Q) What is meant by large scale and small scale.

$\Rightarrow \quad \theta \approx \frac{180^\circ}{\ell}$; (large ℓ smaller θ)

- $\ell = 1 \Rightarrow$ Dipole $\Rightarrow \theta \approx 180^\circ$
- $\ell = 10 \Longrightarrow \theta \approx 18^\circ$
- $\ell = 100 \Longrightarrow \theta \approx 1.8^\circ$
- $\ell = 1000 \Longrightarrow \theta \approx 0.18^\circ \approx 10'$ (arcminutes)

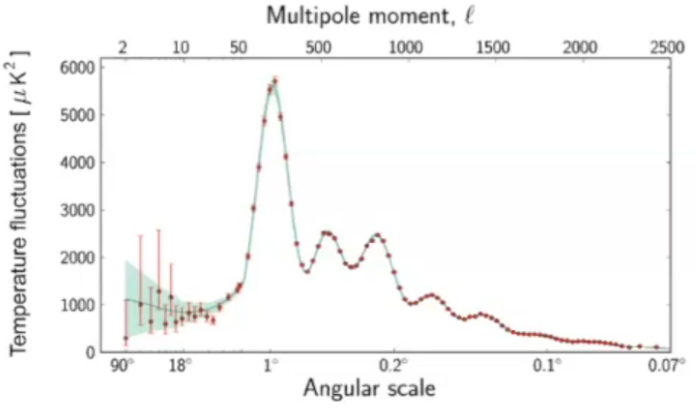
By looking at the angular power spectrum of the CMB, what is the characteristic angular scale of temperature fluctuations?

A. Around 10 degrees

B. Around 1 degree ✓

C. Around 0.1 degrees

D. Uniform across all angular scales

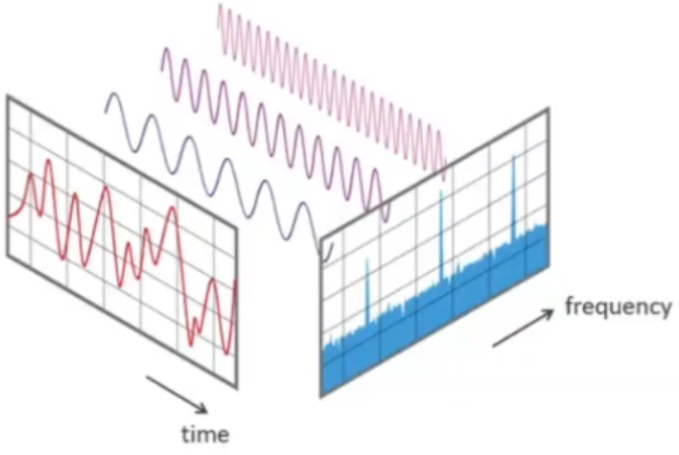


→ So, huge fluctuation at 1°. This implies majority of characteristic angular scale fluctuation happen around 1°.

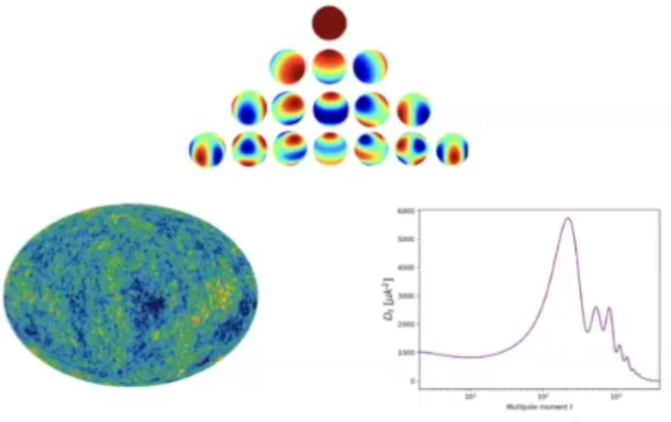
Q) Why are we using spherical harmonics?

A Rough Intuition on the **CMB** Angular Power Spectrum

1D Flat space, Fourier Transform



2D Sphere, Spherical Harmonics



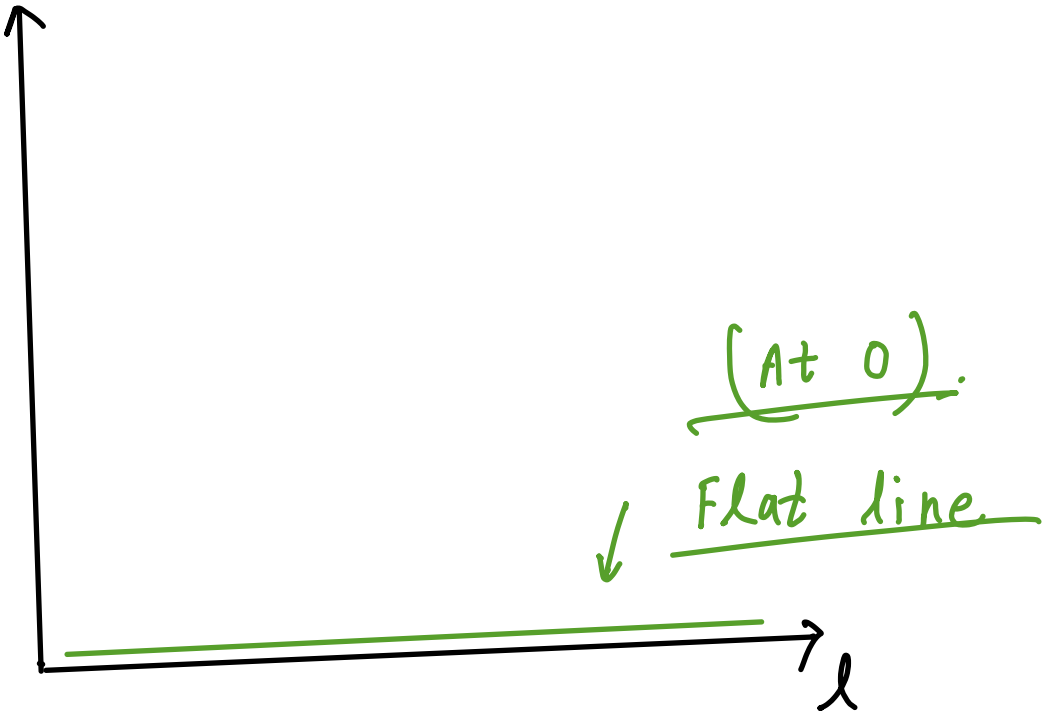
→ For complex signal, you can decompose into basis (Fourier series). And by taking Fourier transform we can see which building block are contributing the most / dominant signal.

→ In CMB, fluctuation on S^2, we decompose into spherical harmonics.

Q) What will happen to power spectrum if CMB had no anisotropy.

→ you will have only multipole.

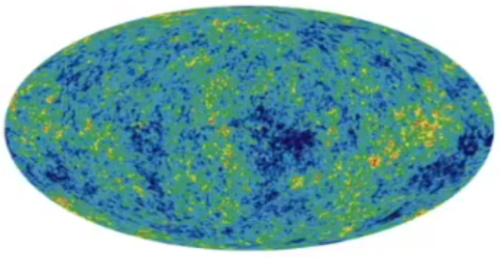
It's like white noise each scale have same power spectrum.

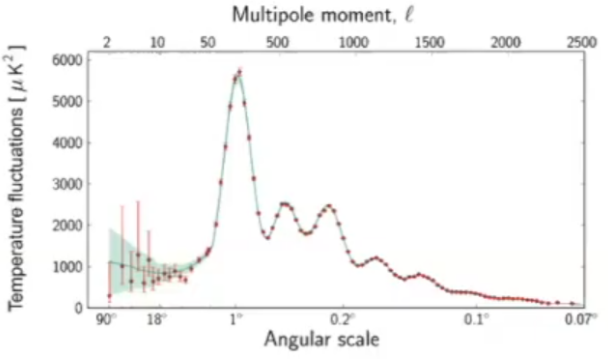


Q) What is power spectrum.

The **CMB** Angular Power Spectrum

- Due to the statistical isotropy and Gaussianity of the CMB temperature fluctuations, all cosmological information is encoded in its **angular power spectrum**.
- The power spectrum represents the variance of temperature fluctuations as a function of angular scale





Extremum	Multipole	Amplitude [μK^2]
***TT* power spectrum**		
Peak 1	220.6 ± 0.6	5733 ± 39
Trough 1	416.3 ± 1.1	1713 ± 20
Peak 2	538.1 ± 1.3	2586 ± 23
Trough 2	675.5 ± 1.2	1799 ± 14
Peak 3	809.8 ± 1.0	2518 ± 17
Trough 3	1001.1 ± 1.8	1049 ± 9
Peak 4	1147.8 ± 2.3	1227 ± 9
Trough 4	1290.0 ± 1.8	747 ± 5
Peak 5	1446.8 ± 1.6	799 ± 5
Trough 5	1623.8 ± 2.1	399 ± 3
Peak 6	1779 ± 3	378 ± 3
Trough 6	1919 ± 4	249 ± 3
Peak 7	2075 ± 8	227 ± 6
Trough 7	2241 ± 24	120 ± 6

→ power spectrum : variance of temp^{r} fluctuation.

y-axis ⇒ μK unit (Micro − Kelvin).

μK^2 → variance not s.d.

Q) How can we be sure CMB radiation is not from foreground objects.

∋ CMB ⟶ Blackbody

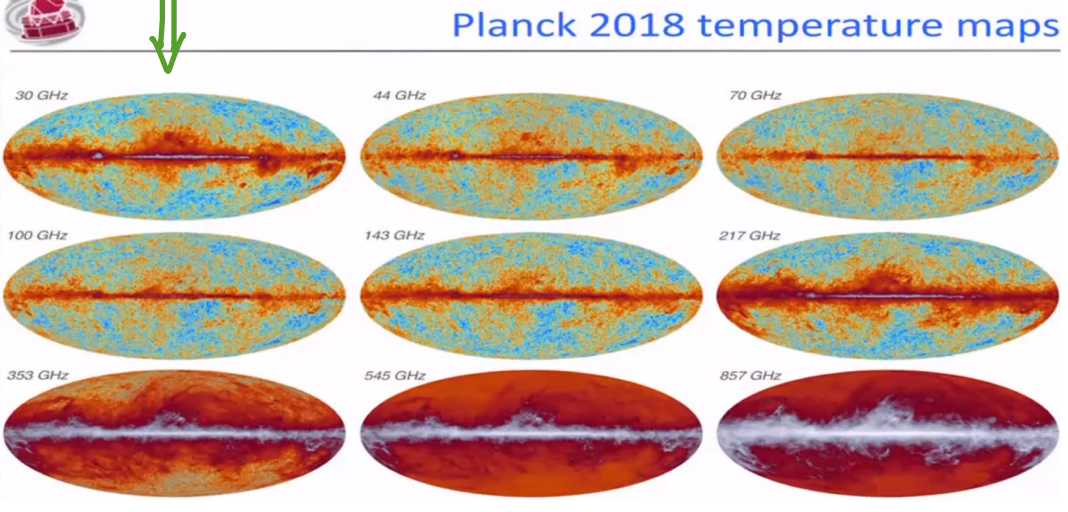
So, its temperature fluctuations have the same spectrum at every frequency band.

We use multifrequency band to filter out other emissions.

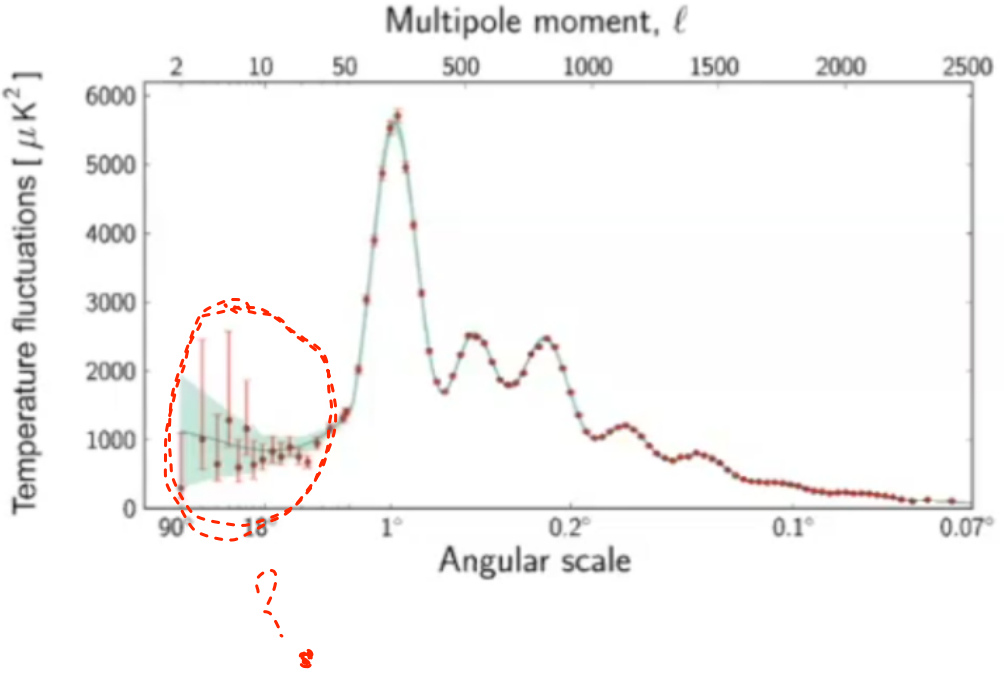
COBE : 3 frequency Band.

WMAP : 5 band

Planck : 9 frequency band.



Q) Why larger error bars on power spectrum of CMB.



⇒ Cosmic Variance.

→ It's not an instrumental error.
It is a fundamental limit imposed by the universe.

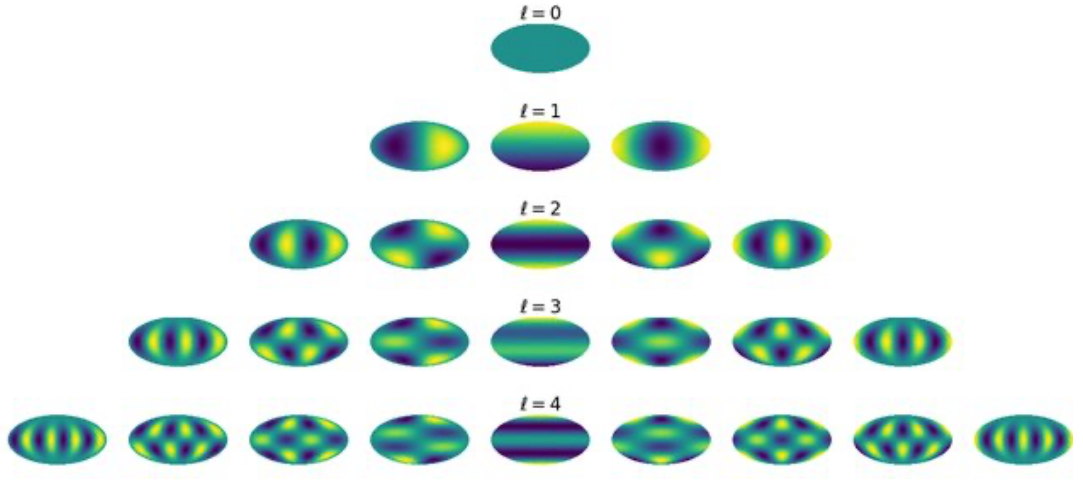
→ The problem at large scale (low-l):
large scale (dipole) corresponds to low l.
There are limited no. of fundamental waves that can truly represent actual fluctuation.

For high l, we have too much fundamental waves (spherical harmonics).

· For l, we have $(2l+1)$ modes:

Ex: $l = 1$, 3 Fundamental modes.
(dipole)

$l = 2$, 5 fundamental modes.



Causes of temp Fluctuations

Primary anisotropy in the CMB

- Fluctuations in the gravitational potential causes anisotropy via the Sachs Wolfe effect.
- Arises from acoustic oscillations in a plasma of Baryons and Photons under Gravity.
- Interplay between pressure and Gravity.
- Photons at maximum compression will be hotter and at maximum expansion will be cooler.
- Doppler shifts induces an additional anisotropy.
- Precisely measured by the WMAP satellite.

Secondary Anisotropies

- Fluctuations in the CMB due to its interaction with matter in the late Universe.
- Dominant in much smaller scales.

- **Rees Scaima effect**
- **Gravitational Lensing of the CMB**
- **Integrated Sachs Wolfe effect**
- **Ostriker Vishniac effect**
- **Sunyaev-Zeldovich effect**

Resources: Wayneh Website.

planck 2018 result I → Data, maps.

planck 2018 result I → DE models

(focus on cosmology)