The Constantly Changing Hubble Constant

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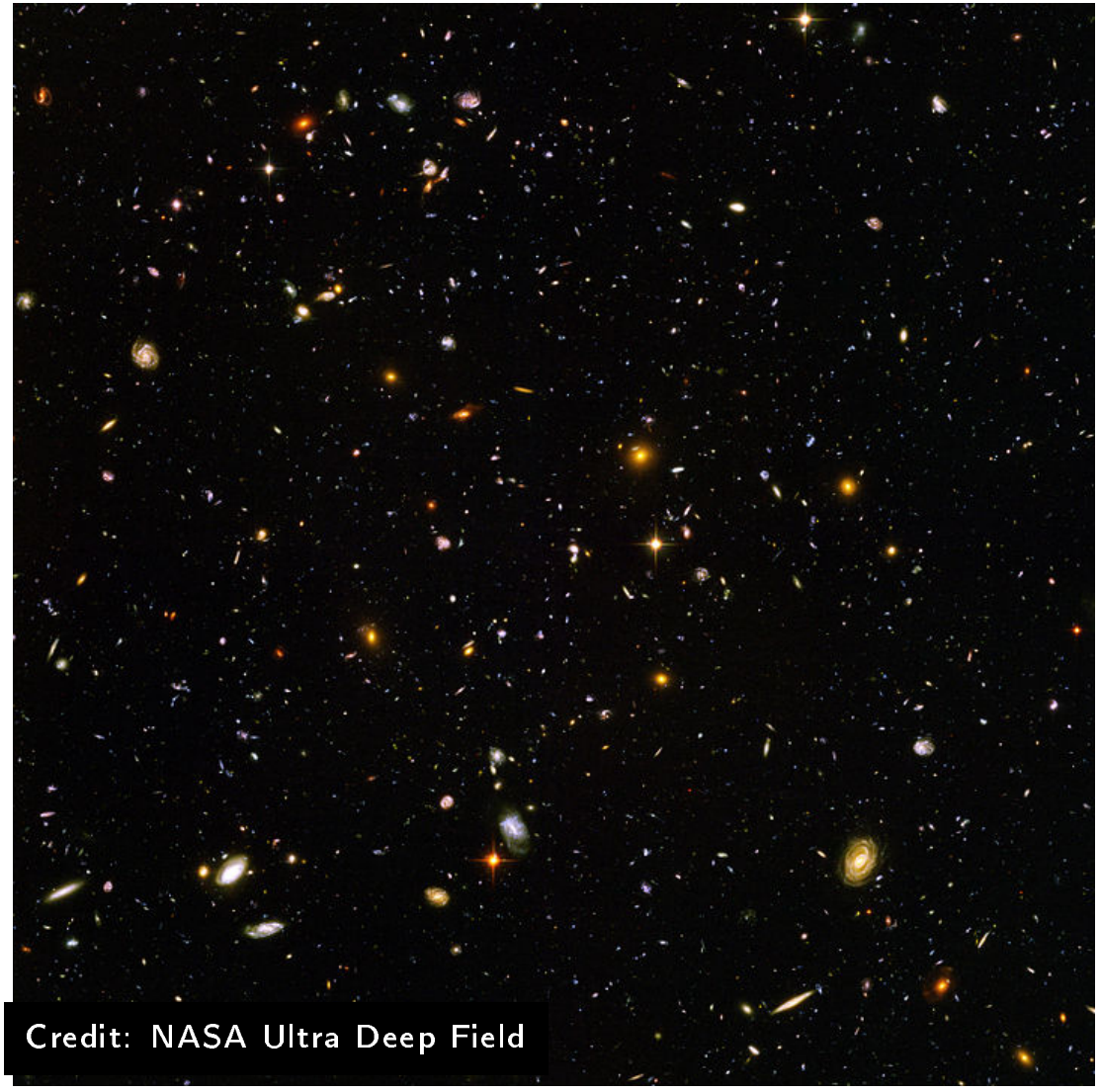
You are invited to go to www.menti.com and enter code
14 11 05 9.

The Universe is expanding!

- But what does this actually mean?
- How do we know it is expanding?
- Why is it expanding?
- How fast is it expanding?
- Are cosmologists completely realistic about the uncertainties in their results?

How do we know?

- Everywhere we look, distant galaxies are receding; more distant galaxies are receding faster.
- So either we are at the centre of a cosmic conspiracy, or all the space between all the galaxies is expanding.



Credit: NASA Ultra Deep Field

Is the solar system expanding? Are *we* expanding?

Go to `www.menti.com` (code 14 11 05 9) and choose one possibility:

1. Yes, a lot
2. Yes, but only a tiny amount
3. No

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Is the solar system expanding? Are *we* expanding?

- Other forces - molecular forces between the molecules in your body, and gravitational forces between the Sun and the planets - are far more than strong enough to overcome the effect of cosmic expansion.

- Gravity is even strong enough to keep the Andromeda Galaxy from receding from us.

Credit: David Dayag

- It's only the furthest objects - where gravity becomes negligible - that recede.

What does *recession velocity* actually mean?

- We say 'distant galaxies are moving away from us'. This is informal language.
- They aren't really moving, they just appear to be - because the intervening space is expanding.
- Sometimes this makes a difference - for example, the recession velocity can exceed the speed of light.

Which 'Ed' first had the idea that the Universe is expanding?

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1. Edmond Halley
2. Edwin Hubble
3. Edgar Allan Poe

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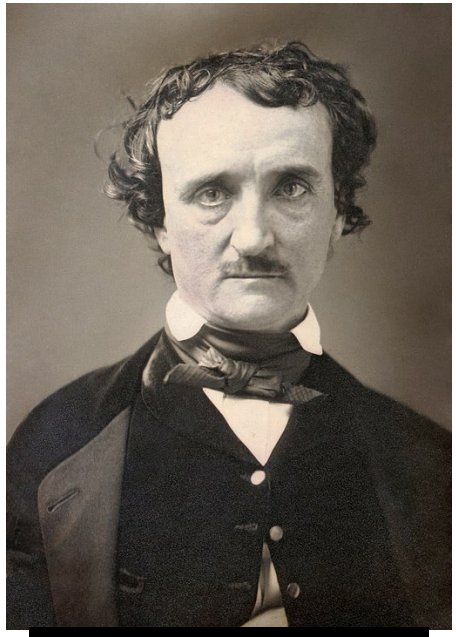
History

- In 1848 Edgar Allan Poe published *Eureka*, which included a description of expanding space.



Credit: Public domain

- Expansion is not obvious without large telescopes and so isn't usually part of pre-modern cosmologies. Full understanding only came in the 20th century.

So how fast is the expansion?

- For every additional distance of one megaparsec, there's an additional recession velocity of about 70 kilometers per second.
- So the expansion speed is about 70 kilometers per second per megaparsec.

- One megaparsec is about three million light years. It's the typical distance between galaxies.
- 70 kilometers per second is about 150,000 miles per hour.

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13.5 million years later it will be 1% longer:

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Continental drift is about six times faster...

H_0

- The current expansion rate is called the *Hubble constant* or *Hubble parameter* and is denoted 'H_0'.

- The 'H' commemorates Edwin Hubble (1889-1953), who was one of the first to measure it.

Credit: Johan Hagemeyer

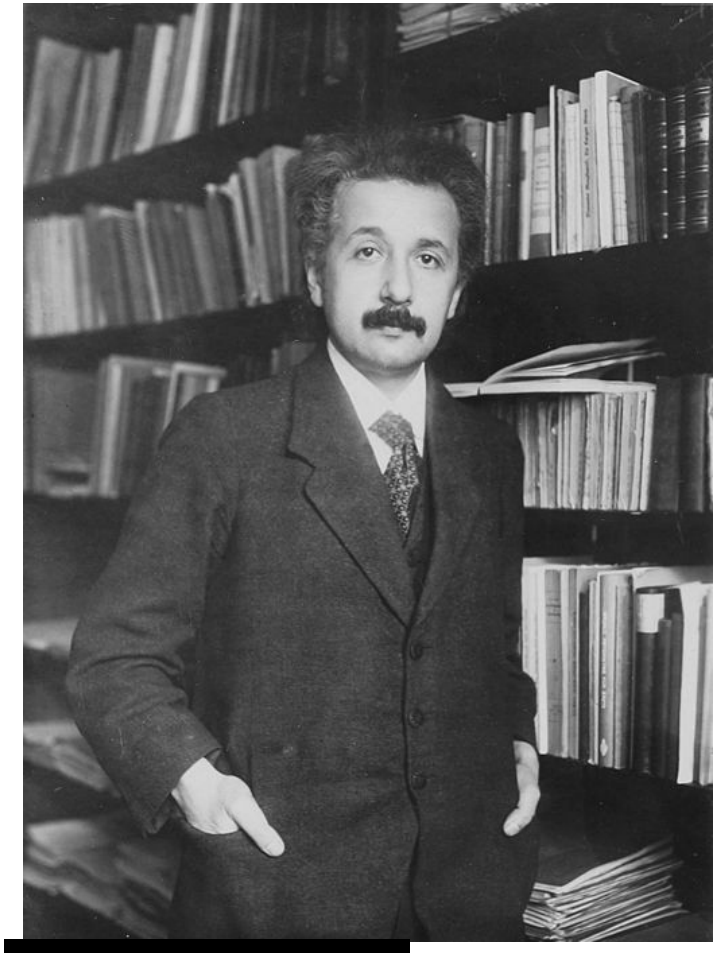
- The '0' refers to today. The expansion rate was different in the distant past.

Why does the Universe expand?

- Science is not so good with 'why?' questions...
- There's an *initial condition*: the Universe started expanding at the Big Bang.
- The later behaviour of the expansion (does it slow down? speed up?) then depends, essentially via gravity, on *what's in the Universe*.

Why does gravity play a role?

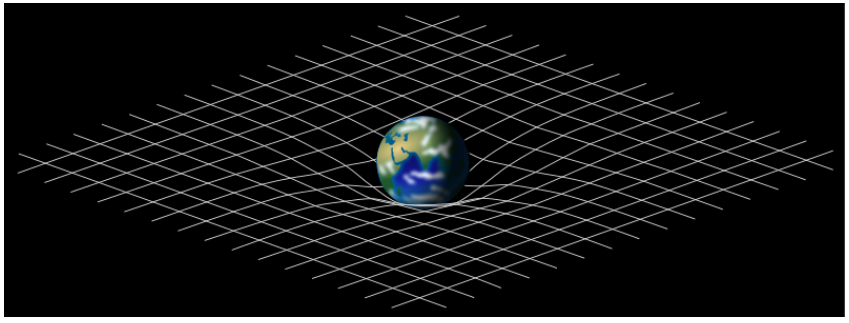
- *General relativity*, our modern theory of gravity, is due to Einstein (1916).



Credit: Paul Ehrenfest

Why does gravity play a role?

- Remember *mass* and *energy* are the same ($E = mc^2$).
- Mass/Energy *bends* spacetime, essentially changing distances and angles.



Credit: Mysid

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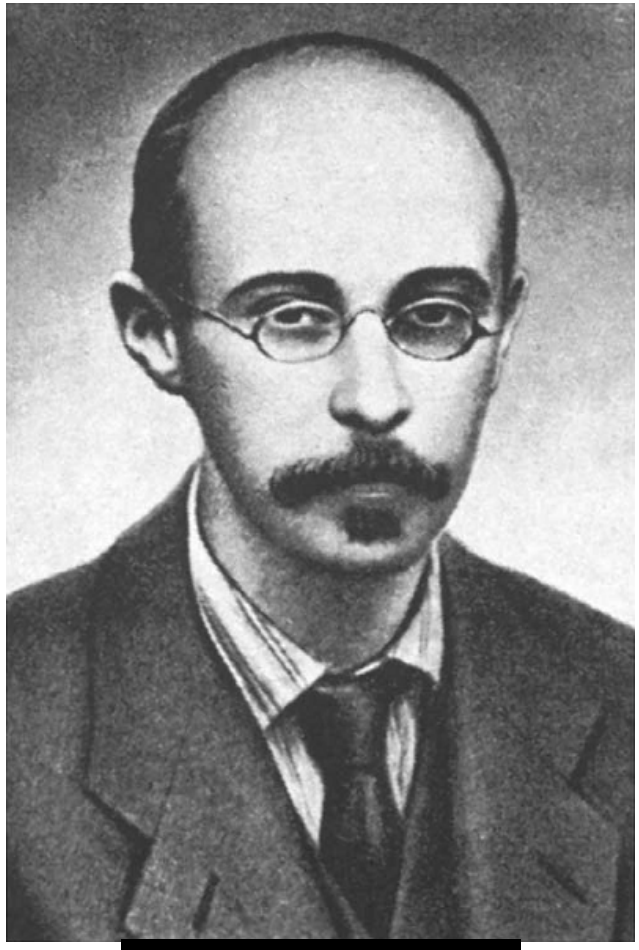
- This 'changing of distances and angles' works locally; the distorted spacetime governs how objects move, and this leads e.g. to the apple falling from the tree.
- But it also works on the Universe as a whole - mass/energy can cause distances to change *everywhere* in the Universe - and in particular can lead to increasing distances everywhere. This is the expansion that we see.

Contents of Universe control expansion

- It was Alexander Friedmann (Алекса́ндр Алекса́ндрович Фри́дман) (1888-1925) who first realised this (1922).



Credit: Public domain

What if we go backwards in time?

- George Lamaître (1894-1966) realised that if the Universe was expanding then it must, at an earlier stage, have been very small; he thereby invented the idea of the 'Big Bang'.

Credit: Public domain

How do we measure the expansion rate?

- In theory it's easy: find a distant galaxy, measure its recession velocity and its distance, and take the ratio.
- Example: a galaxy is receding at 1600 kilometers per second and is 20 megaparsecs away;
  then H_0 is 80 kilometers per second per megaparsec.

For a distant galaxy, which is harder to measure?

Go to `www.menti.com` (code 14 11 05 9) and choose one possibility:

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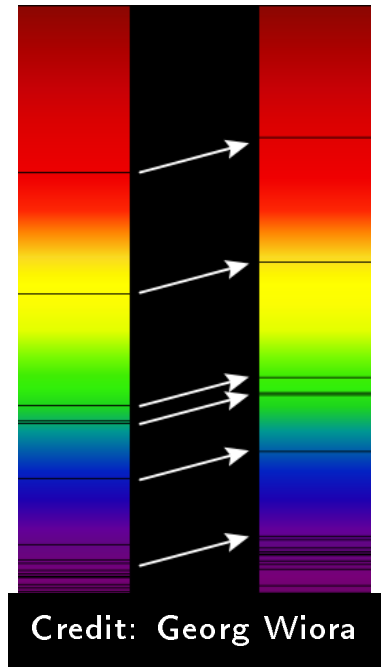
Can use *redshift* to measure recession velocity

- Light from distant galaxies gets streeeetched by the expansion; this makes it turn redder.
- It's fairly easy to measure the amount of red-shifting, as spectral lines are a convenient reference point. The redshift then immediately gives the velocity.



V M Slipher

- The first redshifts for galaxies (known then as nebulae) were made in 1912 by Vesto Slipher (1875 - 1969) at the Lowell Observatory in Flagstaff Arizona.

Recession velocity for galaxy M77

From Slipher's 1917 'Lowell Observatory Bulletin 80':

These recent spectrograms have been measured for radial velocity. The results for the four spectrograms — two of 1913 and two of 1917 — are as follows:

Plate	1913,	November 6,	Velocity −1060 km.
Plate	1913,	November 22, 23,	Velocity −1150
Plate	1917,	November 6, 7, 8,	Velocity −1080
Plate	1917,	November 12 to 16, two prisms	Velocity −1130 *s*
			Velocity −1145 *c*
			Velocity −1135 *c*
		Mean Velocity	−1120 km.

Modern value (from NASA/IPAC Extragalactic database):

BASIC DATA for MESSIER 077 (Back to INDEX)

```
Helio. Radial Velocity     :      1137 +/-        3 km/s
Redshift                   :  0.003793 +/- 0.000010        2014MNRAS.440..696A
```

Distance measurements - Cepheids

- Cosmic distances can be estimated using variable stars called *Cepheids*. We know how much light they produce (it's related to their period). Their observed brightness then tells us their distance.

- The brightness/period relation was discovered by Henrietta Swan Leavitt (1868 - 1921) at Harvard.

Credit: Public Domain

How distant is that Cepheid?

A and B are two identical Cepheids; A is 100 parsecs distant; B is 4% of the brightness of A. How far is B?

Go to `www.menti.com` (code 14 11 05 9) and choose one possibility:

1. 500 parsecs
2. 2500 parsecs
3. 4 parsecs

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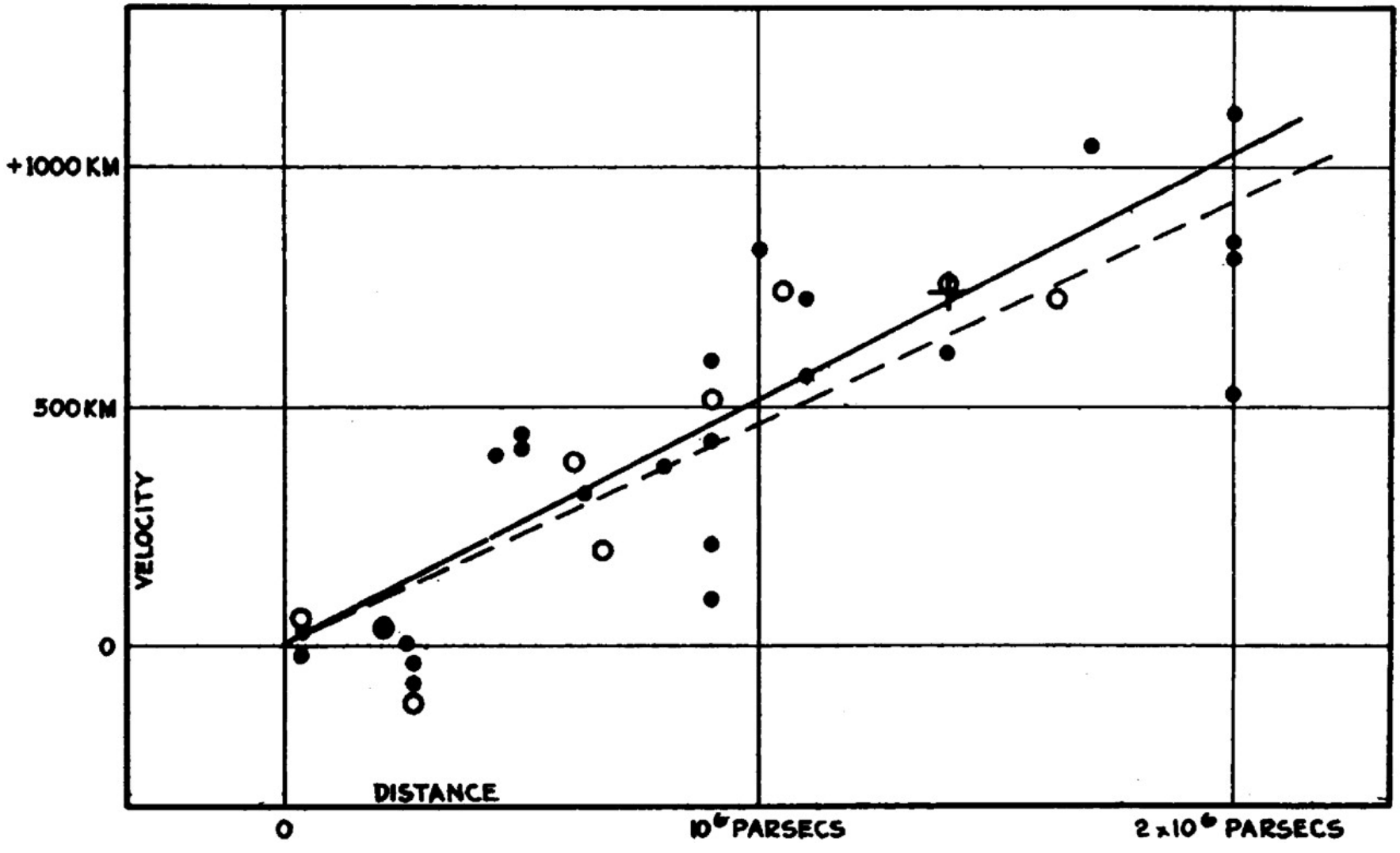
Linear relationship between recession velocity and distance

- It was Lamaître who first suggested a linear relationship between recession velocity and distance.
- Hubble then provided supporting evidence - he used the 100 inch telescope at Mt Wilson to spot Cepheids in a range of galaxies.

Hubble's plot - from 1929 PNAS paper



Where to find this document

- You can find the presentation at
  https://tinyurl.com/bycke8v6

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