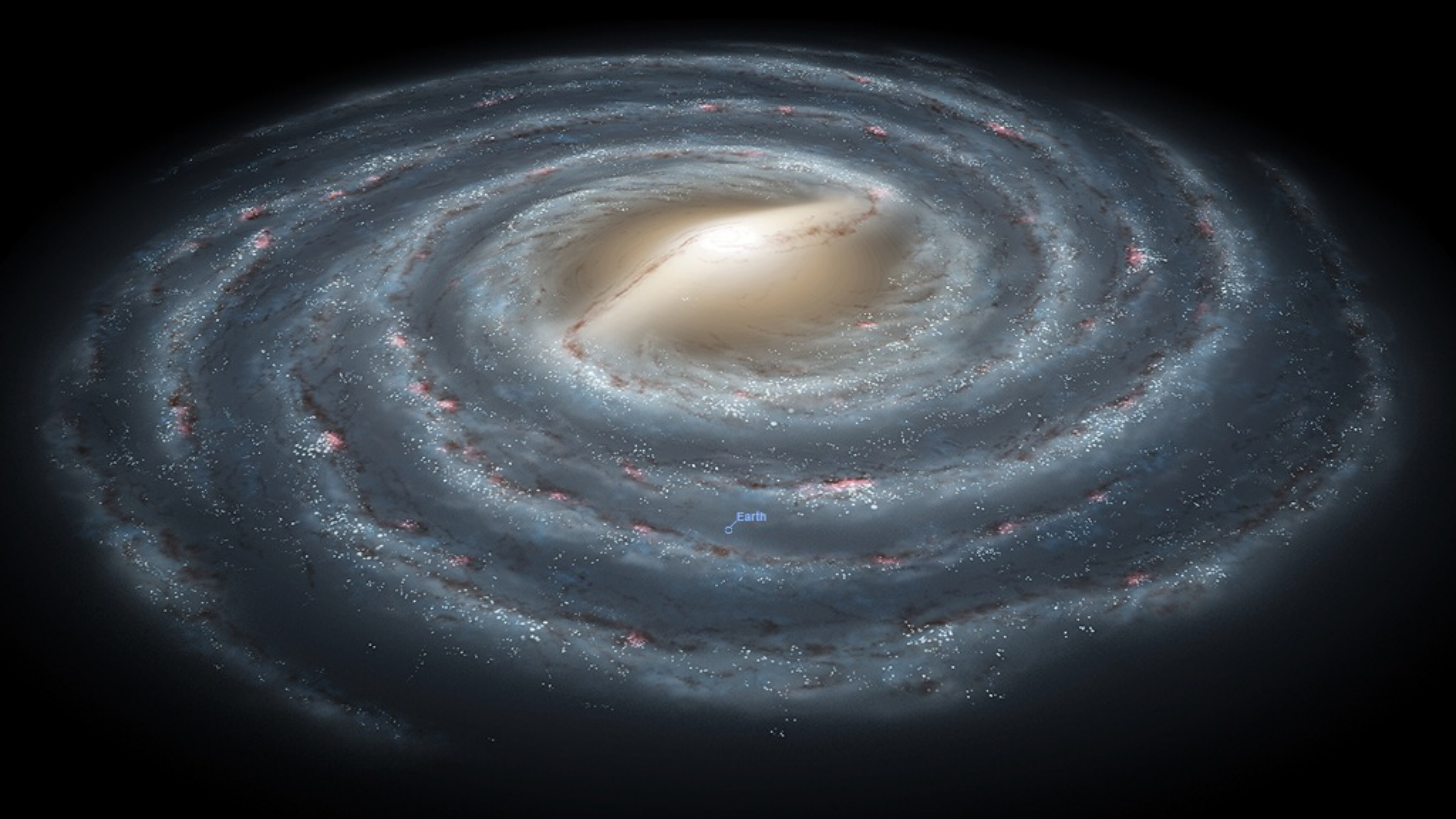


How fast is the Universe expanding?

Dr Matt Bothwell, University of Cambridge



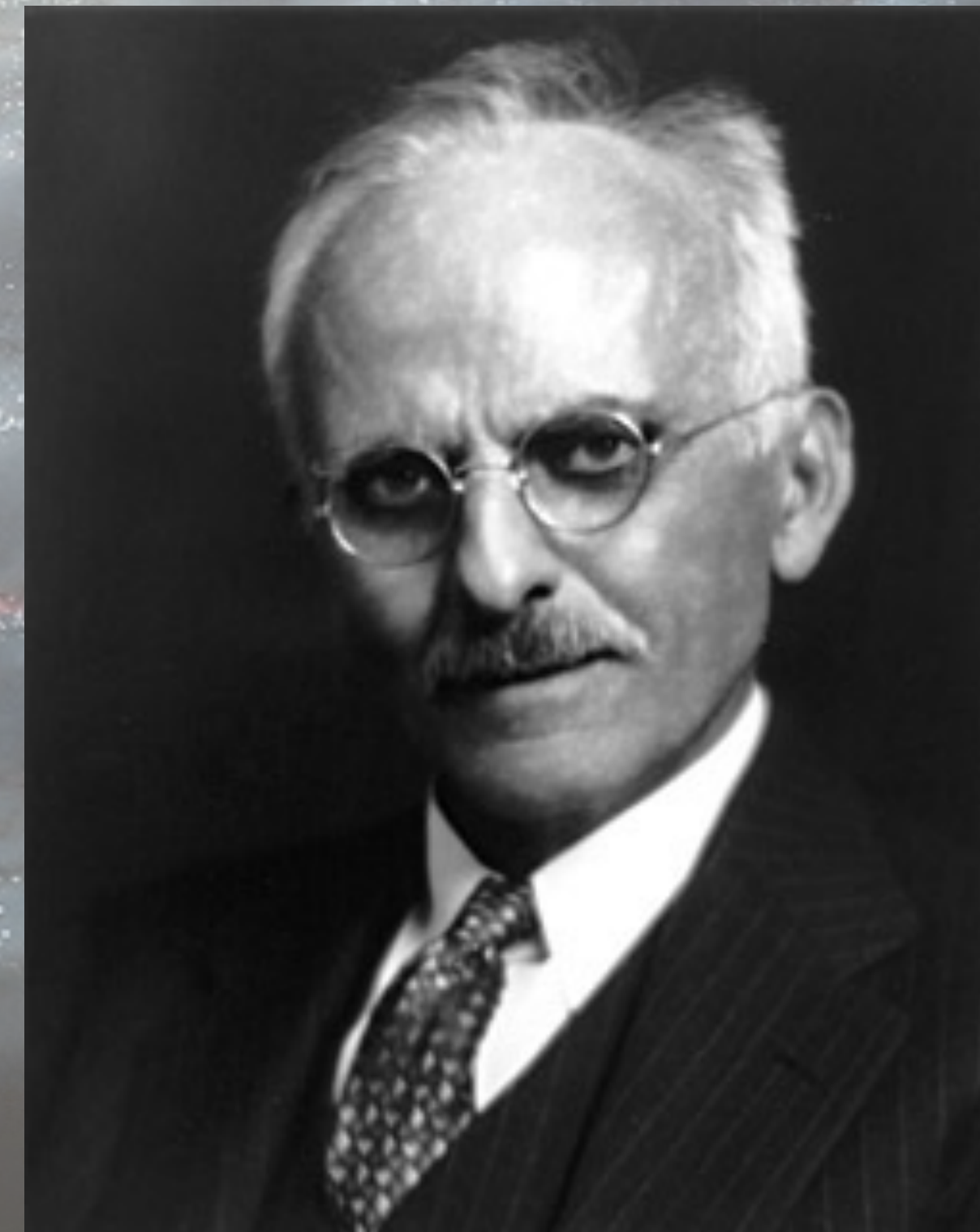


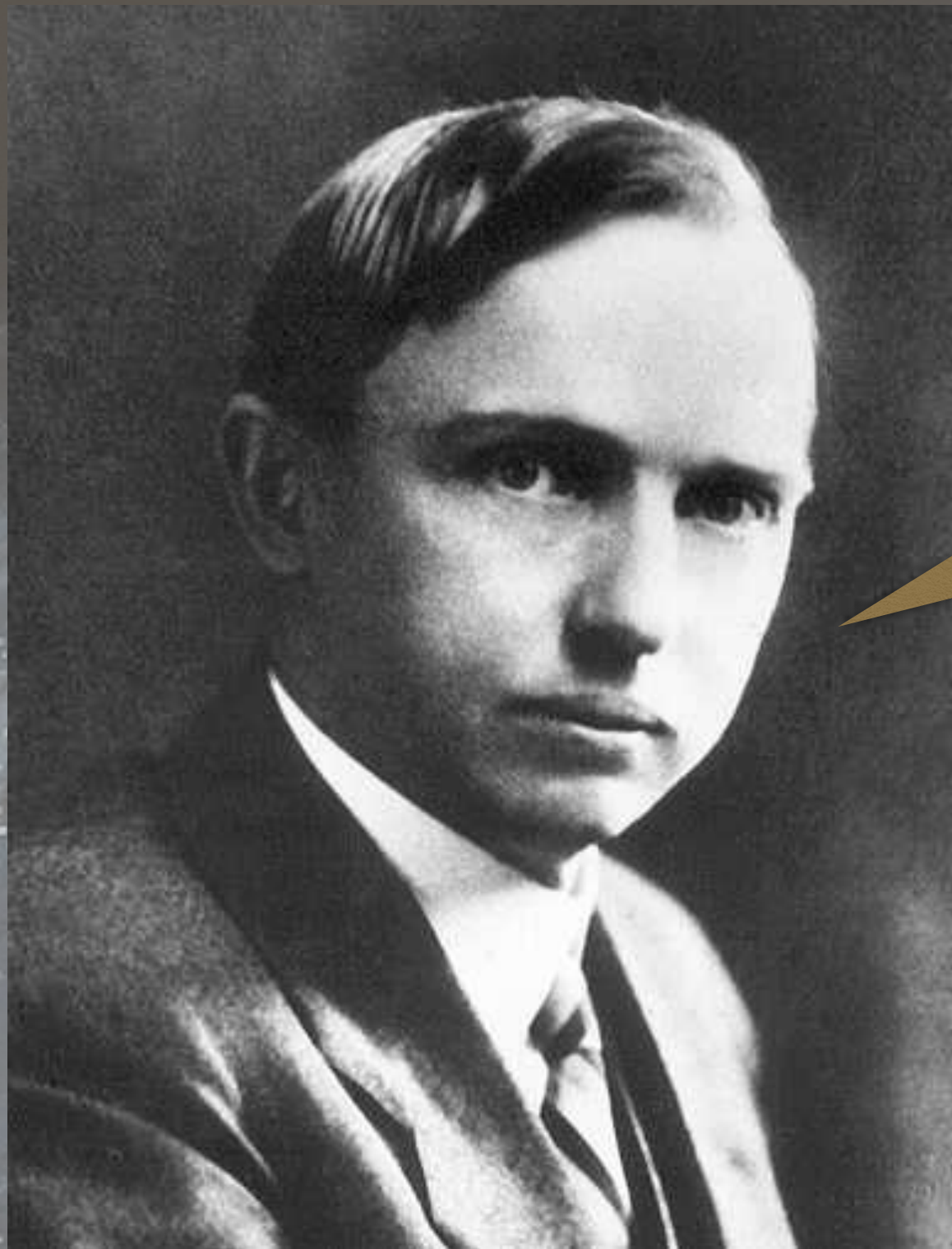


Harlow Shapley

Vs.

Heber Curtis



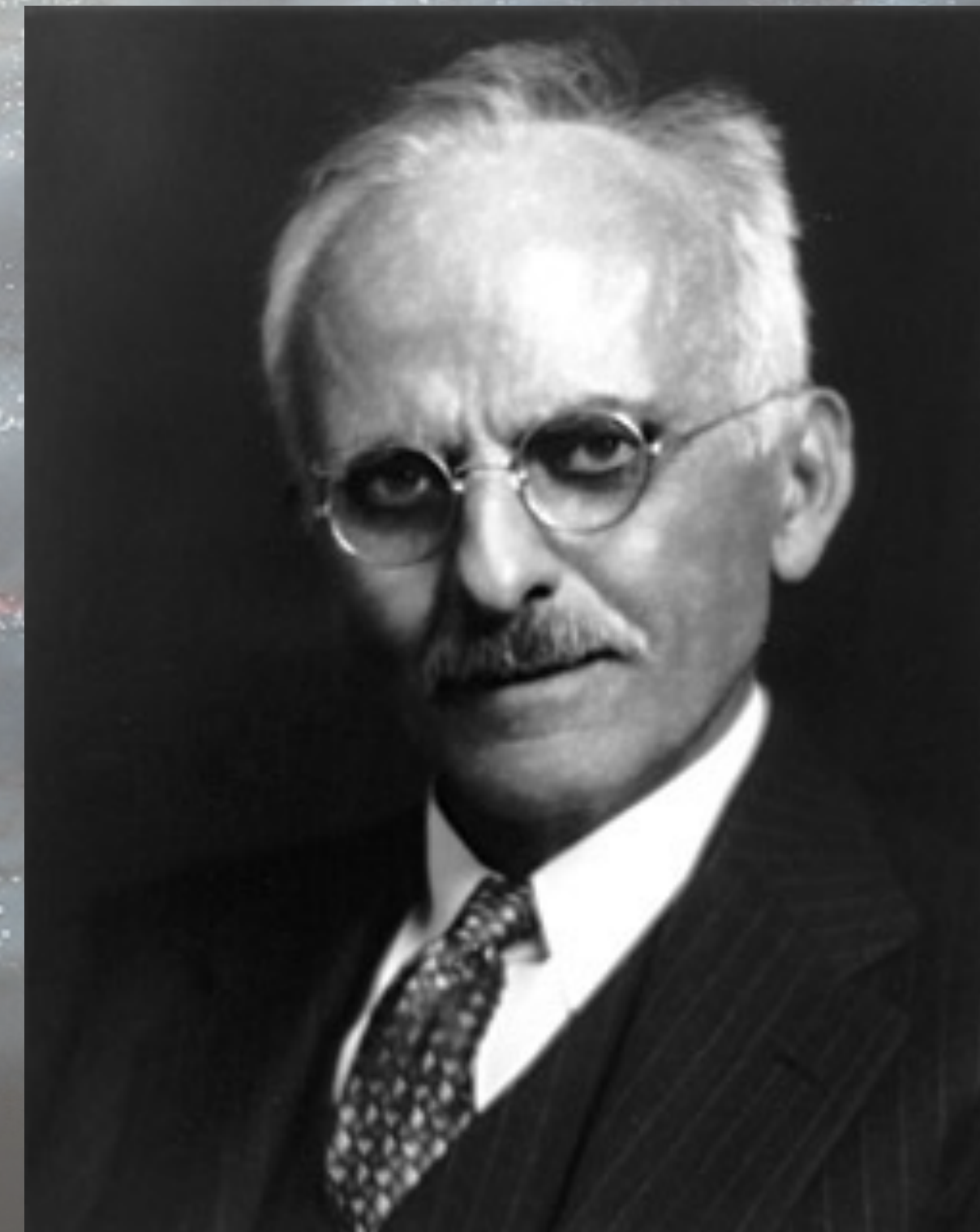


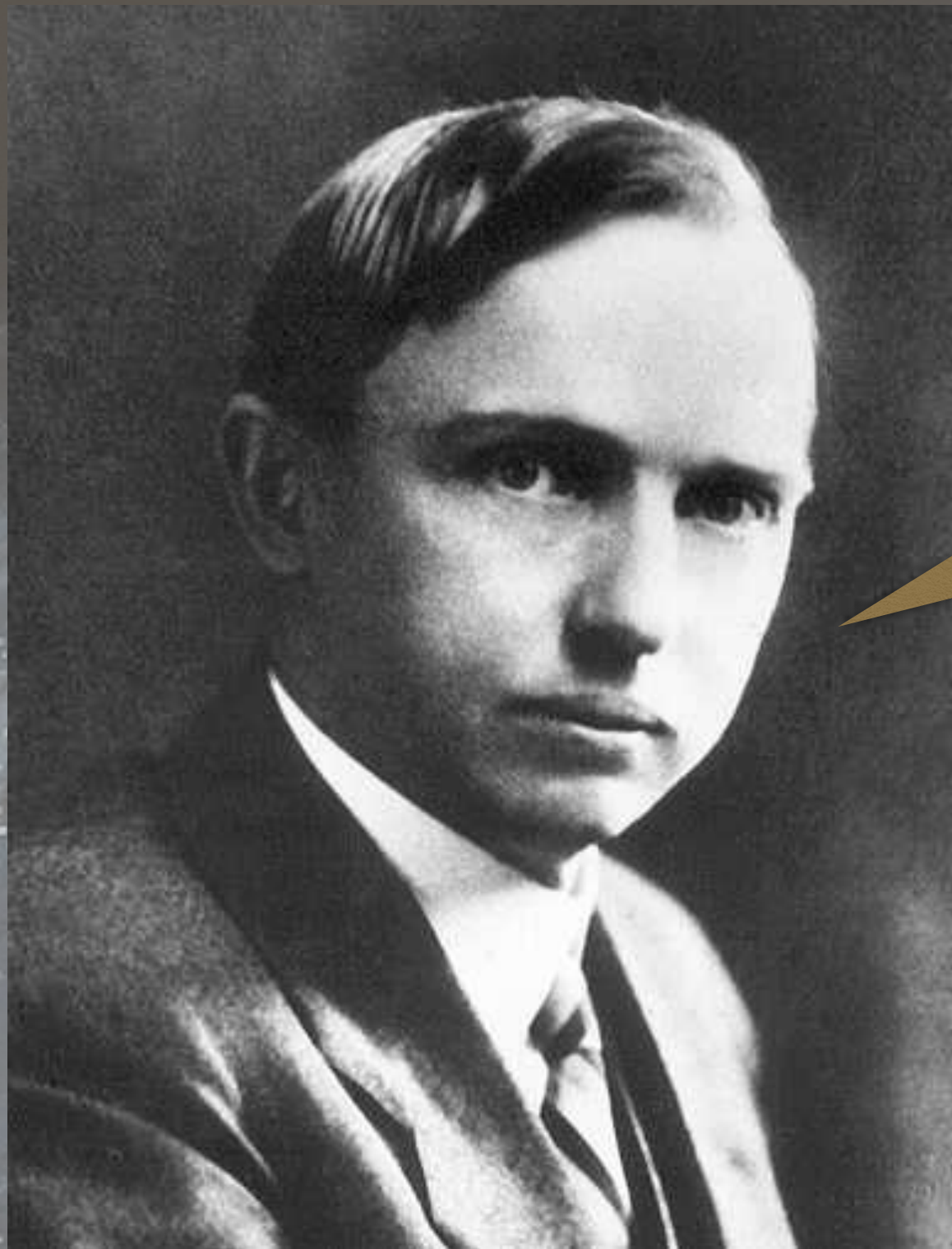
Harlow Shapley

The Milky Way is the
entire Universe!

Vs.

Heber Curtis





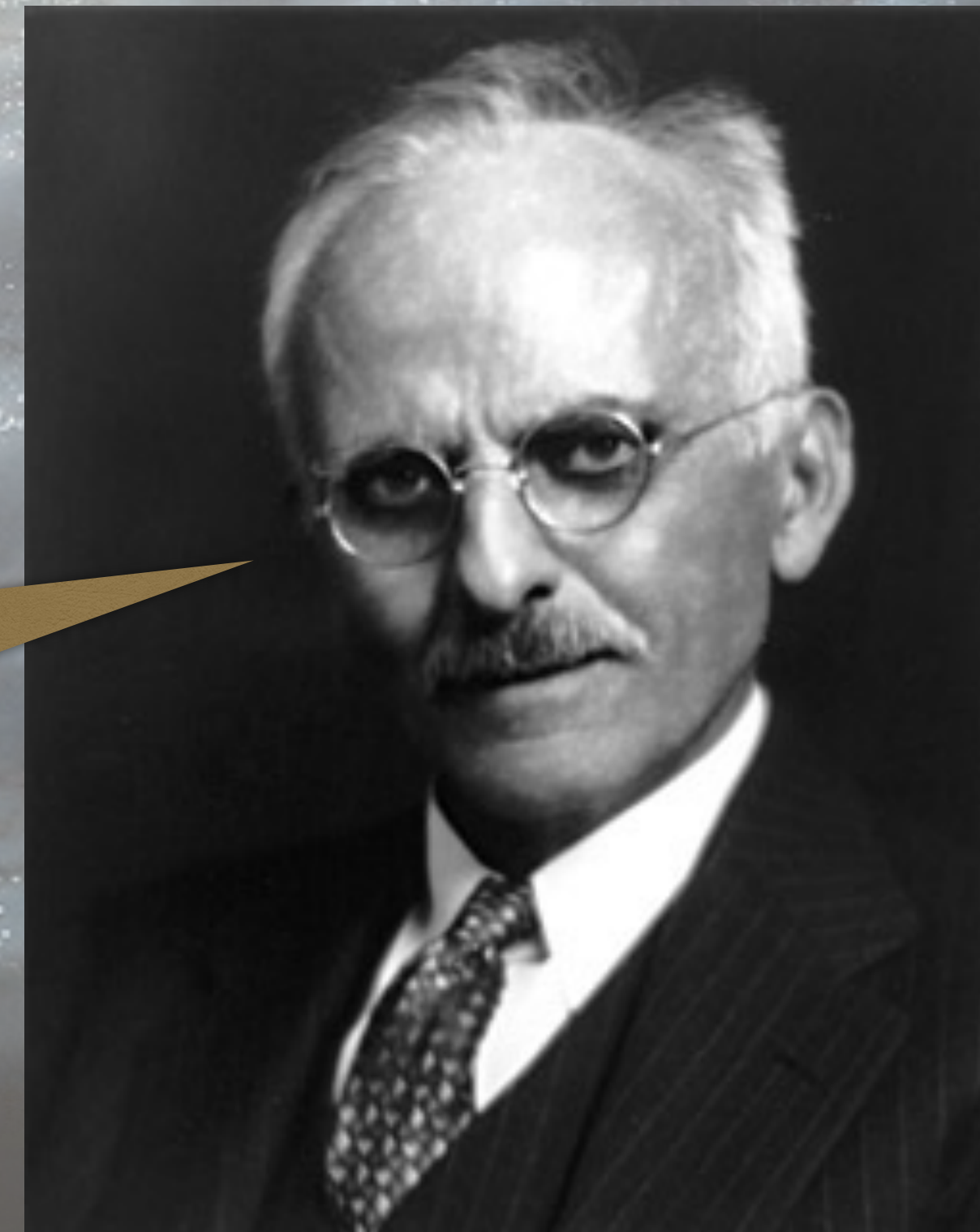
Harlow Shapley

The Milky Way is the
entire Universe!

Vs.

The Milky Way is just
one galaxy among many!

Heber Curtis





Harlow Shapley

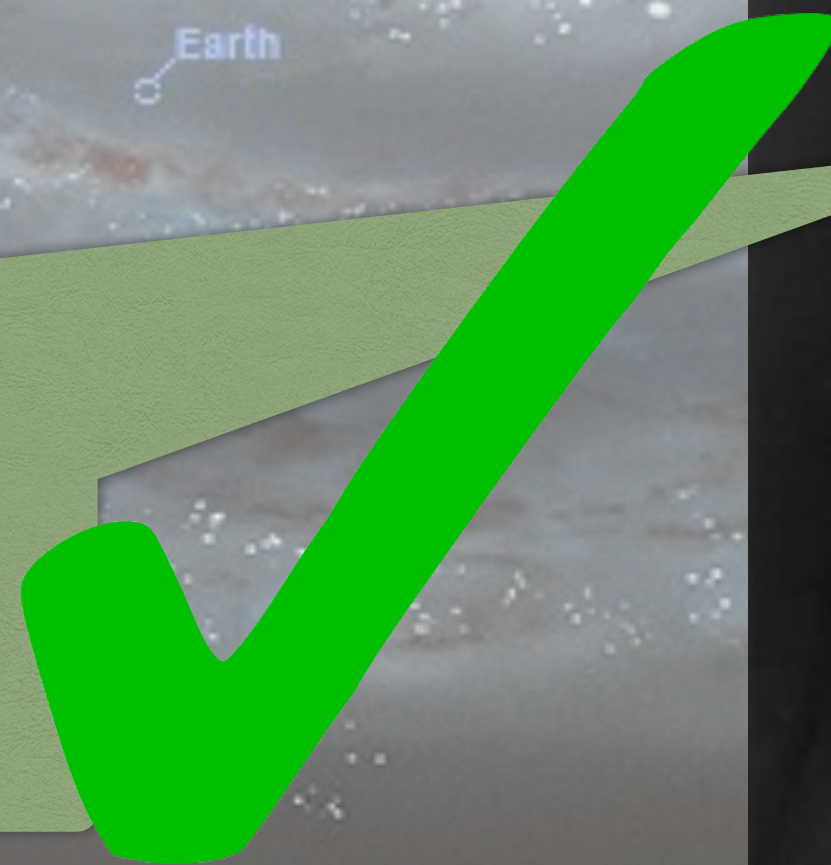


The Milky Way is the
entire Universe!

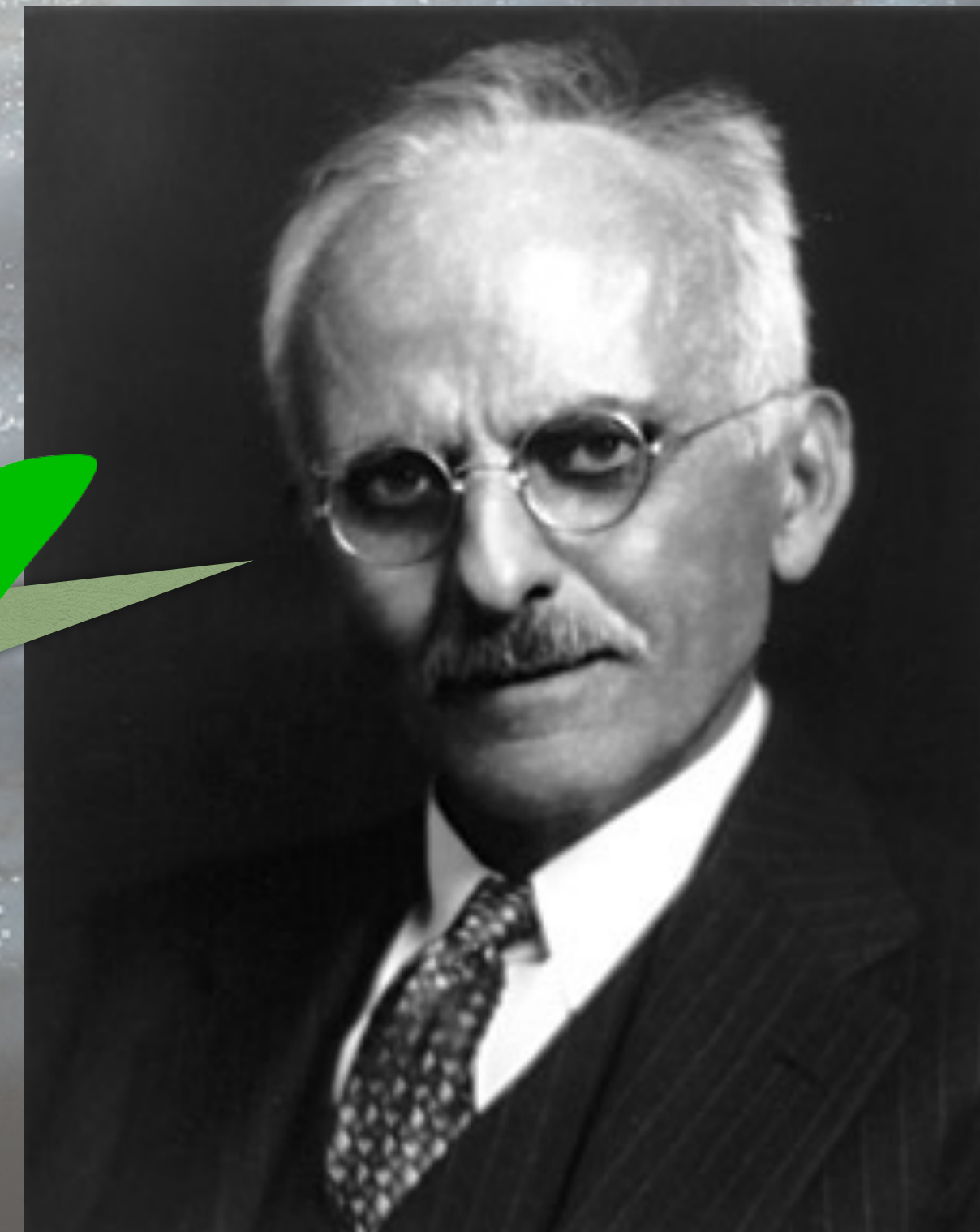
Vs.

Earth

The Milky Way is just
one galaxy among many!



Heber Curtis



**How was this
settled?**



Edwin Hubble



Hubble Space Telescope



Hubble's first
breakthrough was to
measure **accurate**
distances to nearby
galaxies

Edwin Hubble



Washington, Nov. 22. Confirmation of the view that spiral nebulae, which appear in the heavens as whirling clouds, are in reality distant stellar systems, or 'island universes', has been obtained by Dr. Edwin Hubble of the Carnegie Institution's Mount Wilson Observatory, through investigations carried out with the observatory's powerful telescopes. The number of spiral nebulae, the observatory officials have reported to the institution, is very great, amounting to hundreds of thousands, and their apparent sizes range from small objects, almost star-like in character, to the great nebula in Andromeda, which stretches across an angle of some 3 degrees in the heavens, about six times the diameter of the full moon.

New York Times,
22 November 1924

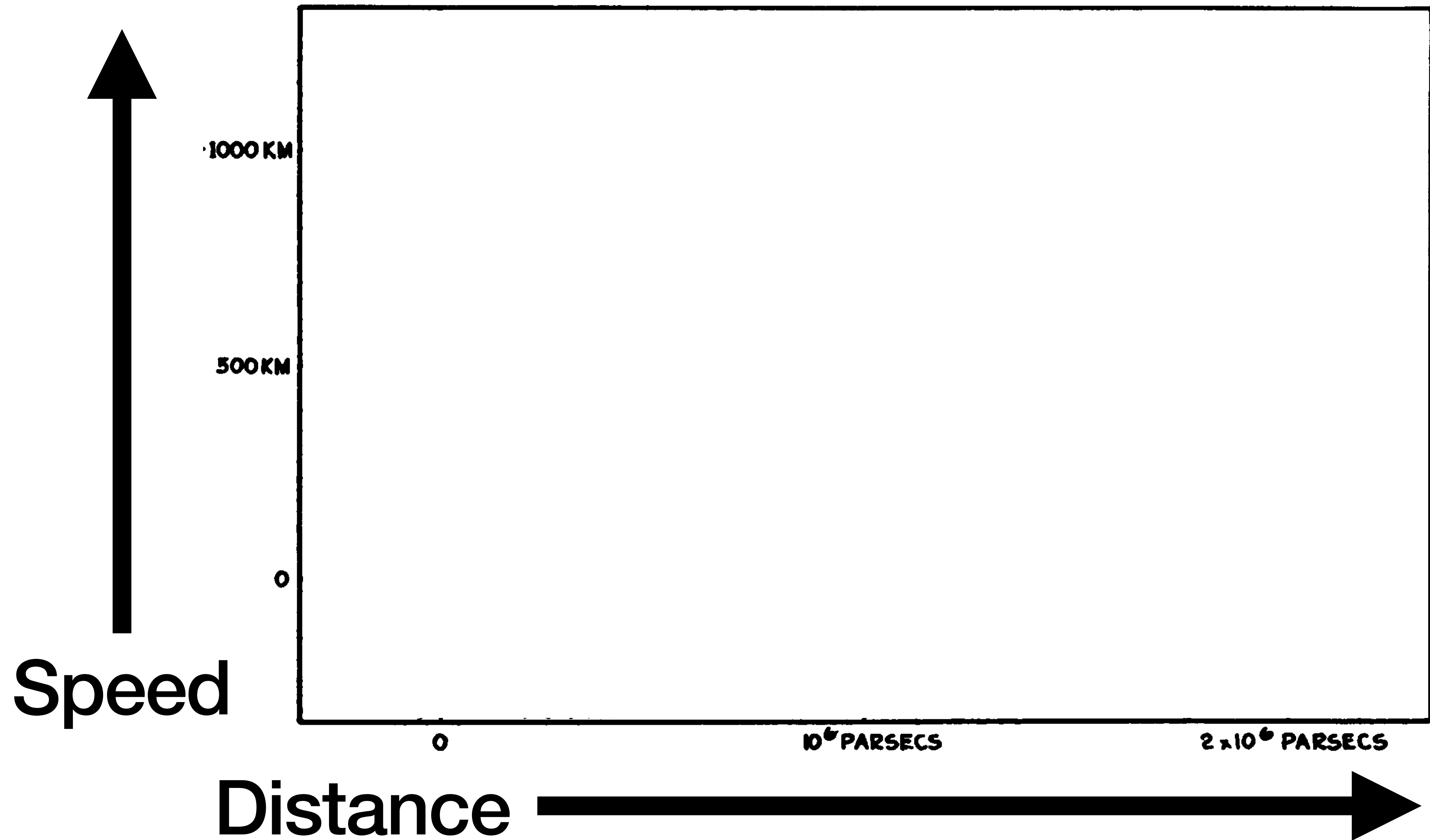
Edwin Hubble

Washington, Nov. 22. Confirmation of the view that spiral nebulae, which appear in the heavens as whirling clouds, are in reality distant stellar systems, or 'island universes', has been obtained by Dr. Edwin Hubbell of the Carnegie Institution's Mount Wilson Observatory, through investigations carried out with the observatory's powerful telescopes. The number of spiral nebulae, the observatory officials have reported to the institution, is very great, amounting to hundreds of thousands, and their apparent sizes range from small objects, almost star-like in character, to the great nebula in Andromeda, which stretches across an angle of some 3 degrees in the heavens, about six times the diameter of the full moon.

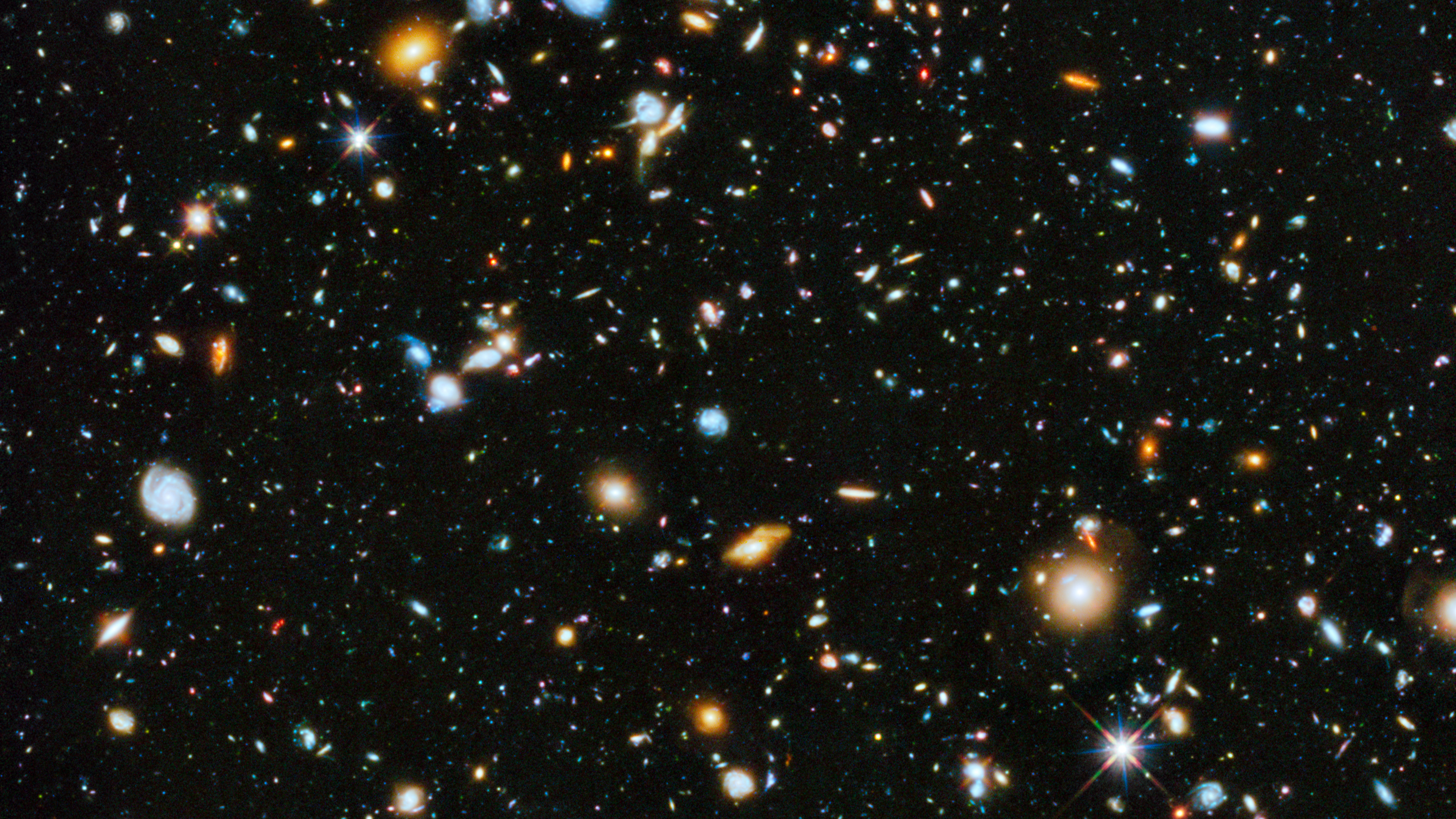
New York Times,
22 November 1924

Astronomers already knew how to measure the velocity of
galaxies

Breakthrough came when comparing these velocities with
Hubble's new, accurate distances...



**The Universe
is expanding!**







**Measuring
distances in
astronomy is hard**

κ-Cygnids

Vega...25 light years away

Deneb
...about 2500 light
years away
(Estimates range
from ~1500 - 3000 Ly)

Altair...16 light years
away

E

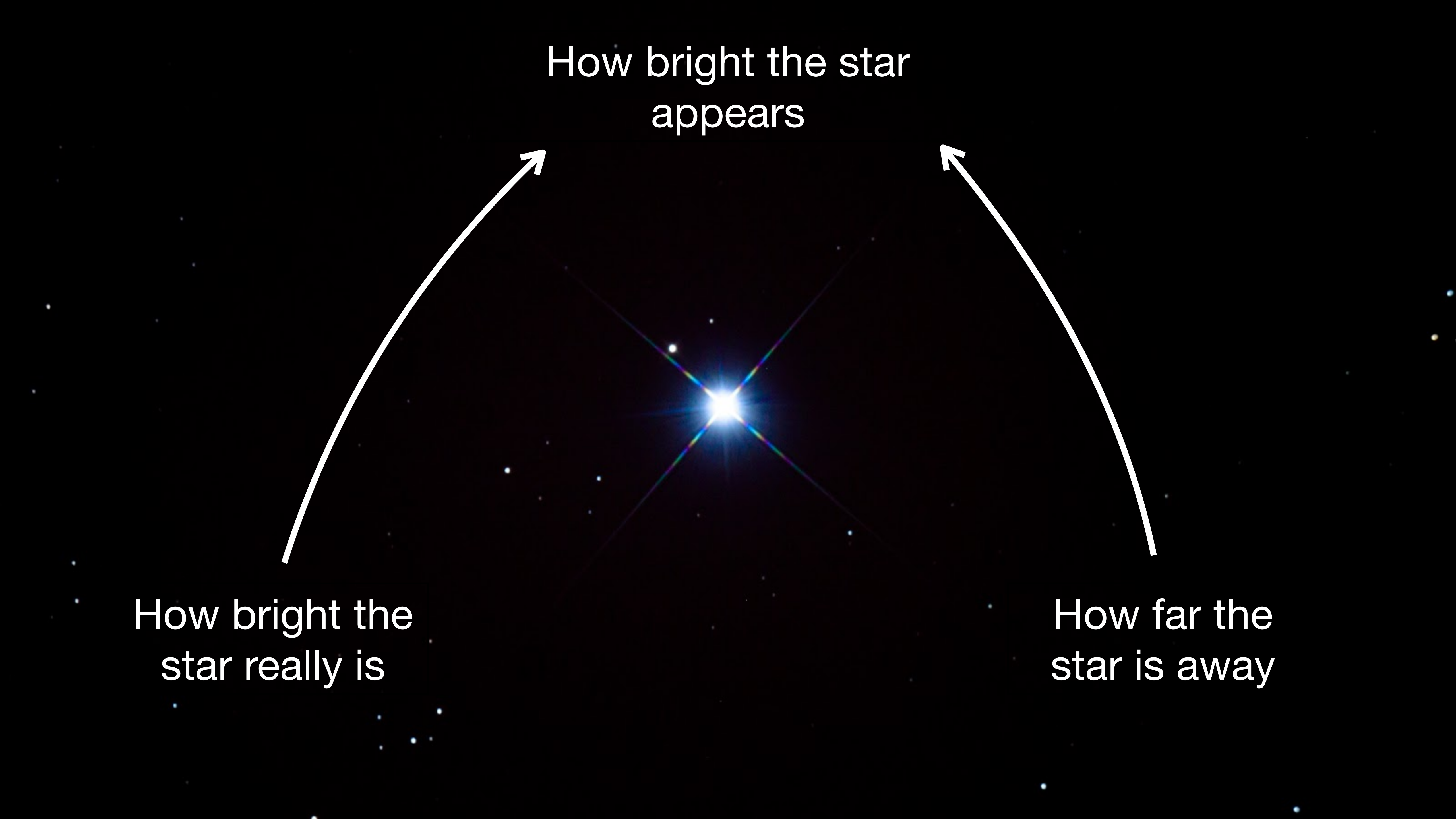
SE

How bright the star
appears



How bright the
star really is

How far the
star is away



Standard Candles

- Henrietta Swan Leavitt (at Harvard College Observatory)
- Discovered a an important fact about variable stars...
- How fast they pulse depends on their intrinsic brightness ('luminosity').
- If you measure how fast they pulse (which is easy!), you can work out their luminosity... which gives you their *distance*

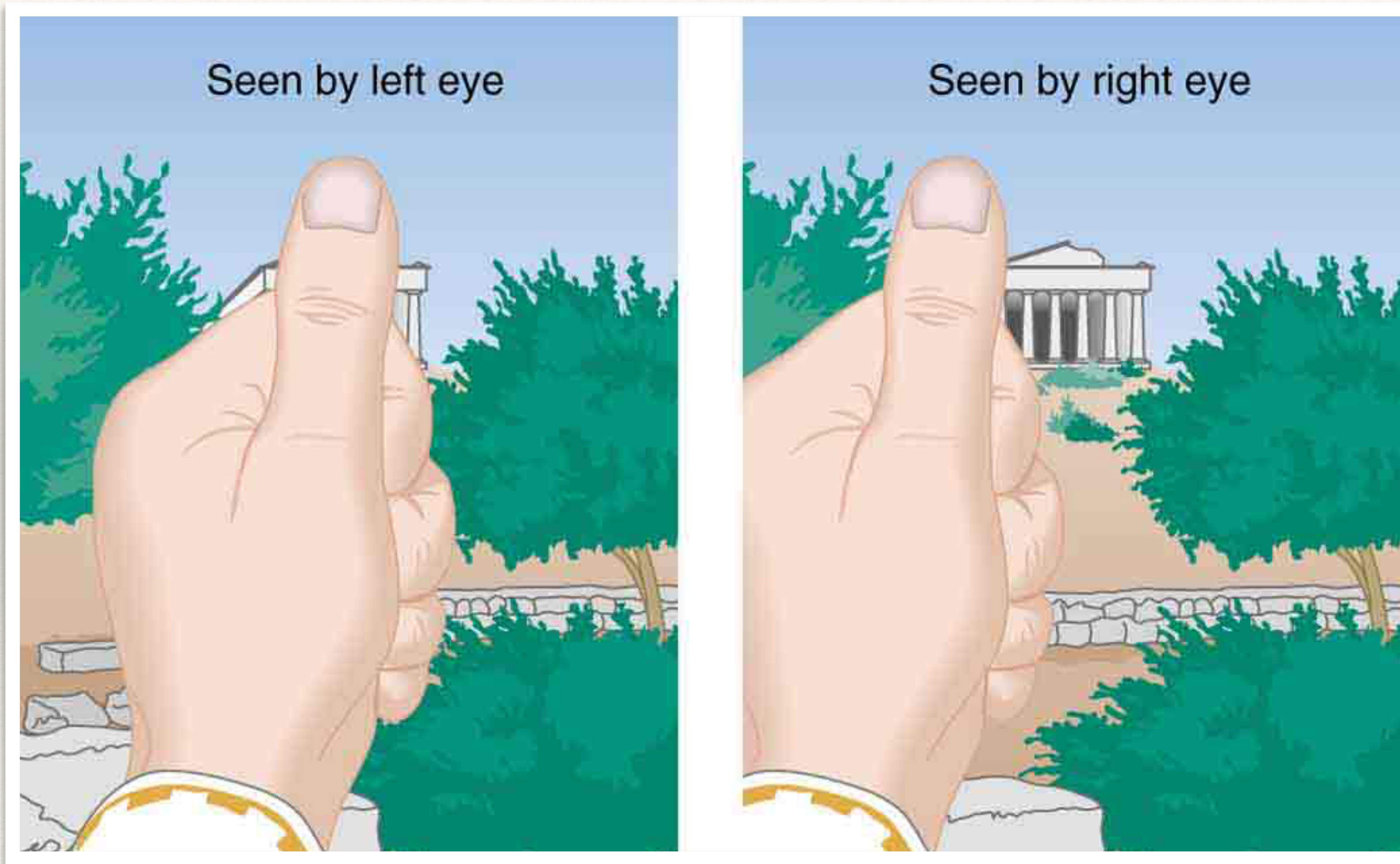




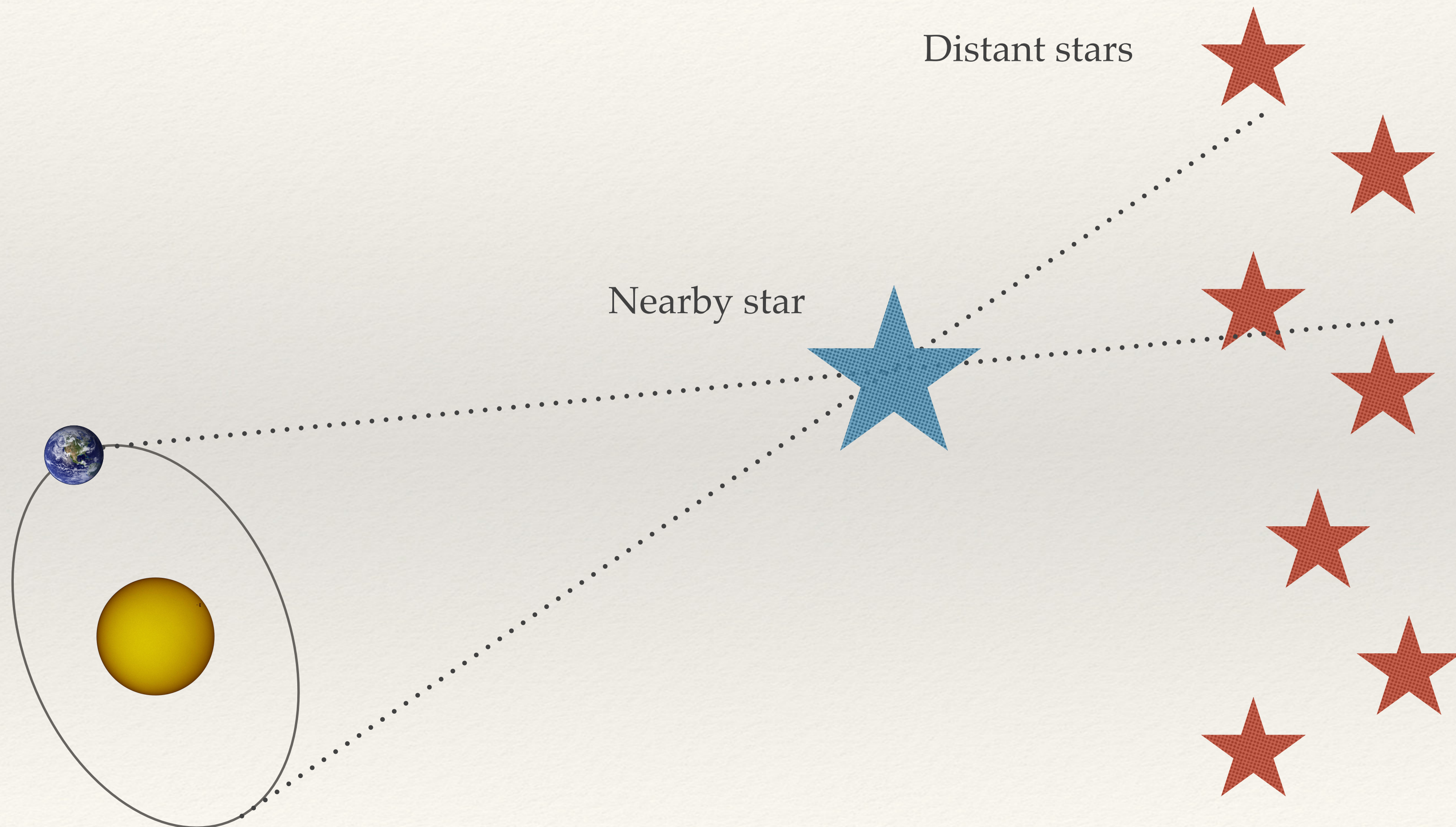
Wait... how was this relationship discovered?

**Wouldn't we have to actually know the distance to
some Cepheids first?**

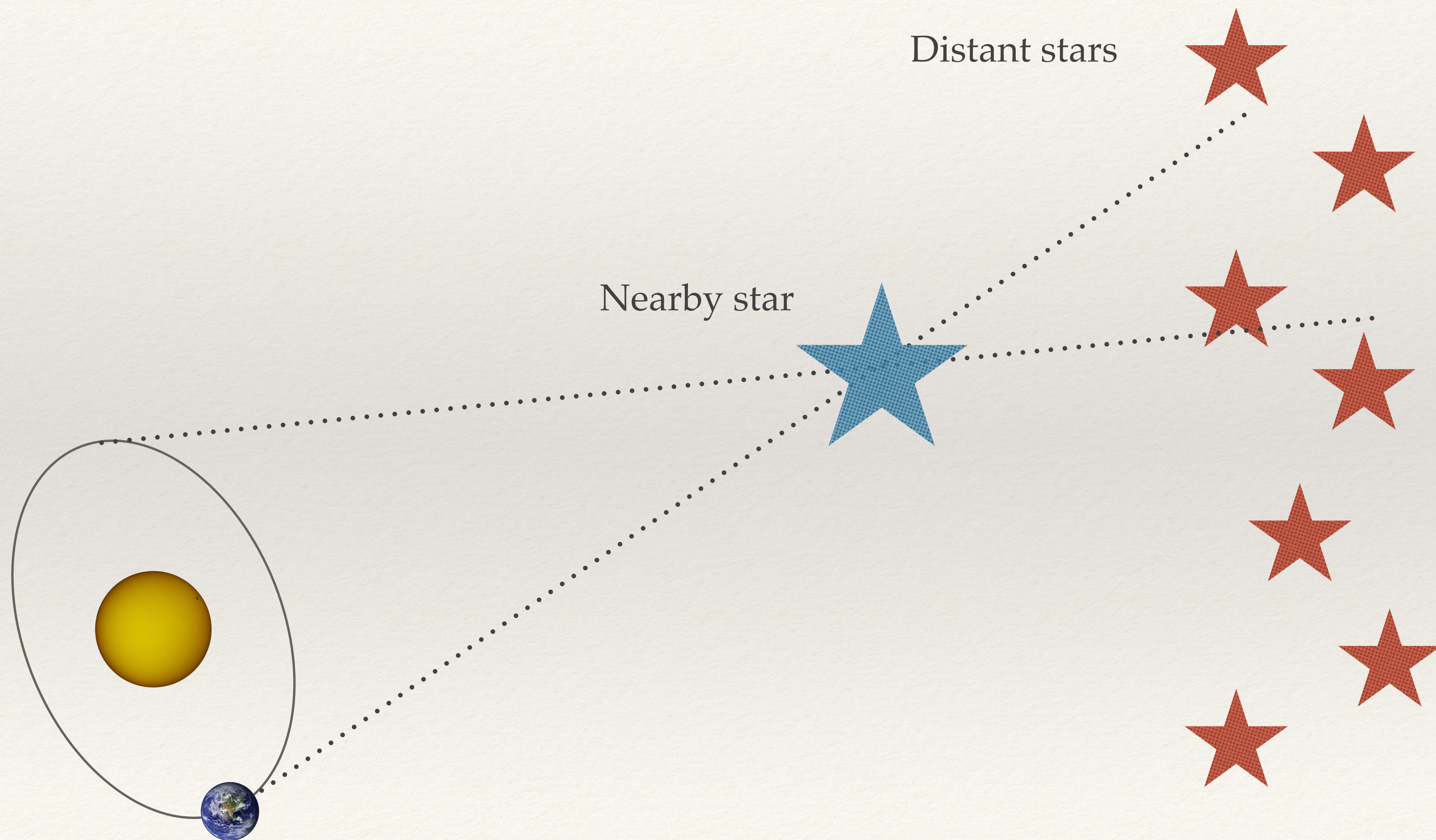
Parallax

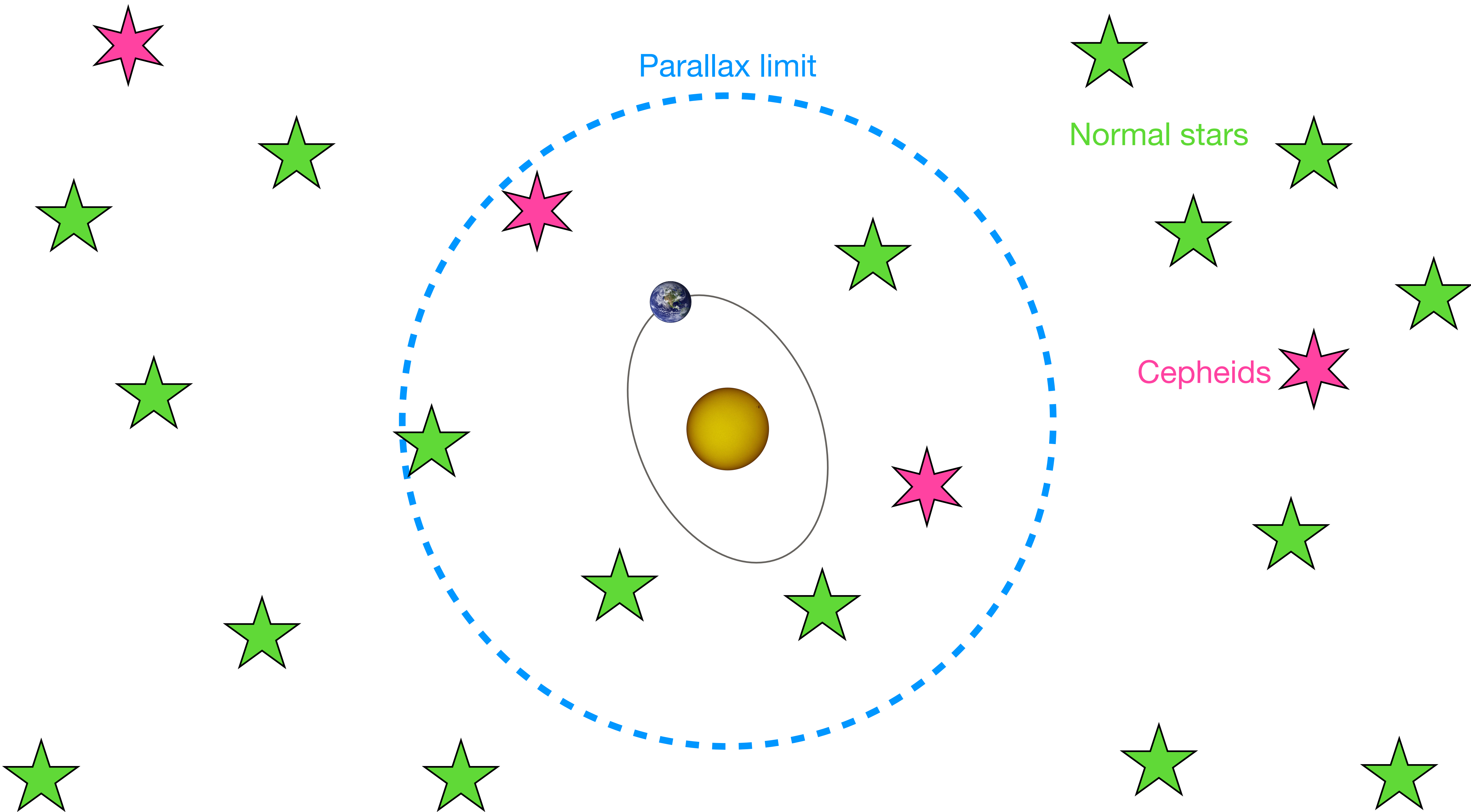


Parallax



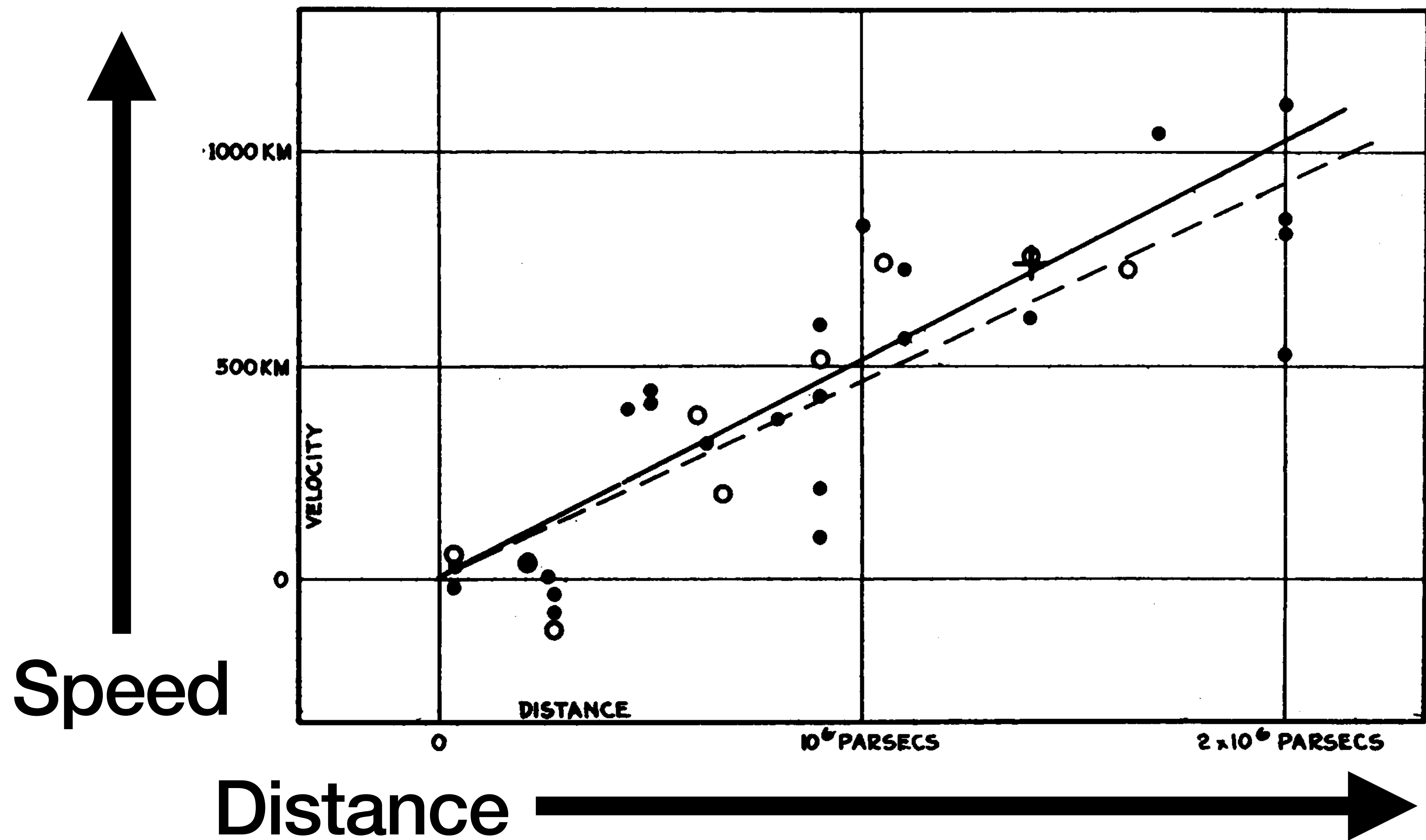
Parallax





‘The Cosmic Distance Ladder’

(This will be important later)

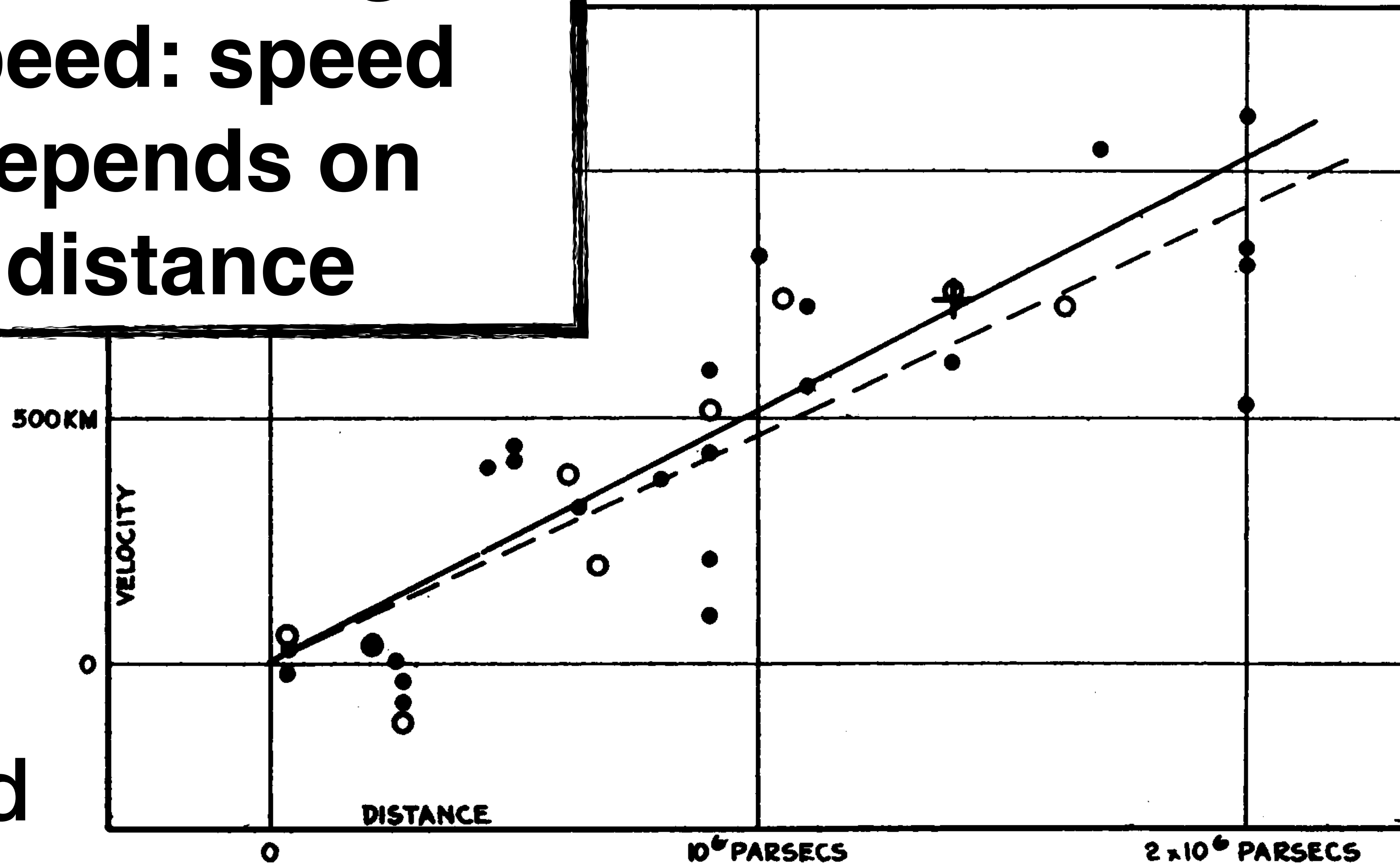


The Universe is expanding!

But how fast?

**Not one single
speed: speed
depends on
distance**

Speed

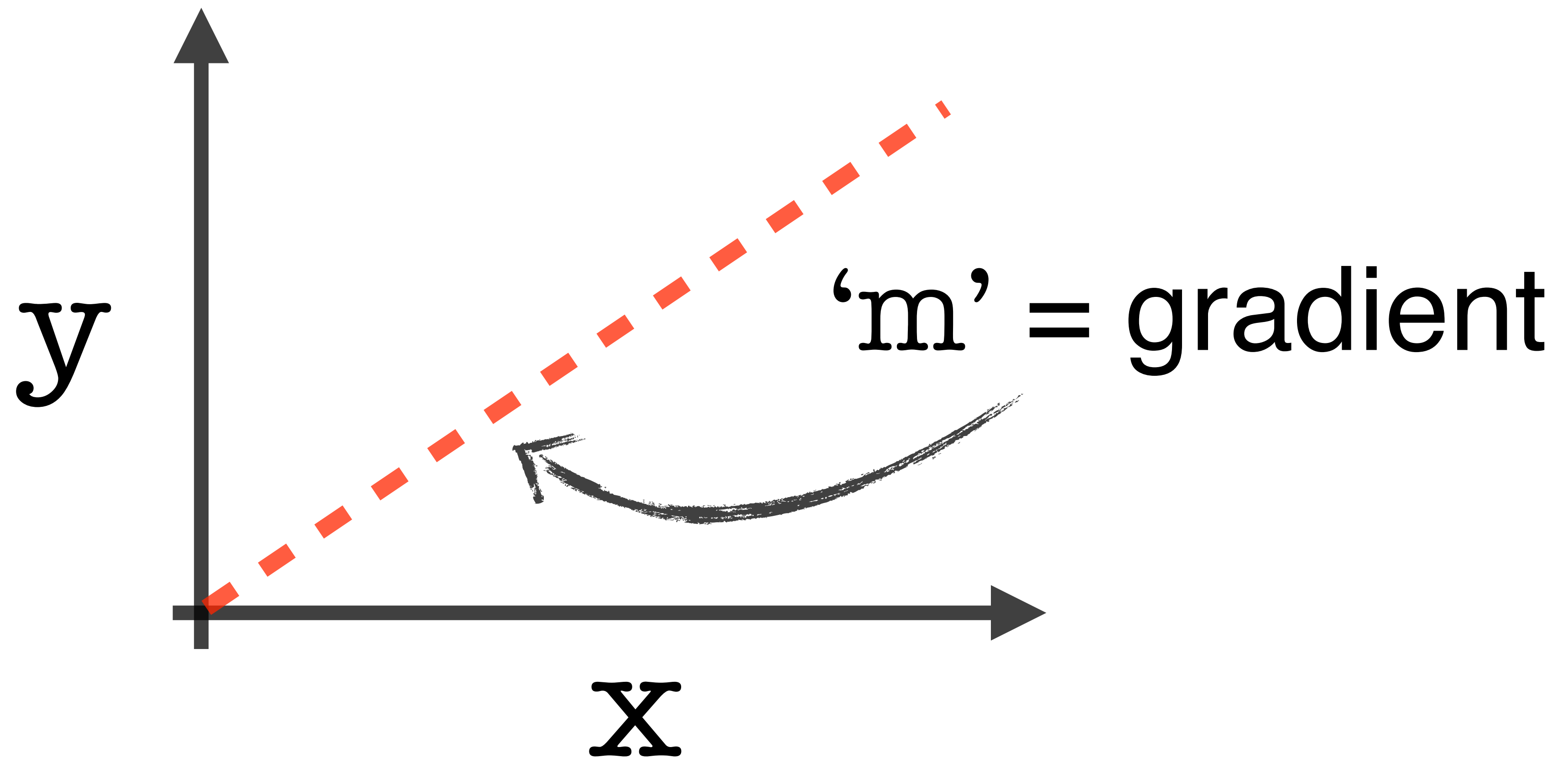


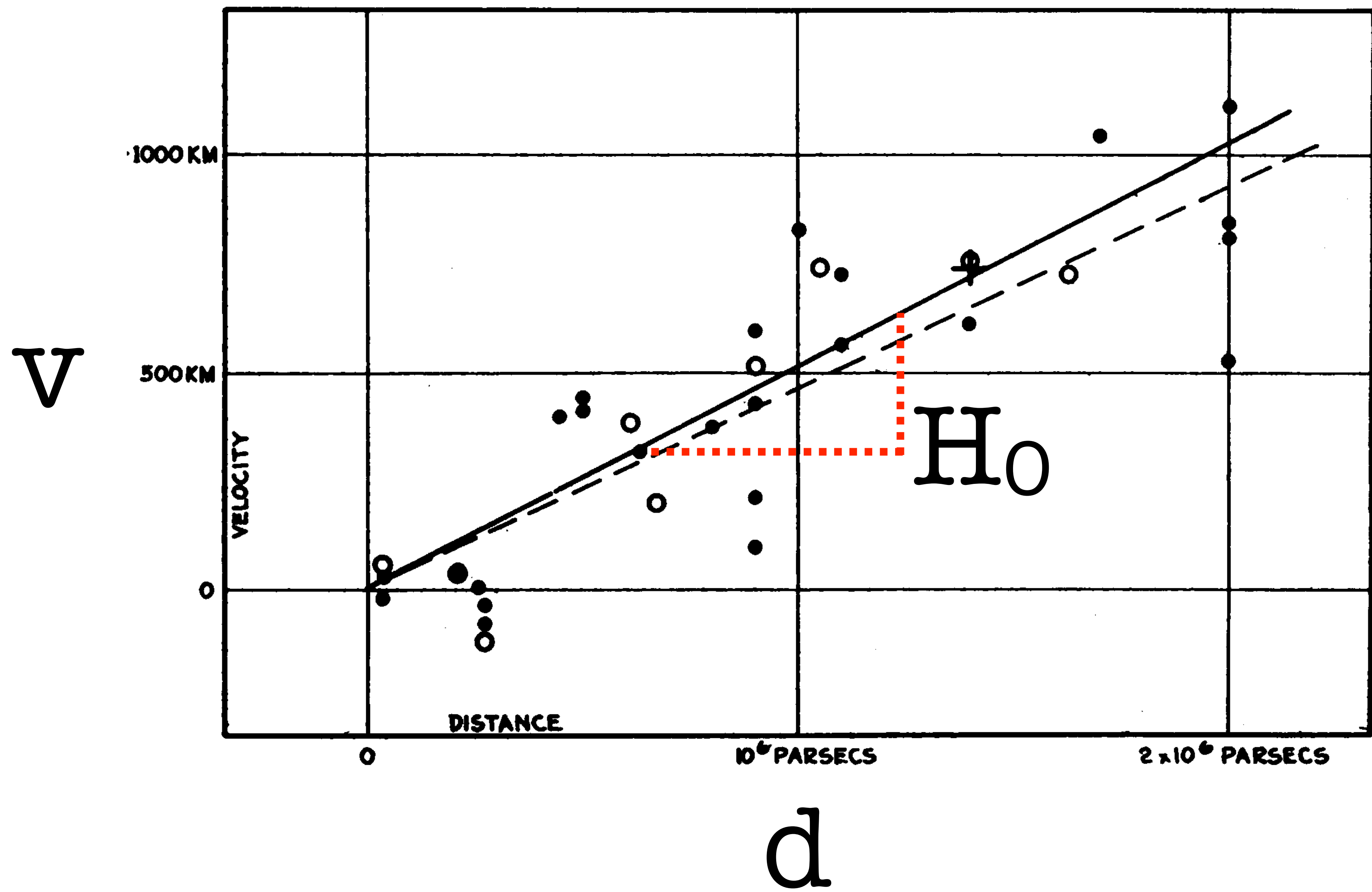
Distance

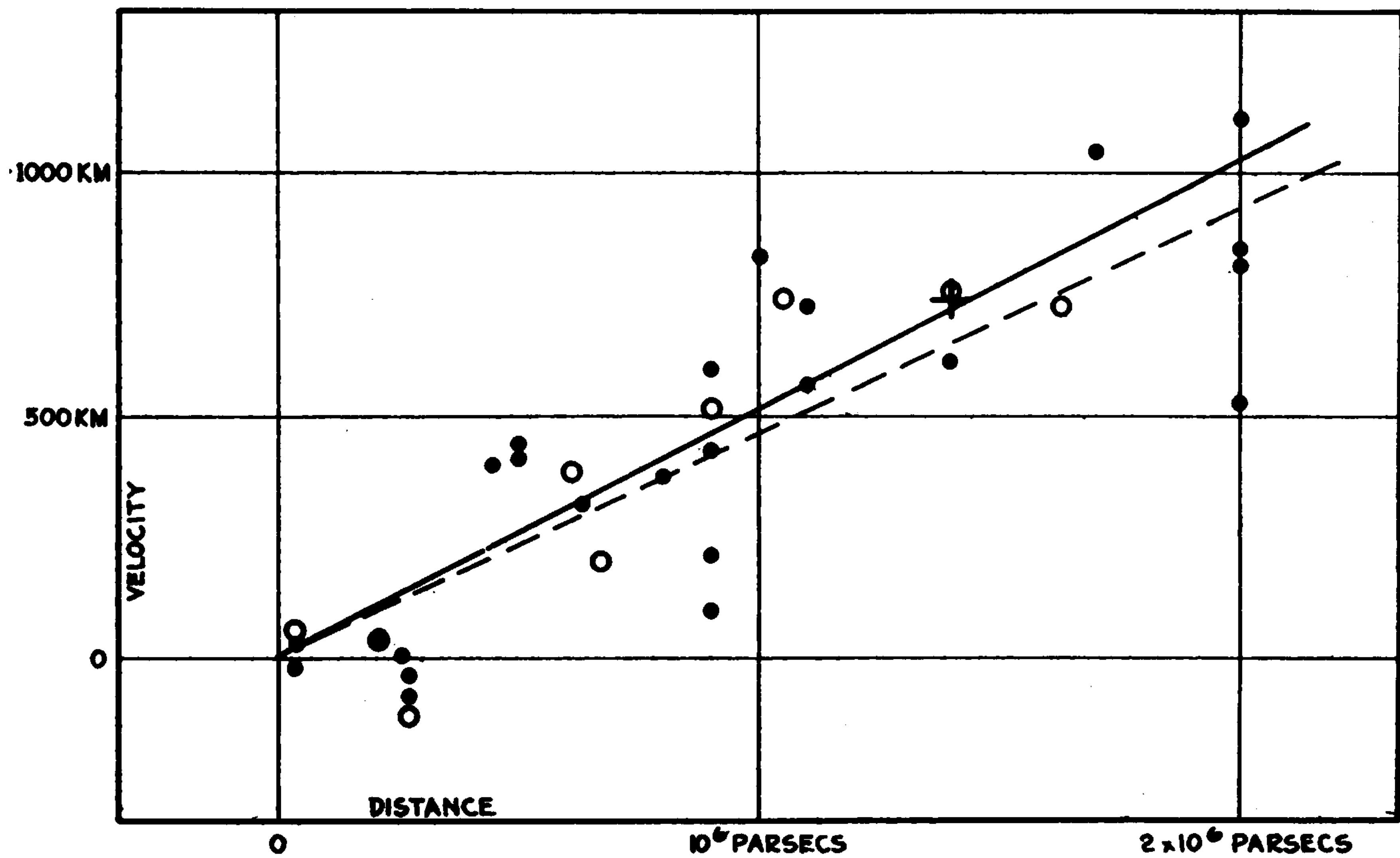
$$y = mx$$

(Equation of a straight line)

$$y = mx$$



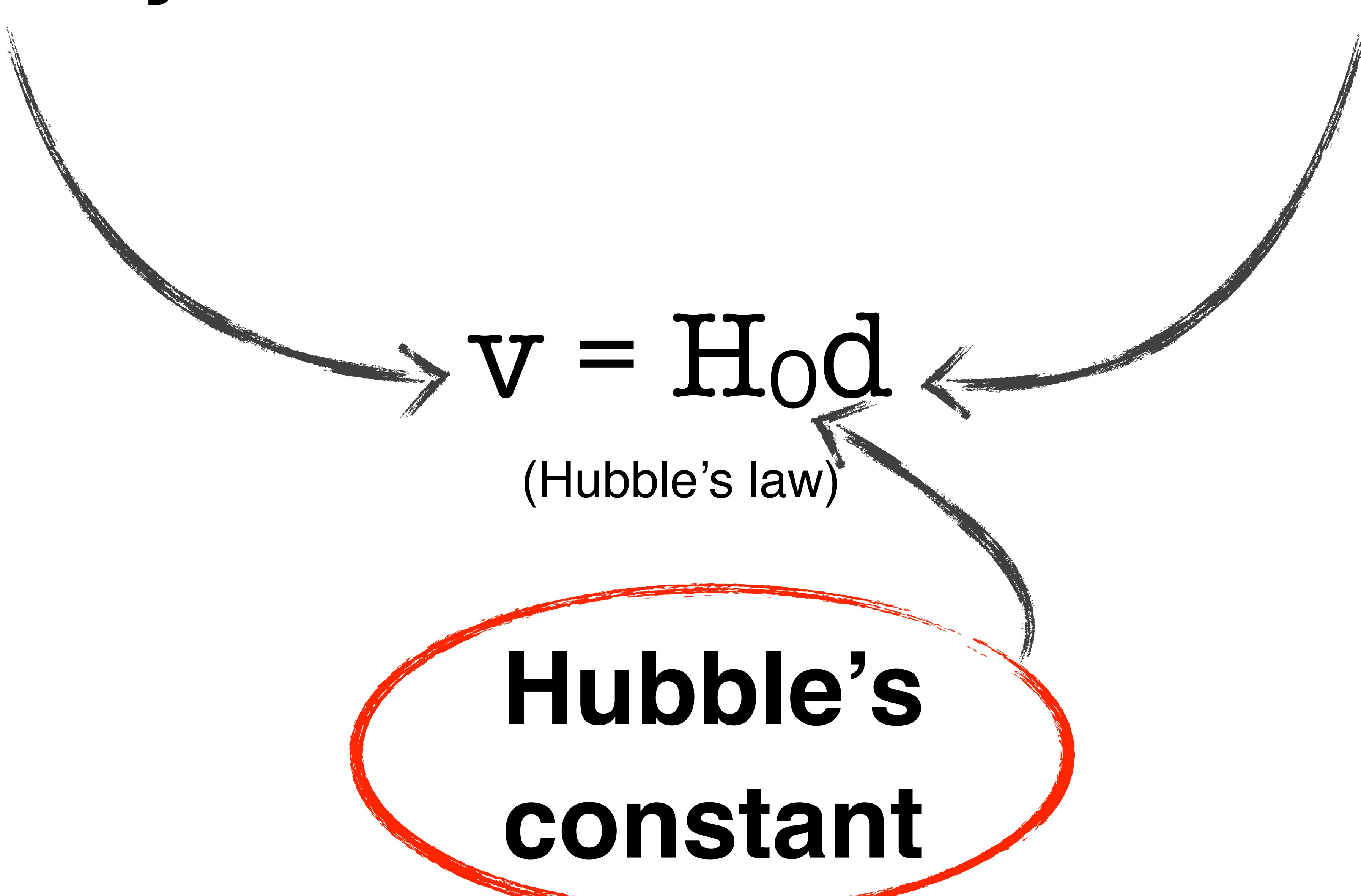




$$v = H_0 d$$

Velocity

Distance

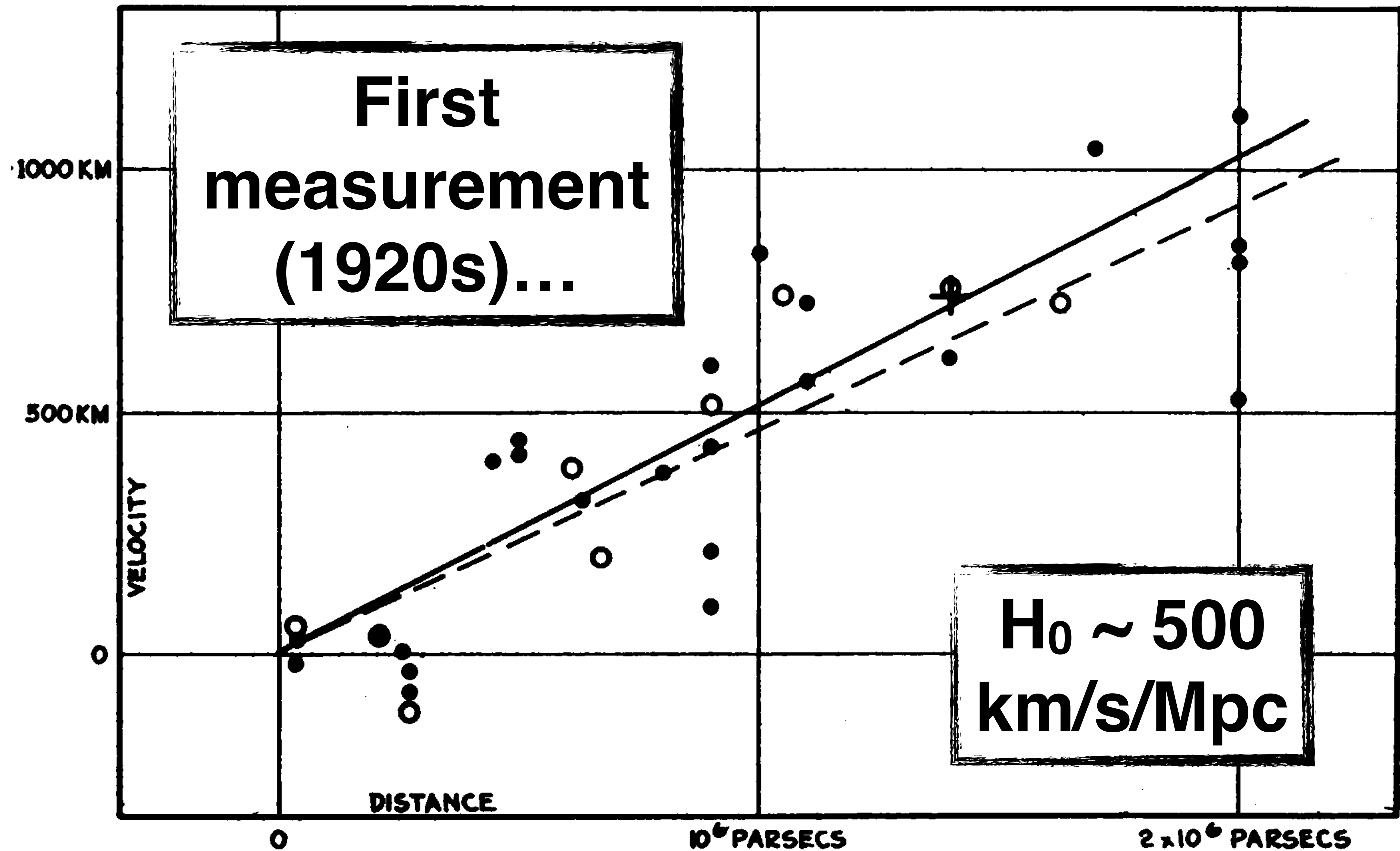

$$v = H_0 d$$

(Hubble's law)

**Hubble's
constant**

Hubble's Constant

- Is the way astronomers measure how fast the Universe is expanding
- Measured in kilometres per second per megaparsec (km/s/Mpc)
- (1 megaparsec = 1 million parsecs, or about 3 million light years)
- i.e., is in units of *speed per distance*



km/s/Mpc

~~Distance~~

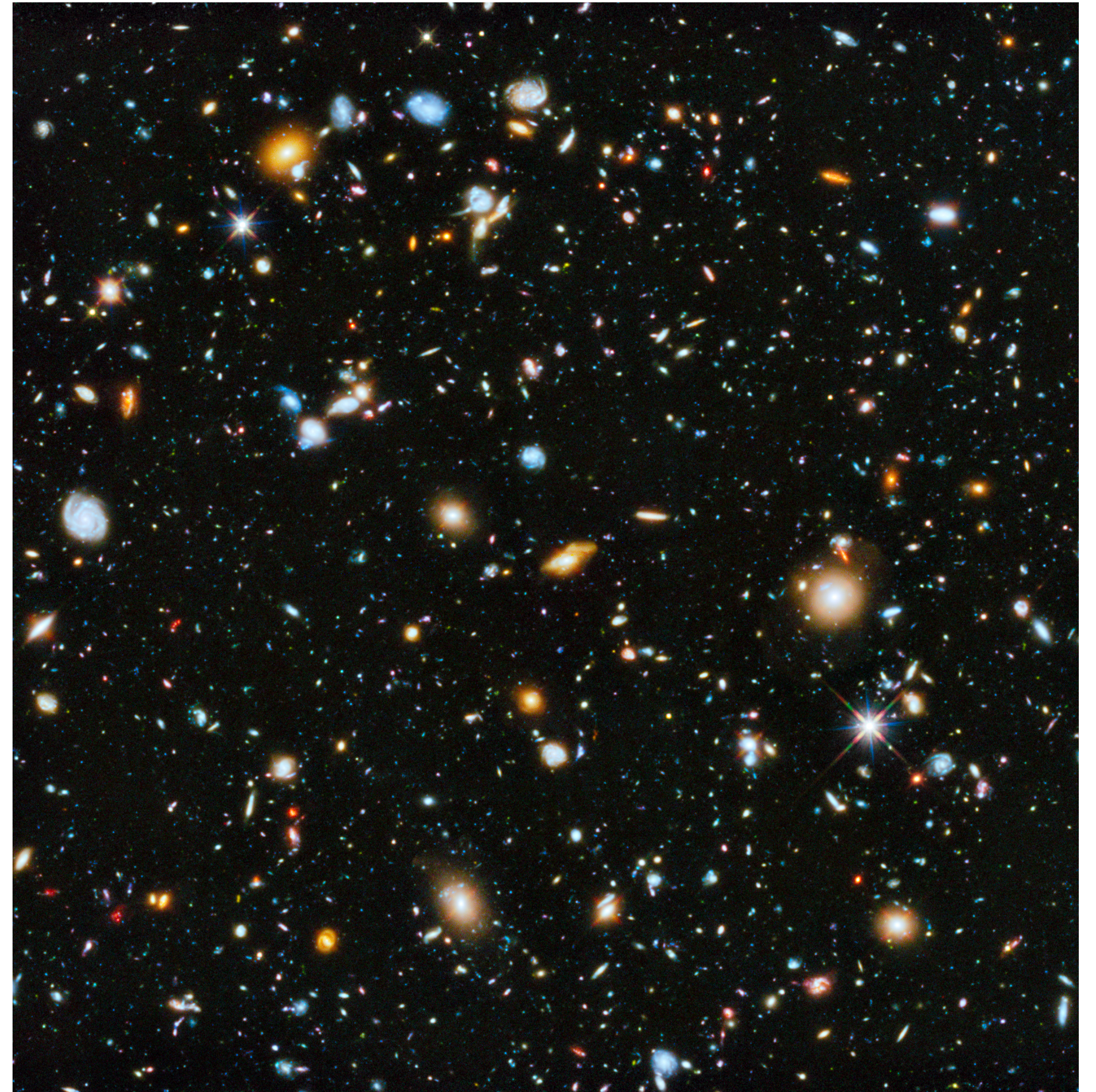
Per time

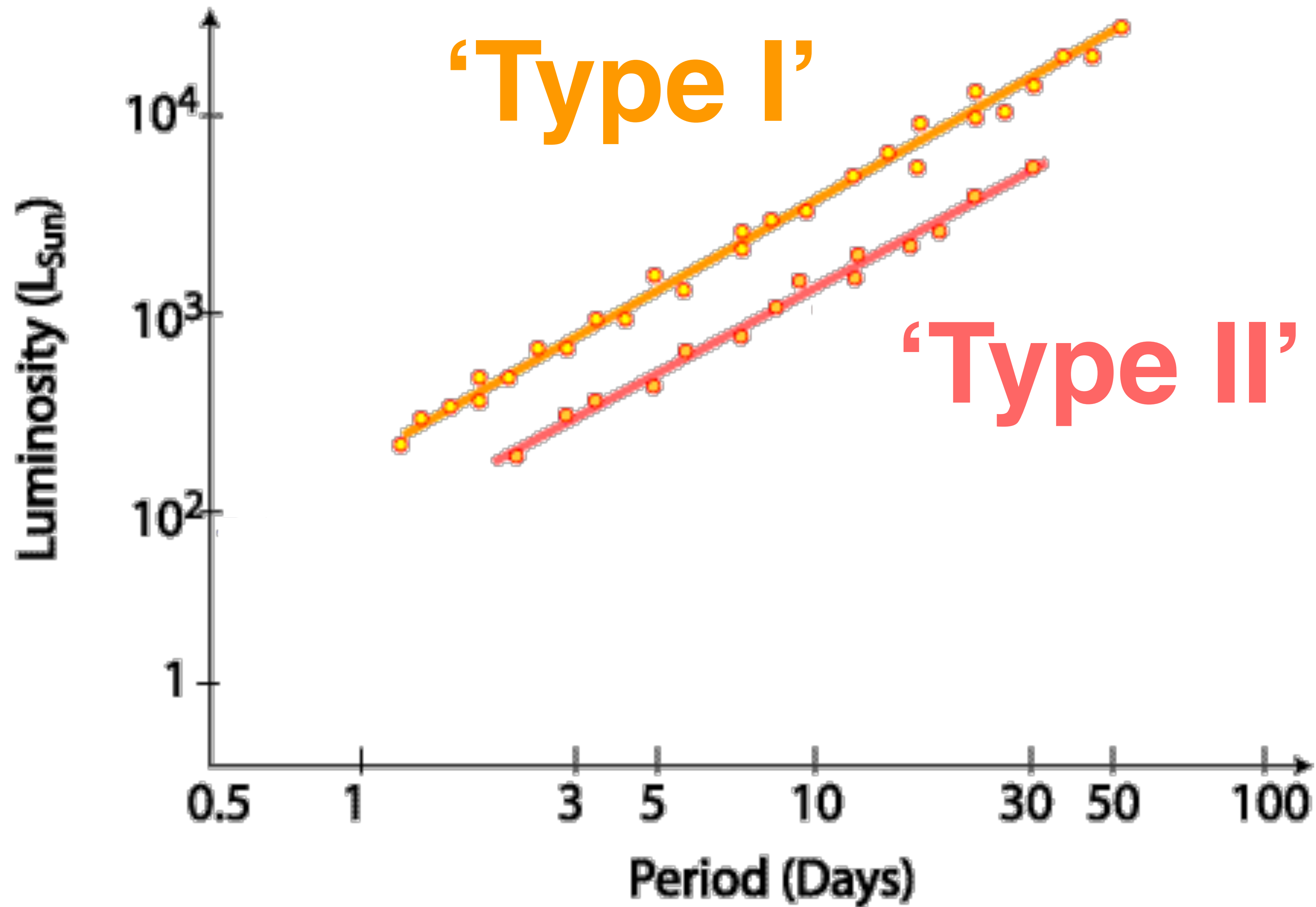
~~Per distance~~

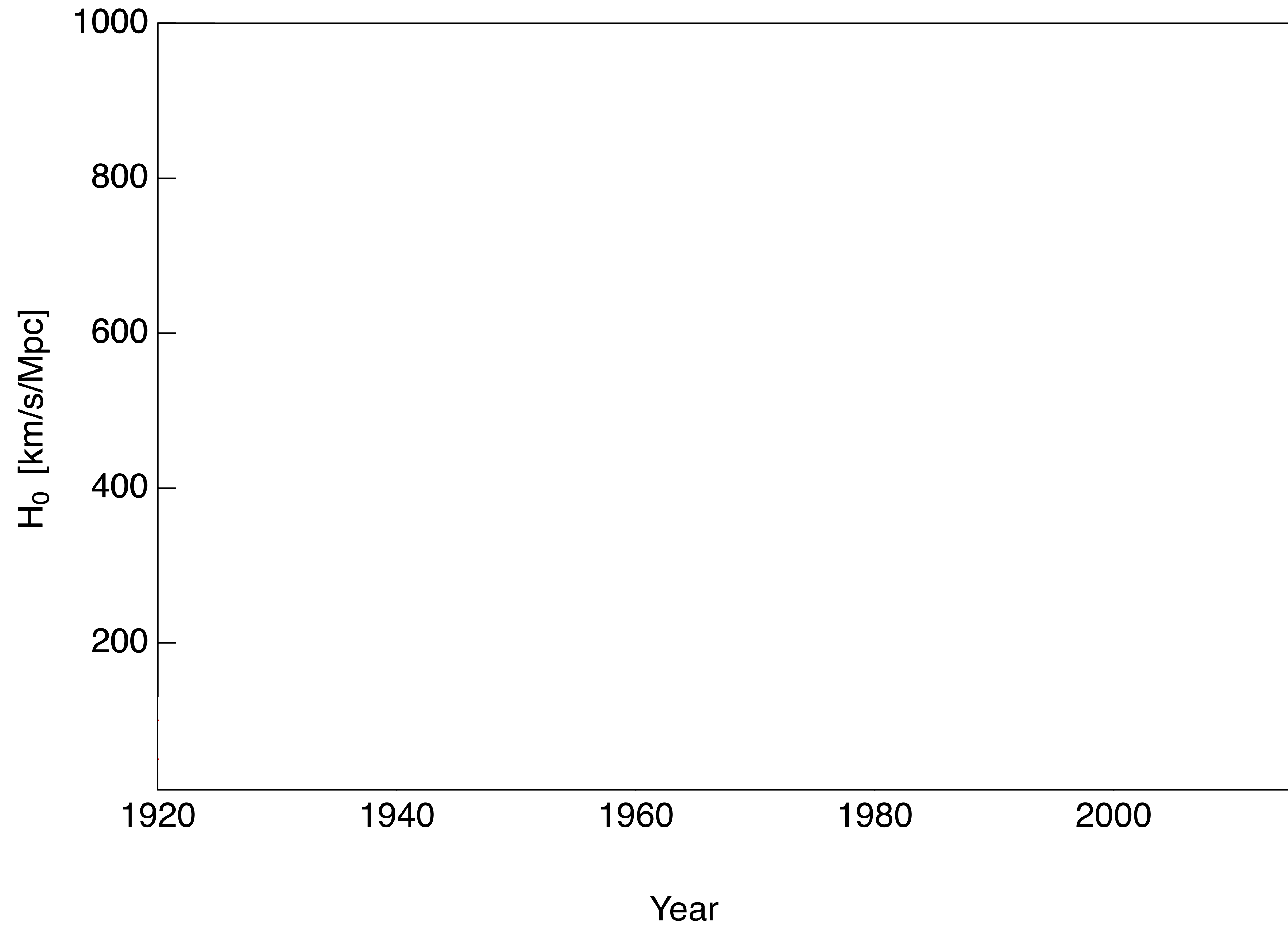
The units of the Hubble constant are 1/time

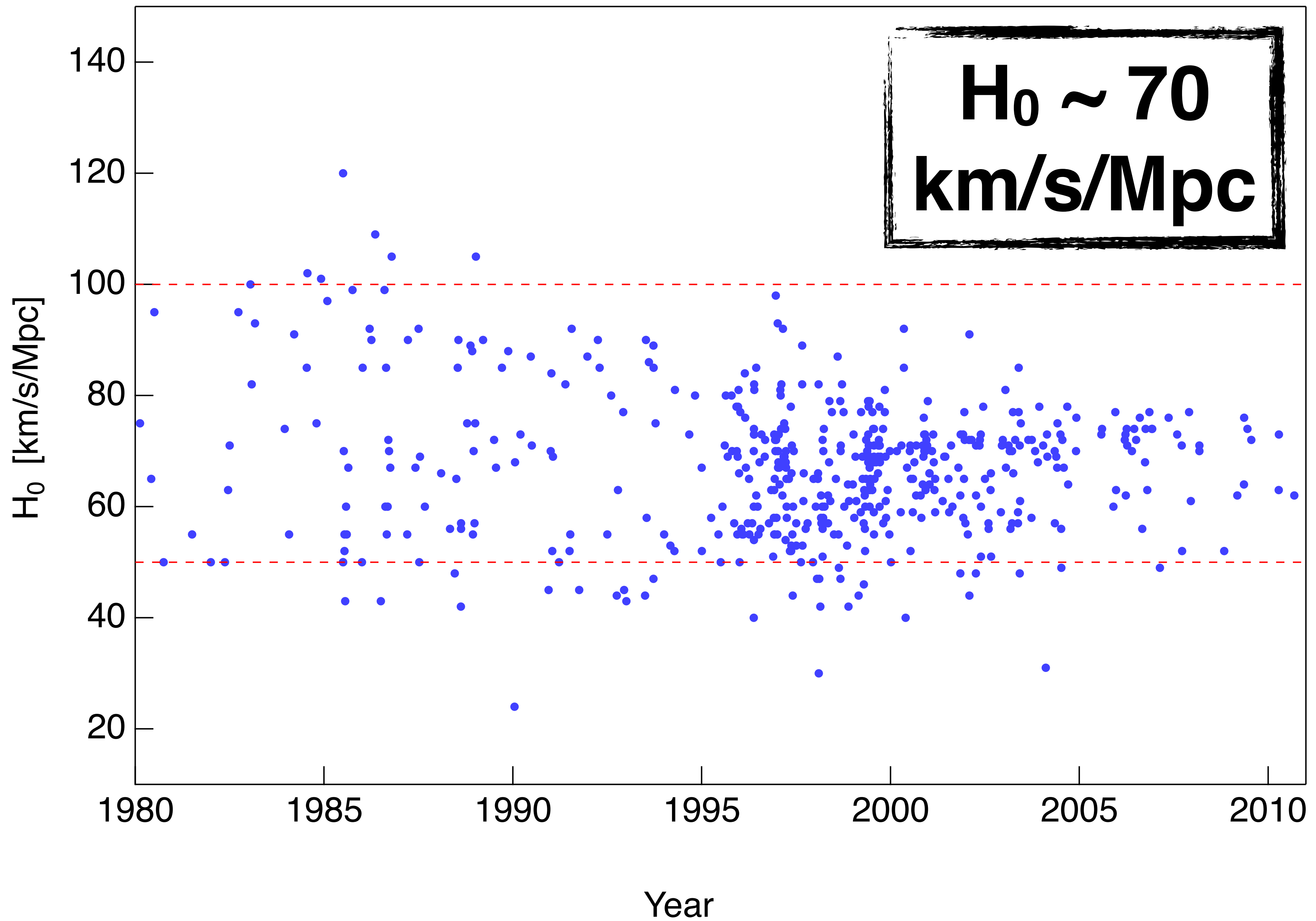
From Hubble to the Universe

- The units of the Hubble constant are $1/\text{time}$
- $1/H_0$ will give you... the rough age of the Universe!
- Hubble's original value of 500 km/s/Mpc results in a Universe just 1-2 billion years old... younger than the Earth

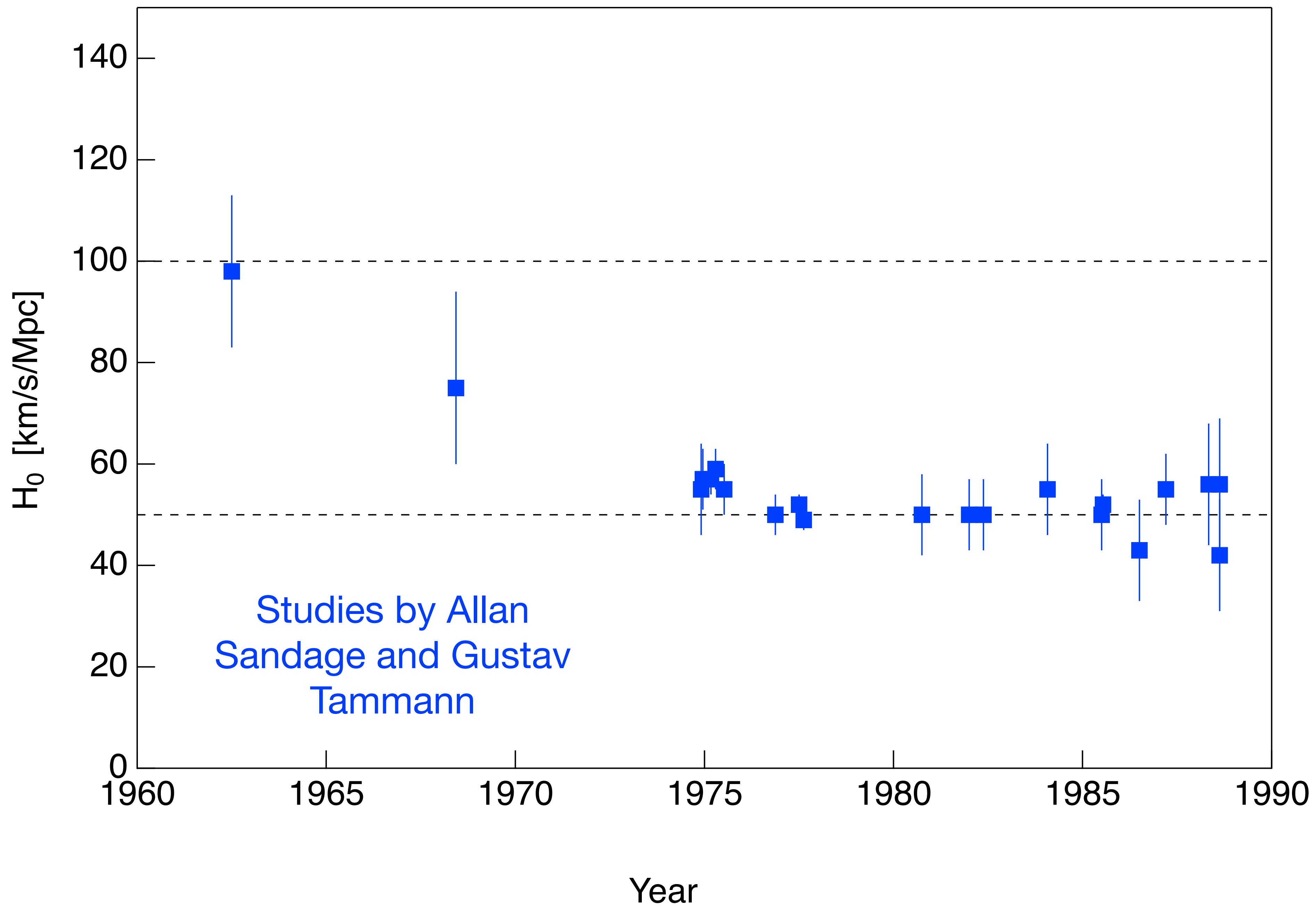


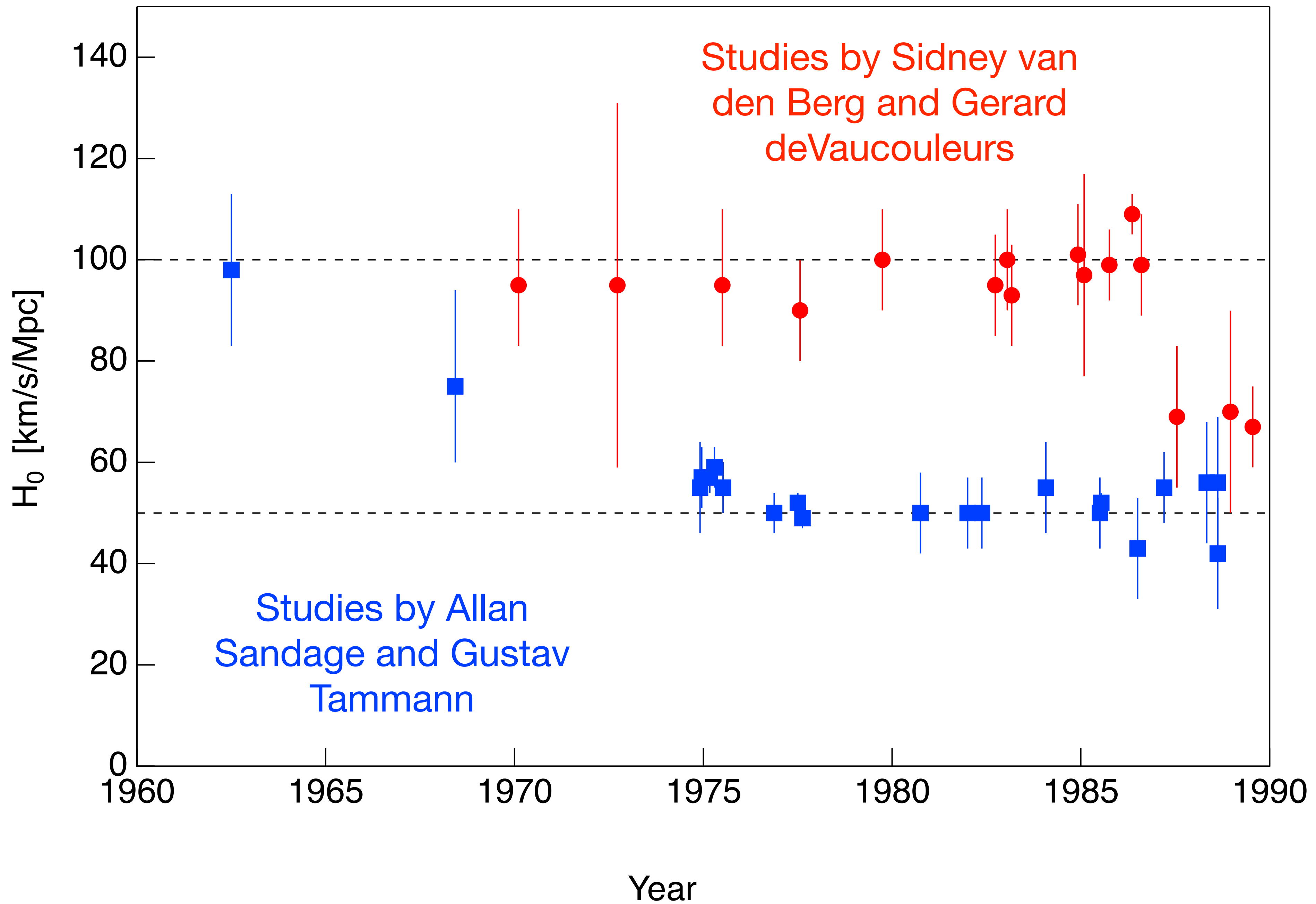


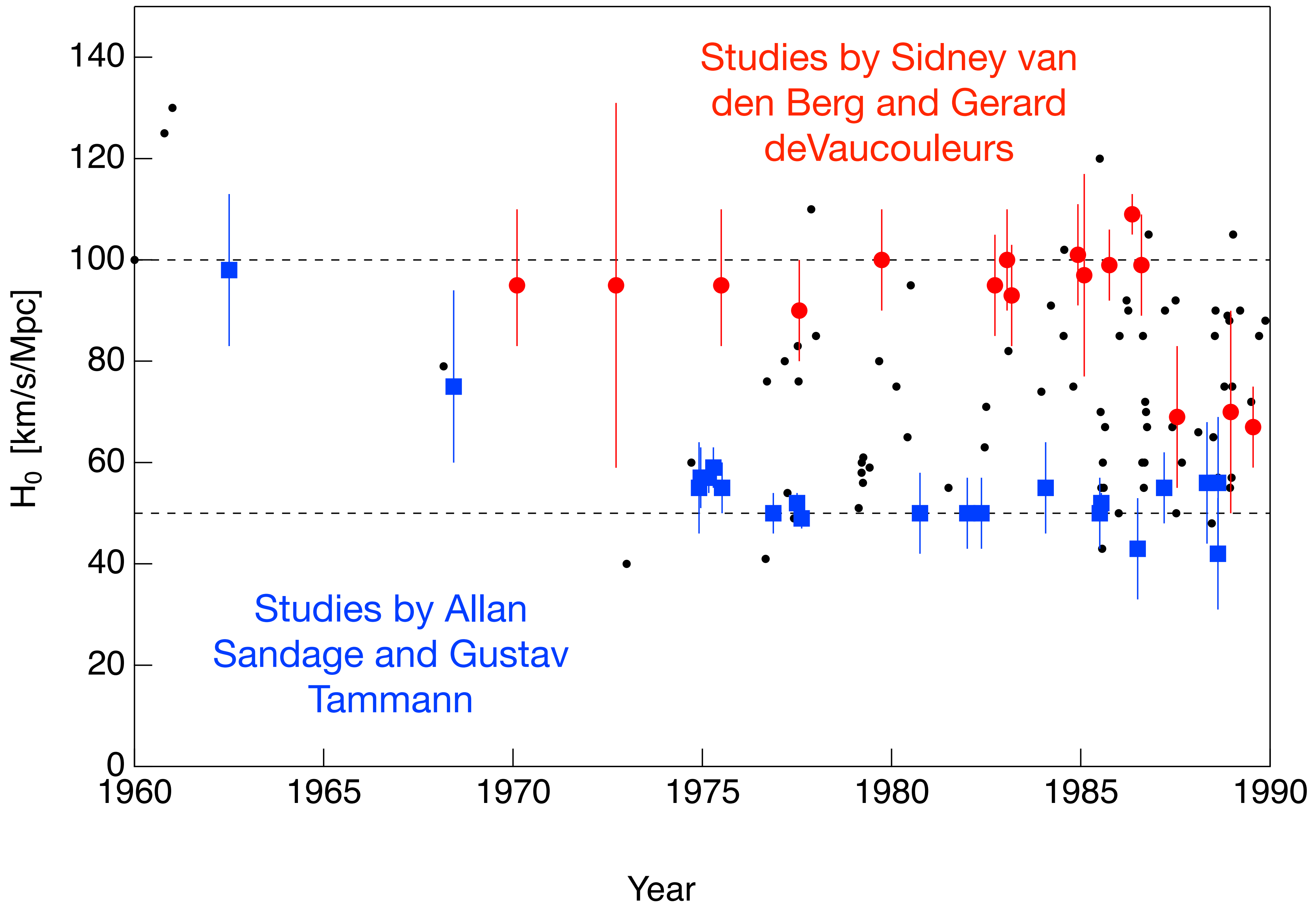


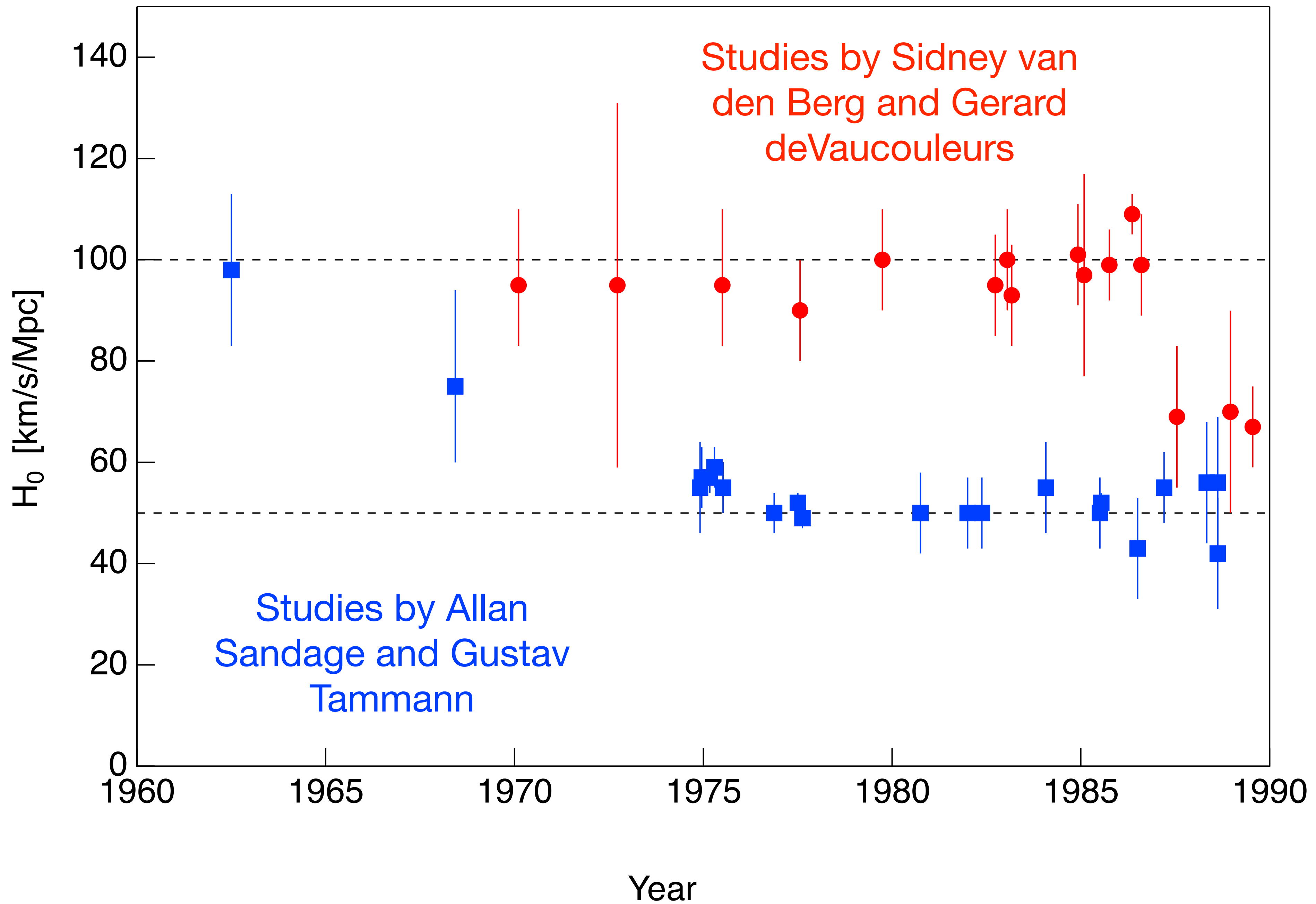


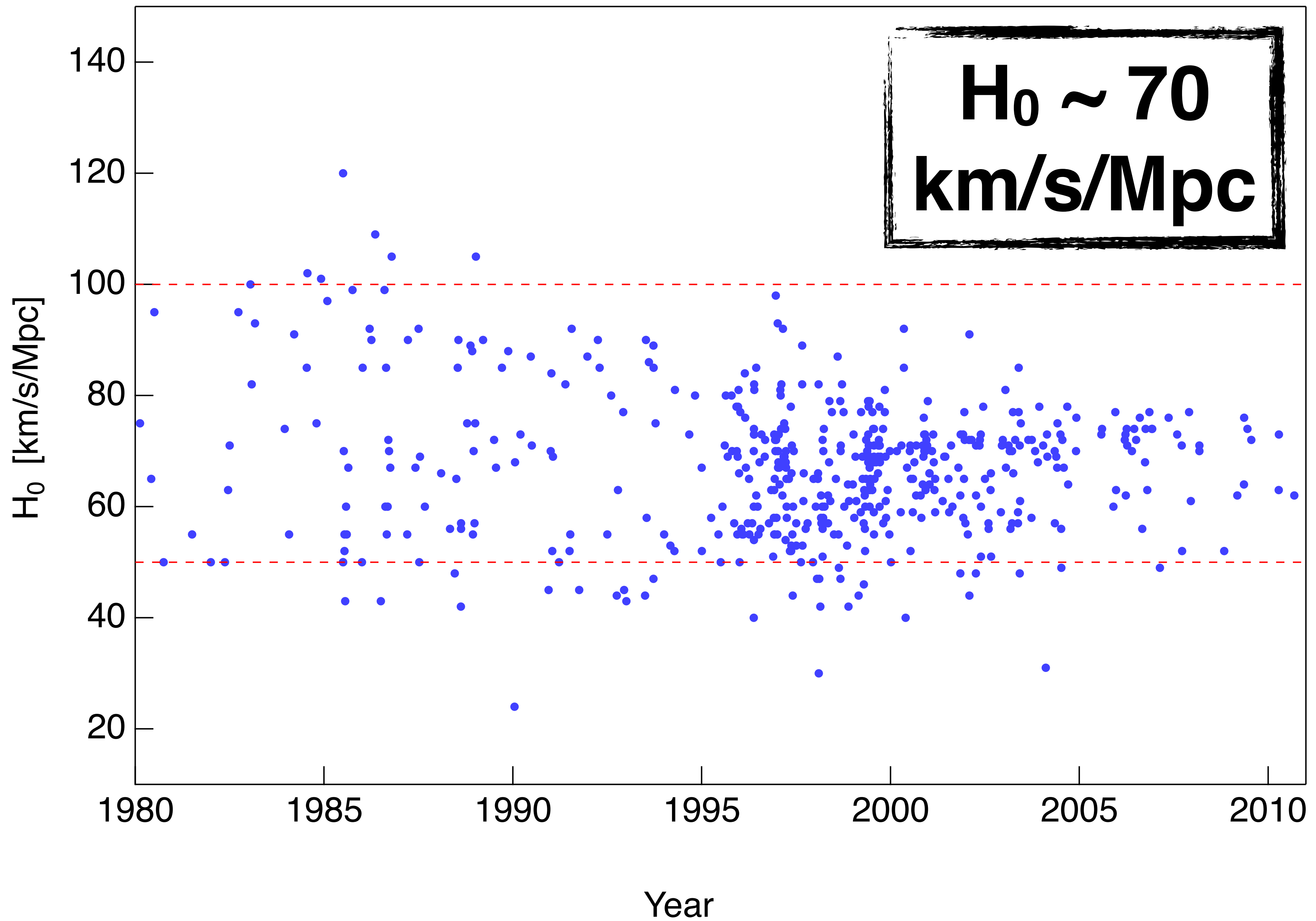
A bit of strange history...

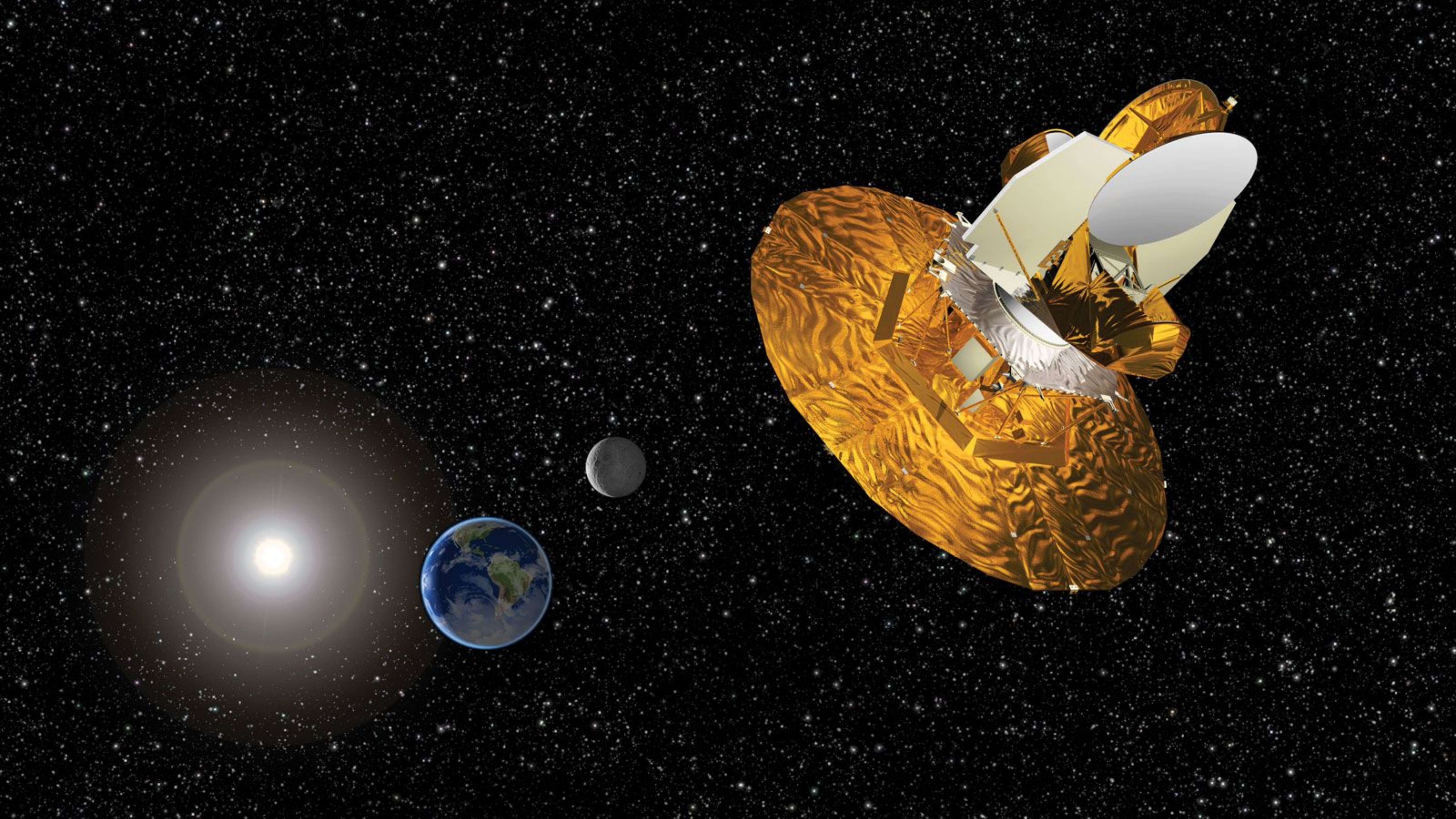






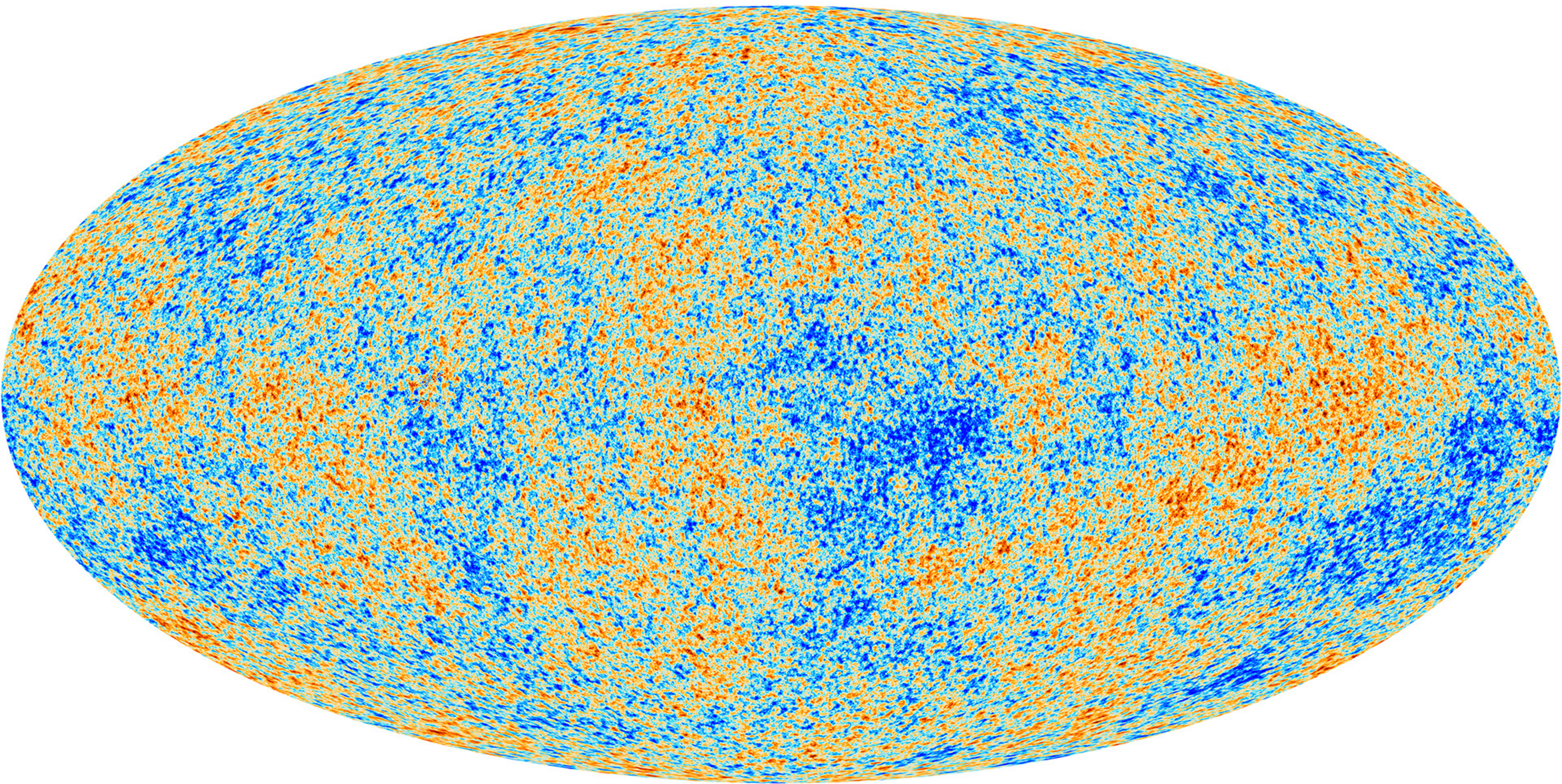


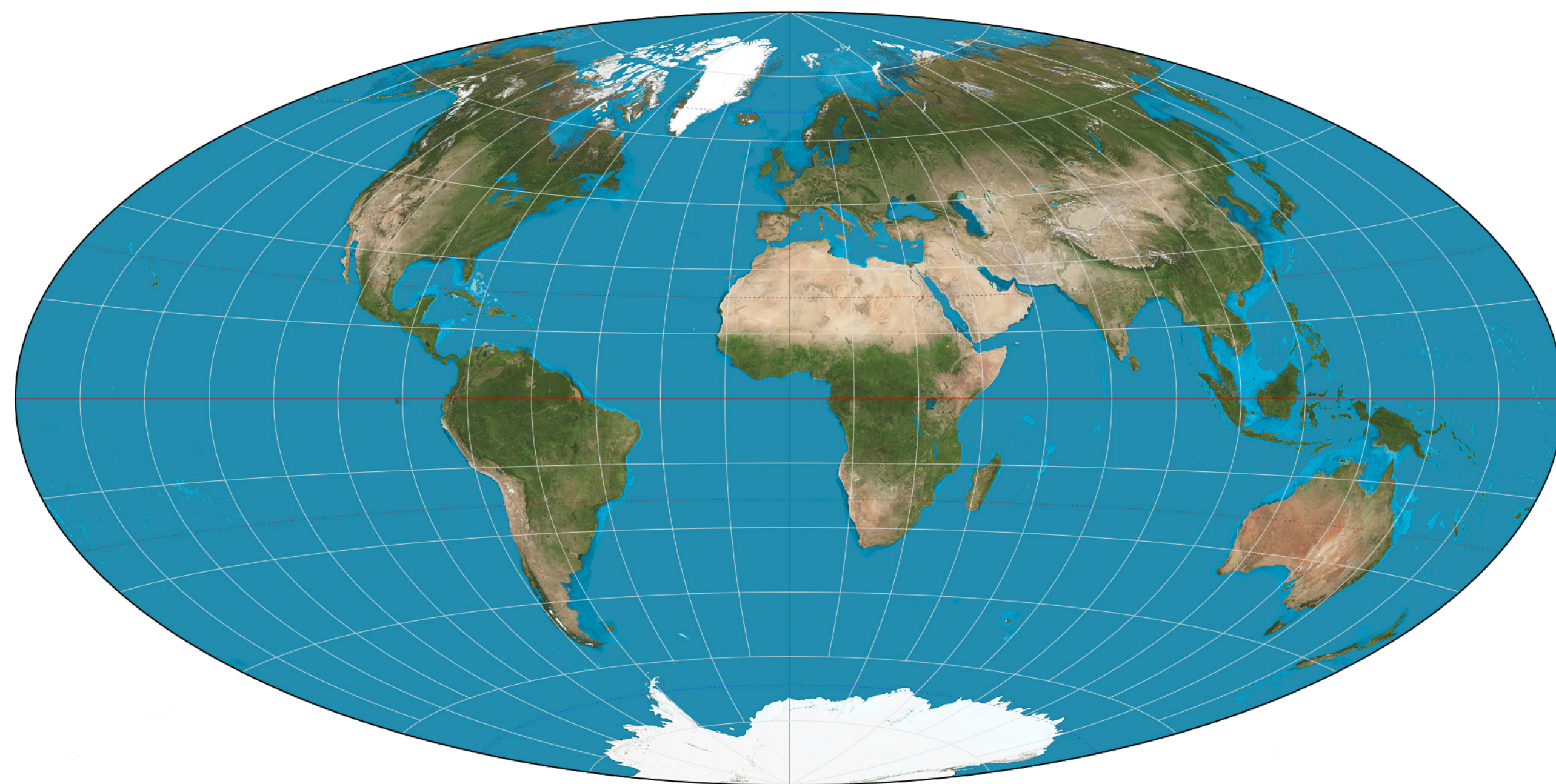


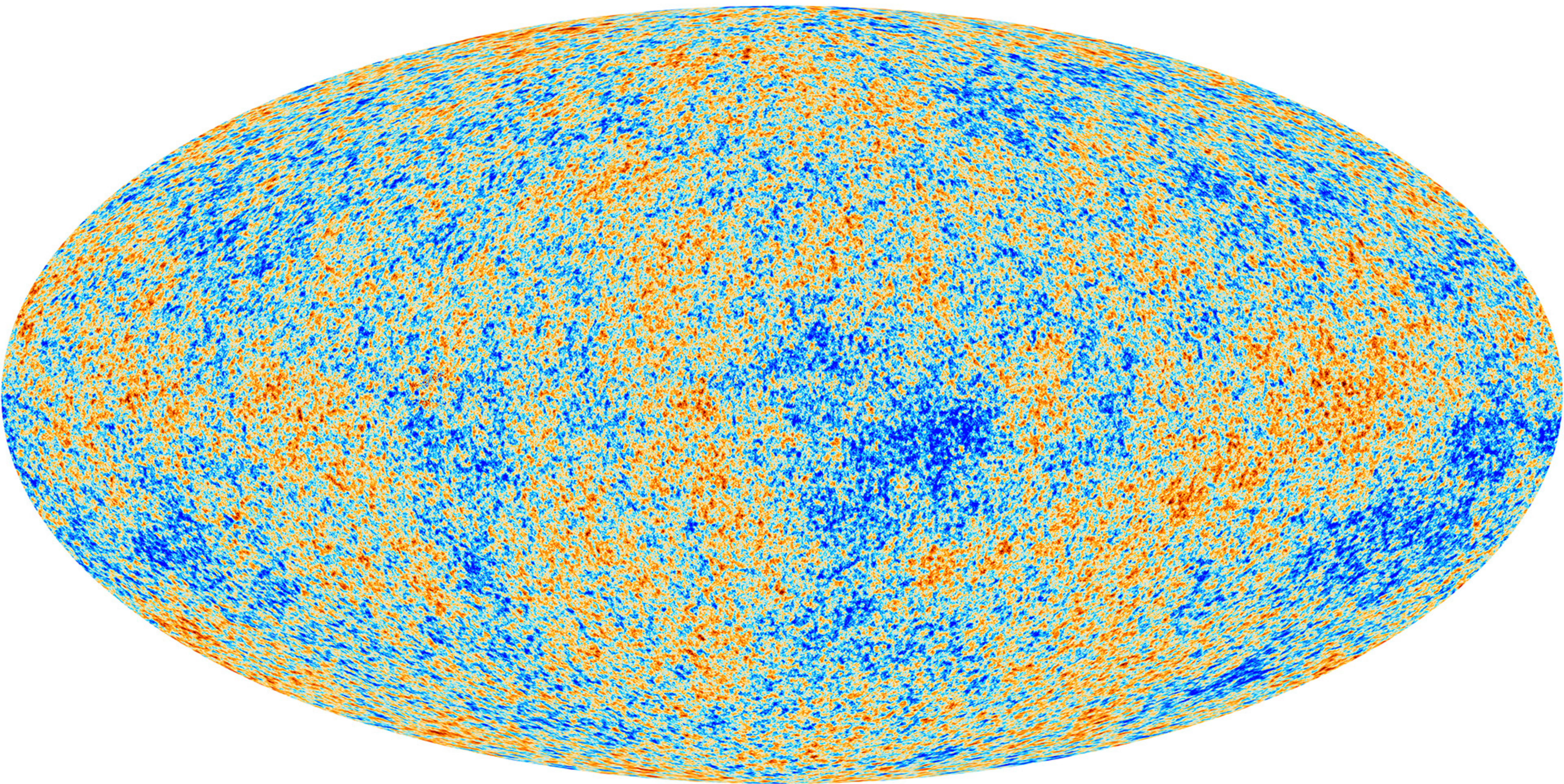


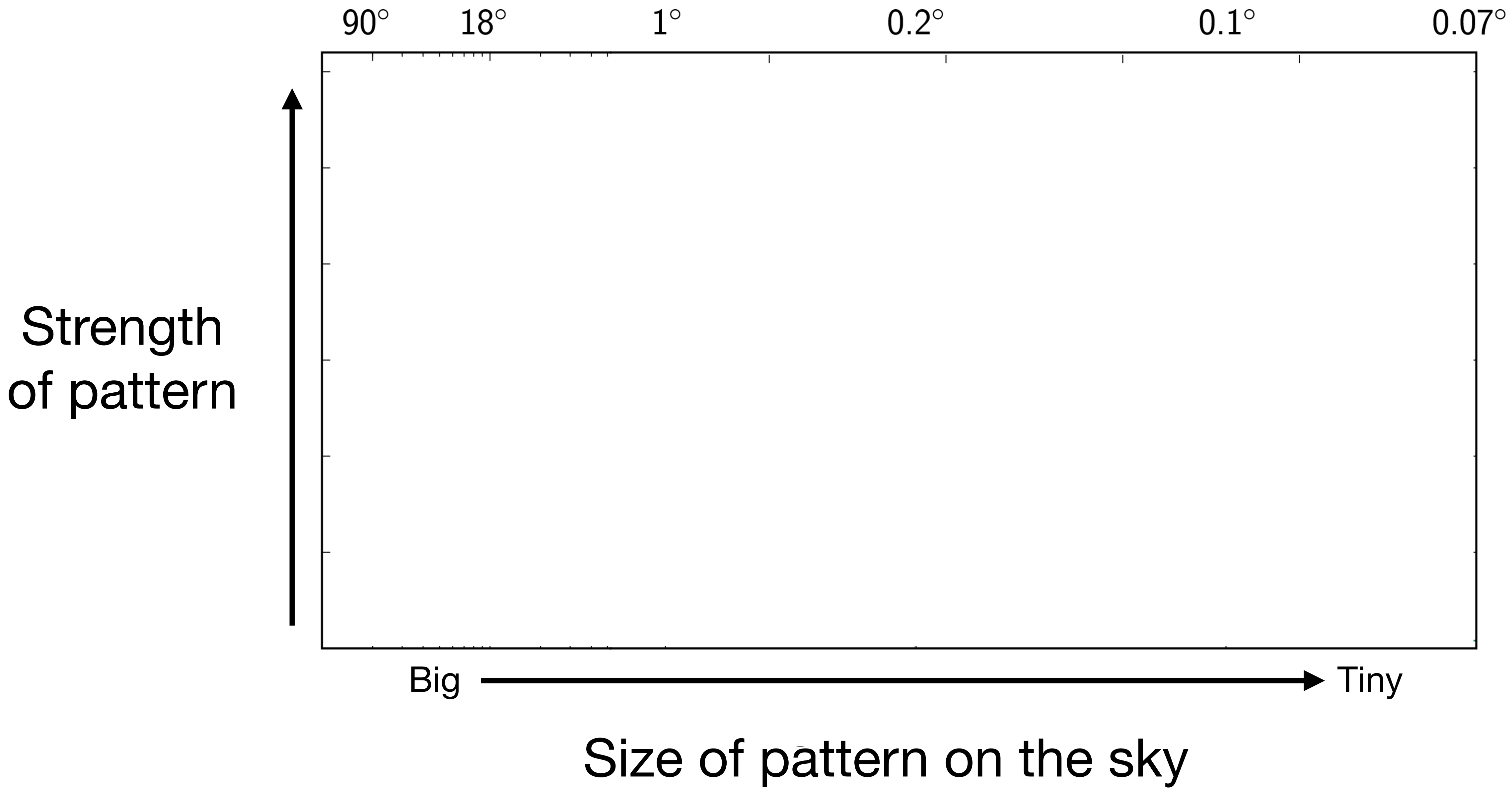
A new way to measure H_0 ...

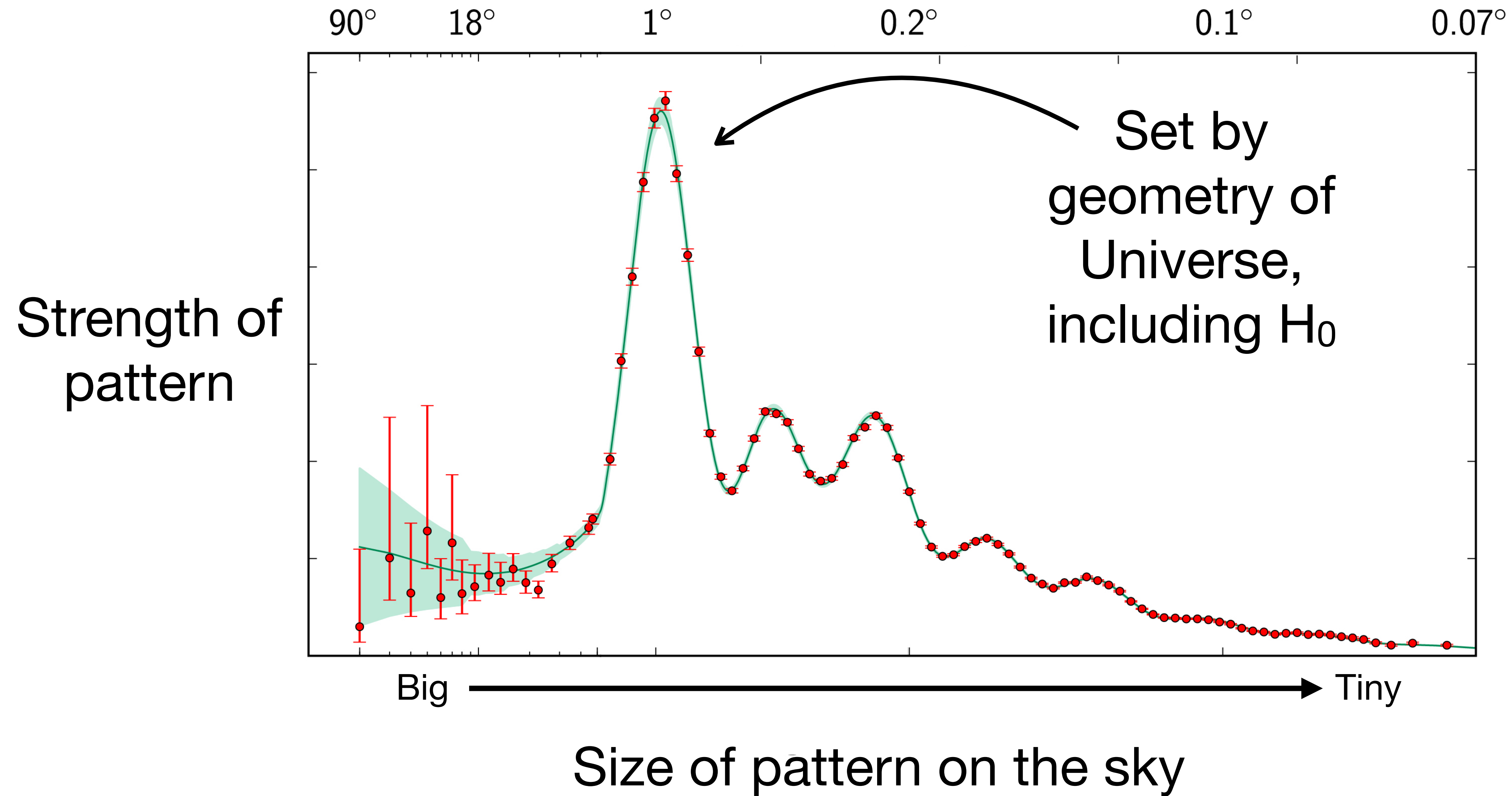
The Cosmic Microwave Background

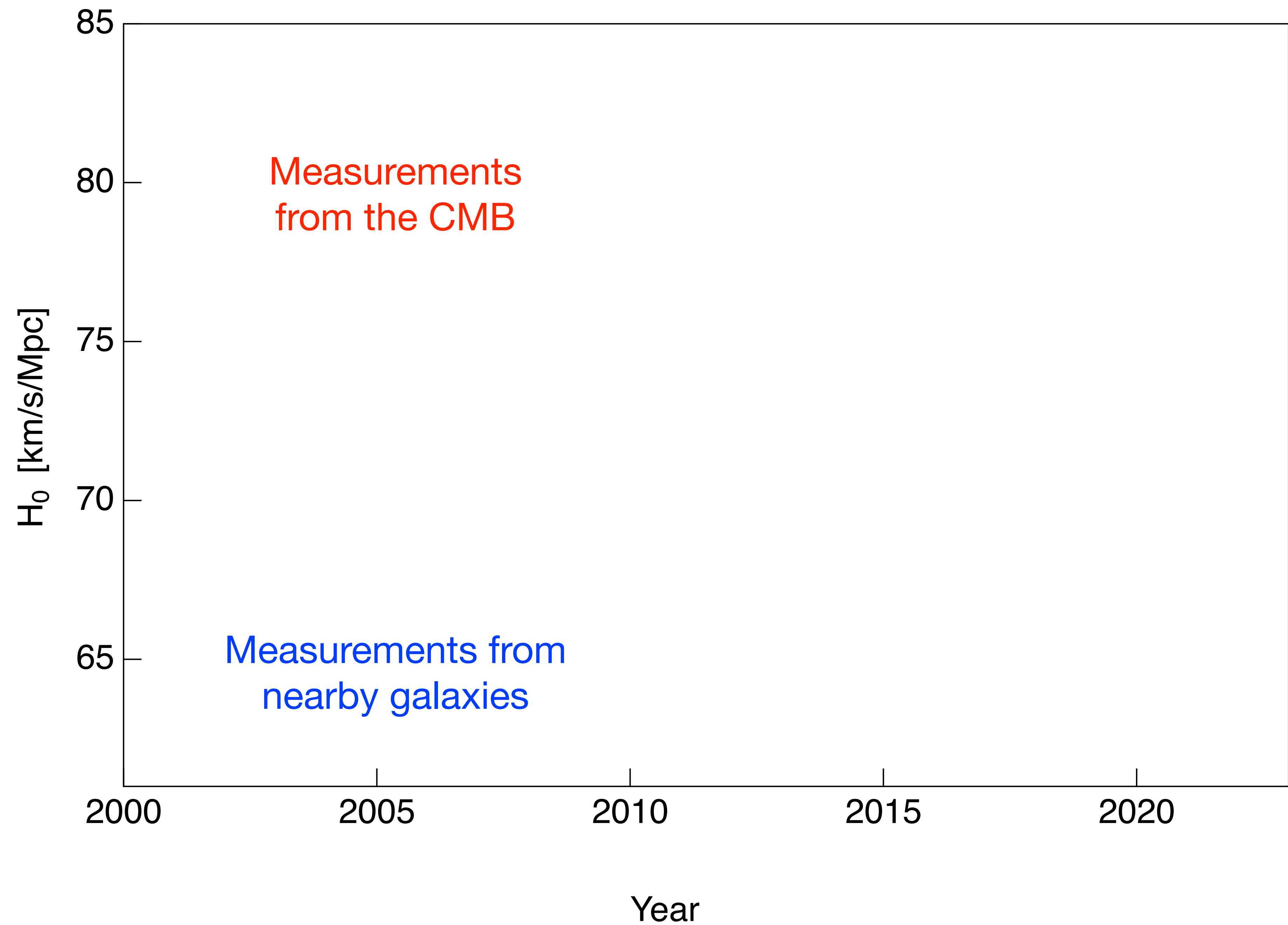












**CMB: Hubble constant is
 67 ± 0.6 km/s/Mpc**

**Nearby Universe: Hubble
constant is 73 ± 1 km/s/Mpc**

What is going on?

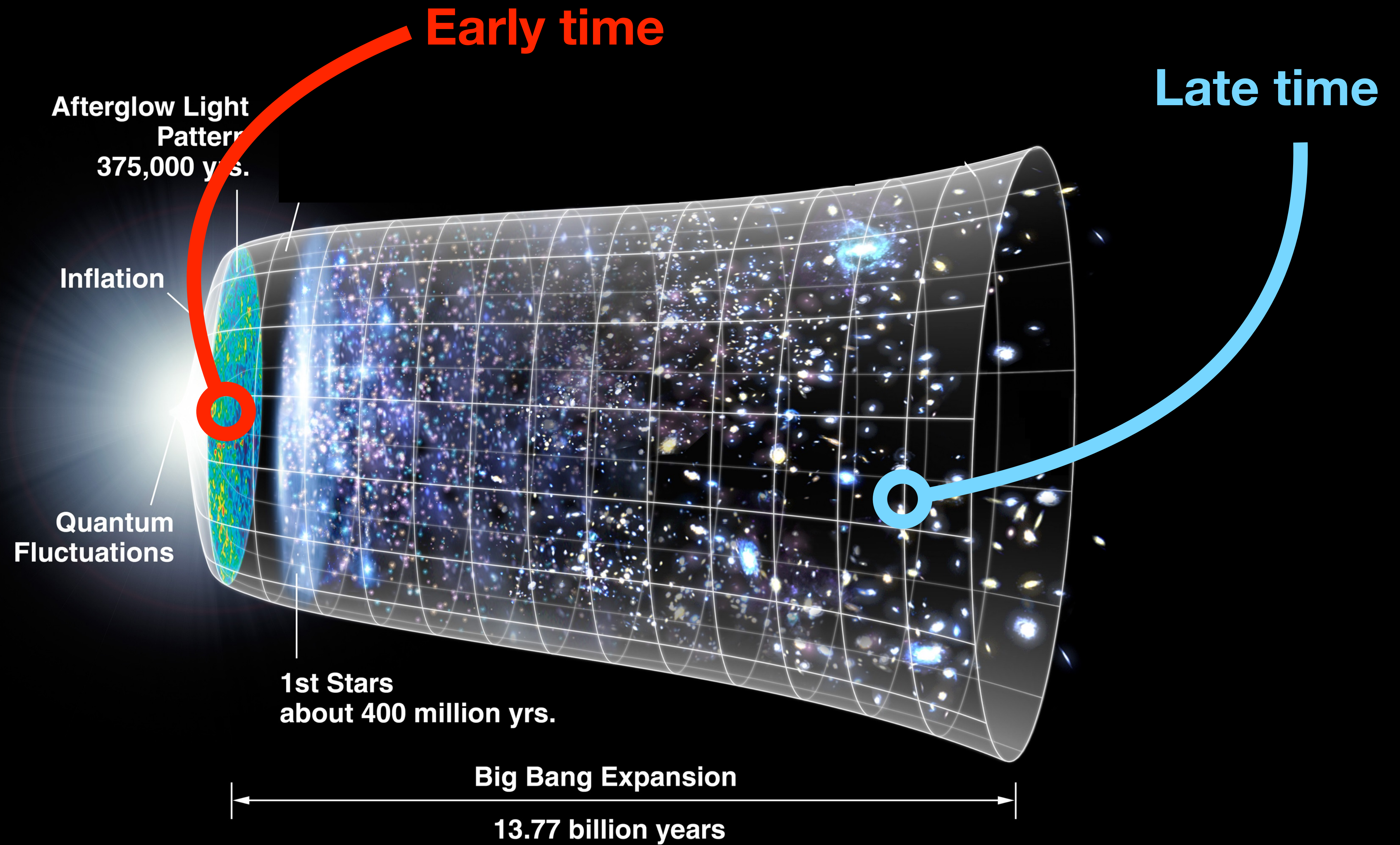
Is there a 'crisis' in cosmology? ... maybe

What is going on?

- Solution 1: we are seeing evidence of new physics
- Solution 2: there is a mistake somewhere

What is going on?

- Solution 1: we are seeing evidence of new physics
- Solution 2: there is a mistake somewhere



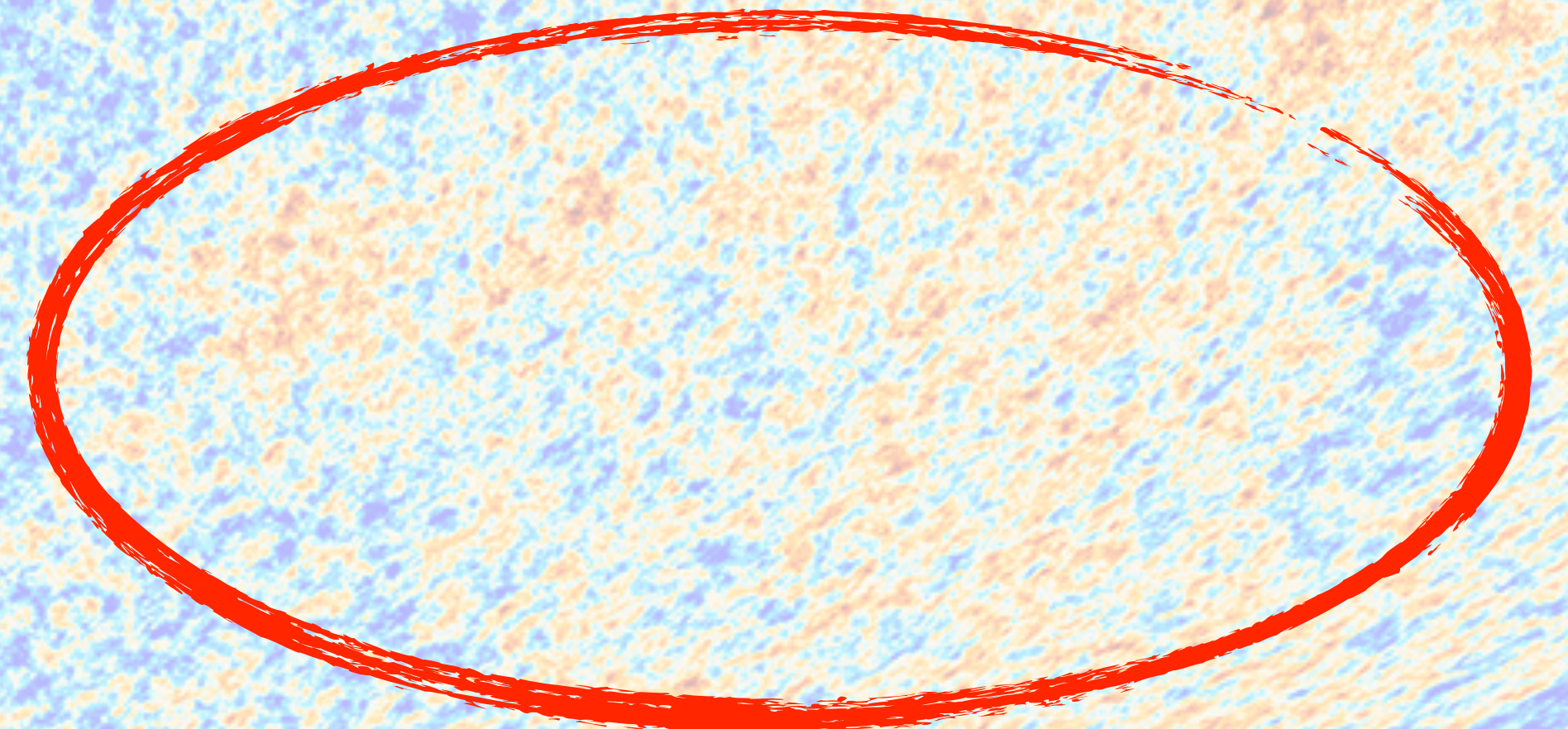
**‘Early time’
CMB data**

**‘Late time’
measurement
of H_0**

*(Evolve using
known
physics)*

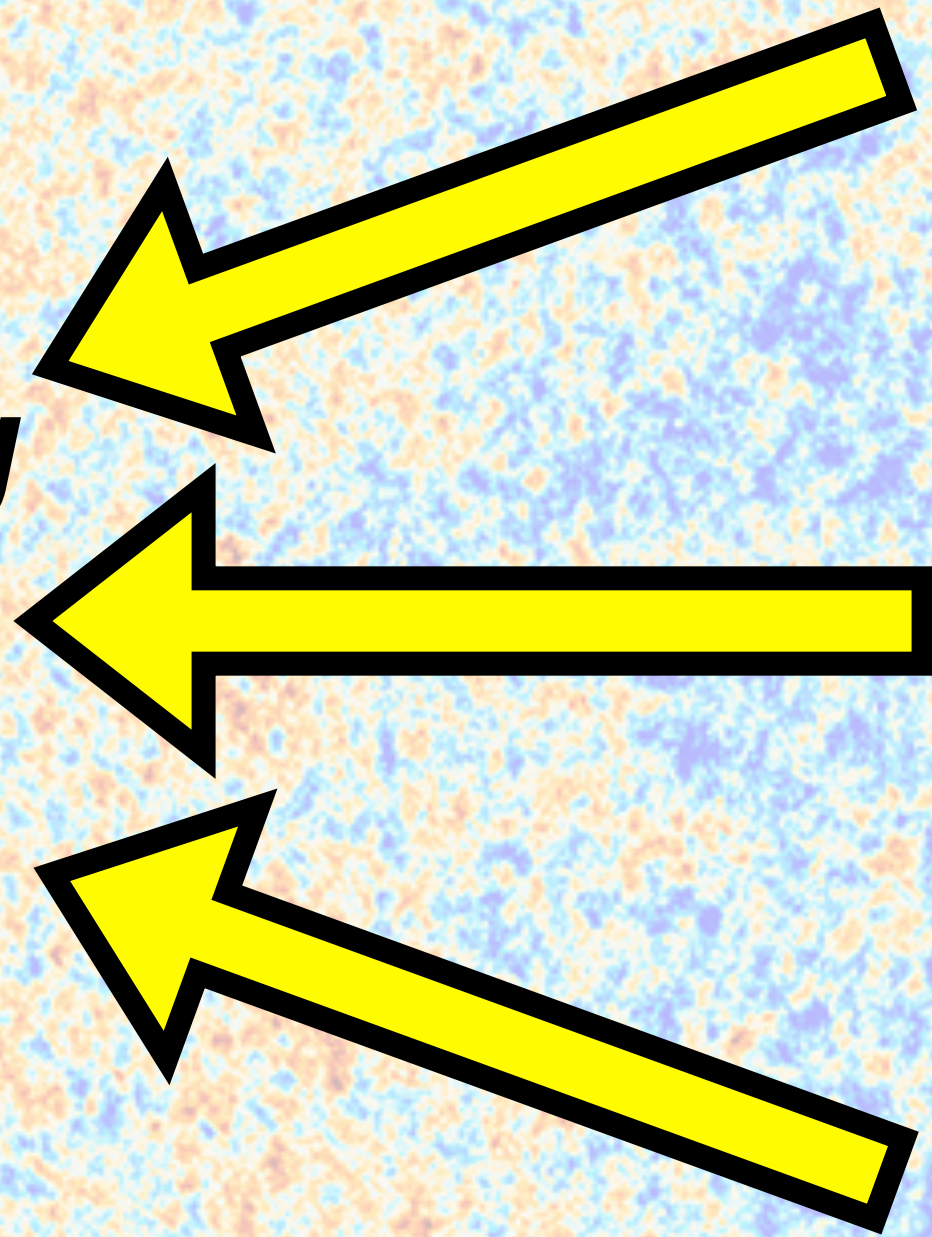


**‘Late time’
 H_0 prediction**



**‘Early time’
CMB data**

*(Evolve using
known
physics)*



**‘Late time’
H0 prediction**

**‘Late time’
measurement
of H0**

Early dark energy?
Time-dependent dark energy?
A curved Universe?
Interacting dark matter?
New particles?

... something else?

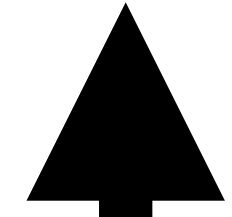
What is going on?

- Solution 1: we are seeing evidence of new physics
- Solution 2: there is a mistake somewhere

‘The Cosmic Distance Ladder’

(This will be important later)

Far



Size of whole Universe

**Means a big
error here!**

Type Ia Supernova

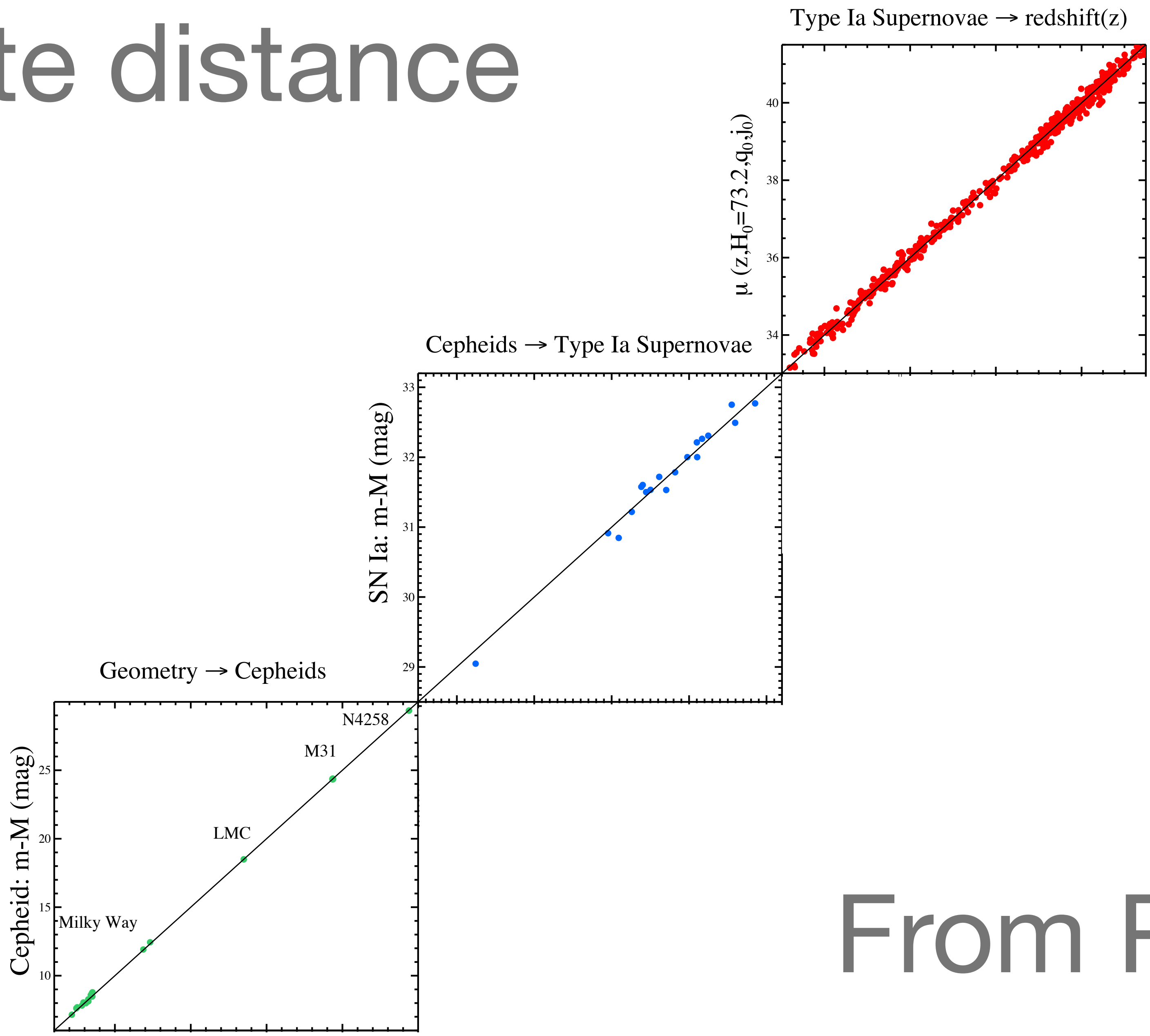
Cepheid Variables

**A small error
here...**

Parallax

Near

Complete distance ladder



From Reiss et al.
(2016)

