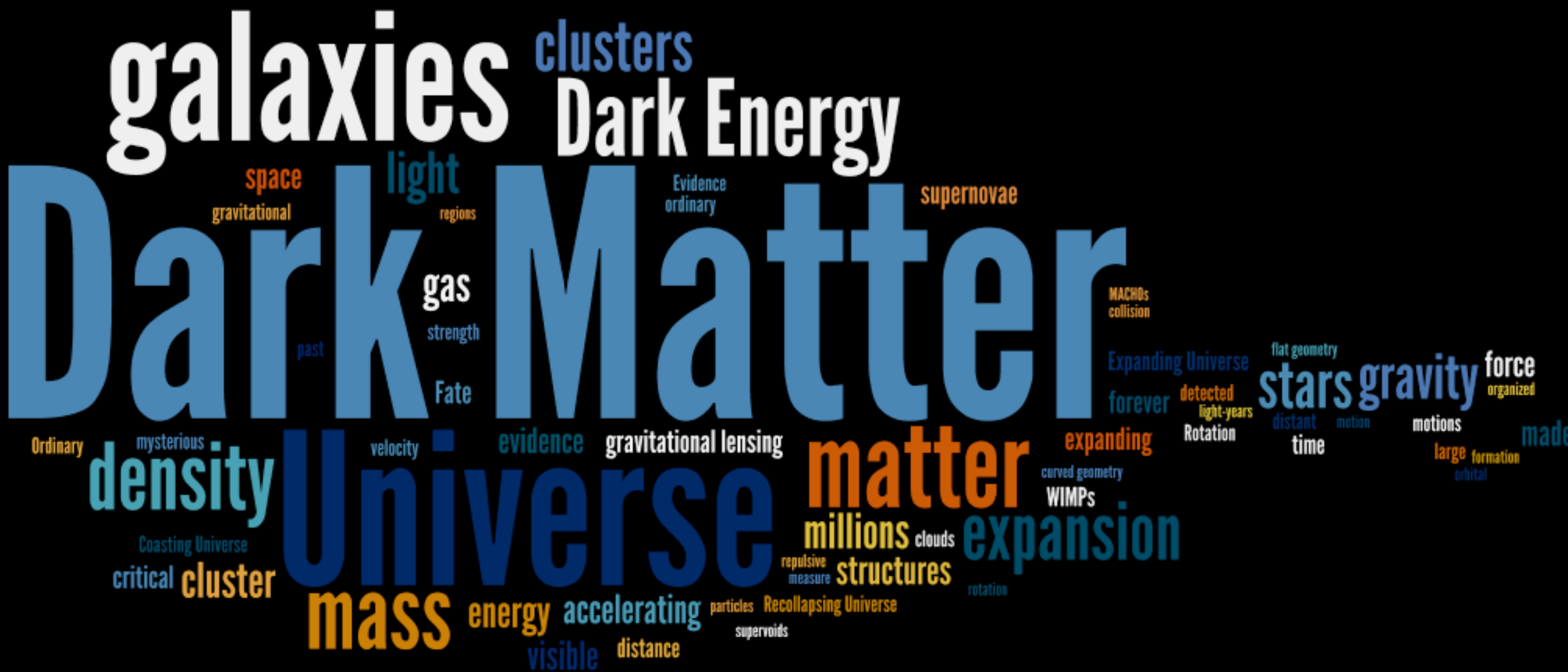
Dark Matter, Dark Energy, & The Fate of the Universe

Chapter 16


galaxies
clusters
Dark Energy
space
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Evidence
ordinary
supernovae
gravitational
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Dark Matter
gas
MACHOs
collision
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past
Expanding Universe
flat geometry
Fate
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detected
light-years
stars
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organized
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Ordinary
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gravitational lensing
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Rotation
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matter
curved geometry
WIMPs
millions
clouds
expansion
Coasting Universe
repulsive
measure
structures
critical
cluster
rotation
mass
energy
accelerating
particles
Recollapsing Universe
supervoids
visible
distance

Dark Matter and Dark Energy?

* This is our current situation

1. Gravity (from luminous & dark matter) holds galaxies together and attracts each galaxy to all others and fights against expansion

2. Yet space is expanding and carries galaxies away from one another, weakening gravitational forces

Dark Matter and Dark Energy?...

* The crucial question
    * how will that affect the future of our Universe?
* Are there variations to that future, depending on the amount of gravity versus dark energy?

Unseen Influences in the Cosmos

* Careful studies have shown that

  a. galaxies do not have enough mass (that we can see) to hold together (yet they do...) hence more matter is needed

  b. the expansion of the Universe is accelerating hence some energy is doing this

Missing Mass

* Galaxies are not flying apart as they rotate: there has to be more mass in and around each galaxy and we cannot see it

An Additional Energy?

- When Einstein wrote the General Theory of Relativity he believed the Universe was static
- But his equations showed that the Universe was either expanding or contracting (with a constant rate)
- He then introduced a quantity that fought against gravity: the cosmological constant, Λ

General Relativity

These terms (R and g) describe the curvature of spacetime (they tell matter and energy how to move)

This term (T, the stress-energy tensor) describes the distribution of matter and energy (it tells spacetime how to curve)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8 \pi G}{c^4} T_{\mu\nu}$$

The cosmological constant (Λ) behaves gravitationally like matter and energy except that it has negative pressure.

Einstein's Cosmological Constant

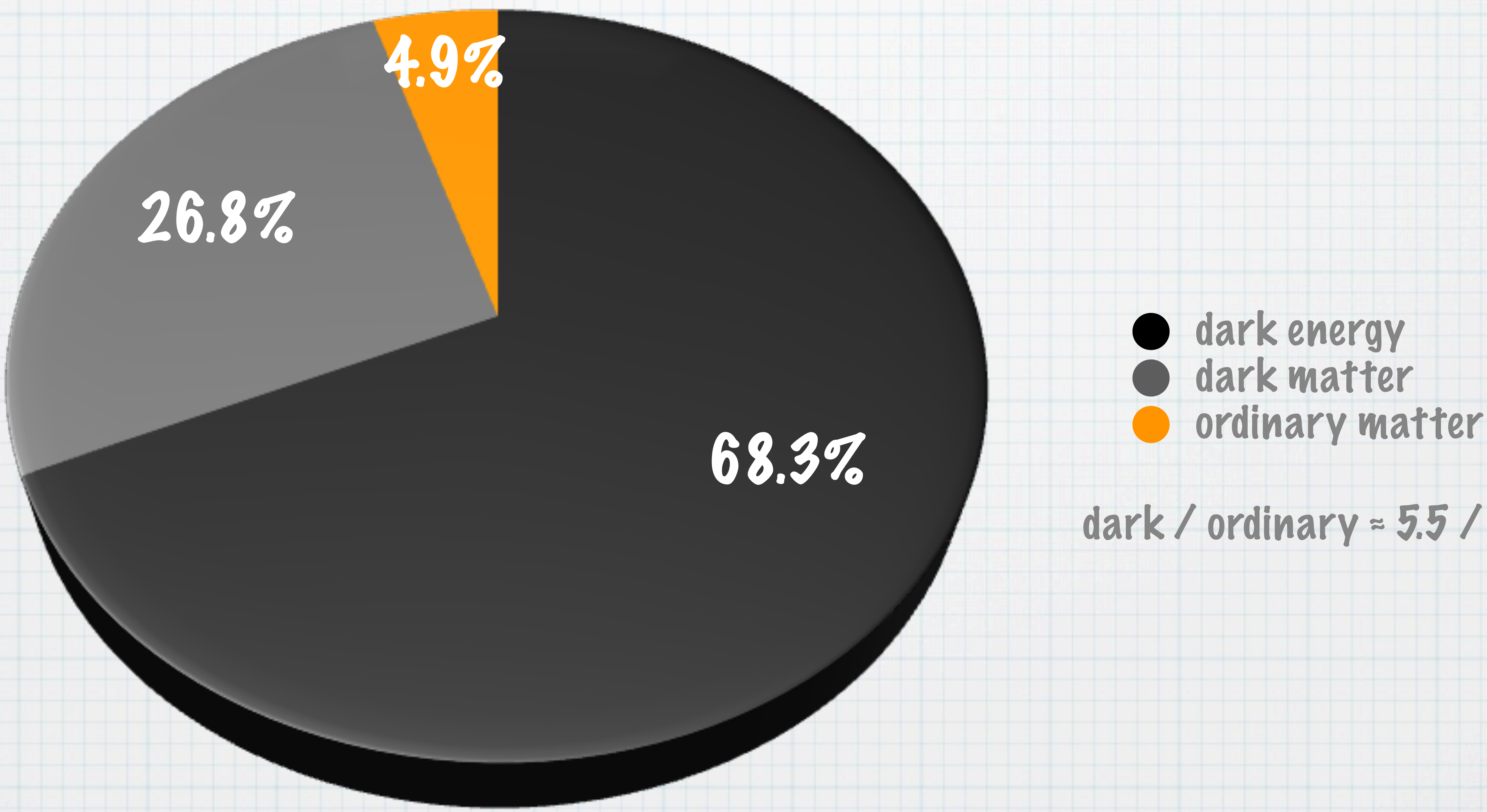
* When Hubble showed the Universe was not static but expanding, Einstein removed the term out of the equations thinking he had made a blunder by forcing the Universe to be static

* However, we now are capturing data showing that the Universe expansion rate is accelerating and the constant is back: empty space has an intrinsic energy

Unseen Influences

* Dark Matter: the invisible mass: a recently detected form of matter which does not interact with the electromagnetic force but whose presence is inferred from its gravitational influence
* Dark Energy: the invisible energy: an unknown form of energy that seems to be the source of a repulsive force causing the expansion of the Universe to accelerate

The Composition of the Cosmos now



dark / ordinary ≈ 5.5 / 1

Contents of the Universe

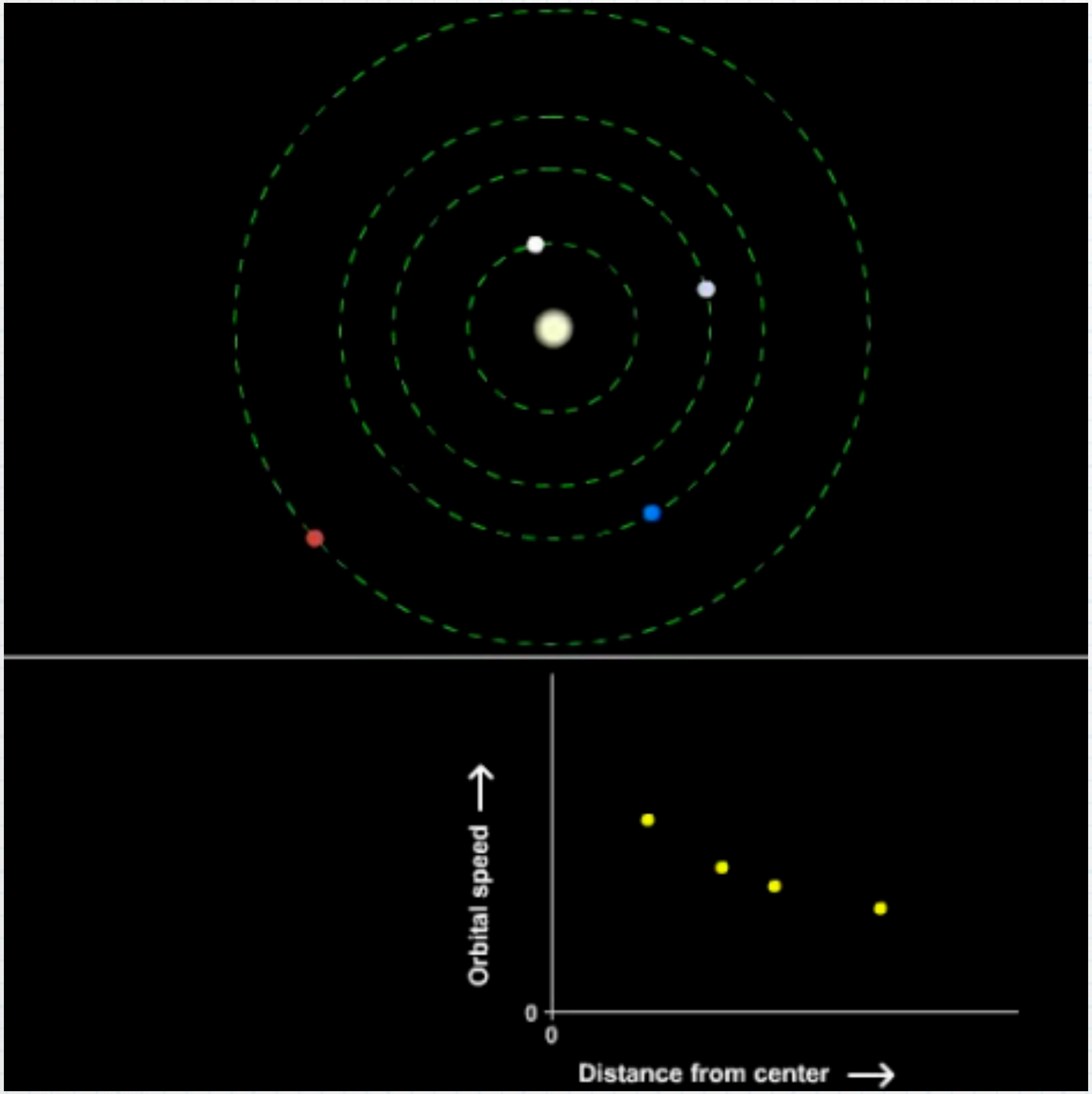
Ordinary Matter	~4.9%
inside stars	~0.4%
outside stars	~4.5%
Dark Matter	~26.8%
Dark Energy	~68.3%

Snapshot

* **Dark matter** is the name given to the invisible mass whose gravity governs the observed motions of stars and gas clouds
* **Dark energy** has never been directly observed, but it has been proposed to exist because it seems the simplest way to explain a set of observed motions in the Universe
* **Dark energy** is the name given to whatever may be causing the expansion of the Universe to accelerate

What is the evidence for dark matter in galaxies?

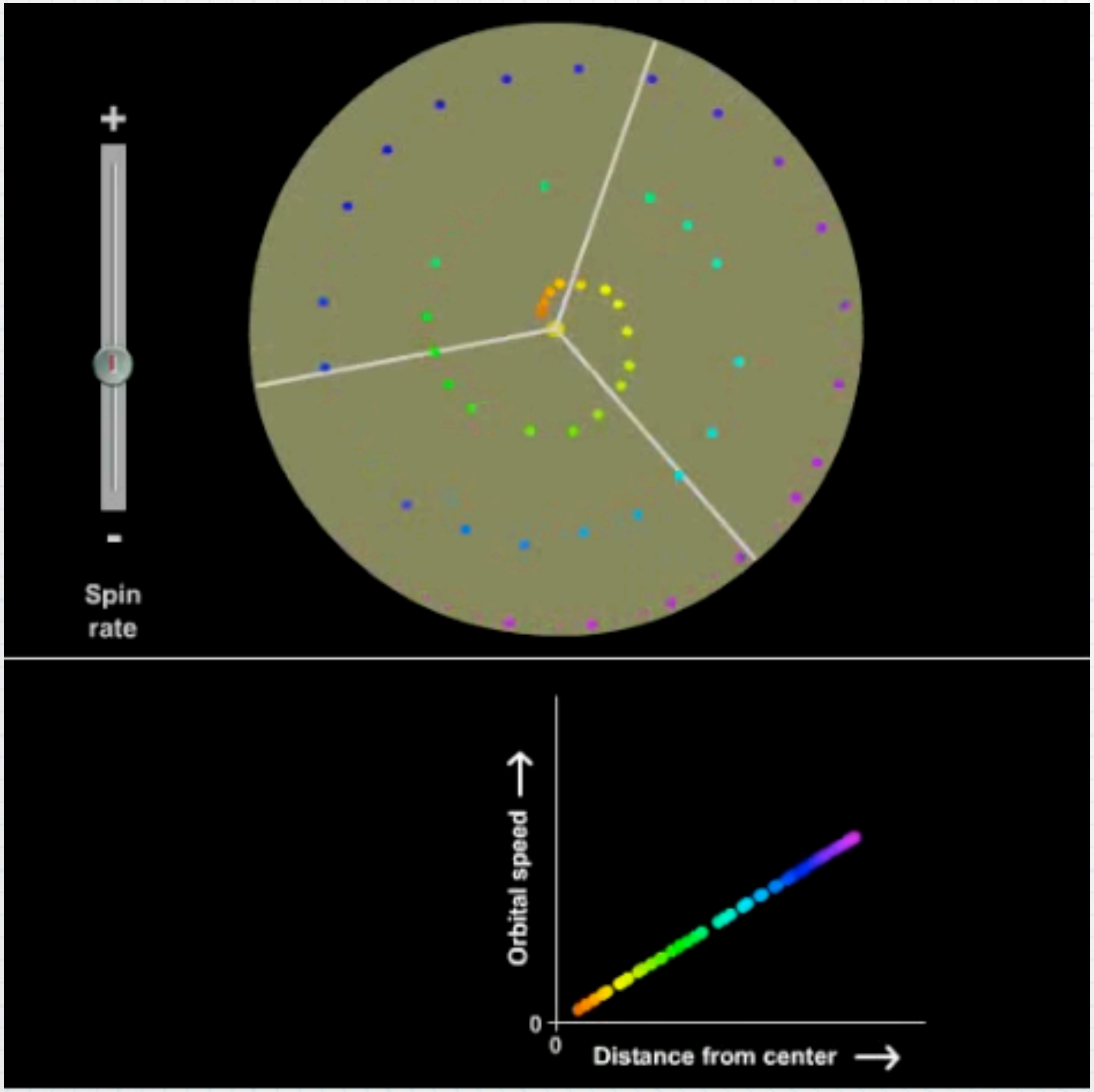
* Let's compare how different systems rotate
  * the Solar System
  * a merry-go-round
  * a spiral galaxy



Rotation curve

A plot of orbital velocity versus orbital radius

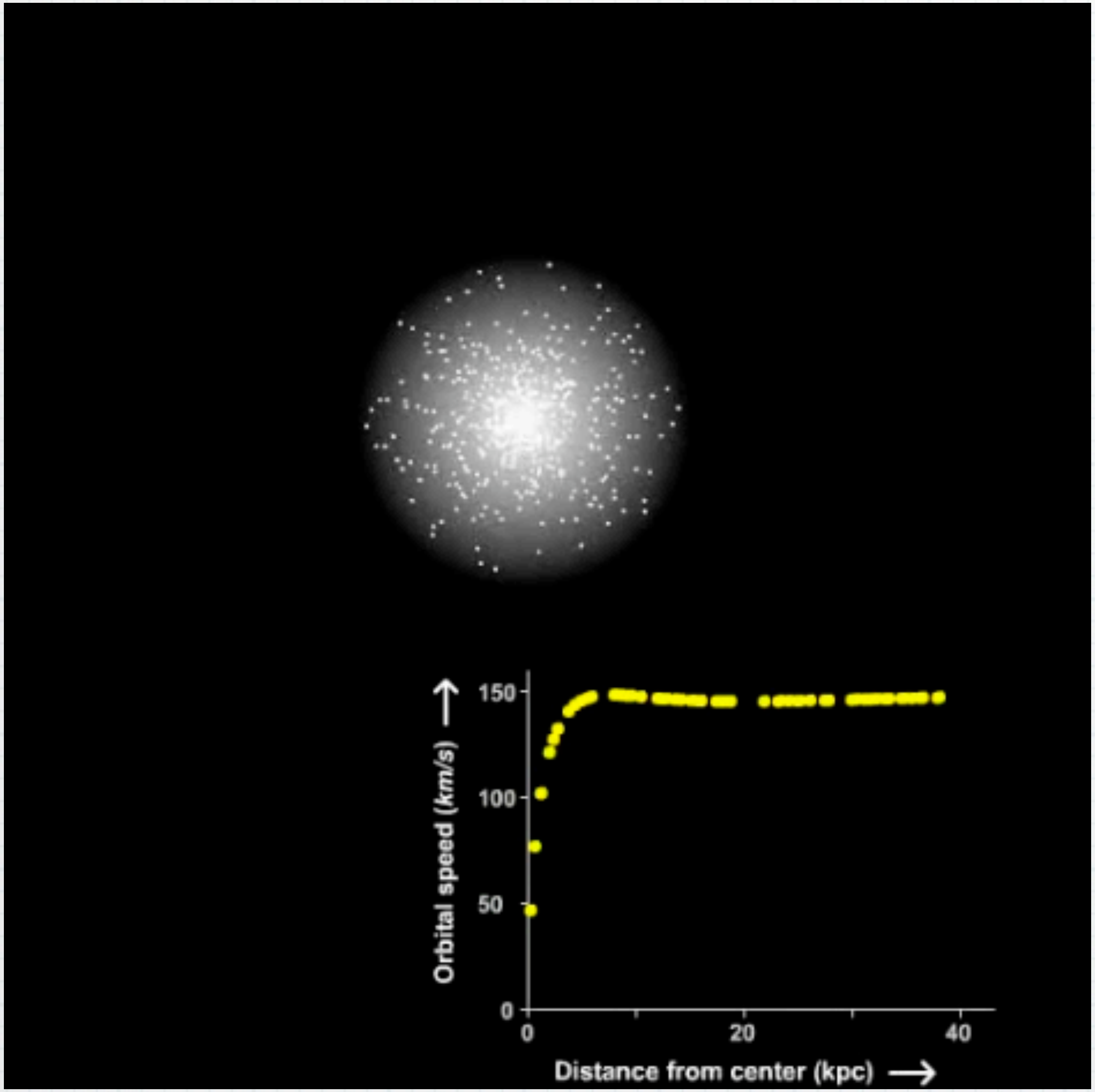
Solar System's rotation curve declines because Sun has almost all the mass



Rotation curve

A plot of rotational velocity versus radius

Rotation curve of merry-go-round rises with radius



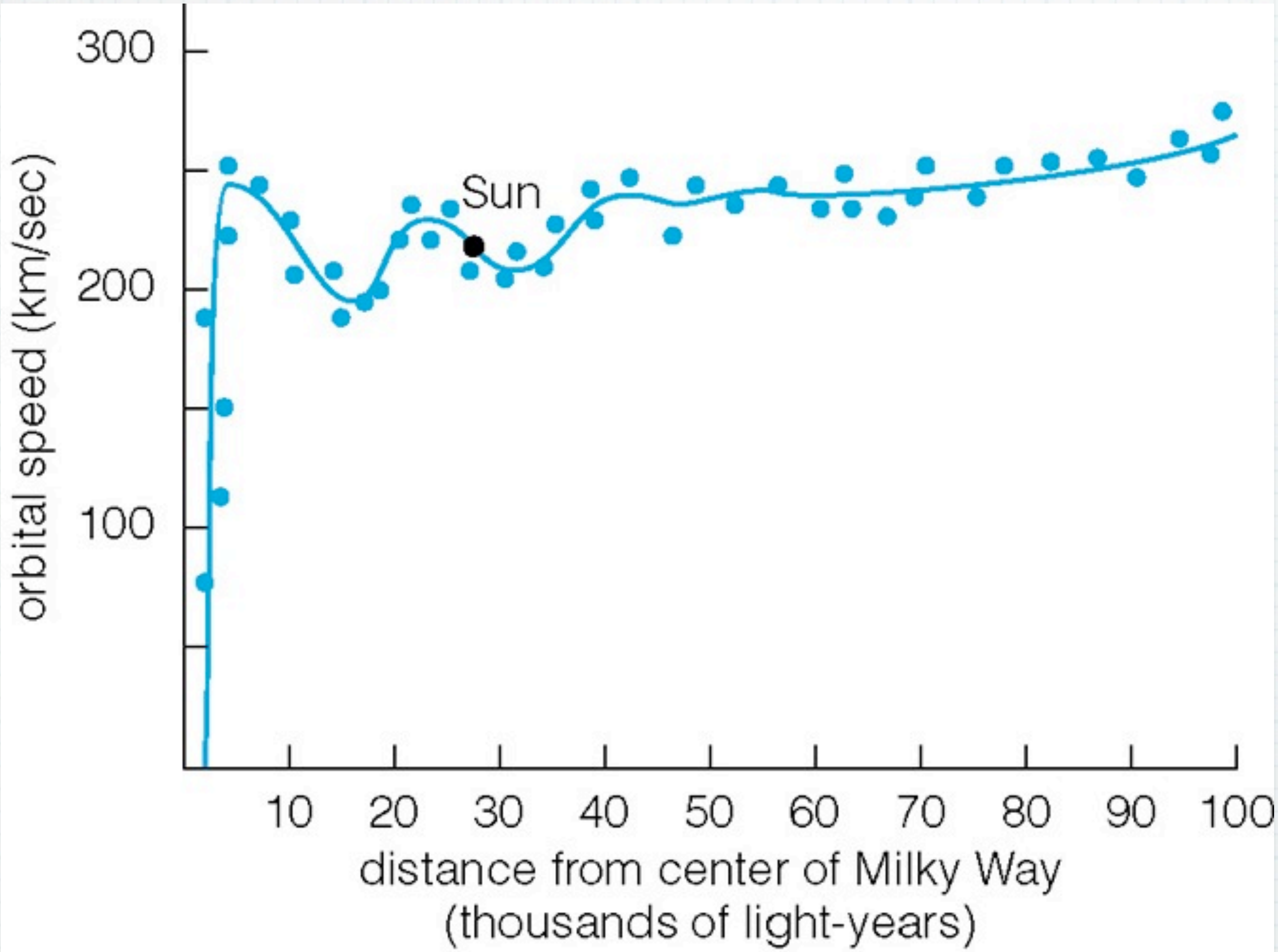
Rotation curve

Rotation curve of Milky Way stays flat with distance

Mass must be more spread out than in Solar System

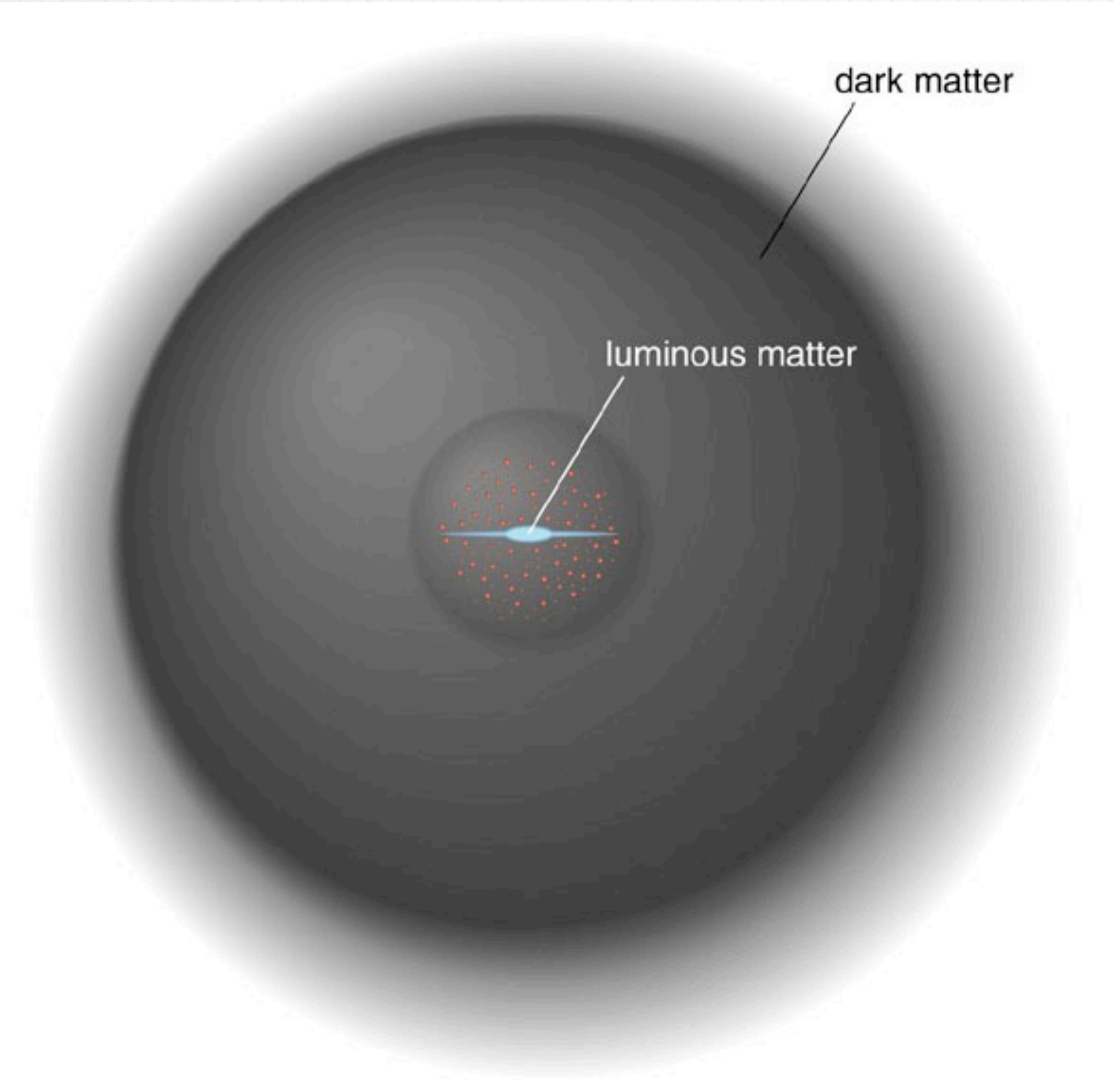
Milky Way rotation curve

Its flatness indicates that our galaxy's mass extends well past the Sun's orbit



A large amount of **unseen matter** lies beyond our galaxy's visible regions

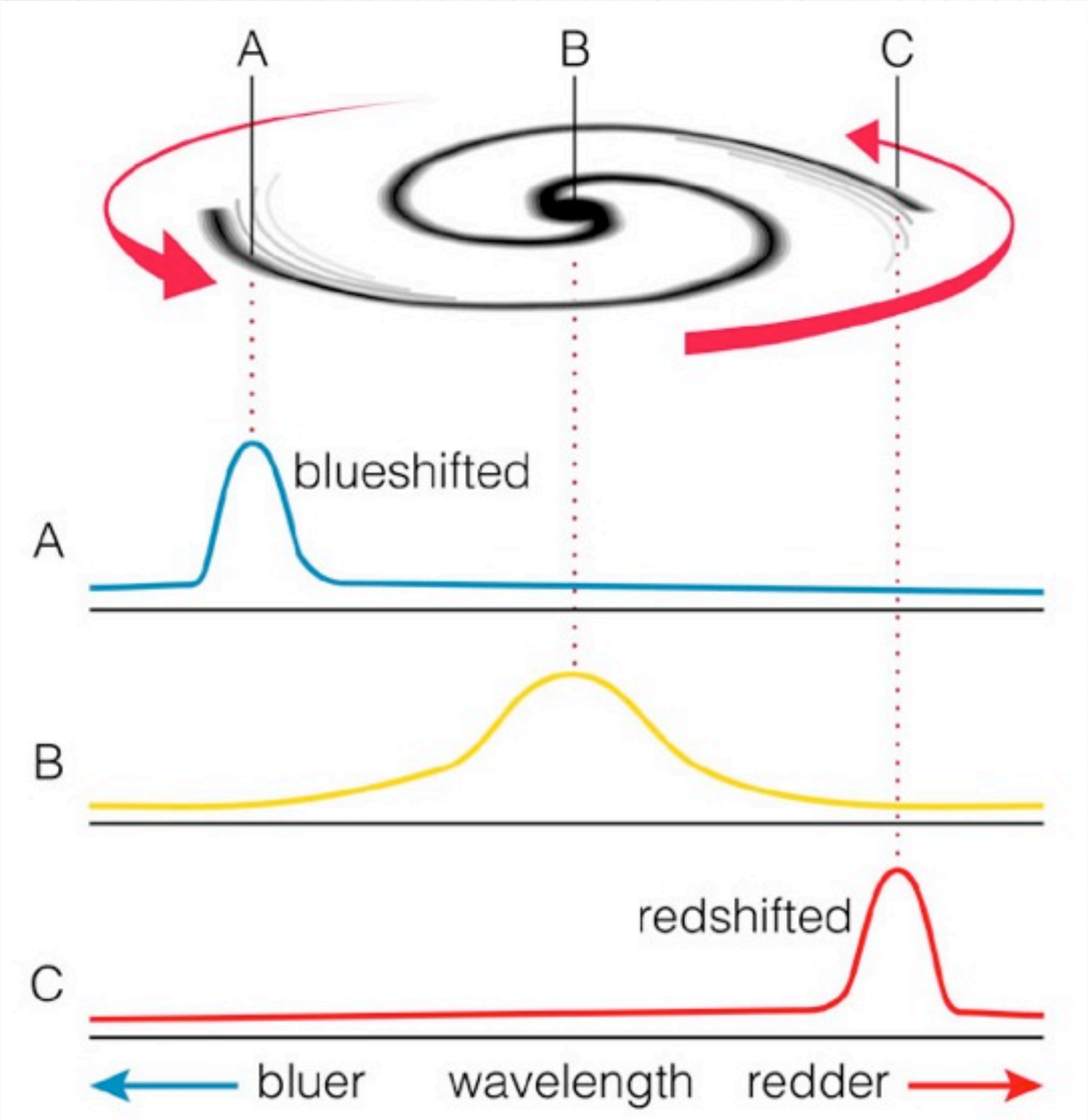
Most of the Milky Way's mass seems to be dark matter!



The visible portion of a galaxy lies deep in the heart of a large halo of dark matter

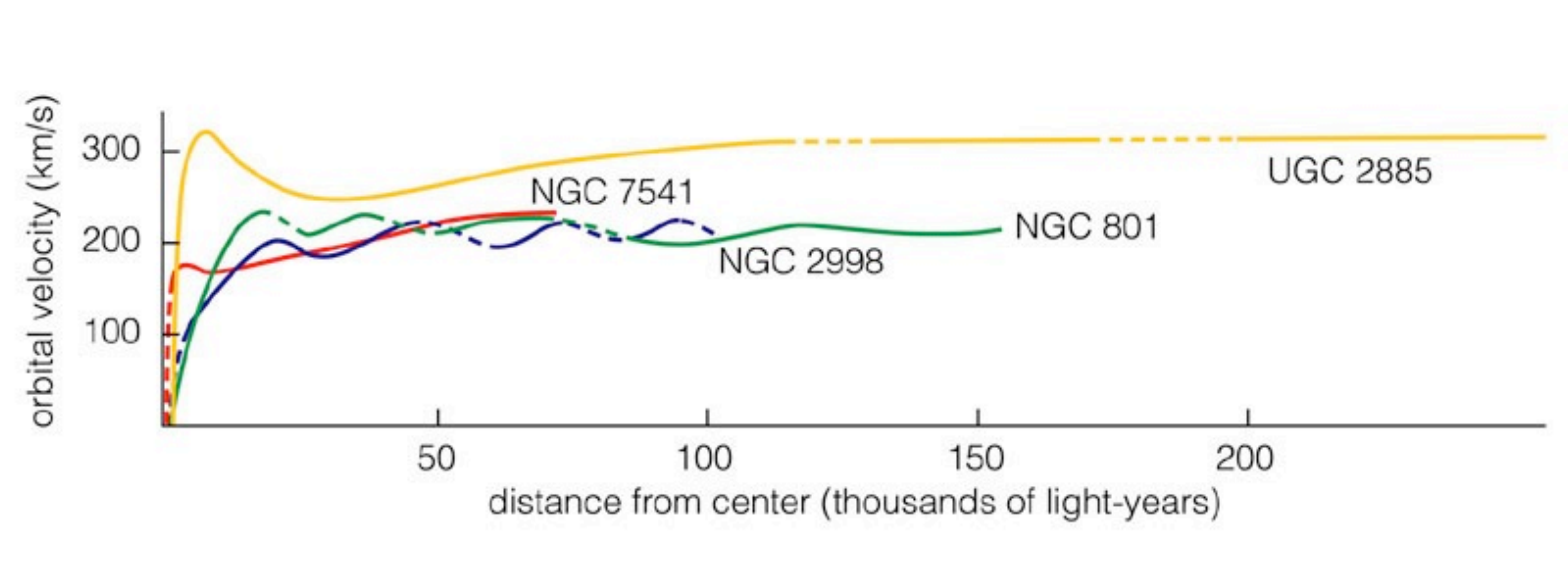
The radius of this dark matter halo may be 10 times as large as the galaxy's halo of stars

What about other galaxies?

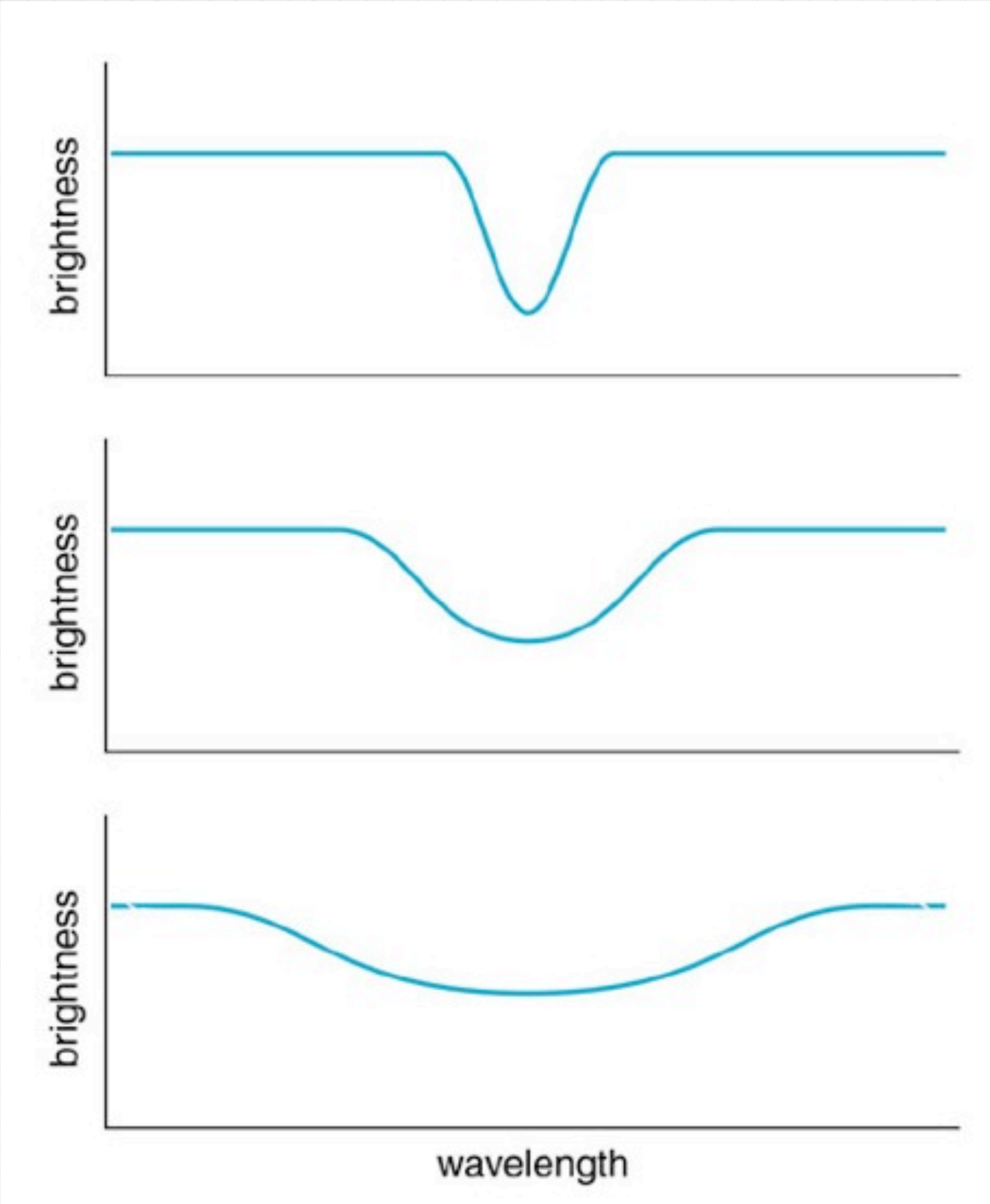


We can measure rotation curves of other **spiral galaxies** using the Doppler shift of the 21-cm line of atomic hydrogen

Spiral galaxies all tend to have flat rotation curves indicating large amounts of dark matter



Elliptical galaxies do not have enough atomic gas to measure their 21-cm radiation



Instead we measure the motion of their inner stars

Broadening of spectral lines in elliptical galaxies tells us how fast the stars are orbiting

These galaxies also have dark matter

Question

* What would you conclude about a galaxy whose rotational velocity rises steadily with distance beyond the visible part of its disk?

A. Its mass is concentrated at the center

B. It rotates like the solar system

C. It's especially rich in dark matter

D. It's just like the Milky Way

Question

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What is the evidence for dark matter in clusters of galaxies?

matter	visible	dark	factor
within galaxy	10%	90%	10x more (10 + 90) / 10
within galaxy cluster	2%	98%	50x more (2 + 98) / 2

Fritz Zwicky

* He was one of the first astronomers to think of galaxy clusters as huge swarms of galaxies bound together by gravity

* He measured the redshifts of galaxies in clusters and found that their motions implied that they had much greater masses than their luminosities implied

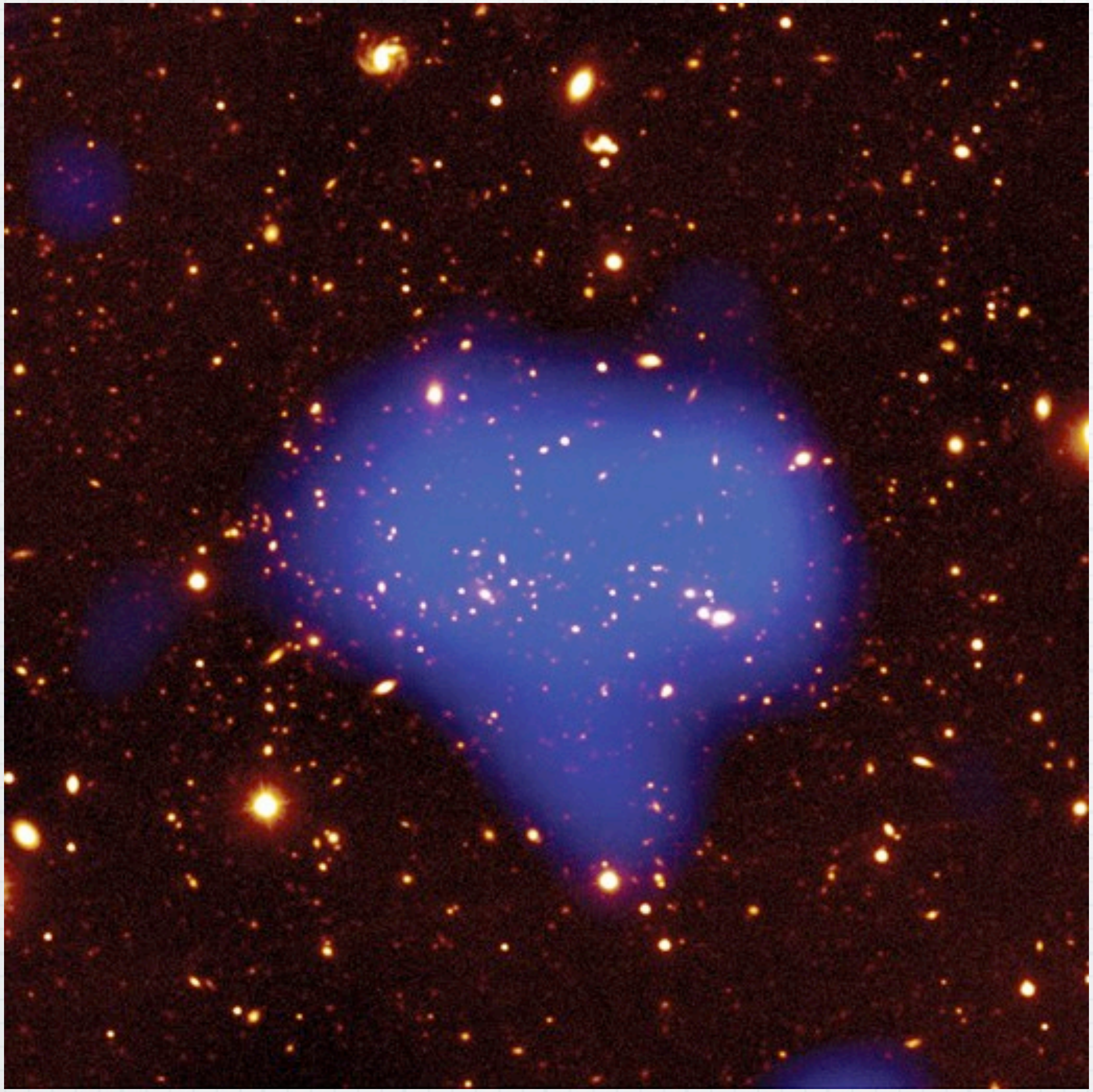
An eccentric personality, and strange ideas for the 1930s that proved to be correct decades later

Method 1: Orbits of galaxies in clusters

We can measure the velocities of galaxies in a cluster from their Doppler shifts

The mass we find from galaxy motions in a cluster is about 50 times larger than the mass in stars!
(which means 2% visible, 98% invisible)

Method 2: Hot gas in clusters

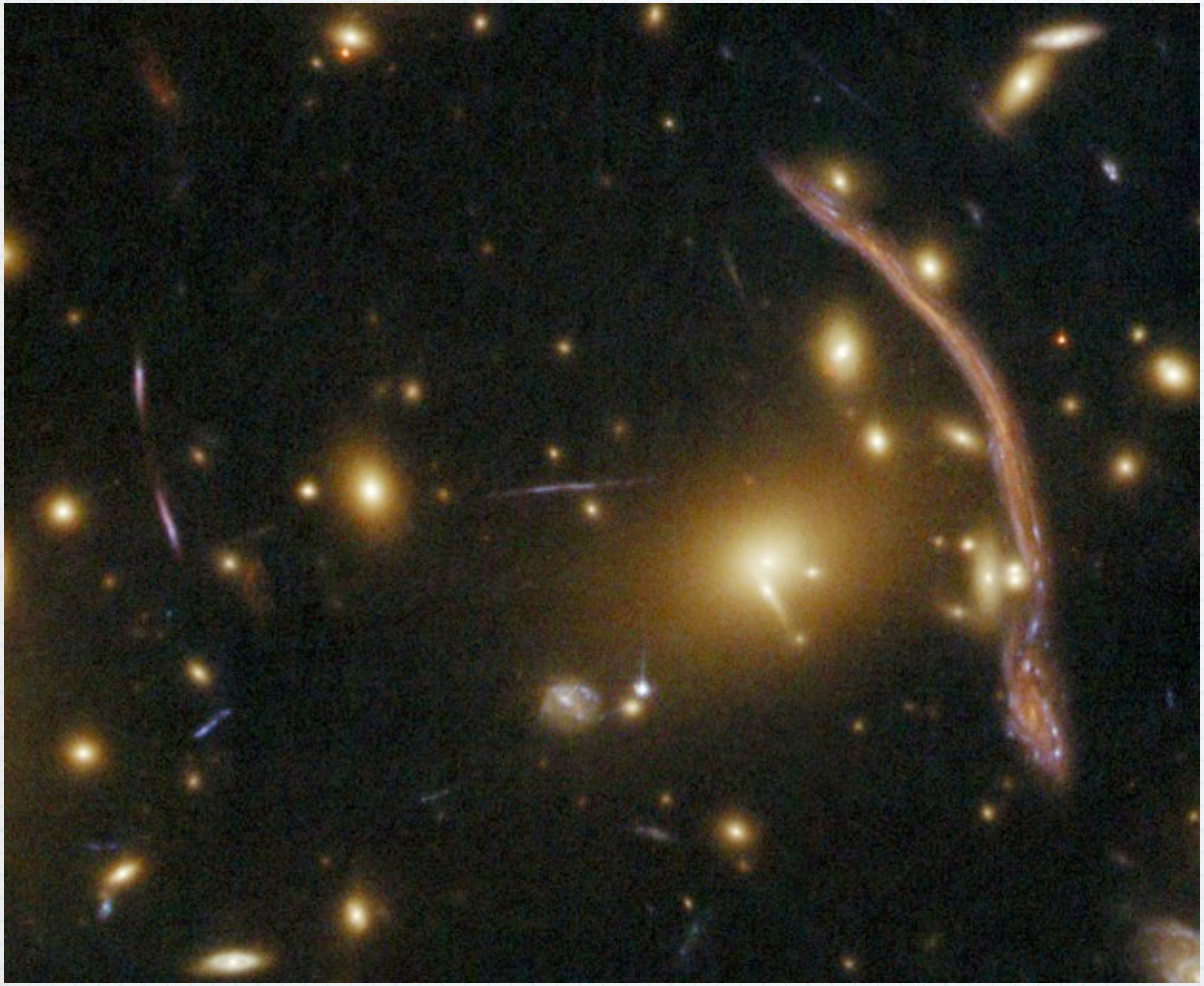


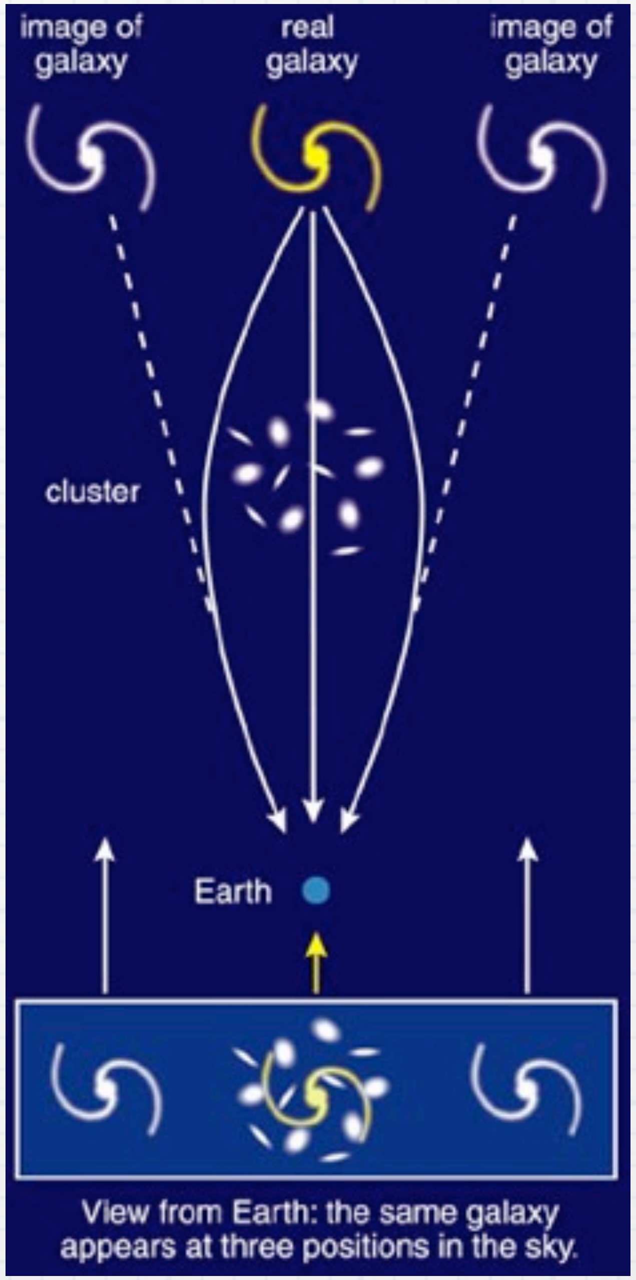
X-ray observations detect lots of hot gas filling space between galaxies

Temperature of this hot gas (particle motions) depends on the total (visible and invisible) mass of the cluster:

85% dark matter
13% hot gas
2% stars

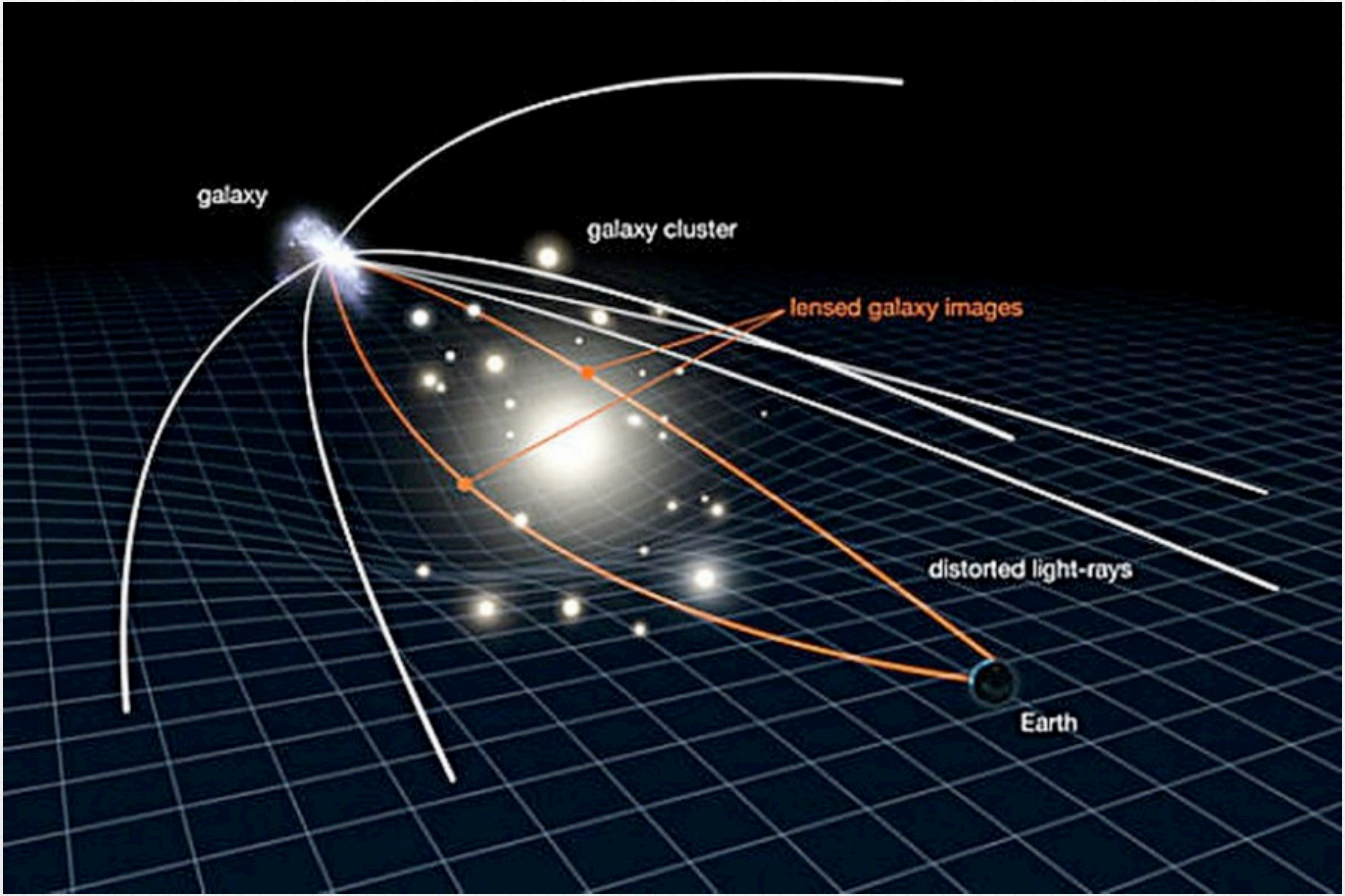
Method 3: Gravitational lensing





Gravitational lensing, the bending of light rays by gravity, can also tell us a cluster's mass

A gravitational lens distorts our view of things behind it

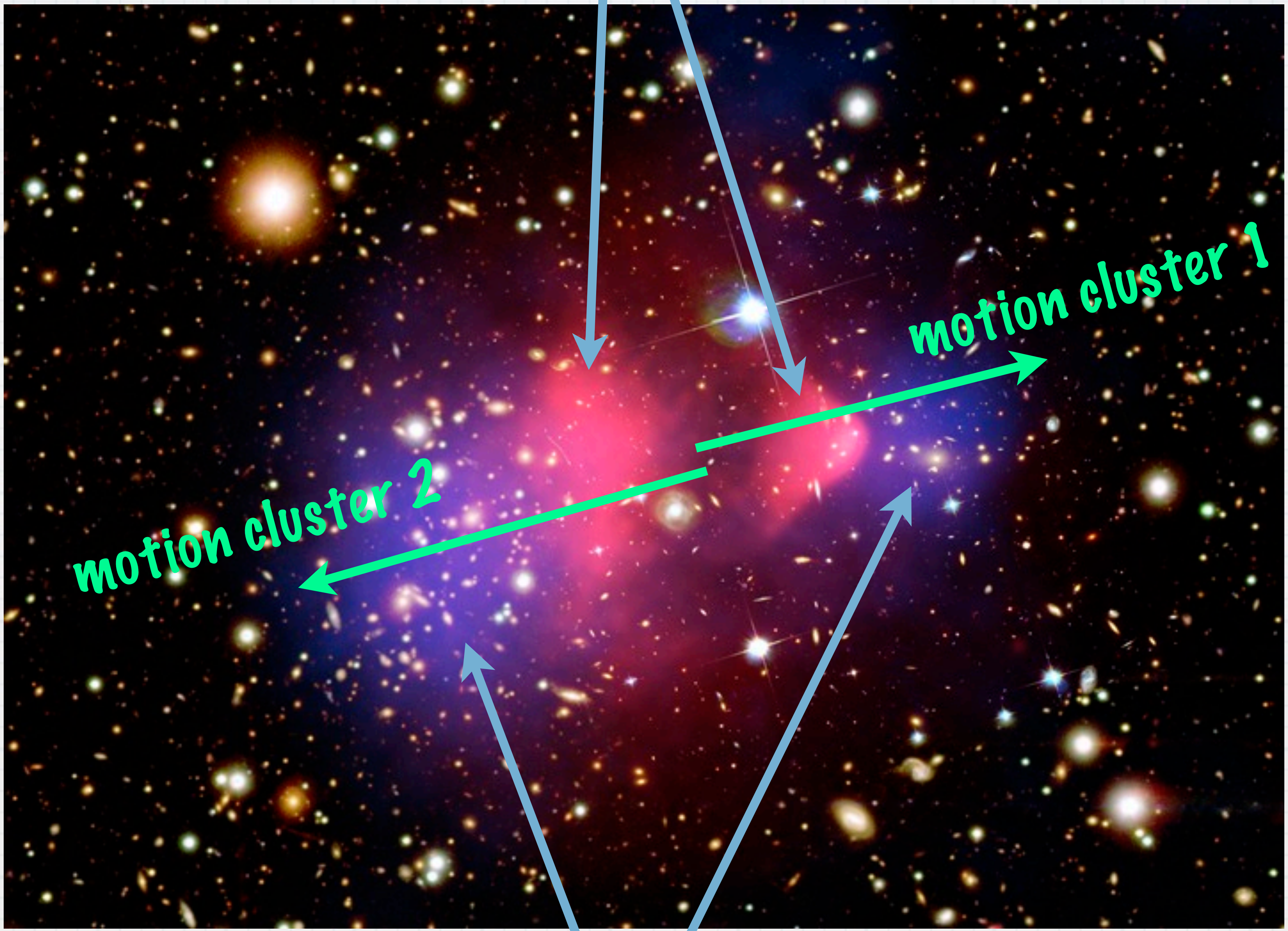


A gravitational lens distorts our view of things behind it

Direct Evidence of Dark Matter Found

* As recently as 2006, dark matter has gone from a theoretical matter to a real one:
* By looking at distortions due to gravitational lensing, the influence of dark matter has been directly detected in a collision of two galactic clusters

"normal" matter clumps



dark matter clumps

Visual Evidence of Dark Matter

* The hot gas in each cluster was slowed by a drag force, similar to air resistance, during the collision. In contrast, the dark matter was not slowed by the impact because it does not interact directly with itself or the gas except through gravity. Therefore, during the collision the dark matter clumps from the two clusters moved ahead of the hot gas, producing the separation of the dark and normal matter seen in the image

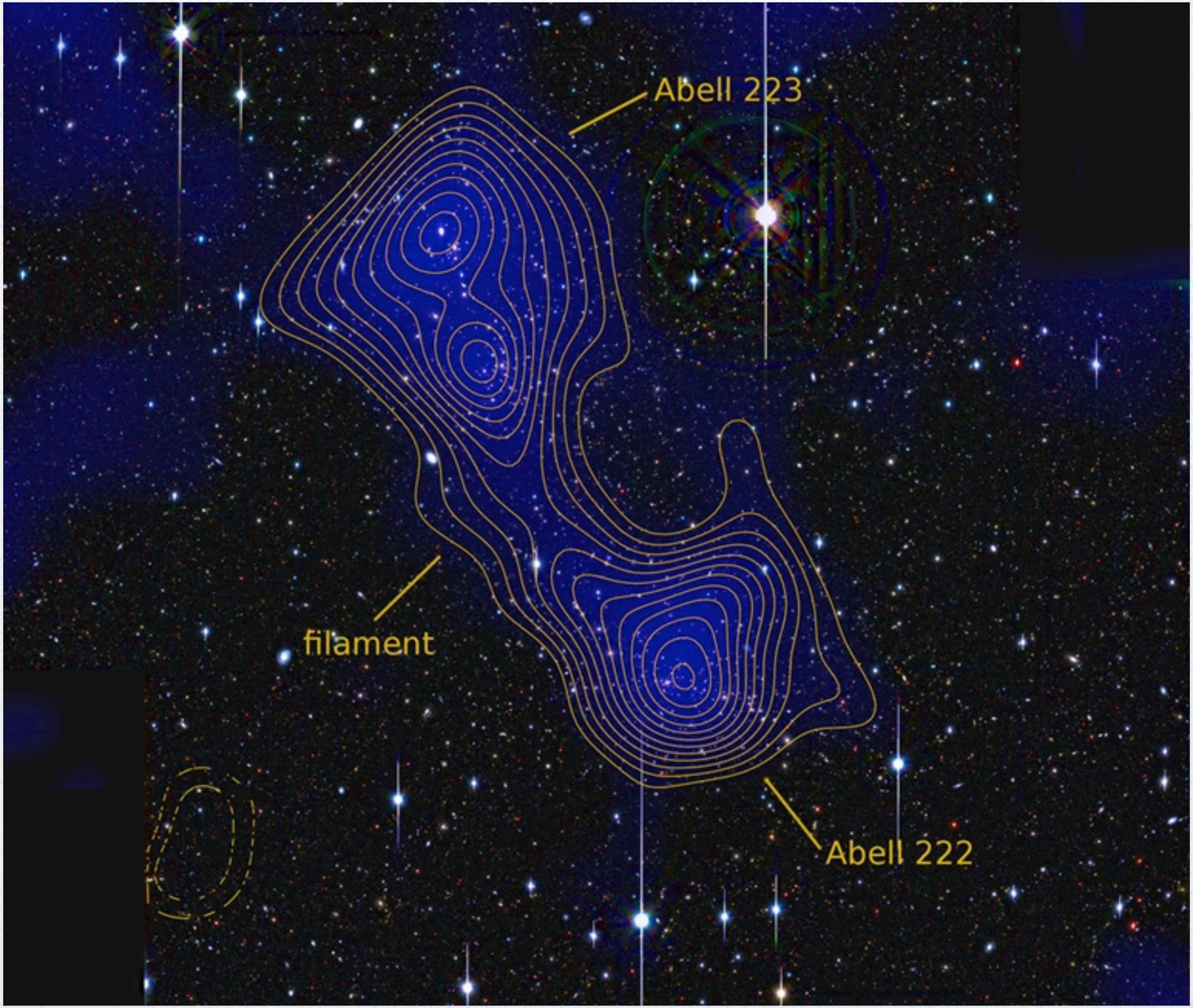
All three methods of measuring cluster mass indicate similar amounts of dark matter:

There is about 5 to 6 times more dark matter than luminous one

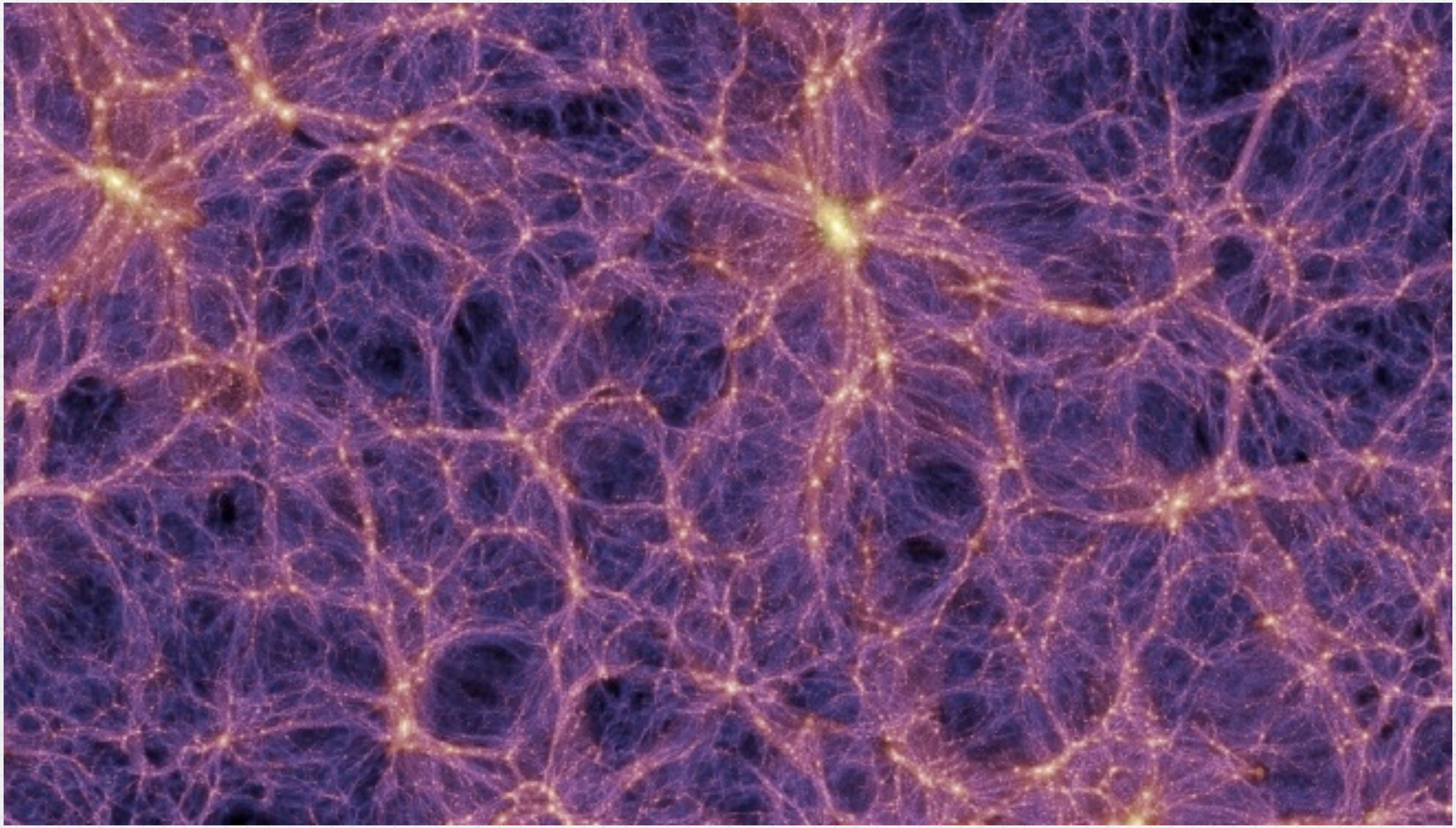
Dark Matter Filaments

* More recent observations shows that clusters of galaxies are connected with dark matter filaments
* Theoreticians had predicted this: they stated that
* dark matter is distributed in our Universe along a gigantic web of interconnected filaments (which also includes normal ionized matter emitting X-rays.) The filaments' mass is at least 90% dark matter

Dark matter filament linking two galactic clusters



Dark matter web linking clusters of galaxies



Theoretical (computed) image

What might dark matter be made of?

* We cannot expect to be able to visually see all ordinary matter, some is too faint to be detected
* Dark matter, then, can be split in two

1. Ordinary dark matter
2. Extraordinary dark matter

Ordinary Matter

* Protons and neutrons (which make up most of the mass of ordinary matter) belong to a category of particles called baryons (made of 3 quarks)
* Ordinary matter is also called baryonic matter (fermions include baryons and leptons [electrons and neutrinos])

Extraordinary Matter

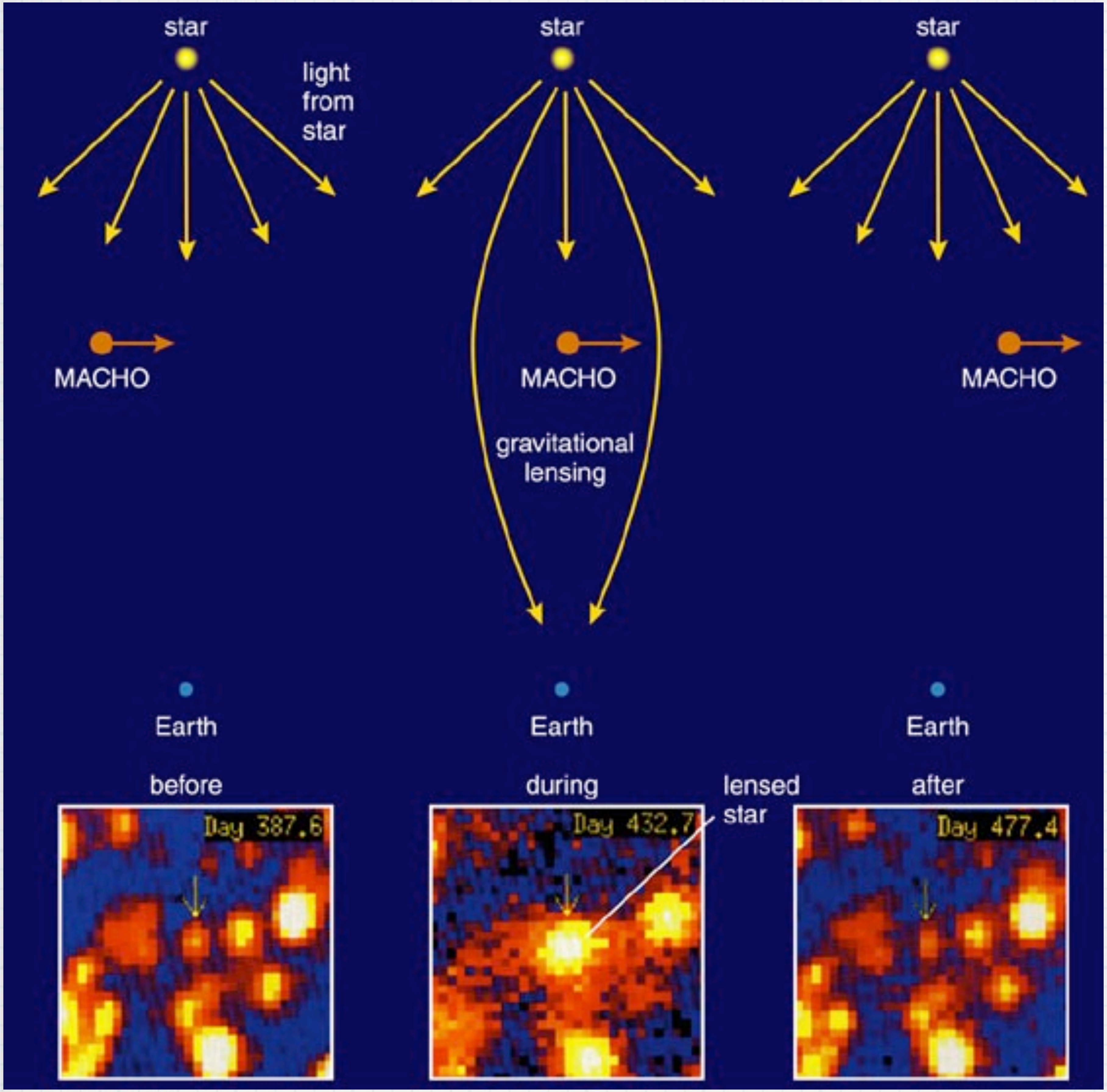
* Known:
    * Neutrinos and free electrons
* Unknown:
    * Extraordinary dark matter and black holes (we do not know what is inside a black hole - maybe quark soup?)

Dark Matter
Two Basic Options

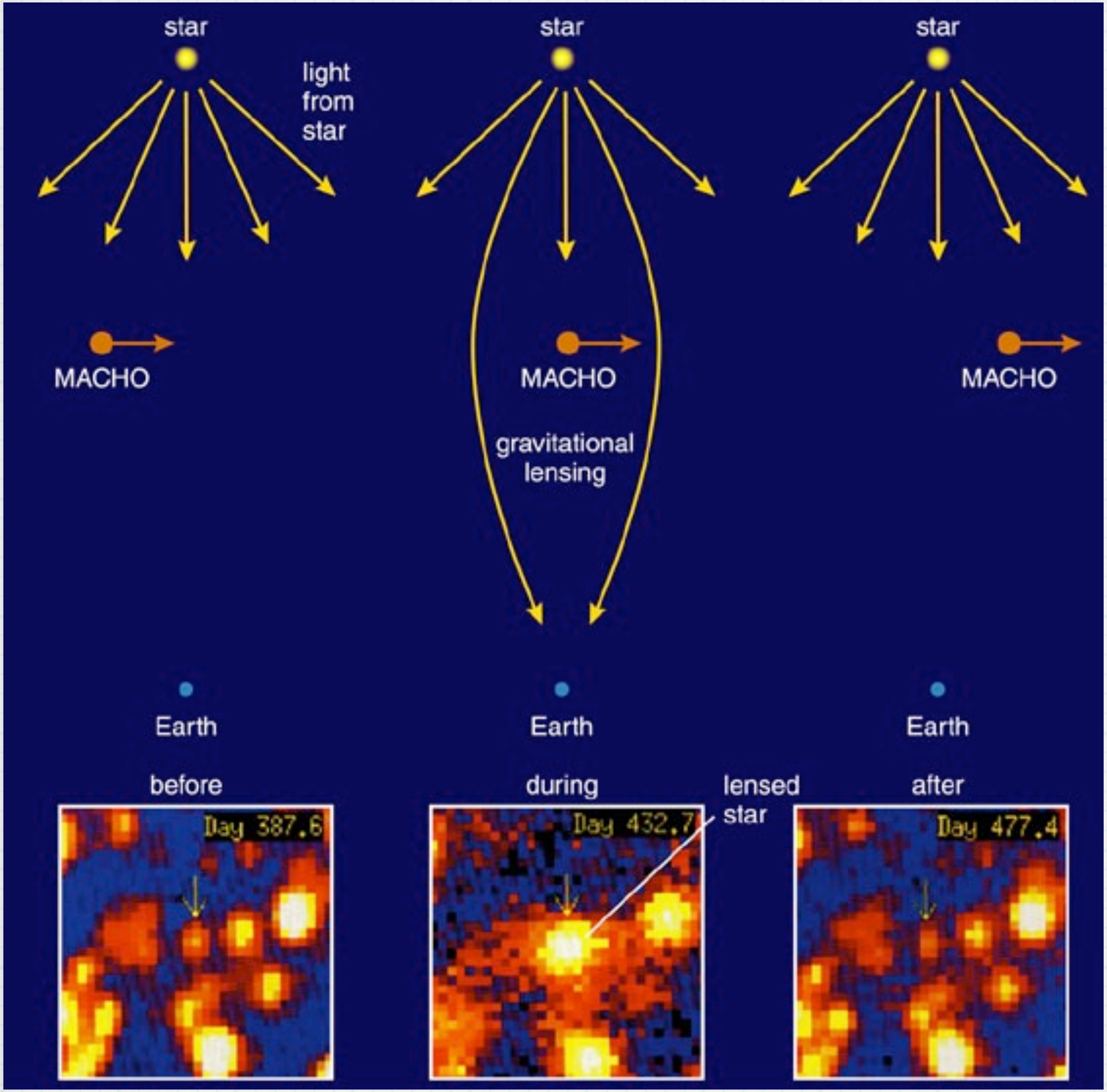
1. Ordinary Dark Matter, made of MACHOs
2. Extraordinary Dark Matter, made of WIMPs

Ordinary Dark Matter

* MACHOs: Massive Compact Halo Objects
    1. trillions of dead or failed stars in the halos of galaxies
    2. trillions or more planets
* all are too faint to be detected with our current instruments, though we are getting better at detecting them "nearby"



MACHOs occasionally make other stars appear brighter through lensing



MACHOs occasionally make other stars appear brighter through lensing

... but not enough lensing events to explain dark matter

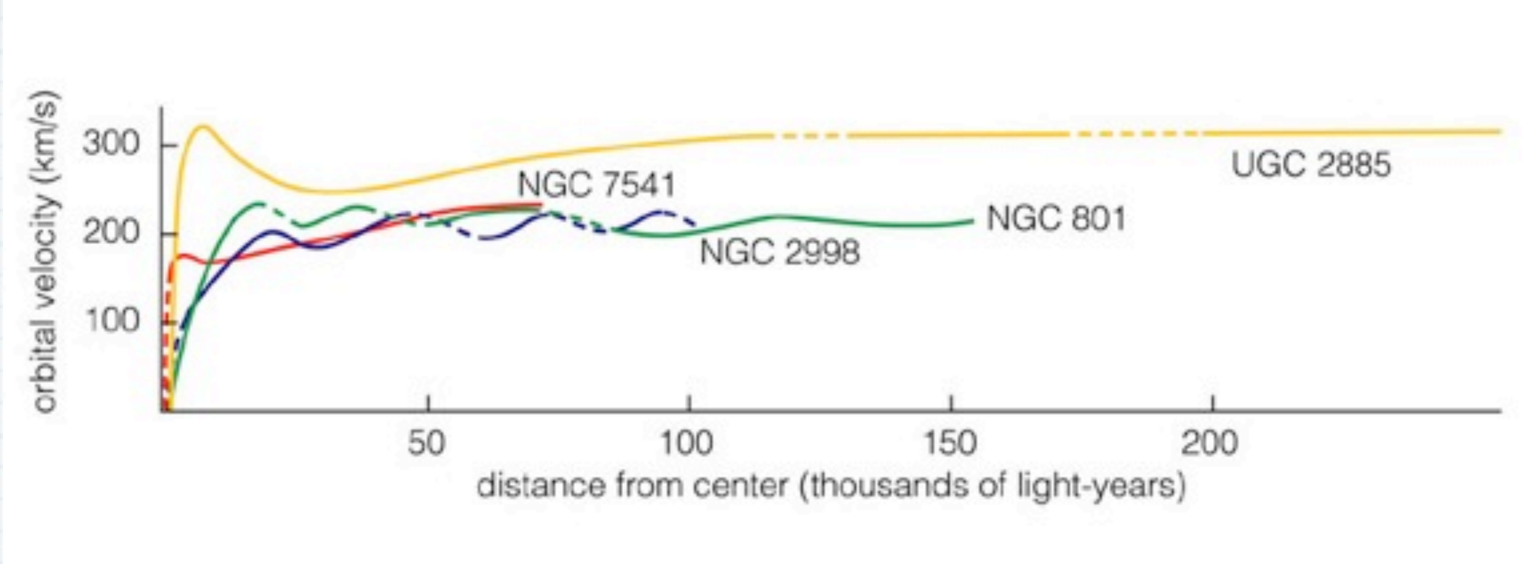
Extraordinary Dark Matter

* WIMPS: Weakly Interacting Massive Particles
    * mysterious neutrino-like particles but much heavier
    * sometimes called **cold dark matter** to separate them from the faster moving neutrinos

Why Believe in WIMPs?

1. There's not enough ordinary matter to explain why galaxies keep whole
2. Models involving WIMPs explain how galaxy formation works
3. WIMPs could be leftovers from Big Bang

Snapshot

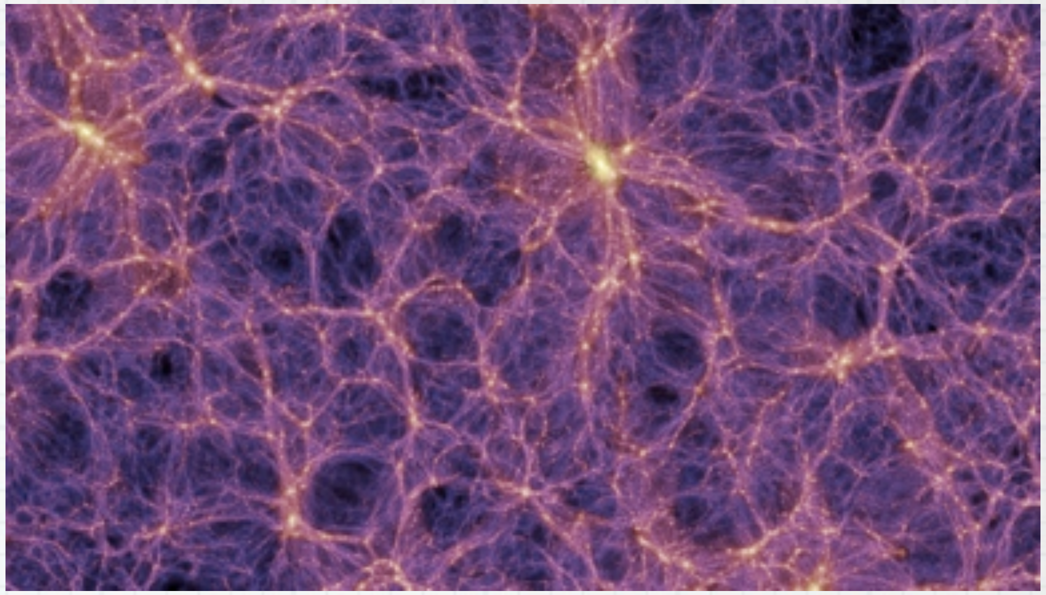


* What is the evidence for dark matter in galaxies?
* The orbital velocities of stars and gas clouds in galaxies do not change much with distance from the center of the galaxy. Applying Newton's laws of gravitation and motion to these orbits leads to the conclusion that the total mass of a galaxy is far larger than the mass of its stars. Because no detectable visible light is coming from this matter, we call it dark matter

Snapshot

* What is the evidence for dark matter in clusters of galaxies?
* We have three different ways of measuring the amount of dark matter in clusters of galaxies: from galaxy orbits, from the temperature of the hot gas in clusters, and from the gravitational lensing predicted by Einstein. All of these methods agree that the total mass of a cluster is about 50 times the mass of its stars, implying huge amounts of dark matter

Snapshot

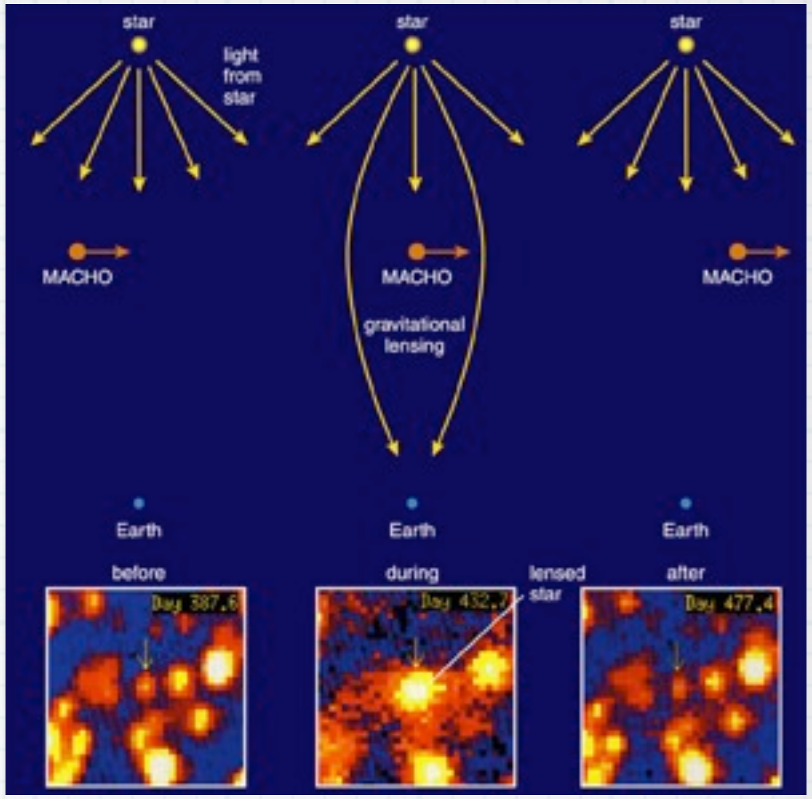


* What is the evidence for dark matter filaments linking clusters of galaxies?
* Gravitational lensing and a spike in X-ray emissions along filaments (due to an excess of ionized ordinary matter being pulled by gravity toward the filaments)
* All estimations calculate that 90% or more of the filaments' mass is dark matter

Snapshot

* Does dark matter really exist?
* Yes. We now have direct evidence of dark matter seen in the collision of two galaxy clusters. The dark matter is "seen" via the gravitational lensing it creates on objects far behind it and in our line of sight

Snapshot

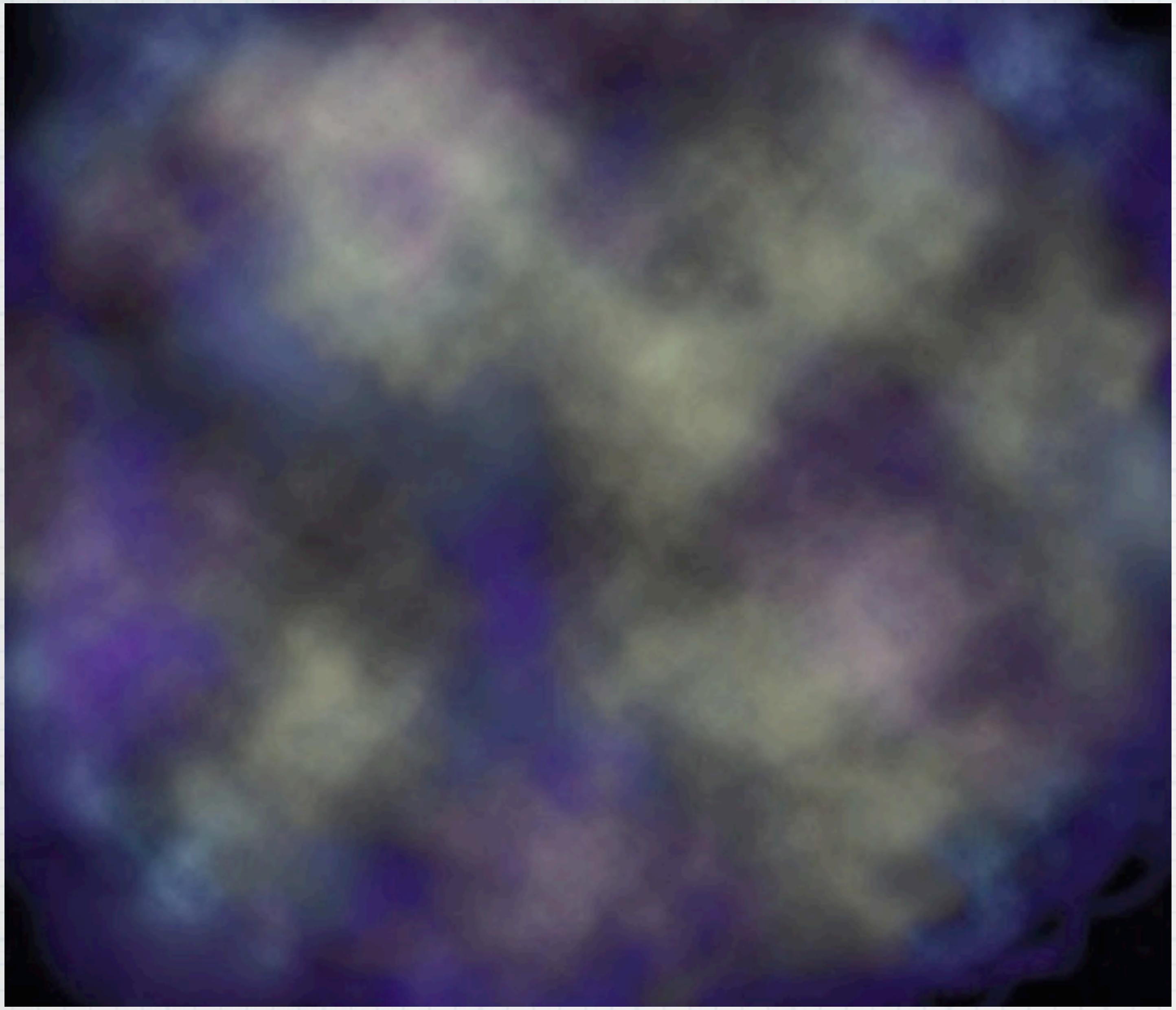


* What might dark matter be made of?
* Some of the dark matter could be ordinary or baryonic matter in the form of dim stars or planet-like objects, but there does not appear to be enough ordinary matter to account for all the dark matter. Most of it is probably extraordinary or non-baryonic matter consisting of undiscovered particles that we call WIMPs

The role of dark matter in galaxy formation

* Dark matter's gravity was probably the main force that caused protogalactic clouds to become galaxies and galaxies to group into clusters of galaxies as
* the hydrogen and helium gas in the protogalactic clouds collapsed inward and gave birth to stars and
* dark matter couldn't radiate its energy and so remained distributed throughout the cluster

Gravity of dark matter is what caused protogalactic clouds to contract early in time



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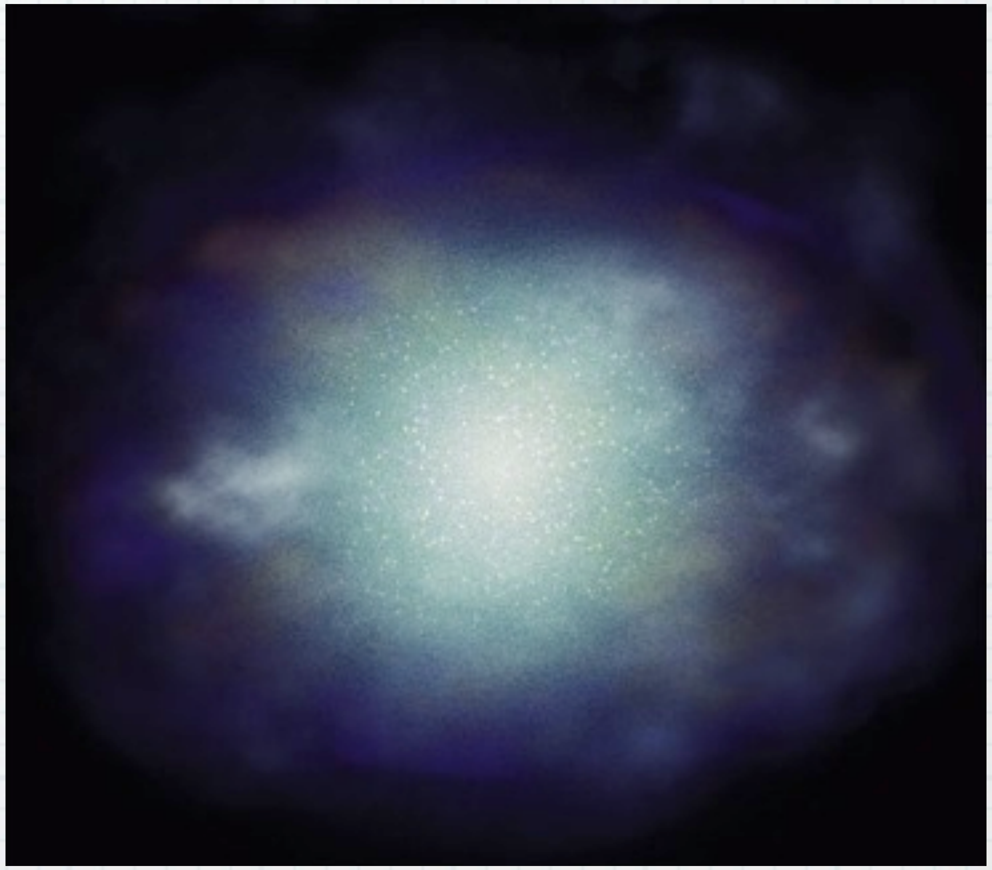
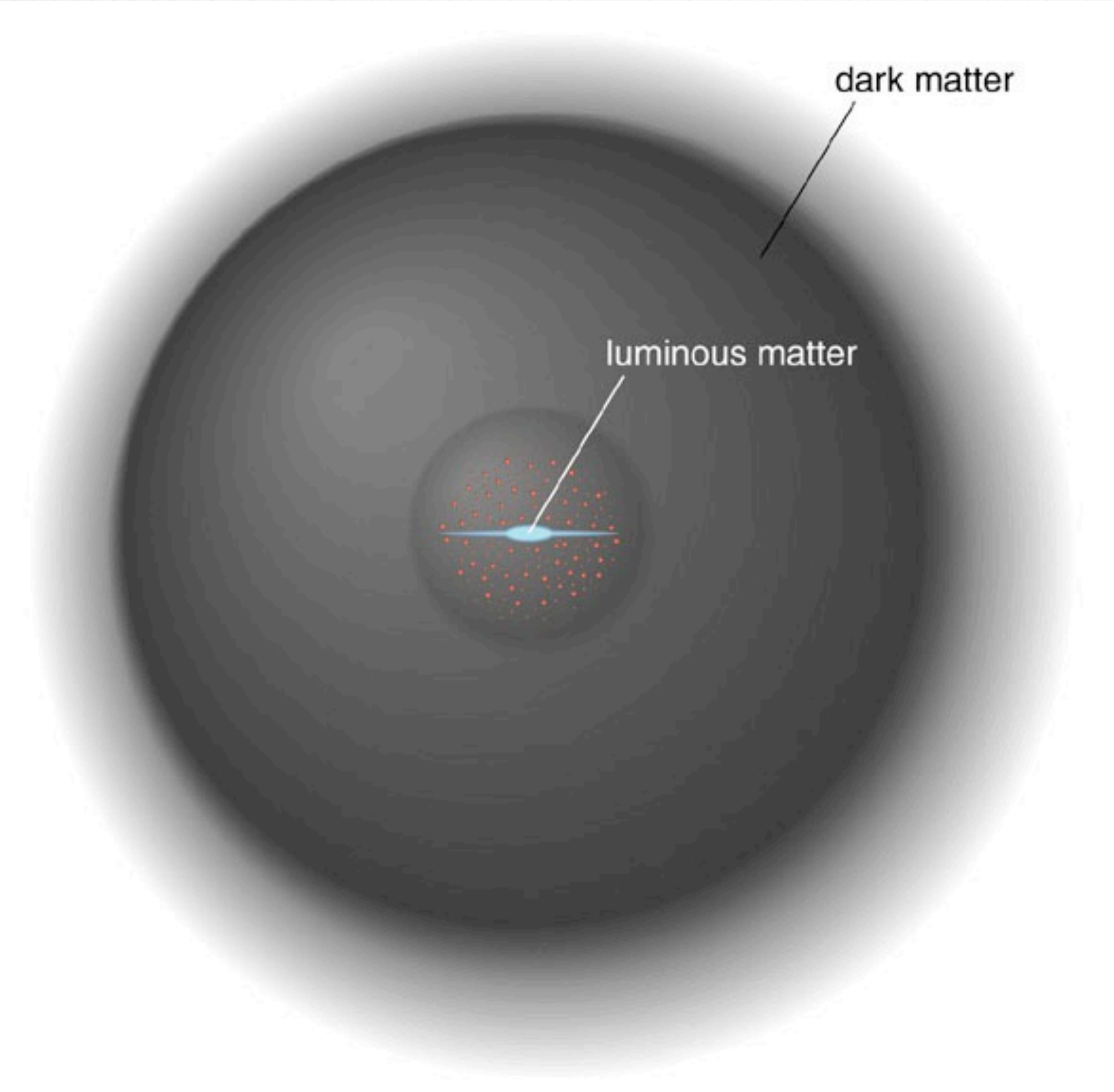
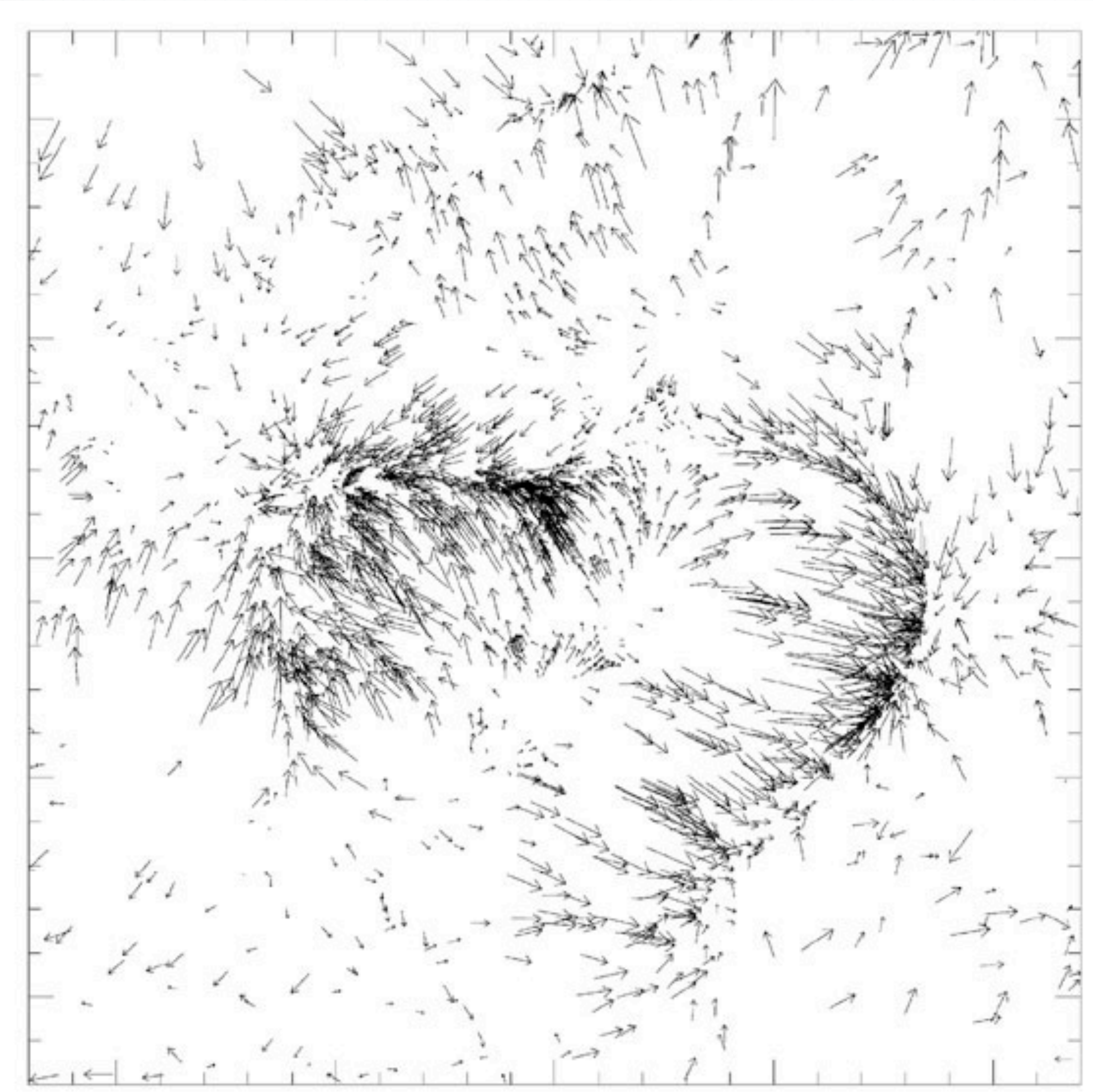




WIMPs can't contract to center because they don't radiate away their orbital energy because they do not lose energy via radiation



Dark matter is still pulling things together

After correcting for Hubble's Law, we can see that galaxies are flowing toward the densest regions of space

The largest known structures in the Universe

* Beyond 300 million light-years from us, the gravitational tugs of galaxies becomes insignificant
* Hubble's law becomes the primary method of determining distances to galaxies

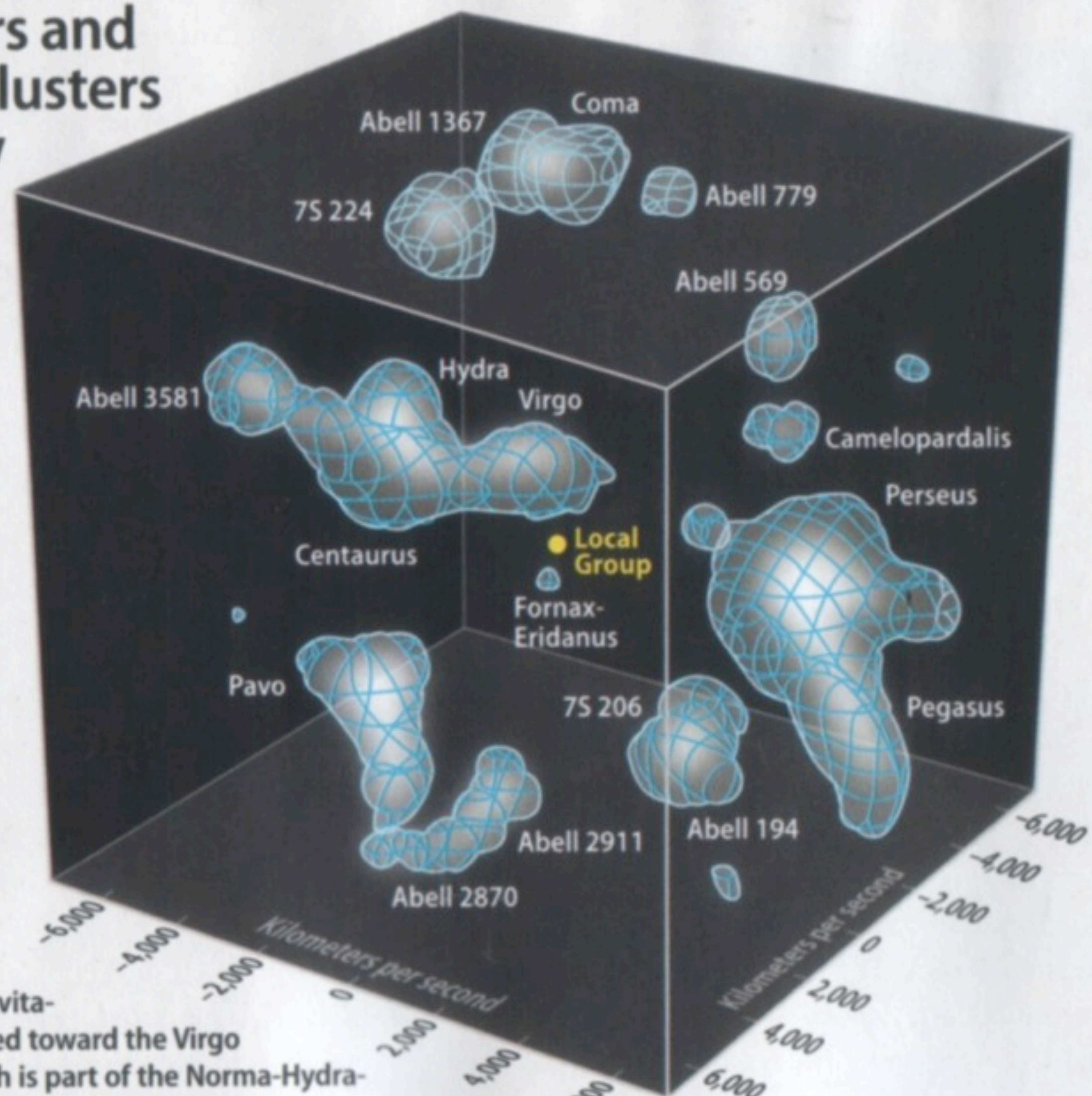
Superclusters and Supervoids

* We saw how galaxies come in groups and clusters
* Clusters like company: they form superclusters (clusters of clusters)
* An "average" supercluster has upward of 50,000 galaxies contained within a diameter of some 200 to 300 million light-years

Superclusters and Supervoids...

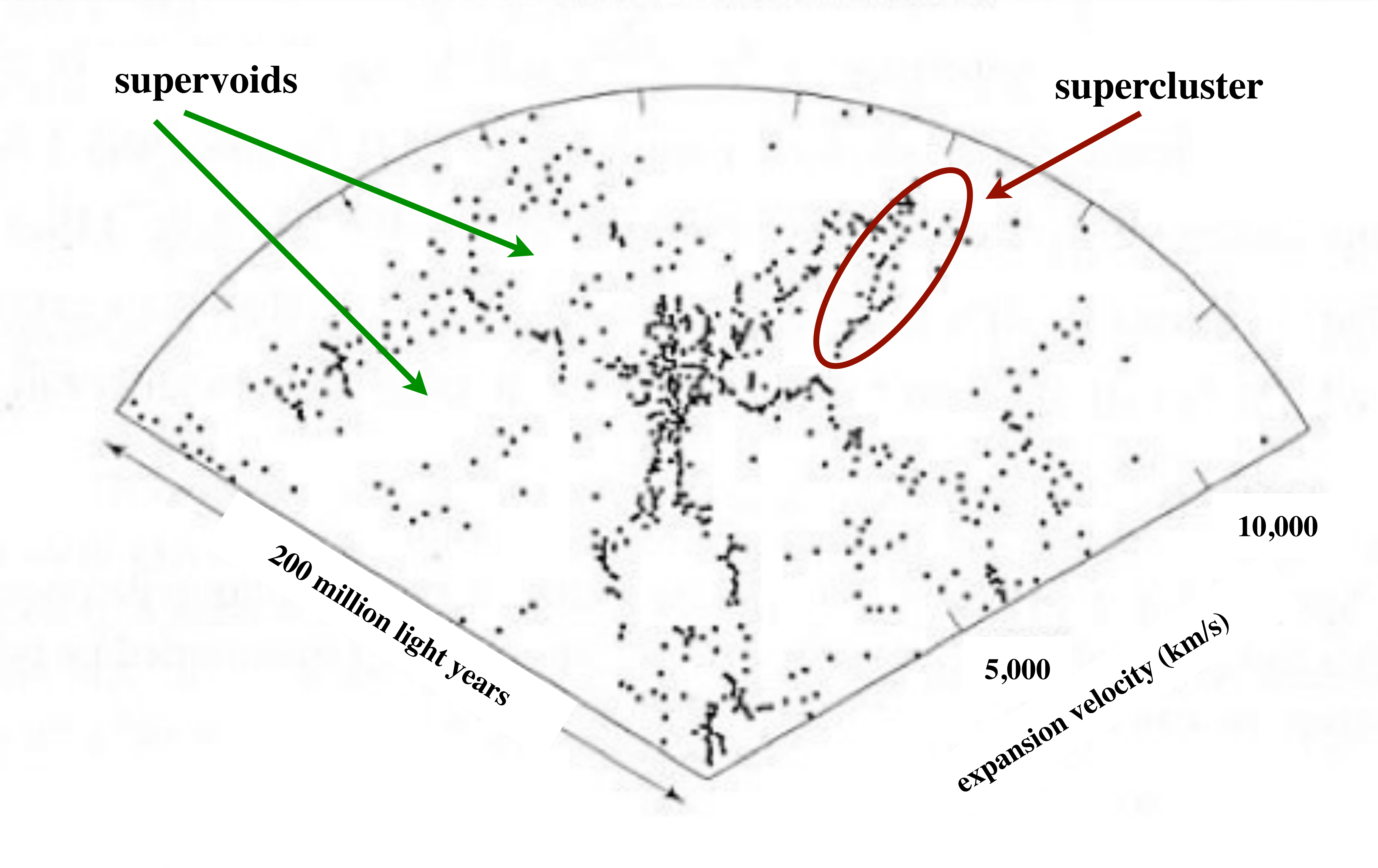
* Superclusters are not evenly distributed in space: they form supercluster complexes which are separated by huge voids, called supervoids
* Yet superclusters are linked (filament-like) across the sky on the "surface" of the supervoids
* 90% of the Universe appears to consists of voids while the remaining 10% seems to be superclusters linked by a web of filaments

A 3-D map of the nearest Superclusters

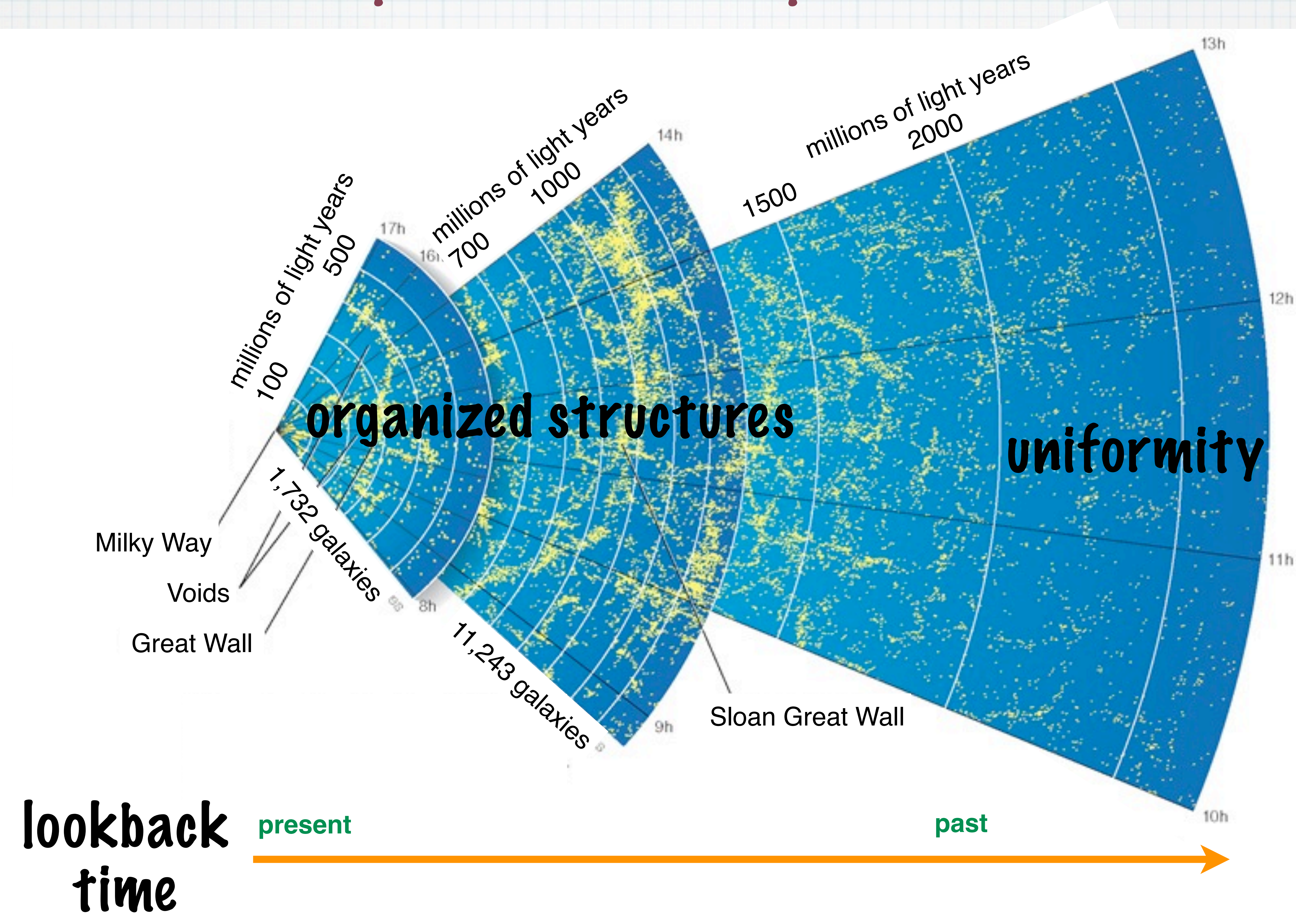


Our Local Group is gravitationally pulled toward the Virgo cluster, which is part of the Norma-Hydra-Centaurus Supercluster. *Astronomy: Roen Kelly; after M. Hudson*

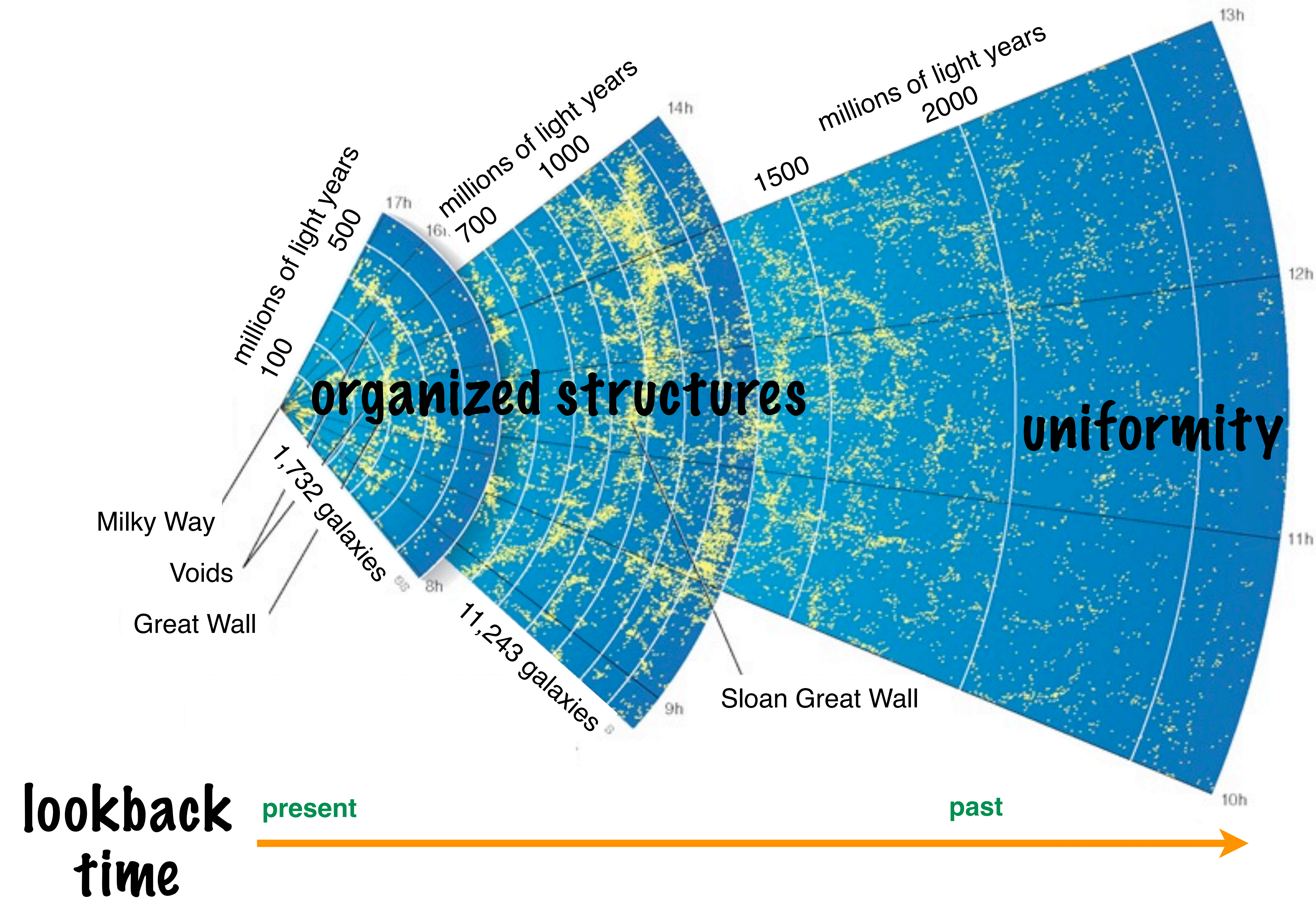
A map of the nearest Superclusters and Supervoids



Maps of galaxy positions reveal extremely large structures:
superclusters and supervoids

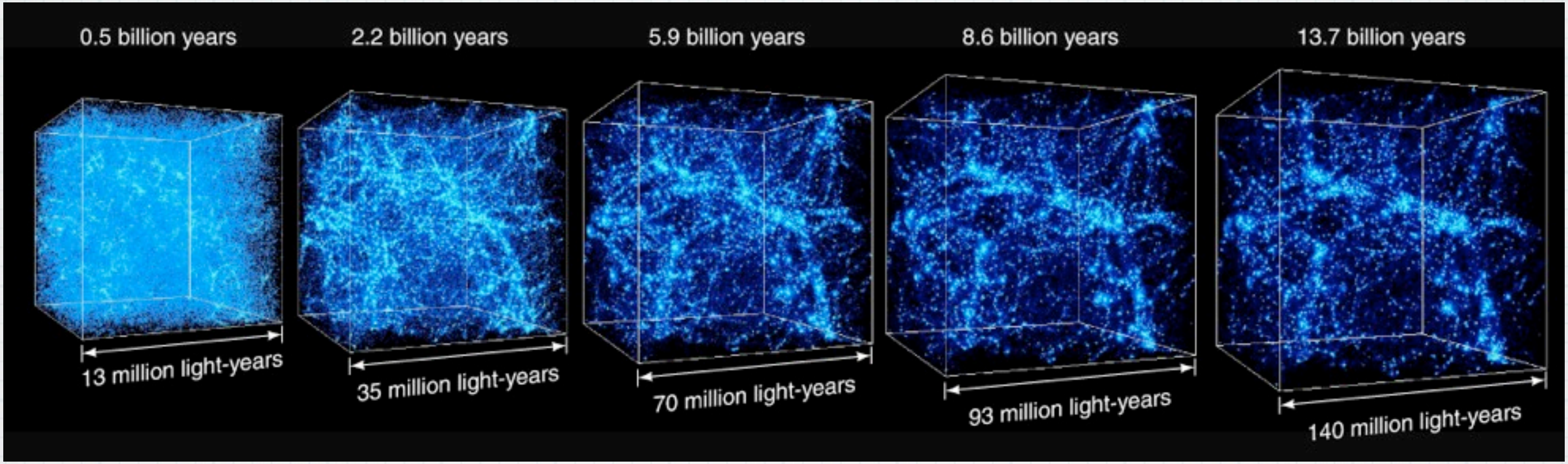


Notice how the structure is organized close to the present and gets more and more uniform as we look to the past



Time in billions of years

0.5 2.2 5.9 8.6 13.7



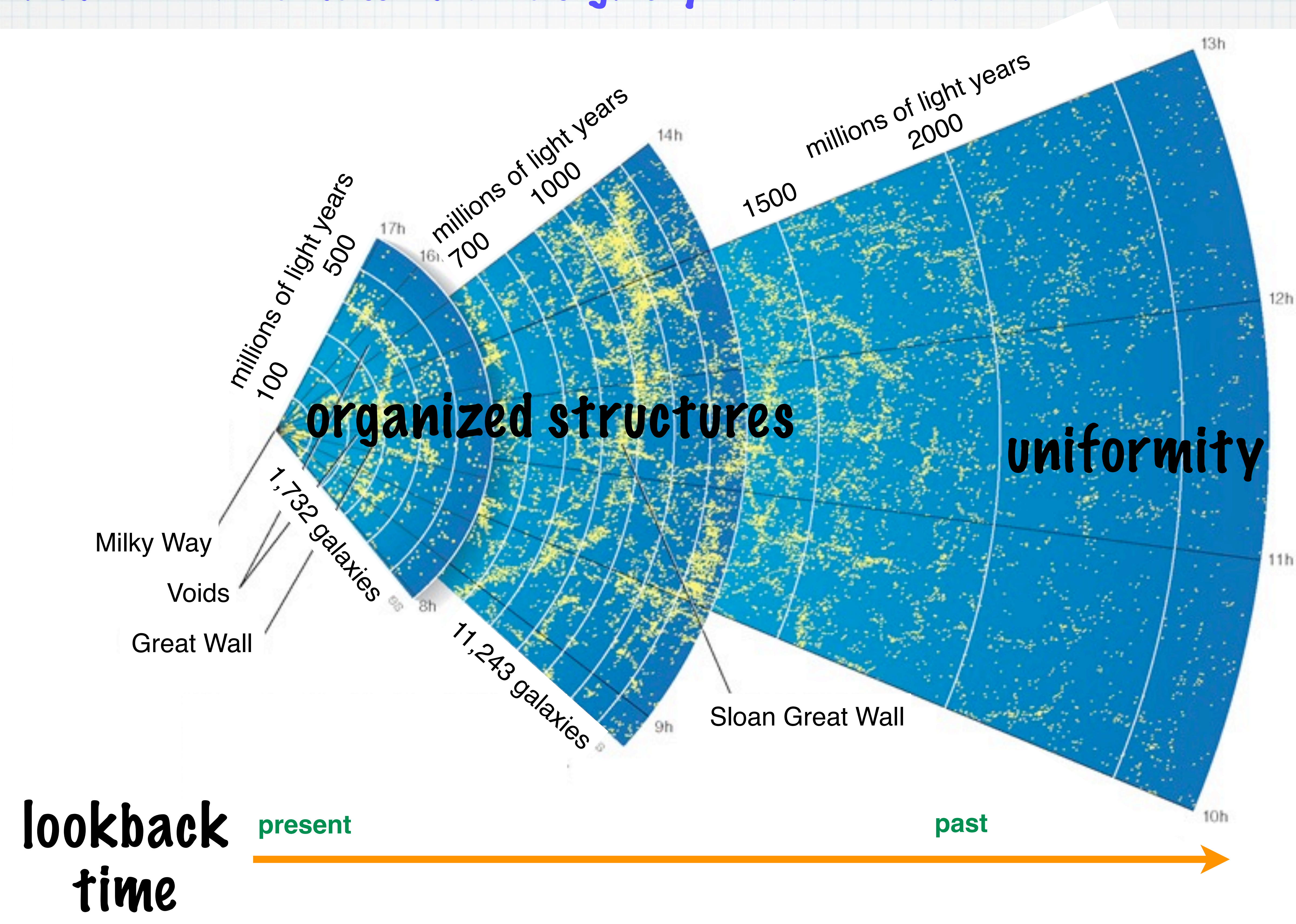
13 35 70 93 140

Size of expanding box in millions of light-years

Models show that gravity of dark matter pulls mass into denser regions (the Universe grows lumpier with time)

Dark matter creates a Universe-sized scaffolding (or web)

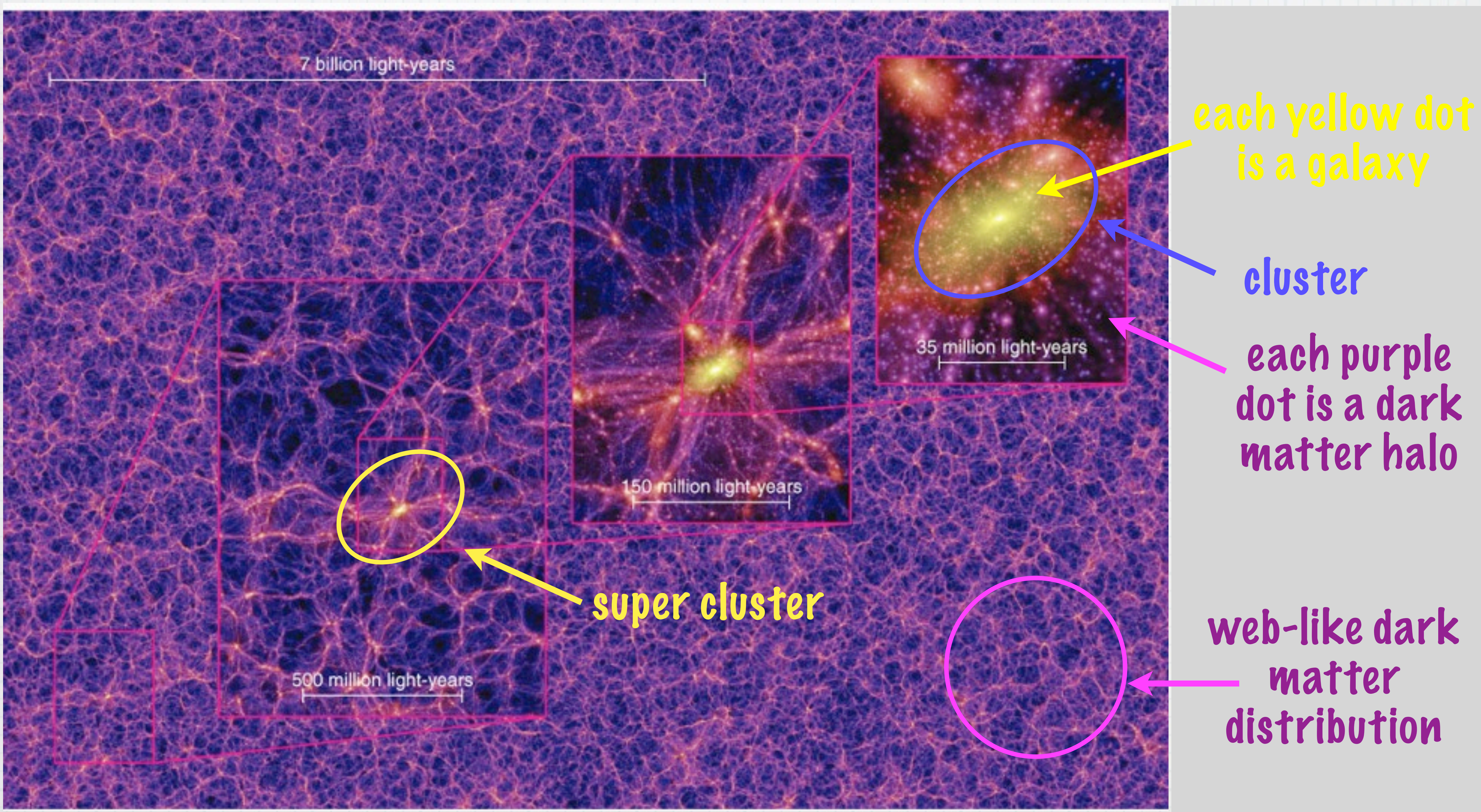
Galaxies appear to be arranged in immense structures hundreds of millions of light-years across



The Shape of Dark Matter's Distribution

* Using gravitational lensing effects, researchers made detailed measurements of the spatial distribution of dark matter in about 20 massive galactic clusters
* The team obtained clear evidence that the distribution of dark matter in the clusters has, on average, an extremely flattened shape rather than a simple spherical contour (or flat string-like)

The Shape of Dark Matter's Distribution...



The Shape of Dark Matter's Distribution...

* This research strongly supports the prevailing dark matter model, which begins with the assumption that **dark matter consists of weakly interacting massive particles that are relics of the Big Bang**
* These particles are assumed to be "cold" - they have negligibly small thermal motions

Snapshot

* **What is the role of dark matter in galaxy formation?**
* Because most of a galaxy's mass is in the form of dark matter, **the gravity of that dark matter is probably what formed protogalactic clouds and then galaxies** from slight density enhancements in the early Universe

Snapshot

* What is origin of dark matter?
* The prevailing theory is that dark matter consists of weakly interacting cold massive particles that are relics of the Big Bang

Snapshot

* What are the largest structures in the Universe?
* Galaxies appear to be distributed in gigantic chains and sheets that surround great voids, or supervoids. These giant structures trace their origin directly back to regions of slightly enhanced density early in time

The Universe's Fate

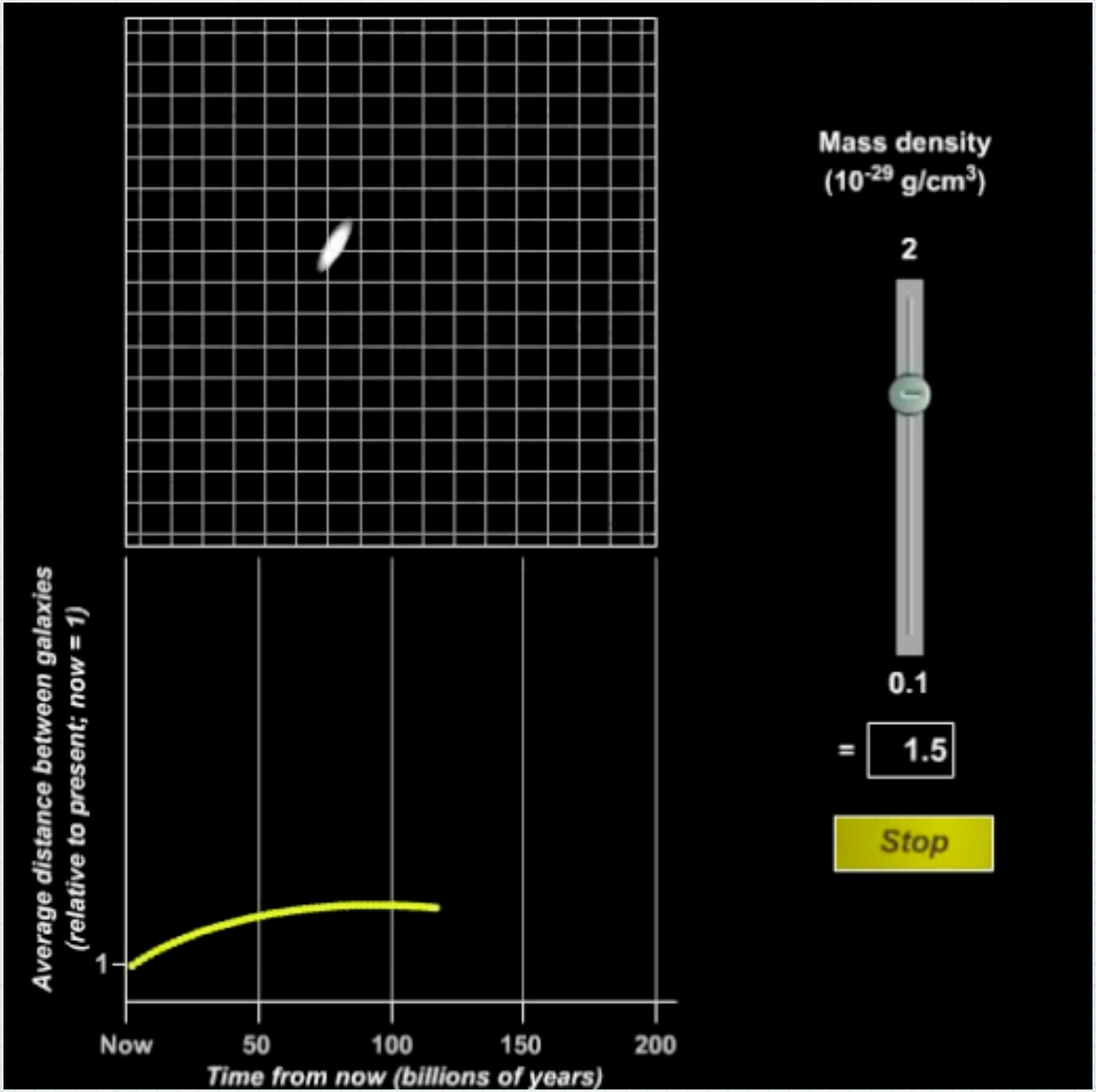
* With the addition of dark matter which adds to the force of gravity and dark energy which fights against it, what is the future like?
  * Will the Universe continue expanding forever? Or will it collapse?
  * Is the expansion of the Universe accelerating? What is gravity doing?

Will the Universe continue expanding forever?

* How will the Universe end?

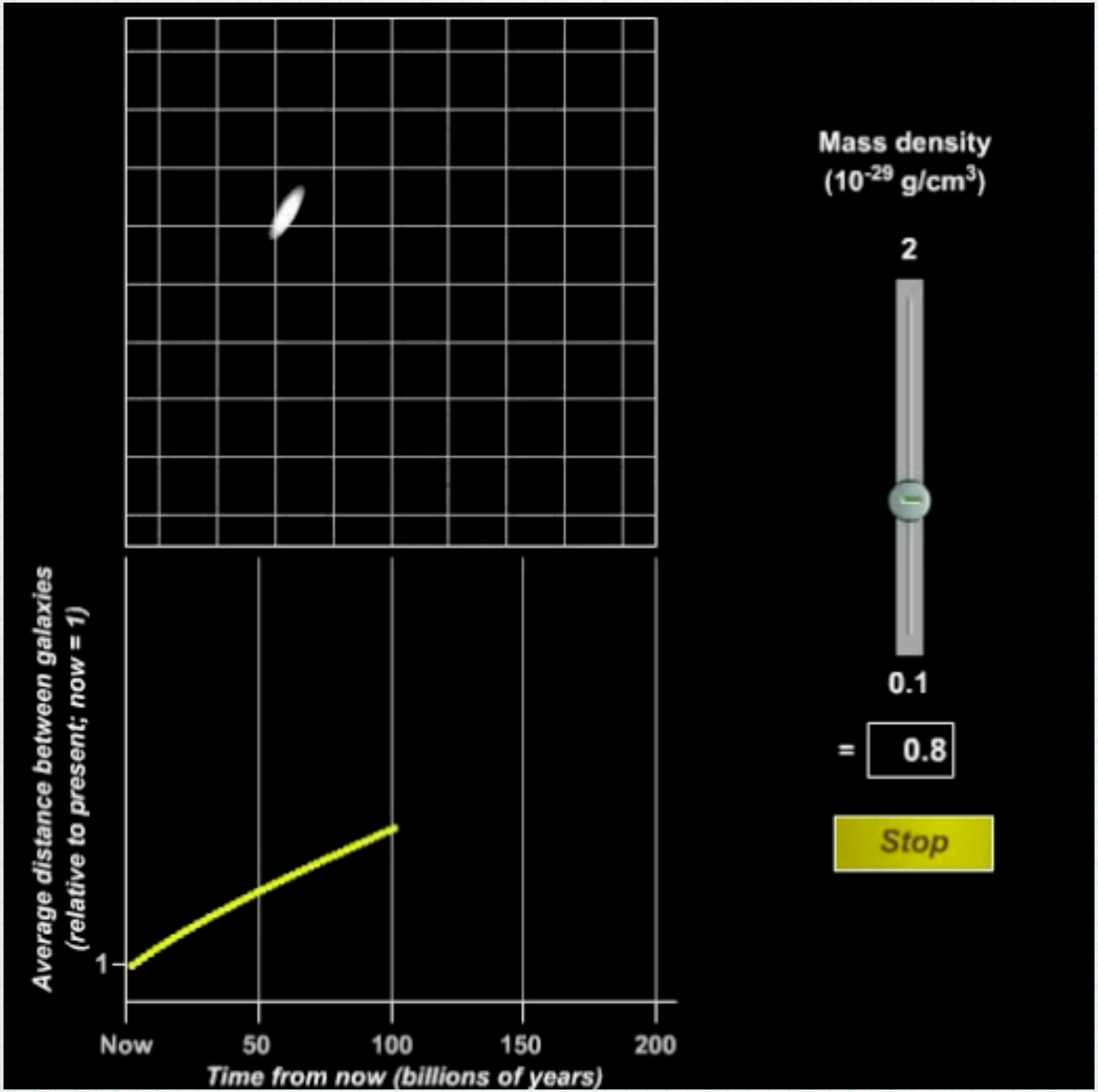
    a. With enough gravity, the expansion will someday halt and the Universe will start a collapse (ending in a Big Crunch!)

    b. Else, the Universe will keep on expanding forever, get colder and matter will eventually "evaporate" as the porosity of space will not allow particles to exist



Does the Universe have enough kinetic energy to escape its own gravitational pull?

When the Universe's density is larger than the critical density... it all ends in a Big Crunch!

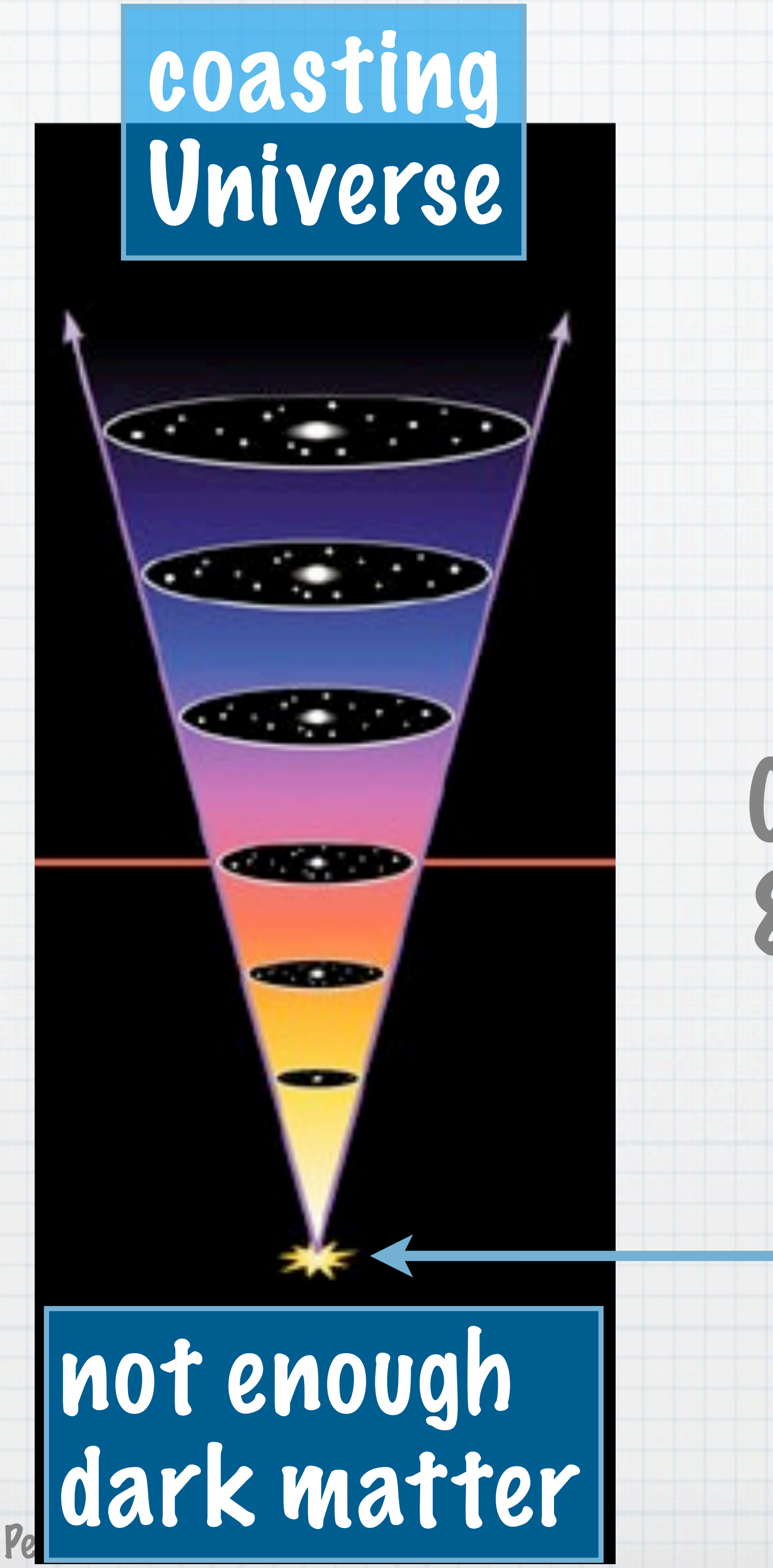


Does the Universe have enough kinetic energy to escape its own gravitational pull?

When the Universe's density is less than the critical density... it expands forever

Fate of Universe depends on amount of dark matter

The impact of gravitational force depends on the density of matter in the Universe

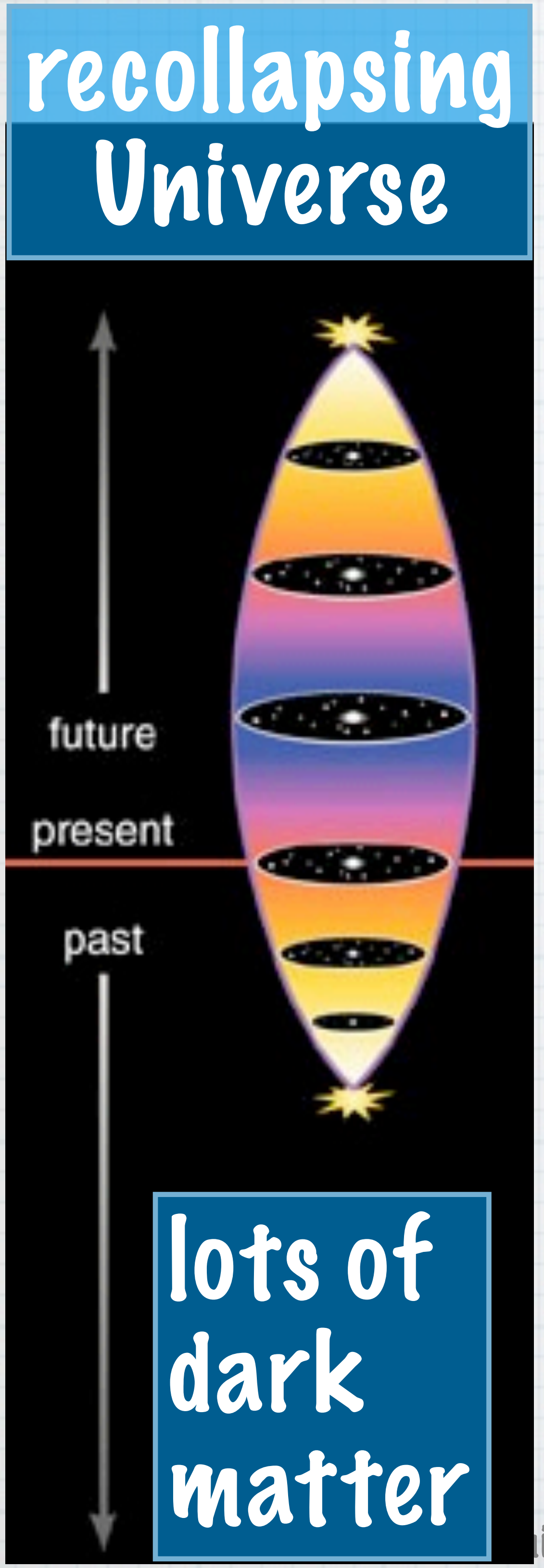


Critical density:
8×10^{-30} gram per cm^3

Big Bang

Fate of Universe depends on amount of dark matter

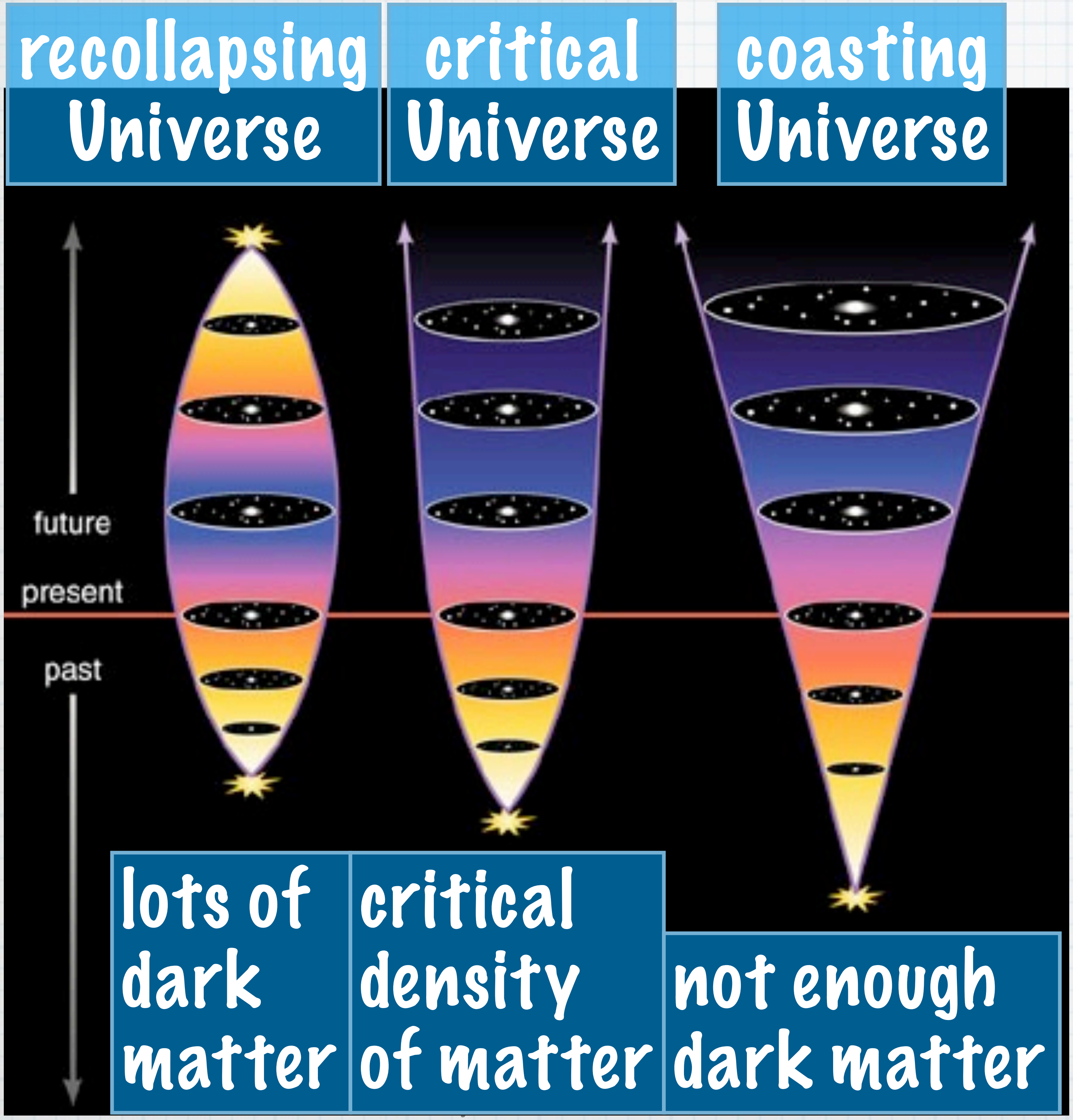
The impact of gravitational force depends on the density of matter in the Universe



Critical density:
8×10^{-30} gram per cm^3
(about a few hydrogen atoms in a volume the size of a closet)

Fate of Universe depends on amount of dark matter

The impact of gravitational force depends on the density of matter in the Universe



Critical density:
$8x10^{-30}$ gram per cm^3

Fate of Universe depends on amount of dark matter

Assuming no dark energy presence, luminous matter is 0.5% of the total energy density needed to halt the expansion.
Is there 200 times more dark matter than luminous one? We only find about 55 times.
So we would assume that the Universe will expand forever

Amount of dark matter is ~25% of the critical density suggesting fate is eternal expansion

but...

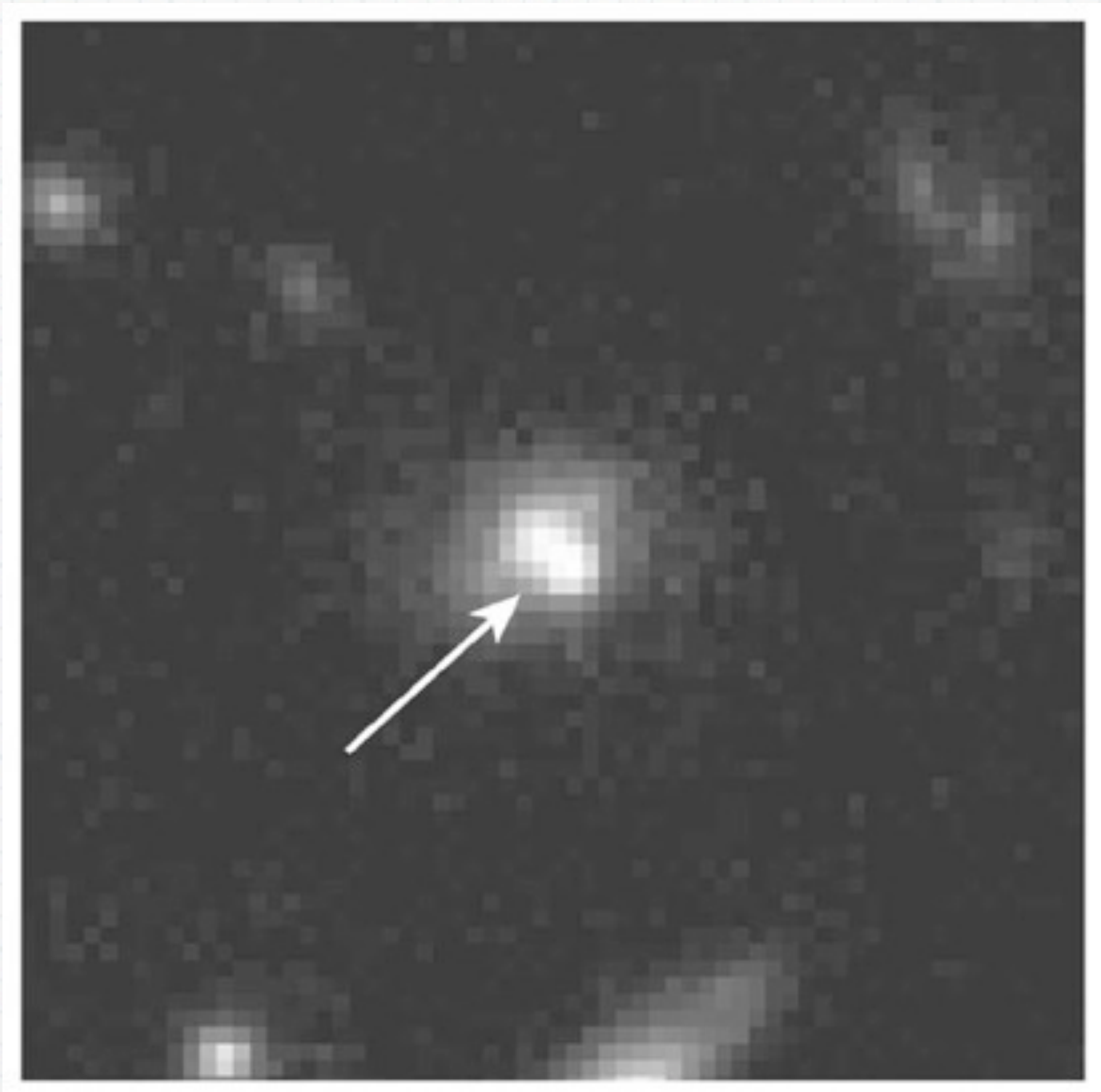
The expansion of the Universe is accelerating

* Observations of distant white dwarf supernovae seem to indicate the Universe's expansion is not coasting but accelerating
* A mysterious repulsive force is needed to explain this acceleration: dark energy
* This repulsive force only acts at galactic-like distances

Dark Energy...

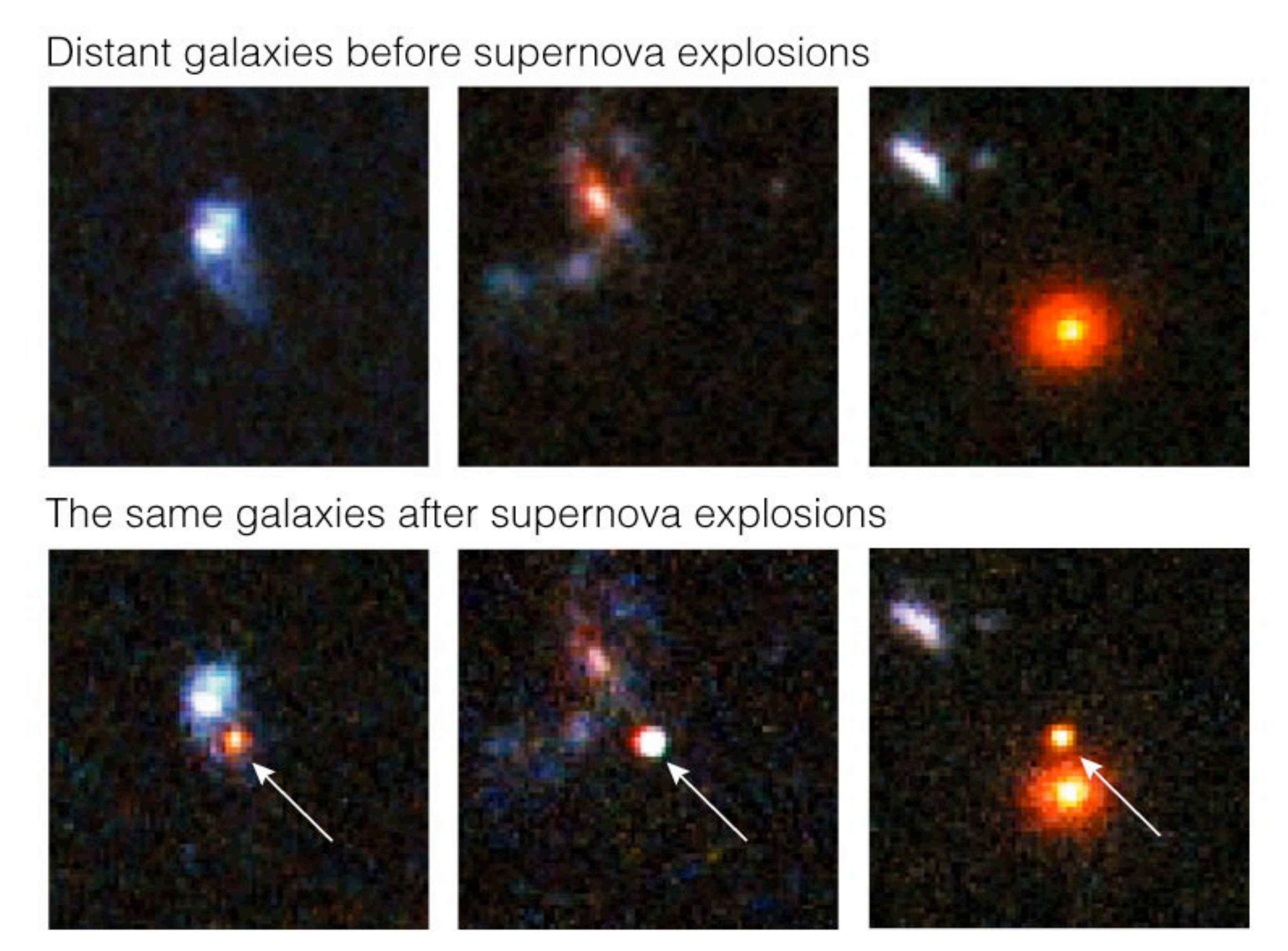
* Imagine throwing a rock upward from where you stand
* Depending on its initial velocity, it will go up a certain distance, slow down and then come back down
* What would you think if once you have thrown the rock upward, its velocity would not slow down but get faster instead? What would cause that?

Using white-dwarf supernovae as standard candles



From the white-dwarf supernova's measured brightness, we find the distance to a very distant galaxy which is usually too faint for us to get a good measurement on its distance

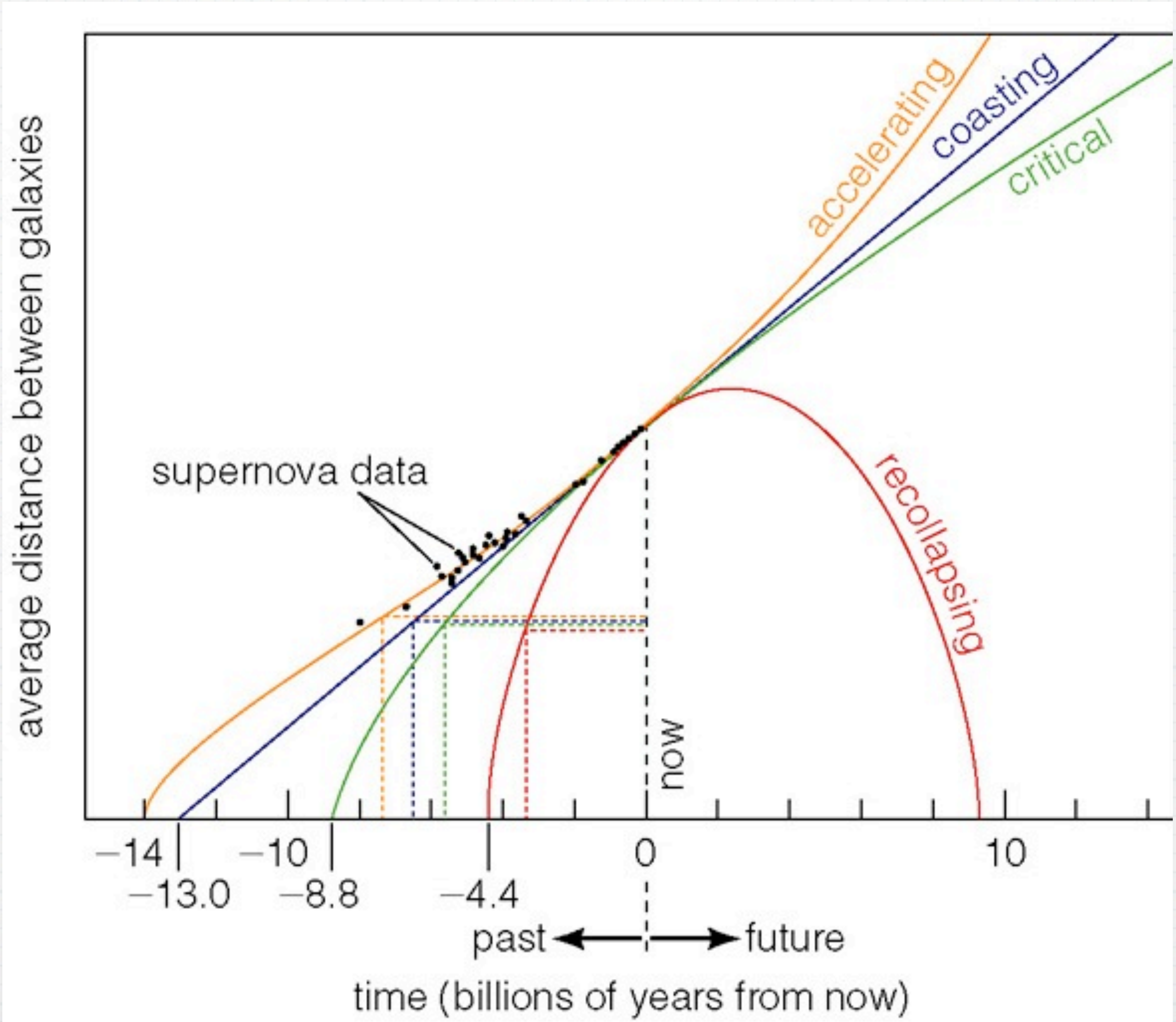
Brightness of distant white-dwarf supernovae tells us how much Universe has expanded since they exploded



Distances from Hubble Law and White Dwarf Supernovae

* Comparing the distances obtained via calculating the absolute magnitudes of these supernovae and the distances obtained from their galaxies red-shifts we find differences that increase with distance
* This indicates that Hubble's Law is not linear: the expansion's speed is not constant

Accelerating Universe is best fit to supernova data



A mysterious repulsive force is needed to explain this acceleration

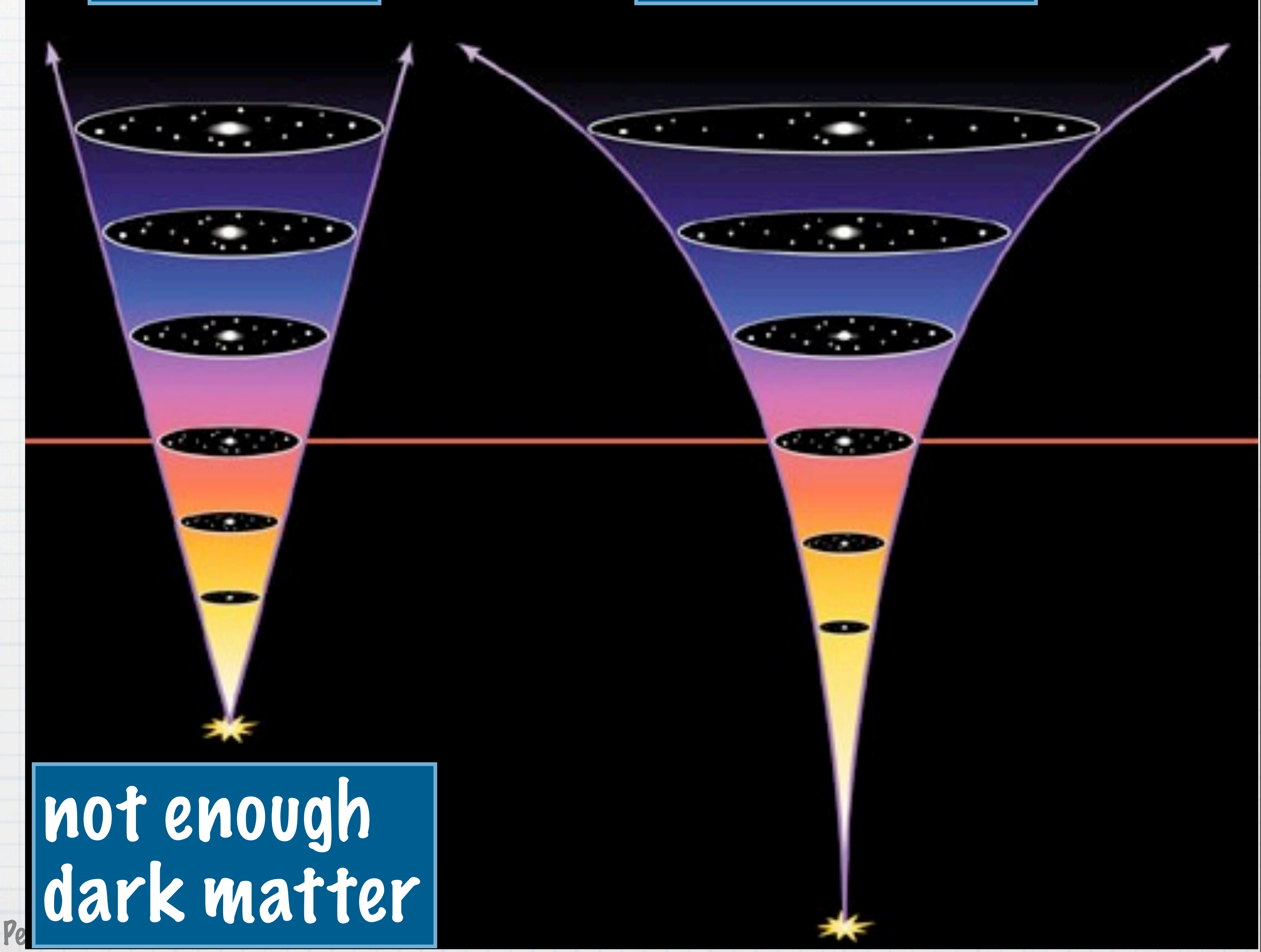
we call it dark energy

Universe expansion appears to be speeding up!

Observations of distant white dwarf supernovae seem to indicate the Universe's expansion is not coasting but accelerating

coasting Universe

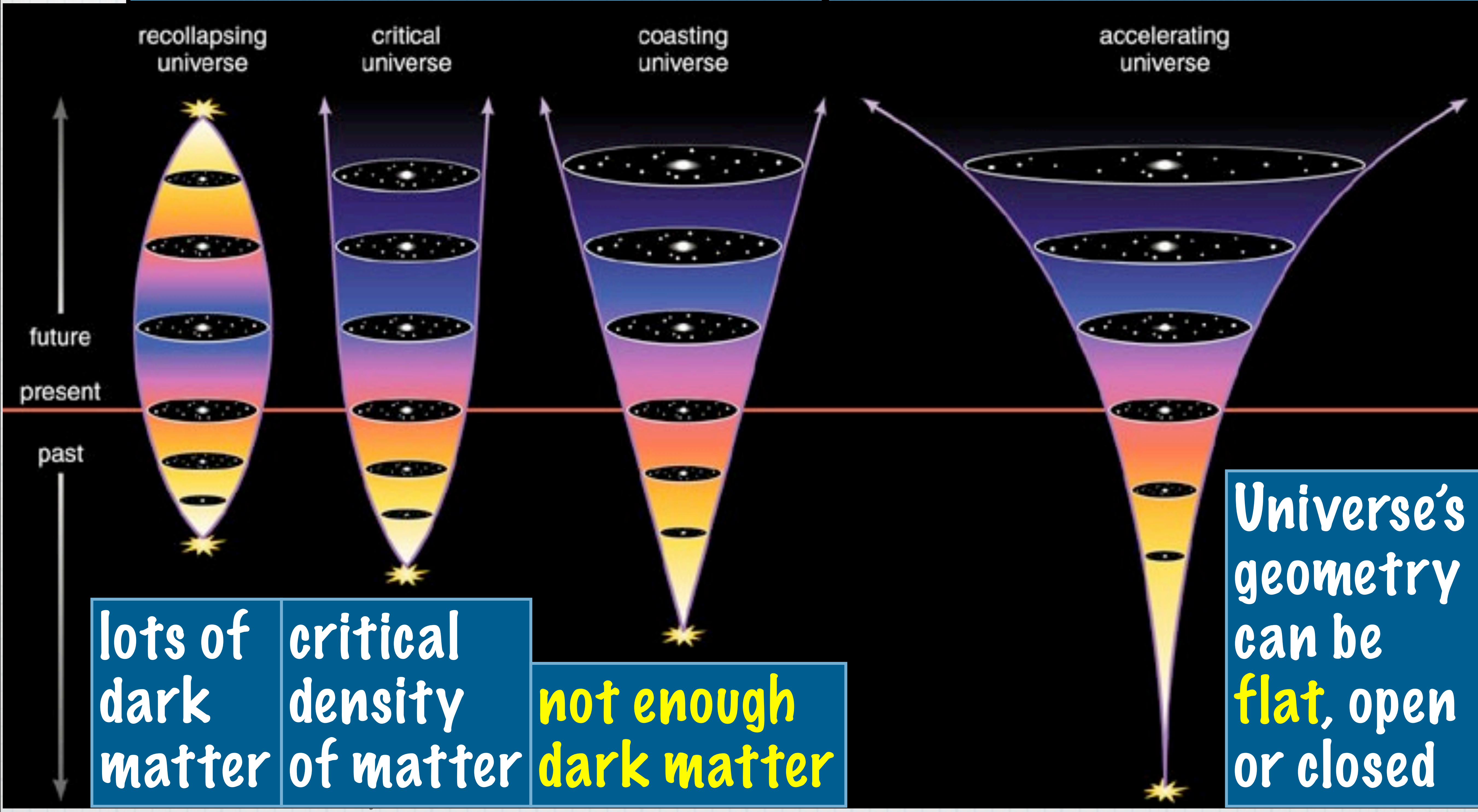
accelerating Universe



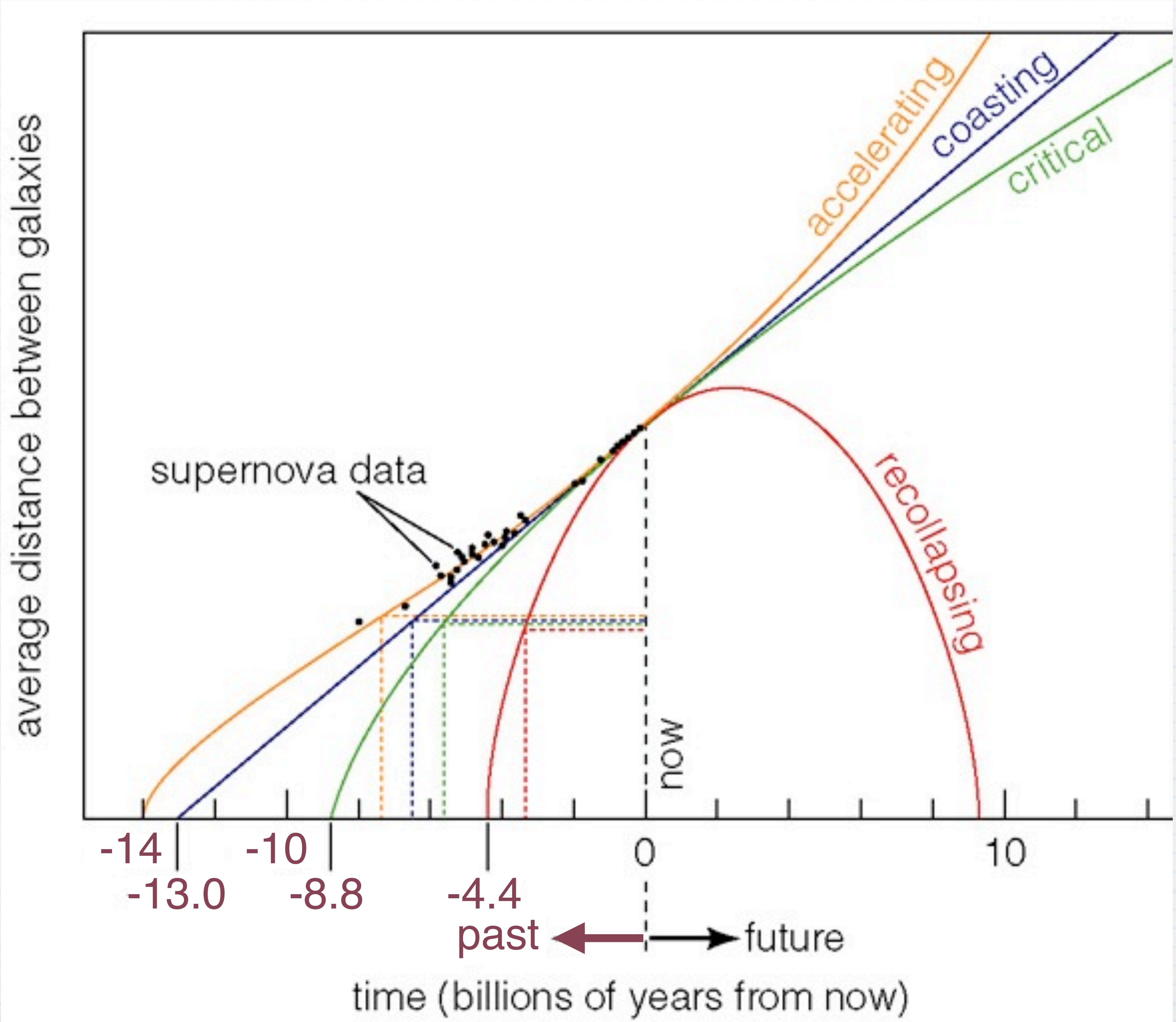
not enough dark matter

The Fate of the Universe depends on amounts of dark matter and dark energy

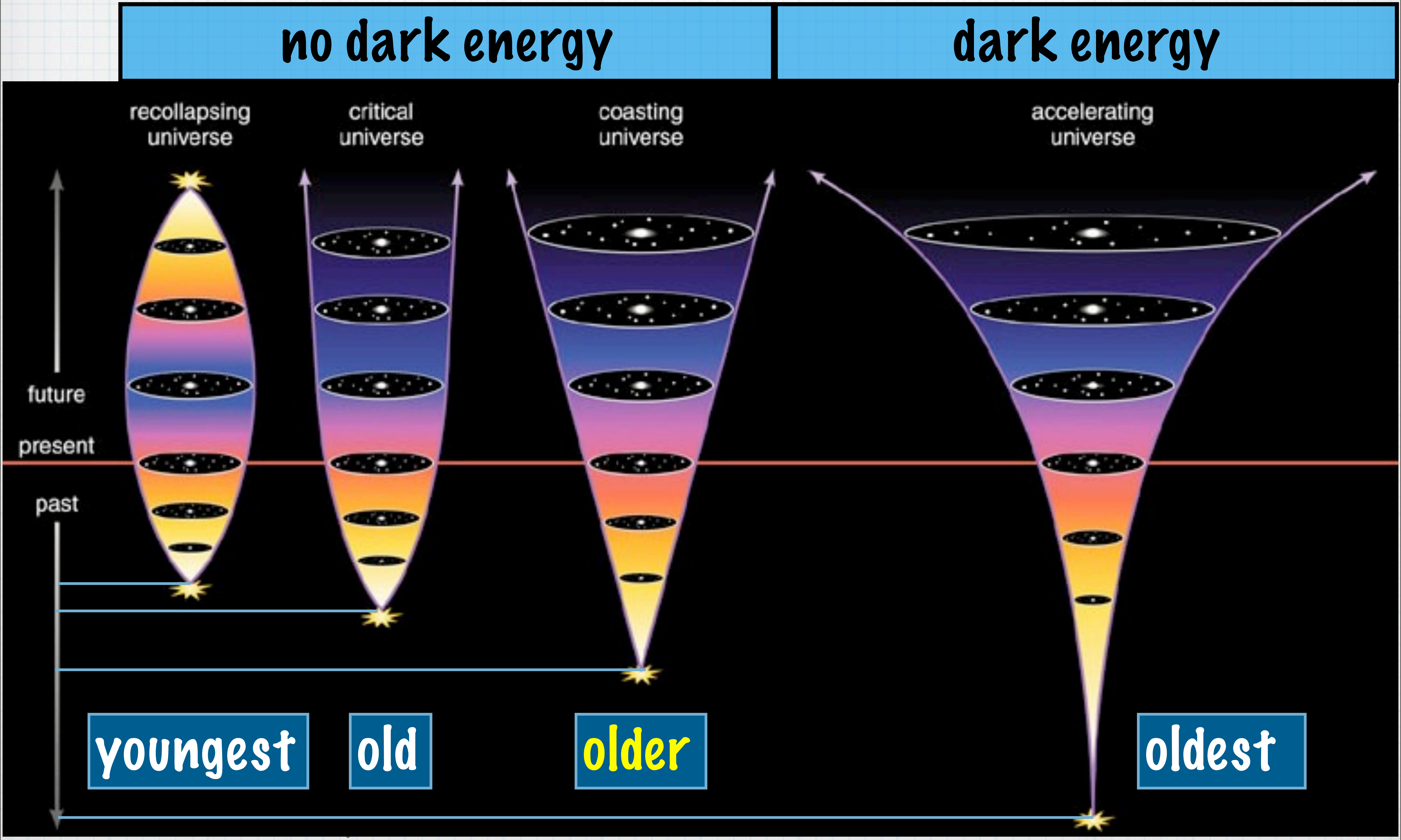
no dark energy	dark energy



The more energy there is in the Universe, the older it is



The Age of the Universe depends on amounts of dark matter and dark energy



Age of the Universe

* Latest studies (Mar. 2013) coming out of detailed analysis of the Wilkinson Microwave Anisotropy Probe indicate that the Universe is 13.798 billion years old
* The error range is +/- 37 million years

Question

* Suppose that the Universe has more dark matter than we think there is today - how would that change the age we estimate from the expansion rate

A. Estimated age would be larger (older)

B. Estimated age would be the same

C. Estimated age would be smaller (younger)

Question

* Suppose that the Universe has more dark matter than we think there is today - how would that change the age we estimate from the expansion rate

A. Estimated age would be larger (older)

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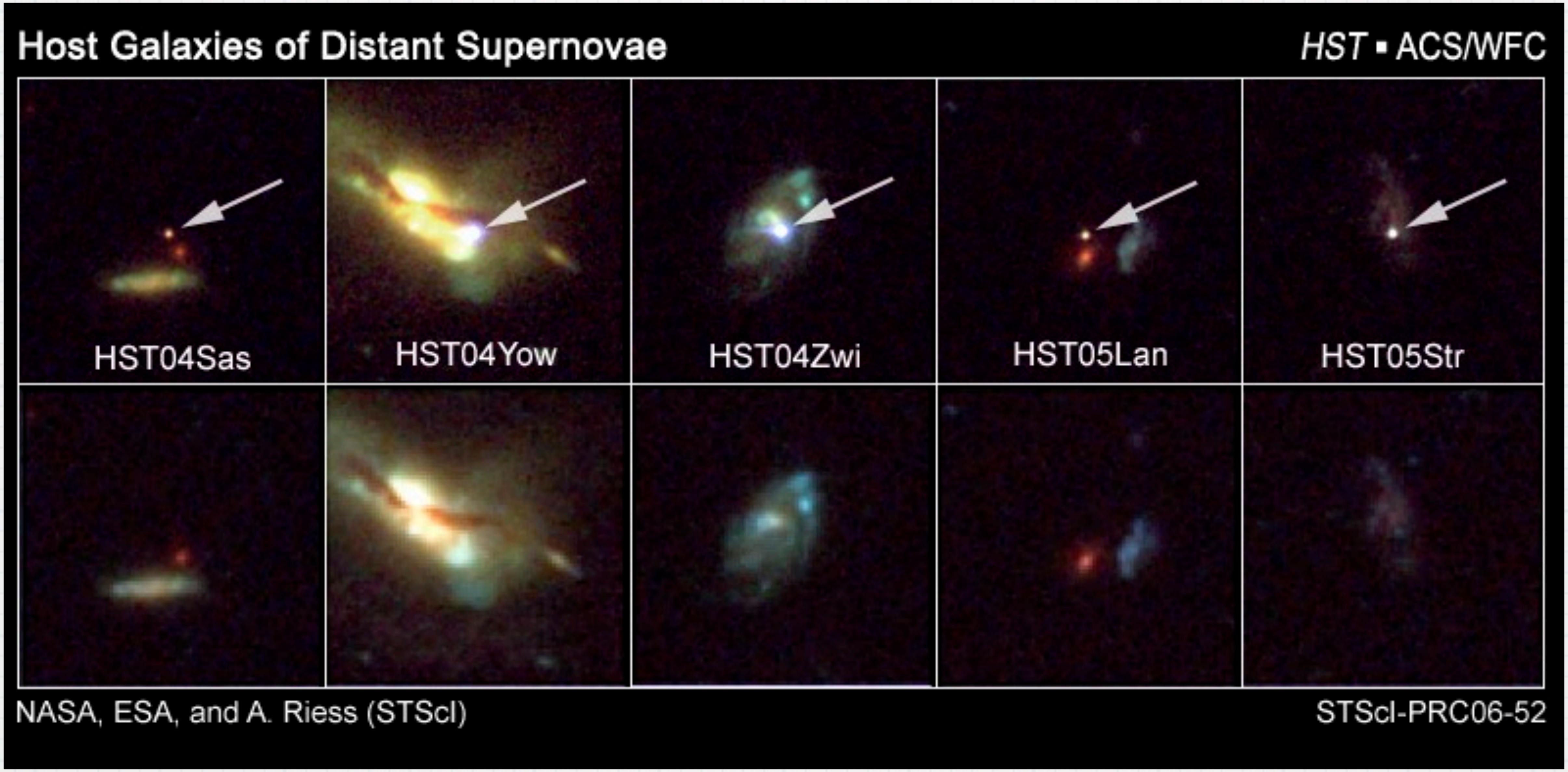
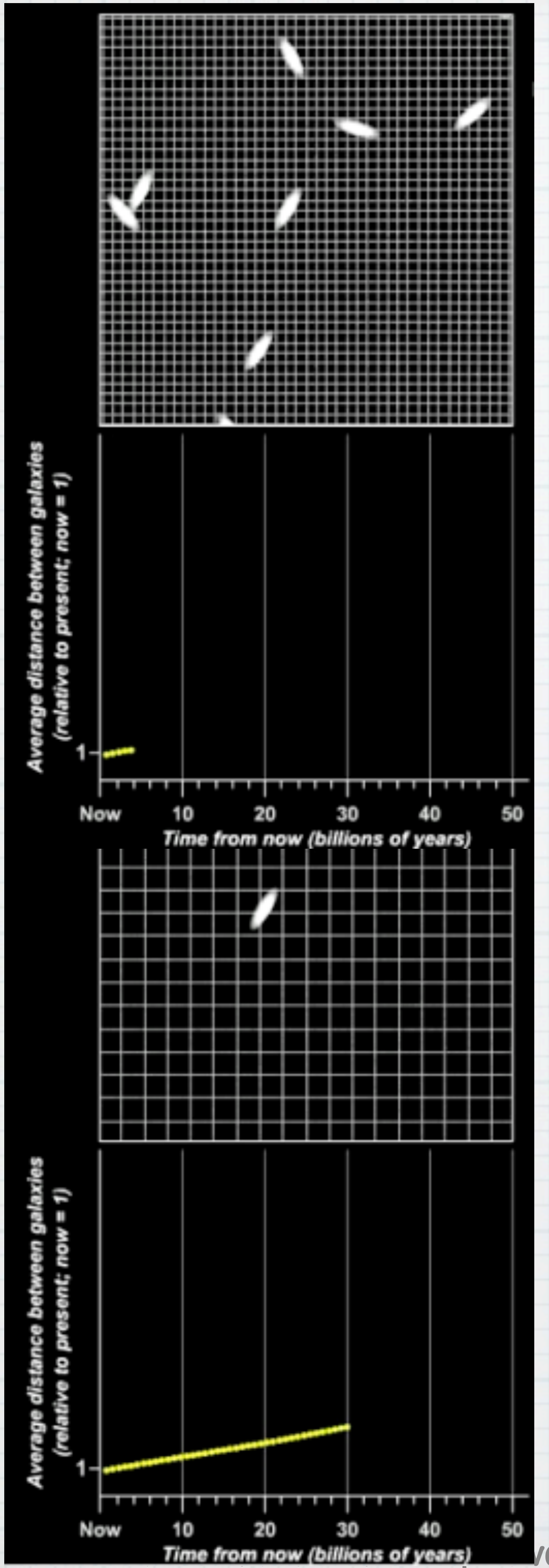
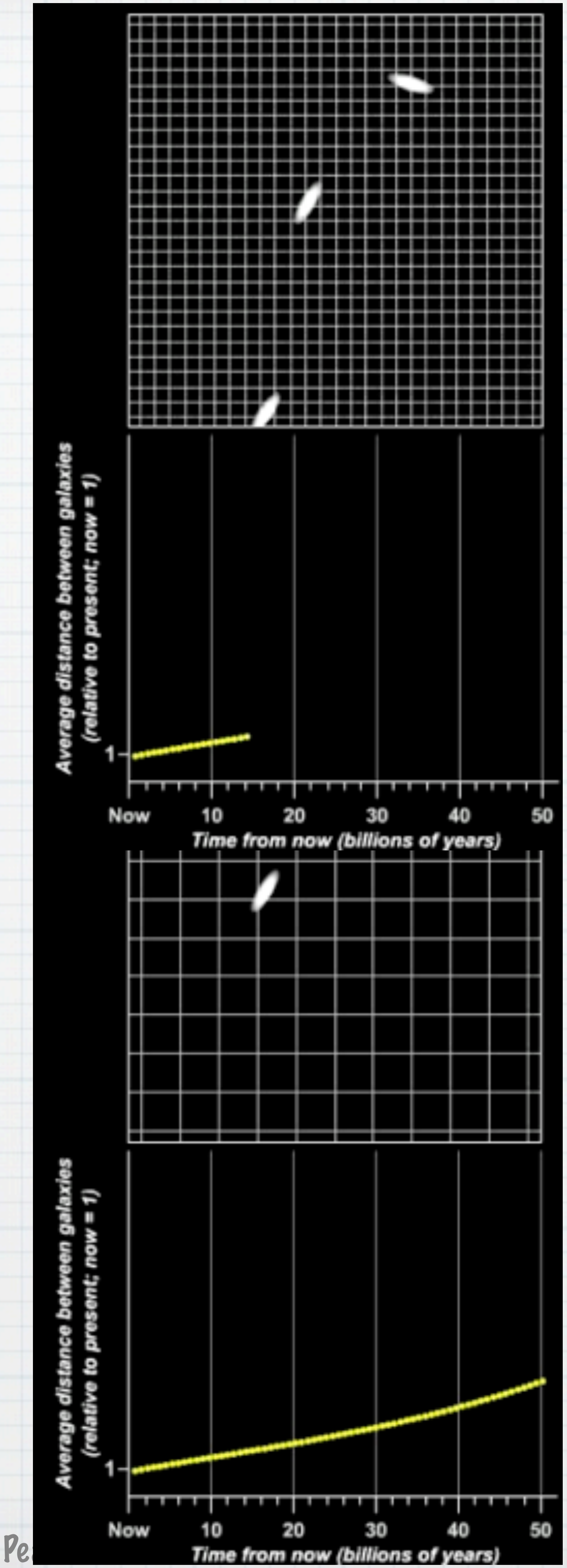
Dark Energy is not a "recent" force



These 5 supernovae are between 3.5 to 10 billion light-years away

Measurements indicate that the dark energy was present 10 billion years ago. It is not a new constituent of space





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Without dark energy being present, the mass density set here is a closed Universe

However, with a minimal dark energy amount, the Universe is accelerating

Hence if dark energy exists, even a little, the Universe expands forever

Evidence for Dark Energy

1. Type Ia supernovae
2. Presence detected as far as 10 billion years ago

And, to be seen in the next lecture:

3. Cosmic Microwave Background (CMB, WMAP)
4. Gravitational Lensing
5. Large scale structure of the Universe

What is "Dark Energy"?

* Empty space has a fundamental energy: empty space is not "nothing" (Einstein)
* It is not dense: 10^{-29} g/cm^3
* Its strength gets effective only at great cosmic distances (sum effect)
* It is also called the vacuum energy
* It applies a negative pressure on space (positive pressure: compression; negative: repulsion = expansion)

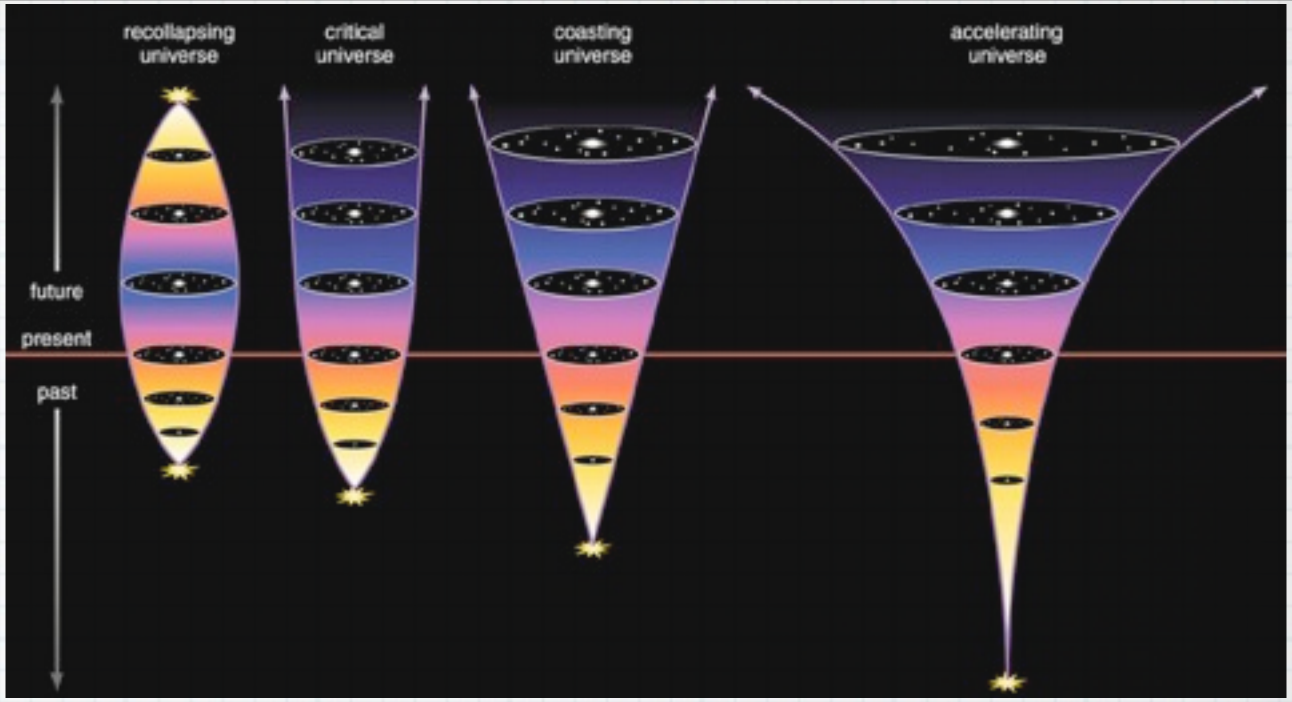
What is "Dark Energy"?

* Two more possibilities (but both raise more questions)
* 1: QM states that empty space is full of virtual particles that continually appear and disappear - but energy calculations are off by 10^{120} times too large!
* 2: Dark energy is a kind of dynamical negative energy field which fills space (called "Quintessence") and is similar in concept to the Higgs field. No one knows why it would exist

What is "Dark Energy"?

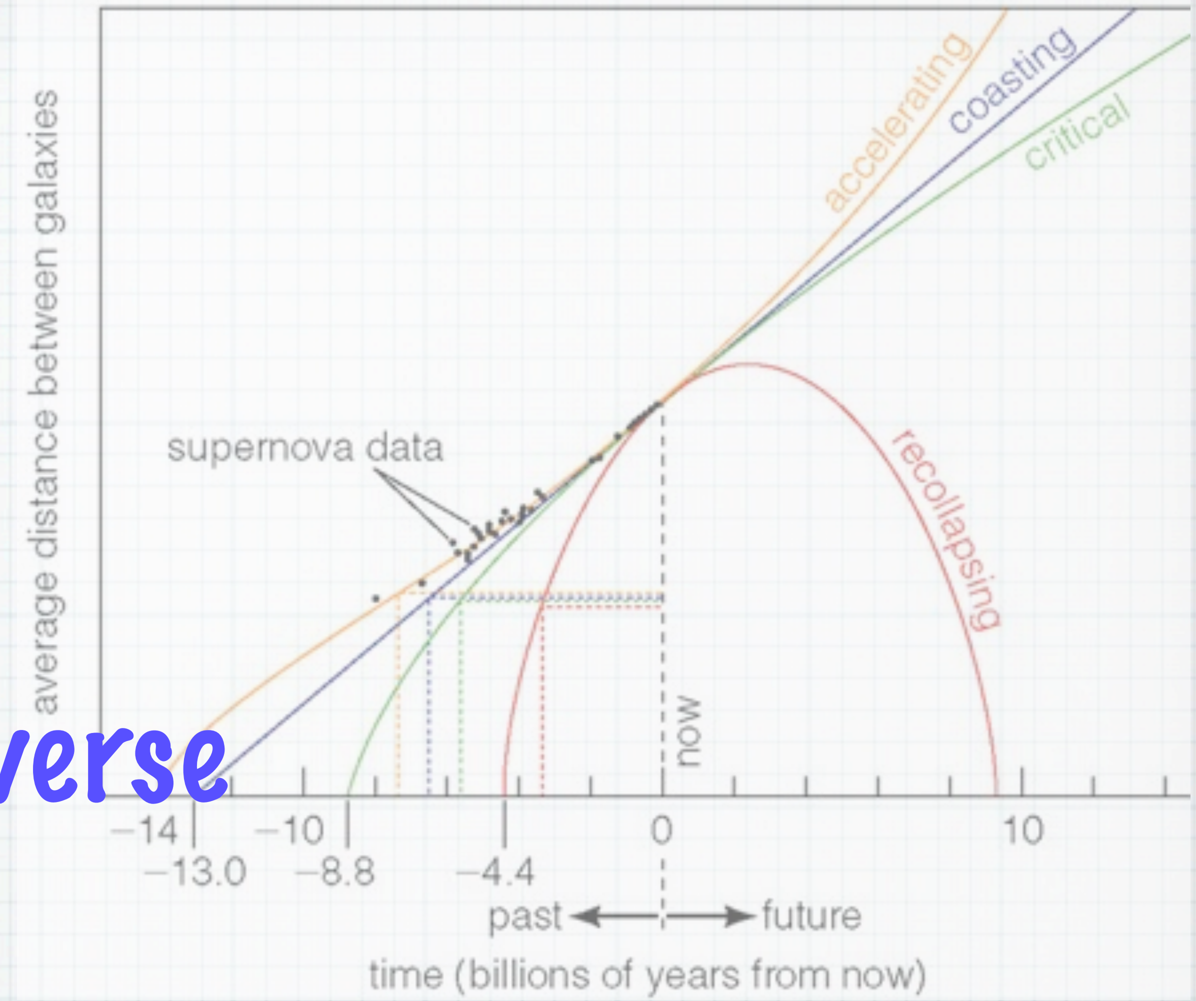
* Could Einstein Theory of Gravity be wrong?
* That would not only affect the expansion of the Universe, but it would also affect the way that normal matter in galaxies and clusters of galaxies behaves
* There are candidate theories, but none are compelling
* The research for Dark Energy continues!

Snapshot



* Will the Universe continue expanding forever?
* Even before we consider the possibility of a mysterious dark energy, the evidence points to eternal expansion. The critical density is the average matter density the Universe would need for the strength of gravity to eventually halt the expansion. The overall matter density of the Universe appears to be only about 25% of the critical density needed to stop the expansion

Snapshot



* Is the expansion of the Universe accelerating?
* Observations of distant supernovae indicate that **the expansion of the Universe is speeding up**. No one knows the nature of the mysterious force (powered by the dark energy) that could be causing this acceleration

References

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    * http://www.youtube.com/watch?v=74IsySs3RGU
* Large Scale Structure of the Universe
    * http://www.youtube.com/watch?v=VJpC_oQQxPI
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    * http://www.youtube.com/watch?v=zqb1lSdqRZY