

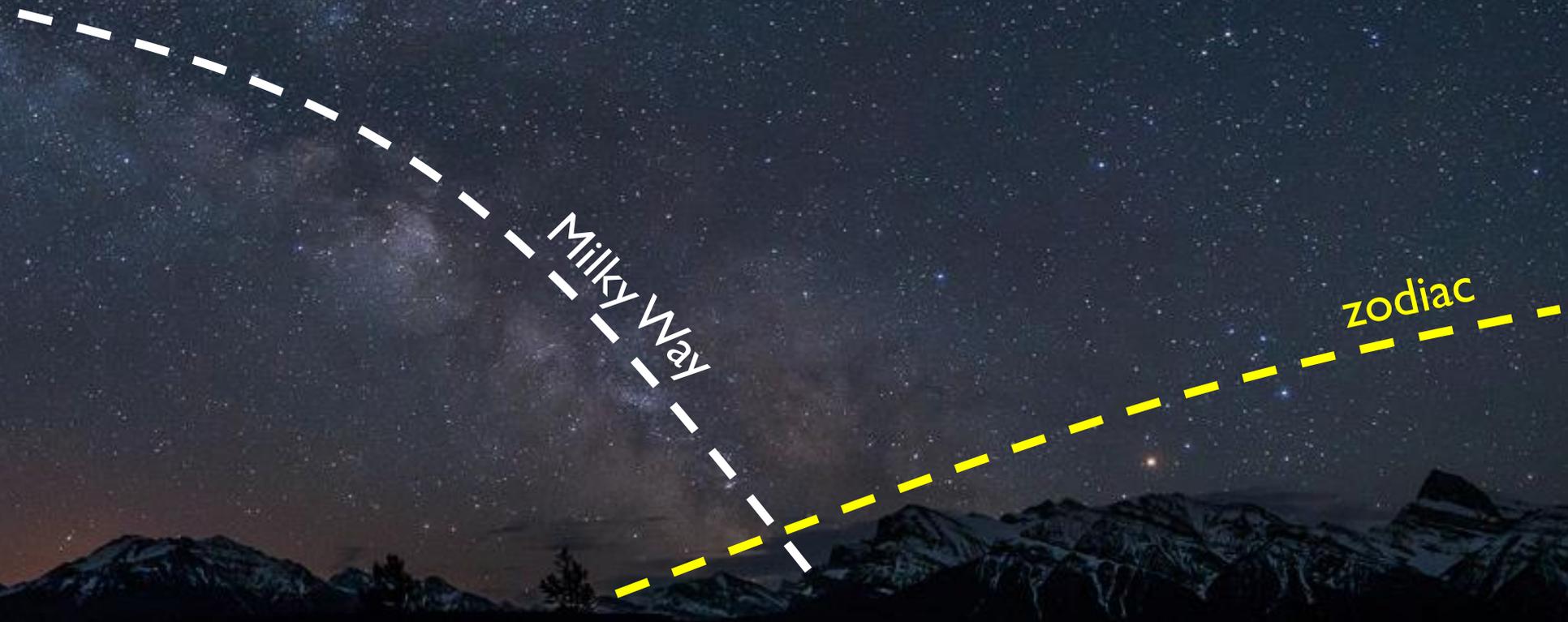
Our universe's story

from *chaos* to *cosmos*

Stephen Portillo
Zachary Slepian
Kate Alexander

Harvard University Department of Astronomy
Harvard-Smithsonian Center for Astrophysics

The Cosmos

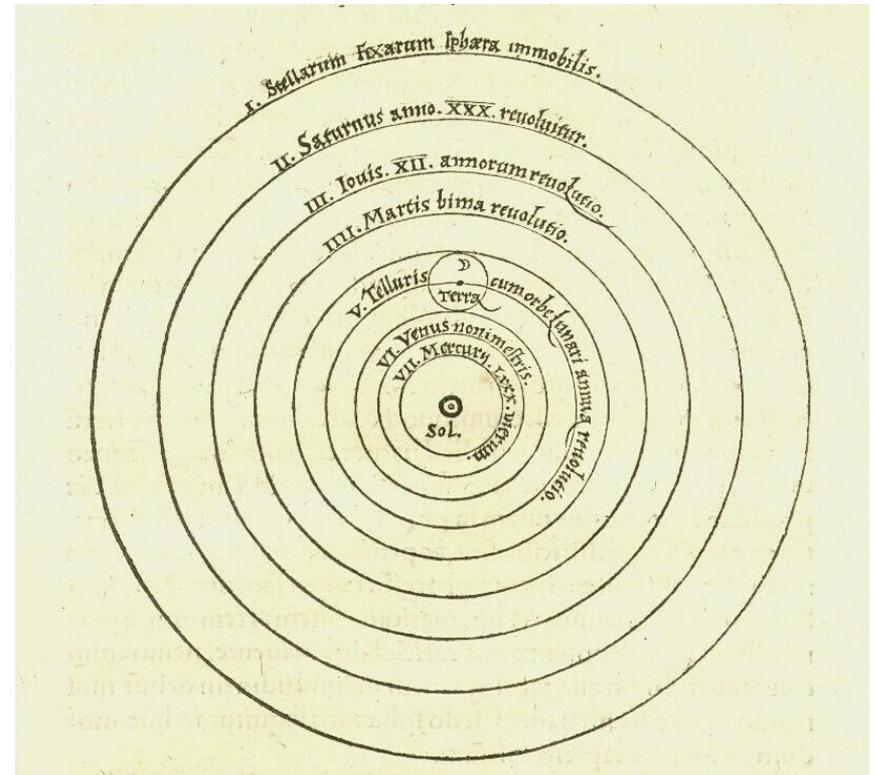


Copernican Revolution (c. 1600)

Uraniborg Observatory and Tycho Brahe

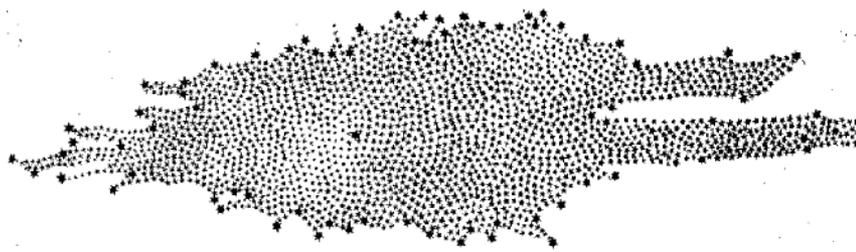


Heliocentric Solar System

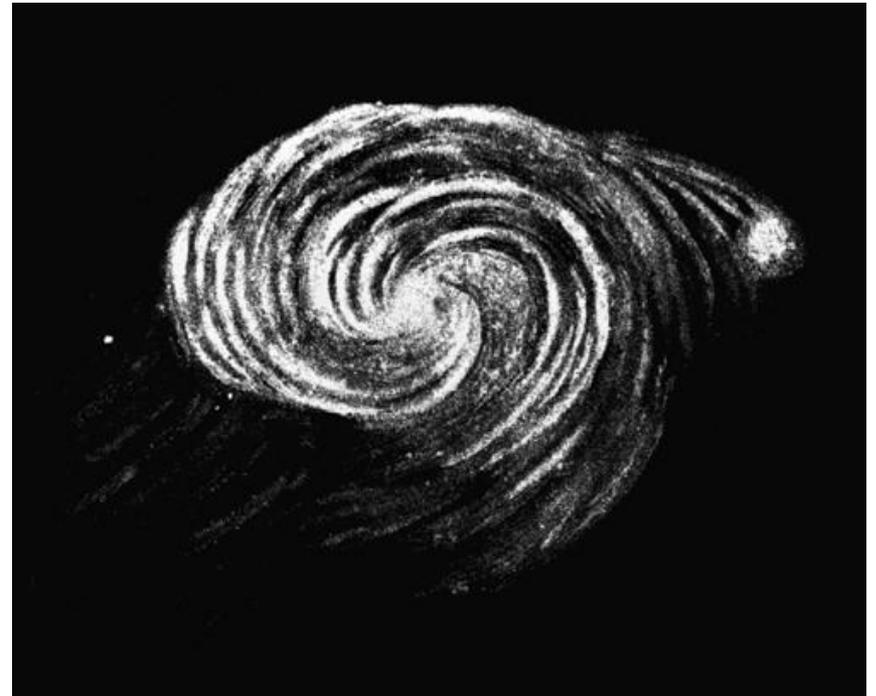


Galaxies and Nebulae (c. 1800)

Milky Way is a galaxy

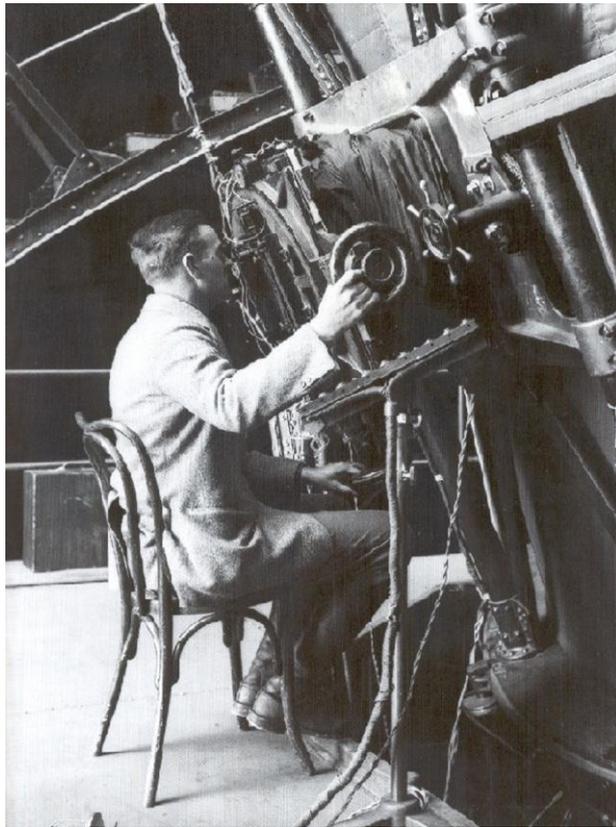


What are spiral nebulae?

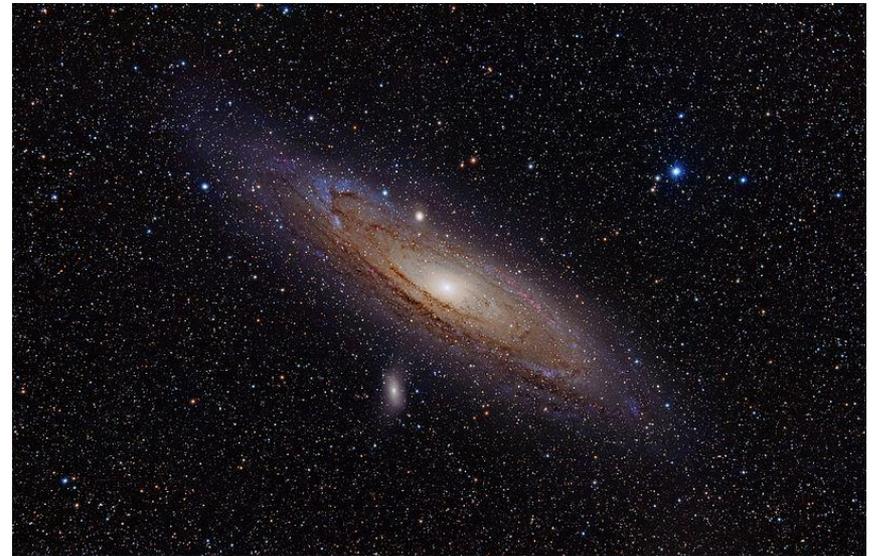


Shapley-Curtis Debate (c. 1920)

**Mt. Wilson Observatory
and Edwin Hubble**



Spiral nebulae are galaxies



The Big Bang Cosmology



Part III:
Inflation



Part II:
Growth of Structure
+ Galaxy Clustering



Part I:
State of the Cosmos

hot + dense
nearly formless
chaos

cool + sparse
structured
cosmos

Our universe's story

Part I: State of the Cosmos

Stephen Portillo

State of the Cosmos

- 1. The universe is expanding**
2. Galaxies are arranged in structures
3. These structures are made of dark matter

Hubble's Law

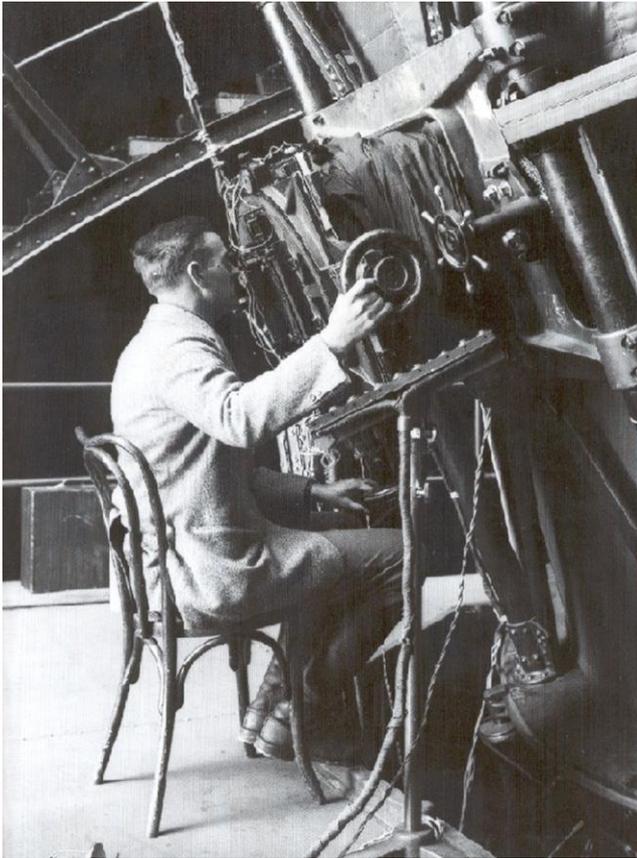
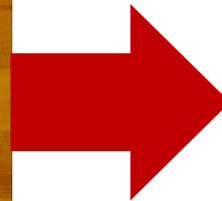


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

The Universe is Expanding

hot and dense



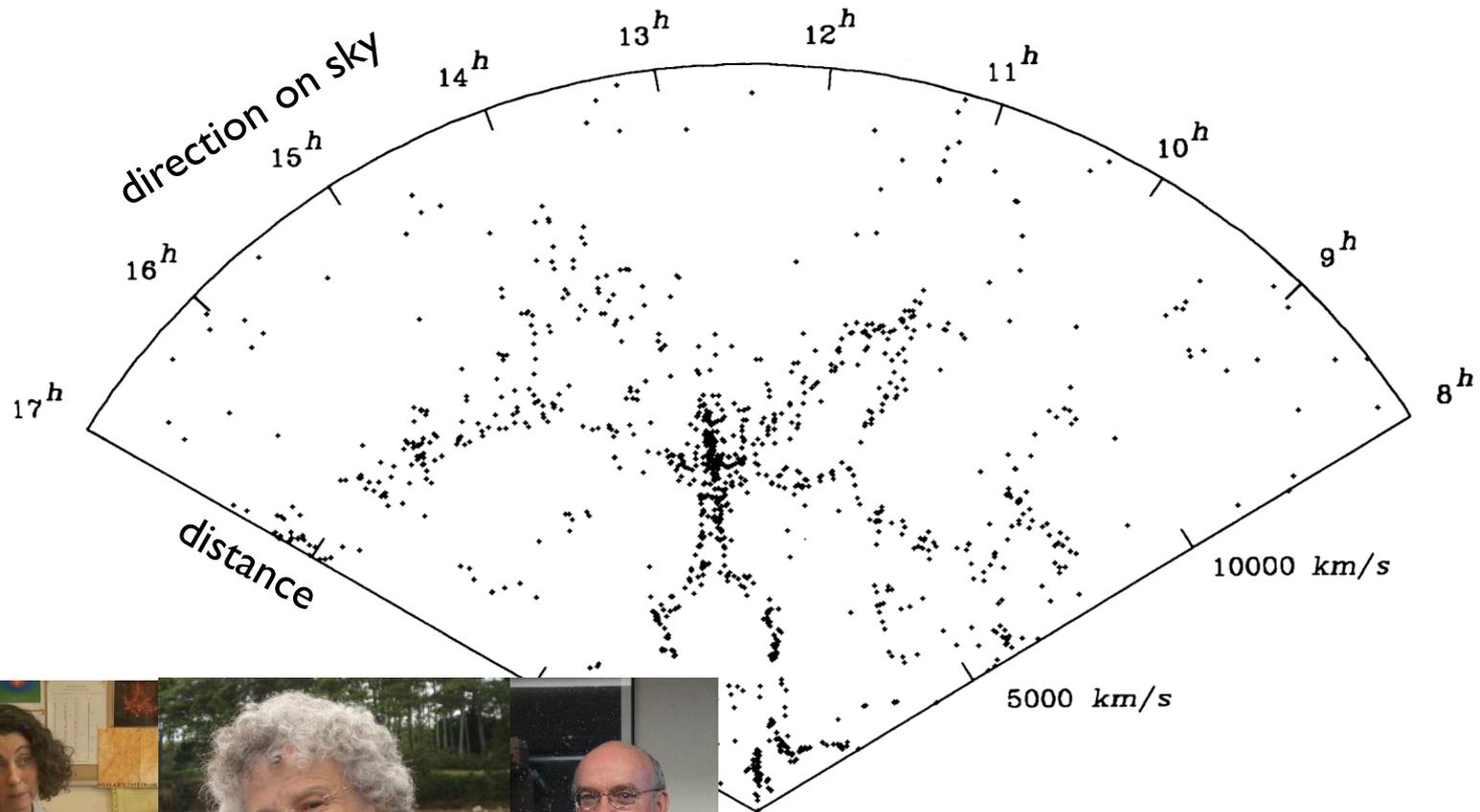
cold and sparse



State of the Cosmos

1. The universe is expanding
2. **Galaxies are arranged in structures**
3. These structures are made of dark matter

The Distribution of Galaxies



CNRS, Margaret Geller, John Huchra de Lapparent, Geller, and Huchra (1986)

Questions?

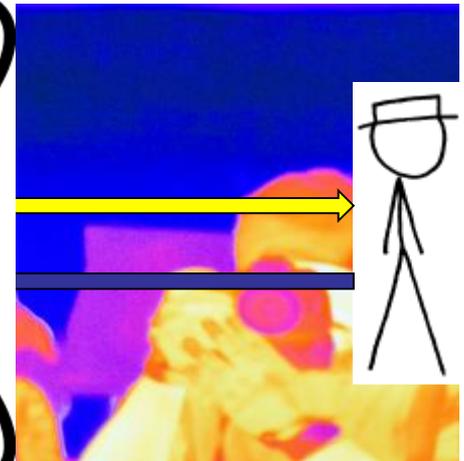
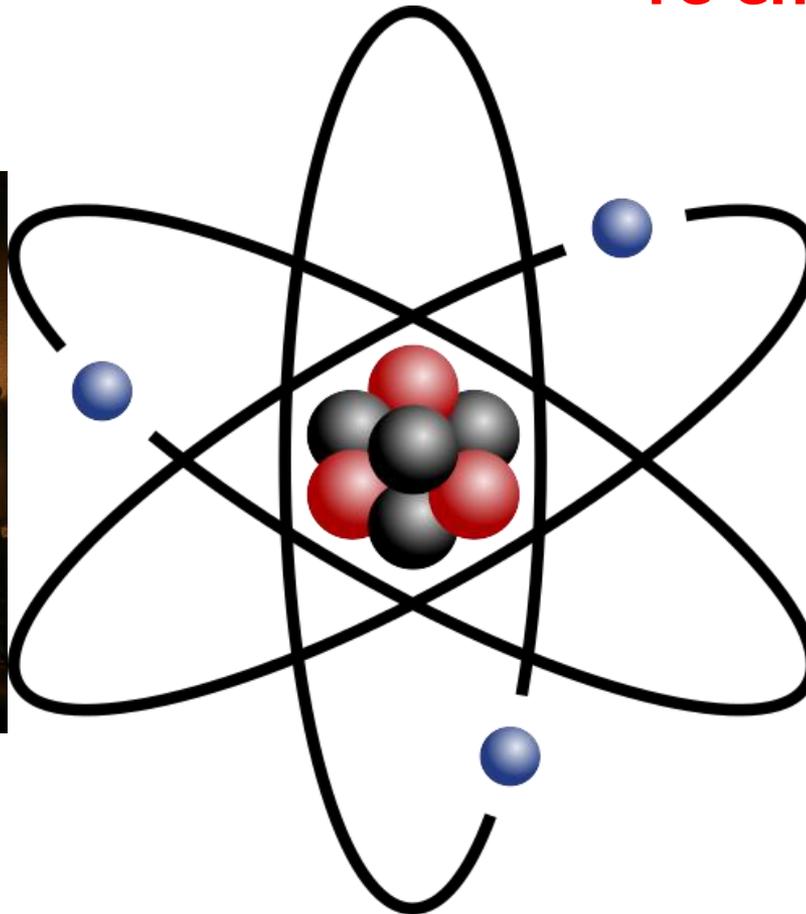
State of the Cosmos

1. The universe is expanding
2. Galaxies are arranged in structures
3. **These structures are made of dark matter**

Baryonic (Visible) Matter

emits light

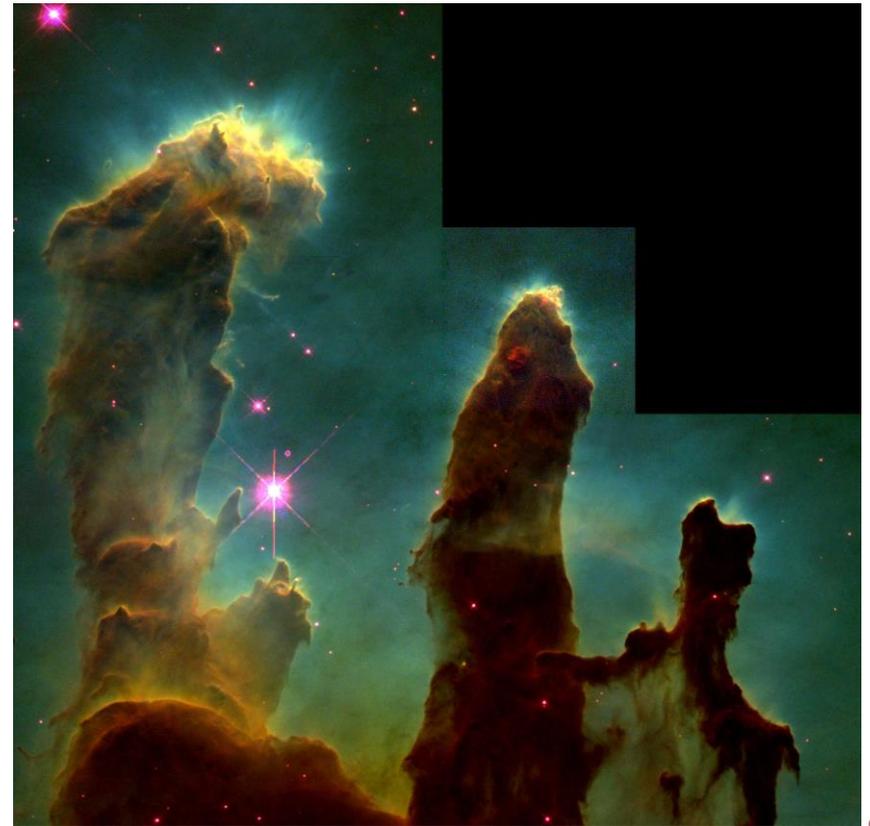
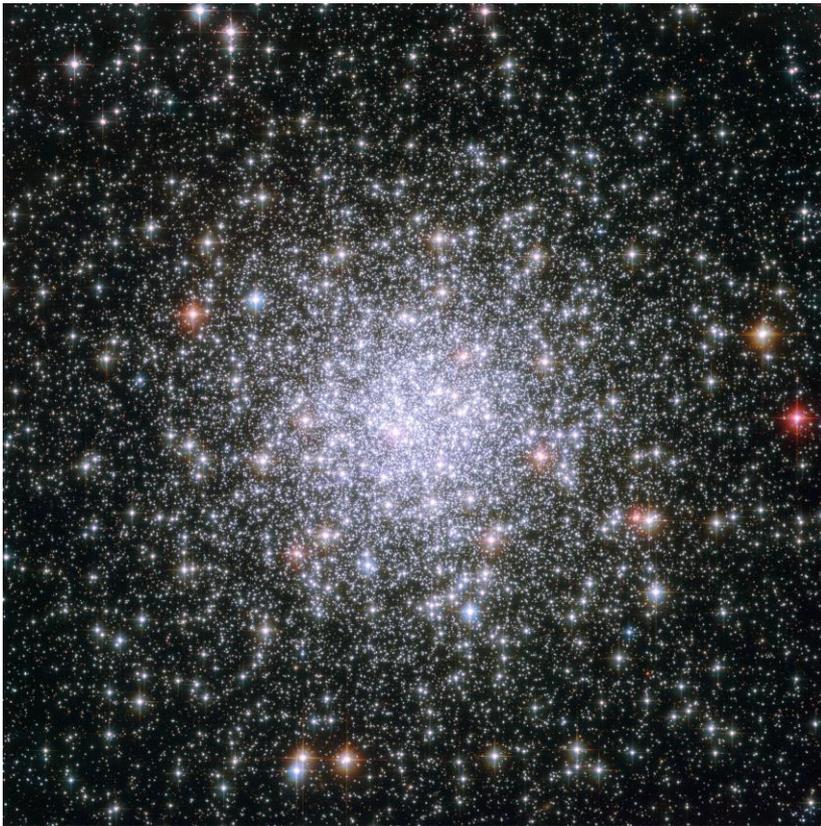
reflects & absorbs light
re-emits light



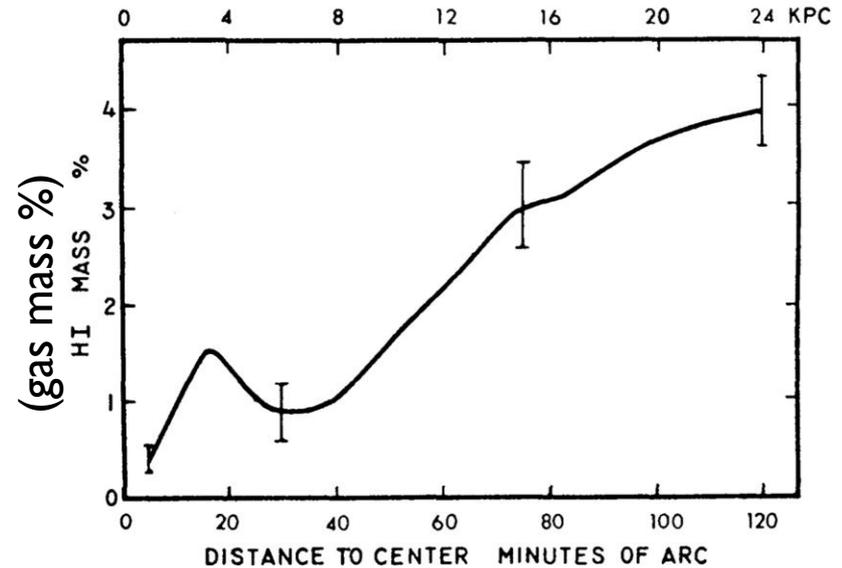
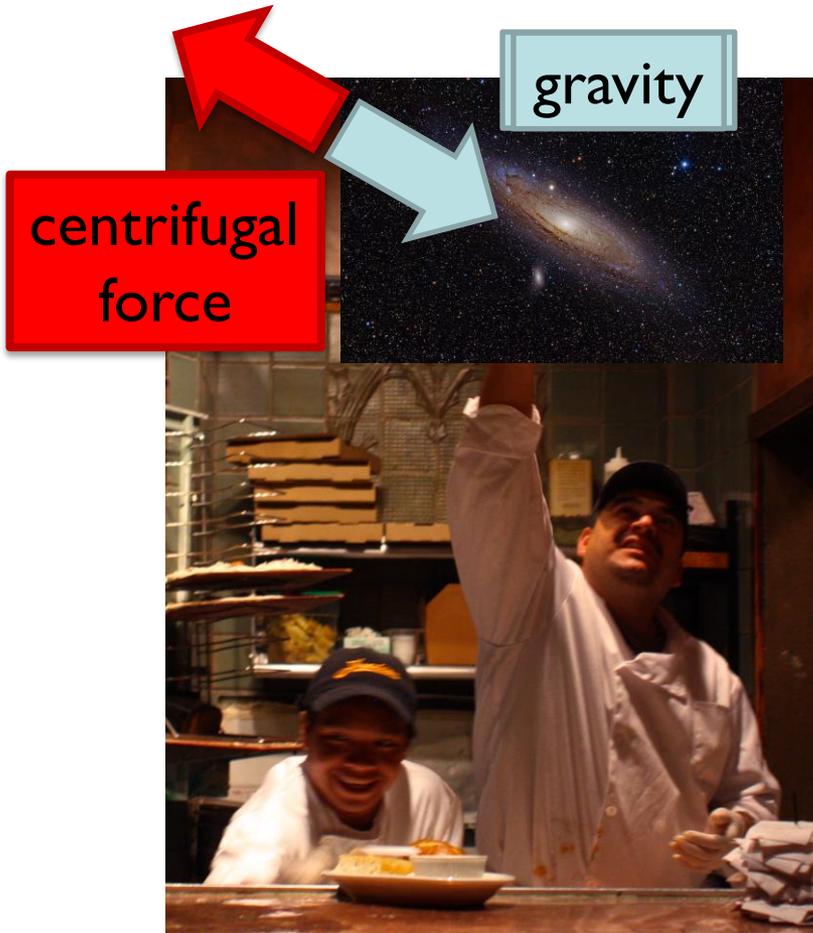
Visible Matter

emits light

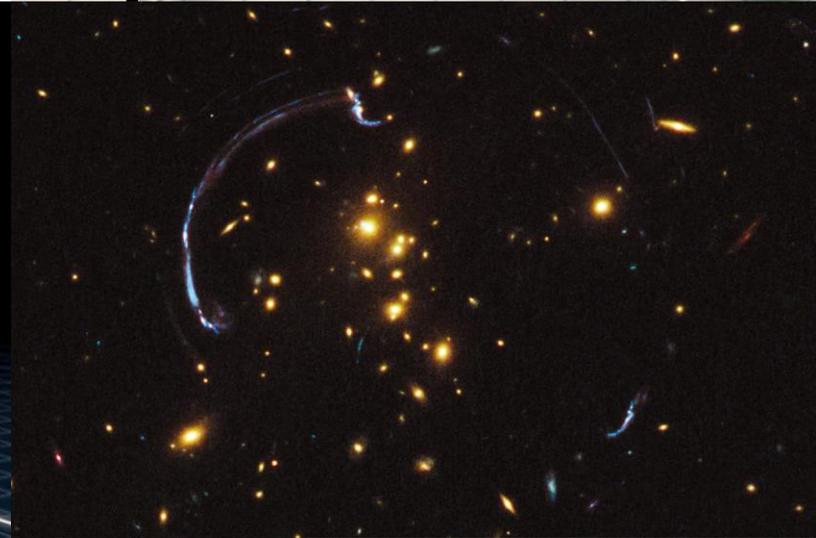
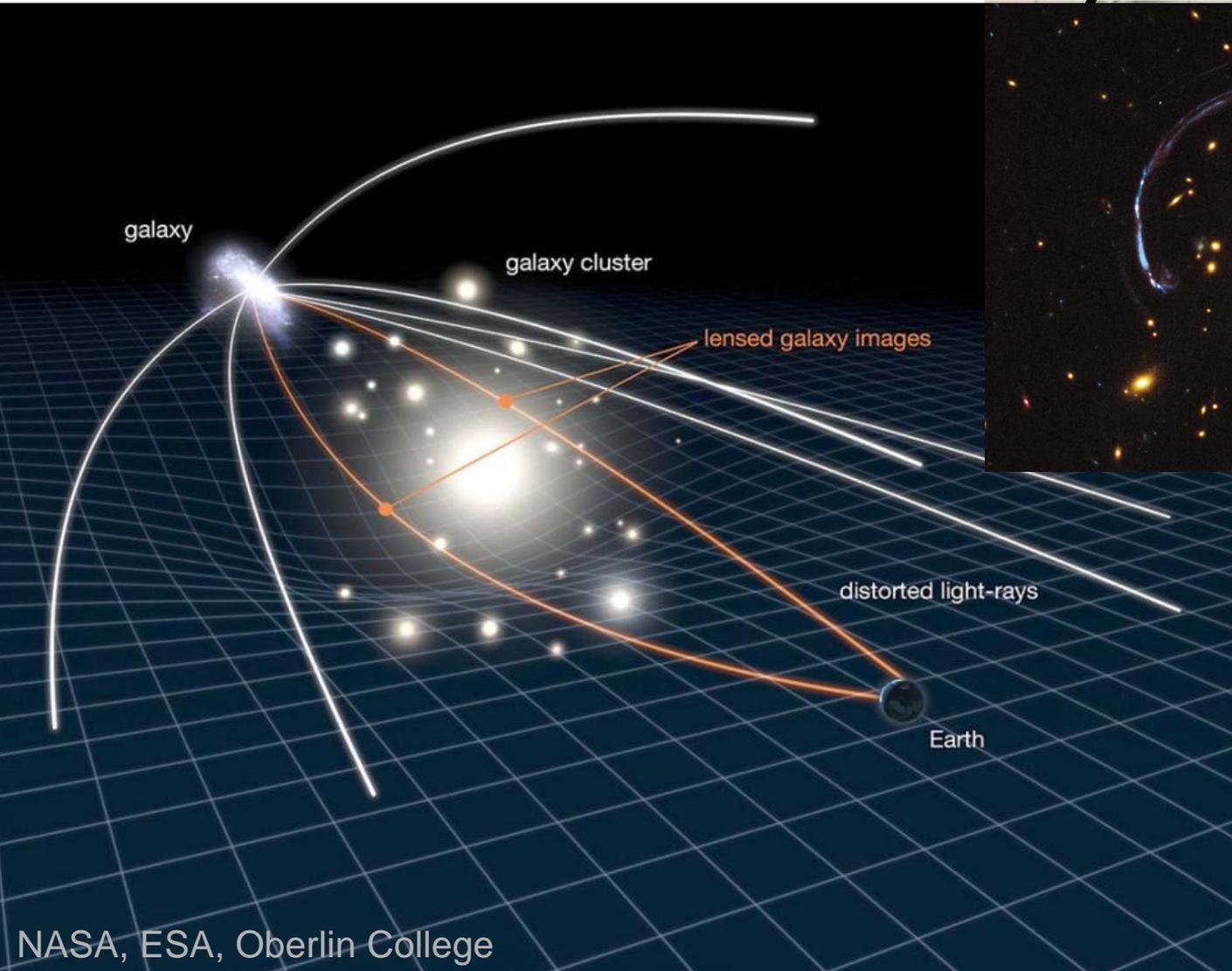
reflects & absorbs light
re-emits light



Dark Matter in Galaxies



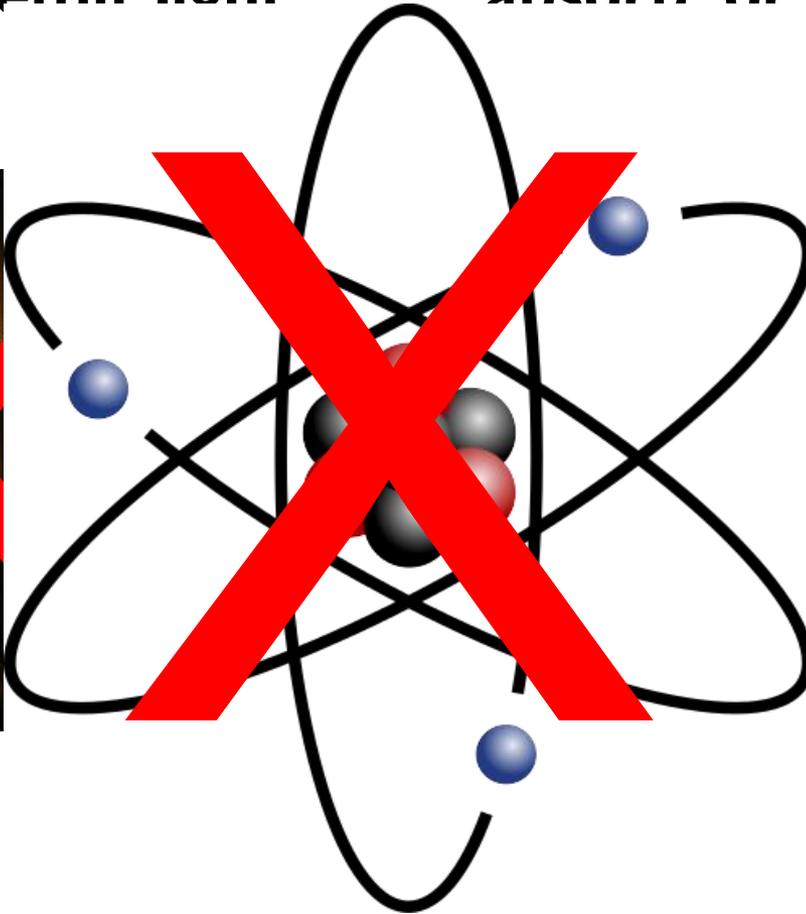
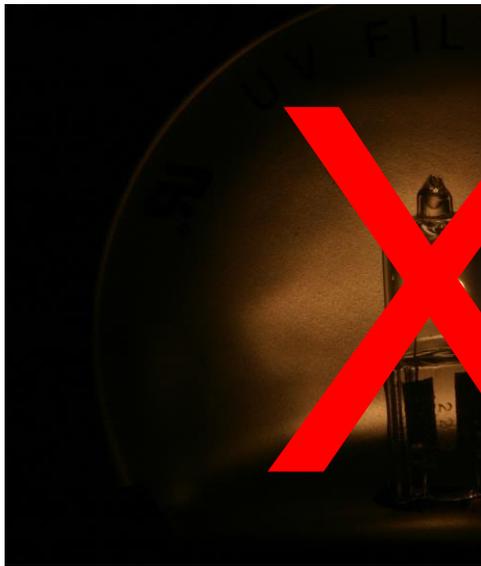
Dark Matter in Galaxy Clusters



Dark Matter

DOES NOT emit light

DOES NOT reflect,
absorb or re-emit light



The game is afoot



Douglas Finkbeiner, NASA, Tim Linden
The Sherlock Holmes Museum, 221b Baker Street, London, England

How important is visible matter?

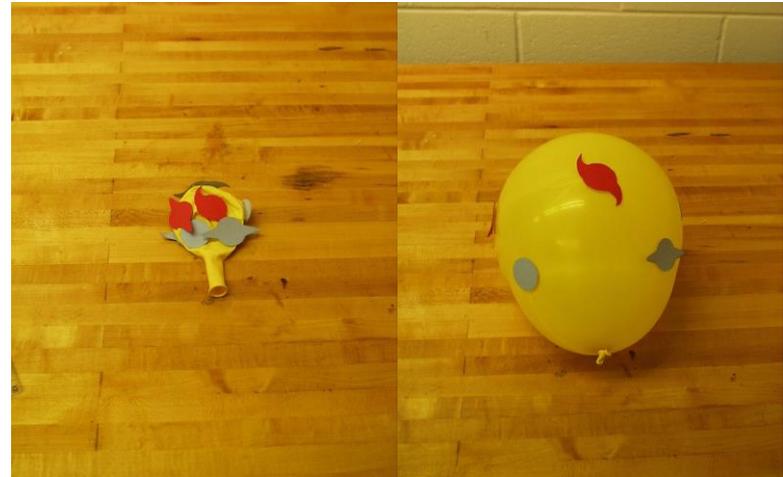
The visible matter just follows the dark matter

But everything we see is visible matter



The universe used to be hotter and denser

Visible matter and light interacted **much** more



Summary

What is the state of the cosmos?

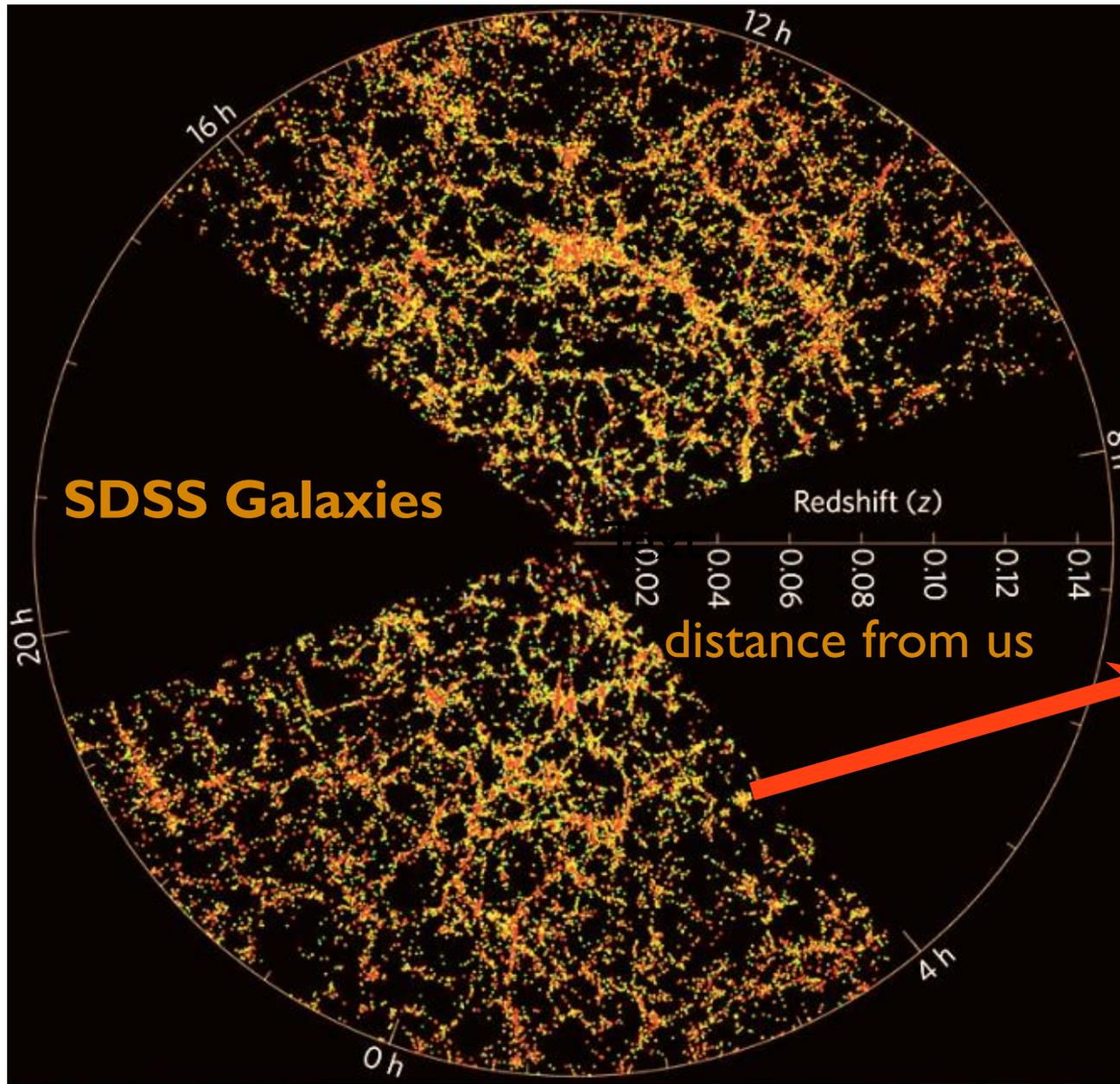
- The Universe is expanding
- There is a large-scale structure of galaxies
- These structures are made of dark matter

Our cosmology is only as precise as our observations

Our universe's story

Part II: Why do galaxies cluster as they do?

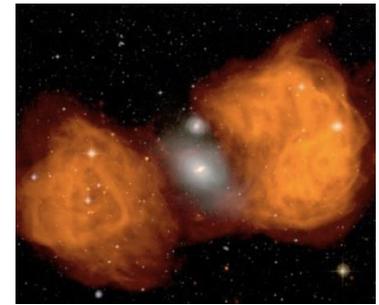
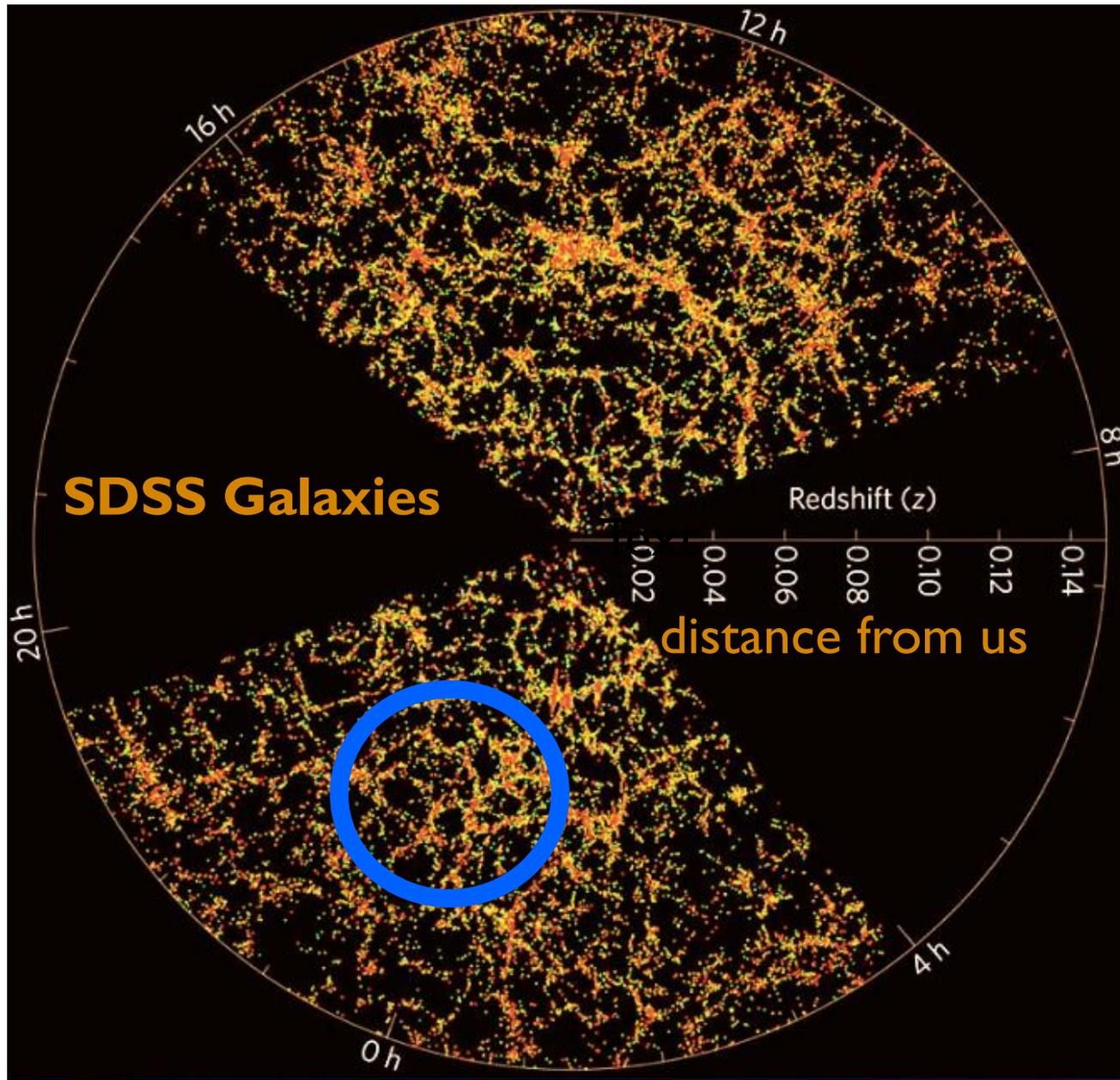
Zachary Slepian



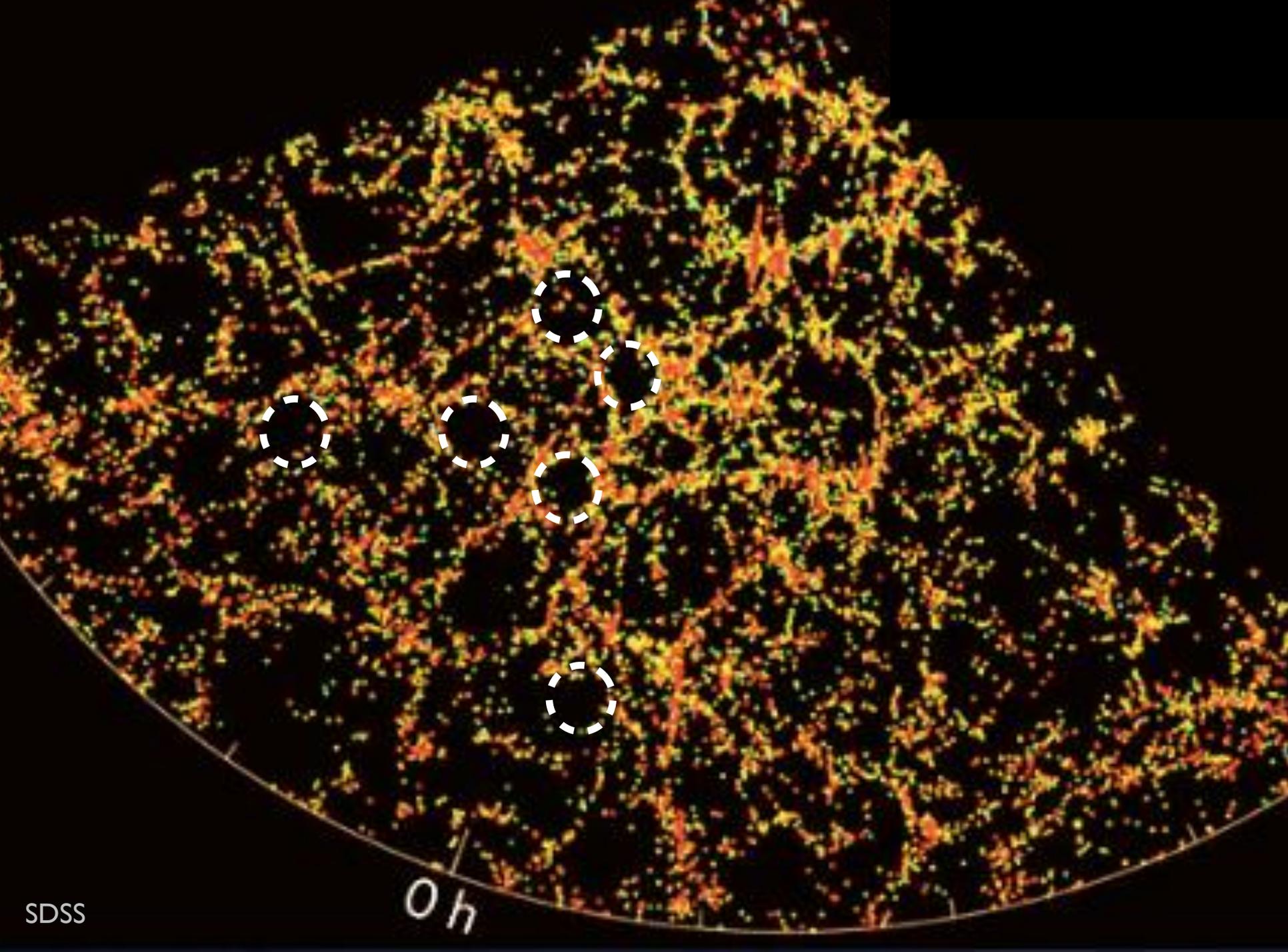
SDSS
telescope



Each point
is a galaxy!



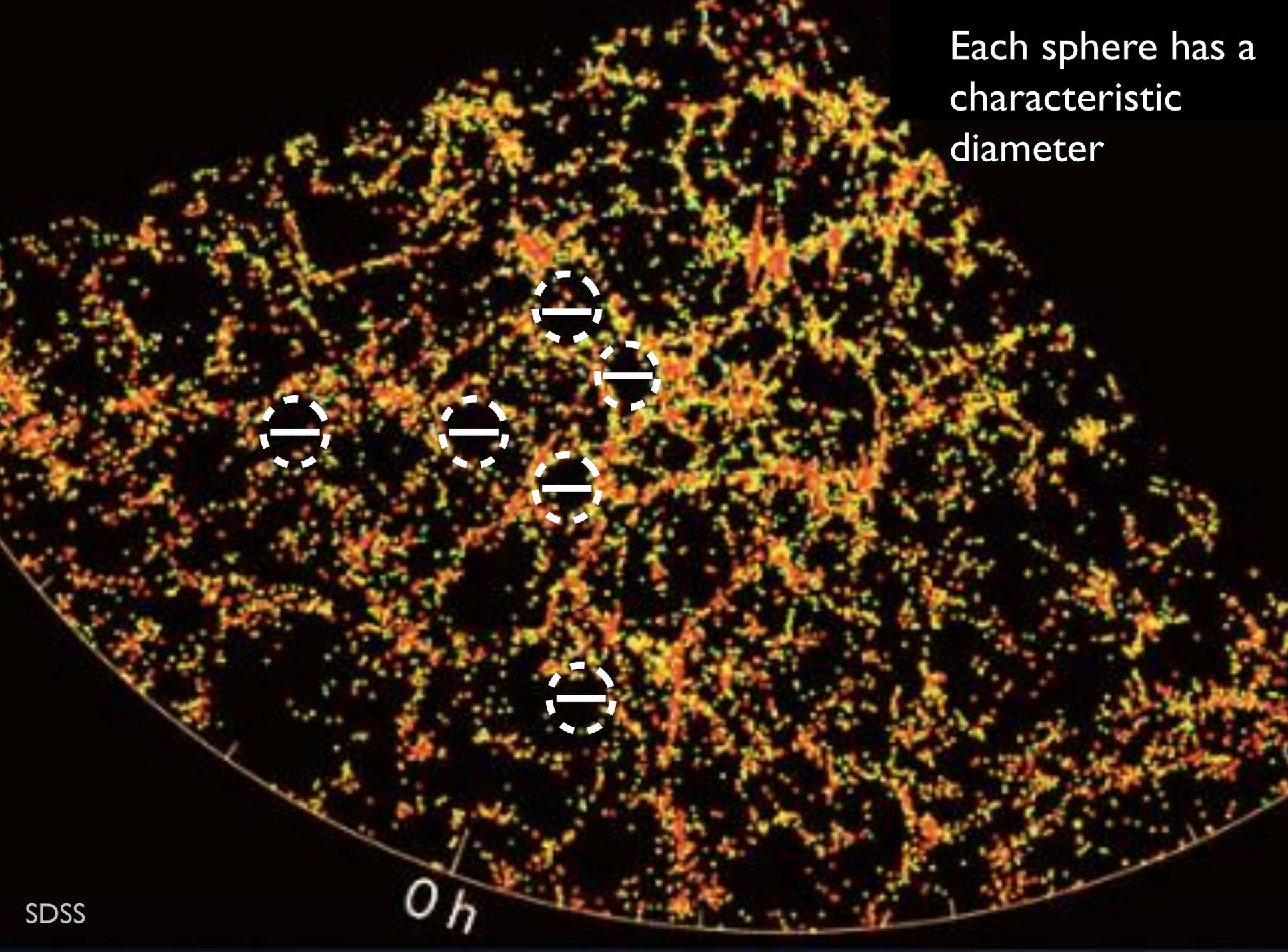
Each point
is a galaxy!



SDSS

0 h

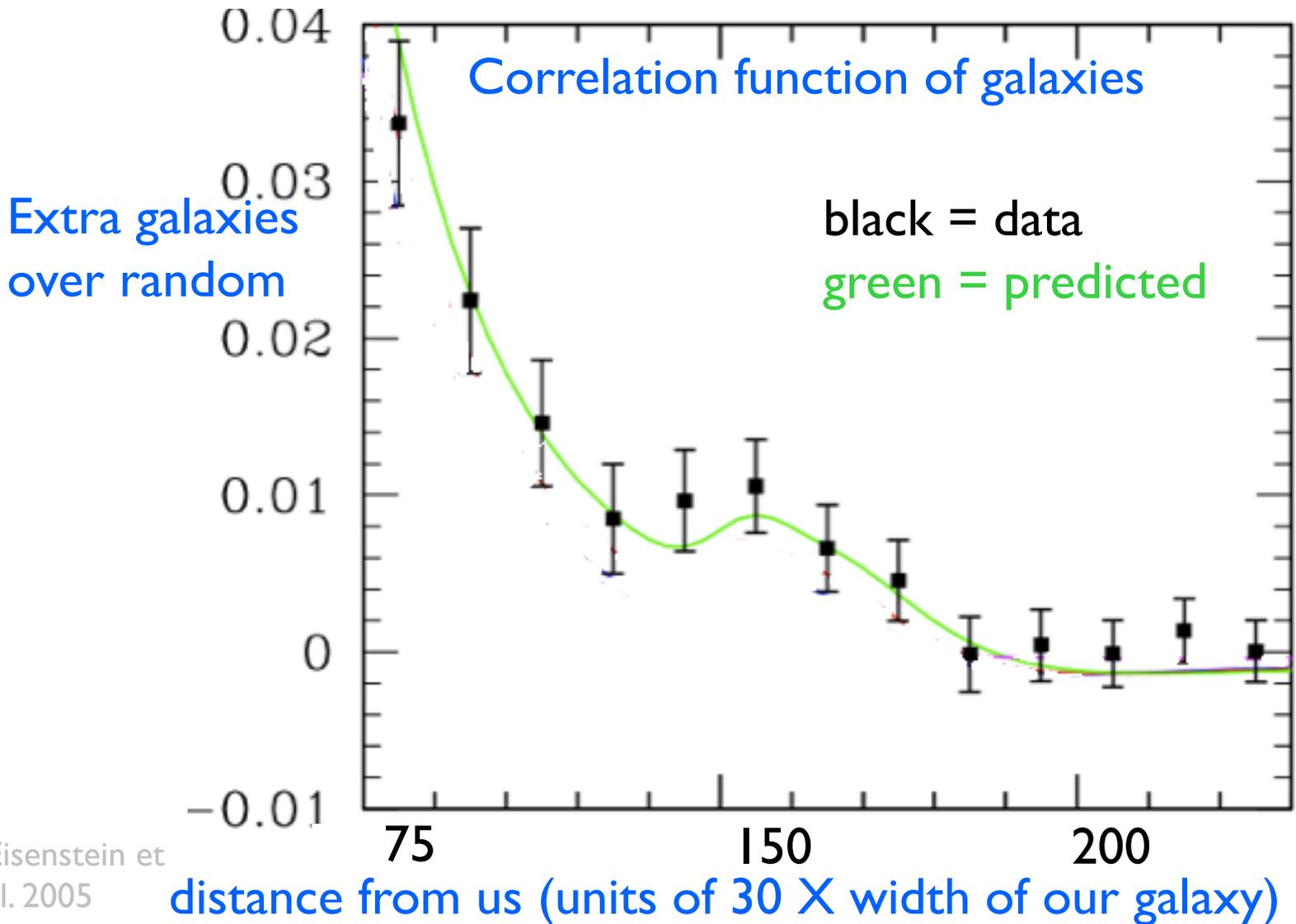
Each sphere has a
characteristic
diameter



SDSS

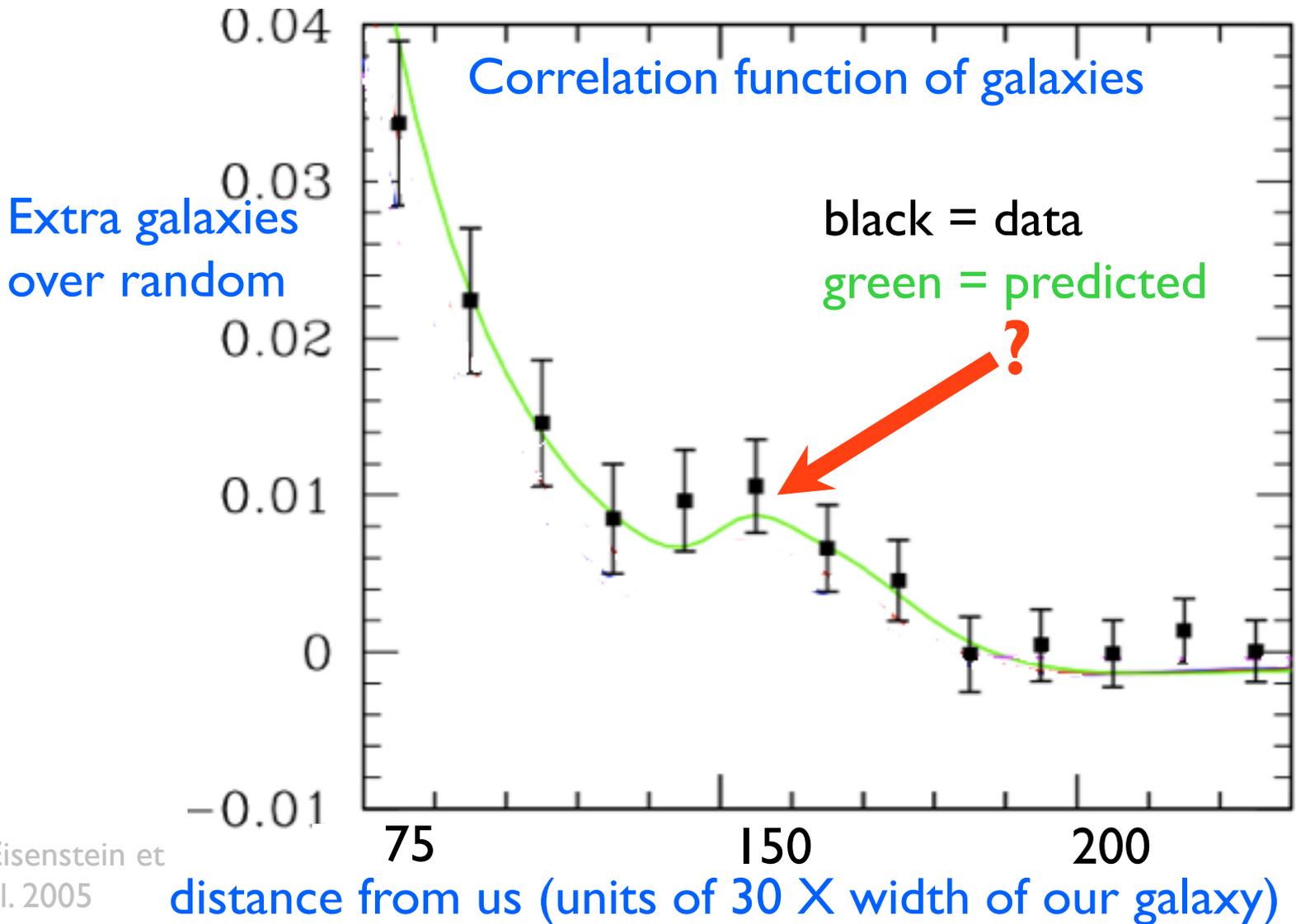
0 h

Why do galaxies cluster?

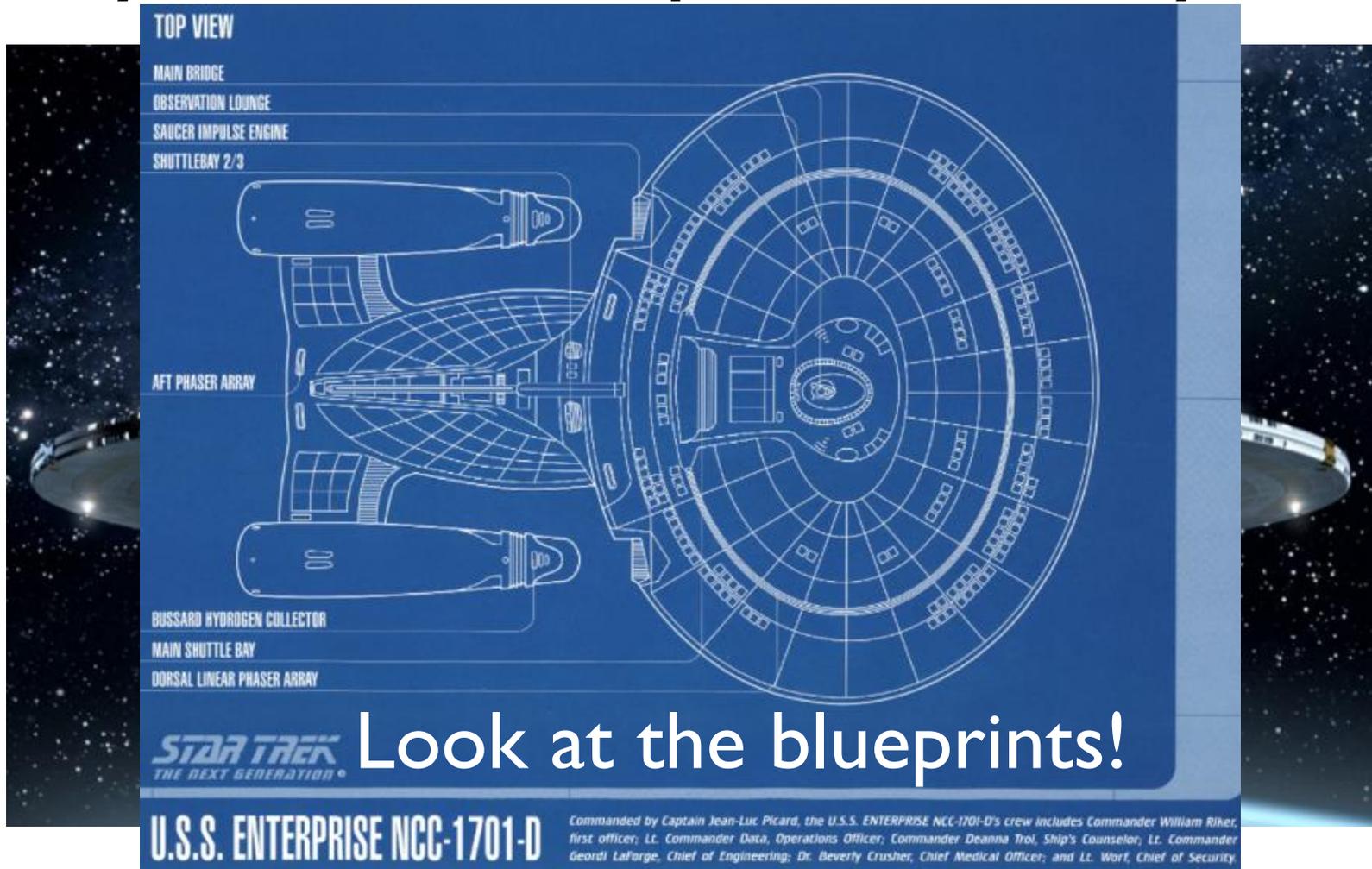


Daniel Eisenstein

Why do galaxies cluster?

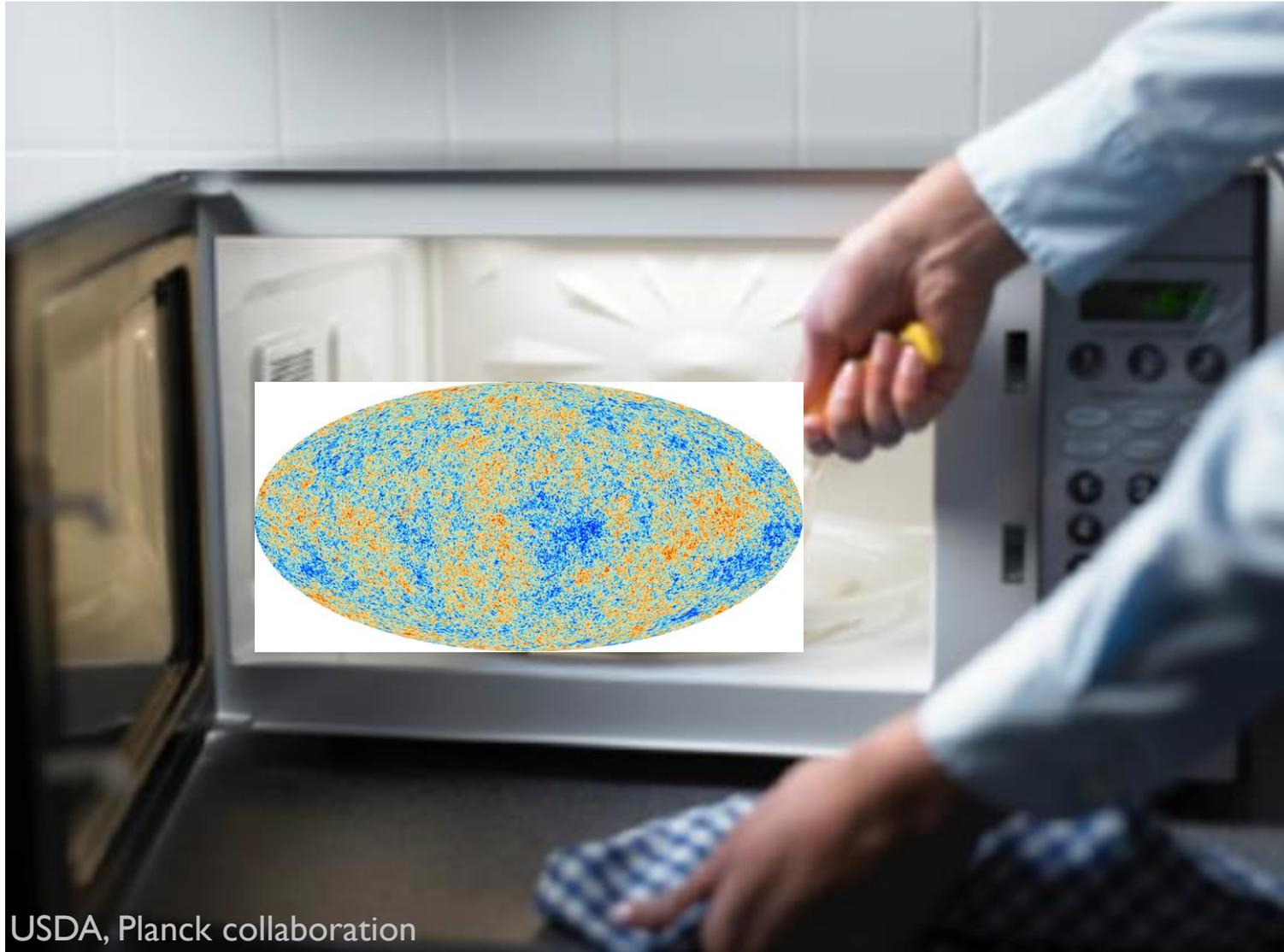


Why is the Enterprise the way it is?



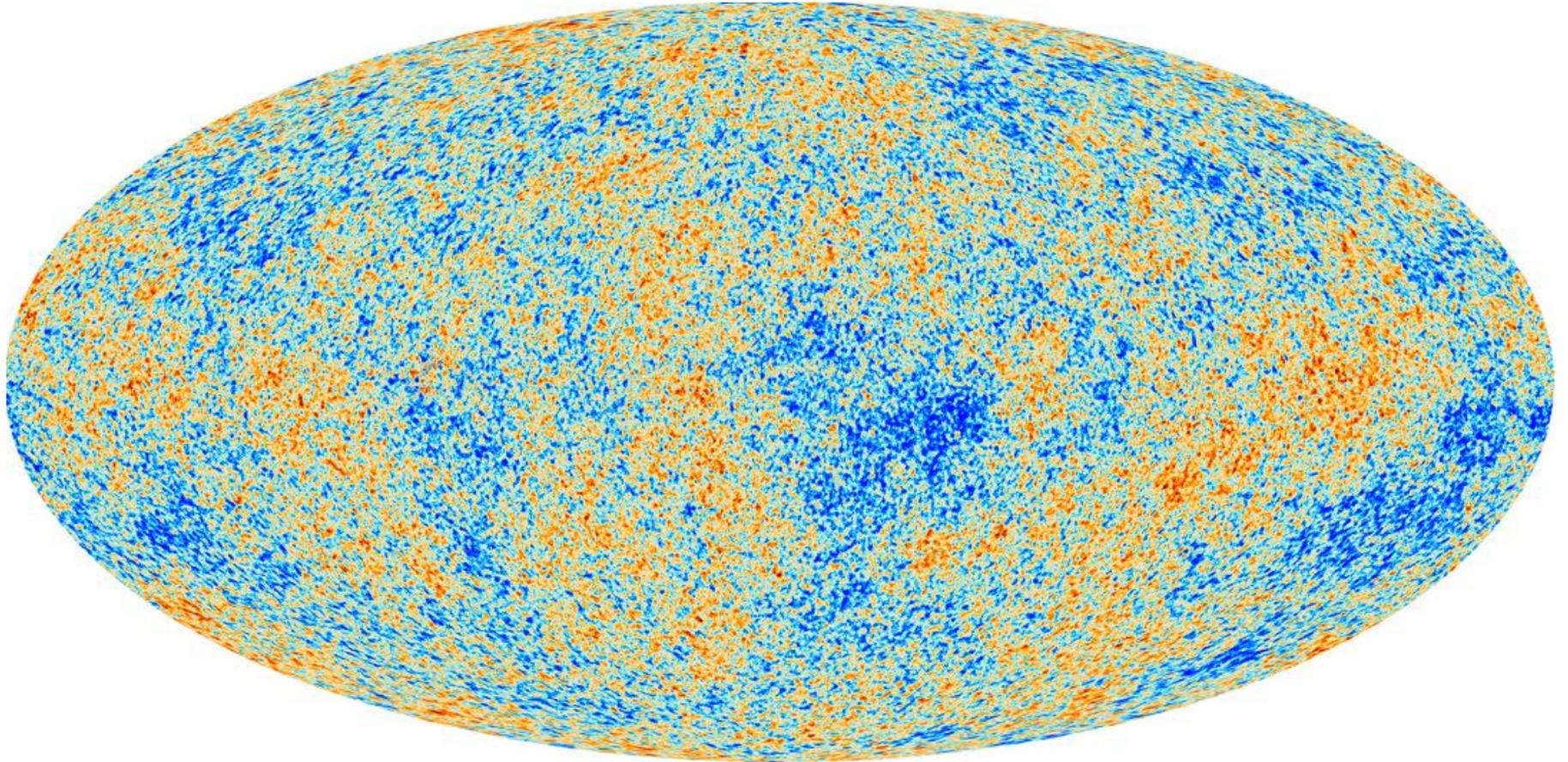
Look at the blueprints!

Astronomy with Kitchen Devices



USDA, Planck collaboration

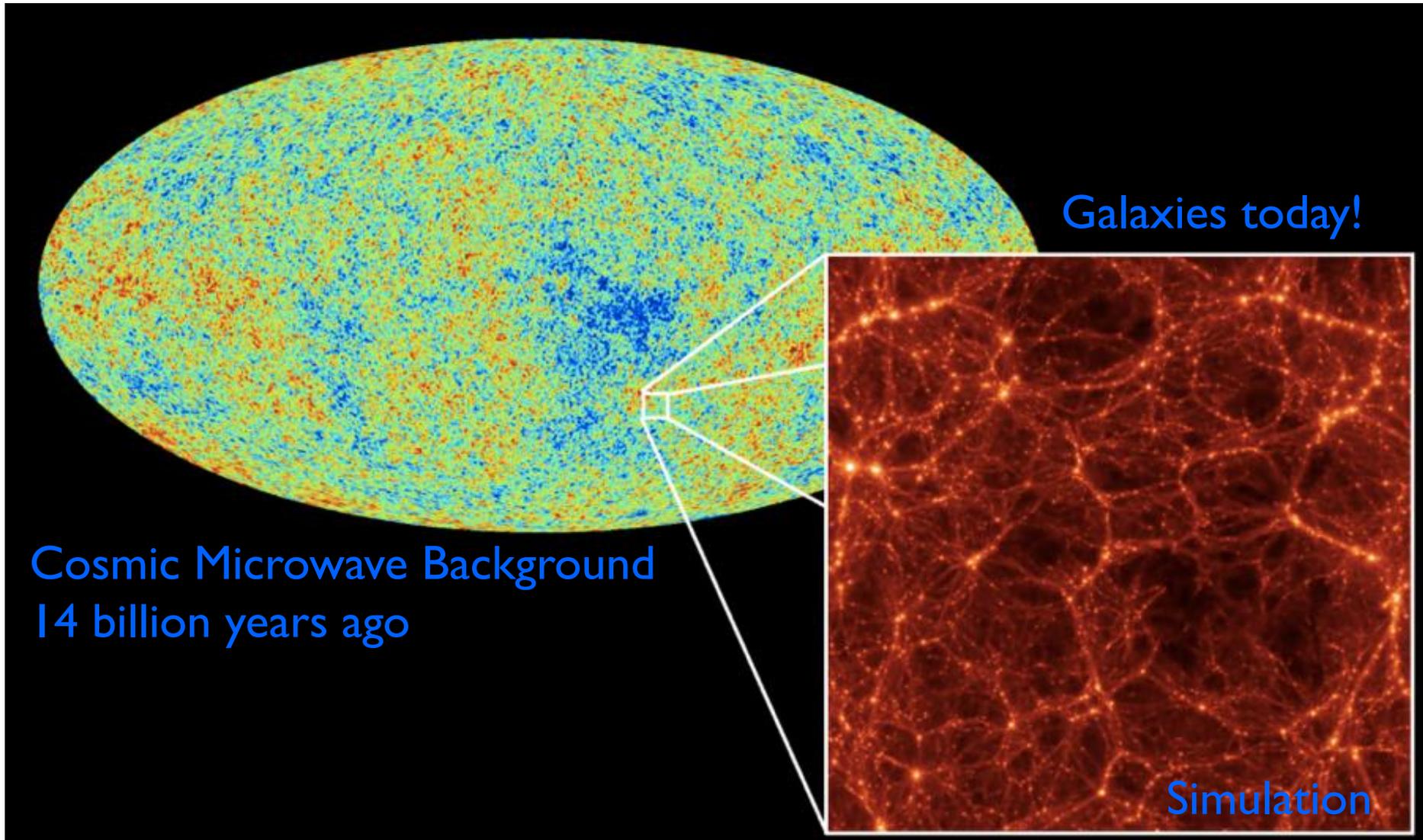
The Cosmic Microwave Background



map of temperature of left over radiation from
moment Universe became neutral

Planck collaboration hi-resolution map; Planck website

Zooming in



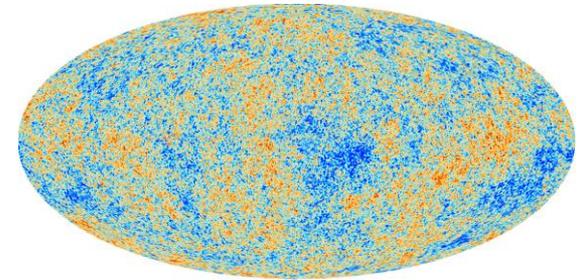
Understand why Cosmic Microwave Background has these structures

- Since CMB is blueprint for structures today
- ... understanding why these features are in the CMB ...
- should tell us why they are here today

So what gives the Cosmic Microwave Background these hot and cold spots?

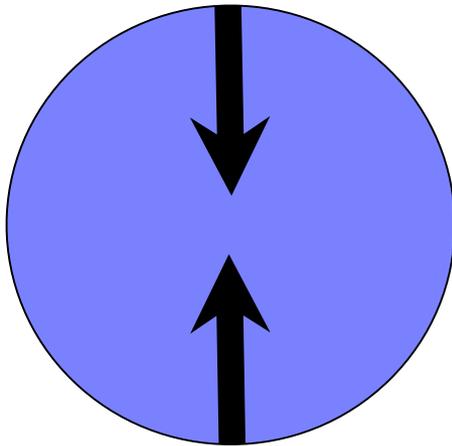
Let's focus on one hot spot

- Hot spot = more matter there
- We call that “overdense”
- How does one overdense region evolve in time from nearly the beginning of the Universe ..
- to the formation of the CMB?

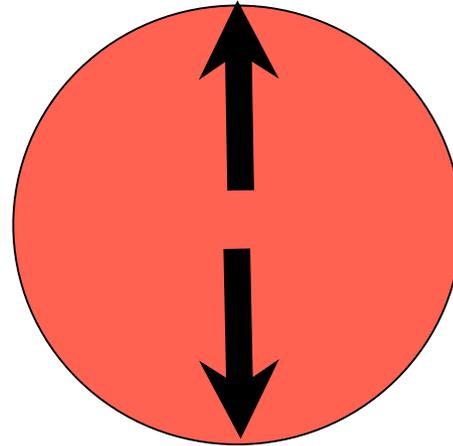


2 important forces

Gravity



Pressure



Gravity

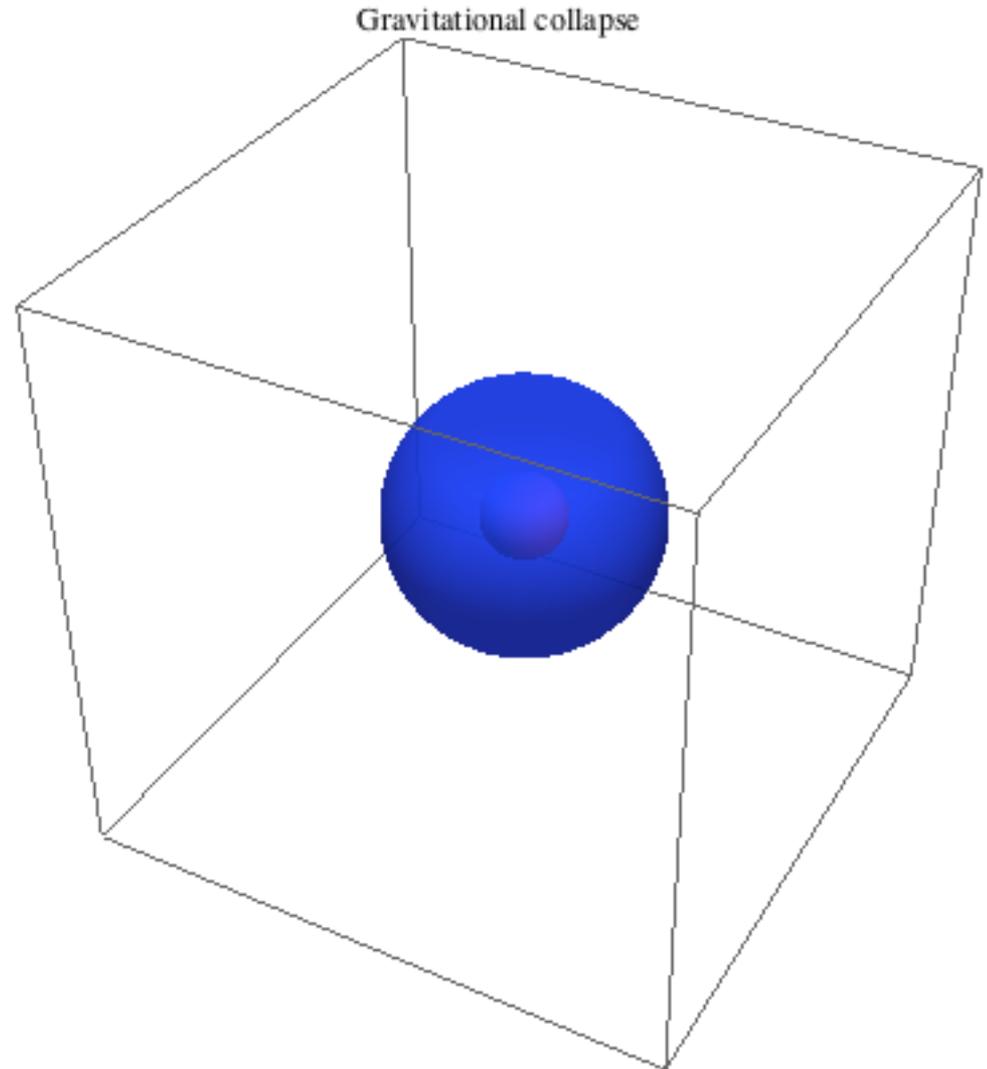
Mass in sphere is proportional
to overdensity

Gravitational force is
proportional to the mass

Sphere contracts

This raises density

Overdensity grows!



Gravity

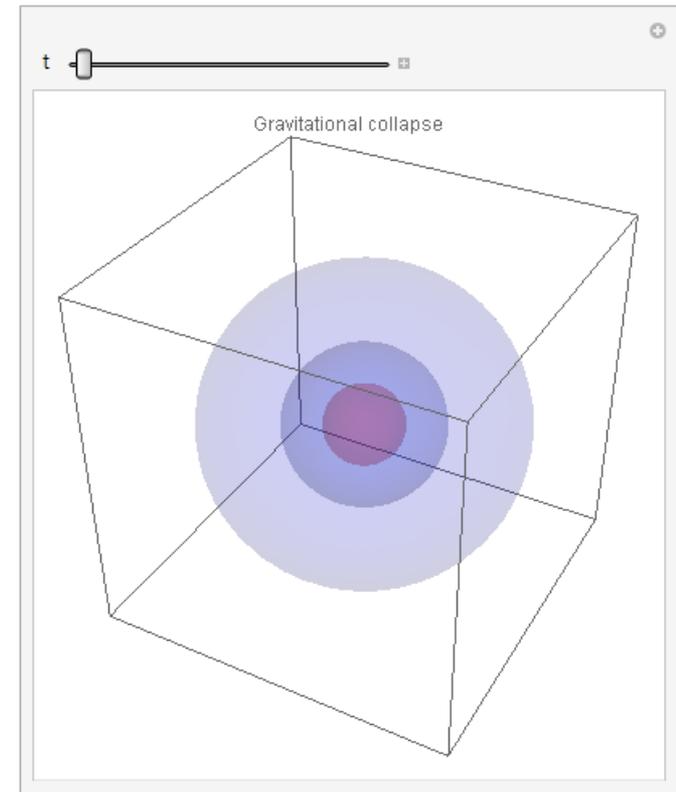
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Pressure

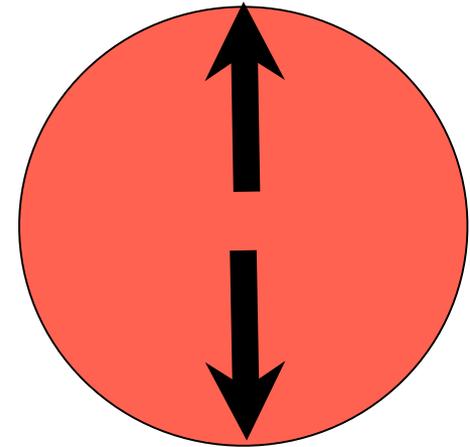
Pressure is proportional to the overdensity

Pressure leads to expansion of sphere

Expansion lowers density of sphere

Overdensity gets diluted!

Pressure



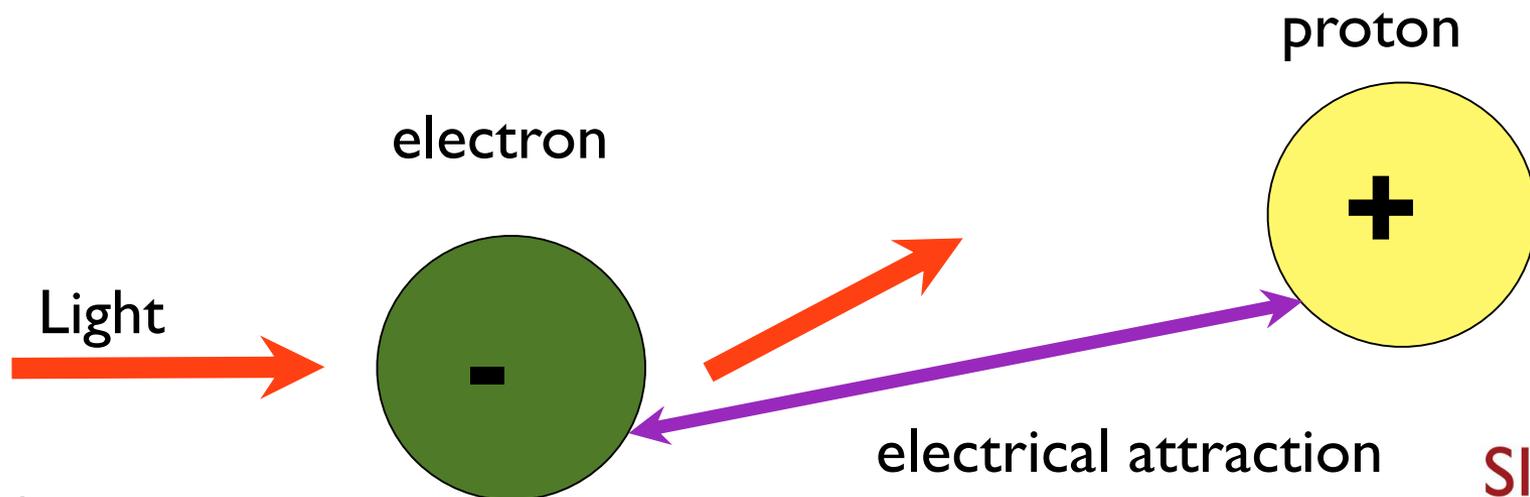
These 2 forces both work on regular matter

- Gravity causes initial contraction
- But then pressure pushes regular matter out

What provides the pressure?



- Early times: pressure from radiation (light)
- Electrons interact strongly with light
- Electrons pull protons along for the ride
- So all the regular matter follows the light!



What about the Dark Matter?

- Why is DM the most relaxed substance in the Universe?
- Doesn't interact with light
- Therefore ...
- DM doesn't feel pressure
- Only feels gravity

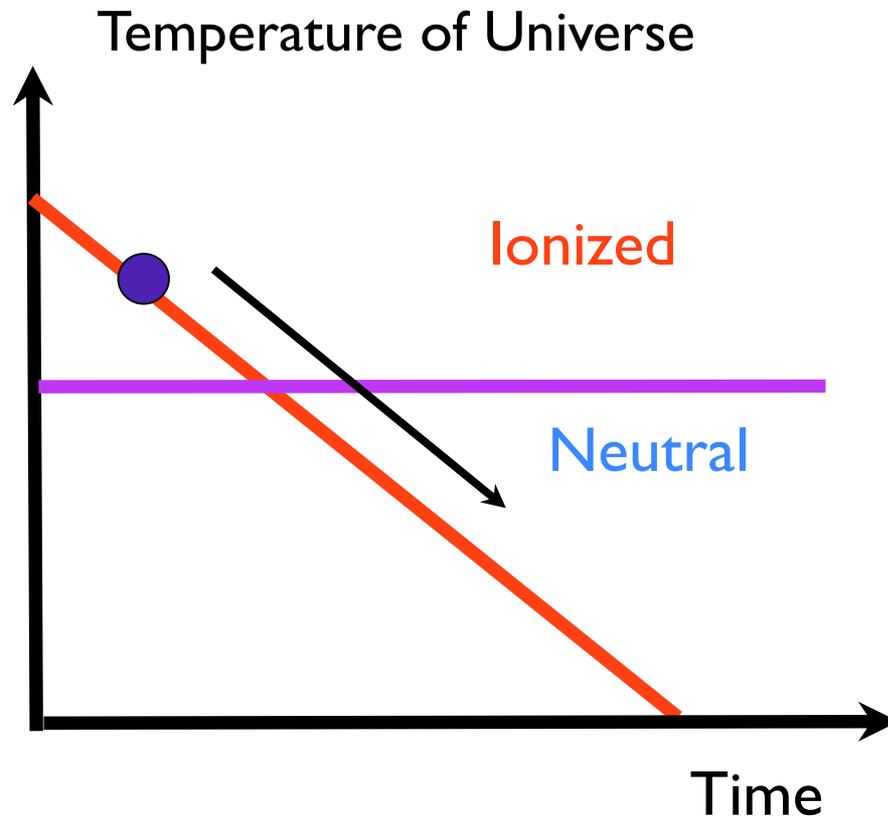


Putting it together

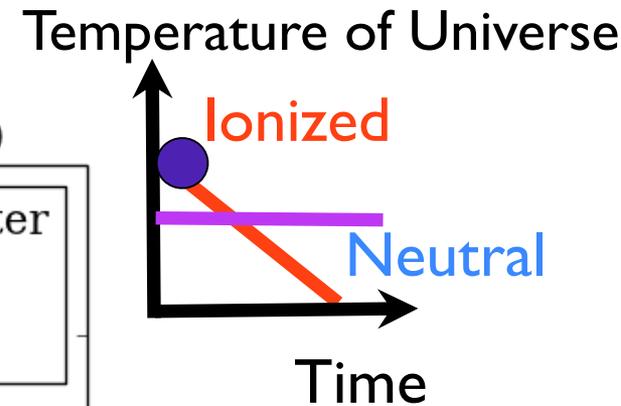
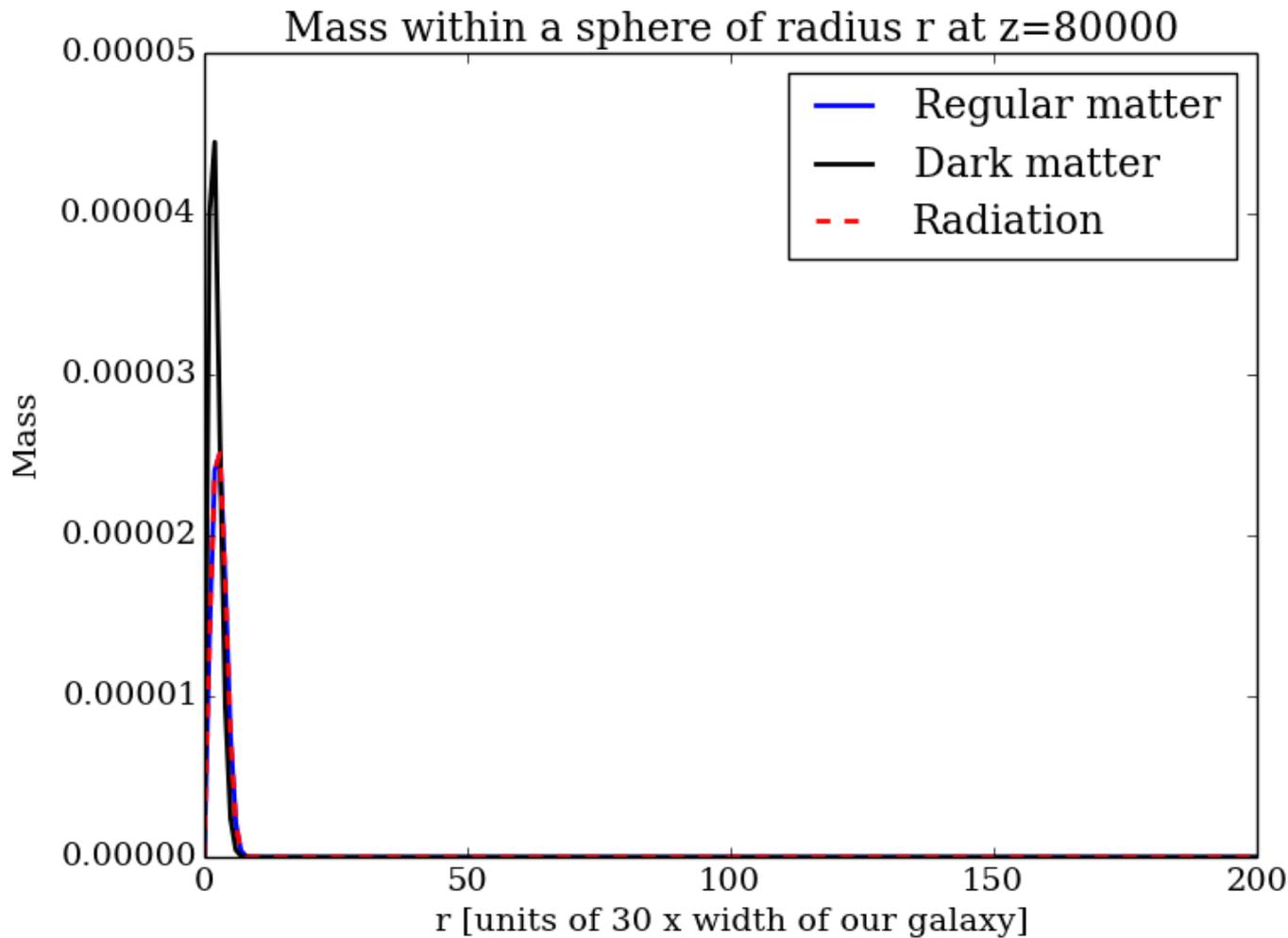
- Start with an overdense region at some very early time
- How does it evolve?
- **Regular matter**: gravity compresses, pressure pushes outwards
- Pressure is due to photons' interaction with electrons
- **Dark matter** feels only gravity, so always compresses

Questions?

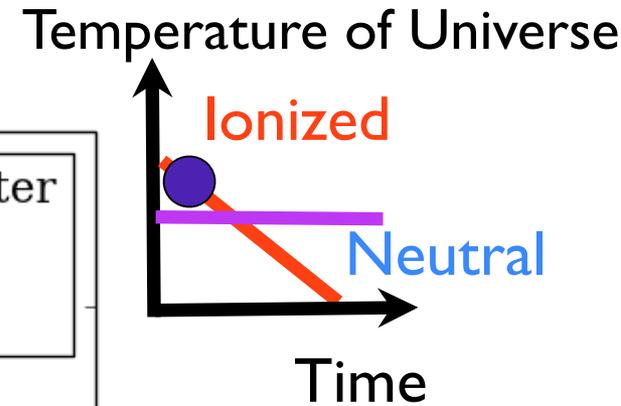
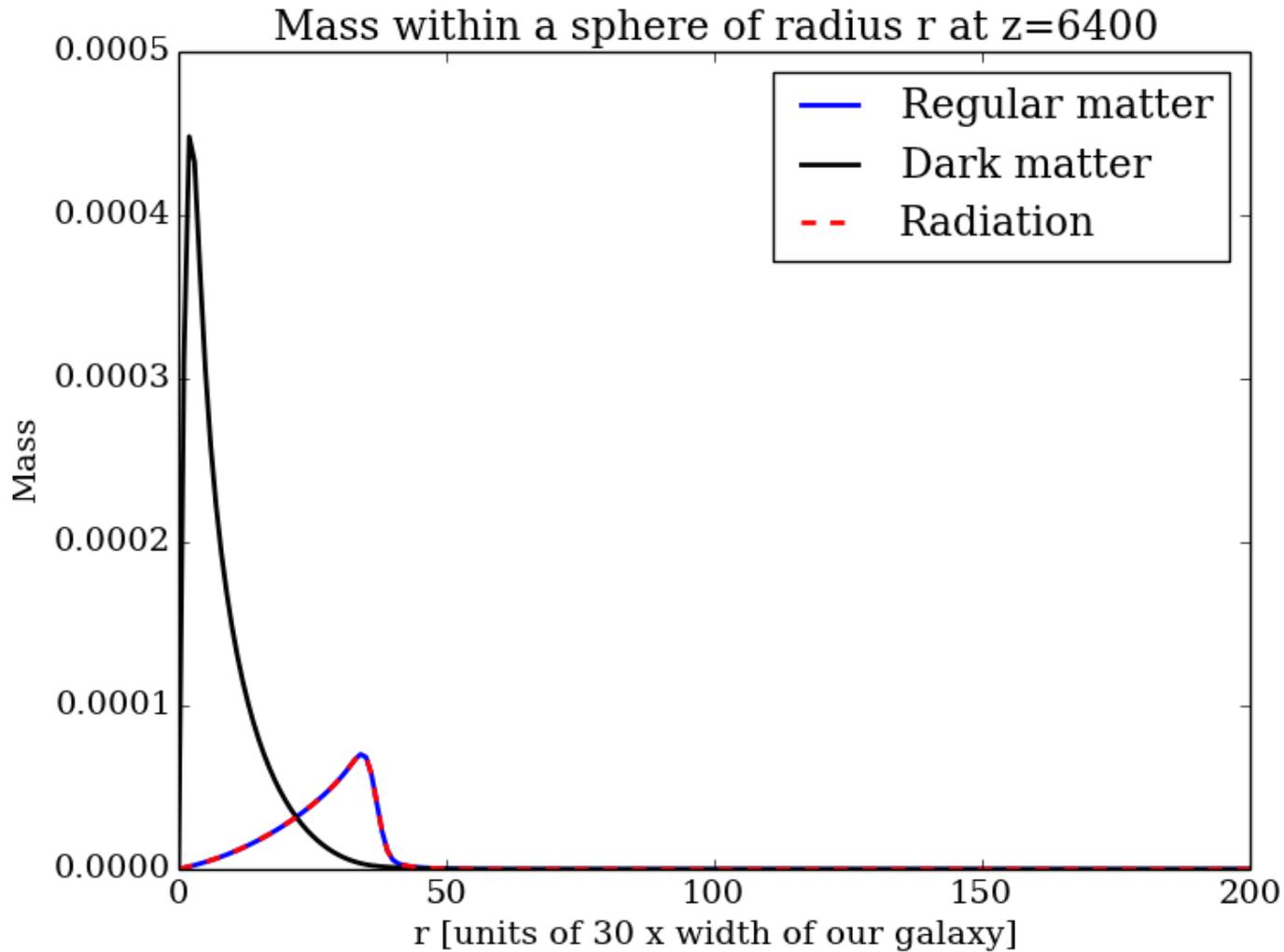
Universe is expanding . . . and cooling!



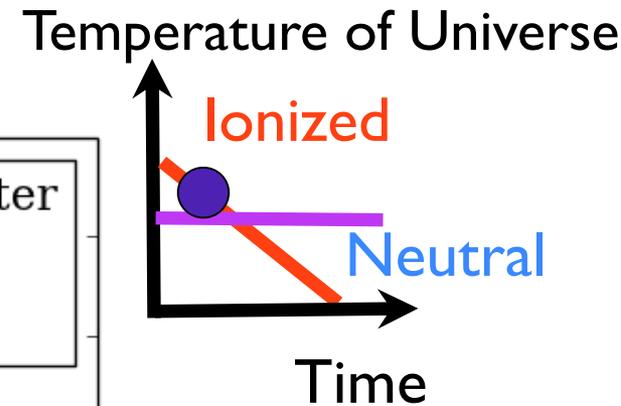
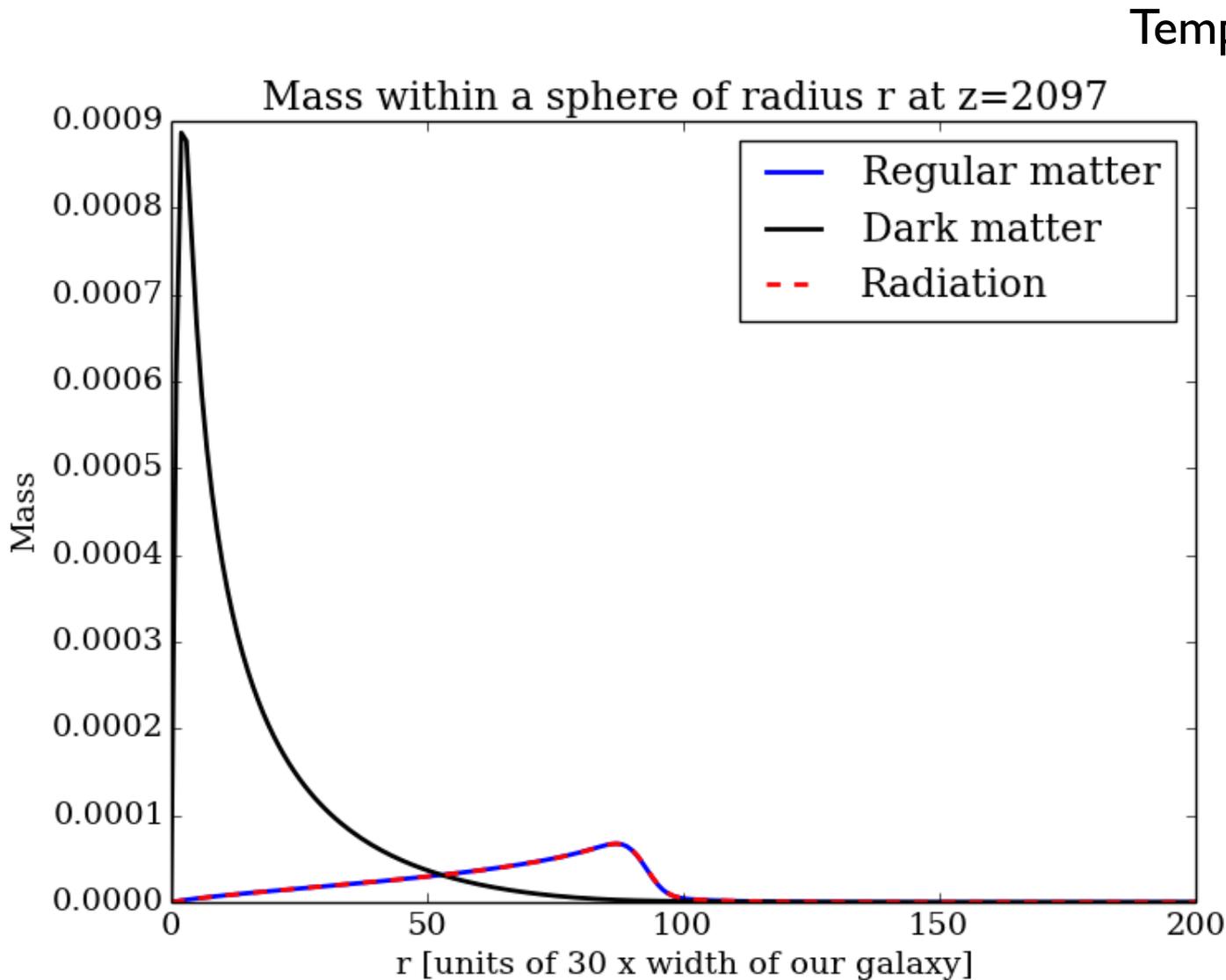
Initial conditions



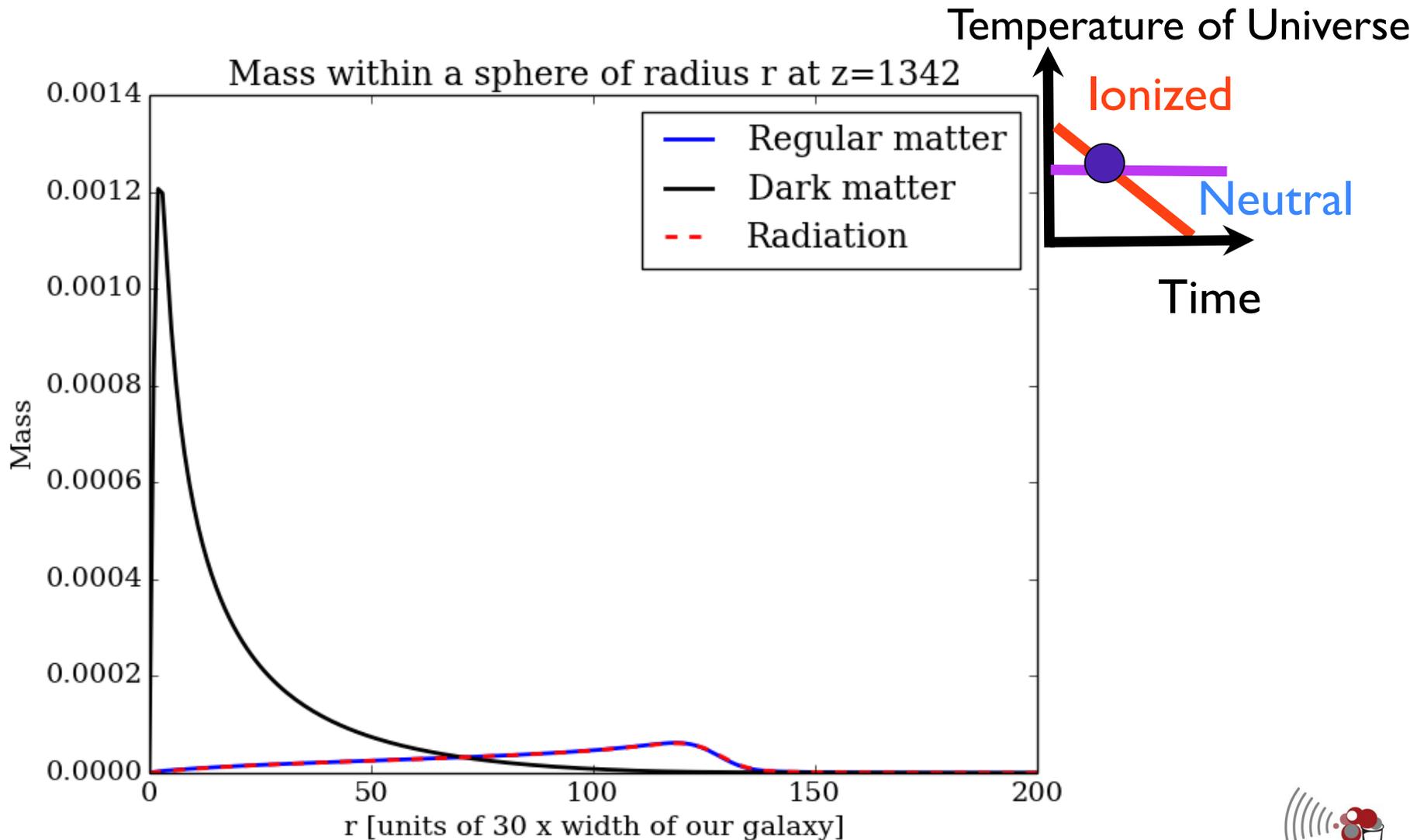
Later



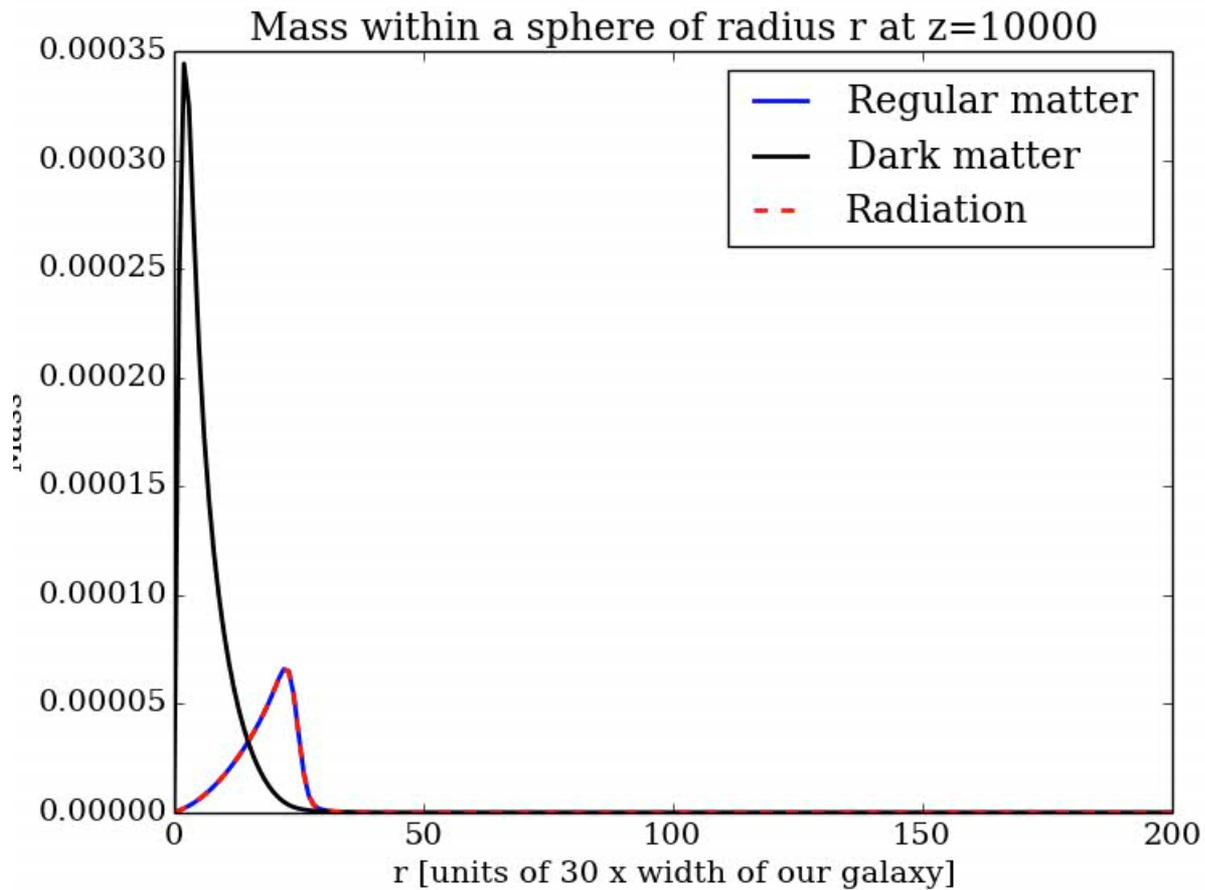
Even later ...



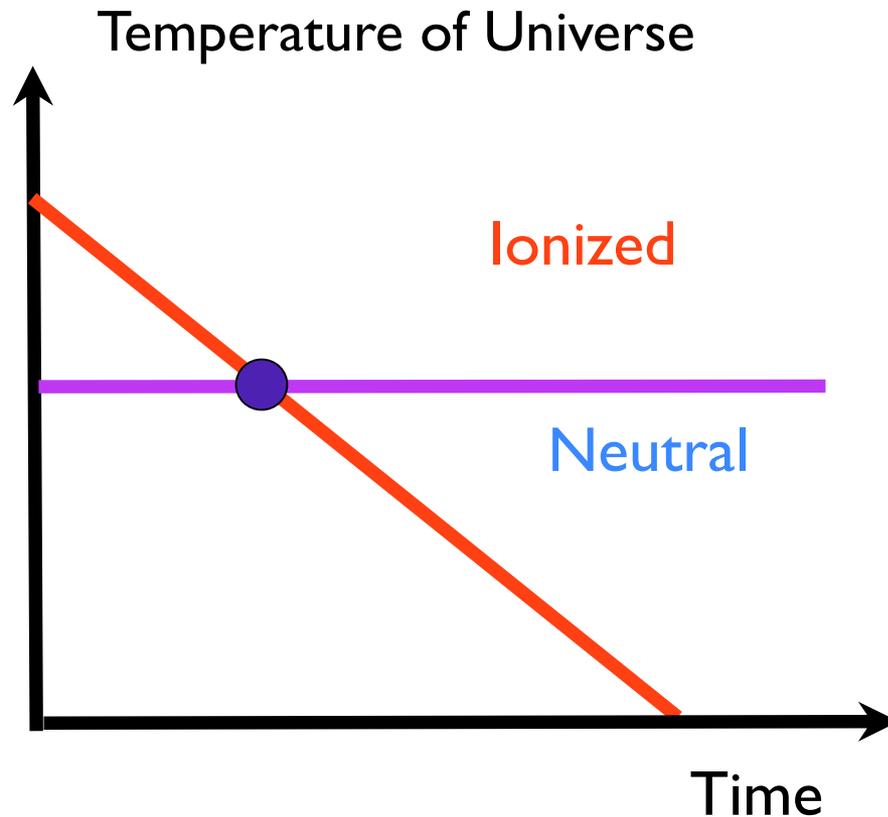
So close to neutral!



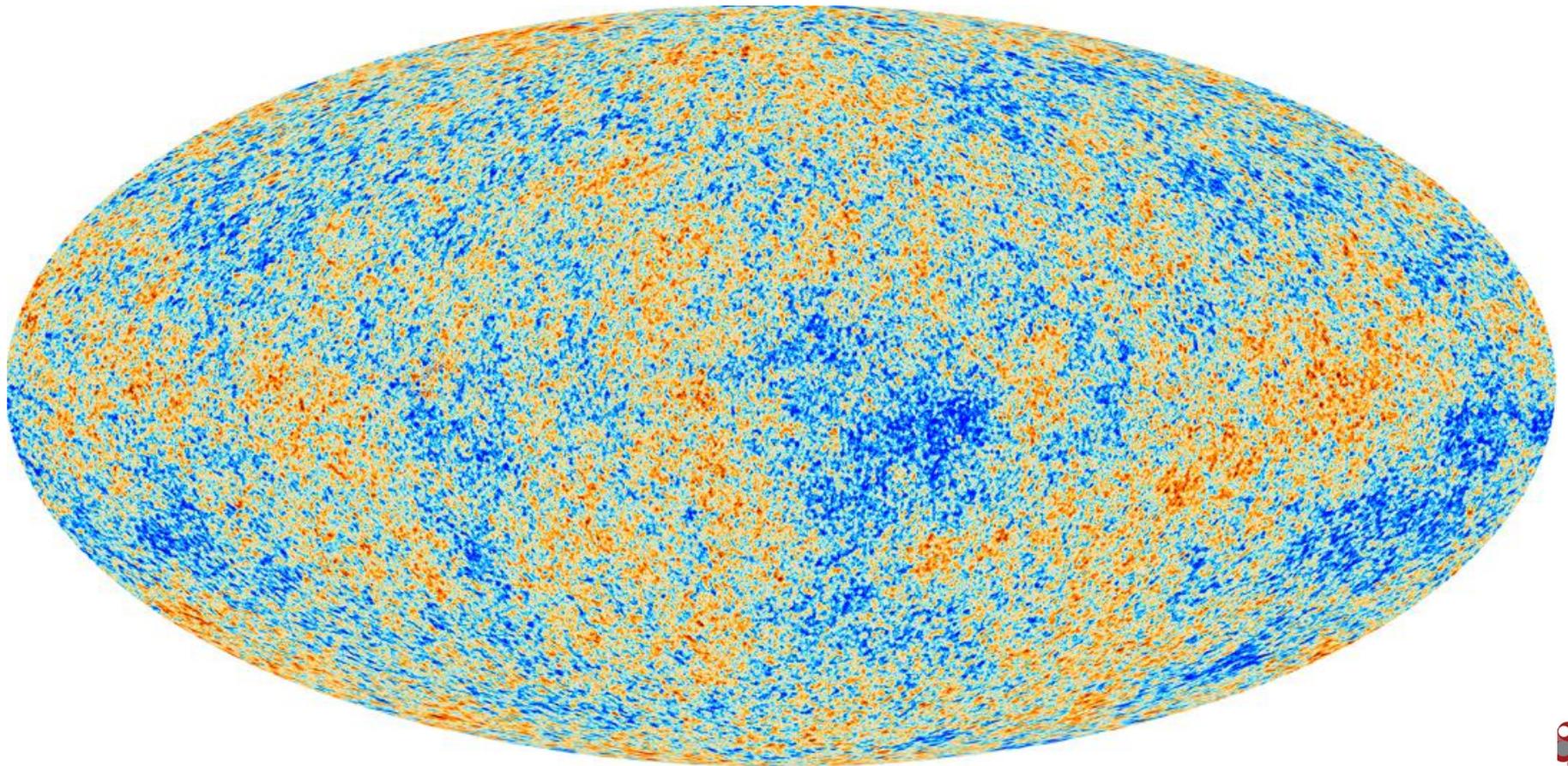
Video!



What happens when Universe becomes neutral?



Cosmic Microwave Background forms at moment Universe becomes neutral



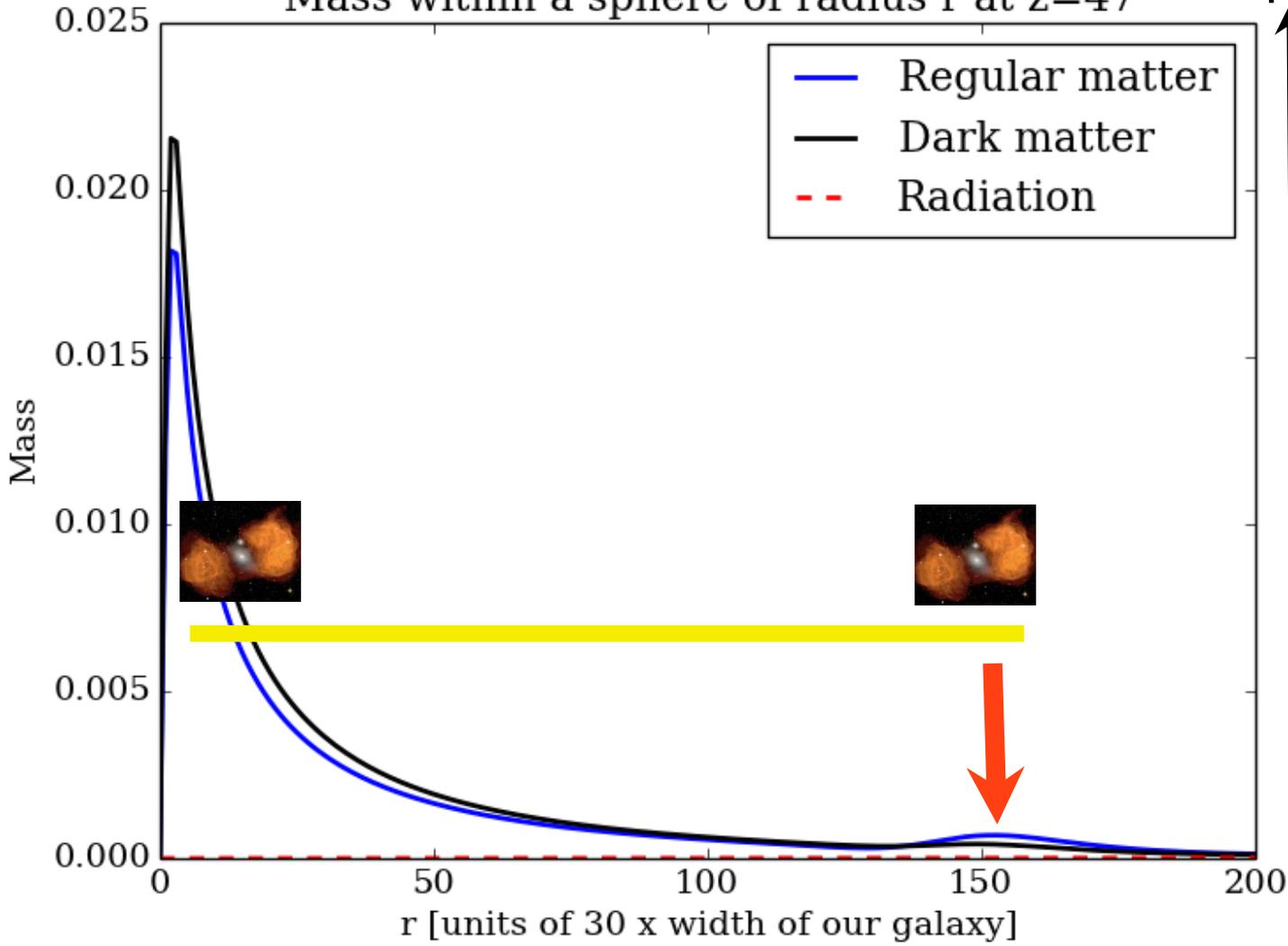
And photons release regular matter

- Neutral means “no more electrons”
- So no more strong interaction between regular matter and light
- No more radiation (light) pressure!

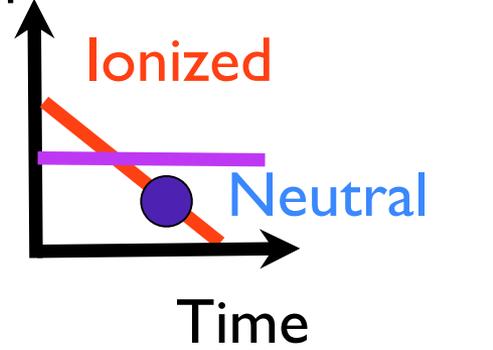
Universe is now neutral

Mass within a sphere of radius r at $z=47$

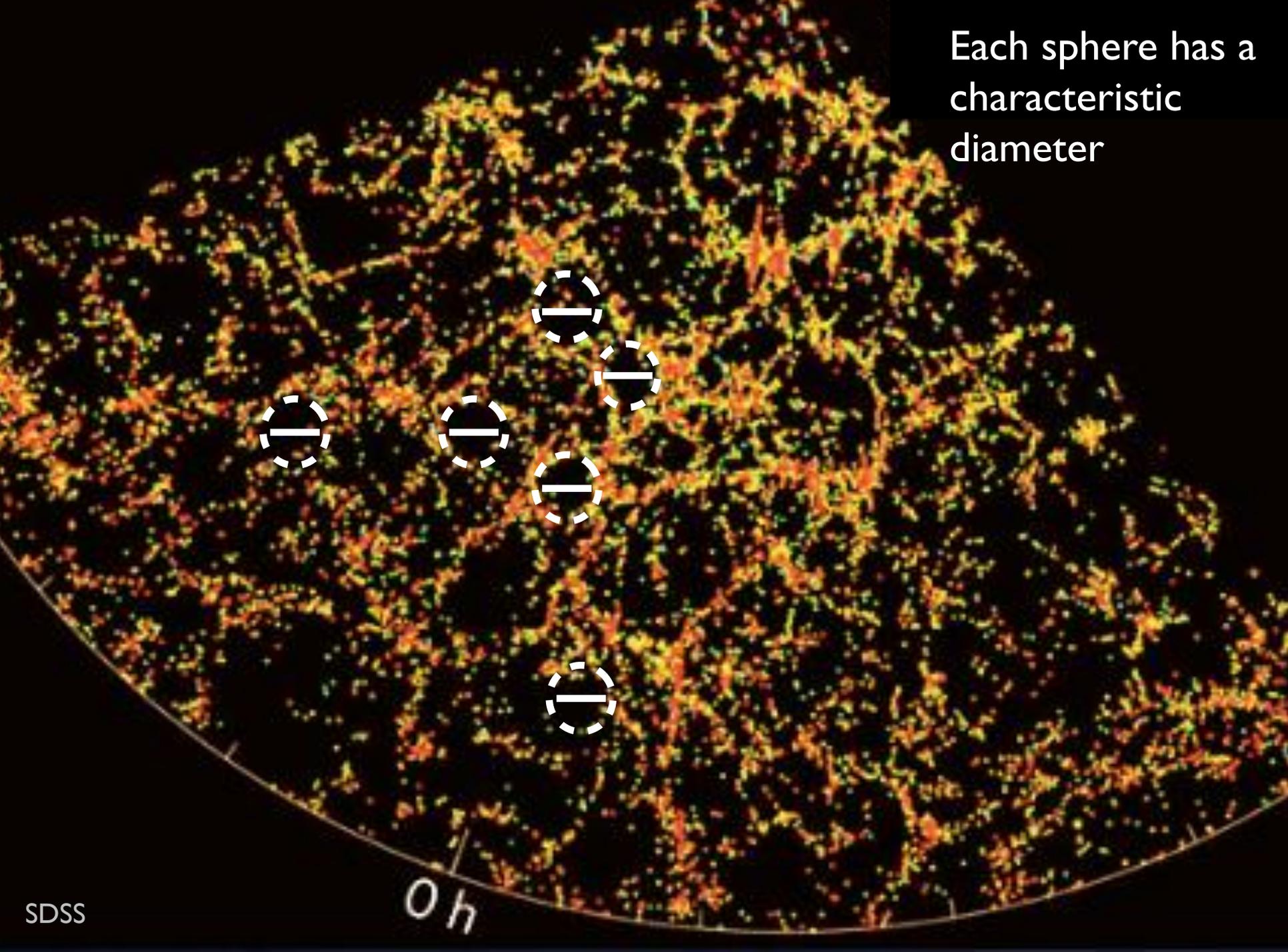
Temperature of Universe



- Regular matter
- Dark matter
- - - Radiation



Each sphere has a characteristic diameter



SDSS

0 h

Questions?

Our universe's story

Part III: Back to the beginning

Kate Alexander

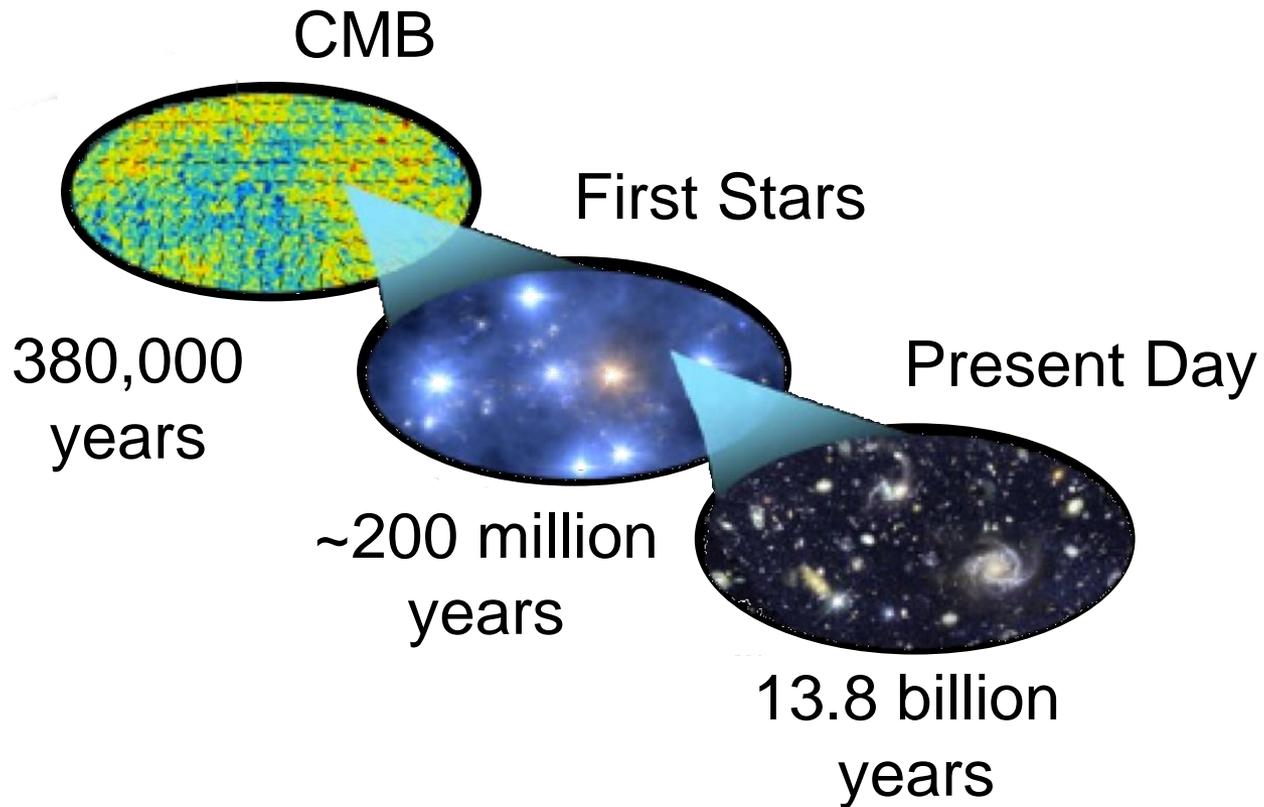
Outline

- What is inflation and why do we need it?
- How do we test inflation?
- Recent scientific results

Recall the picture thus far...

1. Today the Universe is full of structure: galaxies, clusters, dark matter
2. These structures began as tiny perturbations, which grew over time because gravity overcame pressure and the expansion of the Universe

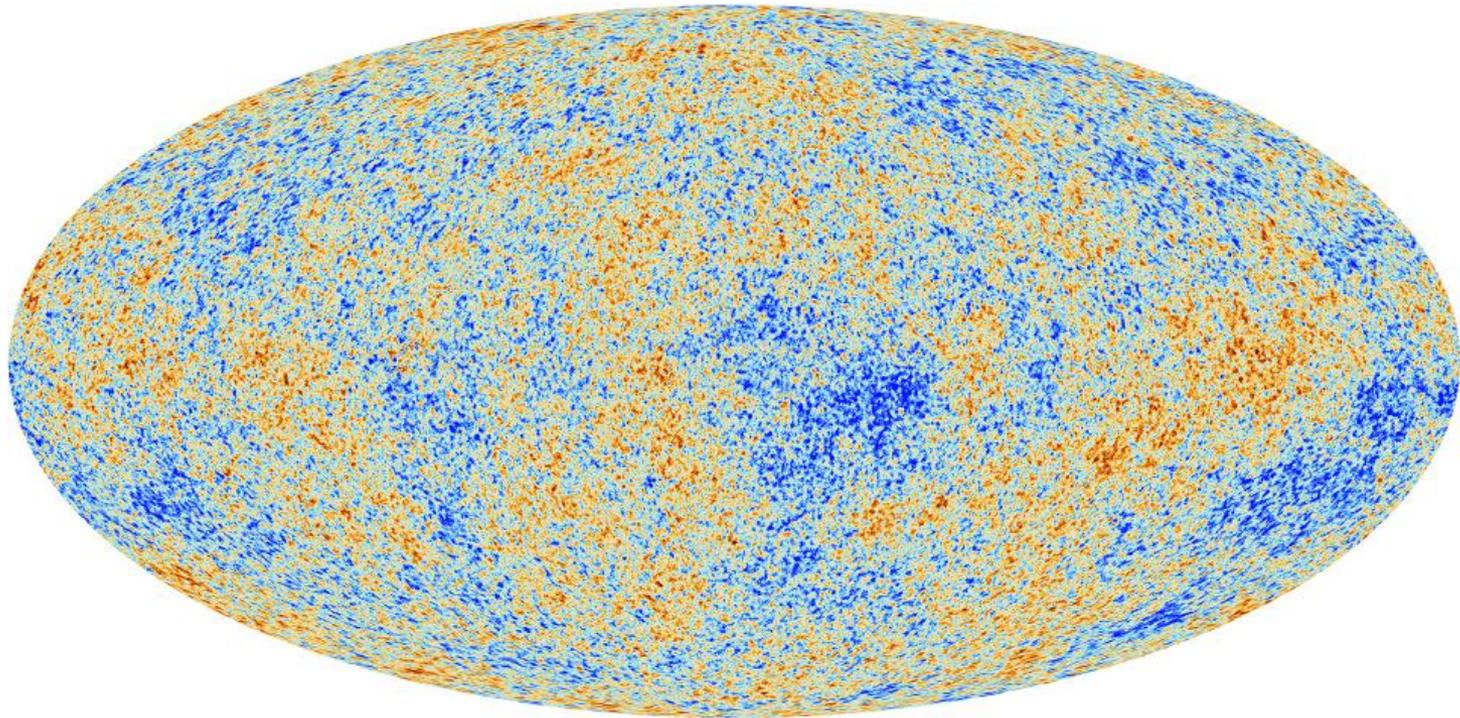
Looking back in time



Outstanding Questions

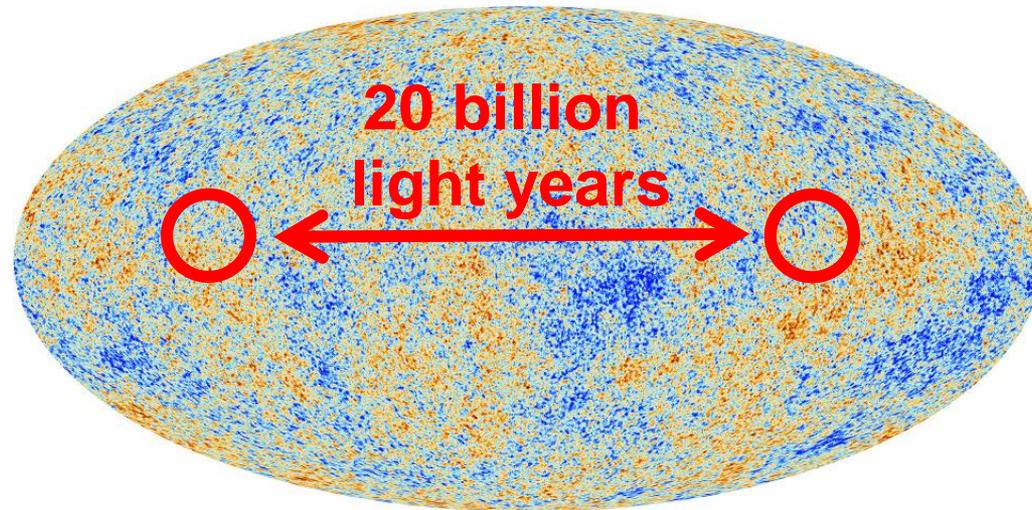
Outstanding Questions

- How did the initial perturbations form?



Outstanding Questions

- How did the initial perturbations form?
- The **Horizon Problem**: Why does the Universe look the same in every direction?

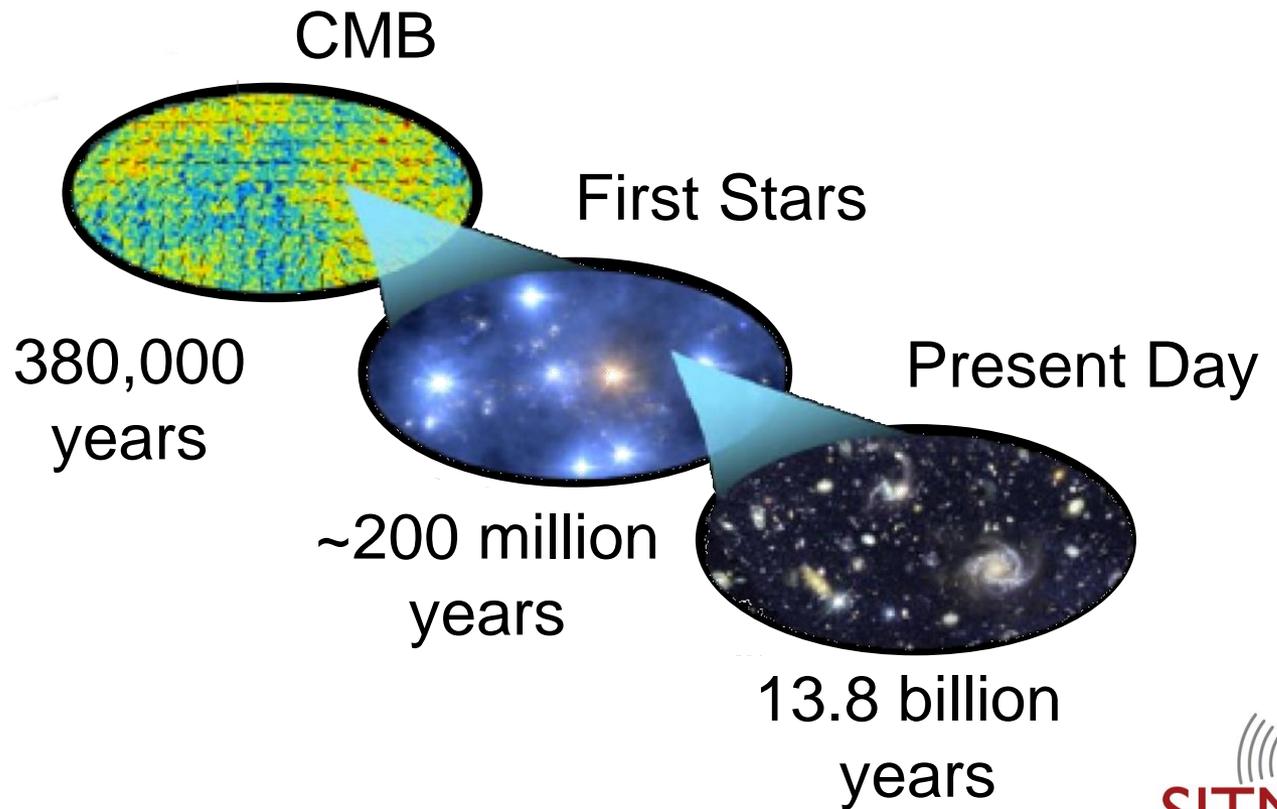


Outstanding Questions

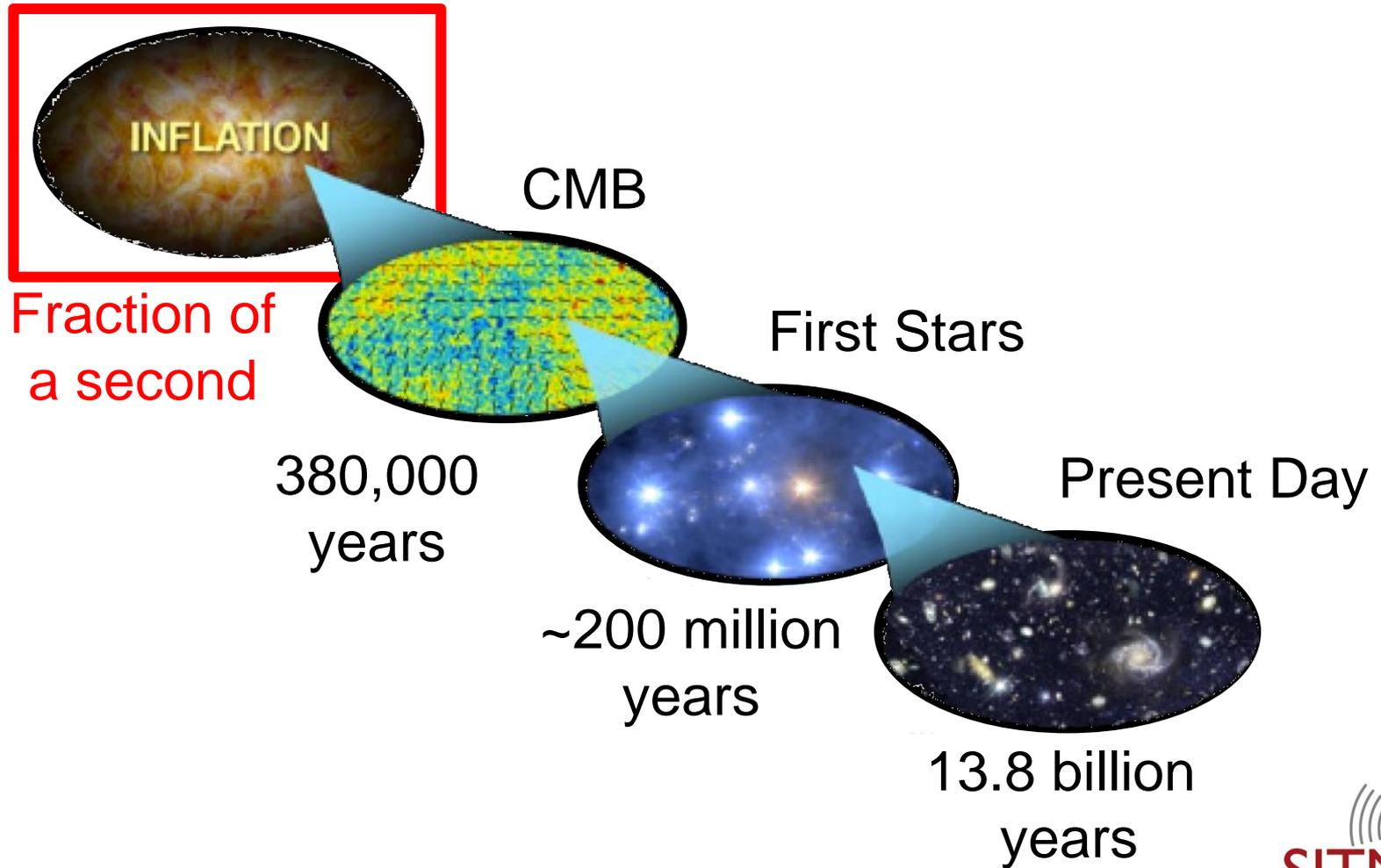
- How did the initial perturbations form?
- The **Horizon Problem**: Why does the Universe look the same in every direction?
- The **Flatness Problem**: How did the Universe end up almost perfectly flat?



Stepping back even further...

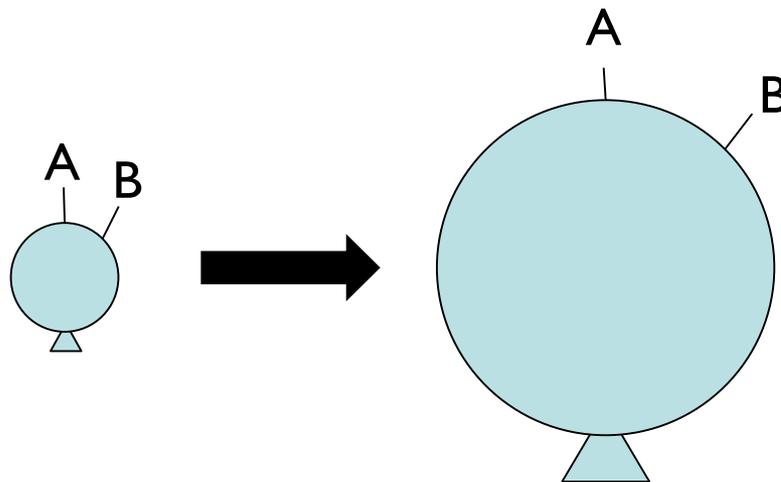


Stepping back even further...

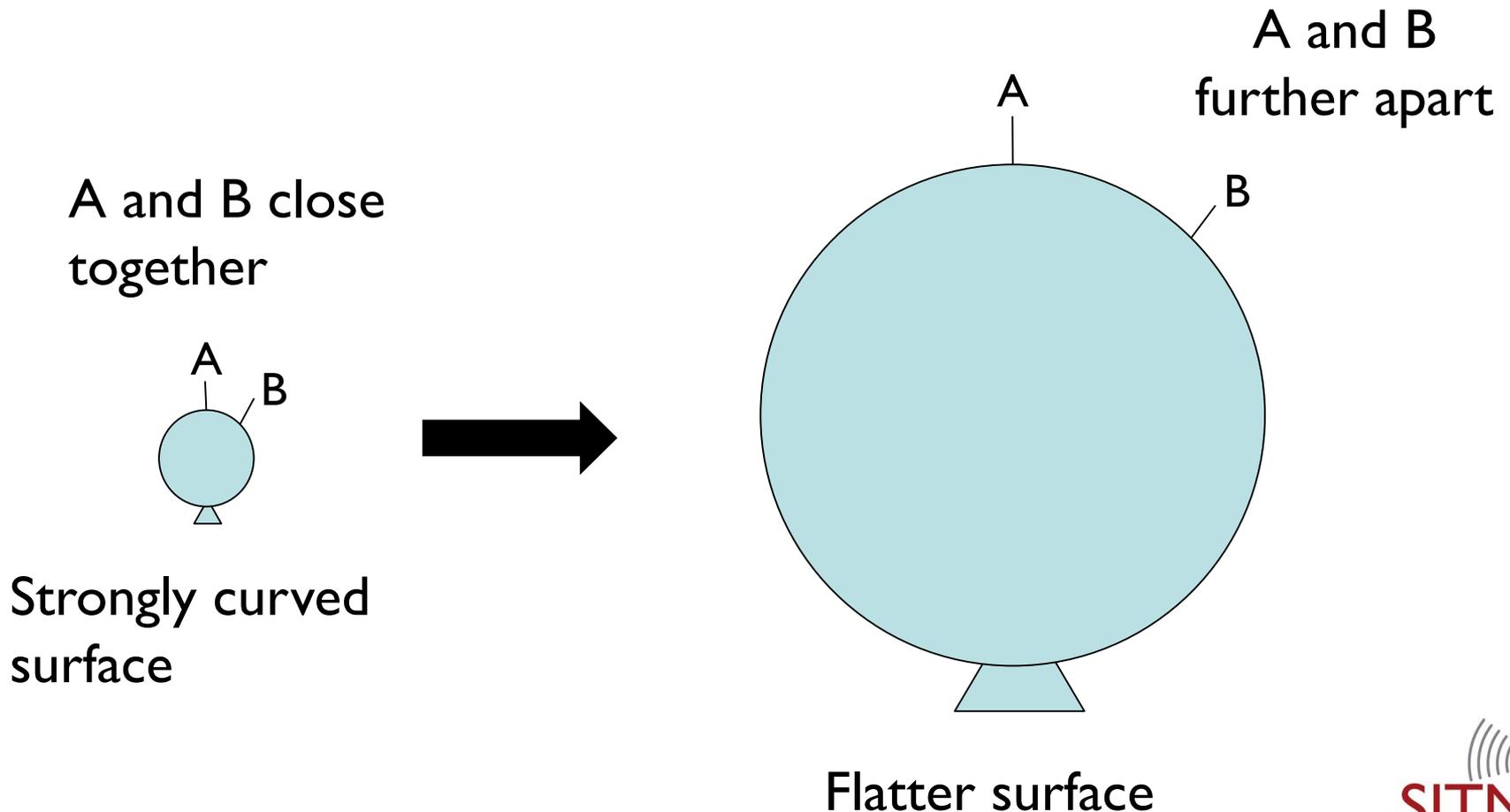


What is inflation?

- A brief time period where the size of the Universe increased very quickly (exponentially)
- **Space itself** expanded – like blowing up a balloon

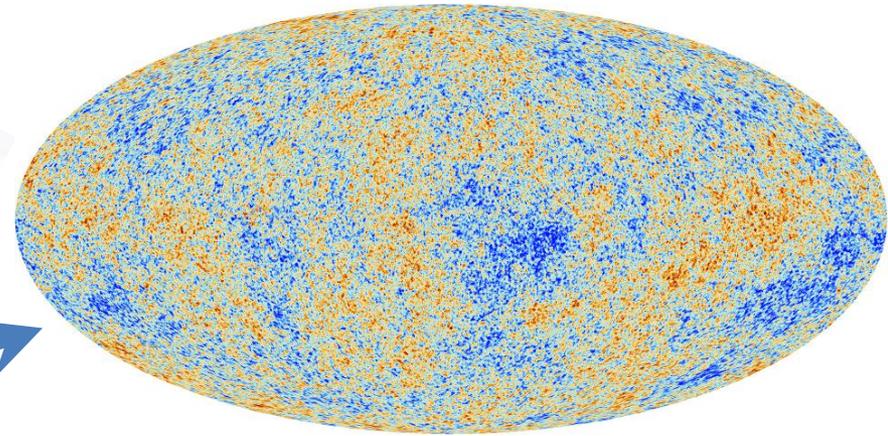
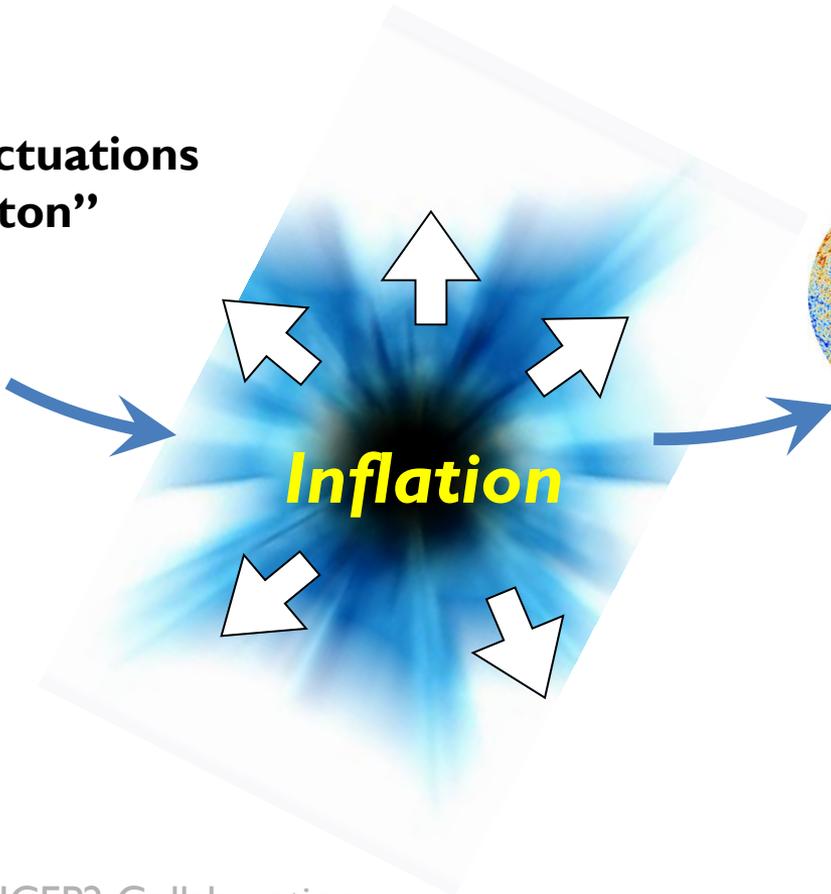


This solves the horizon and flatness problems



The initial density perturbations come from small-scale physics

Tiny fluctuations of “inflaton”



CMB density perturbations

What caused inflation?

What caused inflation?

- We still don't know for sure!

What caused inflation?

- We still don't know for sure!
- Theoretical physicists model a particle called an “inflaton” that decayed into more familiar light and matter particles when inflation ended.

What caused inflation?

- We still don't know for sure!
- Theoretical physicists model a particle called an “inflaton” that decayed into more familiar light and matter particles when inflation ended.
- Today the Universe is entering another period of accelerated expansion – caused by the equally mysterious “dark energy.”

Inflation Summary

- During inflation, space itself doubled its size many times very quickly
- It explains the flatness problem, the horizon problem, and the origin of structure
- We still don't know what caused it, but a similar effect is causing the Universe to expand increasingly quickly today.

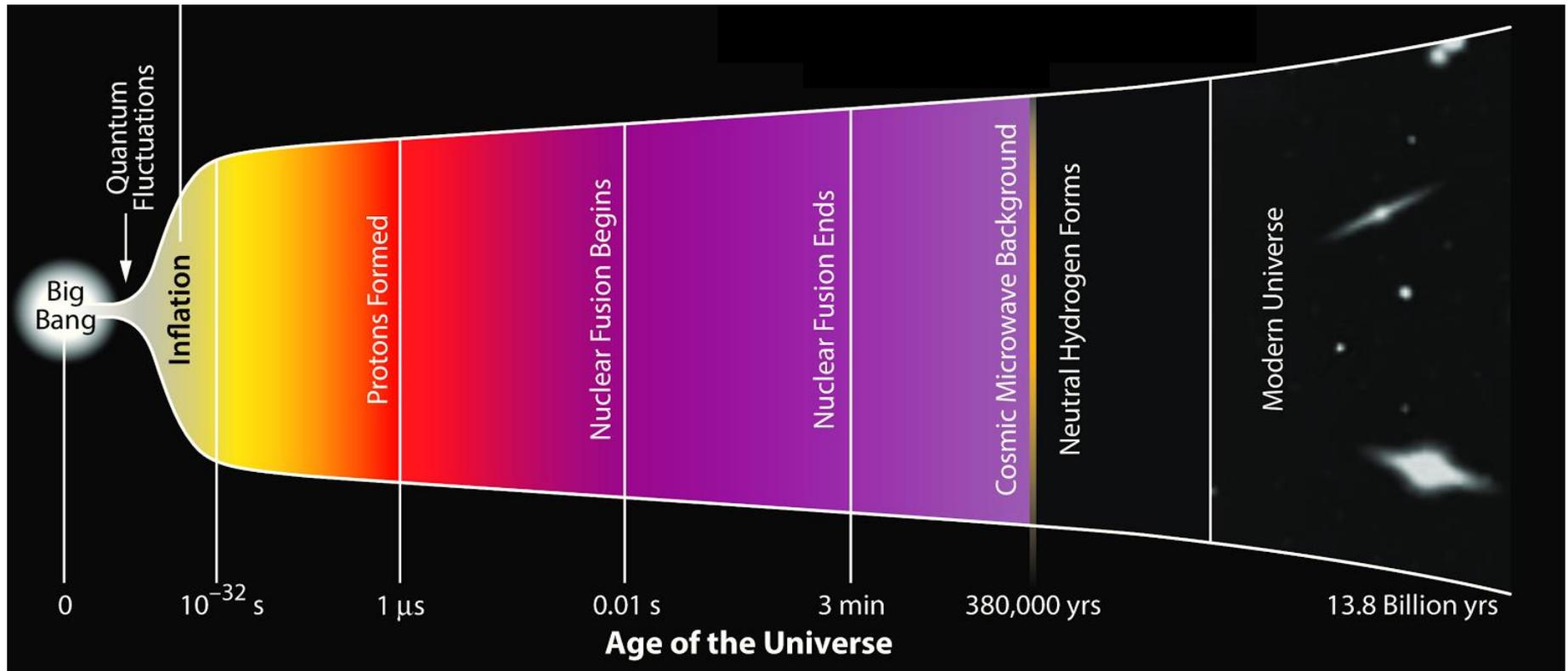
Questions?

How do we prove it?

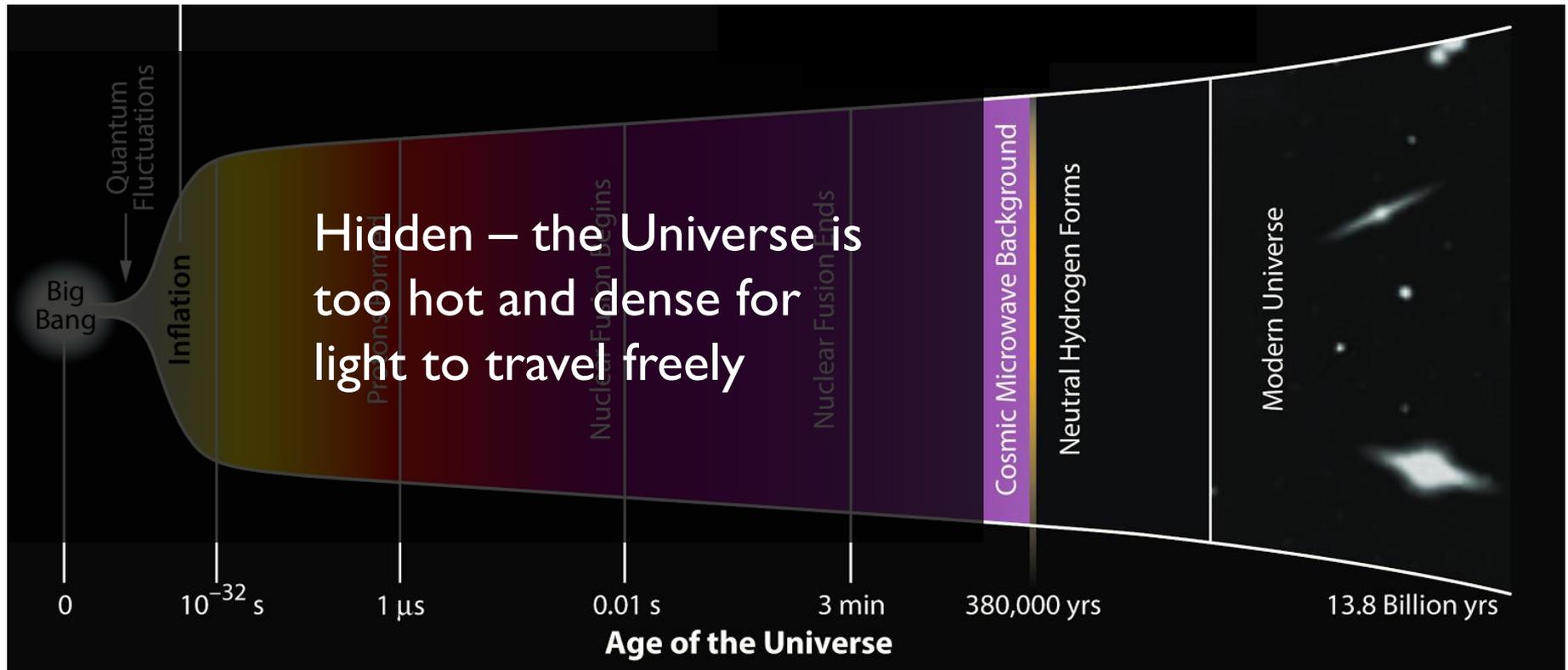
How do we prove it?

- Inflation solves a lot of problems. But to be a proper scientific theory, it needs to also make **experimentally testable predictions**.
- This is harder than you might think...
 - Must be something we don't know already
 - Must be something we can actually measure

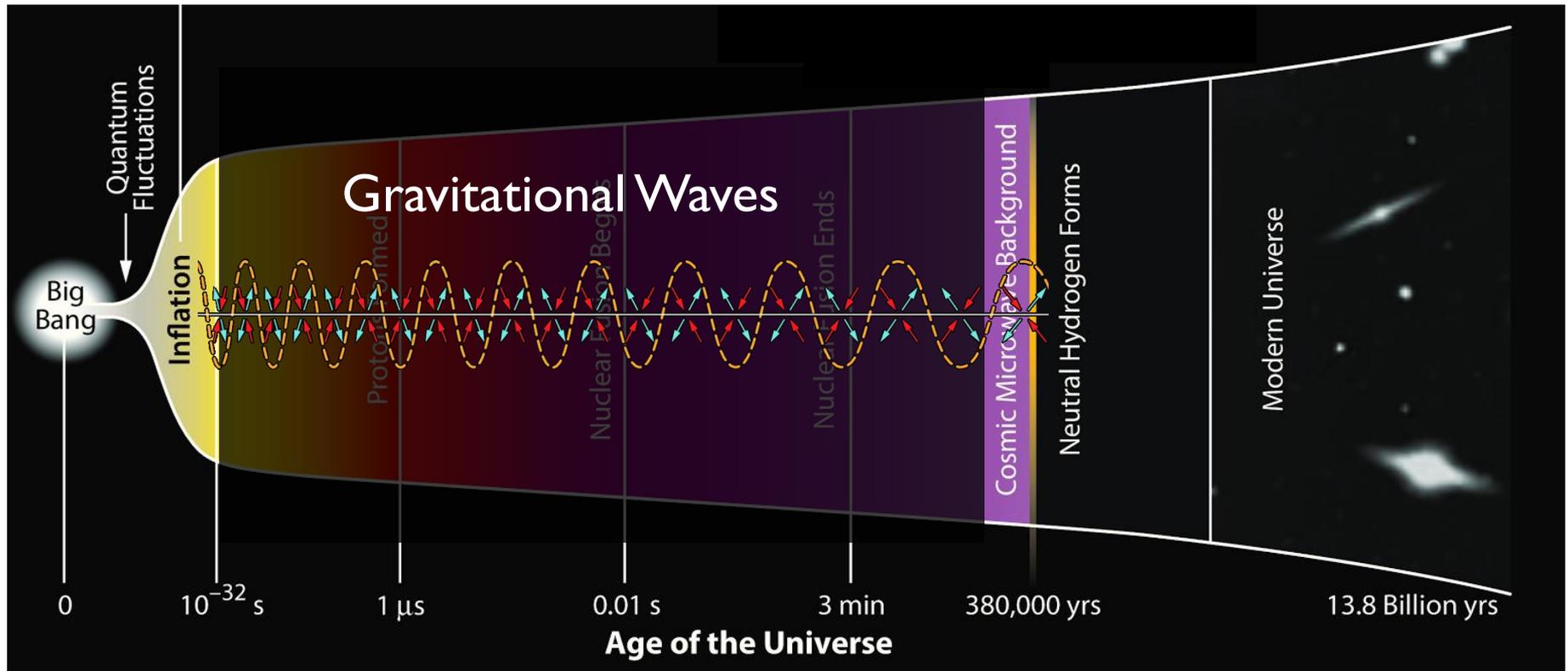
Problem: We need to observe the very beginning...



...but we can only use light to see back in time as far as the CMB

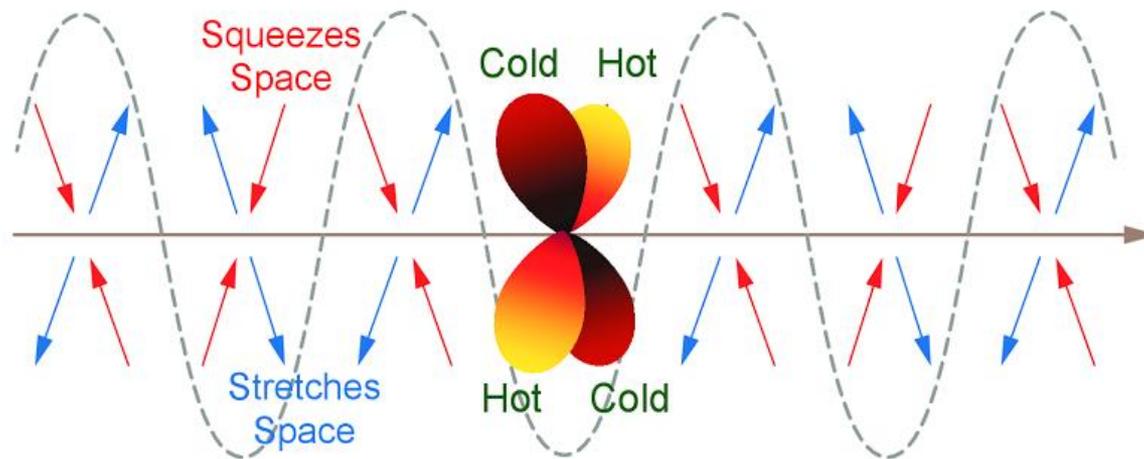


Solution: Look for a different kind of signal



What are Gravitational Waves?

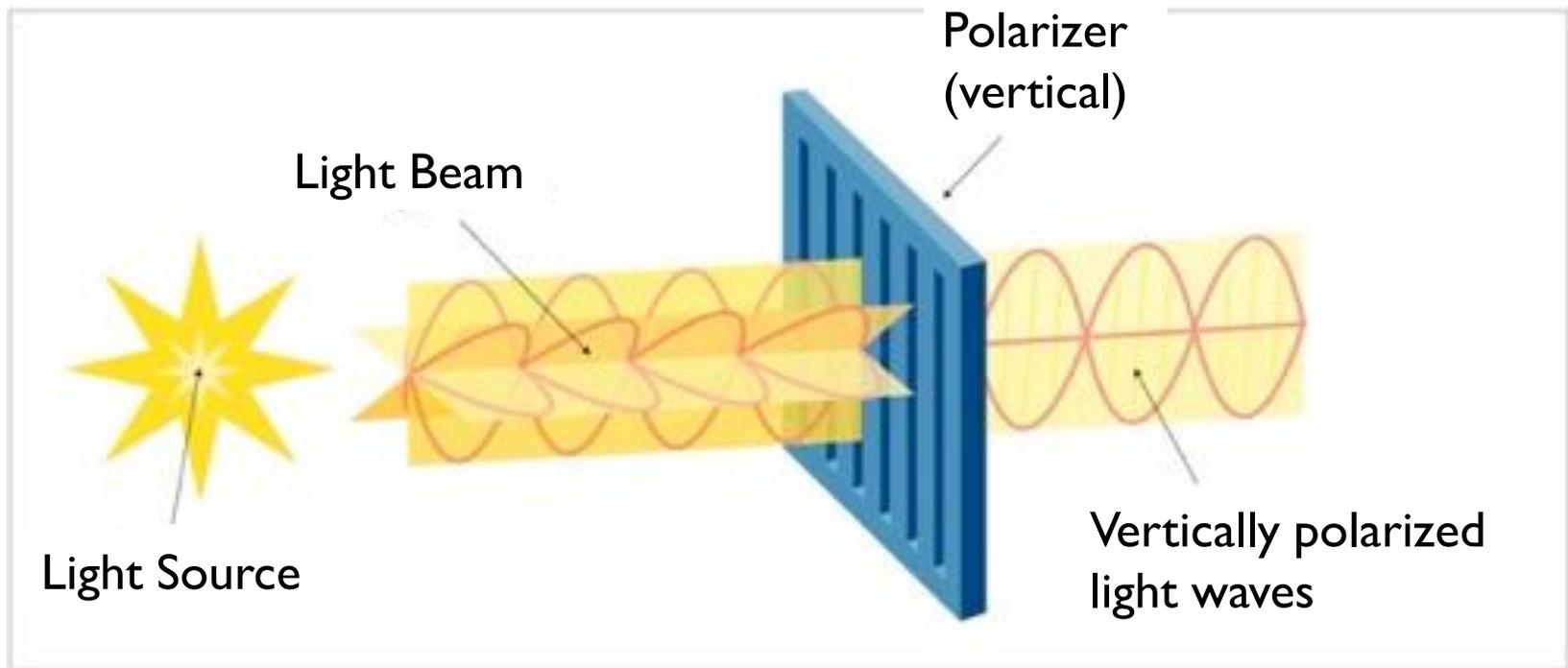
- “Stretching” and “squeezing” of space
- Produced during inflation, propagate freely throughout the Universe



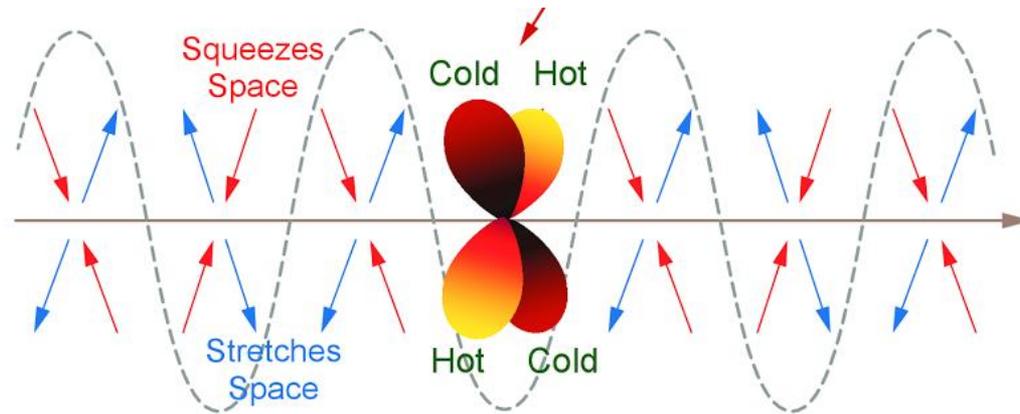
How do we see them?

- Gravitational waves create a unique polarization pattern in the CMB (“B-mode” polarization)
- But first, let’s talk about what polarization is...

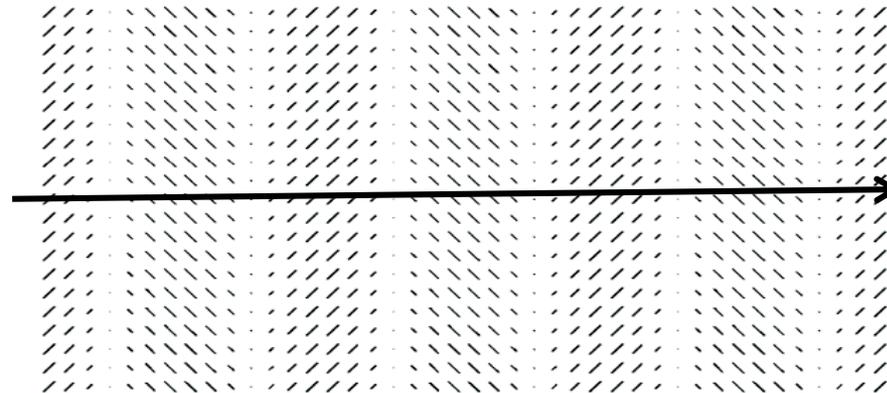
Light Polarization: A Brief Intro



How do we see them?



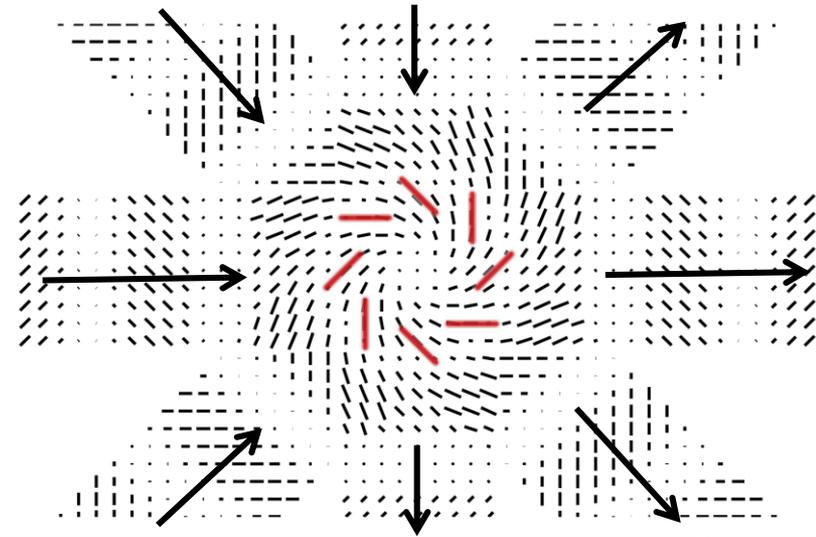
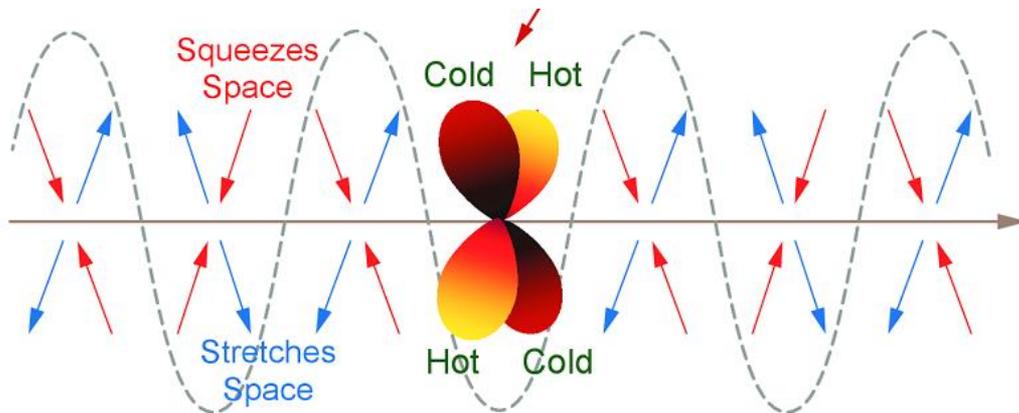
A single
gravitational
wave



Polarization
pattern from
this wave

How do we see them?

- The overall polarization pattern comes from many waves traveling in different directions



Pattern from many waves

Questions?

How do we see them?

- Gravitational waves can test inflation – now we have to detect them.
- We need a microwave telescope and a really great observing site...

The South Pole

South Pole CMB telescopes

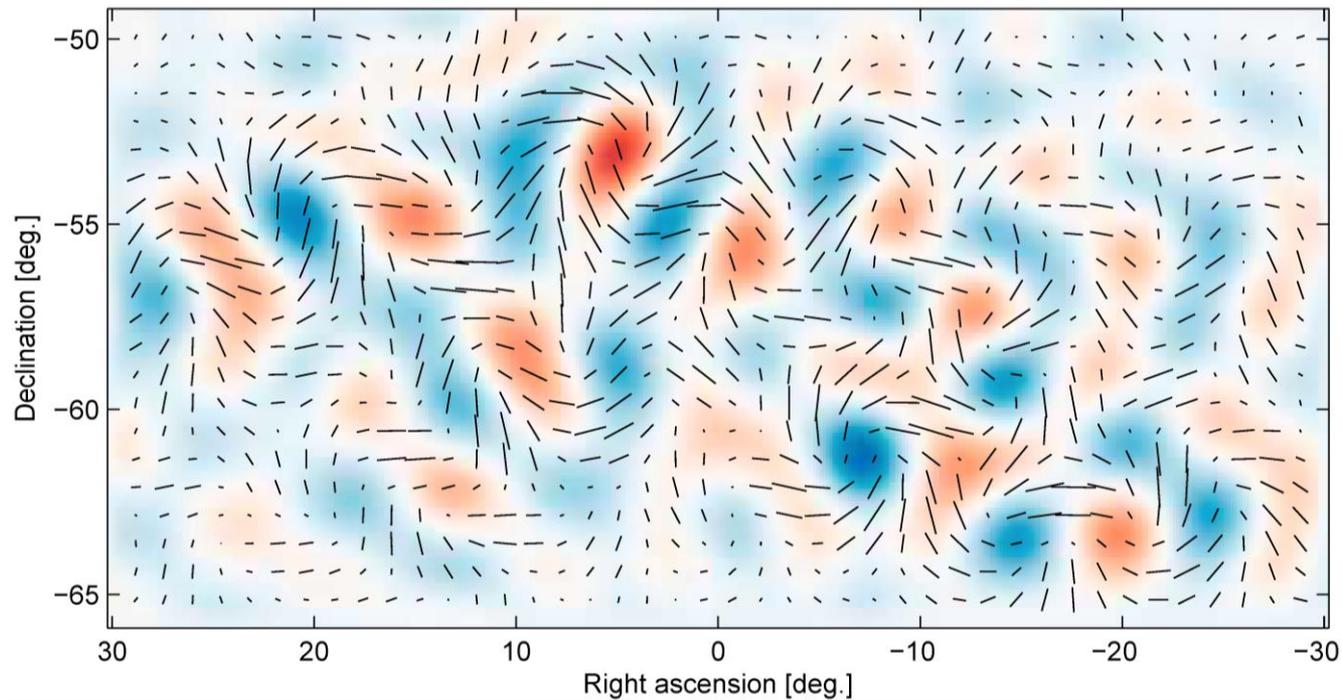


BICEP2

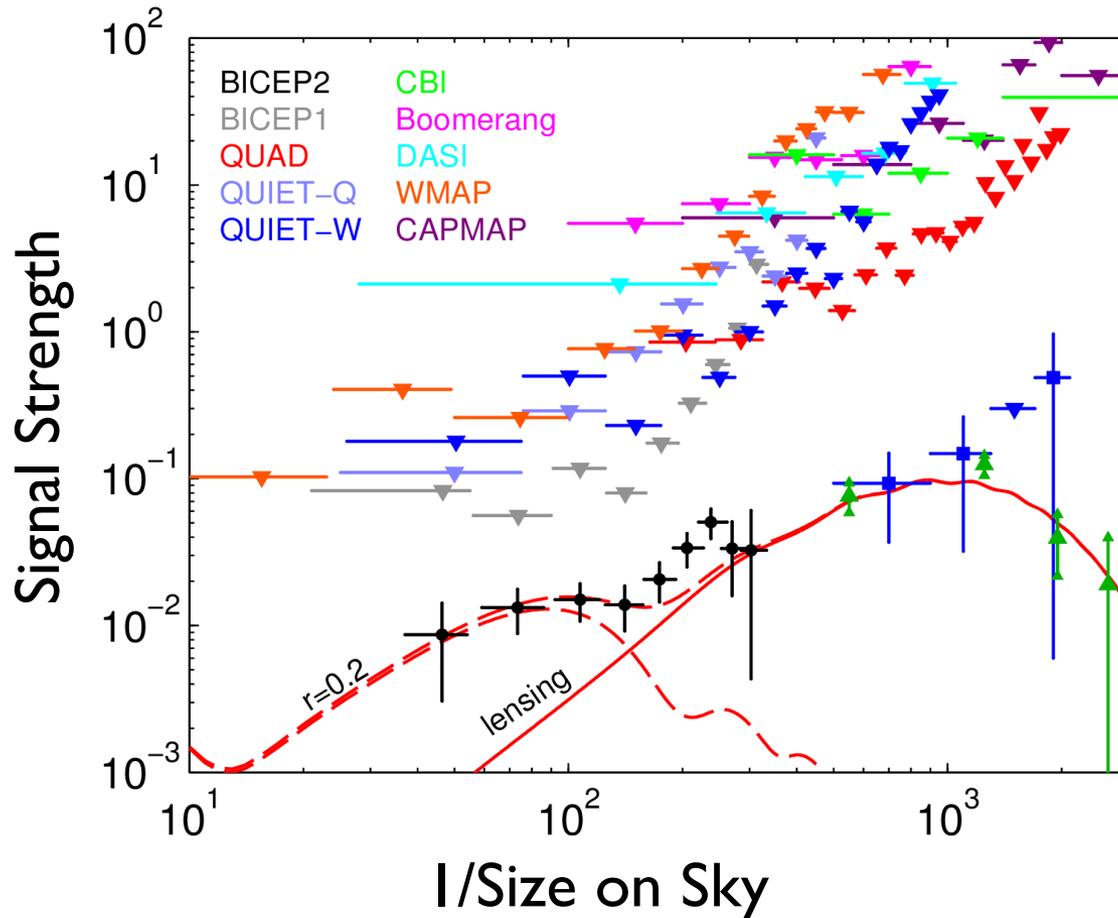


BICEP2 results

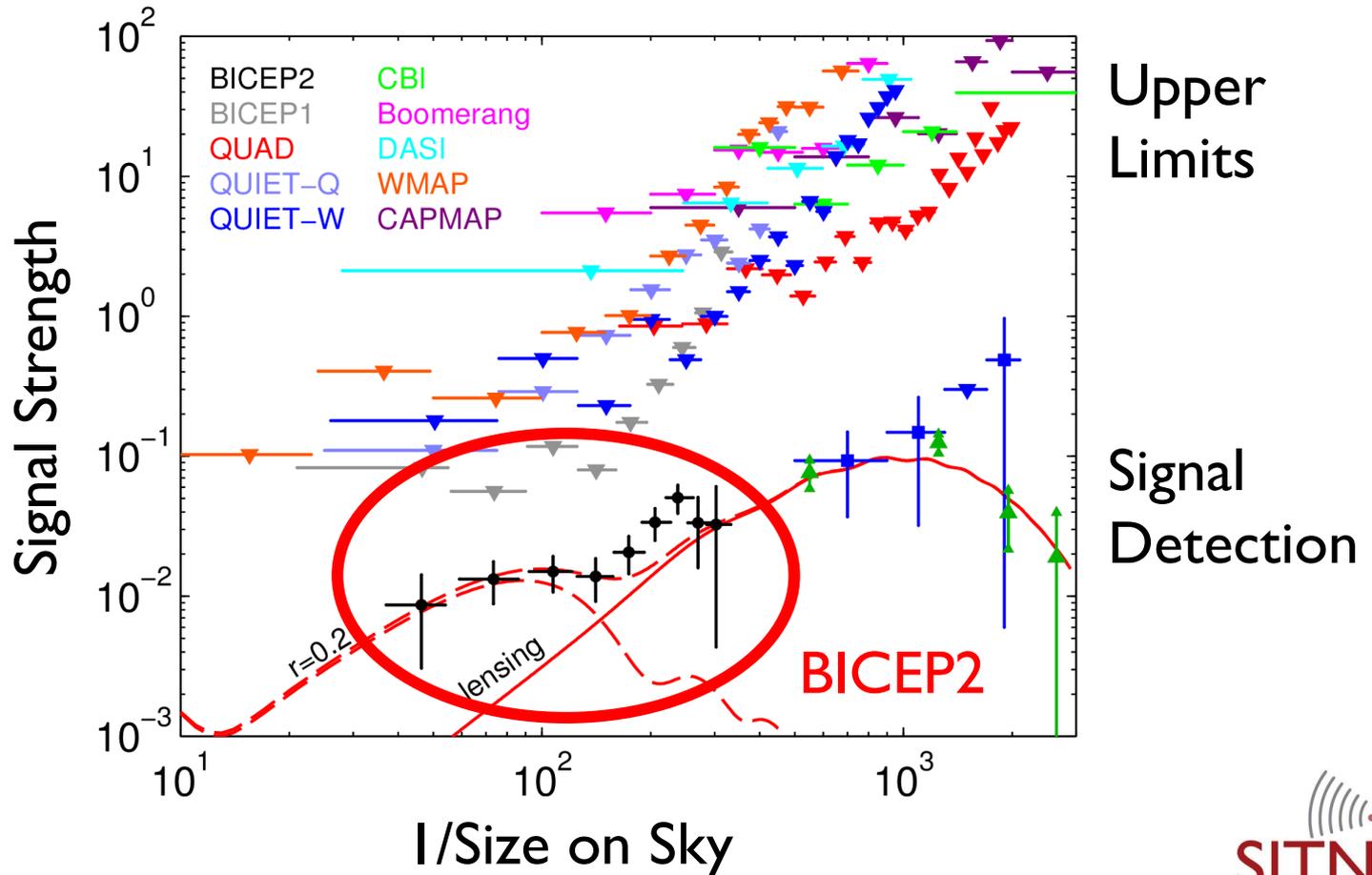
- March 17, 2014 – B modes detected!



Comparison to earlier results

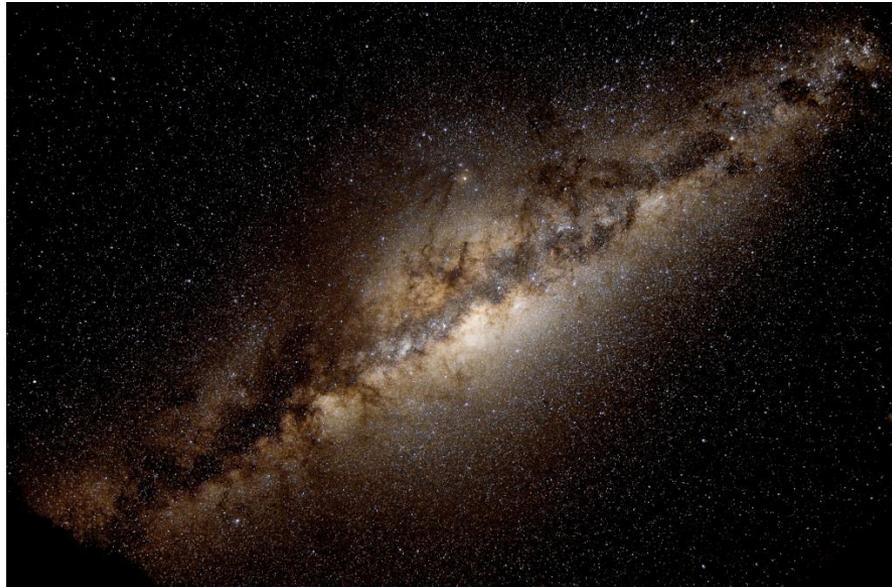


Comparison to earlier results



Is it really inflation?

- Gravitational waves...or dust?
- Need more data – results coming soon!



Summary

- Gravitational waves are a “smoking gun” for inflation
- BICEP2 detected a signal that could be gravitational waves!
- Scientists around the world are still working hard to figure out the signal’s origin – dust, gravitational waves, or both?

Final Summary



hot + dense
nearly formless
chaos

cool + sparse
structured
cosmos

Thank you!

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