HOW BIG IS THE UNIVERSE?
HOW IS IT CHANGING?
AND HOW DO WE KNOW?

Jacob Jencson
U of Arizona

AST 296LB
Pima Community College

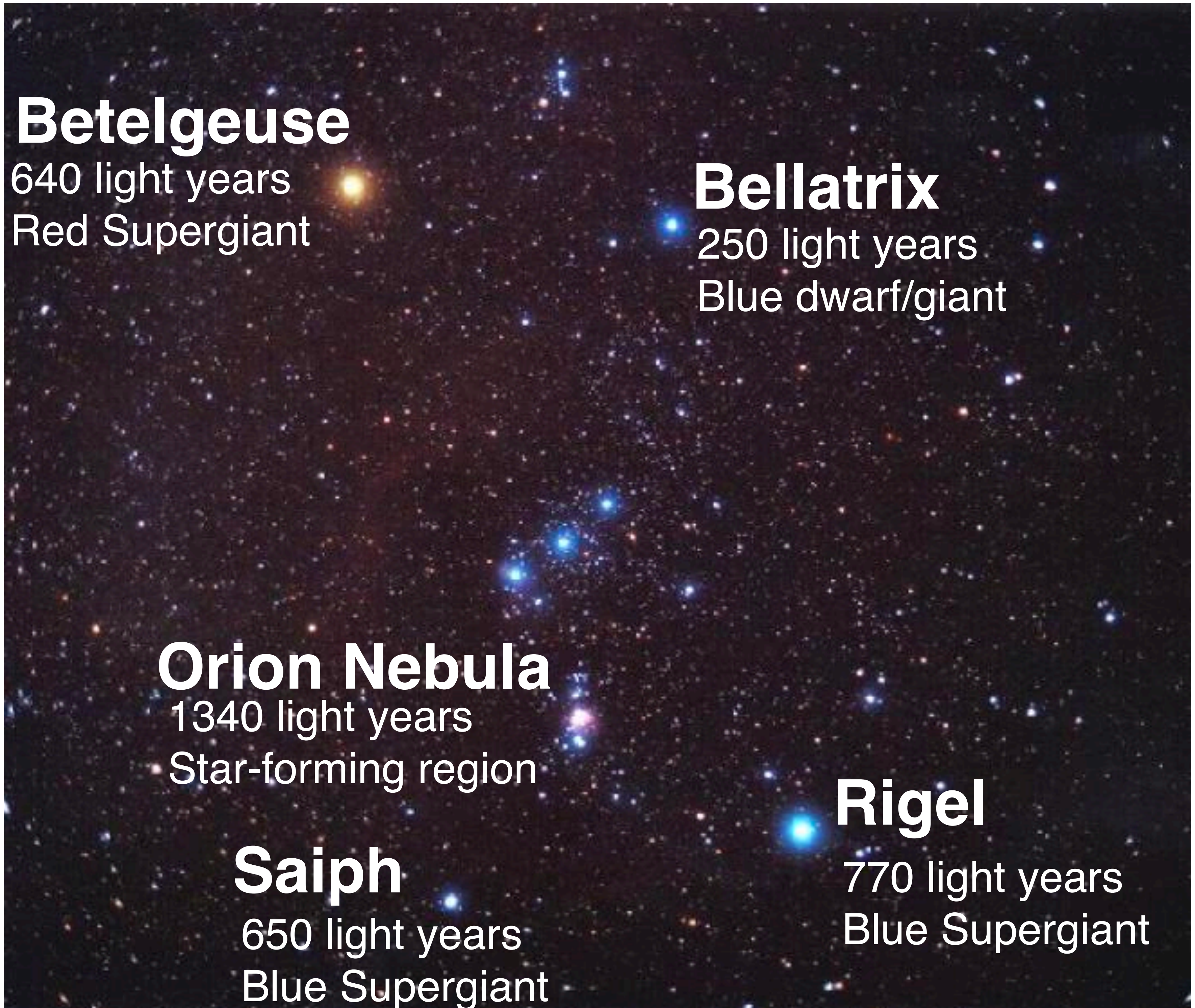
Who am I?

Jacob Jencson

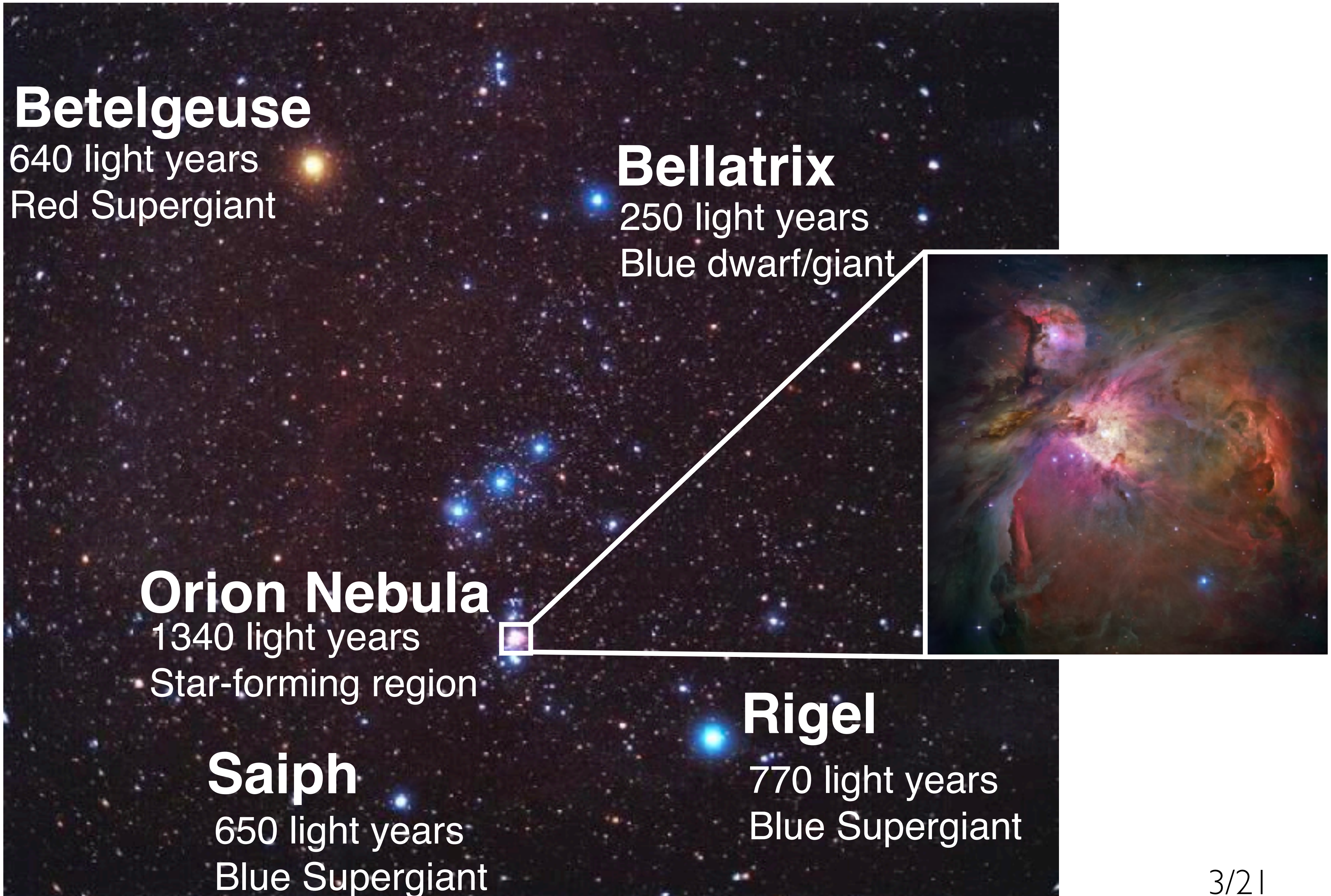
- Did my undergrad in Physics and Astronomy at Ohio State (2009-2014)
- PhD at Caltech (2014-2019)
- On my first postdoc position at the U of Arizona
- Live in Tucson with my cat, Mab
- Interested in all kinds of stellar eruptions and explosions

Our view of the sky is 2D… but the Universe is 3D

Our view of the sky is 2D… but the Universe is 3D



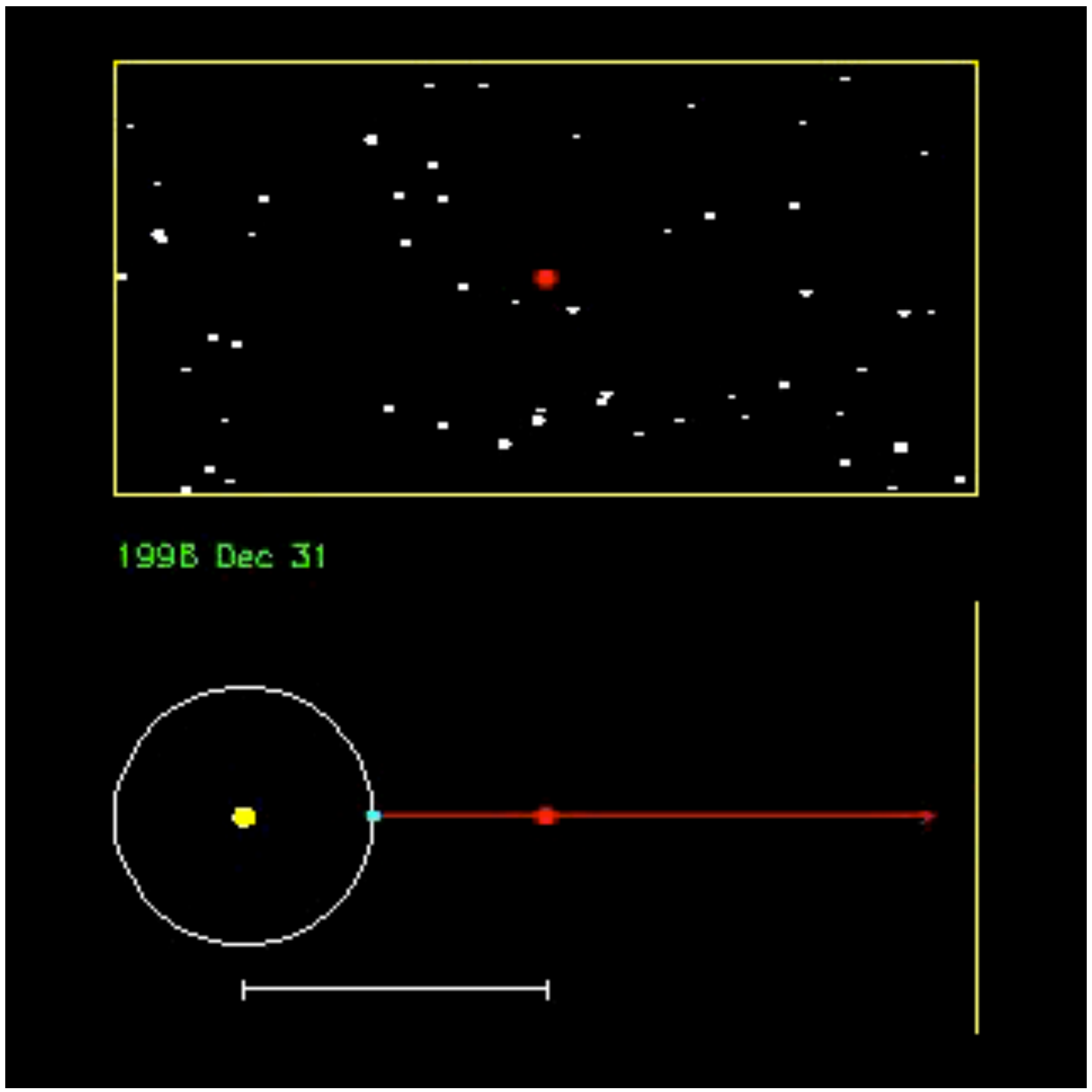
Our view of the sky is 2D… but the Universe is 3D



How do we measure distances to stars?

How do we measure distances to stars?

Trigonometric Parallax



Credit: R. Pogge, OSU

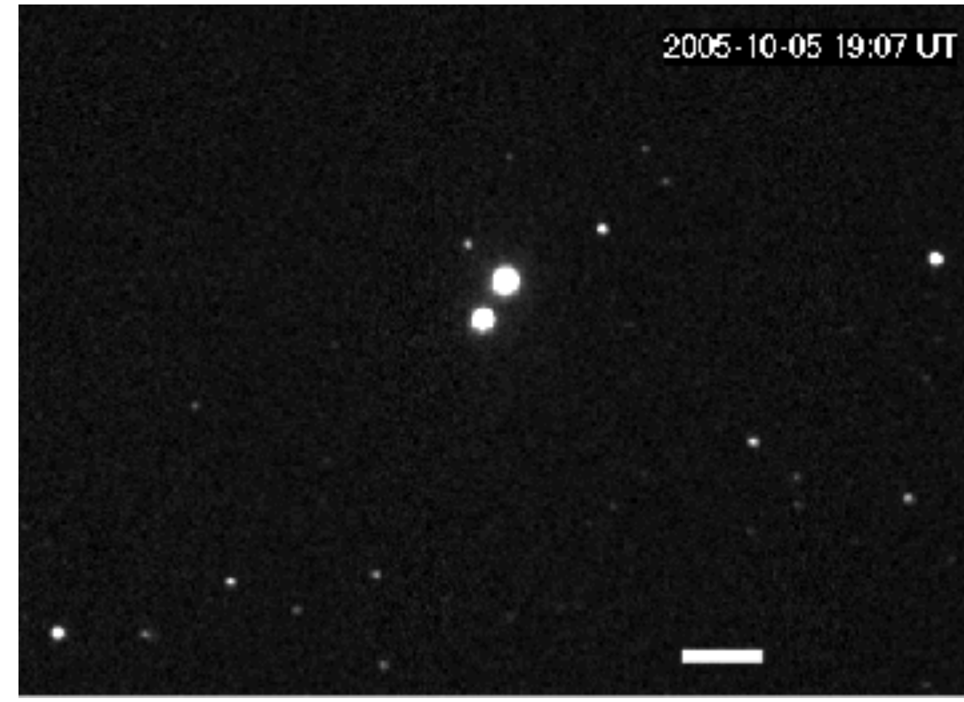
http://www.astronomy.ohio-state.edu/~pogge/Ast162/Movies/parallax.html

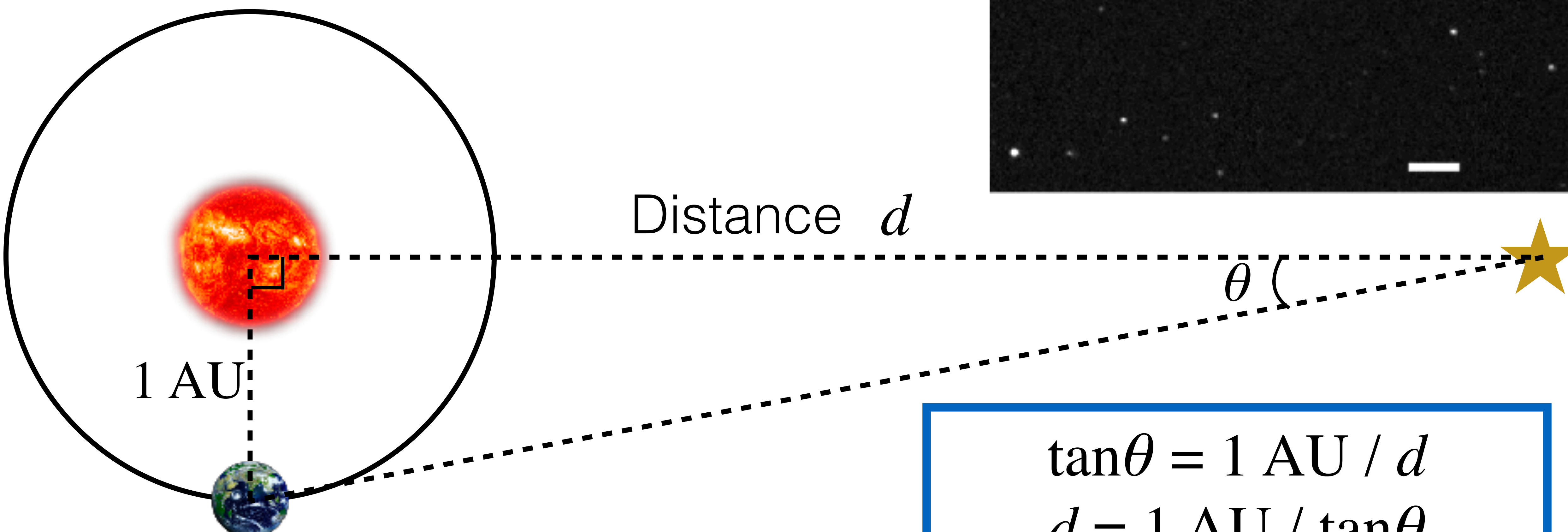
The apparent motion of stars on the sky as the Earth travels in its orbit around the Sun.

This effect is larger for objects that are closer to the Earth, allowing us to infer their distance.

How do we measure distances to stars?

Trigonometric Parallax





$\tan\theta = 1\text{ AU} / d$
$d = 1\text{ AU} / \tan\theta$
$d \approx 1\text{ AU} / \theta$ (in radians)

AU = "Astronomical Unit"
$= 1.5 \times 10^{13}$ cm

How do we measure distances to stars?

Trigonometric Parallax

Astronomers use a base-60 system for positions on the sky or "celestial sphere" (similar to latitude and longitude for coordinates on the Earth)

360 degrees (°)
60 arcminutes (') per degree
60 arcseconds ('') per arcminute

Conversion to radians
$1'' = 1/(60 \times 60)$ deg $\times (\pi/180)$

How do we measure distances to stars?

Trigonometric Parallax

Astronomers use a base-60 system for positions on the sky or "celestial sphere" (similar to latitude and longitude for coordinates on the Earth)

360 degrees (°)
60 arcminutes (') per degree
60 arcseconds ('') per arcminute

Conversion to radians
1'' = 1/(60 × 60) deg × (π/180)

So for a parallax angle of 1'':

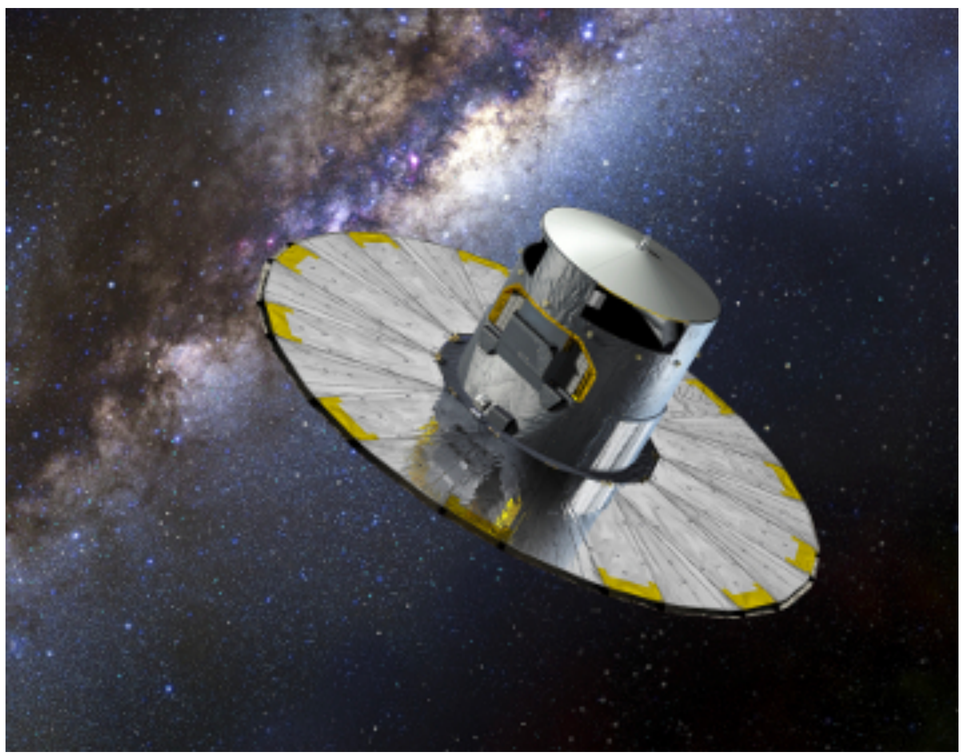
$$d = \frac{1 \text{ AU}}{1''} = \frac{1 \text{ AU}}{(1/206265 \text{ radians})} = 206265 \text{ AU} = 3.086 \times 10^{18} \text{ cm}$$

$\equiv$ 1 parsec or "**par**allax arc**sec**ond"

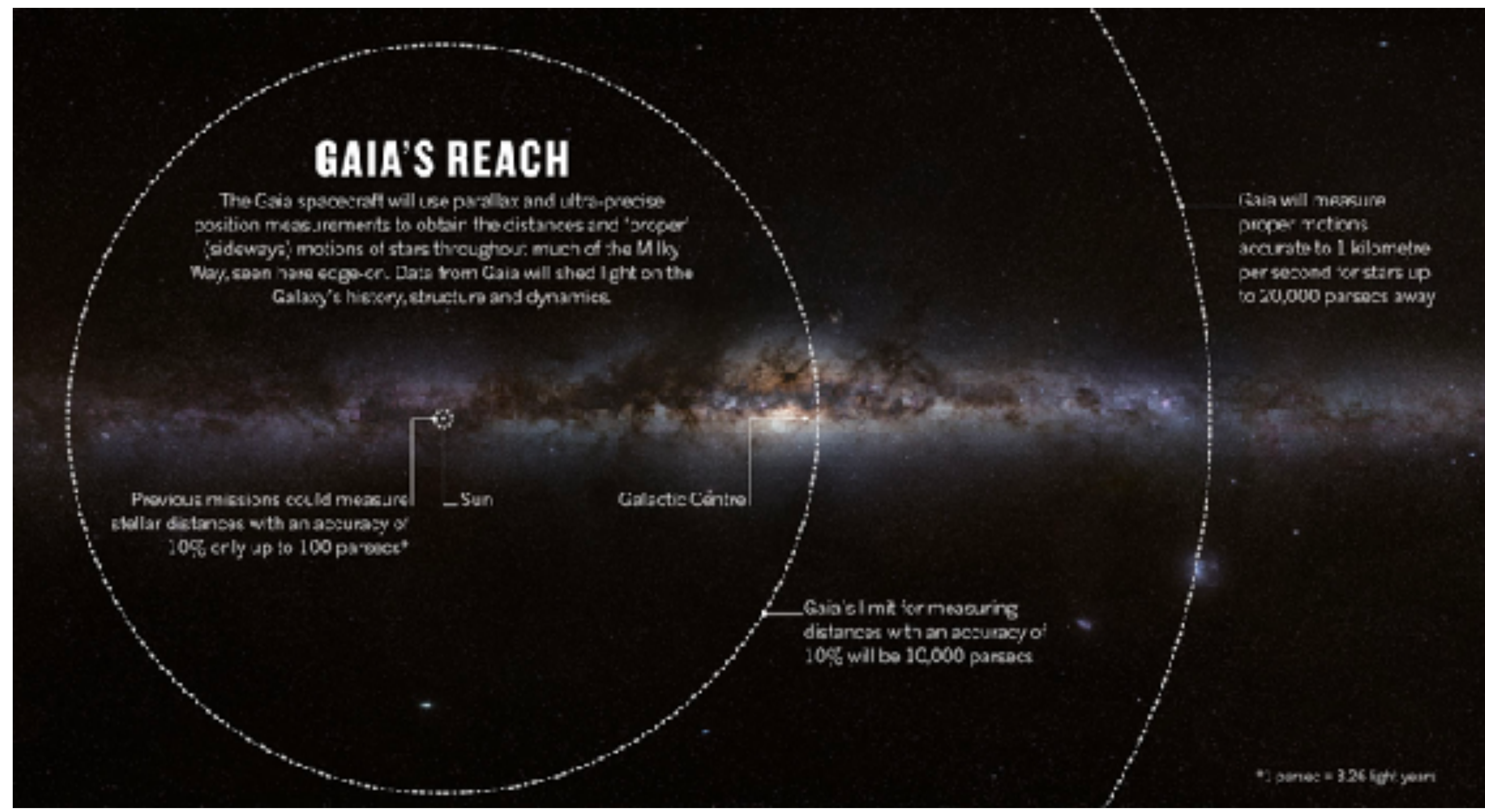
= 3.26 light years

How do we measure distances to stars?

Trigonometric Parallax



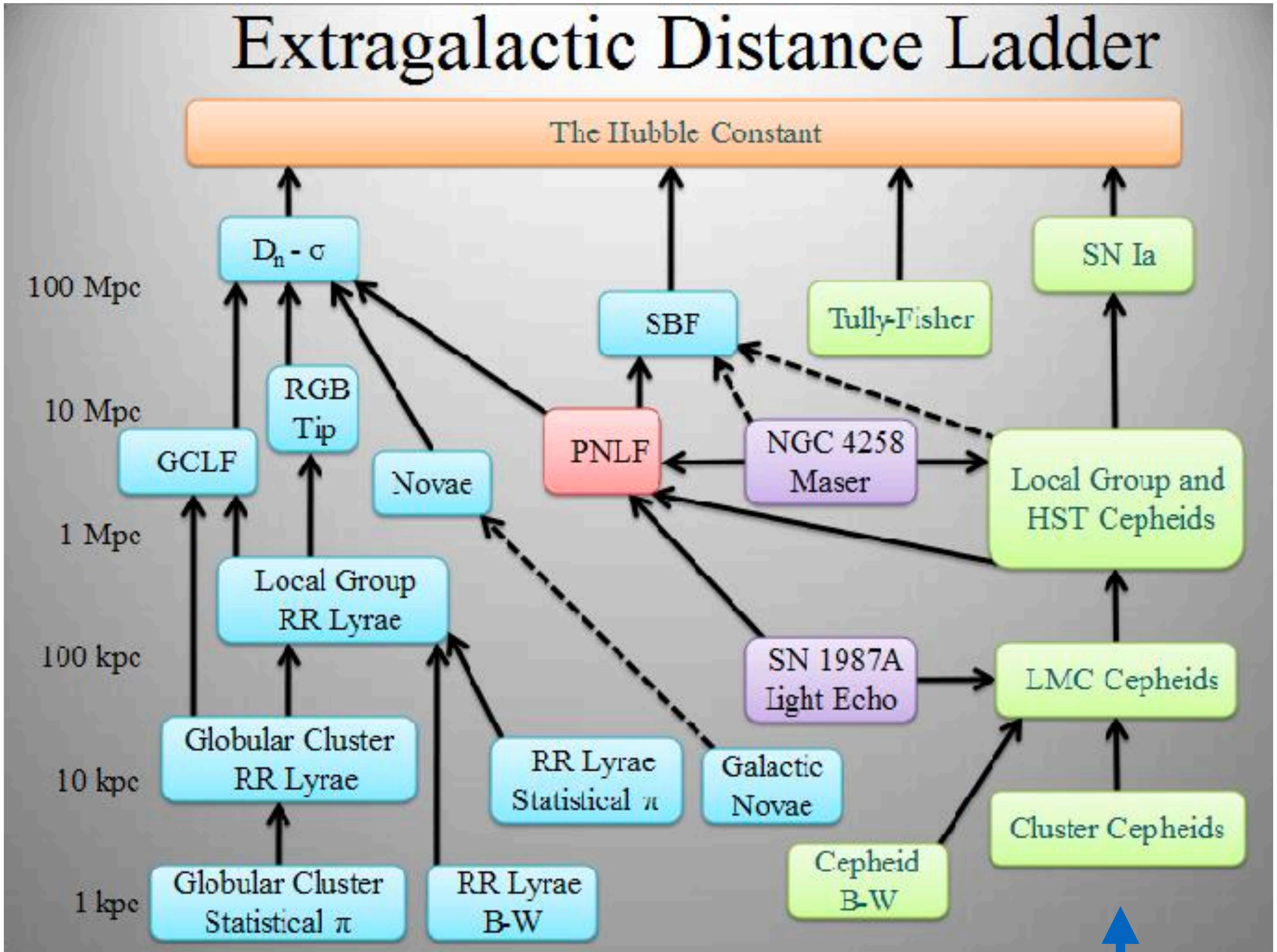
Gaia satellite is current state of the art



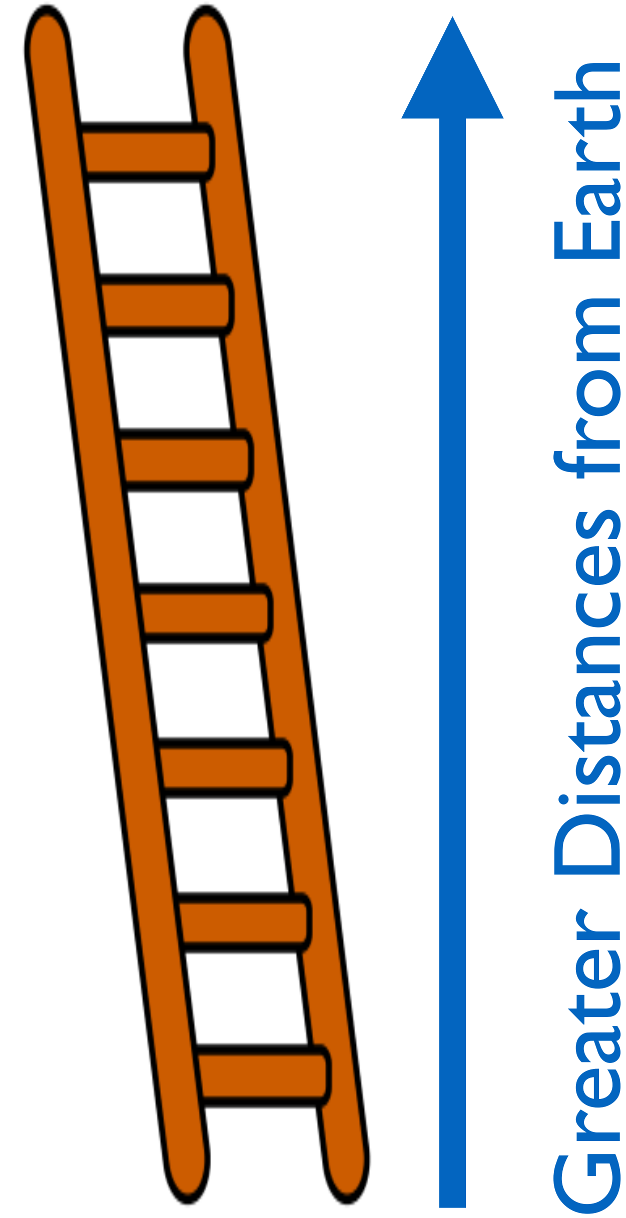
How to we get to larger distances?

… We build a ladder!

The Cosmic "Distance Ladder"

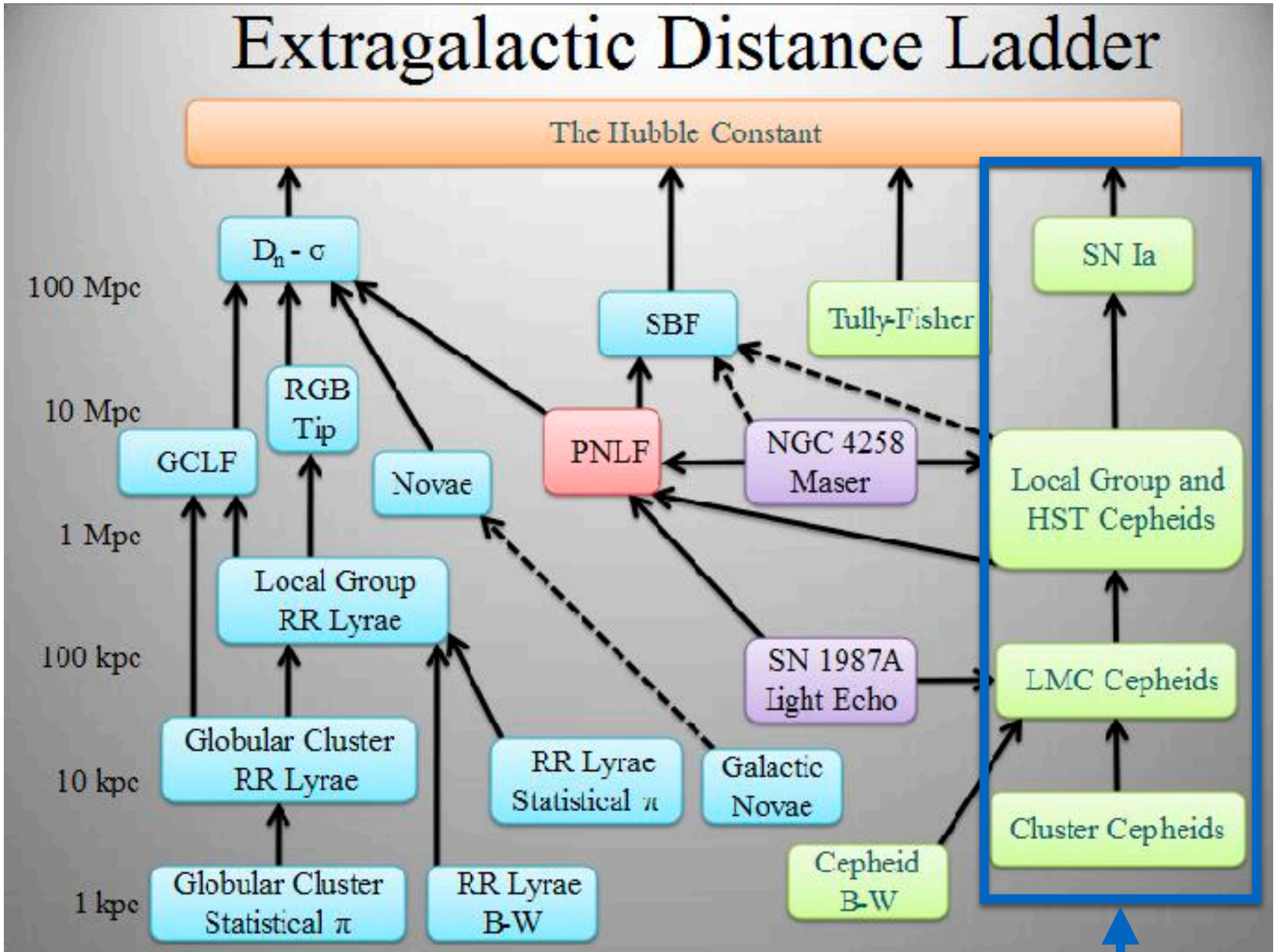


https://en.wikipedia.org/wiki/Cosmic_distance_ladder

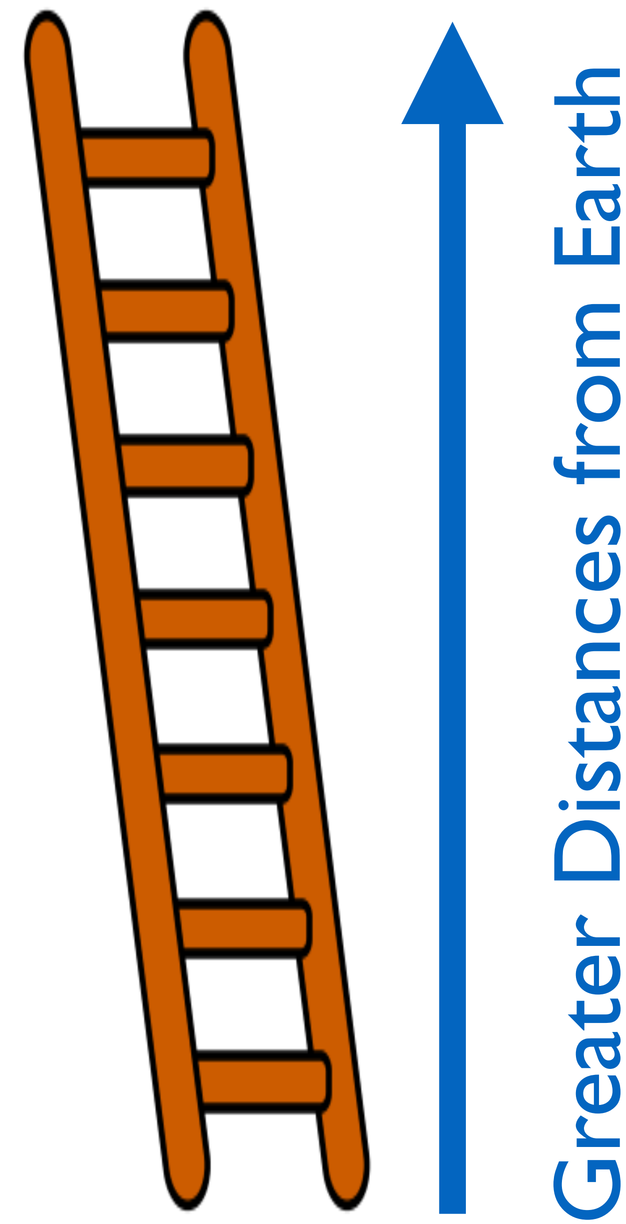


Trigonometric Parallax

The Cosmic “Distance Ladder”



https://en.wikipedia.org/wiki/Cosmic_distance_ladder



Trigonometric Parallax

A little bit of history

The Great Debate

April 6, 1920 at the Smithsonian Museum of Natural History in Washington, D.C.

On the nature of the "spiral nebulae" and the size of the Universe

Harlow Shapley

- True extragalactic distances seemed implausibly vast
- Some "novae" would be too energetic
- **Concluded "spiral nebulae" are contained within the Milky Way**

VS

Heber Curtis

- Andromeda has more novae than the entire Milky Way
- Andromeda has dark lanes of dust similar to those in the Milky Way
- **Concluded they are "Island Universes" external to the Milky Way**

A little bit of history

The Great Debate

April 6, 1920 at the Smithsonian Museum of Natural History in Washington, D.C.

On the nature of the "spiral nebulae" and the size of the Universe

Harlow Shapley
- True extragalactic distances seemed implausibly vast
- Some "novae" would be too energetic
- ~~**Concluded "spiral nebulae" are contained within the Milky Way**~~

actually "supernovae"

VS

Heber Curtis
- Andromeda has more novae than the entire Milky Way
- Andromeda has dark lanes of dust similar to those in the Milky Way
- **Concluded they are "Island Universes" external to the Milky Way**

But how were these vast distances actually measured?

The key to this problem was a special class of variable star…

But how were these vast distances actually measured?

The key to this problem was a special class of variable star…

Recall from last week…

apparent magnitude

$$(m_1 - m_2) = 2.5 * log_{10}\frac{F_2}{F_1}$$

absolute magnitude

distance of the star (pc)

$$\overbrace{m - M}^{\text{distance modulus}} = 5log_{10}(\frac{d}{10})$$

apparent magnitude

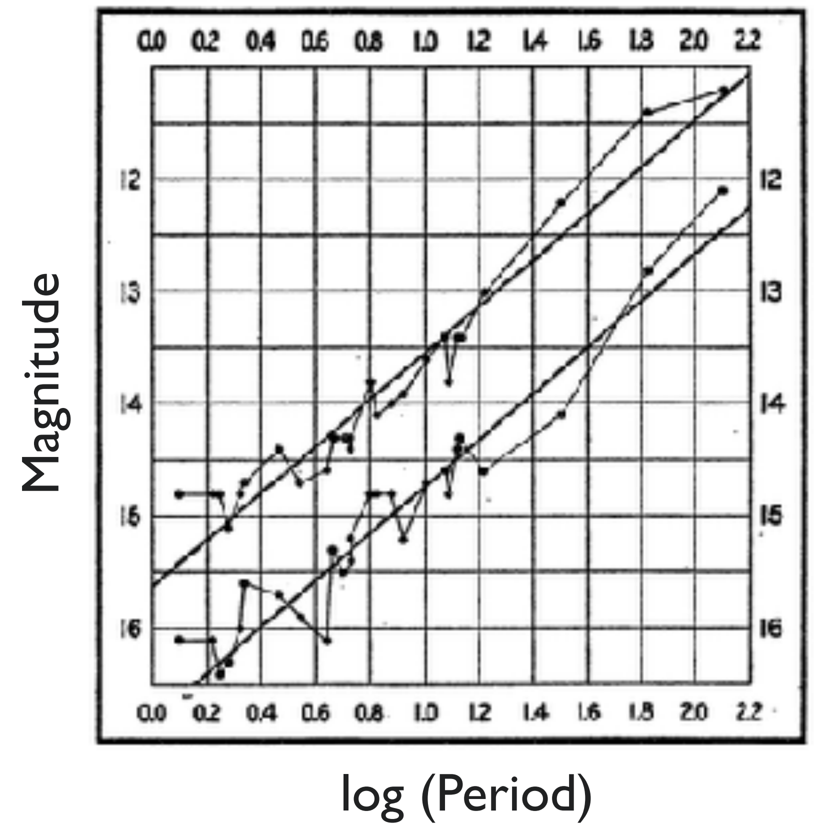
absolute magnitude

Henrietta Swan Leavitt and Cepheid variables

Leavitt worked along side other women at Harvard College Observatory as a "computer" where she measured stellar brightnesses from photographic plates.

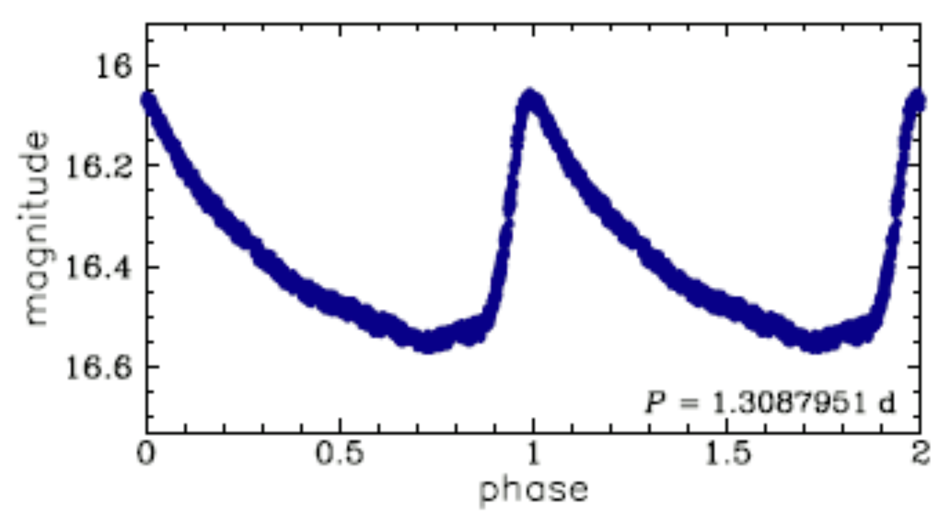
She began studying variable stars and made a remarkable discovery…

Henrietta Swan Leavitt and Cepheid variables

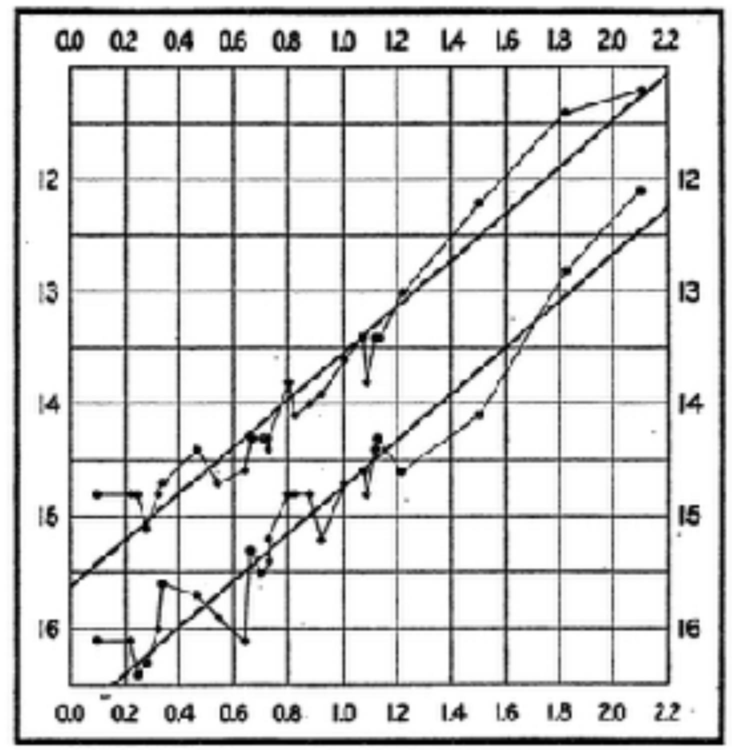


Small Magellanic Cloud

"A straight line can be readily drawn among each of the two series of points corresponding to maxima and minima, thus showing that there is a simple relation between the brightness of the Cepheid variables and their periods." - 1912



Henrietta Swan Leavitt and Cepheid variables

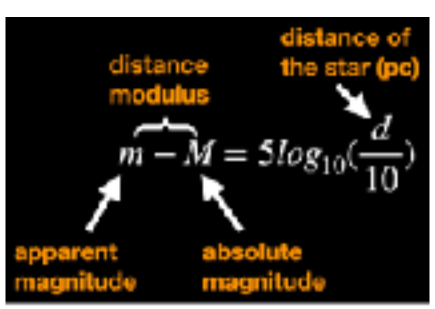


Magnitude

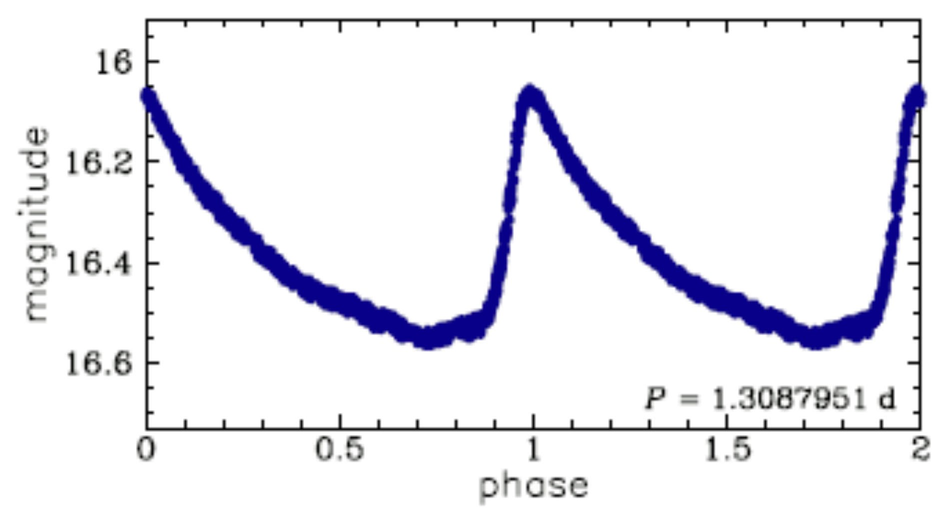
log (Period)

Small Magellanic Cloud

Measuring the period of a Cepheid allows you to **convert between its apparent and absolute magnitude**



You can measure its distance!



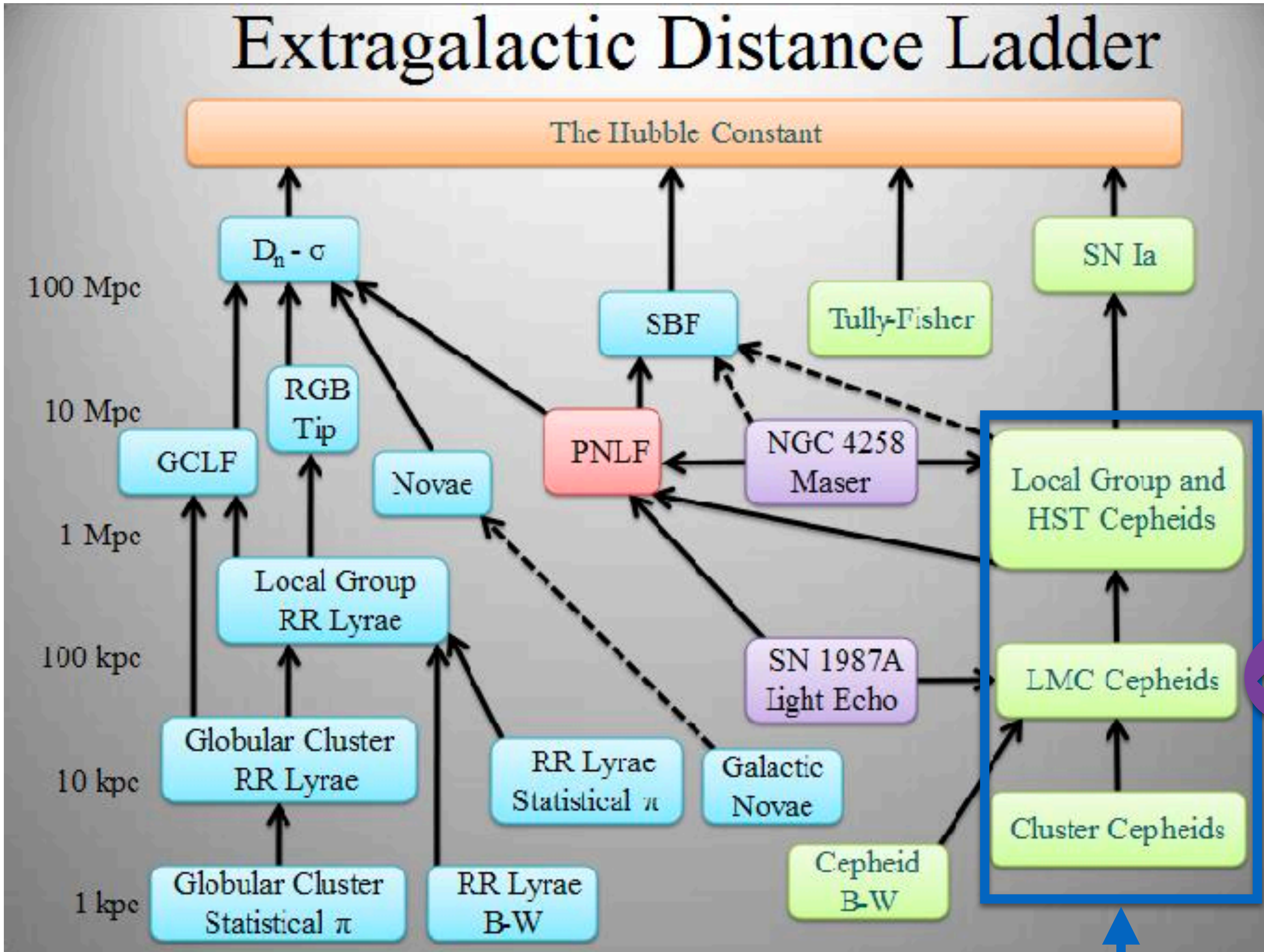
Henrietta Swan Leavitt and Cepheid variables

The Cepheid Period-Luminosity relation, or "Leavitt's Law" can be calibrated using nearby Cepheids with parallax measurements.

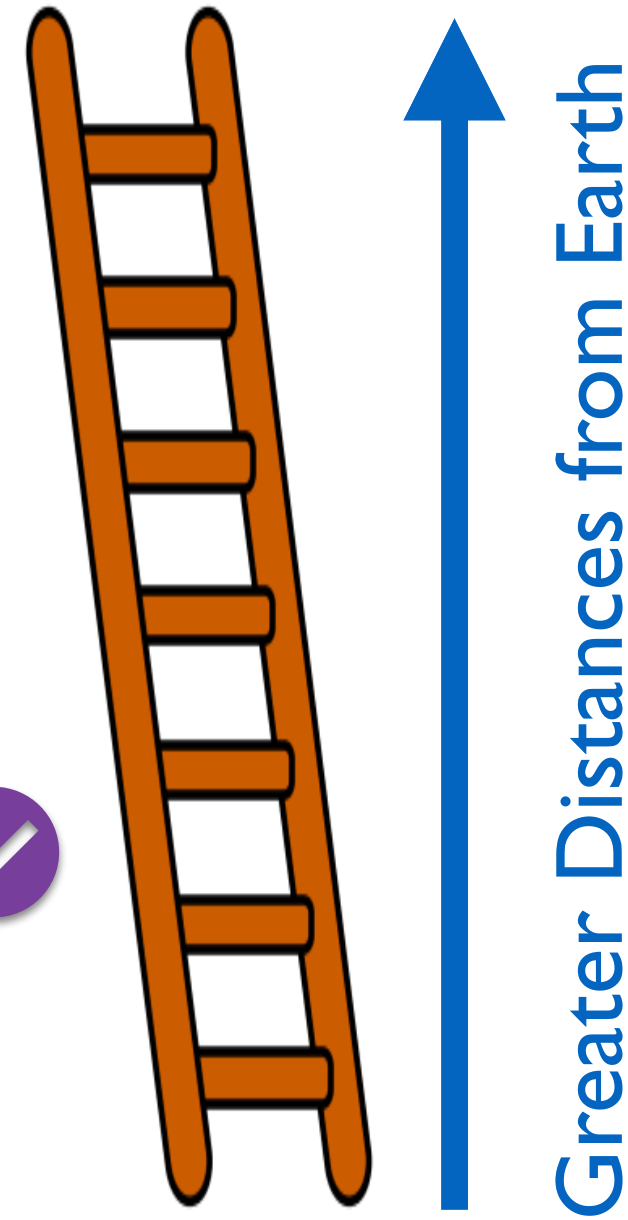
Astronomers call these sources "standard candles":

sources whose intrinsic luminosity can be known from an easily measurable property (like a pulsation period)

The Cosmic “Distance Ladder”



https://en.wikipedia.org/wiki/Cosmic_distance_ladder

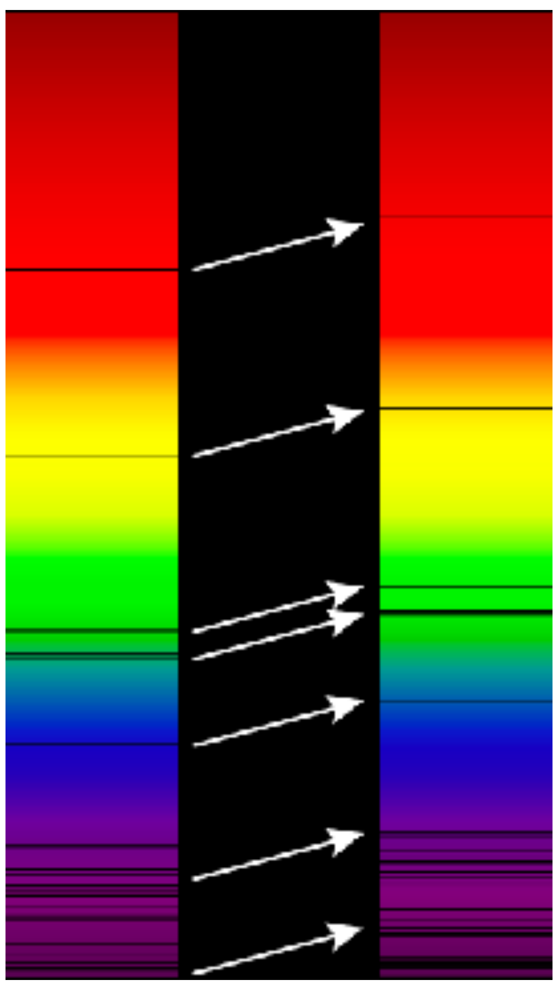


Trigonometric Parallax

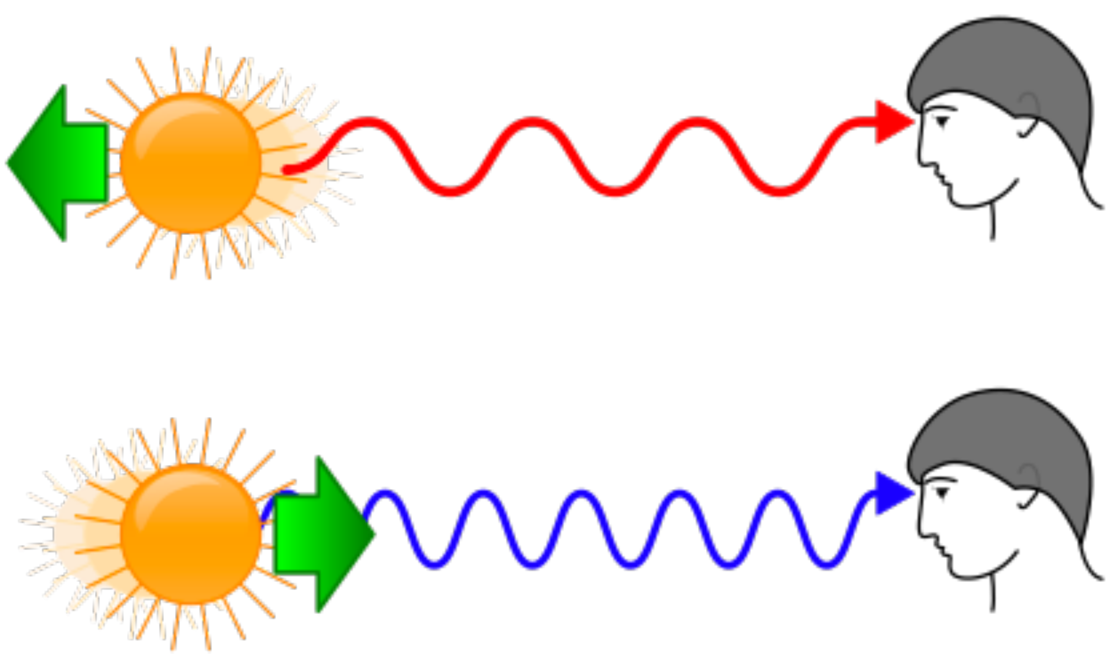
Now we are able to measure distances on vast, extragalactic scales.

How are distant galaxies moving relative to Earth?

The positions of spectral lines are "shifted" for a moving object



Similar to the Doppler effect for sound waves.



Redshift: moving away

Blueshift: moving closer

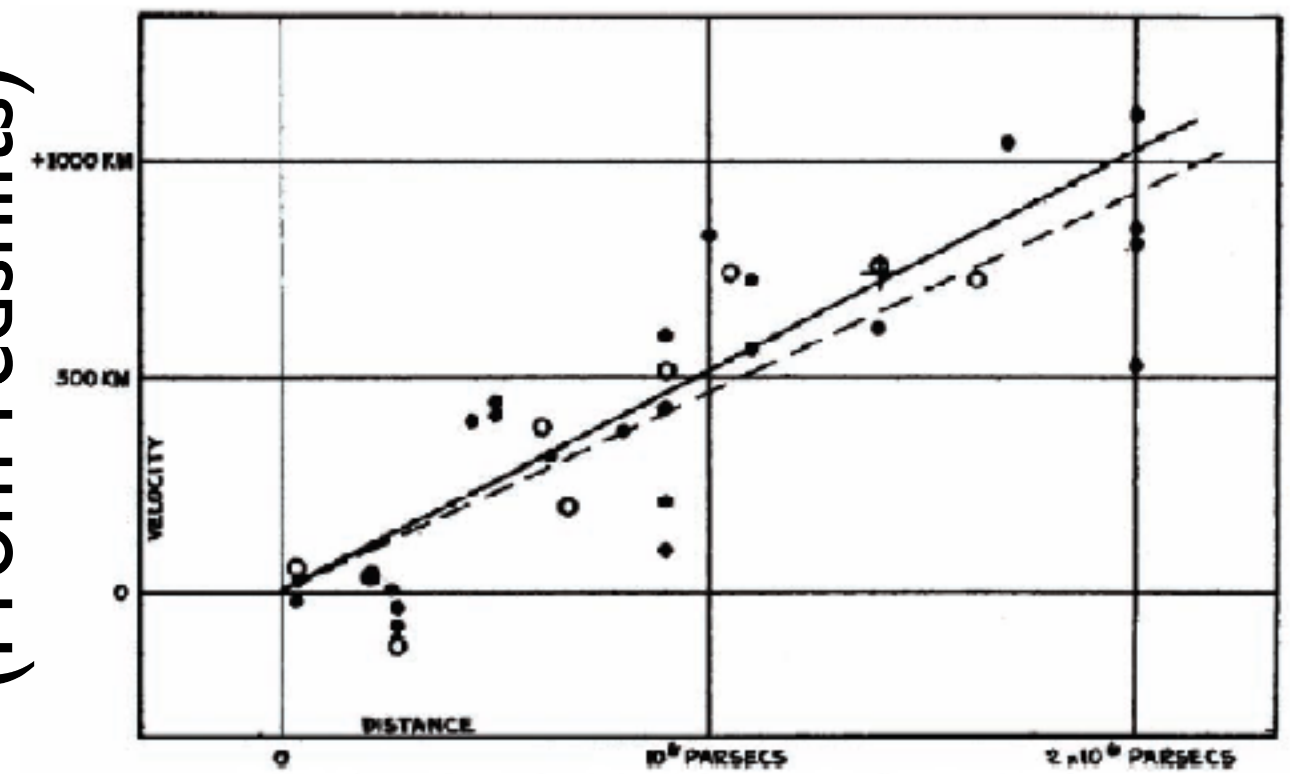
$$\text{redshift} \quad z \approx \frac{v}{c} \quad \begin{matrix}\text{velocity} \\ \text{speed of light}\end{matrix}$$

Edwin Hubble and the Expanding Universe

Using the 100-in. Hooker Telescope at Mt. Wilson Observatory in California.

More distant galaxies are receding at a higher velocity: **The space between galaxies is growing!**

Recession velocity
(From redshifts)



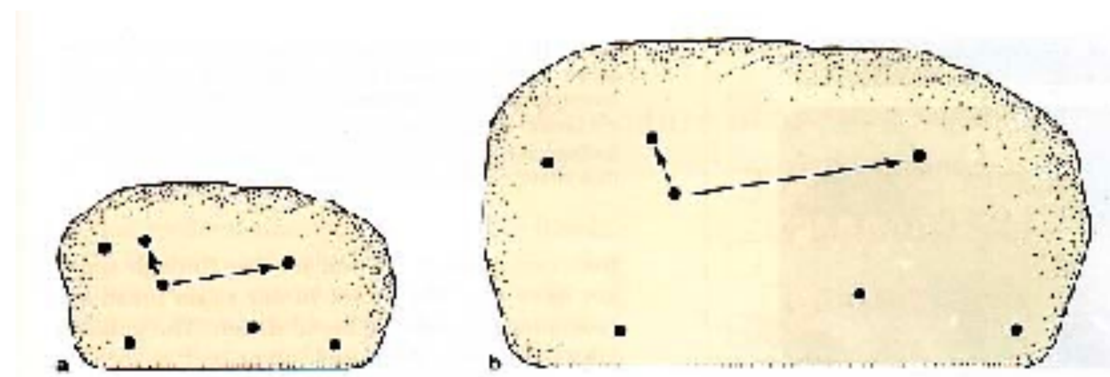
Distances to galaxies
(From Cepheid measurements)

This confirmed an earlier result from Belgian astronomer, Georges Lemaitre

The Hubble Constant: H_0

- Hubble found that at a distance of 1 Mpc (one million parsecs), the recession velocity was ~500 km/s
- This was wrong by almost a factor of 10 due to errors in the distance calibration
- Today the best measurements are ~70 km/s per Mpc of distance
- Leads to the idea of the “Big Bang” that the Universe has expanded from an extremely dense and hot initial state.

Like raisins in rising bread:

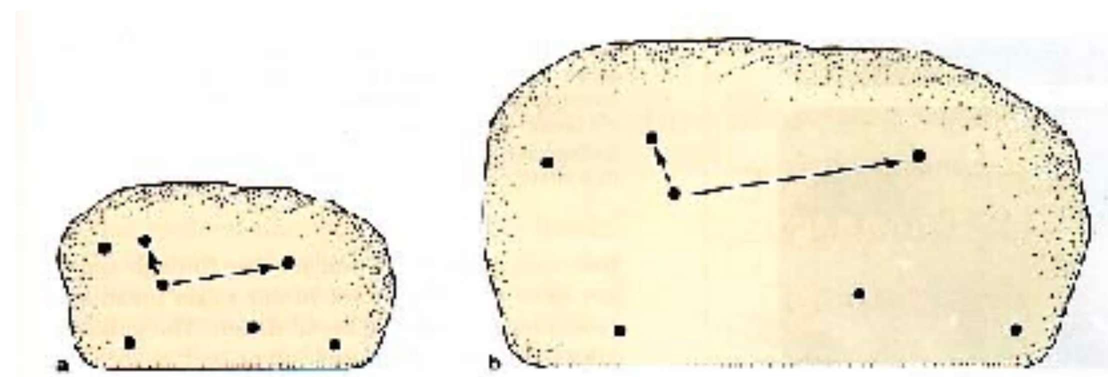


The space between any pairs of galaxy grows with time. From the vantage point of any galaxy, all others appear to be moving away.

The Hubble Constant: H_0

- Hubble found that at a distance of 1 Mpc (one million parsecs), the recession velocity was ~500 km/s
- This was wrong by almost a factor of 10 due to errors in the distance calibration
- Today the best measurements are ~70 km/s per Mpc of distance
- Leads to the idea of the “Big Bang” that the Universe has expanded from an extremely dense and hot initial state.

Like raisins in rising bread:



The space between any pairs of galaxy grows with time. From the vantage point of any galaxy, all others appear to be moving away.

...But is the expansion rate really constant, or could it be changing?

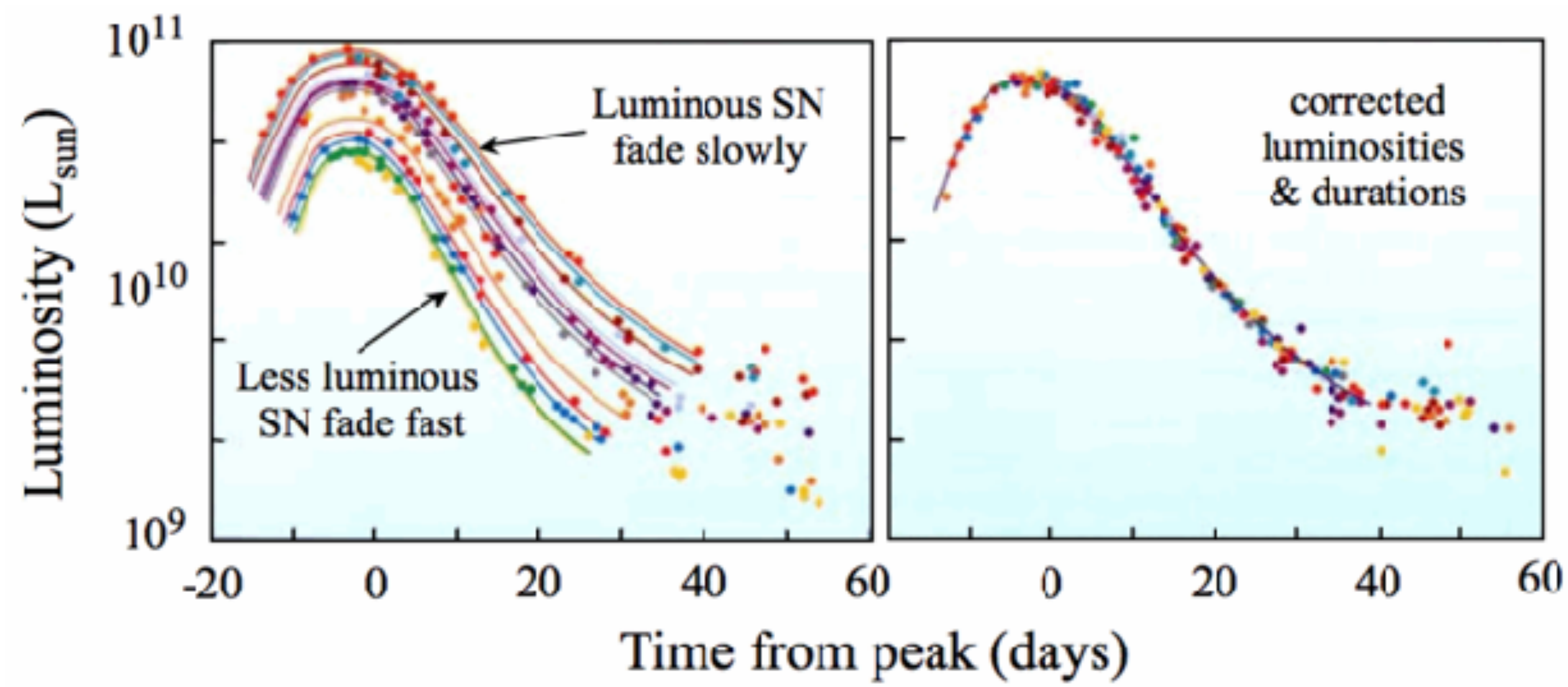
Type Ia Supernovae: "standardizable candles"

Type Ia (pronounced like "one-A") Supernovae are a specific type of hydrogen-deficient explosion from white dwarf stars that grow too massive.

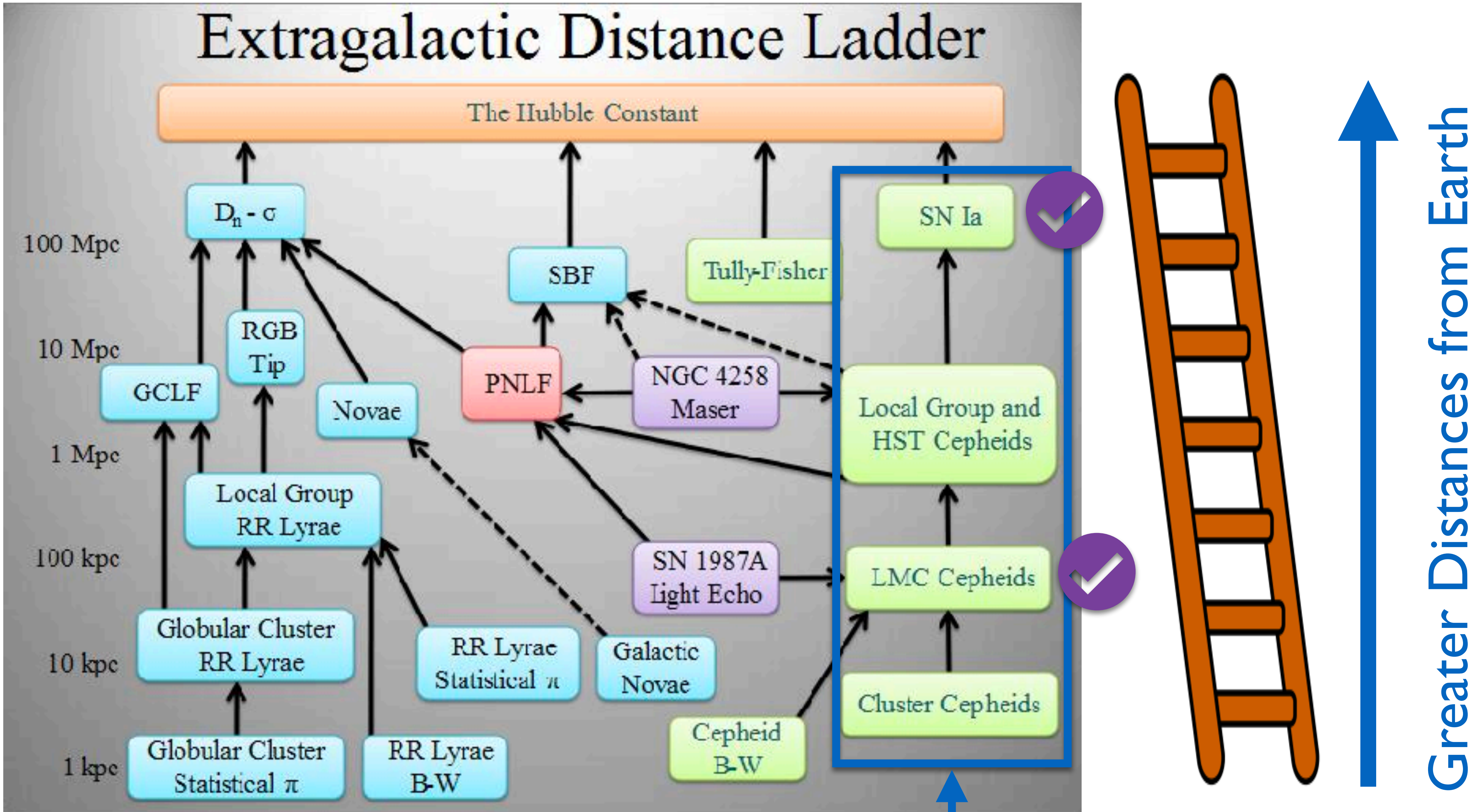
Their light curves can be standardized by the width of their rise and fall.

We can then infer their absolute luminosities, and hence their distances!

Supernovae are extremely bright, and can be observed from great distances across the Universe.



The Cosmic "Distance Ladder"



https://en.wikipedia.org/wiki/Cosmic_distance_ladder

Trigonometric Parallax

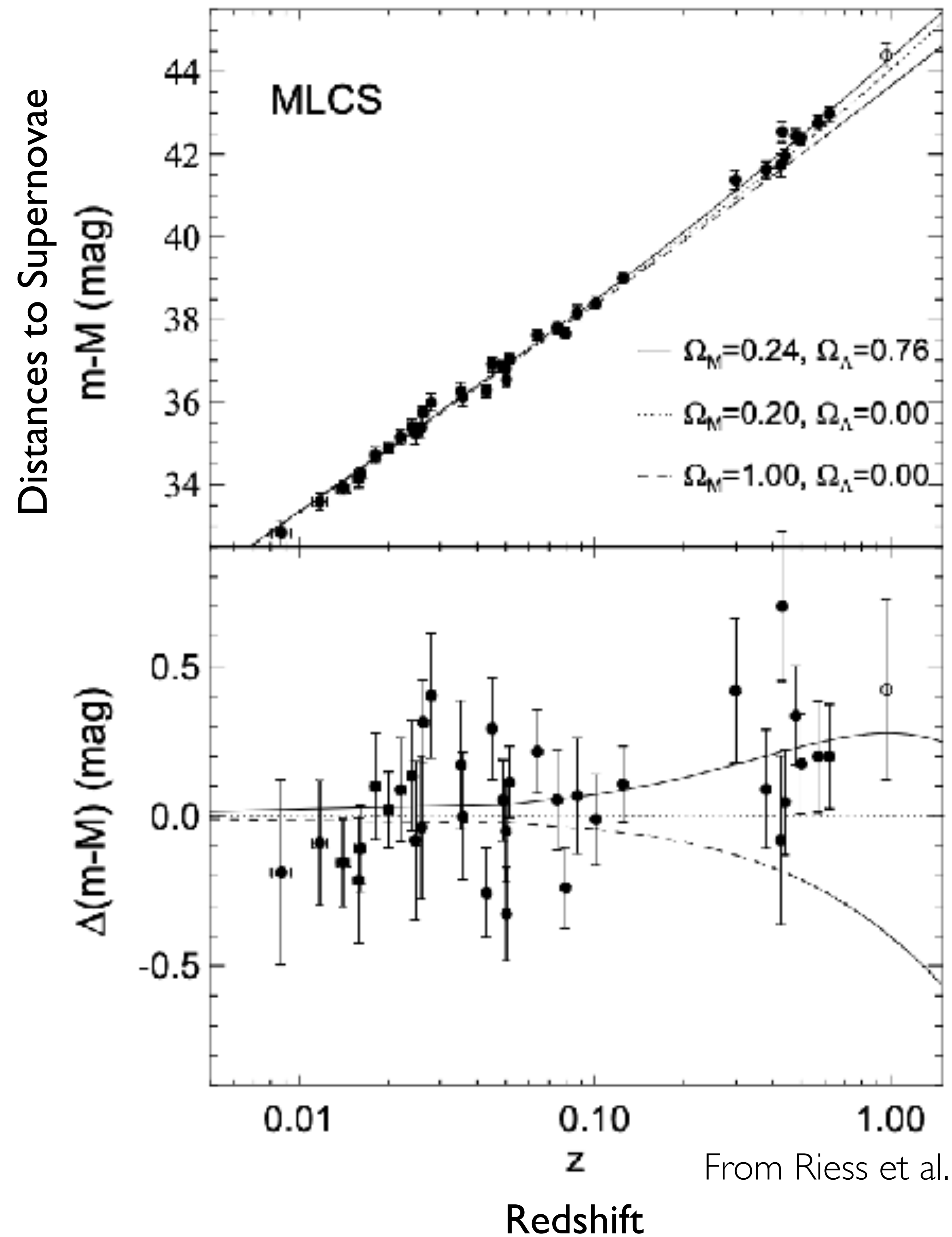
The accelerating Universe

Distant supernovae are a bit further away than we would expect if the expansion rate were not changing.

The data suggest the expansion rate is currently accelerating.

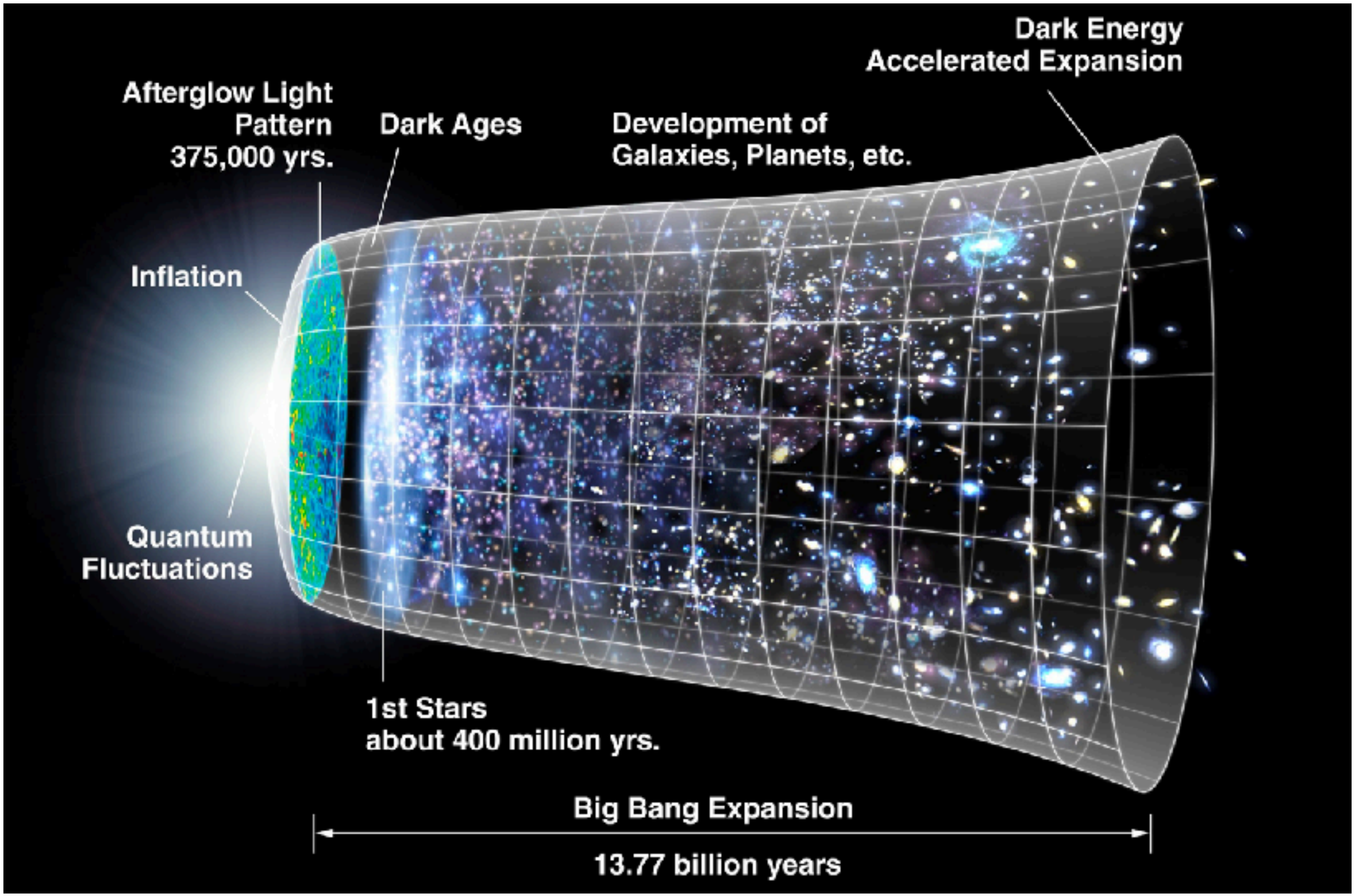
This discovery was recognized with the 2011 Nobel Prize in Physics.

We don't know what is causing this acceleration, but refer to it as "Dark Energy".



From Riess et al. 1998

The accelerating Universe



NASA/WMAP Science Team