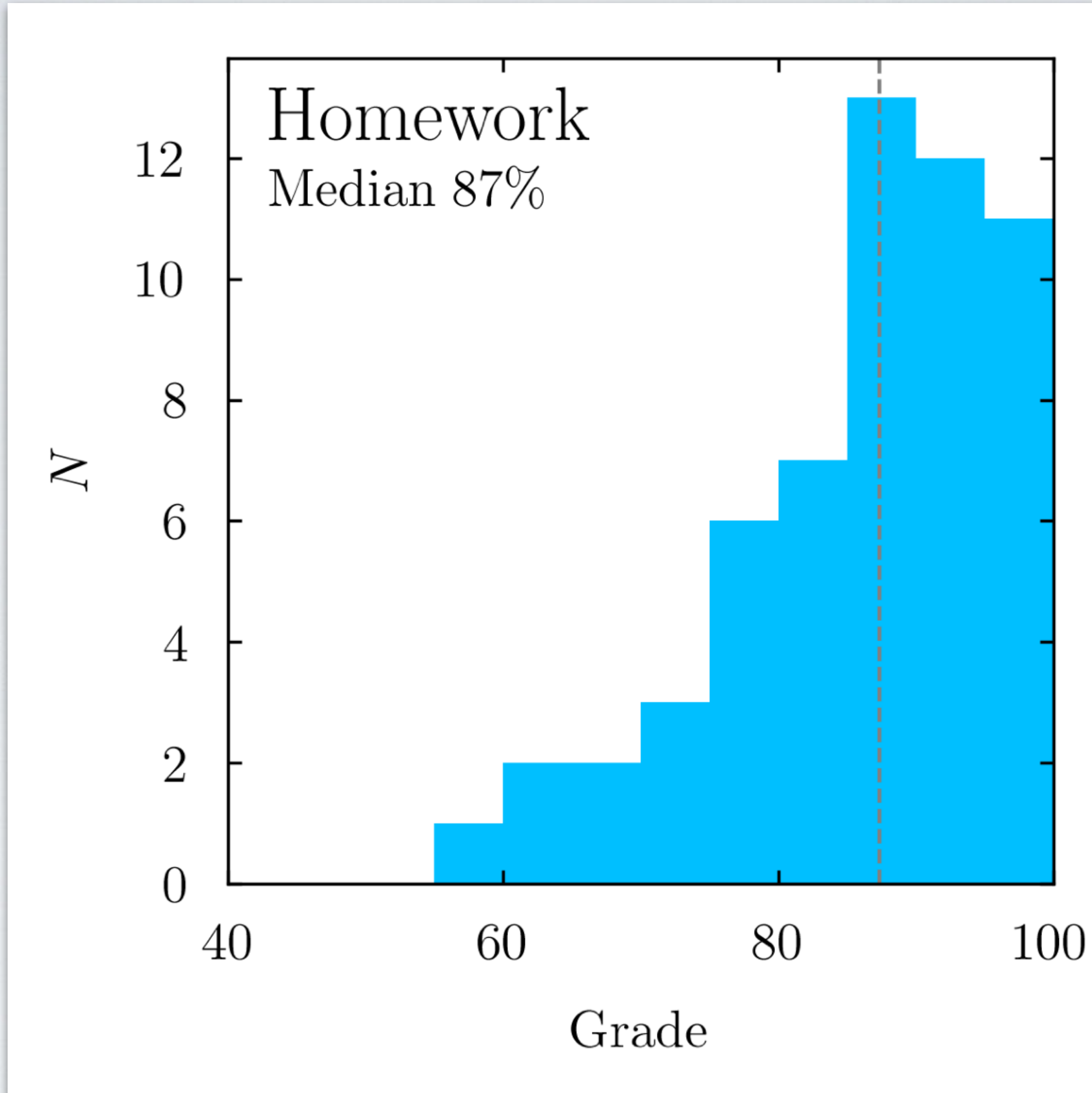
ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 18 • Measuring the invisible

11/04/2021

Grades



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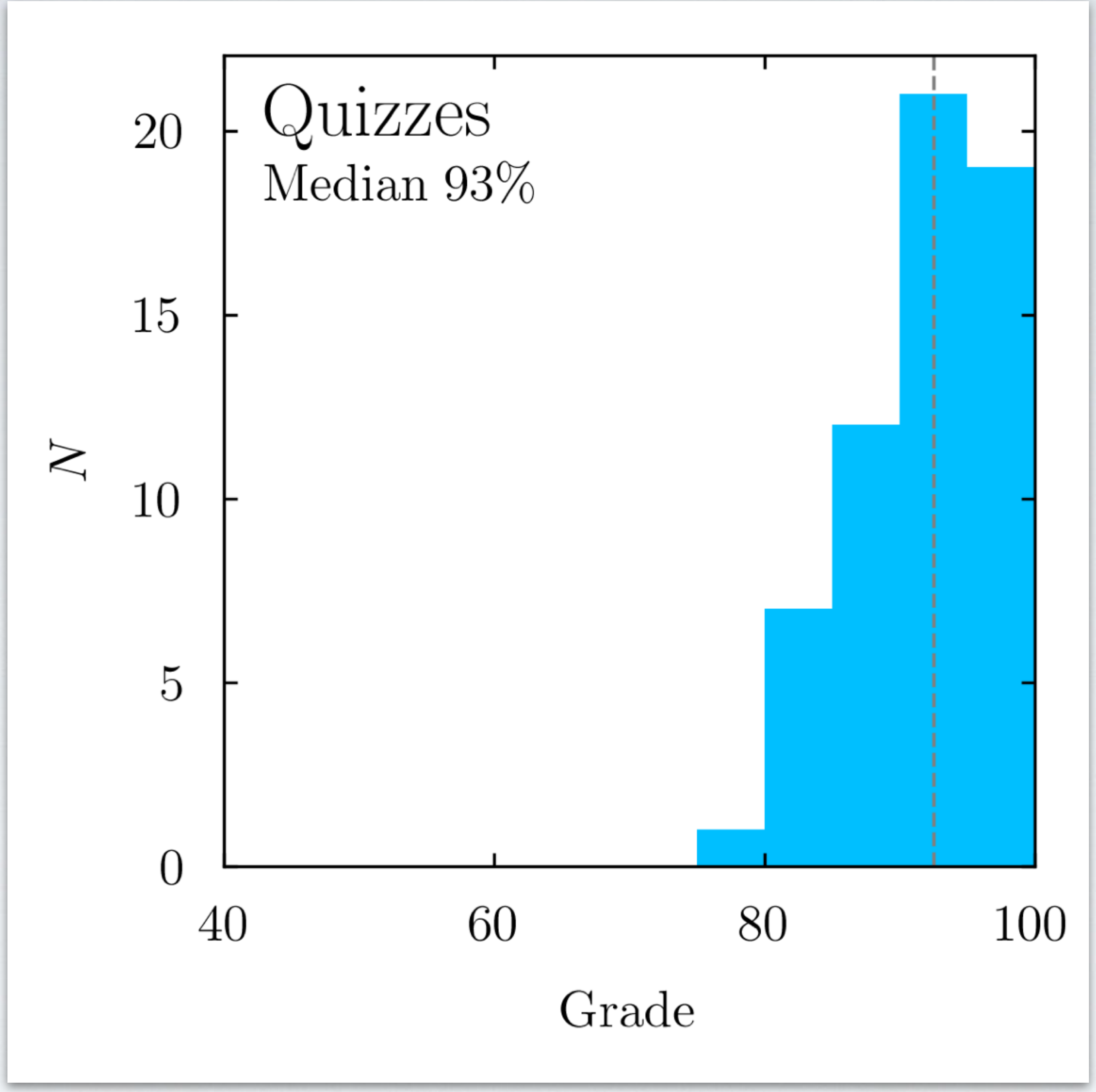

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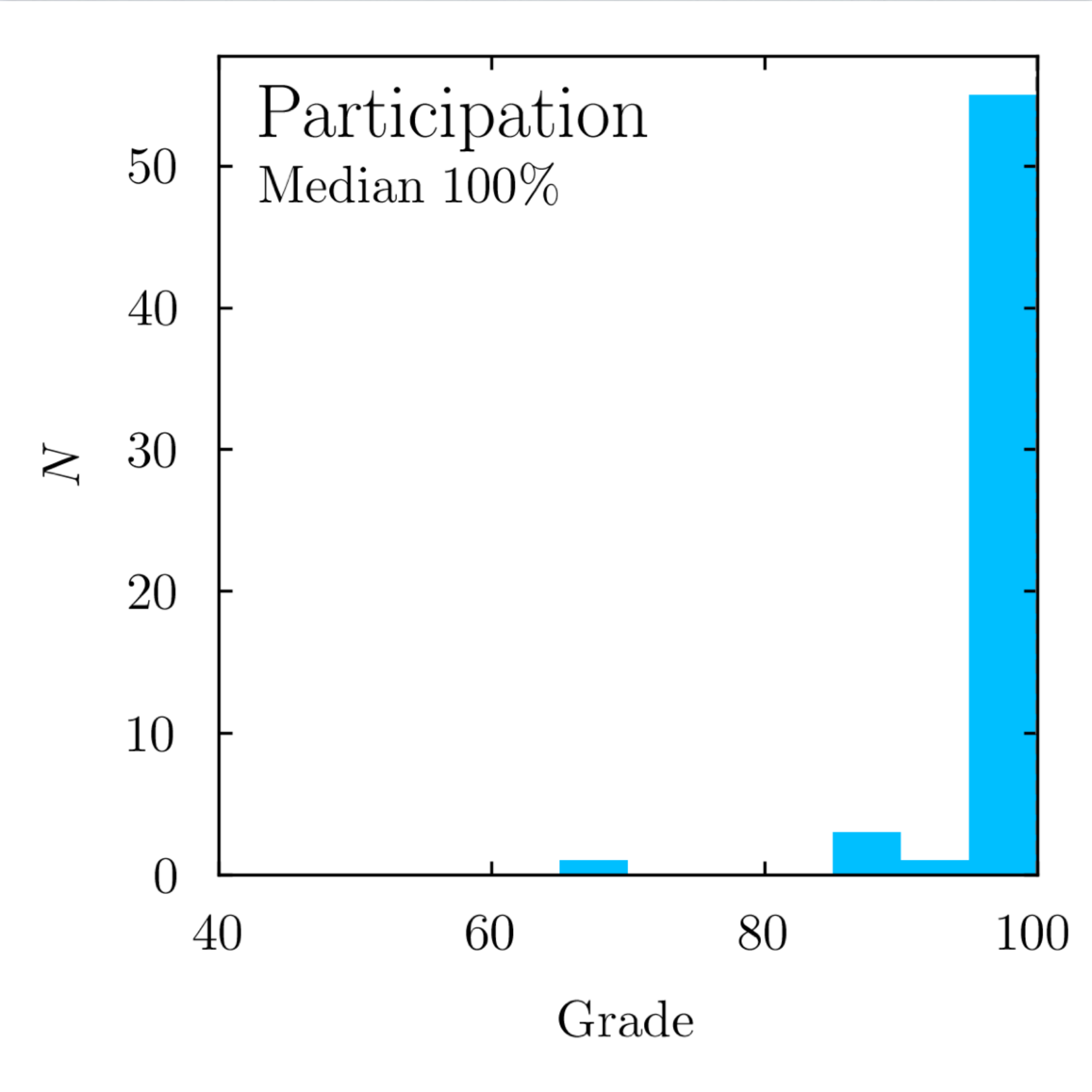

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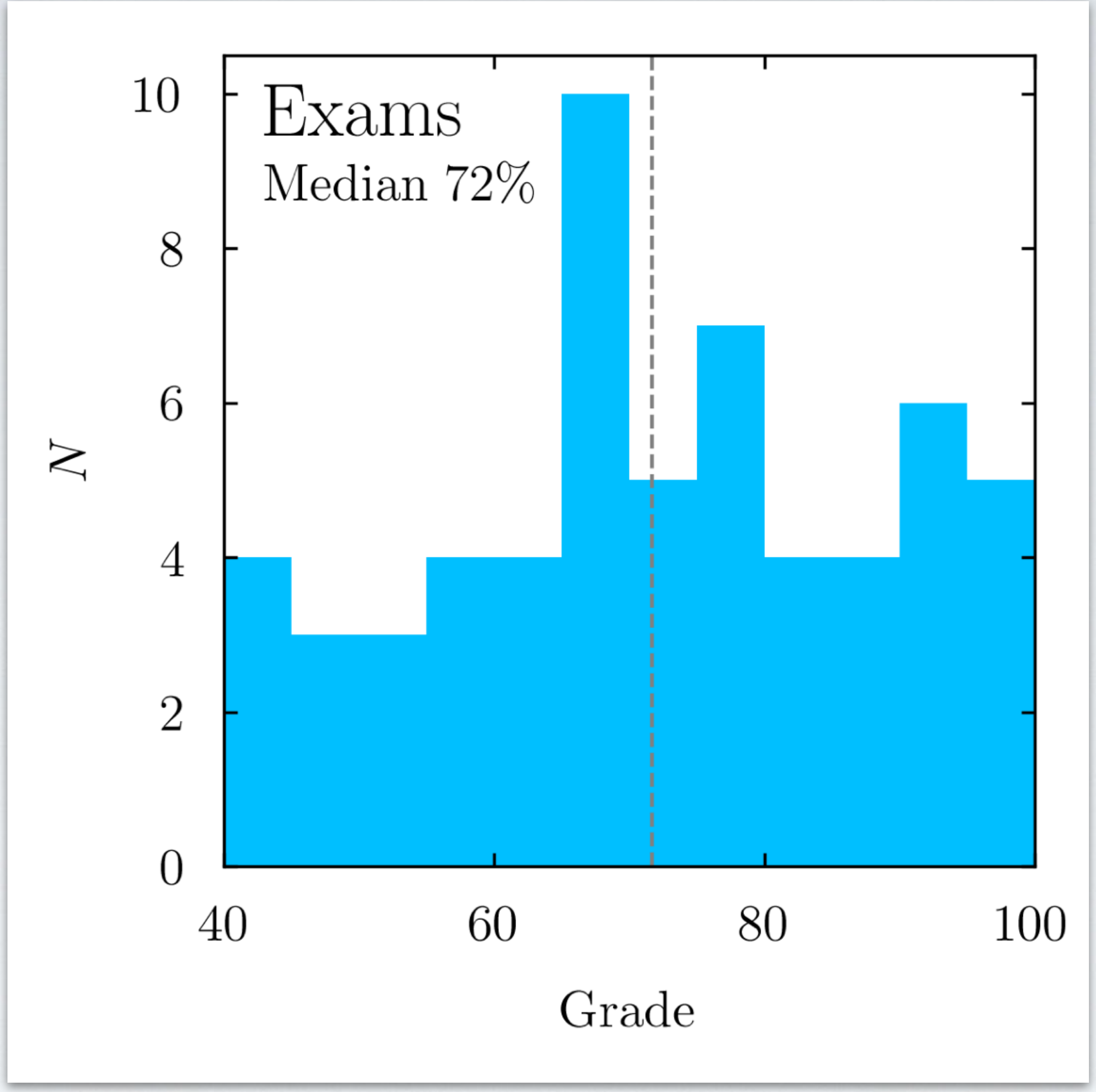

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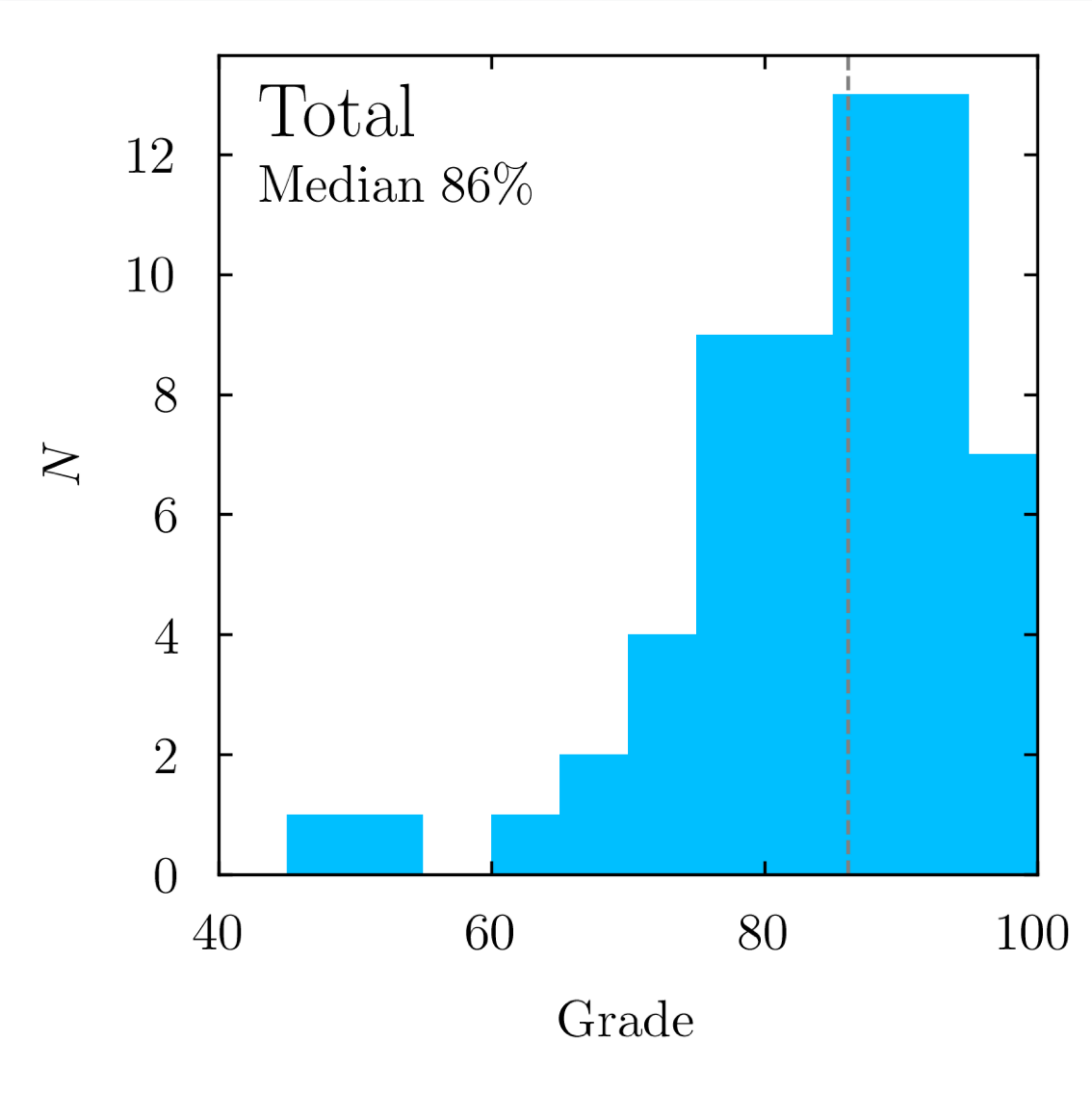


Recap

Participation: Recap #1

TurningPoint:
What is the critical density?

Session ID: diemer

30 seconds

Participation: Recap #2

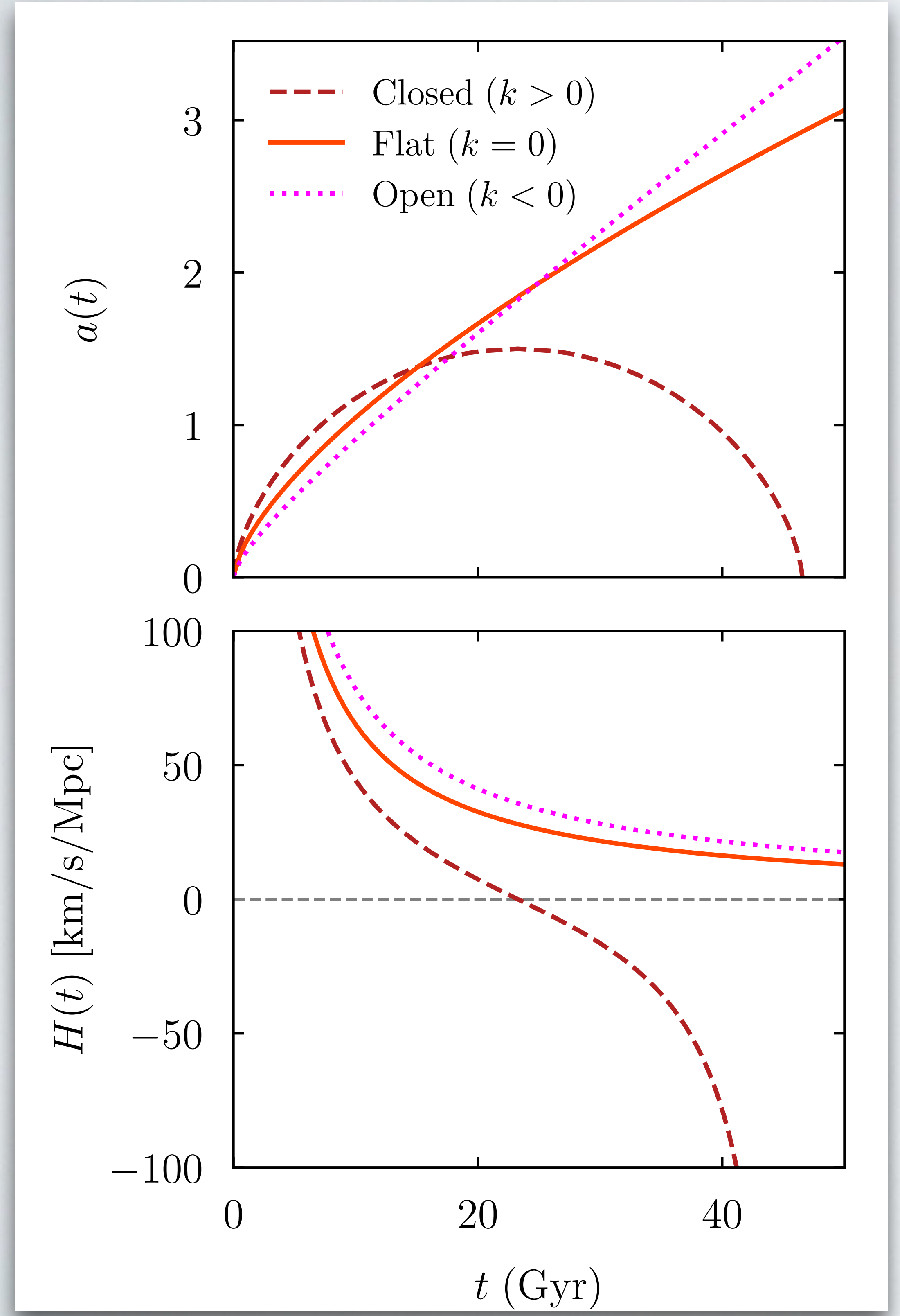
TurningPoint:
What happens to a Universe with Omega_m > 1
and no dark energy?

Session ID: diemer

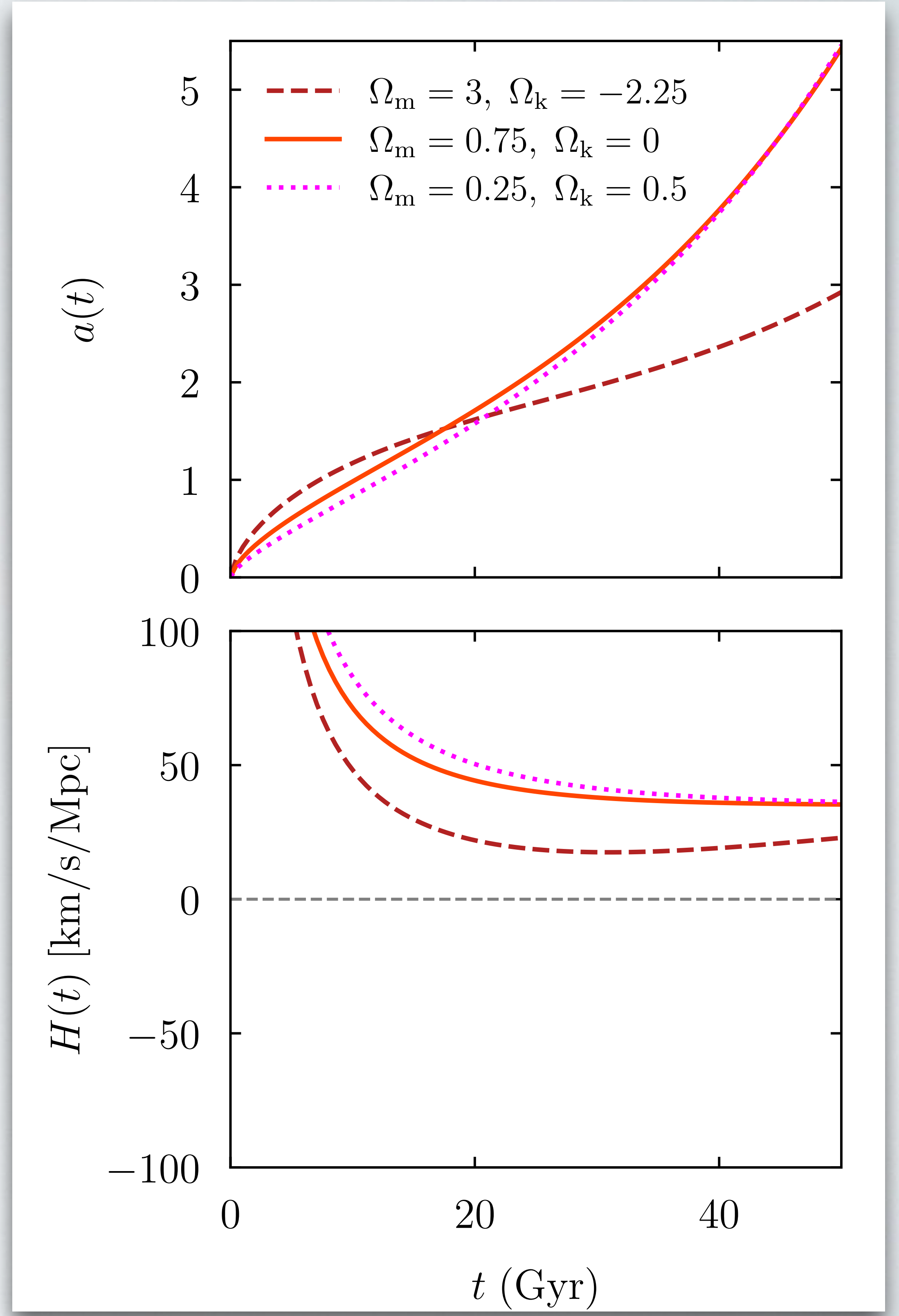
30 seconds

Matter + Dark Energy

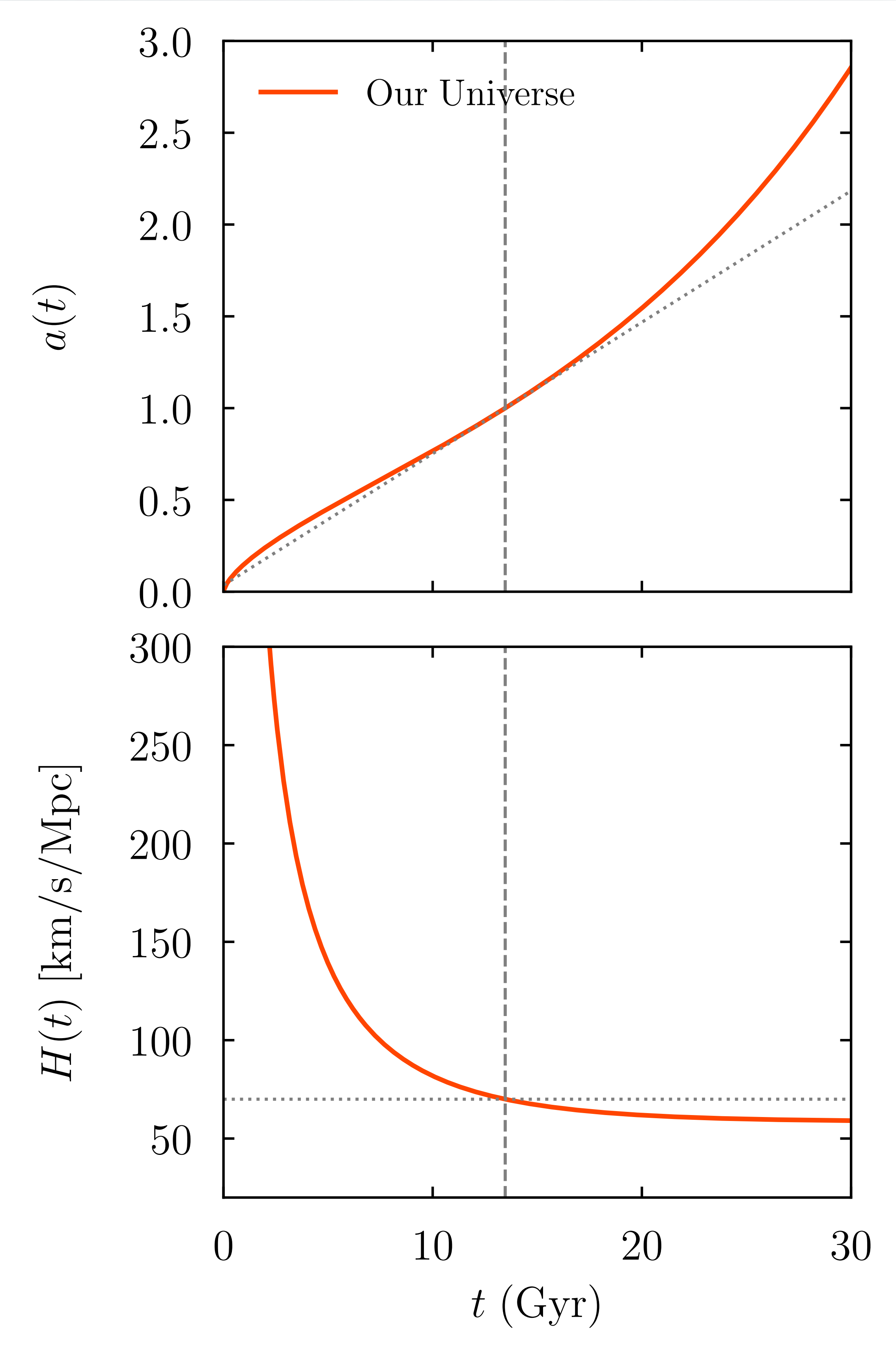
No dark energy ($\Omega_m + \Omega_k$)



With 25% dark energy ($\Omega_m + \Omega_k + \Omega_\Lambda$)



Our Universe



$$\Omega_{\mathrm{m},0} \approx 0.3$$

$$\Omega_{\Lambda,0} \approx 0.7$$

$$\Omega_{\mathrm{k},0} \approx 0$$

$$H_0 \approx 70 \text{ km/s/Mpc}$$

- **Flat** (as far as we can tell)
- Dominated by **dark energy** (since $t \approx 10$ Gyr)
- DE looks like **cosmological constant**
- Will undergo **accelerated expansion** forever (unless we're missing something)
- Hubble time is (coincidentally) quite close to true age of Universe

Participation: Recap #3

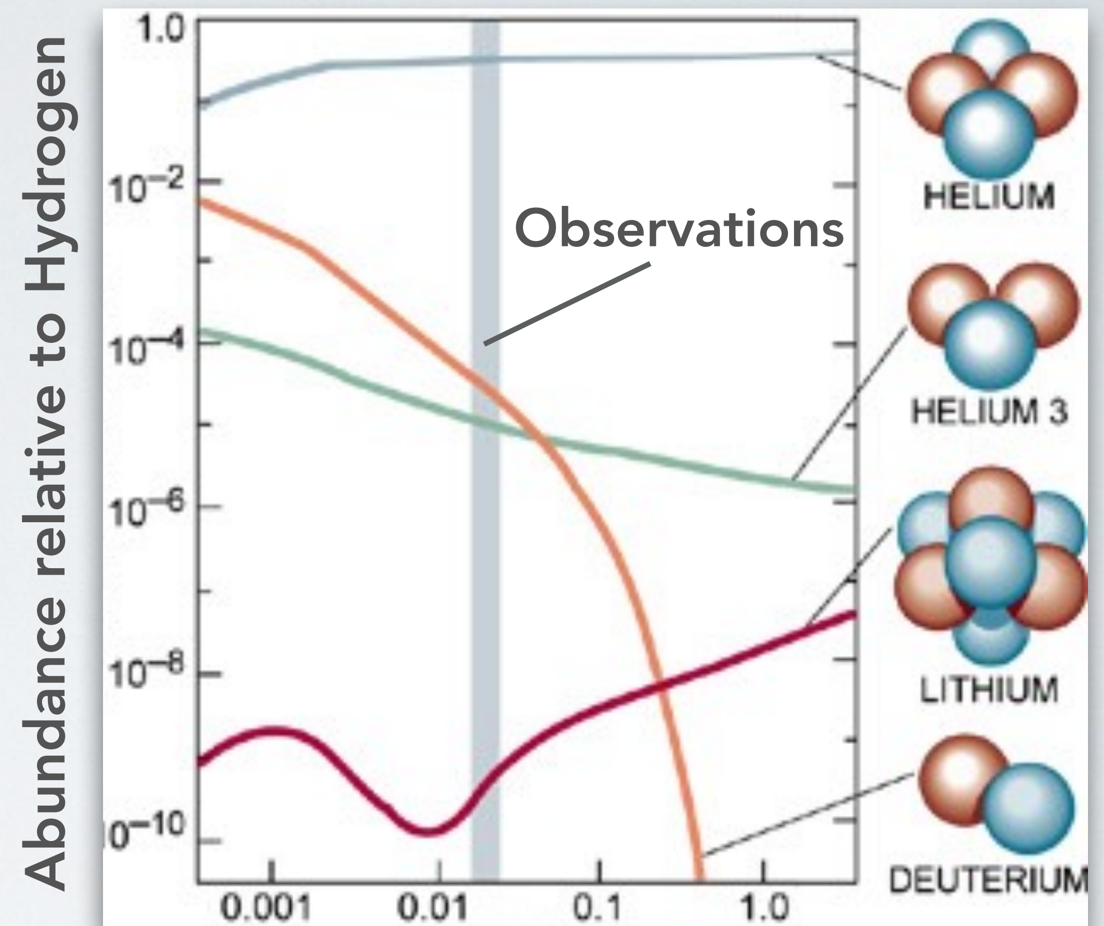
TurningPoint:
From Big Bang nucleosynthesis we concluded that the density of baryons in units of the critical density, Omega_b, is?

Session ID: diemer

30 seconds

Baryon Density

- In astromomy, **"baryons" means "normal matter"** (i.e., standard model particles that we know and understand)
- Abundances are determined by evolving **density** (how often particles hit each other) and **temperature** (how hard they hit), and **neutron decay**
- Can be worked out by computer; depends on **baryon density relative to critical density**
- We can use the spectra of stars and nebulae to measure abundances of elements (corrected for reactions inside stars)
- By **measuring the abundance** of H, D, ^{3}He, ^{4}He, and ^{7}Li, we can test the consistency of the Big Bang model - are relative abundances all consistent?



$\Omega_{b,0}h^2$

$$h = \frac{H_0}{100\text{km/s/Mpc}} \approx 0.7$$

$$\Omega_{b,0} \equiv \frac{\rho_{b,0}}{\rho_{c,0}}$$

$$\rho_c(t) = \frac{3H^2(t)}{8\pi G}$$

$$\Omega_{b,0}h^2 \approx 0.019 \implies$$

$$\Omega_{b,0} \approx 0.05$$

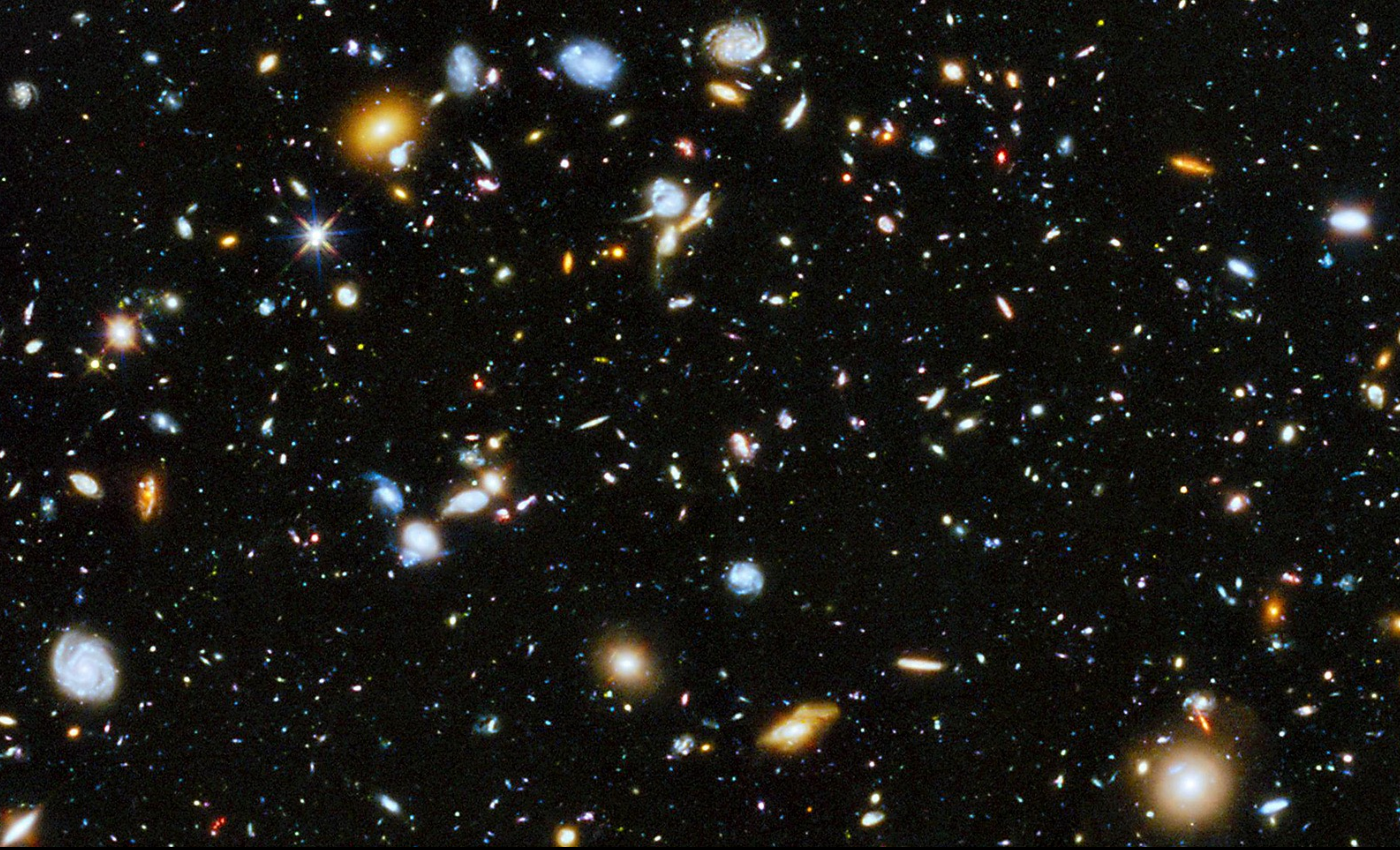
Baryons are only 5% of the critical density!

Plot by Martin White

Today

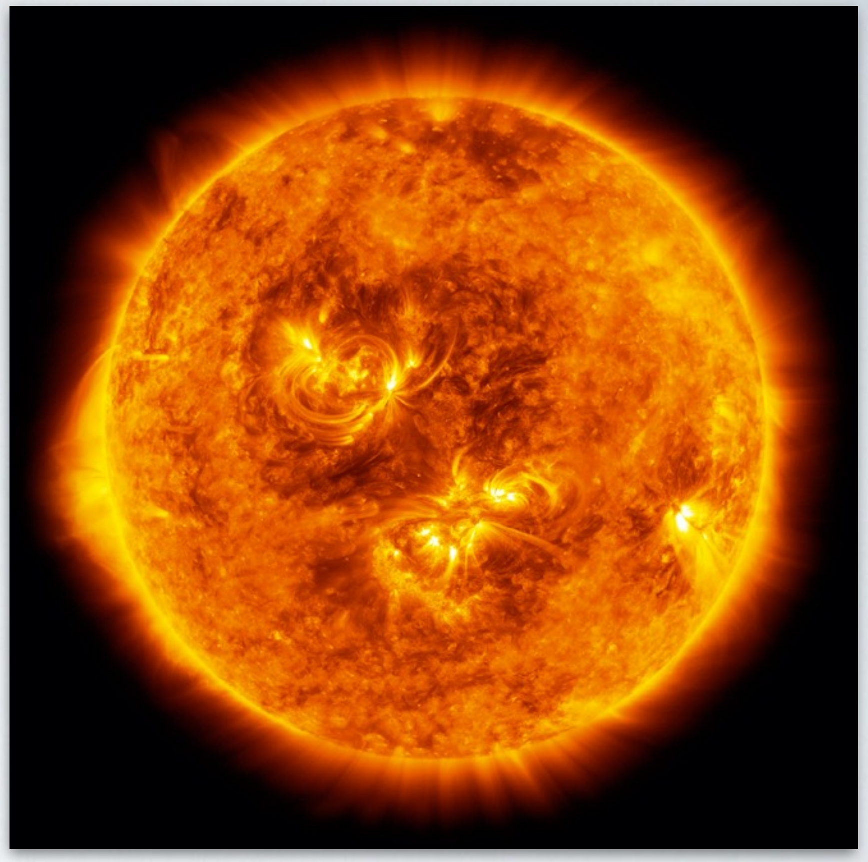
- The need for dark matter
- A new rung in the distance ladder
- Observing acceleration

Part 1: The need for dark matter



Idea: let's count the mass of everything we can see

Counting the mass of stars



- The easiest thing to see: **star light from galaxies**
- But we need to convert from light to mass ("mass-to-light ratio")
- Start by considering the Sun:
  - $M_\odot = 2 \times 10^{33}\text{g}$
  - $L_\odot = 4 \times 10^{33}\text{erg/s}$

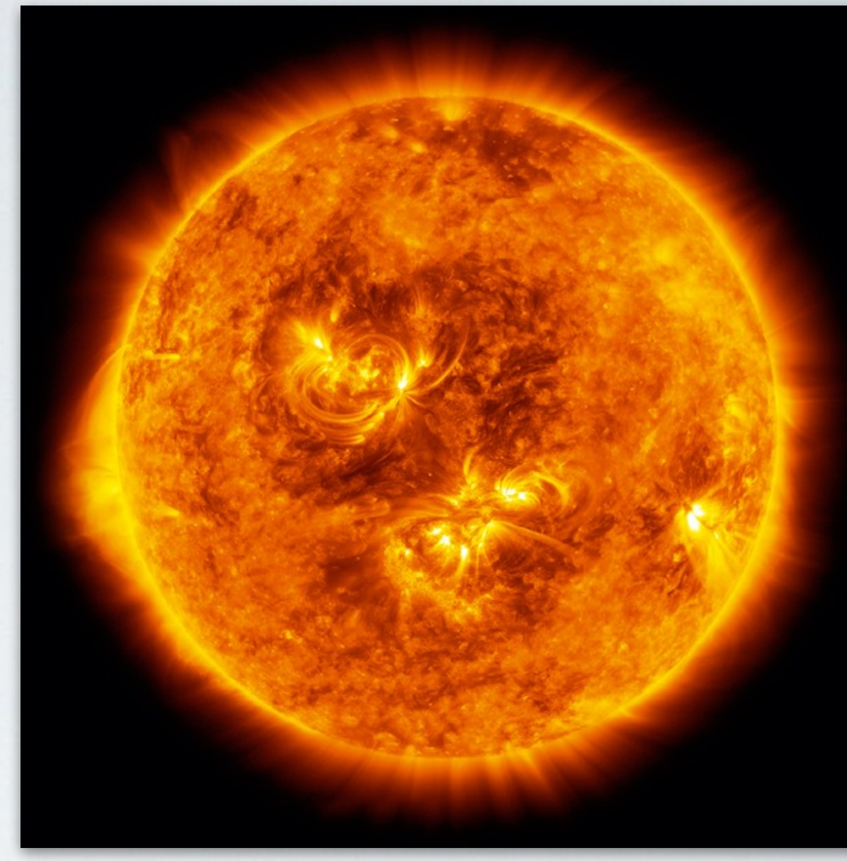
Participation: Mass-to-light ratio

TurningPoint:
Which stars produce more luminosity per mass?

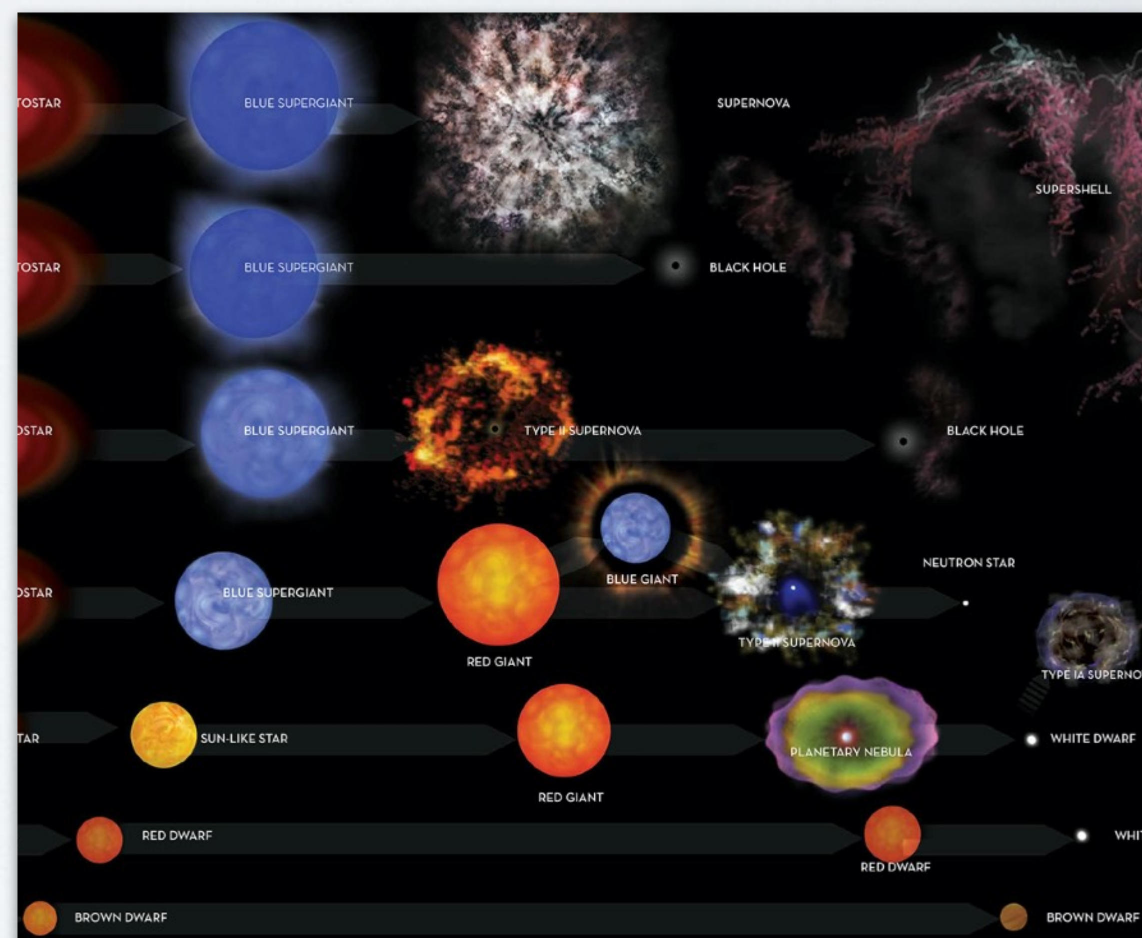
Session ID: diemer

30 seconds

Counting the mass of stars



- The easiest thing to see: **star light from galaxies**
- But we need to convert from light to mass ("mass-to-light ratio")
- Start by considering the Sun:
  - $M_\odot = 2 \times 10^{33}\mathrm{g}$
  - $L_\odot = 4 \times 10^{33}\mathrm{erg/s}$
- Different types of **stars have different mass-to-light ratios**
  - **Massive stars have small M/L** (they shine brightly compared with their mass)
  - **Low-mass stars have large M/L** (they are dim compared with their mass)
- Averaging regular stars near the Sun, we get $\langle M/L \rangle \approx 3 M_\odot / L_\odot$
- But also need to include effect of "dead" stellar remnants (white dwarfs, neutron stars, black holes) and sub-stellar brown dwarfs
- All of these have mass M, but very little light L
- Including everything, we get $\langle M/L \rangle \approx 10 M_\odot / L_\odot$



Counting the mass of stars

- Adding up the visible star light that we see in the Universe, and convert to a mass in stars (luminous and non-luminous) we get $\mathbf{\Omega_{L,0} \approx 0.005 - 0.01}$
- Comparing with $\mathbf{\Omega_{b,0} \approx 0.05}$ from Big Bang nucleosynthesis…
- **Only 10-20% of baryons are in stars!**

Counting the mass of gas

- Galaxy clusters are the largest conglomerations of matter in the Universe, including many galaxies
- Galaxy clusters contain a lot of **hot gas (T = 10-100 million K)** outside of individual galaxies
- Can be seen using X-ray telescopes
- The rest is believed to be in **warm/hot (1 million K) gas** in intergalactic space.
- These gas phases contain a lot of the baryons that are not in stars/galaxies

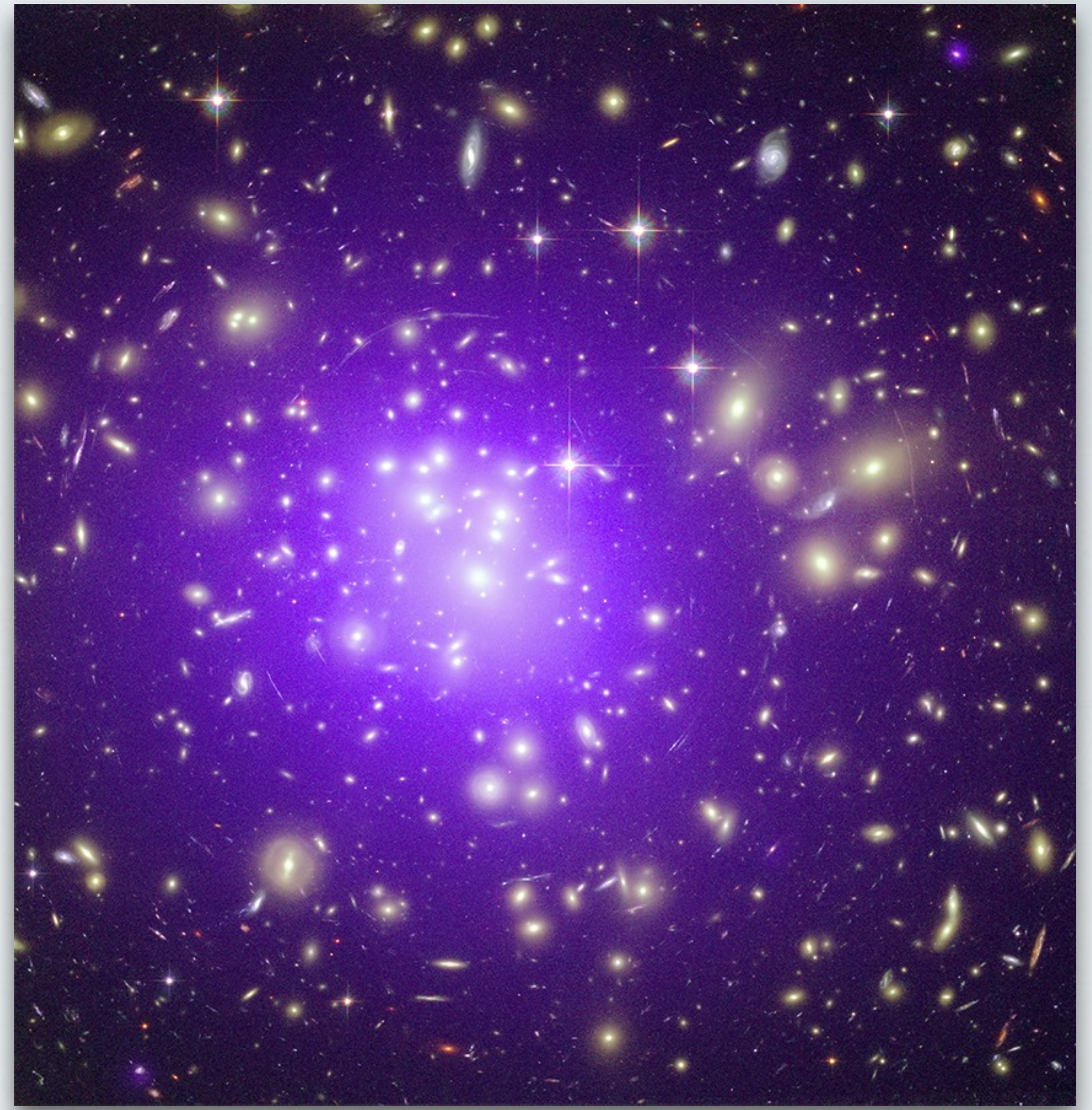


Image: Chandra X-ray center

Measuring the total mass of galaxies

- Unlike light being emitted, there is one effect that happens to **all mass** by definition: **gravity**!
- Can measure the total mass of a galaxy using Kepler's / Newton's laws
- Velocity of orbiting stars / gas tells us about **enclosed mass**

From lecture 4:

$$F = ma = \frac{GMm}{r^2} = \frac{mv^2}{r}$$

gravitation = centripetal force

$$\Longrightarrow \quad P^2 = \frac{4\pi^2}{G(M+m)}a^3$$

But can also solve for velocity:

$$v(r) = \sqrt{\frac{GM(<r)}{r}}$$

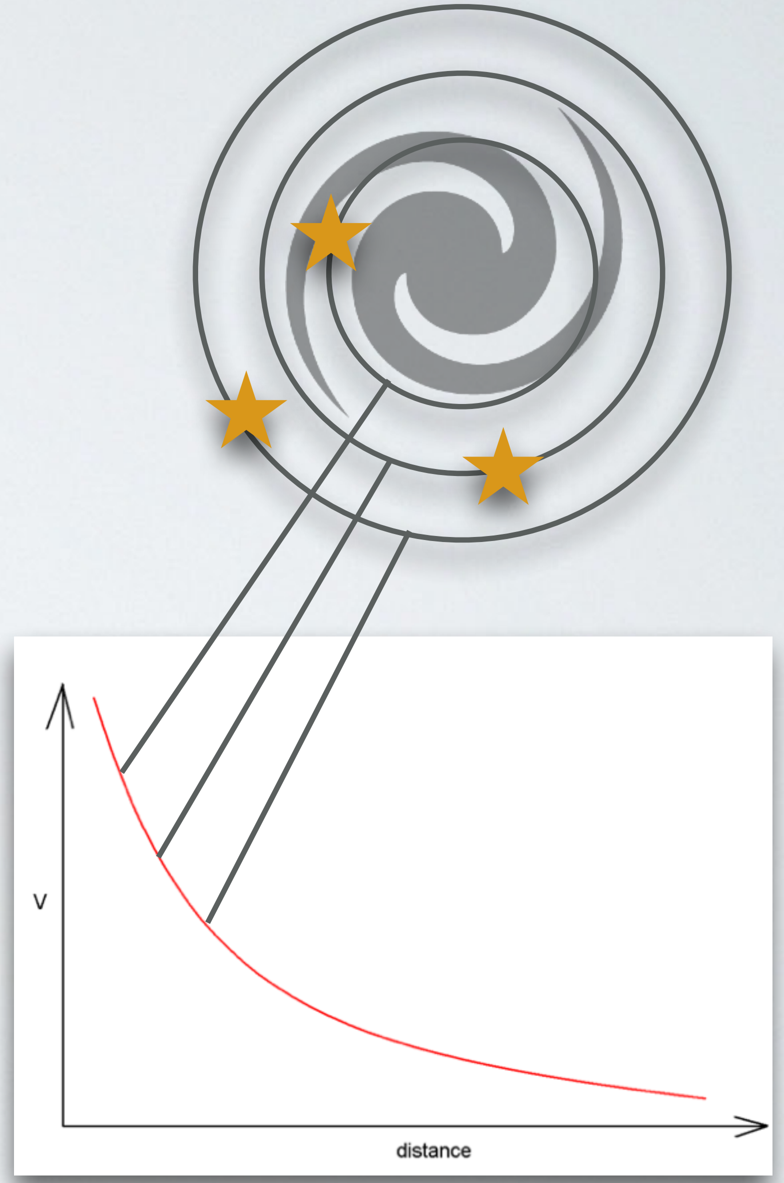
Here, M(<r) is the mass inside of radius r!
Does not have to be a point mass

Measuring the total mass of galaxies

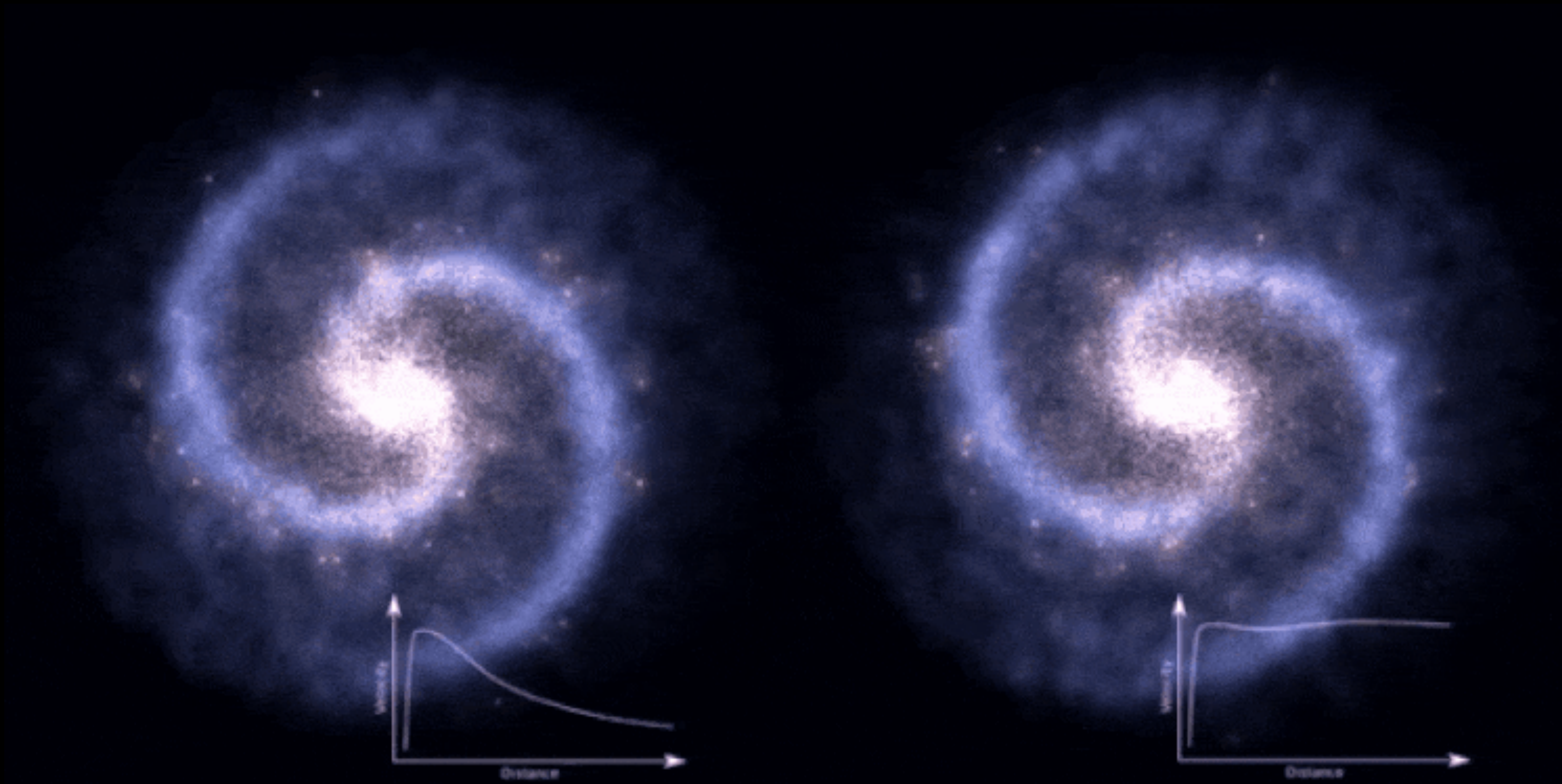
$$v(r) = \sqrt{\frac{GM(<r)}{r}}$$

$$\implies M(<r) = \frac{v^2 r}{G}$$

- If enclosed mass is like point mass (constant), $v \propto 1/\sqrt{r}$
- If the mass is extended (keeps growing with r), the velocity falls off more slowly



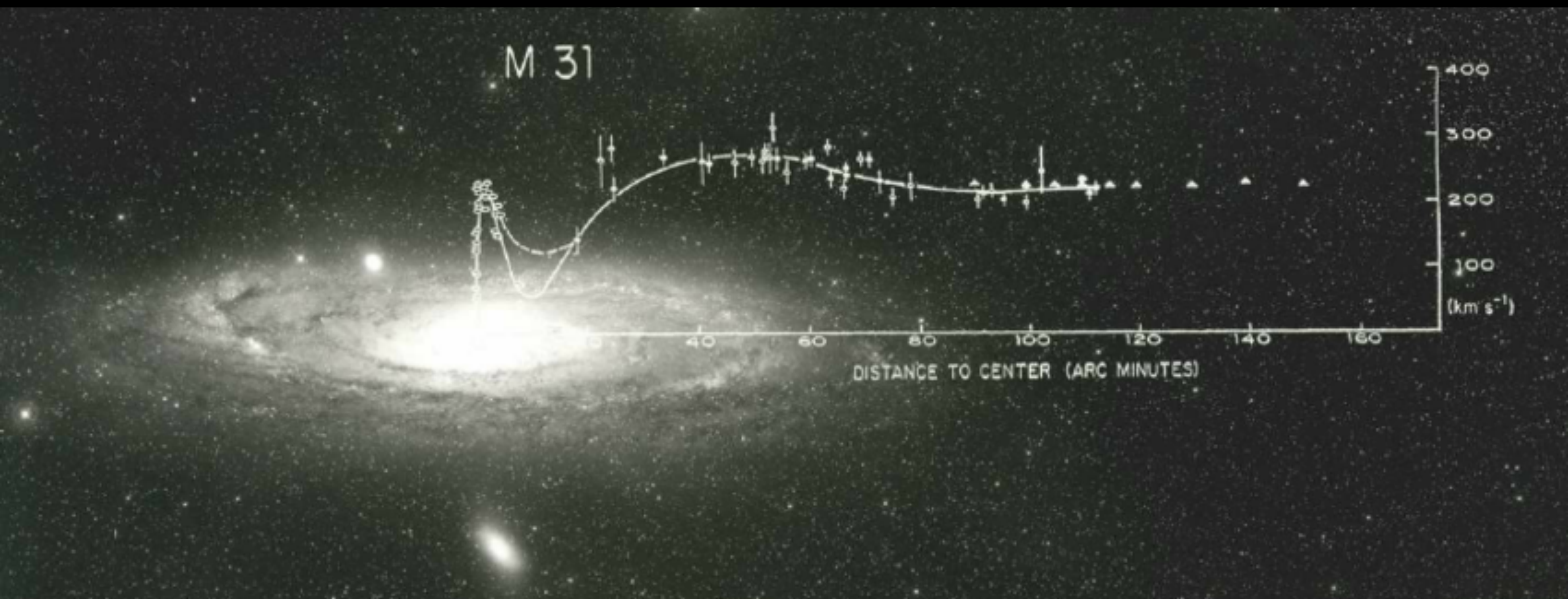
Rotation curves



Ethan Siegel

Measuring the total mass of galaxies

Vera Rubin



Rubin & Ford 1970

Measuring the total mass of galaxies

- In the outermost parts of galaxies, v(r) is measured from hydrogen gas rather than stars
- While there is enough diffuse gas to measure v(r), it adds only a tiny amount of mass
- Orbital velocity stays **almost constant** as far out as we can track it
- Means that **enclosed mass increases linearly with distance**, even beyond the radius where starlight stops
- Meaning… there is a lot of non-luminous matter in galaxies: **dark matter!**

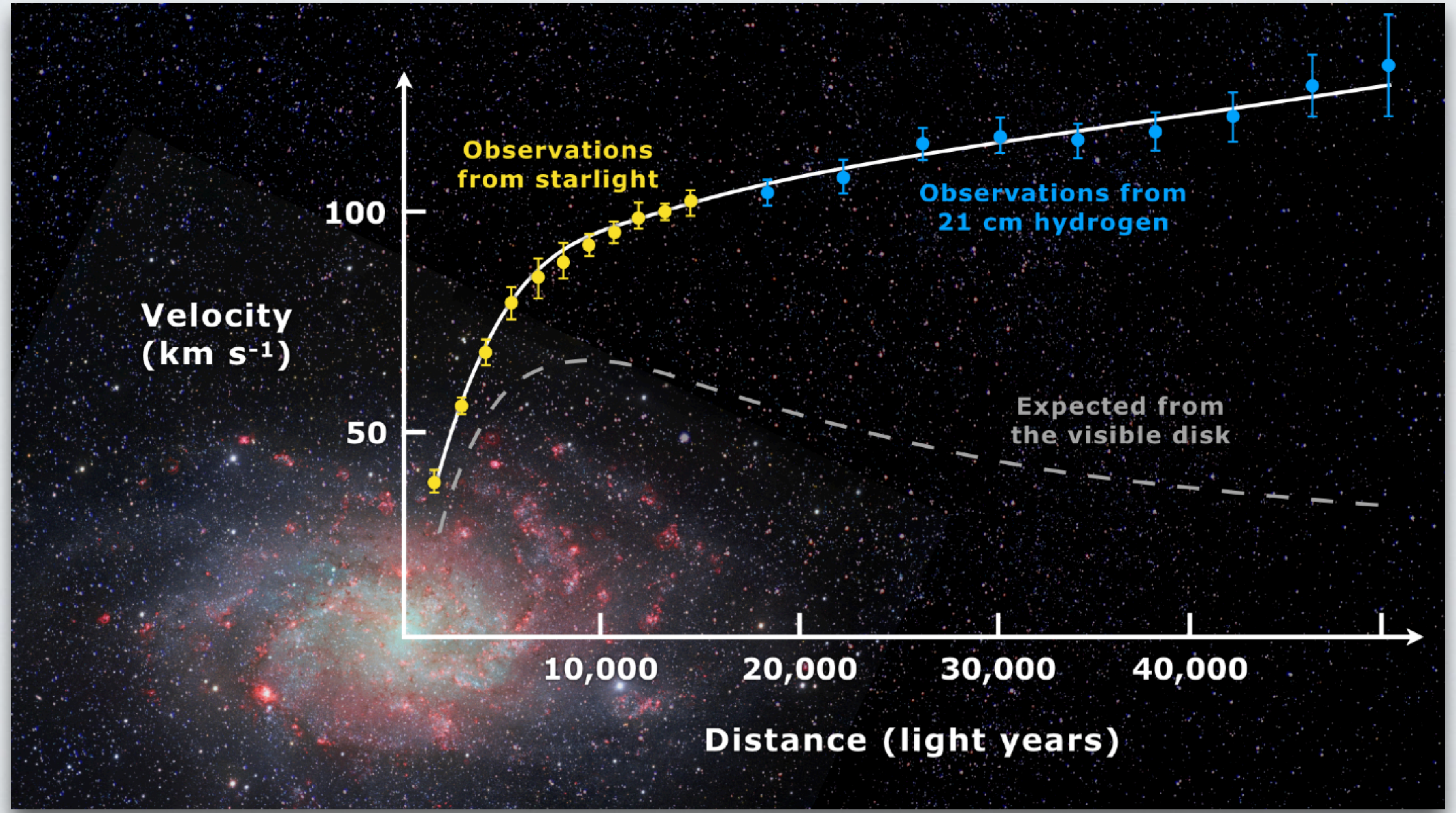
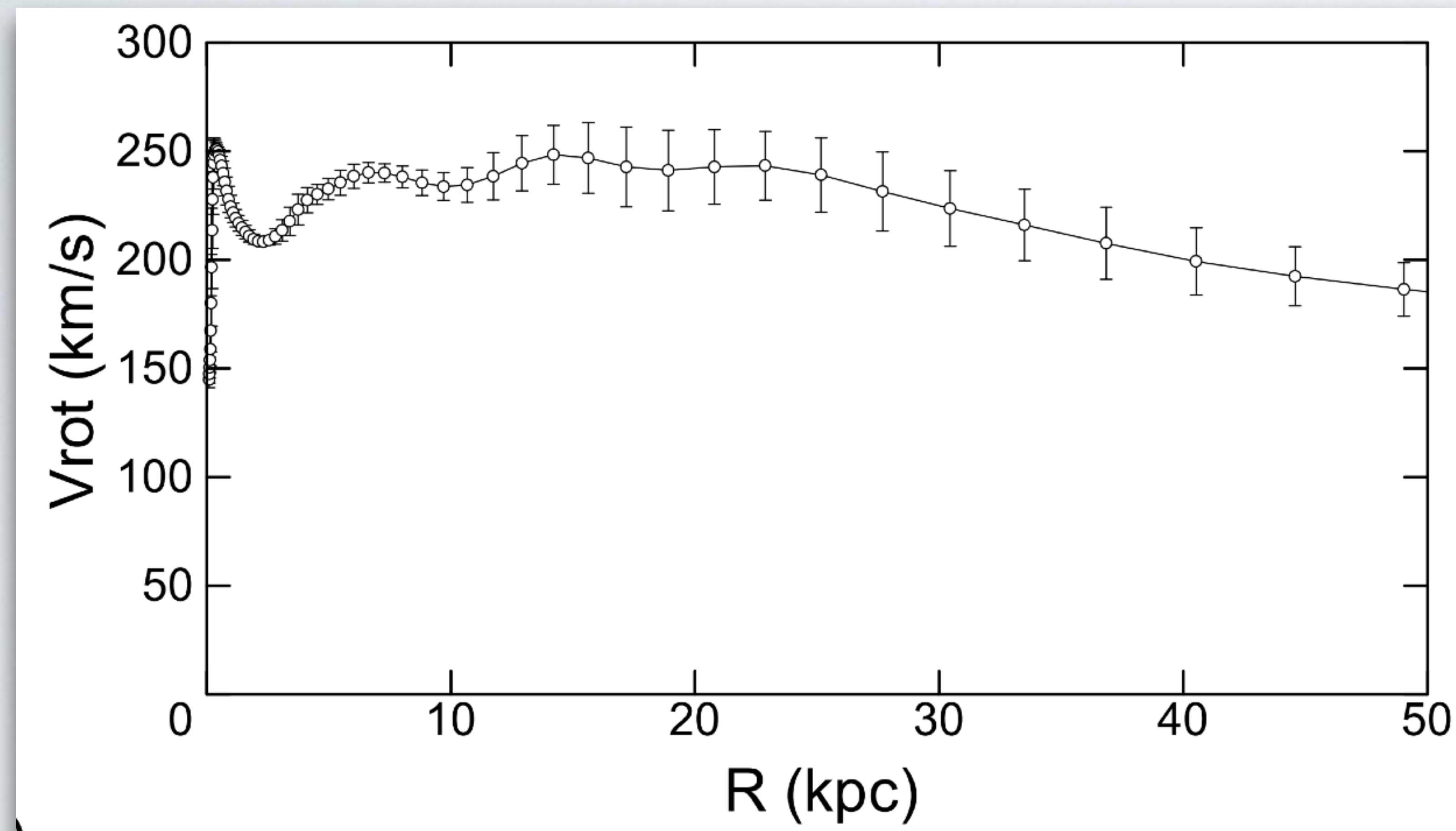
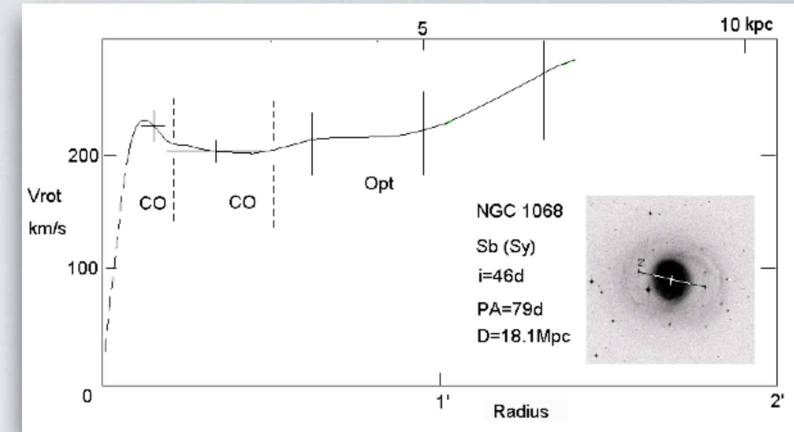


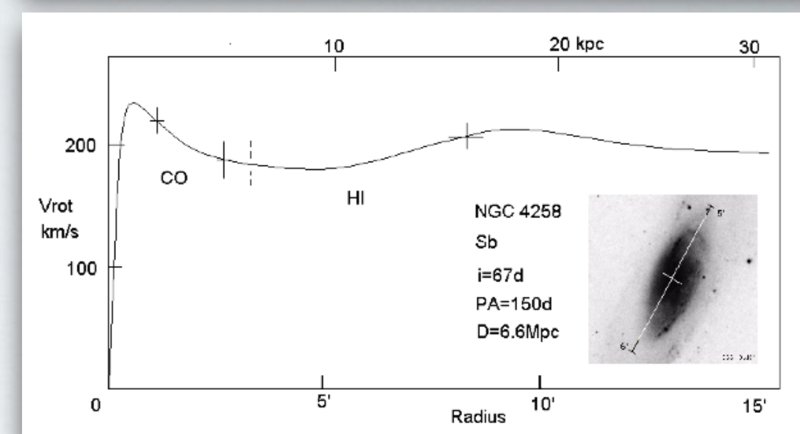
Image: Wikipedia

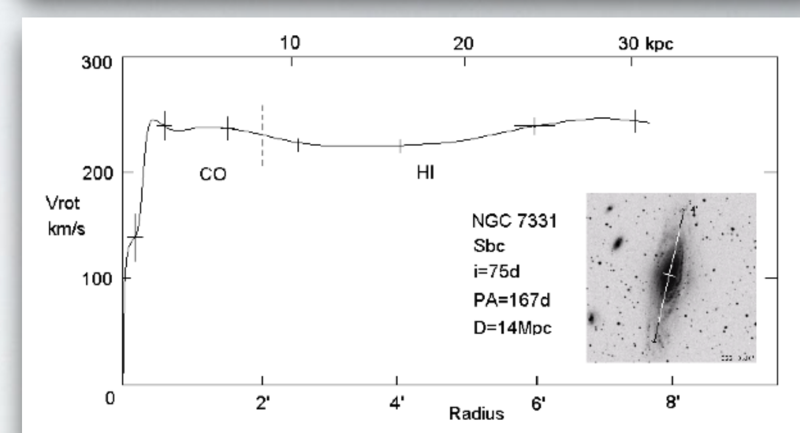
Measuring the total mass of galaxies

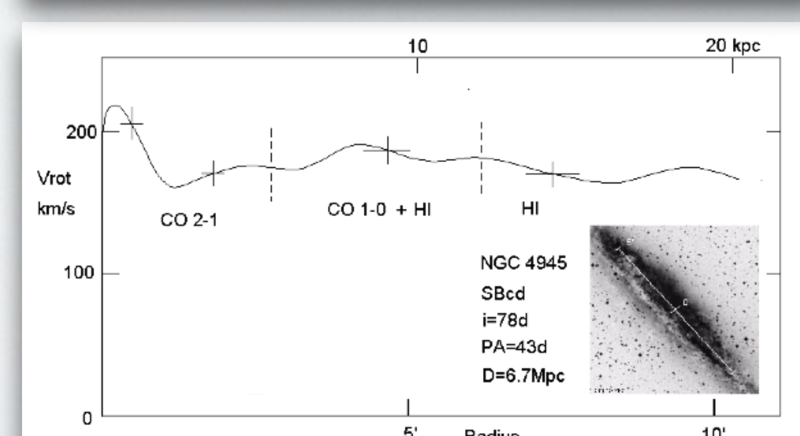
Milky Way rotation curve:











Sofue et al. 2020

Dark matter halos

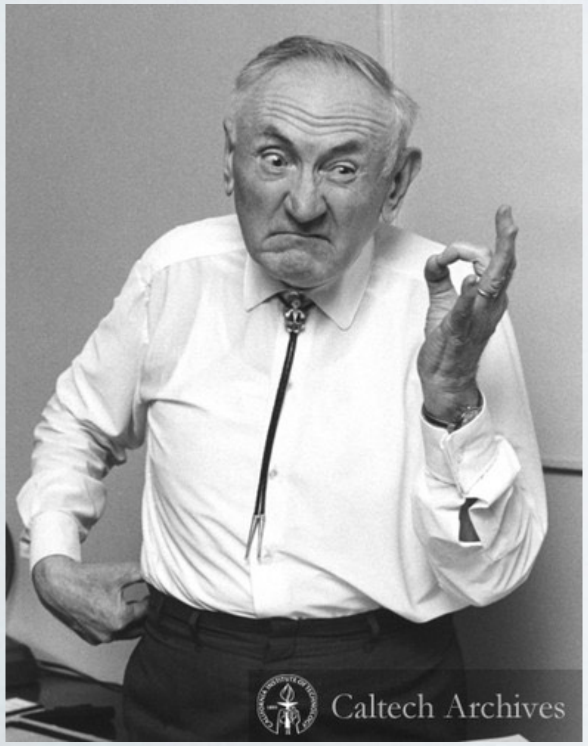
- Galaxies are surrounded by **dark matter halos**
- **Size of galaxies is 1-2%** the size of halos
- Halos are often very roughly spherical, but can have complex shapes
- Higher density of dark matter at the center

Galaxy clusters

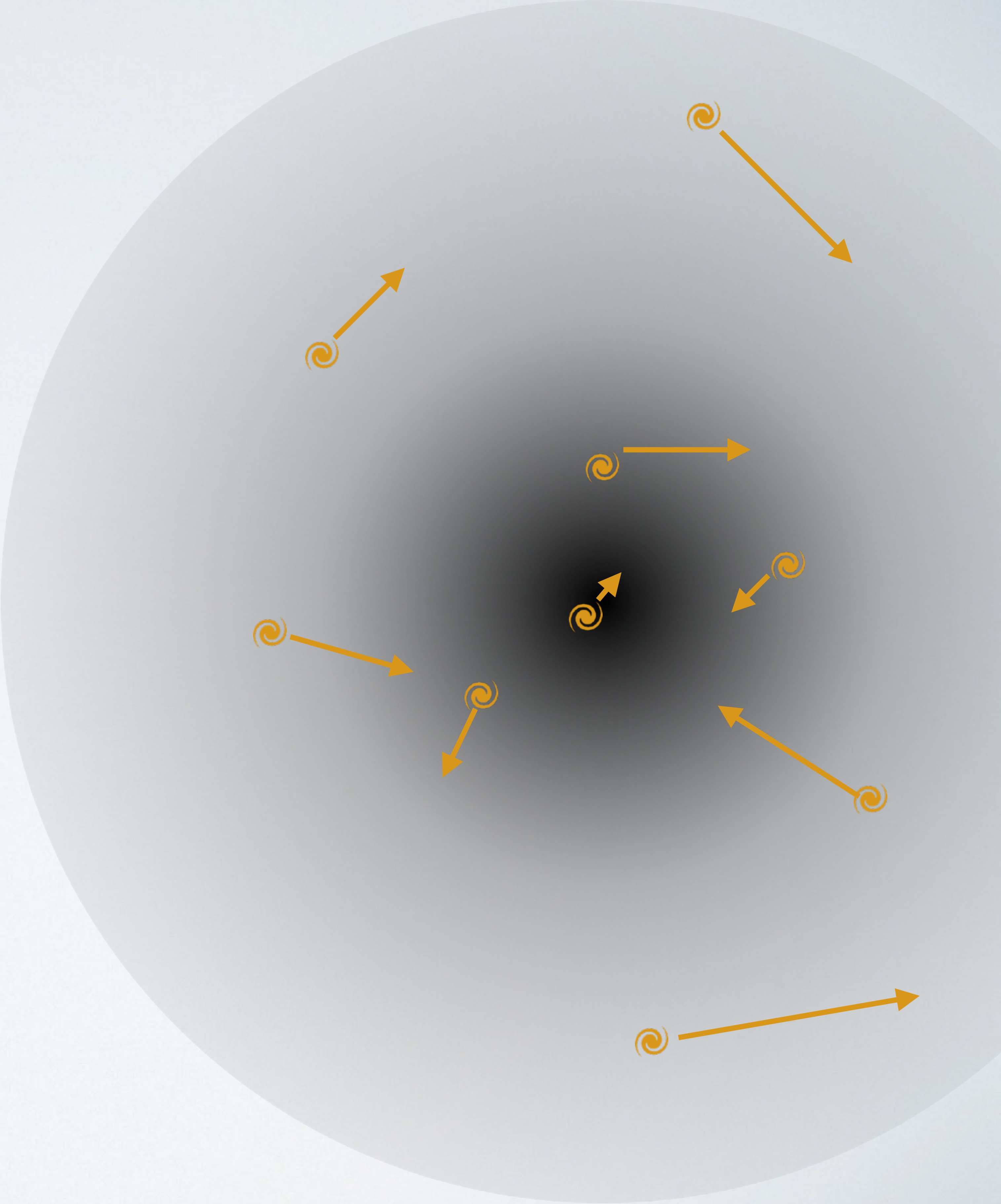
Coma cluster by Hubble Space Telescope

Galaxy clusters

- Galaxy clusters are very large dark matter halos with many galaxies in them
- Bound by gravity
- Can measure **velocities of galaxies** (not stars!) and apply a similar logic
- If there was only visible matter, velocities are high enough that cluster **would be ripped apart**
- Fritz Zwicky "discovered" dark matter this way in 1933!



Fritz Zwicky



Mass census for Coma cluster (1993)

- $M_{\text{galaxies}} \approx 1.4 \times 10^{13}\ M_{\odot}$
- $M_{\text{gas}} \approx 1.3 \times 10^{14}\ M_{\odot}$
- $M_{\text{total}} \approx 1.6 \times 10^{15}\ M_{\odot}$
- $\implies M_{\text{total}} \approx 10 \times (M_{\text{galaxies}} + M_{\text{gas}})$

White et al. 1993 • Image: NASA

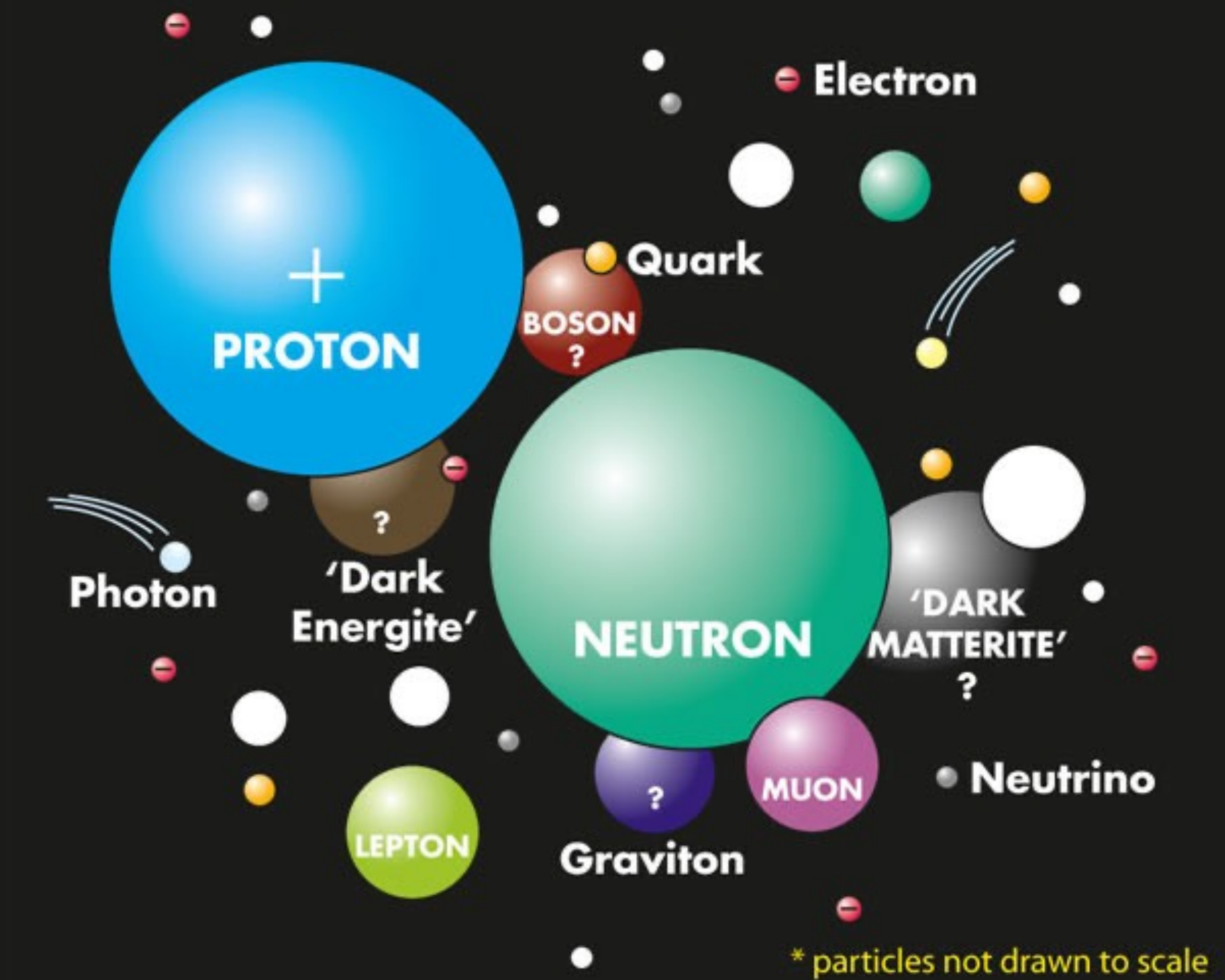


Image: Tim Jones

Participation: World Wide Telescope

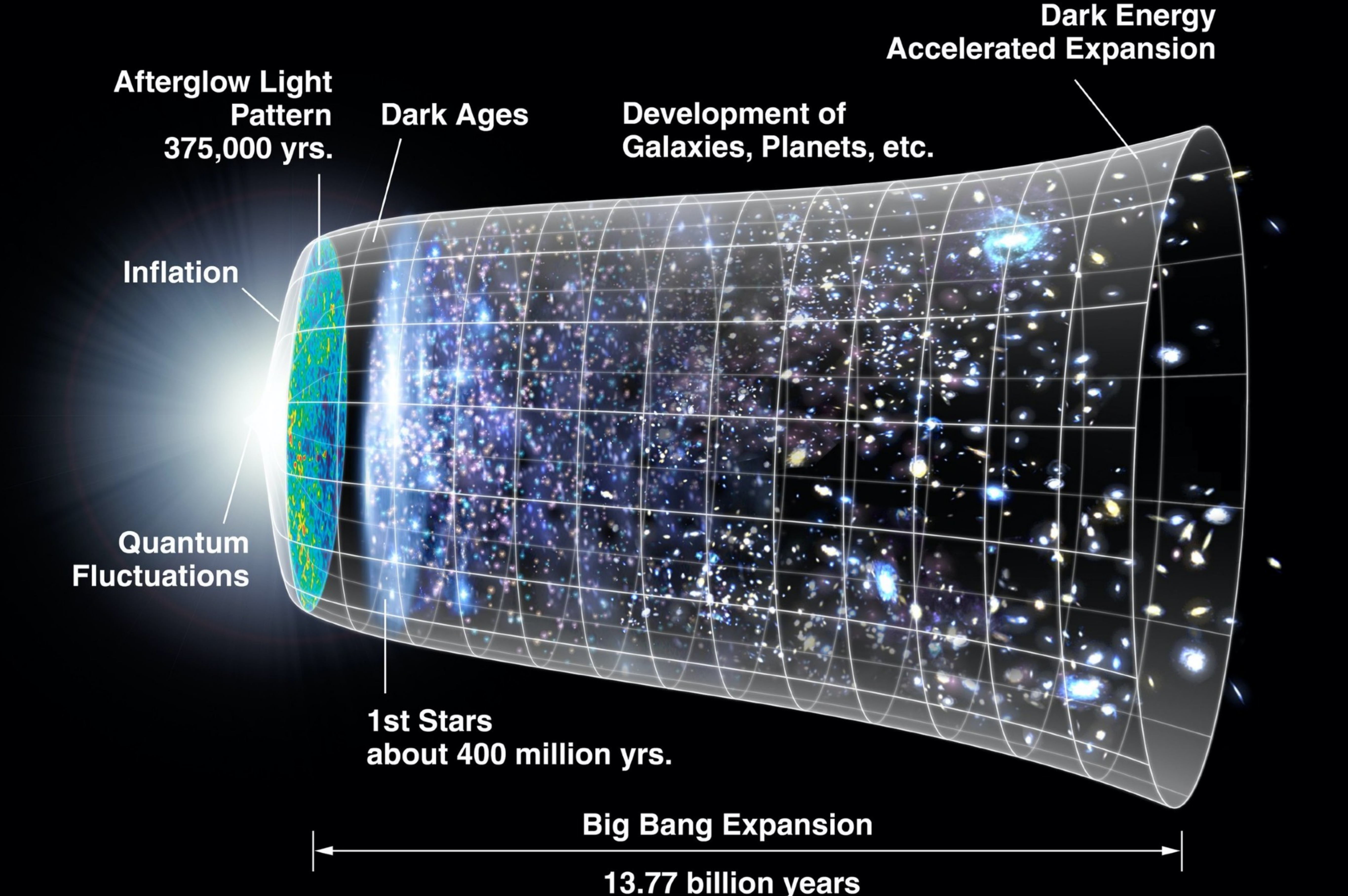
Instructions

Go to Discussion #18 on Canvas and follow the instructions.

8 minutes

Part 2: A new rung in the distance ladder

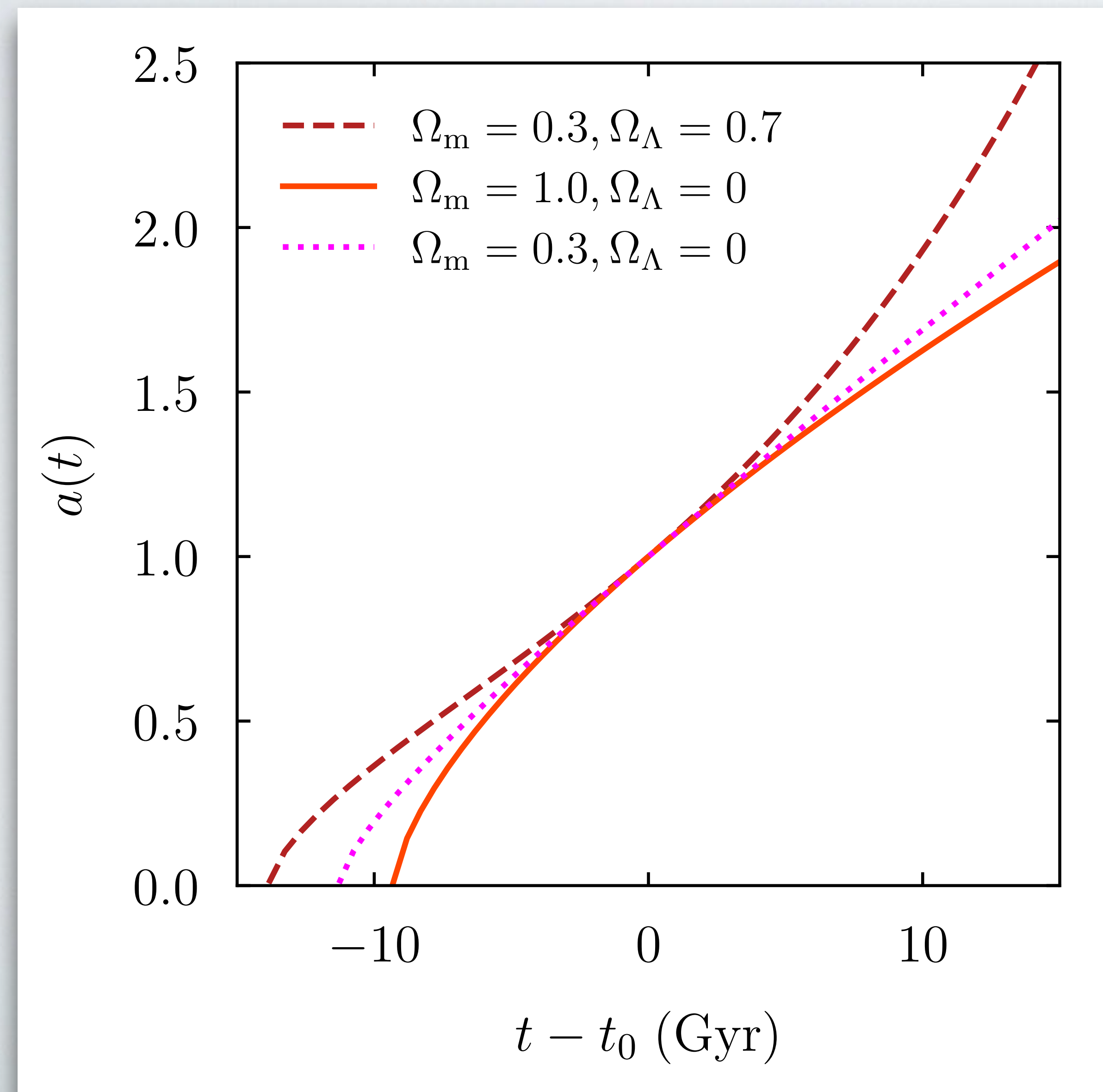
History of the Universe



NASA / WMAP

Matter + Dark Energy

- We can measure redshift (z) and thus scale factor (a) for galaxies, but not time (light does not tell us when it was sent out)
- However, we can measure the **distance** to galaxies



Participation: Distances

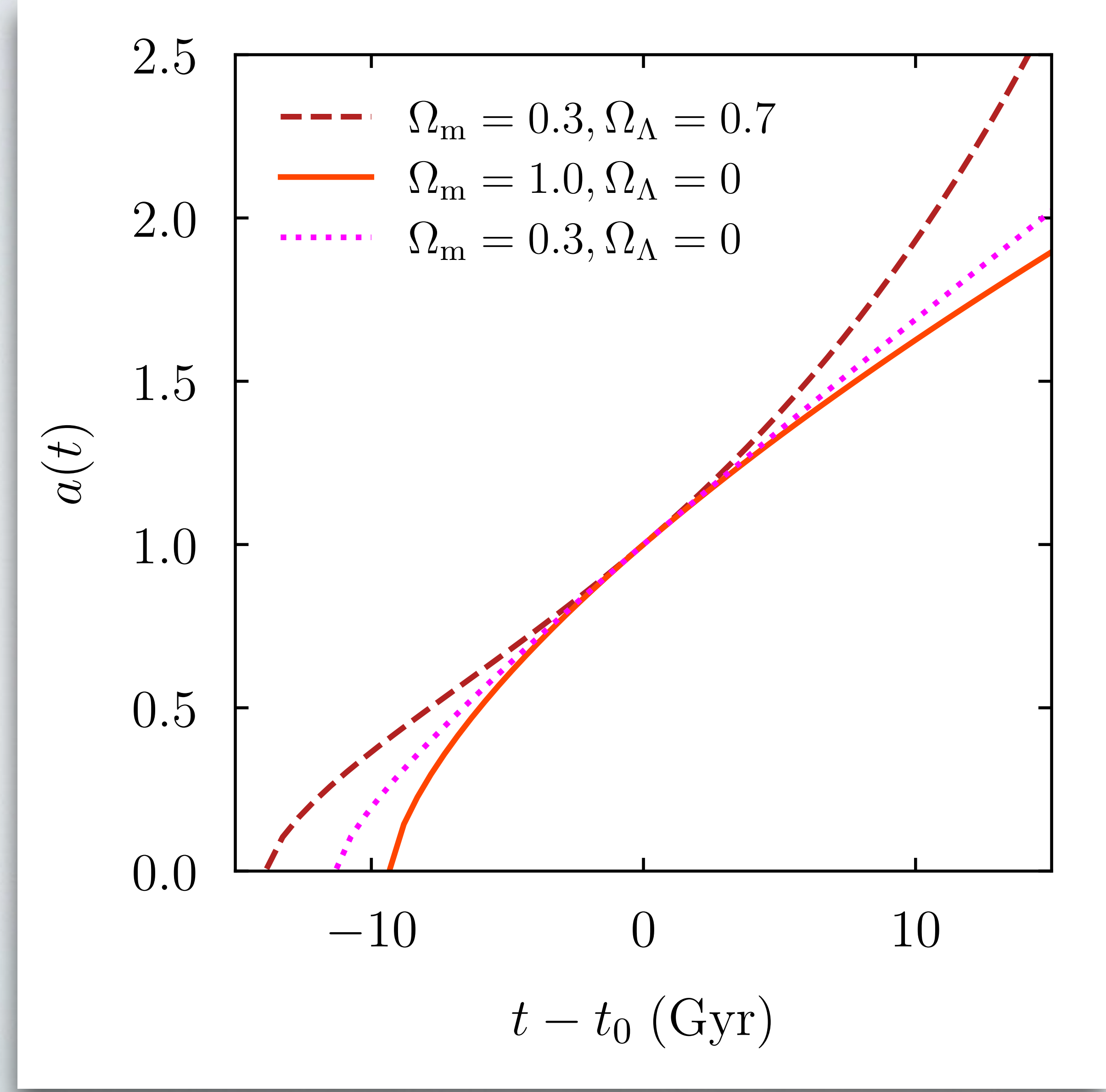
TurningPoint:
Does an accelerated expansion make the distances to far-away galaxies larger or smaller?

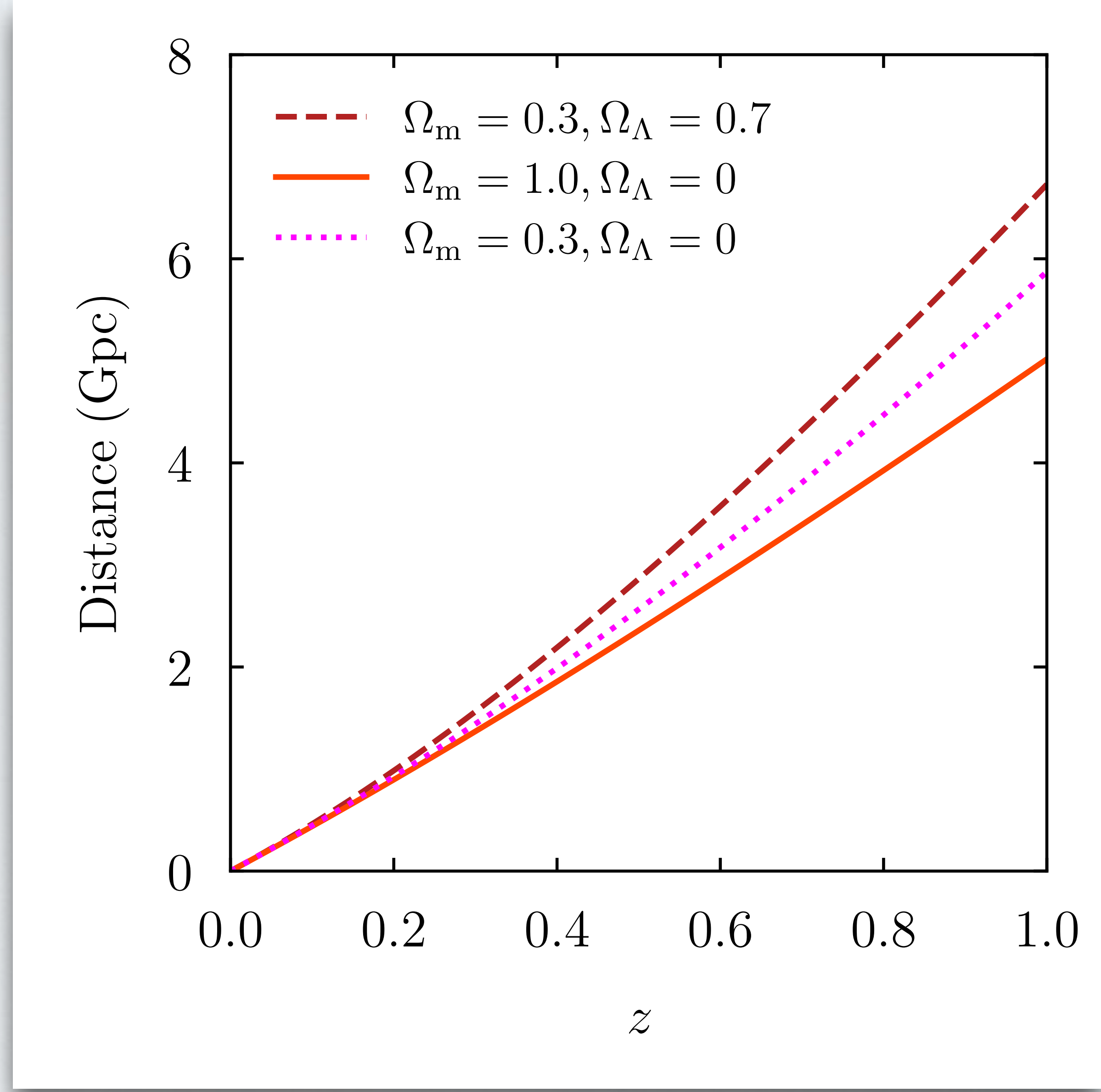
Session ID: diemer

30 seconds

Matter + Dark Energy

- We can measure z and thus a for galaxies, but not time (light does not tell us when it was sent out)
- However, we can measure the **distance** to galaxies
- Distance is directly related to age of the universe via light travel time (equation is complicated)



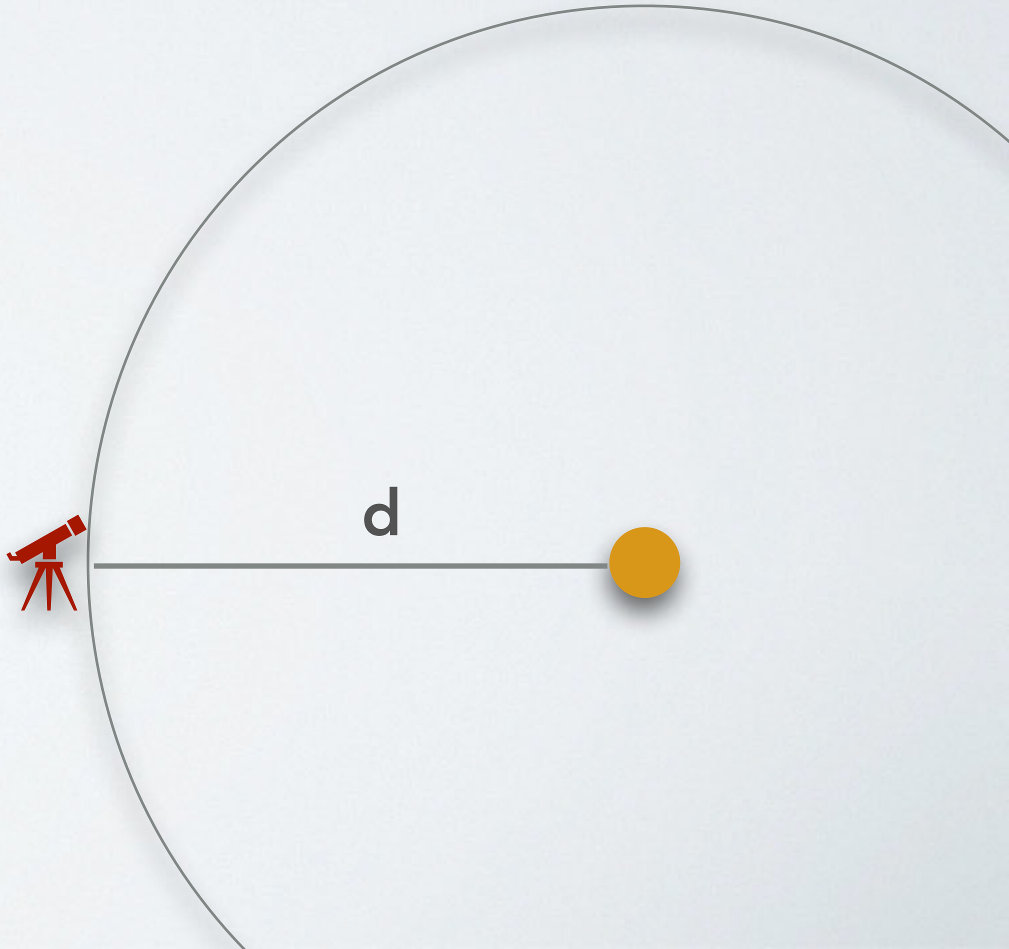


Standard Candles

- Fundamental issue: we cannot discern between an object being **dim** and being **far away**
- Need objects whose **absolute luminosity** we know; then:
  - Total luminosity is L_{std} (energy/time, e.g. erg/s or $L_{\odot}$)
  - Observed brightness b_{obs} (energy/time/area, e.g. erg/s/cm^2)
  - Distance is d, then

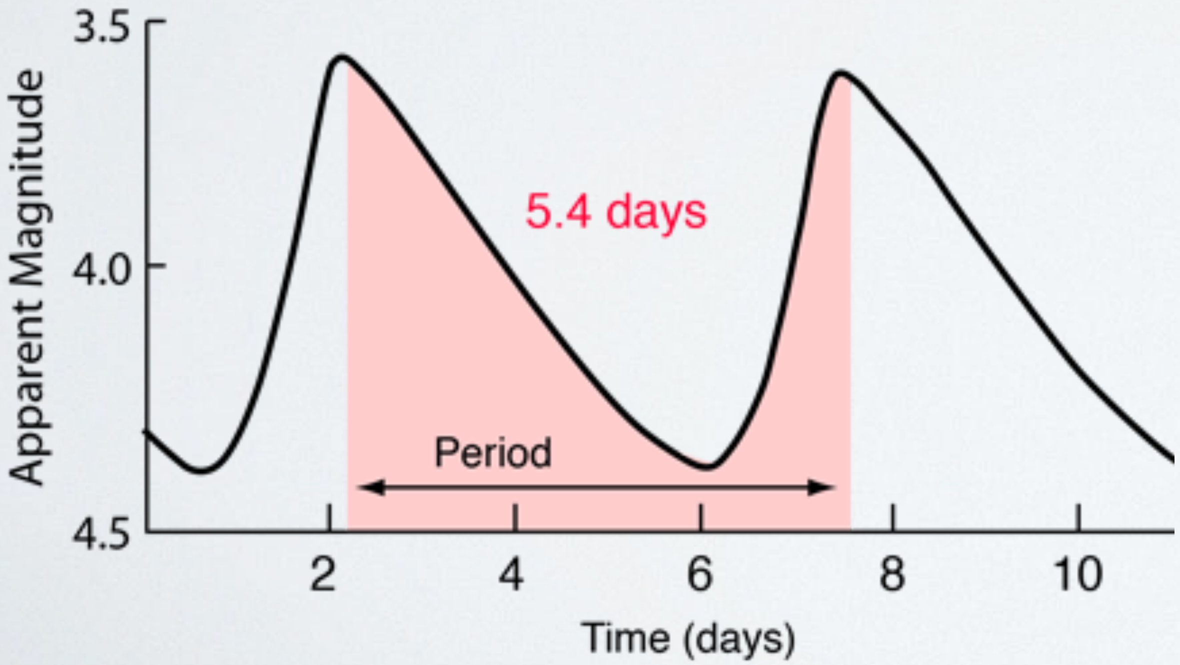
$$b_{\mathrm{obs}} = \frac{L_{\mathrm{std}}}{4\pi d^2}$$

$$\implies d = \sqrt{\frac{L_{\mathrm{std}}}{4\pi b_{\mathrm{obs}}}}$$



The first standard candle: Cepheid Variables

- In 1912, Henrietta Swan Leavitt observed a type of **variable star** called Cepheids
- Instrinsic luminosity can then be obtained from apparent brightness and **parallax distance**
- She discovered that Cepheids' total luminosity is related to the **period of fluctuations**
- Cepheids can be used as **standard candles!**



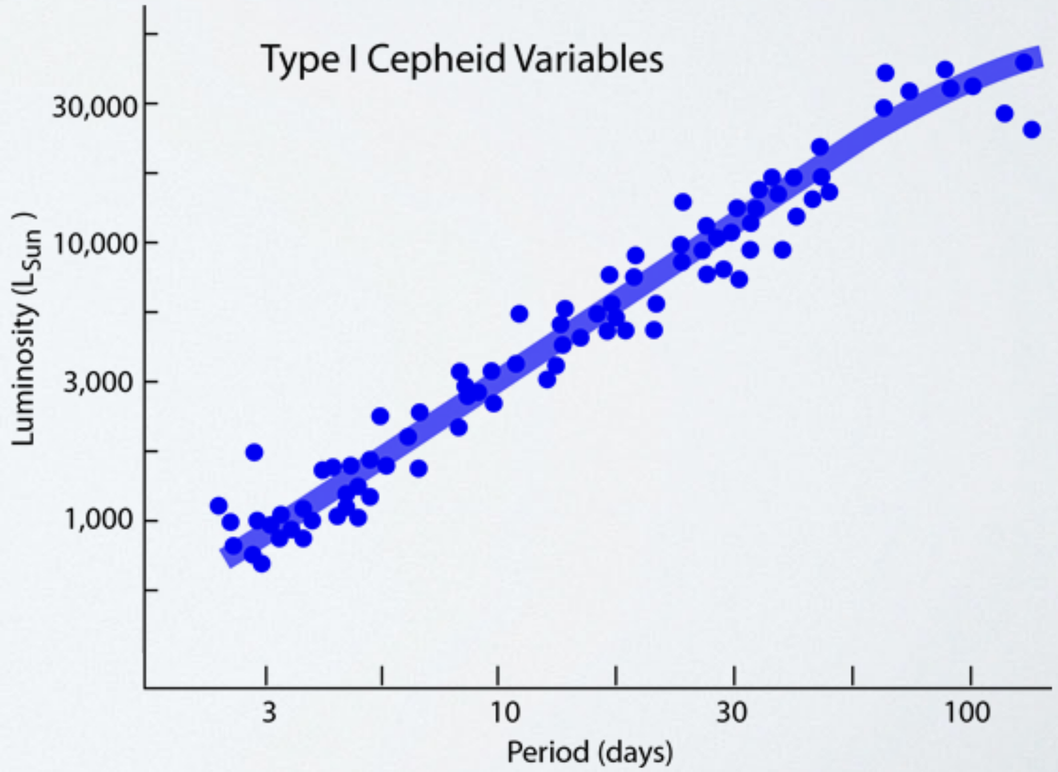
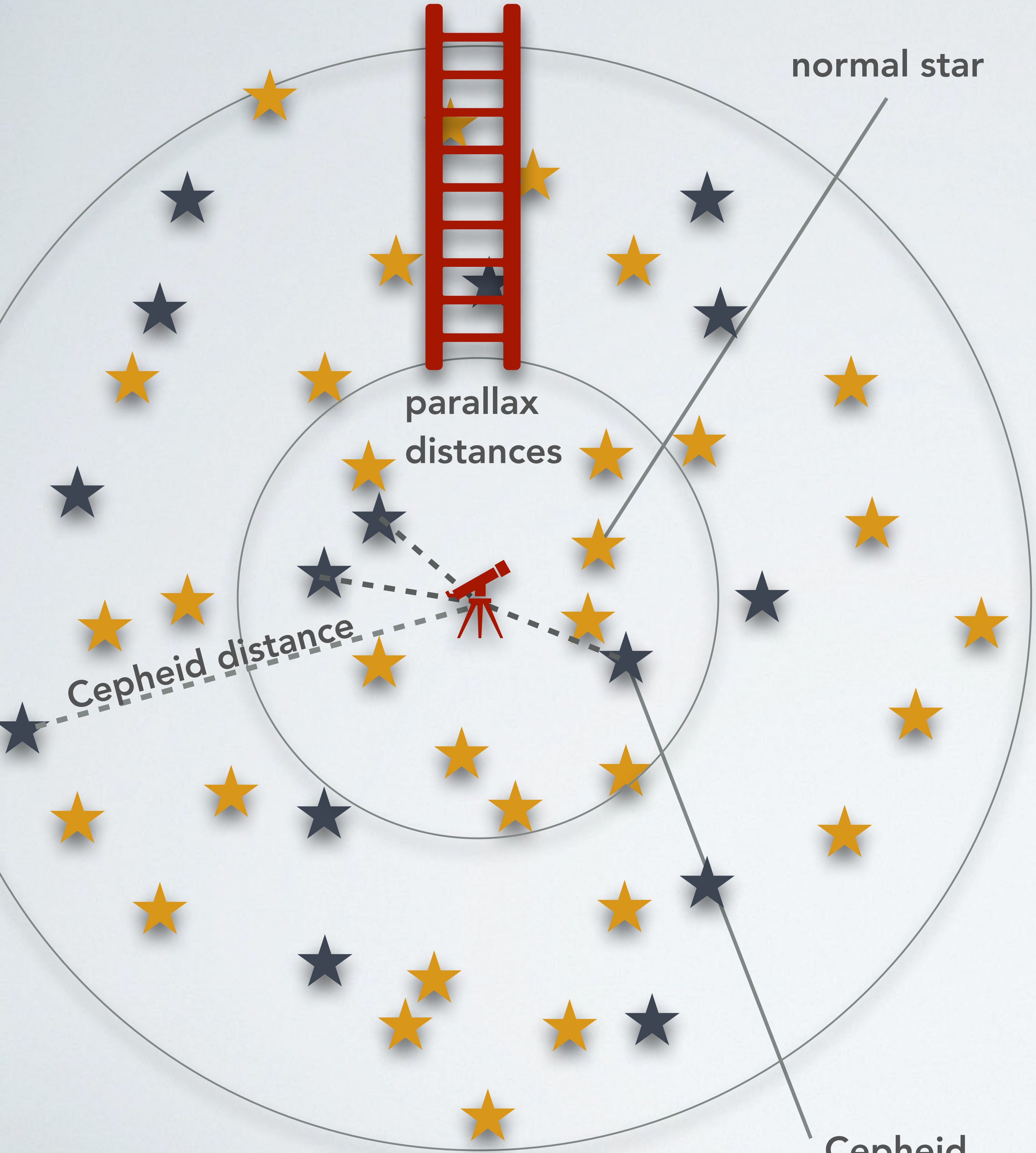
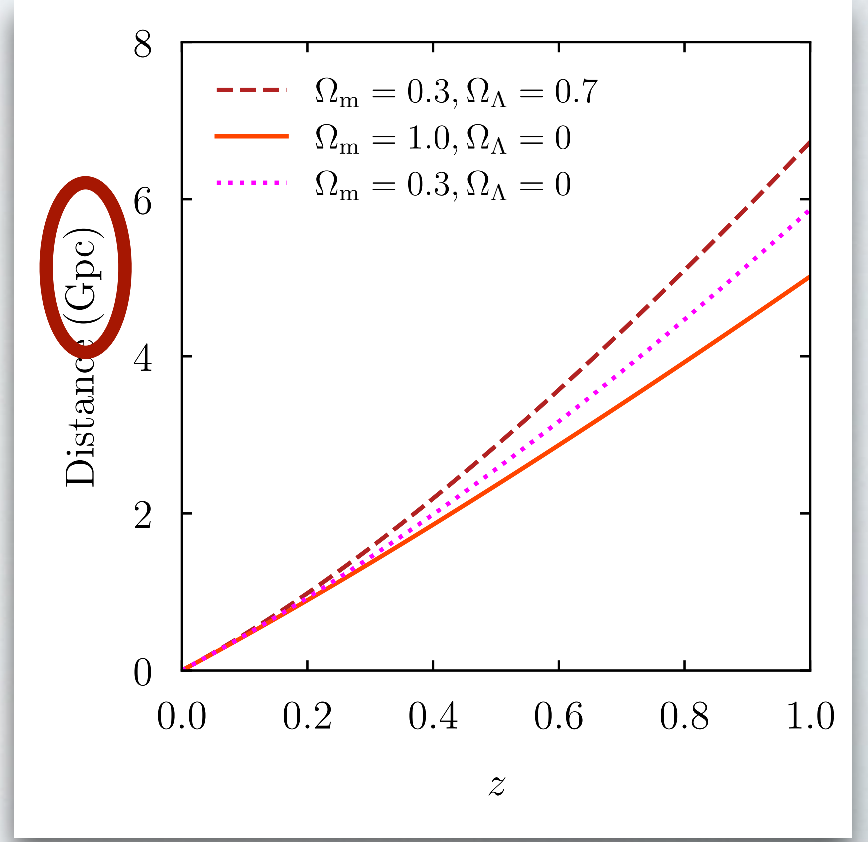


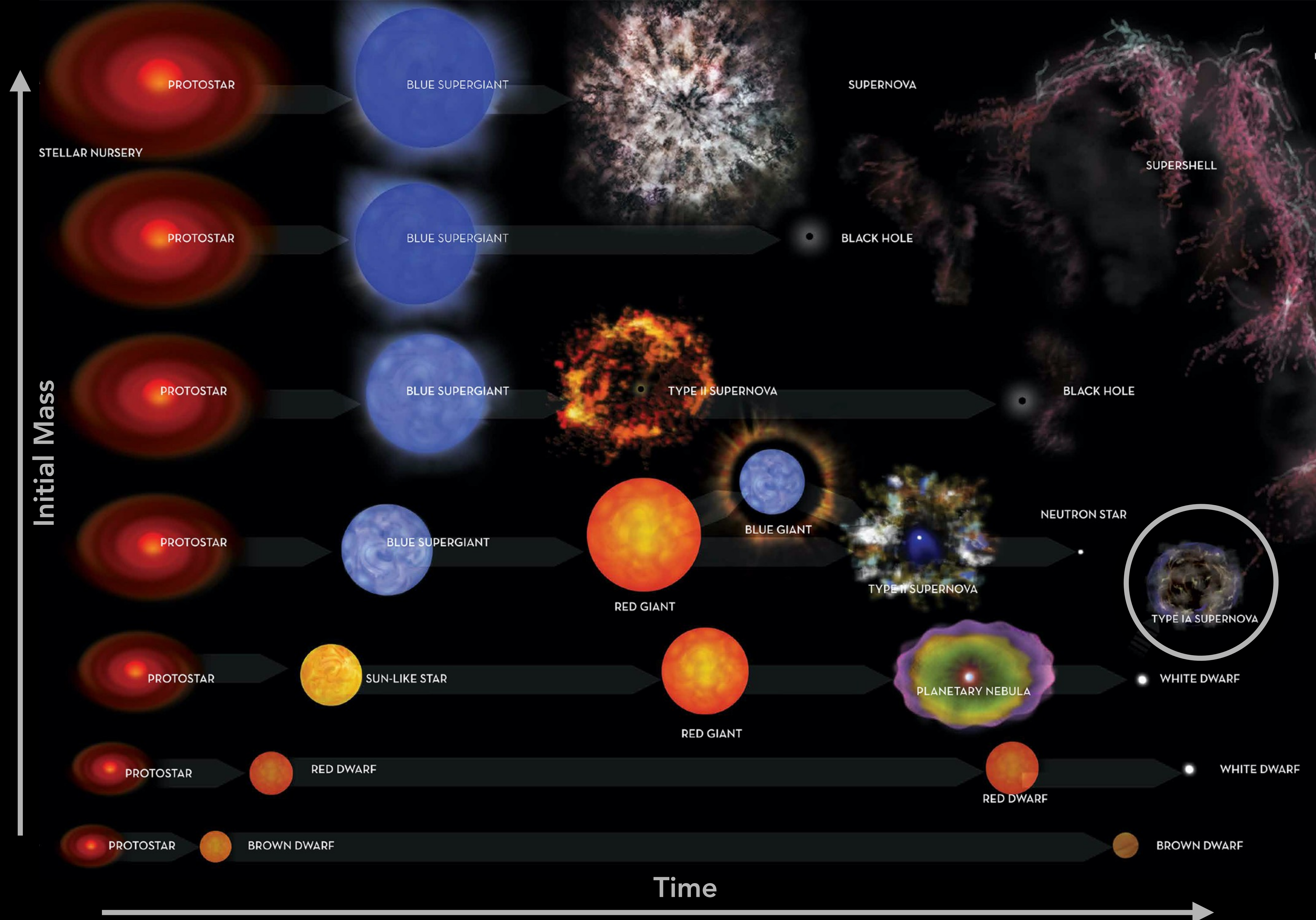
Image: hyperphysics.phy-astr.gsu.edu

The distance ladder



- Cepheids are bright, but they are still individual stars. We can see them to no more than about **10 Mpc**.
- The distances we need to measure the expansion history are **a few Gpc!**
- Thus, we need to add another "rung" to the distance ladder (that can be observed farther out)

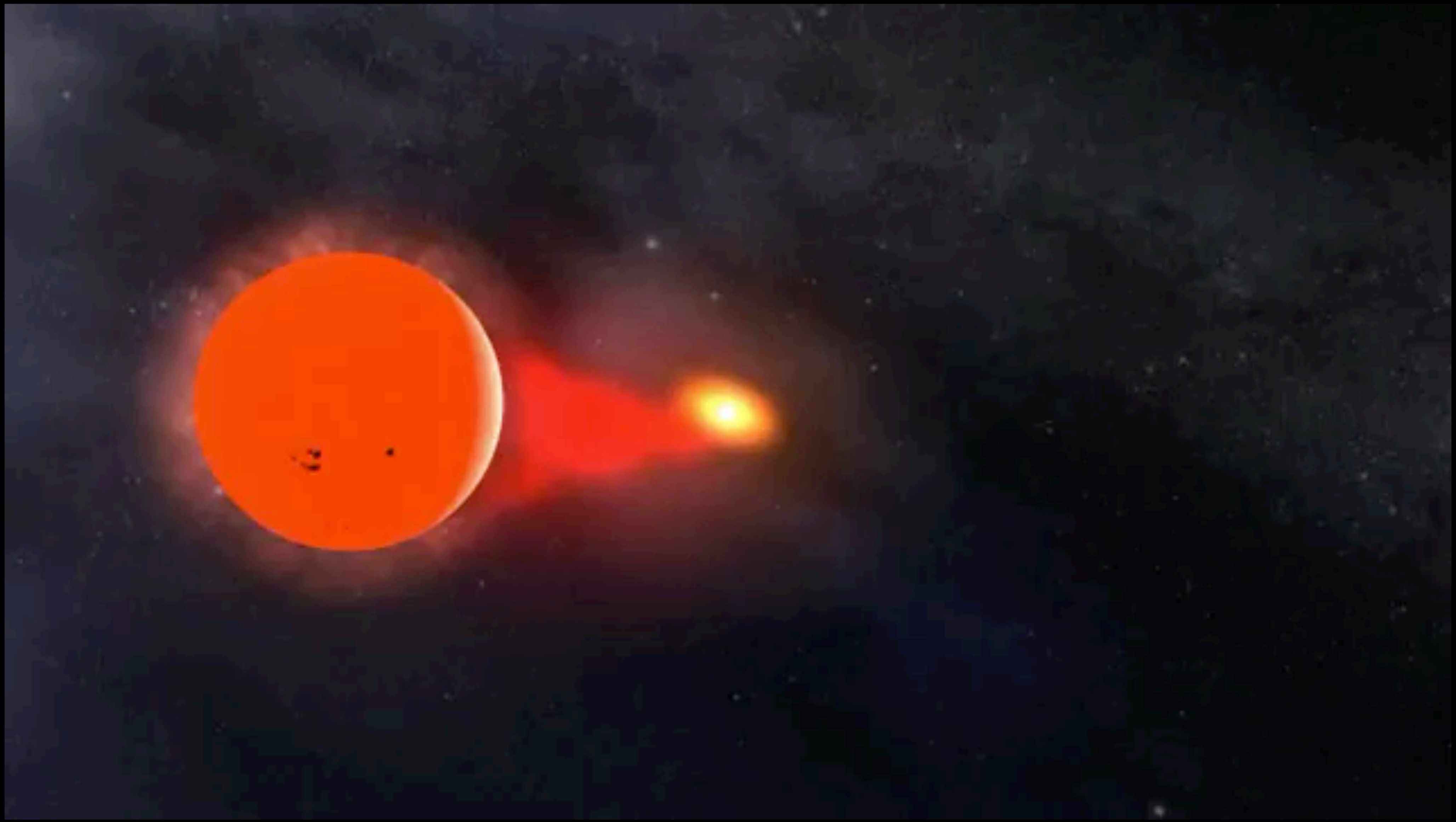




Summary of stellar evolution

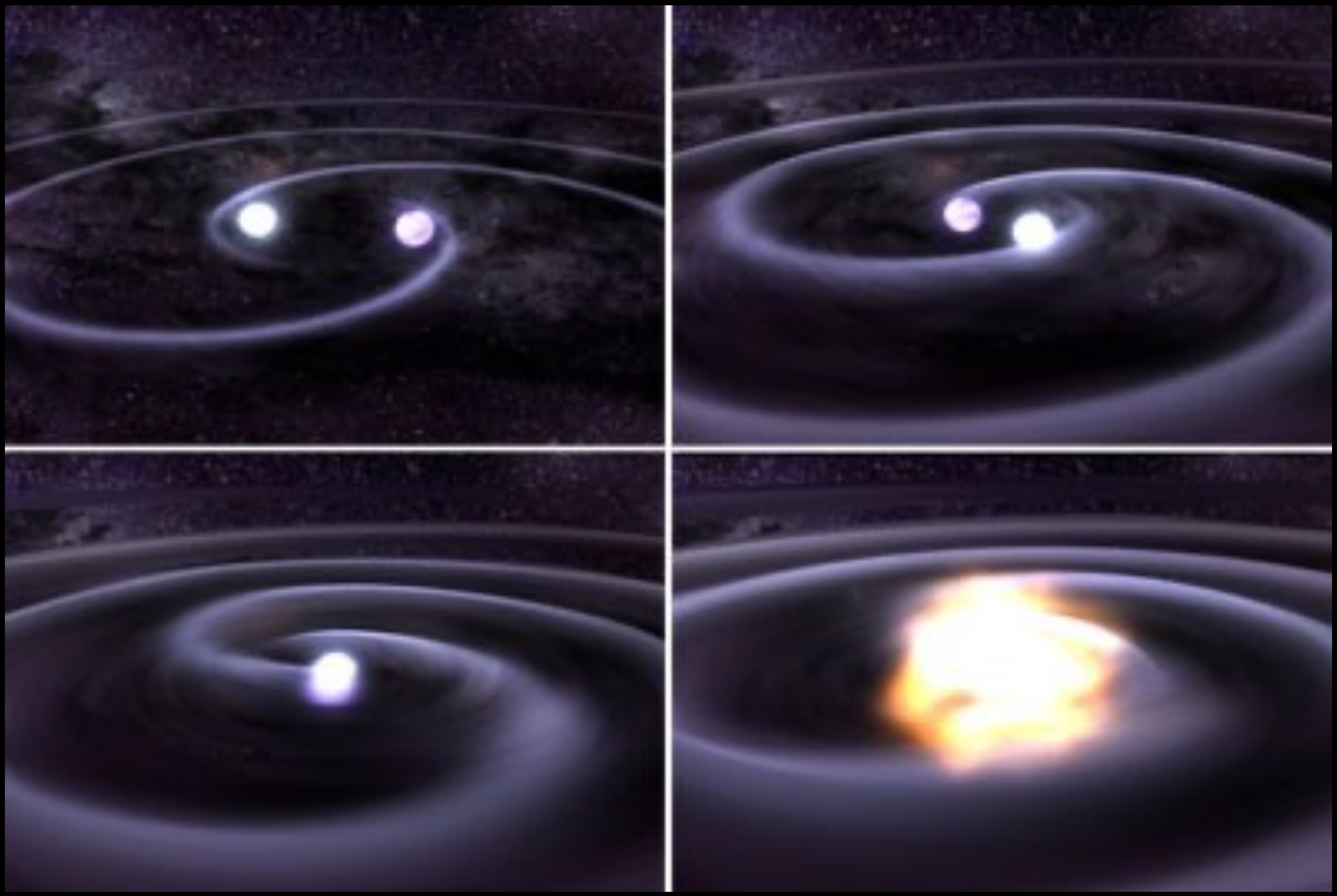
NASA

Supernova from White Dwarf + Red Giant



NASA/Goddard

Supernova from two White Dwarfs



NASA Goddard / Dana Berry

Type Ia (white dwarf) supernovae

- **Critical mass** of $1.4 M_\odot$
- No remnant left
- Since all white dwarfs explode almost exactly at that mass, the explosions are fairly **similar in luminosity**
- About $5 \times 10^9 L_\odot$, so can see very far away!
- Great **standard candle**
- But: too rare to be observed regularly in our own Galaxy

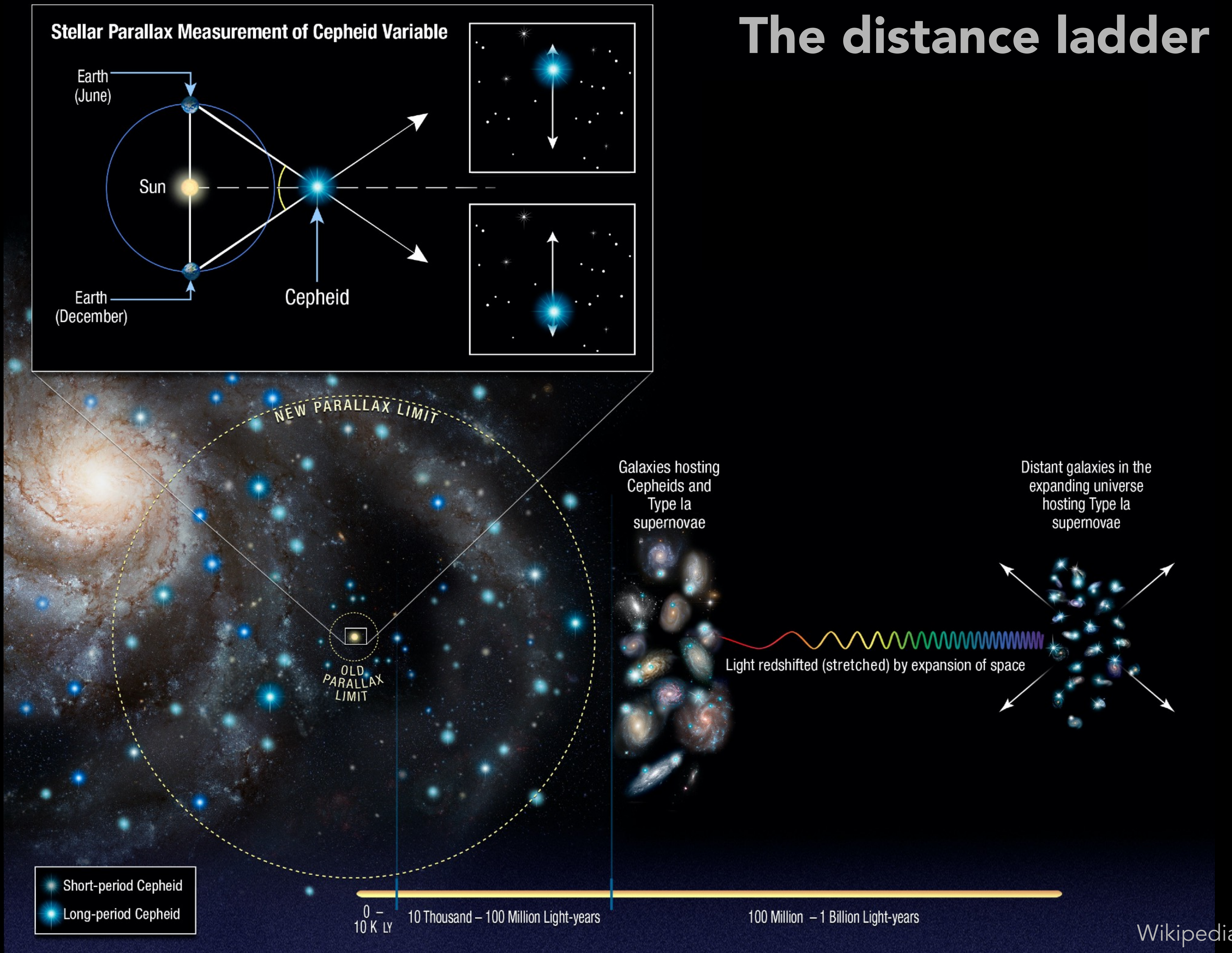
The distance ladder

Step 1: parallax distances to measure luminosity of cepheids (~kpc)

Step 2: cepheid distances to measure luminosity of Type Ia SNe (~10 Mpc)

Step 3: use Type Ia SNe to measure distance to far-away galaxies (~Gpc)

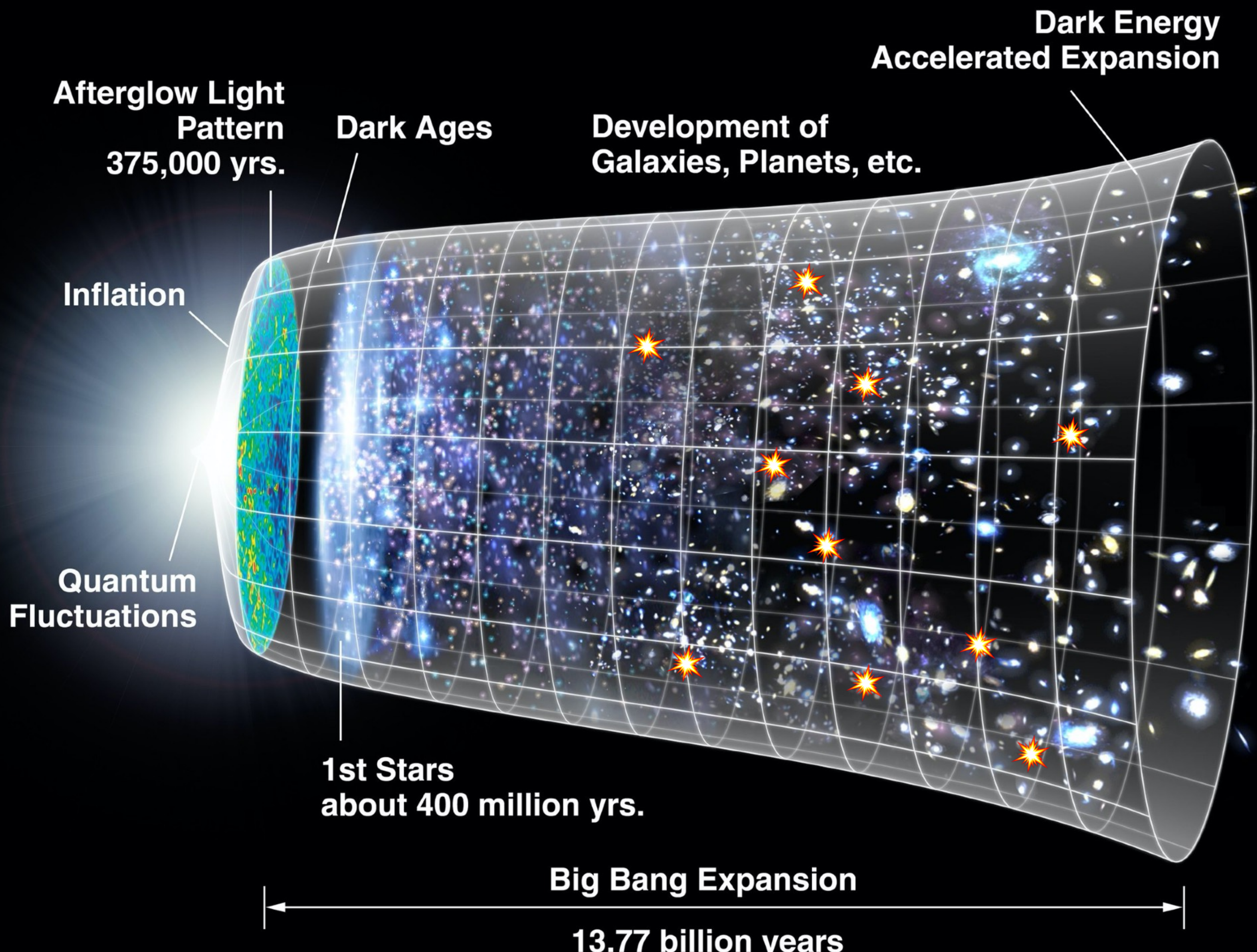
The distance ladder



Wikipedia

Part 3: Measuring acceleration

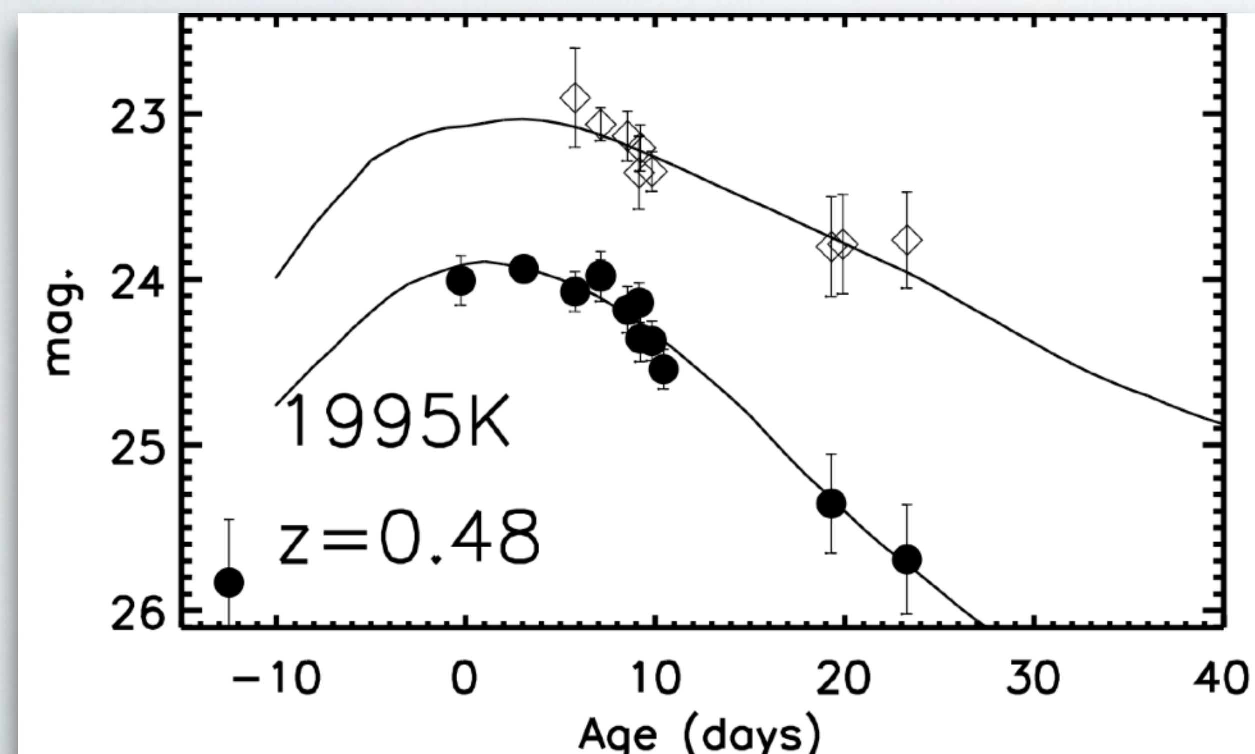
History of the Universe

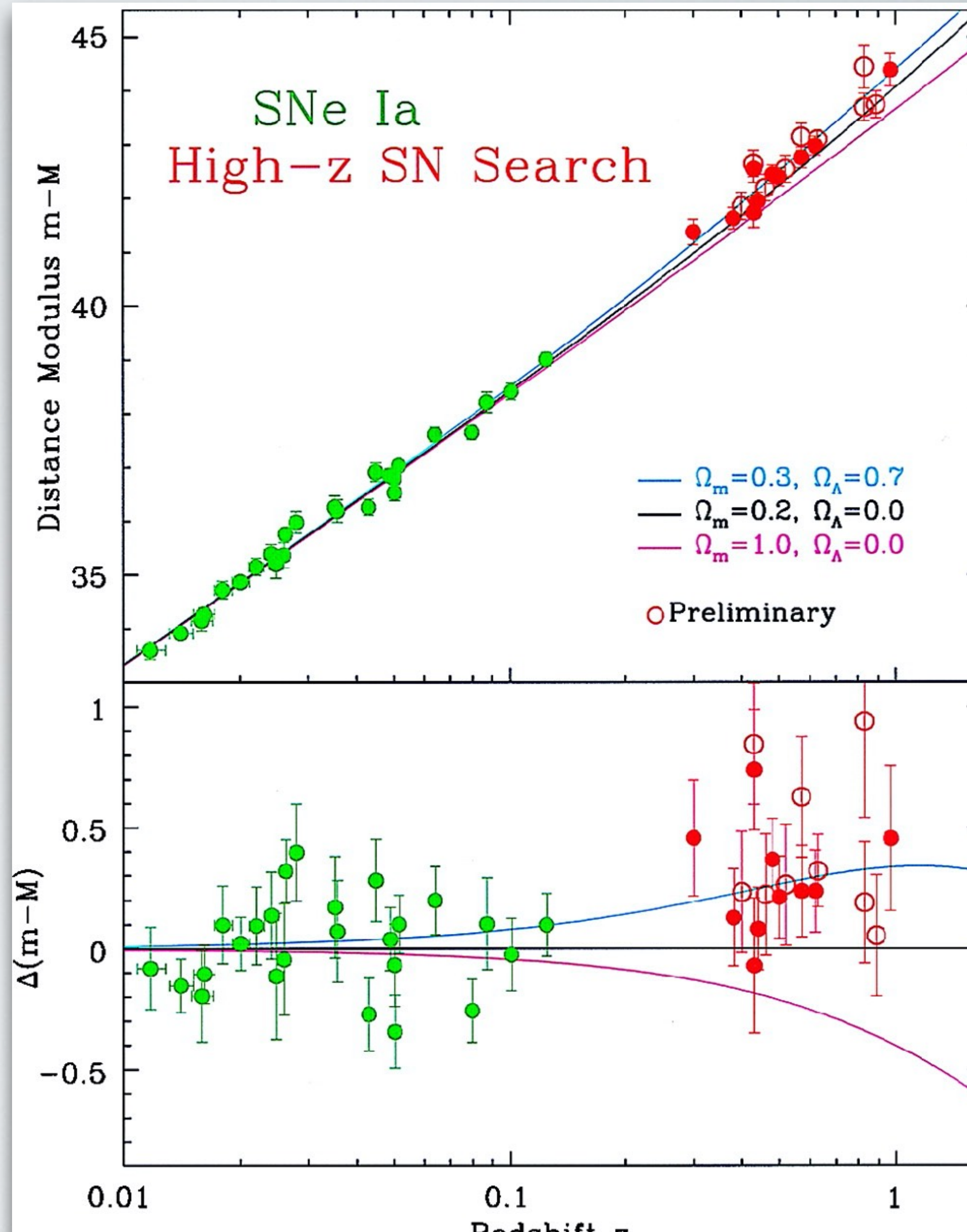


NASA / WMAP

First measurement of accelerating expansion

- Not always easy to even find the peak luminosity of a supernovae
- Data shows very slim preference for model with dark energy

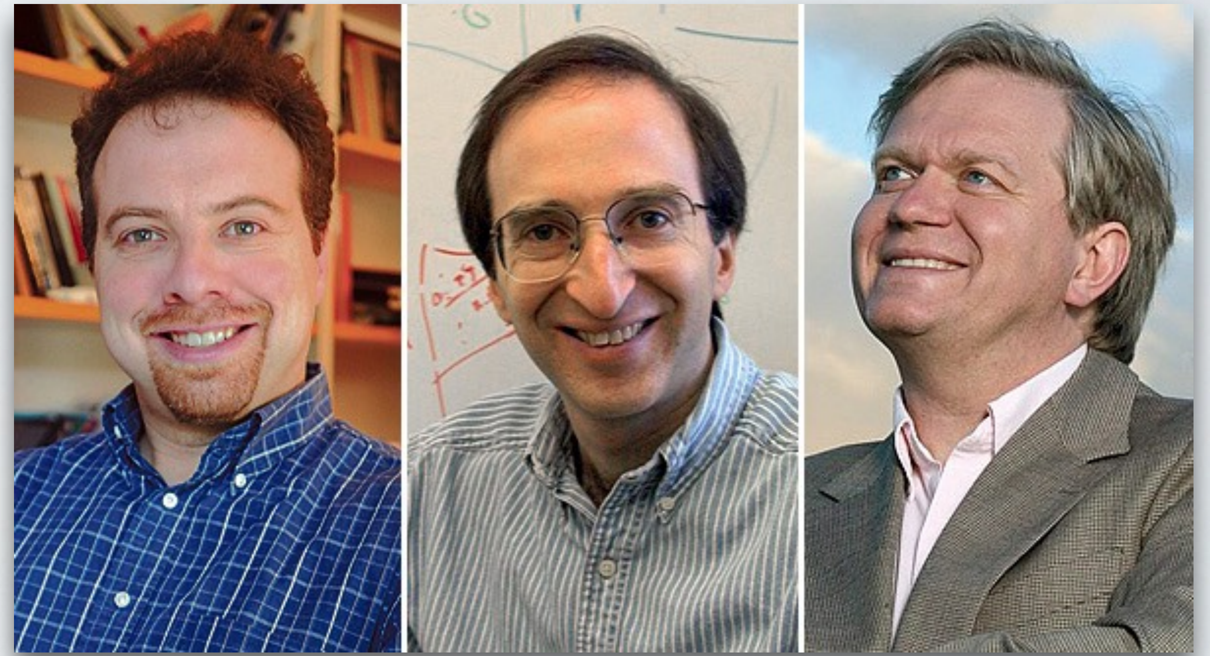




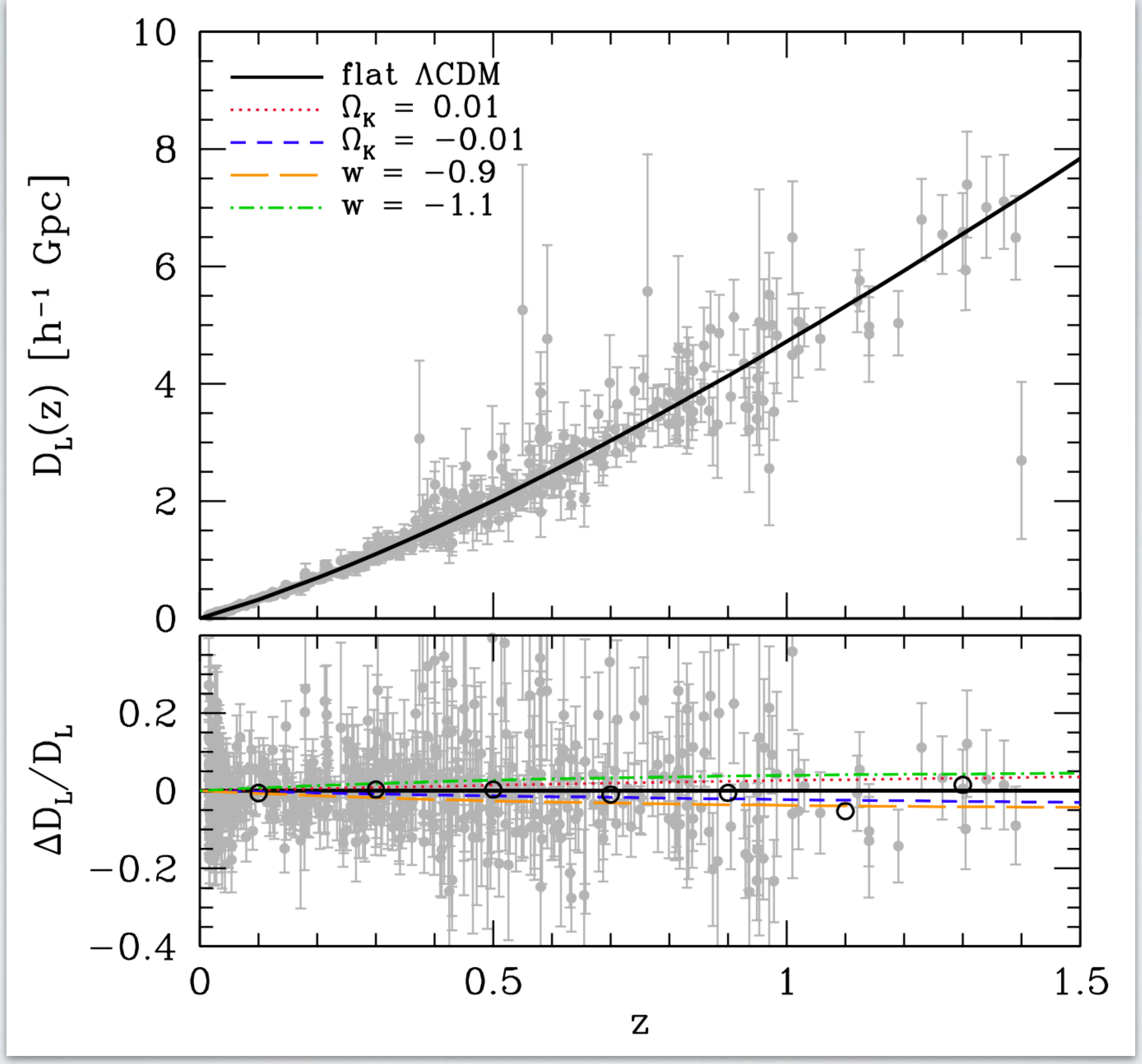
Riess et al. 1998 • Perlmutter et al. 1999

First measurement of accelerating expansion

- Result published by two teams at the same time (and in competition)
- Nobel prize for team leaders (Riess, Perlmutter, Schmidt)
- Measurement tells us that **expansion is accelerating**, not necessarily that this is due to a cosmological constant
- Could also be other form of what we call **dark energy**

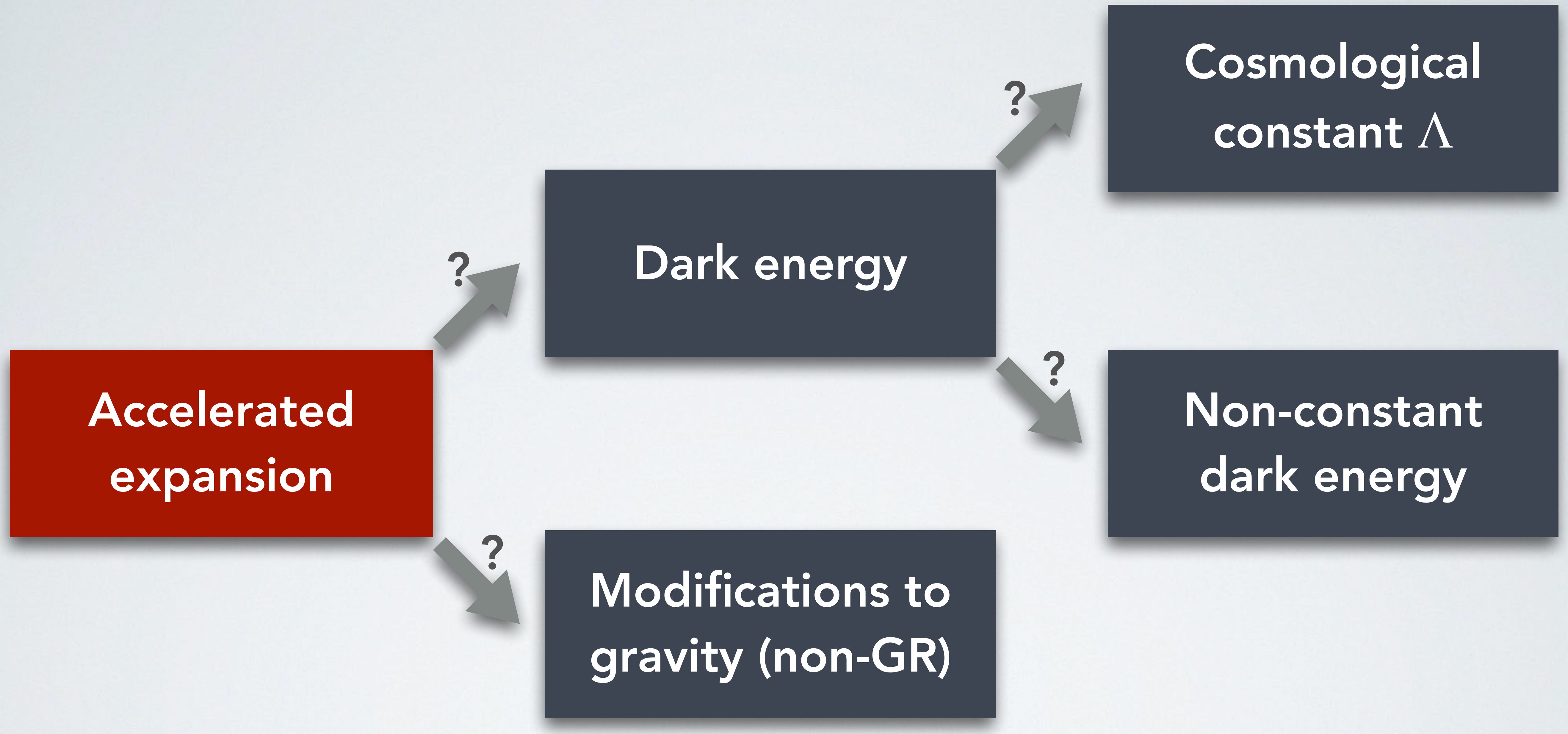


Modern supernova redshift-distance diagram



Weinberg et al. 2013

Does it have to be dark energy?



Dark matter vs. Dark energy

Dark matter: yet-to-be-found particle(s) that make up most of the matter in the Universe

Dark energy: property of spacetime that makes space "want to expand"

Take-aways

- The majority of matter in the Universe is dark, meaning **not composed of any known particle**
- The influence of **dark matter** is seen in the **motions** of stars/gas in galaxies and galaxies in clusters
- Type Ia (white dwarf) **supernovae** are an extremely bright **standard candle** that can be seen to $z > 1$
- The **accelerating expansion** was discovered with a redshift-distance diagram using supernovae

Next time…

We'll talk about:

- Concordance cosmology

Assignments

- Post-lecture quiz (by tomorrow night)
- Homework #4 (due Thursday 11/11)

Reading:

- H&H Chapter 13