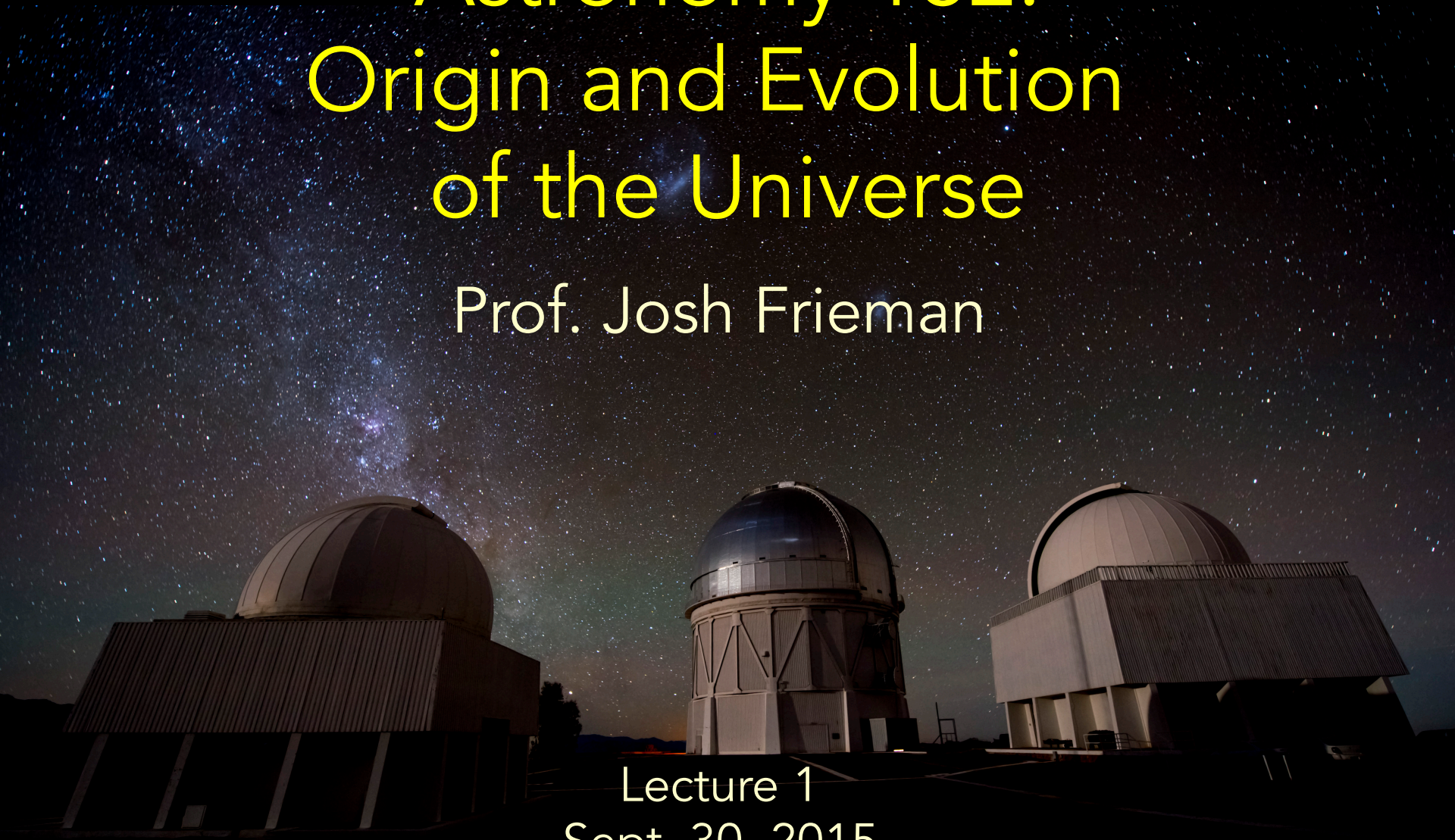
Astronomy 182: Origin and Evolution of the Universe

Prof. Josh Frieman



Lecture 1
Sept. 30, 2015

Course Information

- Class meets Wed., Fri. 4:30-5:50 pm in ERC 576
- Prof. Josh Frieman (ERC 453):
  - Email: frieman@fnal.gov, jfrieman@uchicago.edu
  - Tel: 702-7971 (UC); 847-274-0429 (cell)
  - Office hours: WF 1-2 pm or by appointment

- TA Jason Poh (ERC 450):
  - Email: jasonpoh@uchicago.edu
  - Office hours: M 4-5 or by appointment

Course Information

- Class website:
  - http://astro.uchicago.edu/~frieman/Courses/A182-2015/
  - Includes lecture schedule, lecture slides, course syllabus, required work, textbook info, links to cosmology websites
- U. Chicago Chalk site:
  - ASTR 18200 (Autumn 15)
  - Plan to migrate/duplicate all of the above.
  - Will use for labs, announcements, grading, uploading of assignments.

Textbooks & References

- Primary text:
  - *Foundations of Modern Cosmology*, by S. Hawley and K. Holcomb, 2nd ed., Oxford UP
- Secondary text:
  - *Big Bang: The Origin of the Universe*, by S. Singh
- Both books available at UC Bookstore
- HH also available on-line through UC Library (links from Chalk and course websites)
- Course website lists a few other texts that may be of interest as well as a list of cosmology sites I'd like your help in updating.

Required Work

- Two write-ups on computer-based labs that Jason will go over with you next week (25%).
- Four short essays on assigned HH chapters (50%):
  - ~3 page summaries in your words, plus ~1-2 pages of questions on topics you least understood or related questions you may have. Will use these to identify topics to clarify in class or in FAQ that Jason will provide.
- Final Essay (25%):
  - 3-page essay in style of newspaper or magazine article on a current topic in cosmology. Should discuss choice of topic & primary reference with me beforehand.

Course Level

- There are no prerequisites for this course: no prior exposure to cosmology is assumed.
- Although mathematics is the language of physical science, this course will be largely conceptual and descriptive and non-mathematical.
- The 2nd lab will involve simple mathematical manipulations: plugging numbers into a formula, making an x-y plot of the results, and calculating the slope of a line (with instructions).
- For those who *do* want to delve further into the mathematics, I can provide supplementary material.

Course Goals

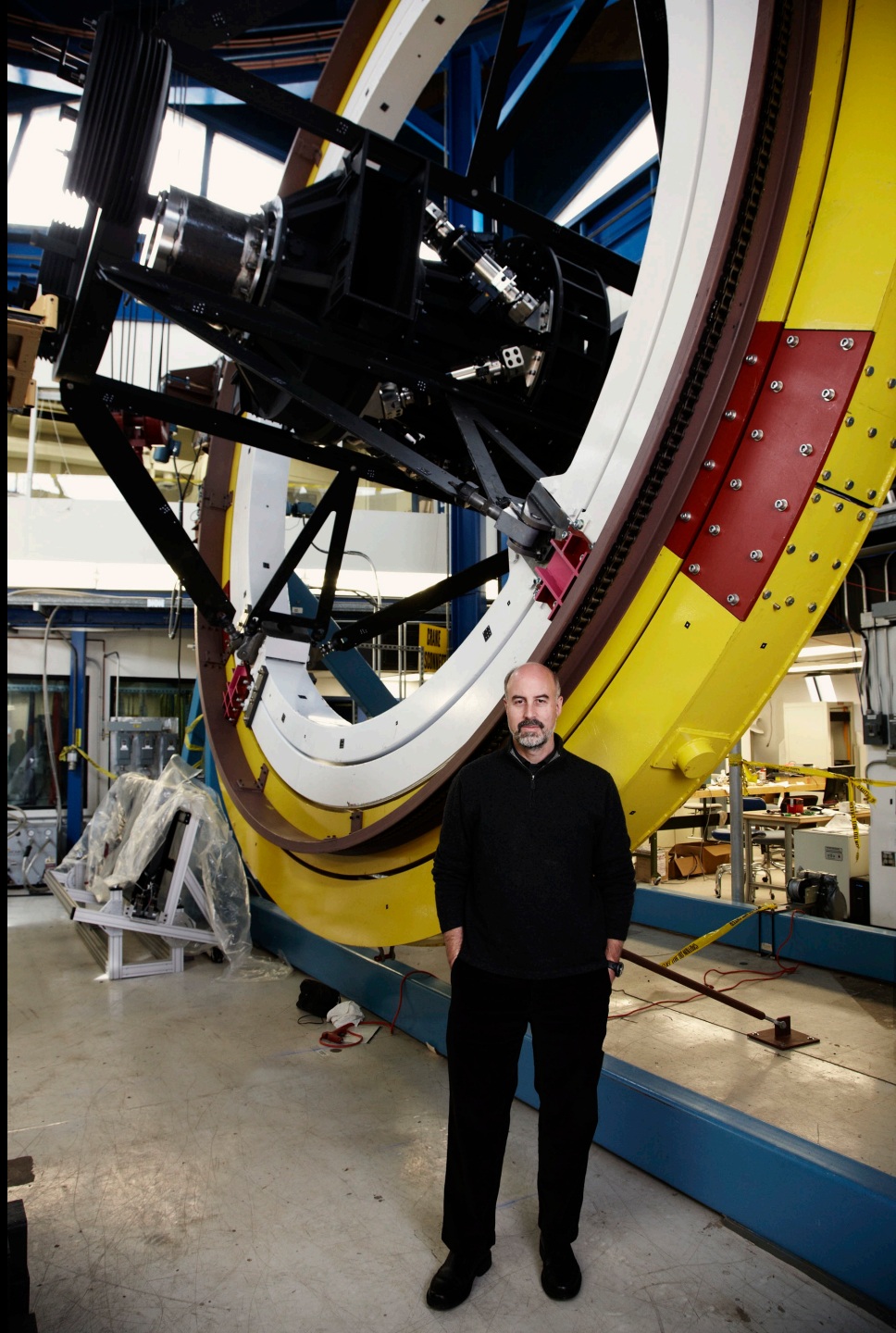
- Course will focus on the Big Ideas in modern cosmology and aim to convey the intellectual excitement of this endeavor.
- Develop an appreciation for and understanding of the current renaissance of cosmology, stemming from the marriage of particle physics and astrophysics and from rapid technological developments.
- Cosmology as a data-rich science: interplay of observations with fundamental theory.
- Distinguish well-established facts from speculative ideas: science as the evolution of some of the latter into the former.

Ask Questions!

- Interrupt me if I don't see your hand.
- If something isn't clear to you, chances are it's not clear to some others as well.
- There are no stupid questions.

About Me

- Prof. of Astronomy & Astrophysics, Kavli Institute for Cosmological Physics
- Staff Scientist, Fermilab
- BS Stanford 1981
- PhD U. Chicago 1985
- Theoretical & Observational Cosmology
- Cosmic Surveys: Sloan Digital Sky Survey, Dark Energy Survey (Director)



Understanding the Cosmos provides meaning and a profound connection to it

The sky will be much friendlier then than now,
A part of labor and a part of pain,
And next in glory to enduring love,
Not this dividing and indifferent blue.

Wallace Stevens
``Sunday Morning"

Today

Overview of the course:

Some themes and highlights that we'll later cover in more detail

This week: read first 2 Chapters of HH (historical background).

Cosmology

The study of the origin and evolution of the Universe as a whole

Cosmology: an ancient endeavor

- How did the world around us come into being?
- Has it always been like this or has it evolved?
  - Static vs. Dynamic Universe
- If the Universe is changing, what was it like before and what will it be like in the future?
- (How) did it begin? (How) will it end?

- Cosmos: order

Creation Myths

- The Universe evolved from a beginning in time.
- Examples:
  - Babylonian: Enuma Elish
  - Judeo-Christian: Genesis
  - Hindu: Rig-Veda
  - Chinese: Pan Gu
  - …

Enuma Elish

2nd millenium BC, Mesopotamia: creation story grounded in observations of Tigris & Euphrates river deltas

`When a sky above had not been mentioned
And the name of firm ground below had not been thought of;
When only primeval Apsu, their begetter,
And Mummu and Ti'amat--she who gave birth to them all--
Were mingling their waters in one;
When no bog had formed and no island could be found;
When no god whosoever had appeared,
Had been named by name, had been determined as to his lot,
Then were gods formed within them.'

Universe began in watery chaos. Apsu: sweet waters. Ti'amat: sea (chaos). Mummu: mist? From this chaos came new gods of silt, horizon, and sky.

Aristotle

- Earth surrounded by nested, crystalline spheres that constitute the heavens.
- Spheres rotate around the stationary Earth, carrying heavenly bodies with them.
- Separation of heavenly & earthly realms.
- Perfect spherical structure finite in extent but infinite in time: no beginning or end: heavens are *static*, unchanging.

Static vs. Dynamic Universe in modern times

- Big Bang Model:
  - The Expanding Universe originated in a singular beginning in time, roughly 14 billion years ago. Now overwhelming evidence for this, as we shall explore in this course.
- Steady State Model:
  - The Universe is expanding but its large-scale properties are not evolving in time. Popular theory in the 1950's to early 1960's.

Modern Science

- The Universe is knowable through repeatable observations or experiments.
- The Universe can be described in terms of universal physical laws.

- This approach first codified in the Scientific Revolution, through the work of Copernicus, Brahe, Kepler, Galileo, and Newton.

Modern Cosmology

- We cannot yet create Universes in the laboratory and study them.
- We observe stars, galaxies, cosmic radiation, etc., and use them as an archaelogist uses pottery shards, to reconstruct what the Universe was like at earlier times. The goal is to weave a coherent story of cosmic evolution based on our evolving understanding of physical laws.
- This approach has (so far) been enormously successful: we have a coherent cosmic history going back to a tiny fraction of a second.

Basic Facts about the Universe

1. It's very OLD. How old is it?

Basic Facts about the Universe

1. It's very OLD. 13.8 billion years

Basic Facts about the Universe

1. It's very OLD. 13.8 billion years

   How do we know?

Basic Facts about the Universe

1. It's very OLD. 13.8 billion years

   How do we know?
   It contains old artifacts:
   - Earth: 4.5 billion years (radioactivity)
   - Sun: 5 billion years
   - Oldest stars: ~13 billion years
   - +Cosmic Microwave Background measurements


Globular
Star Cluster:
very old stars
~13 billion years

Basic Facts about the Universe

2. It's very BIG. How big?

Basic Facts about the Universe

2. It's very BIG. The most distant objects we can see are about

100,000,000,000,000,000,000,000 miles away
~30 billion light-years

Light travels at 186,000 miles per second.
In one year, light travels 6 trillion miles:
6,000,000,000,000 miles = 1 light-year
The sun is 8 light-minutes away.
The nearest stars are a few light-years away.

Basic Facts about the Universe

3. The visible Universe contains billions of galaxies.

Galaxies visible with the naked eye in the Southern hemisphere

Galaxies: ~60,000 light-years across, contain ~10 billion stars,
Rotation period ~ 200 Million years (typically)

Image taken with the Dark Energy Camera

Galaxies do not exist in isolation

They live in and are shaped by a variety of environments--proximity to other galaxies with which they occasionally interact:

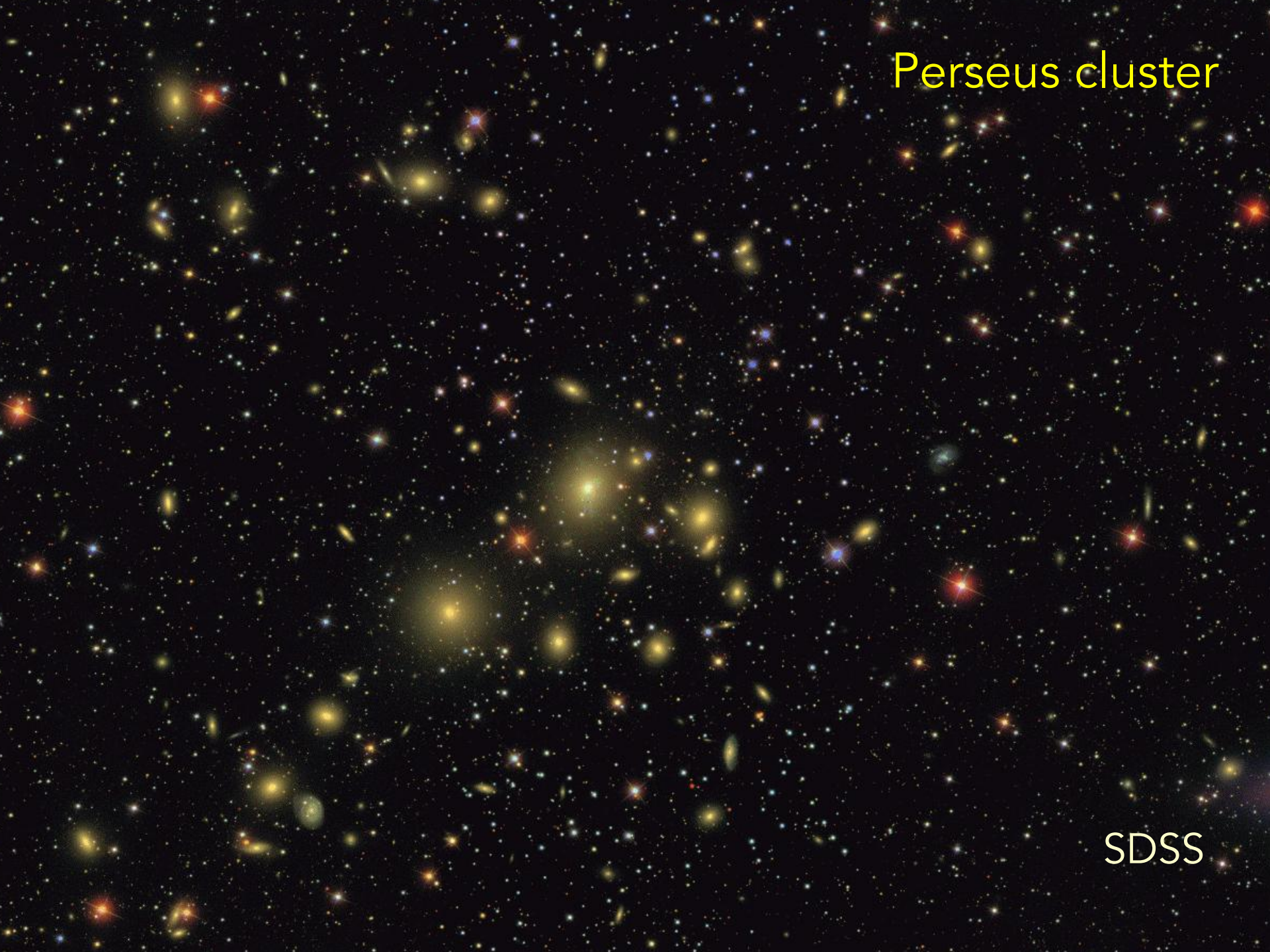
- Pairs
- Groups
- Clusters
- "Superclusters" (Cosmic Web)

- Hierarchy of Structure

Galaxies clump together into Galaxy Clusters

Image taken with the Dark Energy Camera

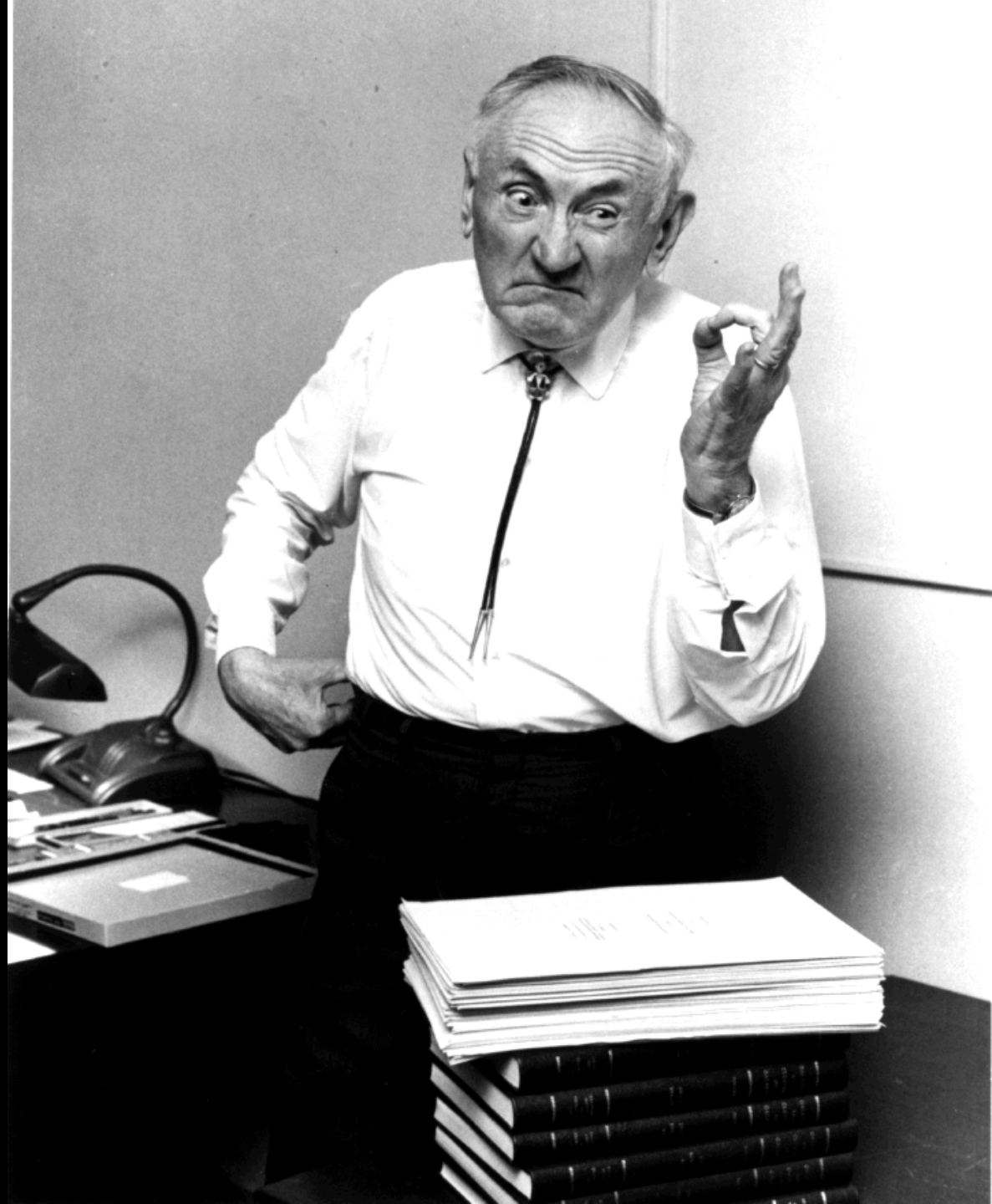
Clusters of Galaxies: Size ~ few Million light years
Mass ~ 1 quadrillion (1000 x 1 trillion) M_{sun}
Contain ~10s to 1000s of galaxies
Evolution time scale: ~few billion years


Perseus cluster
SDSS

Coma Cluster of Galaxies

Fritz Zwicky
(1898-1974)

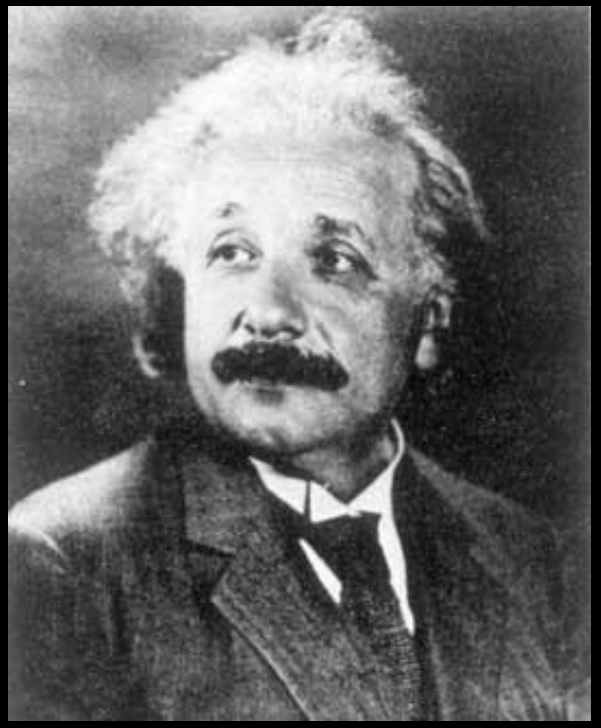
1930's: studied the motions of galaxies within the Coma cluster, found they are moving too fast, ~1000 km/sec, to remain confined by Coma's gravitational field. Why is Coma still there?



Dark Matter (F. Zwicky)

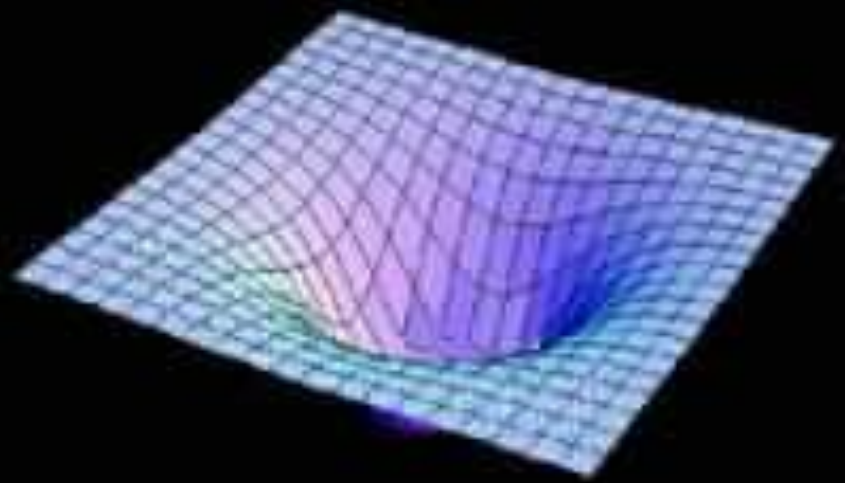
- The galaxies in Coma cluster are moving around faster than we can explain.
- The gravity of something *that we can't see* must be keeping the galaxies from flying off into space: Dark Matter
- Clusters are mostly made of dark matter: galaxies are like sprinkles on dark matter ice cream.
- We know dark matter is there because it exerts gravitational pull on the galaxies we can see in clusters.

Einstein's Theory of Gravity: General Relativity



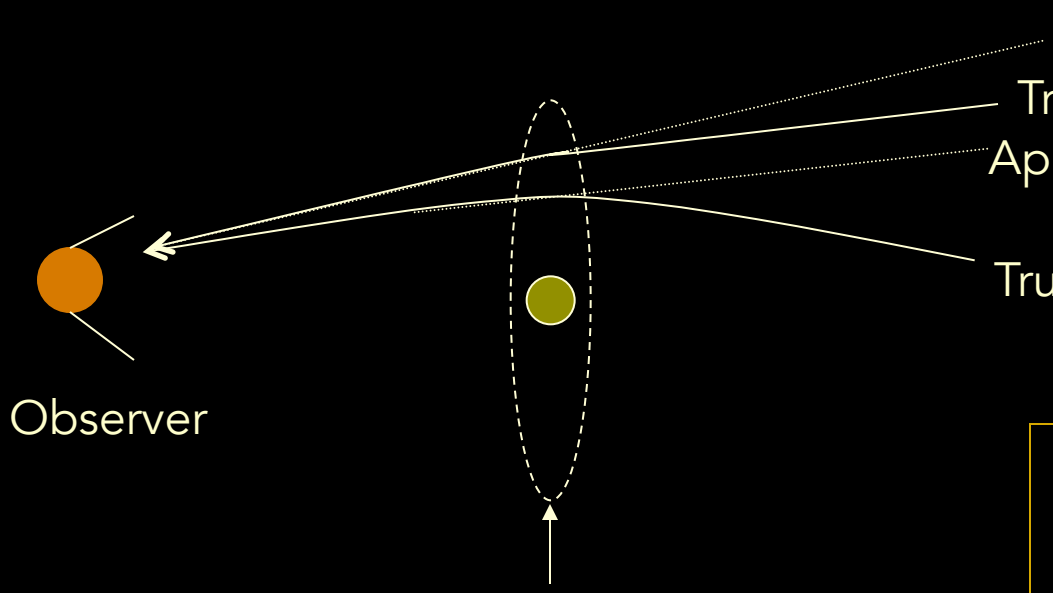
Matter and Energy curve Space-Time

Everything, including light, moves in this curved Space-time

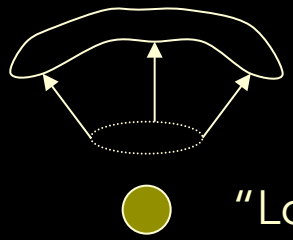


A massive star attracts nearby objects by distorting spacetime

Gravitational Lensing



Objects farther from the line of sight are distorted less.



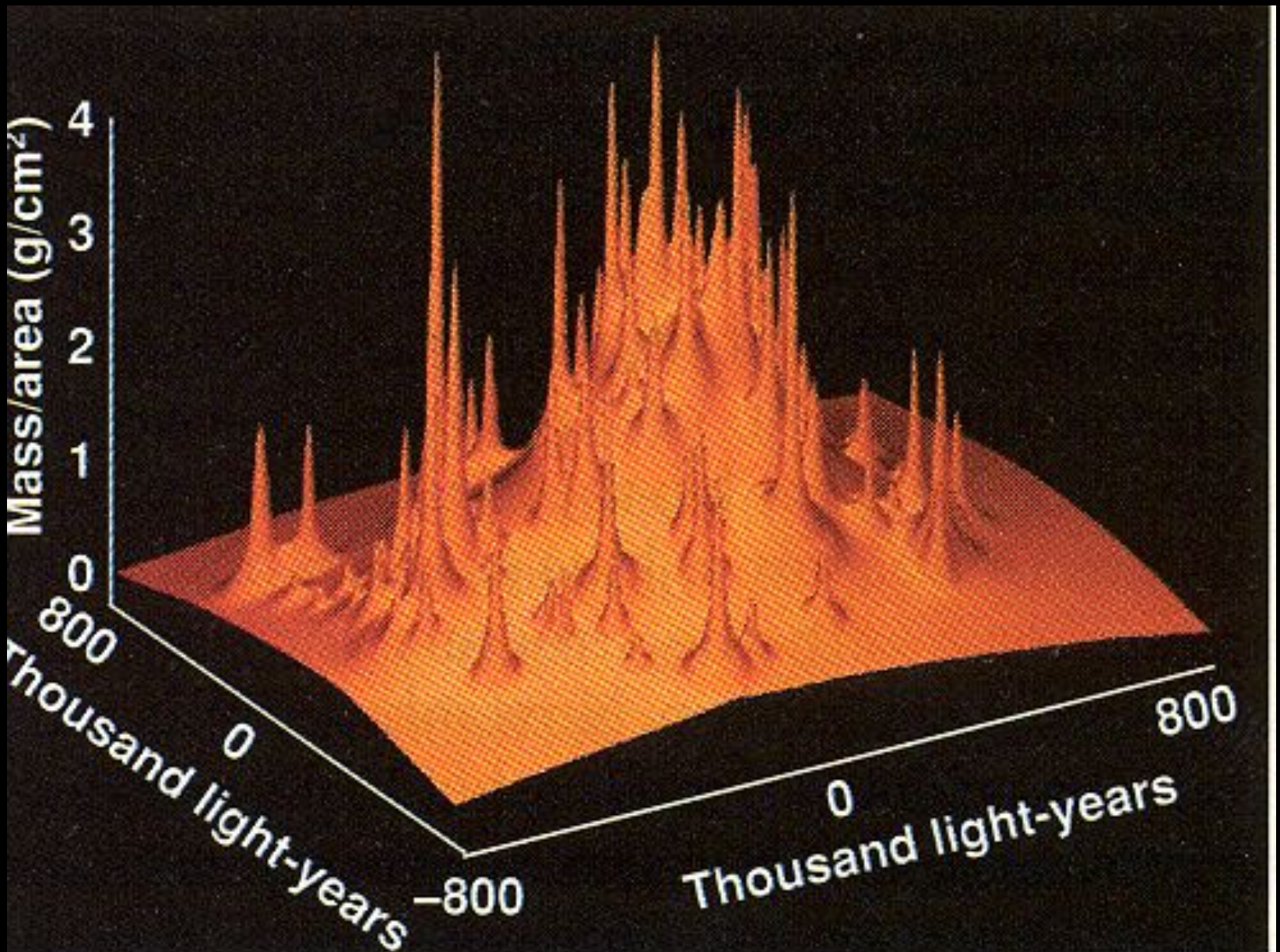
"Looking into" the lens: extended objects are tangentially distorted...

“Seeing” Dark Matter in a Cluster

Abell 2218 HST

Mass Distribution in a Cluster of Galaxies

inferred from gravitational lensing



Mass Distribution in a Cluster of Galaxies

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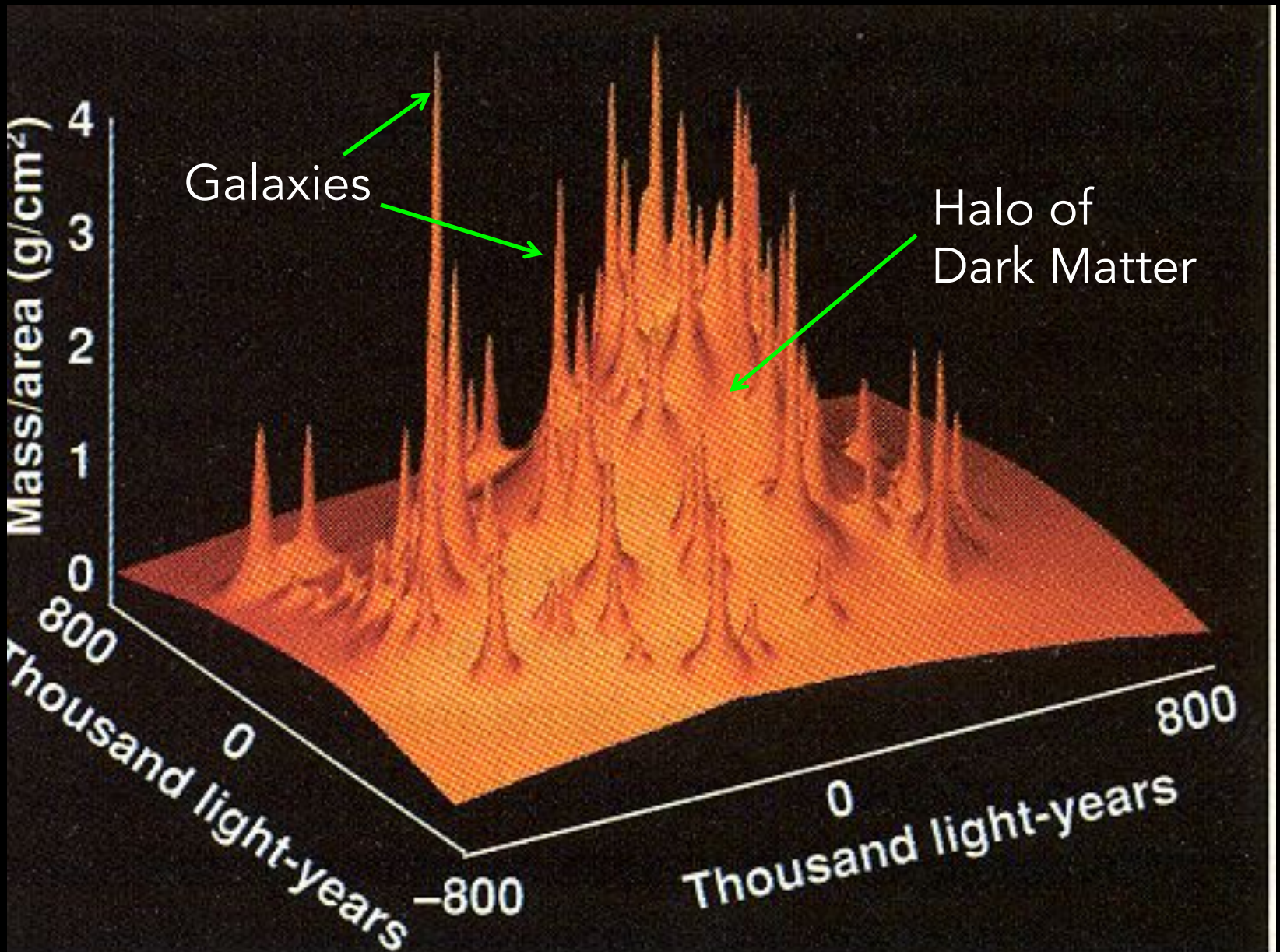
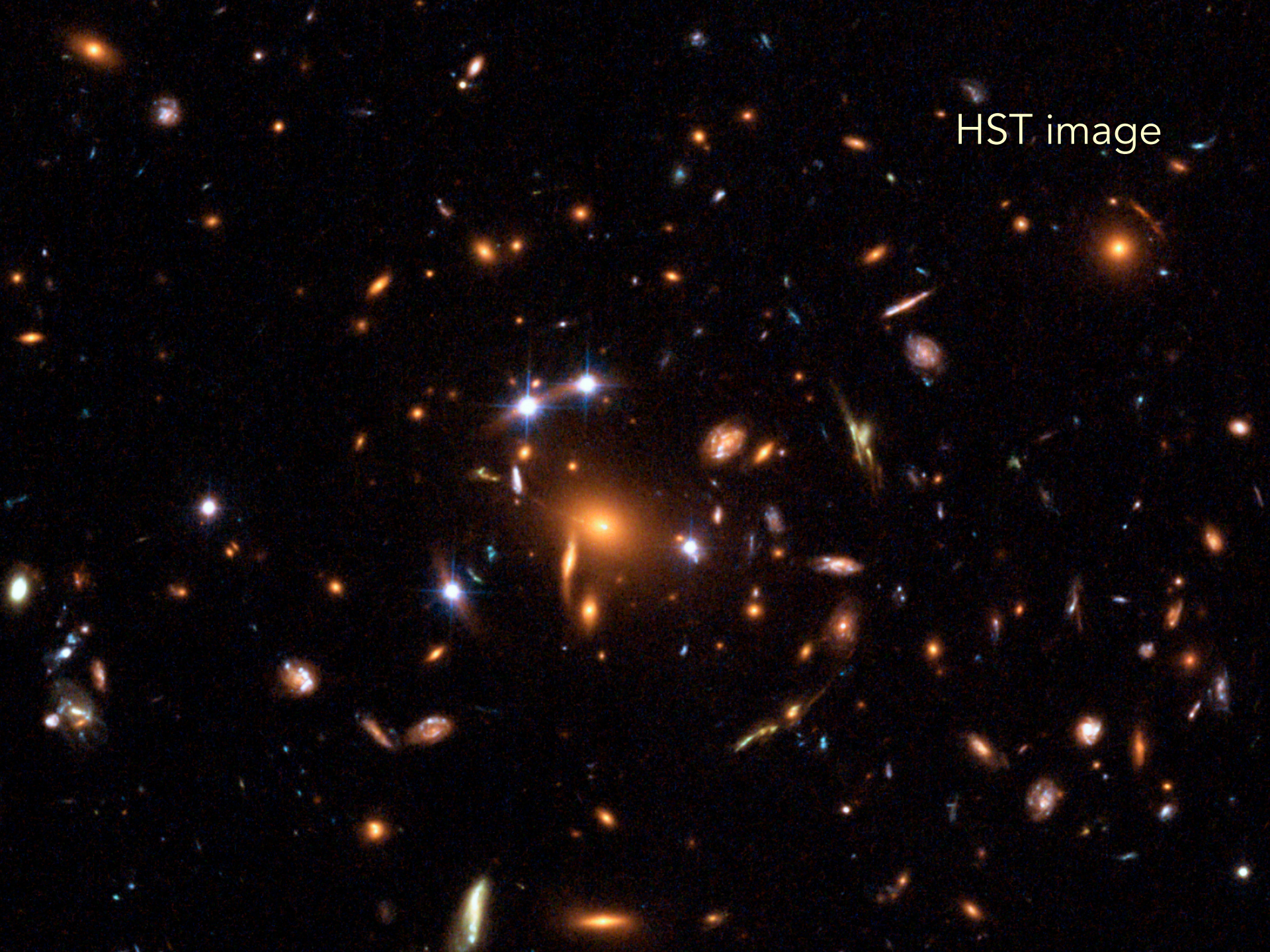
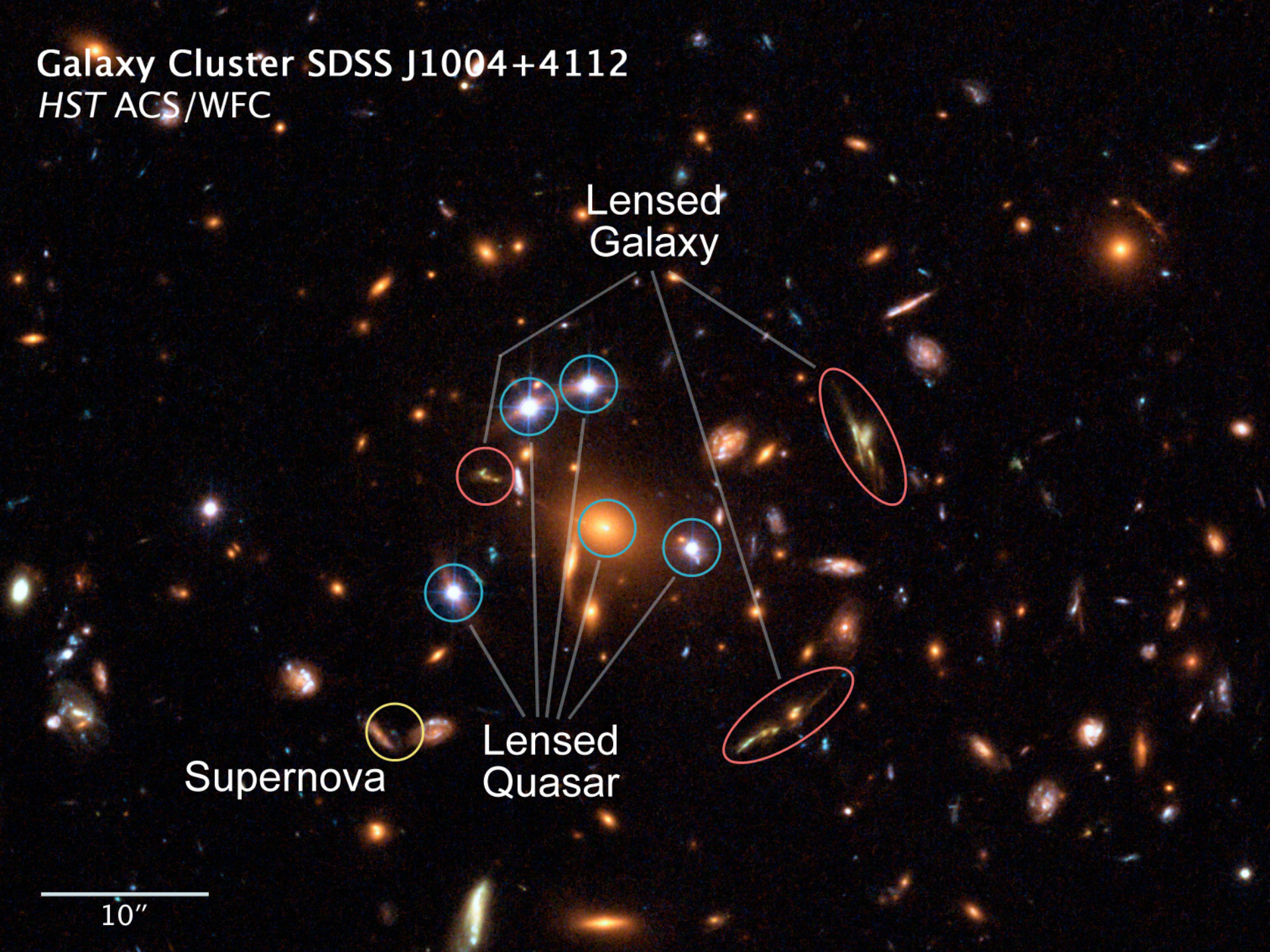
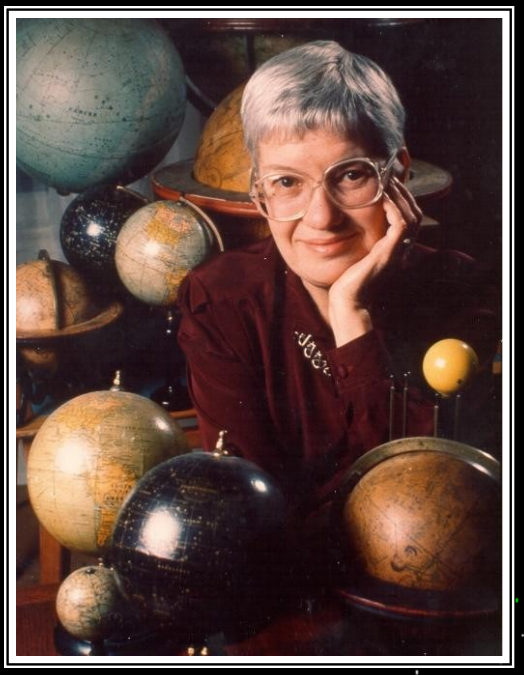



HST image


Galaxy Cluster SDSS J1004+4112
HST ACS/WFC
Lensed Galaxy
Supernova
Lensed Quasar
10″

Rotation of Stars around Galaxies



Vera Rubin
(1970's)

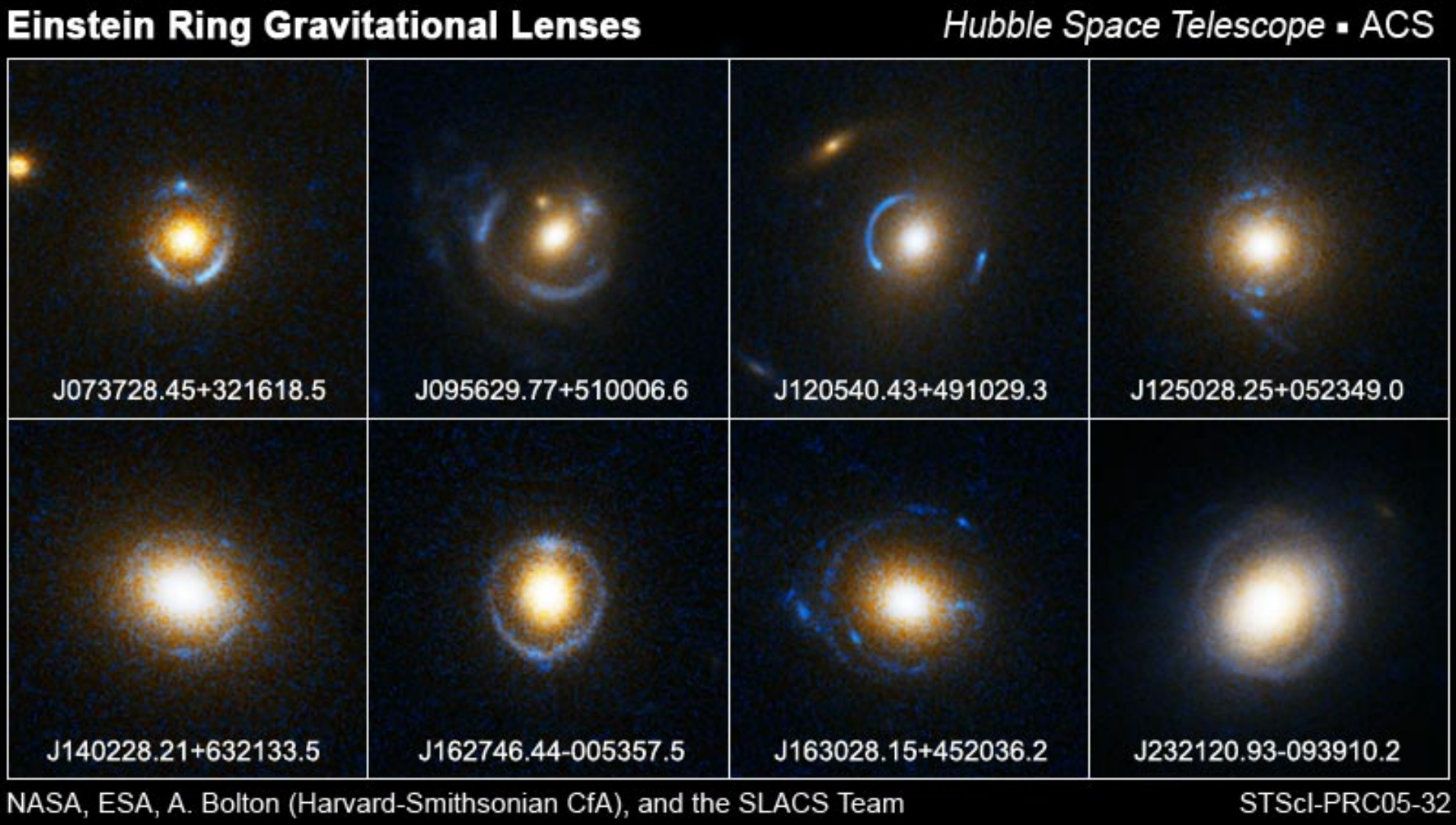
Most of
the mass
in galaxies
and clusters
is dark

M33 rotation curve
(contrast Solar System)

Dark Matter (V. Rubin)

- The stars in a galaxy are moving around faster than we can explain.
- The gravity of something *that we can't see* must be keeping the stars from flying off into space: Dark Matter
- Galaxies are mostly made of dark matter: stars are like sprinkles on dark matter ice cream.
- We know dark matter is there because it exerts gravitational pull on the stars we can see in galaxies.

Gravitational Lensing by Dark Matter in Galaxies



Gravitational Lensing Indicates:

Luminous Galaxies are surrounded by Massive Halos of Dark Matter

December 14, 1999

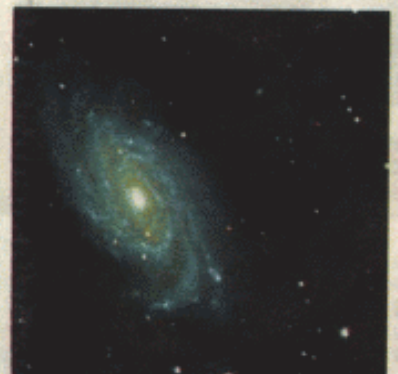
Science Tim

The New York Times

Galaxies' Vastness Surprises Scientists

By JAMES GLANZ

Using a technique akin to overlaying thousands of faint X-ray images to create one sharp picture, astronomers have discovered that typical galaxies may be twice as large and contain twice as much mass as suggested by previous measurements. The new observations, which have emerged from a five-year census of the heavens called the Sloan Digital Sky Survey, indicate that an average galaxy extends invisibly for well over a million light-years into space and weighs the equivalent of at



1

2

A portrait of a woman far different from the cavewoman stereotype is emerging from these Stone Age Venuses: above is Venus of Willendorf in Austria; at right, the back and front views of Venus of Kostenki in Russia; far right, Venus of Lespugue, with prominent buttocks and a "grass" skirt, in southwest France.

Furs f
But
The
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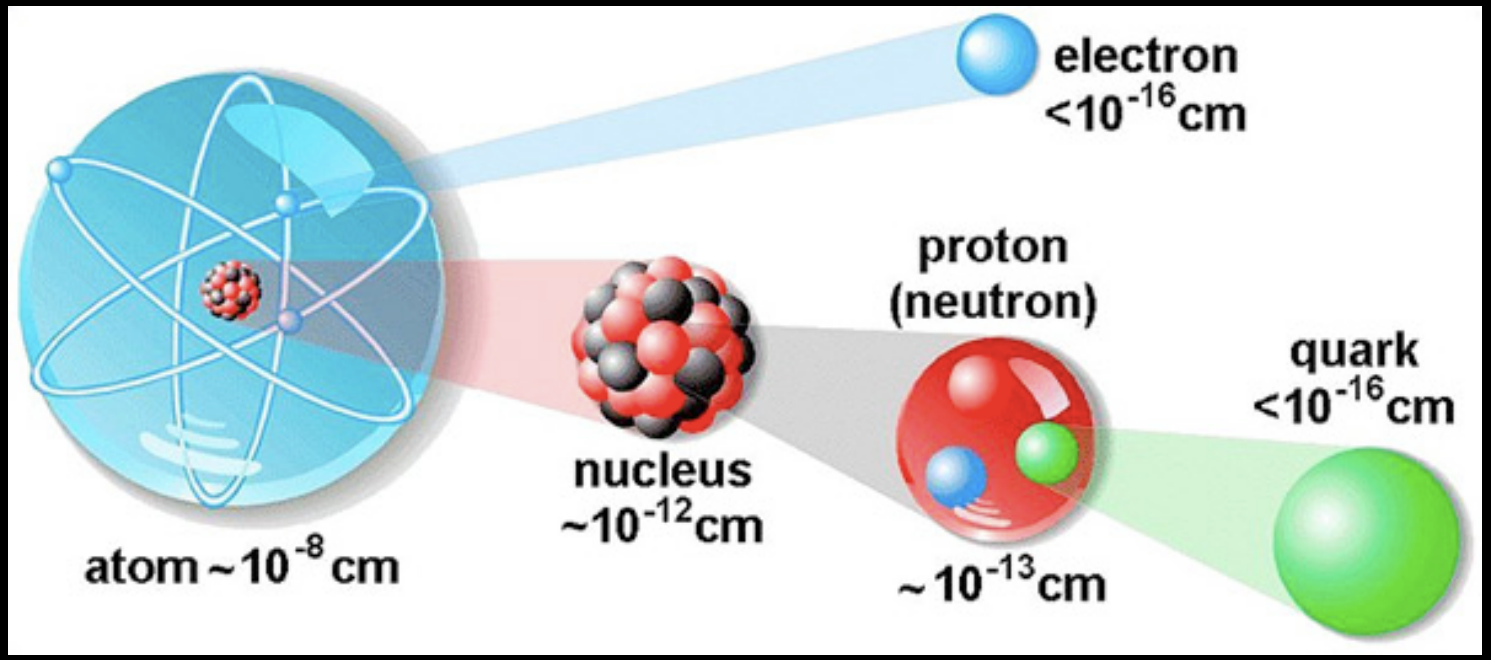
By NATALIE ANGIER

Ah, the poor Stone Age woman of our kitschy imagination. When she isn't getting bonked over the head with a club and

"Normal" Matter: stuff made of atoms



1 1/10,000 1/100,000 1/100,000,000

Dark Matter

- What is dark matter made of?

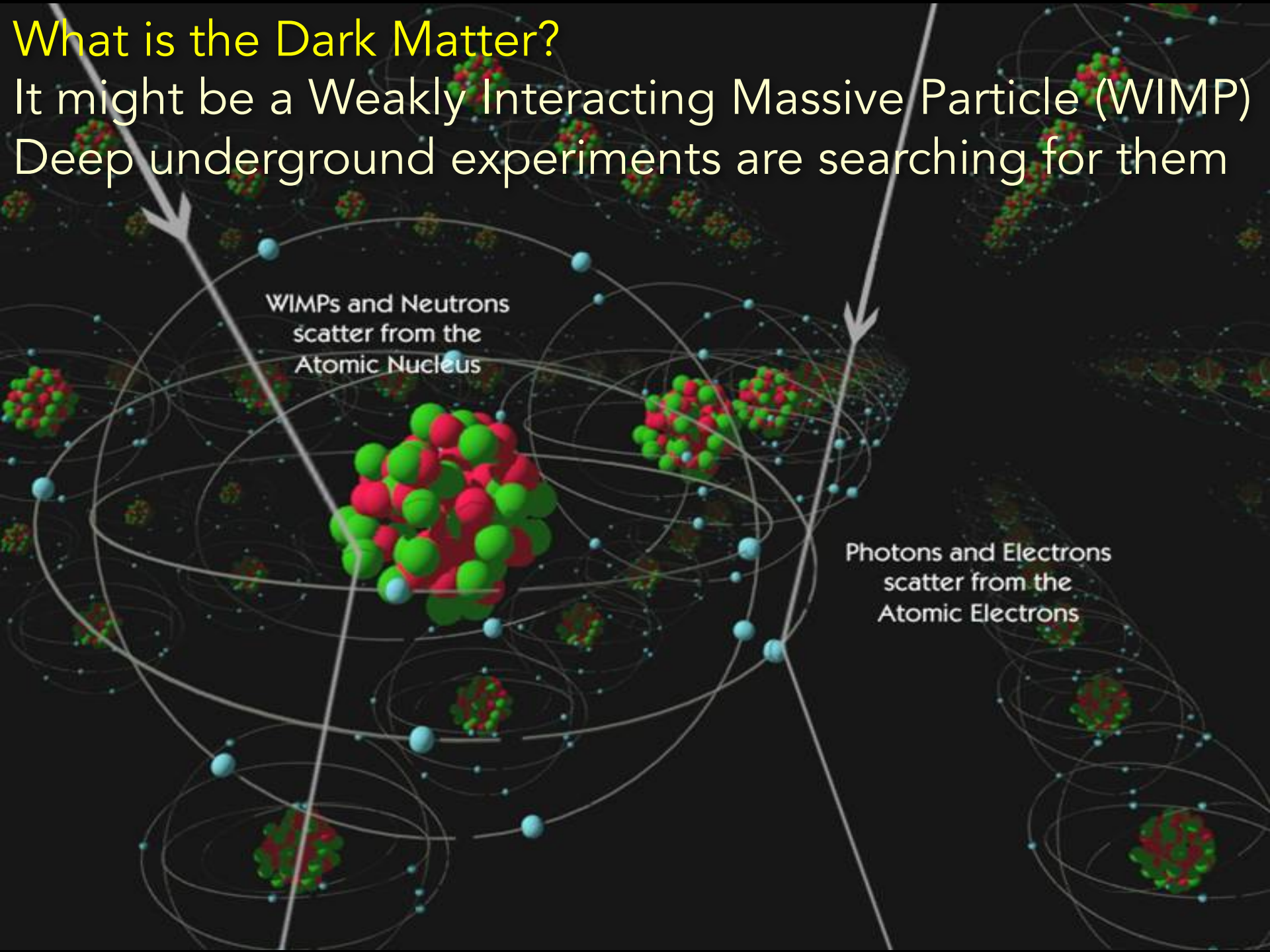
Dark Matter

- What is dark matter made of?
  - Very faint stars, planets, and other things made of atoms can't do it: there aren't enough atoms in the Universe to account for all the dark matter we infer in galaxies.
  - Dark matter must be made of something other than atoms (or quarks): perhaps a new kind of elementary particle that we've never seen before.

What is the Dark Matter?

It might be a Weakly Interacting Massive Particle (WIMP)

Deep underground experiments are searching for them



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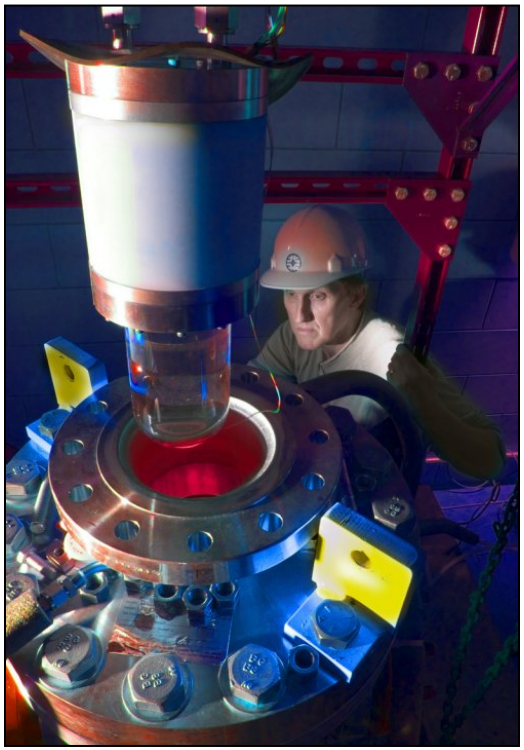
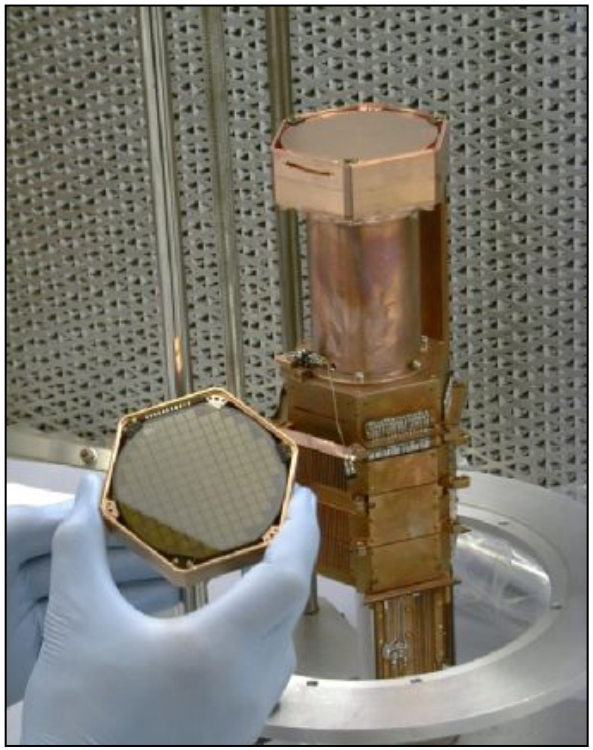


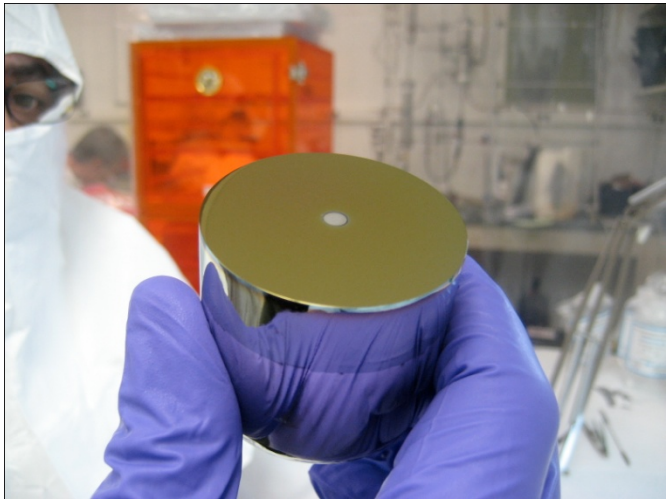
CDMS



XENON

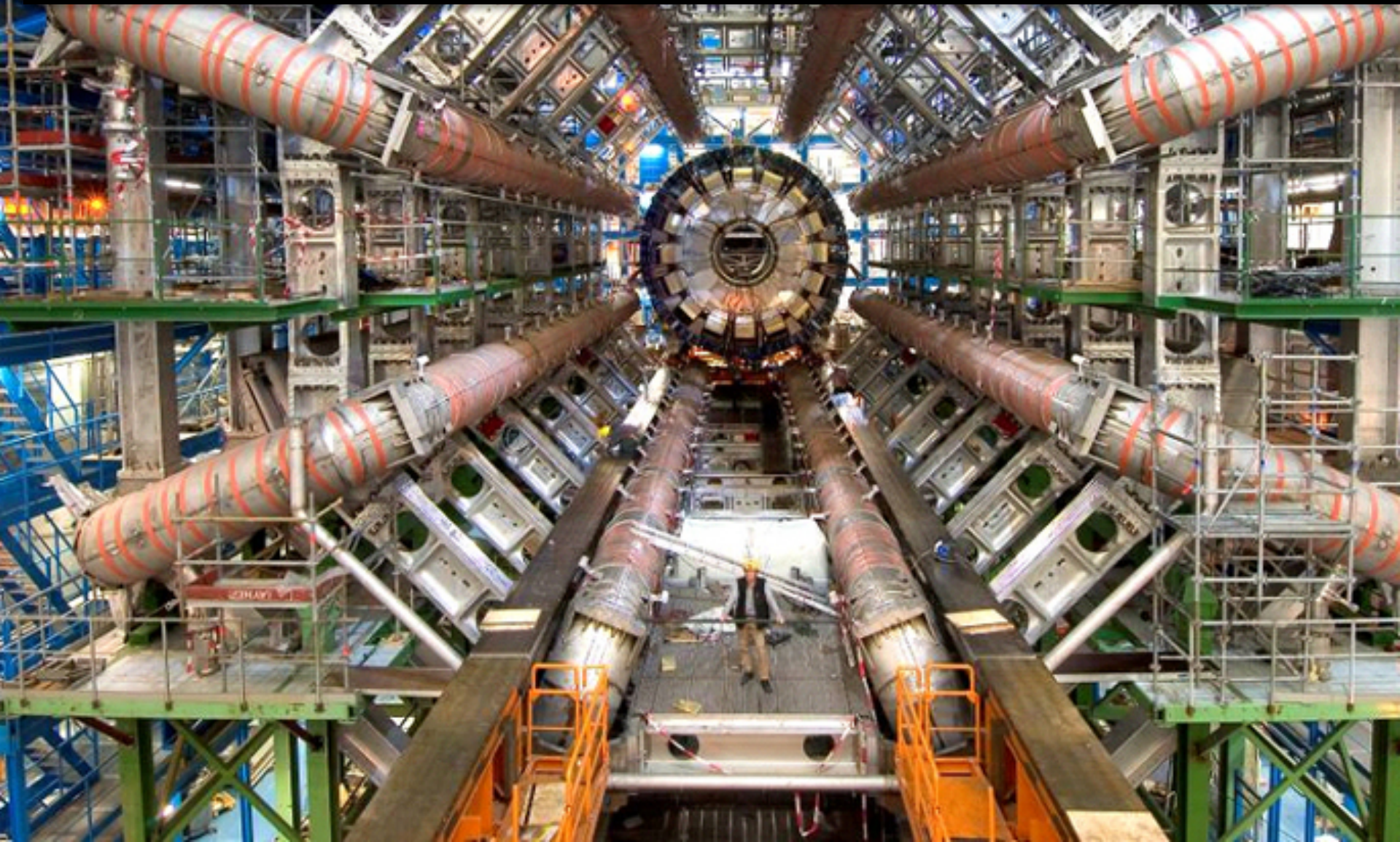
Experiments to search for Dark Matter particles

CoGeNT



DAMA/LIBRA

Dark matter particles might also be produced at the Large Hadron Collider now operating in Switzerland. This is where the Higgs Boson was discovered.



Basic Facts about the Universe

4. The Universe is EXPANDING.

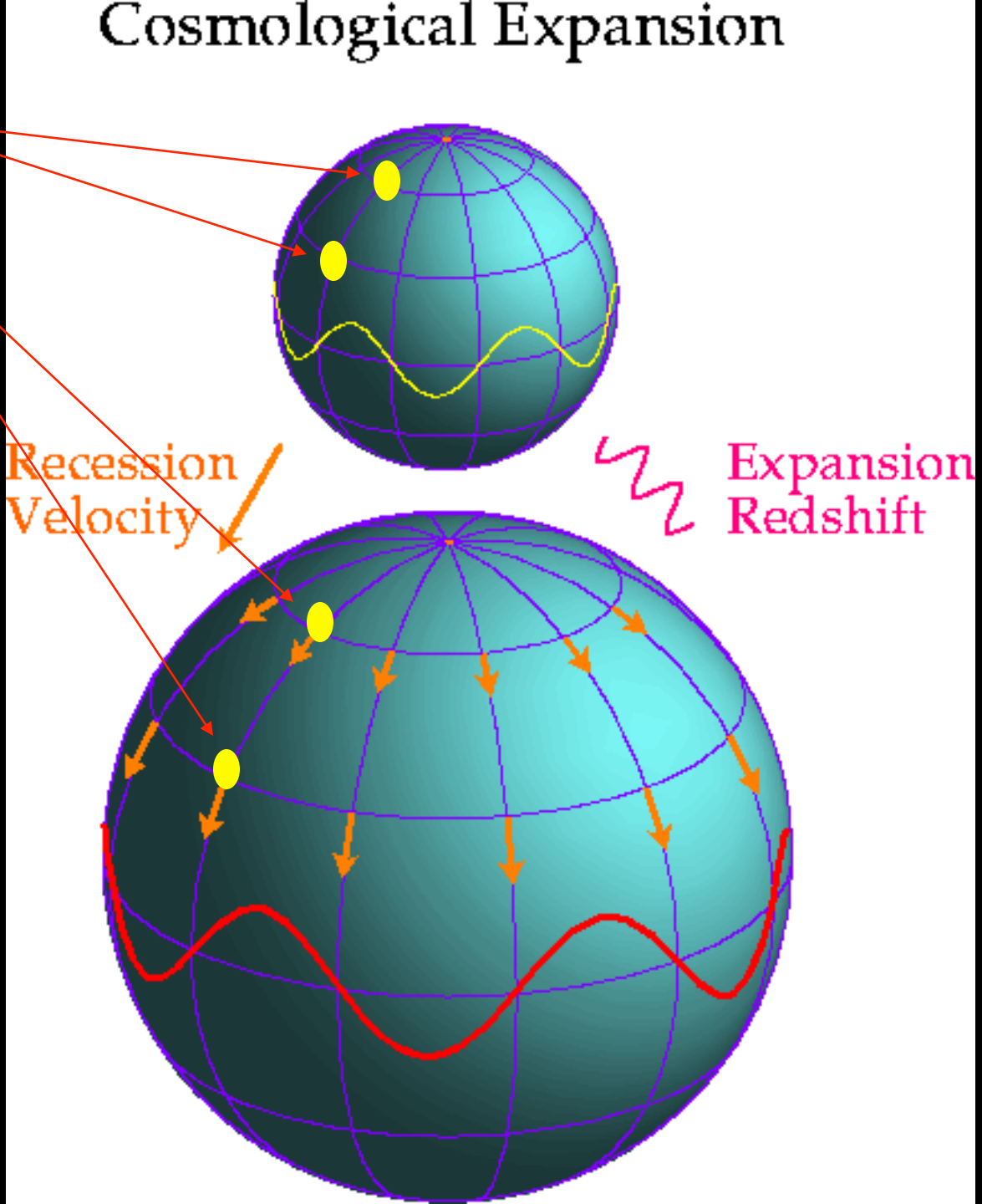
The Expanding Universe

Run it backward: expansion started in a Big Bang 13.8 billion years ago

The distance *between* galaxies increases with time

A galaxy 100 Million light years away is moving away from us at 2000 miles per second.

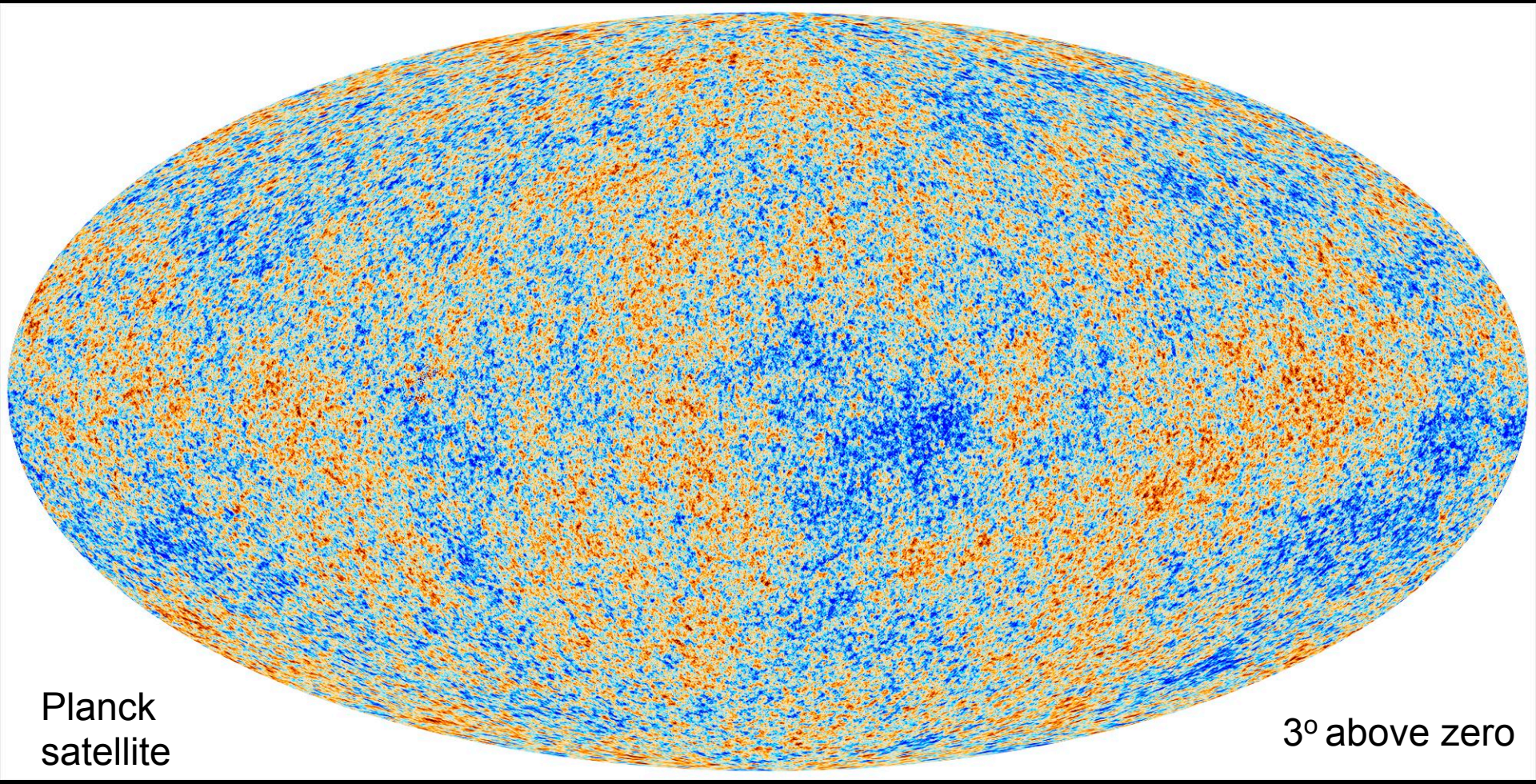
Galaxies are not expanding: they are bound together by the gravity of dark matter.



Expansion of the Universe and the Big Bang

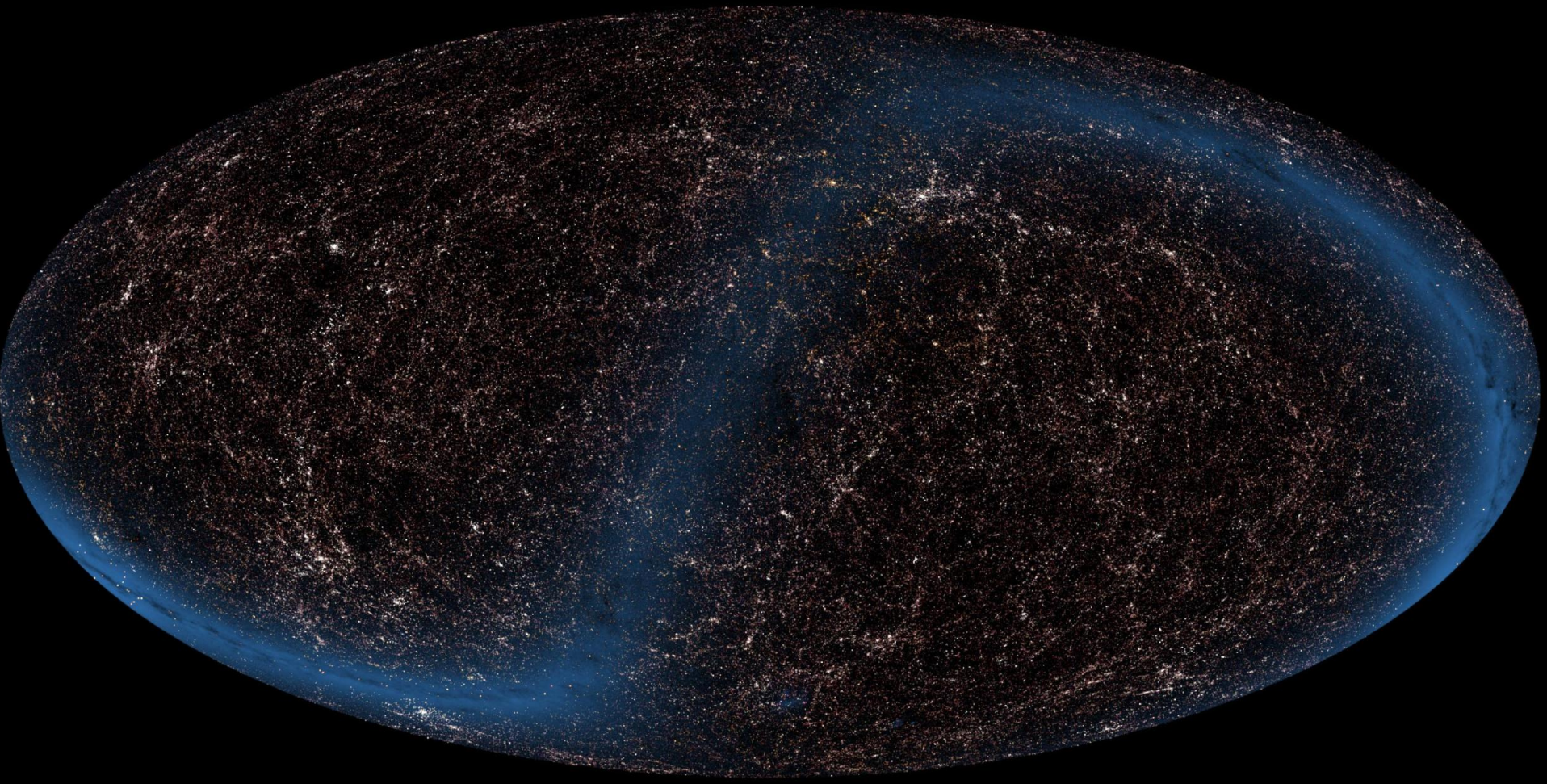
- The Universe has no center and no edge (that we can see): it looks the same everywhere.
- The expansion is happening everywhere: the Universe is not exploding into empty space.
- At the Big Bang, the Universe was extremely hot and dense. Today it is very cold and diffuse.

Cosmic Microwave Background Radiation



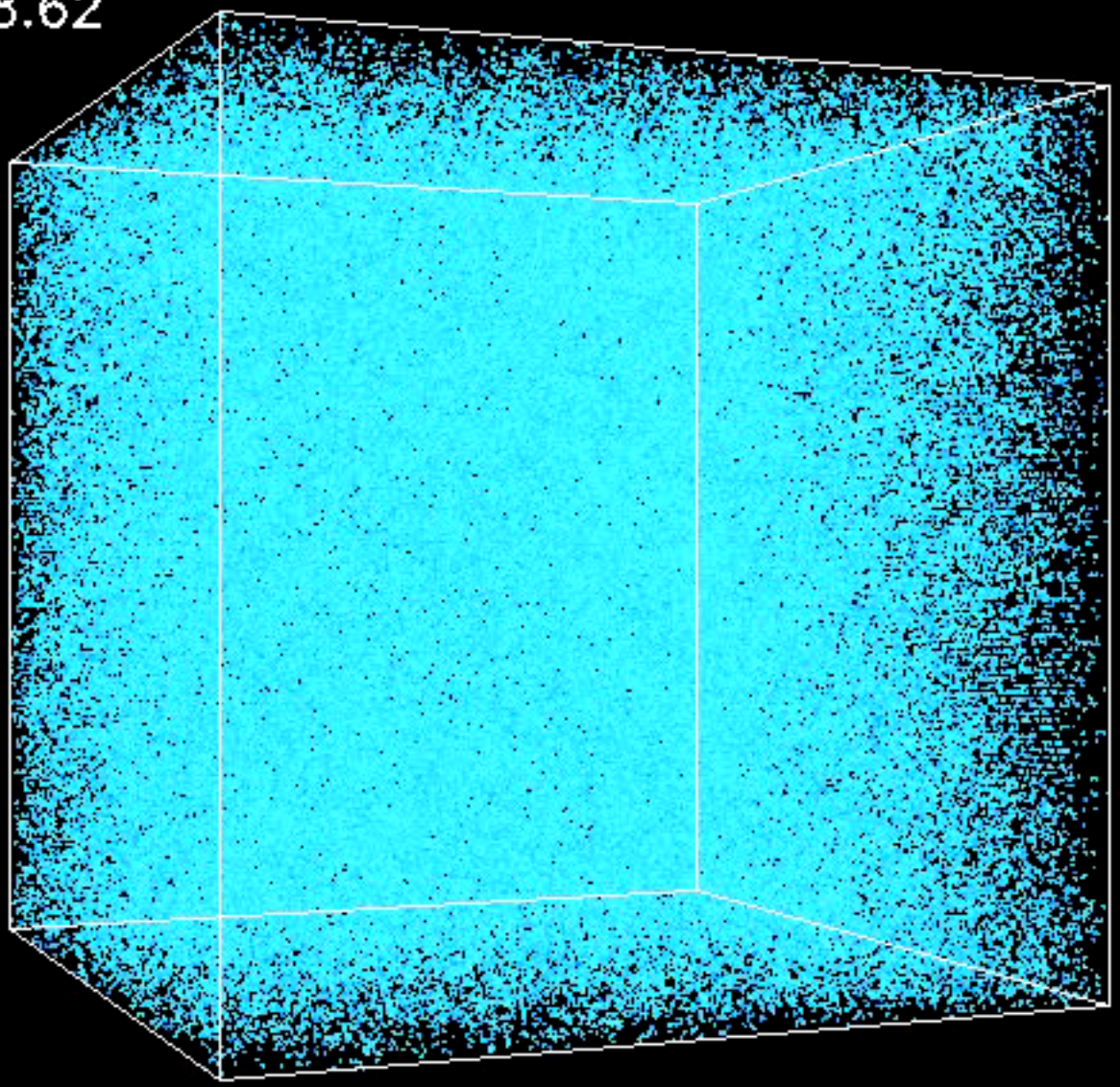
Snapshot of the Universe when it was only 400,000 years old

Large-scale Map of Galaxies Today



2MASS Infrared Sky Survey

Universe much lumpier now



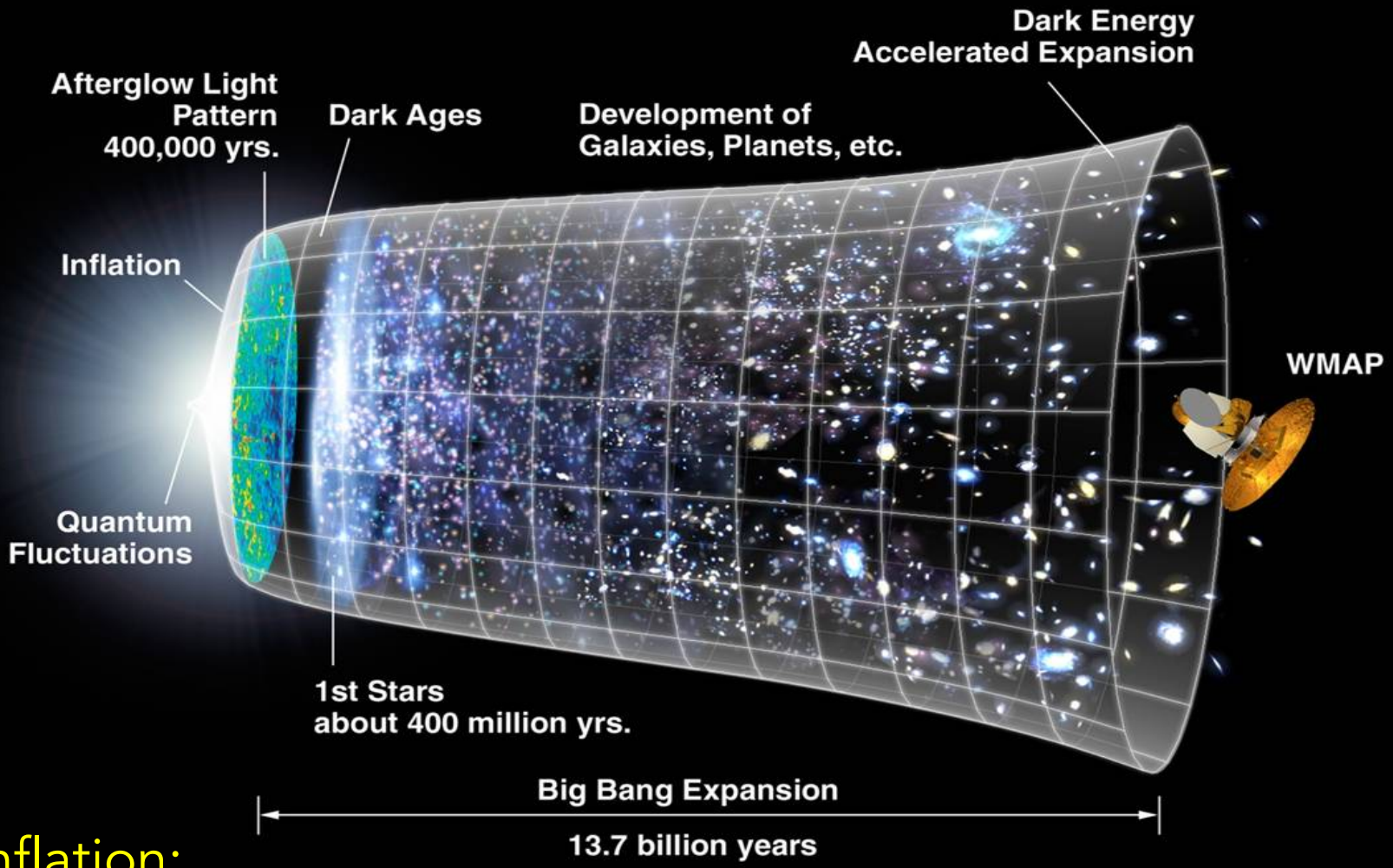
Computer Simulation of the formation of Galaxies and Clusters in Expanding Universe

Gravity is the engine of structure formation

Formation of a (lumpy) halo of Dark Matter

Kravtsov

Brief History of the Universe



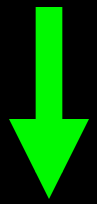
Inflation:
burst of rapid expansion a tiny fraction of a second after the Big Bang

Does the expansion of the Universe change over time?

Does the expansion of the Universe change over time?

Gravity:

everything in the Universe attracts everything else

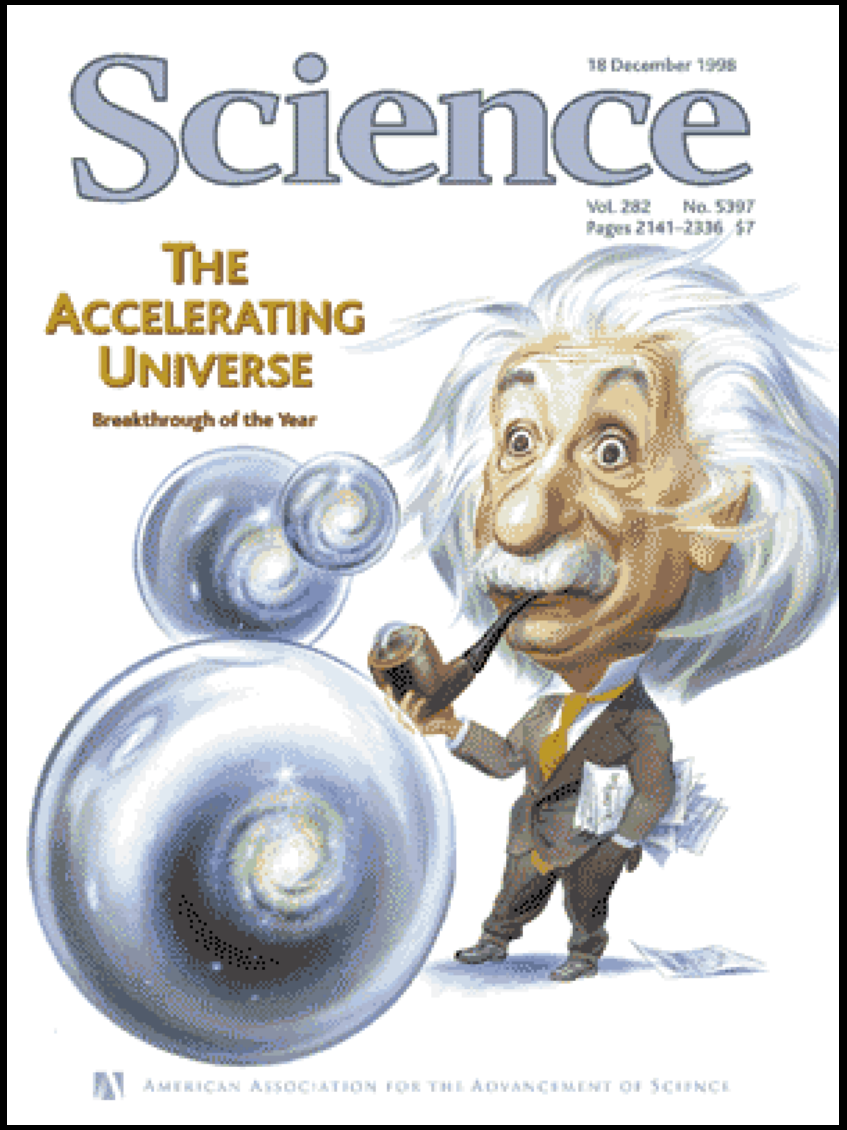


the expansion of the Universe should slow down over time

5. The Expansion is Speeding Up

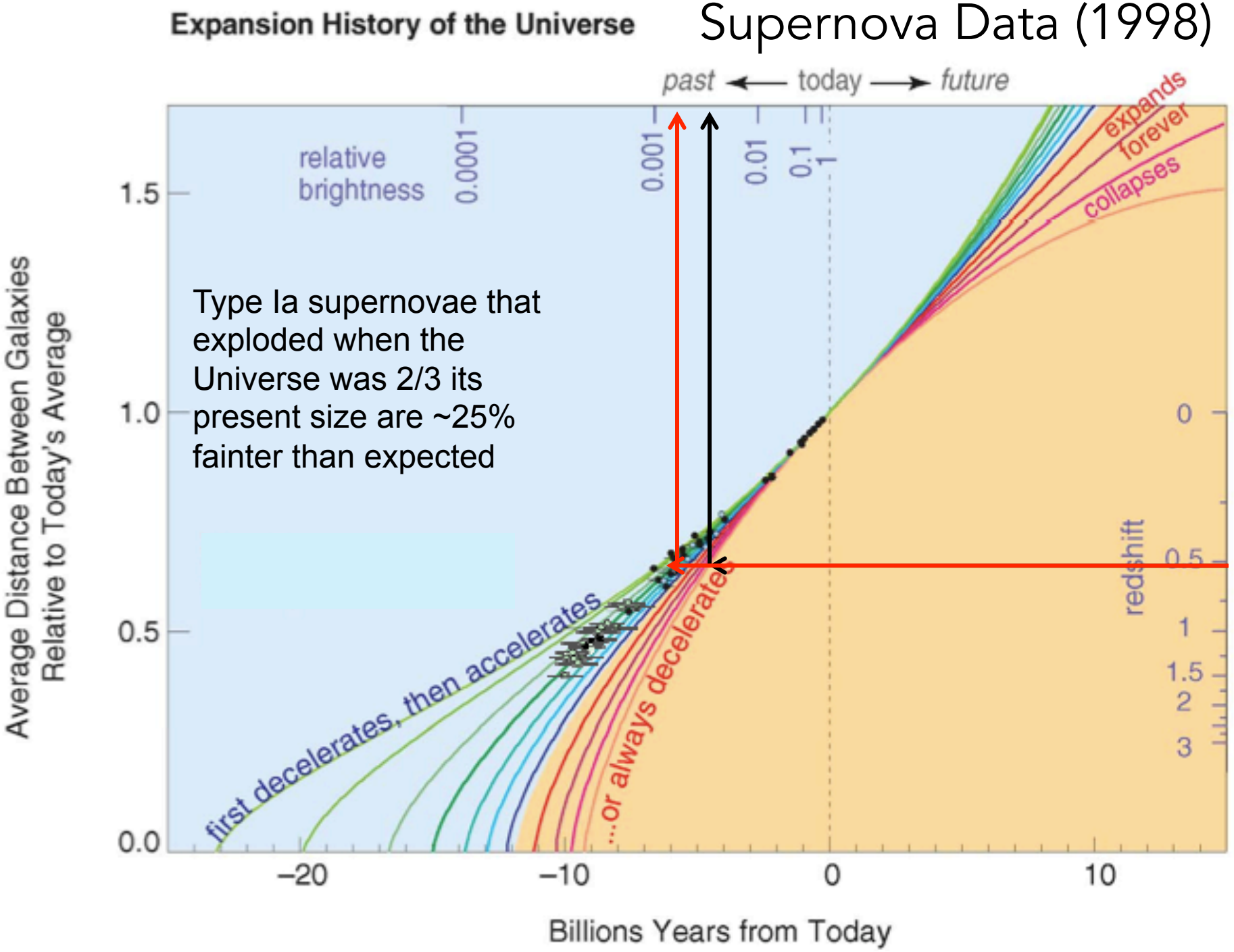
Discovered in 1998 by 2 teams of astronomers.

Nobel Prize in 2011 for this discovery.



Supernova: an exploding star. The brightness of distant supernovae showed that expansion is speeding up.

Supernova Data (1998)



Why is this a mystery?

When you throw a ball straight up in the air, imagine it first slows down but then, instead of falling back to Earth, it starts speeding up and rockets out of the atmosphere. That's what the Universe appears to be doing.

What causes Cosmic Speed-up?

Two possibilities:

1. The Universe is filled with stuff that gives rise to `anti-gravity'. We now call this

   Dark Energy

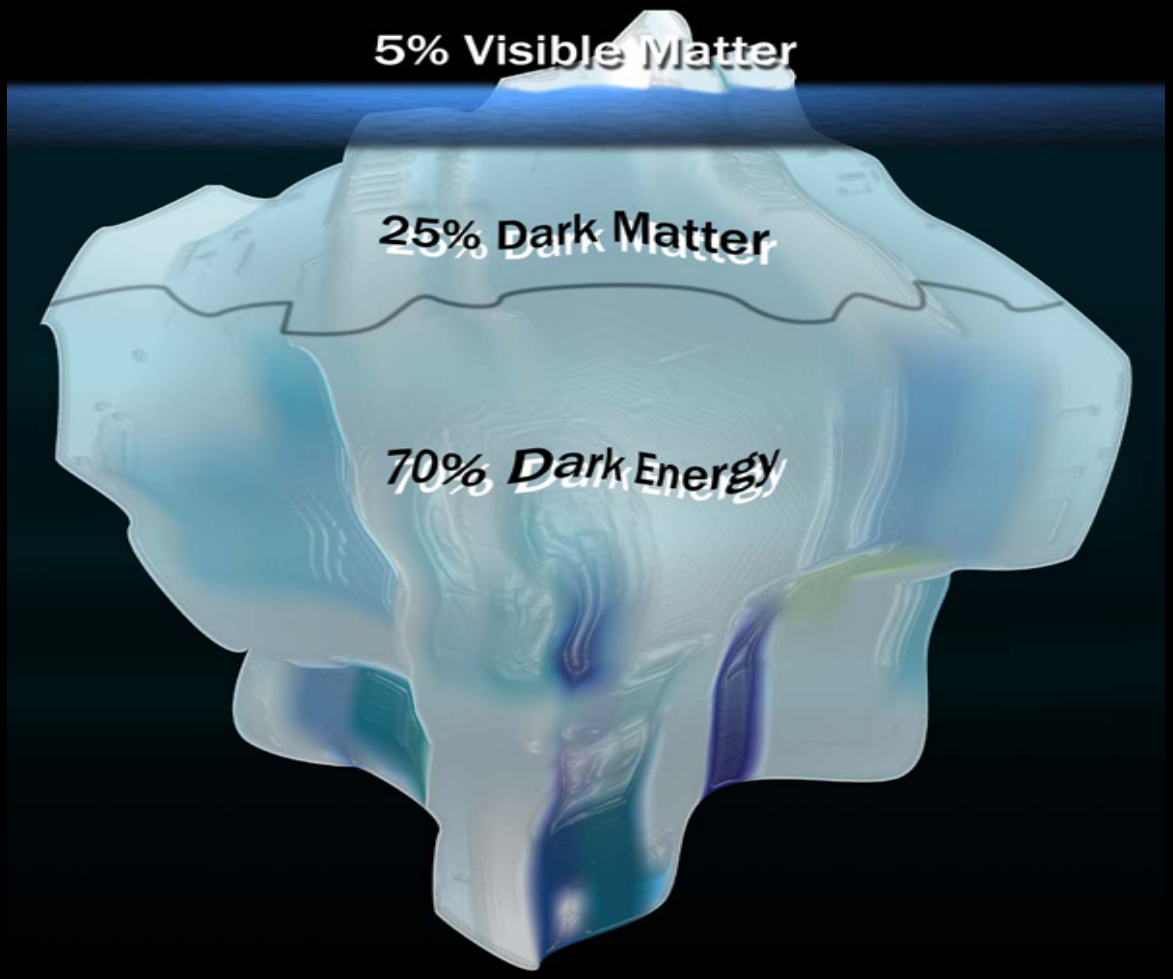
2. Our understanding of gravity (which comes from Einstein) is wrong.

6. 95% of the Universe is Dark

Ordinary Matter: atoms

Dark Matter: holds galaxies together, helps them form

Dark Energy: `gravitationally repulsive' stuff that speeds up cosmic expansion

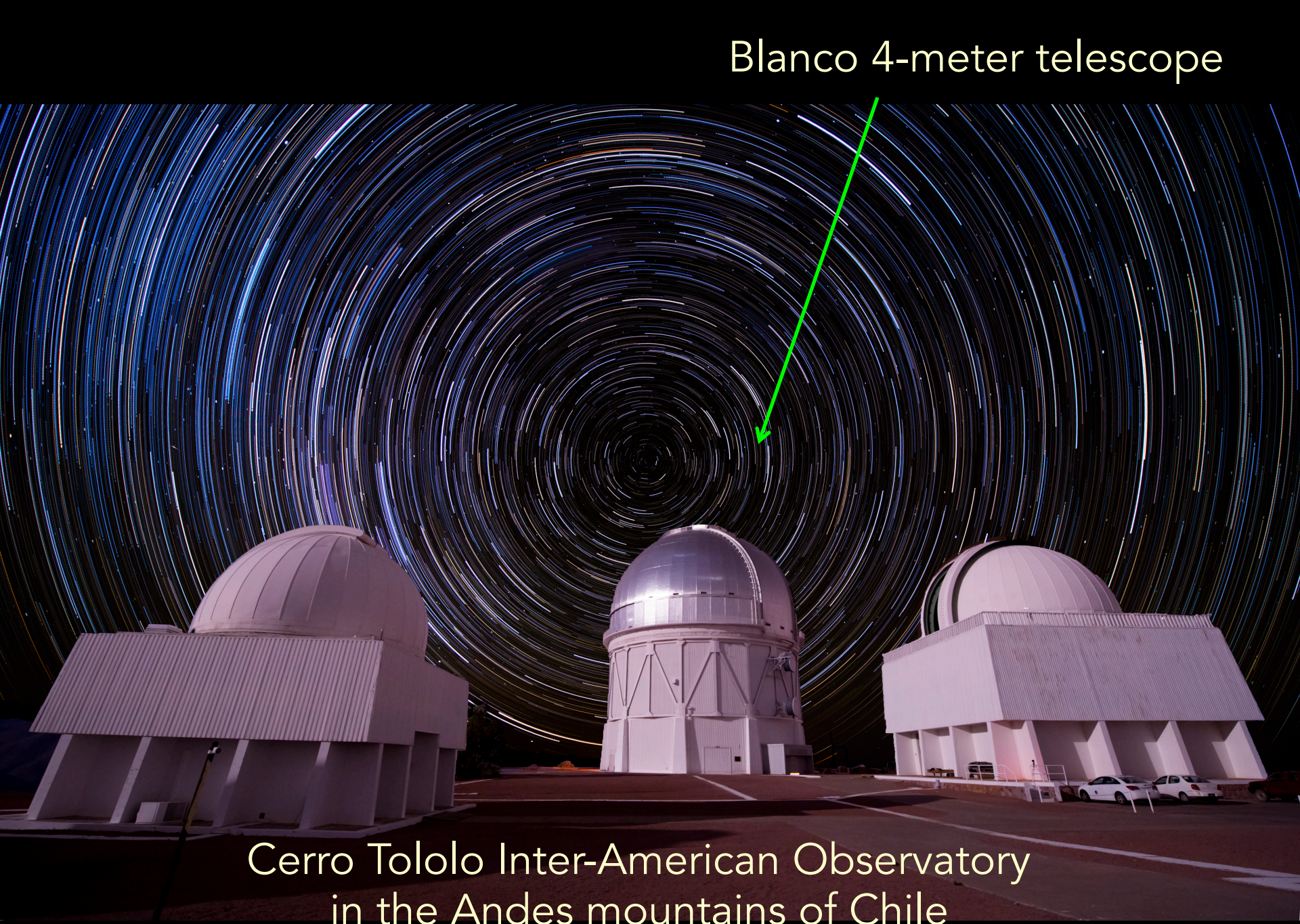


What is Dark Energy?

- We don't know.
- Most conservative hypothesis is that it's the energy of empty space.
- Quantum theory predicts that energy should be infinite.
- Other ideas even more speculative.

Why is Dark Energy important?

- Nature of Dark Energy will determine the future evolution of the Universe (but its effects on Earth or in our galaxy are now extremely tiny).
- It's 70% of the Universe.
- Mapping the Universe can give us clues to what Dark Energy is.


Blanco 4-meter telescope
Cerro Tololo Inter-American Observatory
in the Andes mountains of Chile

Summary

- The Universe is:
  - old
  - big
  - filled with galaxies that are mostly dark matter
  - expanding from a Big Bang
  - speeding up, likely due to Dark Energy
- With new cosmic surveys, we are aiming to address this mystery and learn more about the evolution of the cosmos.