Observational Cosmology

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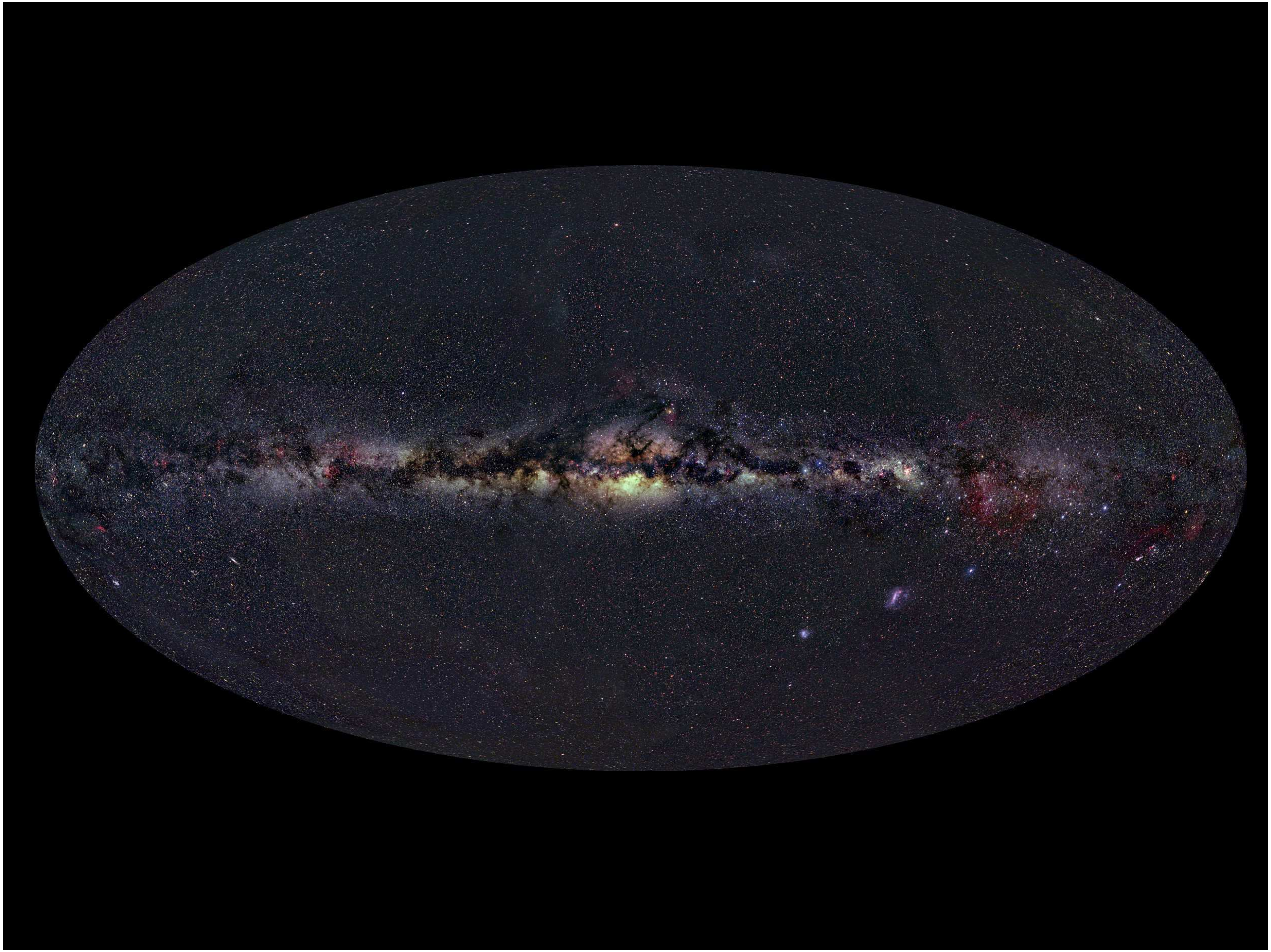
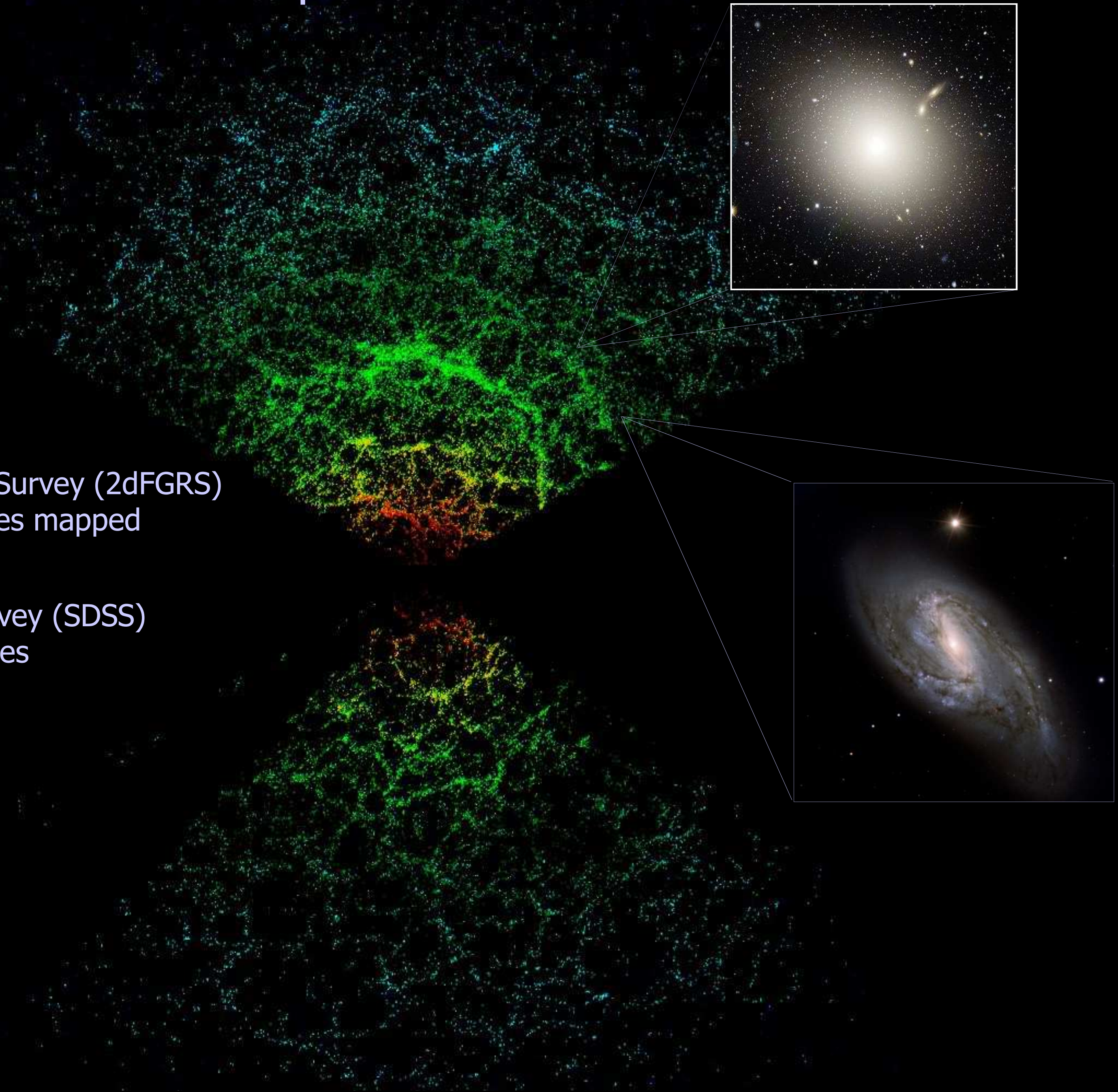


3D Map of the Universe



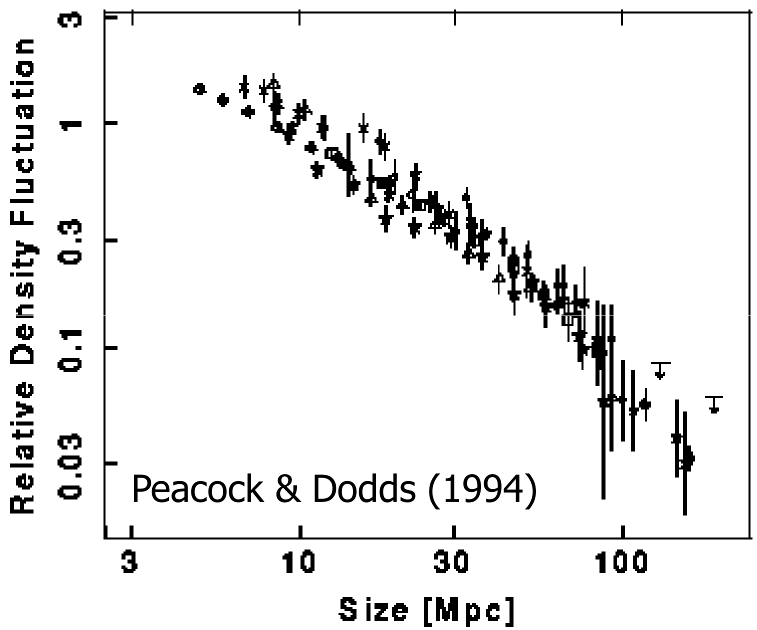
2dF Galaxy Redshift Survey (2dFGRS)
Goal: 250,000 galaxies mapped

Sloan Digital Sky Survey (SDSS)
Goal: 1 million galaxies
100,000 QSO

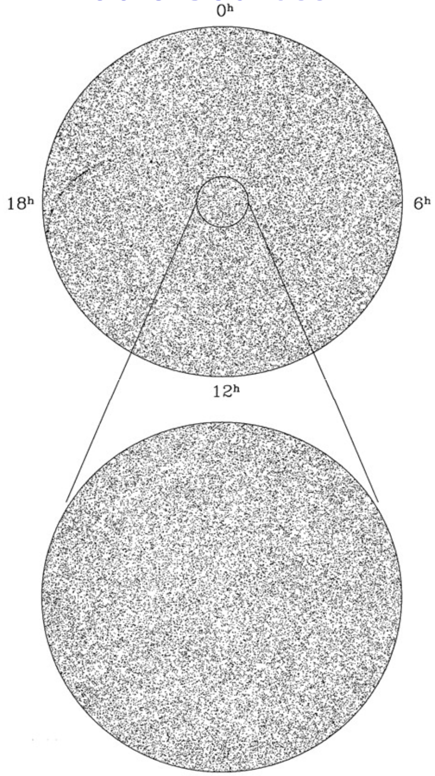
Observational evidence of isotropy (& homogeneity?)

"Cosmological principle"

Large scale distribution of galaxies

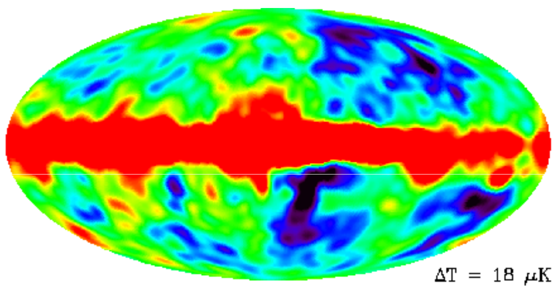


Extragalactic Radio Sources



Cosmic microwave background

COBE-DMR – Smoot et al (1992)



At scales >100 Mpc the universe appears isotropic within few percent

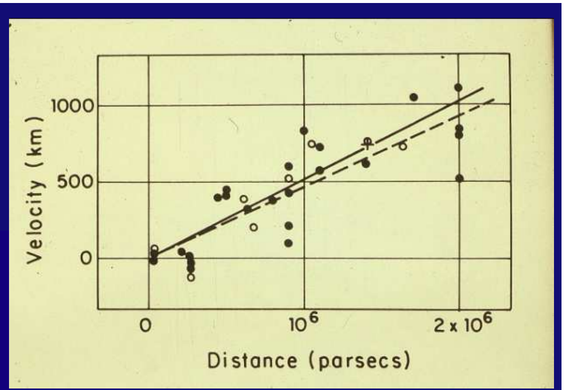
CMB provides very stringent confirmation, at level $\sim 10^{-5}$ at $z \sim 10^3$

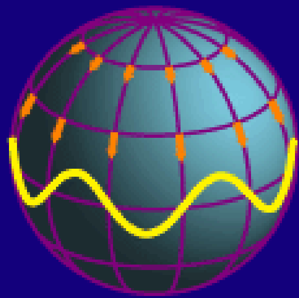
Cosmic expansion

Edwin Hubble - 1929

$$v_r = H_0 \cdot d$$

$$1 + z \equiv \frac{\lambda_{Observed}}{\lambda_{Emitted}} = \frac{R(t_{Observed})}{R(t_{Emitted})}$$





$$\lambda_1 = \frac{R_1}{R_E} \lambda_E$$

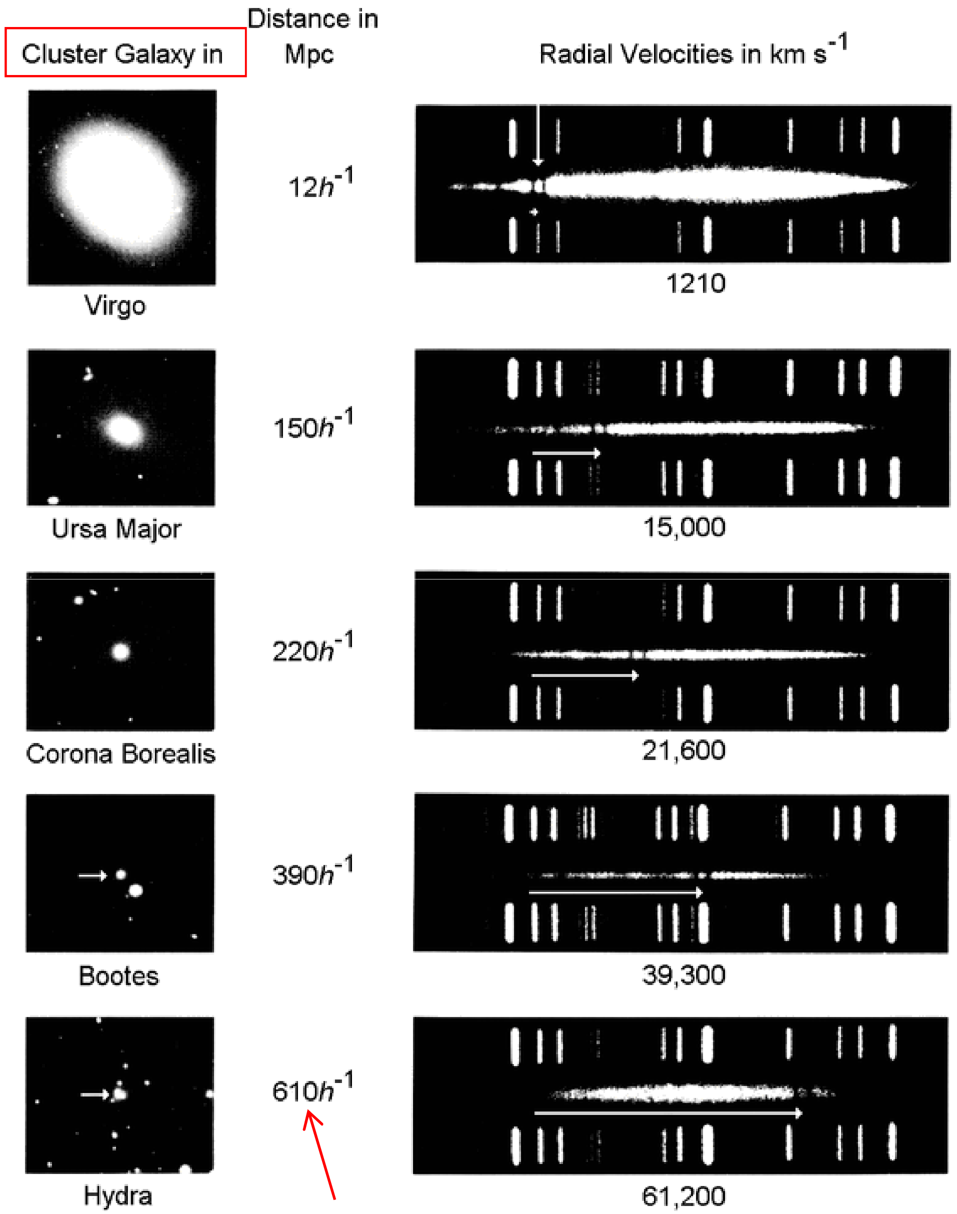
$$\lambda_2 = \frac{R_2}{R_E} \lambda_E$$

$$\lambda_3 = \frac{R_3}{R_E} \lambda_E$$

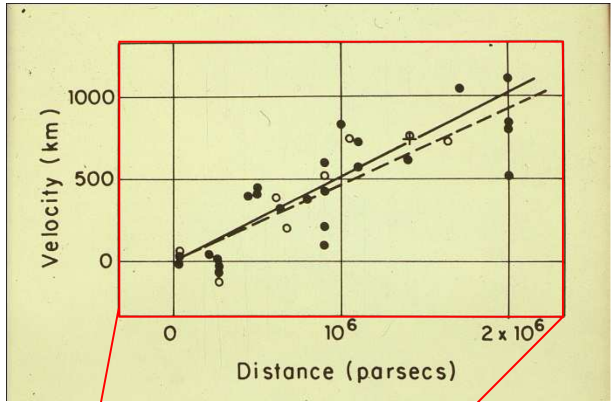
The expansion of space stratches the wavelength of light

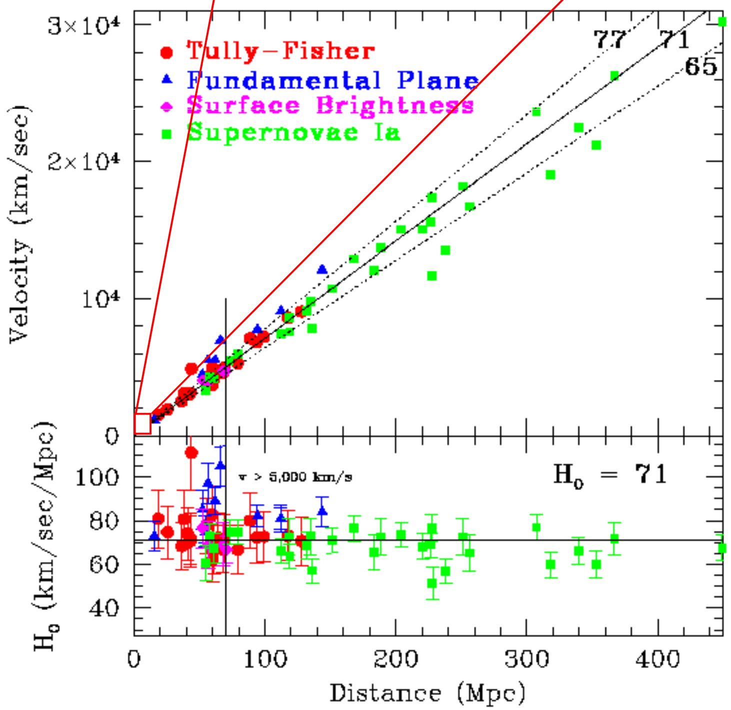
The early universe was chatacterised by high temperature and high density

Cosmic expansion

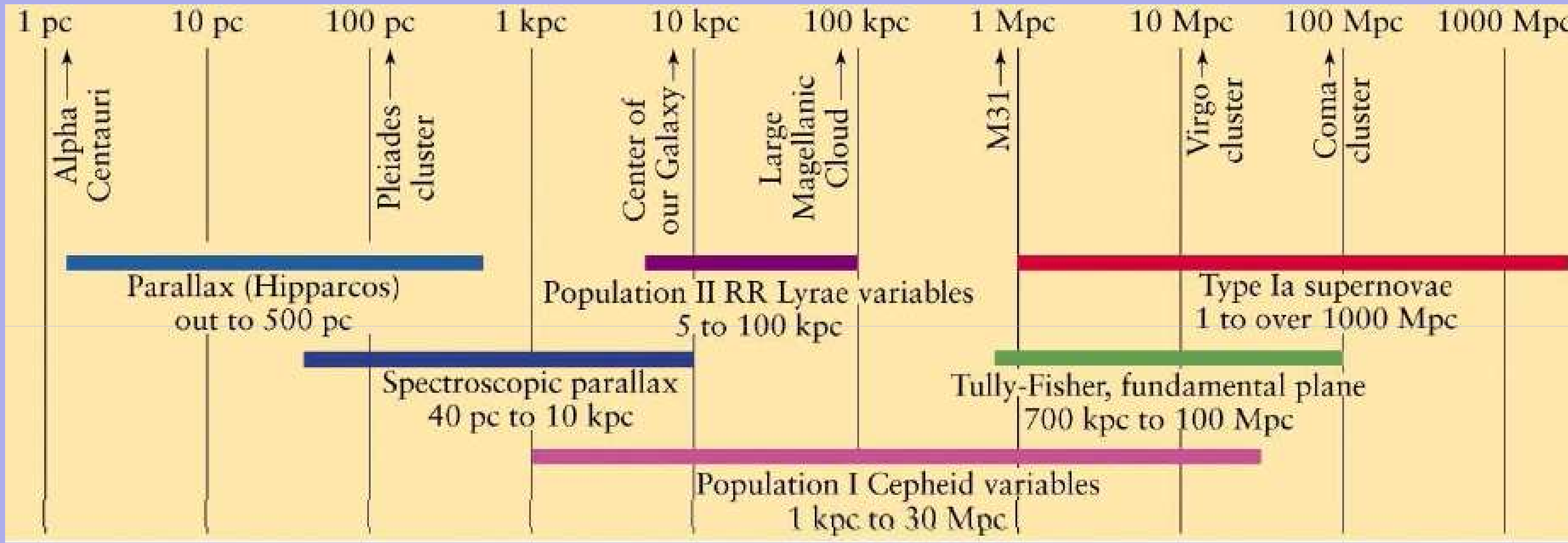


Distance: Brightest galaxy in cluster





The Cosmic Distance Ladder



Standard candles

$$l = \frac{L_0}{4\pi d^2}$$

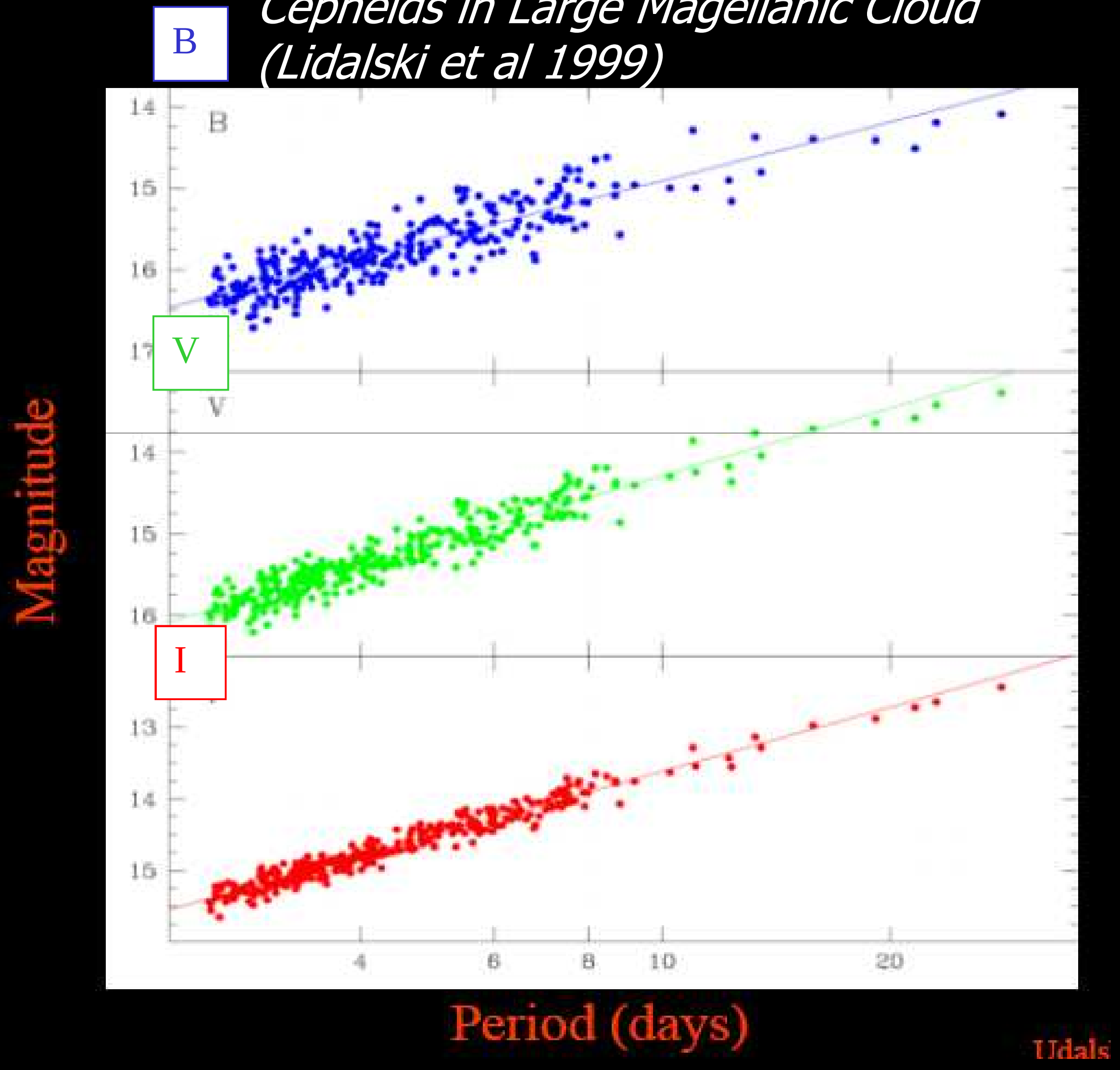
Standard rods

$$\theta = \frac{r_0}{d}$$

Cepheids as distance indicators

• Variable (pulsating) stars with well defined relation between period and luminosity

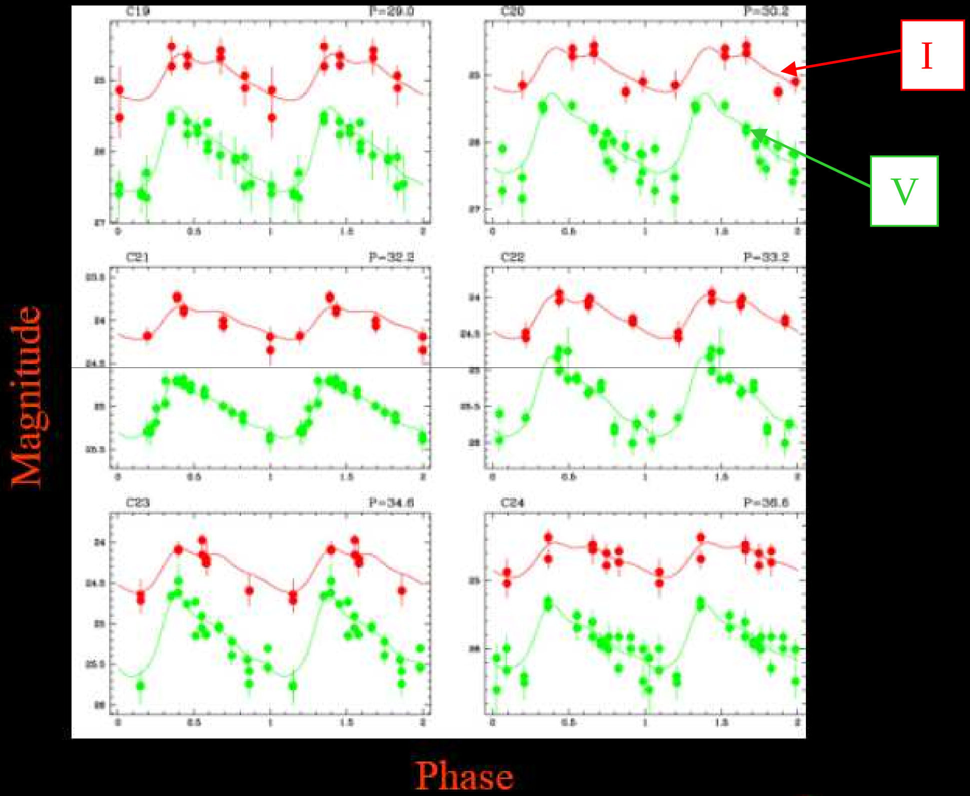
Cepheids in Large Magellanic Cloud (Lidalski et al 1999)

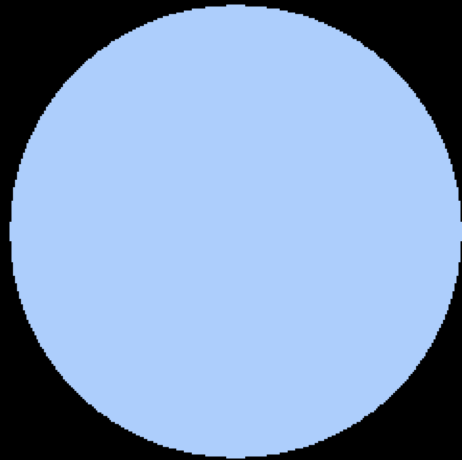


Cepheids as distance indicators

- HST WFPC2 can determine Cepheid distances out to 20 Mpc

Representative light curves of distant Cepheids





Period-luminosity relation must be calibrated by observing Cepheids in some object with a distance known by other techniques

→ Potential sources of systematic uncertainty

→ Hipparcos measurements

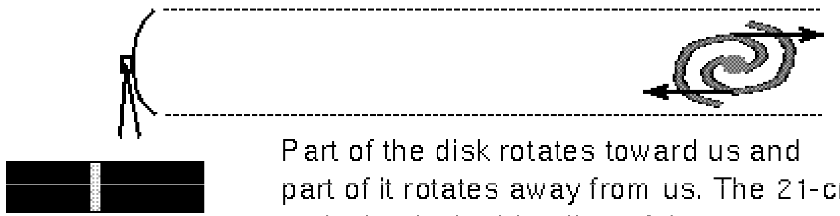
Galaxies as distance indicators

"Luminosity – Linewidth relation"

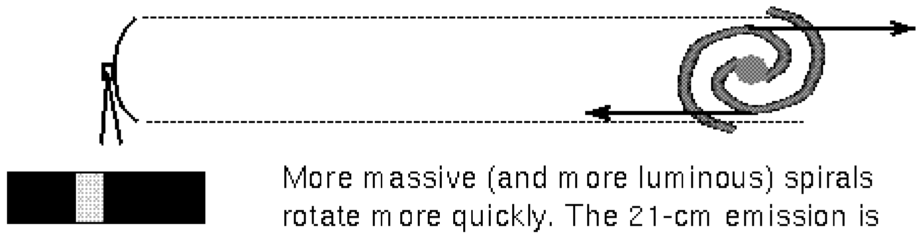
• 1977: Tully & Fisher find (empirically) correlation between lumonisity and rotational velocity of spiral galaxies

Velocity is an indicator of its mass, thus of its luminosity

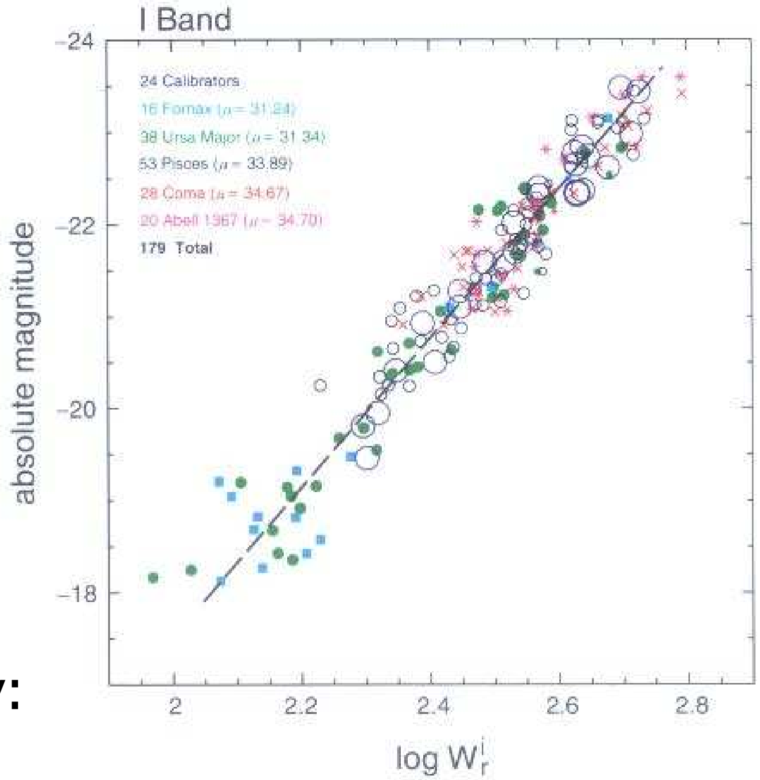
$\Delta v_{20} =$ Velocity width λ = 21 cm (neutral H) at 20% of the peak power.



Part of the disk rotates toward us and part of it rotates away from us. The 21-cm emission is the blending of the individual lines.



More massive (and more luminous) spirals rotate more quickly. The 21-cm emission is broader.



The relationship is found approximately:

$$L \propto (\Delta v_{20})^{\beta} \qquad \beta \approx 4$$

Similarly for elliptical galaxies: luminosity vs velocity dispersion (Faber-Jackson)

Galaxies as distance indicators

The basis of Faber-Jackson and Tully-Fisher relations

Four measurable properties of galaxies:

$$I = l/\theta^2 \qquad \theta = R/d \qquad l = L/4\pi d^2 \qquad v^2 \approx GM/R \quad \text{(Virial theorem)}$$

Surface brightness (I); Angular size (θ); Apparent luminosity (l); Velocity dispersion (v)

$$I = l/\theta^2 = \frac{1}{\theta^2}\frac{L}{4\pi d^2} = \frac{L}{4\pi R^2} = \frac{Lv^4}{4\pi G^2 M^2}$$

Independent of the distance

$$= \frac{v^4}{4\pi G^2 (M/L)^2}\frac{1}{L}$$

$$L = \frac{v^4}{I}\frac{1}{4\pi G^2 (M/L)^2} \propto I^{-1} v^4$$

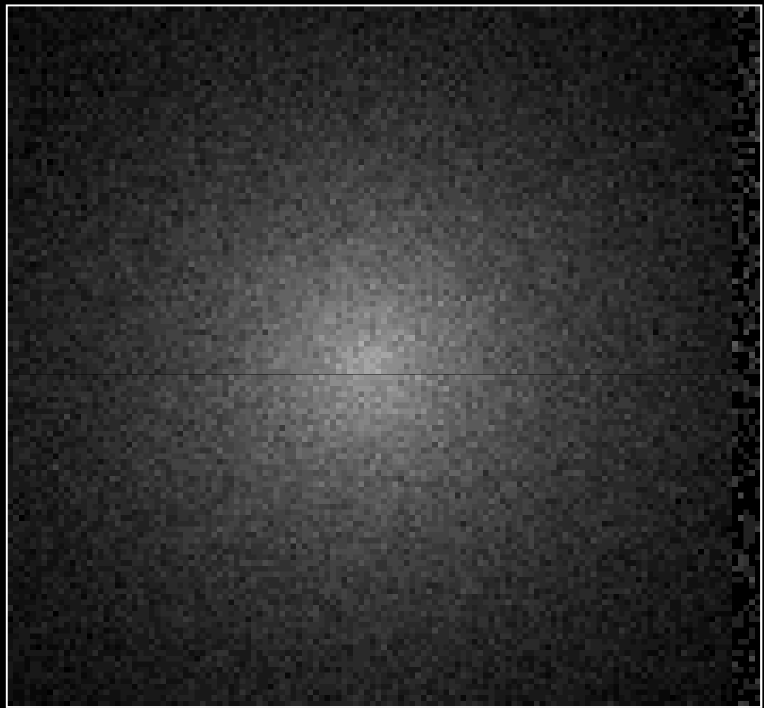
Empirical finding:

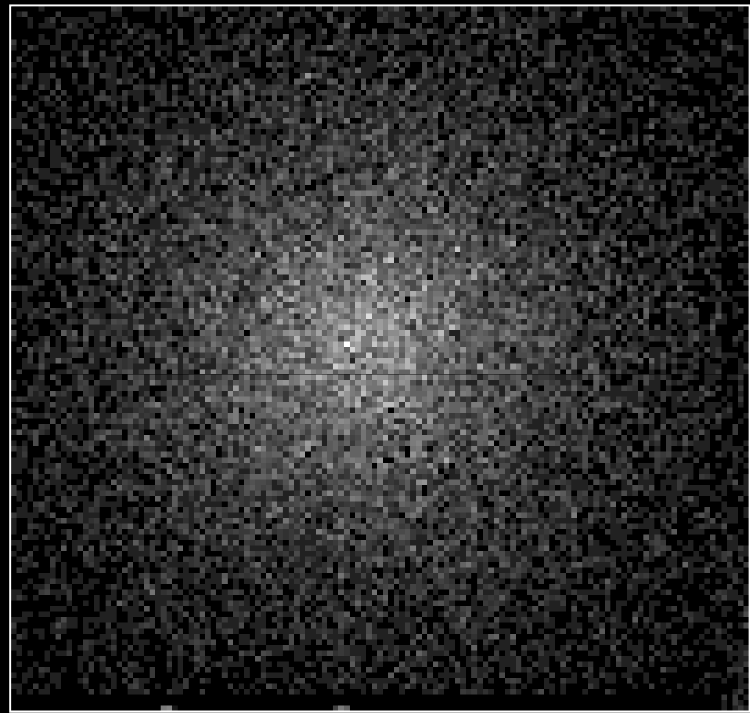
$$L \propto I_0^x \sigma_v^y \approx I_0^{-0.7} \sigma_v^{3.5}$$

Typical values of mass-to-light ratio (galaxies):

$$\left\langle \frac{M}{L} \right\rangle \approx k_s \frac{M_{Sun}}{L_{Sun}}, \qquad k_s \approx 30 - 70$$

Which galaxy is more distant?



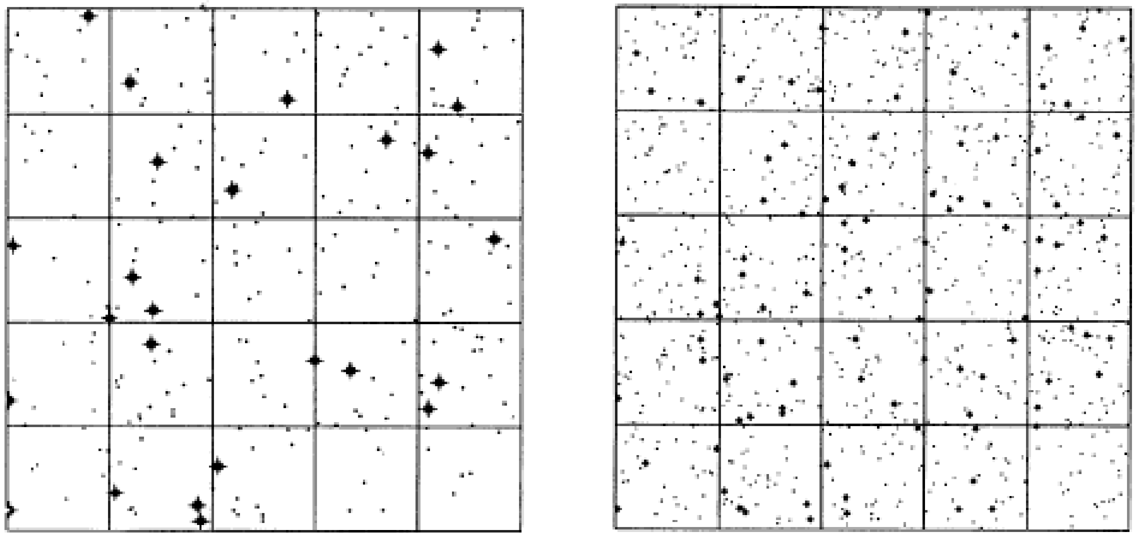


“Surface Brightness Fluctuations”

Measure of fluctuations of the surface brightness in the image of elliptical galaxies

These fluctuations reflect the statistics in the count of number of stars in each resolution element of detector (e.g. CCD)

Tonry and Schneider (1988)



SBF effect – Images taken by CCD of two galaxies with same apparent luminosity, one twice further away as the other

If there are on average N stars per pixel, then we expect fluctuations between pixels of order $N^{-1/2}$

$$\sigma_L \propto \frac{1}{\sqrt{N}}$$

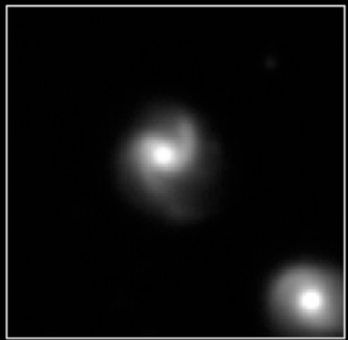
$$\sigma_L^2 \propto \frac{1}{N} \propto \frac{1}{L_{pixel}} \propto \frac{1}{d^2}$$

for a given angular size

$$\sigma_L \propto 1/d$$

Measuring expansion

Reference image

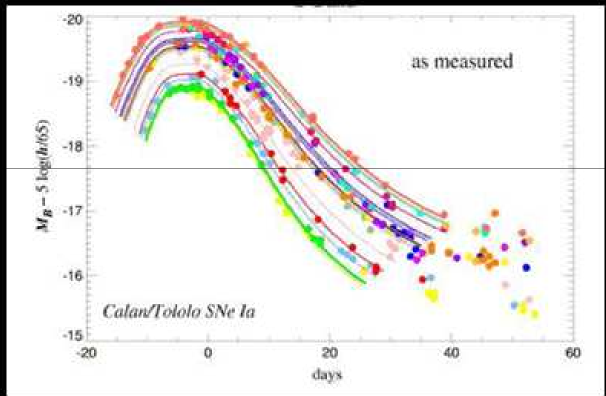


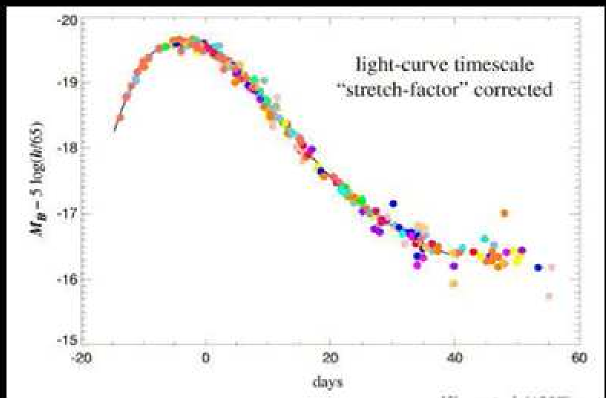
SN event

Subtraction image

Type Ia supernovae

Chandrasekhar limit ($M = 1.44\ M_{sun}$) reached by white dwarf in binary systems





Peak absolute luminosity relatively constant

$$M_{peak} \approx -19.5$$

$$\Delta M \approx 0.5$$

Residual magnitude dispersion after applying "Stretch factor correction":

$$\sigma_M < 0.1\,\mathrm{mag}$$

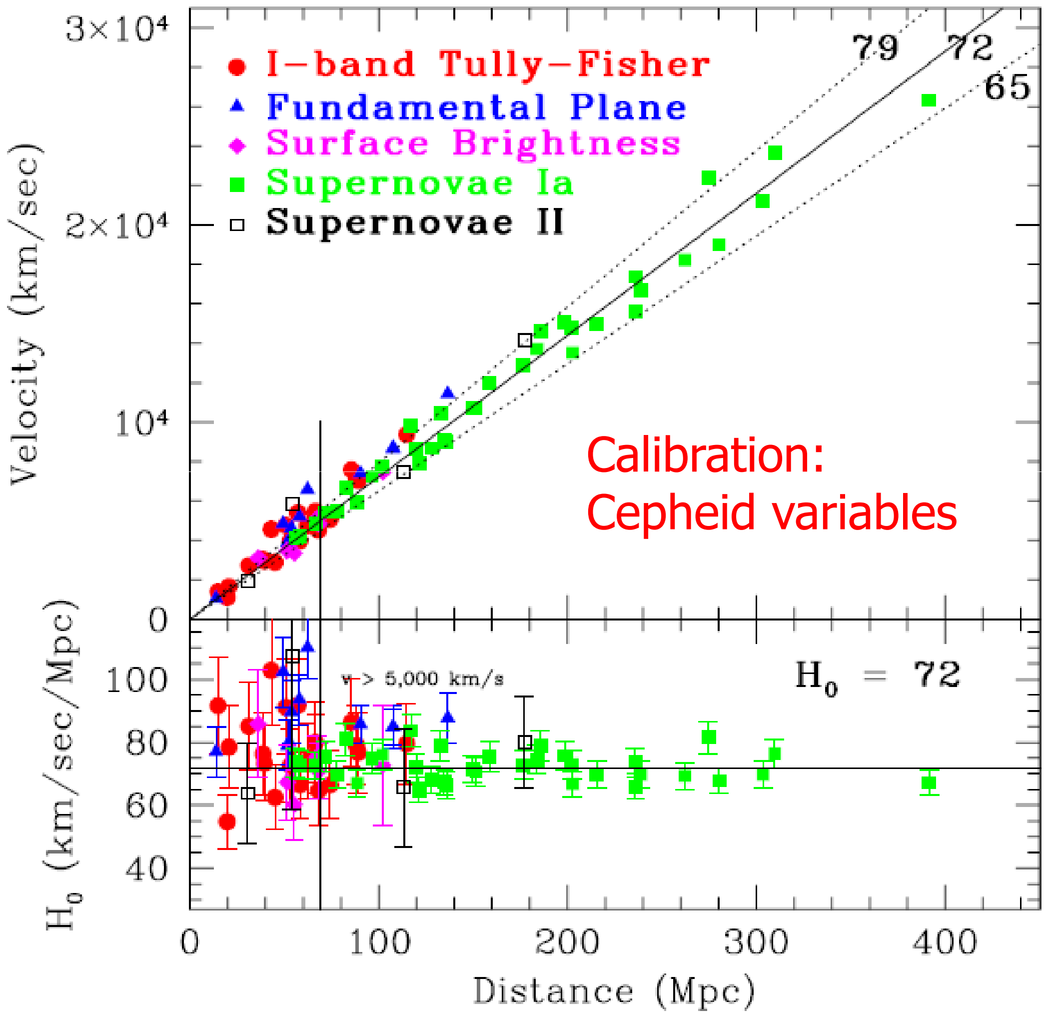
Empirical relationship:

$$M_{peak} \approx 0.8 \cdot (\Delta m_{15} - 1.1) - 19.5$$

Systematic effects?

Measuring expansion

Hubble diagram– HST key programme



Calibration:
Cepheid variables

Measuring expansion

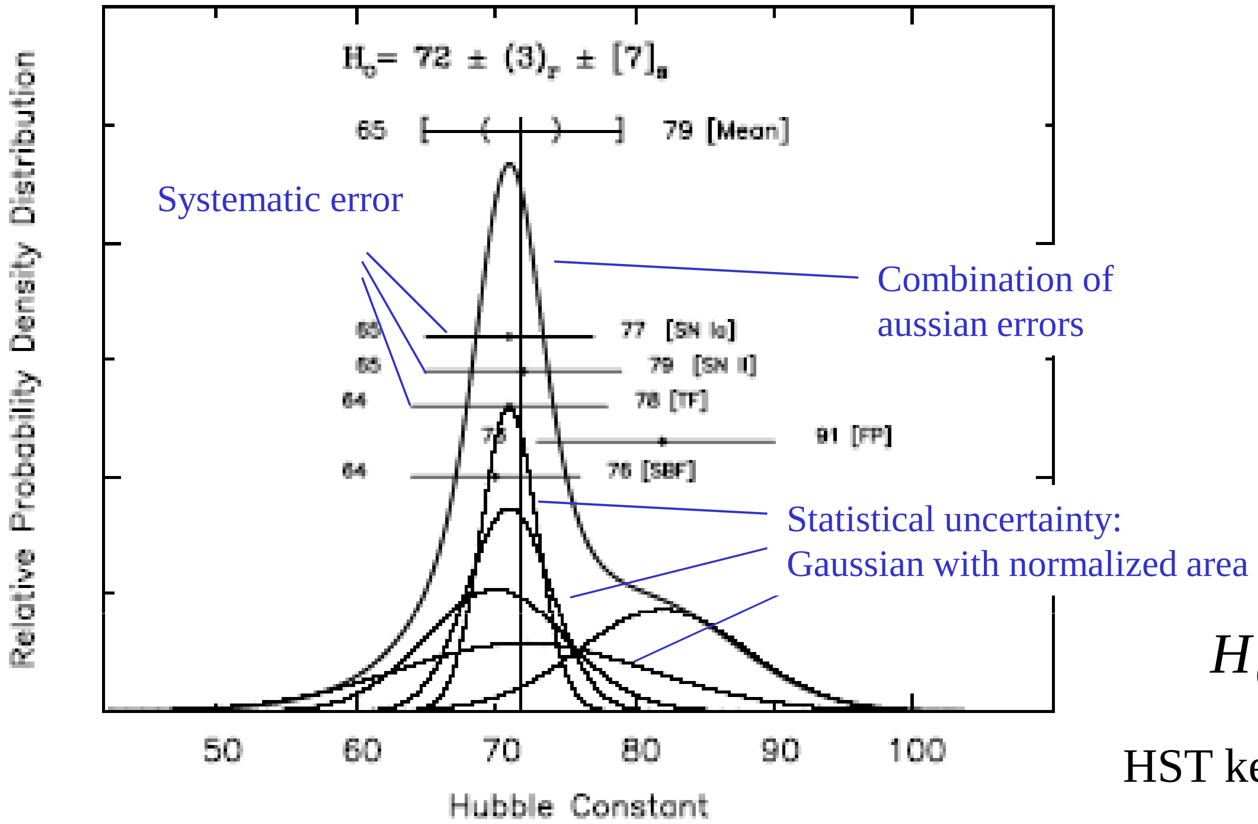


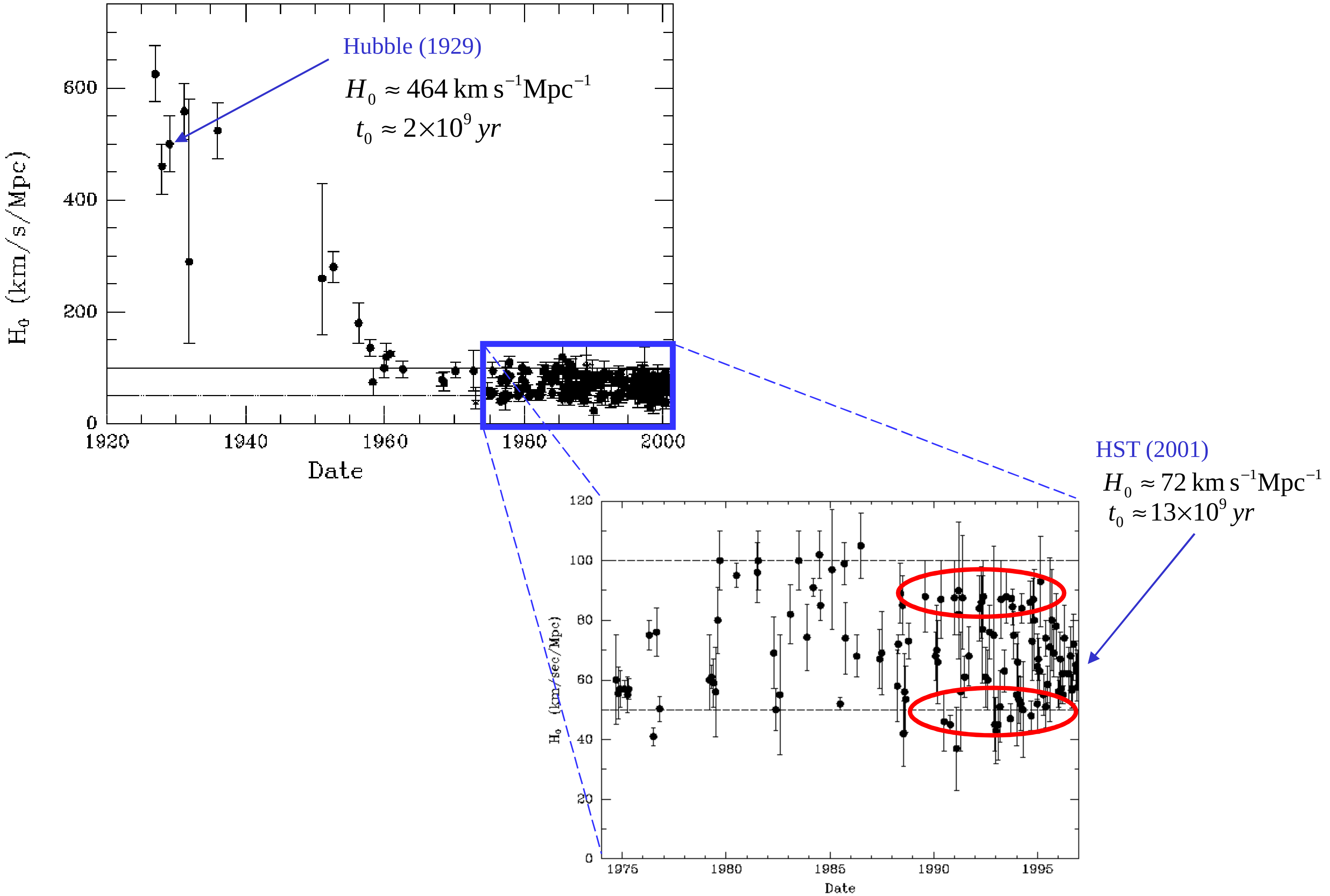
FIG. 3.—Frequentist probability density; values of H_0 and their uncertainties for Type Ia supernovae, the Tully-Fisher relation, the fundamental plane, surface brightness fluctuations, and Type II supernovae, all calibrated by Cepheid variables. Each value is represented by a Gaussian curve (*joined dots*) with unit area and a 1 σ scatter equal to the random uncertainty. The systematic uncertainties for each method are indicated by the horizontal bars near the peak of each Gaussian. The upper curve is obtained by summing the individual Gaussians. The cumulative (frequentist) distribution has a midpoint (median) value of $H_0 = 72(71) \pm 4 \pm 7$ km s^{-1} Mpc^{-1}. The overall systematic error is obtained by adding the individual systematic errors in quadrature.

$$H_0 \equiv 100h \text{ km/s/Mpc}$$

HST key programme:

$$h = 0.72 \pm (0.03)_{stat} \pm (0.07)_{sys}$$

Measuring expansion



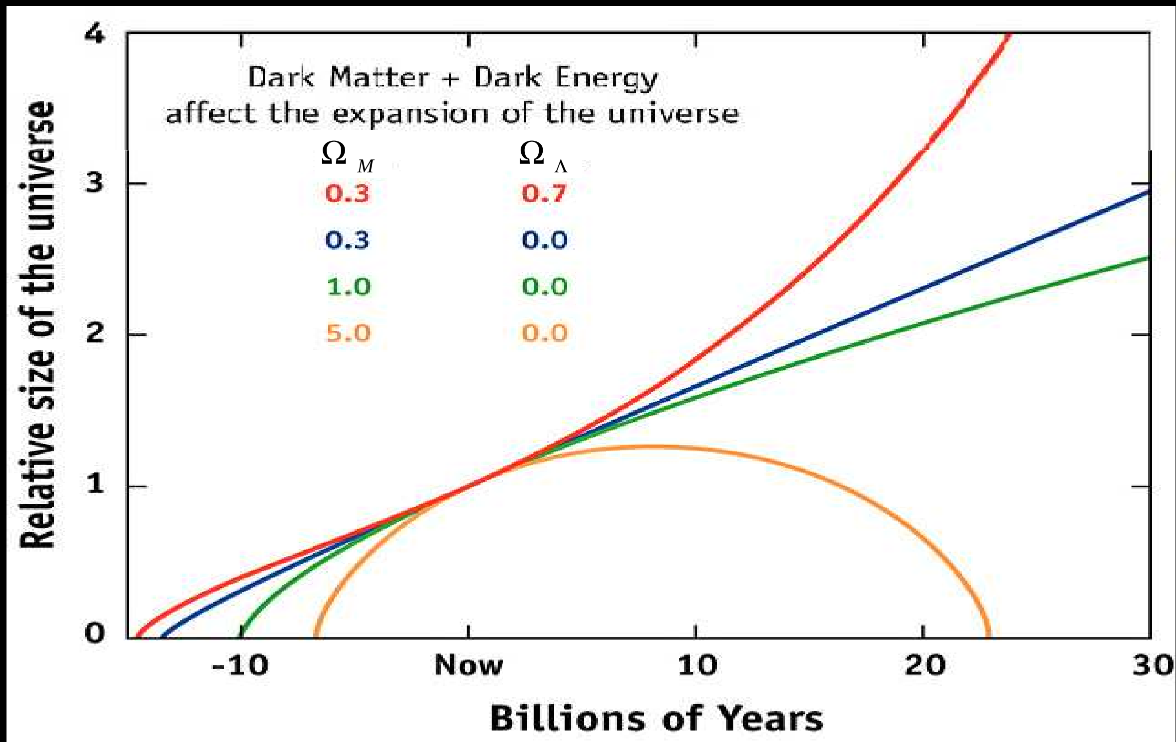
Evolution and Geometry

Radiation Matter Vacuum

Evolution

Geometry

Freedmann Equation



Albert Einstein

Alexander Friedmann

Georges Lemaitre

Evolution and Geometry

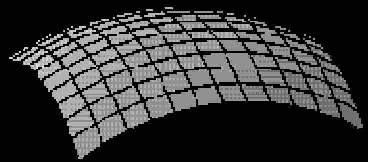
Radiation Matter Vacuum

Evolution

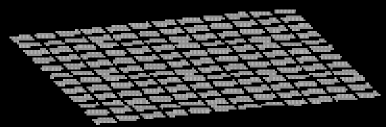
Geometry

Freedmann Equation

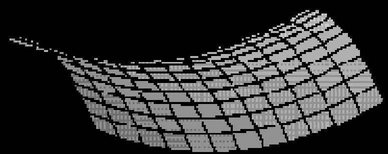
Total density – Determins global geometry



spherical



flat



hyperbolic

Albert Einstein

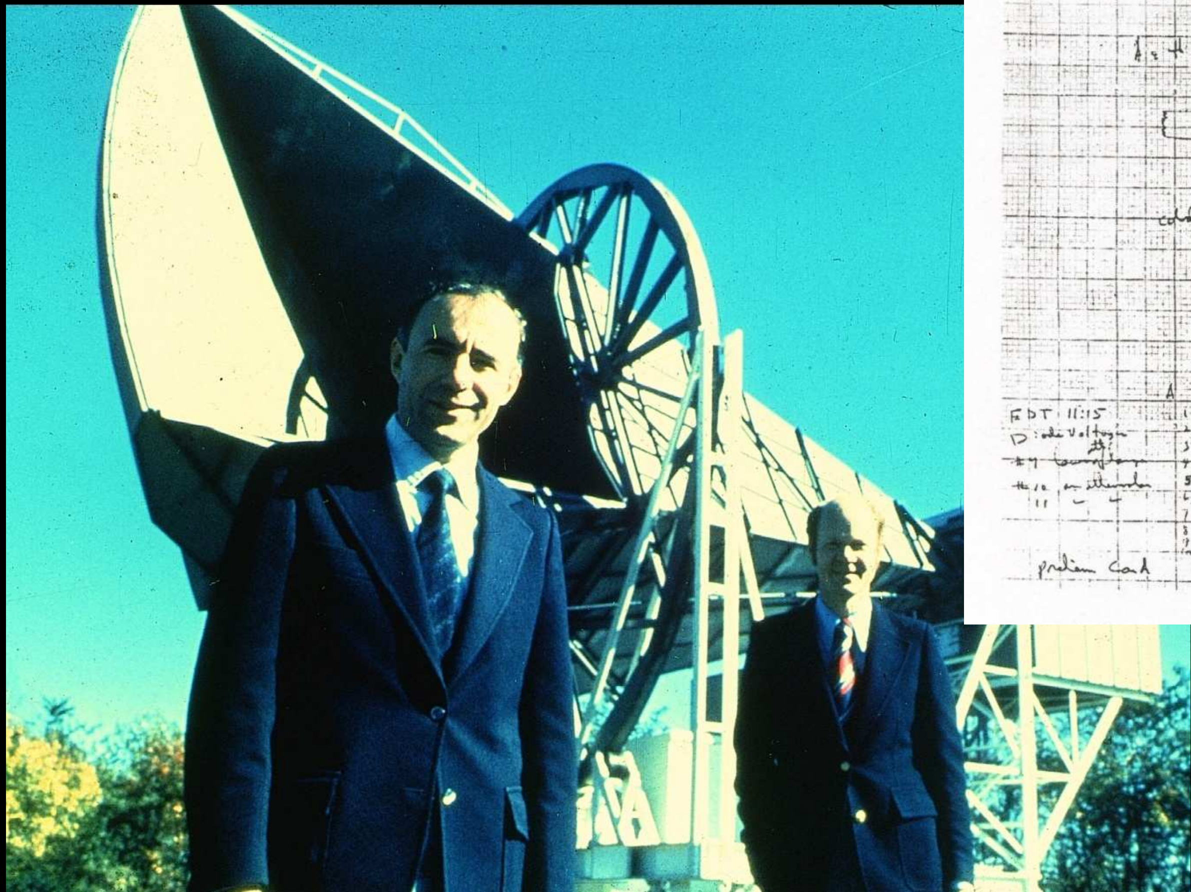
Alexander Friedmann

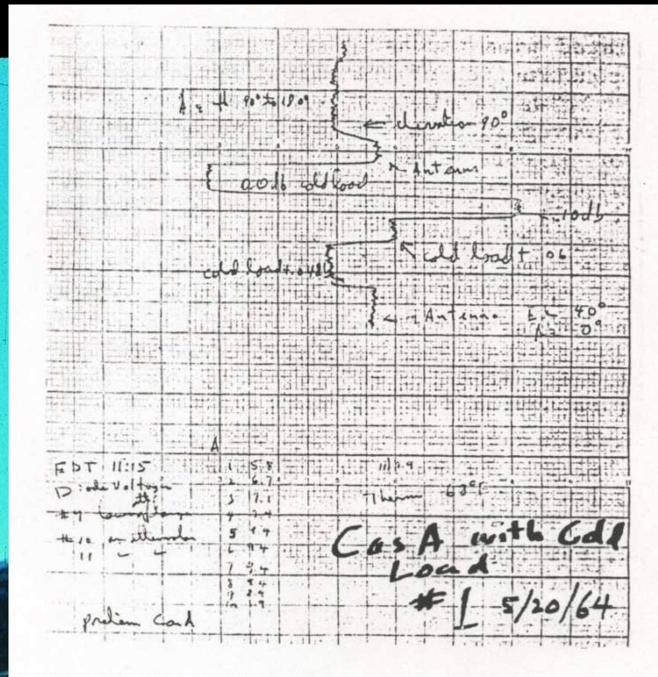
Georges Lemaitre

1964-65, Bell Telephon Labs, New Jersey

The first light in the universe

The cosmic microwave background

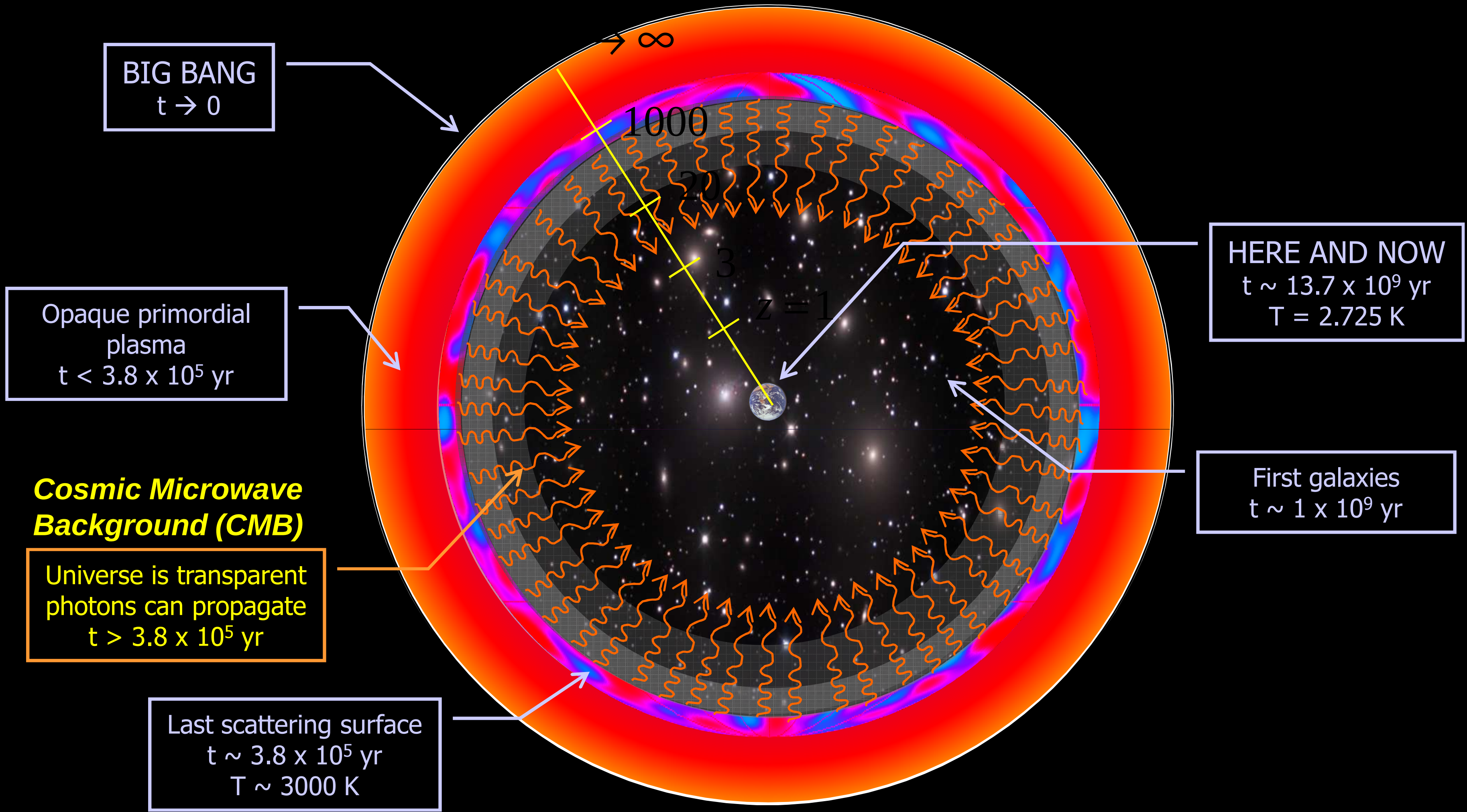


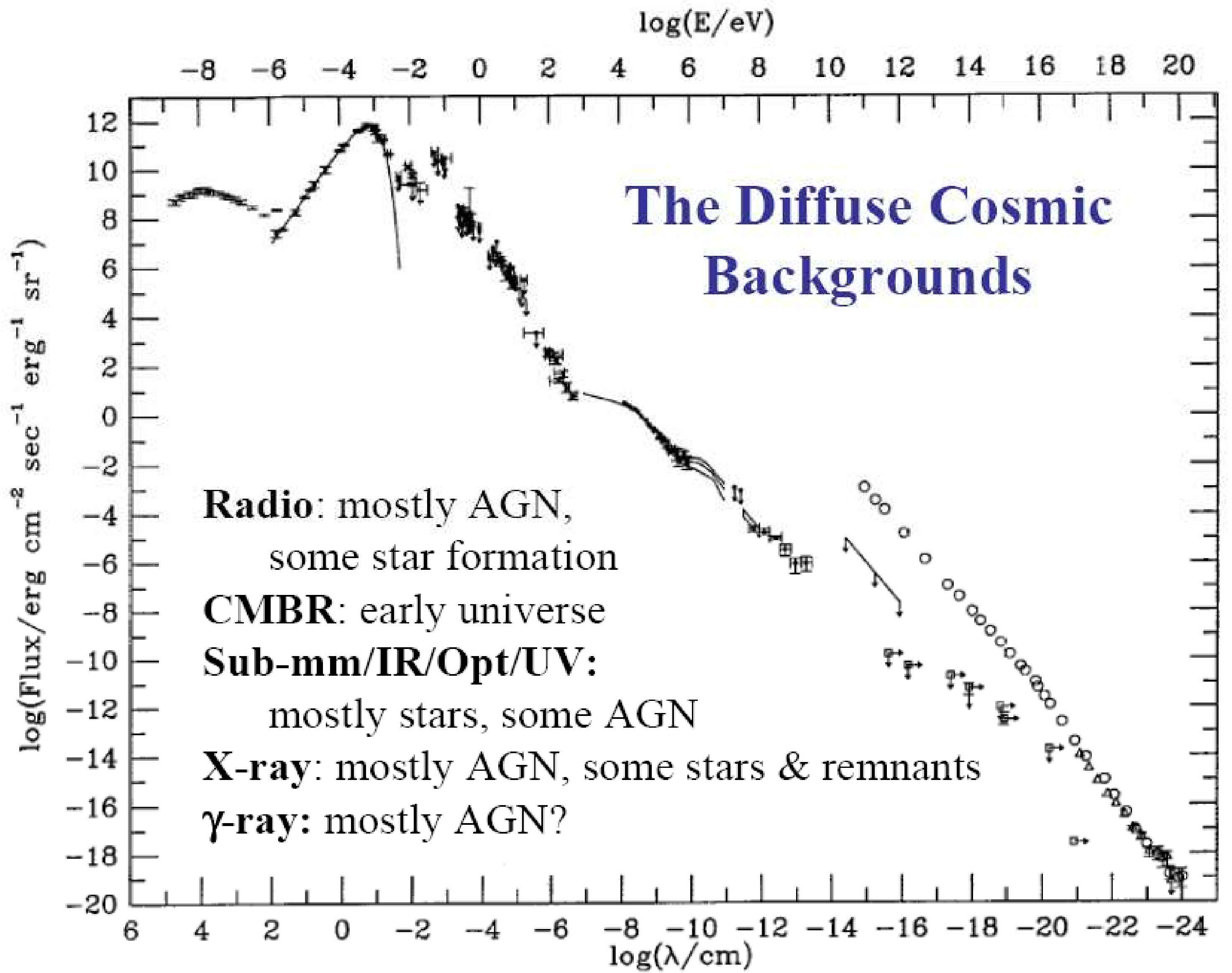


A.Penzias & R.Wilson

Nobel Prize in Physics 1978

Cosmic Microwave Background: A direct view on the early universe

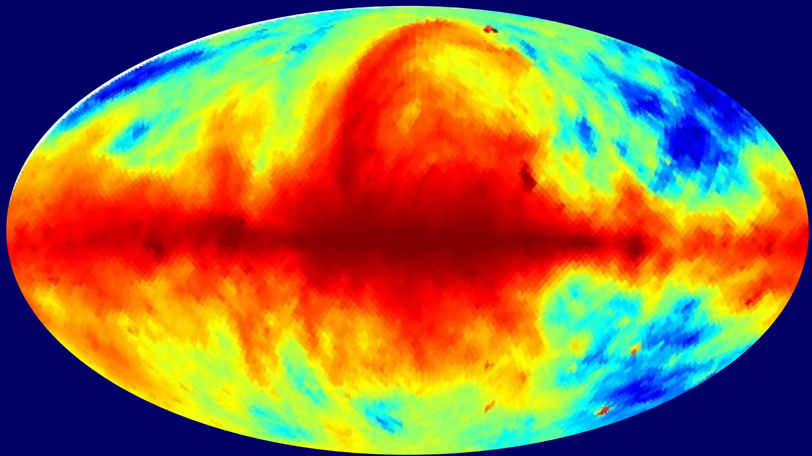


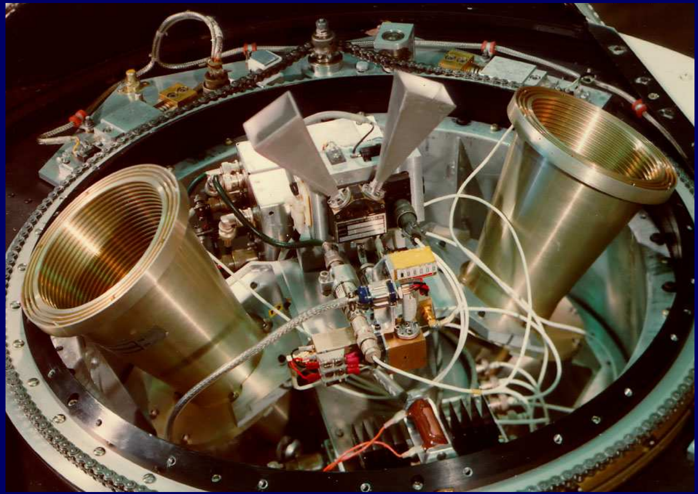

The Diffuse Cosmic Backgrounds
Radio: mostly AGN,
some star formation
CMBR: early universe
Sub-mm/IR/Opt/UV:
mostly stars, some AGN
X-ray: mostly AGN, some stars & remnants
γ-ray: mostly AGN?
log(E/eV)
log(λ/cm)
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})

"To argue is easier than to observe"
(A. Carrell)

Precise measurements of the CMB are a great experimental challenge

- Absolute signal ~ 3 K
- Temperature differences ~ 100 μK
- Polarisation ~ 3 μK

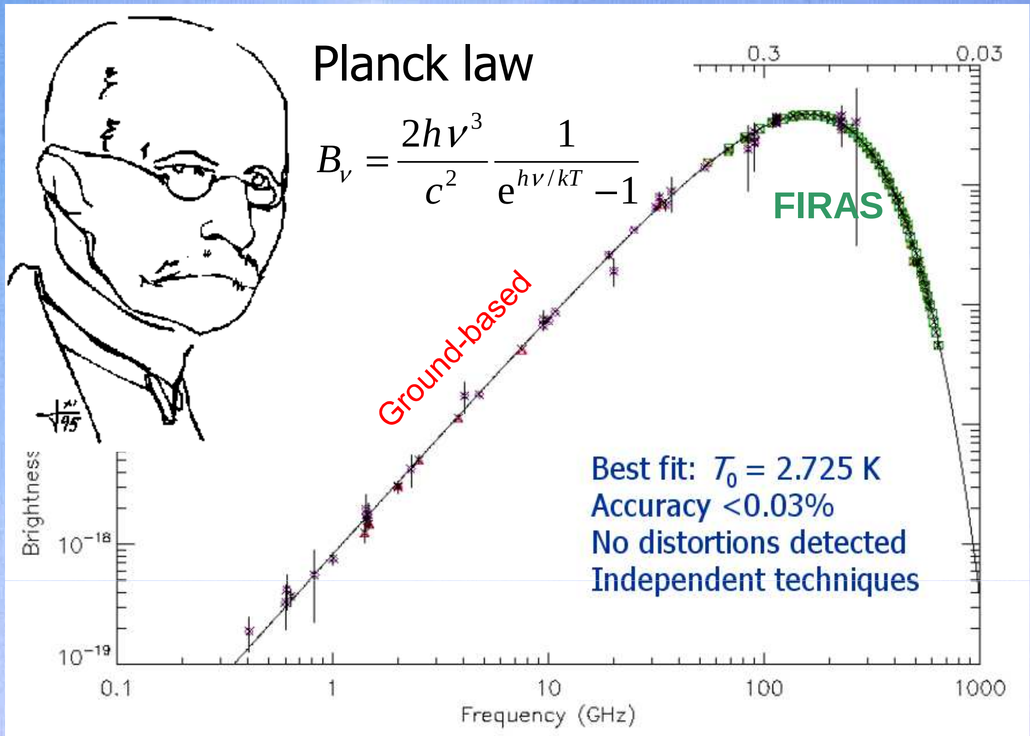


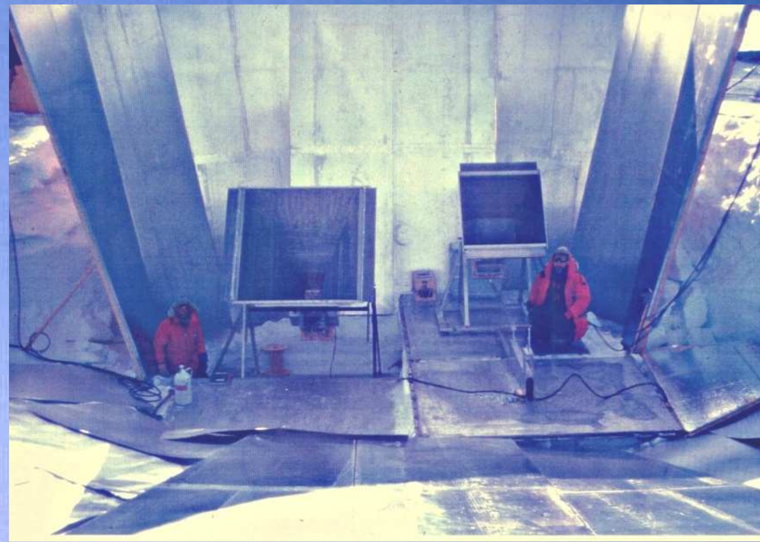


- Dramatic progress in mm-wave detector technology and cryogenics
- Instrumental systematic effects
- Atmospheric effects (remote sites, balloon, space)
- Our own Galaxy, and extragalactic sources, emit radiation in the microwaves

→ Multi-frequency measurements to disentangle cosmic radiation from "foreground" sources

The CMB spectrum

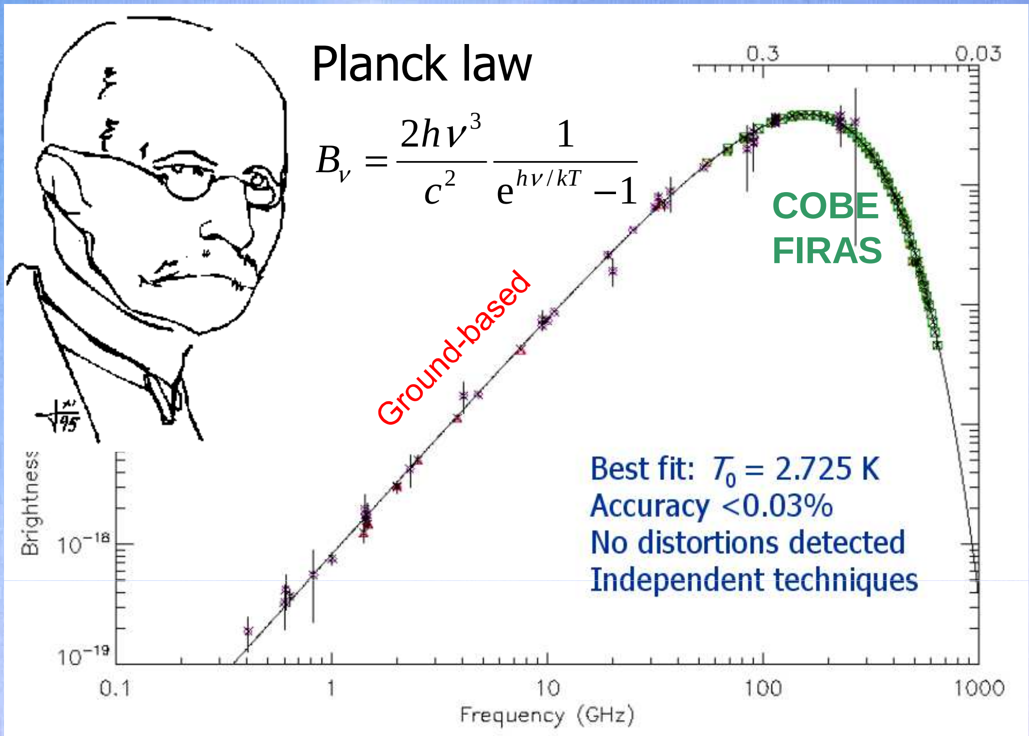




The CMB spectrum

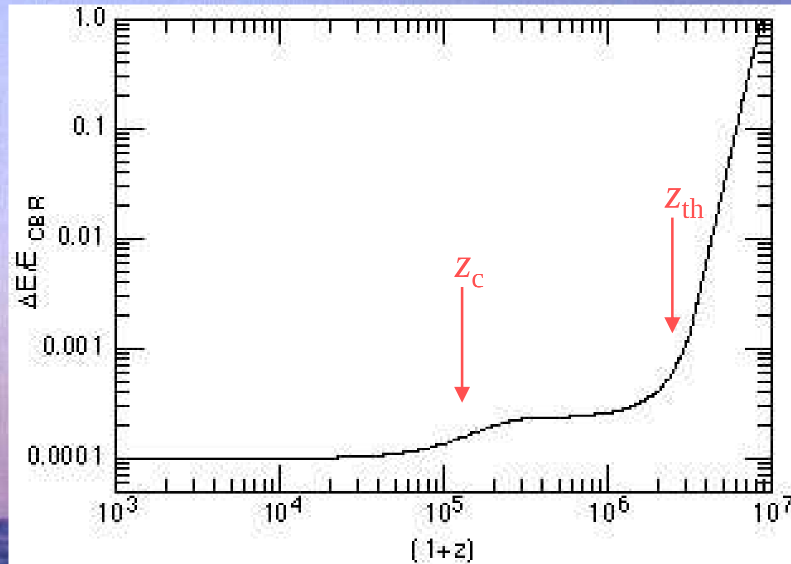
$$T_0 = 2.725 \pm 0.002\,\mathrm{K}$$

High precision in cosmology!



$$\rho_R = \frac{4\pi}{c}\int B_\nu d\nu = \frac{8\pi h}{c^3}\int \frac{\nu^3}{e^{h\nu/kT}-1}d\nu$$

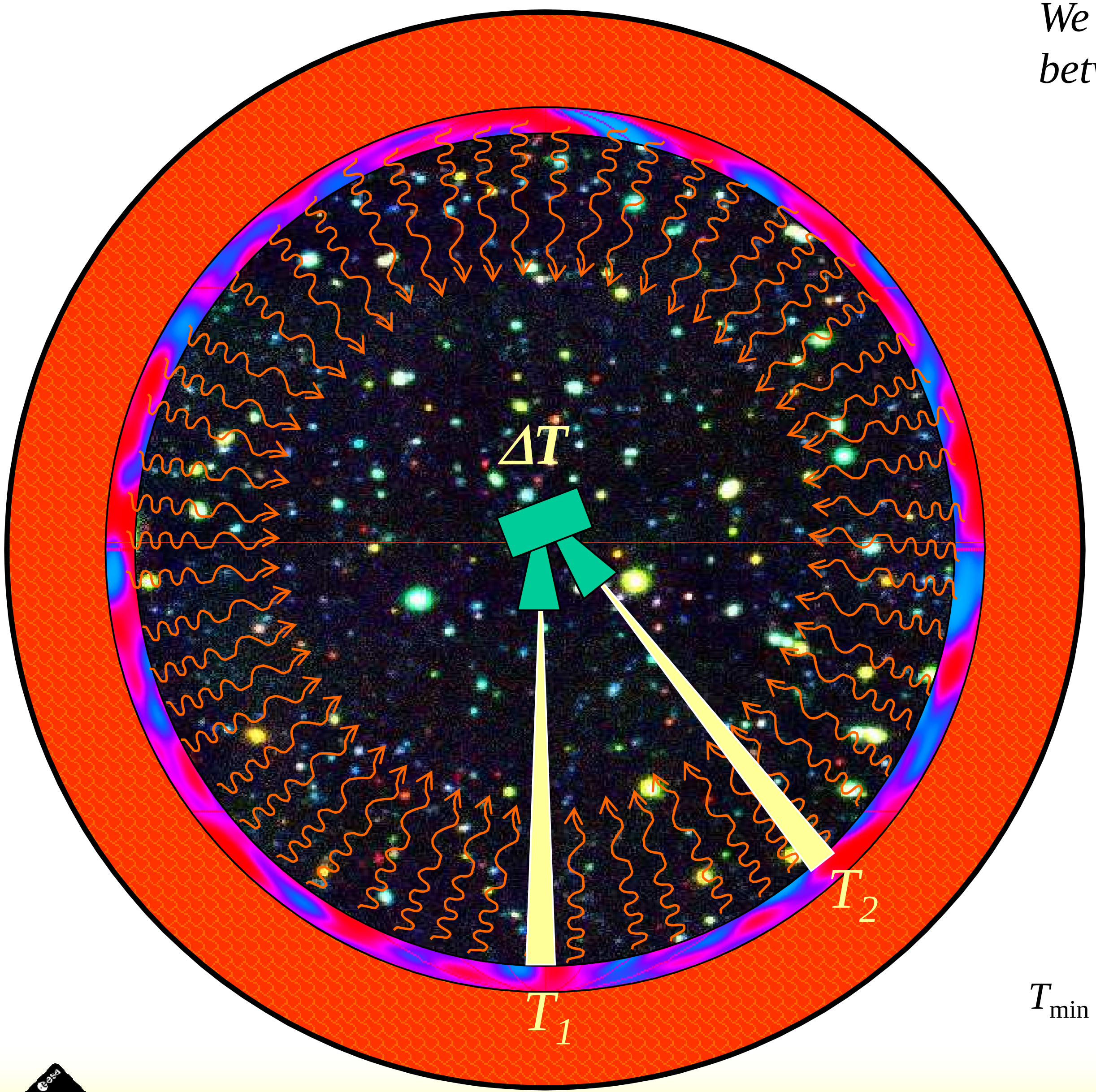
$$\Omega_R = \frac{\rho_R}{\rho_C} \approx 2.3\times10^{-5}h^{-2} \approx 4.6\times10^{-5}$$



Constraints on distortions →

Tight limits on energy releases in the early universe

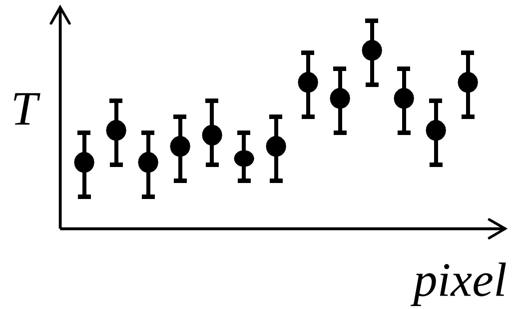
CMB Anisotropy



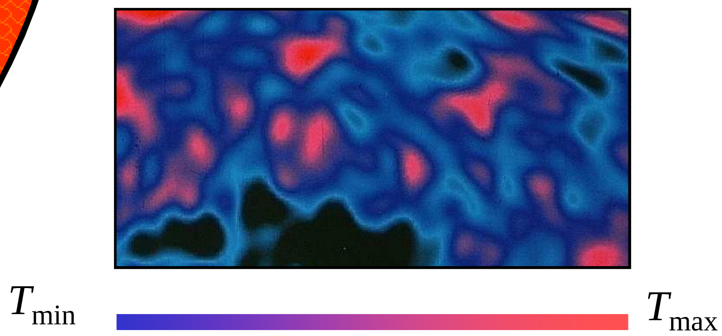
Differential measurements:

We want the difference ΔT between sky regions

Variations of T along a given direction in the sky



Two-dimensional maps of temperature fluctuations



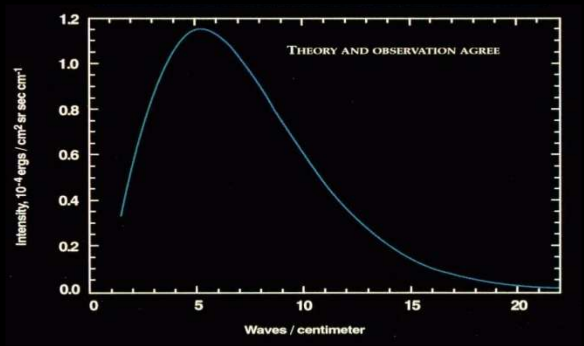
The Nobel Prize in Physics 2006

"For their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

John C. Mather

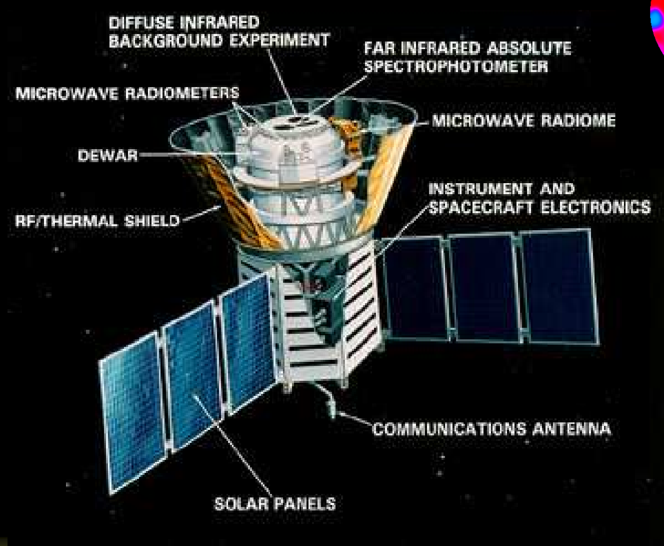
George F. Smoot

COBE-FIRAS

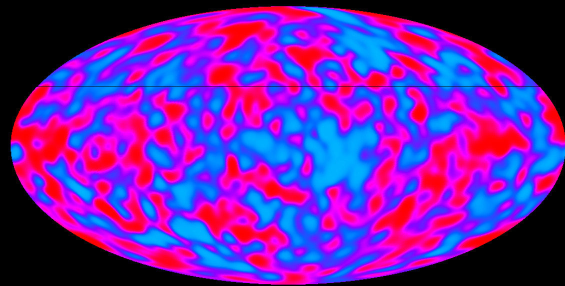


High precision

Cosmic Background Explorer

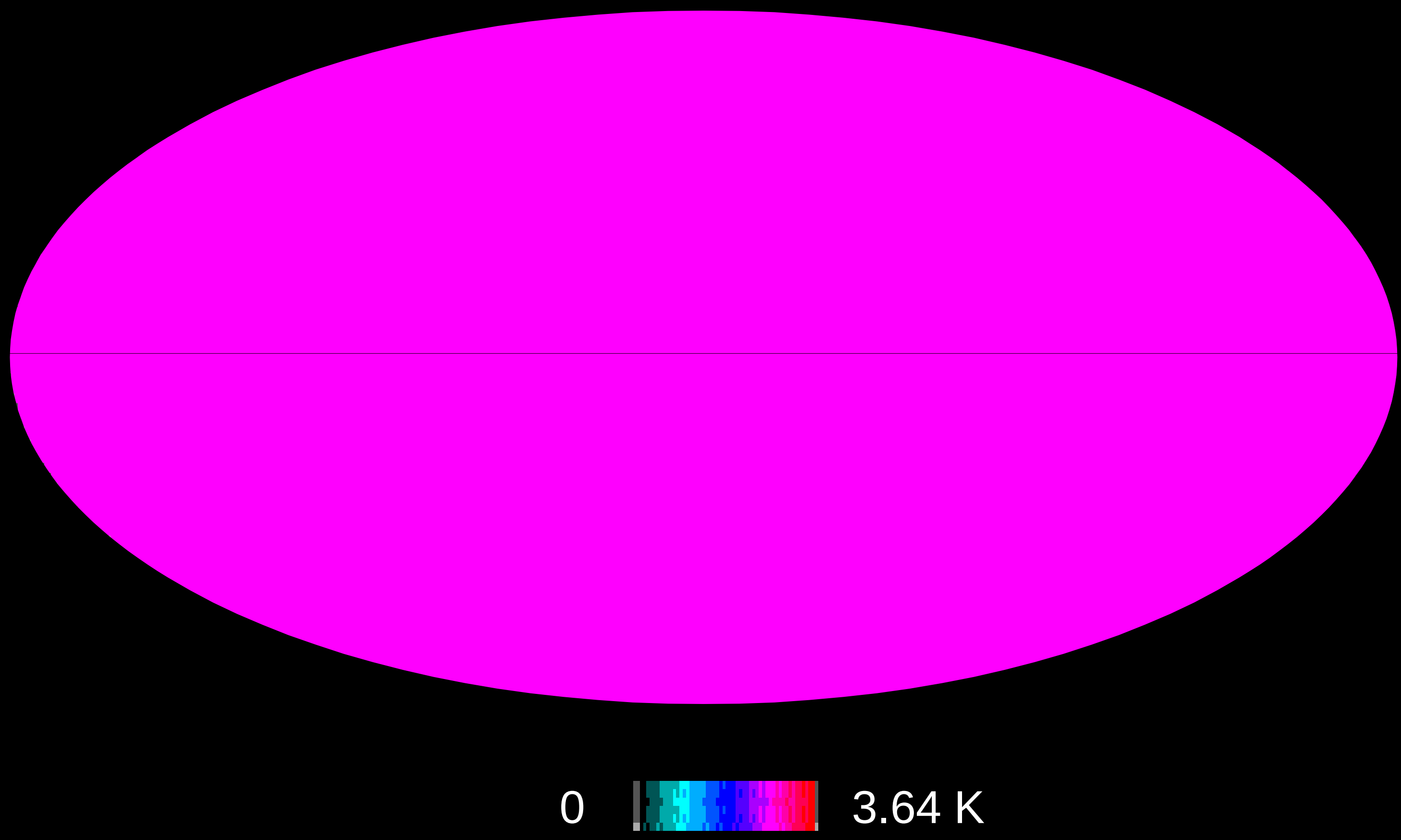


COBE-DMR



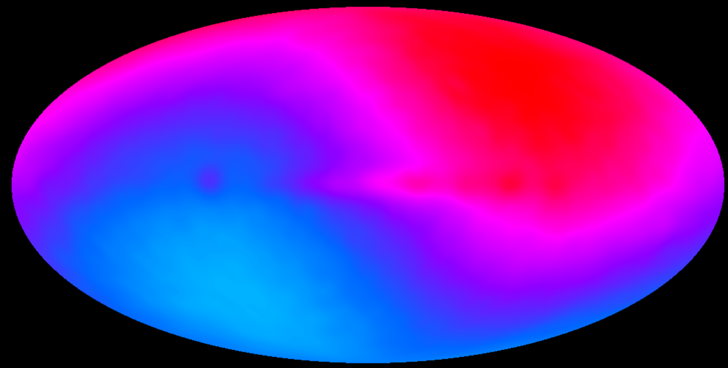
New discovery

COBE – DMR full-sky map

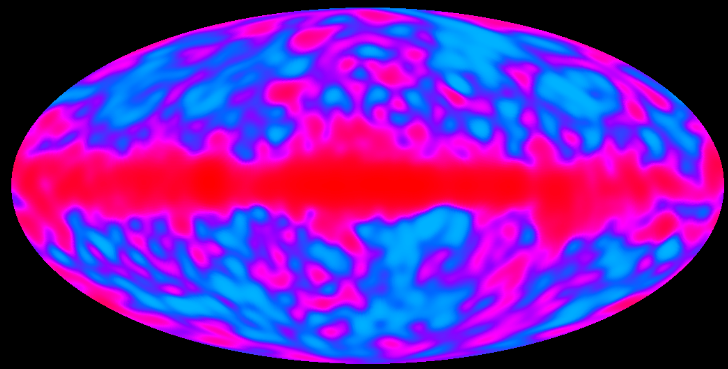


COBE – DMR full-sky map

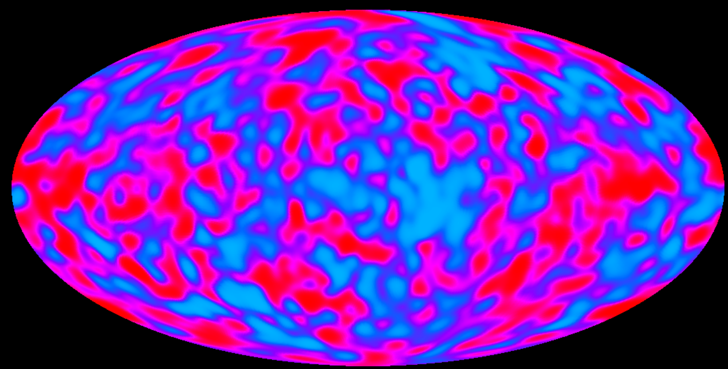
Dipole-dominated map
$\Delta T \sim 3.5$ mK



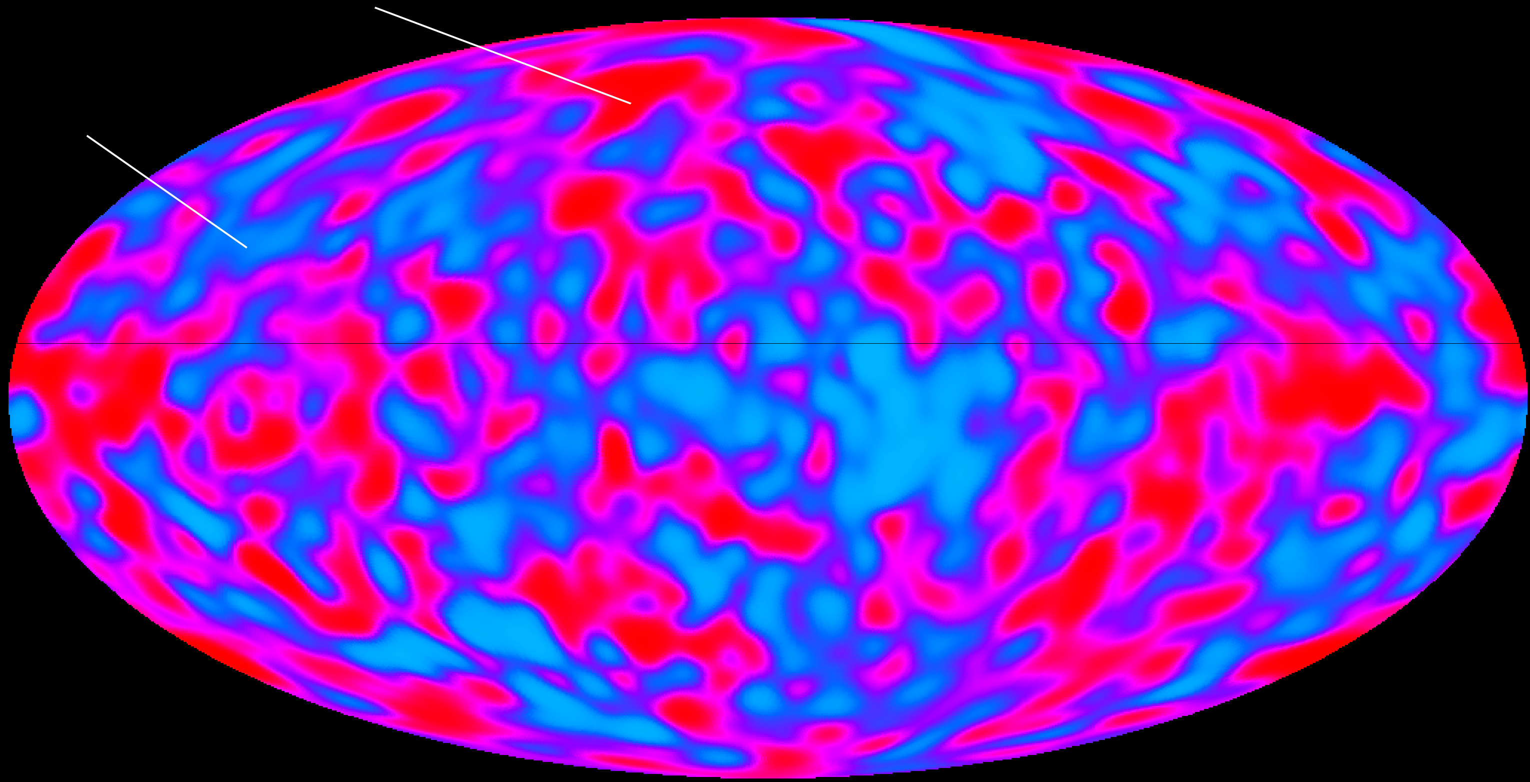
Fluctuations from Galaxy,
background and instrument noise
$\Delta T \sim 0.1$ mK



Fluctuations from CMB
(with instrument noise)
$\Delta T_{CMB} \sim 35$ μK



COBE – DMR full-sky map



CMB Angular Power Spectrum

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

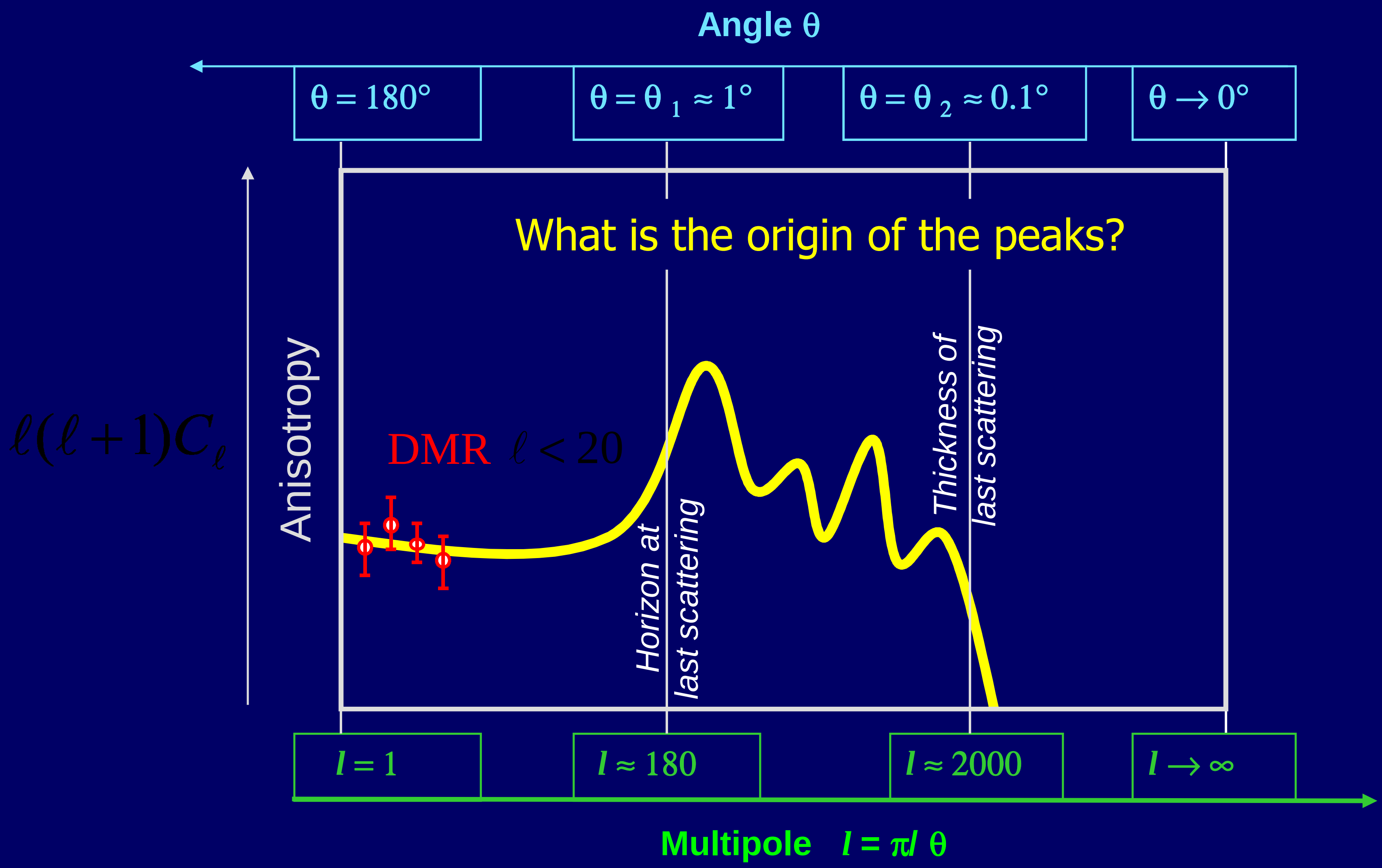
We represent the temperature distribution on the sky as:

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

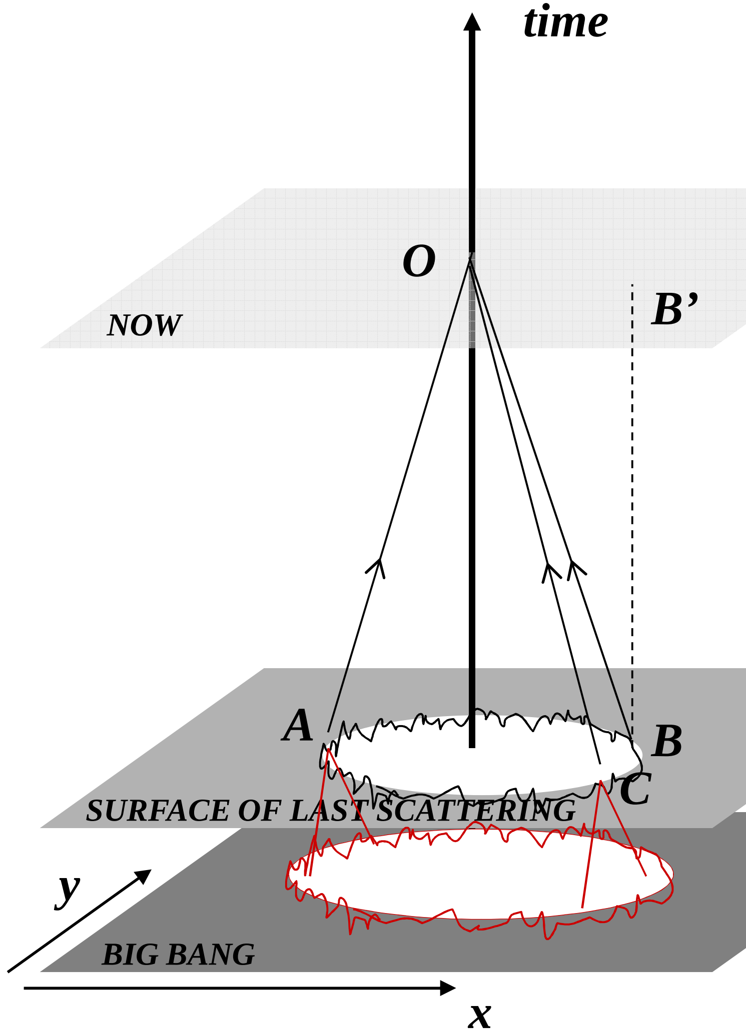
The angular power spectrum is:

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

Qualitative shape of expected CMB power spectrum



COSMOLOGICAL SPACE-TIME AND LAST SCATTERING SURFACE

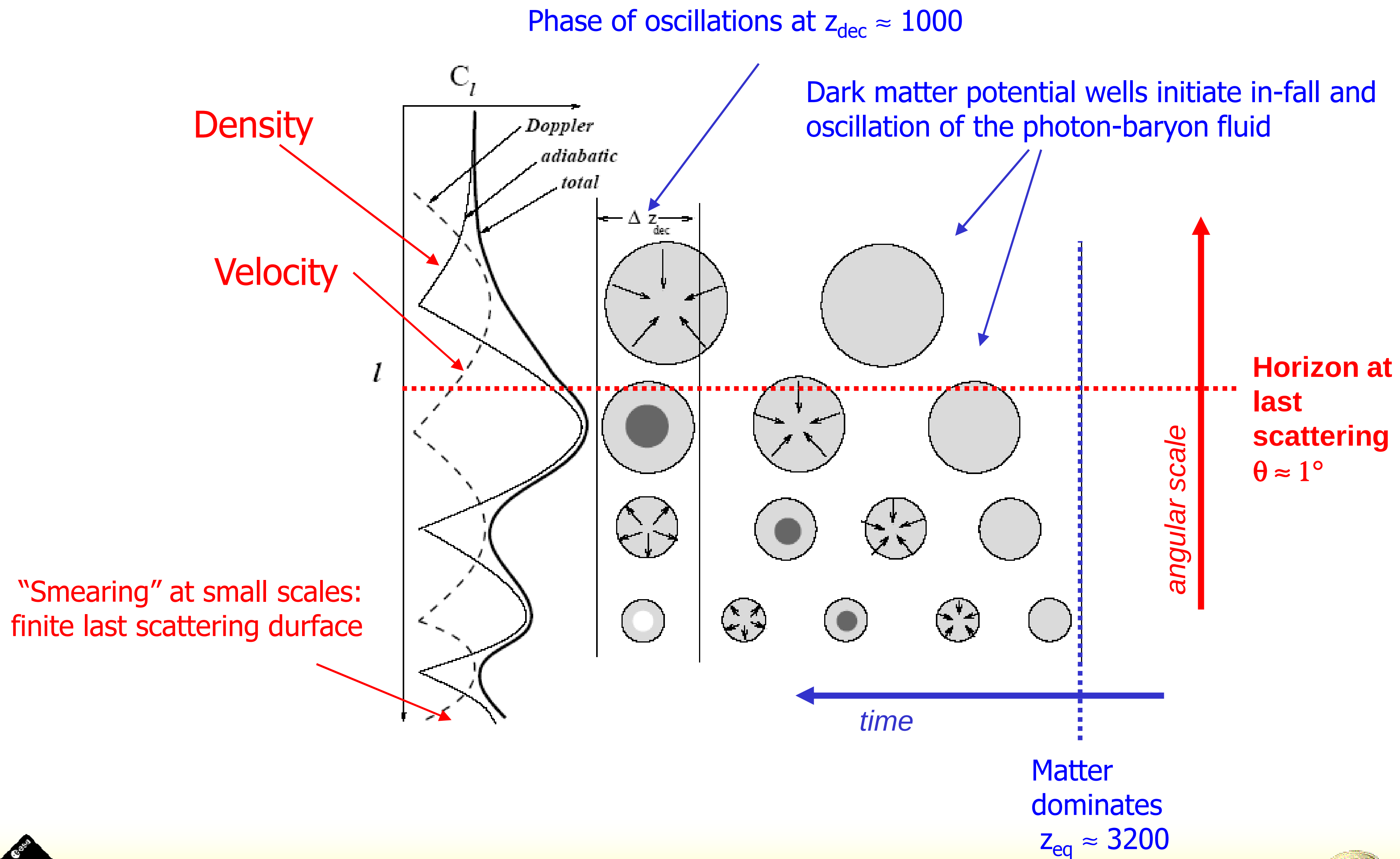


$$t = t_0 \cong 1.5\times10^{10}\ \mathrm{yr}$$
$$T = T_0 \cong 2.7\ \mathrm{K}$$
$$z = 0$$

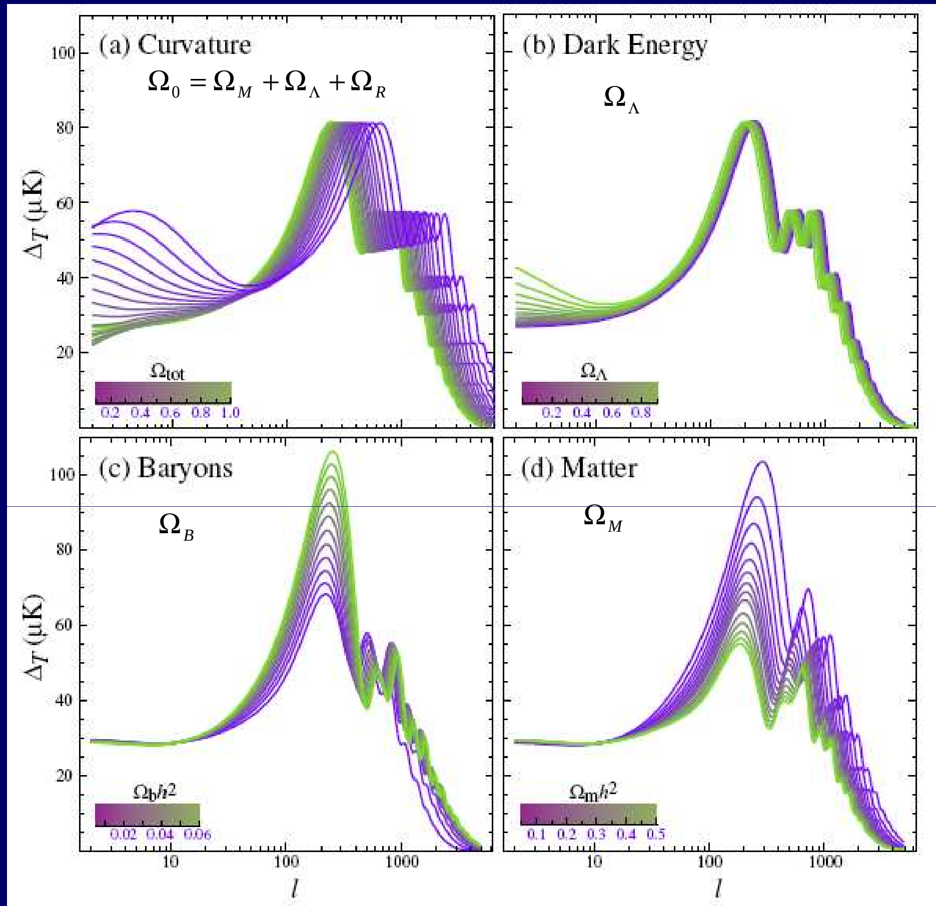
$$t = t_{dec} \cong 3.8\times10^{5}\ \mathrm{yr}$$
$$T = T_{dec} \cong 3000\ \mathrm{K}$$
$$z \cong 1100$$

$$t \rightarrow 0$$
$$T \rightarrow \infty$$
$$z \rightarrow \infty$$

Acoustic oscillations and the CMB power spectrum

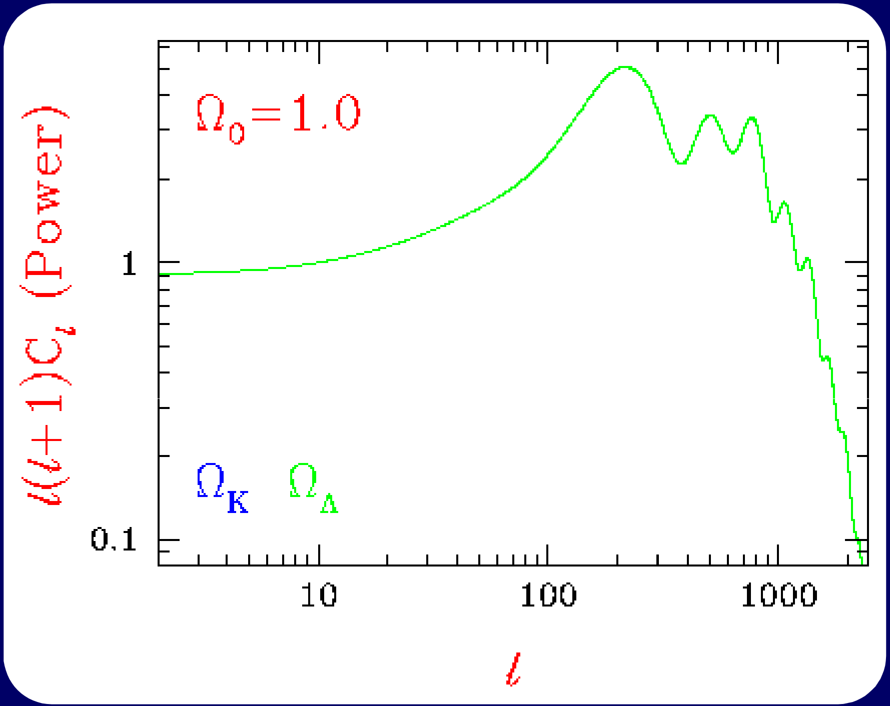


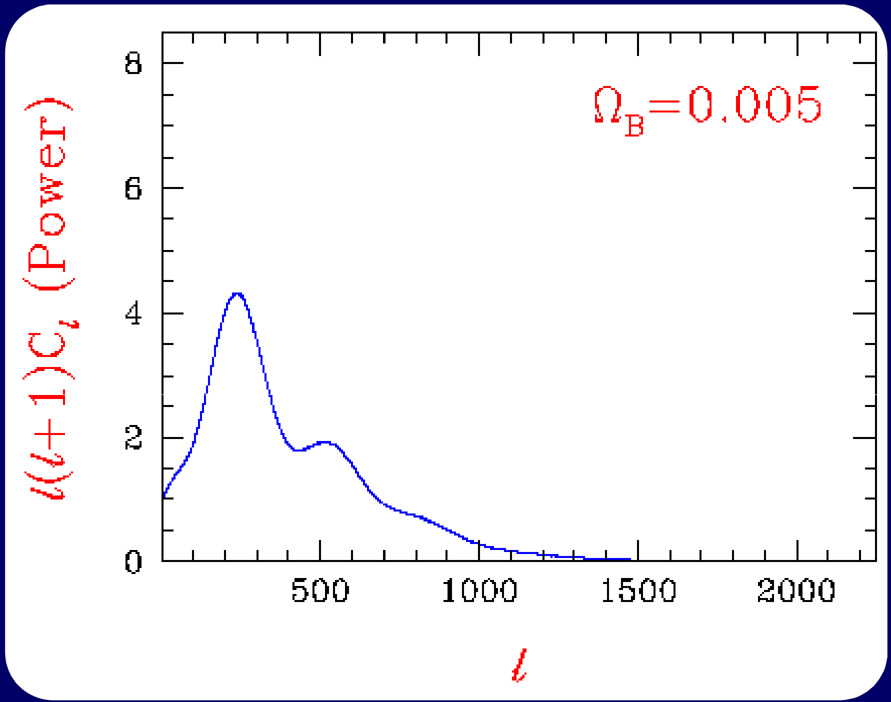
The details of the angular power spectrum depend on the value of the main cosmological parameters



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

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 *high precision* determination of parameters

Accuracy in reconstruction of angular power spectrum

$$\frac{\delta C_\ell}{C_\ell} = f_{sky}^{-1/2} \sqrt{\frac{2}{2\ell+1}} \left[1 + \frac{A\sigma_{pix}^2}{N_{pix} C_\ell W_\ell^2} \right]$$

"Cosmic variance" *Instrument*

f_{sky} = fraction of observed sky

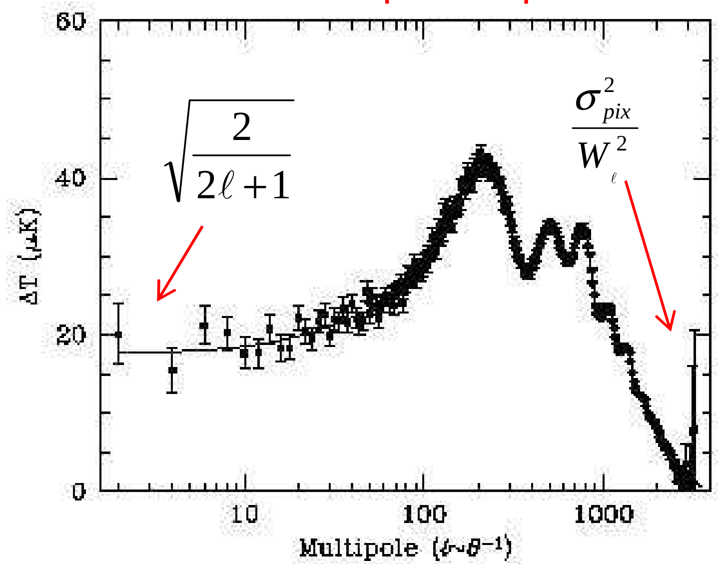
W_ℓ^2 = "Window function"

A = Sky area surveyed

N_{pix} = Number of pixels

σ_{pix} = Noise per pixels

Simulated T power spectrum



This is still an ideal case!

→ "Ideal instrument" (systematic effects are neglected)

→ "Ideal sky" (astrophysical foregrounds not considered)

Sensitivity

$$\frac{\delta C_\ell}{C_\ell} = f_{sky}^{-1/2}\sqrt{\frac{2}{2\ell+1}}\left[1+\frac{A\sigma_{pix}^2}{N_{pix}C_\ell W_\ell^2}\right]$$

$$\sigma_{pix} = k_R \frac{T_{sys}+T_{sky}}{\sqrt{(n_{det}\tau)\Delta\nu}}$$

$k_R \approx 1$ receiver constant

T_{sys} = System temperature

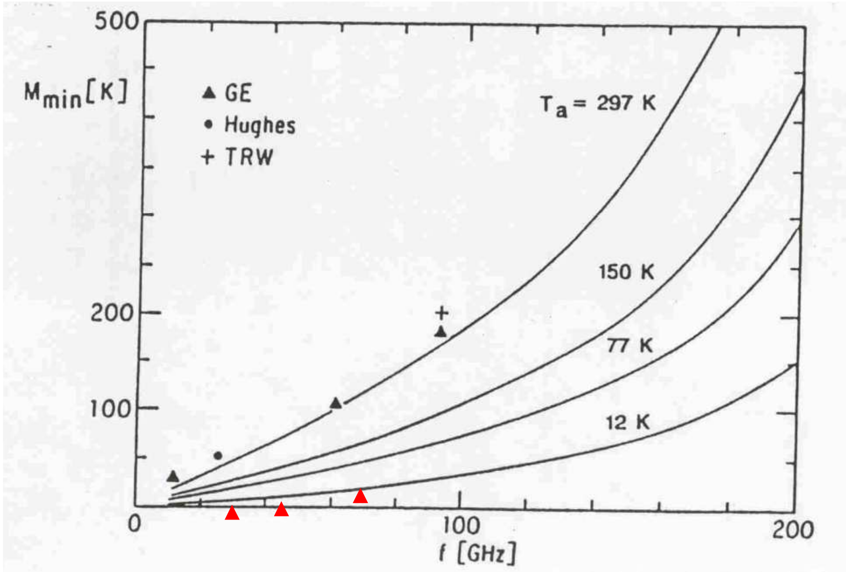
T_{sky} = Sky (input) brightness temperature

n_{det} = Number of detectors

τ = Integration time

$\Delta\nu$ = Bandwidth

Noise temperature is function of physical temperature and frequency



Planck (20K)

30 GHz	12K	
44GHz	18K	$\Delta\nu/\nu$~20%
70GHz	30K	

Window function

$$\frac{\delta C_\ell}{C_\ell} = f_{sky}^{-1/2}\sqrt{\frac{2}{2\ell+1}}\left[1+\frac{A\sigma_{pix}^2}{N_{pix}C_\ell W_\ell^2}\right]$$

For a Gaussian beam scan

$$W_\ell^2 = \exp\left[-\ell(\ell+1)\sigma_B^2\right]$$

$$\sigma_B = \frac{\theta_{HPBW}}{\sqrt{8\ln 2}} = (1.235\times10^{-4})\theta_{HPBW}\,[\mathrm{arcmin}]$$

Measured power spectrum:

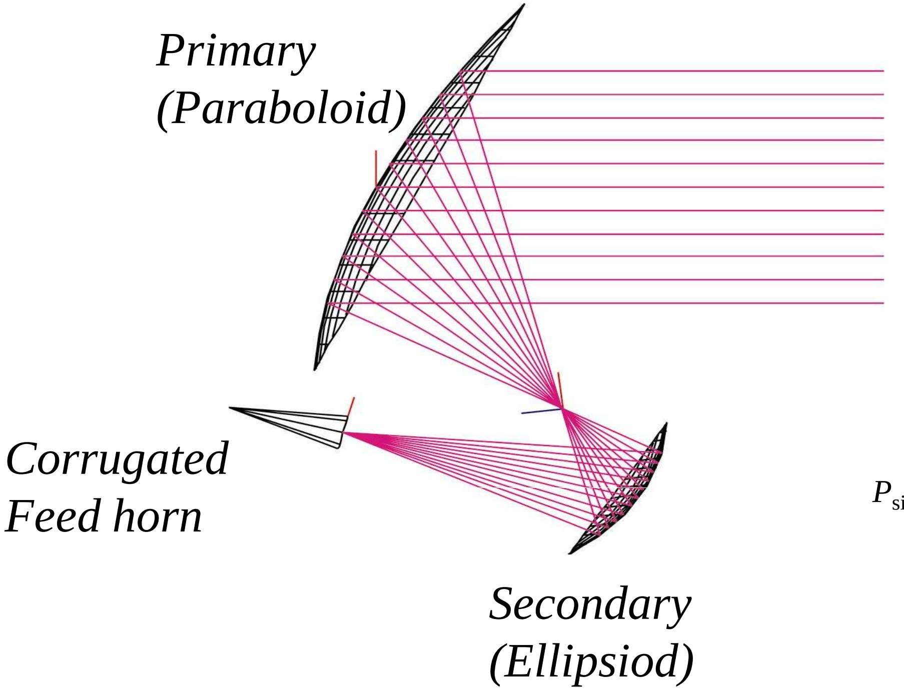
$$C_{\ell-MEAS} = C_\ell W_\ell^2$$

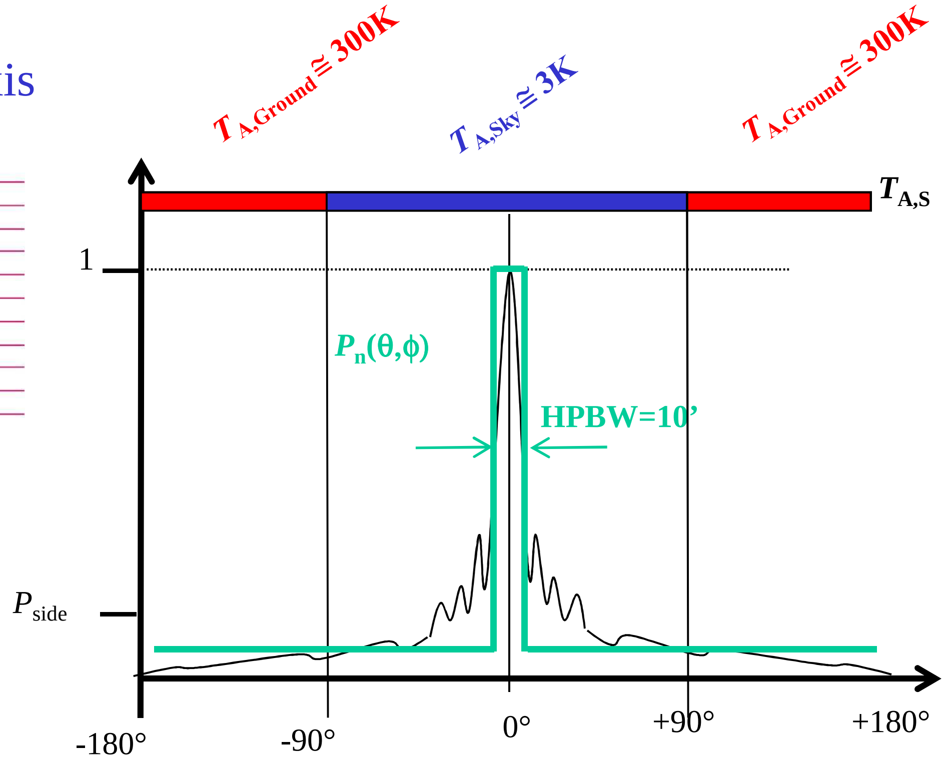
$$C_\ell = \frac{C_{\ell-MEAS}}{W_\ell^2} = C_{\ell-MEAS}\exp\left[\ell(\ell+1)\sigma_B^2\right]$$

Requirement: precise a-priori knowledge of σ_B

Telescope and beam pattern

CMB instruments: Double reflector off-axis





→ Antenna temperature

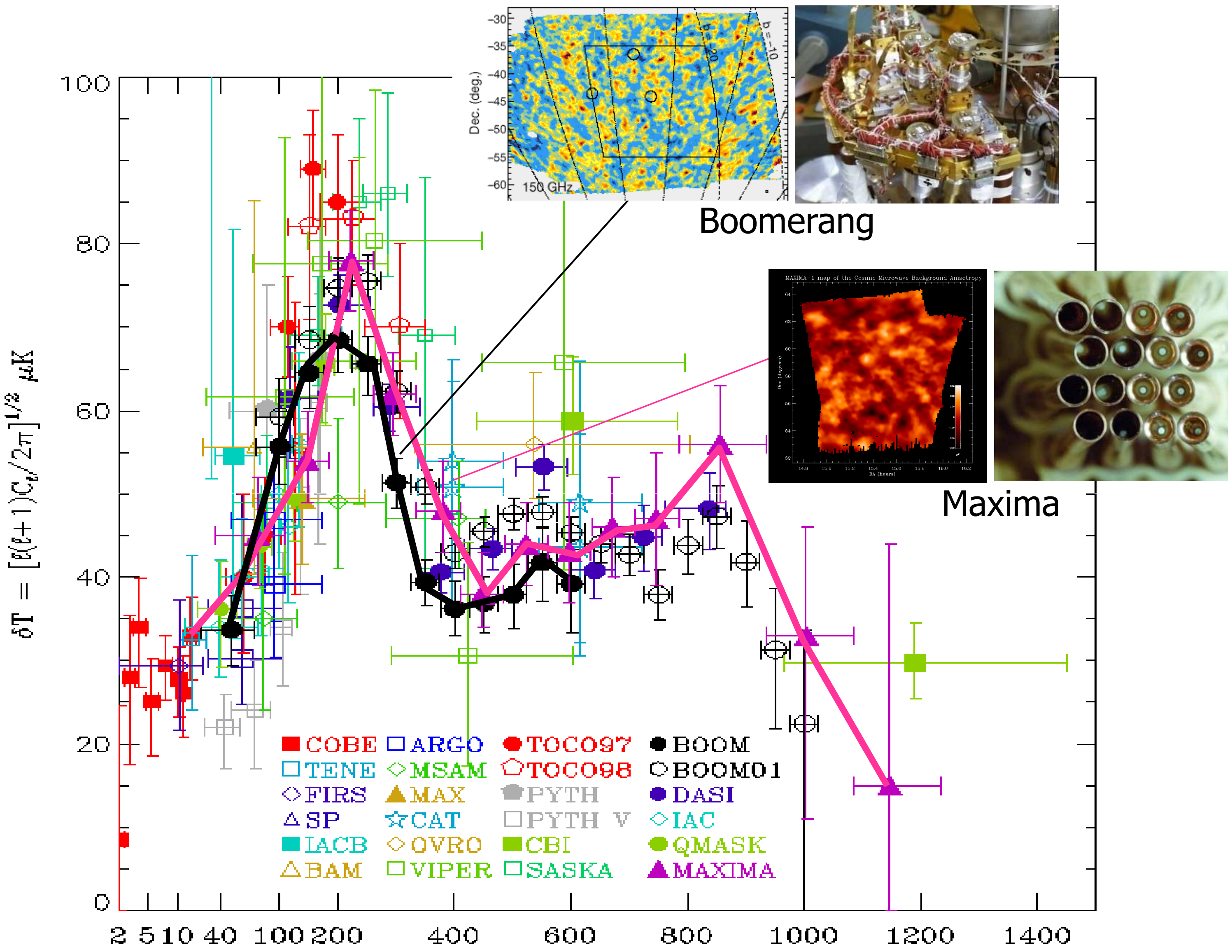
→ No diffraction from secondary mirror

→ Can be optimised for aberration effects

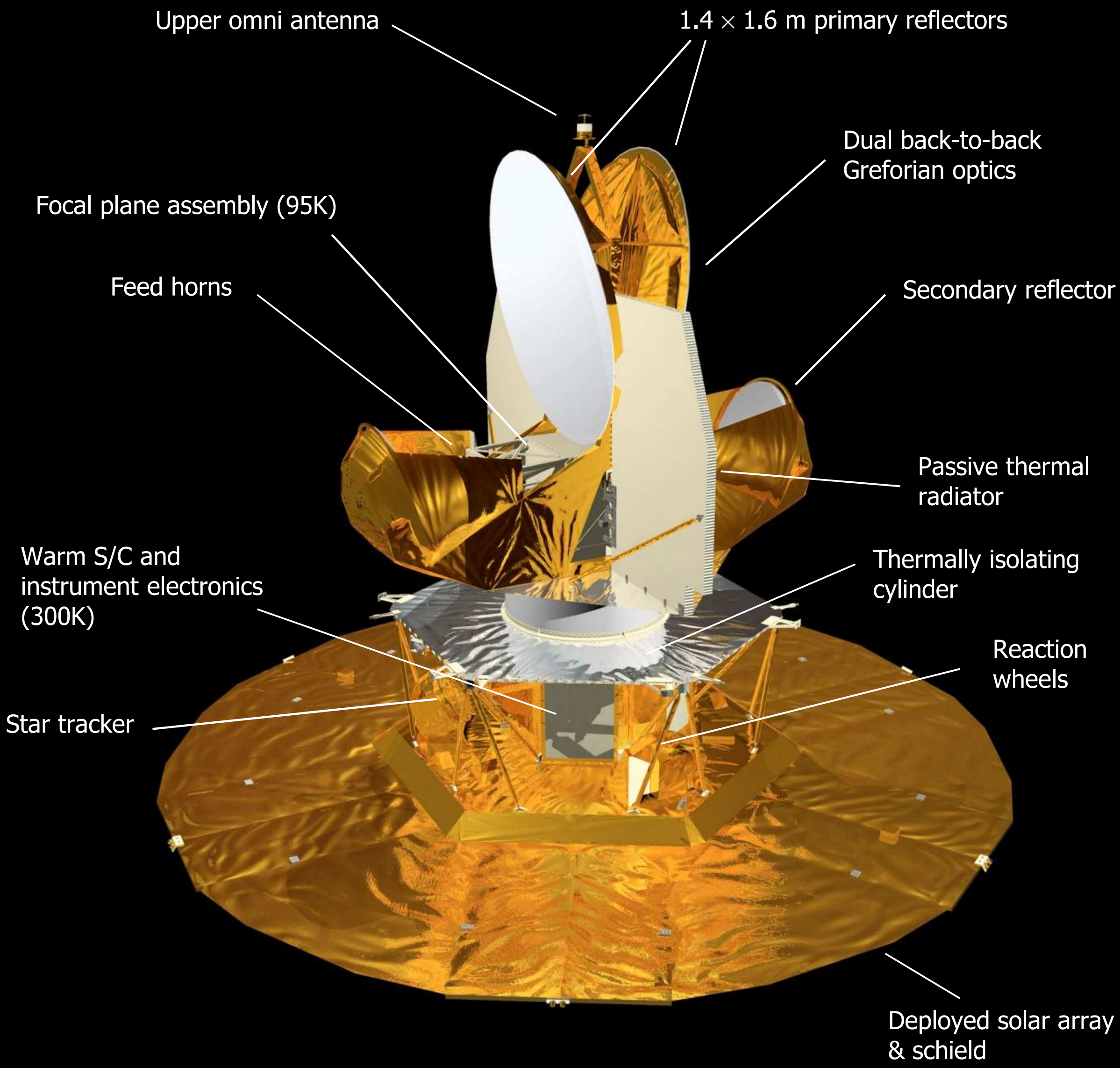
$$\vartheta_{FWHM}[rad] \approx \frac{\lambda}{D}$$

$$T_A(\theta_0, \phi_0) = \frac{\iint_{4\pi} T_{B,S}(\theta,\phi) P_n(\theta,\phi) d\Omega}{\iint_{4\pi} P_n(\theta,\phi) d\Omega}$$

Anisotropy experiments – Nov 2002

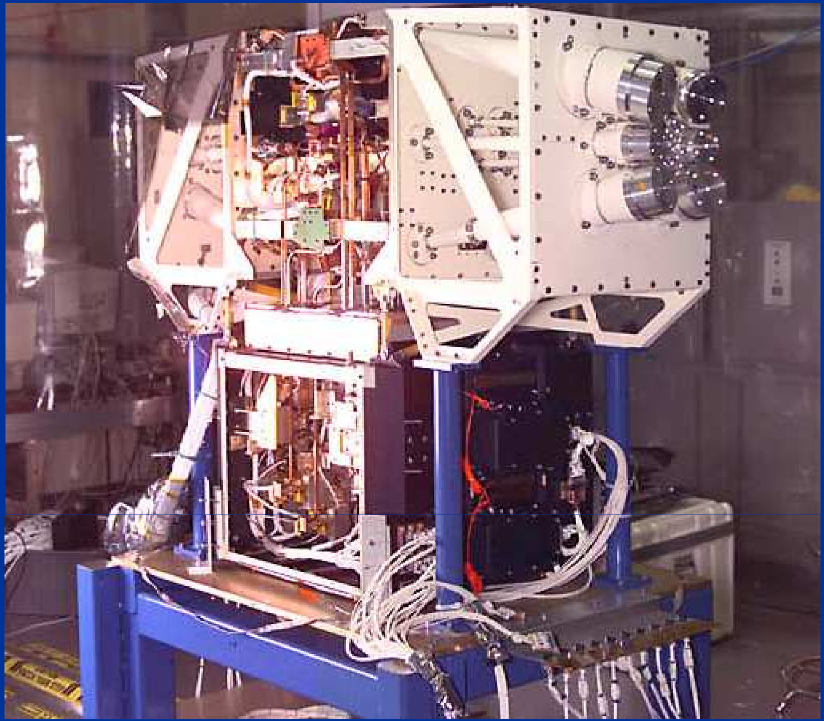


WMAP (launched 2001)



WMAP Instrument Assembly

Pseudo-correlation HEMT coherent radiometers

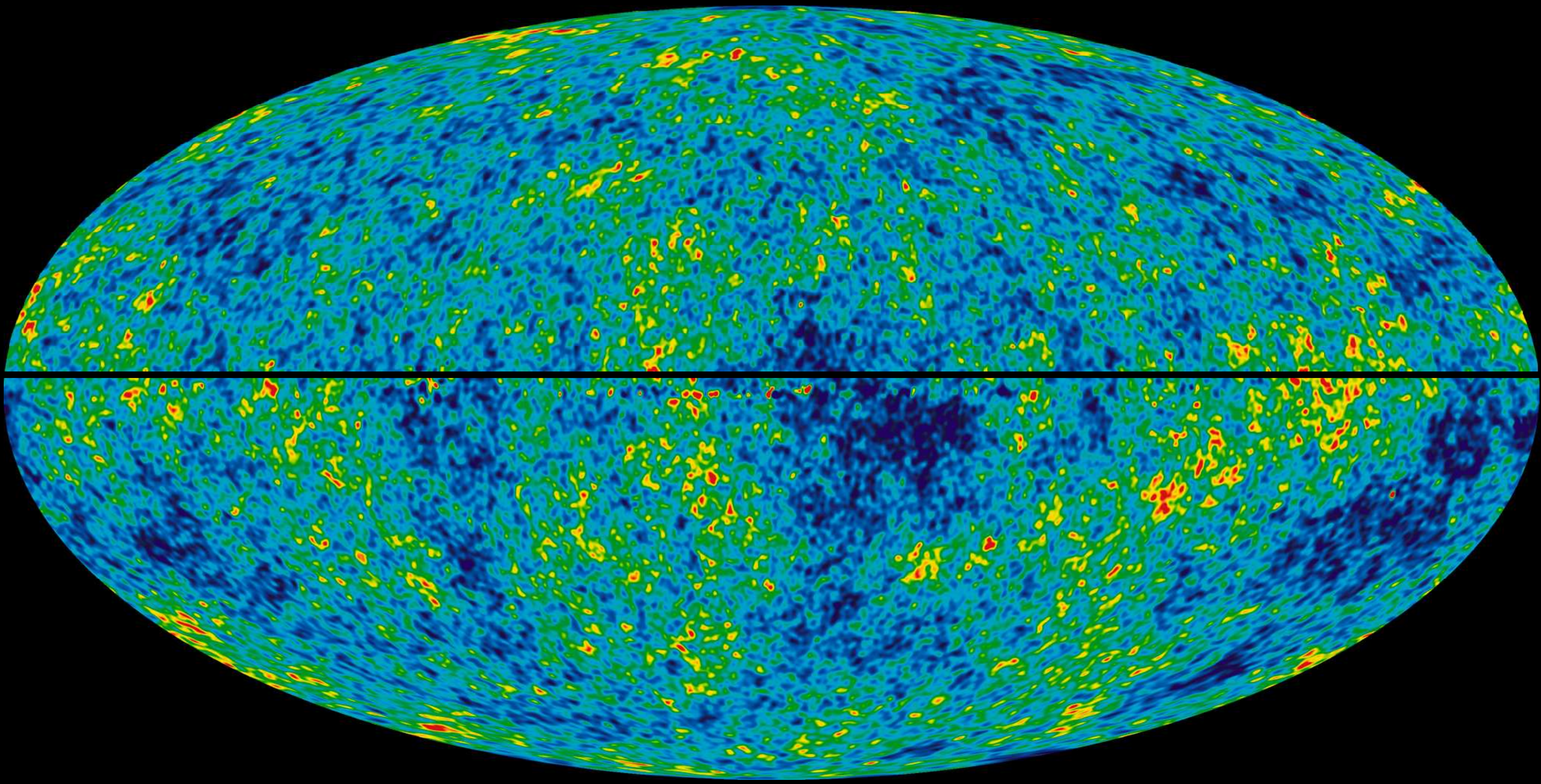


Instrument Front-end Assembly

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° x 0.3° 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° x 3.5° field of view				
Pointing accuracy	0.6° control (elevation); 1.8' knowledge				

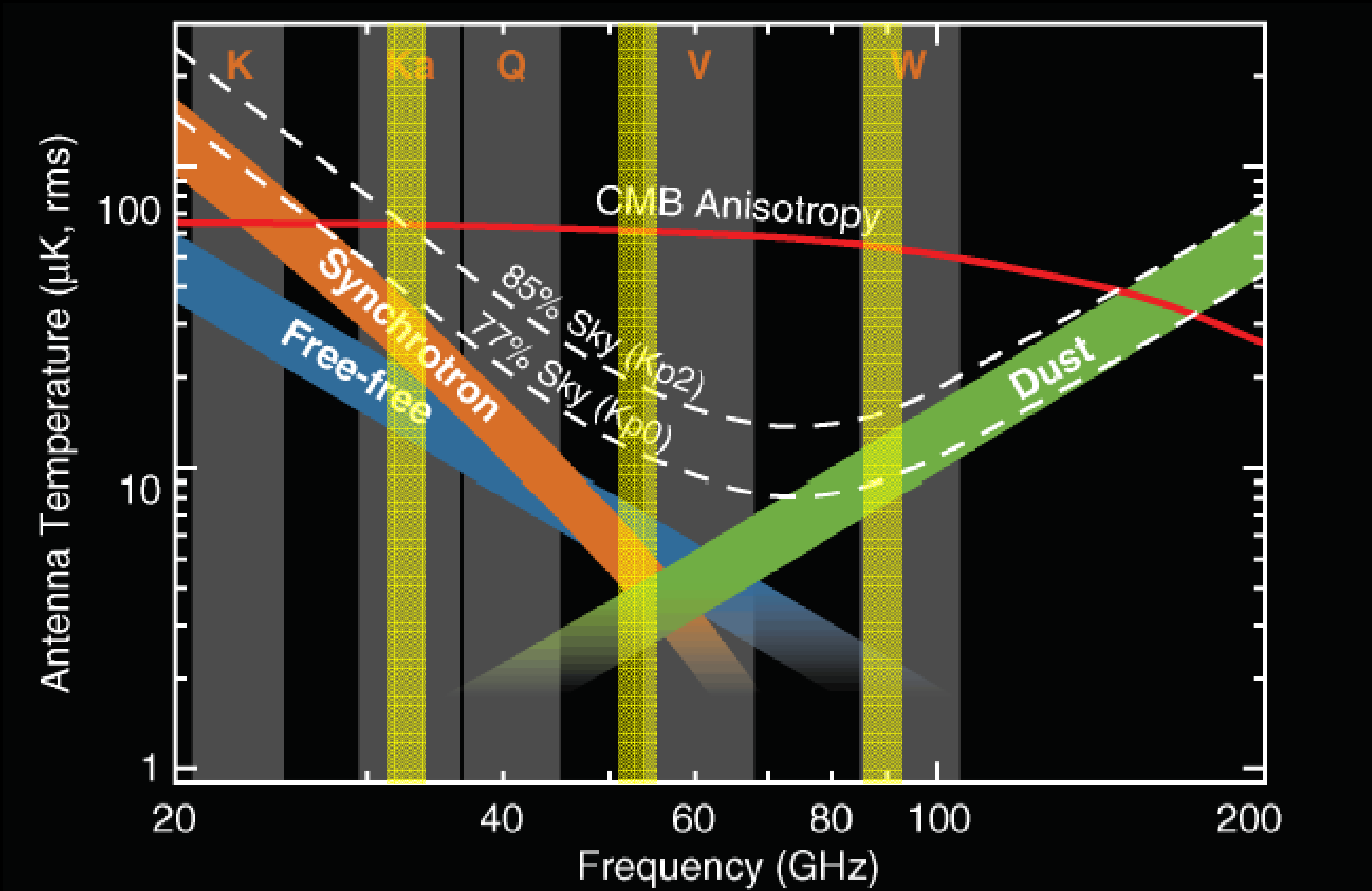
WMAP W-band feed horn

The universe 13.7 billion years ago



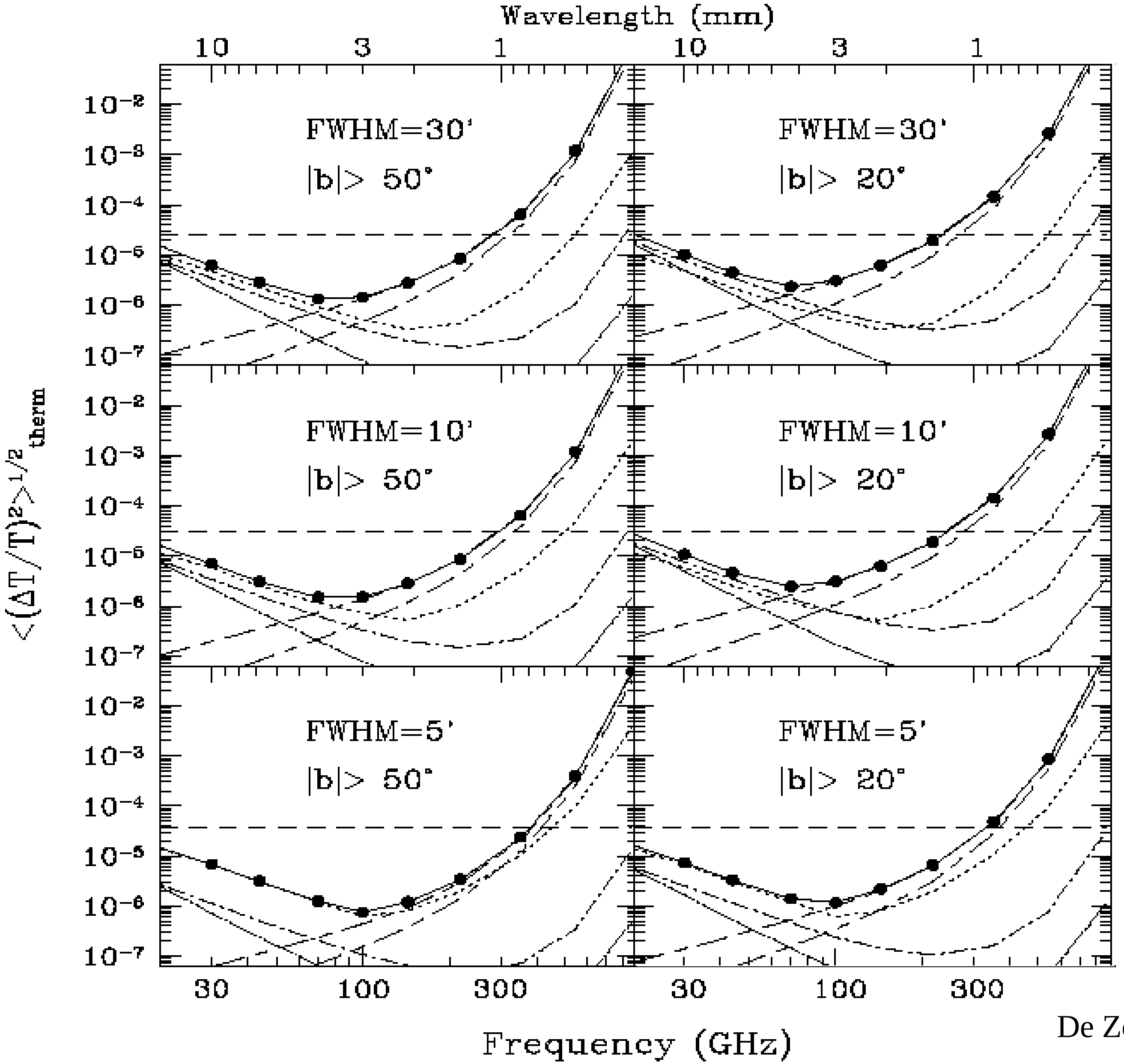
WMAP, 2000

Foreground contributions to microwave sky fluctuations



WMAP: 23 GHz, 31 GHz, 41 GHz, 60GHz, 90 GHz

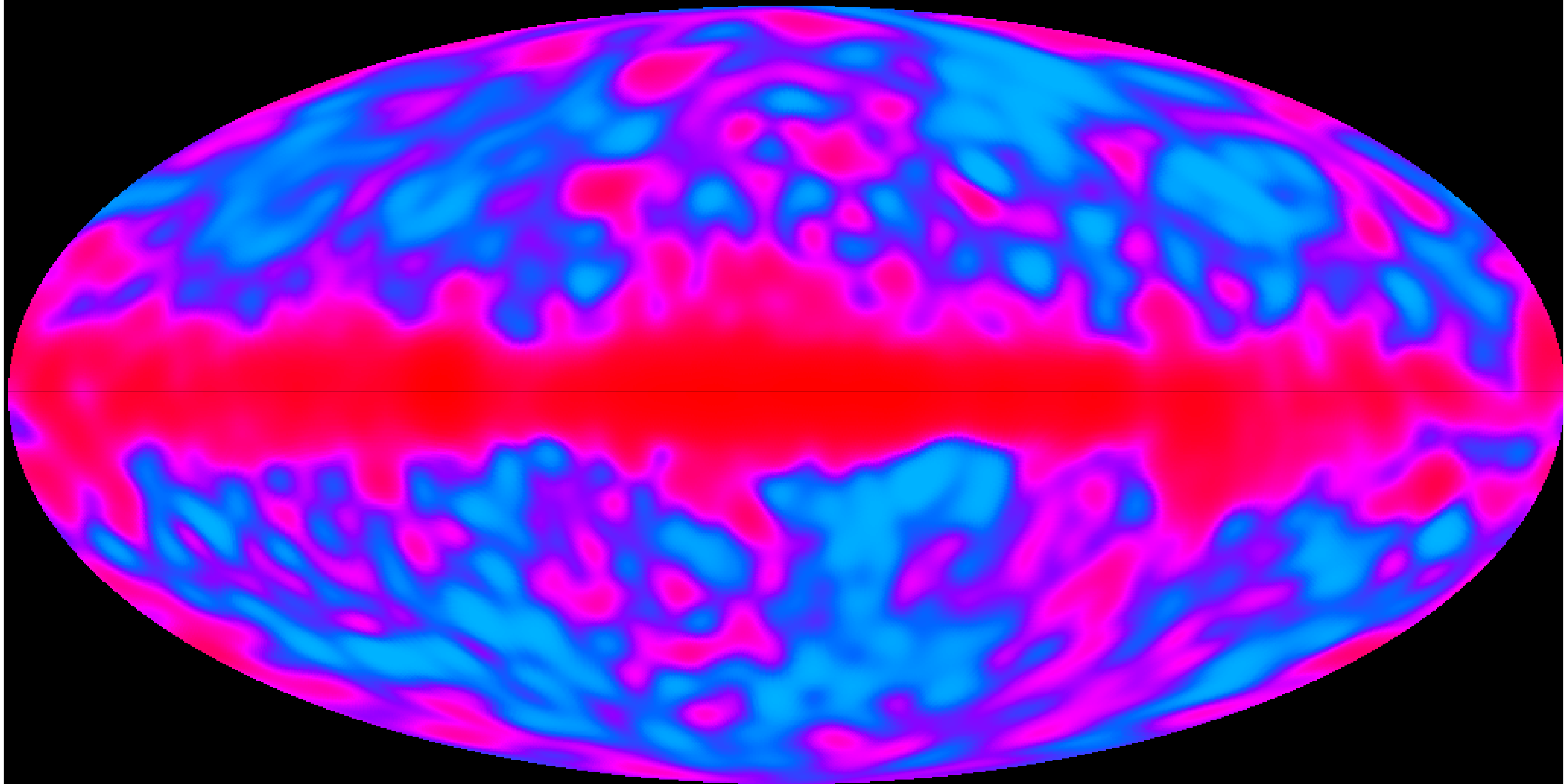
COBE–DMR: 31.5 GHz, 53 GHz, 90 GHz



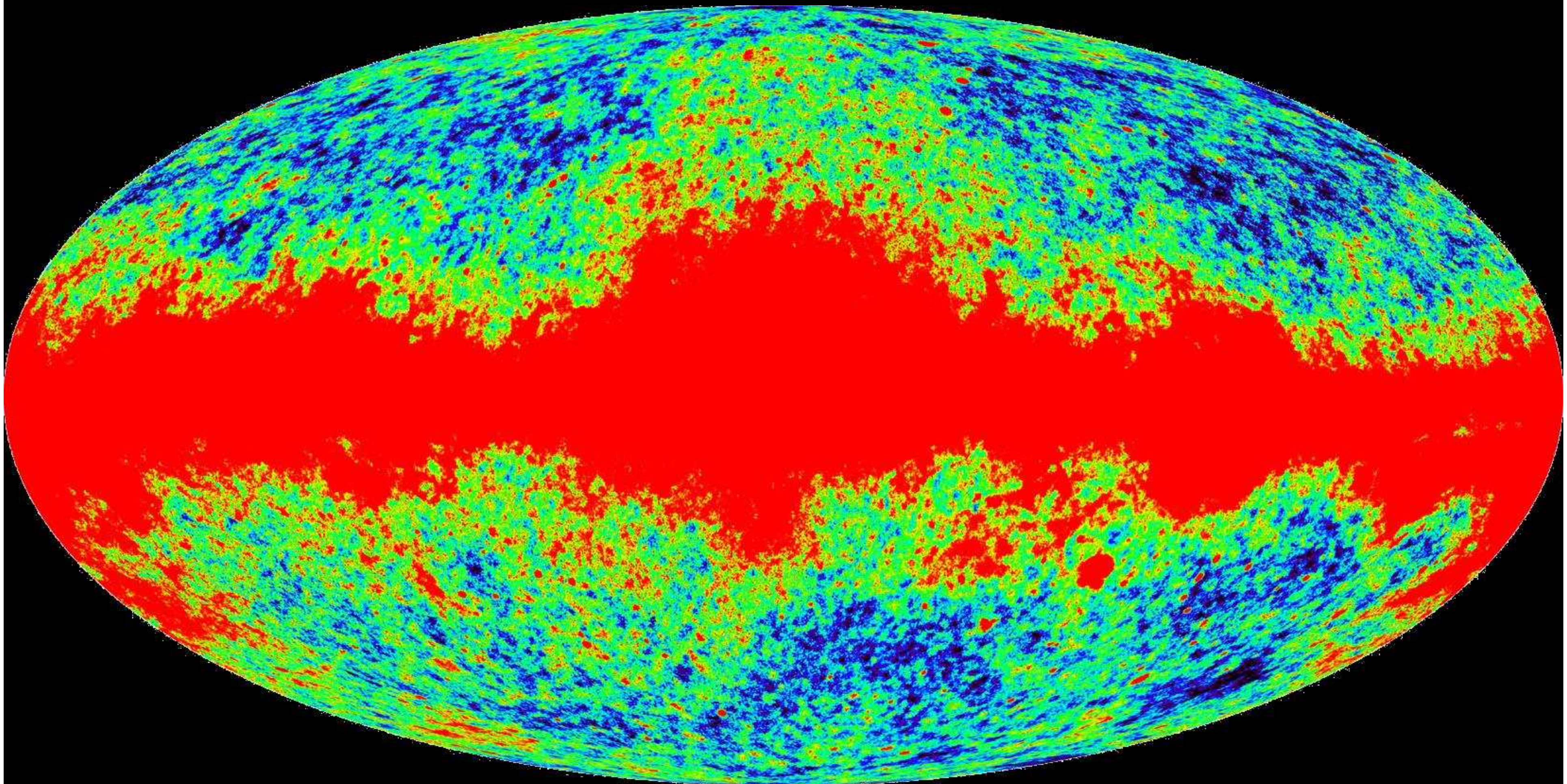
De Zotti et al 2005

Minimum of foregrounds near 70GHz

From COBE…

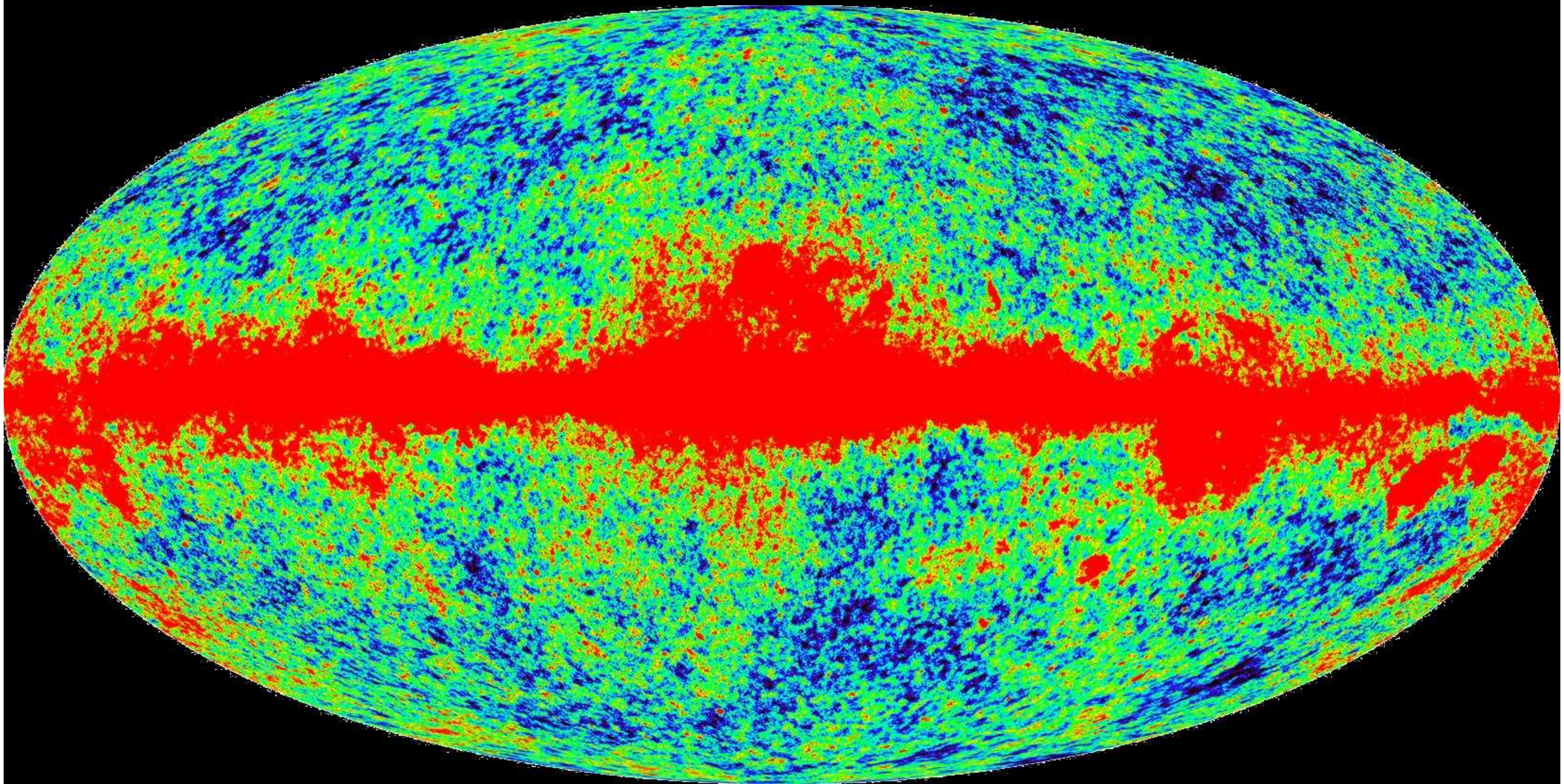


… to WMAP



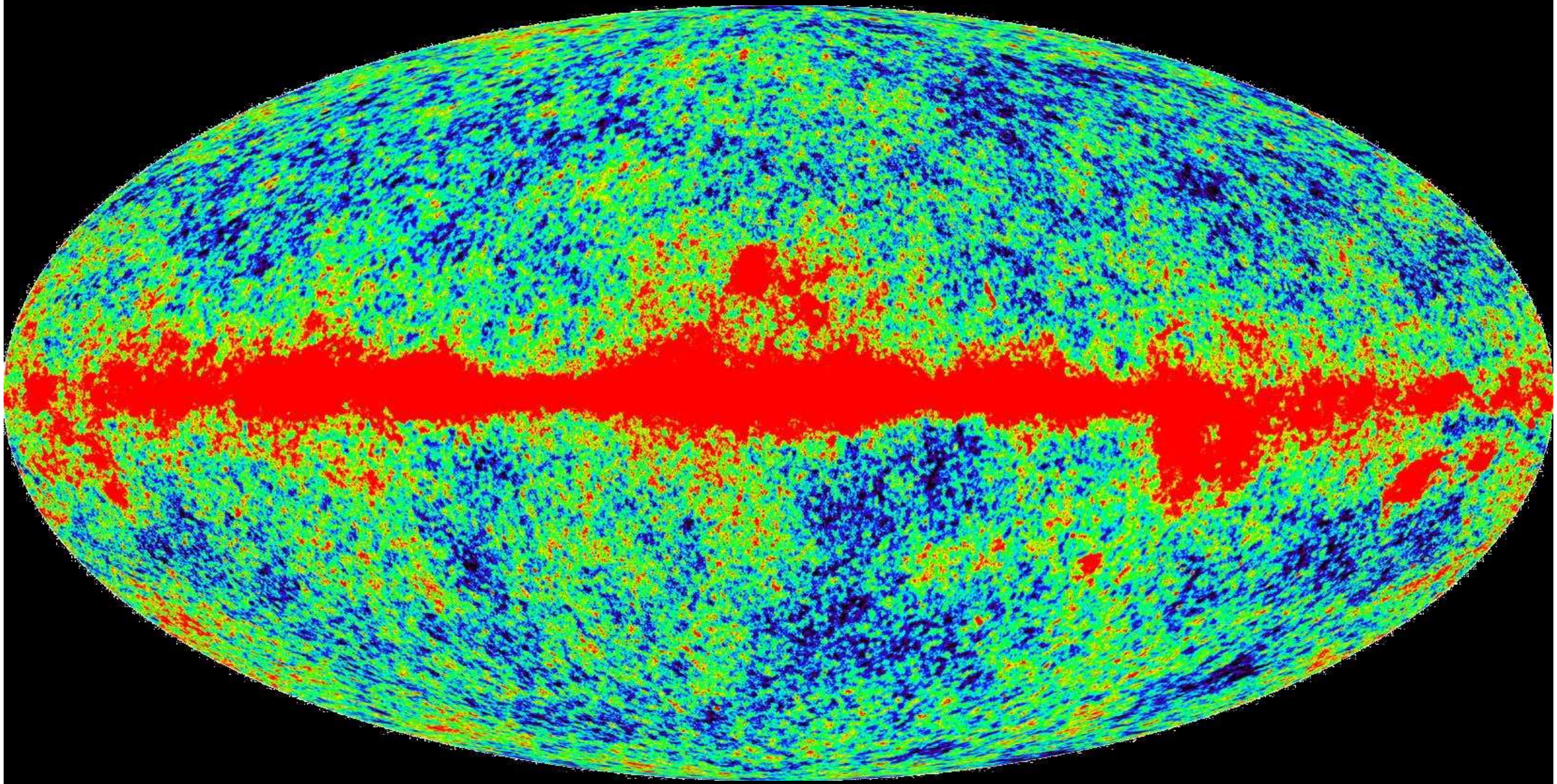
22 GHz

... to WMAP



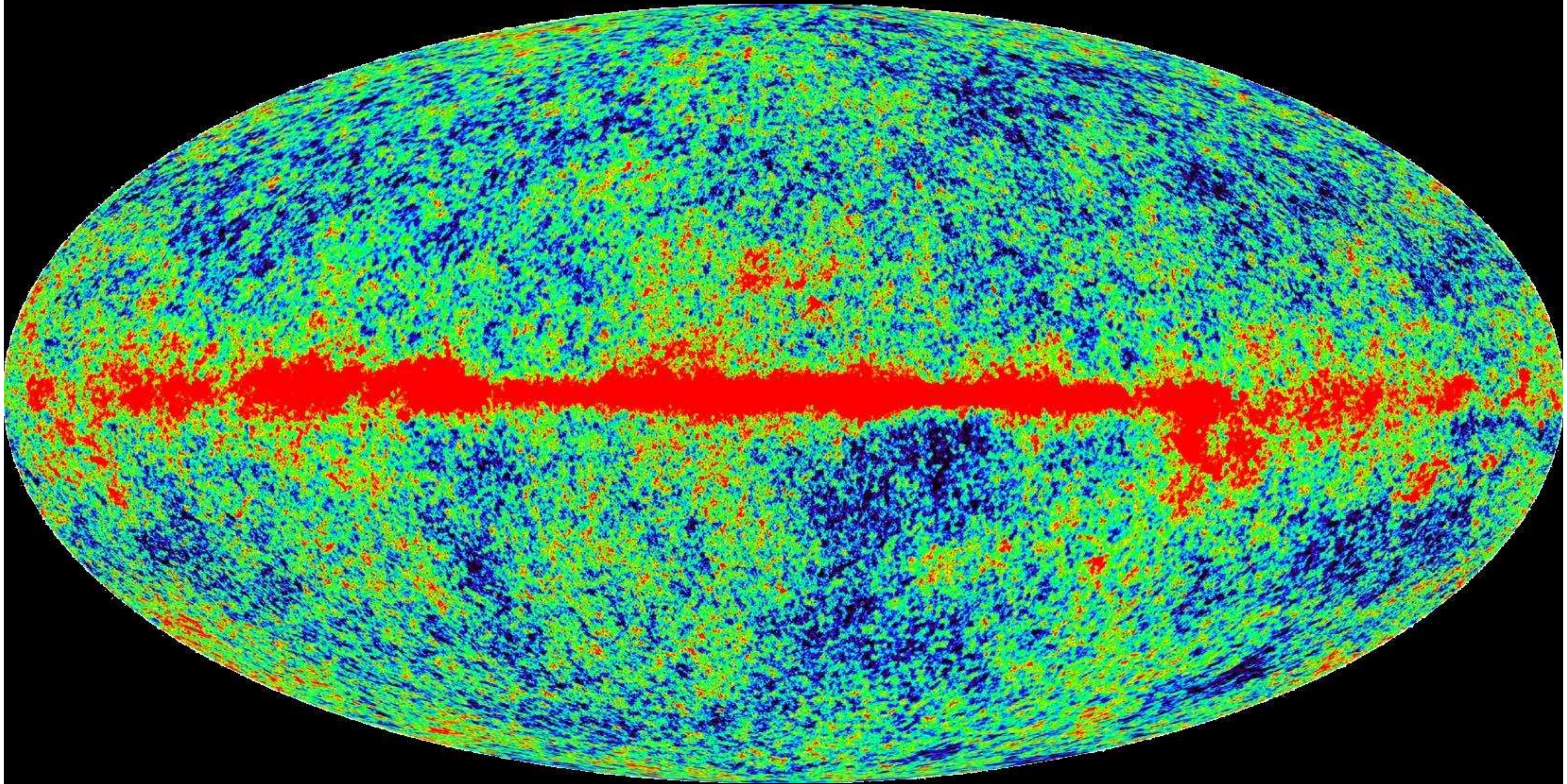
30 GHz

... to WMAP



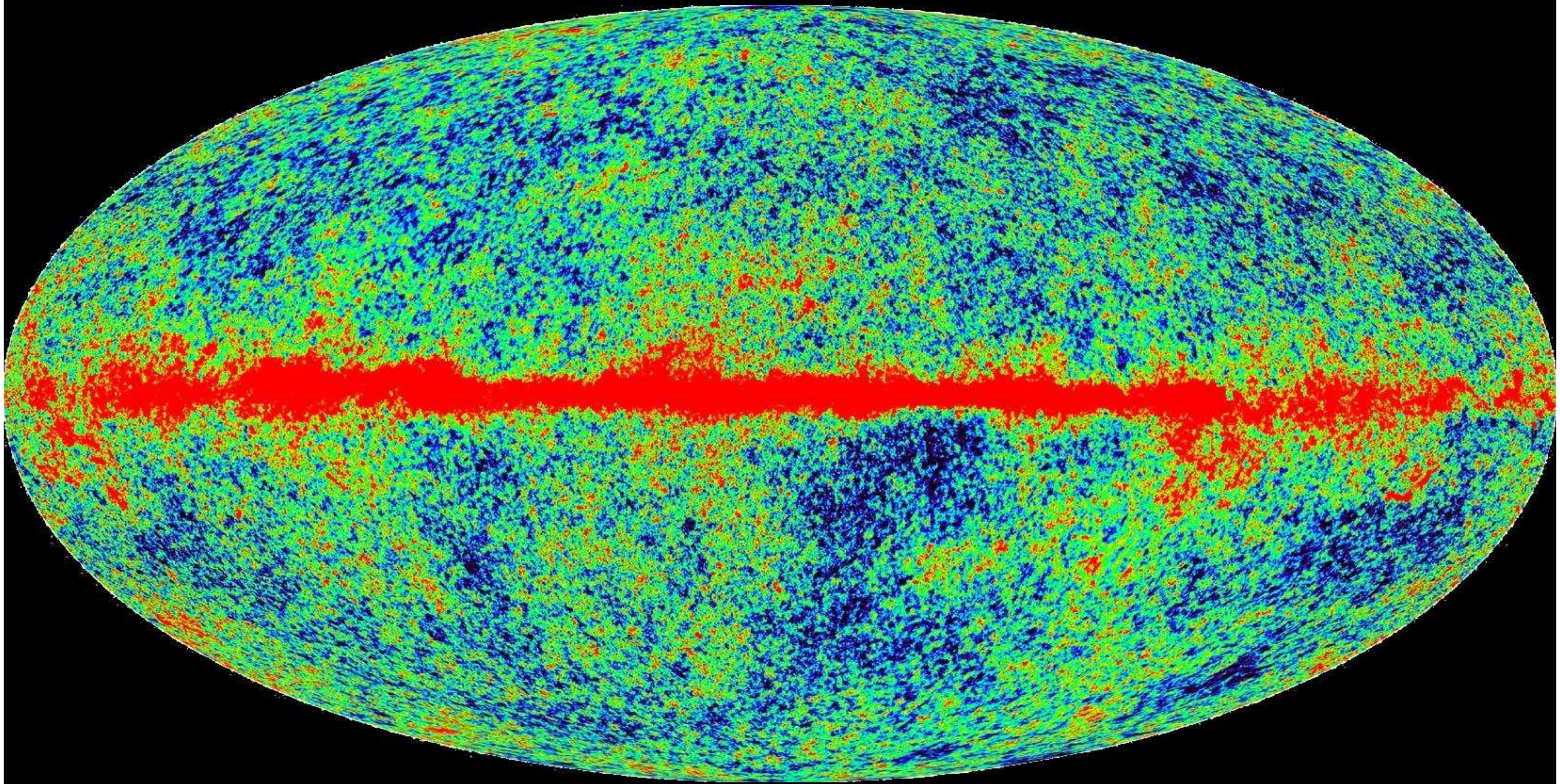
40 GHz

... to WMAP



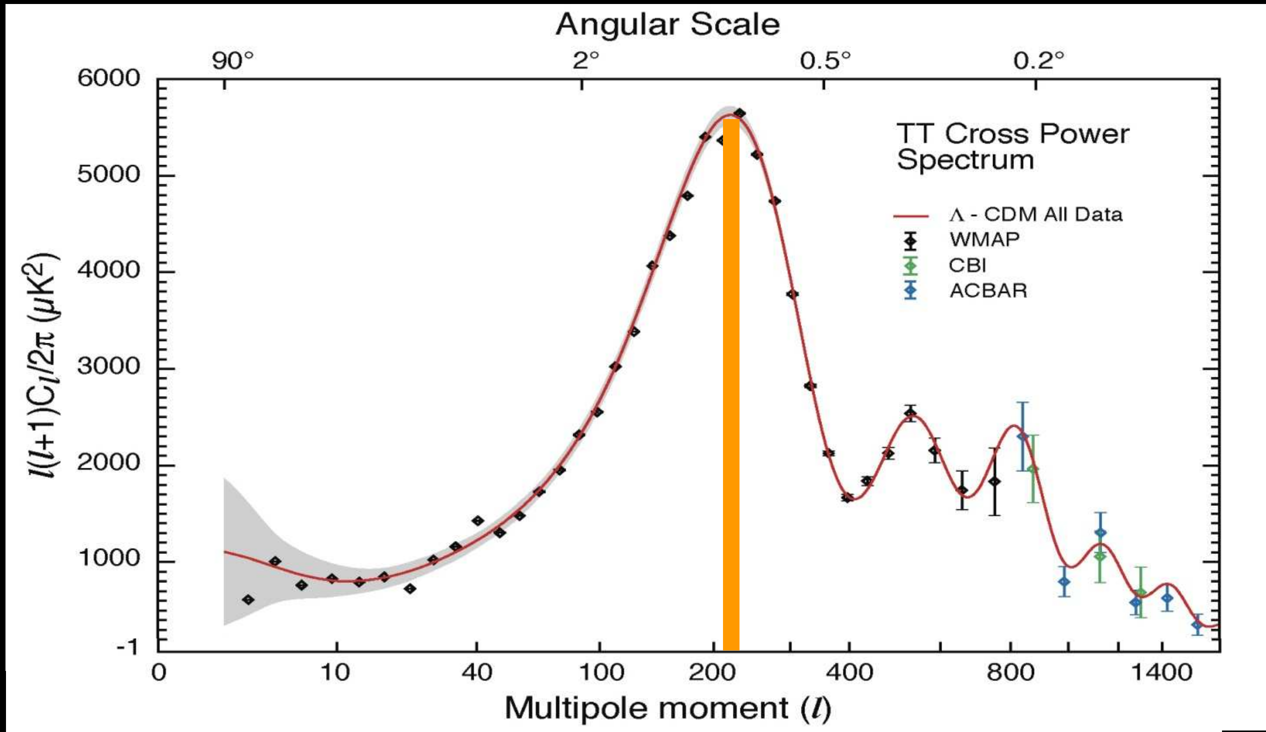
60 GHz

... to WMAP



90 GHz

Measuring cosmological parameters



Cfr HST key project!!

Consistent with inflation

We do not understand 96% of our universe!

Derived by difference

For details see:
Komatsu et al. 2008

Measurements of distant SN Ia

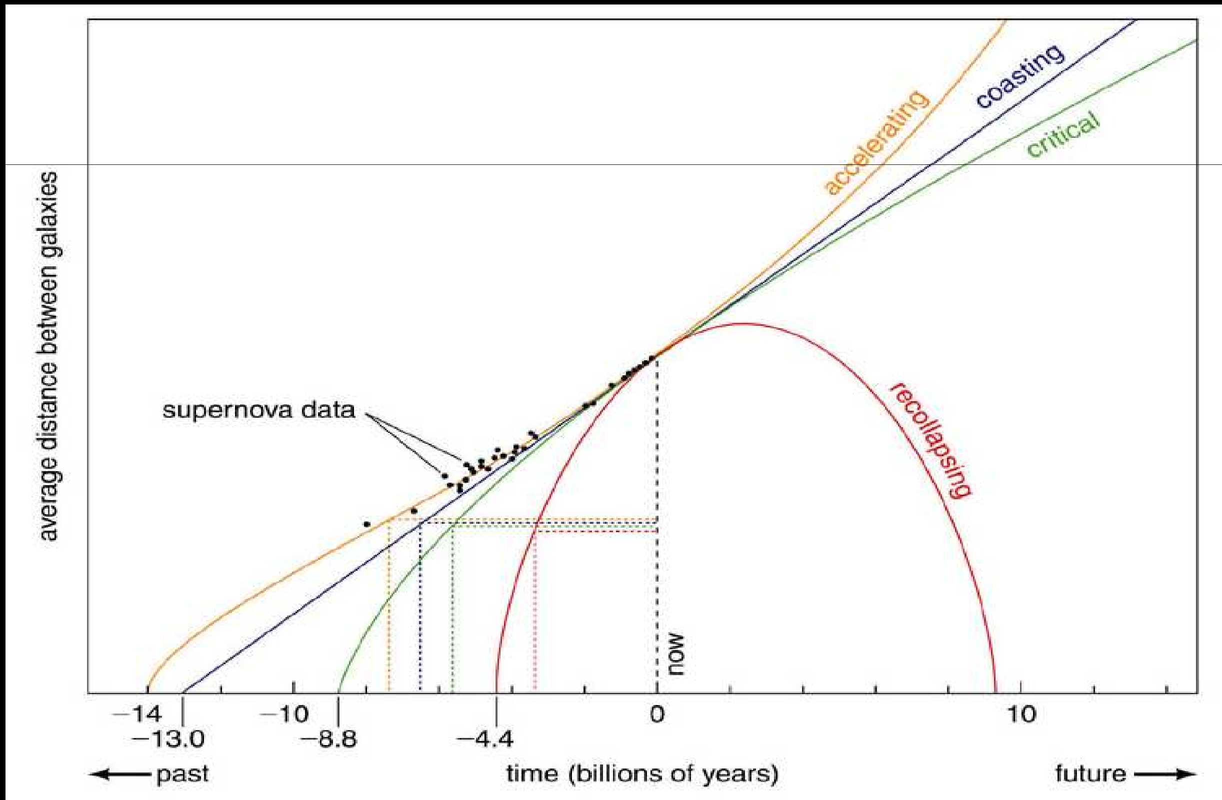
Radiation Matter Vacuum

$$\left(\frac{\dot{R}}{R}\right)^2 = H_0^2\left[\frac{\Omega_R}{R^4} + \frac{\Omega_M}{R^3} + \frac{\Omega_\Lambda}{R^0}\right] - \frac{kc^2}{R^2}$$

Evolution

Geometry

Freedmann Equation



Albert Einstein

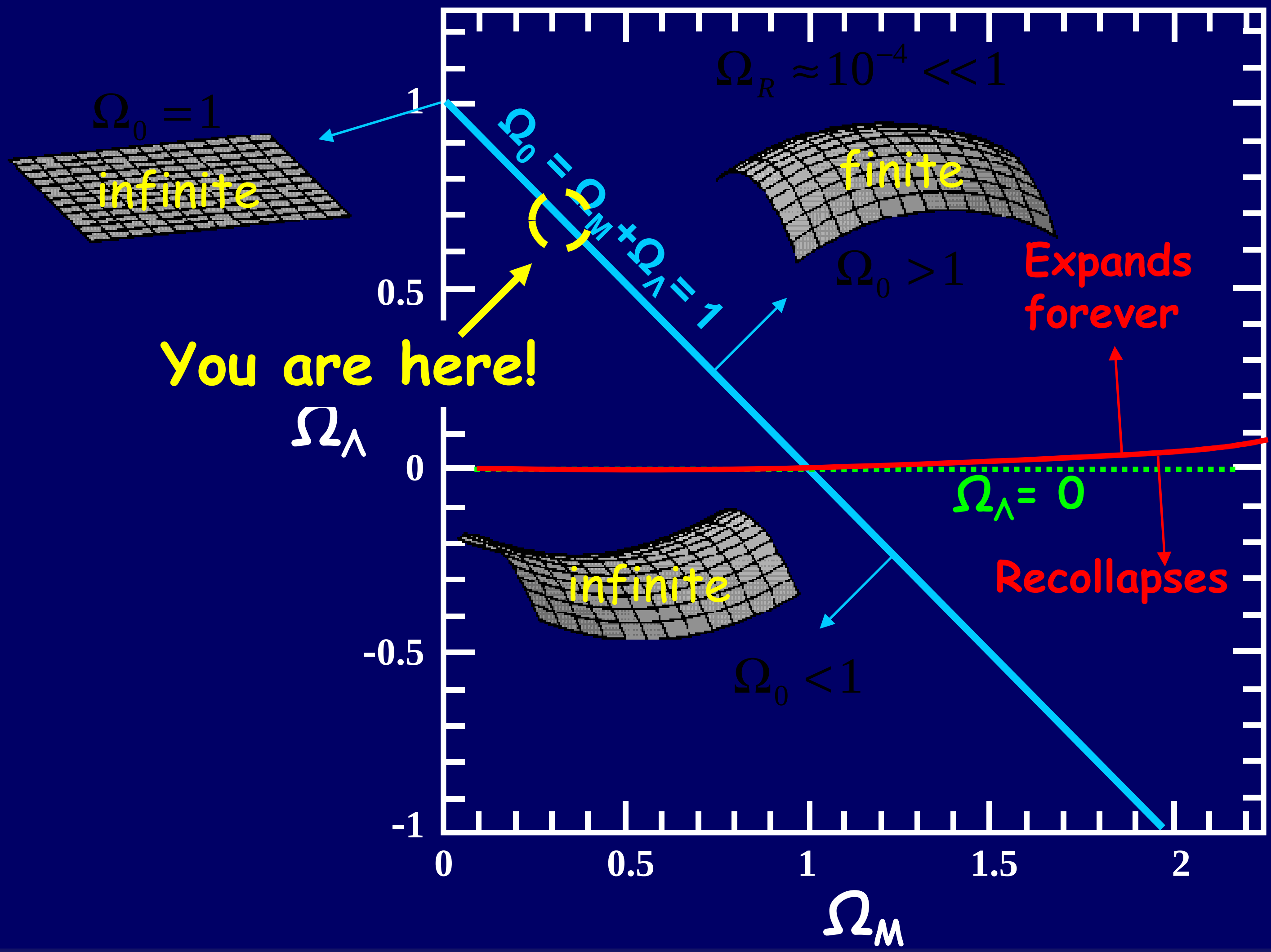
Alexander Friedmann

Georges Lemaitre

Parameter space

1. General relativity   2. Cosmological principle, RW metrics

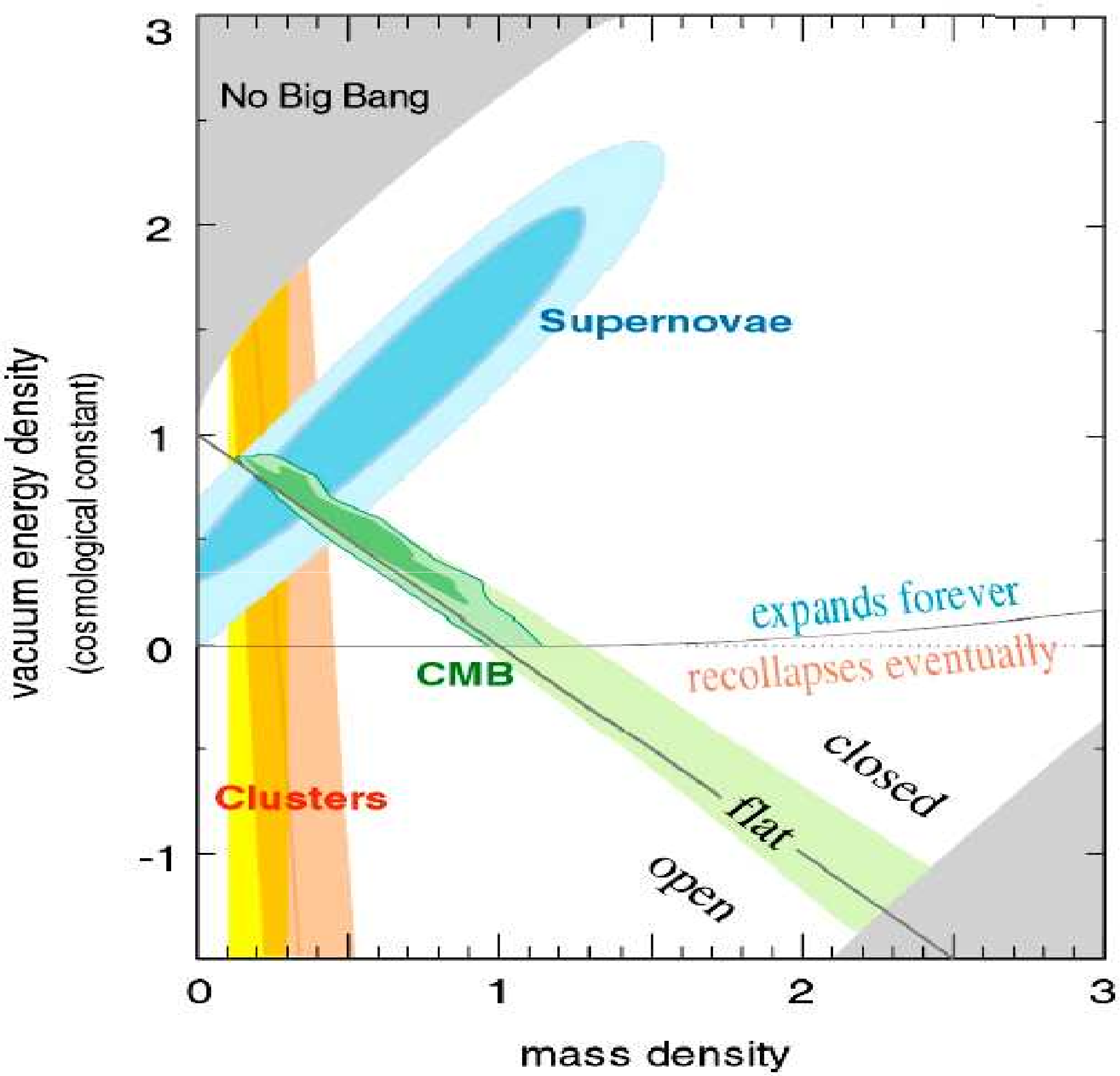
3. Simply connected topology



Non-zero Ω_Λ

A closed Universe can expand forever

An open Universe can recollapse

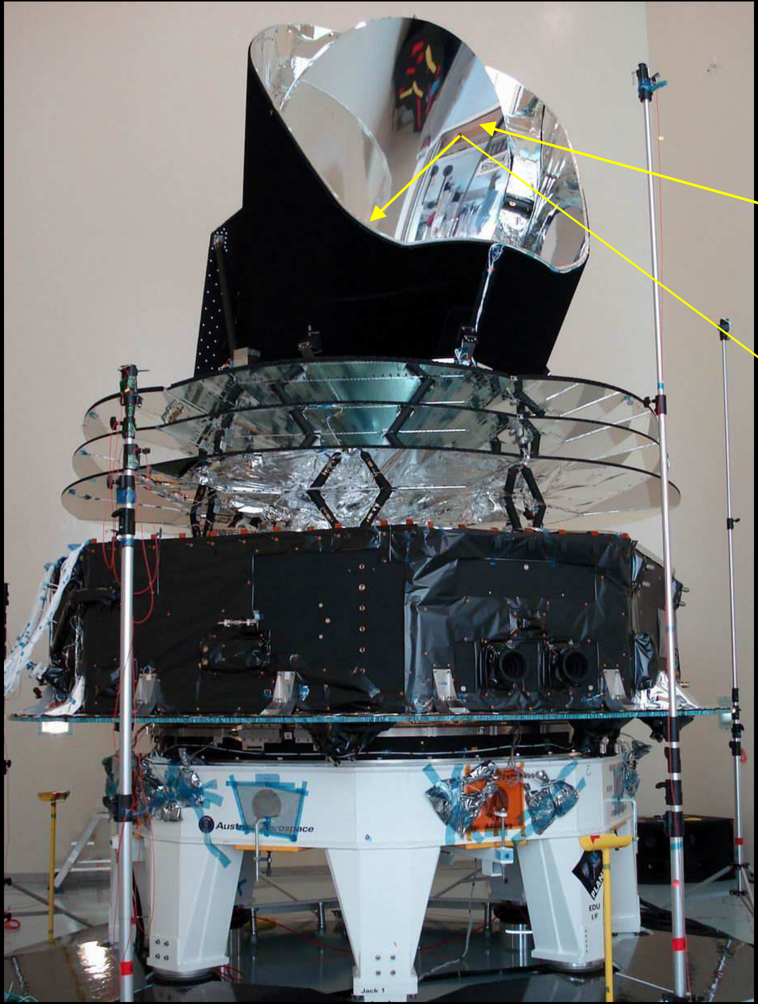

3
2
1
0
-1
No Big Bang
Supernovae
expands forever
recollapses eventually
CMB
closed
Clusters
flat
open
0
1
2
3
mass density
vacuum energy density
(cosmological constant)

Unknown universe

- What are the constituents of the universe?
- What is the destiny of cosmic expansion?
- What happened in the very first moments (inflation)?

PLANCK

Looking back to the dawn of time

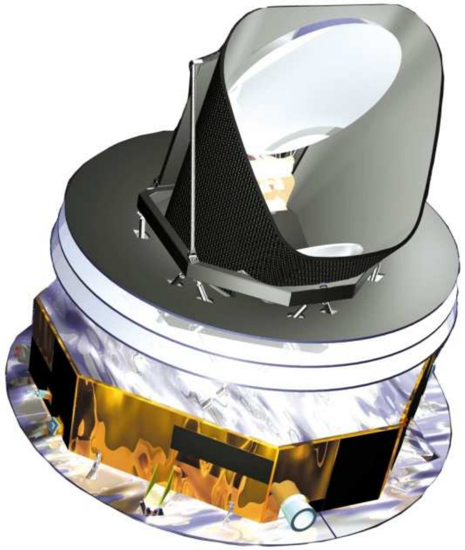


Planck Telescope
1.5x1.9m off-axis
Gregorian
T = 50 K

LFI Radiometers
27-77 GHz, T = 20 K

HFI Bolometers
100-850 GHz, T = 0.1 K

PLANCK



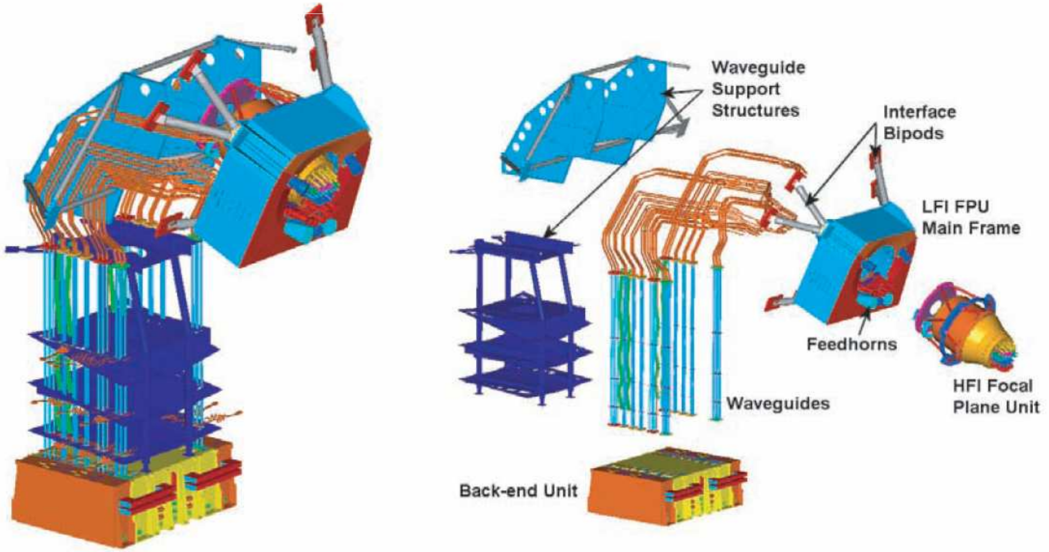
Design goals

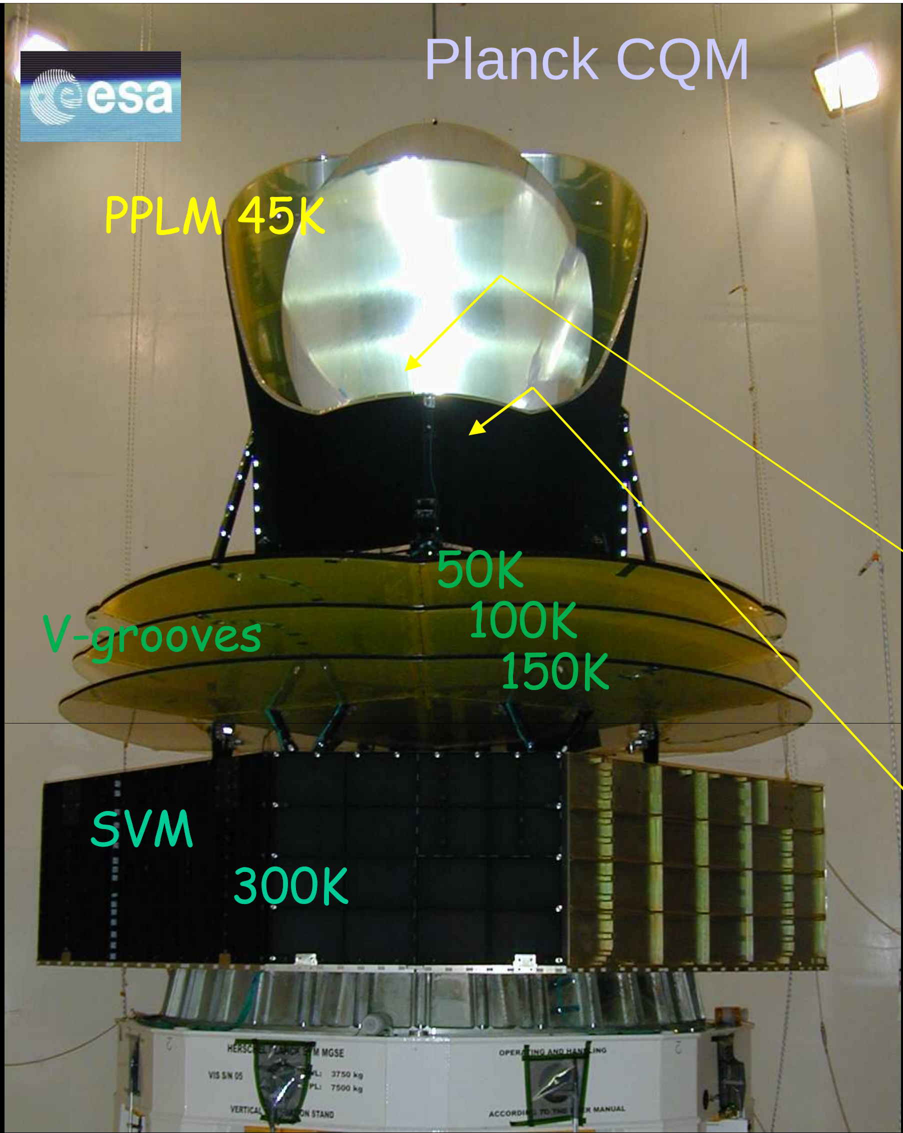
- Angular resolution: ~10'
- Sensitivity per pixel: < 10 μK
- Full frequency range: 30-900 GHz
- Polarisation sensitive in CMB channels
- Sky coverage: 100%
- High control of systematics

Two complementary cryogenic instruments in focal plane:

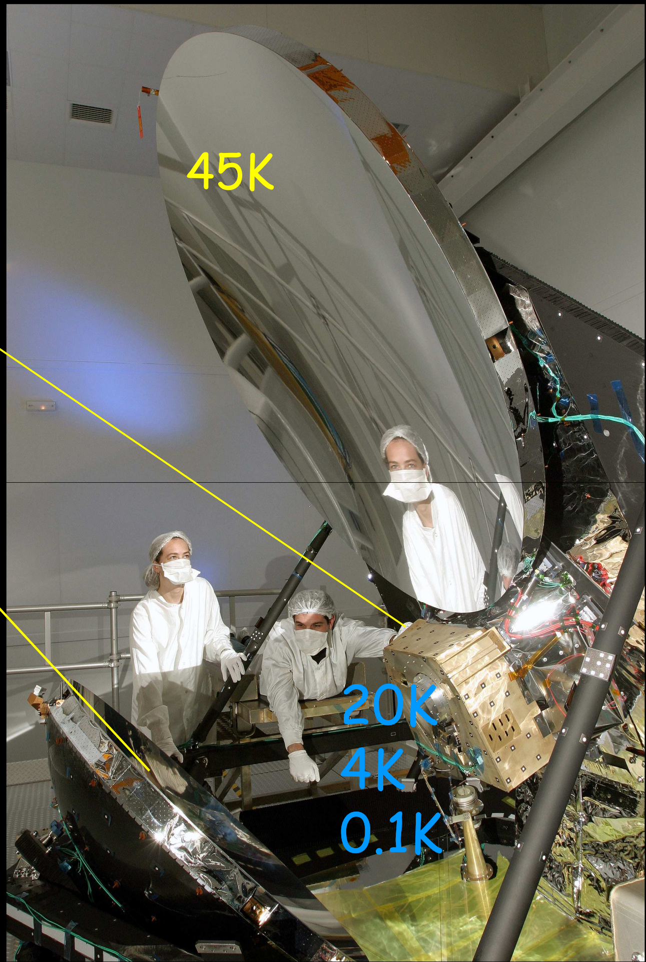
LFI: Radiometer array (20K)

HFI: Bolometer array (0.1K)



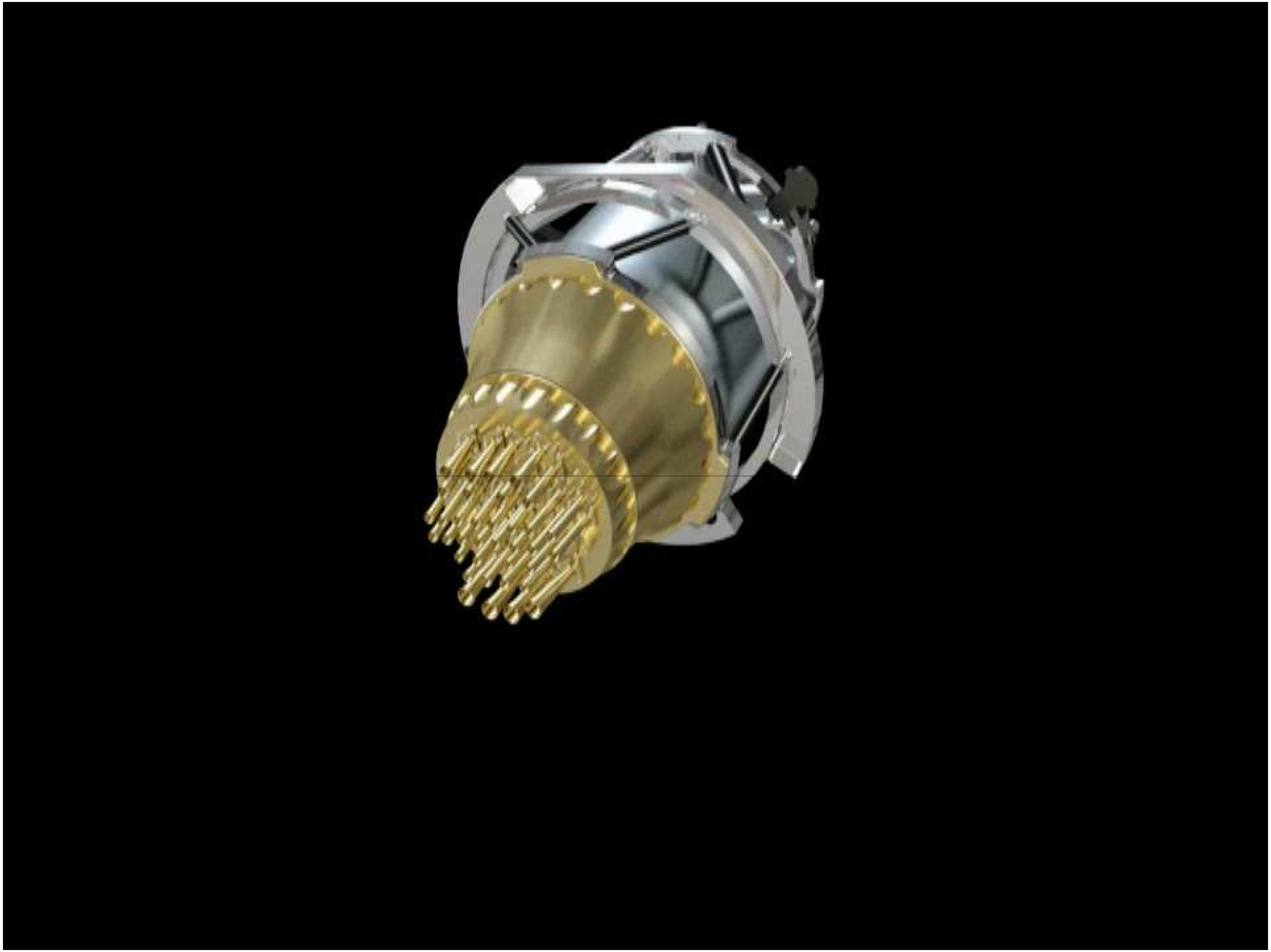


PLANCK



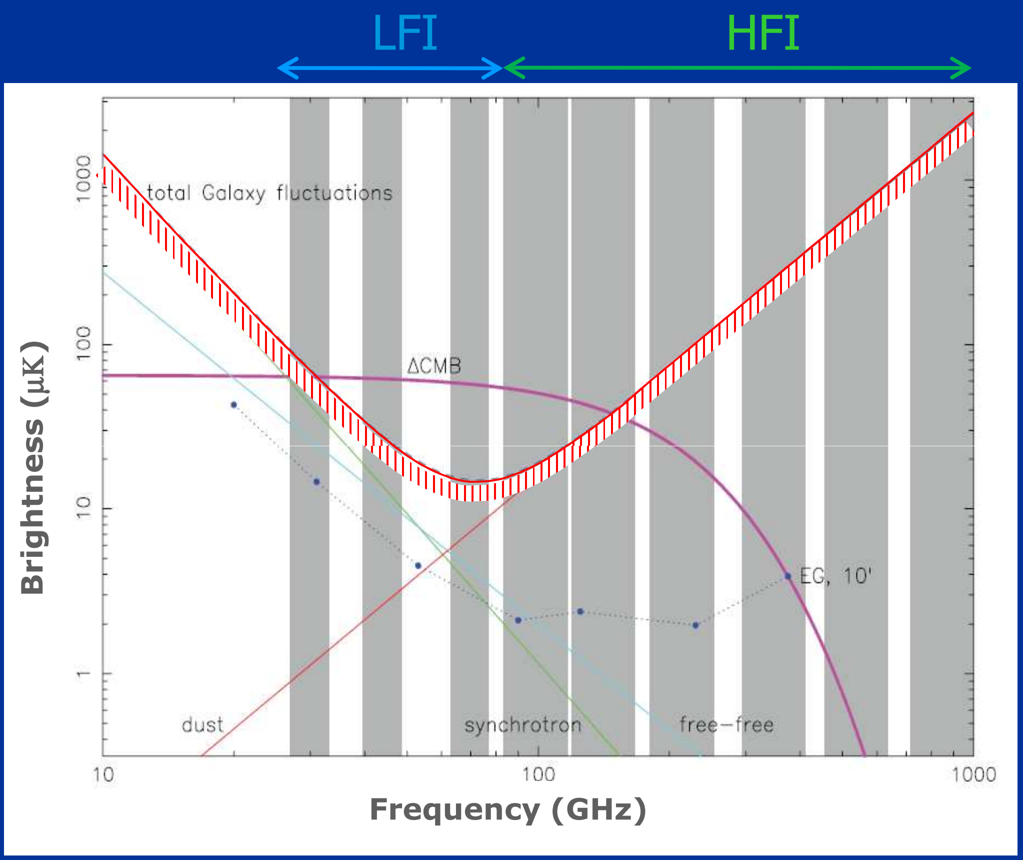
Focal plane unit

Measured thermal performance meets or surpasses design requirements



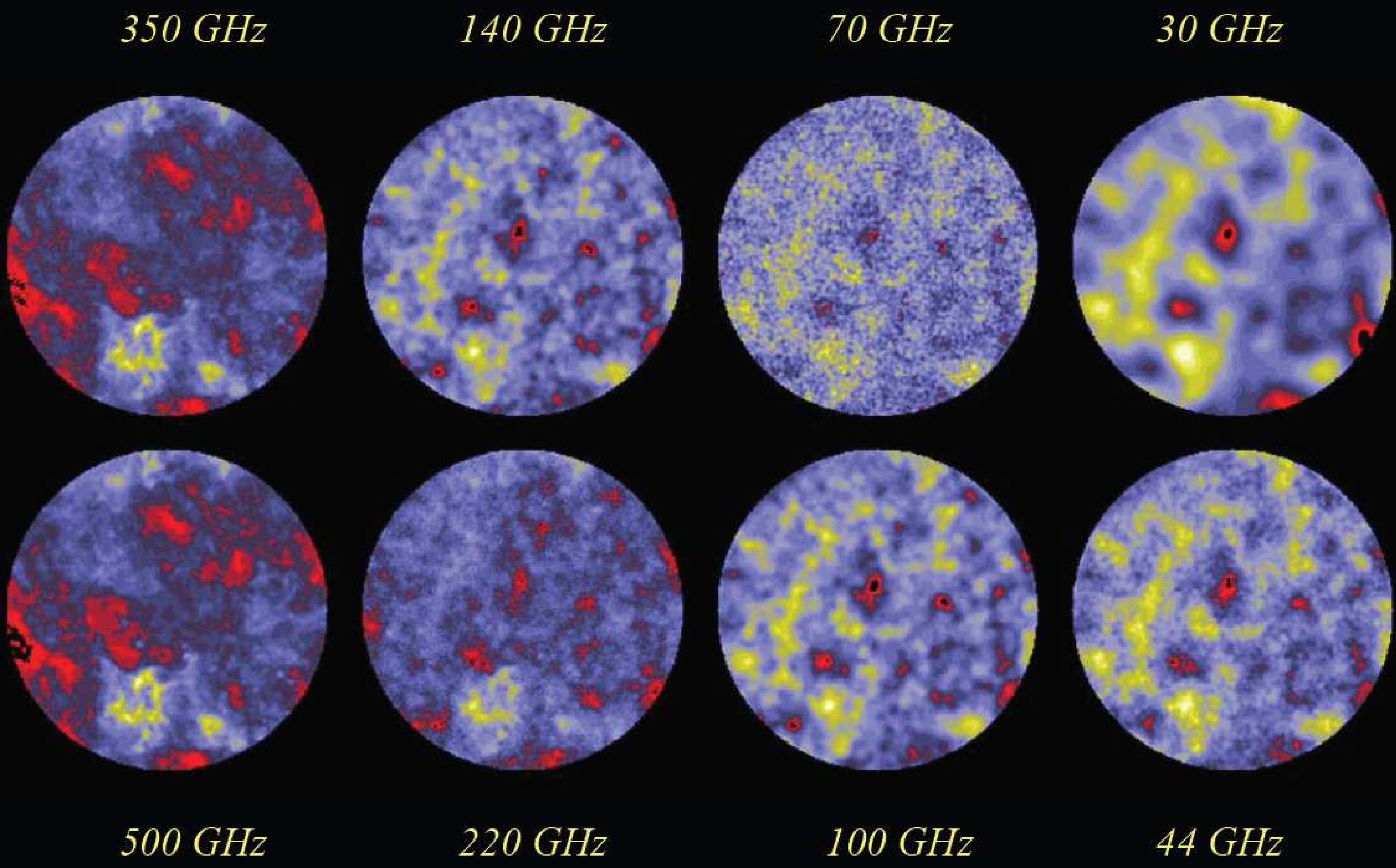
Foregrounds

Multifrequency observations are needed to disentangle non-cosmological contributions



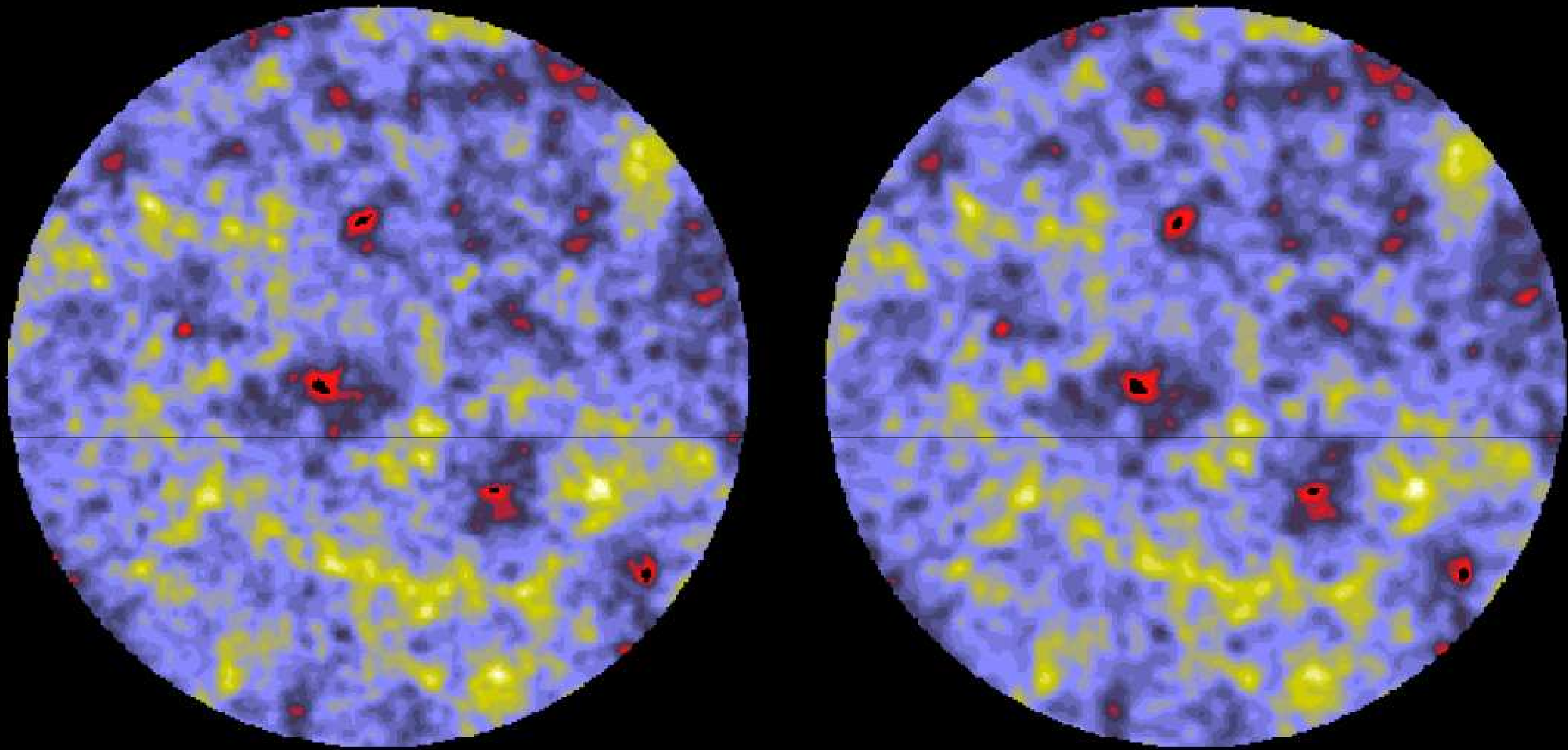
- Galactic diffuse emission (synchrotron, free-free, dust)
- Extragalactic point sources

PLANCK



PLANCK

CMB Input *CMB Recovered*

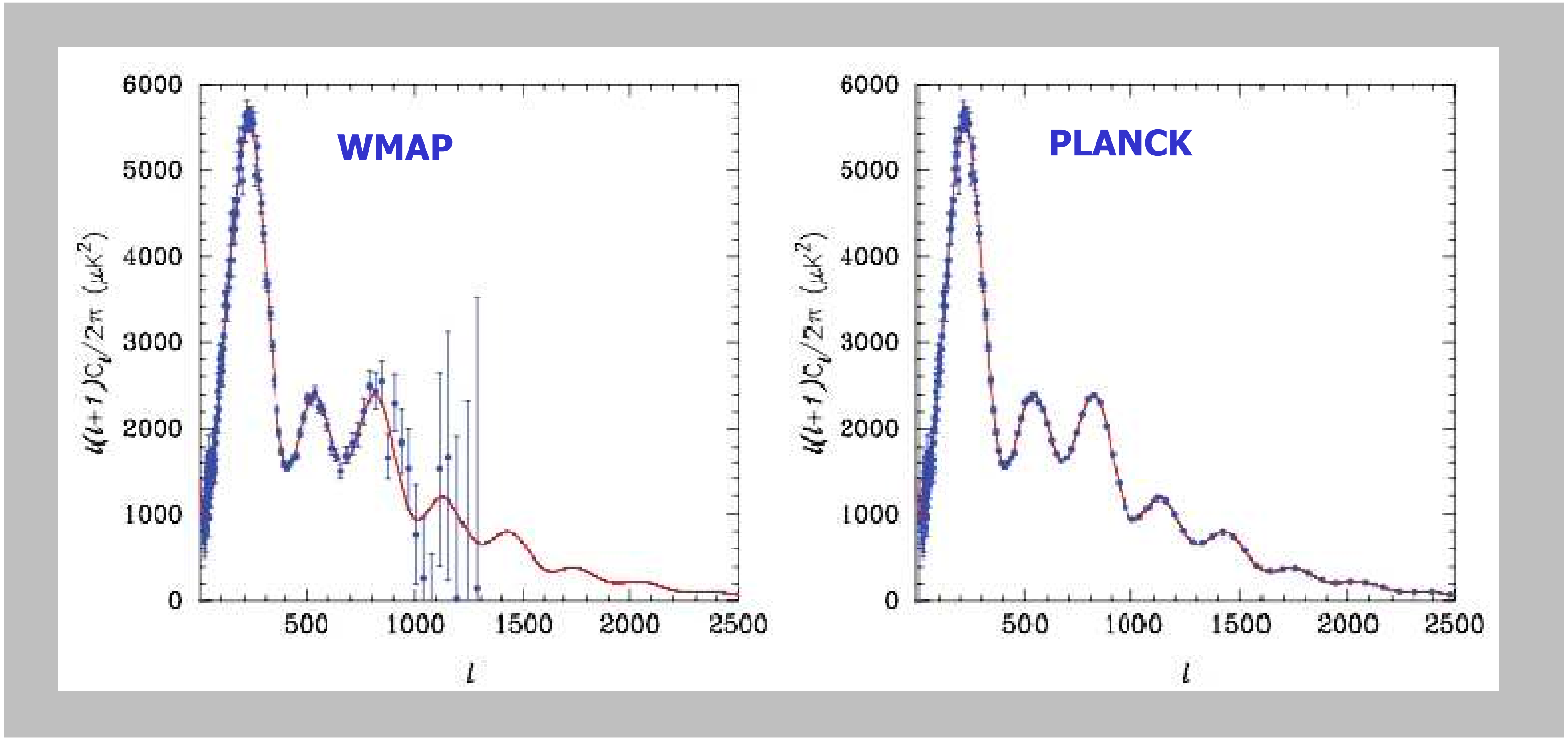


Not only statistical measure, but high singal-to-noise imaging

	WMAP	PLANCK
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	4+ yr	>14 months
Spectral coverage	23-95 GHz	27-900 GHz
Detector technology	HEMT	HEMT+BOL
Detector temperature	90 K	20K/4K/0.1K
Cooling	Passive	Active

Precision cosmology with Planck

ESA-SCI(2005)1 ("Blue book")



Precision cosmology with Planck: Temparature anisotropy

ESA-SCI(2005)1 ("Blue book")

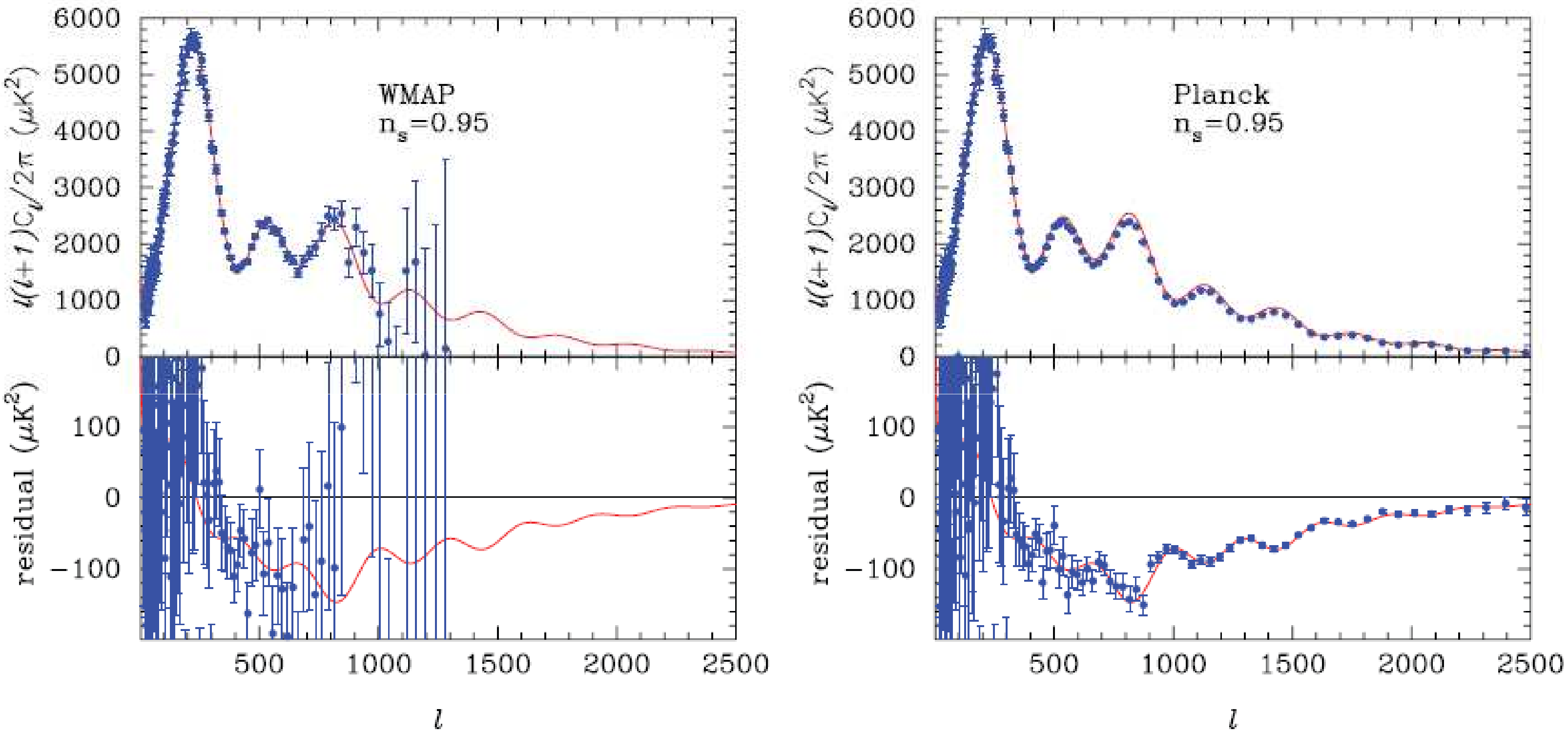


FIG 2.11.—The solid lines in the upper panels of these figures show the power spectrum of the concordance ΛCDM model with an exactly scale invariant power spectrum, $n_S = 1$. The points, on the other hand, have been generated from a model with $n_S = 0.95$ but otherwise identical parameters. The lower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

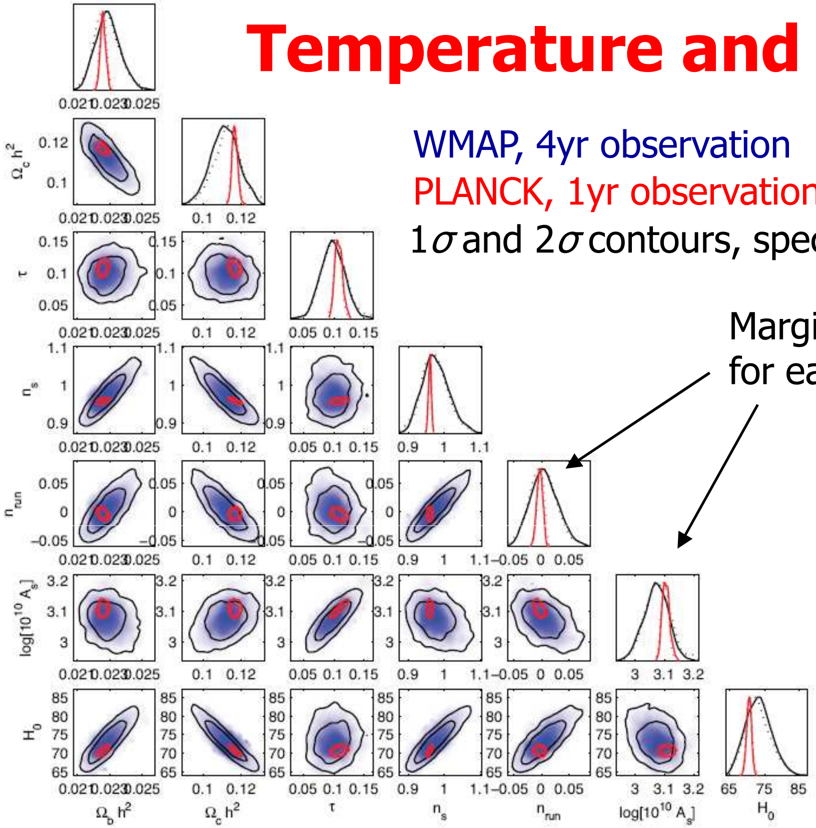
Precision cosmology with Planck

Cosmological parameters

Temperature and Polarisation power spectra

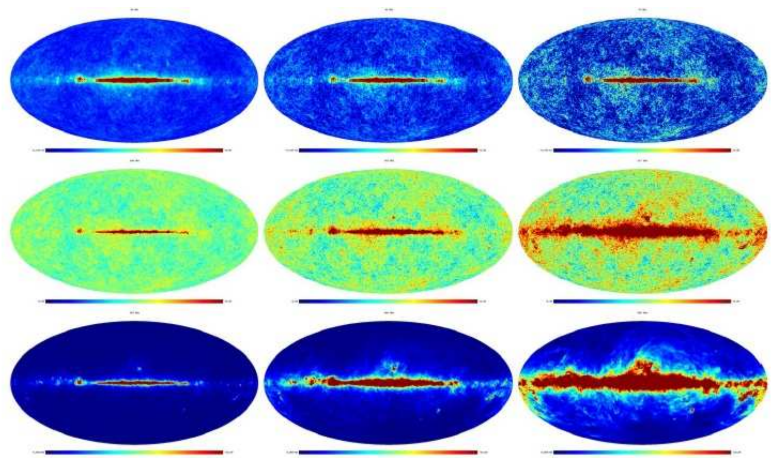
WMAP, 4yr observation
PLANCK, 1yr observation
1σ and 2σ contours, spectral index allowed to run

Marginalized posterior distributions
for each parameter



Imaging

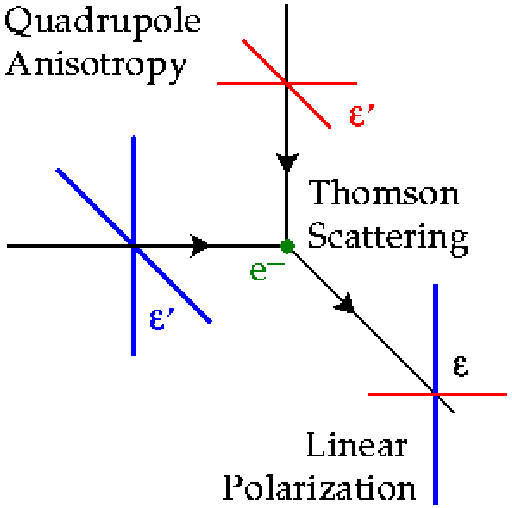
Beyond the power spectrum

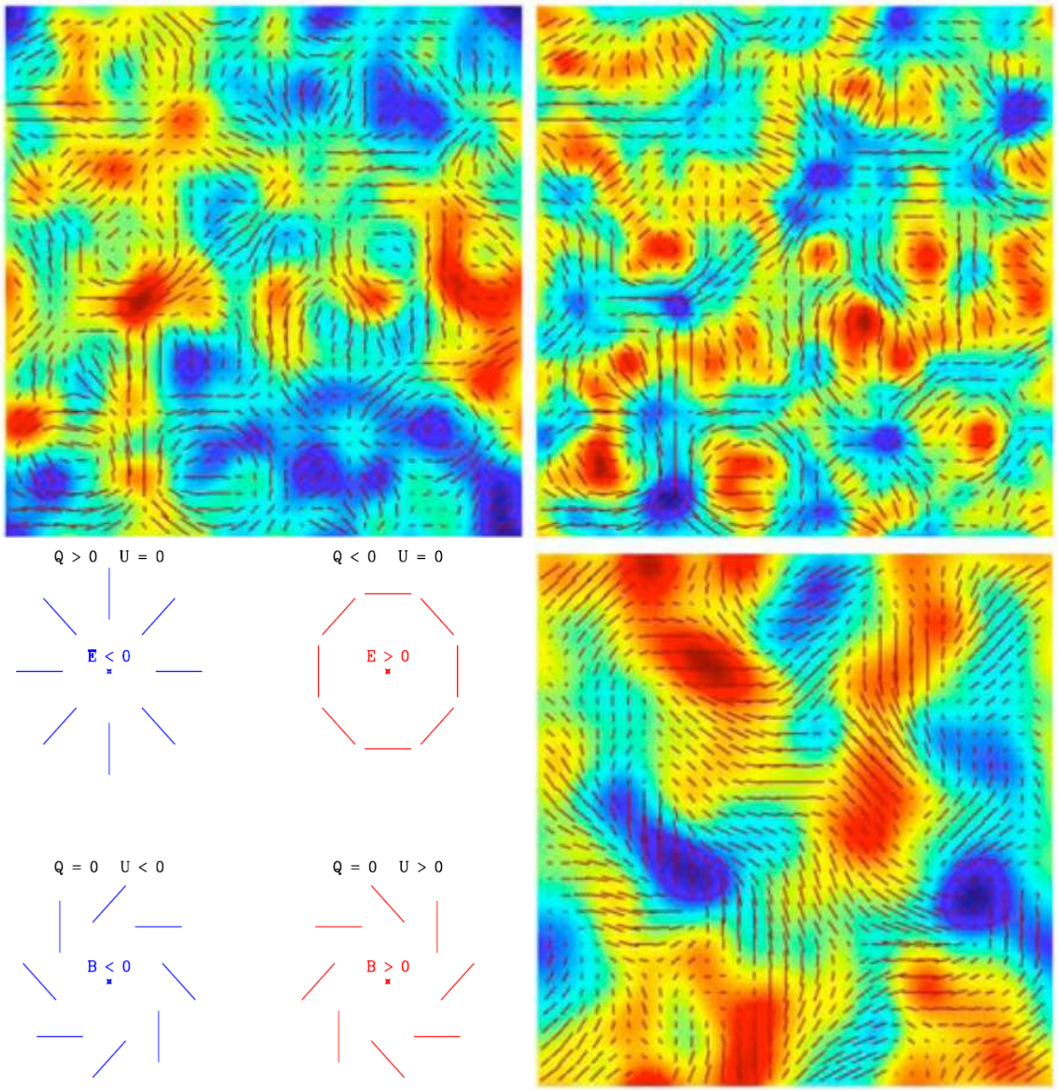


Cosmology (non-Gaussianity)

Astrophysical studies

CMB Polarisation





- Polarisation is generated in the last scattering layer
- Primordial gravitational waves can only produce B-modes
- Reionisation also adds a polarised B-mode signal – at large angular scales
- Weak lensing produces an additional perturbation

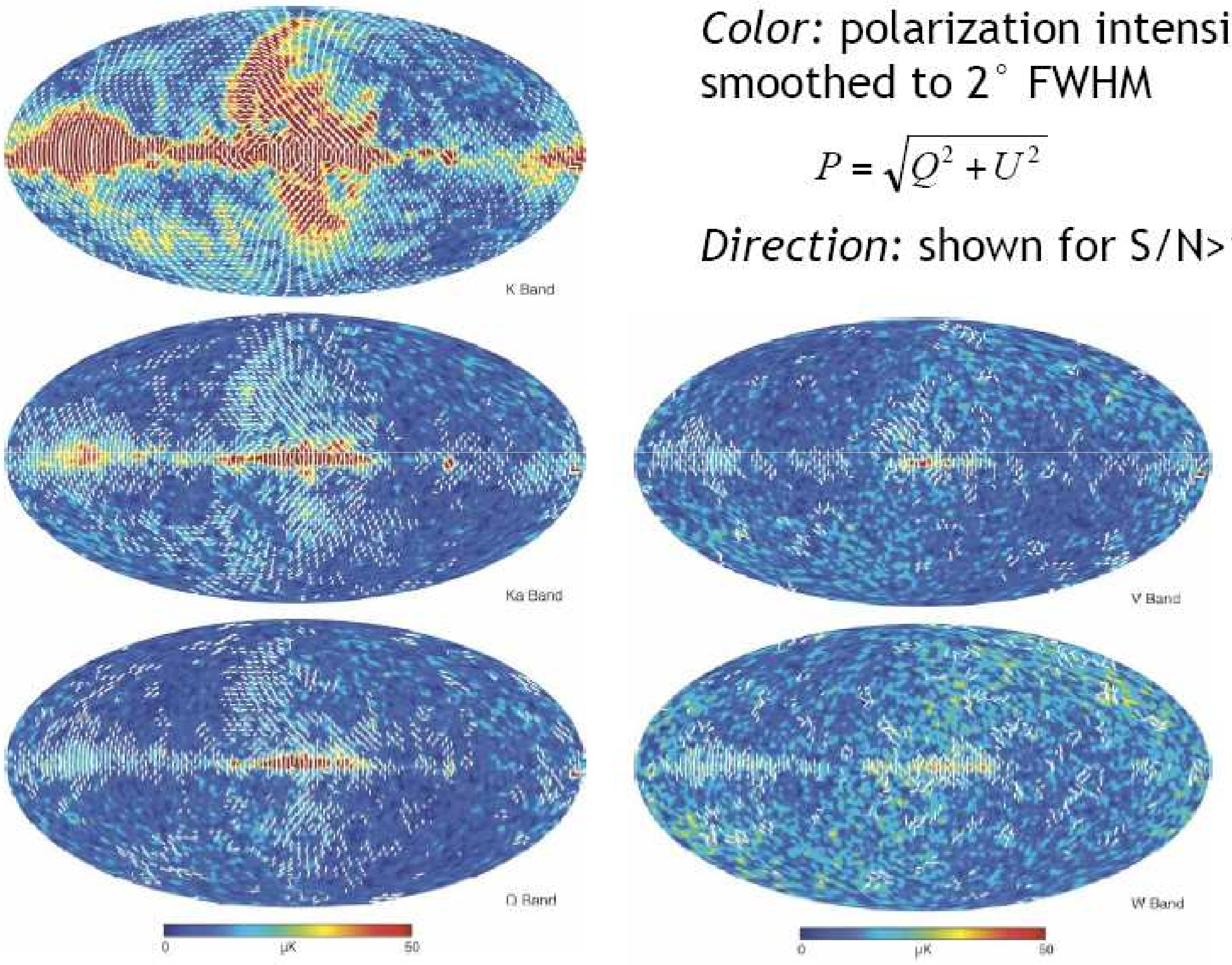
WMAP polarisaiton maps

$$\frac{\Delta P}{P} \approx 0.1 \frac{\Delta T}{T} \approx 10^{-6}$$

Color: polarization intensity, smoothed to 2° FWHM

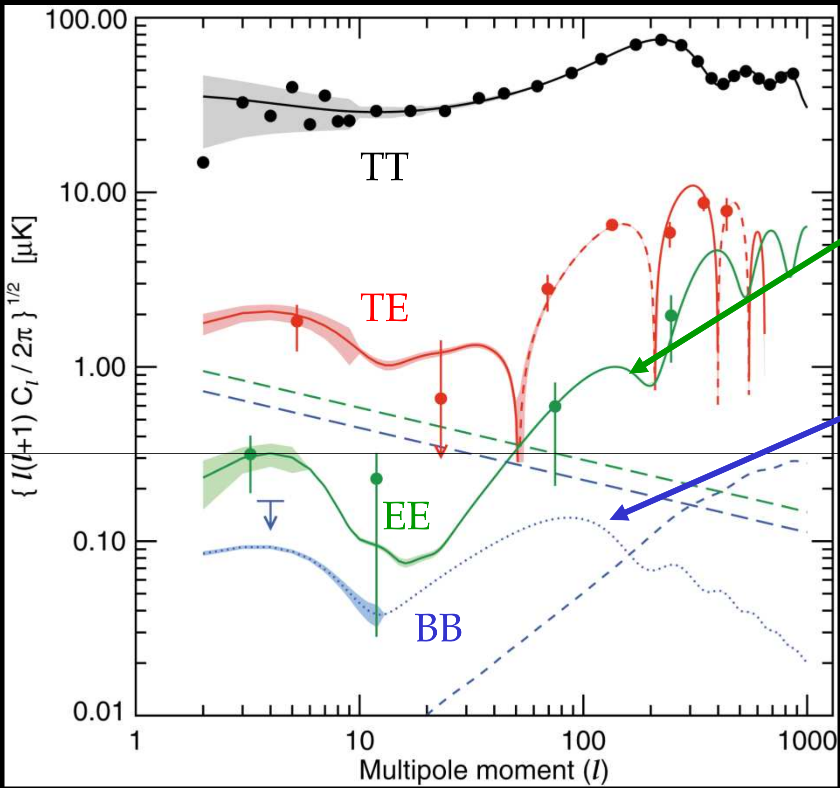
$$P = \sqrt{Q^2 + U^2}$$

Direction: shown for S/N>1

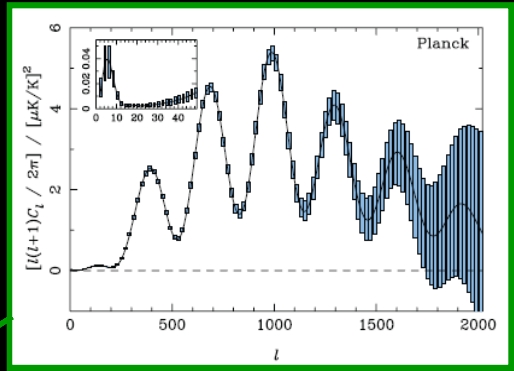


Probing inflation with CMB polarisation

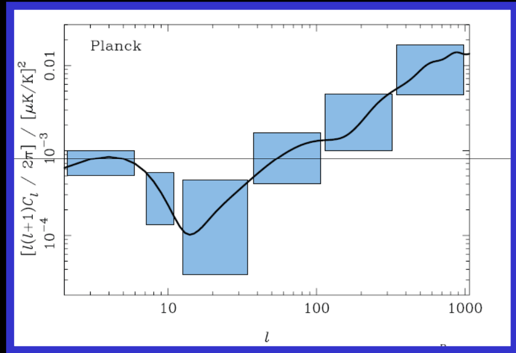
WMAP data



PLANCK simulations



"E-mode" from last scattering surface



"B-mode" polarisation from primordial gravitational waves

If detected:

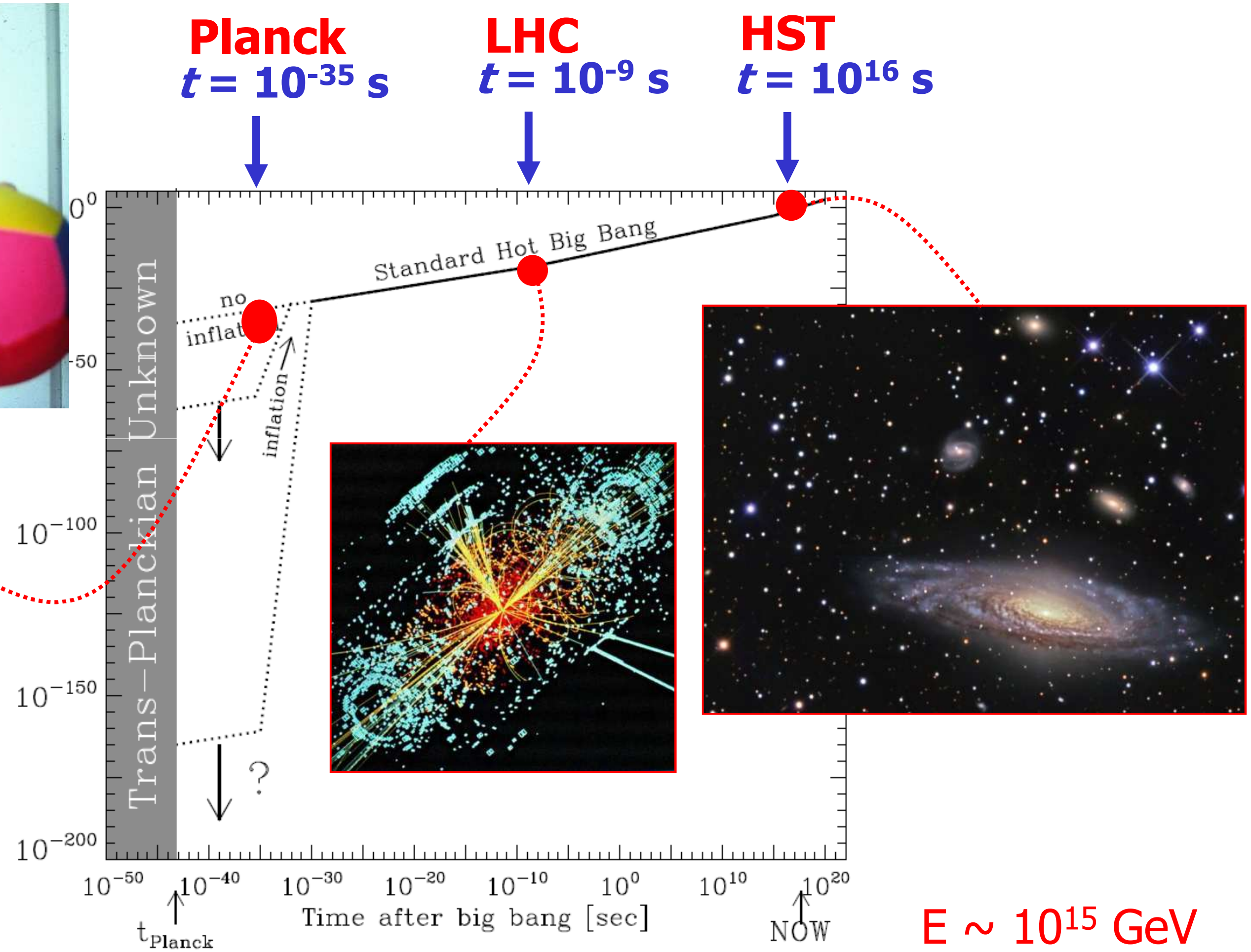
- strong confirmation of inflation scenario
- estimate energy scale of inflation

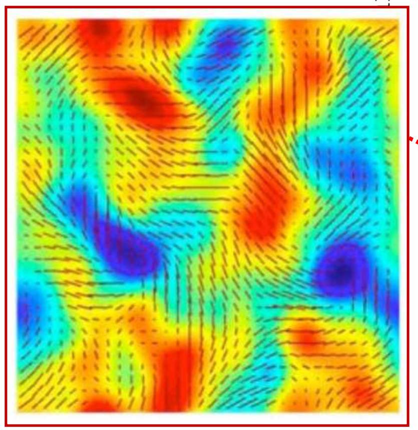
Extremely difficult experimentally
Theoretically poorly bound (several orders of magnitude range!)
→ *Post-Planck mission?*

“Looking back to the dawn of time”

The very early universe: Inflation?

$t = 0{,}000000000000000000000000000000000001$ s



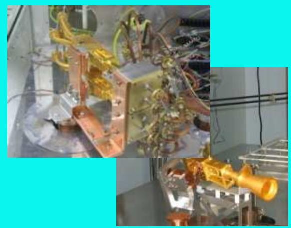
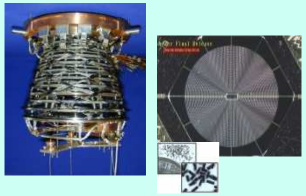
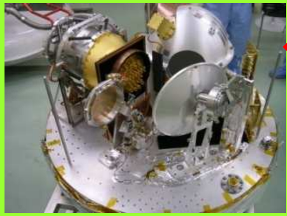


- B-mode polarization
- Non-gaussianity

Inflation: Exponential expansion of space

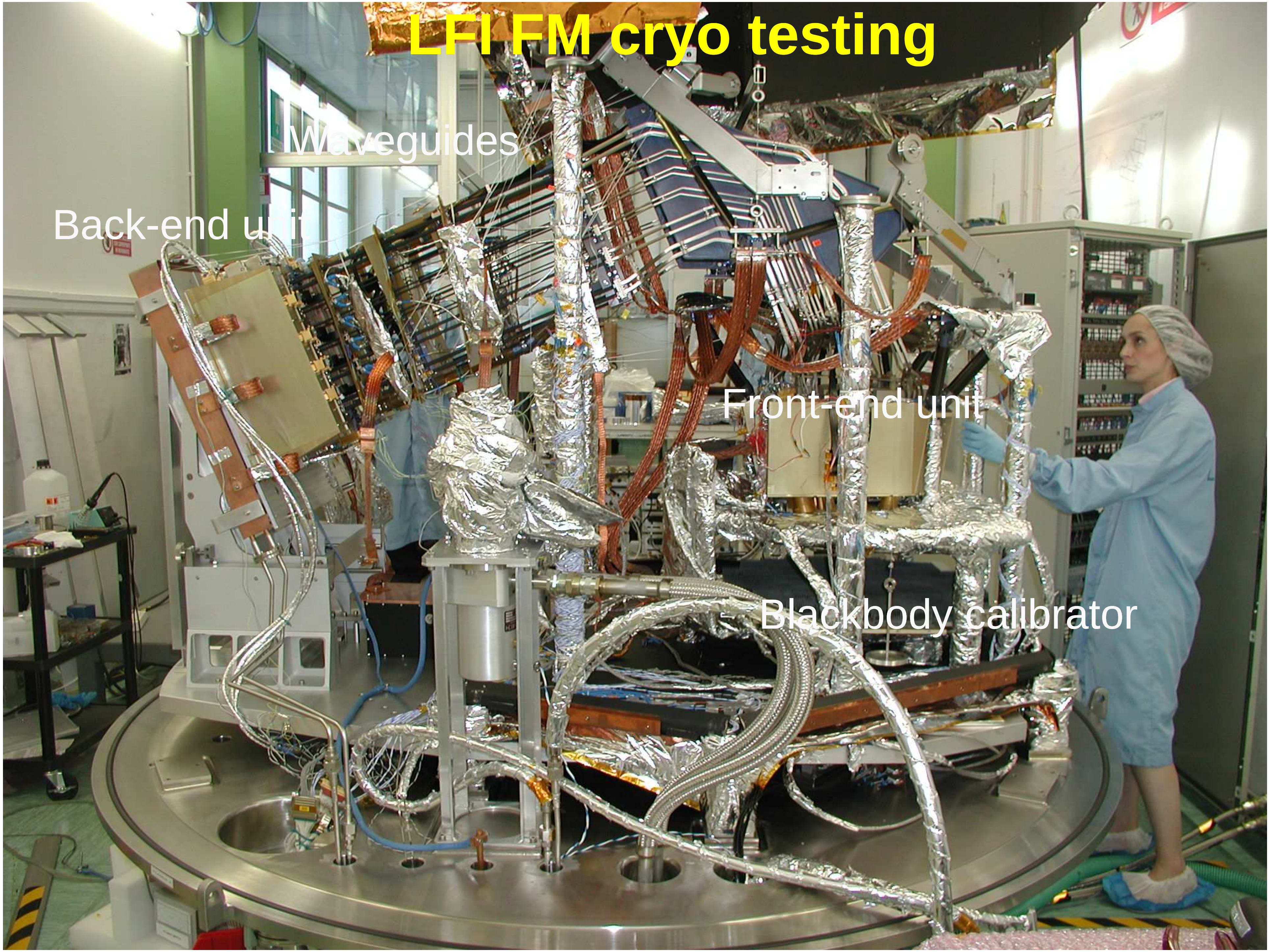
E ~ 10^{15} GeV

Planck Instrument Calibration Plan

	Unit	Assembly	Instrument	Satellite	In-flight
LFI				CSL Campaign 	 CPV & FLS
HFI					
Qualification Model (QM)	***Completed***	***Completed***	***Completed***	***Completed***	
Flight Model (FM)	***Completed***	***Completed***	***Completed***	***Completed***	***Completed***

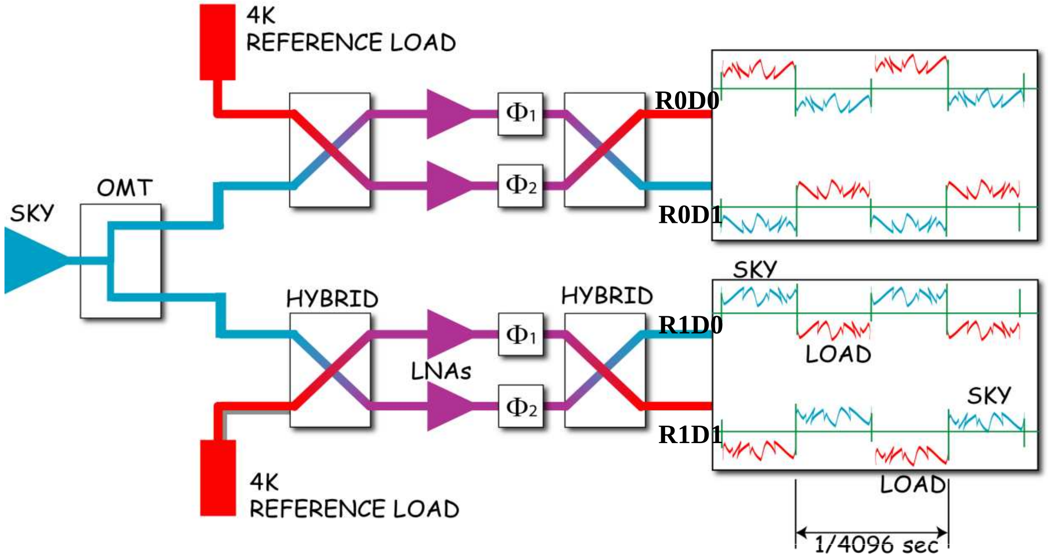
Supported by Data Processing Centers

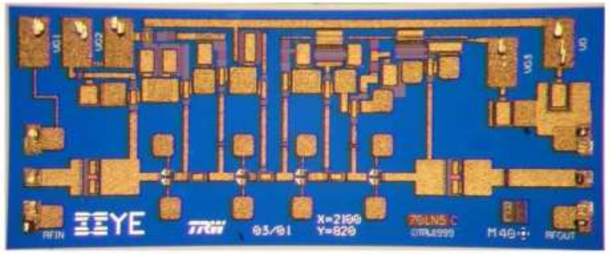
LFI FM cryo testing



Planck-LFI design

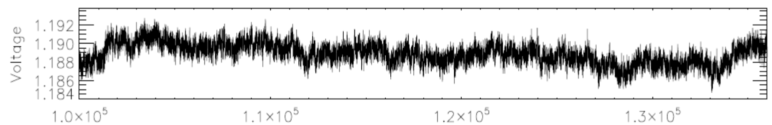
Bersanelli et al 2010



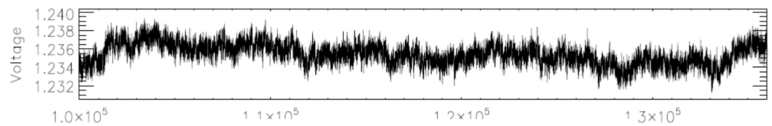


70 GHz MMIC HEMT

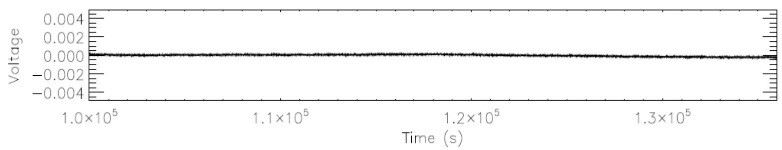
Sky signal

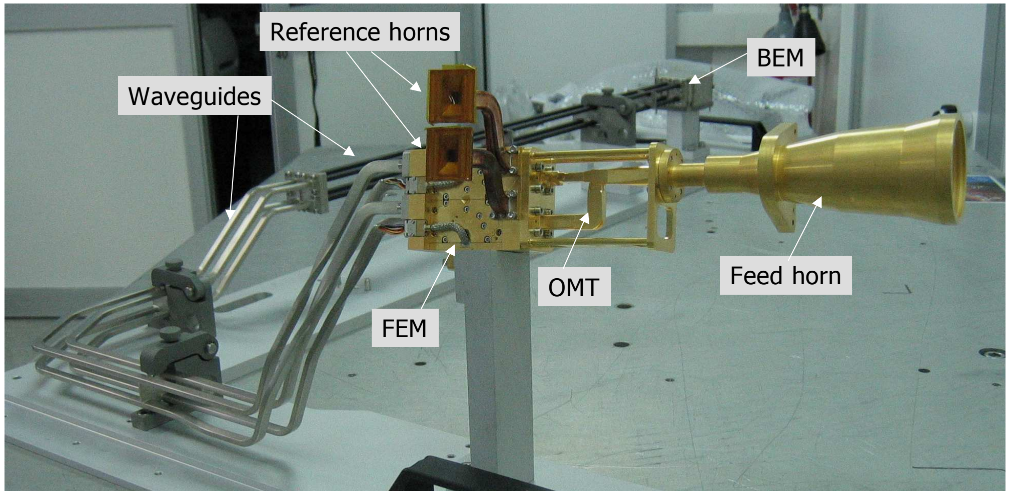


Reference signal



Difference





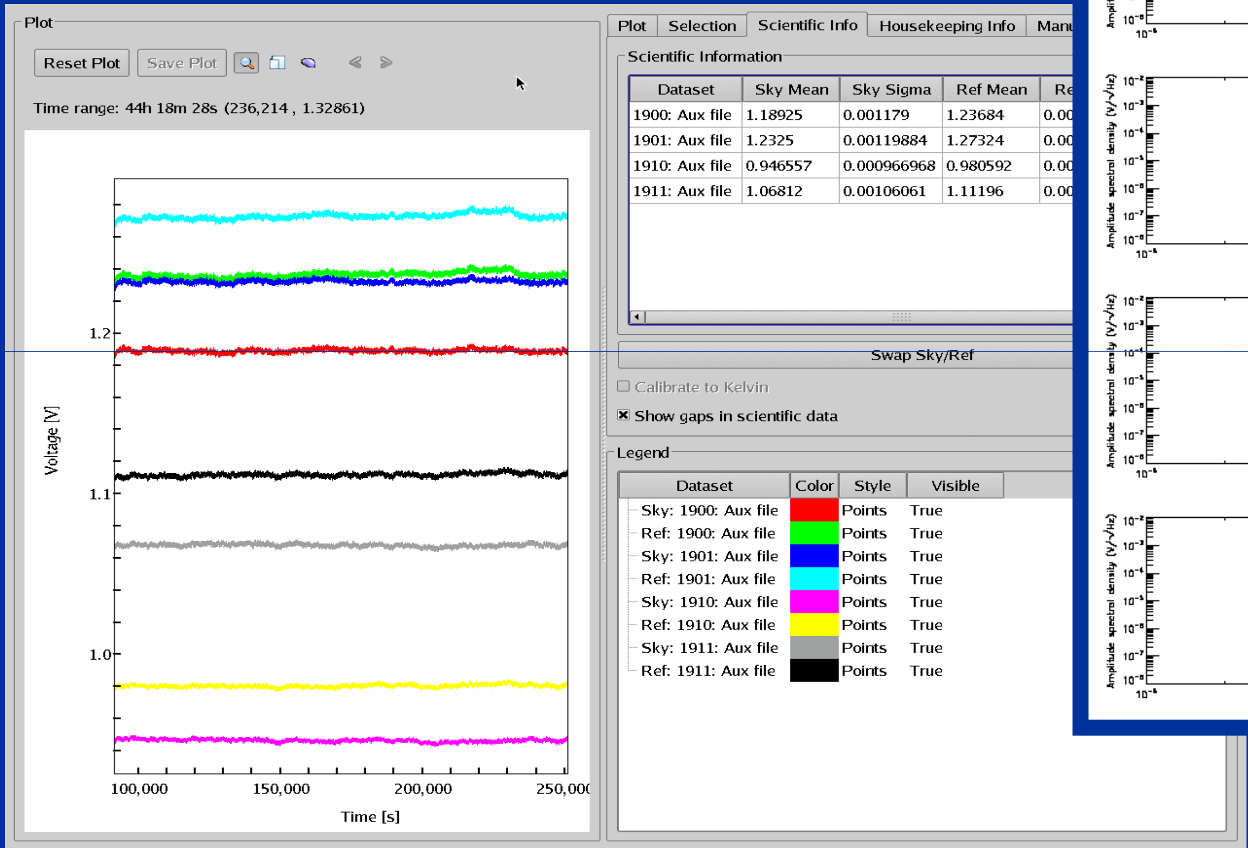
30 GHz FM RCA

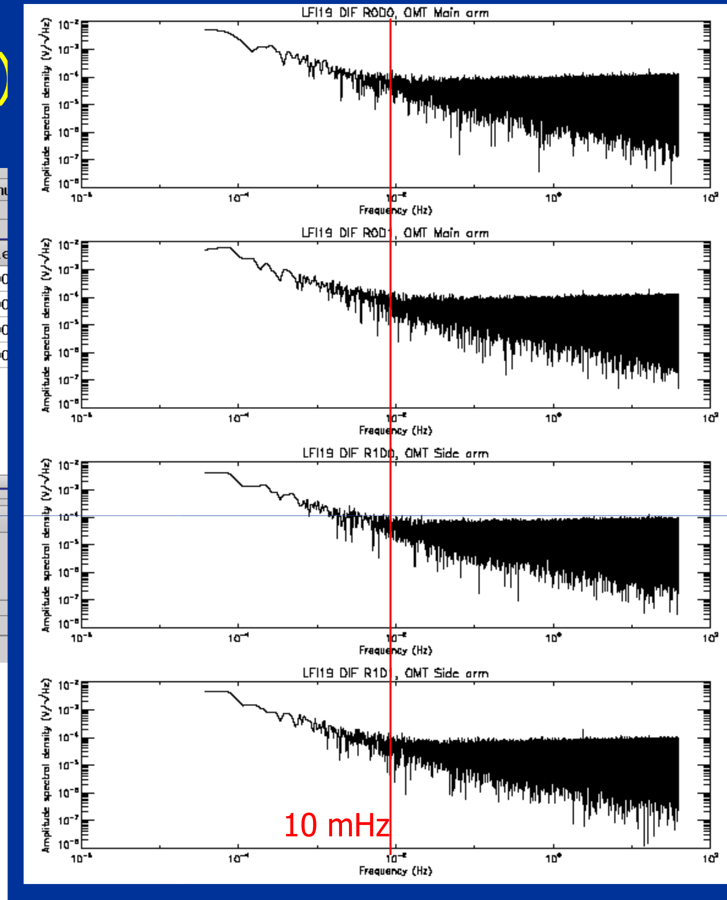
Planck-LFI

Long-duration LFI-RAA data set

45 hours of undisturbed acquisition (MODE 5)

70 GHz LFI#19 02





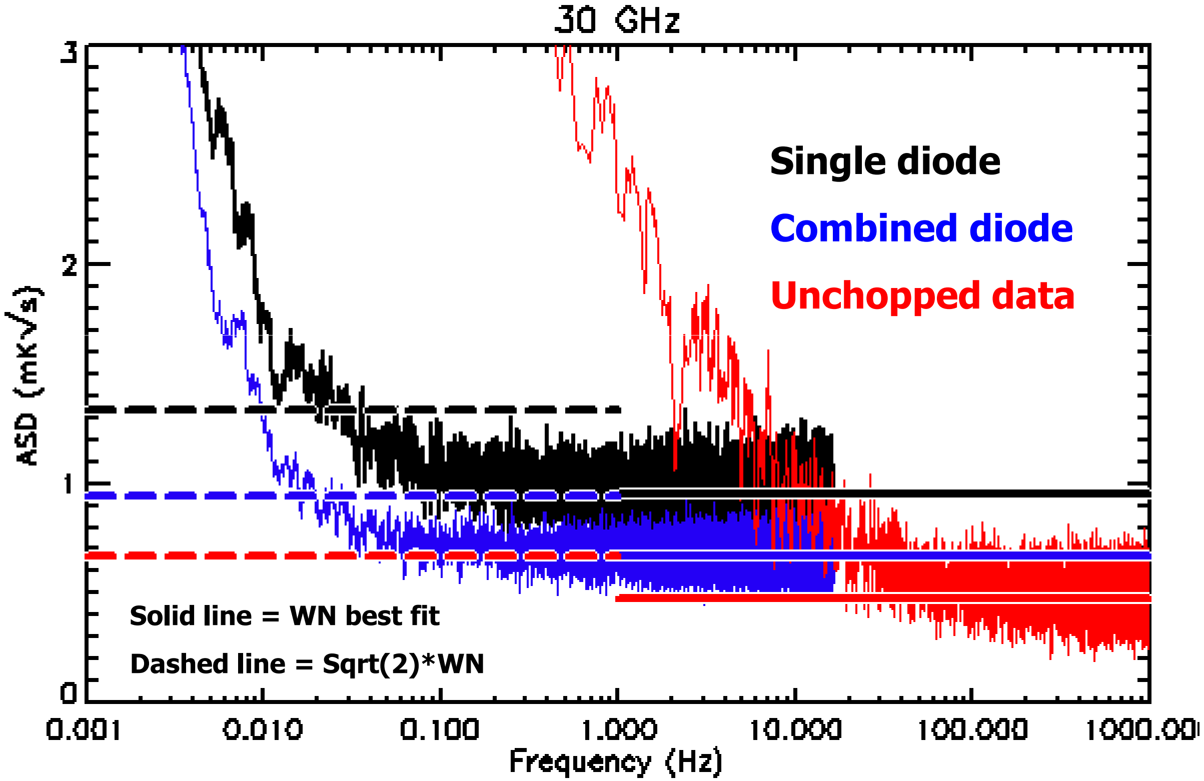
Knee frequency ~10mHz

Planck-LFI

Amplitude spectral density comparison (internal consistency)

Meinhold et al 2009

Basic model: Radiometer Equation $\sigma_T = K \left(\frac{T_{\rm sys} + T_{\rm sky}}{\sqrt{\beta \cdot \tau}} \right)$

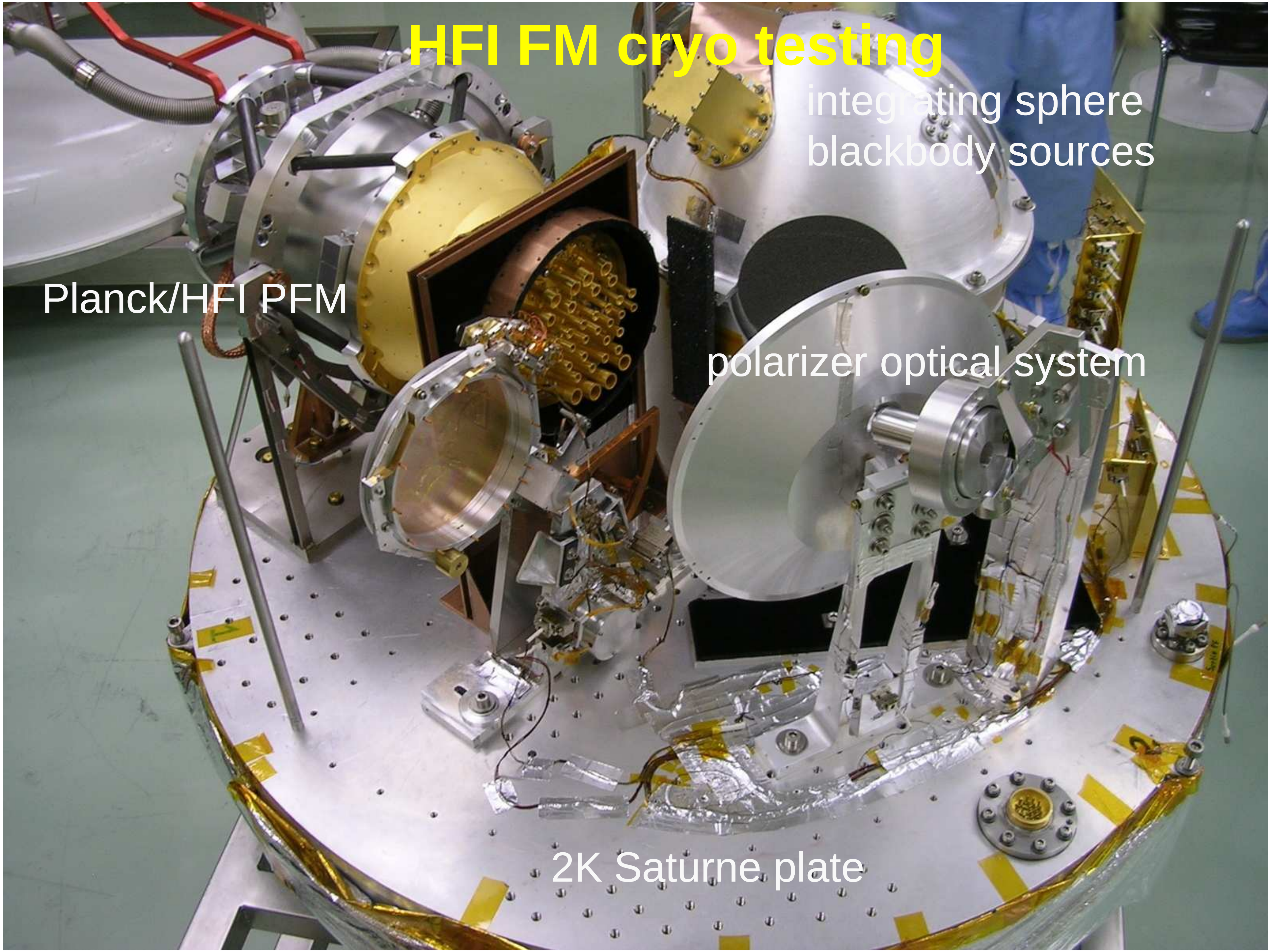


$K = 2$

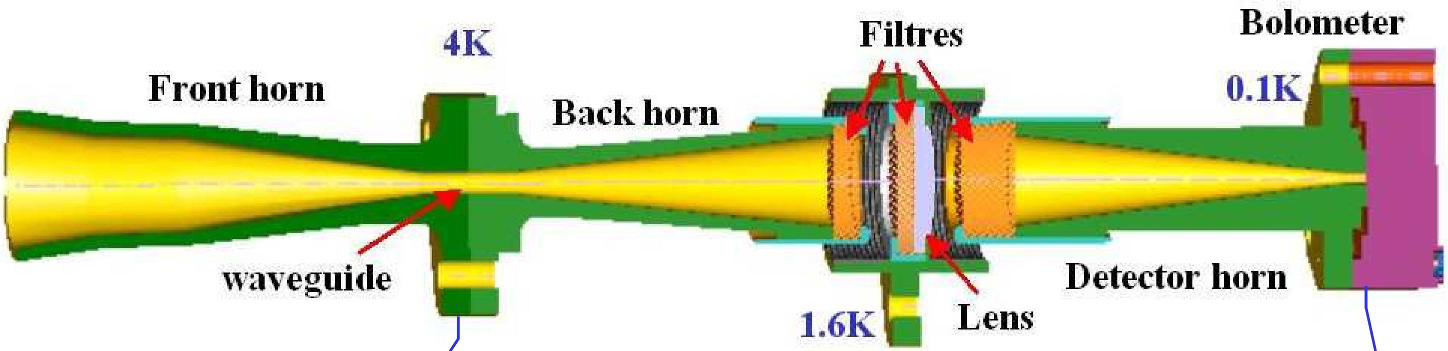
$K = \sqrt{2}$

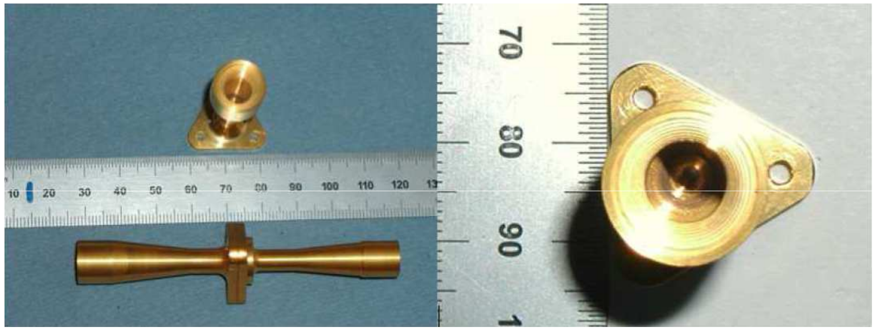
$K = 1$

- Excellent consistency of measured noise ASD with expected behaviour
- LFI differential receiver design provides ~10^3 rejection of radiometer instability

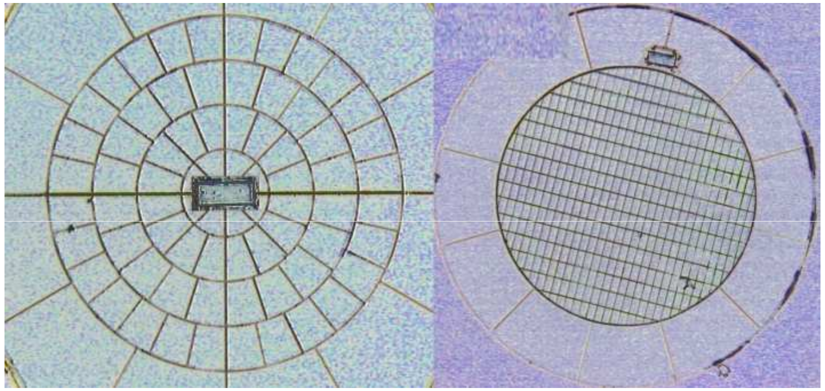

HFI FM cryo testing
integrating sphere
blackbody sources
Planck/HFI PFM
polarizer optical system
2K Saturne plate

Planck-HFI *Lamarre et al 2010*



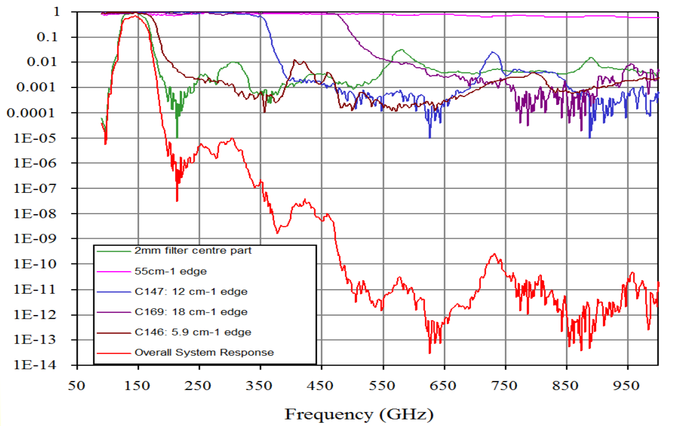


Front-end feed-horn



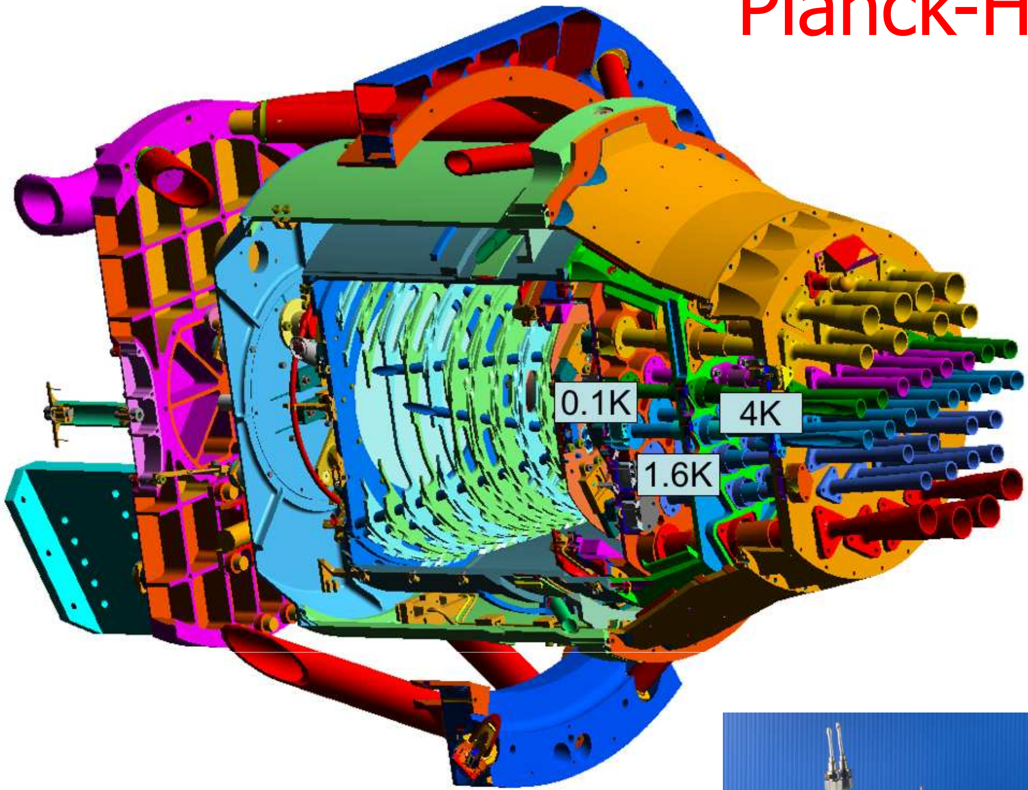
Spider-web and
Polarisation Sensitive
Bolometers

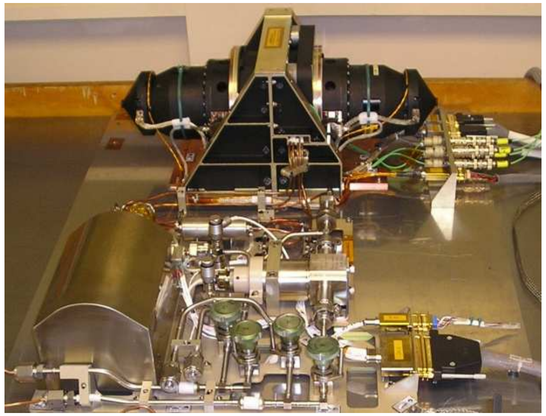
Band-defining filter
(143GHz)



Spider-Web
Bolometer (SWB)

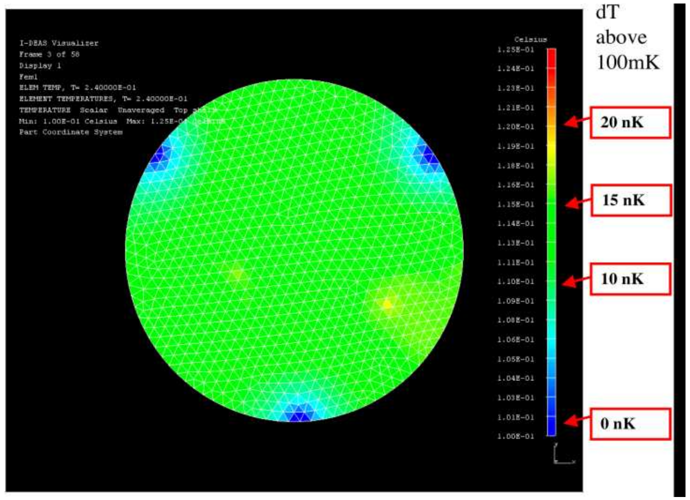
Planck-HFI





4K Stirling cooler

Heat exchanger of the dilution cooler (1.6 – 0.1 K)

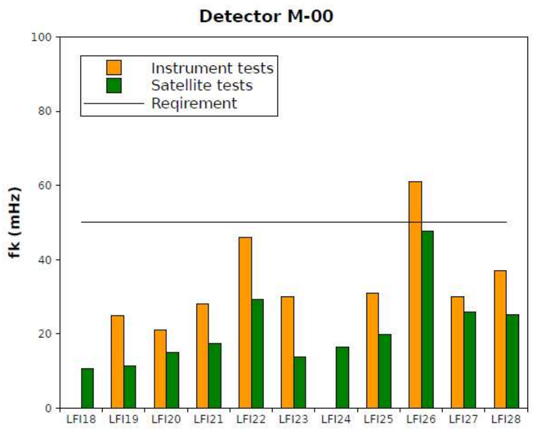


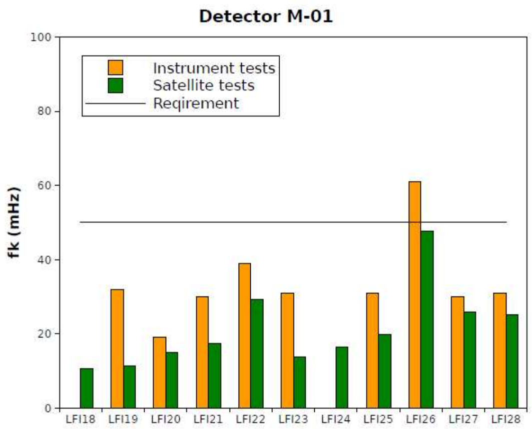
Thermal gradient at 100mK (simulated with HFI thermal model)

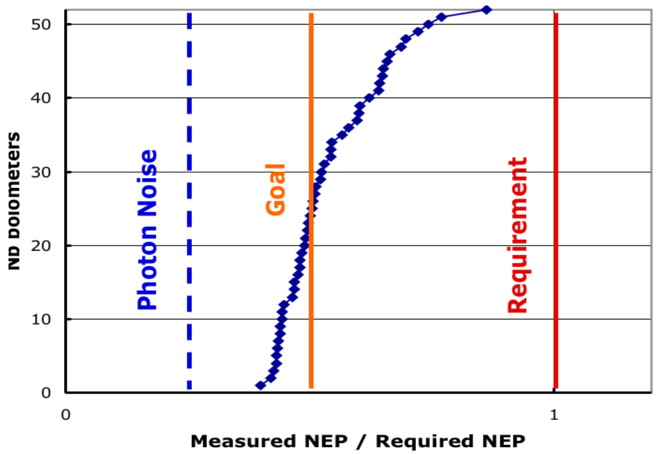
Ground-calibration: Performance

Mennella et al 2010, Lamarre et al 2010

Instrument	LFI			HFI					
Center Frequency [GHz]	30	44	70	100	143	217	353	545	857
Number of Polarised Detectors[a]	4	6	12	4	8	8	4		
Number of Unpolarised Detectors					4	4	2	4	4
Mean[b] FWHM (arcmin)	32.7	29.5	13.0	9.6	7.0	4.6	4.5	4.7	4.3
Mean[c] Ellipticity	1.36	1.50	1.27	1.17	1.05	1.11	1.13	1.03	1.04
Bandwidth ($\Delta\nu$, GHz)	4.5	4.1	12	32	45	68	104	174	258
$\Delta T/T$ per pixel (Stokes I)[d]	3.3	5.2	8.9	3	2.2	4.8	2.0	150	6000
$\Delta T/T$ per pixel (Stokes Q & U)[e]	4.6	7.4	12.7	4.8	4.1	9	38		
Point Source Sensitivity[f] (1σ, mJy)	22	59	46	14	10	14	38	44	45





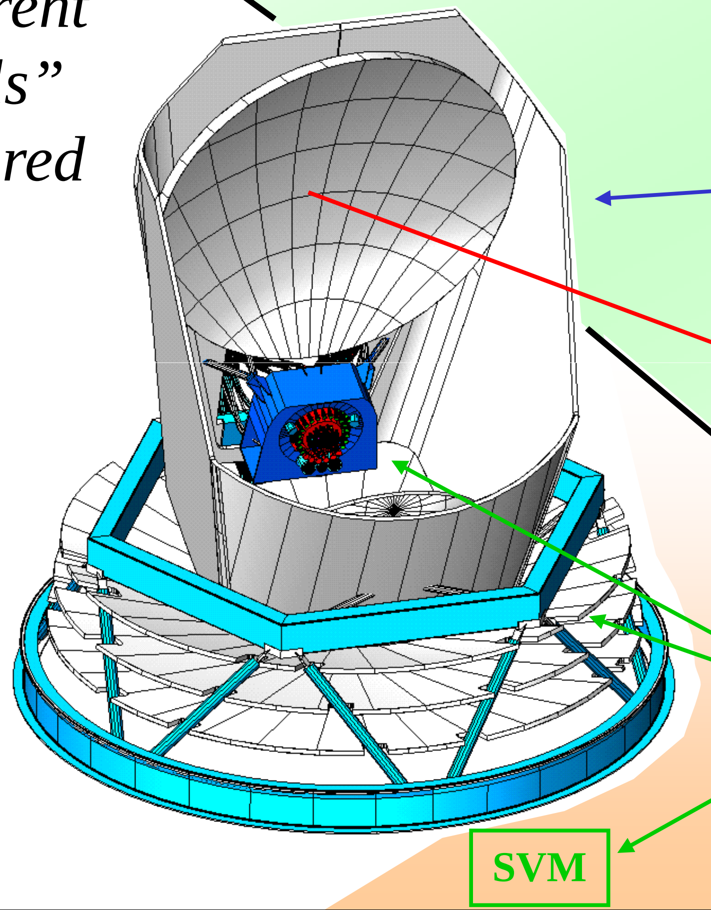


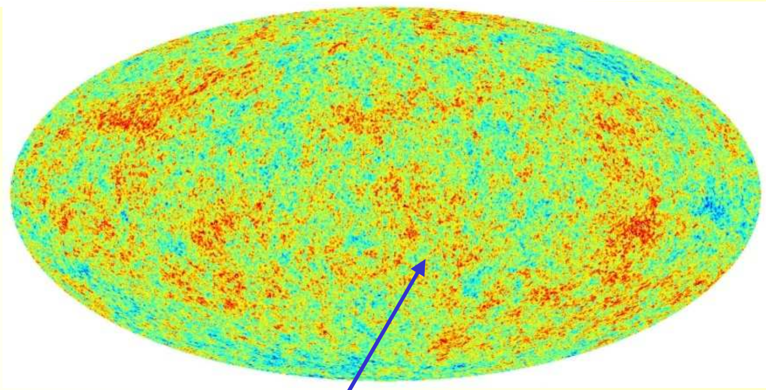
PLANCK Systematic Effects WG

First-level breakdown

M.B., Jean-Michel Lamarre

- *Different "tools" required*





a

Effects due to combination of (instrument beams) + (sky):
- External straylight
- Main beam reconstruction

c

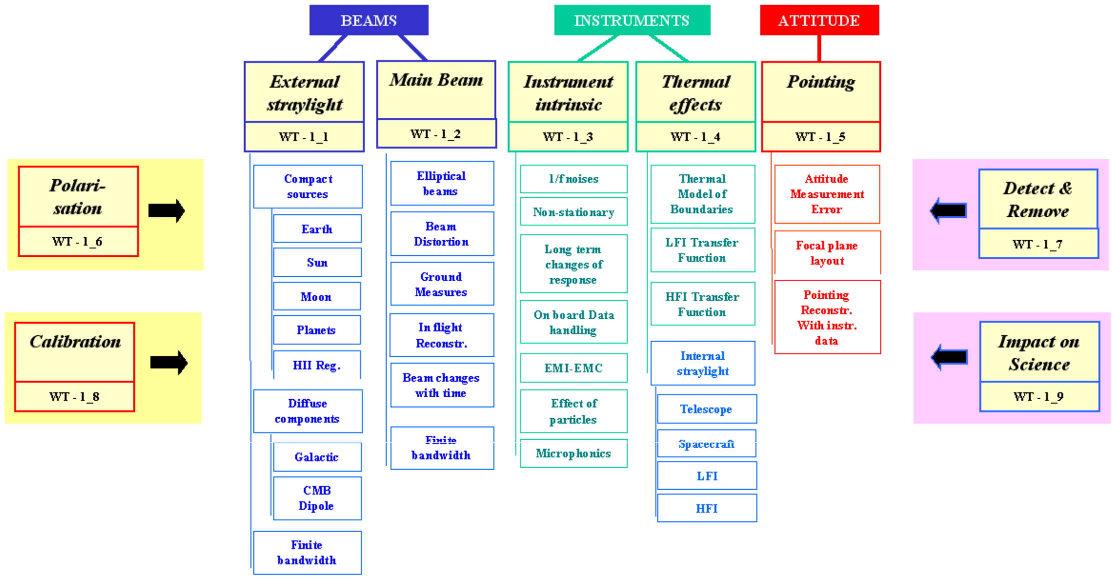
Pointing uncertainties

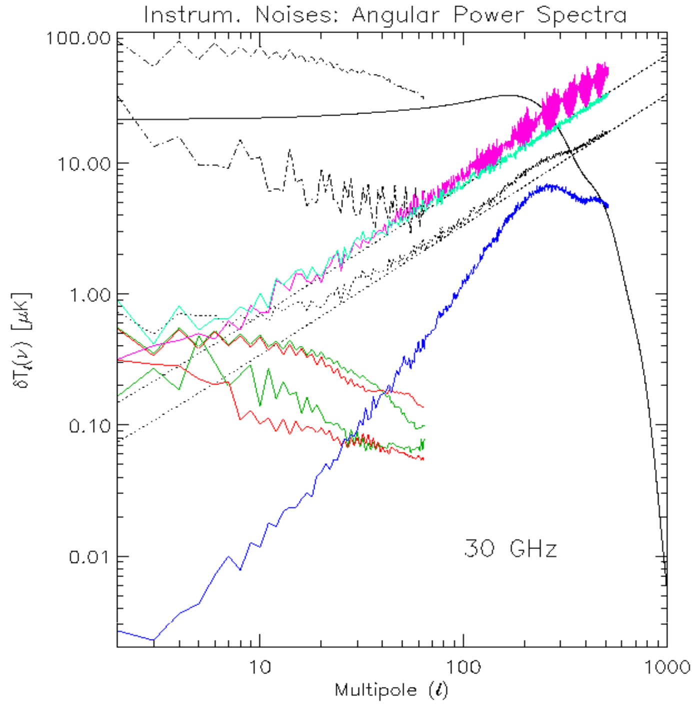
b

Effects generated within the satellite:
- Instrument-specific non-idealities
- Thermal effects from the satellite
- Internal straylight

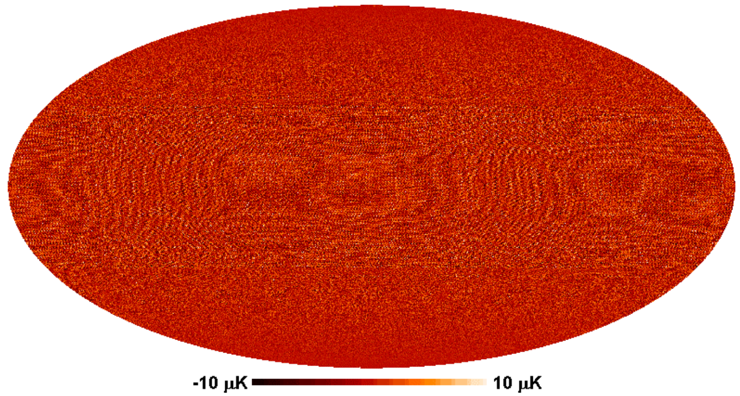
Control of Systematic effects

PLANCK Systematics Breakdown





- At Planck sensitivity, systematics must be controlled at μK level
- LFI/HFI cross-correlation (e.g. 70 vs 100 GHz) is a key tool to be exploited against systematics
- Essential element of data processing strategy

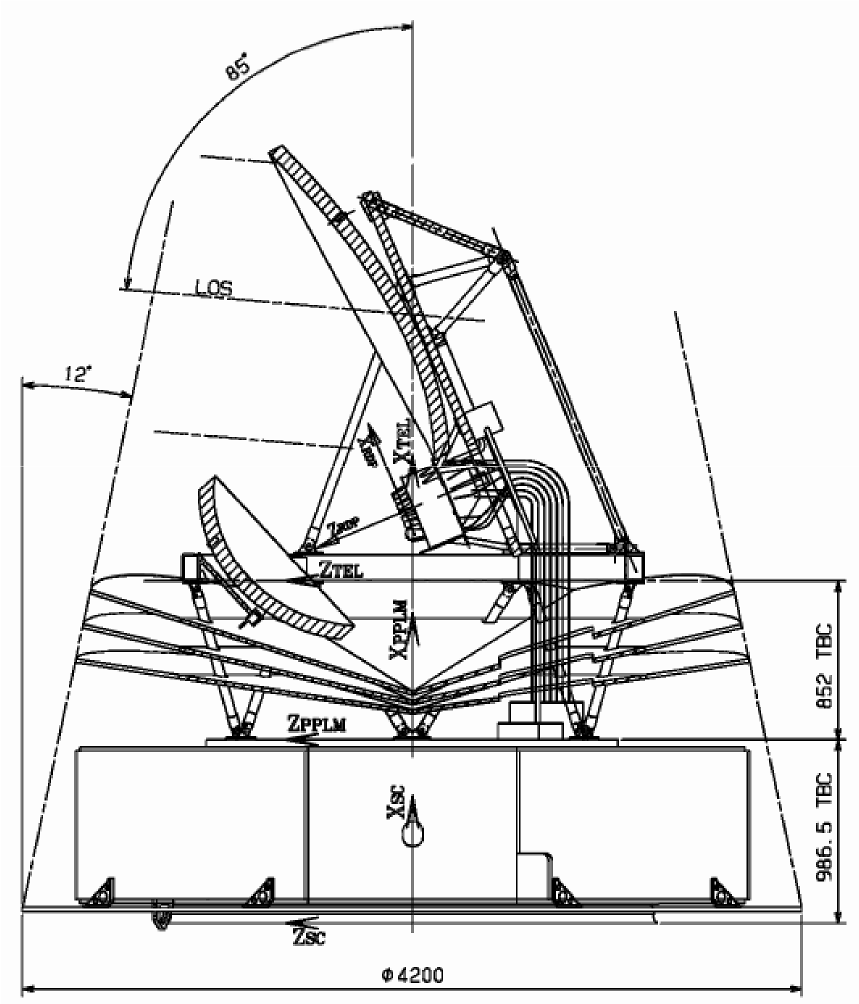


$$F^{-1} = \frac{\sin(\pi \nu_f \tau)}{\pi \nu_f \tau} \frac{1}{N} \sum_{j=1}^{N} \cos\left(2\pi \frac{\nu_f}{\nu_{spin}} j \right)$$

RFQM measurement campaign

ESA, Thales, HFI & LFI Instrument Teams

Tauber et al 2010



Requirement	Primary Reflector	Secondary Reflector
Contour shape	off-axis ellipsoid	off-axis ellipsoid
Size (mm)	1555.98 x 1886.79	1050.96 x 1104.39
Radius of Curvature (mm)	1440±0.25	-643.972±0.2
Conic constant	-0.86940±0.0003	-0.215424±0.0003
Stability of best fit ellipsoid		
along each axis	±0.1mm	
around each axis	±0.1mrad	
Mechanical surface errors rms spec (goal) [a]		
ring 1	7.5μm (5μm)	
ring 2	12μm (8μm)	
ring 3	20μm (13μm)	
ring 4	33μm (22μm)	
ring 5	50μm (33μm)	
Surface roughness	$R_q < 0.2\mu$m on scales < 0.8mm	
Surface dimpling[b]	±2μm PTV	
Reflector thickness	80mm	65mm
Reflectivity 25GHz - 1000GHz		
Beginning of life	> 99.5 per cent	
End of life	> 98.5 (goal 99.0)[c]	
Mass	30.6 kg	14.5 kg
First eigenfrequency	> 120 Hz	
Temperatures		
Operational	45 K	
Qualification	30K - 325K	

PLANCK Optical verification

RFQM campaign:
- QM mirrors and representative FPU and limited number of frequencies
- At room temperature

Videogrammetry test on cold telescope

Software models

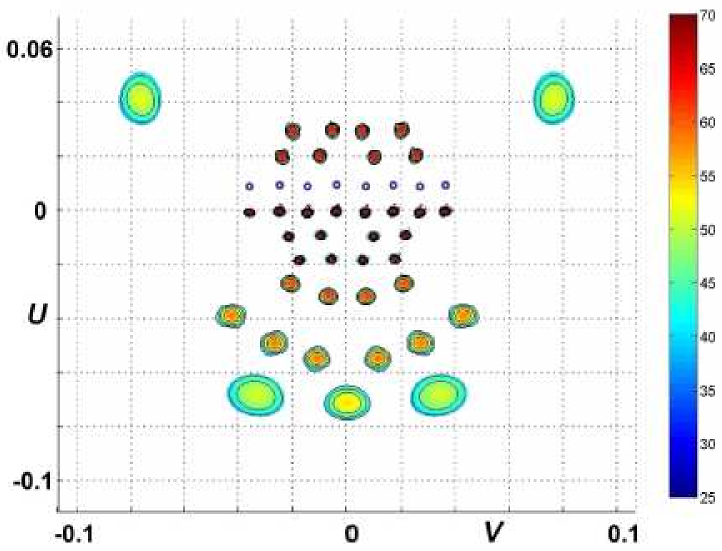
GRASP9 simulations:

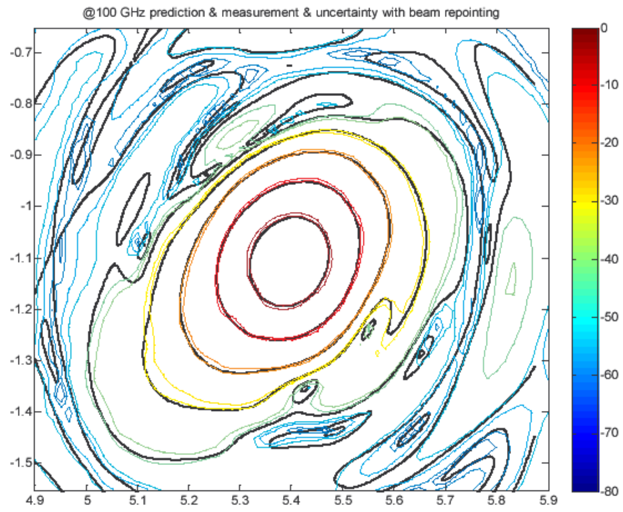
–Main beams

–Intermediate beams

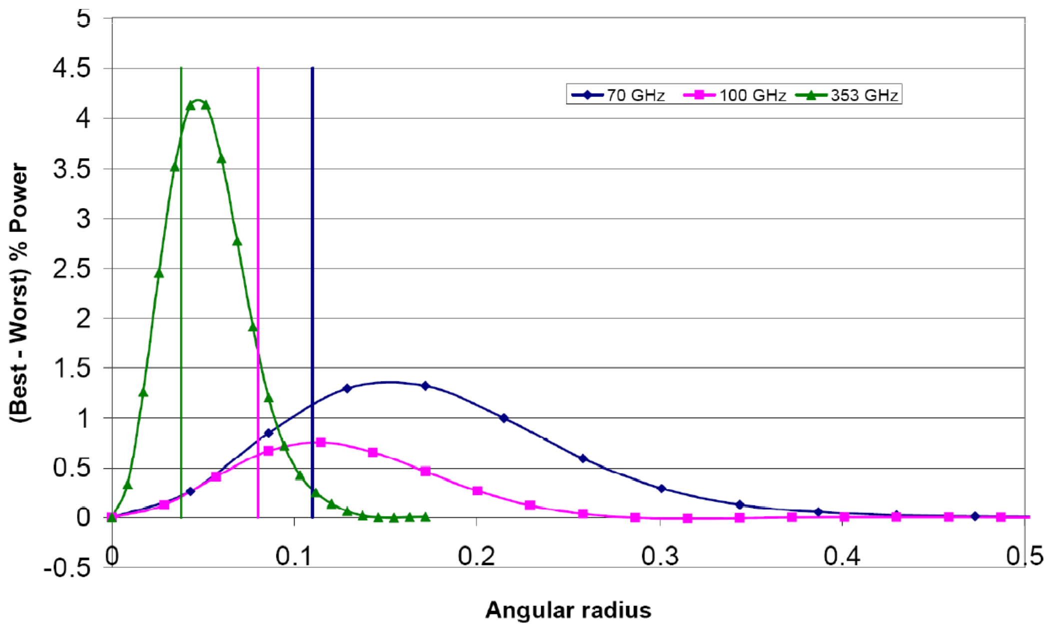
–Full sky beams

Main beams

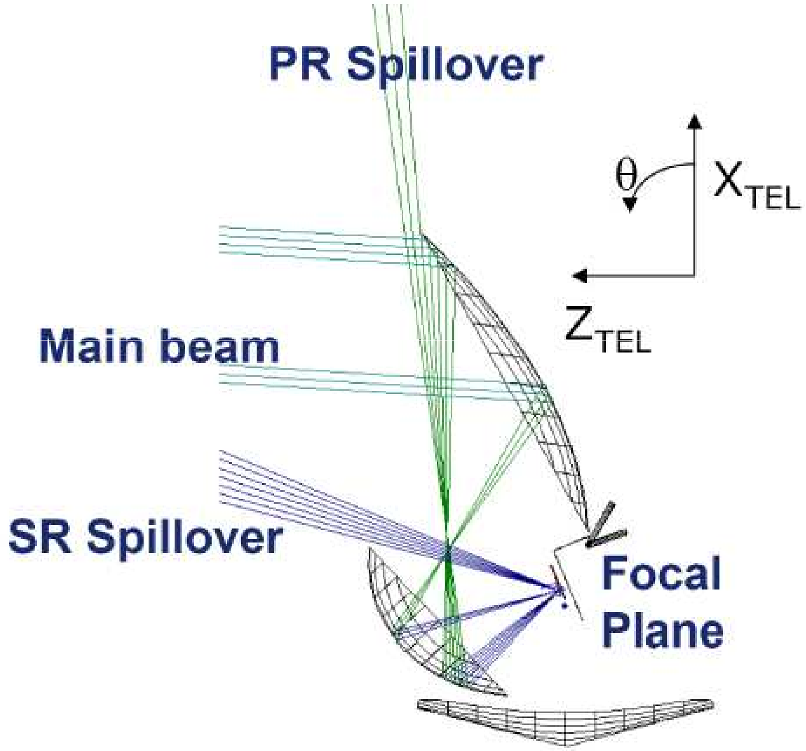


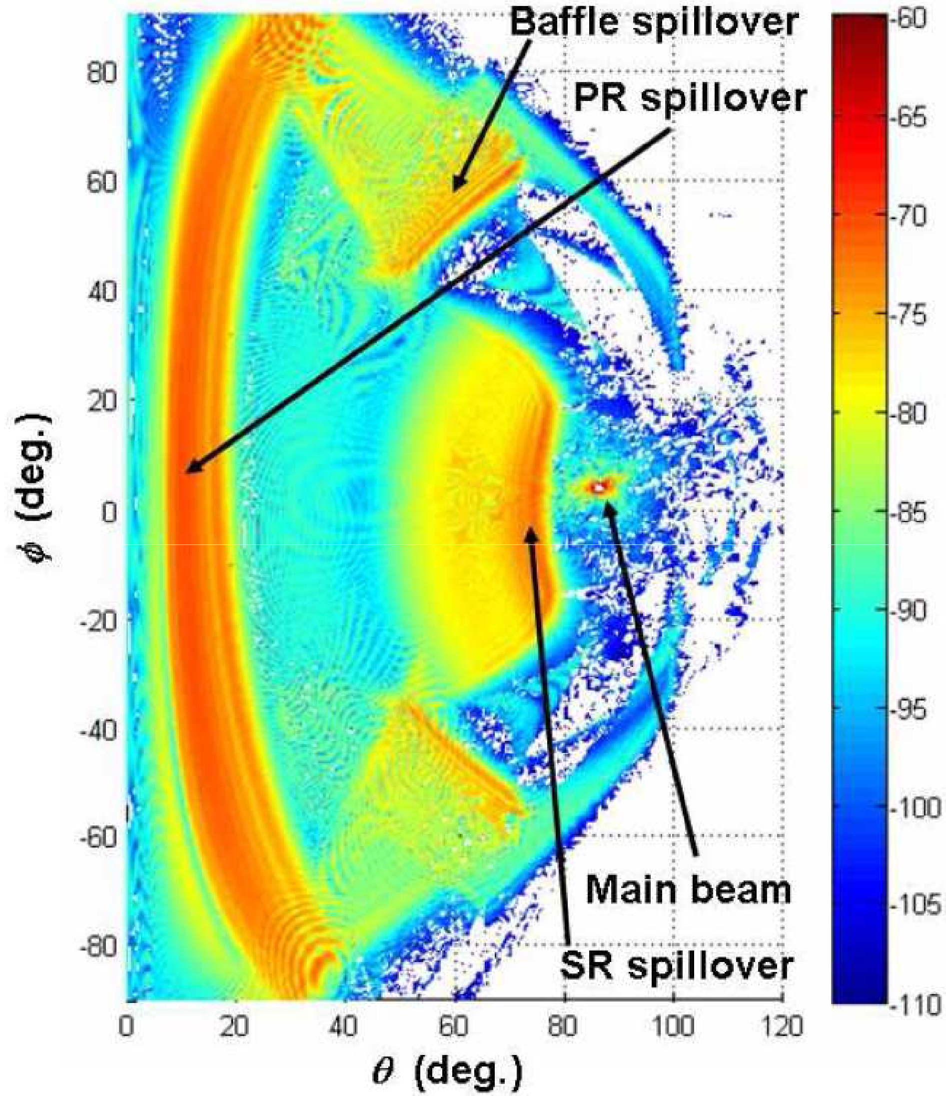


Uncertainty in the main beam shape after ground test campaign (integrated power, in percent of total) as a function of angular radius from peak.
(70 GHz: horn 23); 100 GHz: horn 1; 353 GHz: horn 6).



Straylight and far-sidelobes

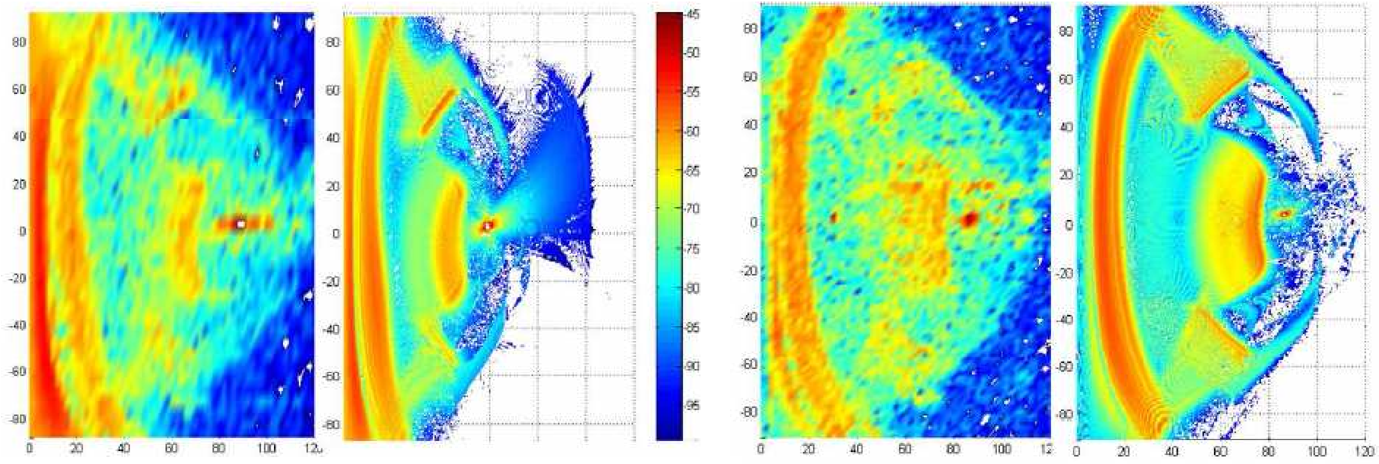


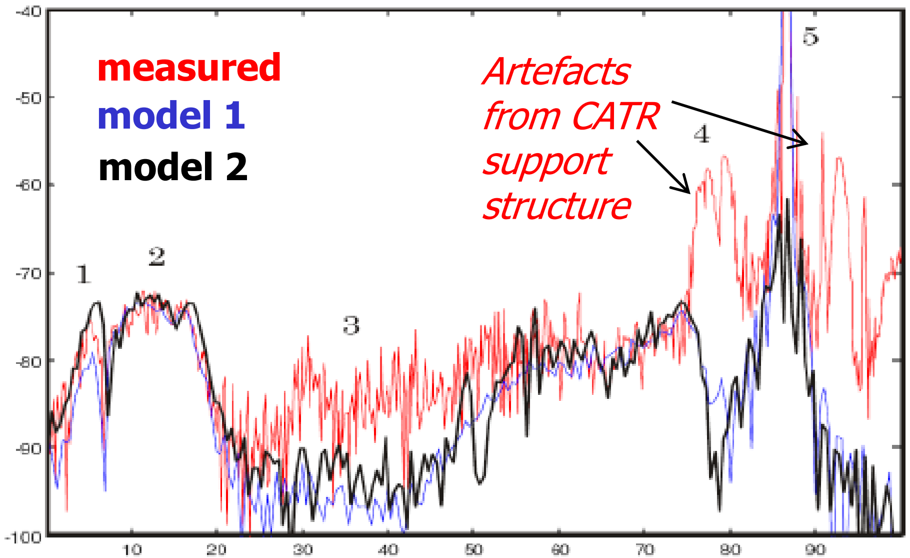


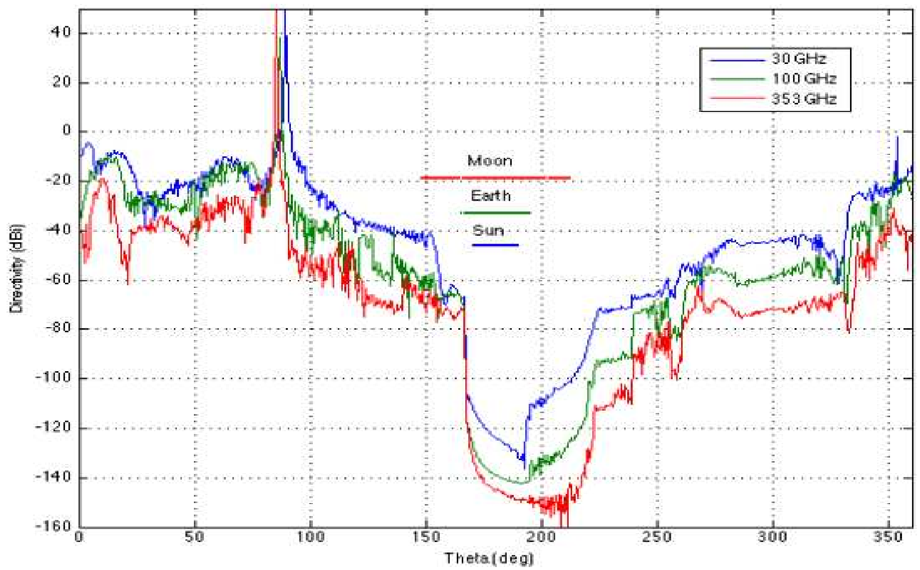
Straylight and far-sidelobes

30 GHz — Predicted / Measured

100 GHz — Predicted / Measured







Planck Collaboration: ~400 scientists!

SCIENCE TEAM: J. Tauber (ESA), M. Bersanelli, F. R. Bouchet, G. Efstathiou, J.-M. Lamarre, C. R. Lawrence, N. Mandolesi, H. U. Nørgaard-Nielsen, J.-L. Puget, A. Zacchei

Planck Core Team

Planck-LFI Instrument Team

Institutions & People Contributing to LFI Hardware Development & Calibration

IASF Sezione di Bologna

IASF Sezione di Milano

DAT

Dipartimento di Fisica Università di Milano

asi agenzia spaziale italiana

IFP-CNR Milano

ThalesAlenia Space

MilliLab

The University of Manchester Jodrell Bank Observatory

VTT

JPL

UCSB

YLINEN

Univ. CANTABRIA Dpto. Ing. Comunicaciones

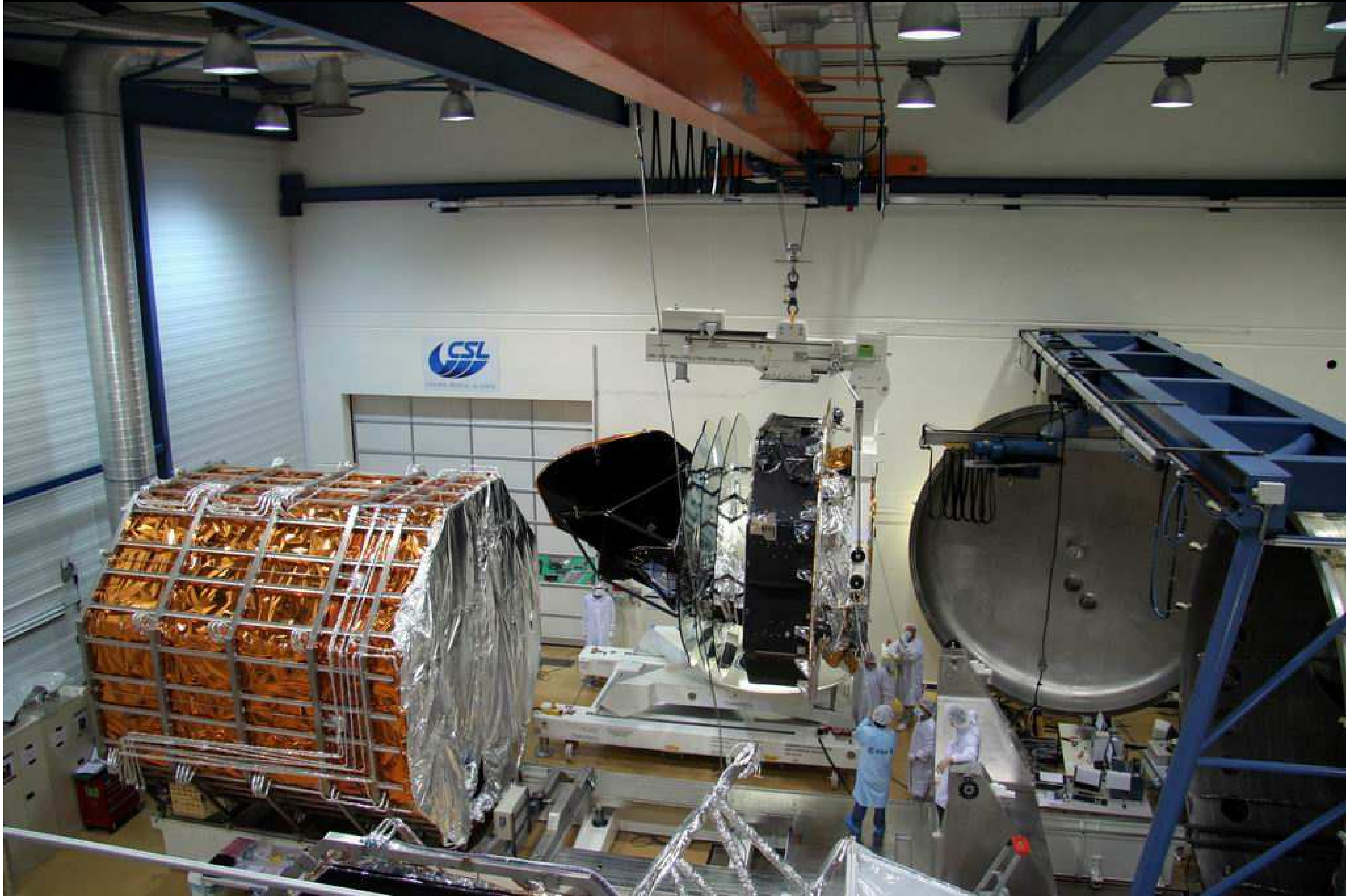
Mier

Instituto de Astrofisica de Canarias

KONGSBERG

Dipartimento di Fisica

Università degli Studi di Milano


CSL


18
Thales


Dutch Space

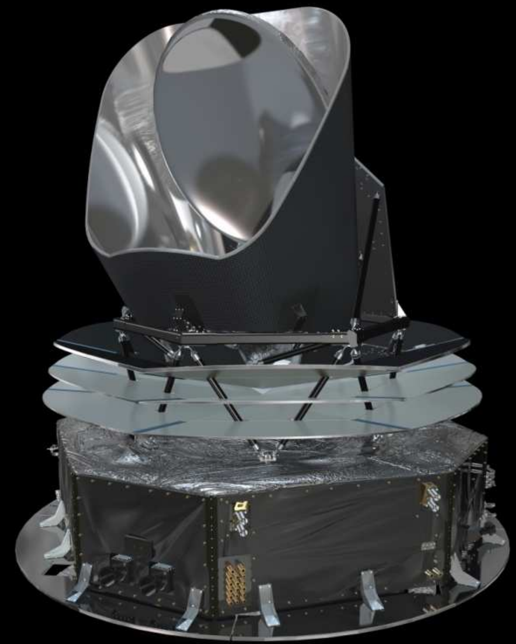
LFI team at CSL, July 2008

(by Stuart Lowe)


Kourou, March 2009

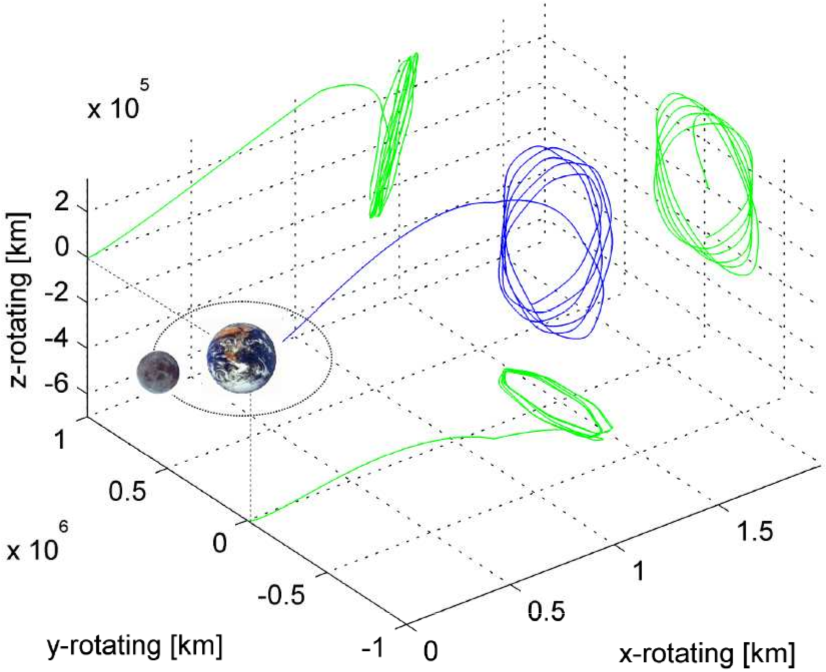
Ariane 5

Herschel

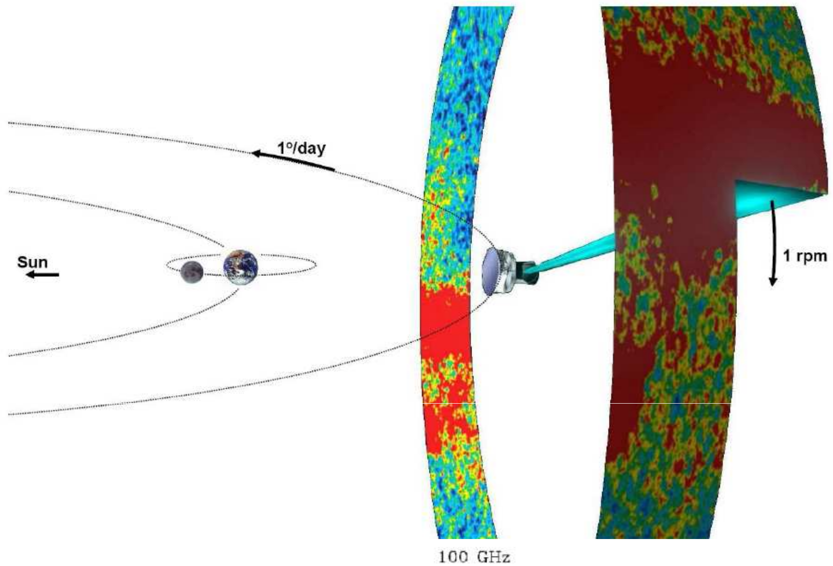


Planck

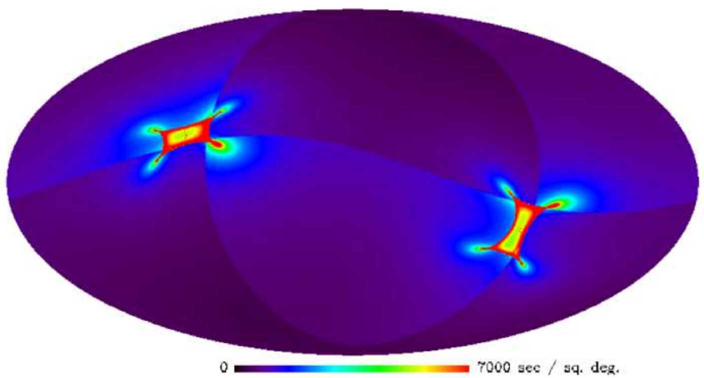
Orbit and scanning strategy



- Far earth orbit (← Straylight, thermal stability)
- Sun-earth L2 Lagrangian point (← TM/TC)
  d ≅ 1.5 Mkm from Earth

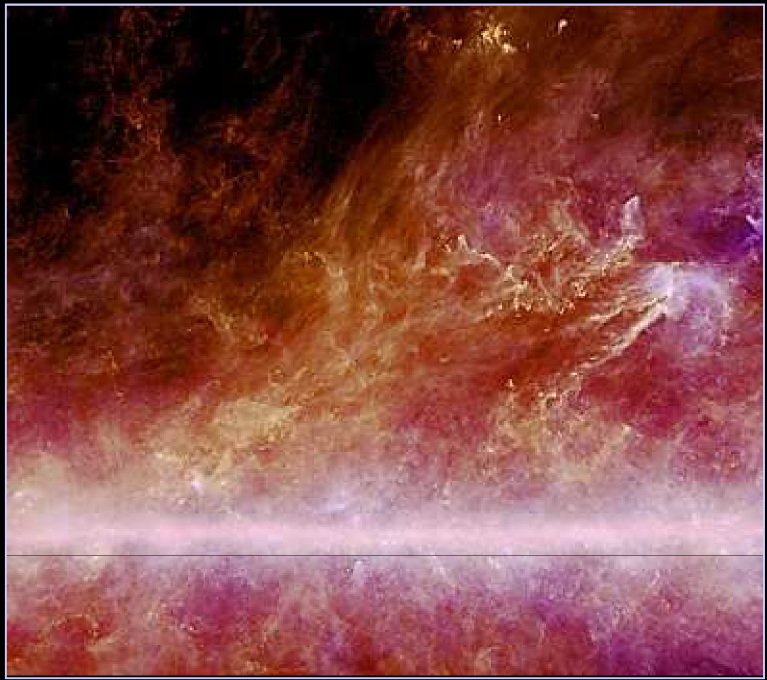


- Spin period: 1rpm (← 1/f, τ_{bol})
- Reorientation: ~1°/day (← SAA)
- Step: 2' (← Sampling at FWHM=5')



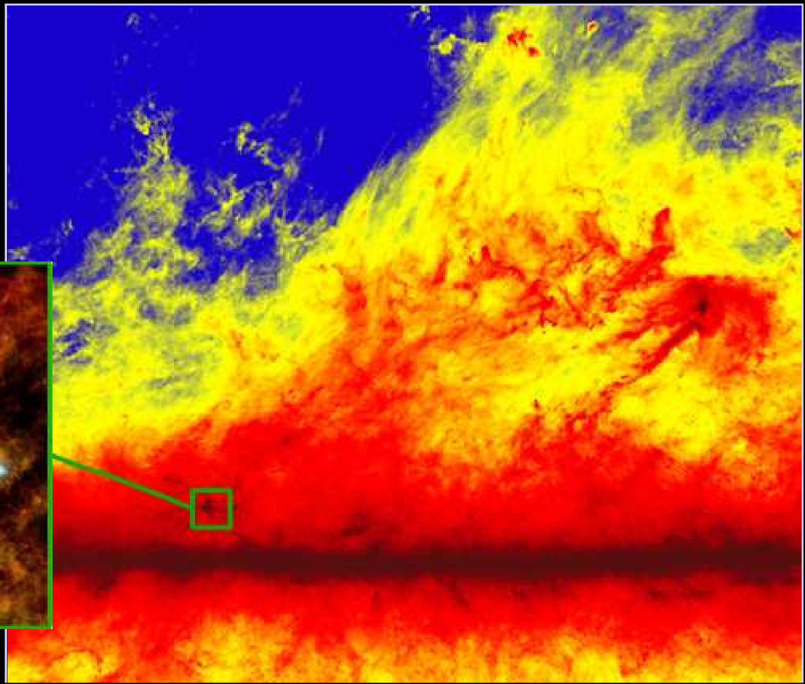
- Precession angle: 7.5° (← Straylight, TM/TC)
- Constant solar aspect angle (← Thermal stability)
- Precession period: 6 months

- Uniform coverage, deep fields at ecliptic poles
- Flexibility (Crab, planets, gap recovery, etc)



λ = 540 µm and 350 µm (557 and 857 GHz)
+ 100 µm IRAS (1983)

Image angular size ~ 50°
Local dust structures within 500 ly of the Sun
T ~ 10 – 50 K

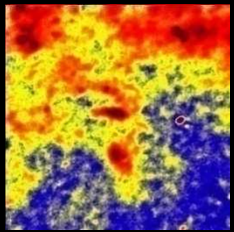


λ = 350 µm (857 GHz)
Image angular size ~ 55°

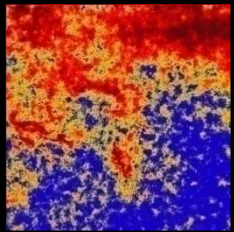
Inset: Herschel image of a region in the Aquila constellation

PLANCK

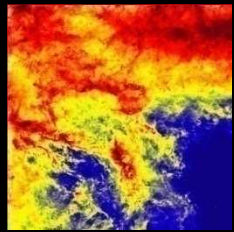
17 March 2010



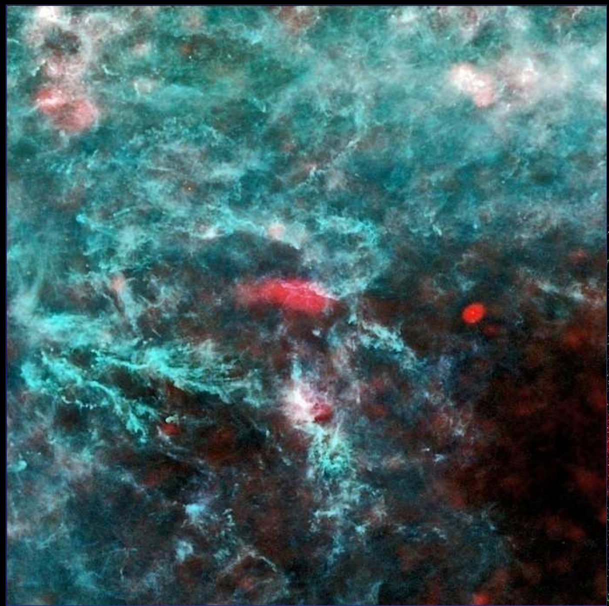
30GHz



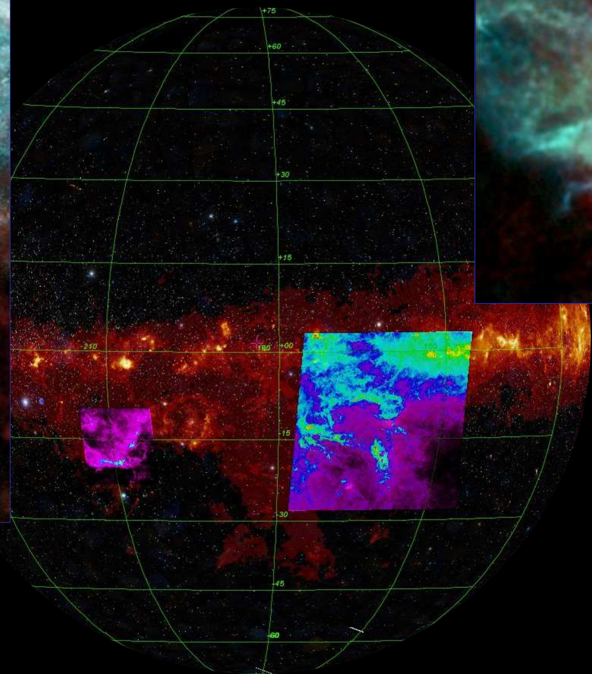
353GHz



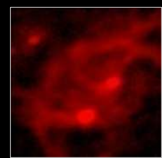
857GHz



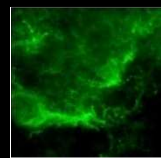
Perseus
30+353+857GHz



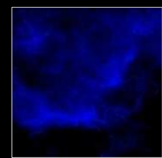
Orion Nebula
30+353+857GHz



30GHz

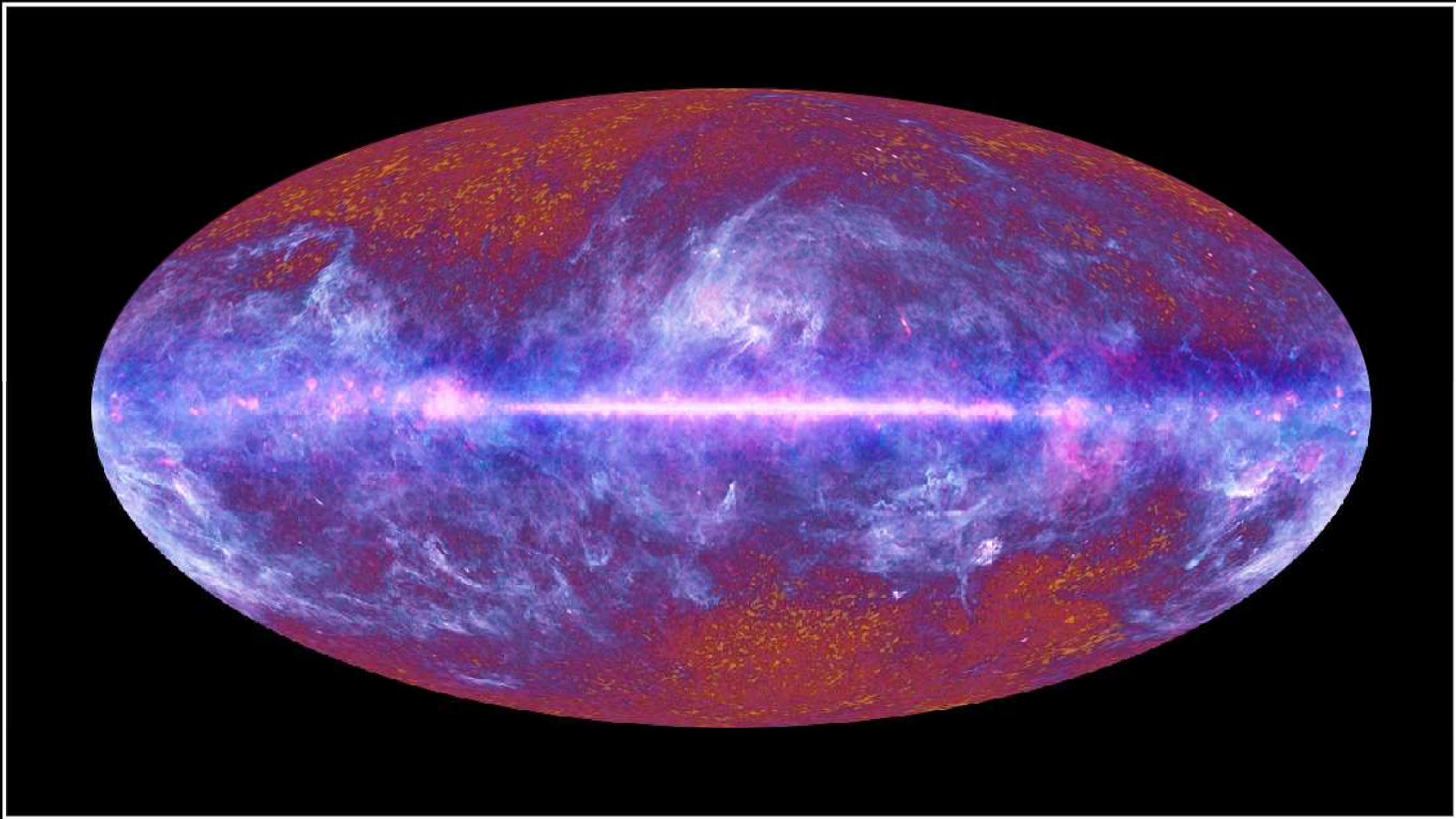


353GHz



857GHz

1 July 2010



The Planck one-year all-sky survey