Cosmology

- **Age of the Universe**
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  - The cosmic calendar
  - Age of the Earth
  - Red shift
- **Structure and evolution of stars**
- **Relativity**
  - Special Relativity
  - Ideas of General Relativity
    - Gravitational lensing
    - Precession of Mercury
- **Size of the Universe**
  - Measurement
    - Parallax
    - Luminosity
  - Earth
    Solar System
    Galaxy ...
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  - Neutron stars
  - Black holes, quasars
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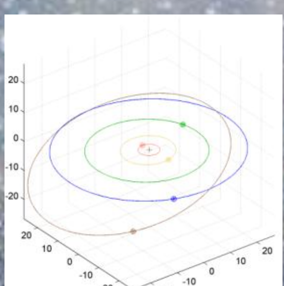
  - Einstein
  - Computer Simulation
- **A human history of cosmology**
- **Planets & moons**
  - Detecting planets orbiting other stars
  - The Solar System
    - The Earth

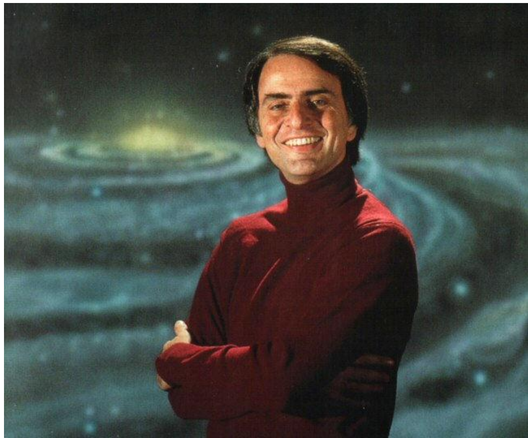


The Cosmos is all that is or ever was or ever will be.

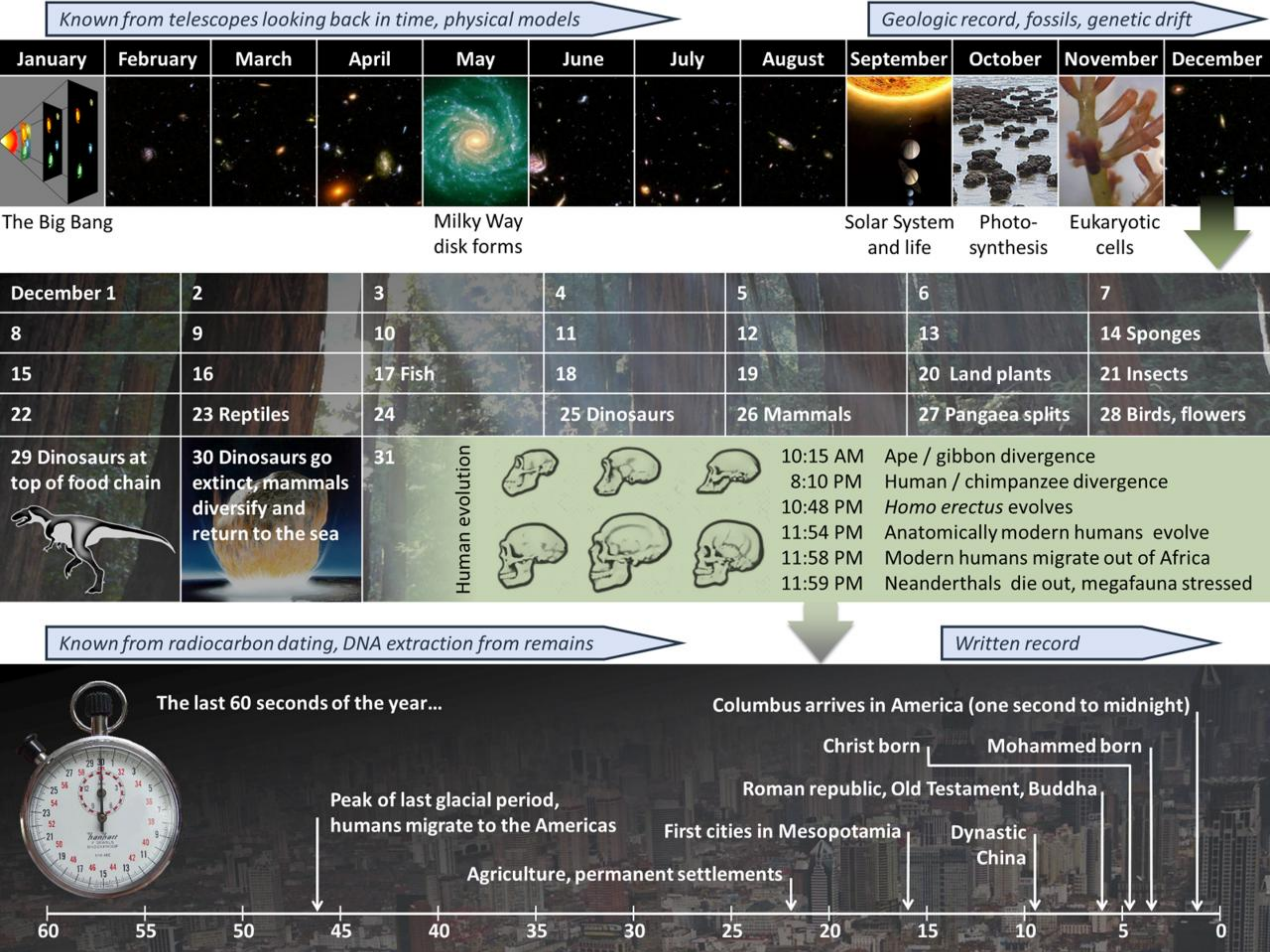
In the last few millennia we have made the most astonishing and unexpected discoveries about the Cosmos and our place within it, explorations that are exhilarating to consider. They remind us that humans have evolved to wonder, that understanding is a joy, that knowledge is prerequisite to survival.

I believe our future depends on how well we know this Cosmos in which we float like a mote of dust in the morning sky.

Carl Sagan (1934-1996)
Cosmos pp20



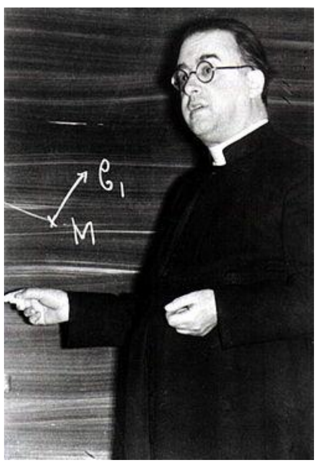
How old is the Universe?
Does it have a beginning,
and an end?

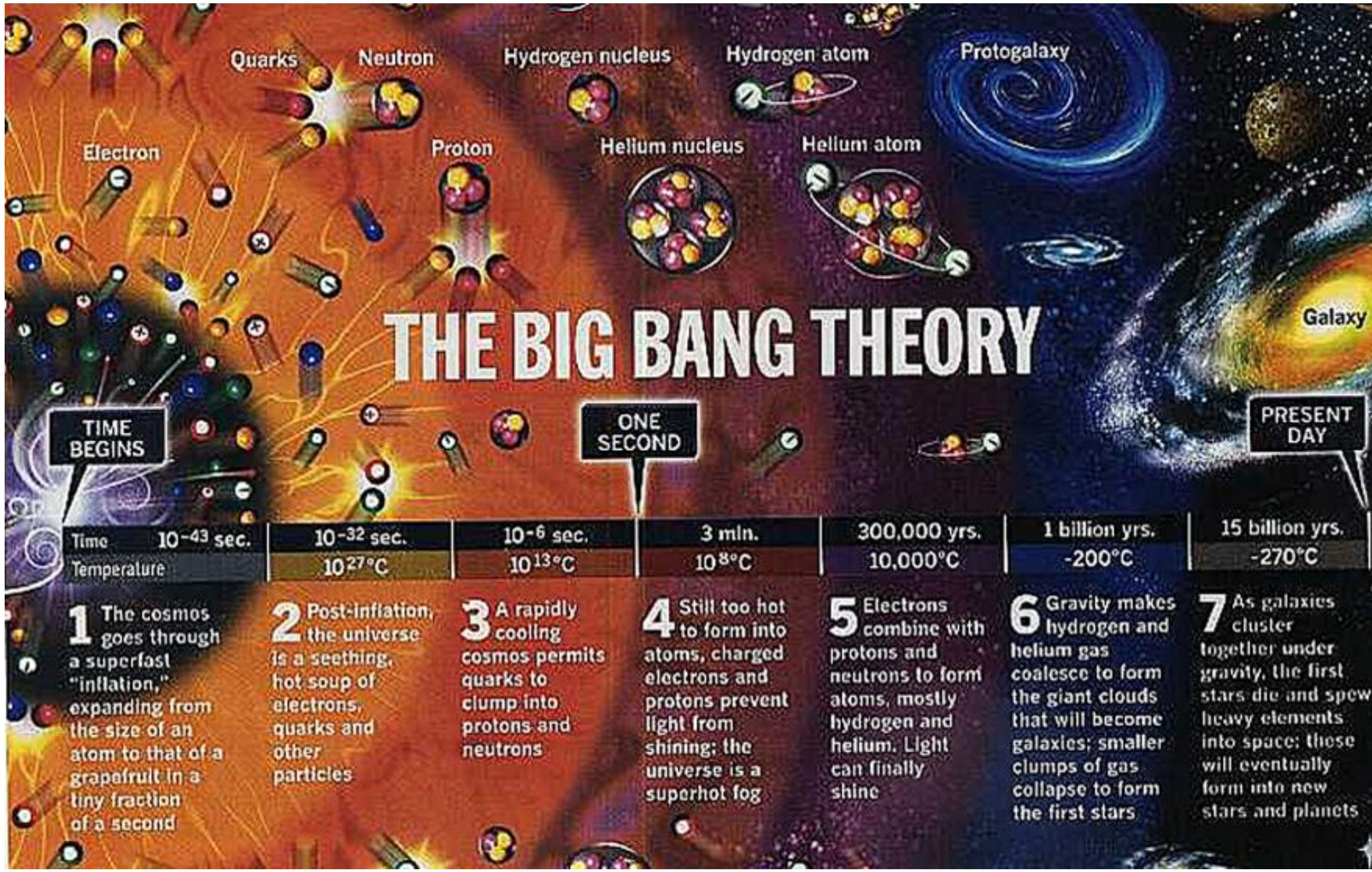

Known from telescopes looking back in time, physical models
Geologic record, fossils, genetic drift
January
February
March
April
May
June
July
August
September
October
November
December
The Big Bang
Milky Way disk forms
Solar System and life
Photo-synthesis
Eukaryotic cells
December 1
2
3
4
5
6
7
8
9
10
11
12
13
14 Sponges
15
16
17 Fish
18
19
20 Land plants
21 Insects
22
23 Reptiles
24
25 Dinosaurs
26 Mammals
27 Pangaea splits
28 Birds, flowers
29 Dinosaurs at top of food chain
30 Dinosaurs go extinct, mammals diversify and return to the sea
31
Human evolution
10:15 AM Ape / gibbon divergence
8:10 PM Human / chimpanzee divergence
10:48 PM Homo erectus evolves
11:54 PM Anatomically modern humans evolve
11:58 PM Modern humans migrate out of Africa
11:59 PM Neanderthals die out, megafauna stressed
Known from radiocarbon dating, DNA extraction from remains
Written record
The last 60 seconds of the year…
Columbus arrives in America (one second to midnight)
Christ born
Mohammed born
Roman republic, Old Testament, Buddha
Peak of last glacial period, humans migrate to the Americas
First cities in Mesopotamia
Dynastic China
Agriculture, permanent settlements
60
55
50
45
40
35
30
25
20
15
10
5
0

How old is the Universe?

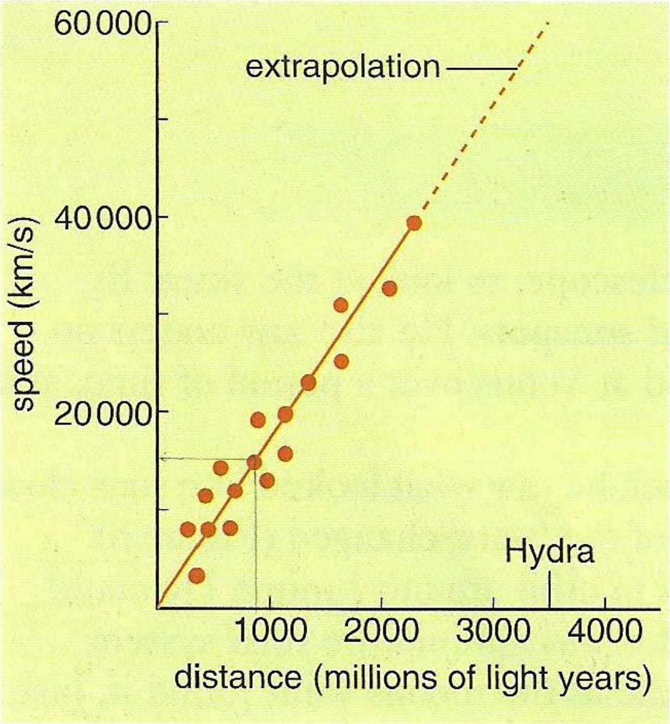
13.8 billion years

George Lemaitre (1894-1966) proposed what is now termed the **Big Bang theory** of the Universe i.e. an expansion from a *singularity*





The galaxy is found in this constellation	Distance of galaxy (millions of light years*)	Speed of galaxy (km/s)
Virgo	72	1200
Perseus	400	
Ursa Major		15 000
Corona Borealis	1200	20 000
Bootes	2400	40 000
Hydra		60 000



Edwin Hubble (1889-1953)

Hubble found that the majority of galaxies were *moving away from each other.* The resulting doppler shift would be towards the *red* end of the spectrum. The line of best fit to the speed vs distance graph gives an idea of the age of the universe

$$t \approx \frac{2300\times10^{6}\times9.46\times10^{15}\,\mathrm{m}}{40{,}000\times10^{3}\,\mathrm{ms^{-1}}}$$

$$t \approx 5.4\times10^{17}\,\mathrm{s}$$

$$t \approx 17.2\,\text{billion years}$$

If one accounts for relativistic effects, inflation etc

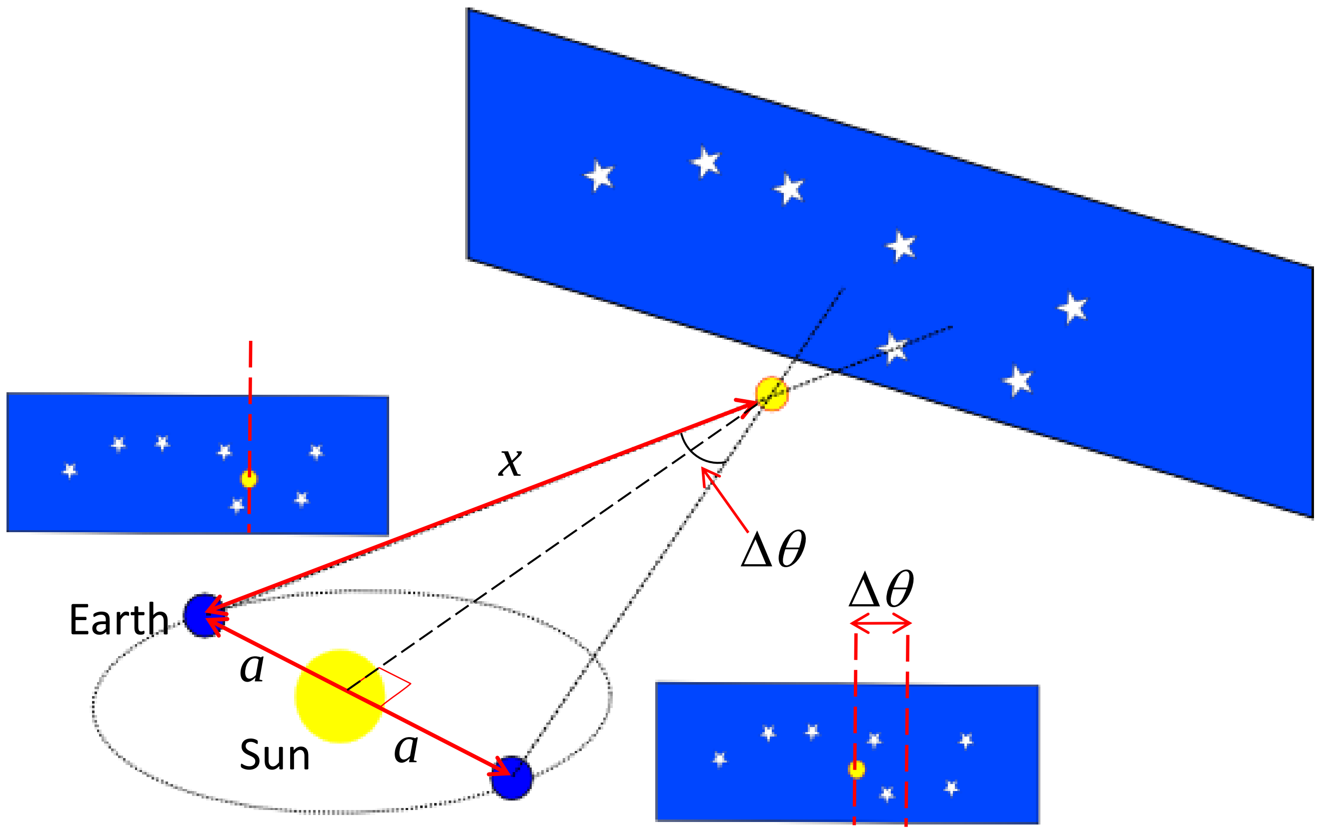
t = 13.8 billion years

Caution! Parallax is often stated as $\Delta\theta/2$

Measuring distance *x* of stars via **Parallax**

Record the angular change $\Delta\theta$ in the position of a star over the course of a year, i.e. as the Earth orbits the Sun

This assumes the stars are fixed relative to the Earth over this timescale!



a = 1AU = 1.496×10^{11} m

$$x \sin \tfrac{1}{2}\Delta\theta = a$$

$$\boxed{x = \frac{a}{\sin \tfrac{1}{2}\Delta\theta}}$$

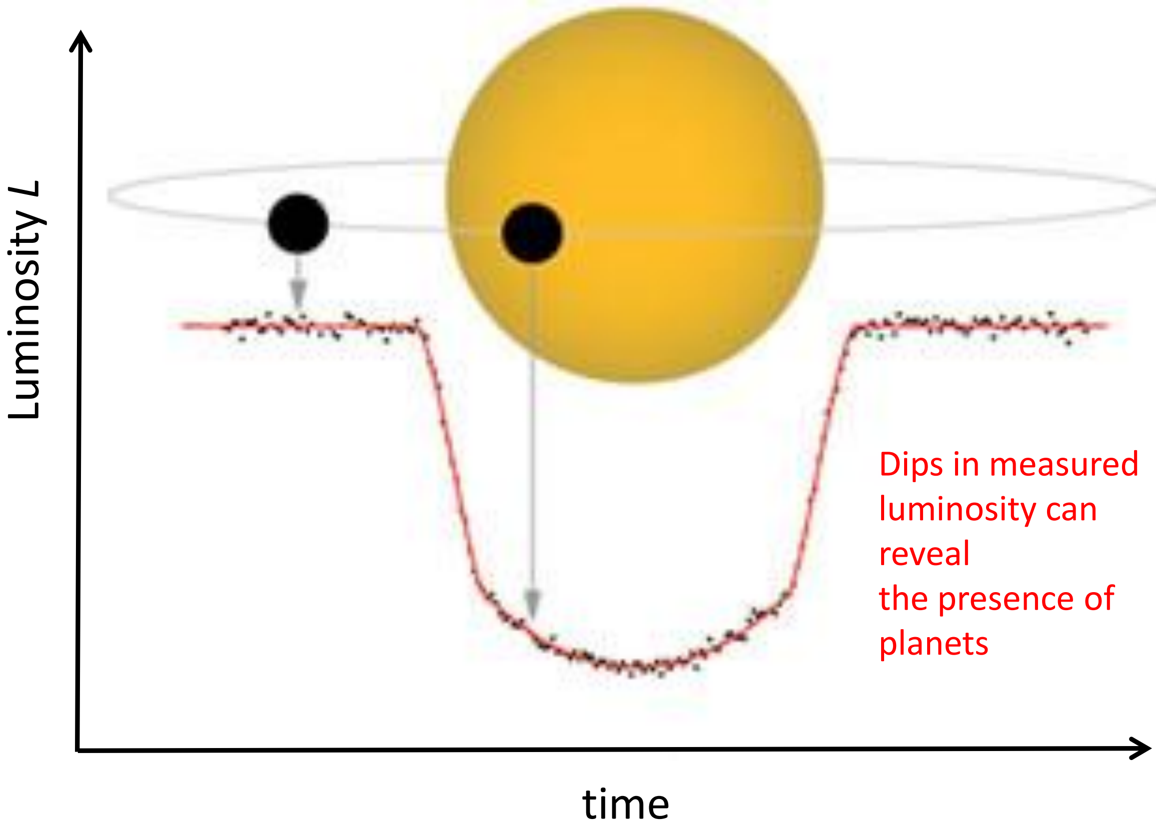
The parallax of our nearest star outside of the solar system (Proxima Centauri) is $\Delta\theta = 1.53626$ arc-seconds

$$\Delta\theta = \frac{1.53626^{\circ}}{3600} \qquad \therefore x = \frac{1}{\sin \tfrac{1}{2}\Delta\theta} = \boxed{268{,}532\,\mathrm{AU}}$$

$$x = \boxed{4.02 \times 10^{16}\,\mathrm{m}}$$

$$x = \frac{4.02 \times 10^{16}}{9.461 \times 10^{15}} = \boxed{4.25 \text{ light-years}}$$

Luminosity method for measuring distances, and detecting planets!



Luminosity L is the light power generated by a star

$$B = \frac{L}{4\pi x^2}$$

If the star is a distance x away then the 'brightness' B (defined as the power per unit area) is L divided by the area of a sphere of radius x

If we know the luminosity of a certain type of star (indicated by its *spectrum*) then we can use the measured brightness to work out how far away it is.

$$L_{\odot} = 3.846 \times 10^{26}\,\mathrm{W}$$

Current luminosity of our Sun

Summary of astronomical distances

Earth – moon = 1.28 light s

Earth – Sun = 8.3 light min

1pc = 3.26 light yr

Nearest star $\sim$ 4 light yr

Sun – centre of galaxy $\sim$ 25,000 light yr (8 kpc)

To nearest galaxy $\sim$ 2 million light yr (0.75 Mpc)

to distant quasars $\sim$ 10 billion light yr (3 thousand Mpc)

1 AU = 1.496×10^{11} m

1 light year = 9.461×10^{15} m

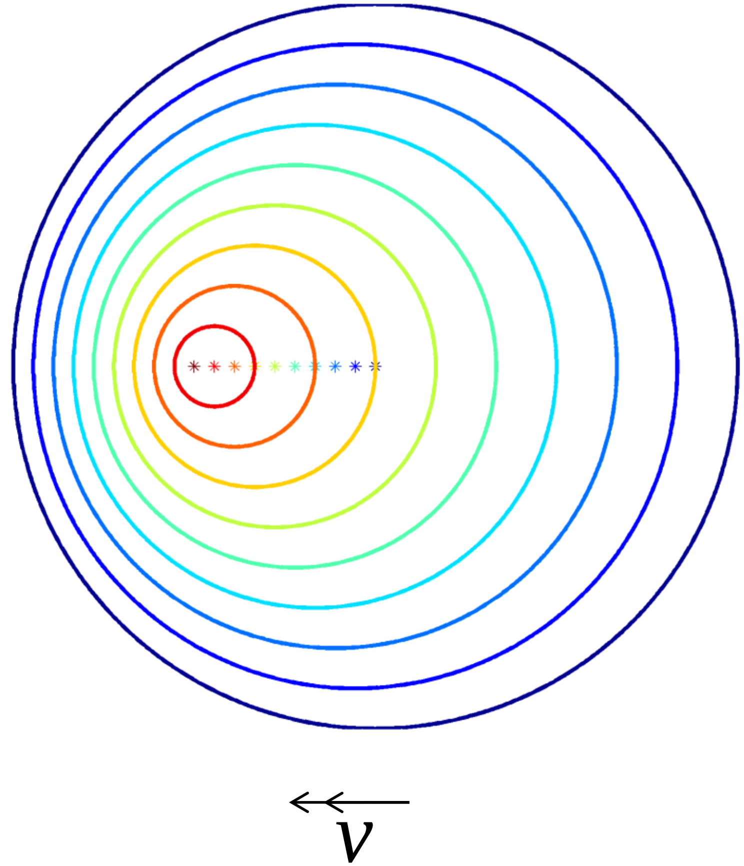
1 parsec = 3.086×10^{16} m

1Mpc = 10^{6} parsecs = 3.086×10^{22} m

Doppler shift method for measuring radial velocity

$$c = f\lambda$$

If an object emitting radiation at frequency *f* moves radially towards an observer at velocity *v*, the observer will measure a *slightly higher frequency* of radiation as the emitted waves 'bunch up'.

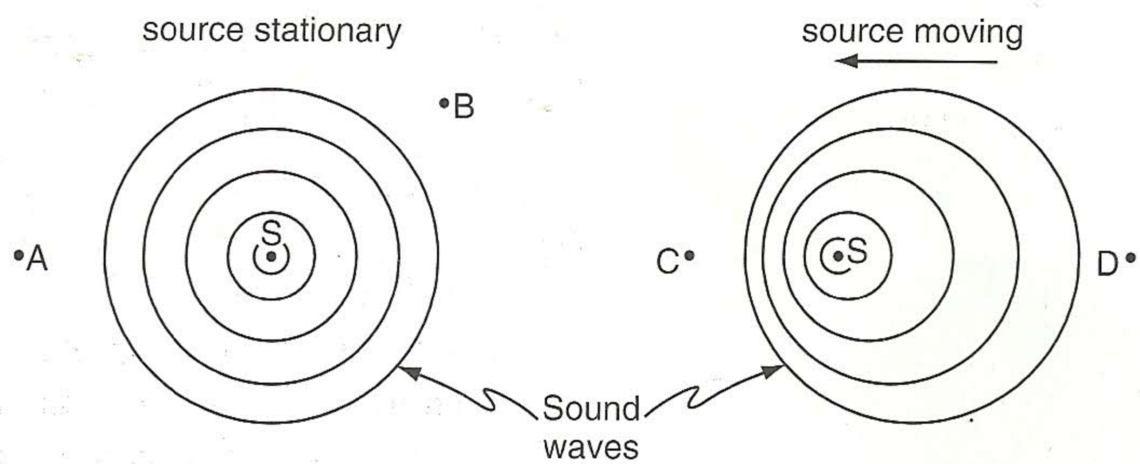


$$\Delta f = \frac{v}{c} f$$

- frequency change → Δf
- Velocity of emitter towards observer → v
- Frequency of emitted radiation → f
- Speed of radiation → c

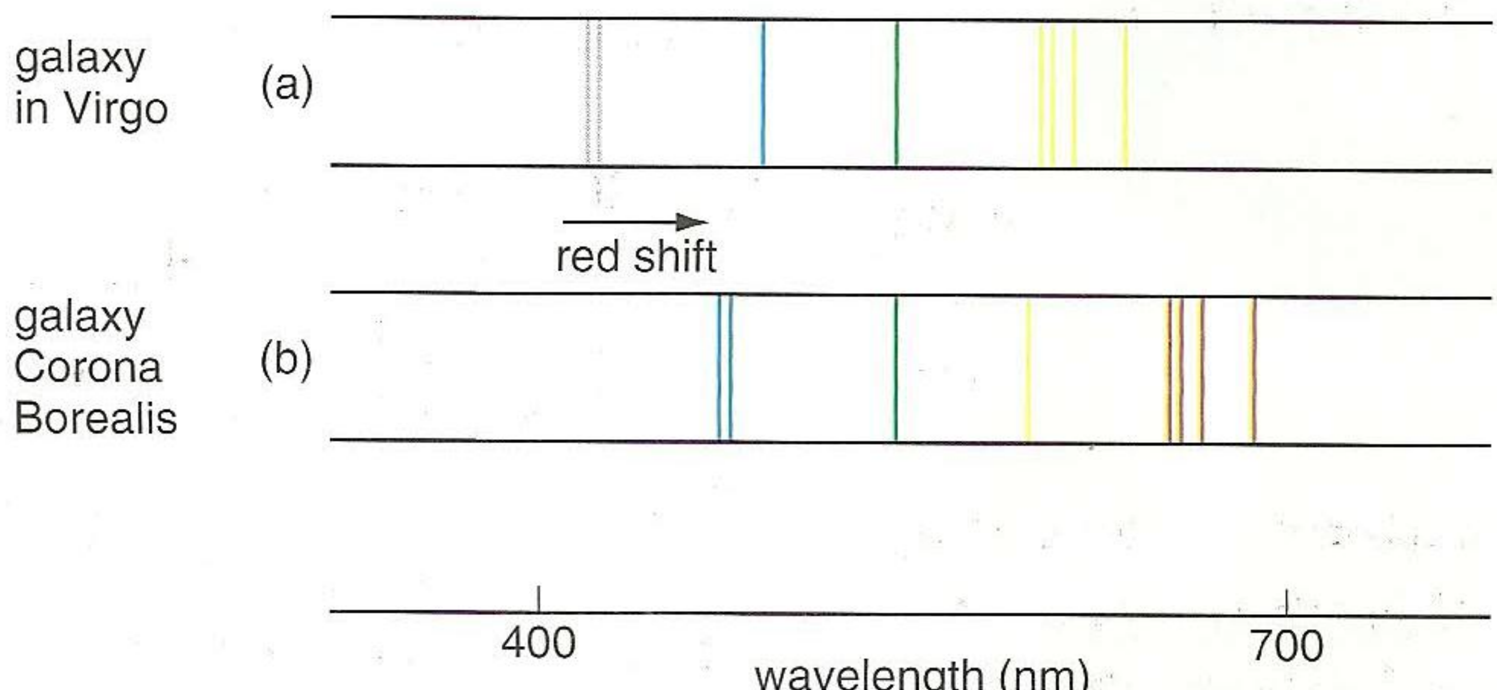
Note this formula is 'Classical'. It is valid when v << c, otherwise a relativistic version must be used

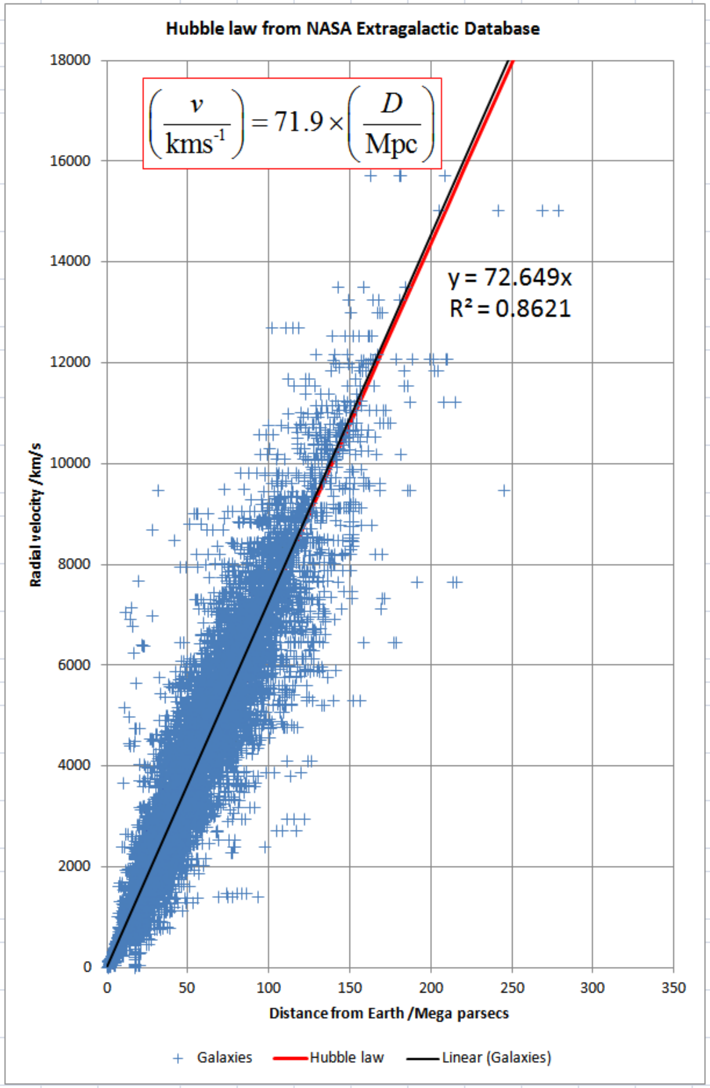
Christian Doppler
1803-1953



Redshift *z* is the fractional change in wavelength of light due to the doppler effect

$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emmitted}}}{\lambda_{\text{emmitted}}}$$





Edwin Hubble was perhaps the first astronomer to show that most galaxies (i.e. objects with distances of 10Mpc or more) have a recessional velocity v which is proportional to the distance d away from Earth*. This is called the *Hubble Law*

$$v = H_0 d$$

H_0 is the 'Hubble constant', which has a modern value of about $H_0 \approx 71.9\,\text{kms}^{-1}/\text{Mpc}$
It is *not really a constant*, as (see below) it relates to the *scale* of Universe expansion, which is thought not to be linear. The zero suffix therefore means 'at the current epoch.'

Hubble's law implies that *the Universe is expanding*. If we consider just the radial motion due to expansion (imagine a sponge being continuously enlarged, and tracking the relative distances between pairs of holes) and assume this is at a *constant* rate throughout time t , we can therefore make an estimate of the age of the Universe.

$$v = \frac{d}{t} \qquad v = H_0 d$$

$$\therefore H_0 d = \frac{d}{t} \quad \therefore t = \frac{1}{H_0}$$

$$t = \left(\frac{71.9 \times 10^3\,\text{ms}^{-1}}{3.086 \times 10^{22}\,\text{m}}\right)^{-1} = 13.6\,\text{billion years}$$

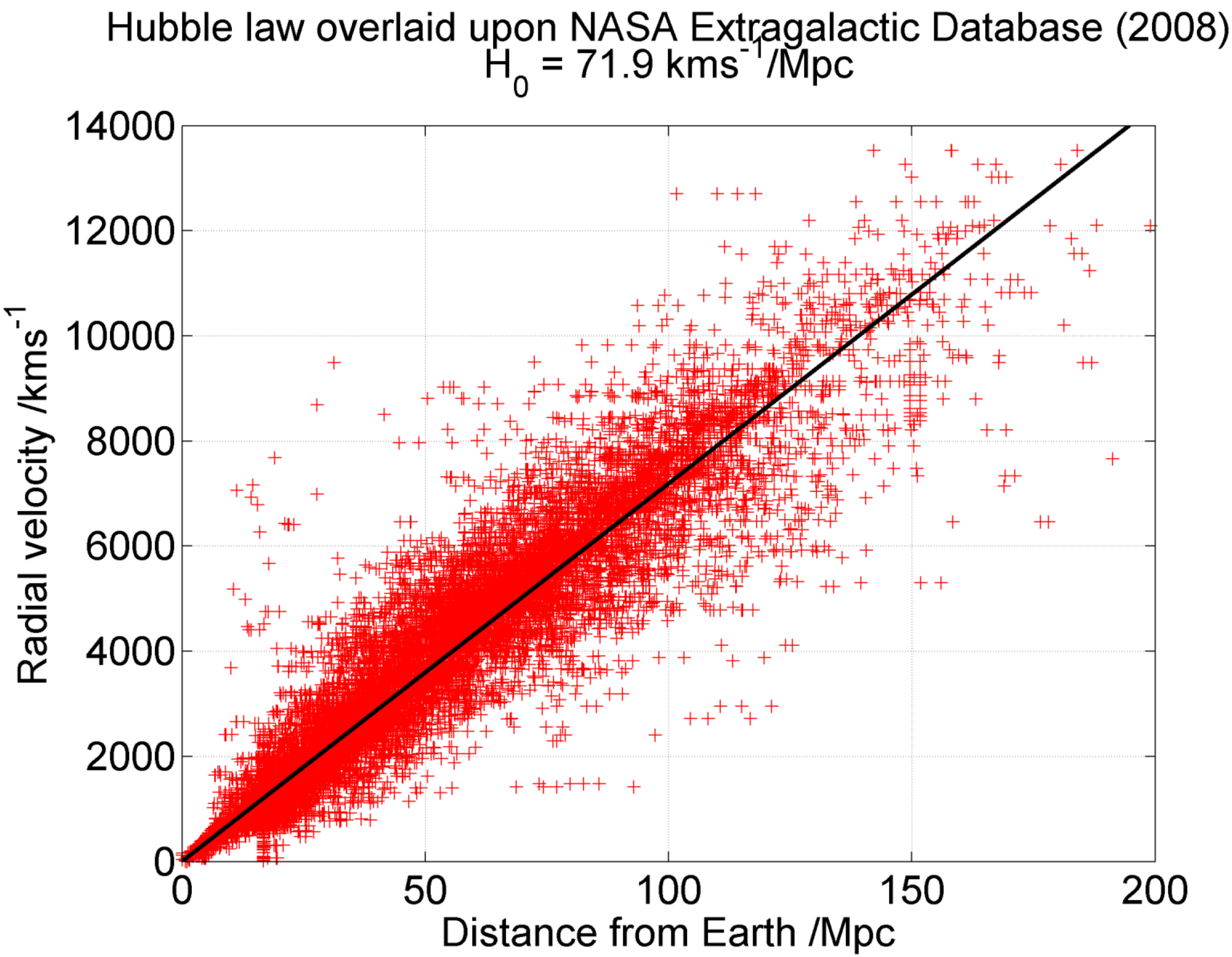
1Mega-parsec (Mpc) = 3.086 x10^{22} m

*The **Cosmological Principle** means *all parts of the Universe are expanding uniformly* relative to everywhere else, *at a given time* since the Big Bang. The Hubble law would therefore be the *same* from the perspective of a planet in another galaxy as it is on Earth.

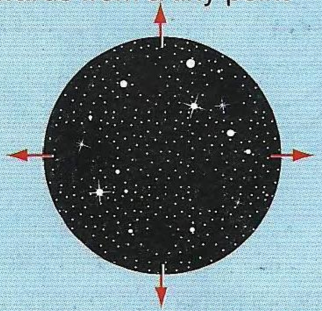
As of 2017, the best estimate for the age of the Universe is **13.799 +/- 0.021 billion years** using the **Lambda-CDM model** and observations of the **Cosmic Microwave Background** (CMB) radiation via **Planck** and **Wilkinson Microwave Anisotropy (WMAP)** probe (and others). The Lamda CDM model assumes a non-constant Hubble parameter, and is based upon the solutions of the *Friedmann equations*

Data downloaded from the NASA Extragalactic Database (NED). (2008)
https://ned.ipac.caltech.edu/level5/NED05D/ned05D_6.html

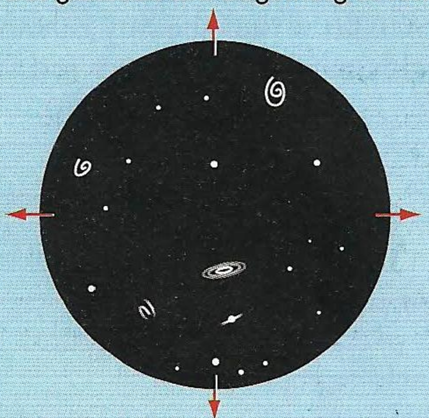
2016 estimate of Hubble constant at present epoch https://en.wikipedia.org/wiki/Hubble%27s_law



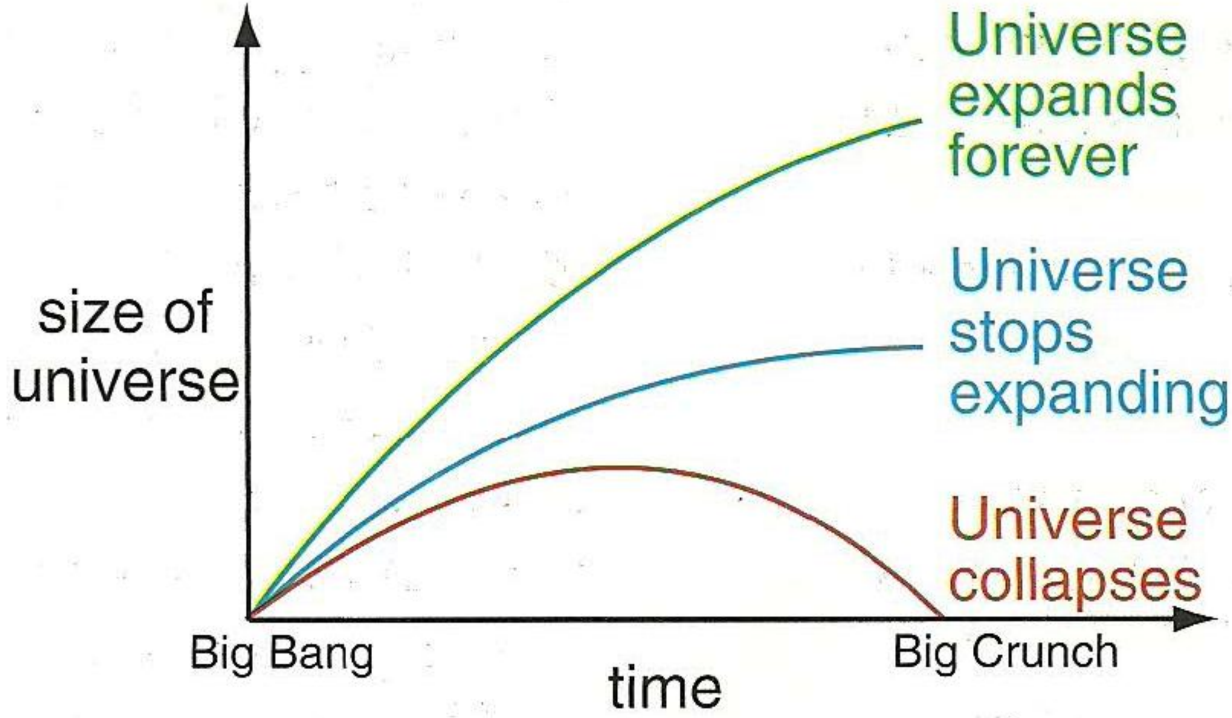
(a) 15 billion years ago: the moment of creation. The universe explodes outwards from a tiny point



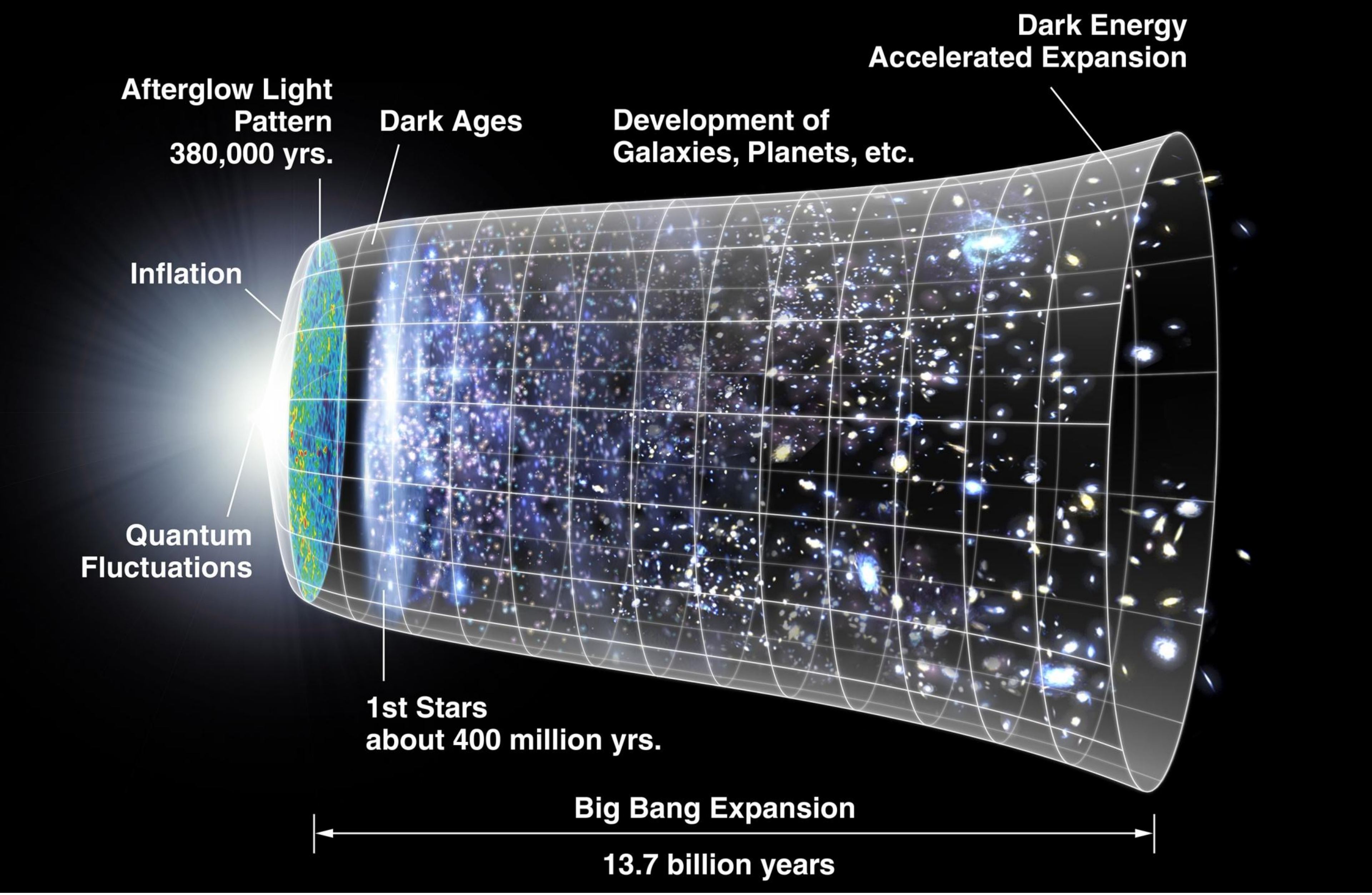
(b) 1 billion years after the 'big bang', the universe is expanding rapidly but galaxies are beginning to form



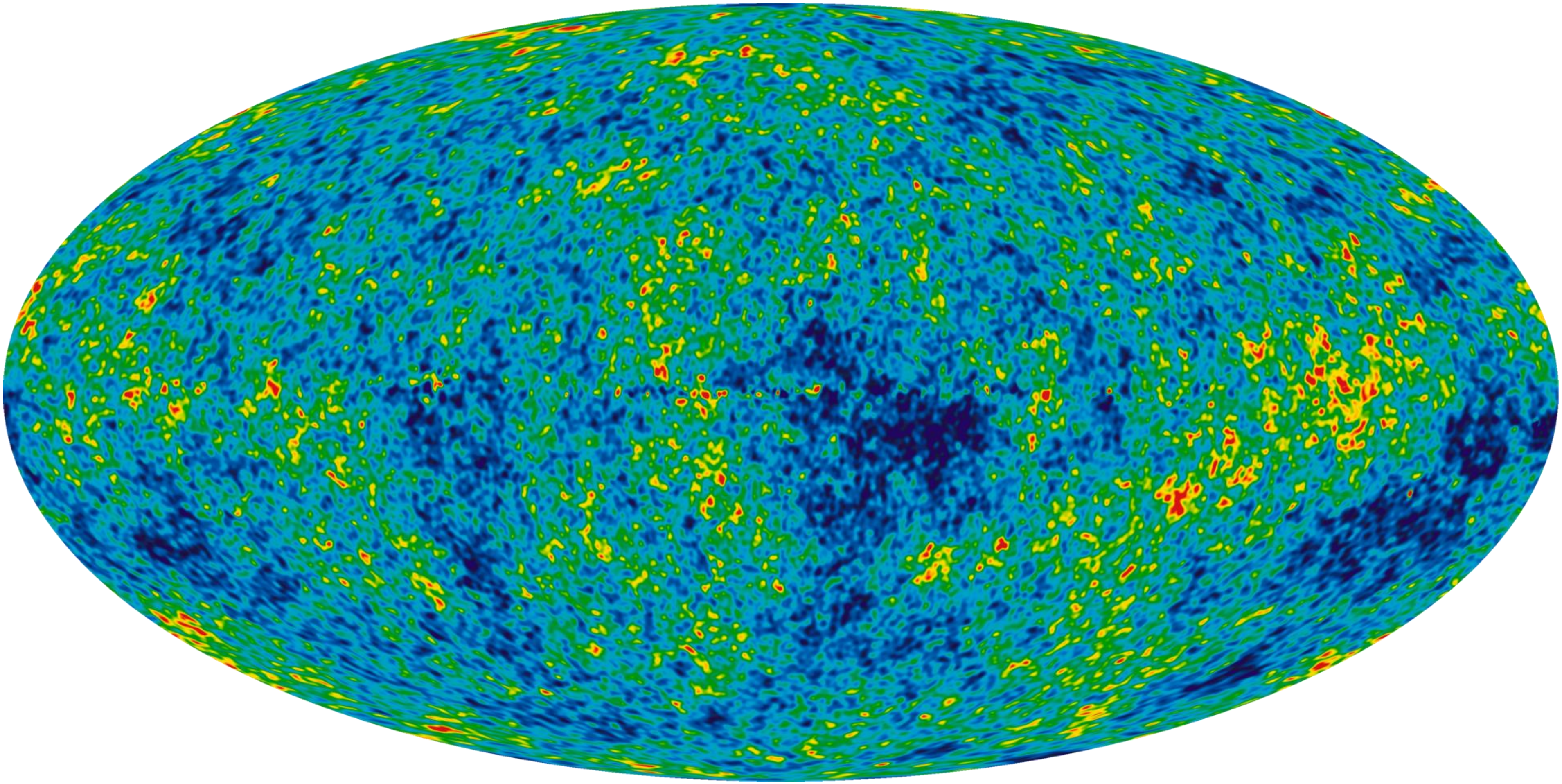
(c) 10 billion years after the 'big bang' galaxies have formed. Our solar system forms in one of them. The universe is expanding less rapidly now. There is gravitational attraction between all galaxies, which tries to pull them all back together. So the galaxies are slowing down. Perhaps eventually all the galaxies will start to fall back towards each other . . .



Does the universe expand forever? Or does it gradually slow down, or does it contract?

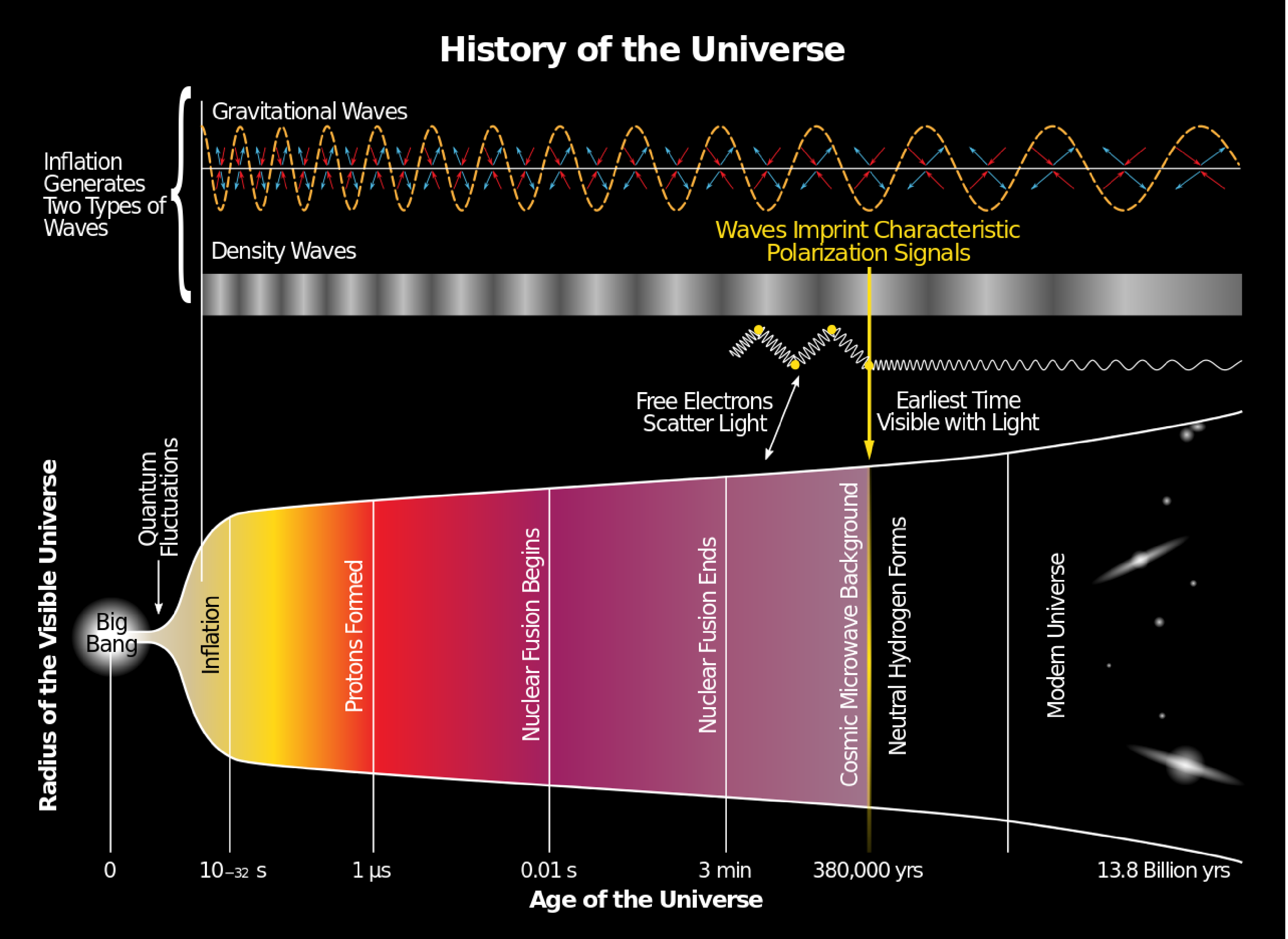


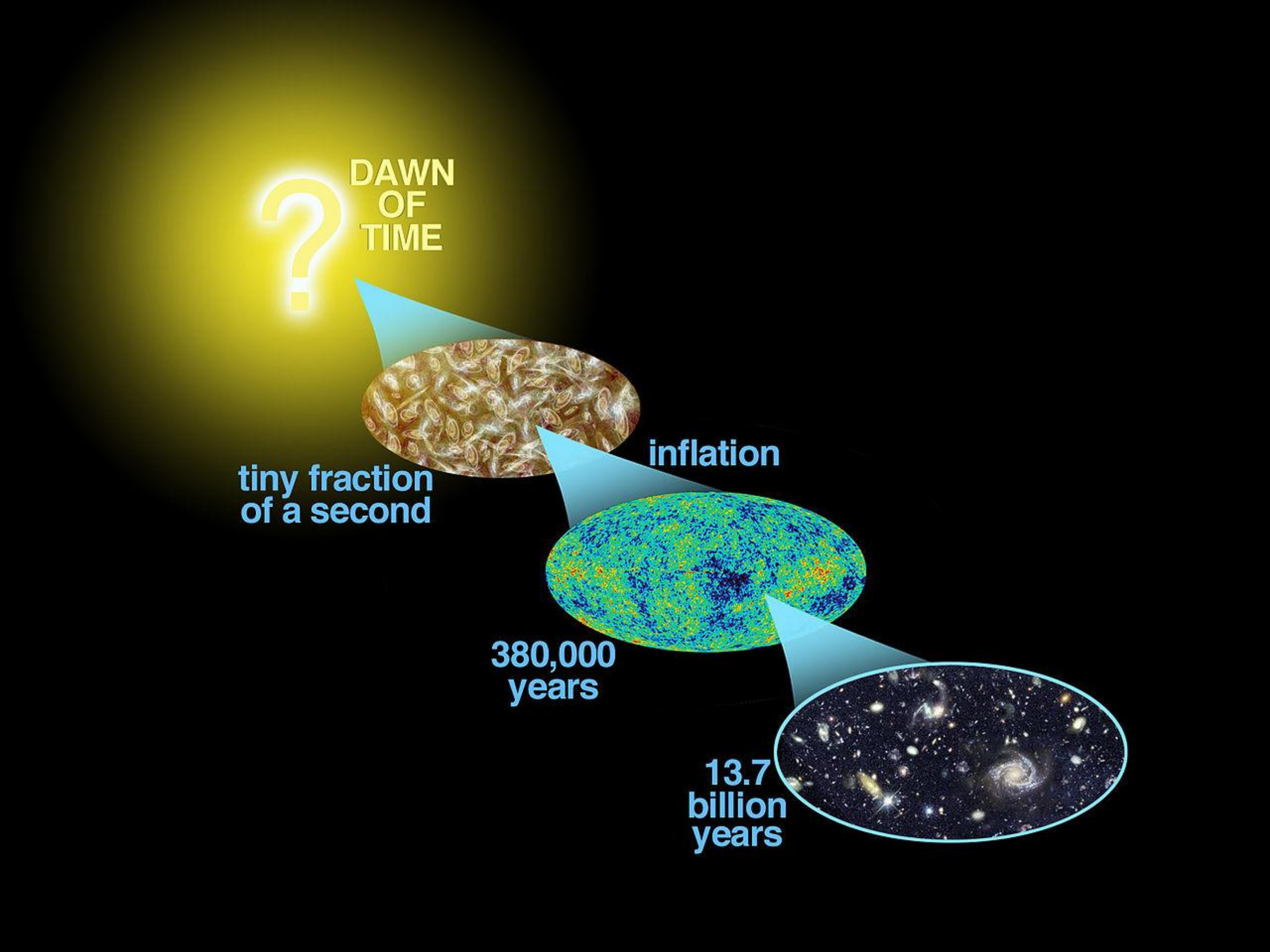
NASA/WMAP Science Team - Original version: NASA; modified by Ryan Kaldari



Nine Year Microwave Sky . The detailed, all-sky picture of the infant universe created from nine years of WMAP data. The image reveals 13.77 billion year old temperature fluctuations (shown as colour differences) that correspond to the seeds that grew to become the galaxies. The signal from our galaxy was subtracted using the multi-frequency data. This image shows a temperature range of ± 200 μK.

NASA / WMAP Science Team WMAP # 121238 Image Caption 9 year WMAP image of background cosmic radiation (2012)


History of the Universe
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10^{-32} s
1 µs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe



DAWN OF TIME
inflation
tiny fraction of a second
380,000 years
13.7 billion years