The background of the slide is a grid of approximately 10x10 small square panels. Each panel contains a different image of a galaxy or nebula, showing various colors like blue, orange, and white against a dark background. The images are slightly blurred and have a soft, ethereal quality.

Subodh Patil

NBIA

Nov 19 2018

# Structure Formation in the Universe — From the Big Bang to the Big Rip?

Physicists like to think in terms of “characteristic” scales...



... the `typical' size of something or some process.

Physicists like to think in terms of “characteristic” scales...



The Universe is full of different structures with vastly different characteristic scales.

Can you conceive of a number this big?

$$10^{27}$$

Can you conceive of a number this small?

$$10^{-35}$$

(I have great difficulty in doing so!)

$10^{-35}$  m

$10^{27}$  m

## Metric Prefixes

**Metric prefixes** are pretty easy to understand and very handy for metric conversions. You don't have to know the nature of a unit to convert, for example, from *kilo-unit* to *mega-unit*. All metric prefixes are powers of 10. The most commonly used prefixes are highlighted in the table.

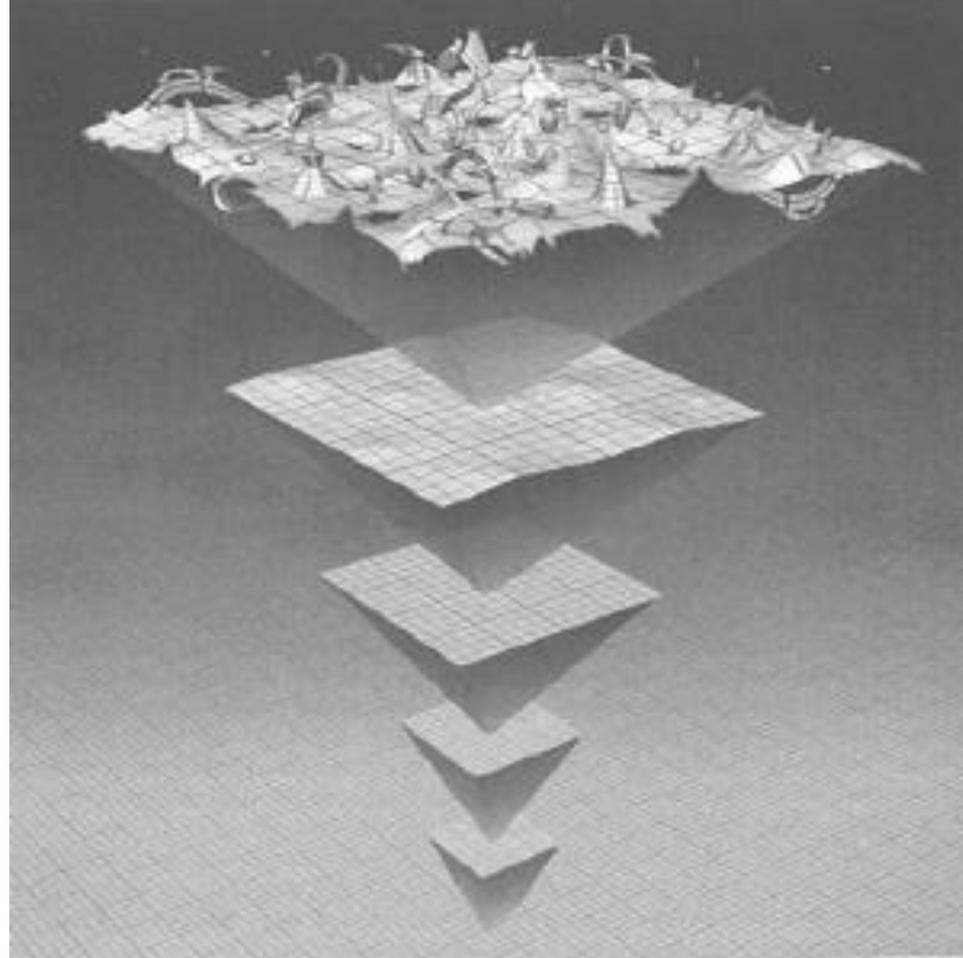
Prefix	Symbol	Factor
yotta	Y	$10^{24} = 1,000,000,000,000,000,000,000,000$
zetta	Z	$10^{21} = 1,000,000,000,000,000,000,000,000$
exa	E	$10^{18} = 1,000,000,000,000,000,000,000,000$
peta	P	$10^{15} = 1,000,000,000,000,000,000,000,000$
tera	T	$10^{12} = 1,000,000,000,000,000,000,000,000$
<b>giga</b>	<b>G</b>	$10^9 = 1,000,000,000$
<b>mega</b>	<b>M</b>	$10^6 = 1,000,000$
<b>kilo</b>	<b>k</b>	$10^3 = 1,000$
hecto	h	$10^2 = 100$
deka	da	$10^1 = 10$
<b>deci</b>	<b>d</b>	$10^{-1} = 0.1$
<b>centi</b>	<b>c</b>	$10^{-2} = 0.01$
<b>milli</b>	<b>m</b>	$10^{-3} = 0.001$
<b>micro</b>	<b>μ</b>	$10^{-6} = 0.000,001$
nano	n	$10^{-9} = 0.000,000,001$
pico	p	$10^{-12} = 0.000,000,000,001$
femto	f	$10^{-15} = 0.000,000,000,000,001$
atto	a	$10^{-18} = 0.000,000,000,000,000,001$
zepto	z	$10^{-21} = 0.000,000,000,000,000,000,001$
yocto	y	$10^{-24} = 0.000,000,000,000,000,000,000,001$

Most people even in the countries where metric system is used only know the most important metric prefixes like 'kilo' and 'milli'. They are very handy for understanding metric conversions. The prefixes like 'zepto' or 'yotta' are very specific and used mostly in science.

The 'Planck length' – the smallest scale at which geometry makes sense.

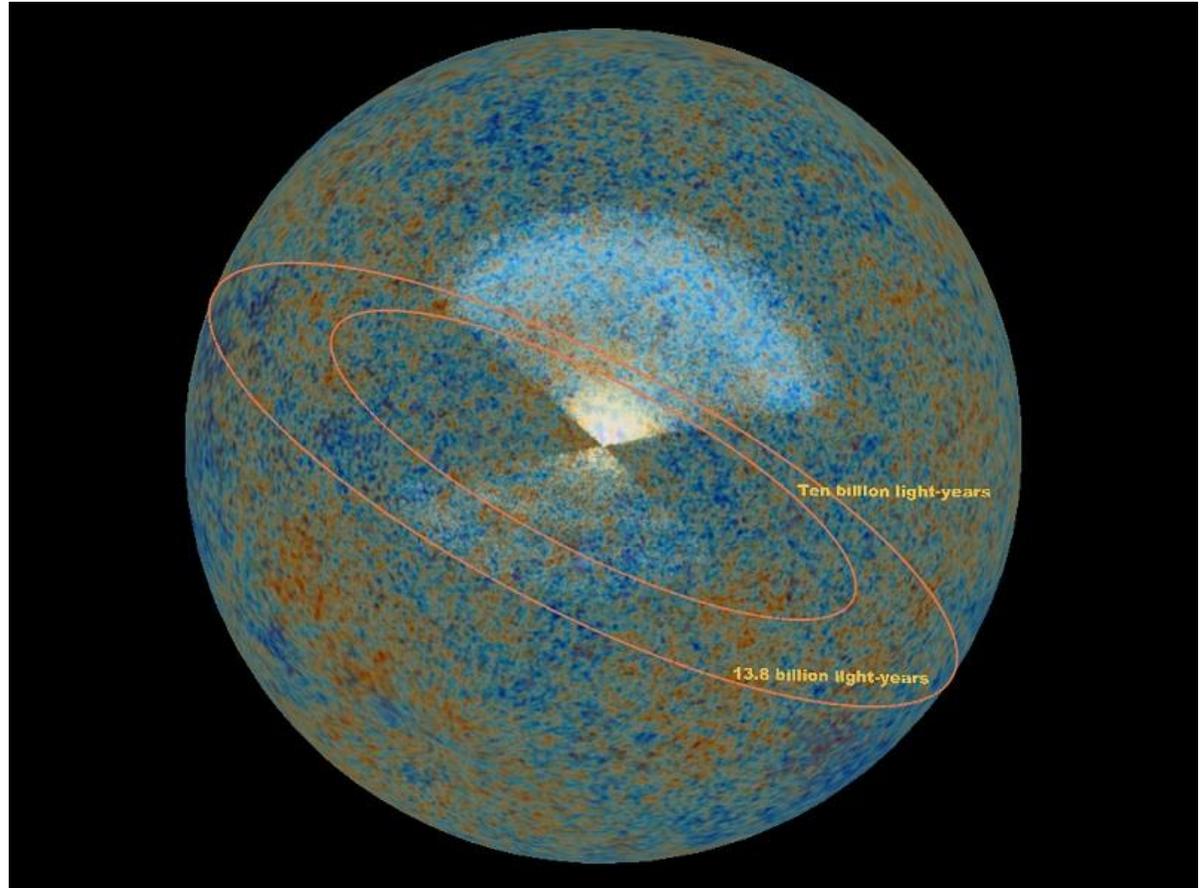
$$10^{-35} \text{ m}$$

$$10^{27} \text{ m}$$

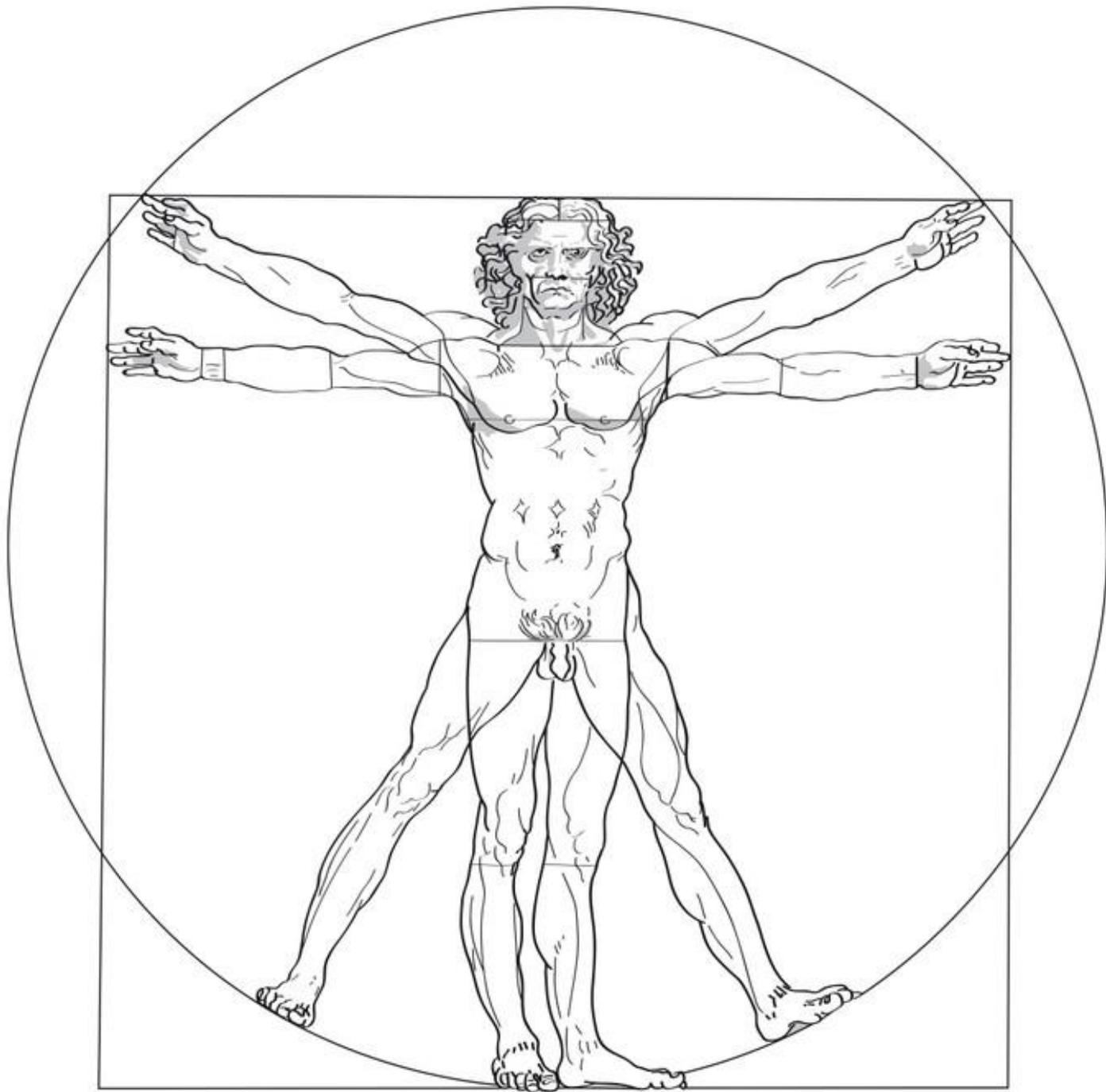


$10^{-35}$  m

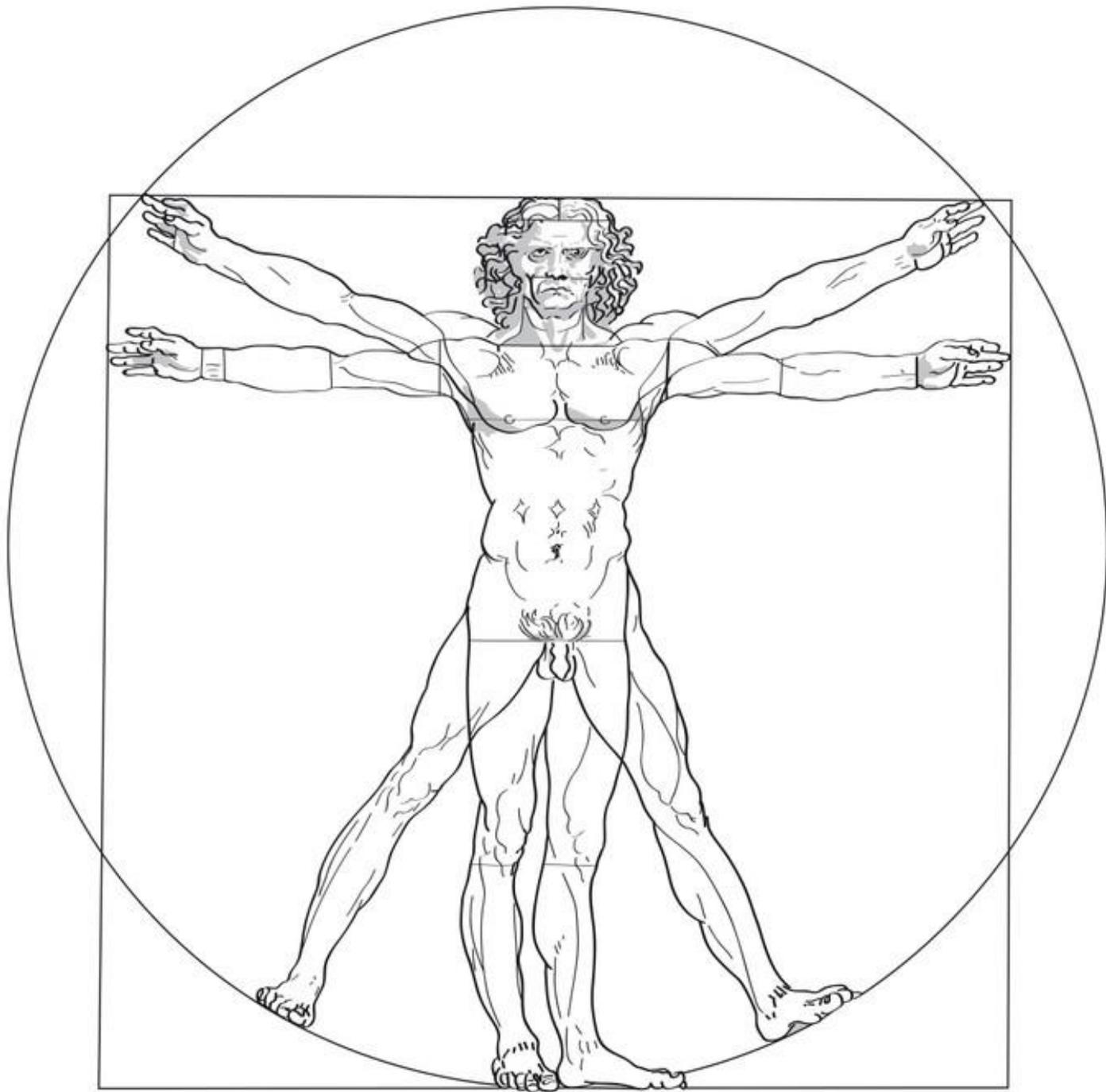
$10^{27}$  m



The Hubble horizon – the edge of the observable universe.



These scales of the Universe are far beyond those of our everyday experience...



But we can bring them back to a more human scale by converting them into time...

$c = \text{speed of light}$

But we can bring them back to a more human scale by converting them into time...

$$c = 299792 \text{ Km/second}$$

But we can bring them back to a more human scale by converting them into time...

$$c = 299792 \text{ Km/second}$$

$$\text{speed} = \text{distance}/\text{time}$$

But we can bring them back to a more human scale by converting them into time...

$$c = 299792 \text{ Km/second}$$

$$\text{speed} \times \text{time} = \text{distance}$$

But we can bring them back to a more human scale by converting them into time...

**1/7 of a second**



**(amount of time light takes to circumnavigate the earth)**

**1 second**



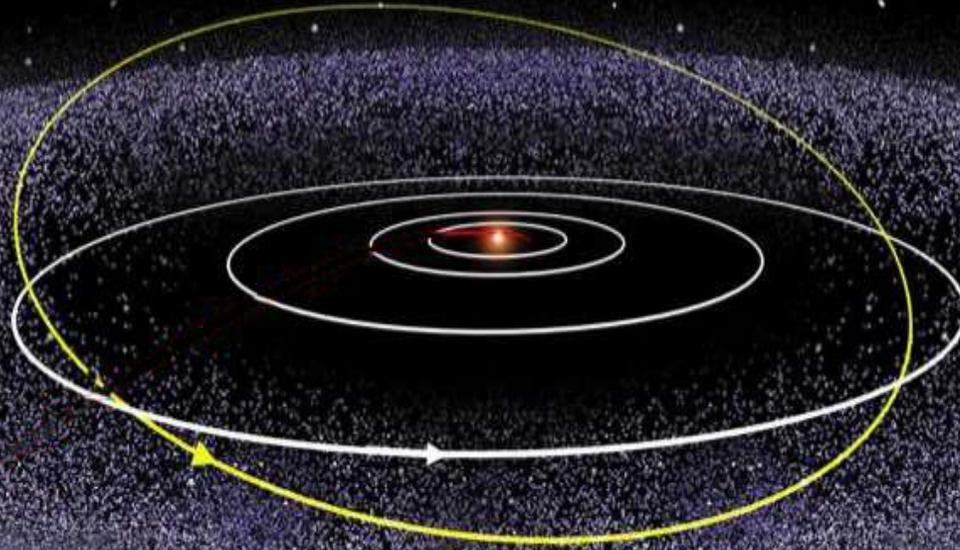
**(amount of time light takes to travel to the moon)**

**8 minutes 20 seconds**

**(amount of time light takes to travel from sun to the earth)**



**5 hours**



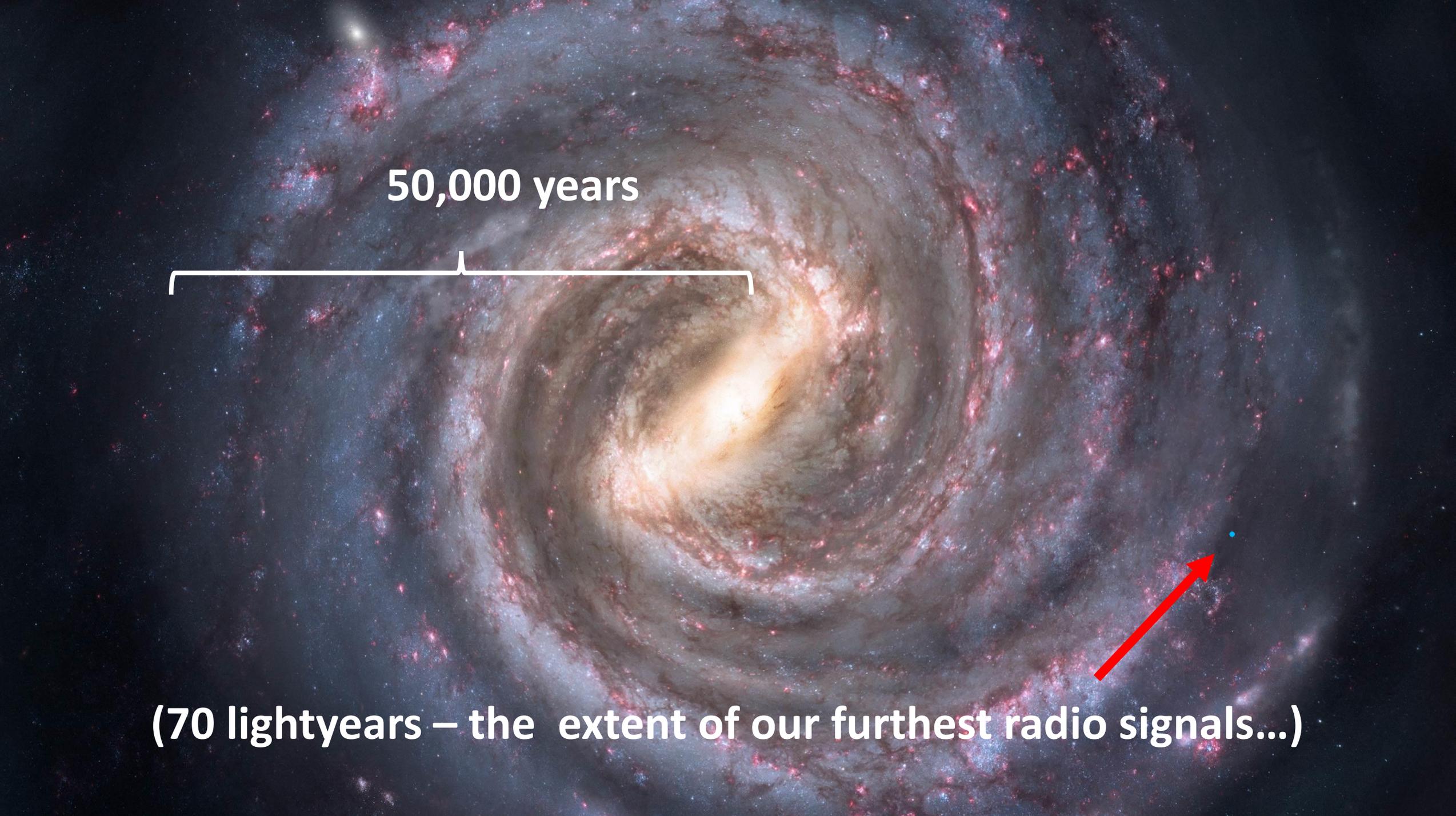
**(amount of time light takes to travel from the Sun to Pluto)**

A wide-field photograph of a star field, likely the constellation Centaurus. Two bright, white stars are prominent in the upper half of the frame. A small red circle is drawn around a fainter star in the lower-middle section. The background is filled with numerous smaller, dimmer stars of various colors.

**4 years, 3 months**

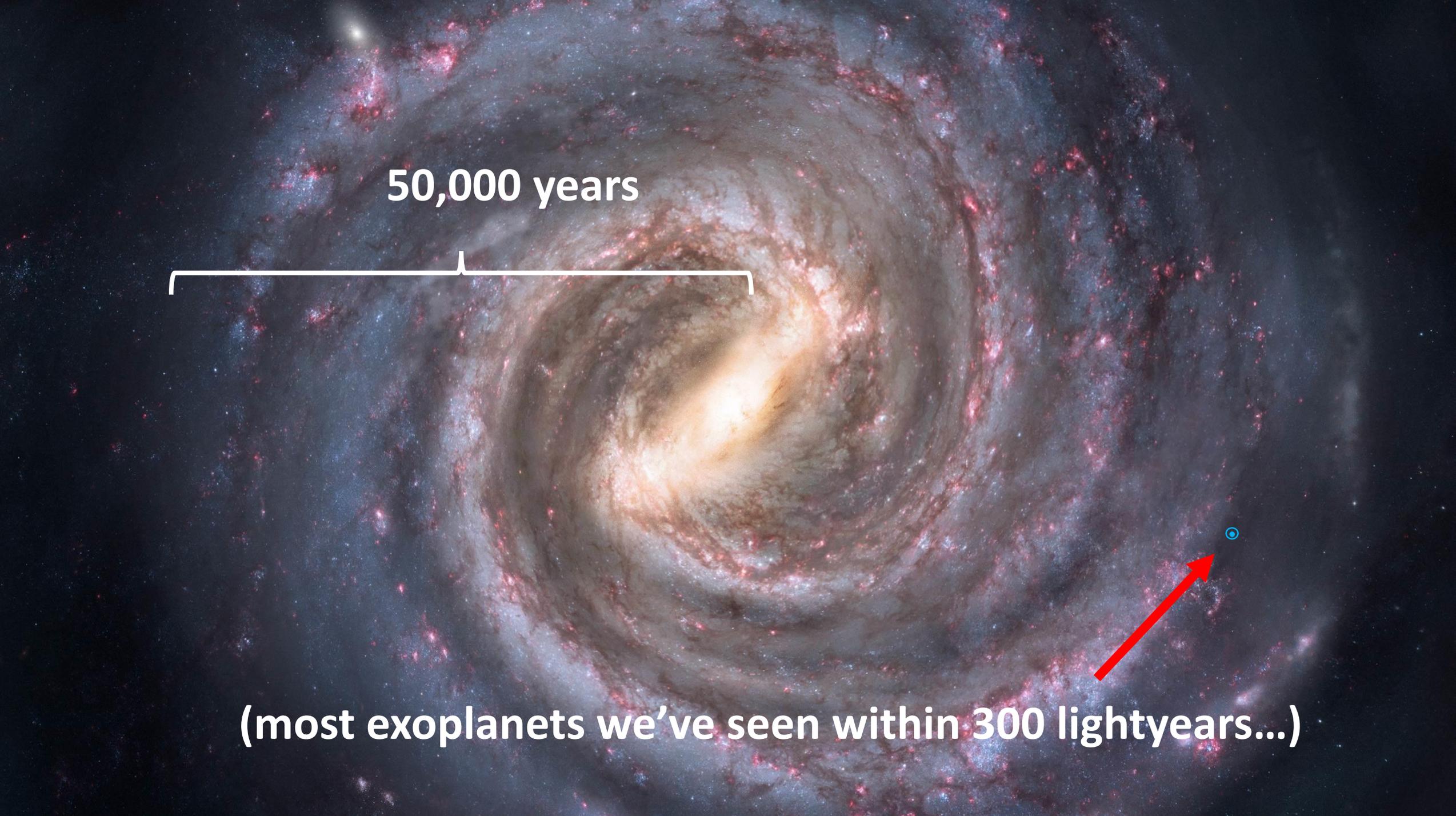
**(distance to Proxima Centauri)**





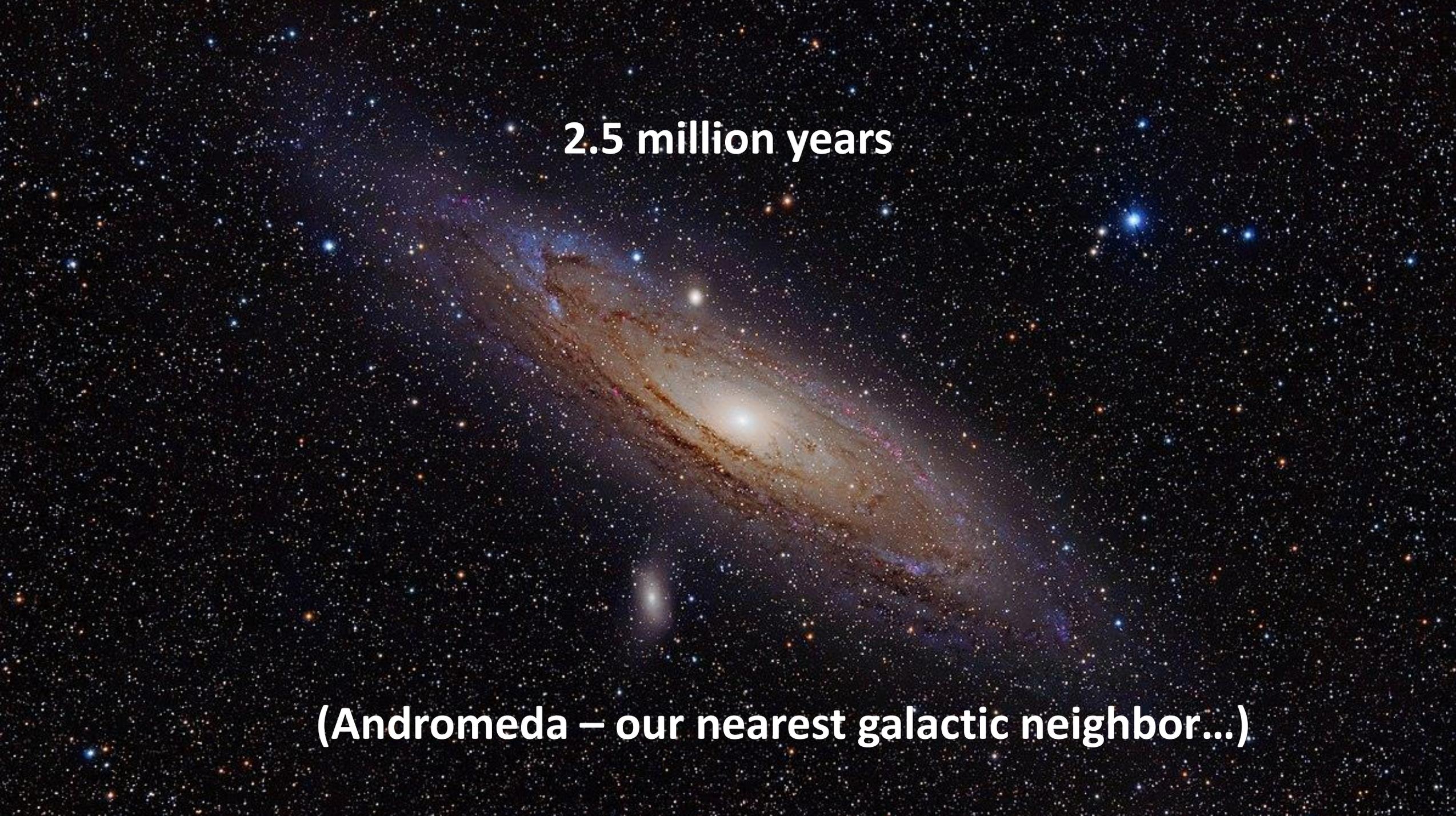
50,000 years

(70 lightyears – the extent of our furthest radio signals...)



50,000 years

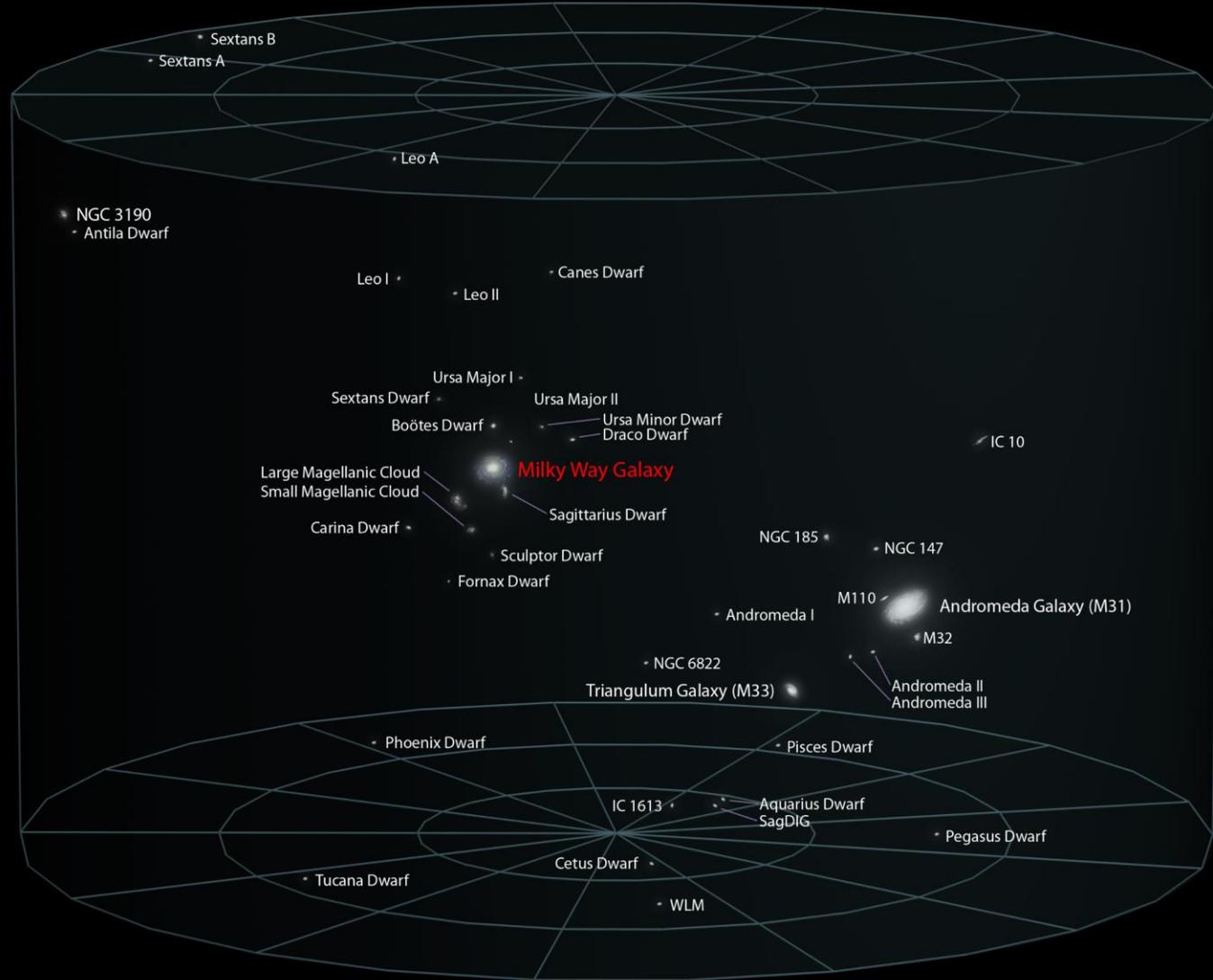
(most exoplanets we've seen within 300 lightyears...)



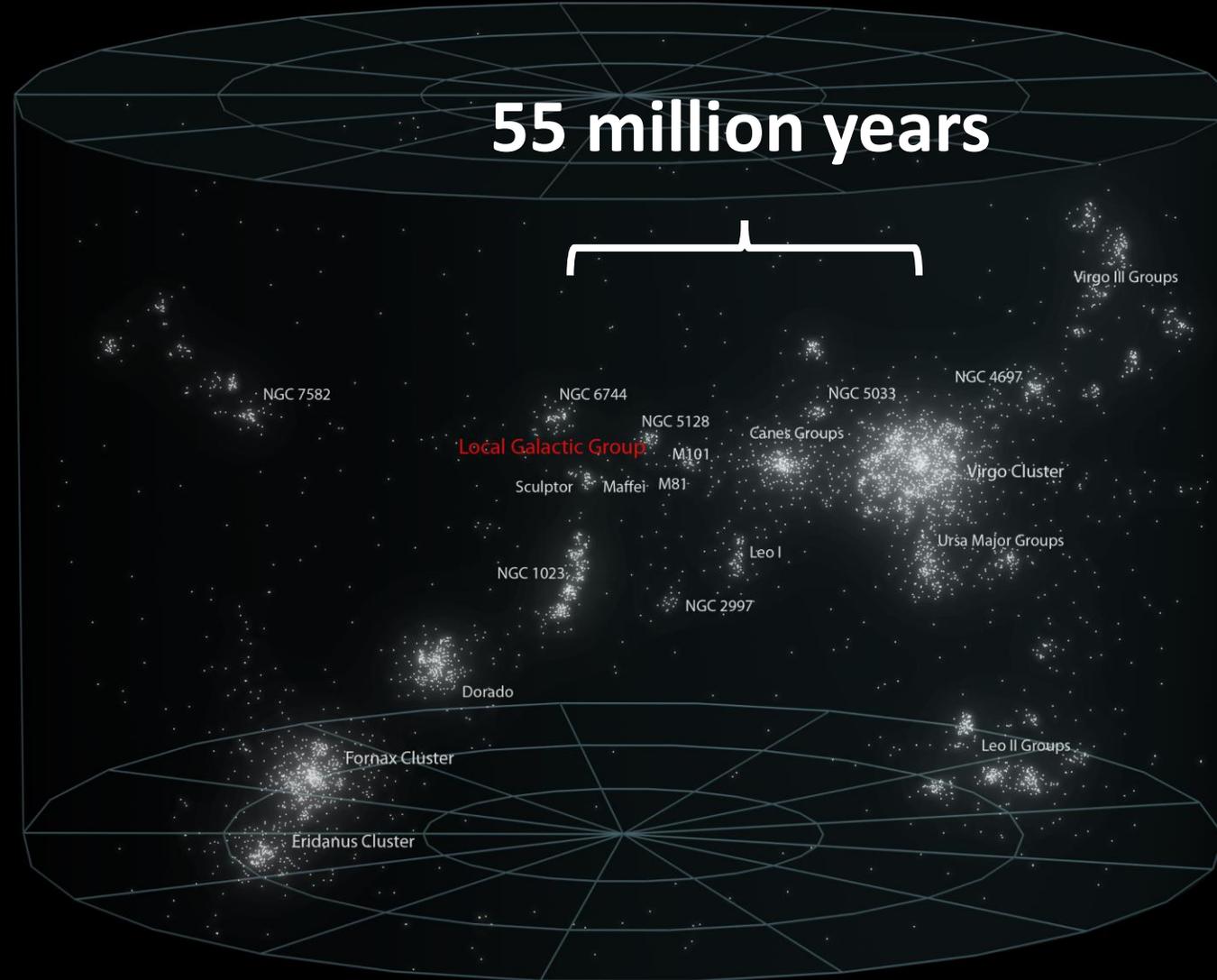
**2.5 million years**

**(Andromeda – our nearest galactic neighbor...)**

# Local Galactic Group

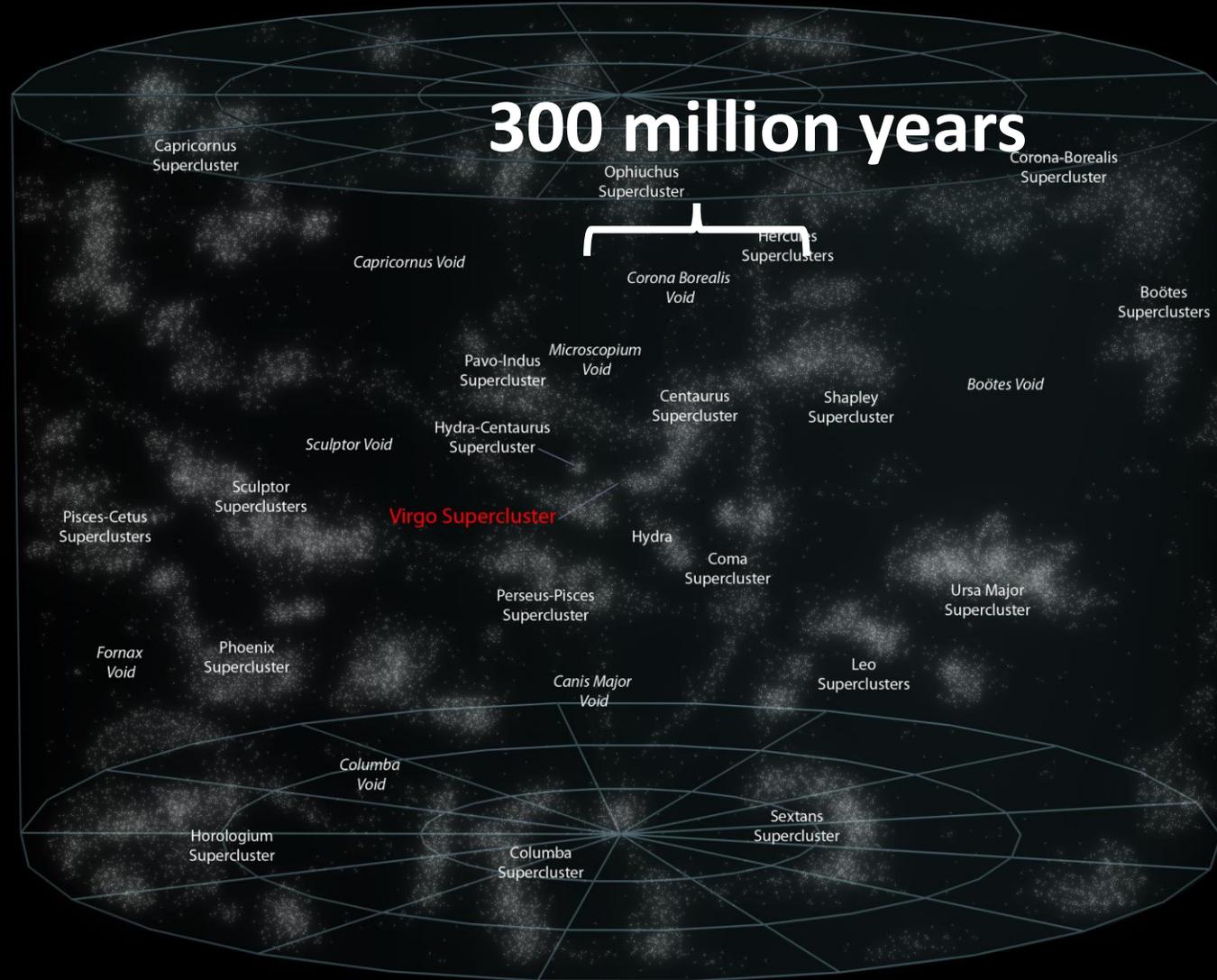


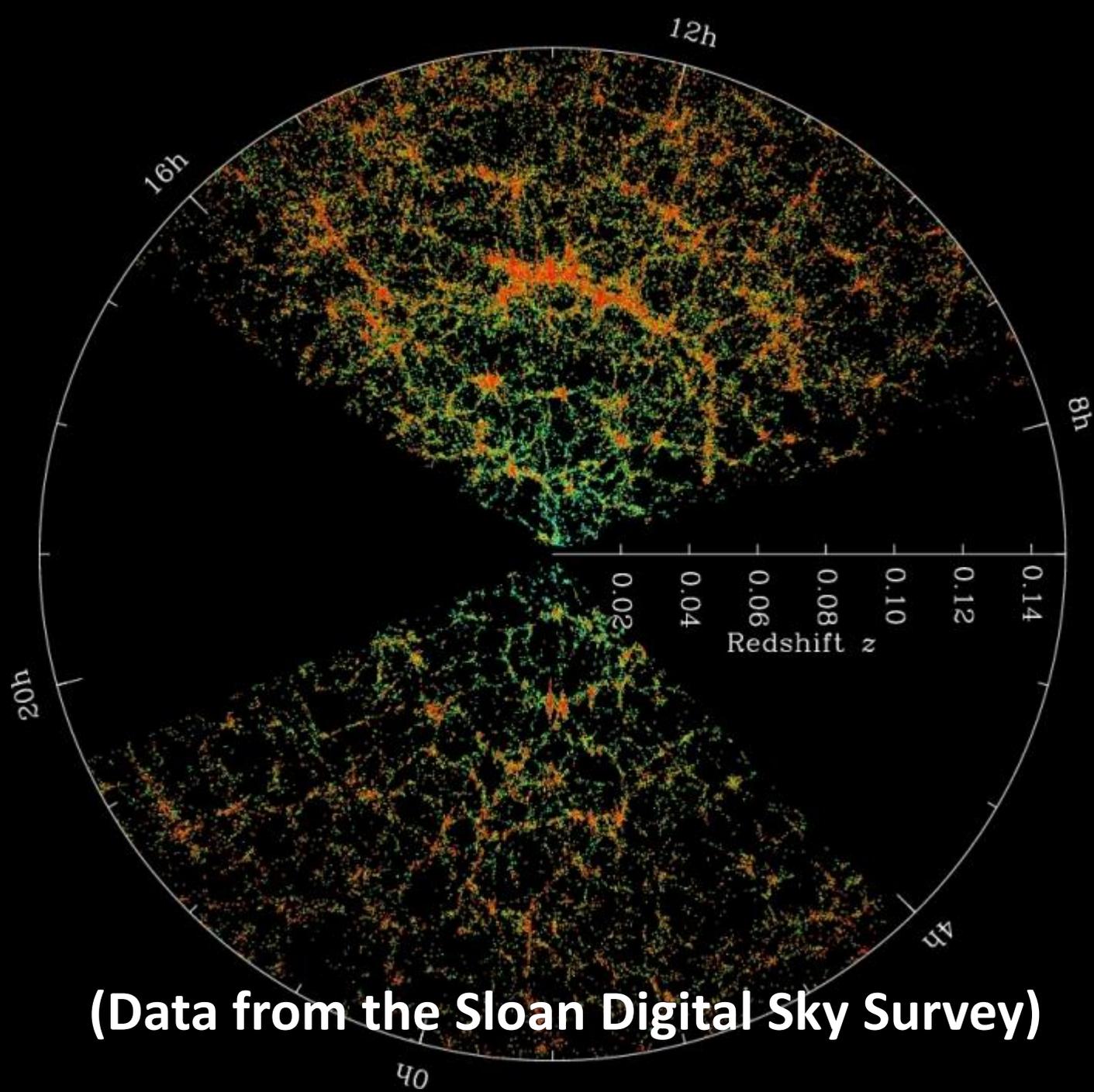
# VIRGO SUPERCLUSTER



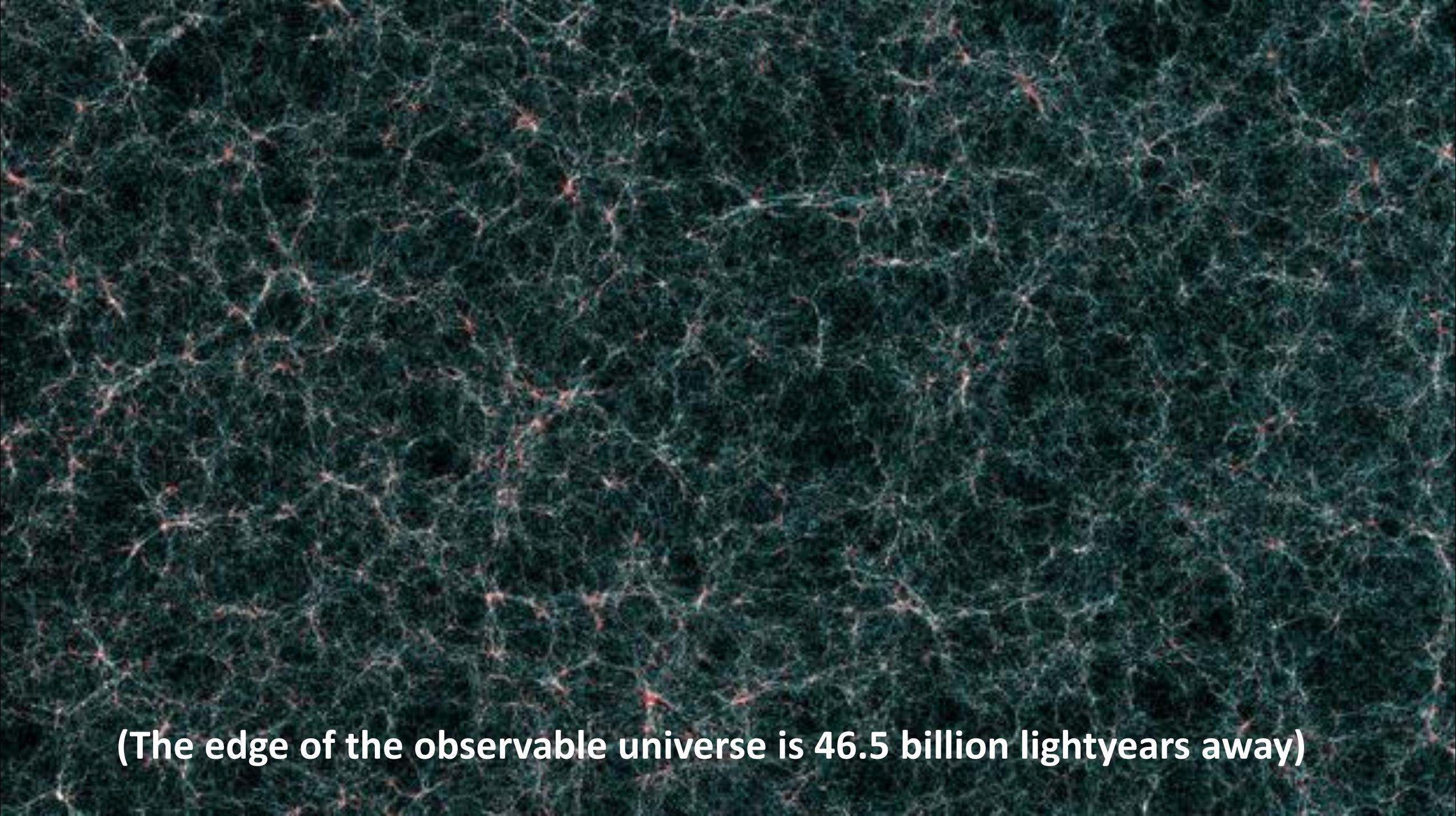
(There are about 10 million superclusters in our observable universe...)

# LOCAL SUPERCLUSTERS





**(Data from the Sloan Digital Sky Survey)**

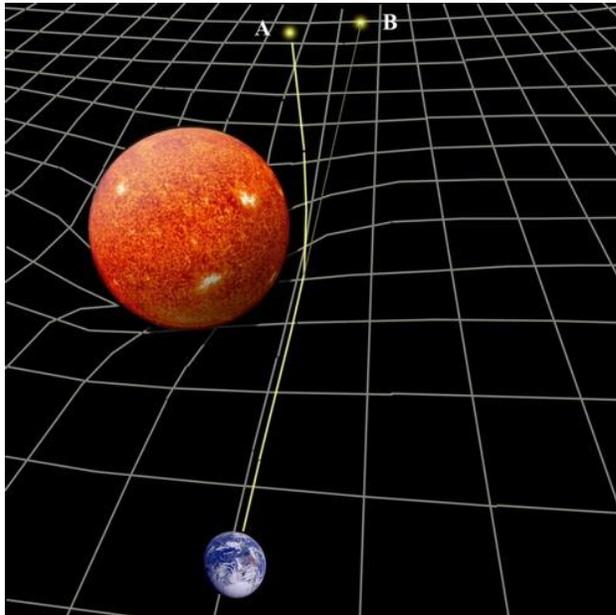
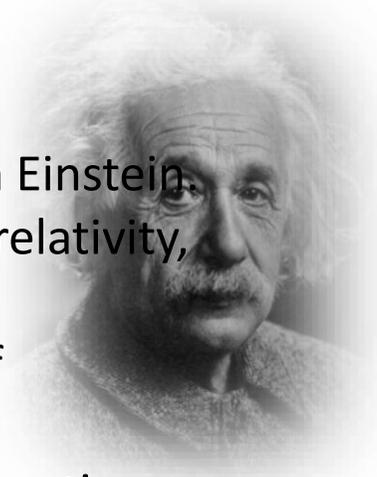


**(The edge of the observable universe is 46.5 billion lightyears away)**

**How did this all come to be?**

## Cosmology– a brief historical overview

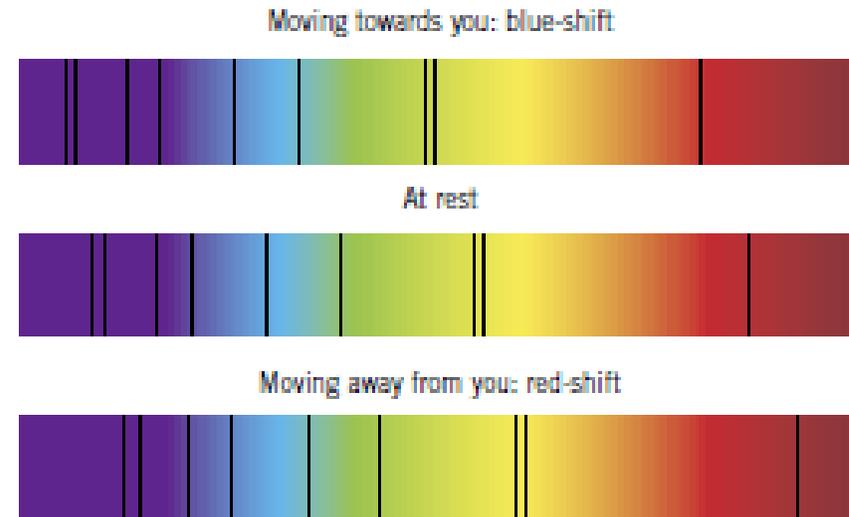
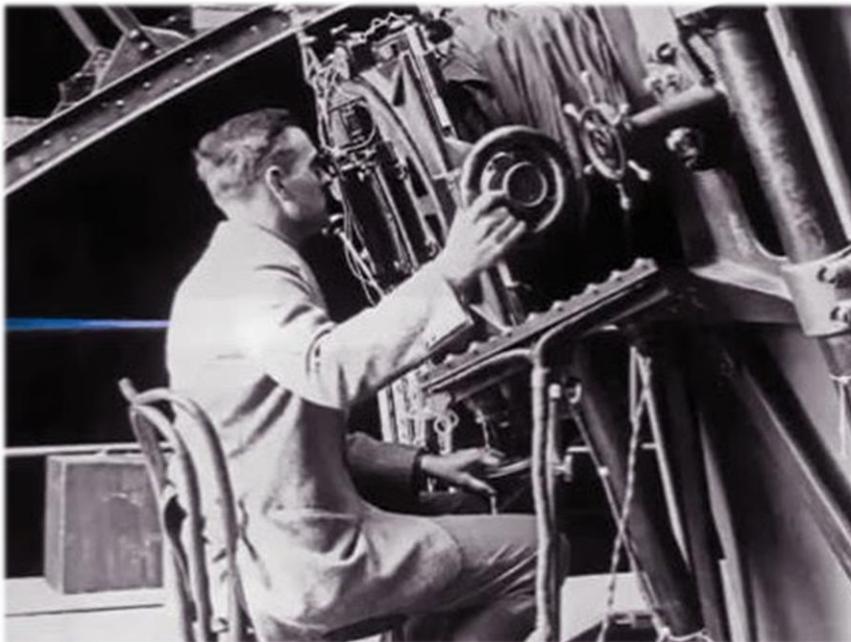
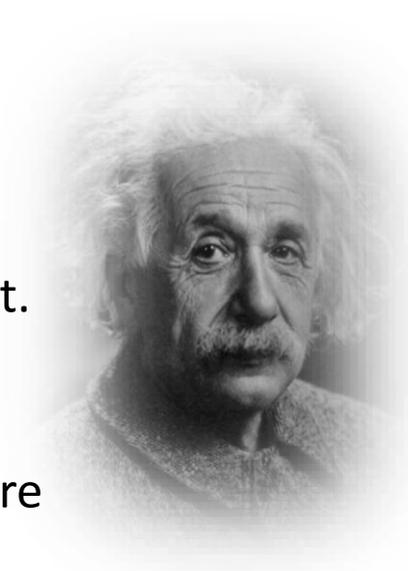
- For all intents and purposes, modern cosmology begins with Einstein.
- In trying to make Newtonian gravity consistent with special relativity, Einstein realized that:
- Gravity isn't so much a force, but a distortion in the fabric of spacetime.
- The 'Einstein equations'  $G_{\mu\nu} = 8\pi G_N T_{\mu\nu}$  determine how spacetime reacts to the presence of masses, and v.v.



- The orbits of planets around stars is simply the consequence of masses moving along straight lines 'geodesics' in a 'curved' geometry.
- Geodesics-- c.f. airplanes on the surface of the earth.
- Spacetime is dynamical!
- The same must be true of the universe on the largest scales.
- But this cannot be, right?

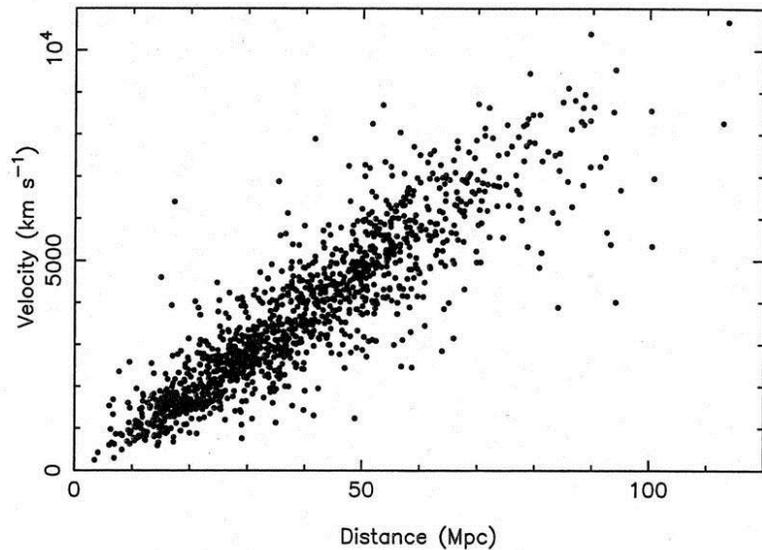
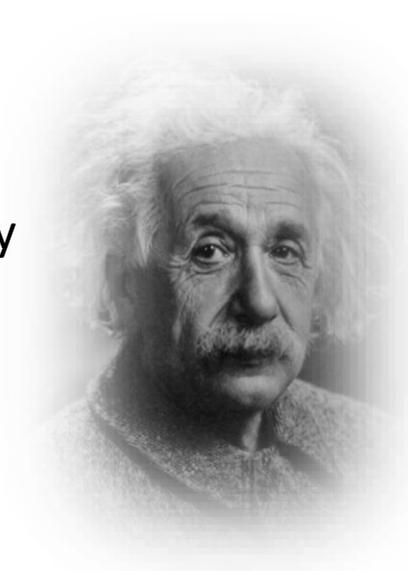
# Cosmology– a brief historical overview

- Einstein was so embarrassed by the fact that his theory predicted an expanding/ contracting universe, he modified it.
- “The biggest blunder of my life”:
- $G_{\mu\nu} = 8\pi G_N T_{\mu\nu} + g_{\mu\nu}\Lambda \leftarrow$  the cosmological constant\*
- Until of course, Hubble observed that all distant galaxies were all moving away from us, by looking at how the spectrum of hydrogen was ‘red-shifted’



## Cosmology– a brief historical overview

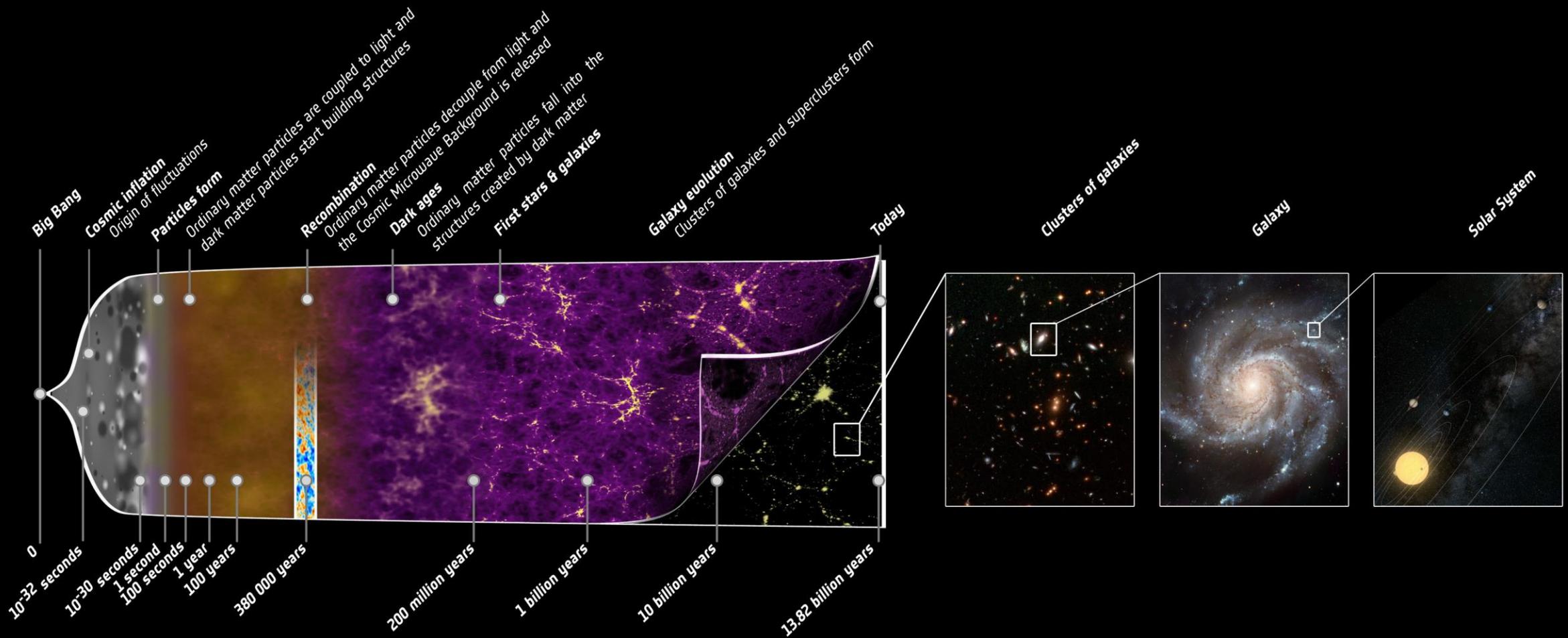
- So stars appear to be moving away from us at a rate given by Hubble's law--  $v = H r$
- This implies that the universe is expanding.
- Rewind the film far back enough, then all matter must have been squeezed into some very hot, dense initial state.



**Figure 2.5** A plot of velocity versus estimated distance for a set of 1355 galaxies. A straight-line relation implies Hubble's law. The considerable scatter is due to observational uncertainties and random galaxy motions, but the best-fit line accurately gives Hubble's law. [The  $x$ -axis scale assumes a particular value of  $H_0$ .]

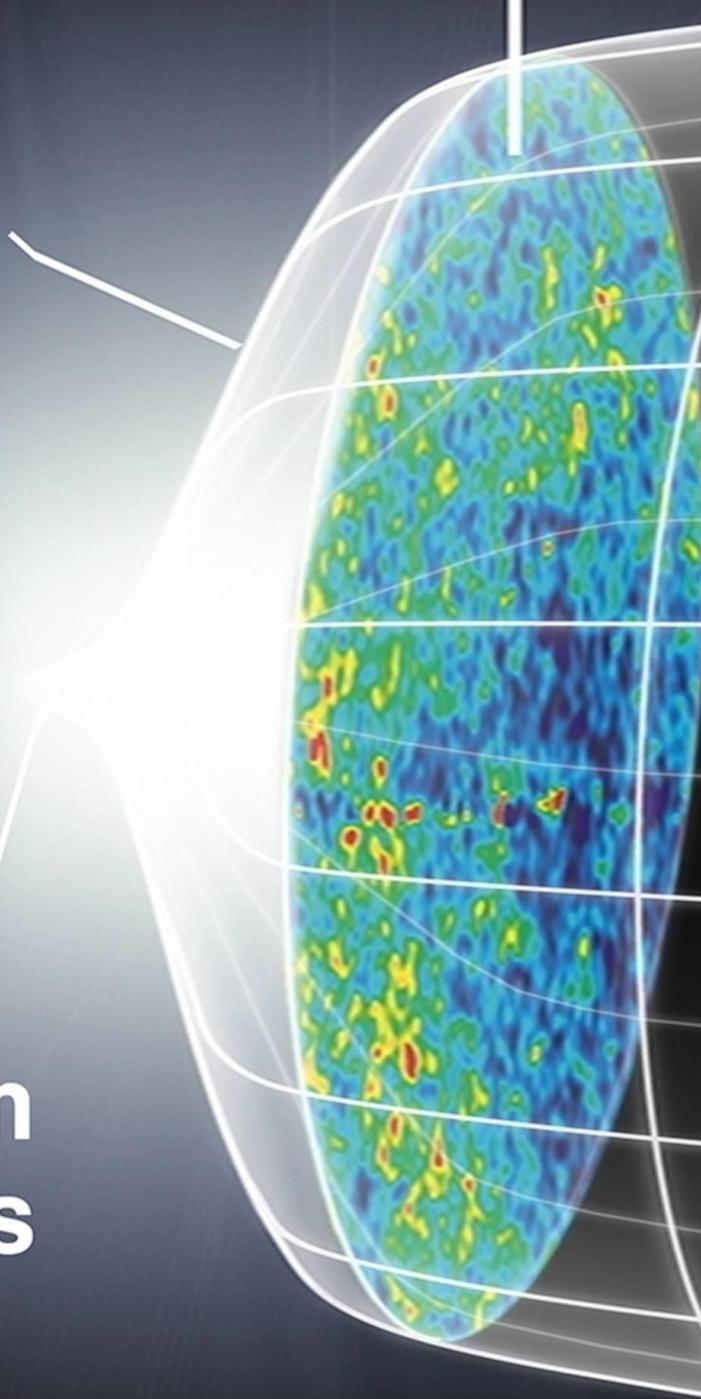
- Friedmann, Lemaitre, Robertson and Walker wrote down solutions to Einstein's equations that reproduced Hubble's law.
- Implies that the universe began in some sort of a 'big bang'.
- Lemaitre referred to the initial state as the 'primeval atom'.

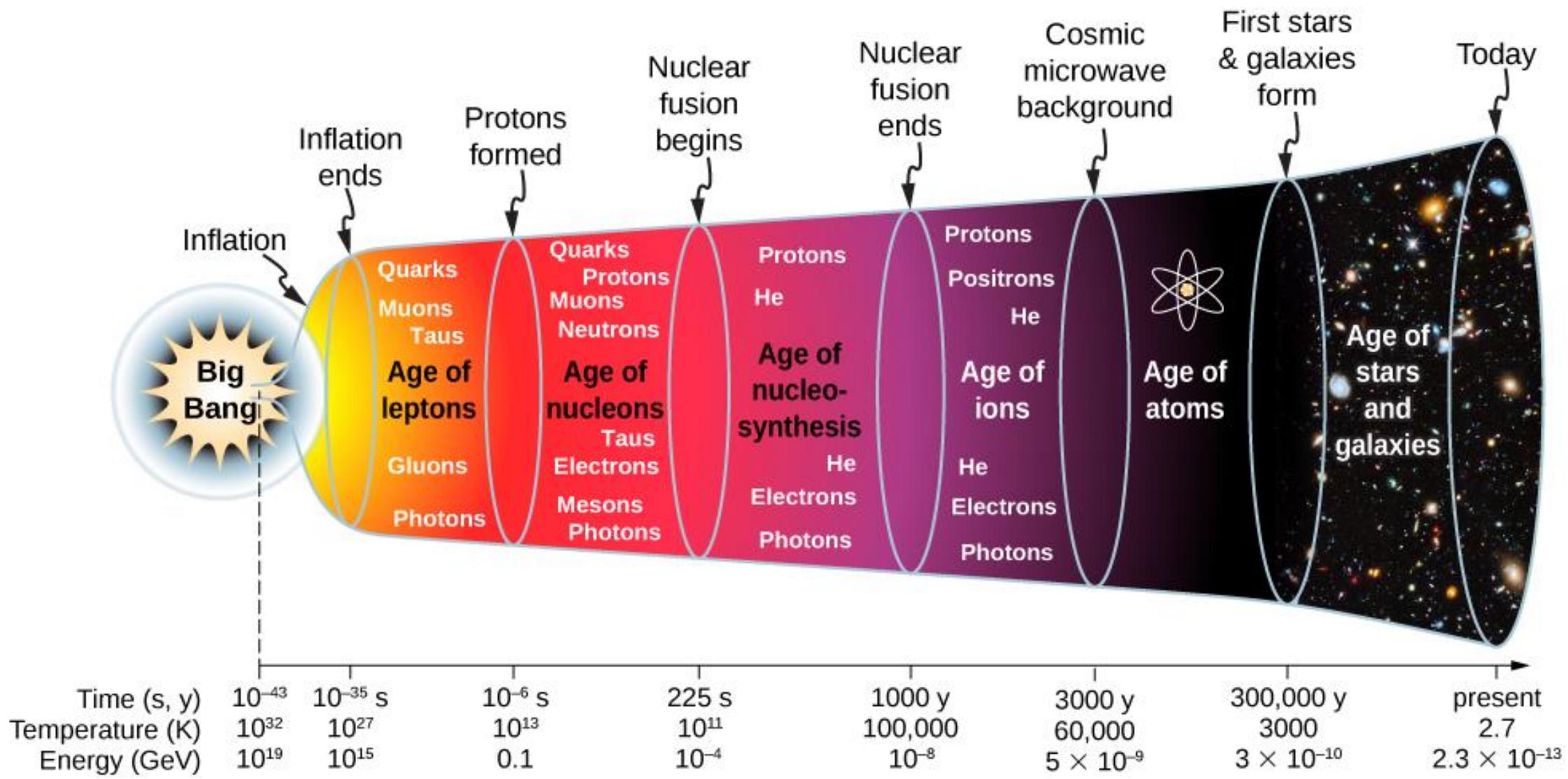
The Big Bang model is the simple result of Einstein's equations, with added simplifying assumptions of symmetry (homogeneity, isotropy) and the properties of matter (thermal equilibrium)... and It makes predictions!

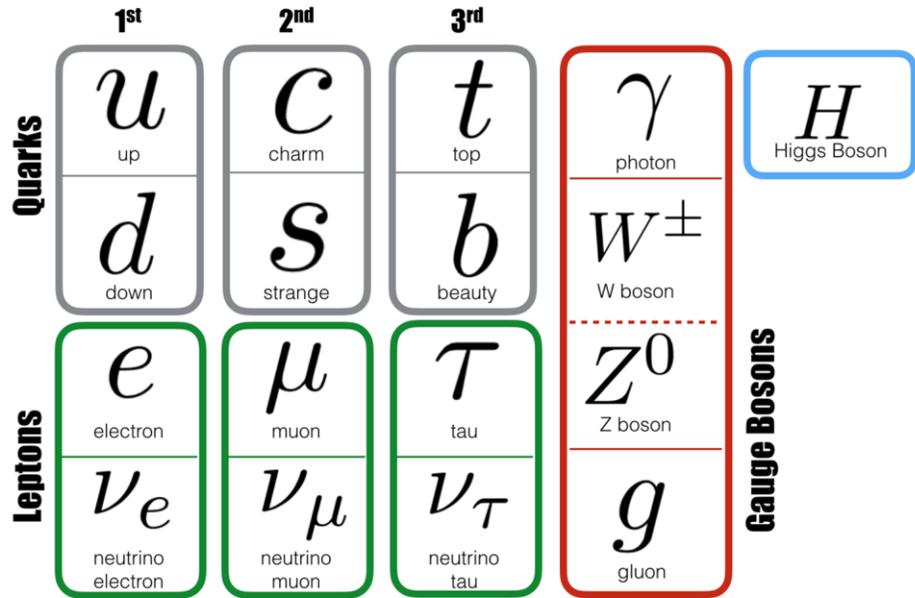


**Inflation**

**Quantum  
Fluctuations**

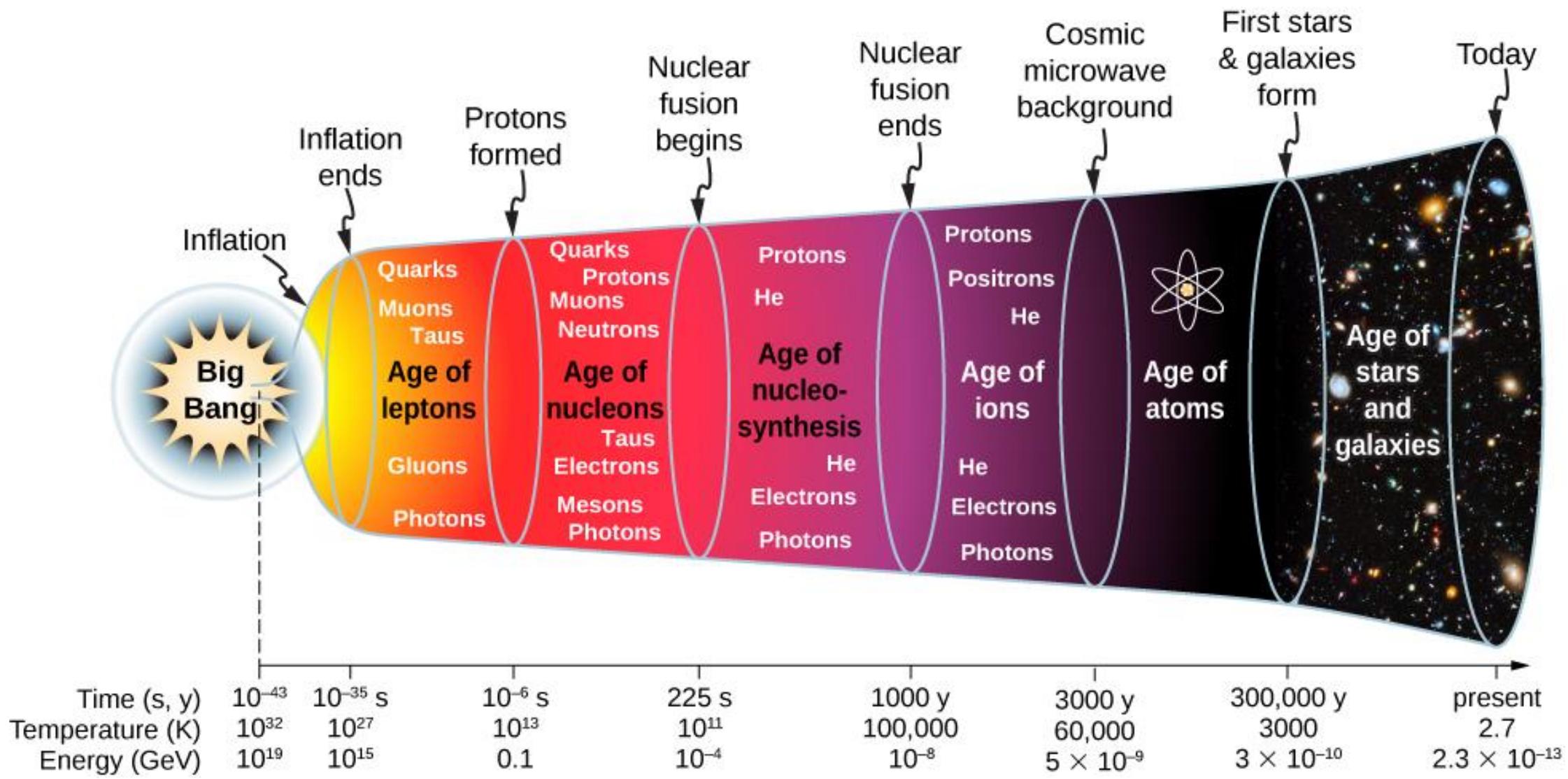


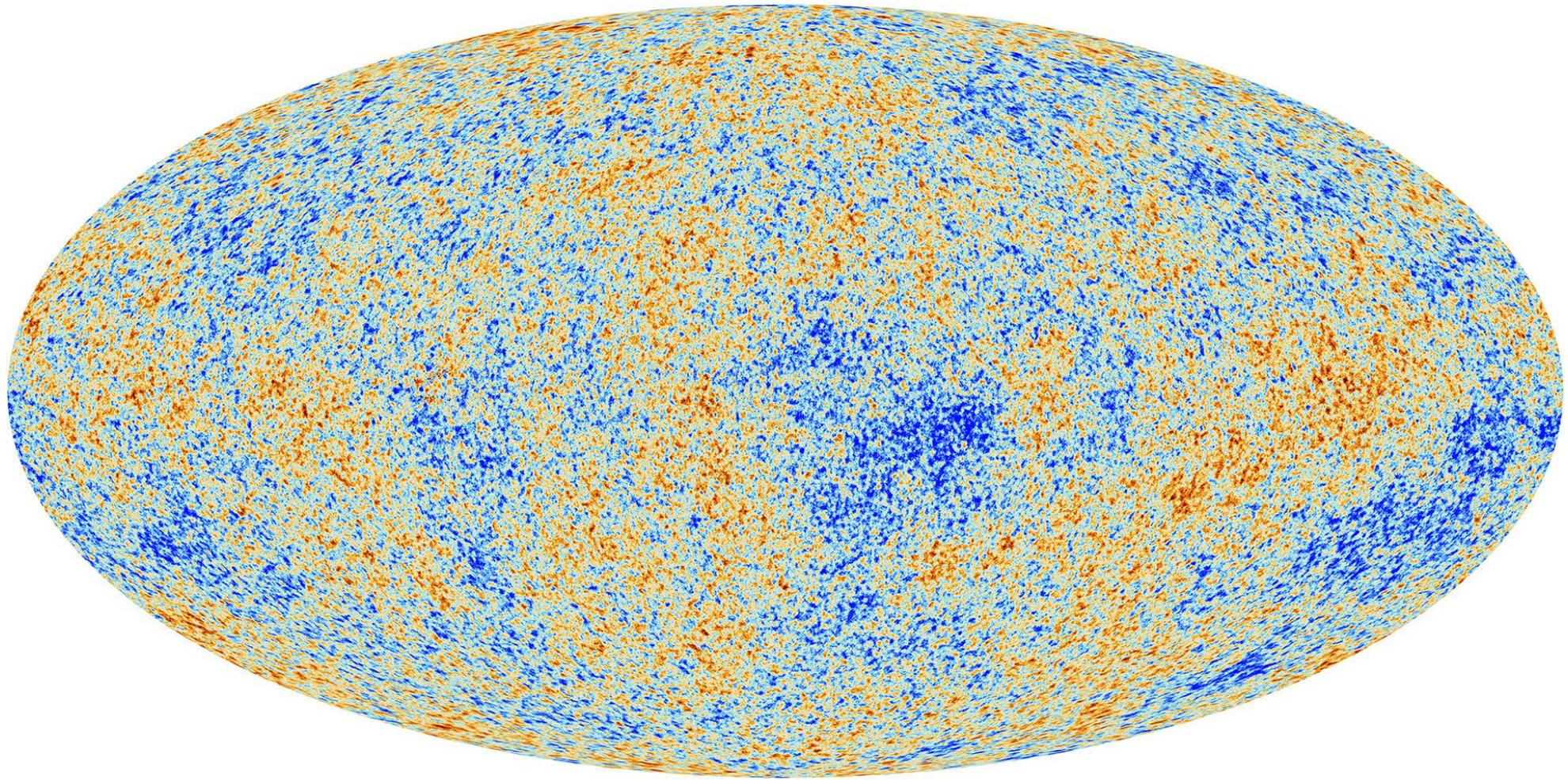




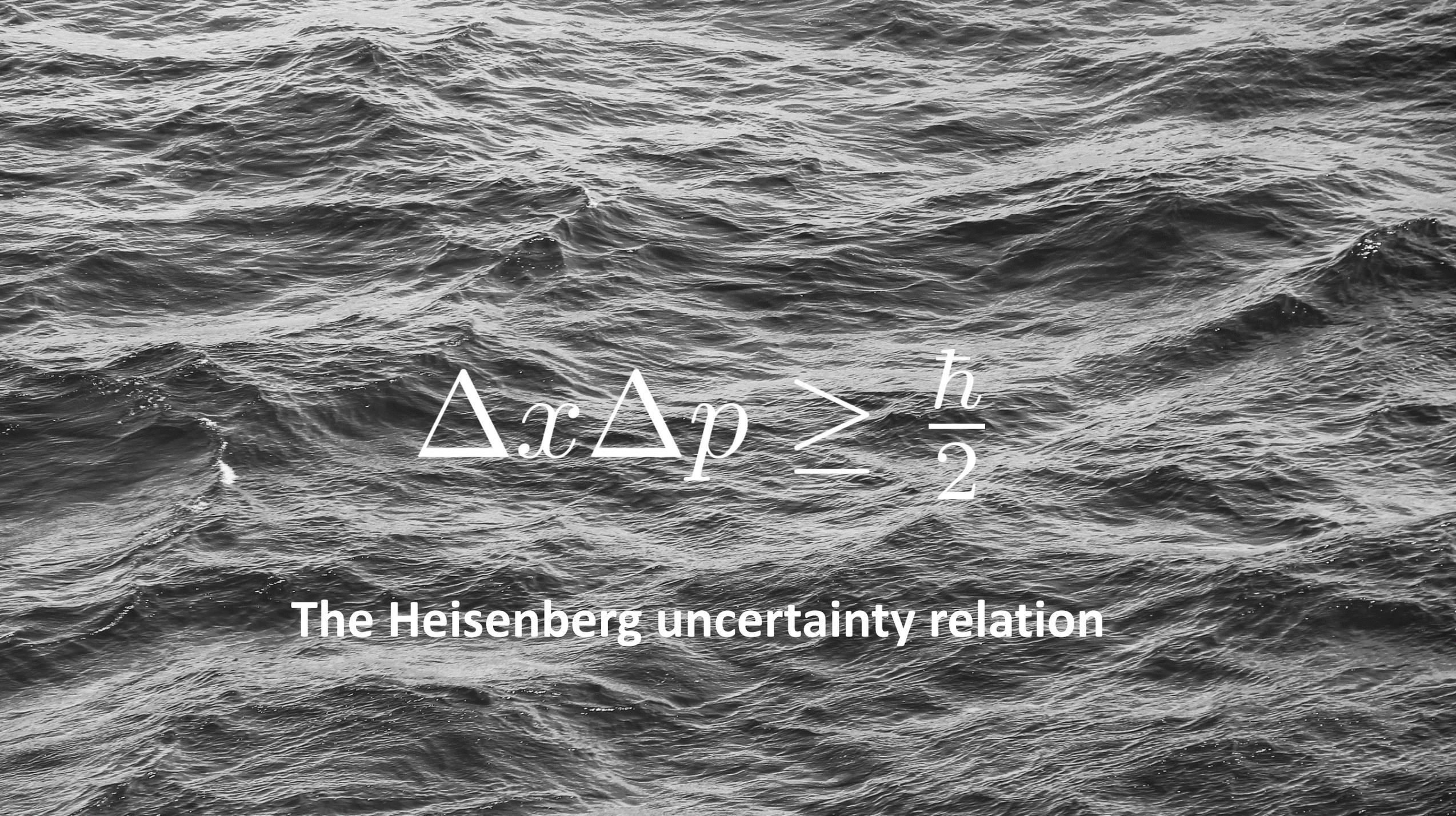
Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La *	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac *	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
				* 58 Ce	* 59 Pr	* 60 Nd	* 61 Pm	* 62 Sm	* 63 Eu	* 64 Gd	* 65 Tb	* 66 Dy	* 67 Ho	* 68 Er	* 69 Tm	* 70 Yb	* 71 Lu	
				* 90 Th	* 91 Pa	* 92 U	* 93 Np	* 94 Pu	* 95 Am	* 96 Cm	* 97 Bk	* 98 Cf	* 99 Es	* 100 Fm	* 101 Md	* 102 No	* 103 Lr	

**Everything we're made up of!**

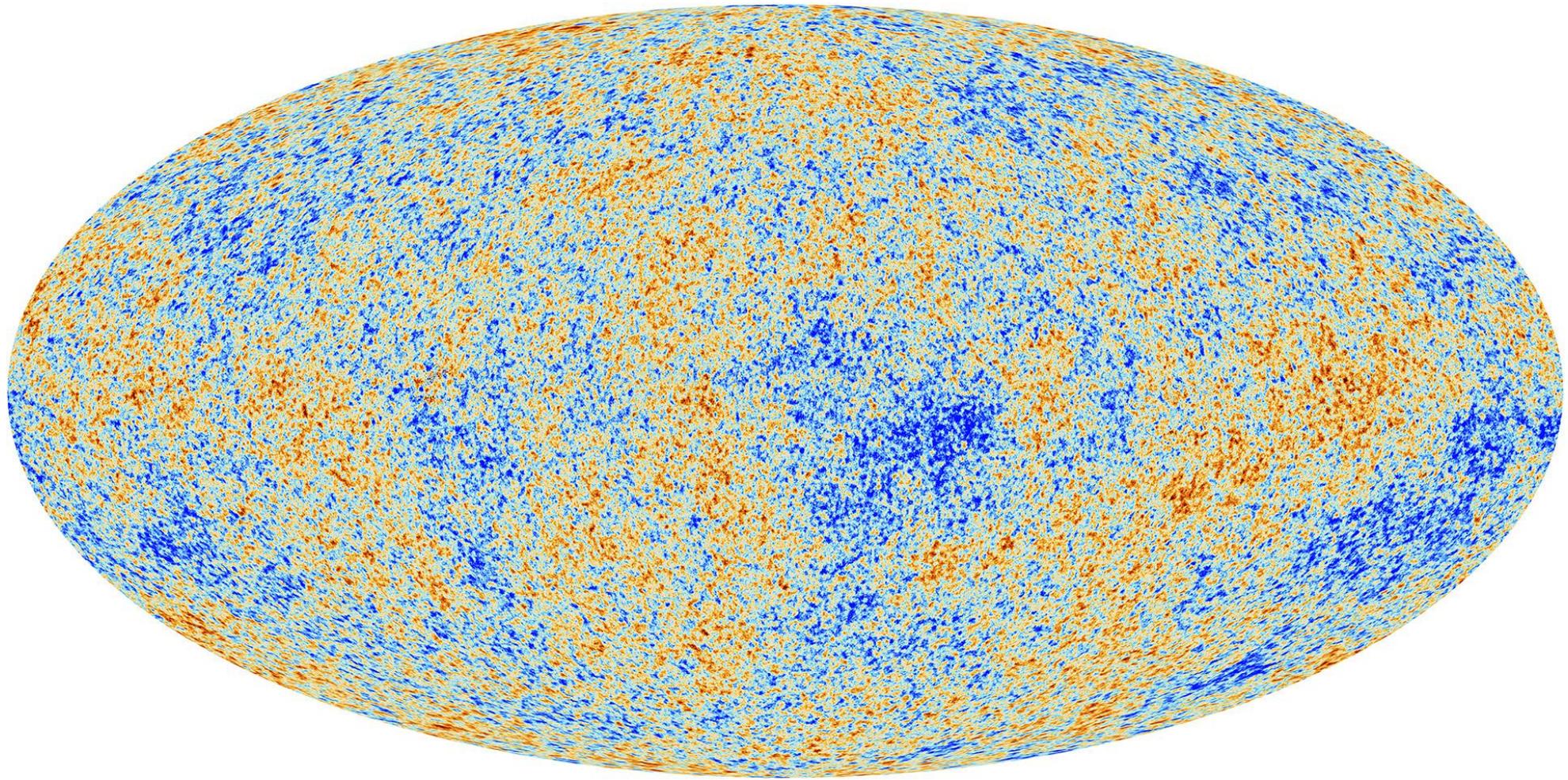




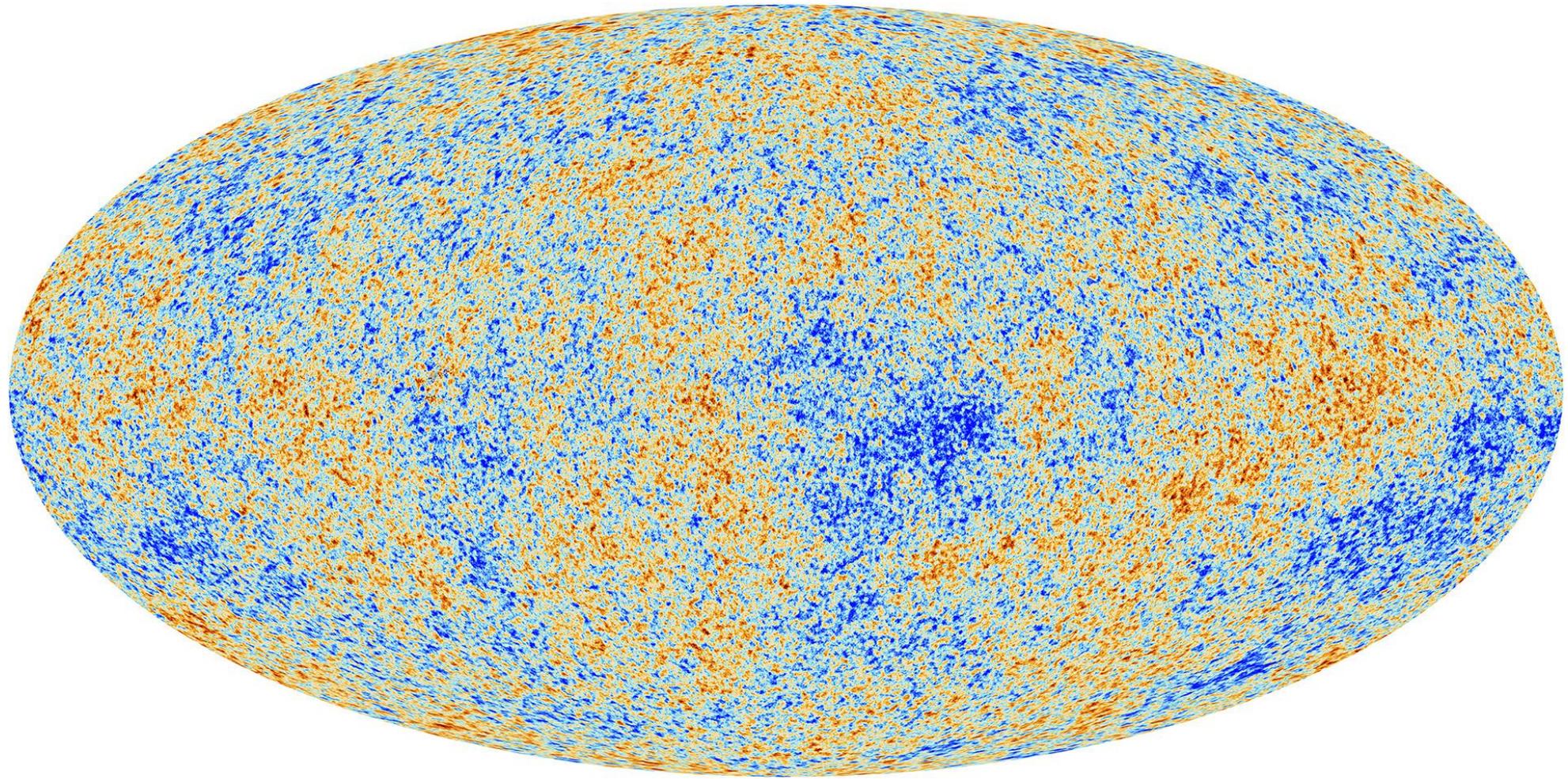
**The Cosmic Microwave Background**


$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

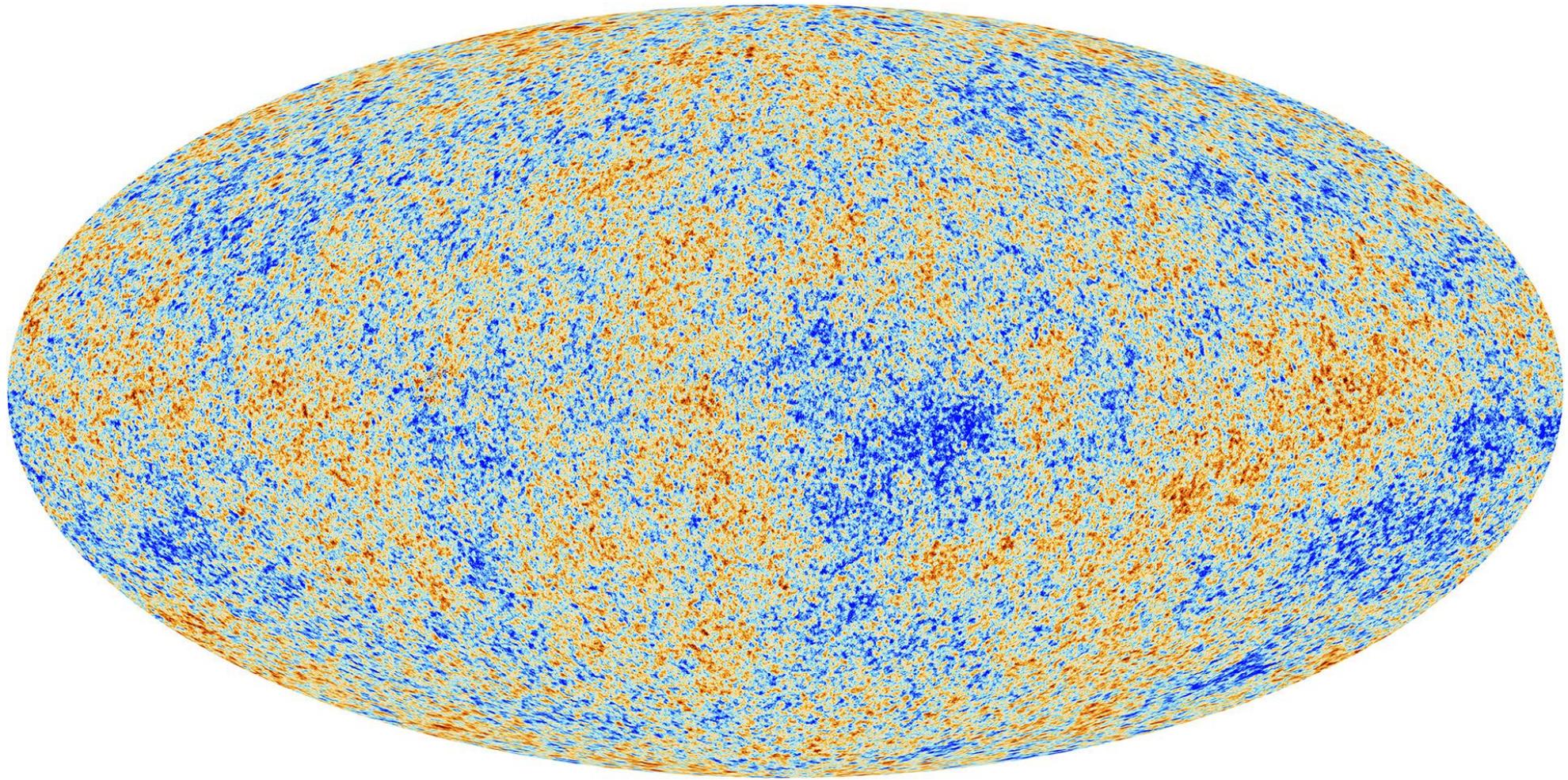
**The Heisenberg uncertainty relation**



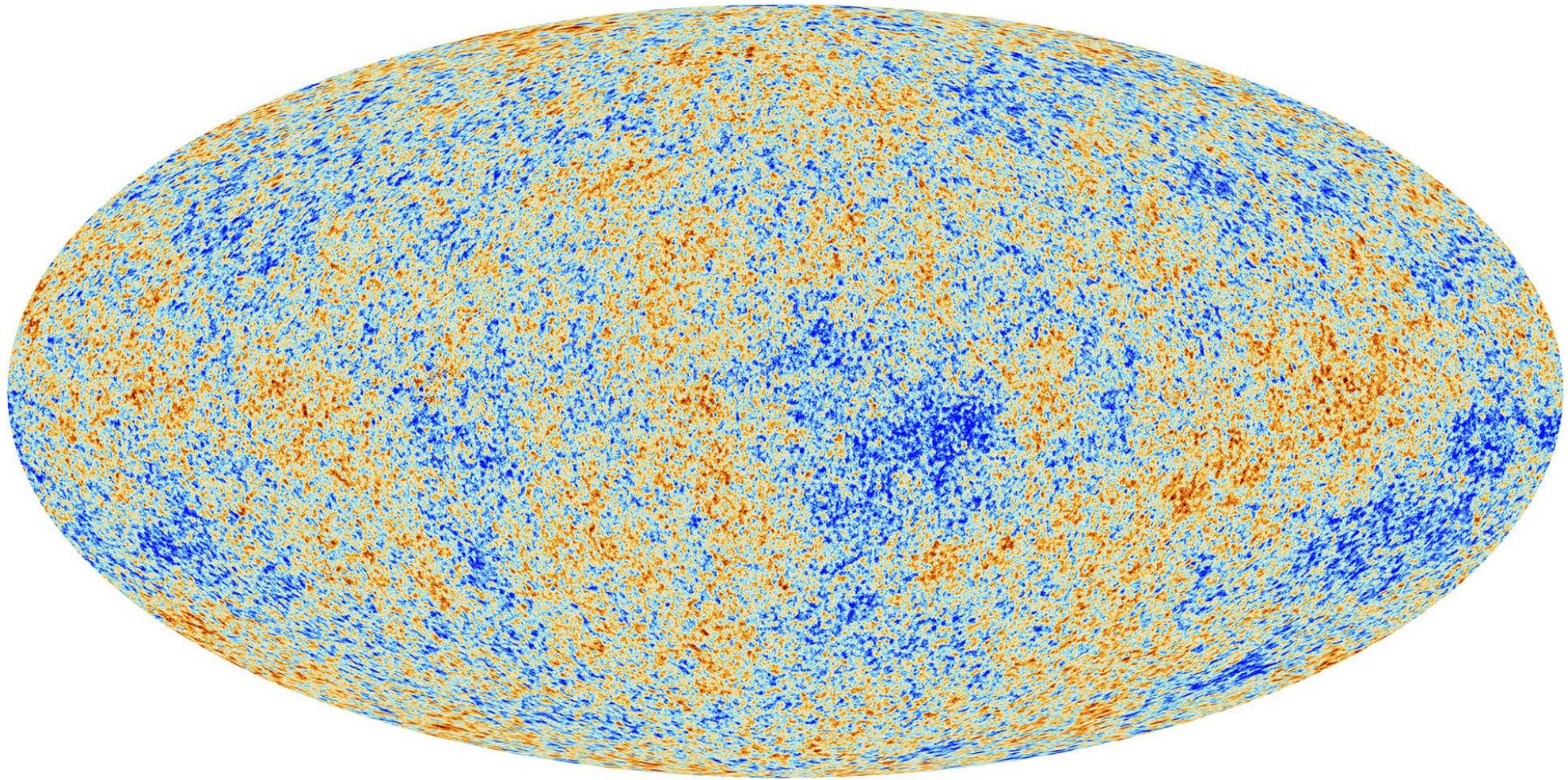
**The Cosmic Microwave Background**



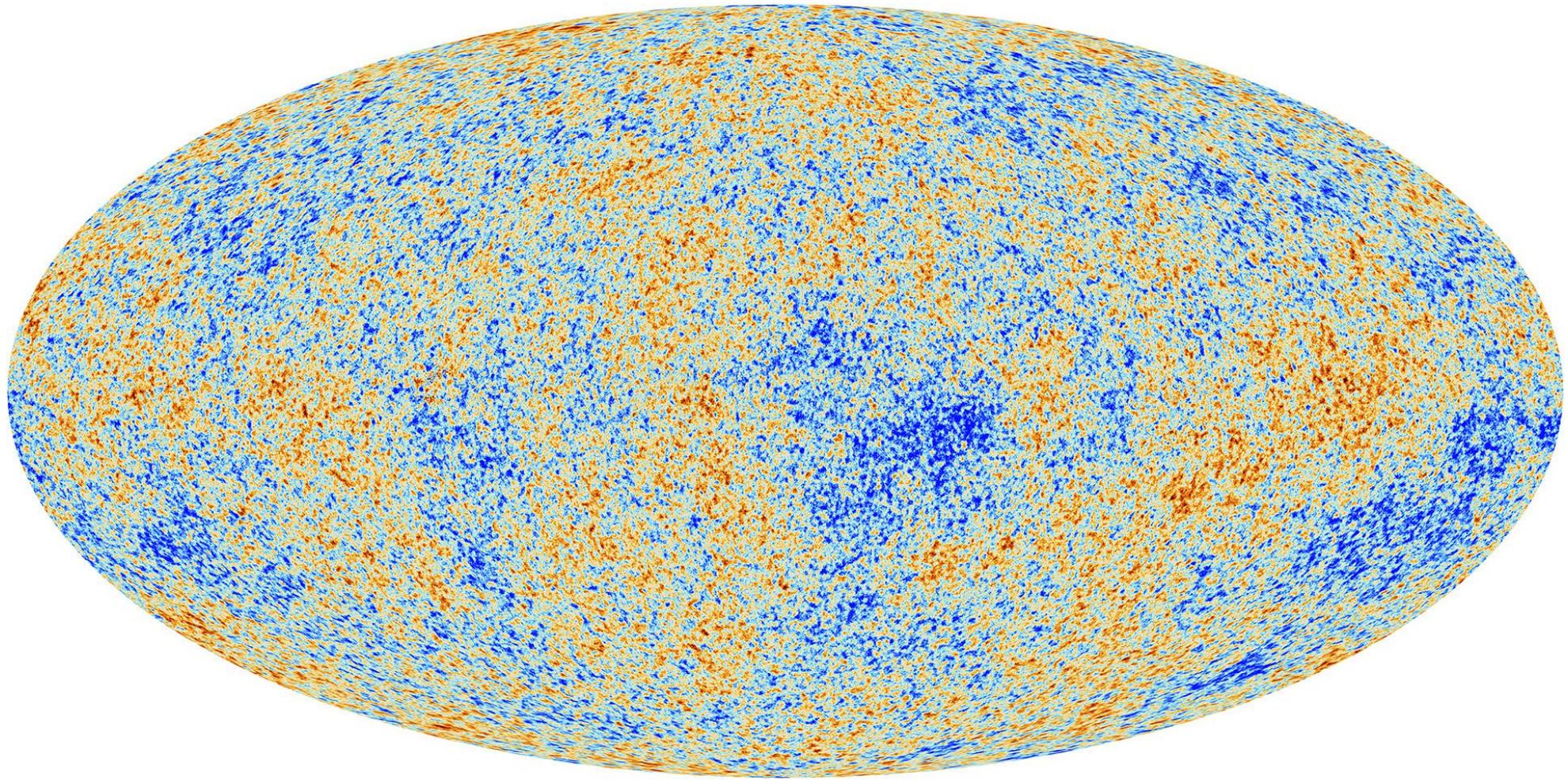
**... an ultrasound of the Universe when it was a baby**



**400 CMB “photons”/cm<sup>3</sup> permeate all of space.  
Approximately 1% of TV static is from this afterglow!**



**Same temperature in every direction but for 1 part in 100,000 fluctuations.**



**A snapshot when the universe cooled enough so that light broke free from matter, around  $t = 378,000$  years...**

# “Can One Hear the Shape of a Drum?”

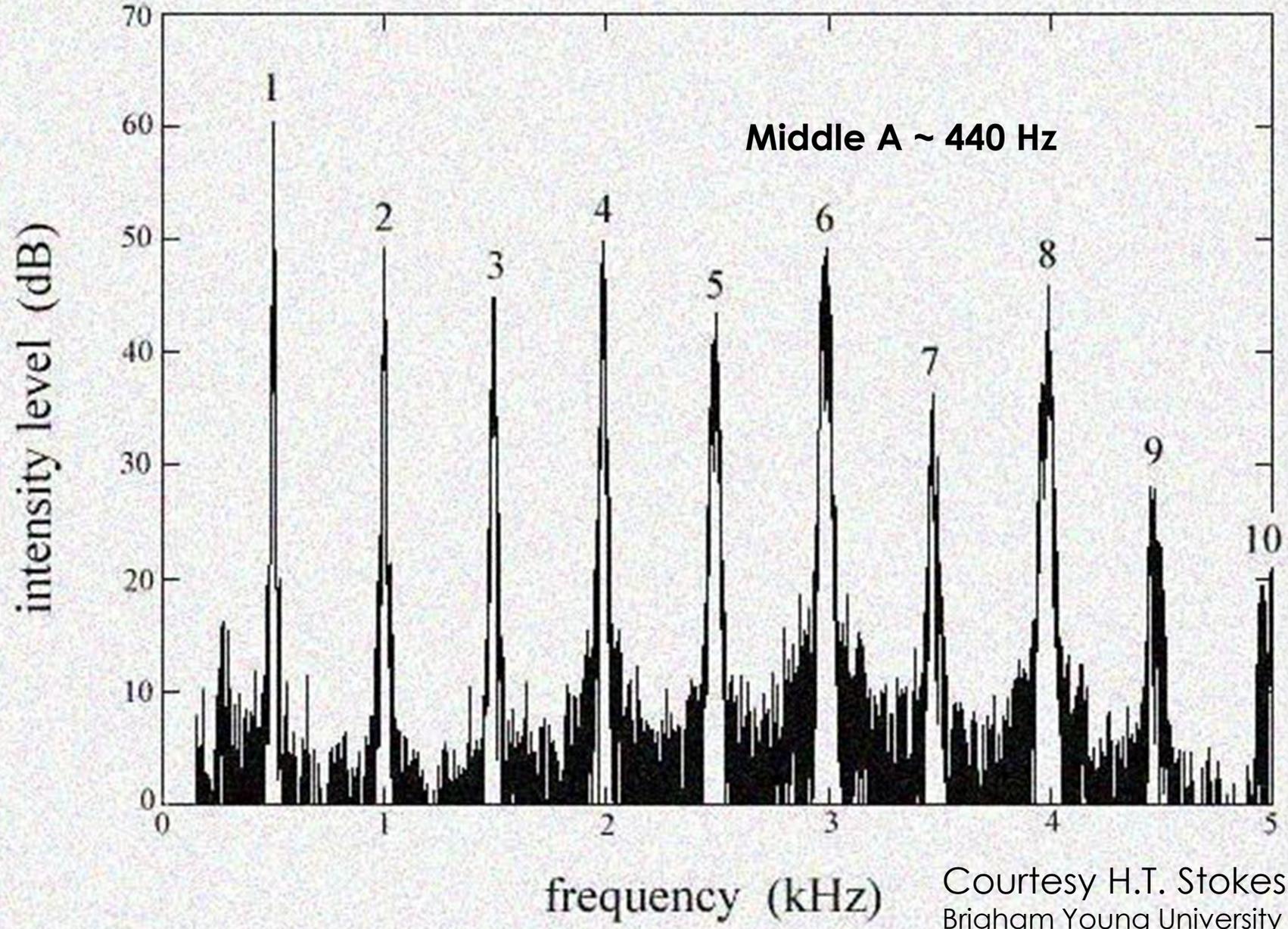
-- Mark Kac

Every sound you hear can be decomposed into a series of constituent harmonics.



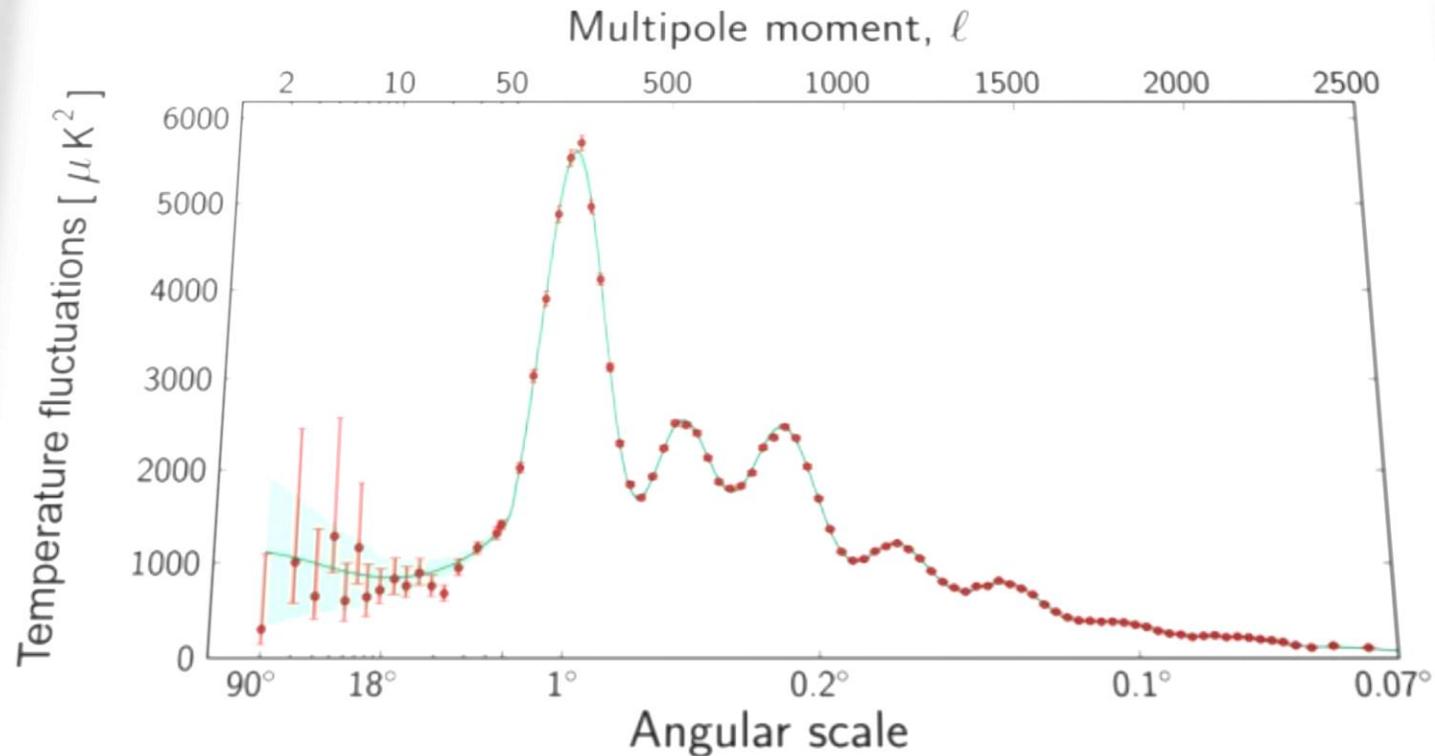
- Musicians know this as “Additive Synthesis”, scientists, as “Fourier Decomposition”, your ears, as “Hearing”.
- By analyzing these harmonics, you can learn about the material properties of whatever is making the sound.
- Can hear the shape of the bell and its material properties!
- In reality, any sound is made up of a continuum of harmonics (and phases).

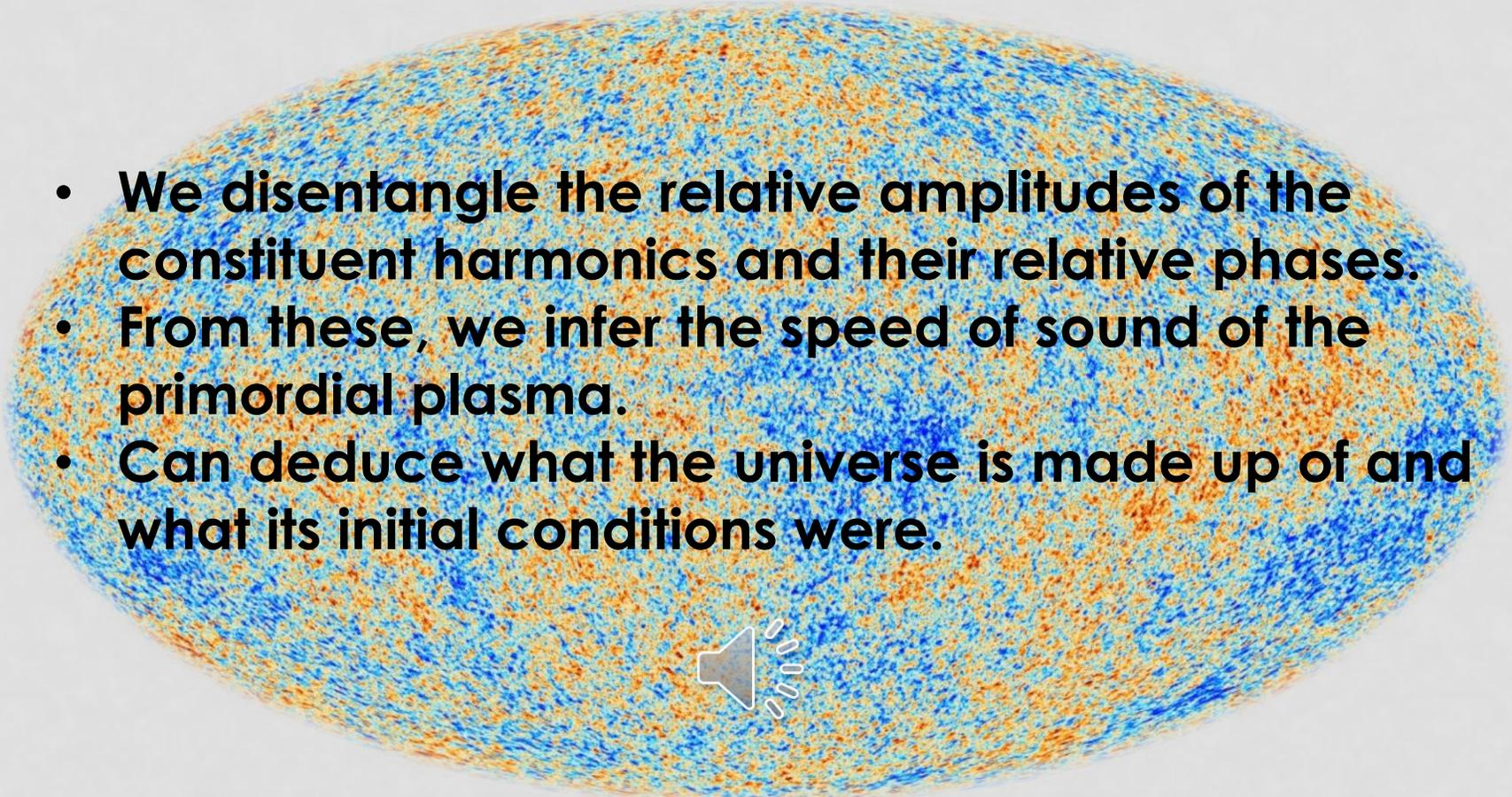
# violin spectrum

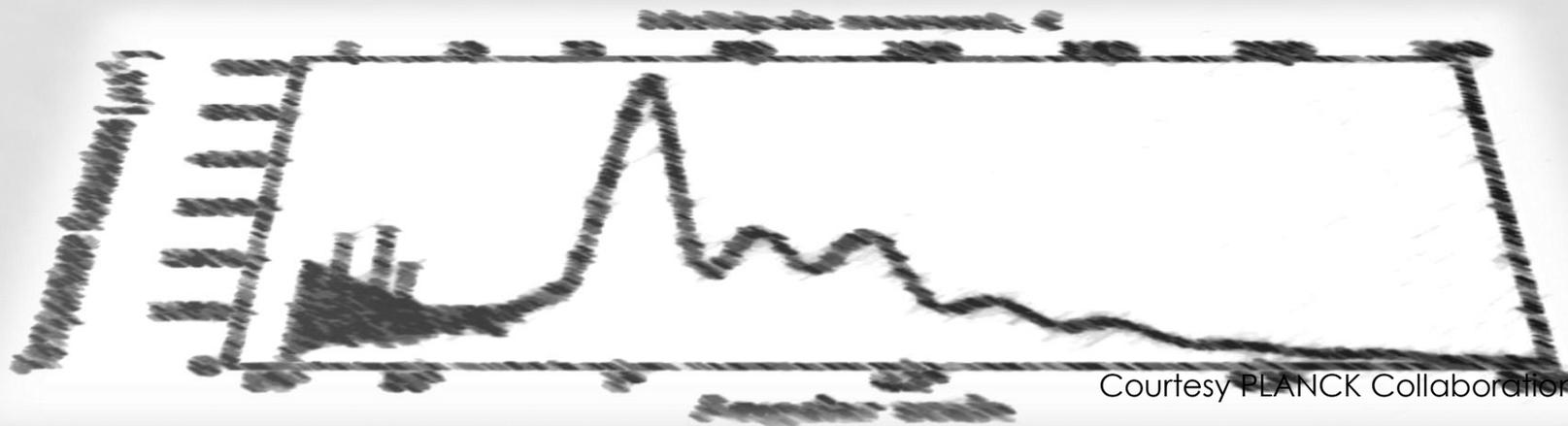


Courtesy H.T. Stokes  
Brigham Young University

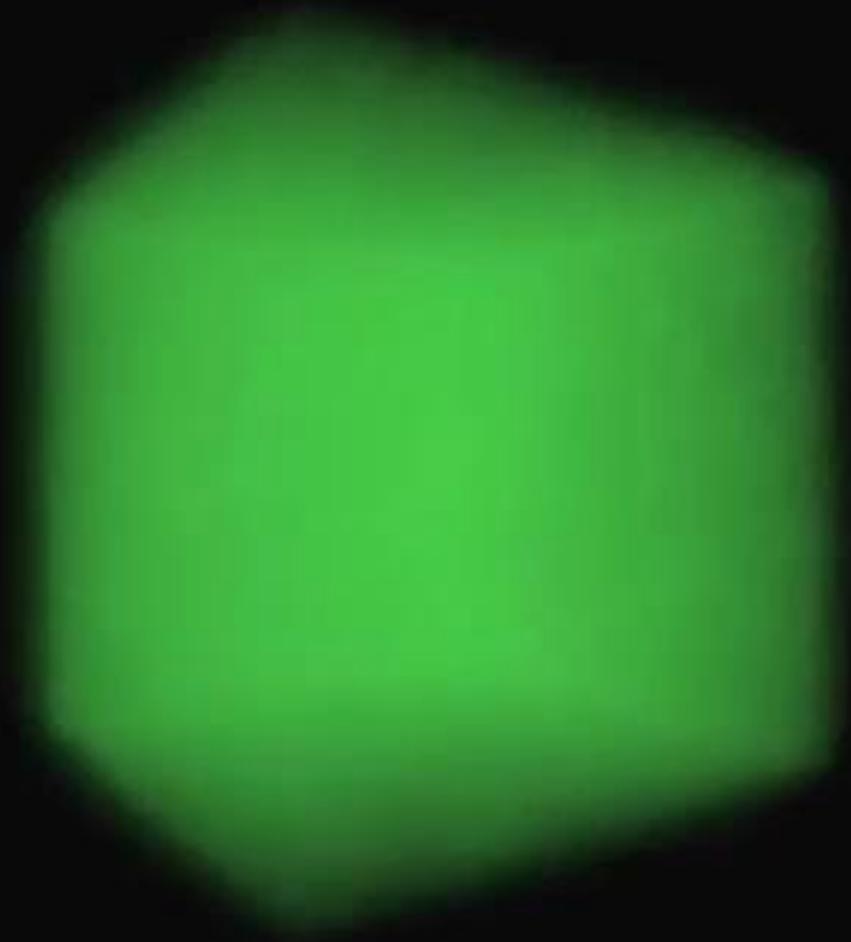
We can generalize this “Fourier analysis” to the sphere, and decompose the acoustic excitations of the CMB last scattering surface into its “spherical harmonics”:

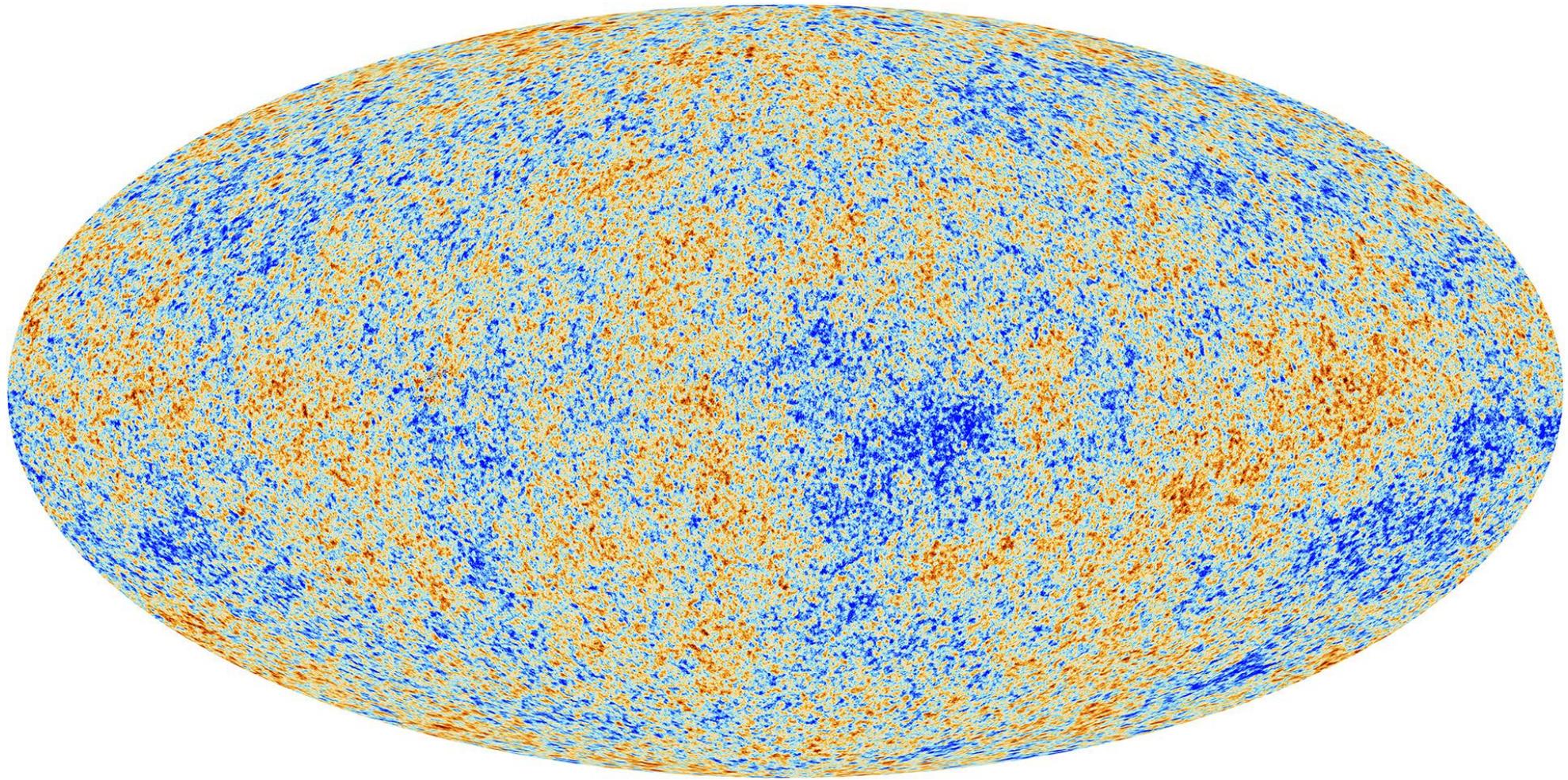


- 
- We disentangle the relative amplitudes of the constituent harmonics and their relative phases.
  - From these, we infer the speed of sound of the primordial plasma.
  - Can deduce what the universe is made up of and what its initial conditions were.

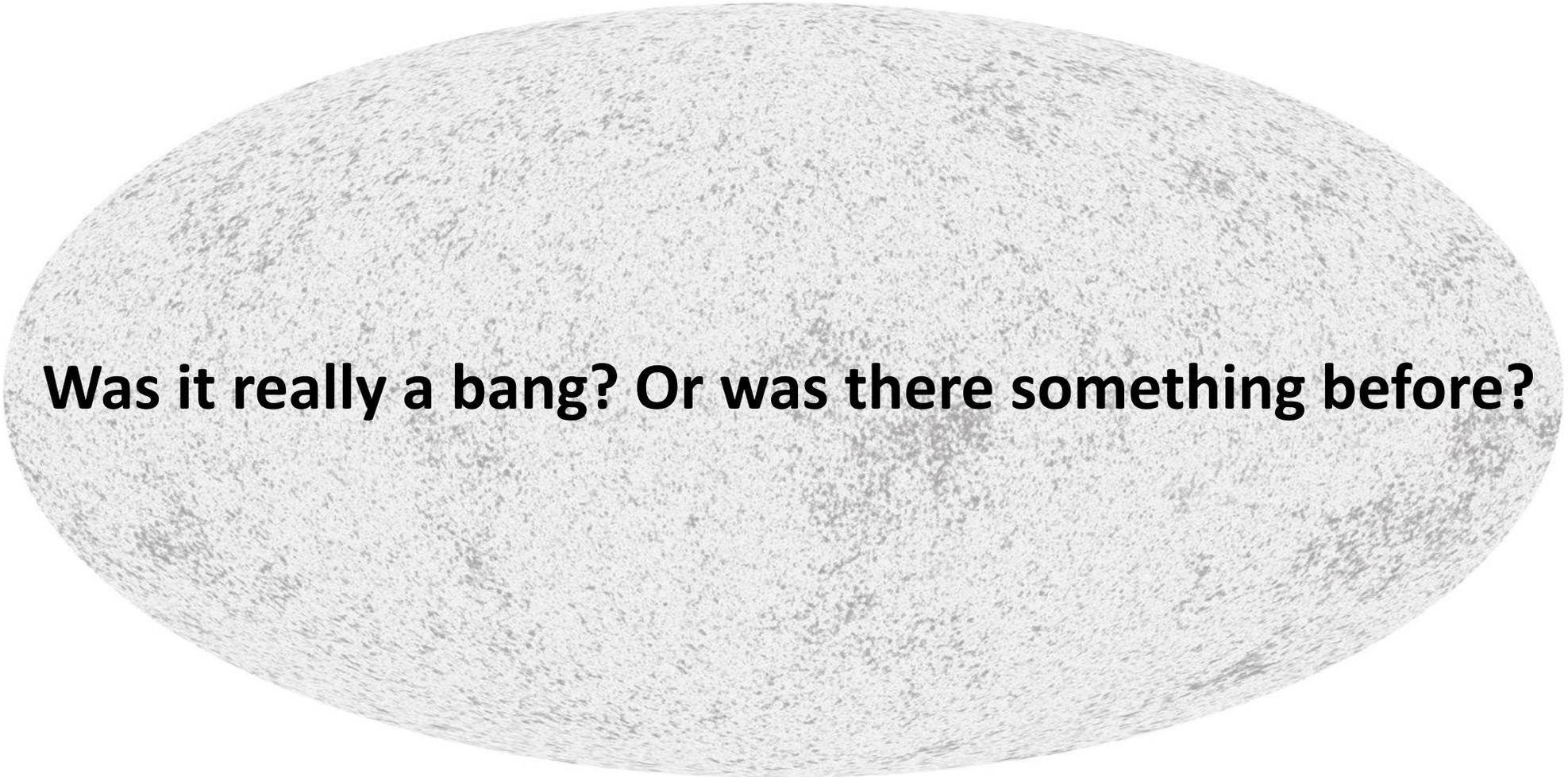


redshift = 24.2

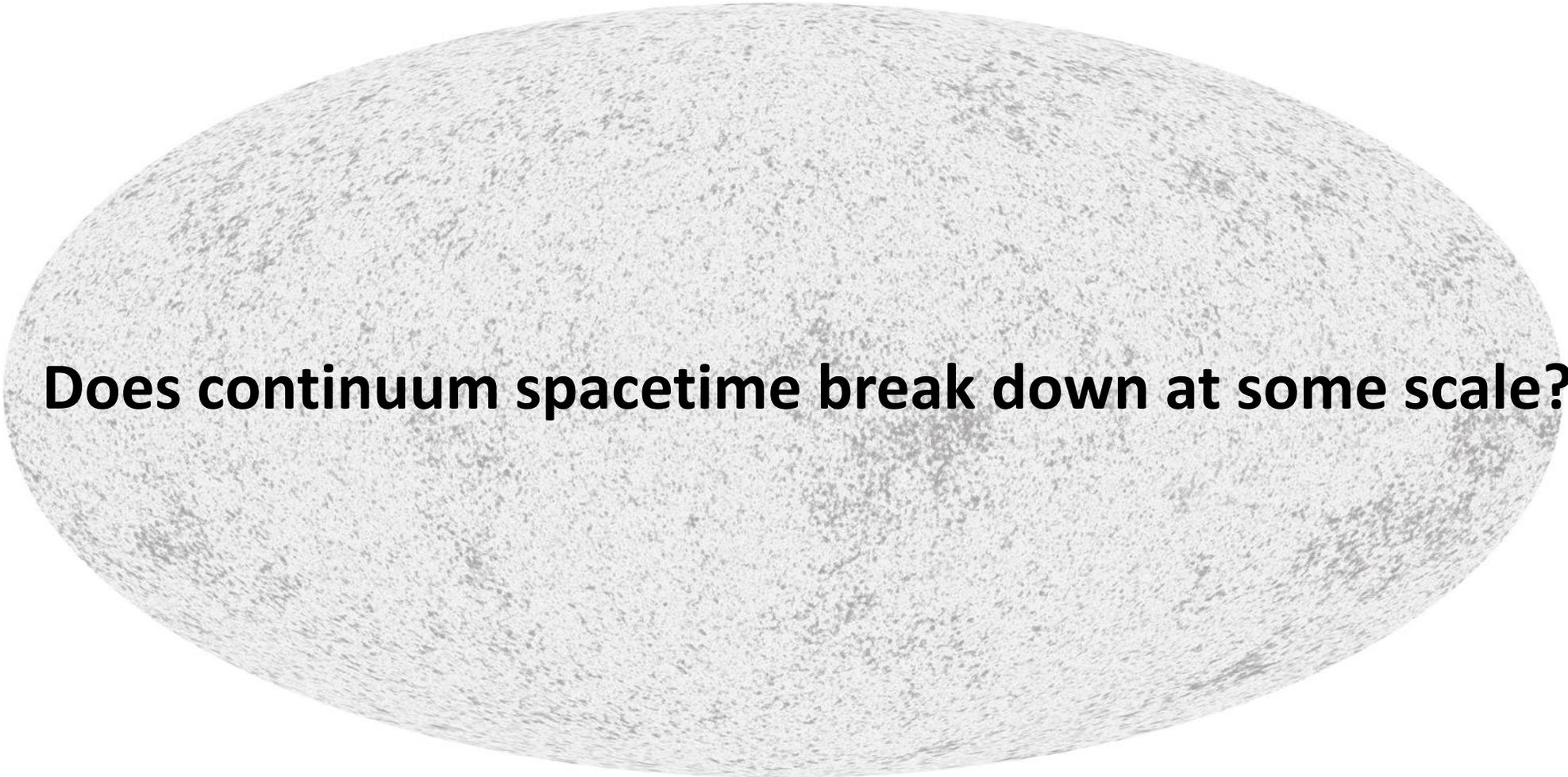




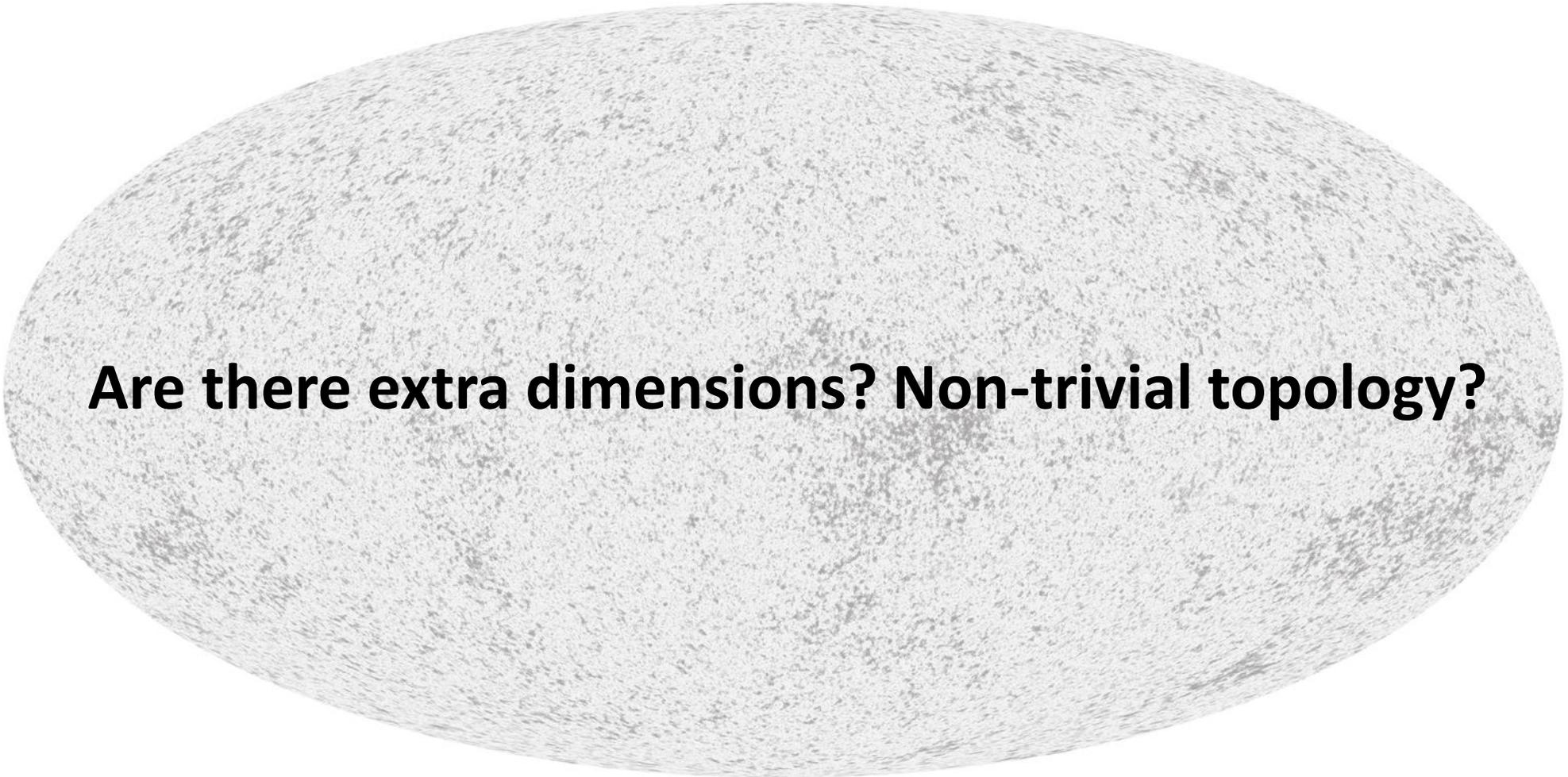
**By looking at the distribution and clustering of matter in the early Universe, we can learn a lot about the big bang...**



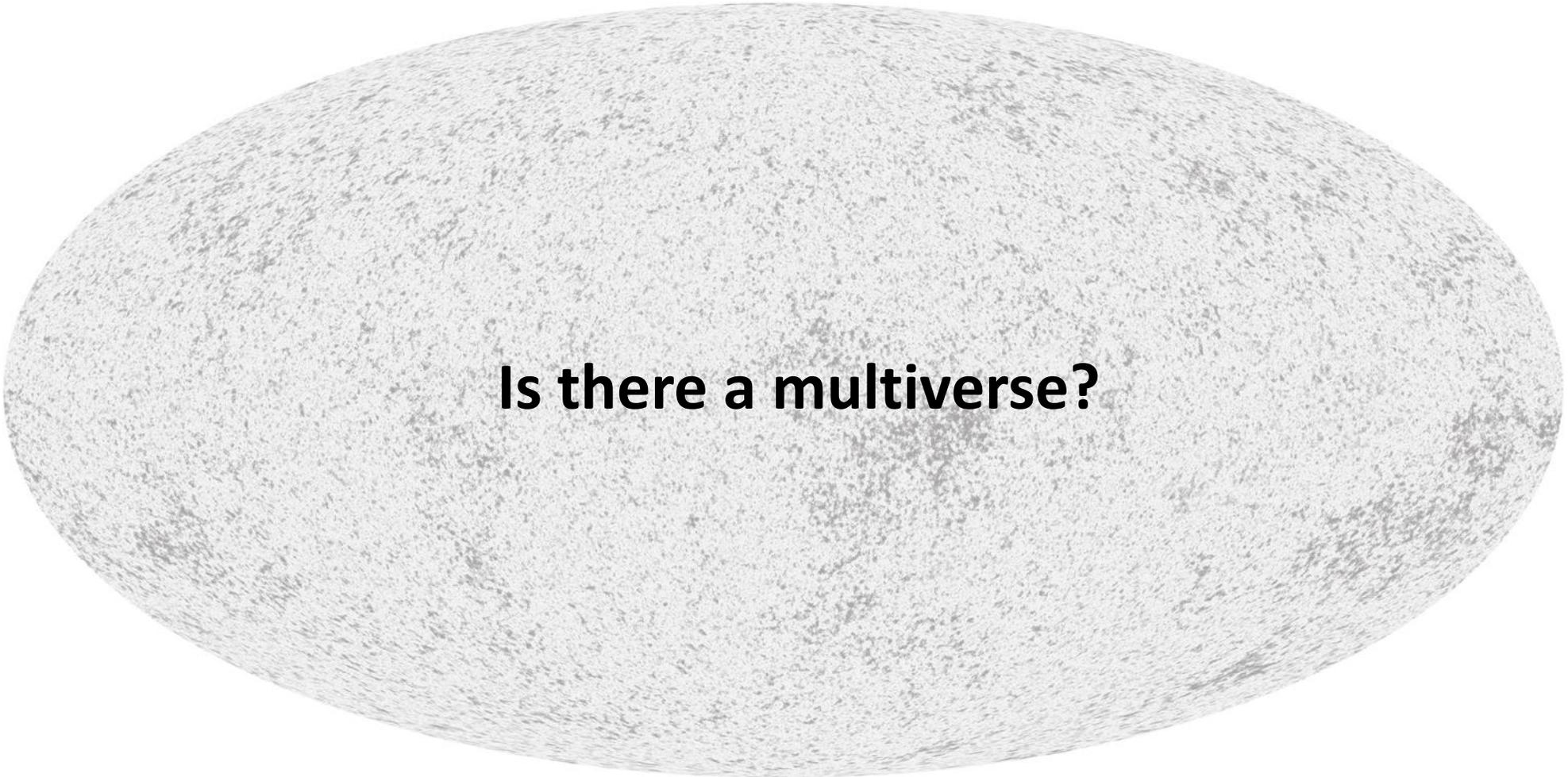
**Was it really a bang? Or was there something before?**



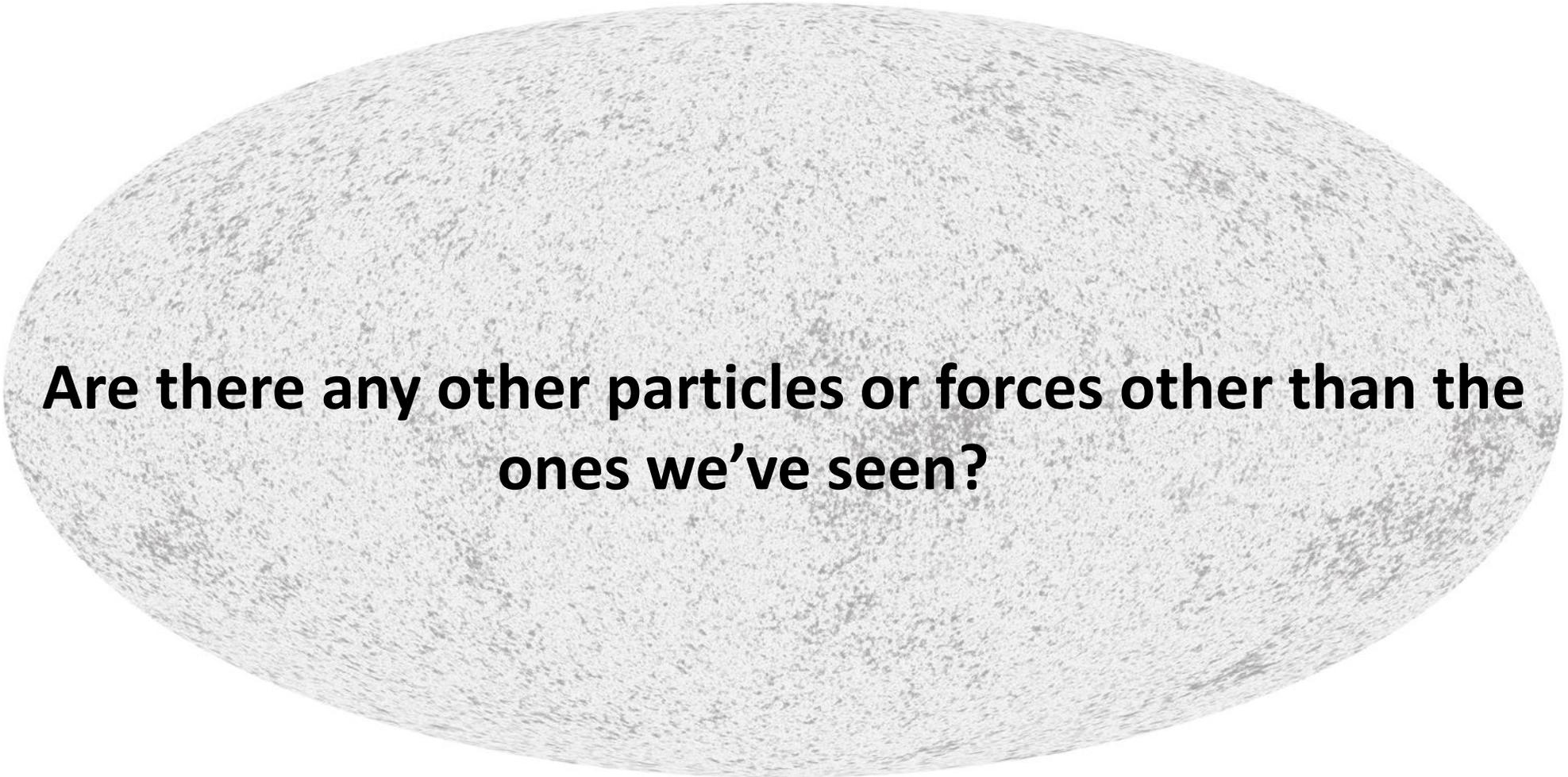
**Does continuum spacetime break down at some scale?**



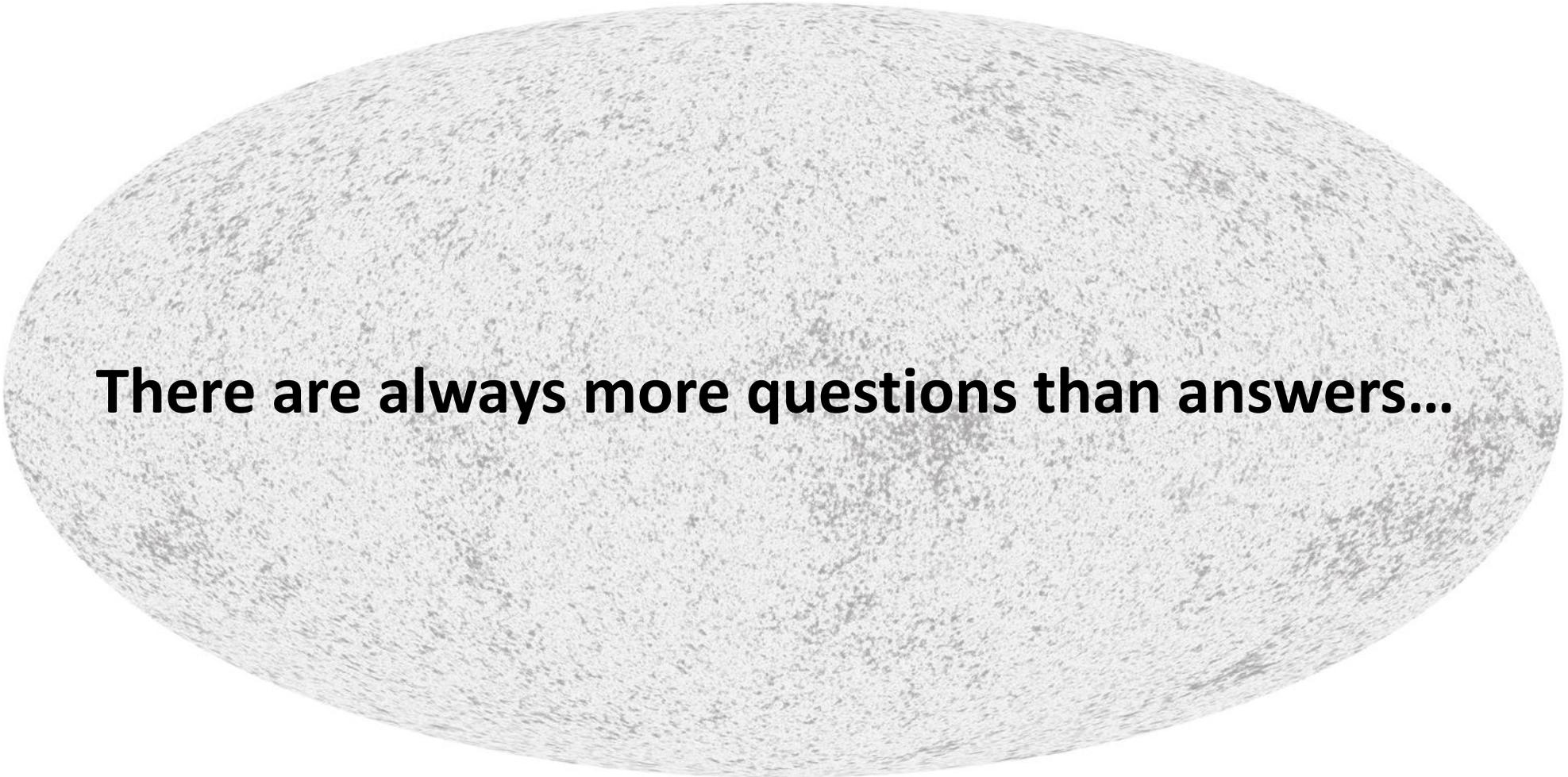
**Are there extra dimensions? Non-trivial topology?**



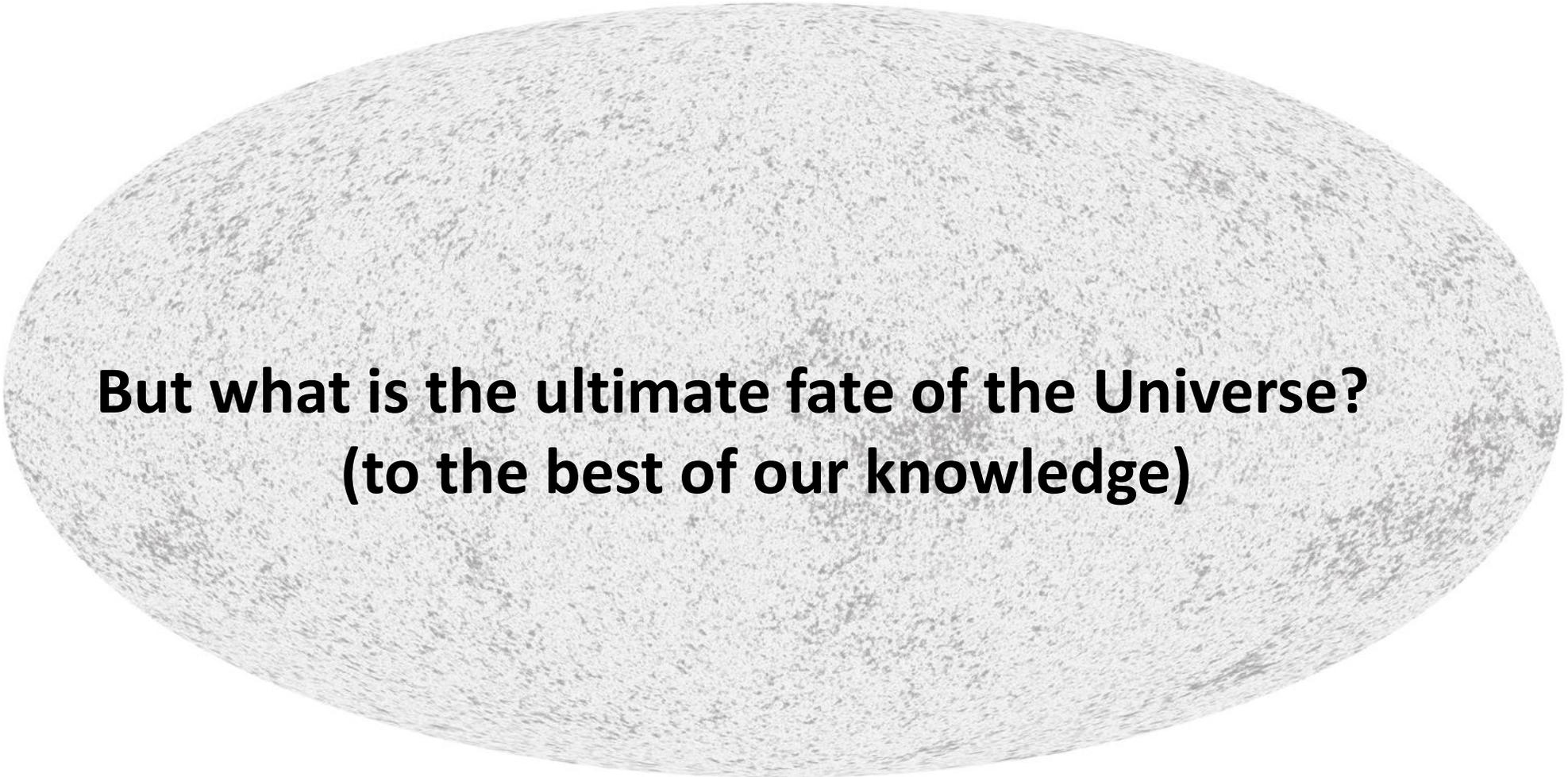
**Is there a multiverse?**



**Are there any other particles or forces other than the ones we've seen?**



**There are always more questions than answers...**



**But what is the ultimate fate of the Universe?  
(to the best of our knowledge)**

**But what is the ultimate fate of the Universe?  
(to the best of our knowledge)**

$$8\pi G_N \Lambda = 10^{-120}$$

**We're entering an era of 'dark energy domination'**

**But what is the ultimate fate of the Universe?  
(to the best of our knowledge)**

$$8\pi G_N \Lambda = 10^{-120}$$

**We're entering an era of 'dark energy domination'**

(Recall gravitational force =  $G_N \frac{m_1 m_2}{r^2}$ )

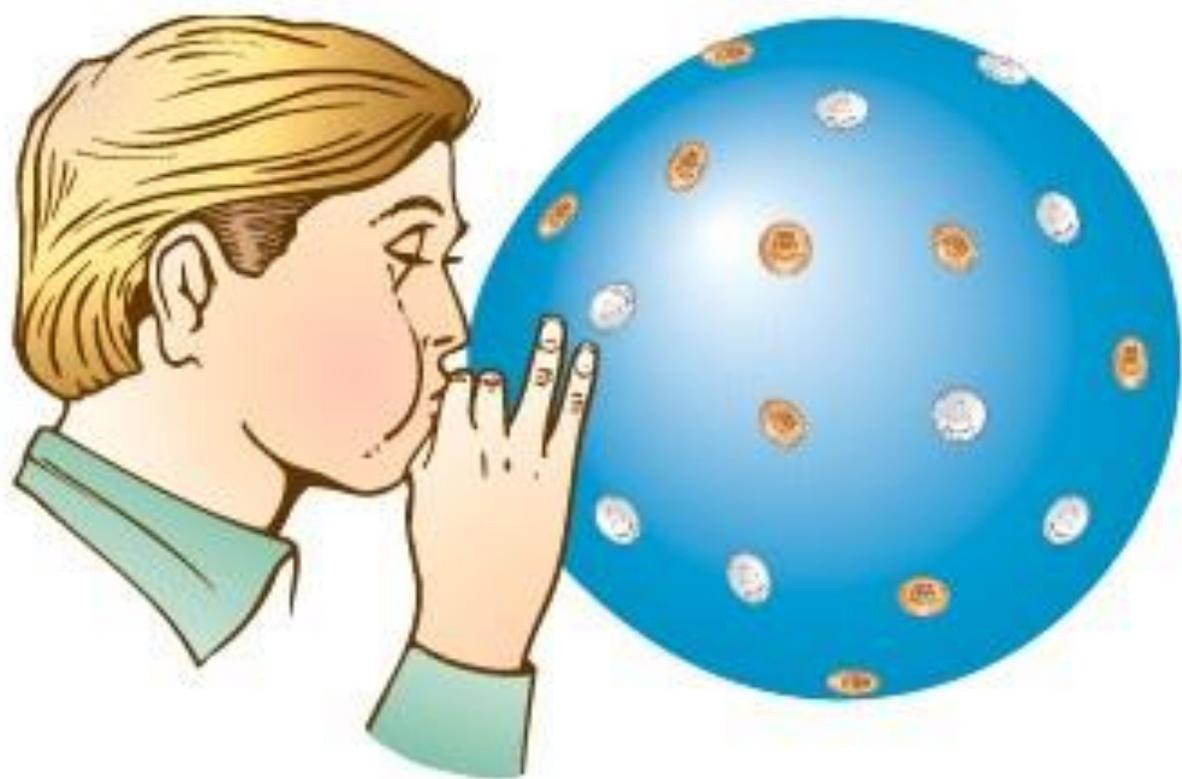
**But what is the ultimate fate of the Universe?  
(to the best of our knowledge)**

$$8\pi G_N \Lambda = 10^{-120}$$

$\ell^2 = a^2(t)r^2$ ;  $a^2(t)$  is the ‘scale factor’ of the universe

For a fixed coordinate separation  $r$ ,  $\frac{d\ell}{dt} = \frac{\dot{a}}{a}\ell$

Define  $\frac{\dot{a}}{a} = H \rightarrow$  Hubble’s law:  $v = H\ell$



**But what is the ultimate fate of the Universe?  
(to the best of our knowledge)**

$$8\pi G_N \Lambda = 10^{-120}$$

$$a(t) \propto t^{1/2} \quad (\text{radiation domination})$$

$$a(t) \propto t^{2/3} \quad (\text{matter domination})$$

$$a(t) \propto e^{8\pi G_N \Lambda t} \quad (\text{dark energy domination})$$

**But what is the ultimate fate of the Universe?  
(to the best of our knowledge)**

$$8\pi G_N \Lambda = 10^{-120}$$

$$a(t) \propto e^{8\pi G_N \Lambda t} \quad (\text{dark energy domination})$$

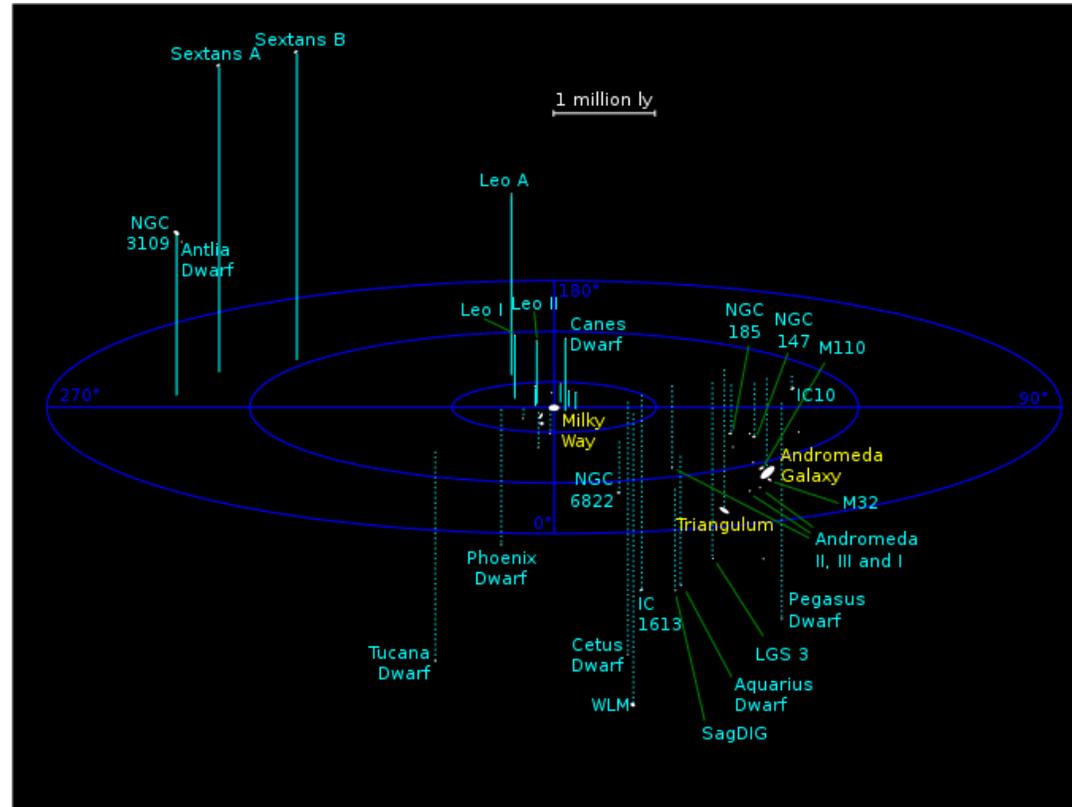
**When dark energy starts to dominate, the expansion of the universe starts to accelerate!**

**About 4 billion years from now...**

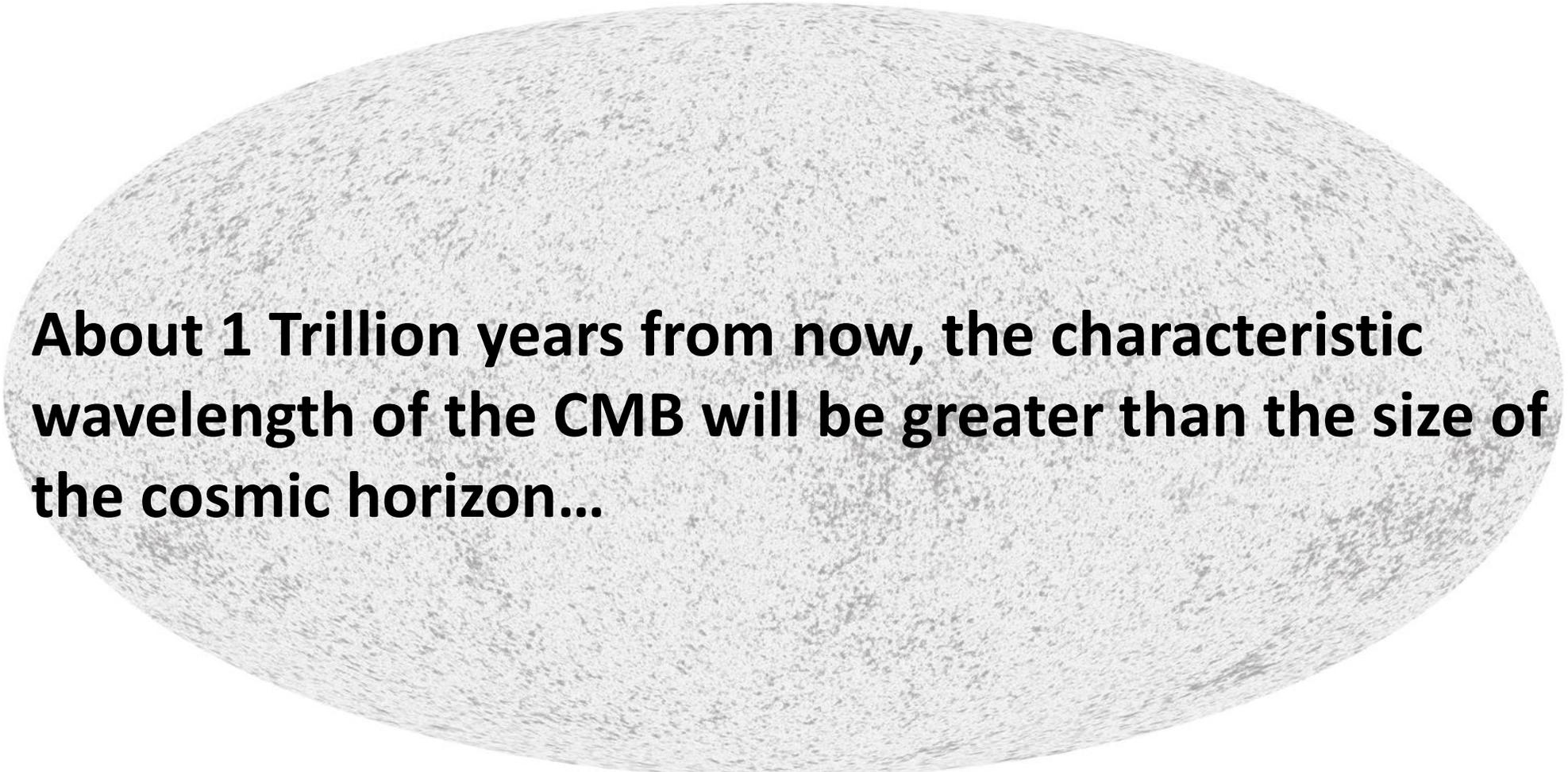


**... the Milky Way and Andromeda are at the midpoint  
of their collision**

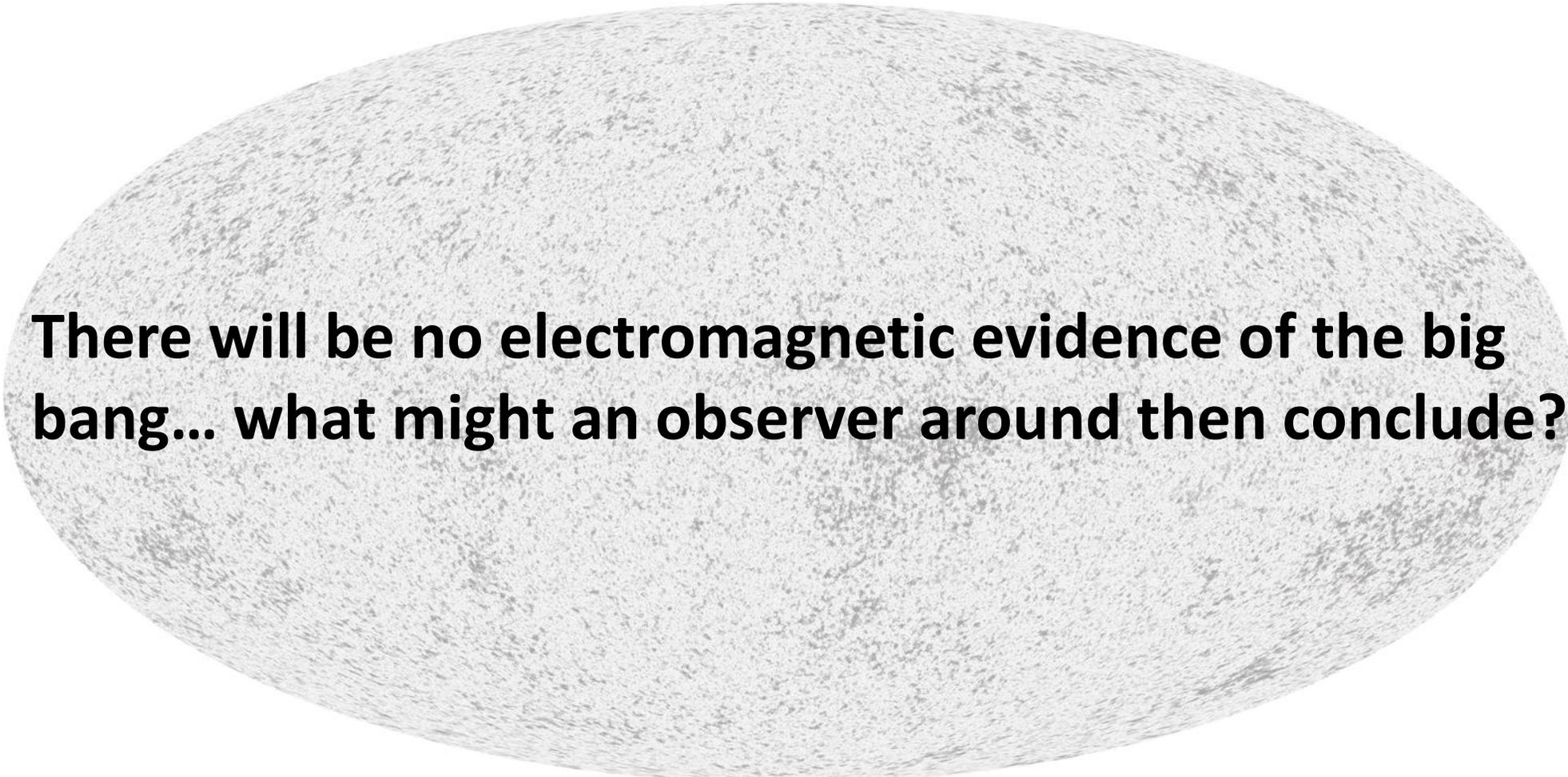
**About 100-150 billion years from now...**



**... only the local galactic group will be inside our cosmic horizon**



**About 1 Trillion years from now, the characteristic wavelength of the CMB will be greater than the size of the cosmic horizon...**



**There will be no electromagnetic evidence of the big bang... what might an observer around then conclude?**

Some observations suggest that dark energy density may not be constant in time, but might actually grow. If this is the case, everything ends in the so-called big rip! However, refined observations continue to converge on a small window around  $\Lambda = \text{const.}$

## END OF EVERYTHING

