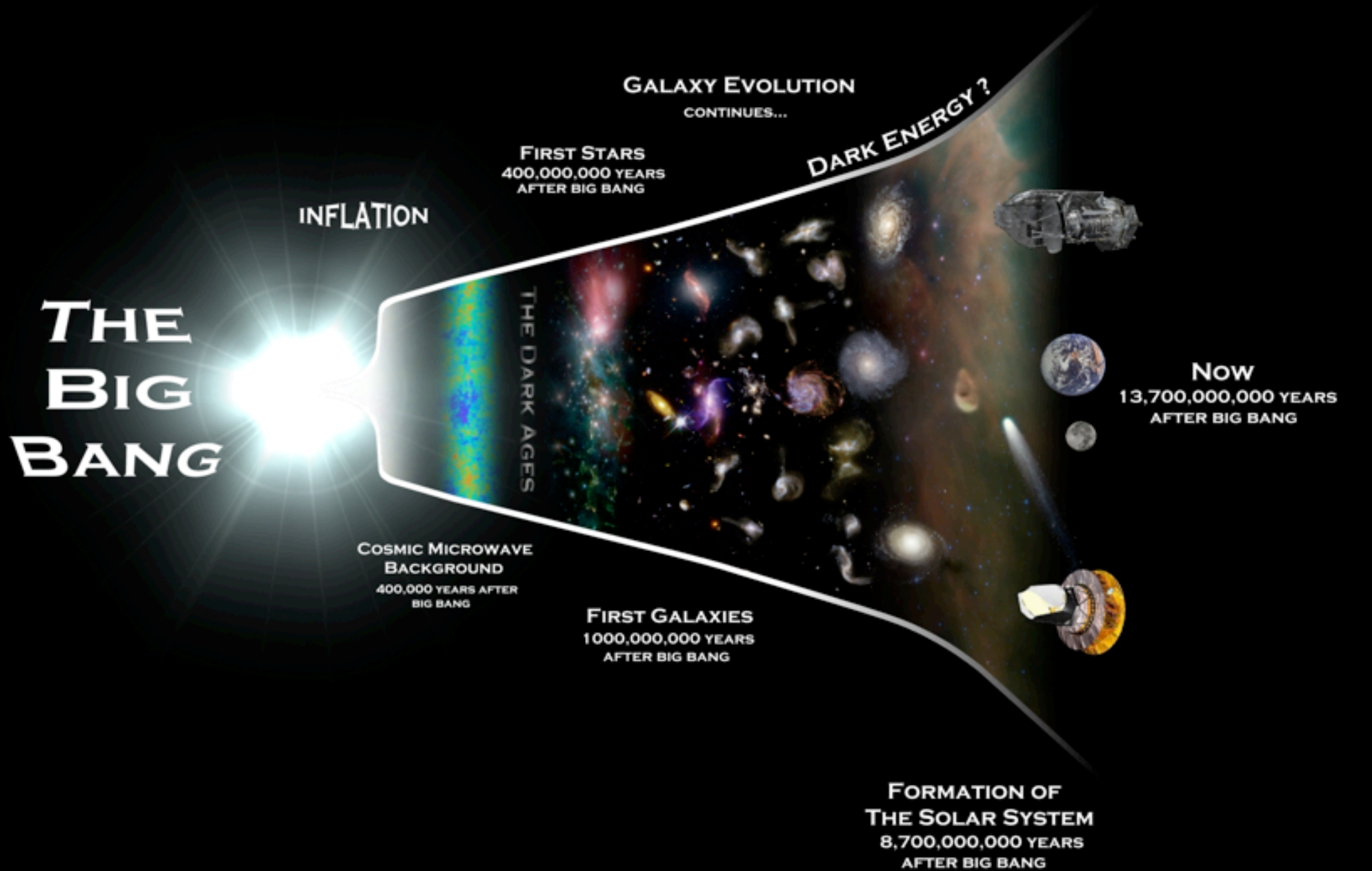


Observing the echoes of the Big Bang
in the Universe's most distant light

The history of the Universe



CV of today's topic

CV of today's topic

- Two Nobel prizes! (1978, 2006)

CV of today's topic

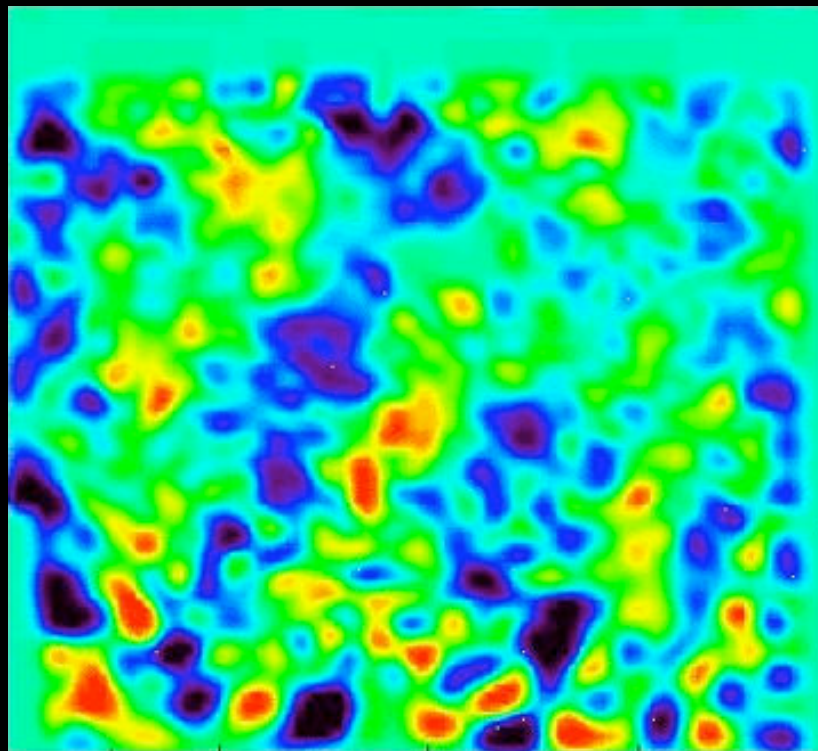
- Two Nobel prizes! (1978, 2006)
- Nothing has told us more about the Universe ...

CV of today's topic

- Two Nobel prizes! (1978, 2006)
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- What is this thing?

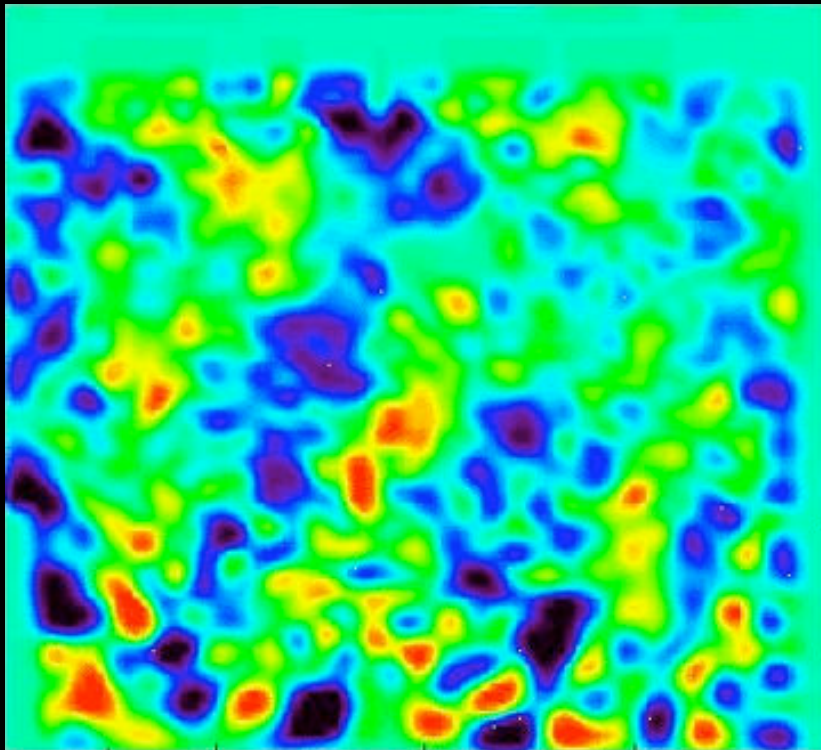
CV of today's topic

- Two Nobel prizes! (1978, 2006)
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CV of today's topic

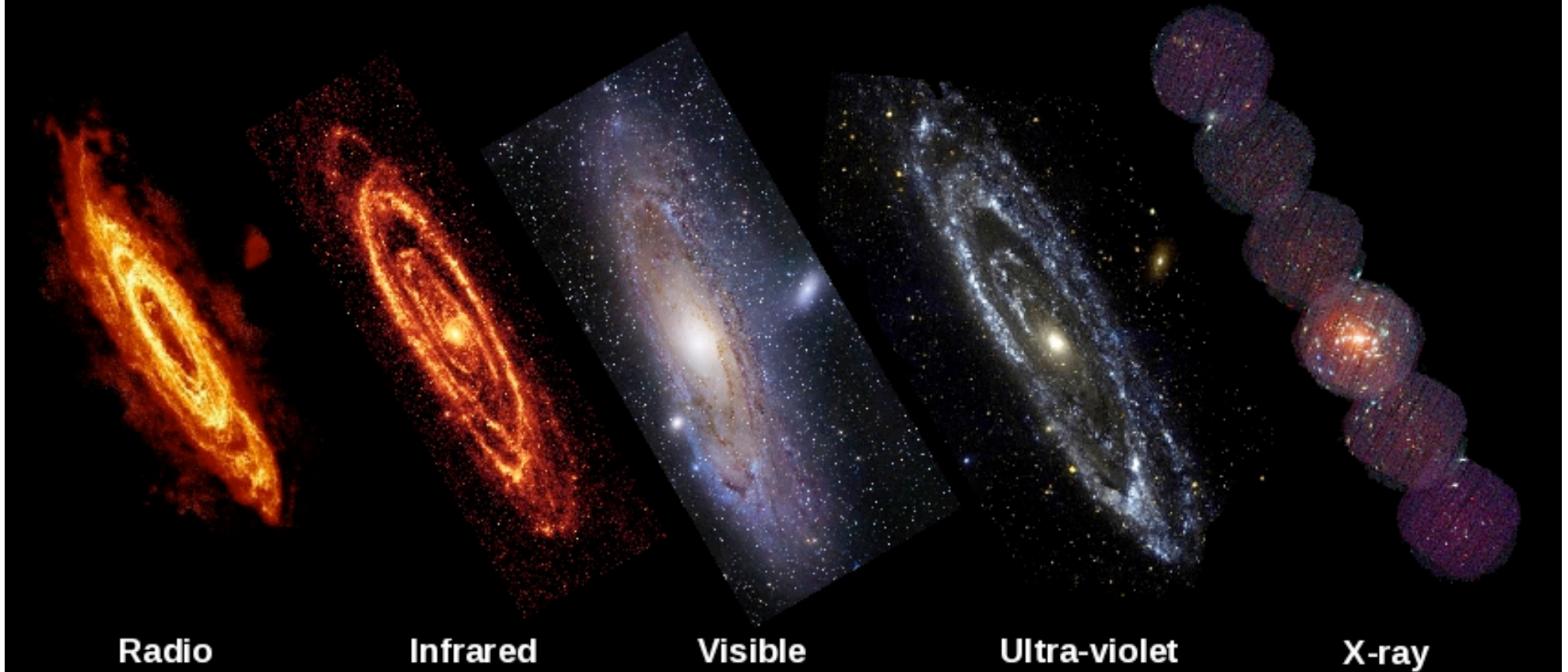
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- Nothing has told us more about the Universe ...
- What is this thing?



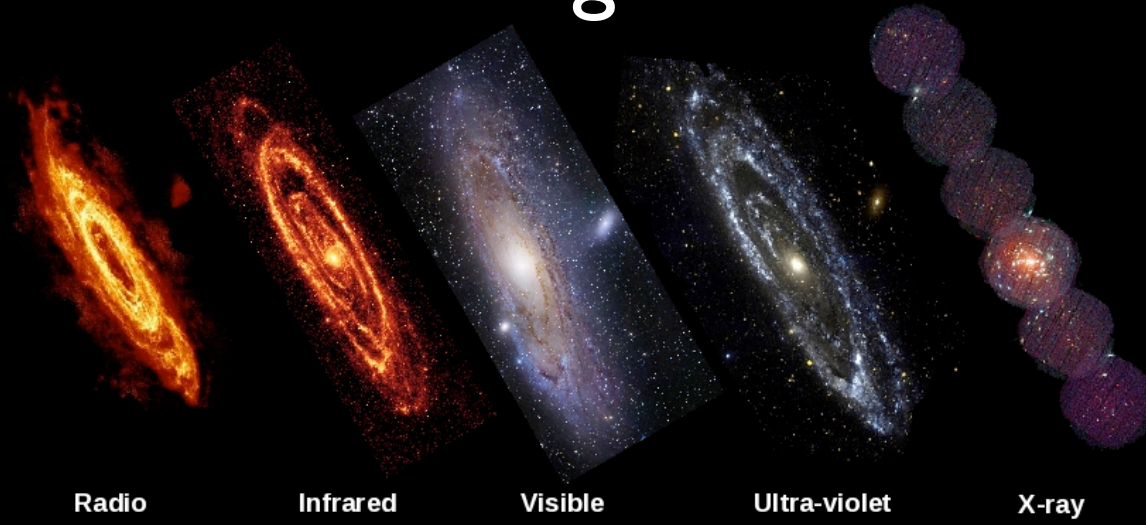
Universe in a different light



Universe in a different light



Universe in a different light



Radio

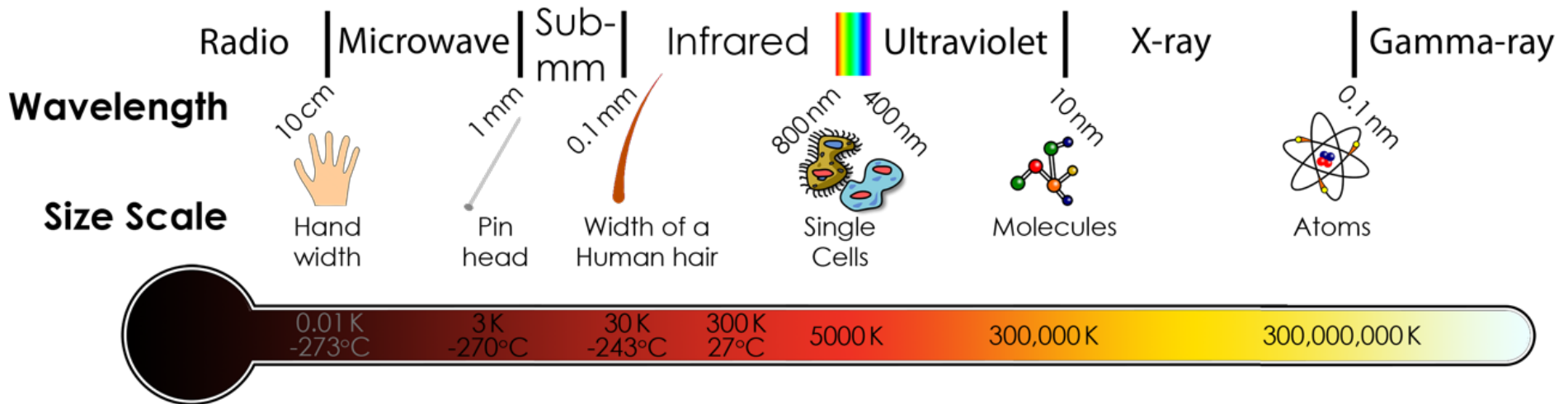
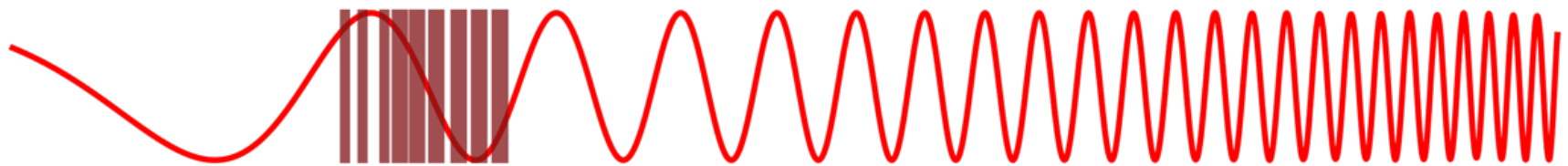
Infrared

Visible

Ultra-violet

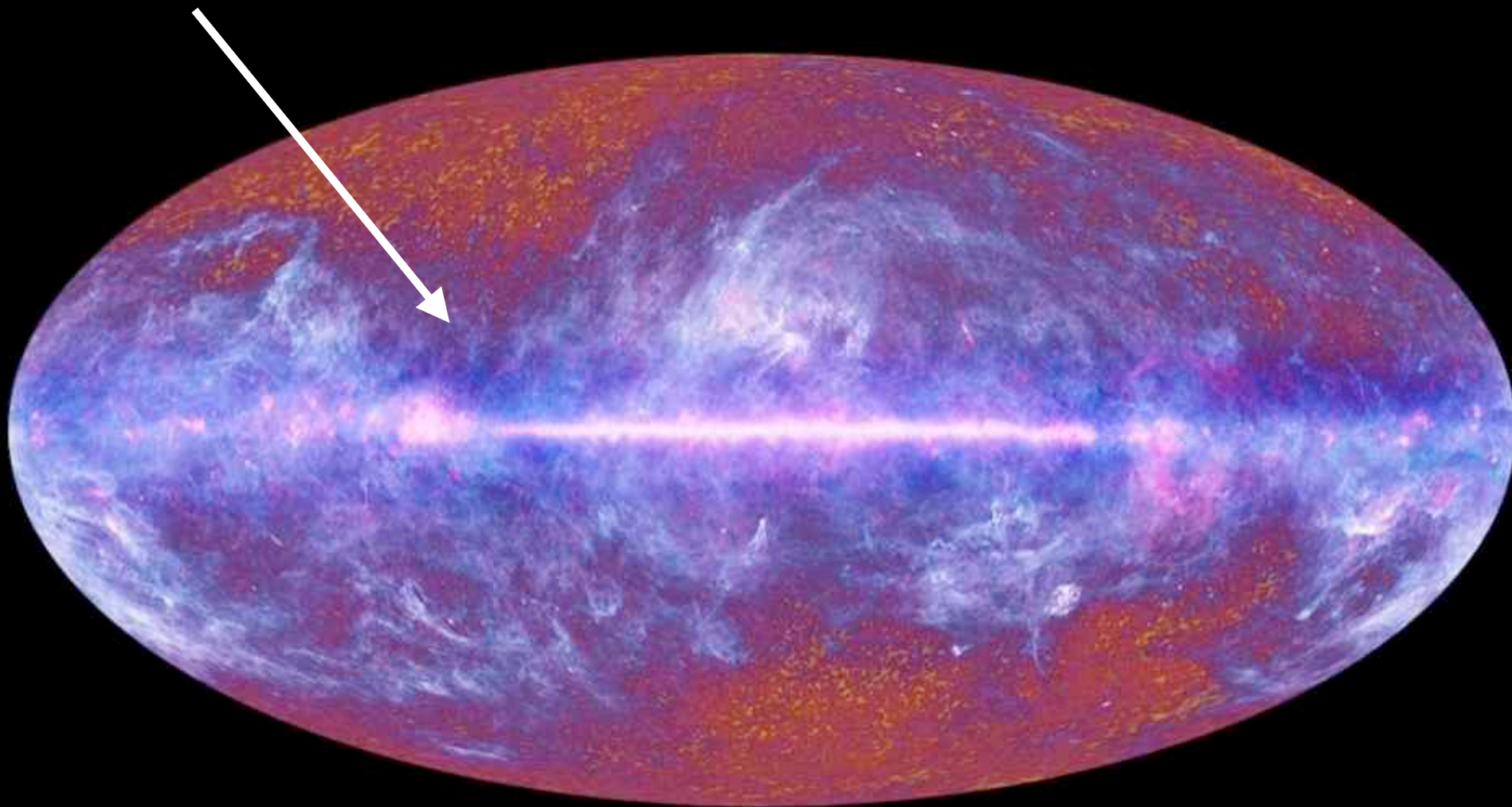
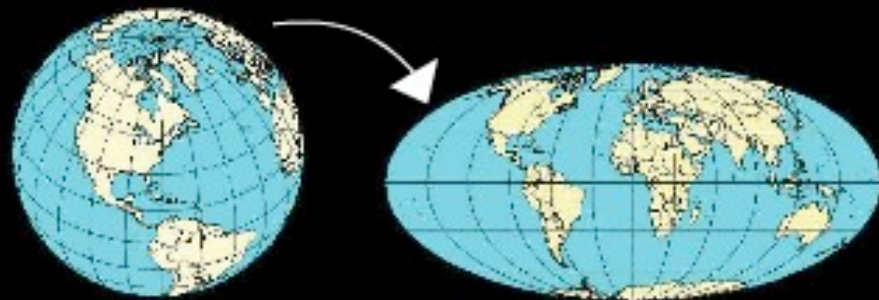
X-ray

Planck



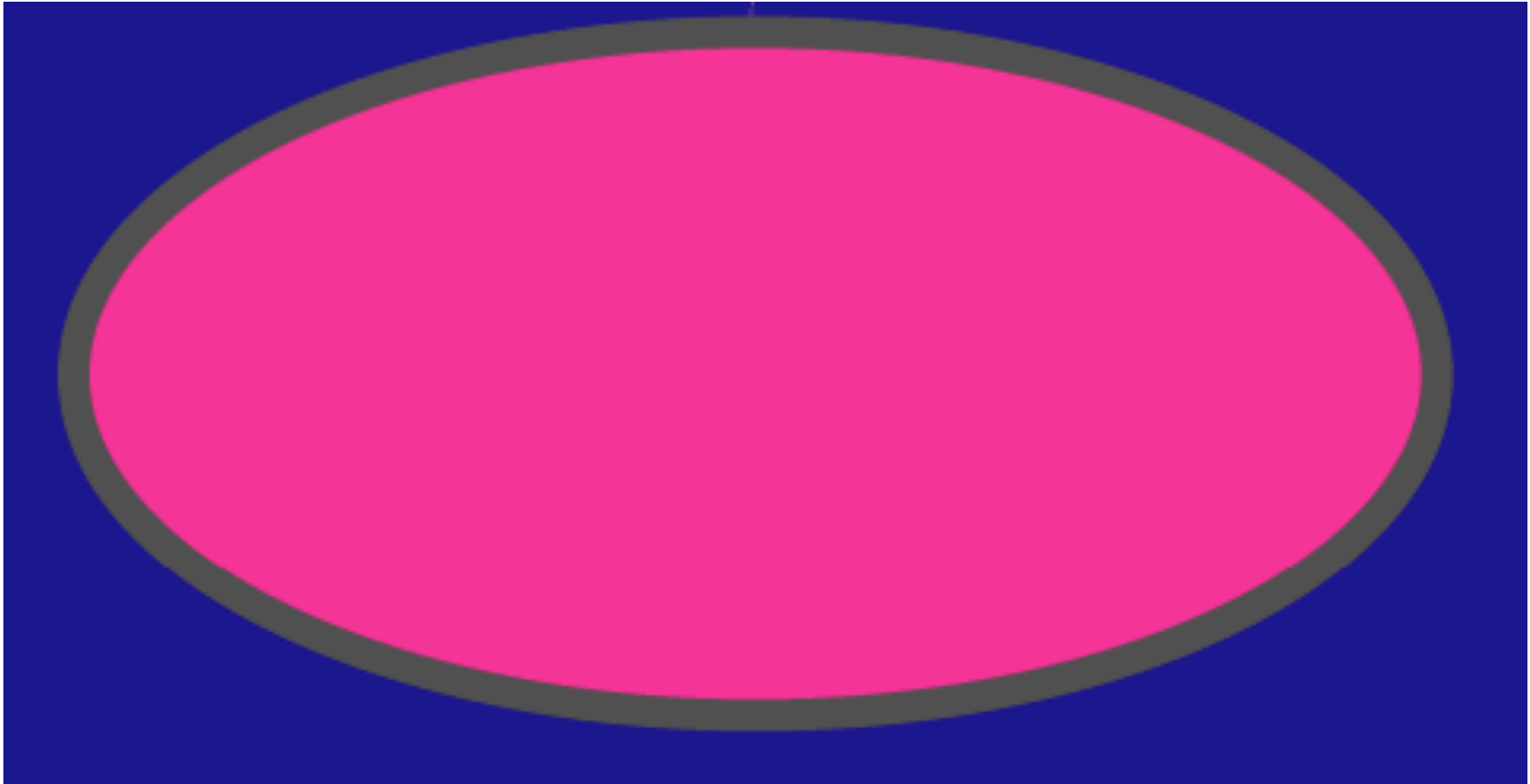
The Microwave sky

Our Milky Way



The Microwave sky

- Uniform glow of microwave light from every direction



The Microwave sky

- Uniform glow of microwave light from every direction

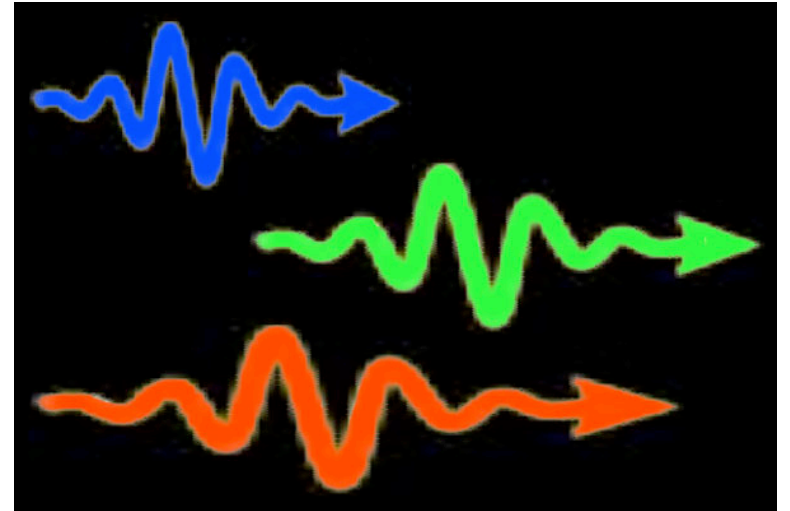


Cosmic Microwave
Background (CMB) :
afterglow of the hot, dense
early Universe !

Fun facts about the microwave background

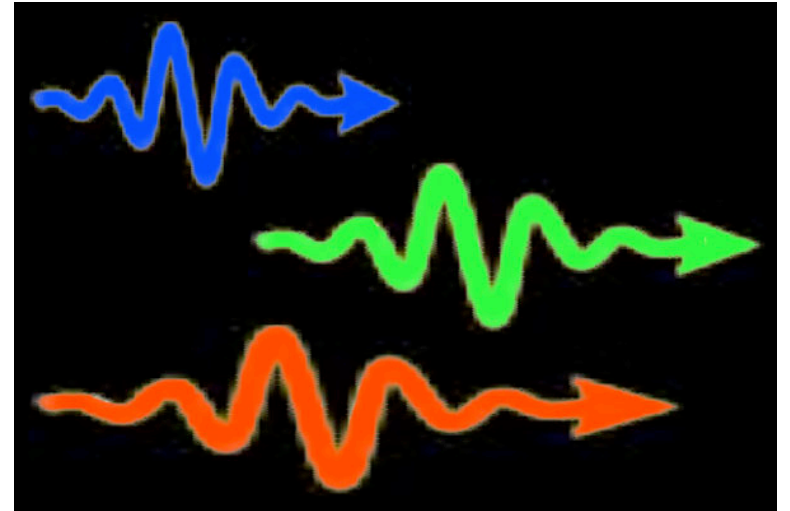
Fun facts about the microwave background

- Most numerous “particles” in the Universe!



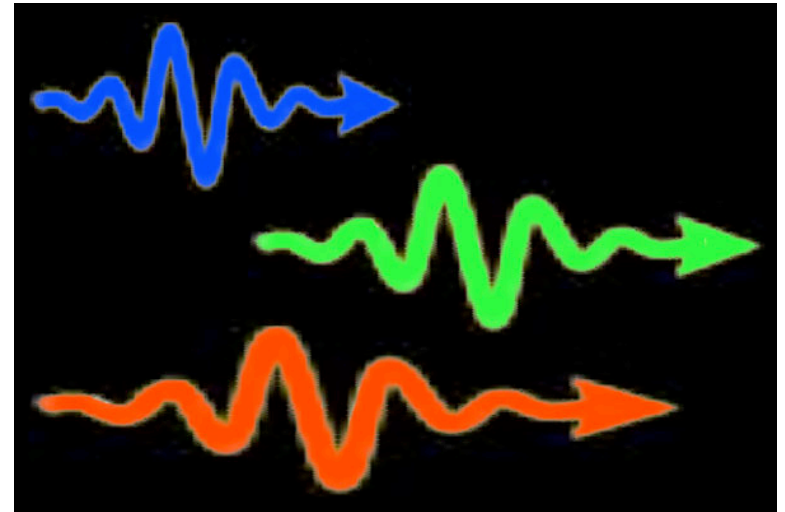
Fun facts about the microwave background

- Most numerous “particles” in the Universe!
- 400 in every cubic centimetre!



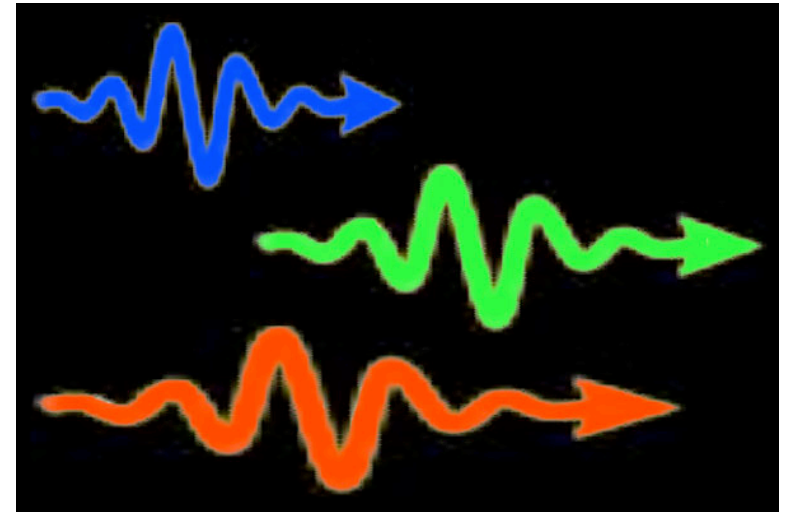
Fun facts about the microwave background

- Most numerous “particles” in the Universe!
- 400 in every cubic centimetre!
- 10 trillion passing through every square cm every second!



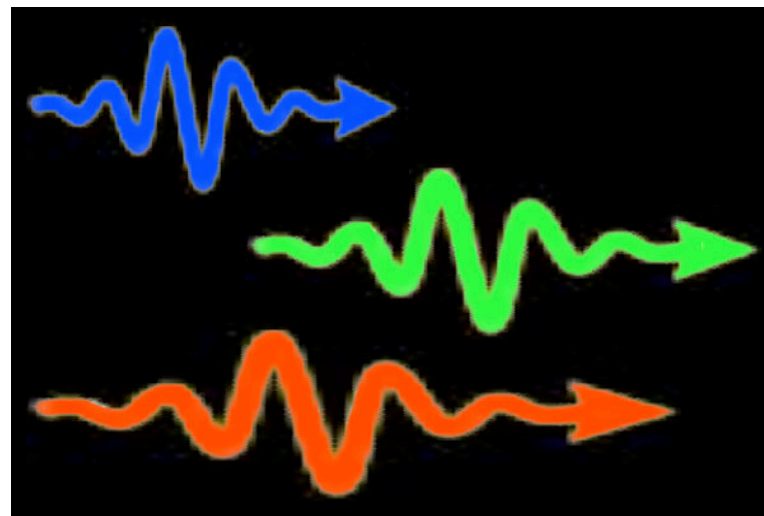
Fun facts about the microwave background

- Most numerous “particles” in the Universe!
- 400 in every cubic centimetre!
- 10 trillion passing through every square cm every second!
- Few per cent of TV static!



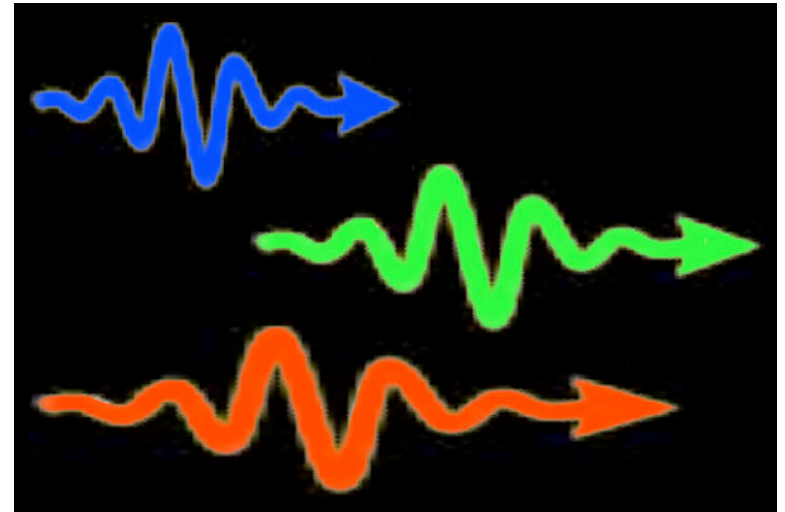
Fun facts about the microwave background

- Most numerous “particles” in the Universe!
- 400 in every cubic centimetre!
- 10 trillion passing through every square cm every second!
- Few per cent of TV static!
- You are bathed in the light of the Big Bang!



Fun facts about the microwave background

- Most numerous “particles” in the Universe!
- 400 in every cubic centimetre!
- 10 trillion passing through every square cm every second!
- Few per cent of TV static!
- You are bathed in the light of the Big Bang!
- The earliest light we can see!



Discovery of the microwave background

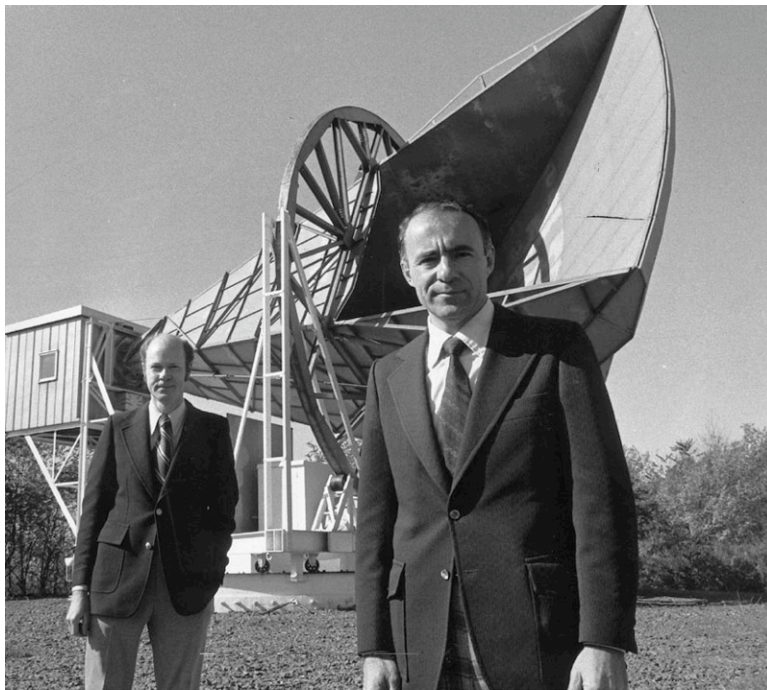
Penzias & Wilson



© 2004 Thomson - Brooks/Cole

Discovery of the microwave background

Penzias & Wilson



© 2004 Thomson - Brooks/Cole

Nobel Prize, 1978

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

1965 April 11

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

The total antenna temperature measured at the zenith is 6.7° K of which 2.3° K is due to atmospheric absorption. The calculated contribution due to ohmic losses in the antenna and back-lobe response is 0.9° K.

The radiometer used in this investigation has been described elsewhere (Penzias and Wilson 1965). It employs a traveling-wave maser, a low-loss (0.027-db) comparison switch, and a liquid helium-cooled reference termination (Penzias 1965). Measurements were made by switching manually between the antenna input and the reference termination. The antenna, reference termination, and radiometer were well matched so that a round-trip return loss of more than 55 db existed throughout the measurement; thus errors in the measurement of the effective temperature due to impedance mismatch can be neglected. The estimated error in the measured value of the total antenna temperature is 0.3° K and comes largely from uncertainty in the absolute calibration of the reference termination.

The contribution to the antenna temperature due to atmospheric absorption was obtained by recording the variation in antenna temperature with elevation angle and employing the secant law. The result, $2.3^\circ \pm 0.3^\circ$ K, is in good agreement with published values (Hogg 1959; DeGrasse, Hogg, Ohm, and Scovil 1959; Ohm 1961).

The contribution to the antenna temperature from ohmic losses is computed to be $0.8^\circ \pm 0.4^\circ$ K. In this calculation we have divided the antenna into three parts: (1) two non-uniform tapers approximately 1 m in total length which transform between the 2½-inch round output waveguide and the 6-inch-square antenna throat opening; (2) a double-choke rotary joint located between these two tapers; (3) the antenna itself. Care was taken to clean and align joints between these parts so that they would not significantly increase the loss in the structure. Appropriate tests were made for leakage and loss in the rotary joint with negative results.

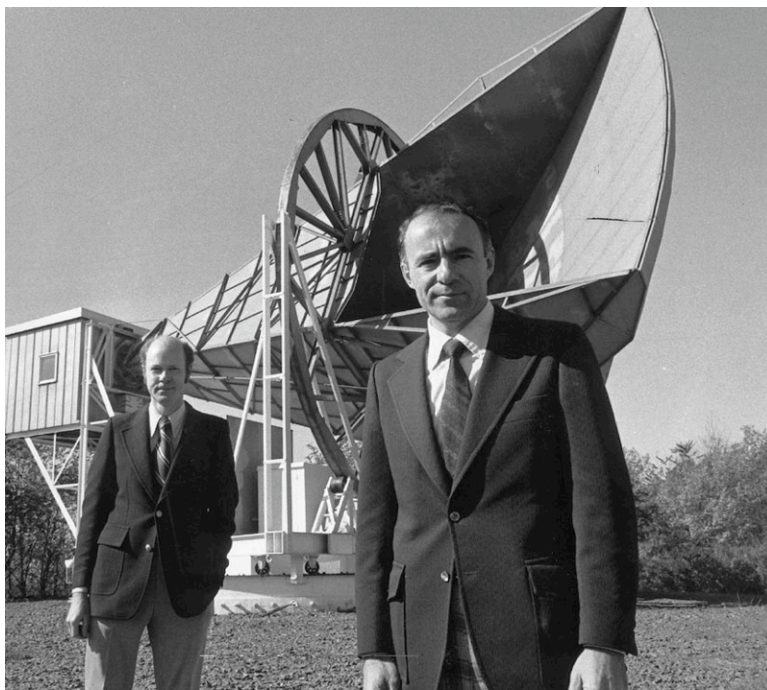
The possibility of losses in the antenna horn due to imperfections in its seams was eliminated by means of a taping test. Taping all the seams in the section near the throat and most of the others with aluminum tape caused no observable change in antenna temperature.

The backlobe response to ground radiation is taken to be less than 0.1° K for two reasons: (1) Measurements of the response of the antenna to a small transmitter located on the ground in its vicinity indicate that the average back-lobe level is more than 30 db below isotropic response. The horn-reflector antenna was pointed to the zenith for these measurements, and complete rotations in azimuth were made with the transmitter in each of ten locations using horizontal and vertical transmitted polarization from each position. (2) Measurements on smaller horn-reflector antennas at these laboratories, using pulsed measuring sets on flat antenna ranges, have consistently shown a back-lobe level of 30 db below isotropic response. Our larger antenna would be expected to have an even lower back-lobe level.

From a combination of the above, we compute the remaining unaccounted-for antenna temperature to be $3.5^\circ \pm 1.0^\circ$ K at 4080 Mc/s. In connection with this result it should be noted that DeGrasse *et al.* (1959) and Ohm (1961) give total system temperatures at 5650 Mc/s and 2390 Mc/s, respectively. From these it is possible to infer upper limits to the background temperatures at these frequencies. These limits are, in both cases, of the same general magnitude as our value.

Discovery of the microwave background

Penzias & Wilson



© 2004 Thomson - Brooks/Cole

Then they found droppings of pigeons nesting in the antenna. They cleaned out the mess and tried removing the birds and discouraging them from roosting, but they kept flying back. "To get rid of them, we finally found the most humane thing was to get a shot gun...and at very close range [we] just killed them instantly. It's not something I'm happy about, but that seemed like the only way out of our dilemma," said Penzias.

“The Big Bang’s Echo”, Schoenstein

Nobel Prize, 1978

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

1965 April 1

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

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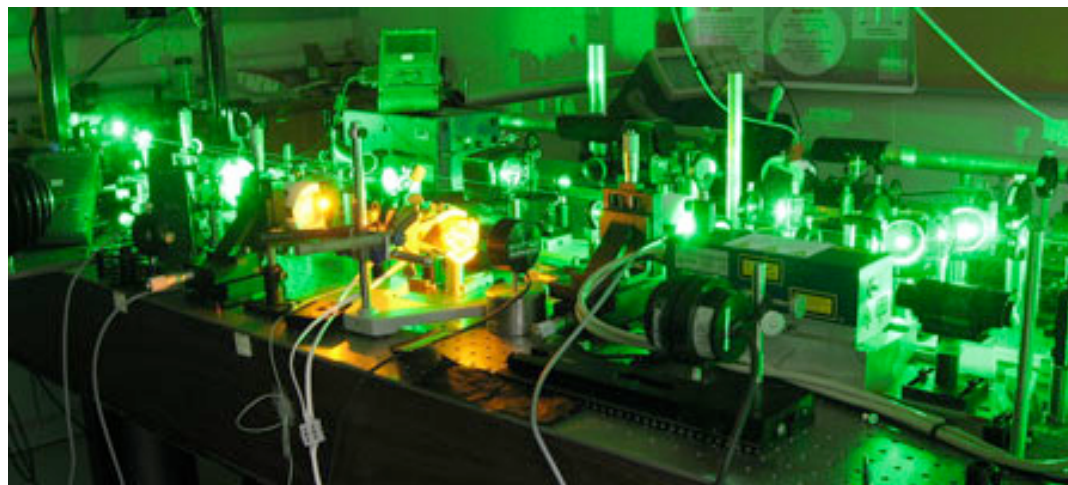
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Discovery of the microwave background

Gamov



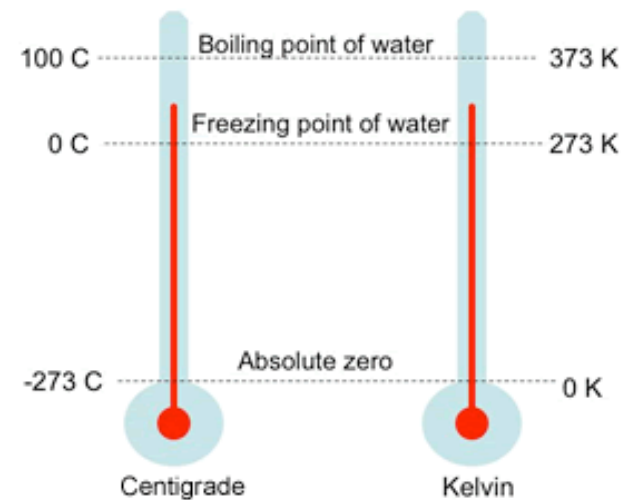
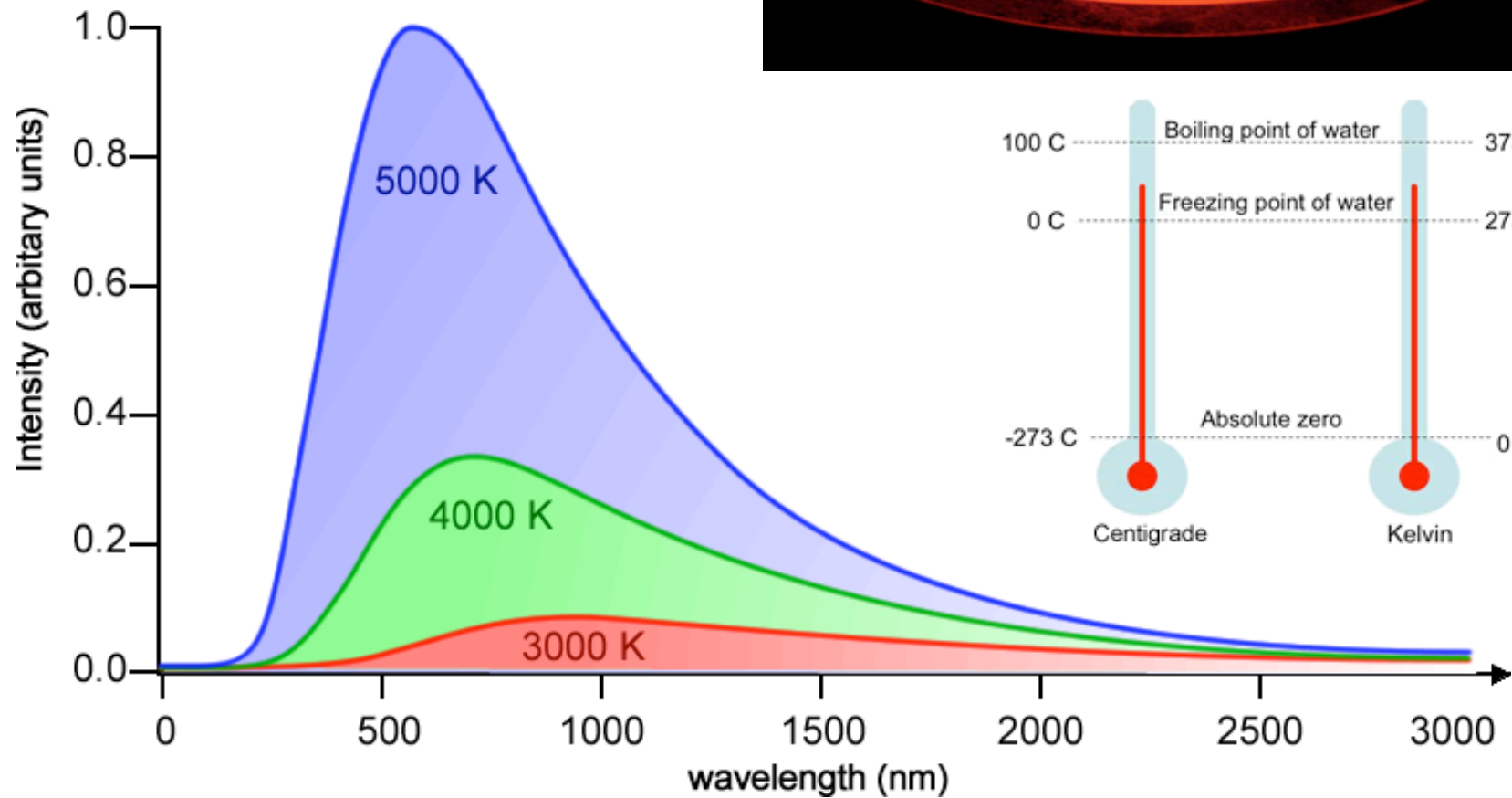
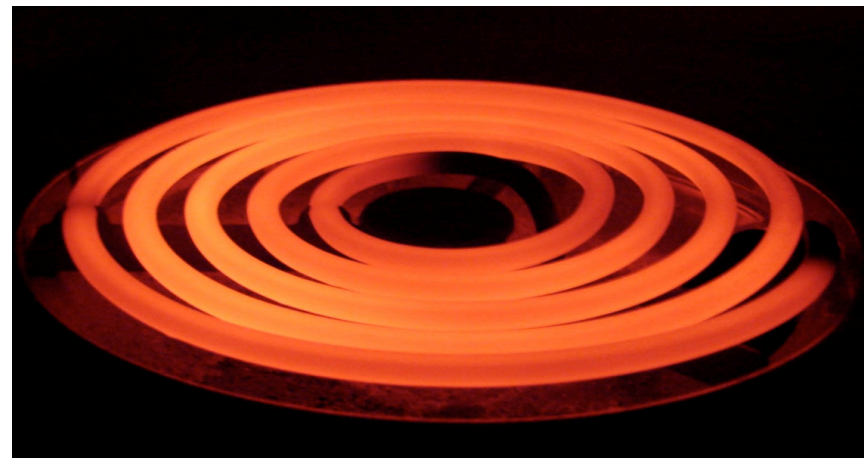
Proposed the Hot Big Bang (1946)



Thermal radiation

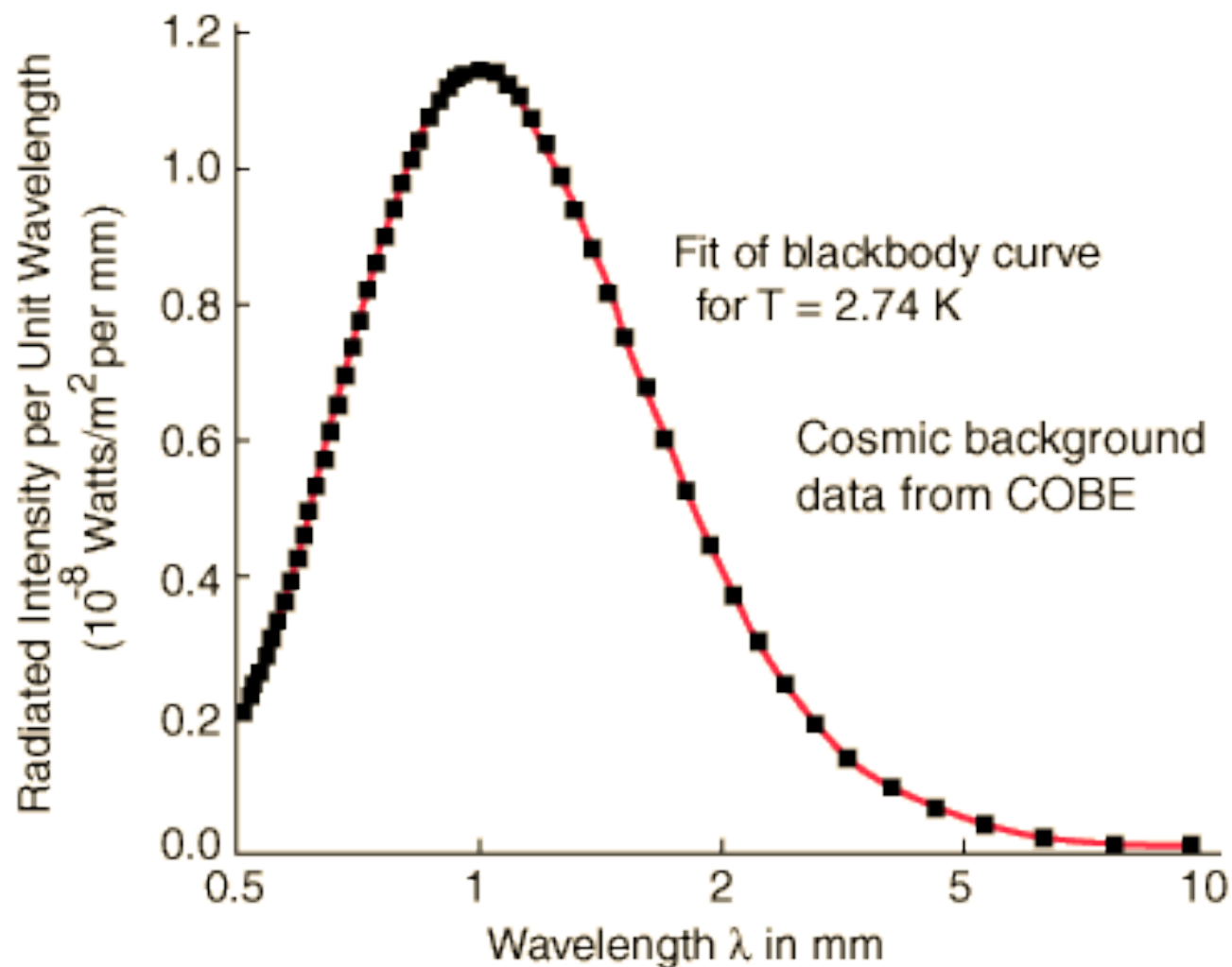


Planck's law

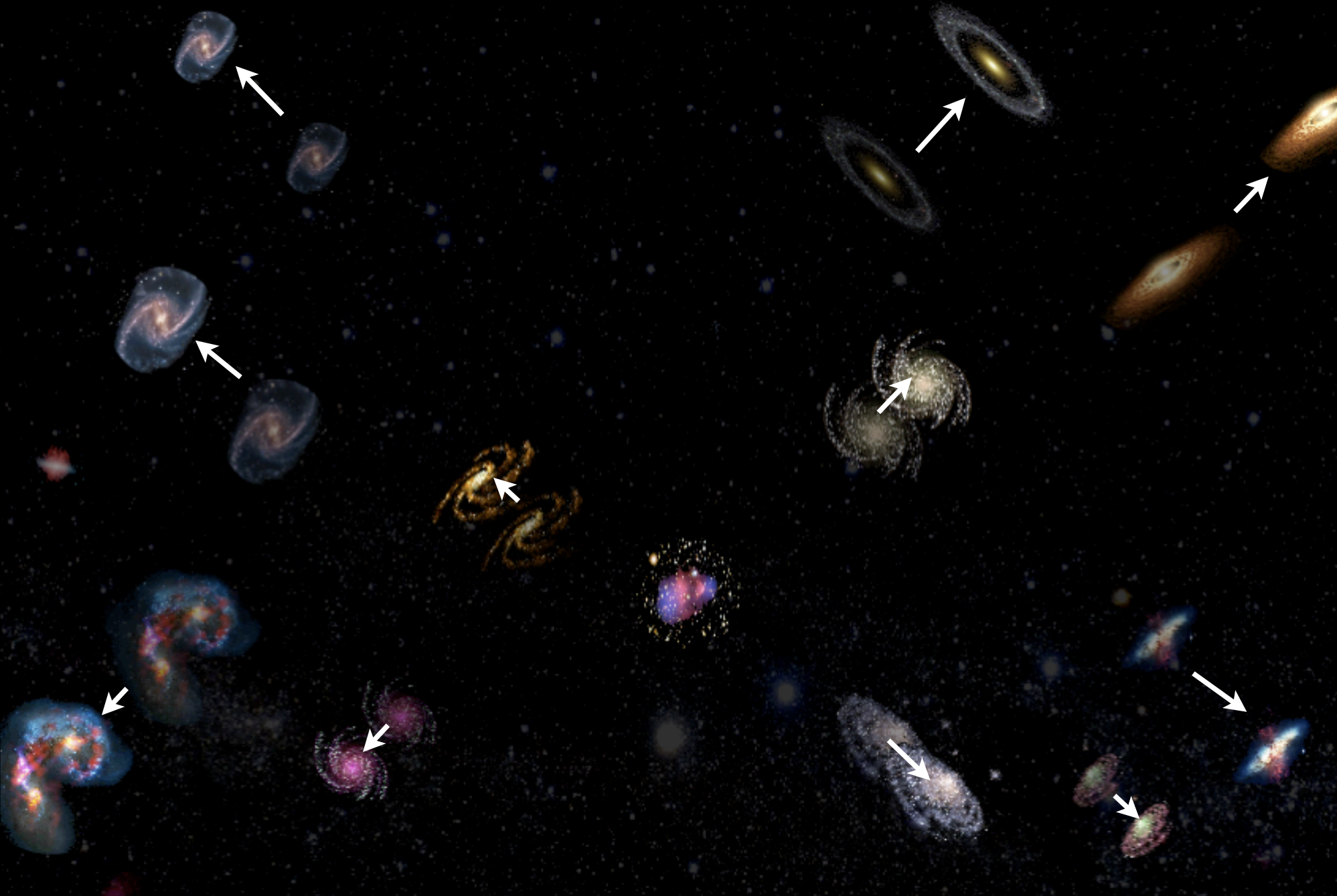


Thermal radiation

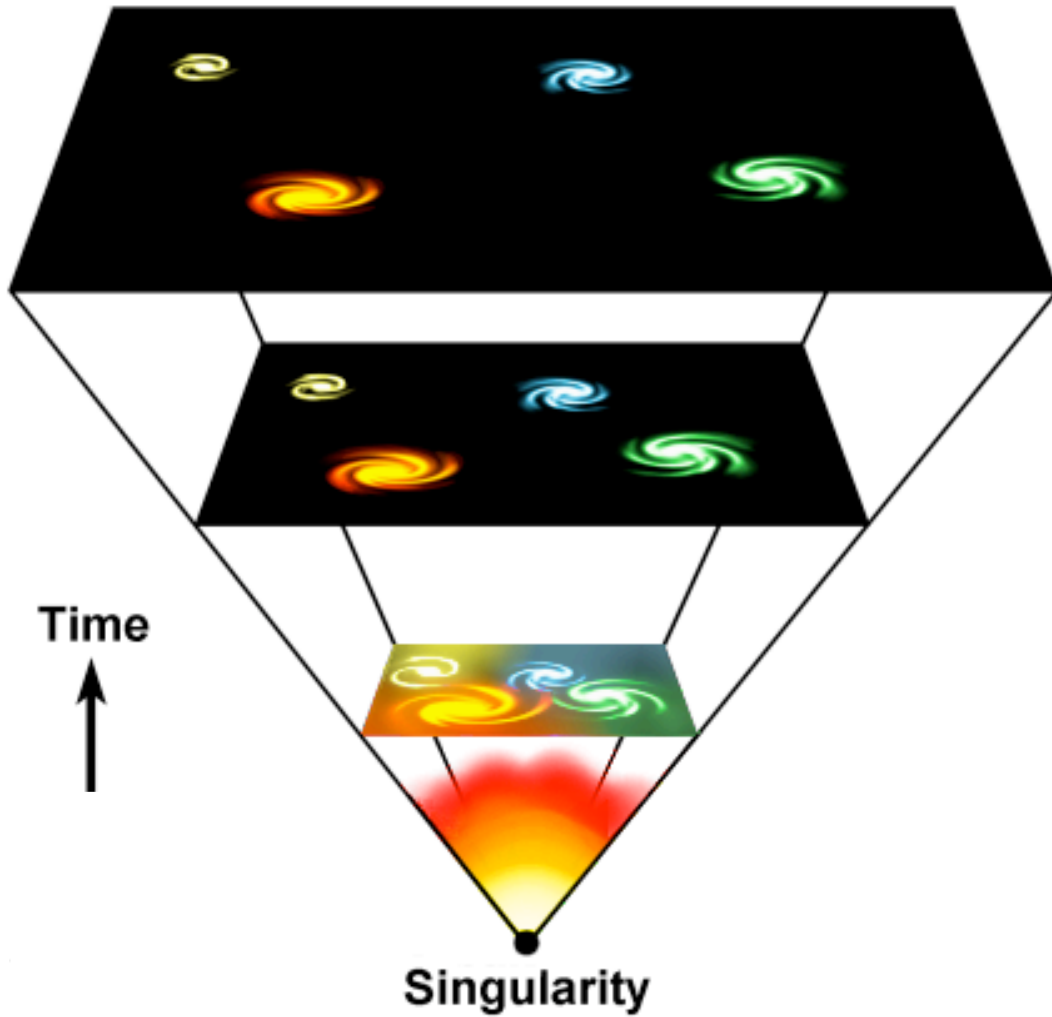
- Microwave background is extremely cold ! (about 3 K)



Expanding universe

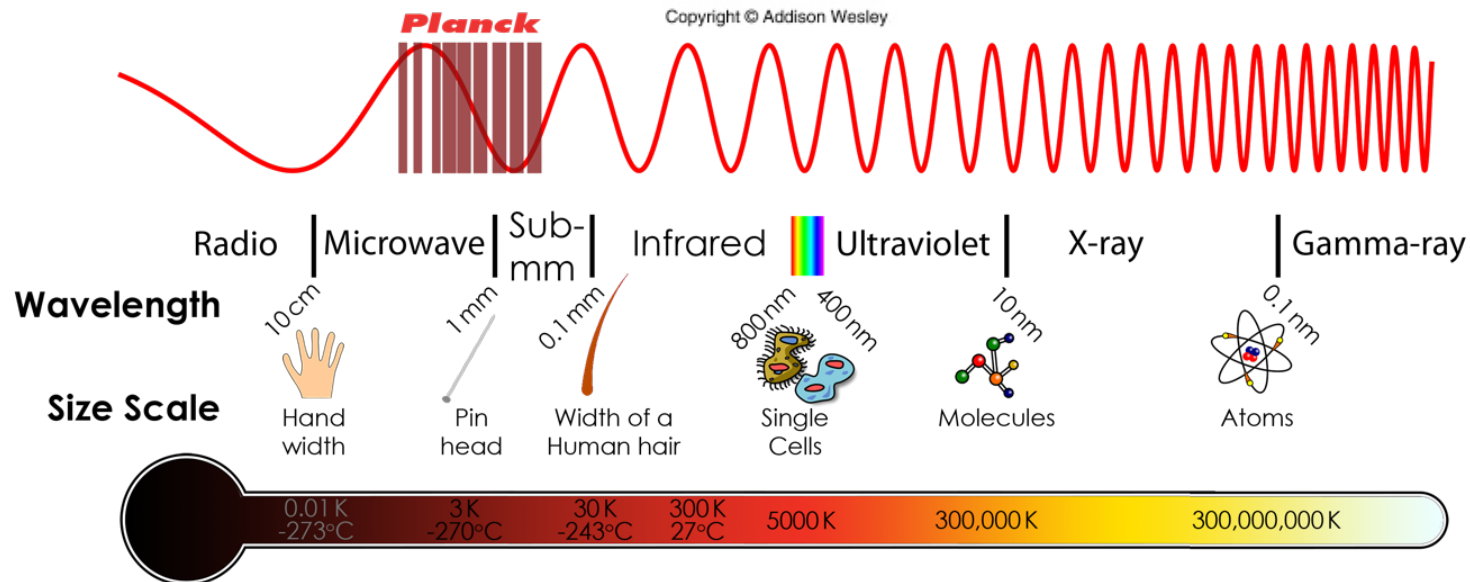
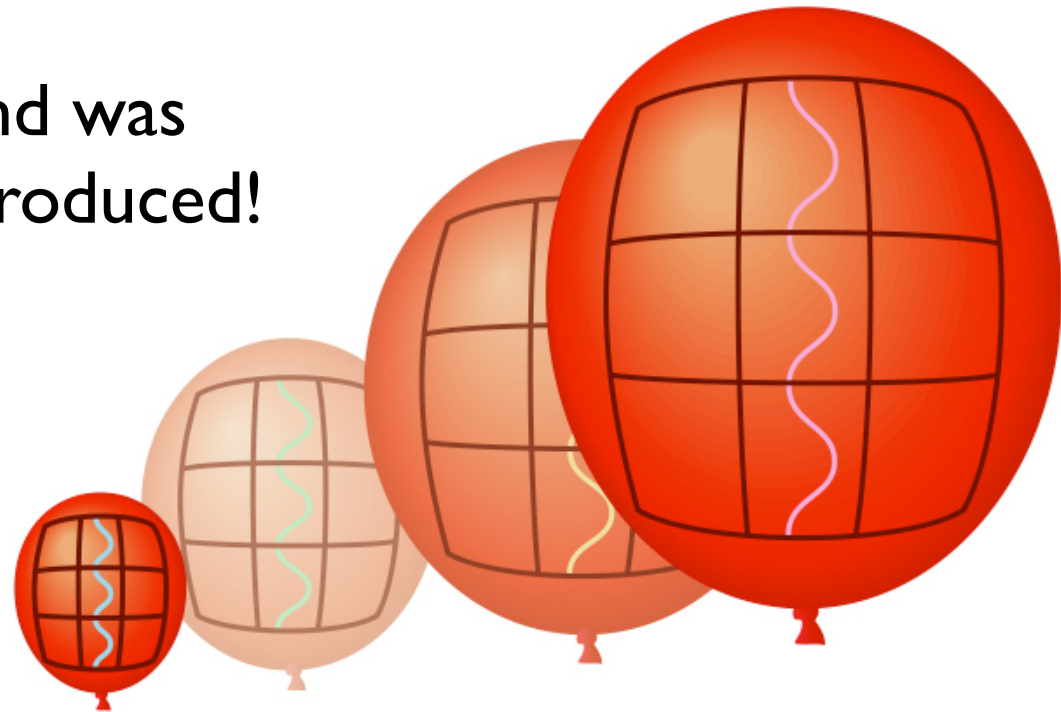
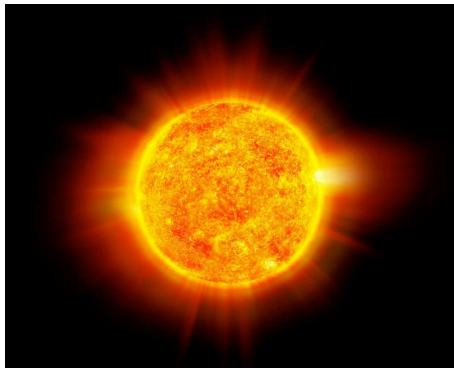


Expanding universe



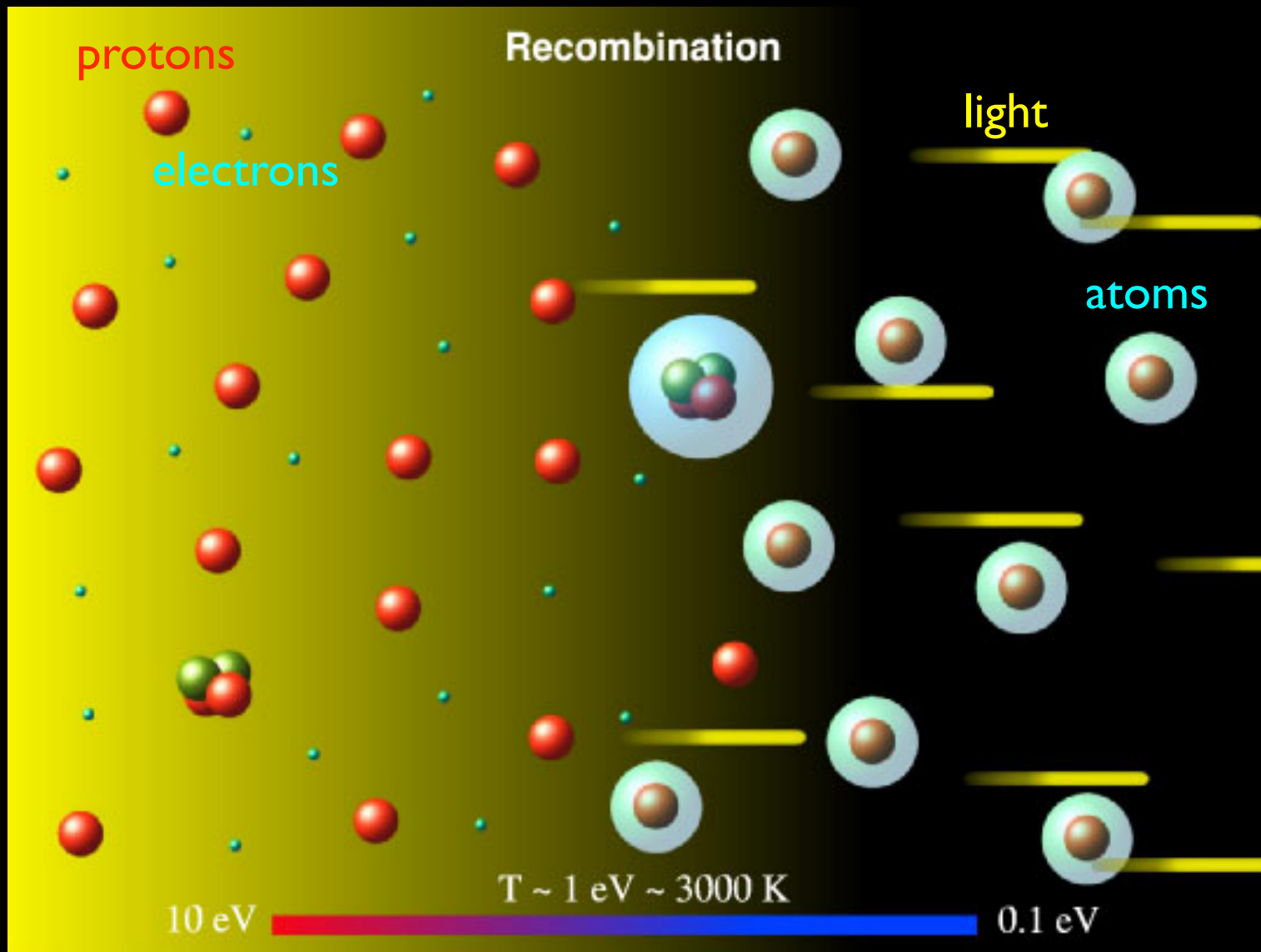
Expanding universe

- Microwave background was 3000K when it was produced!



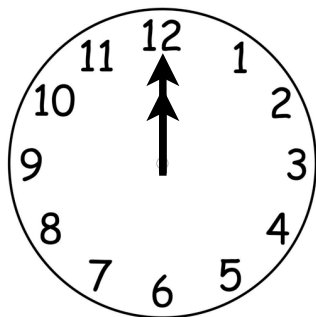
Where the microwave background comes from

→ time

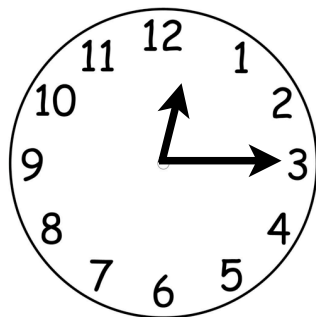


Where the microwave background comes from

Jan 1st

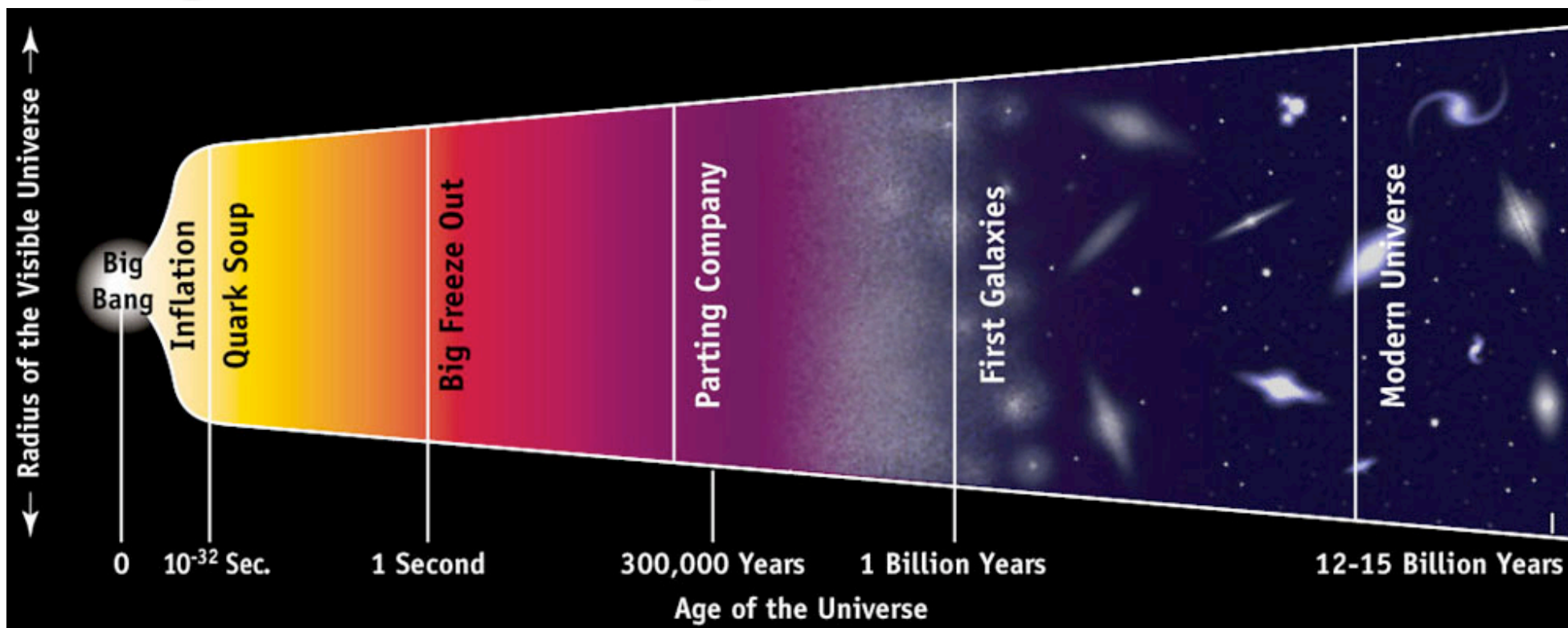


Jan 1st



Feb

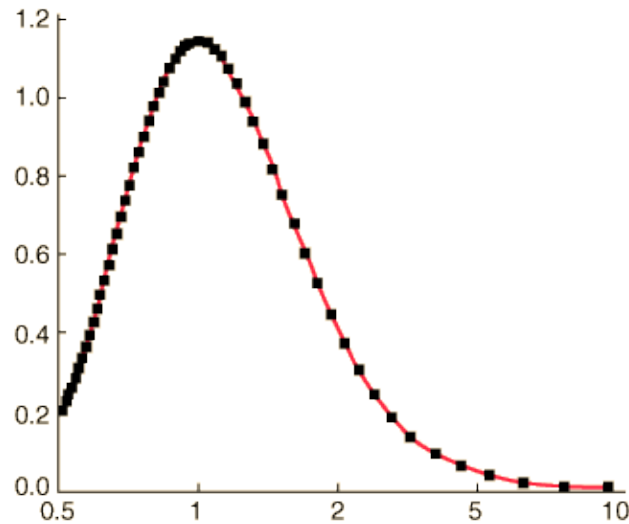
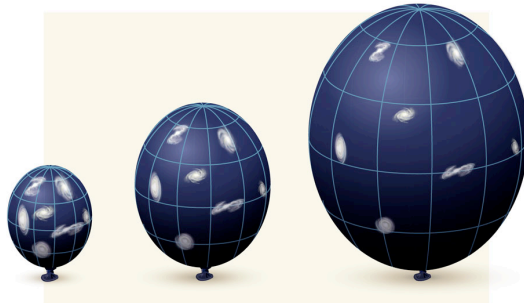
Dec 31st



The Hot Big Bang

Microwave background

Expanding universe



Abundance of light elements

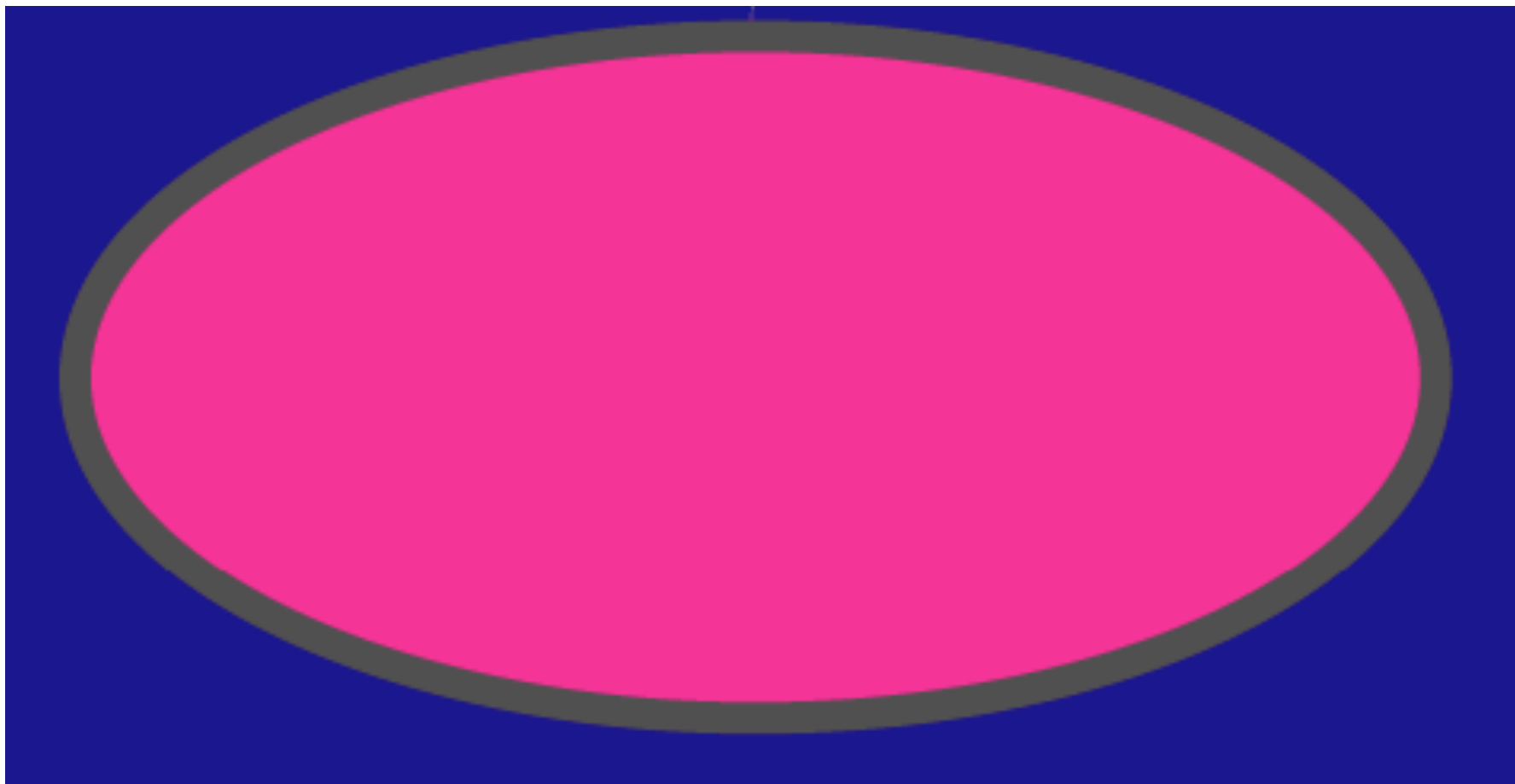
Periodic Table of Elements

1	2											3	4	5	6	7	8	9	10			
H	He											B	C	N	O	F	Ne					
3	4	11	12											13	14	15	16	17	18			
Li	Be	Na	Mg											Al	Si	P	S	Cl	Ar			
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36					
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr					
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54					
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe					
55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86					
Cs	Ba	*La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn					
87	88	89	104	105	106	107	108	109	110													
Fr	Ra	+Ac	Rf	Ha	106	107	108	109	110													
		* Lanthanide Series																				
		Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu								
		+ Actinide Series																				
		Th	Pa	U																		



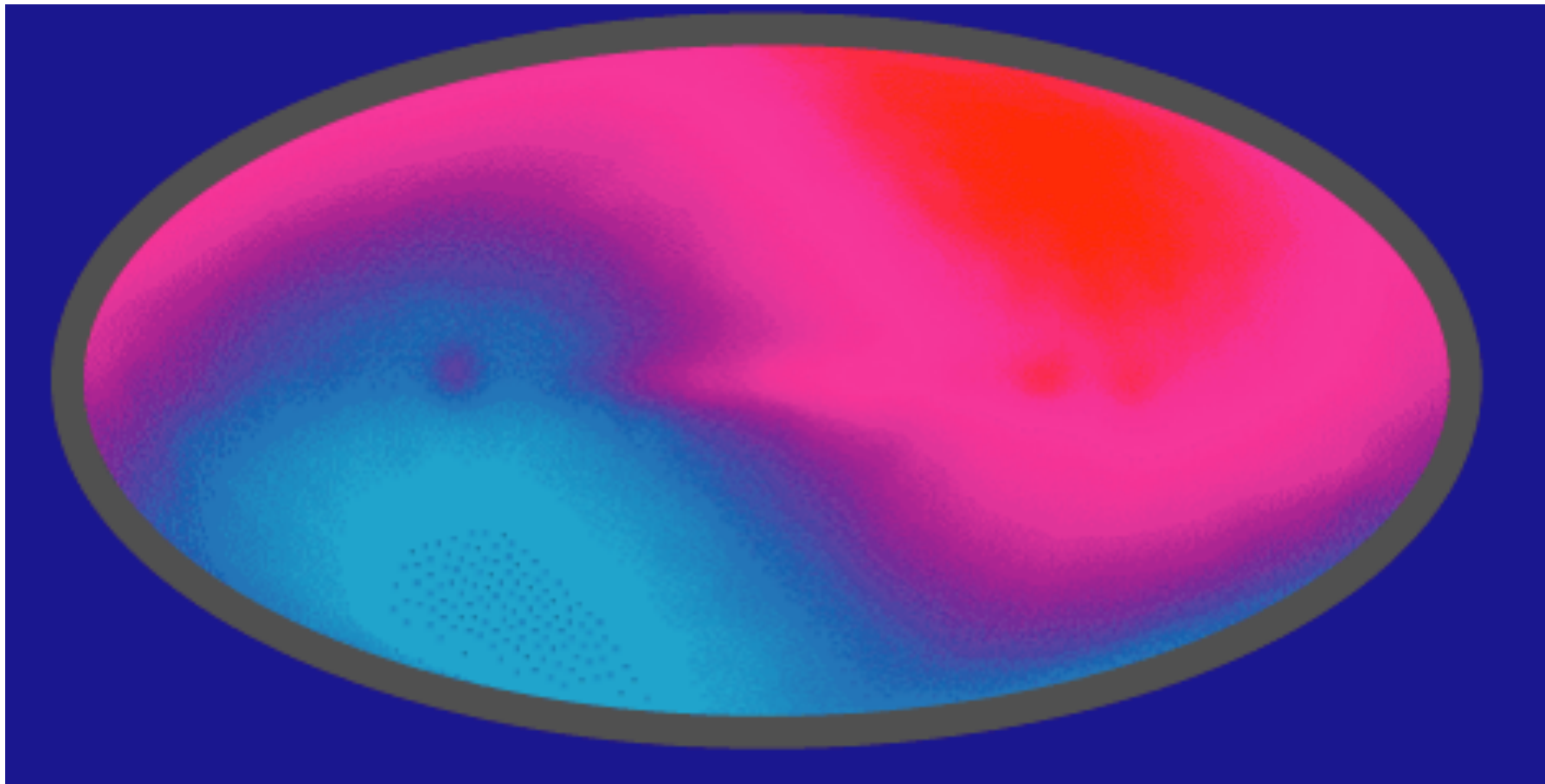
Cosmic motion

- Go back to our map of the microwave sky ...

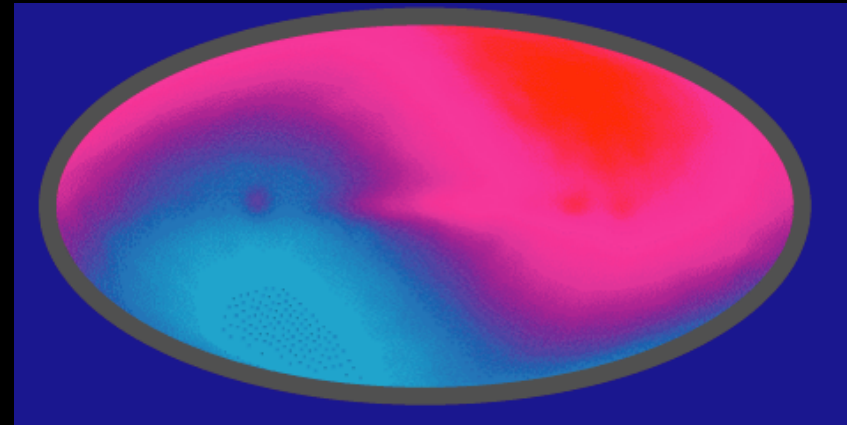
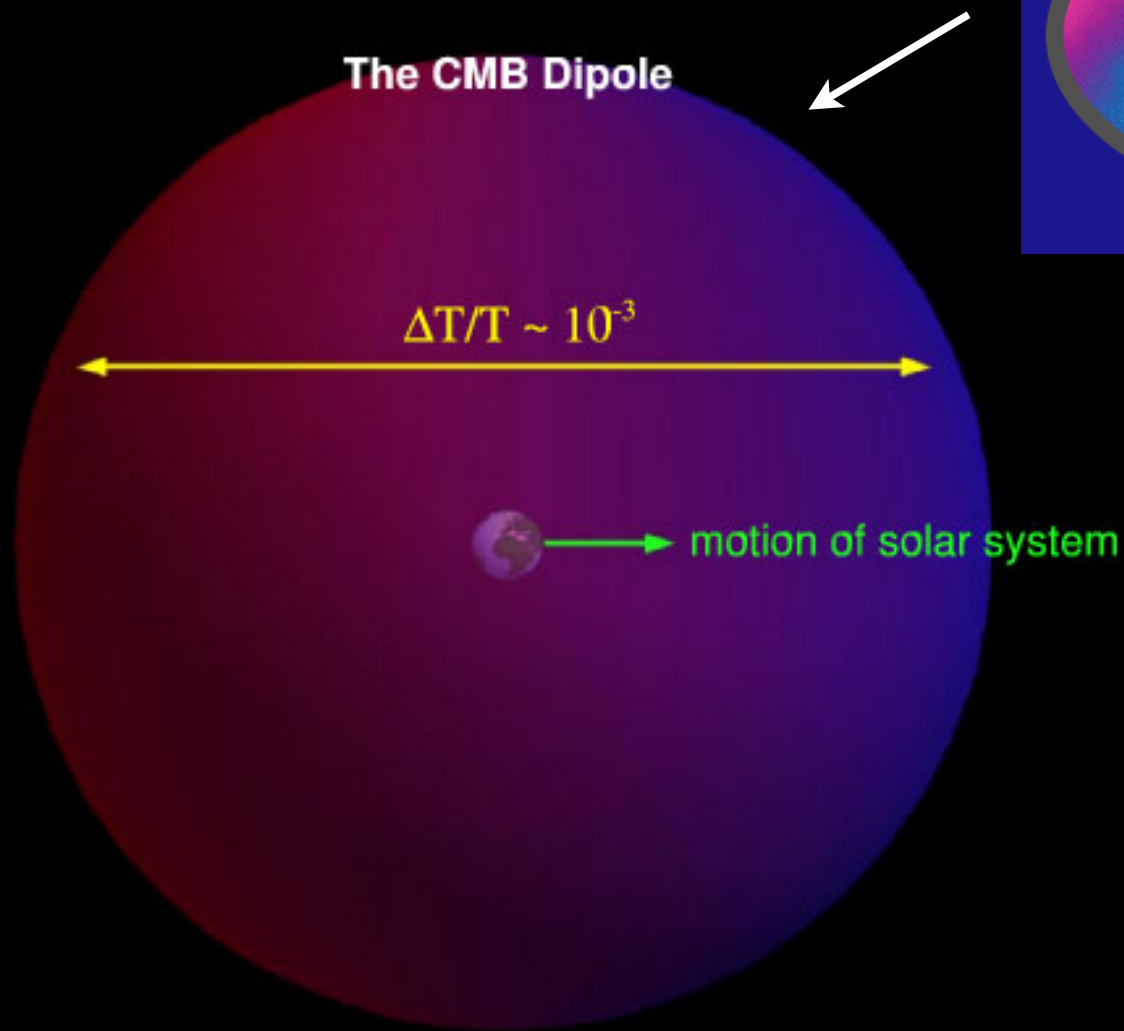


Cosmic motion

- ... and turn up the contrast level! (blue-red is 0.003 K)

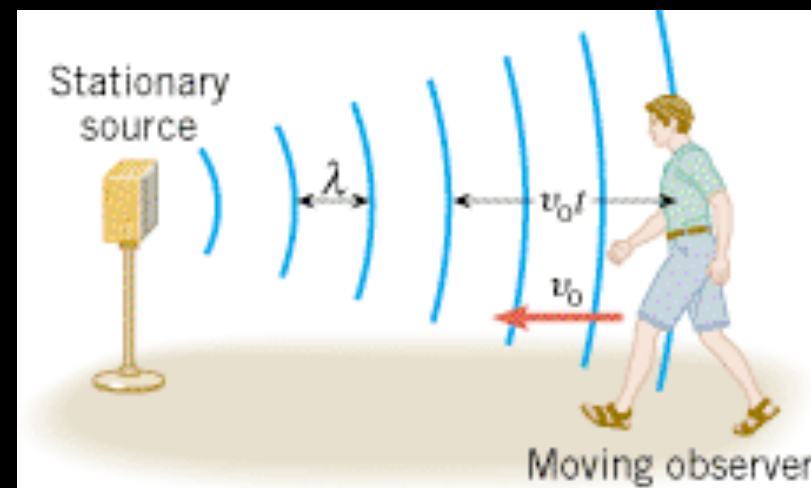
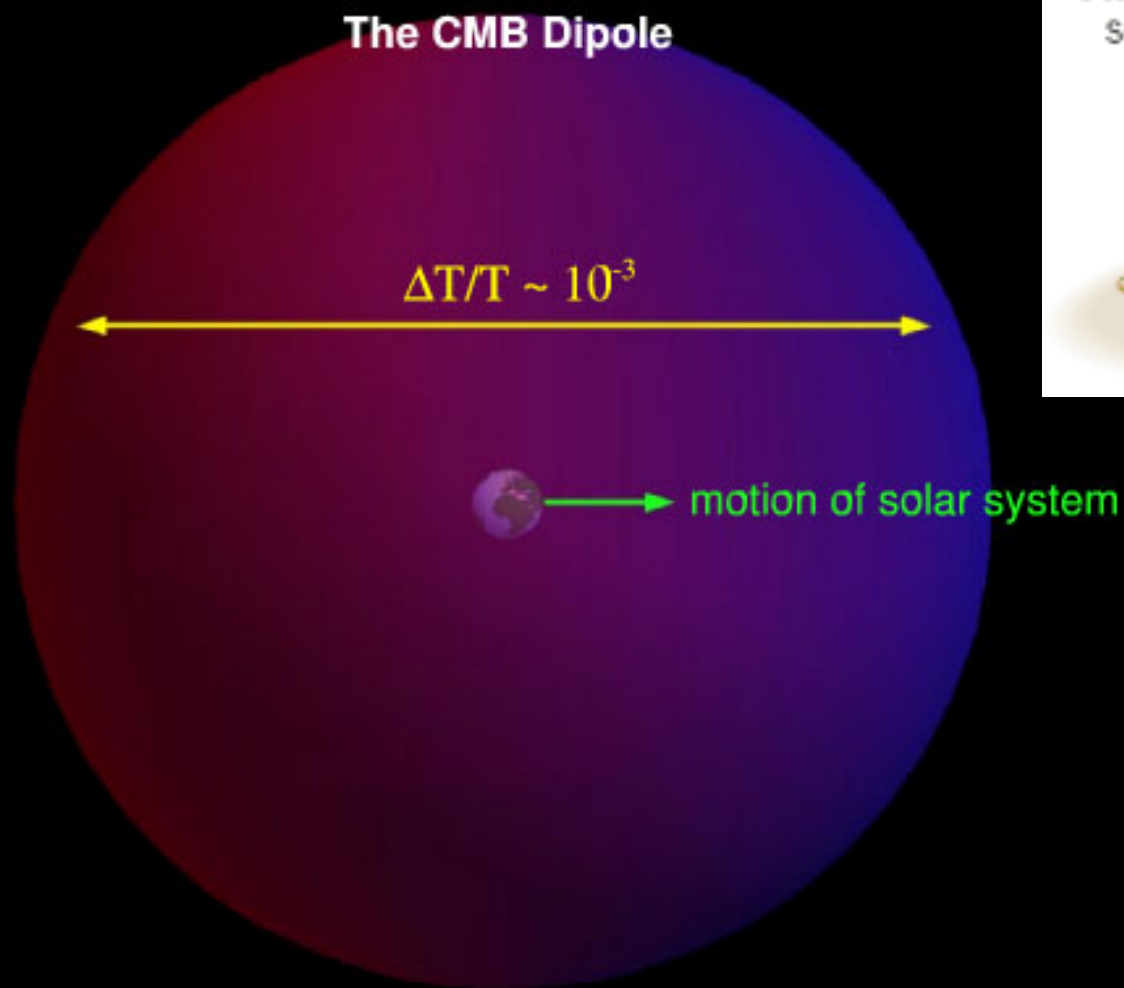


Cosmic motion



Cosmic motion

The Doppler effect ...



Cosmic motion

the Local Supercluster

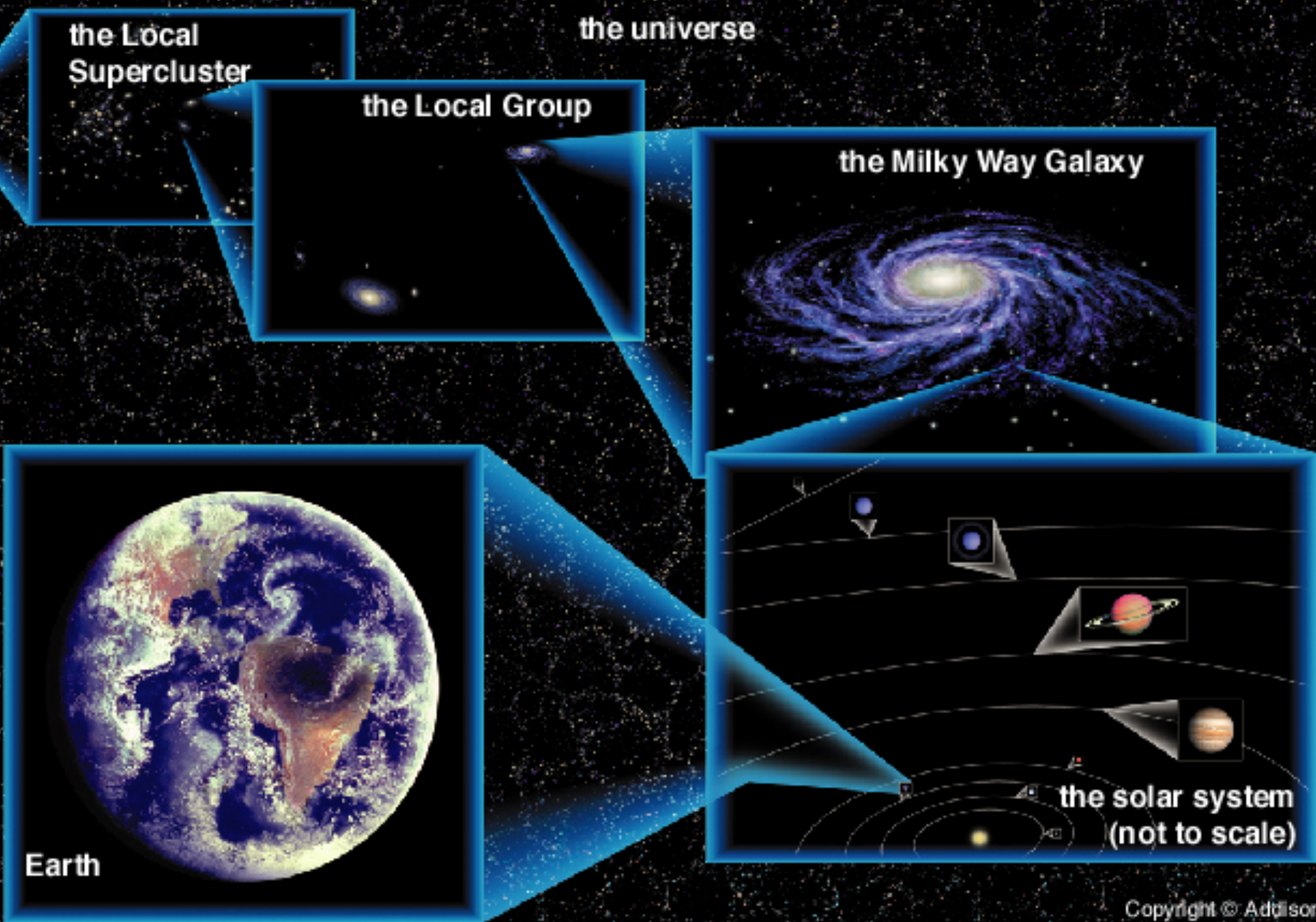
the universe

the Local Group

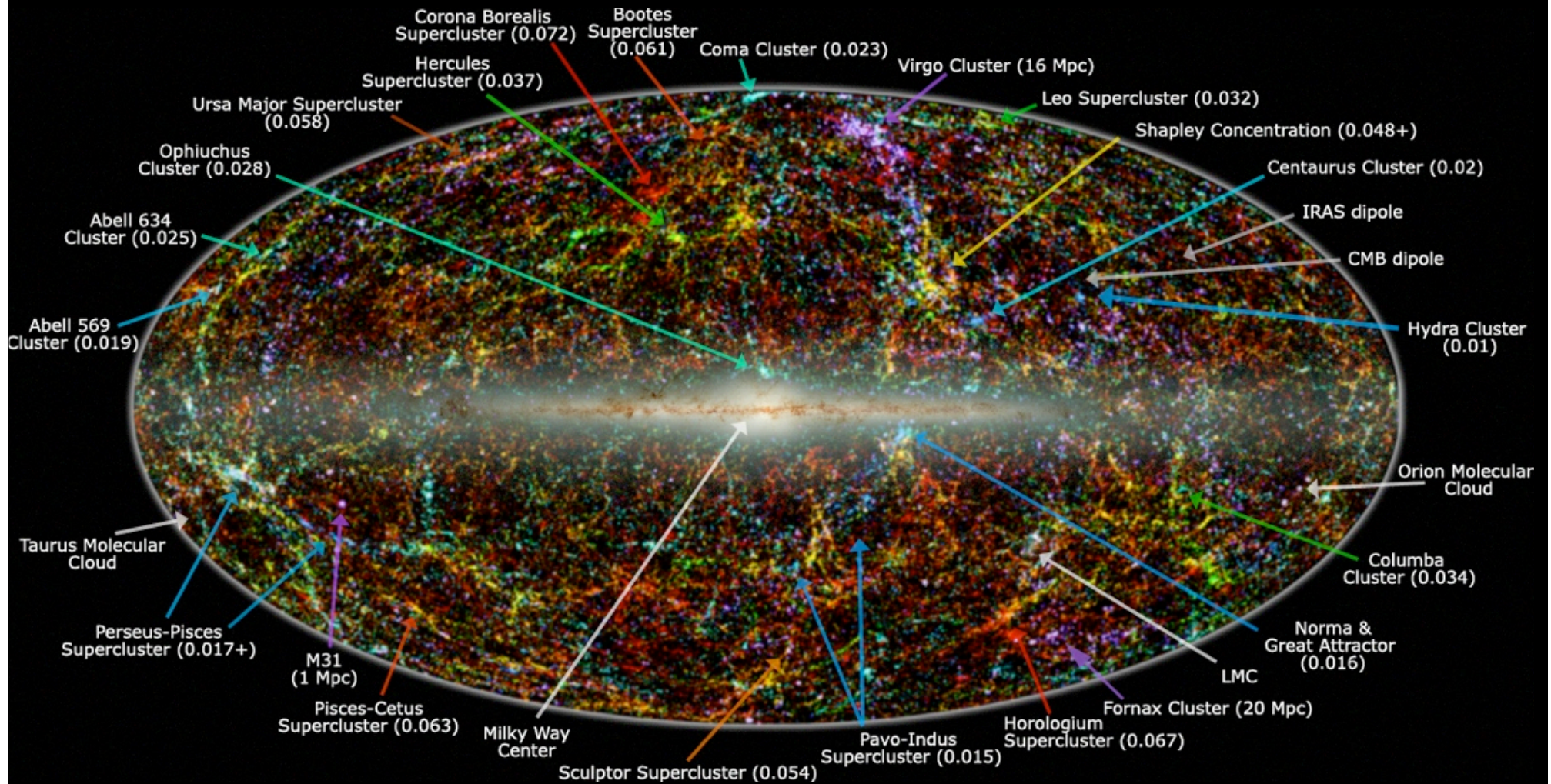
the Milky Way Galaxy

Earth

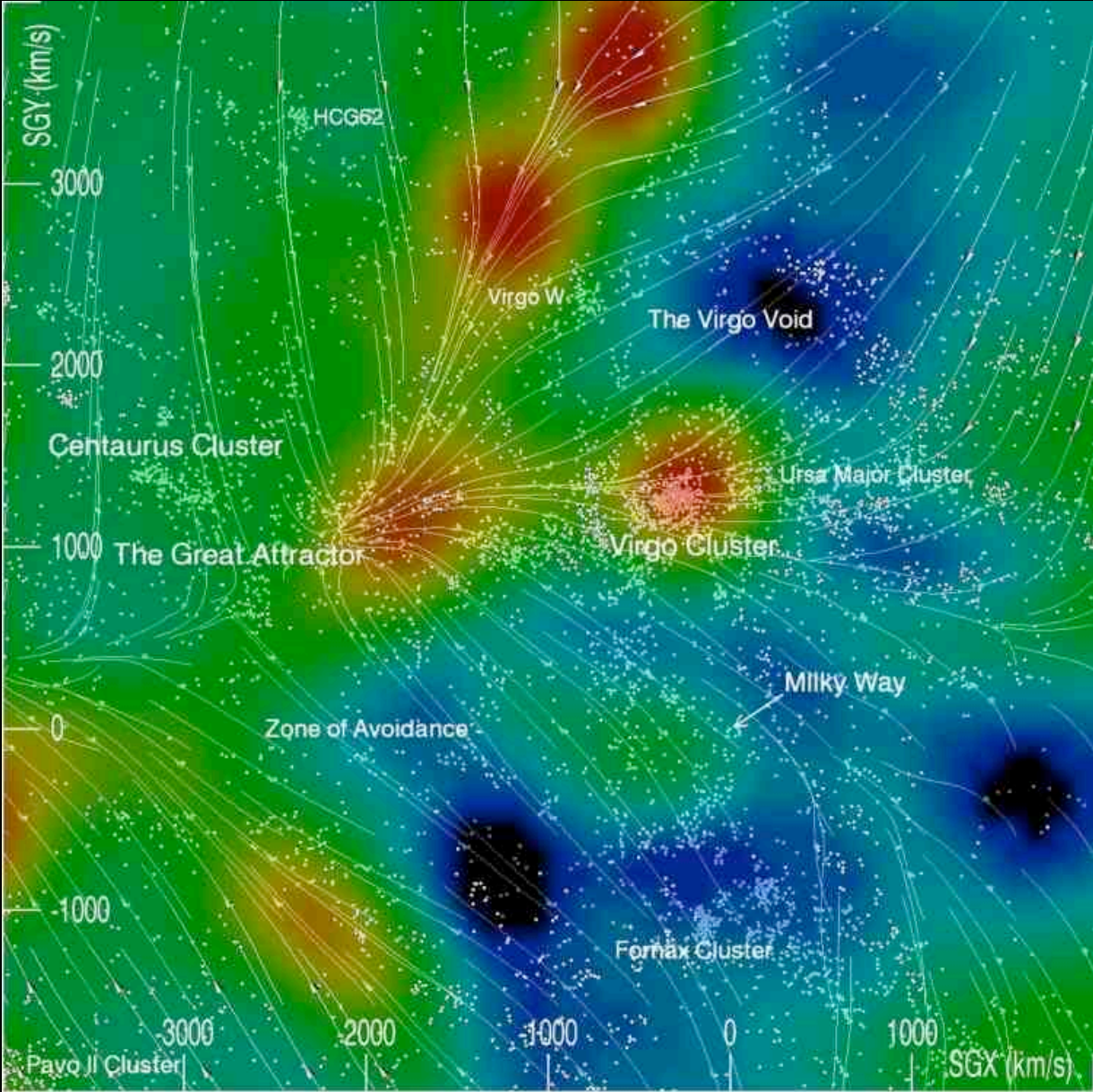
the solar system
(not to scale)



Cosmic motion

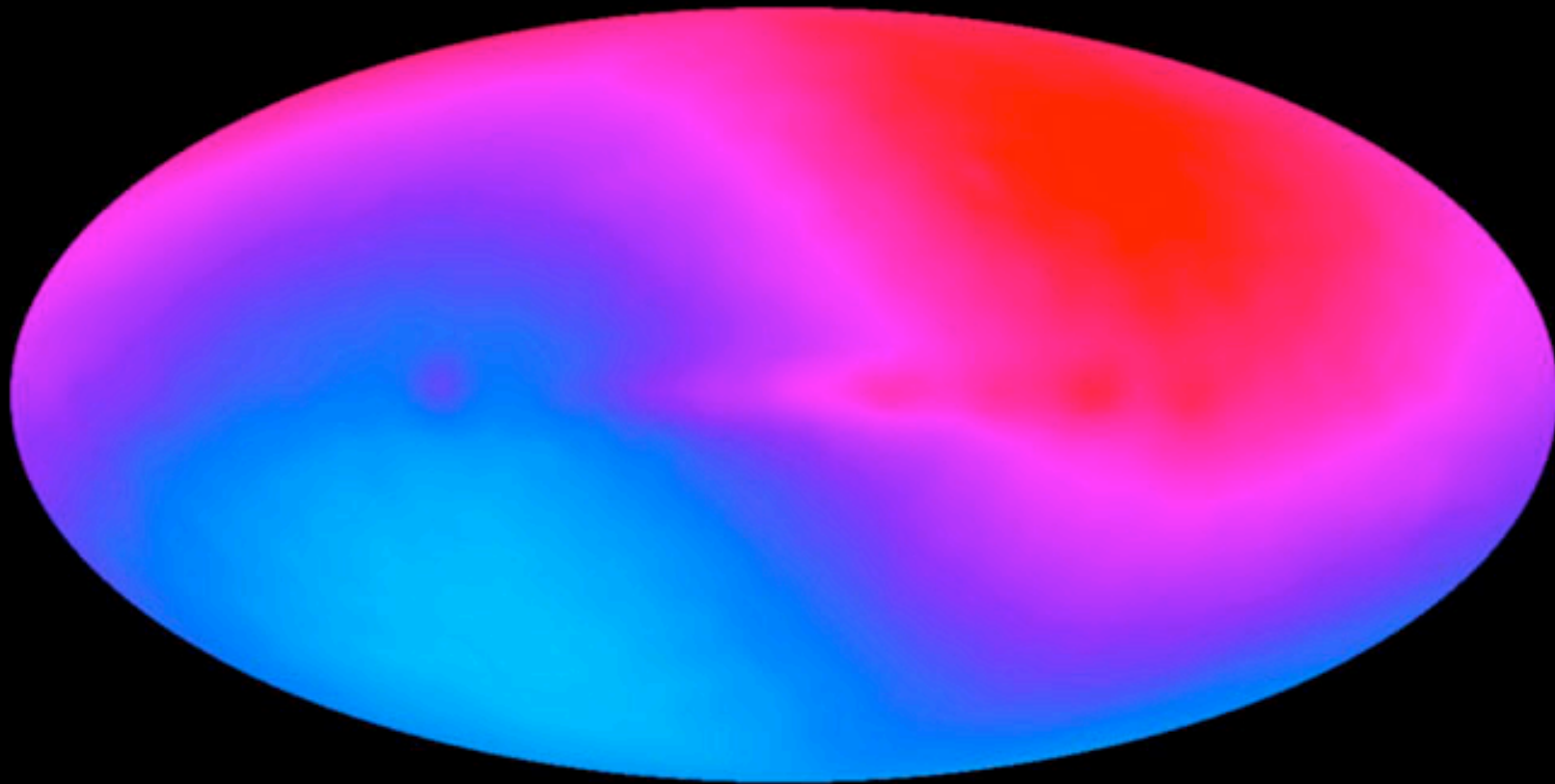


Cosmic motion



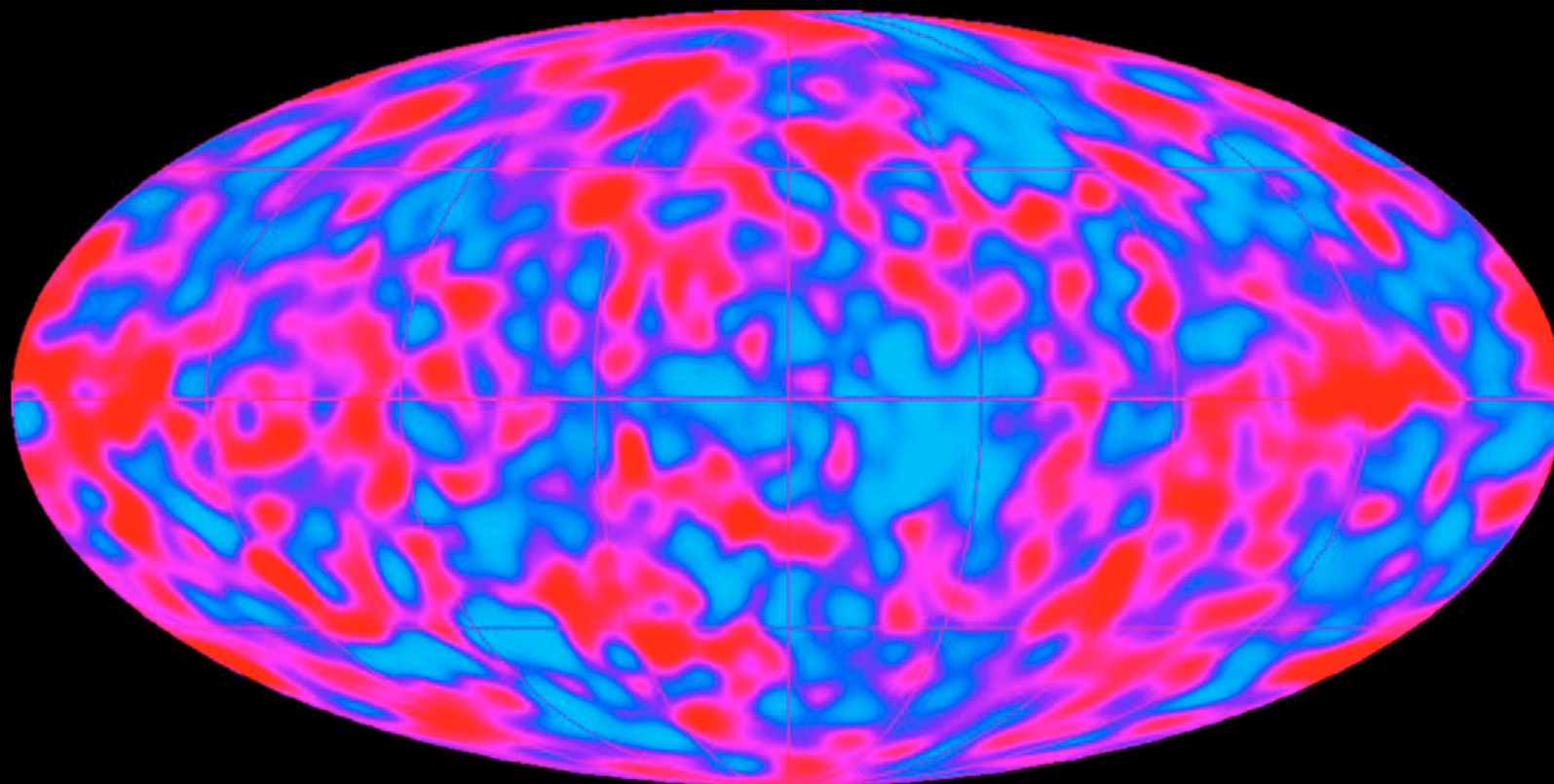
The most interesting thing of all!

- Go back to our map of the microwave sky ...

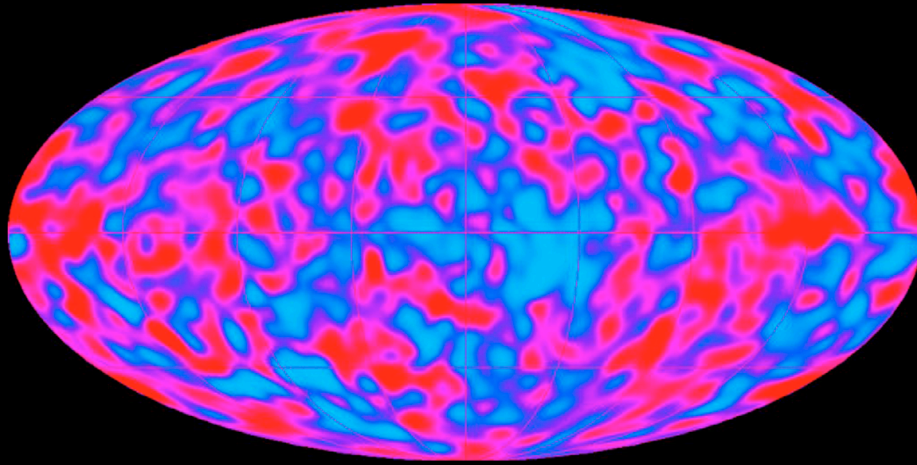


The most interesting thing of all!

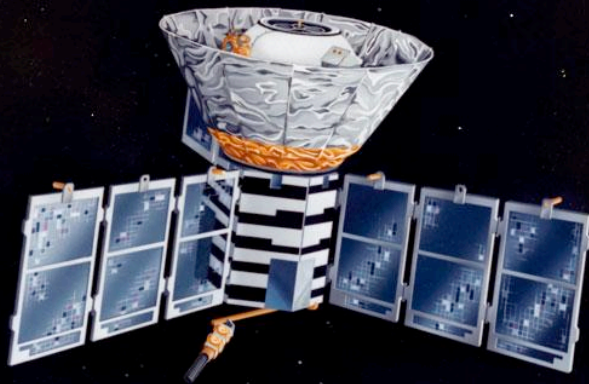
- Turn up the contrast level again! (blue-red is 0.00003 K)



Ripples in the microwave background



Nobel Prize, 2006



THE INDEPENDENT
FRIDAY 24 APRIL 2004

A New spacecraft has detected ripples of the galaxy's birth 380,000 years after the Big Bang. The discovery about the formation of the stars after the Big Bang has been hailed by excited scientists as the Holy Grail of cosmology. Susan Watts and Tom Wible report

How the universe began

SUMMARY

Bosnia ceasefire crumbles

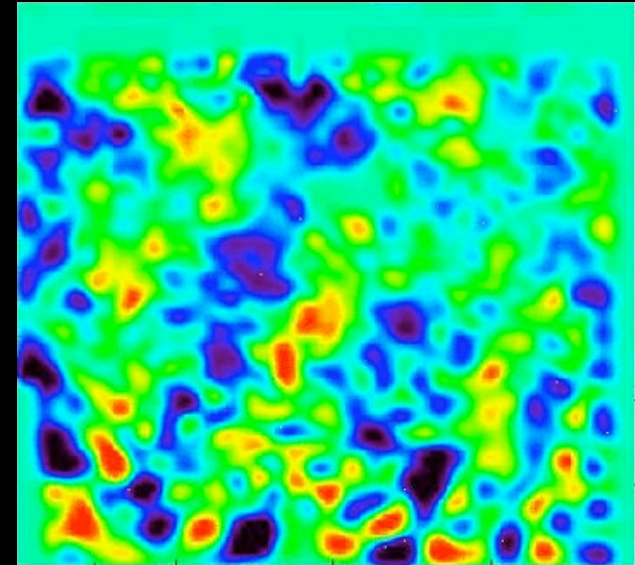
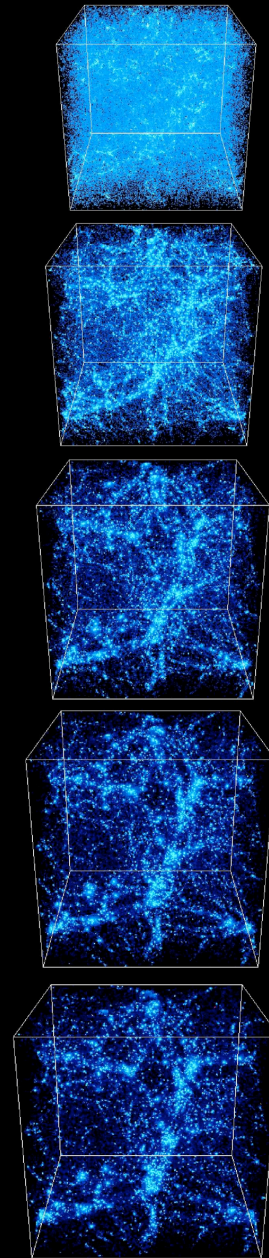
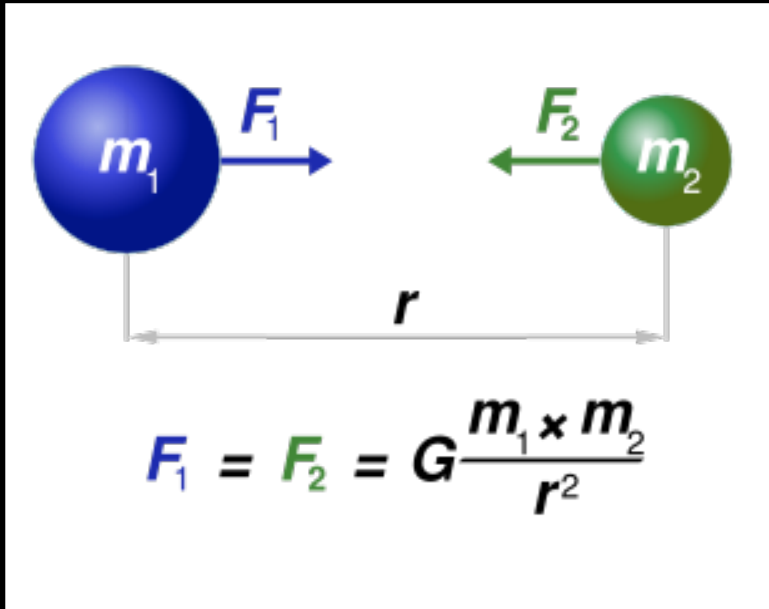
Film maker
Satellite
Ray dies

DO TIPSY ELEPHANTS SEE PINK PEOPLE?

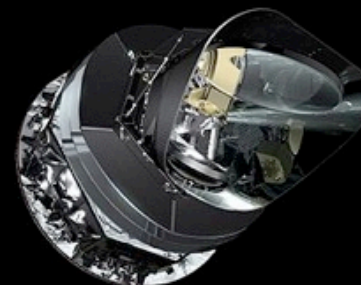
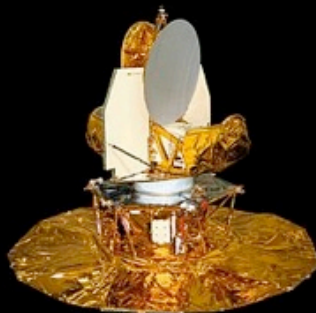
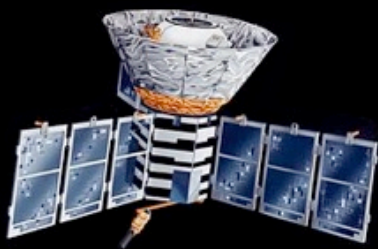
De Klerk concession on hand-over

WORLD
2004

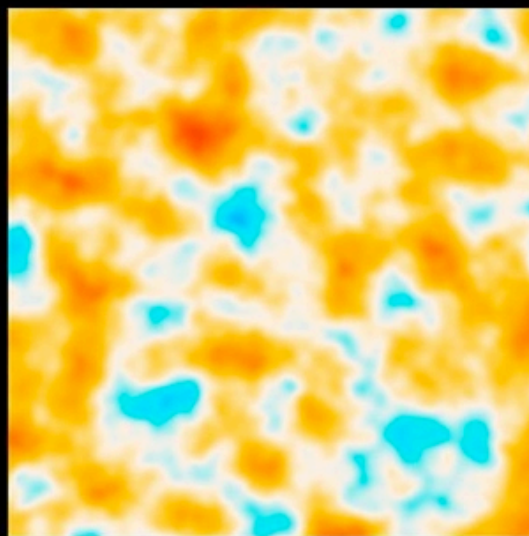
Ripples in the microwave background



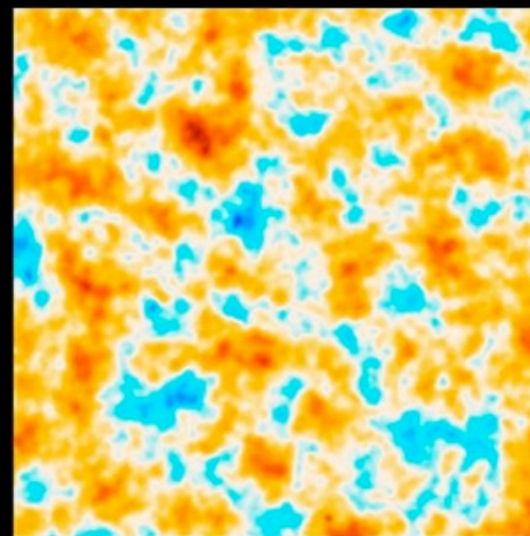
Improving the measurements



COBE

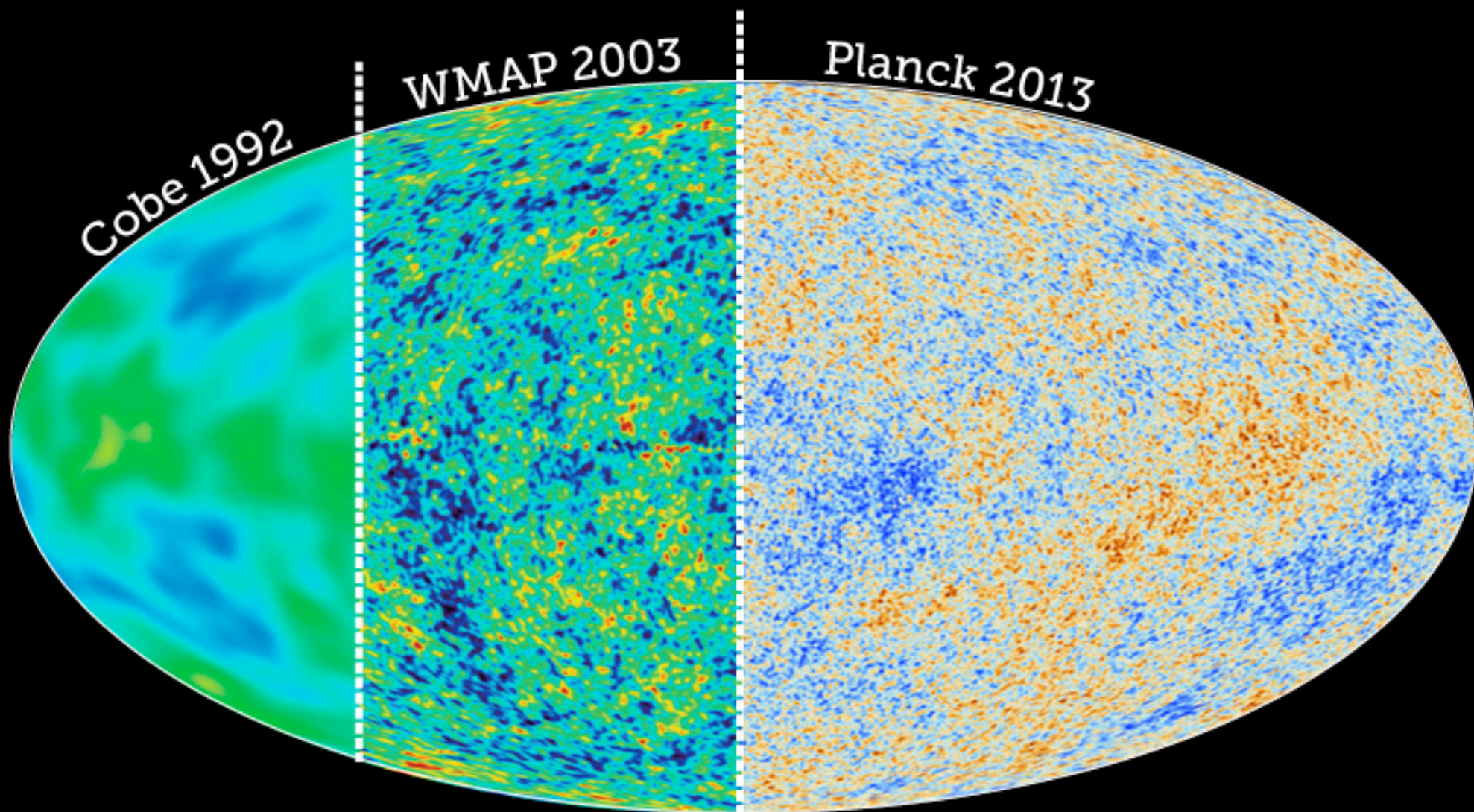


WMAP

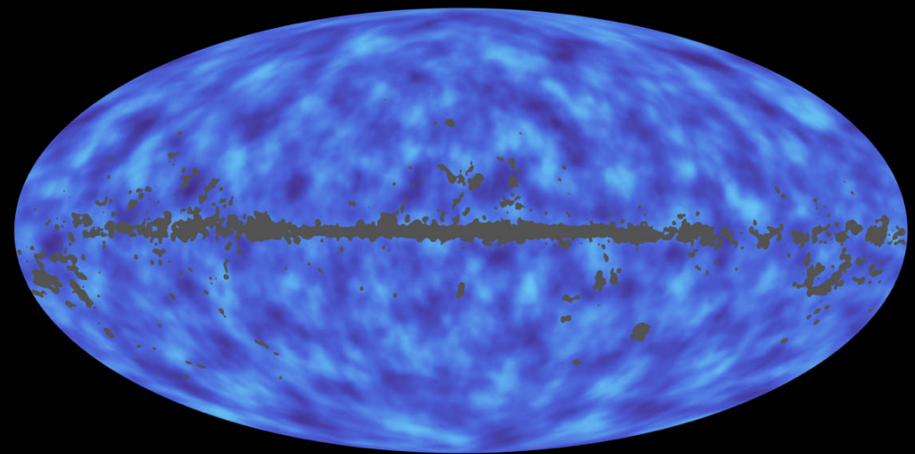
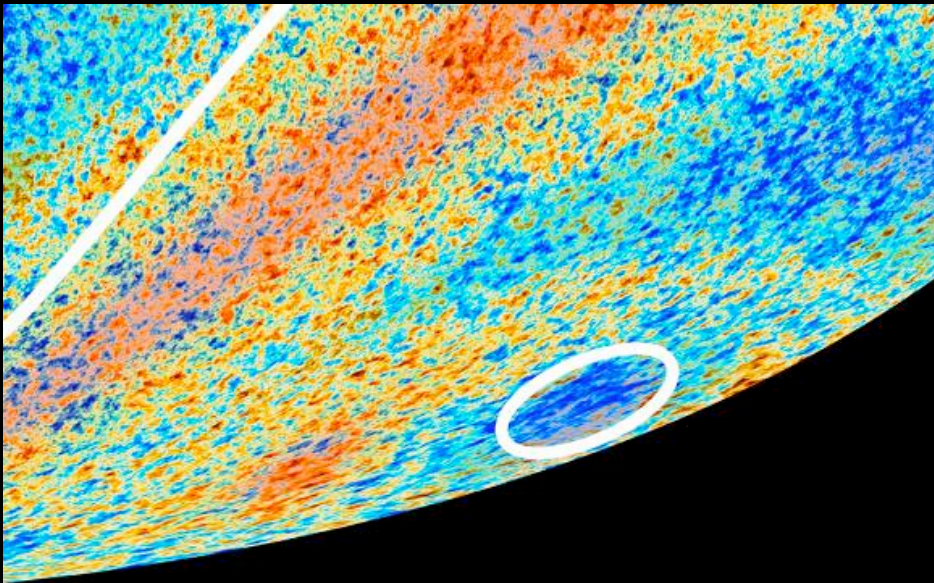
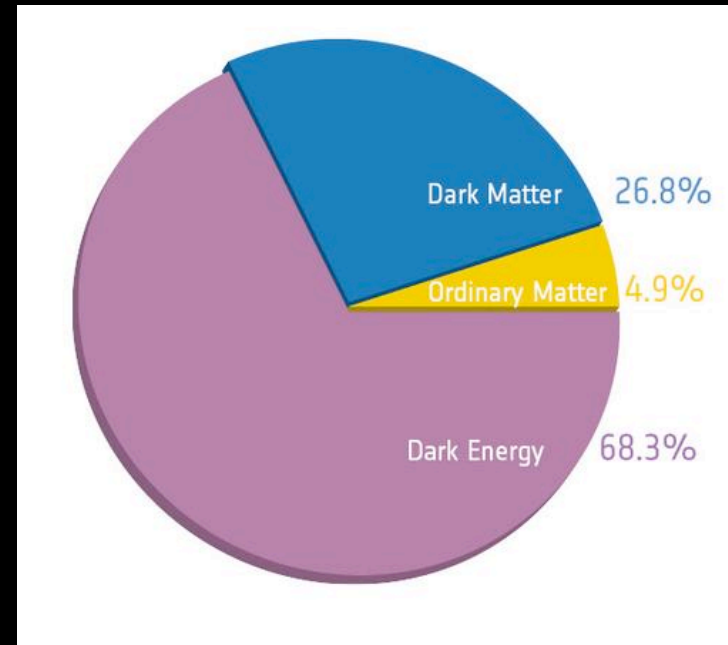
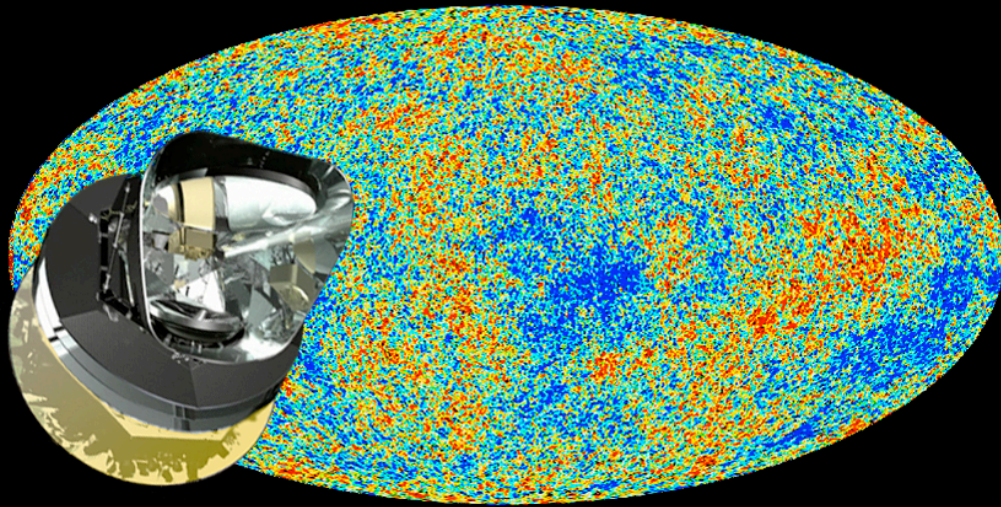


Planck

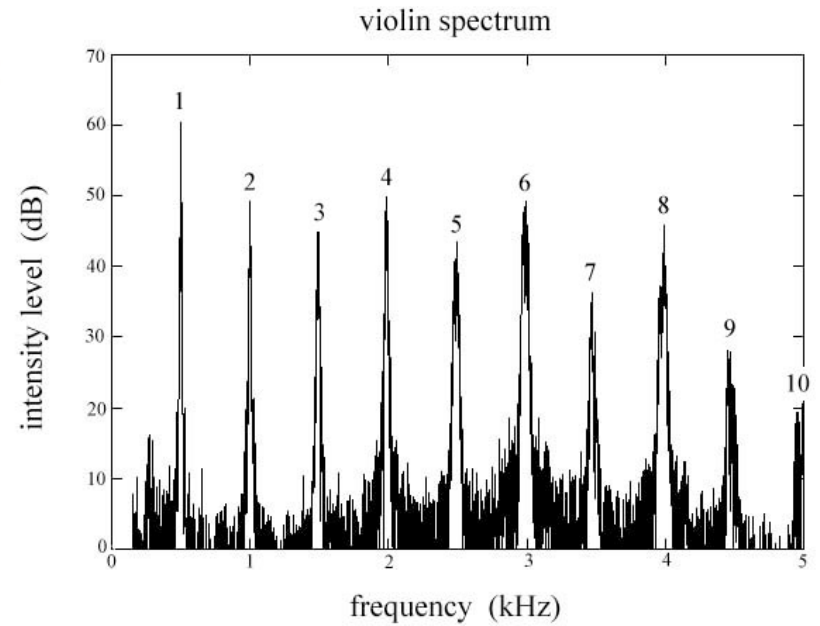
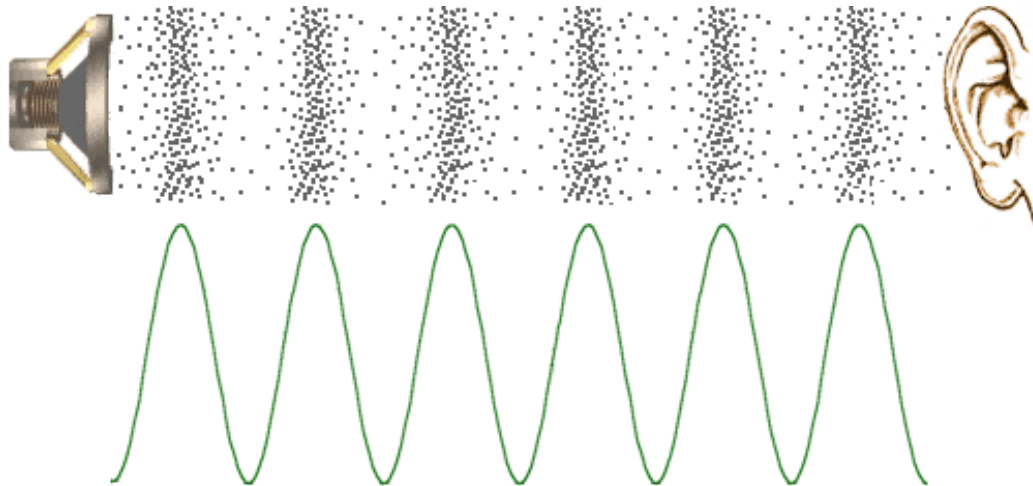
Improving the measurements



Results from the Planck mission



Sound waves!



Fundamental mode
First harmonic



First overtone
Second harmonic



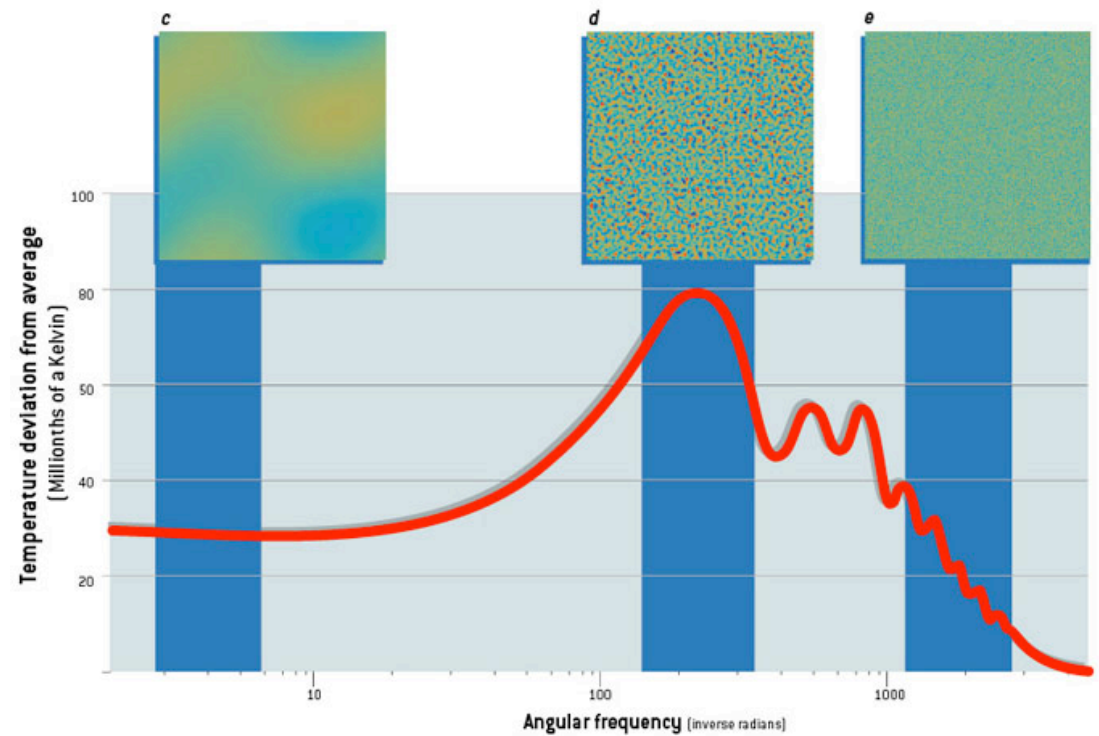
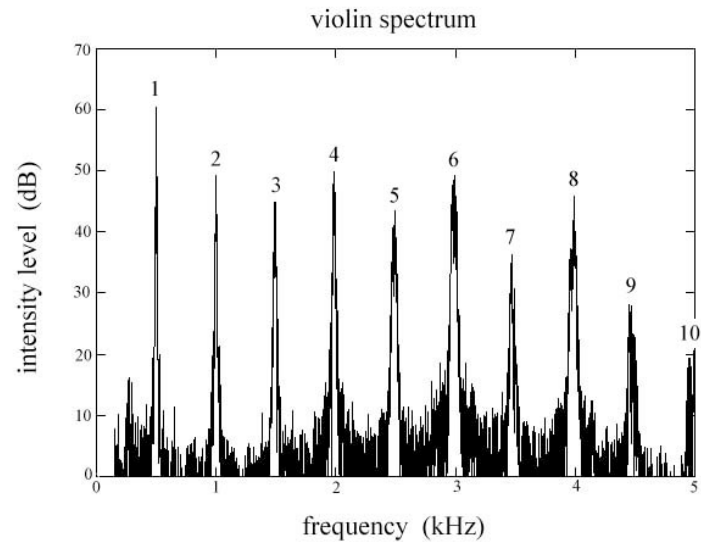
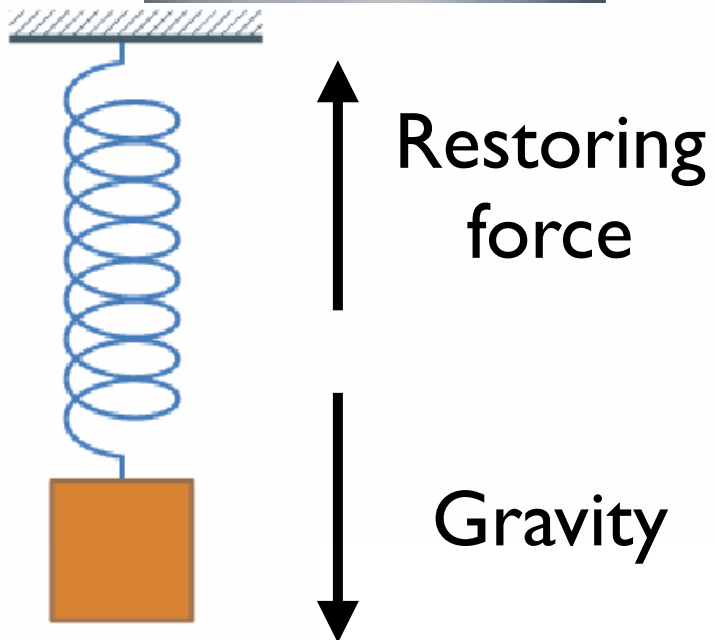
Second overtone
Third harmonic



Third overtone
Fourth harmonic



The acoustic spectrum



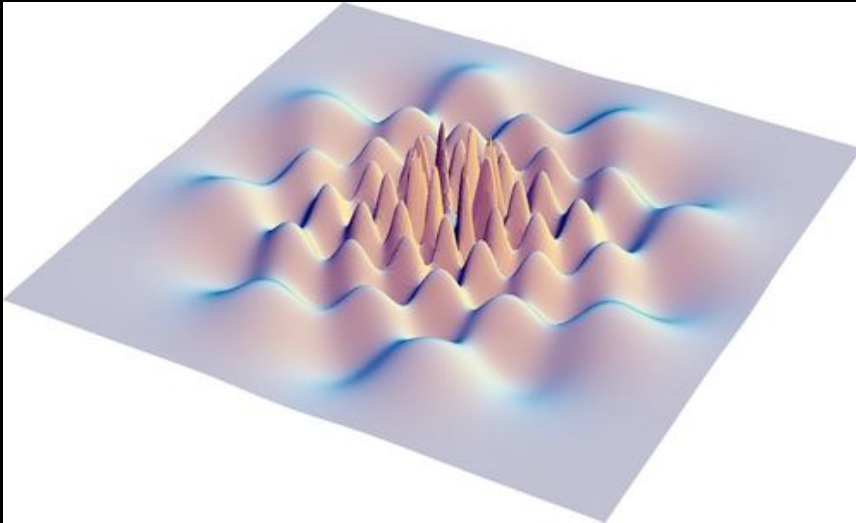
The next question ...

The next question ...

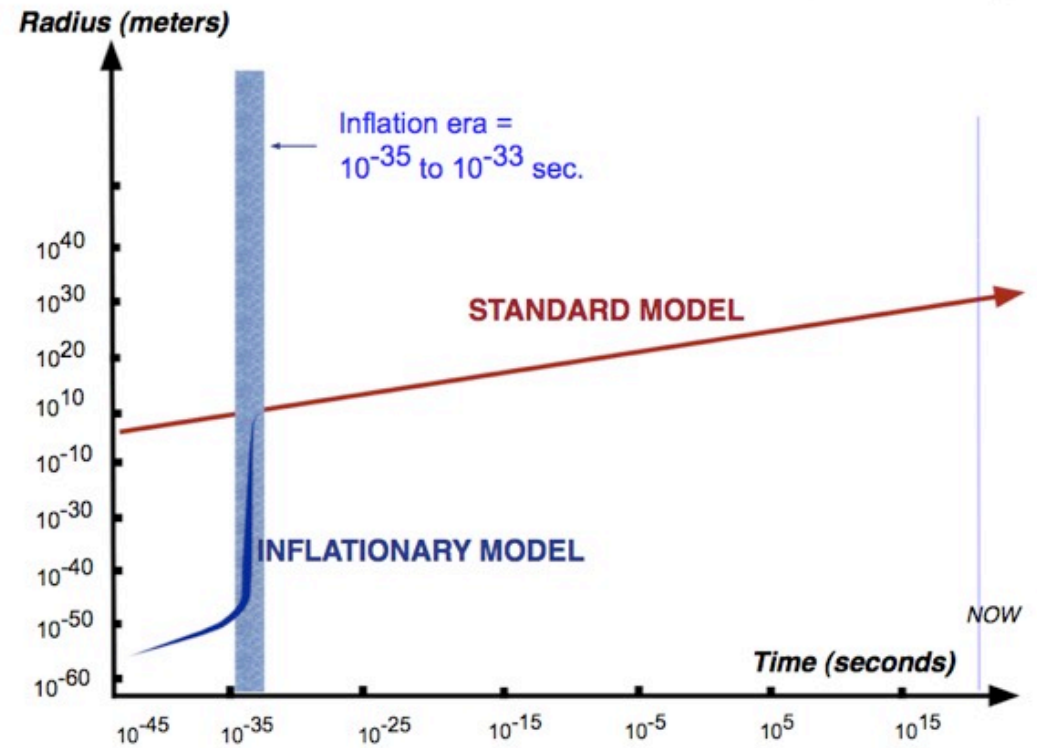
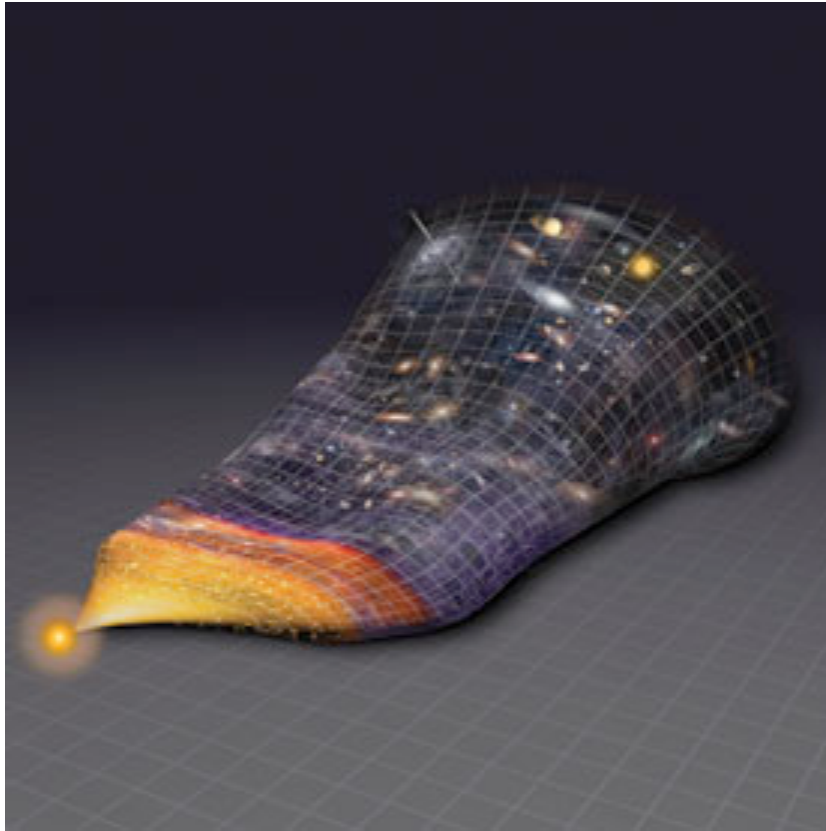
- Where did these ripples come from in the first place?

The next question ...

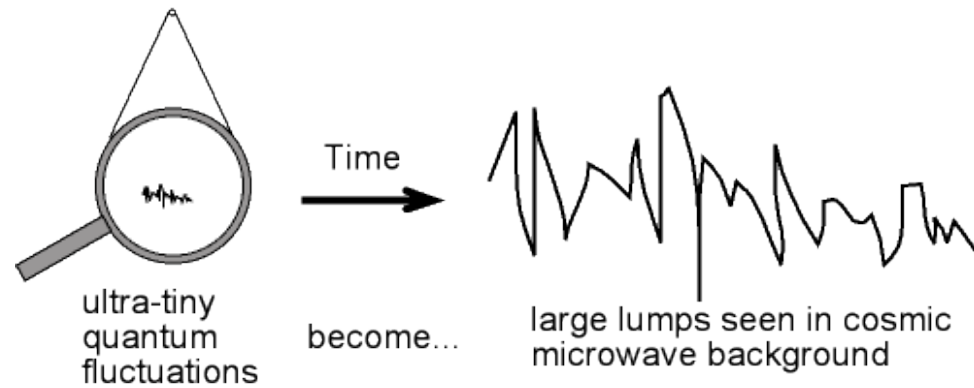
- Where did these ripples come from in the first place?



Inflation

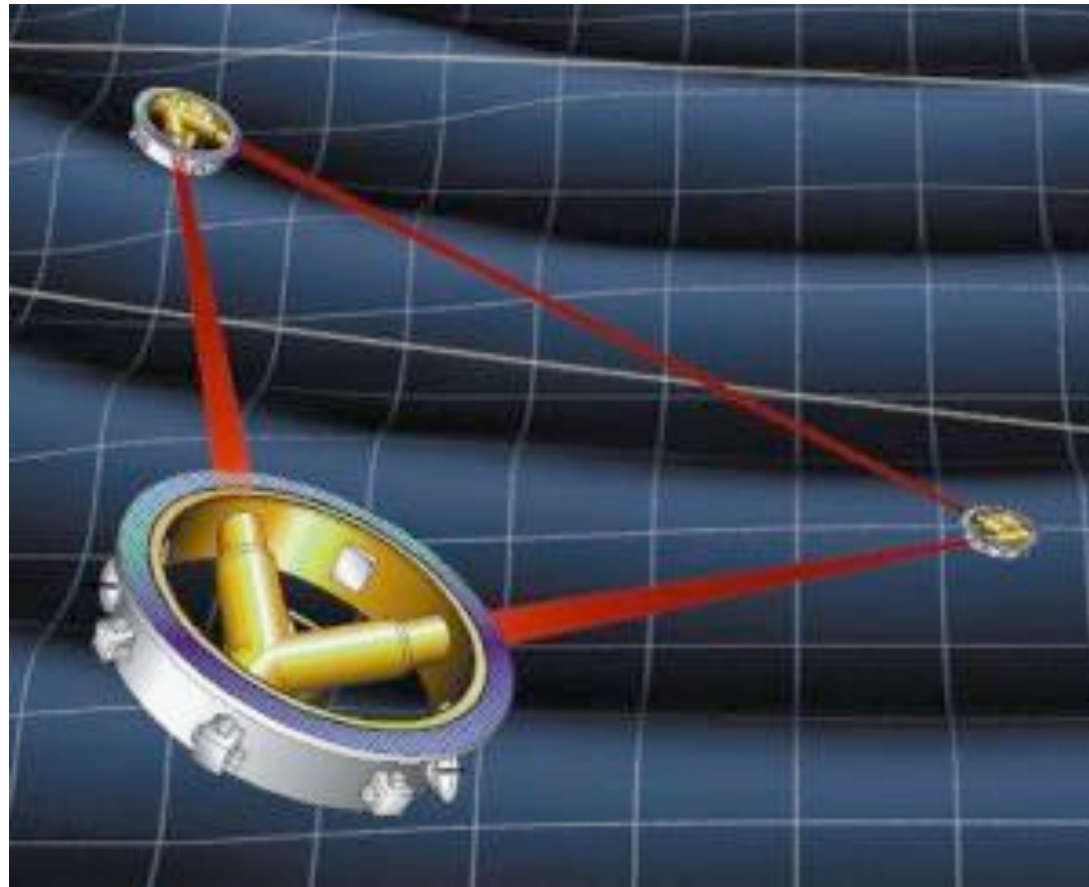


EXPANSION OF THE OBSERVABLE UNIVERSE



Inflation

- Could test by detecting gravitational waves!



The story so far

