

COSMOLOGY

EXPLORING THE ENTIRE

UNIVERSE

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Kavli Institute of Cosmological Physics
University of Chicago

Cosmology

How was the
entire universe born ?



Cosmology

How did the universe grow up?



Cosmology

Can we explain all the things we see in
the universe today?

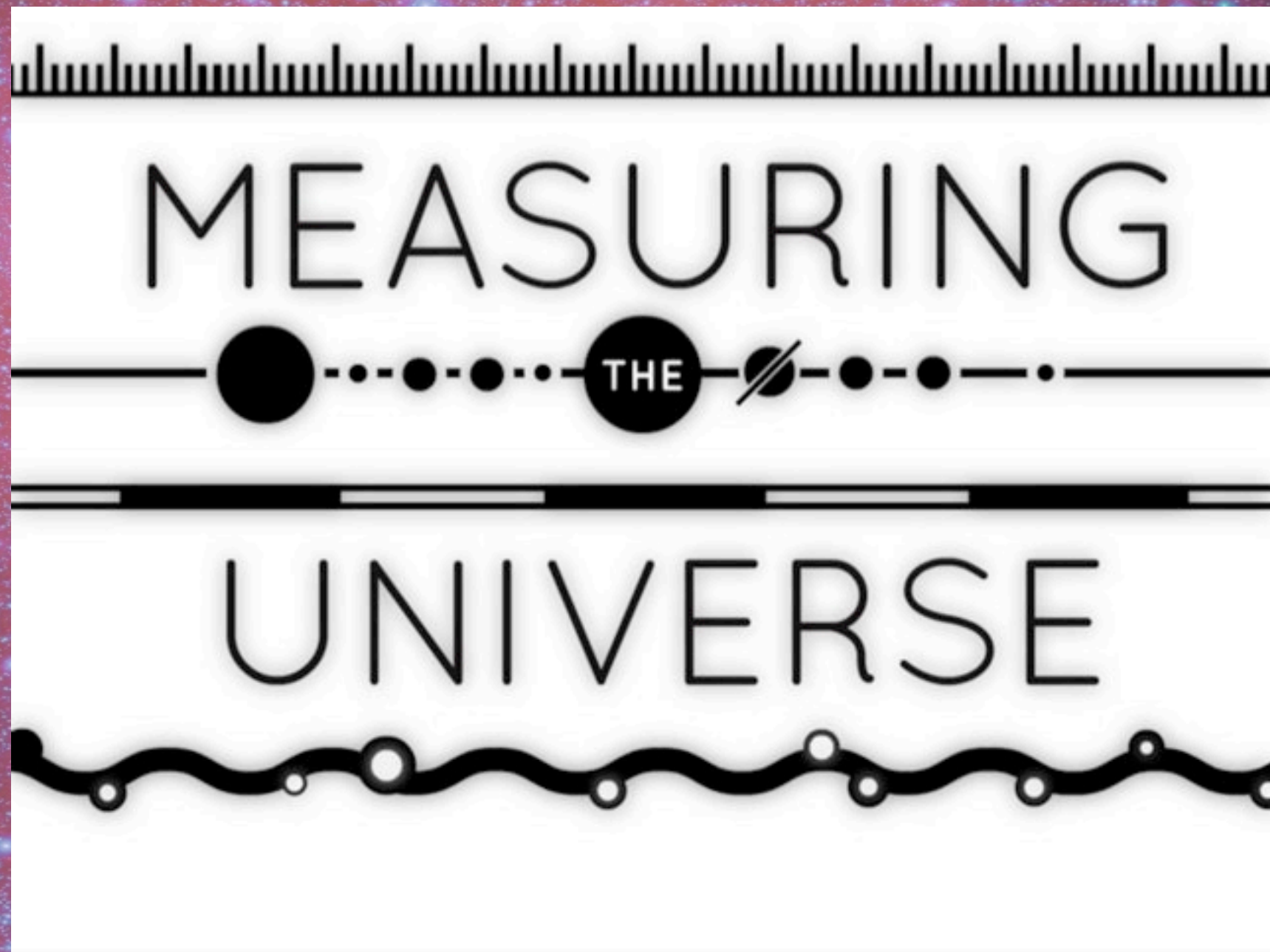


Cosmology

Can we make predictions about how the universe will live out the rest of its life?



Cosmology has only become a precision science in the last ~80 years



Born in Honolulu, Hawaii



Grew up surfing and playing water polo





**Attended public
schools in Honolulu**

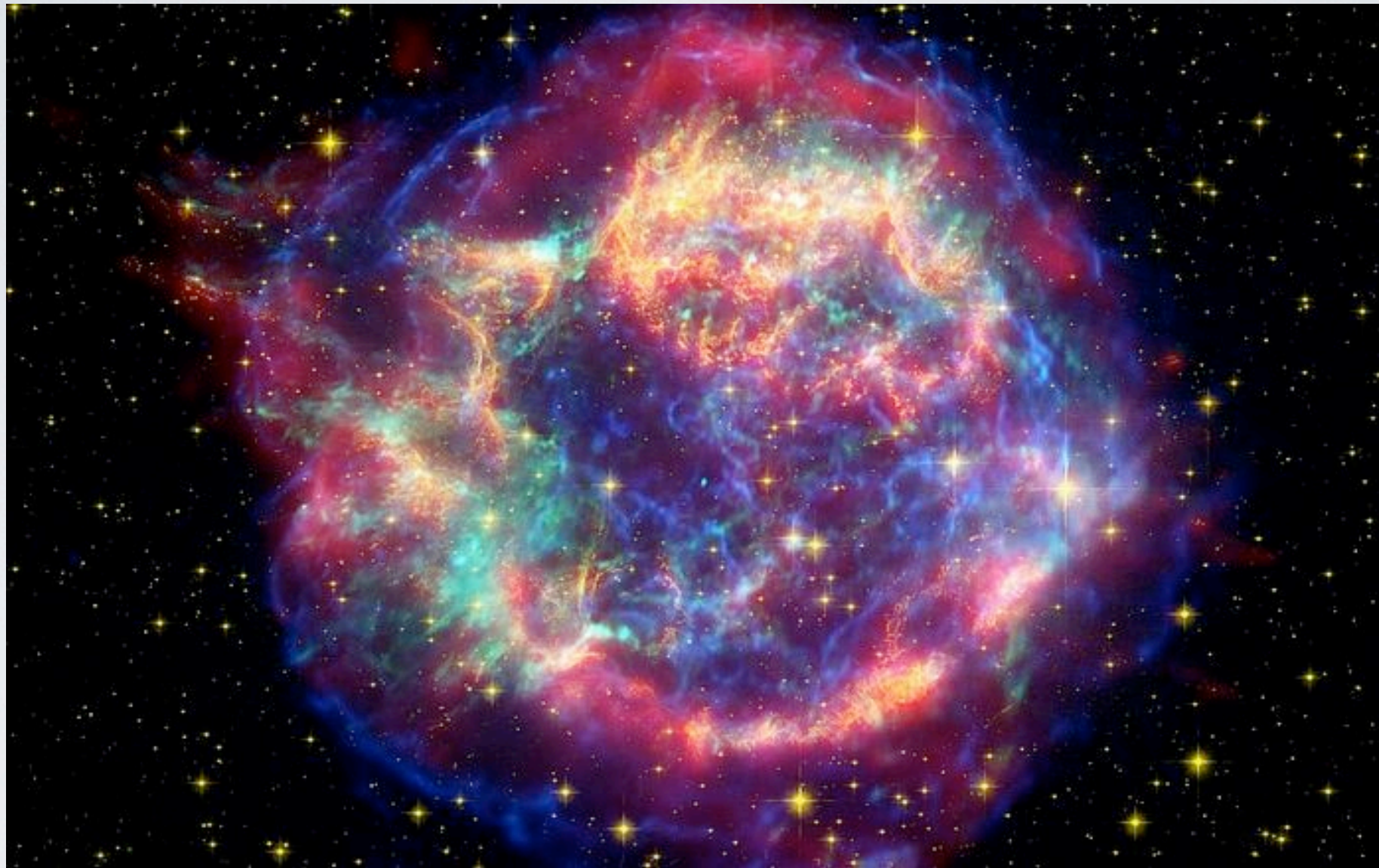


Attended public
schools in Honolulu

Attended the
University of Hawaii,
Manoa



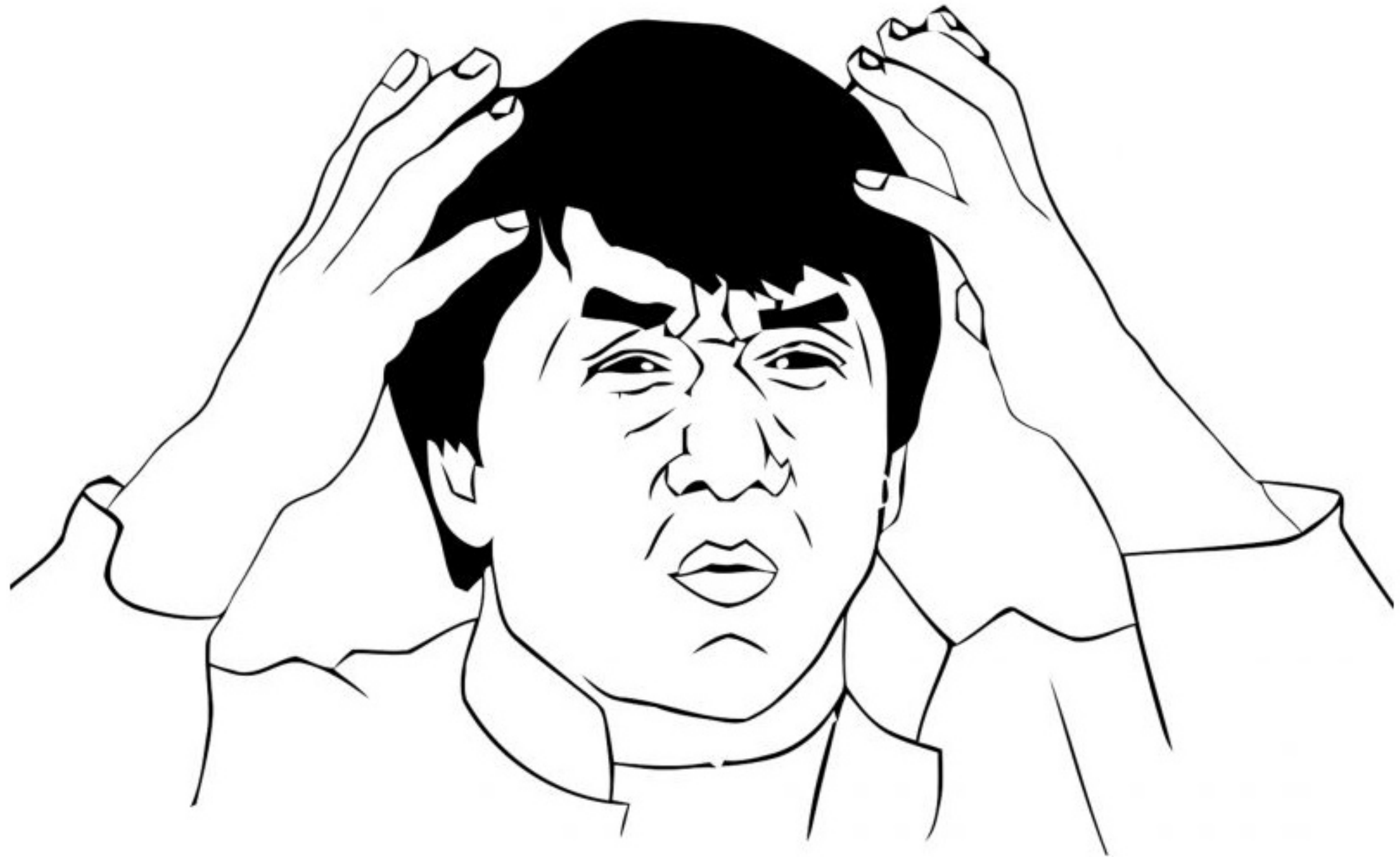
In an introductory *Astronomy* course



I heard something very intriguing ...

***“We can only see 4 %
of the entire
Universe”***

This was my reaction

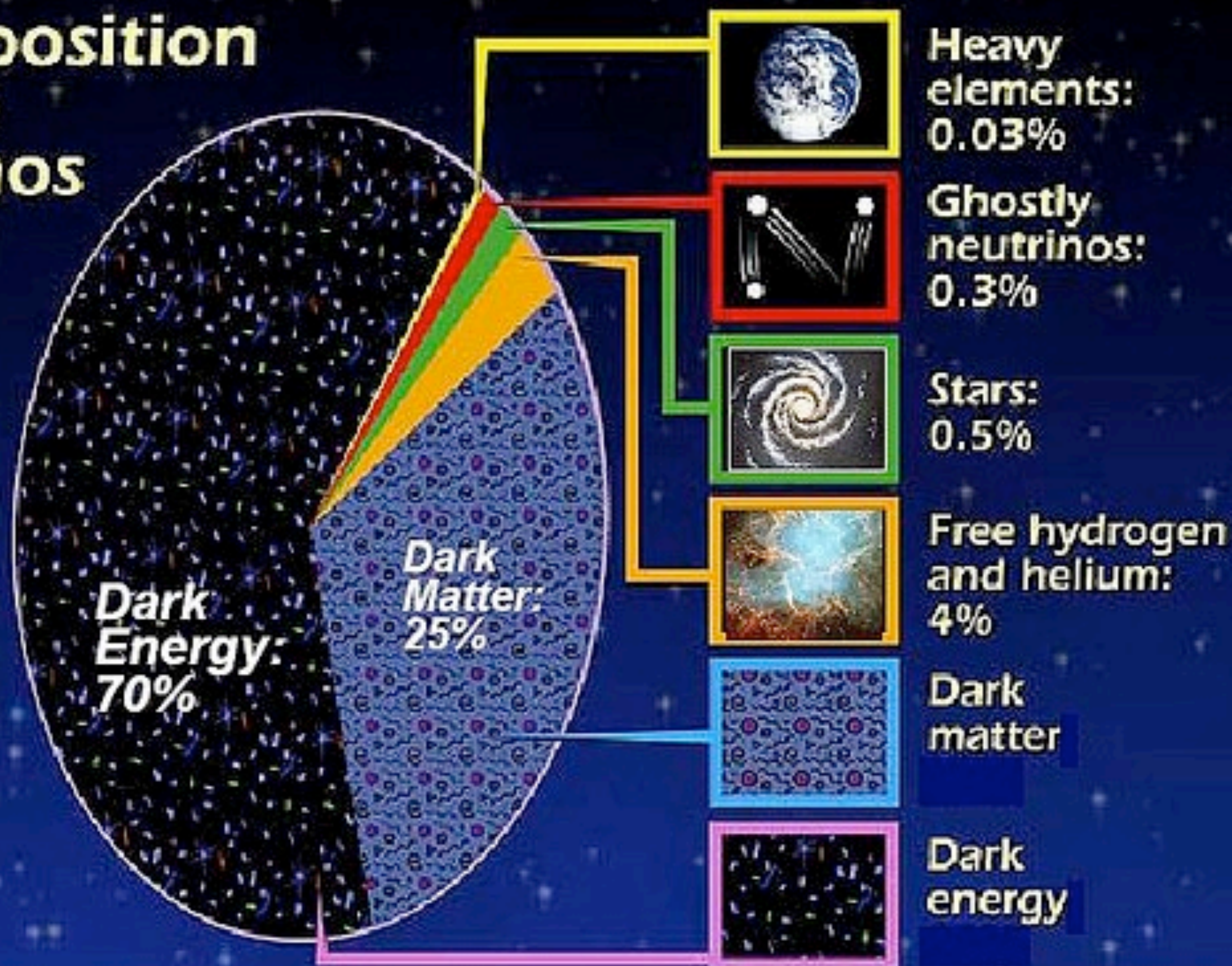


4 %



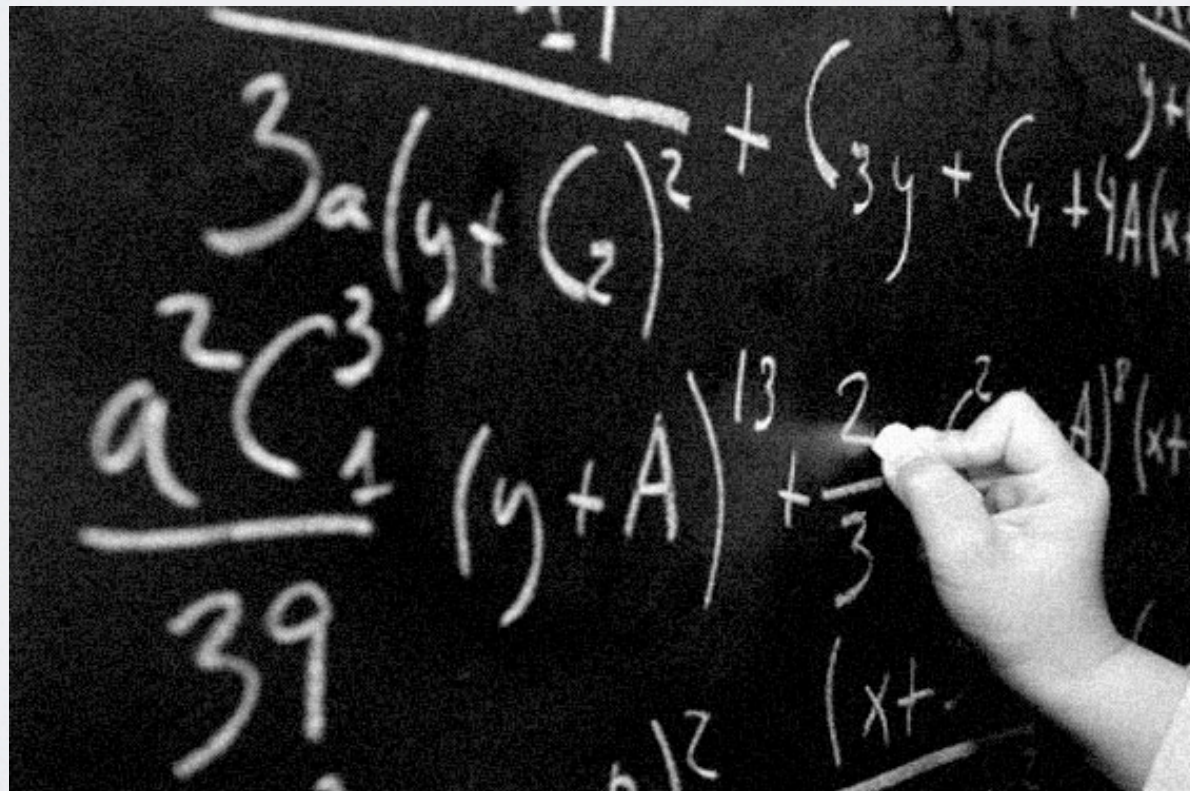
4 %

Composition of the Cosmos

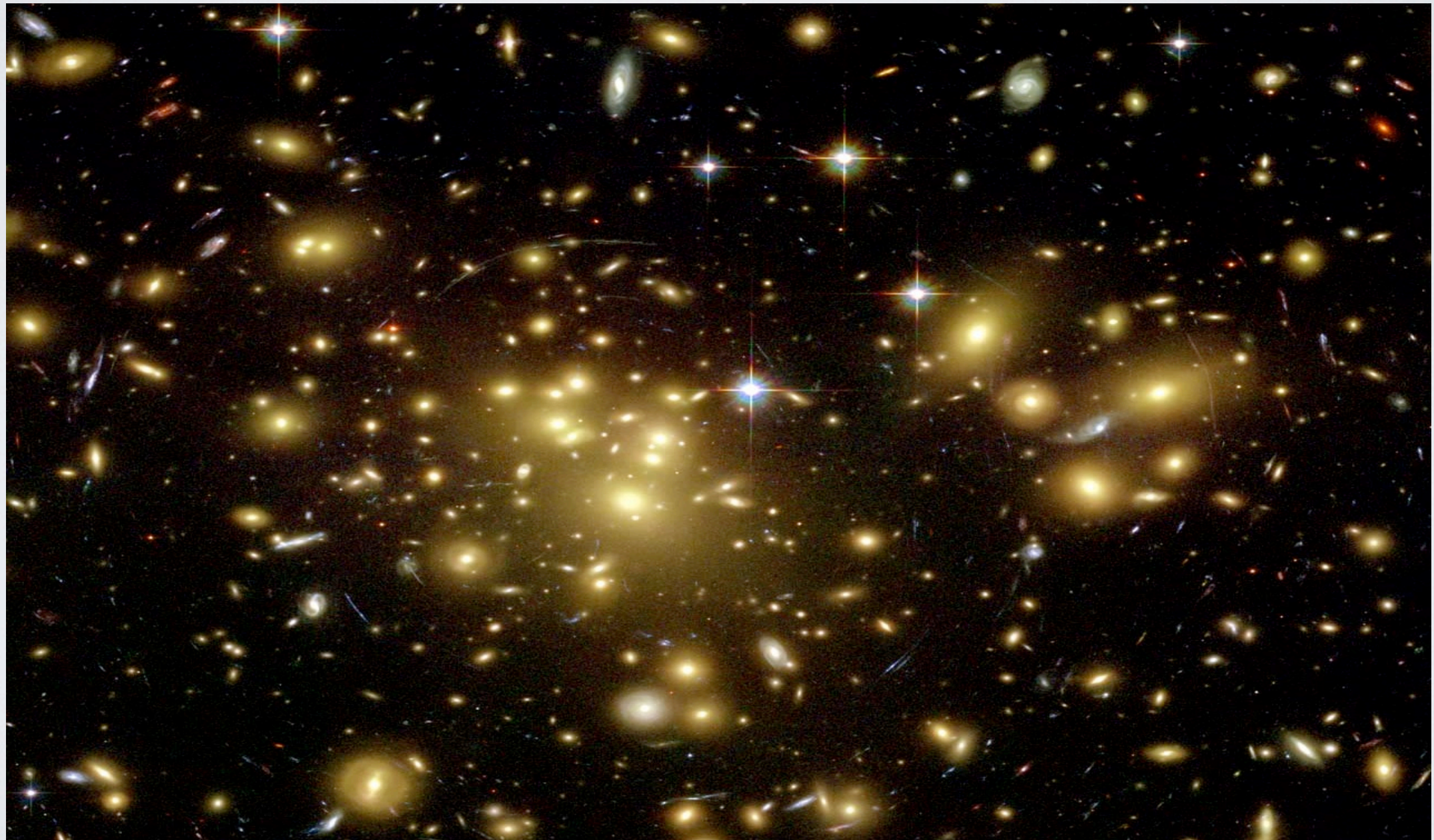


**“We can only see 4 %
of the entire Universe”**

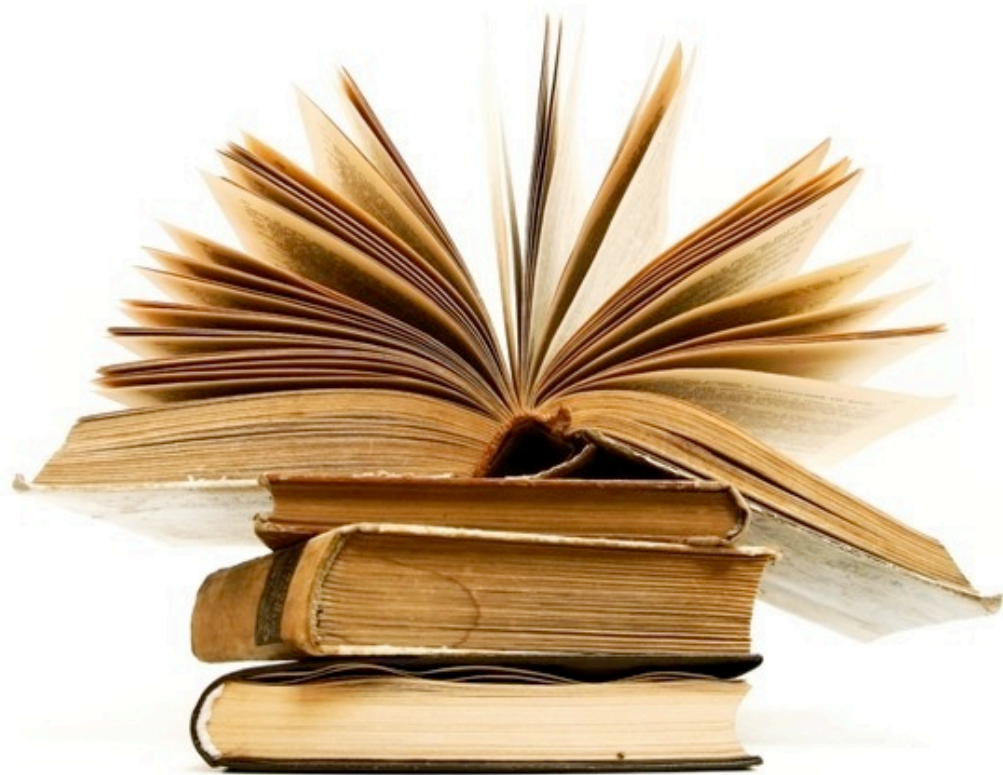
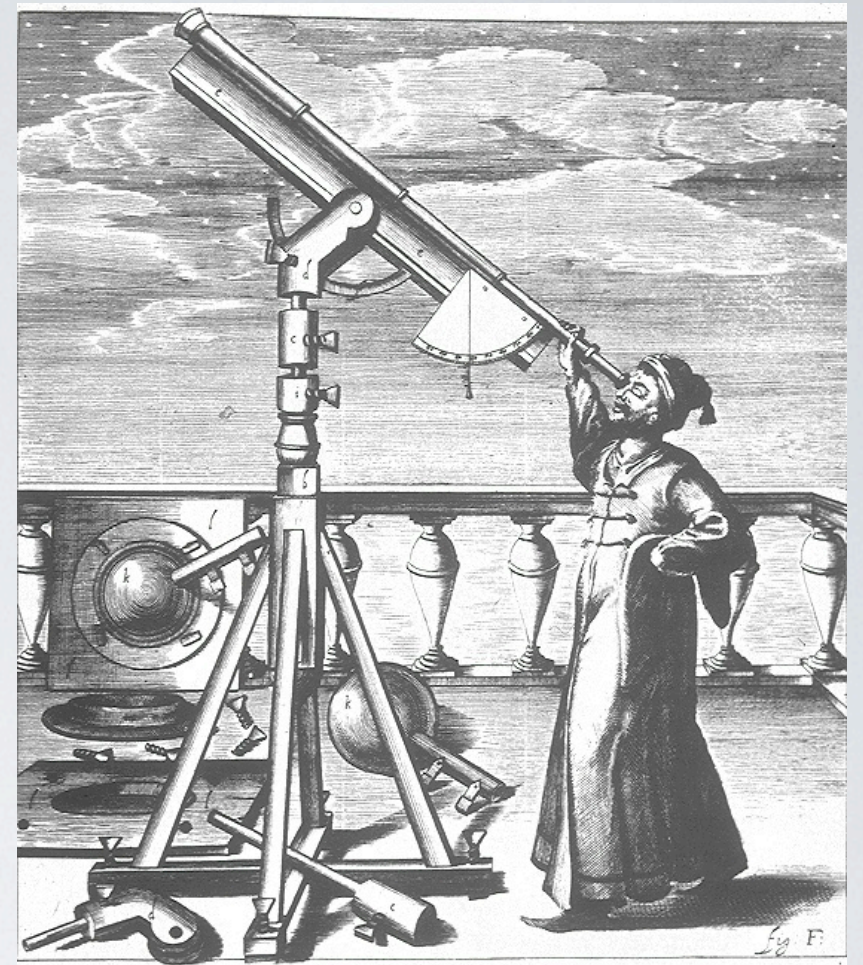
This is why I decided to pursue physics



What **SCIENTIFIC EVIDENCE**
do we have to support
this view of the universe in 2014?



**I am going to walk you
through the timeline of
discovery**



**We are still writing
the books**

Before 1929

Questions

Scientific Evidence

How did the
universe begin?

None

How did the
universe grow-up?

None

What is the universe
made up of?

The same things that
we see here on earth?

1929

What was happening around the world?

What was happening in your life?

1929

**Stock Market Crashed
Began the Great Depression**



Hoover became president



1st Academy Awards

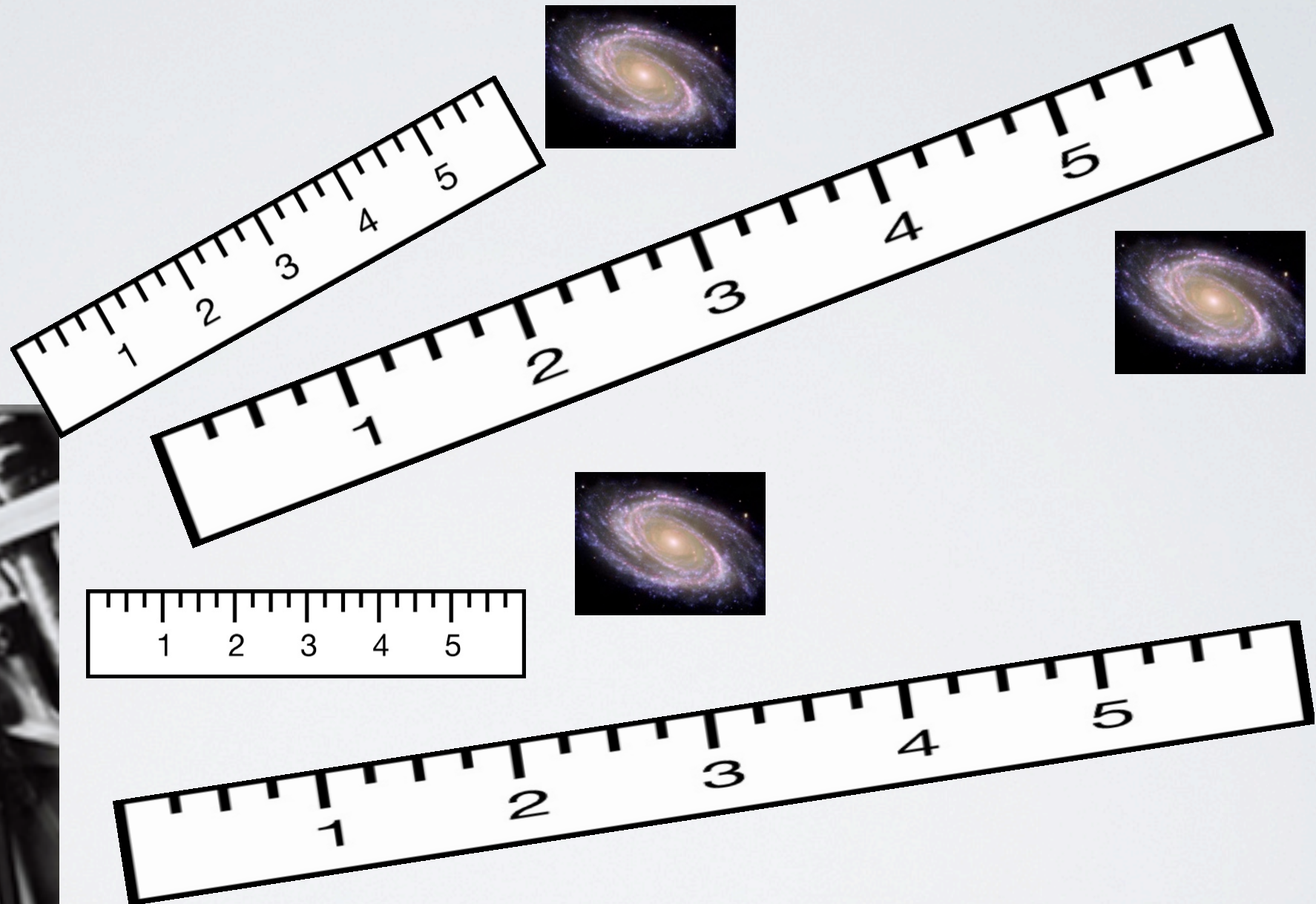
1929

Hubble measures an expanding universe



1929

Hubble measures an expanding universe



Measured distance to galaxies

1929

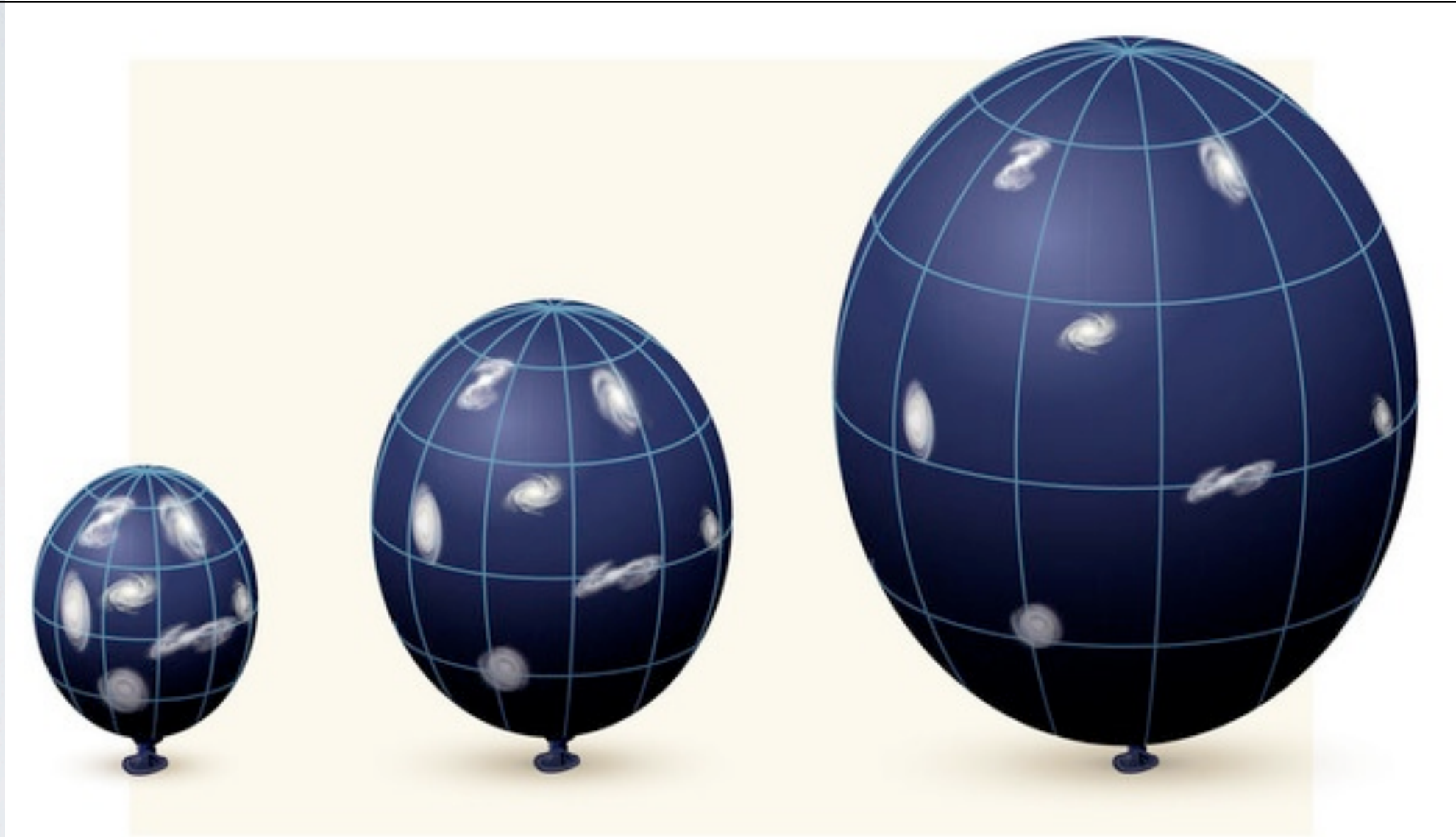
Hubble measures an expanding universe



Measured speed of galaxies

1929

Hubble measures an expanding universe



If the universe is expanding, what happened in the past to create this?

Questions

Scientific Evidence

How did the
universe begin?

humm maybe it had
a beginning?

How did the
universe grow-up?

It must have grown
up in some way?

What is the universe
made up of?

The same things that
we see here on earth?

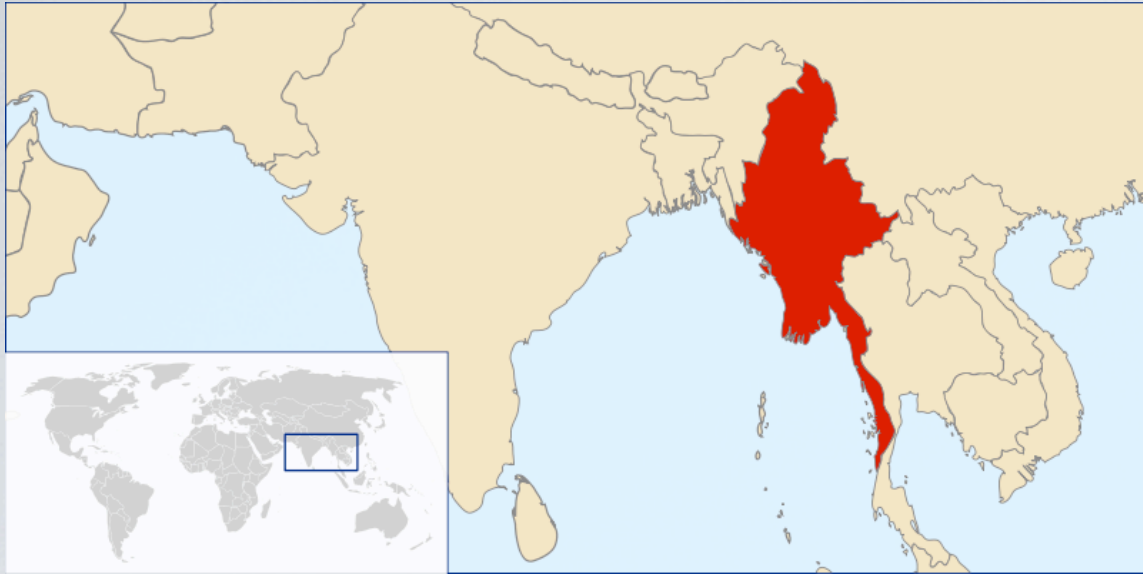
1948

What was happening around the world?

What was happening in your life?

1948

Burma becomes an
independent nation



World Health Organization
was founded



Project Twinkle to monitor
green fireball sighting

1948

Theorist debate

Steady State vs. Big Bang universe

Steady State



Bondi, Gold, Hoyle

Big Bang



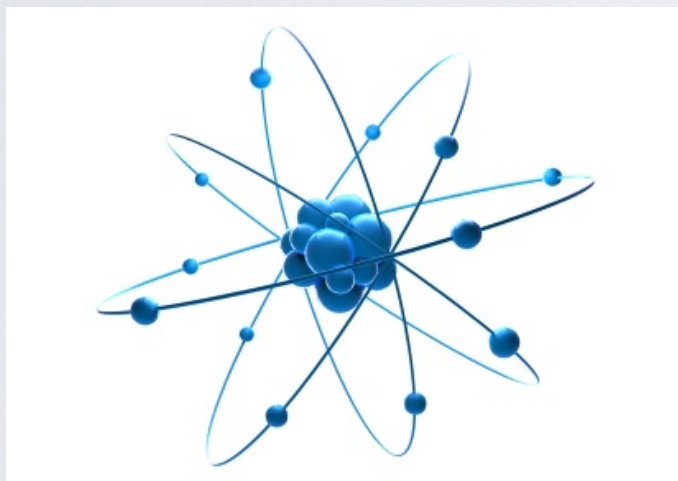
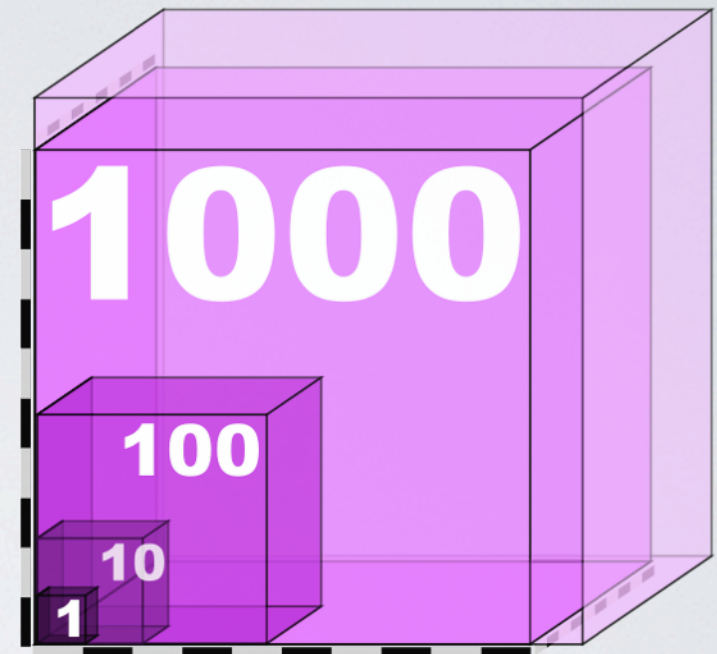
VS.

Alpher, Bethe, Gamow

Steady State explanation

1948

The volume of the universe
may be increasing



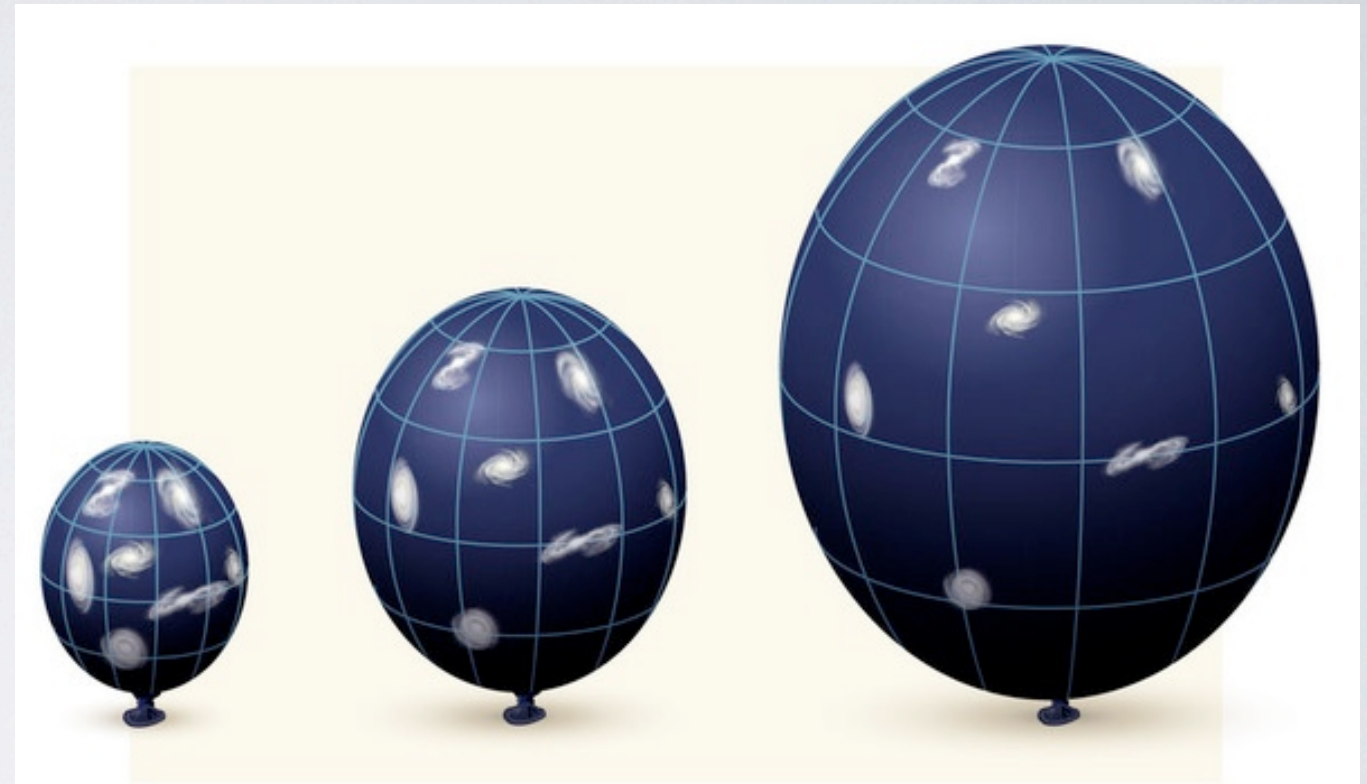
However, new matter was
created to keep the density the
same

The universe was not actually growing up it was
staying the same

Big Bang explanation

1948

If the universe
is expanding



It may have started
from very hot, very
dense beginning

Questions

Scientific Evidence

How did the
universe begin?

humm maybe it had
a beginning?

How did the
universe grow-up?

It must have grown
up in some way?

What is the universe
made up of?

The same things that
we see here on earth?

1965

What was happening around the world?

What was happening in your life?

1965

Sound of Music is released

MLK lead marches from
Selma to Montgomery

Lyndon B. Johnson signs
social security act &
national voting rights act



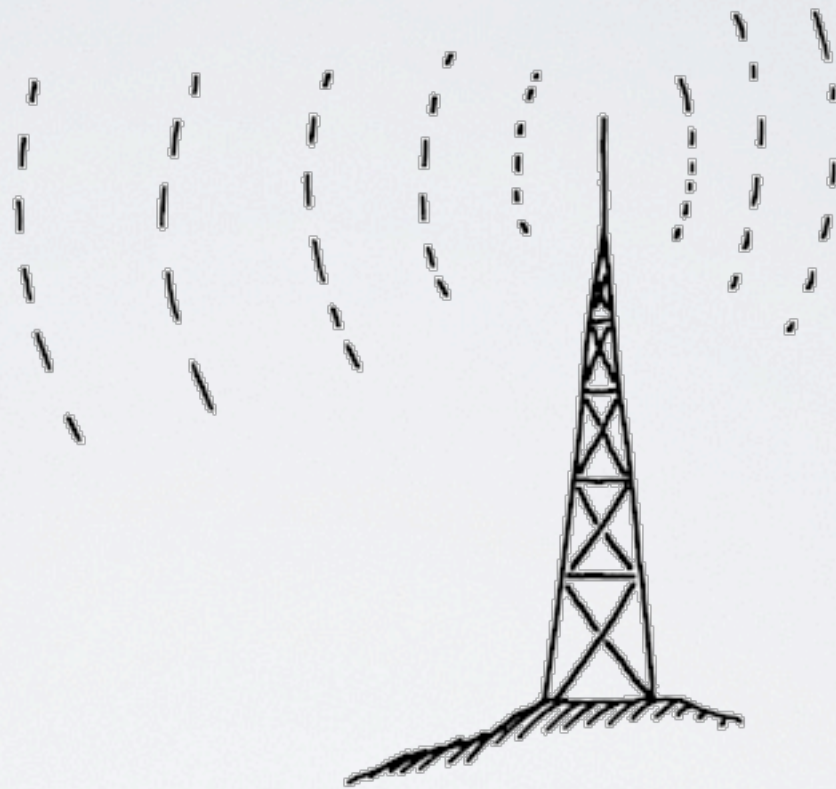
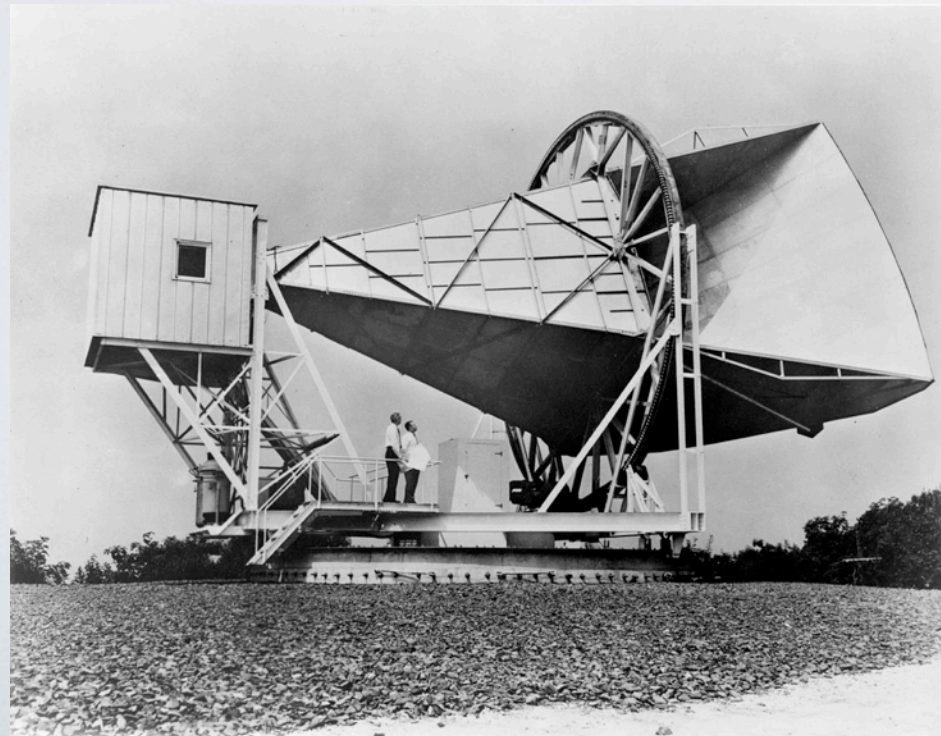
1965

**Penzias + Wilson discover
the entire universe is the same temperature
 3°K / -454.27°F**



Penzias + Wilson discover 1965 **the entire universe is the same temperature**

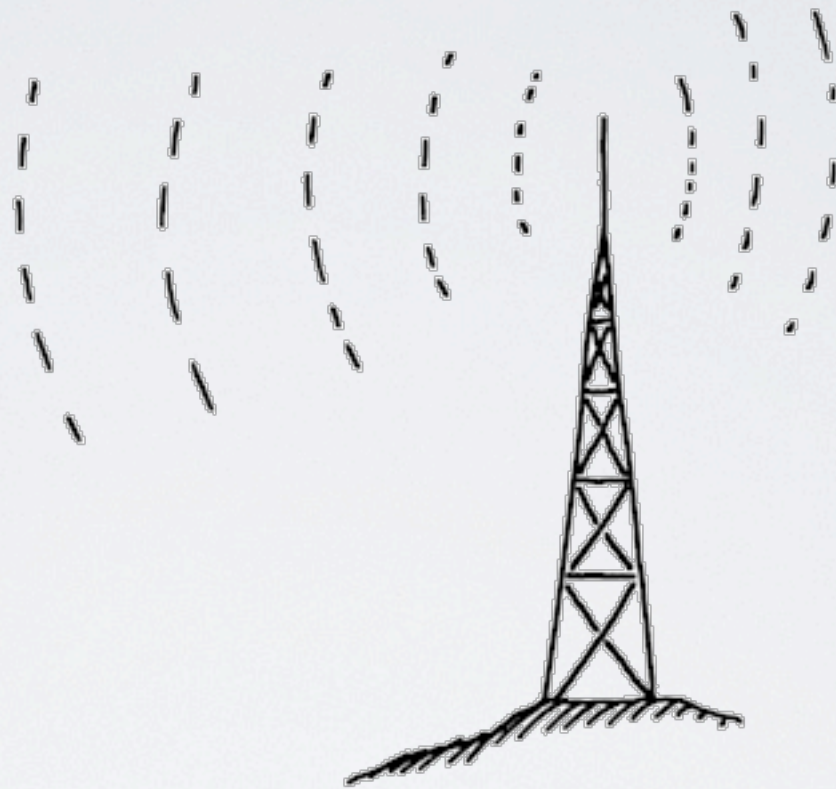
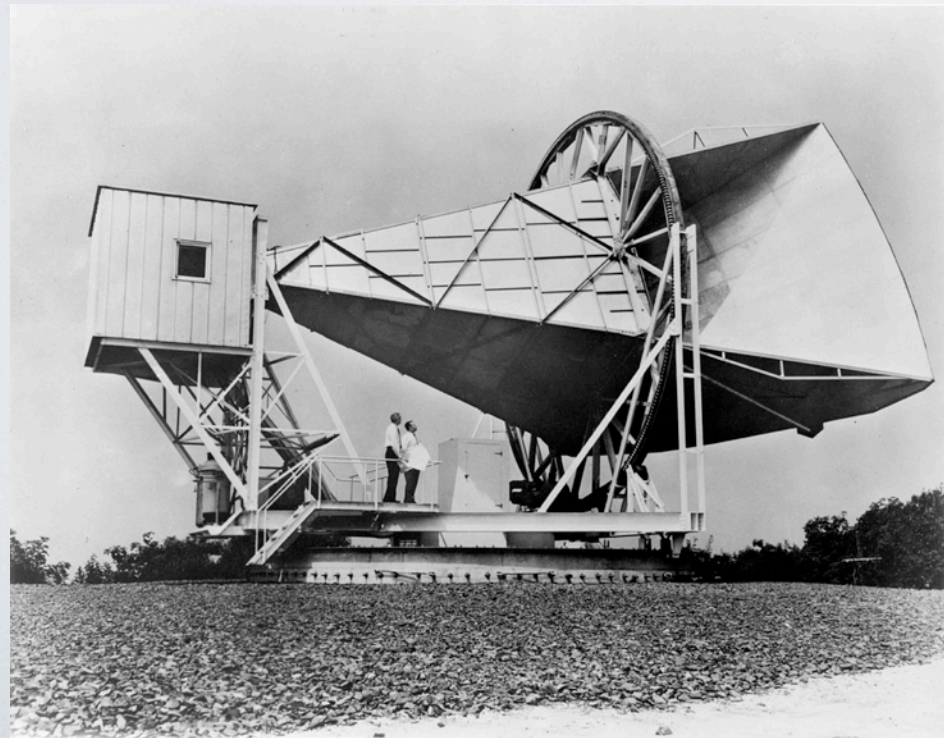
**Using a horn
antenna**



**Bouncing off
Echo balloon
satellites**

**To measure
radio waves**

Penzias + Wilson discover 1965 the entire universe is the same temperature

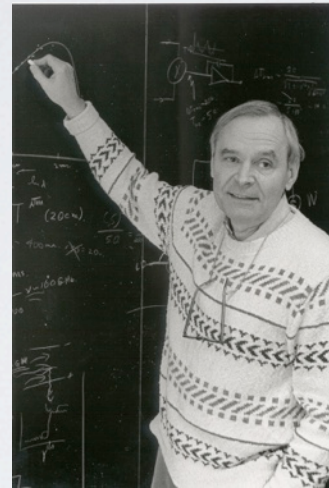


Found an additional
signal that the couldn't
identify its source

Penzias + Wilson discover 1965 the entire universe is the same temperature



Wilkinson



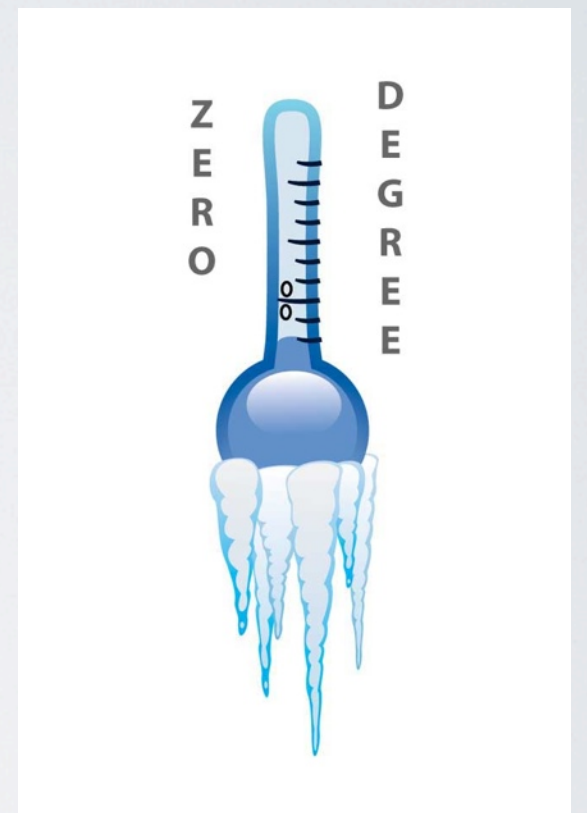
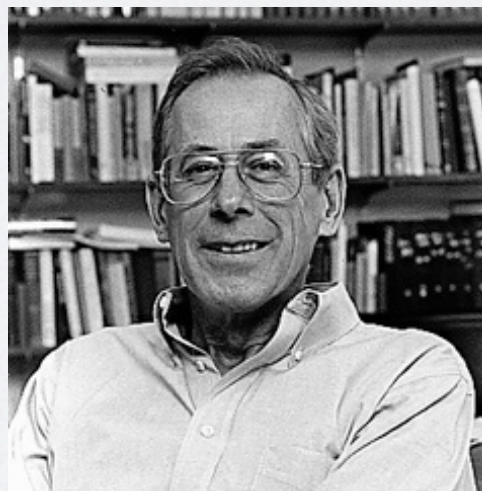
Dicke



3°K
(-454.27°F)

Explanation

Peebles



Left over temperature from hot beginning
of the universe

Questions

Scientific Evidence

How did the
universe begin?

Hot, Big Bang

How did the
universe grow-up?

It must have grown
evolved

What is the universe
made up of?

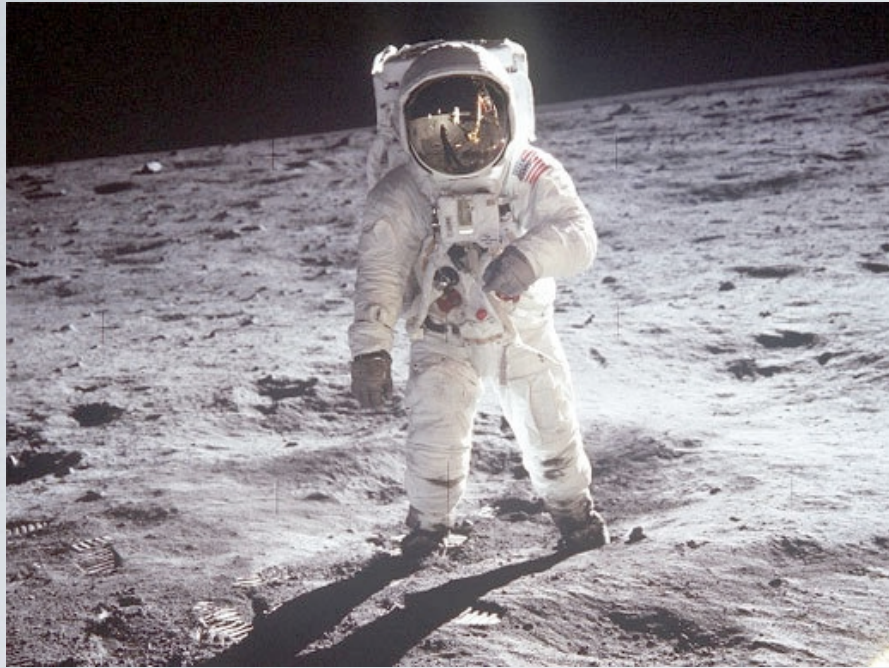
The same things that
we see here on earth?

1969

What was happening around the world?

What was happening in your life?

1969



Apollo 11
the first manned mission
to the moon



Woodstock

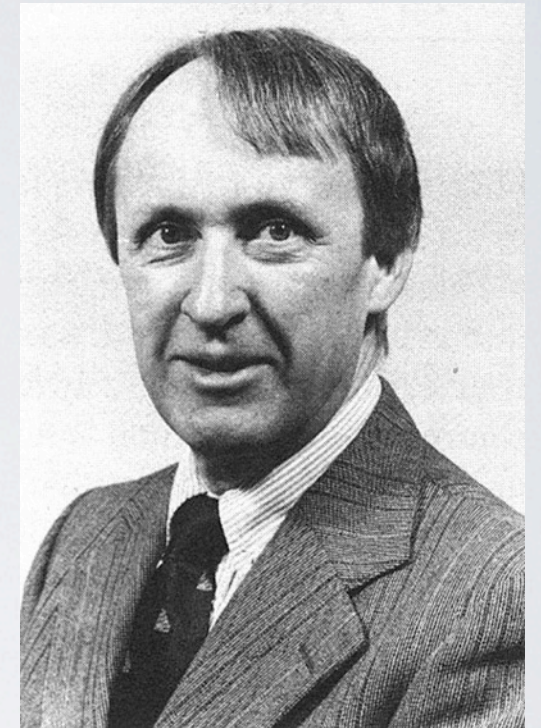


The Stonewall Riots in Greenwich
ignite the Gay Rights Movement

1969

**Two big problems with the Big Bang
that need to be answered...**

**Big Bang Horizon Problem
- Charles Misner**

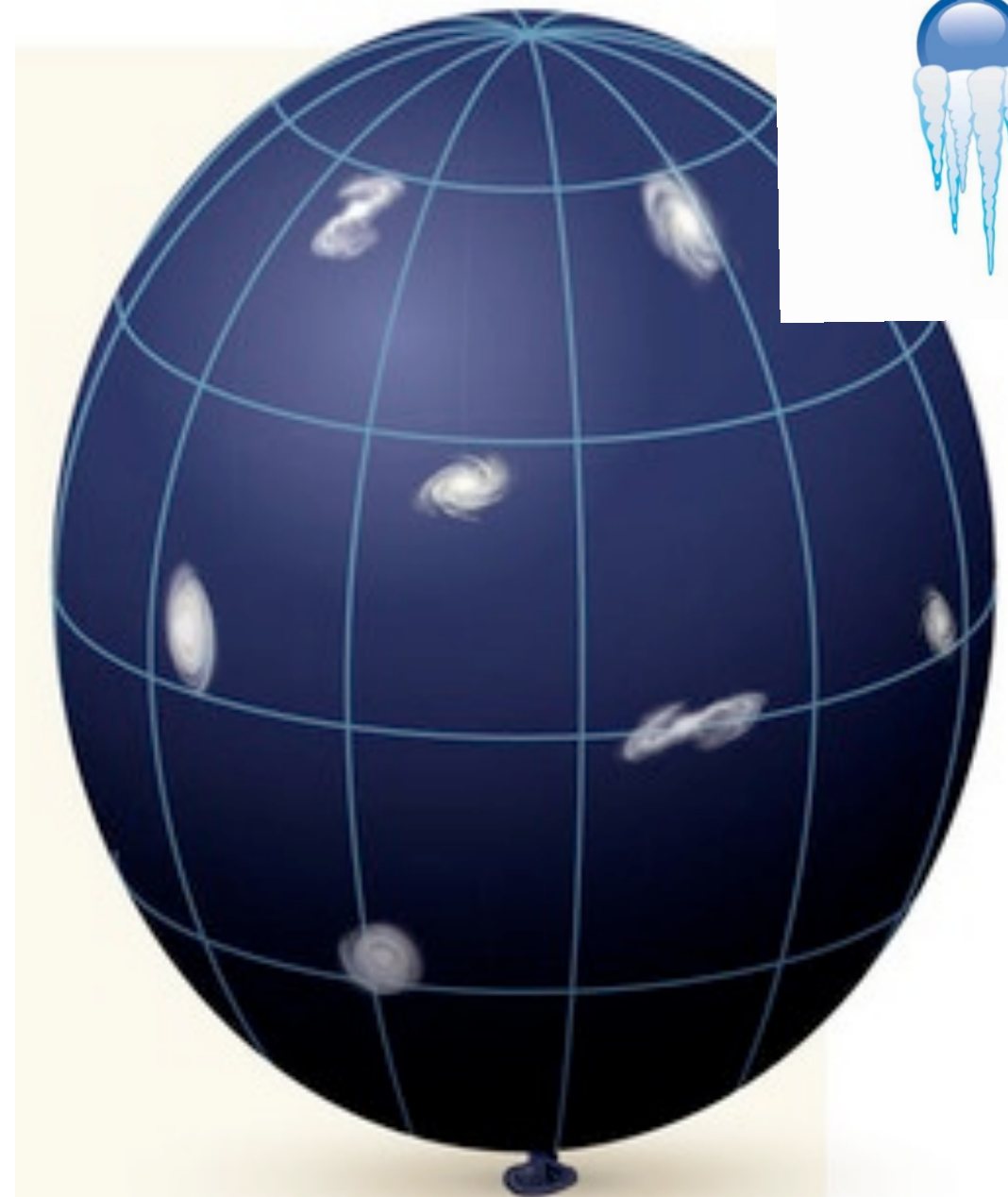


**Big Bang flatness Problem
- Robert Dicke**

Big Bang Horizon Problem

1969

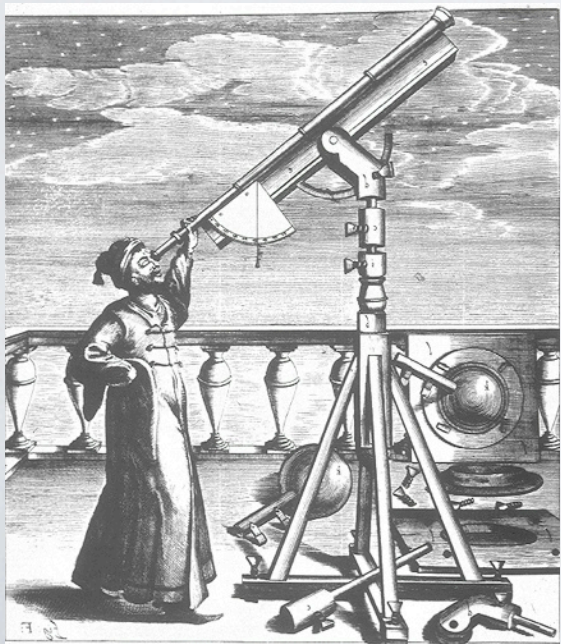
If there were tiny temperature differences in the beginning, how would it ever have the same common temperature today?



Big Bang Flatness Problem

1969

Looking at the
furthest distances



Light travels in straight lines

1969

Big Bang Flatness Problem



a. Spherical shape



b. Saddle shape



Space isn't curved like a balloon
or a saddle

Questions

Scientific Evidence

How did the
universe begin?

Hot, Big Bang

How did the
universe grow-up?

It must have grown
evolved and is flat on
large scales

What is the universe
made up of?

The same things that
we see here on earth?

1970

What was happening around the world?

What was happening in your life?



1970

John Hancock building
is built which is 100
stories - 1,127 ft

Environmental
Protection
Agency is formed



Aerosmith is formed

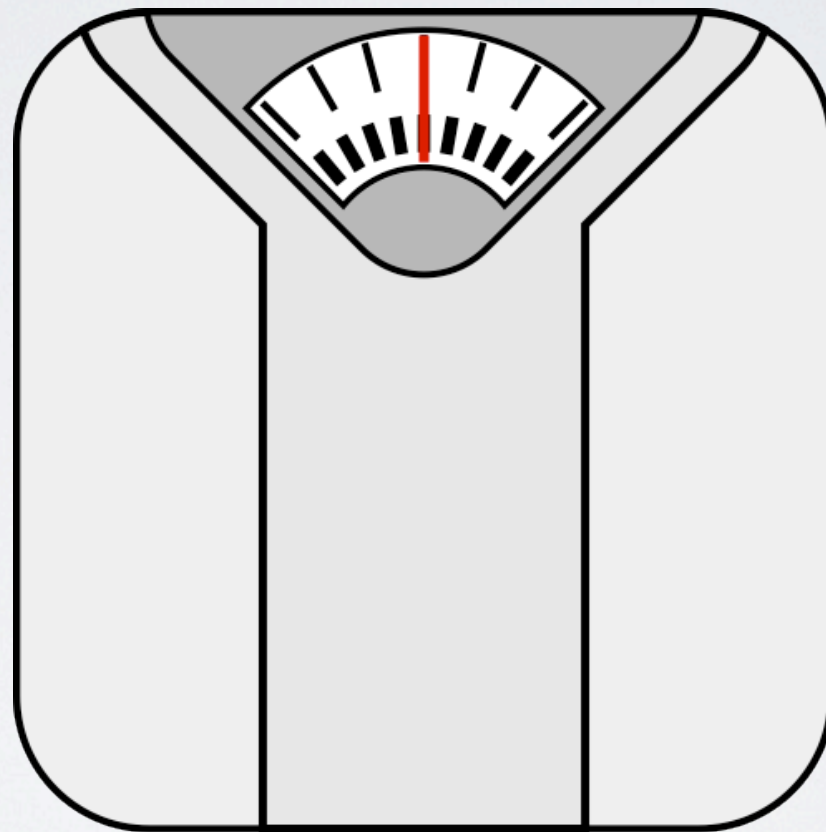
Vera Rubin measures dark matter in galaxies

1970



Vera Rubin measures dark matter in galaxies

1970

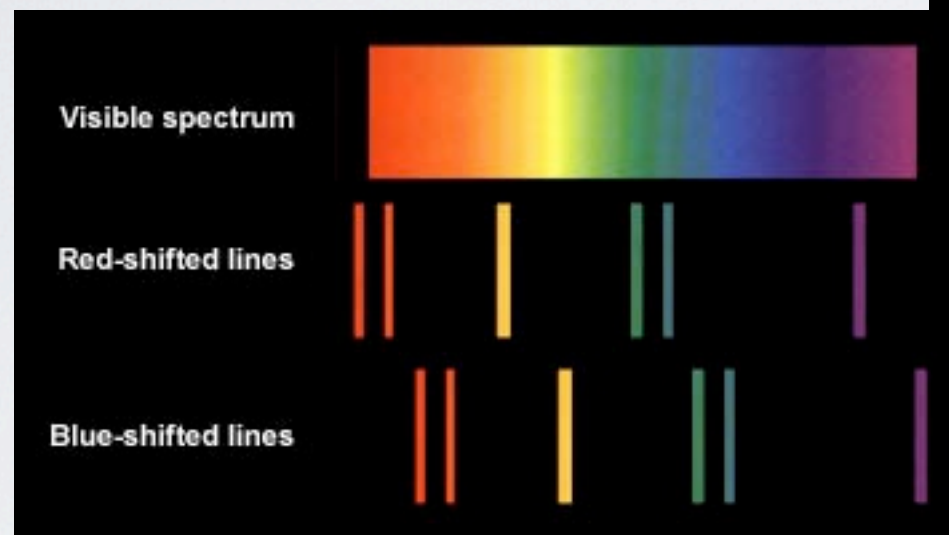


Weighed the galaxies



Vera Rubin measures dark matter in galaxies

1970

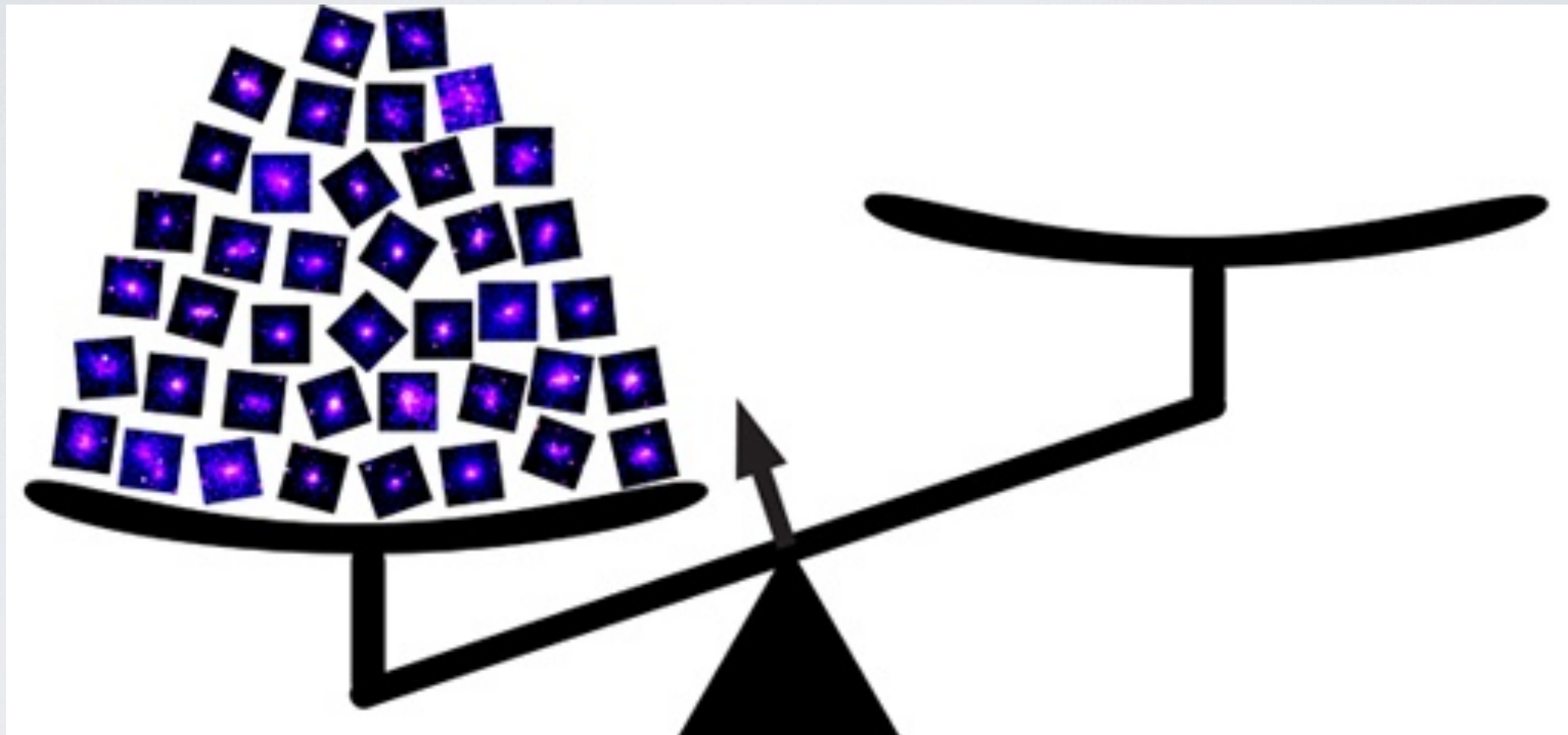


Weighed the galaxies
by measuring how it
rotated



Vera Rubin measures dark matter in galaxies

1970



Found they were much too heavy!

Must be extra missing mass that we can't see

Questions

Scientific Evidence

How did the
universe begin?

Hot, Big Bang

How did the
universe grow-up?

**It must have grown
evolved and is flat on
large scales**

What is the universe
made up of?

**Regular matter and
Dark matter!!**

1980

What was happening around the world?

What was happening in your life?

1980

USA defeats USSR
in Olympics



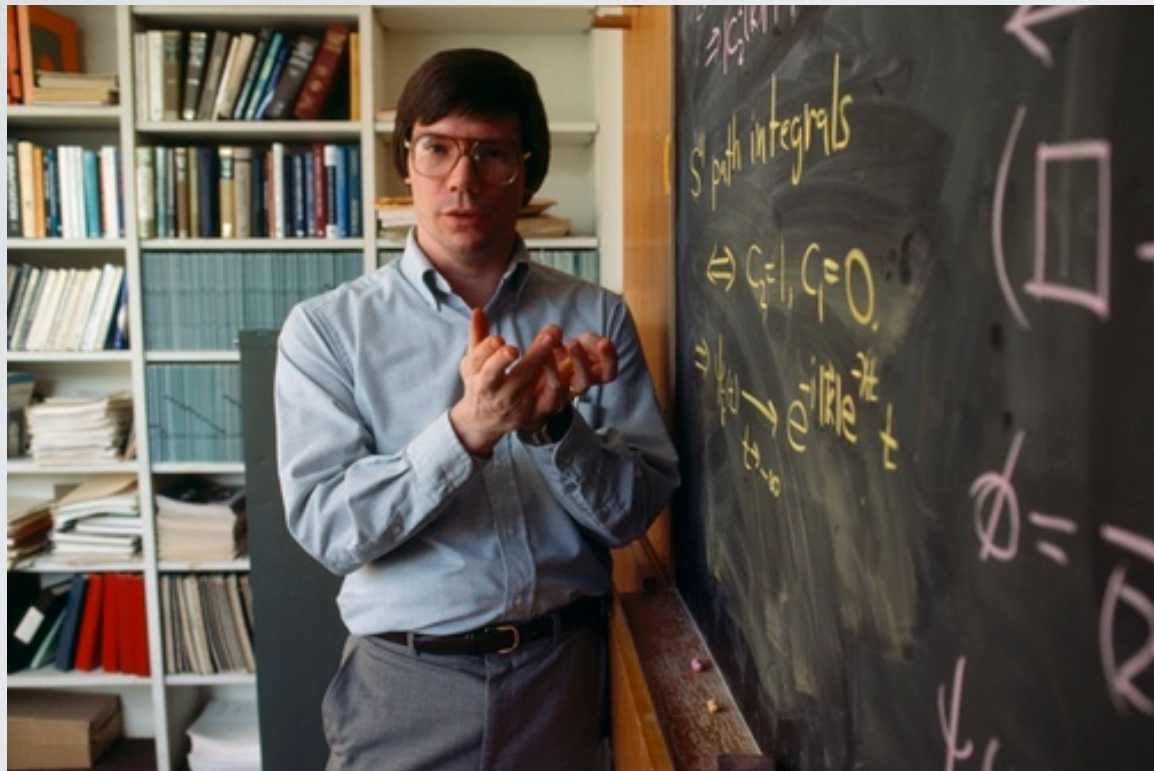
Mount St. Helen
erupts



Ronald Reagan
becomes president

Predict inflation within the first
few seconds of the universe

1980



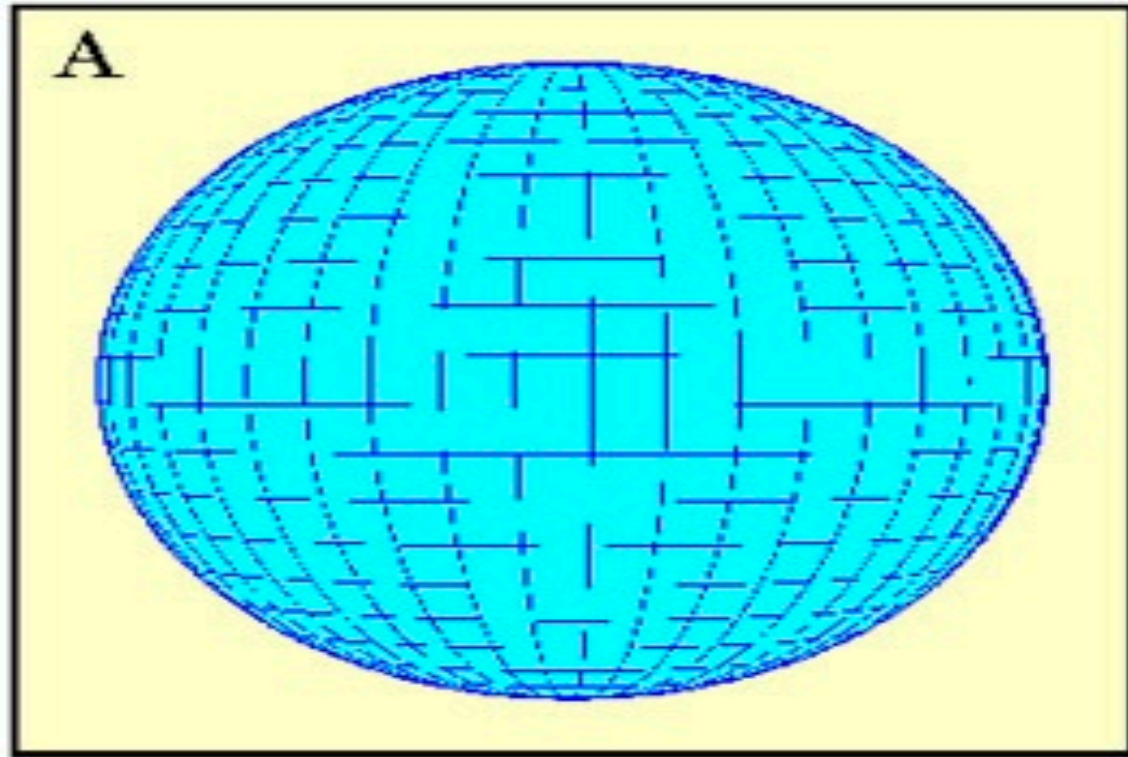
Alan Guth



Alexei Starobinsky

Predict inflation within the first
few seconds of the universe

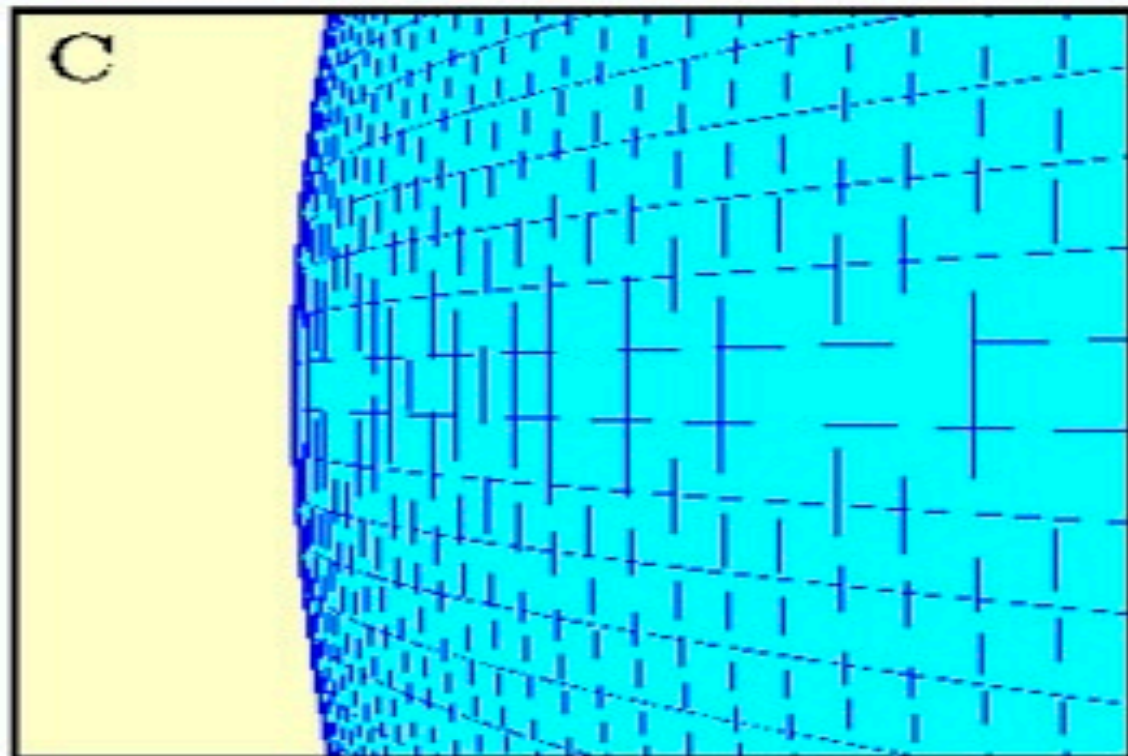
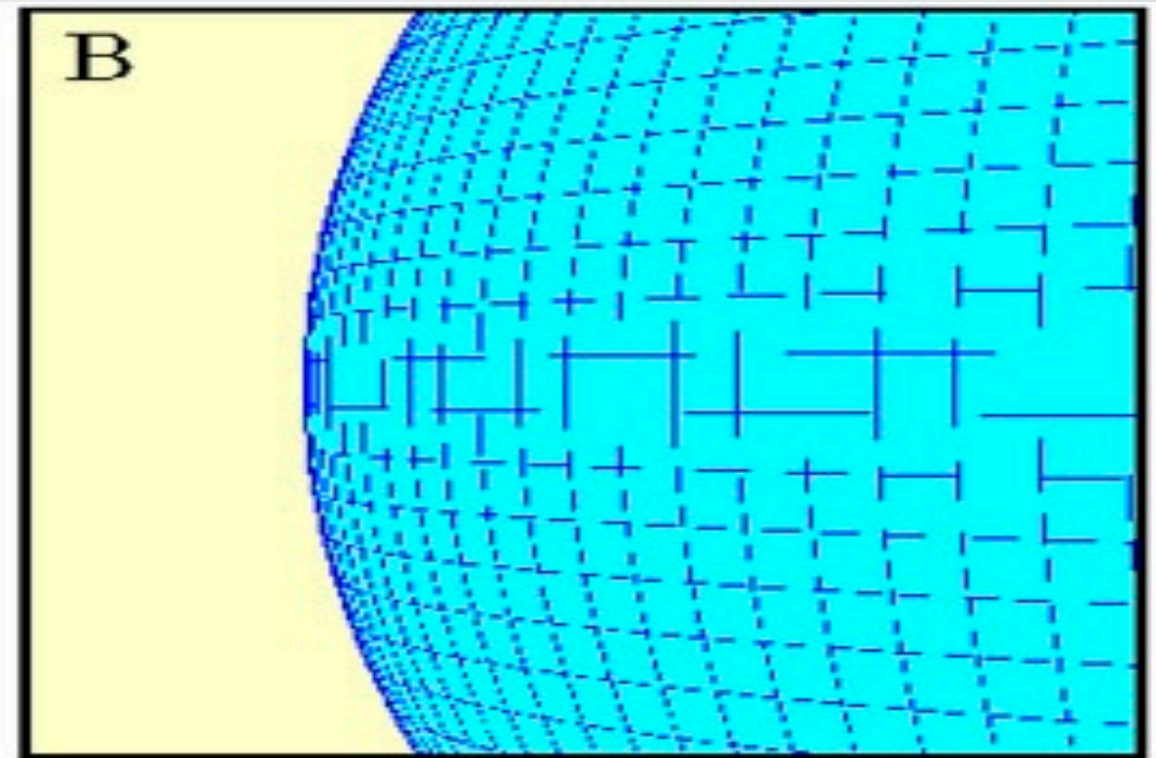
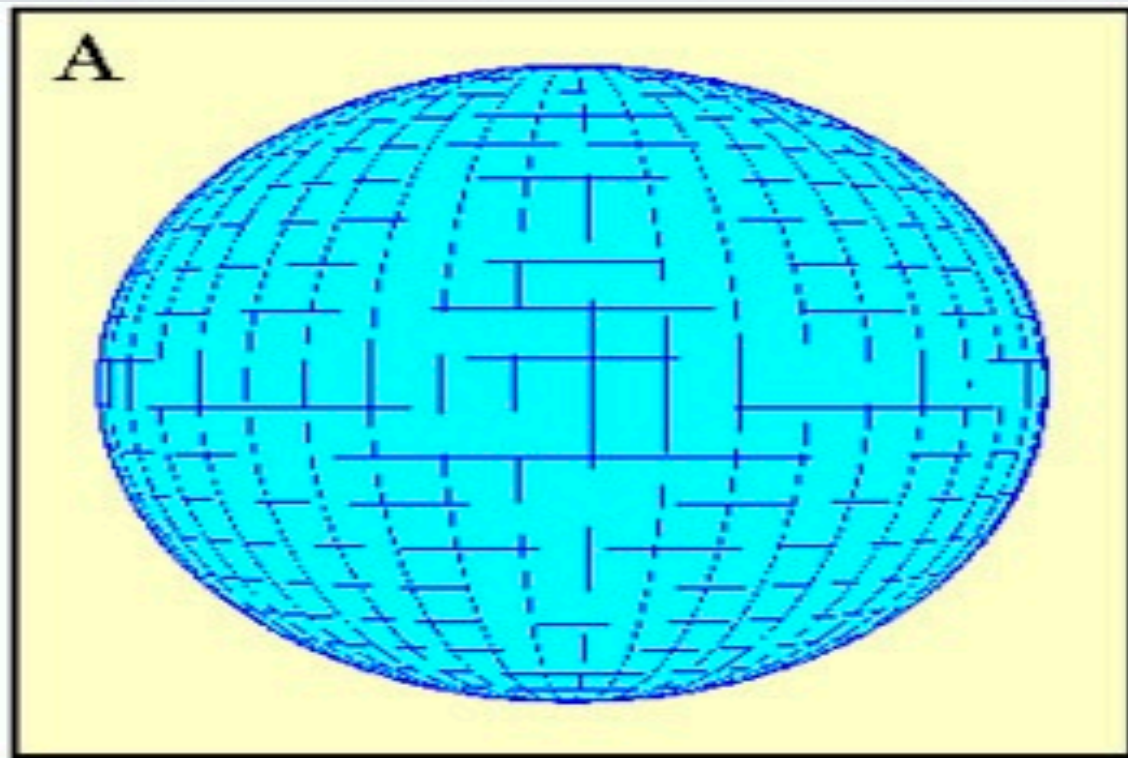
1980



Start with an
empty vacuum

Predict inflation within the first
few seconds of the universe

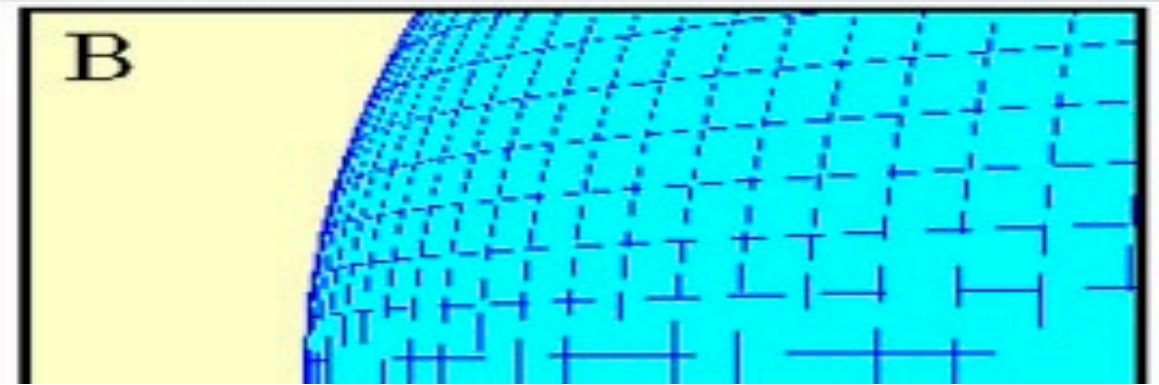
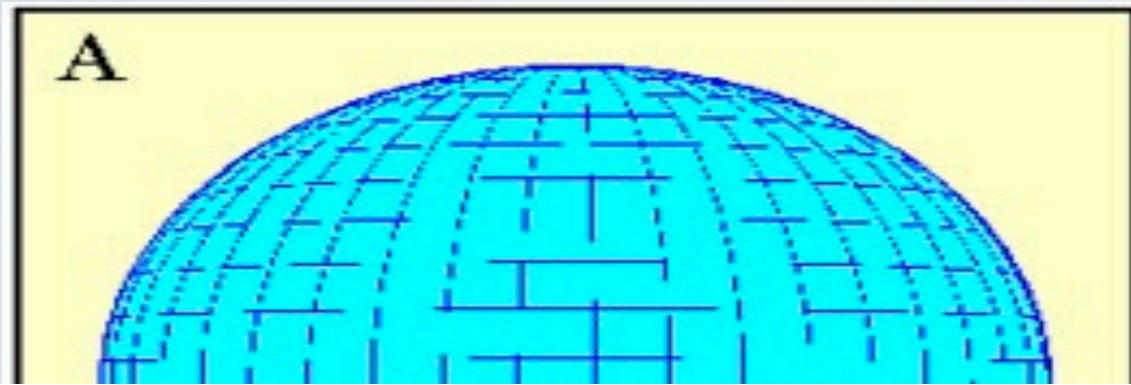
1980



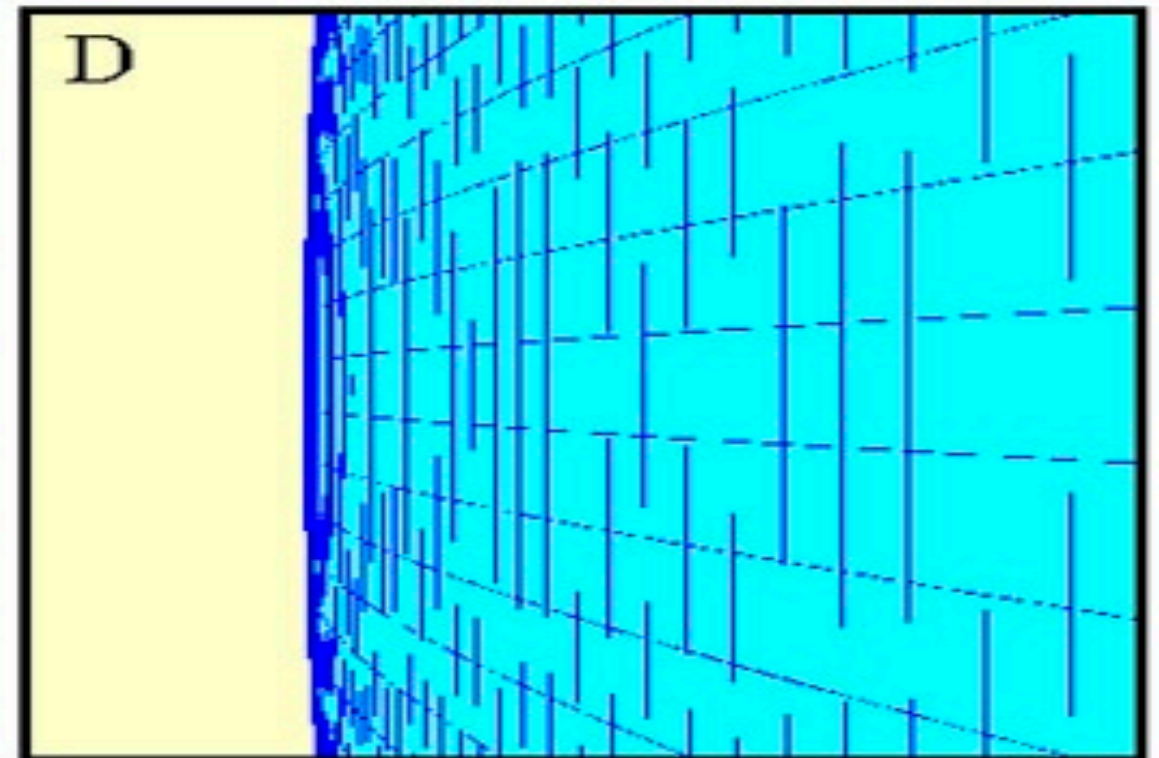
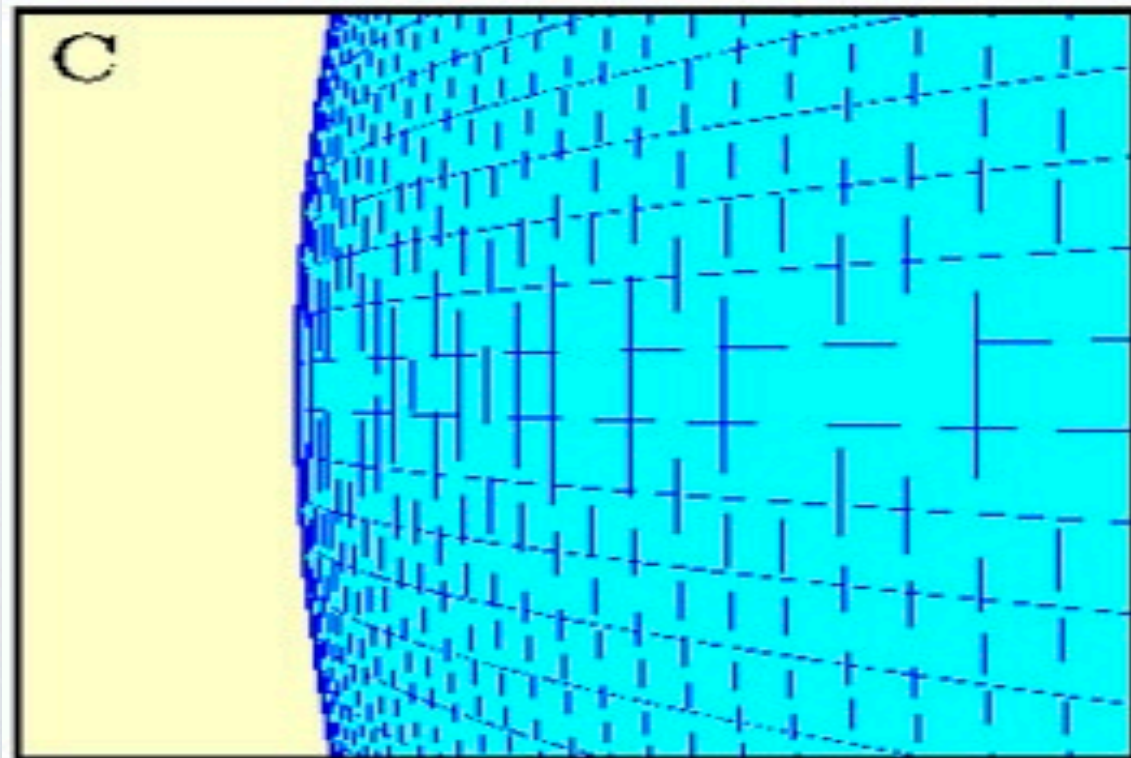
Rapidly
expands

Predict inflation within the first
few seconds of the universe

1980



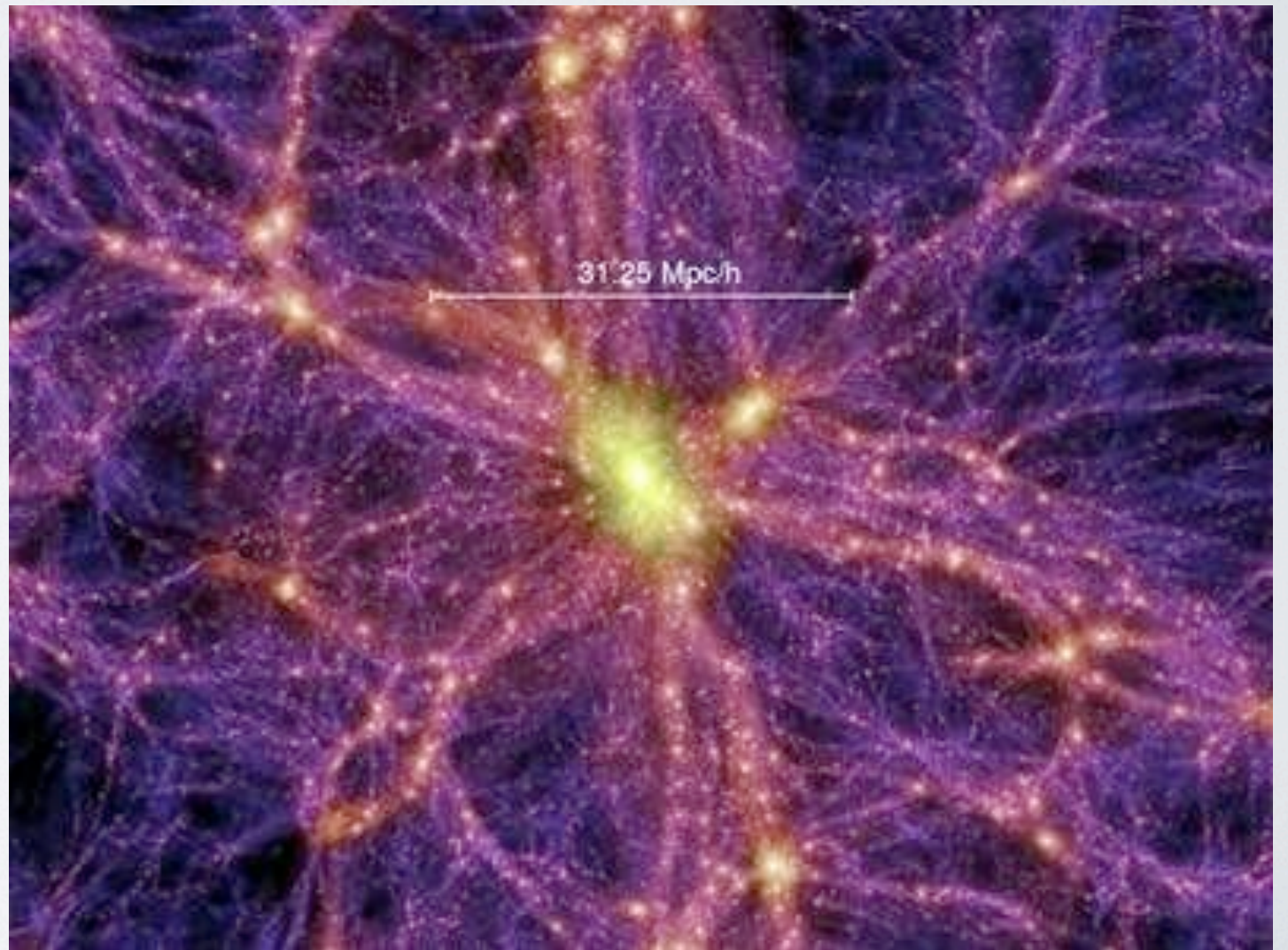
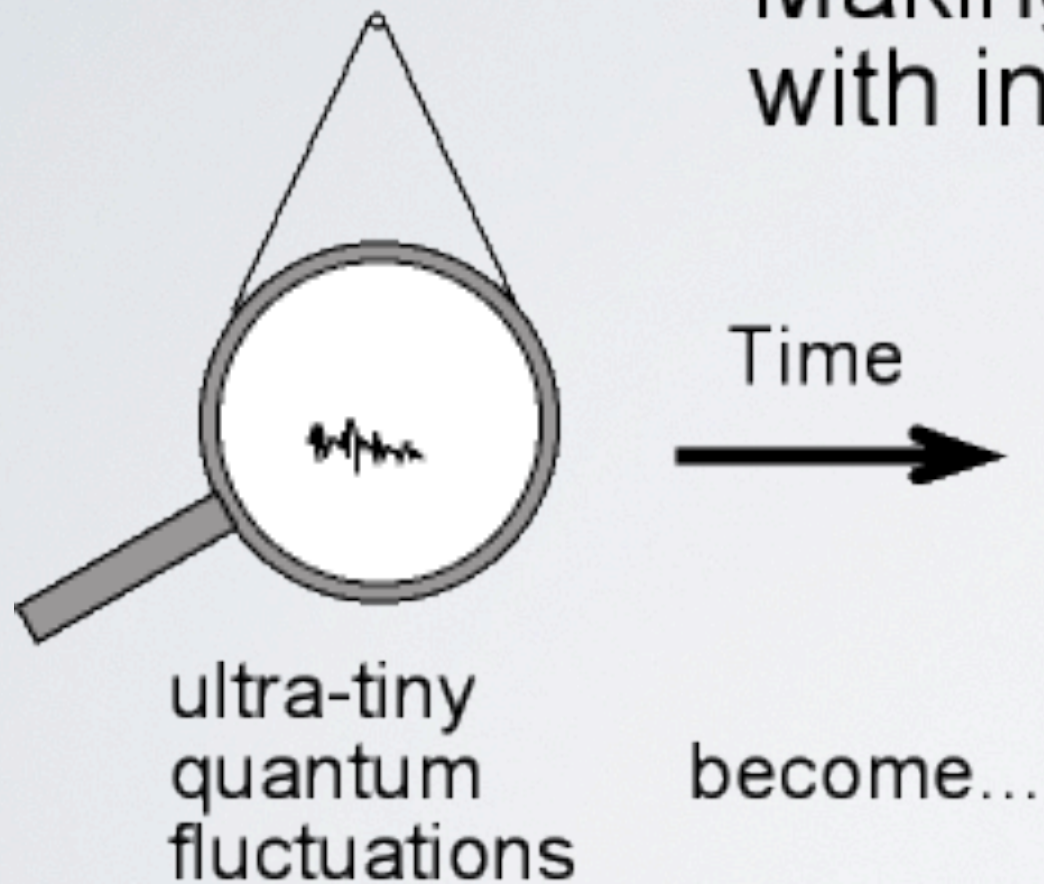
An explanation for the temperature and
flatness problems



Predict inflation within the first few seconds of the universe

1980

Making the “galaxy seeds” with inflation



Predict inflation within the first
few seconds of the universe

1980

Making the “galaxy
with inflation

Time

ome...

This is a prediction from theory and there is
no experimental evidence for it yet...



Questions

Scientific Evidence

How did the
universe begin?

*** Hot, Big Bang**
***Possibly Rapid inflation?**

How did the
universe grow-up?

**It must have grown
evolved and is flat on
large scales**

What is the universe
made up of?

**Regular matter and
Dark matter**

1982

What was happening around the world?

What was happening in your life?

1982

The Lebanon War begins



Metallica plays their first show



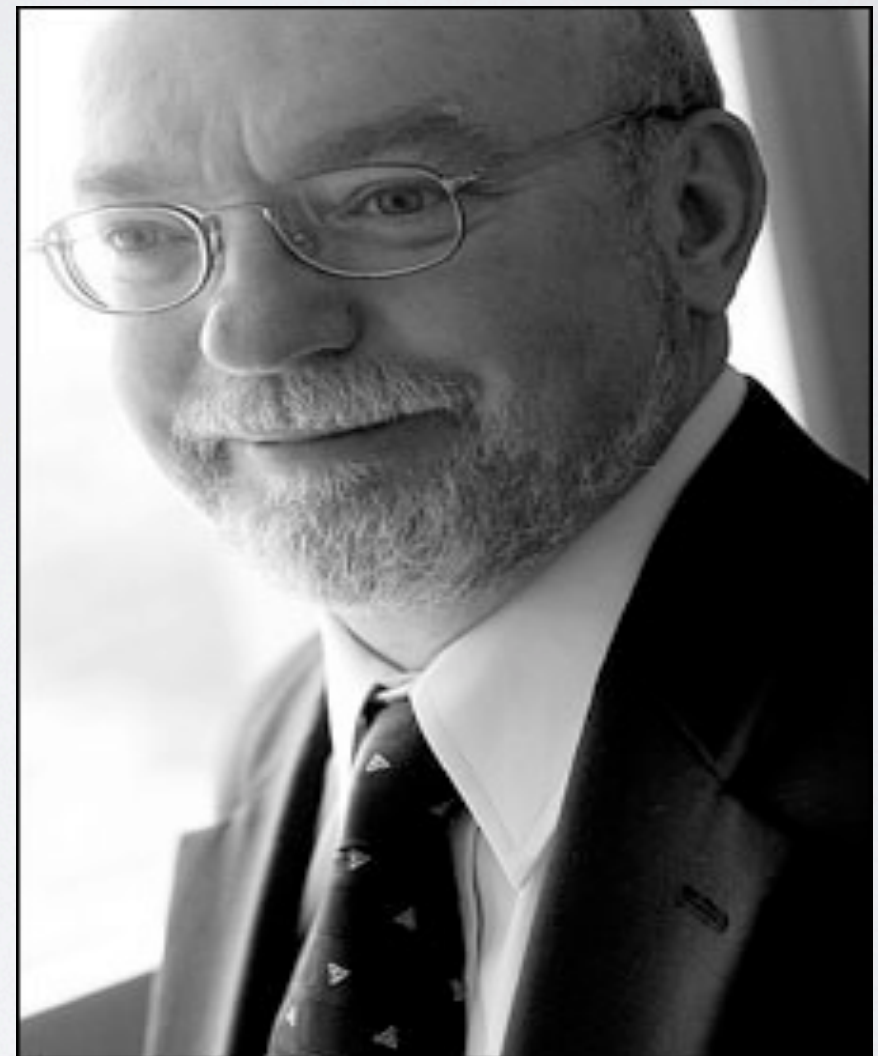
Michael Jackson releases Thriller

1982

First large galaxy survey mapping the
location of millions of galaxies



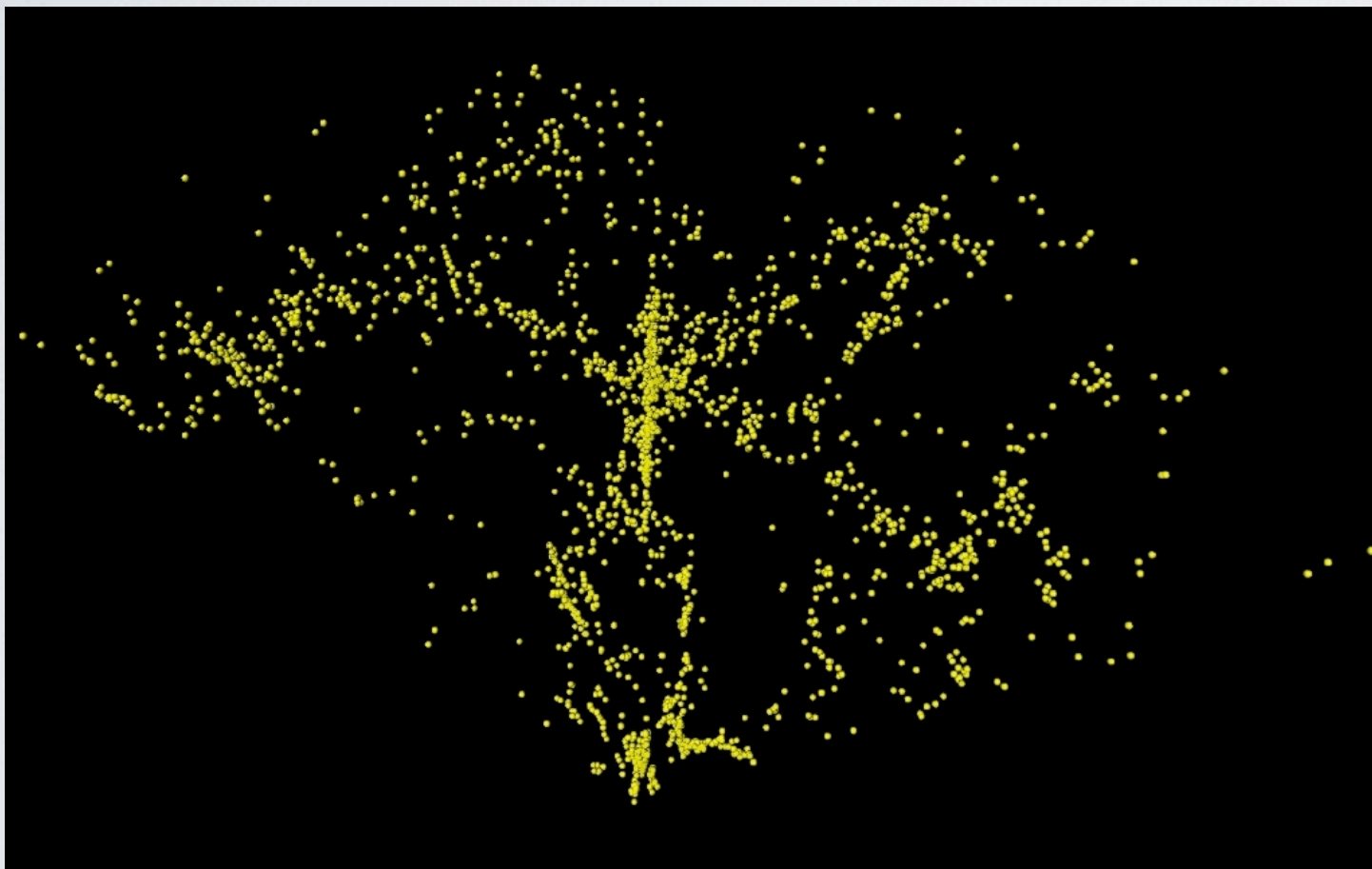
Margaret Geller



John Huchra

1982

First large galaxy survey mapping the location of millions of galaxies



Each point = 1 Galaxy



On the very largest scales galaxies are clustered

1990 - 1992

What was happening around the world?

What was happening in your life?

1990-1992

'90 - Mandela
released from 27
years in prison



'90/'91-Iraq-
Kuwait War
begins



' 91 - Mt. Pinatubo erupts

1990-1992



'91 - Nintendo was first released



'91 - Apple releases 1st laptop



'92 - LA Riots begin

1990-1992

**COBE measures the baby picture of
the universe - tiny temperature
fluctuations**



John Mather



George Smoot



Steve Meyer

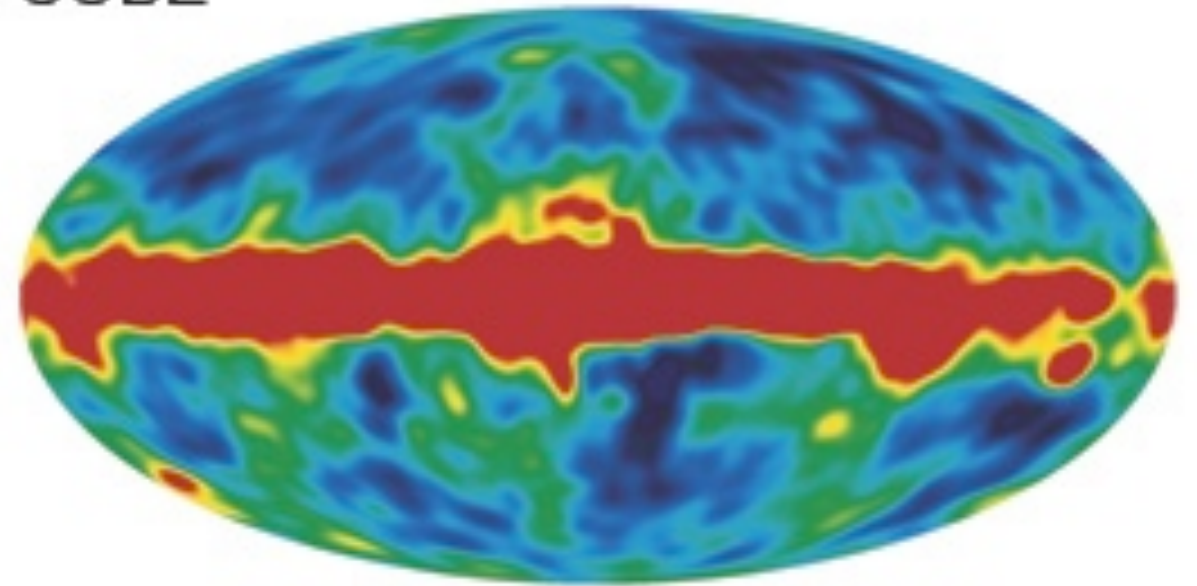
**My advisor and
your speaker next week!**

1990-1992

**COBE measures the baby picture of
the universe - tiny temperature
fluctuations**

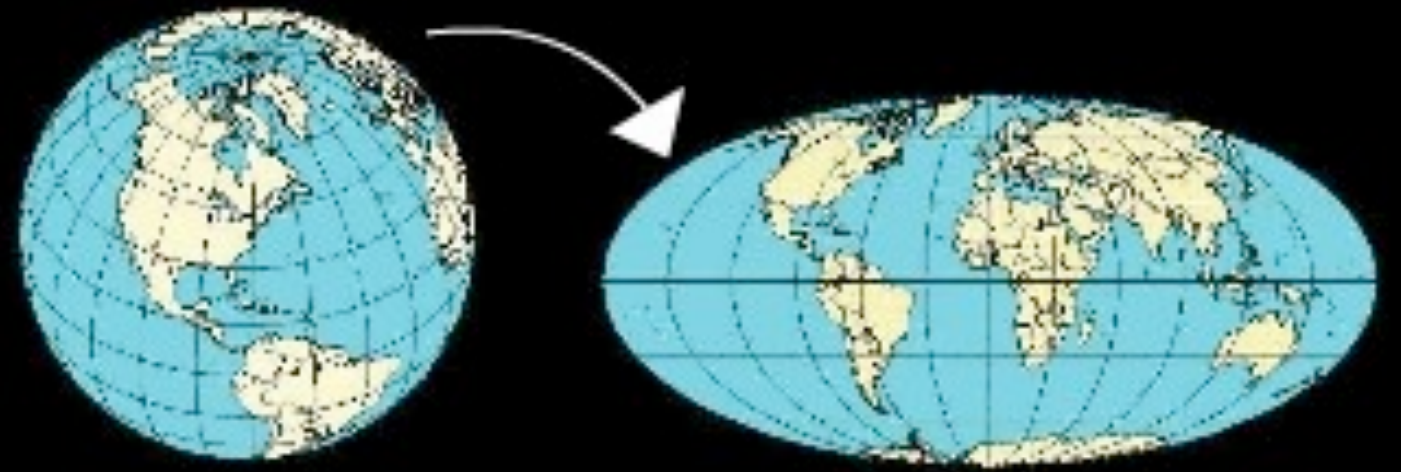


COBE



**COBE measures the tiny
temperature fluctuations**

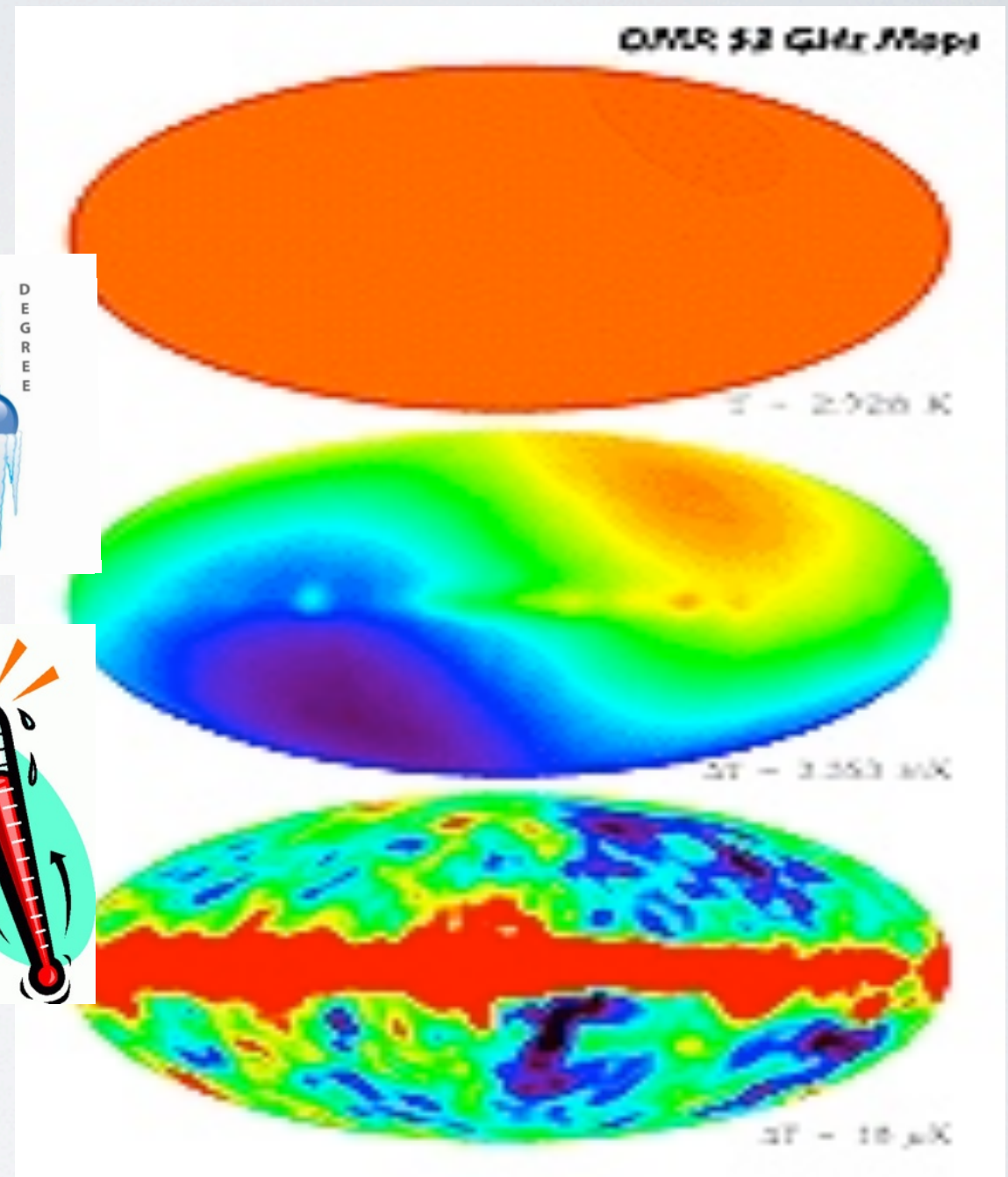
1990-1992



**COBE measures a
temperature map of the
entire sky**

COBE measures the tiny
temperature fluctuations

1990-1992



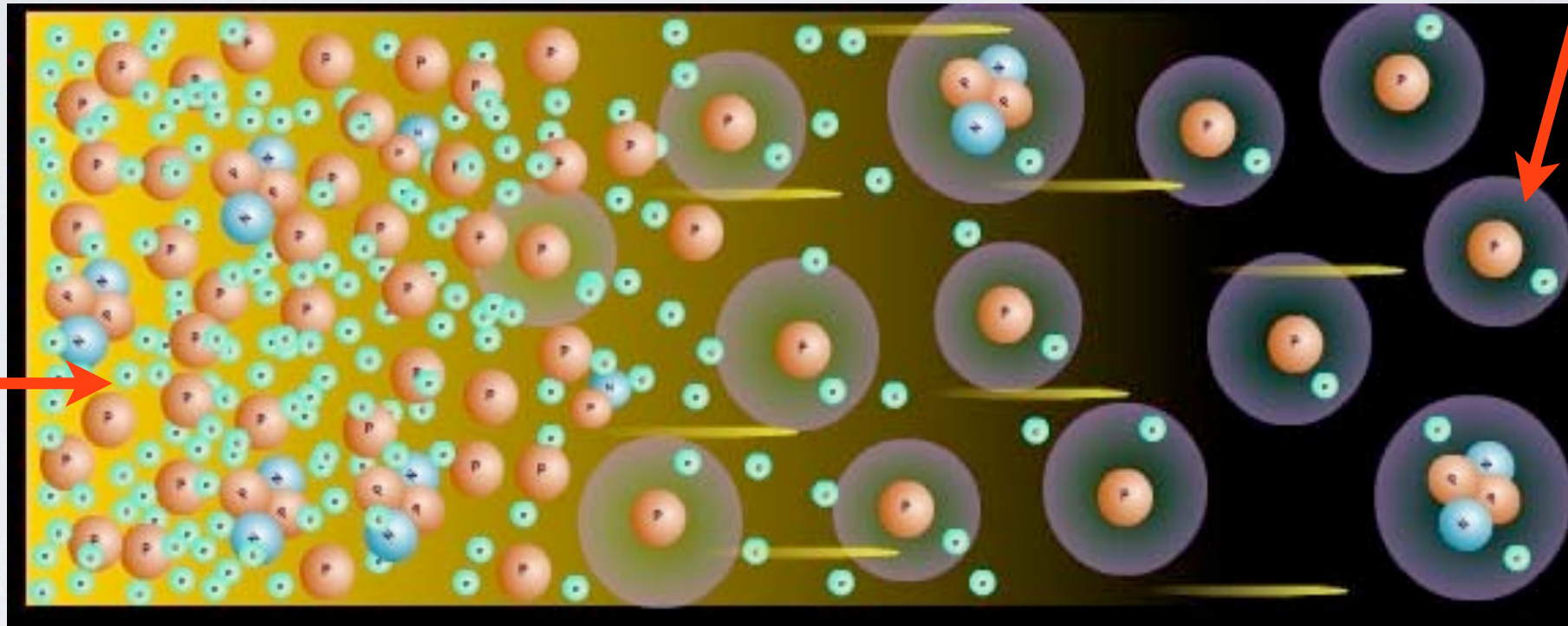
More precise temperature measurement

COBE measures the tiny
temperature fluctuations

1990-1992

Atoms

Protons
Electrons
Neutrons



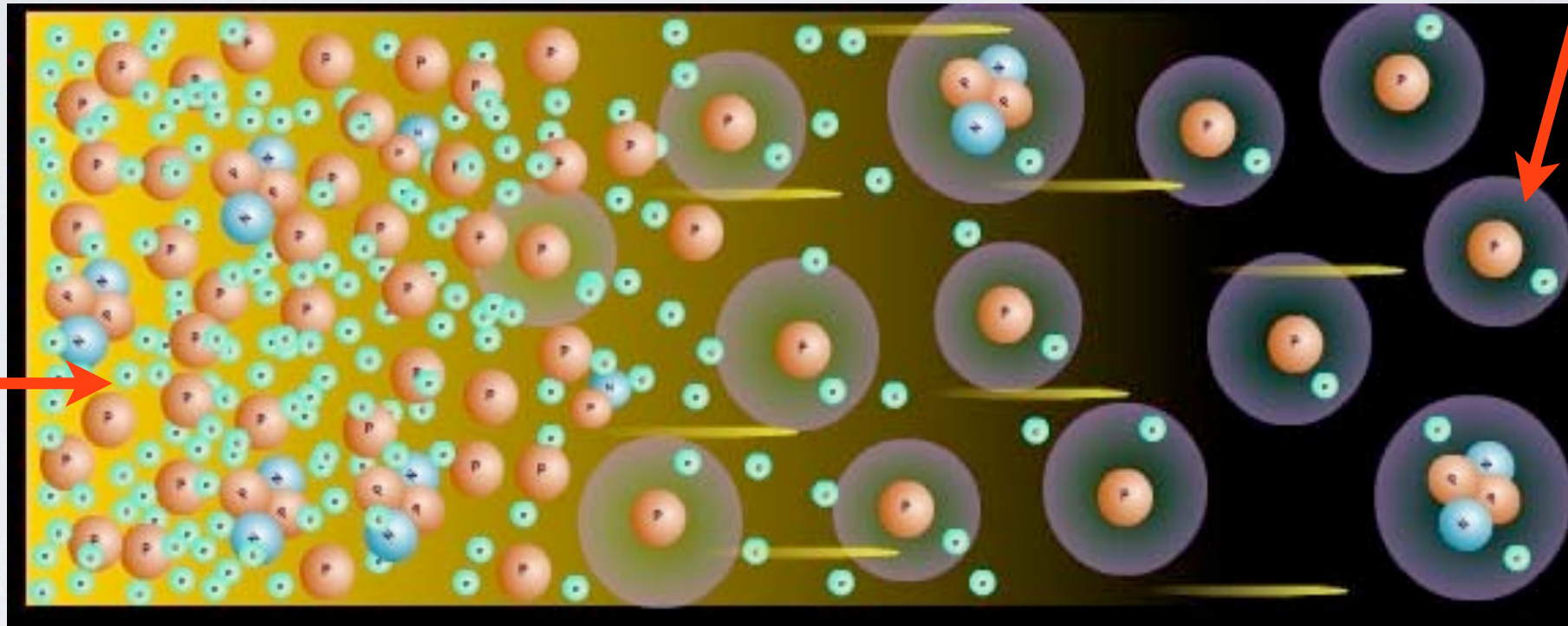
Light

COBE measures the tiny
temperature fluctuations

1990-1992

Atoms

Protons
Electrons
Neutrons



Driving
on a
foggy
road



Light

COBE measures the tiny
temperature fluctuations

1990-1992

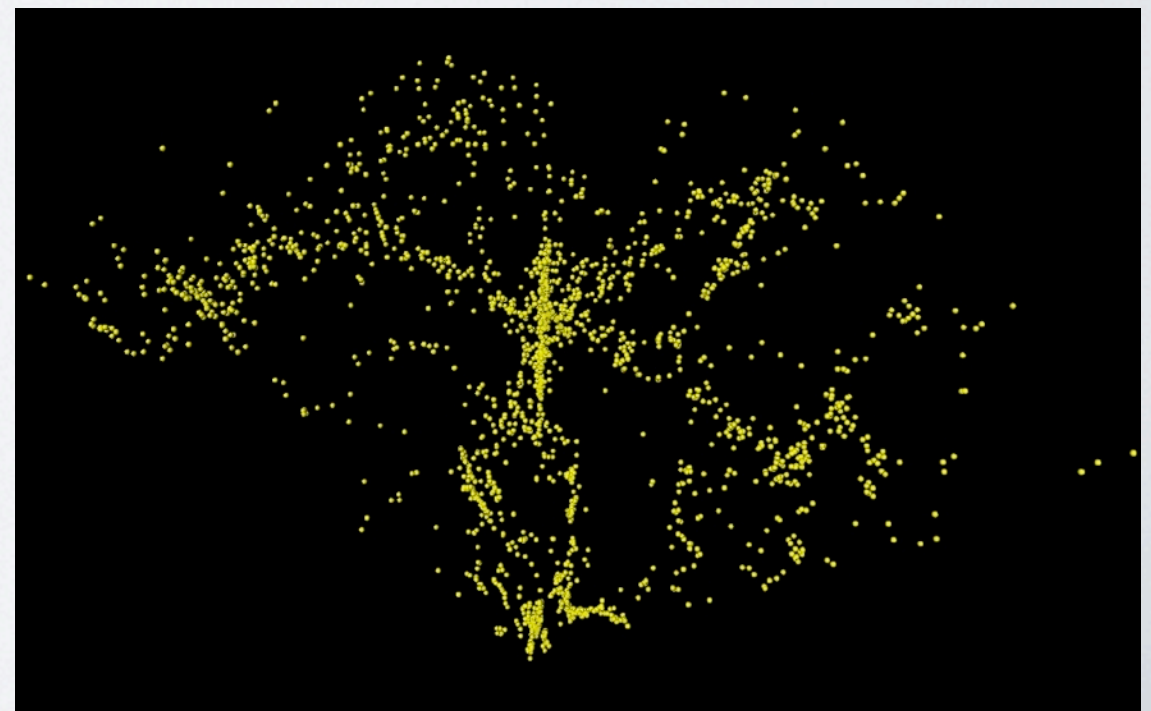
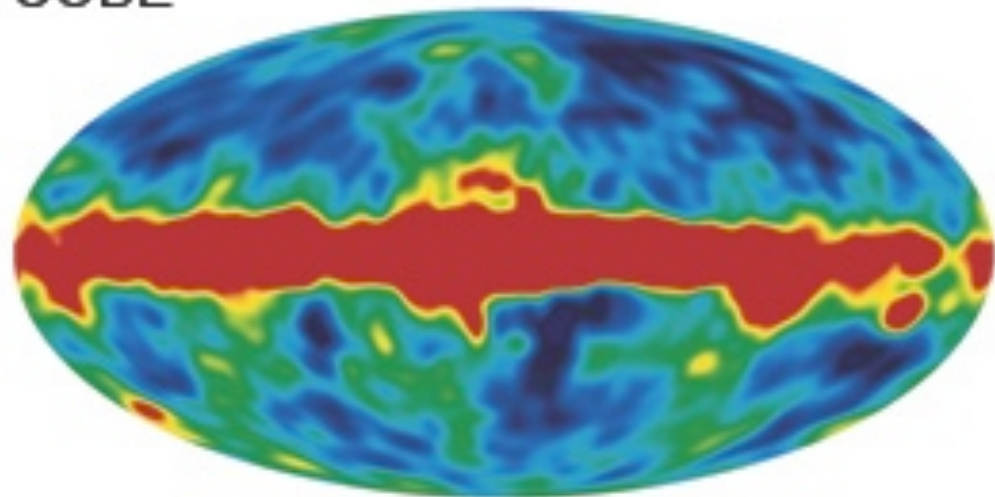


400,000 years old



14 billion years old

COBE



1990-1992

Questions

Scientific Evidence

How did the
universe begin?

*** Hot, Big Bang!!**

*** Possibly Rapid inflation?**

How did the
universe grow-up?

*** started from tiny seeds**

*** Has grown evolved**

*** flat on large scales**

What is the universe
made up of?

**Regular matter and
Dark matter**

Discovery of CMB won the Nobel Prize in 2001



1998

What was happening around the world?

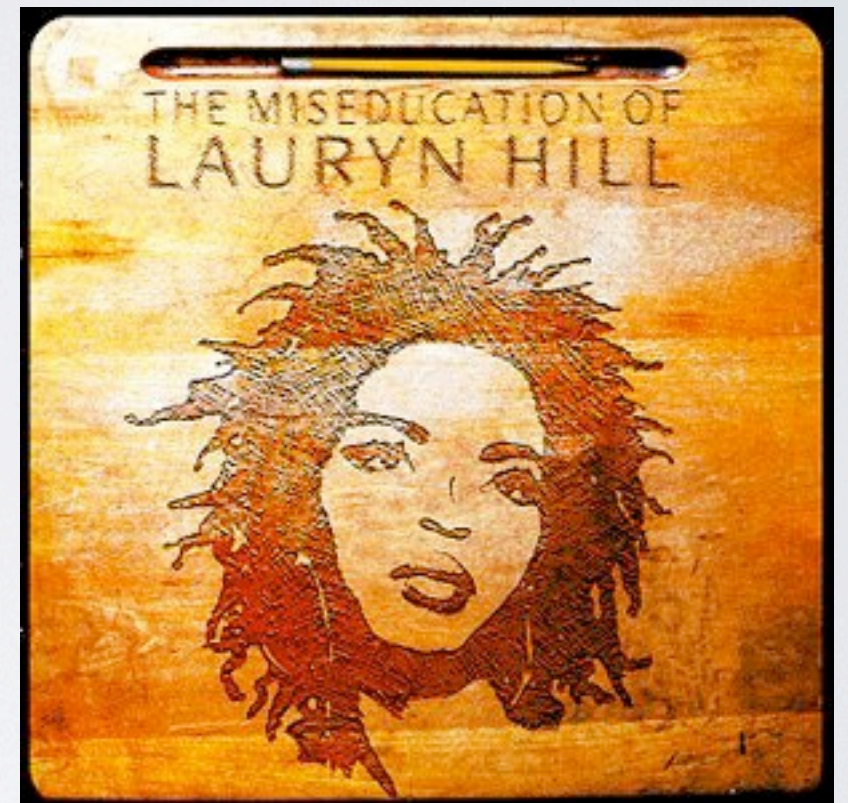
What was happening in your life?

1998



U.S. Embassy bombings in Kenya and Tanzania

‘The Miseducation
of Lauryn Hill’ is
released

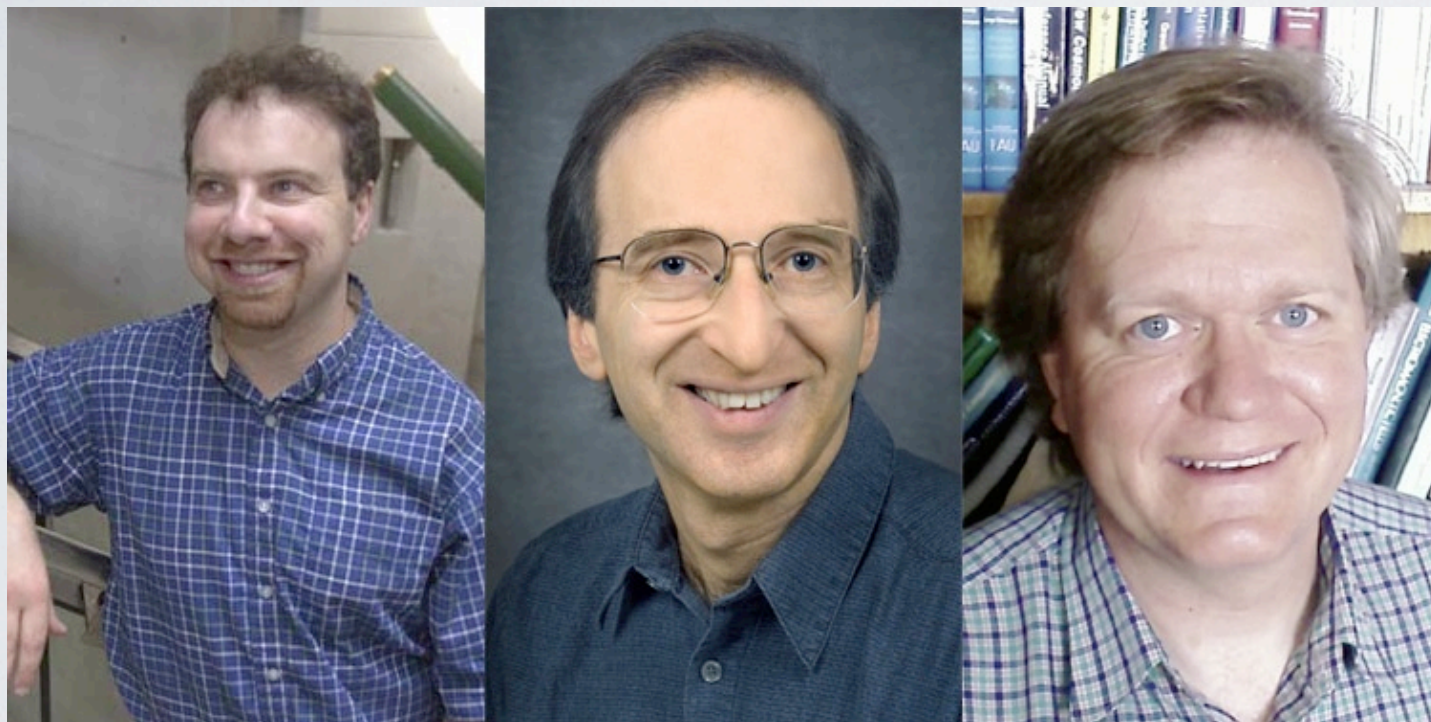


Google

Google is founded

Supernovae Cosmology Project & High-z Supernovae team measure an accelerating universe

1998



Reiss

Schmidt

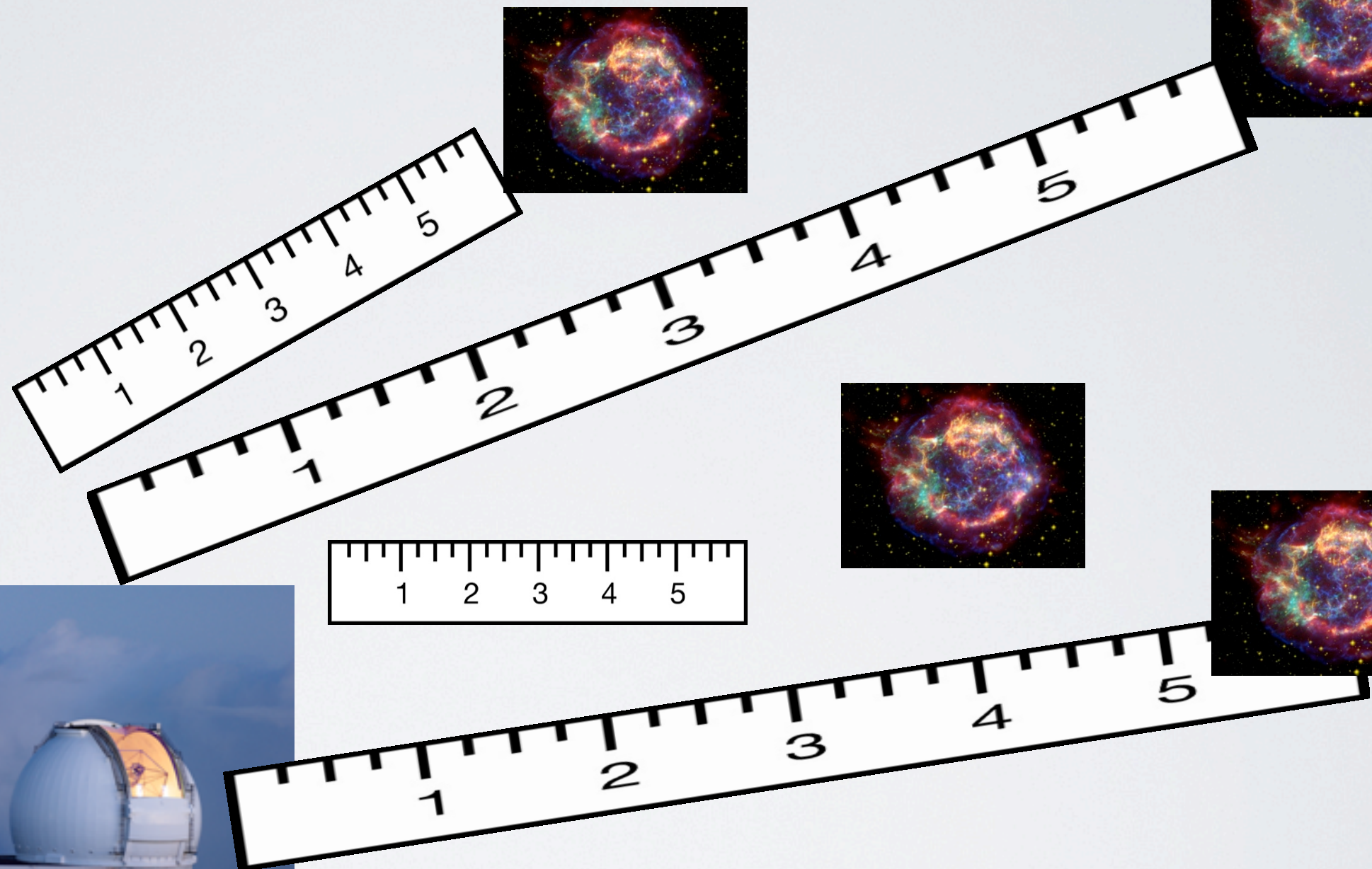
Perlmutter



SN 1994D in the NGC 4526 galaxy (bright spot on the lower left). Image by NASA, ESA, The Hubble Key Project Team, and The High-Z Supernova Search Team

SCP & High-z teams measure an accelerating universe

1998



The twin 10-meter Keck telescope domes on Maunakea, Hawaii.
Image courtesy of the W.M. Keck Observatory.
Image © 2005-2010 W.M. Keck Observatory

Measured distances to supernova

SCP & High-z teams measure an accelerating universe

1998



The twin 10-meter Keck telescope domes on Mauna Kea, Hawaii.
Image courtesy of the W.M. Keck Observatory.
Image © 2005-2010 W.M. Keck Observatory

Measured speed to supernova

SCP & High-z teams measure an accelerating universe

1998

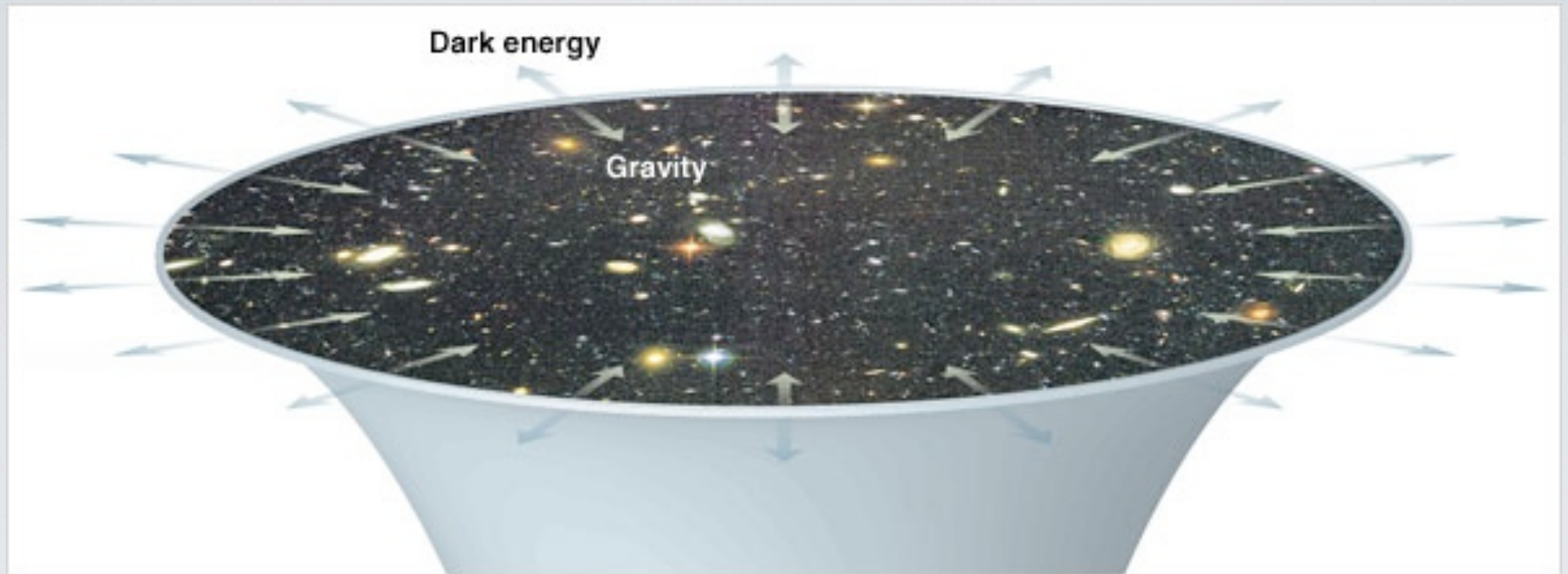


The twin 10-meter Keck telescope domes on Mauna Kea, Hawaii.
Image courtesy of the W.M. Keck Observatory.
Image © 2005-2010 W.M. Keck Observatory

They found the most
distant supernovae
speeding away!

SCP & High-z teams
measure an accelerating universe

1998



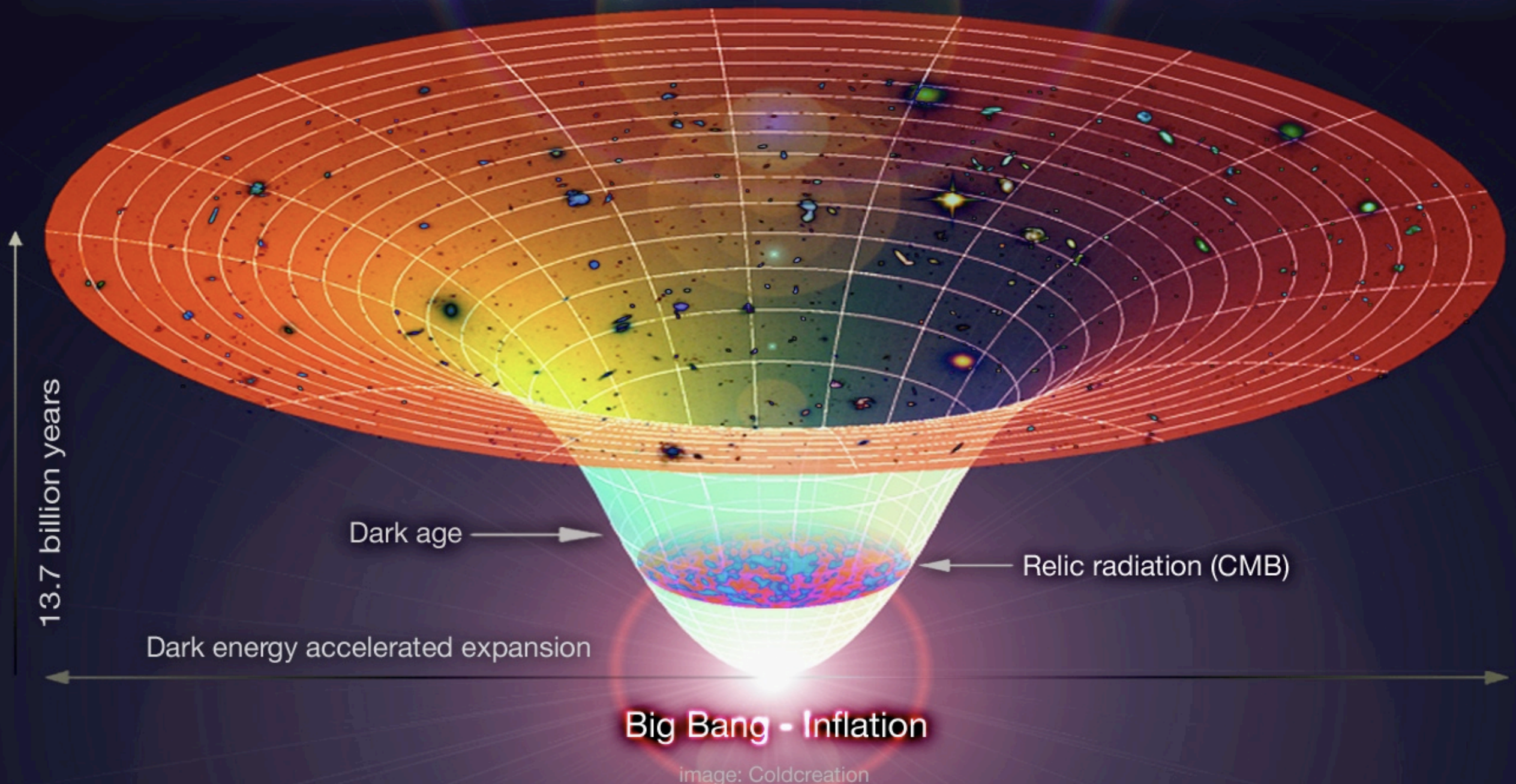
Gravity is pulling all the matter inward

Dark energy is pushing everything outward

SCP & High-z teams measure an accelerating universe

1998

Accelerated Expansion of the Universe



Questions

Scientific Evidence

How did the
universe begin?

***Hot, Big Bang**
***Possibly Rapid inflation?**

How did the
universe grow-up?

*** started from tiny seeds**
***Has grown evolved**
***flat on large scales**

What is the universe
made up of?

**Regular Matter, Dark
Matter and Dark Energy!**

Discovery of Dark Energy won the Nobel Prize in 2011

Craig Hogan
One of my other advisors



2003 - 2005

What was happening around the world?

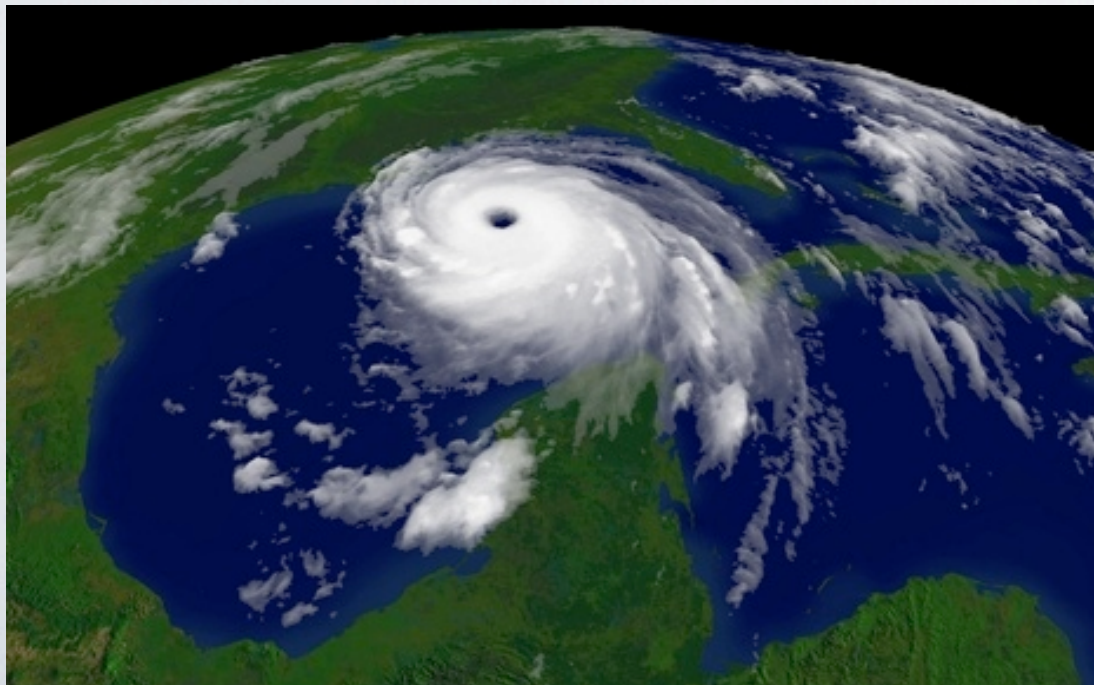
What was happening in your life?

2003-2005



'03 - Columbia disaster

'04 - Facebook was launched

The Facebook logo, consisting of the word "facebook" in white lowercase letters on a blue rectangular background.

'05 - Hurricane Katrina

2003-2005

WMAP measured the
most detailed picture
of the baby universe



Charles Bennett

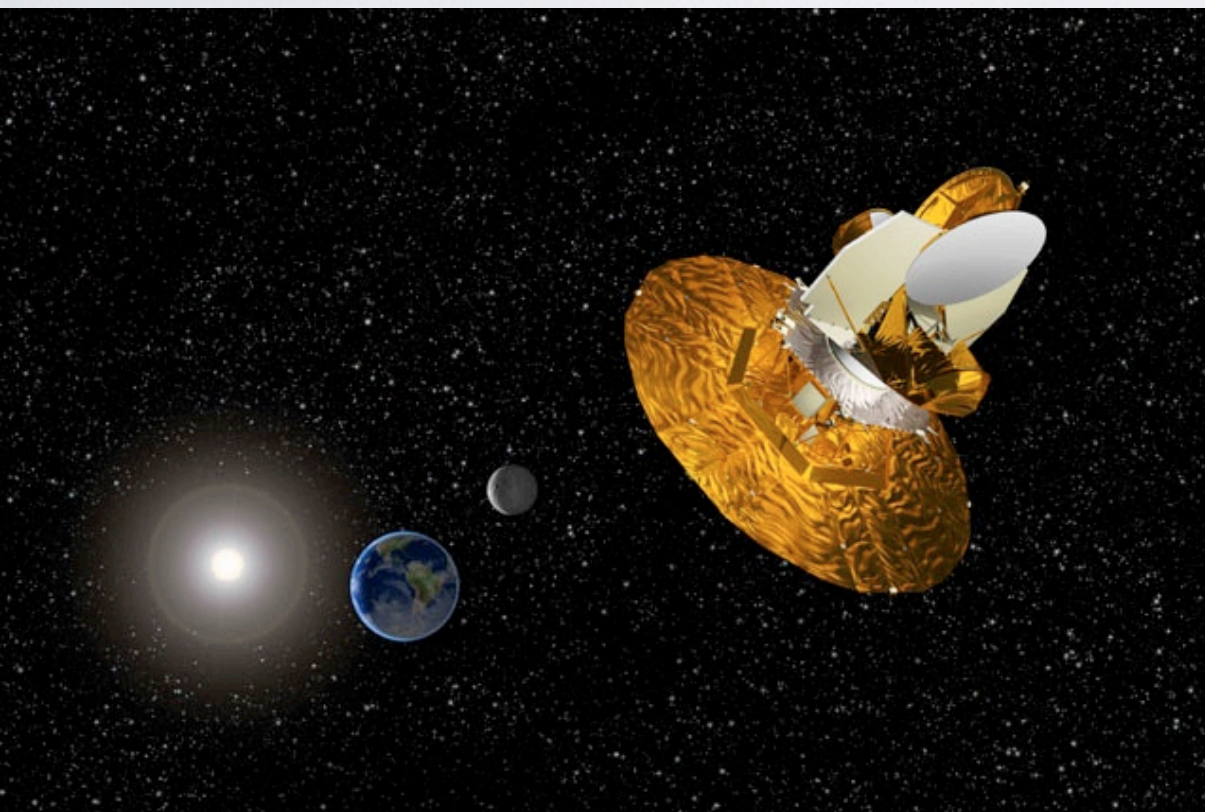
SDSS measures the
most detailed
picture of the
grown-up universe



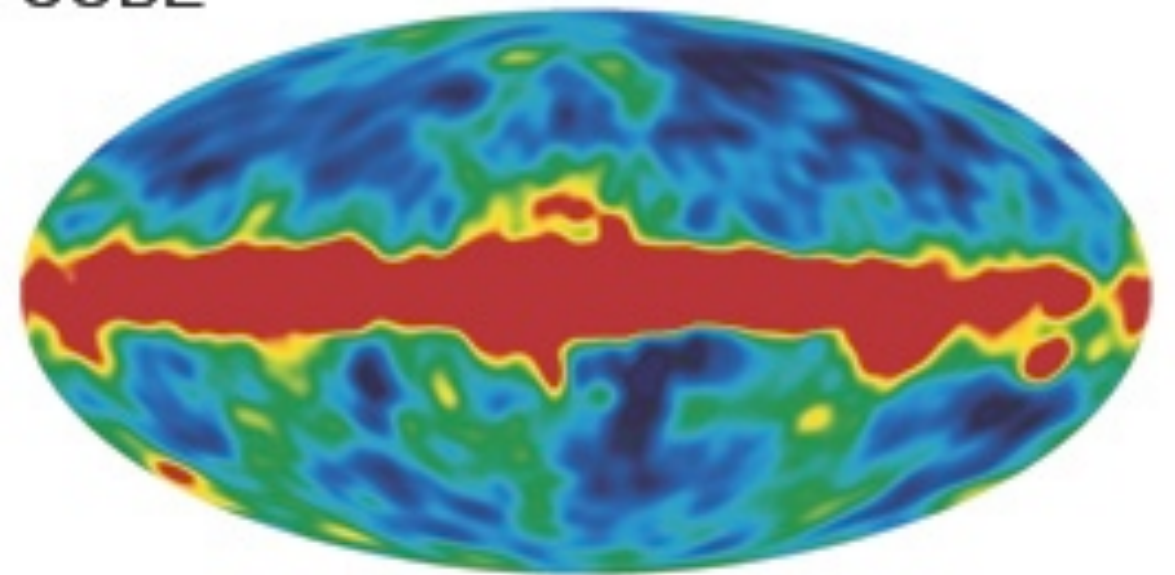
SDSS Collaboration photo

2003-2005

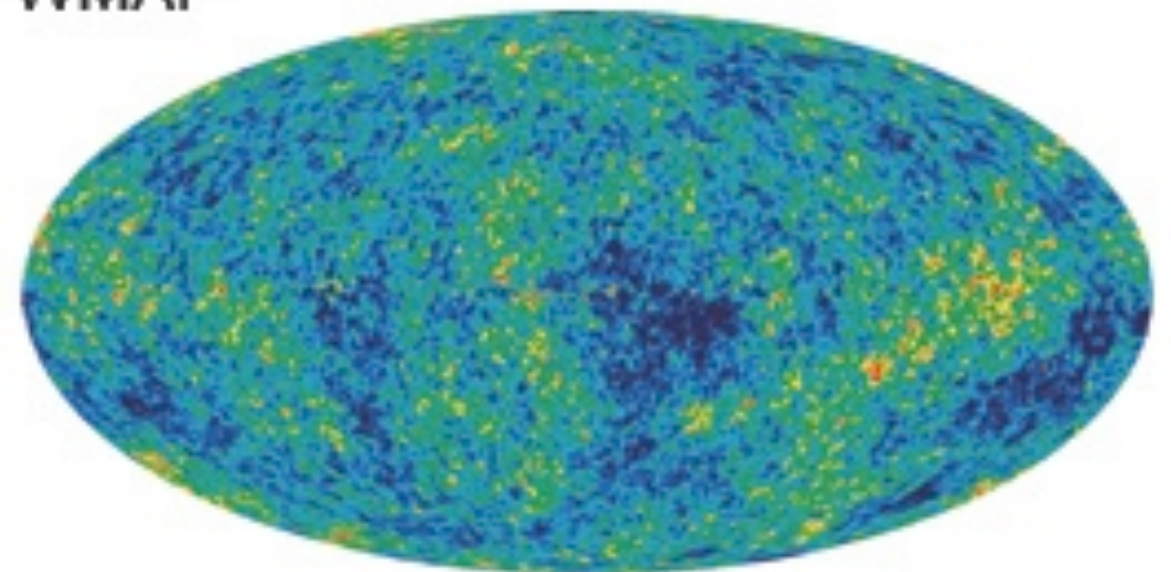
WMAP measures
temperature with
even better
resolution



COBE



WMAP



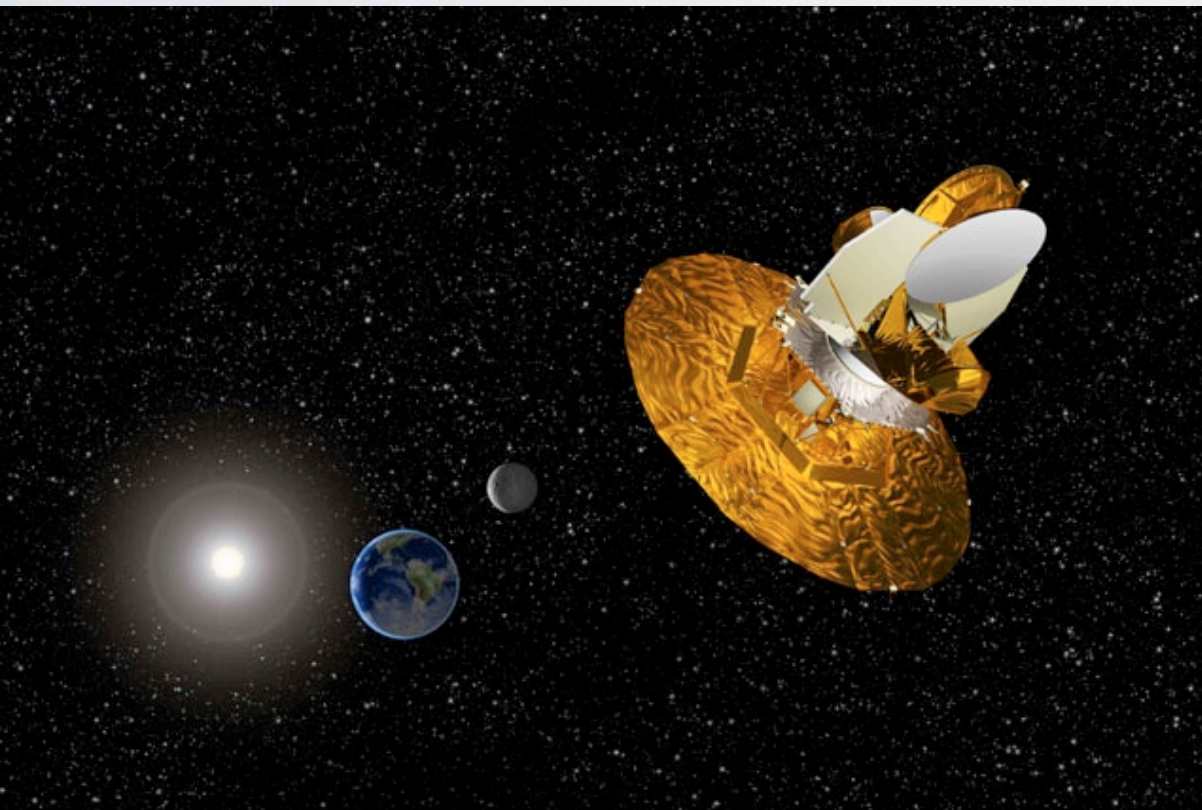
2003-2005

WMAP begins
precision
cosmology

Universe is flat

It is 13.75 billion
years old

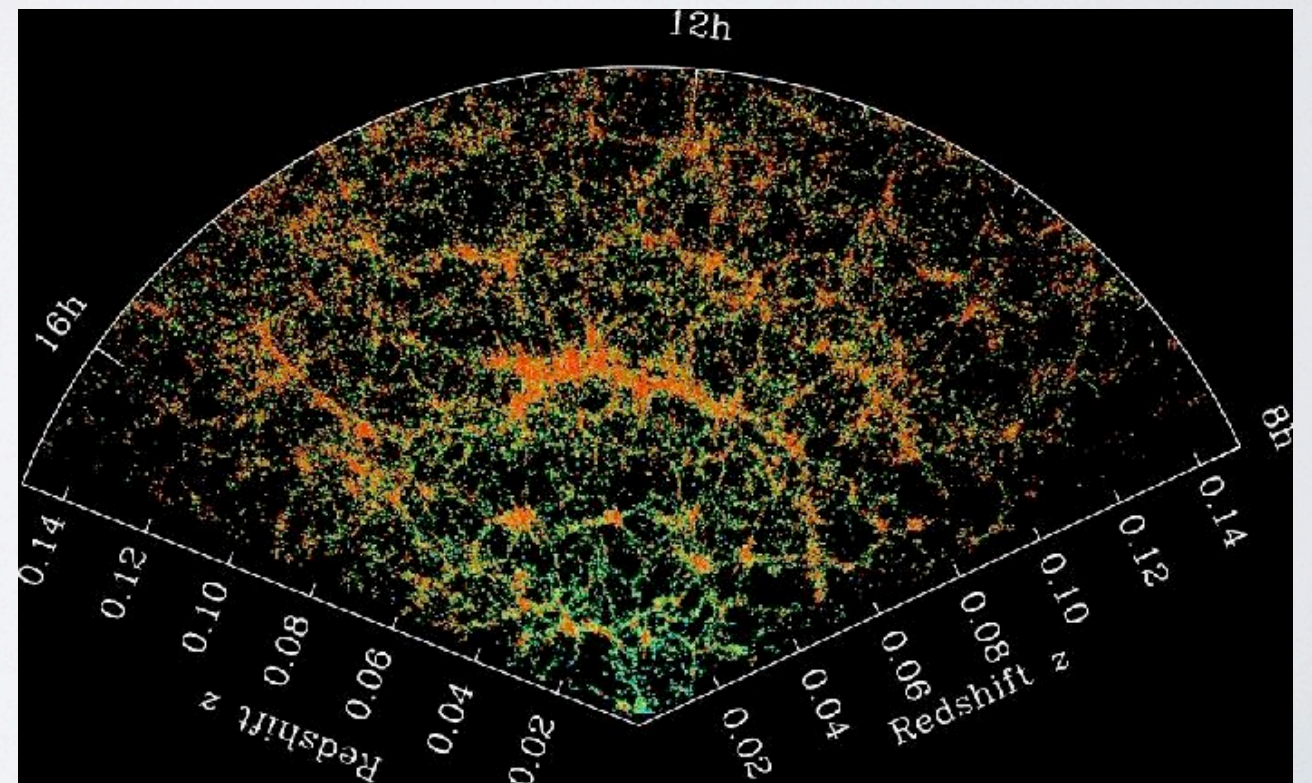
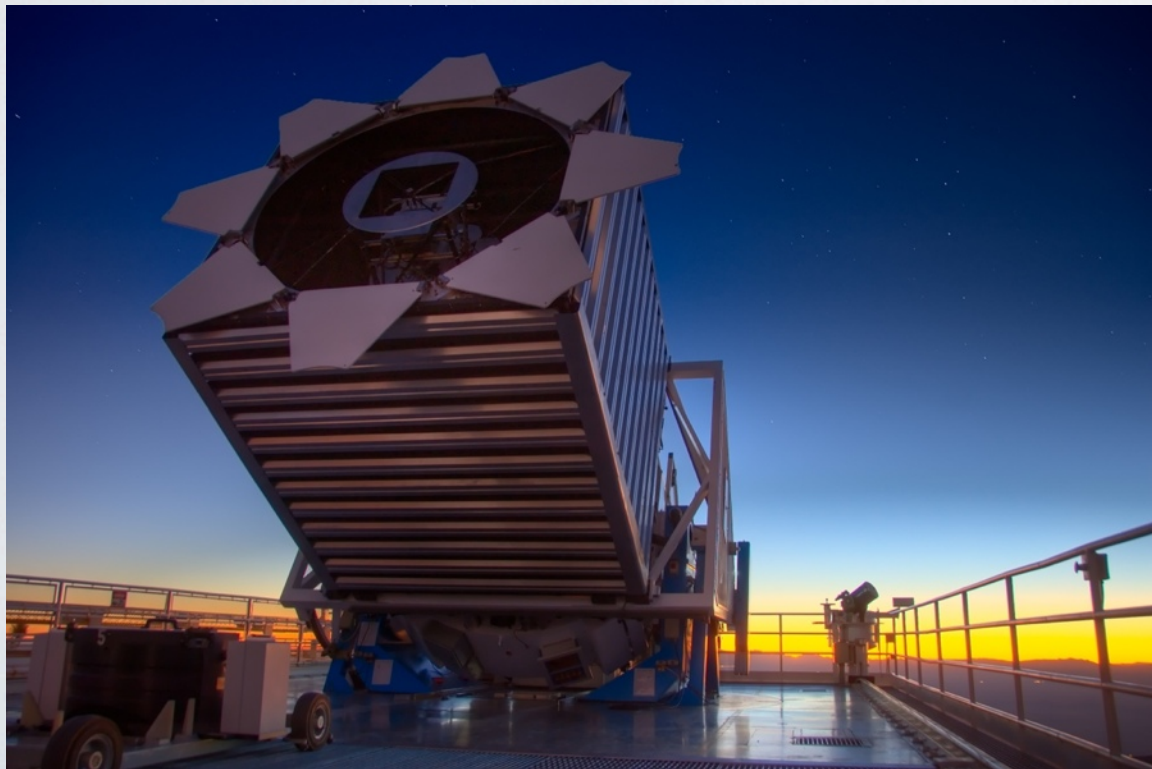
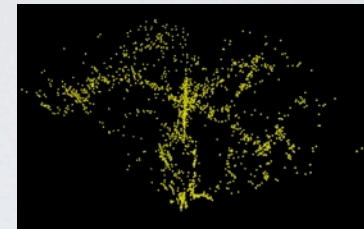
72.8 % dark energy
22.7 % dark matter
4.6 % regular matter



2003-2005

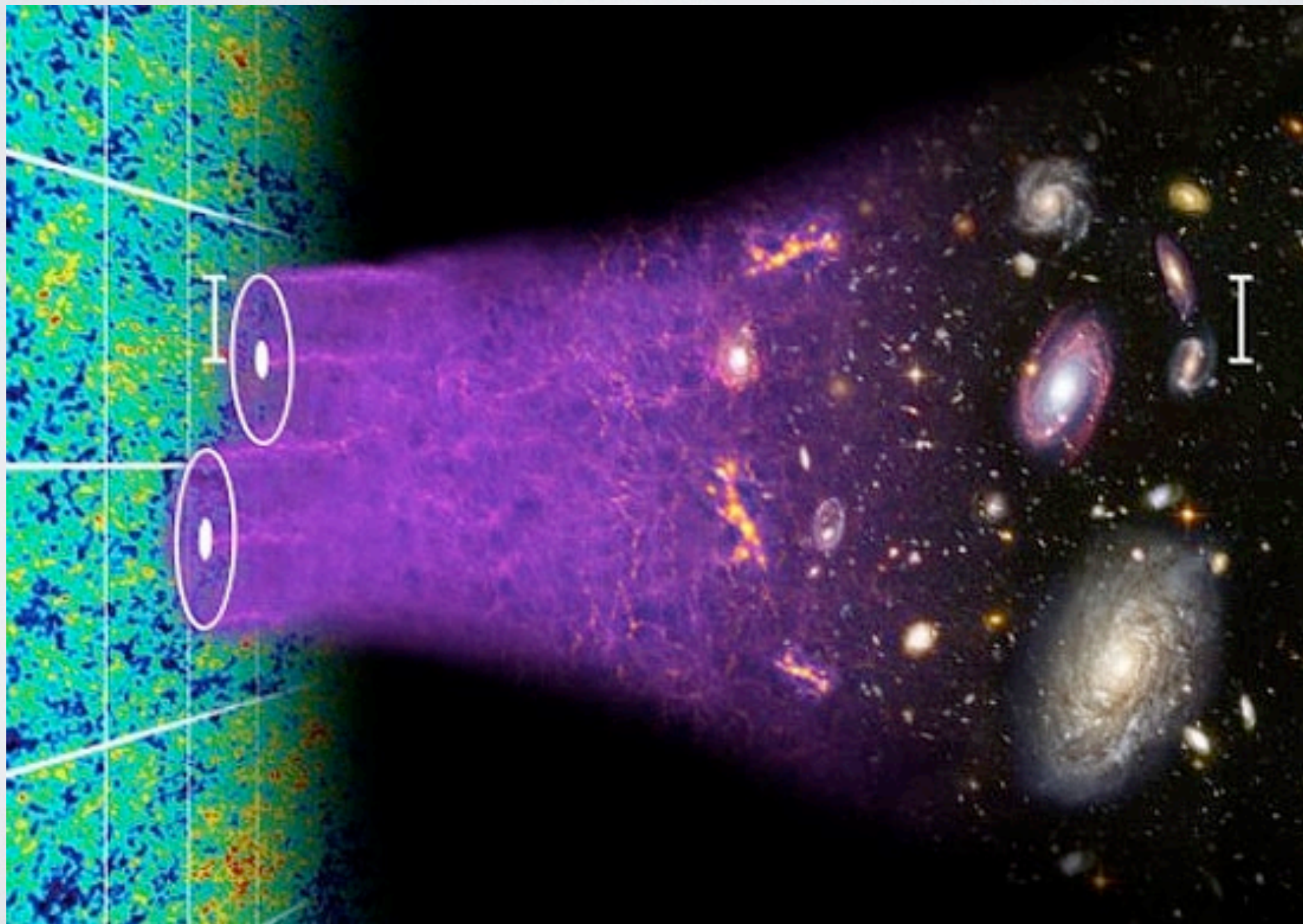
SDSS measures
millions and
millions more
galaxies

First galaxy survey



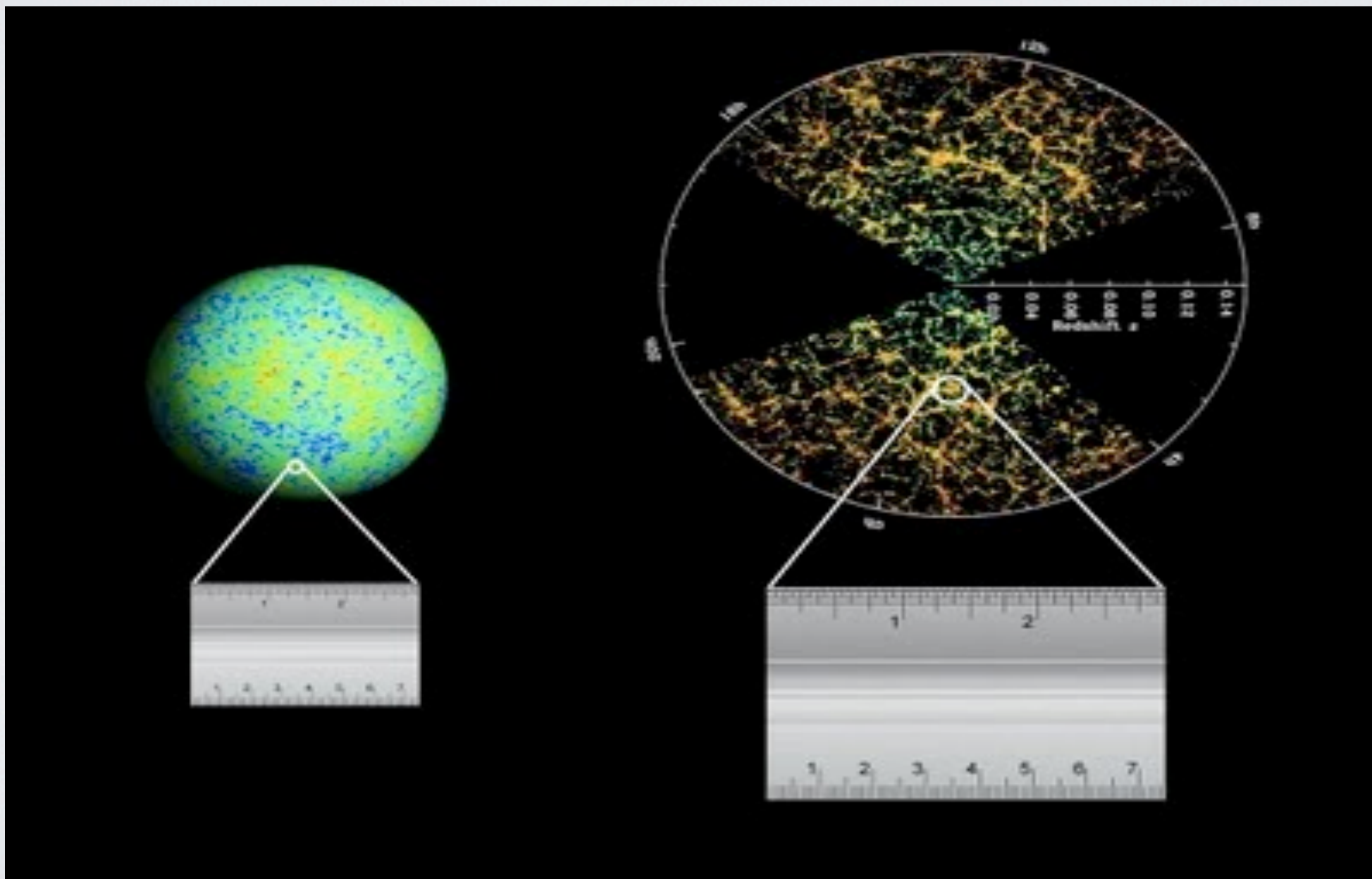
2003-2005

SDSS gives us the growth history of
structure in the universe



2003-2005

SDSS measures the “predicted ruler” in
the way galaxies cluster



2003 - 2005

Questions

Scientific Evidence

How did the
universe begin?

***Hot, Big Bang**
***Possibly Rapid inflation?**

How did the
universe grow-up?

*** started from tiny seeds**
***Has grown evolved**
***flat on large scales**

What is the universe
made up of?

**Regular Matter, Dark
Matter and Dark Energy!**

April 2014

What was happening around the world?

What was happening in your life?

APRIL 2014

Filing Taxes



Total Lunar Eclipse

8.2 Earthquake off the coast of Chile



APRIL 2014

BICEP2 team measures gravitational waves and evidence for inflation

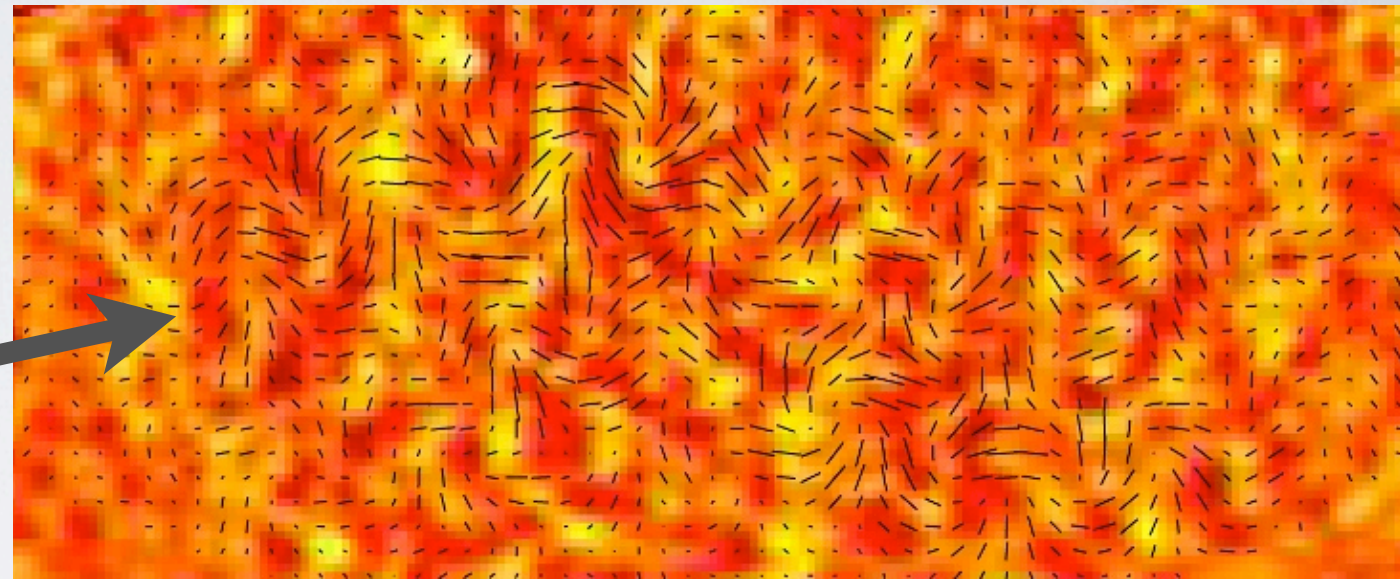


With members from UChicago!

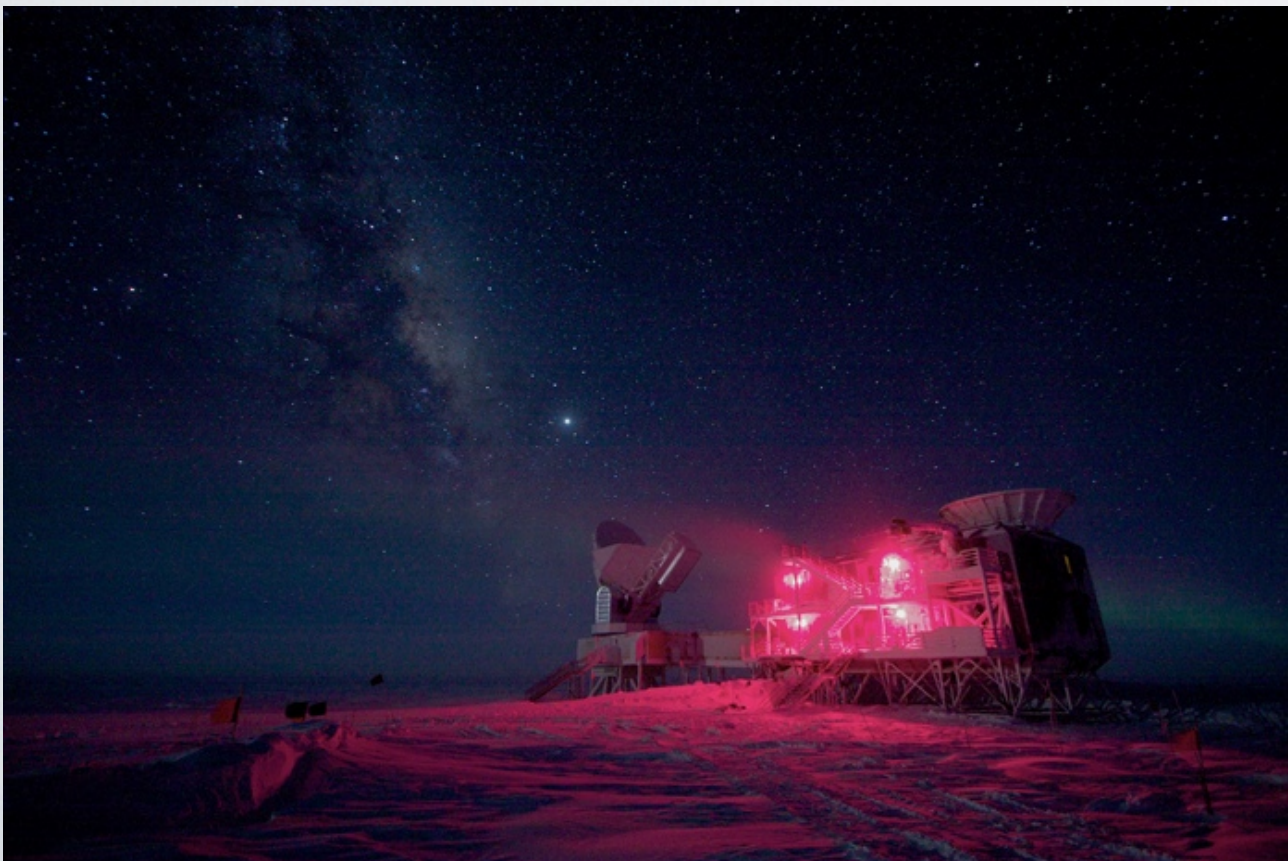
BICEP team evidence for gravitational waves and inflation

2014

Measured a
swirling pattern in
the CMB



Using a telescope
at the south pole



Questions

Scientific Evidence

How did the universe begin?

- * Hot, Big Bang
- * Rapid period of **inflation!!**

How did the universe grow-up?

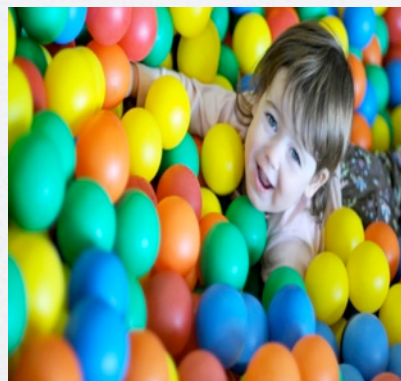
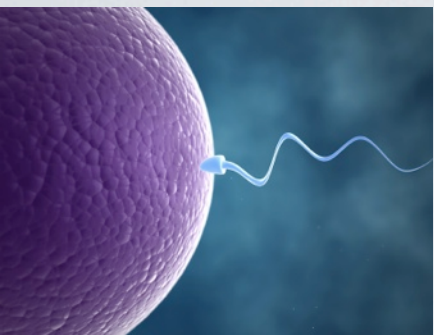
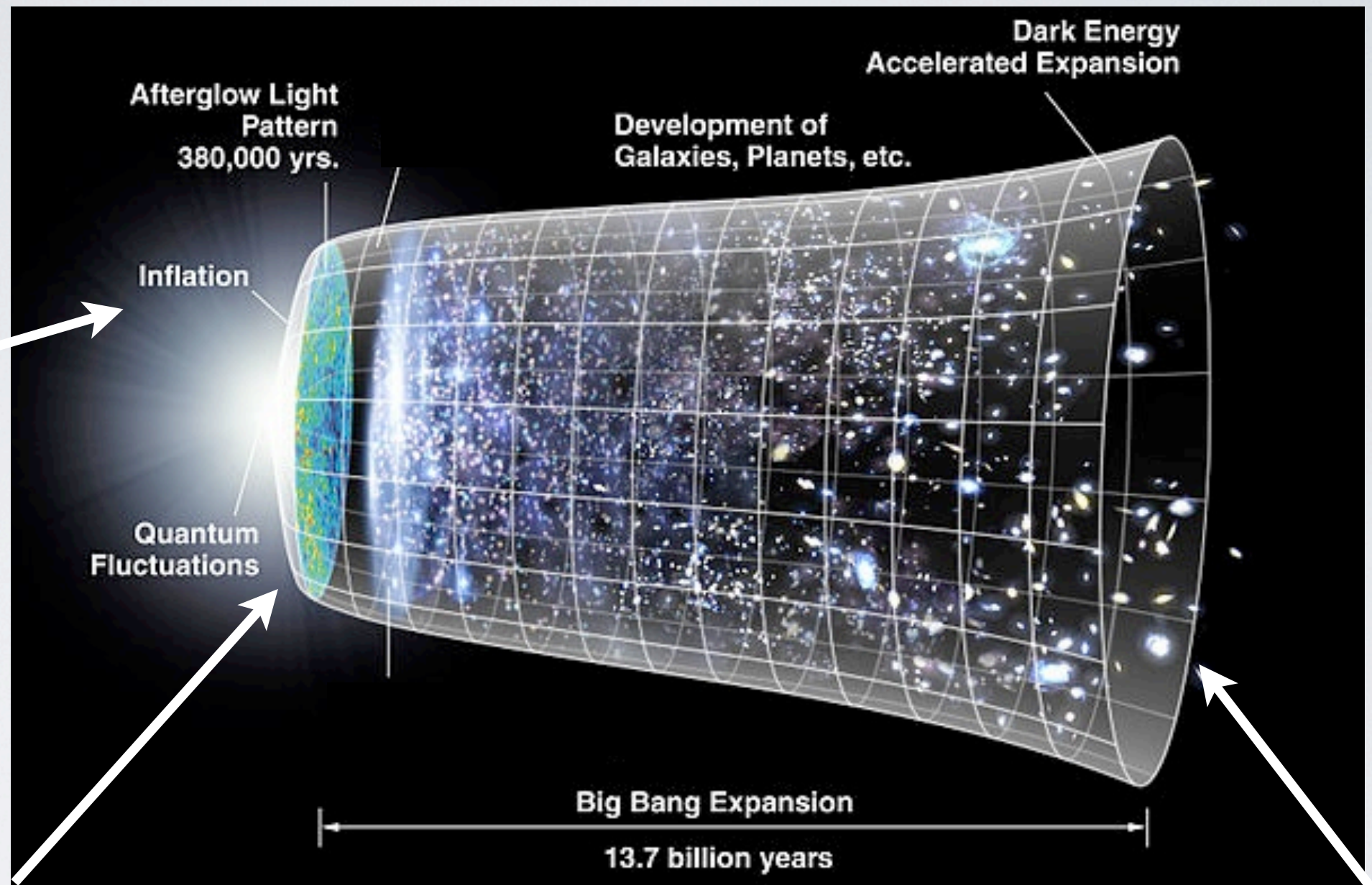
- * started from tiny seeds
- * Has grown evolved
- * flat on large scales

What is the universe made up of?

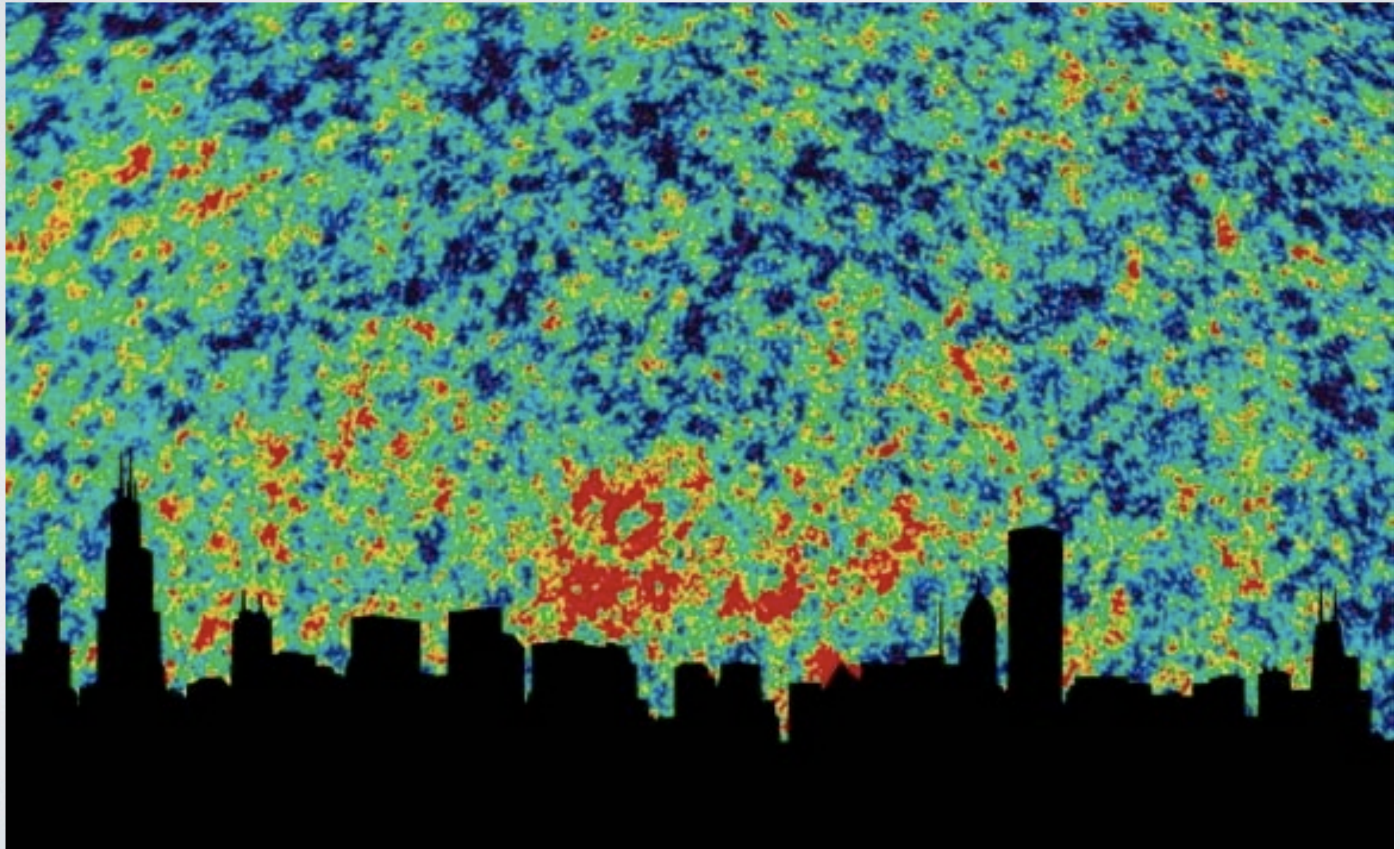
Regular Matter, Dark Matter and Dark Energy!

Timeline of our universe

time →



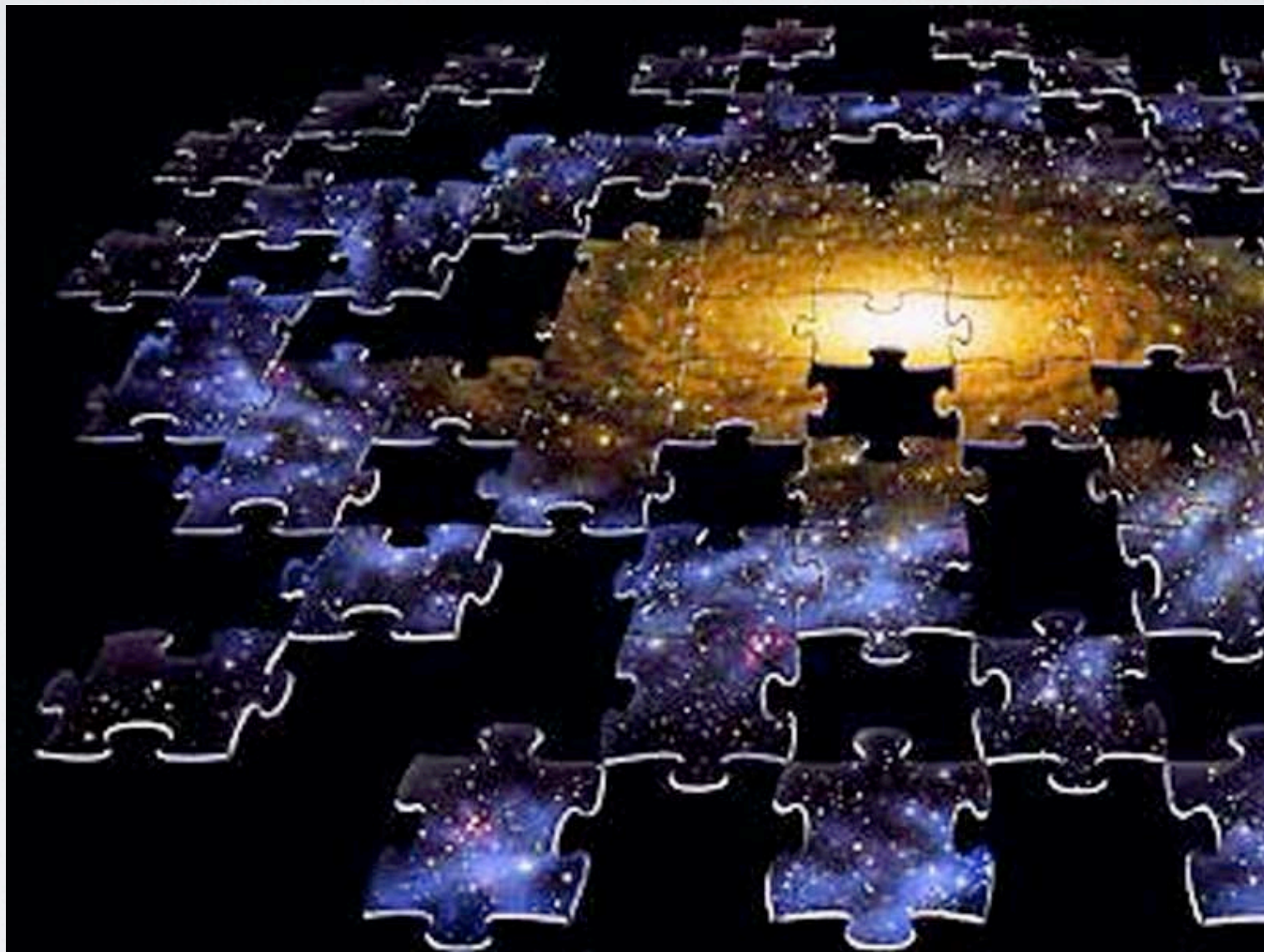
Scientists in Chicago have made huge contributions to our understanding of the universe



What's next in cosmology?

What is Dark Matter?

What is Dark Energy?



*Can we measure
ripples in space-time?*

*Is the universe a hologram
on tiny scales?*

**WE HAVE MADE A LOT OF
PROGRESS IN
COSMOLOGY AND THERE
IS MORE TO COME!!**

