Title: Kendrick Smith, Perimeter Institute

Date: Feb 04, 2015 07:00 PM

URL: http://pirsa.org/15020120

Abstract: Cosmology in the 21st Century

Revolutionary progress has been achieved in the science of cosmology over the past 30 years. Powerful experiments, made possible by new technologies, have transformed our understanding of the universe. We have unveiled the laws of physics that govern time and space on the grandest scales, from the big bang to present day.

The universe, weâ€™ve learned, is full surprises. For instance, dark matter â€“ the invisible gravitational glue that permeates the vast majority of the universe â€“ remains one of the greatest unsolved puzzles of astrophysics. Nor do we yet fully understand the quantum mechanical nature of the big bang, or the universeâ€™s current transition into a new stage of rapid expansion.

Perhaps most surprising is how remarkably simple these phenomena are to describe, yet so vexing to comprehensively explain. But as the pace of discovery continues to accelerate, so too will our ability to decode these grandest of puzzles.

During his public lecture, Perimeter Institute cosmologist Kendrick Smith will take the audience on a journey of discovery through the expanding universe, from the big bang to our present-day understanding of dark matter and other cosmic phenomena. He will explore the yet-unsolved mysteries of the universe, and explain how new research aims to shed light on these deep questions.


PERIMETER INSTITUTE FOR THEORETICAL PHYSICS
PUBLIC LECTURE
Series
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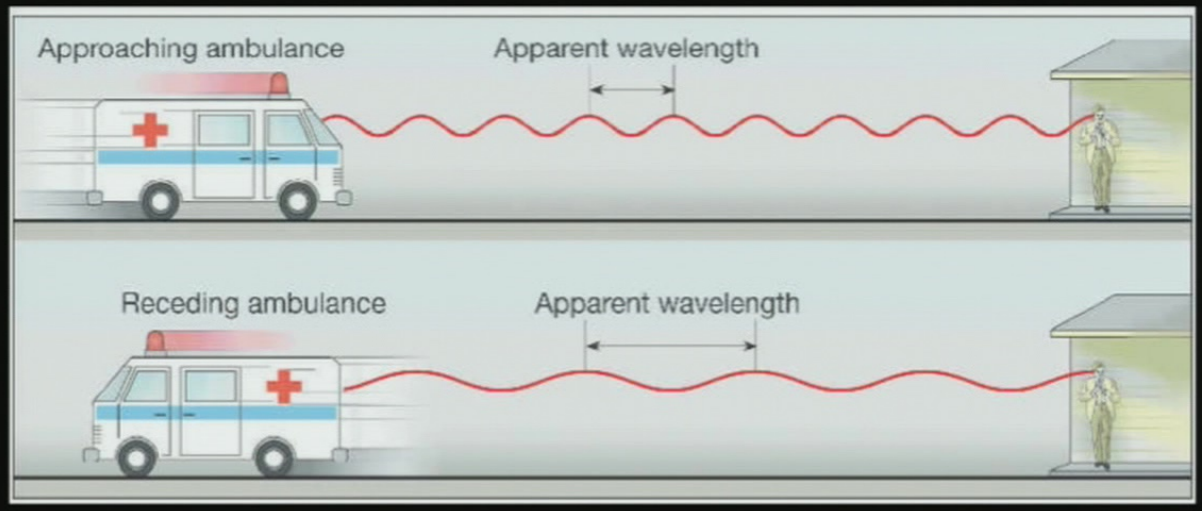
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

1. The expanding universe

2. The cosmic microwave background

3. Three mysteries

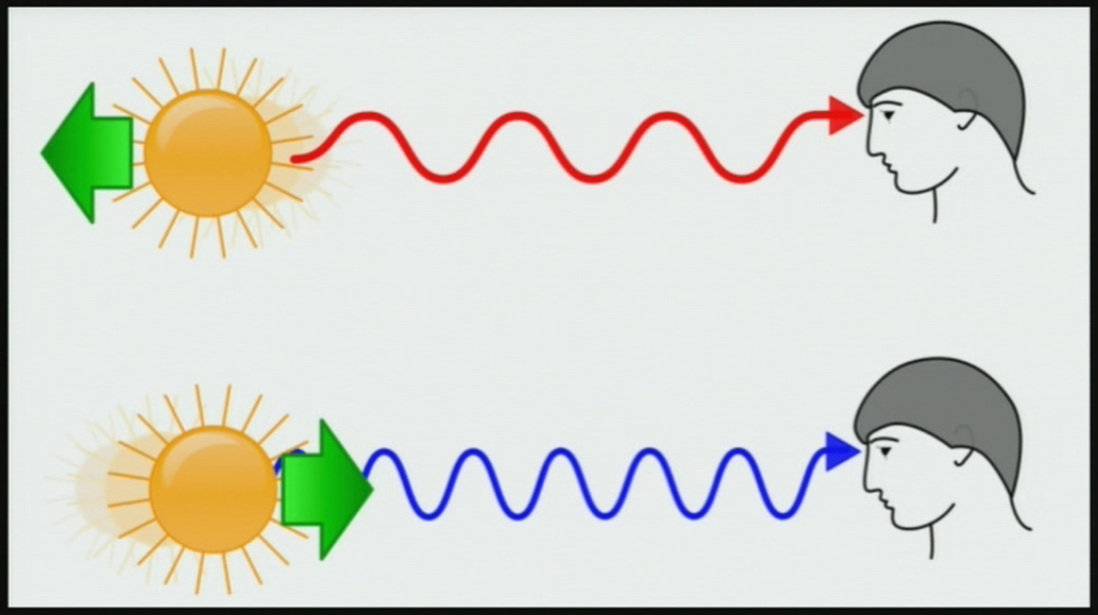
Doppler effect: sound waves



Source moving toward observer:
sound shifted to higher frequency (higher pitch)

Source moving away from observer:
sound shifted to lower frequency (lower pitch)

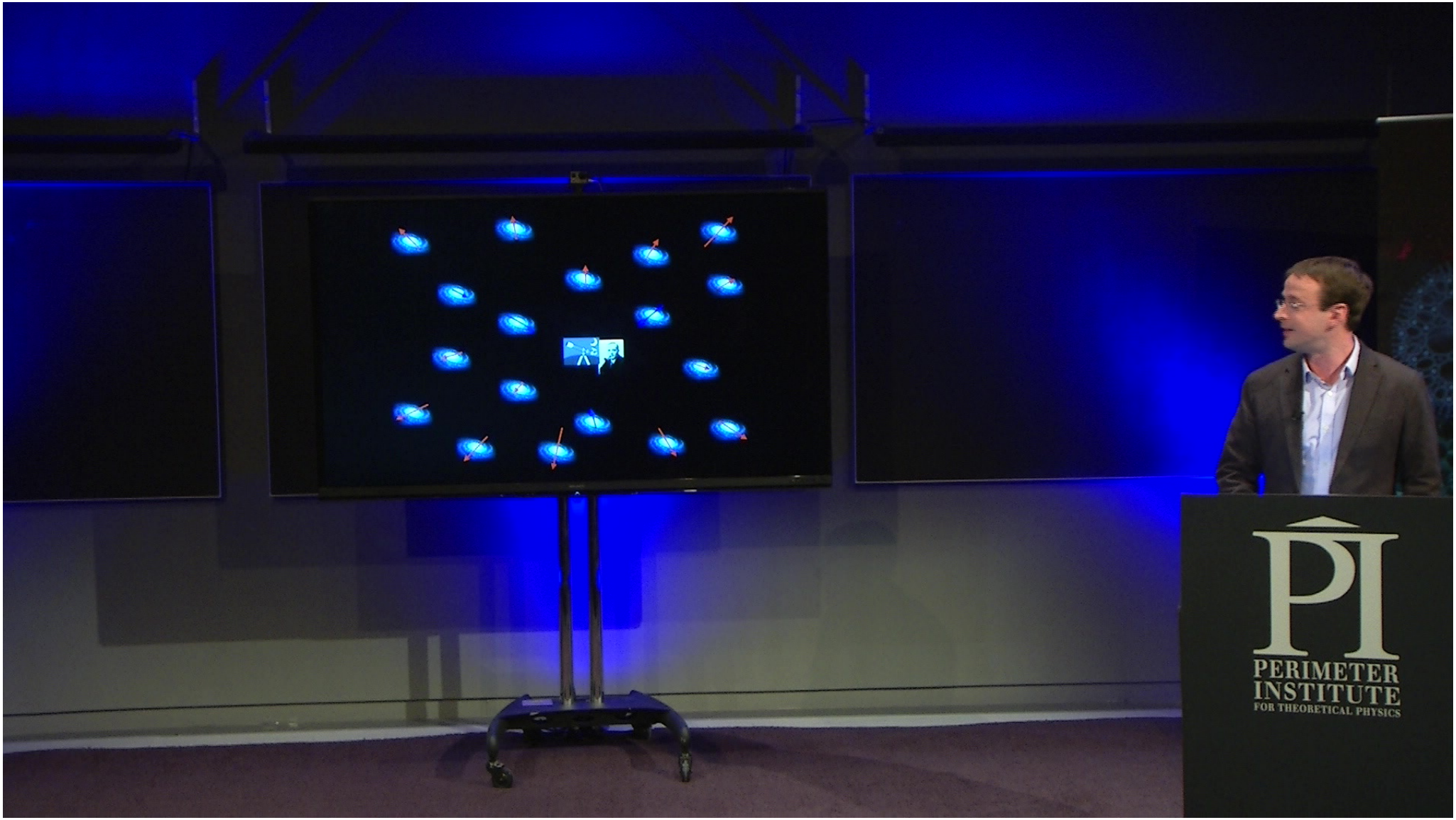
Doppler effect: light waves



Source moving toward observer:
light shifted to higher frequency (bluer color)

Source moving away from observer:
light shifted to lower frequency (redder color)


100 km/sec
200 km/sec
Edwin Hubble (1929)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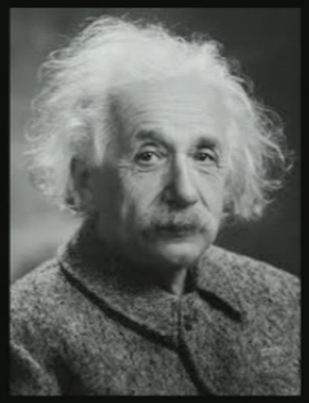
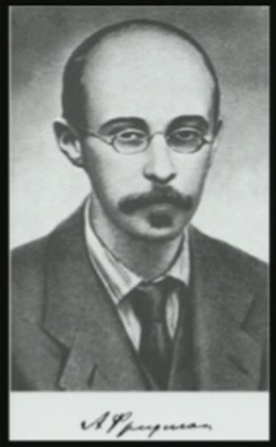


Einstein (1915)

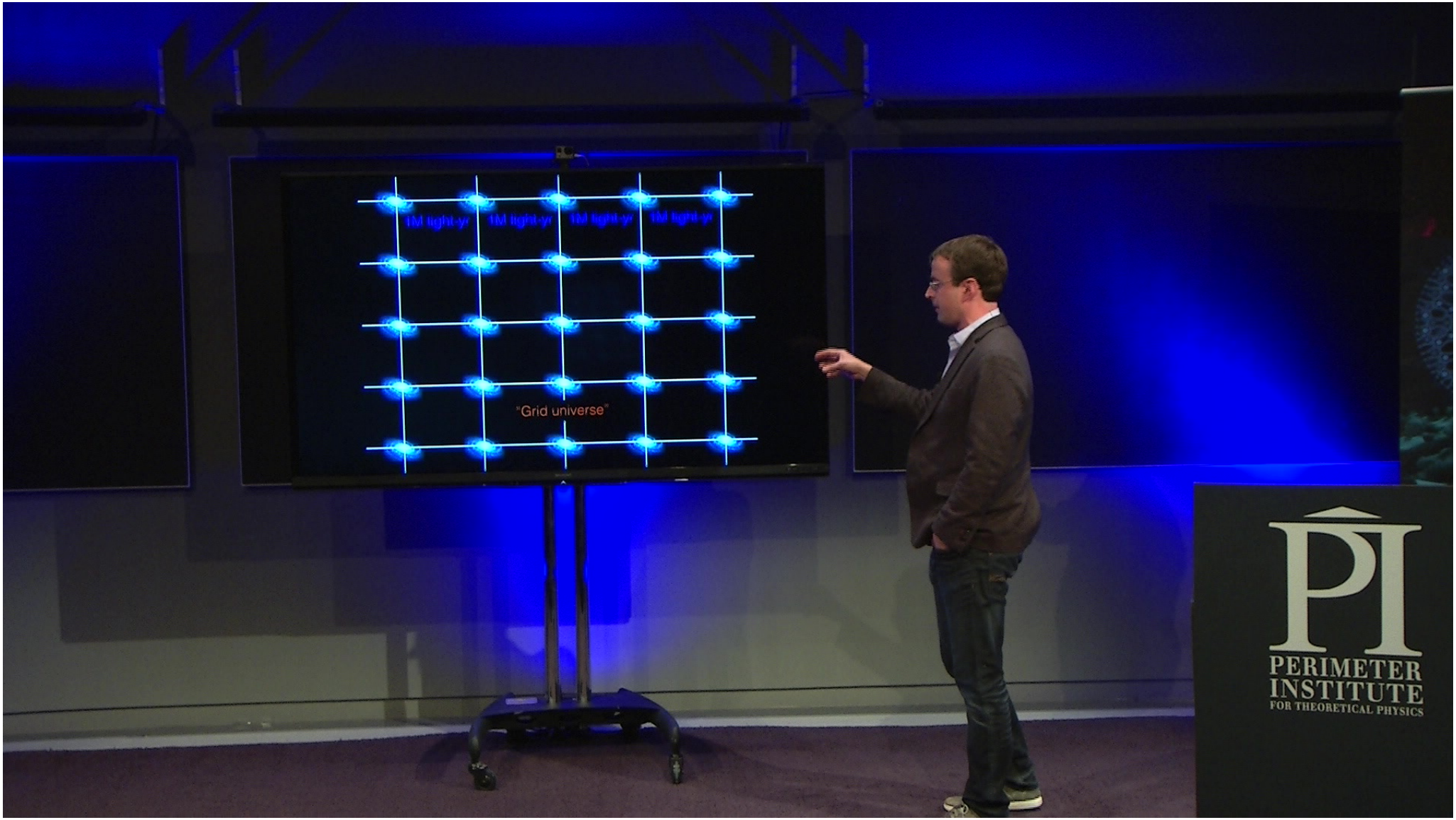
General theory of relativity proposed.
Distances and times are dynamical quantities!



Friedmann
(1922)

Lemaitre
(1927)

The equations of general relativity naturally predict an expanding universe!


1M light-yr
1M light-yr
1M light-yr
1M light-yr
"Grid universe"
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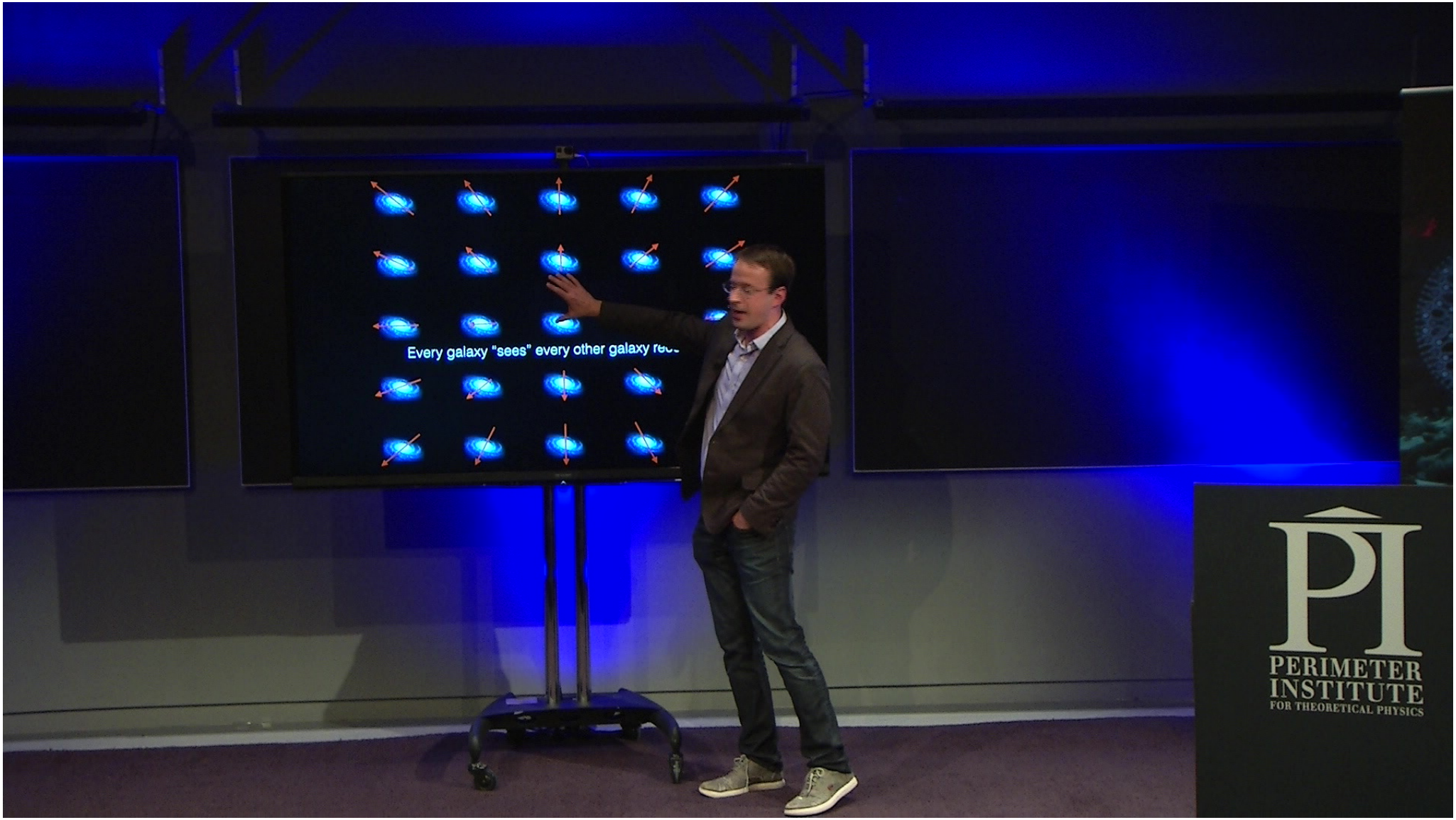
Every galaxy "sees" every other galaxy
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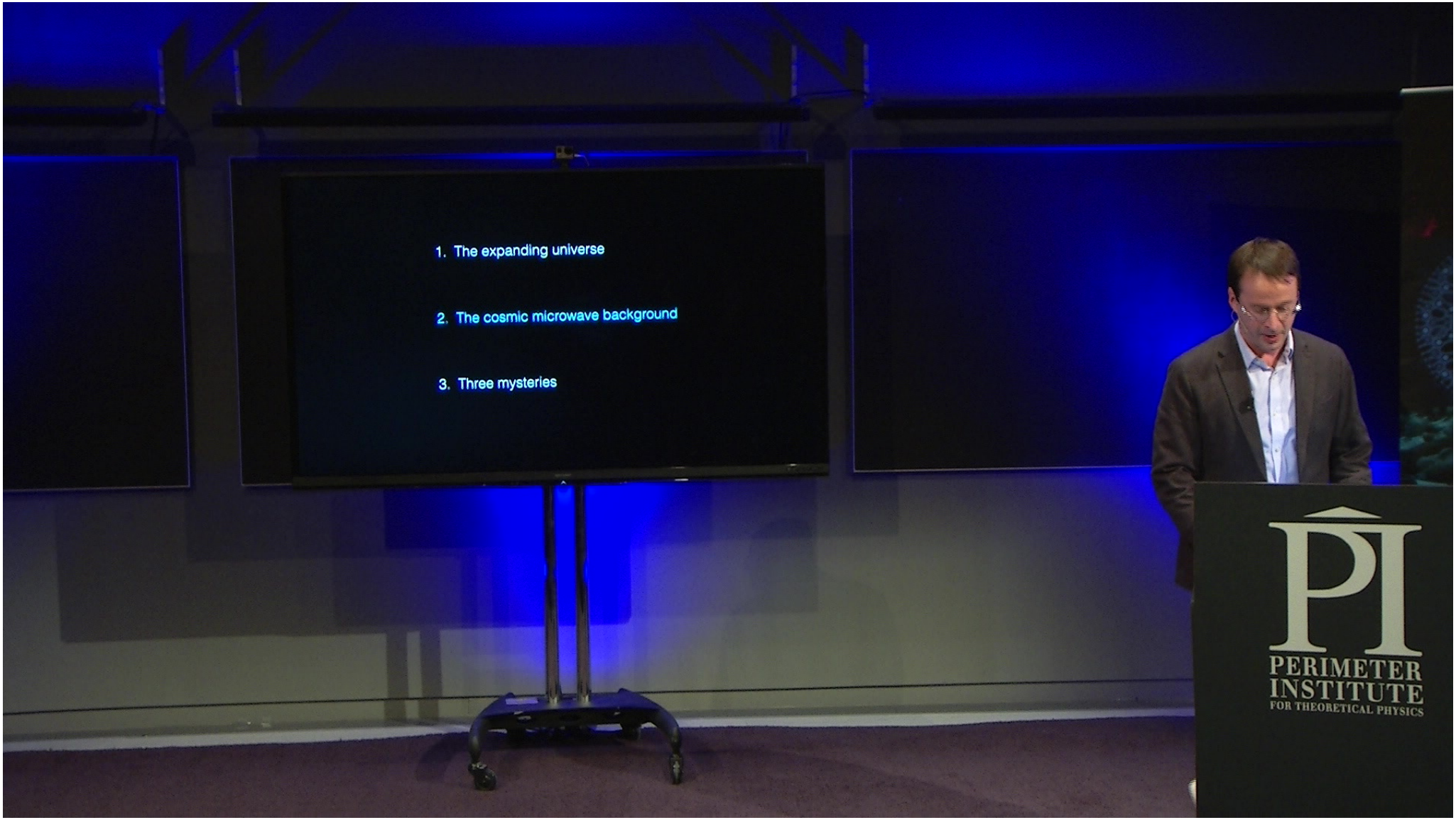
1. The expanding universe
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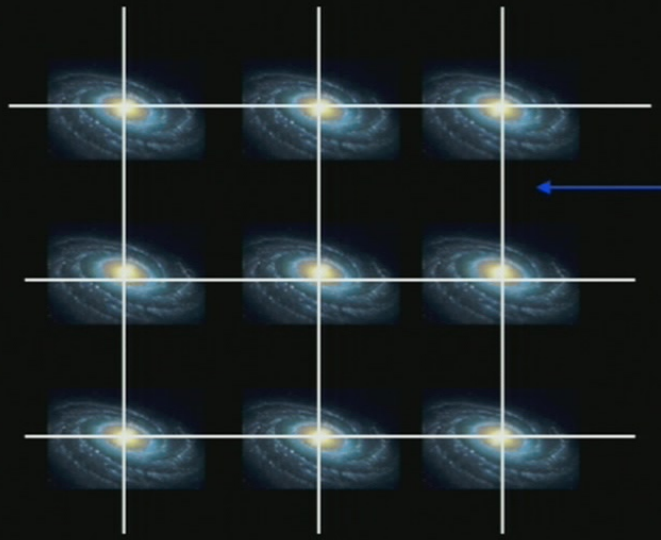
Imagine running the clock backwards…

At minimum, the universe must have been very different in the far past than today



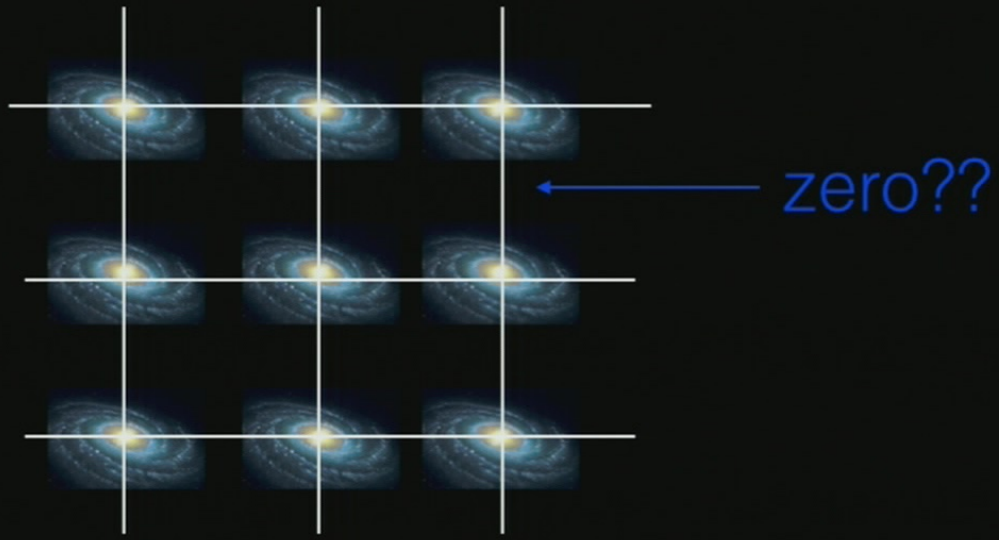
what happens when this distance is…

the size of a galaxy?
1/100th the size?

Imagine running the clock backwards…

At minimum, the universe must have been very different in the far past than today

The equations of general relativity predict a disaster: all distances go to zero a finite time in the past!



Imagine running the clock backwards…

At minimum, the universe must have been very different in the far past than today

The equations of general relativity predict a disaster: all distances go to zero a finite time in the past!

This is the “Big Bang”. A sign that our understanding is incomplete, not a theory for the origin of the universe

Imagine running the clock backwards…

At minimum, the universe must have been very different in the far past than today

The equations of general relativity predict a disaster: all distances go to zero a finite time in the past!

This is the “Big Bang”. A sign that our understanding is incomplete, not a theory for the origin of the universe

We do not live in a special place in the universe, but we do live in a special place in time!

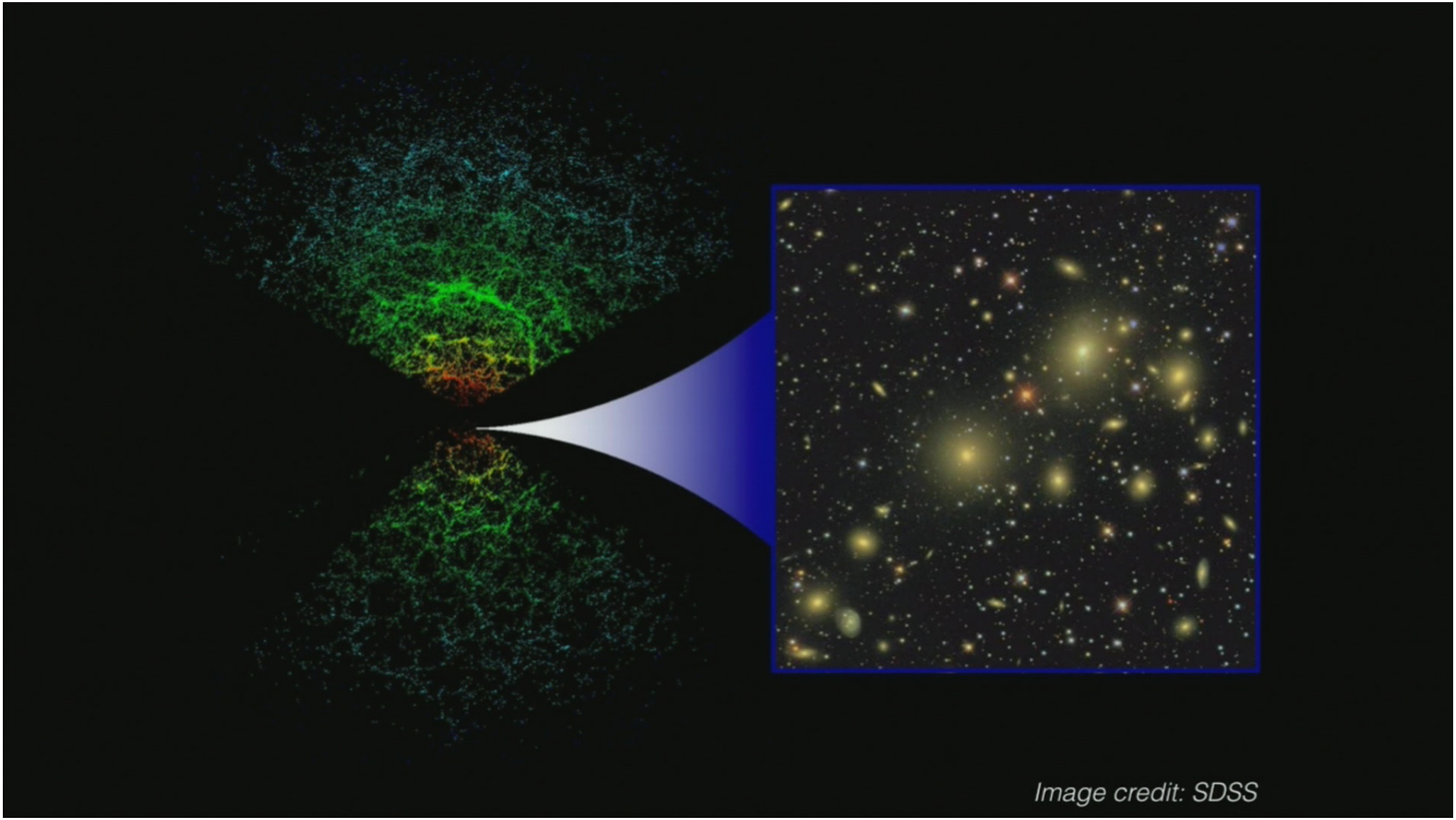
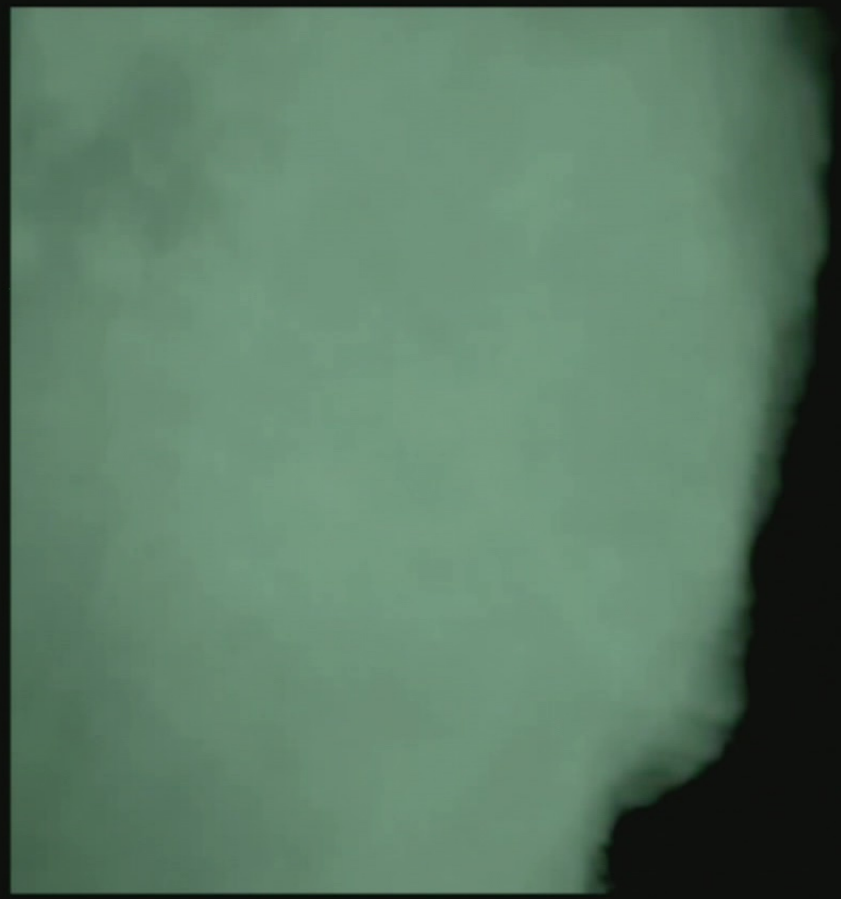


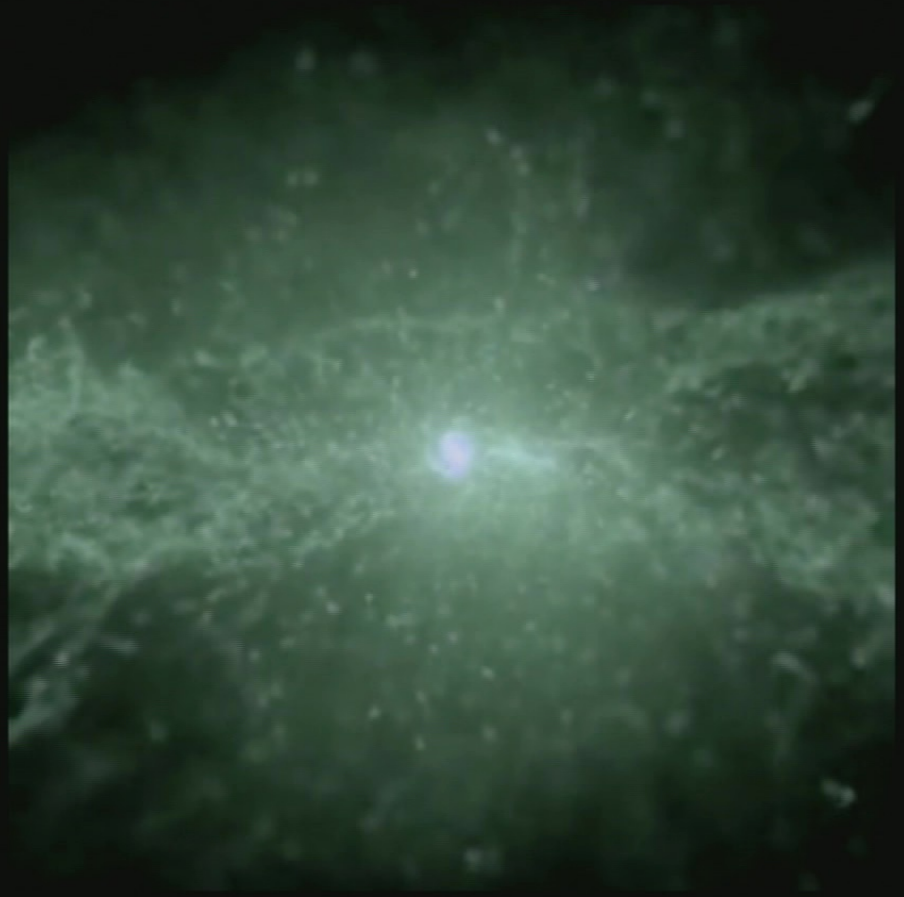
Image credit: SDSS

“Gravitational instability”: universe becomes more structured with time, due to action of gravity



University of Washington

“Gravitational instability”: universe becomes more structured with time, due to action of gravity



University of Washington

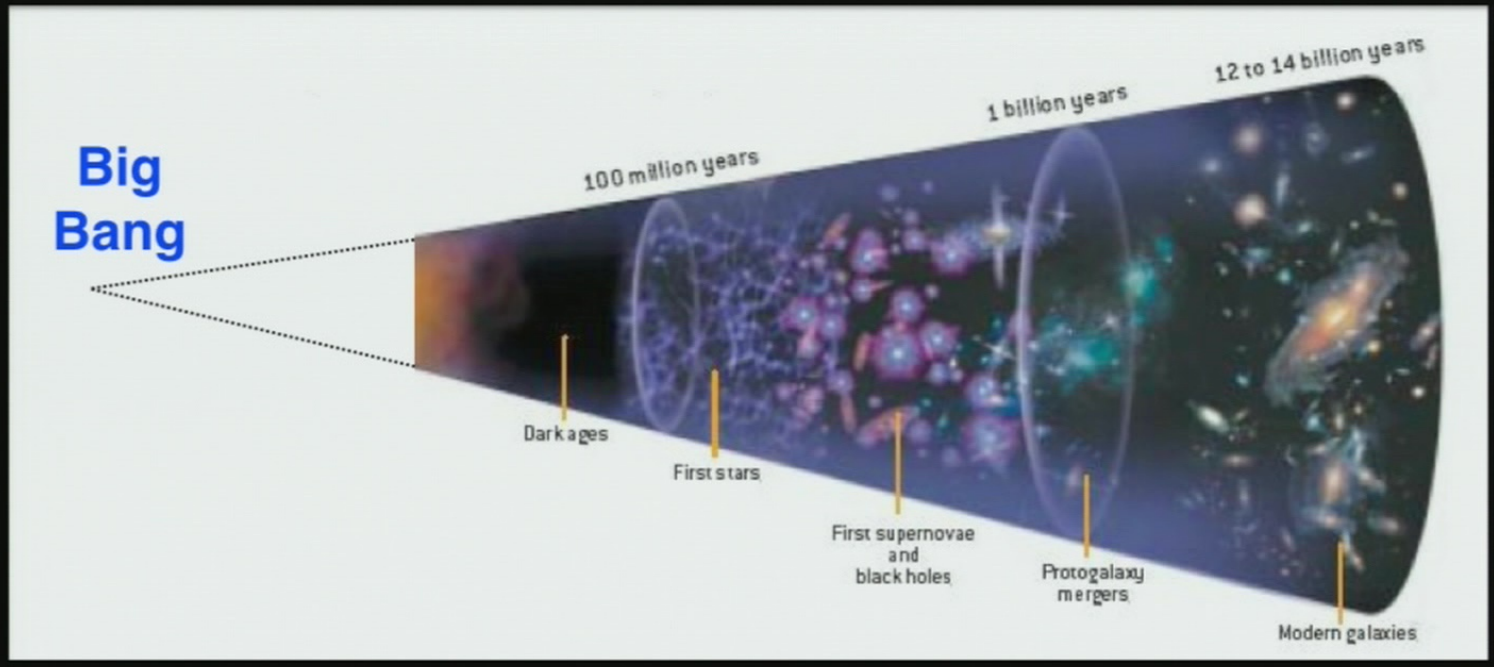
“Gravitational instability”: universe becomes more structured with time, due to action of gravity

Volker Springel

“Gravitational instability”: universe becomes more structured with time, due to action of gravity

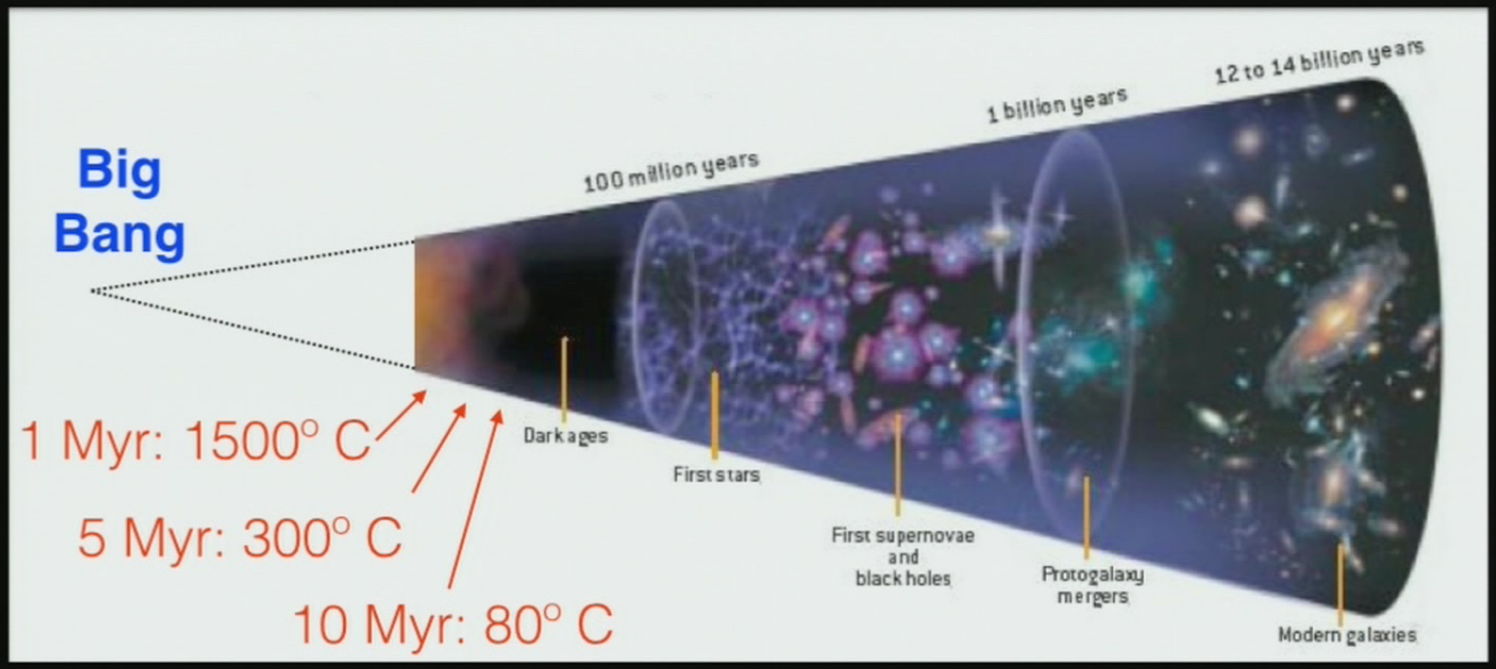
Volker Springel

"Dark ages": early in the history of the universe, no stars and galaxies, just a universe full of gas

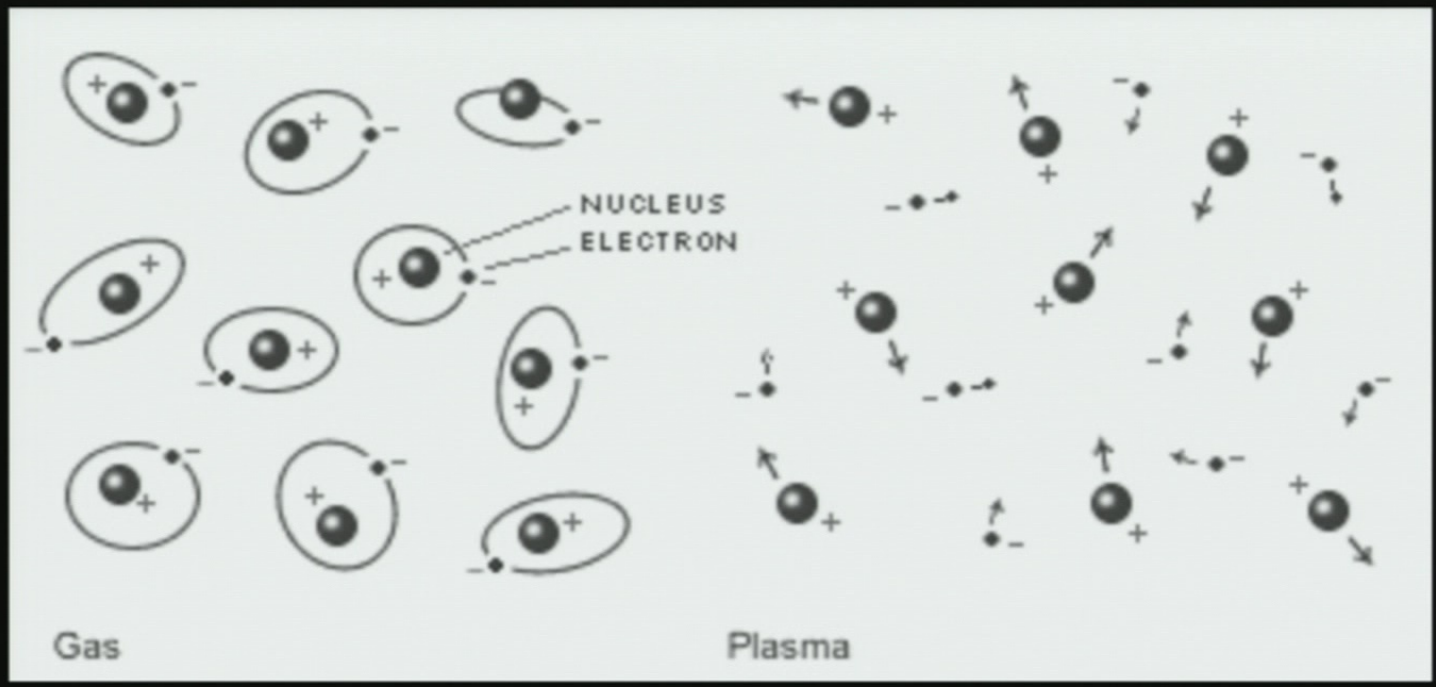


"Dark ages": early in the history of the universe, no stars and galaxies, just a universe full of gas

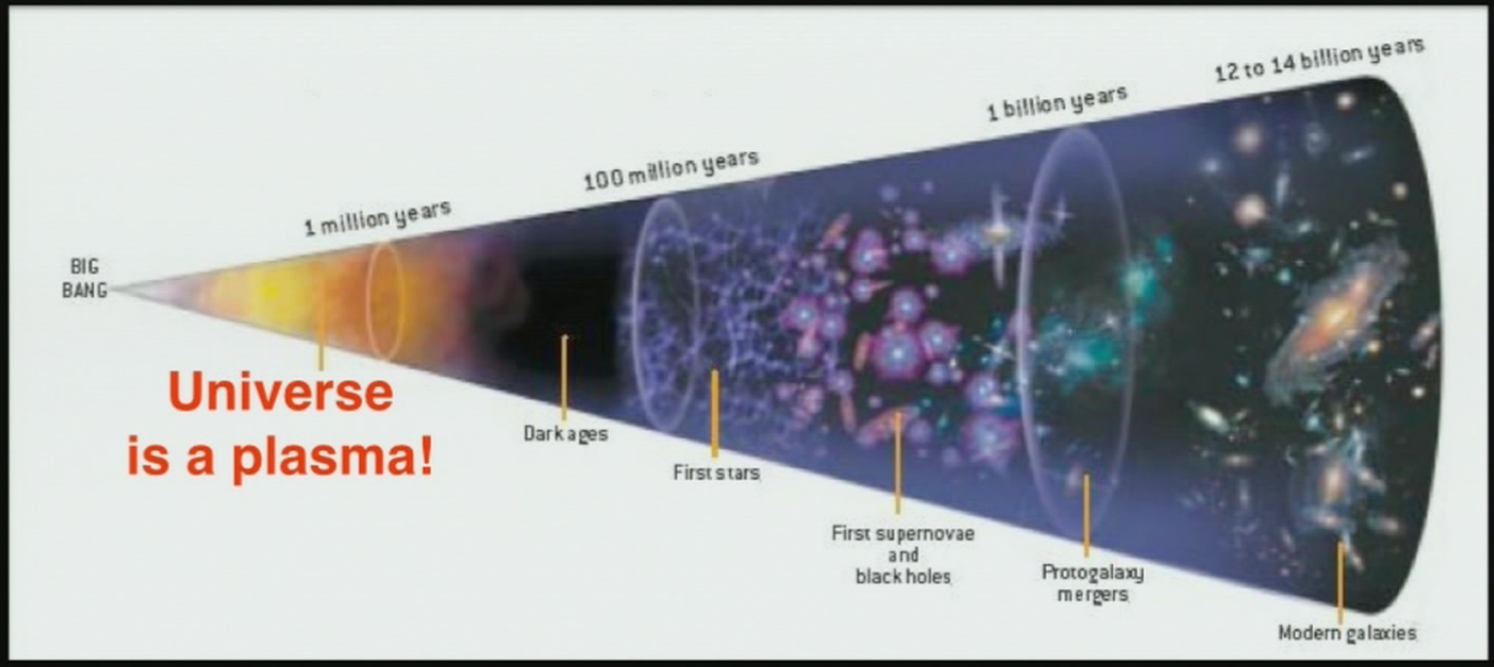
As the universe expands, the gas cools.

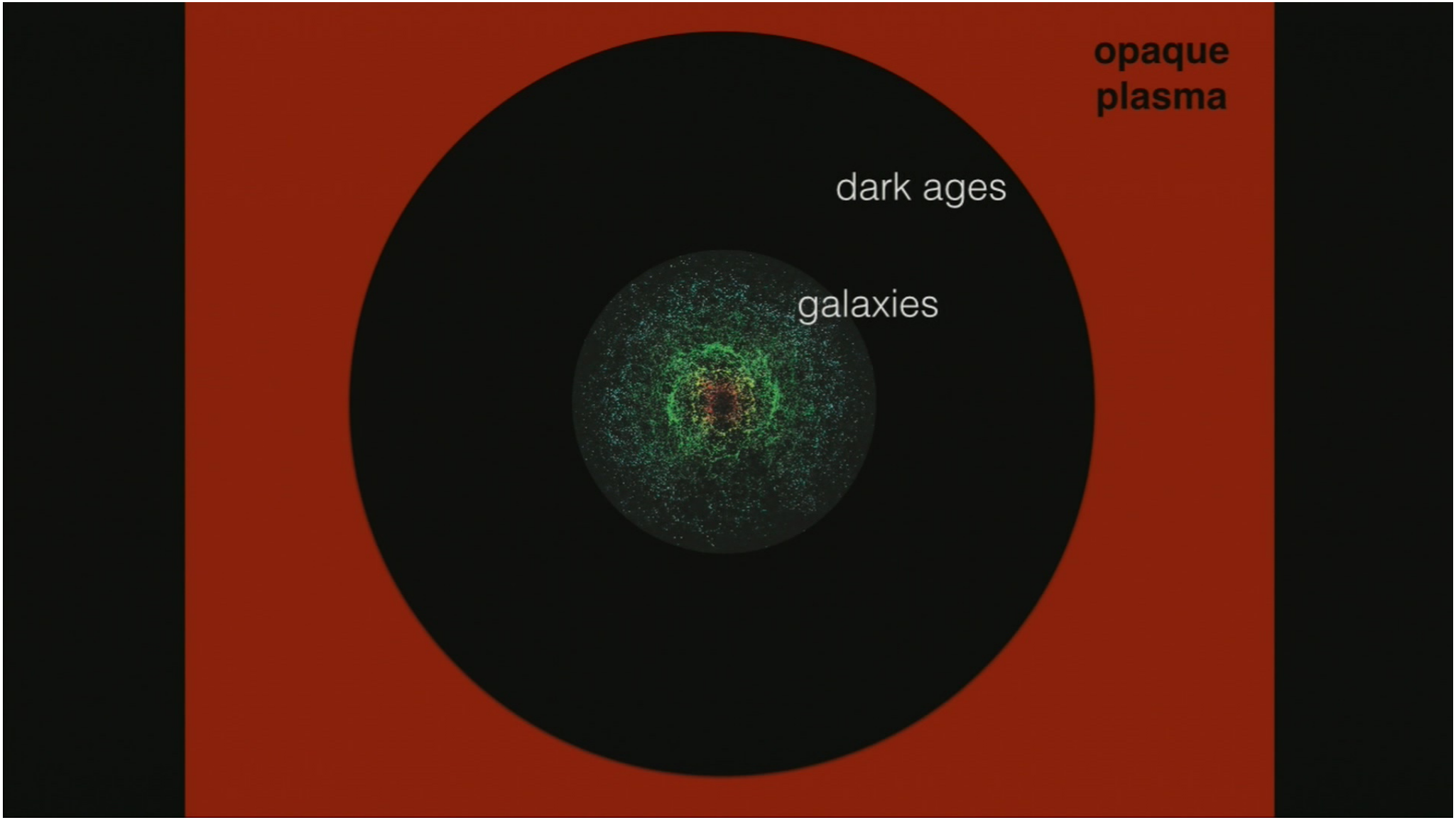


When the gas is heated above a critical temperature (3000° C) it disassociates into a plasma!



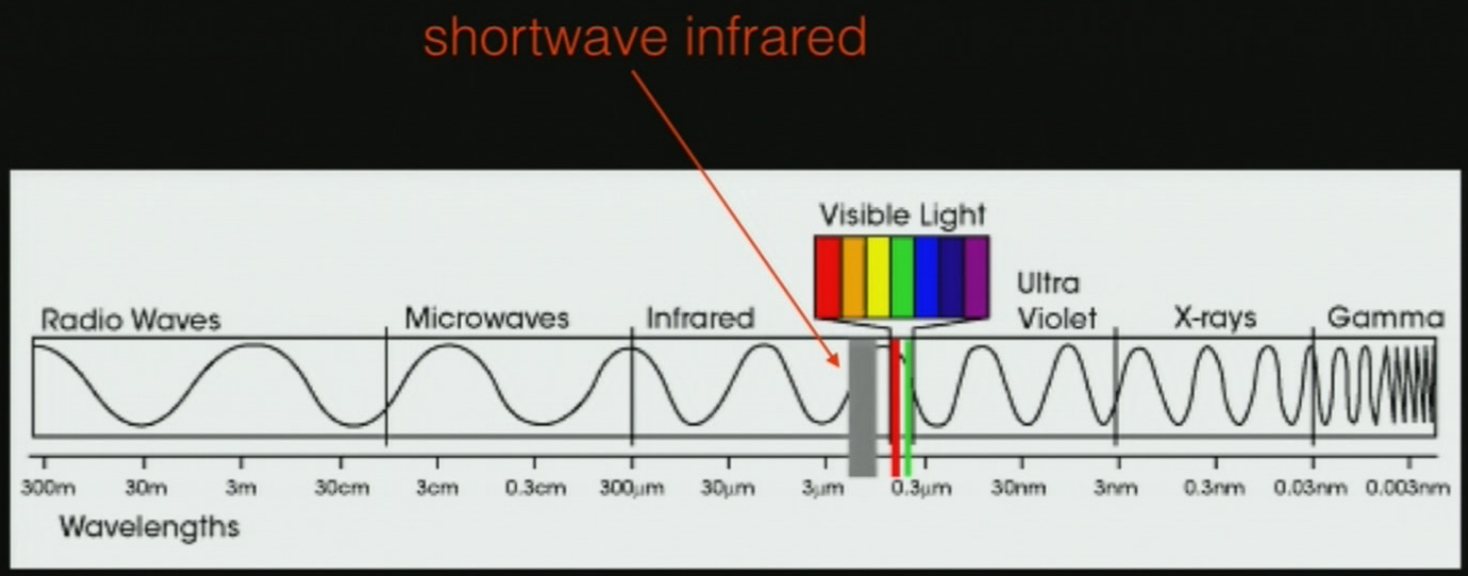
We can predict that the dark ages were preceded by an era when the universe was full of plasma, not gas

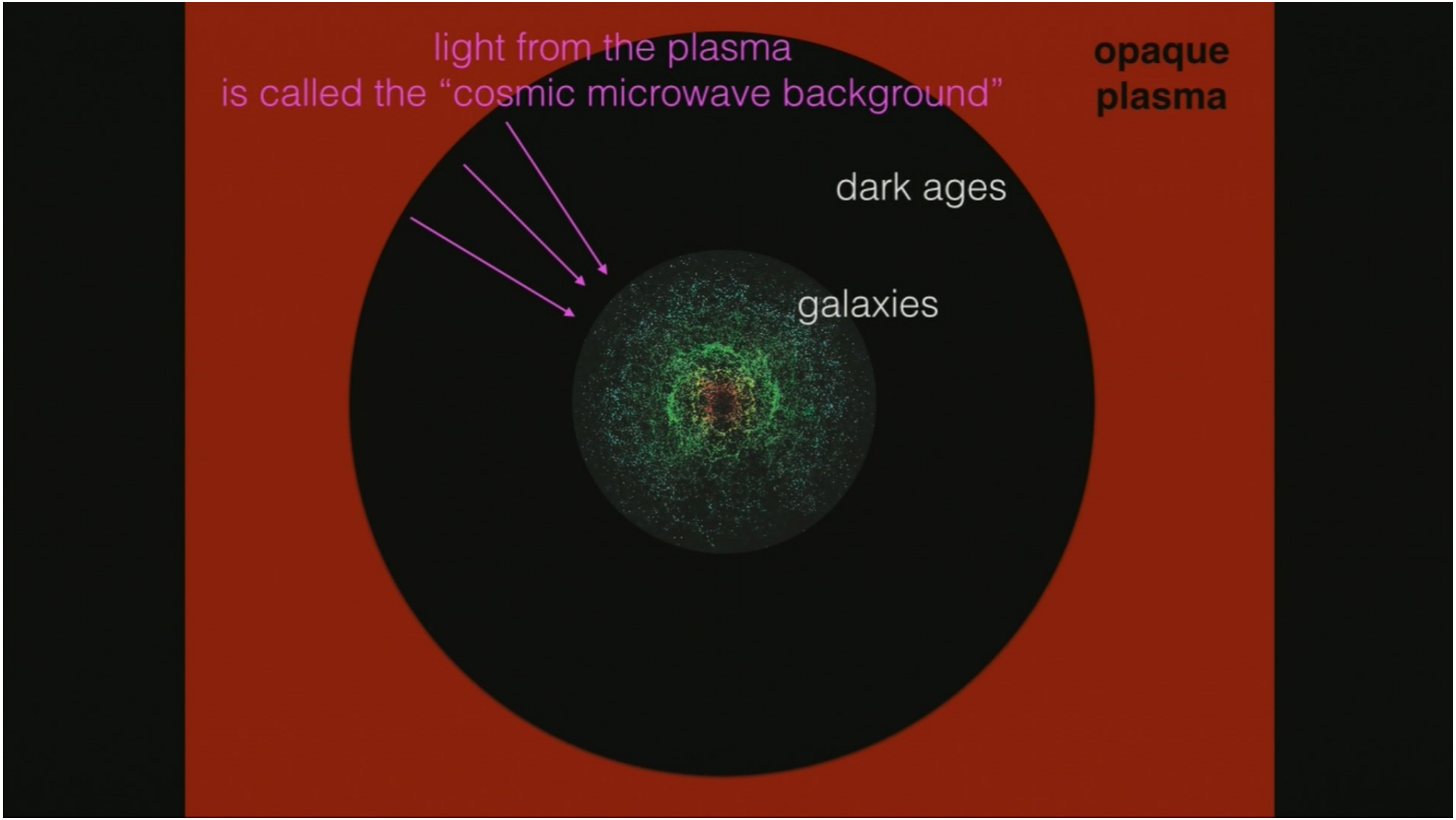



opaque
plasma
dark ages
galaxies

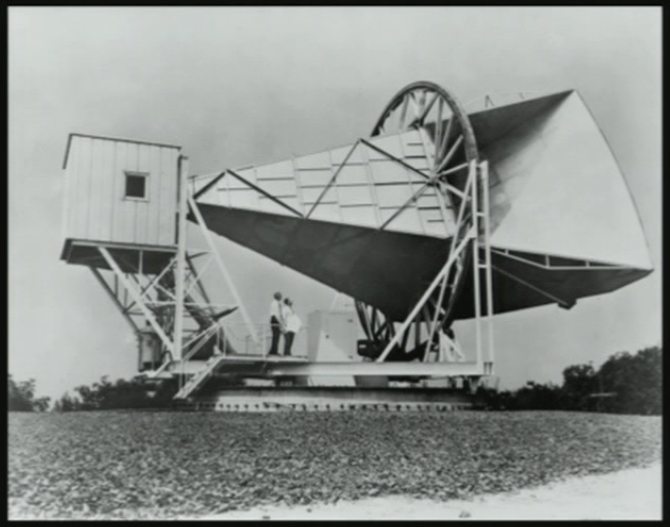
What color is the plasma?

Since we know the temperature (3000° C), we can calculate the color of the light emitted from the plasma…



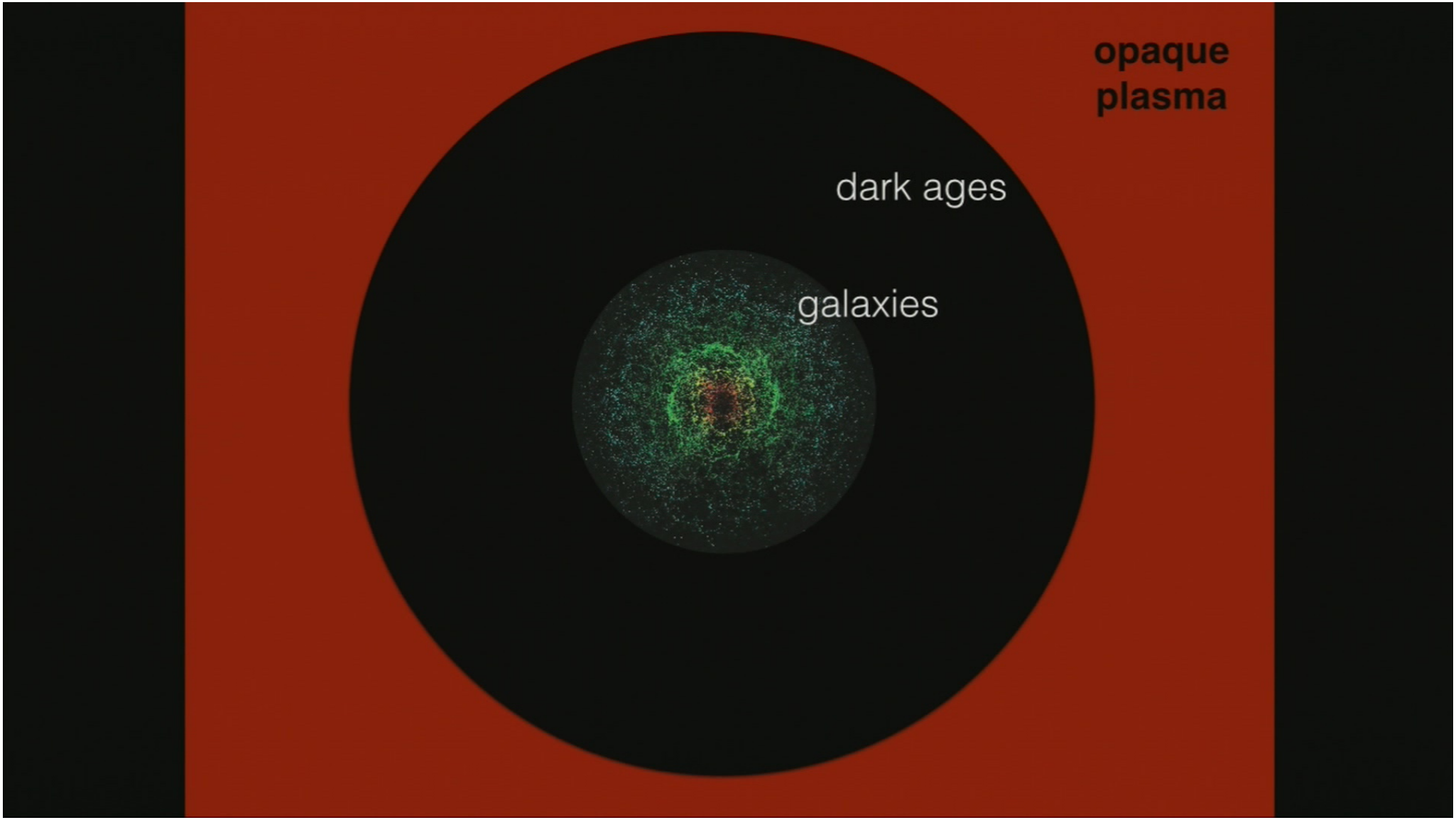

light from the plasma
is called the “cosmic microwave background”
opaque
plasma
dark ages
galaxies

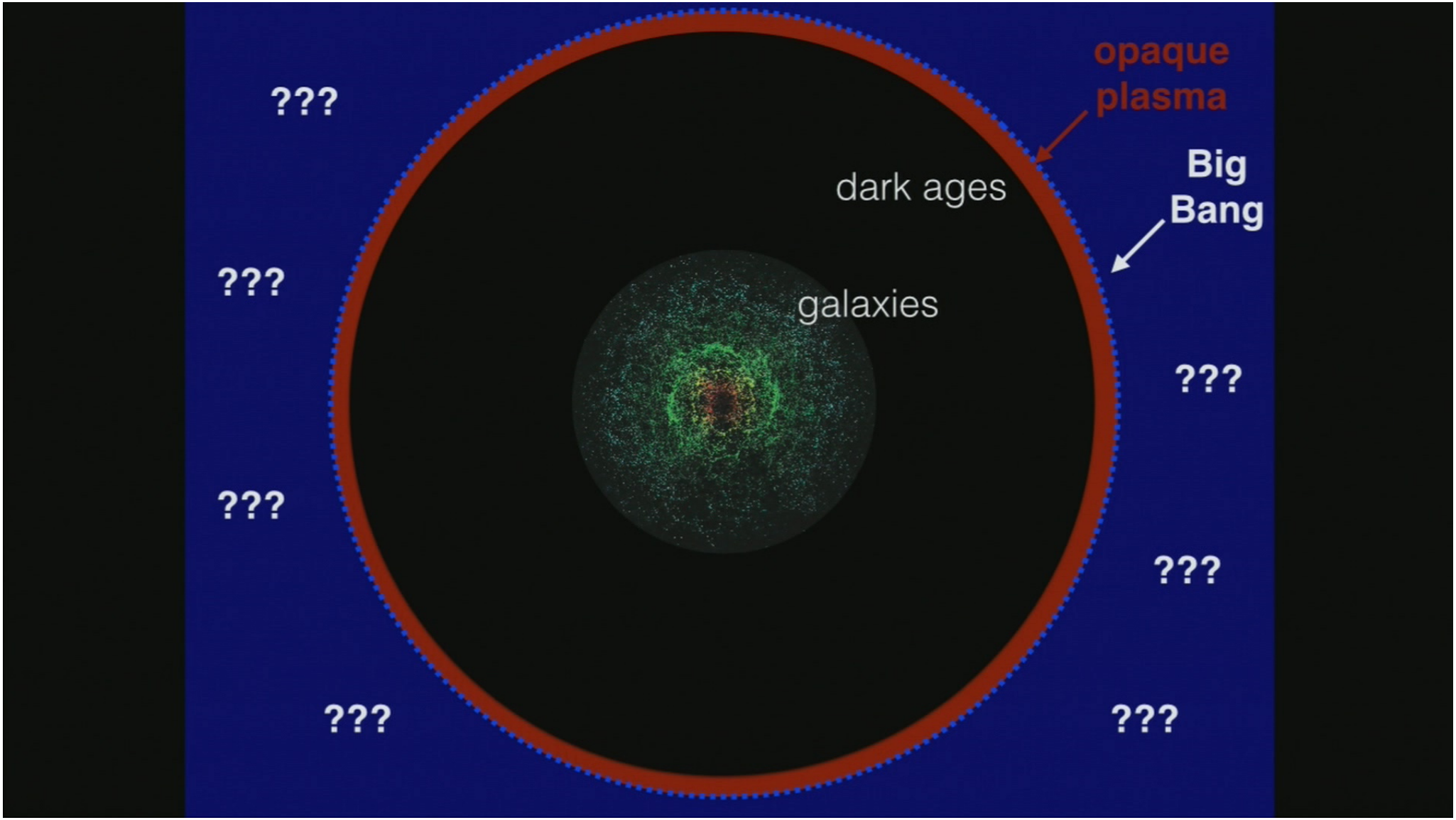
1965: cosmic microwave background observed by Penzias and Wilson!

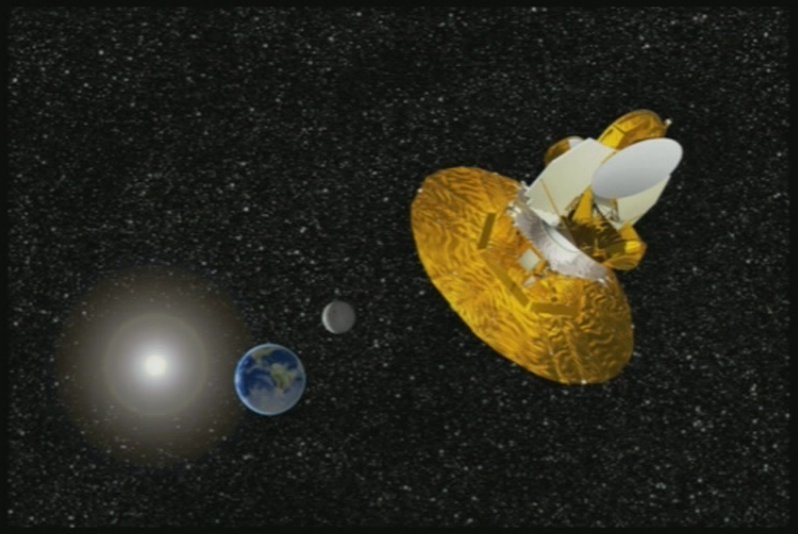


The sky in the visible spectrum

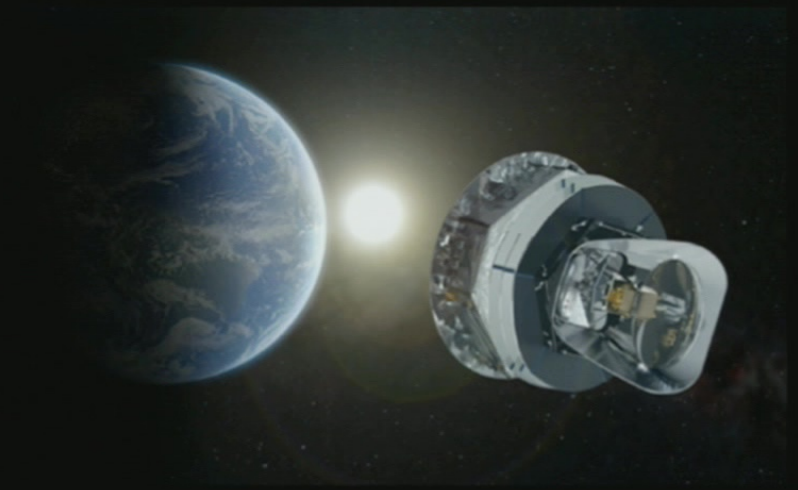

The sky in the microwave spectrum!
0
3.64 K


opaque
plasma
dark ages
galaxies

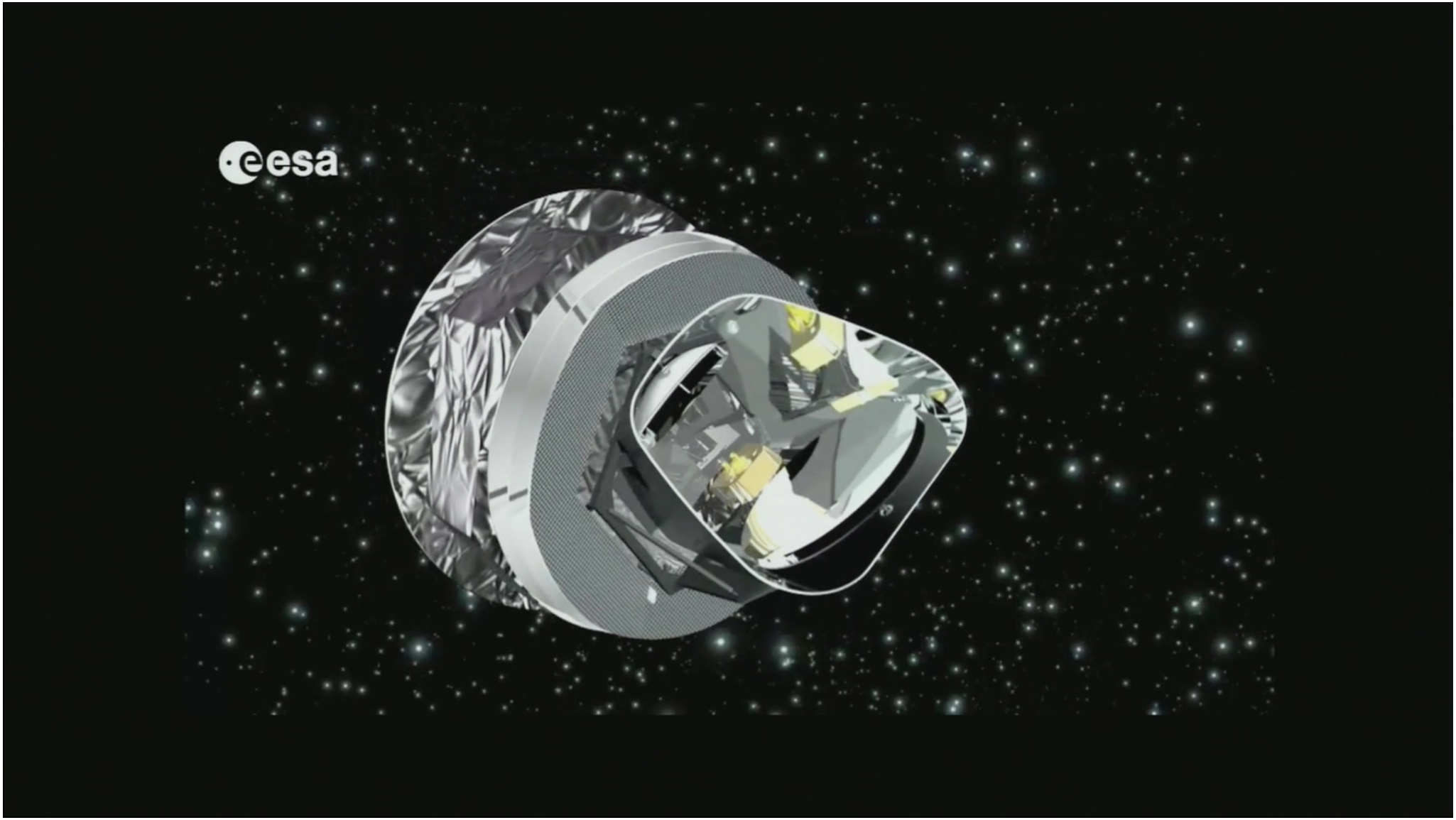

???
opaque
plasma
Big
Bang
dark ages
???
galaxies
???
???
???
???
???

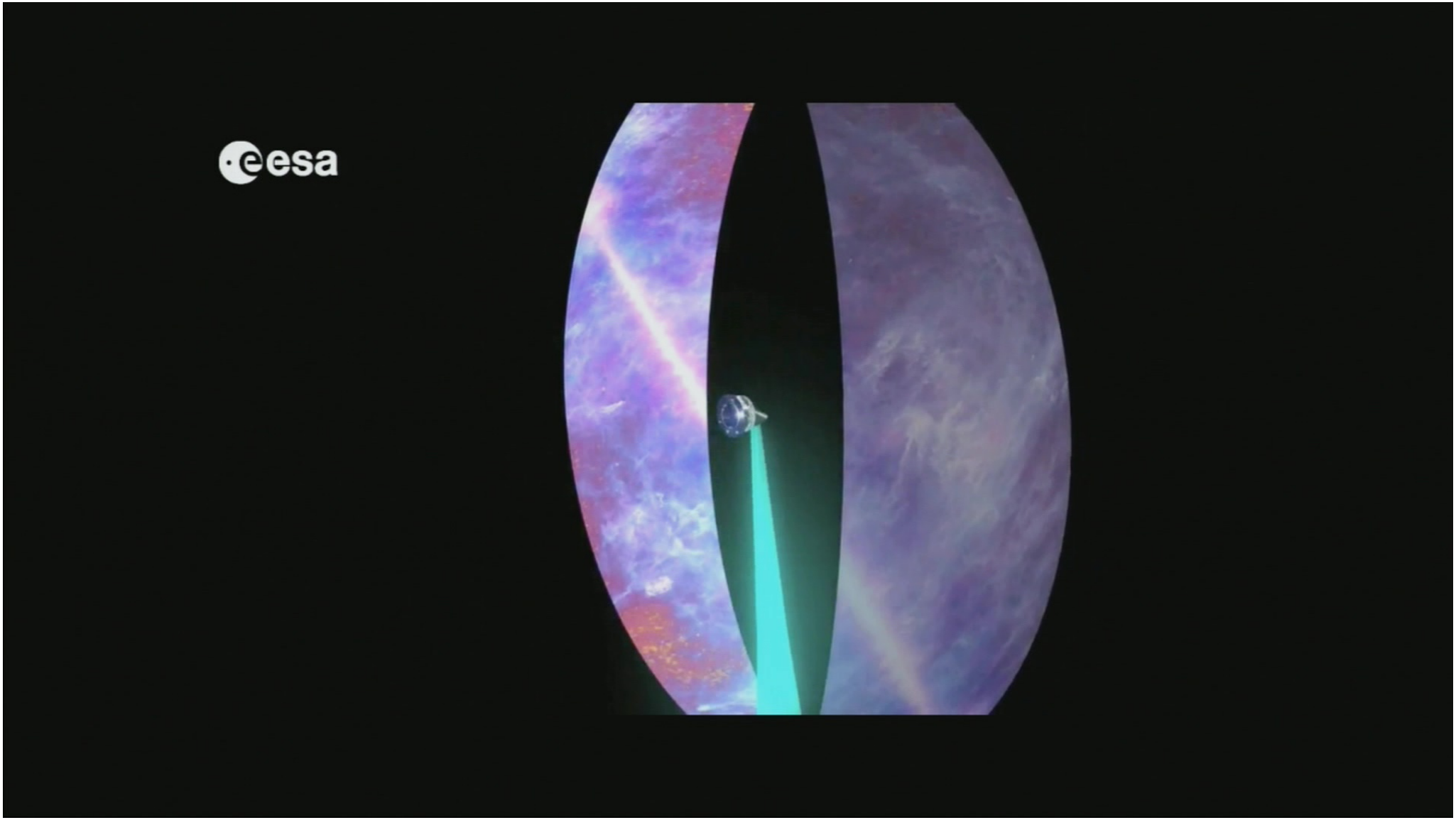


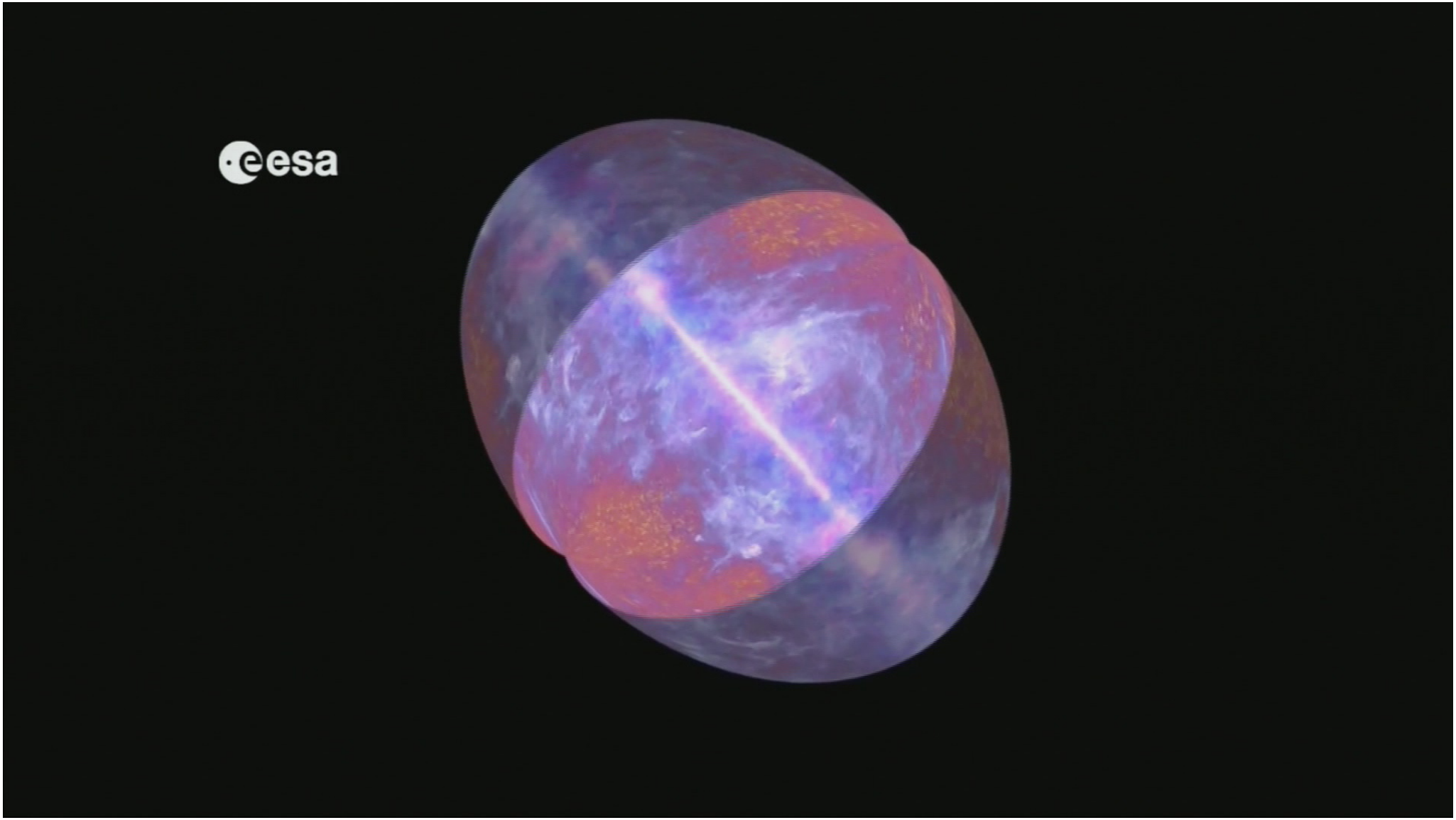
WMAP satellite
(2001-2011)

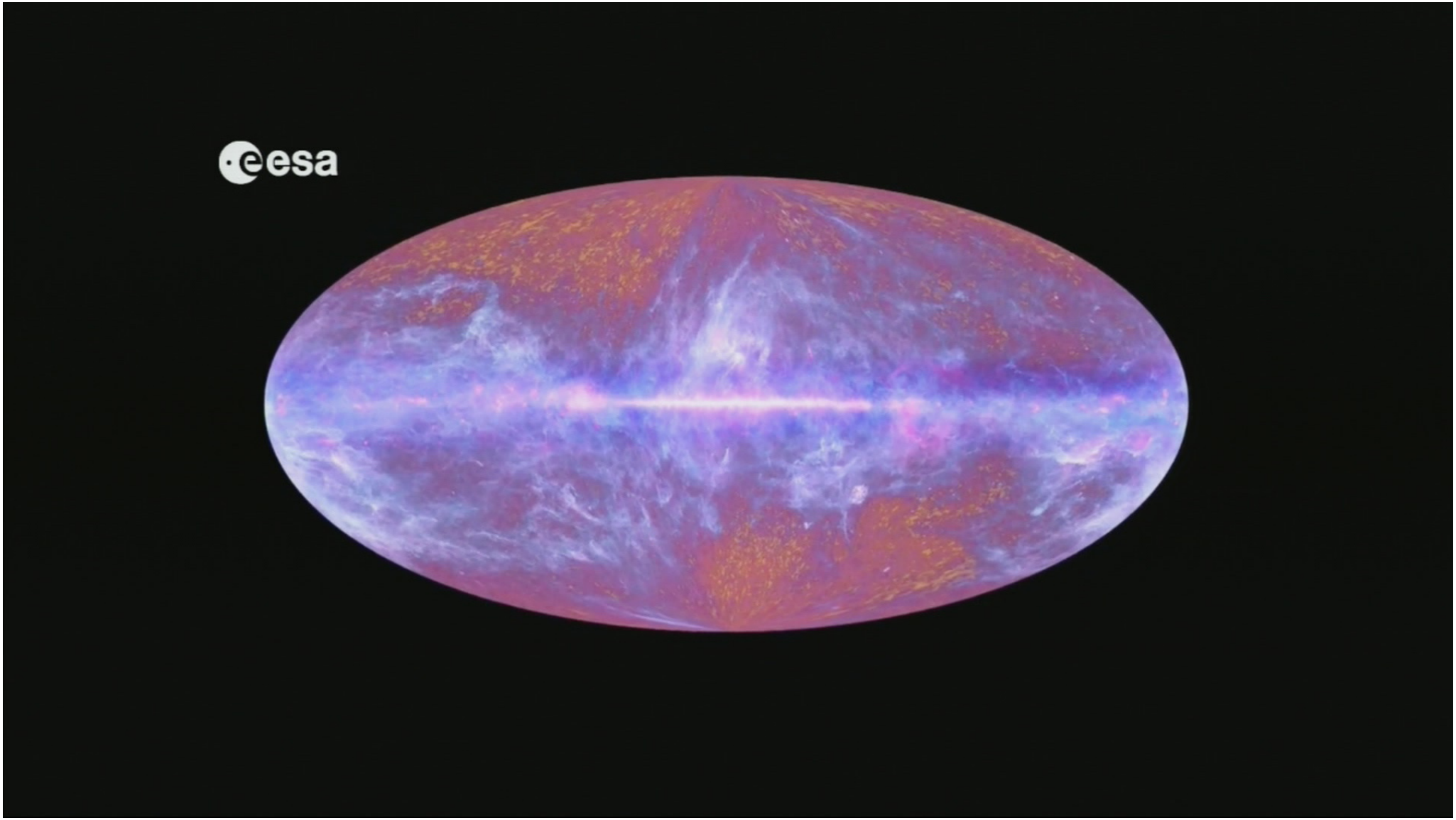


Planck satellite
(2011-2014)

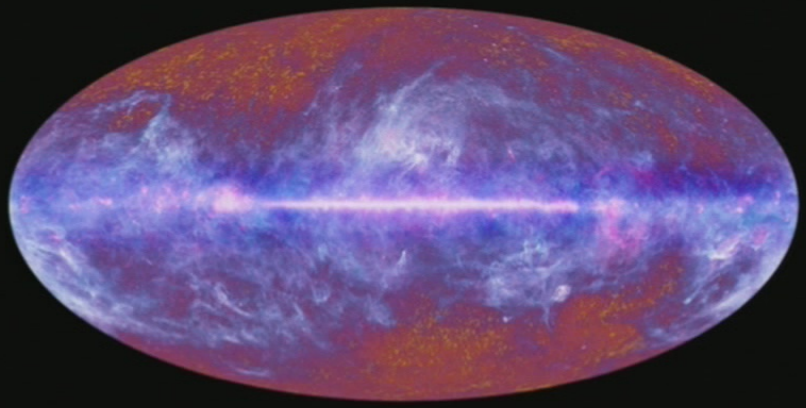

esa


esa

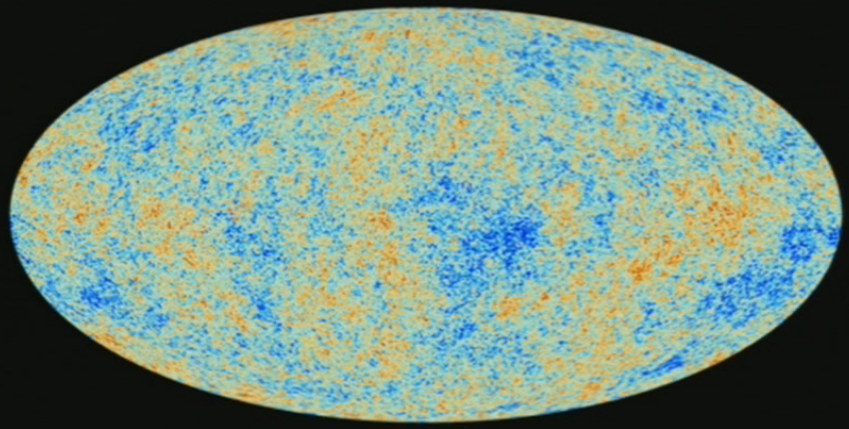

esa


esa

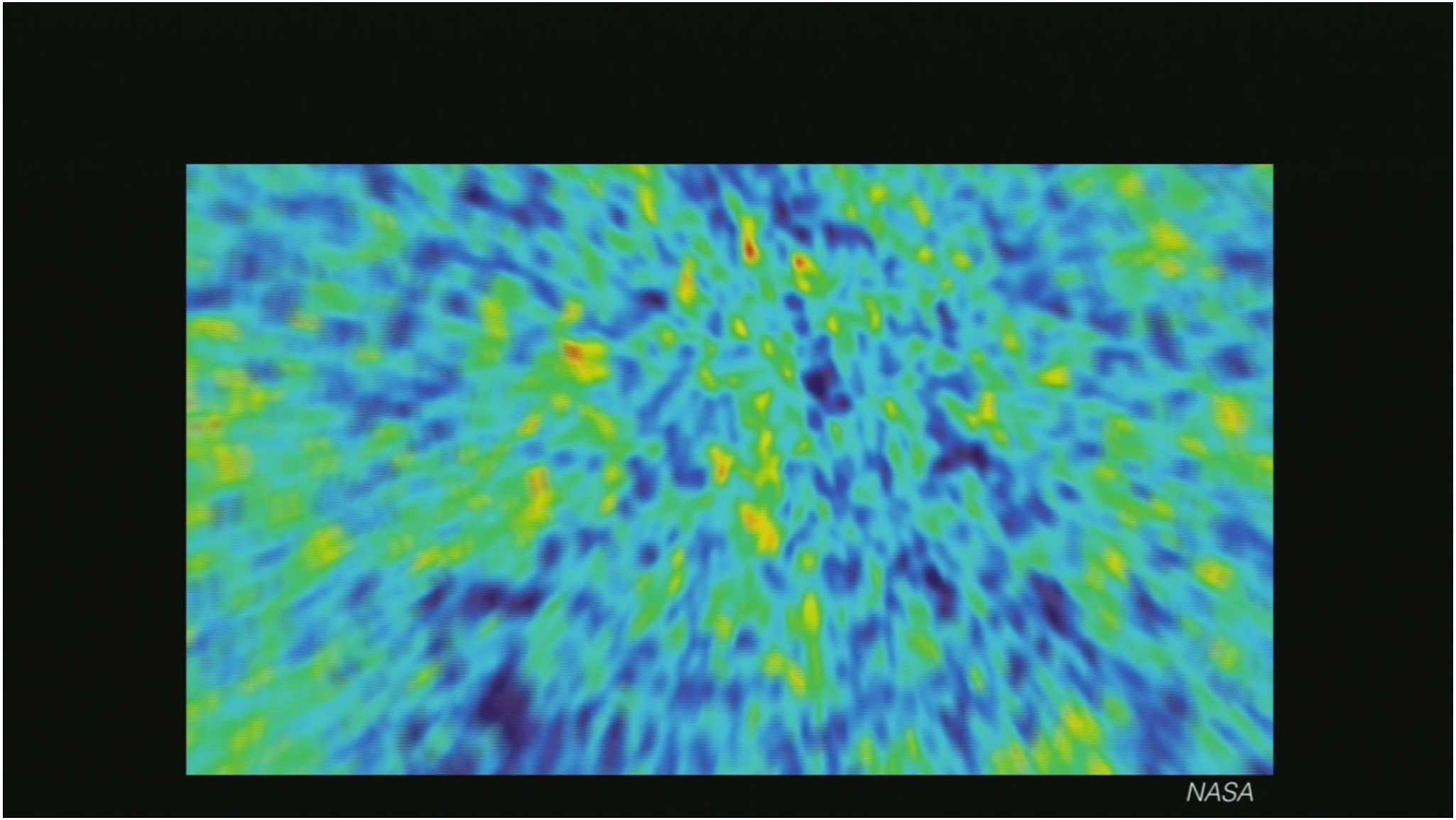
The microwave sky at high contrast

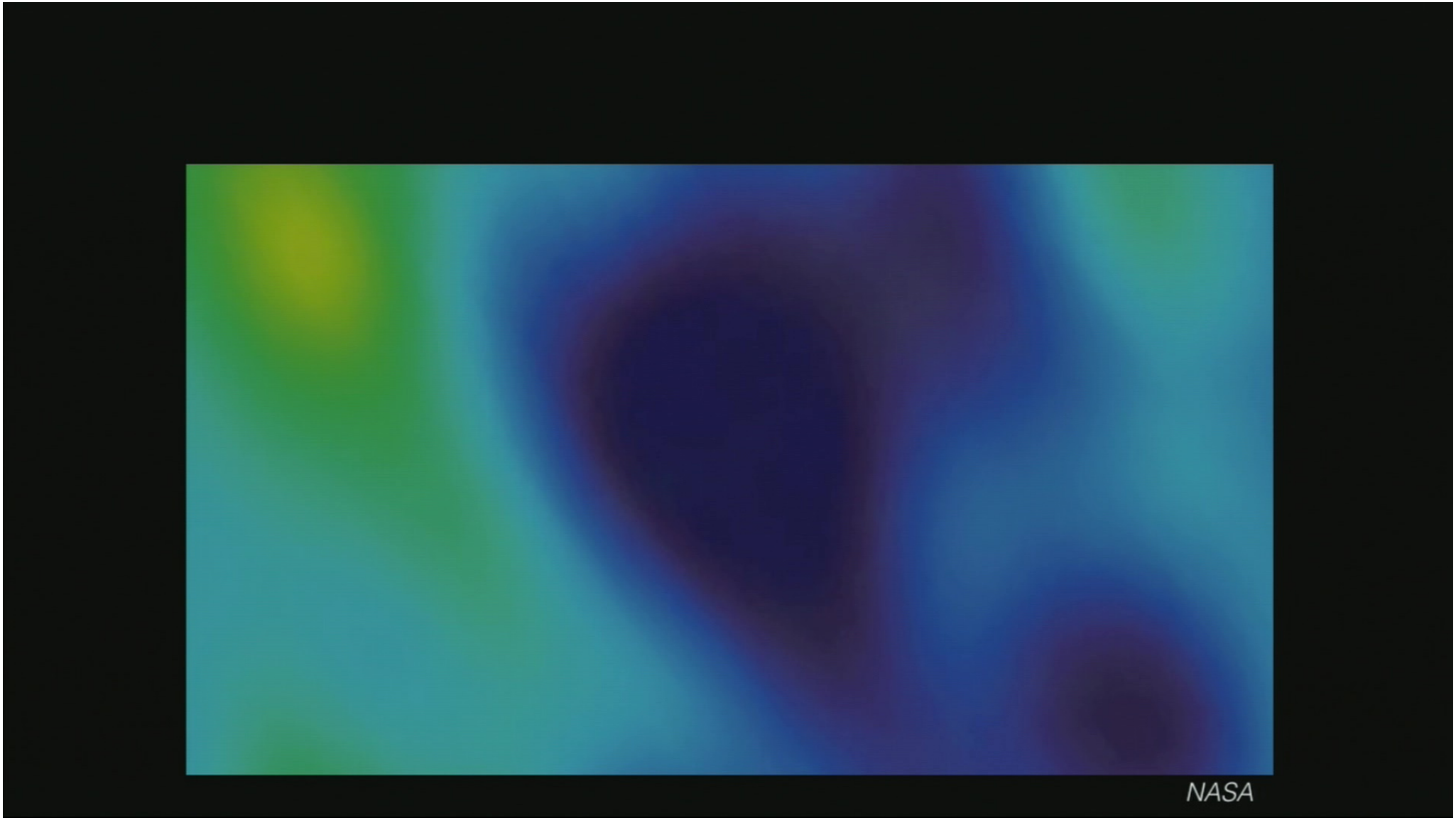


Including dust
from our galaxy



Without dust
from our galaxy


NASA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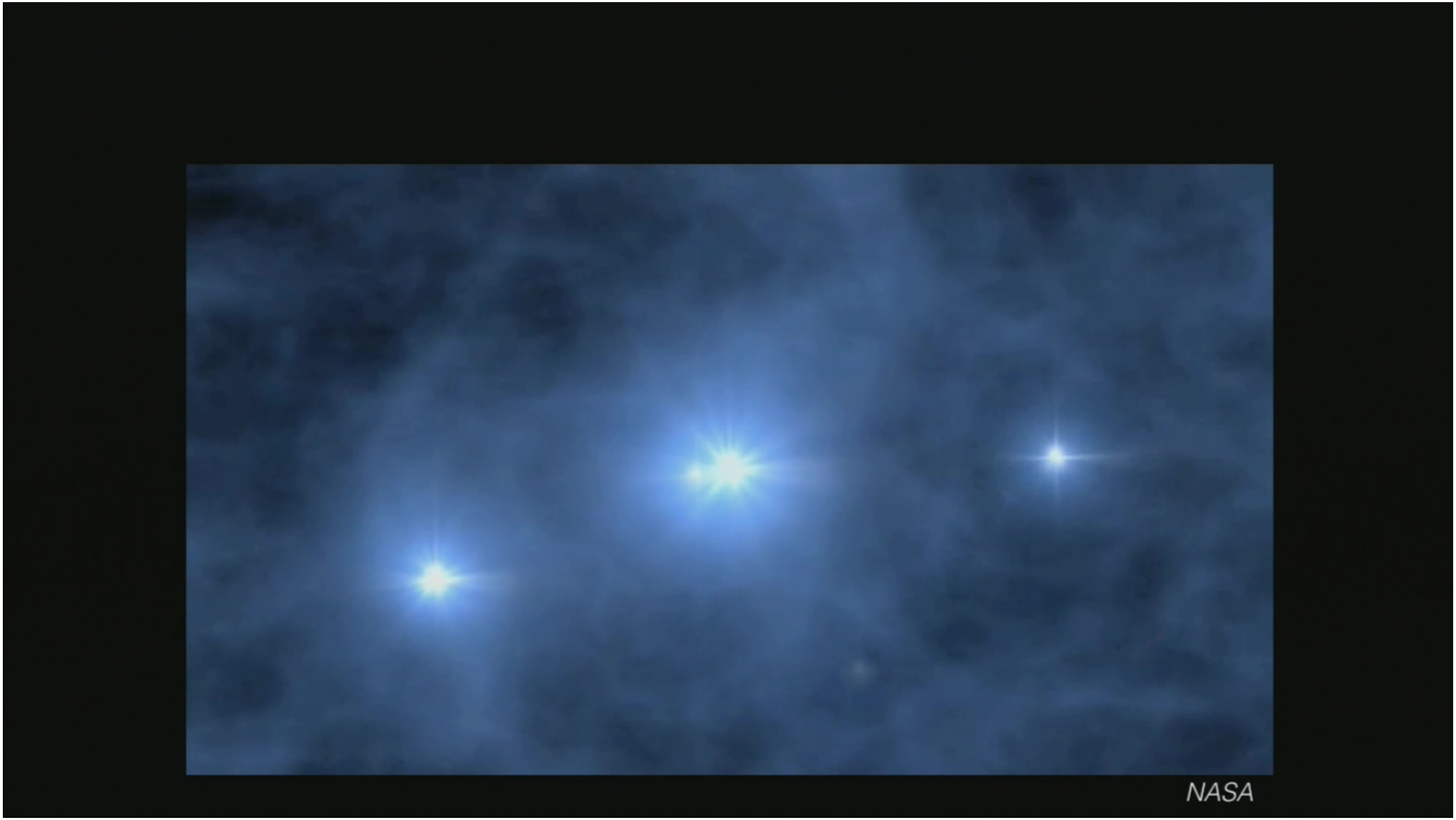
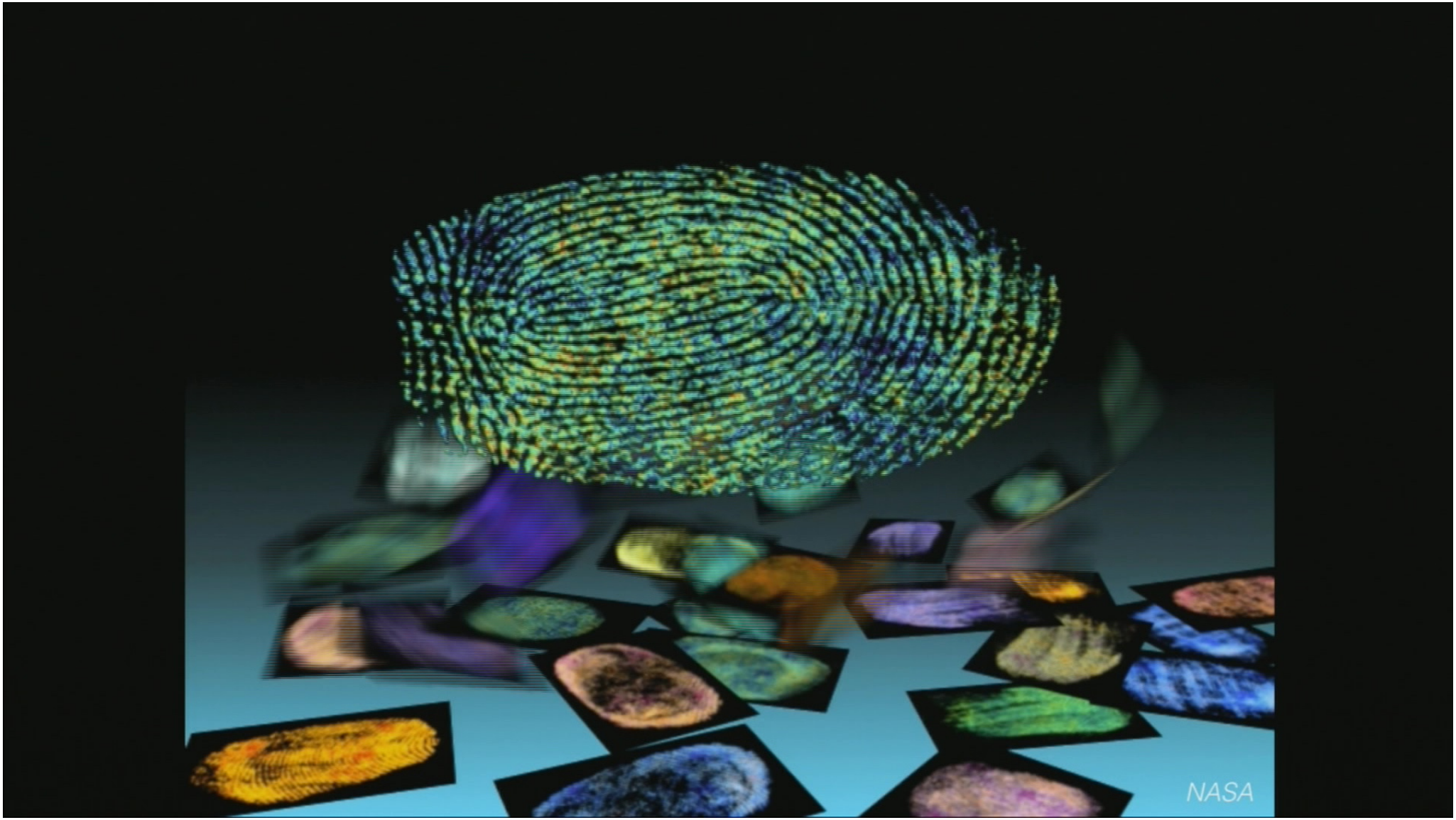

NASA


NASA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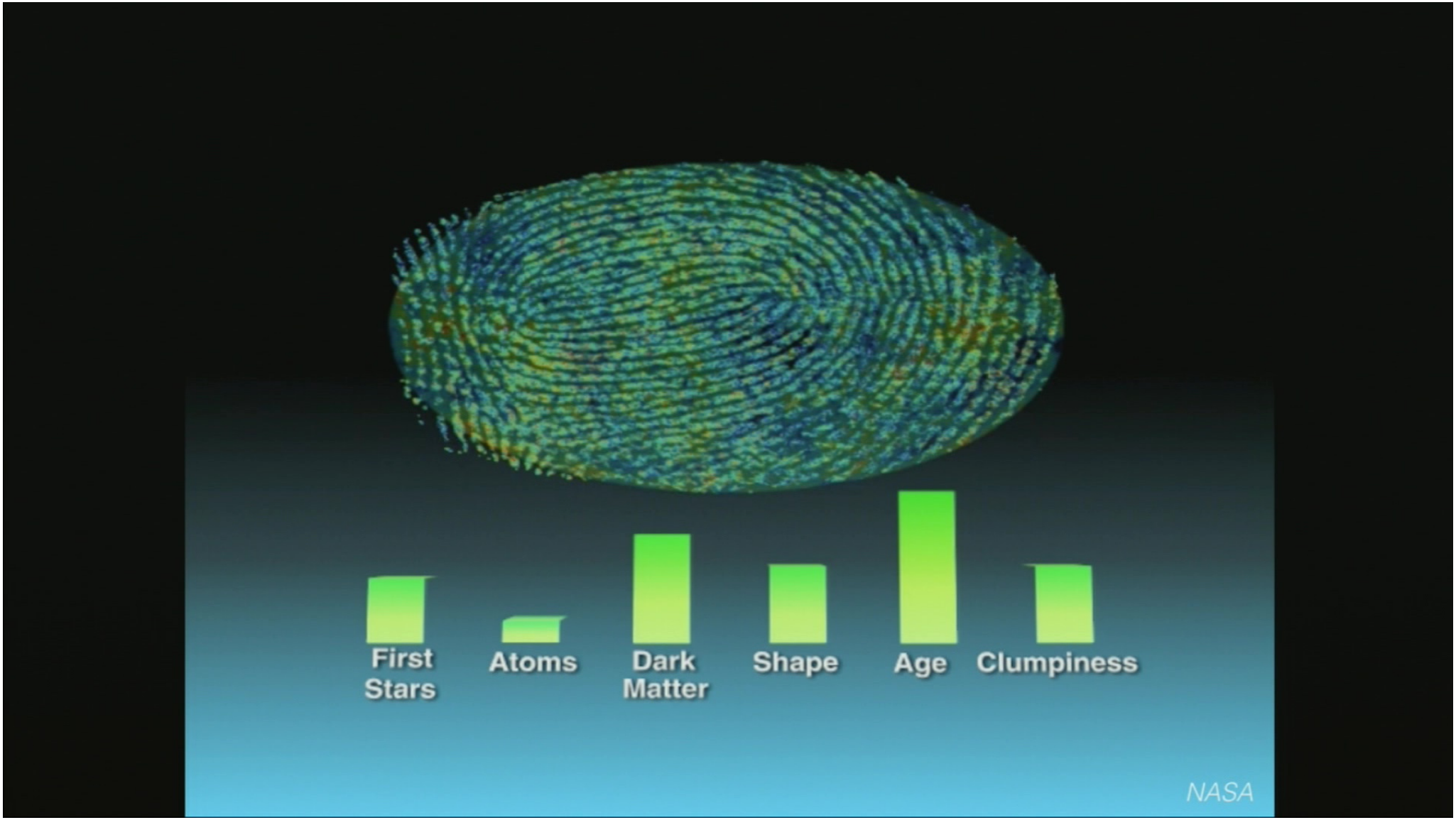
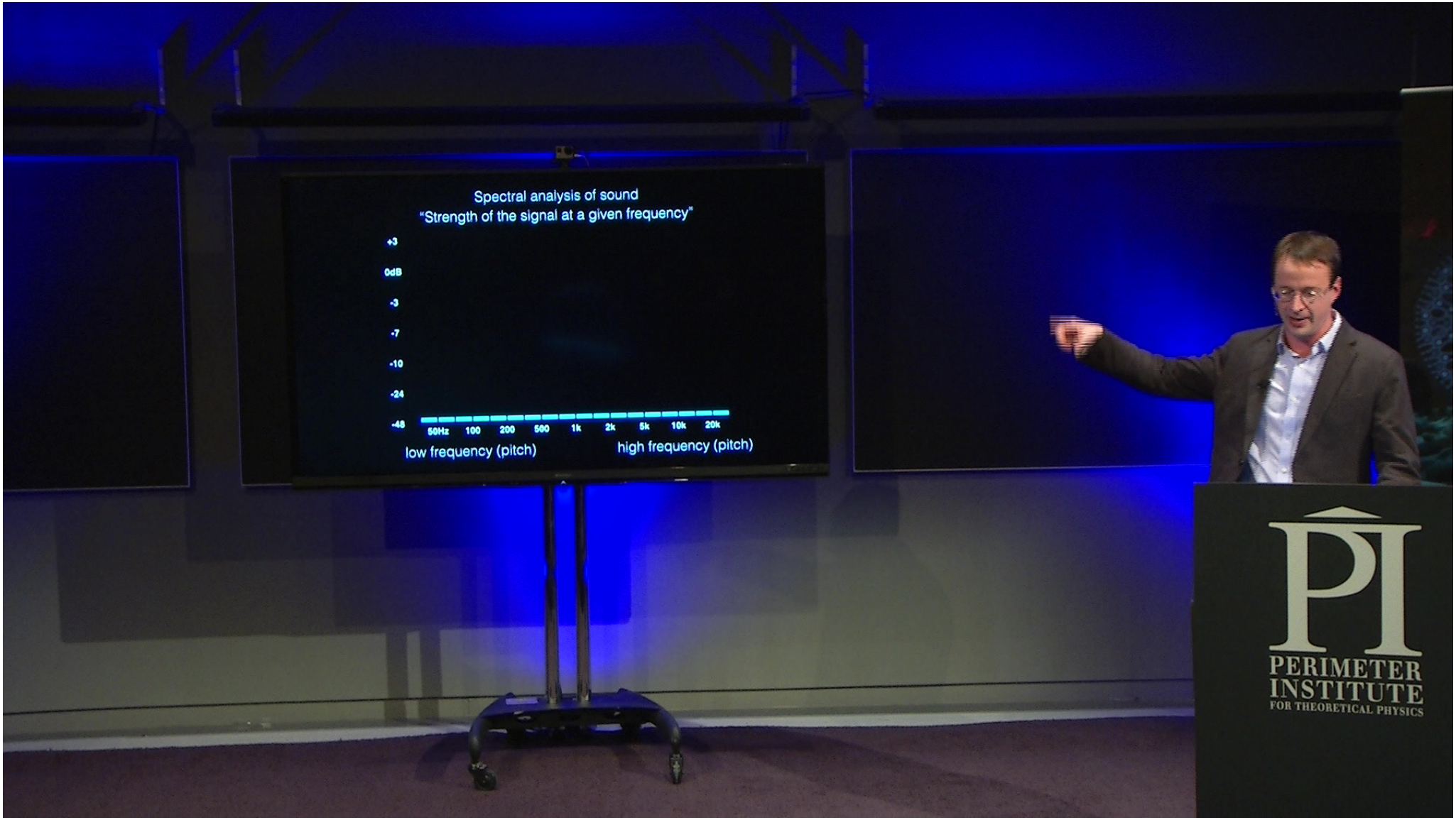

First Stars
Atoms
Dark Matter
Shape
Age
Clumpiness
NASA

How old is the universe?

How old is the universe?

13.68 billion years < Age < 13.92 billion years
(with 95% statistical confidence)


Spectral analysis of sound
"Strength of the signal at a given frequency"
+3
0dB
-3
-7
-10
-24
-48
50Hz
100
200
500
1k
2k
5k
10k
20k
low frequency (pitch)
high frequency (pitch)
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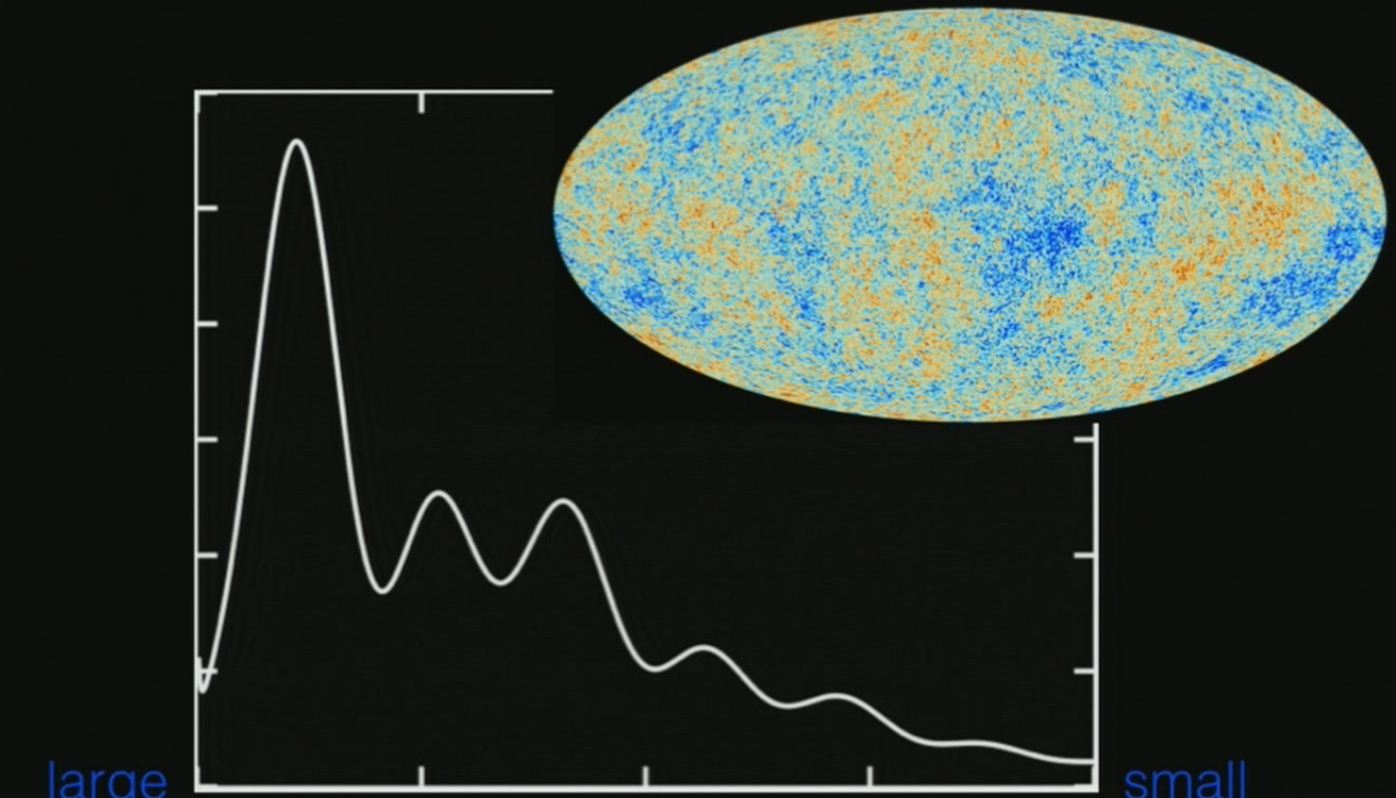
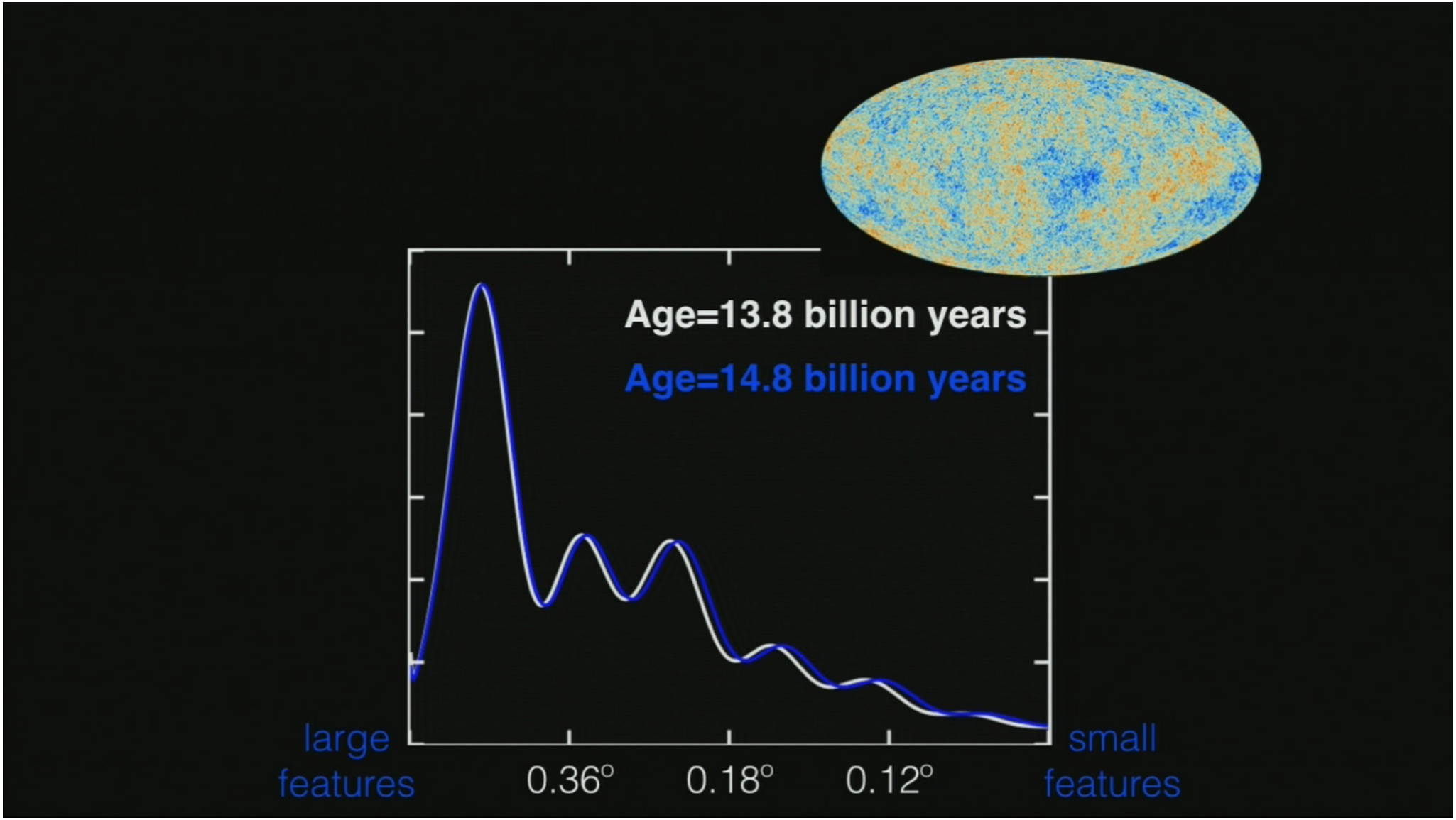
Spectral analysis of CMB: the power spectrum

"Abundance of features of a given size"




Age=13.8 billion years
Age=14.8 billion years
large features
0.36°
0.18°
0.12°
small features

1. The expanding universe

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3. Three mysteries

Mystery #1: Dark matter

Ordinary matter is made of protons, neutrons, electrons

… but the universe at large is mostly made of something else! There is ~5 times more "dark matter" in the universe than the ordinary matter we're familiar with!

Doesn't absorb, reflect or emit light (a better name would be "transparent matter")

Doesn't interact with ordinary matter (there is dark matter streaming through this room right now!)

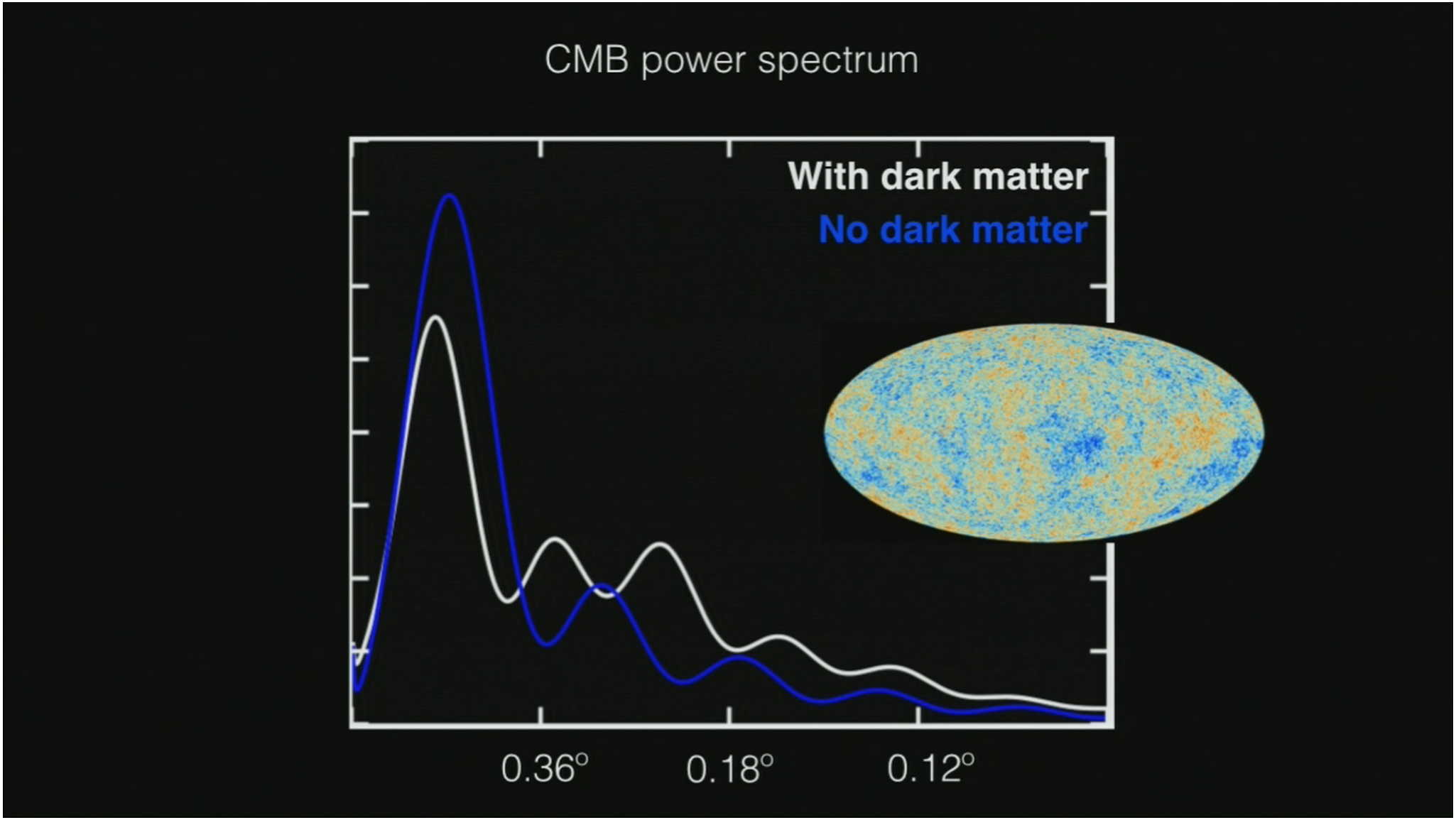
Does gravitate: ordinary matter and dark matter attract each other gravitationally


Galaxies form in dark matter halos
Robert Berrington

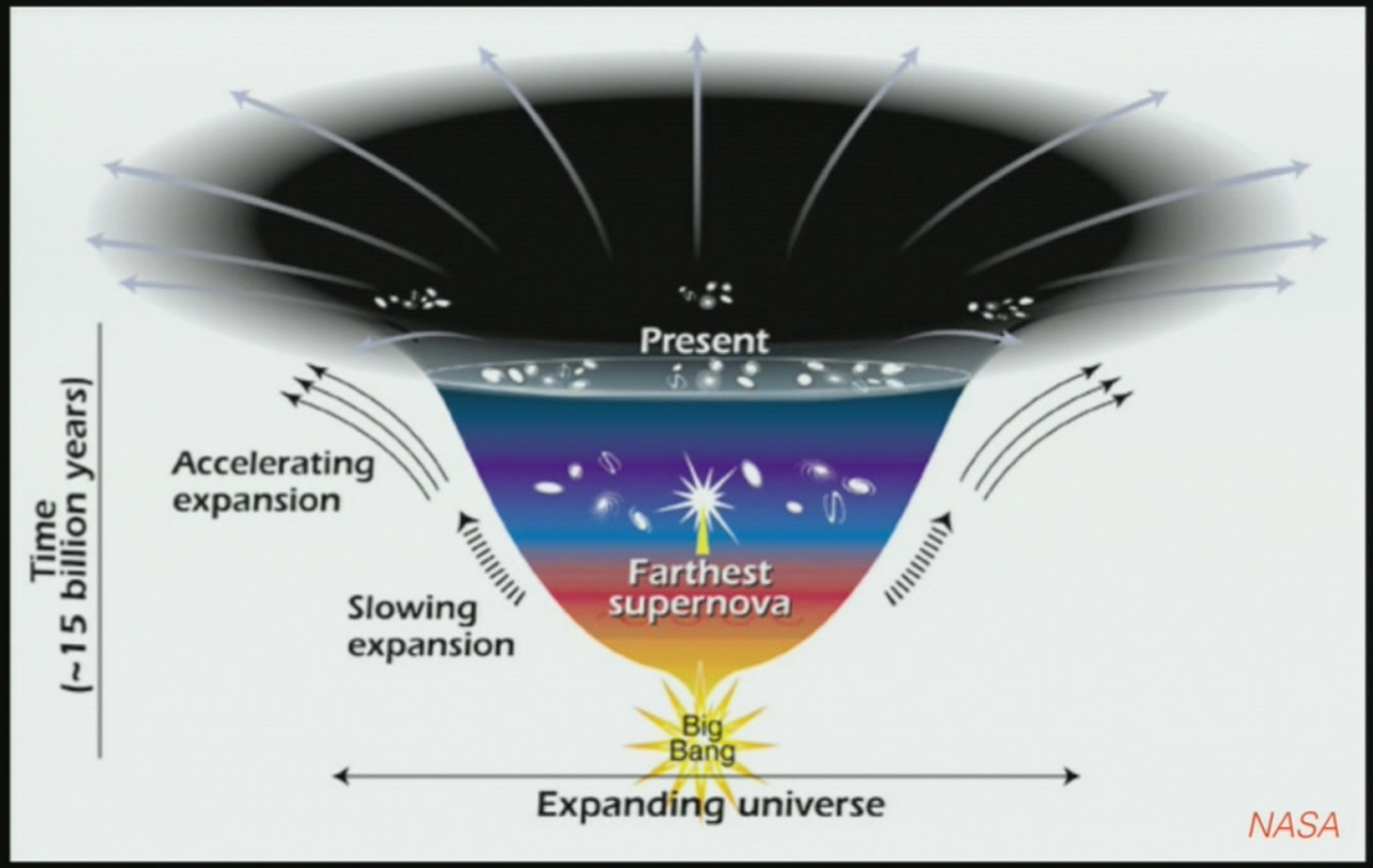
Rotation rate of galaxies

No dark matter

With dark matter

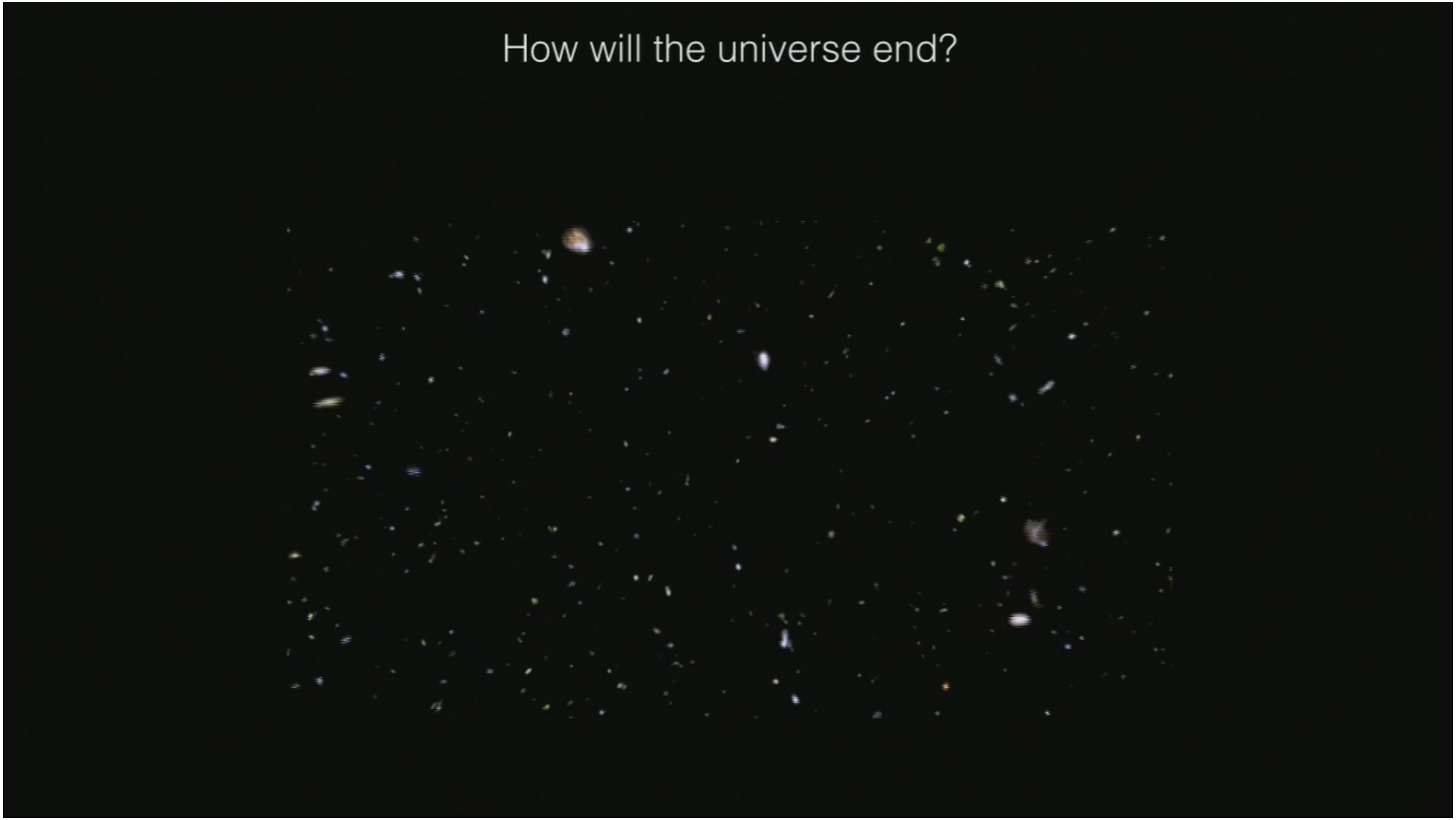

CMB power spectrum
With dark matter
No dark matter
0.36°
0.18°
0.12°

Mystery #2: Dark energy
The expansion of the universe recently started accelerating!

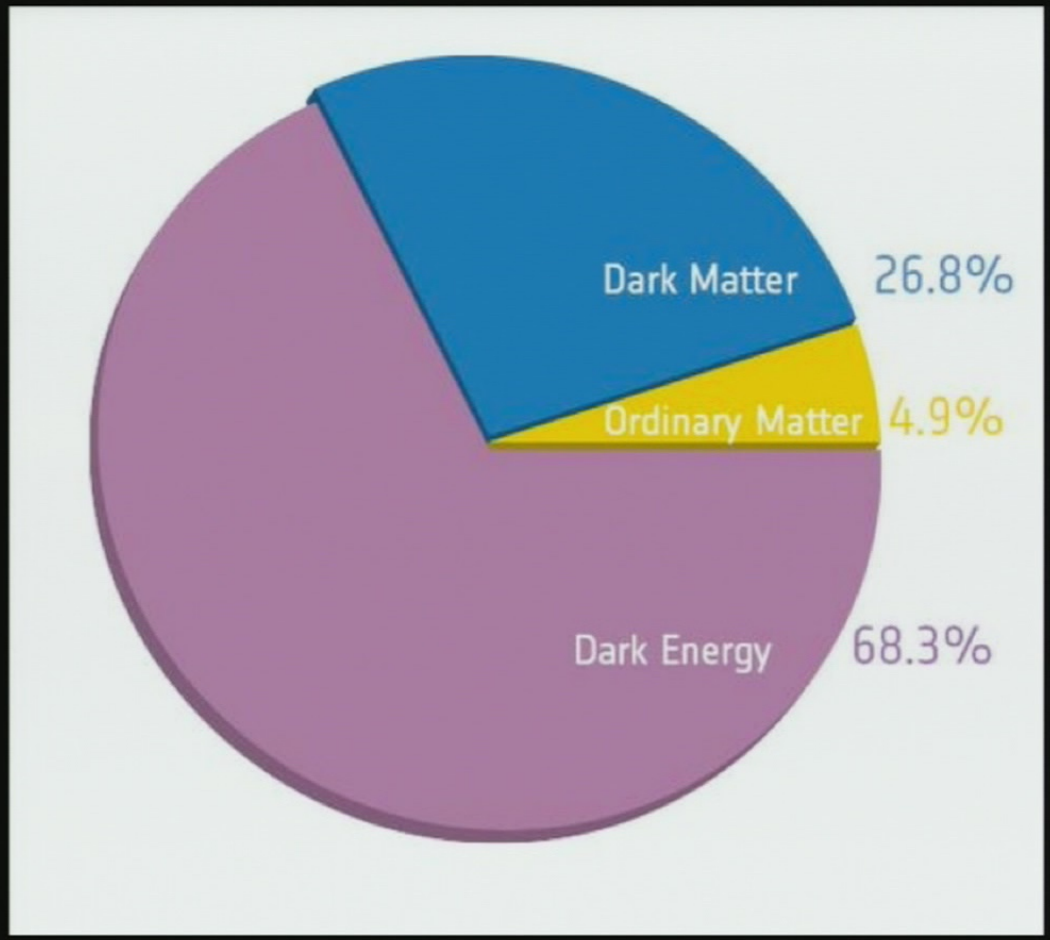


"Dark energy" = "whatever unknown physics is causing the expansion of the universe to accelerate, contrary to predictions"

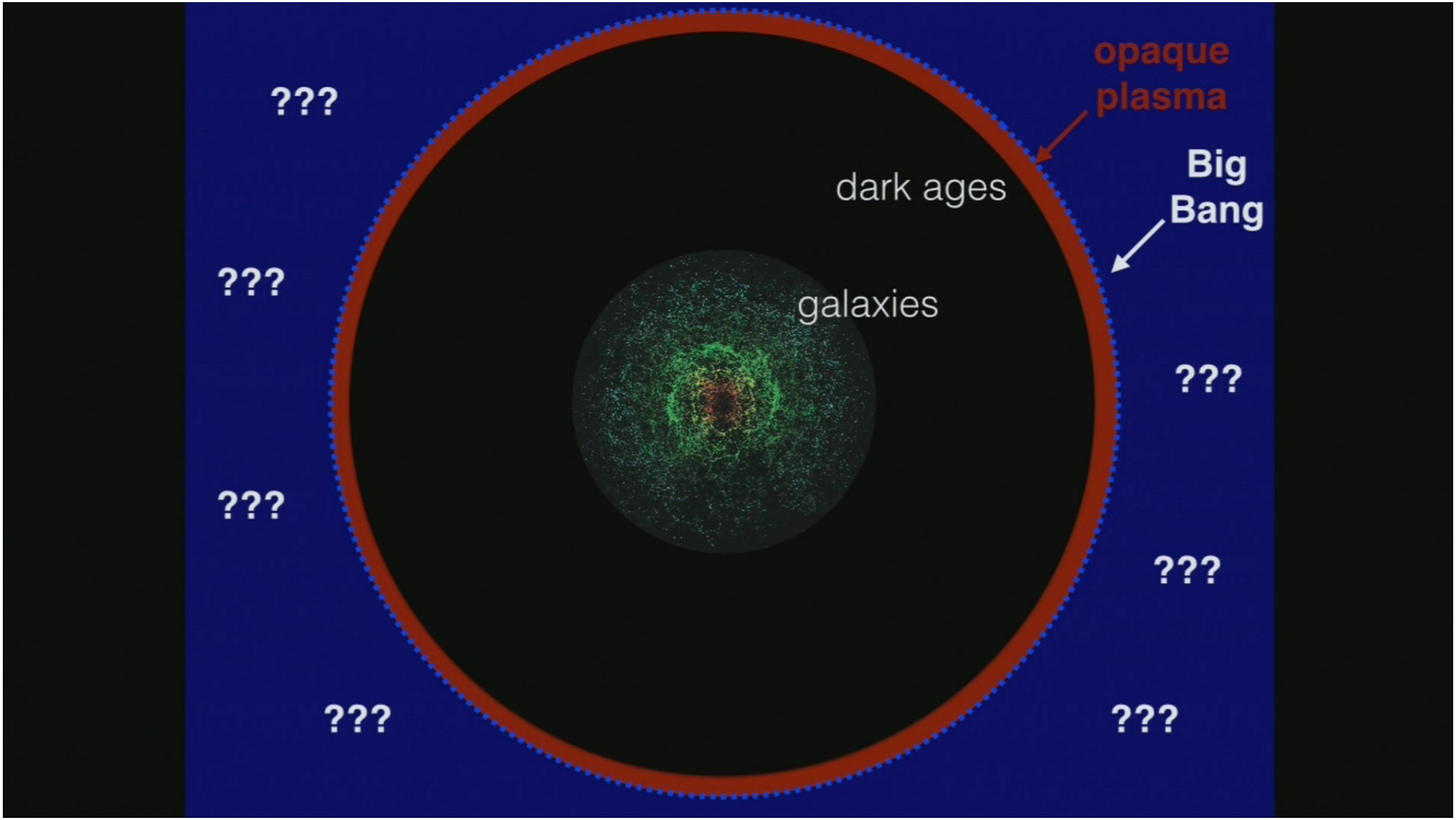
One possibility: slightly modify Einstein's theory of gravity by allowing the vacuum to have a slightly positive energy density ("cosmological constant")


How will the universe end?

What is the universe composed of?

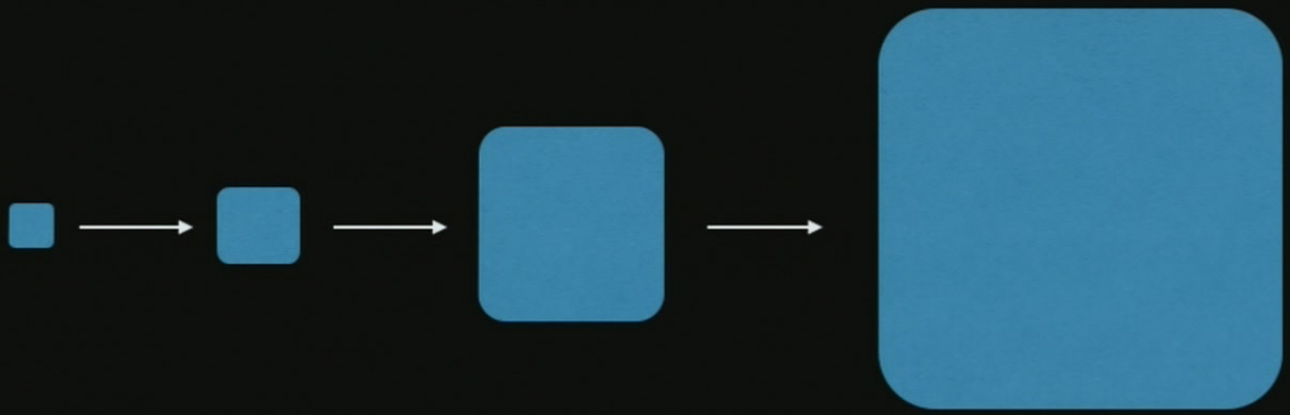


Mystery #3: the physics of the very beginning


???
opaque
plasma
Big
Bang
dark ages
???
galaxies
???
???
???
???
???

Inflation: a candidate theory of the very beginning

The very early universe is full of one or more new particles which drive a phase of exponential expansion



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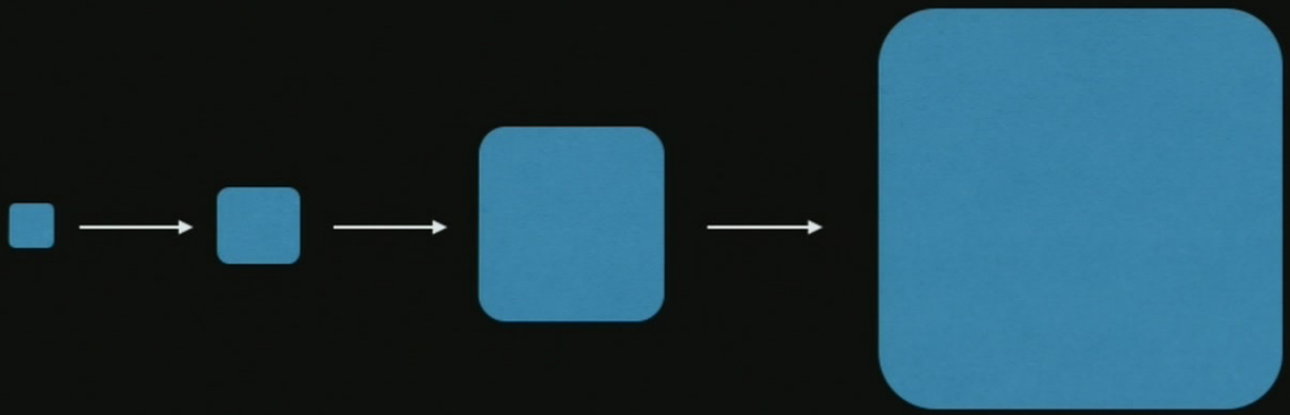
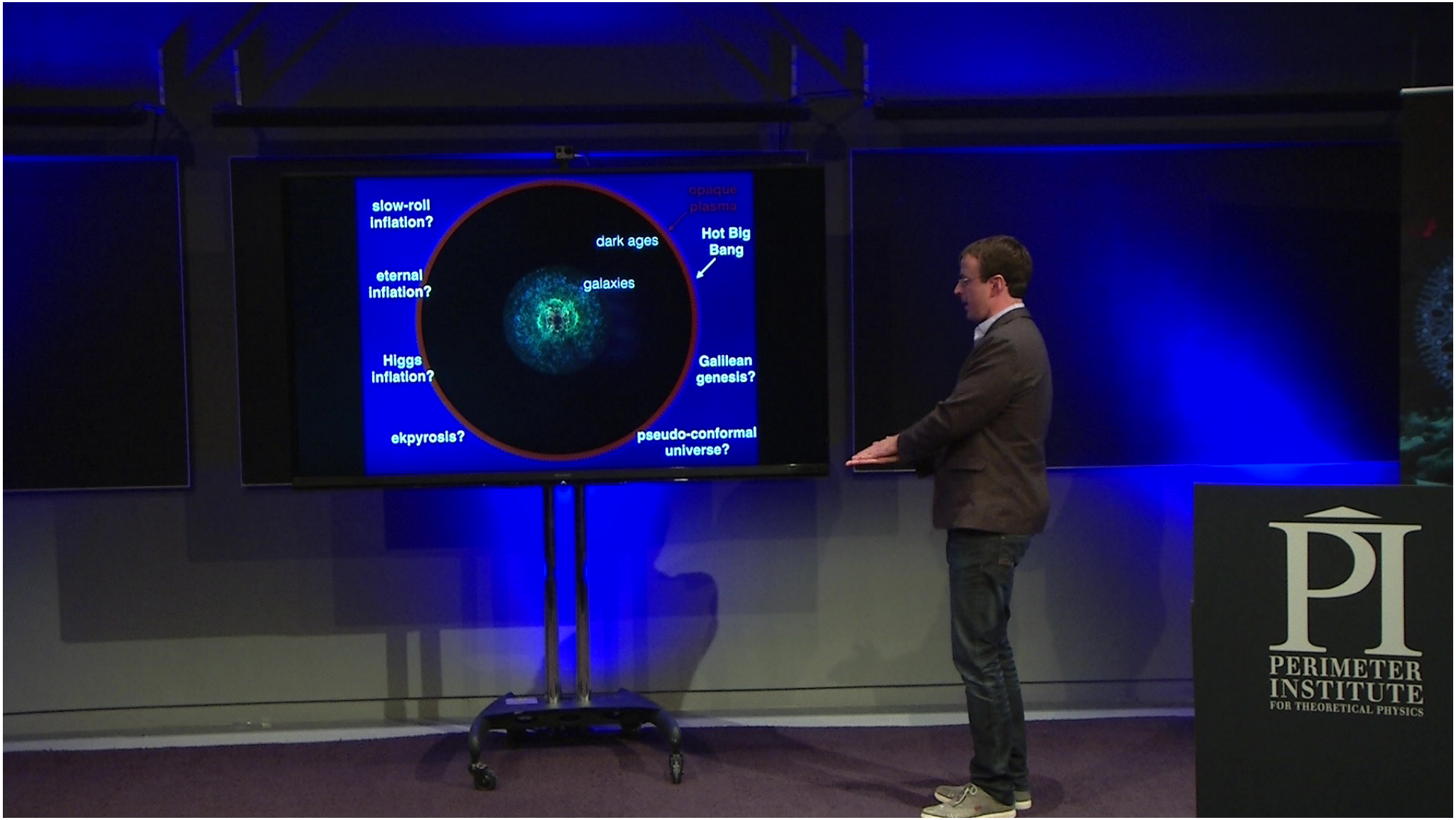


This produces quantum mechanical fluctuations which have precisely the correct statistical properties to be the initial fluctuations in our universe!


slow-roll inflation?
opaque plasma
dark ages
Hot Big Bang
eternal inflation?
galaxies
Higgs inflation?
Galilean genesis?
ekpyrosis?
pseudo-conformal universe?
PERIMETER INSTITUTE
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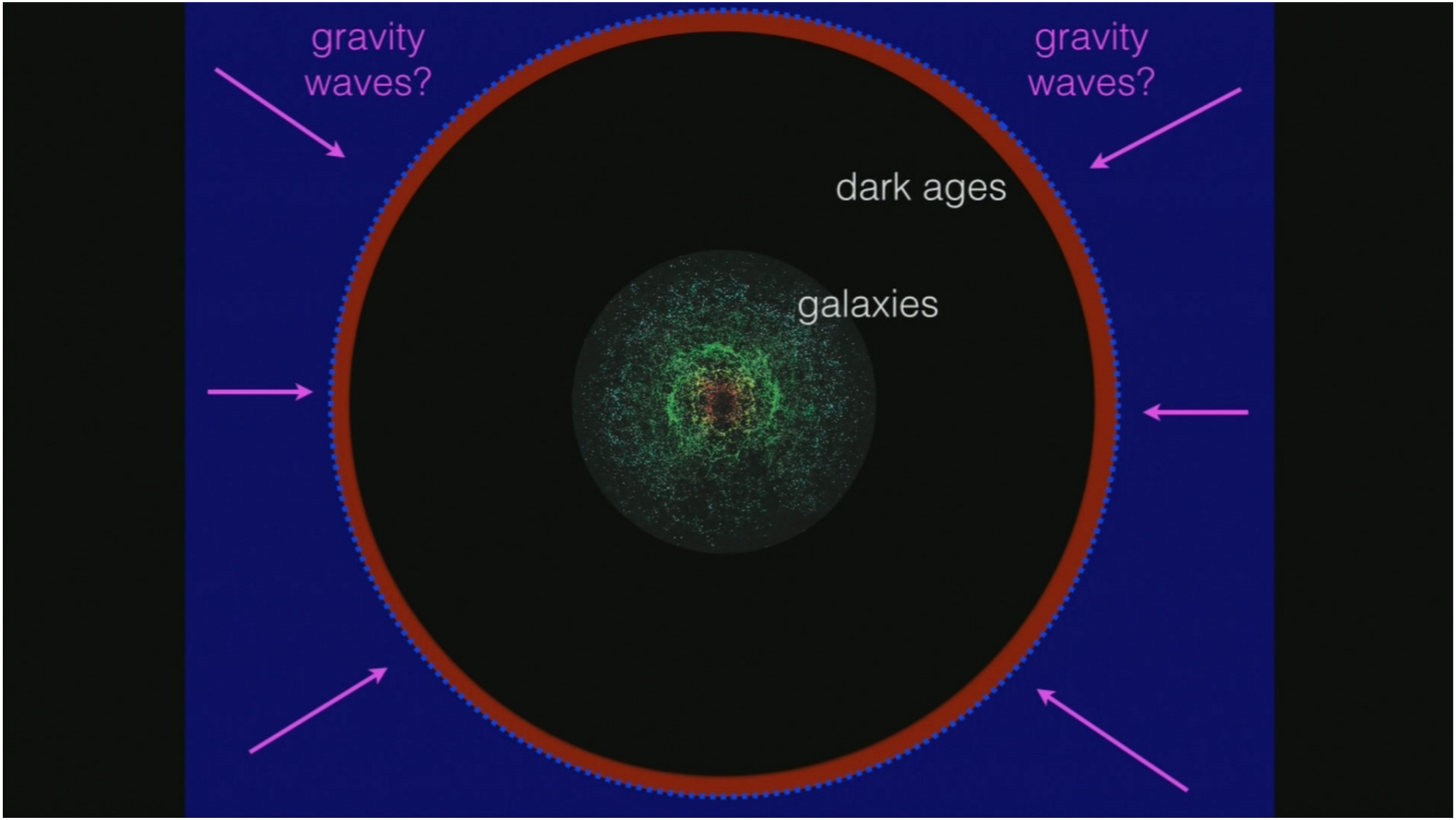
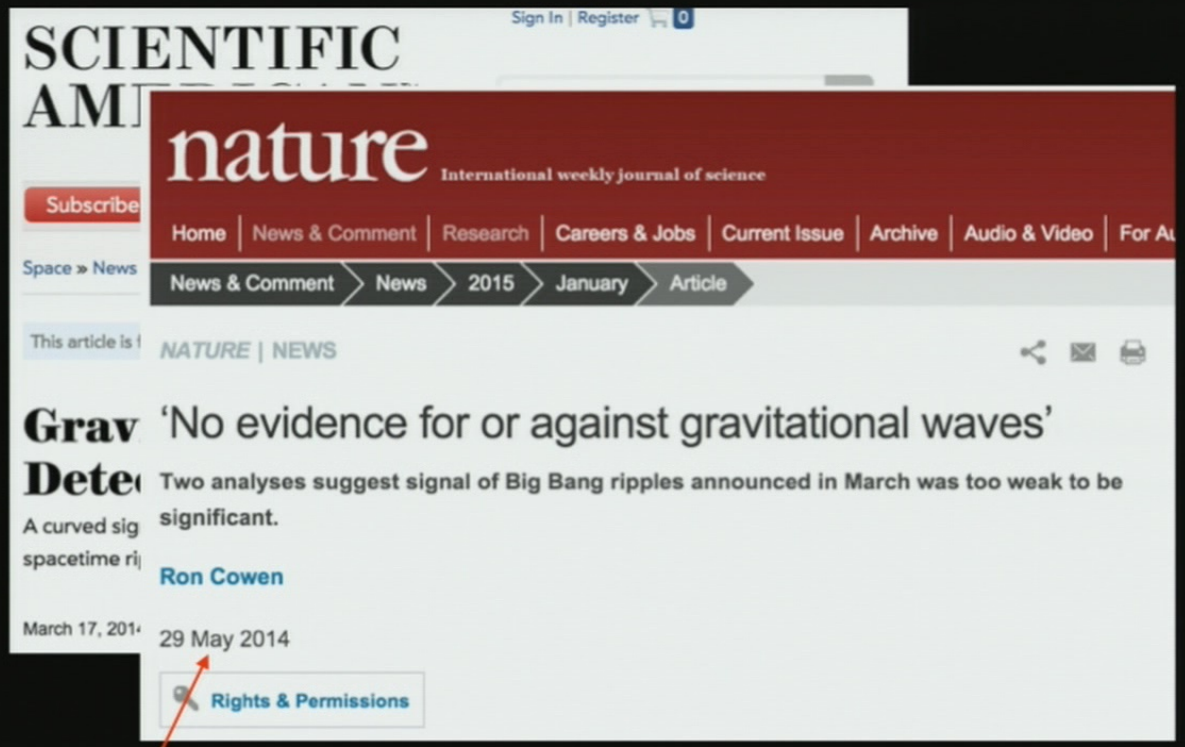

gravity
waves?
gravity
waves?
dark ages
galaxies

Have gravitational waves from inflation been detected?

Yes! (March 2014)

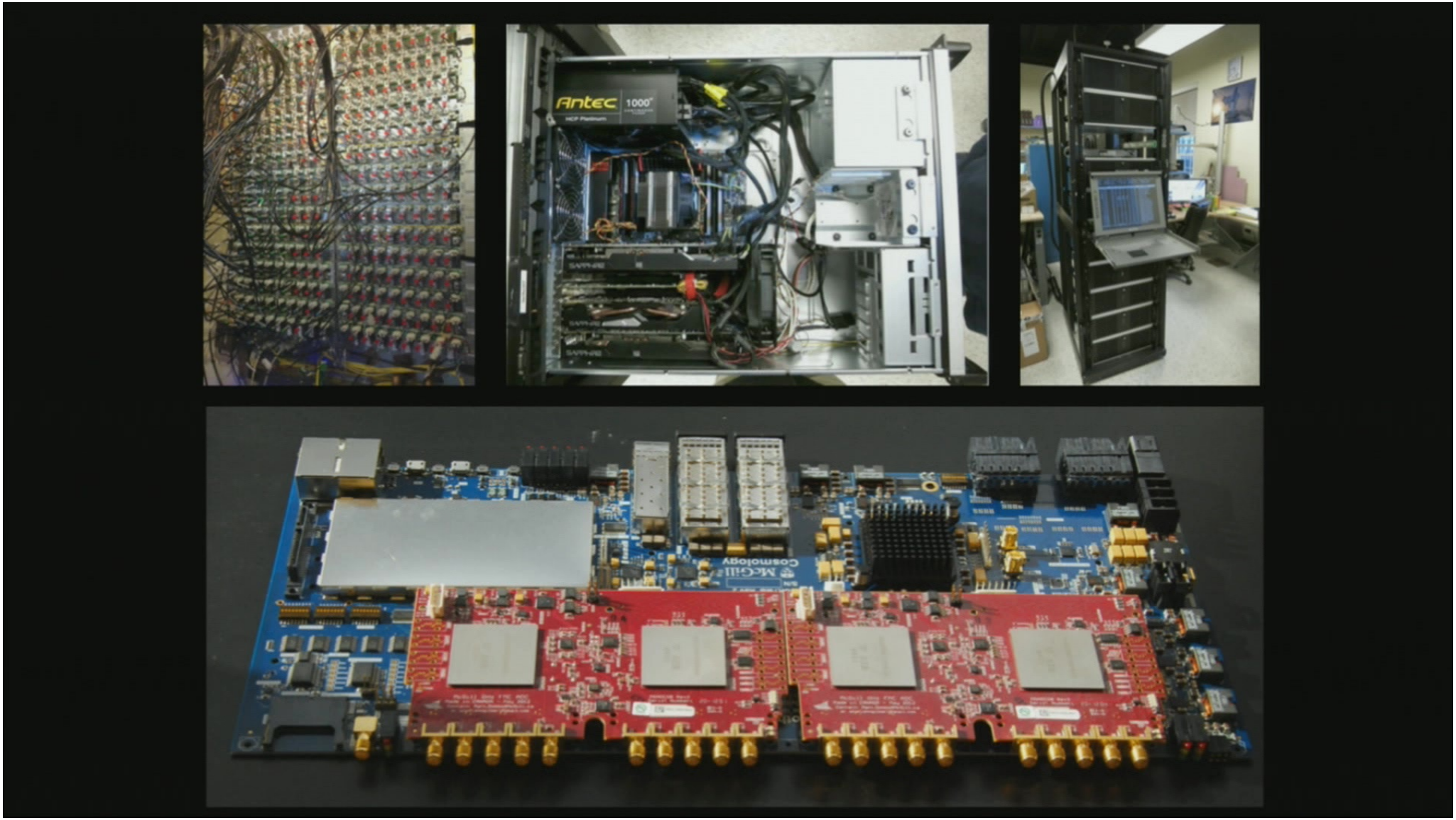
Have gravitational waves from inflation been detected?

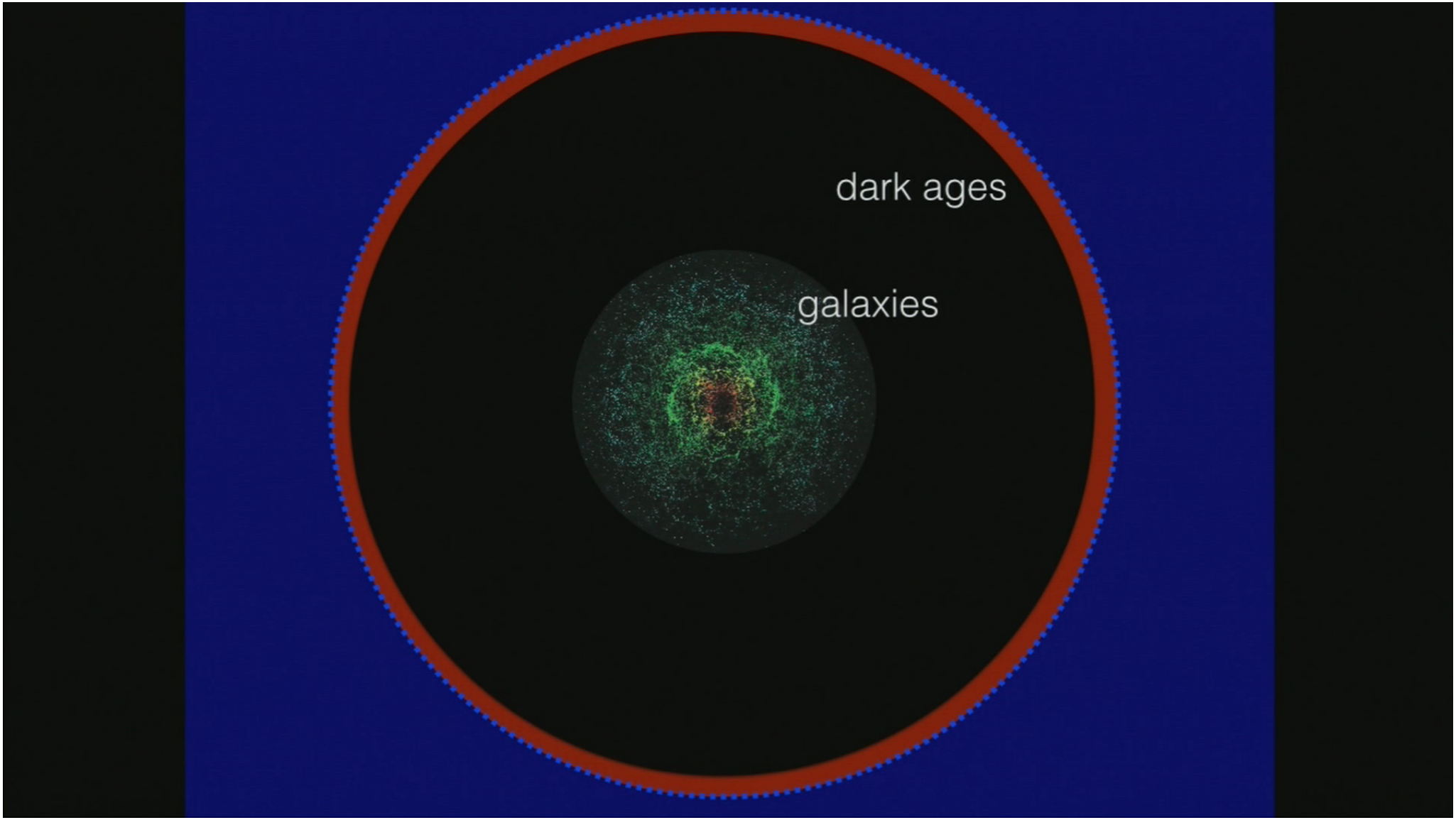


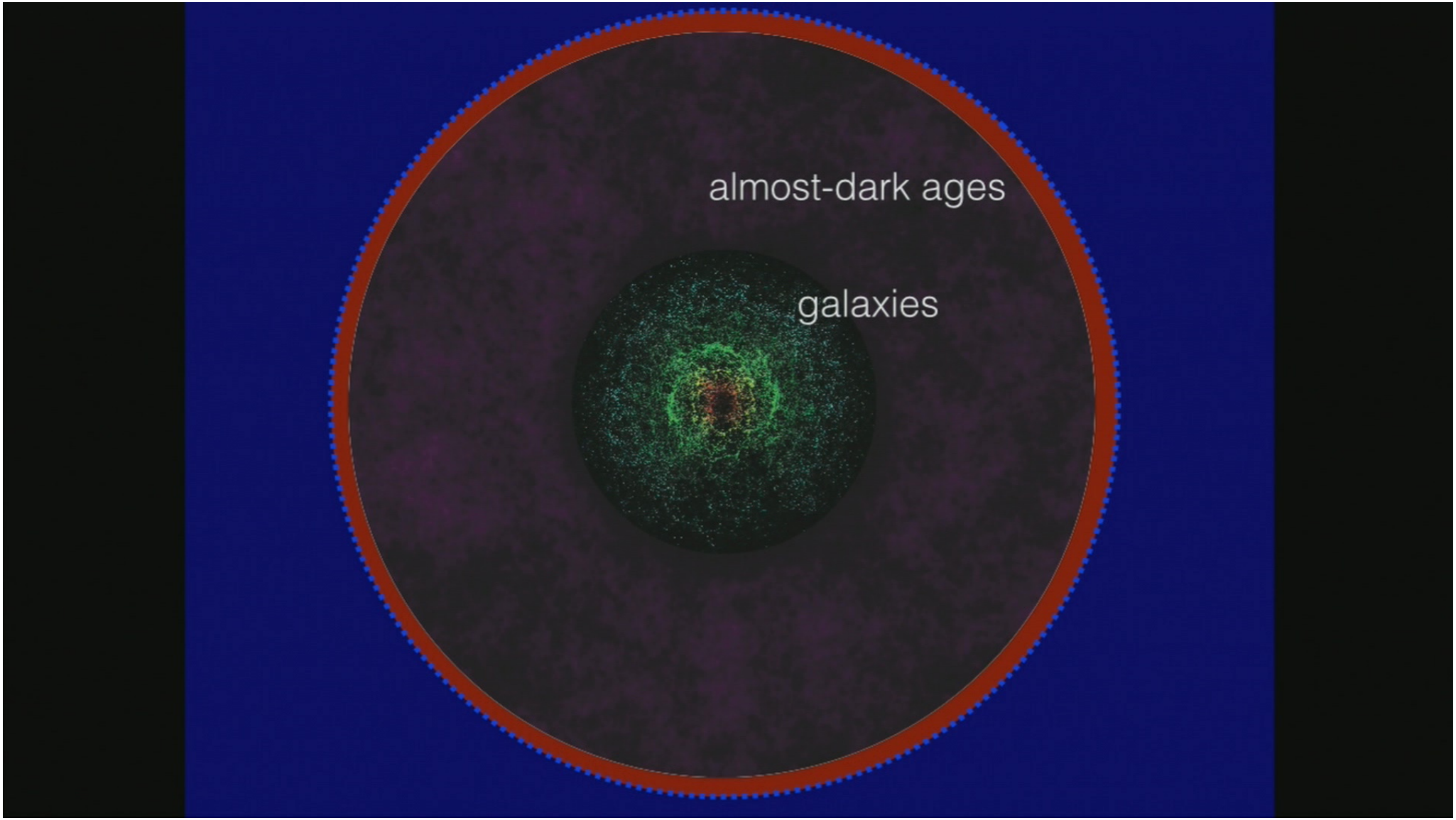
Maybe! (May 2014)

Have gravitational waves from inflation been detected?

No! (January 30, 2015)


Antec
1000
McGill
Cosmology


dark ages
galaxies


almost-dark ages
galaxies

“State of the universe”

We live in an expanding universe full of strange stuff!

We do not live in a special place in space, but we do live in a special place in time, midway between the big bang and dark energy dominated expansion

“State of the universe”

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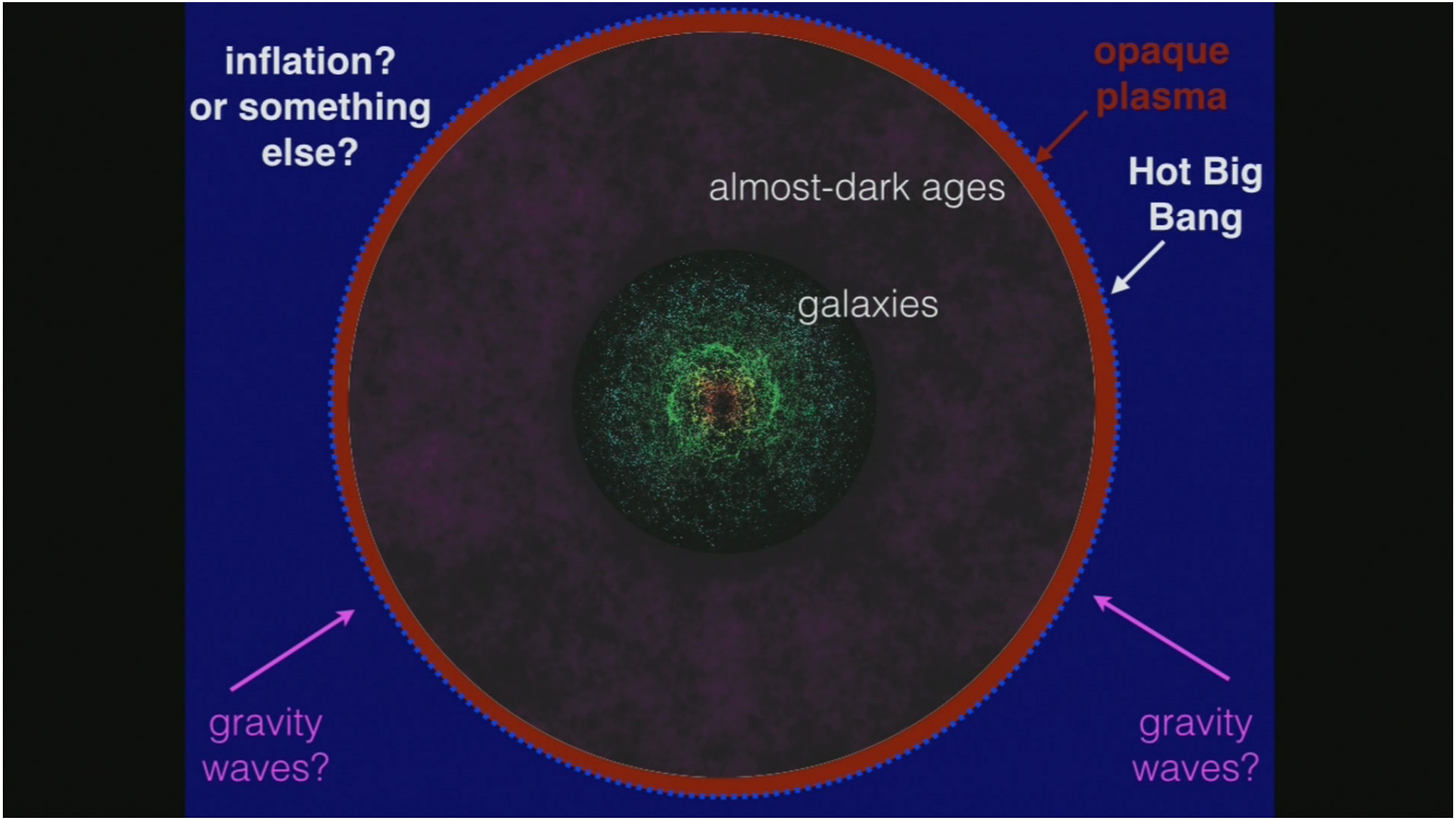
We have a simple working model which explains our observations, but the model has surprising ingredients whose fundamental nature we do not understand (dark matter, dark energy, hints of a quantum mechanical universe before the hot big bang)


inflation?
or something
else?
opaque
plasma
Hot Big
Bang
almost-dark ages
galaxies
gravity
waves?
gravity
waves?