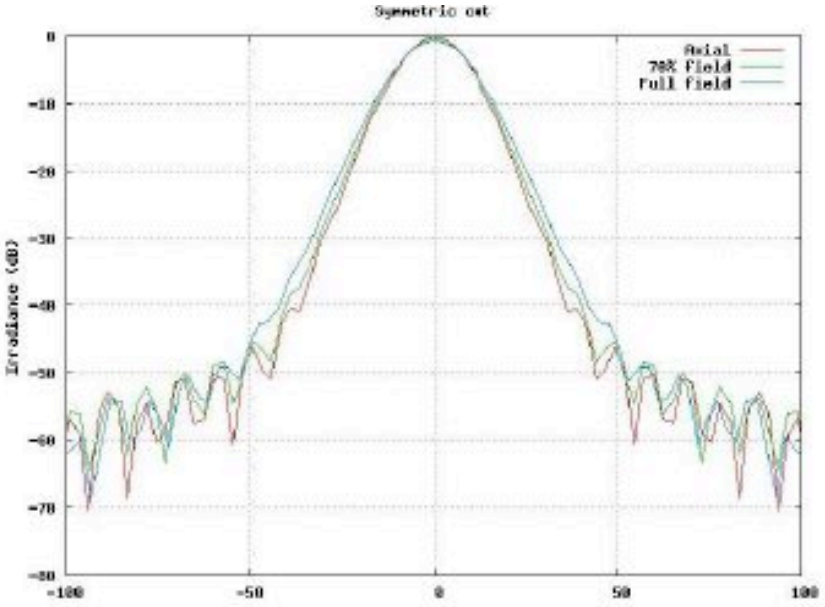




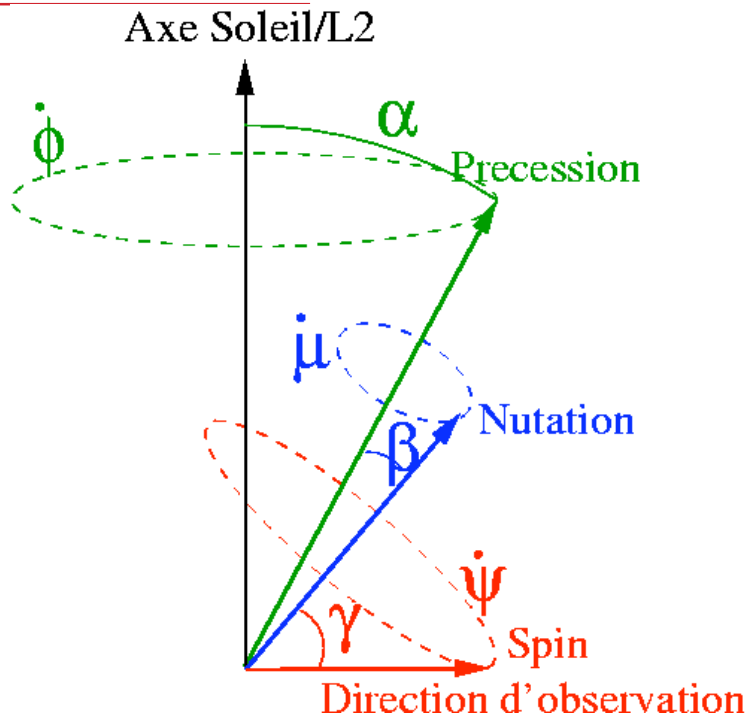
Optical system:

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

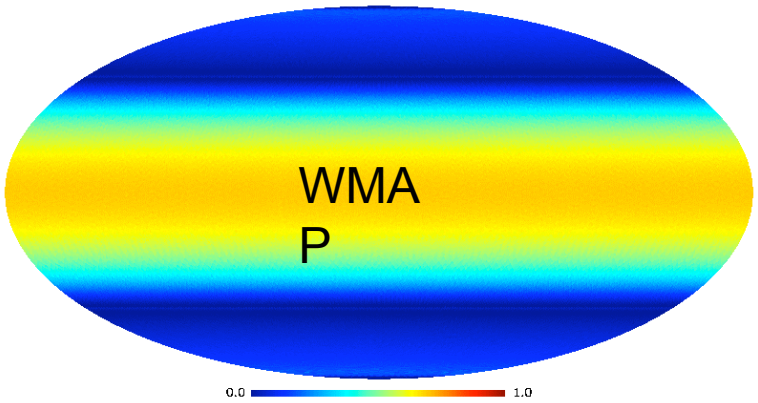
Possible solution: modified telecontric telescope

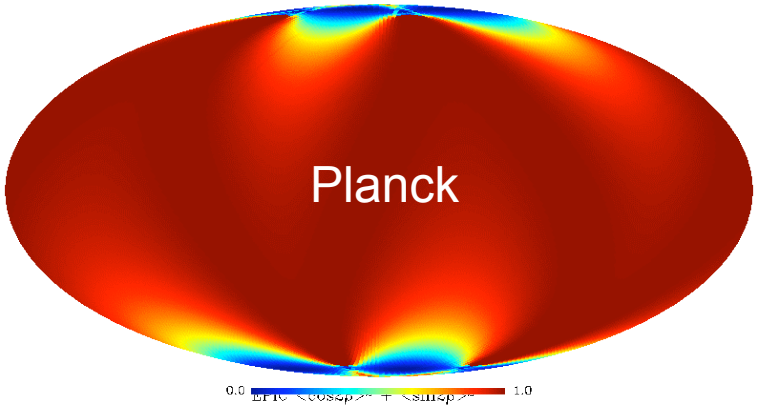


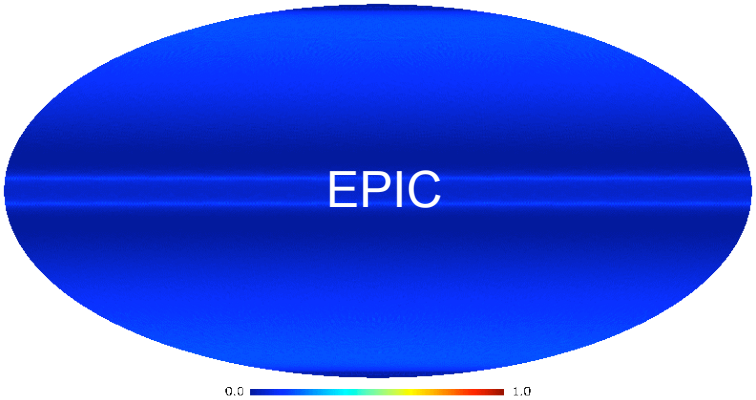
Examples: parameterization



$$\left(\sum_i \cos 2\alpha_i\right)^2 + \left(\sum_i \sin 2\alpha_i\right)^2$$







- Planck
  - γ = 85 deg, T_{spin} = 60 sec
  - a = 10 deg, T_{prec} = 6 months
- EPIC/JPL
  - γ = 45 deg, T_{spin} = 63 sec
  - a = 50 deg, T_{prec} = 3.2 h

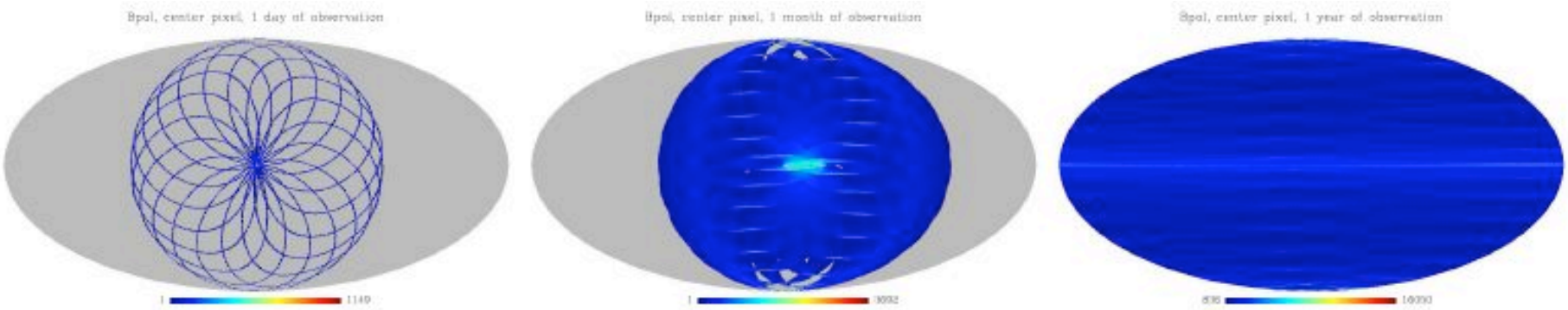


Figure 16: Hit count for a pixel at 1.6 degrees from the center of the B-pol focal plane for observation lasting 1 day (left), 1 month (center) and 1 year (right). The precession and nutation angles are 45 degrees, the precession period is 0.5 days, the nutation period is 40 min. Only one pixel at a fiducial frequency of 10Hz is represented.

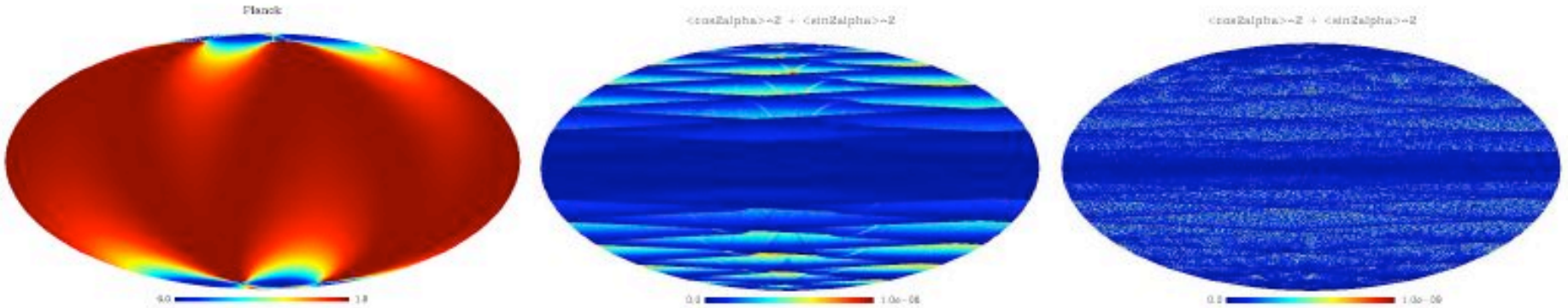
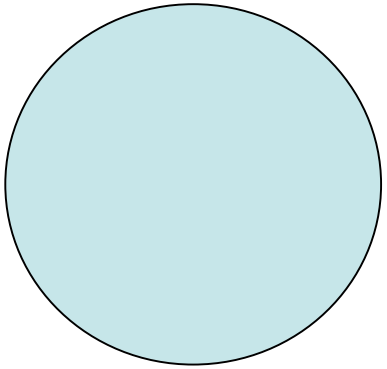


Figure 17: Maps of angular coverage relevant for polarization determination for one year of observation by a pixel at 1.6 degrees from the center of B-pol focal plane. The estimator we chose is $\langle \cos 2\alpha \rangle^2 + \langle \sin 2\alpha \rangle^2$, where α is the angle between the main axis of the polarimeter and a reference direction on the sky. The smaller the better (0=ideal, 1=worst). Compared to Planck, (left) B-pol's angular coverage is a factor 10^6 better without an internal modulator (center), and even 10^9 with a rotating Half Wave Plate (5Hz, right)

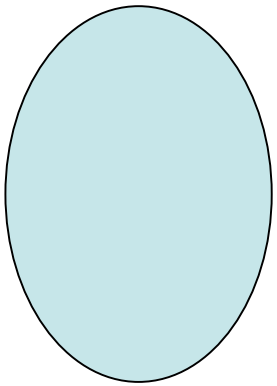
Study from Nicholas Ponthieu

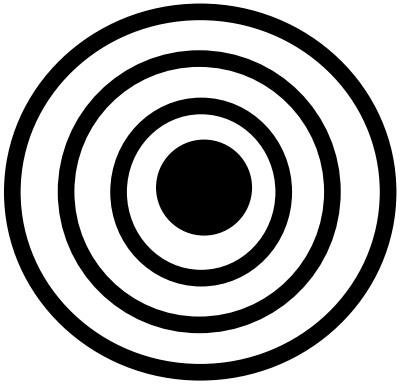
OPTION 1:
NO INTERNAL MODULATORS

- Interesting option:
  - no cryogenic mechanics / electronics
  - payload spinning is natural
- SAPAN baseline
- However:
  - Adds complexity and cost to the mission, because requires a fast spin (avoid 1/f) and a fast repointing of the satellite (to fight systematics and drifts).
  - In a real optical system, with a wide focal plane including thousands of detectors, is prone to systematic effects leaking T in Q and U, and Q into U and U into Q, thus contaminating and mixing E-modes and B-modes

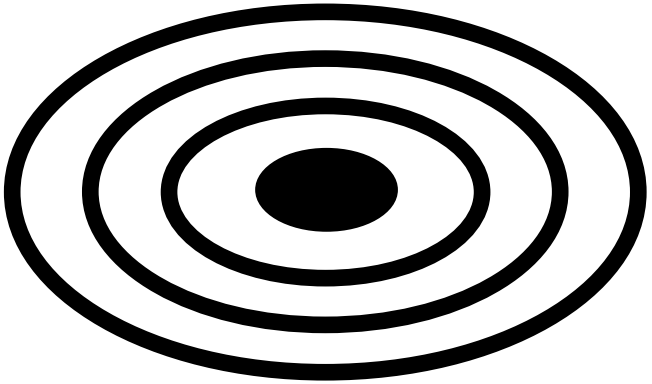


Aperture

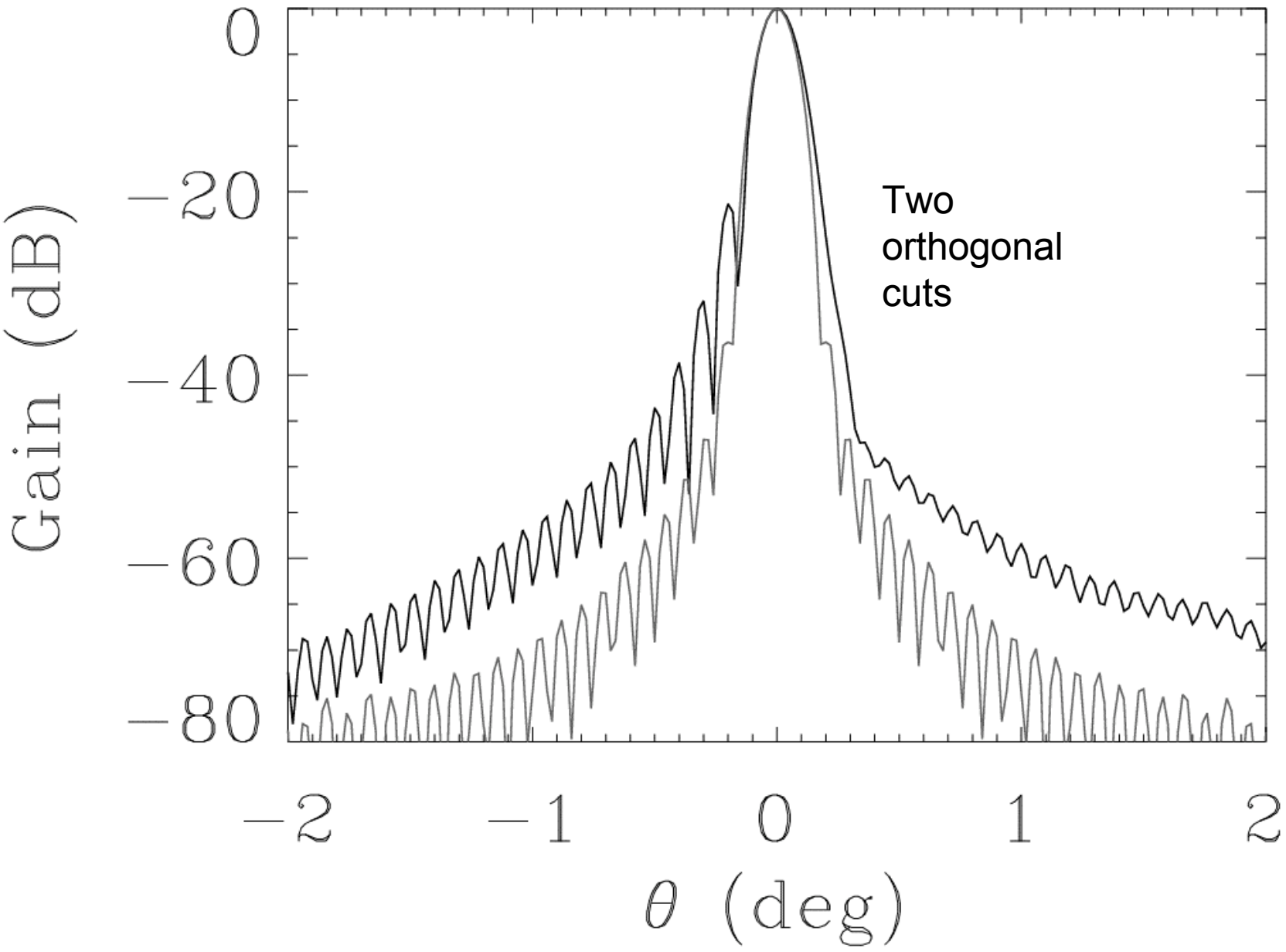


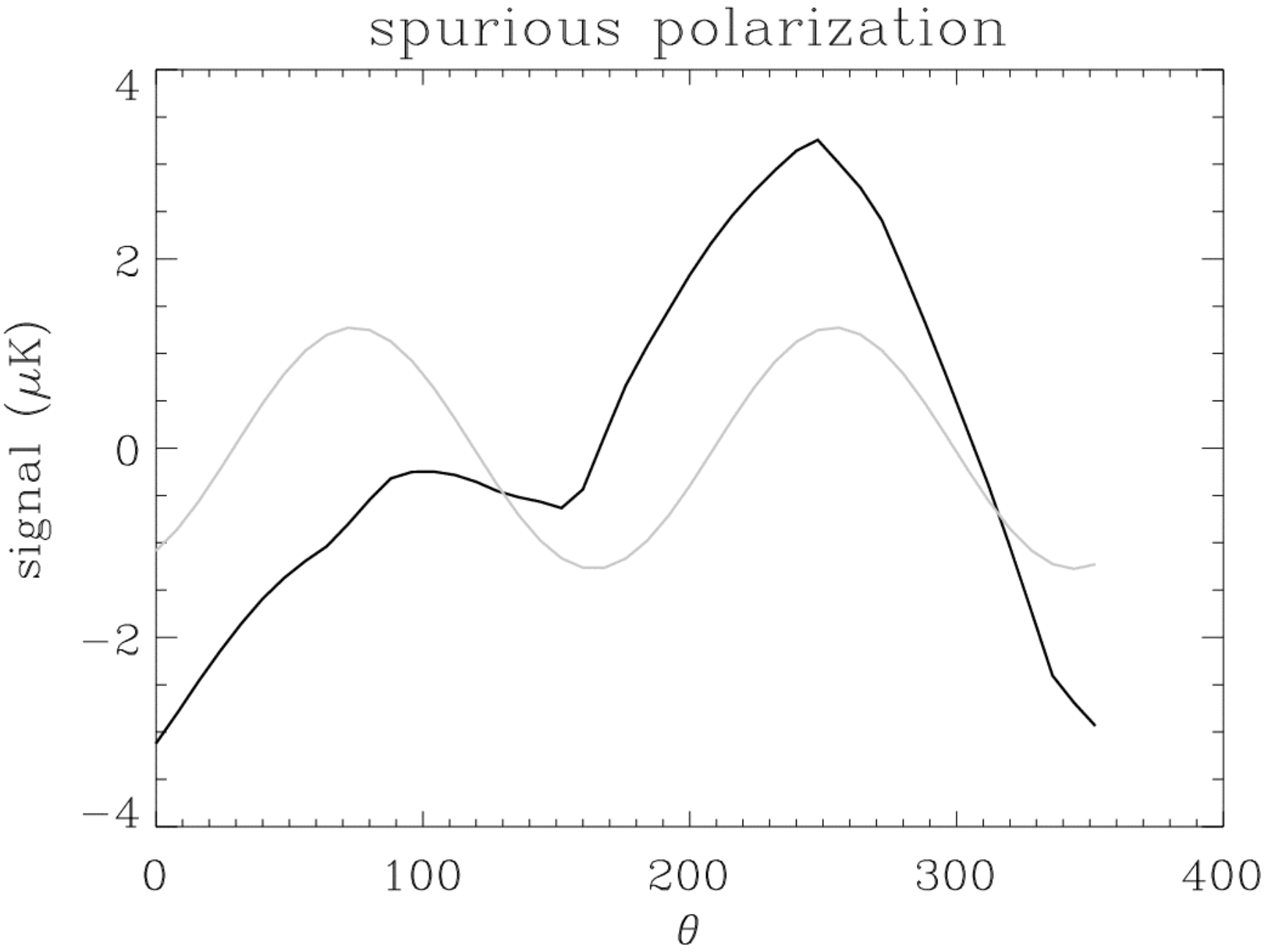


Diffraction
Pattern

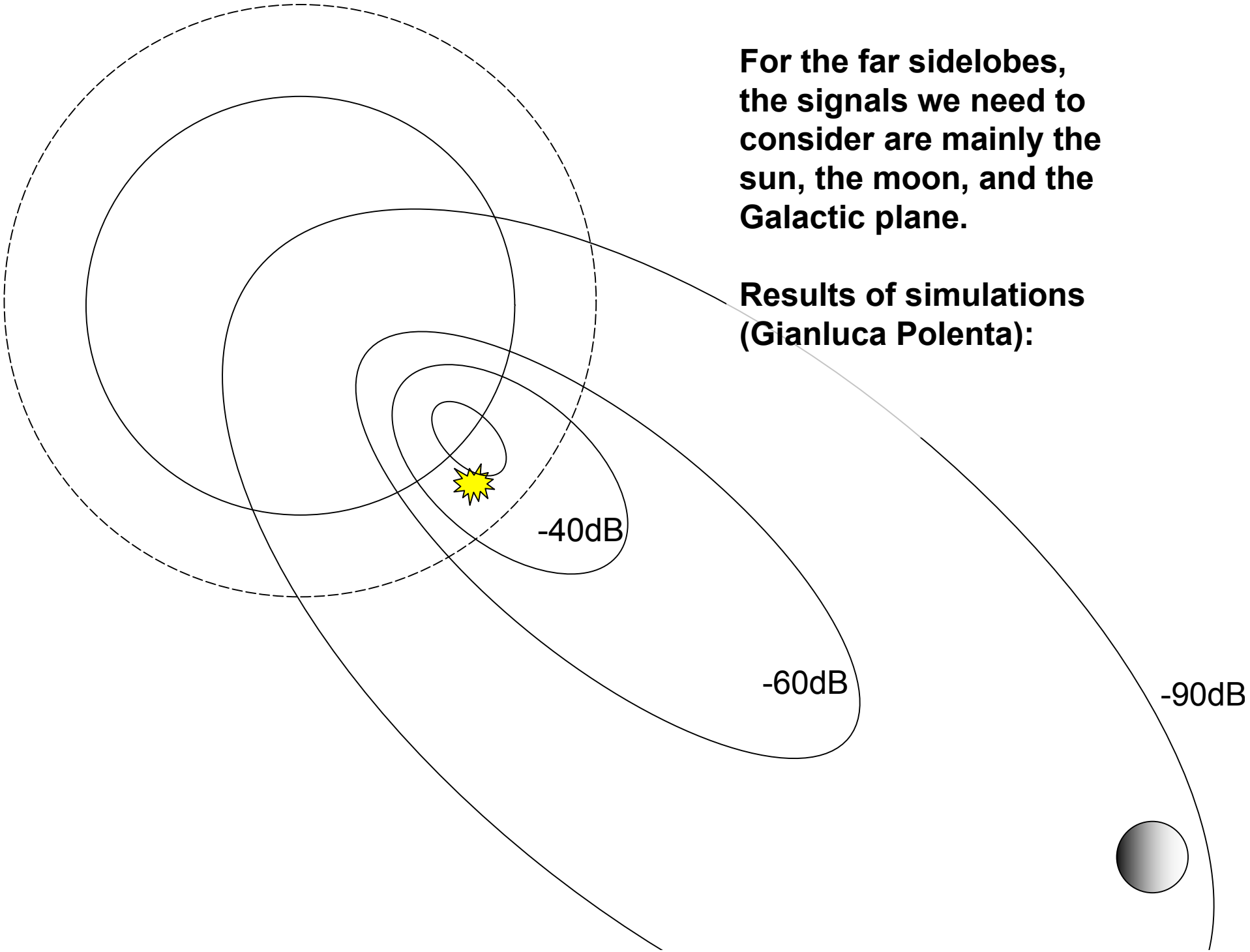


ClOVER beam simulation (side pixel) from B. Maffei





Simulation by Gianluca Polenta



For the far sidelobes, the signals we need to consider are mainly the sun, the moon, and the Galactic plane.

Results of simulations (Gianluca Polenta):

Far sidelobes must be reduced

- Obvious but not easy
- If you add 40dB of rejection at >30 deg with additional absorbing shields, the signal drops to

D(sun-spin axis) (deg)	2θ component (nK)
90	1.9
120	12
150	1
180	1.9

- Still comparable to 10 nK B-modes…

Lessons:

- Whatever configuration we select, we need to analyze this, and set specs for
  - Ellipticity and skewness of main beam
  - Level and symmetry of sidelobes and far sidelobes
- For this, a good help comes from absorbing shields. However, there is a tradeoff with detector loading.

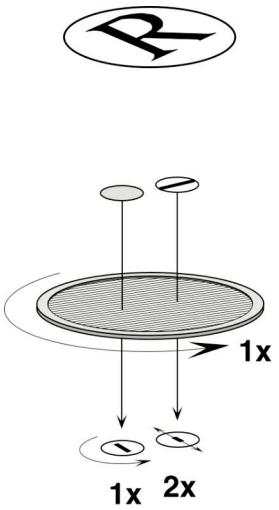
OPTION 2: INTERNAL MODULATORS

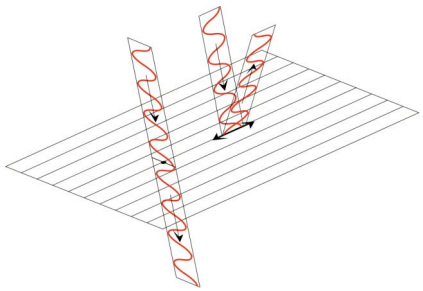
- Allow a fast, controlled modulation of polarization, reducing effects of detector 1/f noise
  - Add complexity inside the instrument
  - Relax problems with the satellite (lower cost to ESA, increase cost and risk for Scientists and National Agencies)
  - Introduce small spurious signals, due to their own non-idealities
- Several families:
  - Modulation of polarization in the beam, before antenna
  - Modulation after OMT
  - Correlation systems
  - ….

Quasi-optical polarisation modulators

G. Pisano

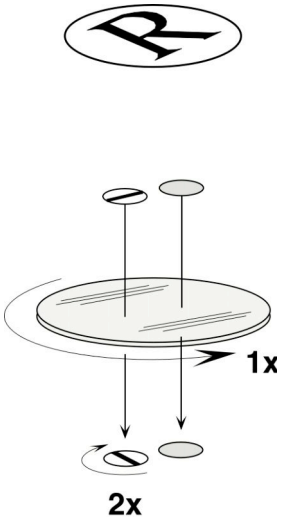
Wire-grid polariser



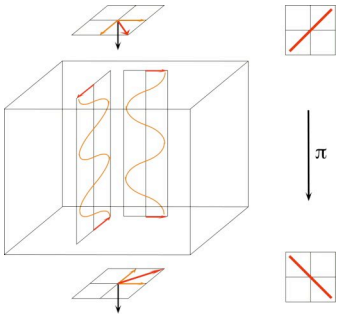


- Achromatic
- Image fixed
- Un-pol light modulated

Half-Wave Plate

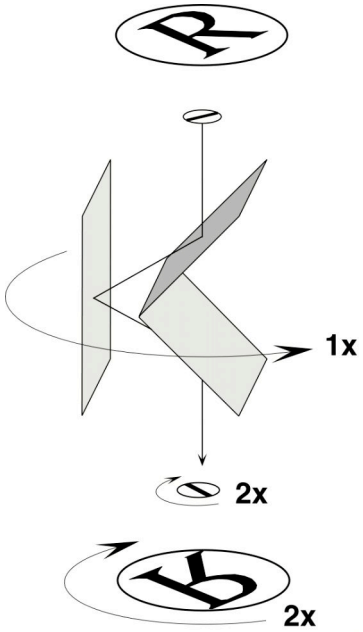


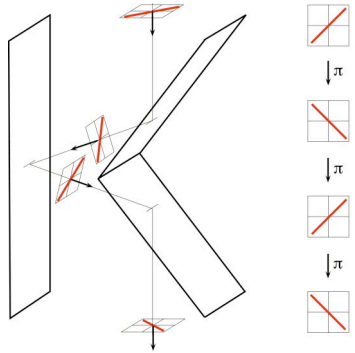
$$\Delta\phi = 2\pi h(n_e - n_o)/\lambda$$



- Monochromatic
- Image fixed
- Un-pol light not modulated

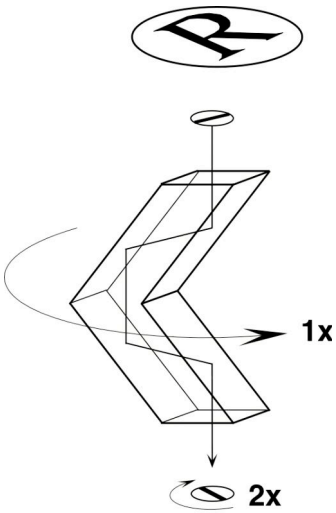
K-Mirror

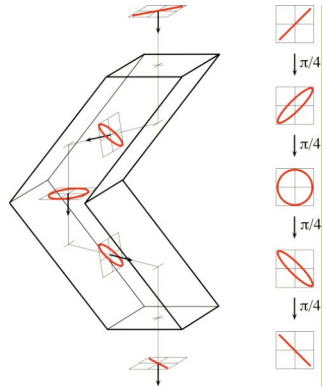




- Achromatic
- Image rotation
- Un-pol light not modulated

Fresnel double-rhomb



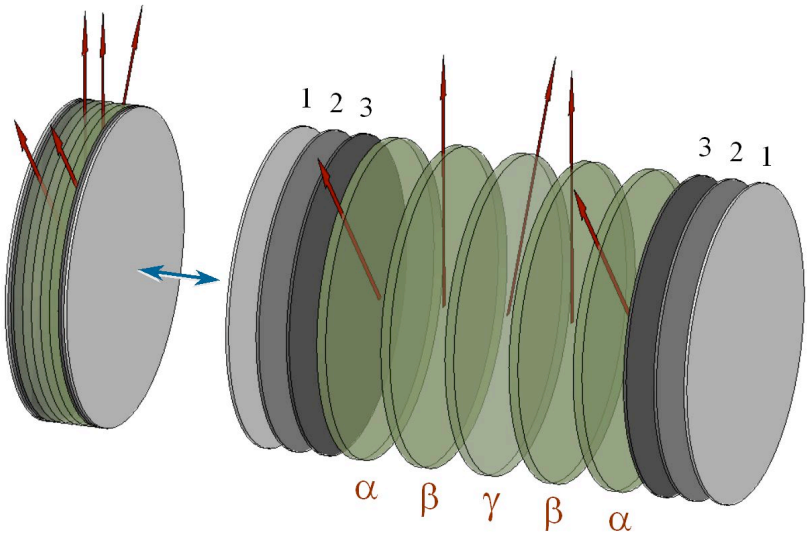


- Achromatic
- Image fixed
- Un-pol light not modulated
- High absorption

Achromatic Sapphire HWP Studies

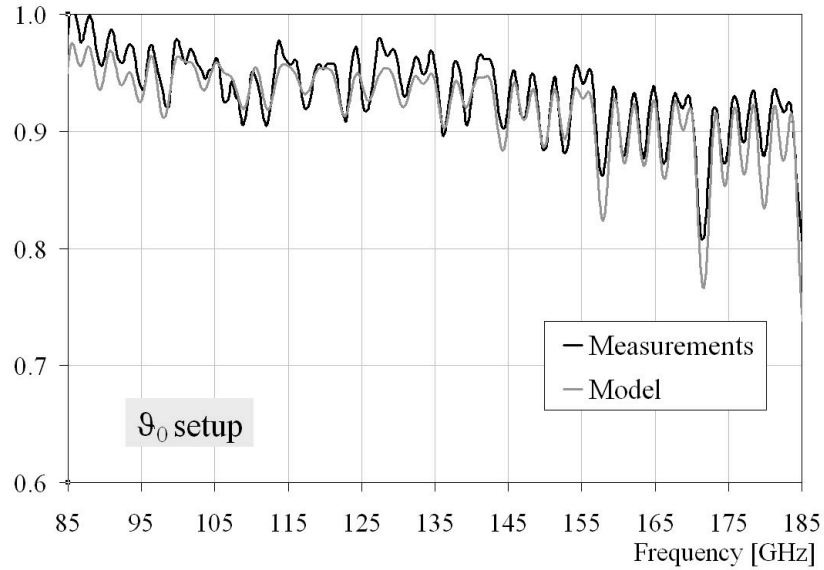
G. Pisano et al., *Applied Optics v45, n26 (2006)*
G. Savini et al., *Applied Optics v45, n35 (2006)*

Model



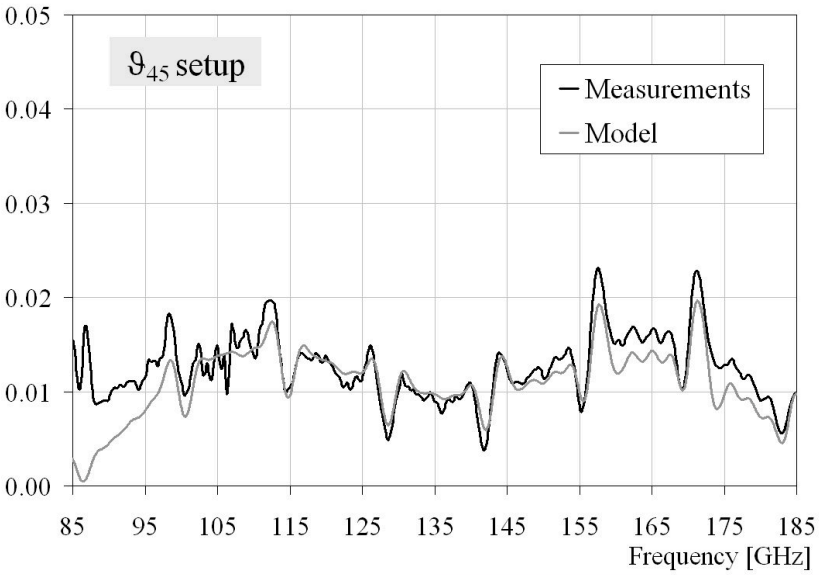
Results

Fast axis Transmission

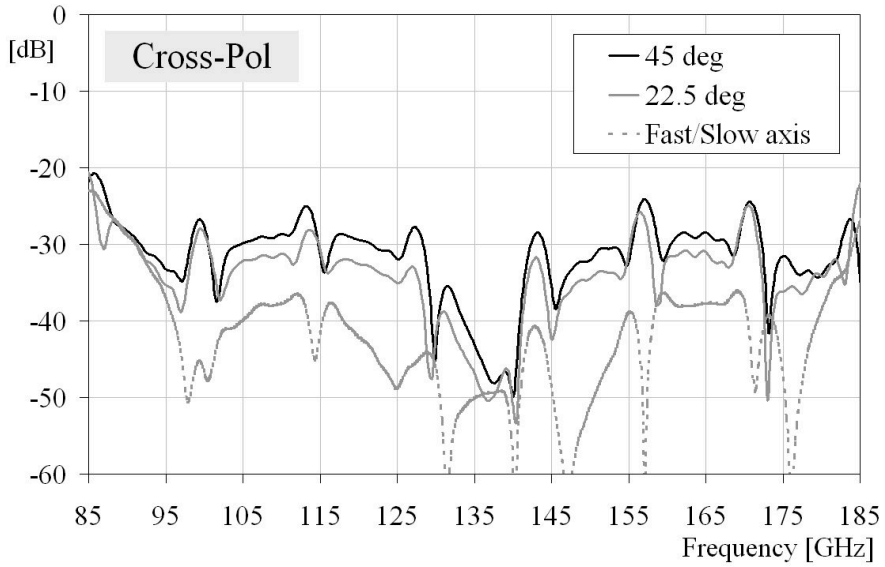


Results

Cross-Polarisation Fit



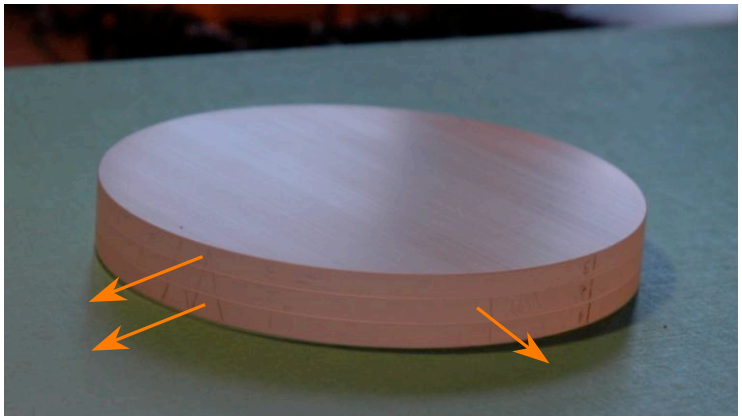
Extrapolated Cross Polarisation



97GHz HWP FTS measurement

G. Savini, B. Johnson

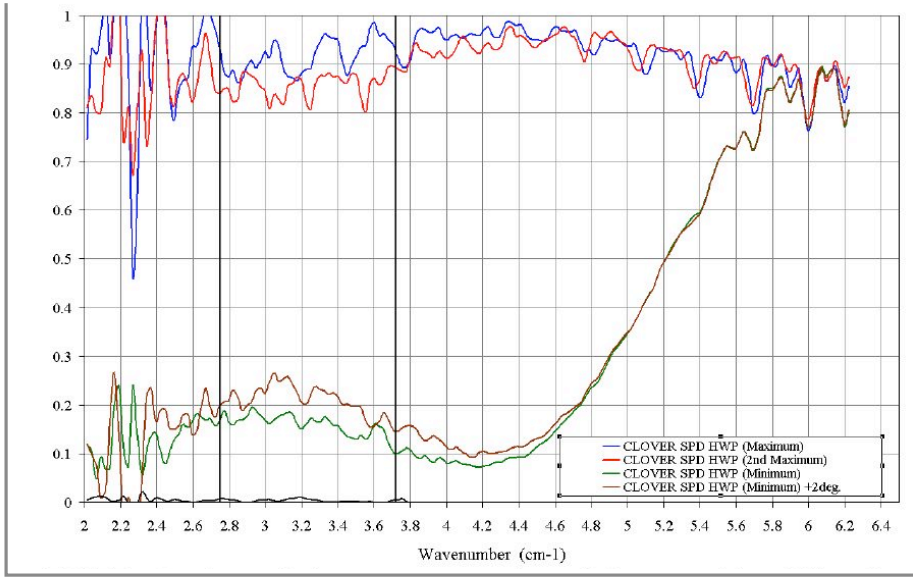
Sapphire HWP Prototype



3-plates Pancharatnam HWP (d=11cm)

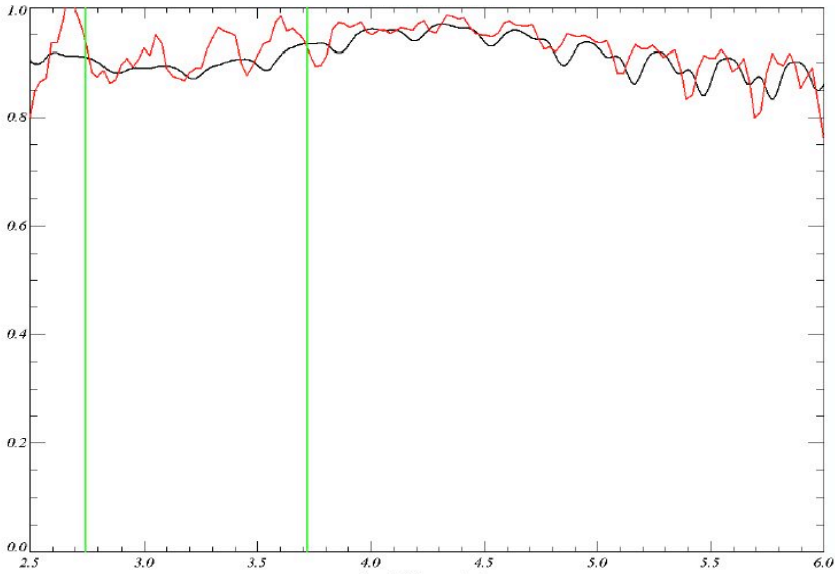
Data

Tx at different angles

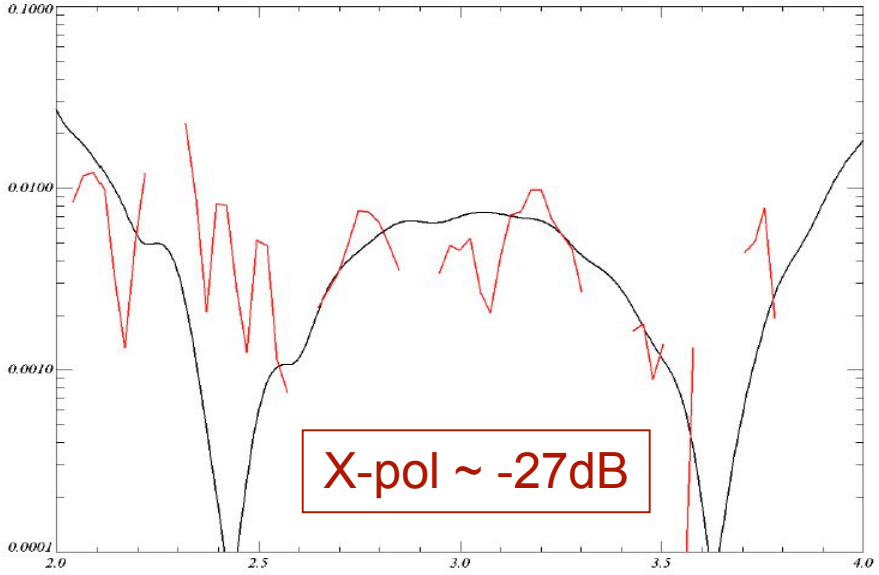


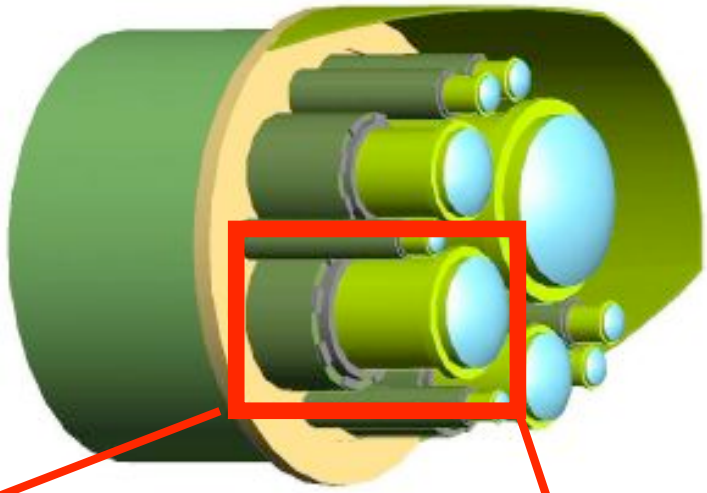
Data & Fits

Fast axis Transmission



Cross Polarisation

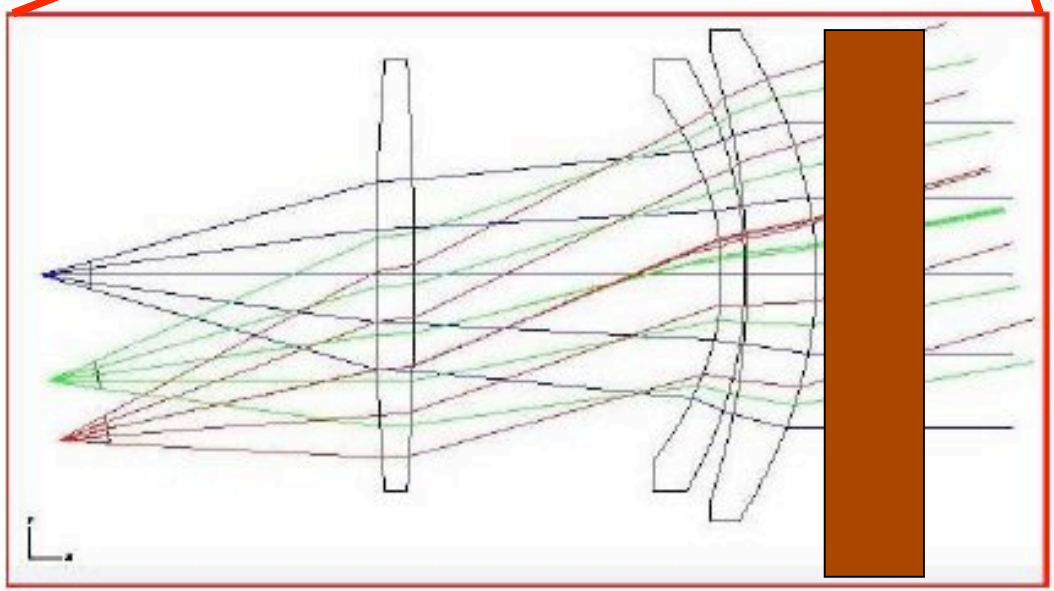




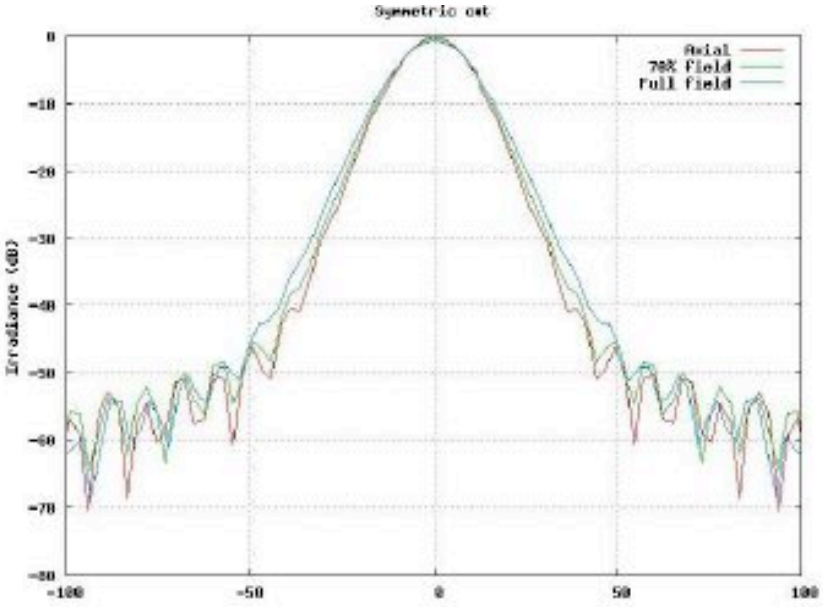
Optical system:

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

Possible solution: modified telecontric telescope



HWP



Further studies

- Polarimeters on chip
  - Studies in Cardiff, Chalmers, Manchester, Oxford, ….

Oxford Physics

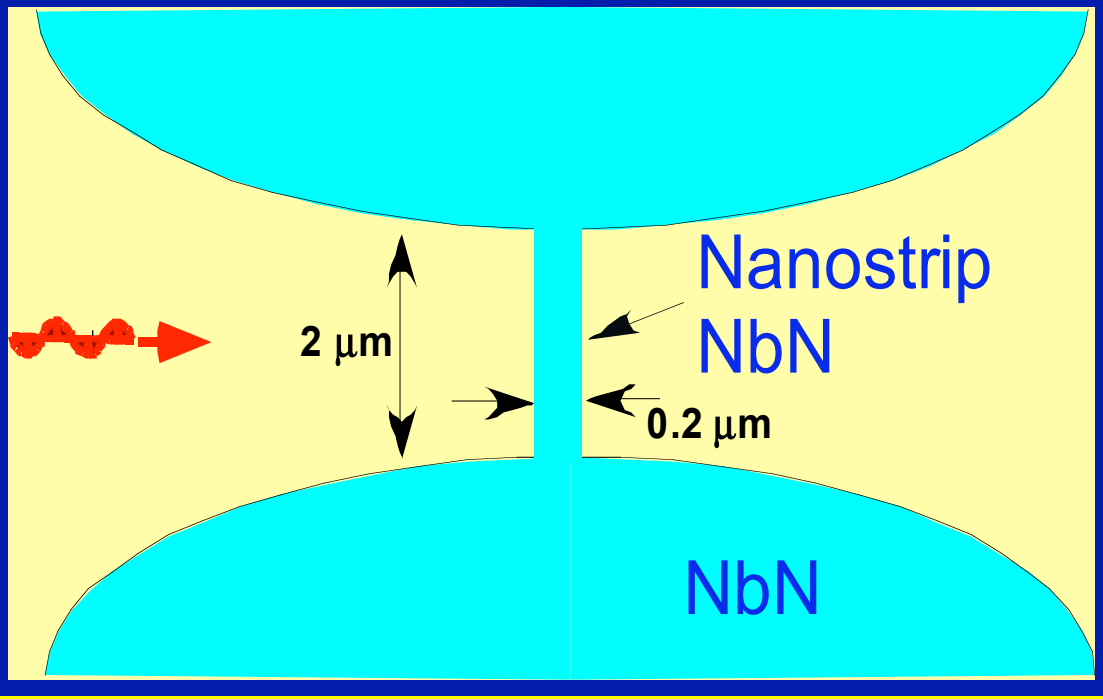
Integrated Phase Modulation

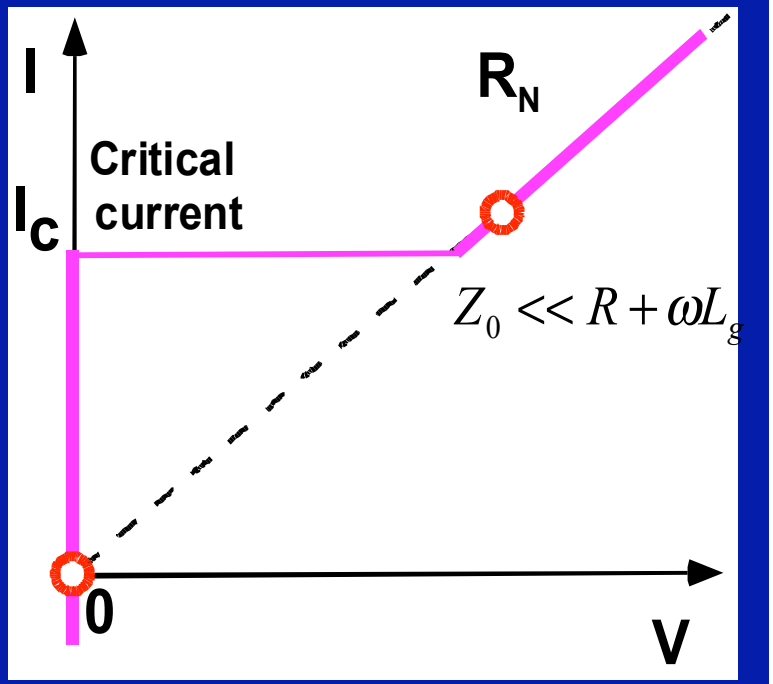
Oxford University, Ghassan Yassin, ...
Chalmers University, Leonid Kuzmin, …
Manchester University, Lucio Piccirillo, …

- Superconducting Circuits: Low loss
- Lithographic Fabrication: reliable, and mass reproducible
- Planar (microstrip): the whole Polarimeter is fabricated in planar structure and integrated in the detector circuits .

NbN Nanostrip Switch

Kuzmin



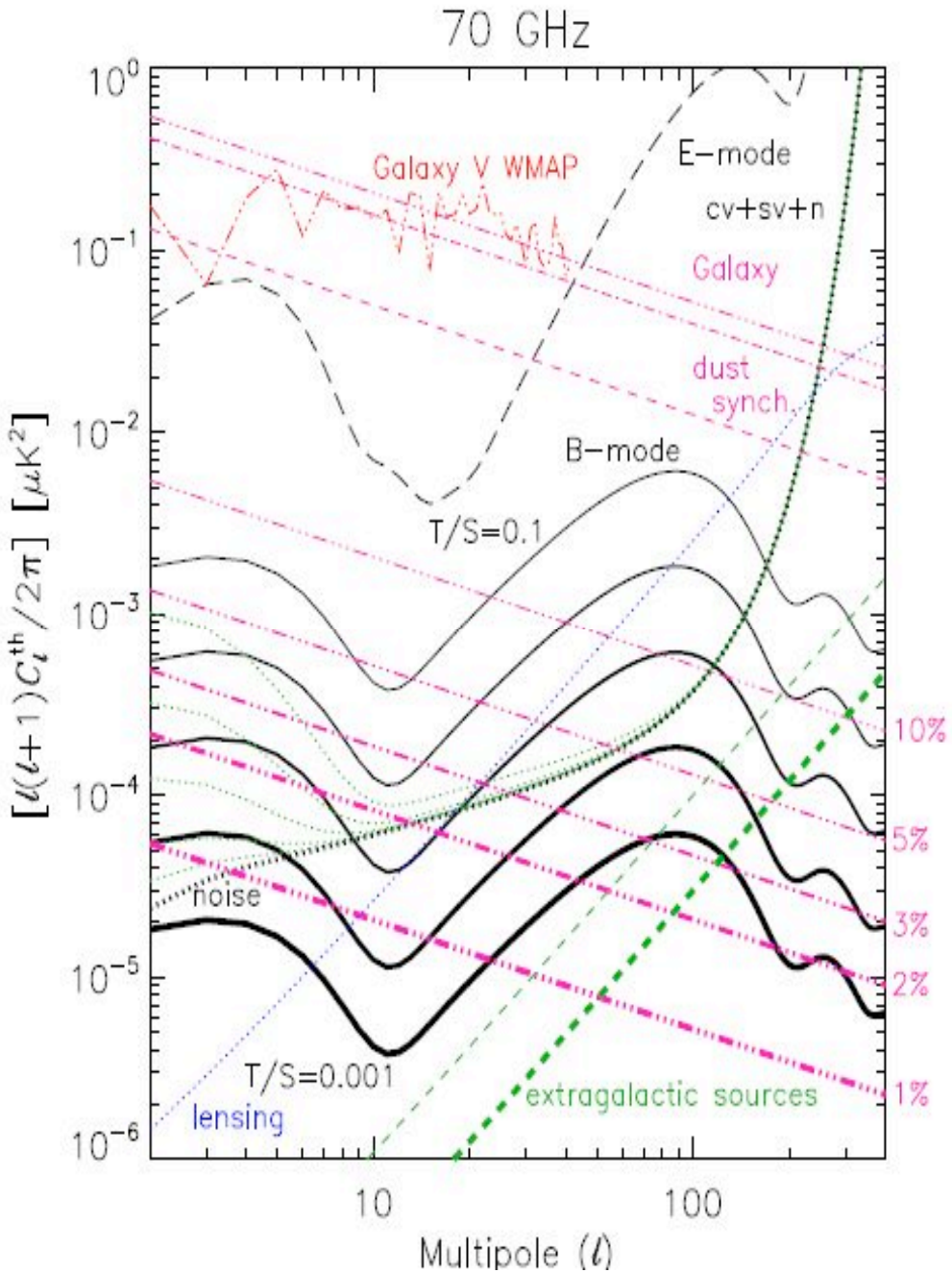


$$\omega L_c + \omega L_g << Z_0 << R$$

$$I_c = j_c * S,\ L_c = \frac{\hbar}{2eI_c},\ R = \rho\frac{l}{S}$$

90, 150, 220 GHz

- *Foregrounds ?*
  - *Tension between covering low frequencies and keeping the cost within the medium mission budget.*
  - *Final configuration to be analyzed in Phase-A*



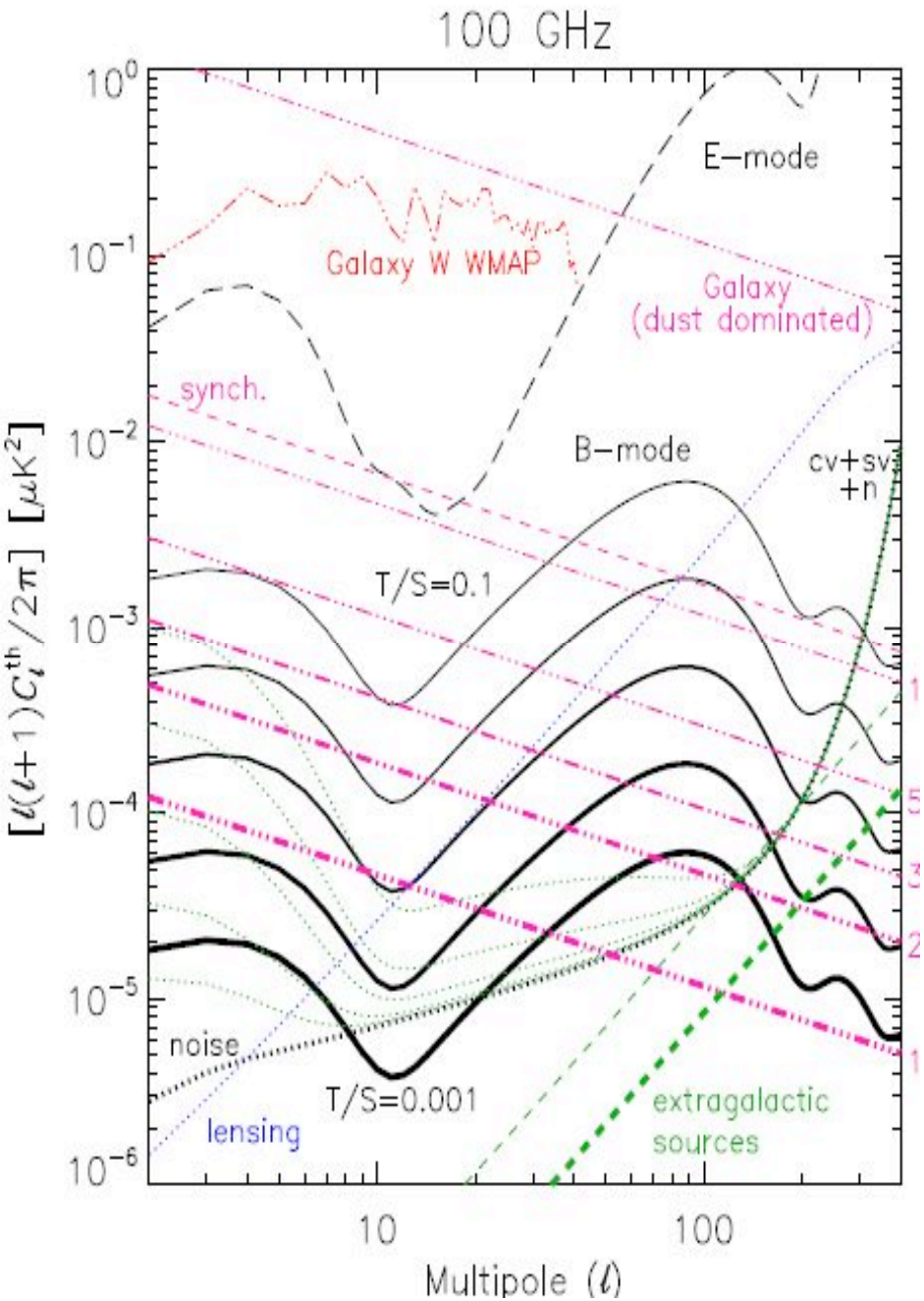


Figure from Carlo Burigana

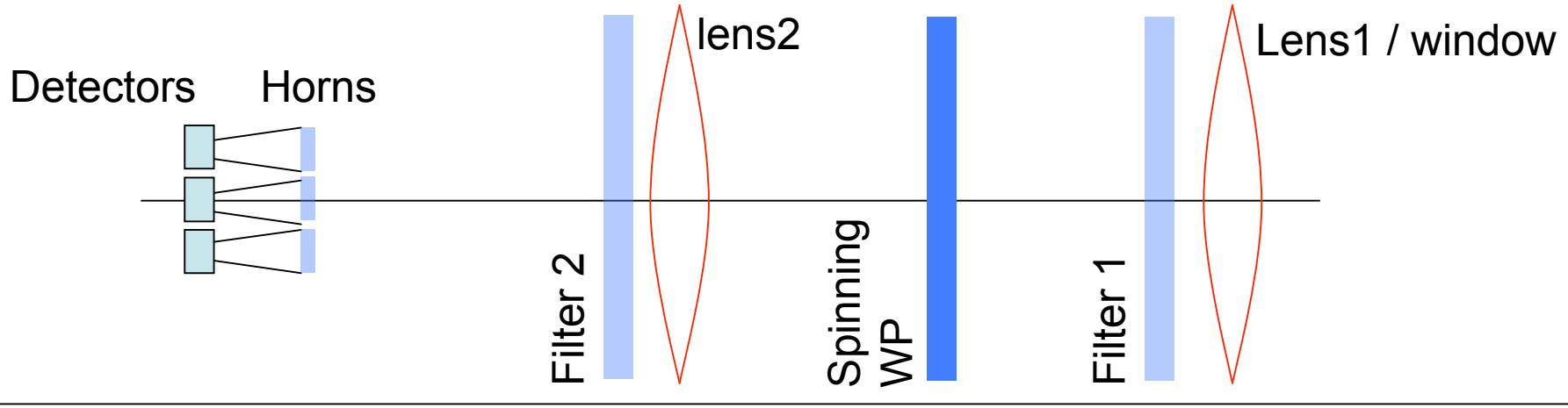
How to remove the polarized foregrounds ?

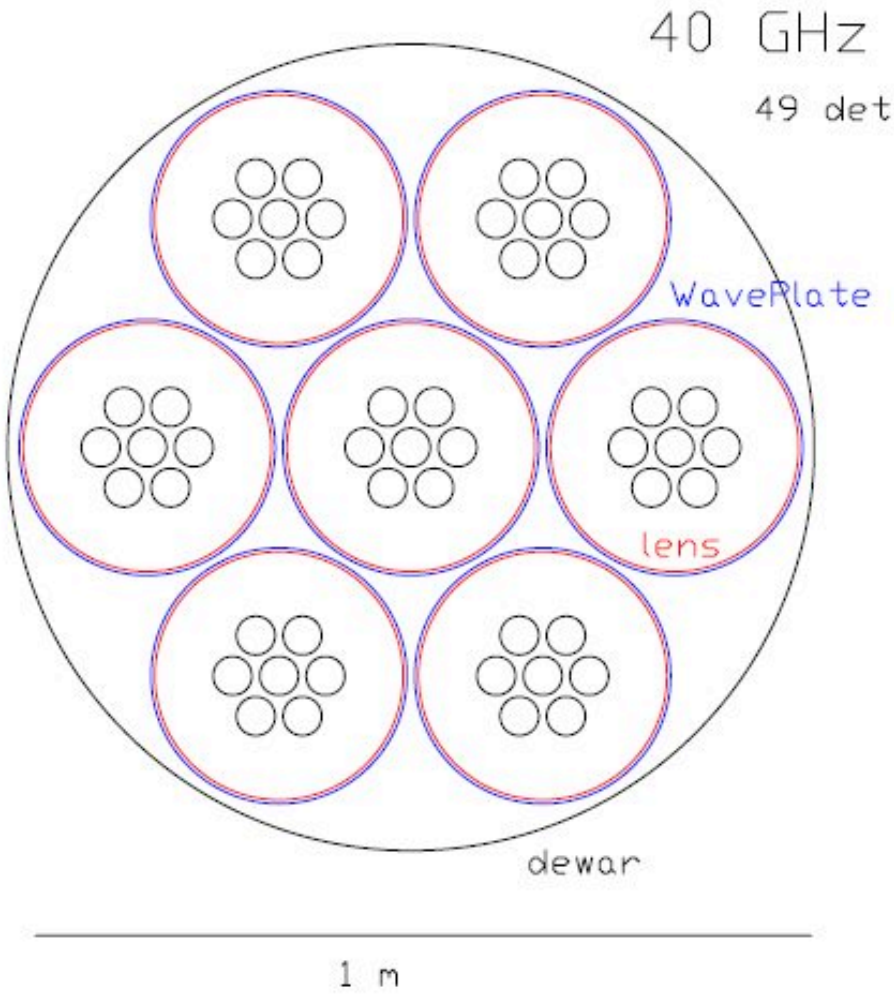
- Template fitting methods (Page et al. 2006)
- Wiener Filtering (Bouchet and Gispert 1999)
- Maximum Entropy (Hobson et al. 1998, Stolayrov et al. 2002)
- Blind methods
  - FastICA (see e.g. Stivoli et al. 2006)
  - Spectral Matching ICA (see e.g. Delabrouille et al. 2003)
  - PolEMICA (see e.g. Aumont & Macias-Perez 2007)
  - ..
- Phase methods (see e.g. Coles et al. 2003)
- ....

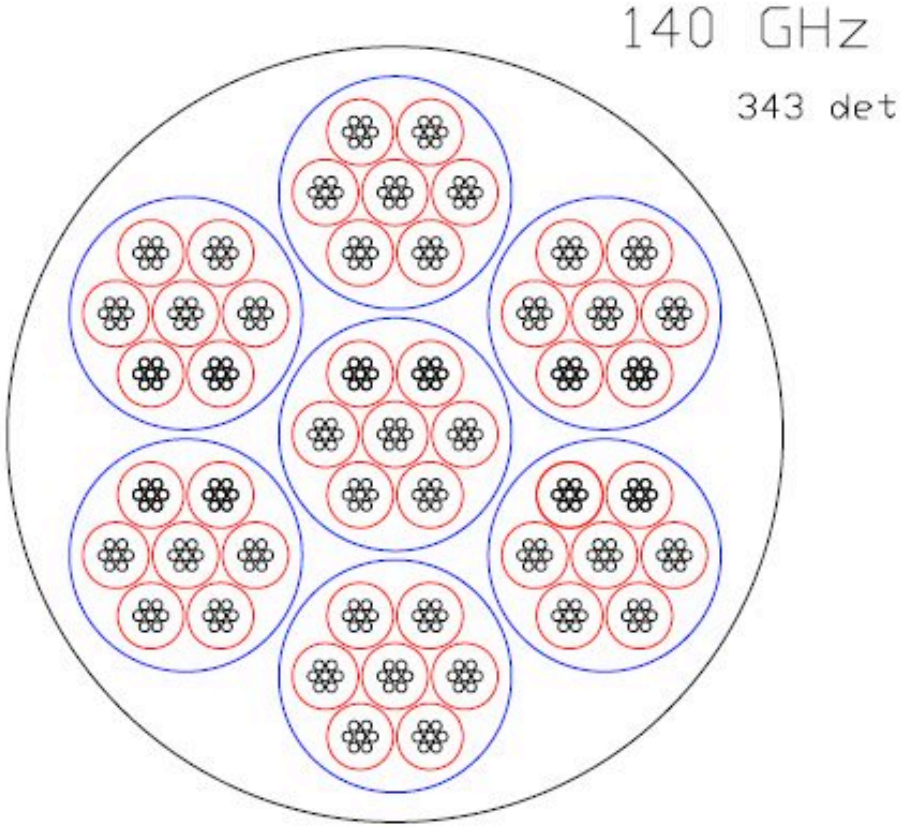
Will this really work at <1% ?
Tradeoff coverage/cleaninless ?
To be studied in phase-A and with pathfinder experiments (BB-Pol) !

A clean polarimeter

- Use sensitive (and many) detectors
- Use corrugated feedhorns
- Avoid off-axis positions in the focal plane
- Use a polarization modulator (waveplate)
- Optimize for narrow freqeuncy bands
- Keep it cold
- Cover a wide frequency range
- Cover a wide fraction of the sky to get the reionization peak and the first peak of B-modes
- BB-Pol: scan the sky from a balloon during the arctic night (an azimuth spinning telescope as in Archeops)
- Arctic LDBs in the polar night are possible


Detectors
Horns
lens2
Lens1 / window
Filter 2
Spinning WP
Filter 1


40 GHz
49 det
WavePlate
lens
dewar
1 m


140 GHz
343 det

- *Will we be able to detect B-modes ?*

  – We do not know for sure.

  – However, it is the only opportunity we have to explore Physics around the Planck scale, where
    - Gravity unifies with the other forces
    - We can test Superstring or M theories
    - … ? …

  – When you explore a new continent you always discover something new.