The new cosmology

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Flammarion 1888: tete des etoiles

University of Durham

The science of the Universe

Modern cosmology is based on:

The laws of Physics: general rules about natural phenomena, derived empirically and expressed mathematically, e.g. Newton's law of gravitation, Boyle's gas law, quantum mechanics, relativity

- Experimentally verified on Earth
- Universal (?)

The building blocks of the Universe

Galaxies are collections of up to a hundred billion stars

Virtual Voyage:
Milky Way to the Virgo Cluster

HDTV Visual Excerpt from "Runaway Universe"

Courtesy NOVA/WGBH, PBS

Tom Lucas Productions

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Pan-STARRS

2008-2015

The Panoramic Survey Telescope and Rapid Response System

ICC participation sponsored by Ogden Trust,
→ leveraged 10x more funding from European & UK Research Councils, Durham Univ,

Pan-STARRS
PS1 Science Consortium

Hawaii, Harvard, John's Hopkins, Max Planck (Heidelberg, Munich), UK (Durham, Edinburgh, Belfast)

- 2.1m telescope in Hawaii (paid by USAF)
- Largest ever ccd camera (1.4 Gigapixels)
- Survey the entire sky in 5 wavelengths

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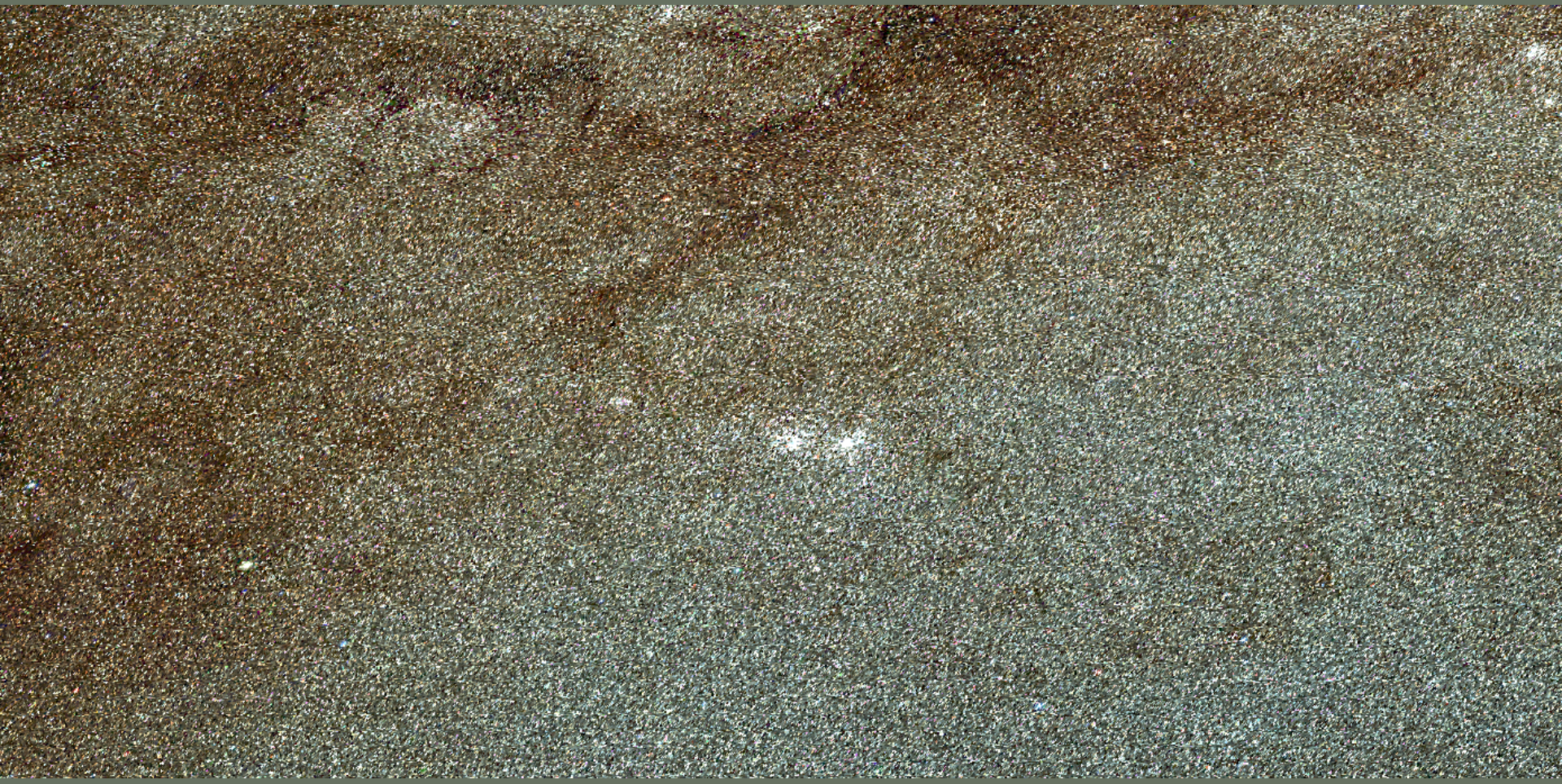
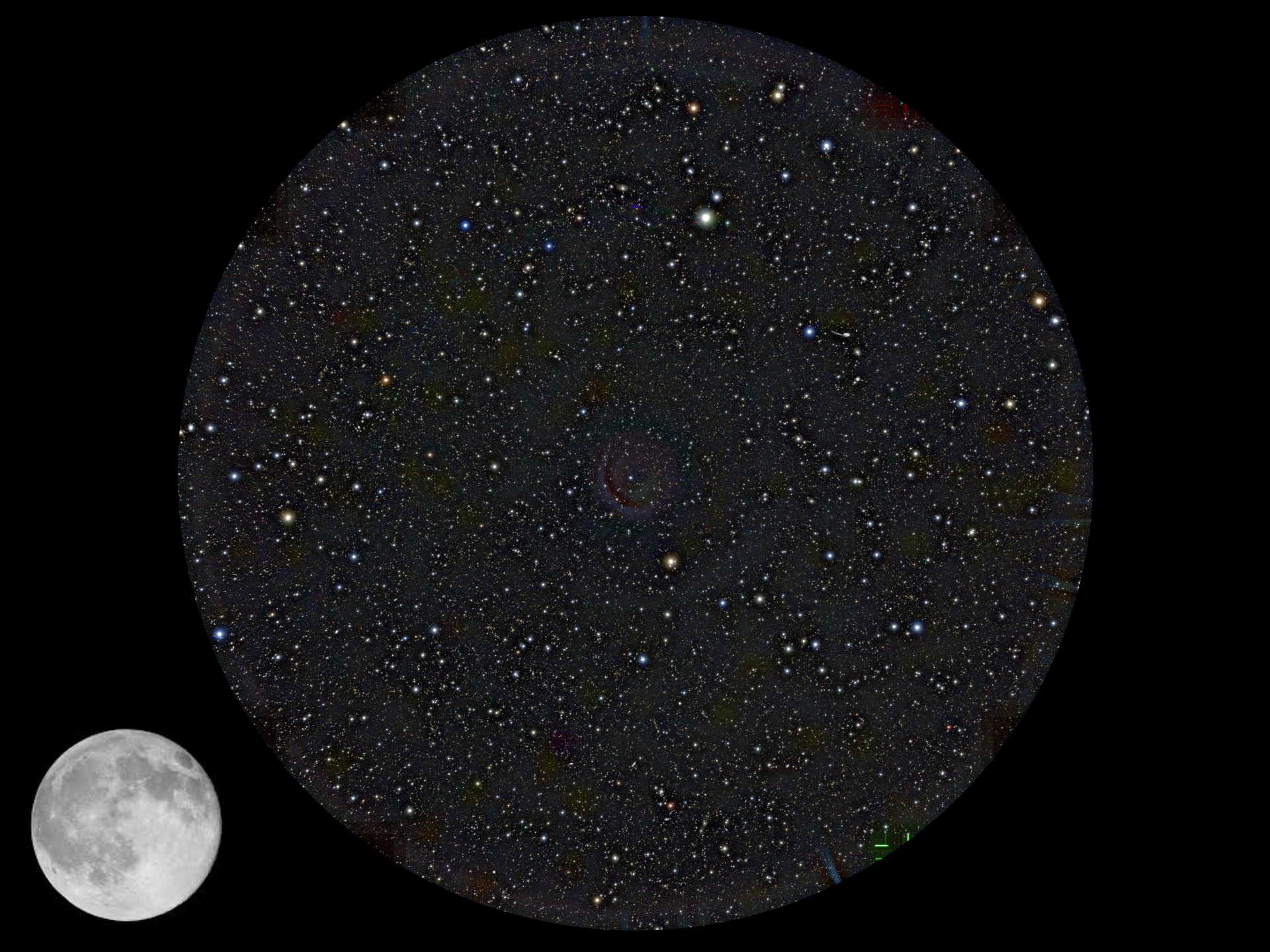
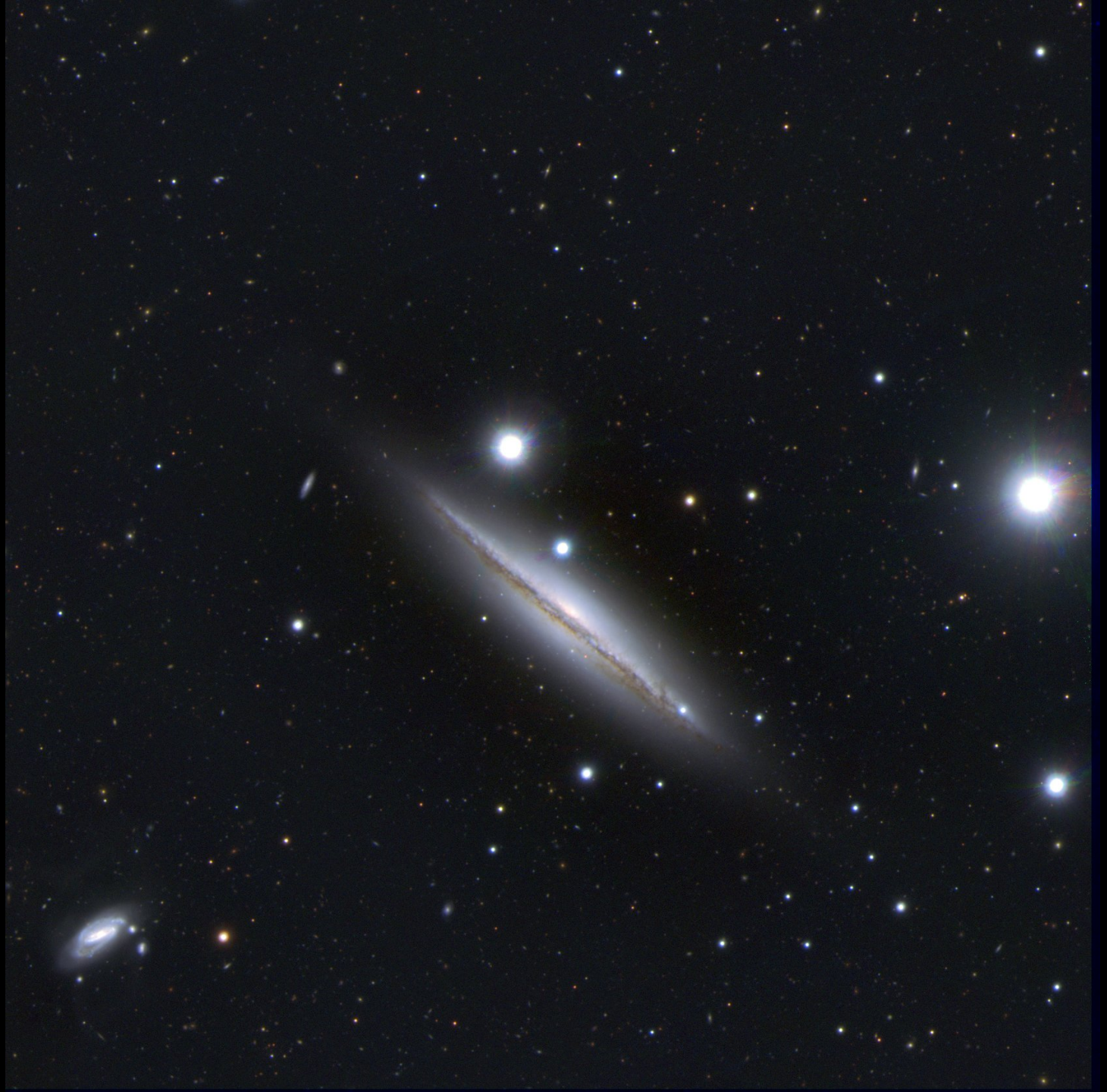


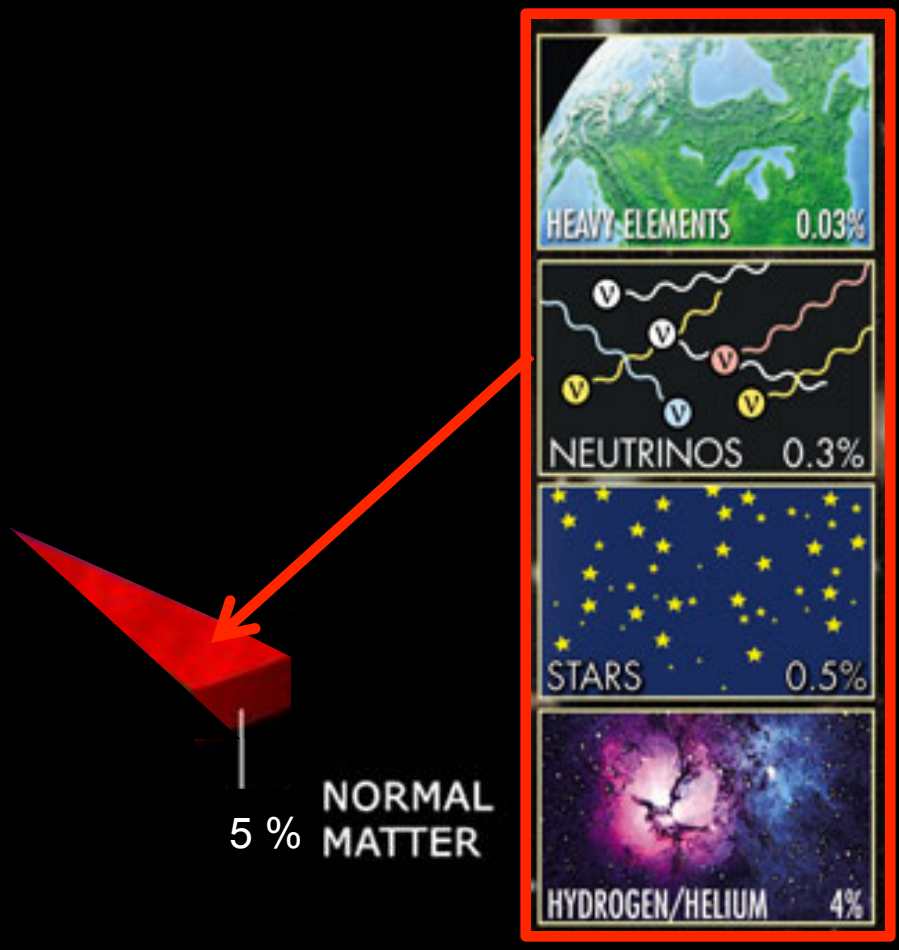
Institute for Computational Cosmology





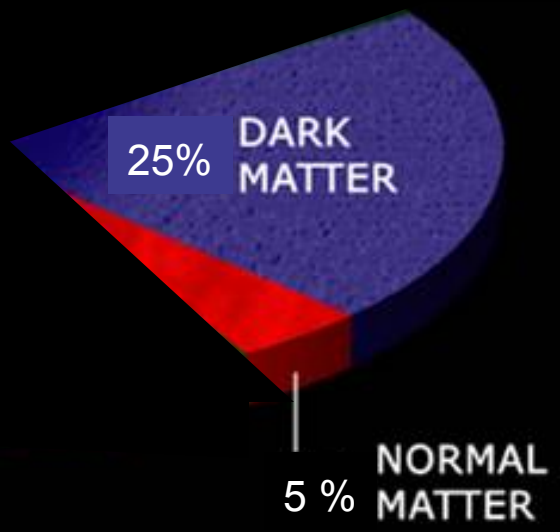
The content of the Universe

The content of our universe



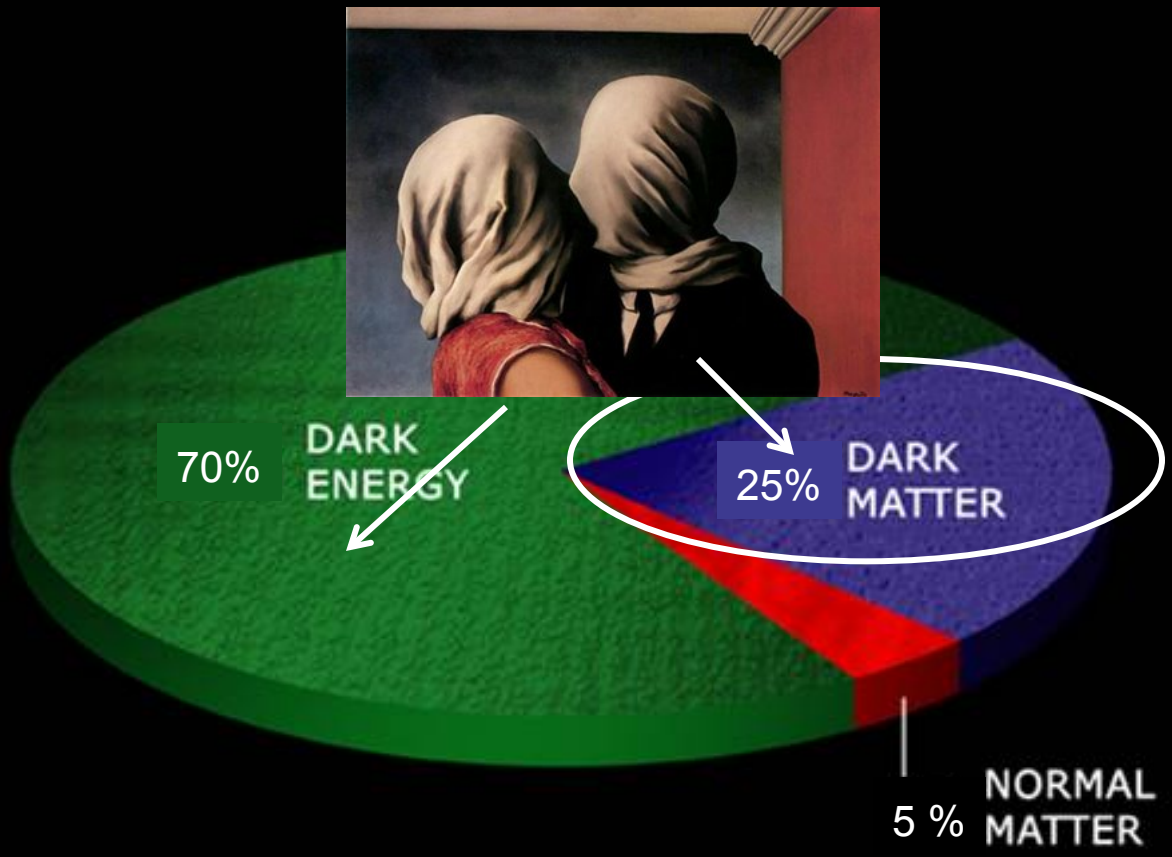
Normal matter ≡ matter made of ordinary atoms

The content of our universe



Dark matter ≡ matter that does not emit light at any wavelength

The content of our universe



Dark energy ≡ mysterious form of energy which opposes gravity

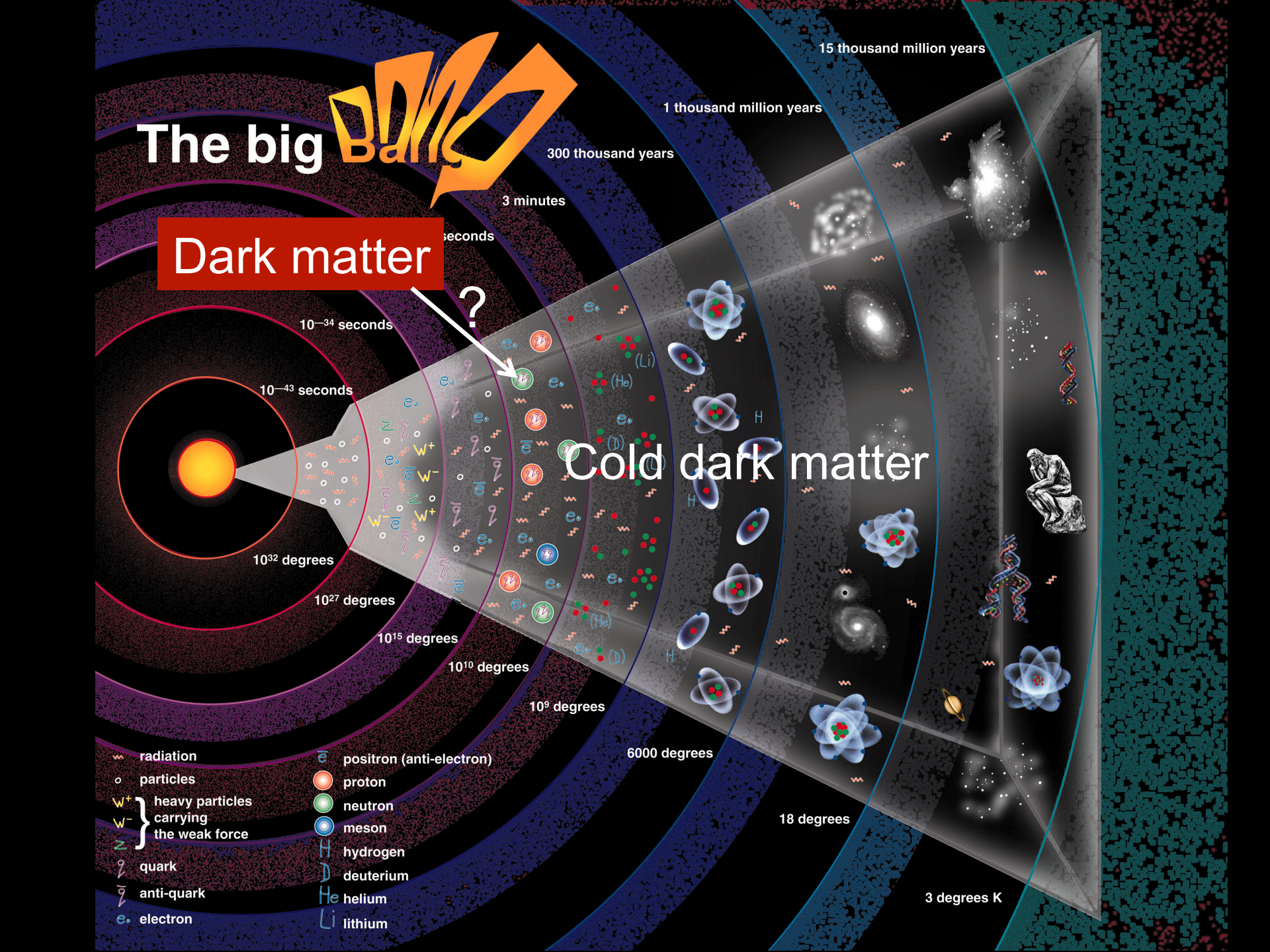
Stars rotate too fast to be held in place by gravity of visible mass

$$V^2 = \frac{GM}{r}$$

Clumps of dark matter: dark halos

→ dark matter keeps galaxy in place

What is the dark matter?


The big Bang
Dark matter
?
Cold dark matter
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

What is the dark matter?

The search for dark matter

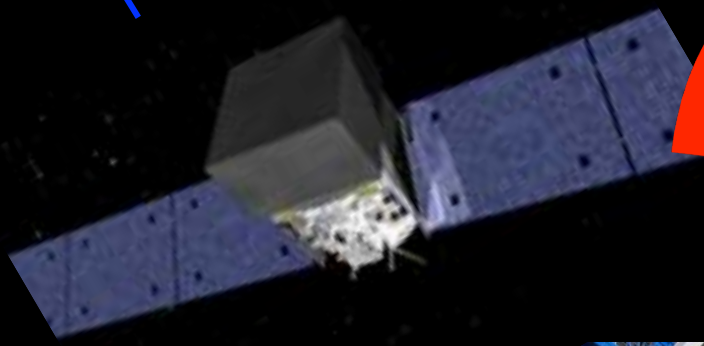
Experimental physics

An experimental physicist

Cold dark matter ?

Dark matter discovery possible in several ways

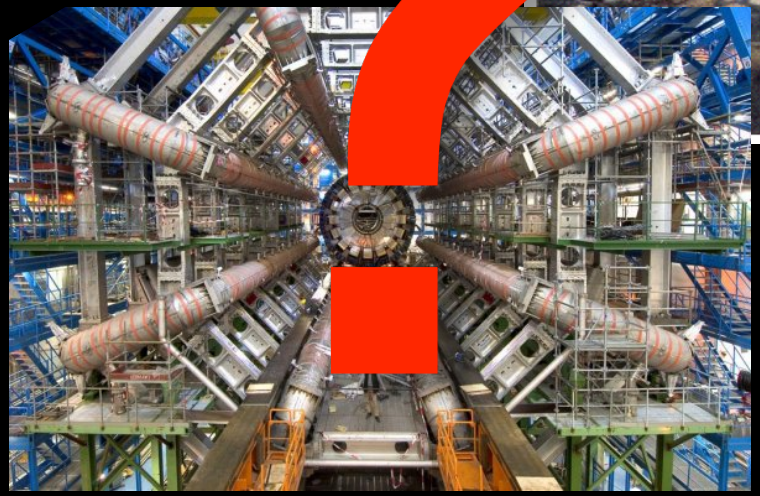
Fermi



Annihilation radiation

Direct detection

UK DM search
(Boulby mine)

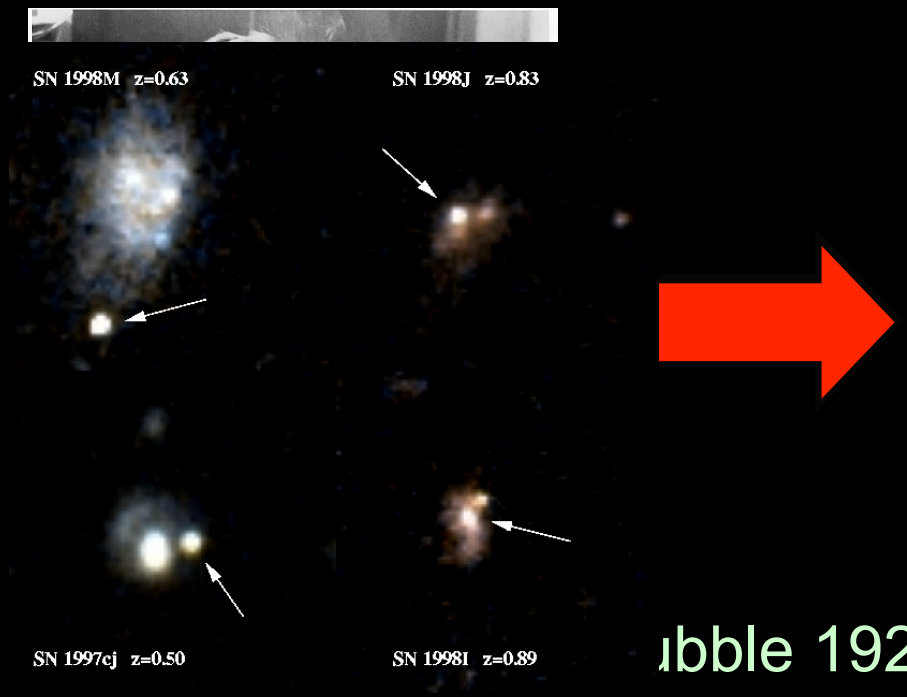


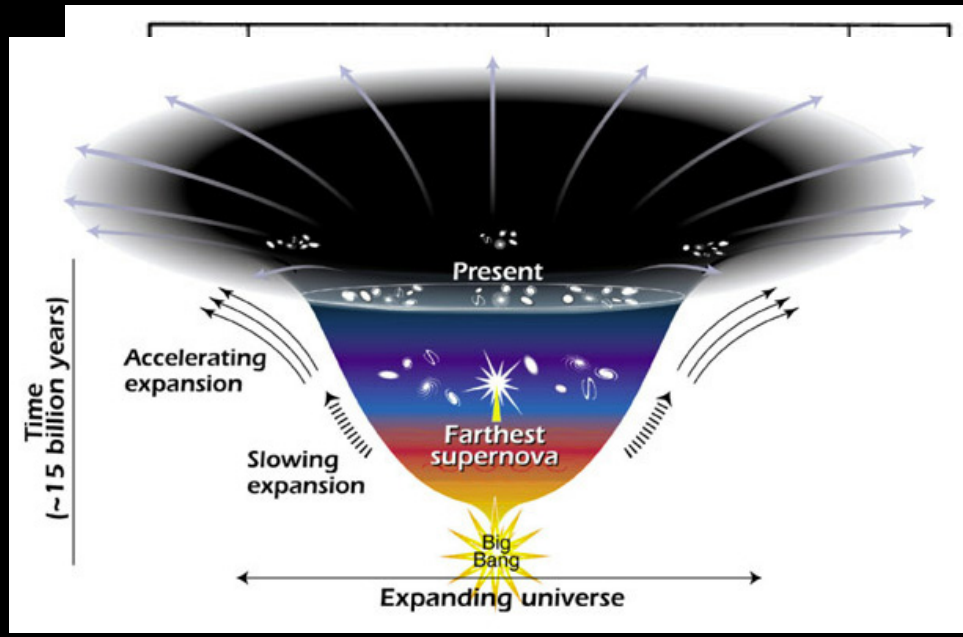
Evidence for SUSY

The content of our universe

Dark energy ≡ mysterious form of energy which opposes gravity

The cosmic expansion





ubble 1929: $v = H_0 d$

Expansion is ...erating

2011 Nobel prize in physics!

➔ Universe full of dark energy

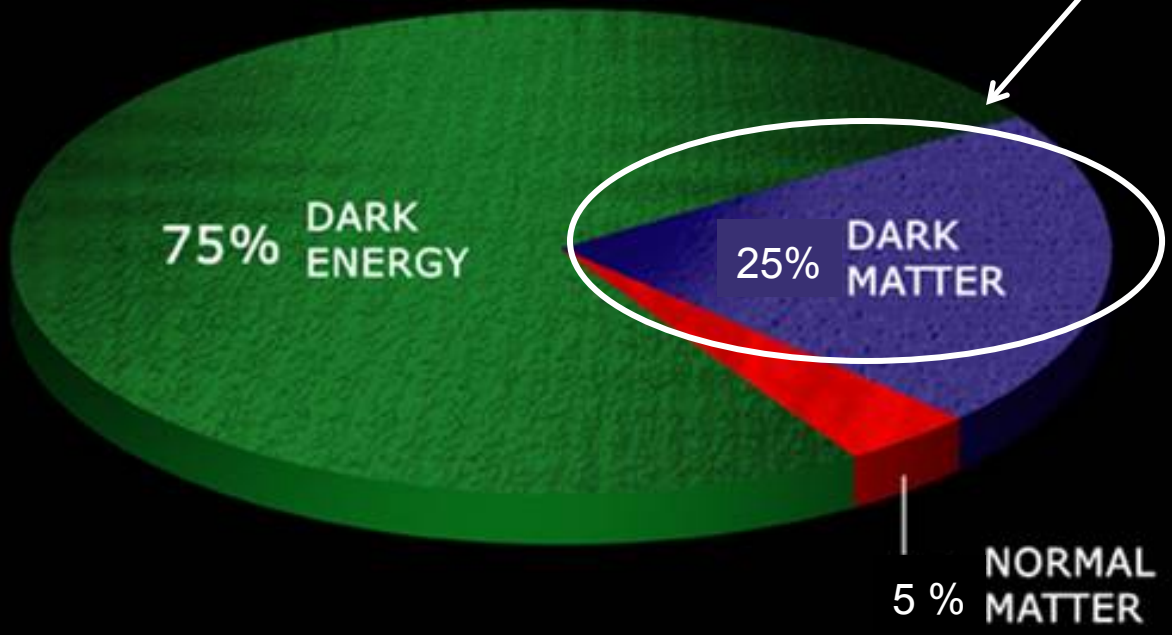
What is the cosmic dark energy?

A form of energy that produces a repulsive force, causing the universal expansion to accelerate

It is likely to be energy associated with empty space – the vacuum

The content of our universe

why is DM so important?



Dark matter ≡ matter that does not emit light at any wavelength

Where do the galaxies come from?

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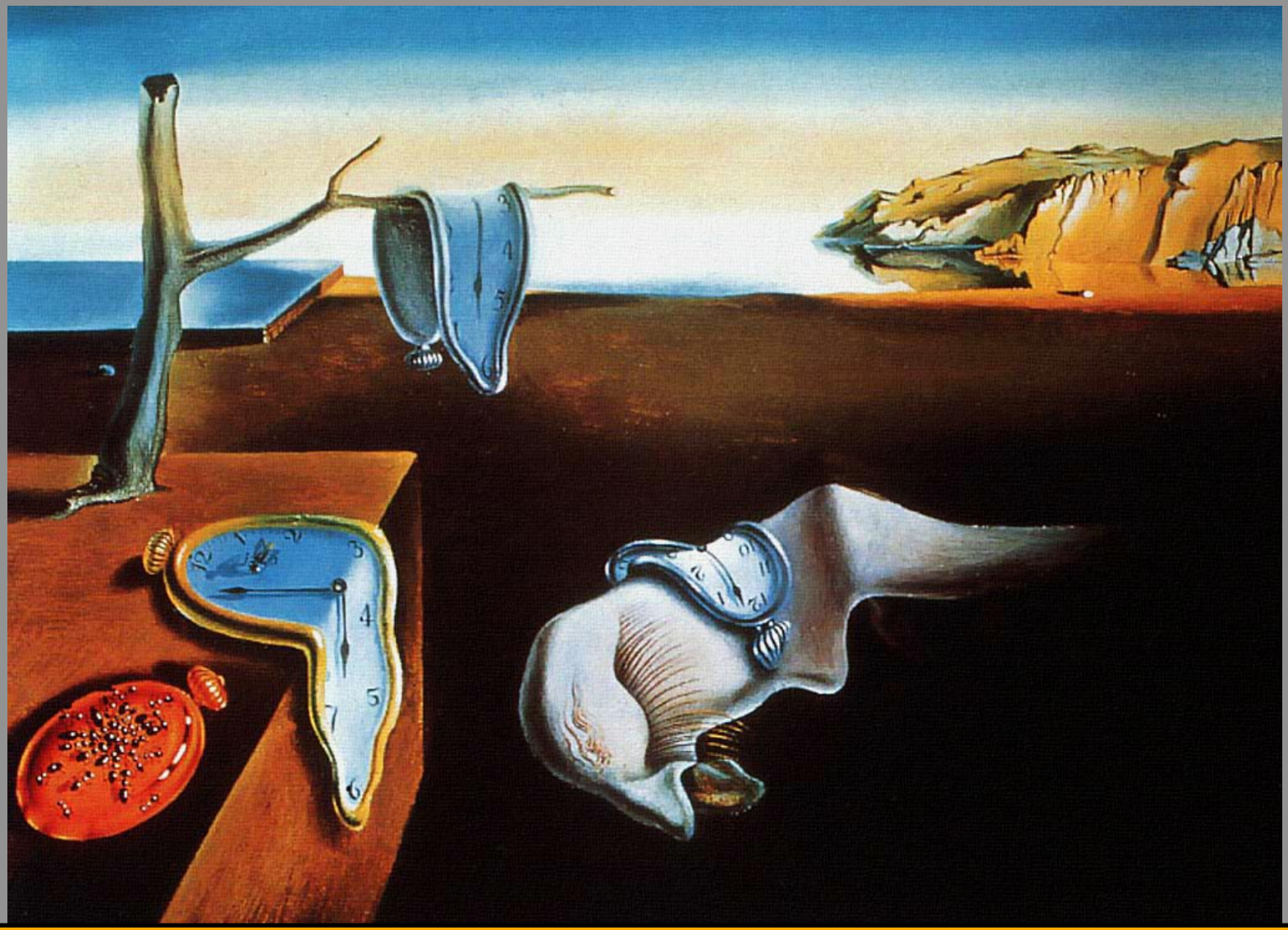
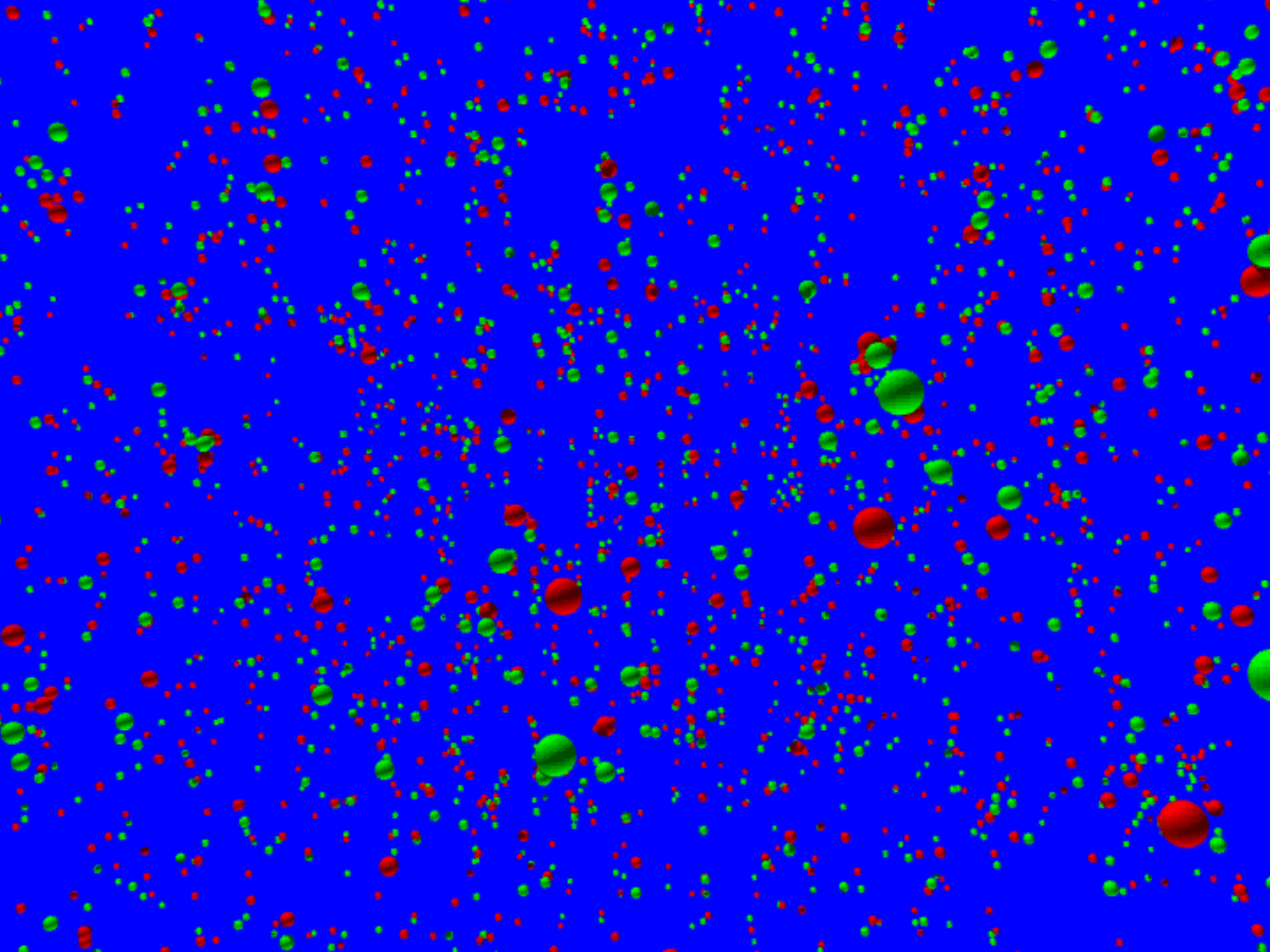
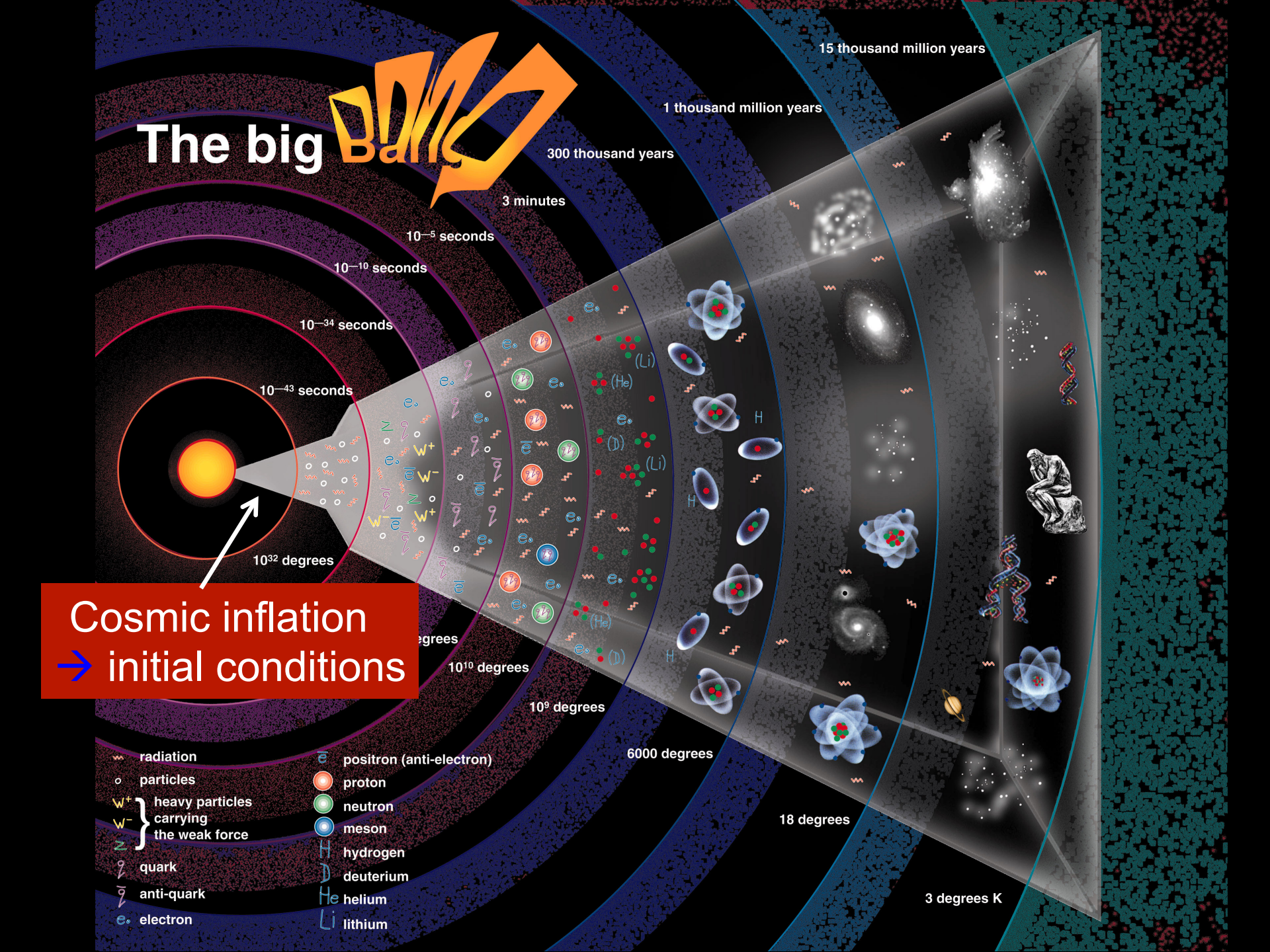
… to the beginning of time (almost)



t=0.00000000000000000000000000000001 seconds




The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10⁻⁵ seconds
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
Cosmic inflation
→ initial conditions
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

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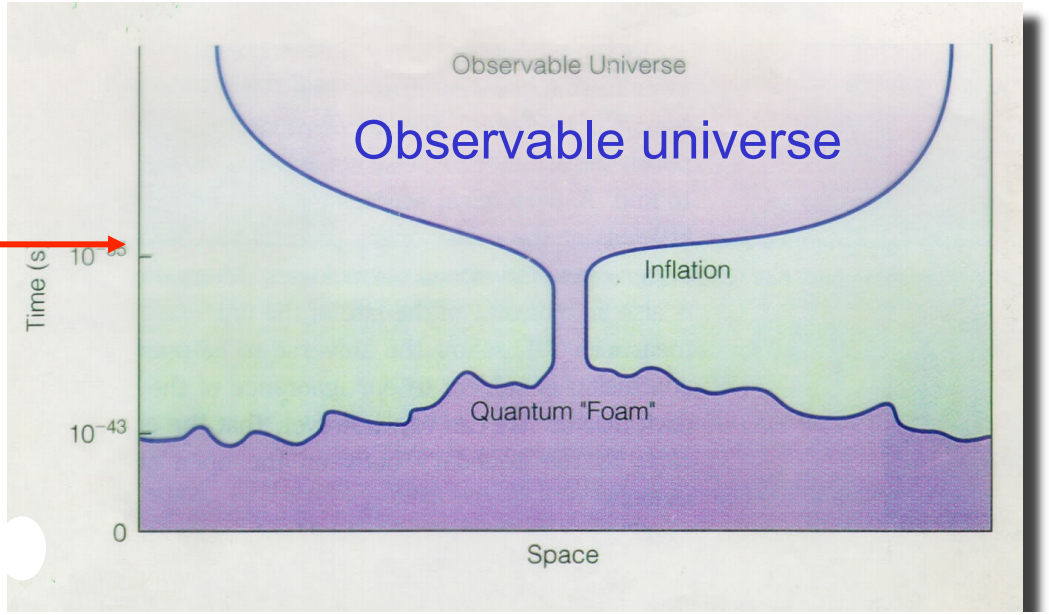
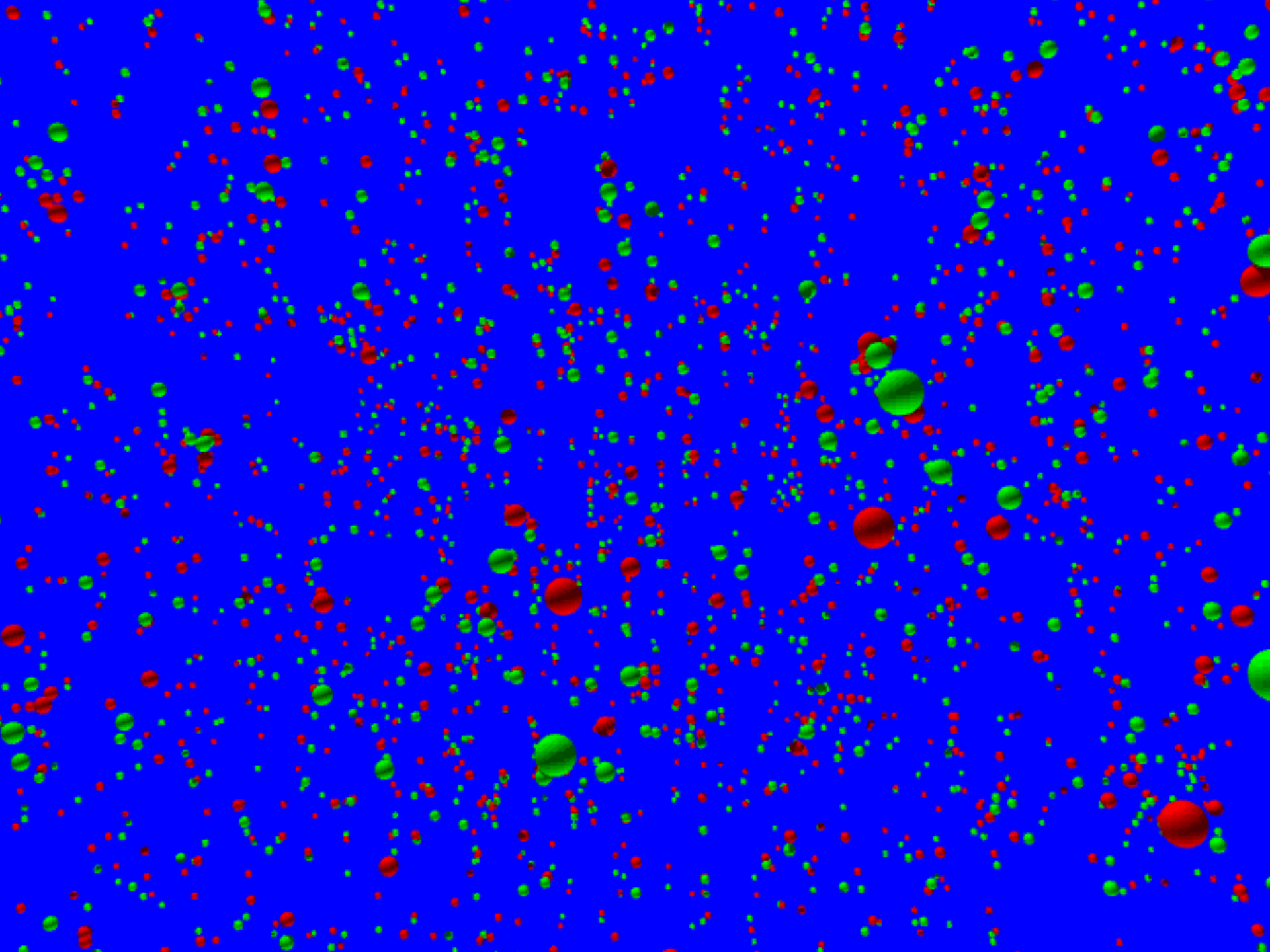
Cosmic Inflation

$t=10^{-35}$ s



> According to theory of cosmic inflation, our visible Universe is a small patch of a much larger region.



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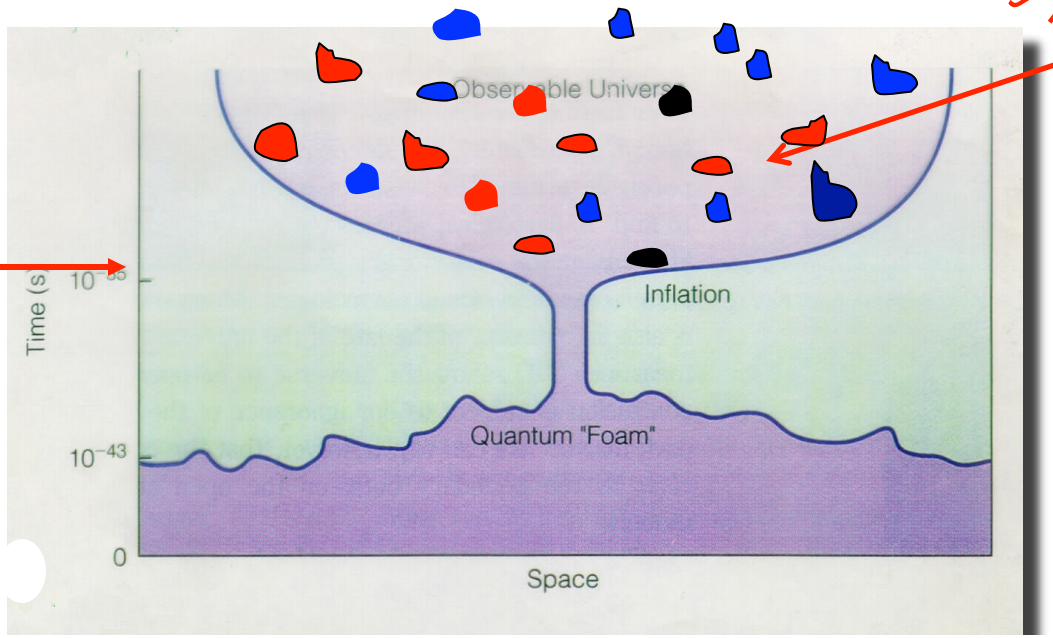
Cosmic Inflation

tiny mass irregularities

$t=10^{-35}$ s



Inflation theory predicts:

early universe seeded by tiny fluctuations in mass produced by quantum processes

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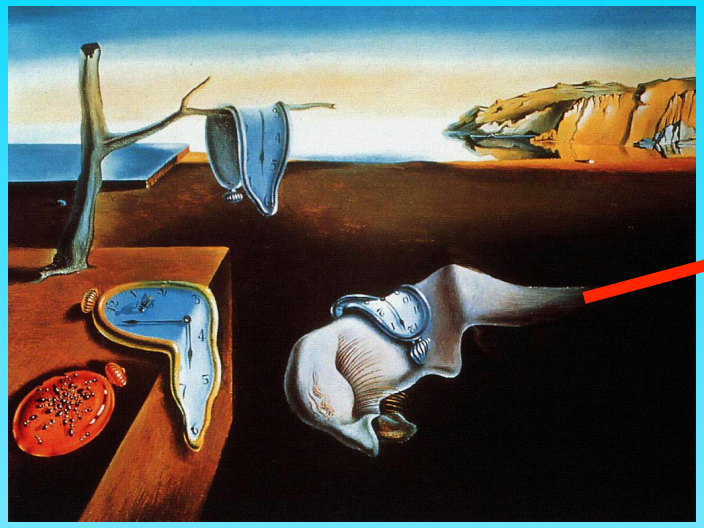
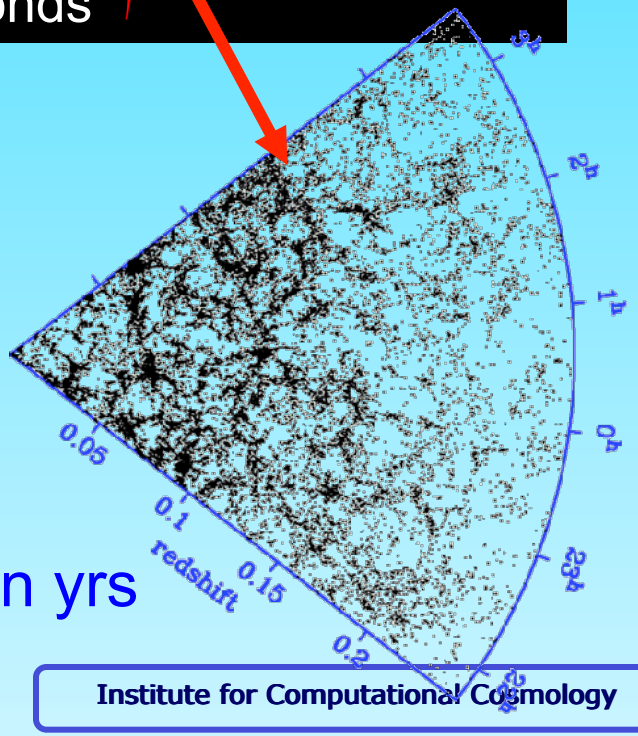
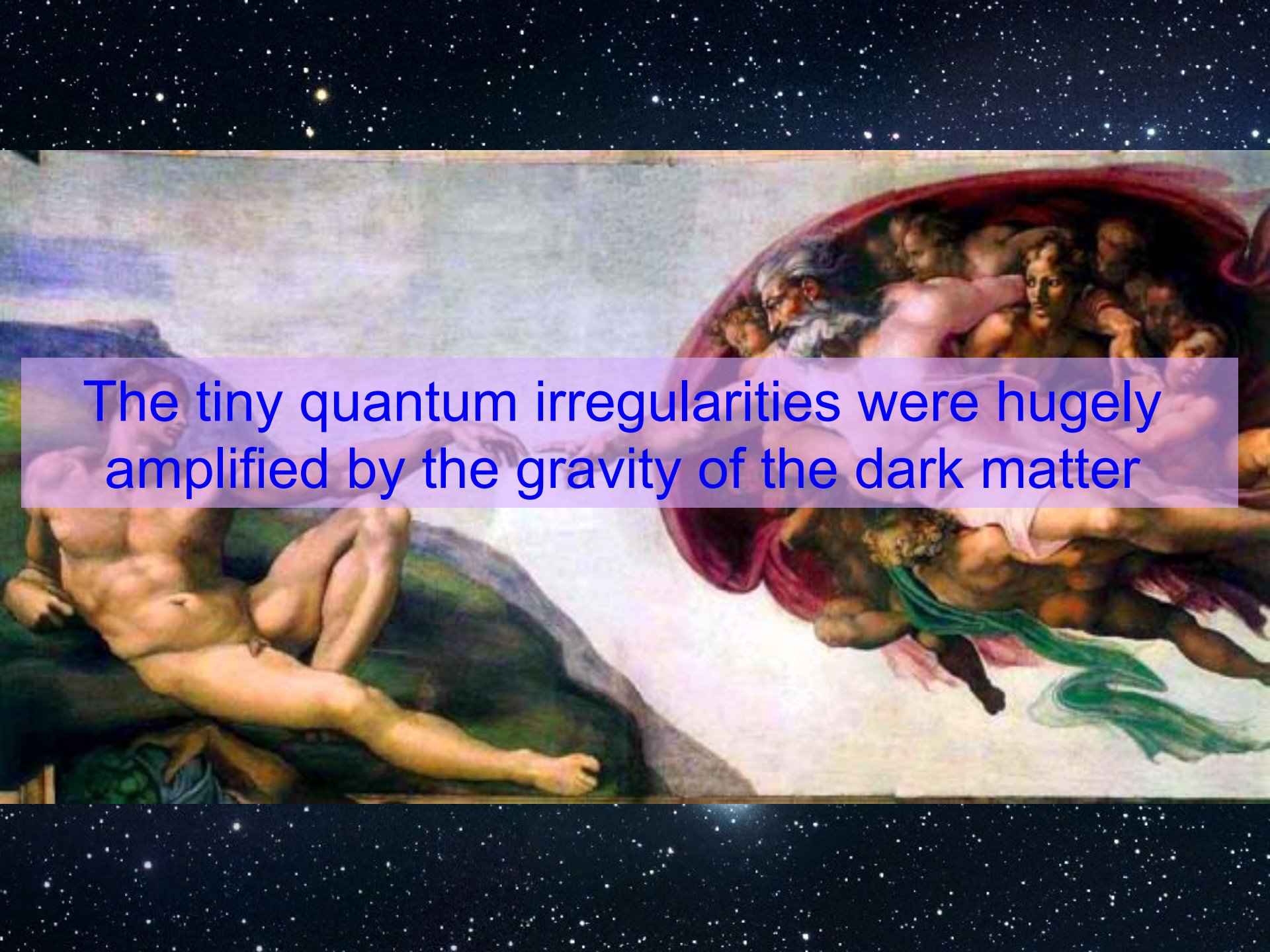
The growth of cosmic structure



According to inflation theory galaxies grew out of tiny, "quantum fluctuations"



t=13.8 billion yrs


The tiny quantum irregularities were hugely amplified by the gravity of the dark matter

Large Scale Structure

Computer simulation

Small irregularities in the early universe grow under the action of gravity:

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The science of the Universe

Modern cosmology is based on:

The laws of Physics: general rules about natural phenomena, derived empirically and expressed mathematically, e.g. Newton's law of gravitation, Boyle's gas law, quantum mechanics, relativity

- Experimentally verified on Earth
- Universal

To be Physics, it must be testable!

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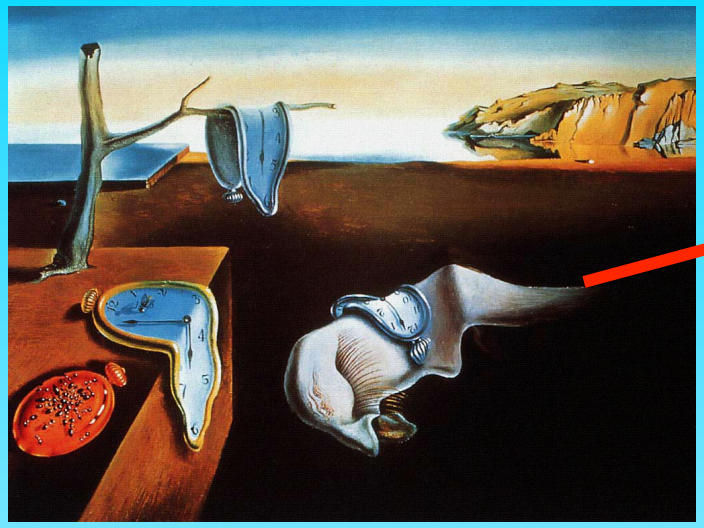
The growth of cosmic structure



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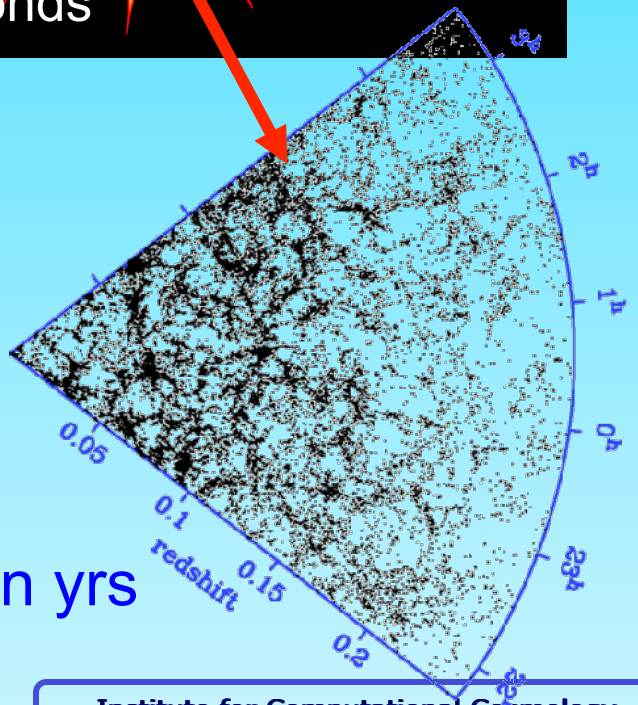

How do we test this?

t=13.8 billion yrs

Need to be able to look into the past!

Light travels at a finite speed (300,000 km/s) and brings us information about the distant past

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The first light

The early universe was very hot

The big Bang

15 thousand million years

350,000 yrs after BB
The cosmic microwave background is emitted

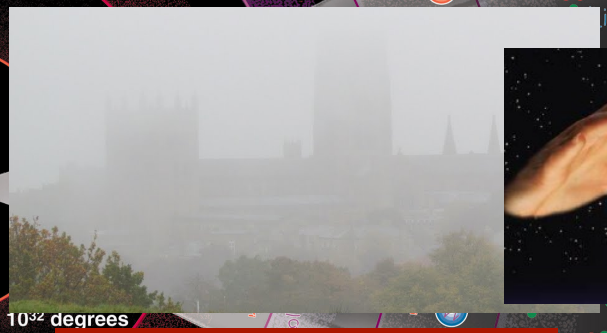
300 tho

3 minutes

10^{-5} seconds

10^{-10} seconds

10^{-34} seconds



10^{32} degrees

The early universe was foggy

10^{15} degrees

10^{9} degrees

6000 degrees

18 degrees

3 degrees K

- radiation
- particles
- W^+, W^-, Z heavy particles carrying the weak force
- q quark
- $\bar{q}$ anti-quark
- e^- electron
- $\bar{e}$ positron (anti-electron)
- proton
- neutron
- meson
- H hydrogen
- D deuterium
- He helium
- Li lithium

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The echo of the Big Bang

Everywhere we look in the Universe we should feel the heat left over from the Big Bang.

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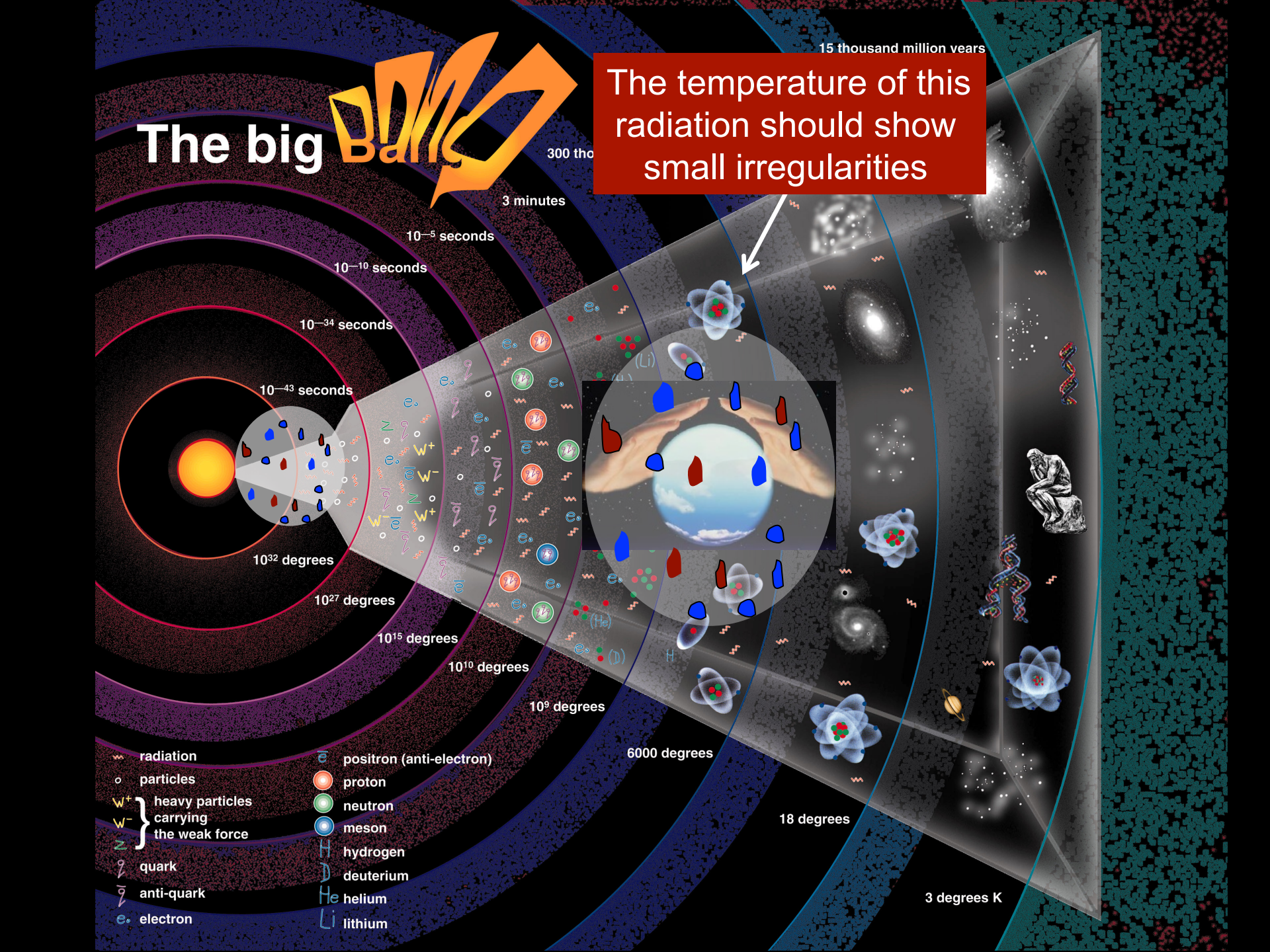
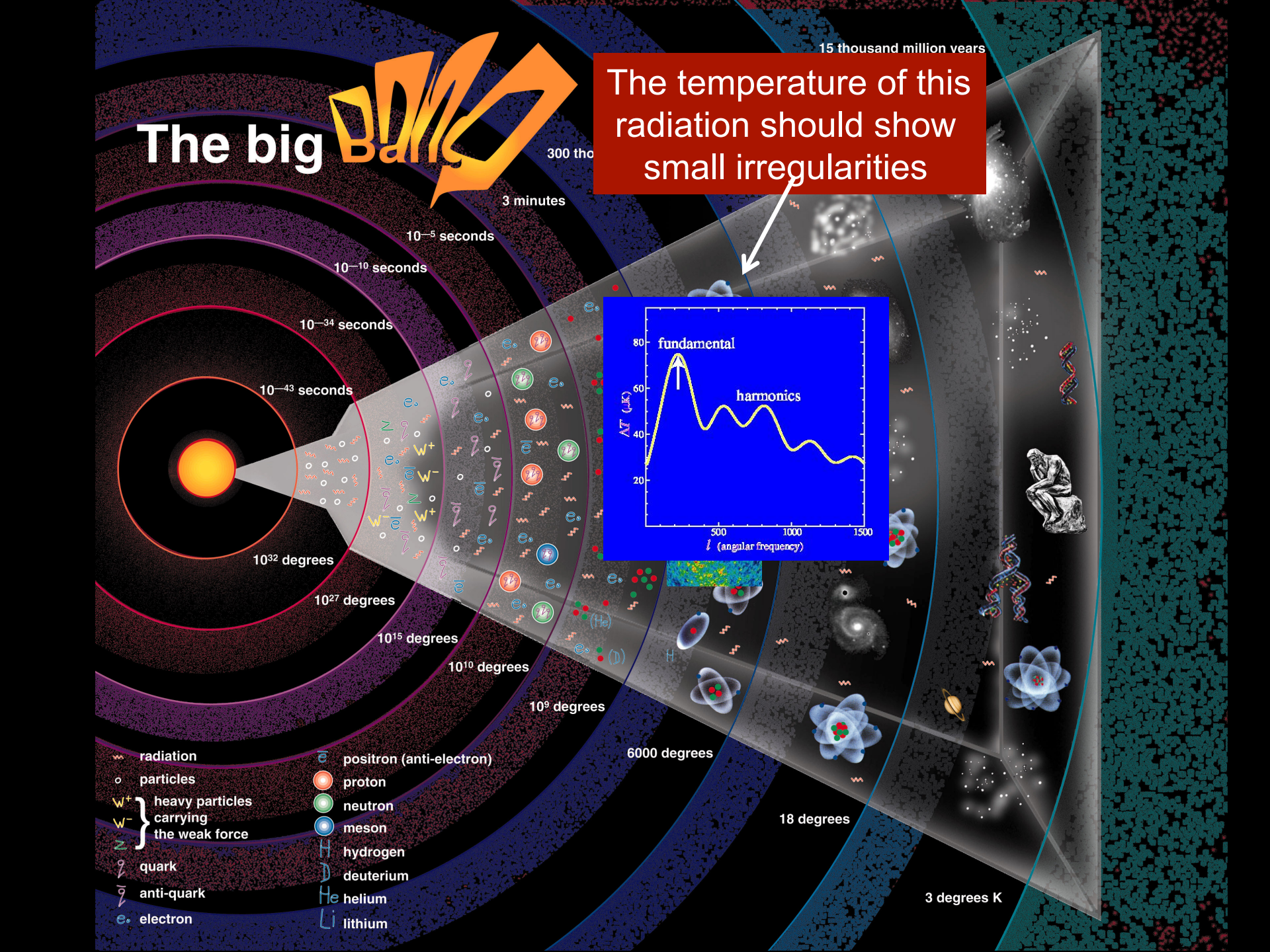
The echo of the Big Bang

In 1964, Arno Penzias & Bob Wilson were carrying out experiments using a microwave antenna for satellite communications.

As they pointed the antenna towards the sky, their receiver registered a faint ‘hiss’ coming from all directions that would not go away.

1978 Nobel Prize in Physics


The big Bang
The temperature of this radiation should show small irregularities
15 thousand million years
300 tho
3 minutes
10⁻⁵ seconds
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium


The big Bang
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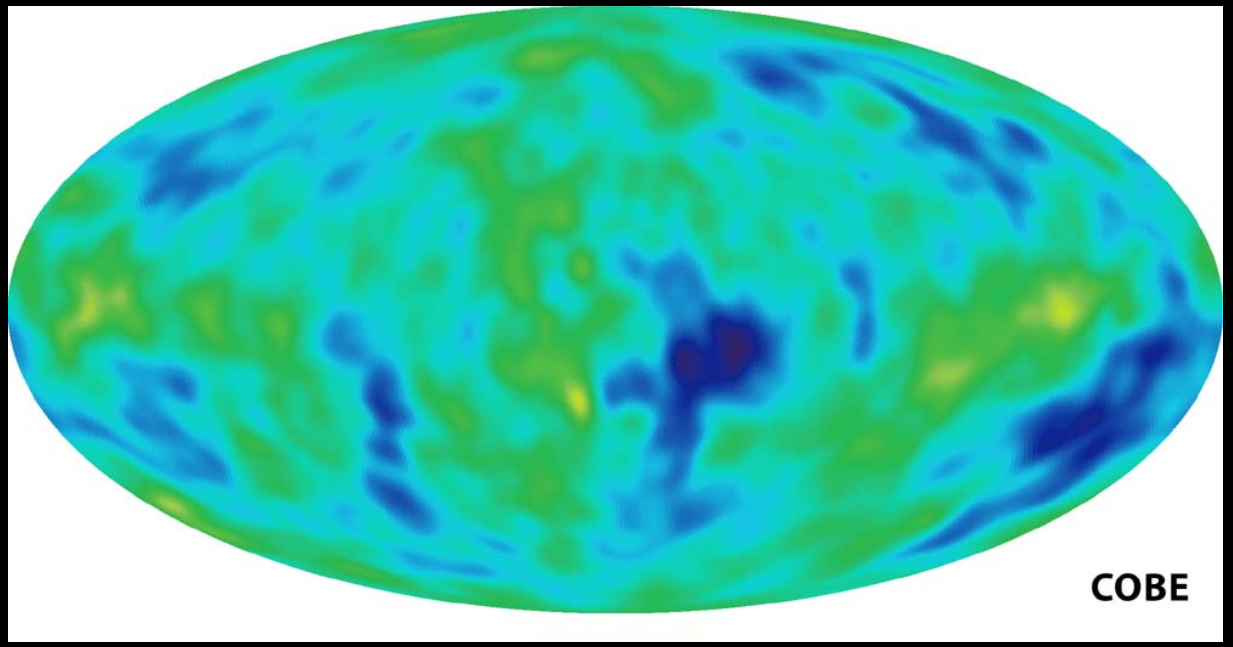
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
fundamental
harmonics
ΔT (μK)
80
60
40
20
500
1000
1500
l (angular frequency)
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

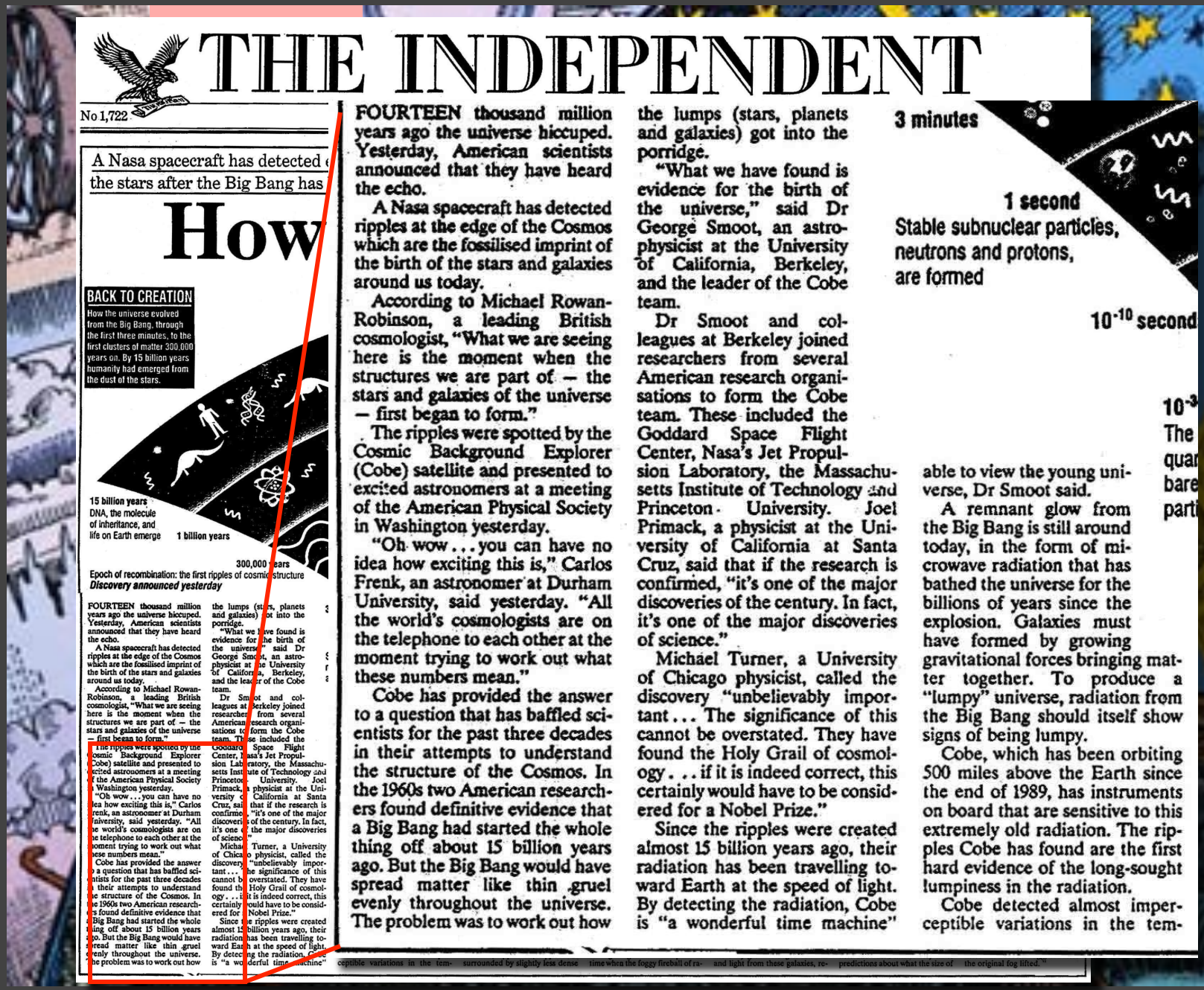
The CMB

1992



The cosmic microwave background radiation (CMB) provides a window to the universe at $t \sim 3 \times 10^5$ yrs

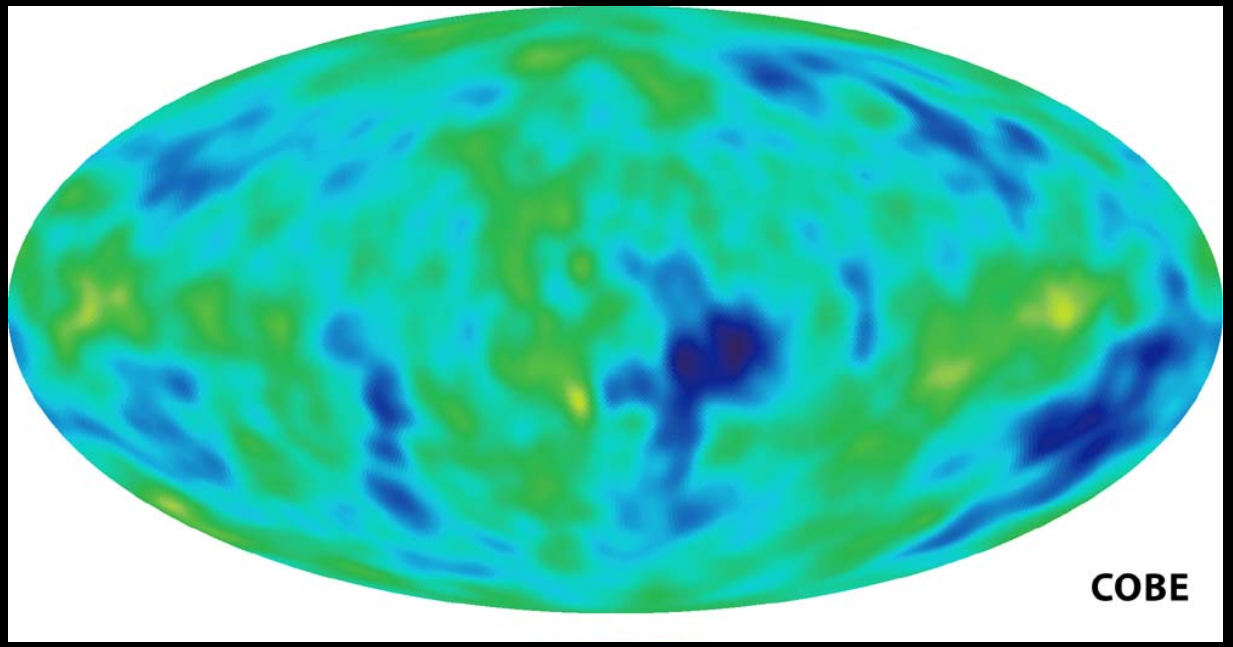
In 1992 COBE discovered temperature fluctuations ($\Delta T/T \sim 10^{-5}$) consistent with inflation predictions



Flammarion 1888: tete des etoiles

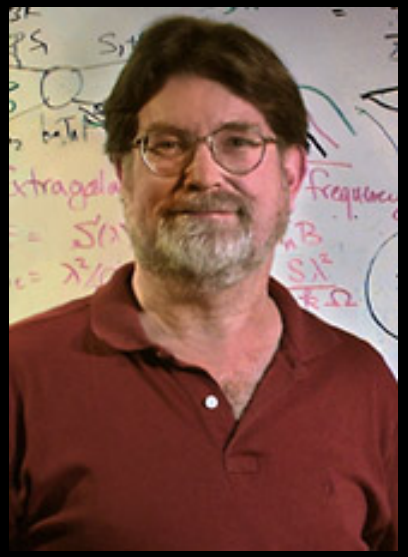
The CMB

1992



George Smoot - Nobel Prize 2006

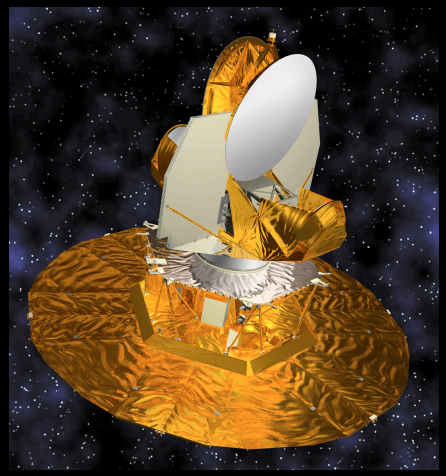
KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

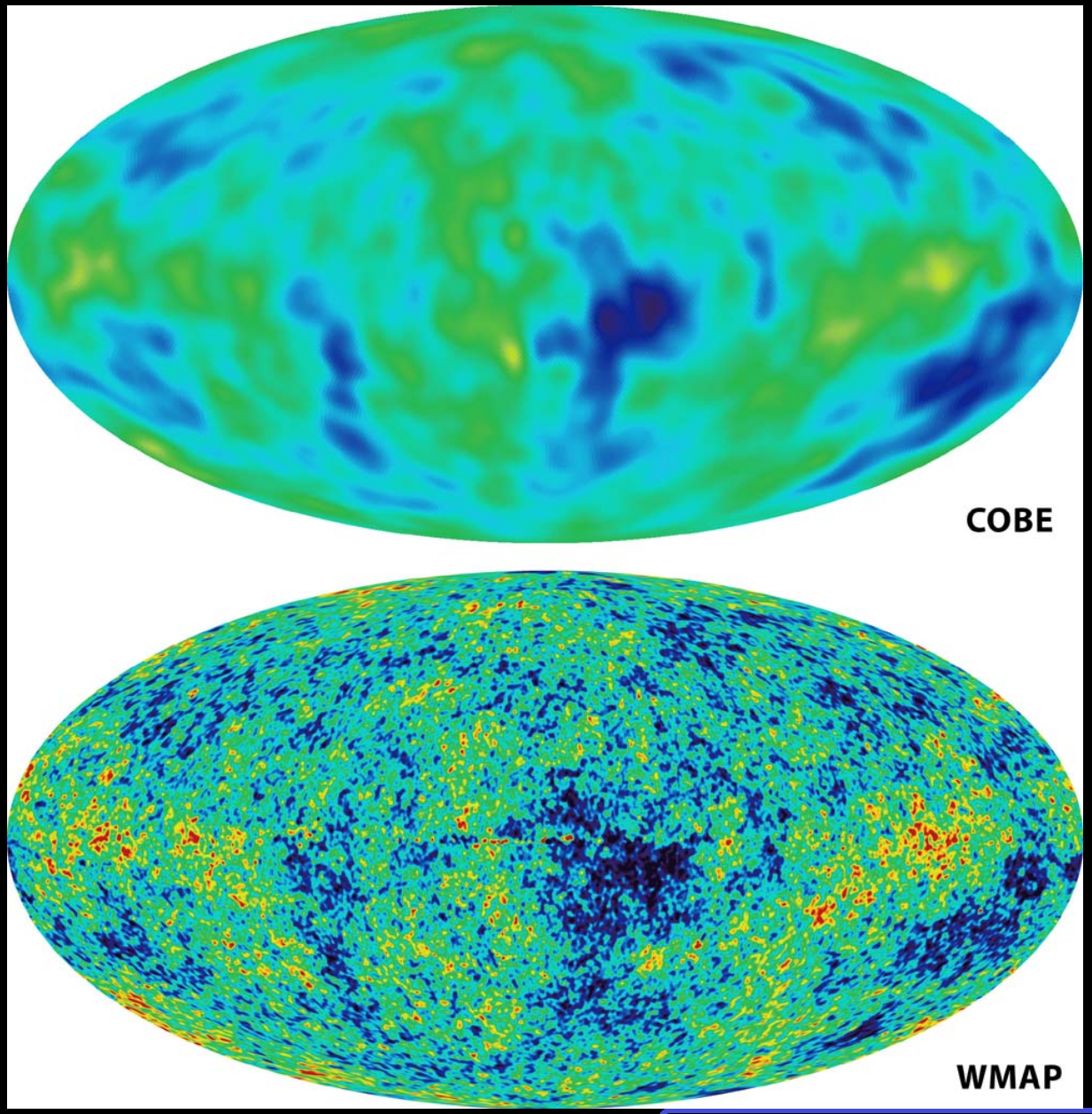


The CMB

1992

2003

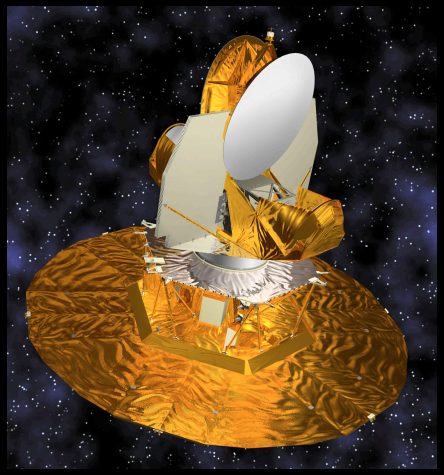


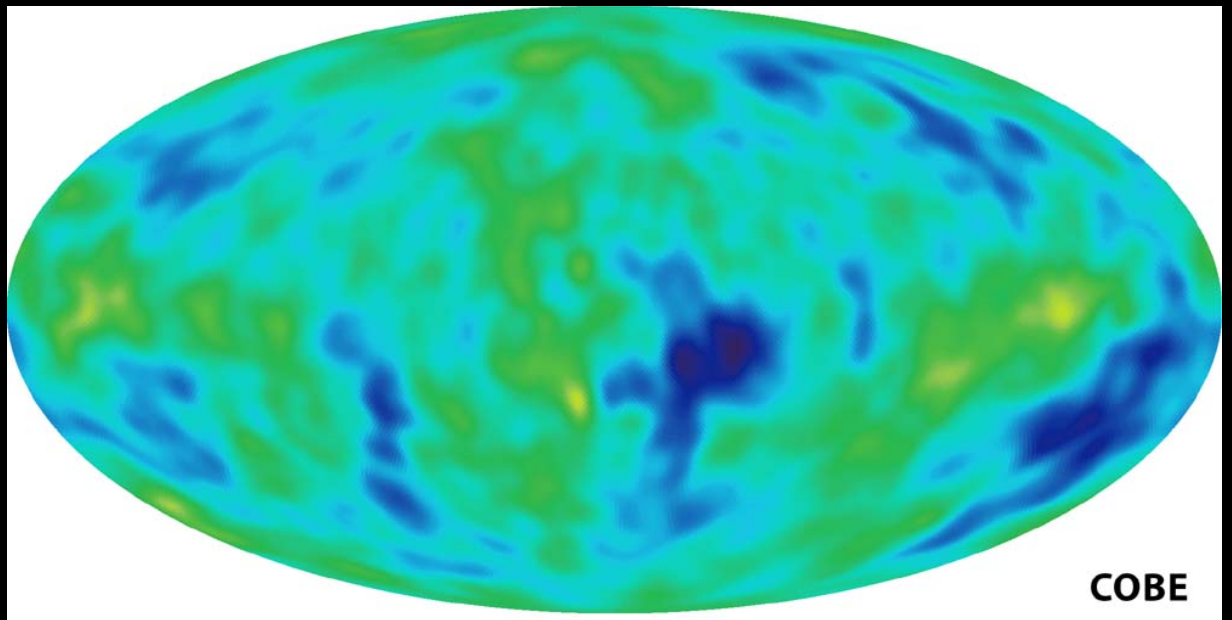


The CMB

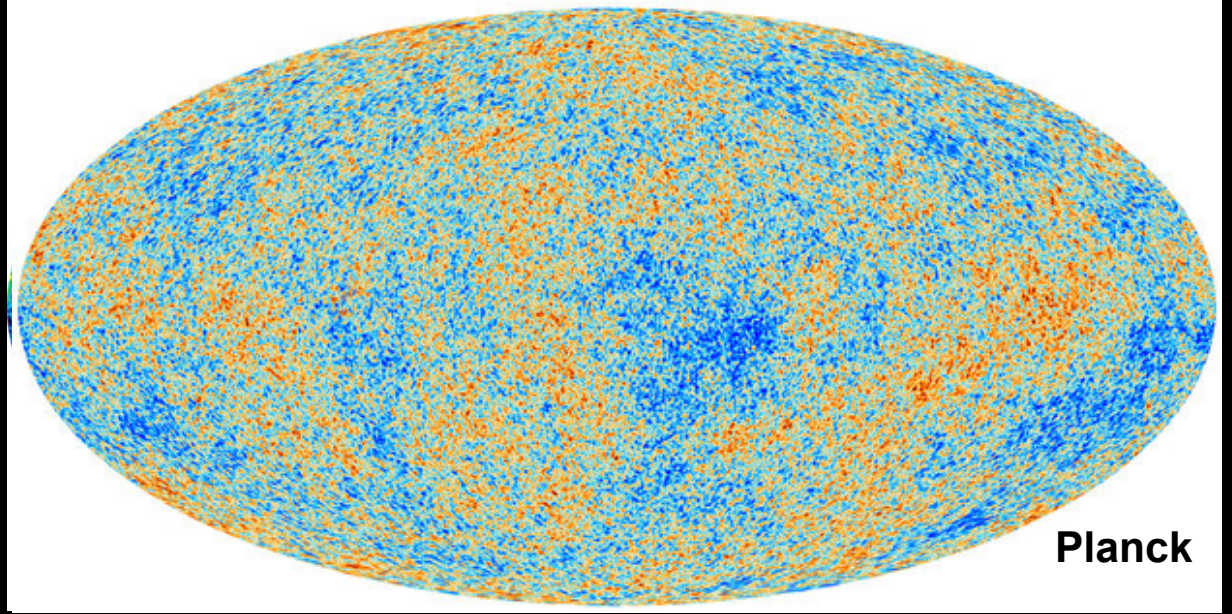
1992

2012





COBE



Planck

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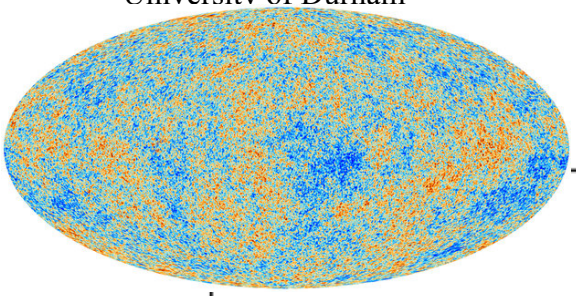
Planck: CMB temperature anisotropies



Planck coll. 2015

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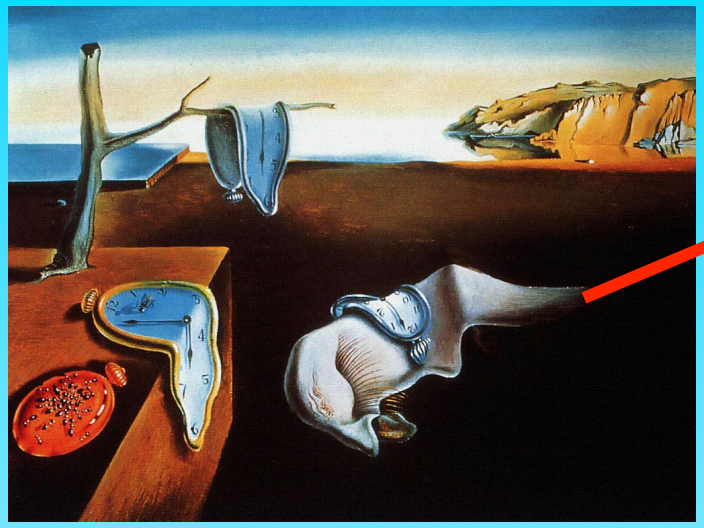
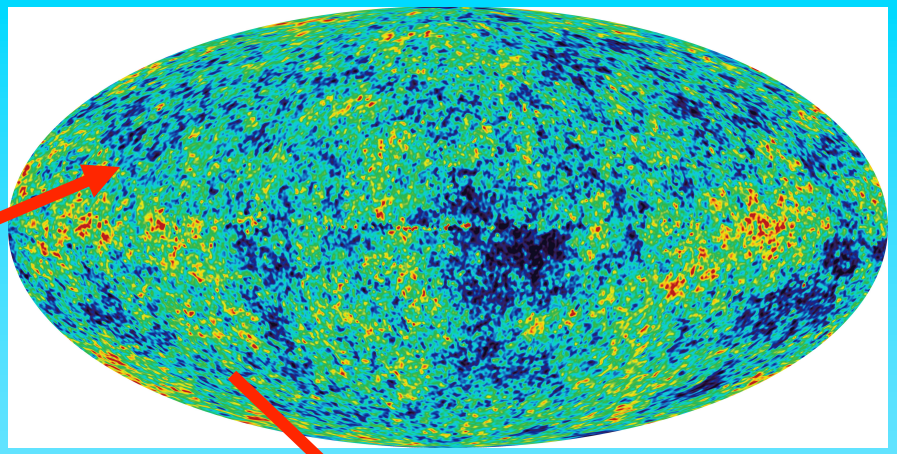
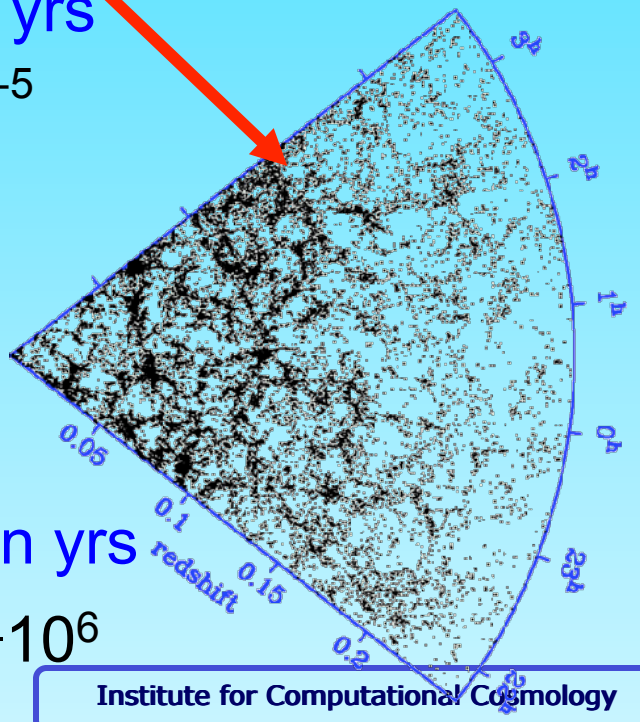
The growth of cosmic structure





t=380,000 yrs

$\delta\rho/\rho \sim 10^{-5}$



t=13.8 billion yrs

$\delta\rho/\rho \sim 1\text{–}10^{6}$

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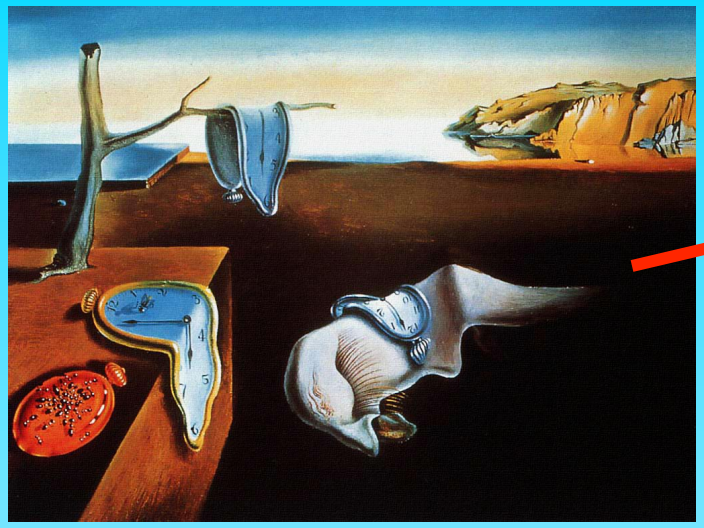
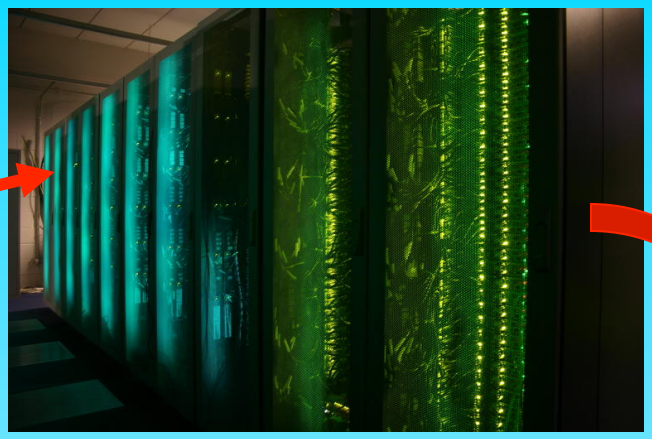
Testing the cold dark matter paradigm

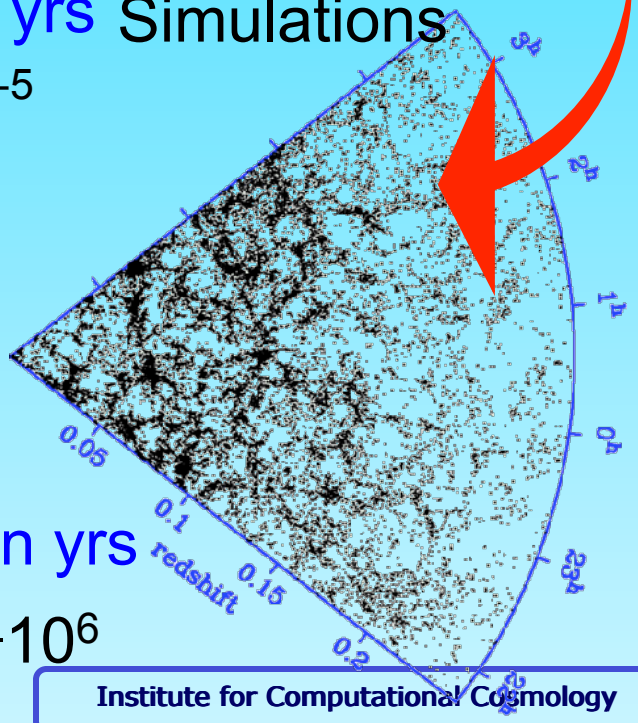


"Cosmology machine"



t=380,000 yrs Simulations

$\delta\rho/\rho \sim 10^{-5}$



Supercomputer simulations use the laws of physics to calculate how small primordial perturbations grow into galaxies today

t=13.8 billion yrs

$\delta\rho/\rho \sim 1-10^{6}$

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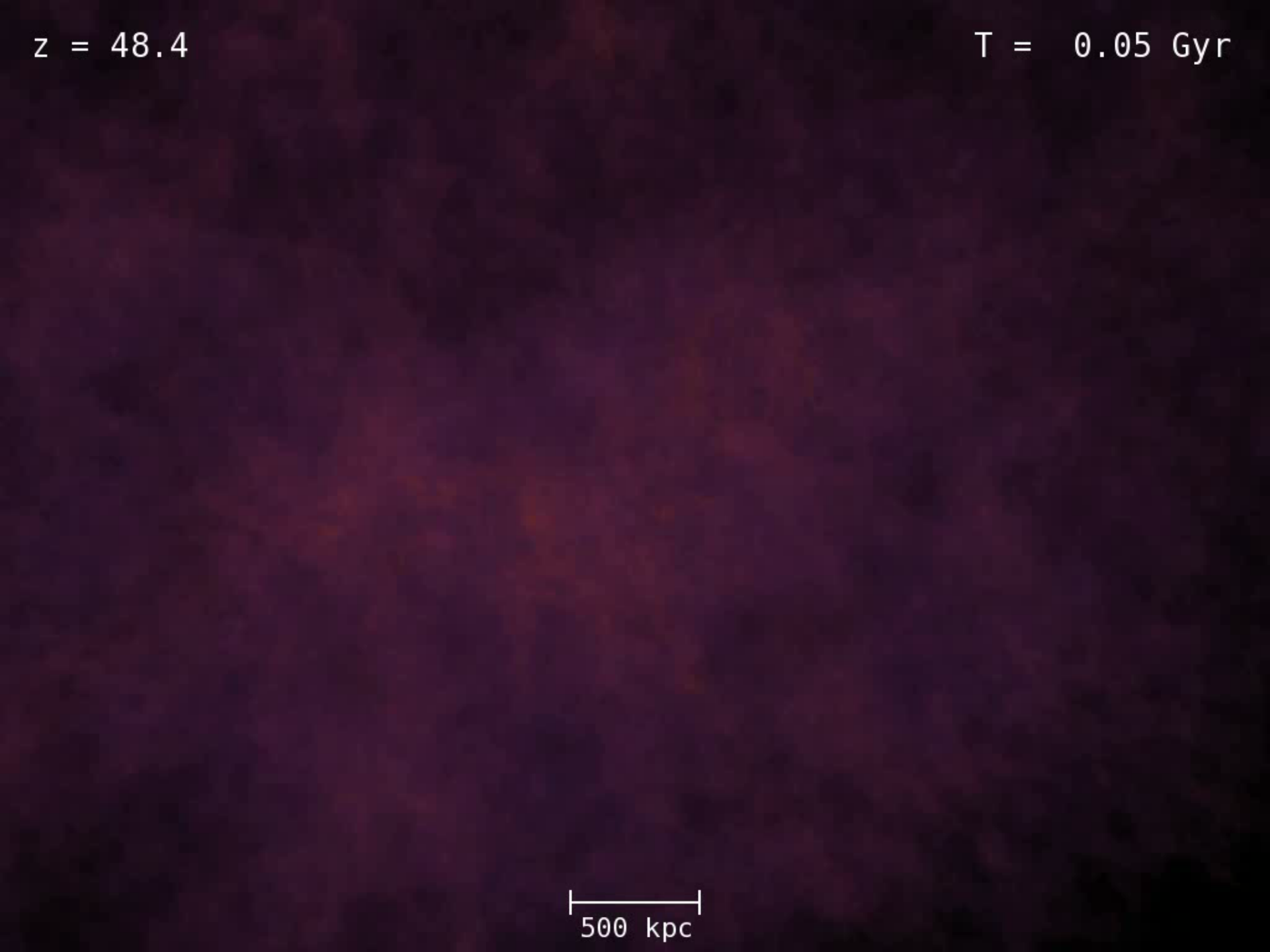
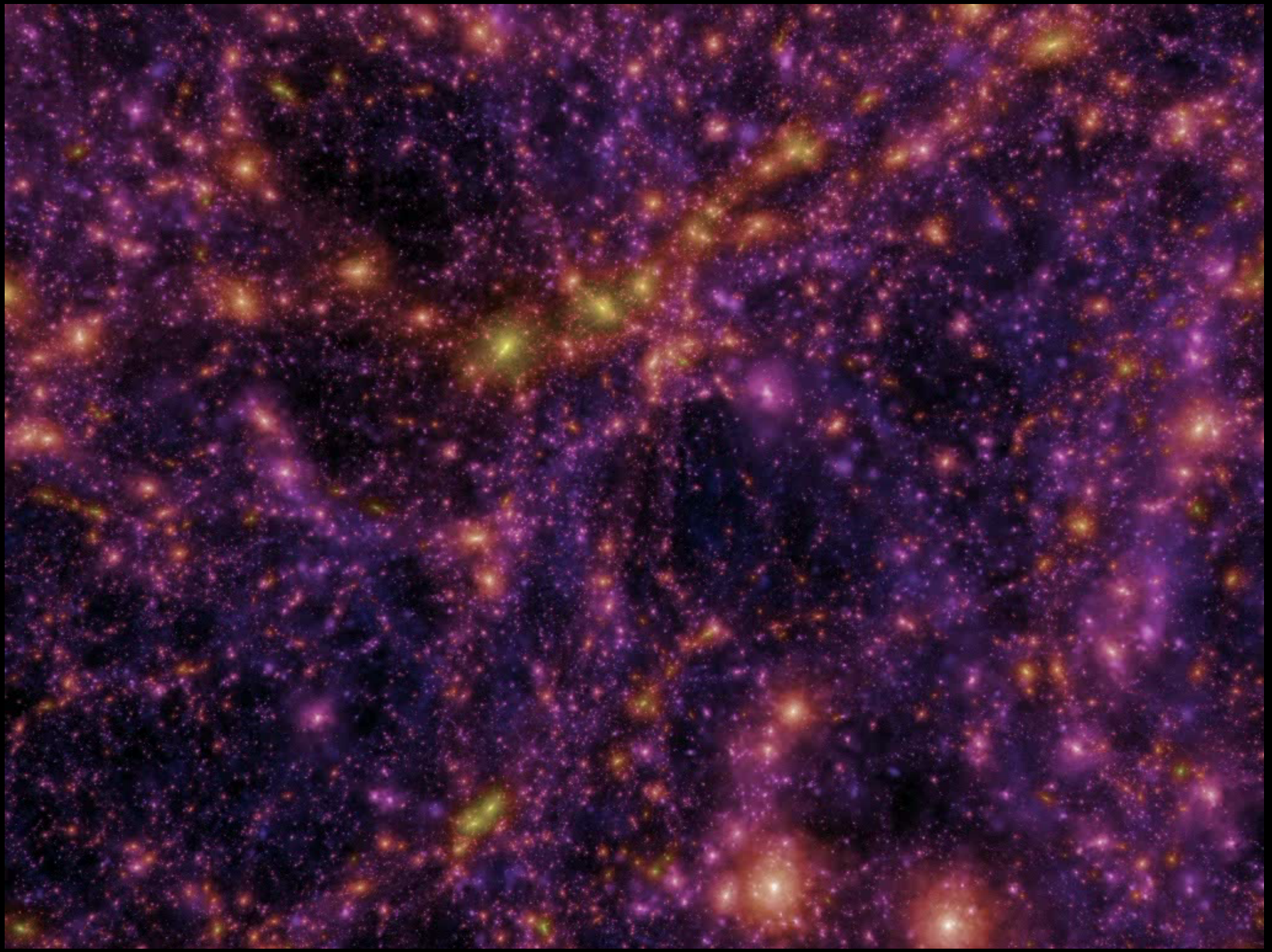

z = 48.4
T = 0.05 Gyr
500 kpc

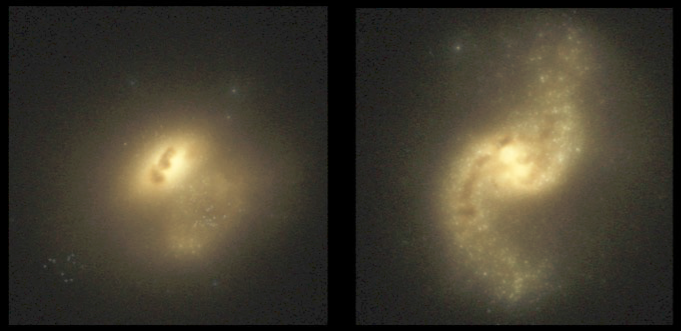


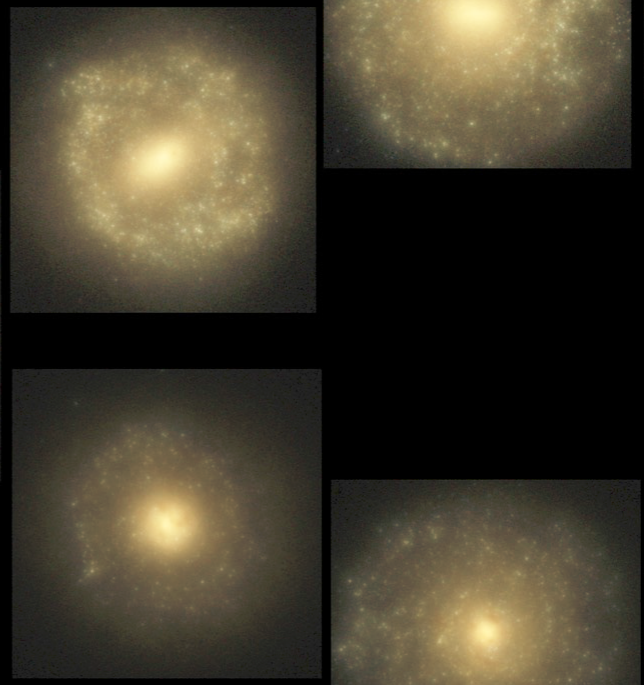

The EAGLE simulations
EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS
A project of the Virgo consortium
z = 19.9
L = 25.0 cMpc
Visible components:
CDM

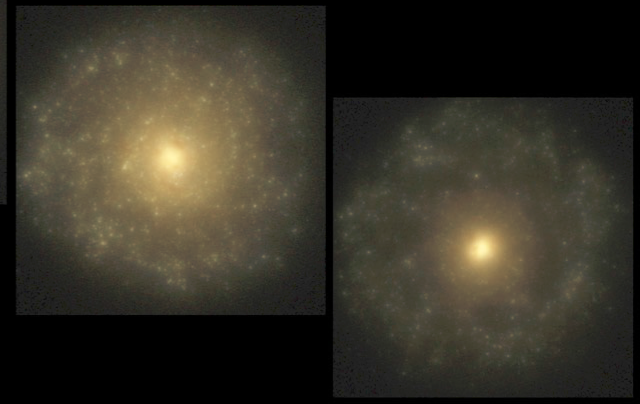
The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations



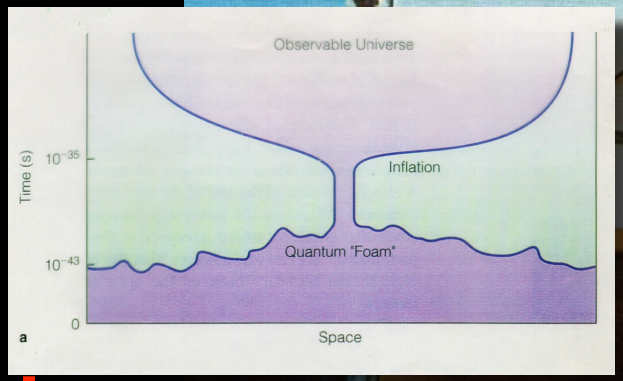




Trayford et al ‘15

The origin of cosmic structure

Inflation (t~10^{-35} s)

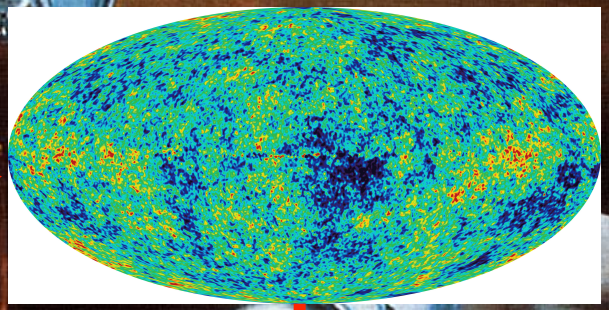


Small (quantum) ripples

CMB (t~3×10^5 yrs)

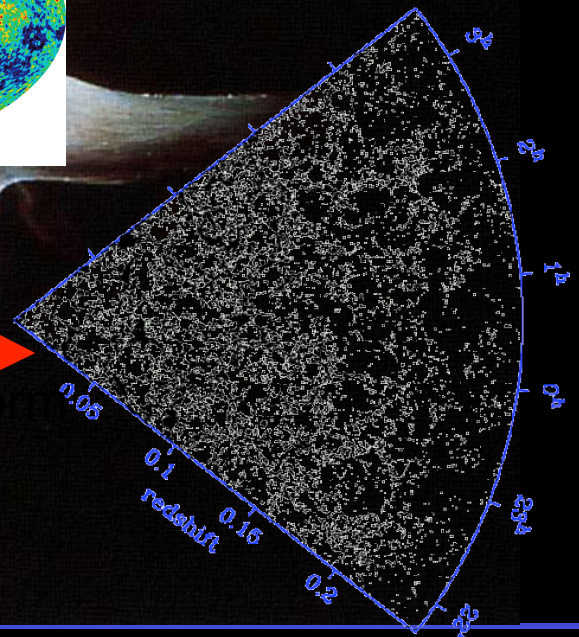
Galaxies (t~13×10^9yrs)

Cold dark matter



Ripples seen as hot & cold spots in cosmic radiation

Galaxies formed



Recent measurements of CMB temperature fluctuations and of the galaxy distribution confirm this paradigm.

Is this the end of the story?

There has been great progress in cosmology in the past 30 years

… but the best is still to come