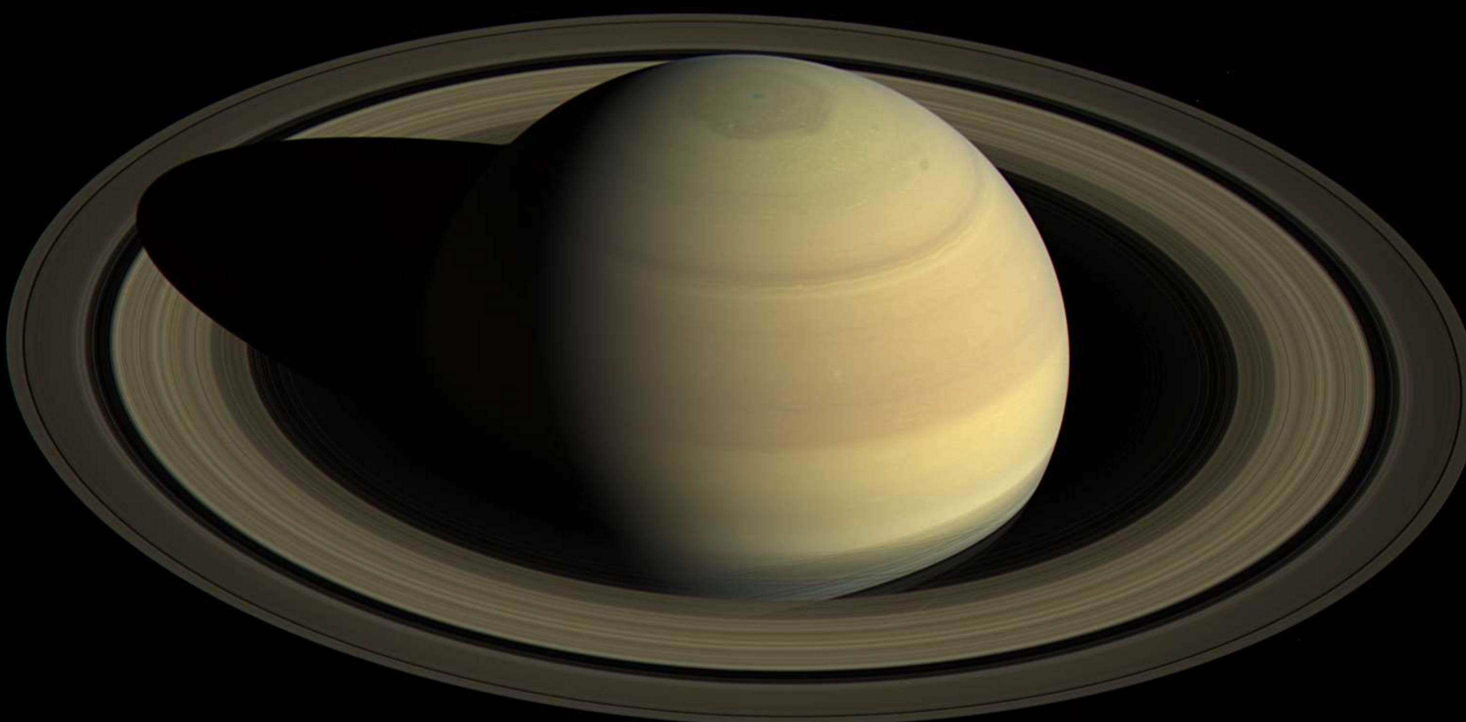
AST 2002
Introduction to Astronomy



A Few Quick Things…

E-mailing me: Must have AST2002 in the subject

Mary Hinkle, Graduate Teaching Assistant:

Office hours: Mon 1:30-3:00pm. PSB 316

My office hours: ~~Mon 3:00-4:00pm. PSB 308~~

~~Tue 3-4 pm. PSB 308~~

I will be in a teleconference next week. Will switch to Wed/Thur at 3 pm.

I will be in DC the week afterwards… Mon-Thur

Will try to get my Graduate student, Amy to cover Mon/Tue on both weeks… also in PSB316

Curved Mid-term results are out on webcourses...

Homework is also out (next slide)

Final: Friday 27th April. 7am-9:50 am. (on all chapters; ~ 100 questions. 25:25:25:25)

LAST Knights Under the Stars Event – Thursday 19th April

Opportunity to make up the 1% extra credit that was offered (if you haven't been yet, worth 2%) – Last chance for extra credit..

Homework (Revised) & Evaluations

There are 3 homework sets on Webcourses:

- HW # 2 is on Chapters 1-5, 15 questions, due April 27th at midnight
- HW # 3 is on Chapters 6-9, 12 questions, due April 27th at midnight
- HW # 4 is on Chapters 10-13, 12 questions, due April 27th at midnight
- The Syllabus quiz has been re-opened and will be available until April 27th at midnight
- HW #1 has been re-opened and will be available until April 27th at midnight

Each quiz is worth 2%. The syllabus will be worth 1% and there will be a bonus 1% for putting up with the 'lack' of homework throughout this course…

Evaluations of the Course & Instructor are available on Webcourses – Please fill out this week!

What Did We Cover Last Time?

Chapter 17: The Birth of the Universe (Abridged)

17.1. The Big Bang Theory

- What were the conditions like in the Early Universe?
- How did the early universe change with time?

17.2. Evidence for the Big Bang

- How do observations of the cosmic microwave background support the big bang theory?
- How do the abundances of the elements support the Big Bang theory?

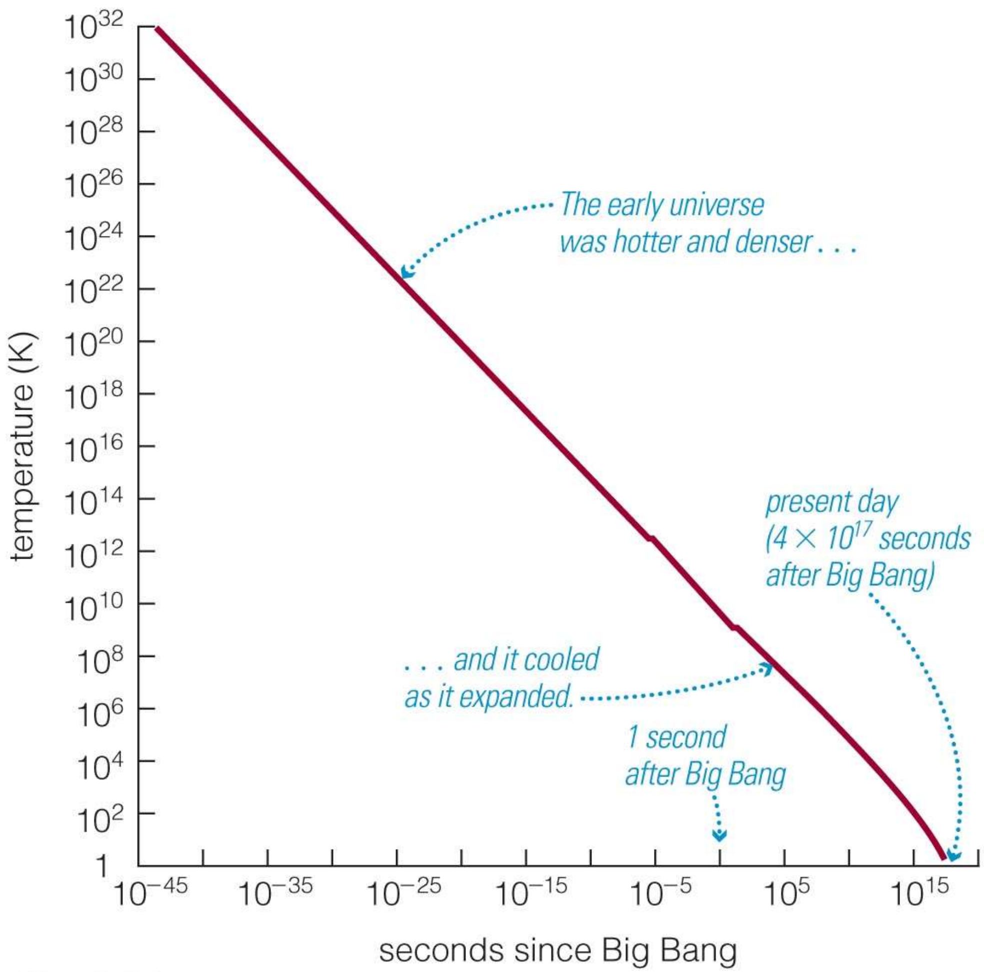
17.3. The Big Bang and Inflation

- What key features of the universe are explained with inflation?
- Did inflation really occur?

17.4. Observing the Big Bang for yourself

- Why is the darkness of the night sky evidence for the big bang?

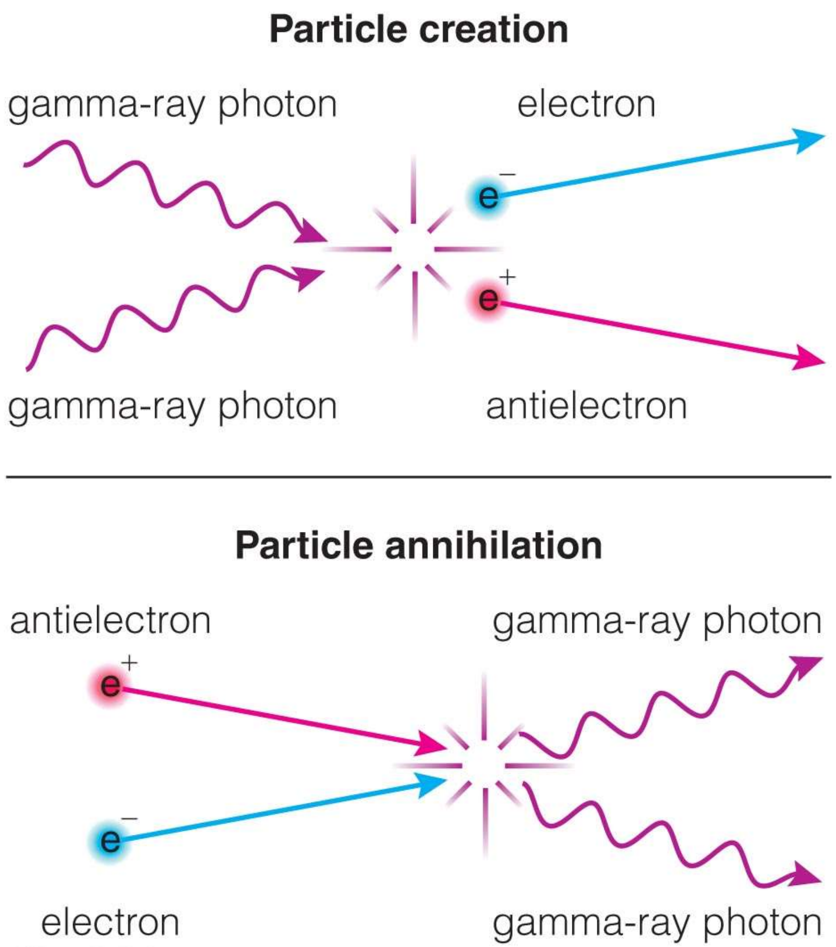
The First Moments of the Big Bang



Extrapolating backwards, we can estimate that the average temperatures would have been exceedingly hot in the beginning…

… So hot in fact, that in the very early stages, the distinction between light and matter would not have been possible.

Light, Matter & Antimatter



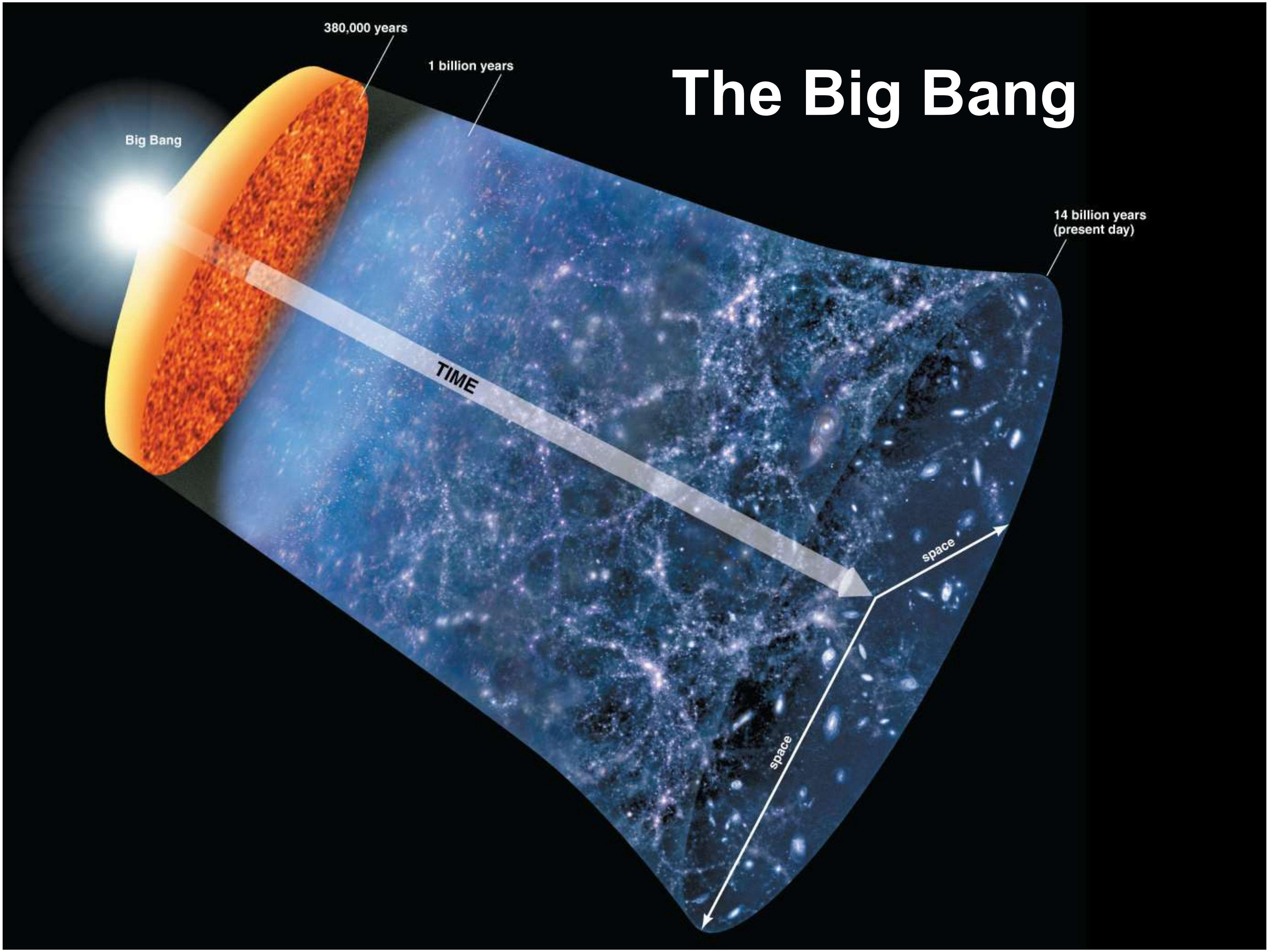
- We saw previously that a positron (an antielectron) and an electron can recombine to form two 0.511 MeV gamma rays…

$E=mc^2$

- The opposite is also true, it is possible to generate matter (both electrons and anti-electrons) from two 0.511 MeV gamma rays…
- The same thing can happen to generate protons and antiprotons, you just need A LOT more energy to do so.
- In our universe, the amount of ordinary matter is in excess of the amount of anti-matter we observe…
- How can this be possible?

→ We don't know! but we know that an imbalance of 1 in 10^9 normal matter particles not being annihilated would be required.

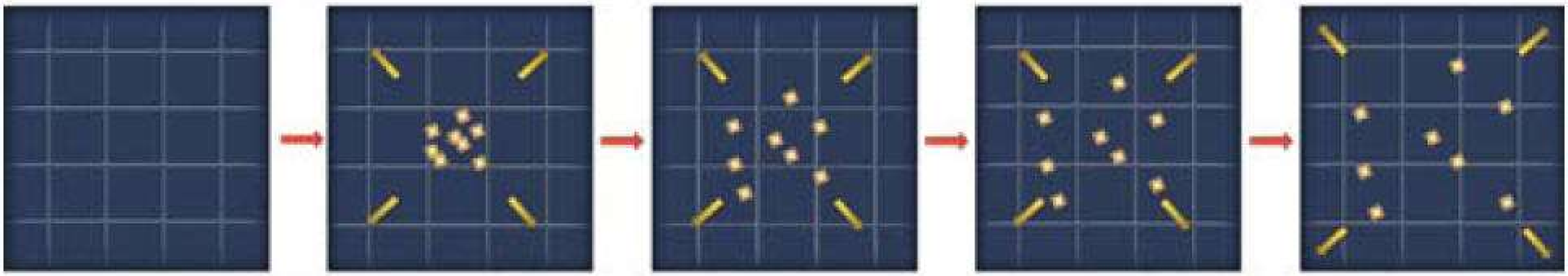
The Big Bang


380,000 years
1 billion years
Big Bang
14 billion years
(present day)
TIME
space
space

WHAT KIND OF EXPLOSION WAS THE BIG BANG?

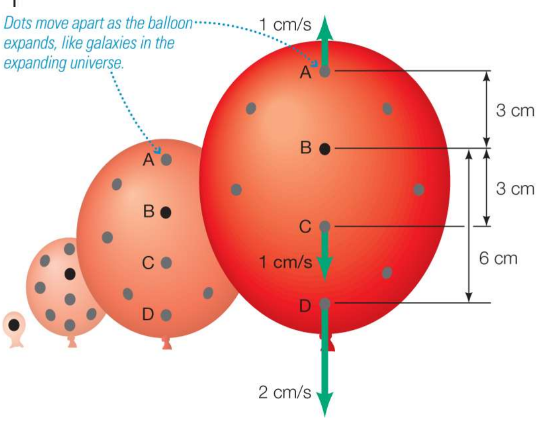
WRONG: The big bang was like a bomb going off at a certain location in previously empty space.

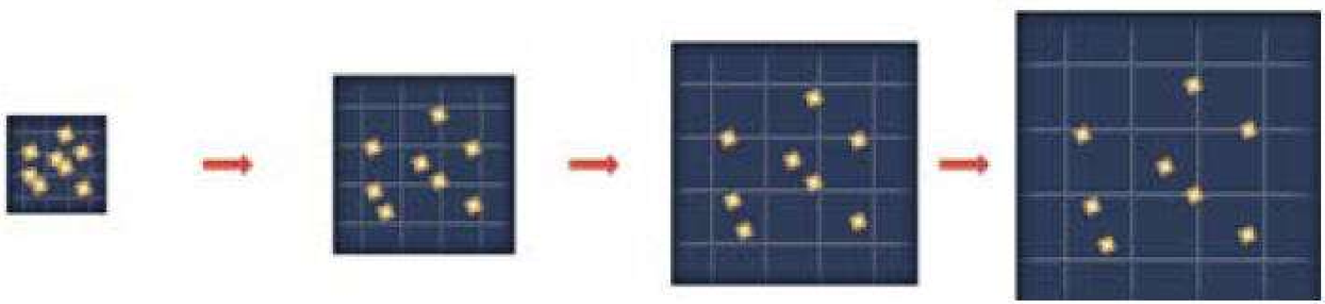
In this view, the universe came into existence when matter exploded out from some particular location. The pressure was highest at the center and lowest in the surrounding void; this pressure difference pushed material outward.



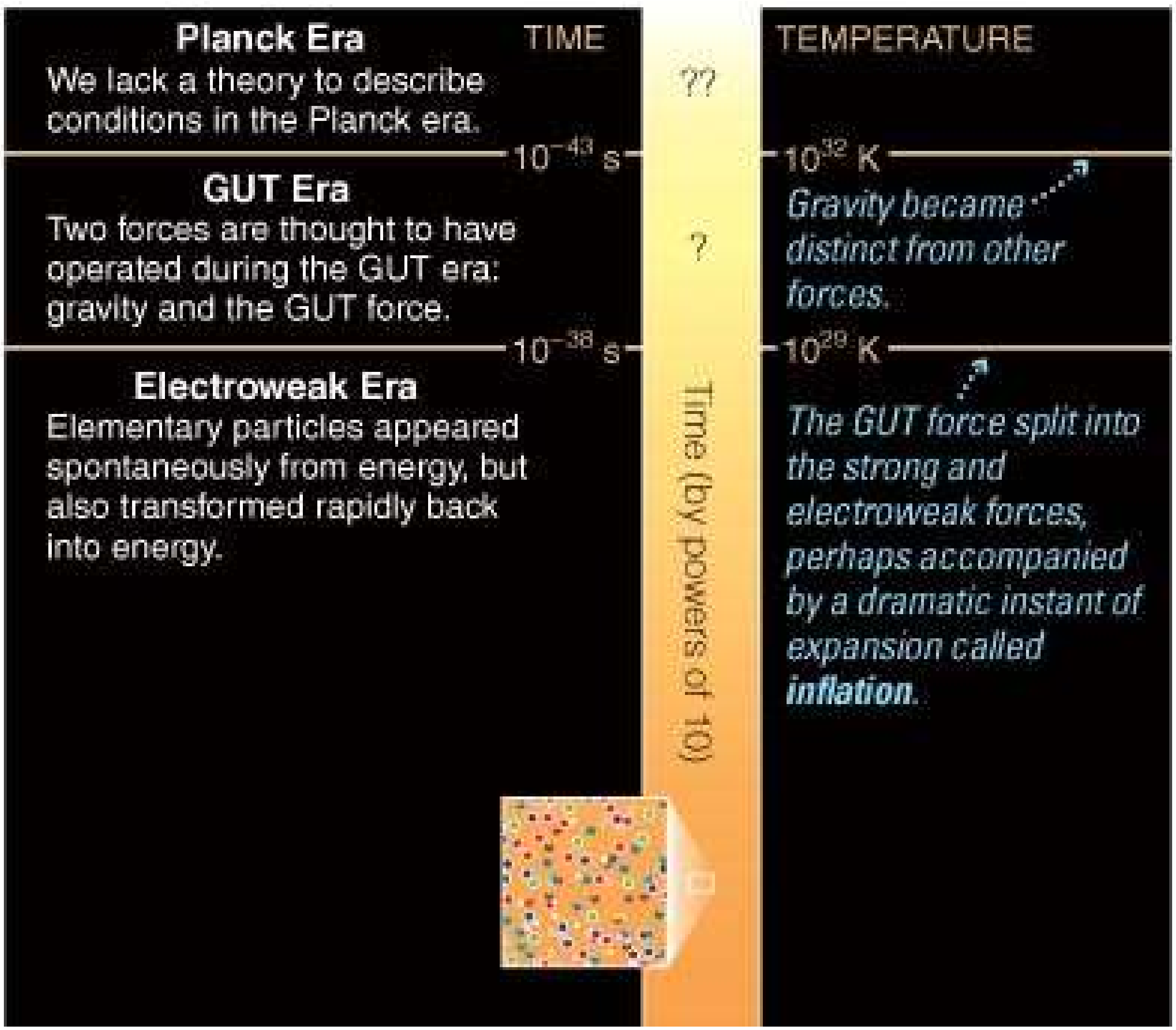
RIGHT: It was an explosion of space itself.

The space we inhabit is itself expanding. There was no center to this explosion; it happened everywhere. The density and pressure were the same everywhere, so there was no pressure difference to drive a conventional explosion.





Break down of the Big Bang The early era's (<10^{-10} s)



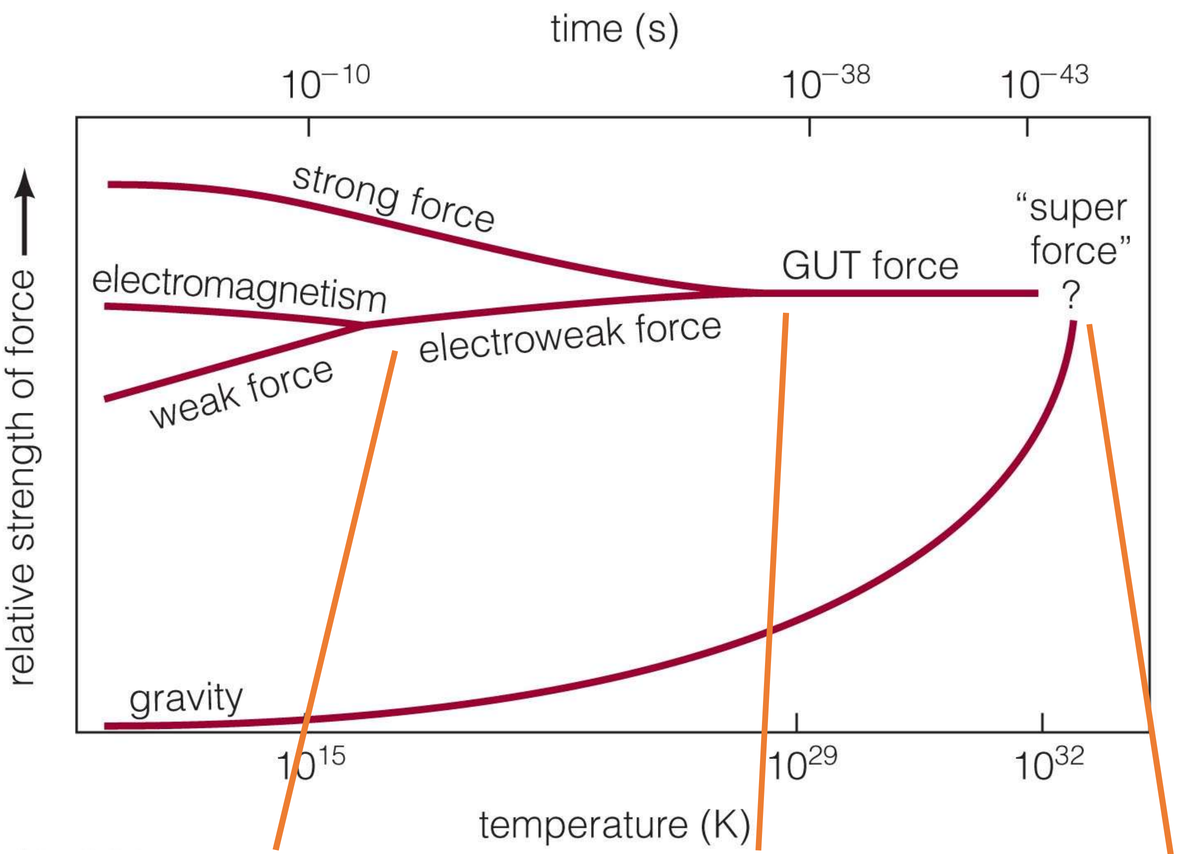
Planck Era:

Time: < 10^{-43} s
Temp: > 10^{32} K

No theory of quantum gravity yet

All forces may have been unified

What Happens to Forces at High Temperatures?



Four known forces in universe (present day):

Strong Force

Weak Force

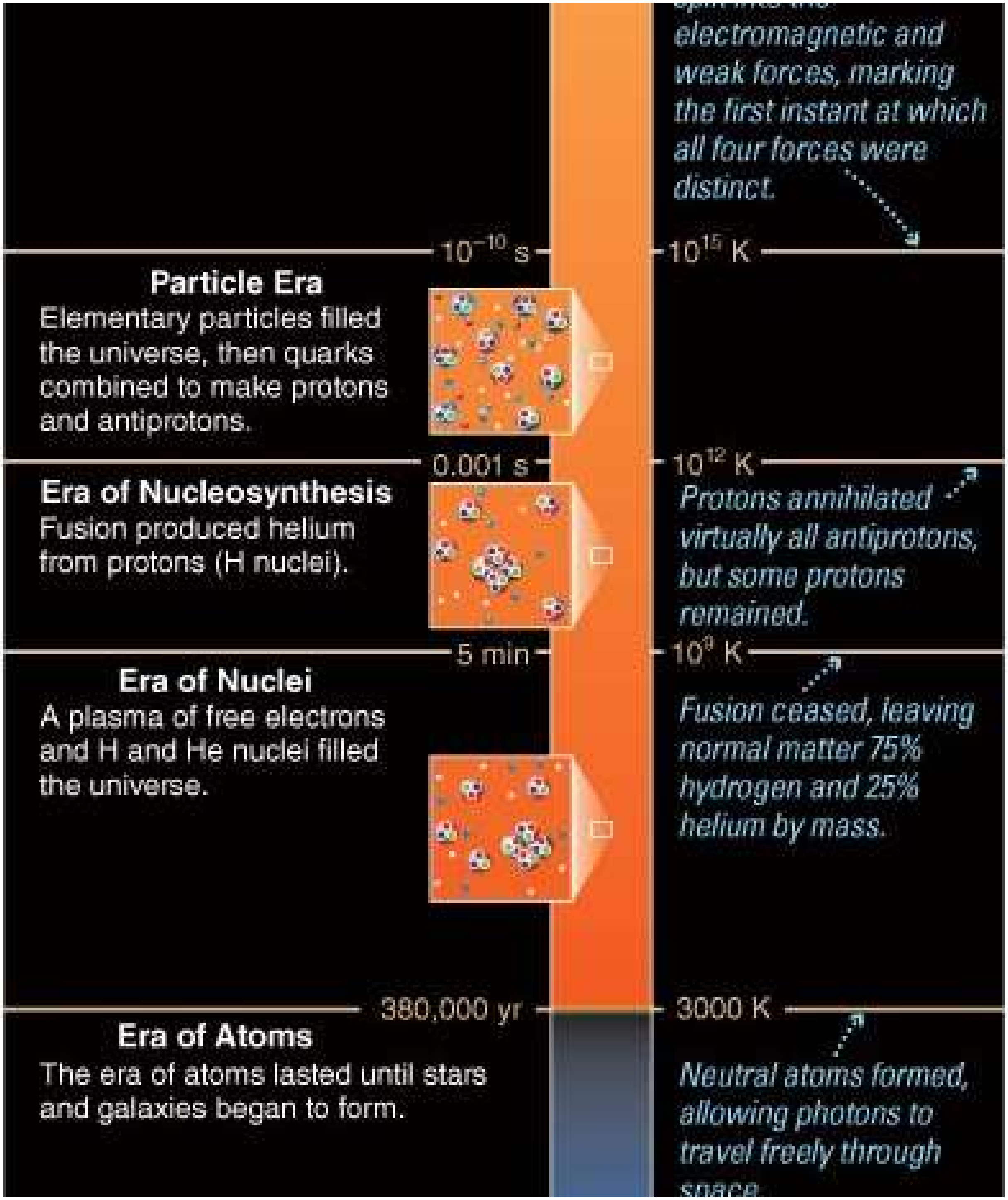
Electromagnetism

Gravity

Yes!
(Electroweak)

Maybe
(GUT)

Who knows?
(Theory of Everything)



The Big Bang: Later Era's

Particle Era:

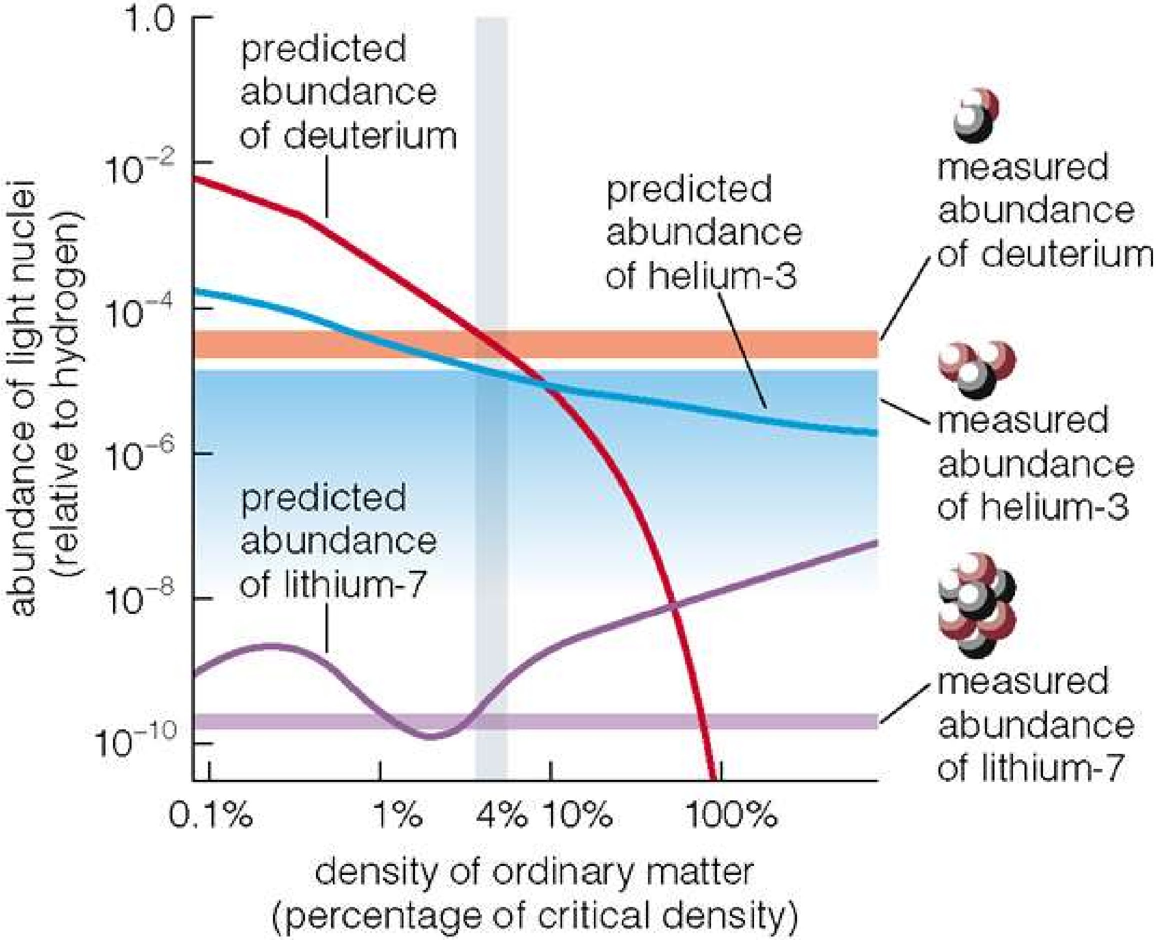
Time: 10^{-10}–0.001 s
Temp: 10^{15}–10^{12} K

Amounts of matter and antimatter are nearly equal.

(Roughly one extra proton for every 10^9 proton–antiproton pairs!)

More Evidence of the Big Bang

- Due to the rapid expansion, fusion only lasted a few minutes…
- Only sufficient time to make a few elements/isotopes



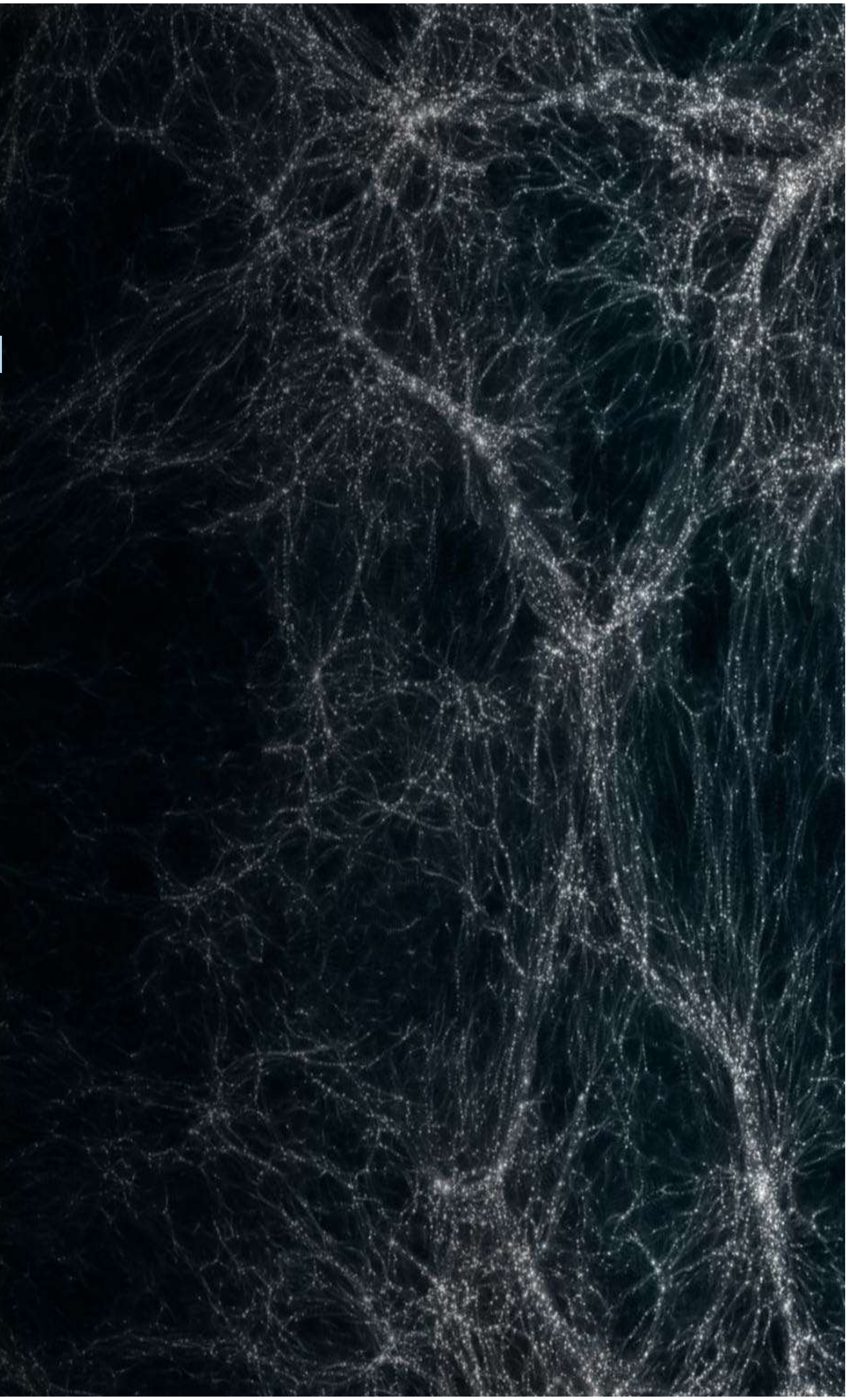
- Based on our knowledge of the efficiency of fusion reactions, we can determine that the approximate temperatures and densities agree with models of the conditions in the Big Bang
- Furthermore, we will use this to constrain how much ordinary matter there is in the universe (chapter 18).
- Abundances of other light elements agree with Big Bang model having 5% normal matter *–evidence for WIMPS?*

Is there any evidence for an era of darkness? Well yes, it would have taken time for gravity to start playing a role and forming stars/galaxies… we will see more with James Webb

Is there any evidence that light suddenly was set free when the first atoms formed? Yes, the CMB…

$\rightarrow$ Recall that free-electrons (not bound to atoms) are really good at stopping light from getting out of the Sun

$\rightarrow$ But what happens when the temperature drops and atoms start forming? ***The light will no longer be trapped!***

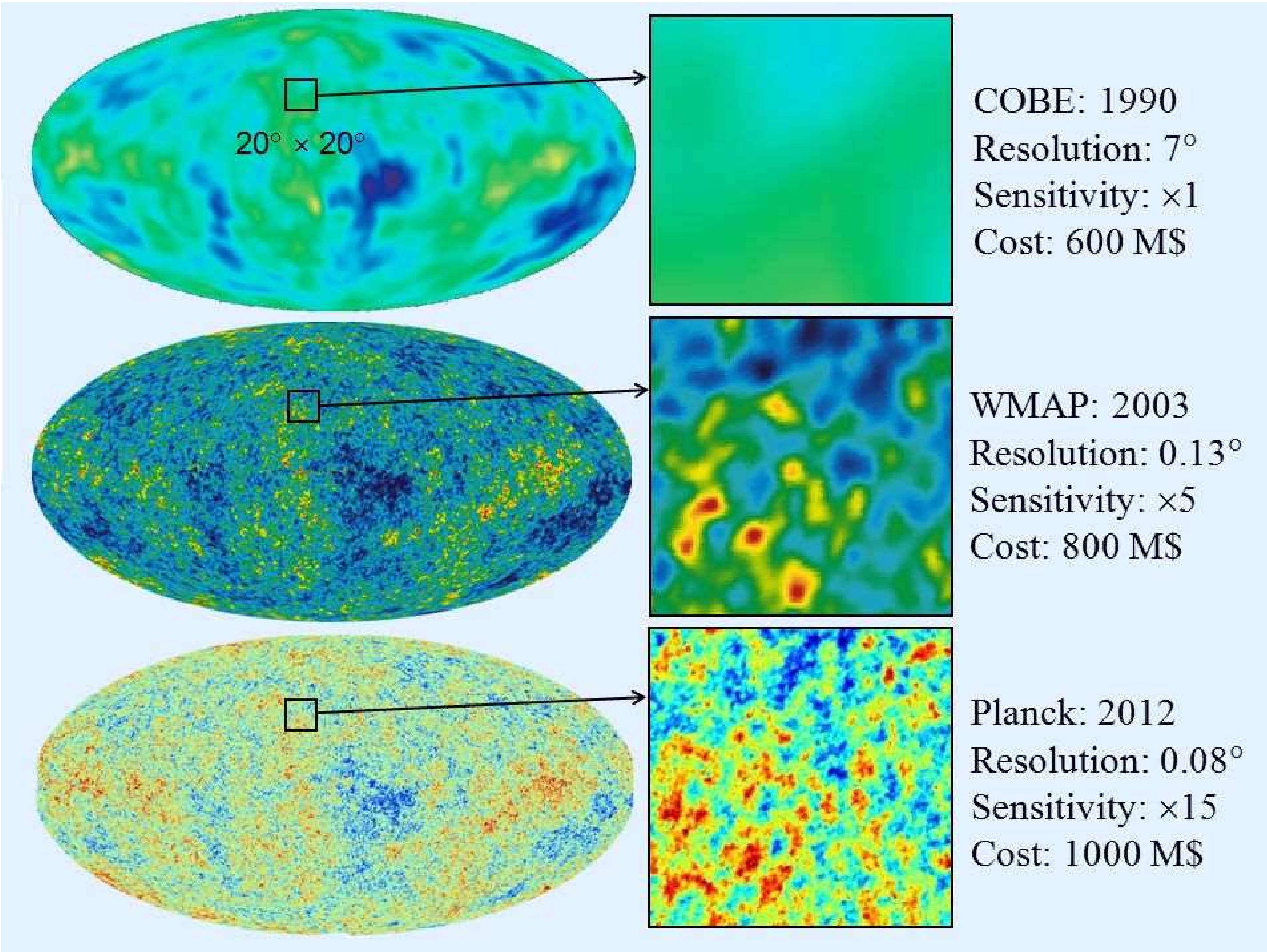


The Cosmic Microwave Background (CMB)

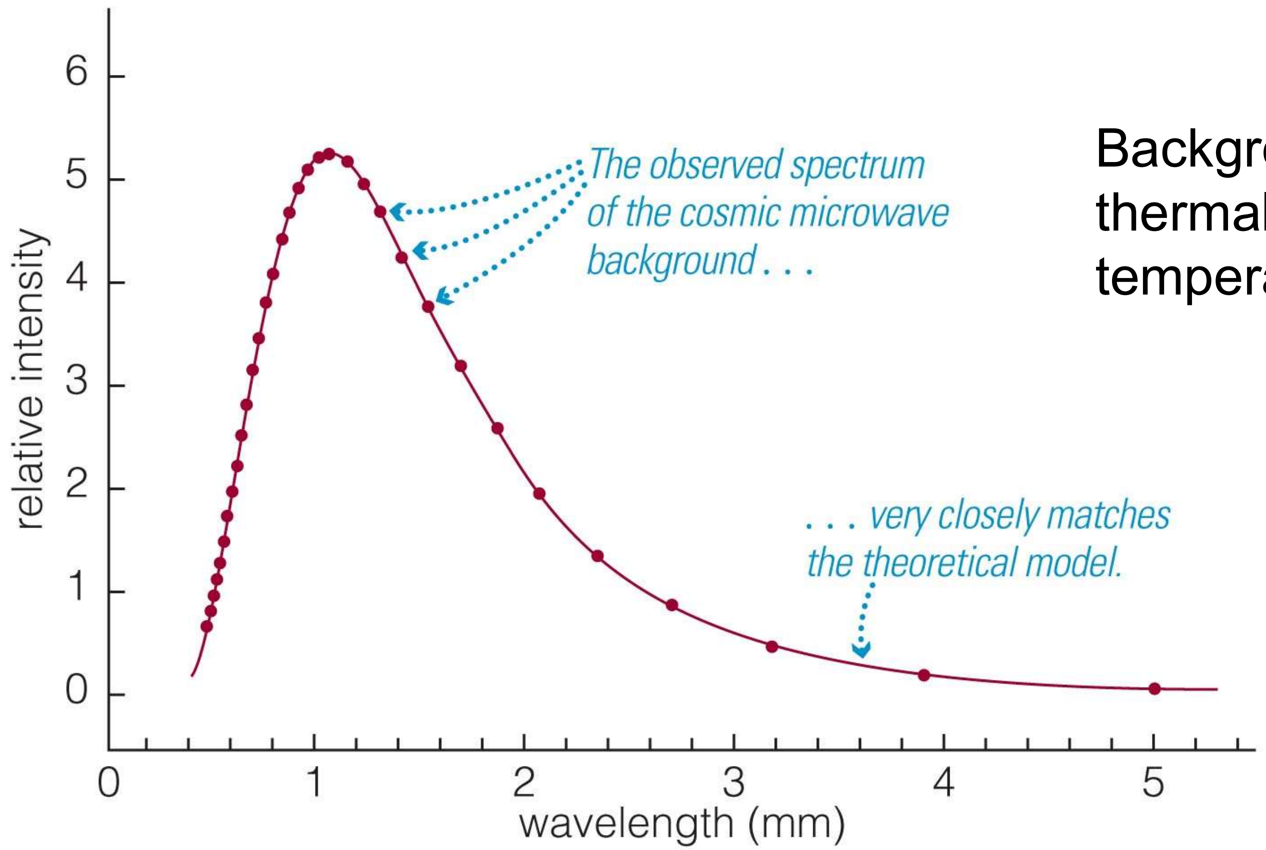
What is this strange noise?

It’s everywhere!

The *cosmic microwave background* – the radiation left over from the Big Bang – was detected by Penzias & Wilson in 1965


20° × 20°
COBE: 1990
Resolution: 7°
Sensitivity: ×1
Cost: 600 M$
WMAP: 2003
Resolution: 0.13°
Sensitivity: ×5
Cost: 800 M$
Planck: 2012
Resolution: 0.08°
Sensitivity: ×15
Cost: 1000 M$

What is The Cosmic Microwave Background (CMB)?



Background has near perfect thermal radiation spectrum at temperature 2.73 K.

→ Expansion of the universe has red-shifted thermal radiation from that time to ~1000 times longer wavelength: *microwaves*.

Today's Lecture?

Chapter 18: Dark Matter, Dark Energy, and the Fate of the Universe (Abridged)

18.1. Unseen influences in the Cosmos

- What do we mean by dark matter and dark energy?

18.2. Evidence for Dark Matter

- What is the evidence for dark matter in galaxies?
- What is the evidence for dark matter in clusters of galaxies?
- Does dark matter really exist?
- What might dark matter be made of?

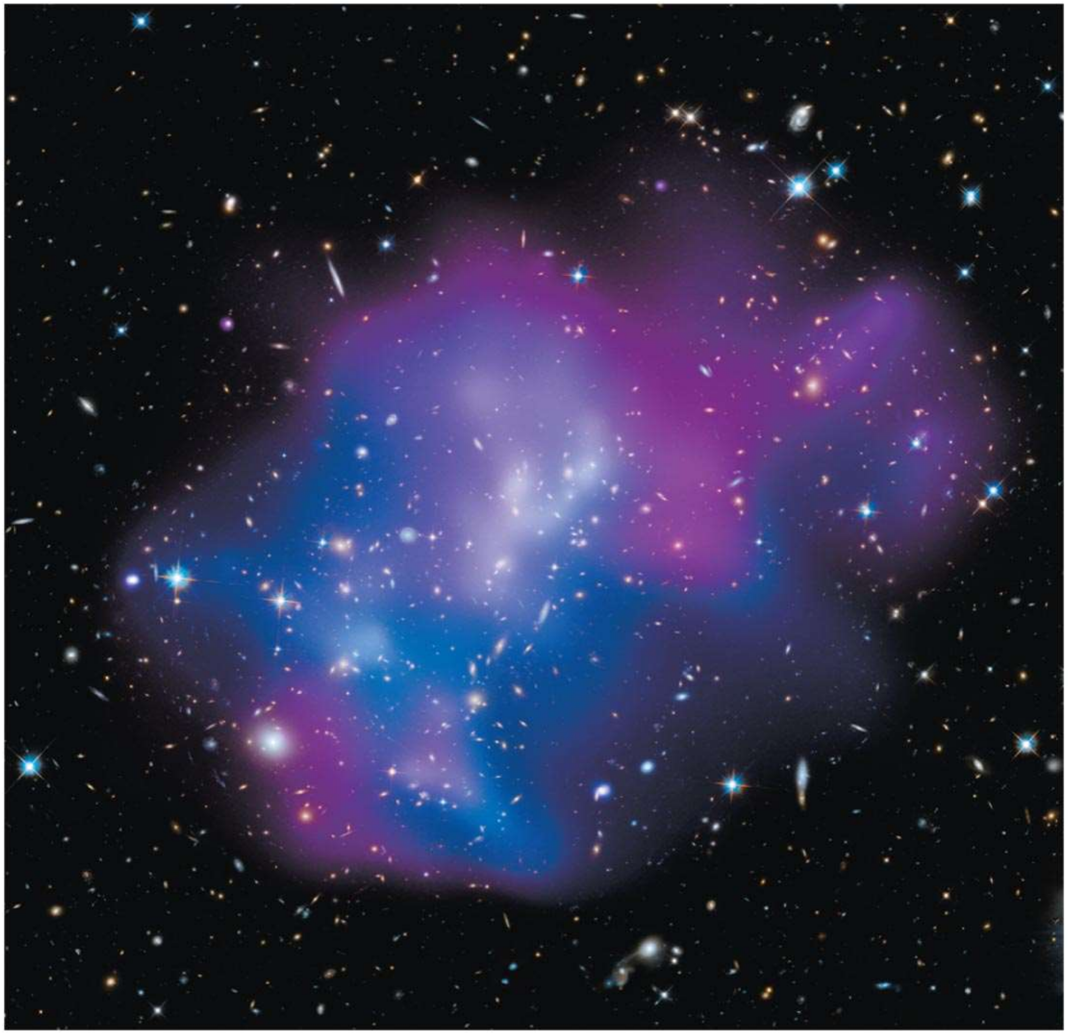
18.3. Structure Formation

- What is the role of dark matter in galaxy formation?
- What are the largest structures in the universe?

18.4. Dark Energy and the Fate of the Universe

- What is the evidence for an accelerating expansion?
- Why is flat geometry evidence for dark energy?
- What is the fate of the universe?

What do we mean by dark matter and dark energy?



Dark matter: An undetected form of mass that emits little or no light but whose existence we infer from its gravitational influence

Dark energy: An unknown form of energy that seems to be the source of a repulsive force causing the expansion of the universe to accelerate

Normal matter: ~ 5%

- Normal matter inside stars: ~ 0.5%
- Normal matter outside stars: ~ 4.5%

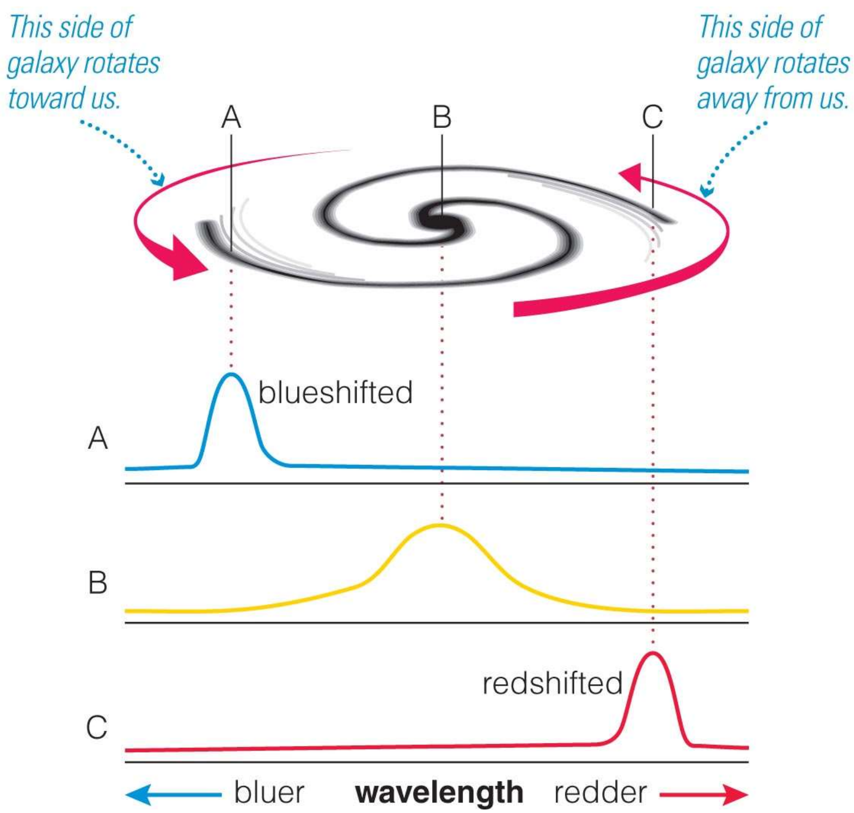
Dark matter: ~ 27%

Dark energy: ~ 68%

What is the Evidence for Dark Matter?

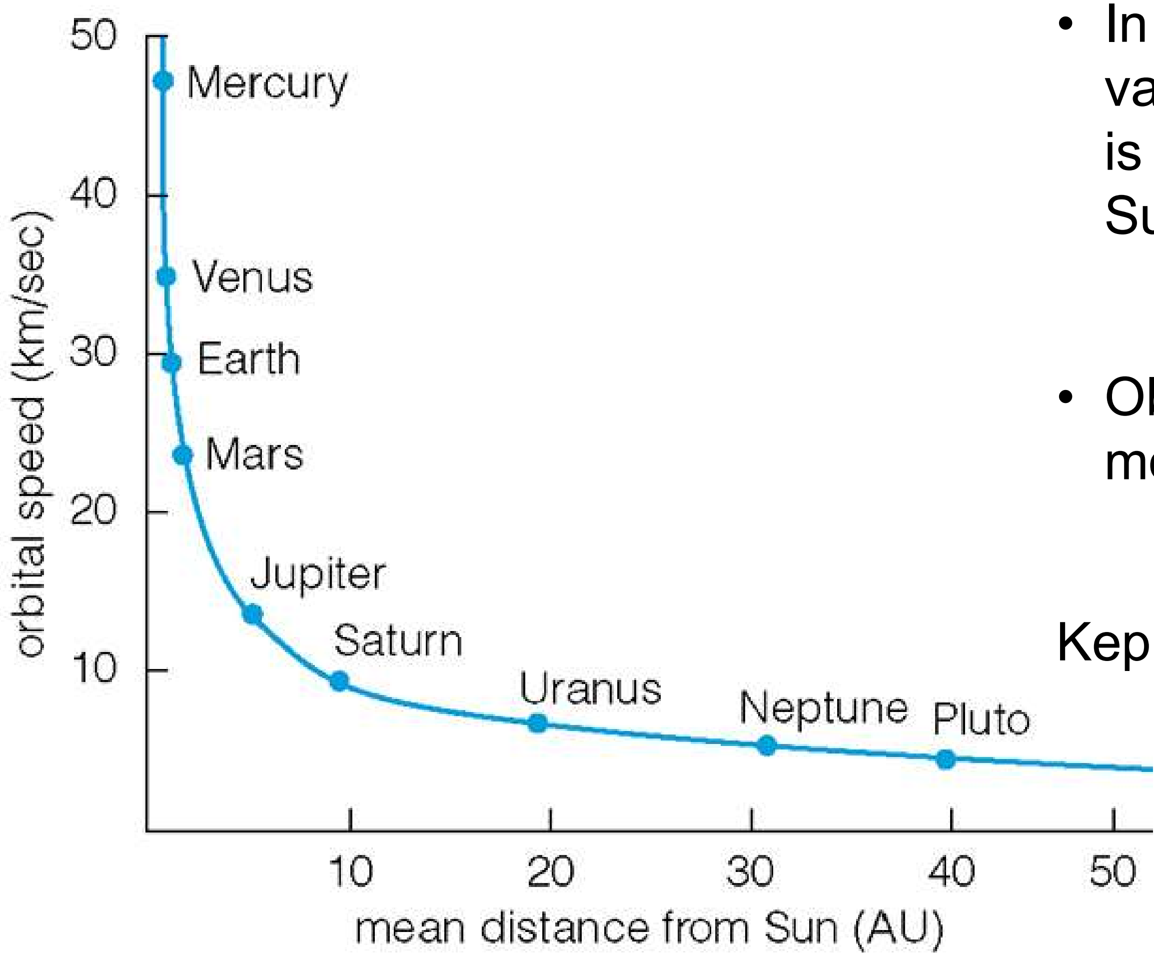
1) Evidence from the Rotational Speeds of Stars within Galaxies
2) Evidence from Gravitational Lensing
3) Evidence from Galaxy Clusters

How can we Measure the Orbital Velocities in Galaxies?



- In our galaxy, we have several methods we can use to trace the orbits of nearby stars or dust clouds
- However, we can only trace stars not blocked by dust towards the galactic center.
- For more distant stars or dust clouds and stars within other galaxies, we use the doppler shift technique on the 21-cm line of atomic hydrogen.

Recap: Orbital Velocities in Our Solar System



- In our Solar System, the vast majority of the Mass is contained within the Sun.
- Objects closer to the Sun move faster in their orbits.

Kepler's 3rd Law:

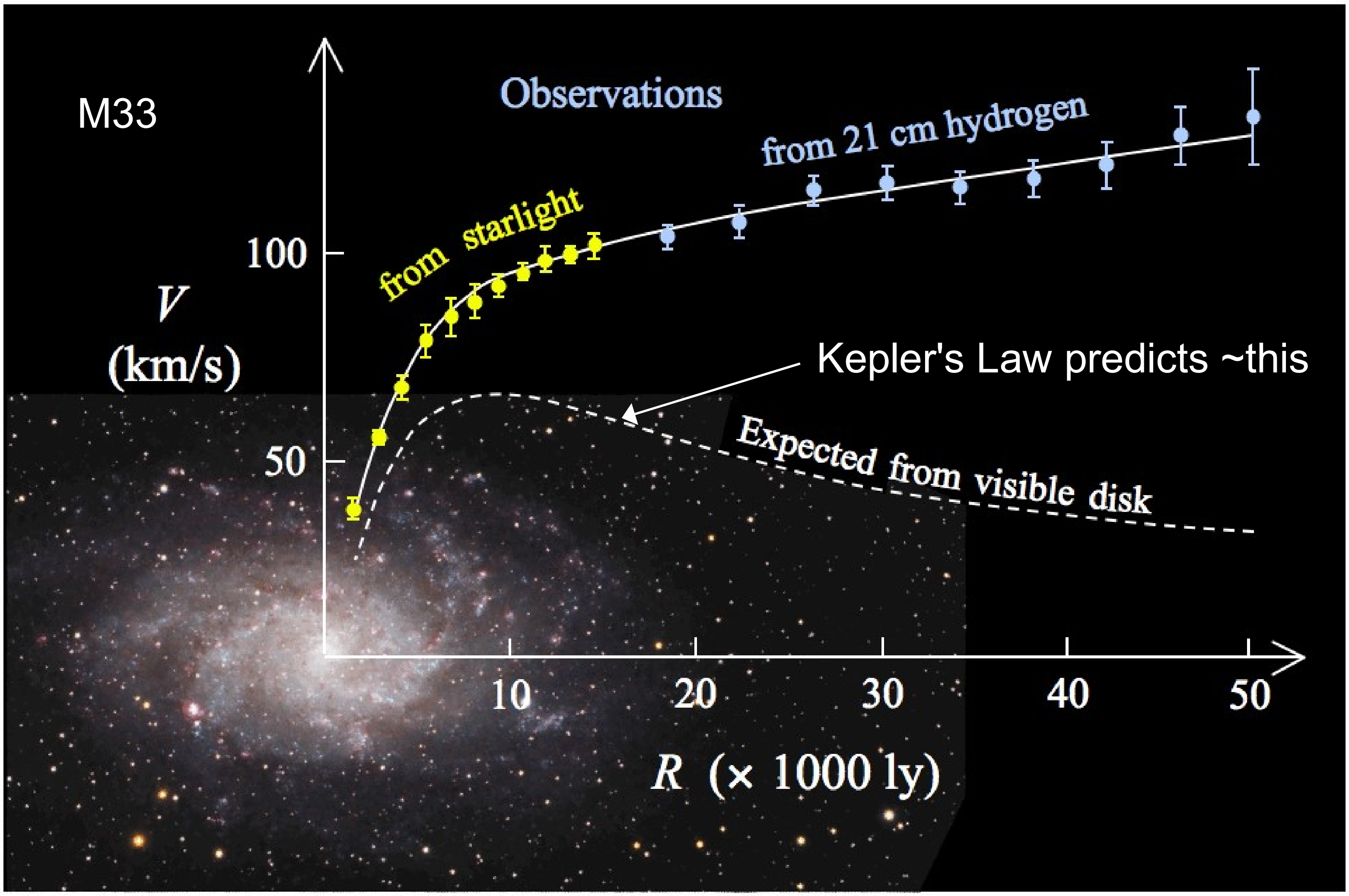
$$p^2 = a^3$$

Thought Question

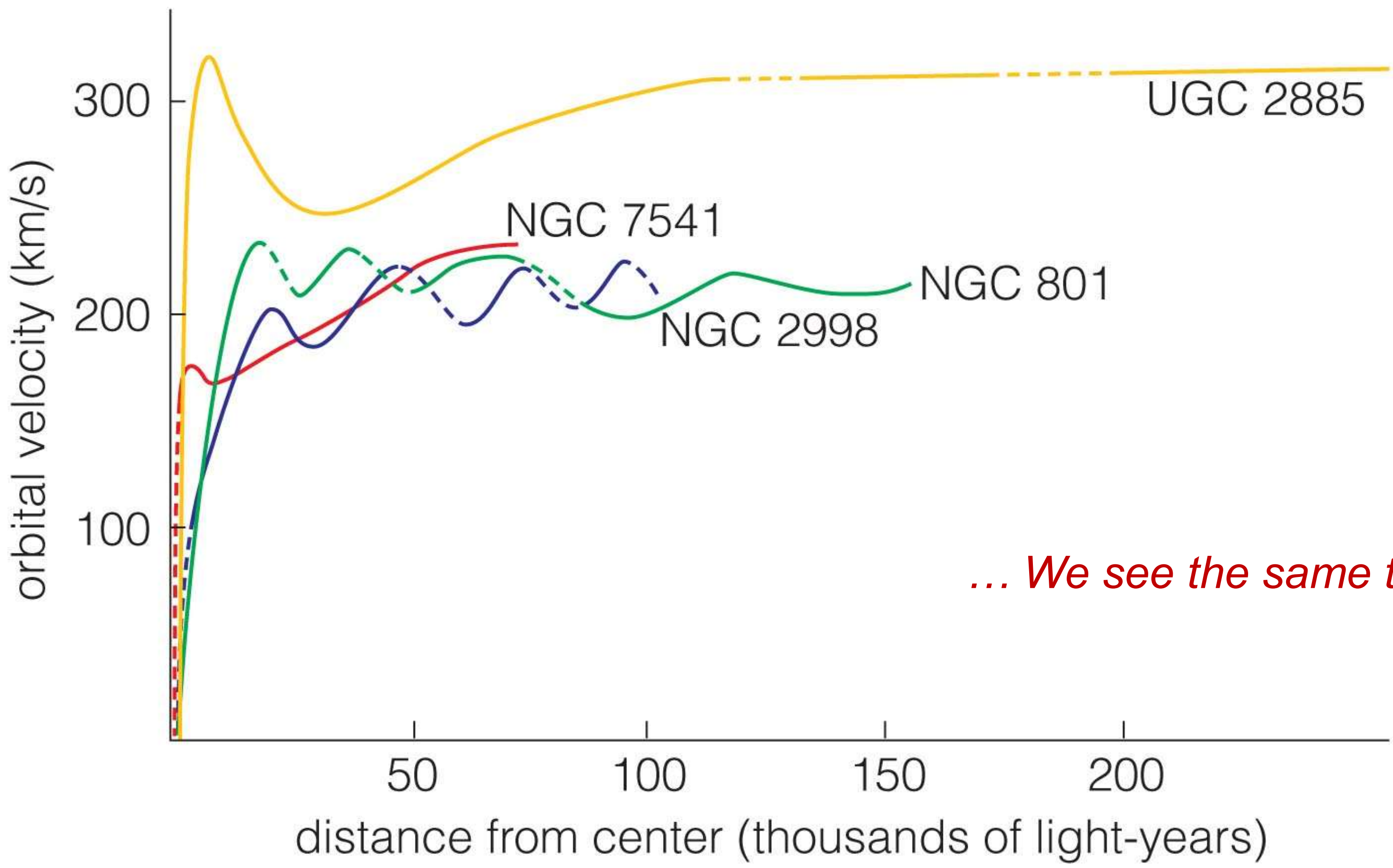
Remember those ‘merry-go-rounds’ we used to enjoy getting thrown from when we were younger?

How does the orbital velocity change as a function of distance from the center?

What do we observe when we look at a Galaxy?

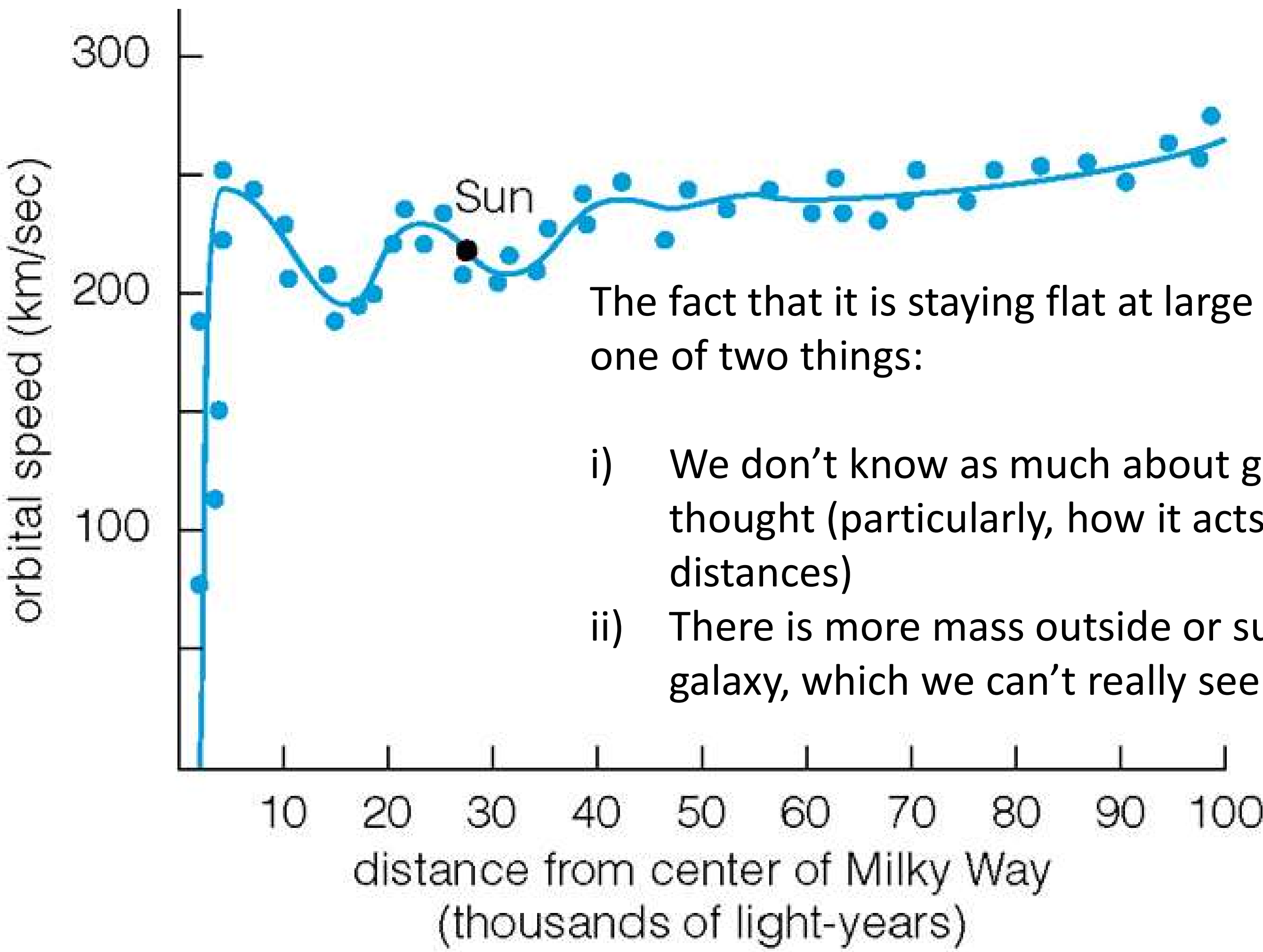


How about when we look at other Galaxies?



… We see the same thing!

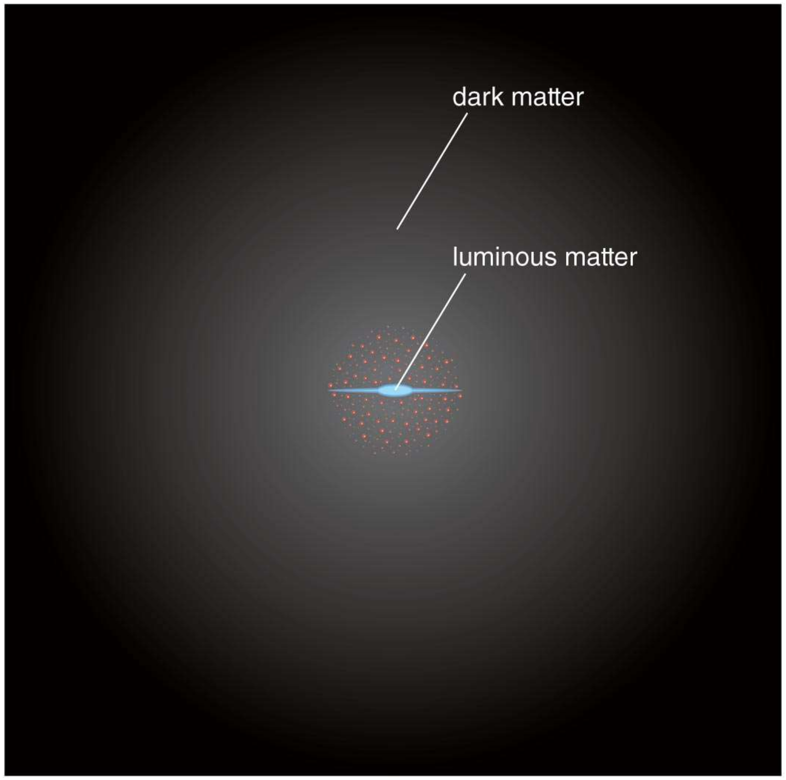
Even for the Milky Way?

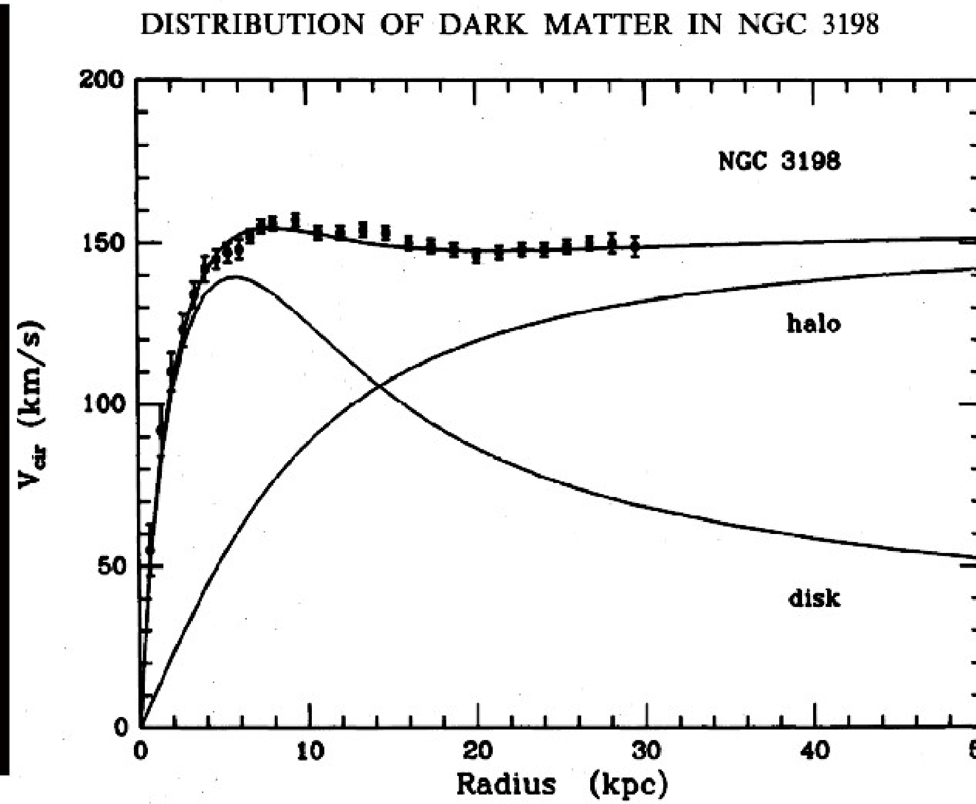


The fact that it is staying flat at large distances implies one of two things:

i) We don’t know as much about gravity as we thought (particularly, how it acts over large distances)
ii) There is more mass outside or surrounding our galaxy, which we can’t really see…

Most of the Mass of Galaxies are Found in an Extended Halo Region





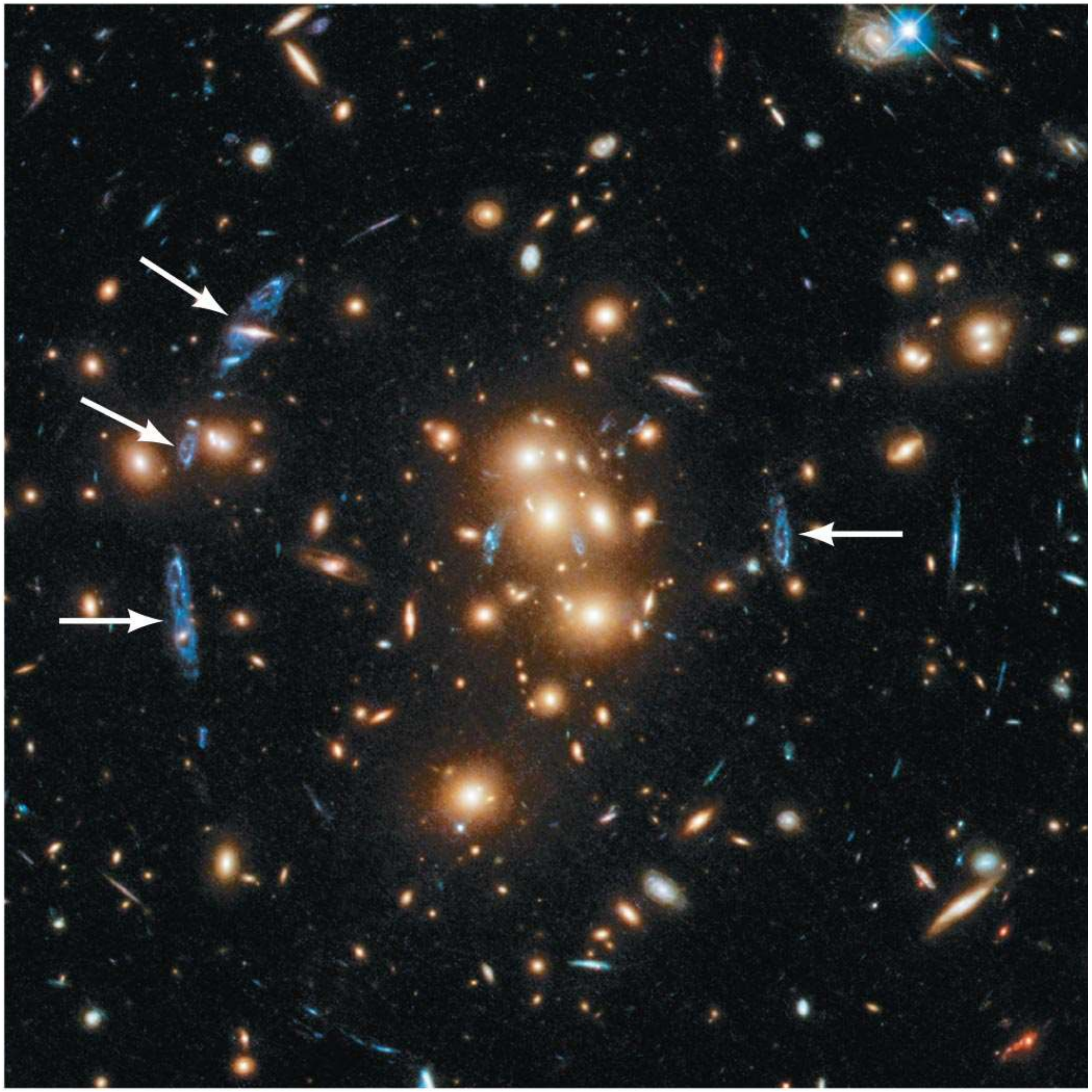
- The amounts of Dark matter required in Galaxies to explain their rotational velocities varies from **0%** dark matter to ~400× the amount of normal matter.
- The Milky Way appears to have 10× more matter than we can account for (so ~90% dark matter), although we can't find any evidence for it close to our Solar System (within a factor of 2; 50% max)

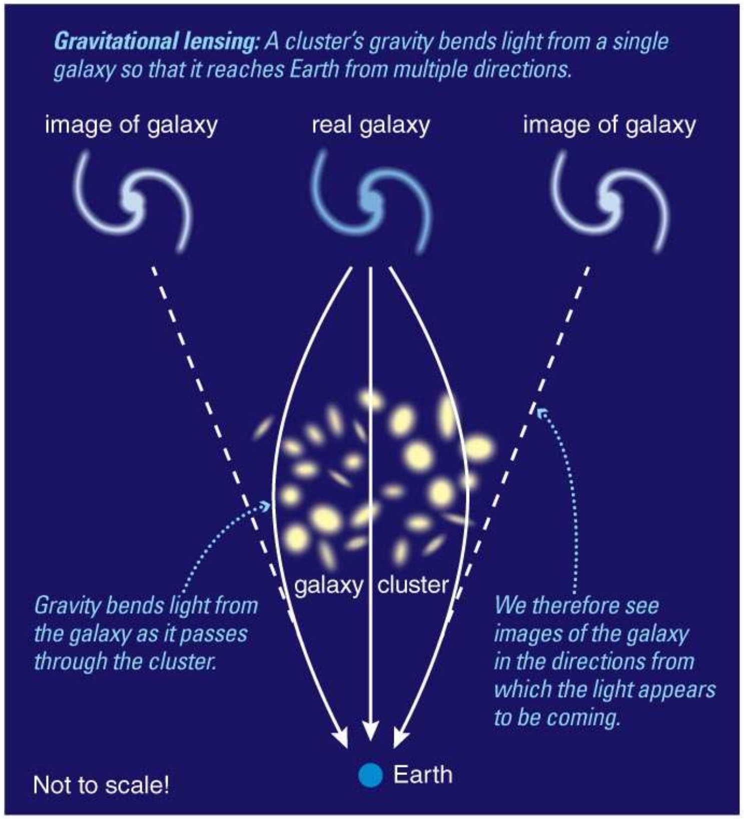
The Mass-To-Light Ratio

Most of our estimates of mass come from the amount of light emitted from stars, or dust clouds, for example, since most matter gives off some level of light.

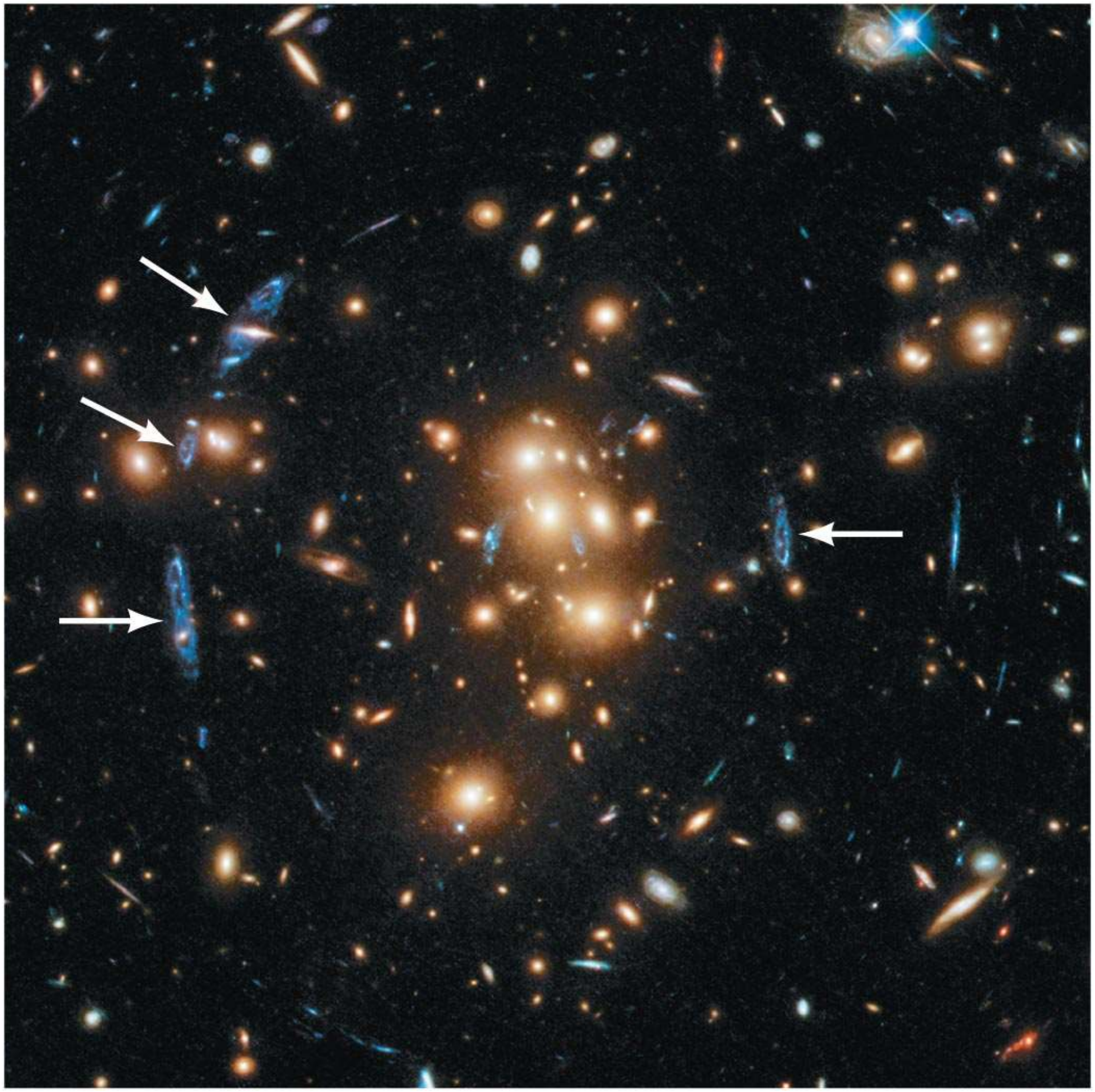
Type of Object	Mass-to-Light Ratio
The Sun	1
Matter near our Solar System	<2
The Milky Way	10
Small Groups of Galaxies	50-150 (and one with ~zero)
Rich Clusters of Galaxies	250-300

Evidence from Gravitational Lensing





Evidence from Gravitational Lensing



Here, the same galaxy that lies behind this cluster can be seen multiple times as the cluster is bending space-time…

If we calculate the mass of the material within the cluster, it falls short of the amount required to bend light by the degree we see it.

By a factor of ~50.

Therefore, there is around 50× the amount of dark matter to normal matter in this cluster…

Evidence from Galaxy Clusters

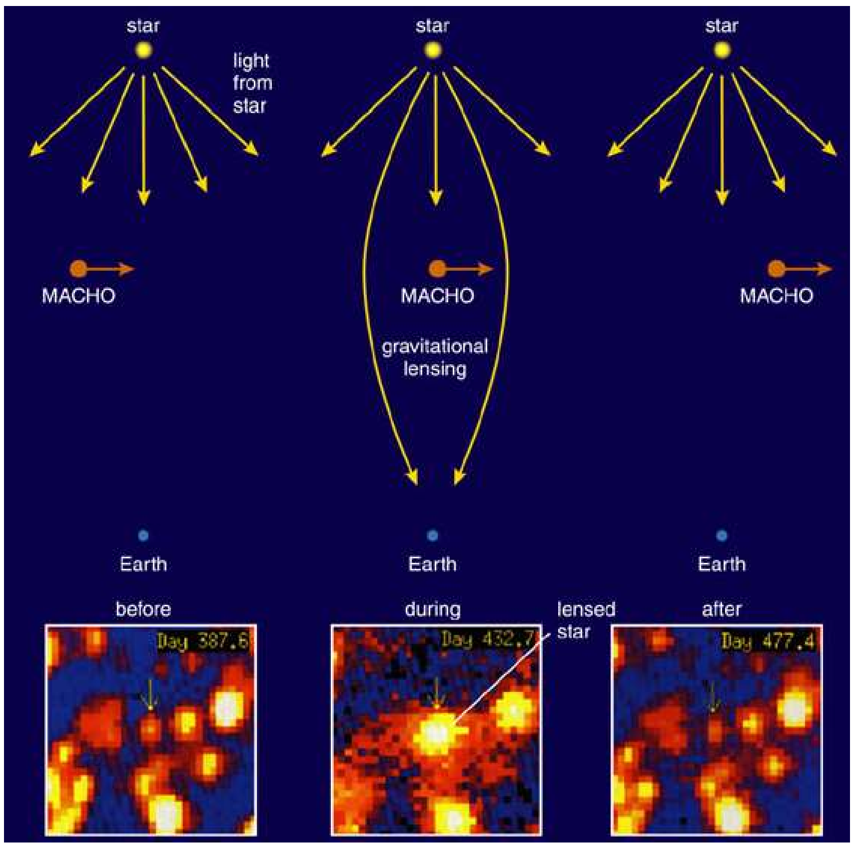
Evidence from Galaxy Clusters

- Bullet cluster has most of the mass in the two blue regions which are clusters of galaxies.
  - These clusters have actually collided…
- The pink/red region is all of the gas which is emitting large amounts of X-rays
- In the case of the Bullet Cluster, gravitational lensing also tells us that the majority of the mass is in the gas between the clusters
- The temperature these gases must be to emit so much X-ray light (from friction) as well as gravitational lensing inform us of the make-up of the gas…

  - 13% hot gas
  - 2% stars
  - 85% dark matter

What is Dark Matter?

Option 1: Massive Compact Halo Objects (MACHOs)



Could the Halo region of galaxies be filled with black holes, and extinct brown dwarfs and white dwarfs (black dwarfs, that no longer emit any light)?

Gravitational Lensing has been used to search for these objects passing in front of stars, with some success.

→ But the number of observations are too few to account for the mass required to explain the observations…

What is Dark Matter?

Option 2: Weakly Interacting Massive Particles (WIMPs)

We are already somewhat familiar with a weakly interacting particle…

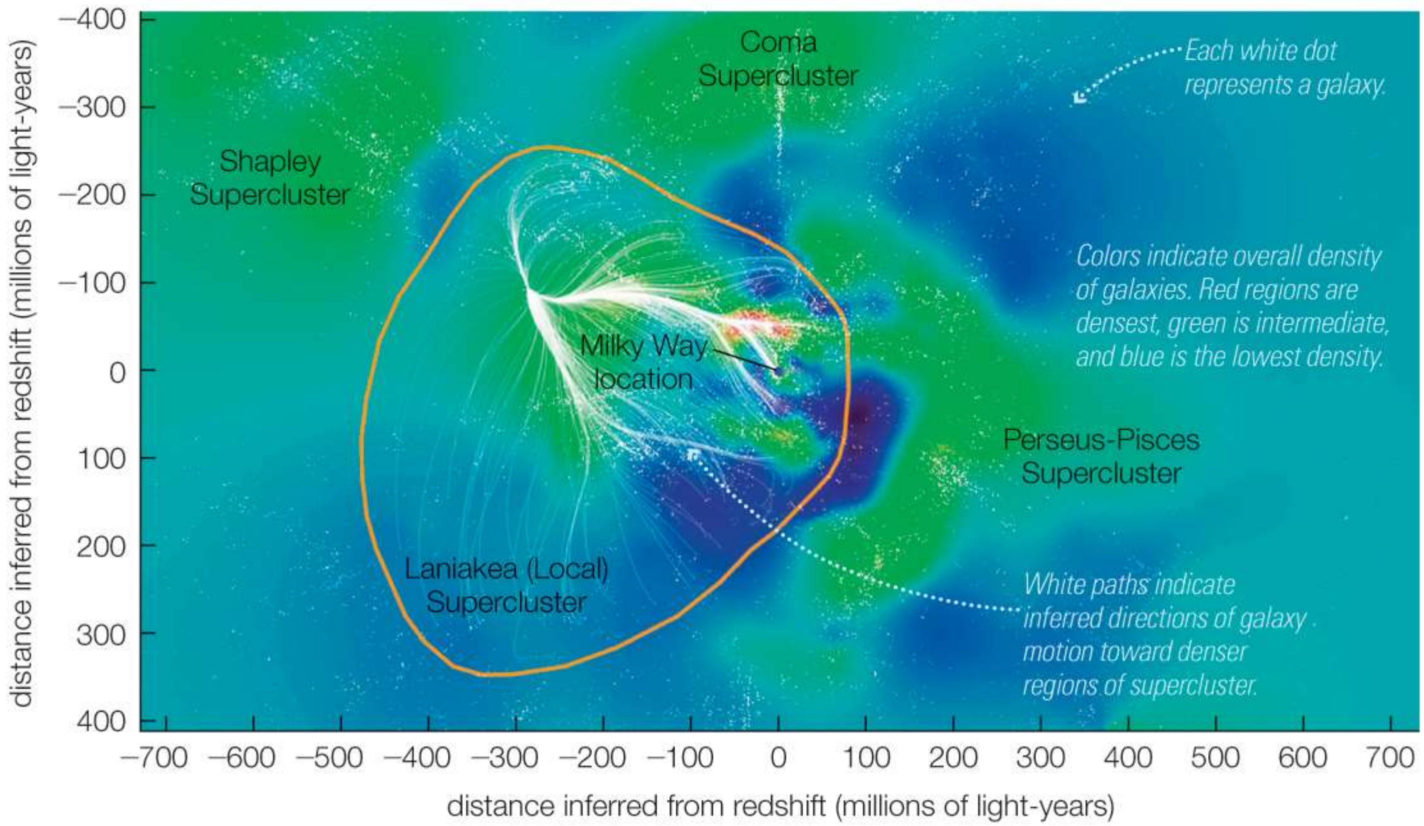
Neutrinos (not massive!)

- Do not seem to interact with photons at all
- Has no electric charge
- Only interacts through weak nuclear force and gravity
  - Pass through most matter almost undisturbed
  - Travel close to the speed of light
- Very difficult to detect!

However, it is possible that during the early stages of the big bang, some exotic particles that are weakly interacting, but have high mass could have been formed.

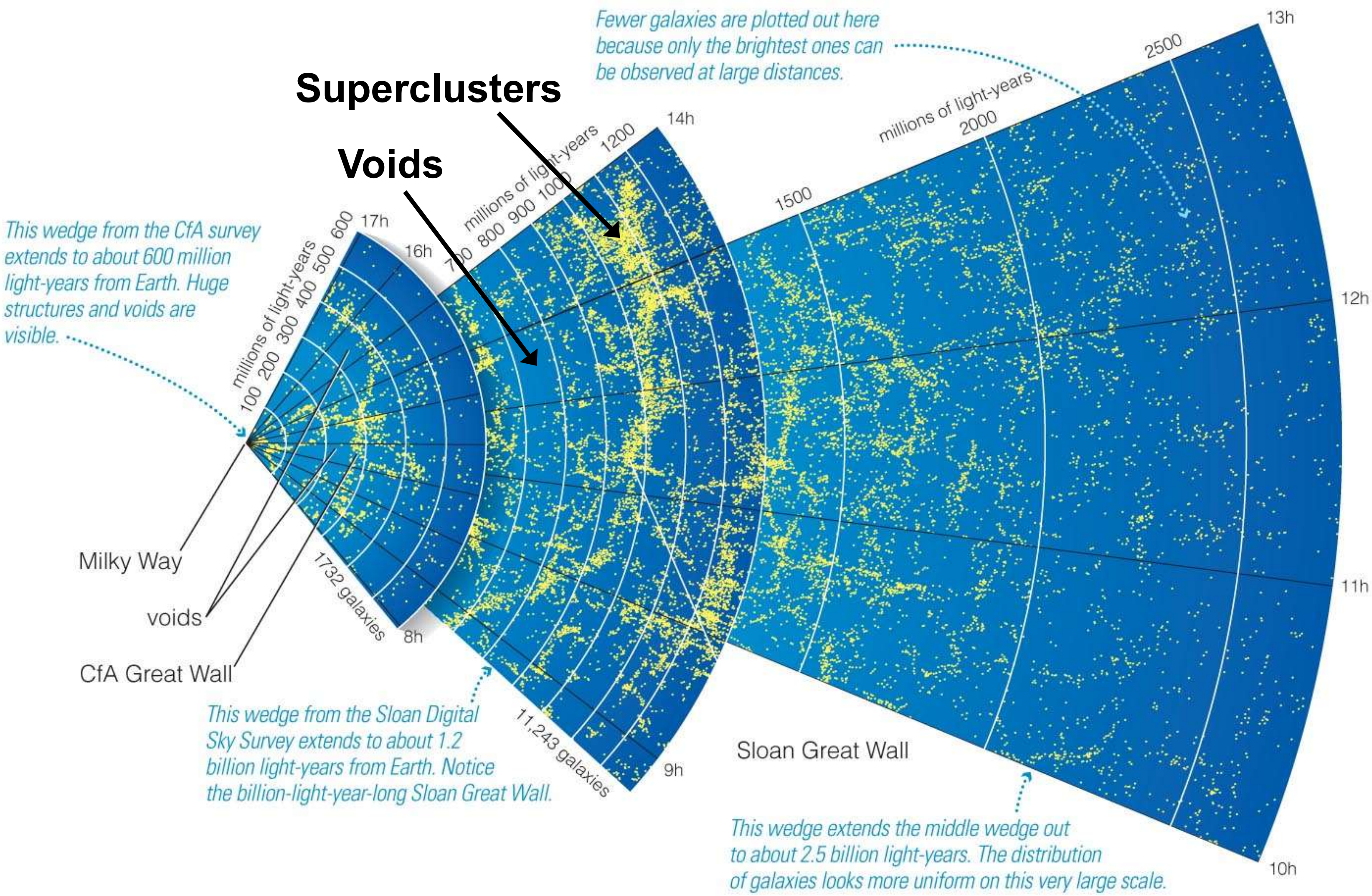
We have already identified one such particle: The Higgs Boson…

The Role of Dark Matter on the Structure of the Universe

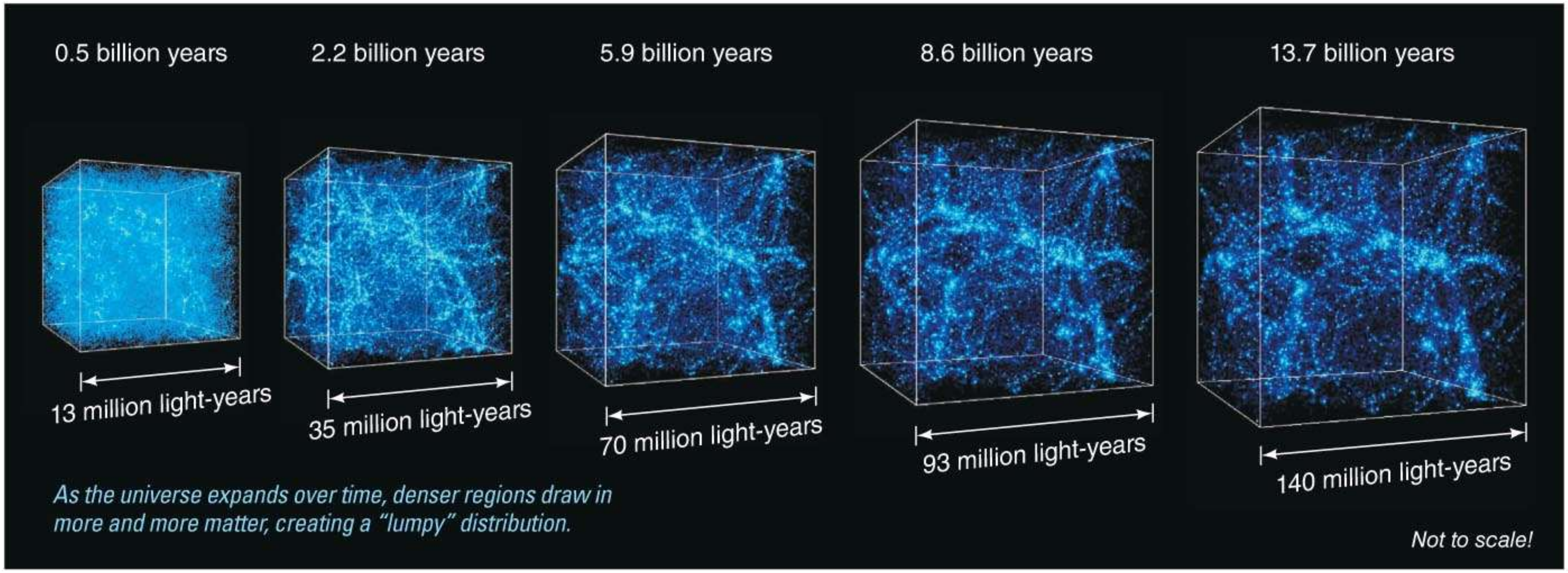


- Dark matter is still pulling things together.
- After correcting for Hubble's law, we can see that galaxies are flowing toward the densest regions of space.

Locations of Nearby Galaxies Determined from Red-Shifts

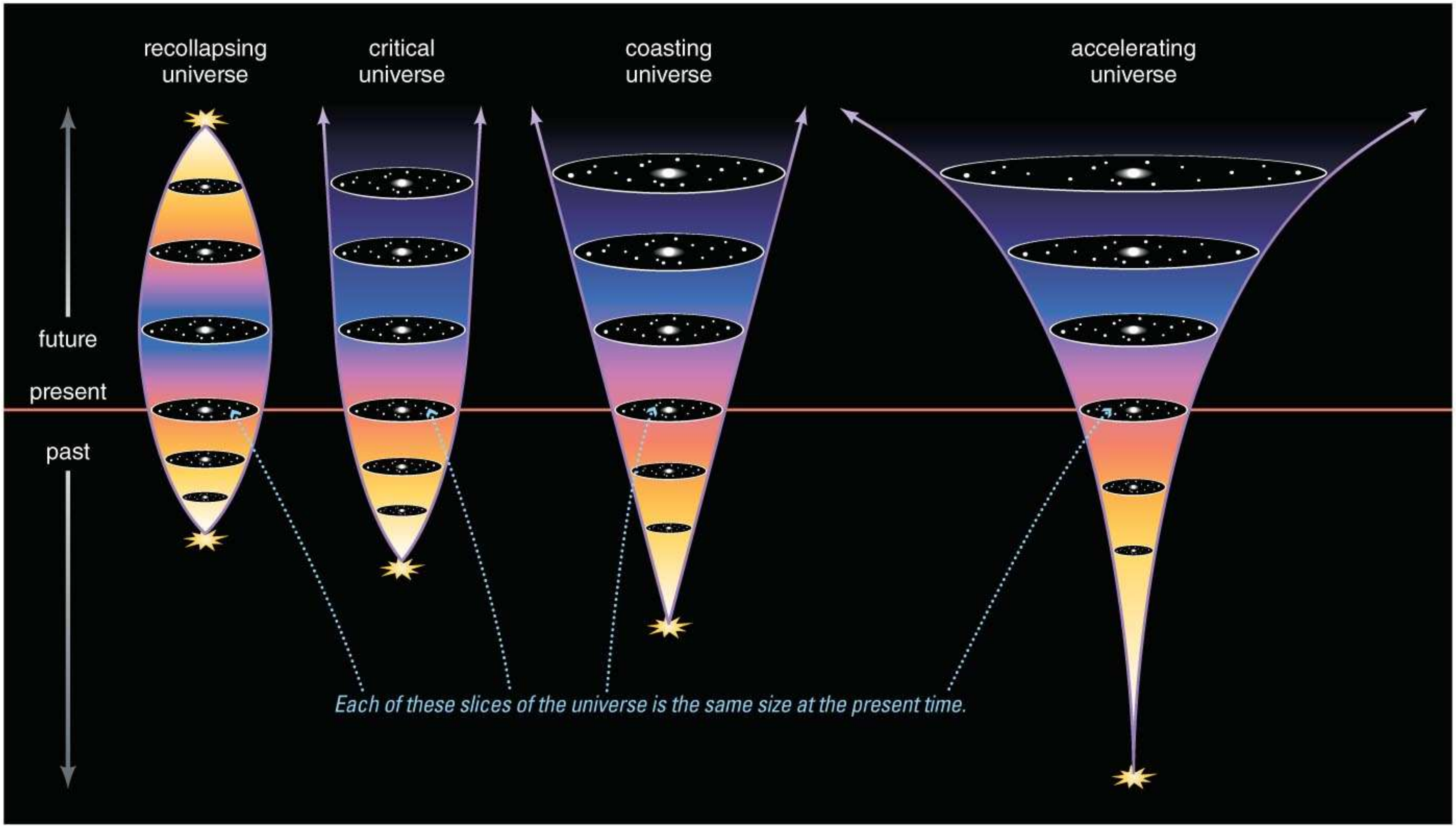


Simulations of Galaxy Evolution Require Dark Matter

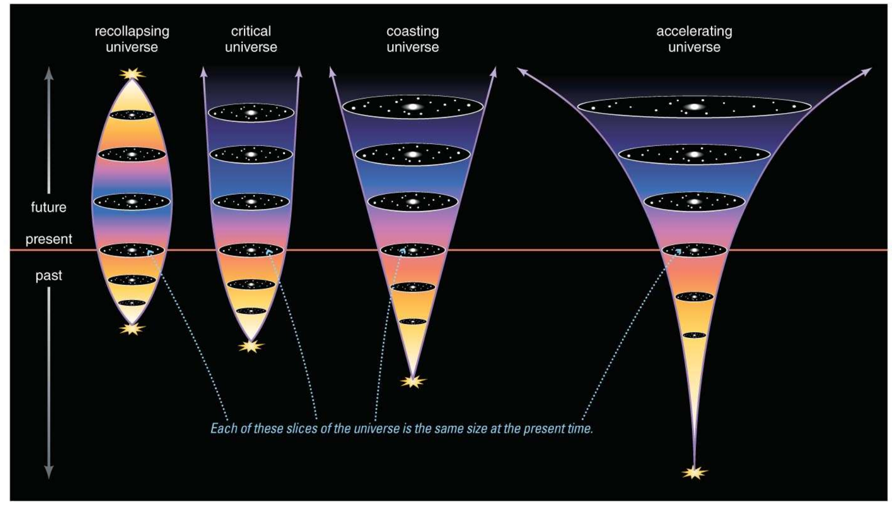


- Models show that the gravity of dark matter pulls mass into denser regions—the universe grows lumpier with time.
- Require dark matter to reproduce filament-like structure of the observed universe (these models usually incorporate WIMPs!)

What is the Fate of the Universe?



What is the Fate of the Universe?



A recollapsing universe: If the gravitational attraction is sufficiently strong, then eventually all of the matter will come back together under the "Big Crunch"

A critical universe: The forces are sufficient to slowly decelerate the universe where it no longer expands or contracts.

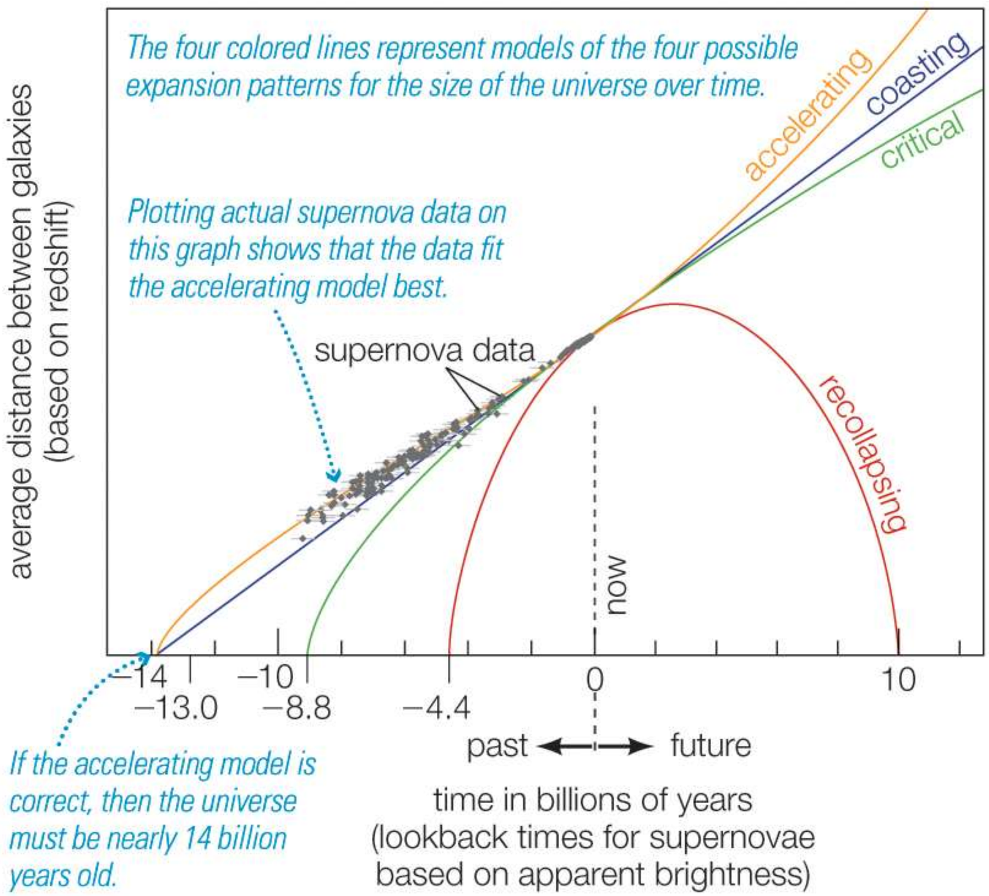
A coasting universe: The universe would continue expanding as if no further forces are acting on it

An accelerating universe: Some mysterious force is causing the expansion to increase with time.

Critical density: The required average density of space needed to meet the case of the critical universe… (roughly 10^{-27} kg/m^3), If the density is higher than this, the universe would collapse, whereas if it is less than this, the universe would expand

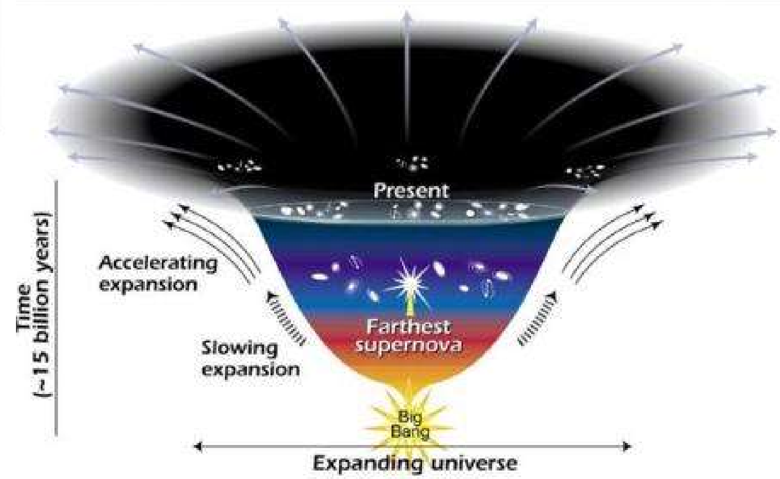
→ $E=mc^2$ counts… spoiler: We would need 73% dark energy to reach critical density

An Accelerating Universe?



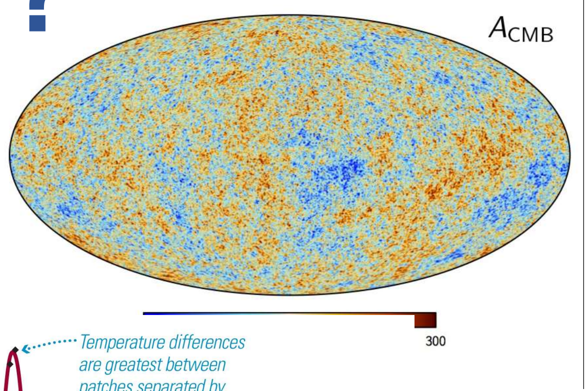
Observations of supernova 1a explosions favor an accelerating universe…

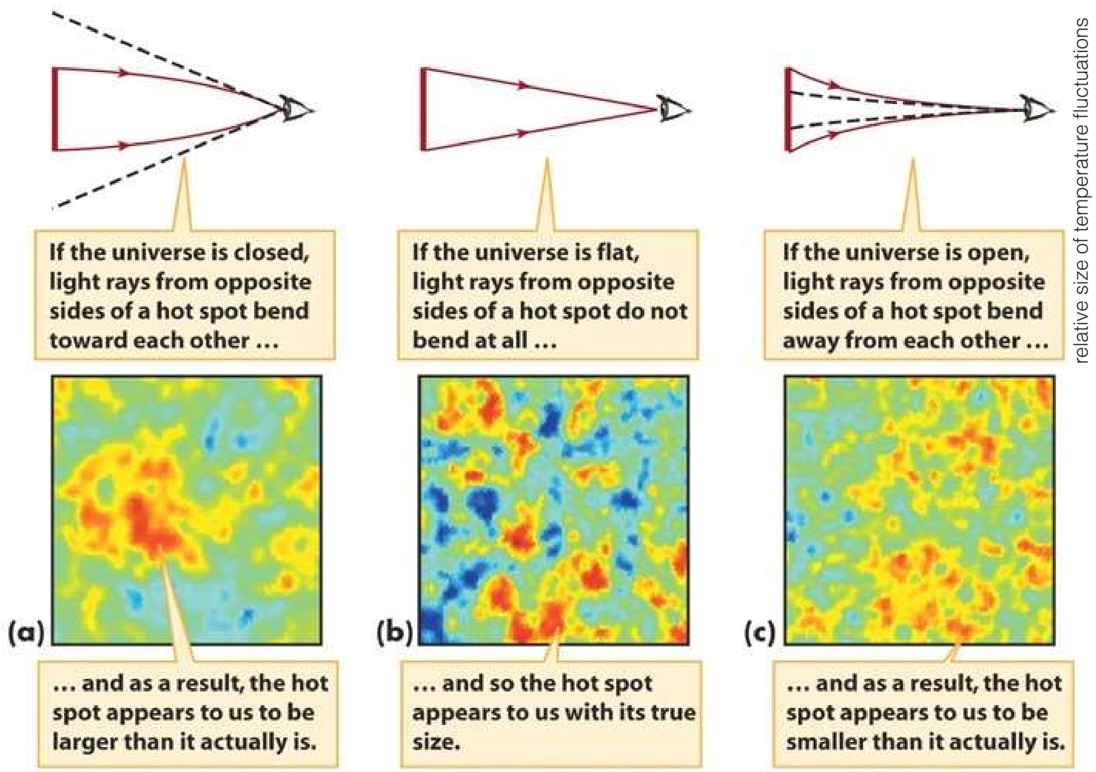
(Also need to account for inflation which was a period early on where the expansion was much more rapid)

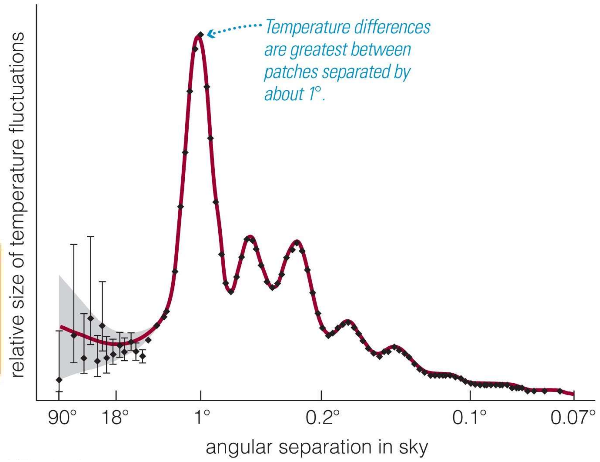


What is Dark Energy?

→ **We have no idea…**

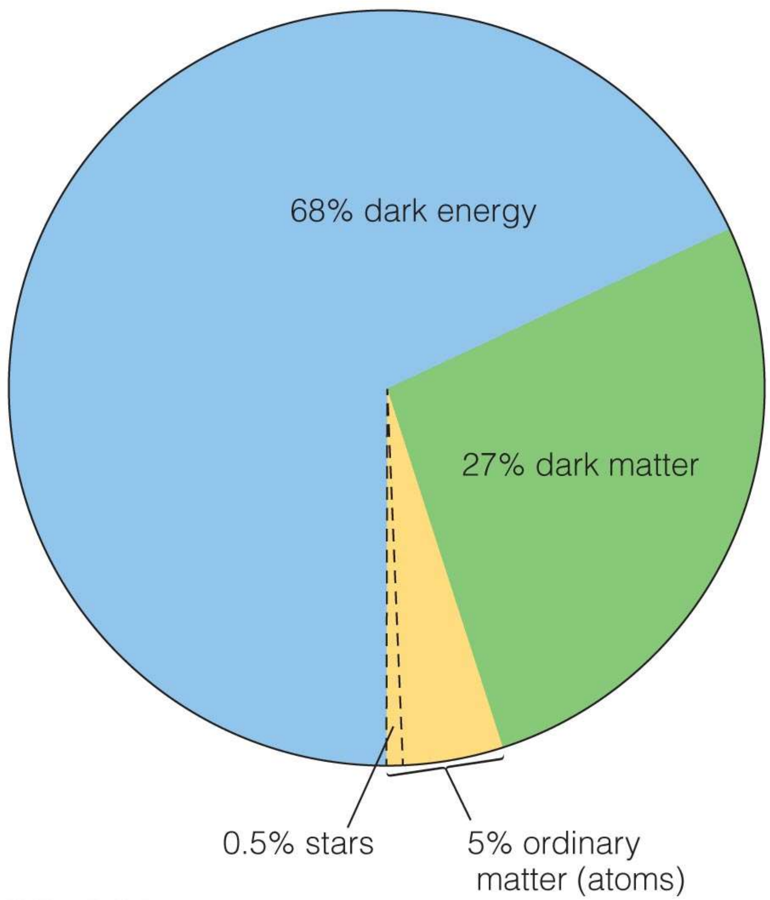






But it is necessary to explain why the universe appears 'flat' in spacetime, and that the Universe is expanding

What is the Current Understanding of What the Universe is Made of?



Observations tell us that the density of the universe is equal to the critical density, but we can only account for 30% of that with matter!

We therefore can conclude that:

- The age of the Universe is 13.799 ± 0.038 billion years
- Hubble constant is 67.31 ± 0.96 kilometers/second/million parsecs
- Fraction of the Universe that is Matter: 31.5 ± 1.3 %
- Fraction of the Universe that is "Dark Energy": 68.5 ± 1.3 % *(less than 73% because the Universe is expanding)*

End of Todays Lecture