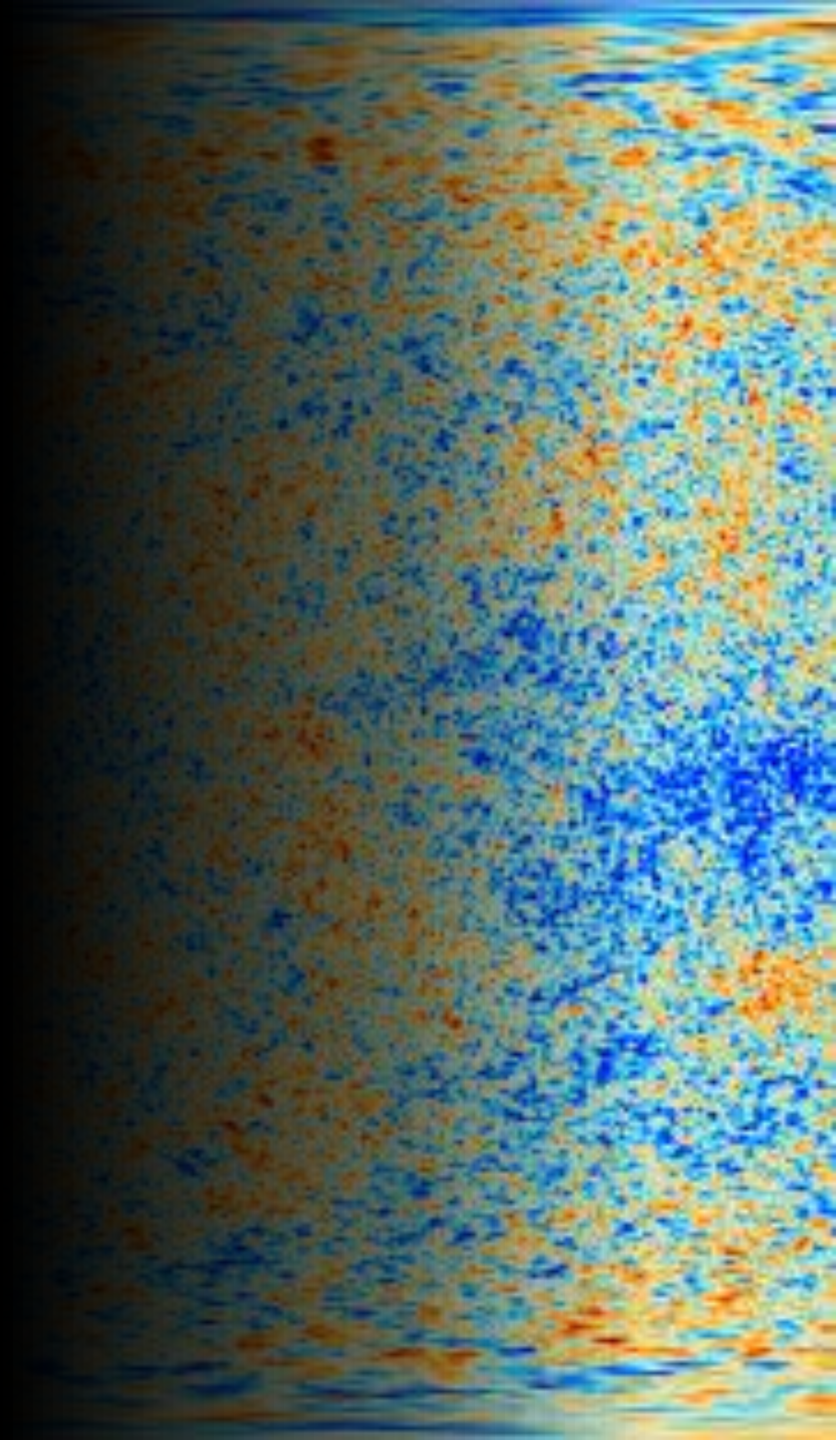
Cosmic Microwave Background

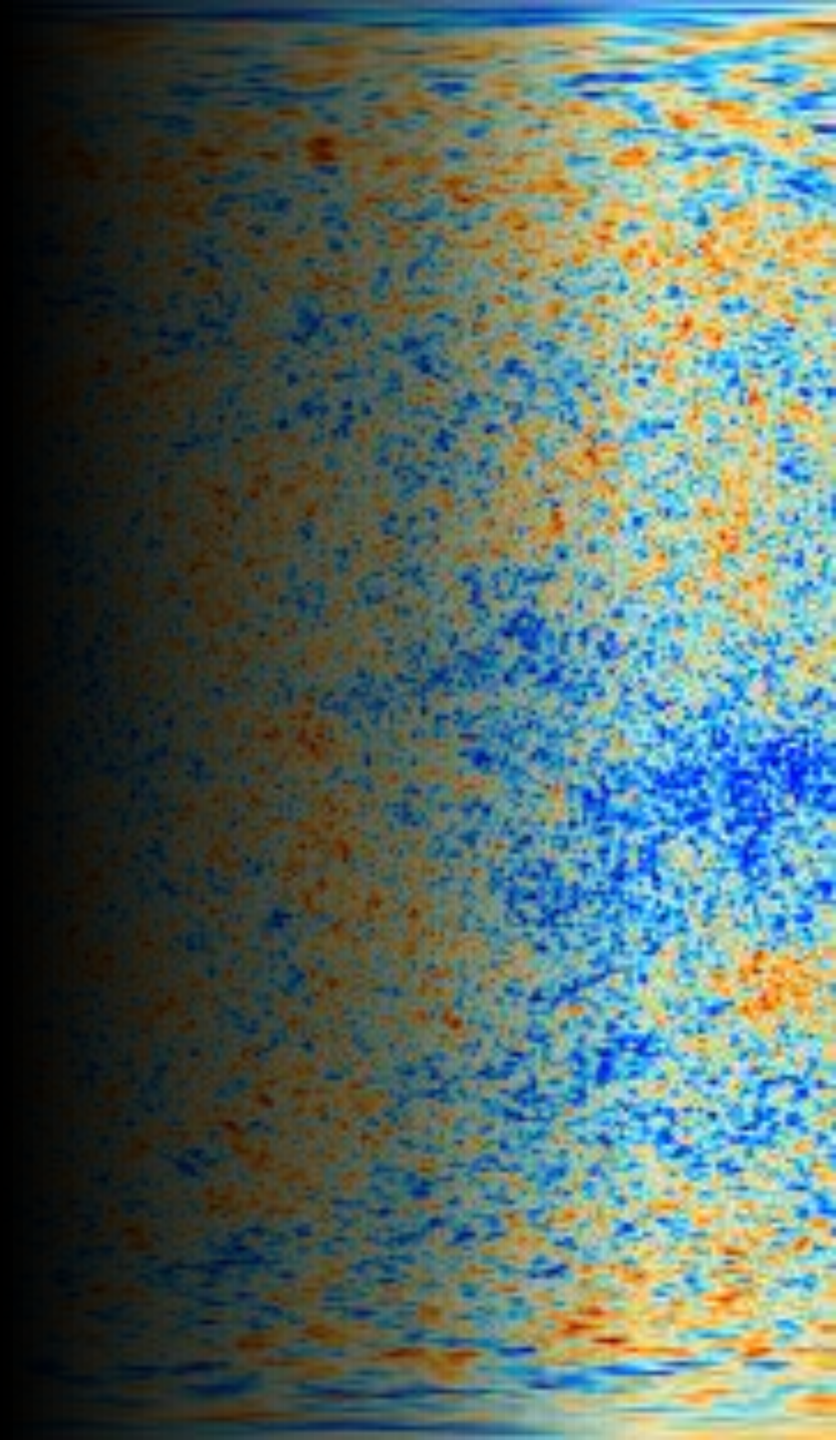


Experiments in Modern Physics Seminar

Adrienn Pataki - 3/3/2022

Cosmic Microwave Background

- What it is
- How it was created
- What are it’s main characteristics
- What were the most important experiments to measure it
- How we can do physics by studying measurement data



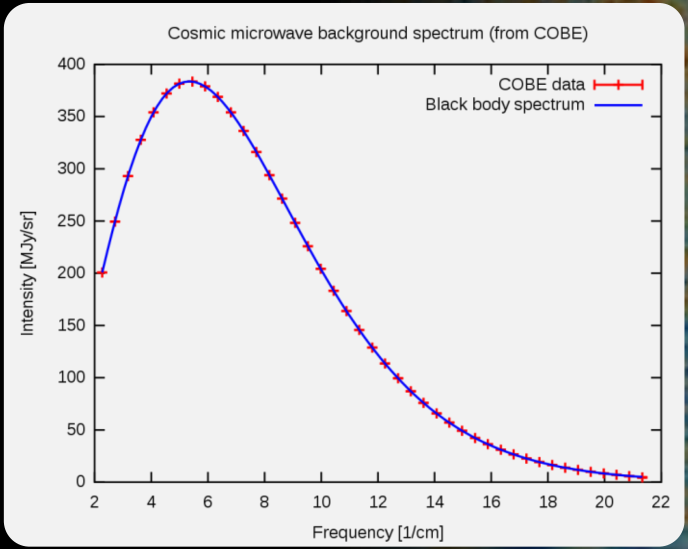
CMB - What is it?

With a traditional optical telescope: the space between stars and galaxies (the background) is completely dark

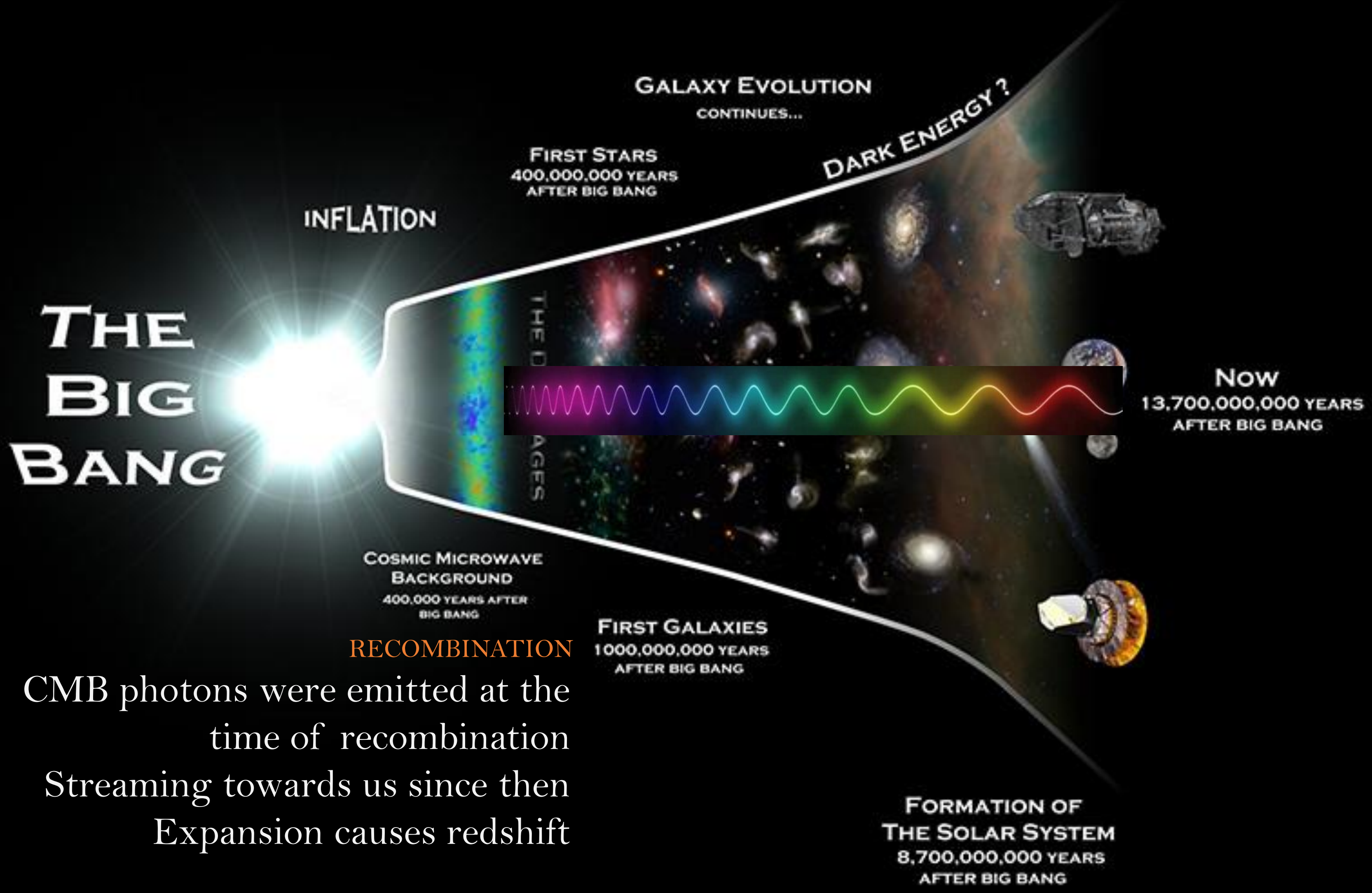
With a sufficiently sensitive radio telescope: faint background noise

- EM radiation in microwave region
- Is not associated with any star, galaxy, or other object
- Comes from all parts of the sky
- Perfect thermal black body spectrum at $T = 2.725\ K$
- Almost isotropic: $\Delta T/T \approx 10^{-5}$

BBT predicted its existence



Brief history of the Universe

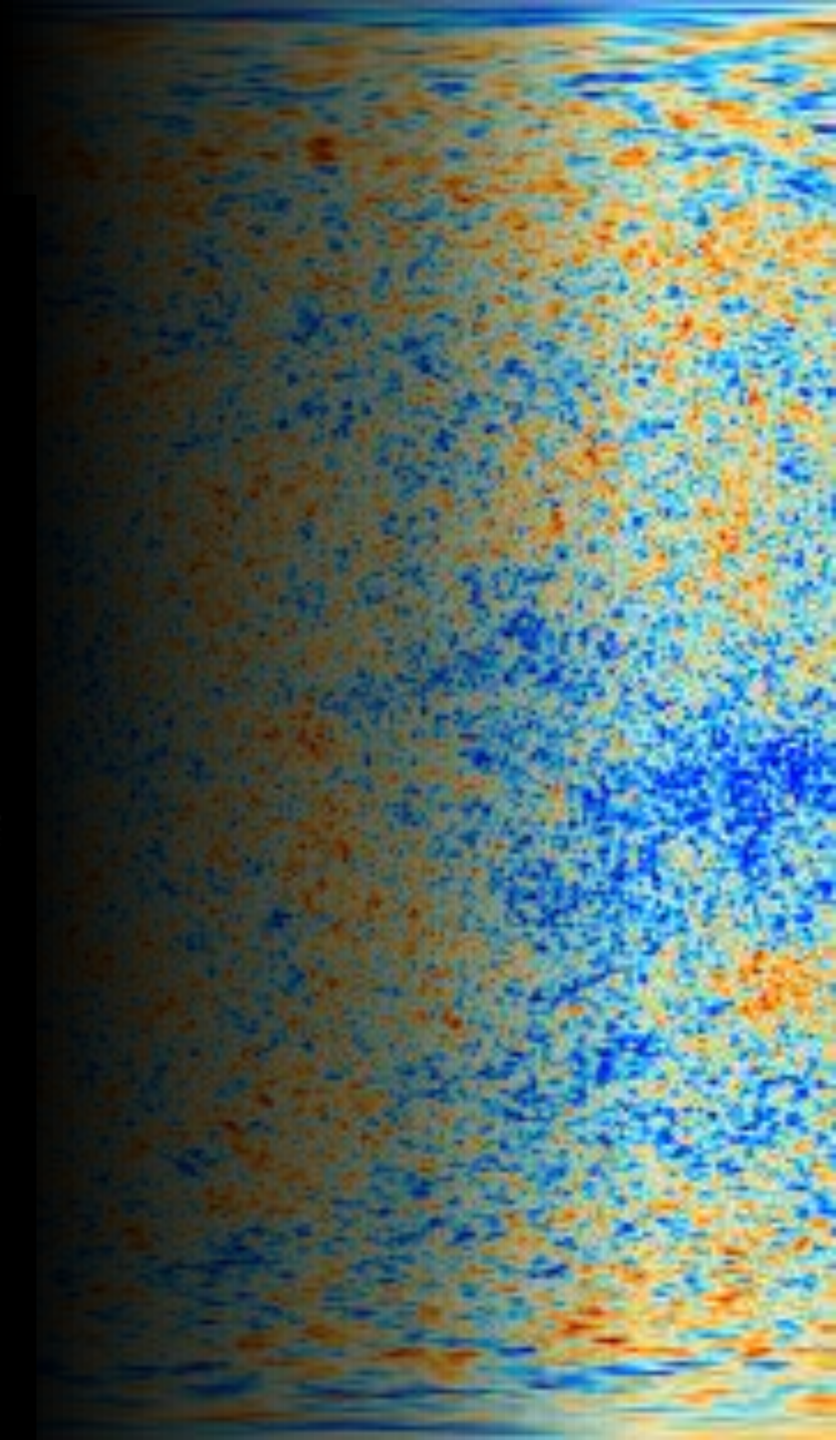


RECOMBINATION

CMB photons were emitted at the time of recombination

Streaming towards us since then

Expansion causes redshift



Epoch of recombination

Before:

- Hot, dense, ionised plasma of p^+ and e^- (and some other light nuclei)
- γ: Thomson scattering on e^- ⇢ opaque Universe (like our Sun)

Temperature dropped to $3000\ K$ $(0.26\ eV)$:

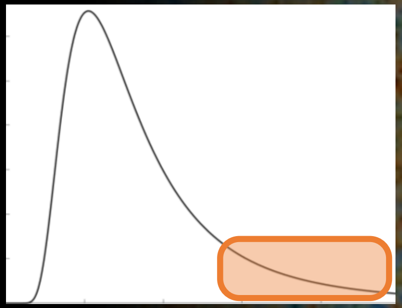
- p^+ and e^- form neutral Hydrogen atoms ⇢ recombination

  When γ has too large E $(\geq 13.6\ eV)$ ⇢ re-ionize the neutral atoms

  But $0.26\ eV \ll 13.6\ eV$. Why?

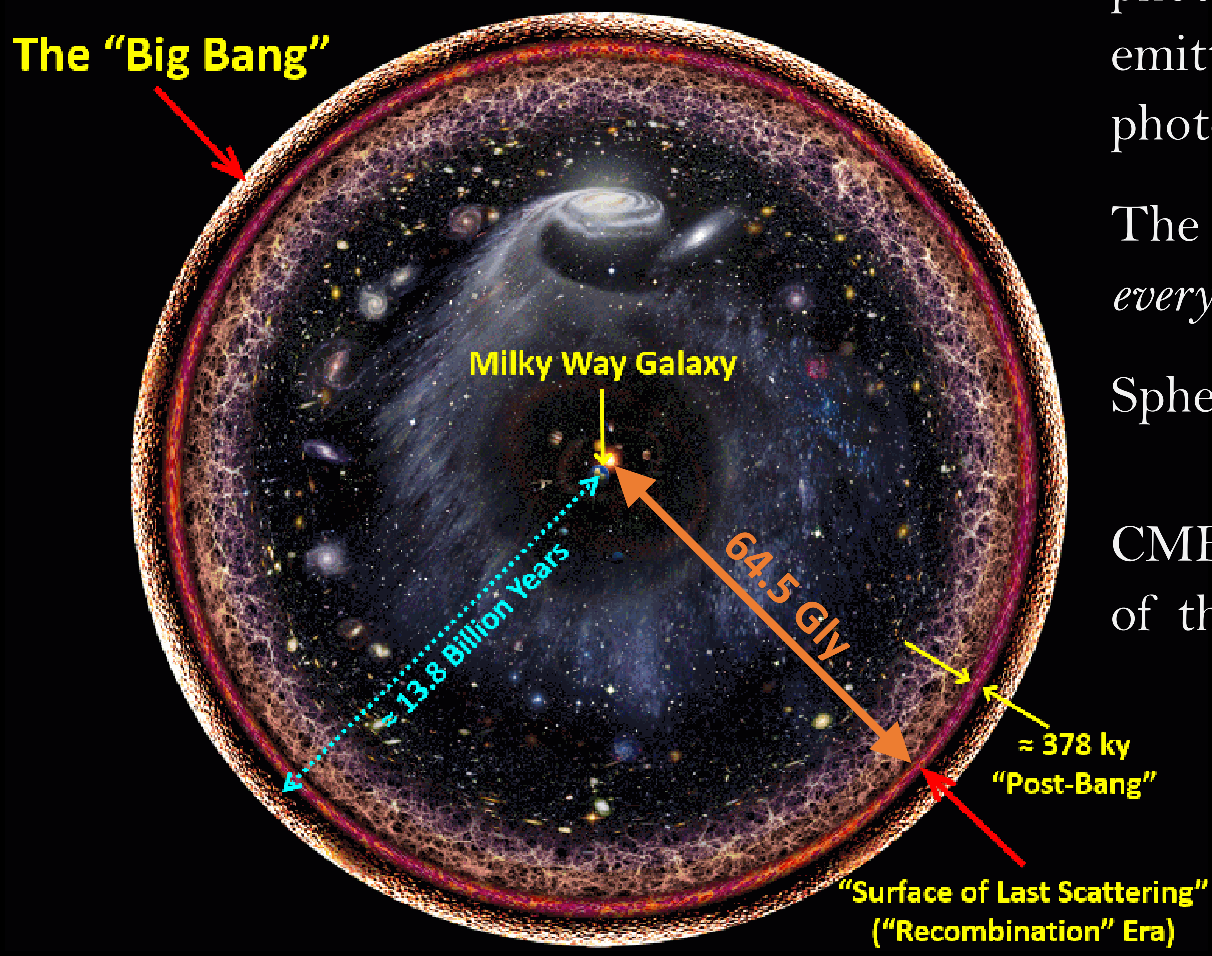
  γ: black body spectrum, peak at $0.26\ eV$, but there are a lot of γ in the tail

  $n_\gamma = 10^9 \times nb_{aryon}$ ⇢ lot of γ with higher E ⇢ can disturb atoms



- Photons cannot interact with neutral atoms ⇢ photon decoupling
- Photons free to propagate through space ⇢ Universe became transparent
- Observed today as CMB - “relic radiation”

Surface of last scattering



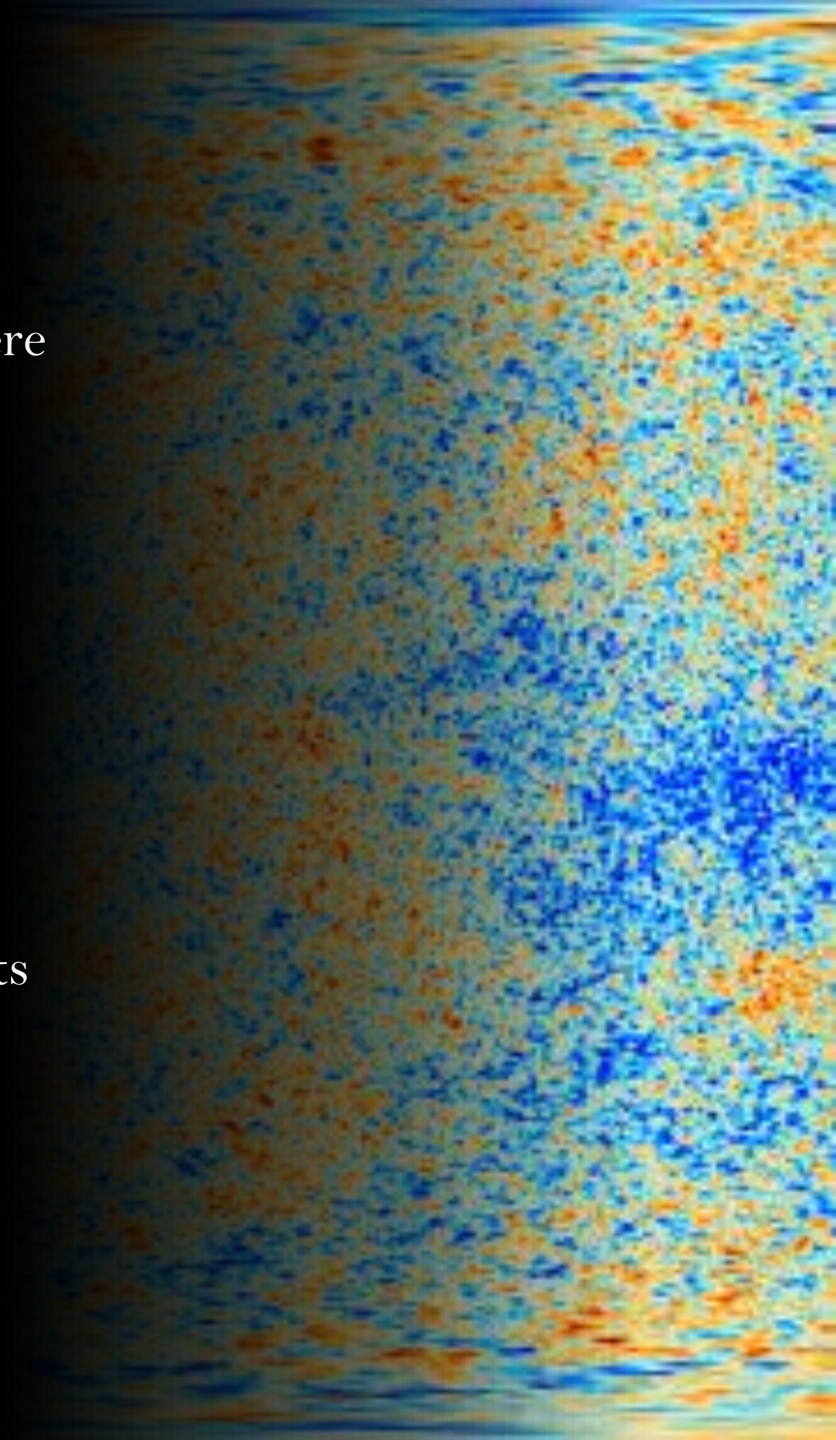
Set of points in space, where photons were originally emitted at the time of photon decoupling

The decoupling happened *everywhere*

Spherical shell around us

⇩

CMBR comes from all parts of the sky

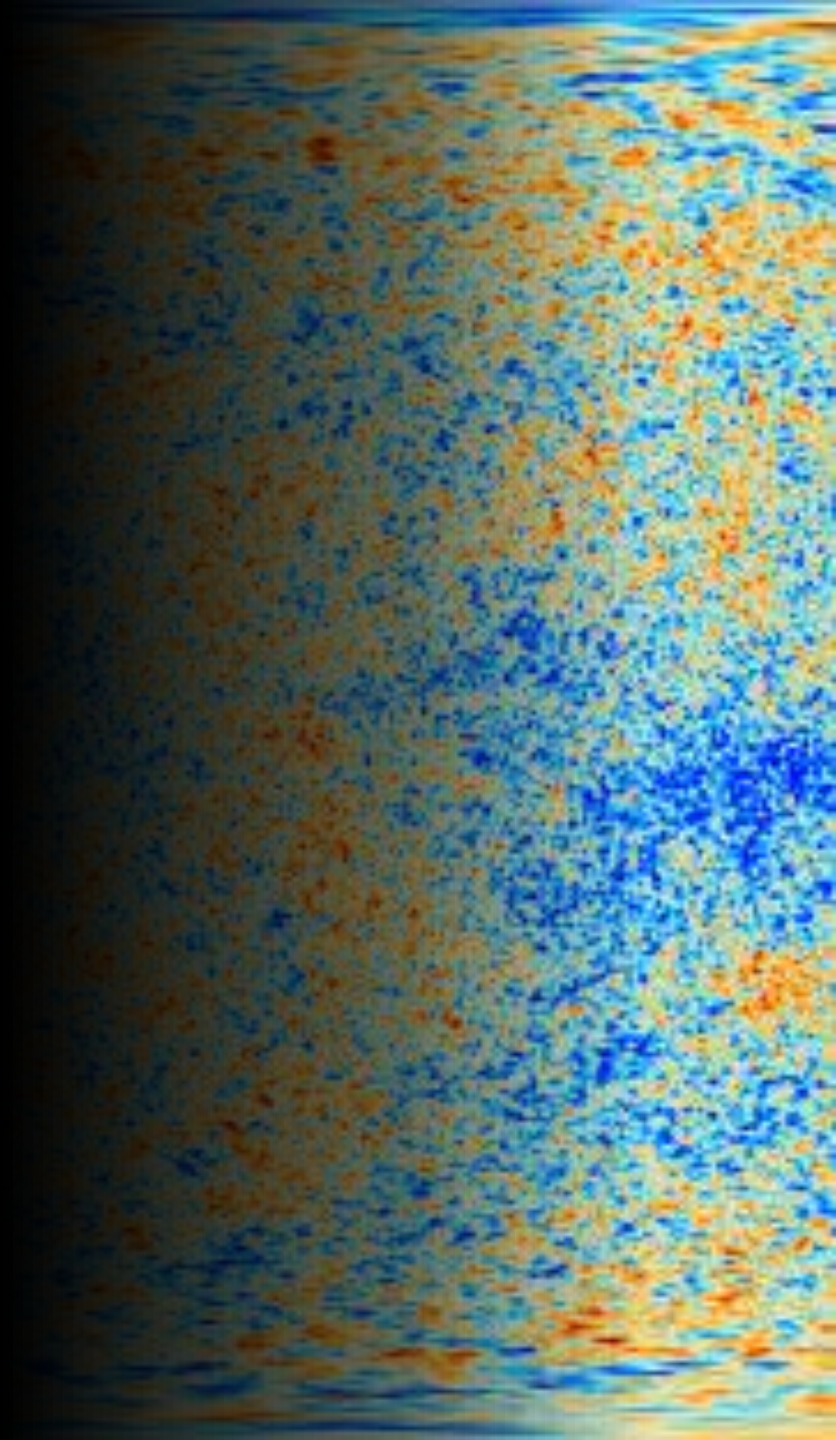


Some figures

	recombination	today
Age of the Universe	380 ky	13.8 Gy
Redshift (z)	1100	0
$T = T_{today} \times (1+z)$	3000 K	2.725 K
$\lambda = \lambda_{today} \div (1+z)$	1.8 μm	2 mm
$f = f_{today} \times (1+z)$	160 THz	150 GHz
	near infrared	microwave

Redshift: relative change in wavelength; $z = (\lambda - \lambda_{today})/\lambda_{today}$

How distance changes: $r = r_{today}/(1+z)$



Temperature anisotropies

Extremely (but not perfectly!) isotropic: $\Delta T / T \approx 10^{-5}$

Two competing interactions in plasma:

- gravity – pulls matter together, makes them tend to collapse
- photon pressure – dilutes matter, tends to erase anisotropies

⇩

oscillation

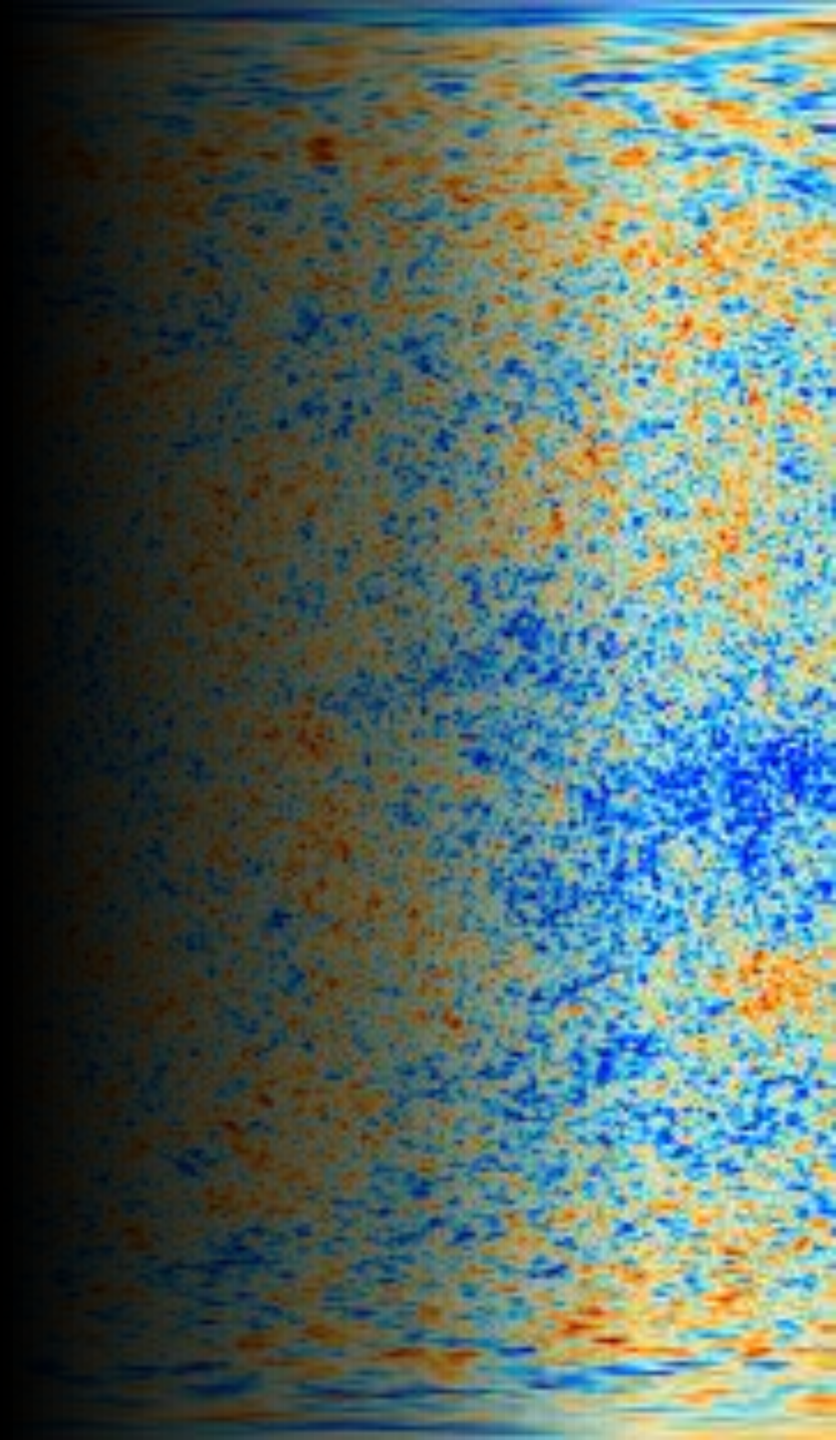
Inhomogeneities in matter distribution at the time of recombination

We can observe it as the anisotropies in the CMB spectrum:

higher ρ_m ⇢ higher T ⇢ higher T of CMB γ coming from that place

Seed for the large scale structures we observe today (galaxies…)

Studying anisotropies ⇢ we can precise our cosmological model



Experiments to measure CMB

Discovered accidentally: A. Penzias, R. Wilson 1964 (Nobel Prize 1978)

- While detecting radio waves bounced off Echo Balloon Satellites
- Evidence of BBT

COBE – Cosmic Background Explorer (NASA) 1989-1993

- Nearly perfect black body spectrum
- Low level of anisotropies ⇢ evidence of dark matter

  We can see $\delta \sim 10^6$ fluctuations in baryonic matter density distribution (stars, galaxies ⇠⇢ void)

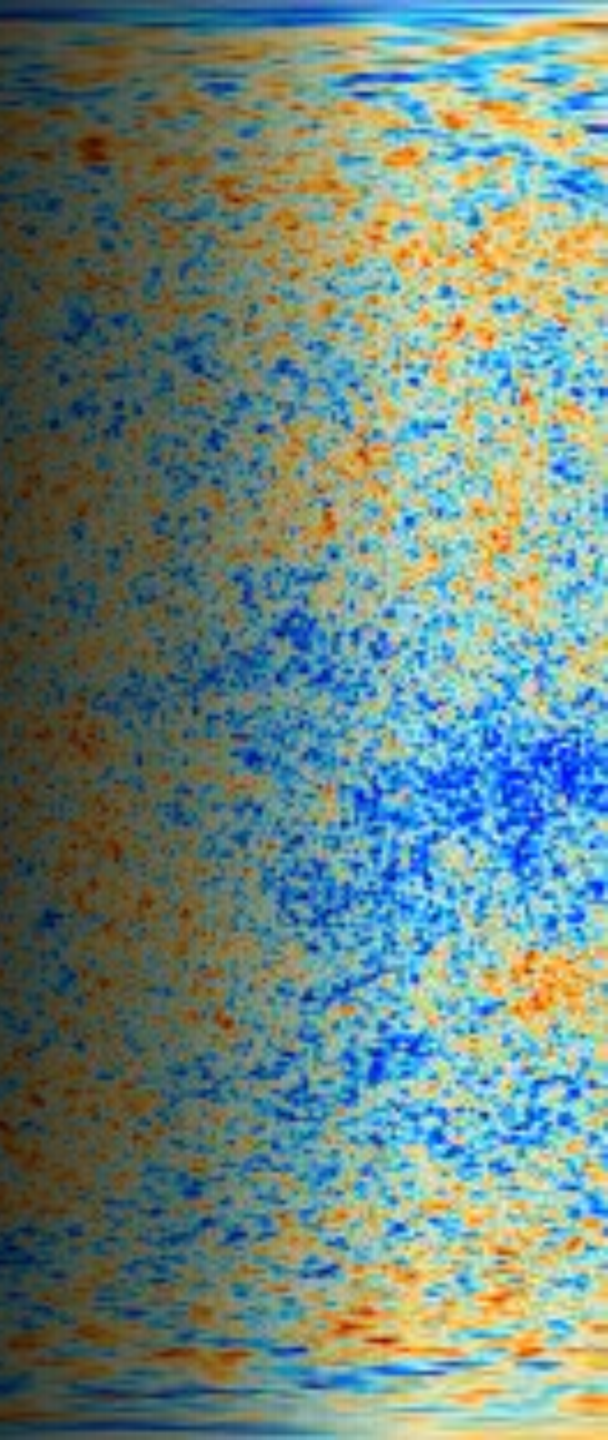
  Calculating back w/o DM ⇢ we would expect $100 \times$ higher level in CMB anisotropies ($\delta \sim 10^{-3}$)

  After baryonic matter decoupled, it could fall into the gravitational potential well of DM perturbations ⇢ speeded up the density fluctuations

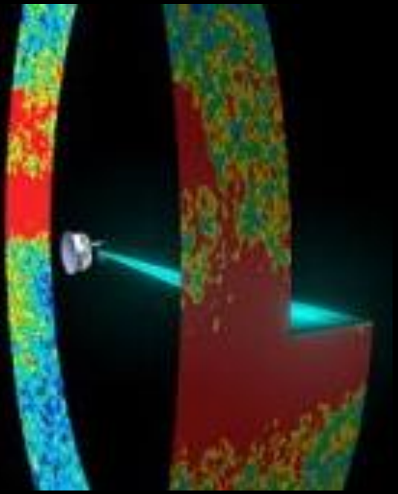
Further goal: higher resolution ⇢ more precise values of cosmological parameters can be obtained

WMAP – Wilkinson Microwave Anisotropy Probe (NASA) 2001-2010

Planck Satellite (ESA) 2009-2013



Planck Satellite



Orbiting around the Sun; on L2 (around L2)

Spinning: one revolution / minute

1° / day ⇢ scans almost every part of the sky twice in a year (every ring has 2 sides)

Never looking towards the Sun or the Earth

Instruments:

LFI (Low Frequency Instrument): 10, 7, 4 mm – cooled to 20 K

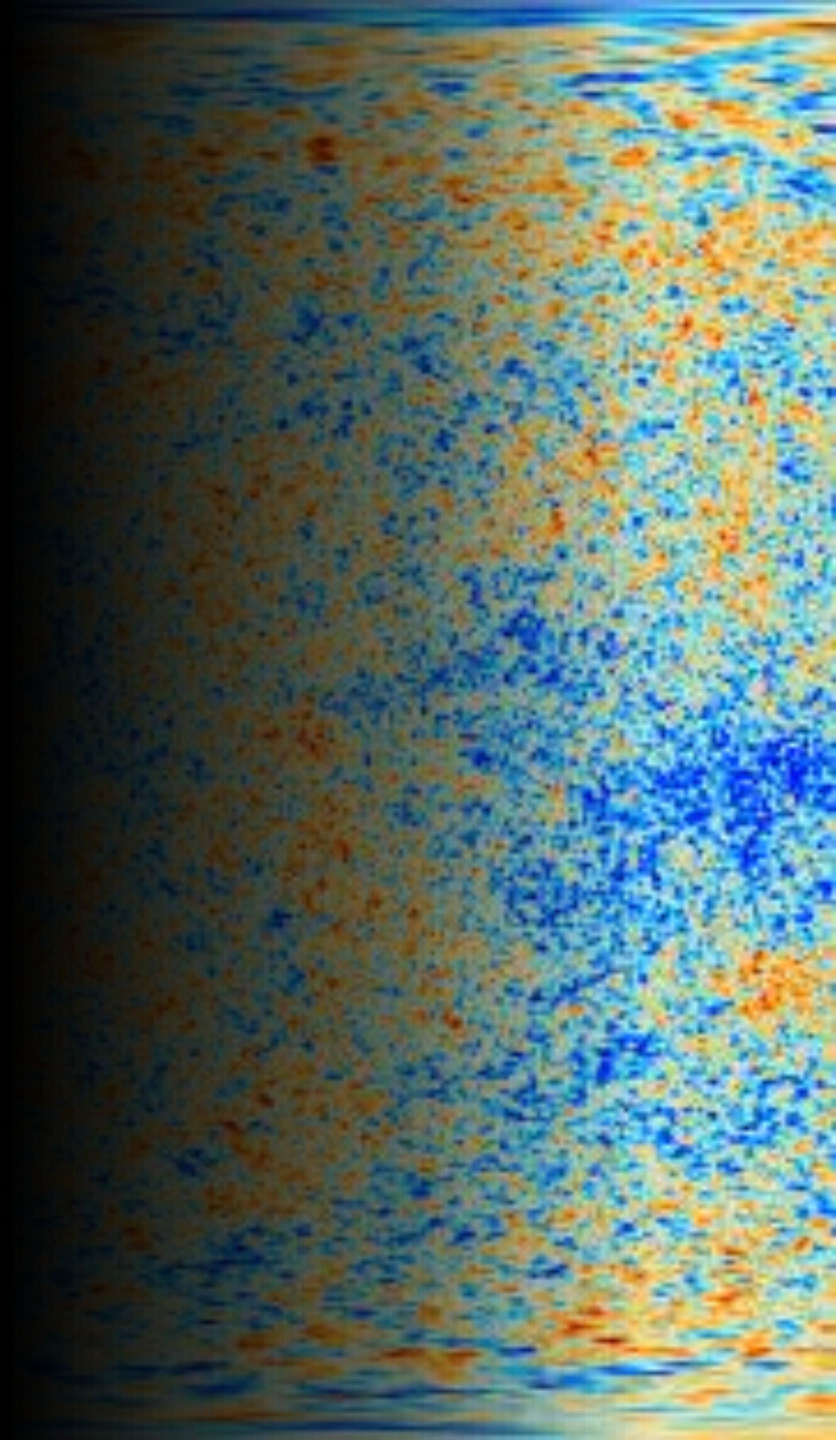
HFI (High Frequency Instrument): 3, 0.3 mm – cooled to 0.1 K

Cooling system:

Low temperatures are to prevent the instruments from only seeing their own thermal glow

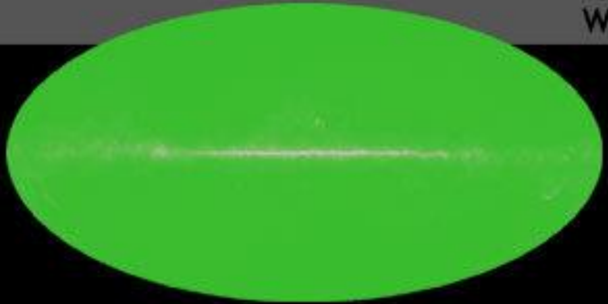
End of mission: ran out of Helium coolant

Telescope: focuses the light onto the detectors in the instruments

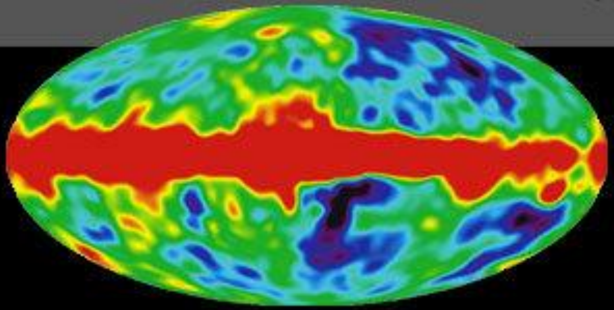


Resolution

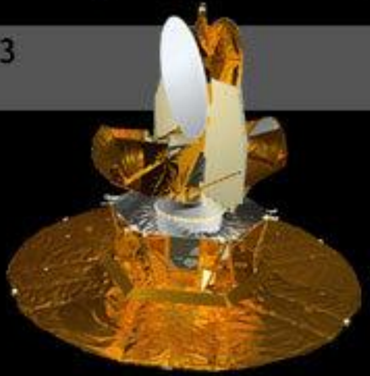
1965 Penzias and Wilson

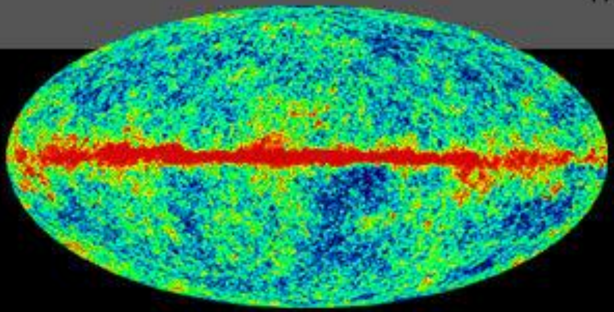


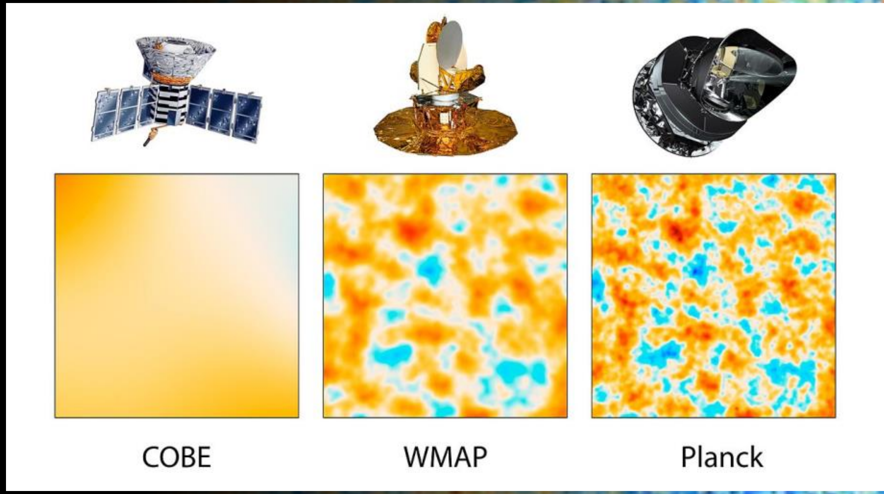
1992 COBE



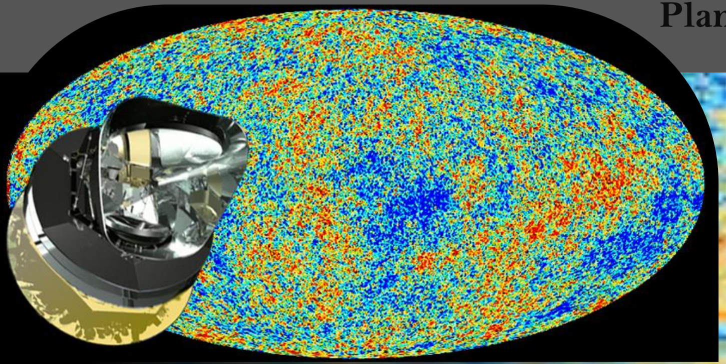
2003 WMAP







2013 Planck



How to create this map?

Measure T at each direction on the sky

We get a scalar function defined on a spherical surface

Expand it on the basis of spherical harmonics $Y_l^m(\theta, \varphi)$

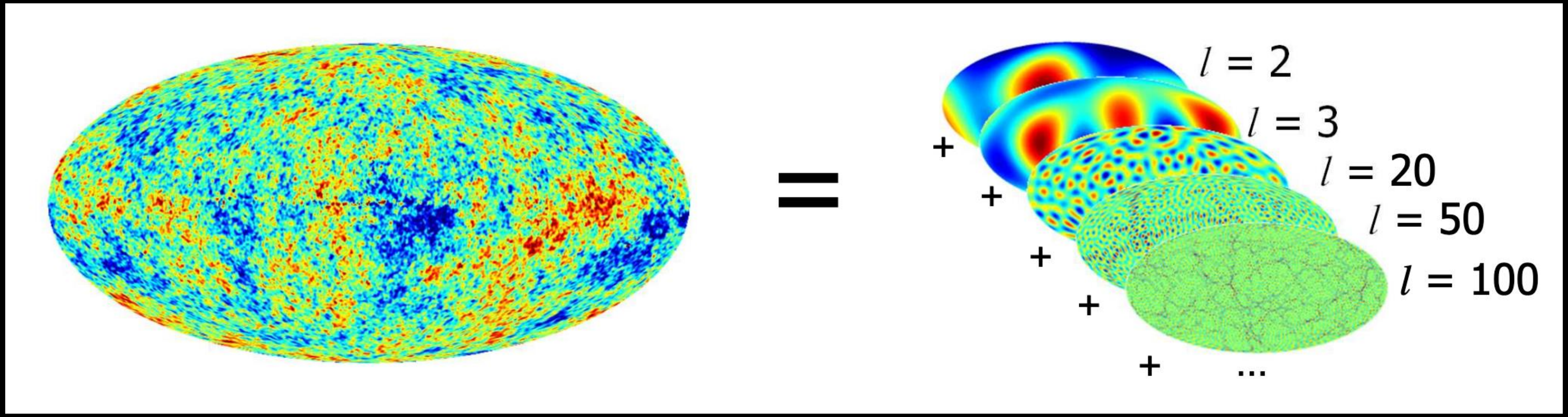
For each l we have $2l + 1$ measured amplitudes ⇢ take the average of them

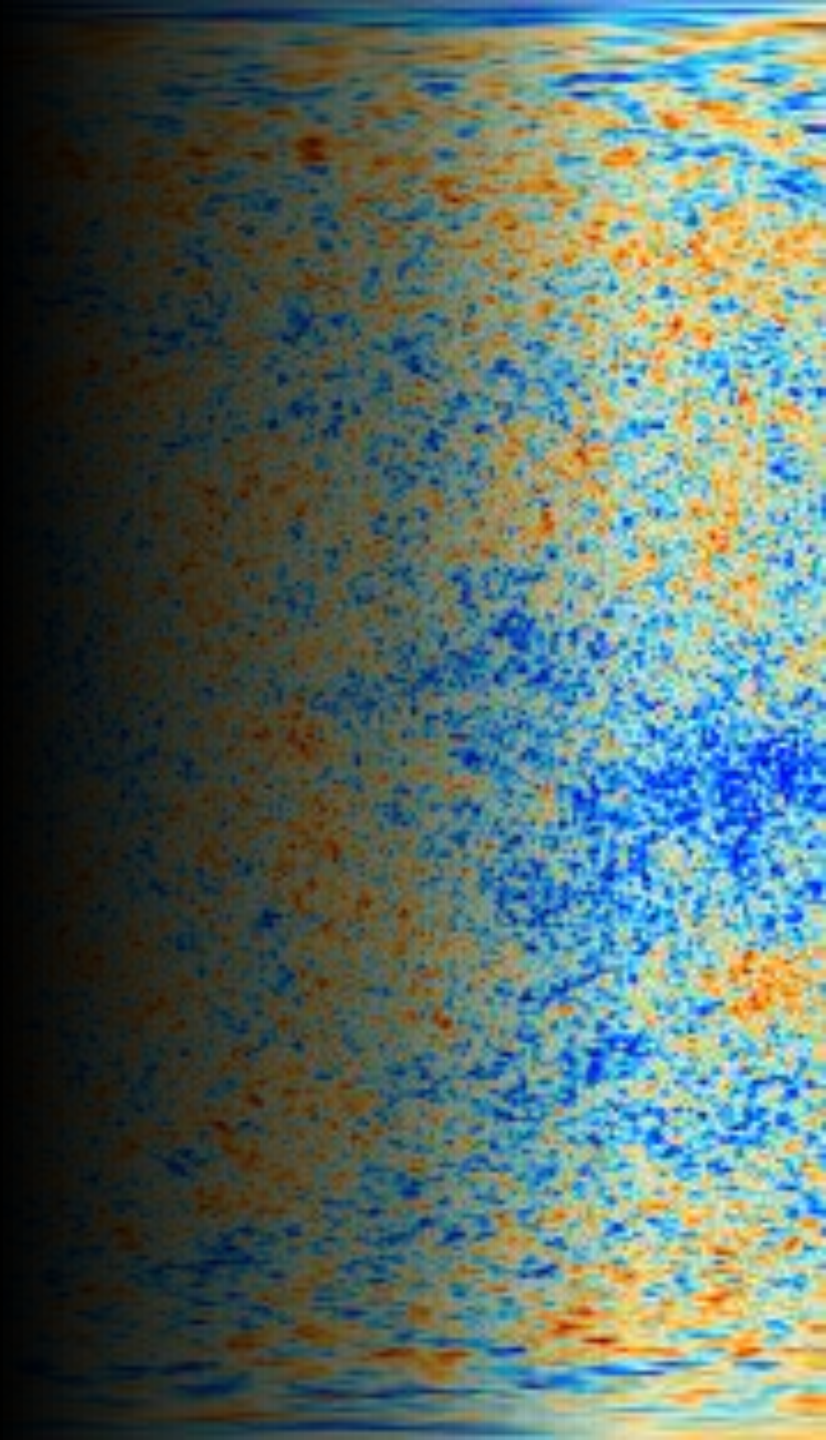
Map doesn't contain:

- $l = 0$ monopole: average T
- $l = 1$ dipole: our relative movement compared to the CMB frame

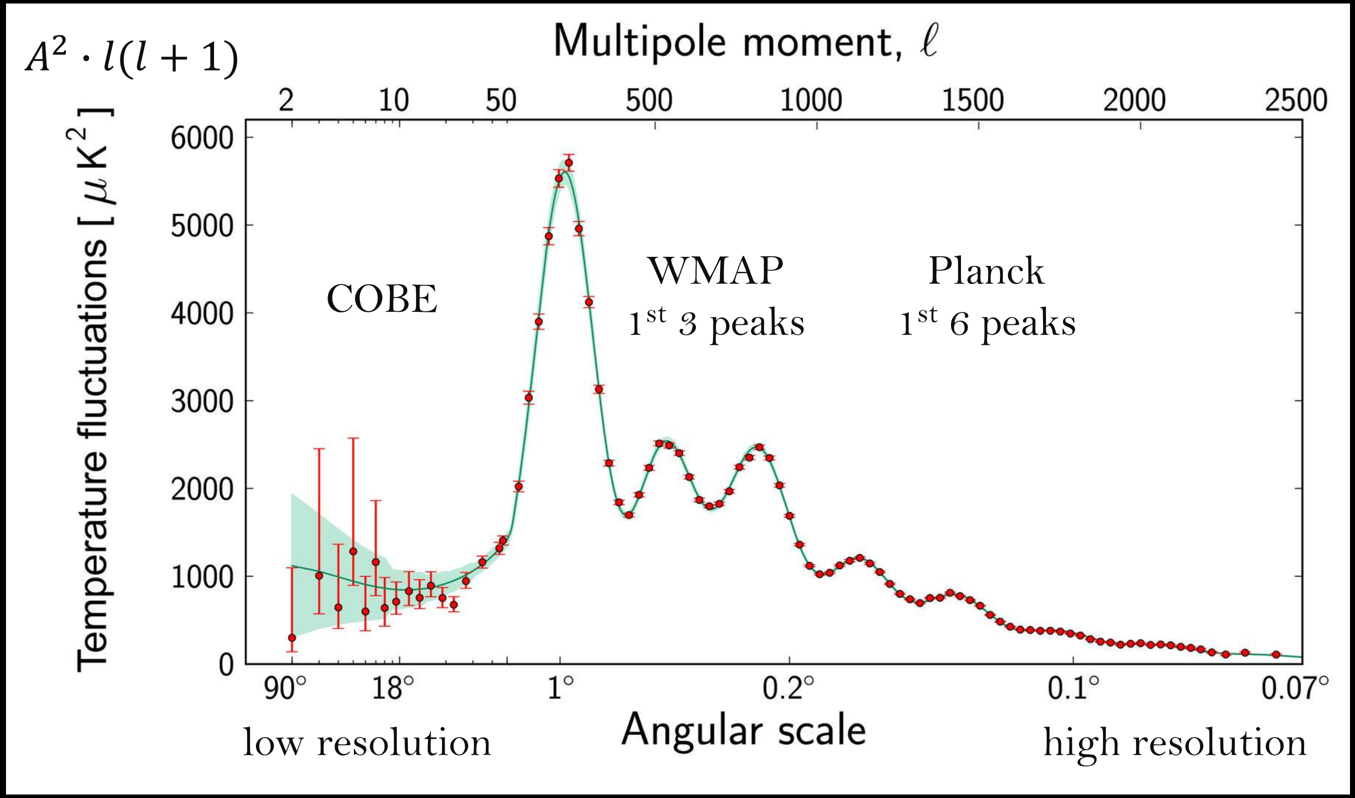
    CMB frame: reference frame in which matter distribution is homogeneous

    Cosmological principle ⇢ there IS such a reference frame



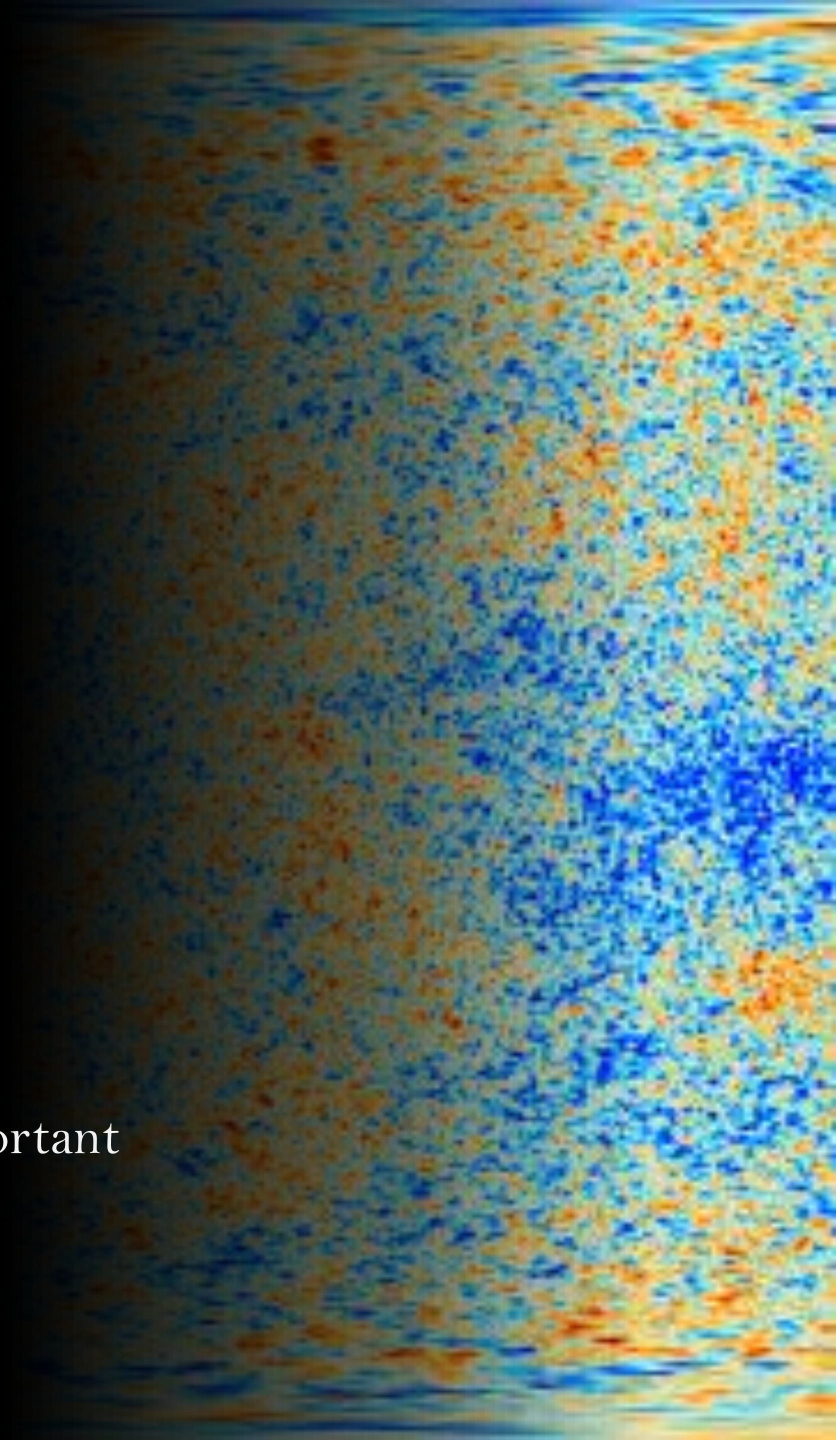


Temperature anisotropy spectrum

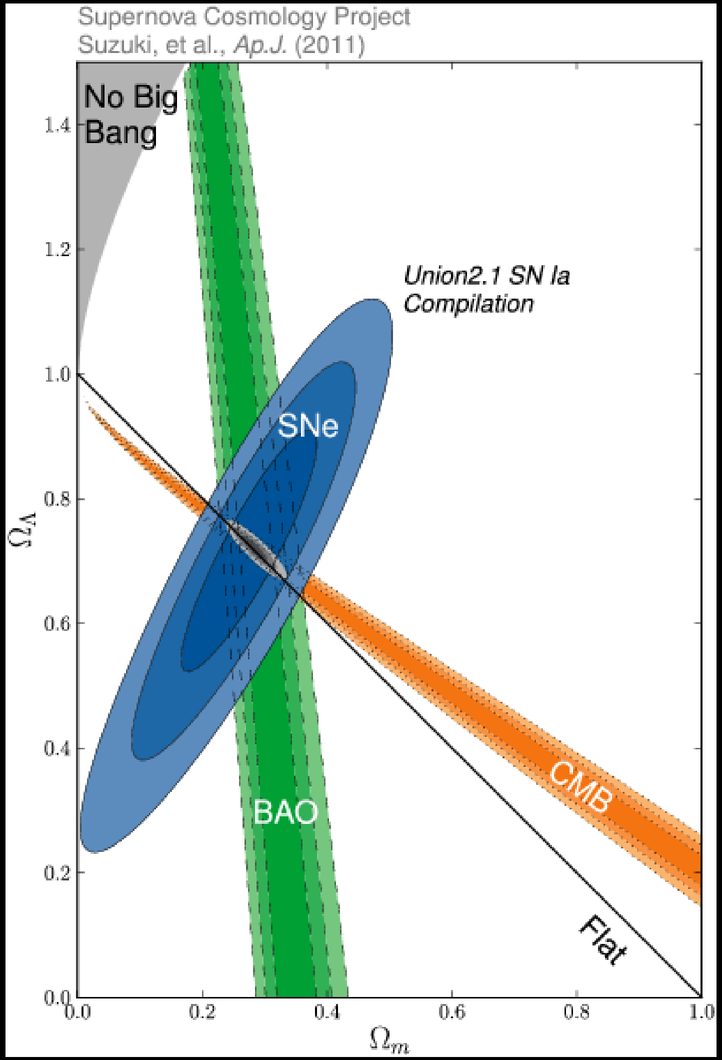


Planck's resolution: below that angular scale we don't expect anything important in cosmological perspective – final and best CMB anisotropy map

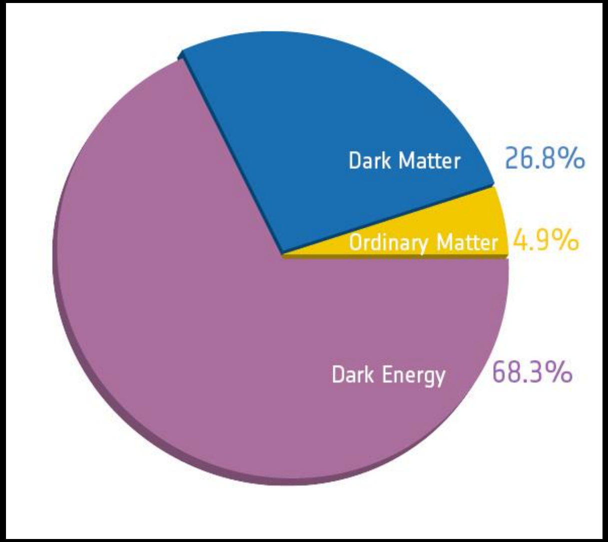
Fit with ΛCDM model ⇢ cosmological parameters



Results: relative amount of m, Λ

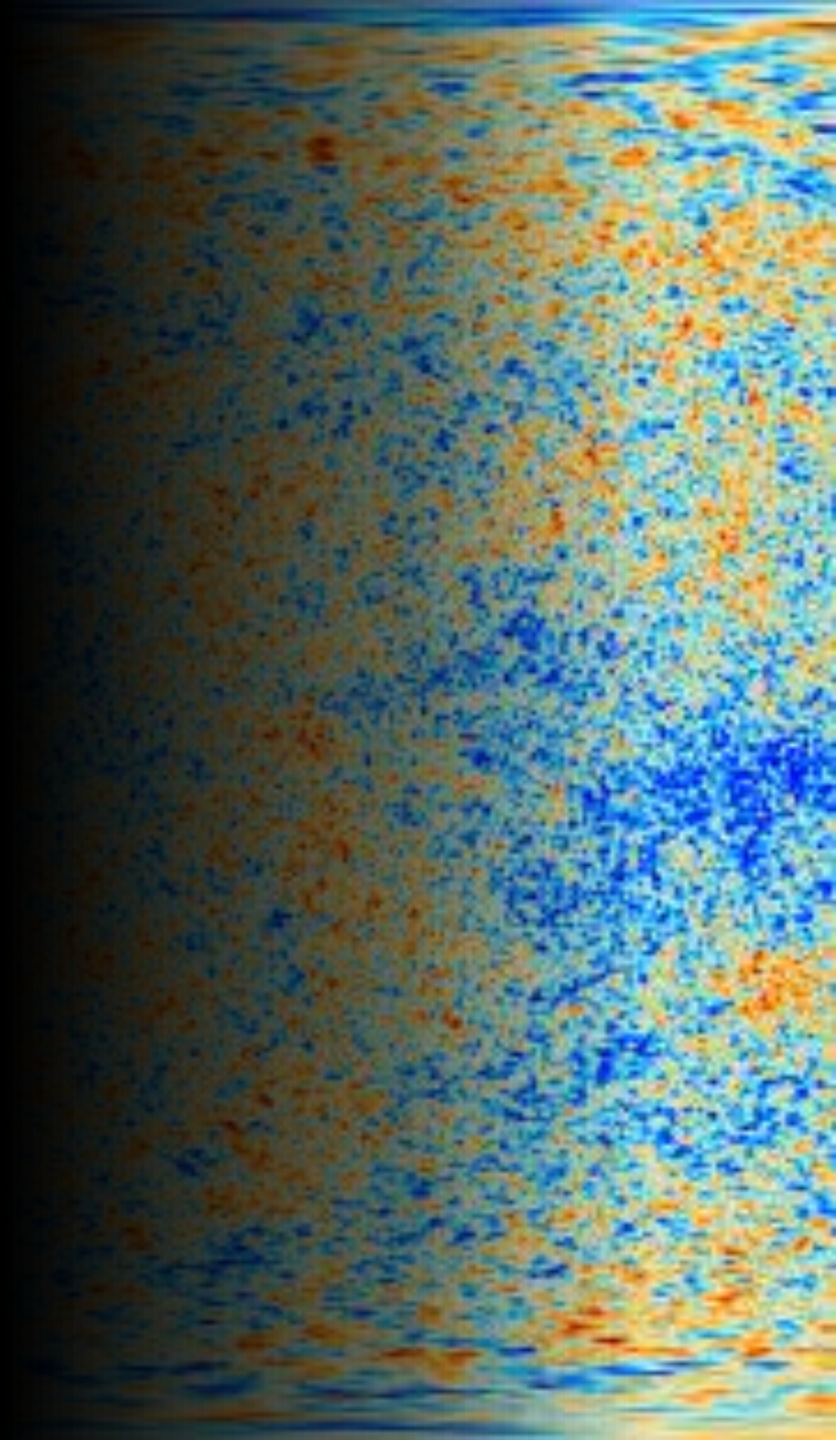


Planck results:



3 different kind of measurements agree when $\Omega_\Lambda \approx 0.7$ and $\Omega_m \approx 0.3$

CMB: Universe is ~flat



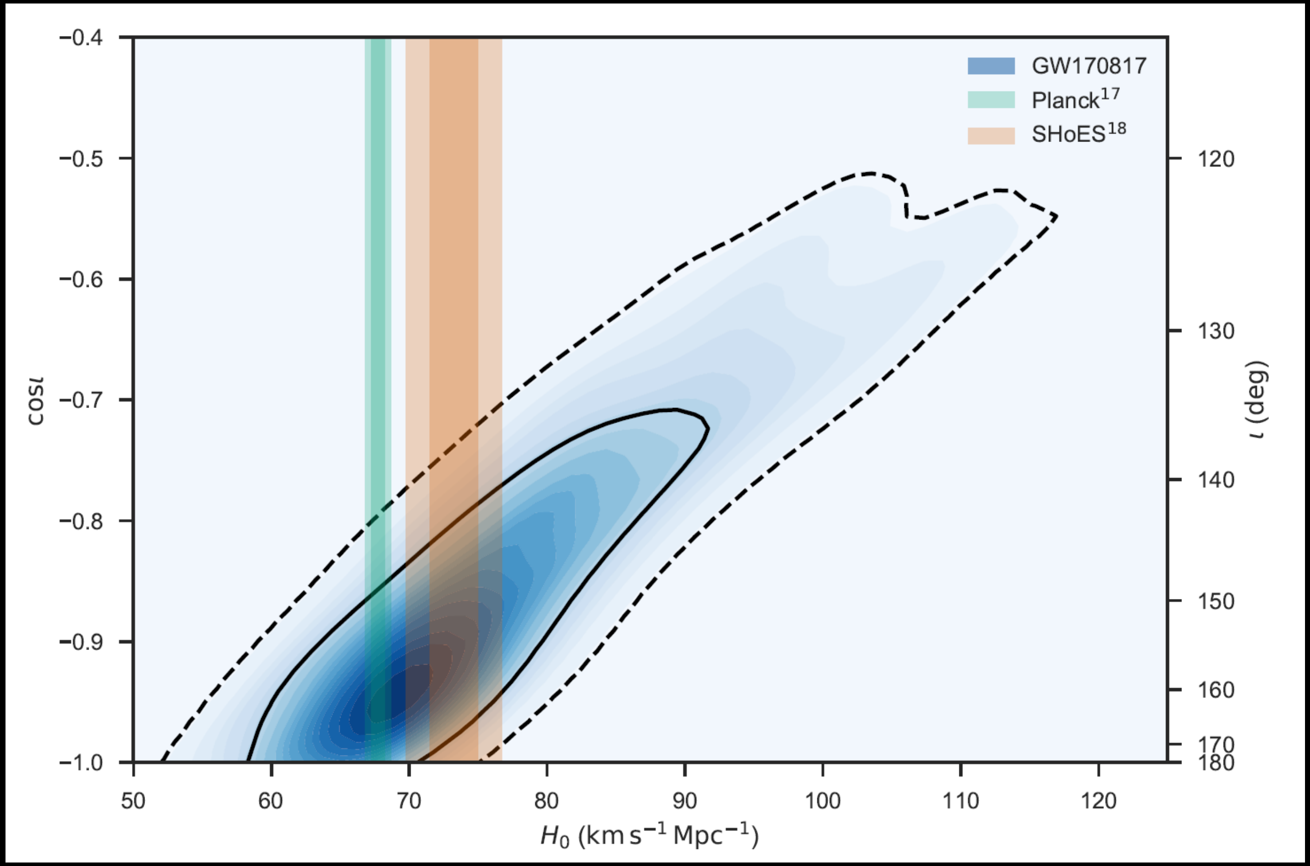
Results: Hubble constant

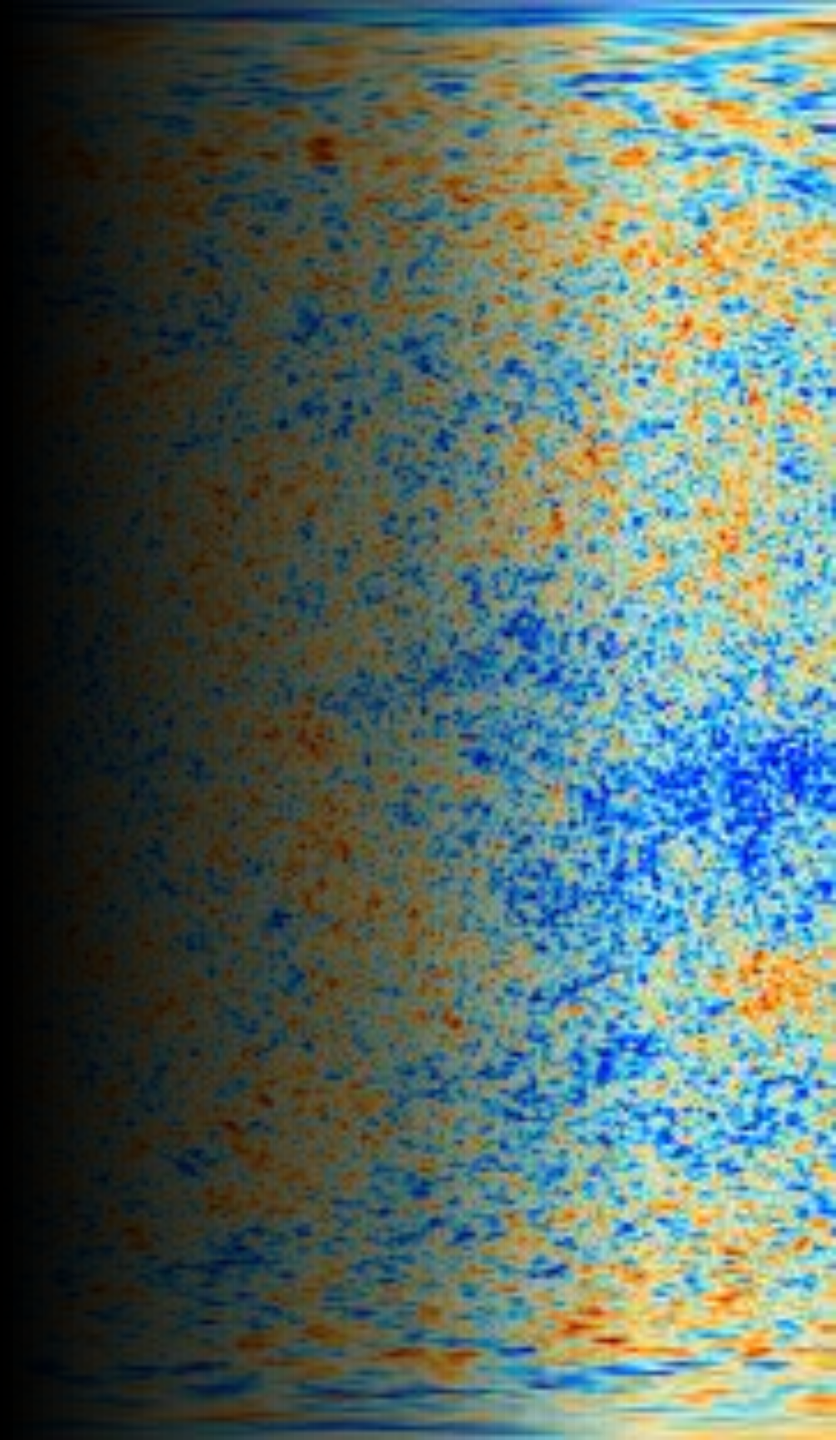
$v = H_0 d$

Planck and SHoES (Cepheids & type Ia SN) don't agree!

GW (LIGO-Virgo) is consistent with both, but only one event

Planck: $H_0 = 67.8\ kms^{-1}Mpc^{-1}$ ⇢ age of the Universe is 13.8 Gy





References

Péter Raffai: Cosmology course

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