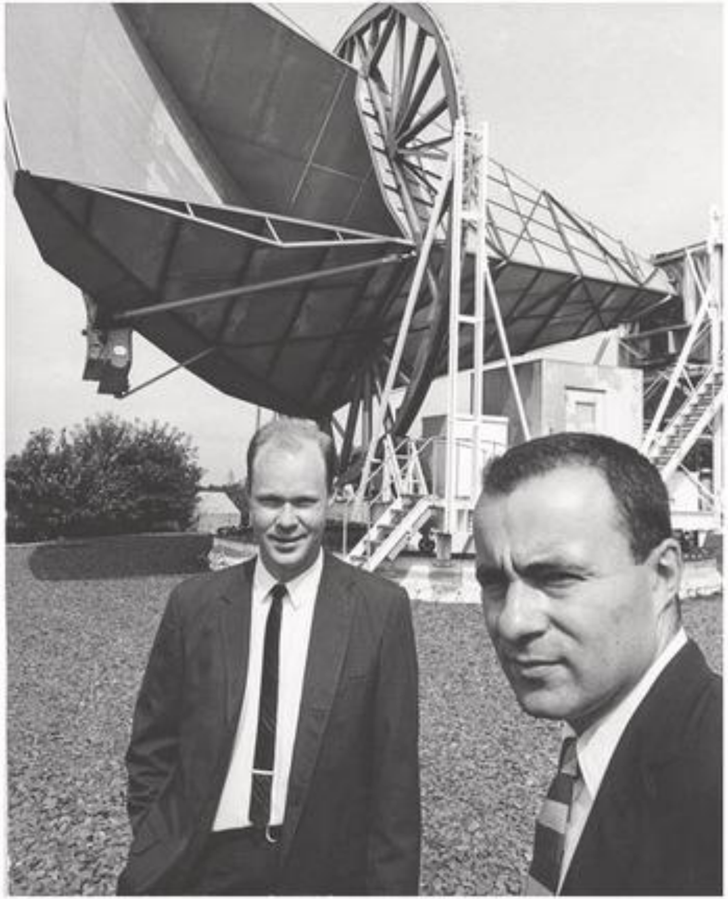
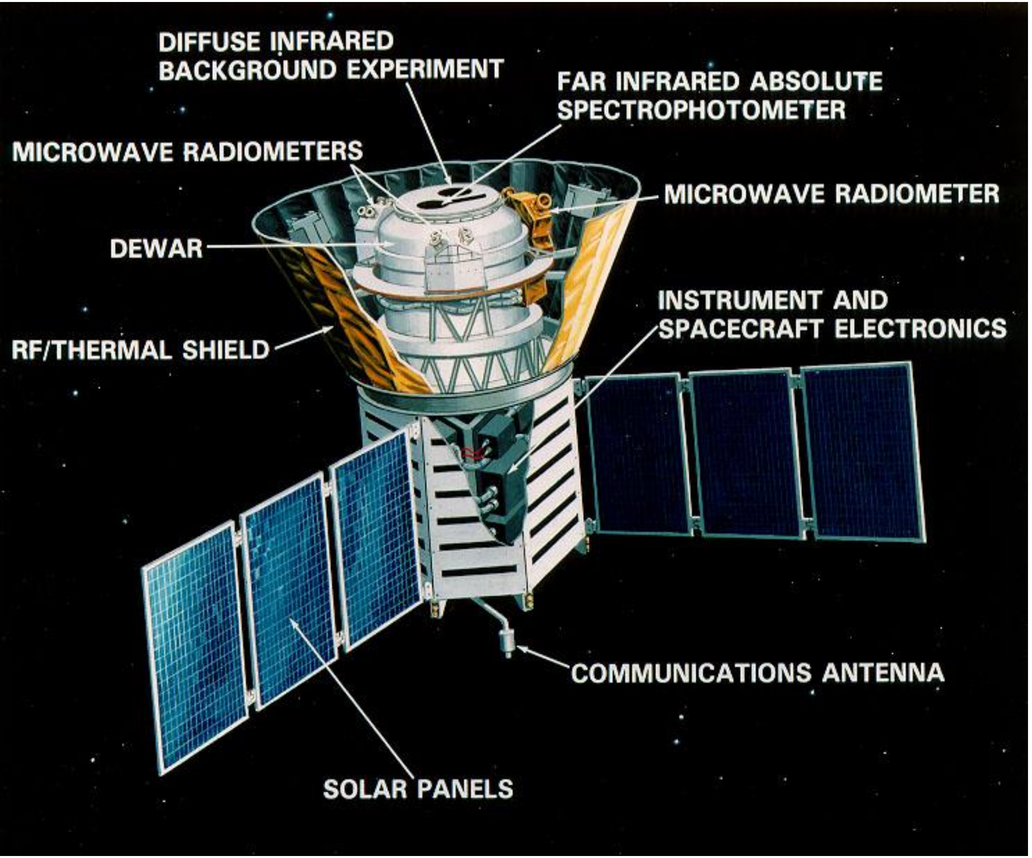
Discovery of the Cosmic Microwave Background (CMB)

- Early signs and speculations in the 1940s
- Arno Penzias & Robert Wilson
  - 1964 discovery using a 6 m horn antenna at Bell Labs, New Jersey
  - published in 1965 with interpretation by Robert H. Dicke, Jim Peebles, and David Wilkinson at Princeton University
  - Nobel Prize in 1978
- Developments in theory in the 1970s
- 1989-1993 operation of the NASA *Cosmic Background Explorer (COBE)* satellite



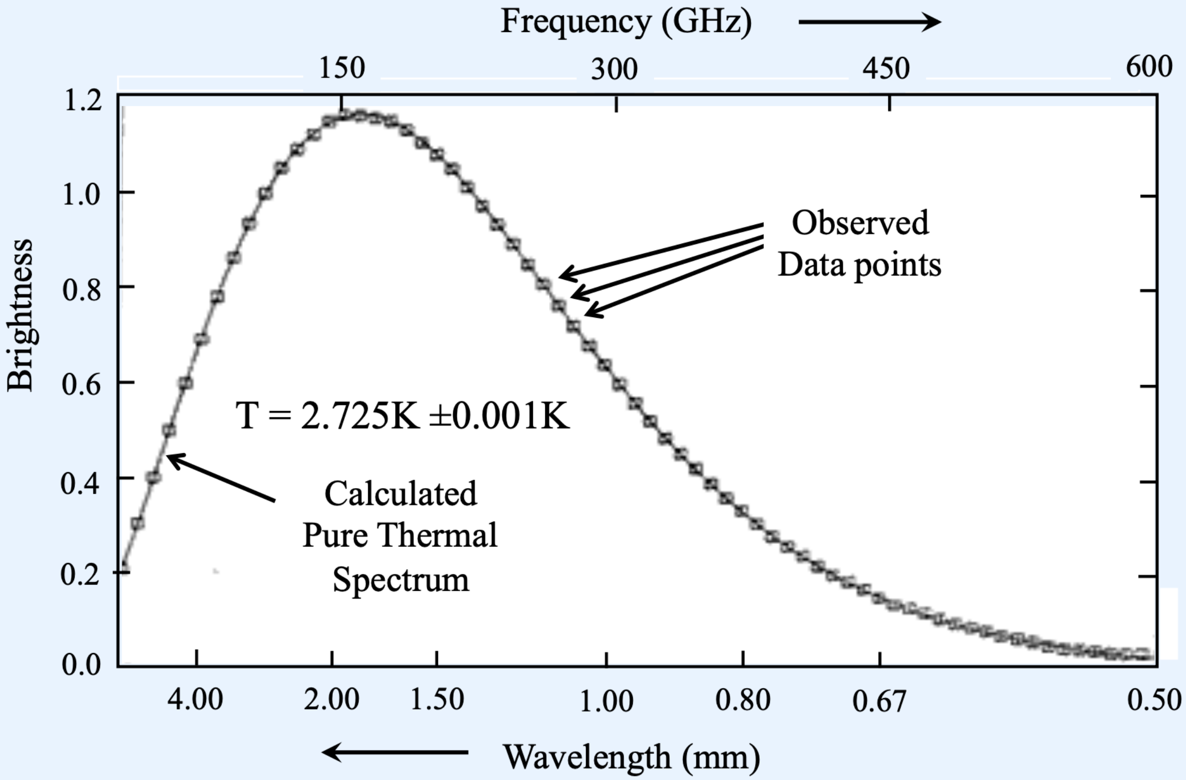
Cosmic Background Explorer (COBE)



- Far-Infrared Absolute Spectrophotometer (FIRAS) [PI: John Mather]
- Differential Microwave Radiometer (DMR) [PI: George Smoot]
- Diffuse Infrared Background Experiment (DIRBE)
- Dewar with 1.4 K liquid helium
- Nobel Prize in 2006

CMB spectrum

$$u(\nu)d\nu = \frac{8\pi h}{c^3}\frac{\nu^3}{\exp(h\nu / k_B T) - 1}d\nu$$



Temperature of recombination

Naively, recombination might happen when $k_B T \sim 13.6$ eV (typical photon energy ~ H binding energy). i.e. T ~ 150,000K.

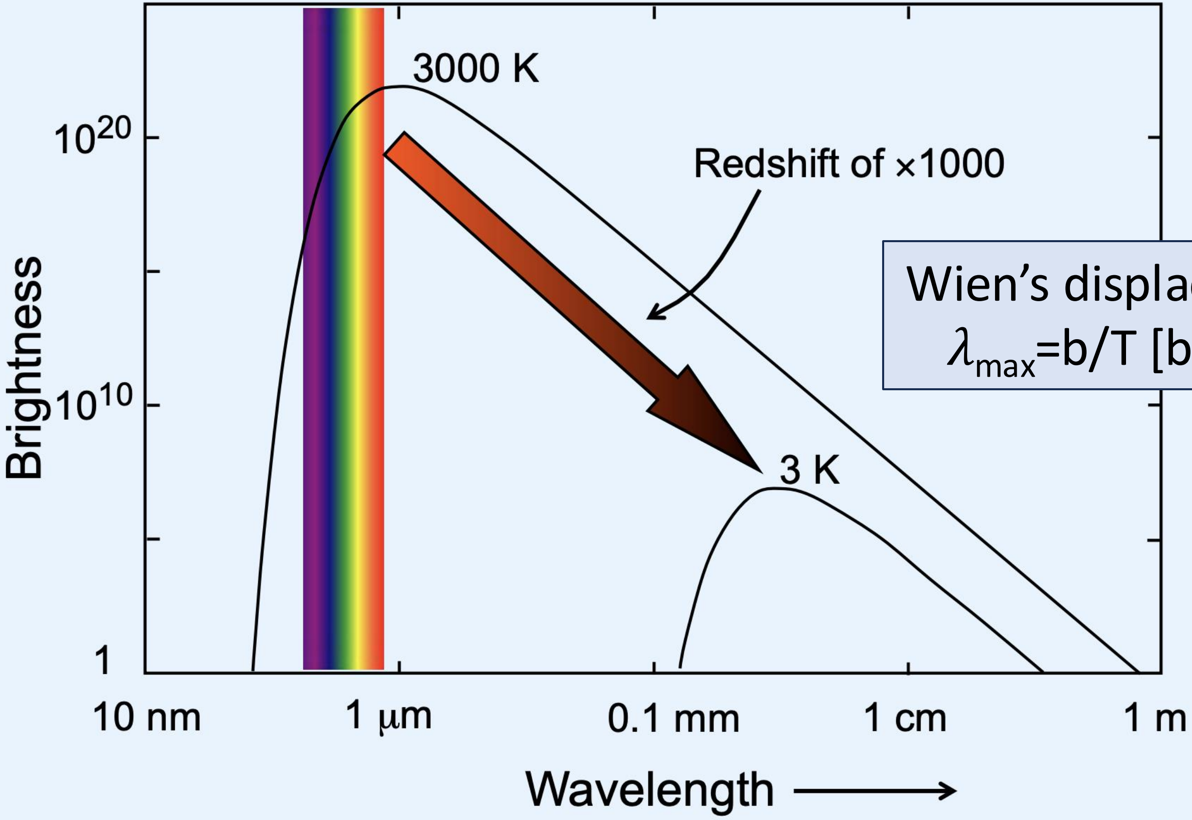
However, photons more abundant than protons, so even at lower temperature, there are many more photons with E > 13.6 eV.

Photon/baryon ratio is large and preserved during expansion:

$$\frac{n_\gamma}{n_b} \approx \frac{\Omega_{\gamma,0} / < E_\gamma >}{\Omega_{b,0} / < E_b >} \approx \frac{5.0\times10^{-5} / 7\times10^{-4} \text{ eV}}{0.04 / 938 \text{ MeV}} \approx 1.7\times10^{9}$$

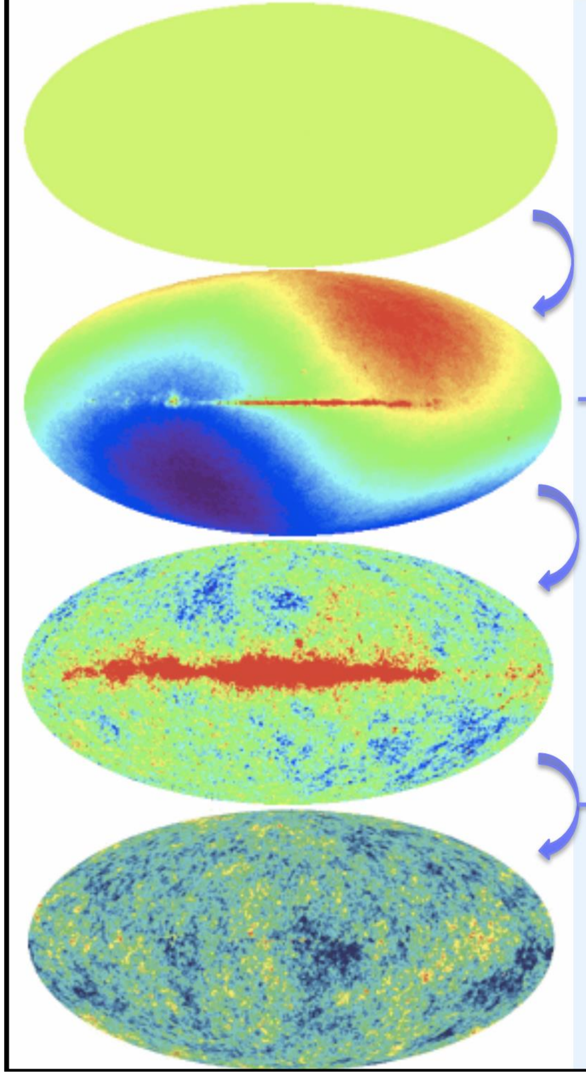
At 5700K, the tail of the black body contains as many photons with E > 13.6 eV as there are protons.

Redshift preserves blackbody spectrum with $T = T_0/a$



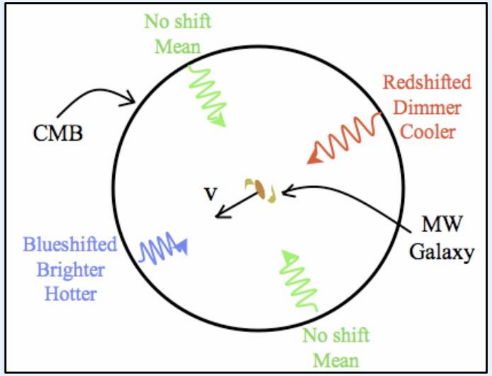
Wien's displacement law:
$\lambda_{max}=b/T$ [b = 3 mm·K]

Features visible in the CMB all-sky map



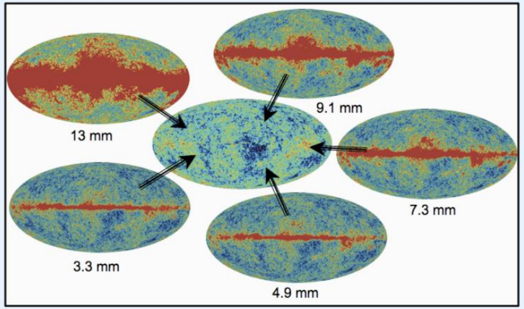
×1000 contrast

dipole



×200 contrast

remove galaxy

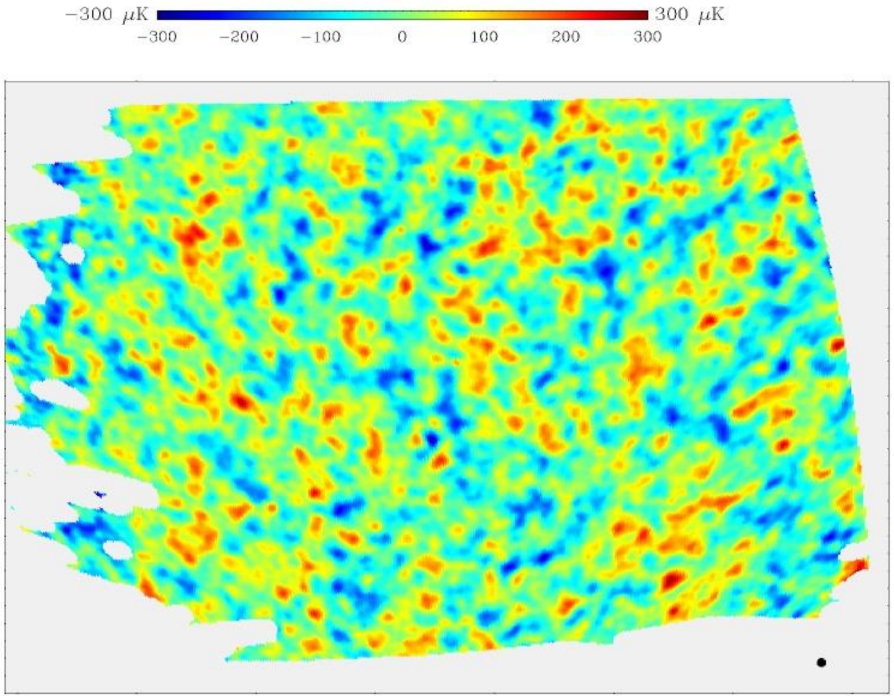


CMB anisotropies

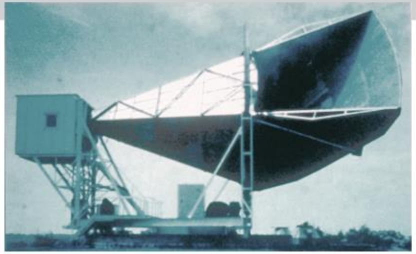
- 1997-1998, 2003 BOOMERanG experiment (Caltech + Sapienza Univ. of Rome)

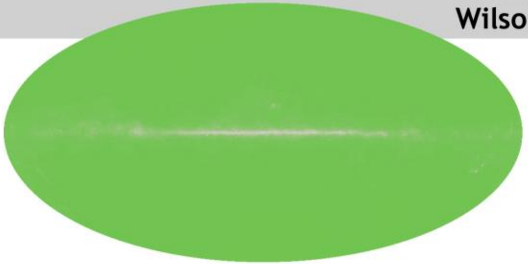
  Balloon Observations Of Millimetric Extragalactic Radiation and Geophysics


Flew 42 km high above Antartica

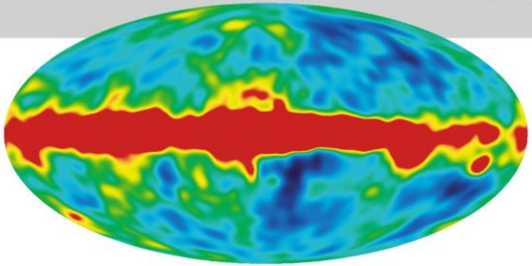


1965 **Penzias and Wilson**

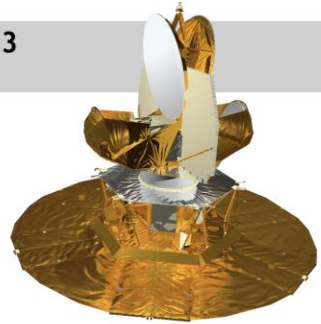


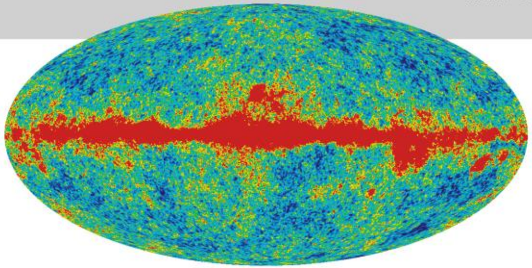


1992 **COBE**

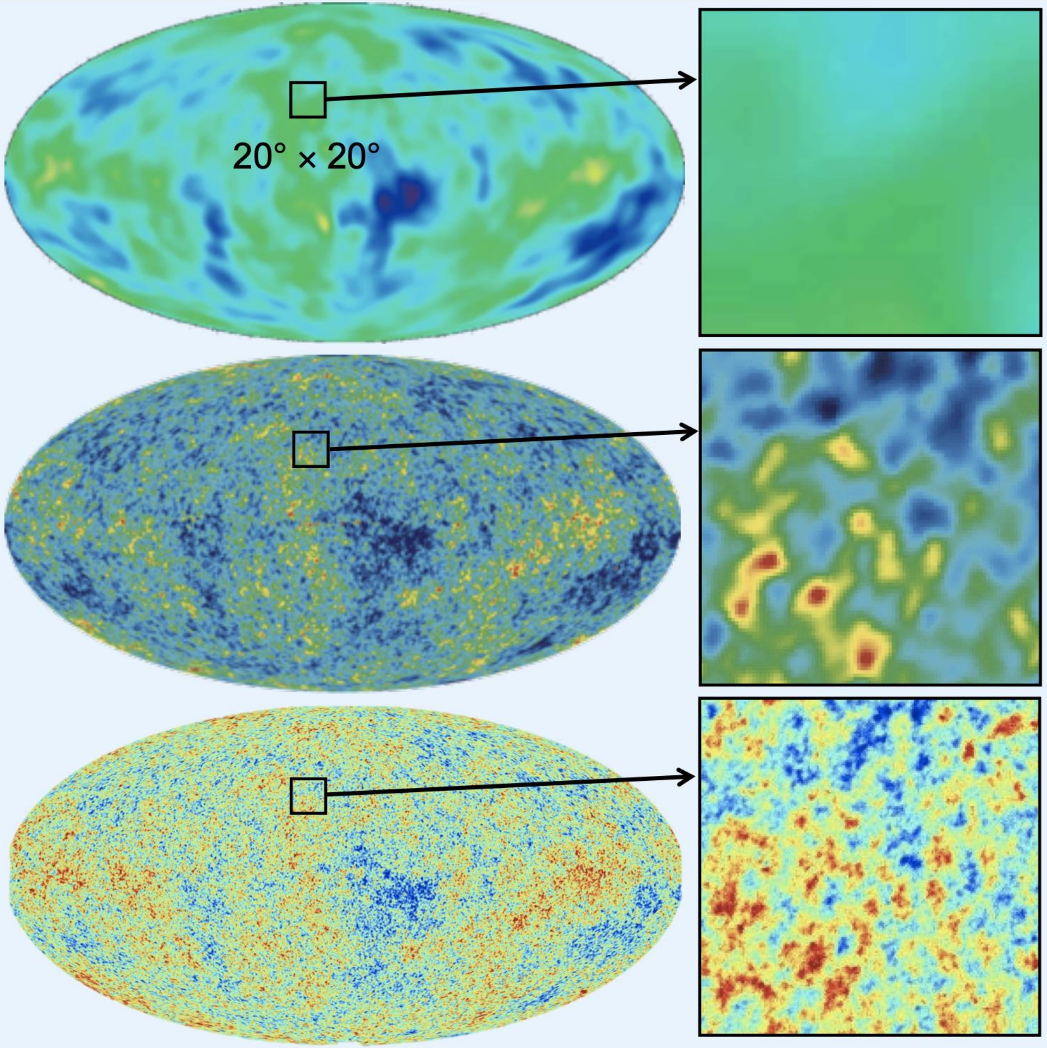


2003 **WMAP**





Wilkinson Microwave Anisotropy Probe (*WMAP*), 2001-2010

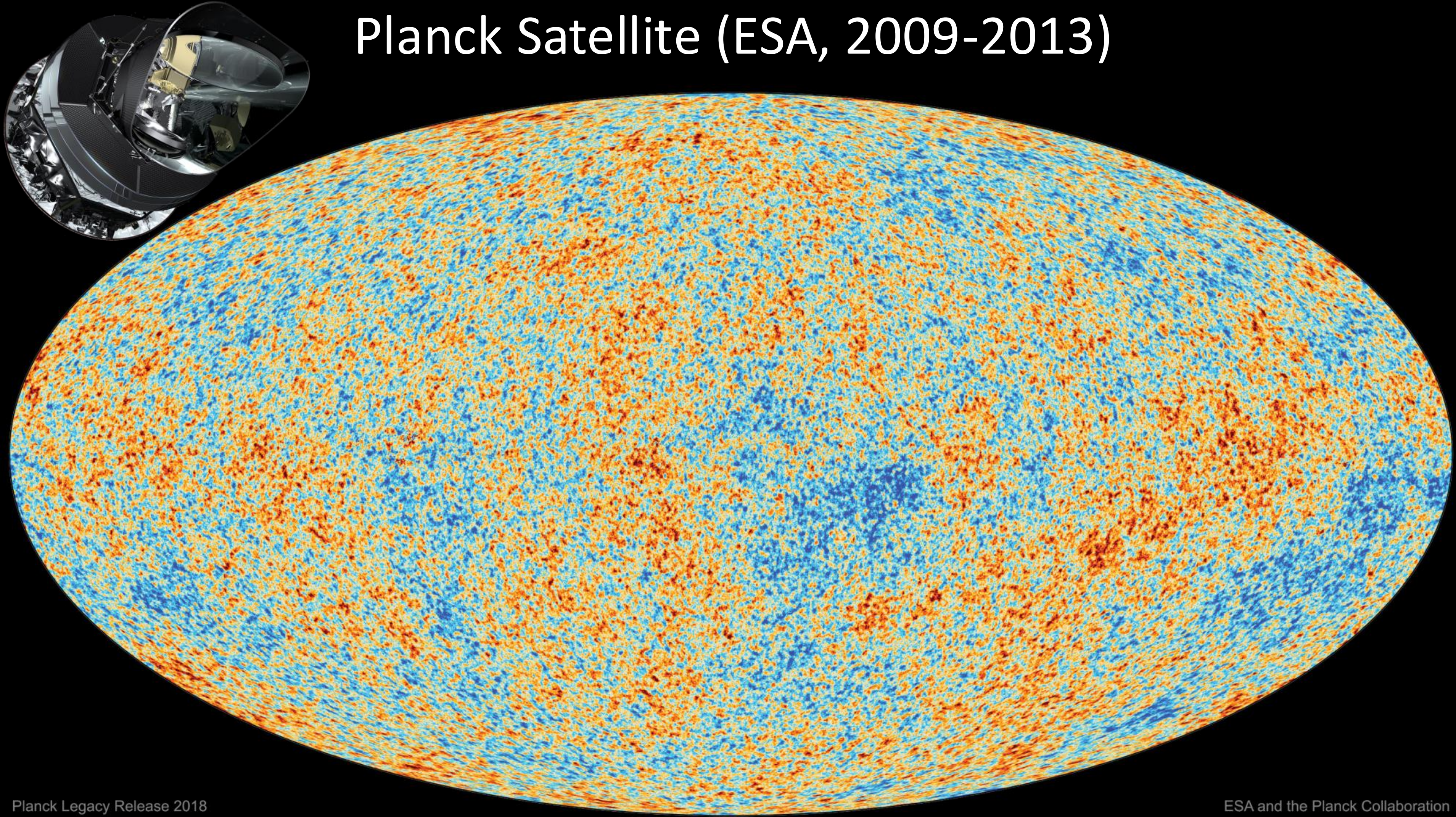


COBE: 1990
Resolution: 7°
Sensitivity: ×1
Cost: 600 M$

WMAP: 2003
Resolution: 0.13°
Sensitivity: ×5
Cost: 800 M$

Planck: 2012
Resolution: 0.08°
Sensitivity: ×15
Cost: 1000 M$

Planck Satellite (ESA, 2009-2013)



Planck Legacy Release 2018

ESA and the Planck Collaboration

Spherical Harmonics

Any quantity which varies with position on the surface on a sphere can be written as the sum of spherical harmonics:

$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$

measured anisotropy map as function of spherical polar angles θ and ϕ

weight - how much of the signal is accounted for by this particular mode

spherical harmonic function

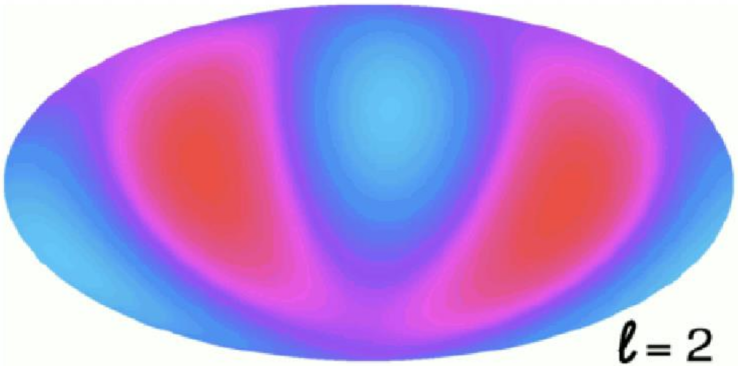
The spherical harmonic functions themselves are just increasingly complicated trignometric functions, e.g.:

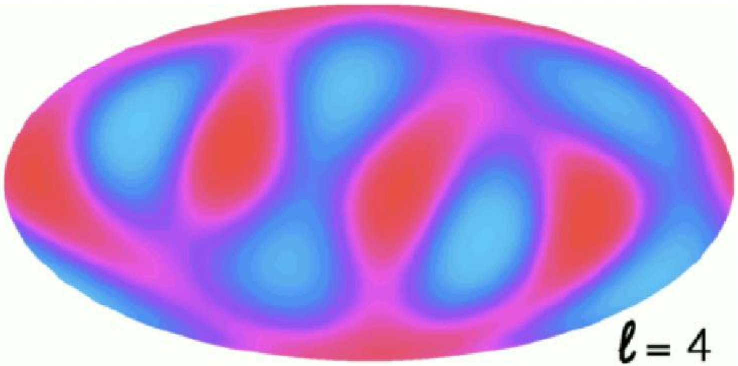
$$Y_{22}(\theta,\phi) = \sqrt{\frac{5}{96\pi}}\, 3\sin^2\theta e^{2i\phi}$$

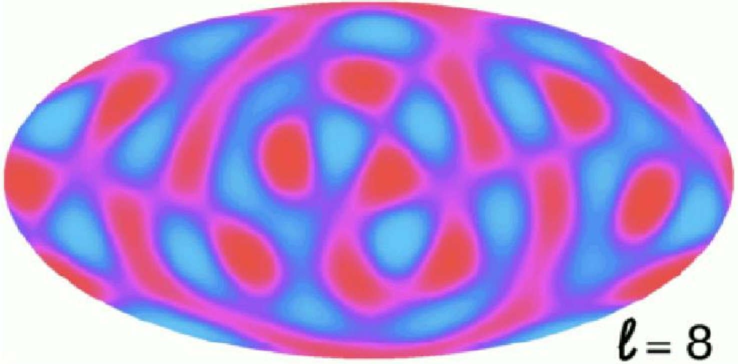
$$C(l) = \frac{1}{2l+1}\sum_{m} a_{lm}^2$$

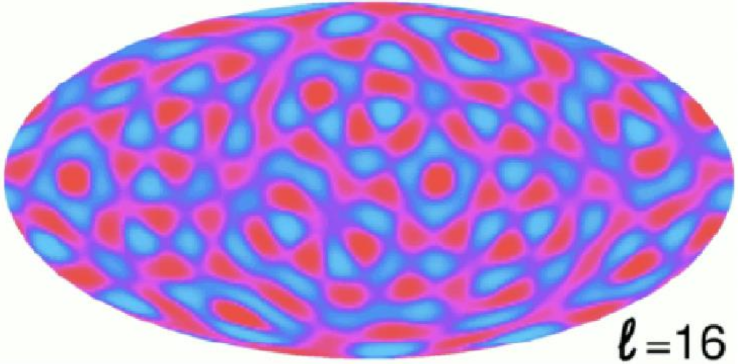
Normally plot $C(l)\, l(l+1)/2\pi$ μK^2 against $l \approx 180/\Delta\theta°$.
This shows relative power per log l.

Spherical harmonic decomposition



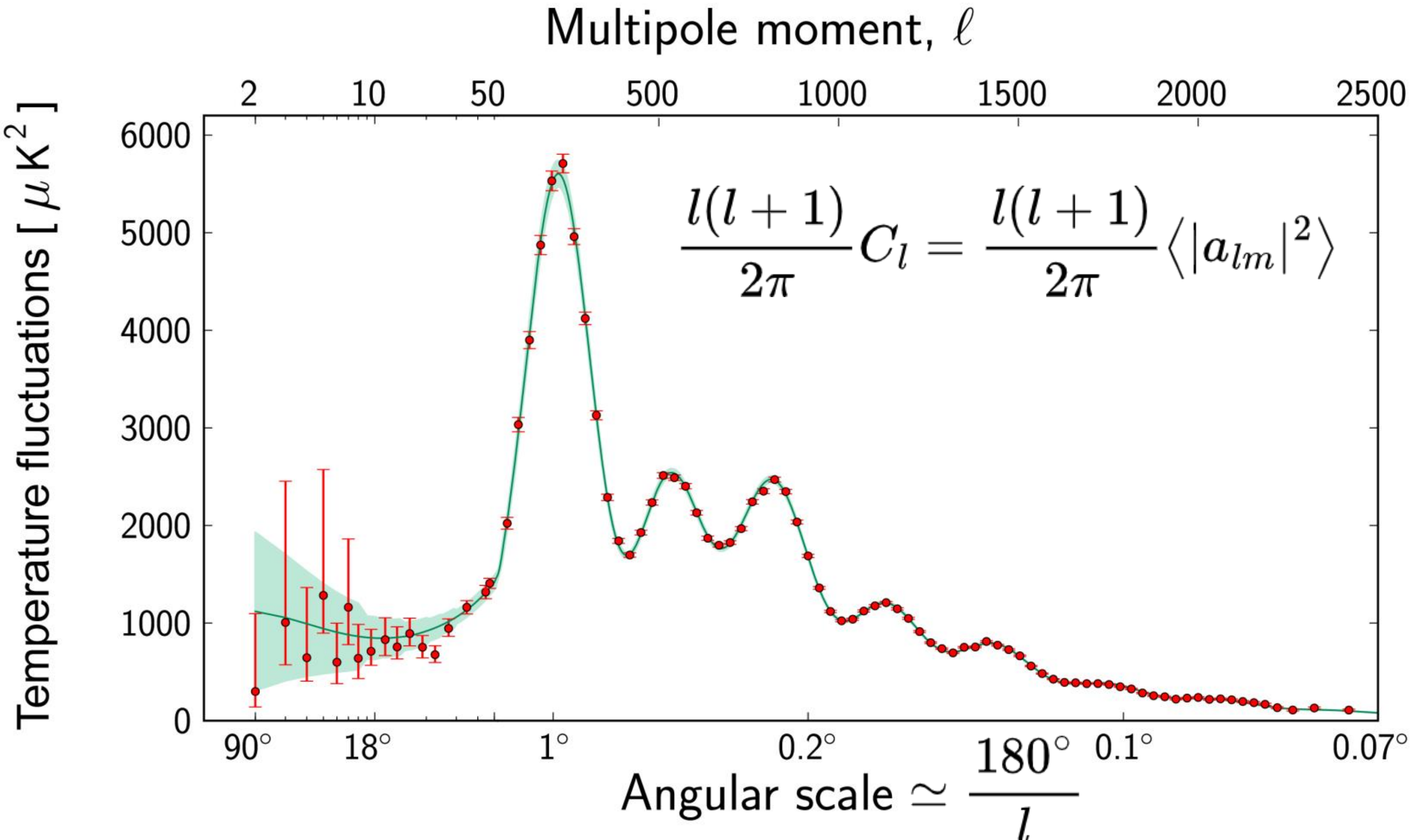


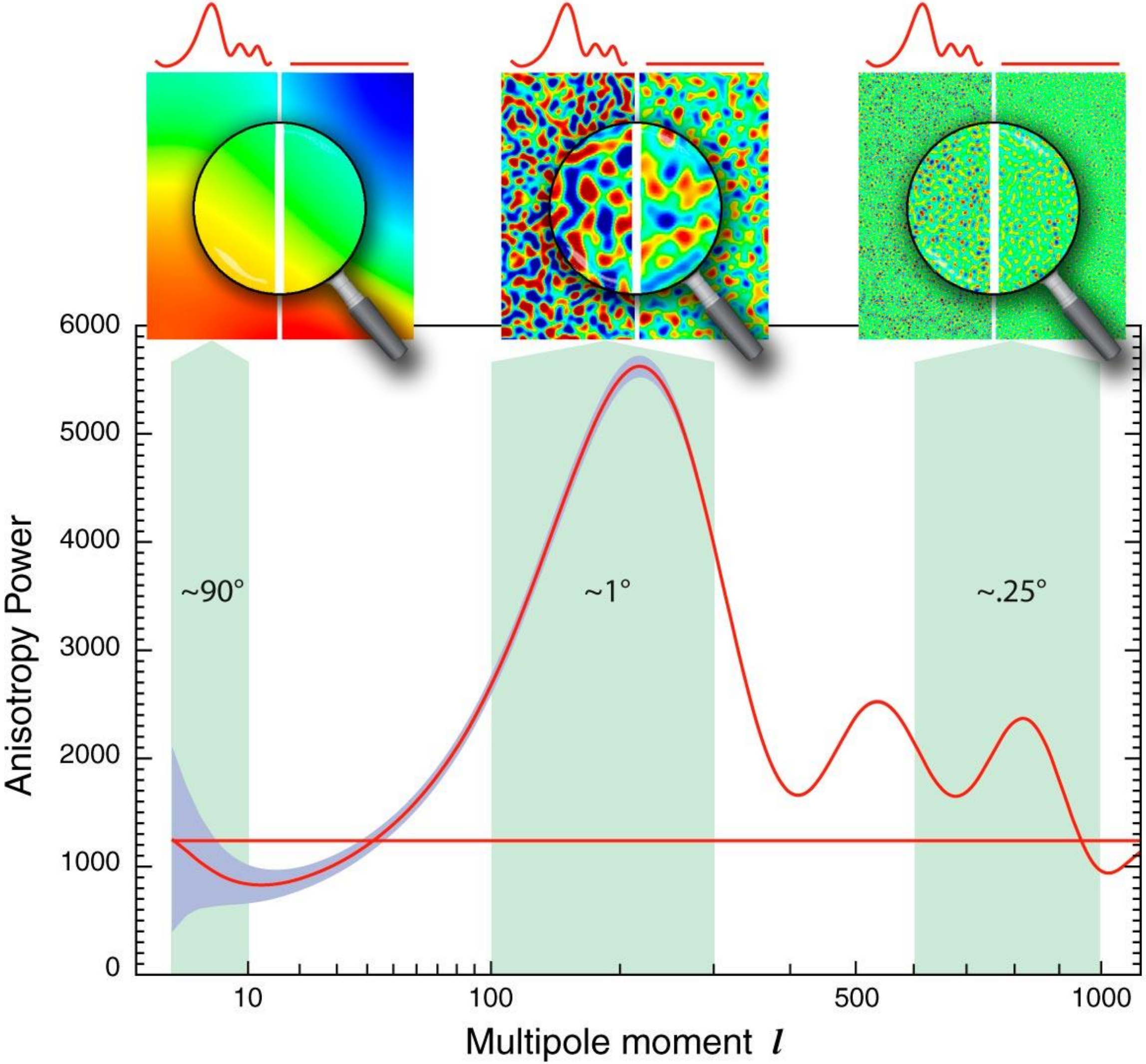




(from N. Wright)

Planck 2018 power spectrum of temperature anisotropies




6000
5000
4000
3000
2000
1000
0
Anisotropy Power
~90°
~1°
~.25°
10
100
500
1000
Multipole moment *l*

Sources of anisotropies

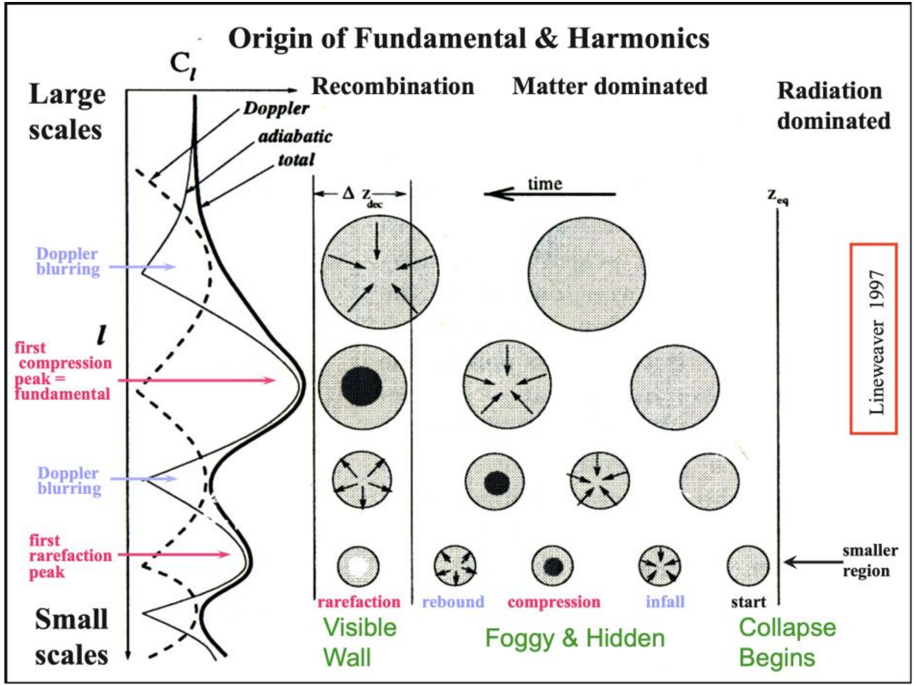
1. **Inhomogeneities in matter density**
   - In baryonic matter: $<(\delta\rho/\rho)^2>^{1/2} \sim 10^{-5}$
   - In dark matter: $<(\delta\rho/\rho)^2>^{1/2} \sim$? (10^{-3} at $a_*=1/(z_*+1) \sim 10^{-3}$)
2. **Non-integrated Sachs-Wolfe effect**
3. **Acoustic oscillations**
   - Highest (= first) peak at $\ell = 180°/\theta_*$ →

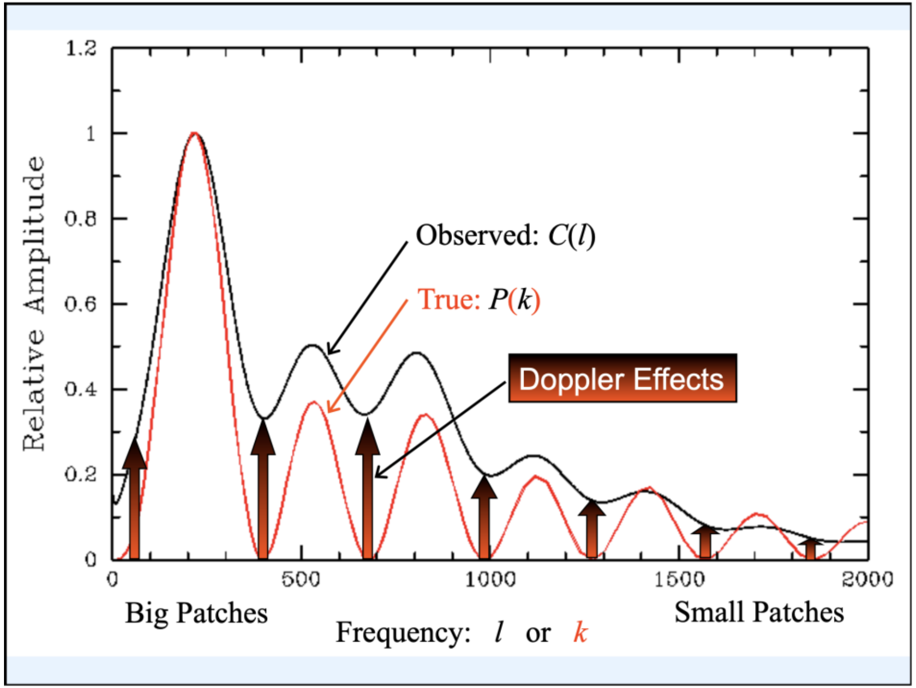
$$\theta_* = \frac{r_s(T_*)}{d_A(z_*)}$$

See extra note
"First acoustic peak in CMB"

4. **Silk damping**
5. **Other secondary and tertiary effects**
   - Secondary: integrated Sachs-Wolfe effect, Sunyaev-Zeldovich effect, etc.
   - Tertiary: scattering on galactic dust, point radio sources, etc.

Acoustic oscillations





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Large-scale structure (LSS) and Baryon Acoustic Oscillations (BAOs)

Galaxy redshift maps compare with large N-body simulations.

Galaxy power spectrum used to make comparison