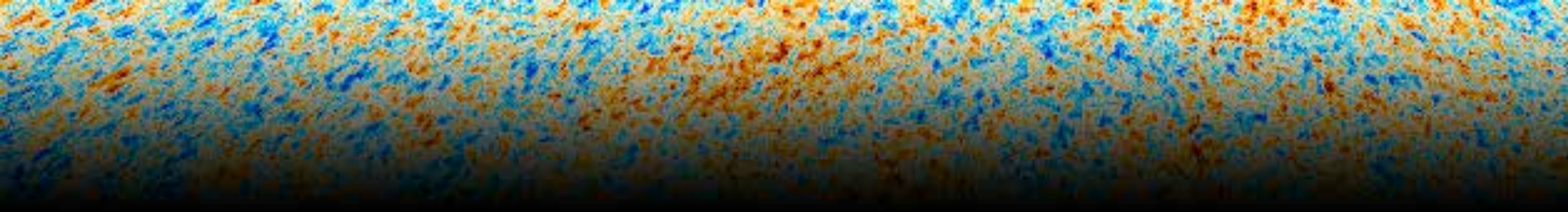


Our Quantum Universe

Raphael Flauger

KITP Chalk Talk, March 4, 2020


Image Credit: NASA


Image Credit: NASA

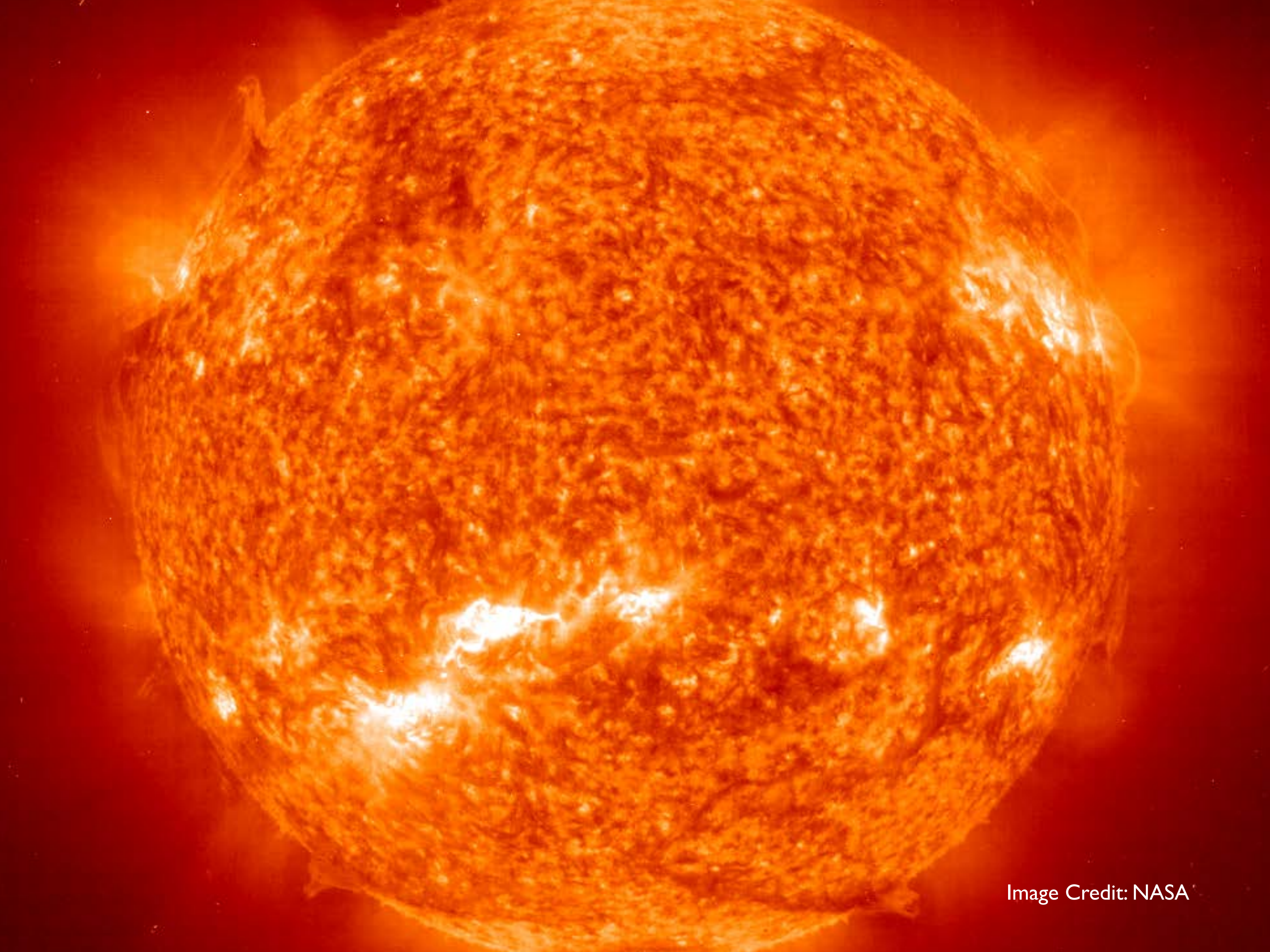


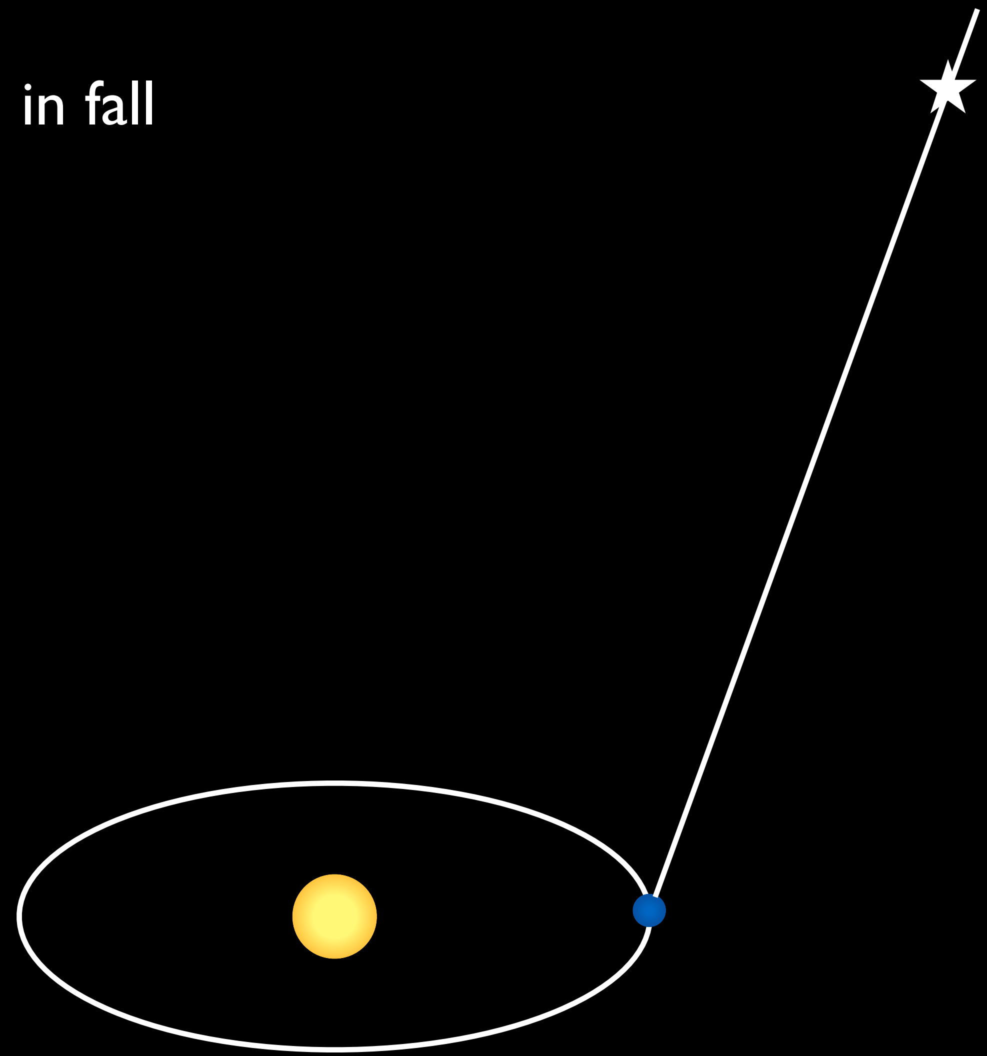
Image Credit: NASA

61 Cyg

Parallax

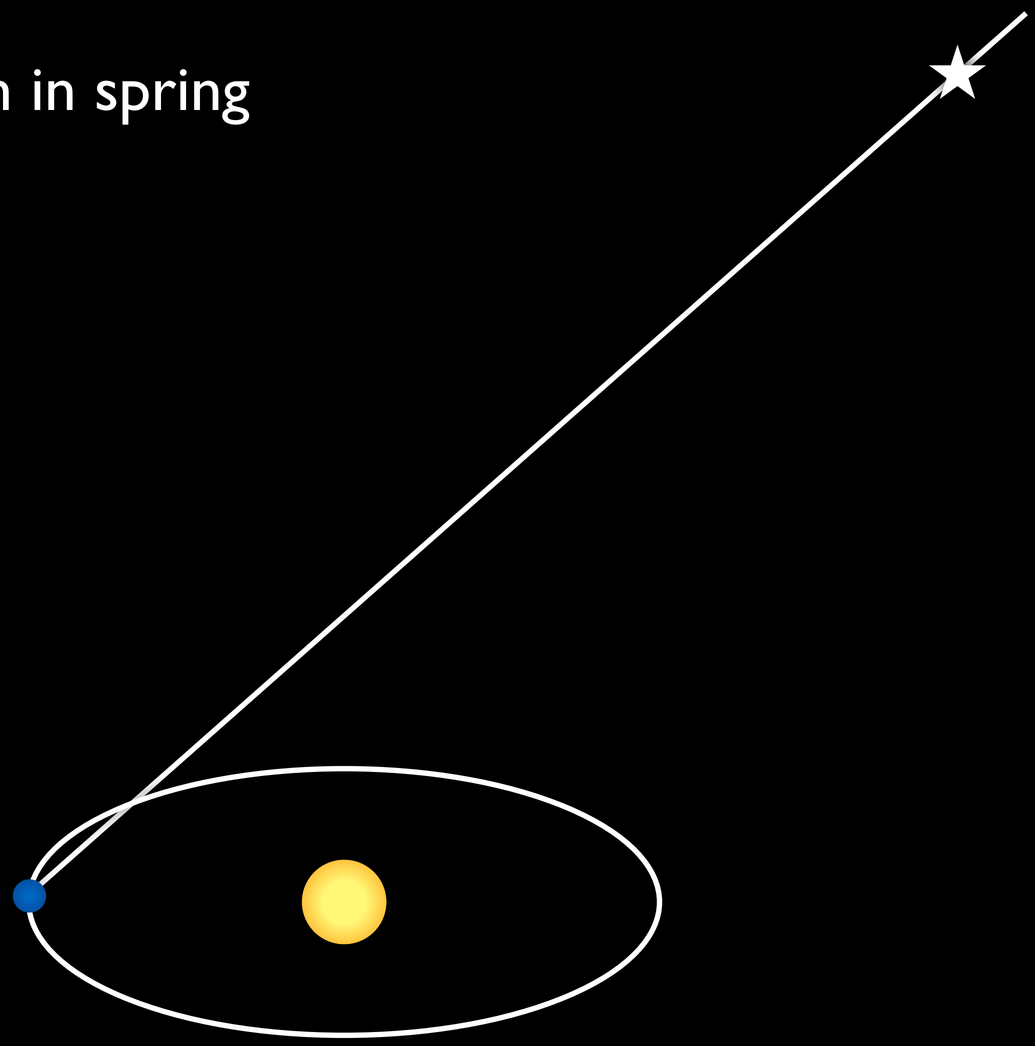
Parallax

Observation in fall

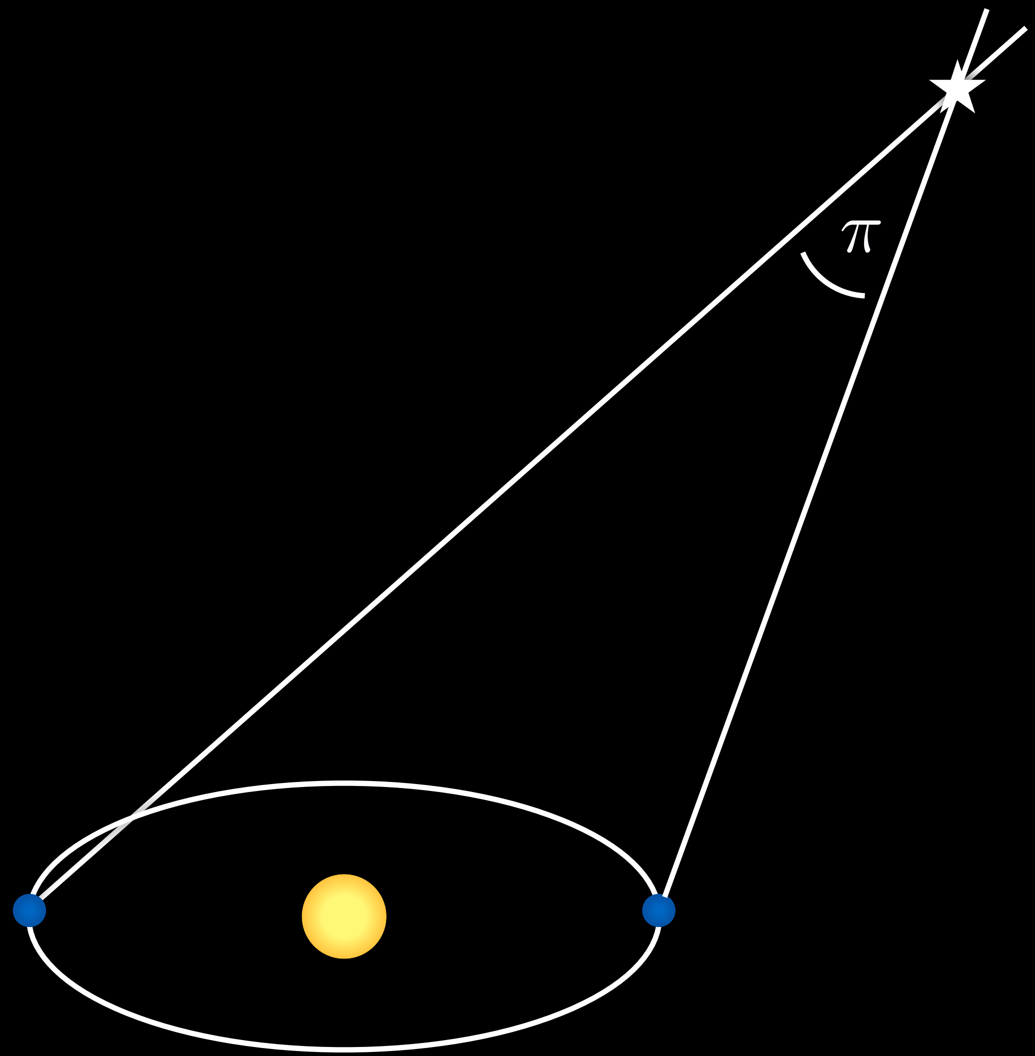


Parallax

Observation in spring

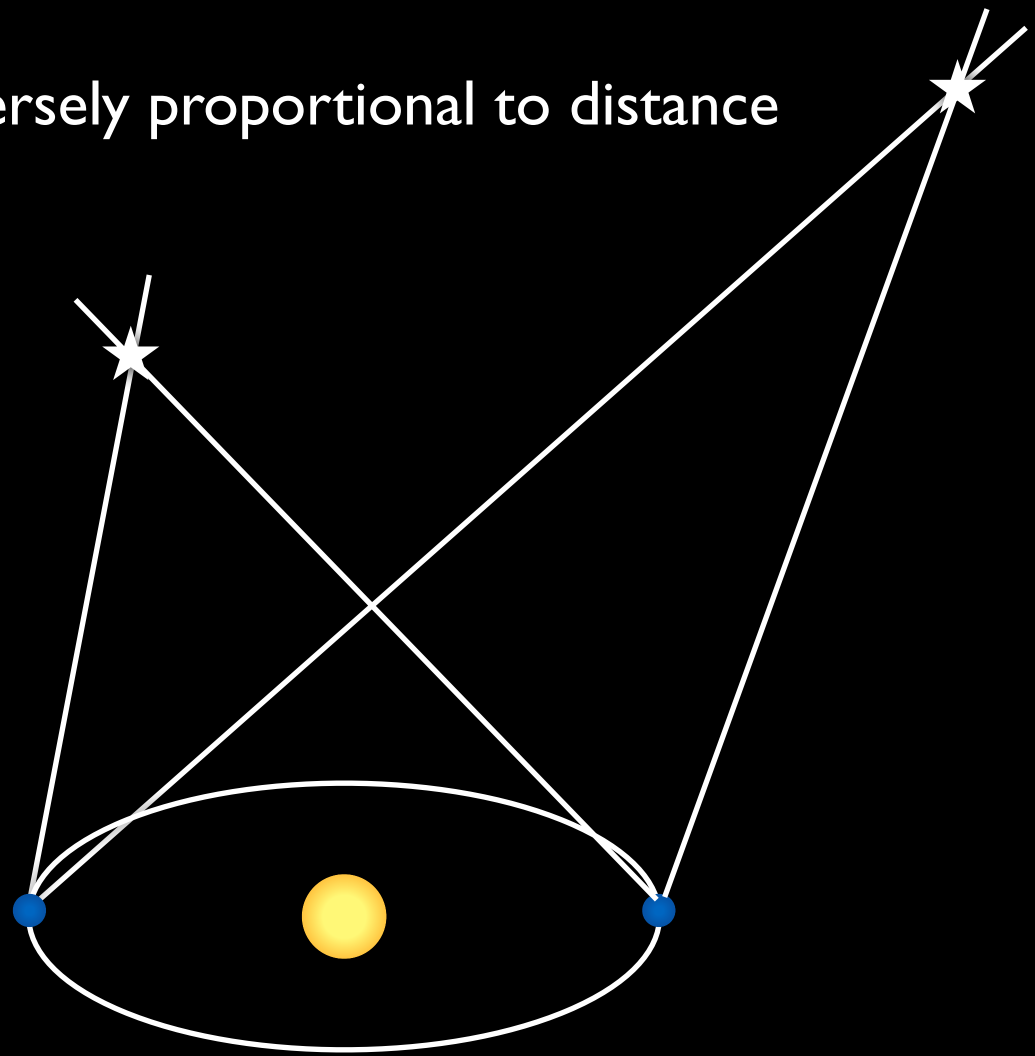


Parallax



Parallax

Parallax inversely proportional to distance



Measuring the distance

H.S. Leavitt

Measuring the distance

1777 VARIABLES IN THE MAGELLANIC CLOUDS.

By Henrietta S. Leavitt.

PERIODS OF VARIABLES IN THE SMALL MAGELLANIC CLOUD.

Harvard No.	Max.	Min.	Range.	Epoch.	Period.	Min. to Max.	Average Dev.	Earliest Observation.	No. Periods.	No. Plates.
					d.	d.				
818	13.6	14.7	1.1	4.0	10.336	1.7	.12	1890	566	44
821	11.2	12.1	0.9	97.	127.	49.	.06	1890	45	89
823	12.2	14.1	1.9	2.9	31.94	3.	.13	1890	184	56
824	11.4	12.8	1.4	4.	65.8	7.	.12	1889	94	83
827	13.4	14.3	0.9	11.6	13.47	6.	.11	1890	448	60
842	14.6	16.1	1.5	2.61	4.2897	0.6	.06	1896	843	26
1374	13.9	15.2	1.3	6.0	8.397	2.	.10	1893	574	42
1400	14.1	14.8	0.7	4.0	6.650	1.	.11	1893	724	42
1425	14.3	15.3	1.0	2.8	4.547	0.8	.09	1893	1042	33
1436	14.8	16.4	1.6	0.02	1.6637	0.3	.10	1893	2859	22
1446	14.8	16.4	1.6	1.38	1.7620	0.3	.09	1896	2052	21
1505	14.8	16.1	1.3	0.02	1.25336	0.2	.10	1896	2335	25
1506	15.1	16.3	1.2	1.08	1.87502	0.3	.09	1896	1560	23
1646	14.4	15.4	1.0	4.30	5.311	0.7	.06	1896	681	24
1649	14.3	15.2	0.9	5.05	5.323	0.7	.10	1893	894	32
1742	14.3	15.5	1.2	0.95	4.9866	0.7	.07	1893	954	28

It is worthy of notice that in Table VI the brighter variables have the longer periods.

Measuring the distance

HARVARD COLLEGE OBSERVATORY. 1912

CIRCULAR 173.

PERIODS OF 25 VARIABLE STARS IN THE SMALL MAGELLANIC CLOUD.

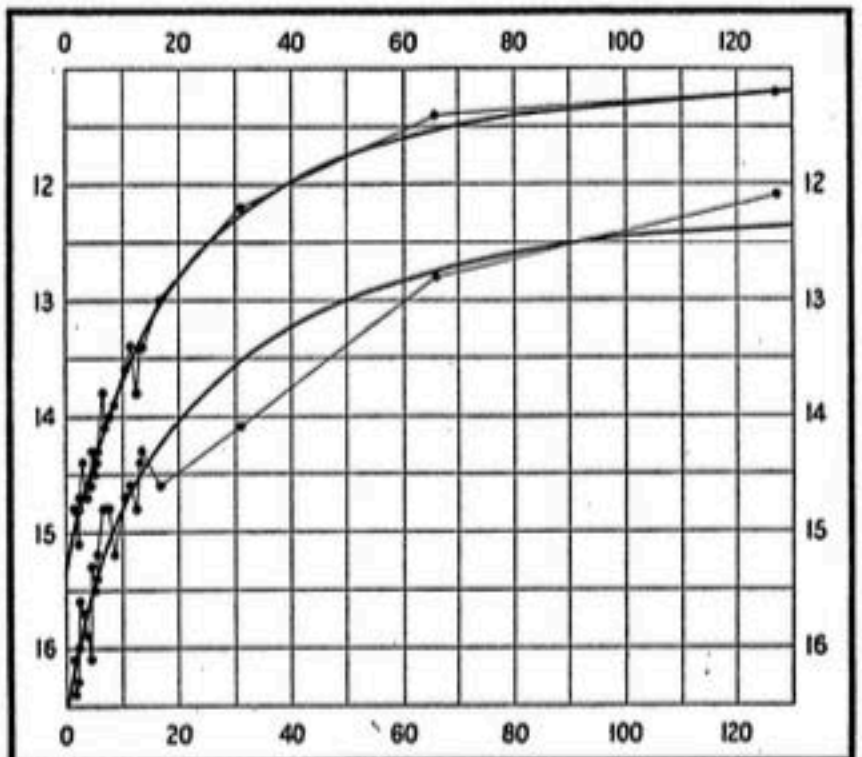


FIG. 1.

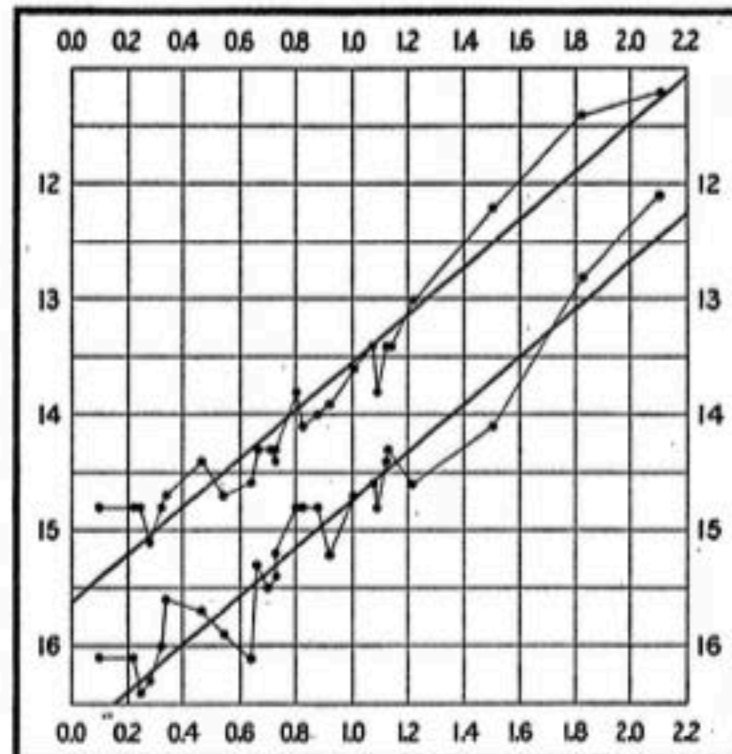
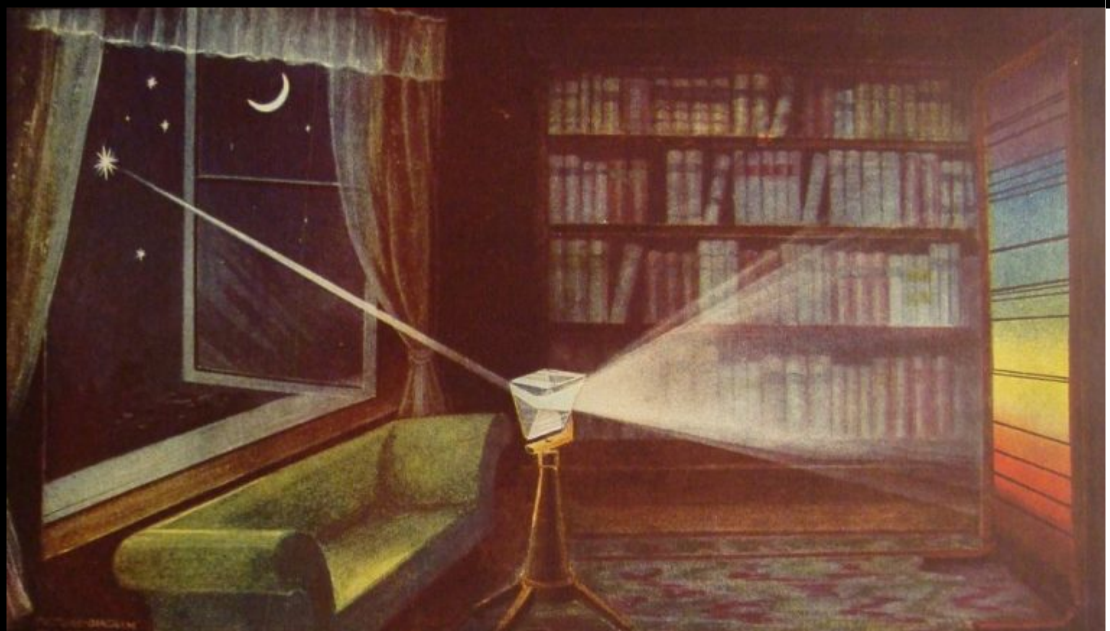
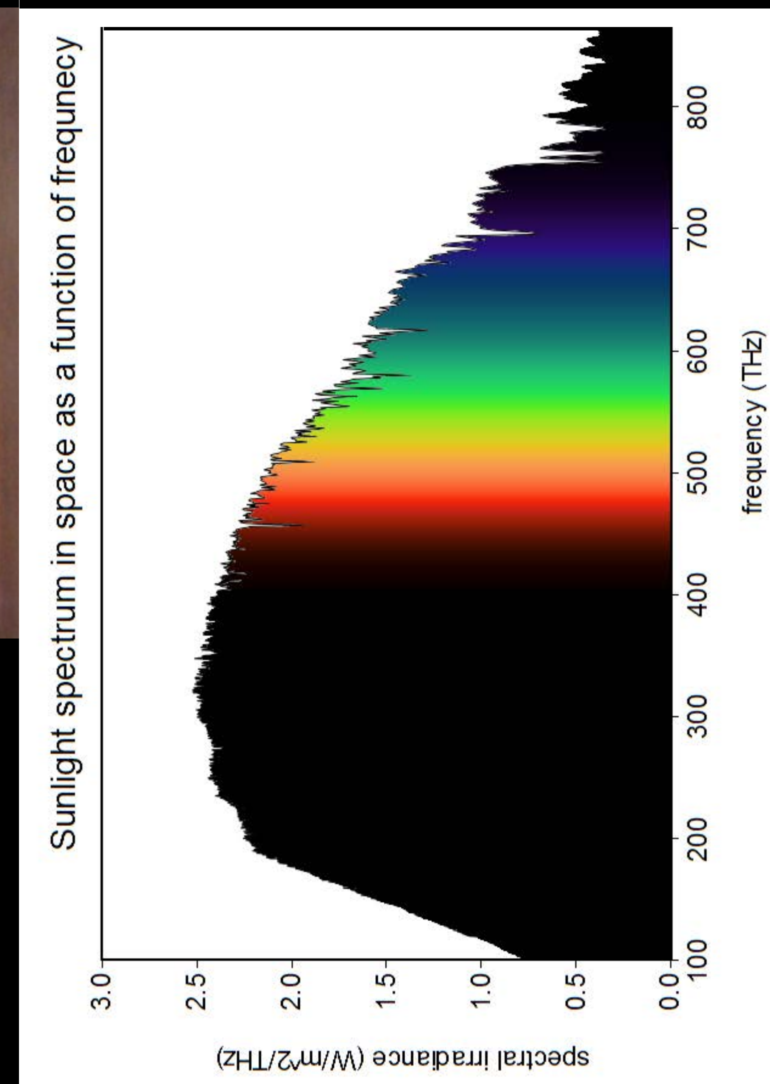


FIG. 2.

Spectrum

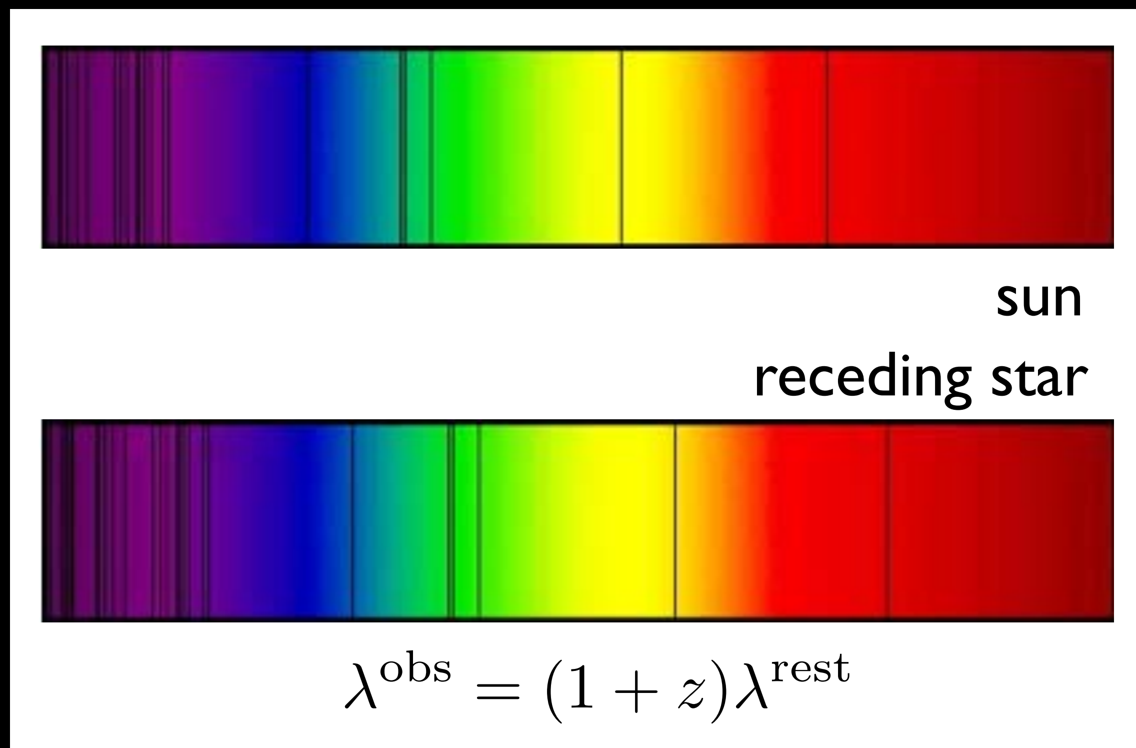




Sunlight spectrum in space as a function of frequency
frequency (THz)
spectral irradiance (W/m^2/THz)
100
200
300
400
500
600
700
800
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Spectra and Doppler effect

We can measure the velocity of stars and galaxies from the positions of spectral features.



$$v \approx zc$$

Spectra of Nebulae

V.M. Slipher

Spectra of Nebulae

SPECTROGRAPHIC OBSERVATIONS OF NEBULAE. 1913

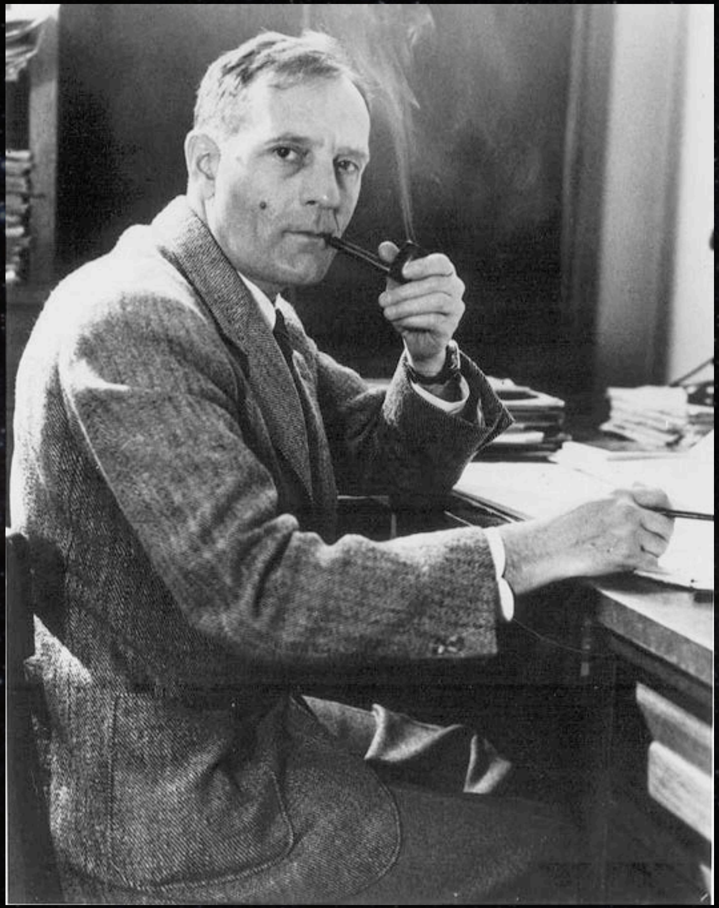
BY V. M. SLIPHER.

During the last two years the spectrographic work at Flagstaff has been devoted largely to nebulae. While the observations were chiefly concerned with the spiral nebulae they also include planetary and extended nebulae and globular star clusters.

N.G.C.	Velocity	
221	— 300 km	These nebulae are on the south side of the Milky Way.
224 †	— 300	
598	—	
1023	+ 200 roughly	
1068	+ 1100	
7331	+ 300 roughly	
3031	+ small	These are on the north side of the Milky Way
3115	+ 400 roughly	
3627	+ 500	
4565	+ 1000	
4594	+ 1100	
4736	+ 200 roughly	
4826	+ small	
5194	± small	
5866	+ 600	

As far as the data go, the average velocity is 400 km.

The expanding universe



The expanding universe

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

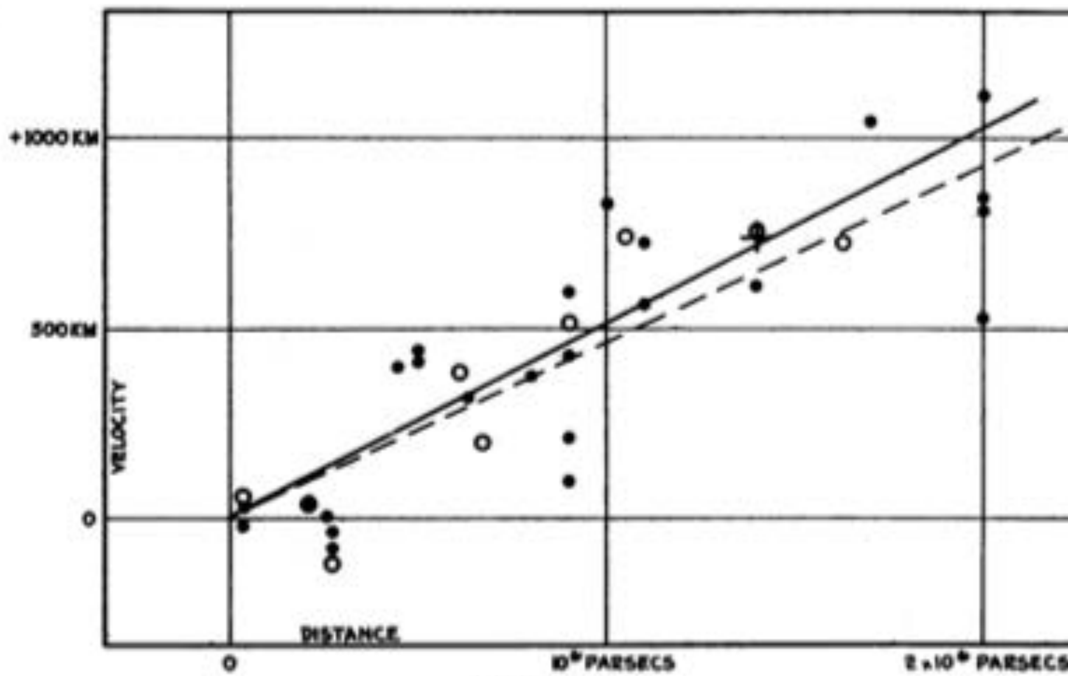
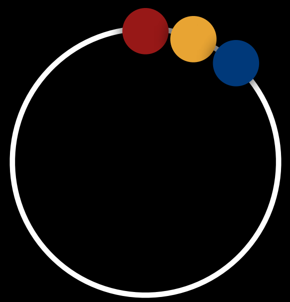


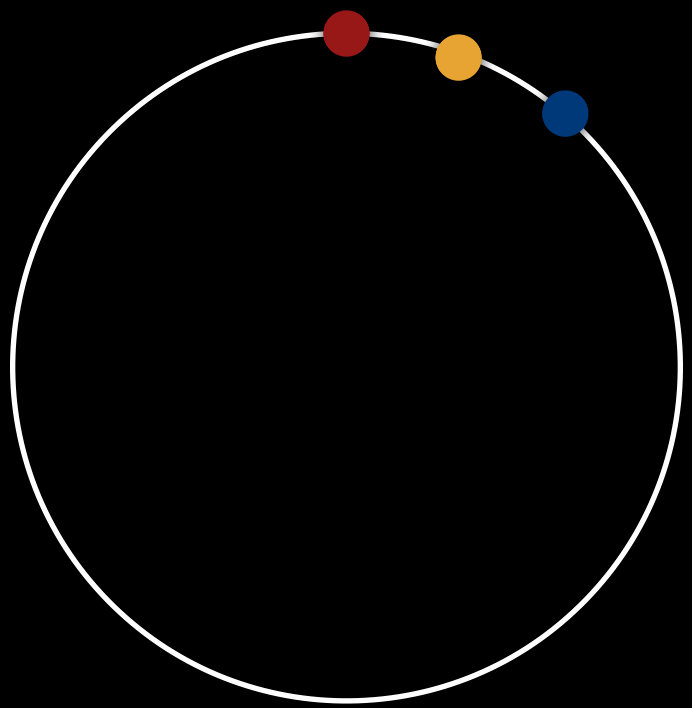
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

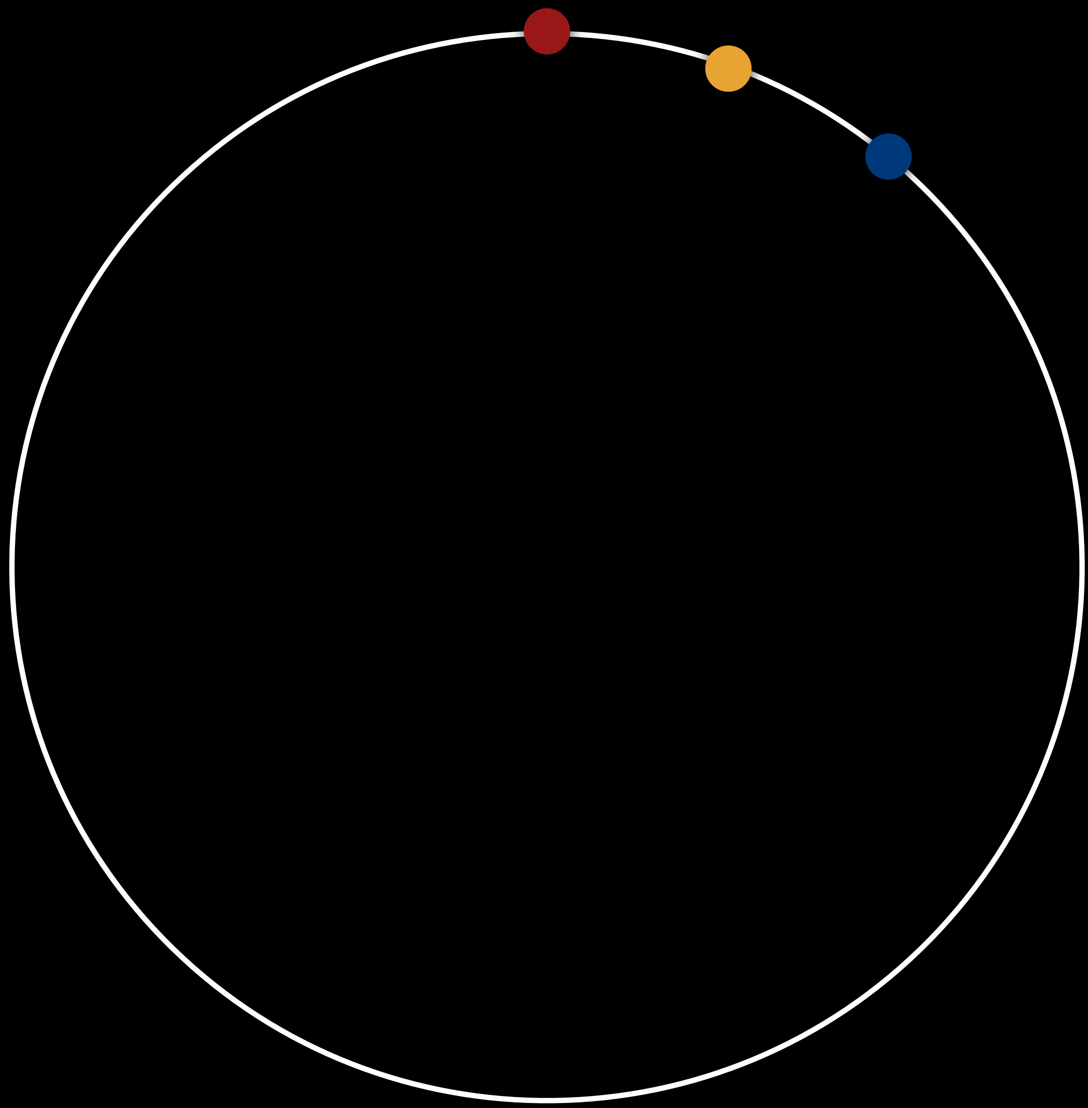
The expanding universe



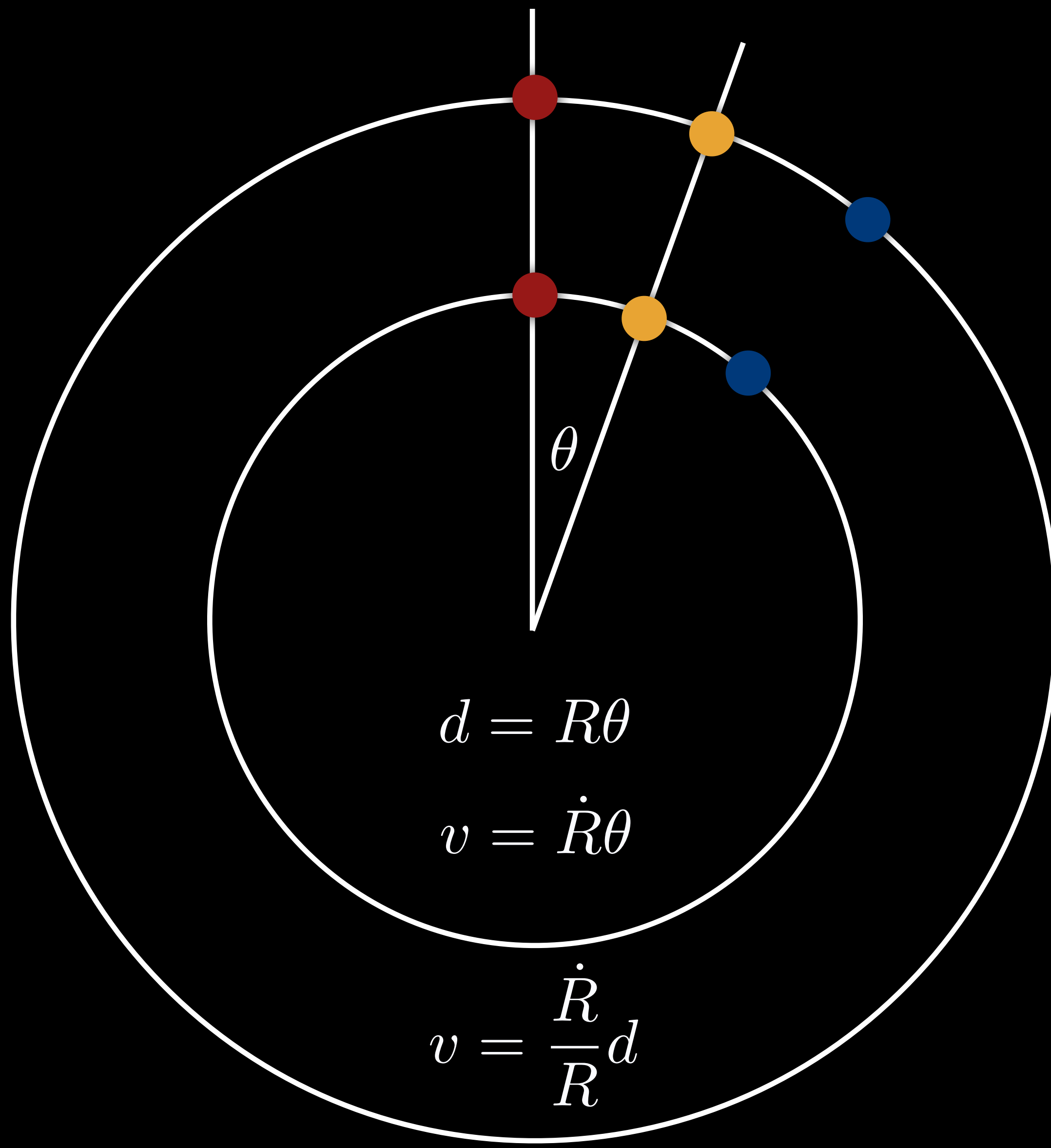
The expanding universe



The expanding universe



The expanding universe

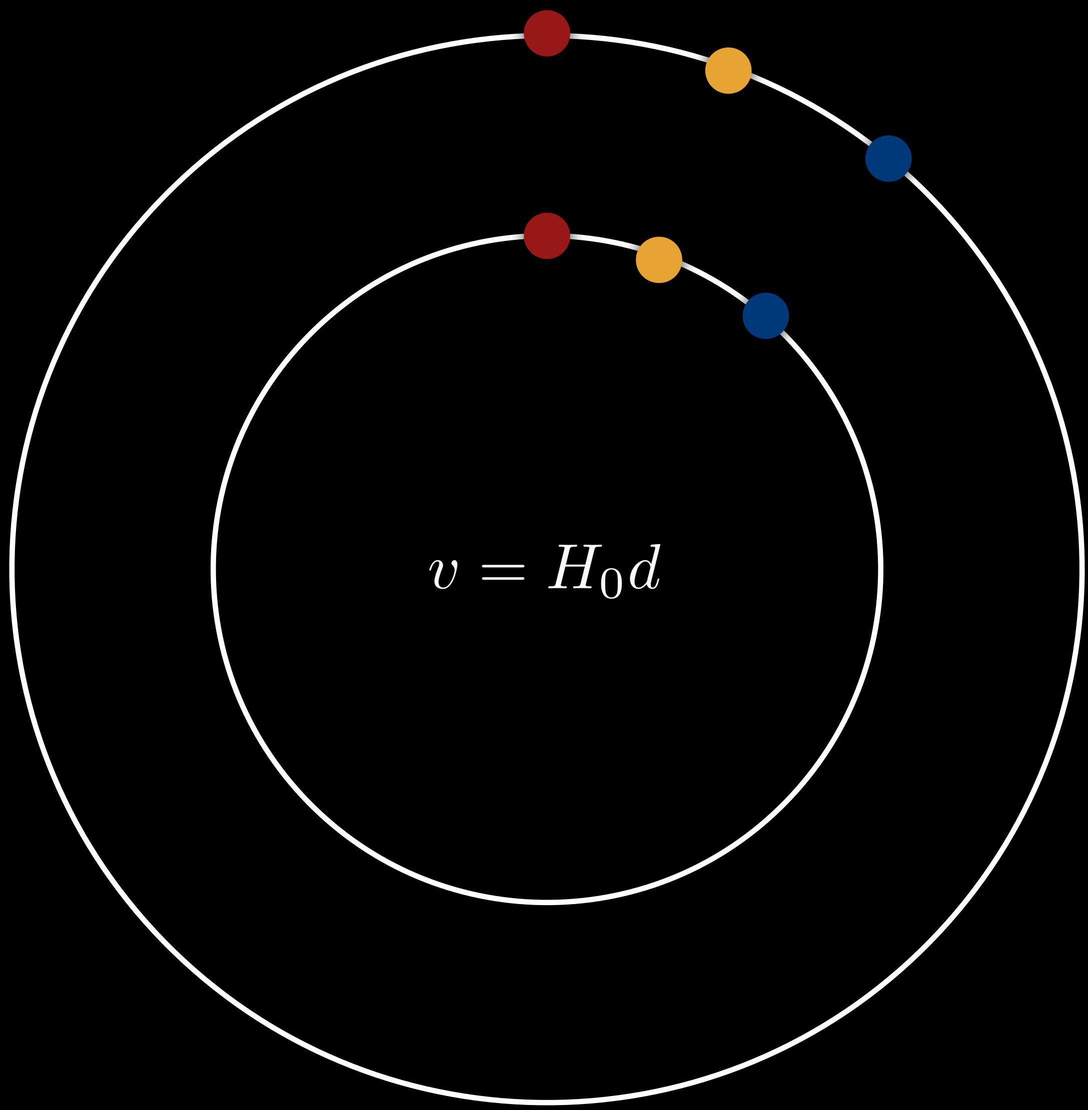


$$d = R\theta$$

$$v = \dot{R}\theta$$

$$v = \frac{\dot{R}}{R}d$$

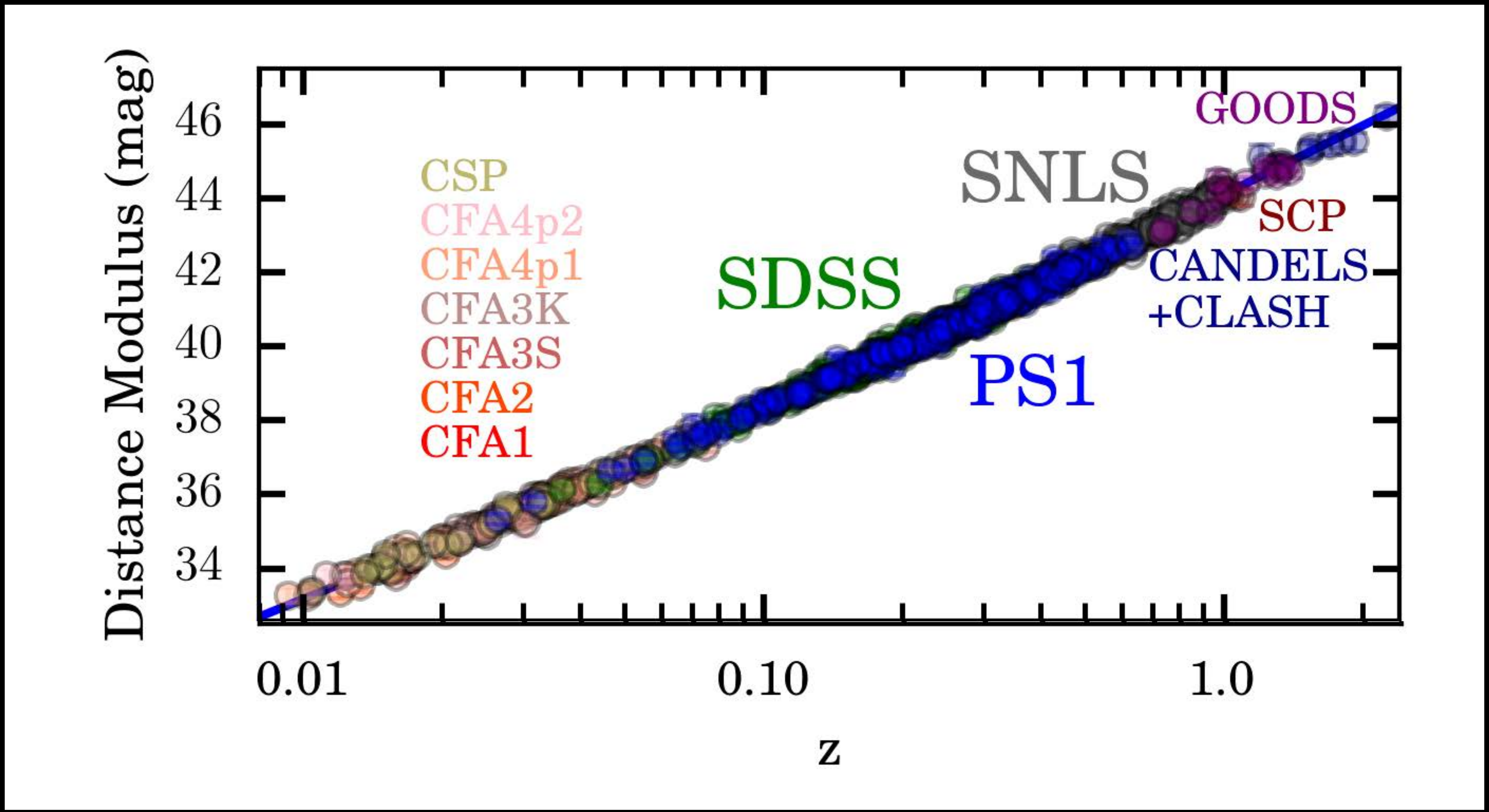
The expanding universe



$$v = H_0 d$$

For distant objects we can infer distance from redshift

The expanding universe



The expanding universe

Distance record holder: GN-z11

light travel time: 13.4 billion years

age of universe at emission: 400 million years

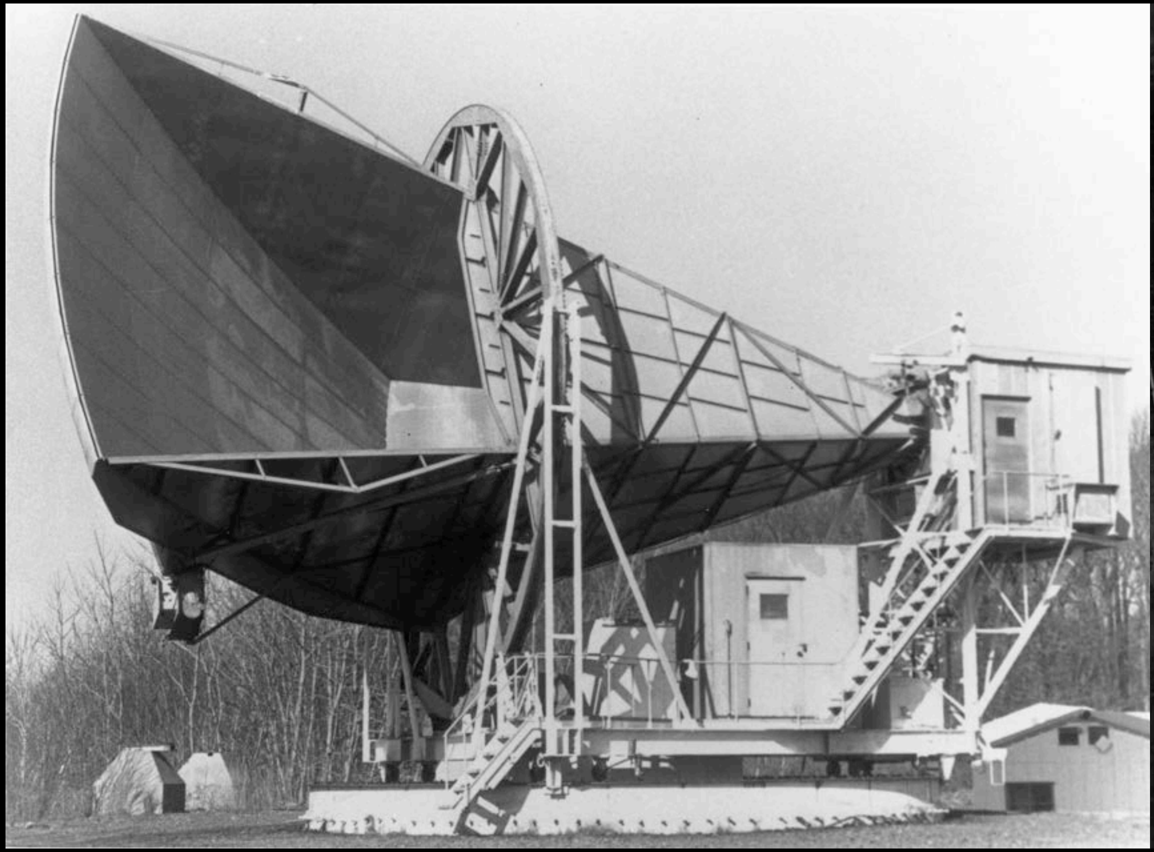
The Cosmic Microwave Background

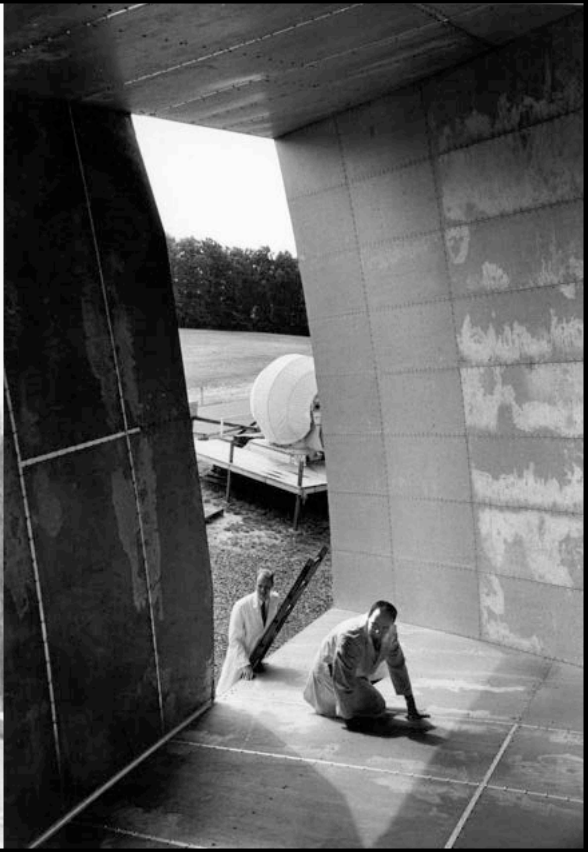
If the universe is expanding, it must have been denser and hotter early on. Could there be radiation left over and detectable today from this hotter period?

Dicke, Peebles, Roll, and Wilkinson hoping to find out.

The Cosmic Microwave Background

Meanwhile 30 miles away:





Penzias and Wilson are troubled by noise in their experiment

The Cosmic Microwave Background

Penzias and Wilson are informed by Bernie Burke who is informed by Ken Turner of a talk given by Jim Peebles

COSMIC BLACK-BODY RADIATION*

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965

Palmer Physical Laboratory
Princeton, New Jersey

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

A. A. Penzias
R. W. Wilson

May 13, 1965

Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

Project Echo

The CMB Dipole

Motion with respect to the CMB should cause a dipolar pattern

First measurement of right ascension, declination, amplitude

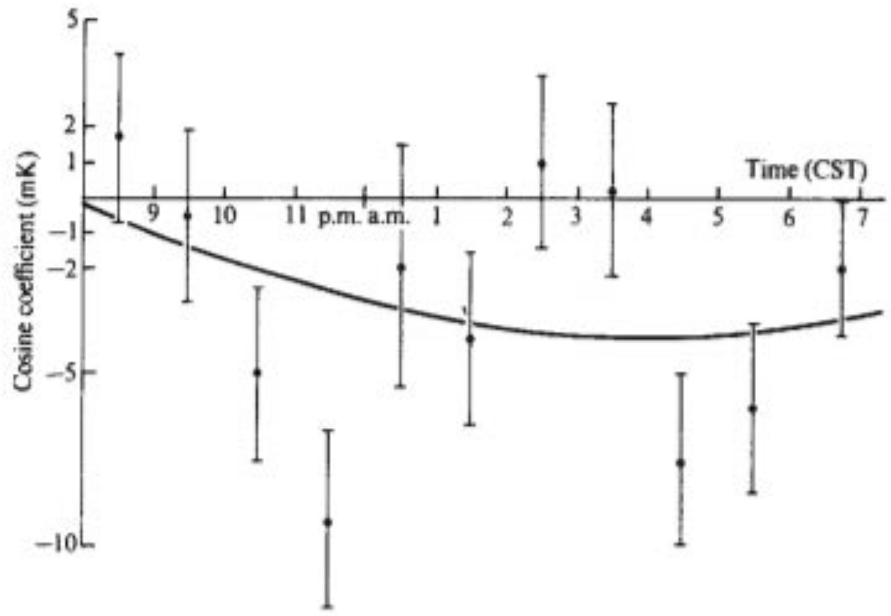
Isotropy of the 3 K Background

3.2 ± 0.8 mK

PAUL S. HENRY*

Joseph Henry Laboratories, Department of Physics, Princeton University, Princeton, New Jersey 08540

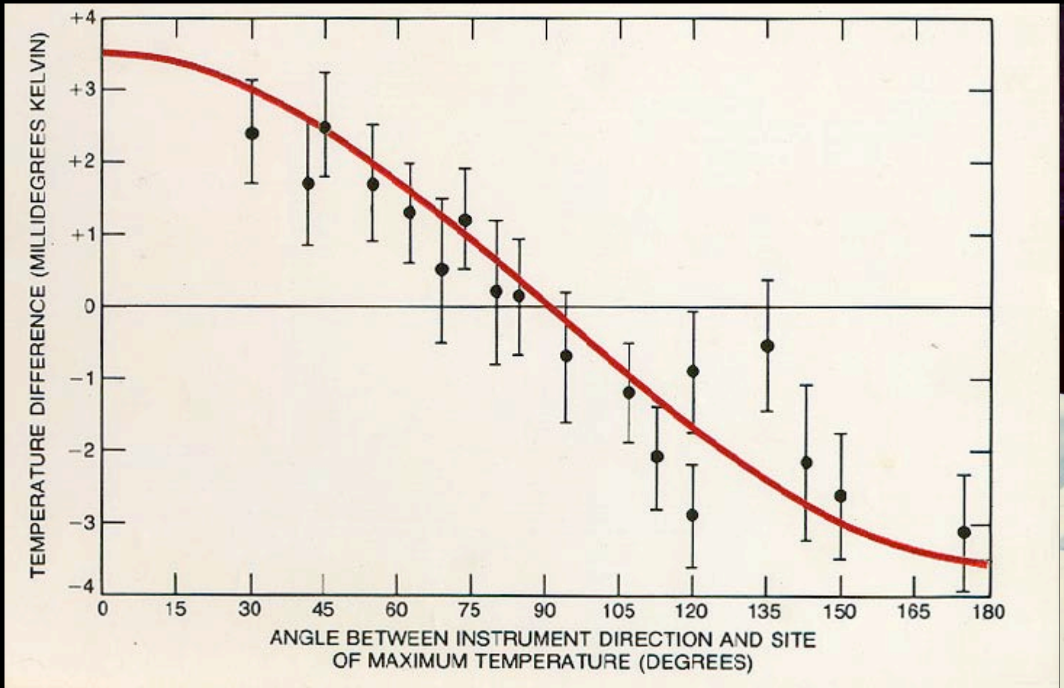
Received May 17, 1971.

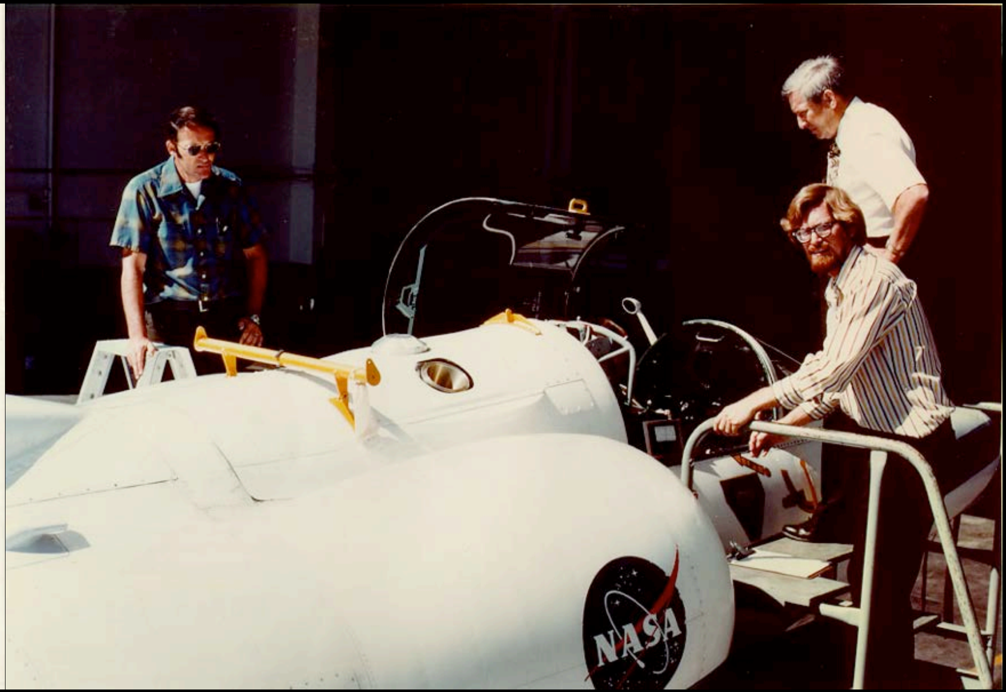


Teaches us about direction and speed of our motion relative to the CMB

The CMB Dipole

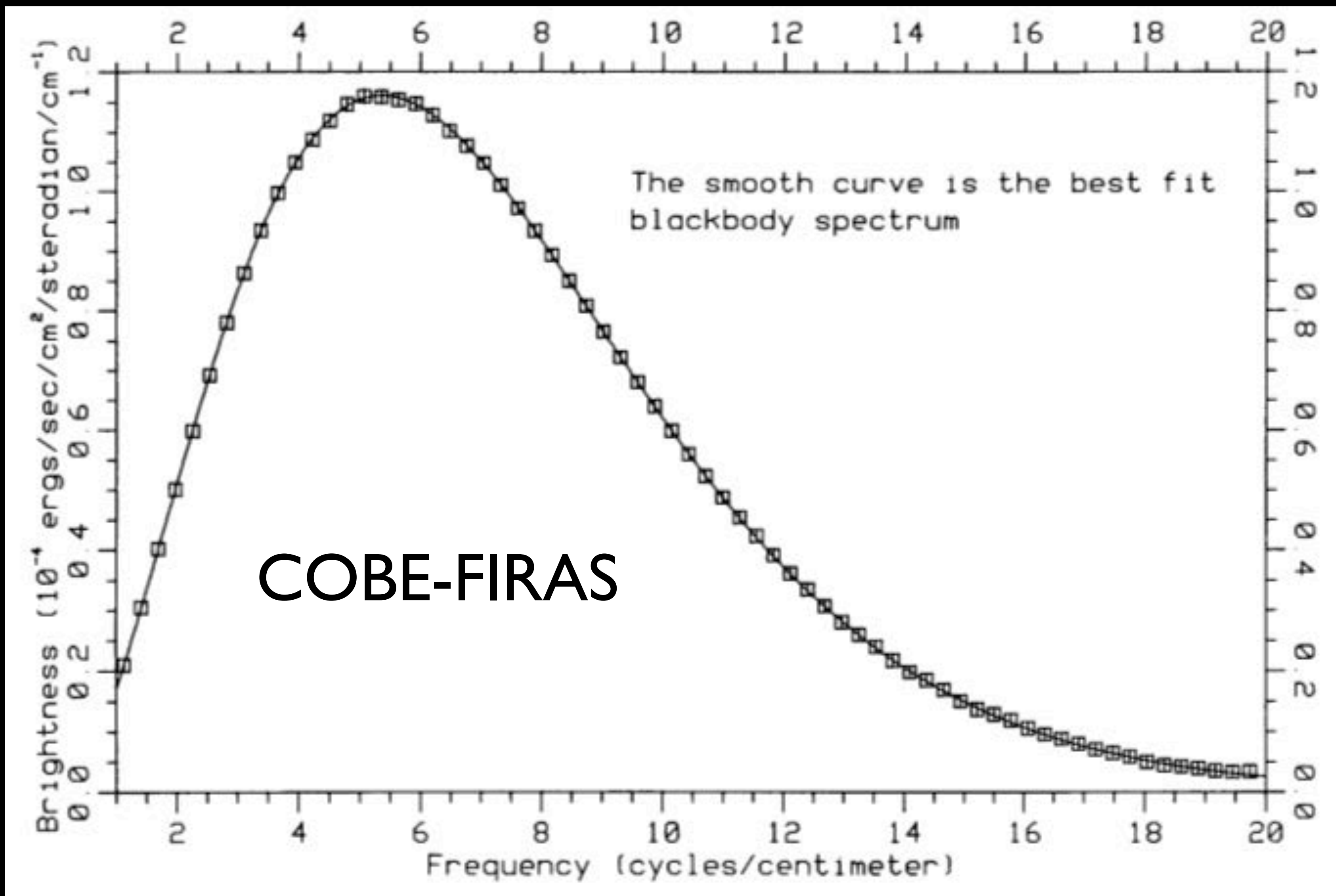
High significance detection





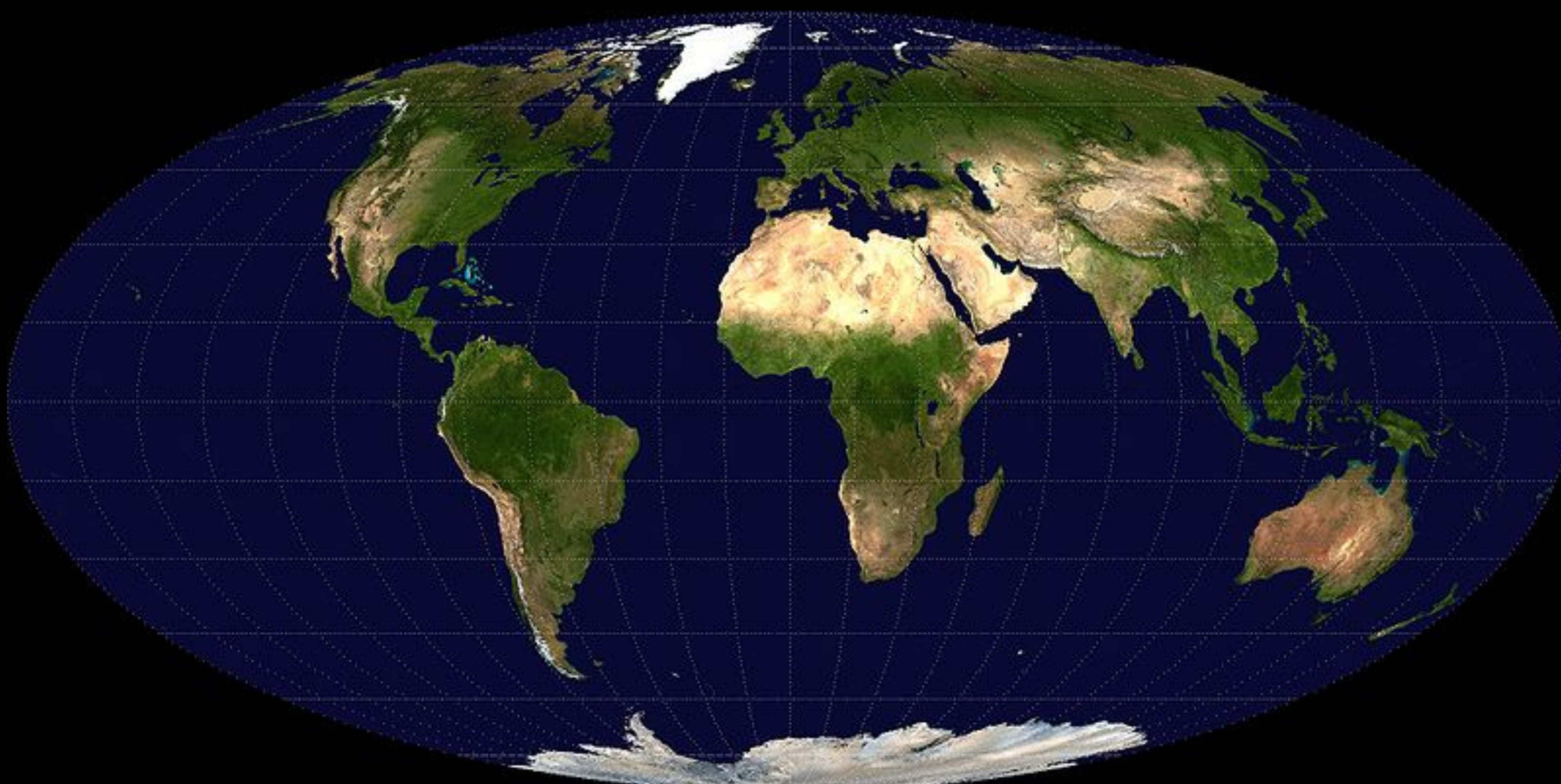
Spectrum of the CMB

Radiation left over from the hot early universe should have a characteristic frequency dependence.

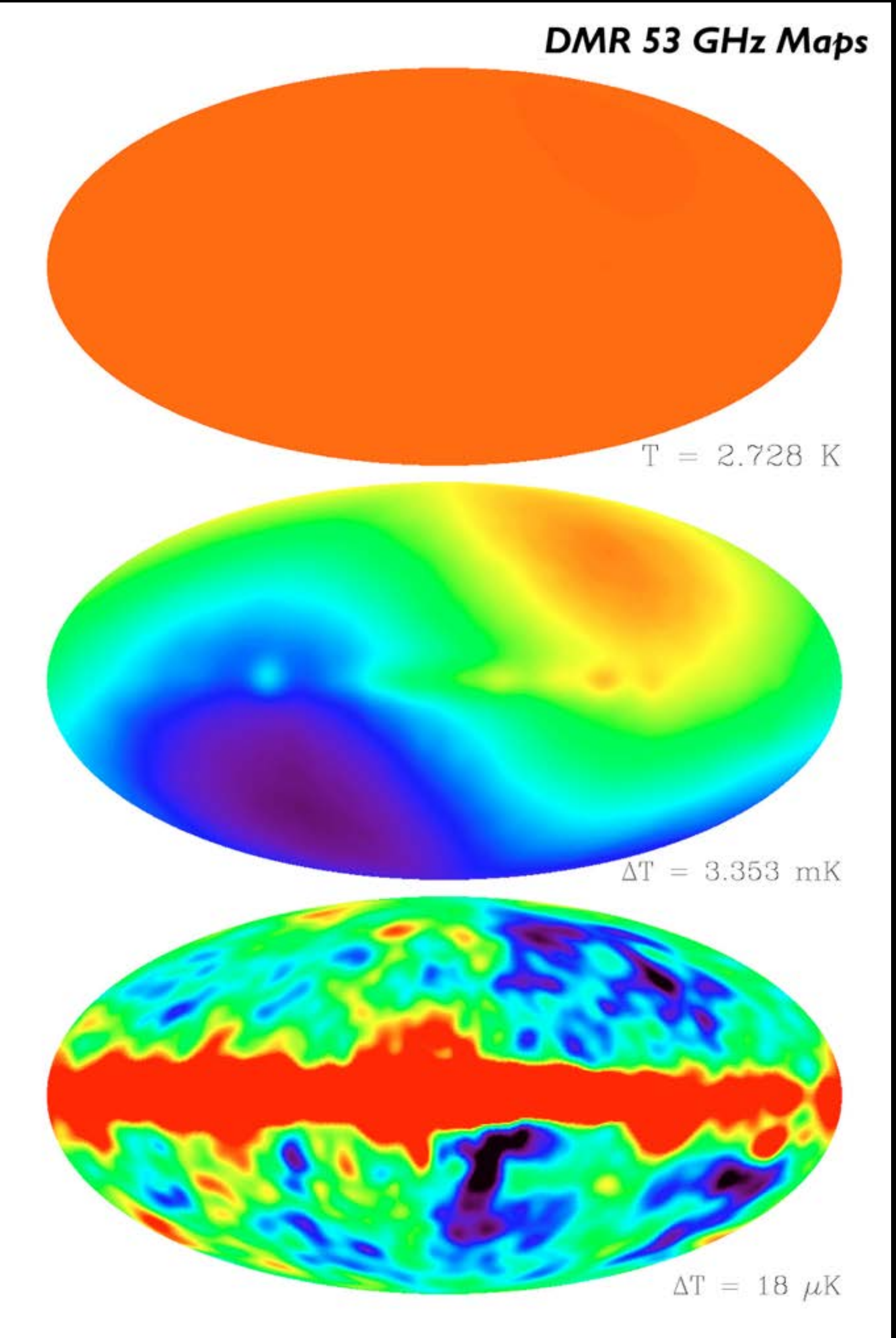


Mollweide projection

A convenient projection of a sphere into the plane traditionally used to show CMB maps is the Mollweide projection.

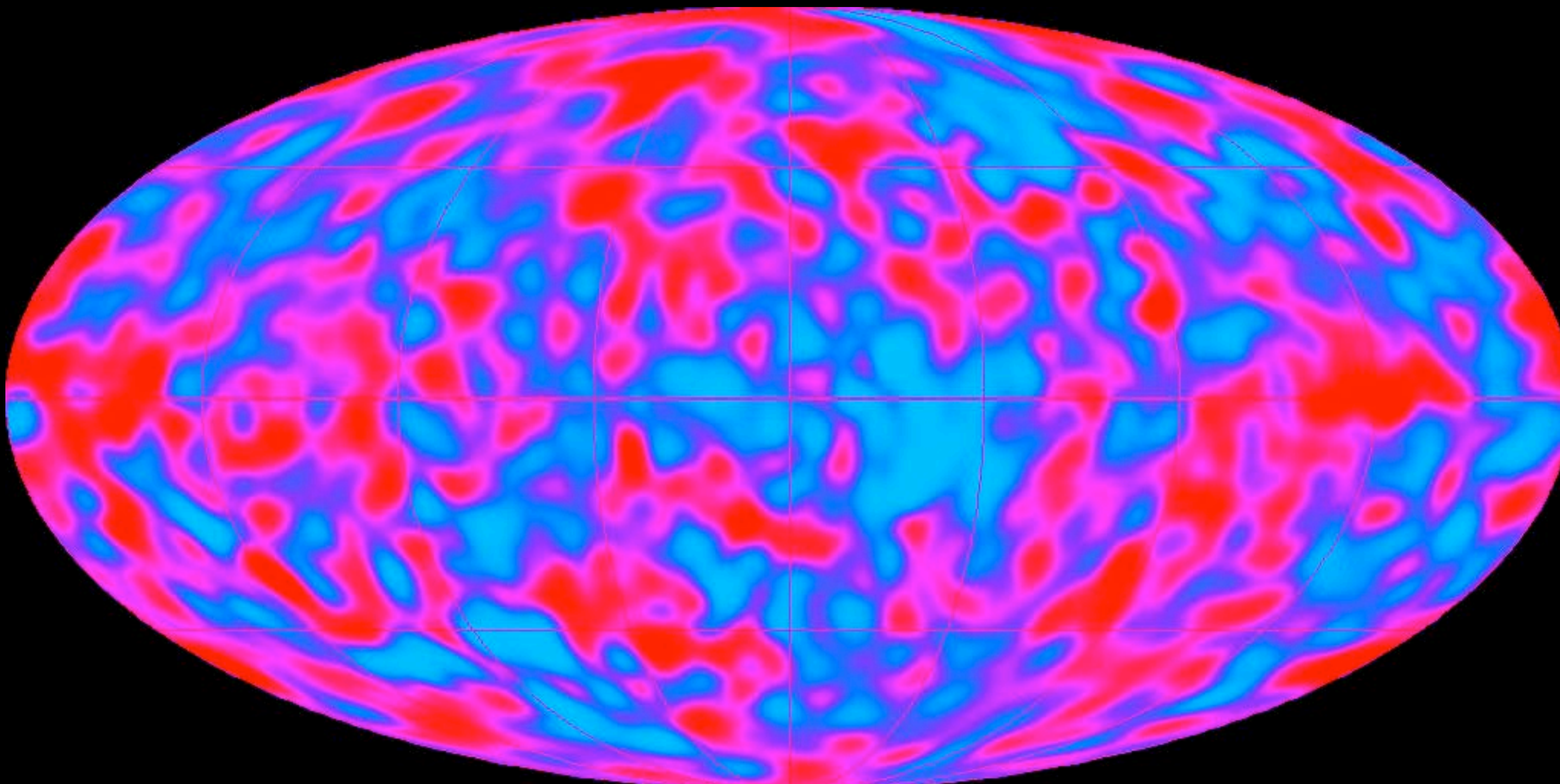


COBE



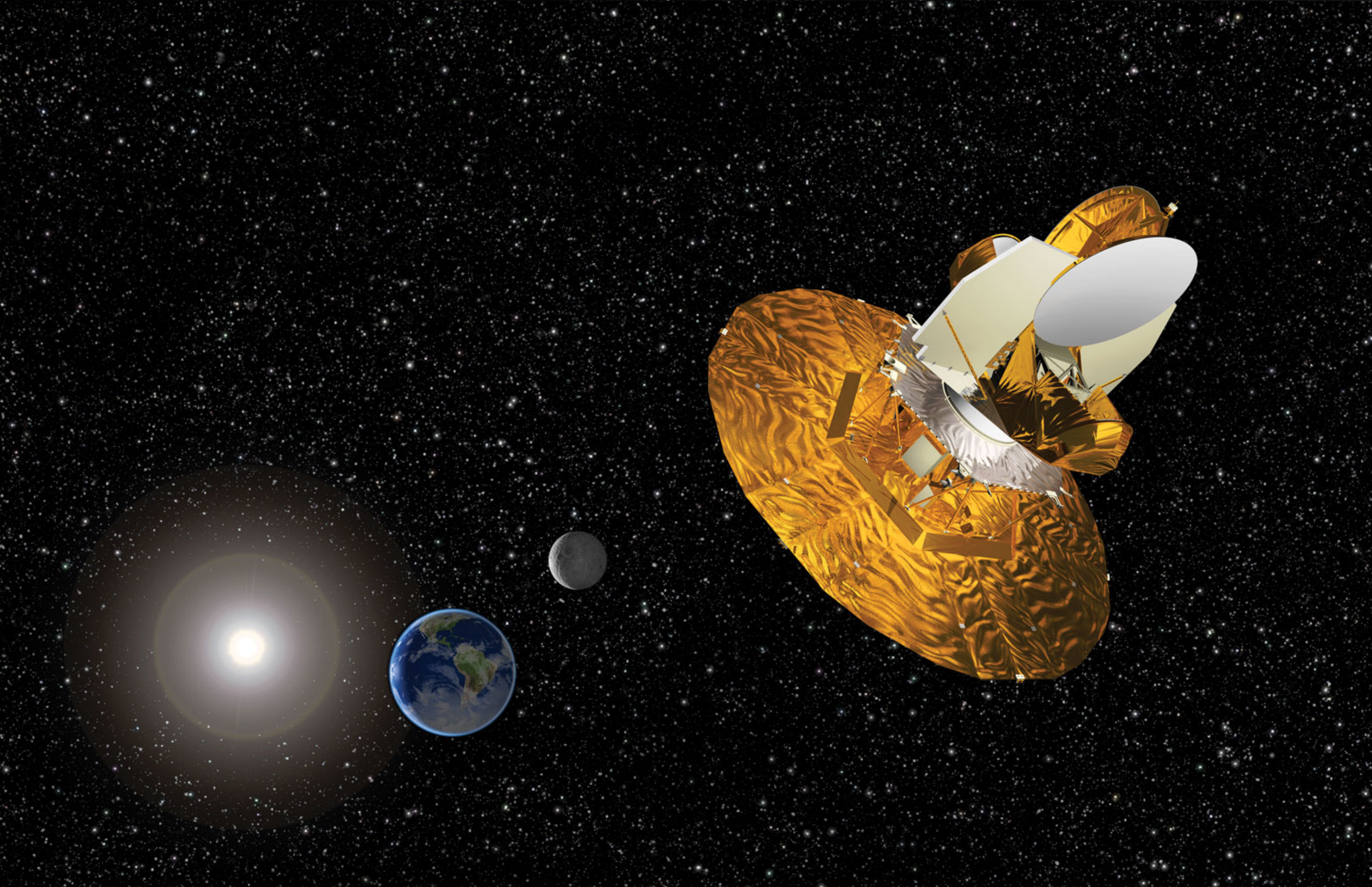
COBE

Observations at 3 frequencies allow to remove galactic emission

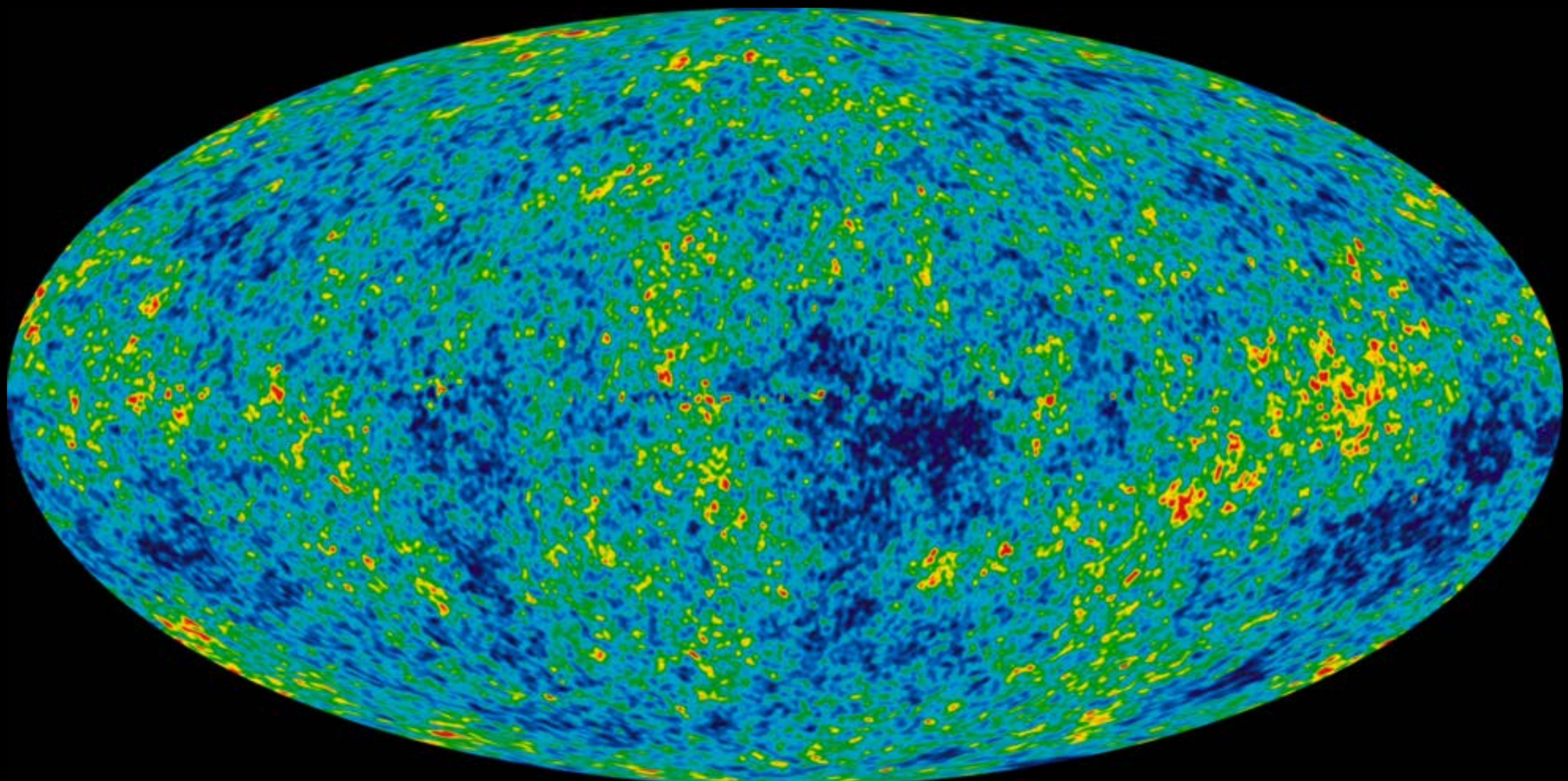


Somewhat noisy, low-resolution picture of the universe at 380,000 years old.

WMAP

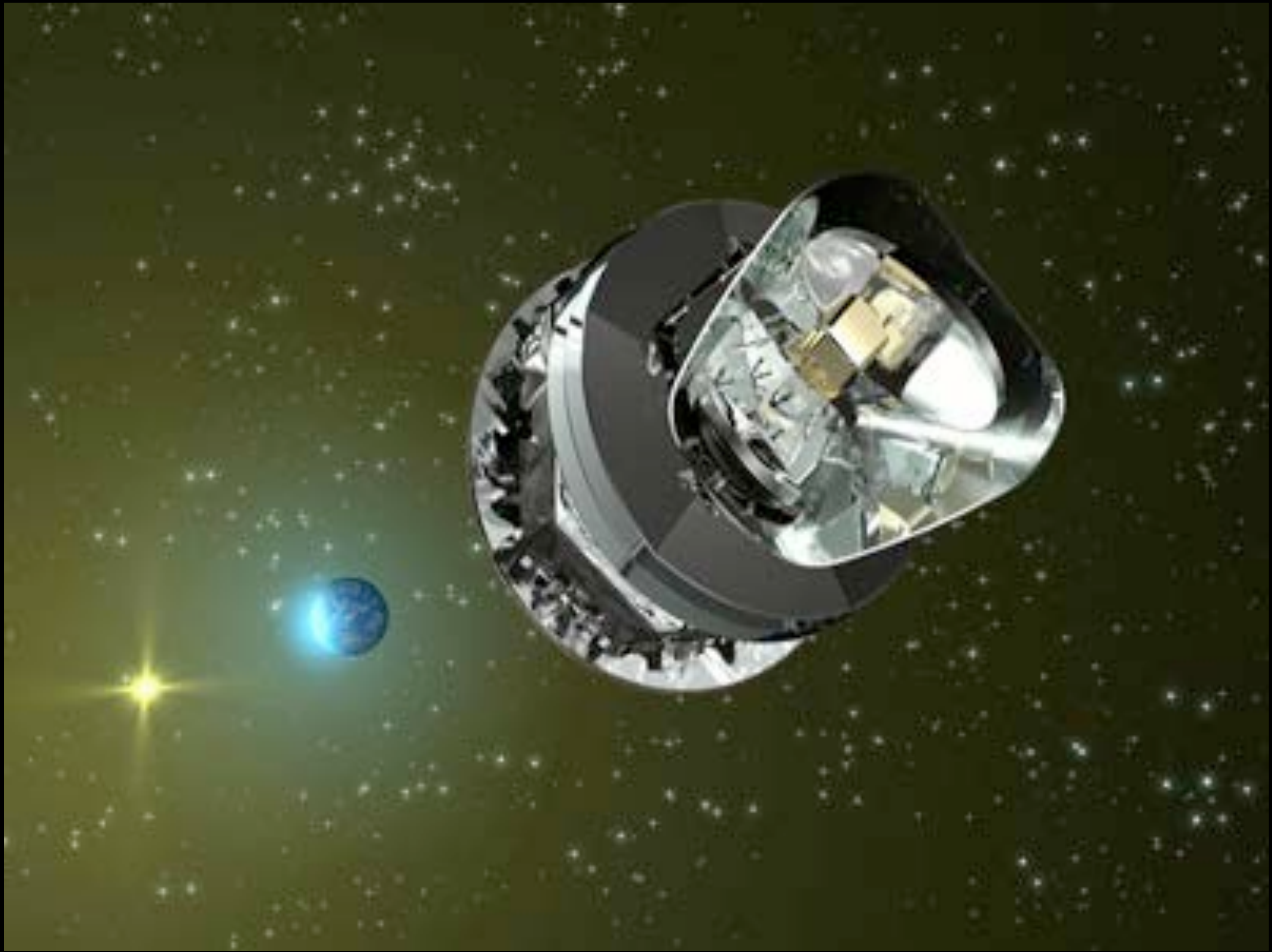


WMAP

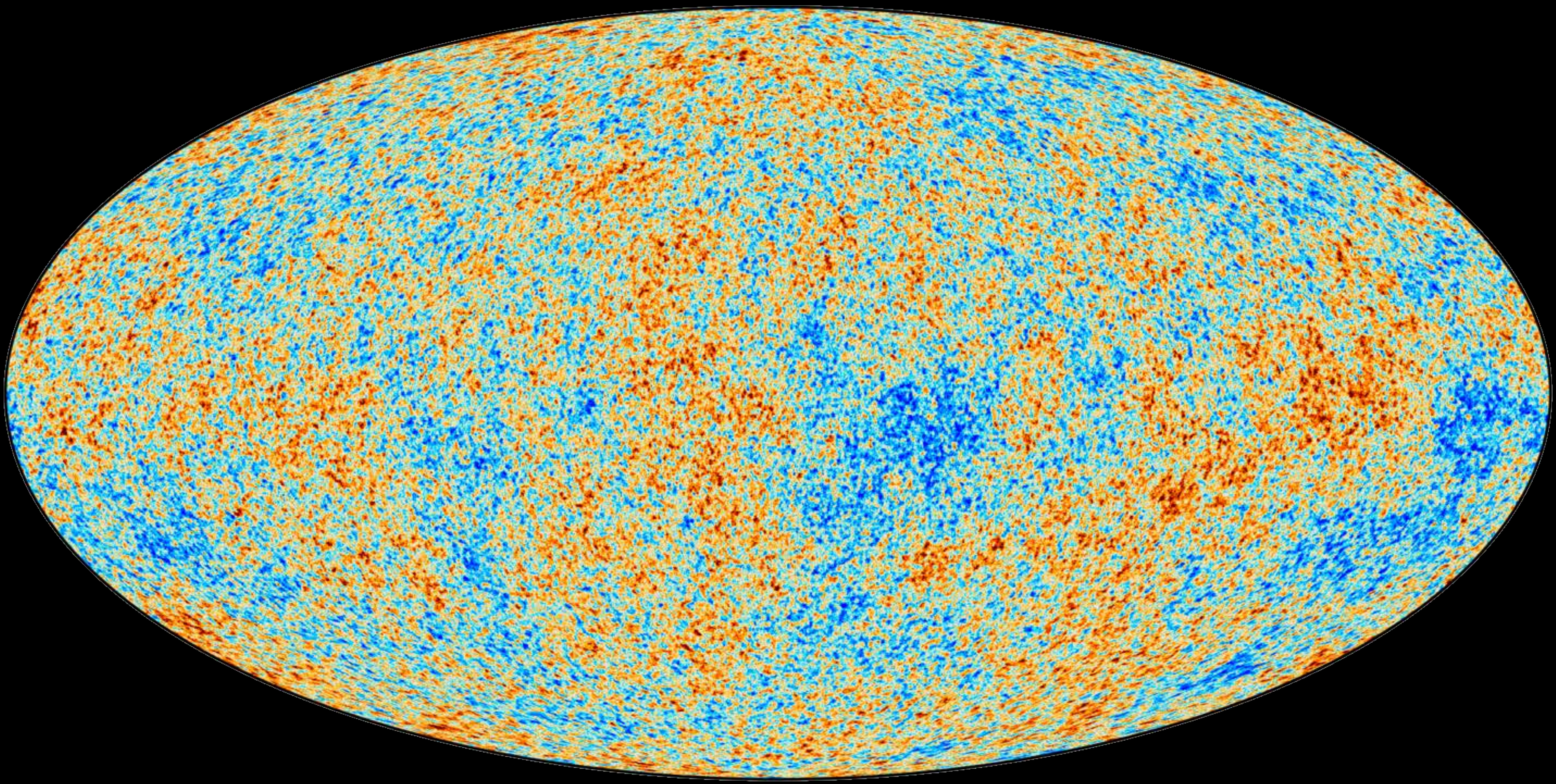


Higher resolution picture of the universe at 380,000 years old

Planck



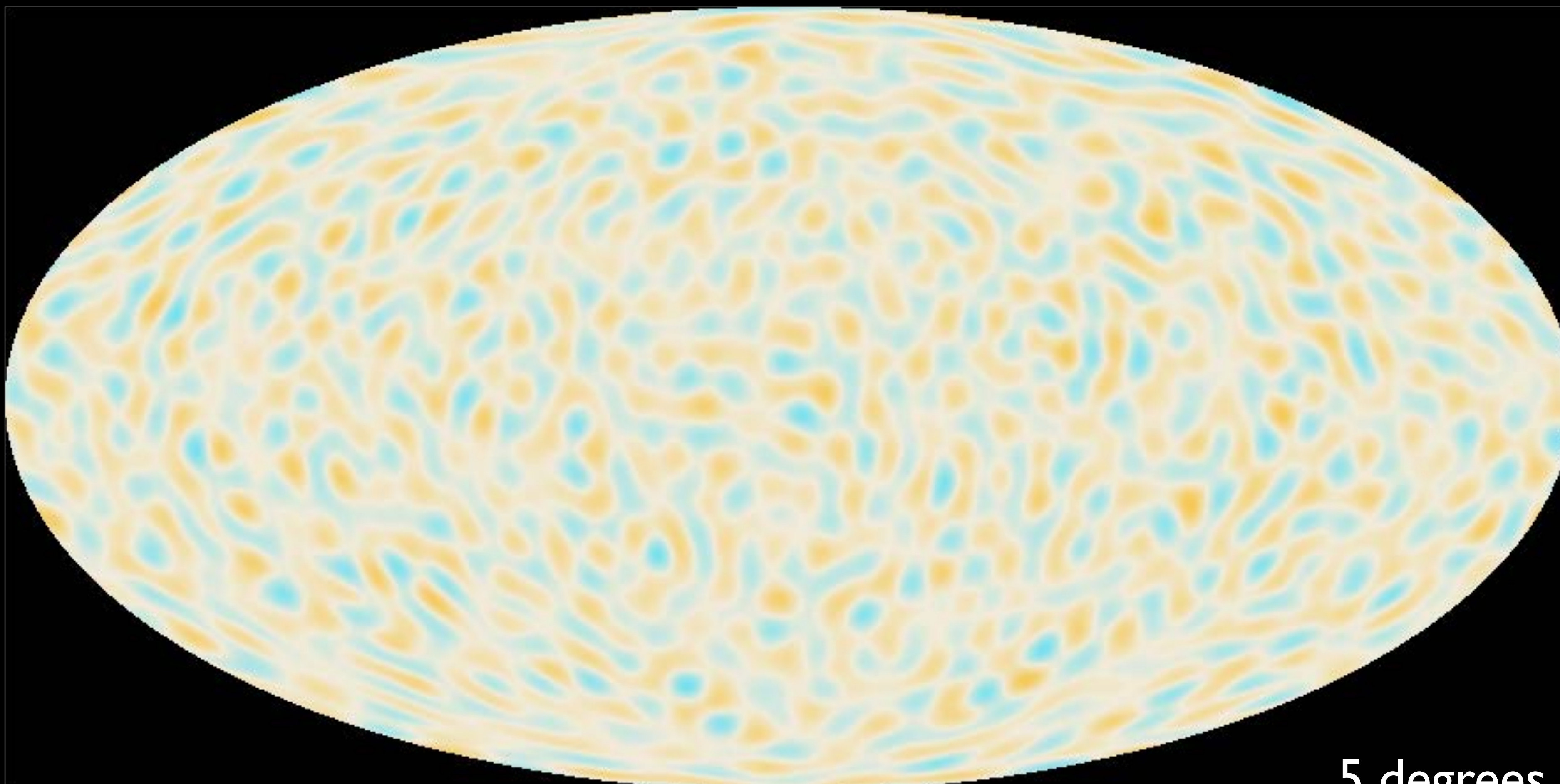
Planck



Current and essentially final picture of the universe at 380,000 years old

Angular Power Spectrum

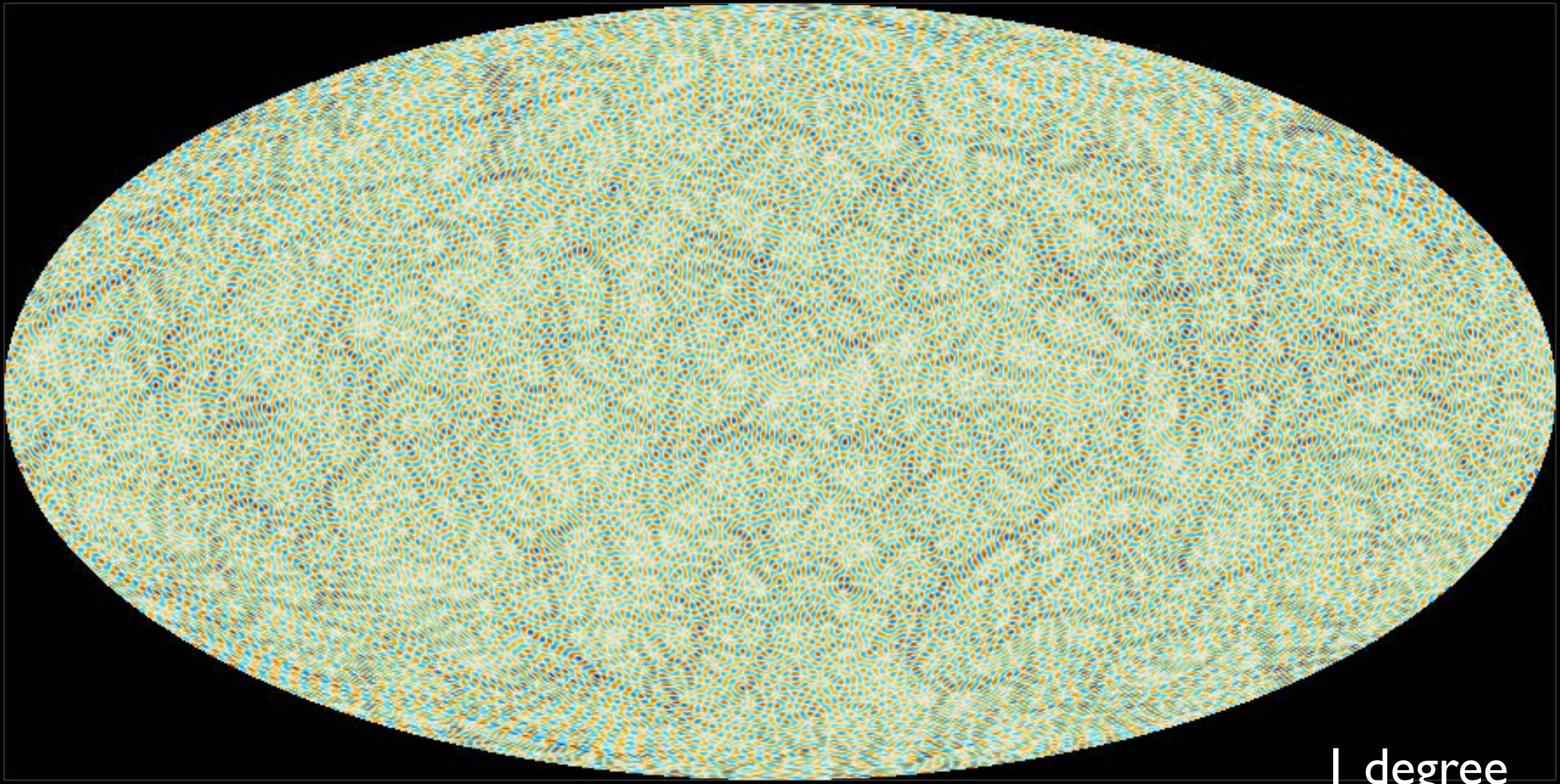
We cannot hope to predict individual features in the map



So we measure the strength of the signal as a function of scale

Angular Power Spectrum

We cannot hope to predict individual features in the map



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Angular Power Spectrum

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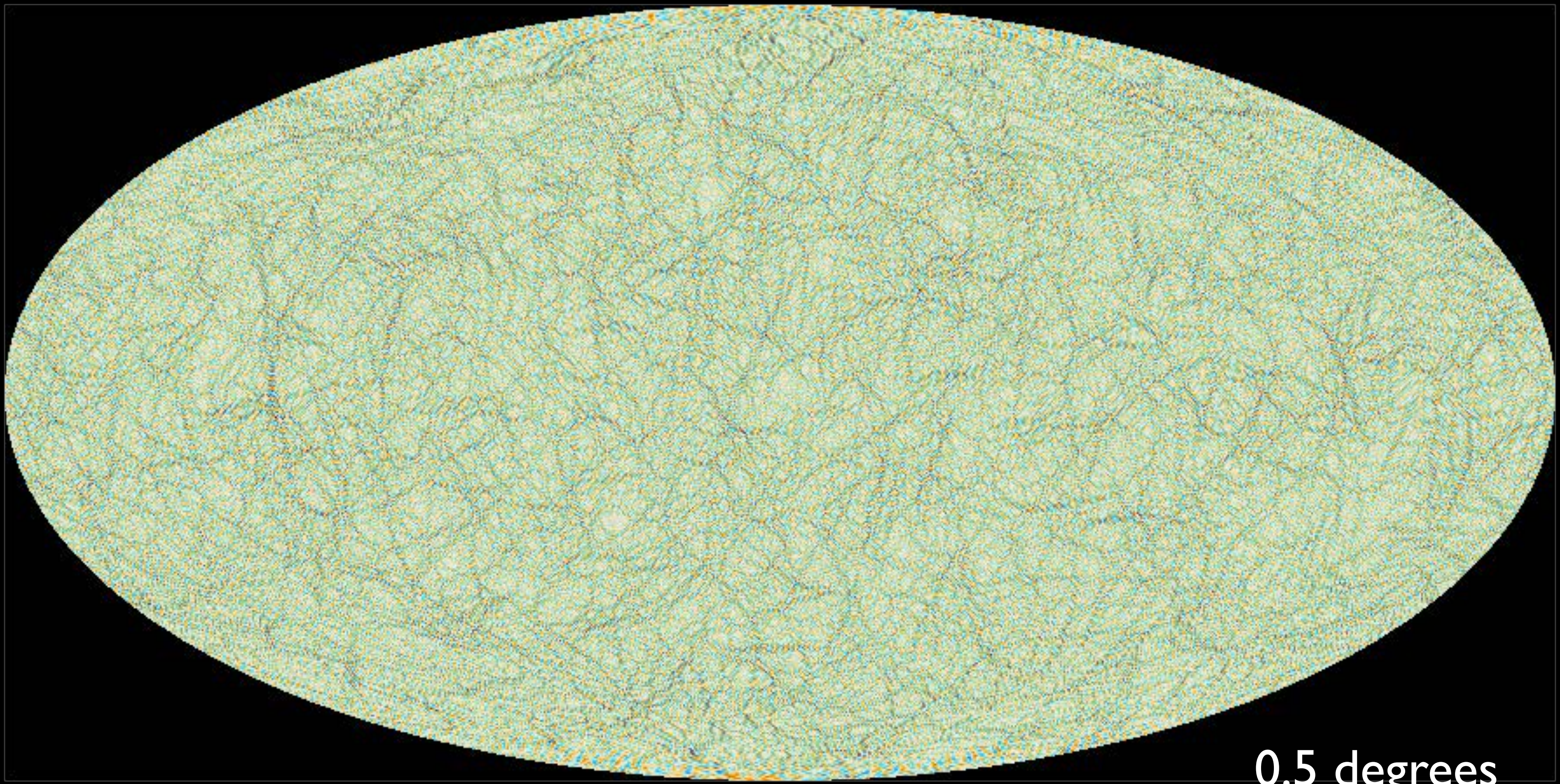
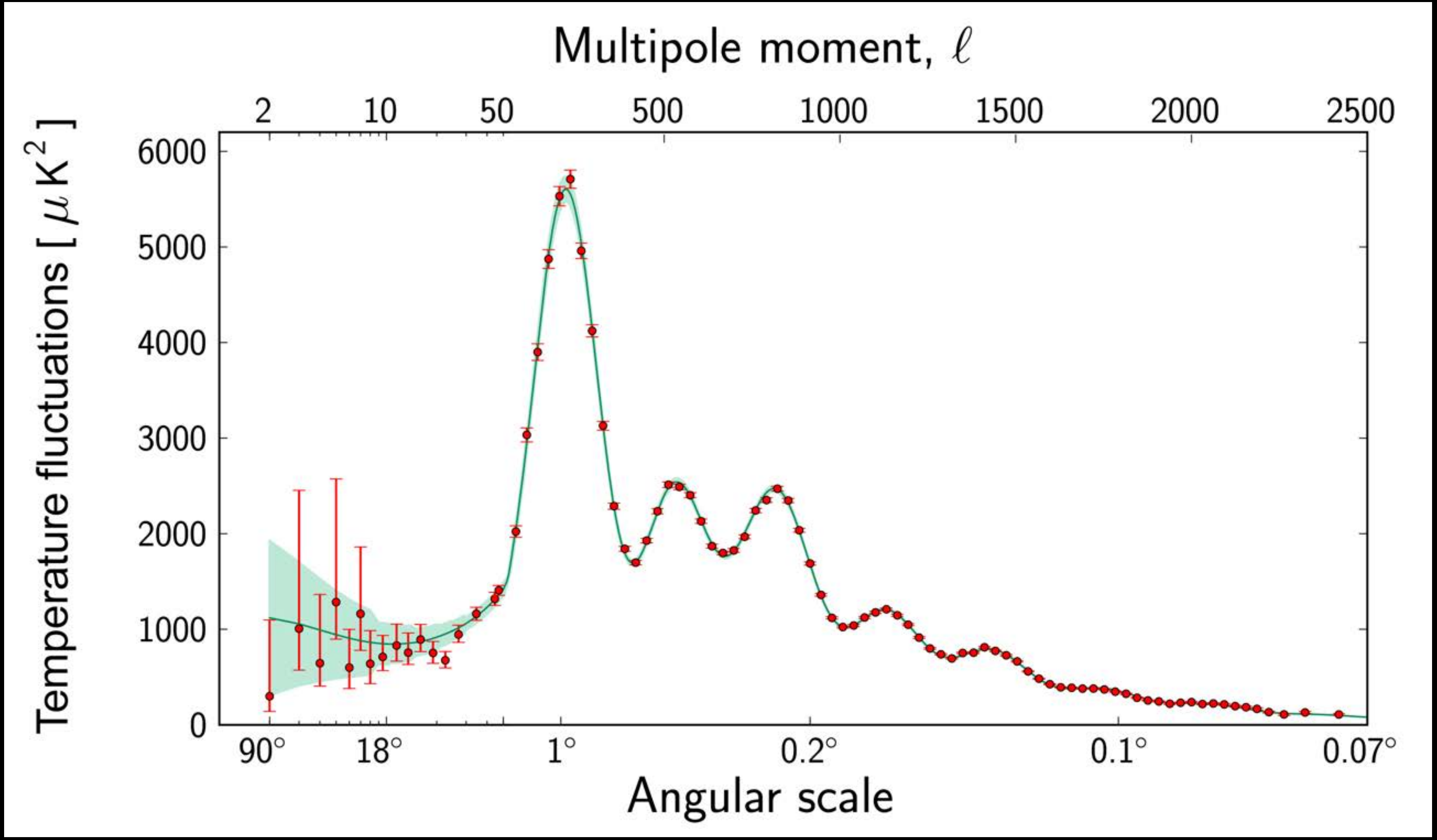


So we measure the strength of the signal as a function of scale

Angular Power Spectrum



Angular Power Spectrum

Comparison between theory and data allows us to measure the composition, geometry, and age of the universe

A very simple model fits the data

- 5% of energy density today in atoms
- 30% of energy density today in matter
- flat universe
- 13.8 billion years old

Angular Power Spectrum

Comparison between theory and data allows us to measure the composition, geometry, and age of the universe

A very simple model fits the data

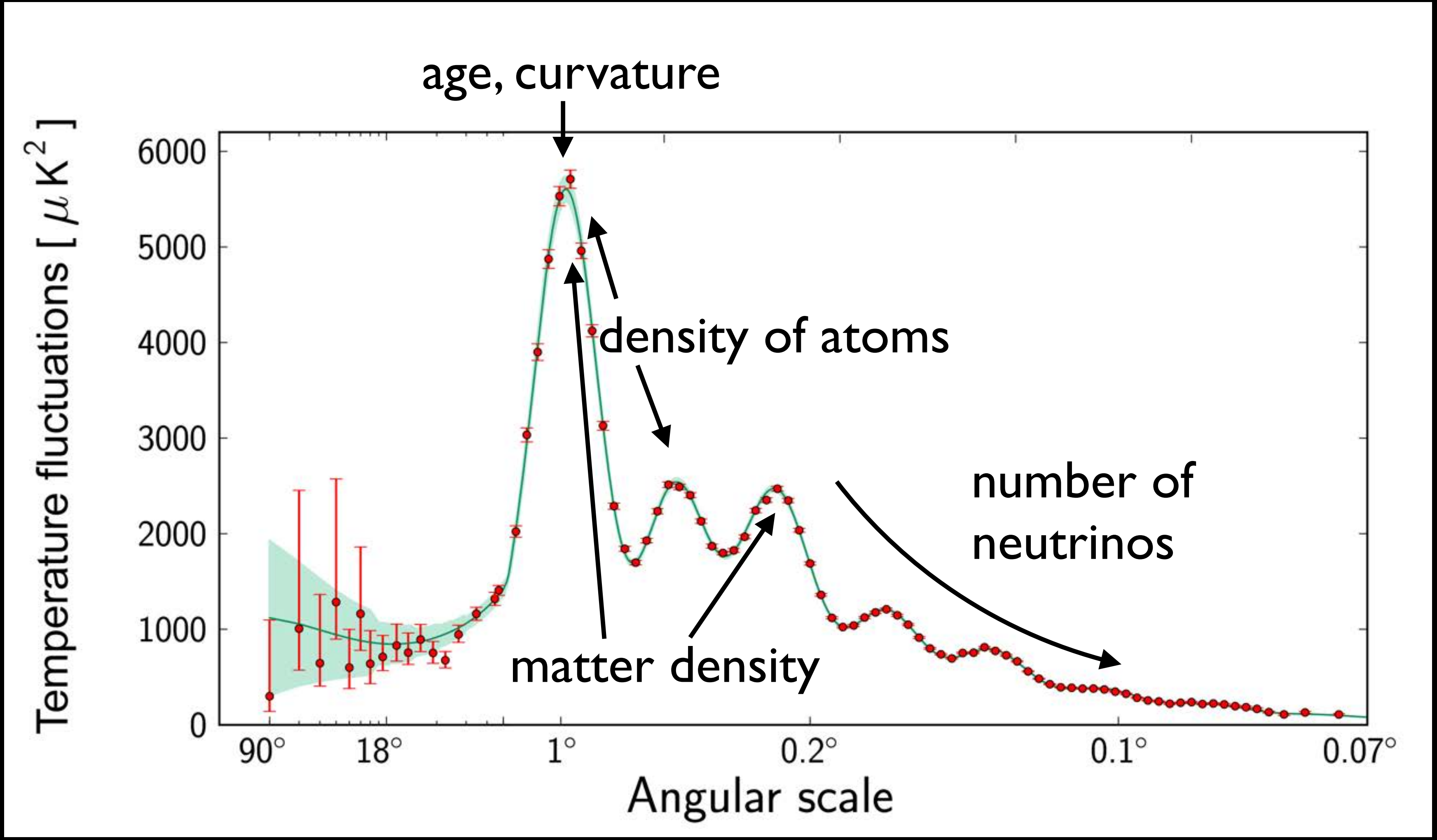
- 5% of energy density today in atoms
- 30% of energy density today in matter
- flat universe
- 13.8 billion years old

Assumes results from terrestrial experiments, e.g. properties of hydrogen, 3 species of neutrinos, …

Can be independently constrained from the data

$$N_{\text{eff}} = 2.99 \pm 0.17$$

Angular Power Spectrum

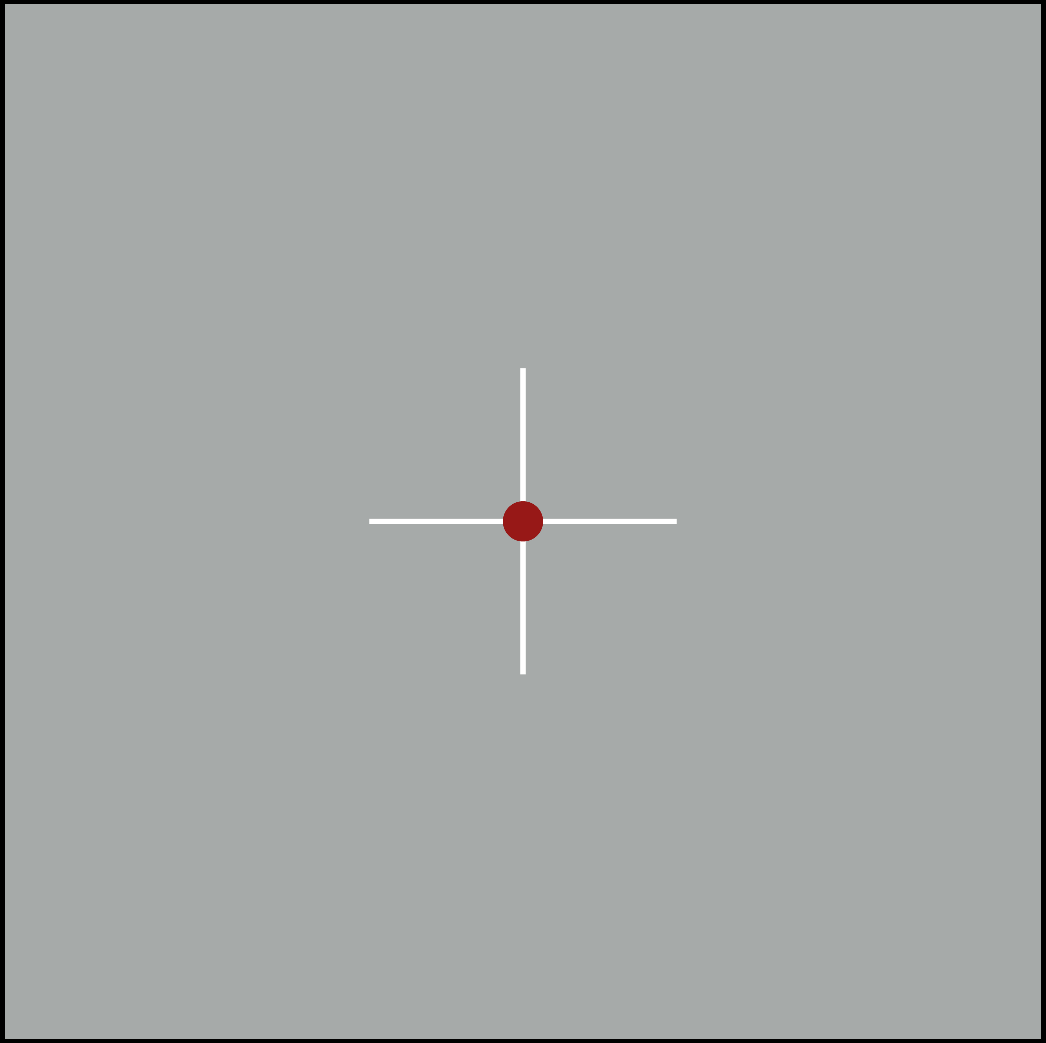


Polarization

un-polarized sunglasses

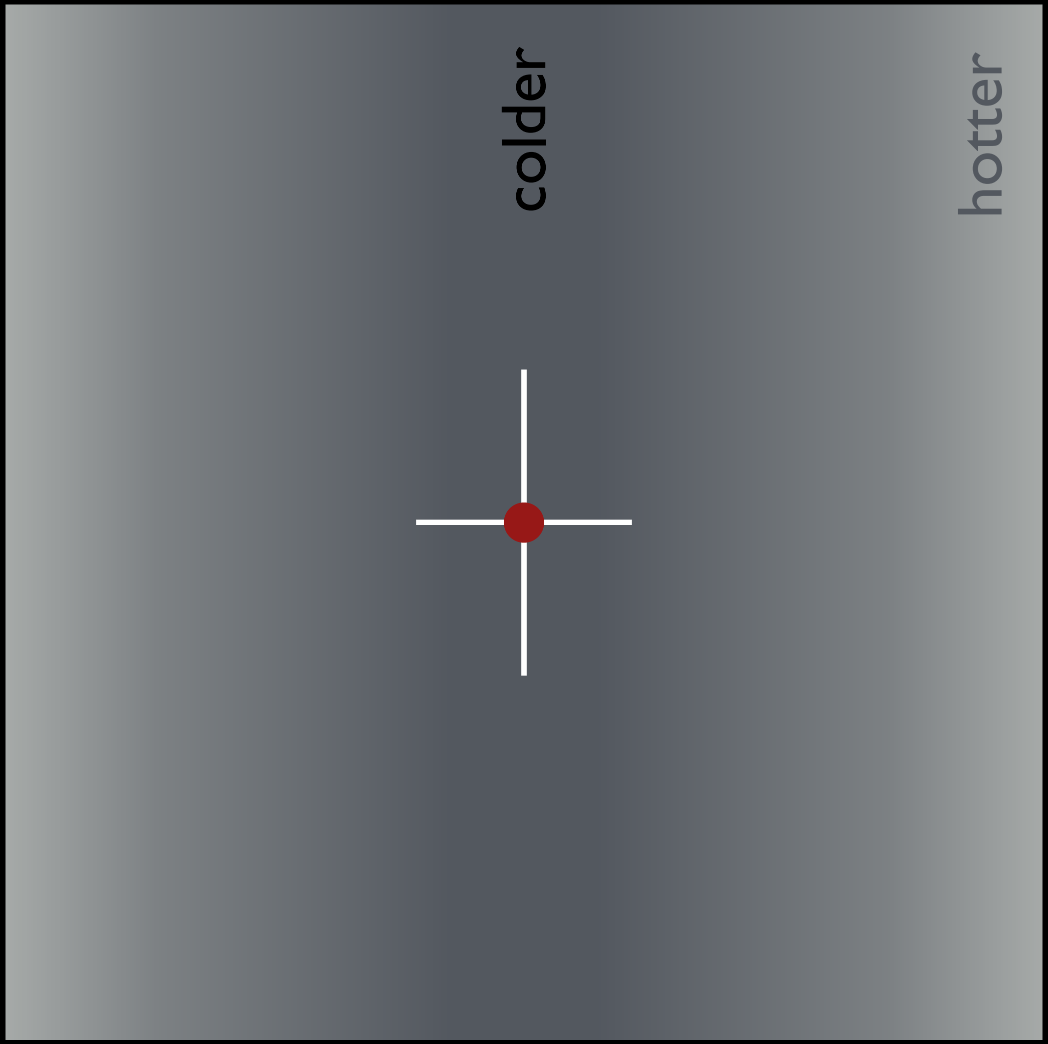
polarized sunglasses

Polarization



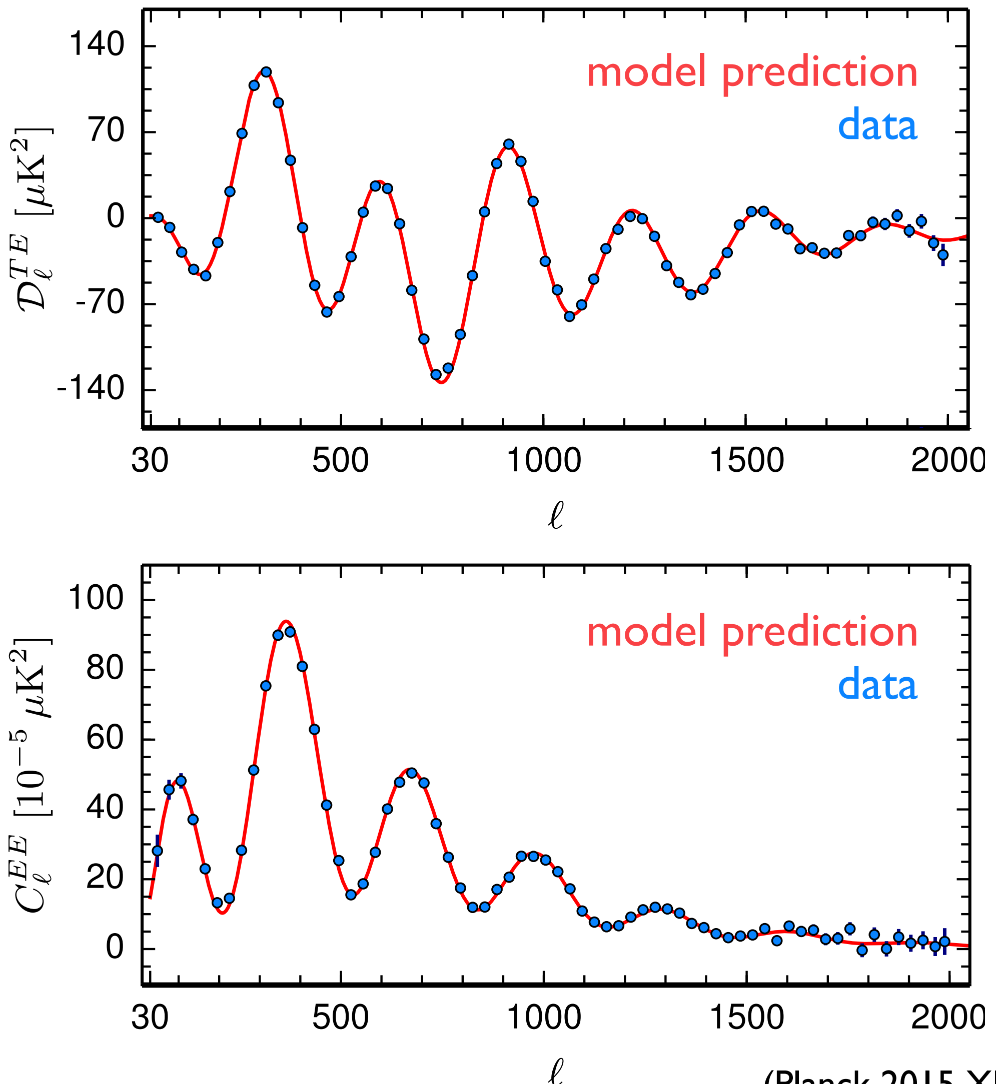
No net polarization in a homogeneous medium

Polarization



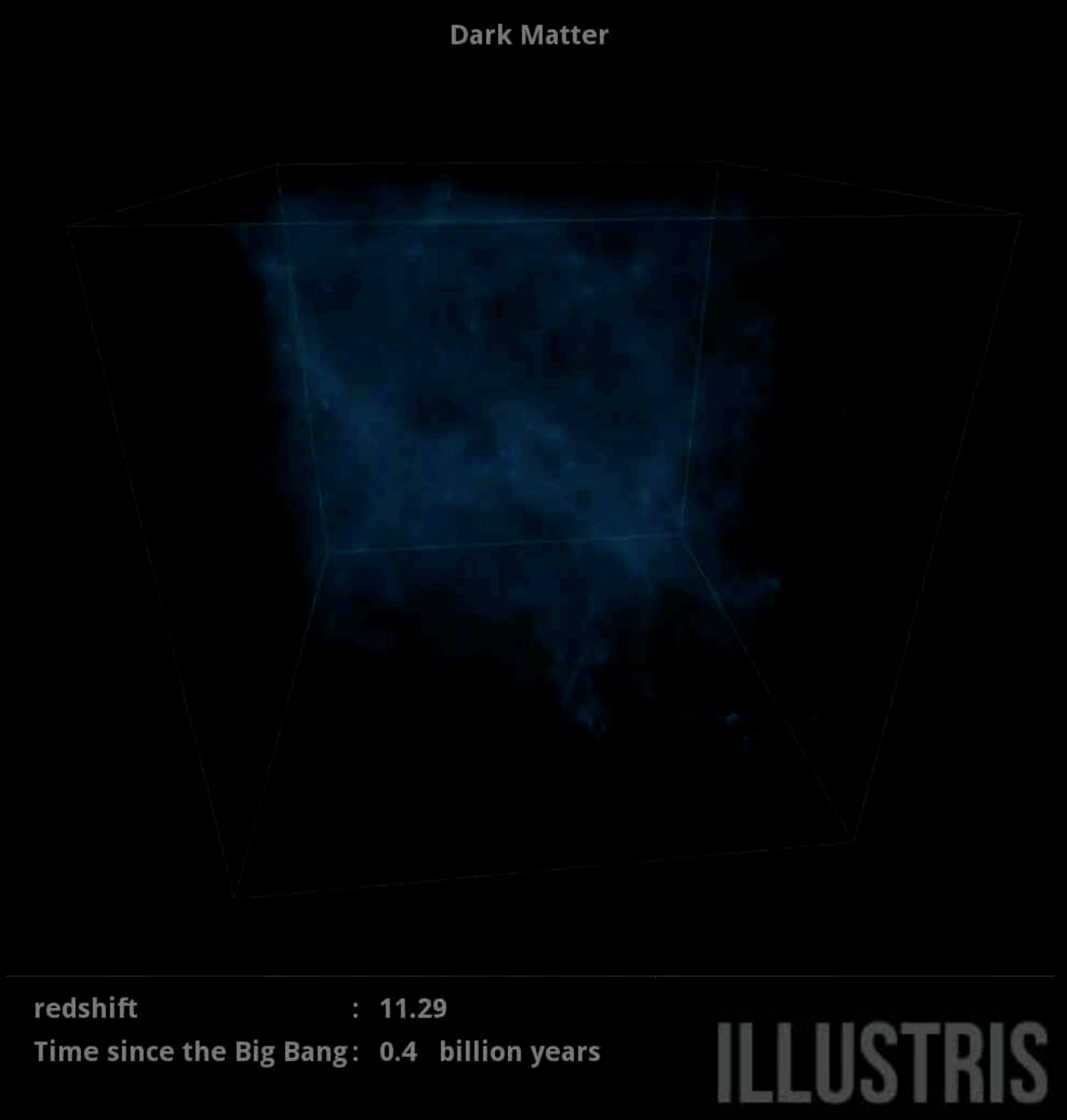
Net polarization for a temperature quadrupole

Polarization

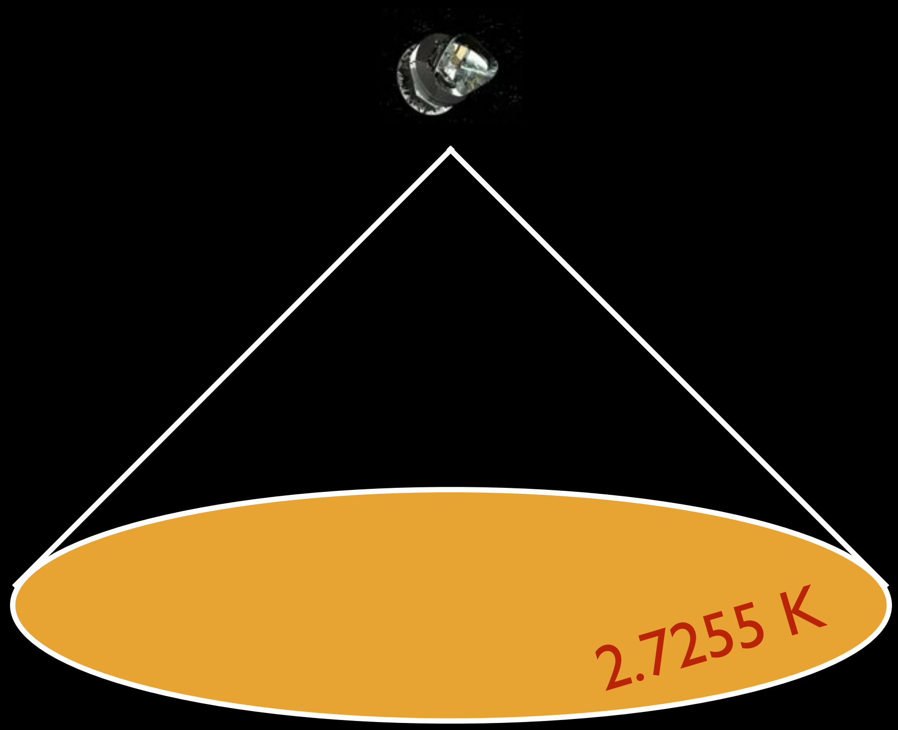


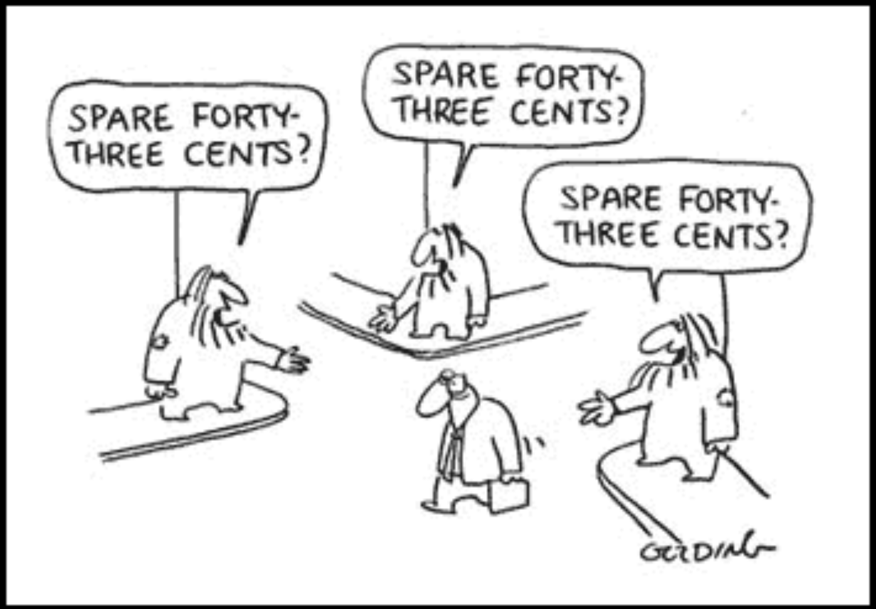
(Planck 2015 XIII)

Predicting large scale structure

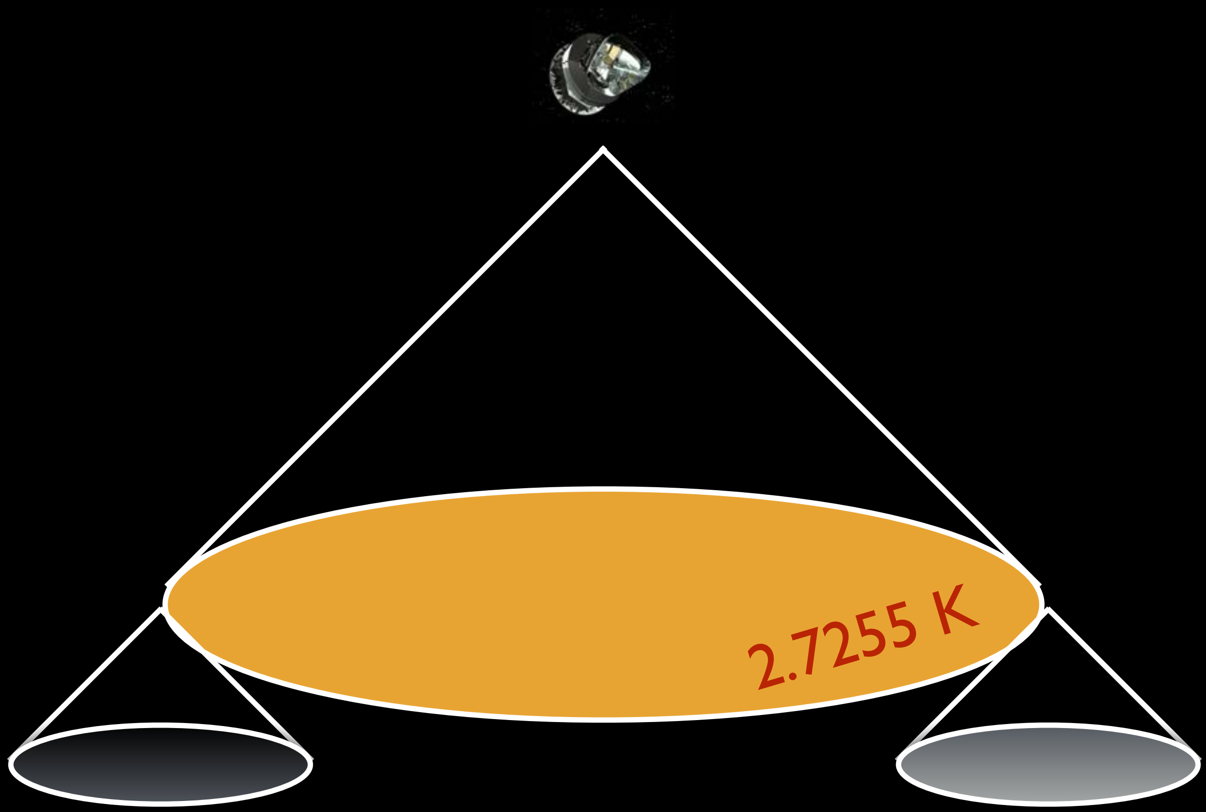


Horizon problem



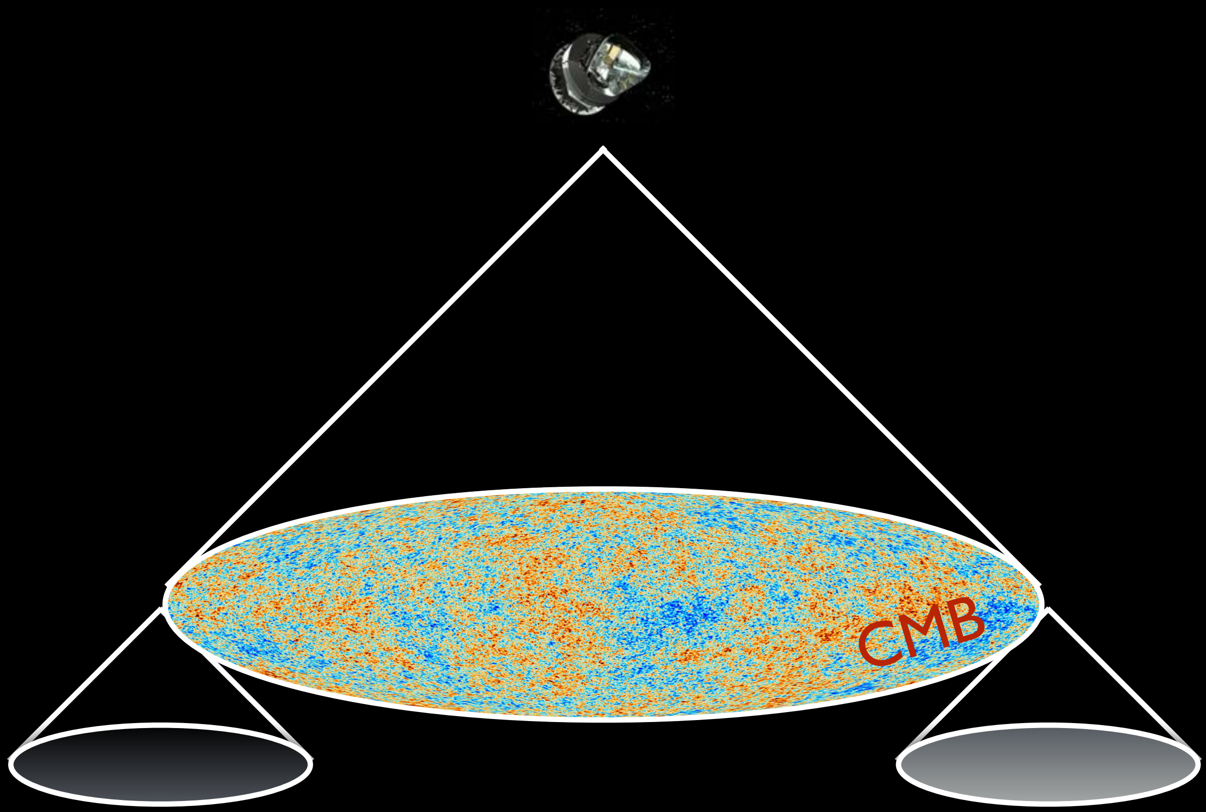


Horizon problem



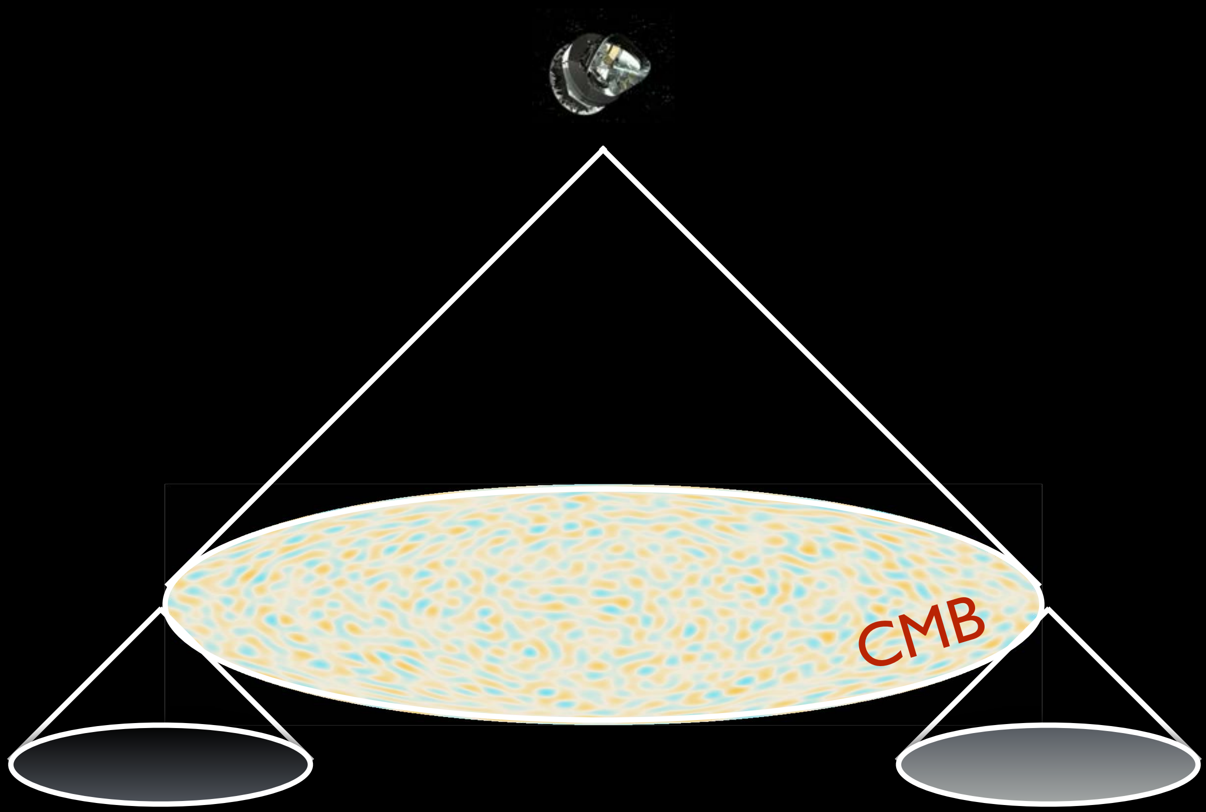
We see the same temperature everywhere, yet according to our model different parts of the sky never communicated with each other.

Horizon problem



The angular power spectrum implies that fluctuations have the same phases across the sky

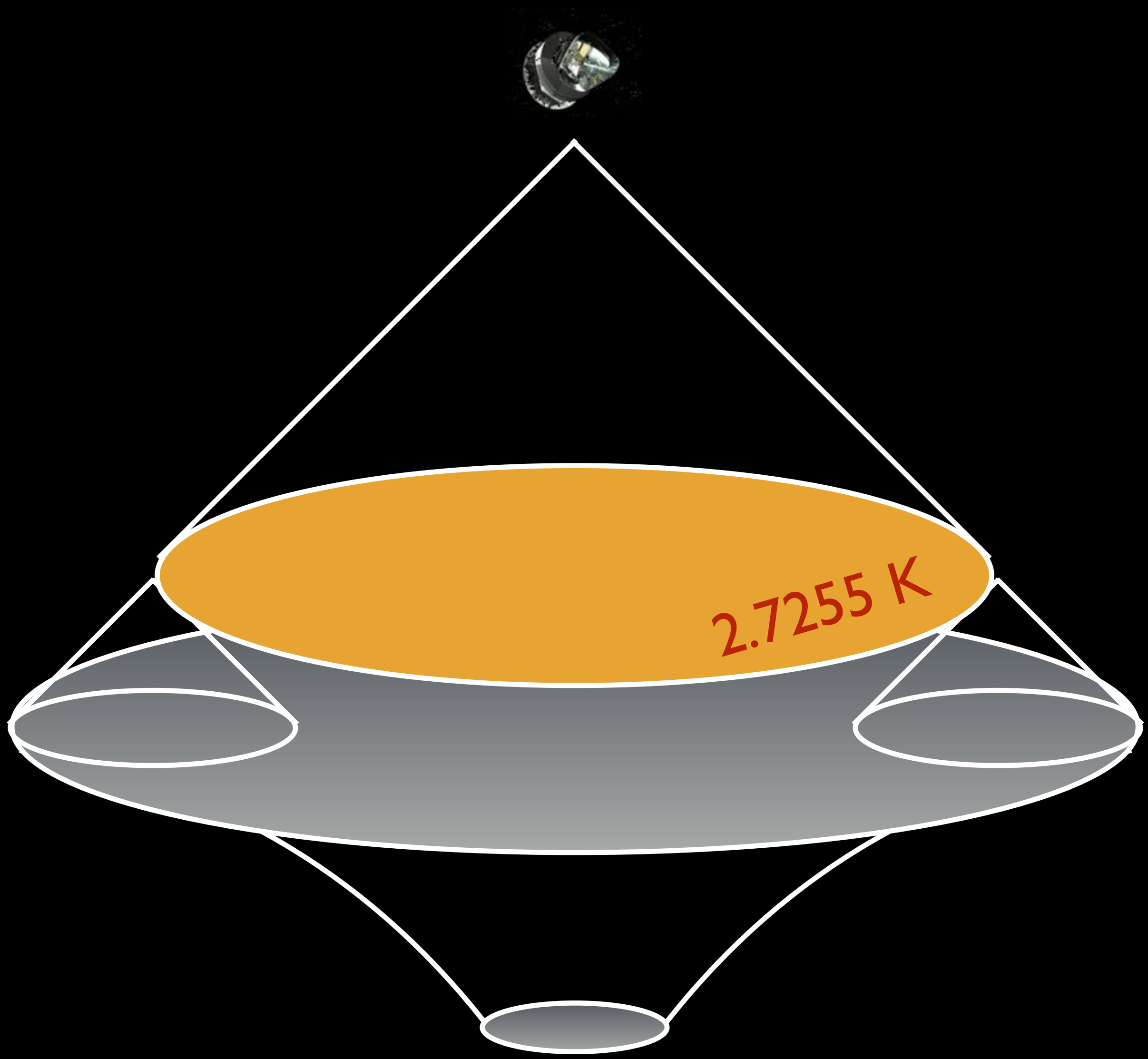
Horizon problem



Polarization measurements provide further evidence for phase coherence.

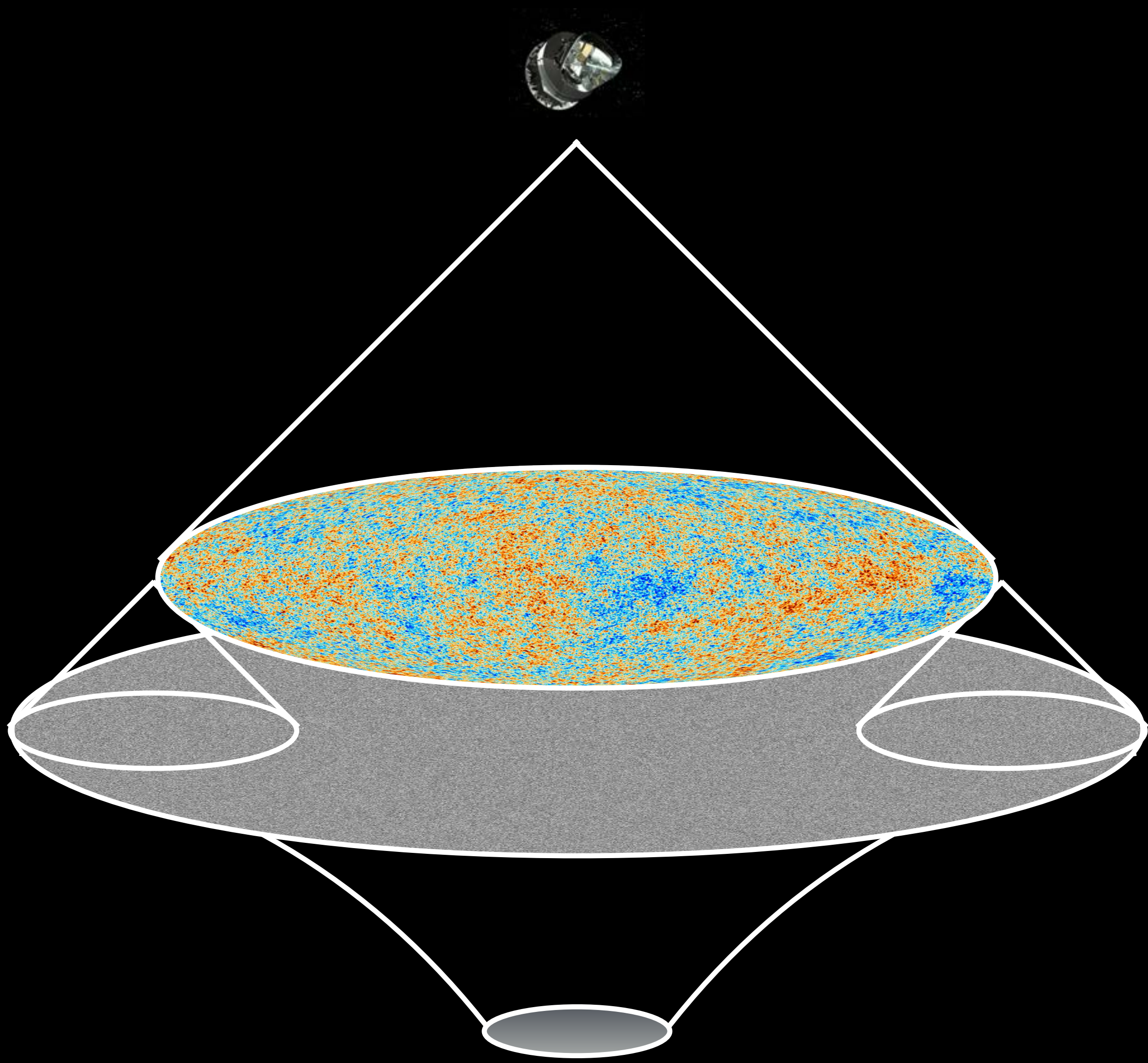
In Einstein's General Relativity, this requires either accelerated expansion or decelerated contraction.

Inflation



According to inflation the early universe underwent a period of nearly exponential expansion when it was merely 10^{-33} seconds old.

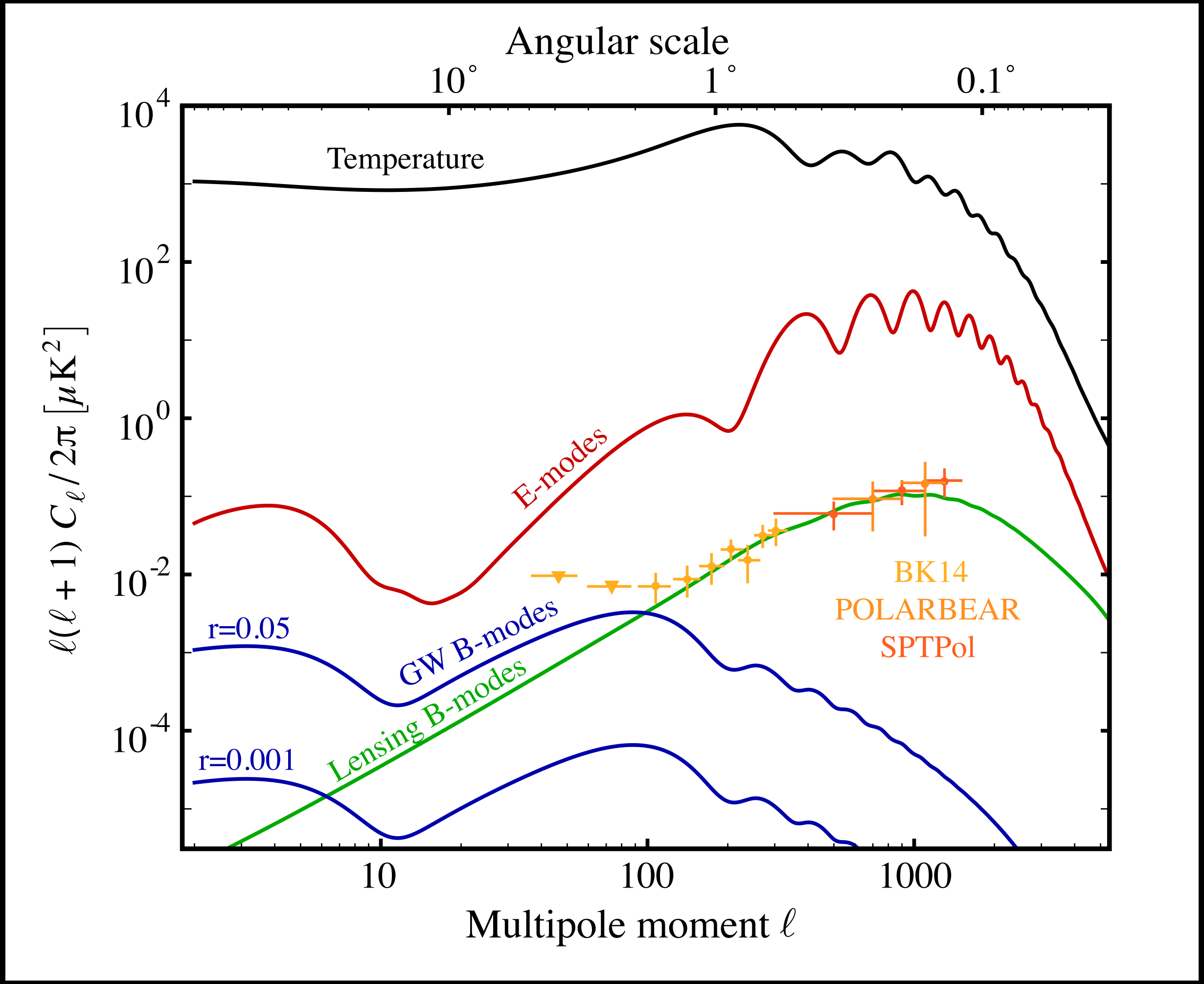
Inflation



A clock is needed to determine the end of inflation. Quantum fluctuations in this clock are the source of the fluctuations we see in the CMB

Inflation

Inflation also predicts quantum fluctuations in spacetime, which lead to a characteristic polarization pattern — "B-modes"



Some of the simplest models have been ruled out, but the search is just getting started.

Current CMB Experiments

Stage III: now

Future CMB Experiments

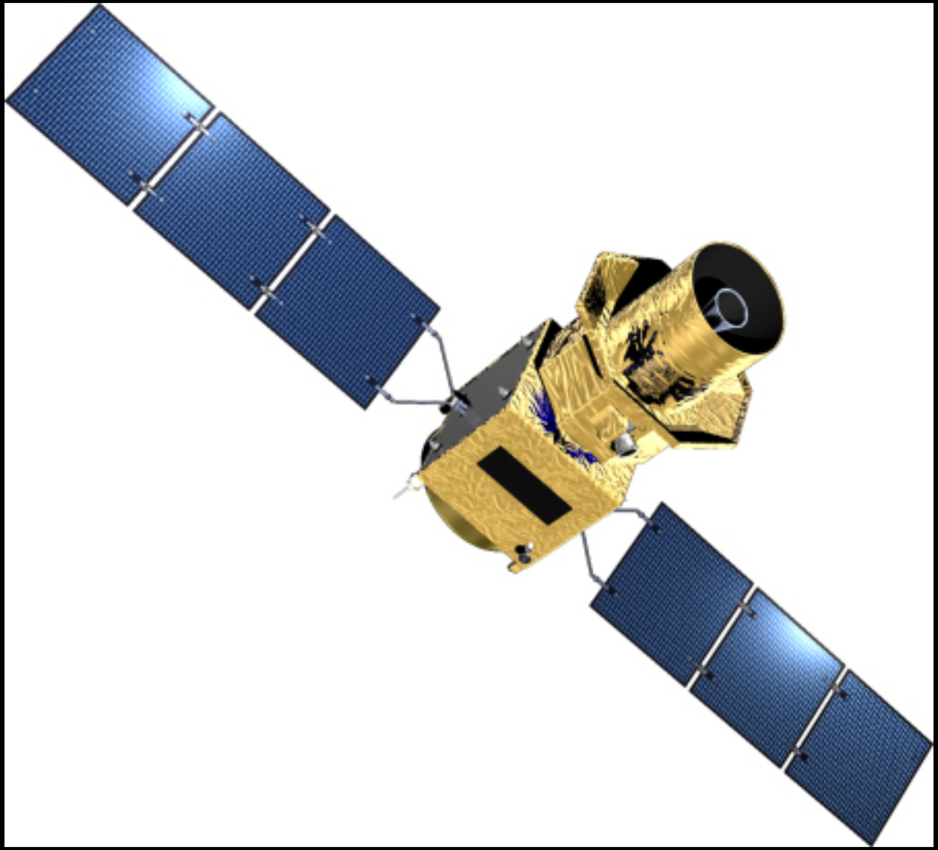
Stage III.5: 2021-2028

Future CMB Experiments

CMB-S4: 2028-2035

Future CMB Experiments

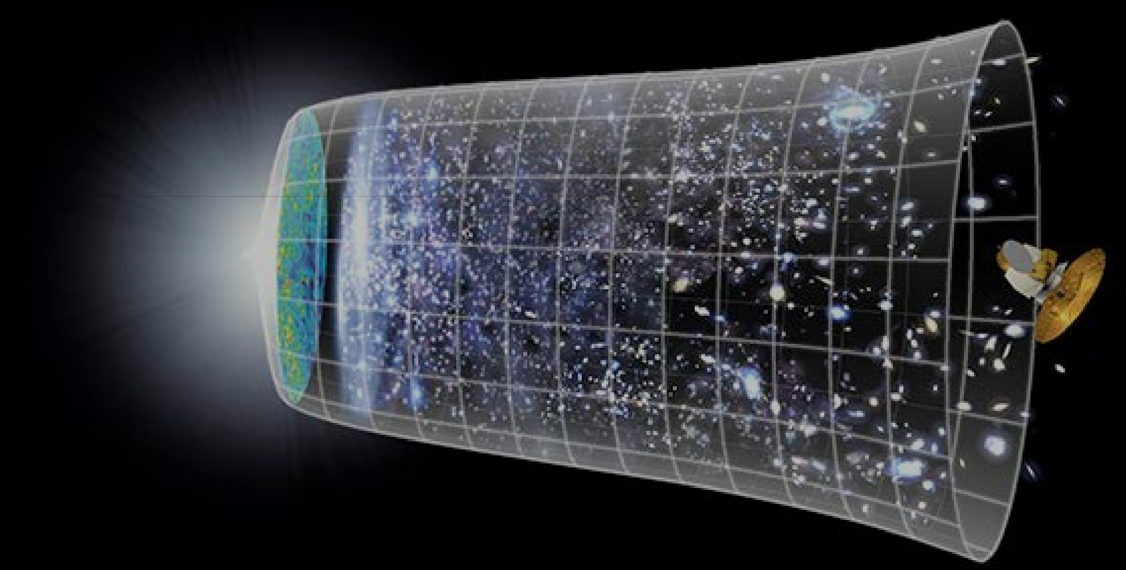
LiteBIRD



Selected by JAXA in 2019

Launch in 2028

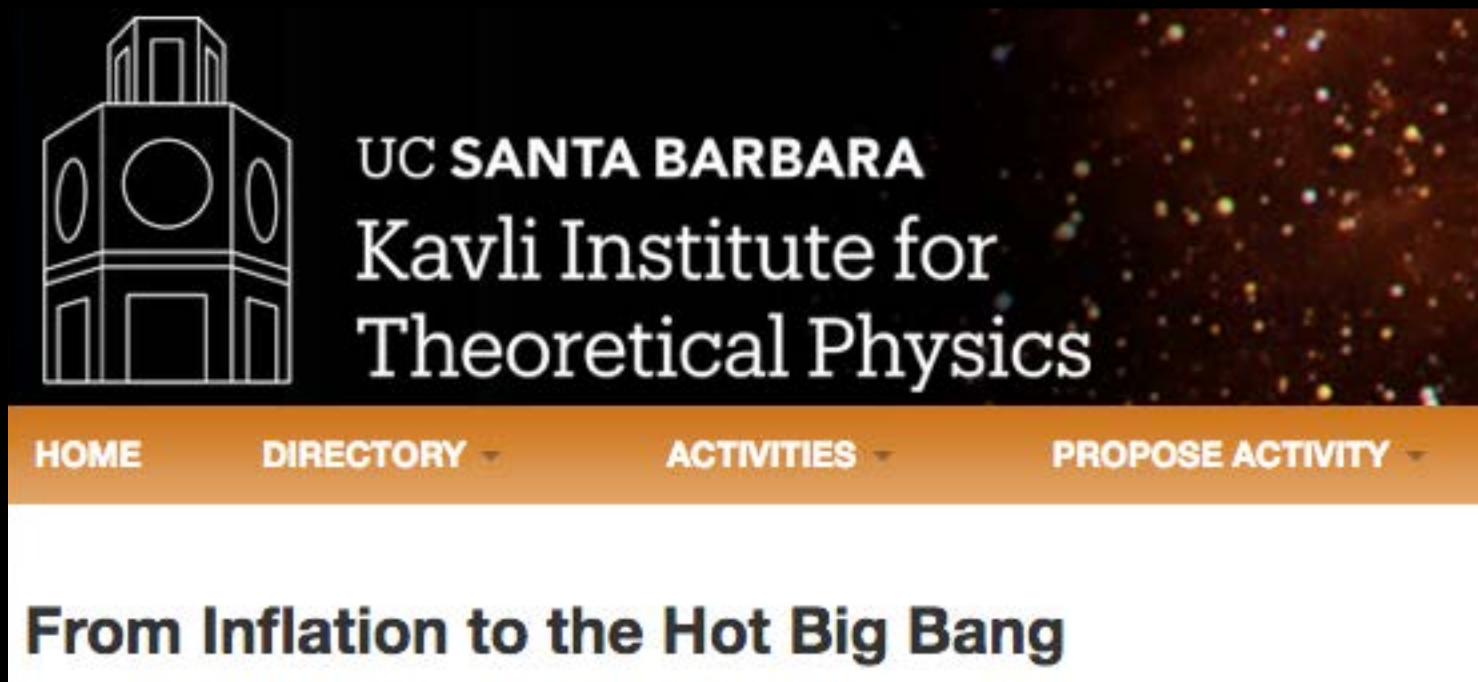
Beyond Inflation



These experiments will not only provide new insights into the earliest moments of our universe, they will also

- measure the content, age, and geometry of the universe with even higher precision
- map the matter in the universe
- map the hot gas in galaxy clusters
- constrain light particles beyond those in the standard model of particle physics
- …

Beyond Inflation



Conclusions

- Looking out into the universe allows us to look back in time.
- The earliest "light" we can see is radiation left over from the hot early universe, the cosmic microwave background
- Observations of the CMB constrain the composition, age, and geometry of the universe to within a per cent.
- The observations reveal a very simple universe.
- The properties of the CMB imply an earlier period that generated the perturbations we see.
- This earlier period may also have generated fluctuations in spacetime itself, which would generate a characteristic polarization pattern in the CMB.
- Work is currently ongoing to look for this signal.
- With luck we may learn a great deal about the first fractions of a second of our universe.

Thank you