45 Years of CMB Science

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Prediction of Cosmic Background Radiation

- The cosmic microwave background was predicted in 1948 by George Gamow, Ralph Alpher, and Robert Herman.
- Alpher and Herman were able to estimate the temperature of the cosmic microwave background to be 5 K,

Relic Radiation from THE BIG BANG

1965 Penzias & Wilson discover isotropic emission at λ=7.35 cm. If a blackbody, T=3±0.5 K. Penzias talks on the phone to Bernie Burke, who heard from Ken Turner about a talk by P.J.E. Peebles (Princeton) who had predicted the universe would be filled with a 5 K radiation.

Discovery of the Cosmic Background Radiation (CBR).

Arno Penzias & Robert Wilson
Nobel Prize (1978)

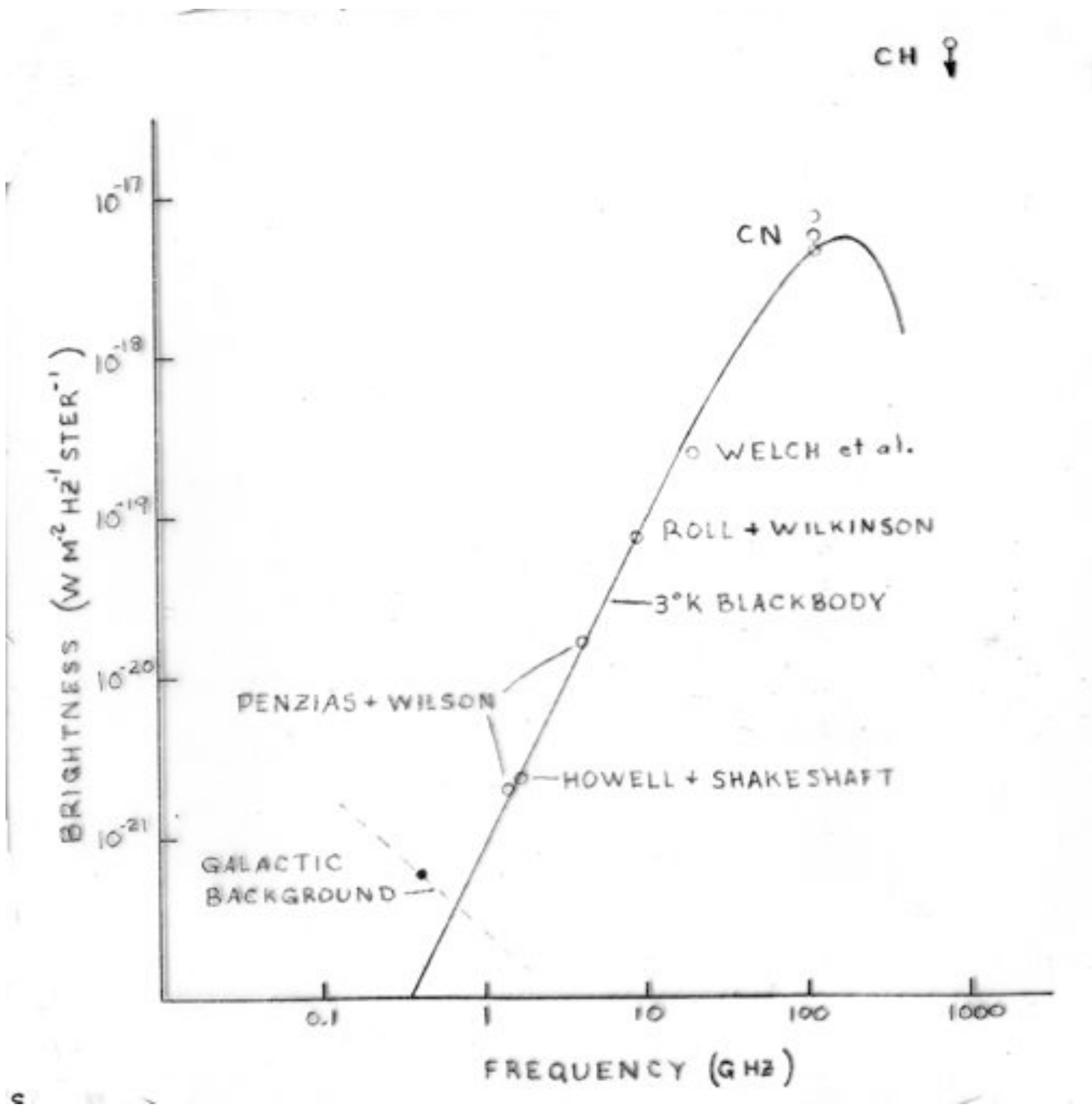
Jim Peebles

Bernie Burke

Confirmation

- The first confirmation came quickly from an unexpected source. From 1939 to 1943 Dunham, Adams and McKellar had measured the rotational excitation of CN molecules in diffuse interstellar clouds from their absorption of star light. Herzberg wrote in his standard book on the interstellar medium.
  - "From the intensity ratio of the lines a rotational temperature of 2.3 degrees follows, which of course has only a very restricted meaning."
- The excitation of CN molecules was remembered by 3 separate groups.
  - Burnie Burke told George Field about the measurements. George had written a paper while an assistant professor at Princeton ...
  - Pat Thaddeus asked Nick Wolfe about tests for radiation and Nick remembered the CN.
  - Iosif Shklovsky remembered the CN.
- By the end of the year Wilkinson and Roll had made a measurement at 3-cm wavelength which agreed with P-W.

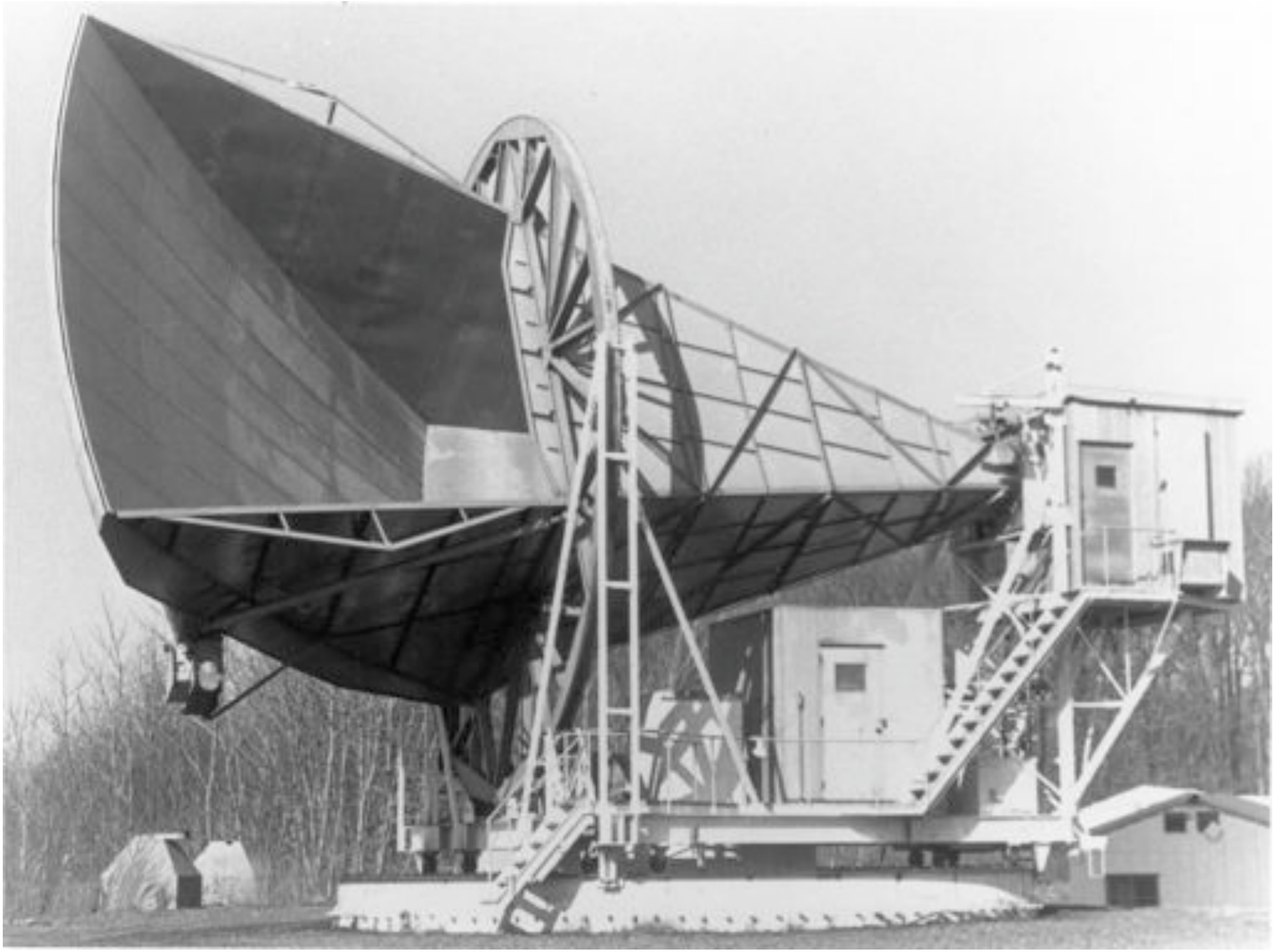
Measurements of the CMBR After a Year



1965: Discovery of the CMB

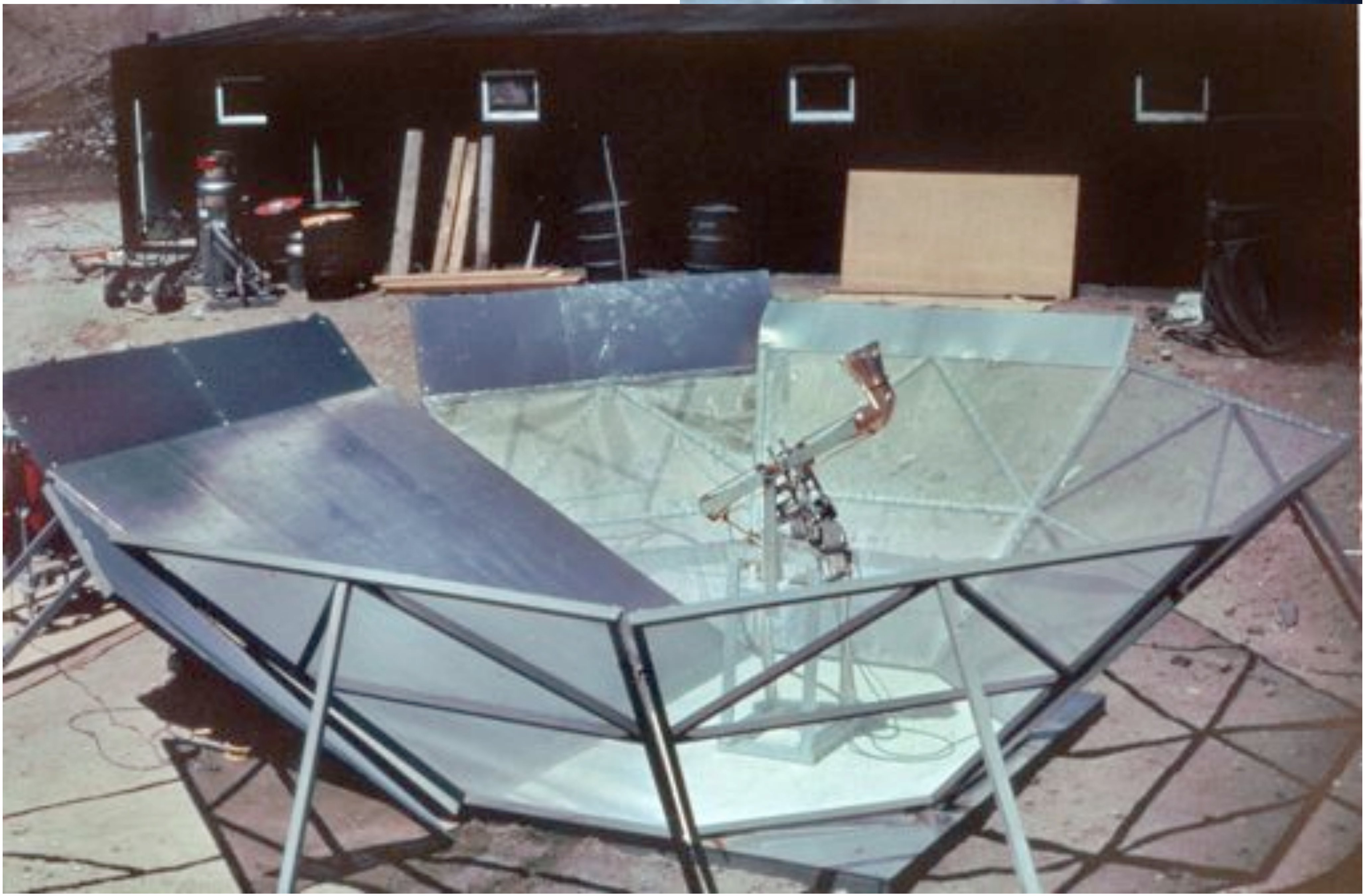

HORN ANTENNA
NATIONAL HISTORIC LANDMARK

The 20-foot (6-m) Horn Reflector



Penzias & Wilson / Bell Labs Receiver at Deutsches Museum

Dave Wilkinson's



Joseph Silk Talk & Paper - 1967

Nature 215, 1155 - 1156 (09 September 1967)

Fluctuations in the Primordial Fireball

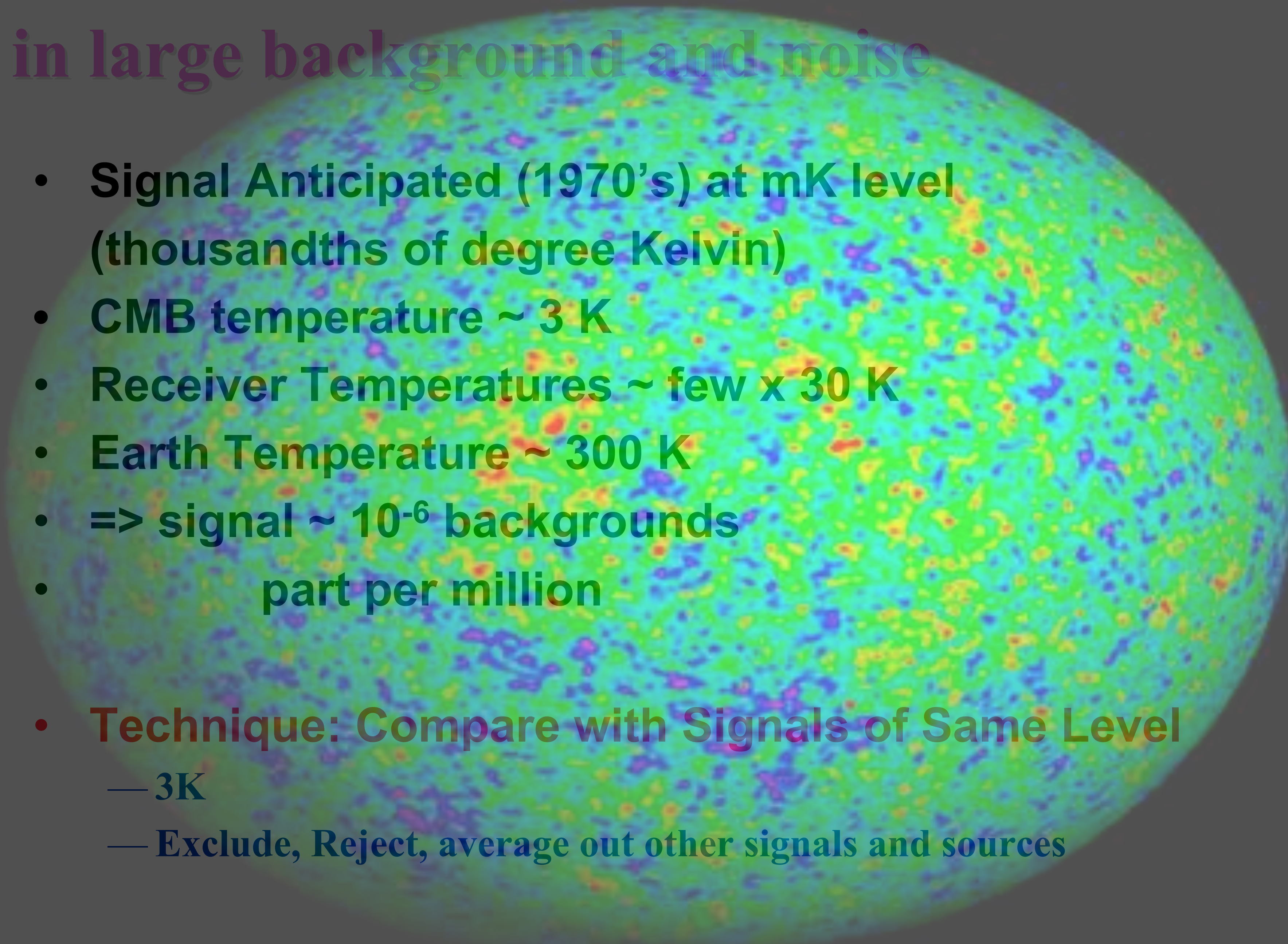
JOSEPH SILK

Harvard College Observatory, Cambridge, Massachusetts.

ONE of the overwhelming difficulties of realistic cosmological models is the inadequacy of Einstein's gravitational theory to explain the process of galaxy formation[1–6]. A means of evading this problem has been to postulate an initial spectrum of primordial fluctuations[7]. The interpretation of the recently discovered 3° K microwave background as being of cosmological origin[8,9] implies that fluctuations may not condense out of the expanding universe until an epoch when matter and radiation have decoupled[4], at a temperature T_D of the order of 4,000° K. The question may then be posed: would fluctuations in the primordial fireball survive to an epoch when galaxy formation is possible

CMB: Seeking a very small signal

in large background and noise

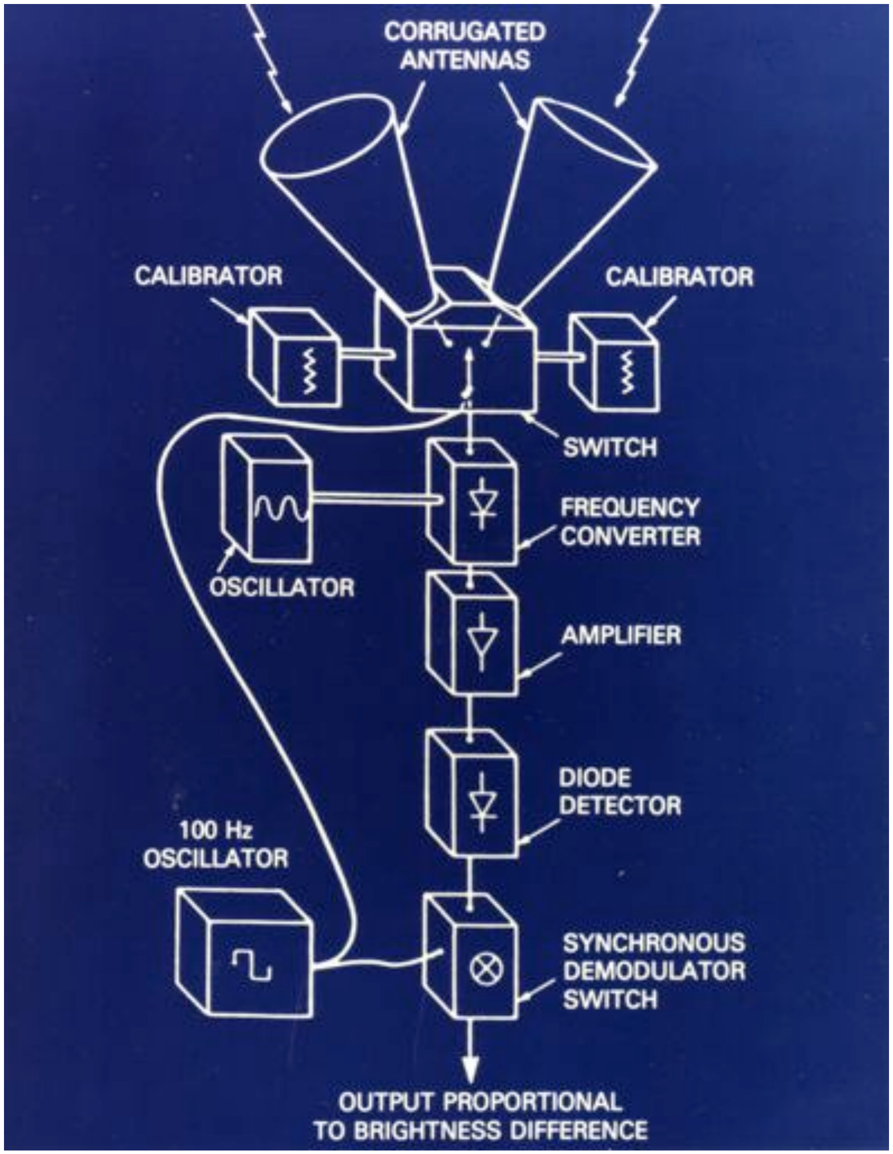


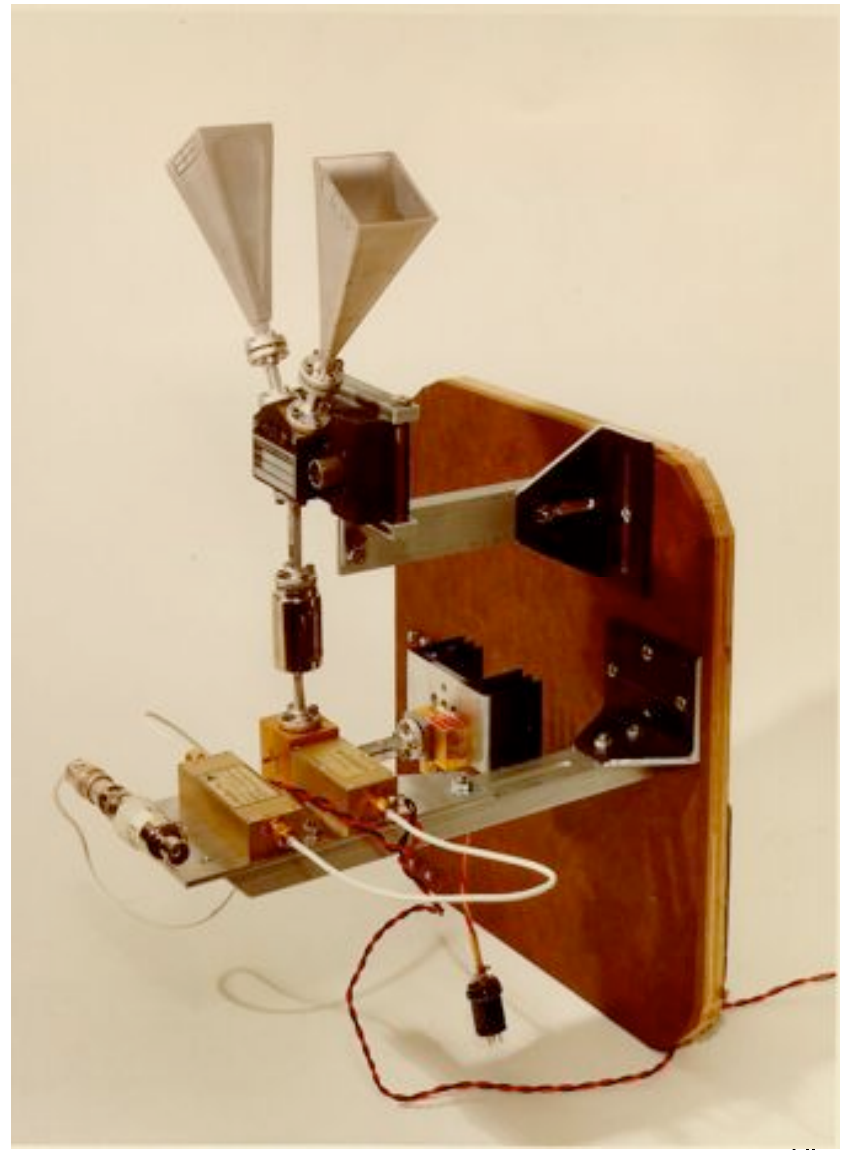
- Signal Anticipated (1970's) at mK level (thousandths of degree Kelvin)
- CMB temperature ~ 3 K
- Receiver Temperatures ~ few x 30 K
- Earth Temperature ~ 300 K
- => signal ~ 10^{-6} backgrounds
- part per million

- Technique: Compare with Signals of Same Level
  - 3K
  - Exclude, Reject, average out other signals and sources

DMR

Differential Microwave Radiometer

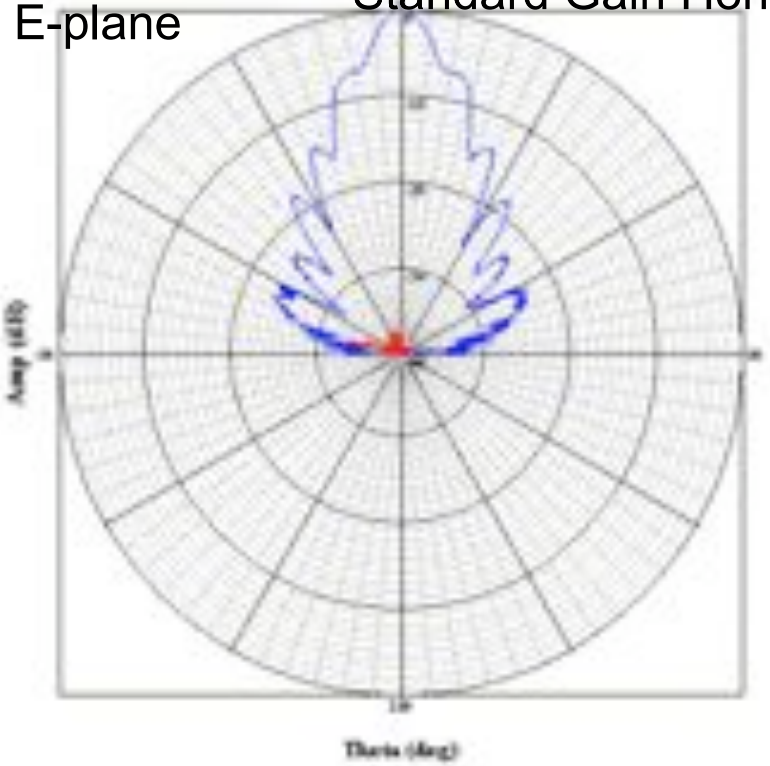




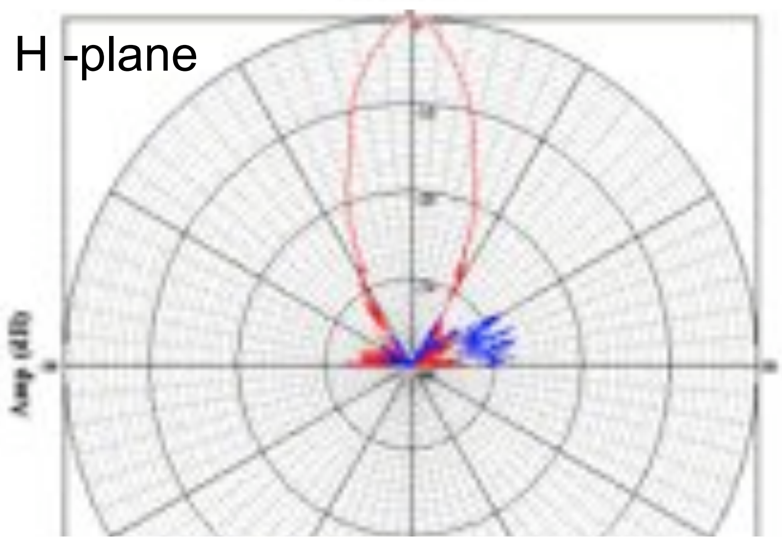
Corrugated Horn Antennas

Standard Gain Horn

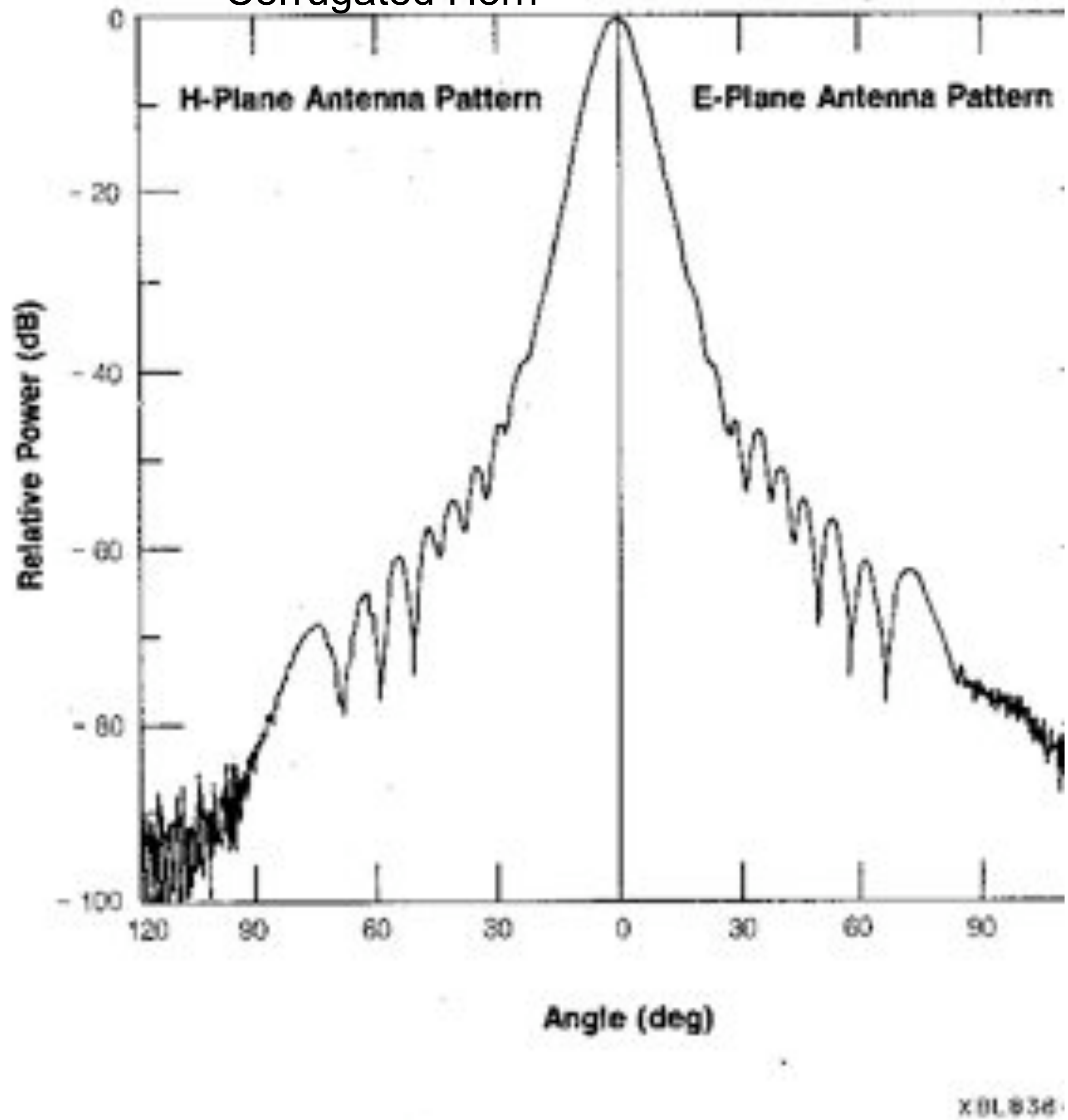
E-plane

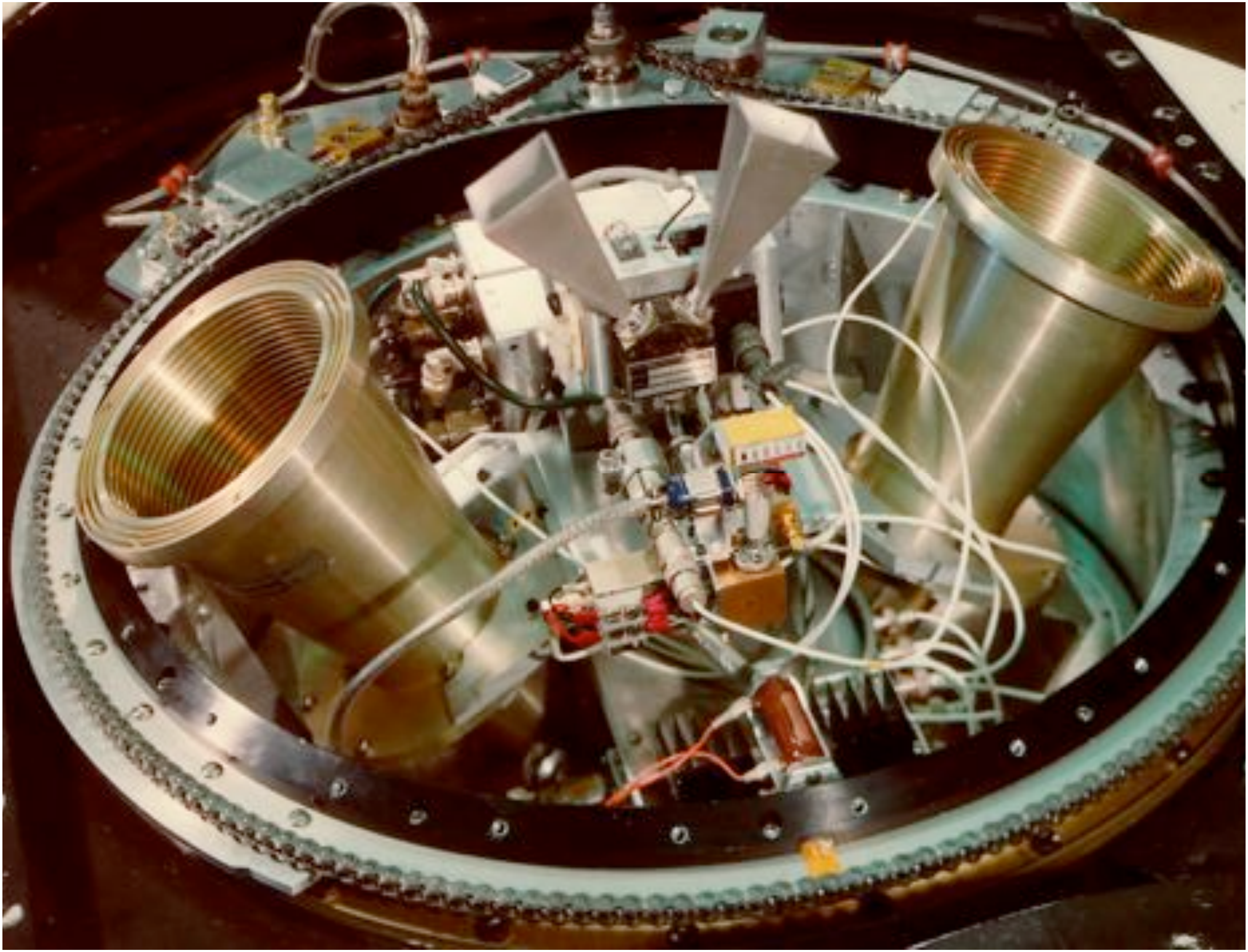


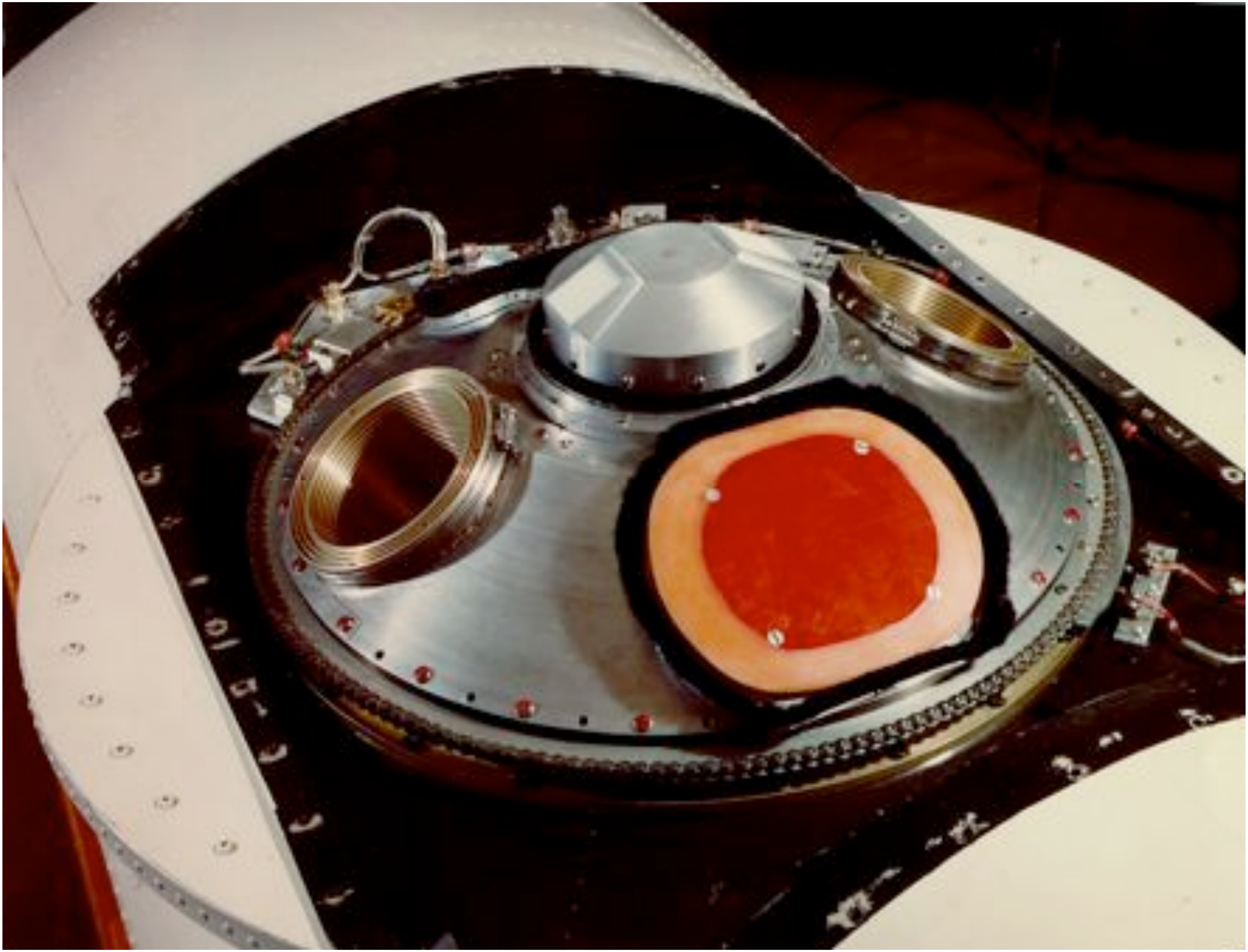
H -plane



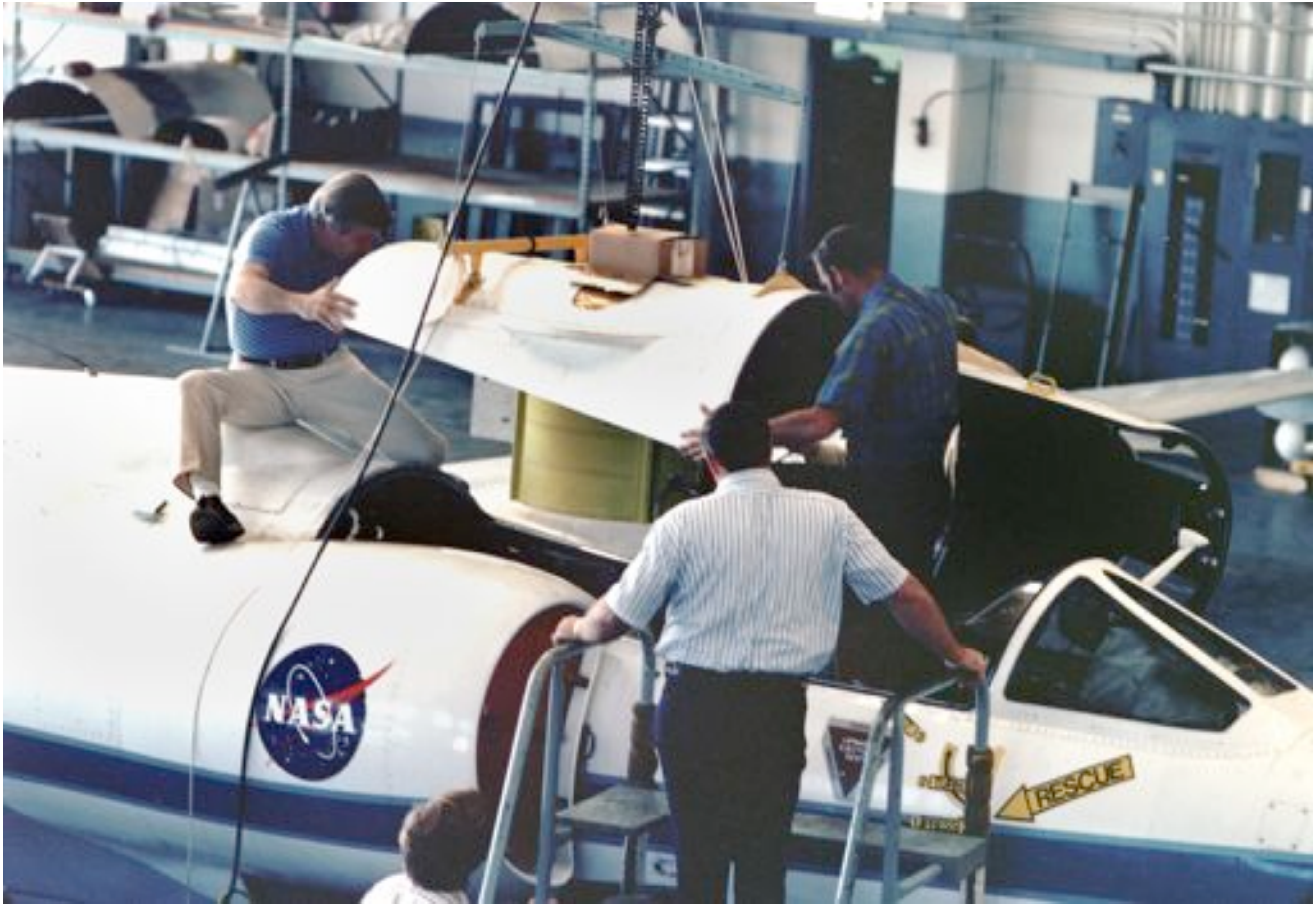
Corrugated Horn



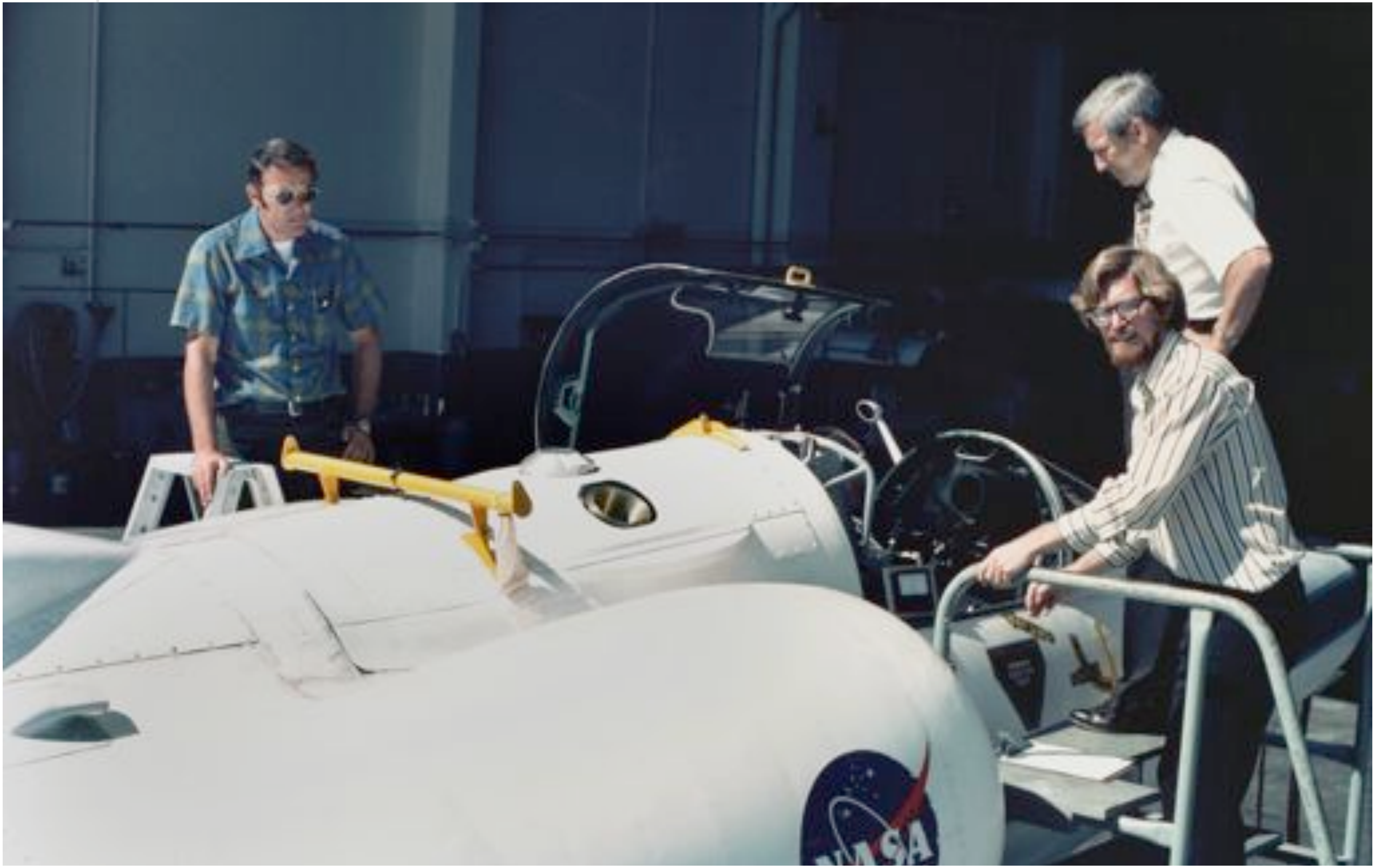




DOE Instrument into NASA craft

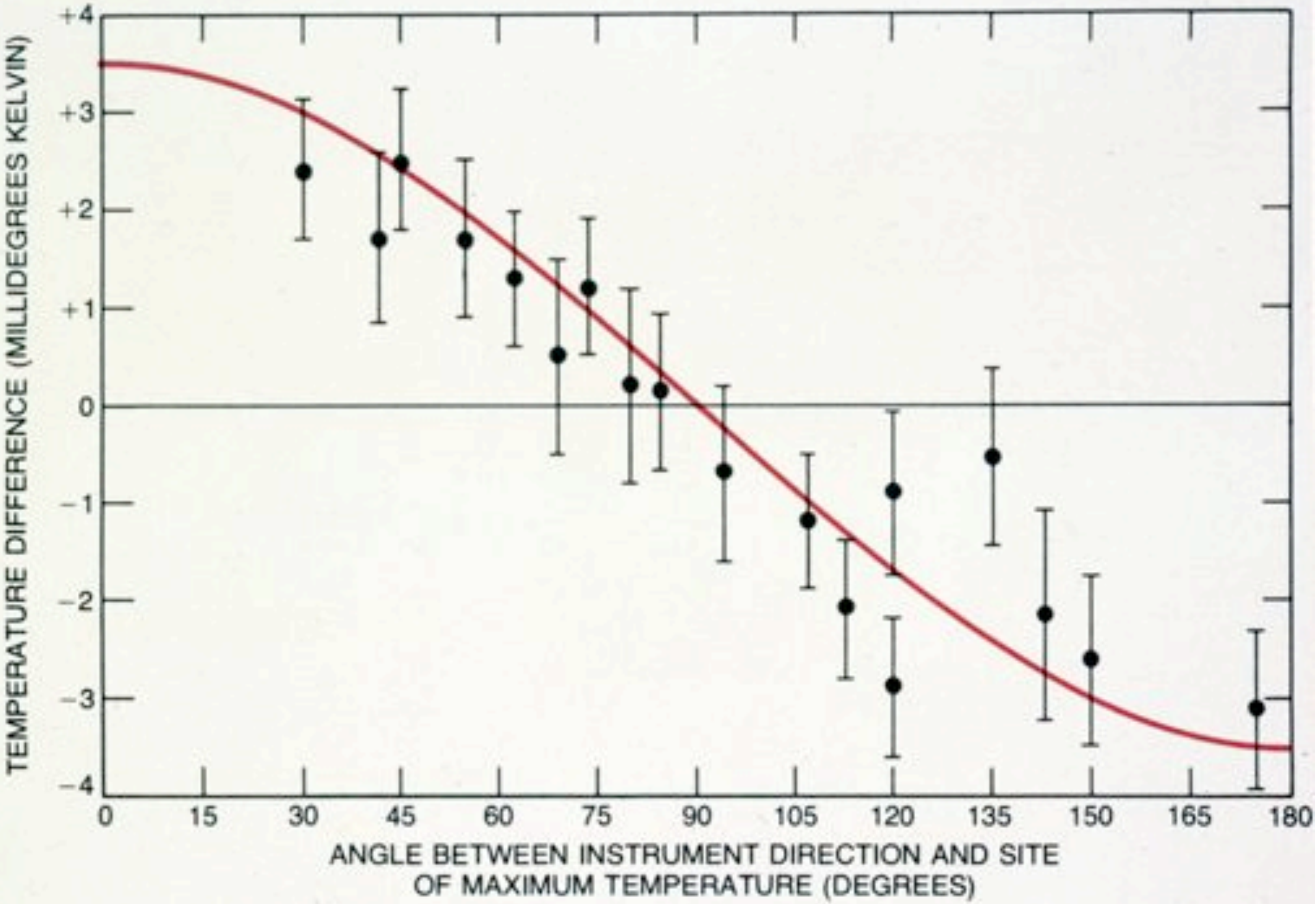


Scientists from DOE Lab puts instrument on NASA Platform



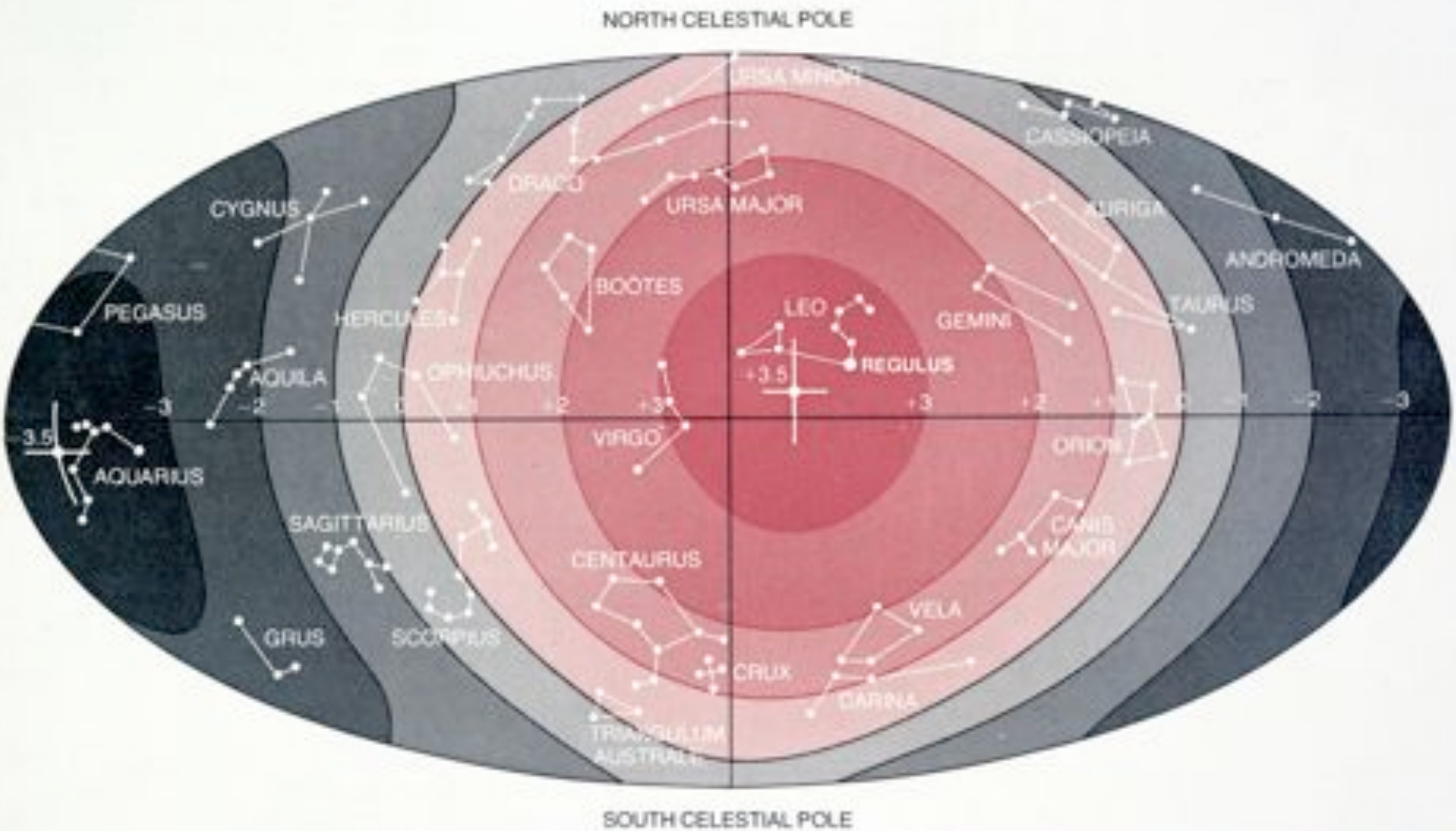

NASA
708

U2 can find

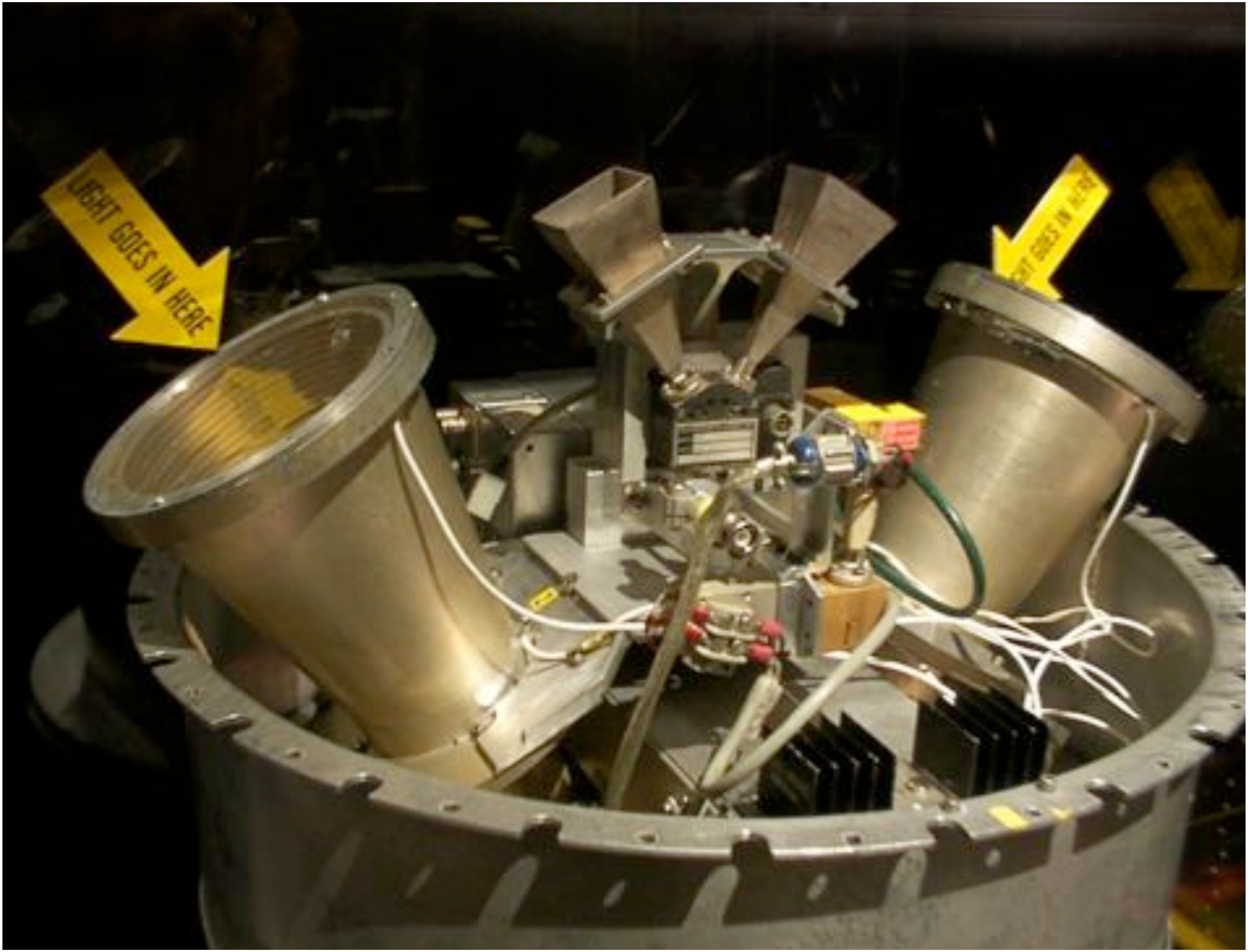


COSINE CURVE provides the best fit for the data (averaged into 18 points) taken by the author and his colleagues in the new aether-drift experiment. The horizontal axis represents the angle made by a line connecting the two horn antennas and the direction of maximum temperature in Leo. The cosine curve is temperature distribution to be expected in the cosmic background radiation if the solar system's peculiar velocity toward Leo is 400 kilometers per second.

Dipole Anisotropy A = 3.5 mK

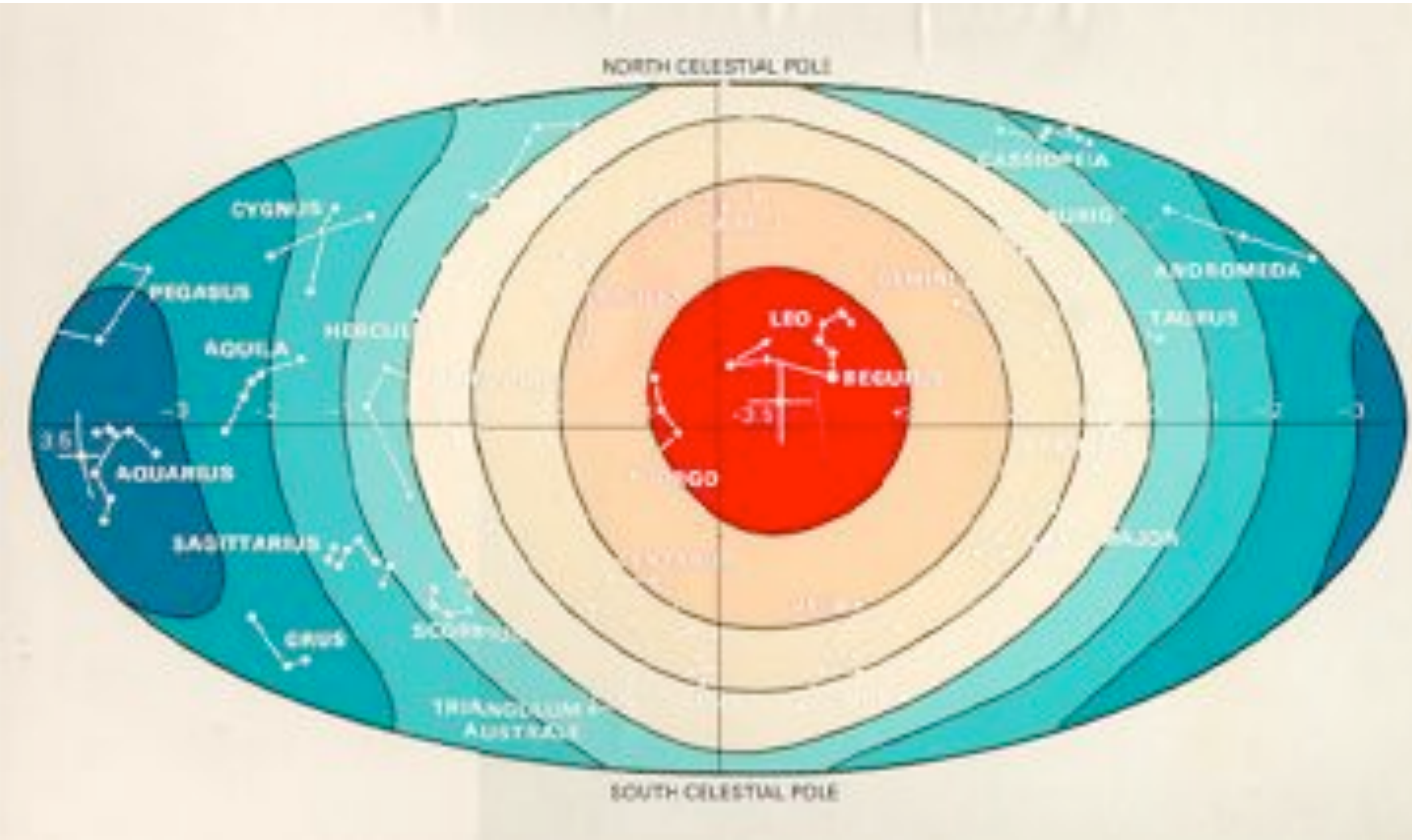


ANISOTROPY OF THE BACKGROUND RADIATION, as deduced from the U-2 survey, is plotted on the celestial sphere in contours of one millidegree K. The "hottest" spot, indicating the direc- (±.5 hour) and latitude six degrees (±10 degrees). The "coldest" spot, the direction in which the radiation is most "reddened" by the earth's relative motion away from the incoming photons, lies 180 degrees

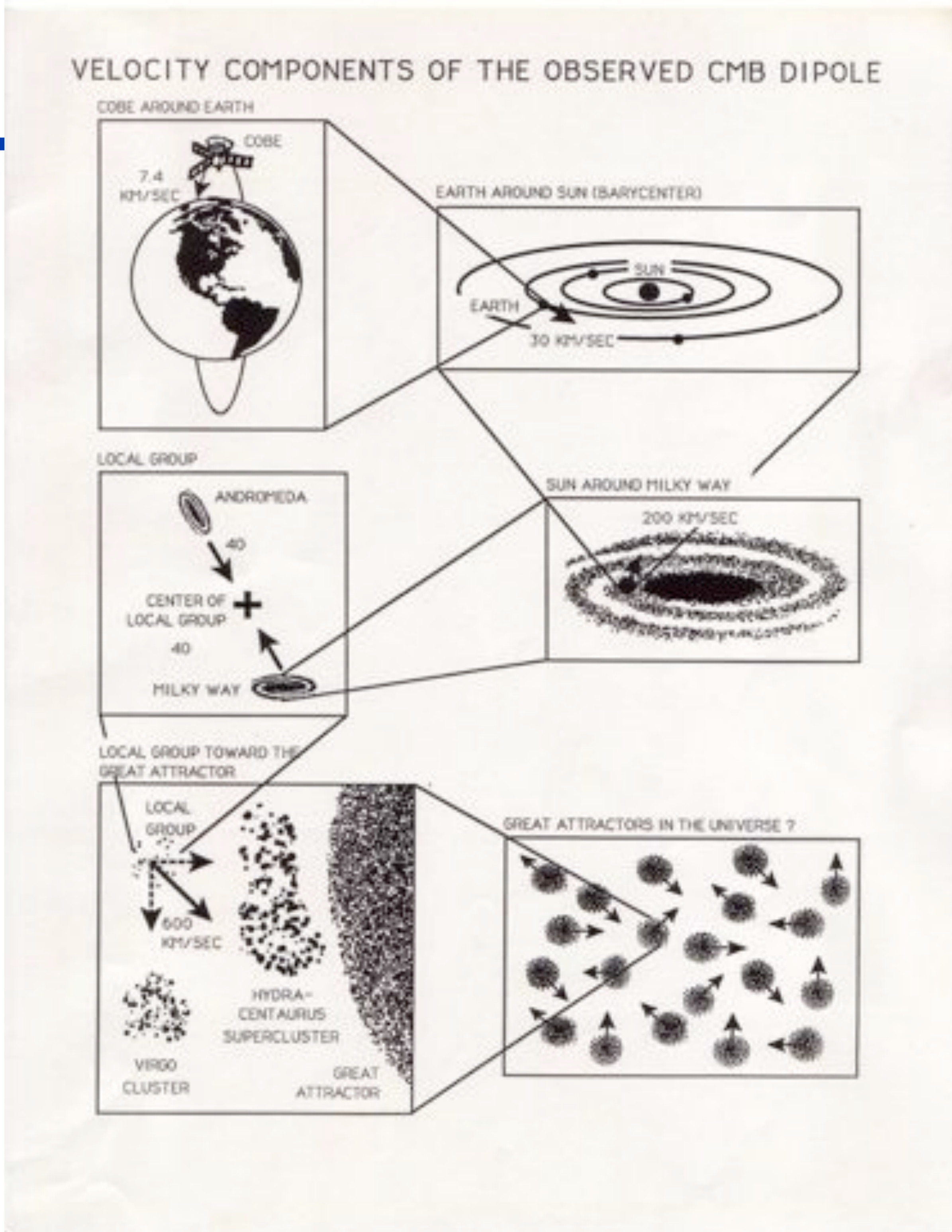

LIGHT GOES IN HERE
LIGHT GOES IN HERE

Best-Fitted Dipole Anisotropy

-3.5 mK to +3.5 mK



What is the motion ?



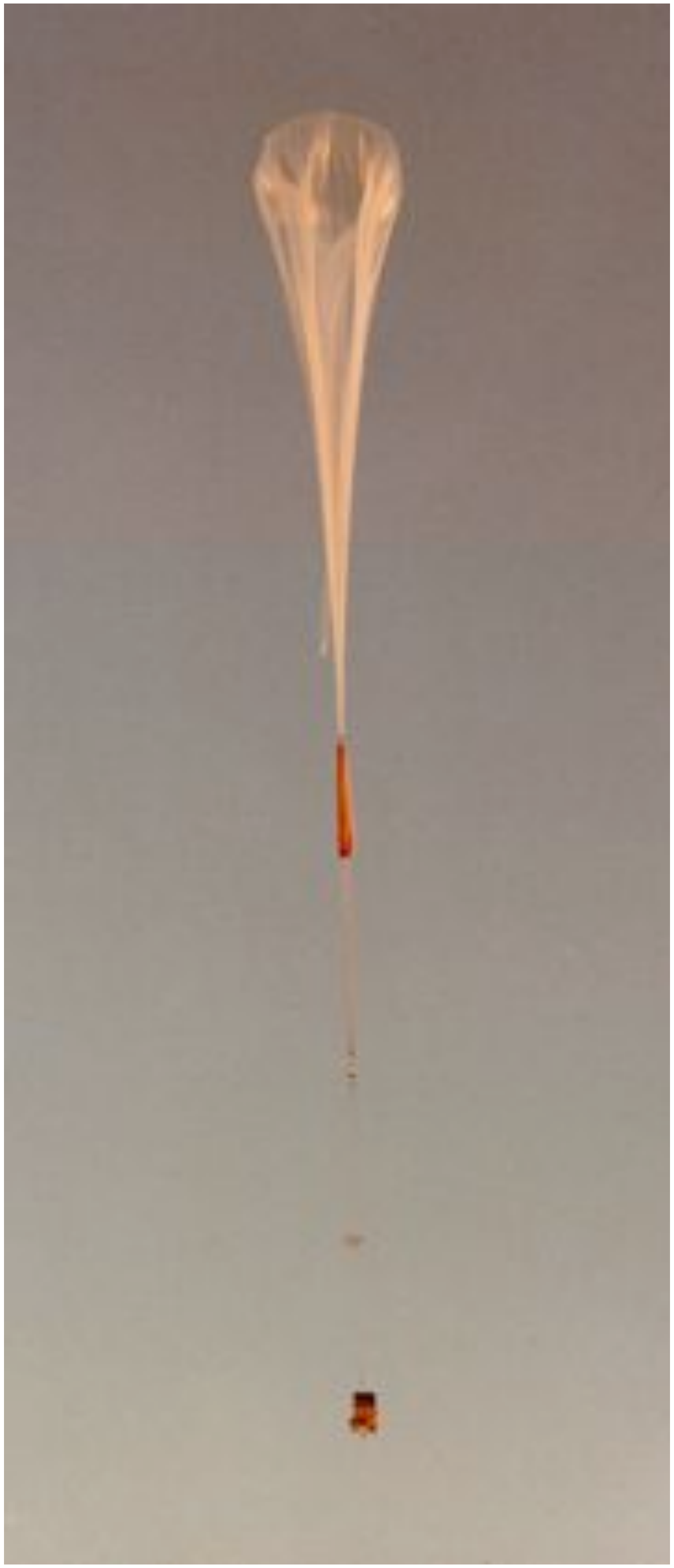
"Eppur si muove"

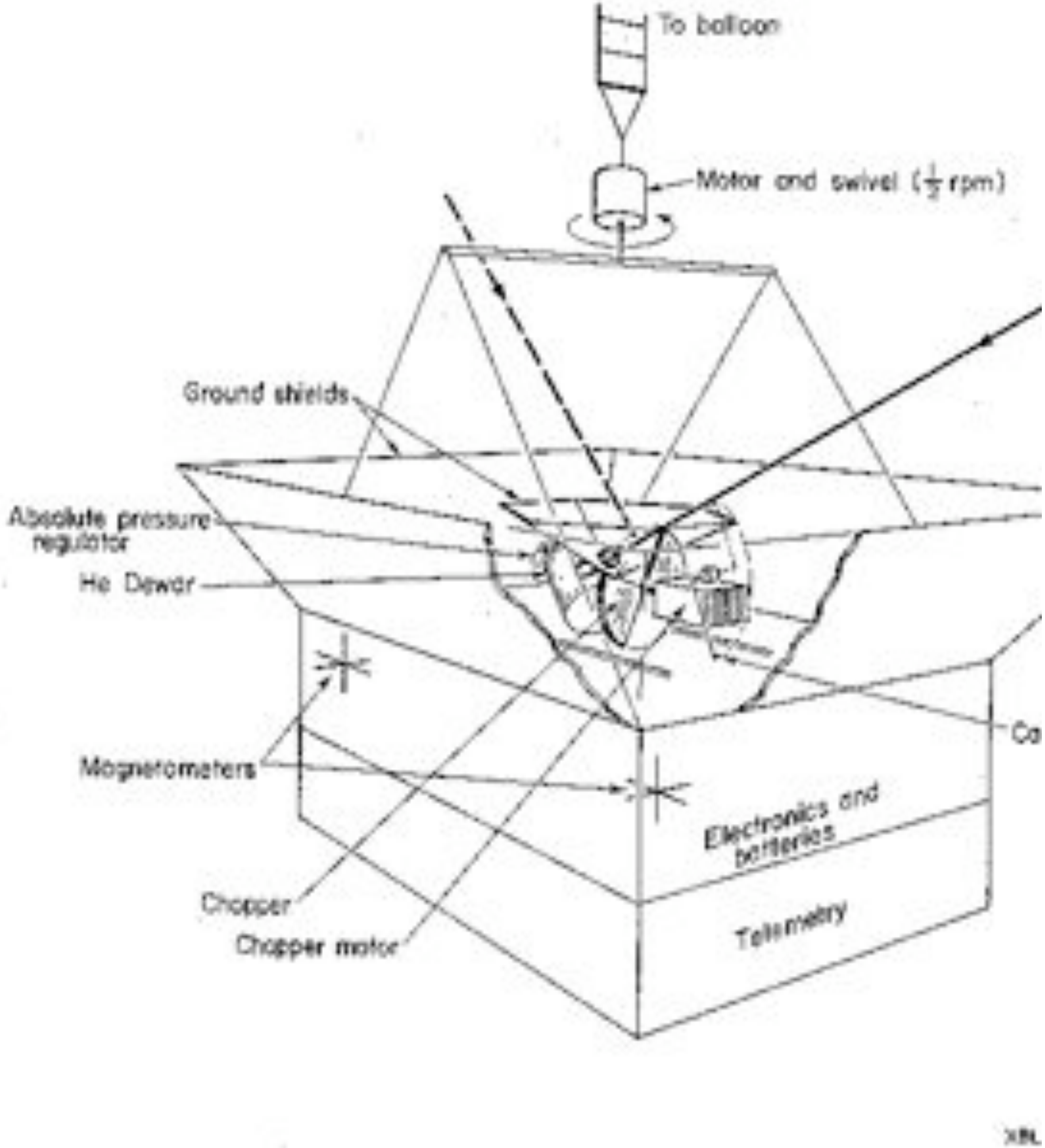
means

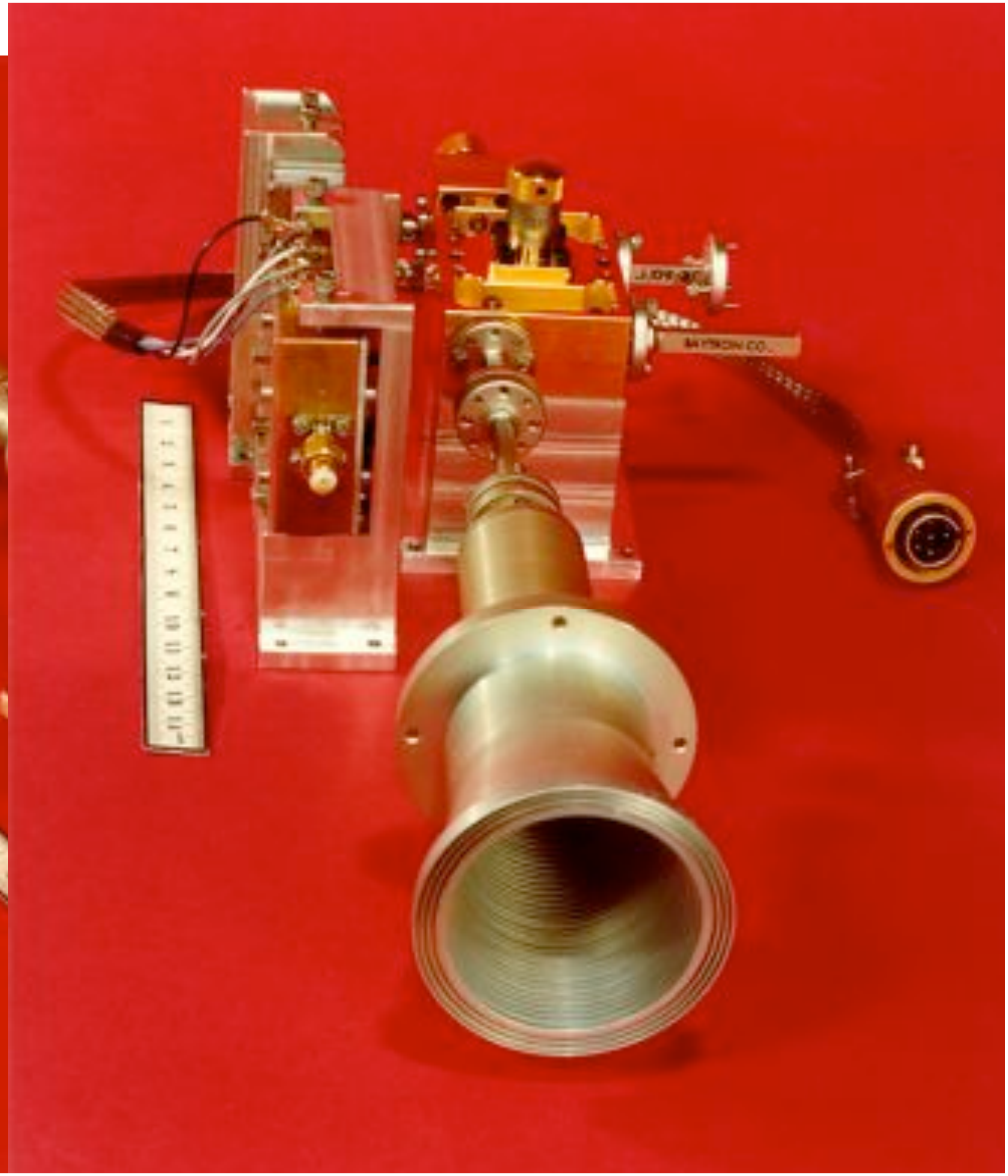
***And yet it moves*.**

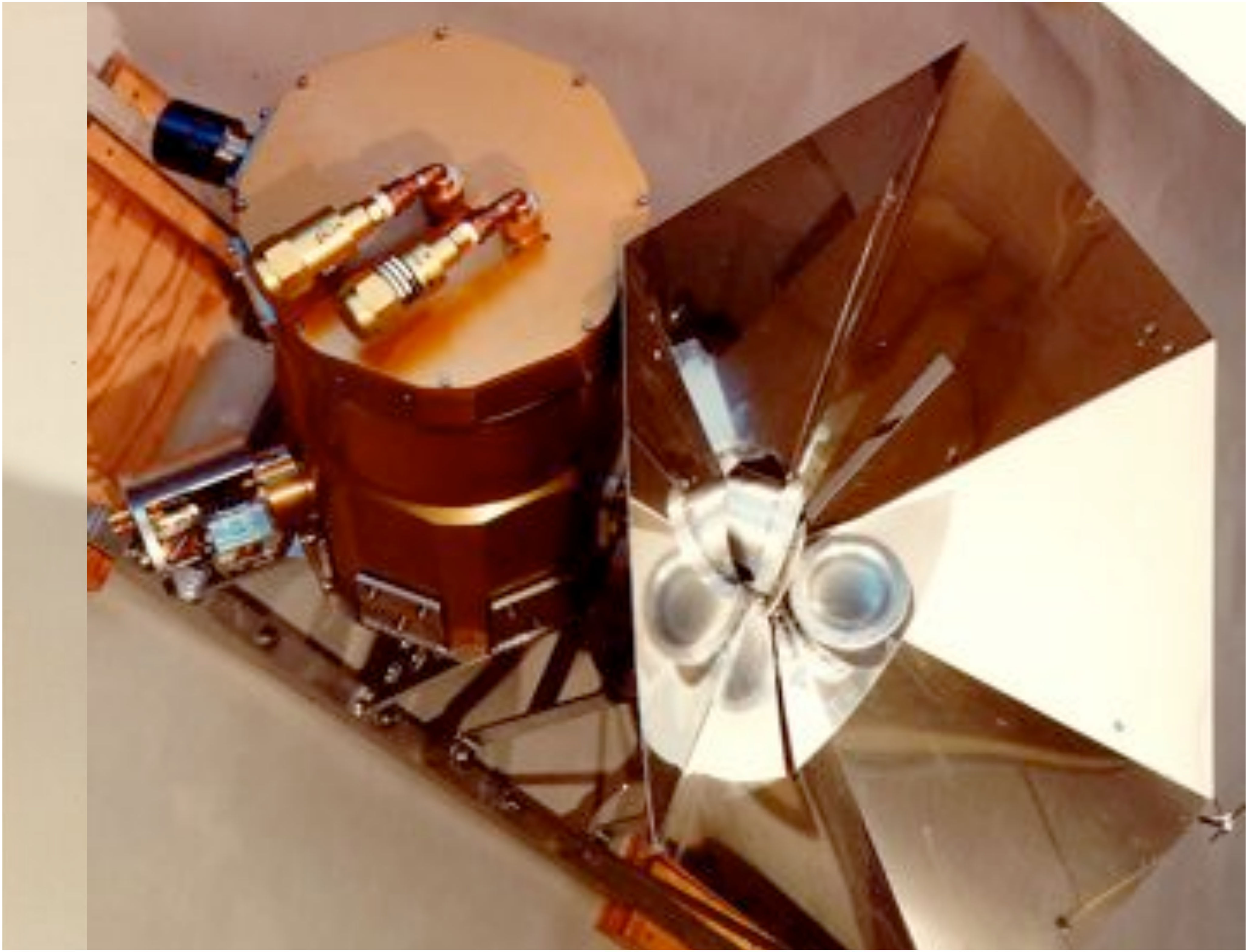
Legend has it that the Italian mathematician, physicist and philosopher Galileo Galilei muttered this phrase after being forced to recant in 1633, before the Inquisition, his belief that the Earth moves around the Sun.

Pioneering C




To balloon
Motor and swivel ($\frac{1}{2}$ rpm)
Ground shields
Absolute pressure regulator
He Dewar
Magnetometers
Electronics and batteries
Telemetry
Chopper
Chopper motor
XBL





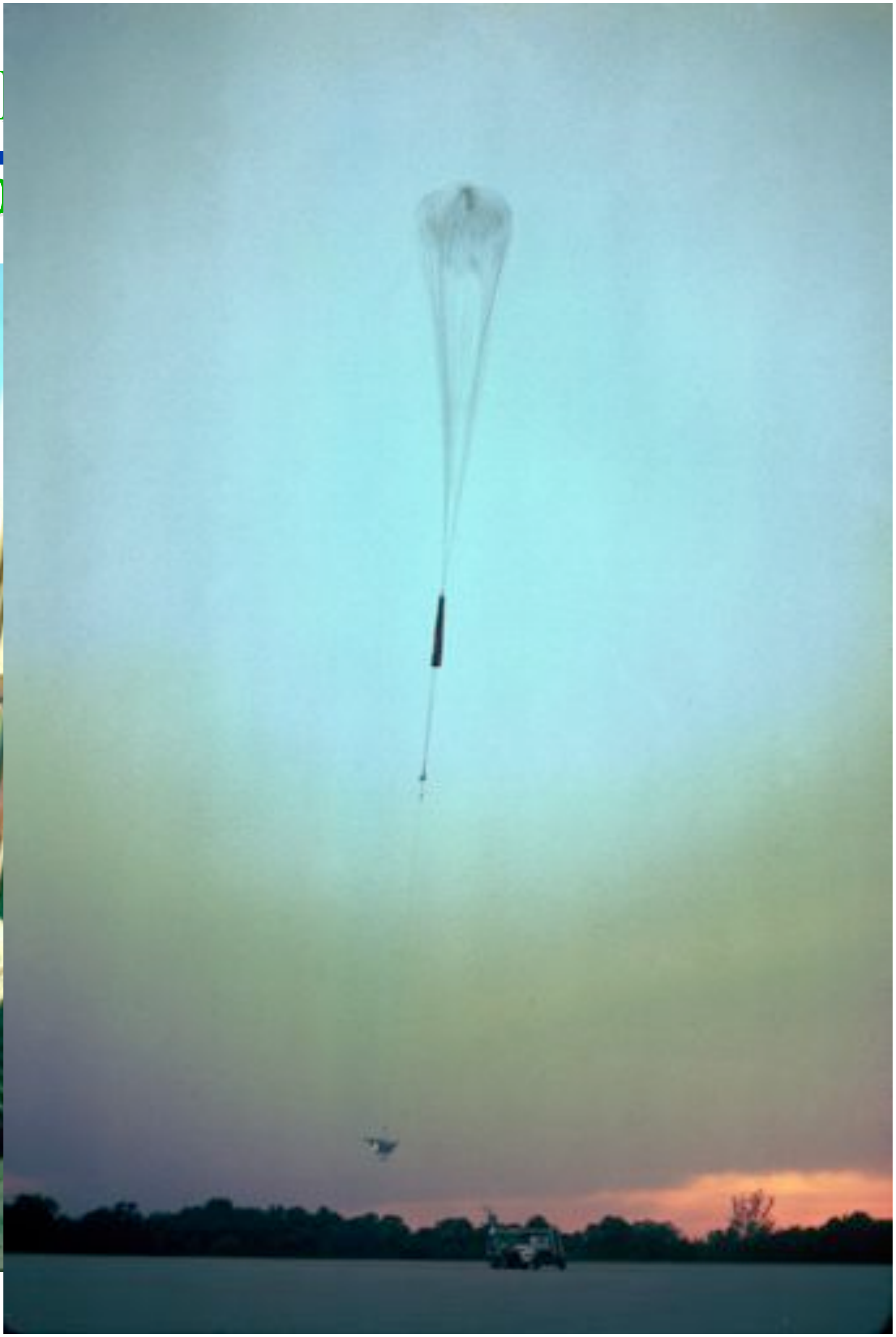
Princeton large-angular scale anisotropy

same epoch as Berkeley 3-mm

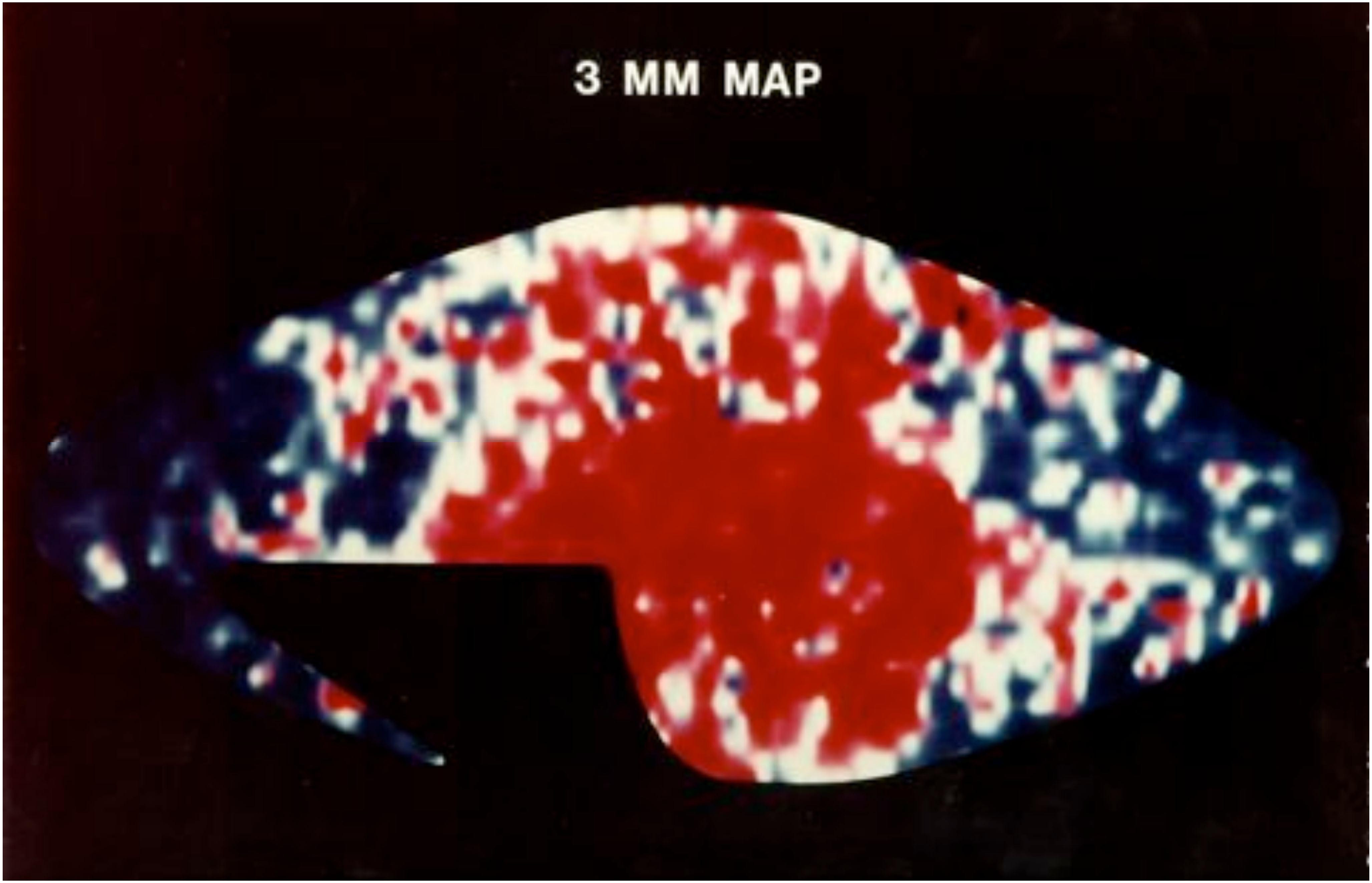
Peter Saulson & assembled payload

Princeton plus Ber
being readied fo

Peter Saulsen Dave Wilkinson



Three Balloon Flights Later



COBE DMR
31.4 GHz (9-mm) Lab Breadboard

Spectrum : My Posse at White Mtn.

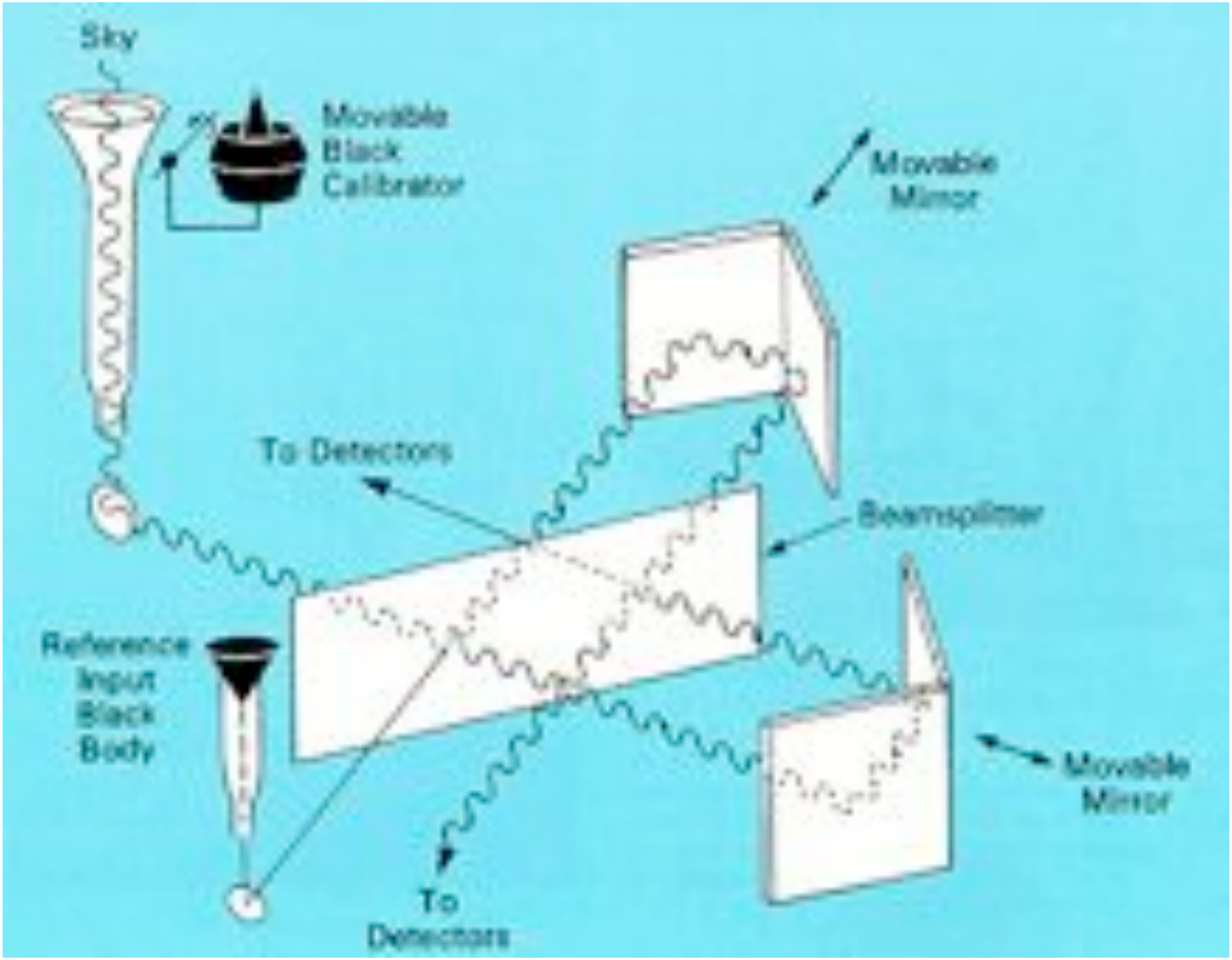
Heavy Manual Operations

George Smoot, Scott Friedman, Alan Benner

South	Steve	John	Bill	Giovanni	Marc	Michele	George	Marco
Pole	Levin	Gibson	Vinje	de Amici	Bensadoun	Limon	Smoot	Bersanelli


MERRY
CHRISTMAS!
X

COBE FIRAS



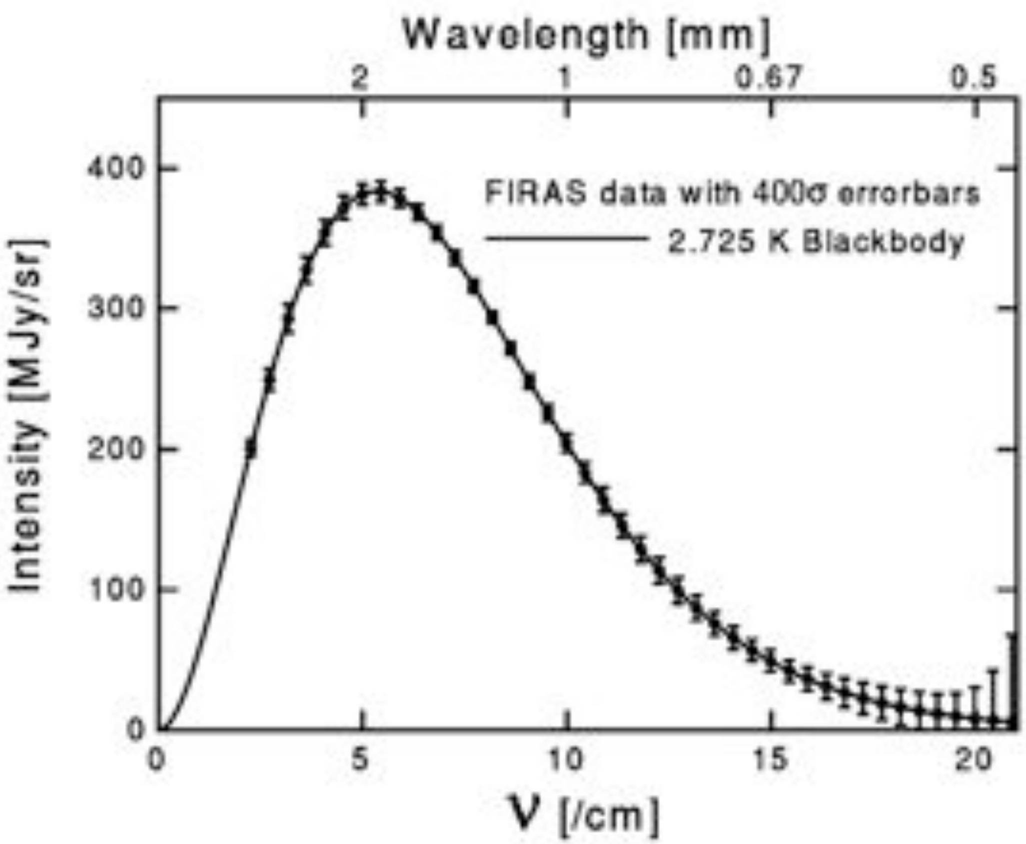
Sky
Movable
Black
Calibrator
Movable
Mirror
To Detectors
Beamsplitter
Reference
Input
Black
Body
Movable
Mirror
To
Detectors

FIRAS Horn & Ext. Calibrator

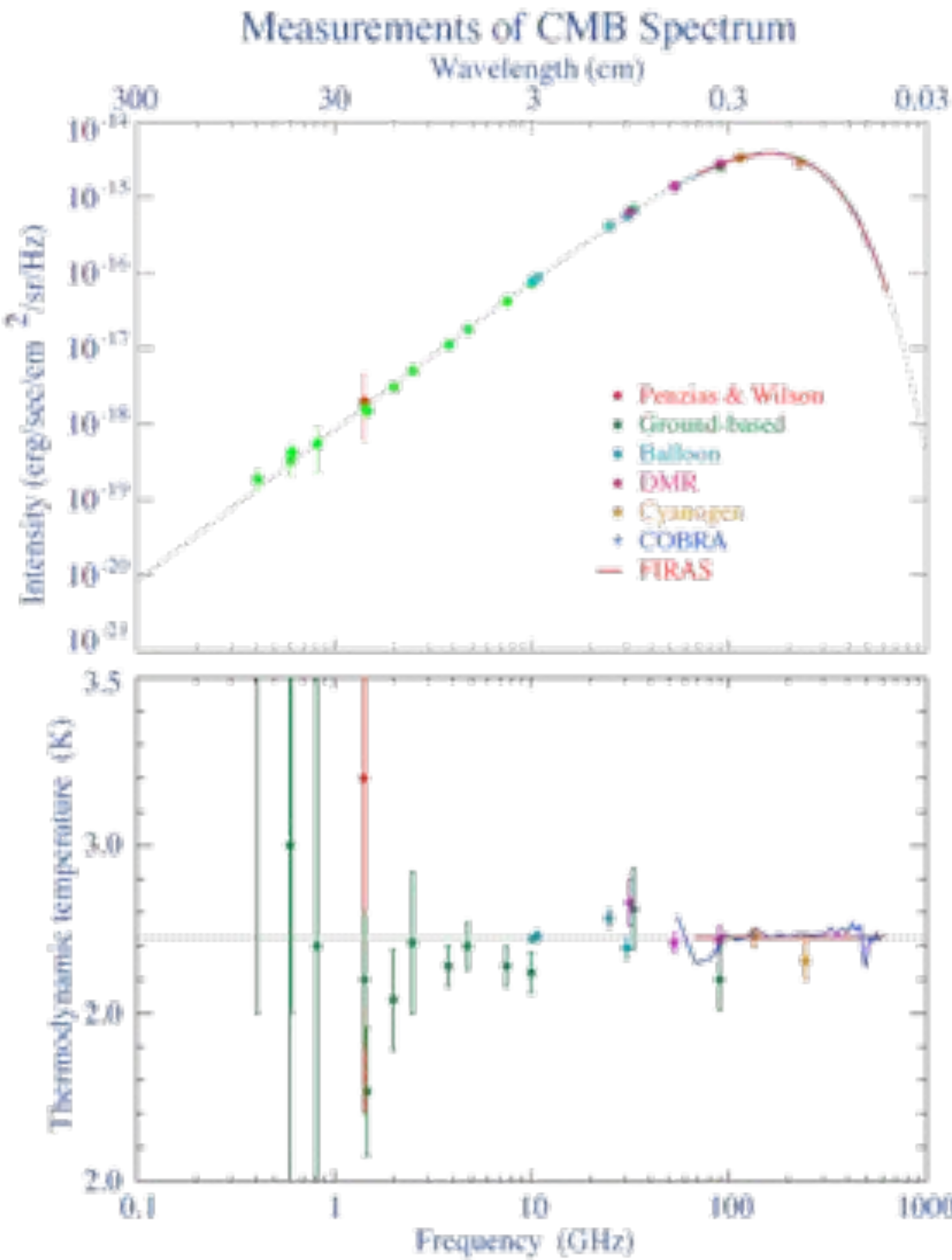
COBE Spectrum of the Universe

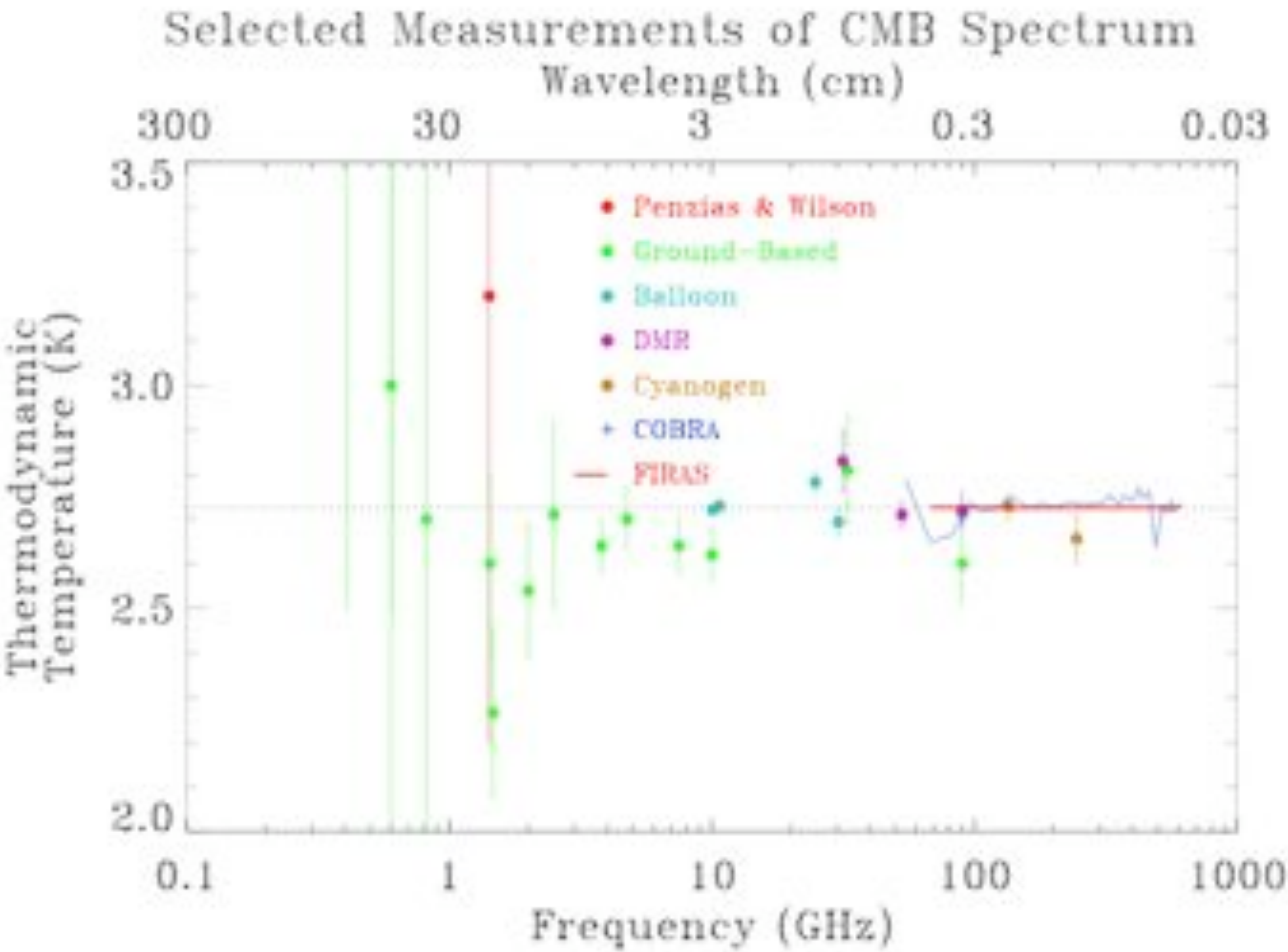
-first 7 minutes of data

-Jan 1990 AAS meeting

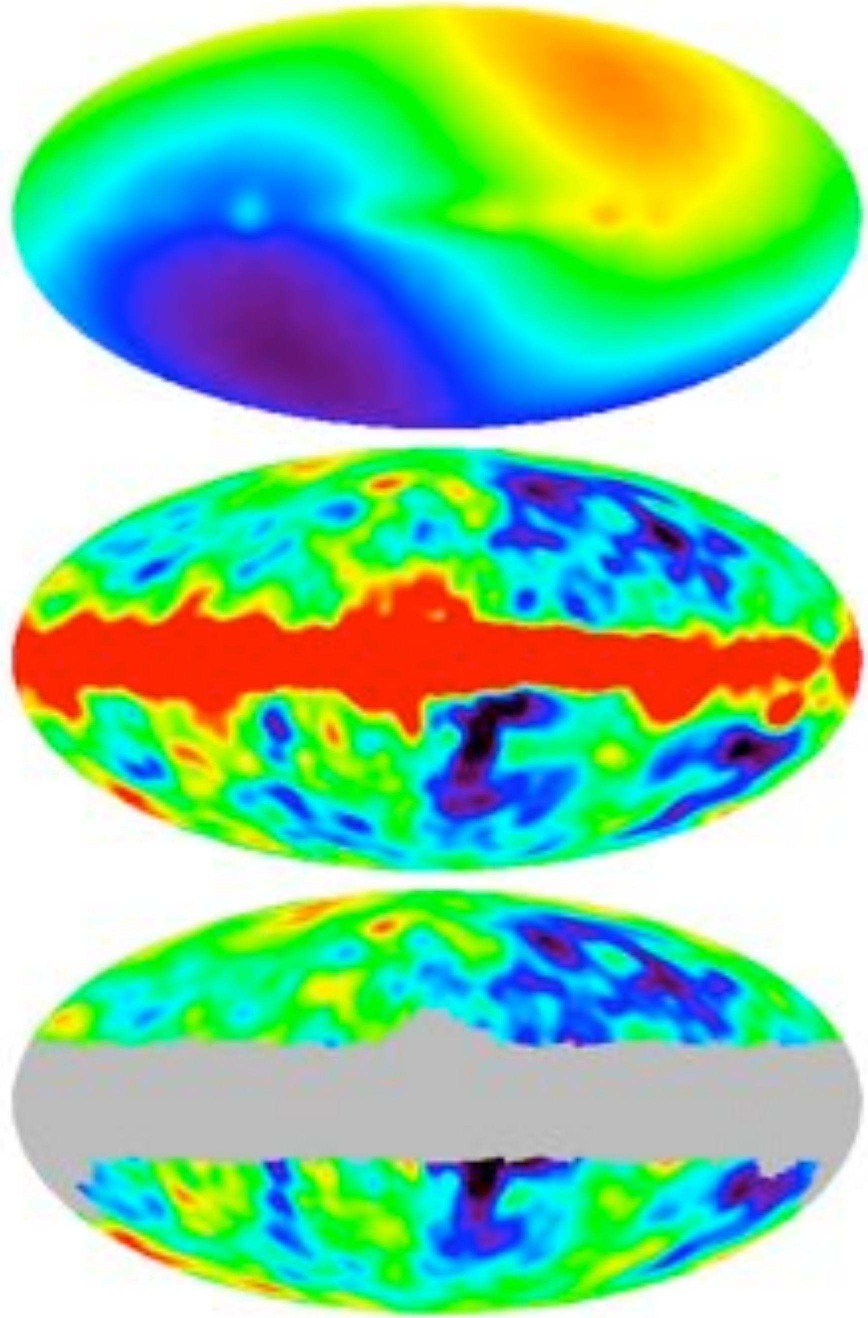


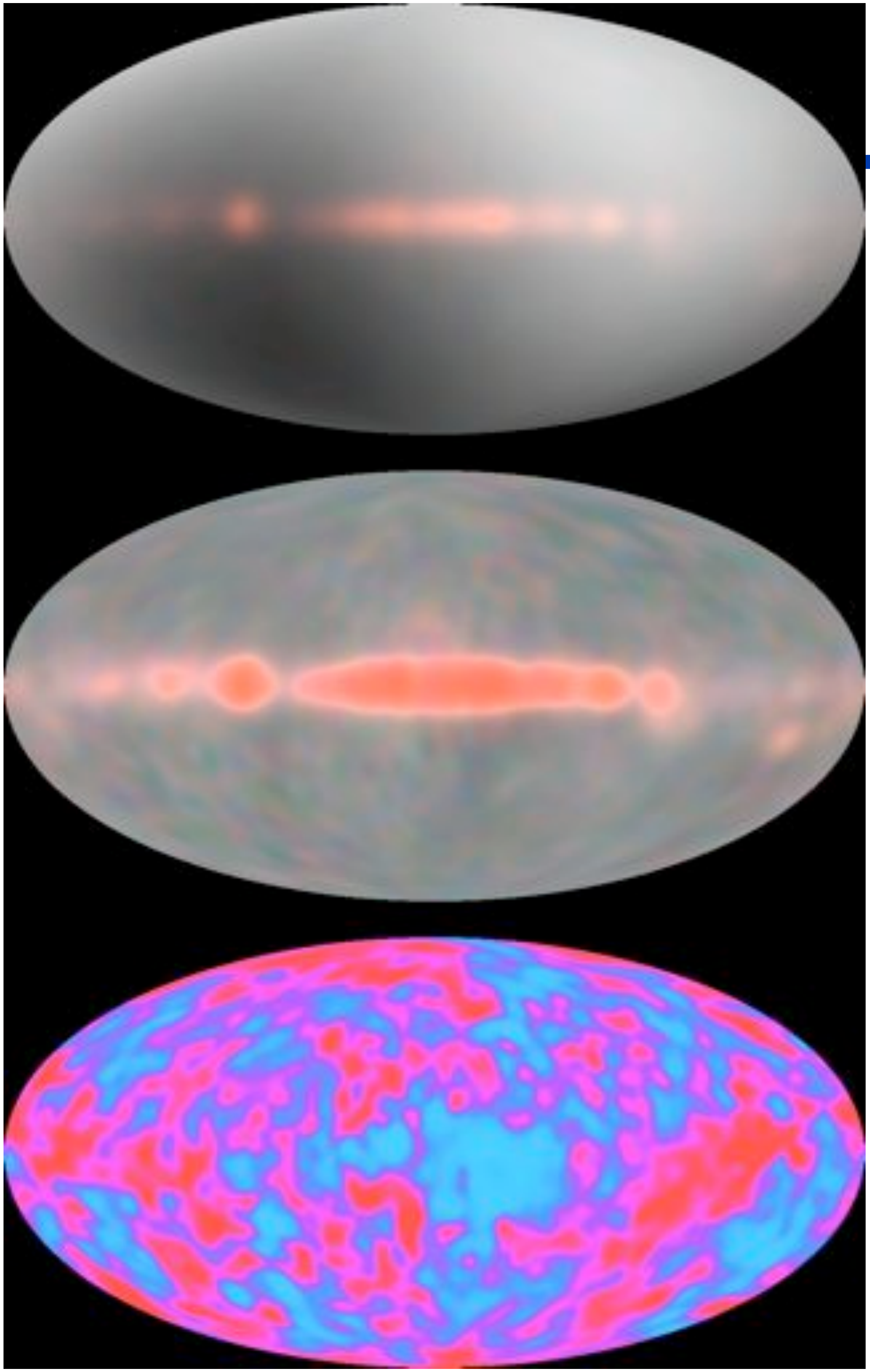
Horn antenna with movable calibrator. Protective plastic covers will be removed.


Measurements of CMB Spectrum
Wavelength (cm)
300
30
3
0.3
0.03
Intensity (erg/sec/cm 2/sr/Hz)
Penzias & Wilson
Ground-based
Balloon
DMR
Cyanogen
COBRA
FIRAS
Thermodynamic temperature (K)
3.5
3.0
2.0
0.1
1
10
100
1000
Frequency (GHz)

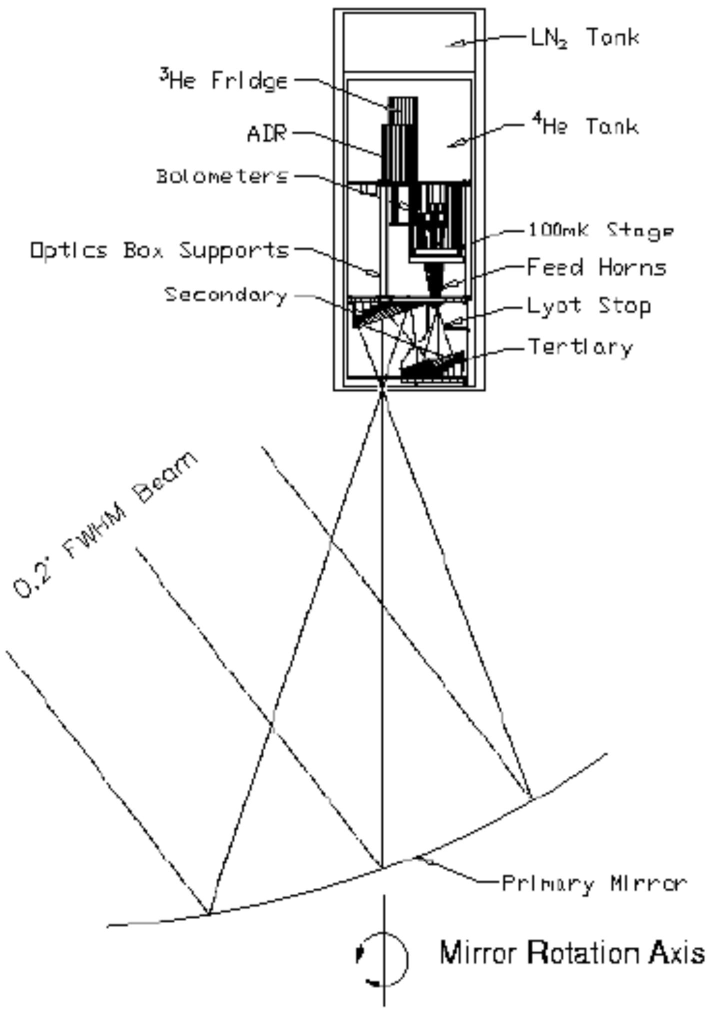

Selected Measurements of CMB Spectrum
Wavelength (cm)
300
30
3
0.3
0.03
3.5
3.0
2.5
2.0
Thermodynamic Temperature (K)
Penzias & Wilson
Ground-Based
Balloon
DMR
Cyanogen
COBRA
FIRAS
0.1
1
10
100
1000
Frequency (GHz)

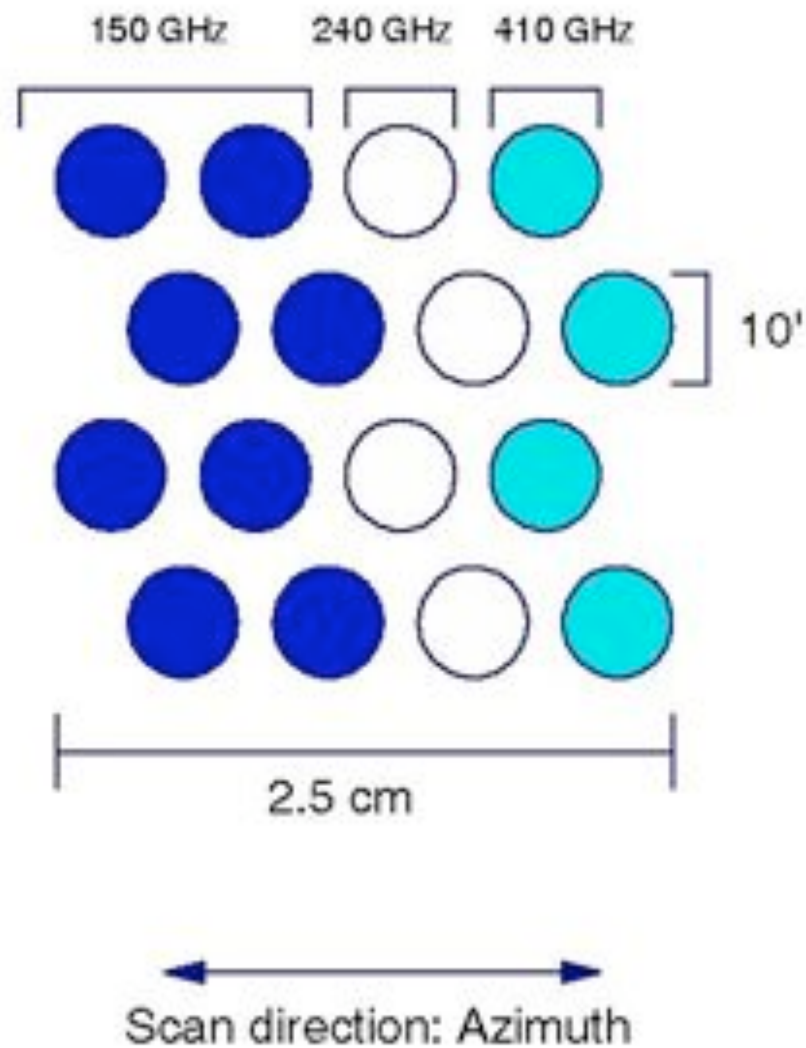
COBE DMR



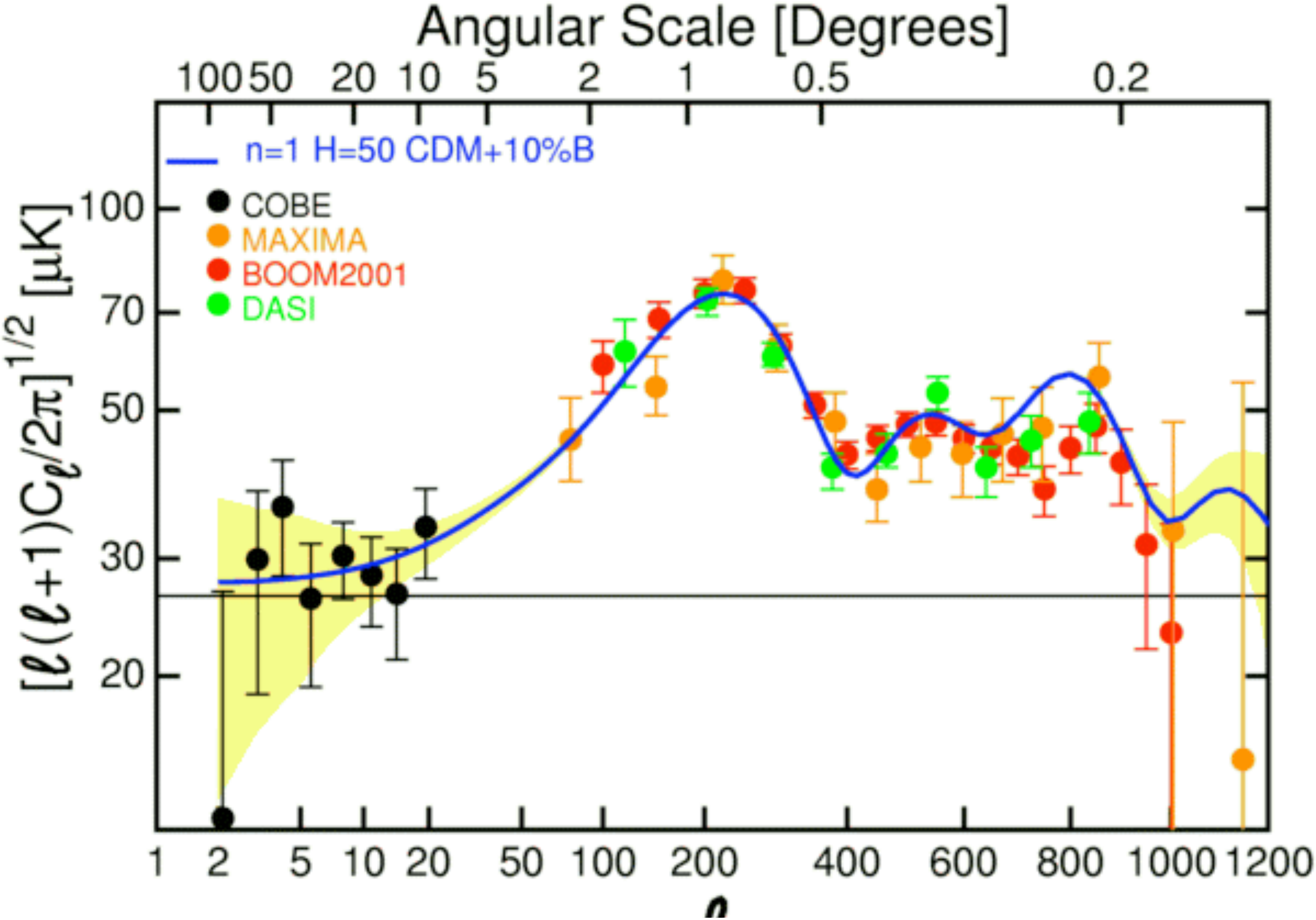


MAX ->The MAXIMA Balloon-Borne Instrument

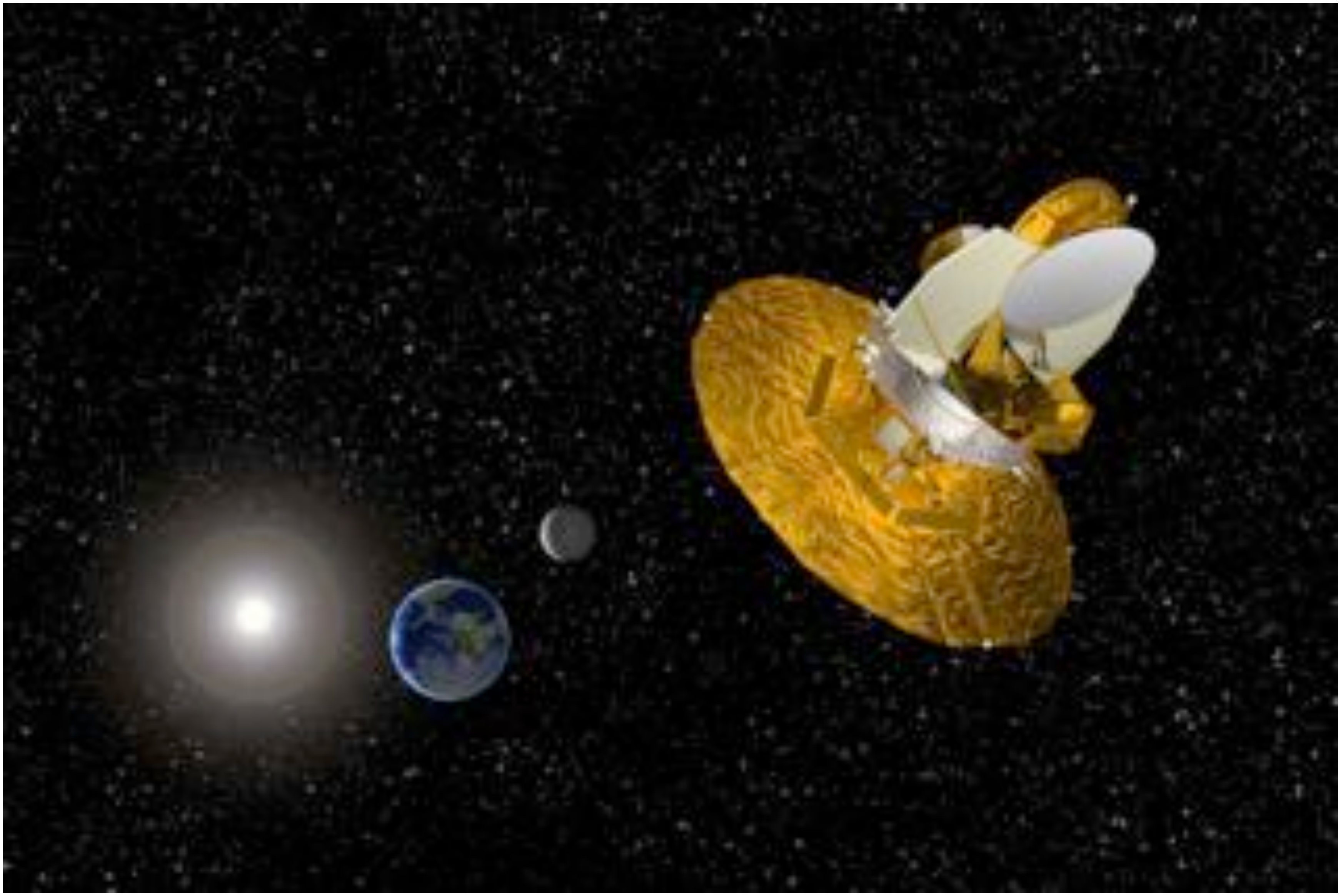




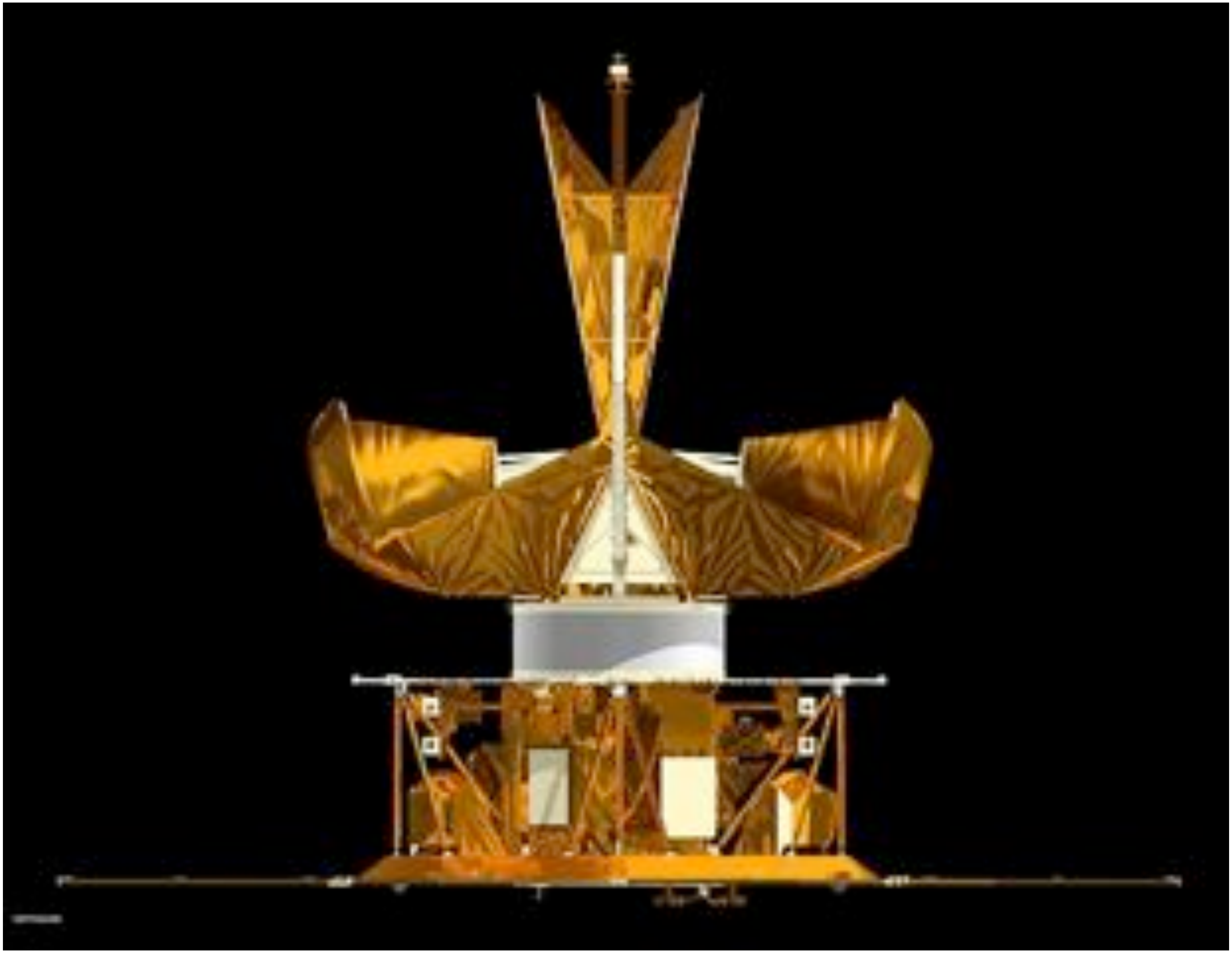
COBE plus Balloons



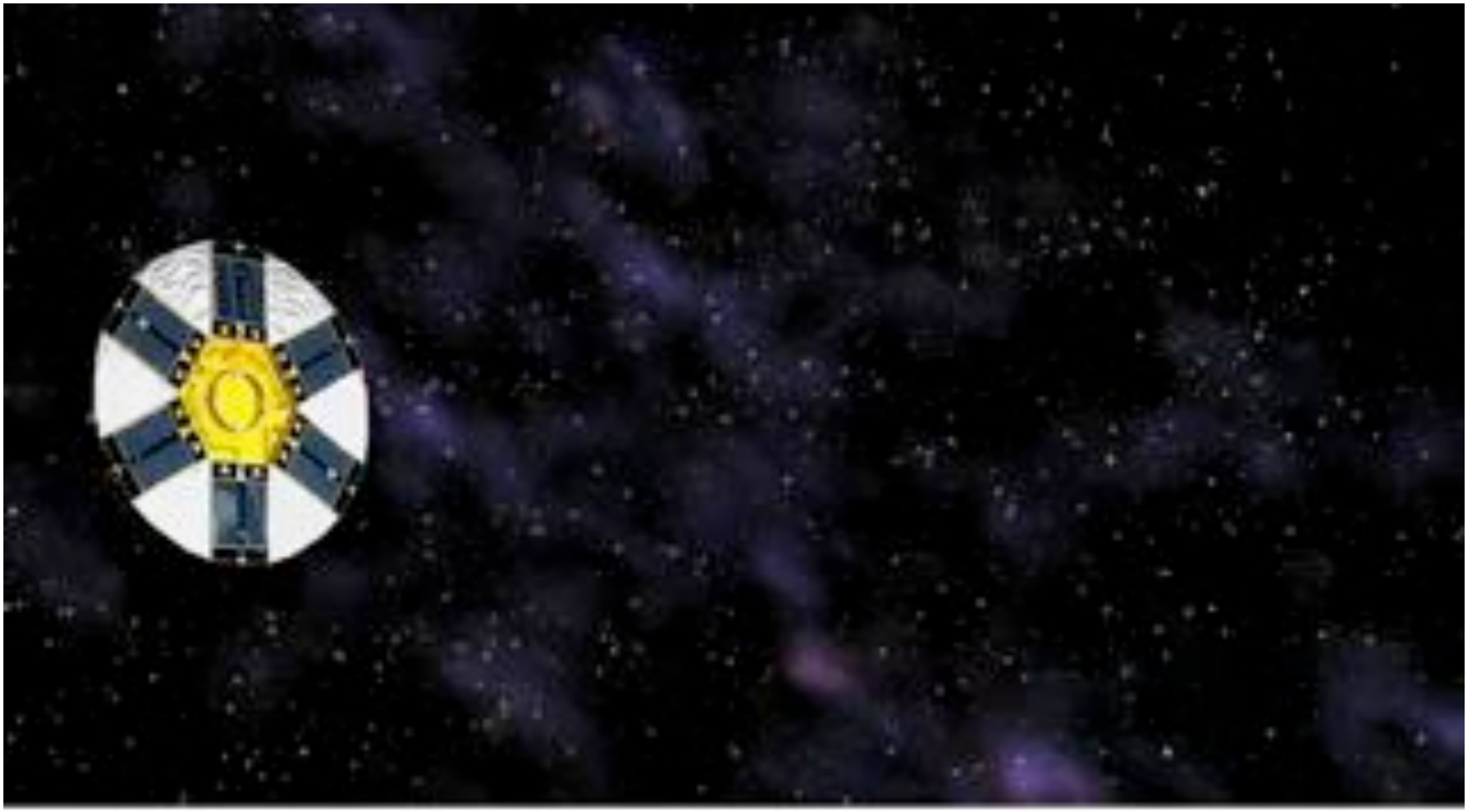
WMAP launched to L2 (Sun-Earth)

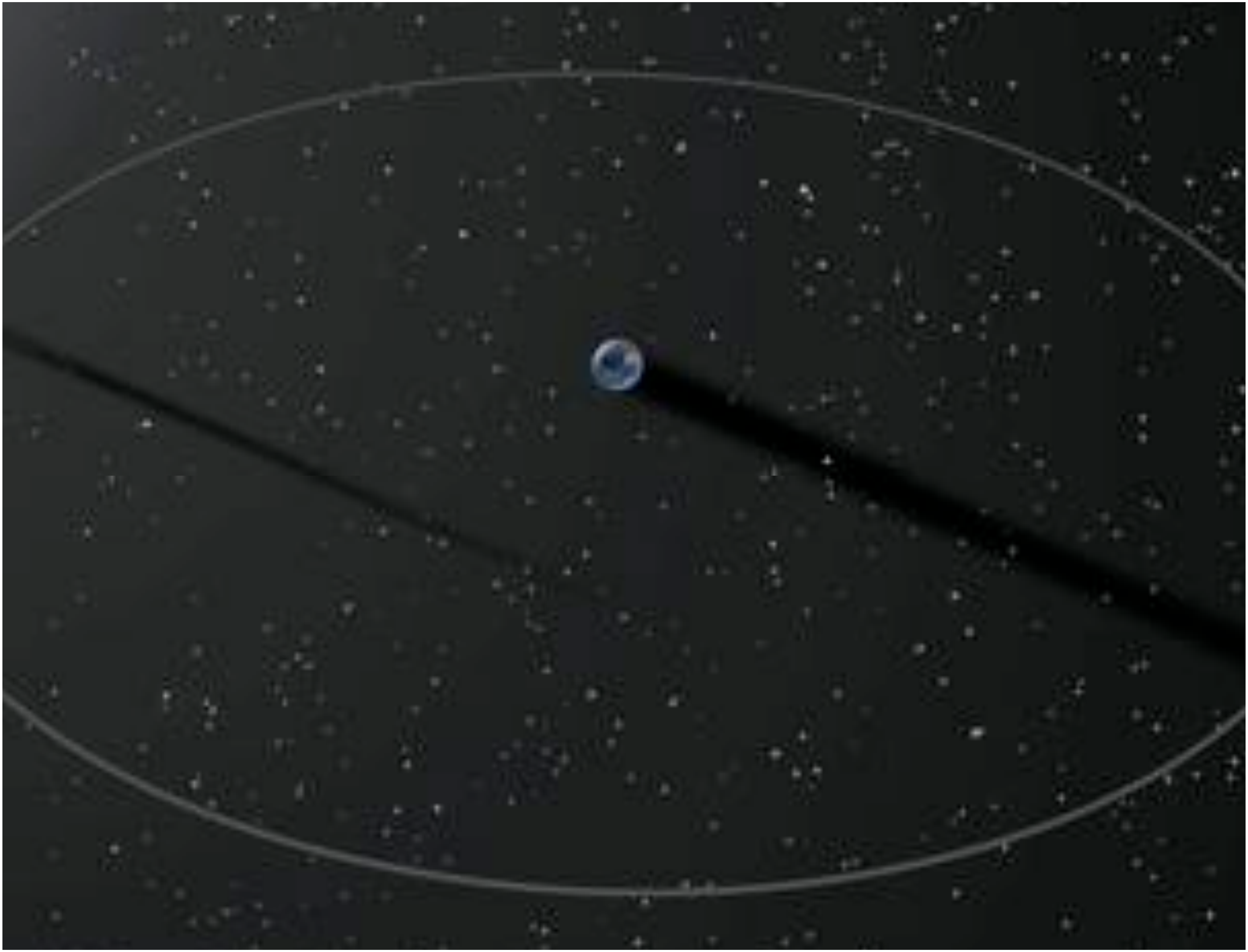


WMAP Side View (back to back dishes)

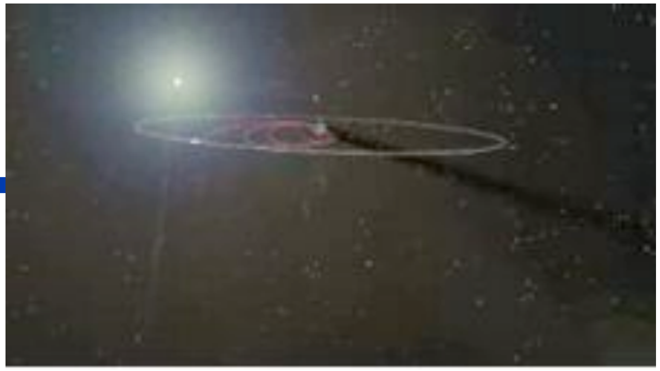


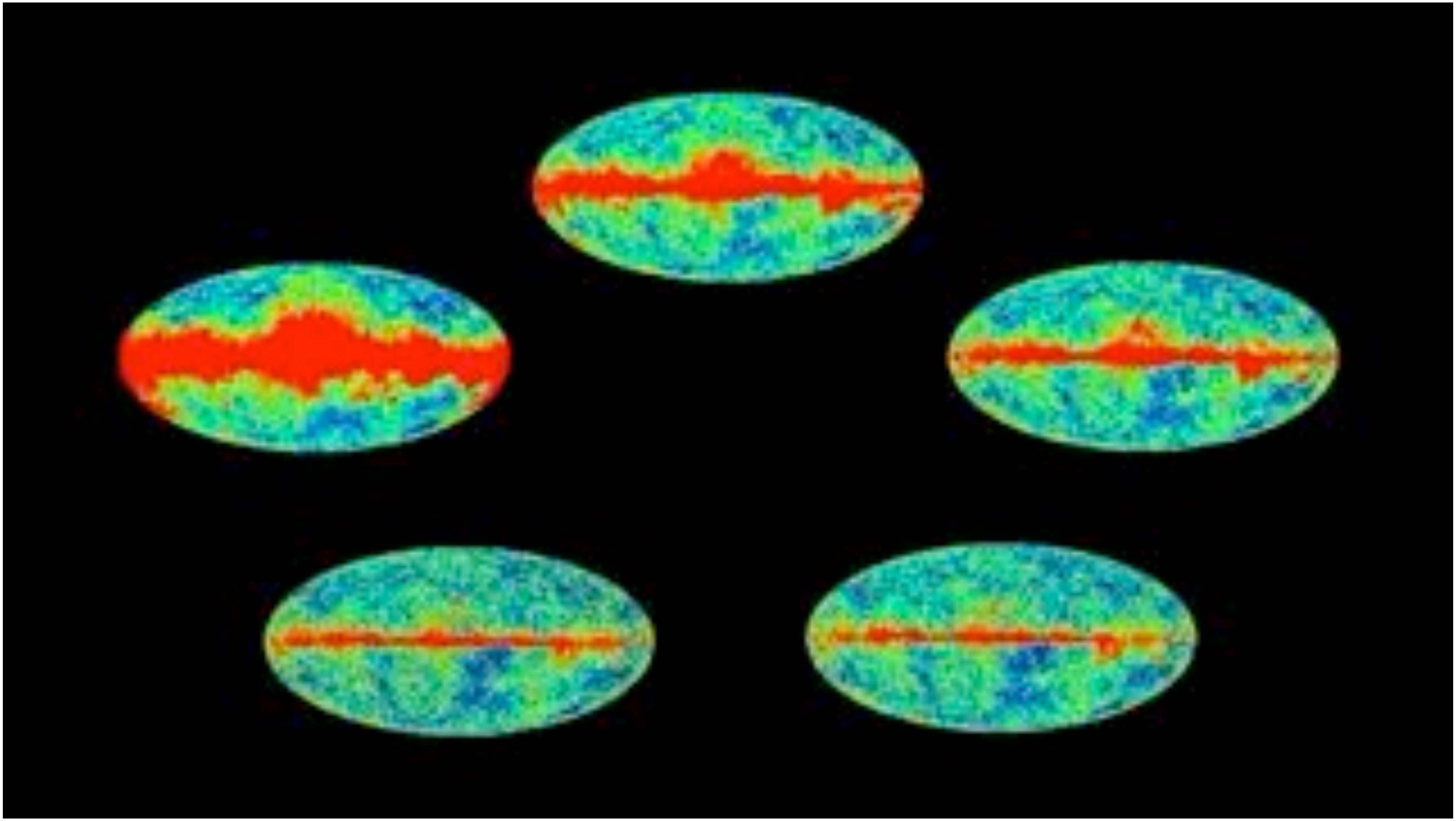
WMAP at L2



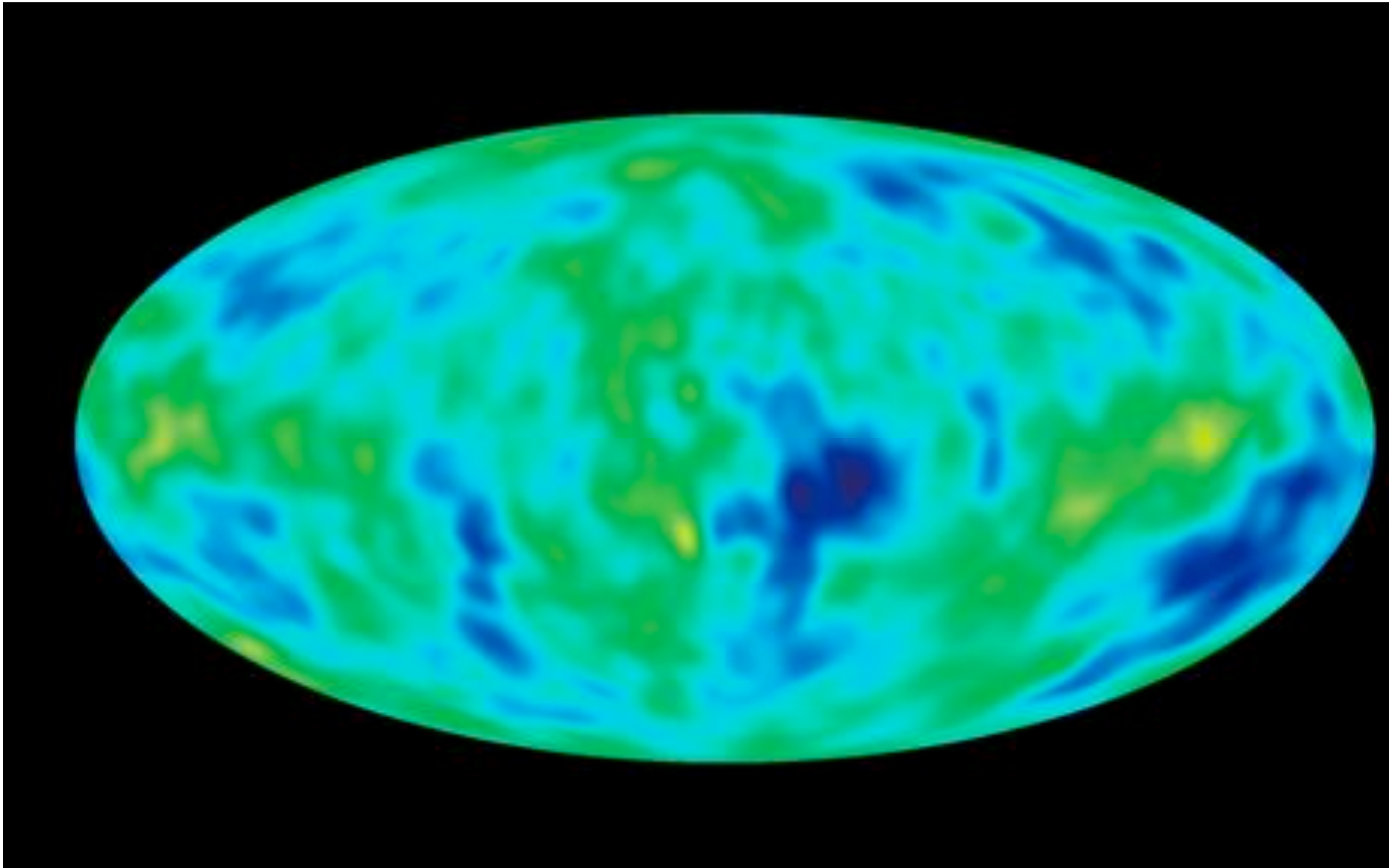


Why multiple wavelengths ?

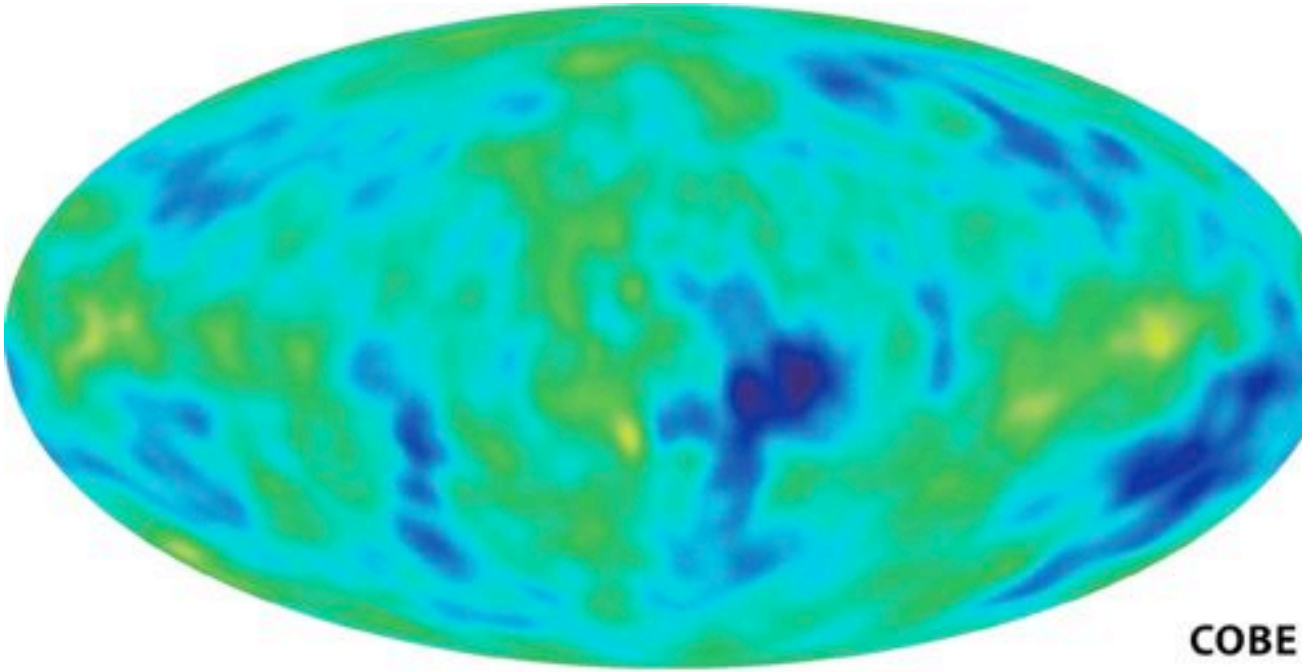


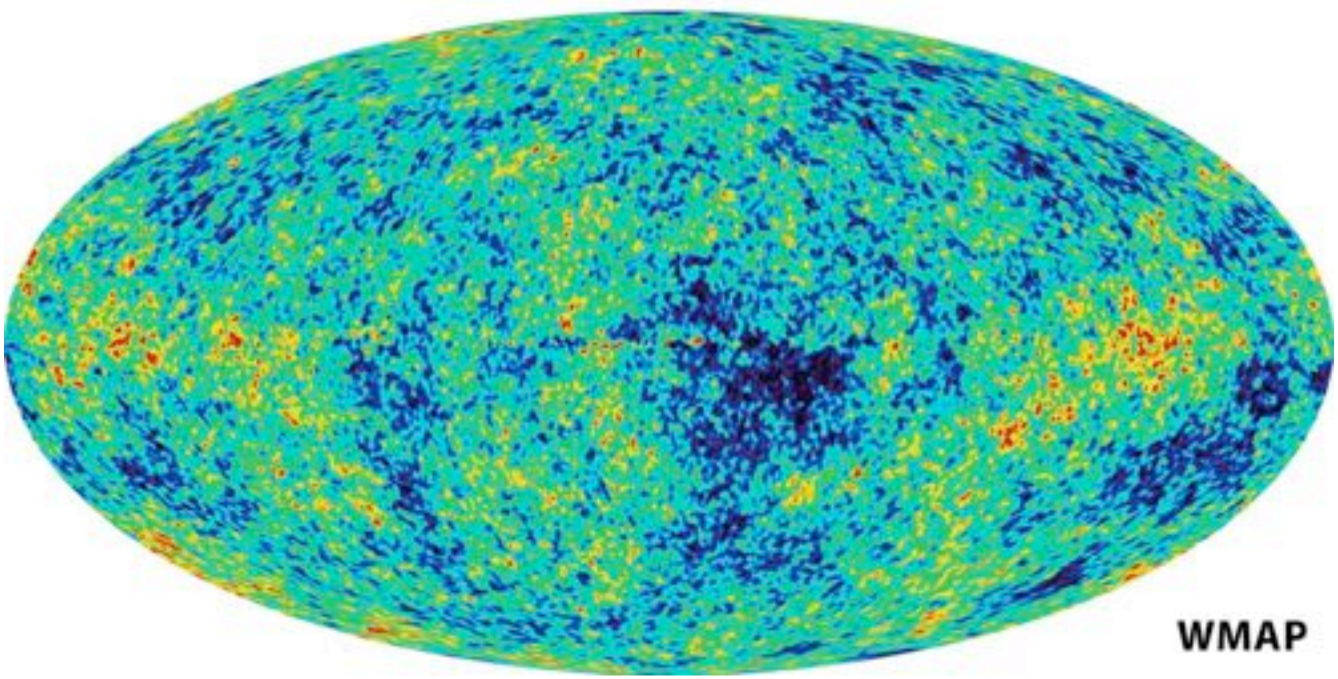


COBE to WMAP

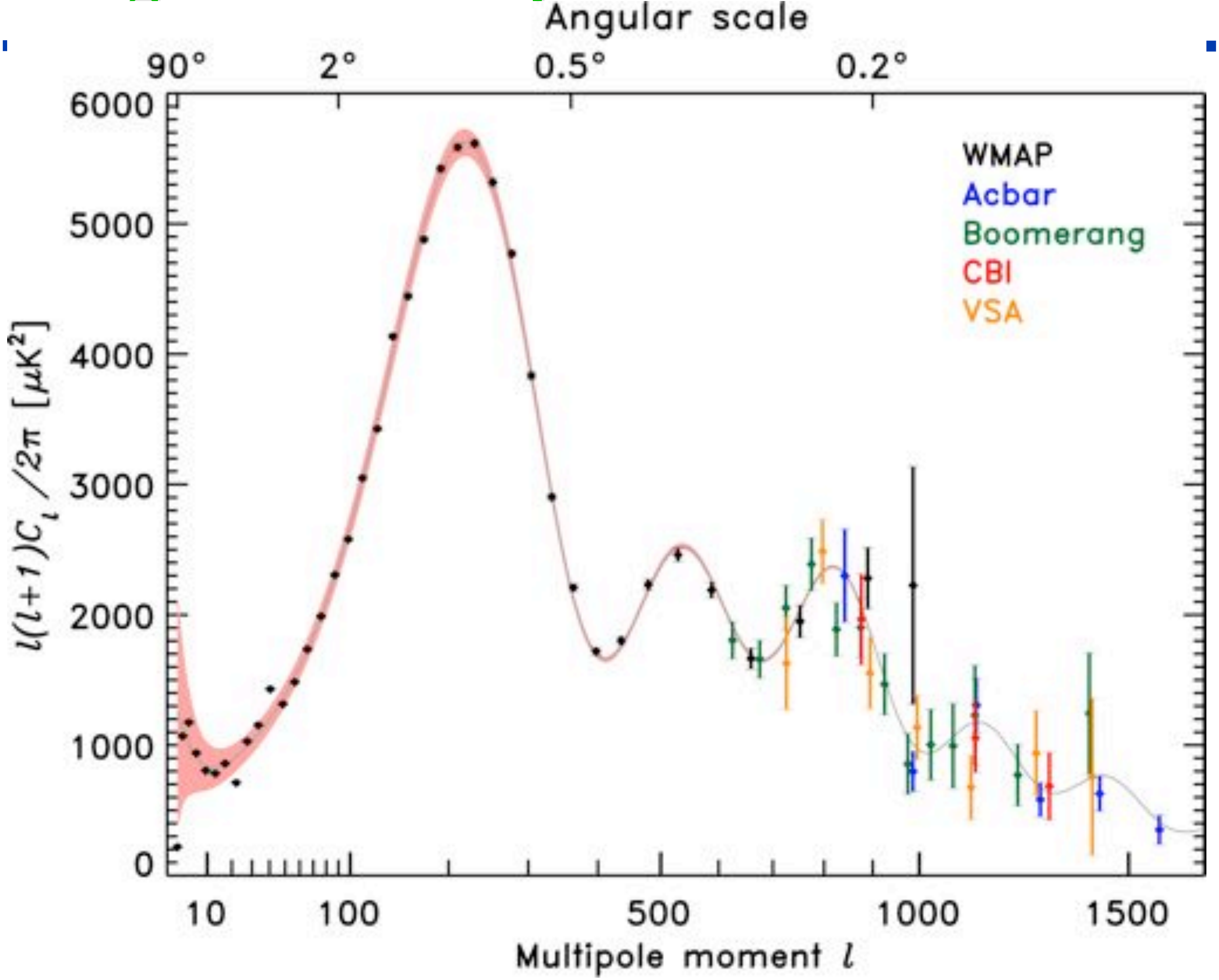


WMAP Continues Effort

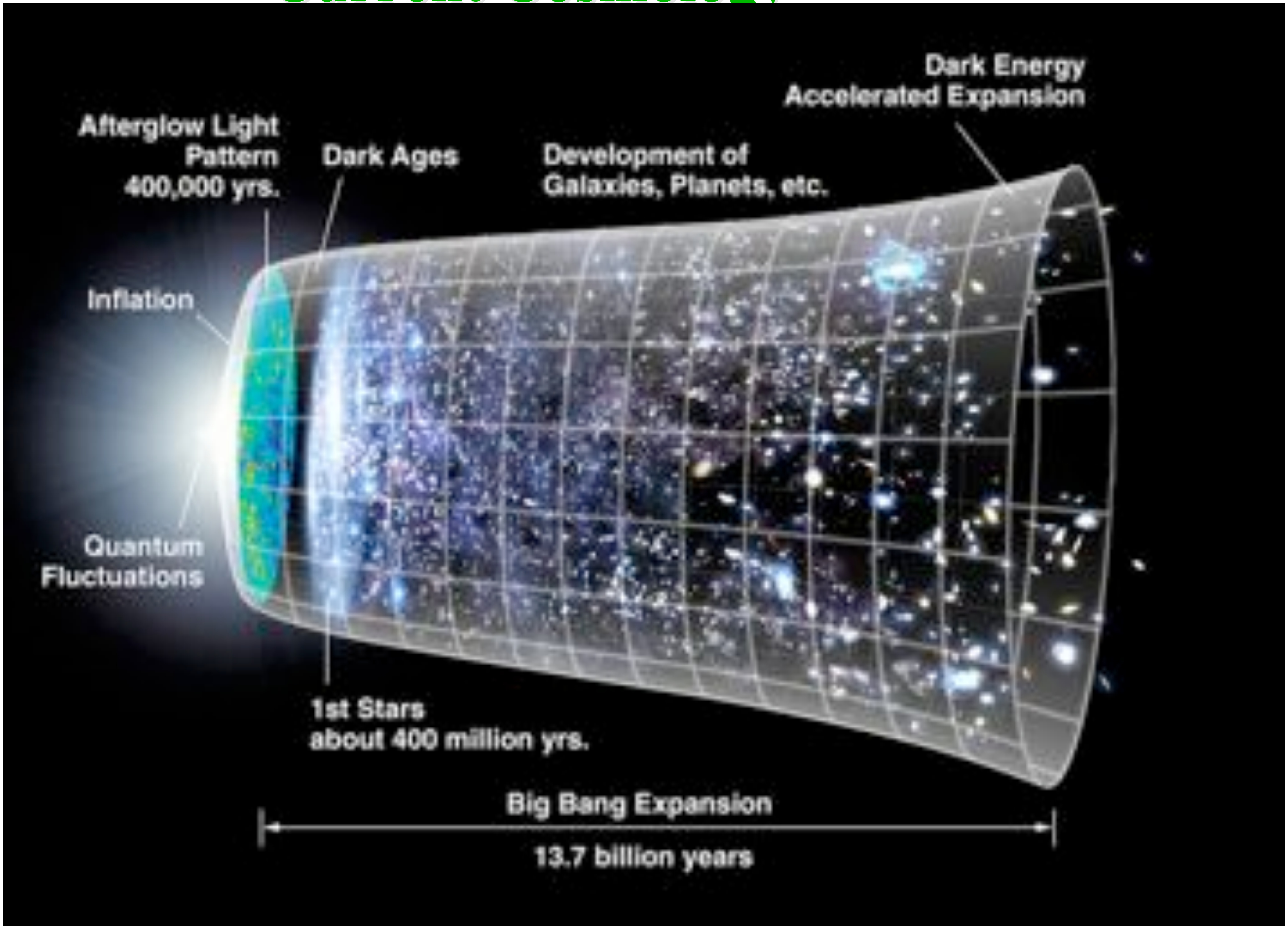




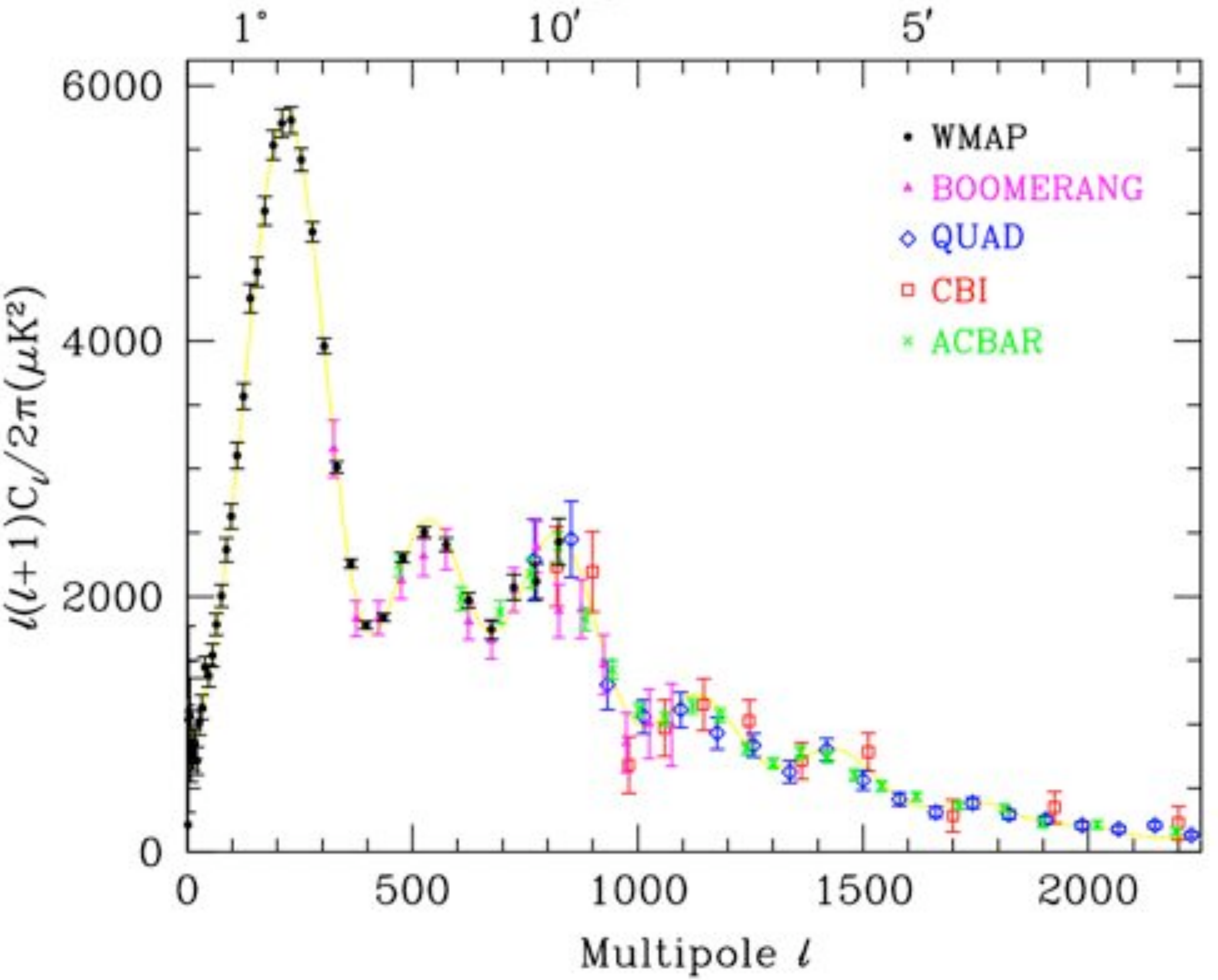
Angular Power Spectrum



Current Cosmology



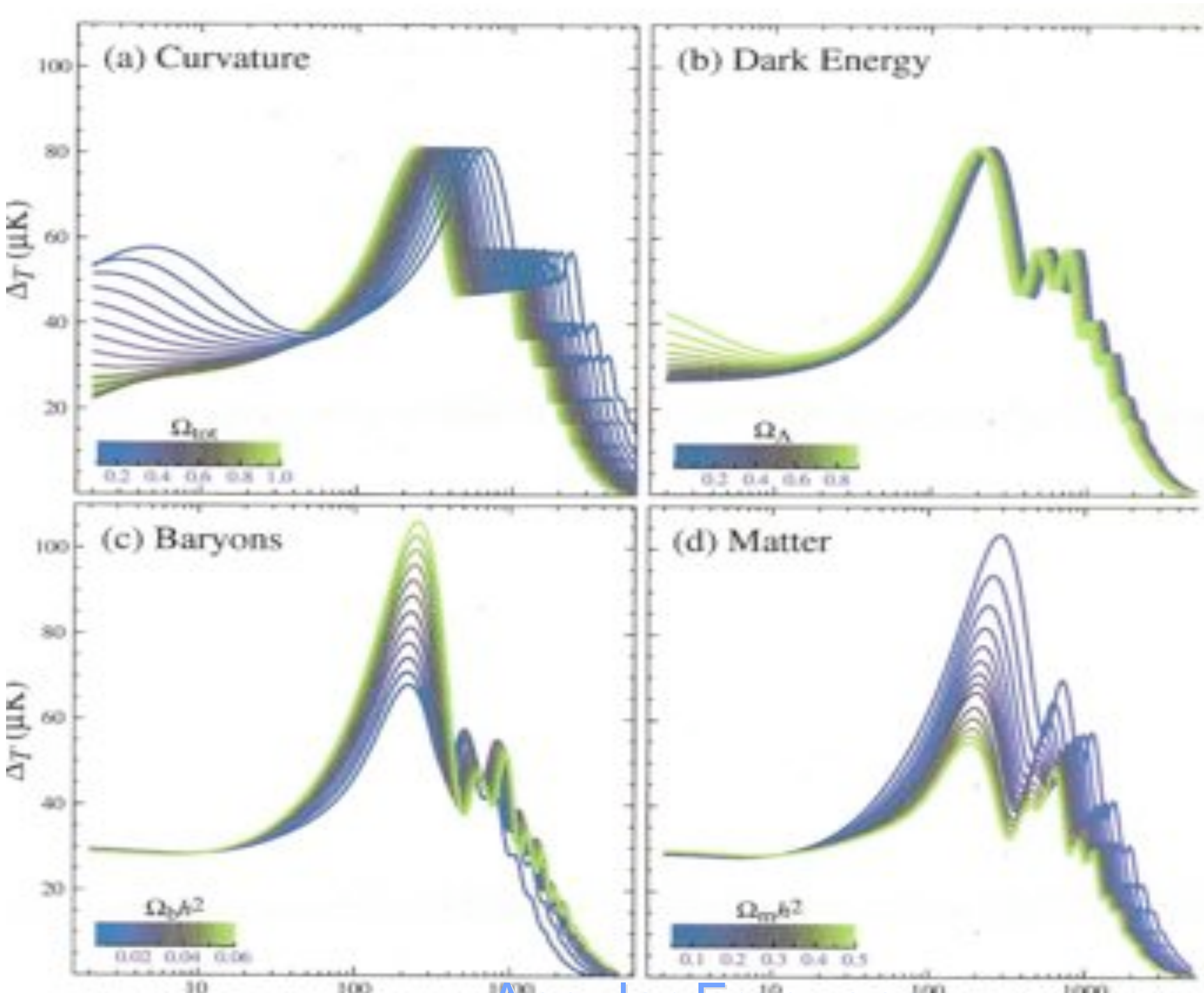
CMB Angular Power Spectrum



No preferred direction means we can average over m's to get power for each ℓ

$C_\ell \equiv \Sigma_m |a_{\ell m}|^2$

What we can learn from Spectral Analysis/Comparison



Angular Frequency

State-of-the-Art of the Universe

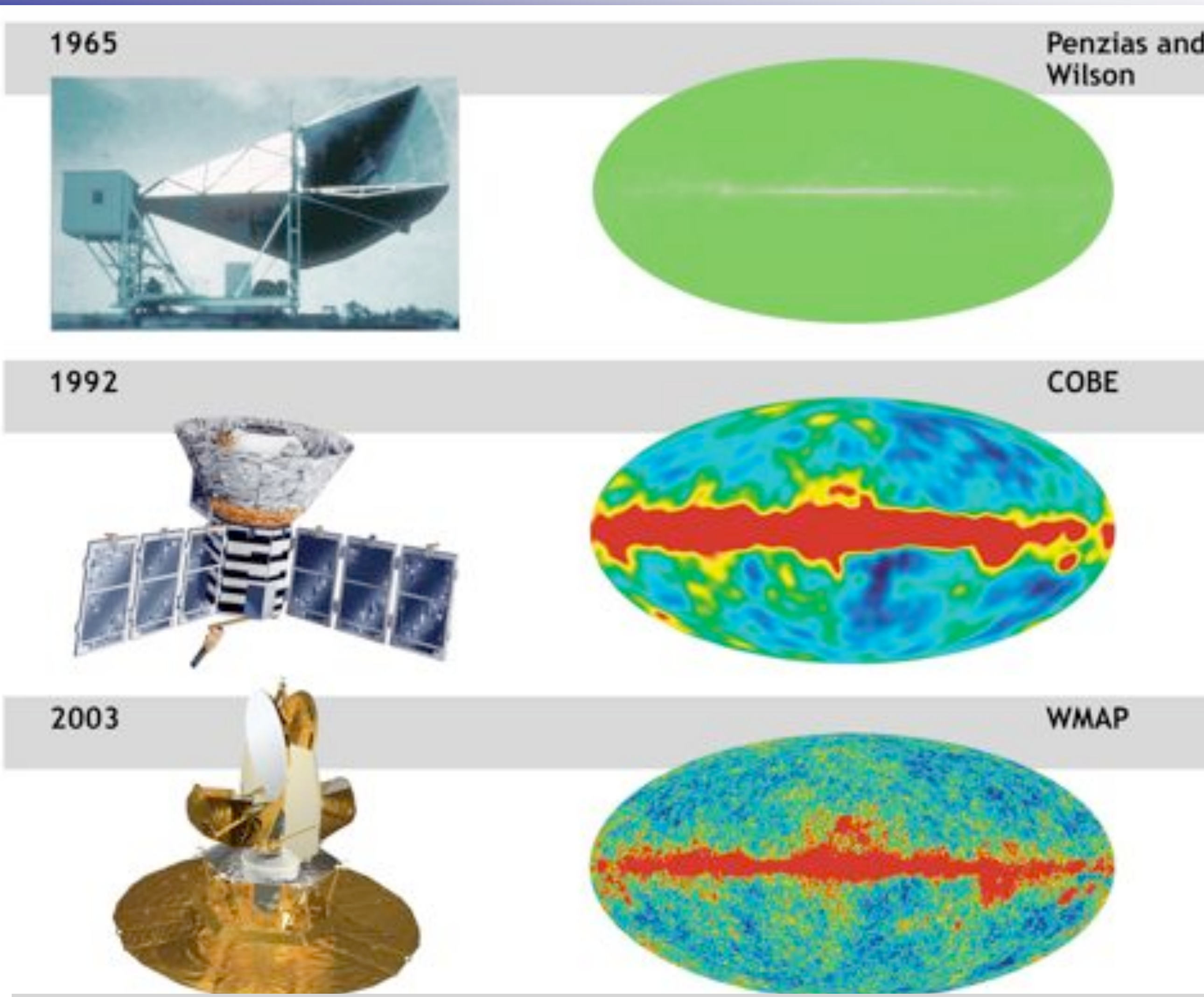
13.7 billion years old, expanding

Composition: 73% dark energy,
23% dark matter,
4% ordinary matter

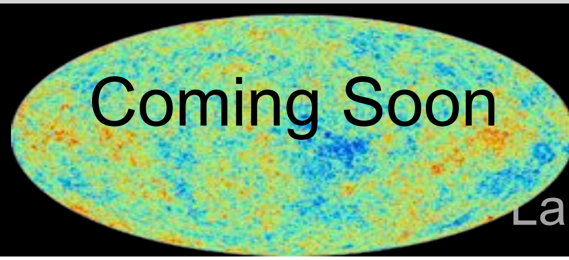
table 28-2 Some Key Properties of the Universe

Quantity	Significance	Value* (2003)	2010
Hubble constant, H_0	Present-day expansion rate of the universe	71^{+4}_{-3} km/s/Mpc	70.0 ± 1.7
Density parameter, Ω_0	Combined mass density of all forms of matter *and* energy in the universe, divided by the critical density	1.02 ± 0.02	0.994 ± 0.011
Matter density parameter, Ω_m	Combined mass density of all forms of matter in the universe, divided by the critical density	0.27 ± 0.04	0.273 ± 0.014
Density parameter for ordinary matter, Ω_b	Mass density of ordinary atomic matter in the universe, divided by the critical density	0.044 ± 0.004	0.456 ± 0.001
Dark energy density parameter, Ω_Λ	Mass density of dark energy in the universe, divided by the critical density	0.73 ± 0.04	0.728 ± 0.016
Age of the universe, T_0	Elapsed time from the Big Bang to the present day	$(1.37 \pm 0.02) \times 10^{10}$ years	
Age of the universe at the time of recombination	Elapsed time from the Big Bang to when the universe became transparent, releasing the cosmic background radiation	$(3.79^{+0.08}_{-0.07}) \times 10^5$ years	
Redshift z at the time of recombination	Since the cosmic background radiation was released, the universe has expanded by a factor $1 + z$	1089 ± 1	

Cosmic Microwave Background Radiation Overview



2009 Planck



The oldest light in universe

La lumiére la plus ancienne en univers

Discovered the remnant afterglow from the Big Bang.
→ 2.7 K

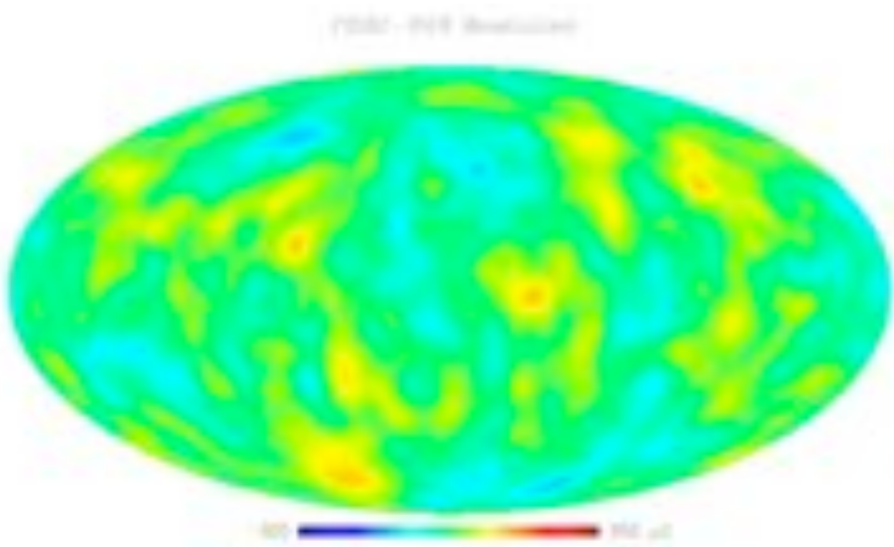
Blackbody radiation, **Discovered the patterns (anisotropy) in the afterglow.**
→ angular scale ~ 7° **at a level $\Delta T/T$ of 10^{-5}**

(Wilkinson Microwave Anisotropy Probe):
→ angular scale ~ 15'

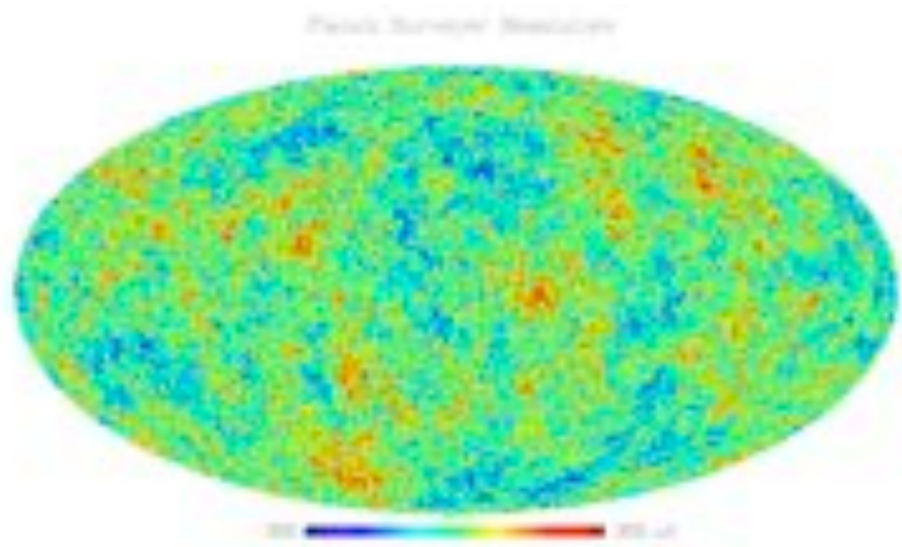
→ angular scale ~ 5',
$\Delta T/T \sim 2 \times 10^{-6}$, 30~867 Hz

La découverte d'or la plus passionnante

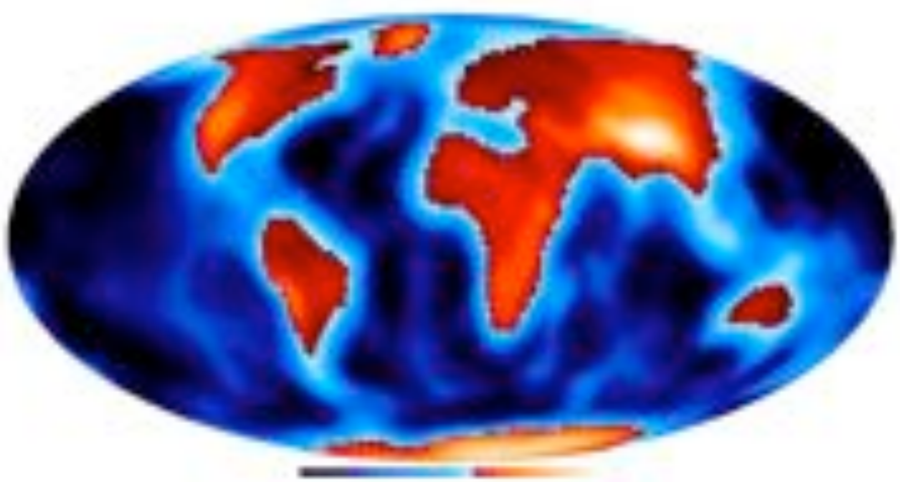
Great Discovery Era Unfolds …

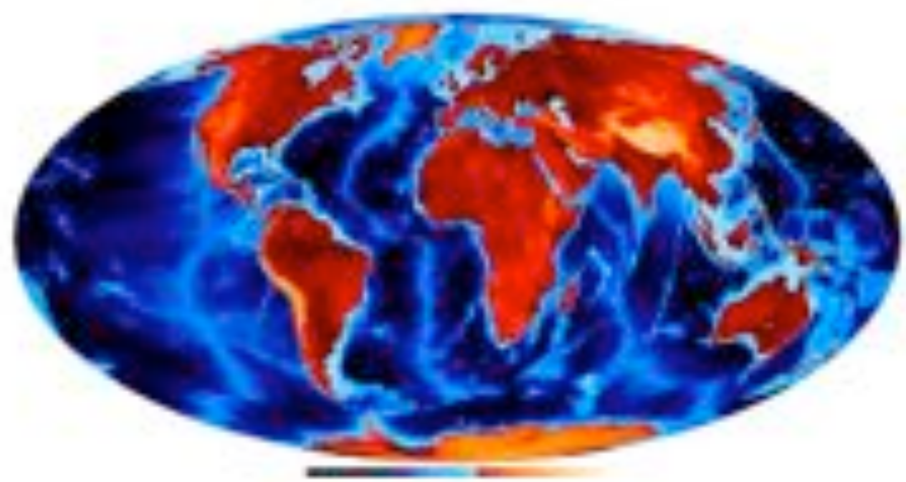


COBE DMR



WMAP & Planck

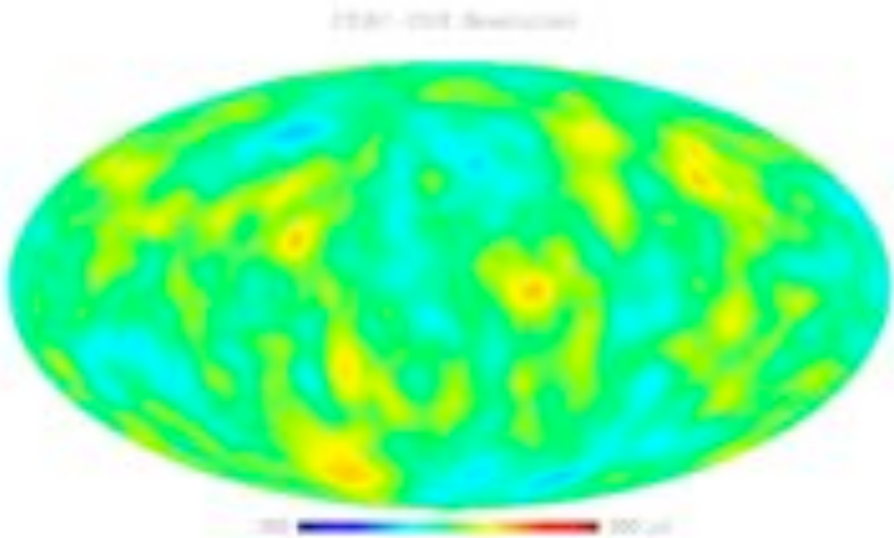




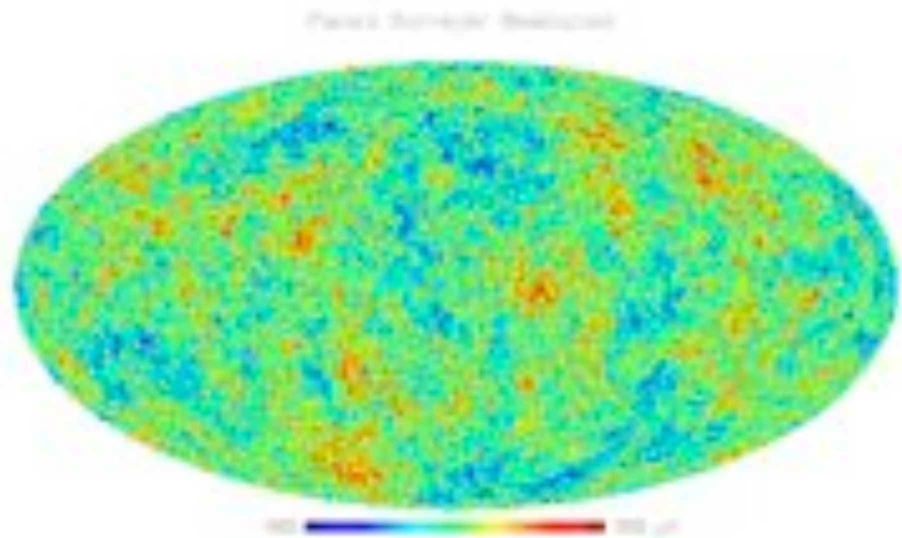
Great Discovery Era Unfolds …

La grande ère de découverte dévoile

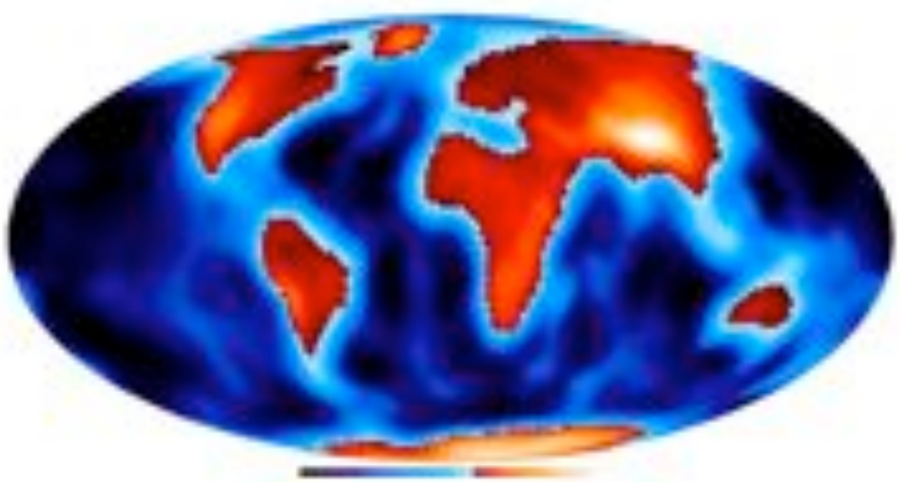
Una gran era de descubrimientos empieza…

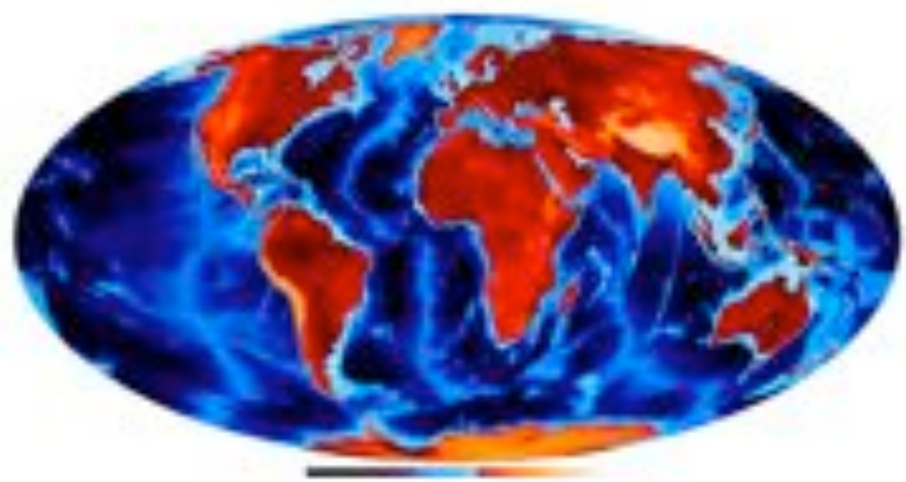


COBE DMR



WMAP & Planck





CMB Experiments at the South Pole

Club Med for CMB Experimentalists

Power, LHe, LN2, 80 GB/day, 3 square meals, and Wednesday Bingo Night.

ACBAR: Arcminute Cosmology Bolometer Array

• 16-pixel, multi-frequency, 240 mK, millimeter-wave bolometer array.
• Observes from 2m Viper telescope at the South Pole with 4-5′ beams.

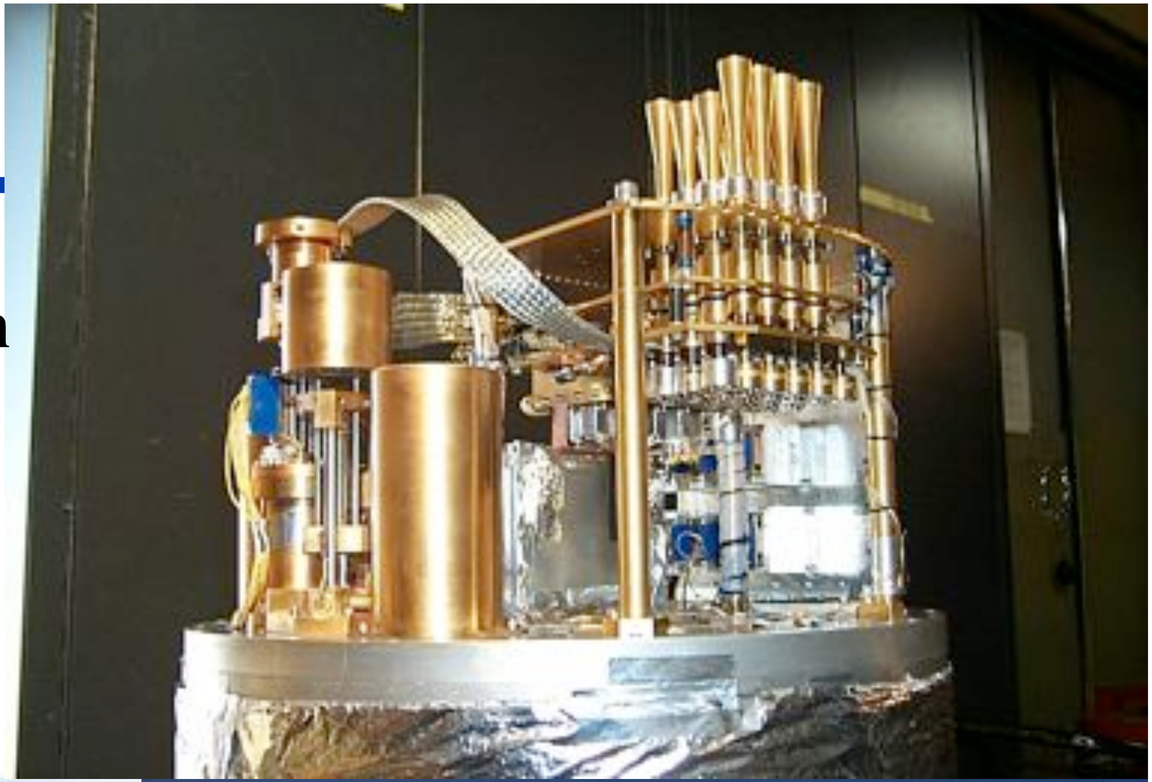
• Bands, filters, detectors, and angular resolution similar to *Planck* HFI.

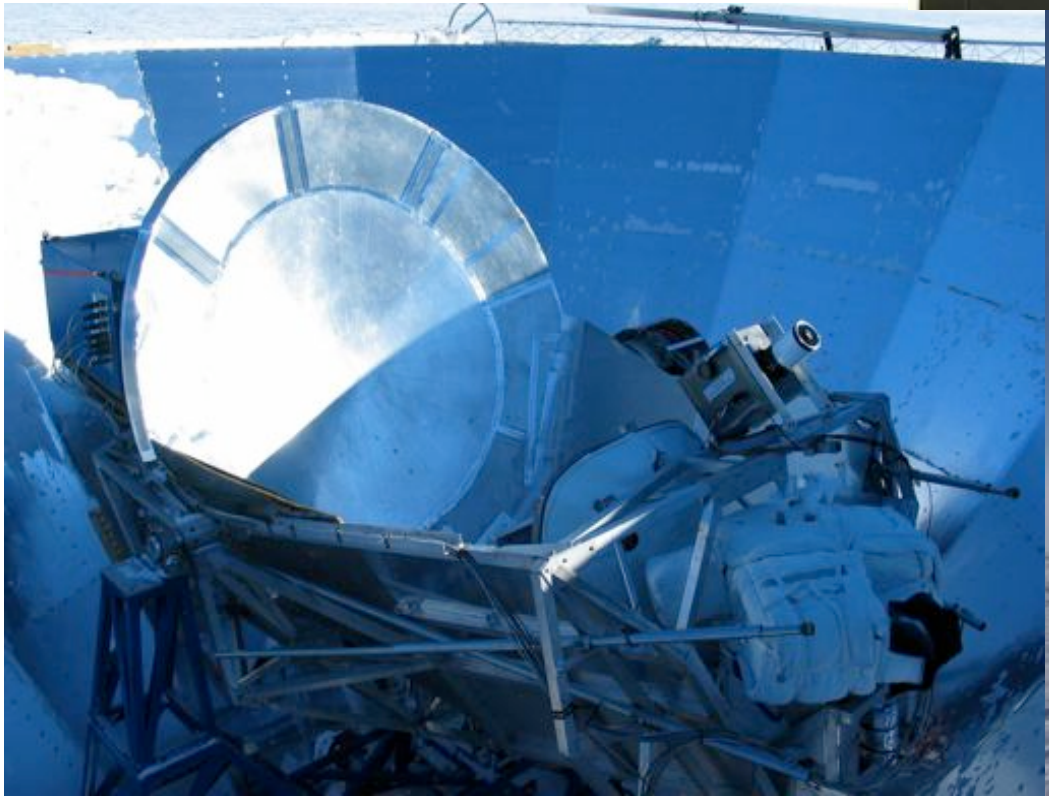
- Assembled: Fall 2000
- Installed: January 2001
- Upgraded: December 2001
- Observed through Nov 2002

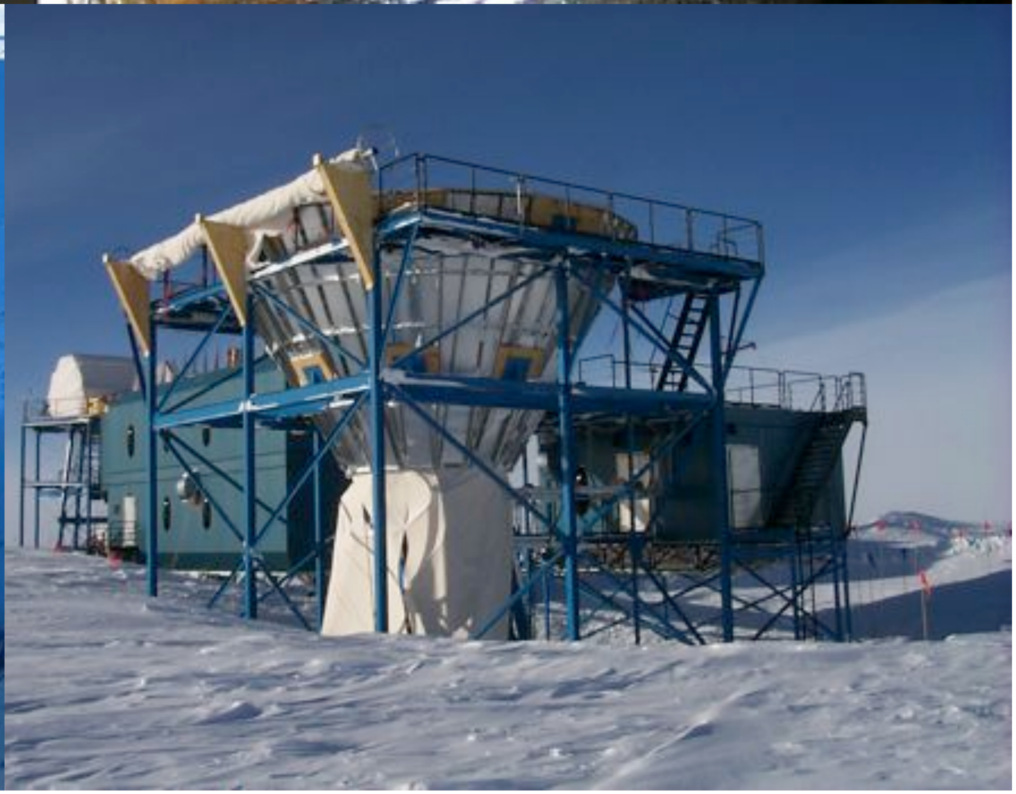
Arcminute Cosmology Bolometer Array Receiver (ACBAR)

Finished observations at South Pole in 2005

New constraints on CMB Damping tail and secondary anisotropies

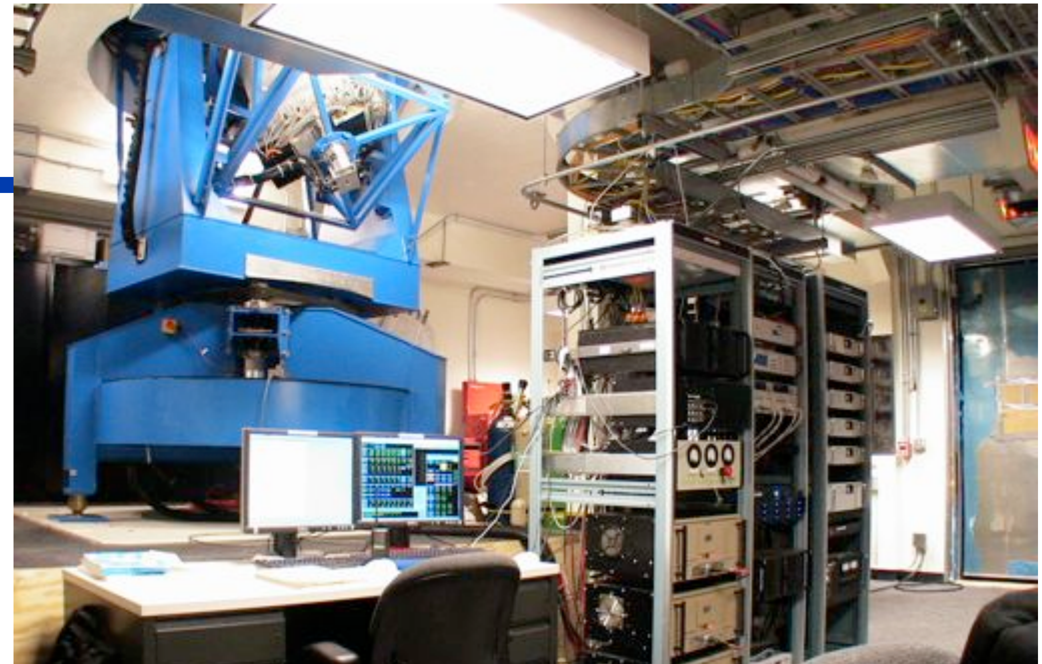


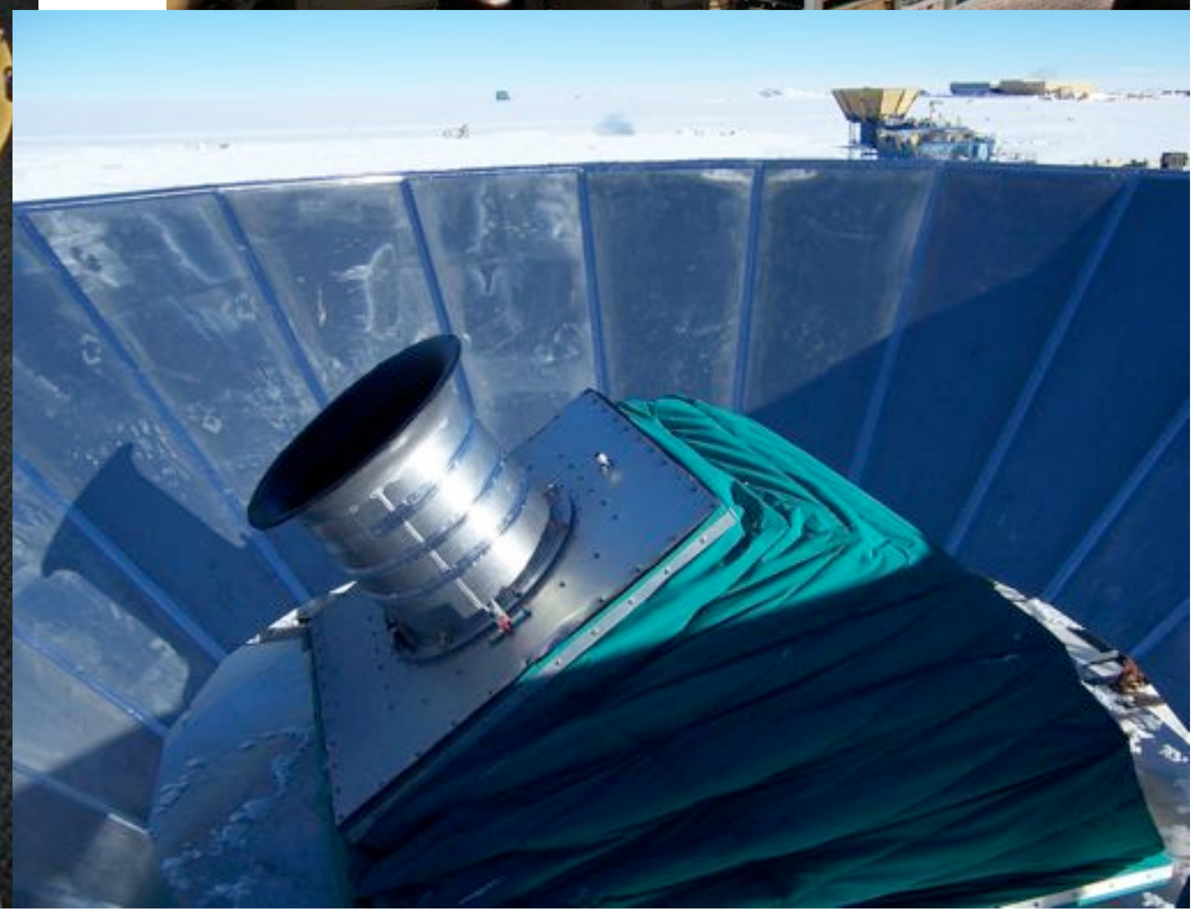




BICEP has just completed its first successful winter of observations

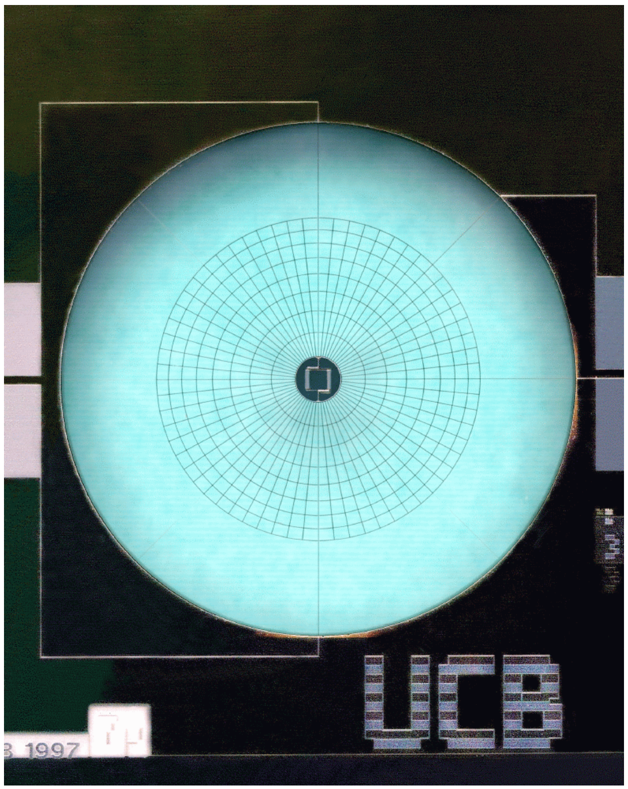
New constraints on CMB Polarization coming soon. - 2005



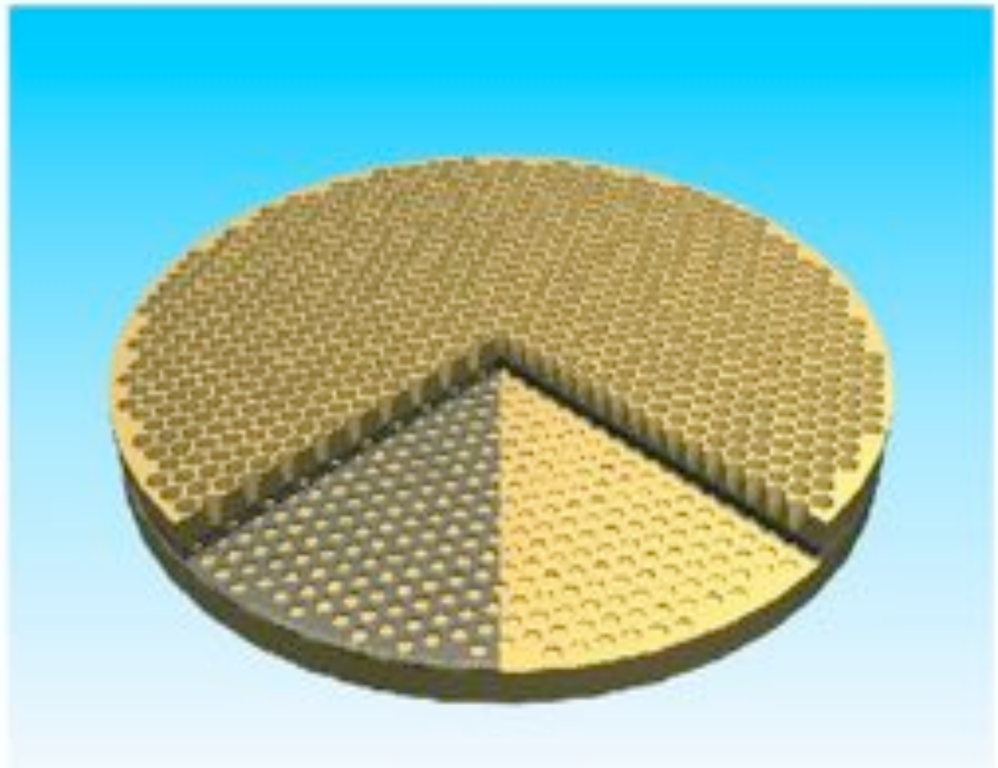


SPIDER (balloon-borne) Array

Spider-Bolometer/horn array for SPT & APEX SZ



3.5 mm

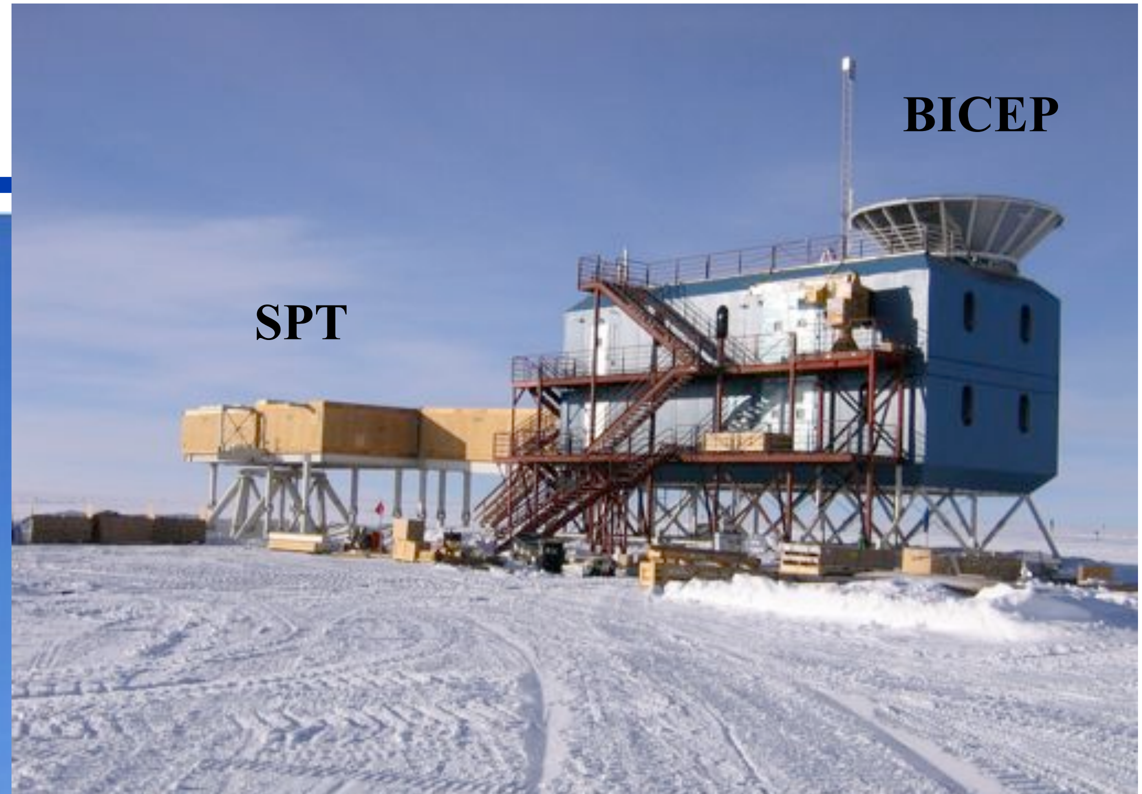


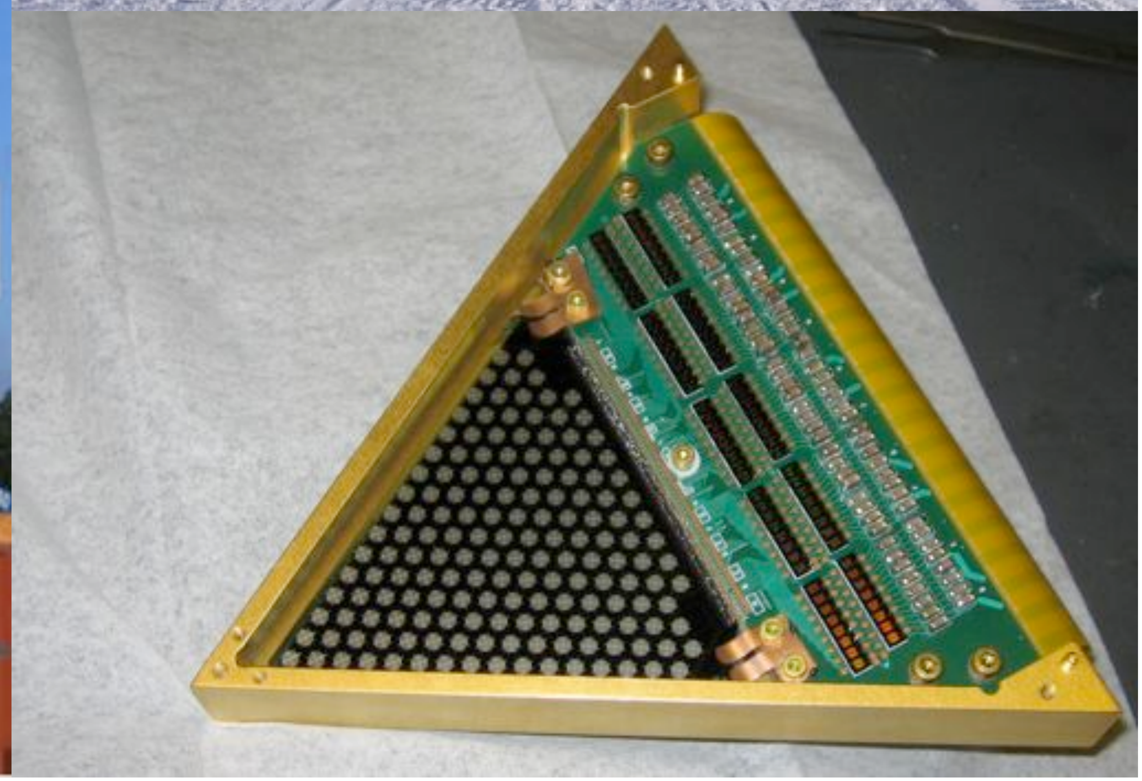
15 cm

Spider Web TES bolometer

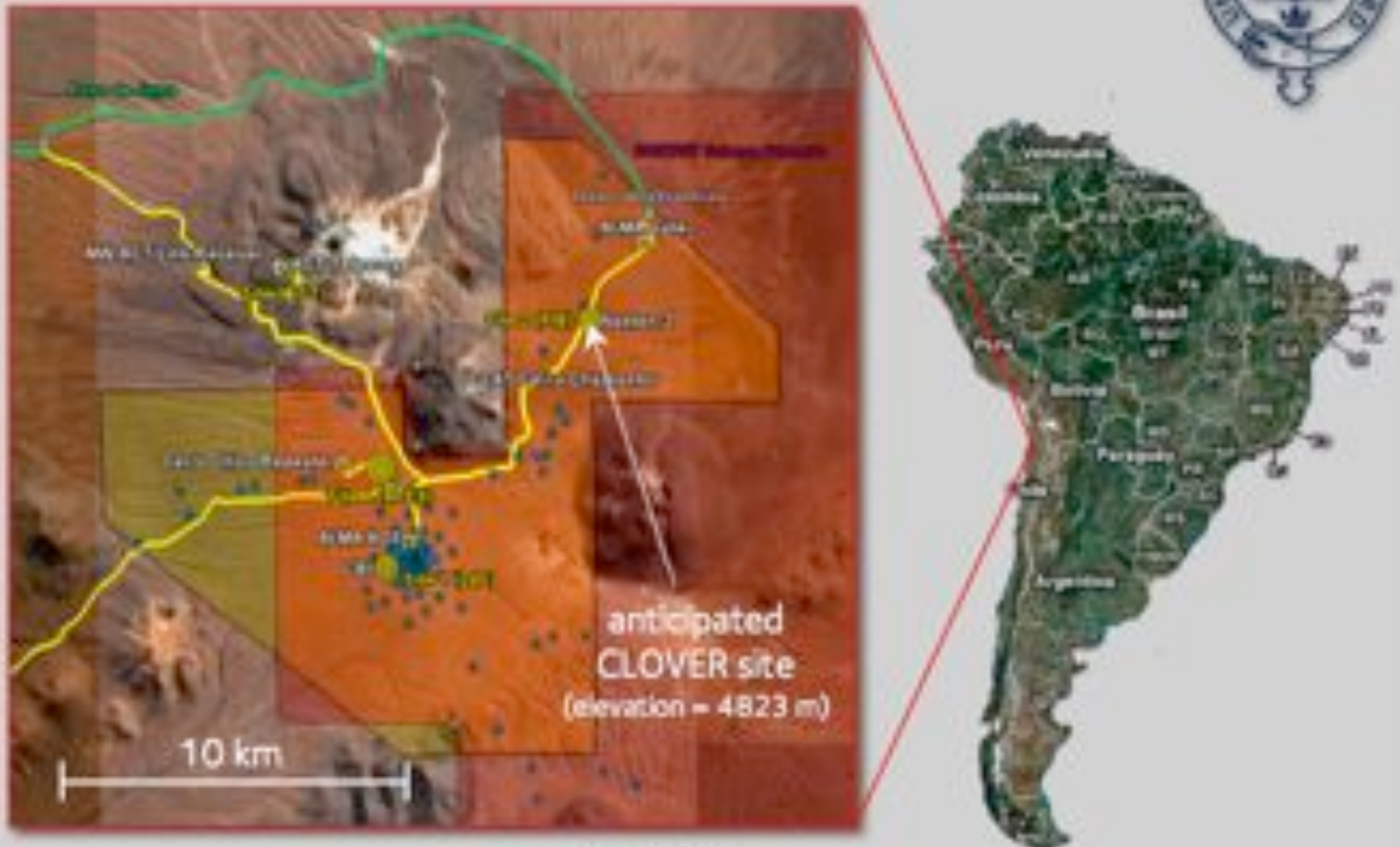
Cutaway of 1000 element array

SPT began observations from the Pole February 2008





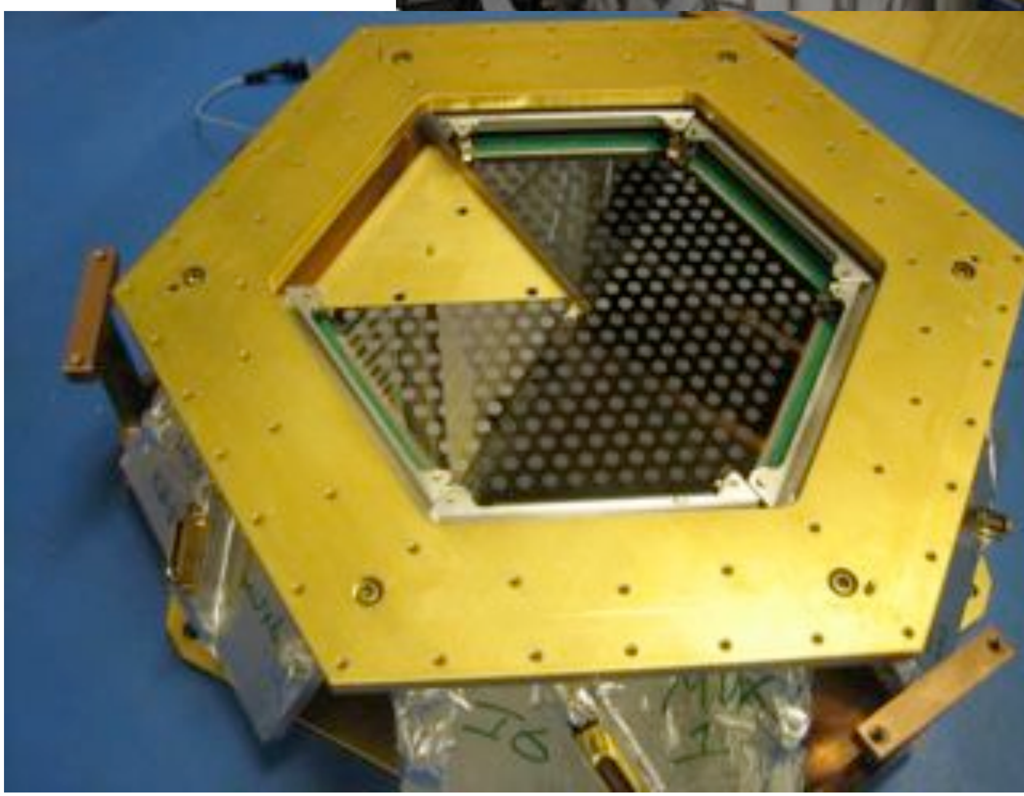
CLOVER Site: Atacama, Chile



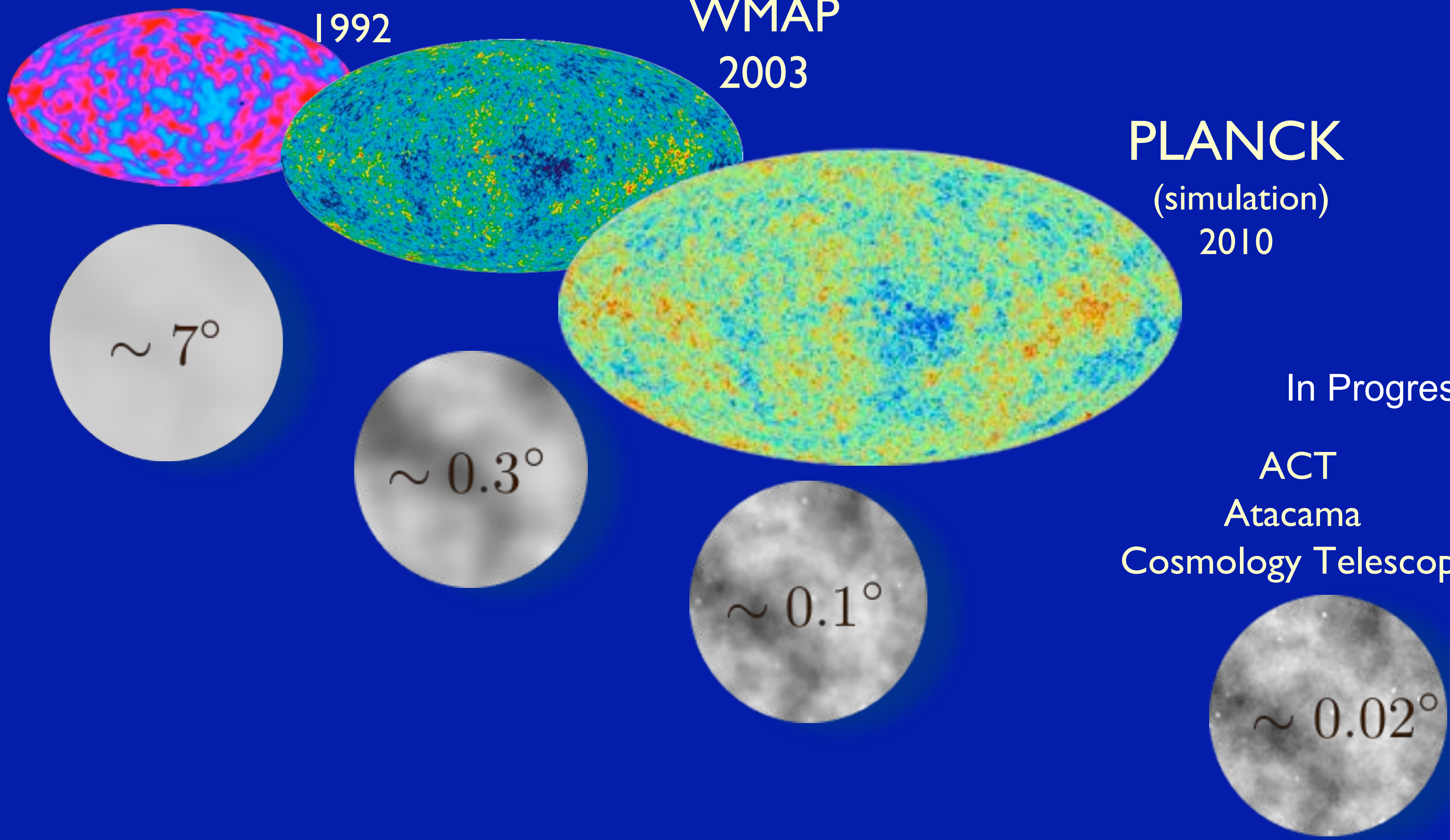
8 of 25

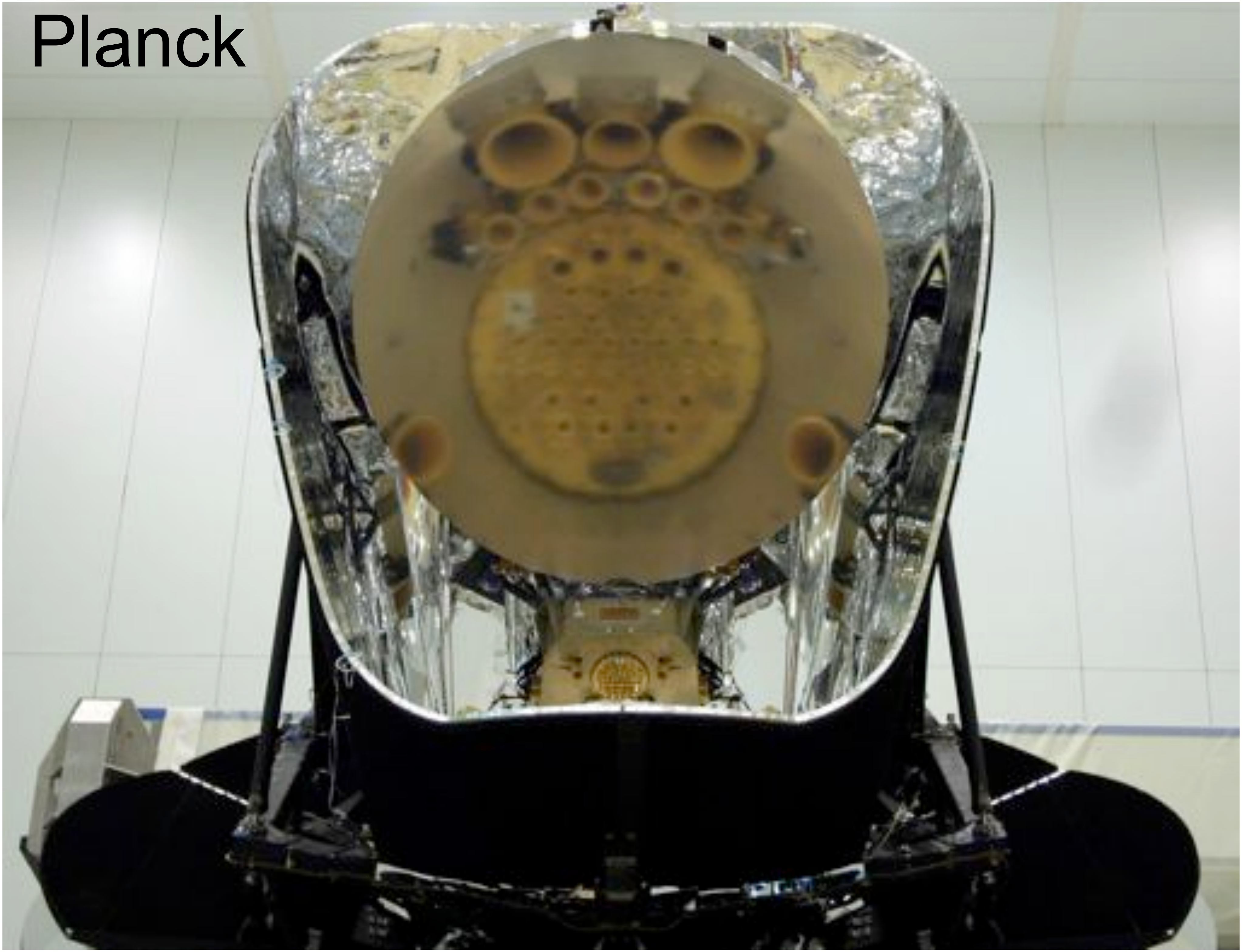
APEX-SZ Receiver being Installed for engineering run

First Science In Spring 07



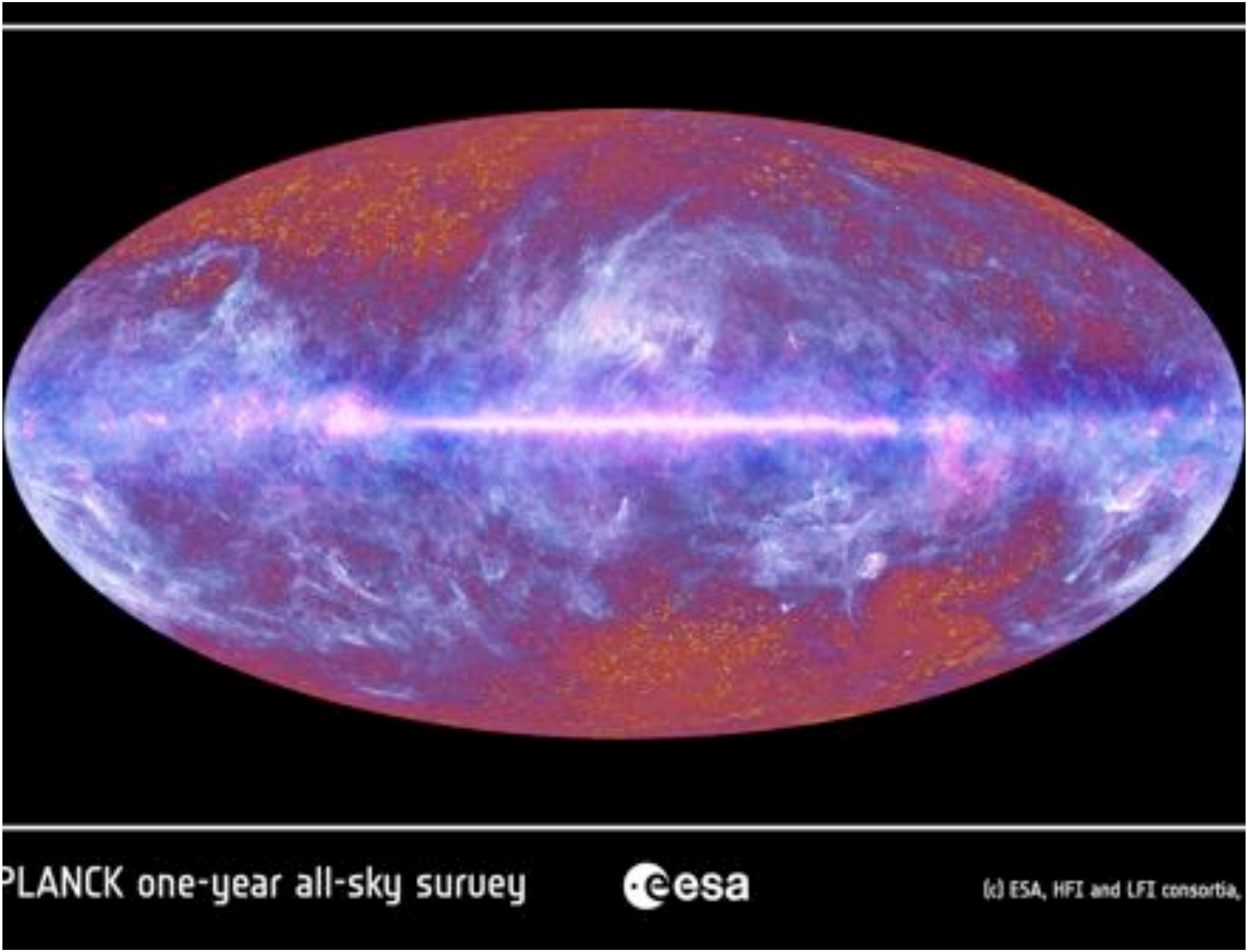
Our Ever-sharpening View of the Embryo Universe ...

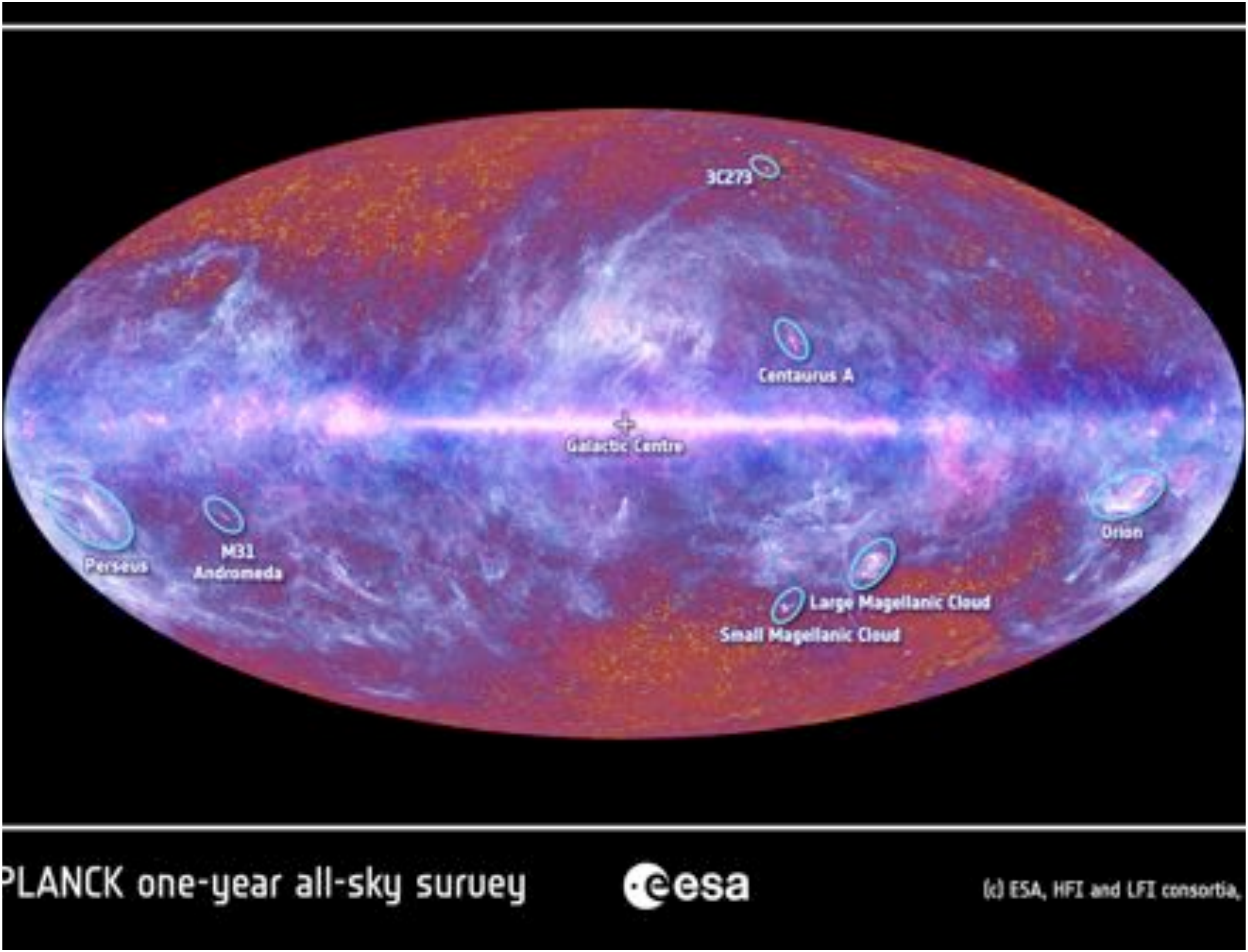



Planck

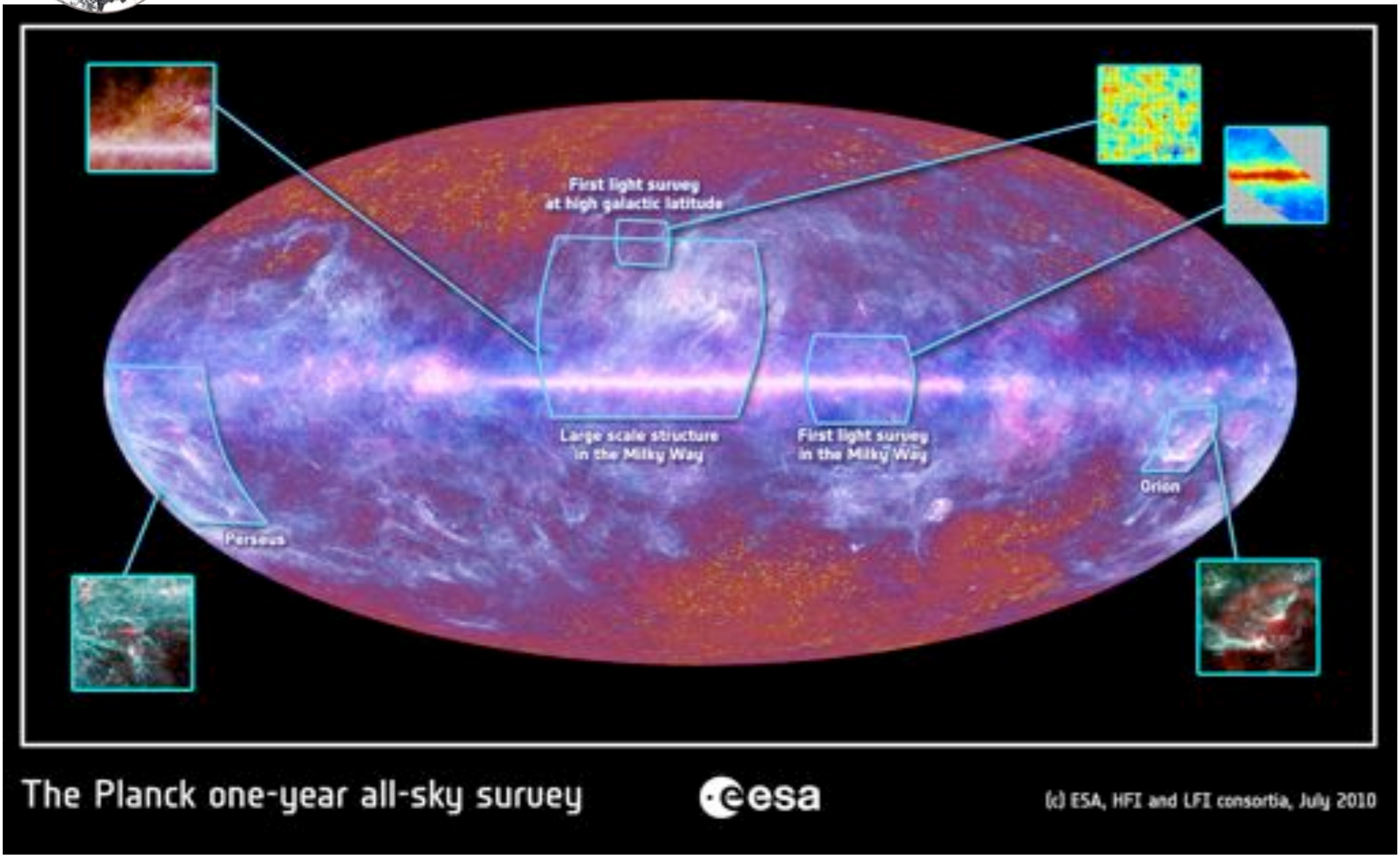
Nuova

Planck 1st Year Full Sky Mapping


PLANCK one-year all-sky survey
esa
(c) ESA, HFI and LFI consortia,

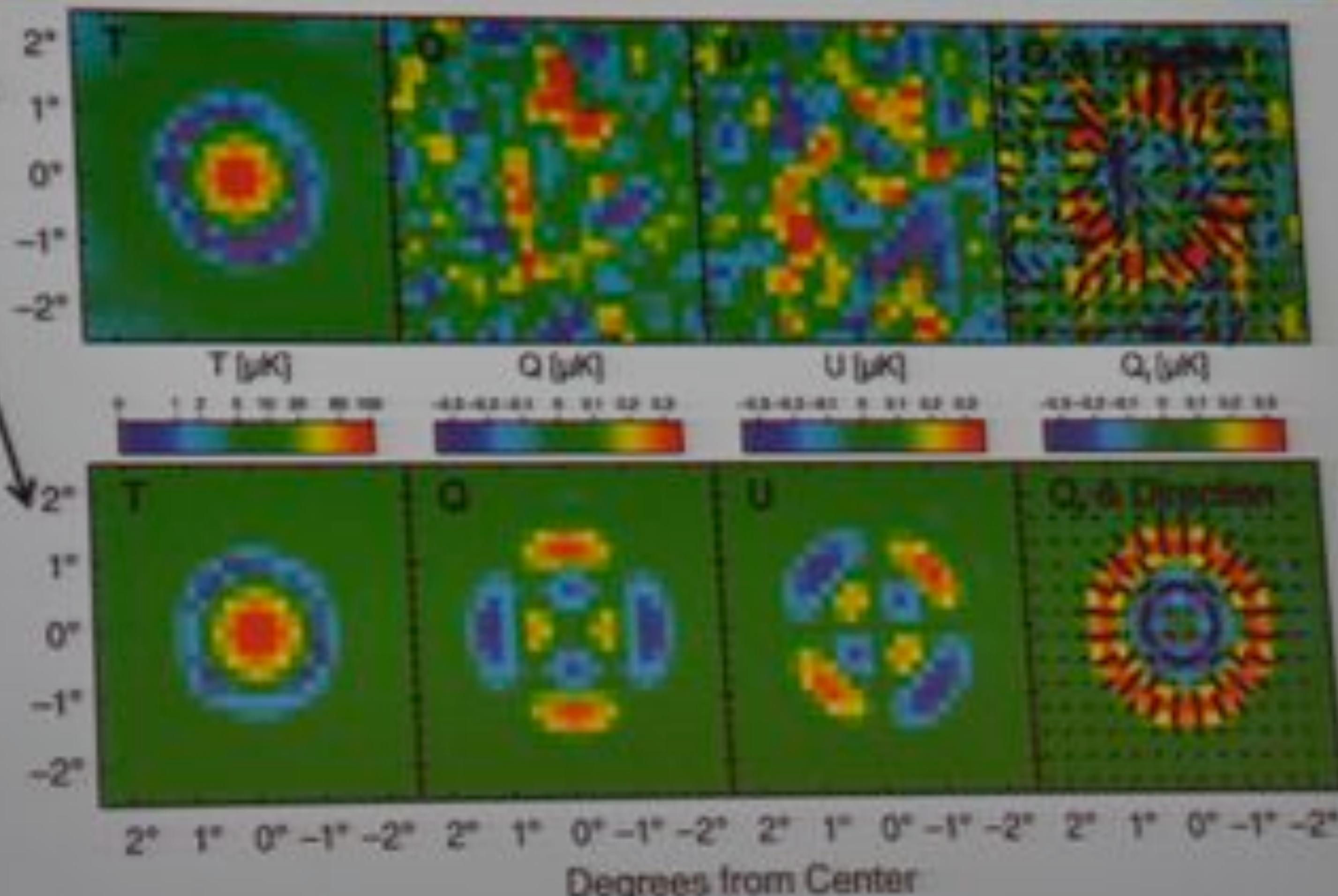

3C273
Centaurus A
Galactic Centre
Perseus
M31
Andromeda
Orion
Large Magellanic Cloud
Small Magellanic Cloud
PLANCK one-year all-sky survey
esa
(c) ESA, HFI and LFI consortia,

Planck 1st Year with call outs



"A typical CMB Hot spot"
Illustration of polarization sensitivity

WMAP 7years
(Komatsu et al.
preprint 2010)
& simulations



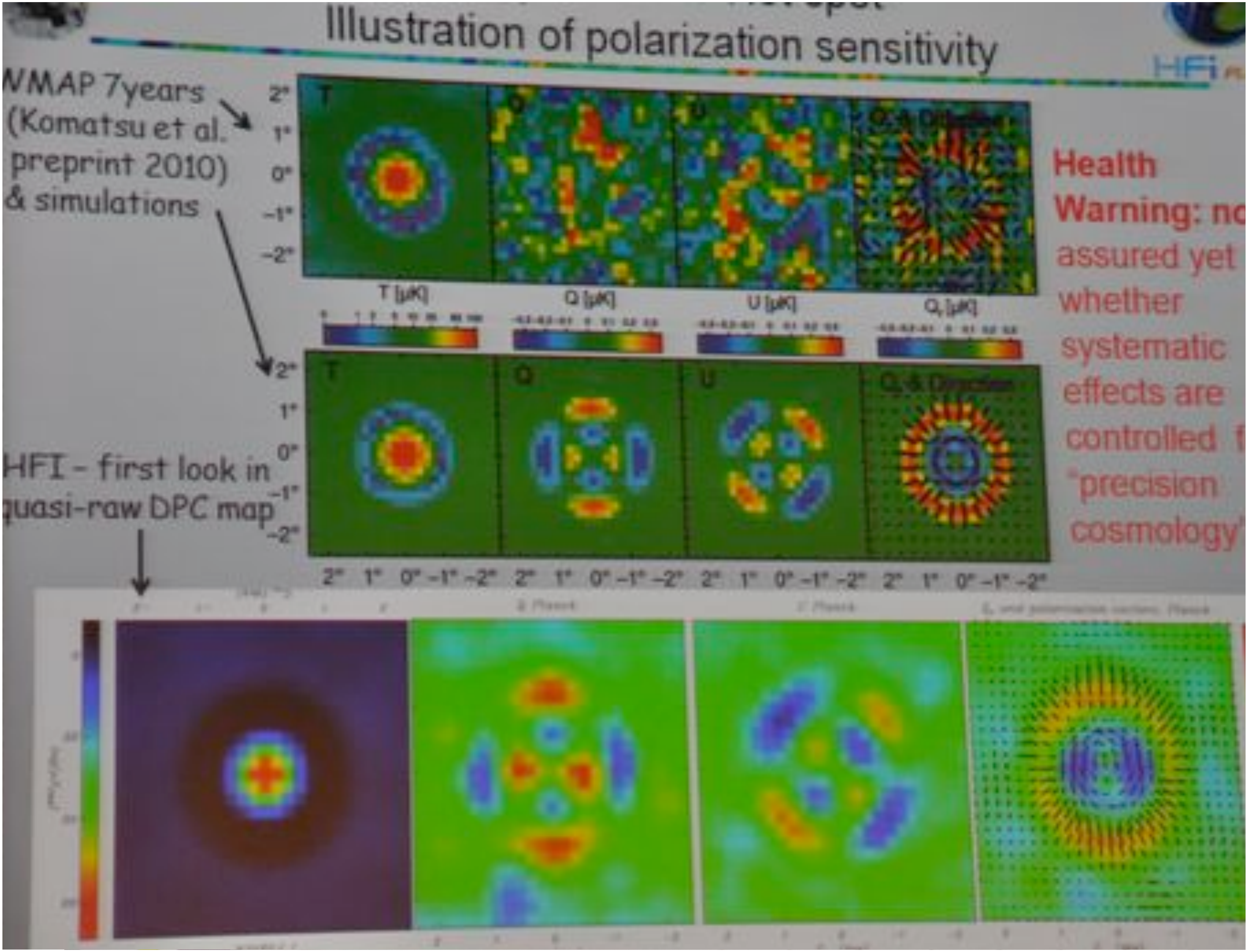
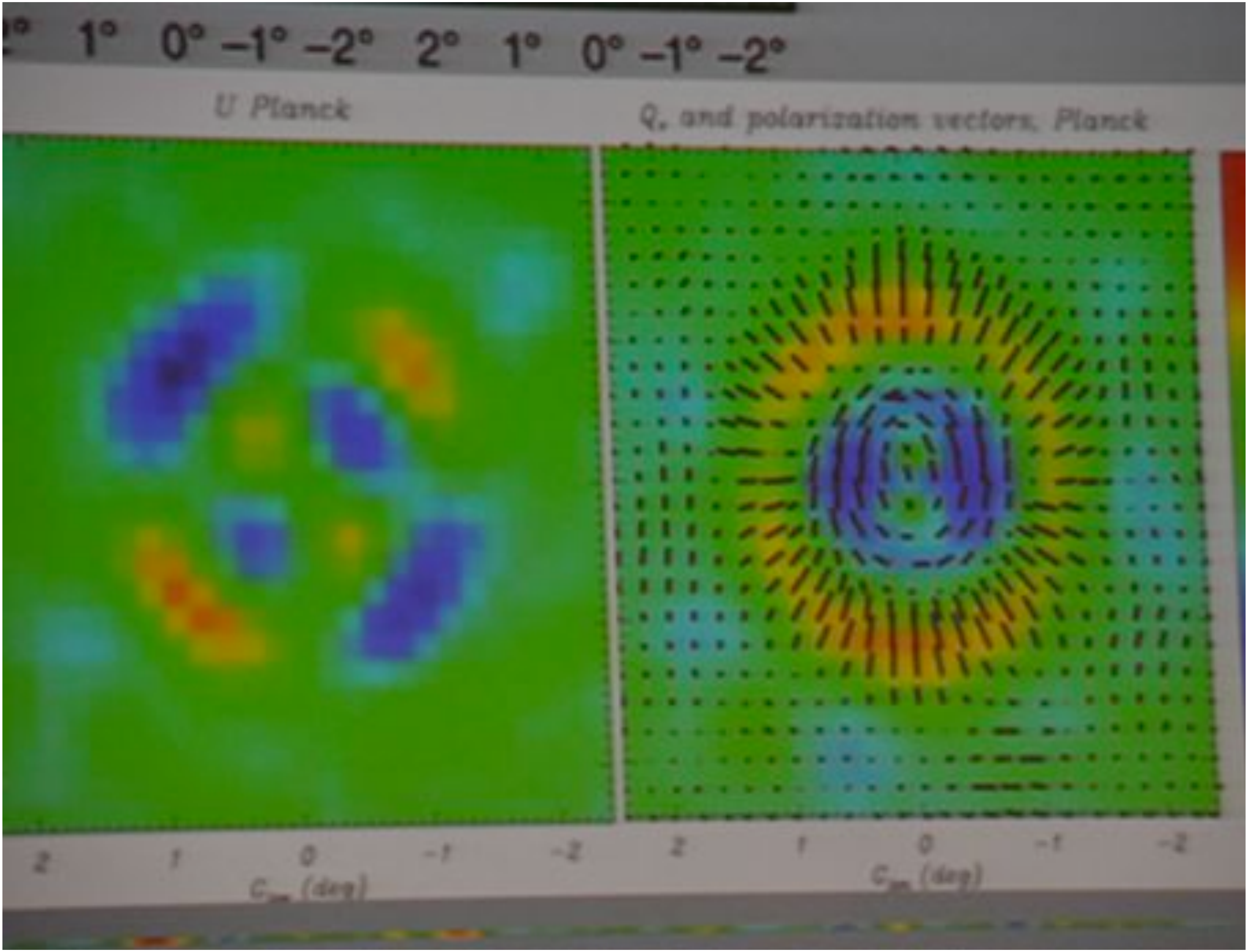
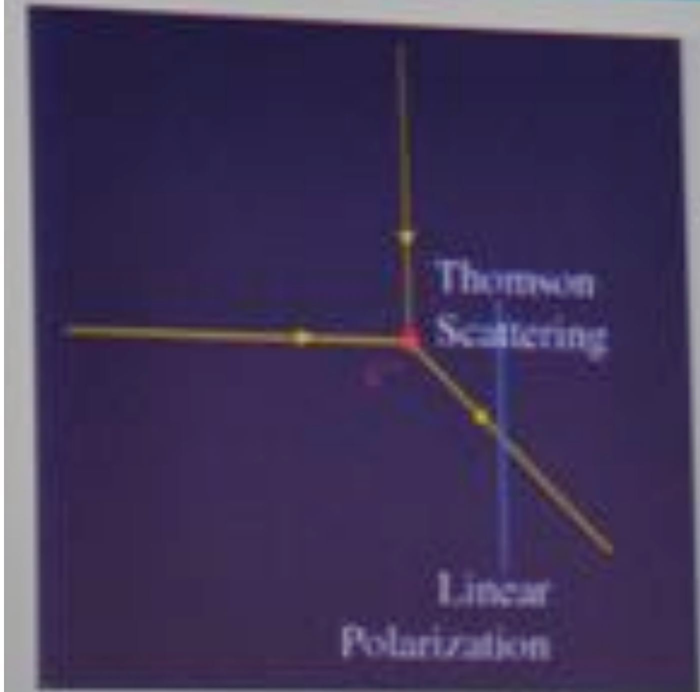


Illustration of polarization sensitivity
WMAP 7years (Komatsu et al. preprint 2010) & simulations
HFI - first look in quasi-raw DPC map
T [μK]
Q [μK]
U [μK]
Health Warning: no
assured yet whether systematic effects are controlled f
"precision cosmology"

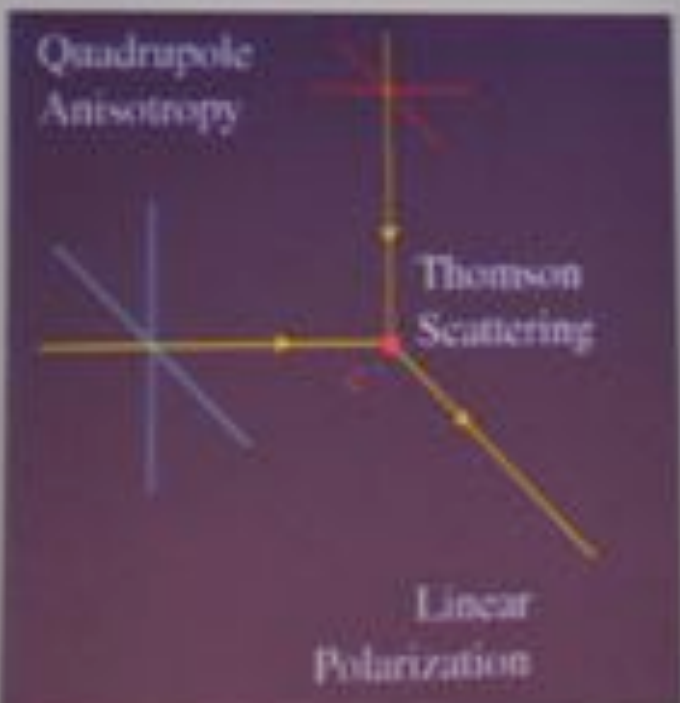


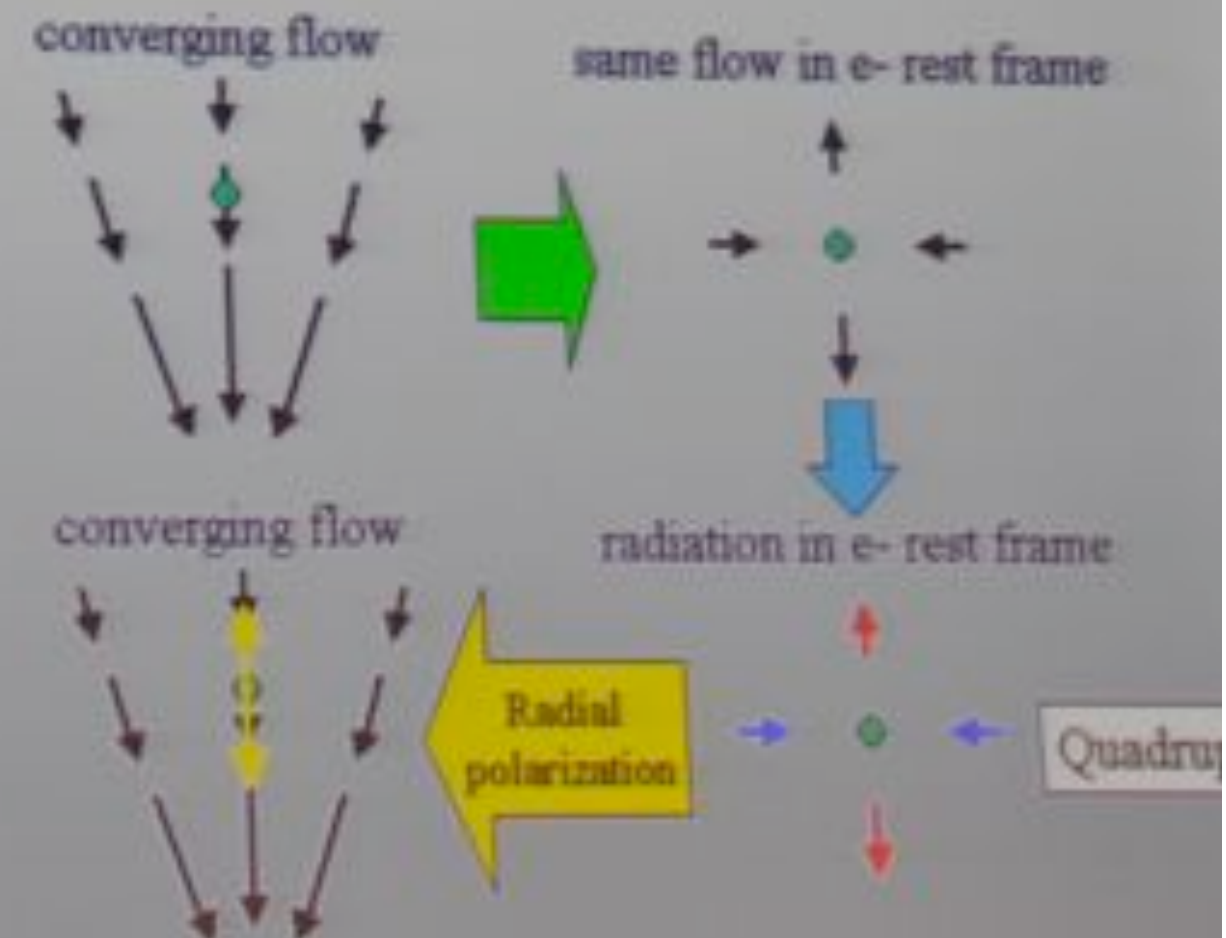
1° 0° −1° −2° 2° 1° 0° −1° −2°
U Planck
Q, and polarization vectors, Planck
2 1 0 −1 −2
2 1 0 −1 −2

Thomson scatterings are polarised

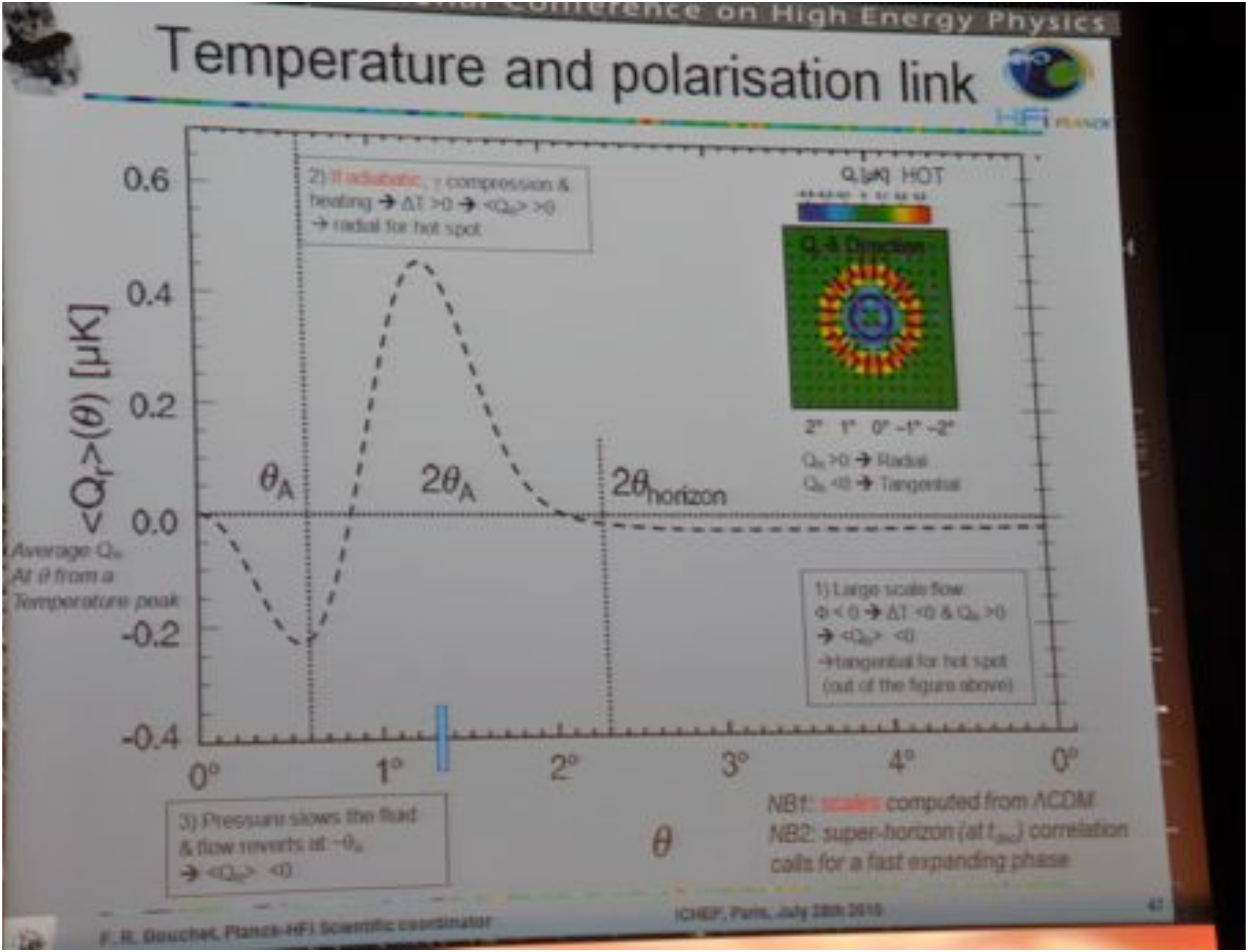


- Before recombination, successive scatterings destroy polarization and the radiation arrives at recombination unpolarized
- During recombination, Gradients in the velocity field can produce a quadrupole in the rest frame of the scattering electron





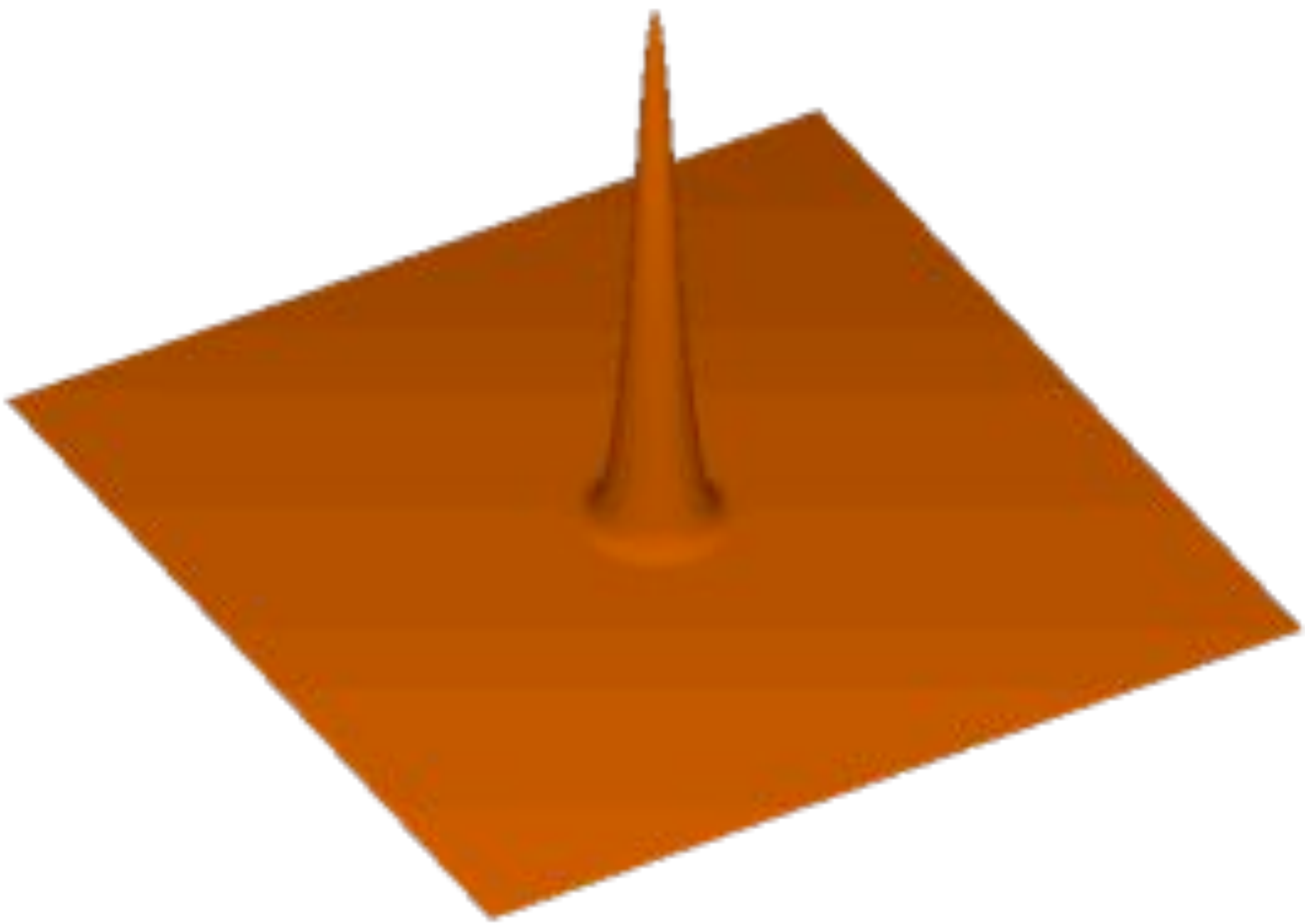
- A diverging flow leads to a tangential pattern of polarisatio



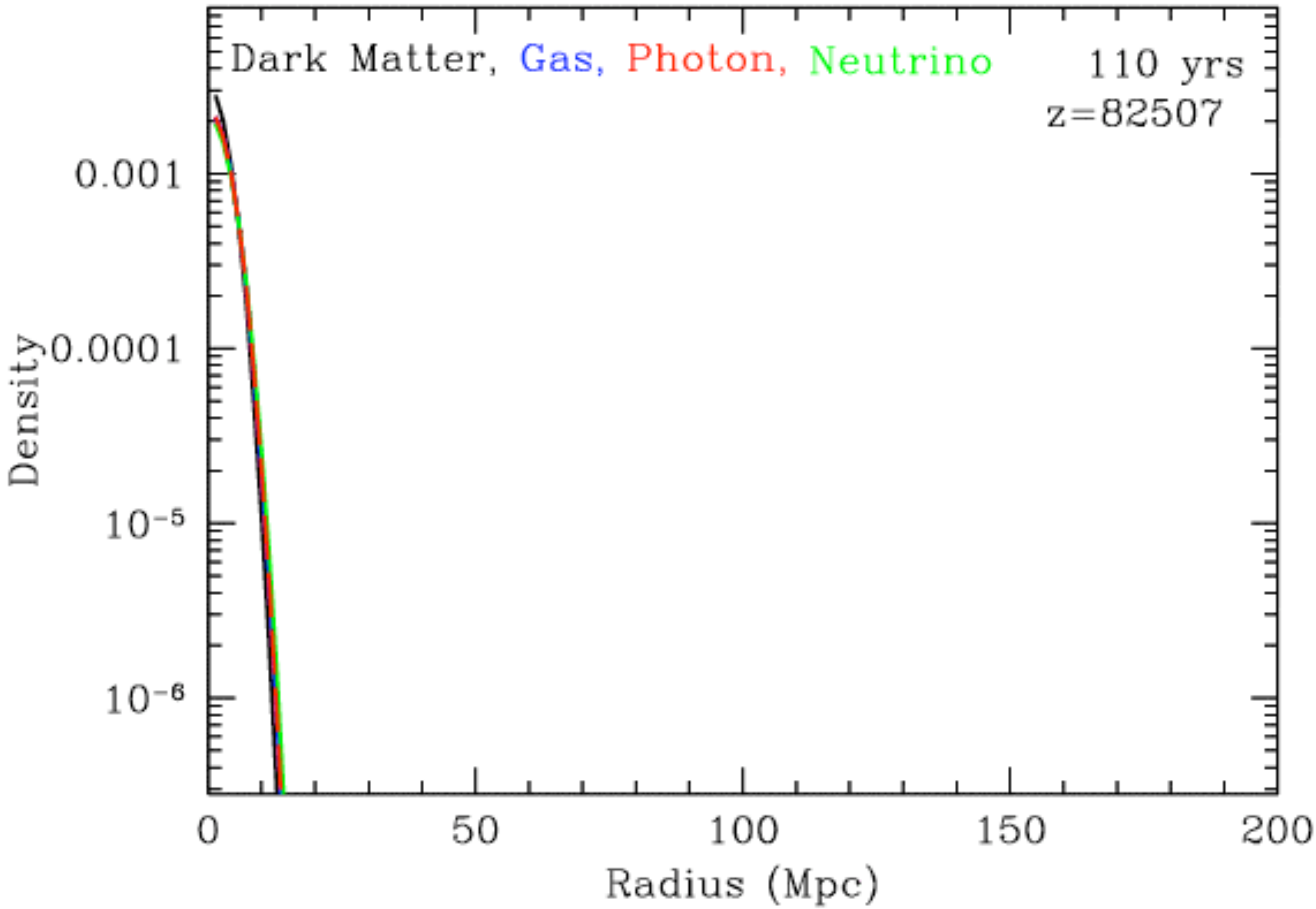
Conference on High Energy Physics
Temperature and polarisation link
0.6
0.4
0.2
0.0
-0.2
-0.4
$<Q_r>(\theta)$ [μK]
Average Q_r
At θ from a
Temperature peak
heating → ΔT >0 → $<Q_r>$ >0
→ radial for hot spot
HOT
2° 1° 0° -1° -2°
Q_r >0 → Radial
Q_r <0 → Tangential
θ_A
$2\theta_A$
$2\theta_{horizon}$
1) Large scale flow
Φ < 0 → ΔT <0 & Q_r >0
→ $<Q_r>$ <0
→tangential for hot spot
(out of the figure above)
0° 1° 2° 3° 4° 0°
θ
3) Pressure slows the fluid
& flow reverts at ~θ_A
→ $<Q_r>$ <0
NB1: scales computed from ΛCDM
NB2: super-horizon (at t_{dec}) correlation
calls for a fast expanding phase
F. R. Bouchet, Planck-HFI Scientific coordinator
ICHEP, Paris, July 28th 2010

Evolution of single over dense lump

comoving coordinates



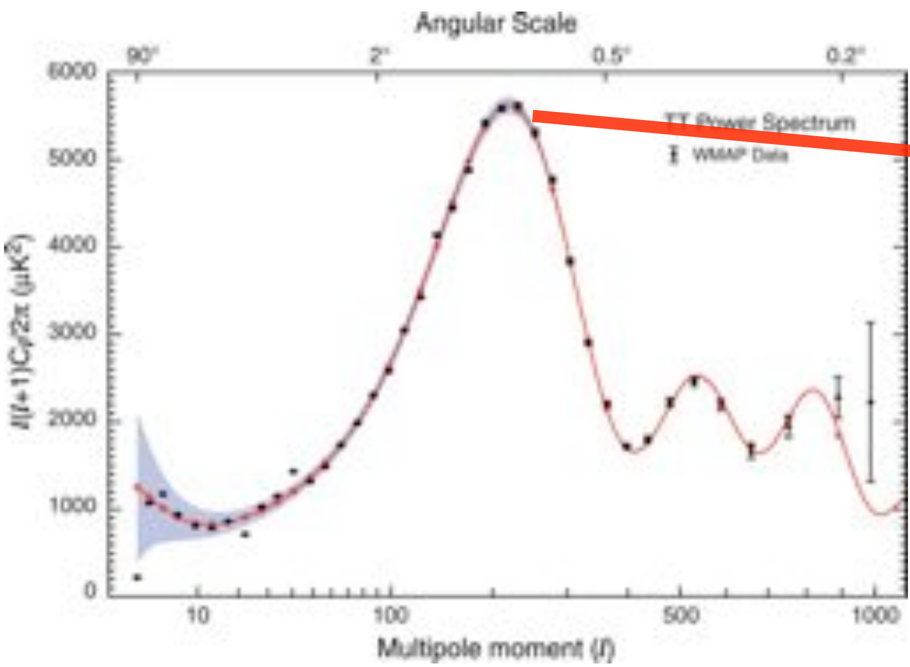
Evolution of Lumps Components



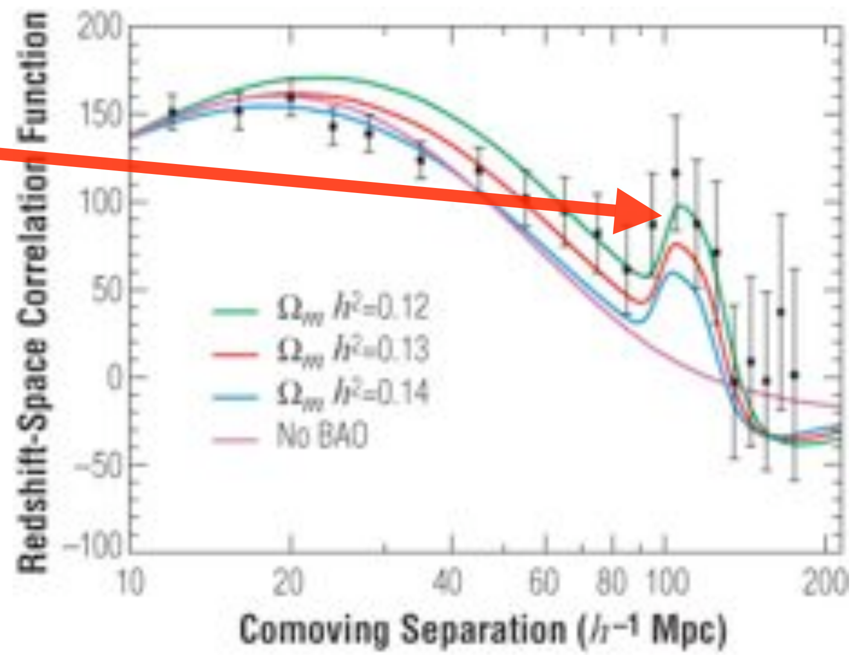
New Dark Energy Tool: Acoustic Oscillations

Fluctuations on all scales, but there is a characteristic scale.

CMB (WMAP 2003): Photon+Baryon



SDSS (2005): Baryons



Eisentein et al. 2005

- Smallest systematic errors (DETF), simple physics
- Angles easier to measure than fluxes and source shapes
- Gives two independent measures, H(z) and D(z), from radial and transverse correlation function
- Can usefully measure w(z) to z~2

Baryon Acoustic Oscillations (BAO)

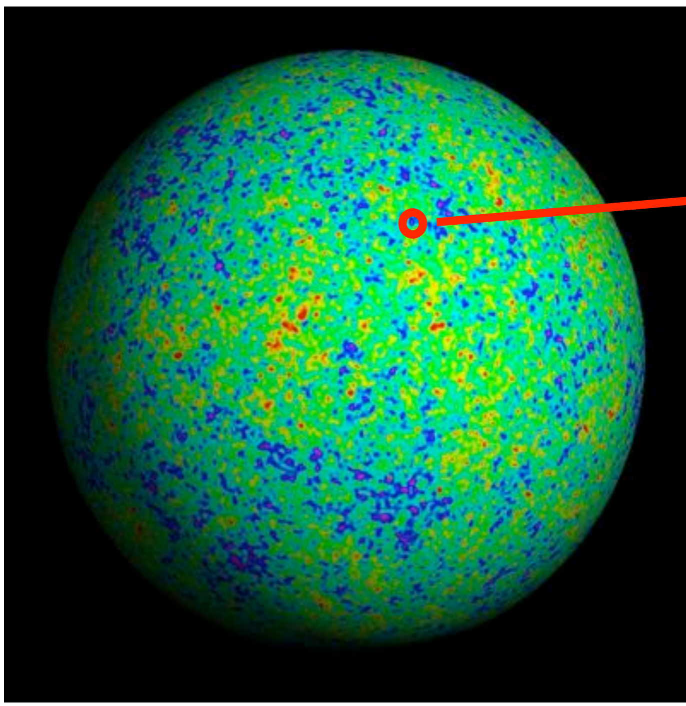
our newest tool...

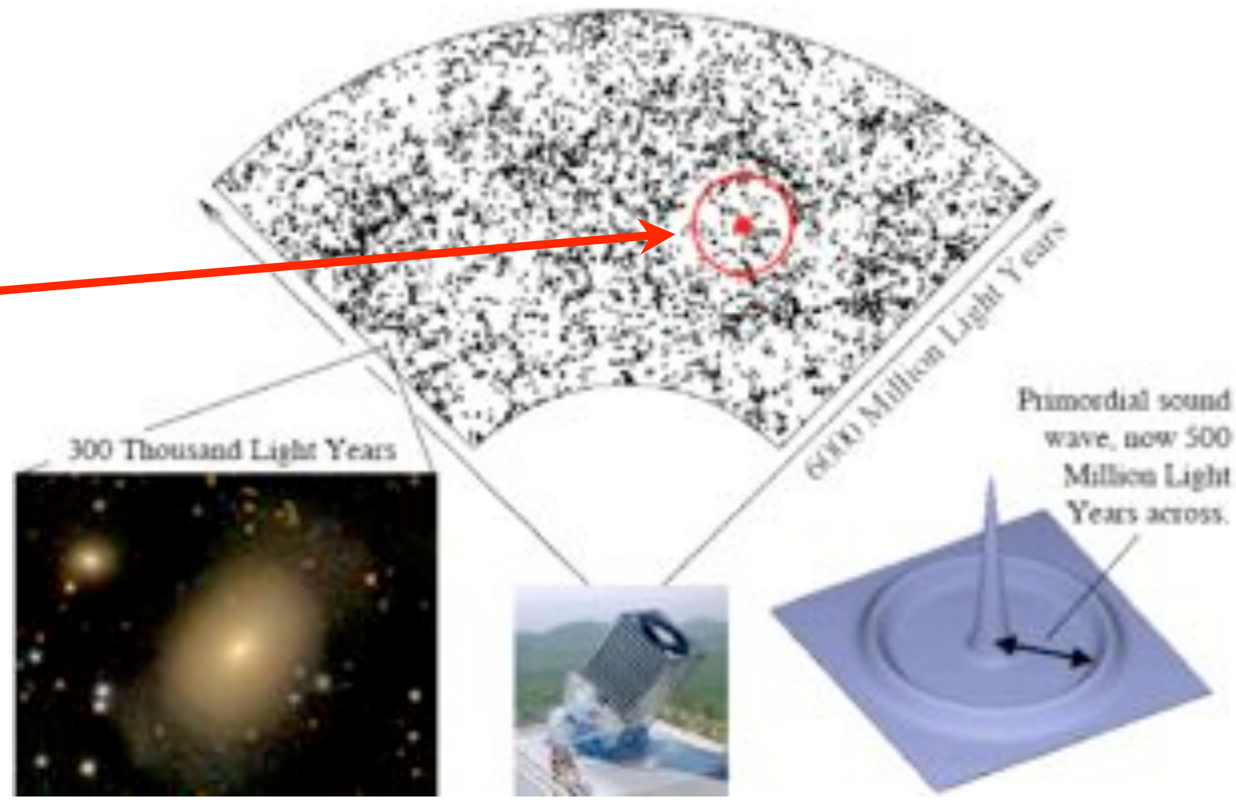
Motivation: BAO is one of the 4 dark energy experimental techniques

- Supernovae -- ***standard candle***, 1st results in 1998
- BAO -- ***standard ruler***, 1st results in 2005
- Weak Gravitational lensing
- Cluster counts

Standard ruler at z=0.3 (galaxy maps)

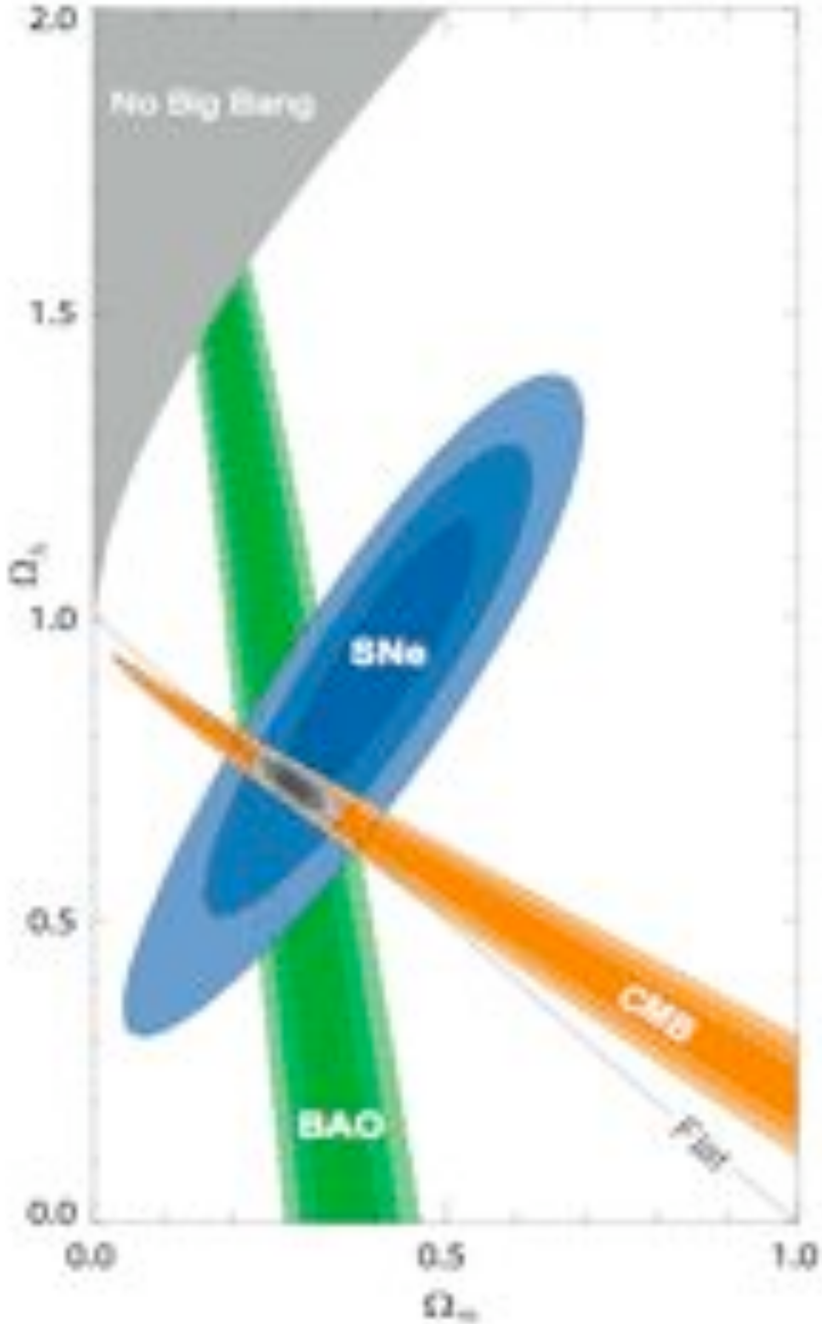
Standard ruler at z=1100 (CMB)

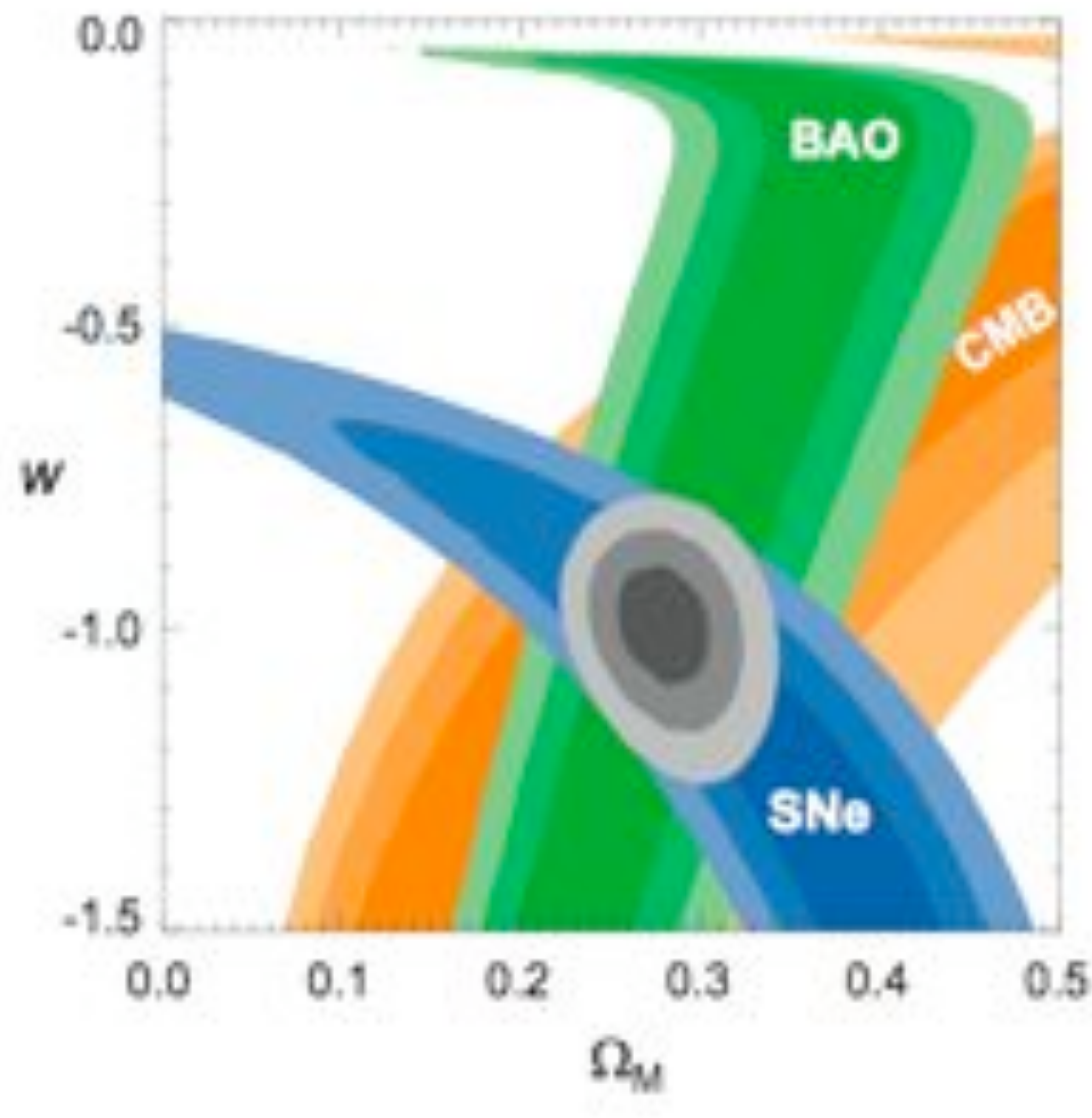




SDSS telescope

$$w = P/\rho$$



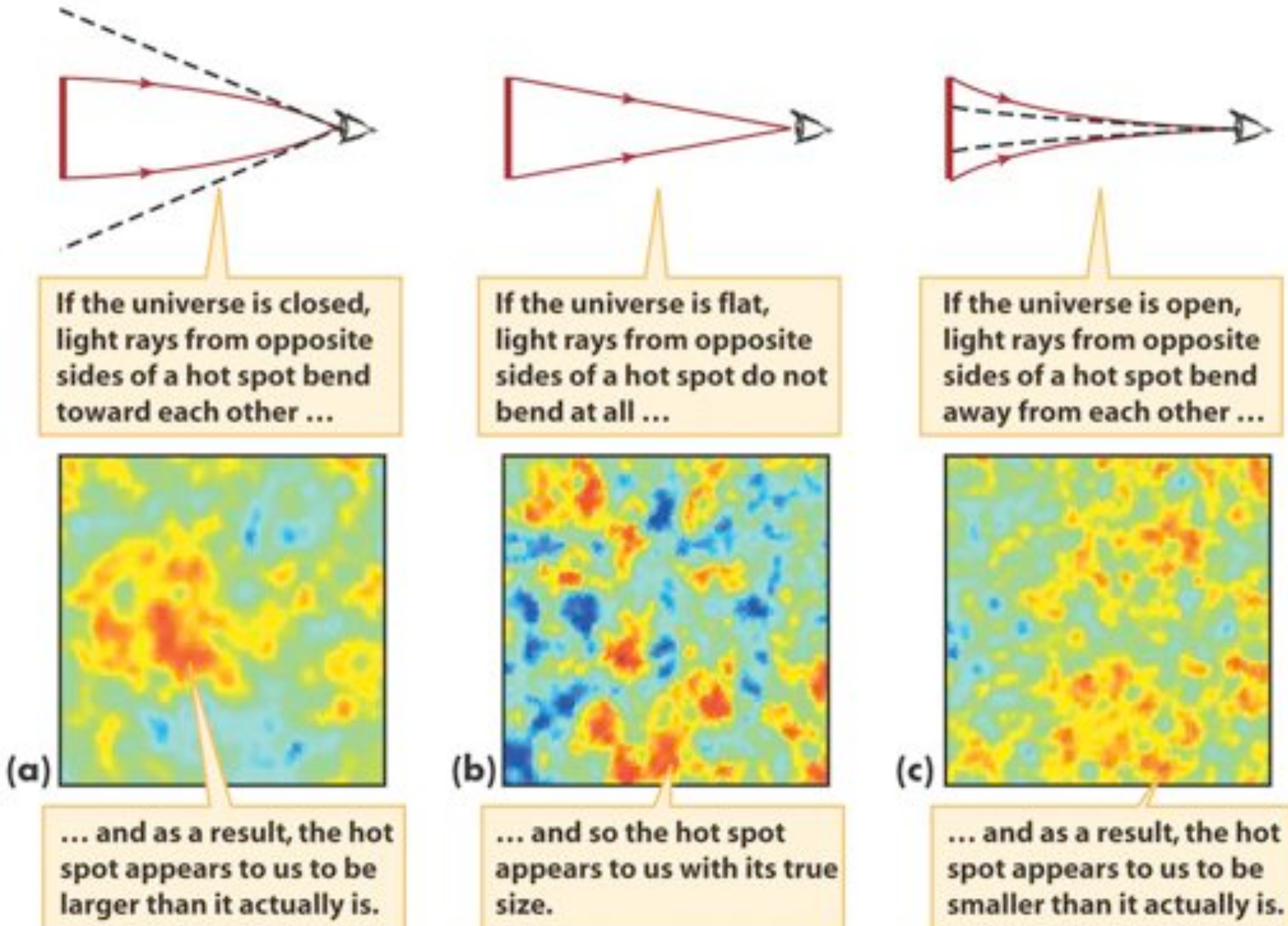


Our Universe is flat - to high accuracy

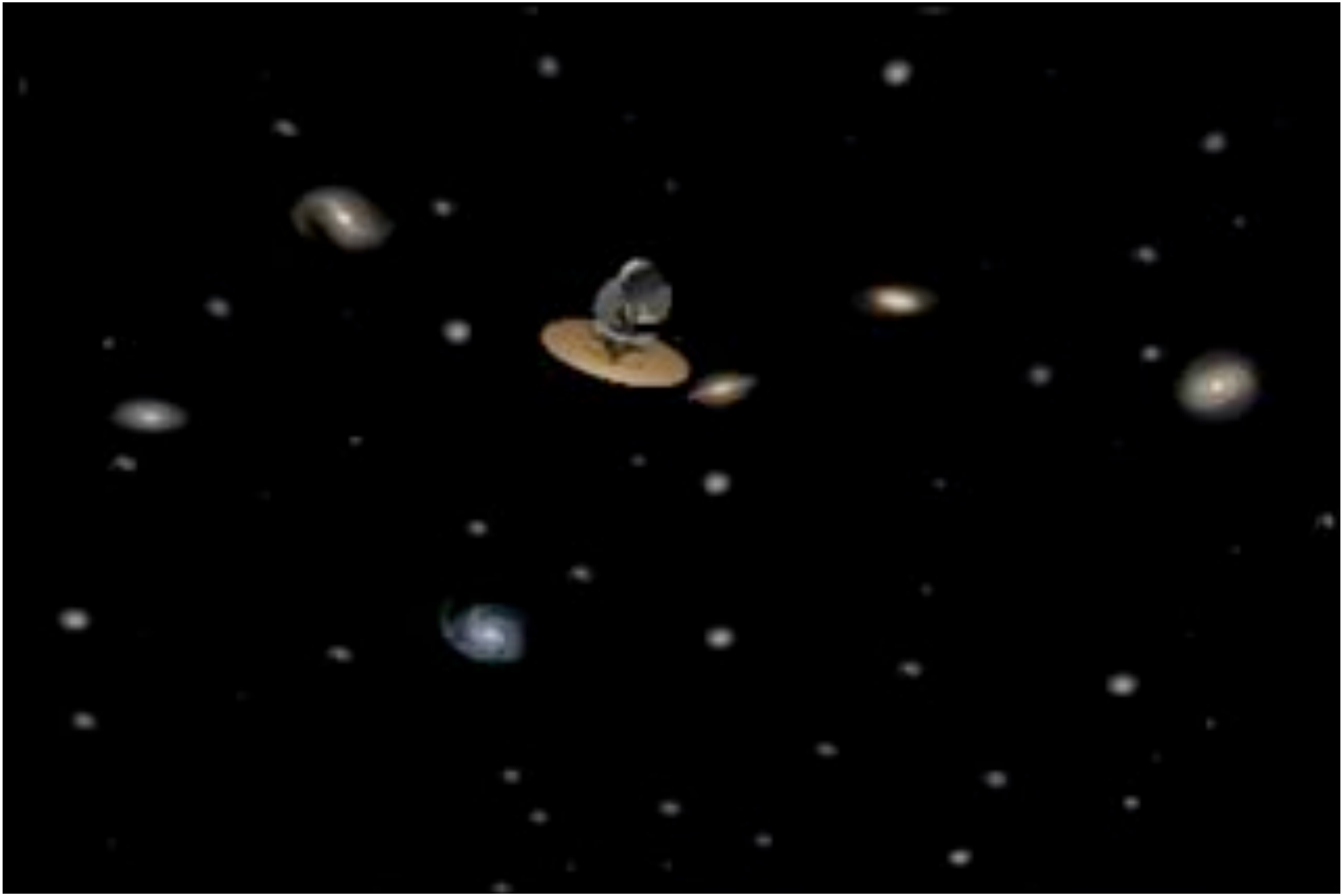
- The theoretically predicted hot spot size (about 1 degree) is very close to what is observed
- Therefore, our universe is flat, or density parameter is ~1.0

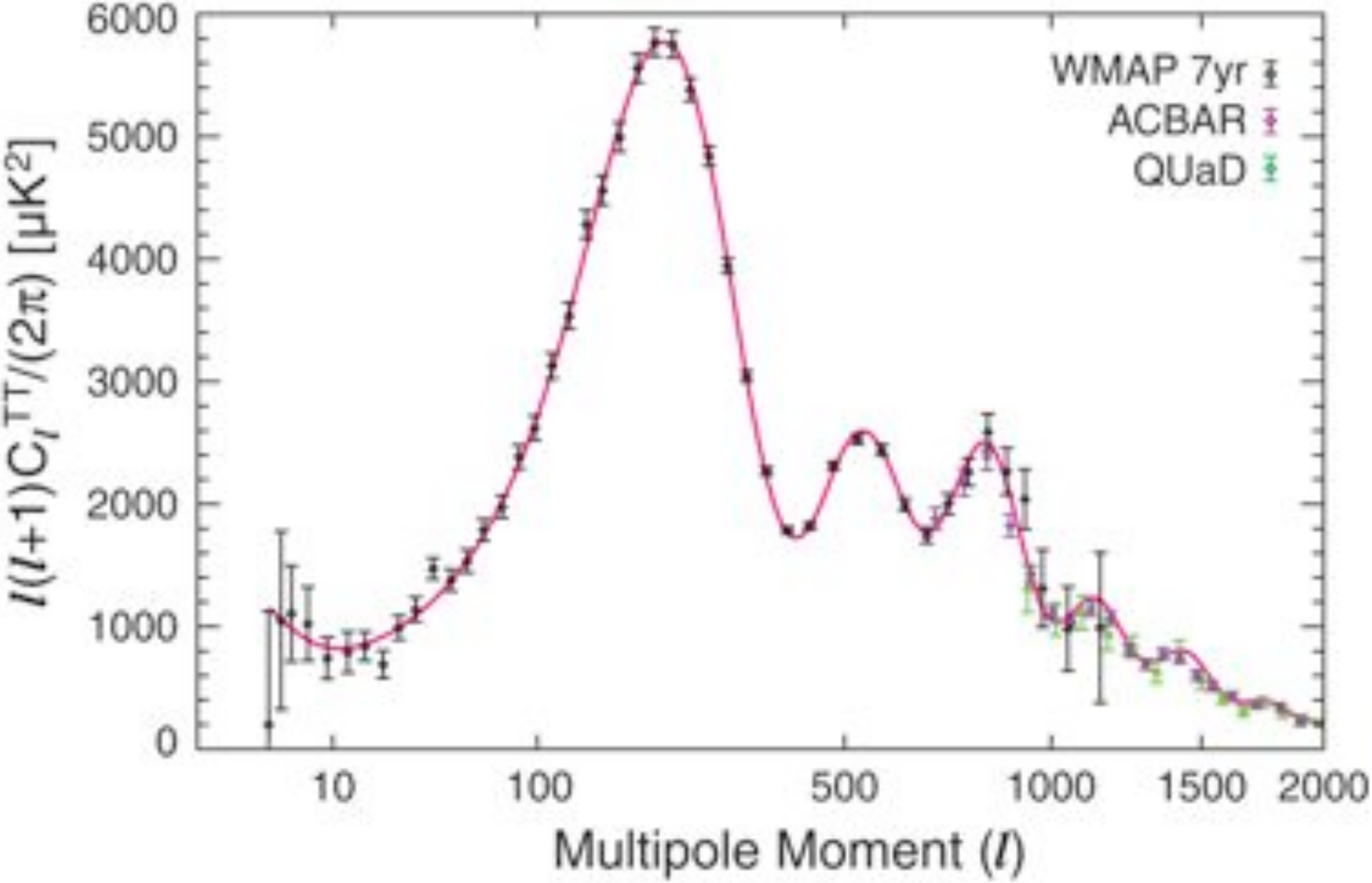
Sound

Horizon



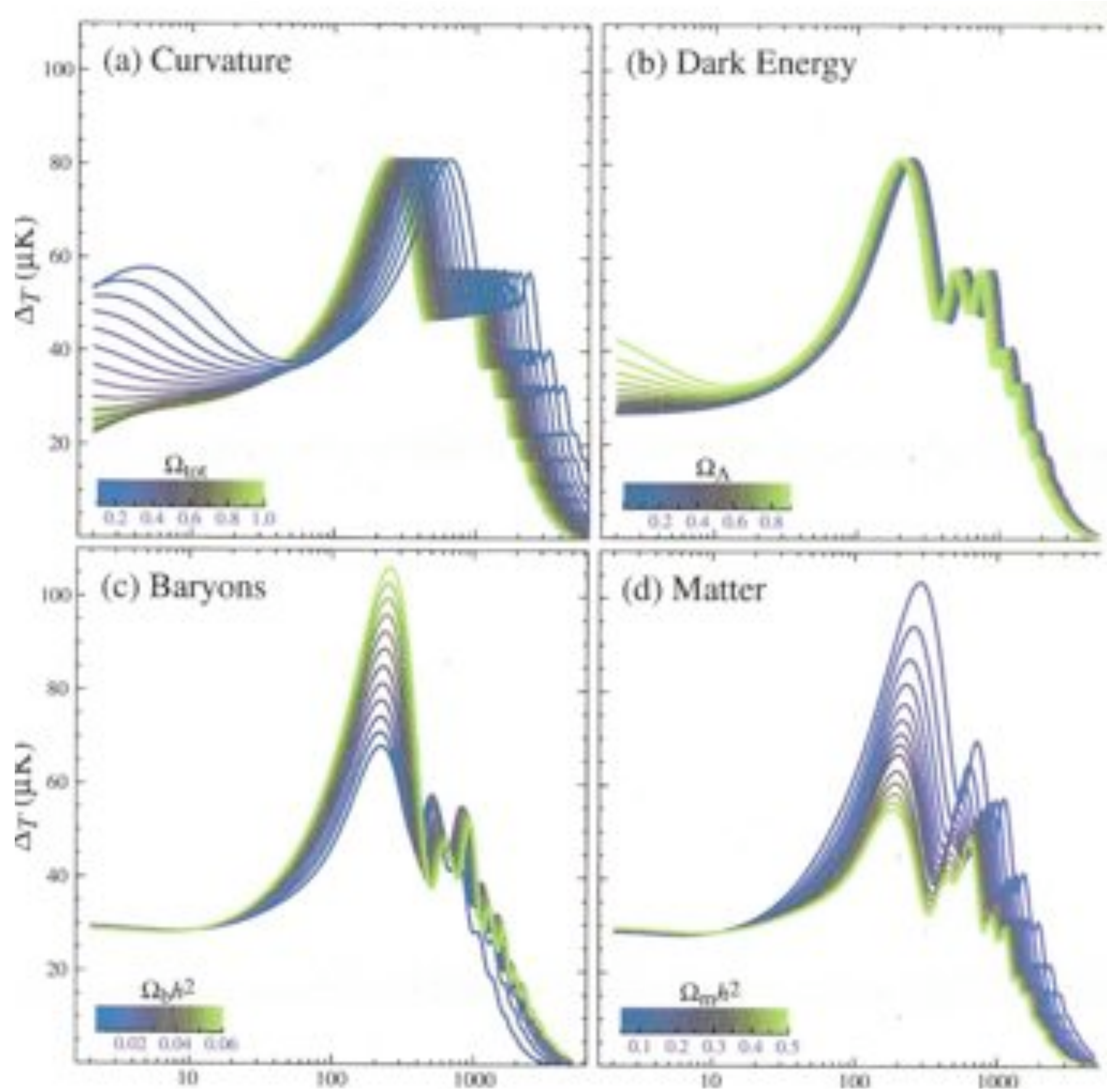
Measuring the Geometry of Space





WMAP 7yr
ACBAR
QUaD
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
2000
Multipole Moment (l)
$l(l+1)C_l^{TT}/(2\pi)$ [μK^2]

What we can learn from Spectral Analysis/Comparison



Angular Frequency

State-of-the-Art of the Universe

13.7 billion years old, expanding

Composition: 73% dark energy,
23% dark matter,
4% ordinary matter

table 28-2 Some Key Properties of the Universe

Quantity	Significance	Value* (2003)	2010
Hubble constant, H_0	Present-day expansion rate of the universe	71^{+4}_{-3} km/s/Mpc	70.0 ± 1.7
Density parameter, Ω_0	Combined mass density of all forms of matter *and* energy in the universe, divided by the critical density	1.02 ± 0.02	0.994 ± 0.011
Matter density parameter, Ω_m	Combined mass density of all forms of matter in the universe, divided by the critical density	0.27 ± 0.04	0.273 ± 0.014
Density parameter for ordinary matter, Ω_b	Mass density of ordinary atomic matter in the universe, divided by the critical density	0.044 ± 0.004	0.456 ± 0.001
Dark energy density parameter, Ω_Λ	Mass density of dark energy in the universe, divided by the critical density	0.73 ± 0.04	0.728 ± 0.016
Age of the universe, T_0	Elapsed time from the Big Bang to the present day	$(1.37 \pm 0.02) \times 10^{10}$ years	
Age of the universe at the time of recombination	Elapsed time from the Big Bang to when the universe became transparent, releasing the cosmic background radiation	$(3.79^{+0.08}_{-0.07}) \times 10^5$ years	
Redshift z at the time of recombination	Since the cosmic background radiation was released, the universe has expanded by a factor $1 + z$	1089 ± 1	