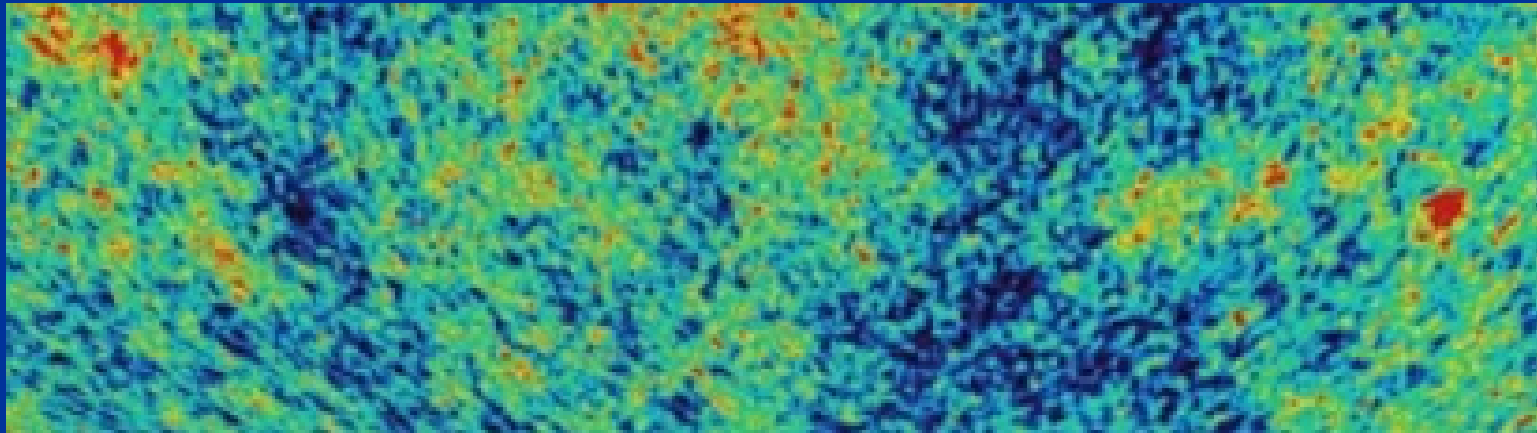


Madonna di Campiglio, 14-19 July 2003
International School on AstroParticle Physics

The cosmic microwave background

Present status and perspectives



Marco Bersnelli
Università degli Studi di Milano



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Bell Labs Horn Reflector Antenna Designed for telecommunication satellites

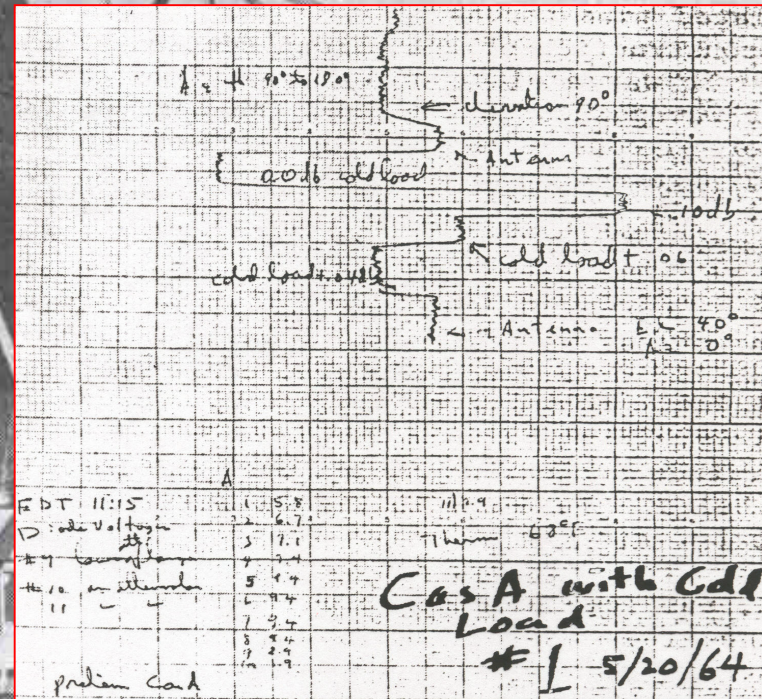
- Low-noise receiver ($T_{sys} < 25K$)
- Accurate cryo absolute calibrator (4K, LHe)
- Low sidelobes antenna (<90 dB)



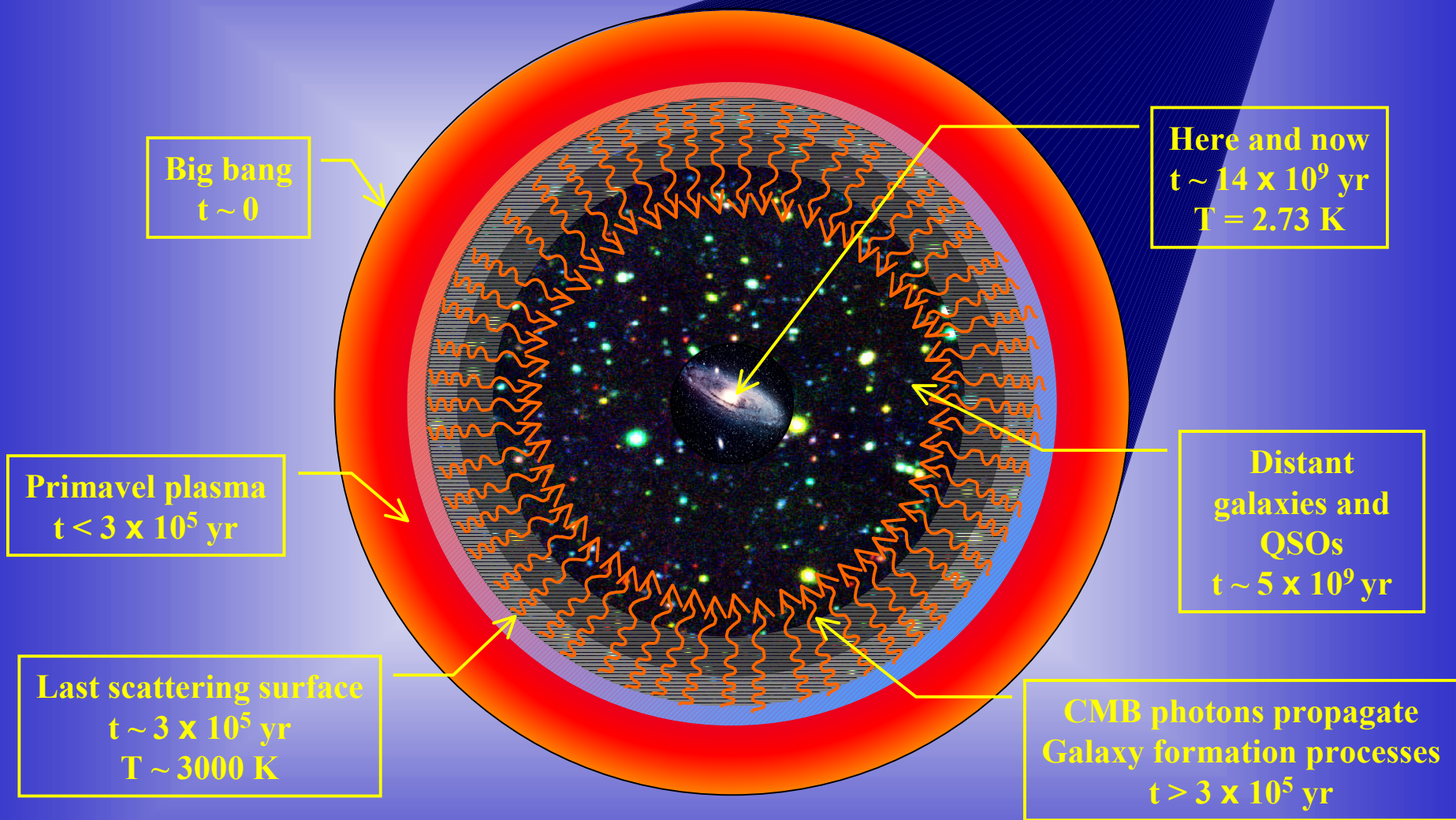
A. Penzias



R. Wilson

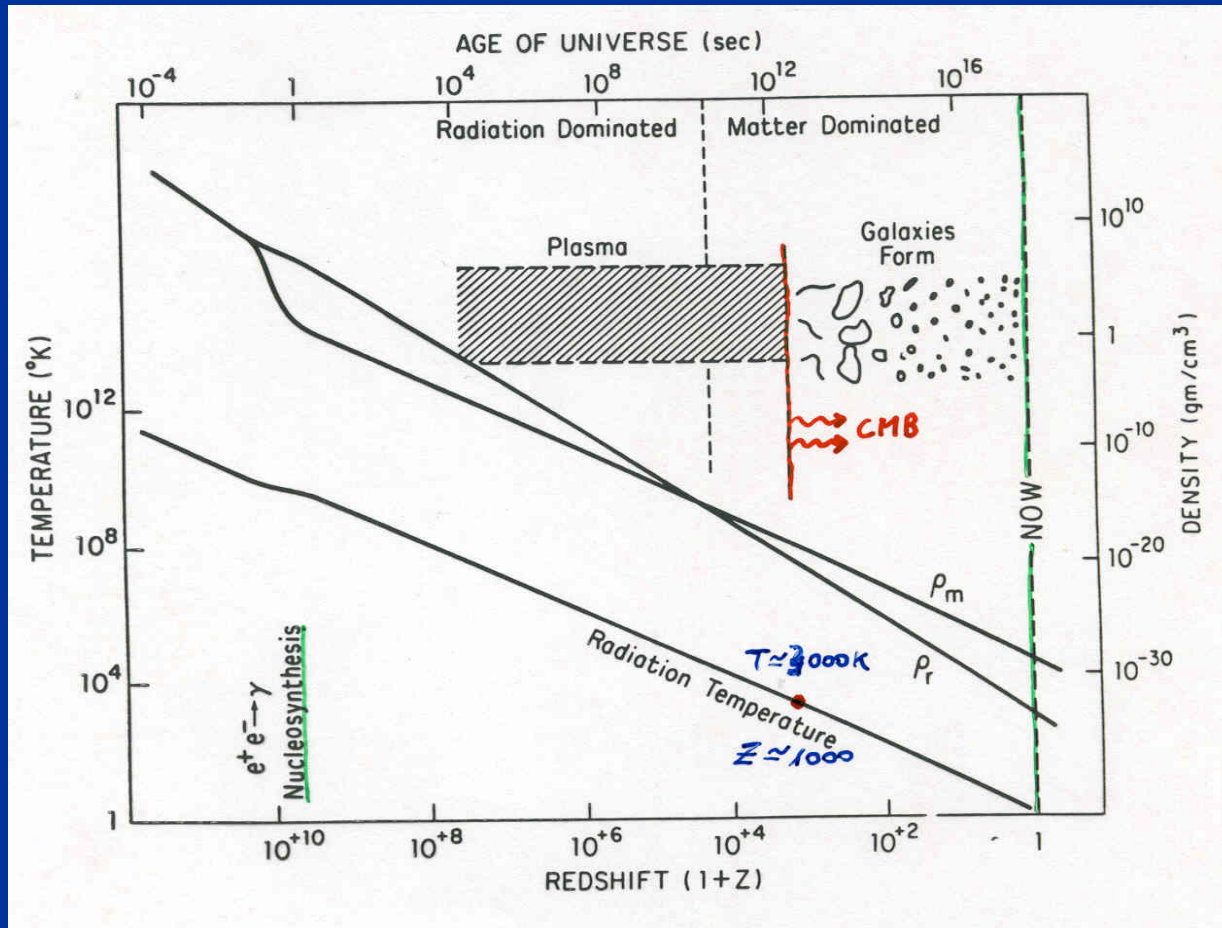


The Cosmic Microwave Background



CMB photons have travelled for $>99.99\%$ of the universe's age

The thermal history of the universe



$$\lambda_{\text{Observed}} \approx 1 \text{ mm}$$

$$\lambda_{\text{Emitted}} \approx 1 \mu\text{m}$$



$$1 + z_{\text{CMB}} = \frac{\lambda_{\text{Observed}}}{\lambda_{\text{Emitted}}} \approx 1000$$

$$T_{\gamma}(z) \sim T_{\gamma,0} (1 + z)$$

- Radiation energy density : $\rho_r \sim R^{-4} \sim (1 + z)^4$
- Matter energy density: $\rho_m \sim R^{-3} \sim (1 + z)^3$

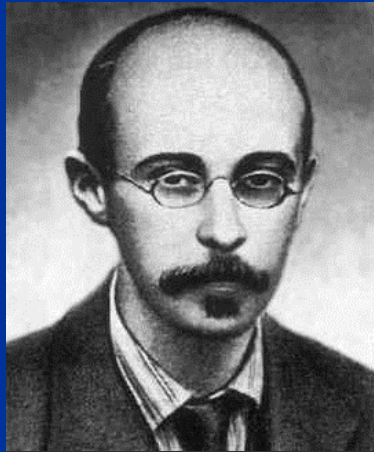


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A. Friedmann

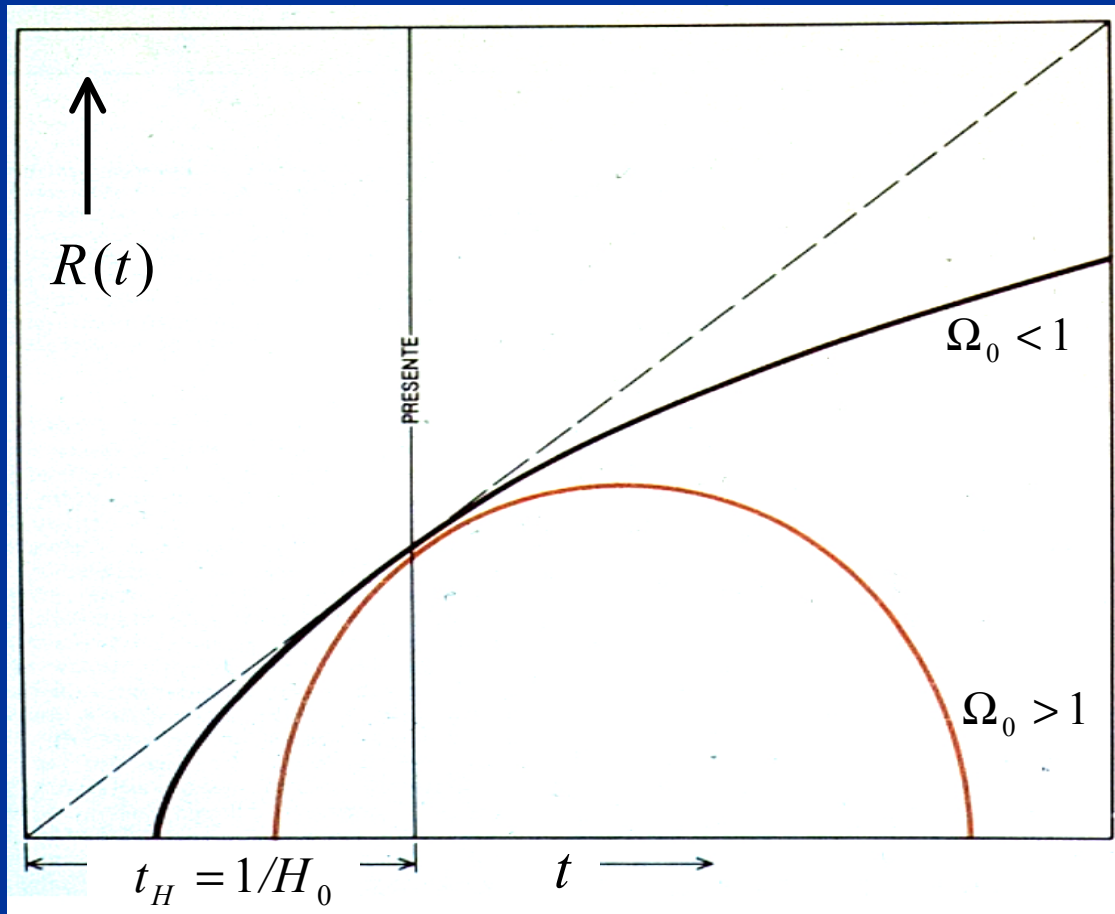
Friedmann's solutions

$$ds^2 = dt^2 - R^2(t) \left\{ \frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right\}$$

$$\Omega_\Lambda = 0$$

$$\Omega_0 \equiv \frac{\rho_0}{\rho_C}$$

$$\rho_C = \frac{3H_0^2}{8\pi G} \approx 10^{29} \text{ g cm}^{-3}$$



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Cosmological Parameters

$$\left(\frac{\dot{R}}{R}\right)^2 = H_0^2 \left[\frac{\Omega_{0,rel}}{R^4} + \frac{\Omega_{0,non-rel}}{R^3} + \frac{\Omega_{0,curv}}{R^2} + \frac{\Omega_\Lambda}{R^0} \right]$$

$$H_0 = \frac{\dot{R}(t_0)}{R(t_0)} \quad \text{Hubble constant}$$

$$\Omega_{0,rel} = \Omega_{HDM} + \Omega_\nu + \Omega_\gamma \quad \text{Density of relativistic matter}$$
$$\Omega_{0,non-rel} = \Omega_{CDM} + \Omega_B \quad \text{Density of non-relativistic matter}$$

} Ω_0

$$\Omega_{0,curv} = -\frac{kc^2}{H_0^2} \quad \text{Curvature term}$$

$$\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_C} = \frac{c^2}{3H_0^2} \Lambda \quad \text{Vacuum density (Cosmological constant)}$$

These parameters are not determined by the theory
The CMB offers a unique opportunity to measure them with high precision



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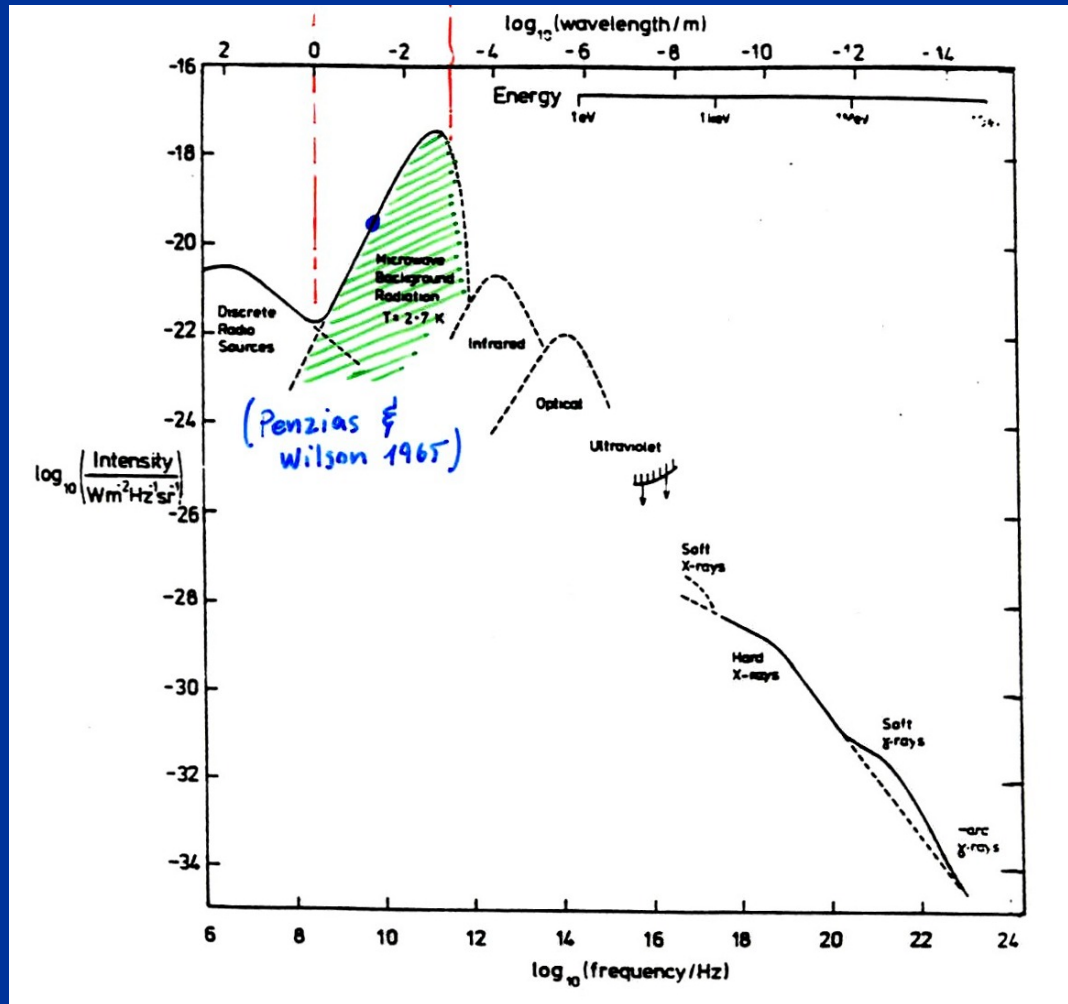
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Diffuse backgrounds through EM spectrum

$$\lambda = 1 \text{ m} \quad \lambda = 1 \text{ cm}$$



If it is a cosmic relic from an early hot phase, then:

- *Blackbody spectrum*
- *Highly isotropic*
- *Nearly unpolarised*



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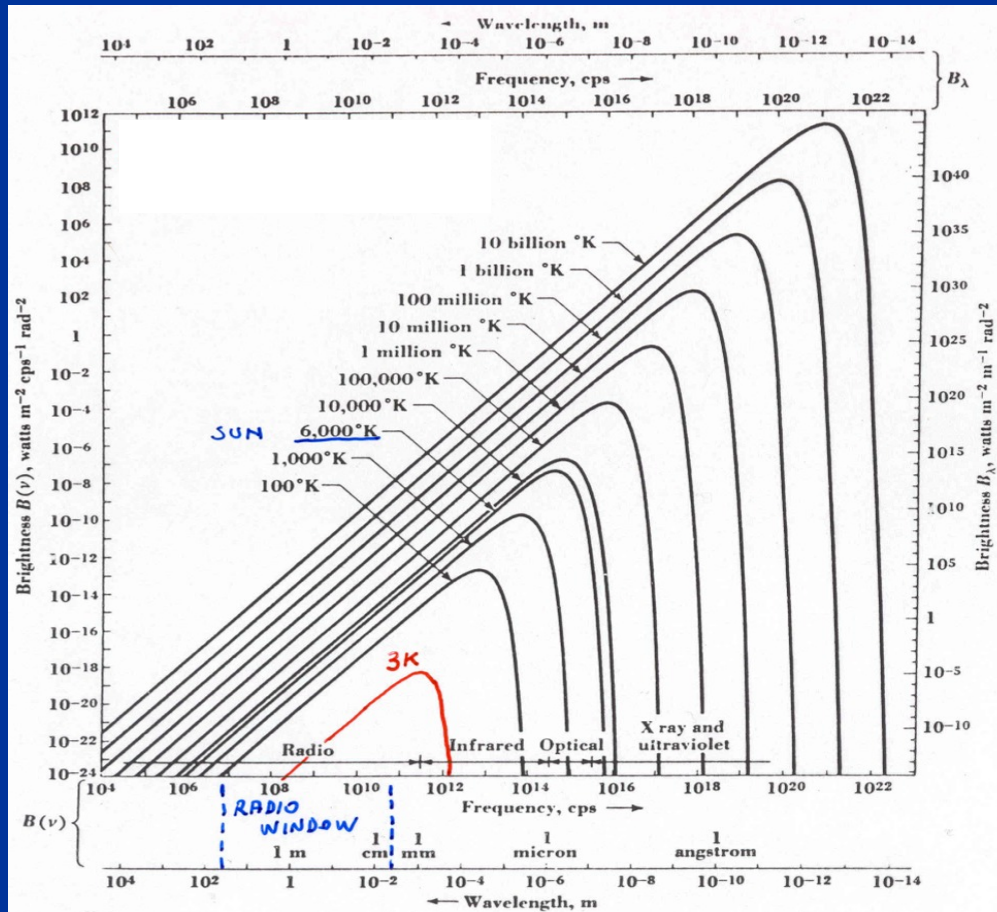
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Blackbody radiation law



Max Planck



$$B_{\nu} = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$



At a given ν , B_{ν} is uniquely specified by T



$$h\nu \ll kT \Rightarrow T_B \equiv \frac{c^2}{2^2} B_{\nu}$$

$n_{\gamma} \sim 500 \text{ cm}^{-3}$
 $\epsilon_{\gamma} \sim 4 \times 10^{-4} \text{ eV}$



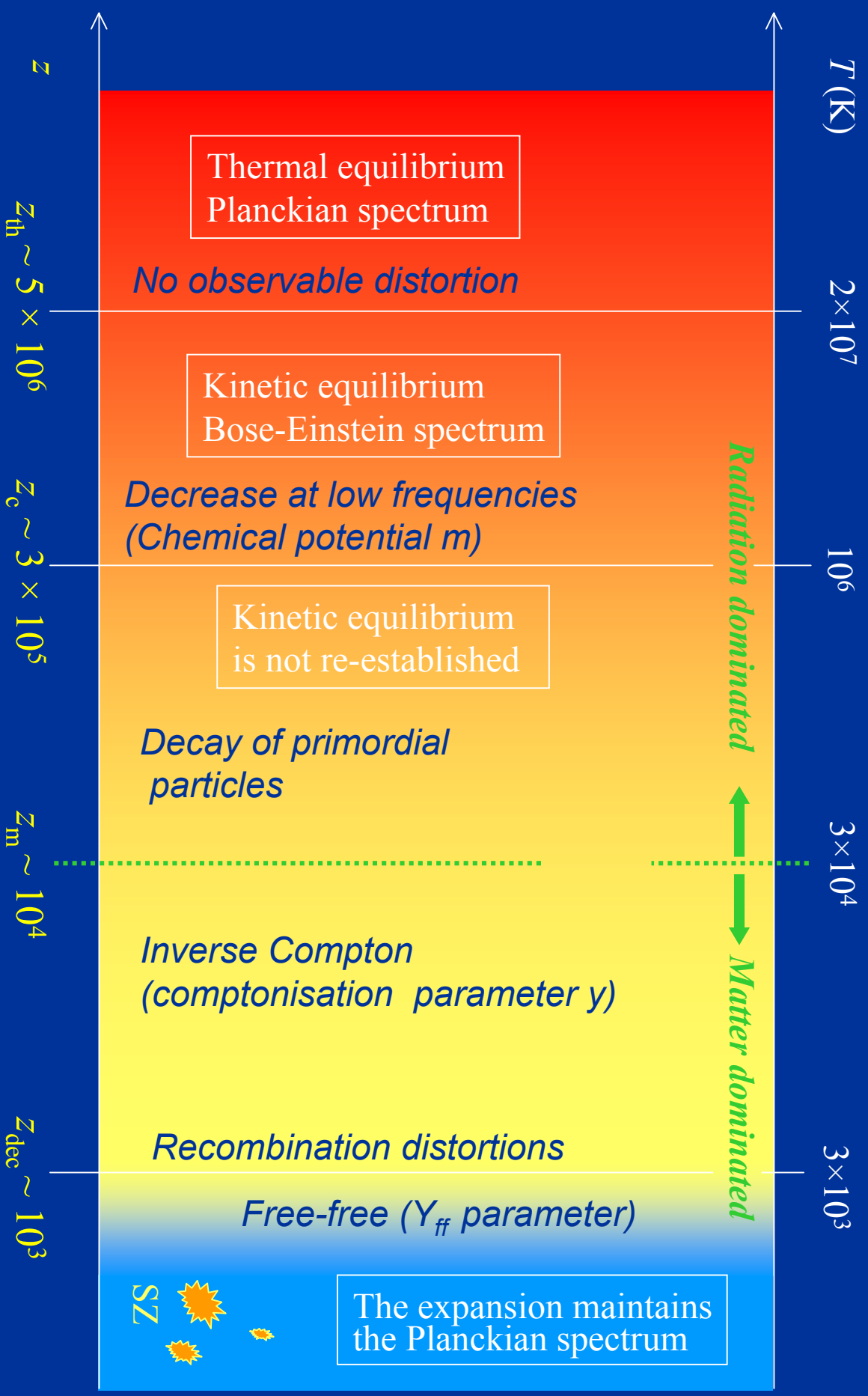
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The origin of the CMB radiation spectrum



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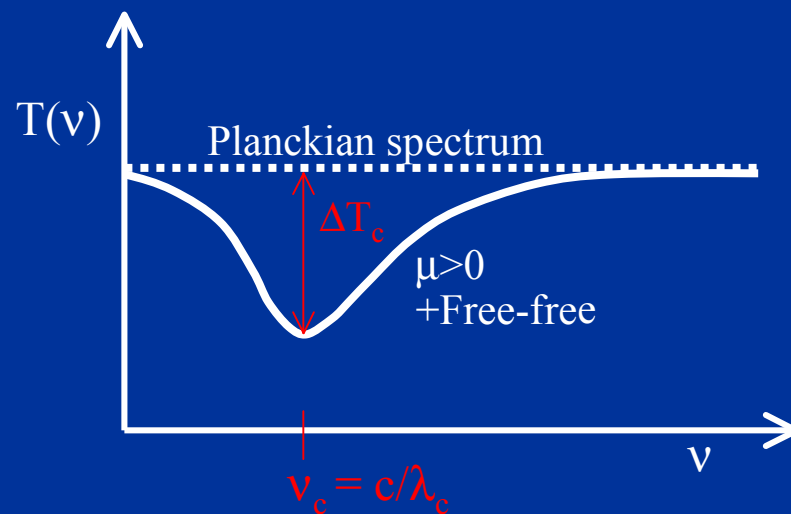


Search for spectral distortions

- Energy releases at $z_i < 5 \times 10^6$ may produce distortions in CMB spectrum
- Detection of distortions yields information on cosmological parameters

(1) Primordial energy releases

For $3 \times 10^5 < z_i < 5 \times 10^6$ we expect to observe a Bose-Einstein partially thermalised at low frequencies



$$\Delta T_c \sim 2.3 \mu (\Omega_b h_{100}^2)^{-2/3}$$
$$\lambda_c \sim 2.2 (\Omega_b h_{100}^2)^{-2/3} \text{ cm}$$



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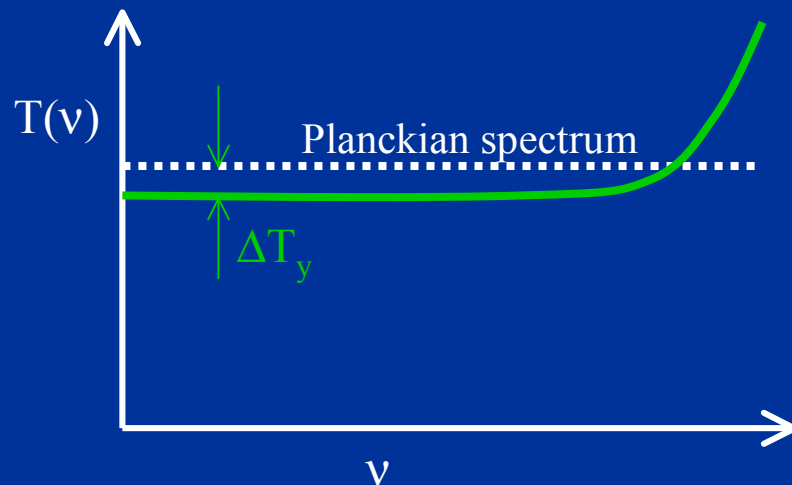


Search for spectral distortions

- Energy releases at $z_i < 5 \times 10^6$ may produce distortions in CMB spectrum
- Detection of distortions yields information on cosmological parameters

(2) “Recent” energy releases

For $z_i < z_c \sim 3 \times 10^5$ kinetic equilibrium
is not re-established
 \Rightarrow spectral distortion expected



$$y = \frac{k\sigma_T}{m_e c^2} \int n_e(z) T_e(z) dz$$
$$\Delta T_y \approx -2y$$
$$\Delta E/E \approx 4y$$



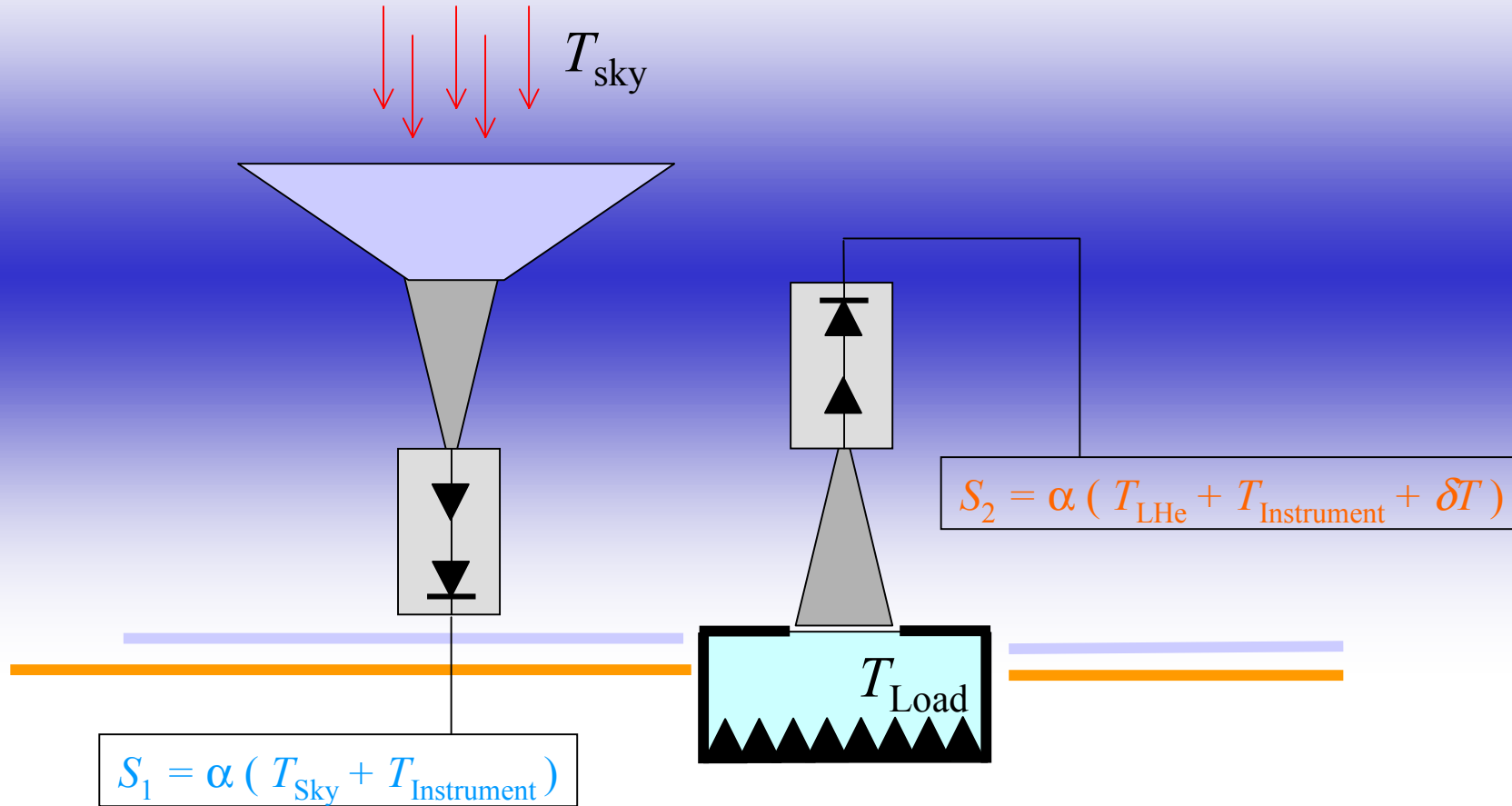
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CMB spectrum observation strategy: (1) absolute calibration



$$\Delta S = S_1 - S_2 = \alpha (T_{\text{sky}} - T_{\text{LHe}} - \delta T)$$

$$T_{\text{Sky}} = \frac{1}{\alpha} \Delta S - T_{\text{LHe}} - \delta T$$

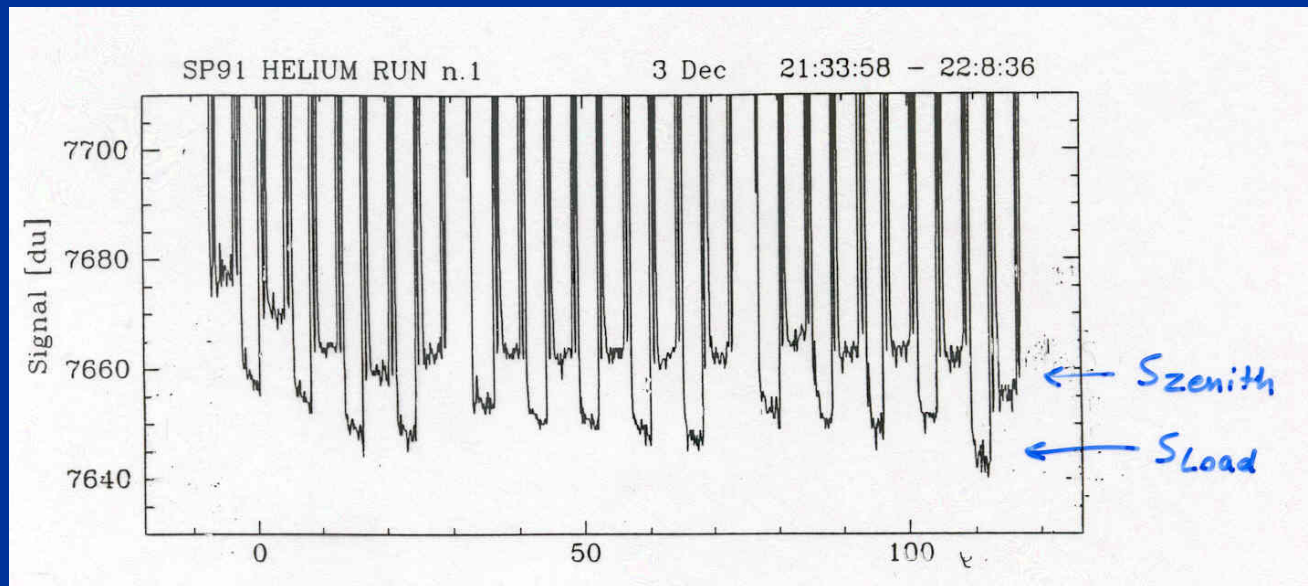
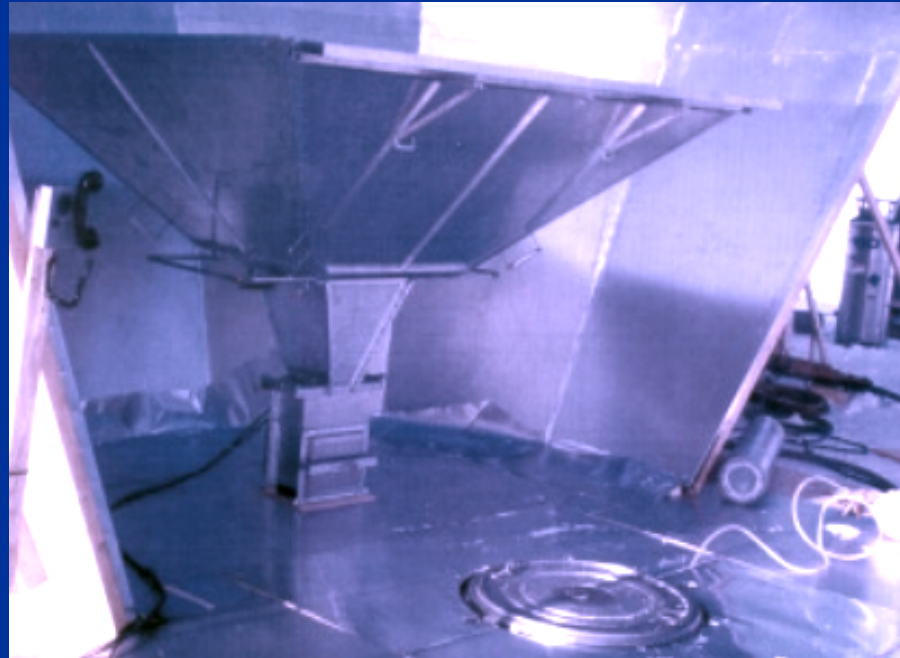
α : from calibration
 ΔS : measured
 T_{LHe} : known "a priori"
 δT : measured in tests

South Pole 1989-1992

2 GHz radiometer

Absolute calibration

Free-space LHe-cooled
blackbody Load



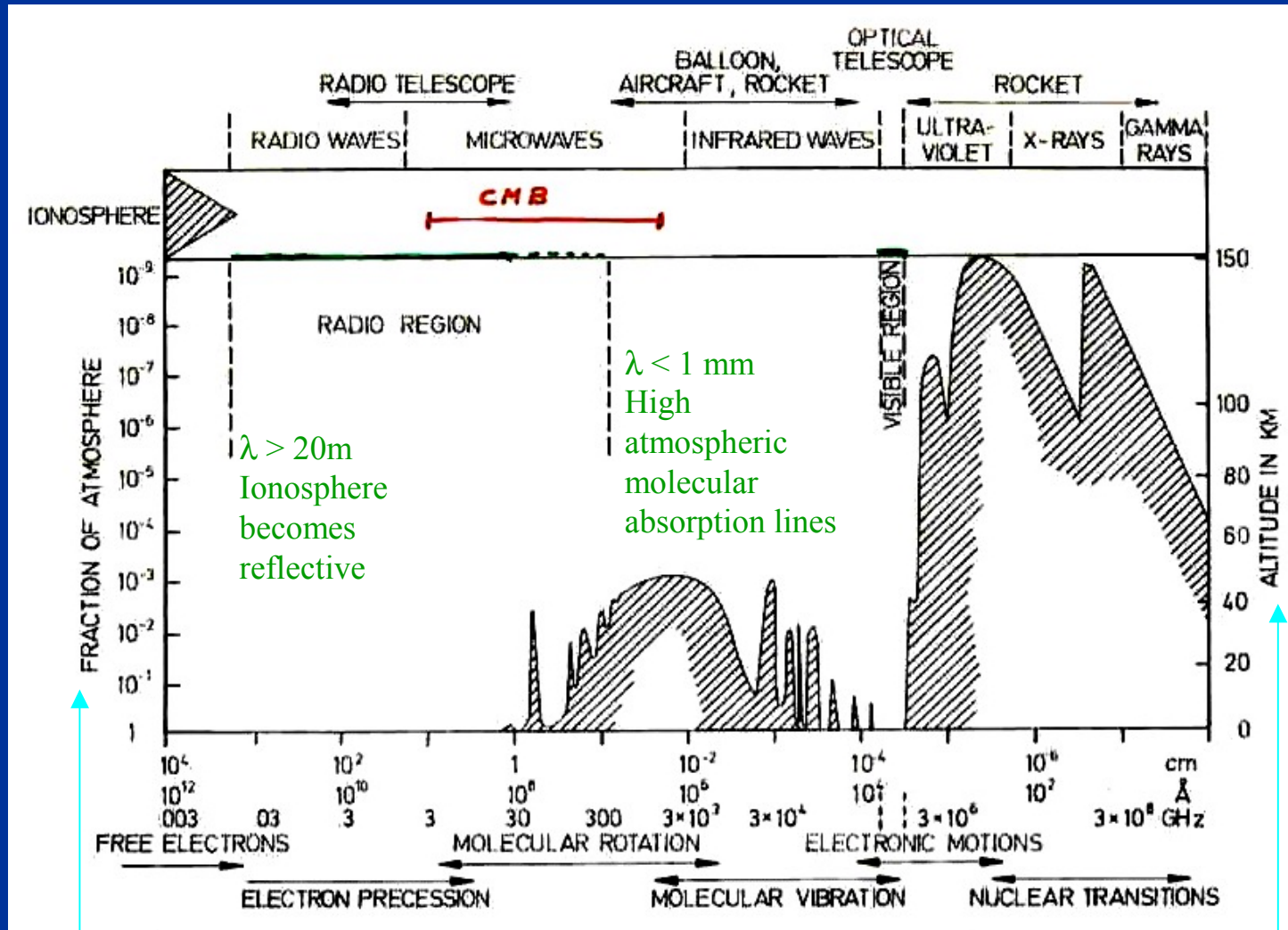
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Earth's Atmosphere



Fraction of atmosphere for which radiation is attenuated by a factor 1/2

Altitude for which radiation is attenuated by a factor 1/2



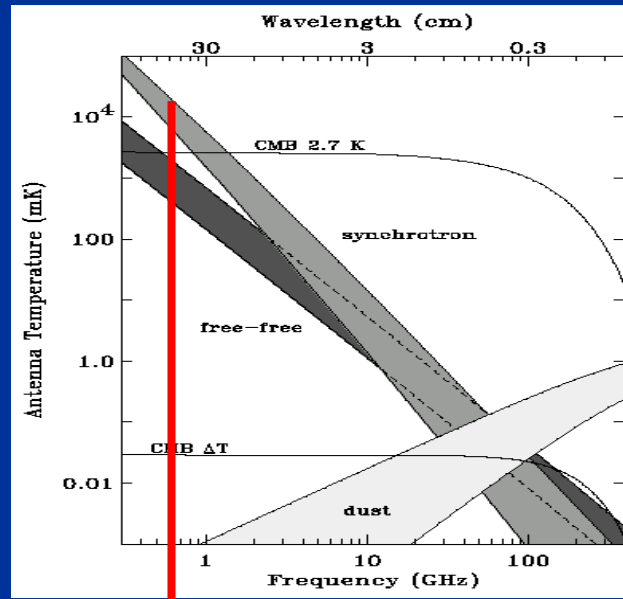
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Galactic emission in the microwaves

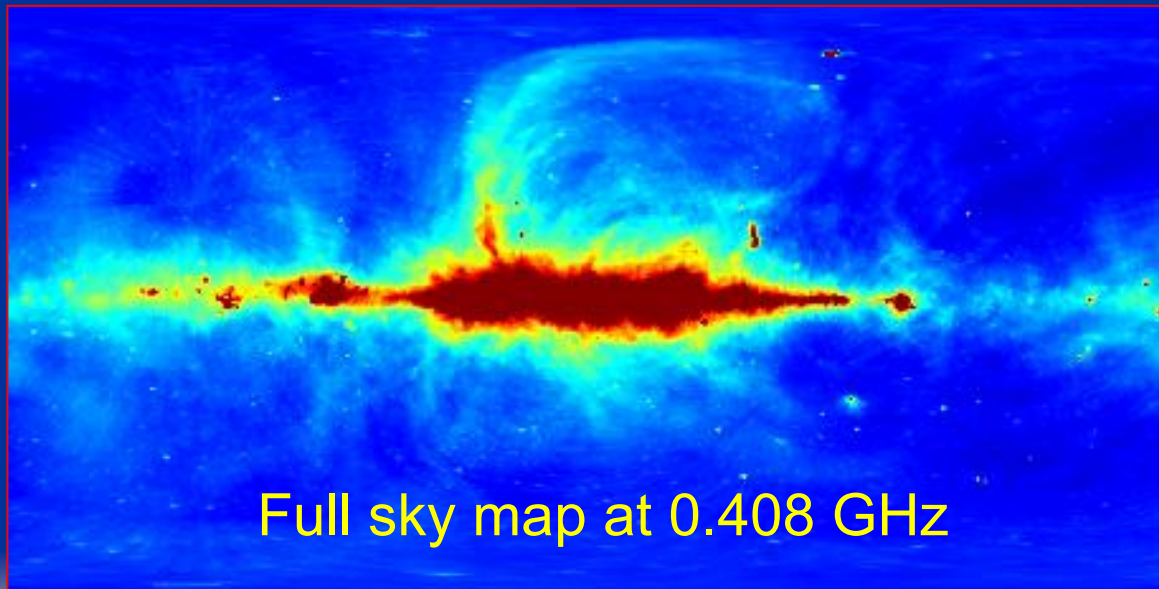


$$T_B(\nu) \propto \nu^\beta$$

$$\beta_{\text{synchrotron}} \approx -2.7$$

$$\beta_{\text{free-free}} \approx -2.1$$

$$\beta_{\text{dust}} \approx +1.5$$



Full sky map at 0.408 GHz



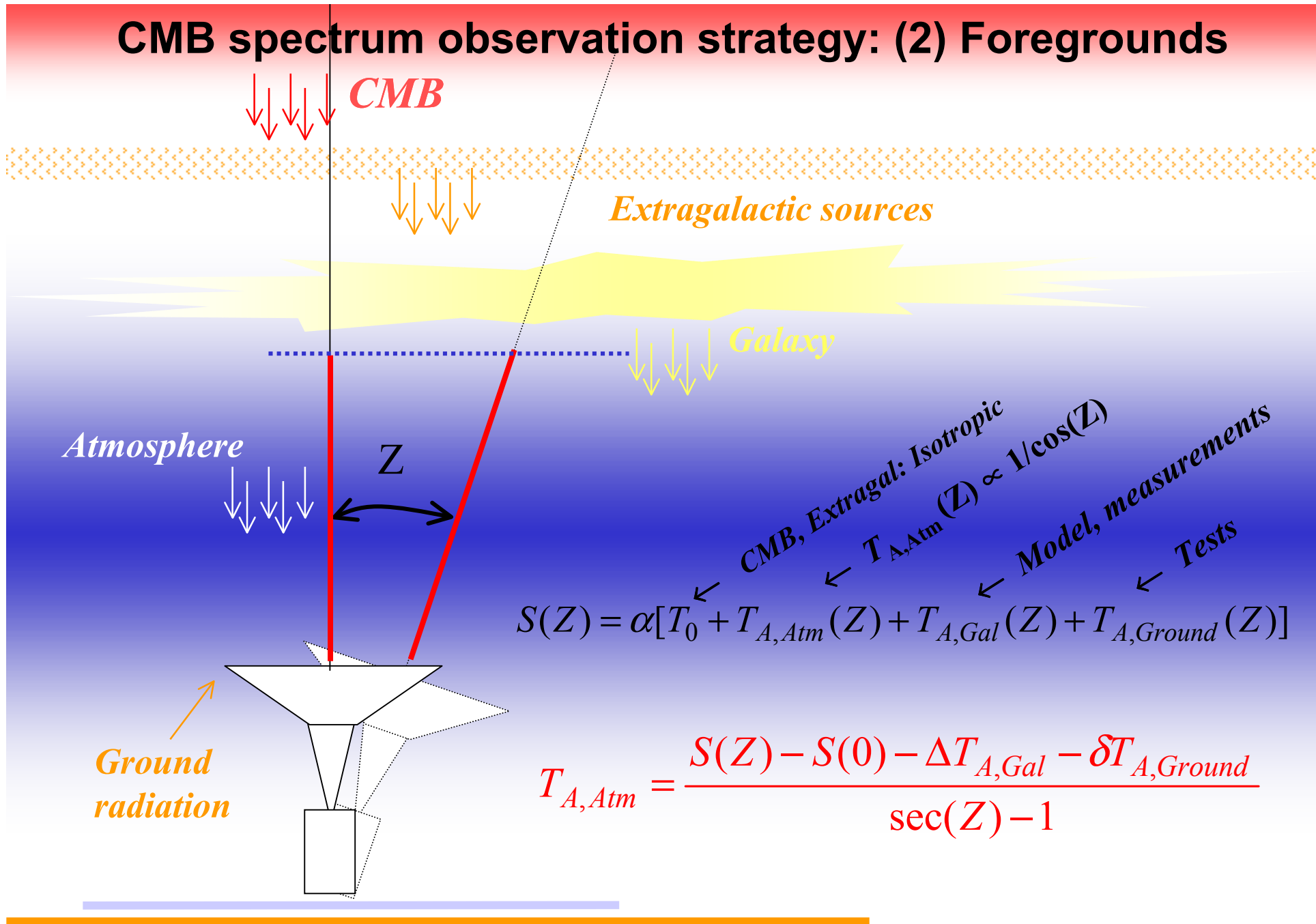
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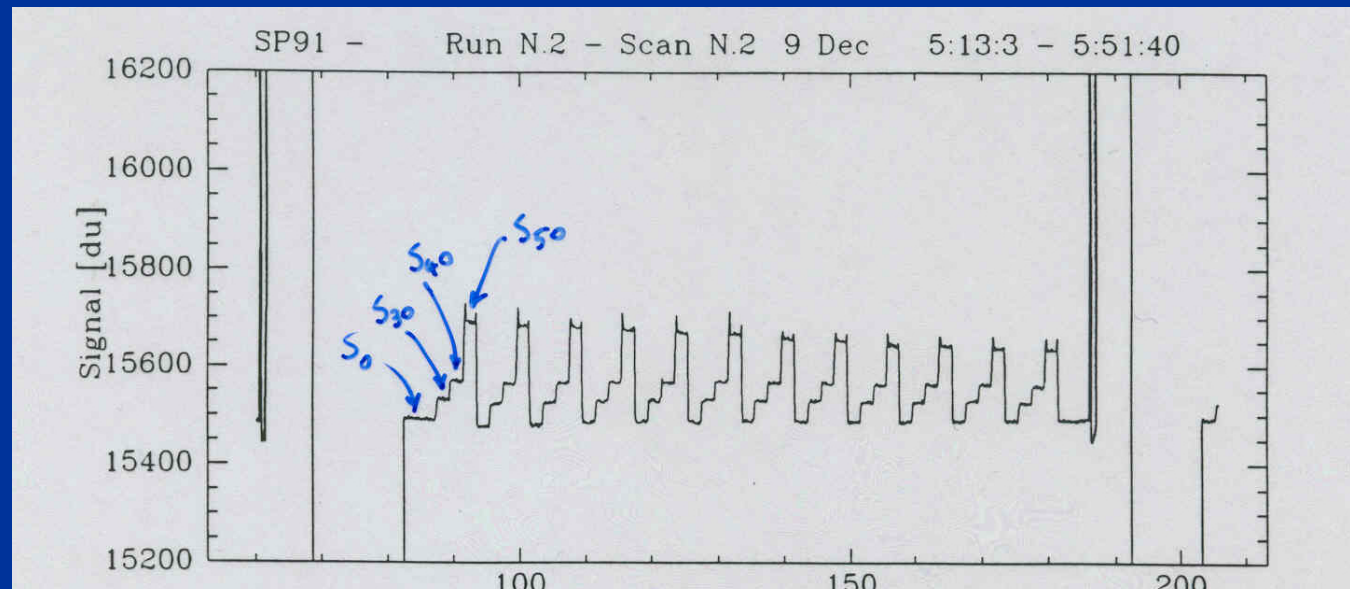
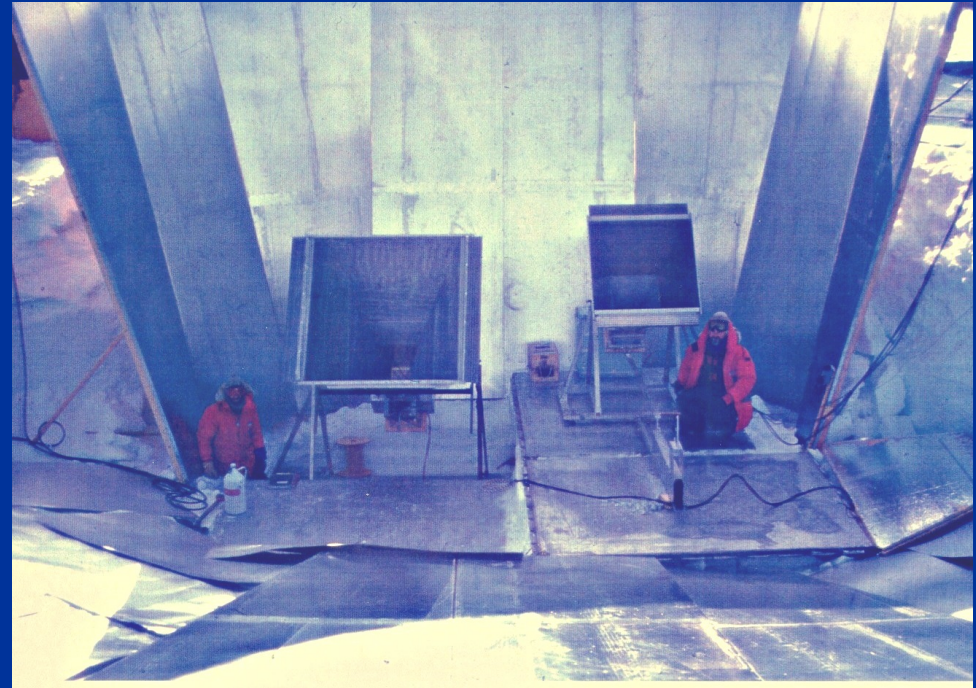
CMB spectrum observation strategy: (2) Foregrounds



South Pole 1989-1992

1.5 GHz & 2.0 GHz
radiometers

Atmospheric and galactic
measurements

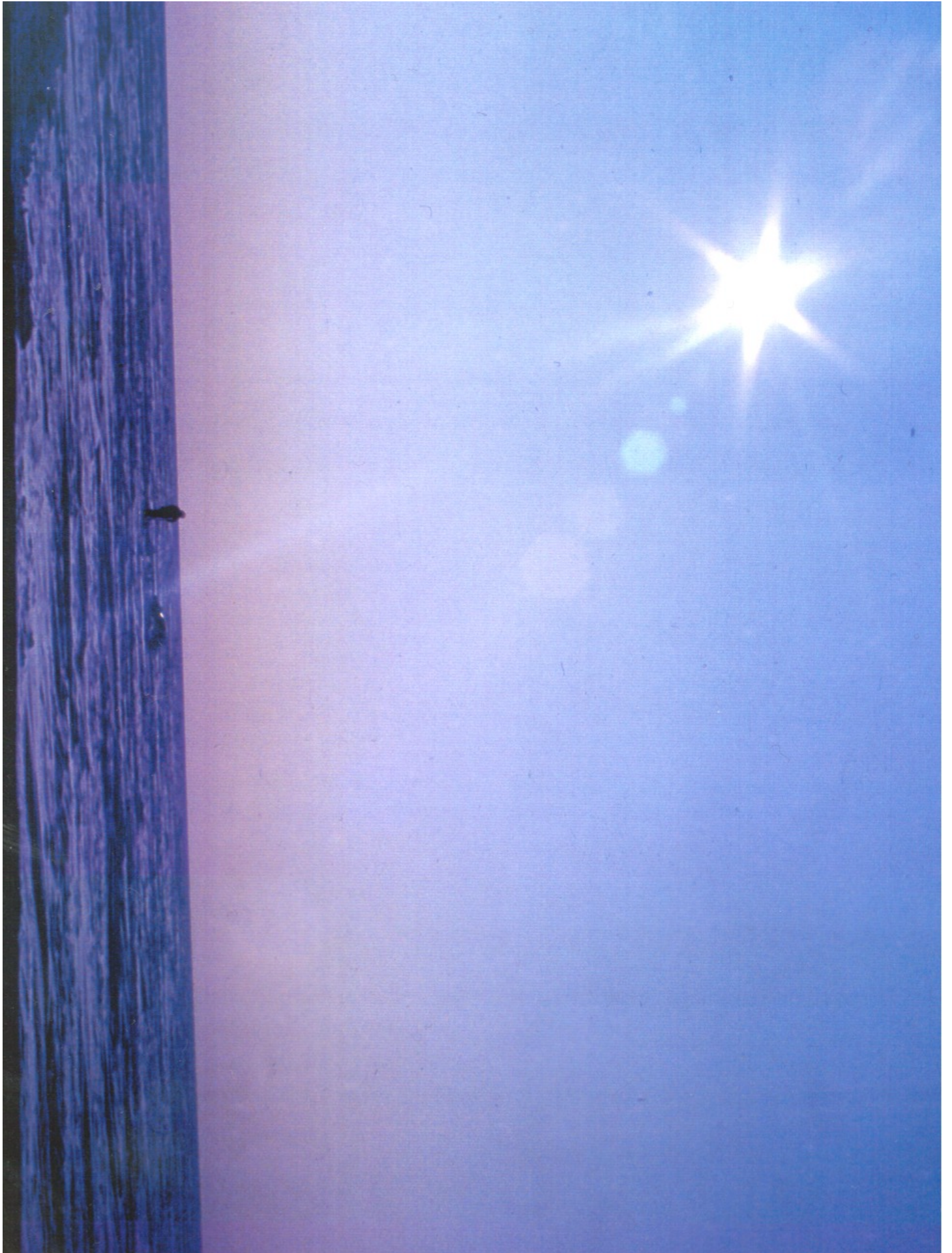


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COBE

Cosmic Background Explorer

Mission:

Launch:
November 1989

Orbit:
900 km LEO

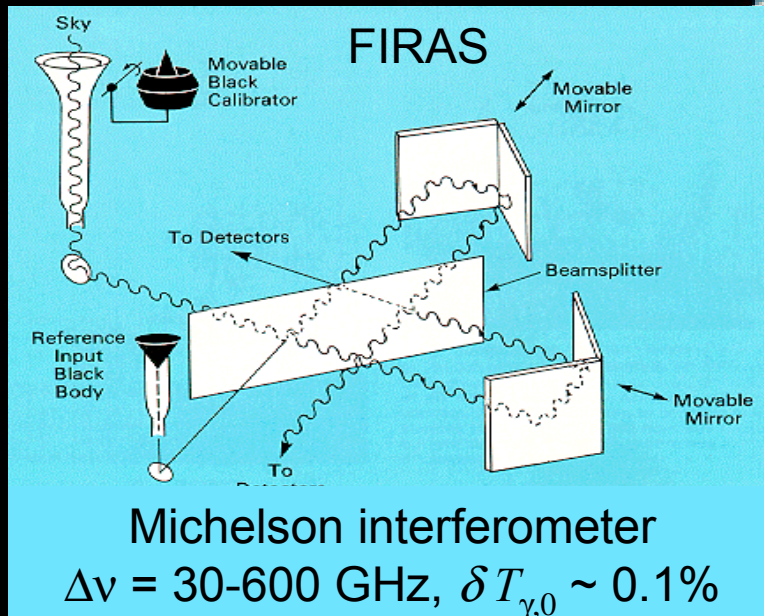
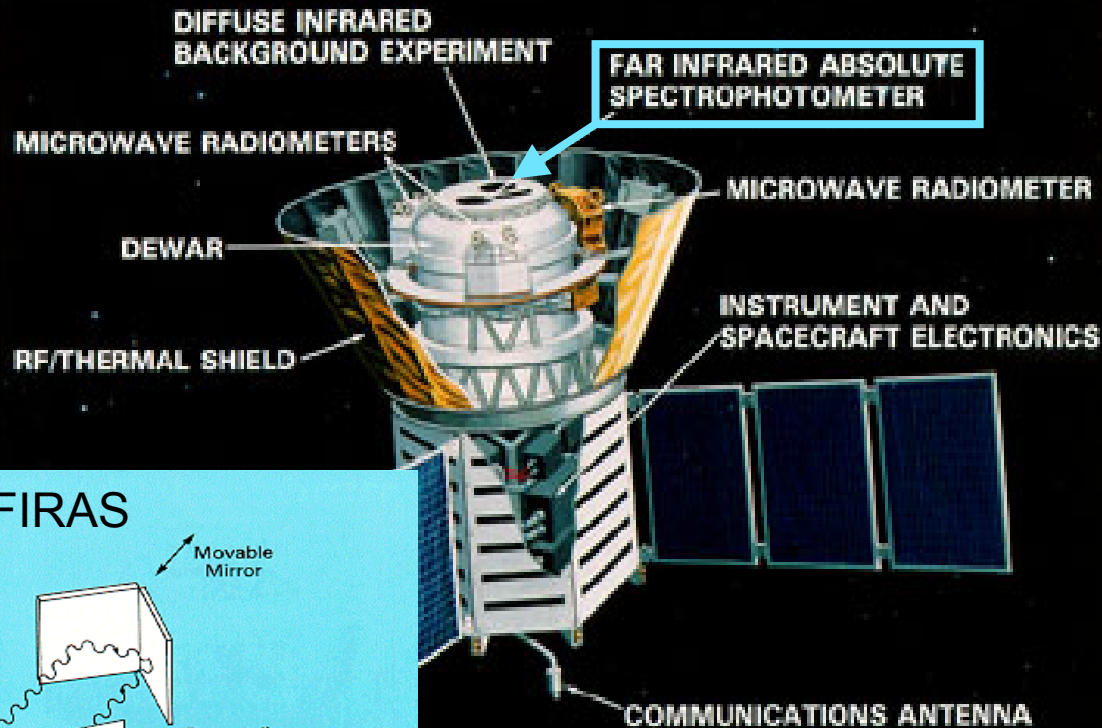
Spinning
Spacecraft

Experiments:

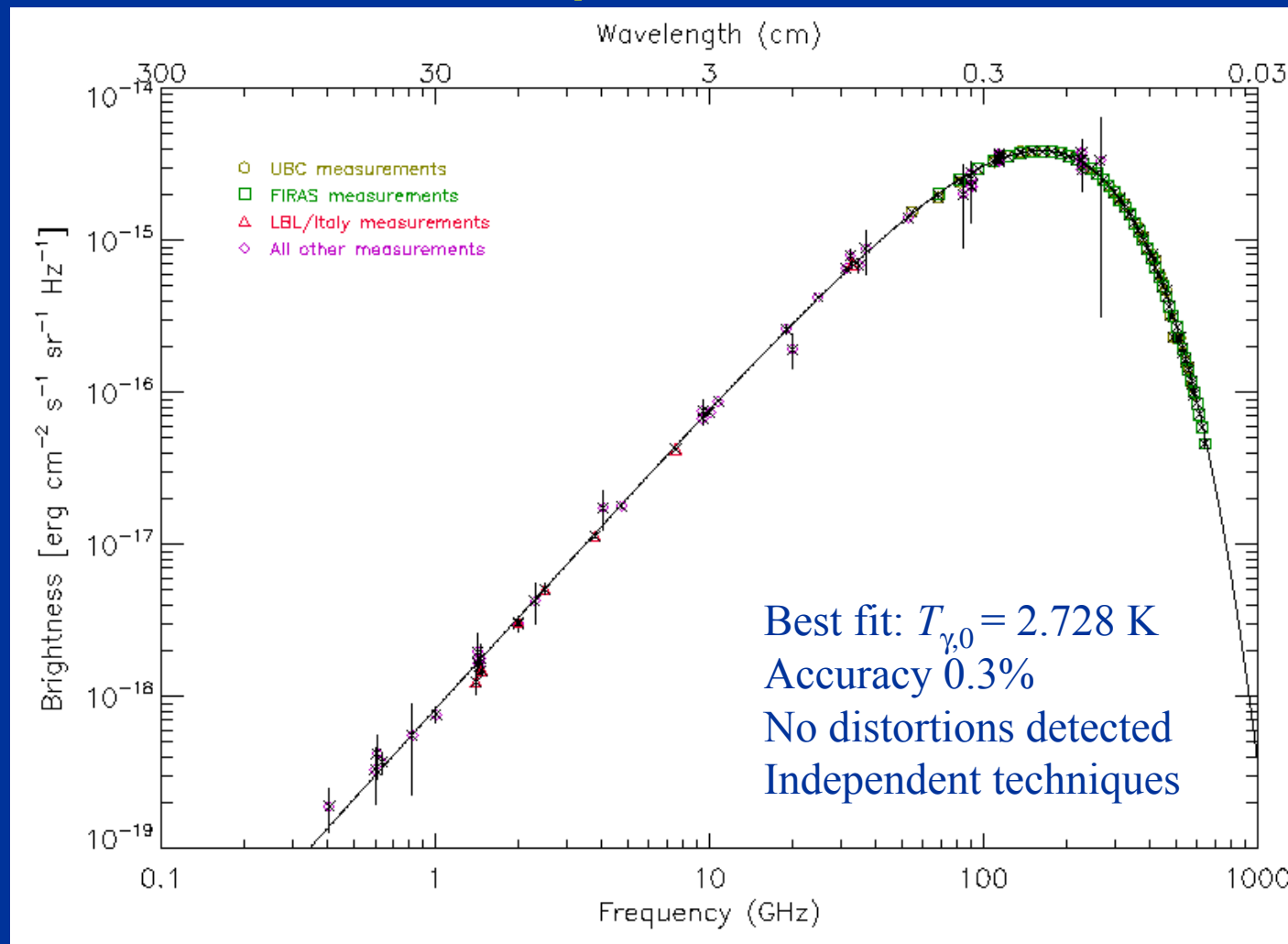
DMR:
CMB Anisotropy

FIRAS:
CMB Specrum

DIRBE:
IR Background



CMB spectrum data



$T_{\gamma,0}$ is by far the best known cosmological parameter



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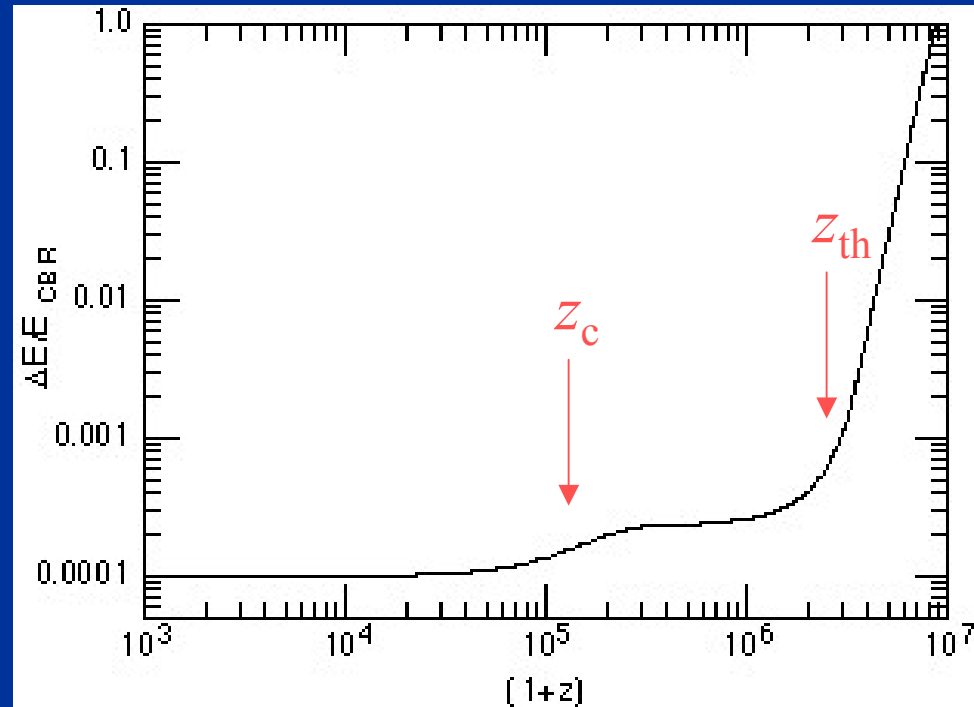
CMB spectrum data set upper limits to energy releases in the early universe

Limits on distortion parameters:

$$\left. \begin{array}{l} |y| \leq 1.5 \times 10^{-5} \\ |\mu| \leq 0.9 \times 10^{-4} \\ |Y_{ff}| \leq 2.2 \times 10^{-5} \end{array} \right\} \Rightarrow \frac{\Delta E_{Max}(z)}{E}$$

⇒ Limits on:

- Mass and half-time of primordial particles
- Density and temperature of IGM (y)
- Spectral index of primordial perturbations (μ)



Future on CMB Spectrum: Higher precision in the 4-30 GHz range



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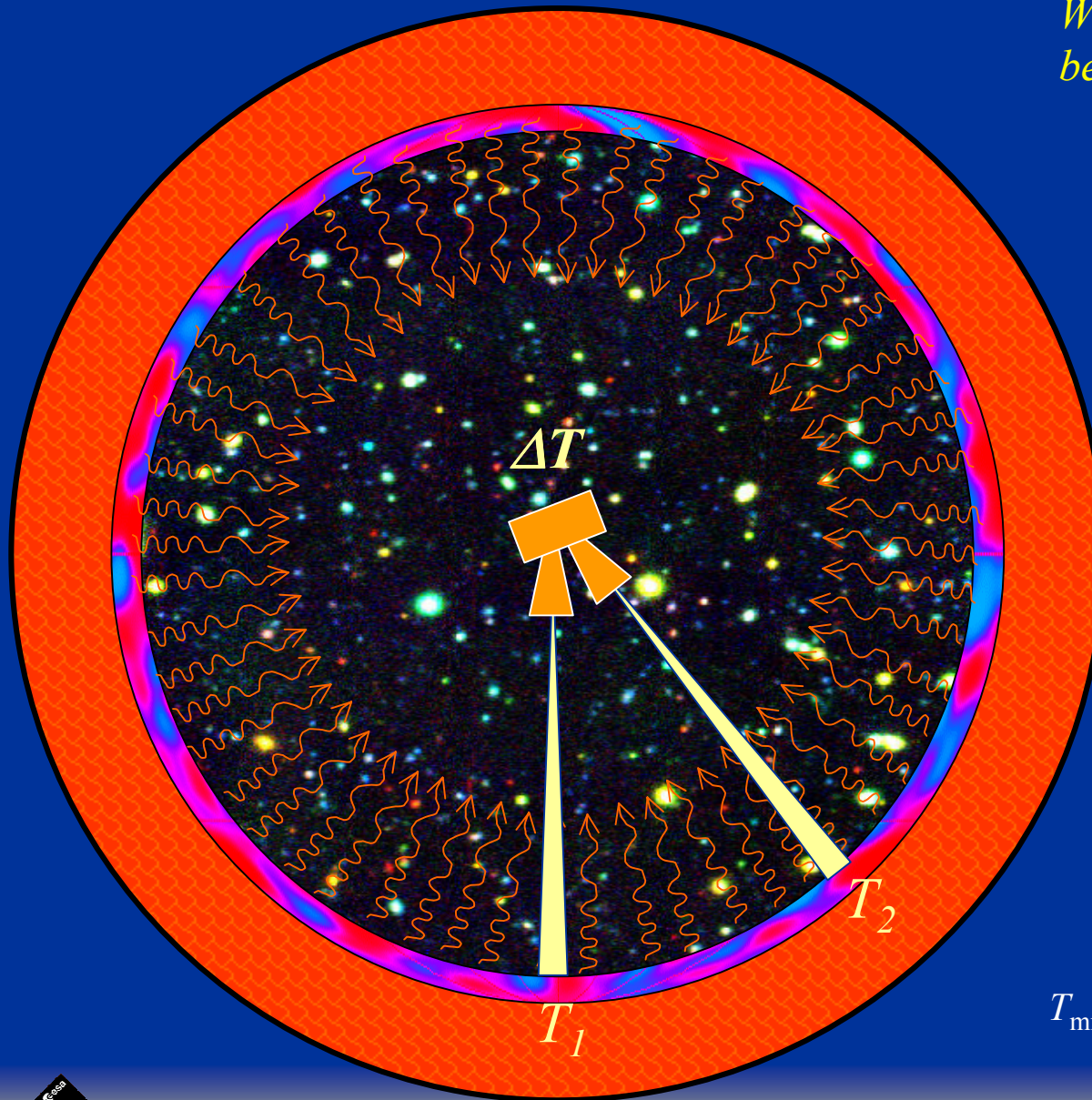
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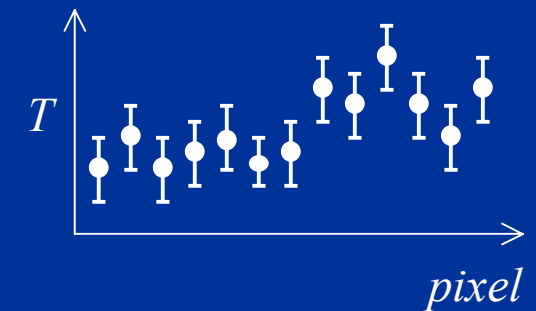


CMB Anisotropy

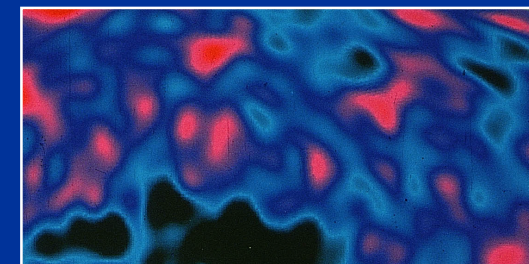
*Differential measurements:
We want the difference ΔT
between sky regions*



Variations of T along a given direction in the sky



Two-dimensional maps of temperature fluctuations



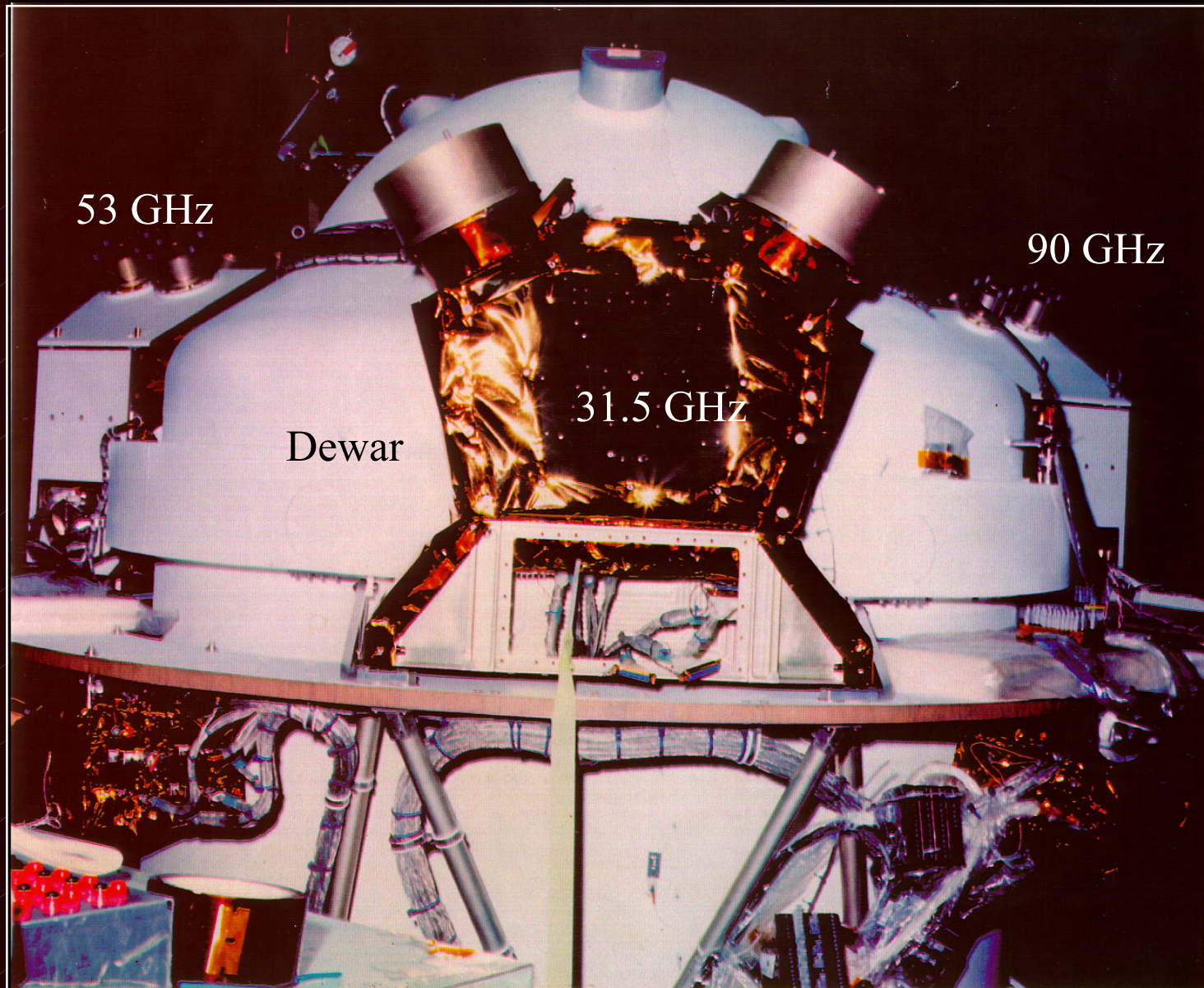
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COBE - Differential Microwave Radiometer



DMR 90 GHz radiometer

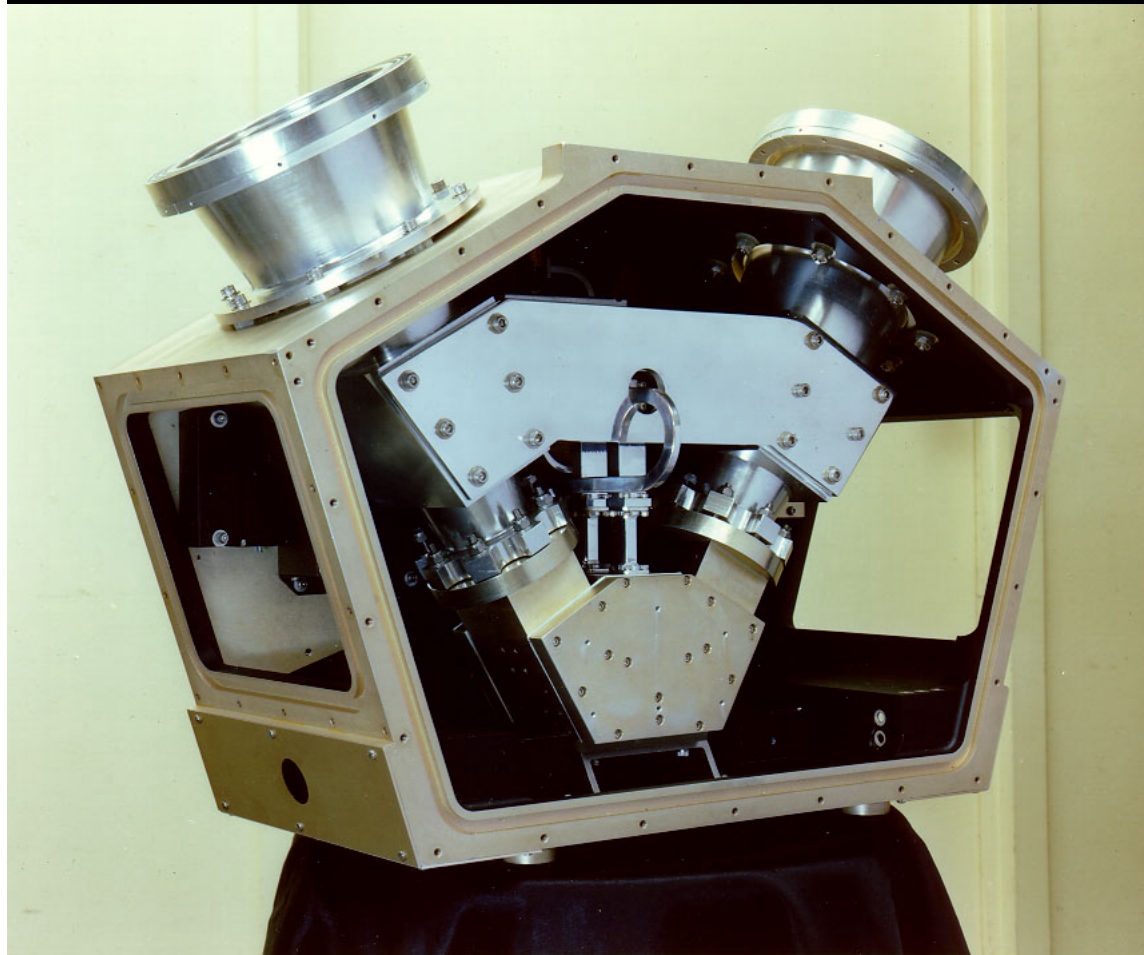
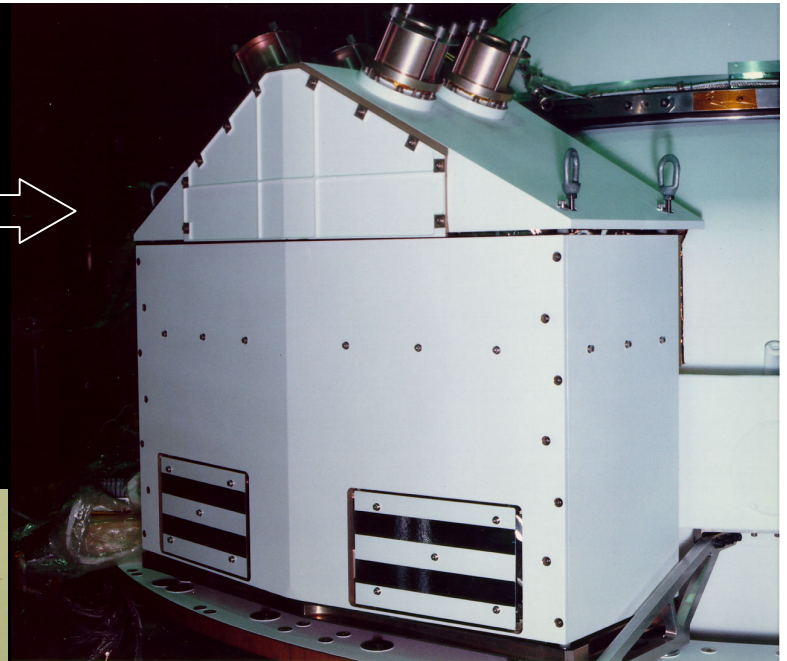
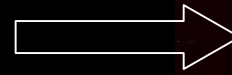
2 Dicke-switched systems

Angular resolution: 7°

Physical temperature: 140K

Sensitivity: 19-27mK Hz^{-1/2}

Separation: 60°



DMR 31.5 GHz radiometer

Dicke-switched system
with OMTs

Angular resolution: 7°

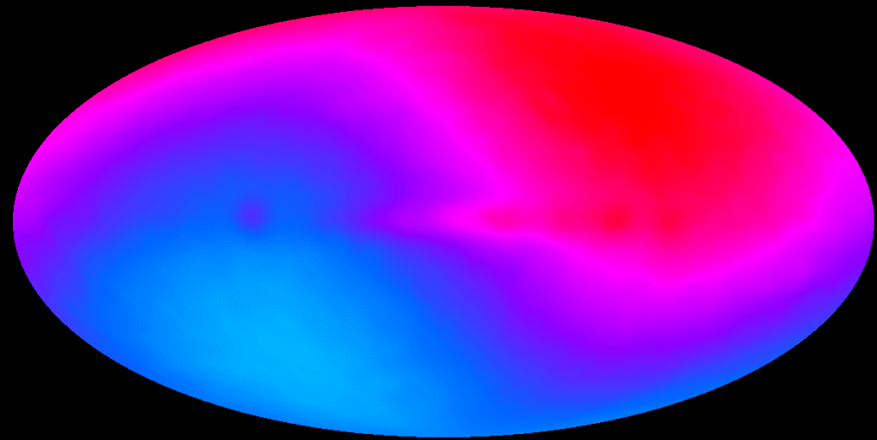
Physical temperature: 300K

Sensitivity: 42-43 mK Hz^{-1/2}

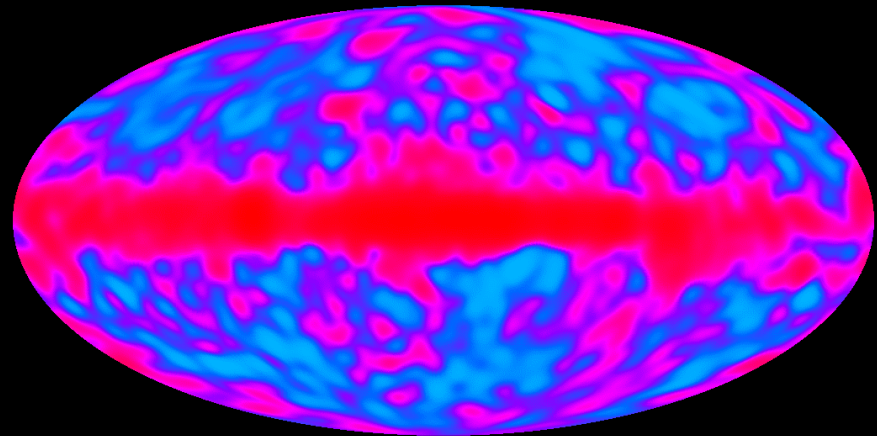
Separation: 60°

DMR 53 GHz Maps

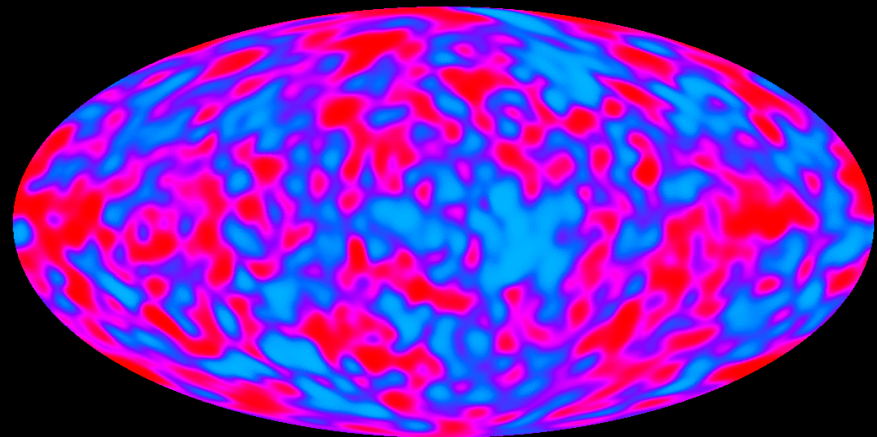
Dipole-dominated map
 $\Delta T \sim \pm 3.5 \text{ mK}$



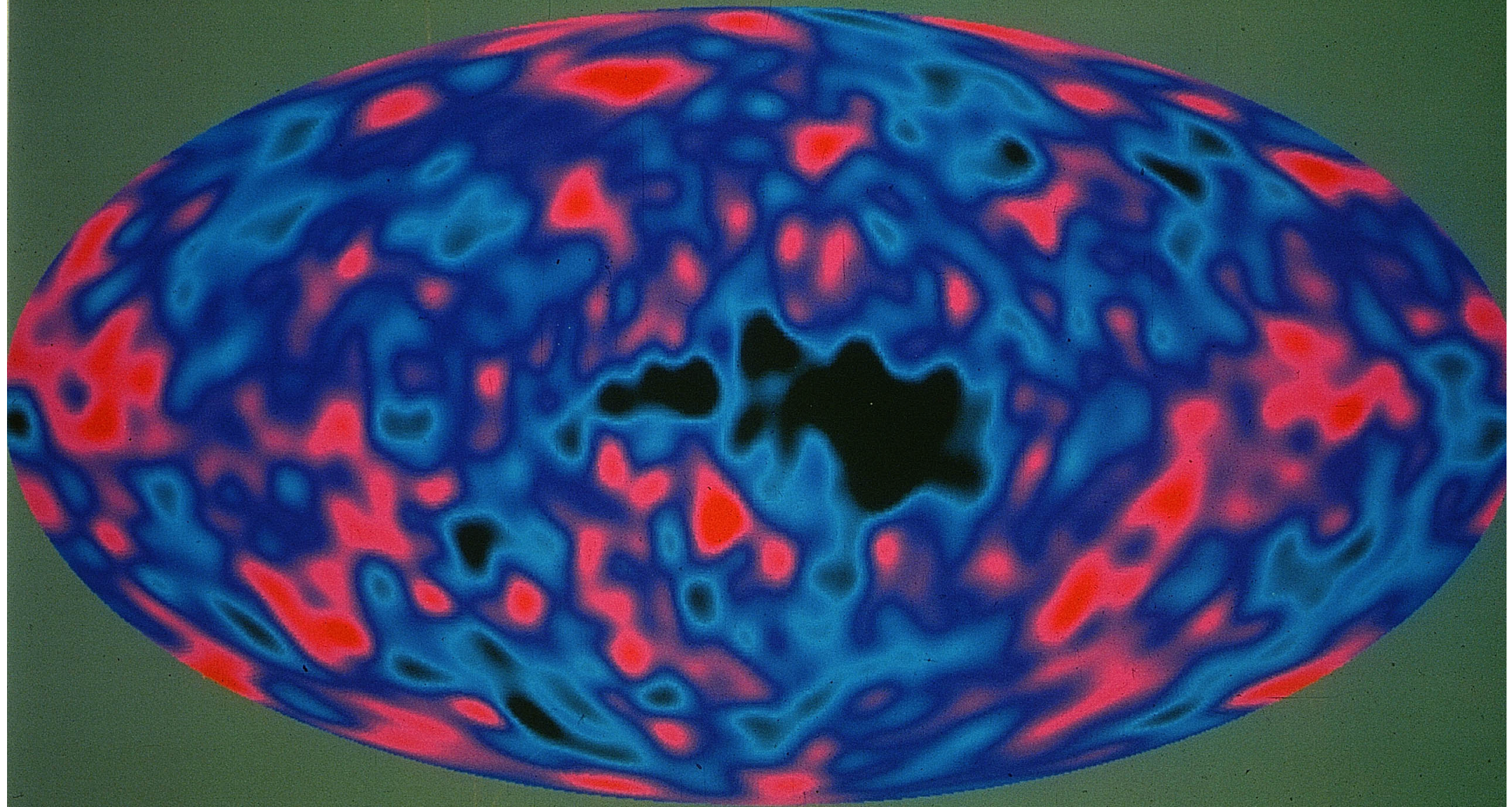
Fluctuations from Galaxy,
background and instrument noise
 $\Delta T \sim \pm 0.1 \text{ mK}$




Fluctuations from CMB
(with instrument noise)
 $\Delta T_{CMB} \sim \pm 35 \mu\text{K}$



COBE – DMR full-sky map



γ

-150 μK  150 μK

We do expect CMB anisotropies

Highly inhomogeneous distribution of matter today
⇒ Density perturbations must be present at $z \sim 1000$

Physical processes responsible for CMB anisotropy

<i>Type</i>	<i>Physical mechanism</i>	<i>Angular scale</i>
Sachs Wolf	Gravitational redshift	$\Delta T(\vartheta) \propto \vartheta^0$
Doppler	Motion of material	$\Delta T(\vartheta) \propto \vartheta^{-1}$
Adiabatic	Density perturbations	$\Delta T(\vartheta) \propto \vartheta^{-2}$

Primary anisotropy: Large angular scales are dominated by Sachs-Wolf
Velocity and density perturbations affect smaller scales

Secondary anisotropy: perturbations in the path between last scattering
and us (e.g. SZ effect)



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CMB Angular Power Spectrum

Spherical harmonics: $Y_{\ell m}(\vartheta, \phi)$ $-l \leq m \leq l$ $l \propto \frac{1}{\vartheta}$

We represent the temperature distribution on the sky as:

$$\Delta T(\vartheta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\vartheta, \phi)$$

The angular power spectrum is:

$$C_{\ell} = \langle |a_{\ell m}|^2 \rangle = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} a_{\ell m}^2$$

$$[a_{\ell m}] \rightarrow [\mu\text{K}]$$

$$[C_{\ell}] \rightarrow [\mu\text{K}^2]$$



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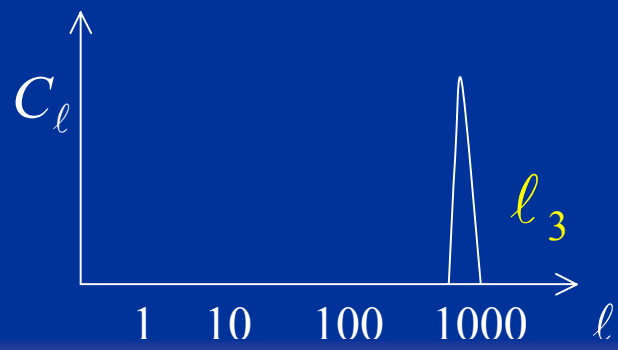
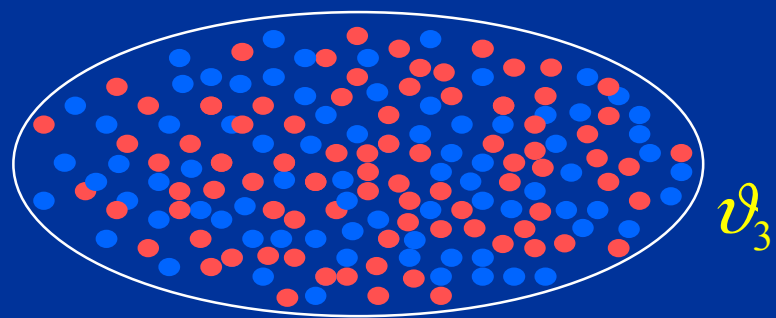
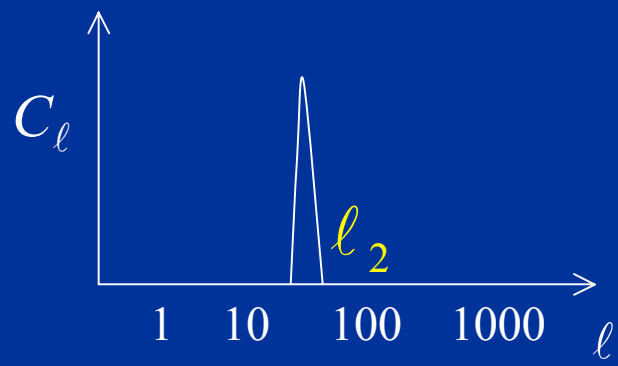
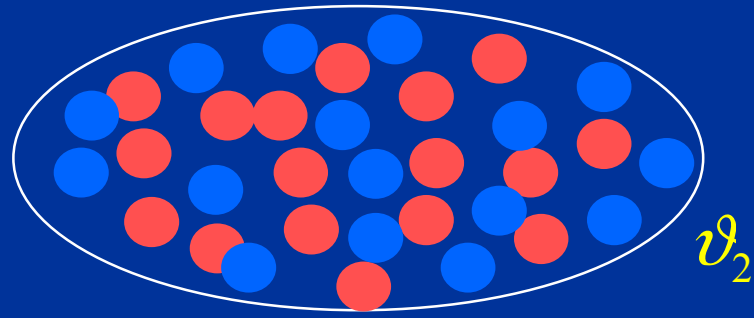
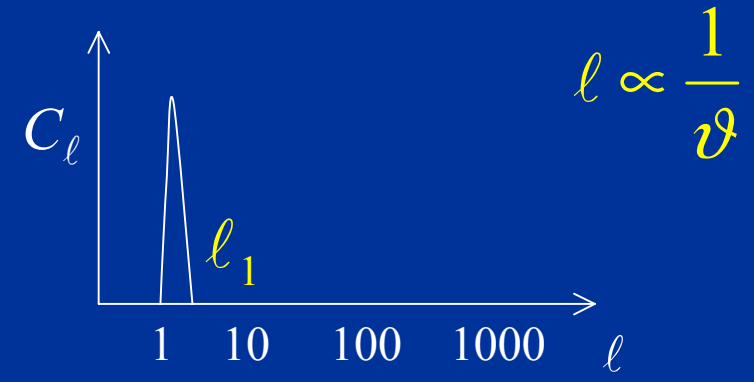
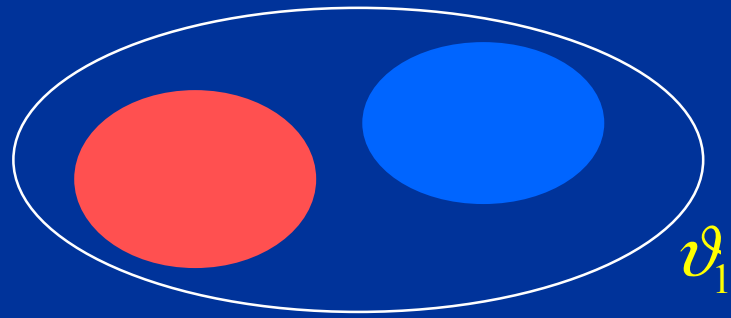
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Sky map

Power spectrum



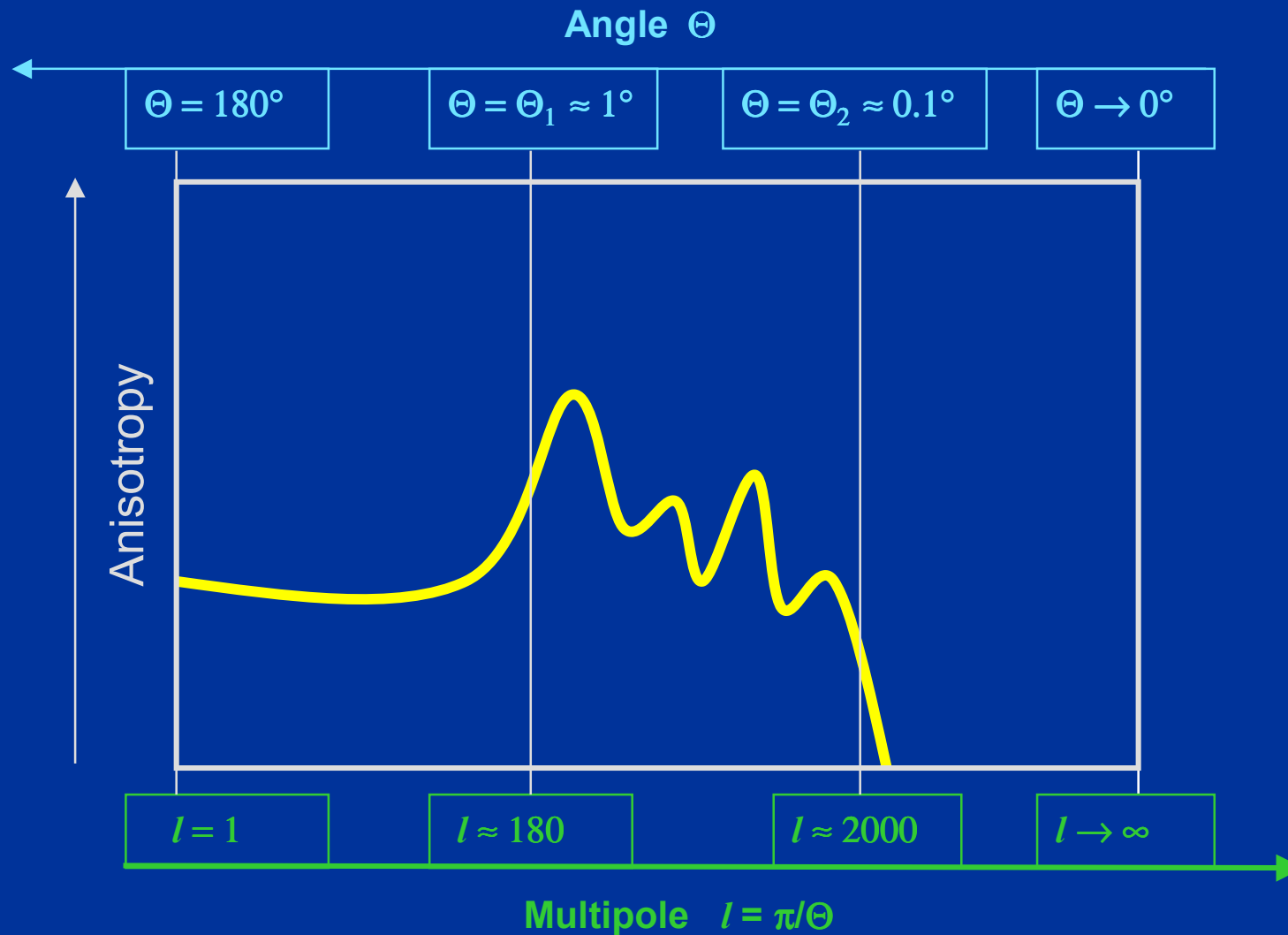
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Qualitative shape of expected CMB power spectrum



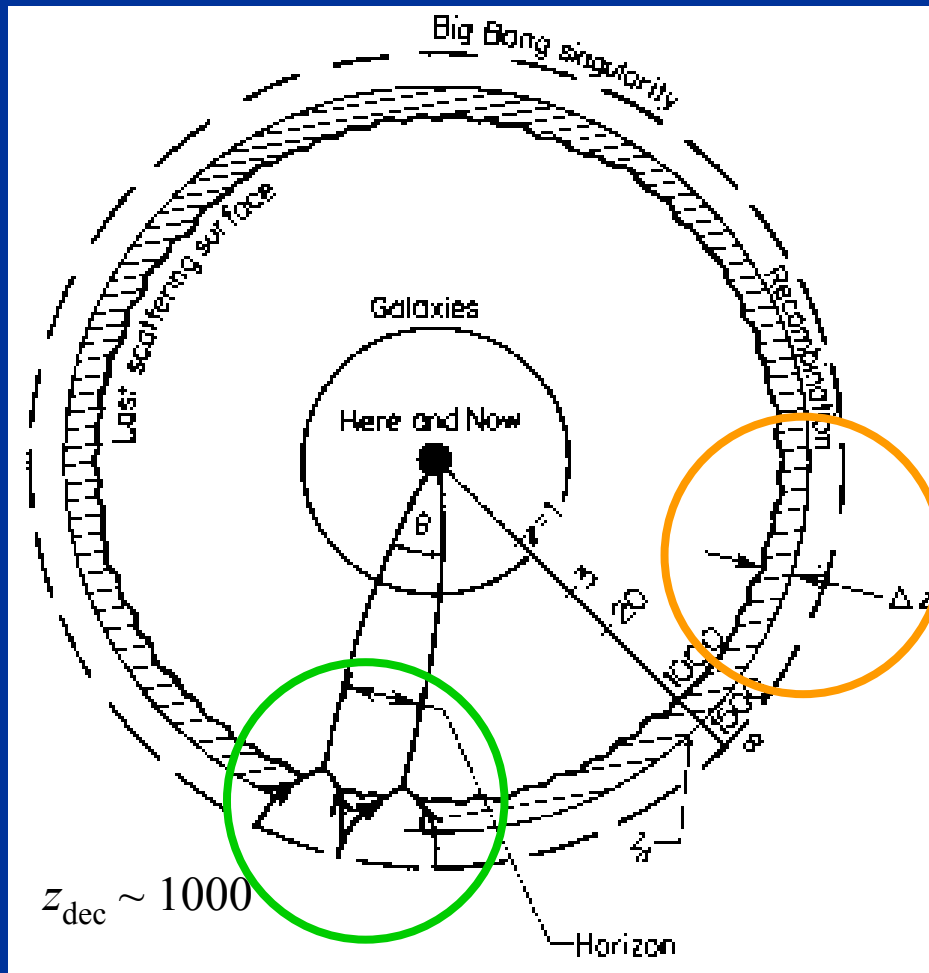
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Critical angular scales



The LSS has a “finite thickness”: anisotropies on small scales are “diluted”

$$\Delta z \sim 100$$

$$\theta = \theta_2 \sim 10'$$

$$l \sim 1500$$

Any physical information at LSS has travelled at most a distance $d \sim ct$, corresponding to an angular scale $\theta \sim 1^\circ$.

This defines the horizon at last scattering

$$\theta = \theta_1 \sim 1^\circ$$

$$l \sim 100$$



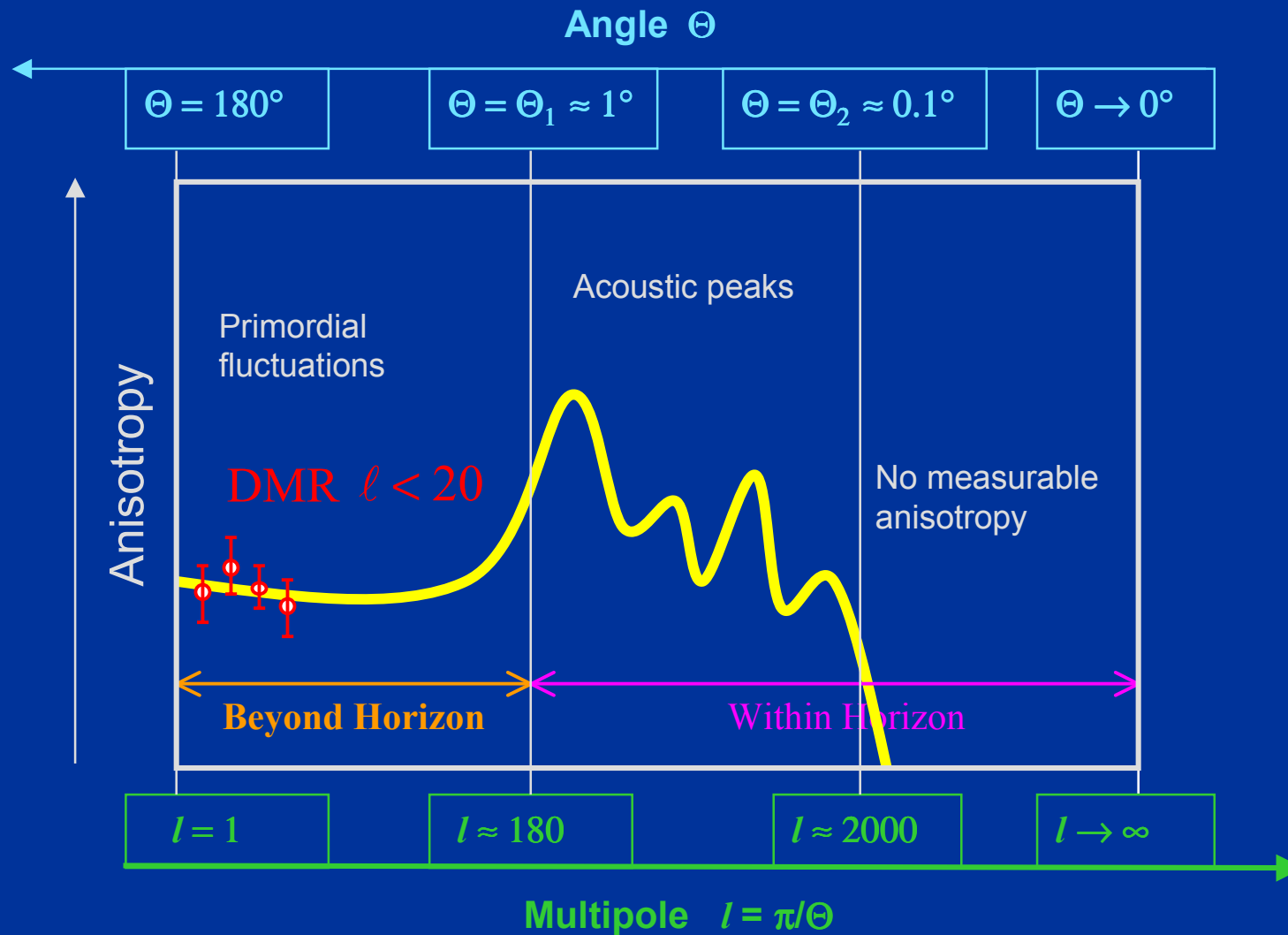
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Qualitative shape of expected CMB power spectrum



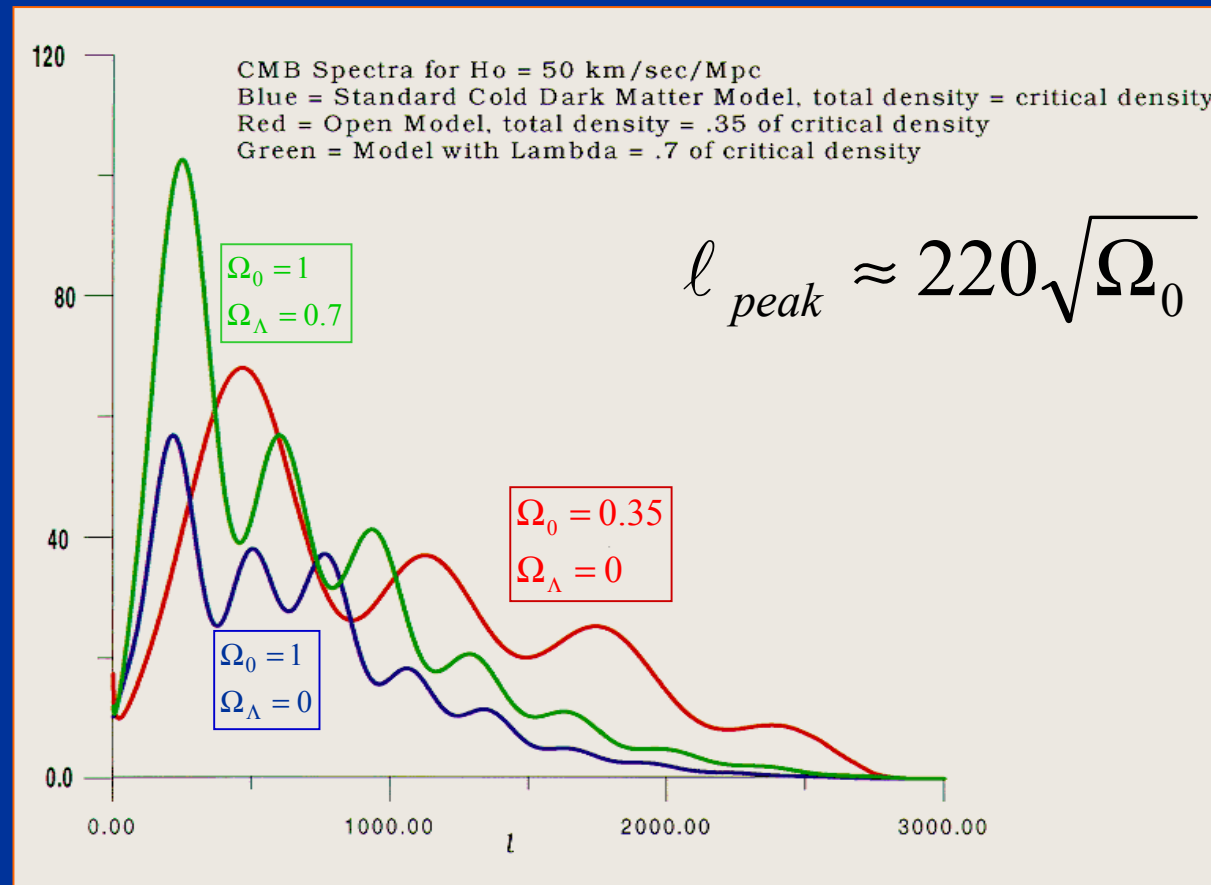
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The details of the angular power spectrum depend on the value of the main cosmological parameters



Accurate *high resolution* measurements of CMB anisotropies lead to potential *high precision* determination of parameters



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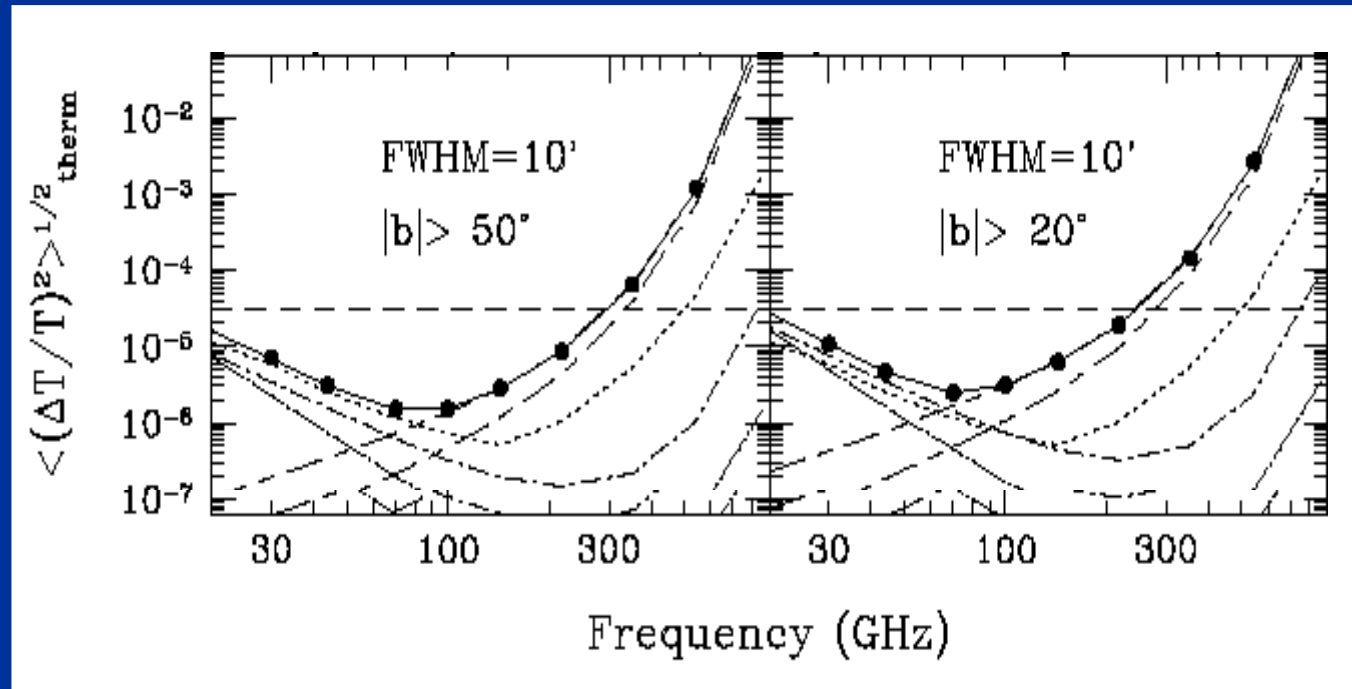
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Foregrounds

Multifrequency observations are needed to disentangle non-cosmological contributions



- Galactic diffuse emission (synchrotron, free-free, dust)
- Extragalactic point sources



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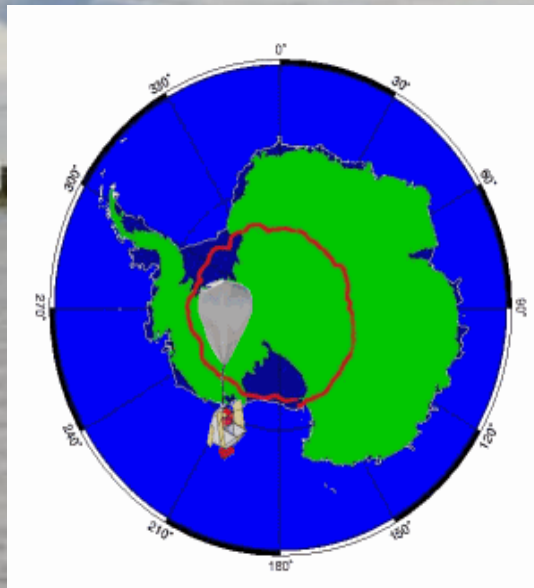


Boomerang

Long-duration Antarctic balloon flight

Focal plane: 16 bolometric detectors cooled at 0.3K

Sensitivity: $\sim 0.2 \text{ mK Hz}^{-1/2}$

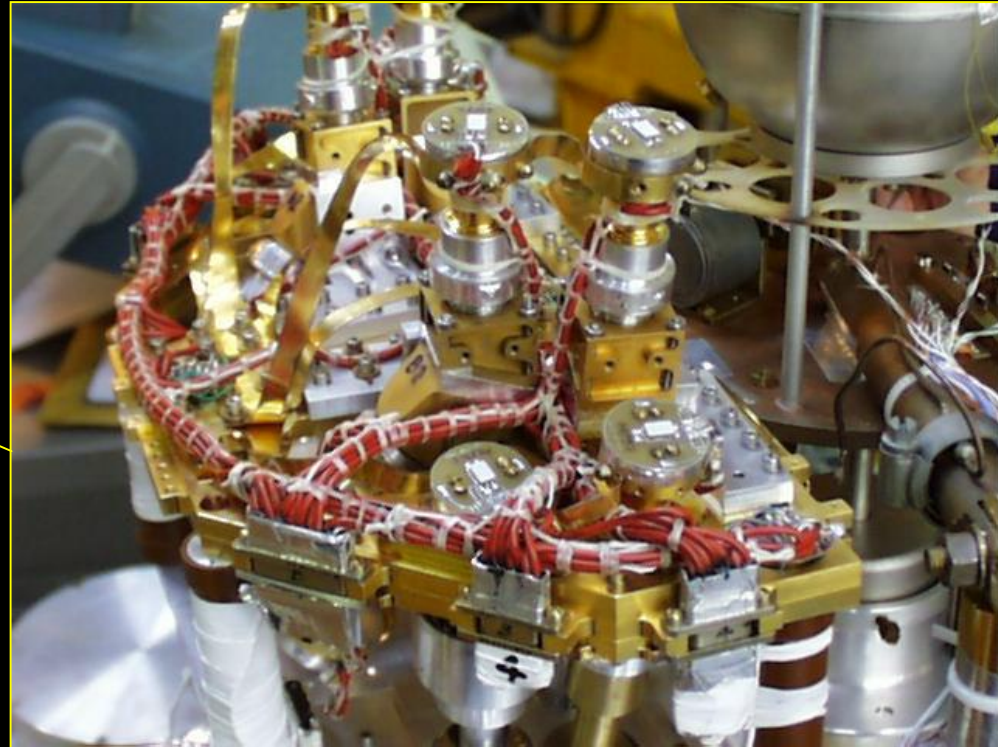


Boomerang Instrument



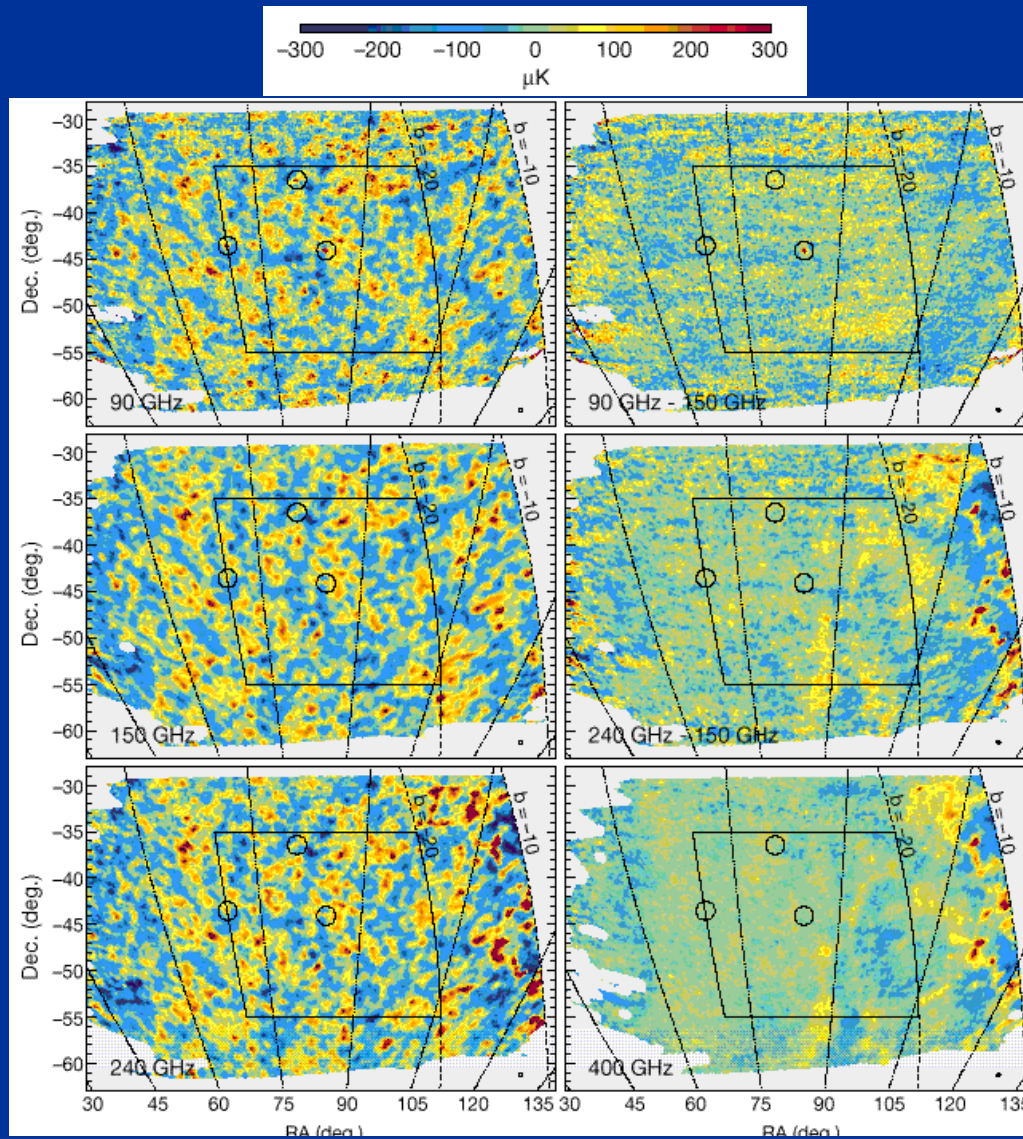
Gondola

Focal Plane: bolometer array



Frequency (GHz)	90	150	240	400
N. Channels	2	6	4	4
Angular resolution	18'	10.5'	14'	13'
Sensitivity (mK/Hz ^{1/2})	0.14	0.17	0.21	2.7

Boomerang sky maps



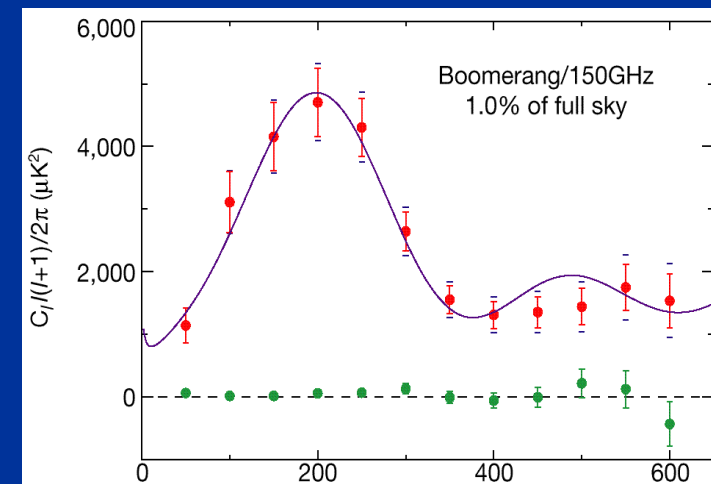
Foregrounds

“Clean” region (no correction)

Upper limits show that fluctuations are dominated by CMB

Power sepctrum

$$0.88 < \Omega_0 < 1.12$$



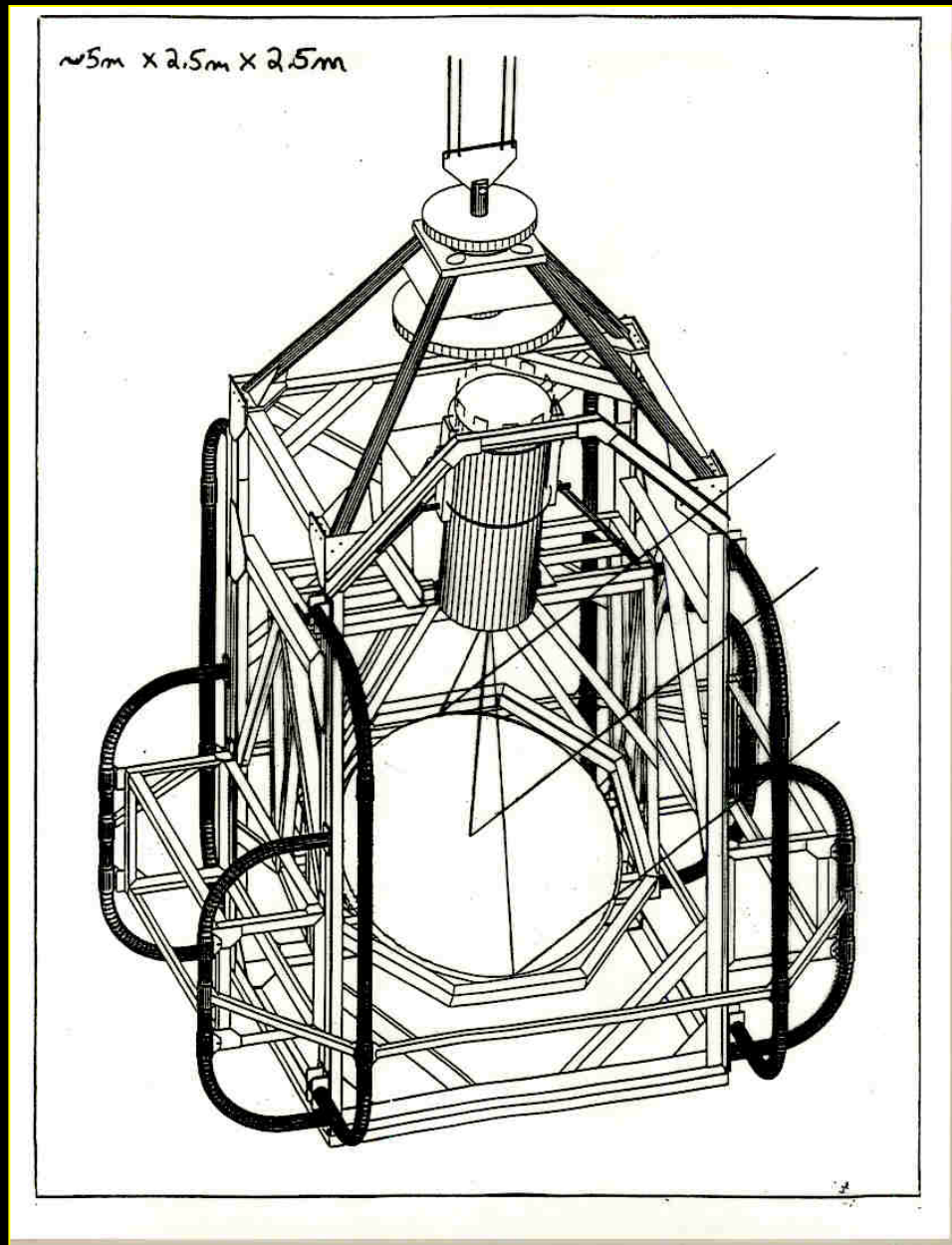
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MAXIMA

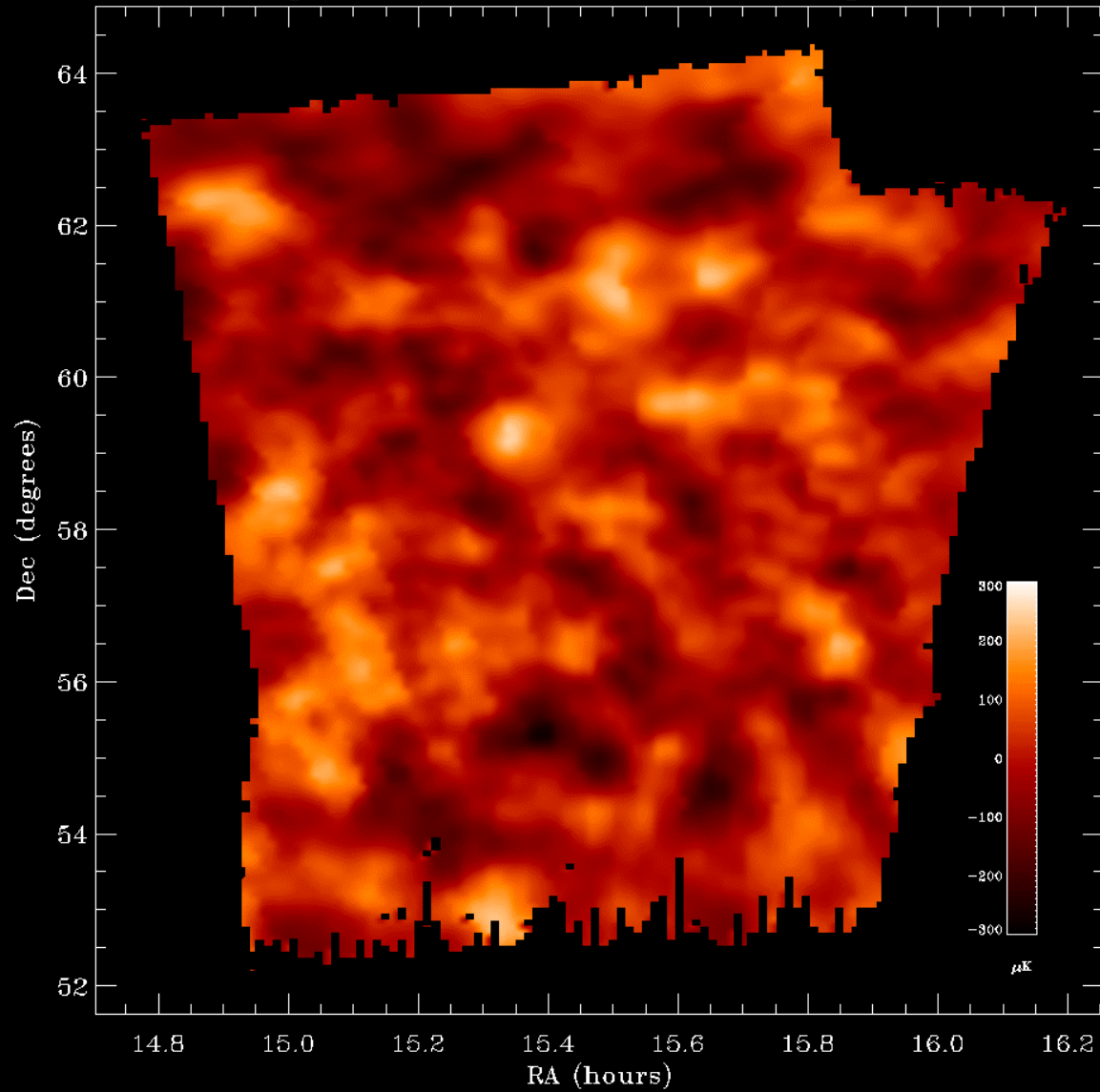


- Launch: Palestine (Texas) August 1999
- Conventional flight
- Telescope: 1.3 m Off-axis
- Frequencies: 140, 240, 410 GHz
- Detectors: spider-web bolometers
- Sensitivity: $\sim 0.5 \text{ mK Hz}^{1/2}$
- Angular resolution: 10-11 arcmin
- Sky coverage: 124 deg^2

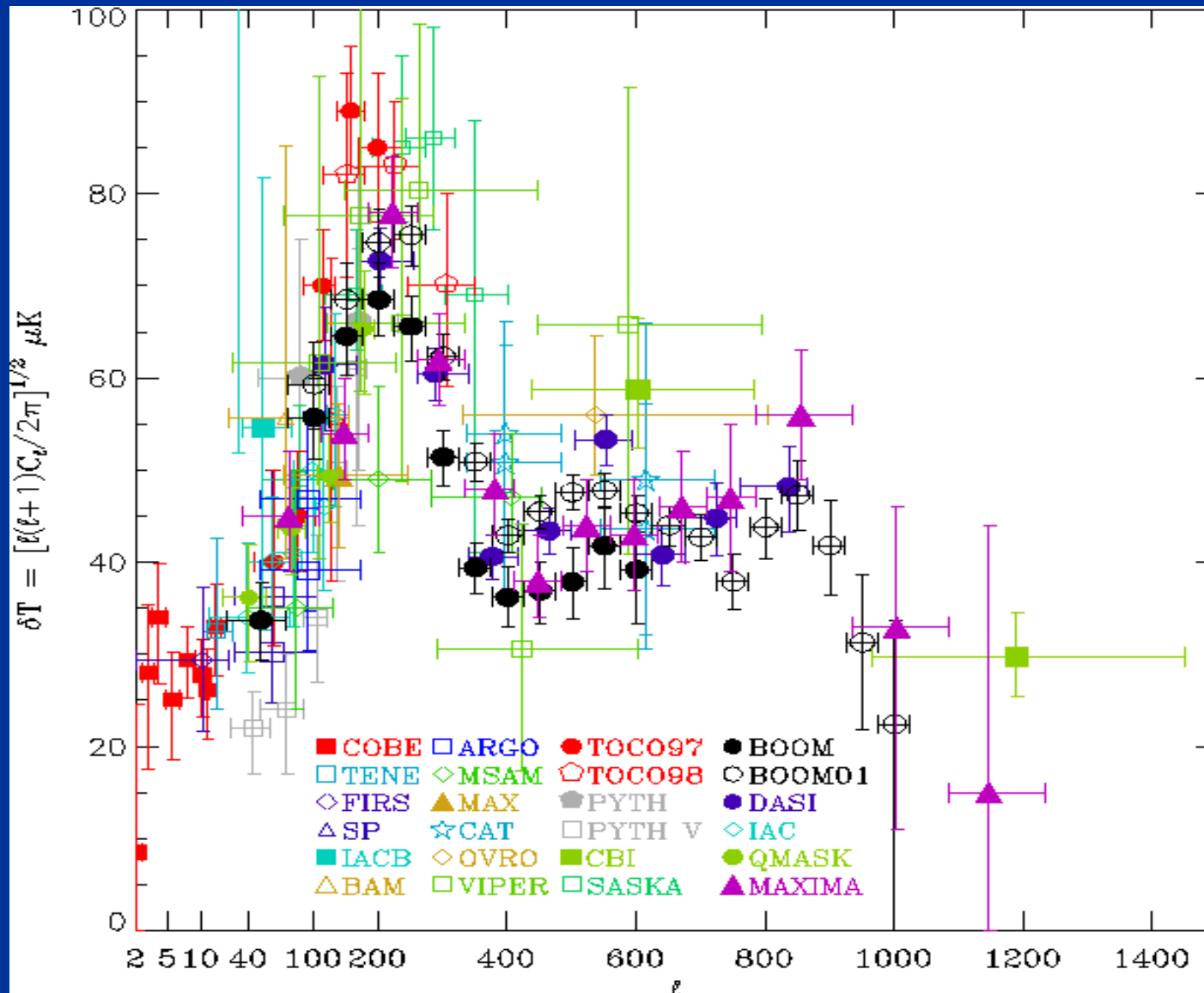


MAXIMA

MAXIMA-1 map of the Cosmic Microwave Background Anisotropy



Anisotropy experiments – Jan 2003



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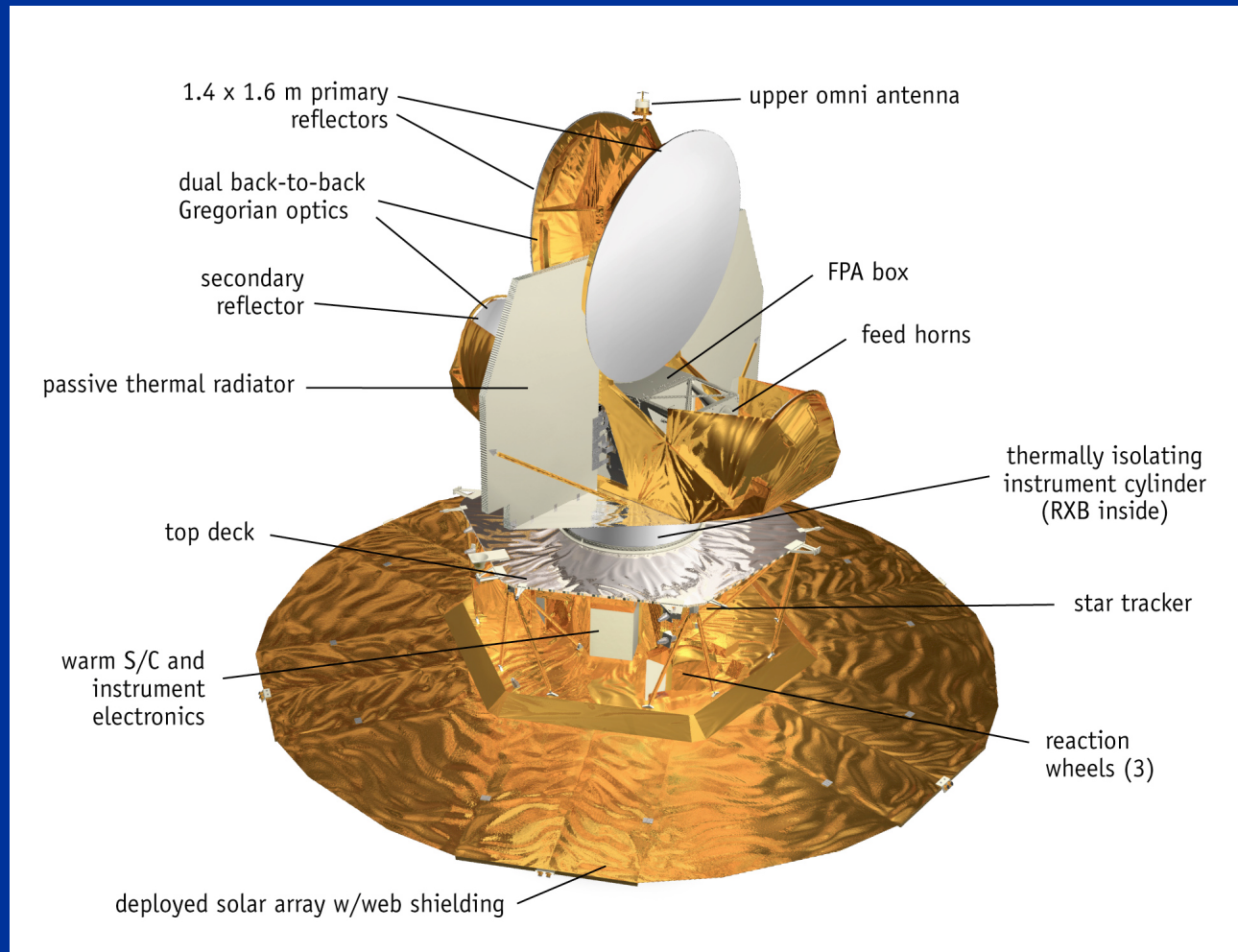
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WMAP

(NASA mission, launched June 2001)



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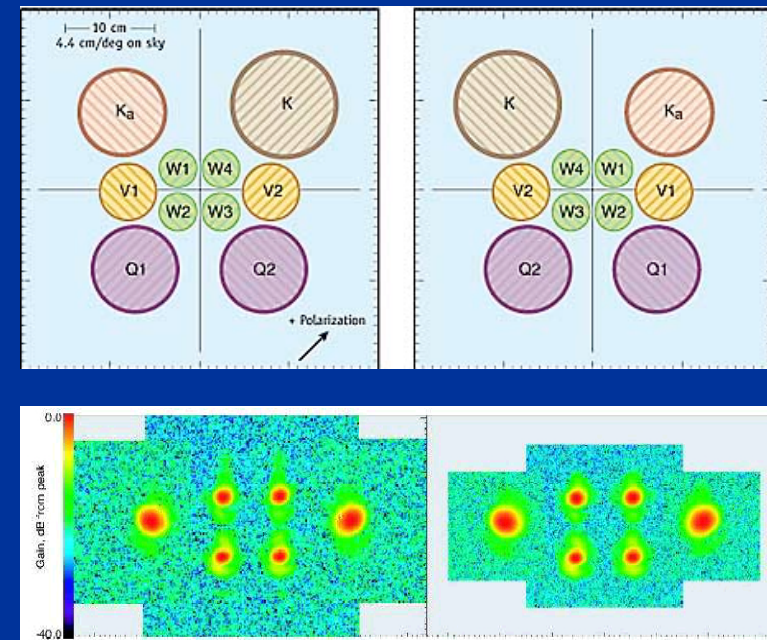
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WMAP Instrument

Frequencies (GHz)	22	30	40	60	90
Wavelengths (mm)	13.6	10.0	7.5	5.0	3.3
# of channels	4	4	8	8	16
Resolution (FWHM, degrees)	0.93	0.68	0.53	0.35	<0.23
Sensitivity (μK , $0.3^\circ \times 0.3^\circ$ pixel)	~ 35	~ 35	~ 35	~ 35	~ 35
Radiometer	Differential pseudo-correlation with polarization				
Reflectors	Dual Gregorian, 1.4 m x 1.6 m primaries				
Thermal	Passive radiative cooling to < 95 K				
Structure	Composite / aluminum				
Focal plane	$3.5^\circ \times 3.5^\circ$ field of view				
Pointing accuracy	0.6° control (elevation); 1.8' knowledge				



Symmetric focal planes



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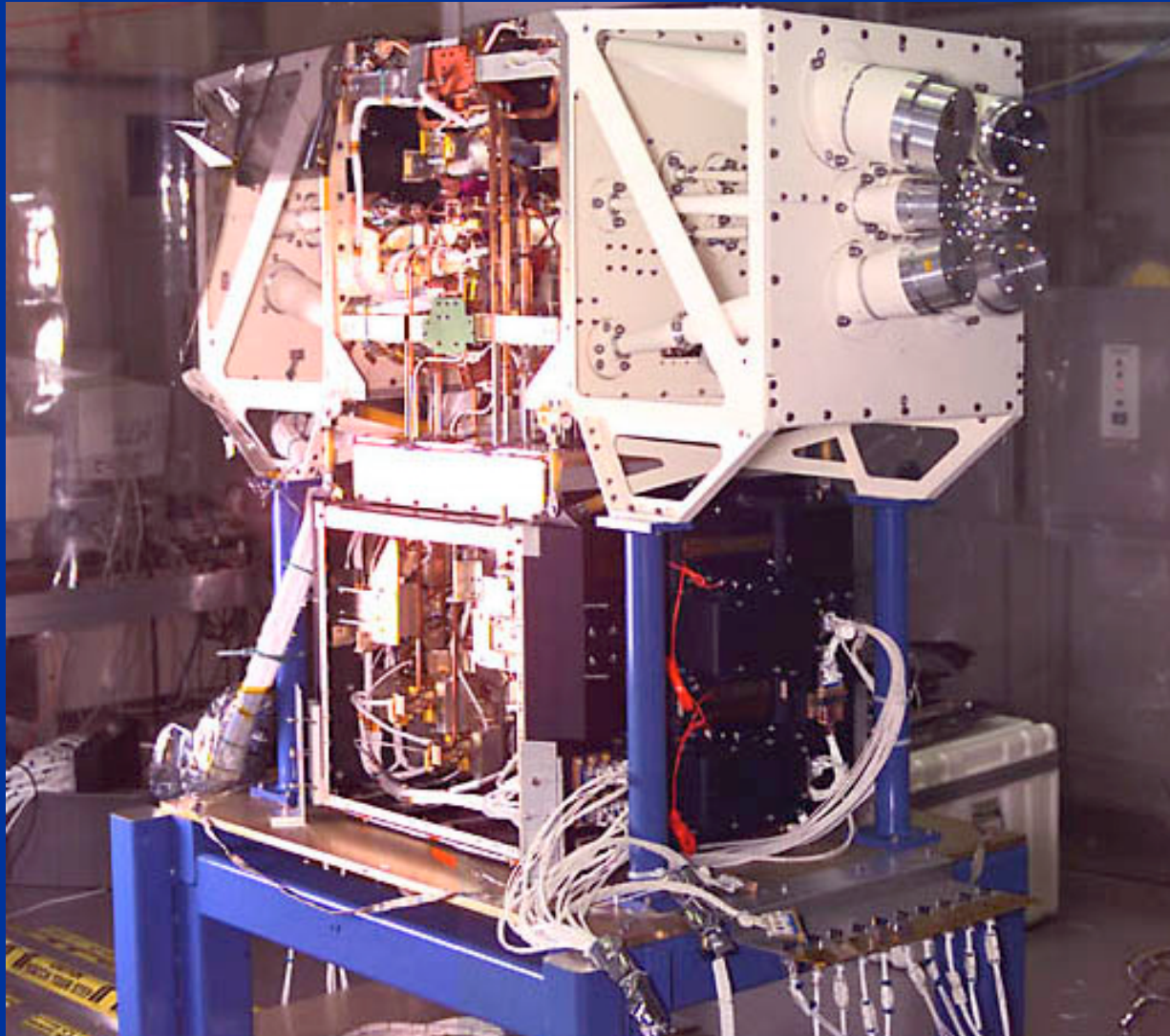
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MAP Instrument Assembly

Front-end: Passive cooling at 90 K



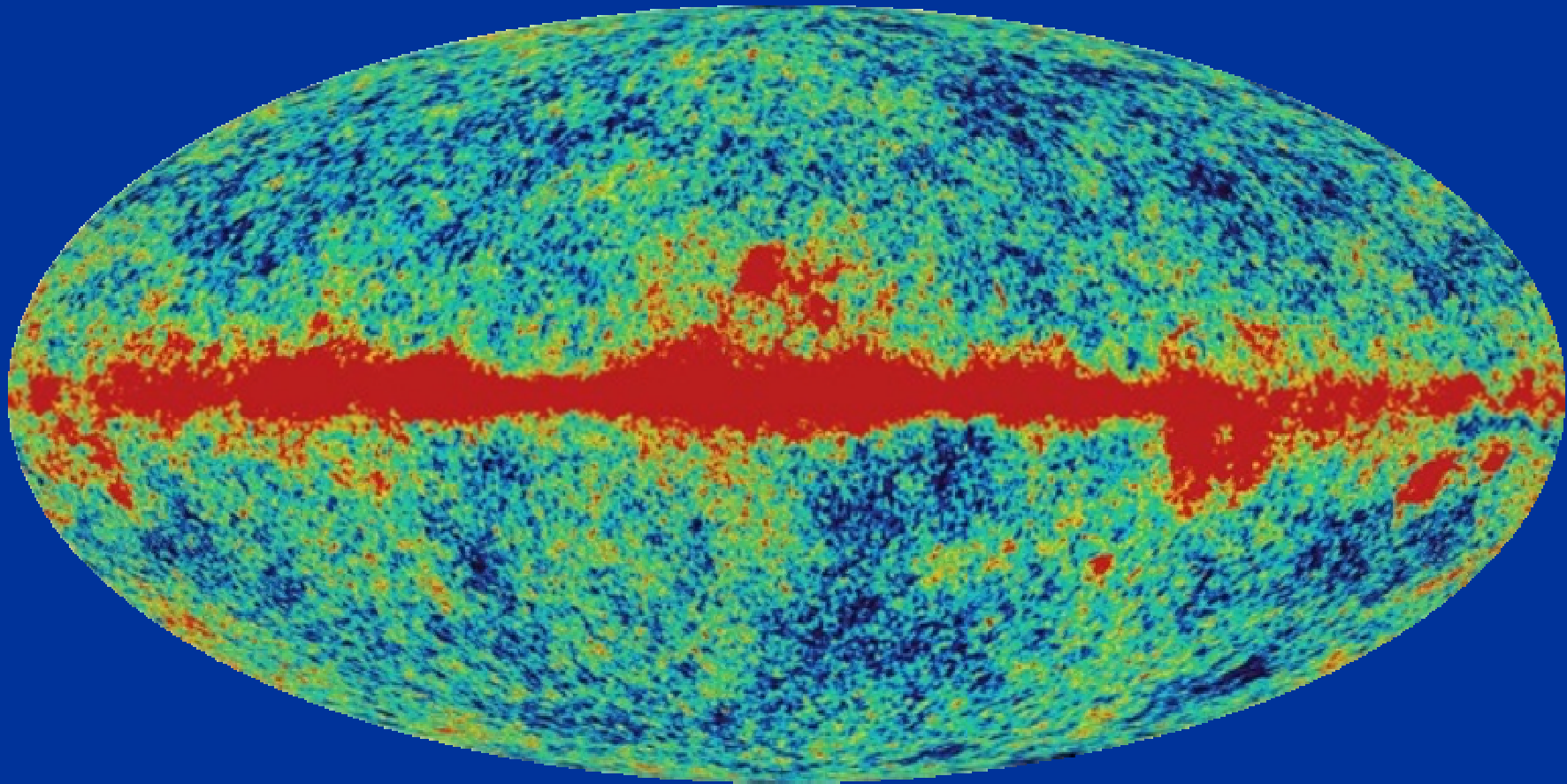
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The WMAP sky maps (Q-band)



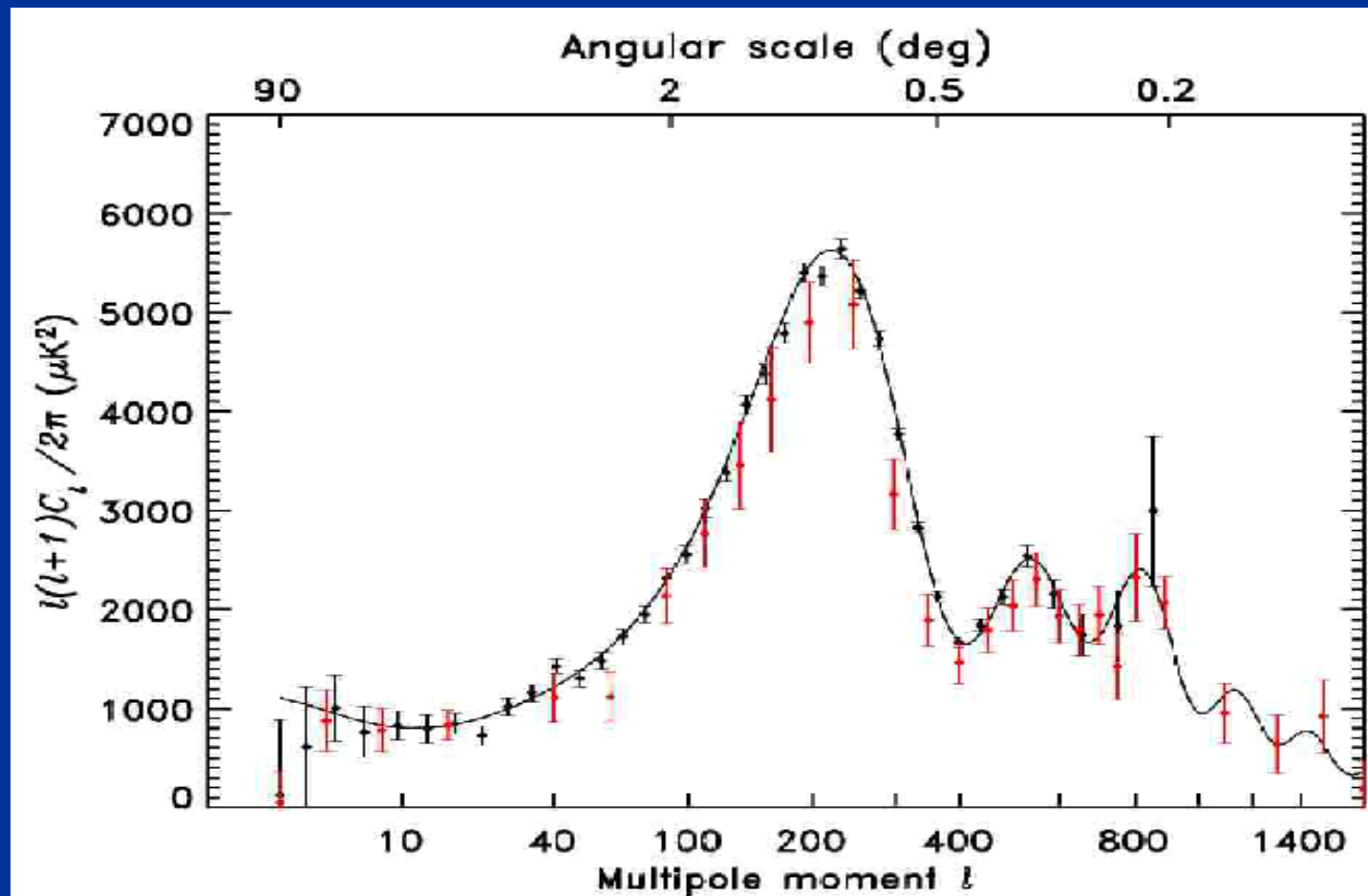
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The WMAP power spectrum



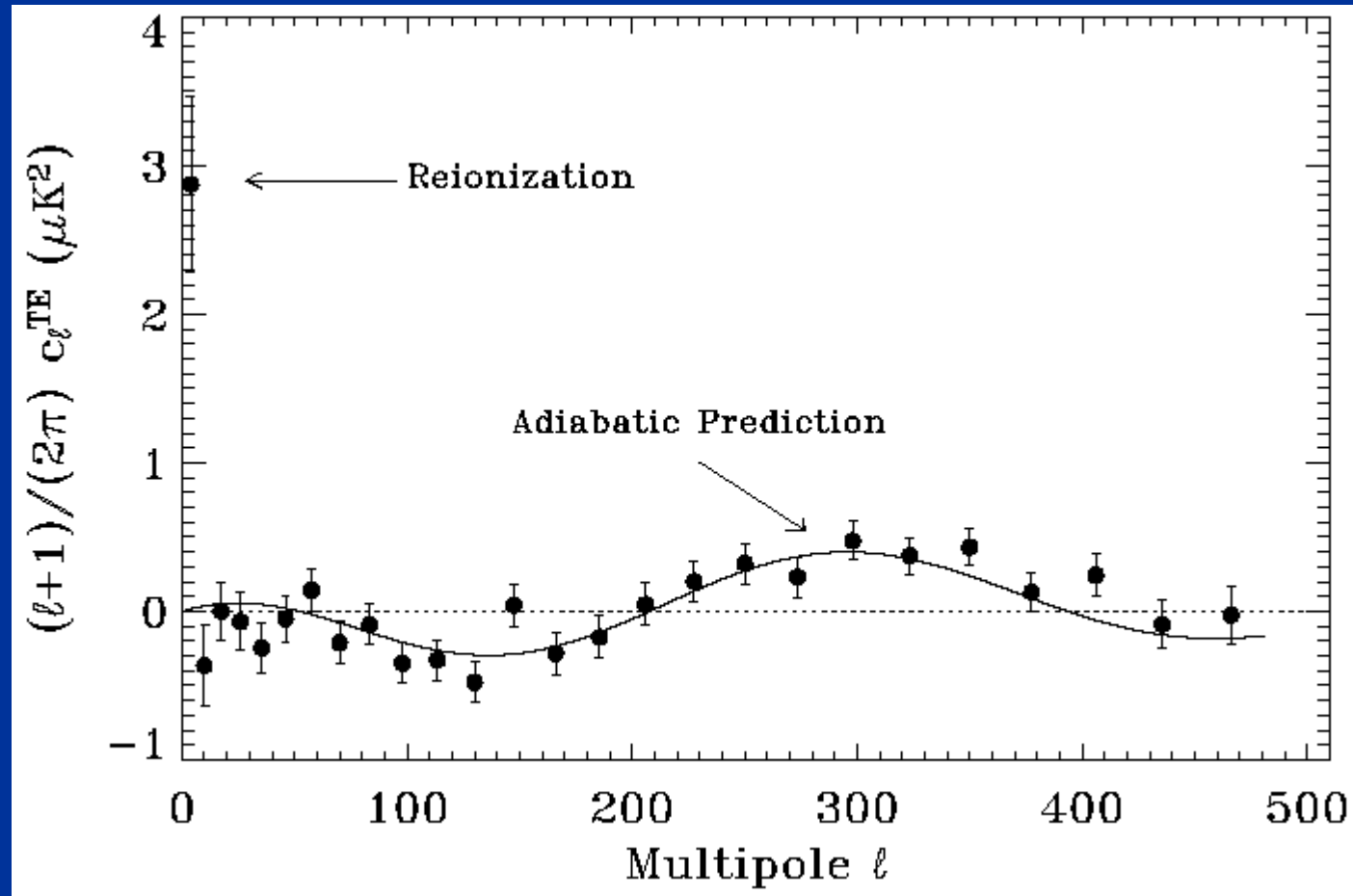
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The WMAP TE correlation



→ Evidence of re-ionisation at $z \sim 20$



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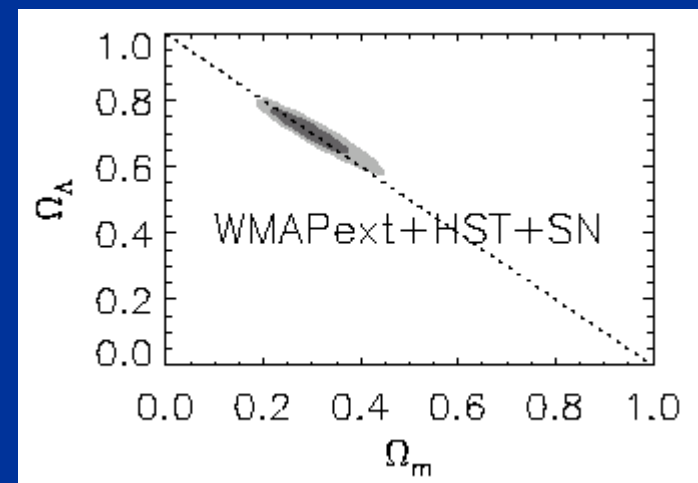
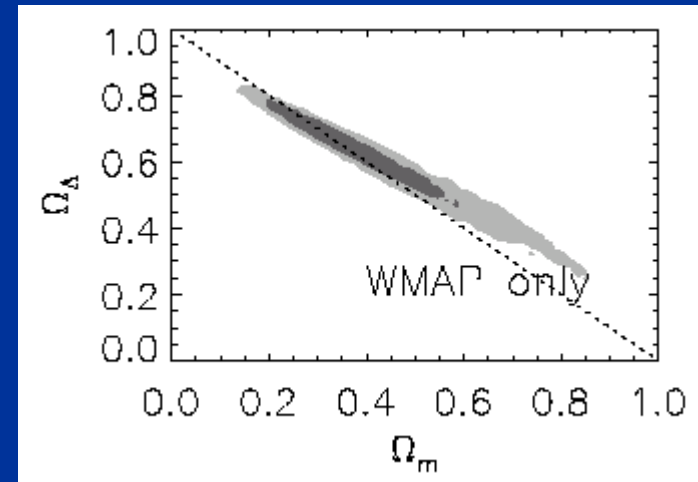
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WMAP: Cosmological parameters estimation

Total density	$\Omega_0 = 1.02 \pm 0.02$ *
Hubble constant	$h = 0.72 \pm 0.05$
Barion density	$\Omega_b = 0.047 \pm 0.006$
Matter density	$\Omega_m = 0.29 \pm 0.07$
Spectral index	$n_s = 0.99 \pm 0.04$
Age of the Universe	$t_0 = 13.7 \pm 0.2$ Gyr

* Combined with other data sets



Constraints on neutrino mass

If neutrinos have non-zero mass, they may contribute significantly to the total energy density of the universe

Significant constraints are obtained by the combination of

- CMB anisotropy (WMAP)
- Galaxy redshift surveys (2dFGRS)

$$\Omega_\nu h^2 < 0.0073$$

Assuming 3 degenerate neutrino states: $m_\nu < 0.23 \text{ eV}$

Atm and solar neutrino experiments: $m_{\nu_\tau} < 0.1 \text{ eV}$ if $m_{\nu_e} \ll m_{\nu_\tau}$

CMB limit holds for $m_{\nu_e} \approx m_{\nu_\tau}$

Will be improved by Planck observations



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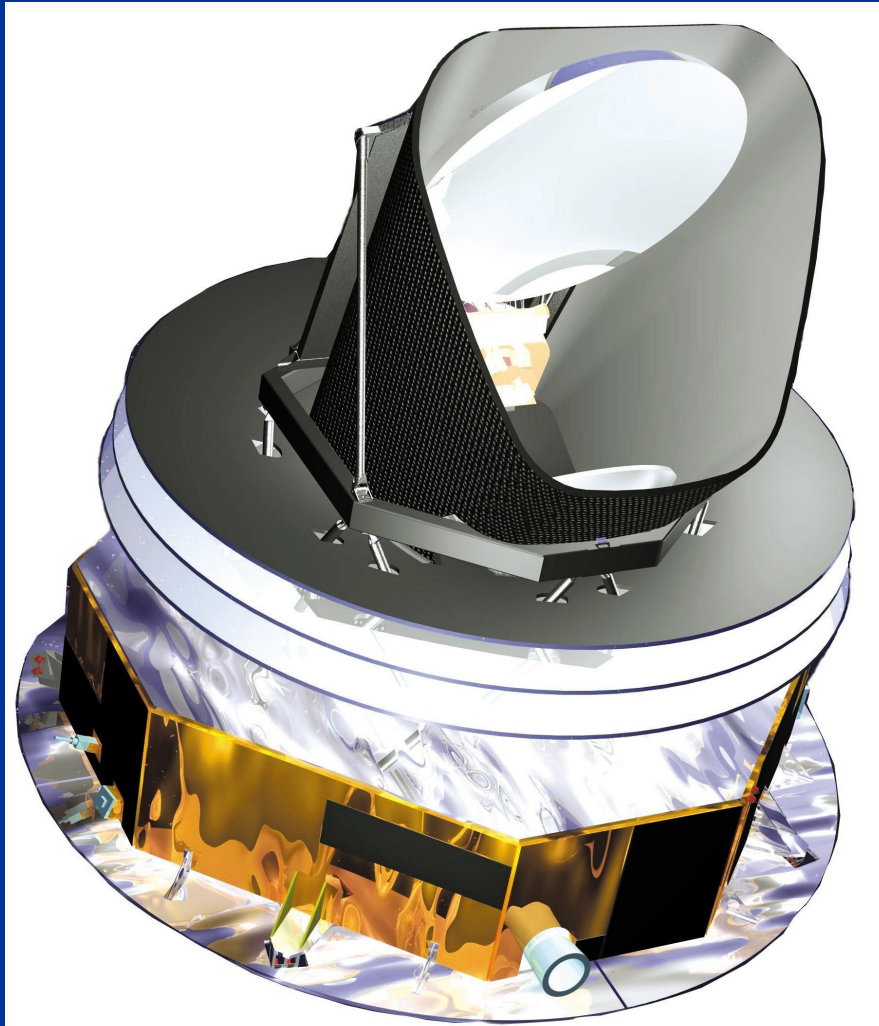
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PLANCK

European Space Agency



Design goals

- Angular resolution: $< 10'$
- Sensitivity per pixel: $< 10 \mu\text{K}$
- Frequency range: 27-900 GHz
- Sky coverage: 100%
- *Systematic errors*: $< 3 \mu\text{K}$

Implementation

- Telescope: 1.5m, Aplanatic, off-axis
- Thermal design: passive + active
- Detectors:
 - Radiometer array (LFI), 20 K
 - Bolometer array (HFI), 0.1 K
- Orbit: Sun-Earth L2 (1.5×10^6 km)
- Launch: 2007, Ariane 5



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WMAP

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Angular resolution	14'-56'	5'-33'
Average $\Delta T/T$ per pixel/yr	40×10^{-6}	2×10^{-6}
Average $\Delta P/P$ per pixel/yr	56×10^{-6}	4×10^{-6}
Mission lifetime	2+2 yr	14 months
Spectral coverage	23-95 GHz	27-900 GHz
Detector technology	HEMT	HEMT+BOL
Detector temperature	90 K	20/4/0.1 K
Cooling	Passive	Active

PLANCK:

Dramatic improvement in parameter estimation accuracy

Testing inflation

Unprecedented mm-wave astrophysical science



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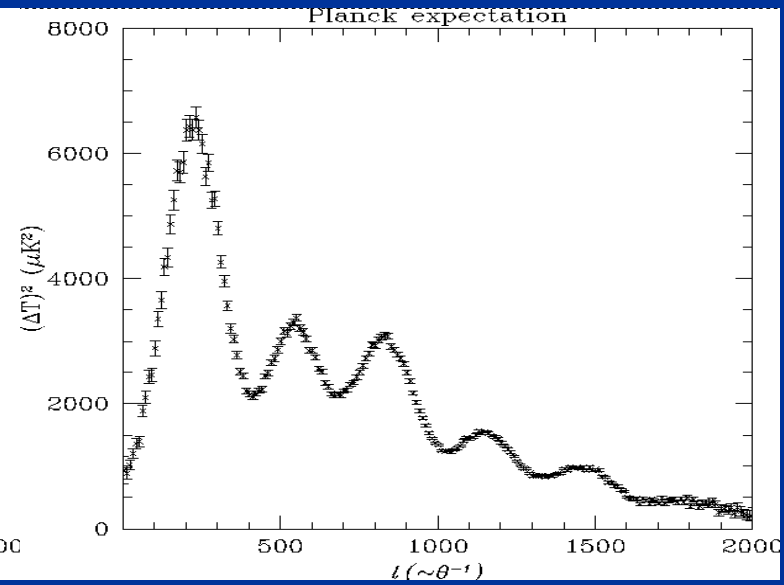
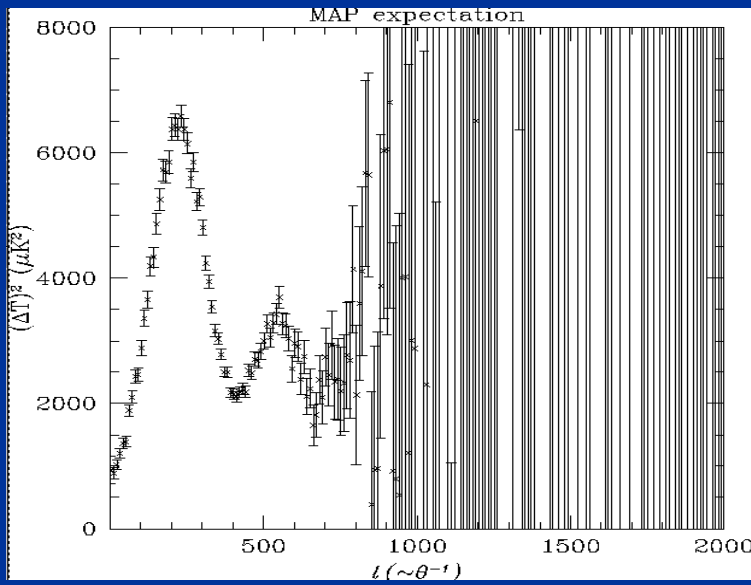
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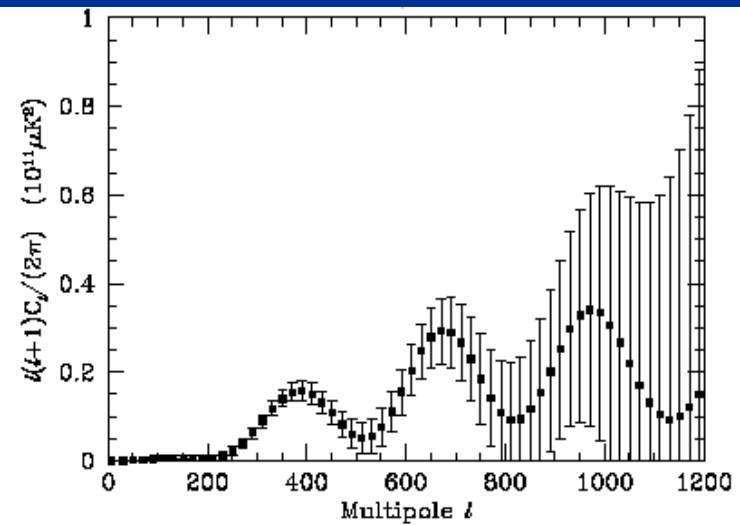
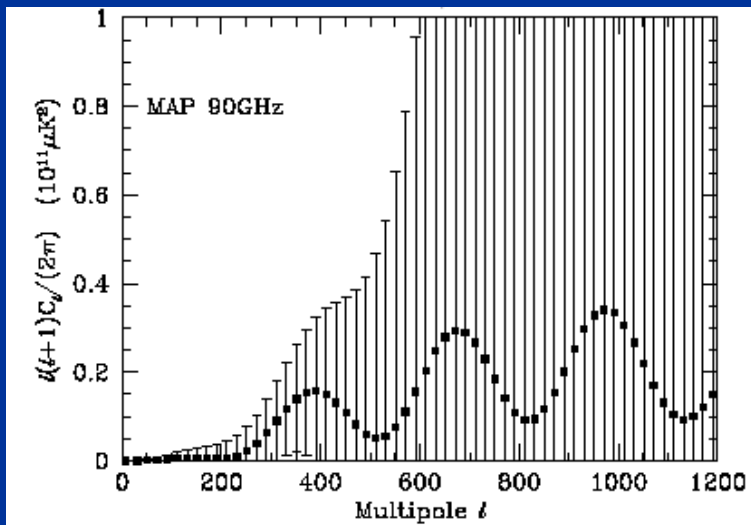
WMAP

Planck

Temperature



Polarisation



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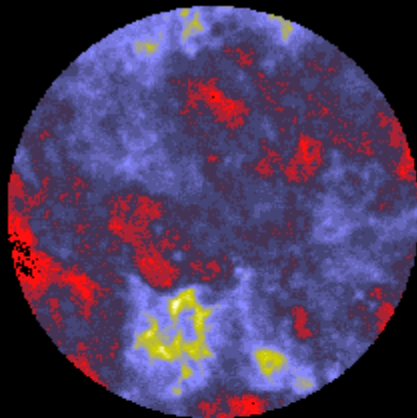
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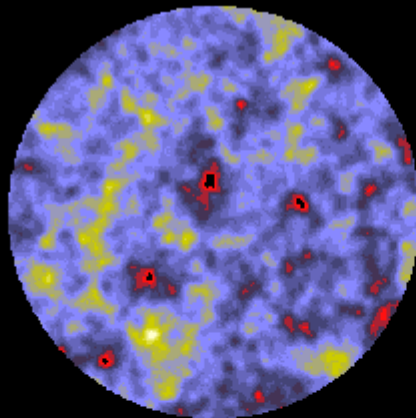


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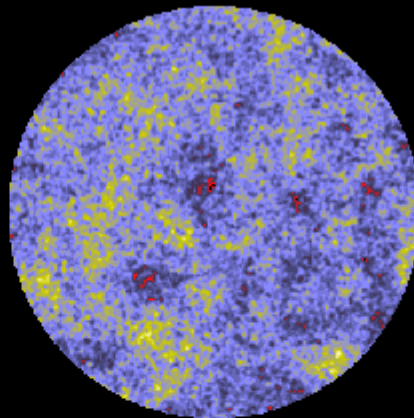
350 GHz



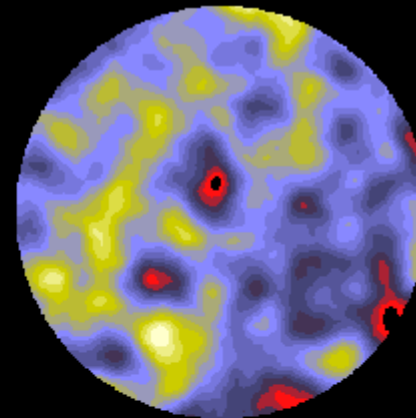
140 GHz



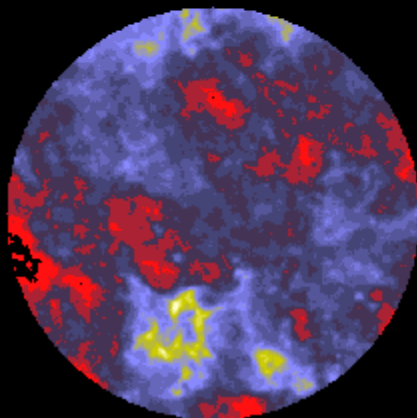
70 GHz



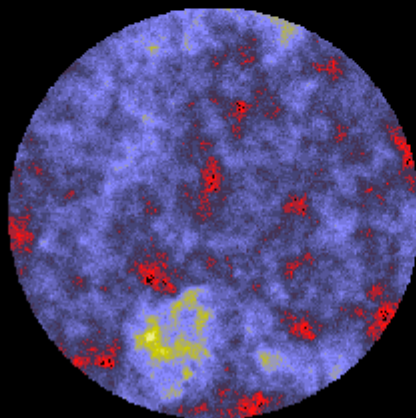
30 GHz



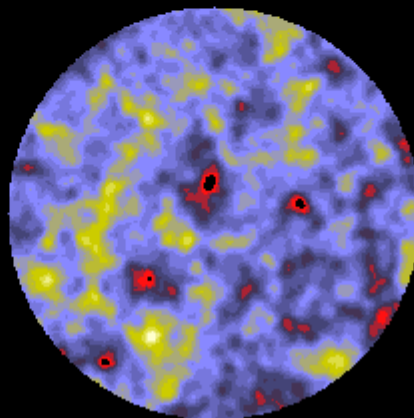
500 GHz



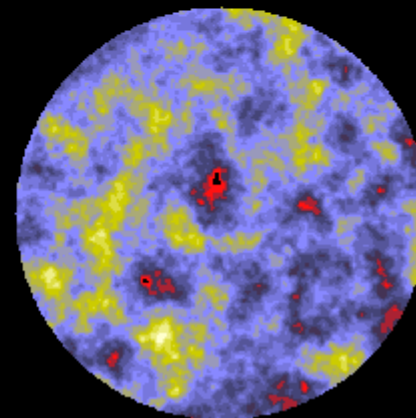
220 GHz



100 GHz

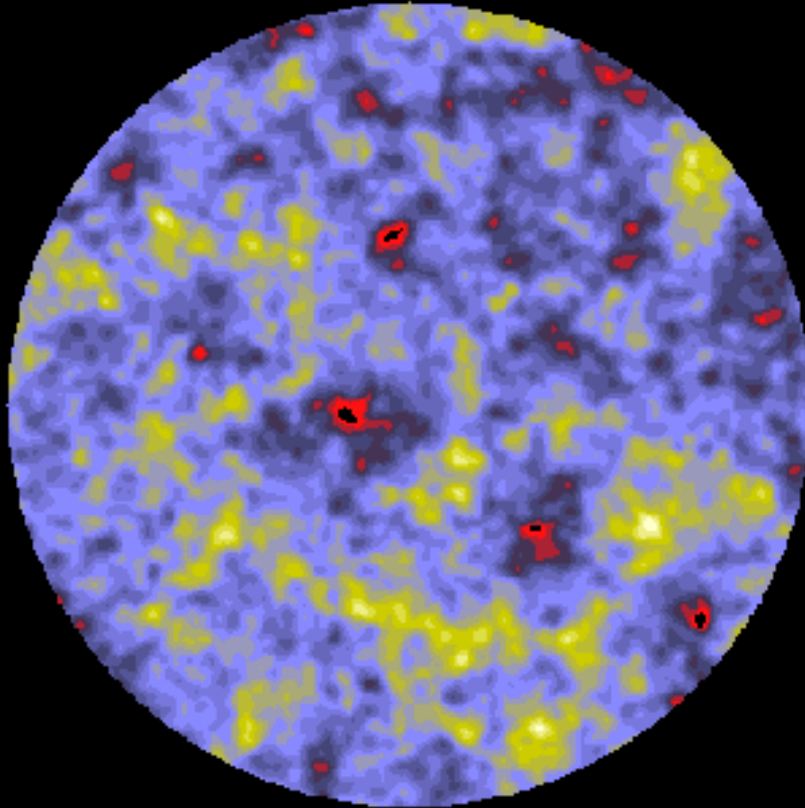


44 GHz

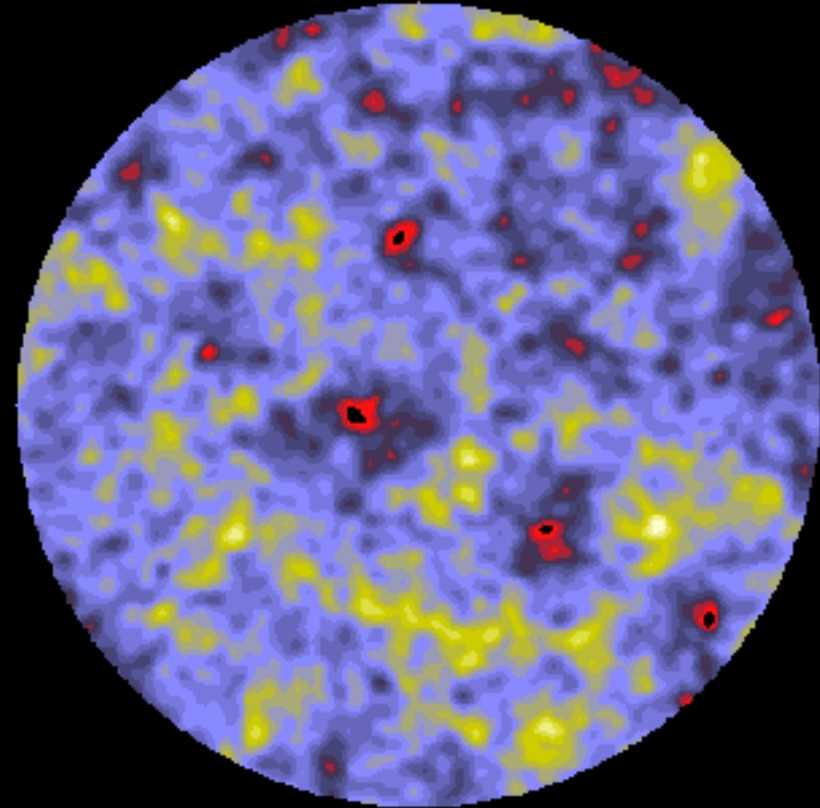


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CMB Input

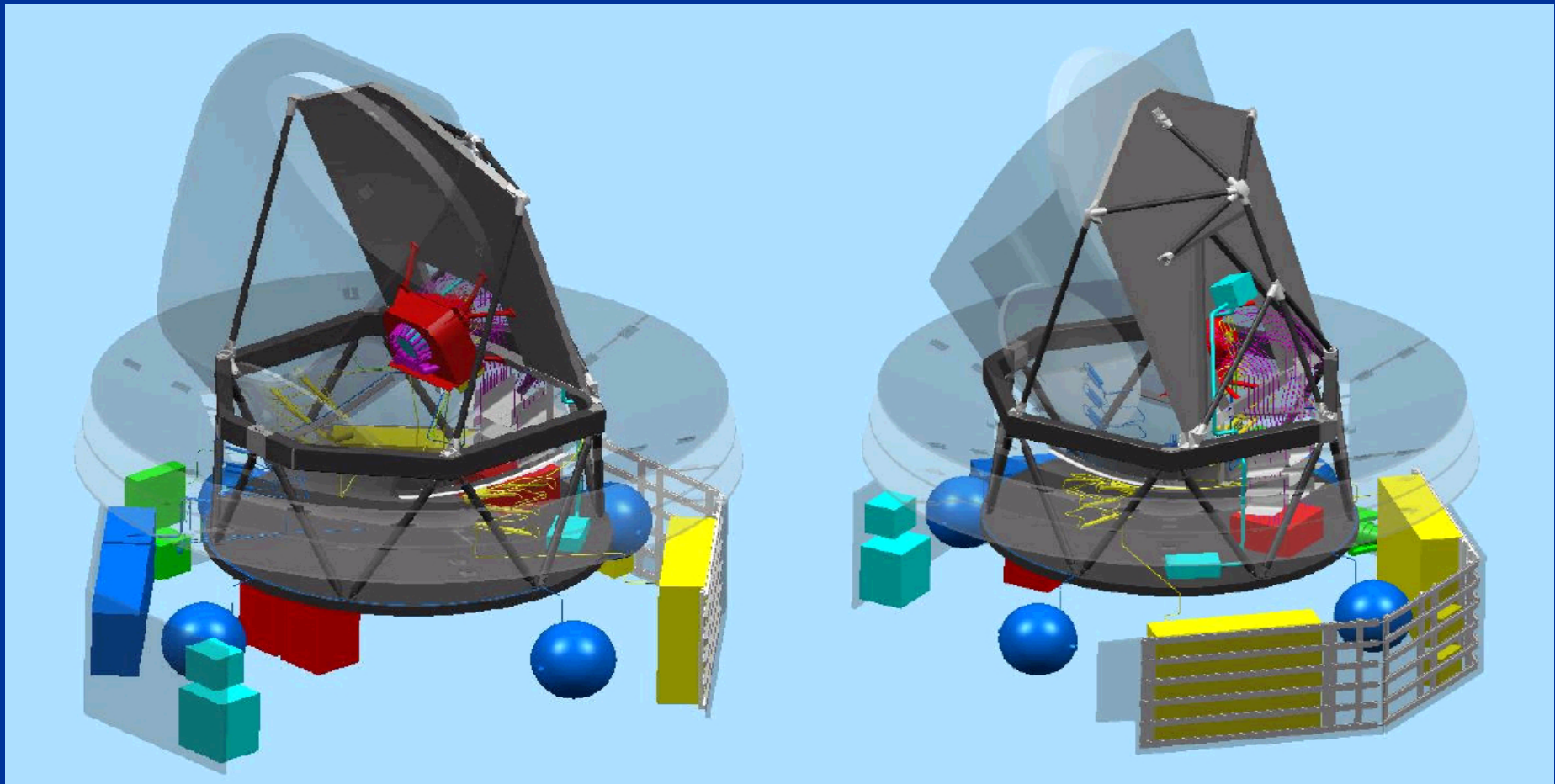


CMB Recovered



Not only statistical measure, but high signal-to-noise imaging

Planck Payload Module



- The spacecraft is “built around” the instruments & coolers
- Complex interfaces
- Thermal design main driver



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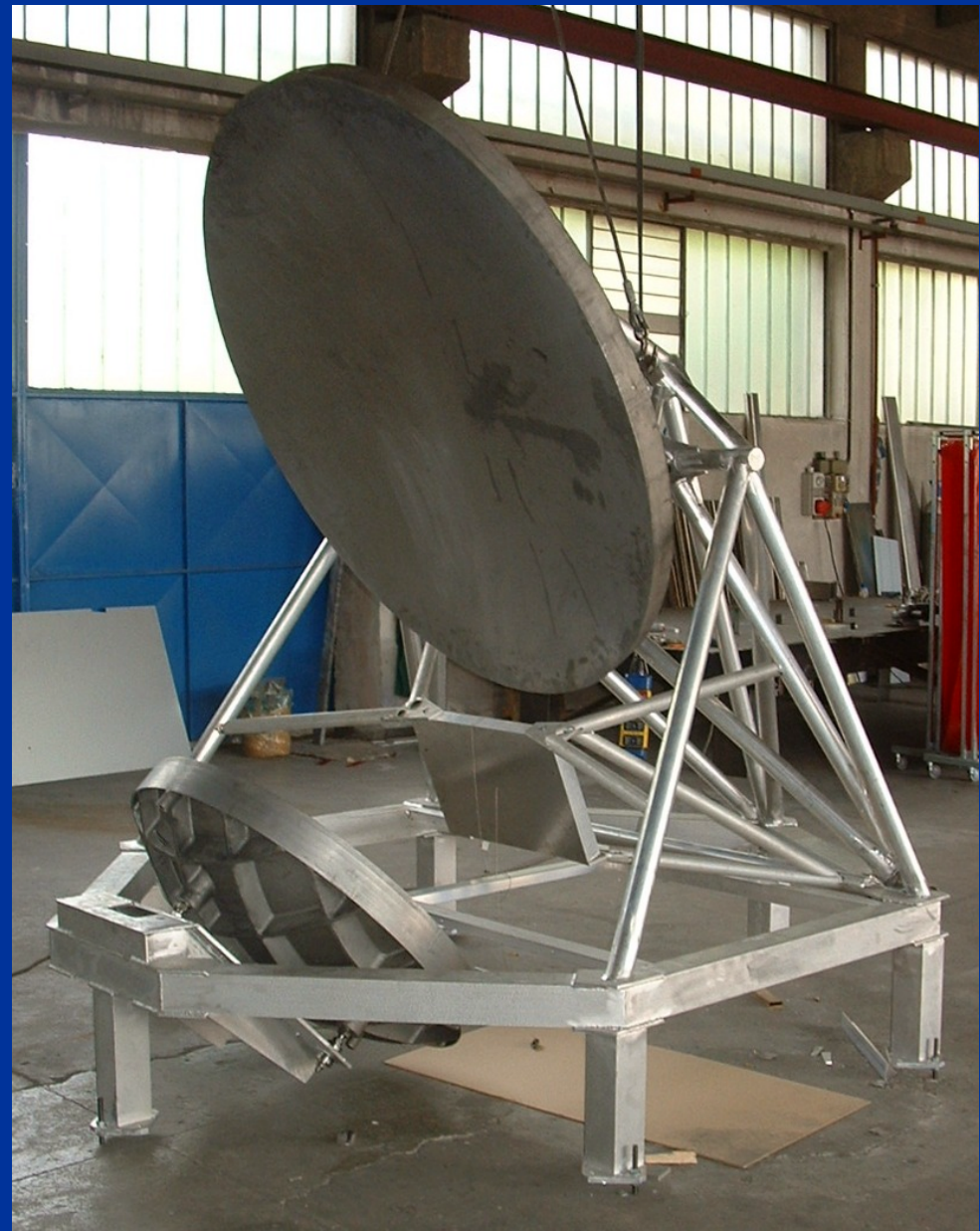
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The Planck telescope

- Gregorian Aplanatic Off-axis
- Primary mirror:
 - Ellissoidal, $\sim 1.9\text{m} \times 1.5\text{m}$
 - Projected Aperture: 1.5 m
- Sub-reflector:
 - Ellissoidal, $\sim 1\text{m} \times 1\text{m}$
- Focal ratio:
 - $F\# = 1.1$
- Field of view:
 - $\pm 5^\circ \times 5^\circ$
- Frequency coverage:
 - 27–900 GHz (LFI+HFI)



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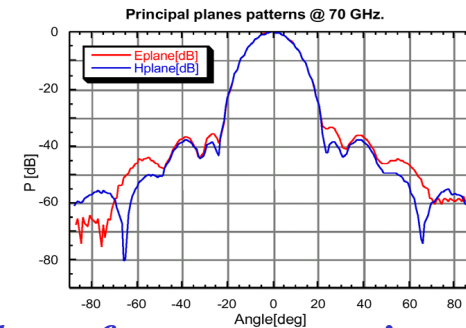
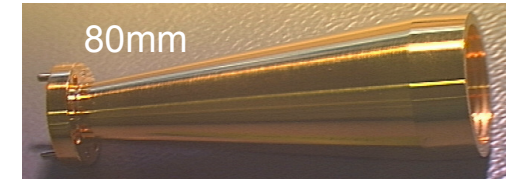
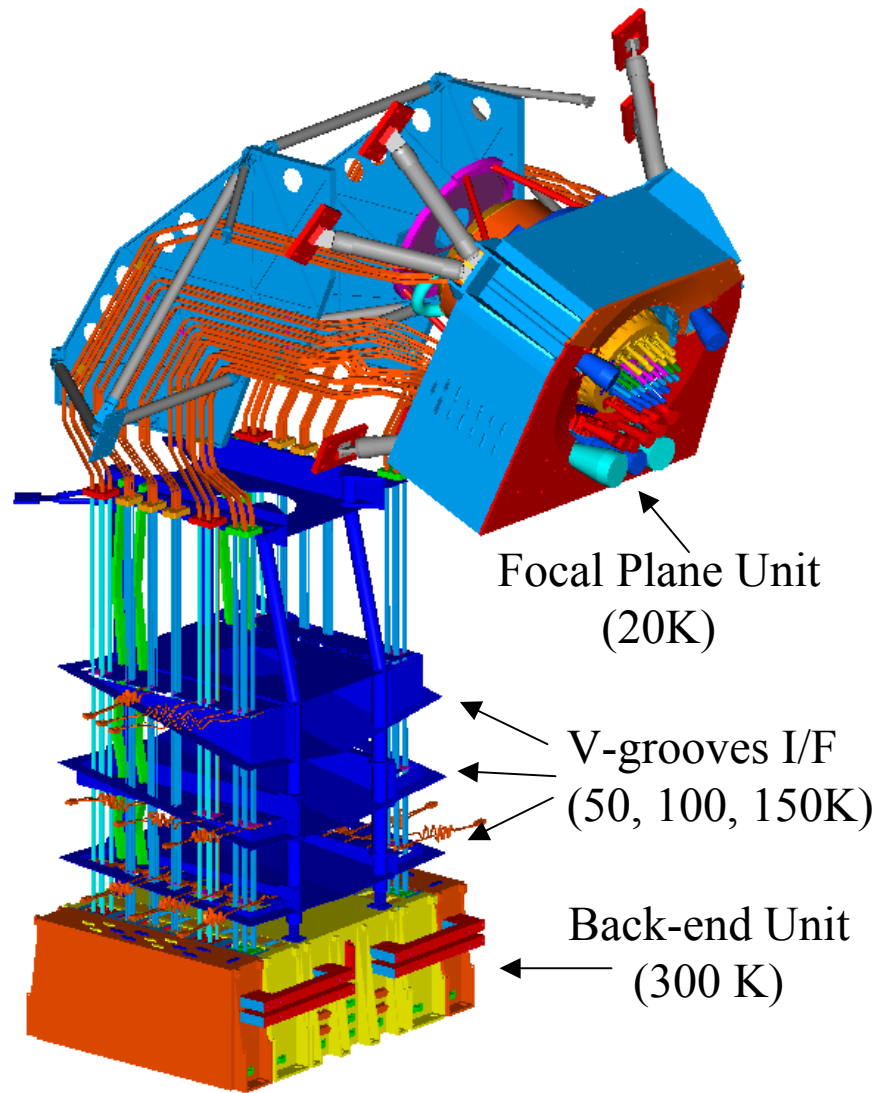
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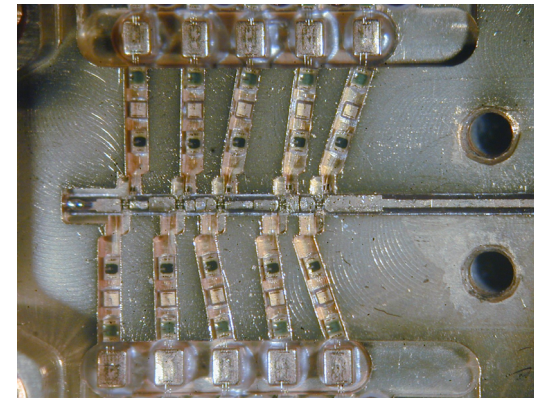


Low Frequency Instrument

27-77 GHz – pseudo-correlation receivers, 20K



High performance passive components



InP cryogenic HEMT LNA @ 44GHz



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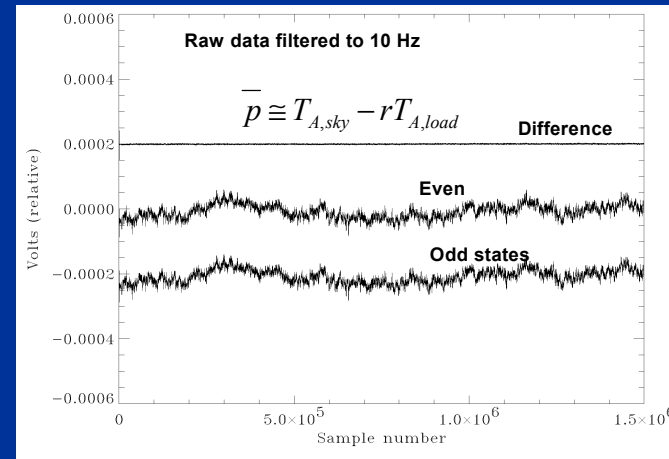
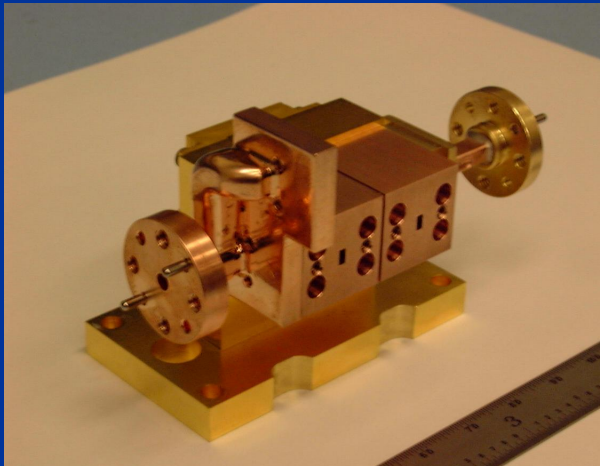
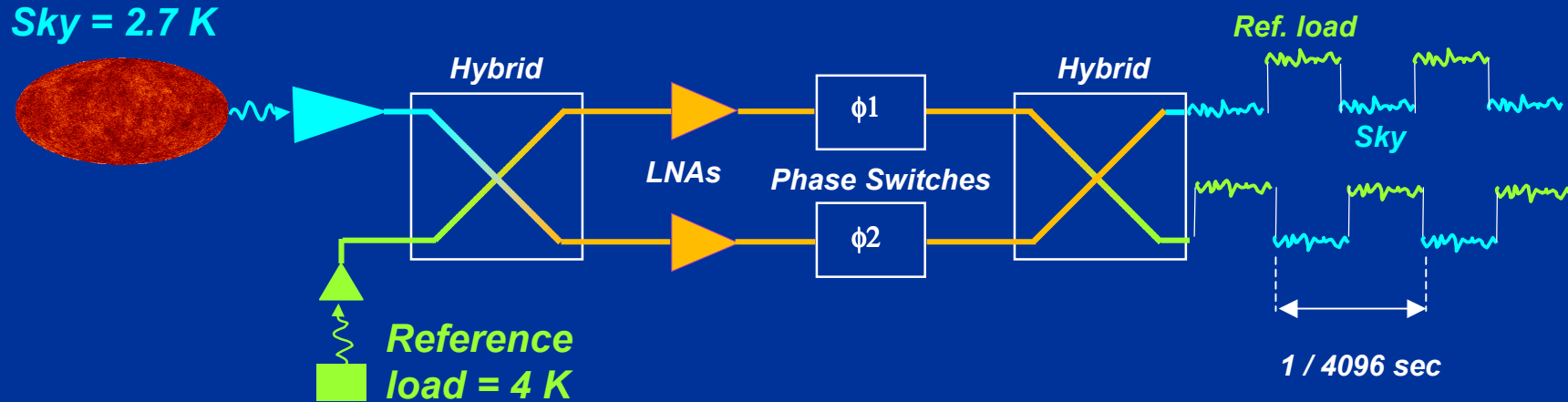
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LFI pseudo-correlation architecture

- Design to minimise 1/f noise impact
- Residual fluctuations are present



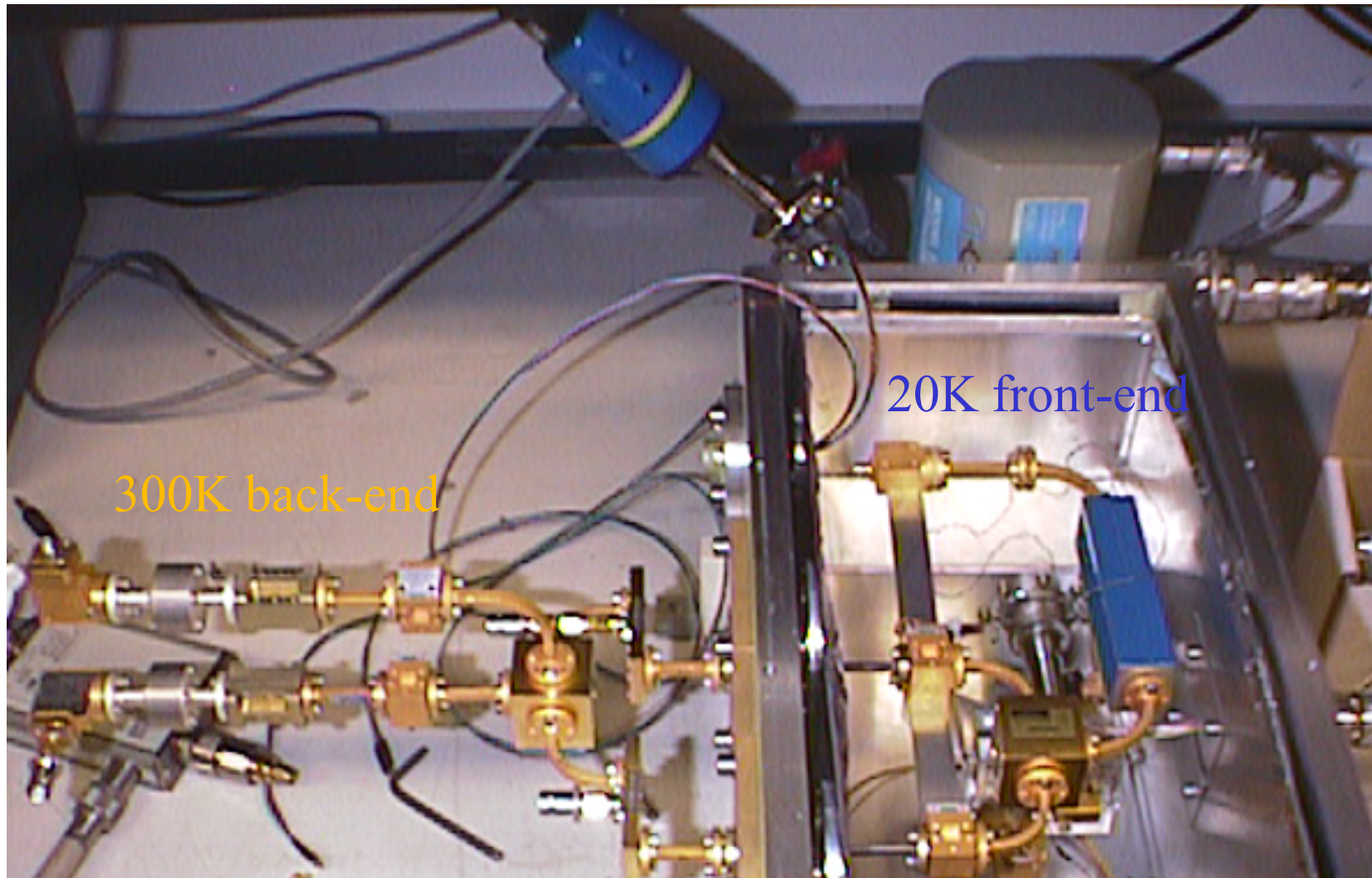
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“Prototype Demonstrator (PD)”



Picture of 70 GHz Prototype Demonstrator



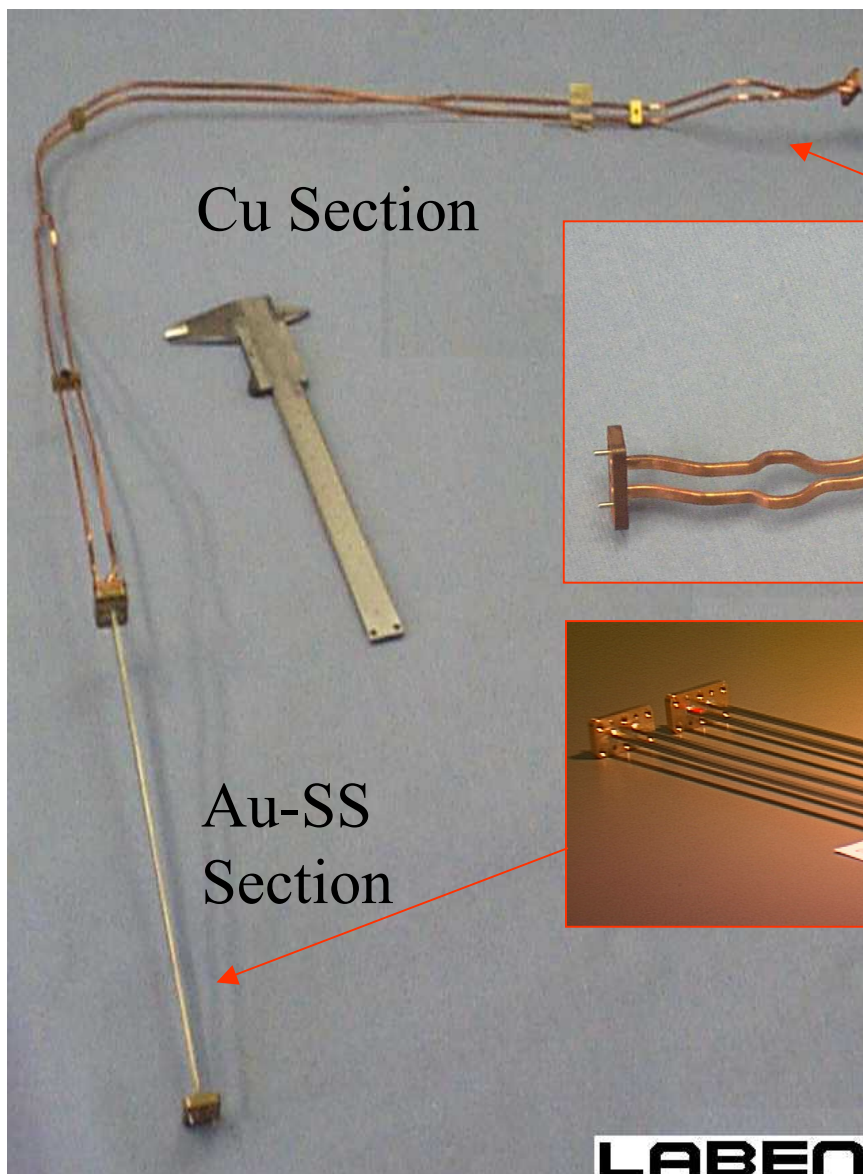
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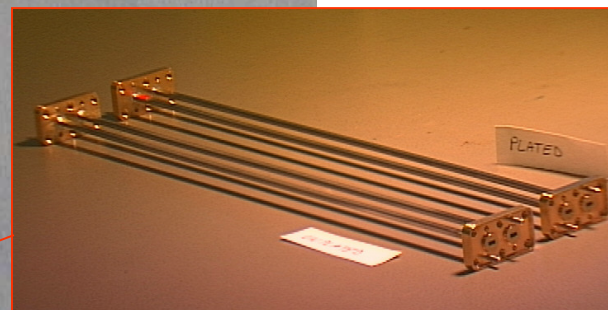
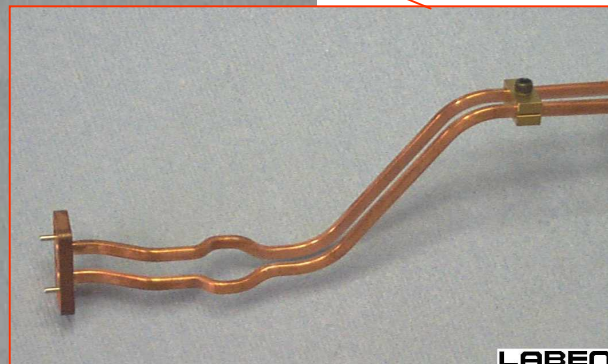


100 GHz Waveguide Prototype



Cu Section

Au-SS
Section



INSERTION LOSS (Room temperature)

	Calculated (dB/m)	Measured (dB/m)
Cu	2.5	2.5-3.0
SS	13.5	16.9
Gold-plated SS	2.9	3.7

RETURN LOSS (Room temperature)

	Measured (dB)	Notes
Cu	< -25	~ 1m long with bends and twists
SS	< -30	~ 23 cm long, straight
Gold-plated SS	< -30	~ 23 cm long, straight

Phase-matched pair
Preliminary tests @ JPL compliant w/ Req.'s
Prototype WG now at IFP-Milano



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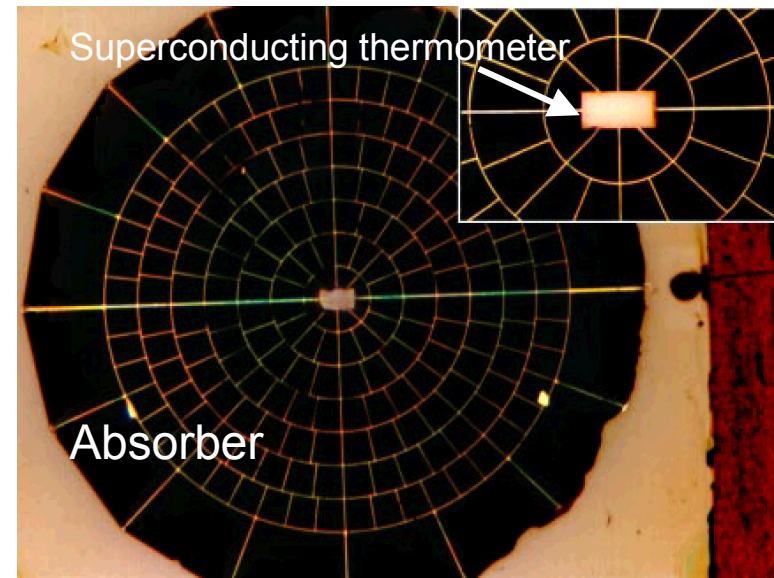
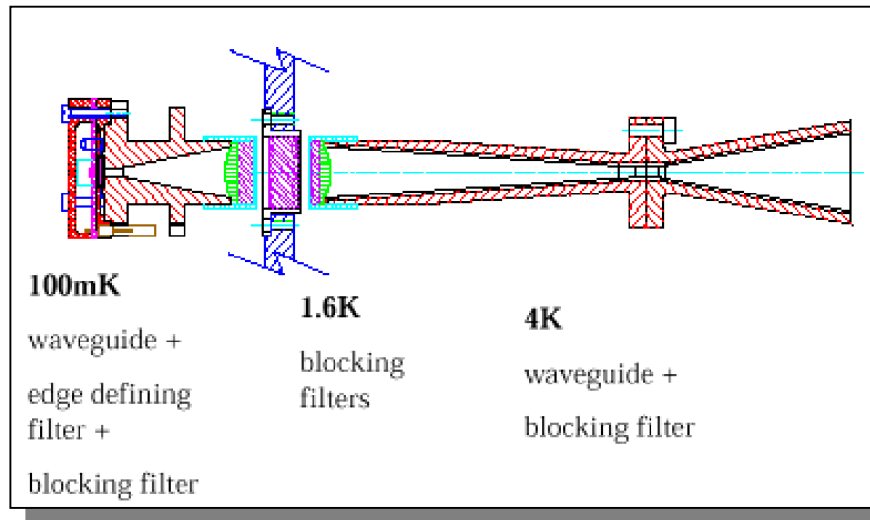
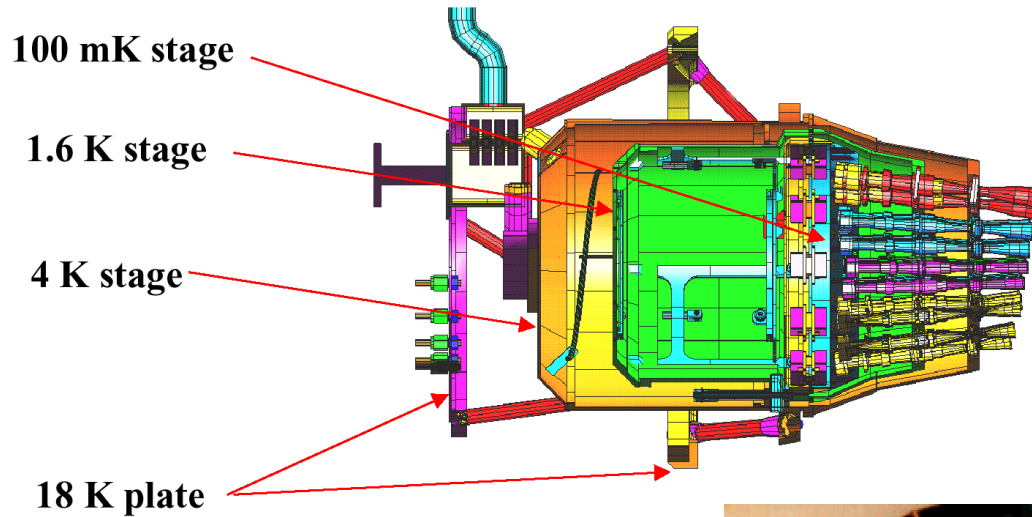
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High Frequency Instrument

90-870 GHz – Spider-web bolometers, 0.1K



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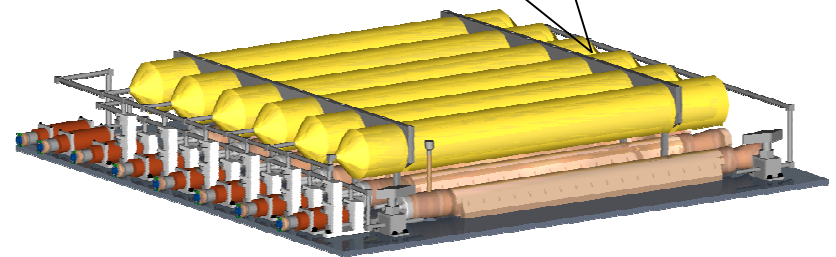
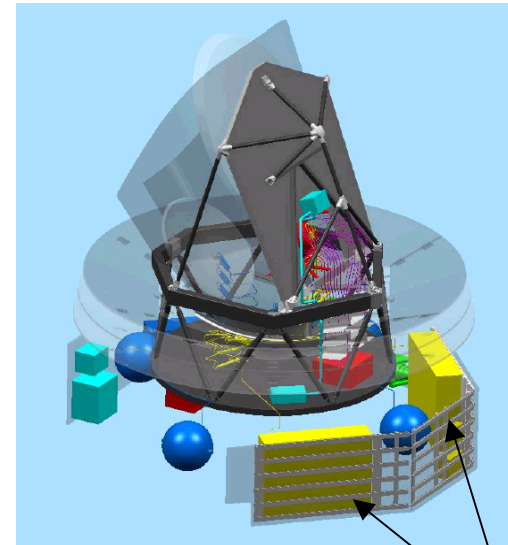
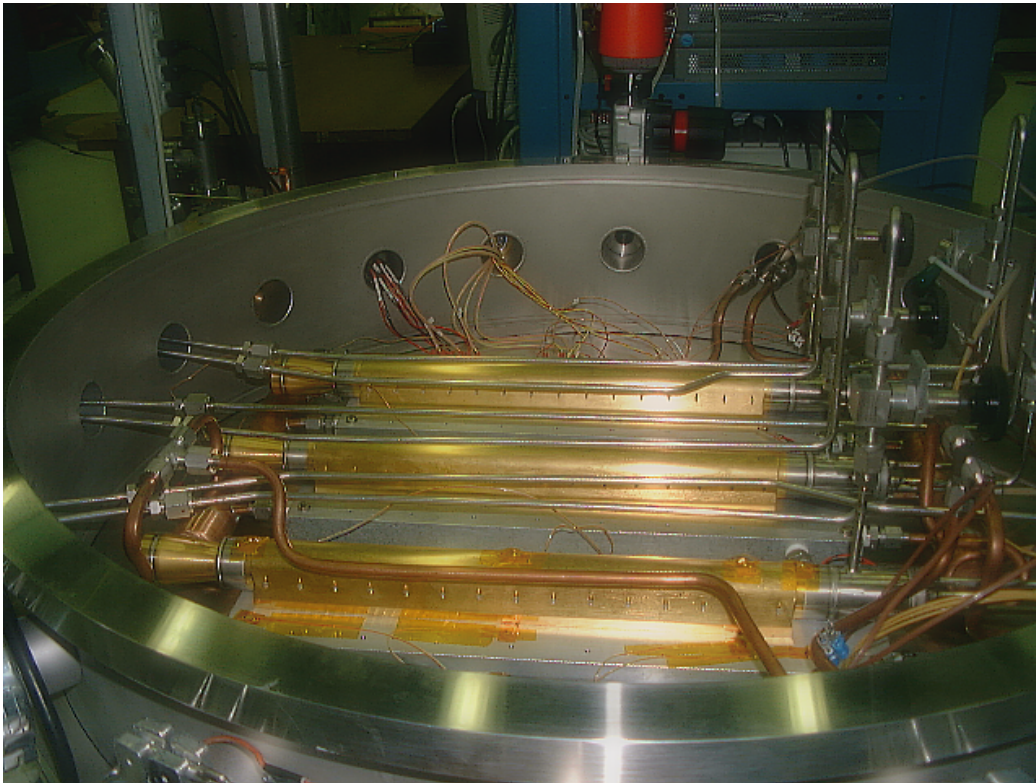
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20K Sorption Cooler

- Sorption cooler provides 18-20K stage to both Planck instruments
- Vibration-less operation exploiting hydride absorption of Hydrogen gas
- Temperature stability controlled to 20-30 mK at cold end
- NASA/JPL development



Compressors Assembly



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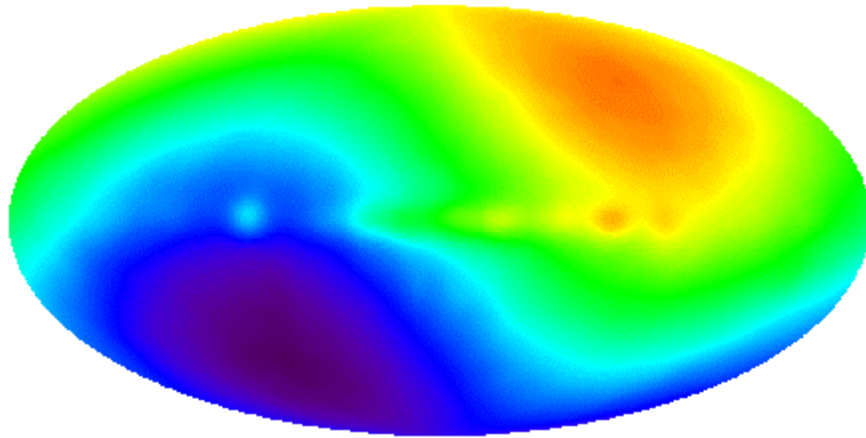


In-flight photometric calibration

CMB Dipole

$$\Delta T_{DIP} = T_0 \beta = 3.372 \pm 0.014 \text{ mK}$$

$$(l, b)_{DIP} = (264^\circ.14 \pm 0.15, 48^\circ.26 \pm 0.15)$$



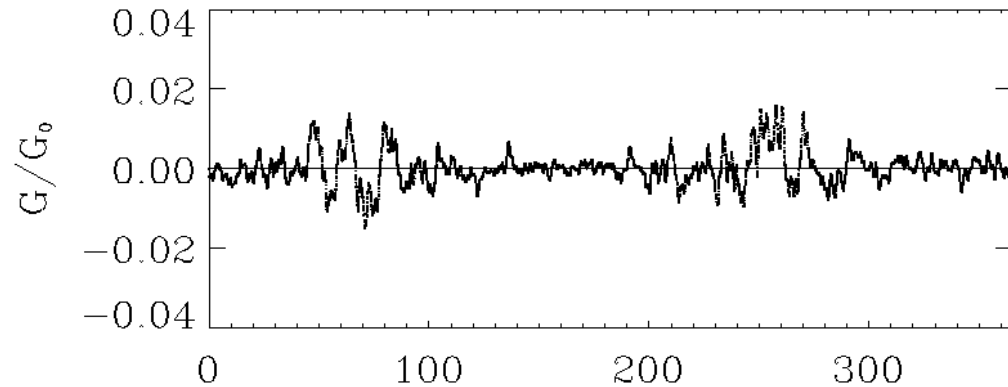
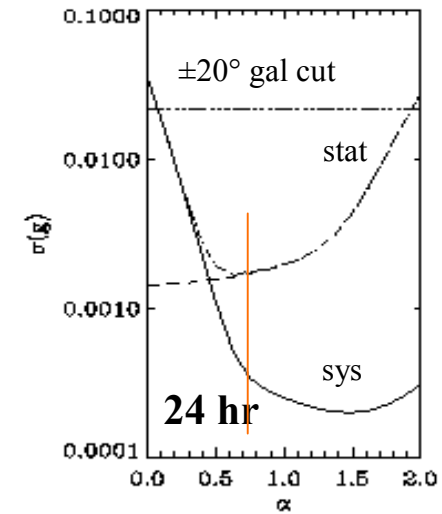
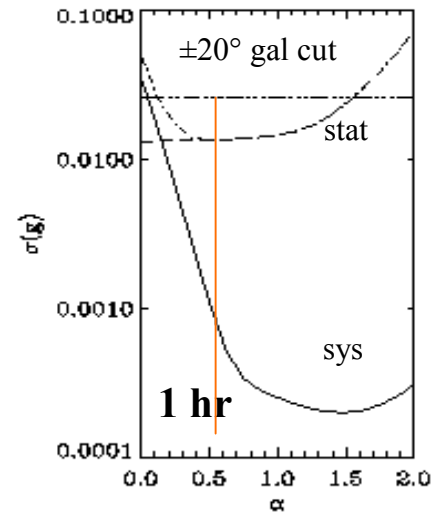
- Galactic emission
- HII Sources
- $\Delta T/T$ CMB
- (Instrument Systematics)

→ Fit with an optimised weight function:

$$W(\sigma_{T_i}) = \frac{1}{(\sigma_{T_i}/\sigma_0)^\alpha}, \quad \alpha \in \mathbb{R}$$

→ Best final absolute calibration using S/C motion: 0.2%

Required accuracy: 1%



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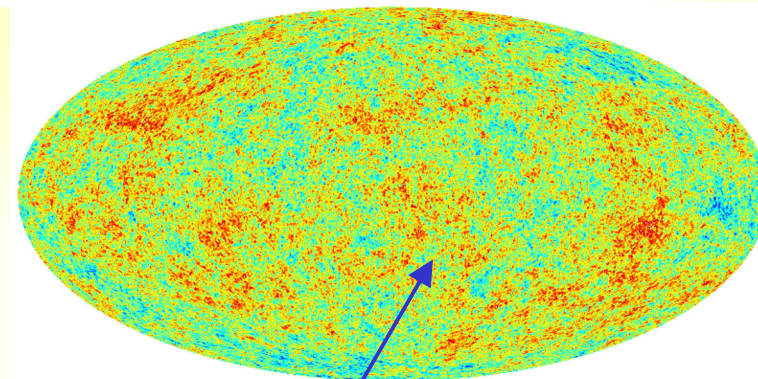
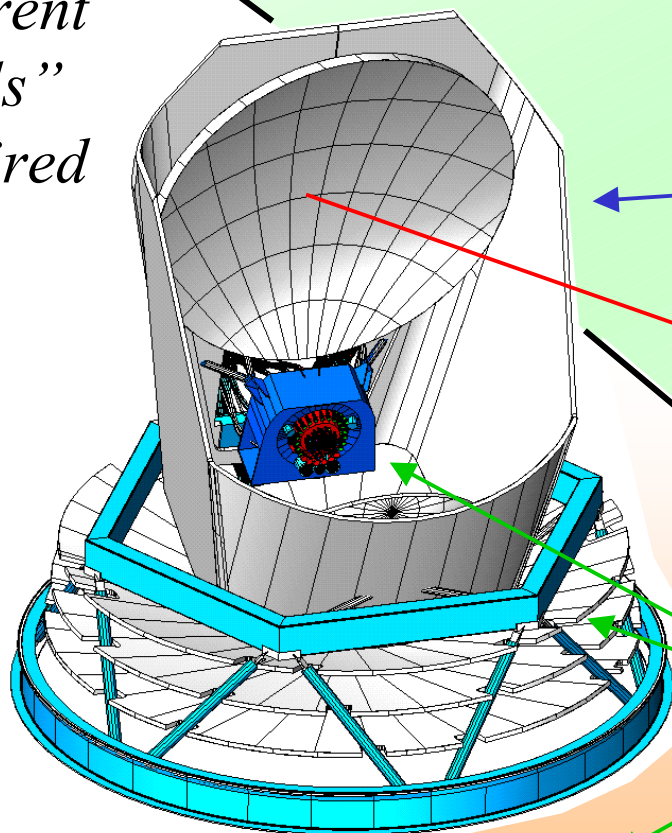
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PLANCK Systematics: First-level Breakdown

- *Different “tools” required*



a

Effects due to combination of (instrument beams) + (sky):

- External straylight
- Main beam reconstruction

b

Pointing uncertainties

c

Effects generated within the satellite:

- Instrument-specific non-idealities
- Thermal effects from the satellite
- Internal straylight



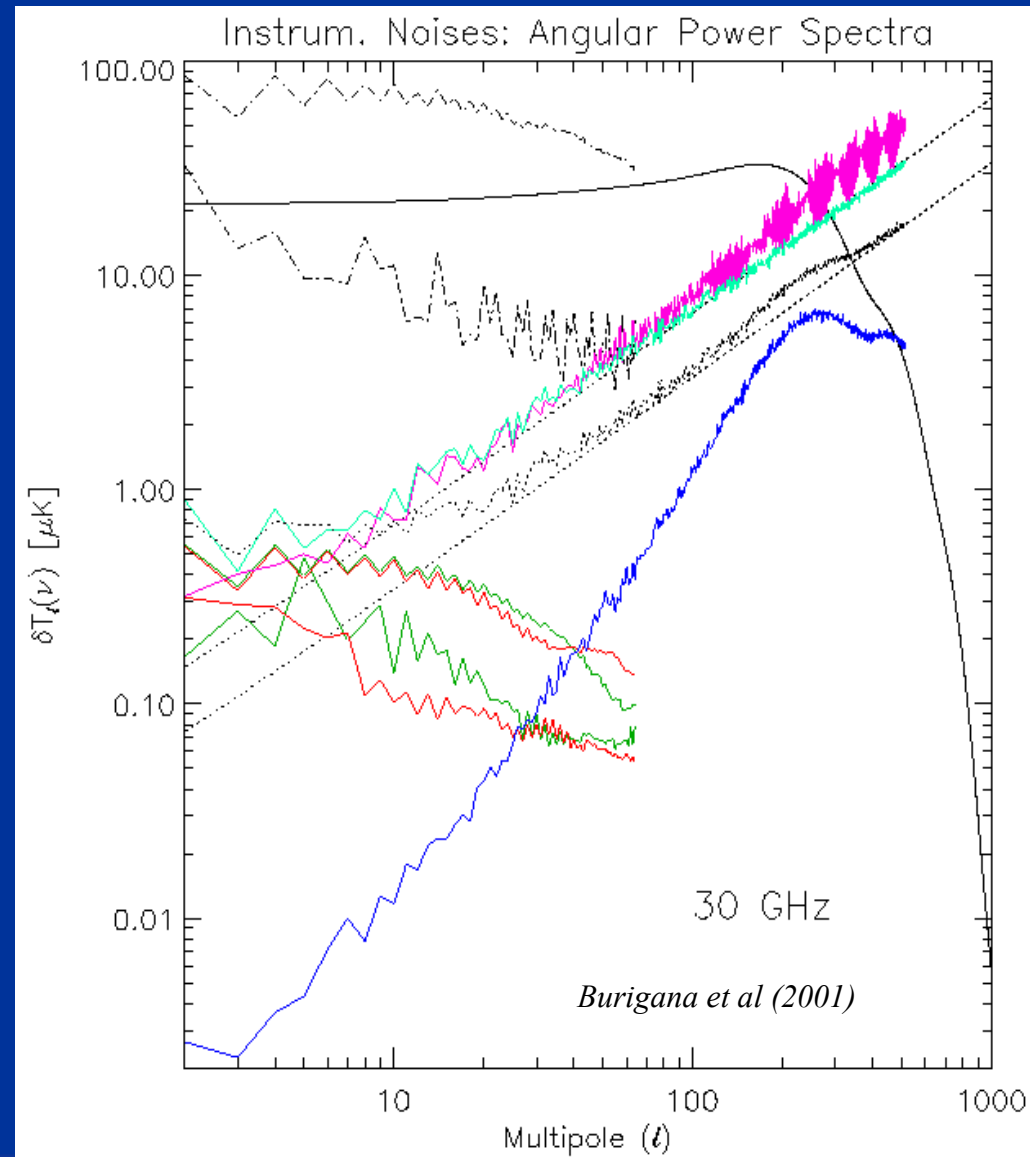
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Systematic effects evaluation



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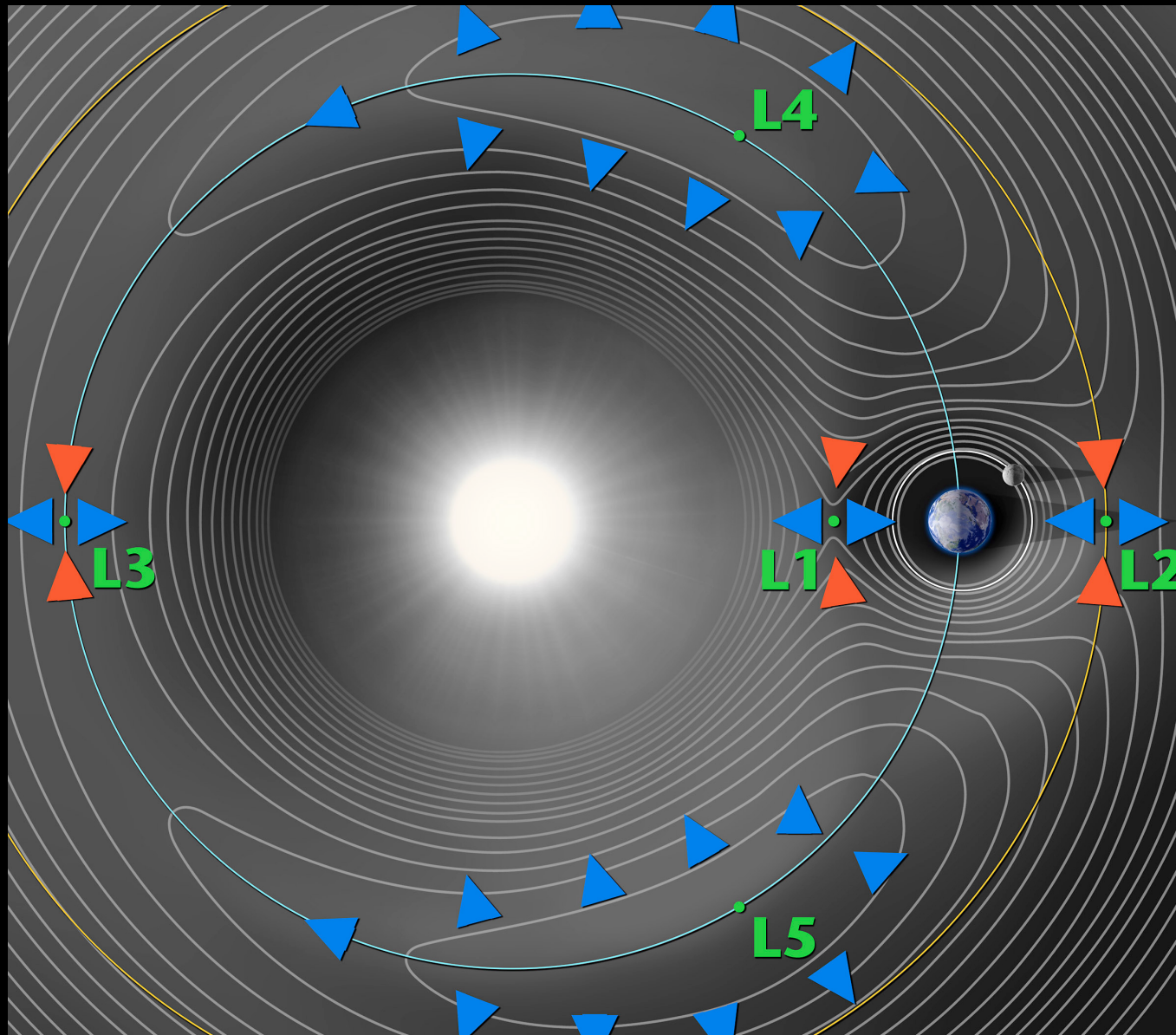
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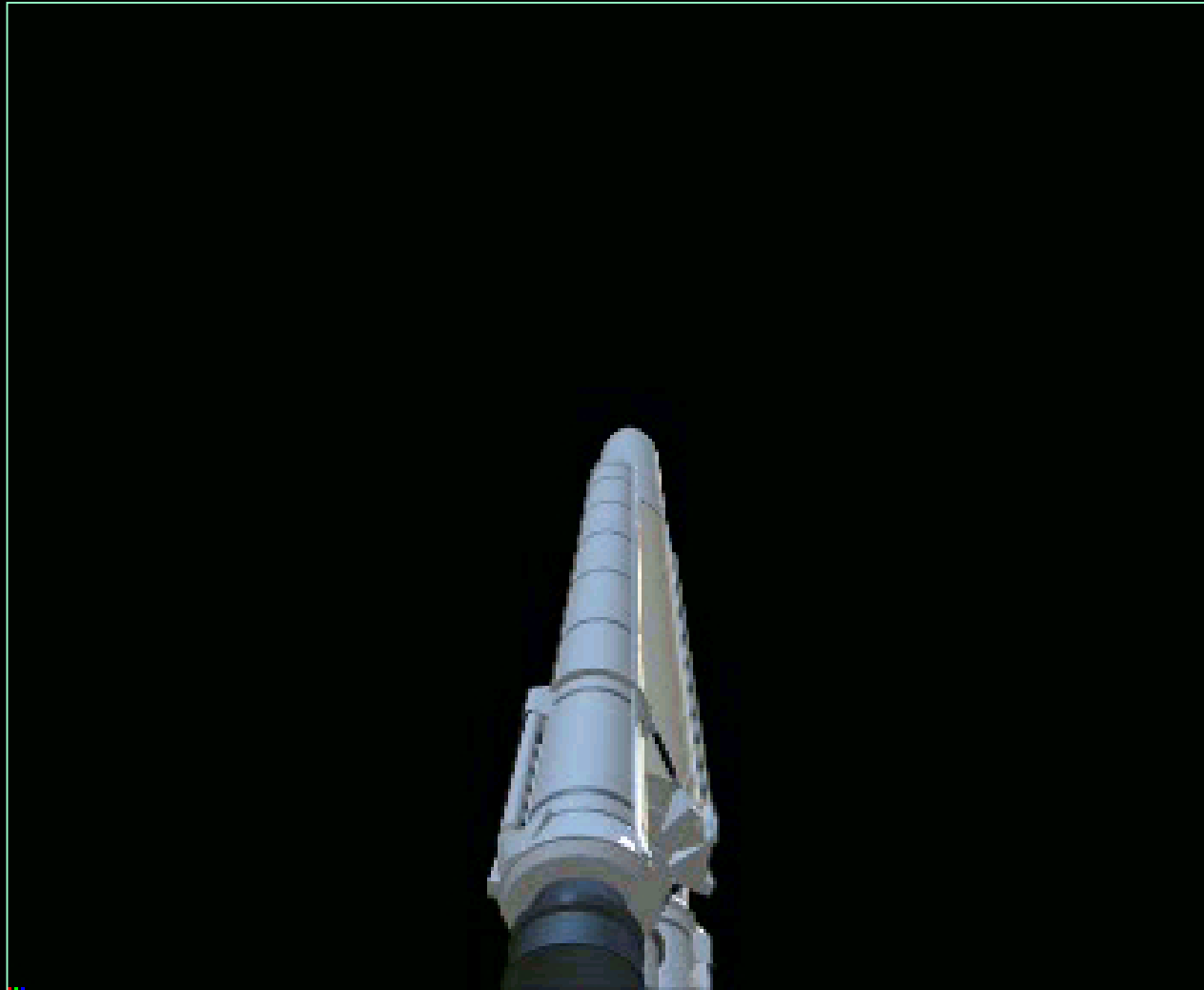
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Sun-Earth L2 Orbits

MAP – PLANCK – HERSCHEL – NGST





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