



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

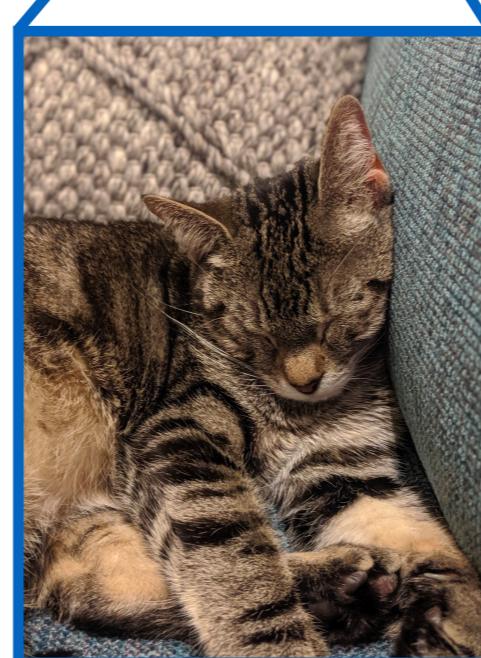
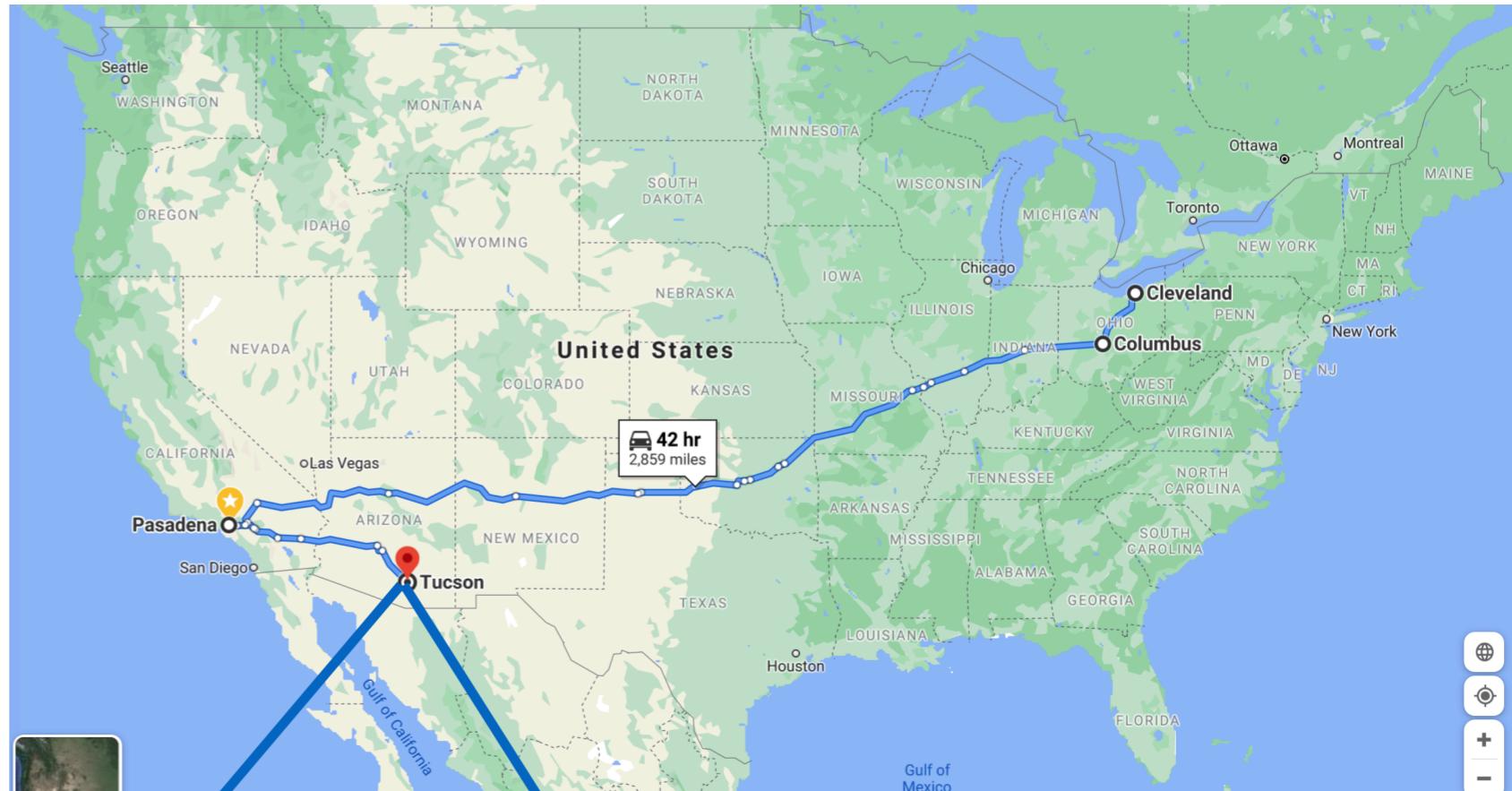
Jacob Jencson  
U of Arizona

AST 296LB  
Pima Community College

# Who am I?

Jacob Jencson

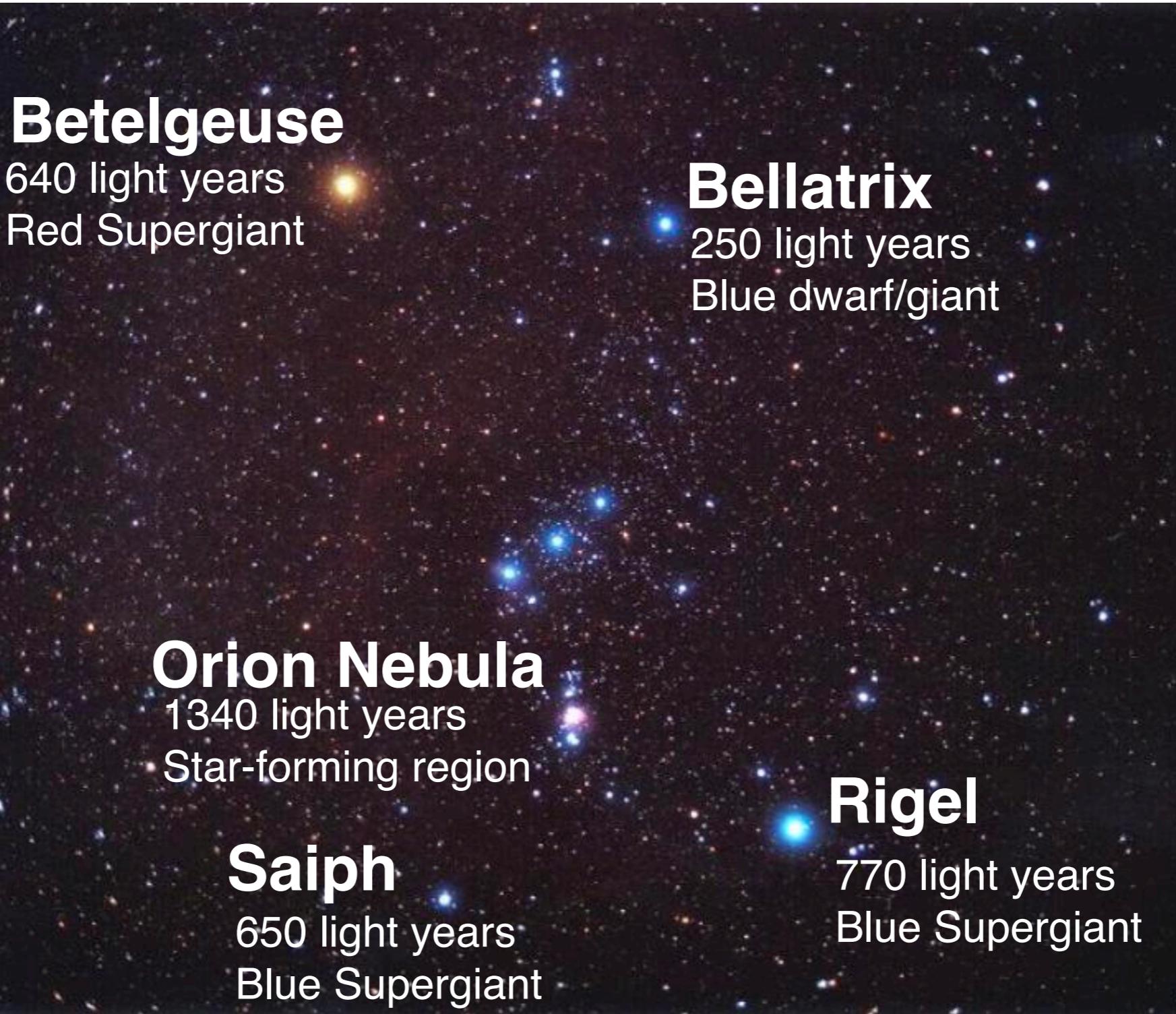
- Did my undergrad in Physics and Astronomy at Ohio State (2009-2014)
- PhD at Caltech (2014-2019)
- On my first postdoc position at the U of A.
- Right now in CA, but I usually live in Tucson with my cat, Turnip
- Interested in all kinds of stellar eruptions and explosions.



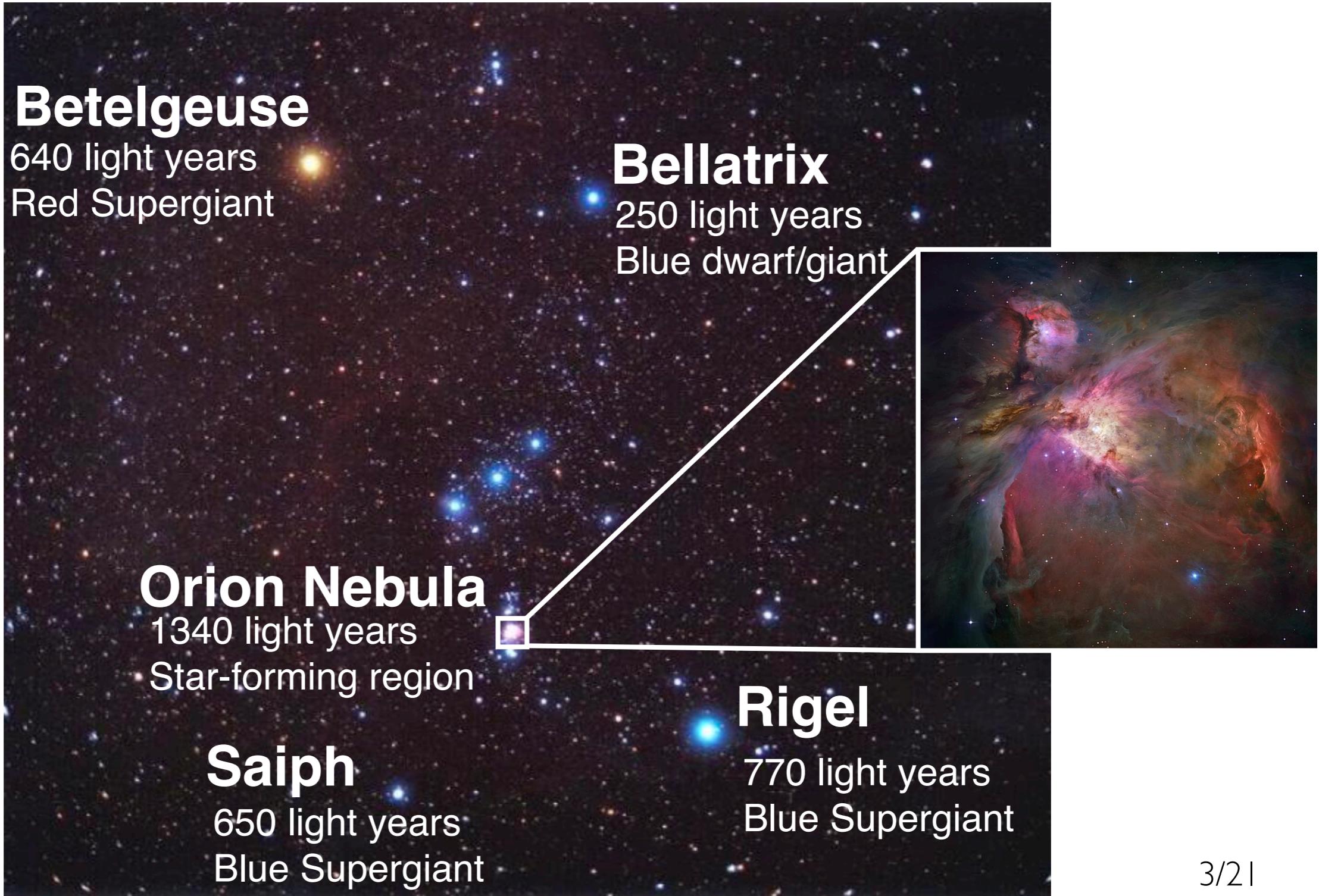
**Our view of the sky is 2D...  
but the Universe is 3D**



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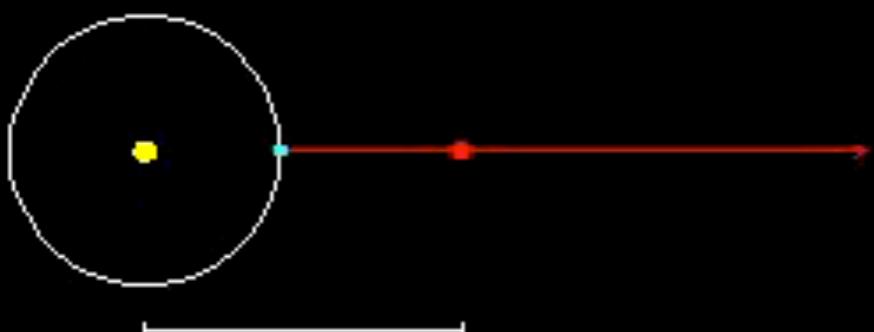
# **How do we measure distances to stars?**

# How do we measure distances to stars?

## Trigonometric Parallax



1998 Dec 31

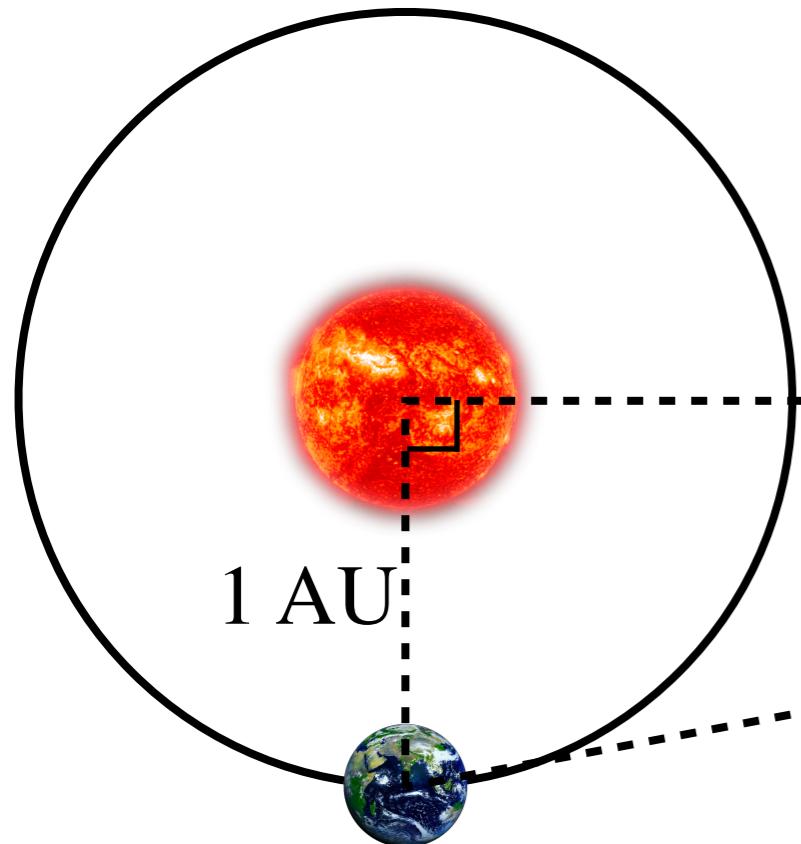


The apparent motion of stars on the sky as the Earth travels in its orbit around the Sun.

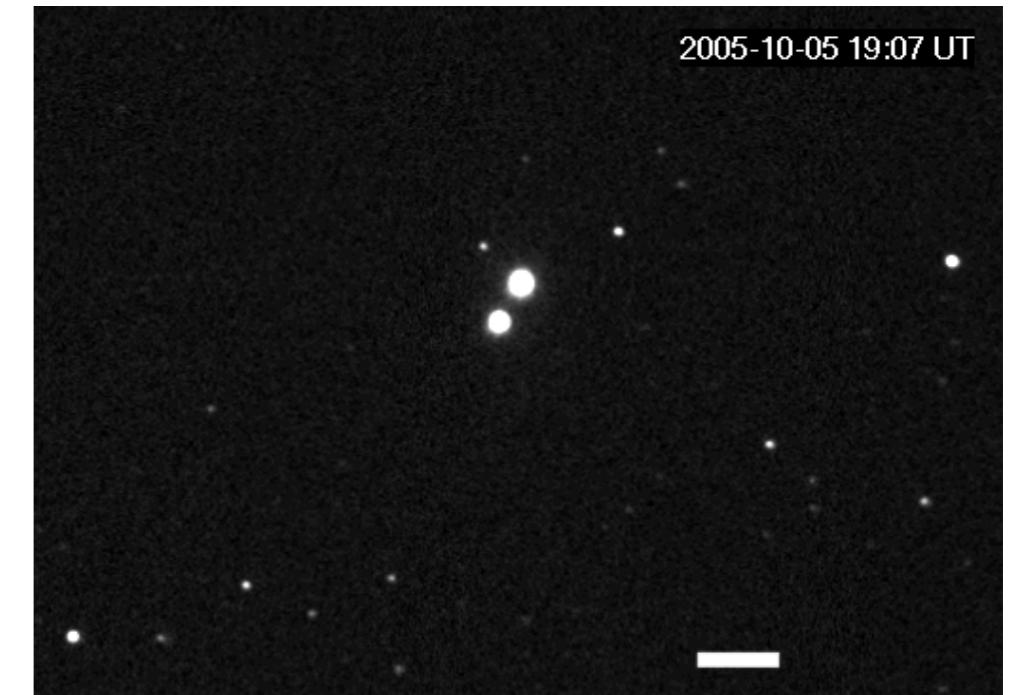
This effect is larger for objects that are closer to the Earth, allowing us to infer their distance.

# How do we measure distances to stars?

## Trigonometric Parallax



AU = “Astronomical Unit”  
 $= 1.5 \times 10^{13} \text{ cm}$



2005-10-05 19:07 UT

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

# 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 ( $^{\circ}$ )

60 arcminutes ( $'$ ) per degree

60 arcseconds ( $''$ ) per arcminute

Conversion to radians

$$l'' = l/(60 \times 60) \text{ deg} \times (\pi/180)$$

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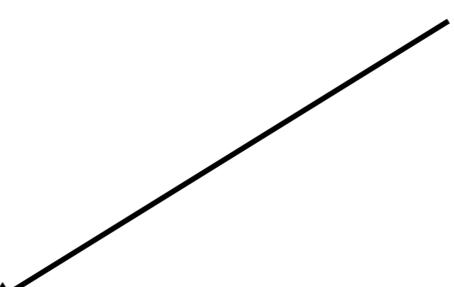
Conversion to radians

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So for a parallax angle of  $l''$ :

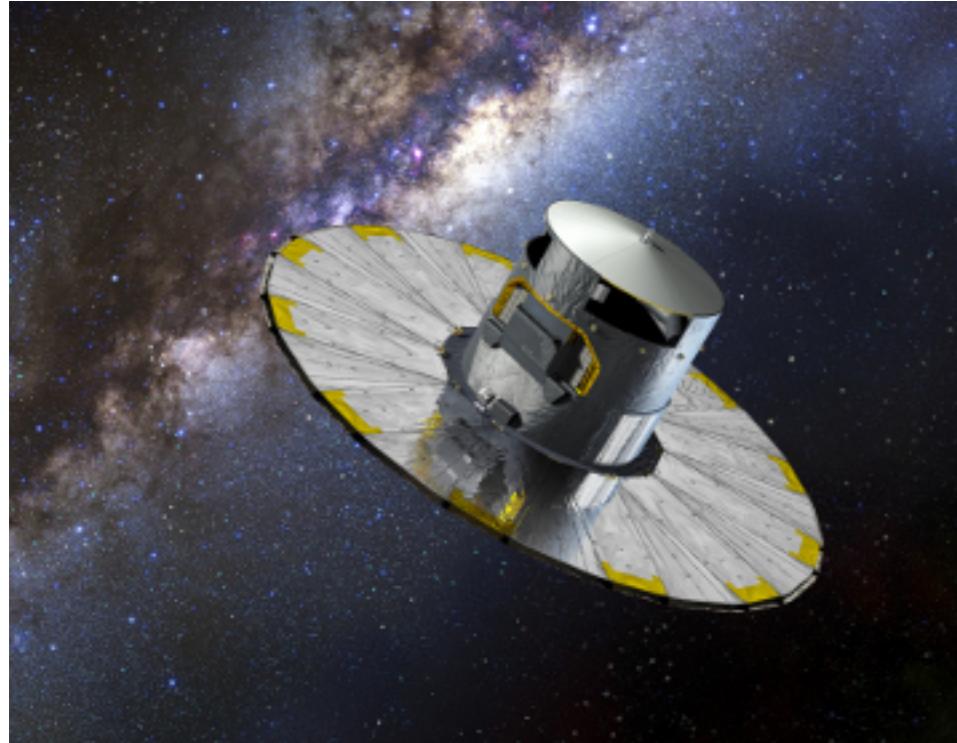
$$d = \frac{1 \text{ AU}}{1''} = \frac{1 \text{ AU}}{(1/206265 \text{ radians})} = 206265 \text{ AU} = 3.086 \times 10^{18} \text{ cm}$$

$\equiv 1 \text{ parsec or “parallax arcsecond”}$   
 $= 3.26 \text{ light years}$

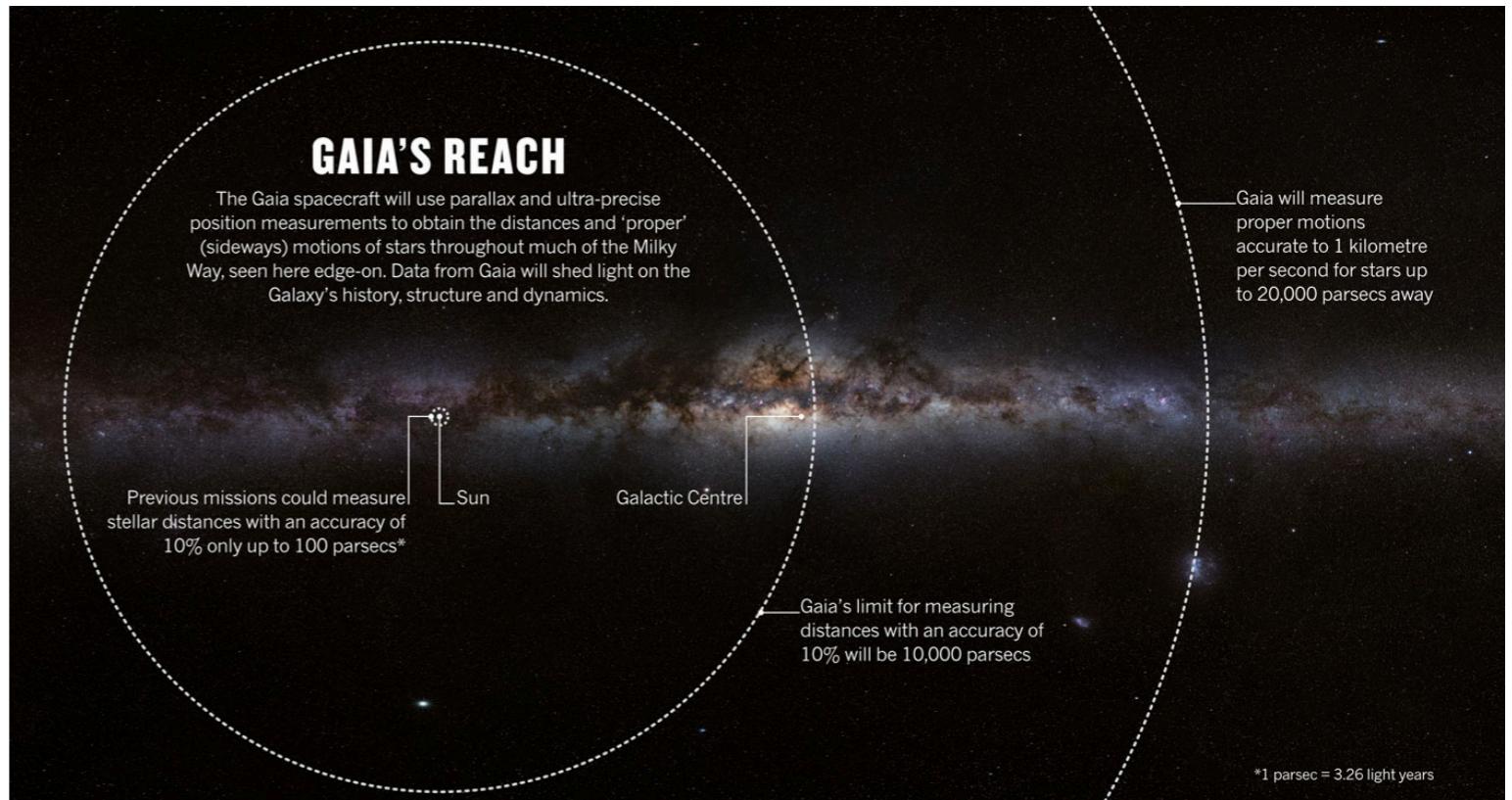


# How do we measure distances to stars?

## Trigonometric Parallax



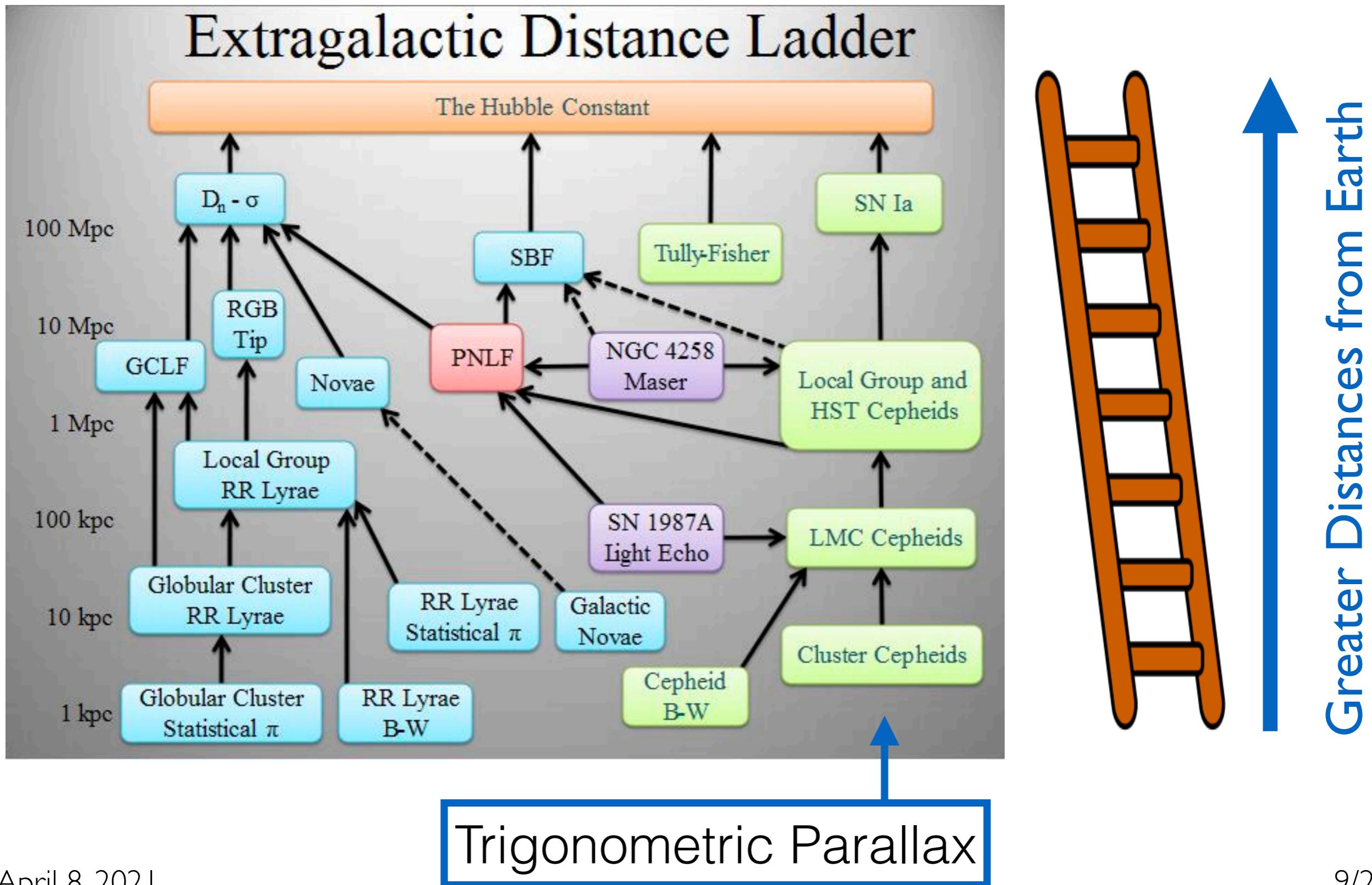
Gaia satellite is current state of the art



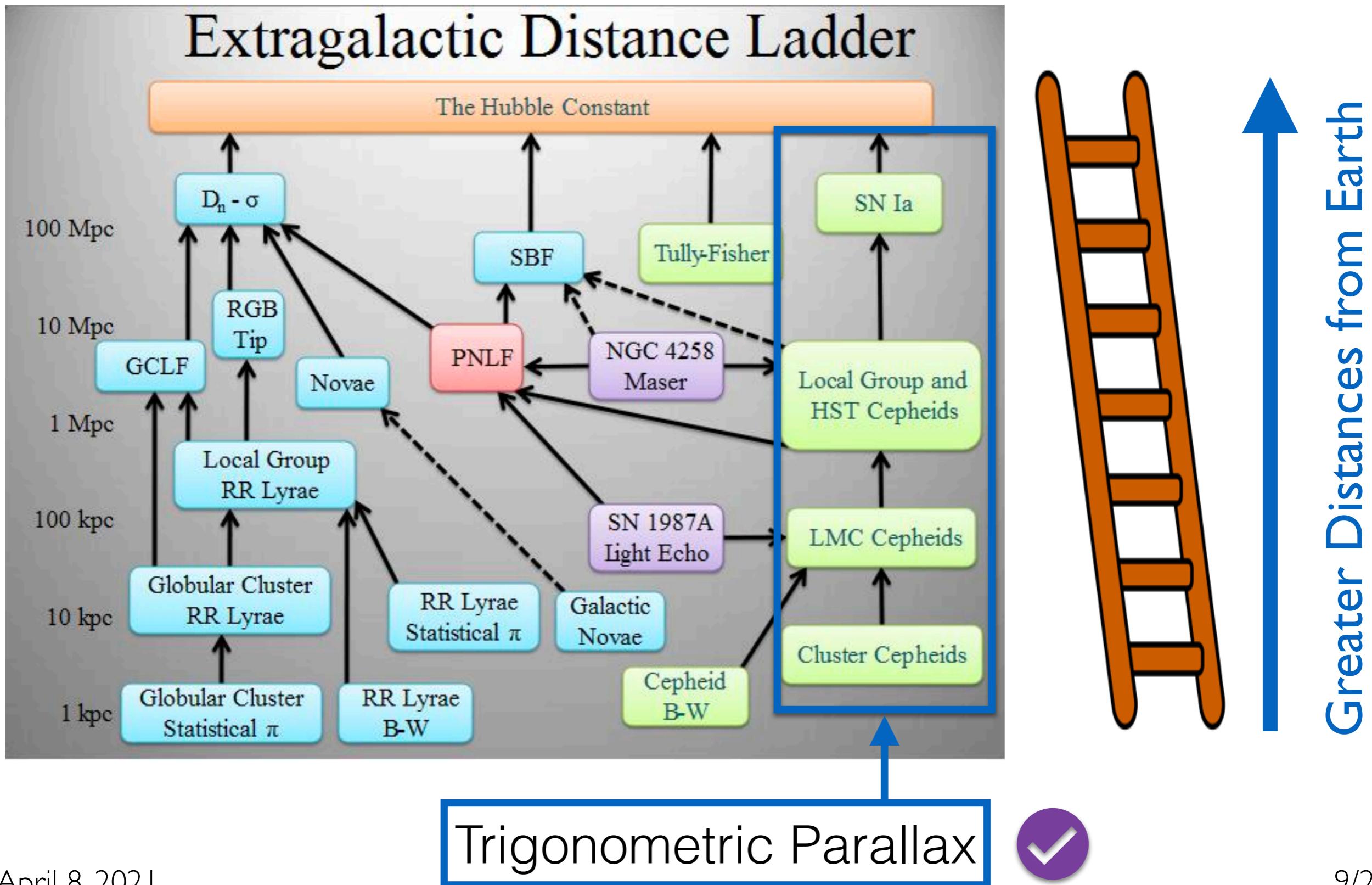
**How to we get to larger  
distances?**

**... We build a ladder!**

# The Cosmic “Distance Ladder”



# The Cosmic “Distance Ladder”

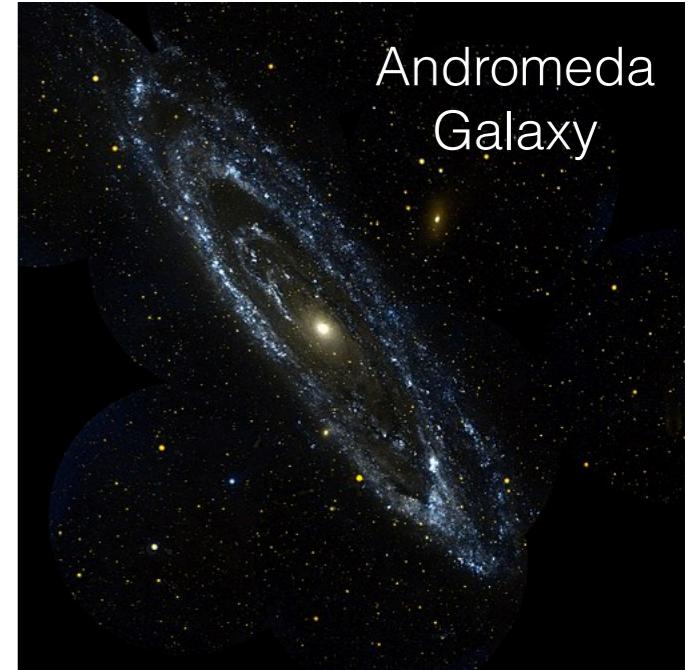


# A little bit of history

## 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

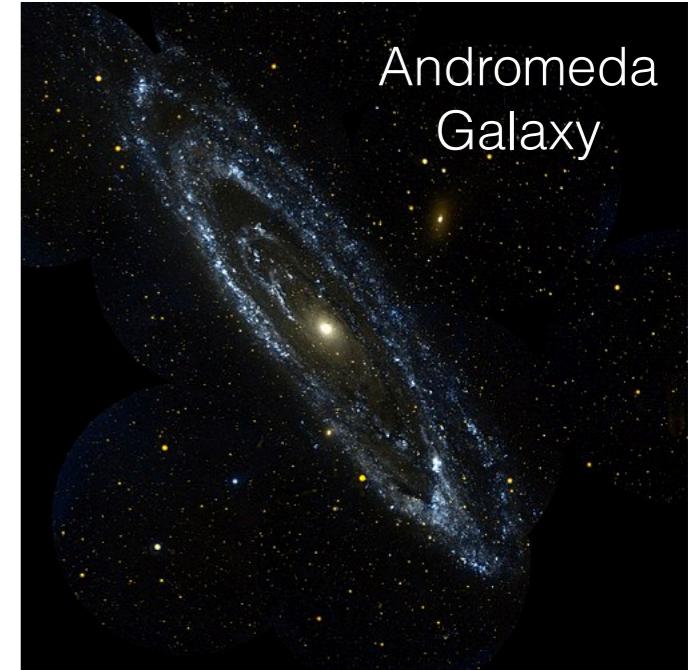
- Andromeda has more novae than the entire Milky Way
- Andromeda has dark lanes of dust similar to those in the Milky Way
- Concluded they are “Island Universes” external to the Milky Way**

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actually  
“supernovae”

VS

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# **But how were these vast distances actually measured?**

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

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Recall from last week...

apparent magnitude

absolute magnitude

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

distance modulus

distance of  
the star (pc)

$$m - M = 5 \log_{10} \left( \frac{d}{10} \right)$$

apparent  
magnitude

absolute  
magnitude

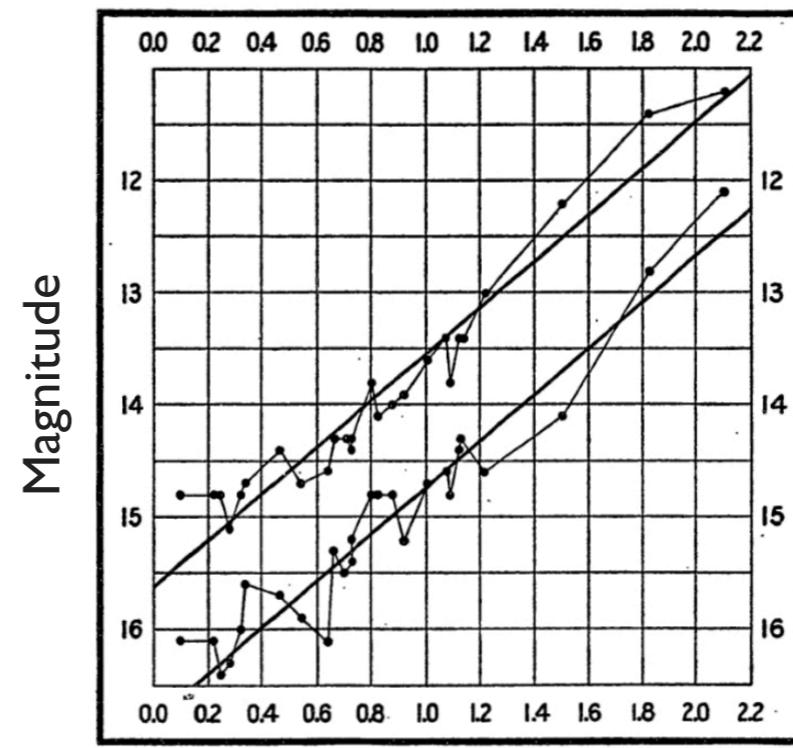
# **Henrietta Swan Leavitt and Cepheid variables**



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...

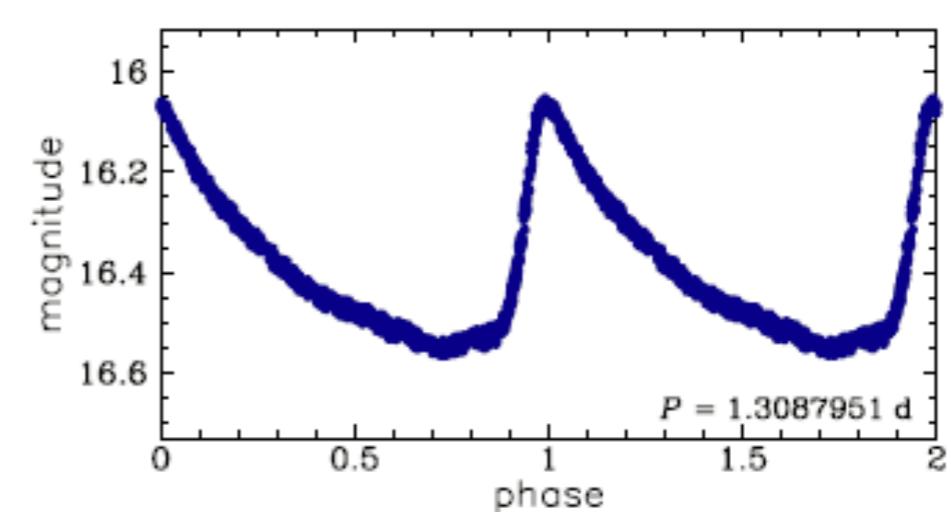
# Henrietta Swan Leavitt and Cepheid variables



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



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

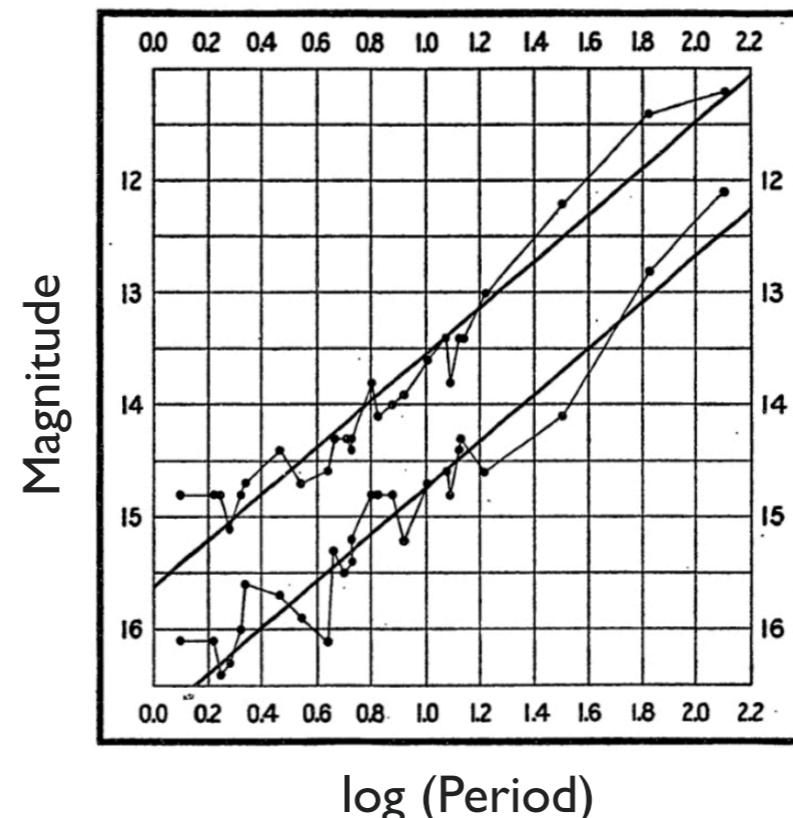


$$m - M = 5 \log_{10} \left( \frac{d}{10} \right)$$

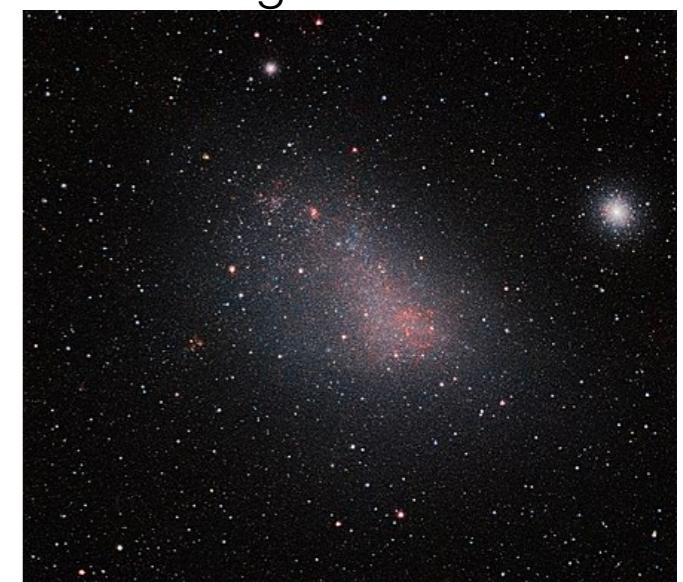
distance modulus  
apparent magnitude  
absolute magnitude  
distance of the star (pc)



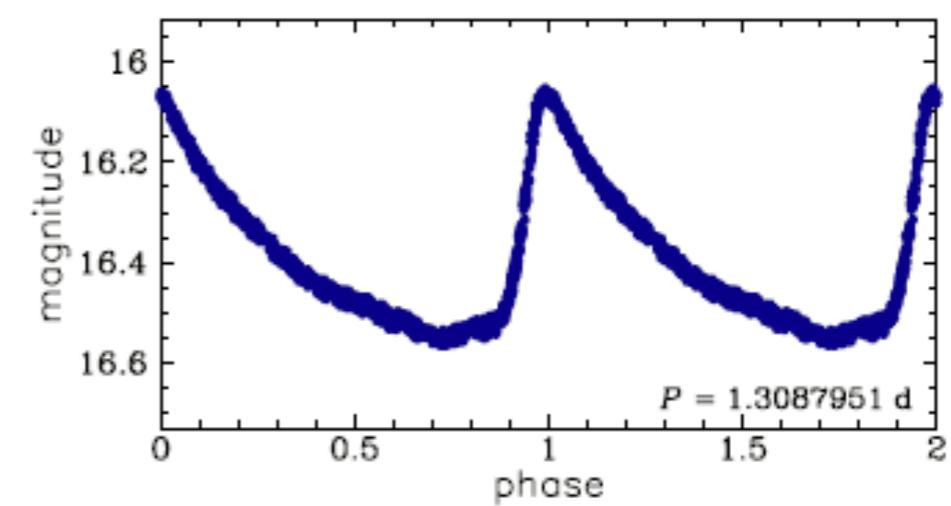
You can measure its distance!



Small Magellanic Cloud



log (Period)



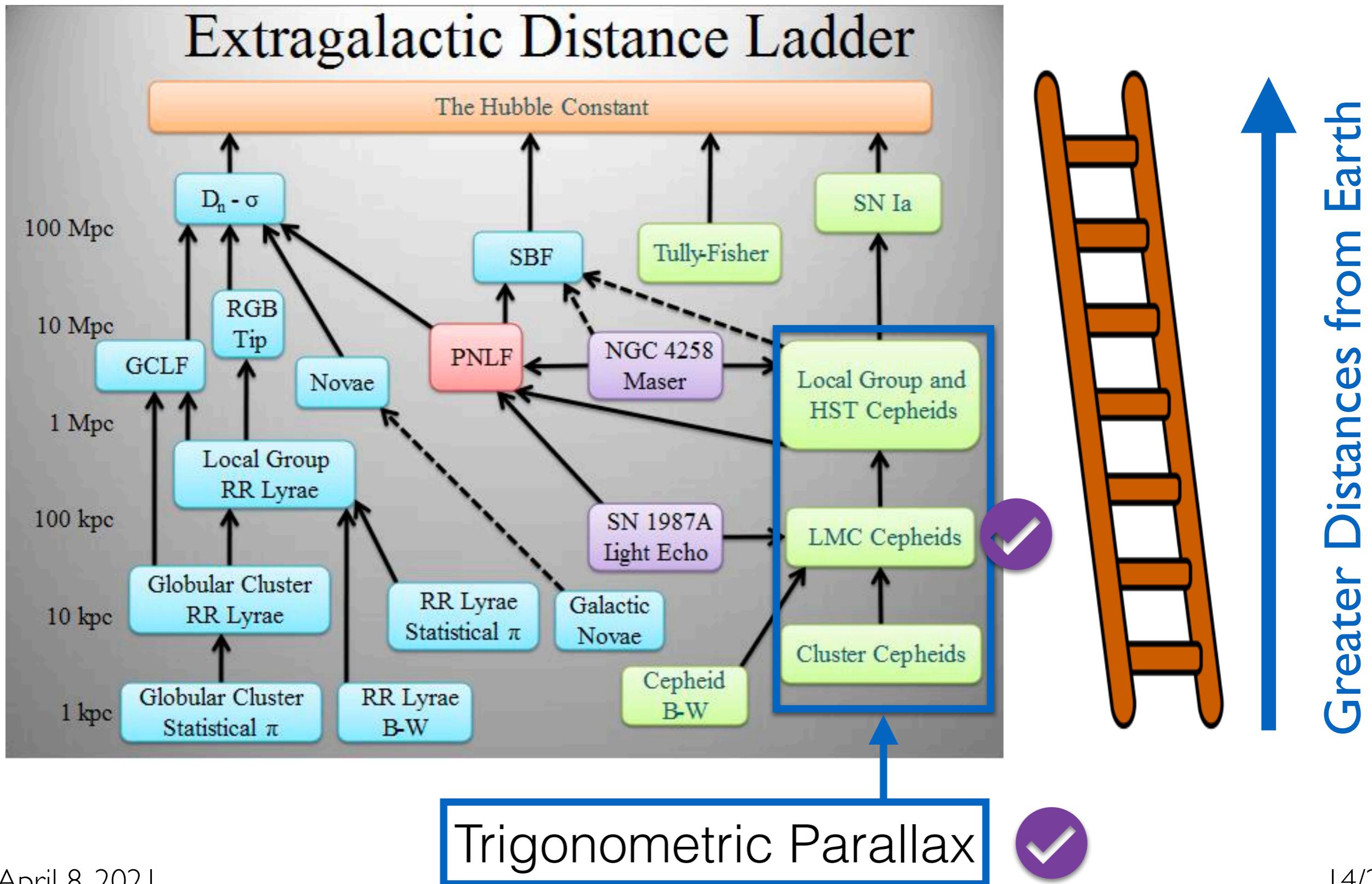
# **Henrietta Swan Leavitt and Cepheid variables**

The Cepheid Period-Luminosity relation, or “Leavitt’s Law” can be calibrated by 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)

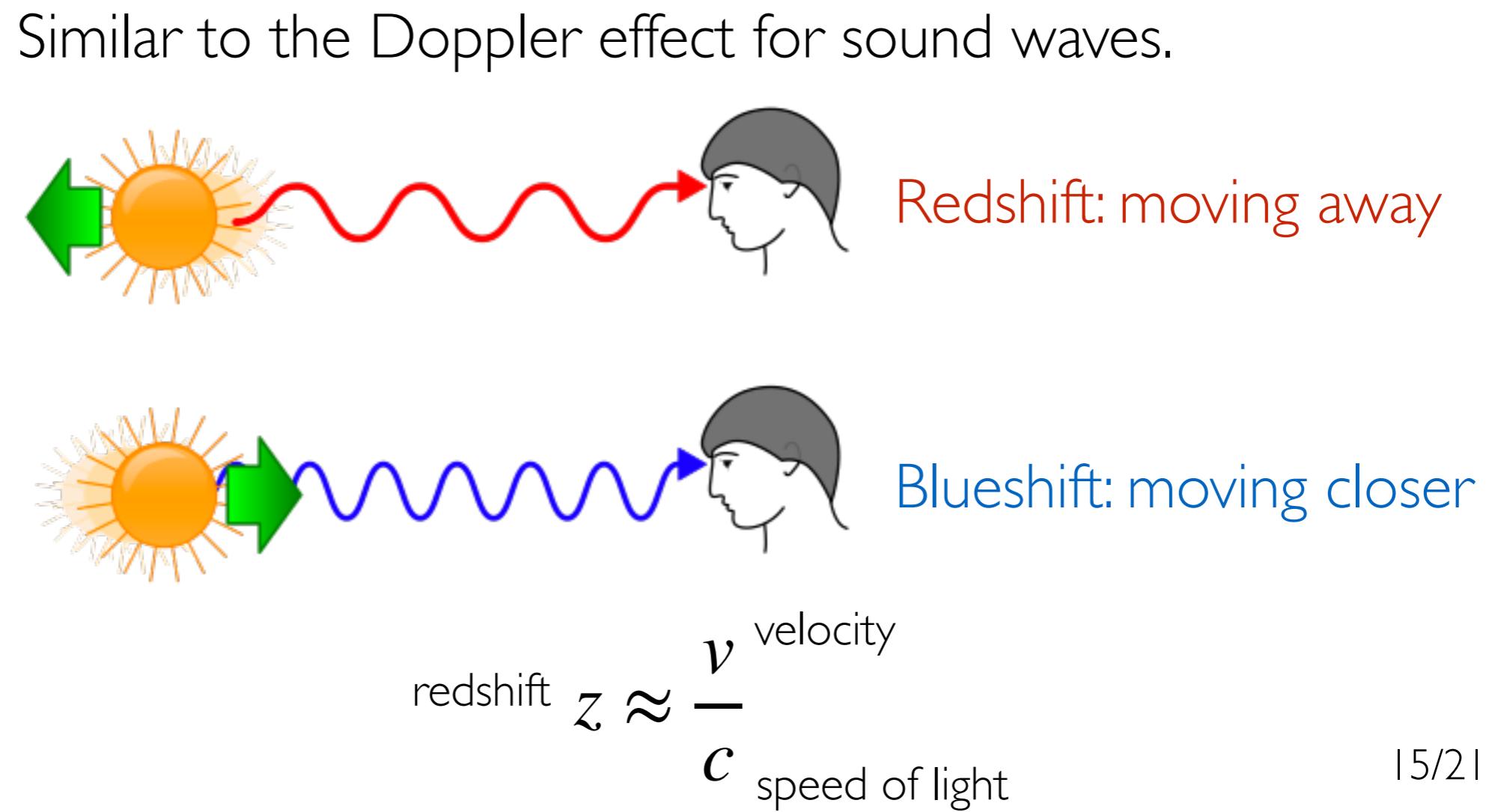
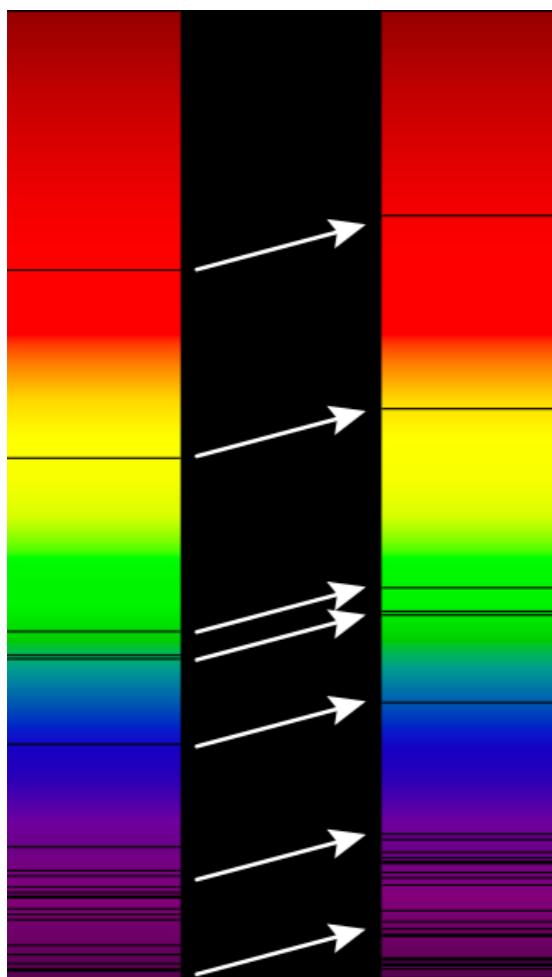
# The Cosmic “Distance Ladder”



# 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

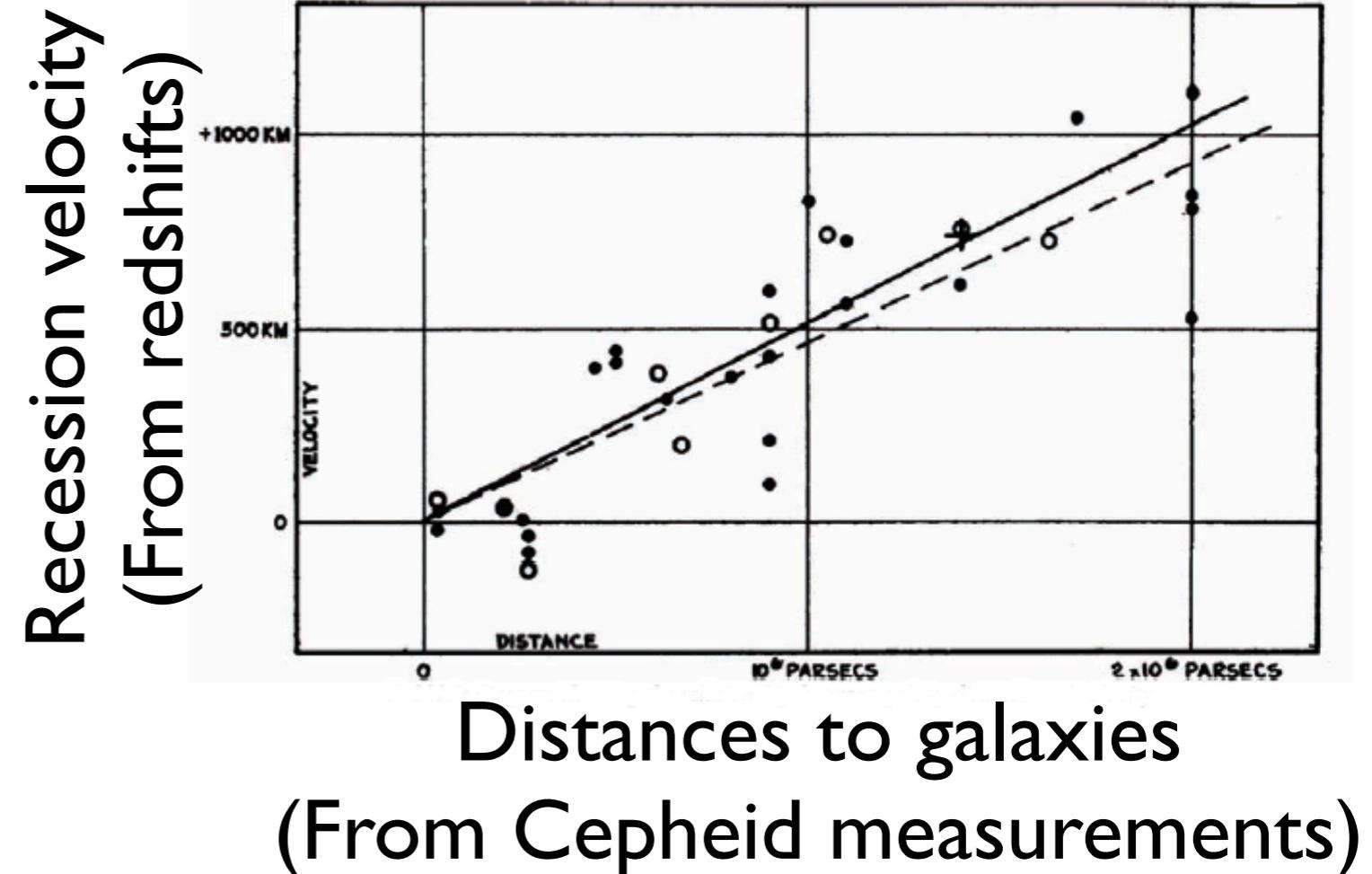


# Edwin Hubble and the Expanding Universe



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!**



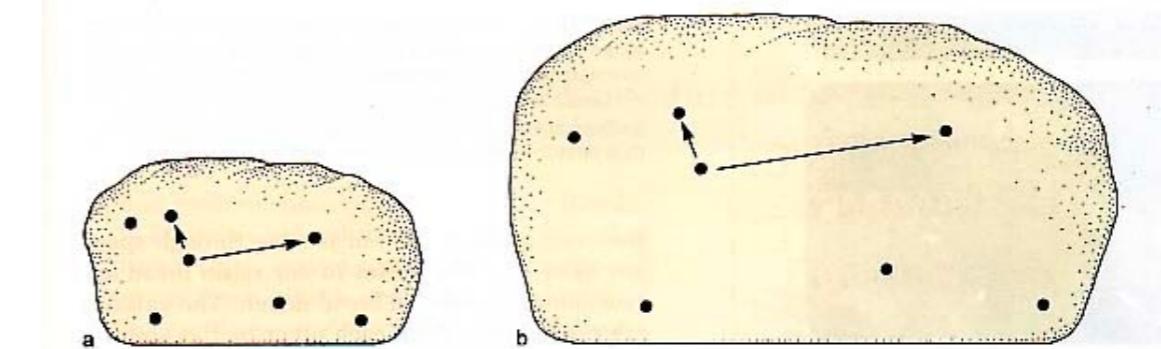
Distances to galaxies  
(From Cepheid measurements)

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  $\sim 500$  km/s
- This was wrong by almost a factor of 10 due to errors in the distance calibration
- Today the best measurements are  $\sim 70$  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 expanding bread:

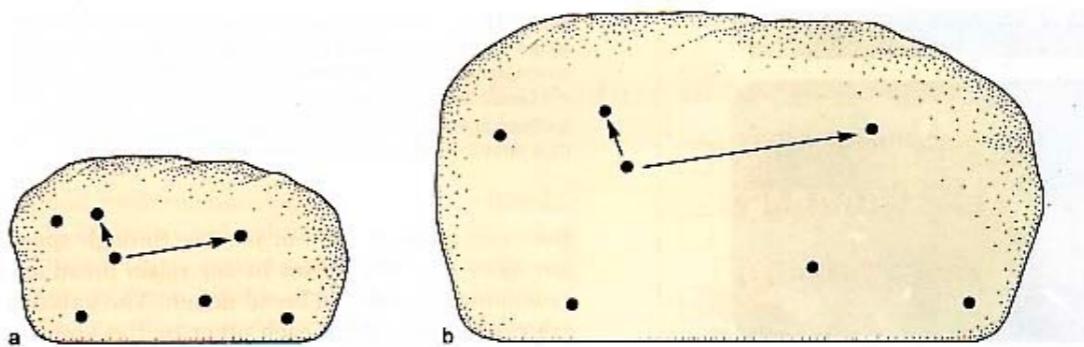


The space between any pairs of galaxy grows with time. From the vantage point of any galaxy, all others appear to be moving away.

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

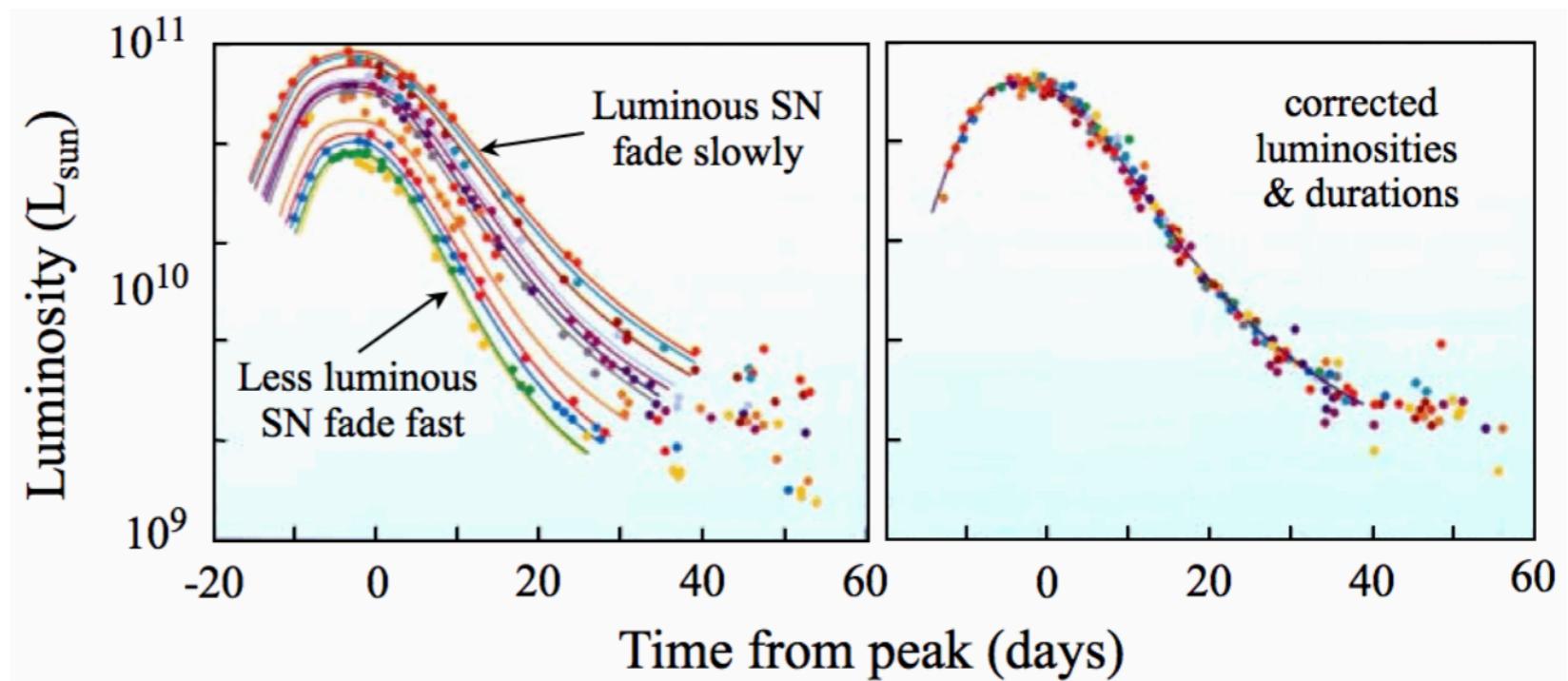
# Type Ia Supernovae: “standardizable candles”

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

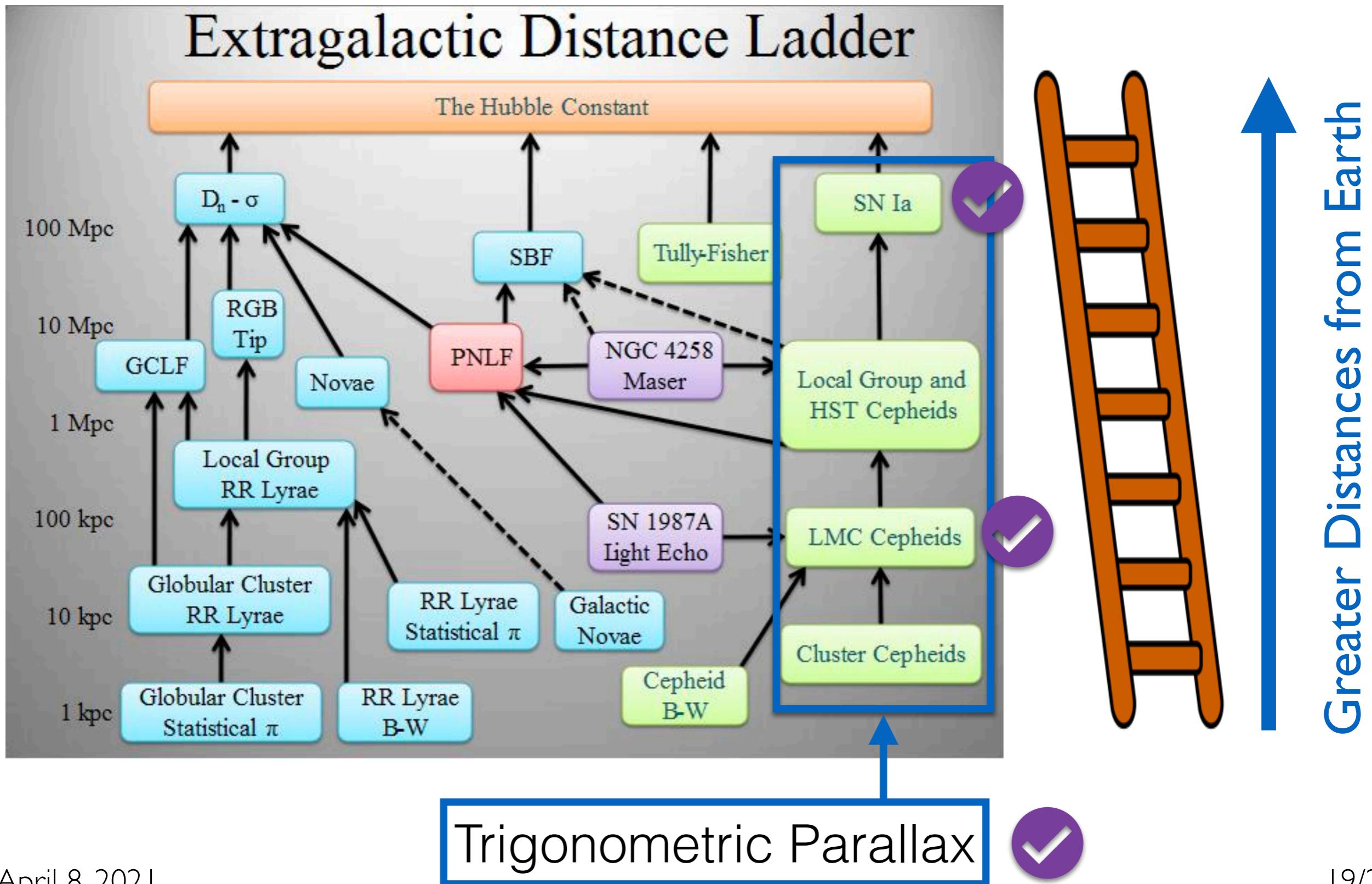
Their light curves can be standardized by the width of their rise and fall.

**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”



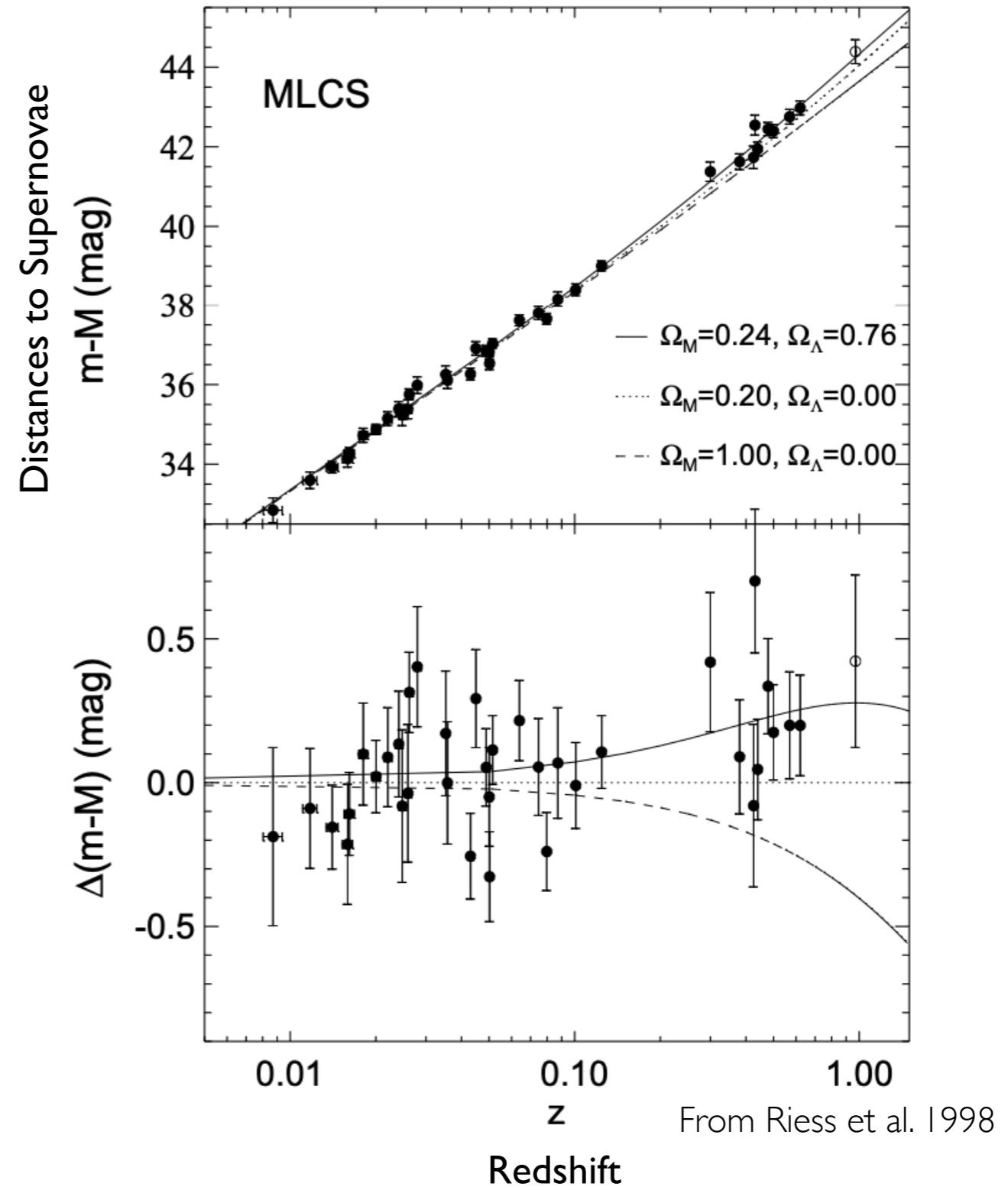
# The accelerating Universe

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".



# The accelerating Universe

