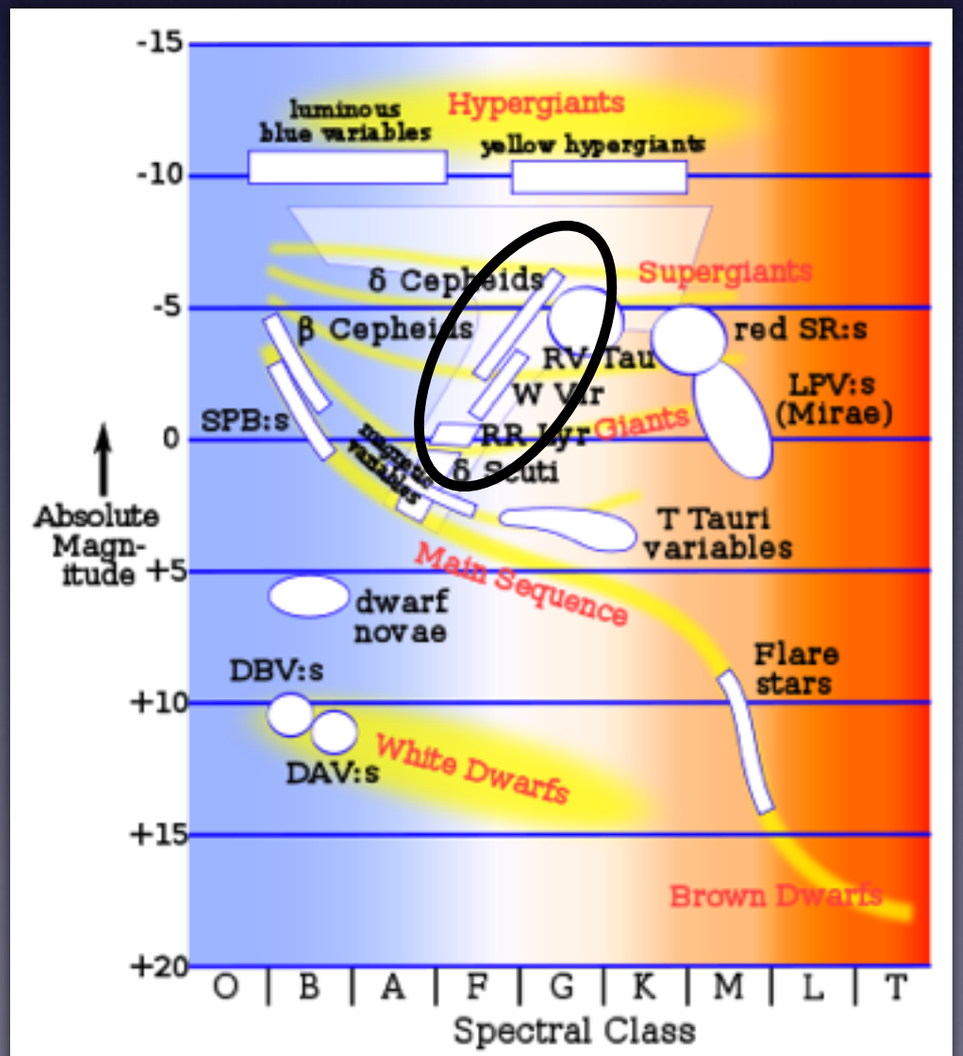
The Cosmic Distance Ladder

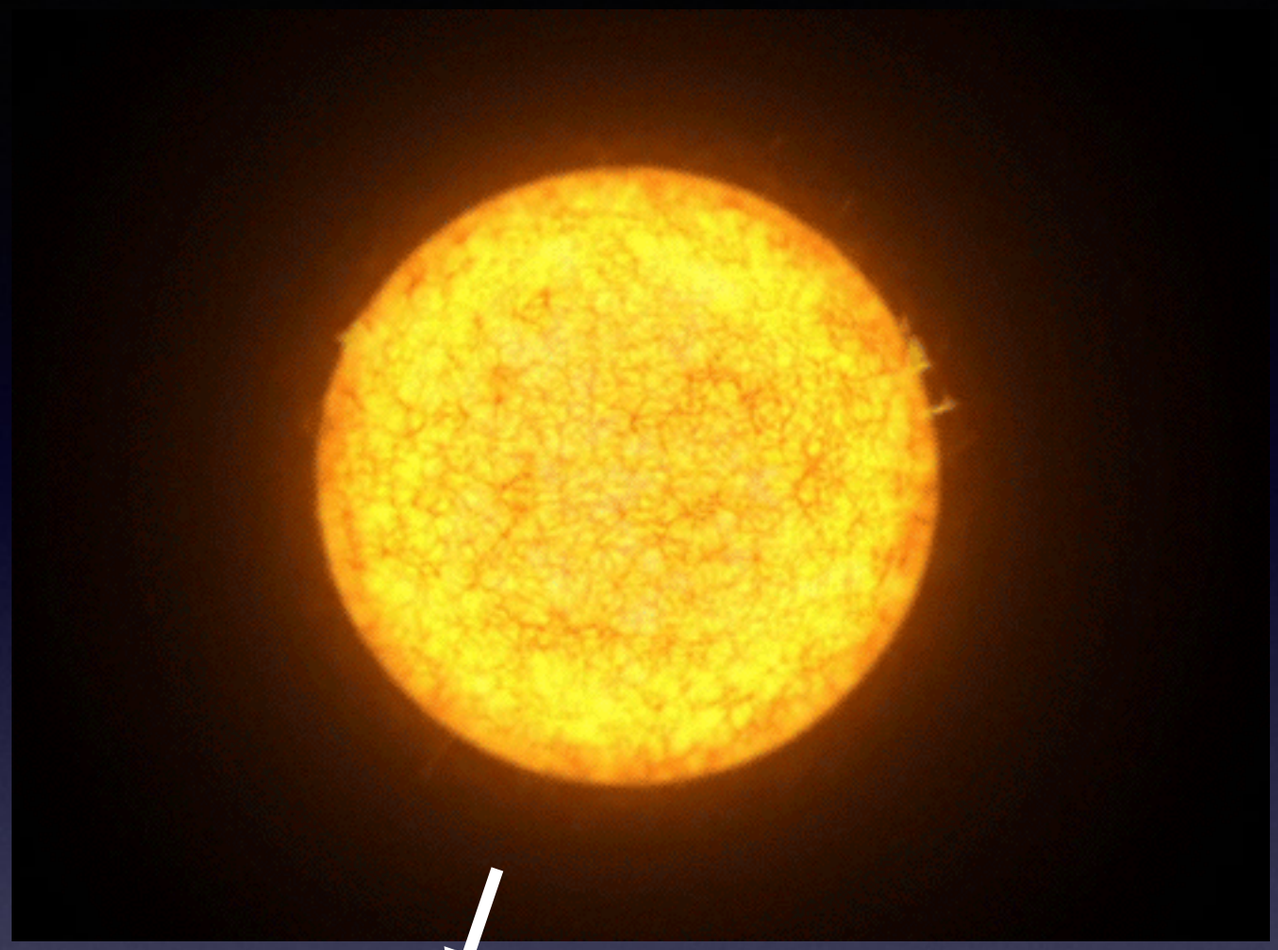
Hubble's Law and the Expansion of the Universe!

Last time: looked at **Cepheid Variable** stars as standard candles.

What ARE cepheid variables?

Massive, off-main sequence stars: at a certain stage between main sequence and red supergiant they are unstable and pulsate. It turns out that pulsation is dependent on the underlying luminosity of the star (outward pressure)





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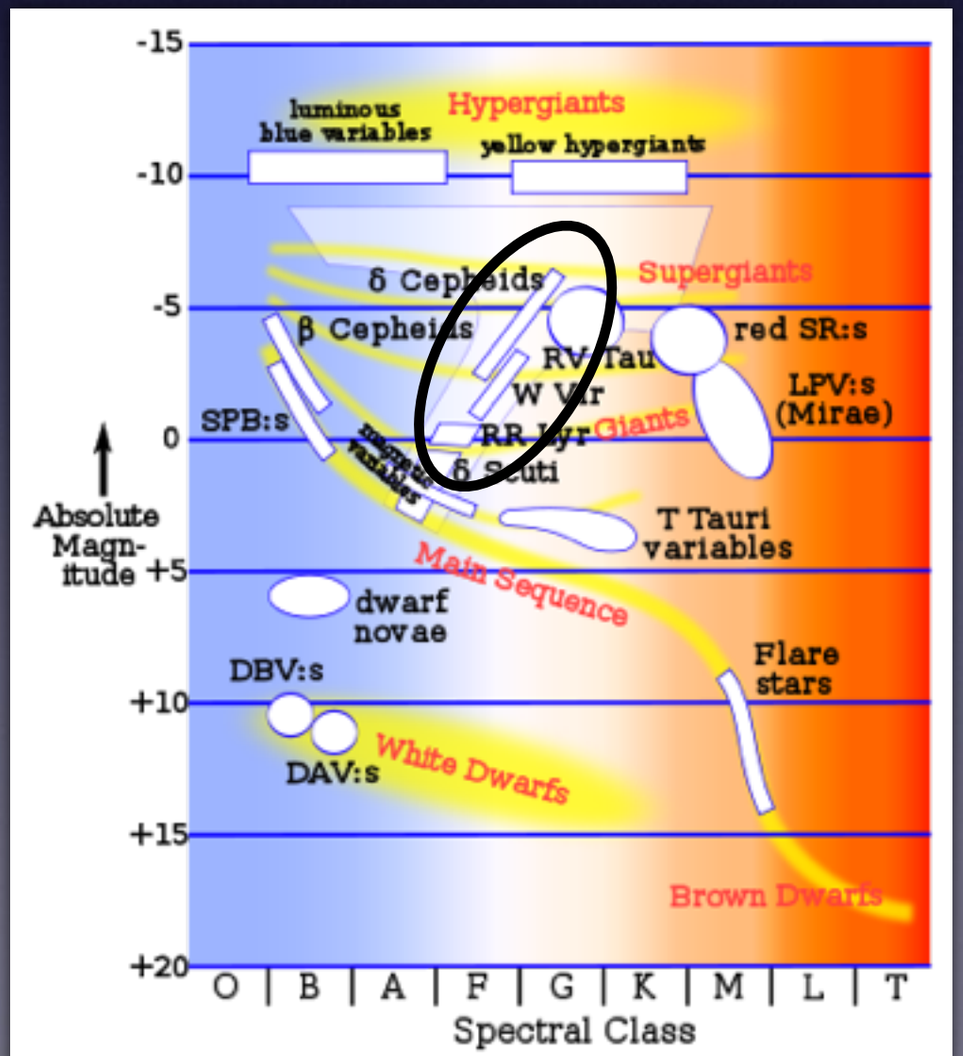
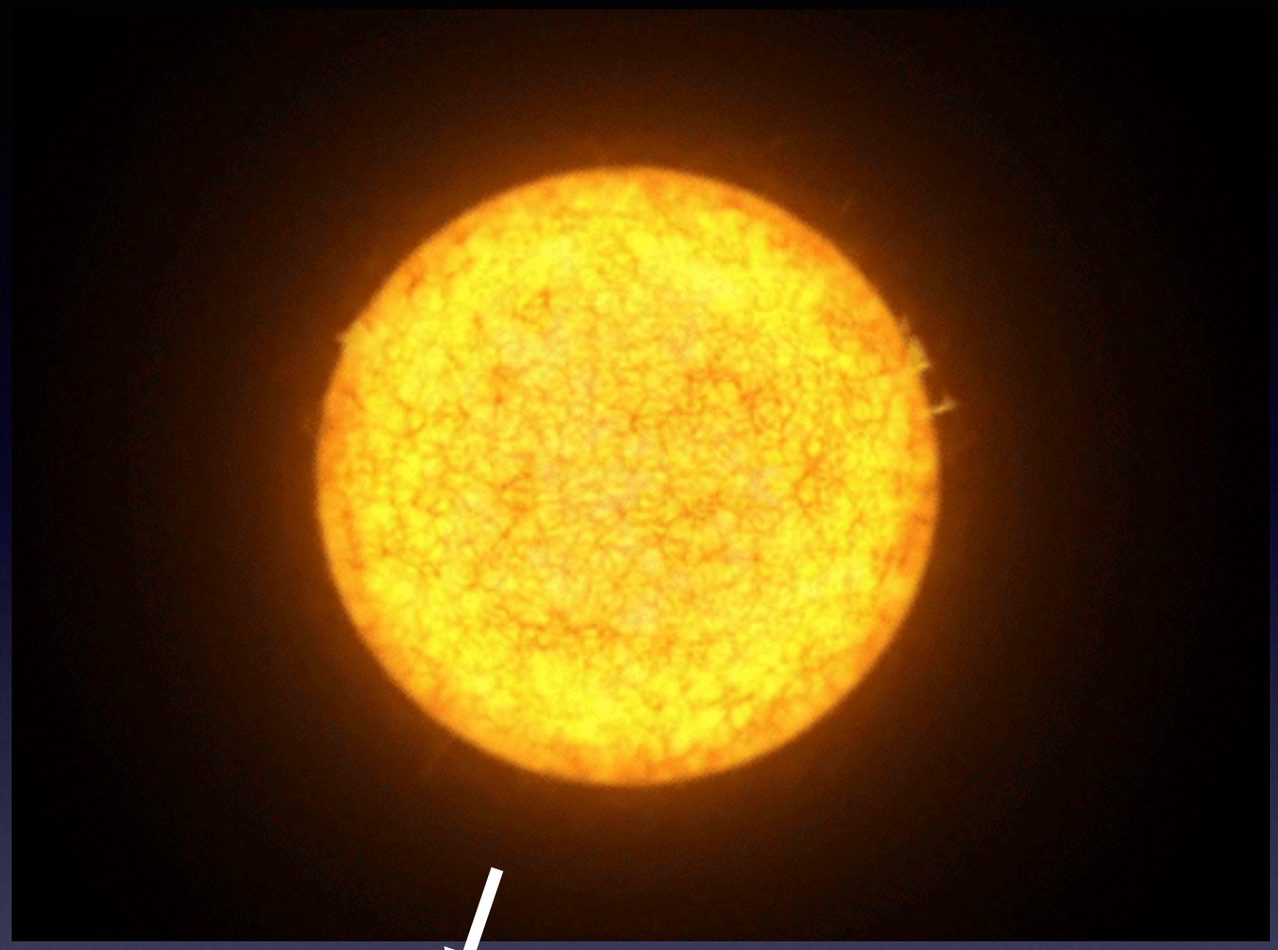
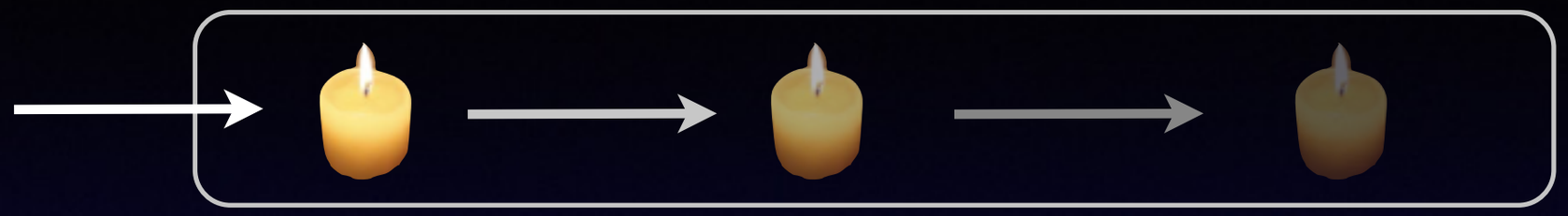


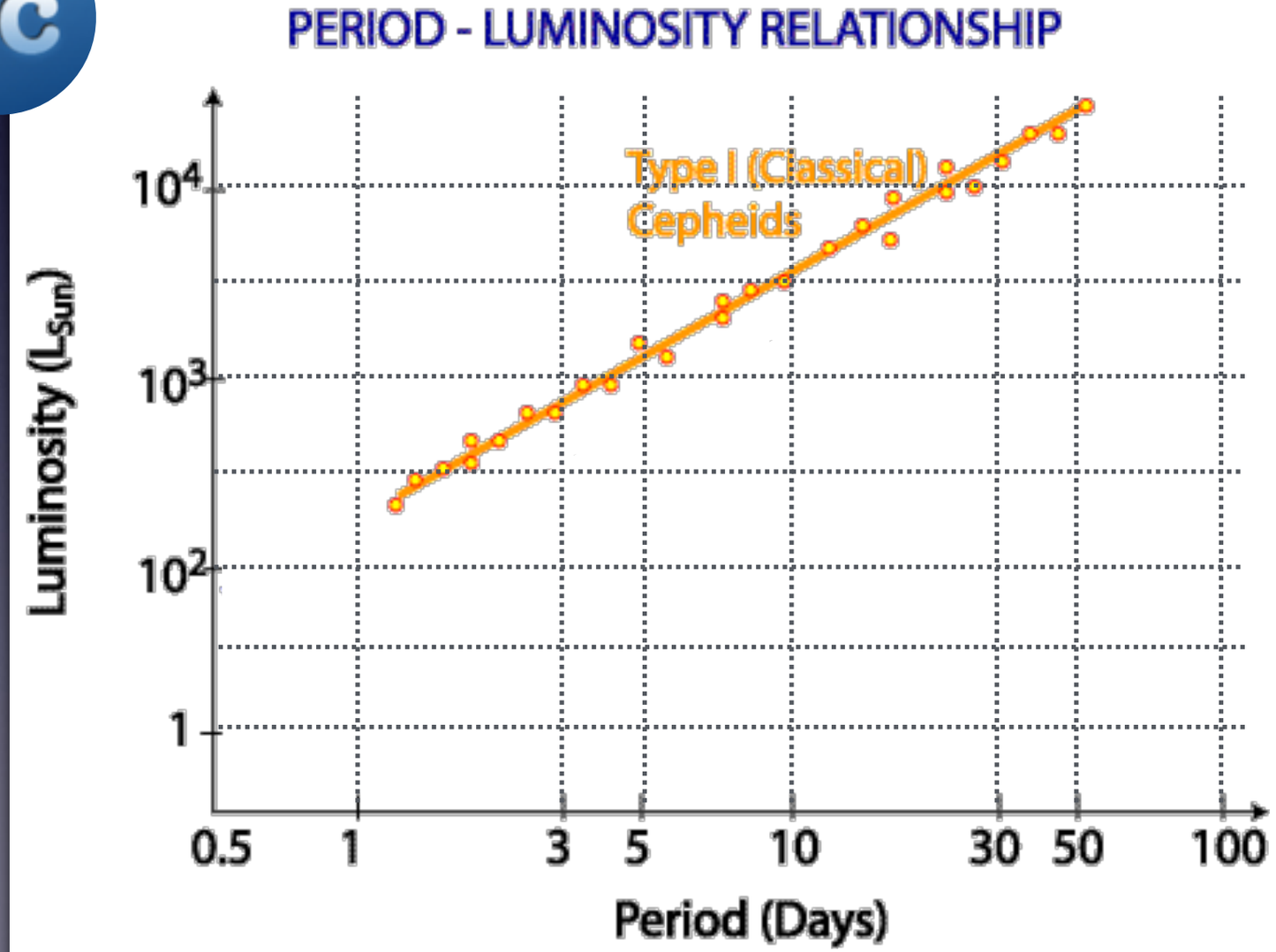


Cepheid Variable stars show a period luminosity relationship.



If we observe a cepheid variable with a 4 day pulsing period and a flux of 1.985×10^{-12} W/m², how far away is it in parsecs? (Recall $L_\odot = 3.8 \times 10^{26}\, W$ and $1\, pc = 3.086 \times 10^{16}\, \mathrm{m}$)

_____ **pc**



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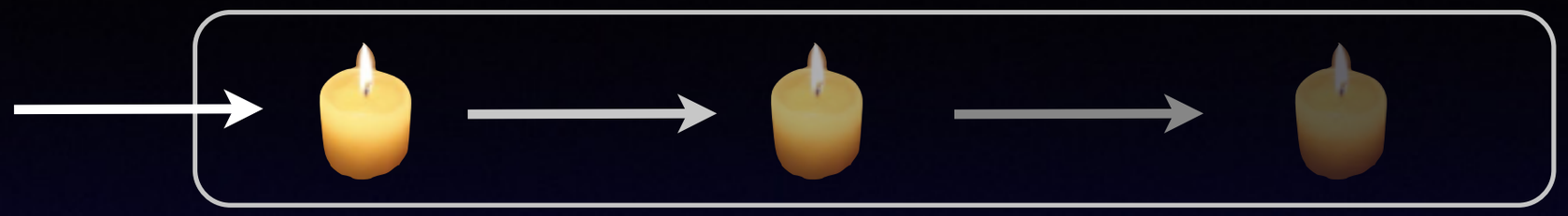

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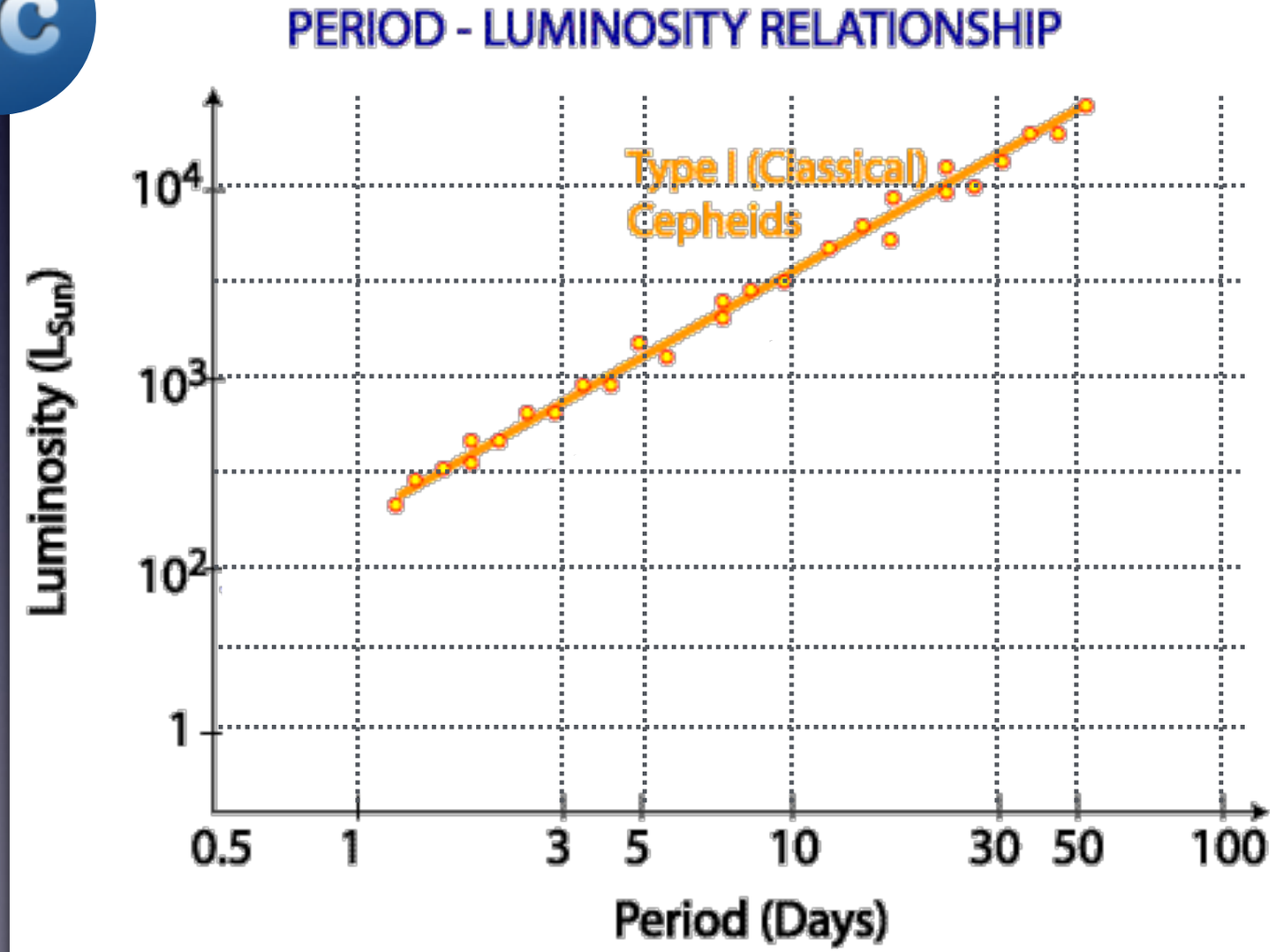
4000 pc



Cepheid Variables aren’t the only standard candles in the Universe:
Meet the MUCH brighter and much more rare Type Ia supernovae / White Dwarf Supernovae

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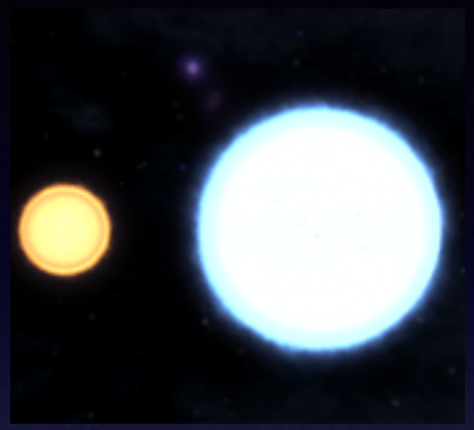
There's a binary star system…



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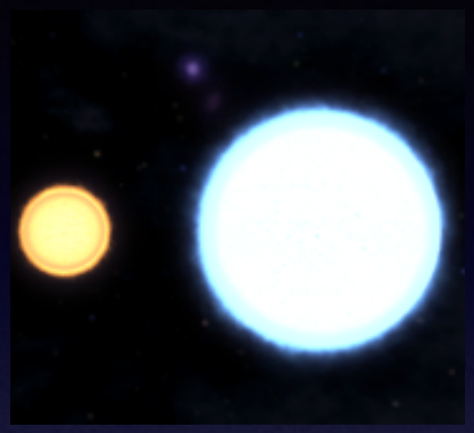

One of those stars turns into a white dwarf! The other could be quite close start "feeding" the white dwarf material as it goes into a giant phase…

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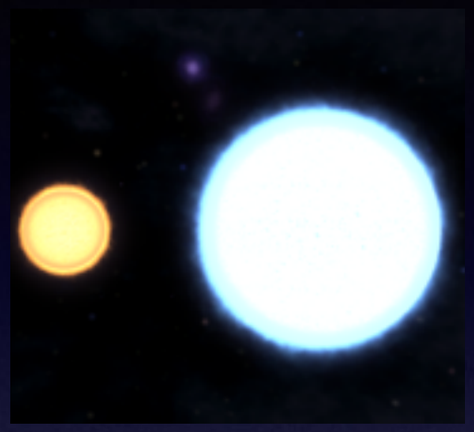

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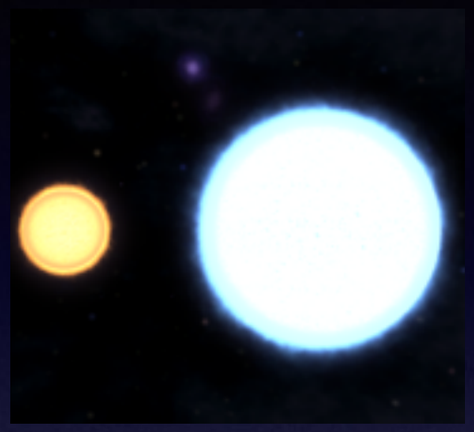

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As a result of us figuring out this is what's happening, it is also a **standard candle** (fixed mass when it explodes) and is visible from the edge of the Universe!

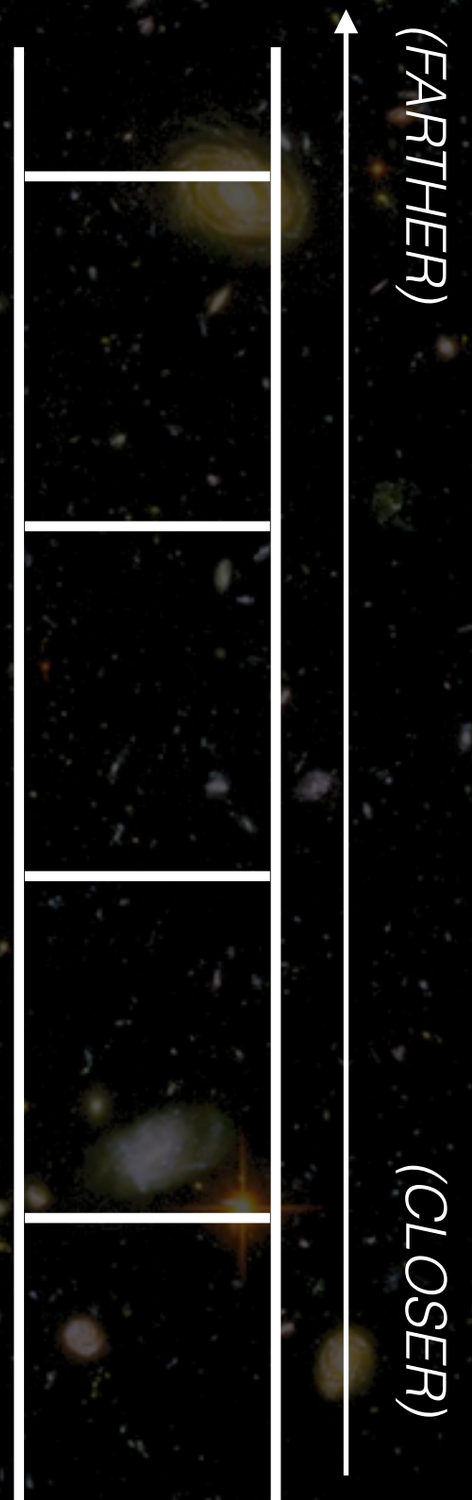
Overview of the the Cosmic Distance Ladder

Distant Galaxies,
Edge of Universe

The Milky Way Galaxy and
some very nearby galaxies

The Solar Neighborhood
(nearby stars)

The Solar System



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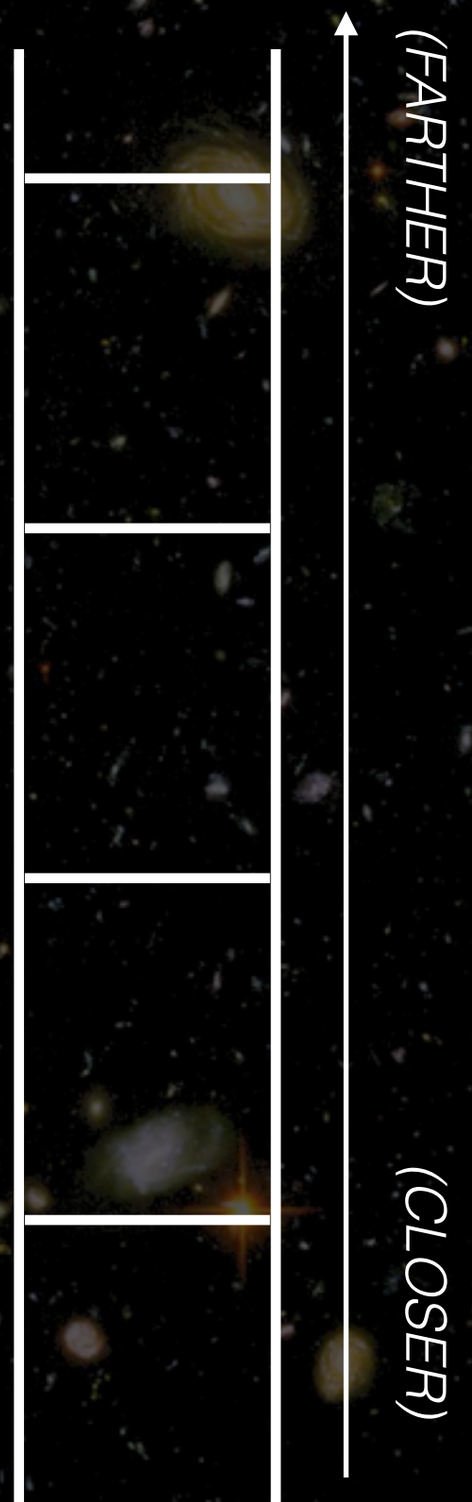

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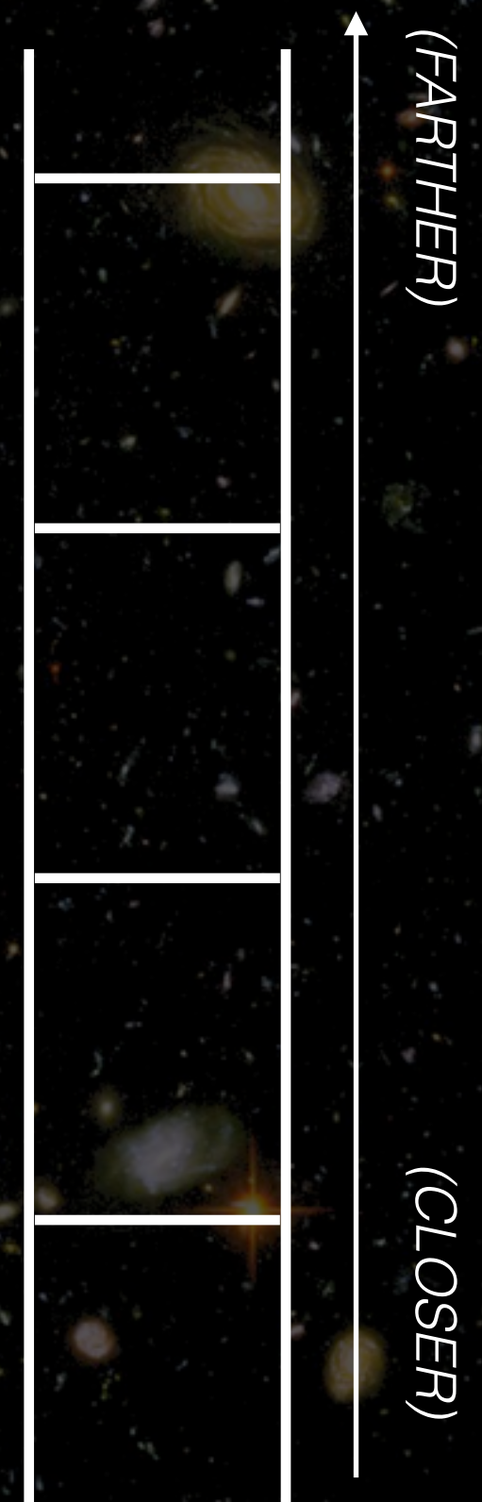

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M.S. Fitting

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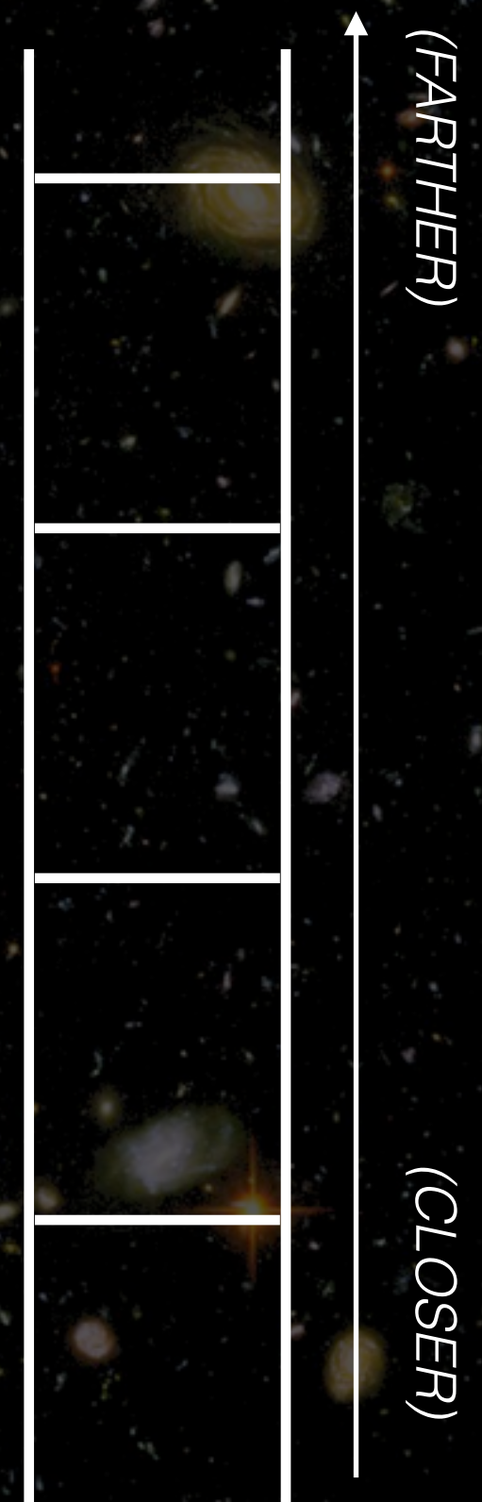

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M.S. Fitting

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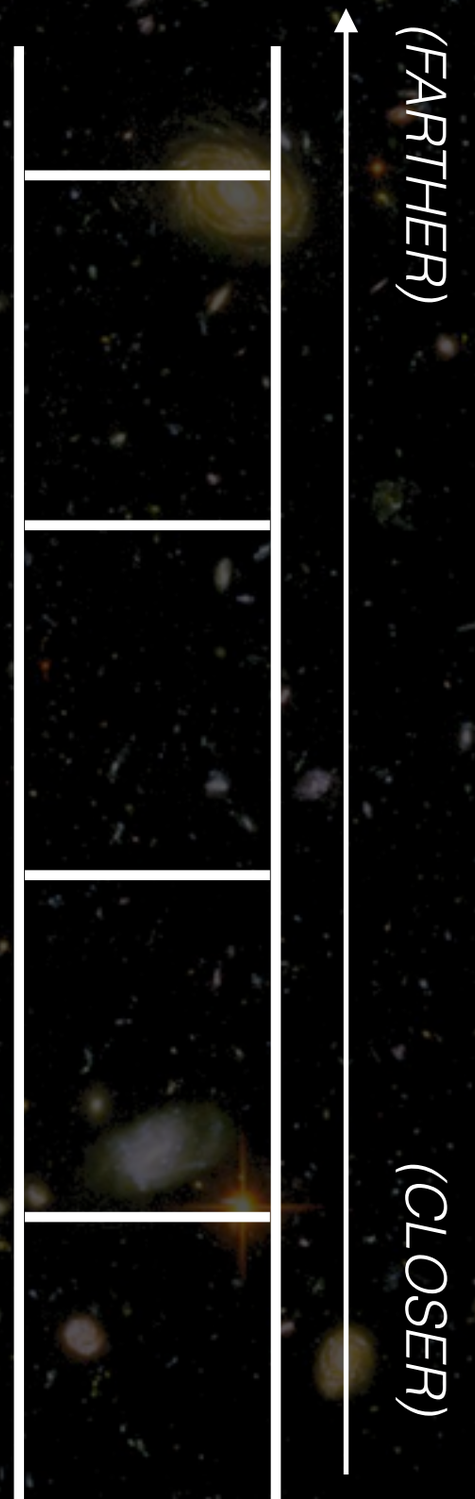

Overview of the the Cosmic Distance Ladder

TYPE 1A SUPERNOVAE

Distant Galaxies, Edge of Universe

CEPHEID VARIABLES

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M.S. Fitting

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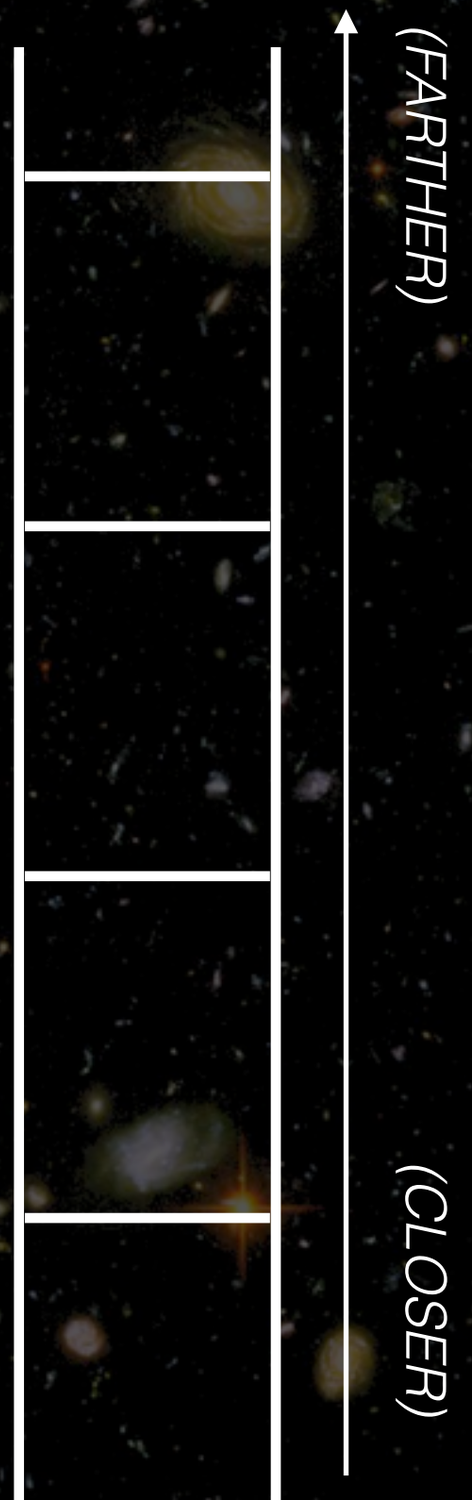

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TYPE 1A SUPERNOVAE
(homework calls this "white dwarf supernovae")

Distant Galaxies, Edge of Universe

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M.S. Fitting

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The Solar Neighborhood (nearby stars)

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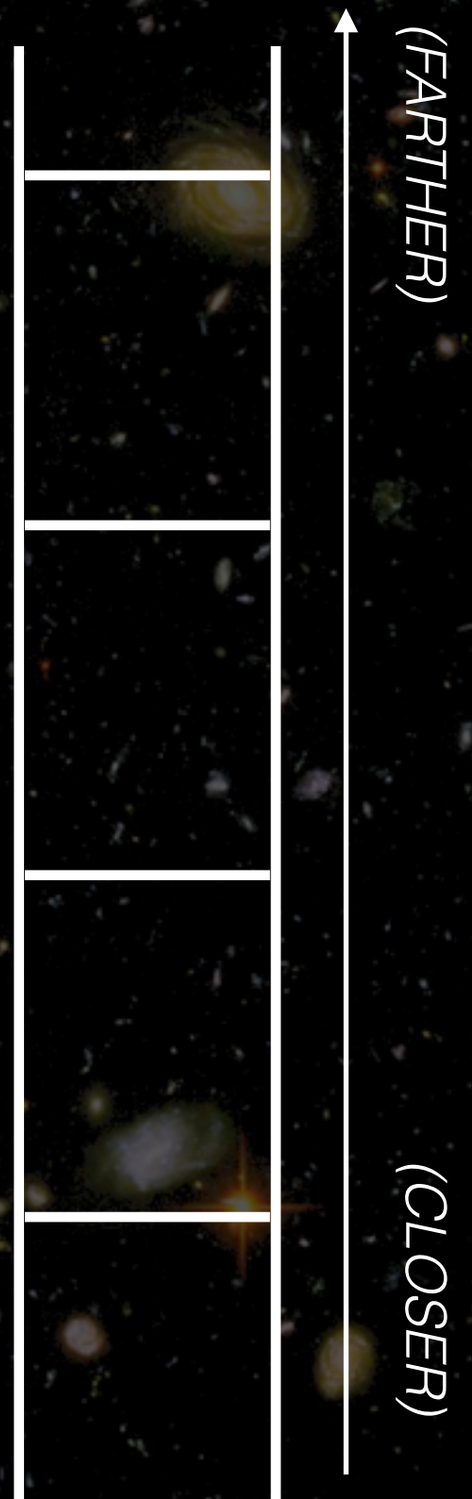

Overview of the the Cosmic Distance Ladder

Key points about the cosmic distance ladder:

** Each step is reliant upon good calibration of the step below (on smaller scales). For example, we couldn't use cepheid variables at all if we couldn't first measure parallax distances to a few cepheids.

** Overlap is needed

** Any distance measurement made far away is only as good as the worst distance measurement it relies on lower in the chain.

SU

(homew
dwa

CEP
VARI

M.S.

F

RADAR

The Solar System

SER)

Hubble's Law and the Expansion of the Universe!

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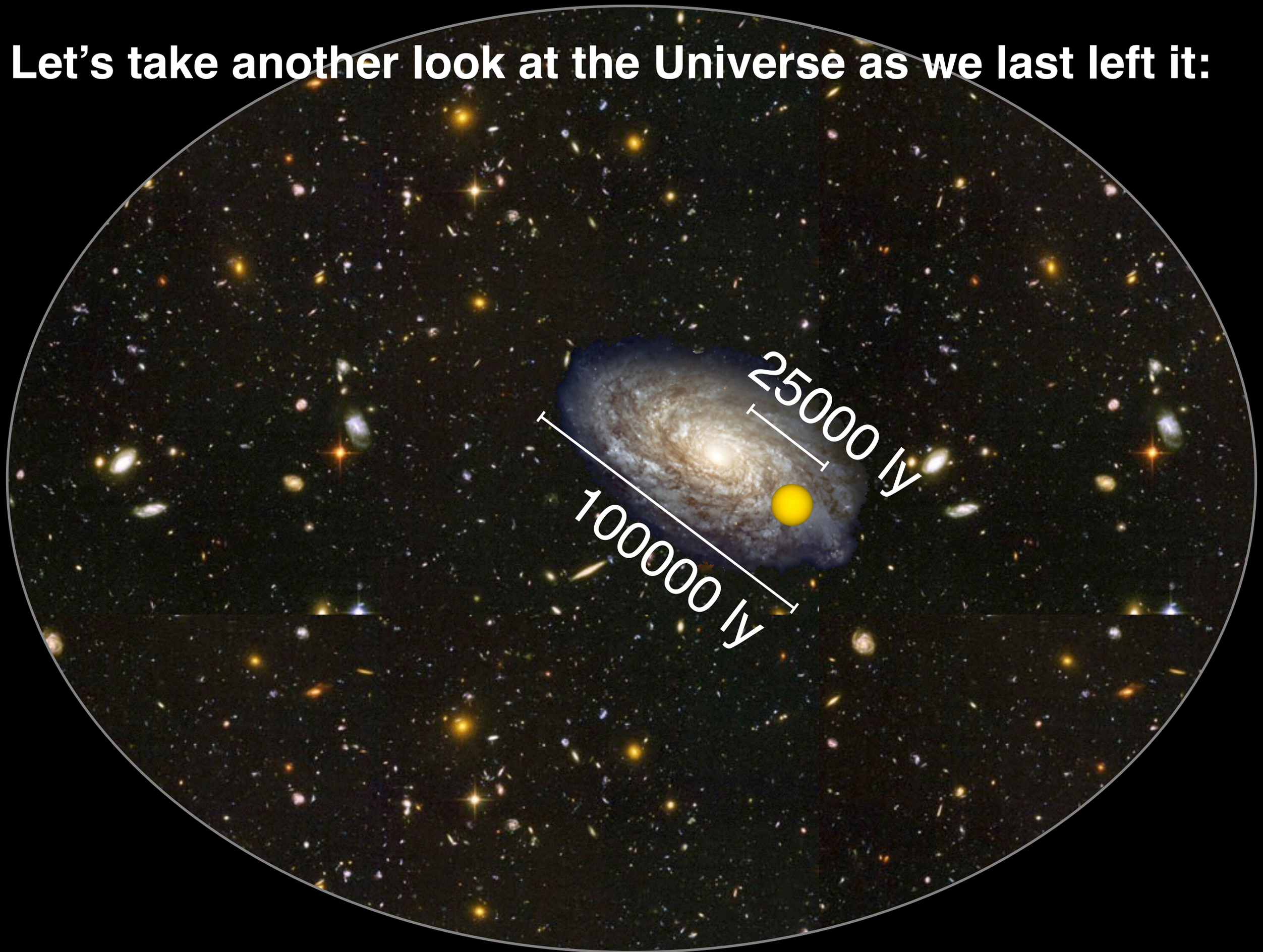


Let's take another look at the Universe as we last left it:

Edwin Hubble

25000 ly

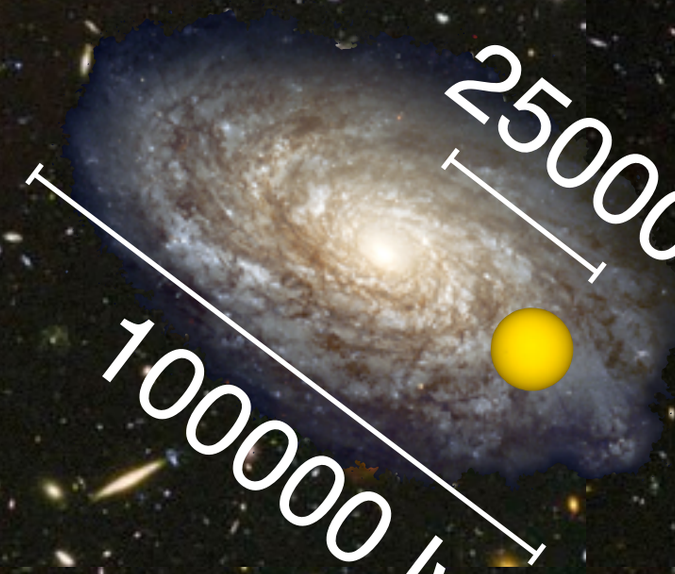
100000 ly

Milton Humason

In the 1920s, these guys were busy trying to measure the distance to nearish galaxies using variable stars.

Let's take another look at the Universe as we last left it:

How BIG is the Universe?!



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Mt. Wilson Observatory, San Gabriel Mountains, California

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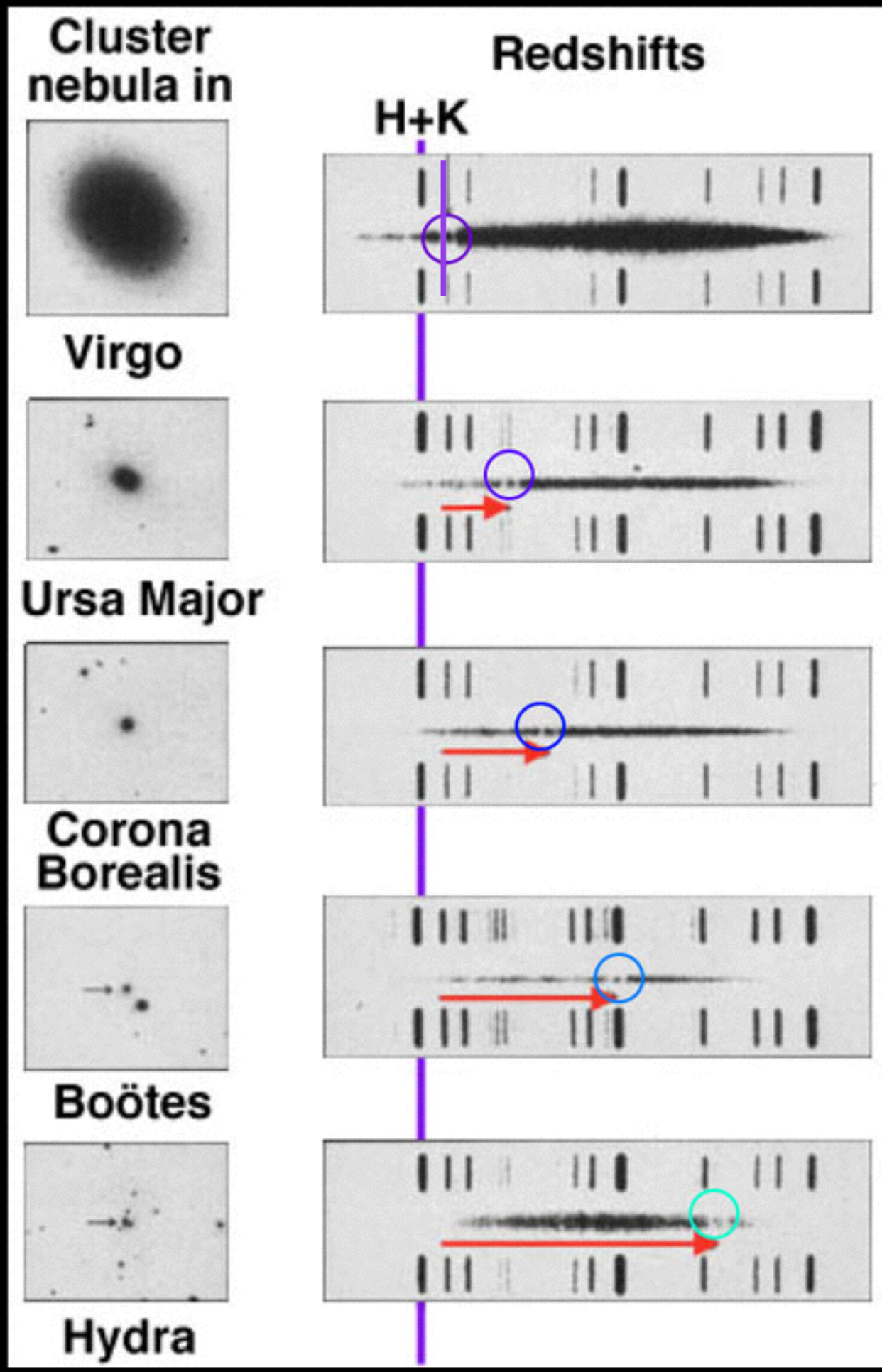
Meanwhile, in Flagstaff, AZ…

measurements of galaxies' spectra were being made. He kept finding a shift…



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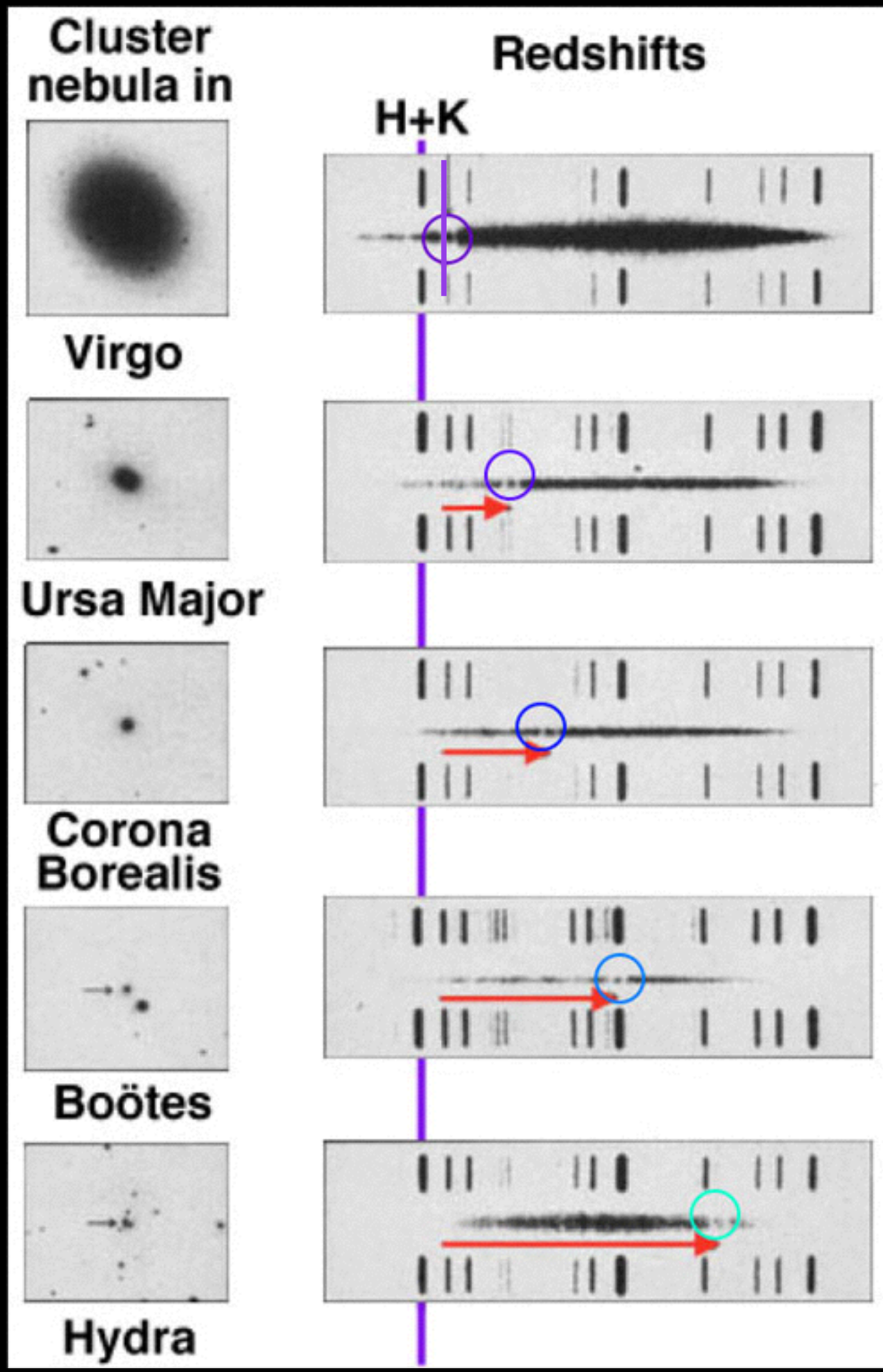

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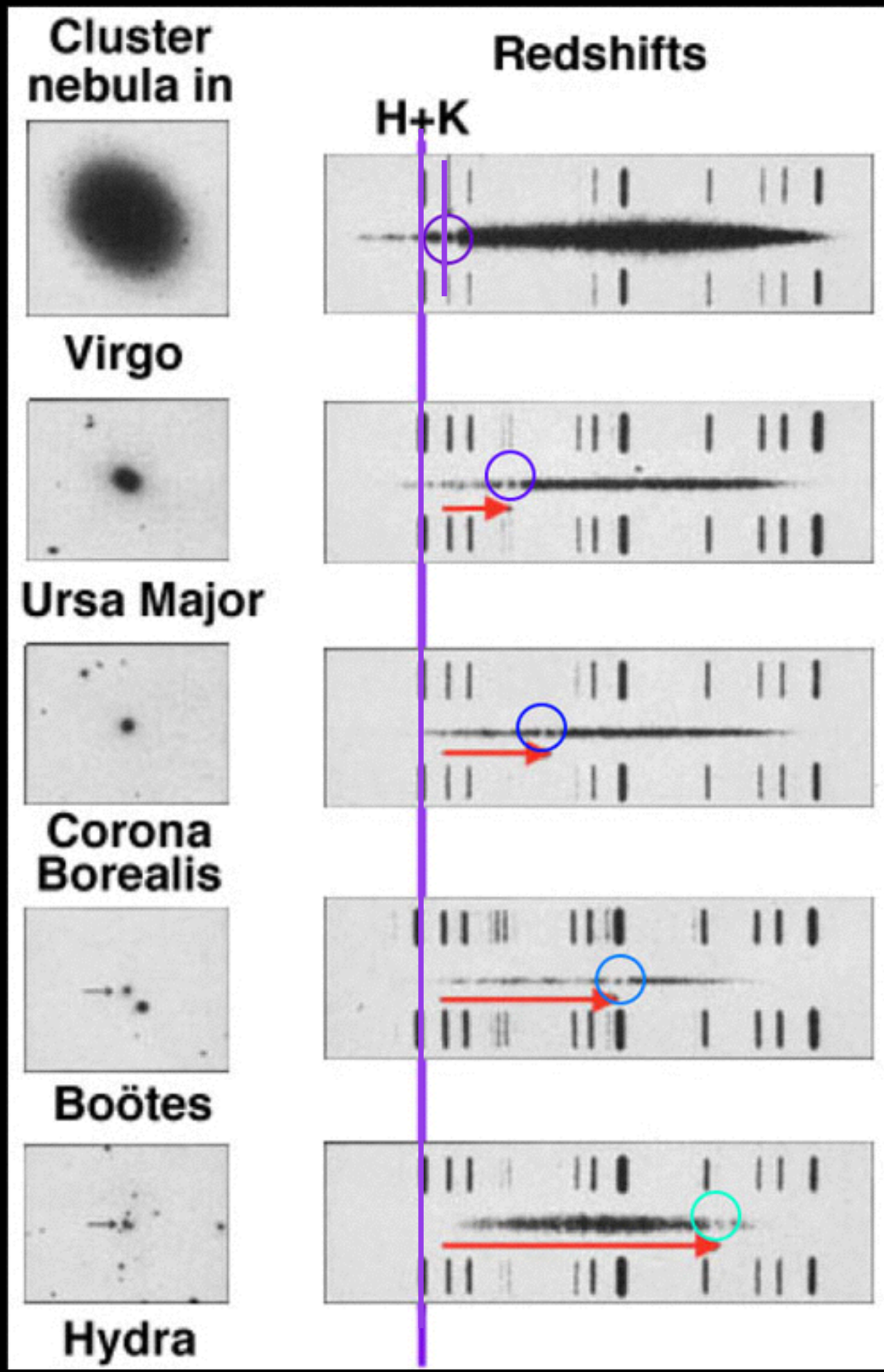

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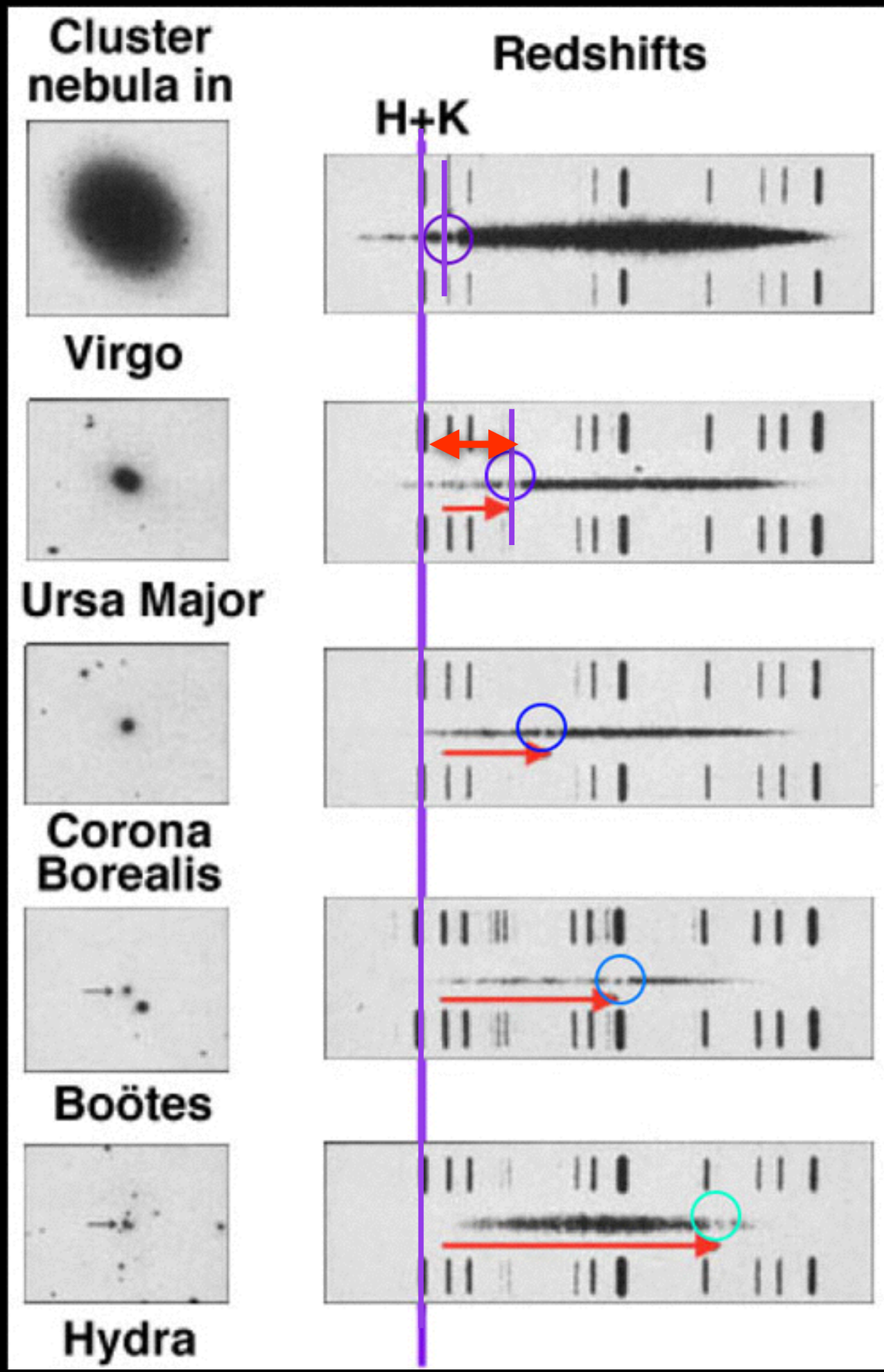

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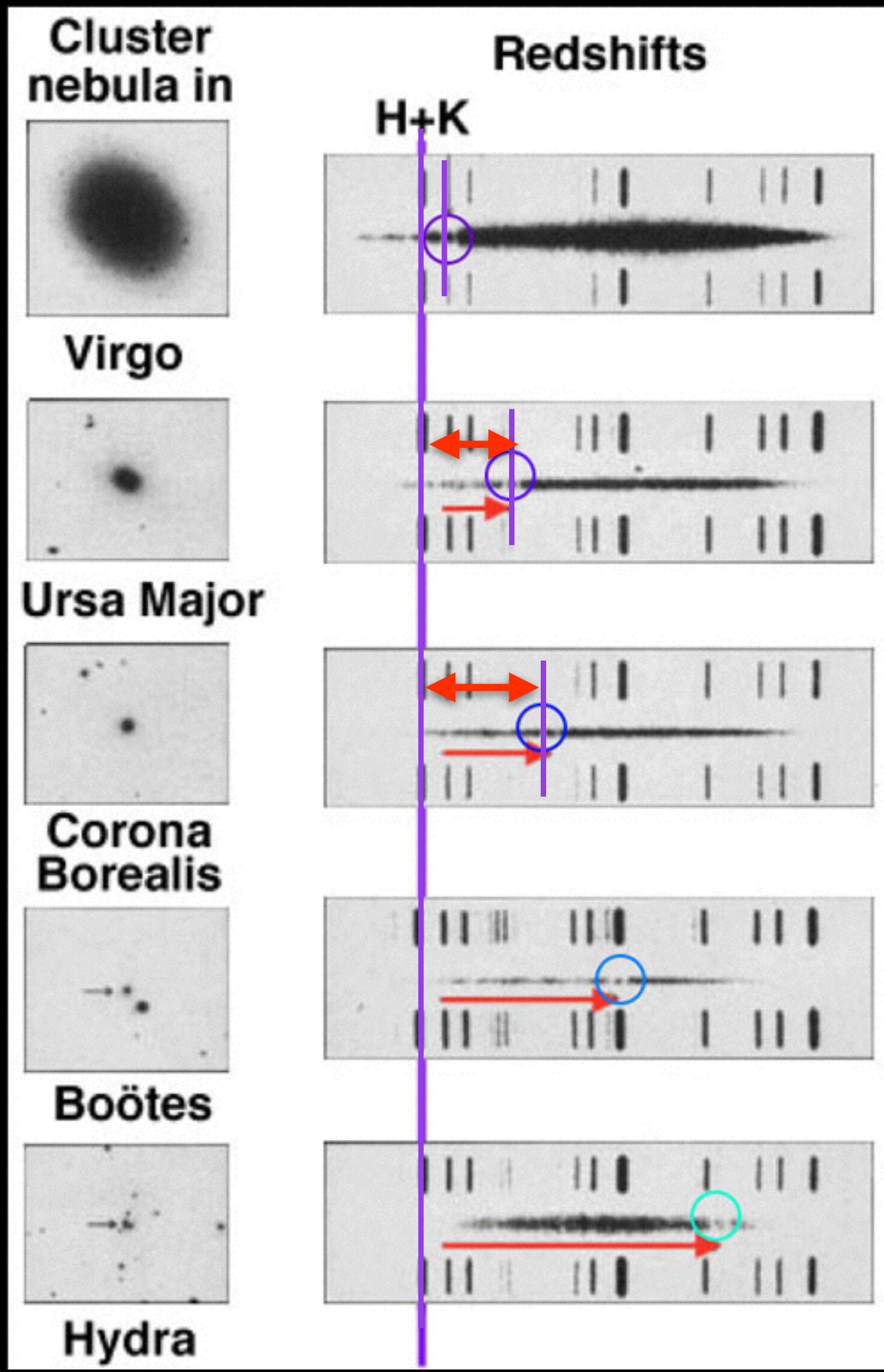

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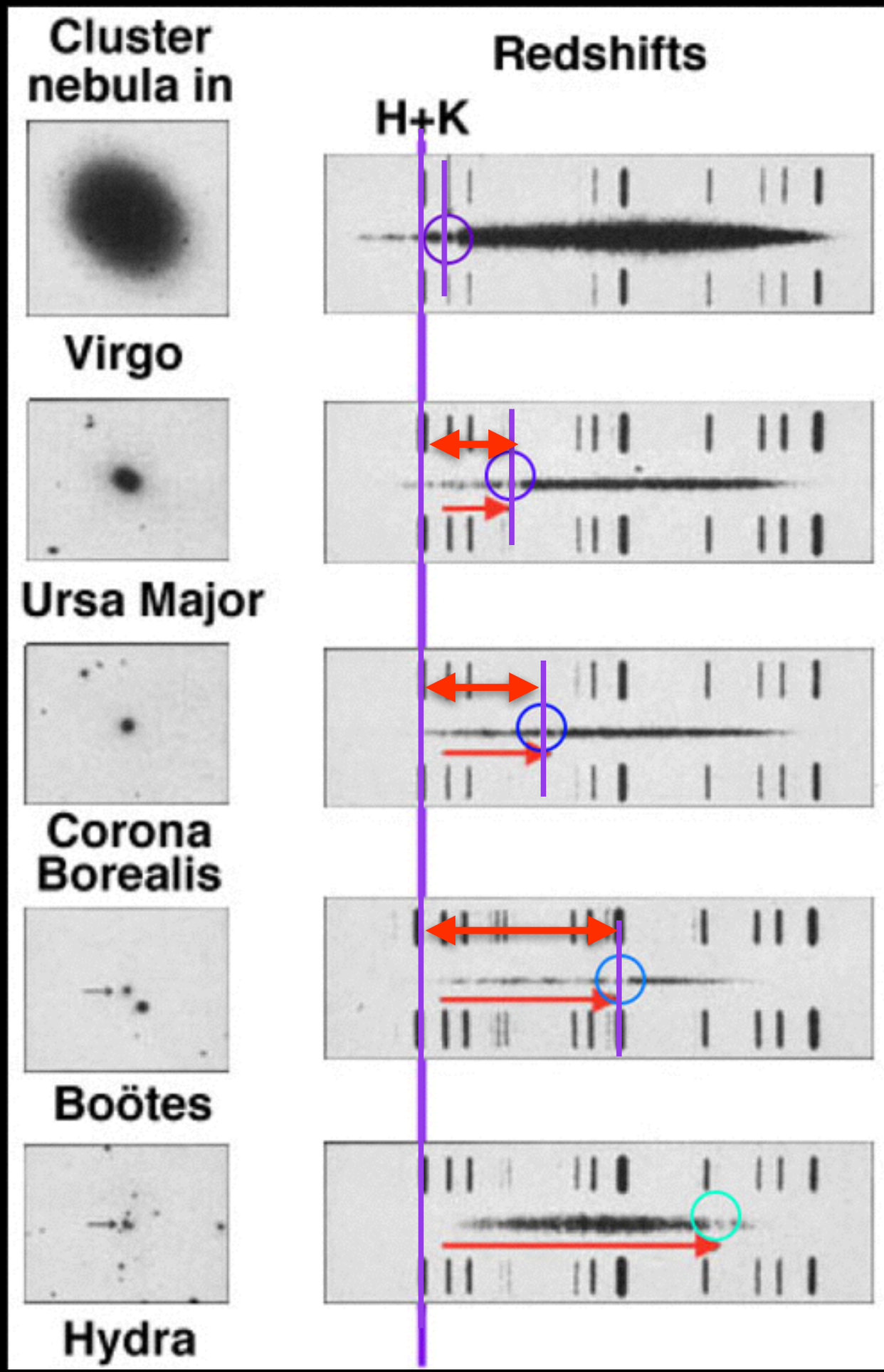

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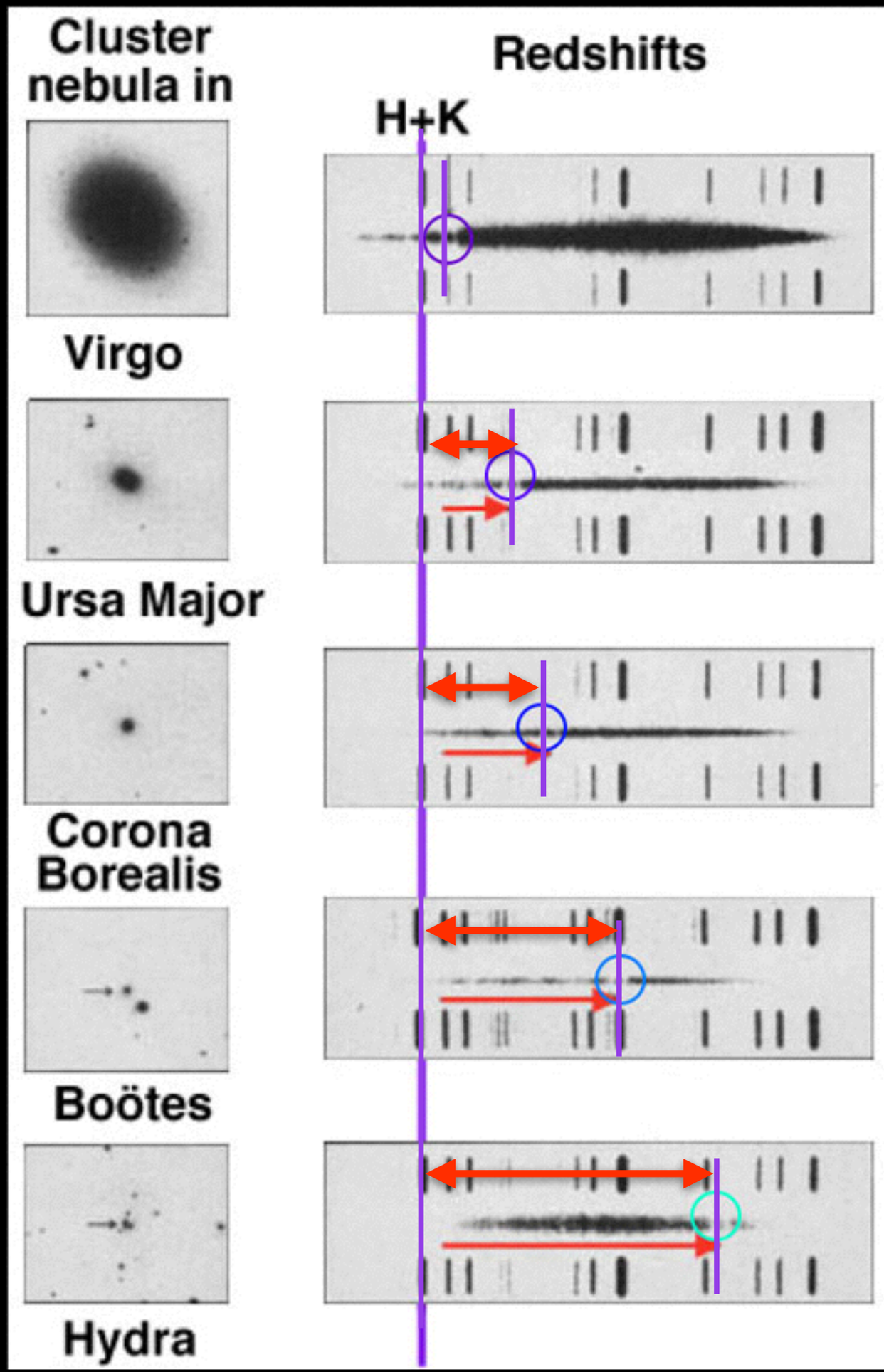

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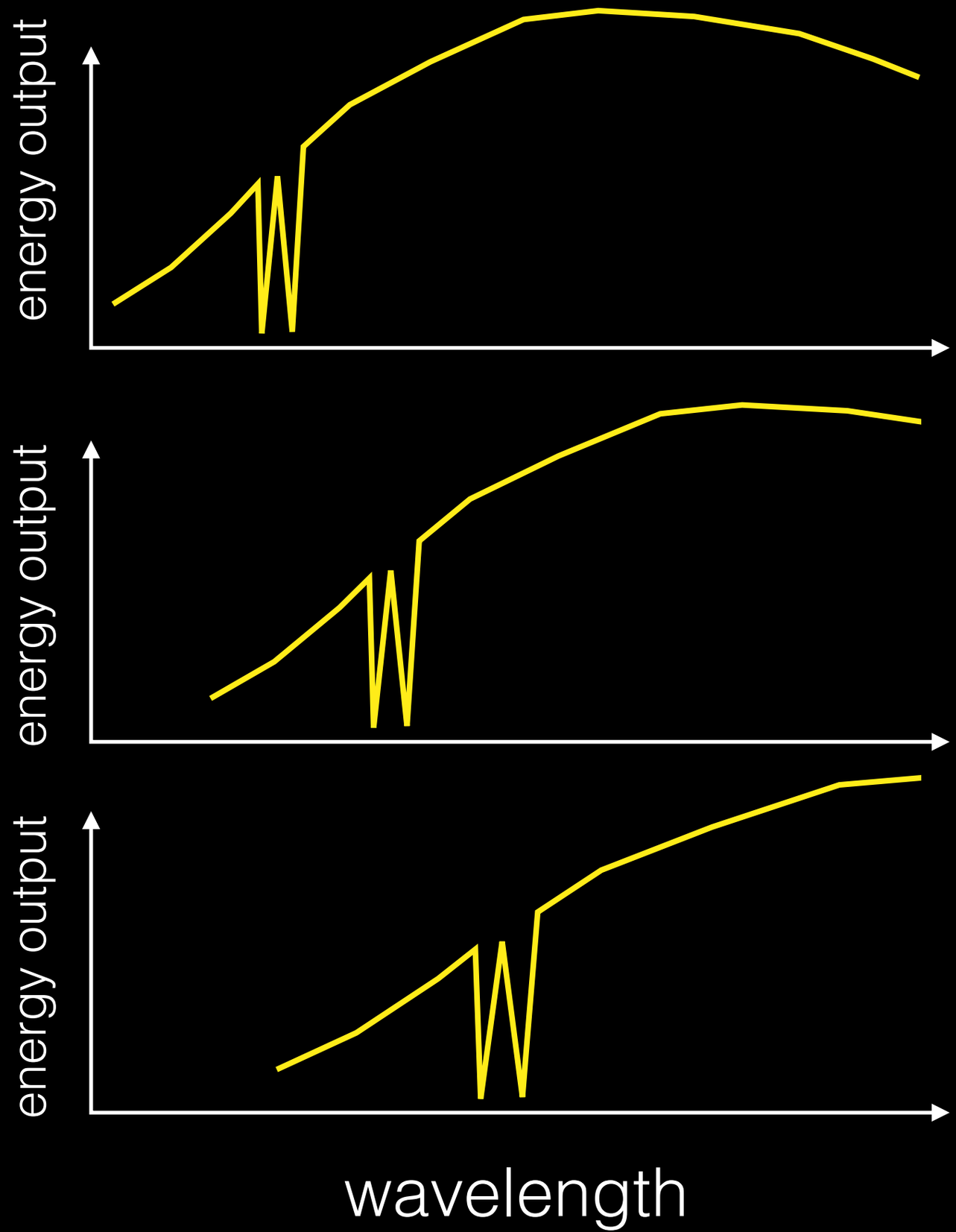

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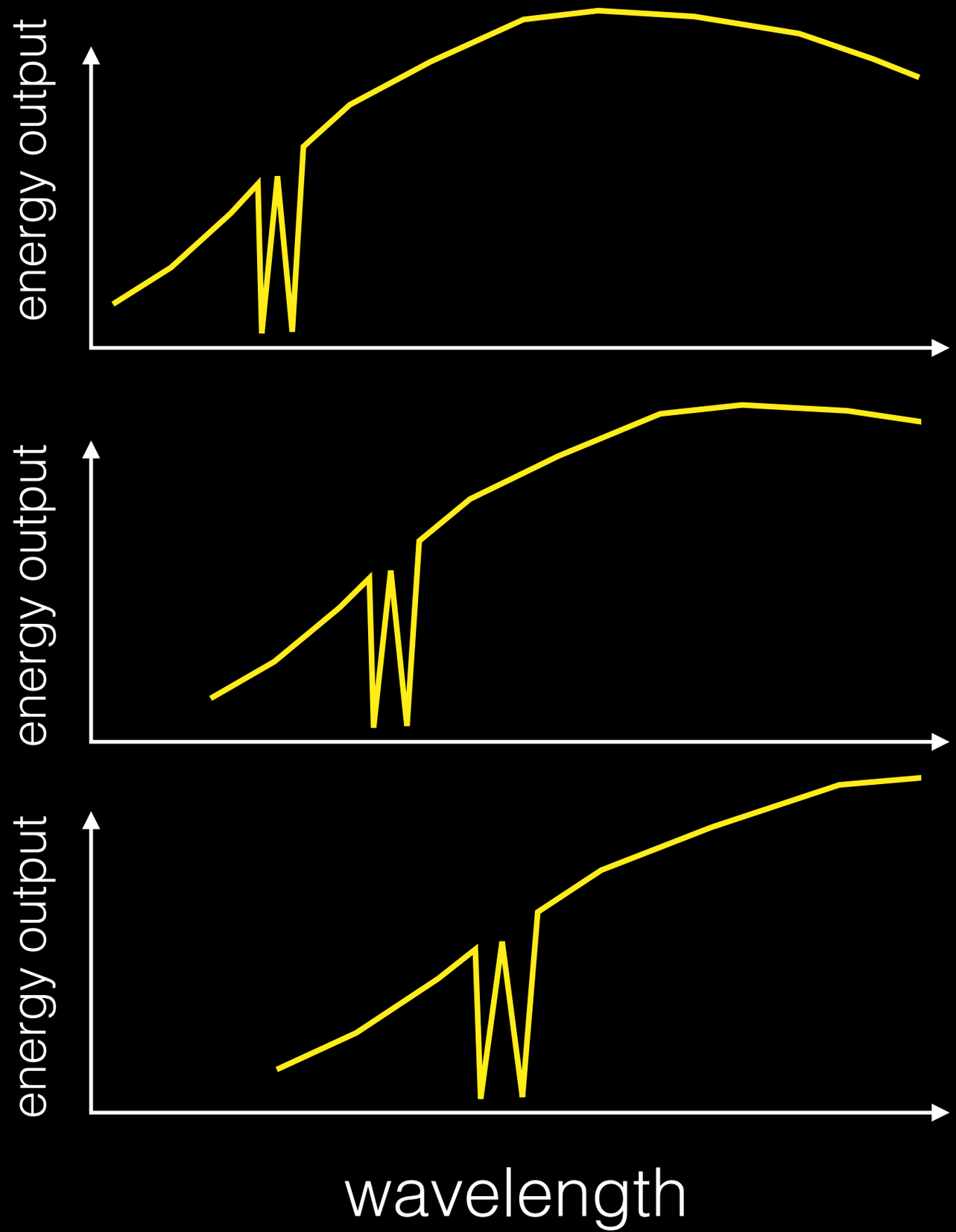

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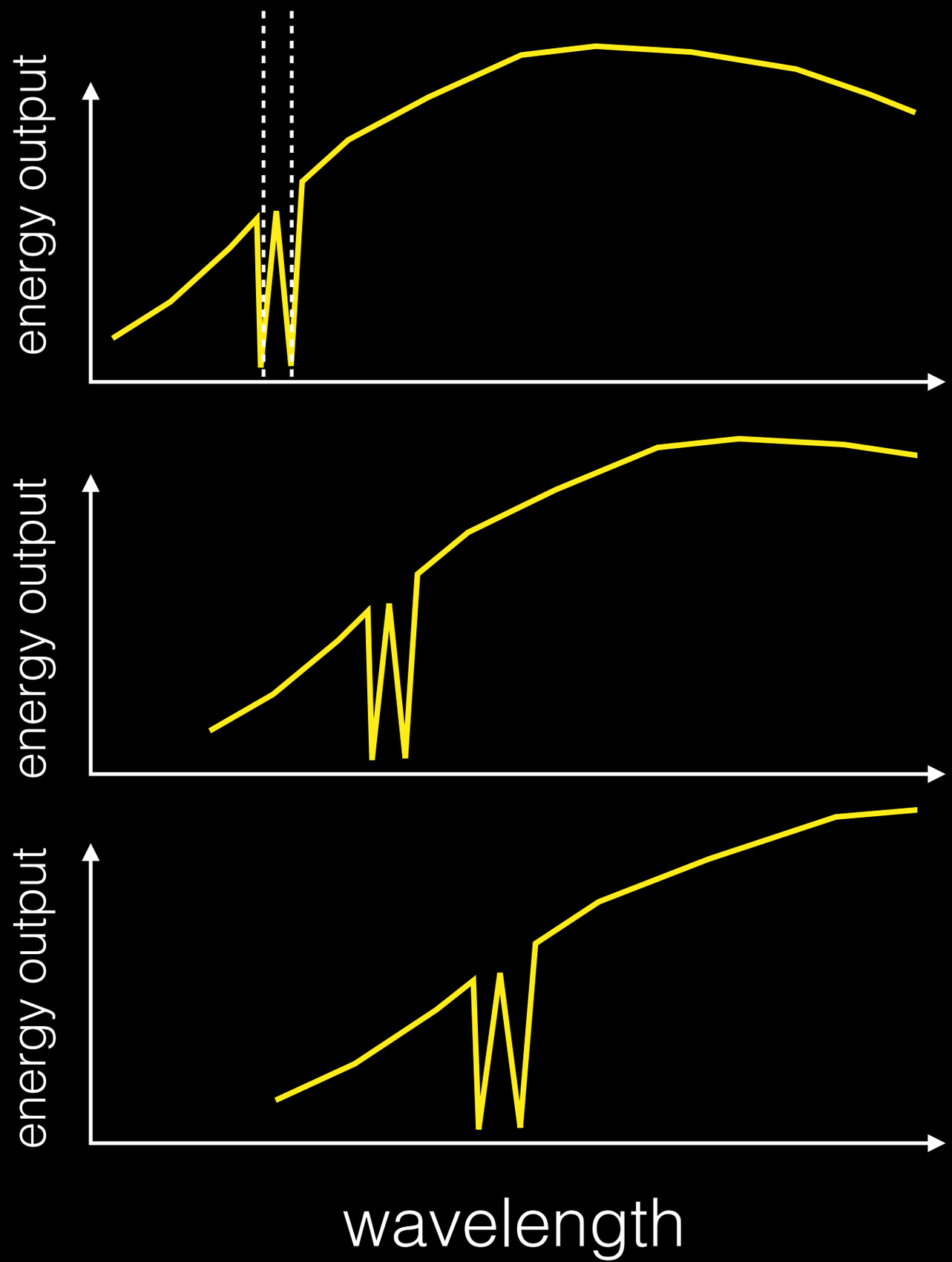

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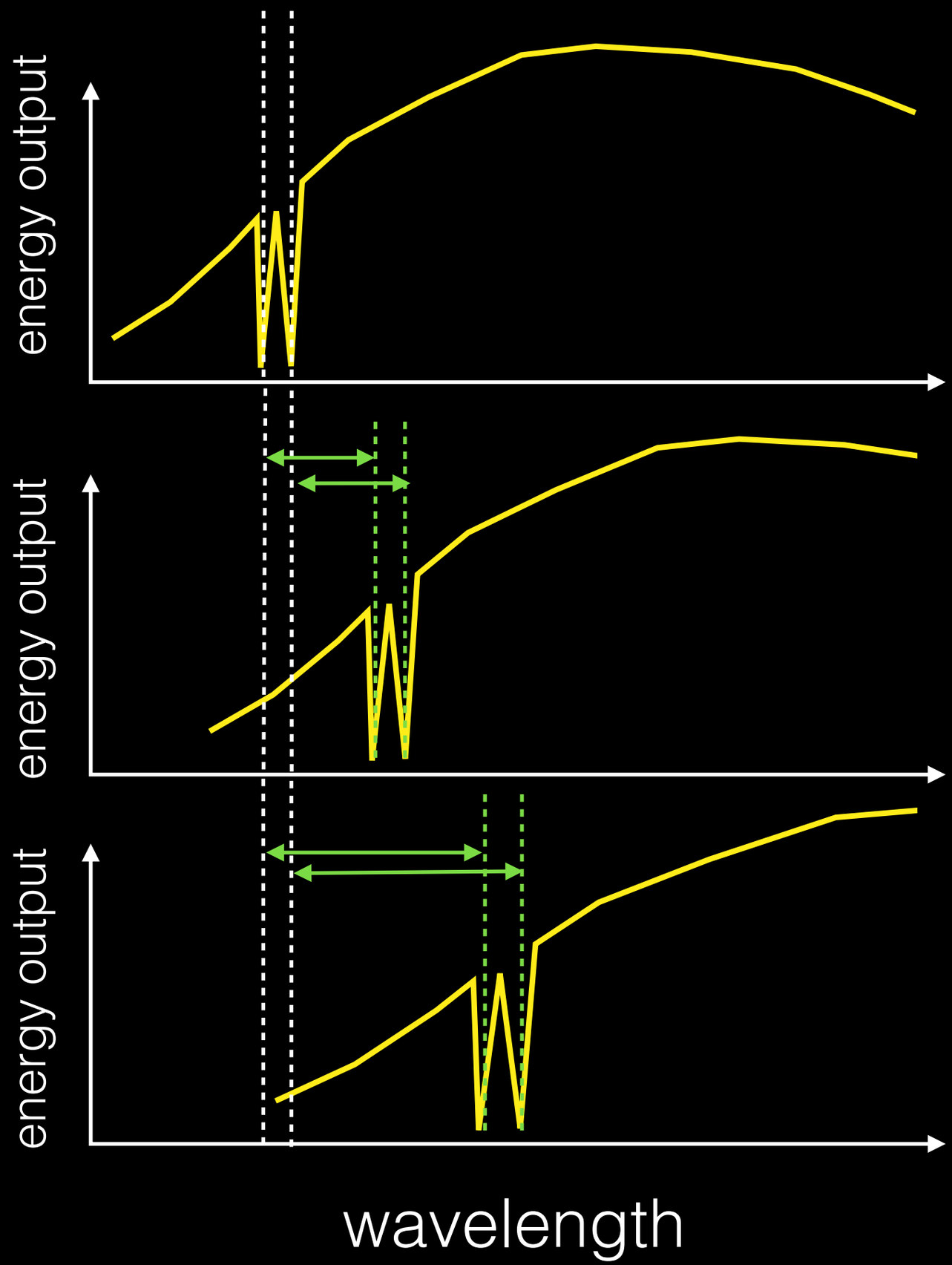
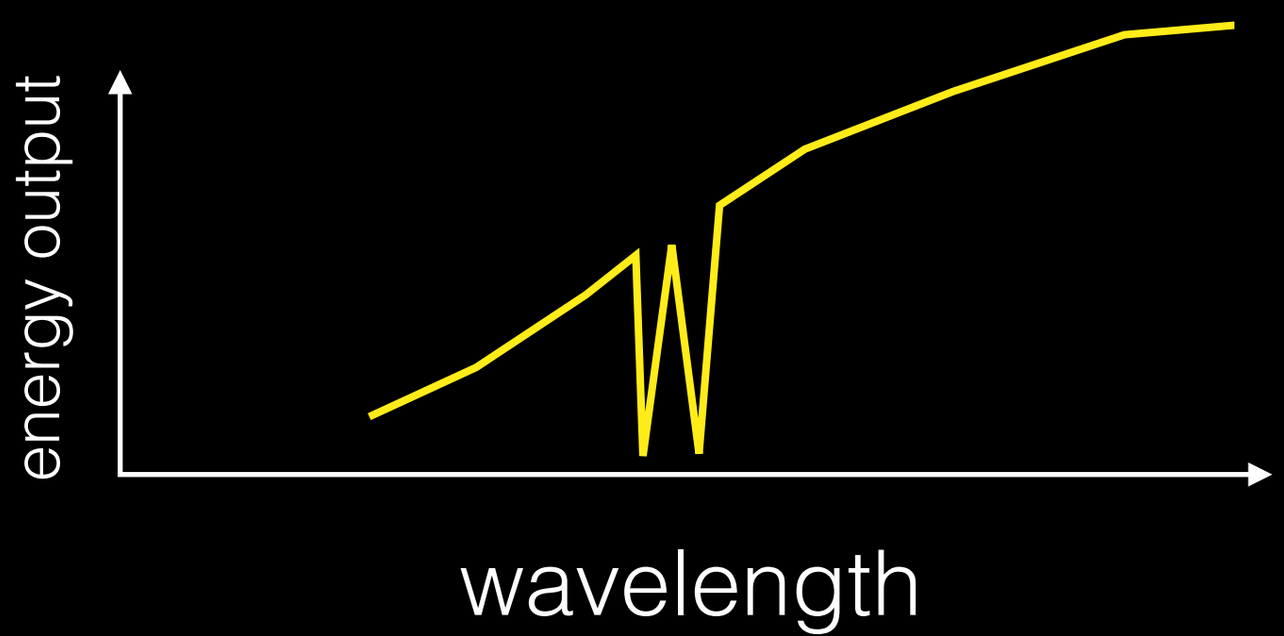


What does this shift tell us?



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(b) the galaxy is moving away from us
(c) the galaxy is moving towards us
(d) the galaxy is made up of billions of stars

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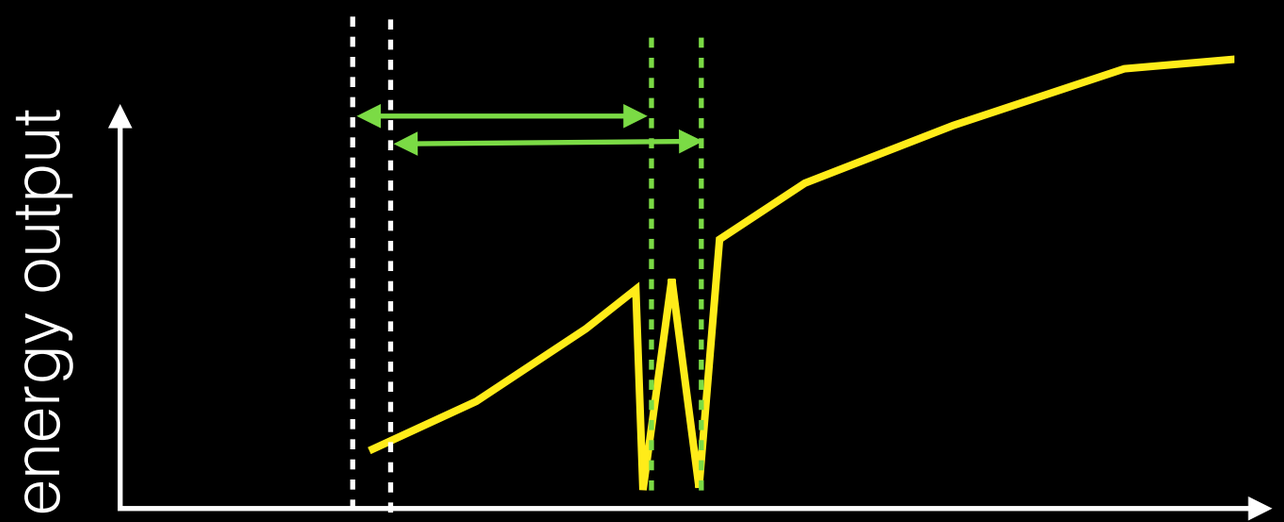

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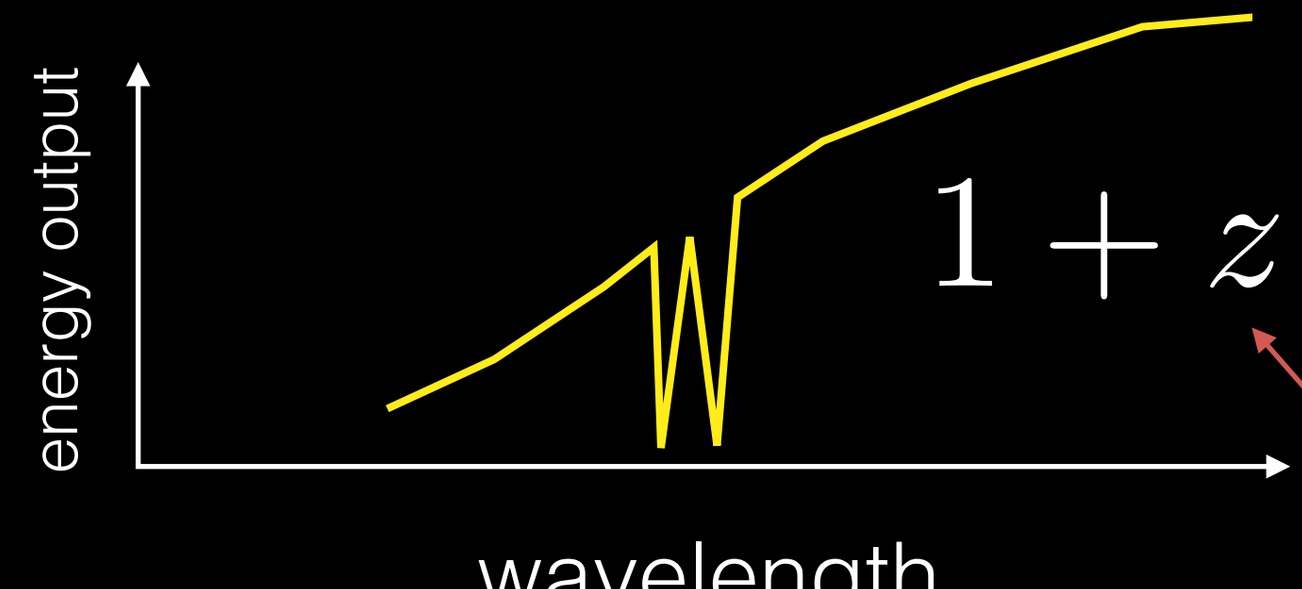

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“redshift”

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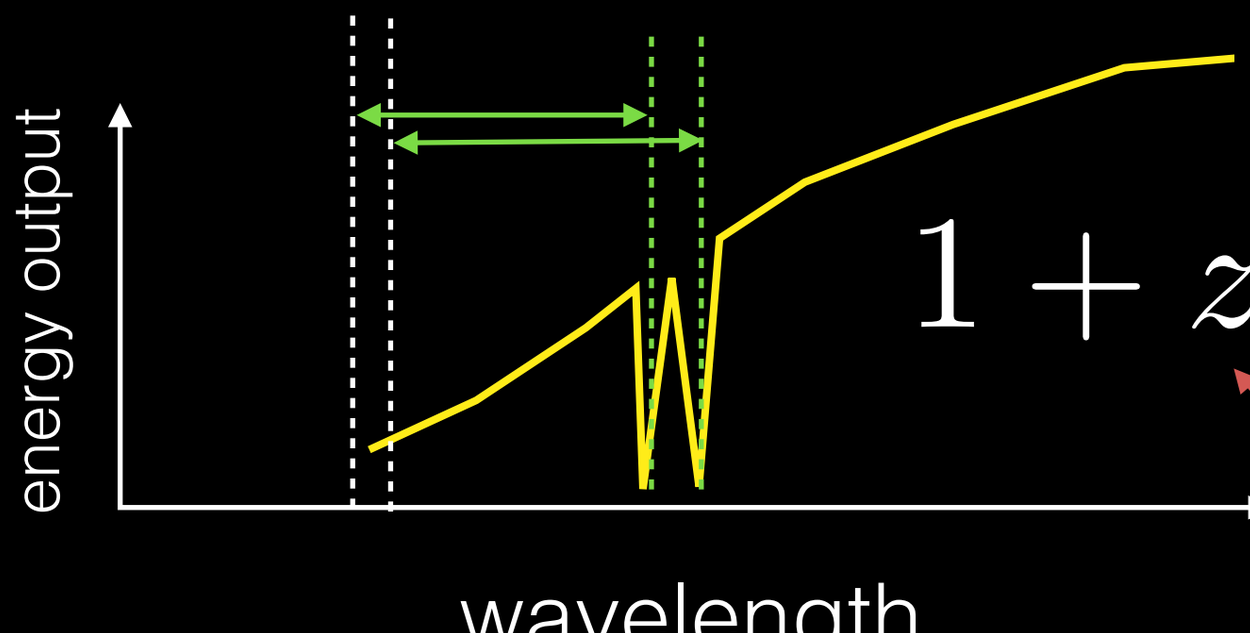

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Holds when v is small

$$z \approx \frac{v}{c}$$

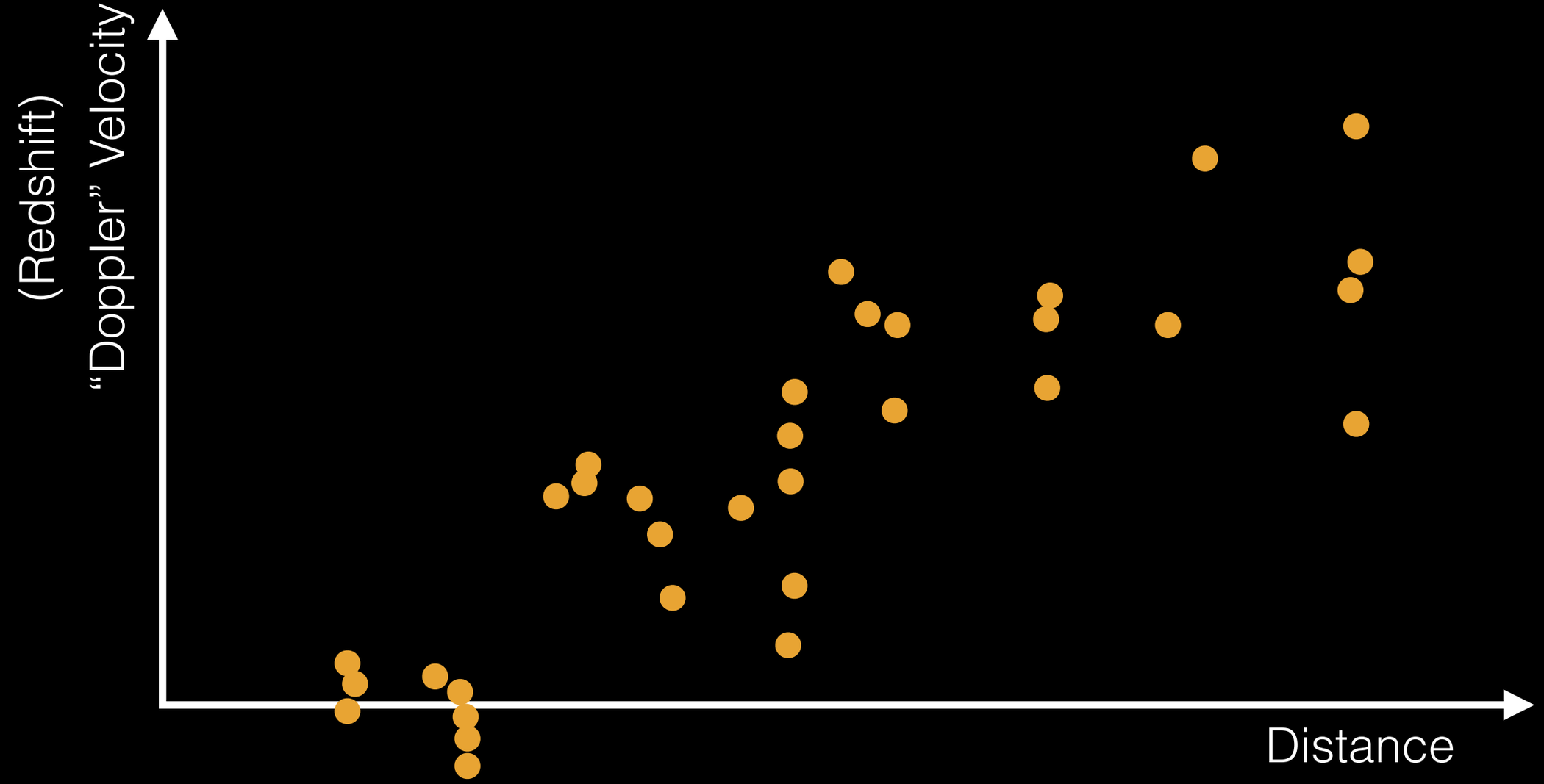
Holds ALWAYS

$$1 + z = \frac{\lambda_{\mathrm{obs}}}{\lambda_{\mathrm{emit}}}$$

“redshift”

And slowly the measurements were compiled…

And slowly the measurements were compiled…



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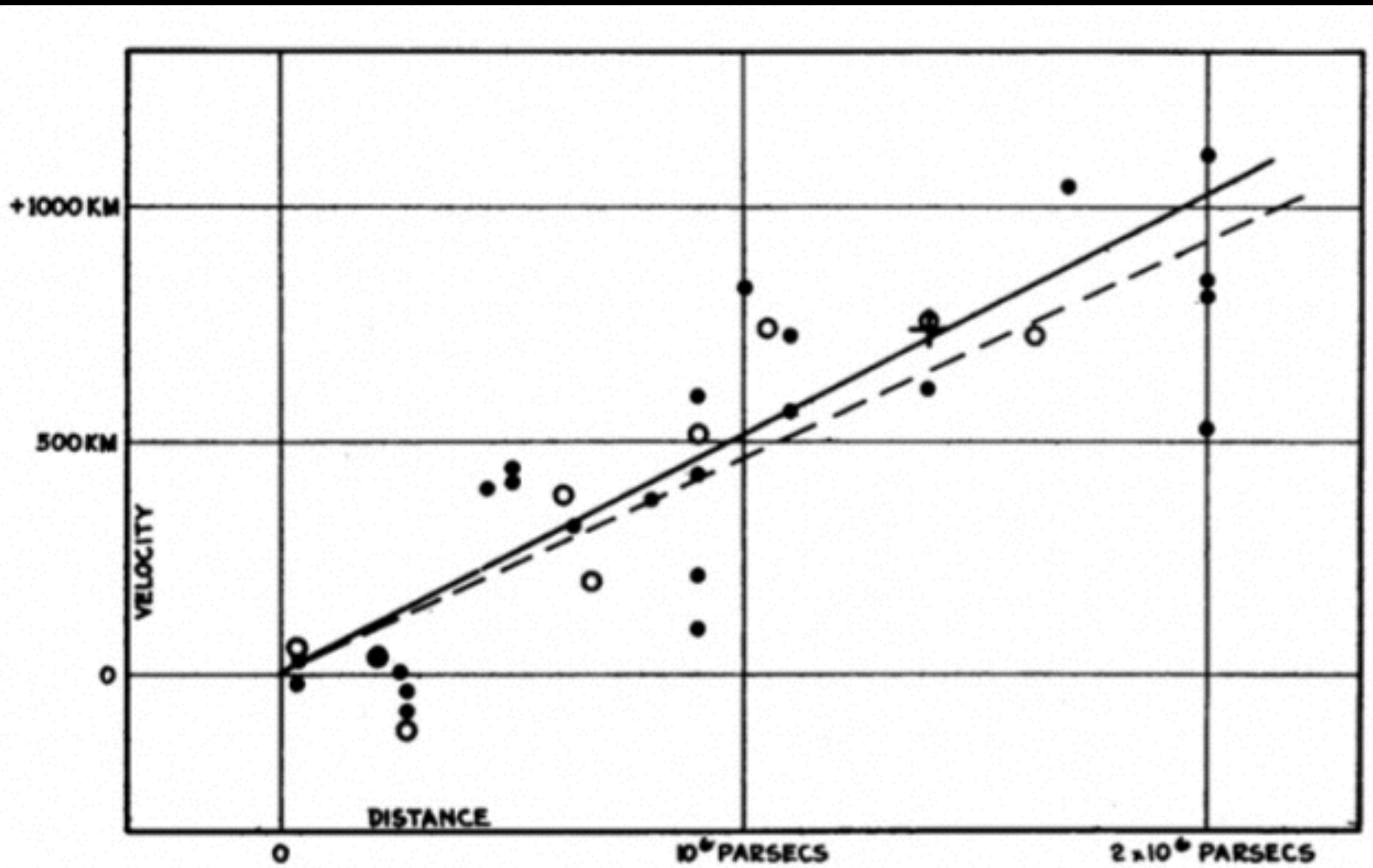


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Where are these galaxies located in the sky?

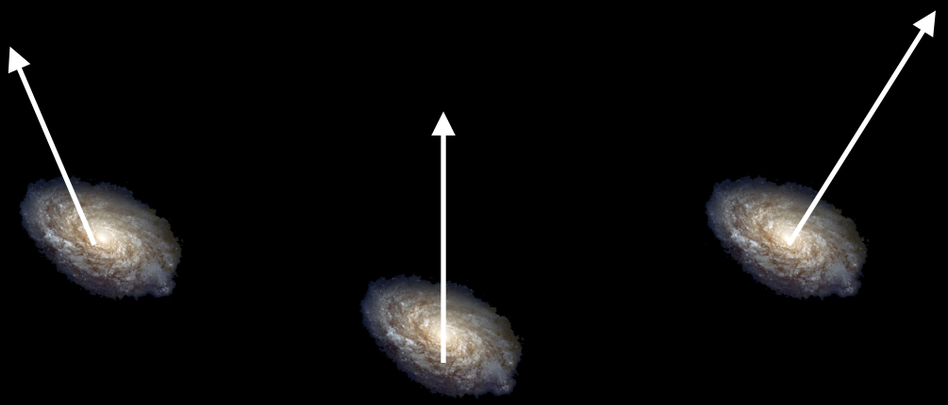
Tunc Tezel

EVERYWHERE

Where are these galaxies located in the sky?

EVERYWHERE (WOAH)

Where are these galaxies located in the sky?



Galaxies further away from us are speeding away from us faster than those closer to us:

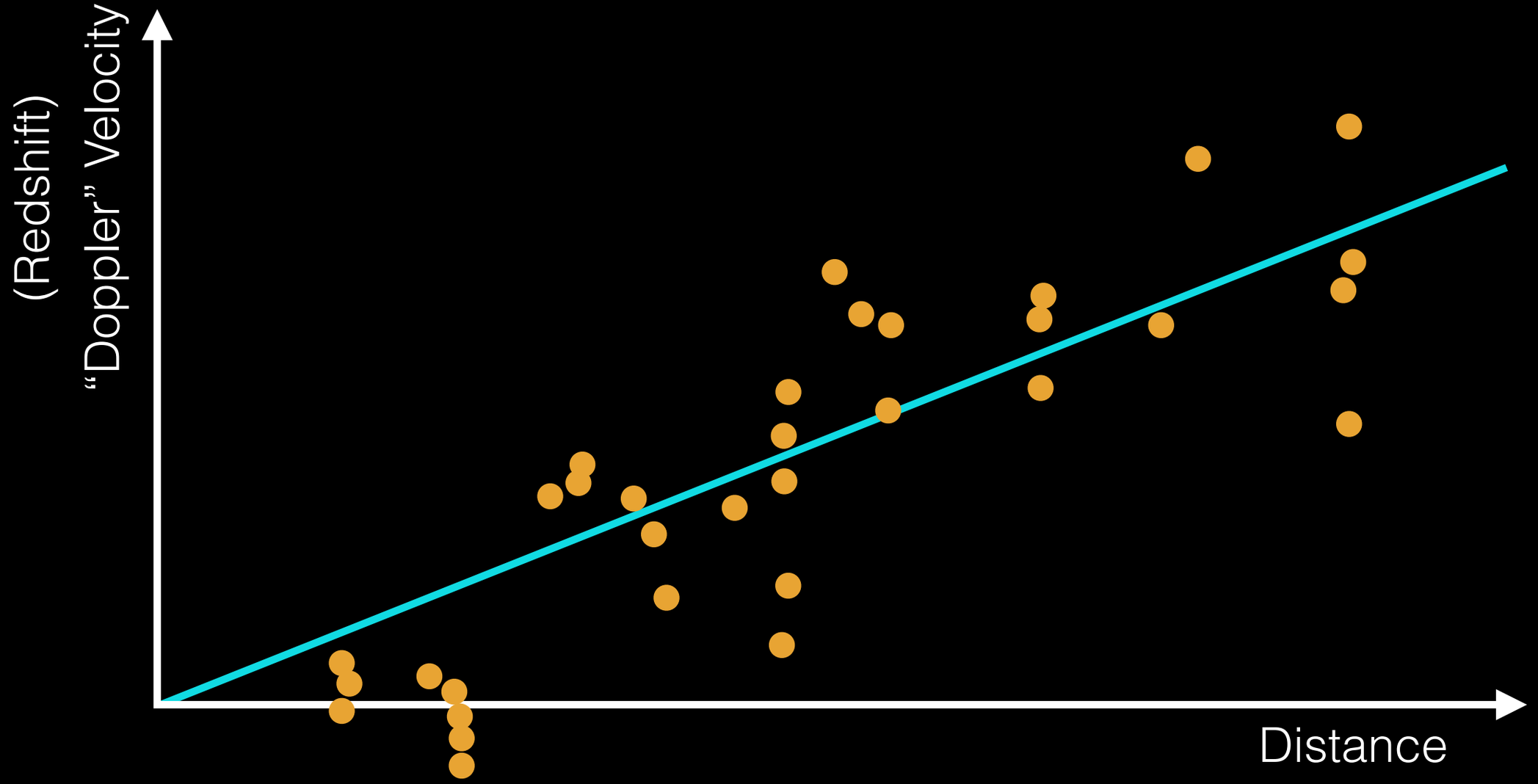
the **Universe is Expanding**

EVERYWHERE (WOAH)

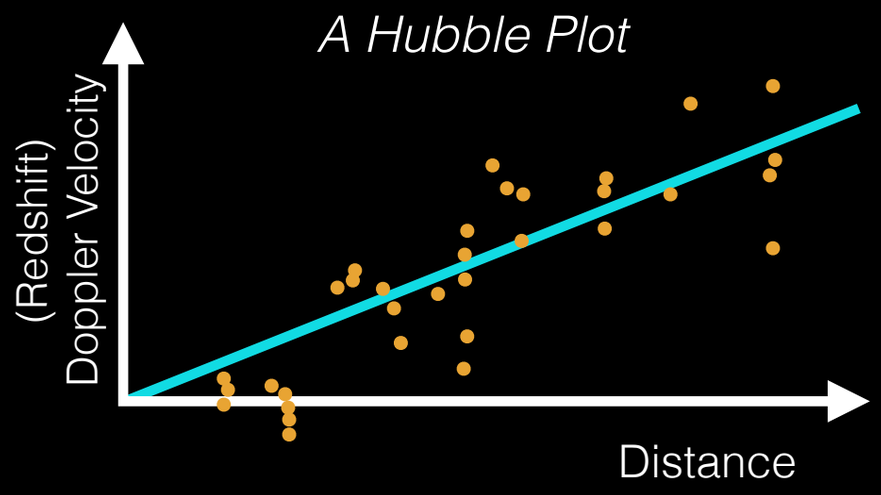
Let’s think about this whole expanding Universe thing. Why isn’t this just something going on with our point of view?

Hubble's Law

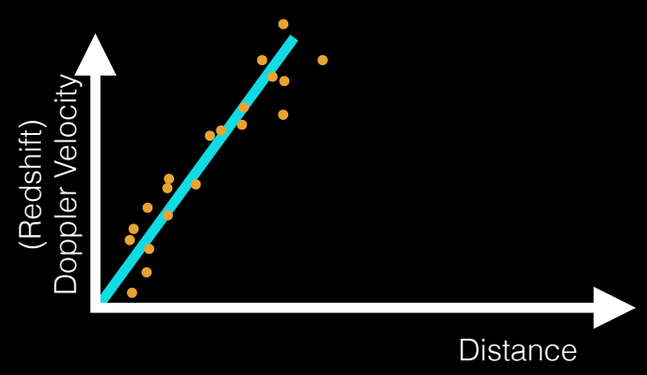
(a) galaxies are mostly receding away from us,
(b) the velocity of their recession is proportional to their distance from us.

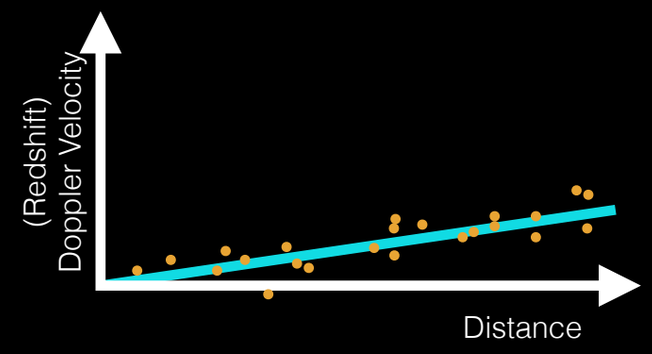


Work through the following with your groups…



1. Imagine the Hubble plot at right represents a universe that doubles in size over a certain amount of time. Which of the Hubble plots below might represent a Universe that triples in size over the same amount of time?





2. The <u>expansion rate</u> of the Universe determines how fast the universe increases in size with time. For example, a universe that is tripling in size has a faster expansion rate than a universe that is doubling in size over the same amount of time. In a Hubble plot, what quantity represents the expansion rate of the Universe?

3. From the plot in the upper left, would you say the Universe has a constant expansion rate, an increase or a decreasing expansion rate with time?

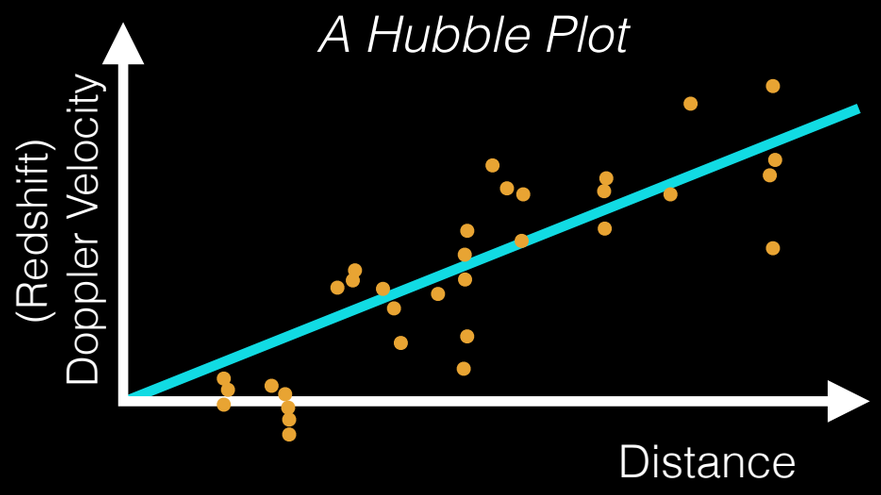
4. Rank the three plots above from fastest (1) to slowest (3) expansion rates.

5. If the expansion rate had been faster than measured, would the Universe have reached its current size earlier in its history or later?

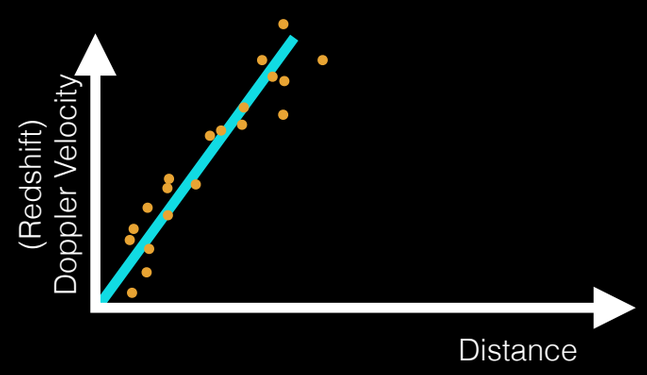
6. Using your answers from #4 and #5, rank the three plots above from youngest (1) to oldest (3) Universe.

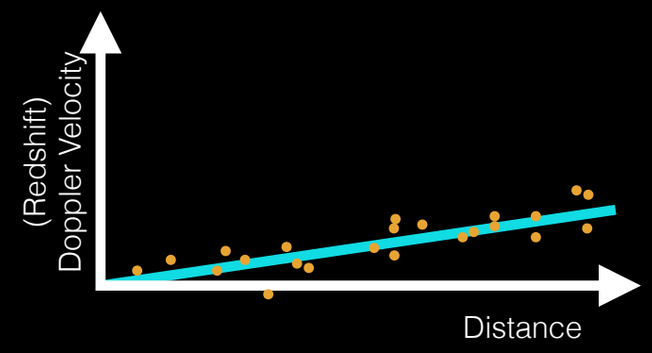
Learning Catalytics Question: On the blank graph at right, draw a Hubble plot for which the expansion rate of the Universe is zero (i.e. no expansion).

Work through the following with your groups…



1. Imagine the Hubble plot at right represents a universe that doubles in size over a certain amount of time. Which of the Hubble plots below might represent a Universe that triples in size over the same amount of time?





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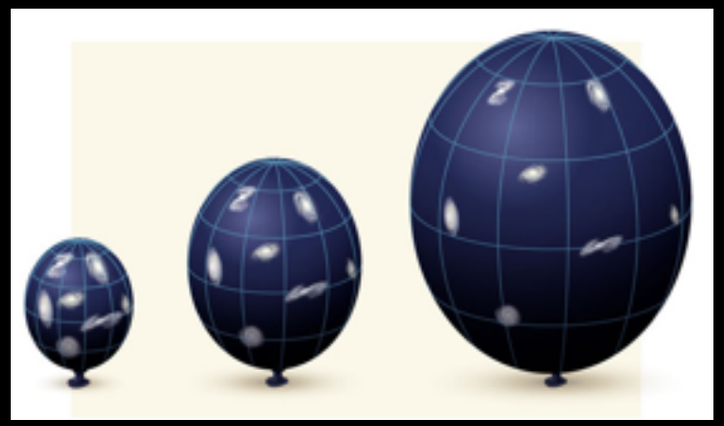
Learning Catalytics Question: On the blank graph at right, draw a Hubble plot for which the expansion rate of the Universe is zero (i.e. no expansion).

The expanding Universe! By Phil

The expanding Universe! By Phil

An expanding Universe implies a **Big Bang**.



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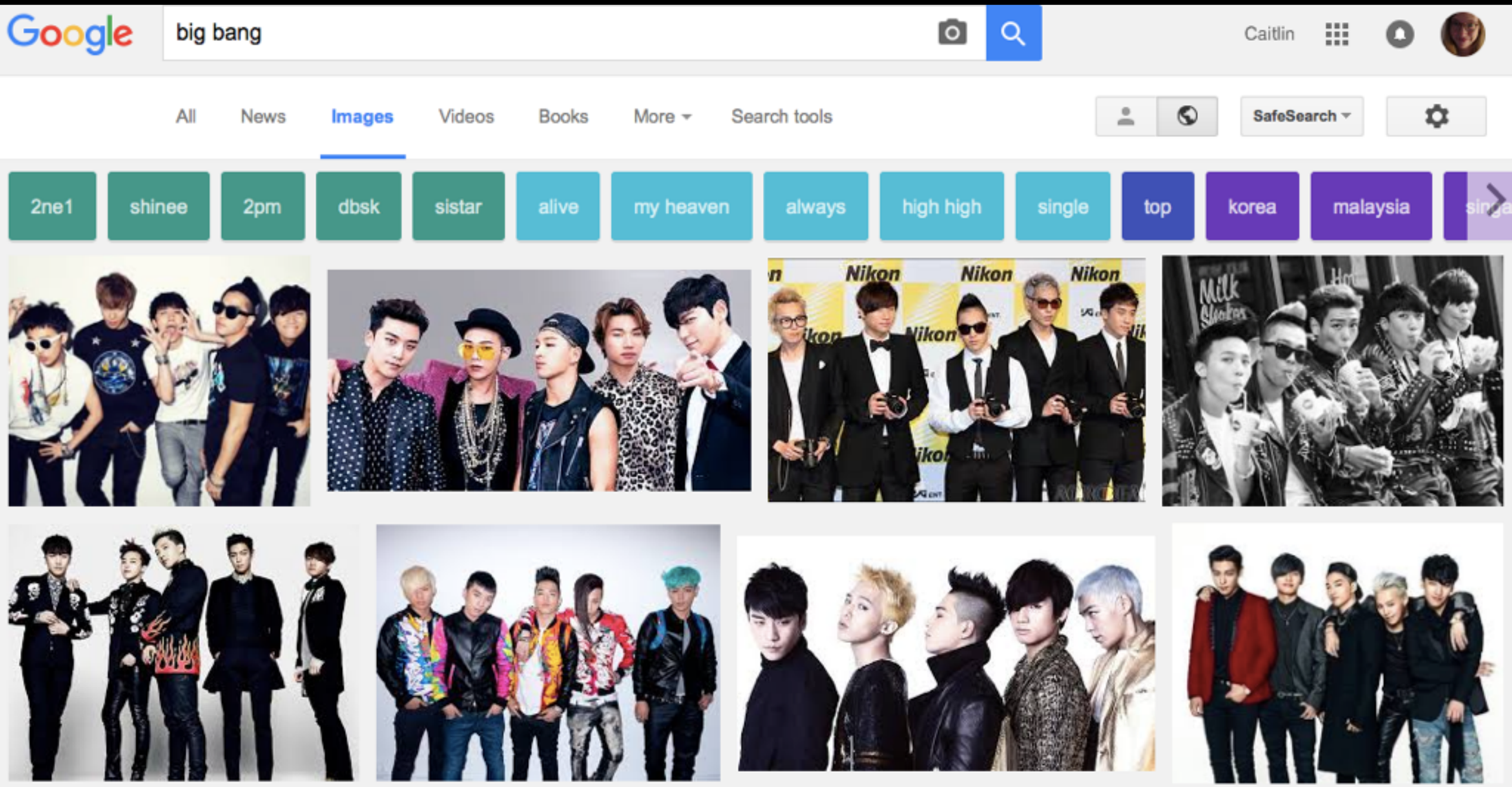
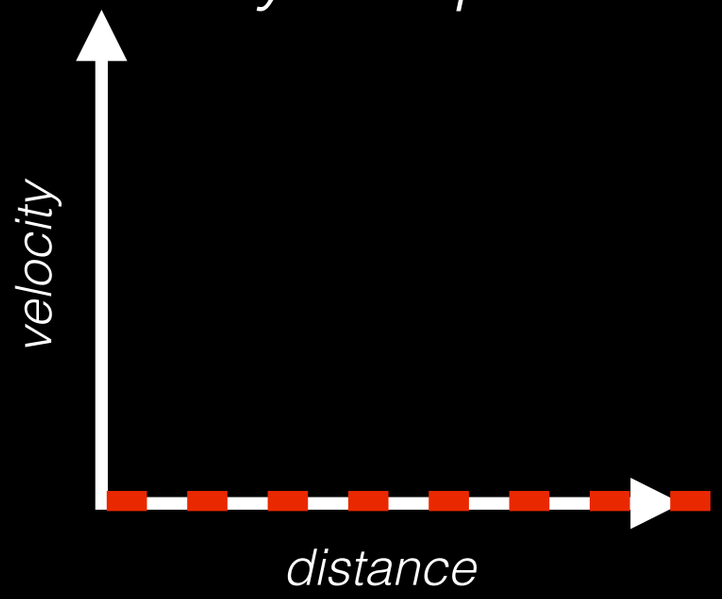
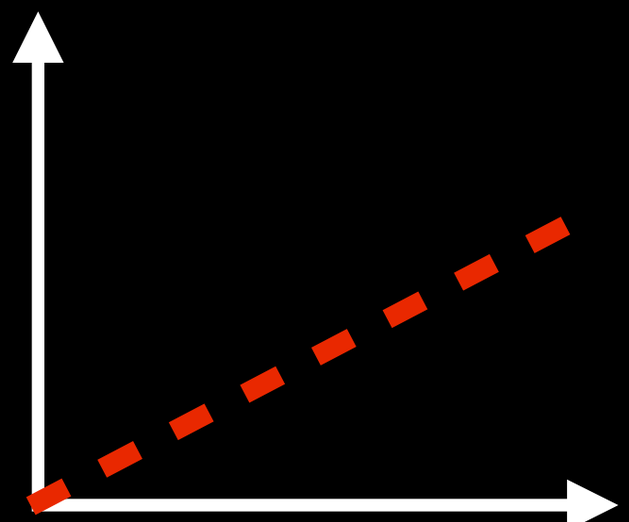


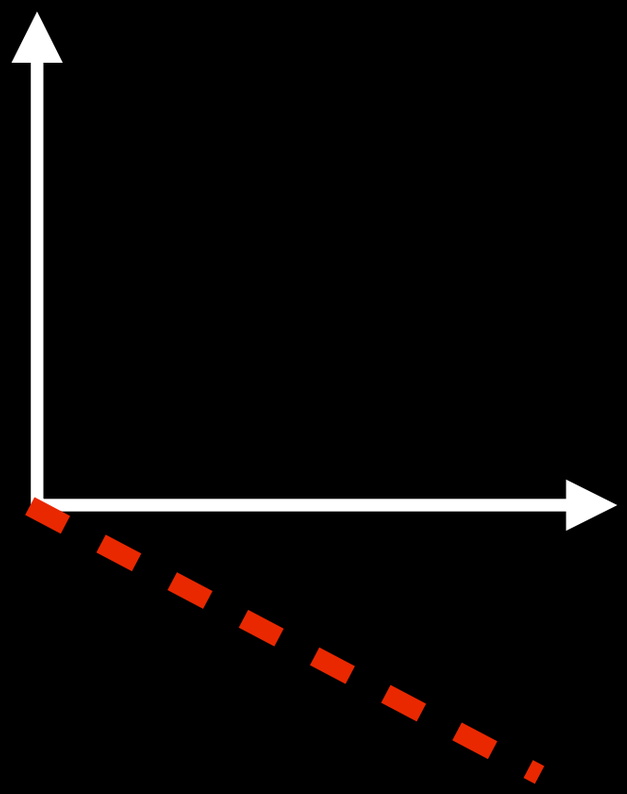
Answer to learning catalytics question.



Expanding



Contracting



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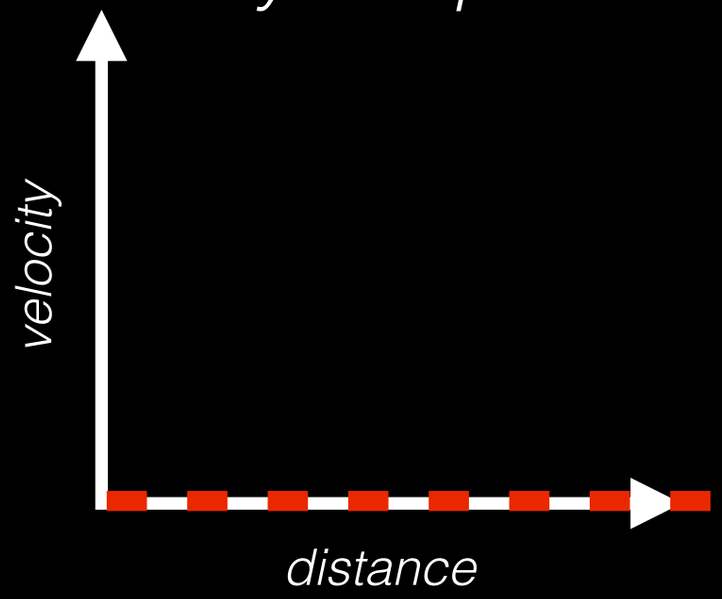
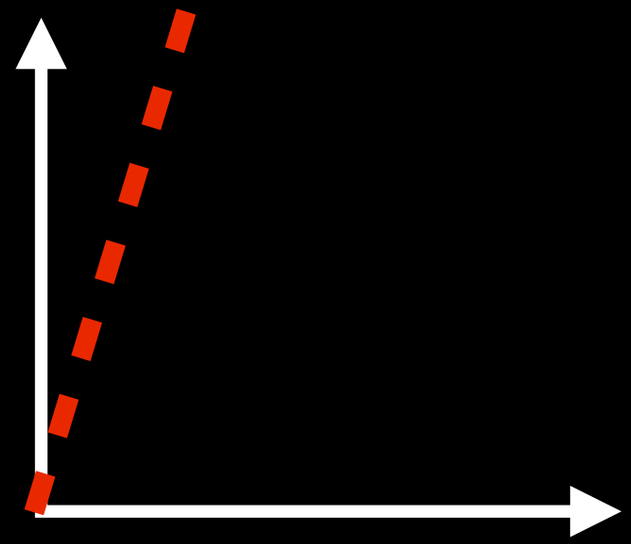
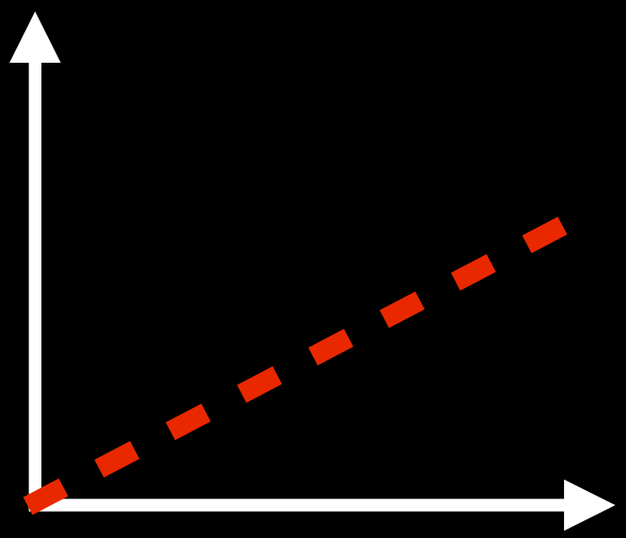


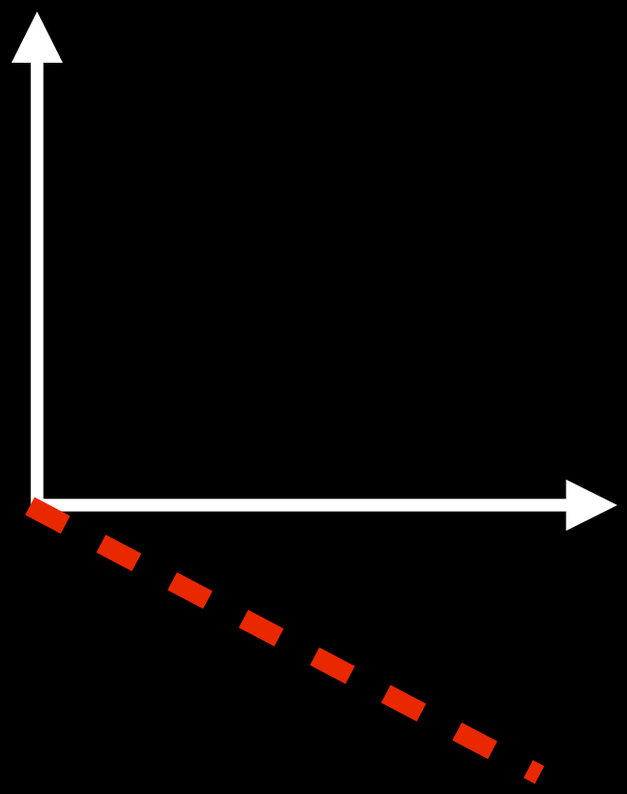
Expanding quickly



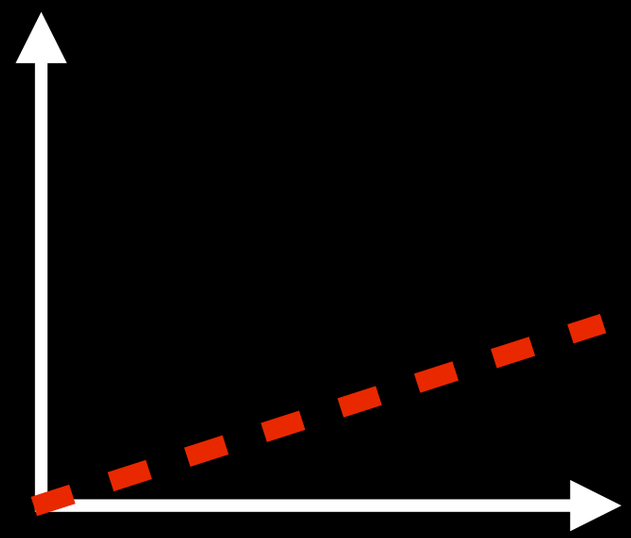
Expanding



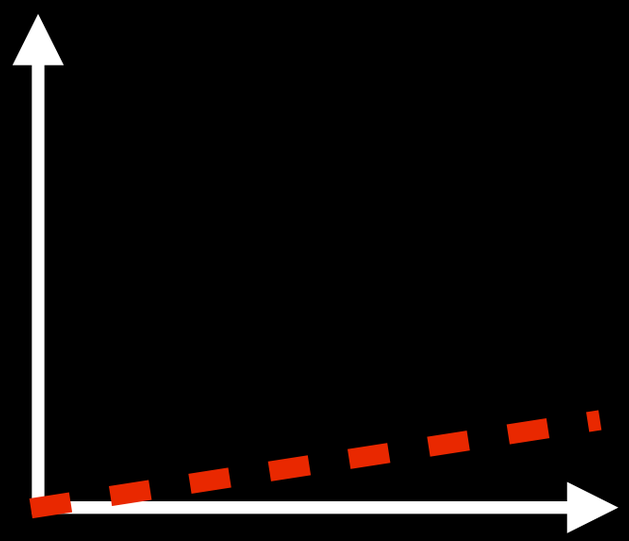
Contracting



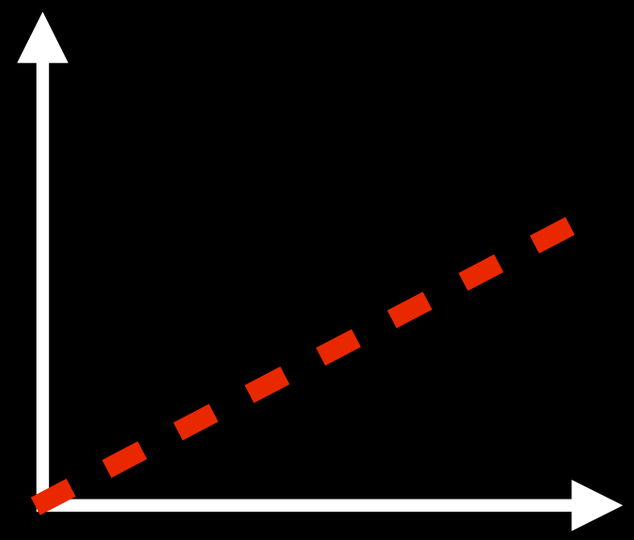
Expanding slowly



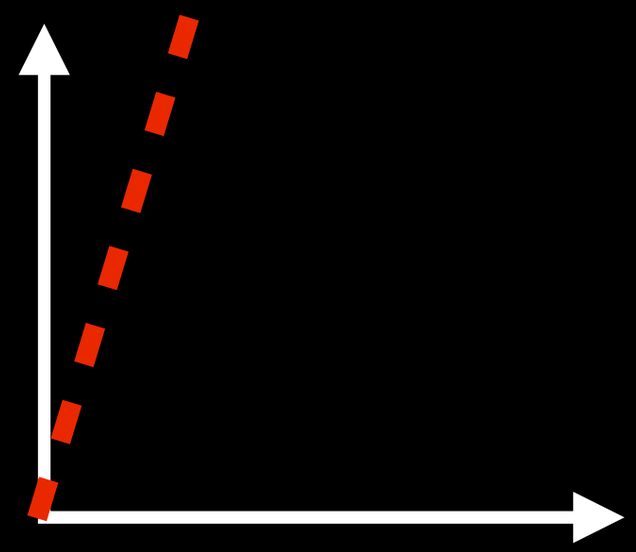
Expanding slowly



Expanding



Expanding quickly



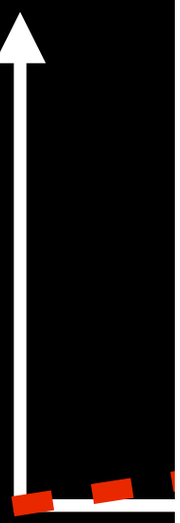
The slope of this line is called the **HUBBLE CONSTANT**, describes the expansion rate of the Universe.

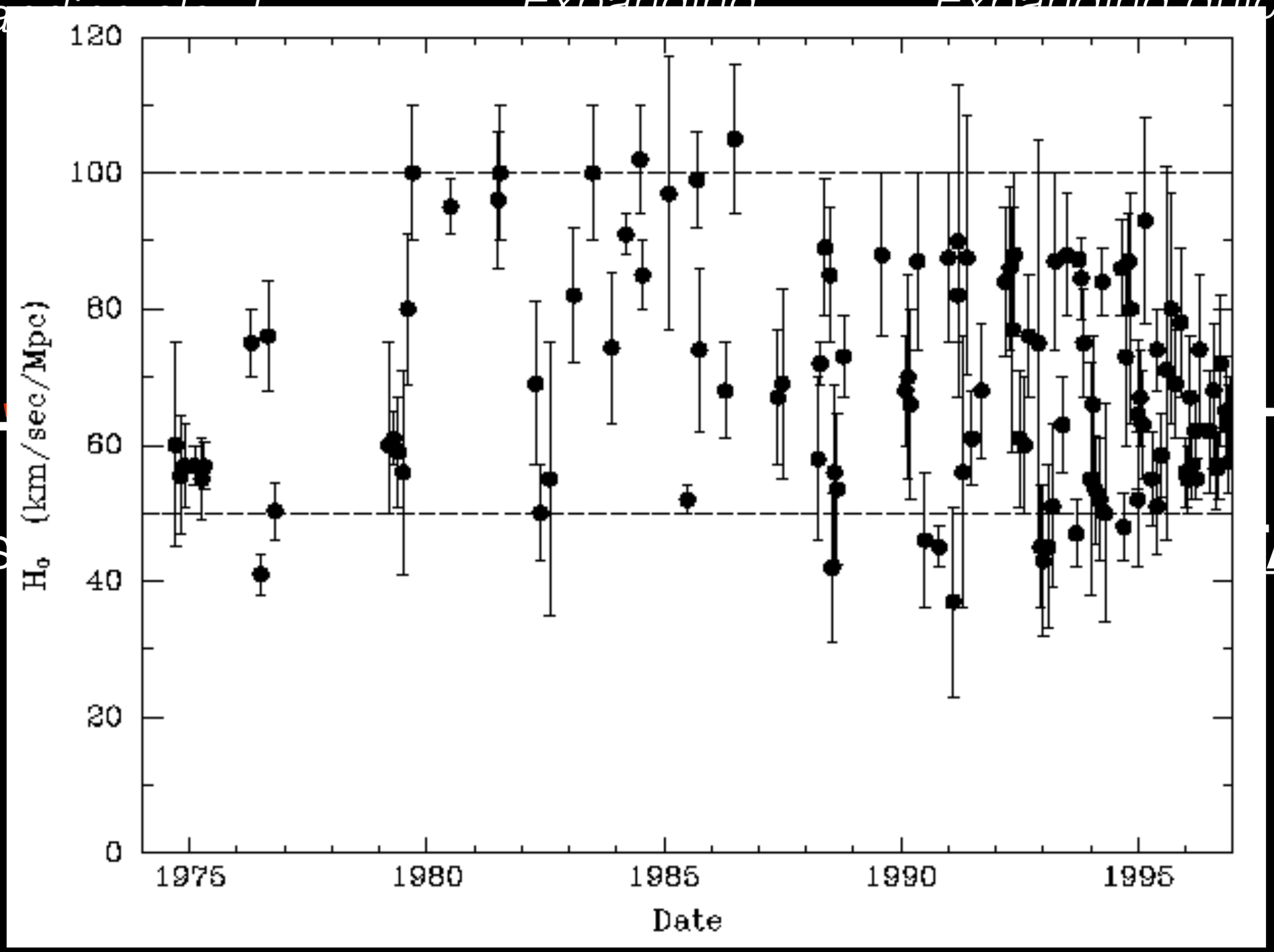
$$v = H_0 D$$

$$\downarrow$$

$$H_0 \approx 70 \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Expa *Expanding* *Expanding quickly*





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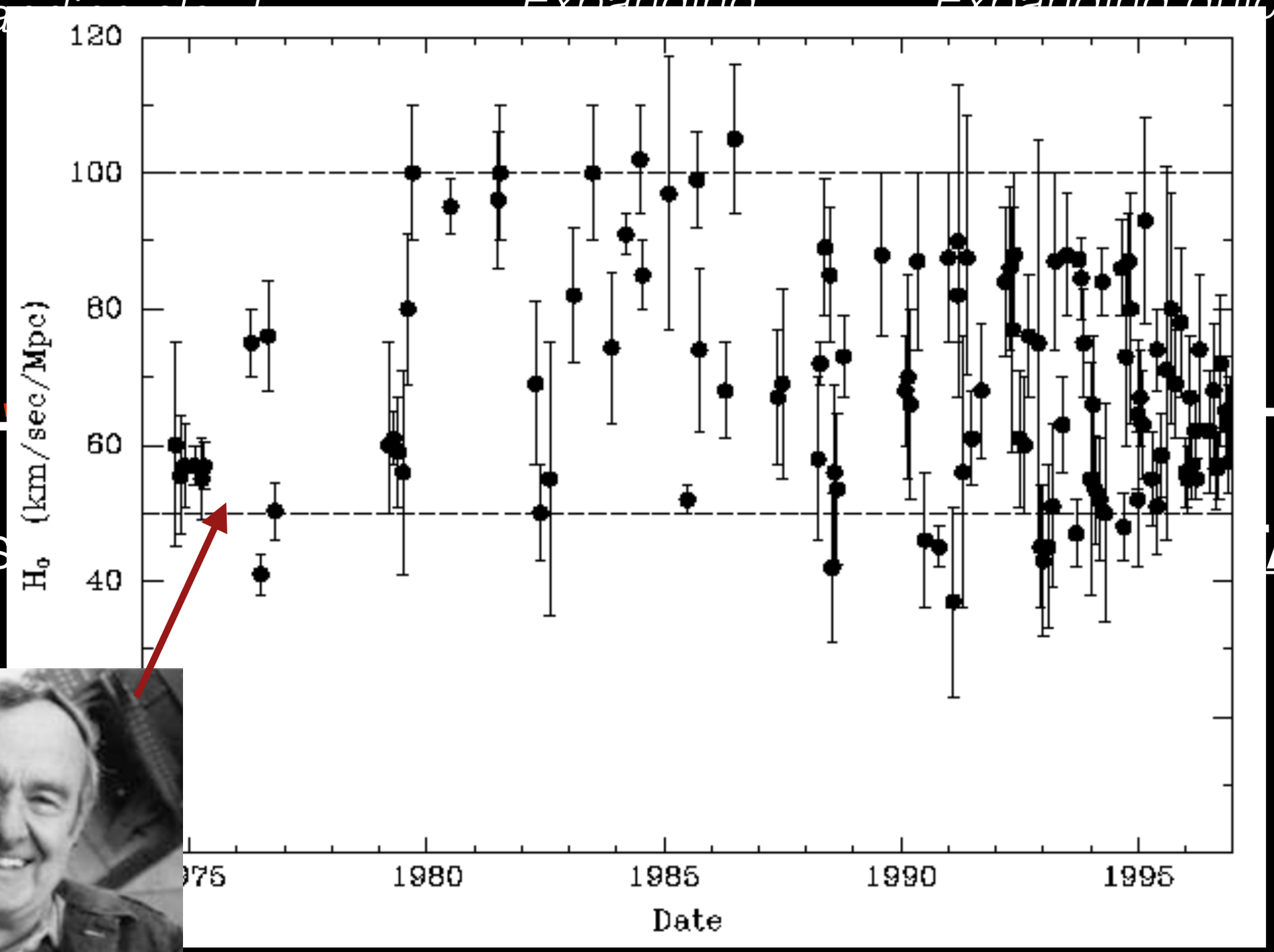

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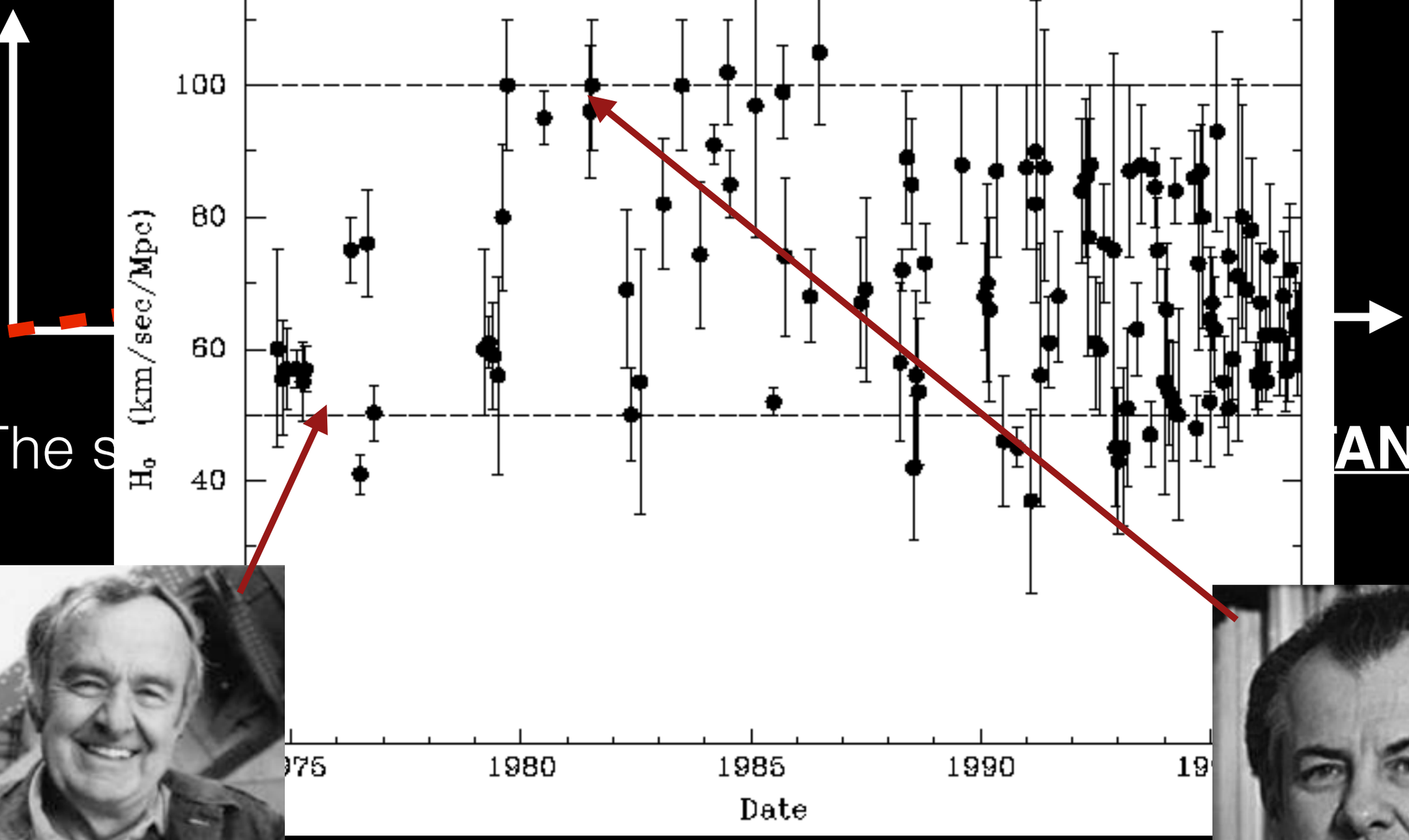
Expa *Expanding* *Expanding quickly*



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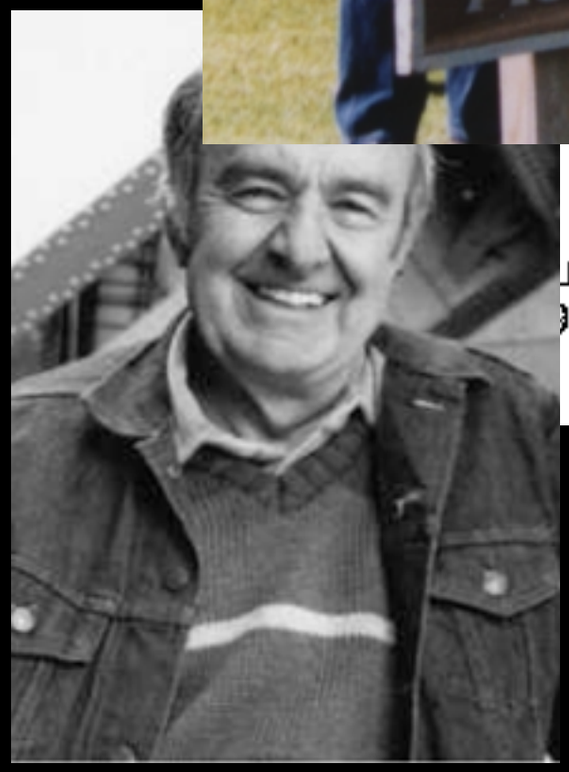
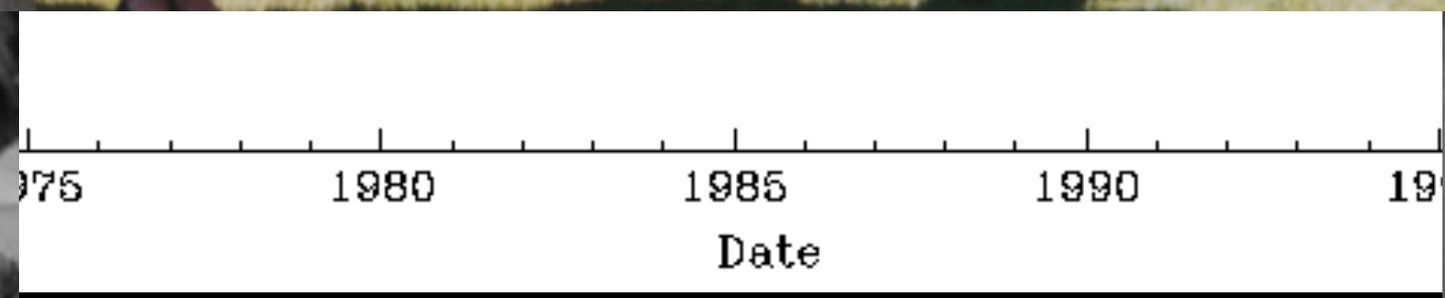
Ex

The





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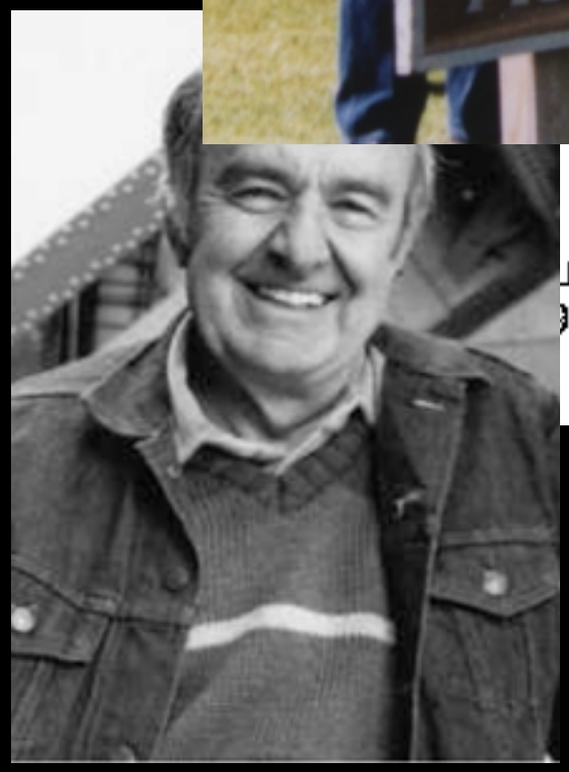
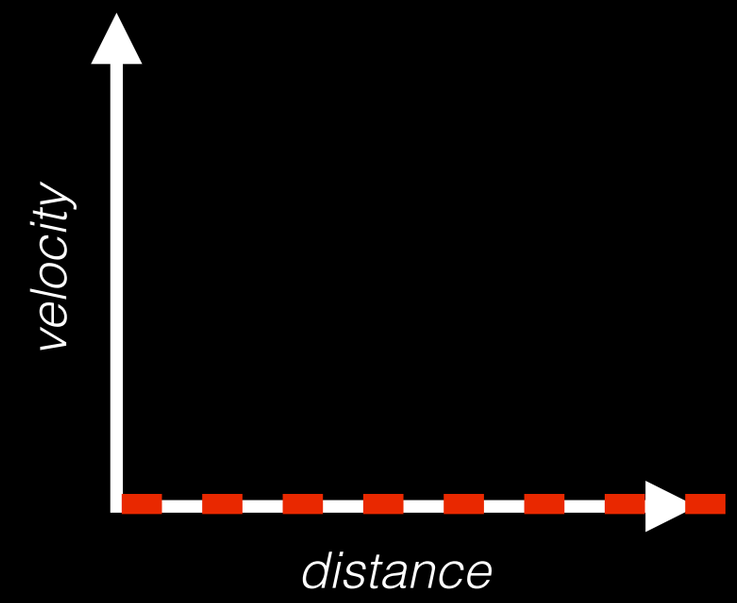
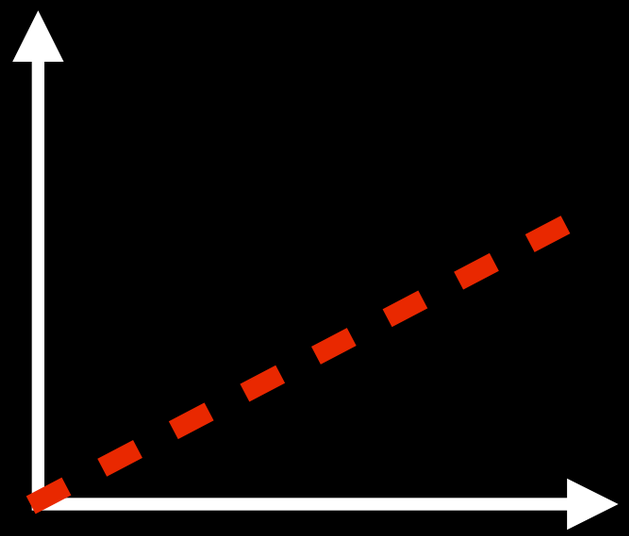


Question 13

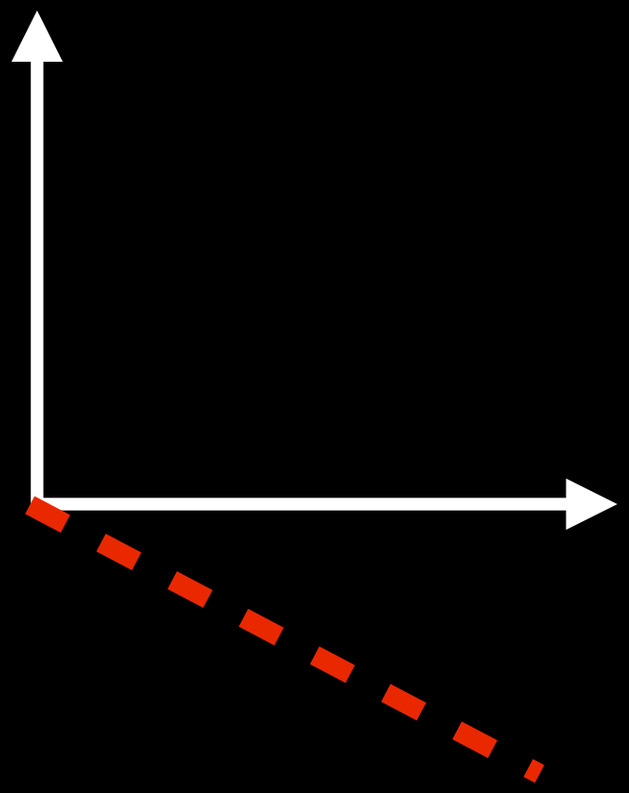


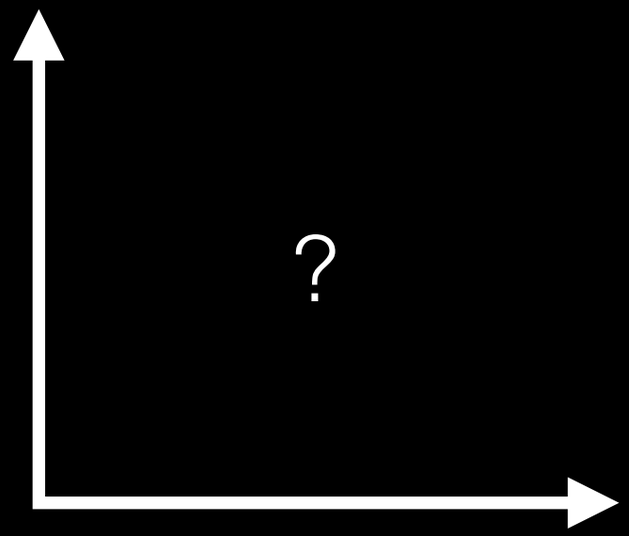
Now sketch what you think you might see for a Universe where the expansion rate increases throughout the lifetime of the Universe.

Expanding

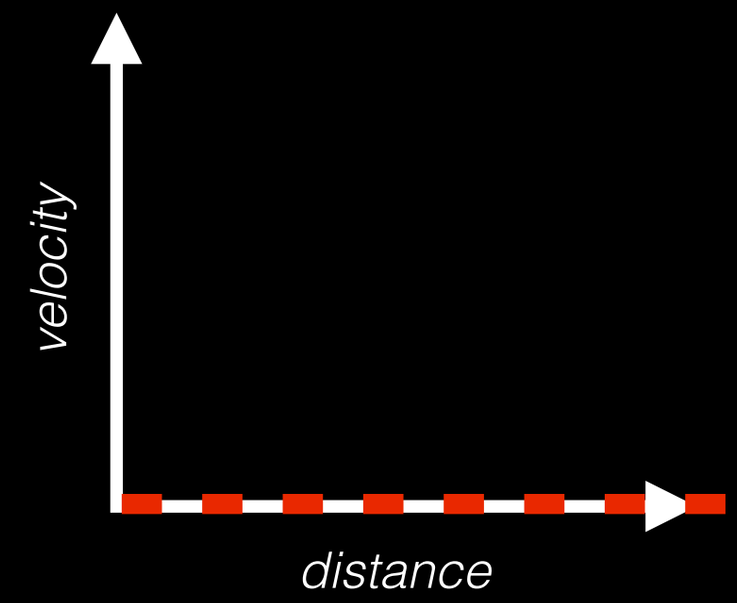


Contracting





Question 13



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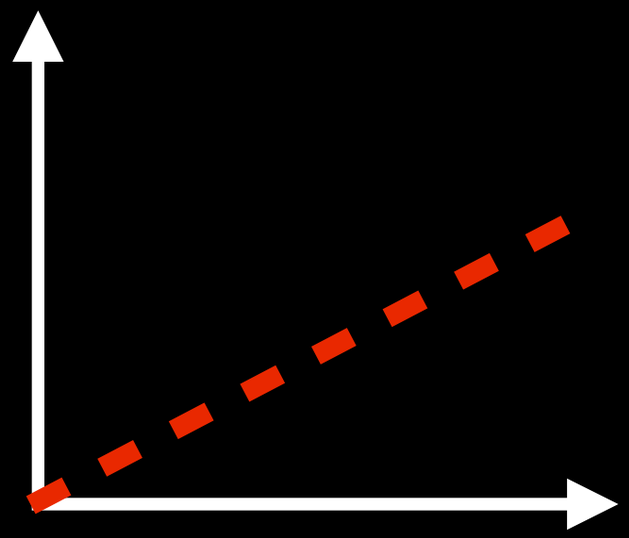

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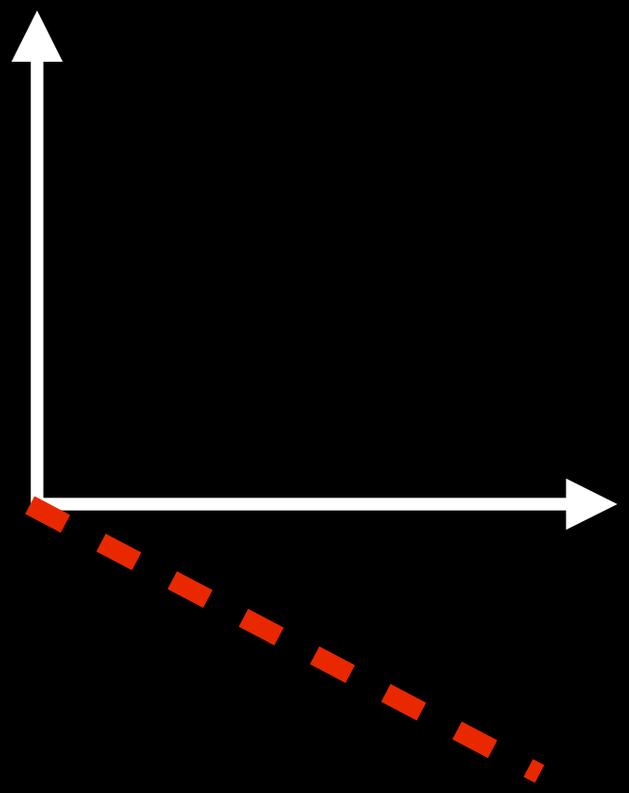
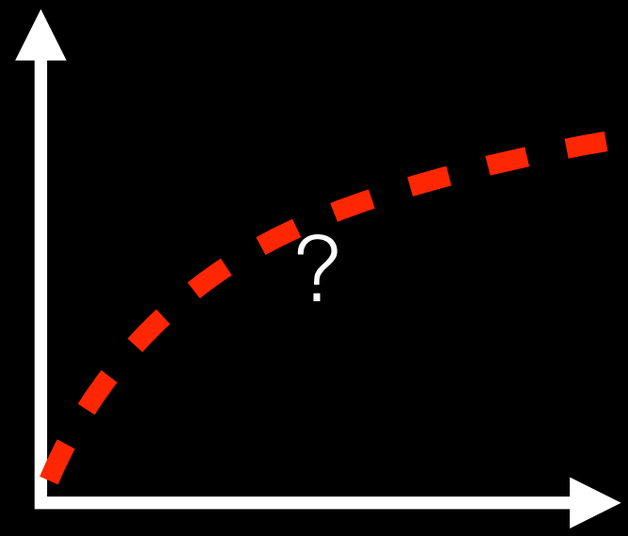
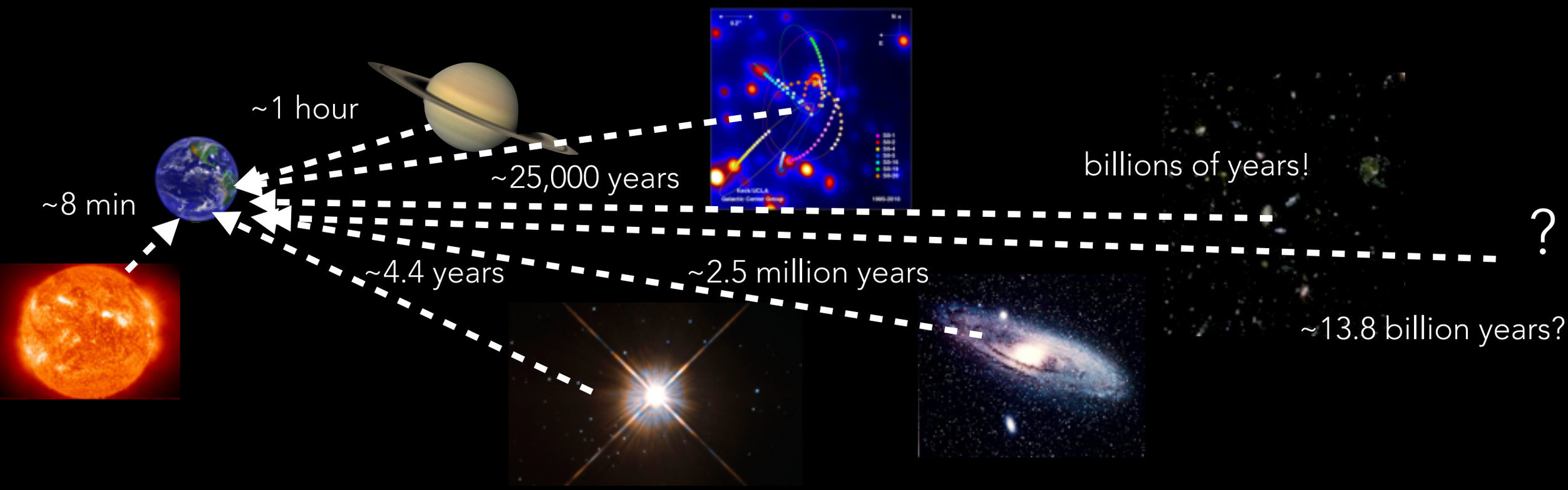




Recall from Lecture #1??



LIGHT is what we measure in the Universe,
and its speed is finite and fixed: 3 x10^8 m/s

THE FURTHER AWAY THINGS ARE THE LONGER IT TOOK THAT LIGHT TO REACH US.

2010s

1960s

1940s

1950s

1990s

1970s

Let’s use events from history to context this…

2010s

1960s

1940s

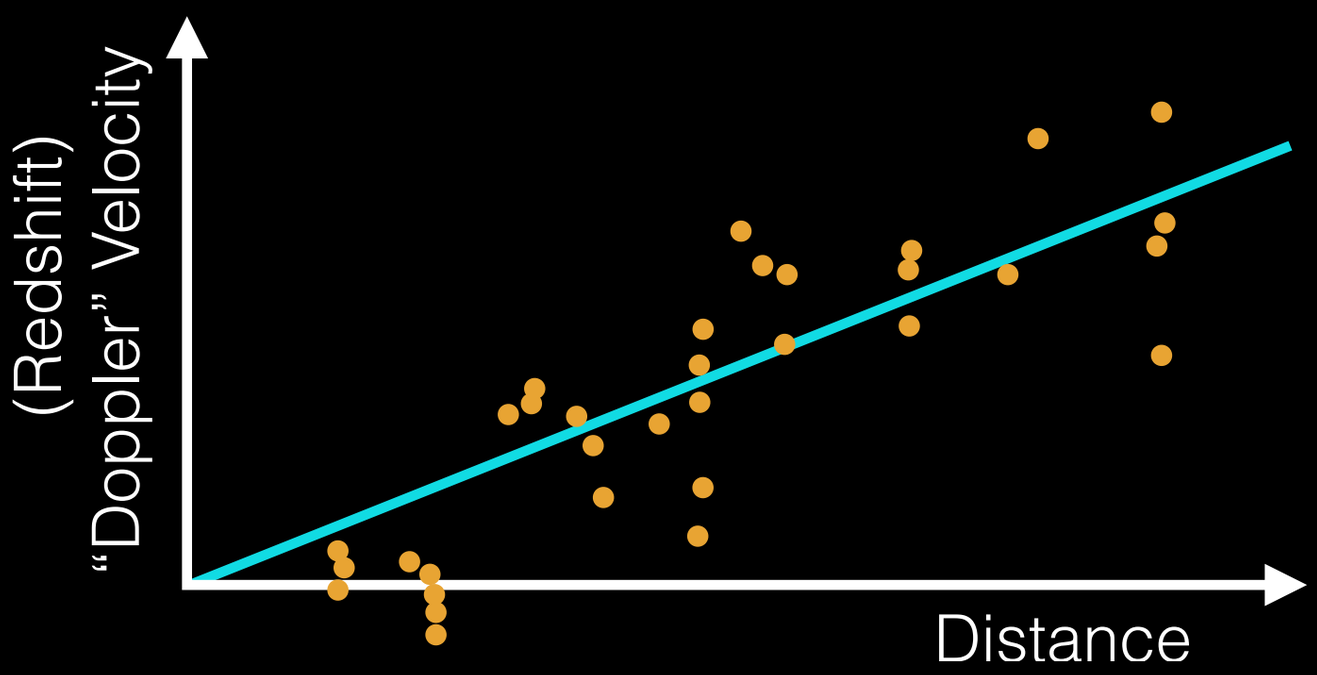
1950s

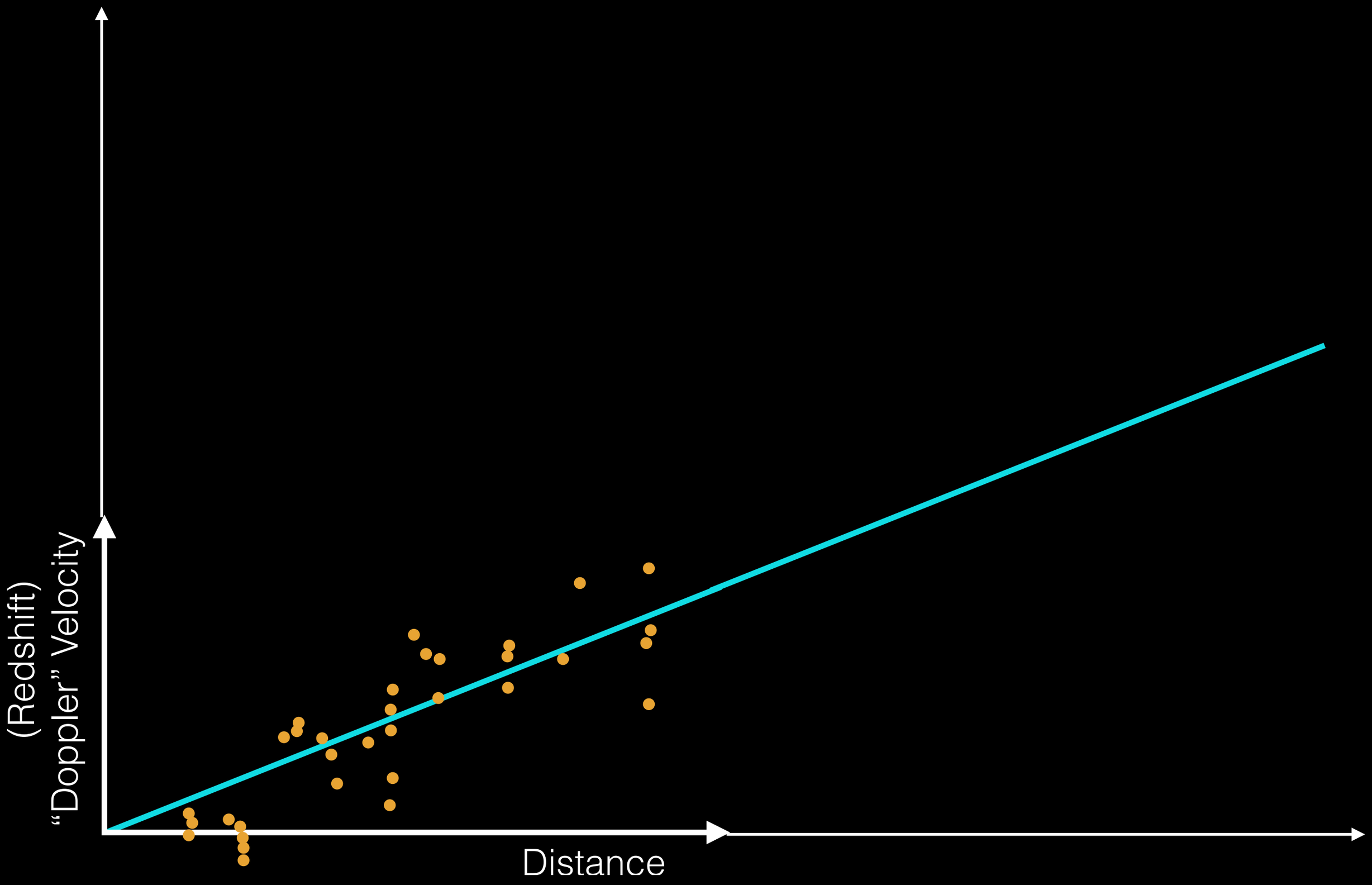
1990s

1970s

Let’s use events from history to context this…

f


(Redshift)
"Doppler" Velocity
Distance


(Redshift)
"Doppler" Velocity
Distance

faster growth

(Redshift)
"Doppler" Velocity

Distance

faster growth

(Redshift)
"Doppler" Velocity

slower growth

Distance

faster growth

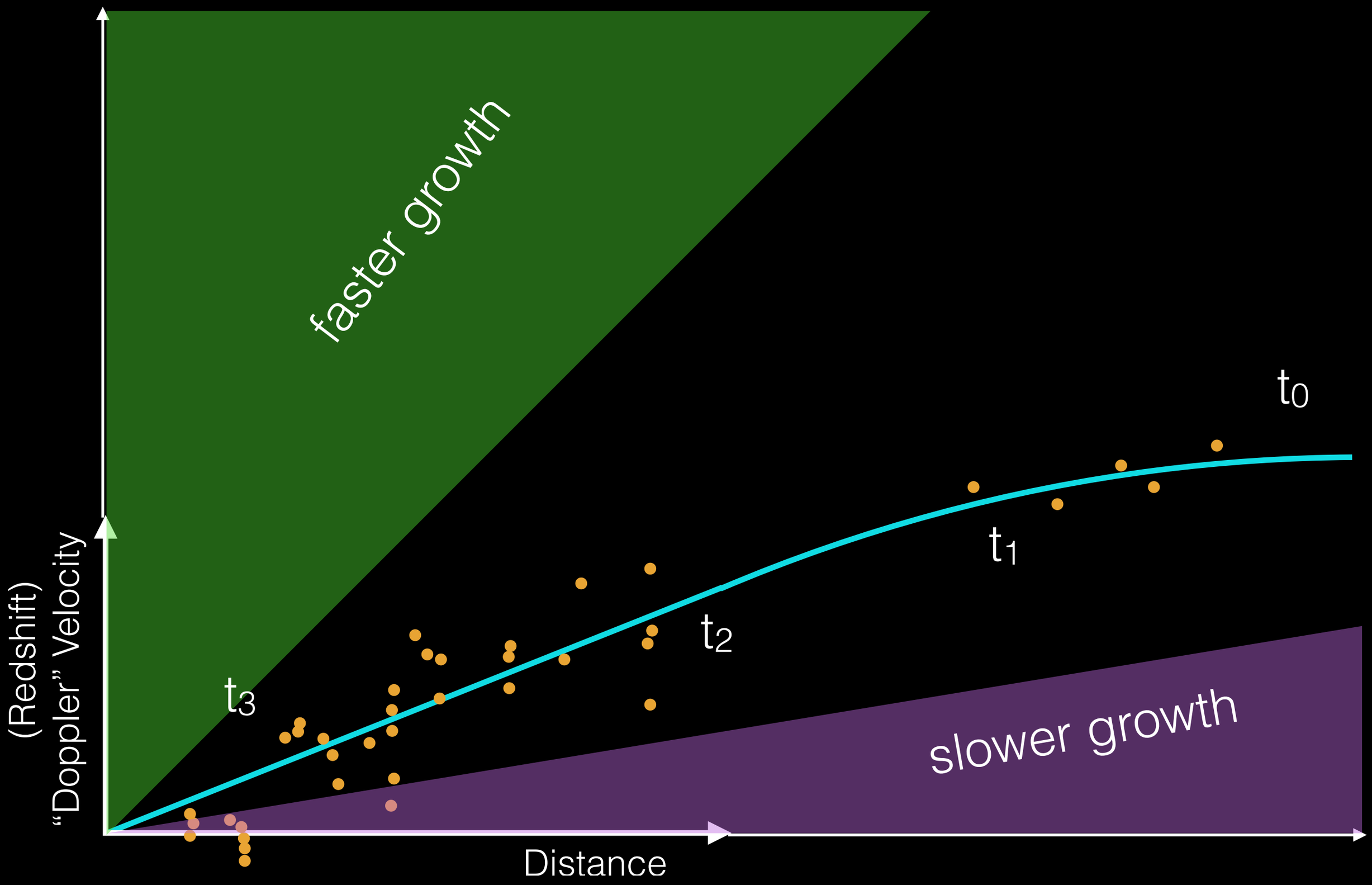
?

(Redshift)
"Doppler" Velocity

slower growth

Distance

How would you describe this type of curve on the Hubble plot?



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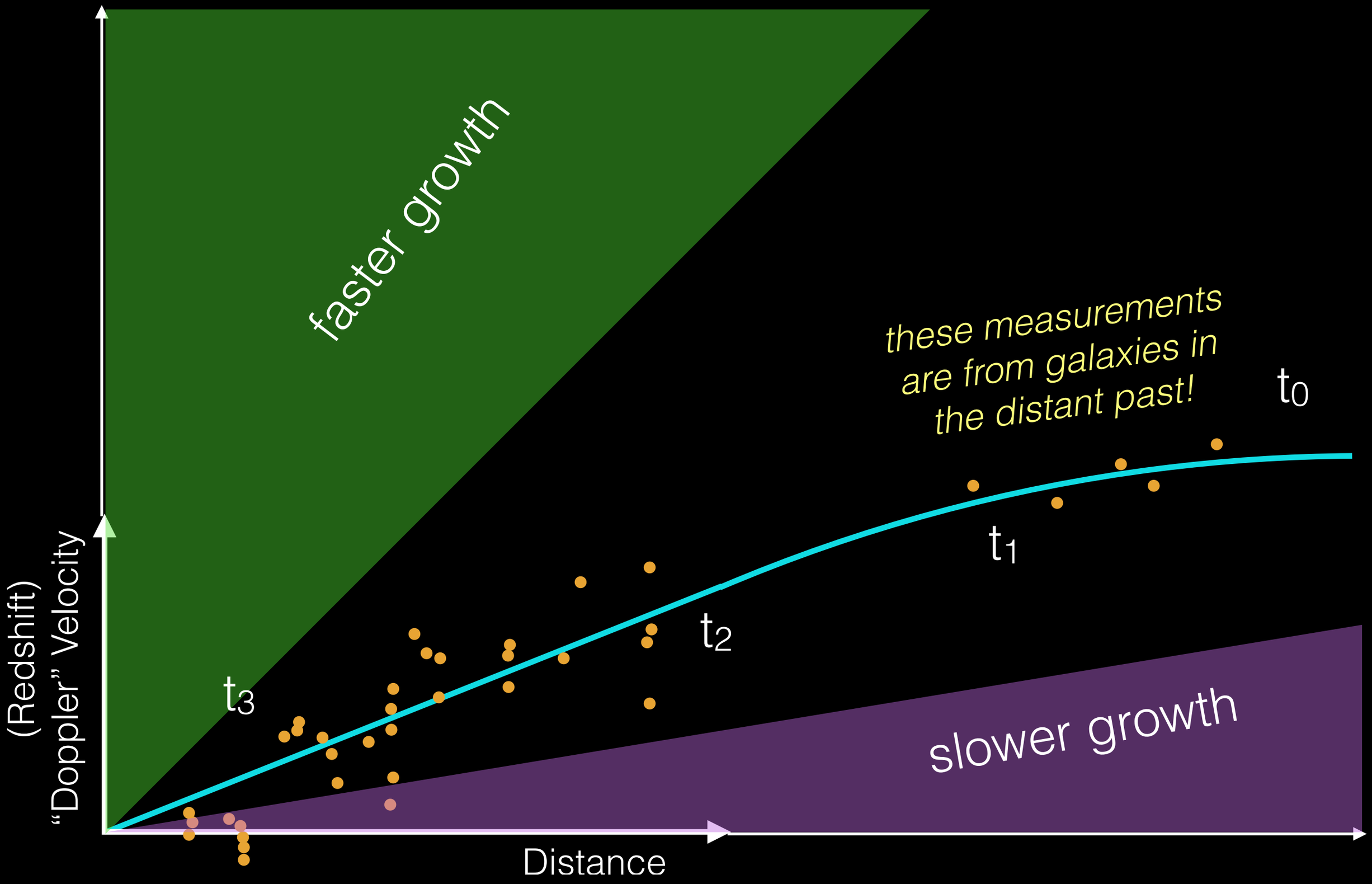


How would you describe this type of curve on the Hubble plot?

faster growth

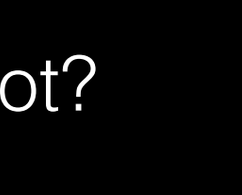
these measurements are from galaxies in the distant past!

t_0

t_1

t_2

t_3



slower growth

(Redshift) "Doppler" Velocity

Distance

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(Redshift) "Doppler" Velocity

Distance

One comment on distances.

The vast majority of galaxies do **NOT** have distance measurements. They only have redshift measurements, because Supernovae are rare, and cepheid variables only take us so far (not bright enough to see across the Universe). Most galaxies only have redshifts. But this is actually used as a distance proxy, in the context of the Hubble plot where we *do* have distances.