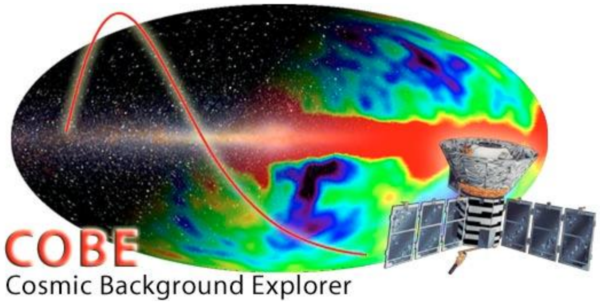
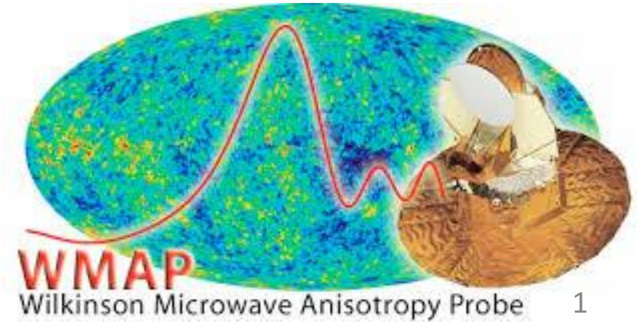


COBE and WMAP

Zhuo Cheng

Supervisors: Yi Mao and Jianfeng Zhou



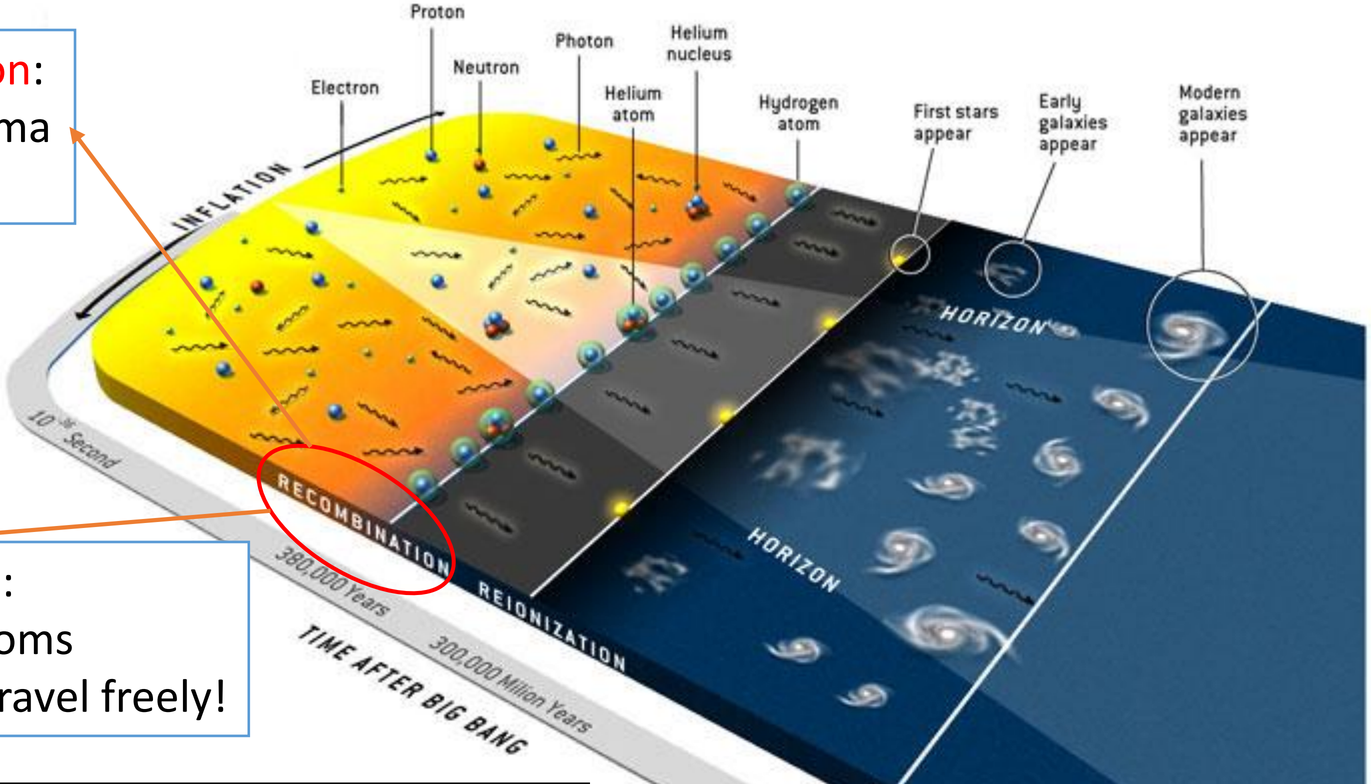
Outline

- An introduction to CMB
- COBE
  - Instrument
  - Scientific results
- Anisotropy of CMB
- WMAP
  - Compare to COBE
  - Scientific results
- Summary

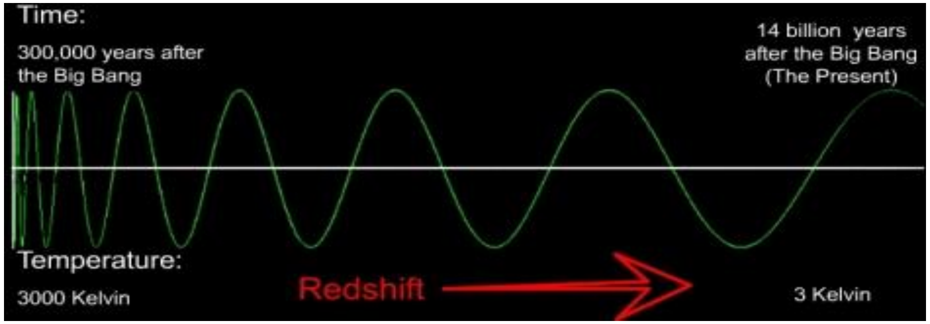
The origin of CMB

Before recombination:
photon-baryon plasma
short free path

$T \sim 3000K$

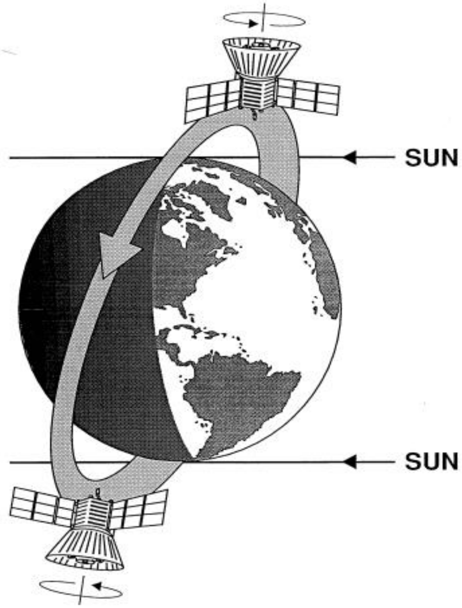


After recombination:
neutral hydrogen atoms
photons started to travel freely!



COBE(Cosmic Background Explorer)

- **Launch Date:** November 18, 1989
- **Deactivated:** December 23, 1993
- **The Orbits** : Sun-synchronous
- **Perigee:** 877.8 km
- **Apogee**: 891.4 km
- **Inclination**: 98.95 deg
- **Spin rate**: 0.8 rpm



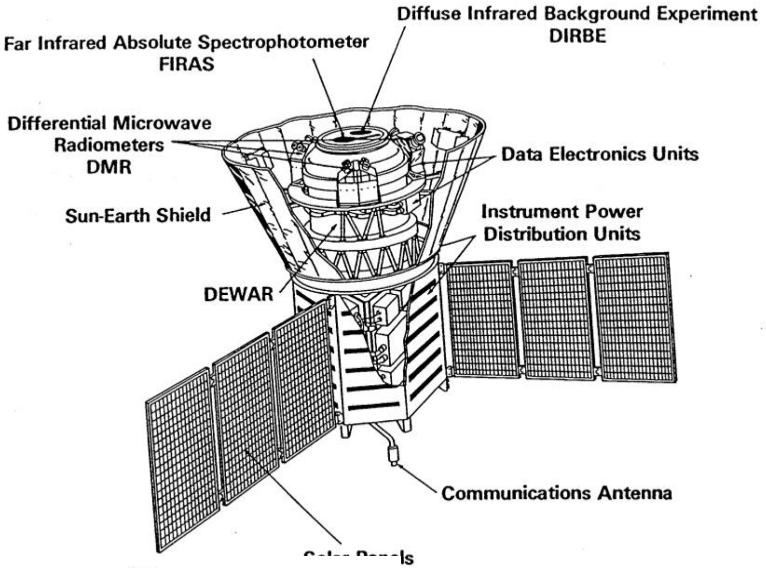
The inclination and altitude are chosen so that the orbital plane precesses 360° in 1 year.

Instruments of COBE

FIRAS: a spectrophotometer used to measure the spectrum of the CMB

DMR: a microwave instrument that would map variations in the CMB

DIRBE: a multi-wavelength infrared detector used to map dust emission



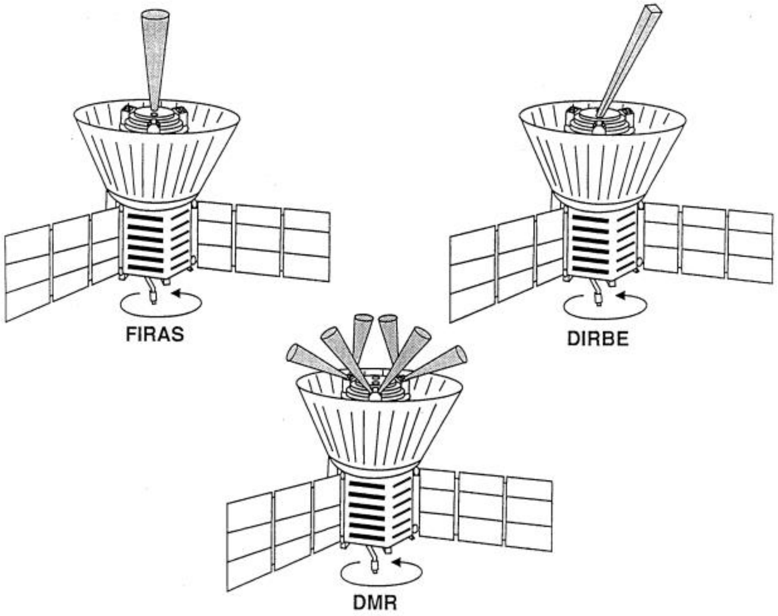
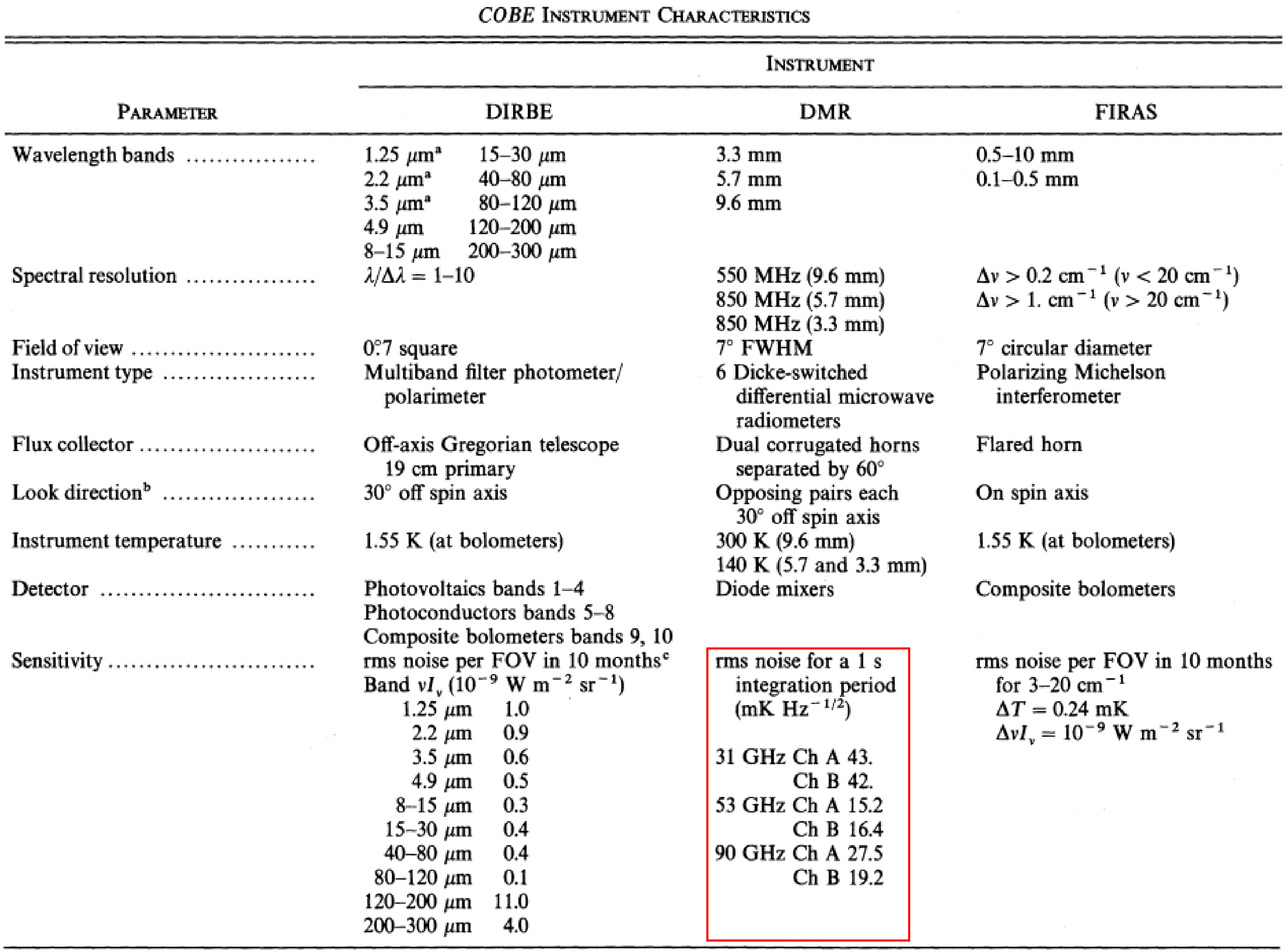


FIG. 3.—Schematic drawing of the viewing direction for each of the three instruments with respect to the spin axis of the spacecraft

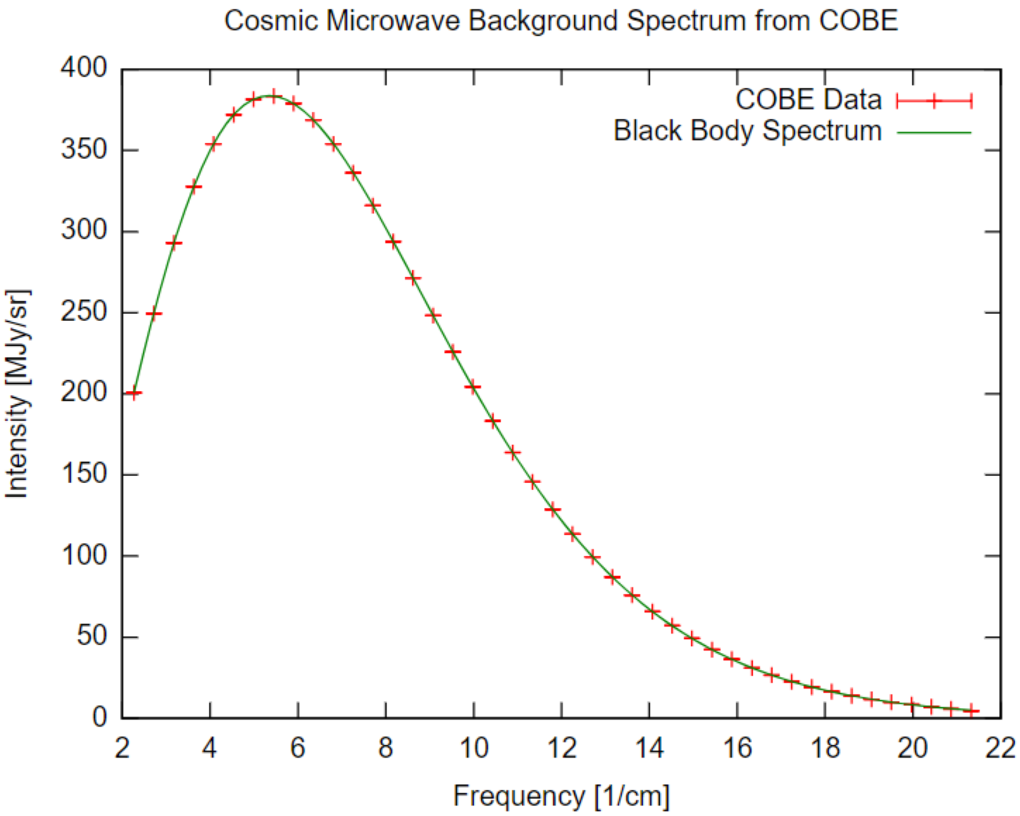


COBE INSTRUMENT CHARACTERISTICS

	INSTRUMENT		
PARAMETER	DIRBE	DMR	FIRAS
Wavelength bands	1.25 μm[a] 15–30 μm 2.2 μm[a] 40–80 μm 3.5 μm[a] 80–120 μm 4.9 μm 120–200 μm 8–15 μm 200–300 μm	3.3 mm 5.7 mm 9.6 mm	0.5–10 mm 0.1–0.5 mm
Spectral resolution	$\lambda/\Delta\lambda = 1$–10	550 MHz (9.6 mm) 850 MHz (5.7 mm) 850 MHz (3.3 mm)	$\Delta\nu > 0.2$ cm^{-1} ($\nu < 20$ cm^{-1}) $\Delta\nu > 1.$ cm^{-1} ($\nu > 20$ cm^{-1})
Field of view	$0\overset{\circ}{.}7$ square	7° FWHM	7° circular diameter
Instrument type	Multiband filter photometer/ polarimeter	6 Dicke-switched differential microwave radiometers	Polarizing Michelson interferometer
Flux collector	Off-axis Gregorian telescope 19 cm primary	Dual corrugated horns separated by 60°	Flared horn
Look direction[b]	30° off spin axis	Opposing pairs each 30° off spin axis	On spin axis
Instrument temperature	1.55 K (at bolometers)	300 K (9.6 mm) 140 K (5.7 and 3.3 mm)	1.55 K (at bolometers)
Detector	Photovoltaics bands 1–4 Photoconductors bands 5–8 Composite bolometers bands 9, 10	Diode mixers	Composite bolometers
Sensitivity	rms noise per FOV in 10 months[c] Band νI_ν (10^{-9} W m^{-2} sr^{-1}) 1.25 μm 1.0 2.2 μm 0.9 3.5 μm 0.6 4.9 μm 0.5 8–15 μm 0.3 15–30 μm 0.4 40–80 μm 0.4 80–120 μm 0.1 120–200 μm 11.0 200–300 μm 4.0	rms noise for a 1 s integration period (mK Hz$^{-1/2}$) 31 GHz Ch A 43. Ch B 42. 53 GHz Ch A 15.2 Ch B 16.4 90 GHz Ch A 27.5 Ch B 19.2	rms noise per FOV in 10 months for 3–20 cm^{-1} $\Delta T = 0.24$ mK $\Delta \nu I_\nu = 10^{-9}$ W m^{-2} sr^{-1}

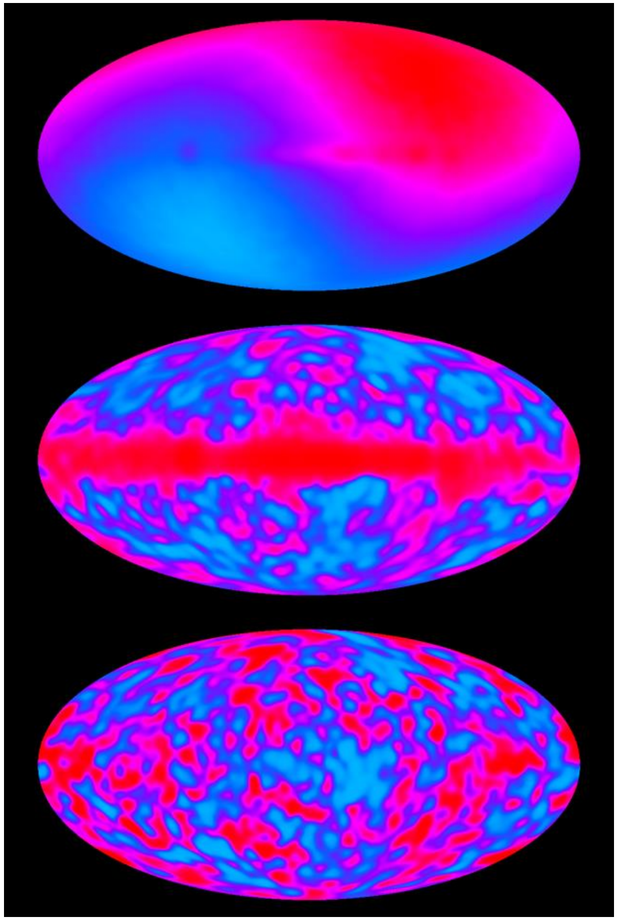
COBE result 1: Black-body curve of CMB

- The CMB spectrum was measured with a precision of 0.005%.
- The results confirmed the Big Bang theory.
- paving the way for NASA's WMAP mission and ESA's Planck mission.



$$T = 2.725 \pm 0.002\text{K}$$

COBE result 2: anisotropy of CMB



- Top: uncorrected
- Middle: after dipole subtraction

  (due to the solar system movement)
- Bottom: after subtraction of the

  Galactic emission

The fluctuations are extremely faint $\frac{\Delta T}{T} \sim 10^{-5}$

Outline

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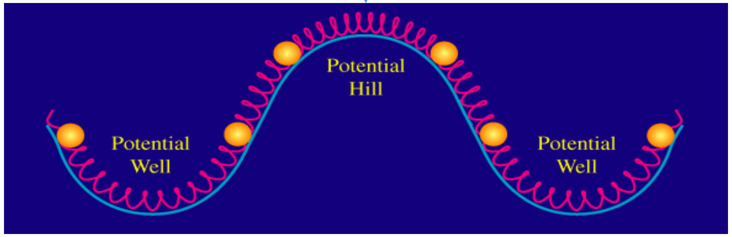
Anisotropy from Inhomogeneity

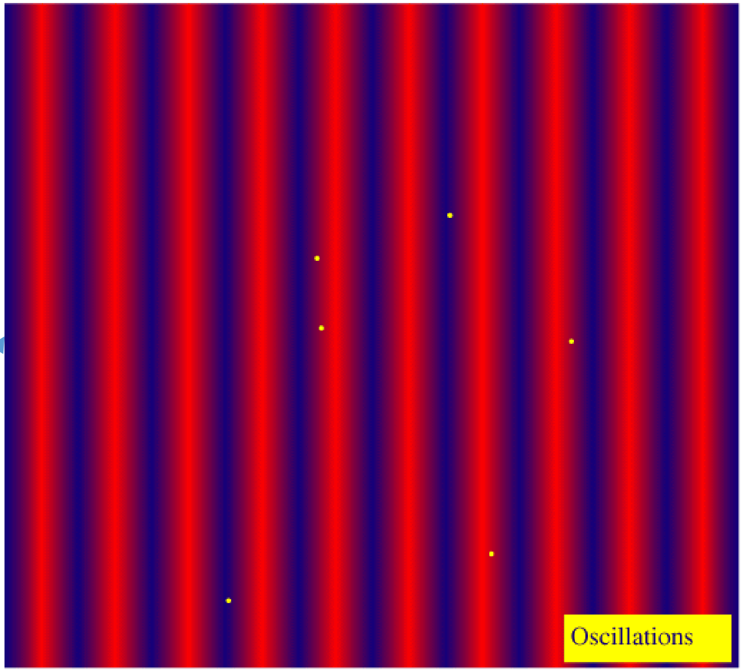
random quantum fluctuations

density enhancements and deficits



(acoustic oscillations)

The photon-baryon plasma stops oscillating at recombination.



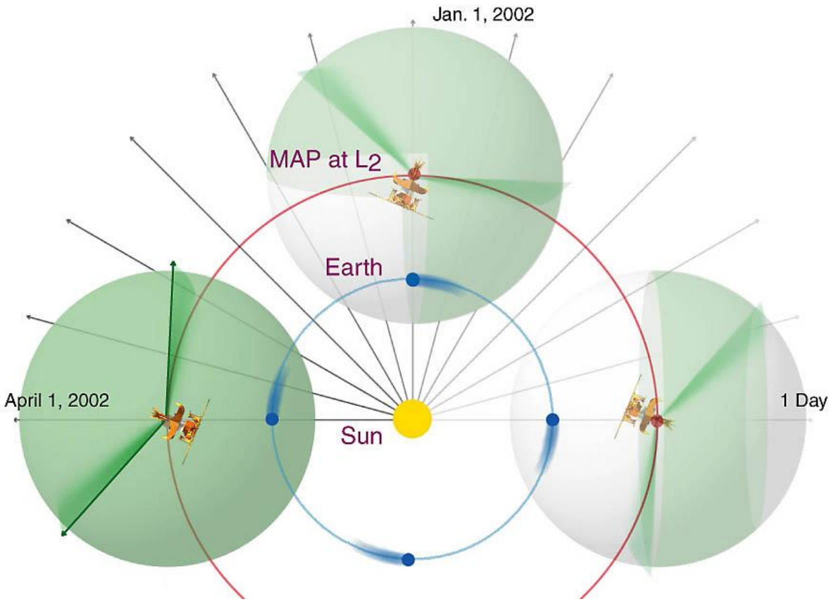
$$\Theta(\hat{\mathbf{n}}) = \frac{T(\hat{\mathbf{n}}) - \bar{T}}{\bar{T}} = \sum_{\ell m} \Theta_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})\,.$$

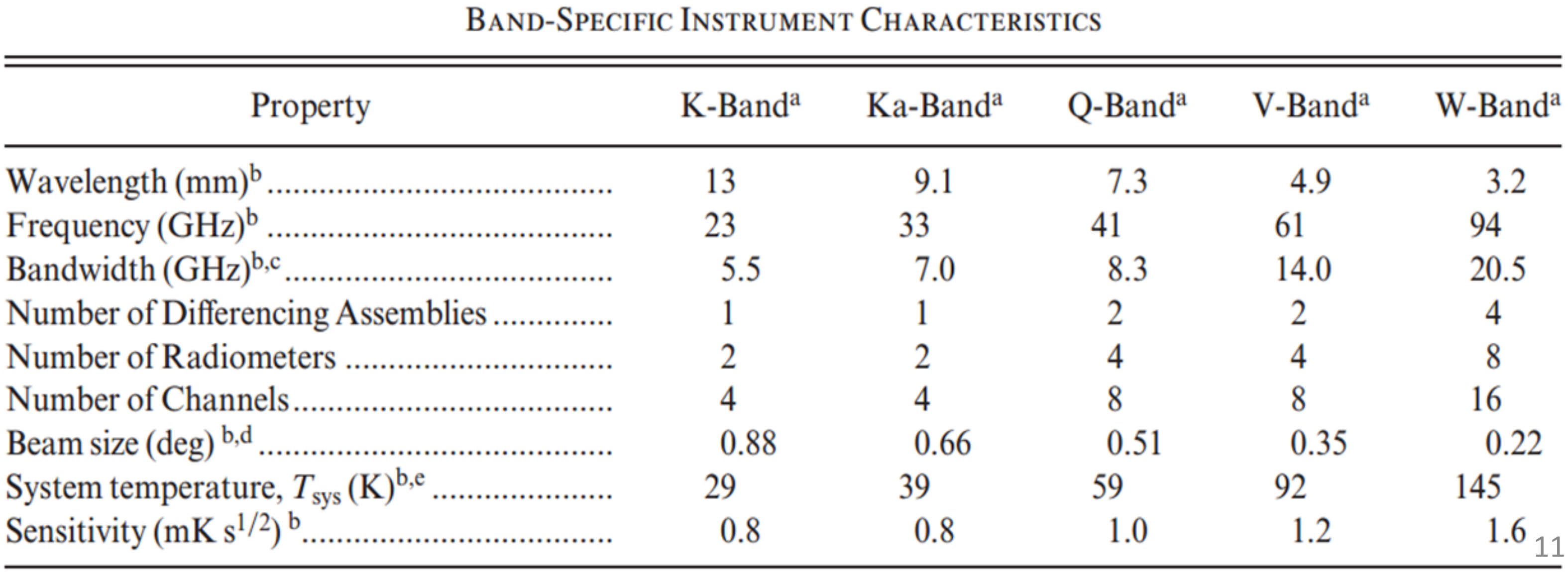
$$\langle \Theta_{\ell m}{}^{*} \Theta_{\ell' m'} \rangle = \delta_{\ell\ell'}\delta_{mm'}C_{\ell}\,.$$

We need more precise measurements about CMB fluctuations!

WMAP(**Wilkinson Microwave Anisotropy Probe**)

- **Launch date:** June 30th, 2001
- **End data collection**: August 19th, 2010
- **The orbits**: 1°–10° Lissajous orbit about second Lagrange point, L2
- **Science Objectives**: measured temperature differences across the sky in CMB





BAND-SPECIFIC INSTRUMENT CHARACTERISTICS

Property	K-Band[a]	Ka-Band[a]	Q-Band[a]	V-Band[a]	W-Band[a]
Wavelength (mm)[b]	13	9.1	7.3	4.9	3.2
Frequency (GHz)[b]	23	33	41	61	94
Bandwidth (GHz)[b,c]	5.5	7.0	8.3	14.0	20.5
Number of Differencing Assemblies	1	1	2	2	4
Number of Radiometers	2	2	4	4	8
Number of Channels	4	4	8	8	16
Beam size (deg) [b,d]	0.88	0.66	0.51	0.35	0.22
System temperature, T_{sys} (K)[b,e]	29	39	59	92	145
Sensitivity (mK $s^{1/2}$) [b]	0.8	0.8	1.0	1.2	1.6

Comparision

	COBE		**WMAP**	
Orbits	Sun-synchronous		Second Lagrange point	
Thermal stability	Dewar(杜瓦瓶)		Passive thermal radiators	
Resolution	7°		0.2°	
Frequency bands and Sensitivity(mK $s^{1/2}$)	31 GHz 53 GHz 90 GHz	43 15.2 27.5	23 GHz 33 GHz 41 GHz 61 GHz 94 GHz	0.8 0.8 1.0 1.2 1.6

Improvements of WMAP

- **5 frequency bands**

  facilitate foreground radiation subtraction

- **A differential experiment**

  measures the temperature difference rather than absolute value

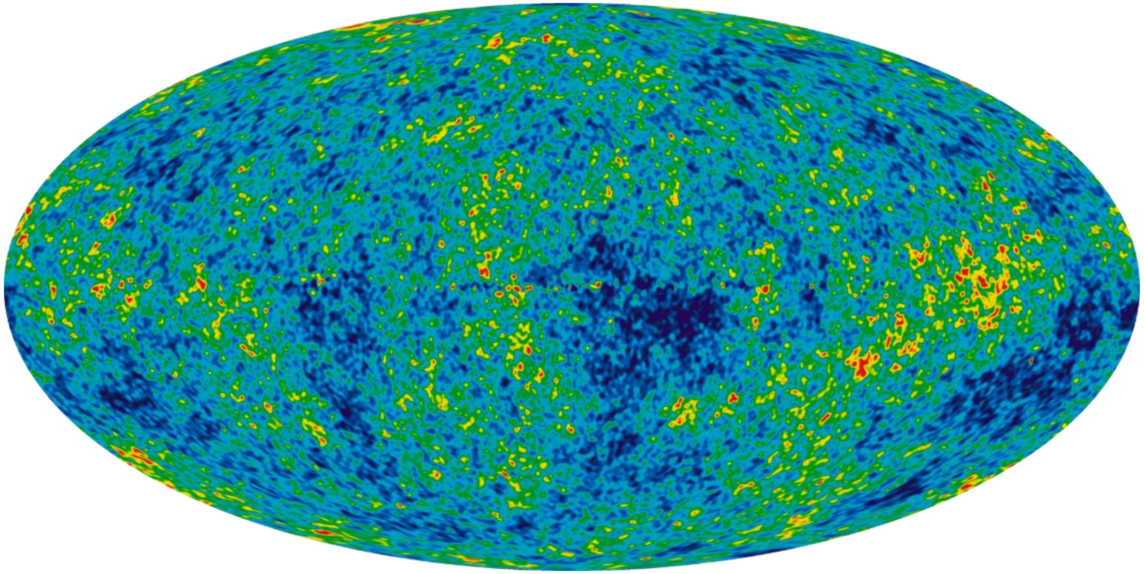
- **Orbit**

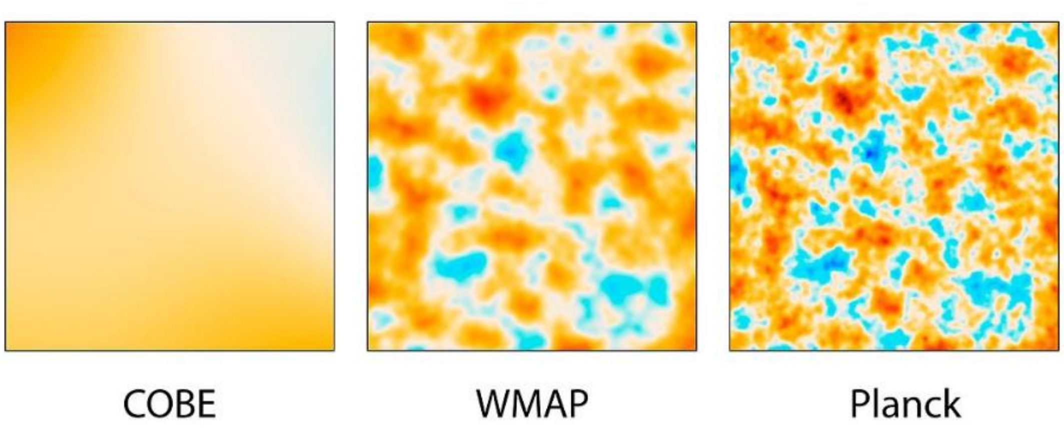
  very stable thermal environment and near 100% observing efficiency

- **Scan strategy**

  allows for a comparison of many sky pixels on many time scales

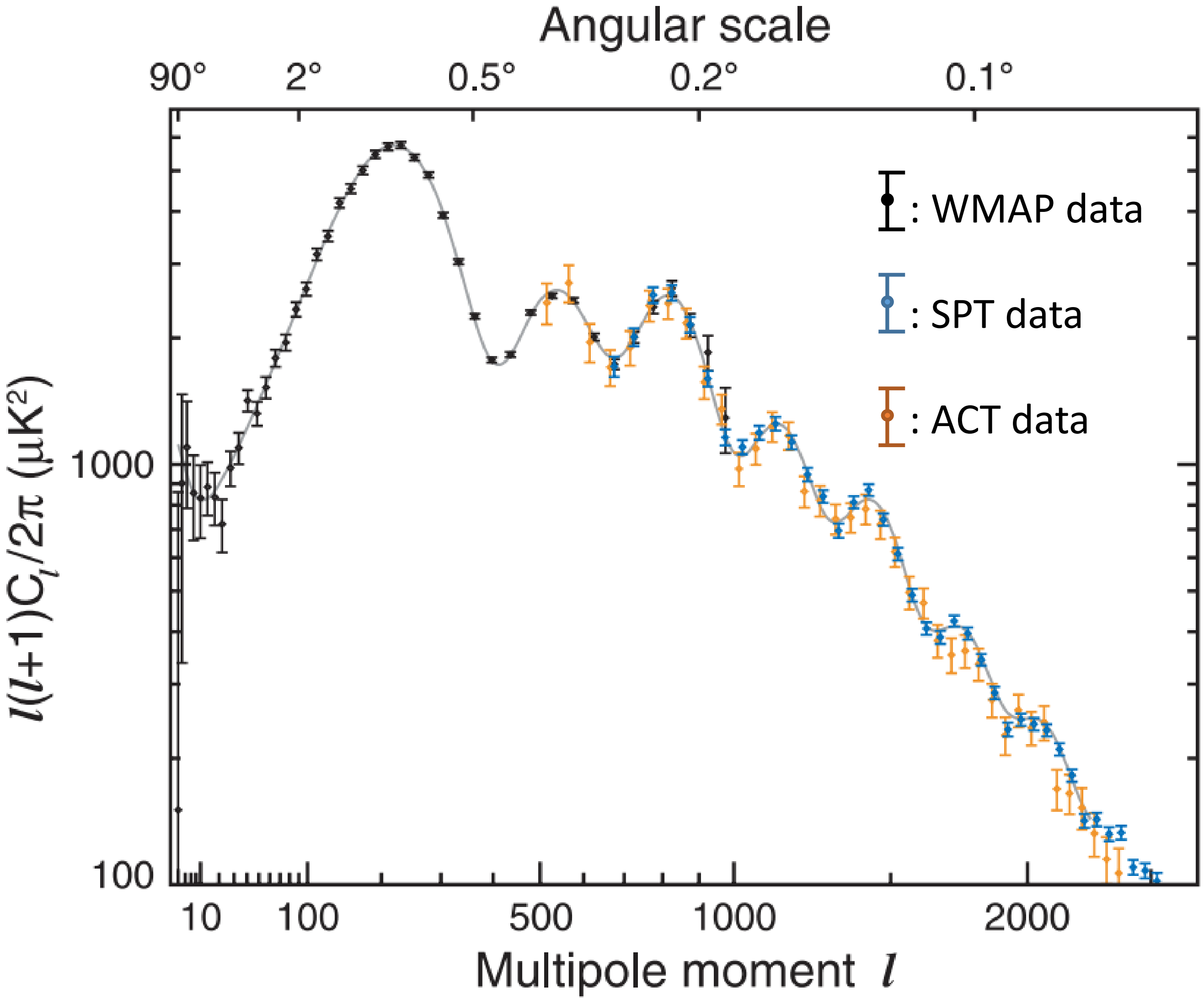
WMAP result: CMB map



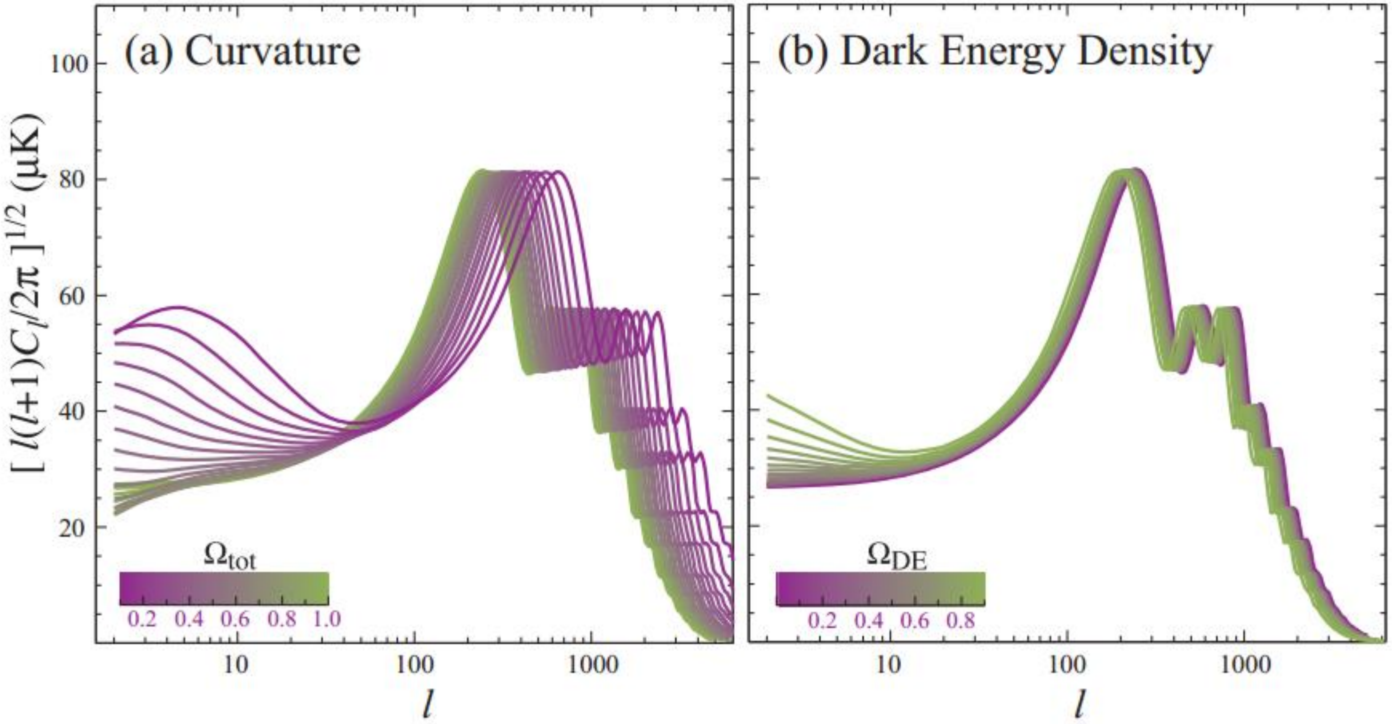


- What can we learn from the anisotropies of CMB?

The gray line is the ΛCDM model fit with WMAP data alone.



First peak: curvature



$$\Omega_{tot} = \Omega_b + \Omega_{DM} + \Omega_{DE} \text{ and } \mathrm{Curvature} = 1 - \Omega_{tot}$$

The first peak in the power spectrum of the anisotropies depend sensitively on the spatial curvature of the universe.

Second peak: baryons

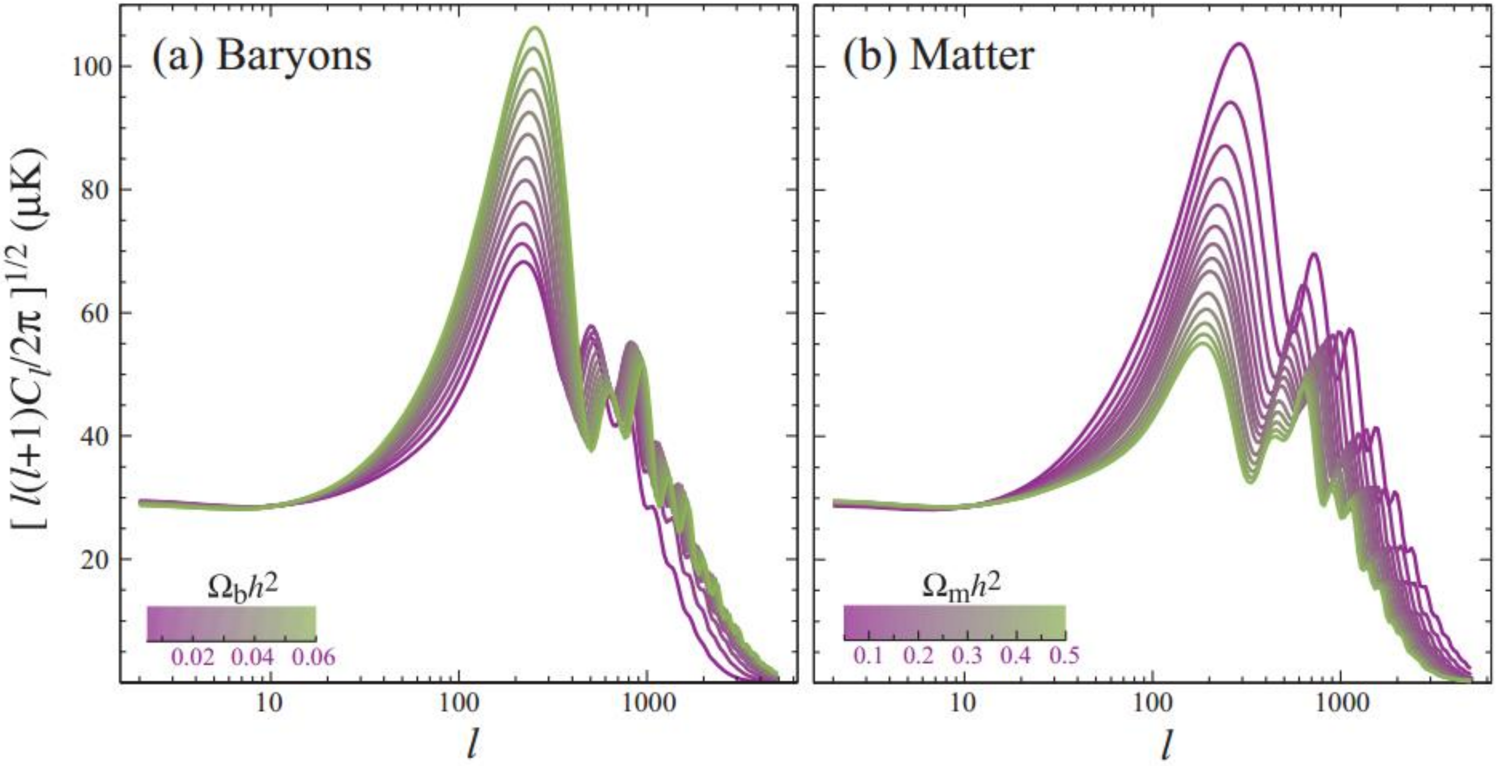
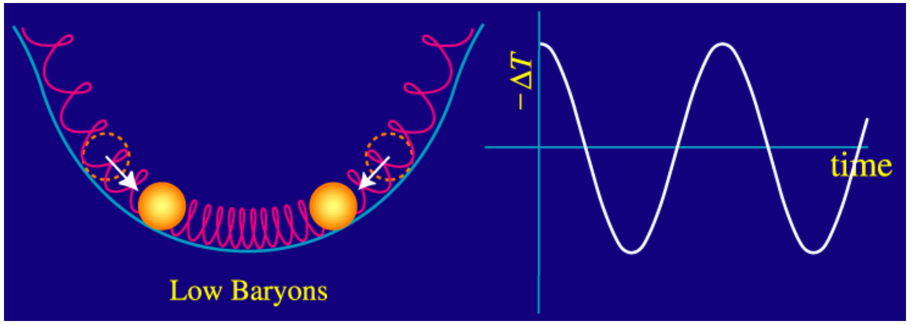
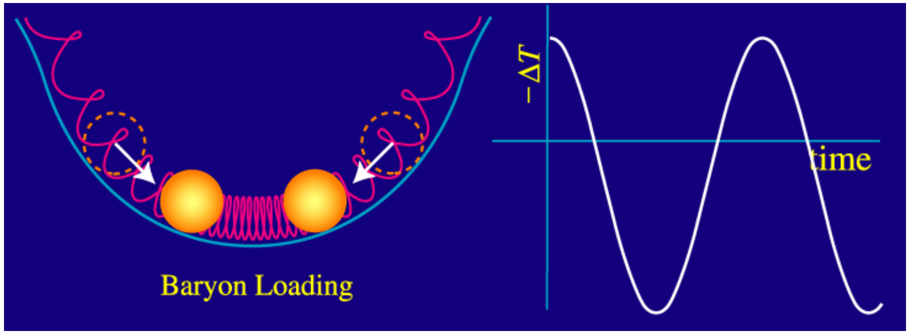
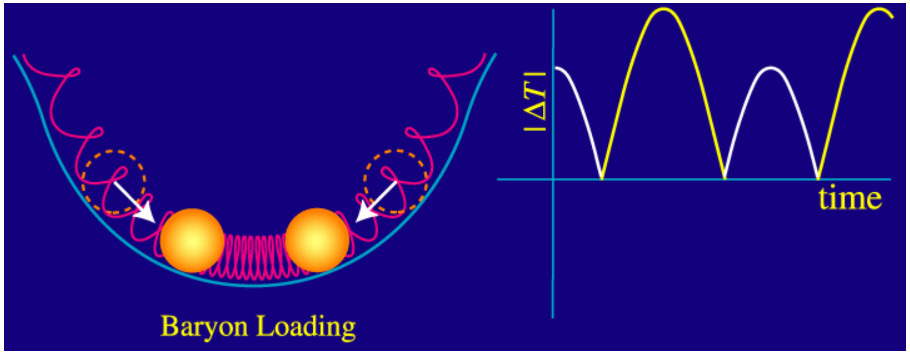


Fig. 15. Baryons and matter. Baryons change the relative heights of the even and odd peaks through their inertia in the plasma. The matter-radiation ratio also changes the overall amplitude of the oscillations from driving effects. Adapted from Hu and Dodelson (2002).

Second peak: baryons



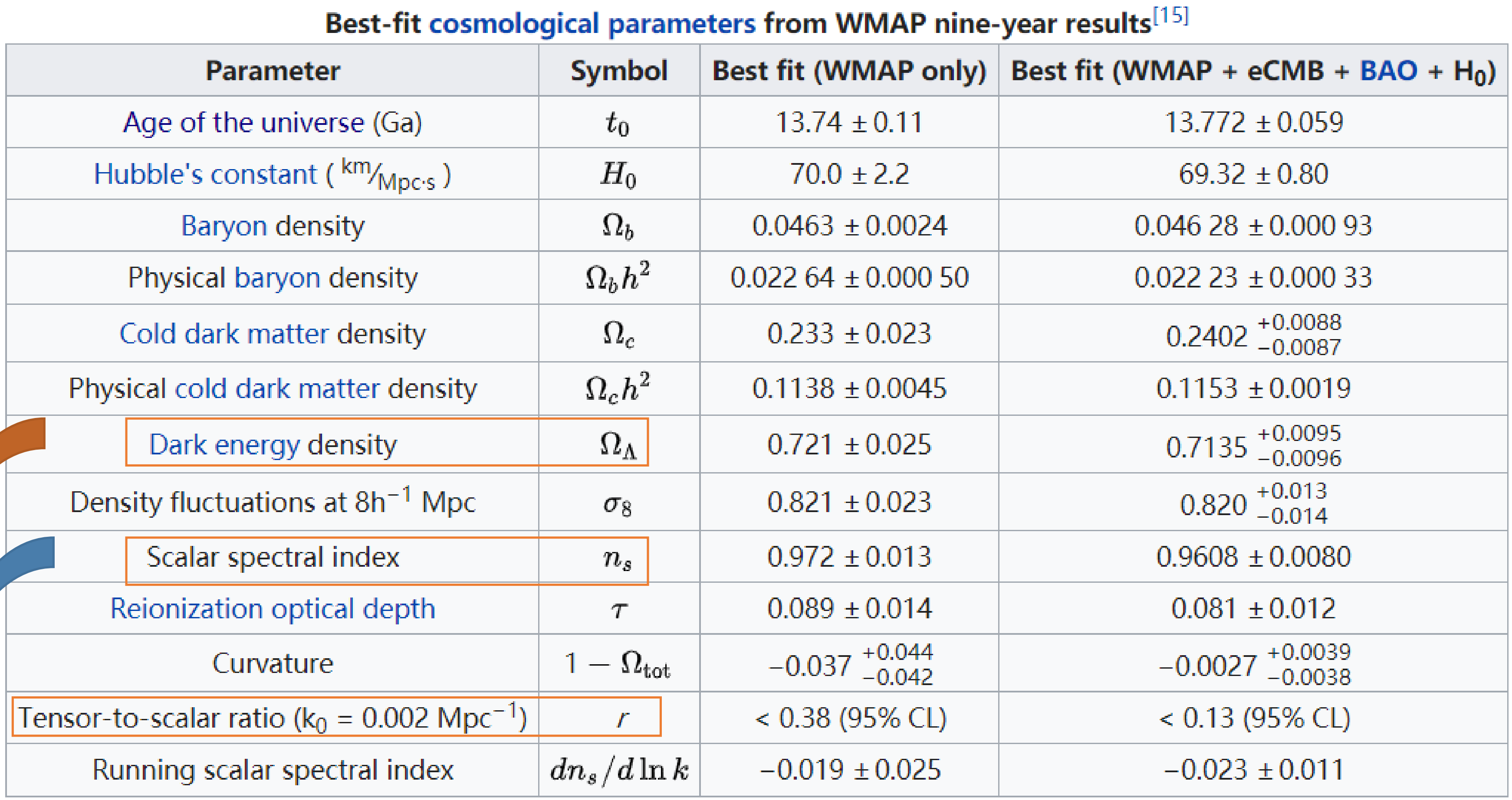




Second peak is suppressed compared with the first and third.

The baryon-photon ratio controls the even-odd modulation of peak heights through the baryon loading effect.

Best-fit cosmological parameters from WMAP nine-year results



Best-fit cosmological parameters from WMAP nine-year results[15]

Parameter	Symbol	Best fit (WMAP only)	Best fit (WMAP + eCMB + BAO + H_0)
Age of the universe (Ga)	t_0	13.74 ± 0.11	13.772 ± 0.059
Hubble's constant ($^{\text{km}}/_{\text{Mpc·s}}$)	H_0	70.0 ± 2.2	69.32 ± 0.80
Baryon density	Ω_b	0.0463 ± 0.0024	$0.046\,28 \pm 0.000\,93$
Physical baryon density	$\Omega_b h^2$	$0.022\,64 \pm 0.000\,50$	$0.022\,23 \pm 0.000\,33$
Cold dark matter density	Ω_c	0.233 ± 0.023	$0.2402^{+0.0088}_{-0.0087}$
Physical cold dark matter density	$\Omega_c h^2$	0.1138 ± 0.0045	0.1153 ± 0.0019
Dark energy density	Ω_Λ	0.721 ± 0.025	$0.7135^{+0.0095}_{-0.0096}$
Density fluctuations at $8h^{-1}$ Mpc	σ_8	0.821 ± 0.023	$0.820^{+0.013}_{-0.014}$
Scalar spectral index	n_s	0.972 ± 0.013	0.9608 ± 0.0080
Reionization optical depth	τ	0.089 ± 0.014	0.081 ± 0.012
Curvature	$1 - \Omega_{\text{tot}}$	$-0.037^{+0.044}_{-0.042}$	$-0.0027^{+0.0039}_{-0.0038}$
Tensor-to-scalar ratio ($k_0 = 0.002$ Mpc^{-1})	r	< 0.38 (95% CL)	< 0.13 (95% CL)
Running scalar spectral index	$dn_s/d\ln k$	-0.019 ± 0.025	-0.023 ± 0.011

Provides an independent evidence for dark energy.

This parameter is related to the Primordial fluctuations.

Primordial fluctuations

Many inflationary models predict that the scalar component of the fluctuations obeys a power law

$$\delta(\vec{x}) \overset{\text{def}}{=} \frac{\rho(\vec{x})}{\bar{\rho}} - 1 = \int \mathrm{d}k \; \delta_k \; e^{i\vec{k}\cdot\vec{x}}$$

$$\langle \delta_k \delta_{k'} \rangle = \frac{2\pi^2}{k^3} \delta(k - k')\, \mathcal{P}(k).$$

$$\mathcal{P}_{\mathrm{s}}(k) \propto k^{n_{\mathrm{s}}-1}.$$

$n_s = 1$ corresponding to scale invariant fluctuations.

The measurement of n_s can help us set constraints on parameters within inflationary theory!

Scalar spectral index: n_s

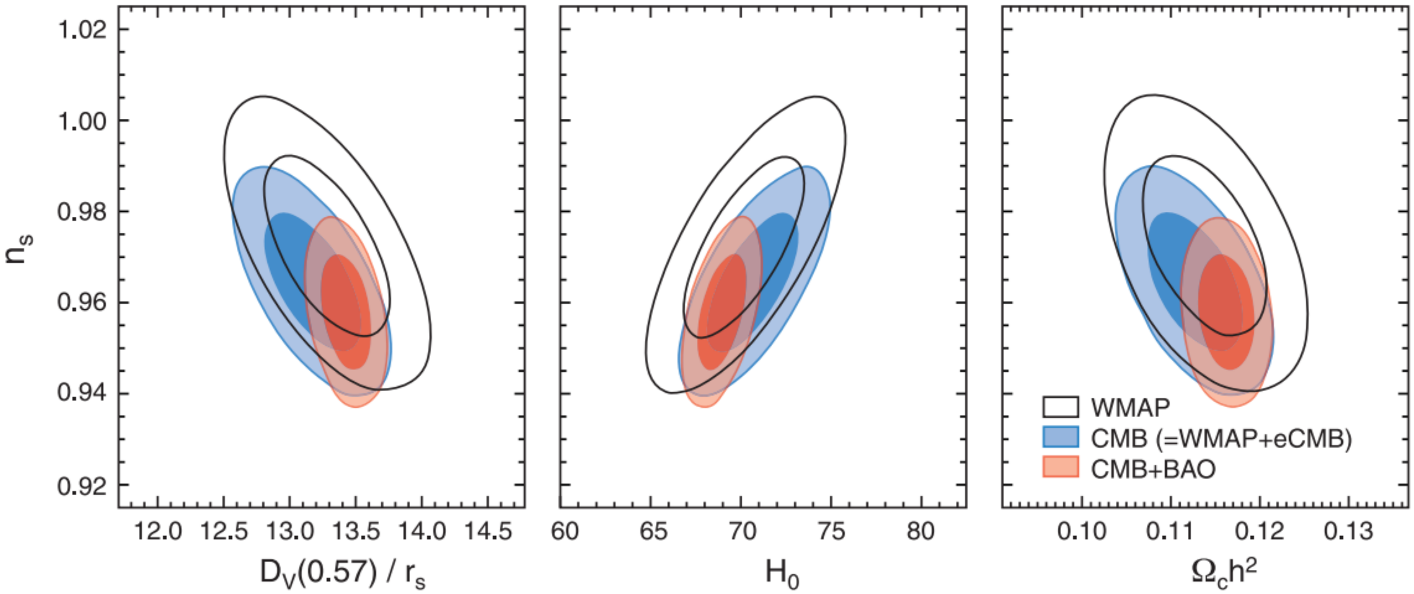


FIG. 4.— Measurements of the scalar spectral index with CMB and BAO data. *Left to right* - contours of ($D_V(0.57)/r_s$,n_s), (H_0,n_s), ($\Omega_c h^2$,n_s). Black contours show constraints using *WMAP* nine-year data alone; blue contours include SPT and ACT data (*WMAP*+eCMB); red contours add the BAO prior(*WMAP*+eCMB+BAO). The BAO prior provides an independent measurement of the low-redshift distance, $D_v(z)/r_s$, which maps to constraints on $\Omega_c h^2$ and H_0. When combined with CMB data, the joint constraints require a tilt in the primordial spectral index ($n_s< 1$) at the 5σ level.

$$n_s = 0.9579^{+0.0081}_{-0.0082}$$

The basic predictions of single-field inflation models for properties of primordial curvature perturbations are well supported by the data.

CMB Polarization

There are two types of polarization.

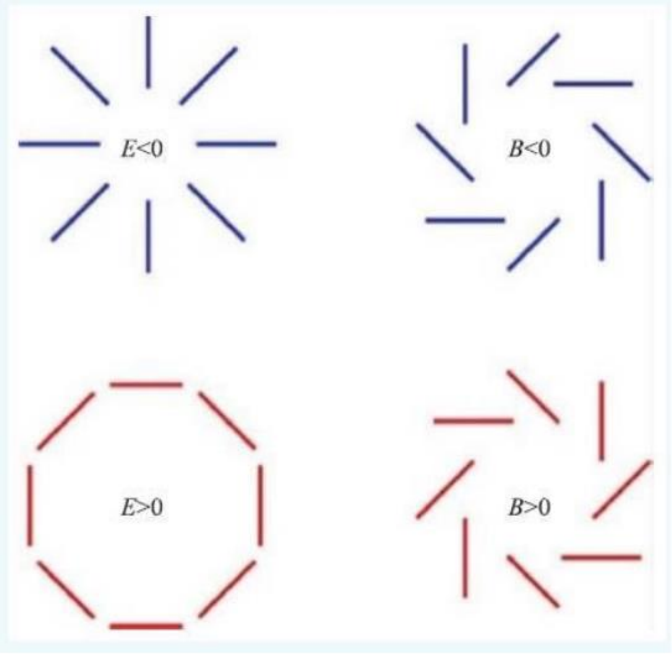
- E-modes

  Thomson scattering.

- B-modes

  gravitational lensing of E-modes.

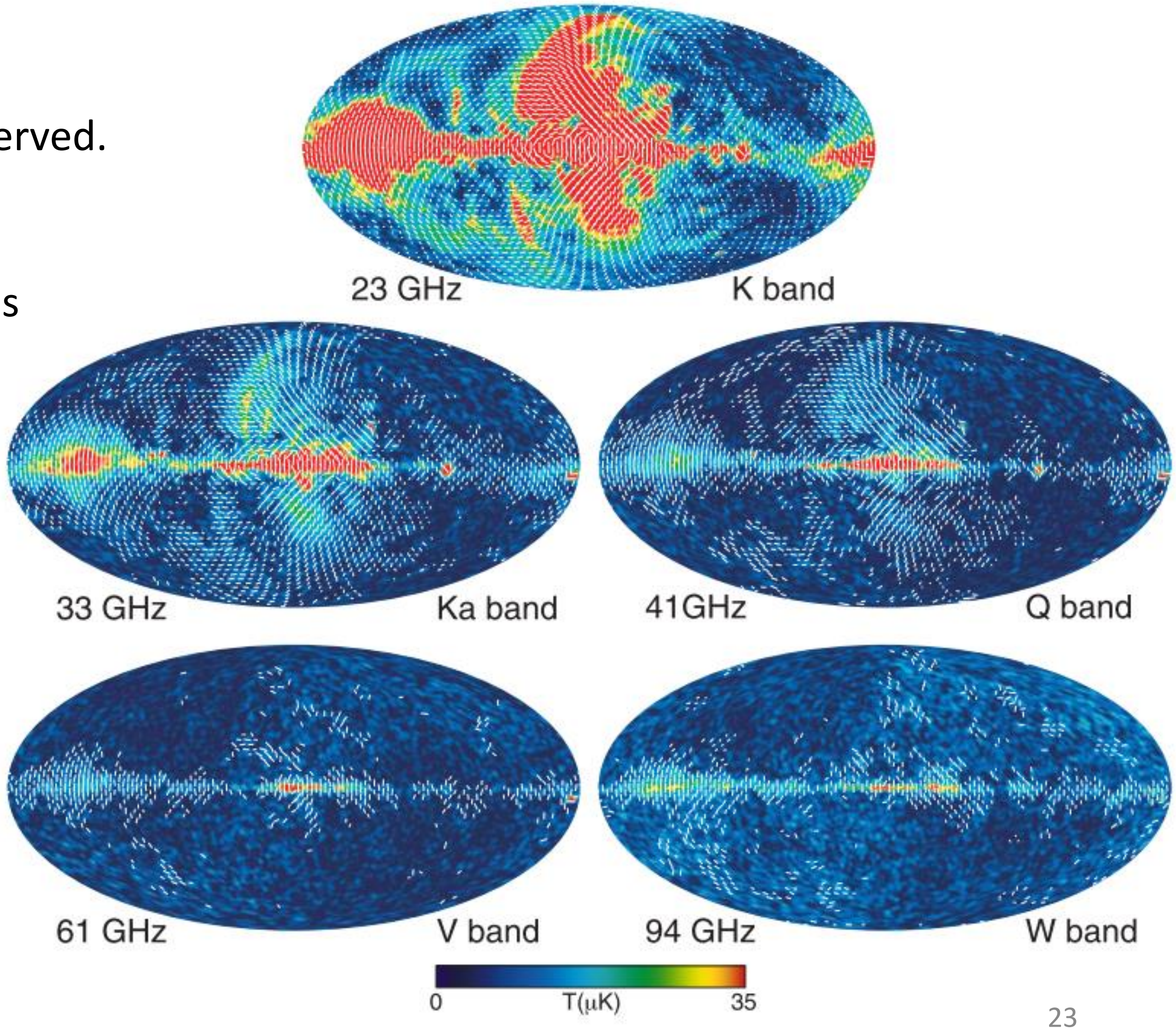
  Primordial gravitational waves



CMB Polarization(WMAP 9-yr result)

- E-modes have been observed.
- No evidence for B-modes caused by Primordial gravitational waves.
- Tensor to scale ratio:

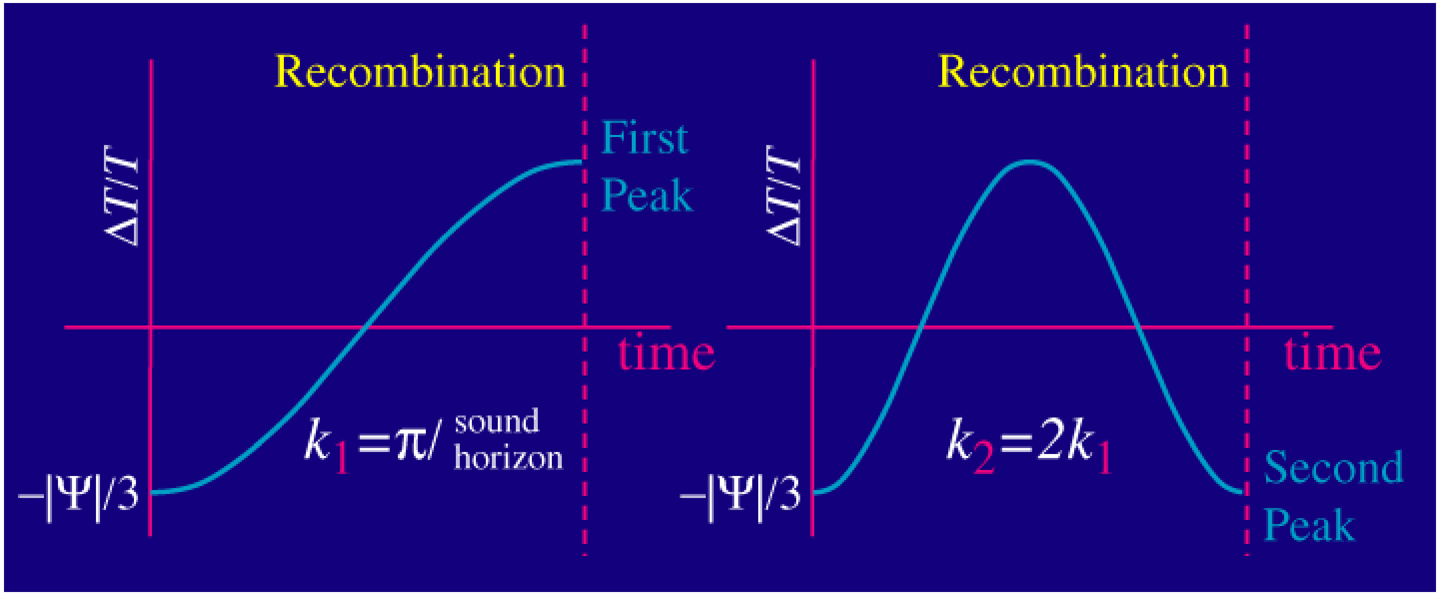
$$r < 0.38(95\%\ CL)$$



Summary

- The COBE-project can be regarded as the starting point for cosmology as a precision science and it provided 2 key evidences for the Big Bang theory.
  - Black-body curve of CMB (high precision 0.005%)
  - Intrinsic anisotropy of CMB ($\frac{\Delta T}{T} \sim 10^{-5}$)
- WMAP's measurements played a key role in establishing the Lambda-CDM model.
  - produced the first fine-resolution (0.2 degree) full-sky CMB map
  - reducing the allowed volume of cosmological parameters by a factor in excess of 68,000

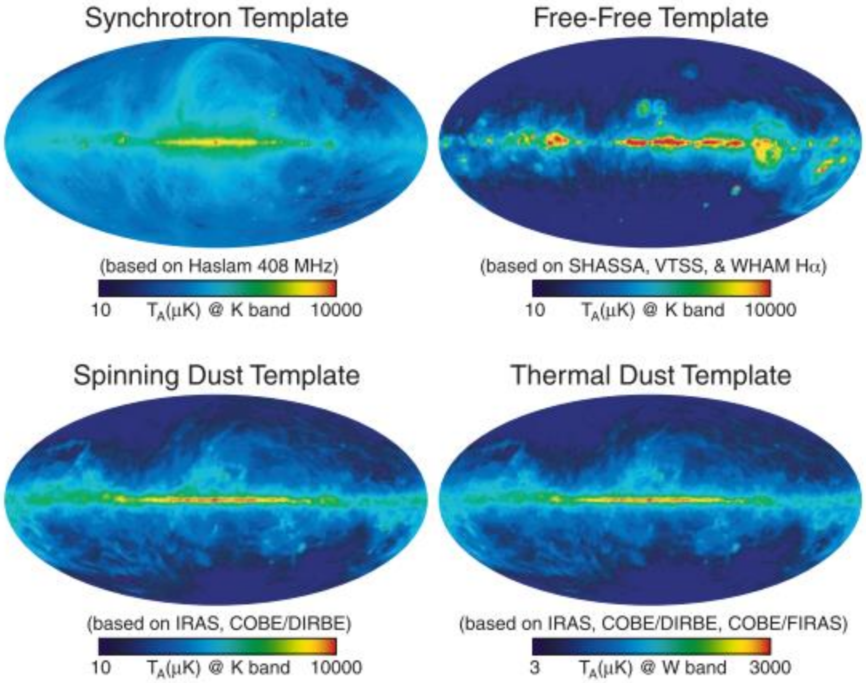
Angular Peaks



Modes caught at extrema of their oscillations become the peaks in the CMB power spectrum.

Galactic emission

- The main emission mechanisms:
  - synchrotron radiation(同步辐射)
  - free-free emission(自由发射)
  - astrophysical dust emissions


Synchrotron Template

(based on Haslam 408 MHz)

Free-Free Template

(based on SHASSA, VTSS, & WHAM Hα)

Spinning Dust Template

(based on IRAS, COBE/DIRBE)

Thermal Dust Template

(based on IRAS, COBE/DIRBE, COBE/FIRAS)