Cosmology
Lecture 8

The Dark Universe

Does matter matter?

Seen that a(t) depends on the various energy densities: $\varepsilon_d, \varepsilon_m, \varepsilon_p$

But, we've also seen that Dark Energy dominates.

So, why does matter, well, matter?

- $\Omega_{d,0} = 0.714, \Omega_{m,0} = 0.286$ is not a unique solution to observed data, meaning that there are other solutions to the Benchmark model. We can isolate the true solution by constraining the matter density.
- While not the dominant component, matter still constitutes a significant fraction of the critical density.
- Until fairly recently (well, about 3.5B years ago) the Universe *was* matter dominated.

All this means that it's important to constrain the matter content of the Universe.

Types of matter

The current consensus is that there are two main types of matter in the Universe:

Baryonic Matter

- Stars
- Planets
- Dust
- Dense gas in galaxies
- Tenuous gas in clusters
- Tenuous gas in voids

Dark Matter

- Dunno
- Dunno
- Maybe neutrinos
- Dunno

Stars and planets

In a typical stellar system, roughly 99% of mass is contained within the star.
So, *we can pretty much forget about planets for now*.

In cosmology, we care about galaxy mass scales, not individual stars. How do we measure the mass of a galaxy?
Measure its luminosity from all its stars and convert to mass using a **mass-to-light ratio**.

What's the mass to light ratio of the Sun (in units of solar masses per solar luminosities)?

$$\mathrm{MLR}_\odot = 1\ M_\odot L_\odot^{-1}$$

But, this is not the same for all stars:
Higher mass stars tend to have lower mass to light ratios meaning they give off more energy per unit mass.

To determine the mass to light ratio for a whole galaxy, we have to figure out the relative proportions of low and high mass stars.

The mass-to-light ratio for a typical galaxy is about $4\ M_\odot L_\odot^{-1}$

Stars and planets

By measuring the luminosity of galaxies, and the number of galaxies per unit volume, then using suitable mass-to-light ratios, astronomers estimate that the mass density due to stars in the local Universe is:

$$4 \times 10^8 \ \mathrm{M}_\odot \ \mathrm{Mpc}^{-3}$$

Which corresponds to about 0.3% of the critical density (compared to the 28.6% in our Benchmark Model)!

Other Baryonic matter: Gas

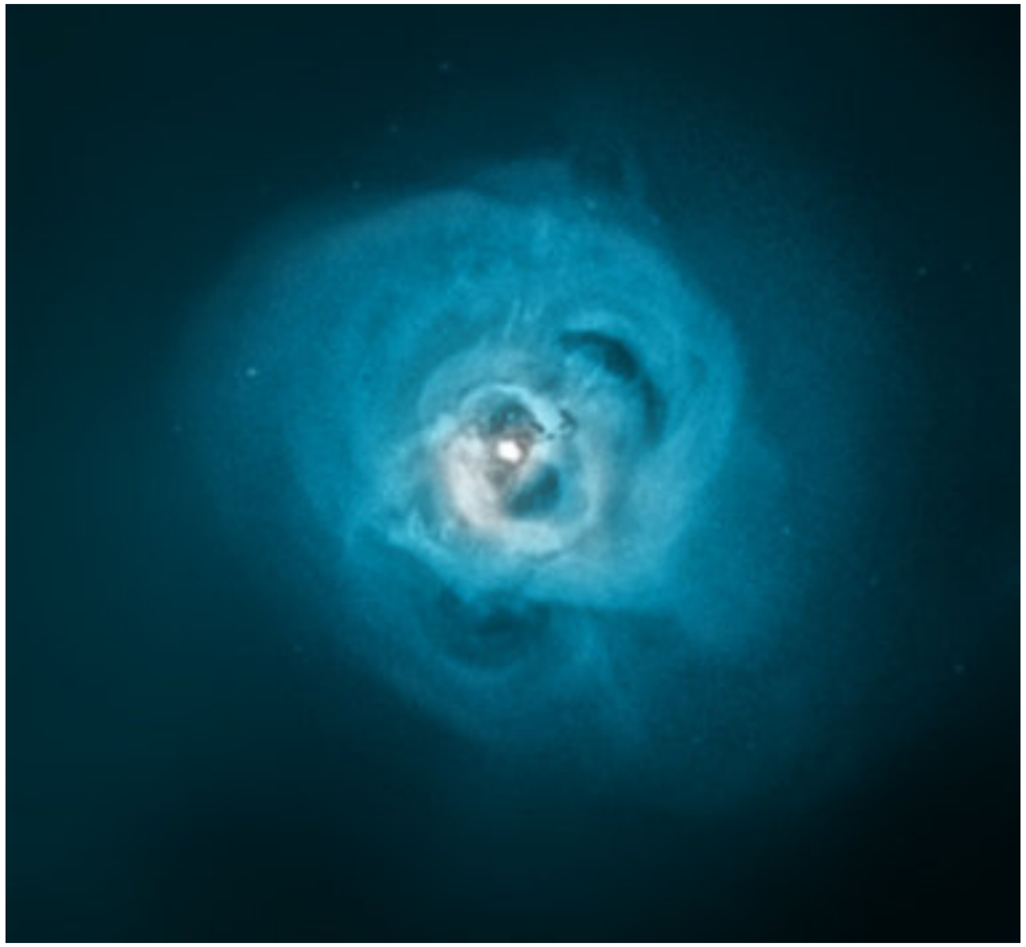
As well as stars, galaxies contain significant amounts of gas.

For example, about 20% (by mass) of all the Baryonic matter in the Milky Way is in the form of gas.

Dust represents about 1/10th of the mass of gas, so it's pretty negligible.

But, this is dwarfed by the amount of gas in the space *between* galaxies.

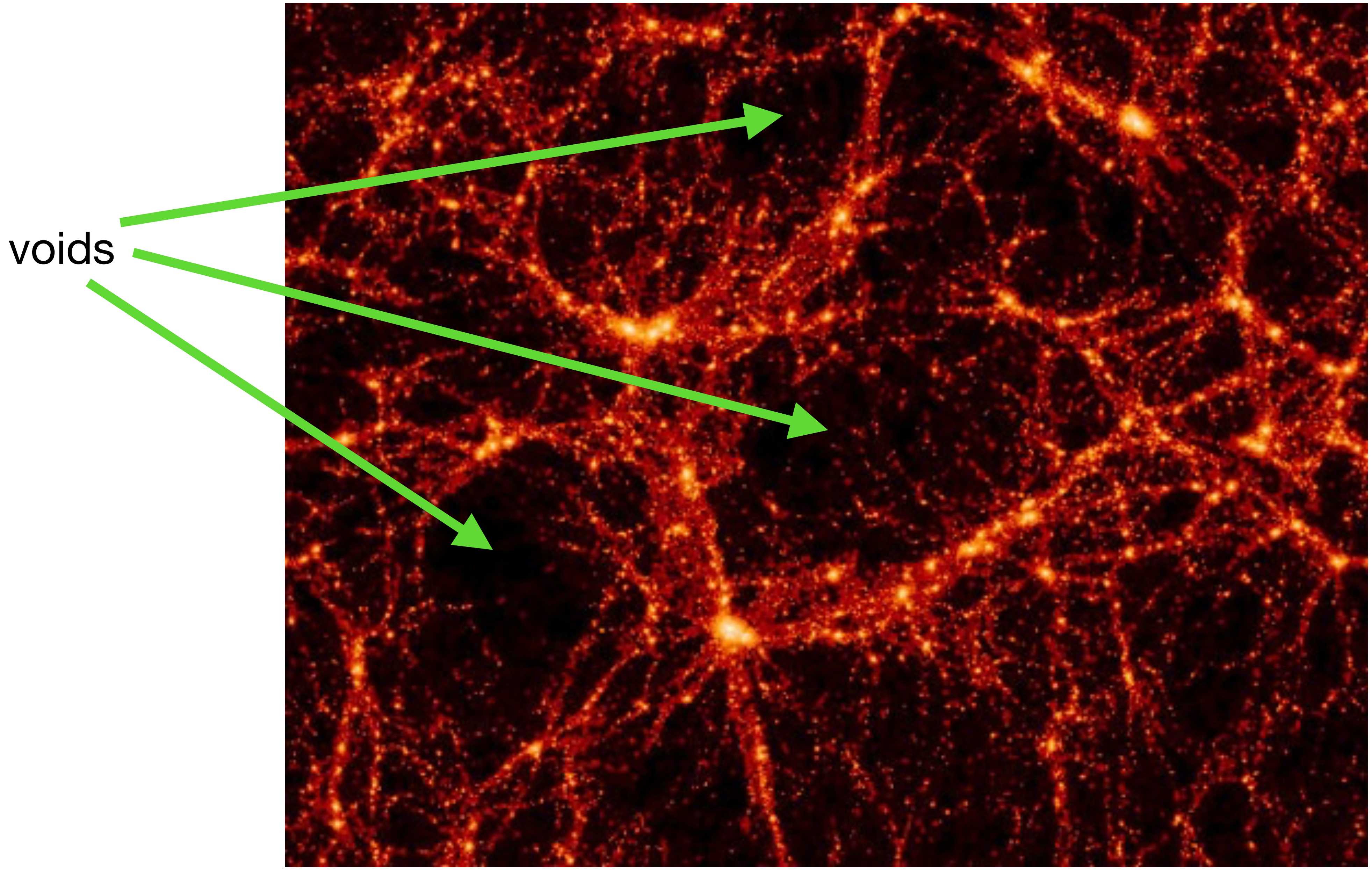
X-ray observations of clusters of galaxies reveal that there is roughly 10 times more tenuous gas in the space between galaxies than there are stars within galaxies.



Other Baryonic matter: Gas

But, gas in clusters is just the tip of the iceberg…

While hard to measure, it’s estimated that about 85% of all Baryonic matter in the Universe is in the form of the extremely tenuous gas that inhabits “voids”.

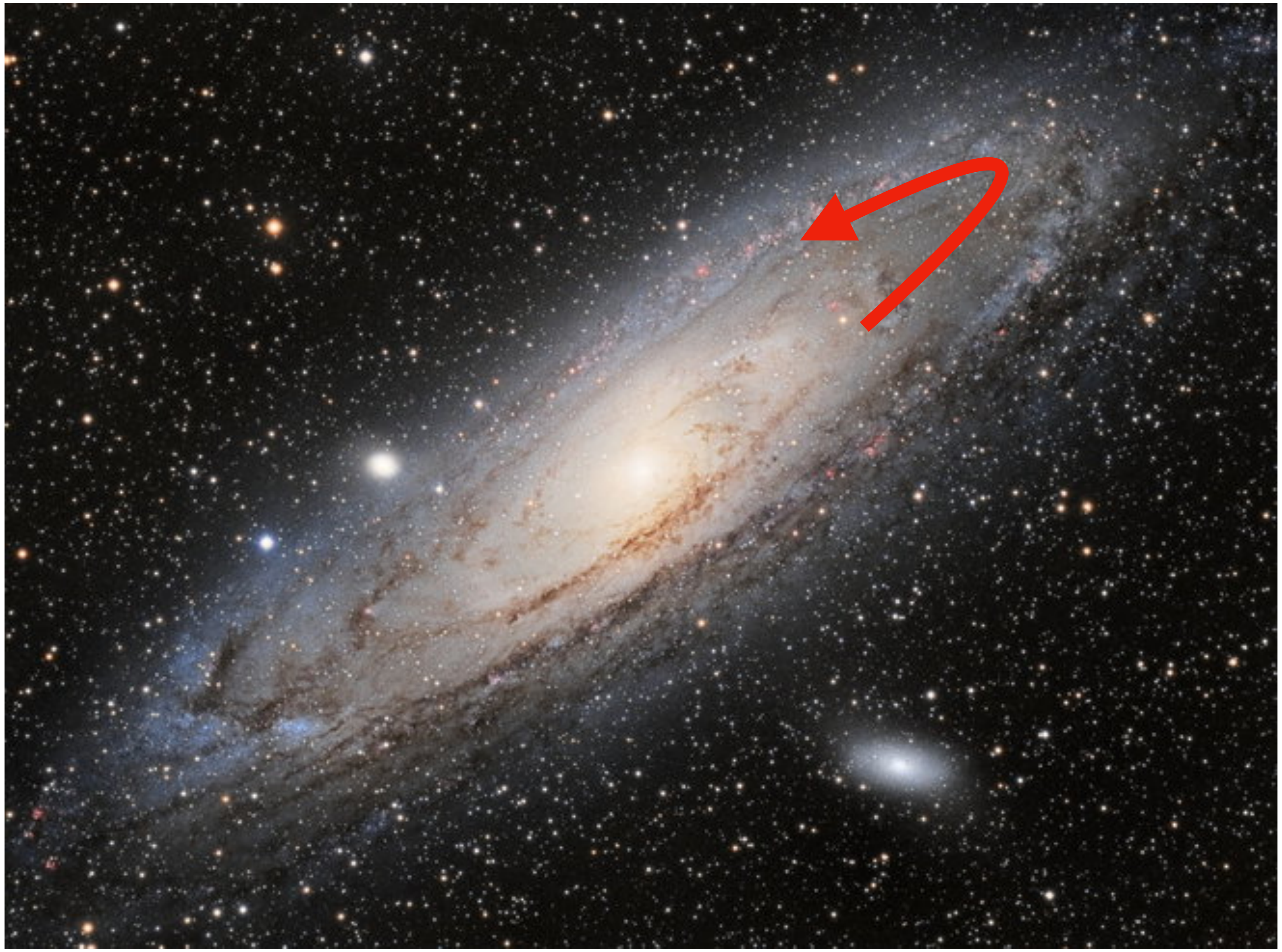


Dark Matter

- All told, Baryonic matter represents about 4.8% of the critical energy density.
- This compares to 28.6% attributed to *all* matter in our Benchmark Model.
- The remaining 23.8% is made up of **Dark Matter**.
- Dark Matter *is not* Baryonic Matter that is difficult to see. We've already account for that.
- Dark Matter *only* interacts with itself and other matter via gravity and it neither absorbs nor emits light.

Dark Matter

The presence of dark matter was first inferred from the rotational velocities of the M31 galaxy:



The rotation curve of a galaxy describes the speed of rotation of the galaxy as a function of distance from the centre.

Galaxy rotation curves

Since the density of stars in a galaxy falls very quickly with increasing radius, at the outskirts we can say that the Baryonic matter within the orbit is essentially constant…

Mass within here…

…is essentially the same as mass within here

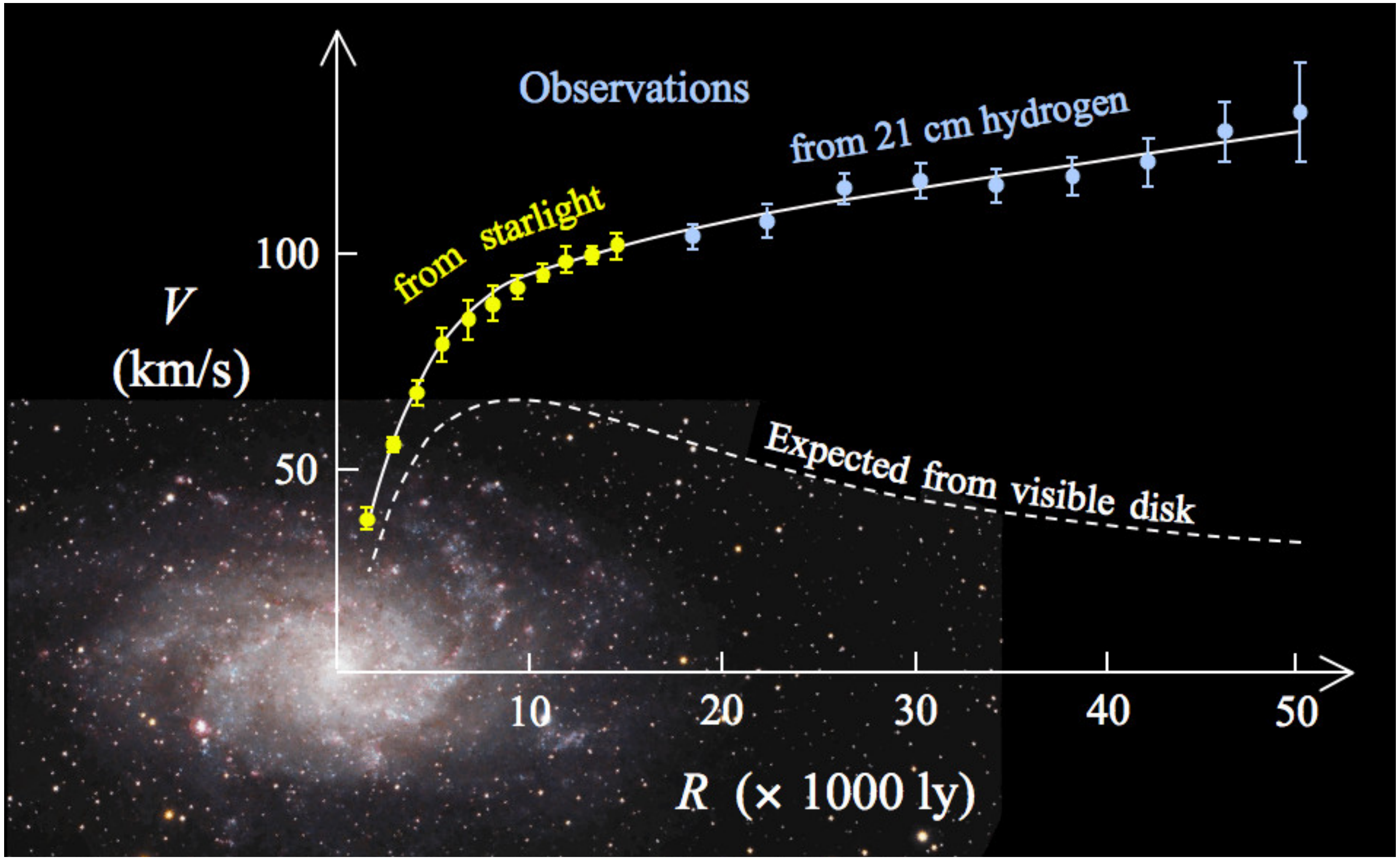
so…

$$\frac{GM}{R^2} = \frac{v^2}{R}$$

or…

$$v = \sqrt{\frac{GM}{R}}$$

“Flat” galaxy rotation curves

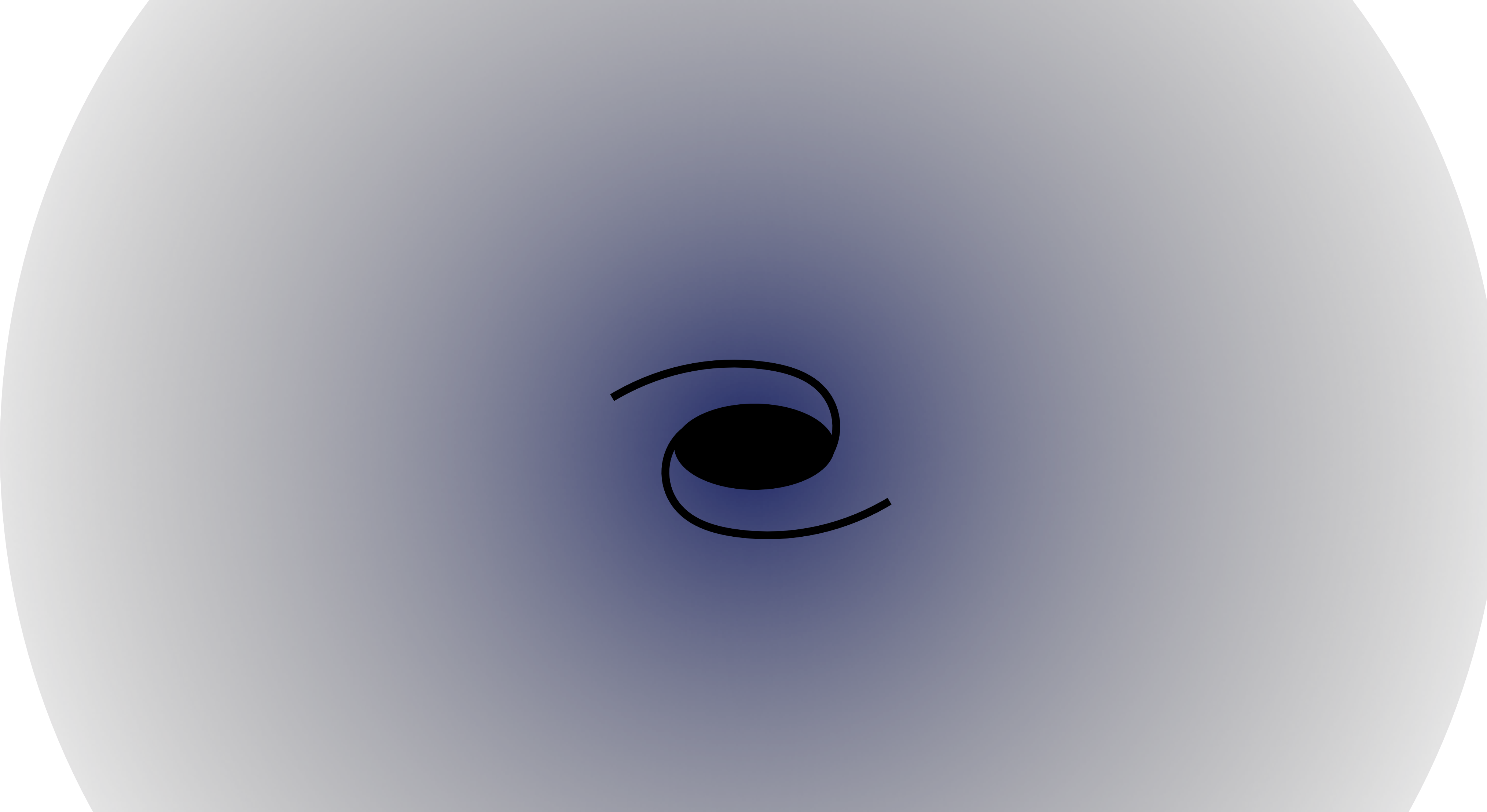


Despite the rotation speed falling with radius, as we’d expect from the starlight alone, the rotational velocity of galaxies either flattens or even increases with radius.

The most widely-accepted theory is that the unexpectedly high velocities in the outskirts is due to the mass continuing to increase with radius.

The Dark Matter Halo

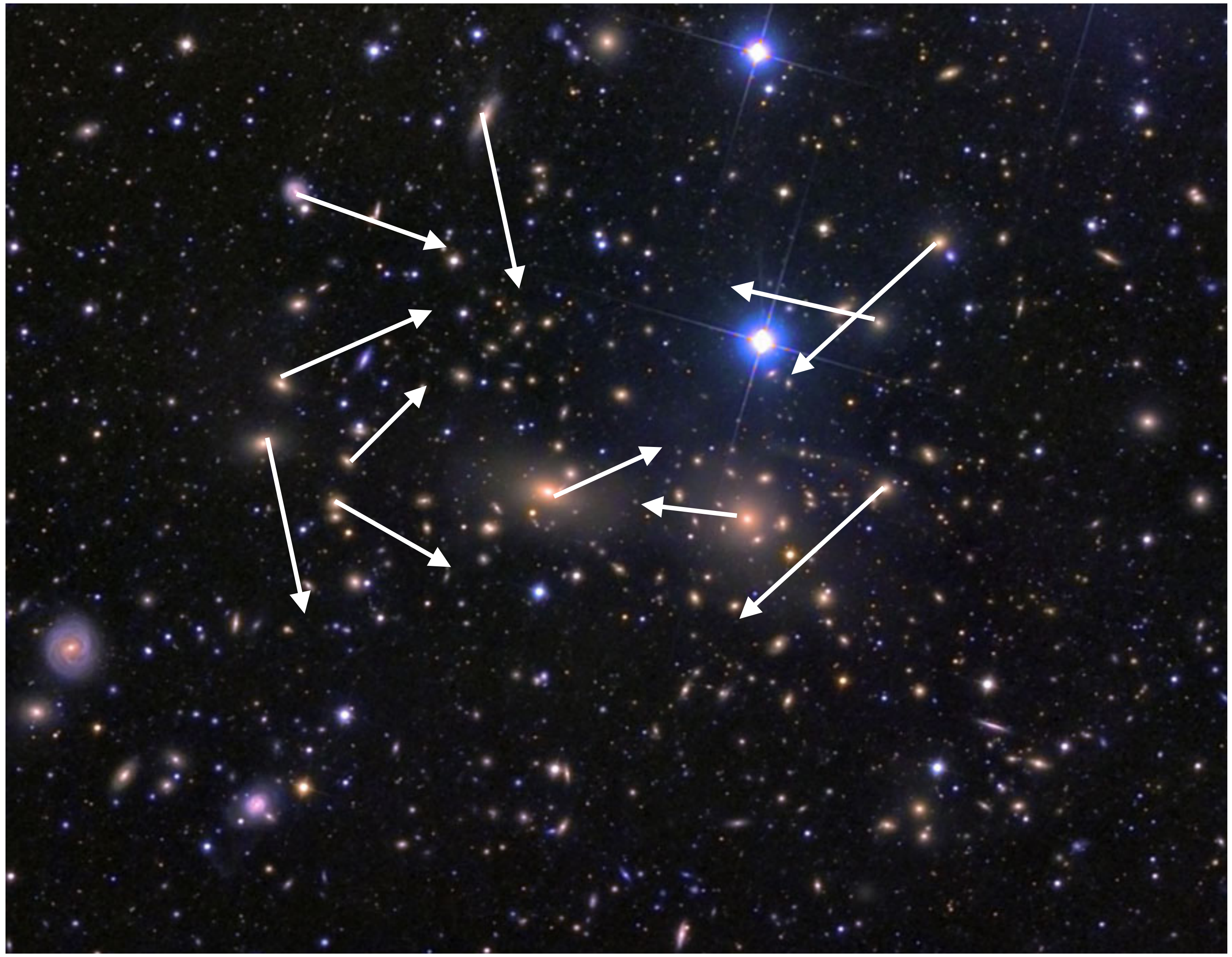
It is now widely accepted that all galaxies lie within a broadly spherical dark matter halo that is far more extended than their stellar contents.



It is hard to know precisely how extended these are, but measurements of the velocities of the outermost stars and gas suggest that the Milky Way's DM halo has a radius of at least 75 kpc, and possibly as large as 300 kpc.

This compares to a radius of about 20-30 kpc for Baryonic matter.

Dark matter in galaxy clusters



On larger scales than individual galaxies…

Measure the average velocity of galaxies within a cluster and use the virial theorem to relate the kinetic energy to the gravitational potential:

$$\underbrace{0 = W}_{\text{Grav. potential}} + 2\underbrace{K}_{\text{Kin. energy}}$$

or

$$\frac{1}{2} M \langle v^2 \rangle = \frac{\alpha}{2} \frac{GM^2}{r_h}$$

half-mass radius of cluster

Dark matter in galaxy clusters


Coma cluster

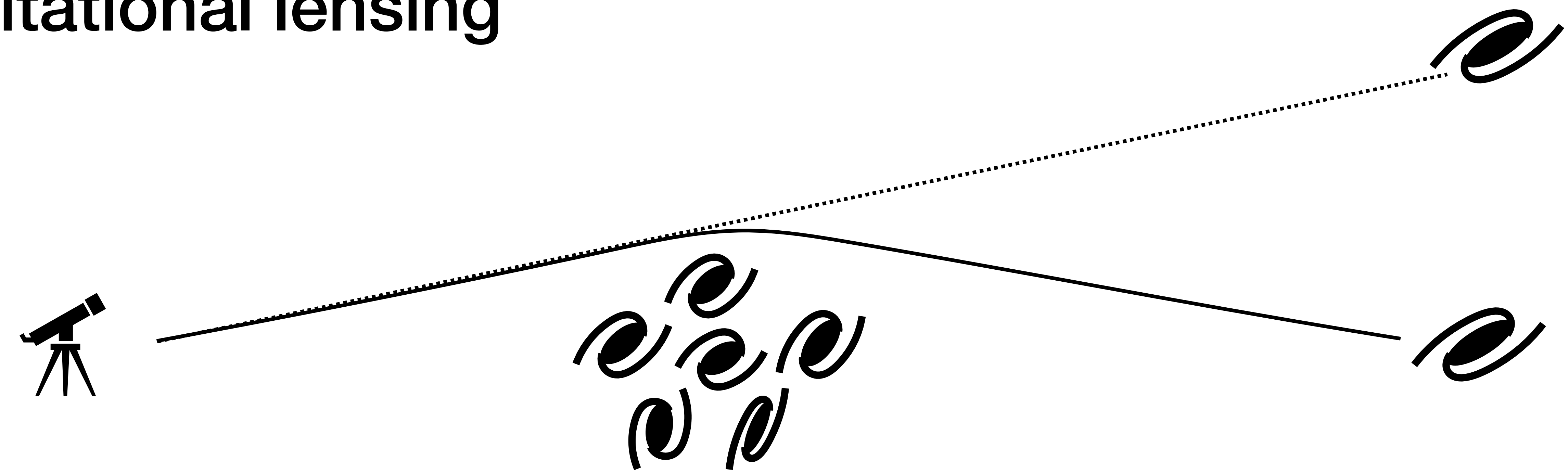
On larger scales than individual galaxies…

$$M_{\mathrm{Tot}} \approx 2 \times 10^{15}\ \mathrm{M}_{\odot}$$

compared to

$$M_{\mathrm{stars}} \approx 2 \times 10^{13}\ \mathrm{M}_{\odot} \quad \text{and} \quad M_{\mathrm{gas}} \approx 2 \times 10^{14}\ \mathrm{M}_{\odot}$$

Gravitational lensing



Something very massive
(e.g. galaxy cluster)

As light from a distant galaxy passes a massive galaxy cluster, its path gets distorted.

The amount of distortion is related to the mass of the galaxy cluster

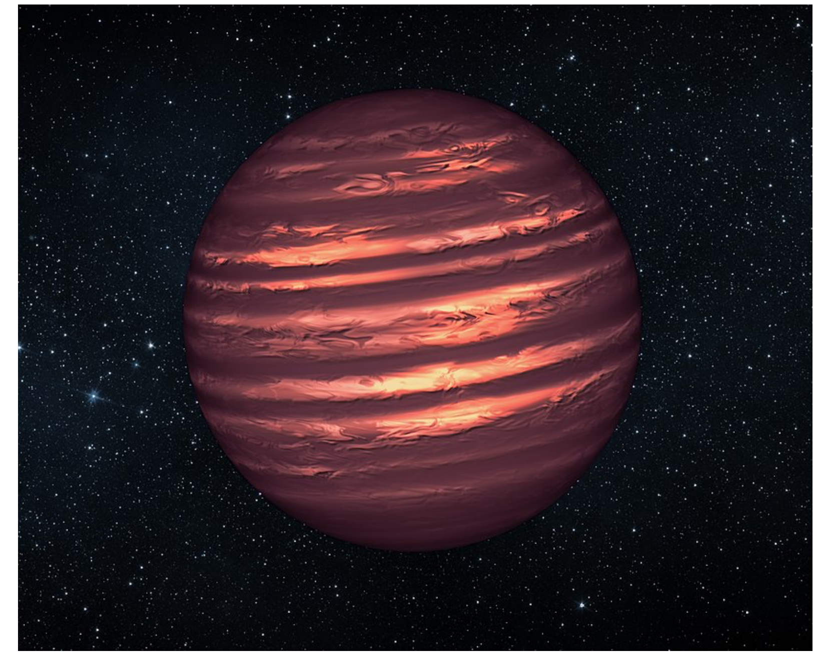
By measuring (actually modelling) the distortion, astronomers are able to calculate the *total* mass of the cluster.

These masses are generally consistent with those obtained using the viral theorem.

Gravitational lensing

What is dark matter?

The MACHOs vs WIMPs debate



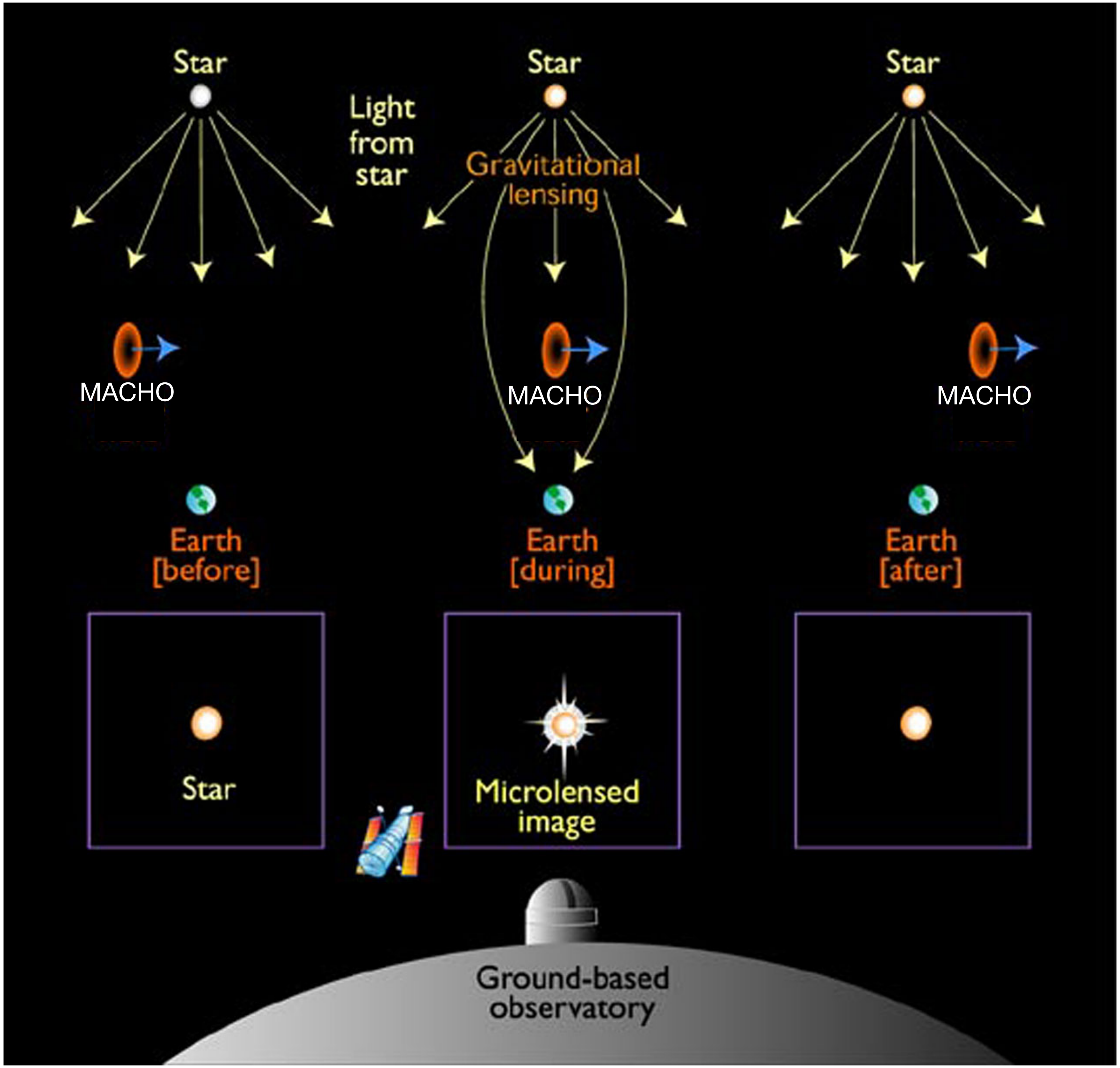
MACHO: MAssive Compact Halo Object:

The dark matter halo contains thousands of trillions of Brown Dwarfs. These are stars that are too low mass to fuse hydrogen, and so do not “shine” and thus are hard to detect.

WIMP: Weakly Interacting Massive Particle

Dark matter consists of one or more different types of subatomic particle which doesn’t interact with normal matter aside from gravitationally.

Testing for MACHOs



WIMPs?

A number of different candidates have been suggested for WIMPs:

- **Axions**: a hypothetical subatomic particle whose mass we don't know, so it's difficult to say whether they are viable.

- **Neutrinos**: A known subatomic particle whose mass we do know, but given the known density of neutrinos, it's mass is about 40 times too small for it to be responsible for the bulk of dark matter.

- **Something else**: My own suspicion is that there are lots of different types of dark matter, so we'll never be able to identify "the one".

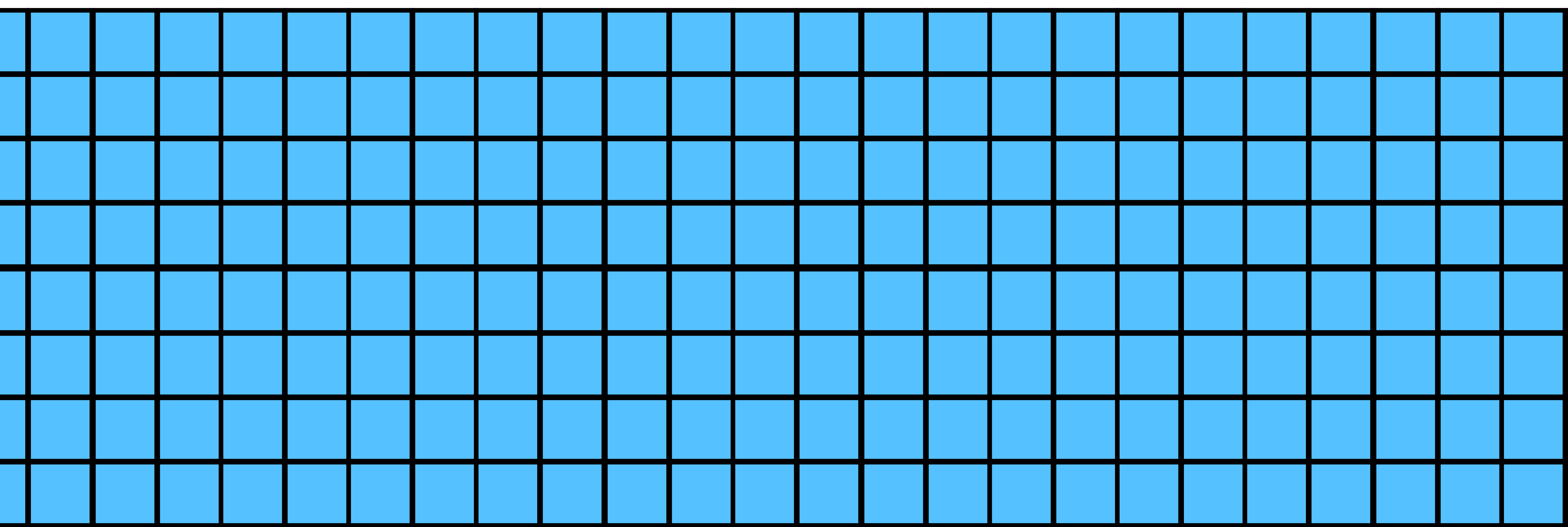
Dark Energy

The Dark Energy energy density

Currently, about 69% of the energy density of the Universe is in the form of dark energy.

Observations suggest that the energy density of Dark Energy is constant.

In an expanding universe, as volume increases, the total amount of Dark Energy increases:



What is Dark Energy?

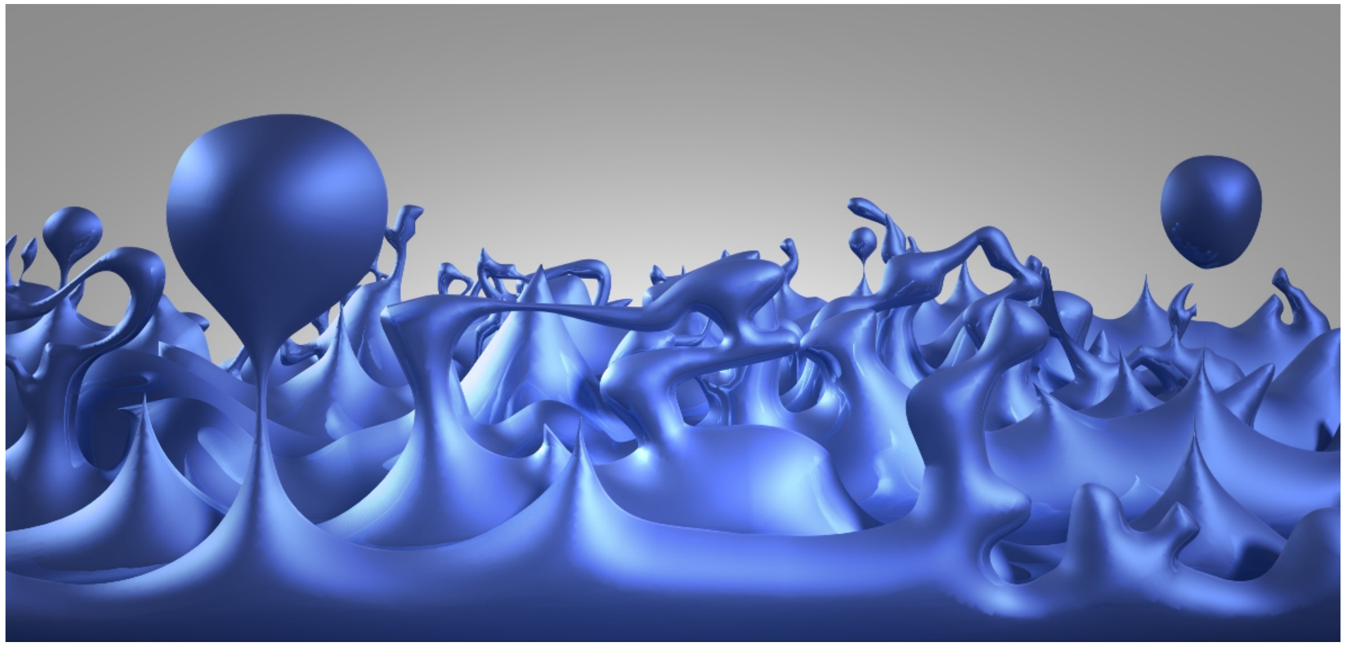
We really don't know.

One idea is that is a "Vacuum Energy" caused by quantum fluctuations.

At a quantum scale, small amounts of energy can be created for short periods of time via:

$$\Delta E \Delta t > \frac{\hbar}{2}$$

Creating a "quantum foam" with positive net energy.



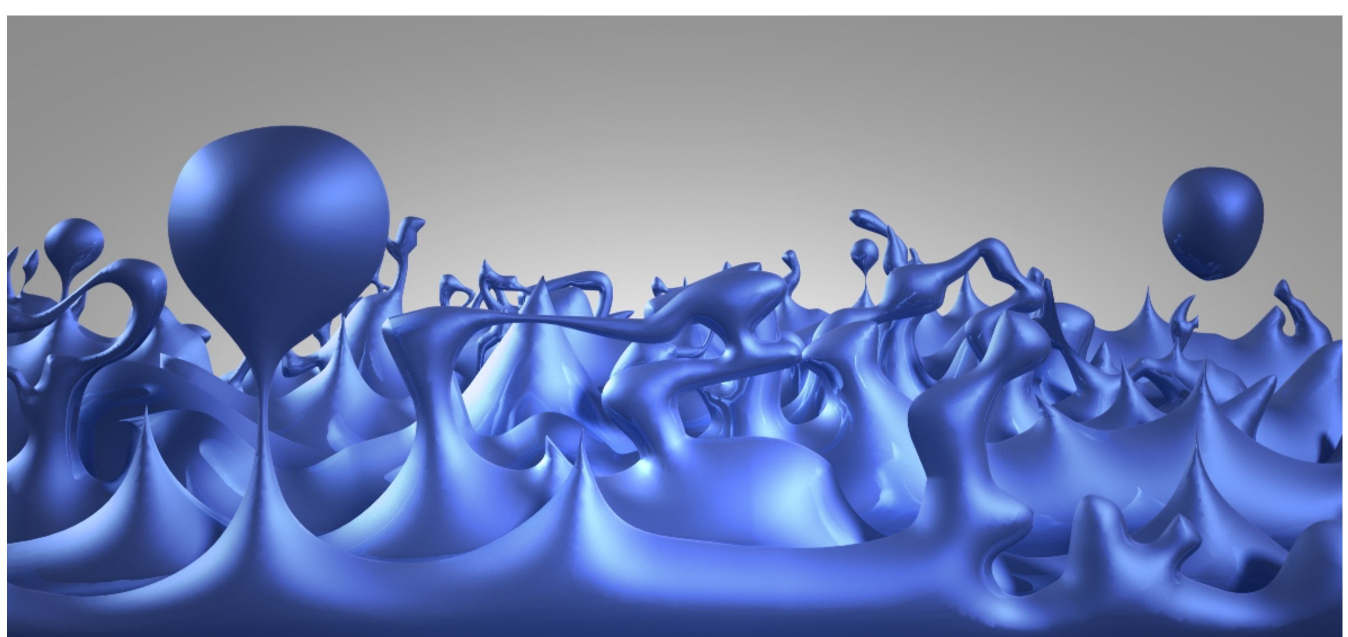
What is Dark Energy?

Because this is a vacuum energy, as more vacuum is created in an expanding universe, more vacuum energy is made.

As such, it fulfils the requirement of a constant density.

The problem, however, is that our theories of quantum mechanics predicts that the vacuum energy is 10^{123} times larger than the current critical density.

In other words, by now, the Universe should have blown itself apart!



Getting the feel of it…

While stars are the most visible form of Baryonic matter, it only forms about 1-2% of all Baryonic matter in the Universe.

By far the majority (~85%) of Baryonic material in the Universe is in the form of tenuous gas within the huge voids between galaxy clusters.

But Baryonic Matter only represents about 20% of all matter in the Universe. The rest is in the form of dark matter.

The most widely-accepted proposal is that dark matter is made up of weakly interacting subatomic particles.

Dark energy represents about 69% of the energy density of the Universe. We have no idea what it is!