Lecture 10

CMB fluctuations

The nature of Dark Matter

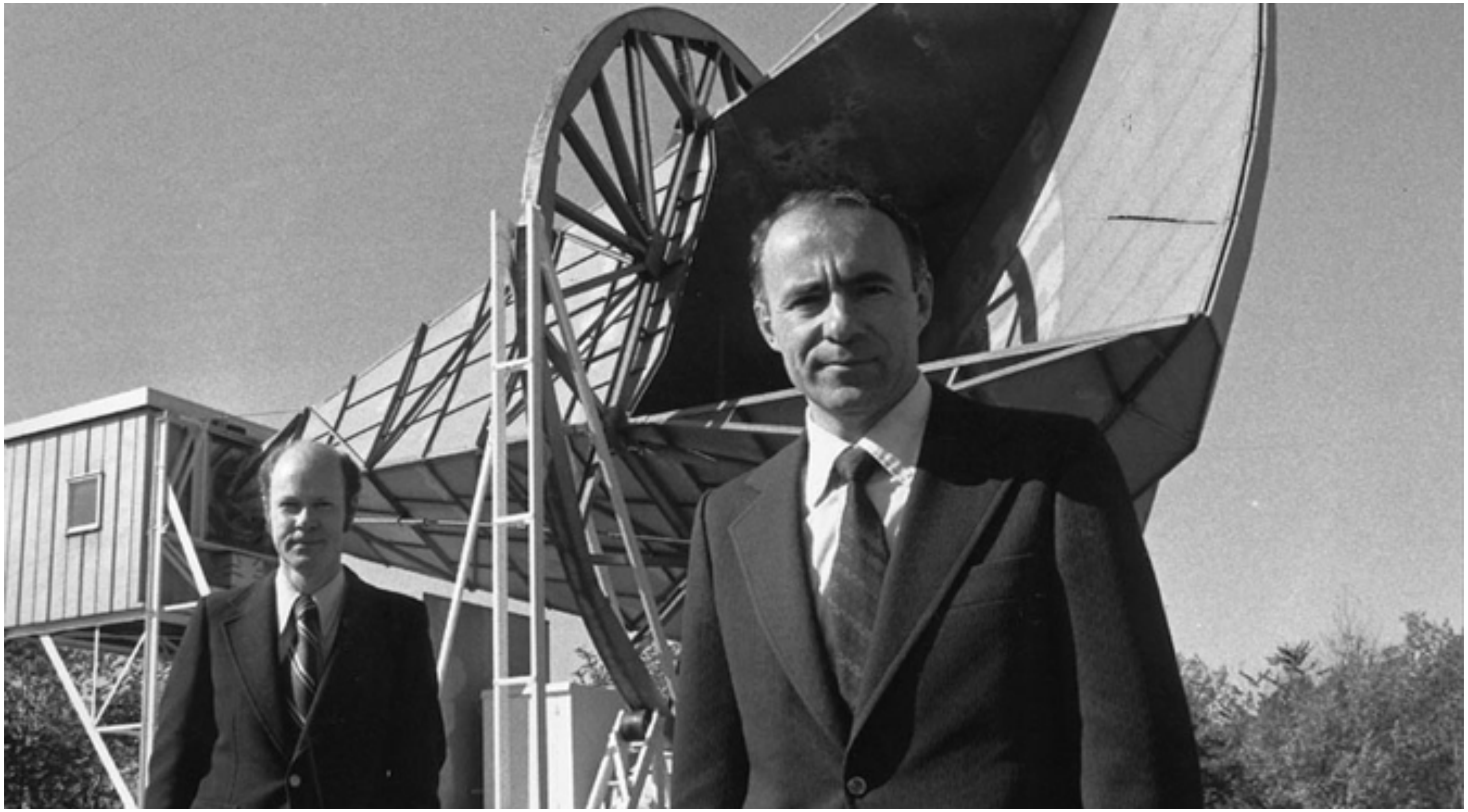
1. What are the connections between the growth of supermassive black holes in the centers of galaxies ($m_{BH} \sim 10^9$ $M_\odot$, $r \sim 3\times10^{12}$ m) and the growth of the rest of the galaxy ($m_{star} \sim 10^{11}$ $M_\odot$, $r \sim 3\text{x}10^{19}$ m)? **We are not sure: Existence of scaling relations and similar evolution of SFRD and BHARD over cosmic time suggest there is a relation**

2. What are the observed scaling relations in present-day galaxies between m_{BH} and the properties of the surrounding galaxy (such as velocity dispersion σ and stellar mass)? **m_{BH} seems to scale closely with velocity dispersion (approx σ^4) and with stellar mass of spheroidal bulge (and less well of total stellar mass)**

3. What are the similarities/differences between the overall cosmic evolution of the star-formation history (SFRD) and the history of black hole accretion (BHARD)? **Both peak around z ~ 2, but the BHARD is likely more sharply peaked.**

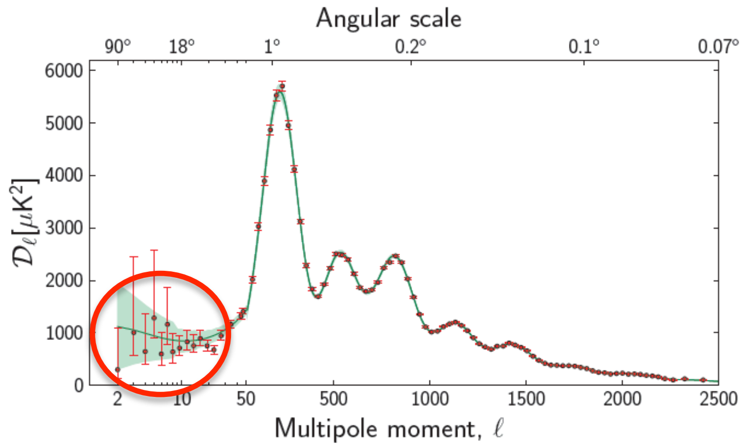
4. What can we learn by comparing the evolution of the galaxy stellar mass function and the AGN luminosity function? **Suggests a model in which BH accretion occurs mostly at the end of SF life of a galaxy. Further suggests typical m_{BH}/m_{star} scaling as $(1+z)^{1.5}$, Eddington ratio increasing like $sSFR_{MS}$ $(1+z)^{2.5}$ to z ~ 2 (producing constant "duty cycle" and then saturating at (interesting) $\lambda \sim 1$.**

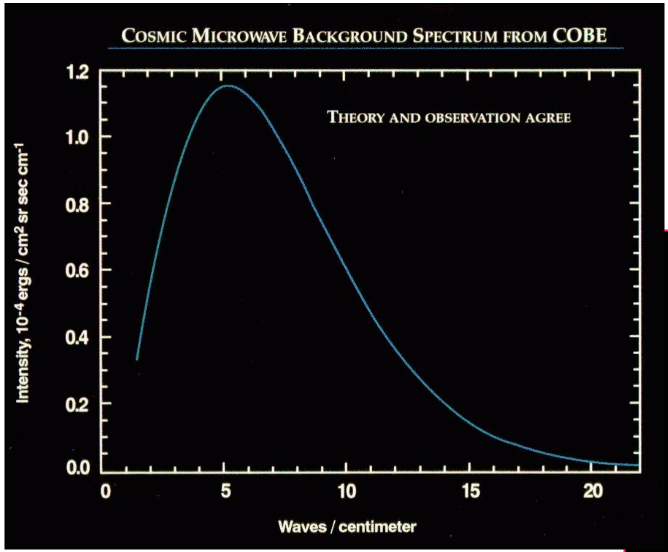
Penzias and Wilson (1964): Accidental discovery at Bell Labs (but nearby Princeton cosmologists had predicted it and were building equipment to search for it!). Story starts in 1948 with Alpher, Hermann, Gamow etc.

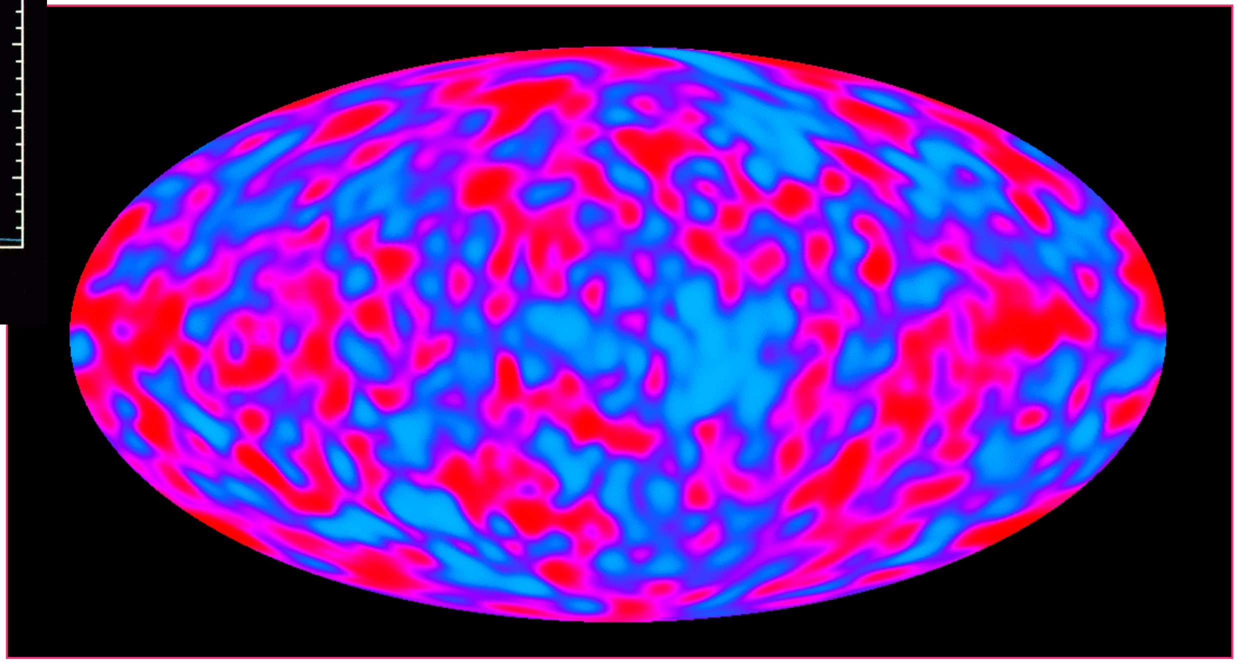


Uniform antenna temperature of 3°

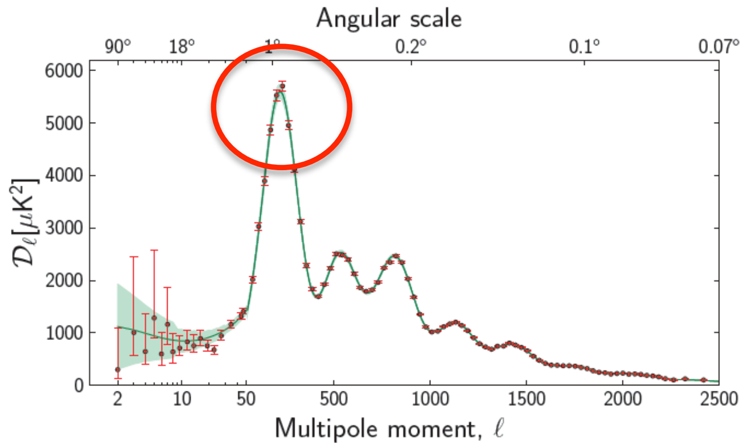
COBE (about 1990)
Establishes perfect Black Body spectrum and sees the fluctuations in the CMB (on large >7^o scales) establishing n = 1 primordial spectrum predicted by inflation

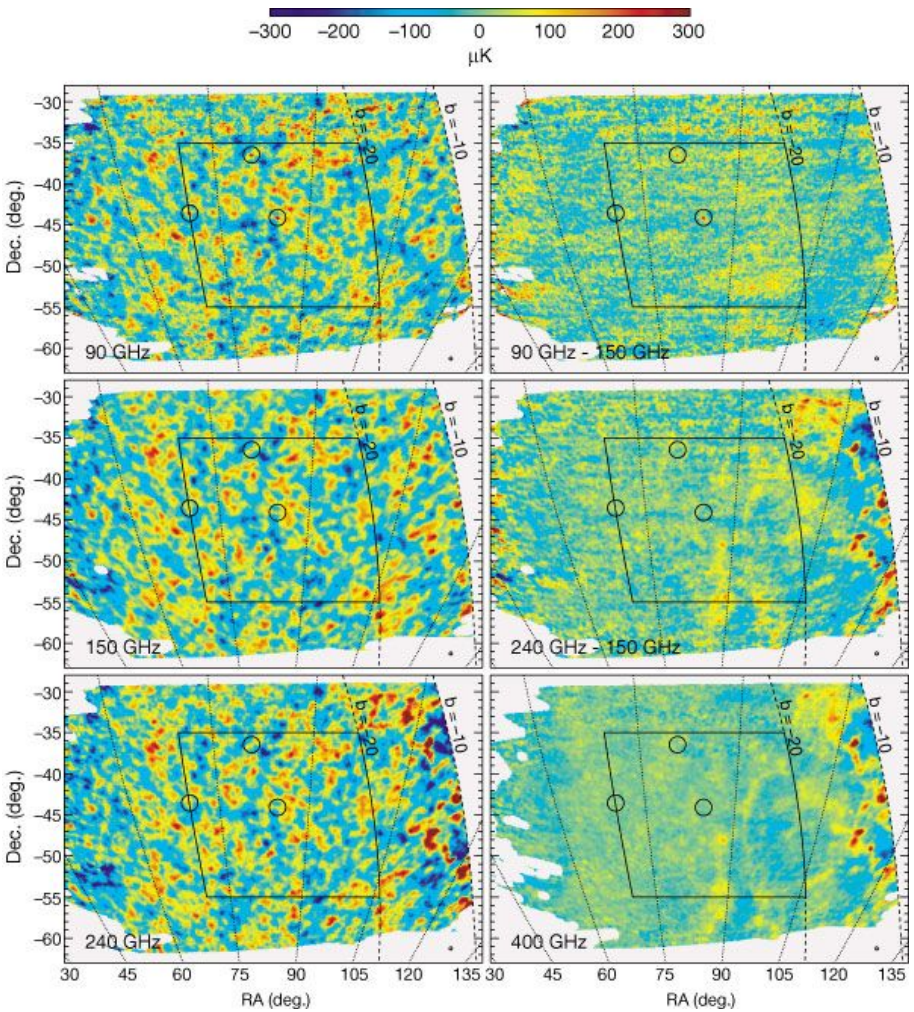


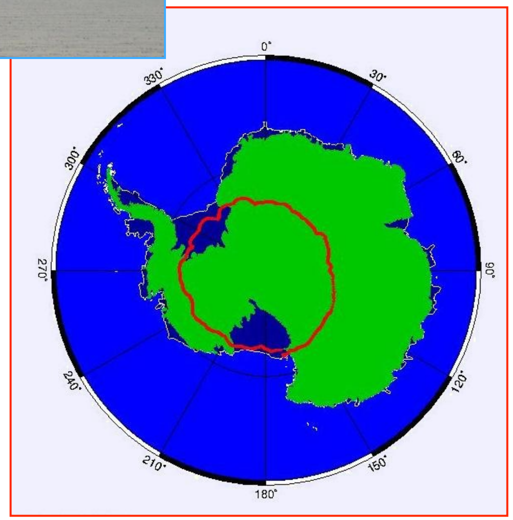




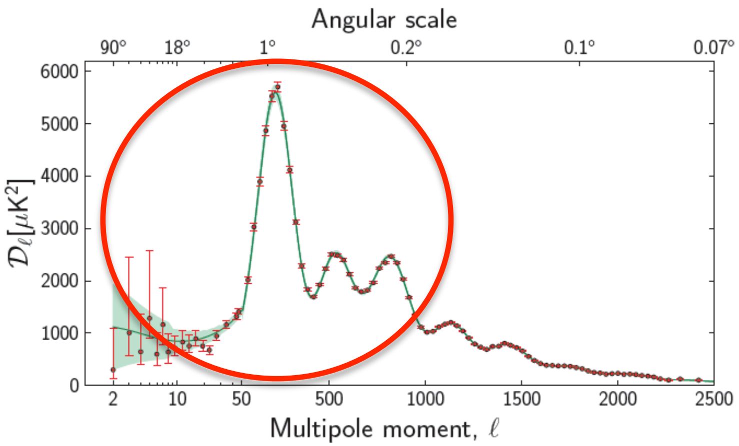
Boomerang (2000)
Establishes sees the peak at 1^{o} scales, establishing that the Universe has a flat geometry (Ω_{tot} ~ 1)

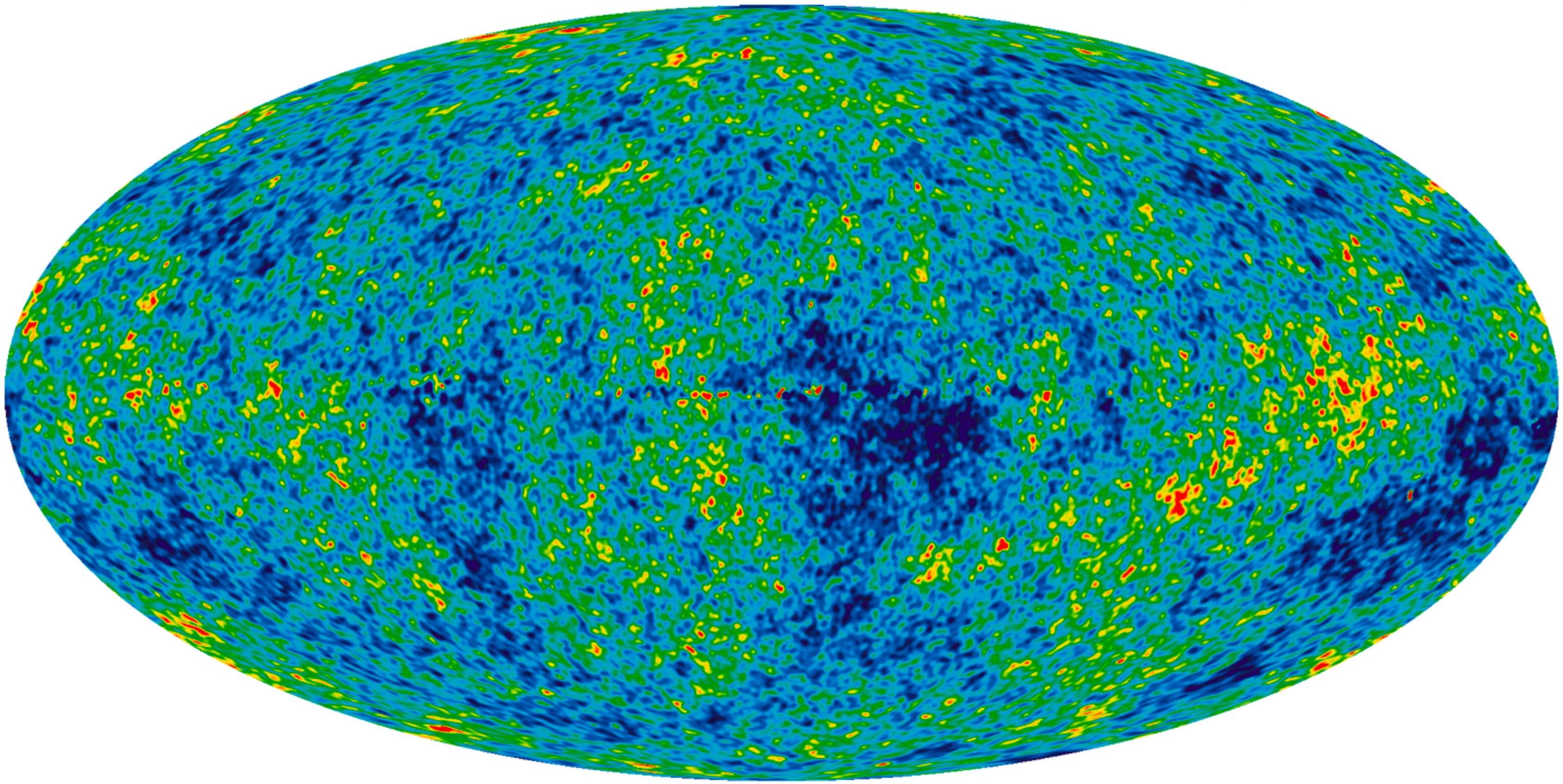




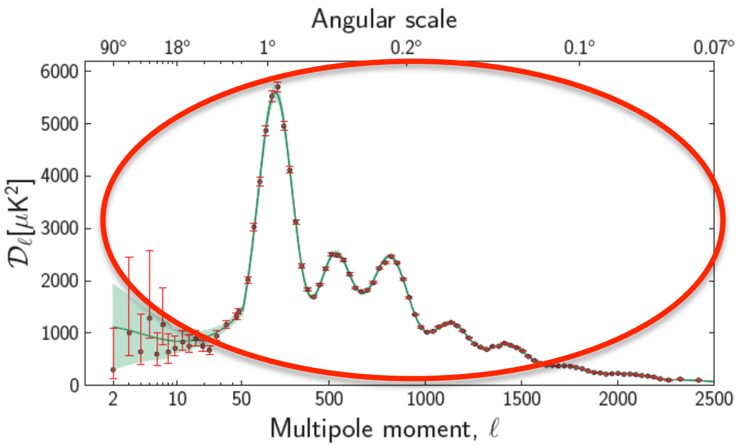


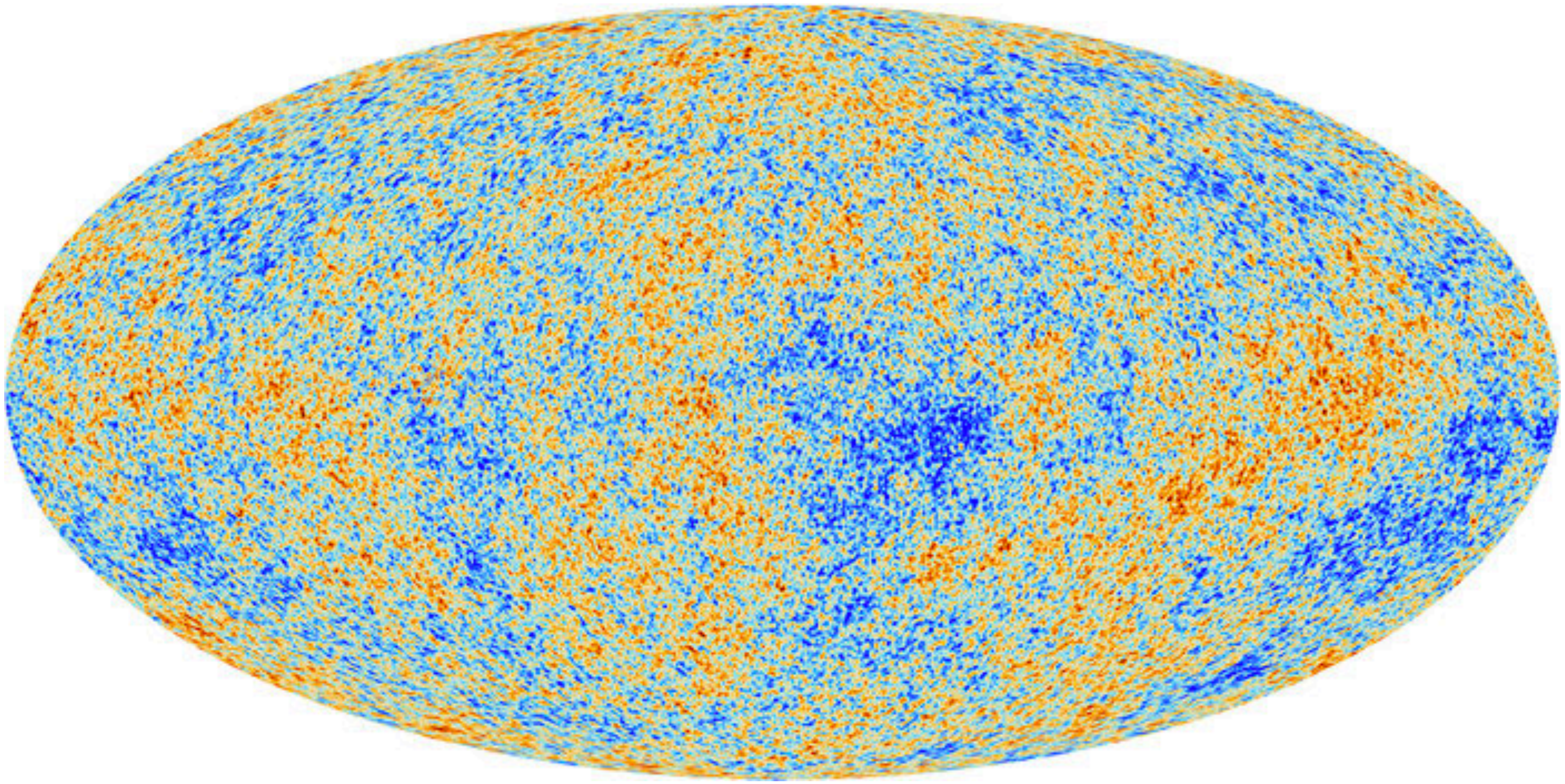
WMAP (~ 2005)
Sees secondary peaks, enabling "precision cosmology" and also measures foreground τ from polarization



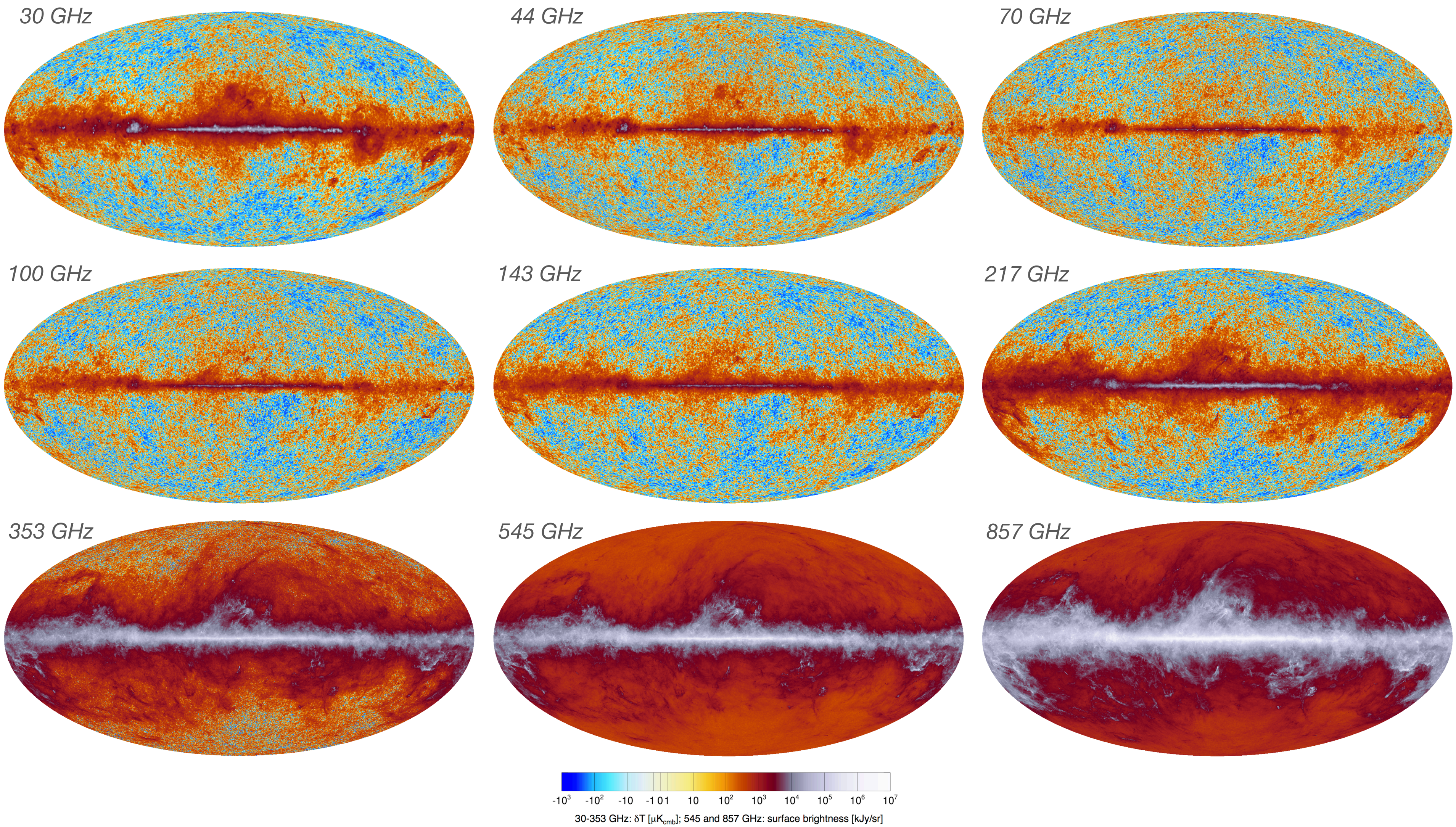


Planck (~ 2015)
Further increases in precision and in angular resolution, plus 12 different frequencies for improved foreground subtraction





Great thing about Planck: 12 frequencies for foreground subtraction



1933: Zwicky points out that velocity dispersion $\sigma \sim 1200\ \mathrm{kms^{-1}}$ of galaxies in Coma implies $5 \times 10^{14}\ M_{\odot}$, much larger than the mass in visible starlight, i.e. $M/L \sim 50 \times (M/L)_{\odot}$

1940: Oort commented on rotation of NGC 3115, interpreted as faint stars or dust etc.

1970's Rubin established flat rotation curves, i.e. mass increasing linearly with radius.

1980's Basic cosmogonic theory of cold dark matter (CDM) worked out. Increasingly well matched to observations of

- galaxy haloes
- large scale structure
- $\Omega_m >> \Omega_{baryon}$ from BBNS
- absence of CMB fluctuations

1990's CDM was the default theory, but in different flavours, because of (confusing) effects of Dark Energy.

Rotation curves of galaxies v(r) indicating less concentrated haloes

Big Bang Nucleosynthesis indicates $\Omega_b \sim 0.04$ from N_γ/N_b at $\tau \sim 1$ sec, much less than lots of evidence that $\Omega_m \sim 0.3$

Evidence that DM is non-baryonic

Silk damping on scales $< 10^{13} M_\odot$ would eradicate galaxy fluctuations before recombination, unless non-baryonic DM fluctuations survive

Baryon content of clusters (dominated by hot X-ray gas) $\sim 0.2\ M_{total}$

Bullet cluster indicating (non-radial) separation of dominant baryonic mass from total mass

Beautiful agreement of observations with predicted CMB fluctuation spectrum