

The new cosmology

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Institute for Computational Cosmology,
Durham



THE KEY QUESTIONS OF COSMOLOGY

- How did the Universe begin?
- What is it made of ?
- How did it evolve to its present state?
- What does the future hold?

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

The Panoramic Survey Telescope and Rapid Response System

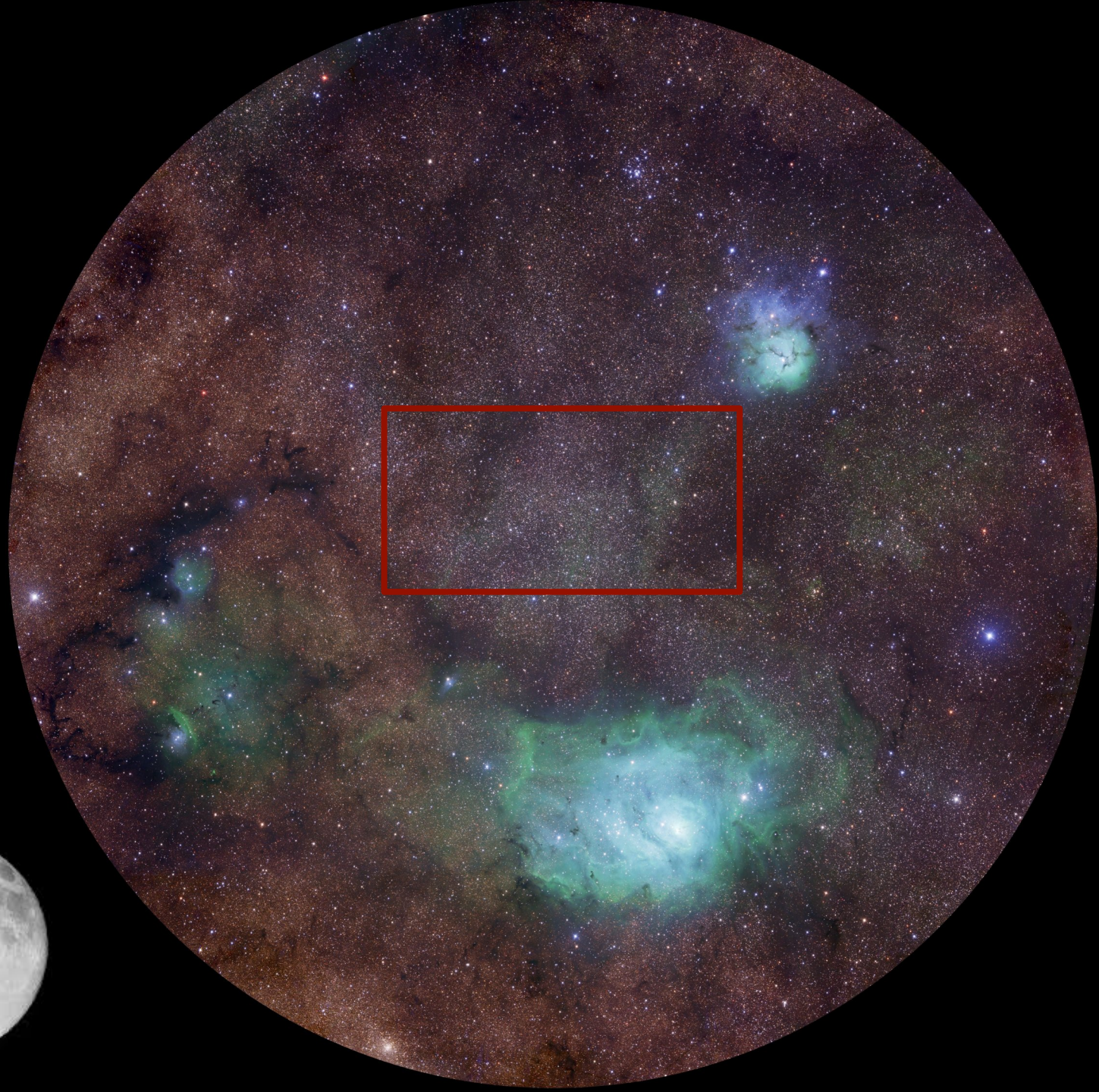
ICC participation sponsored by **Ogden Trust**,
 → leveraged **10x** more funding from European
 & UK Research Councils, Durham Univ,



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

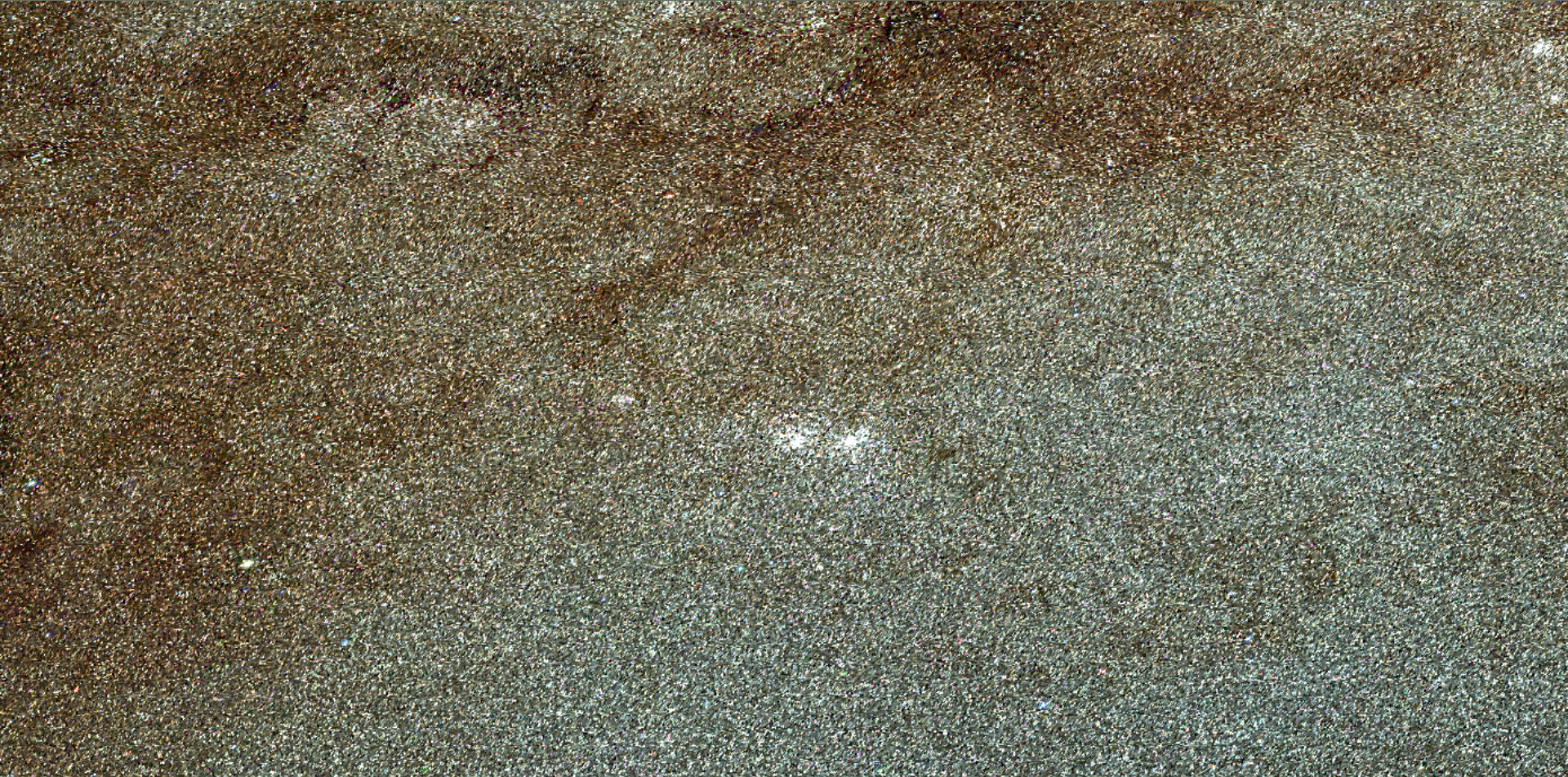
- 2.1m telescope in Hawaii (paid by USAF)
- **Largest** ever ccd **camera** (1.4 Gigapixels)
- **Survey** the entire sky in **5 wavelengths**

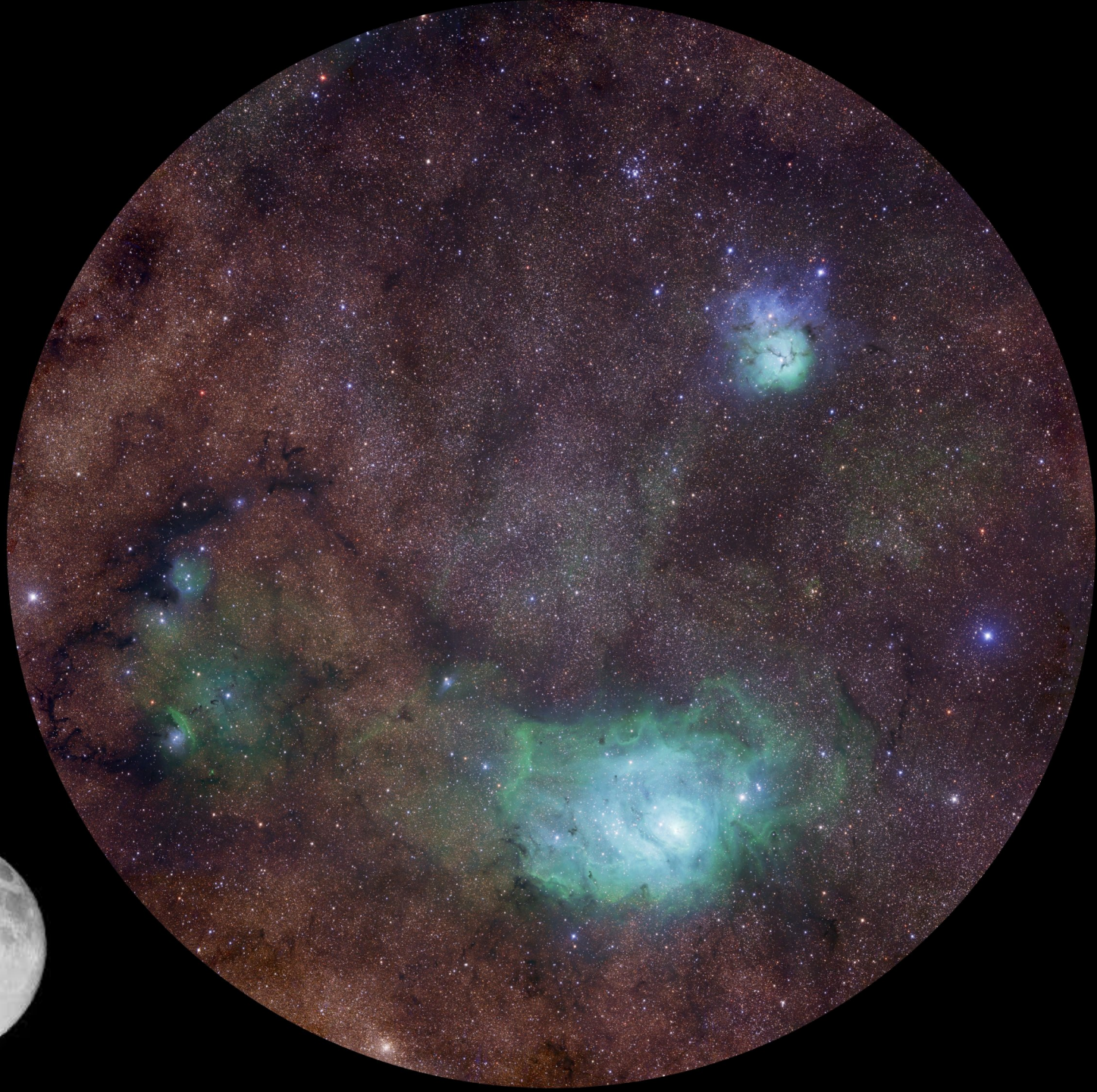






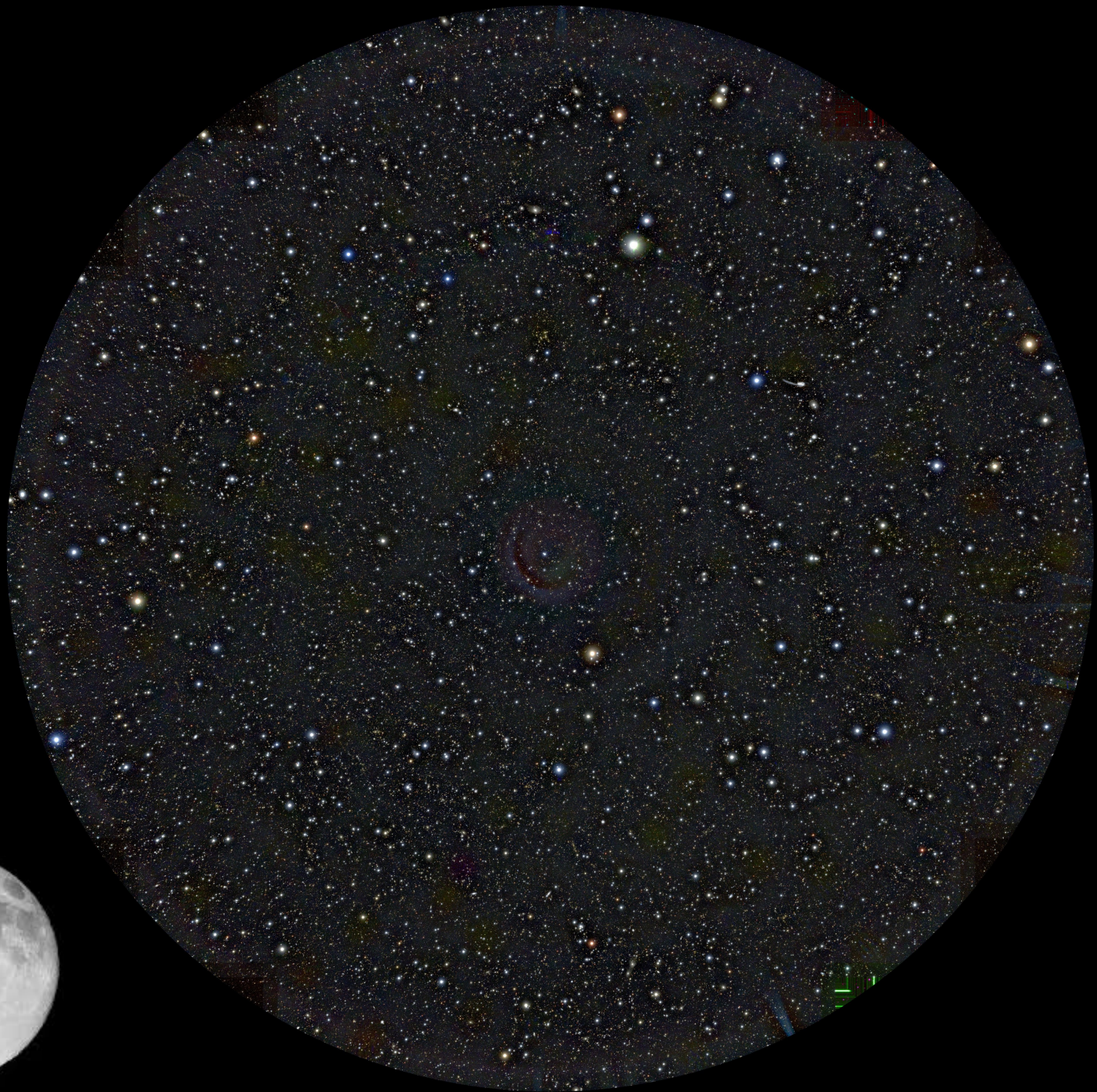
University of Durham



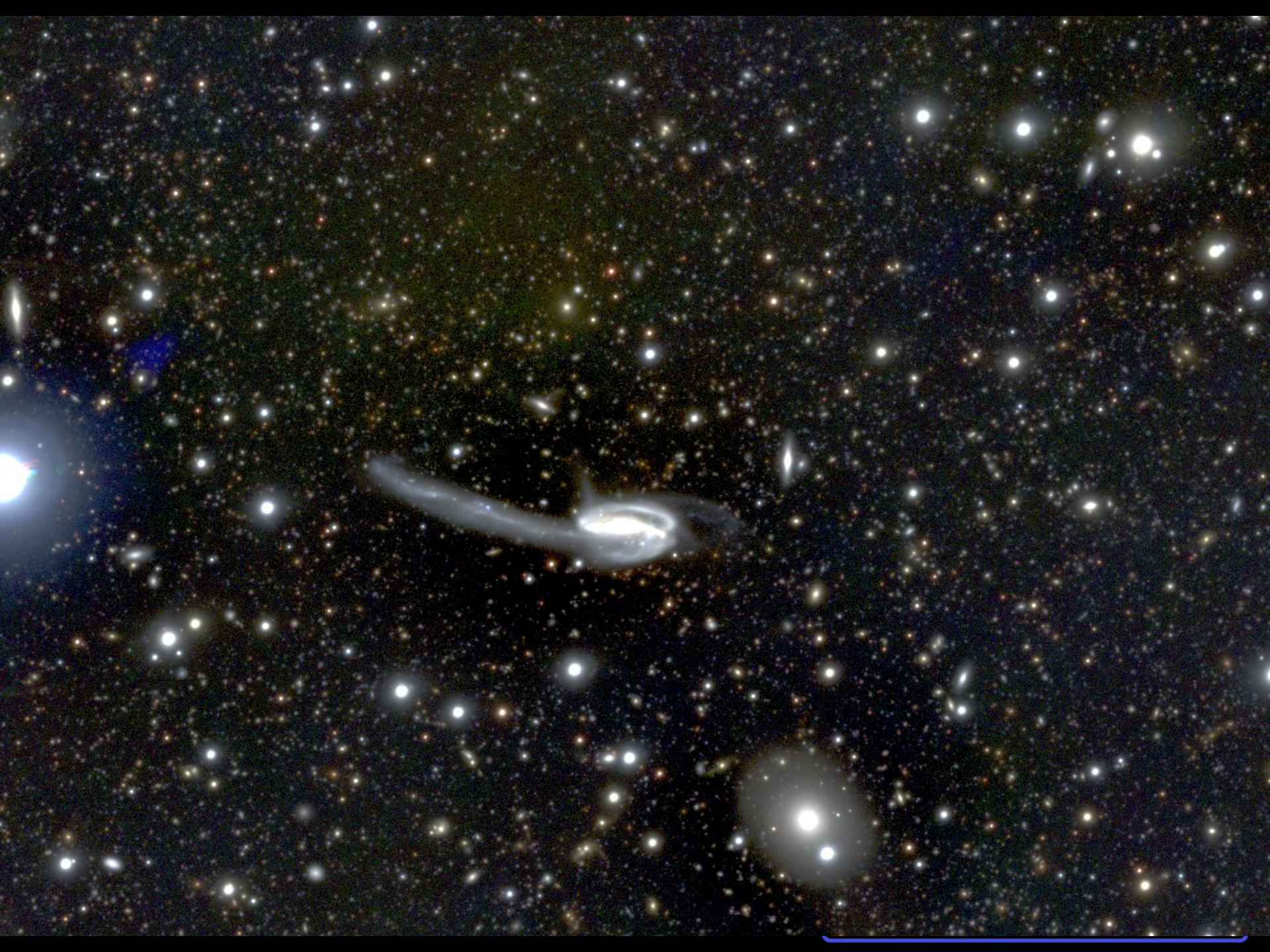


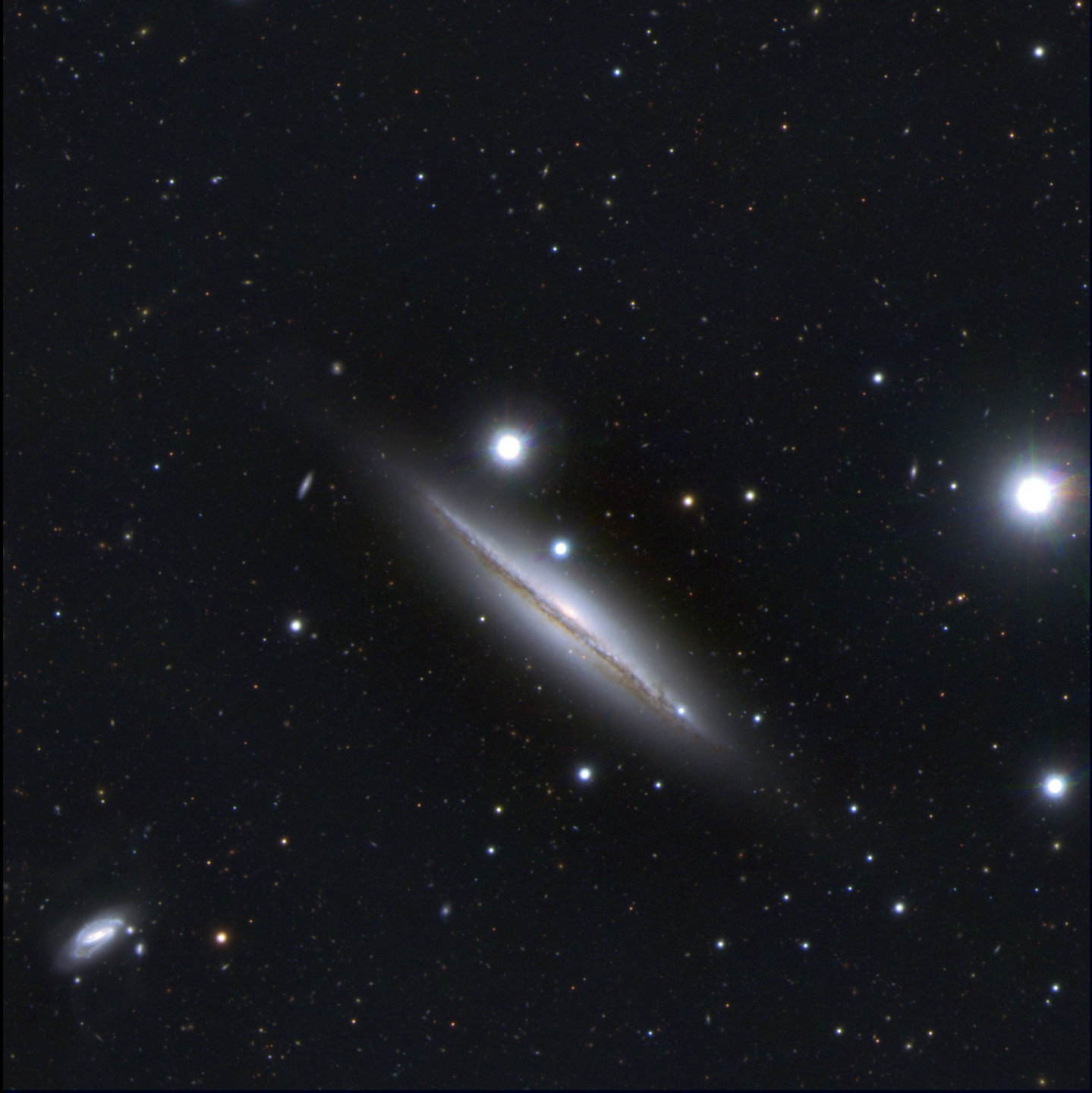










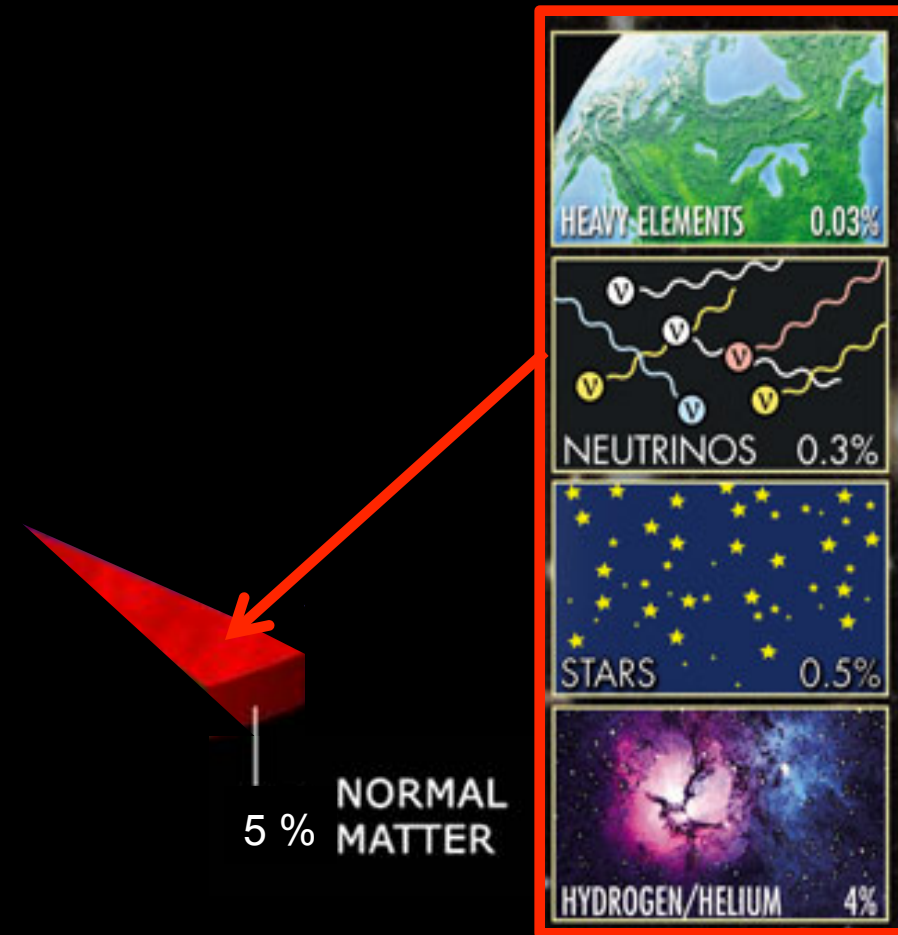






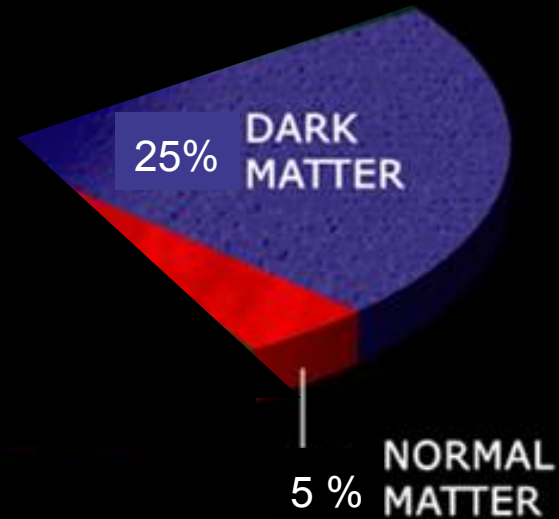
The content of the Universe

The content of our universe



Normal matter \equiv matter made of ordinary atoms

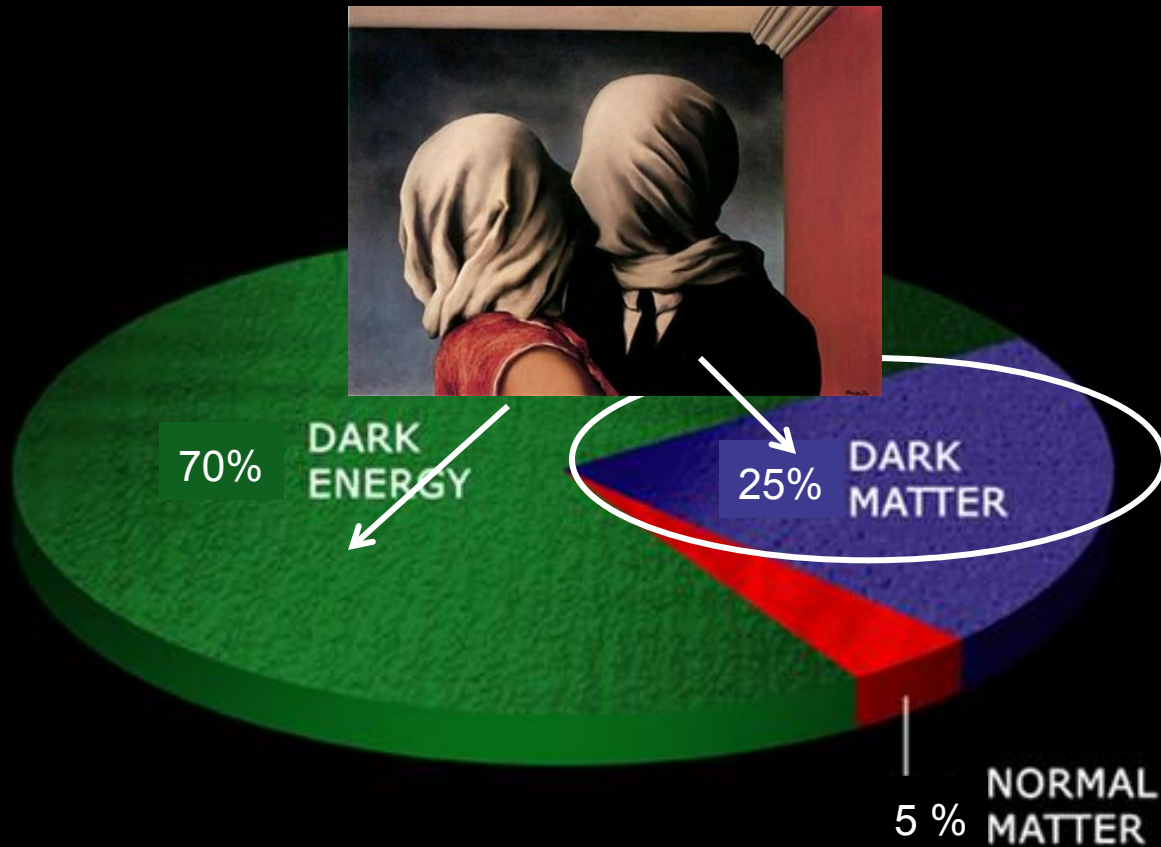
The content of our universe



Dark matter \equiv matter that does not emit light at any wavelength



The content of our universe



Dark energy \equiv 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?

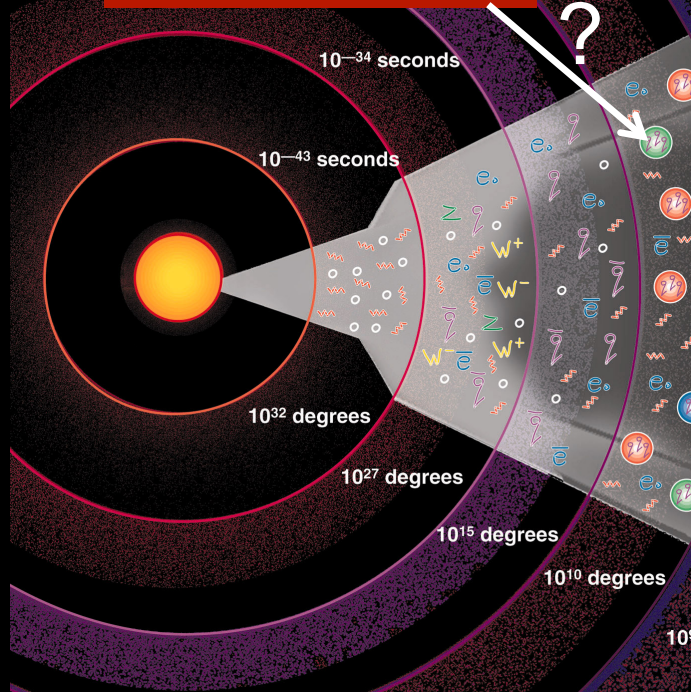
The big Bang



Dark matter

15 thousand million years
1 thousand million years
300 thousand years
3 minutes
seconds

Cold dark matter

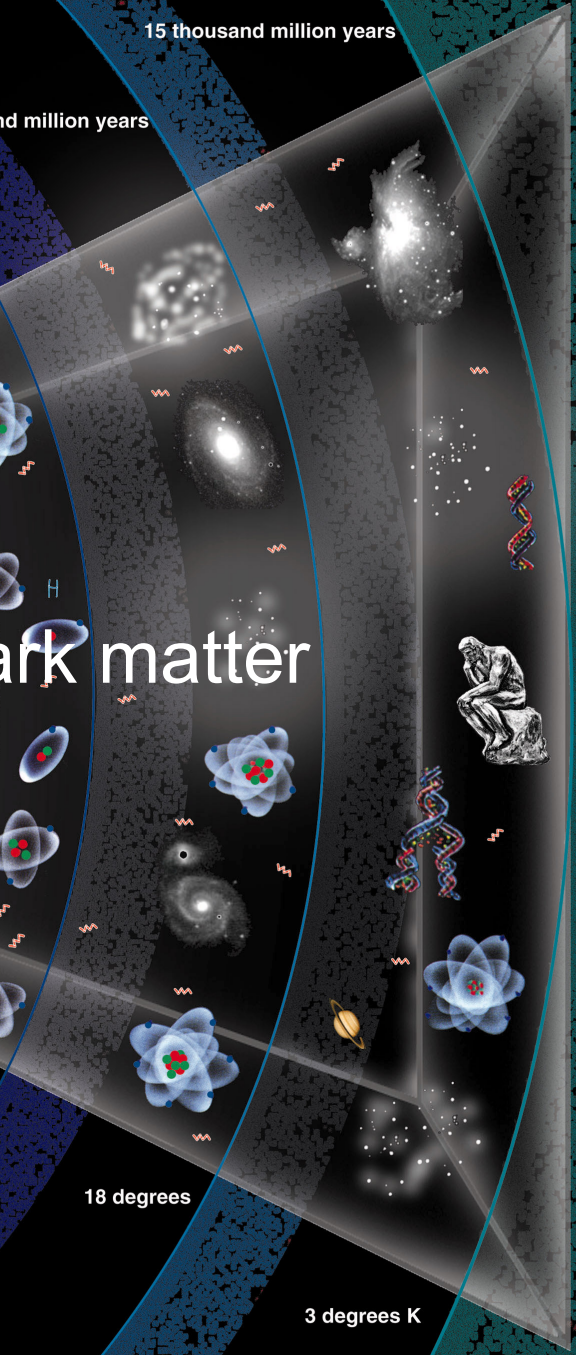


- radiation
- particles
- heavy particles carrying the weak force
- quark
- anti-quark
- electron
- positron (anti-electron)
- proton
- neutron
- meson
- hydrogen
- deuterium
- helium
- lithium

6000 degrees

18 degrees

3 degrees K



What is the dark matter?



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e,

The search for dark matter

Experimental physics



An experimental physicist





FIRE EXTINGUISHER
KEEP CLEAR

THE GREAT WALL
AGREEMENT
1985-1986

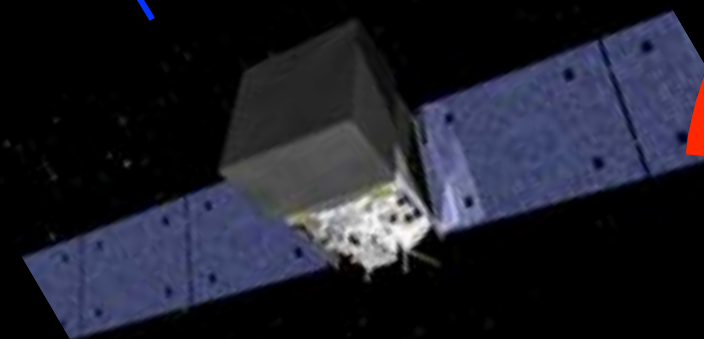
44

38

Cold dark matter ?

Dark matter discovery possible in several ways

Fermi



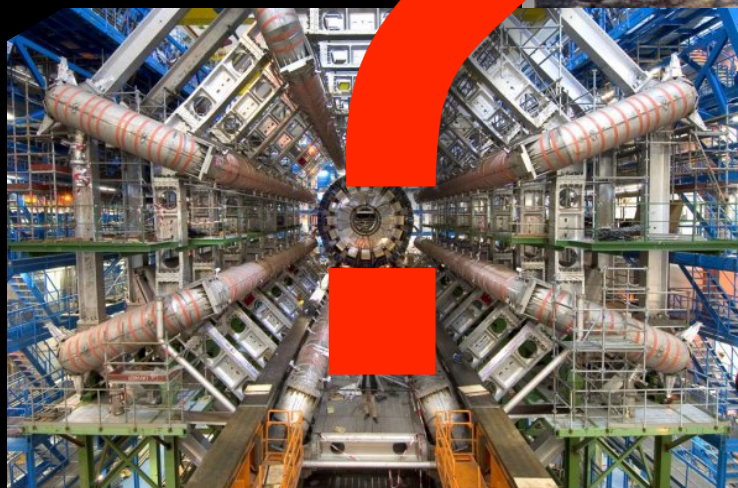
Annihilation radiation



Direct detection



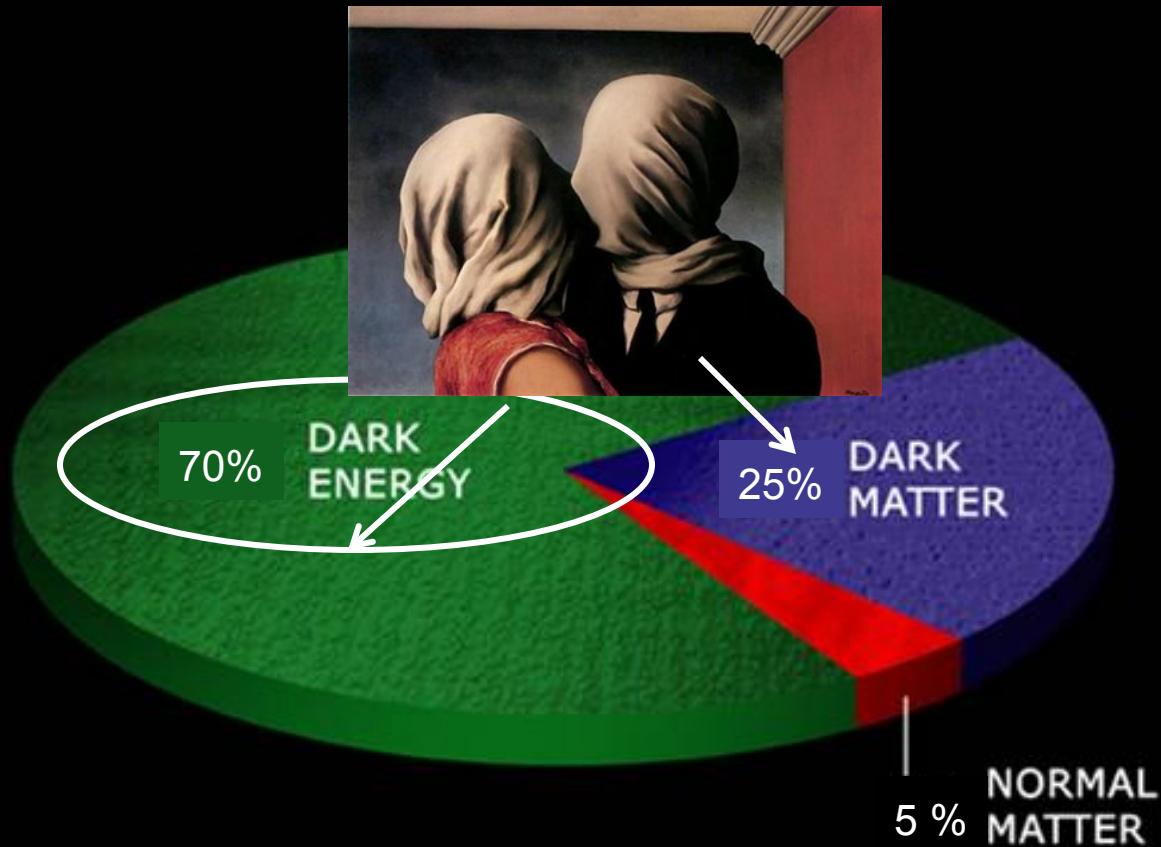
UK DM search
(Boulby mine)



Evidence for SUSY

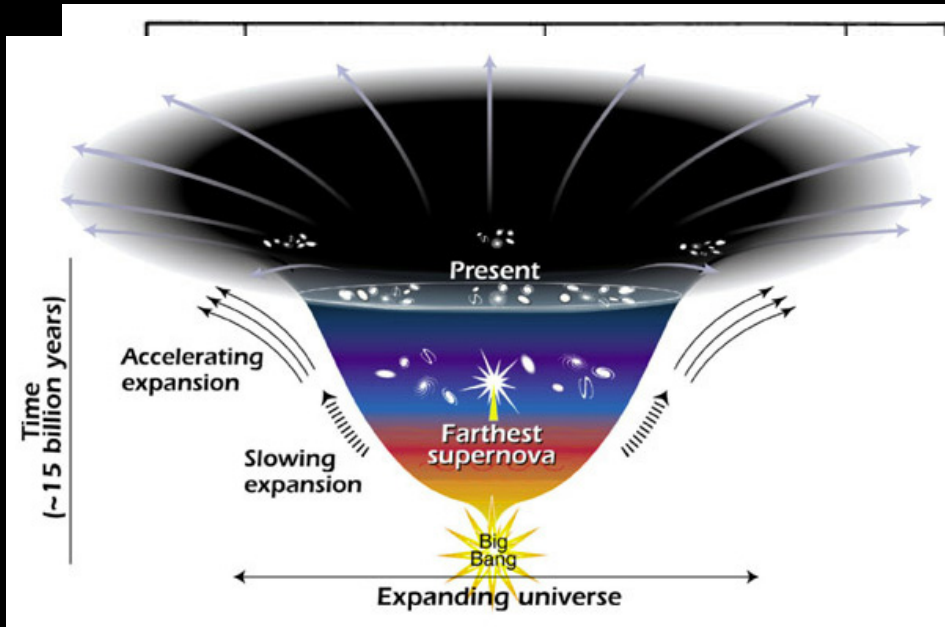
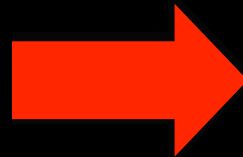
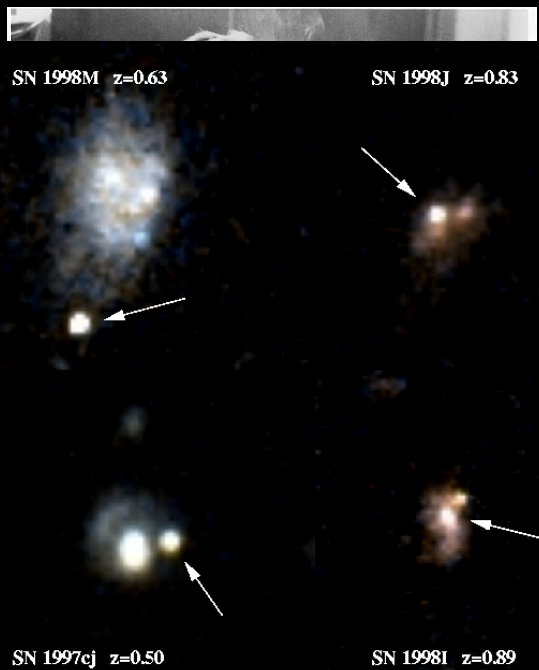


The content of our universe



Dark energy \equiv mysterious form of energy which opposes gravity

The cosmic expansion



Hubble 1929: $v = H \cdot d$

Expansion is accelerating

2011 Nobel prize in physics!

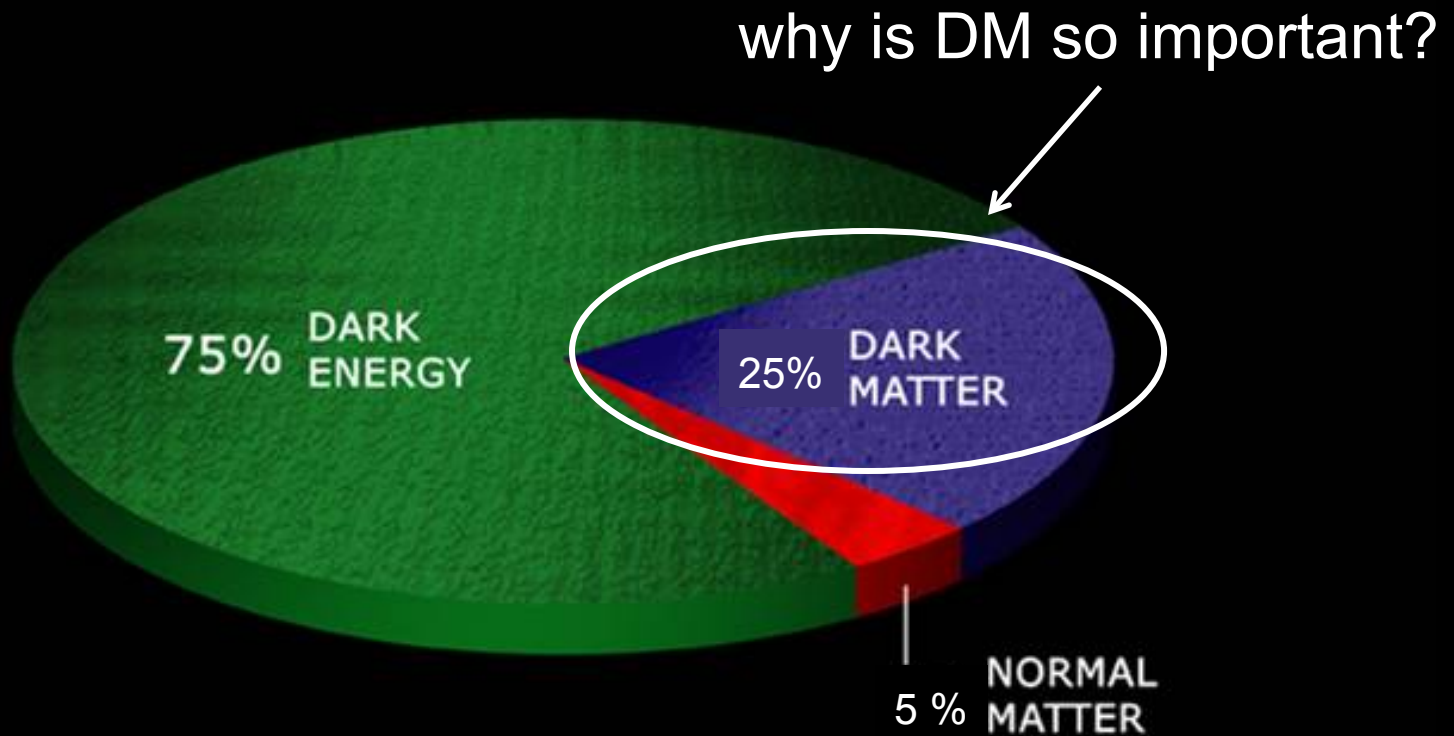
→ Universe full of dark energy

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

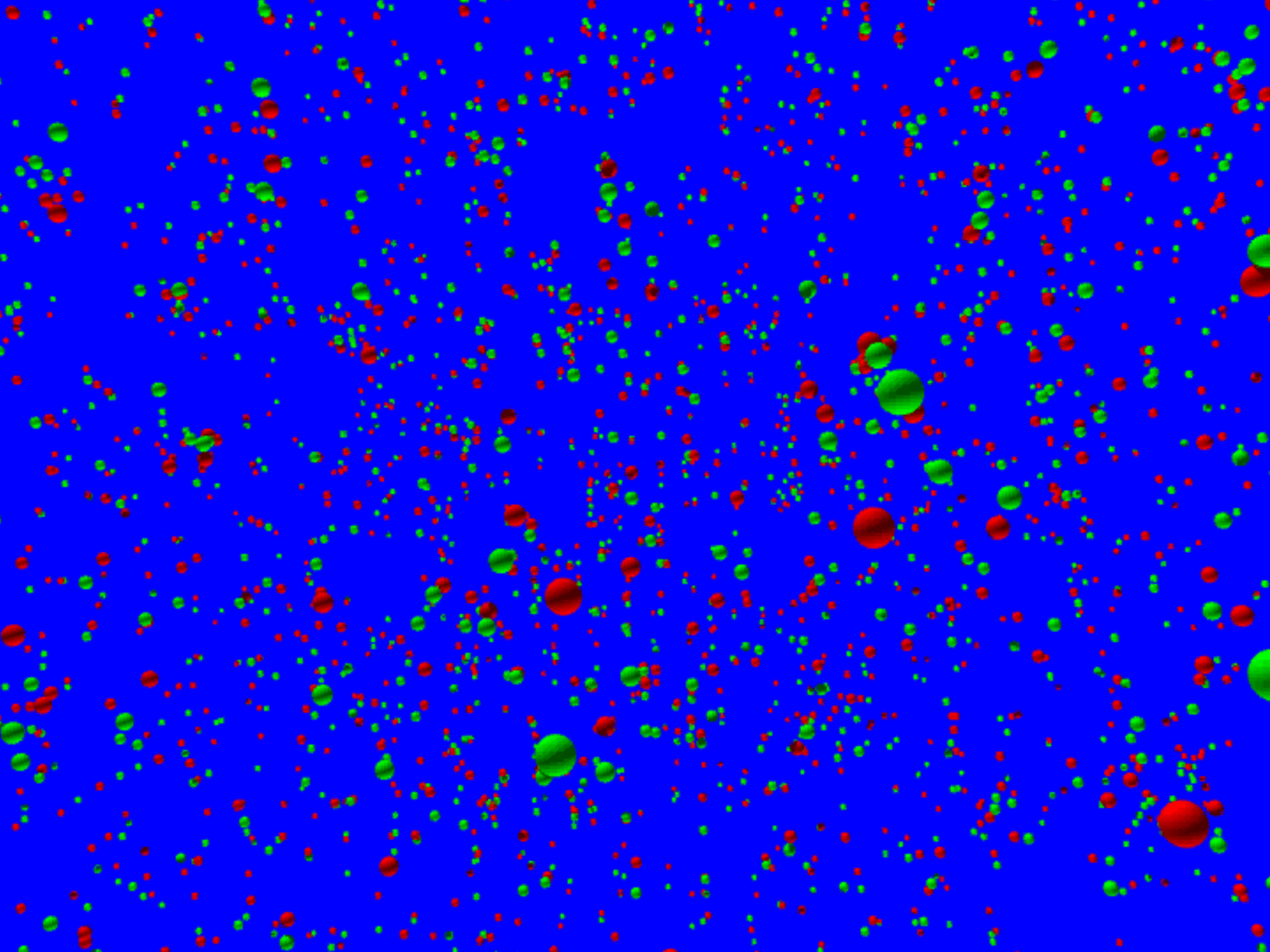
The content of our universe



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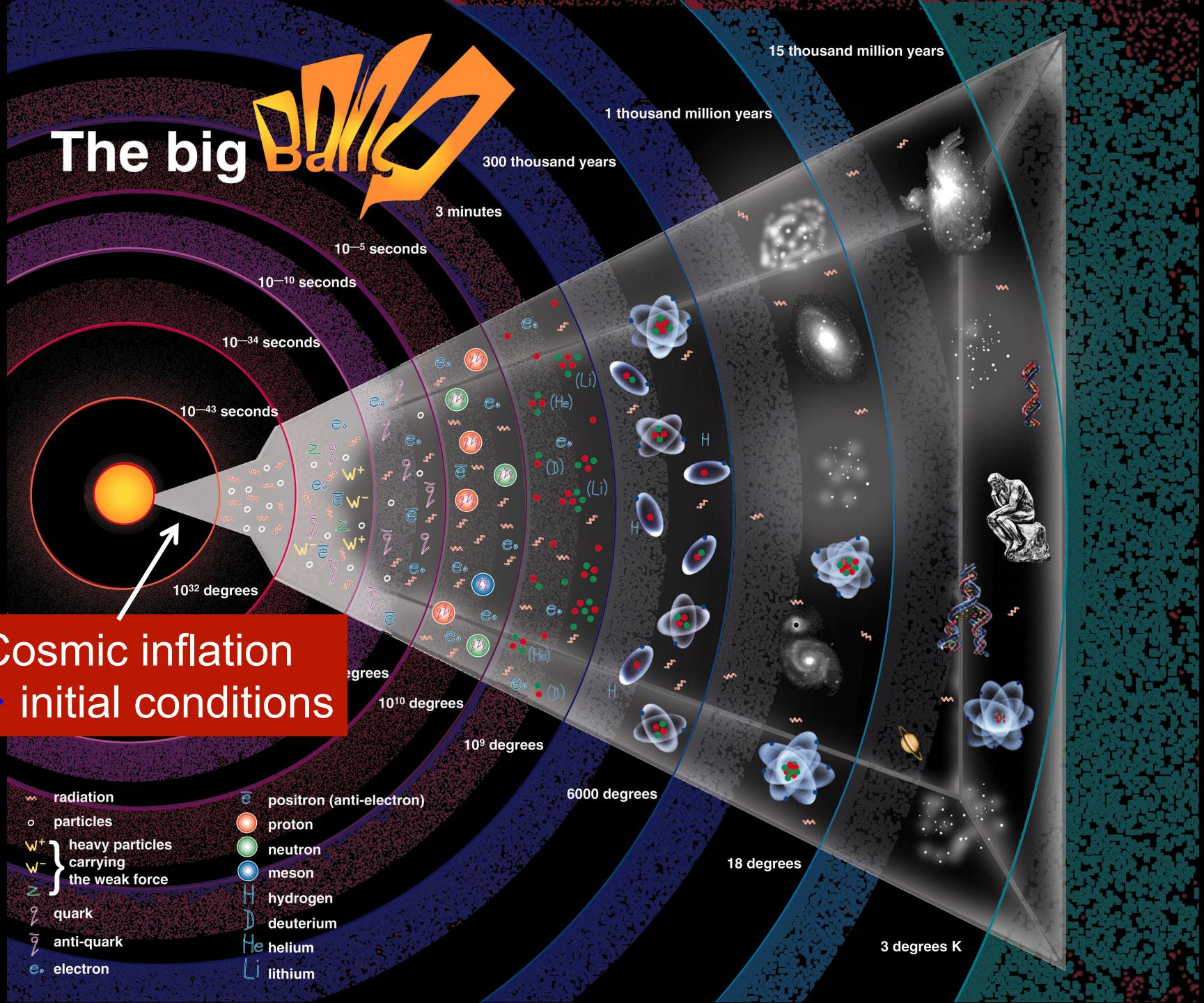
The gravity of the dark matter drives
Where do the galaxies come from?
formation of cosmic structure



The big Bang



Cosmic inflation
 → initial conditions



- ⌡ radiation
- particles
- W⁺ heavy particles carrying the weak force
- W⁻ heavy particles carrying the weak force
- z quark
- q anti-quark
- e⁻ electron
- ε⁺ positron (anti-electron)
- proton
- neutron
- meson
- H hydrogen
- D deuterium
- He helium
- Li lithium

10⁻⁴³ seconds
 10⁻³⁴ seconds
 10⁻¹⁰ seconds
 10⁻⁵ seconds
 3 minutes
 300 thousand years
 1 thousand million years
 15 thousand million years

10³² degrees

degrees

10¹⁰ degrees

10⁹ degrees

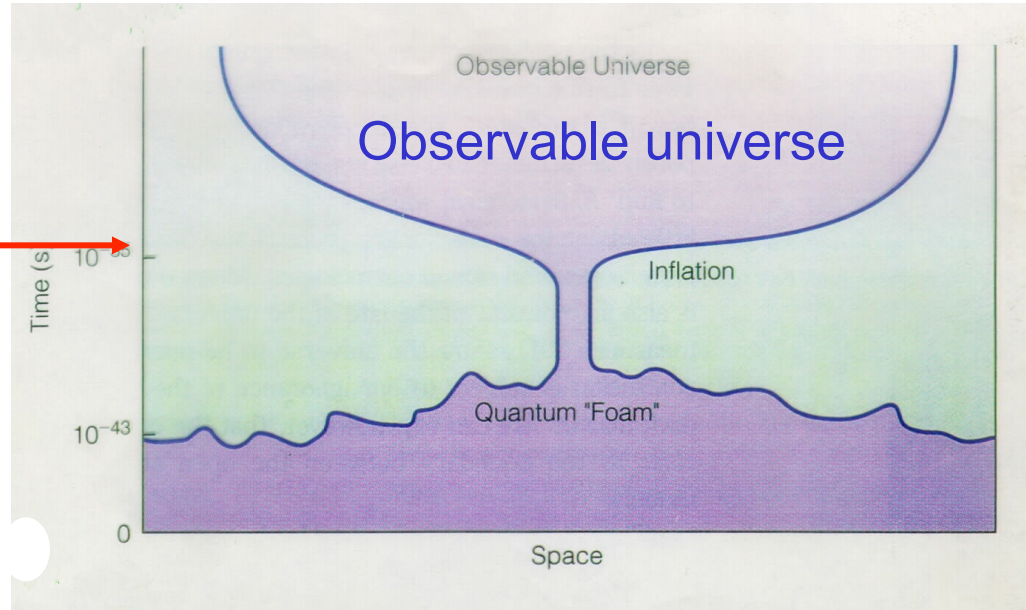
6000 degrees

18 degrees

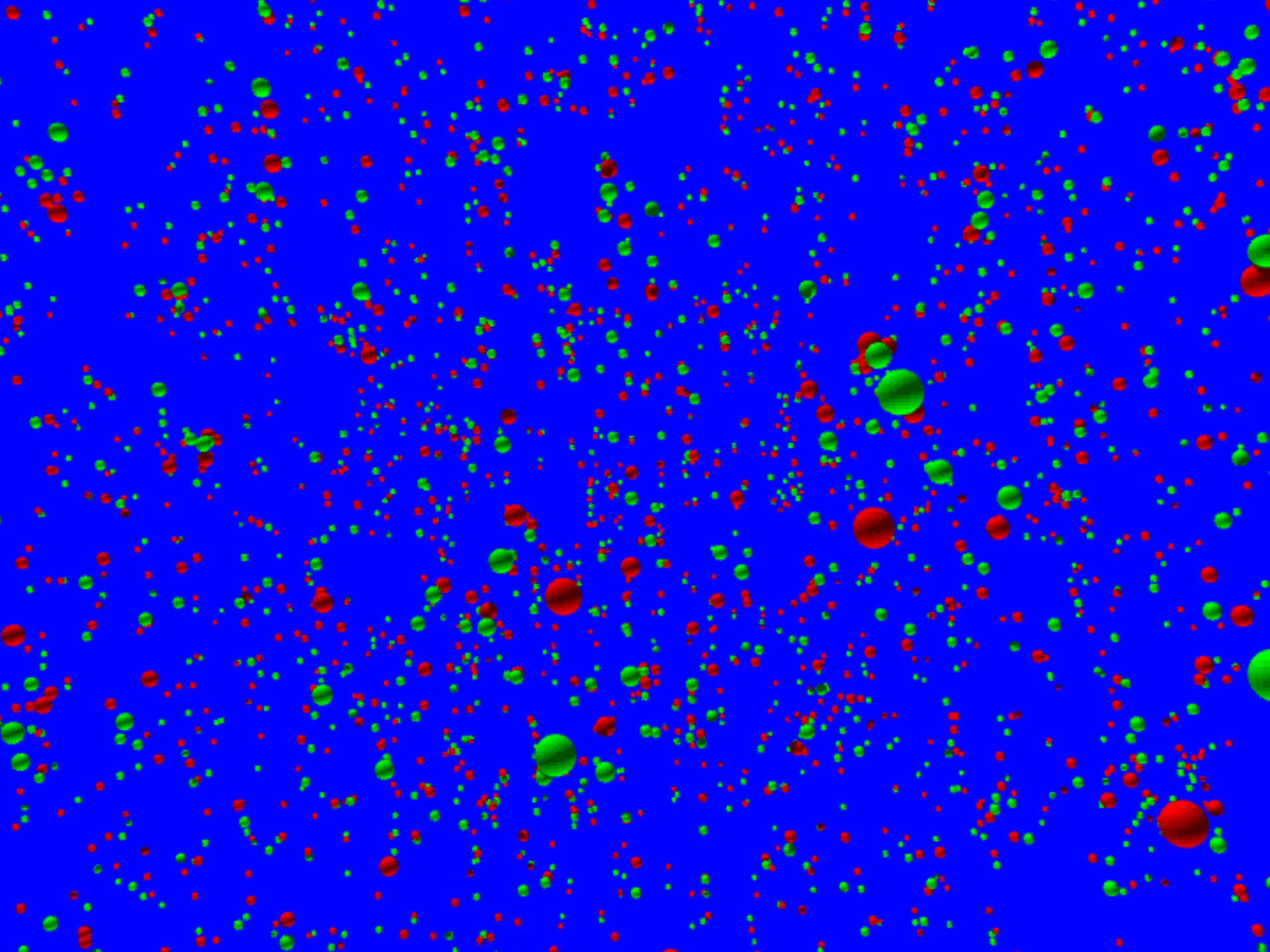
3 degrees K

Cosmic Inflation

$t = 10^{-35}$ s

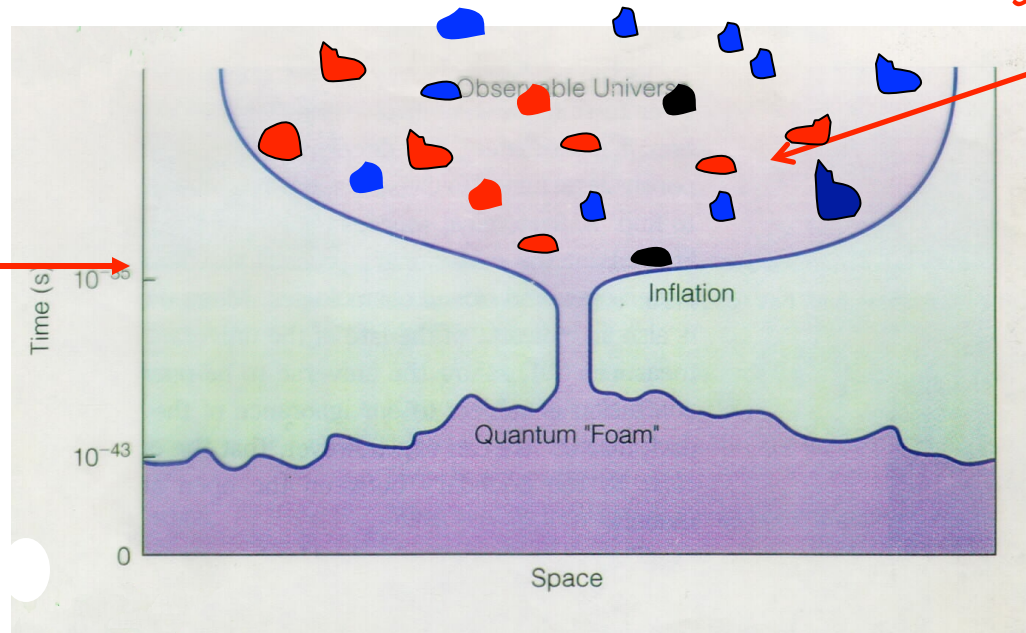


- > According to theory of cosmic inflation, our visible Universe is a small patch of a much larger region.



Cosmic Inflation

$t = 10^{-35}$ s

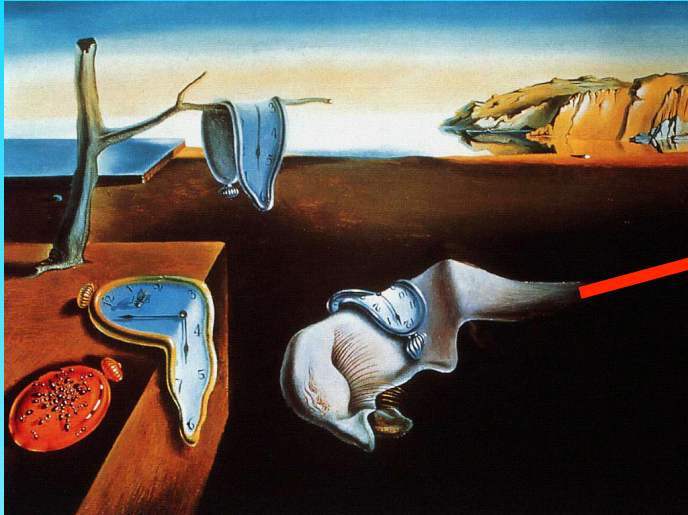


tiny mass irregularities

Inflation theory predicts:

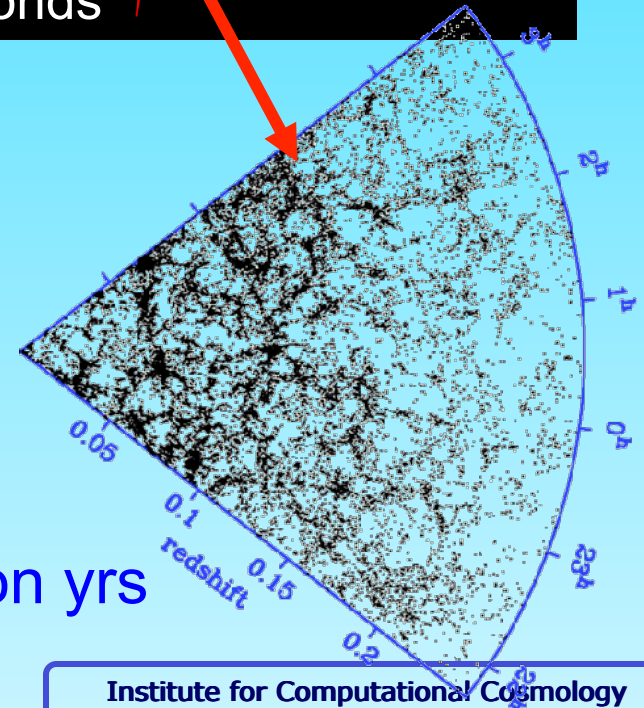
early universe seeded by tiny fluctuations in mass produced by quantum processes

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:*

500 million light years

$t = 0.06 \text{ Gyr}$



The science of the Universe

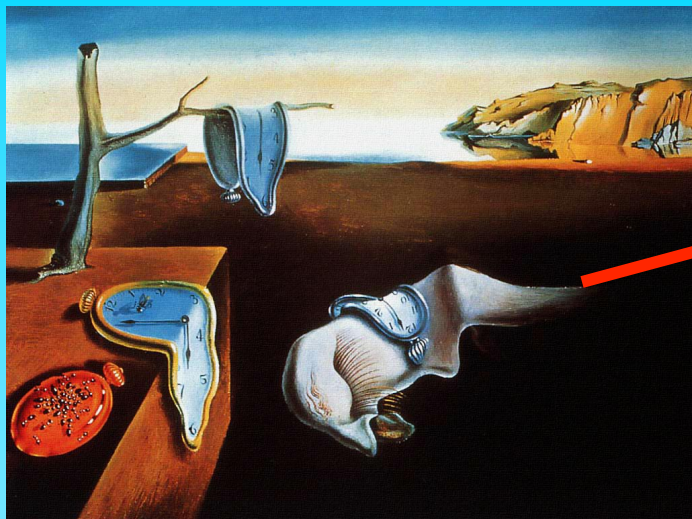
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The laws of Physics: general rules about natural phenomena, derived empirically and expressed mathematically, e.g. Newton's law of gravitation, Boyle's gas law, quantum mechanics, relativity

- Experimentally verified on Earth
- Universal

To be Physics, it must be testable!

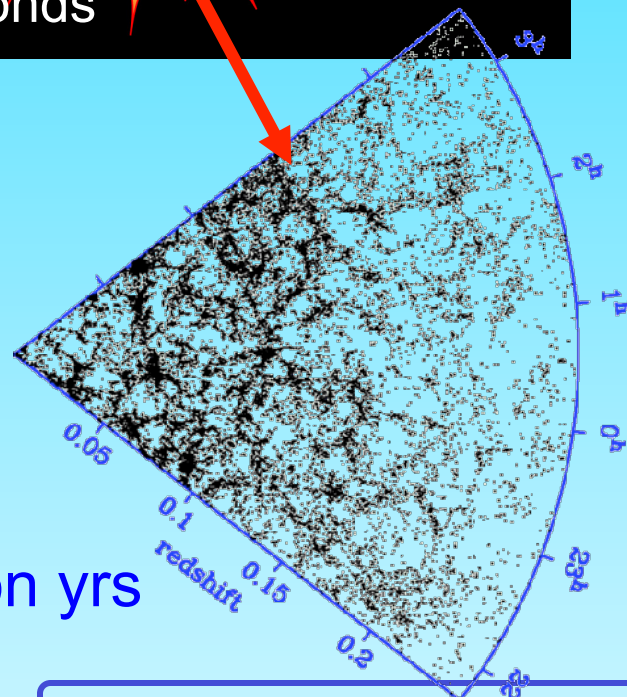
The growth of cosmic structure



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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

The first light



The early universe was very hot

The big Bang



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

15 thousand million years

300 tho

3 minutes

10^{-5} seconds

10^{-10} seconds

10^{-34} seconds

10^{32} degrees

The early universe was foggy

10^{10} degrees

10^9 degrees

6000 degrees

18 degrees

3 degrees K

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- He helium
- Li lithium



The echo of the Big Bang



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

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.



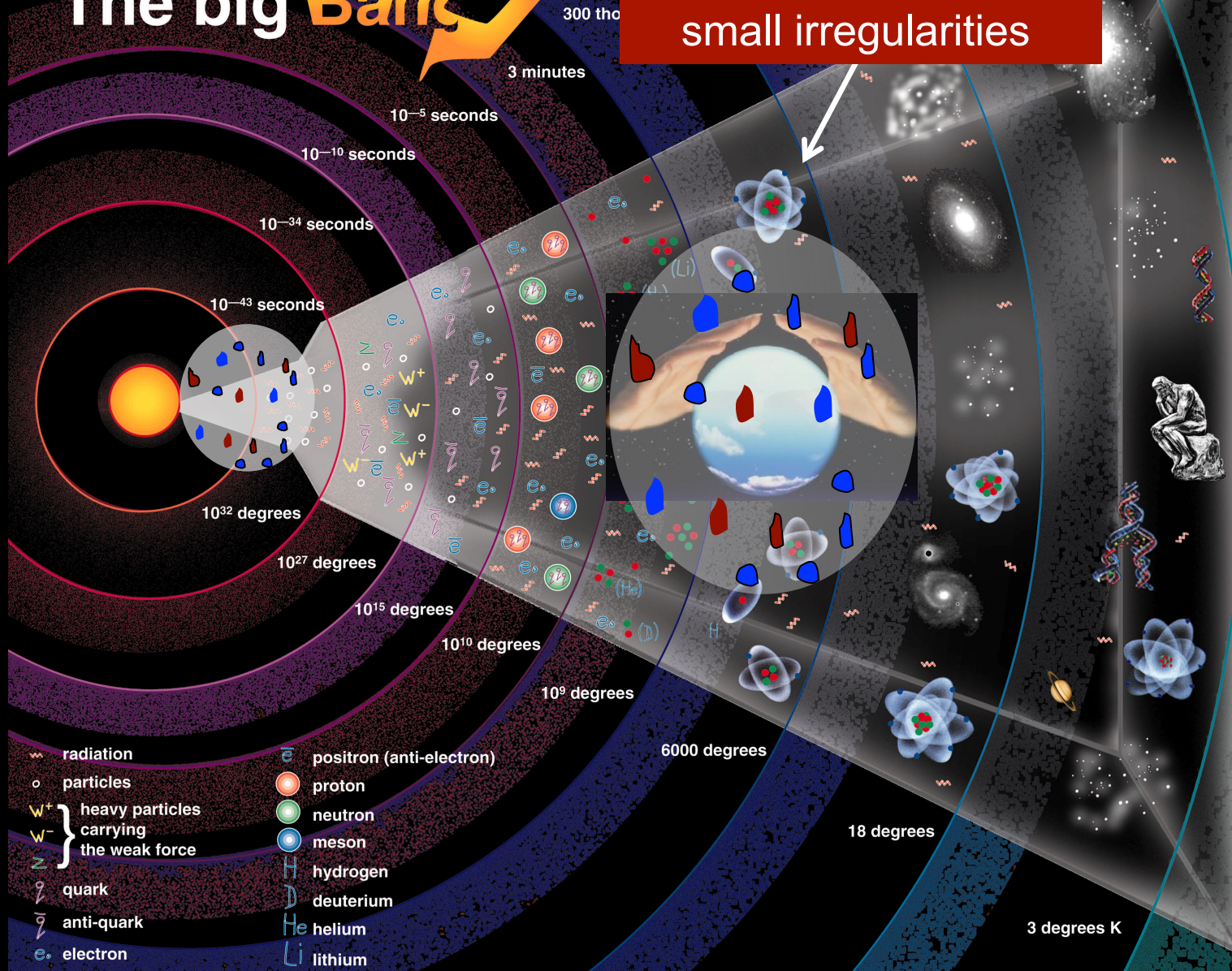
1978 Nobel Prize in Physics

The big Bang



The temperature of this radiation should show small irregularities

15 thousand million years



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The big Bang



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300 tho

3 minutes

10^{-5} seconds

10^{-10} seconds

10^{-34} seconds

10^{-43} seconds

10^{32} degrees

10^{27} degrees

10^{15} degrees

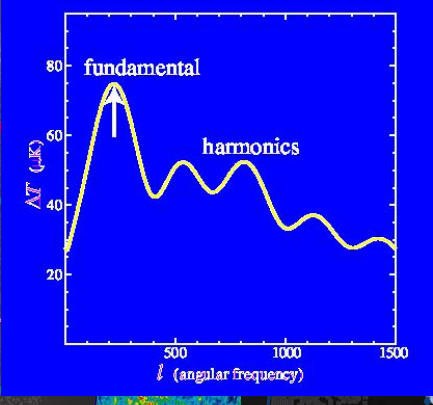
10^{10} degrees

10^9 degrees

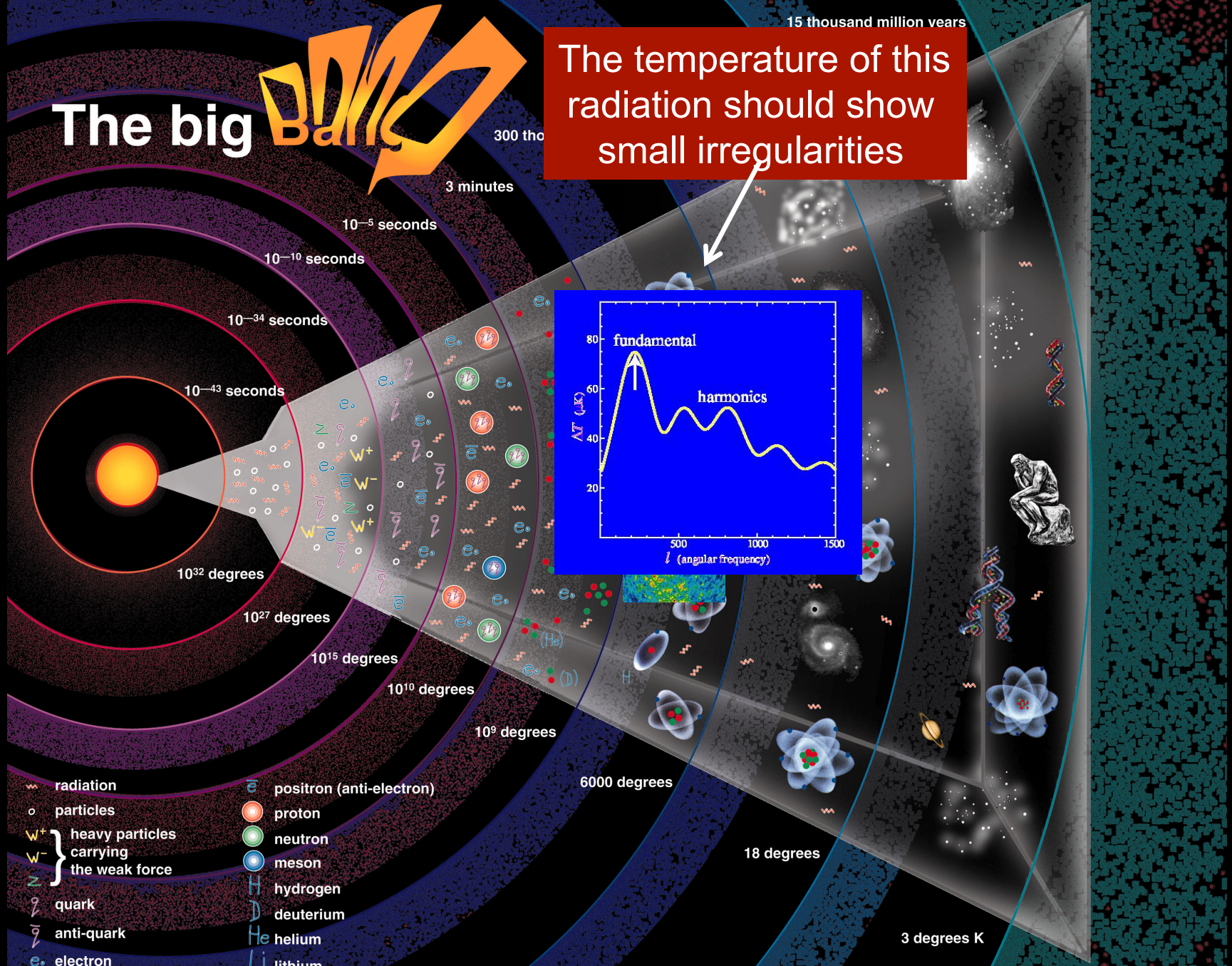
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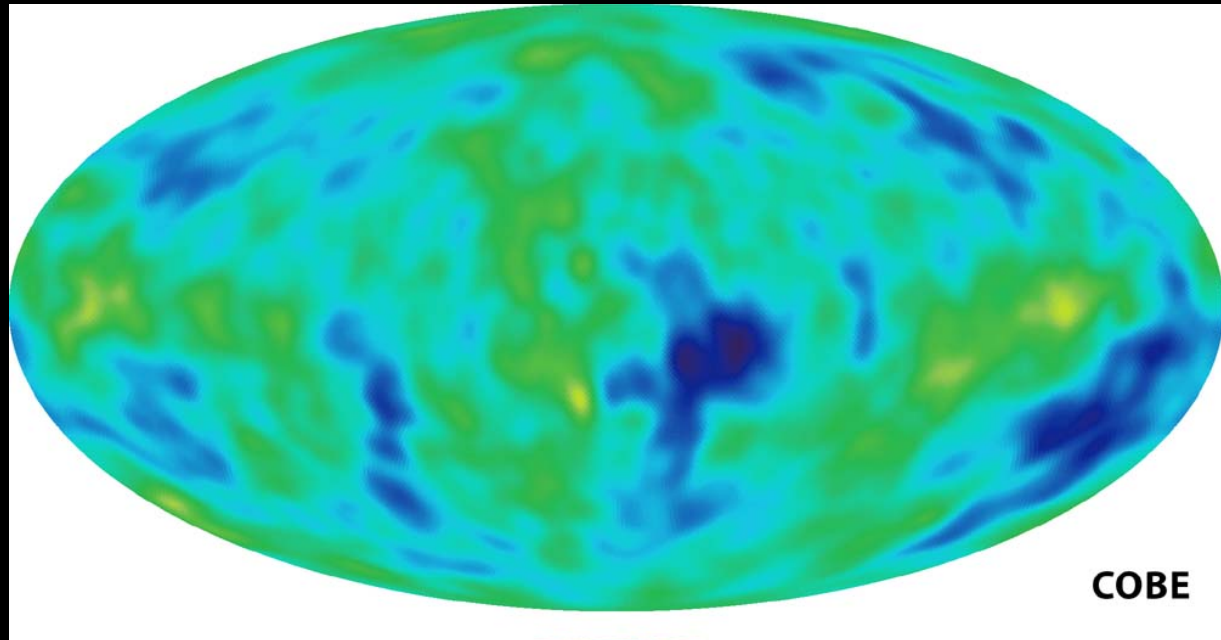
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1992



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



THE INDEPENDENT

No 1,722

A Nasa spacecraft has detected the stars after the Big Bang has

How

BACK TO CREATION

How the universe evolved from the Big Bang, through the first three minutes, to the first clusters of matter 300,000 years on. By 15 billion years humanity had emerged from the dust of the stars.

15 billion years
DNA, the molecule of inheritance, and life on Earth emerge

300,000 years
Epoch of recombination: the first ripples of cosmic structure
Discovery announced yesterday

FOURTEEN thousand million years ago the universe hiccuped. Yesterday, American scientists announced that they have heard the echo.

A Nasa spacecraft has detected ripples at the edge of the Cosmos which are the fossilised imprint of the birth of the stars and galaxies around us today.

According to Michael Rowan-Robinson, a leading British cosmologist, "What we are seeing here is the moment when the structures we are part of - the stars and galaxies of the universe - first began to form."

The ripples were spotted by the Cosmic Background Explorer (Cobe) satellite and presented to excited astronomers at a meeting of the American Physical Society in Washington yesterday. "Oh wow... you can have no idea how exciting this is," Carlos Frenk, an astronomer at Durham University, said yesterday. "All the world's cosmologists are on the telephone to each other at the moment trying to work out what these numbers mean."

Cobe has provided the answer to a question that has baffled scientists for the past three decades: their attempts to understand the structure of the Cosmos. In the 1960s two American researchers found definitive evidence that the Big Bang had started the whole thing off about 15 billion years ago. But the Big Bang would have spread matter like thin gruel evenly throughout the universe. The problem was to work out how

the lumps (stars, planets and galaxies) got into the porridge.

"What we have found is evidence for the birth of the universe," said Dr George Smoot, an astrophysicist at the University of California, Berkeley, and the leader of the Cobe team.

Dr Smoot and colleagues at Berkeley joined researchers from several American research organisations to form the Cobe team. The Space Flight Center, Nasa's Jet Propulsion Laboratory, the Massachusetts Institute of Technology and Princeton University. Joel Primack, a physicist at the University of California at Santa Cruz, said that if the research is "it's one of the major discoveries of the century. In fact, the major discoveries of the century."

Turner, a University of Chicago physicist, called the discovery "unbelievably important... the significance of this cannot be overstated. They have found the Holy Grail of cosmology. It is indeed correct, this could have to be considered for a Nobel Prize."

Since the ripples were created almost 15 billion years ago, their radiation has been travelling toward Earth at the speed of light. By detecting the radiation, Cobe is "a wonderful time machine"

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3 minutes

1 second
Stable subnuclear particles, neutrons and protons, are formed

10⁻¹⁰ second

10⁻³
The quarks bare parti

able to view the young universe, Dr Smoot said.

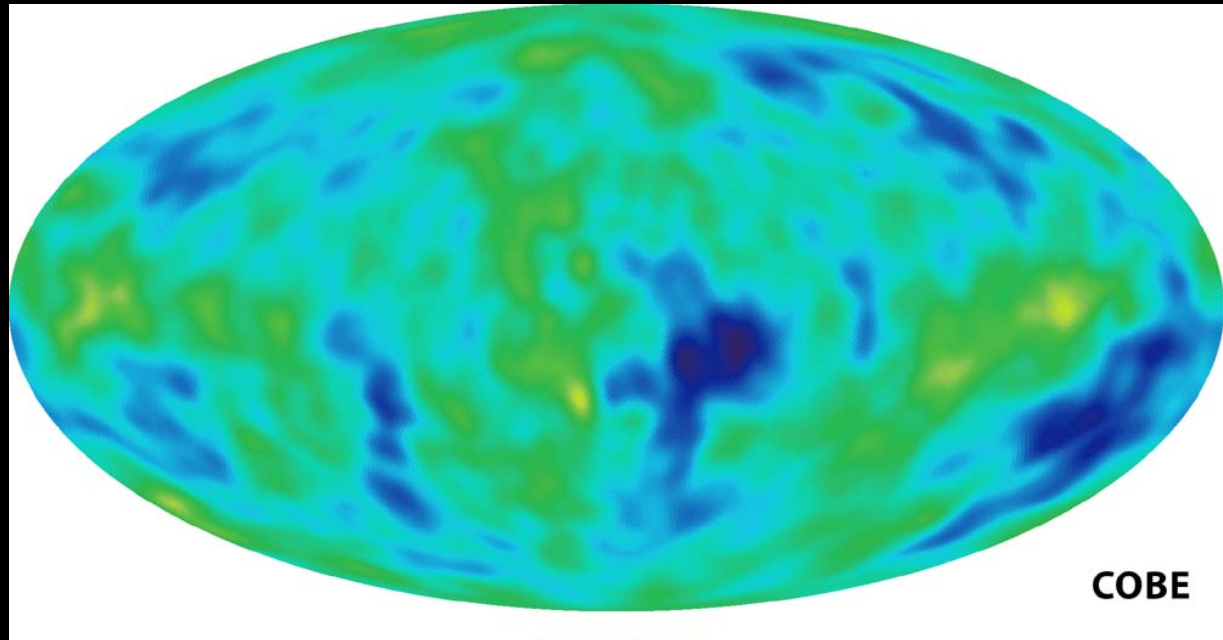
A remnant glow from the Big Bang is still around today, in the form of microwave radiation that has bathed the universe for the billions of years since the explosion. Galaxies must have formed by growing gravitational forces bringing matter together. To produce a "lumpy" universe, radiation from the Big Bang should itself show signs of being lumpy.

Cobe, which has been orbiting 500 miles above the Earth since the end of 1989, has instruments on board that are sensitive to this extremely old radiation. The ripples Cobe has found are the first hard evidence of the long-sought lumpiness in the radiation.

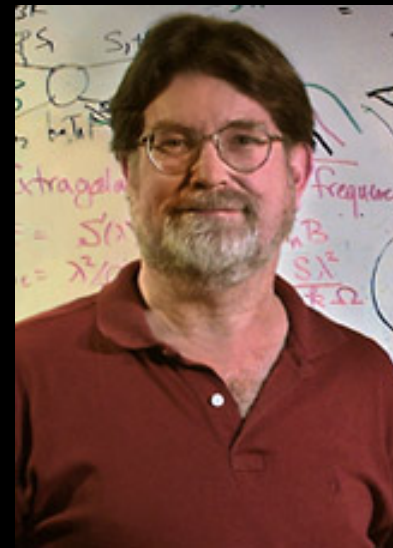
Cobe detected almost imperceptible variations in the tem-

ceptible variations in the temperature... surrounded by slightly less dense matter... time when the foggy fireball of radiation... and light from these galaxies, re-emitted... predictions about what the size of the original fog looked like.

1992

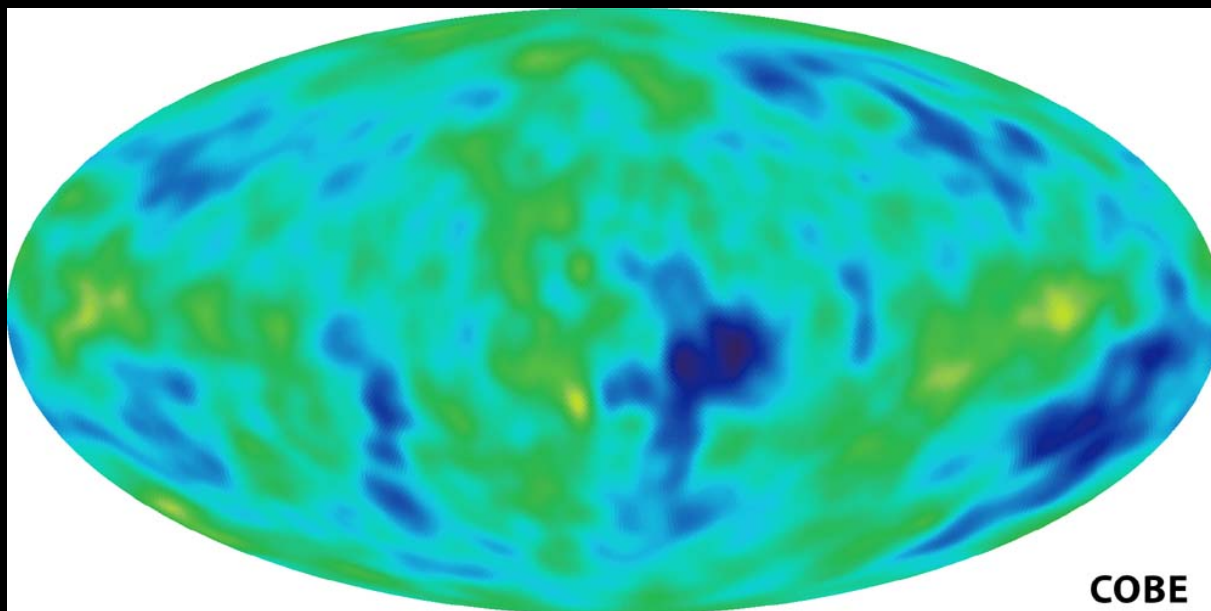


George Smoot - Nobel Prize 2006



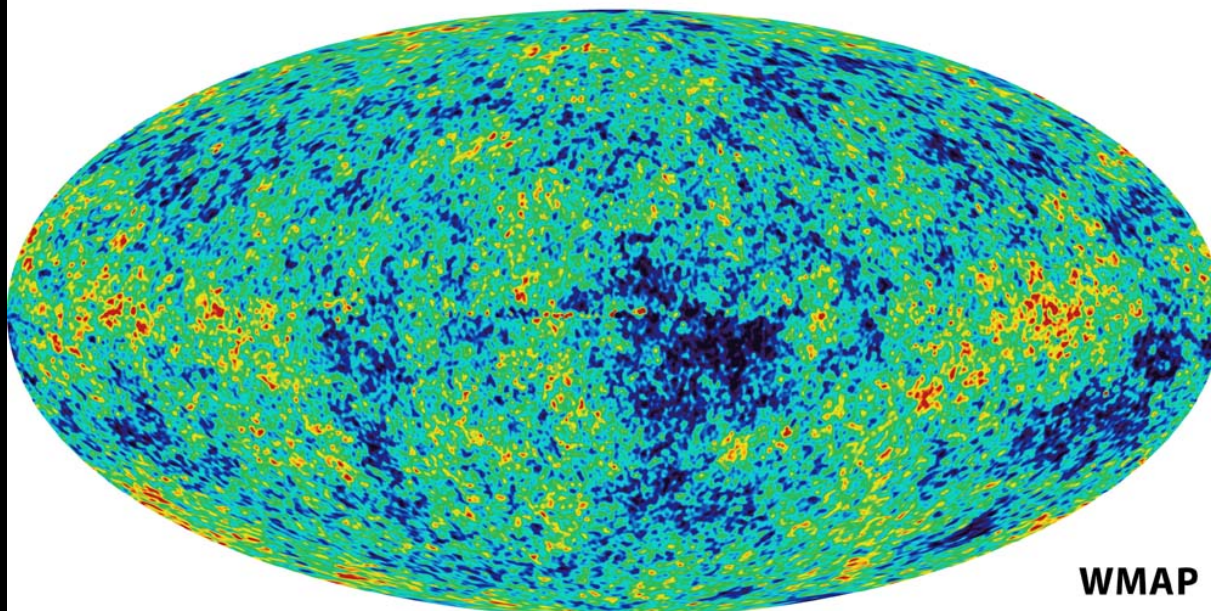
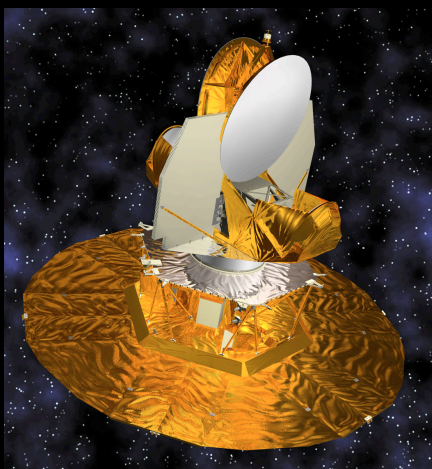
The CMB

1992



COBE

2003

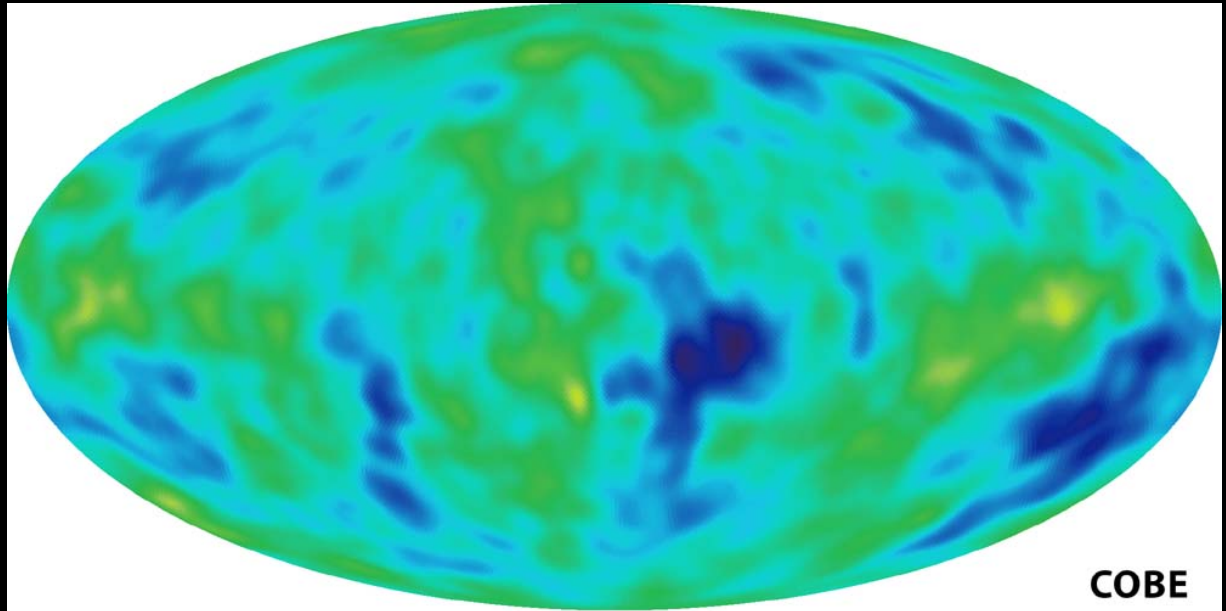


WMAP

ICC

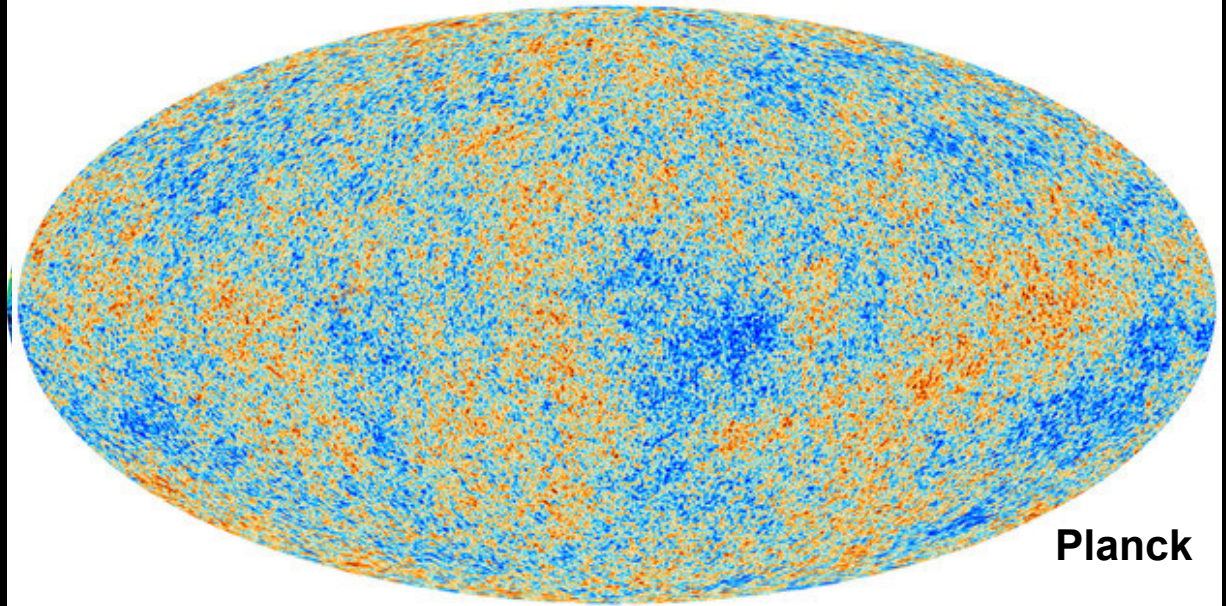
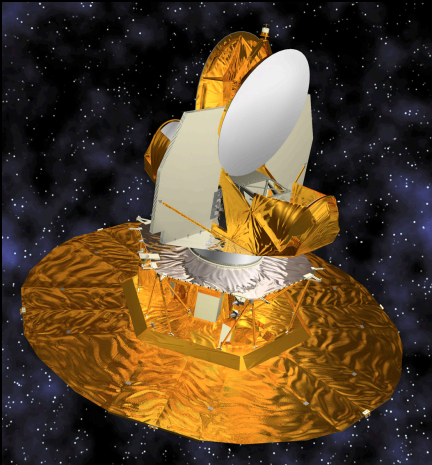
The CMB

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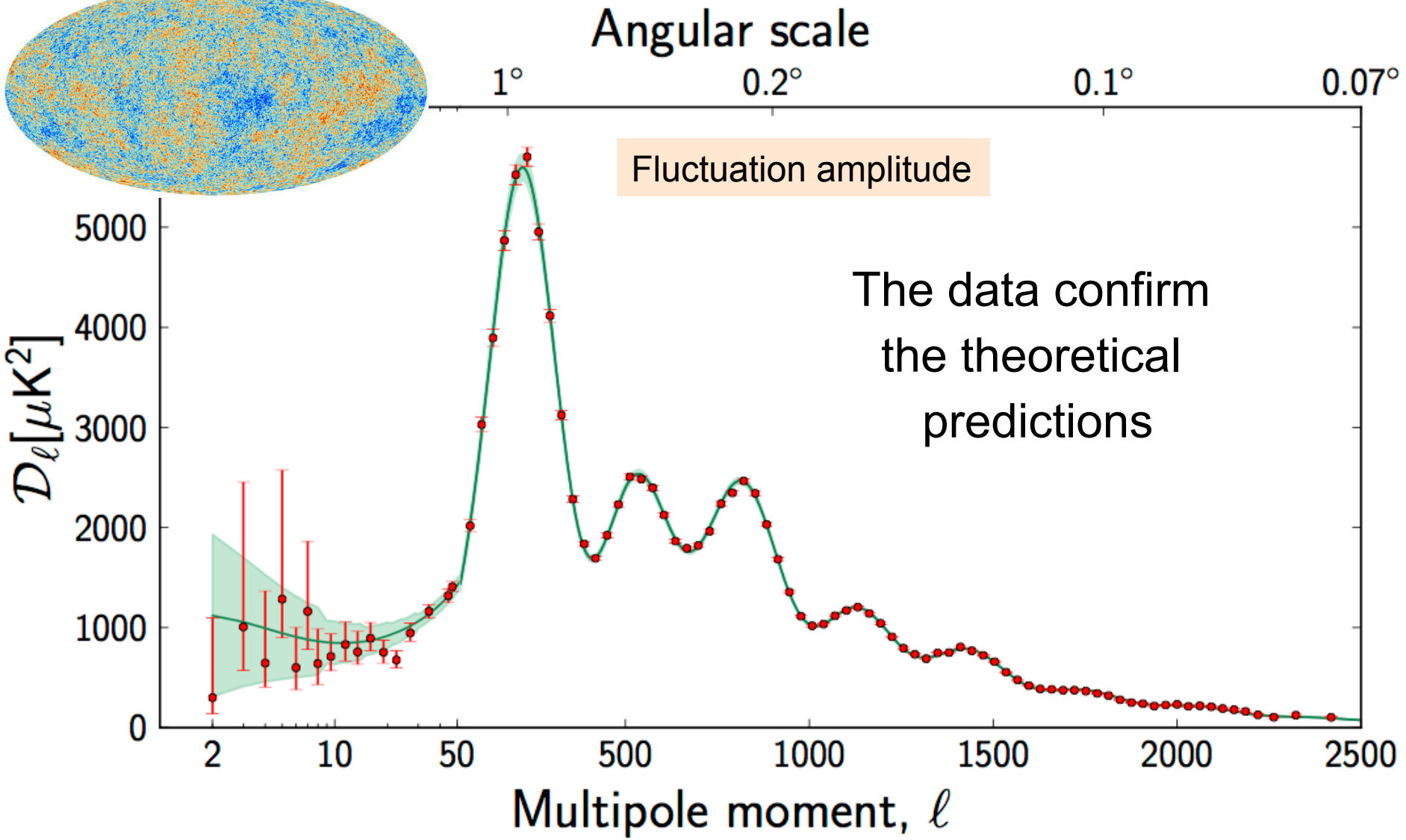
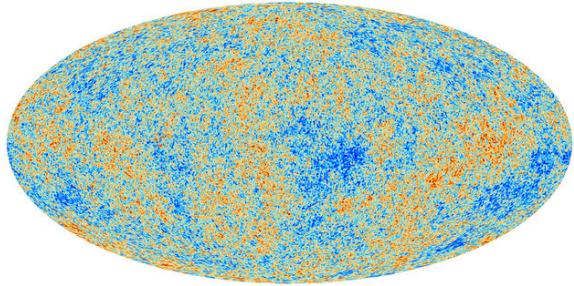
COBE

2012

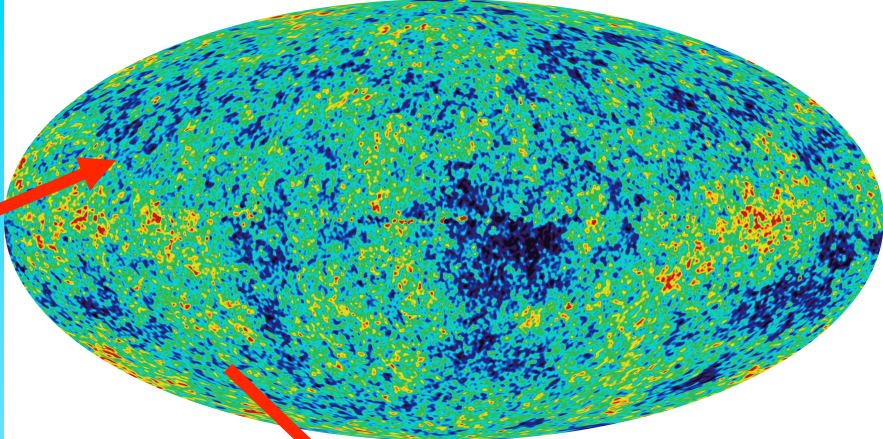
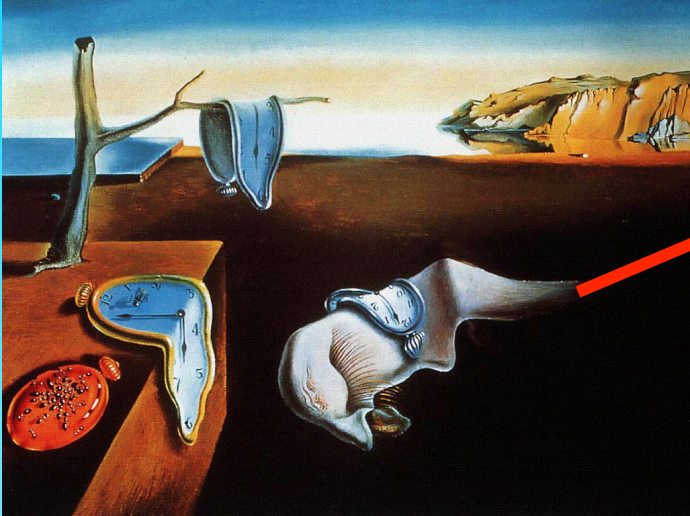


Planck

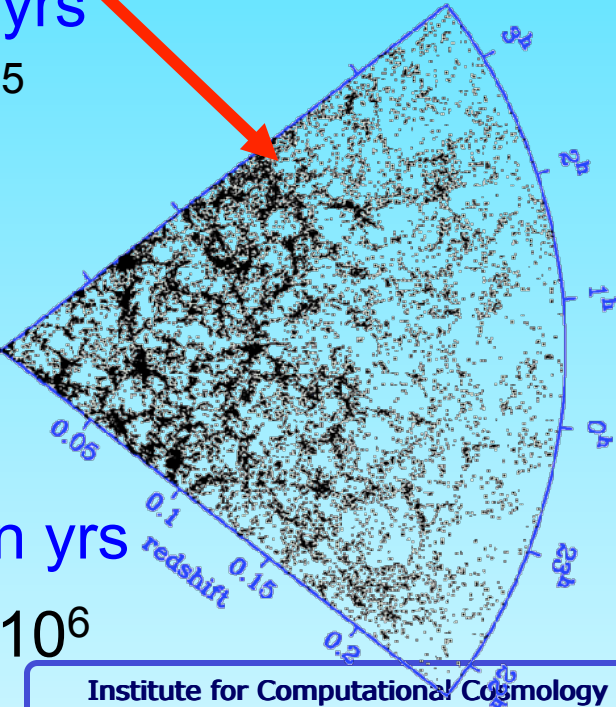
Planck: CMB temperature anisotropies



The growth of cosmic structure



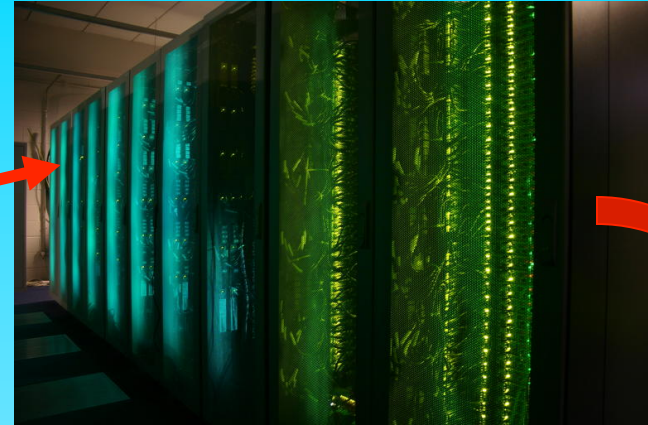
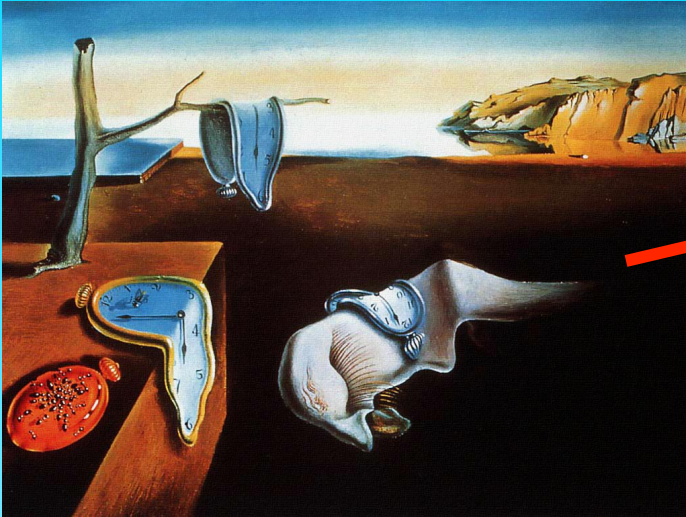
$t=380,000$ yrs
 $\delta\rho/\rho \sim 10^{-5}$



$t=13.8$ billion yrs
 $\delta\rho/\rho \sim 1-10^6$

Testing the cold dark matter paradigm

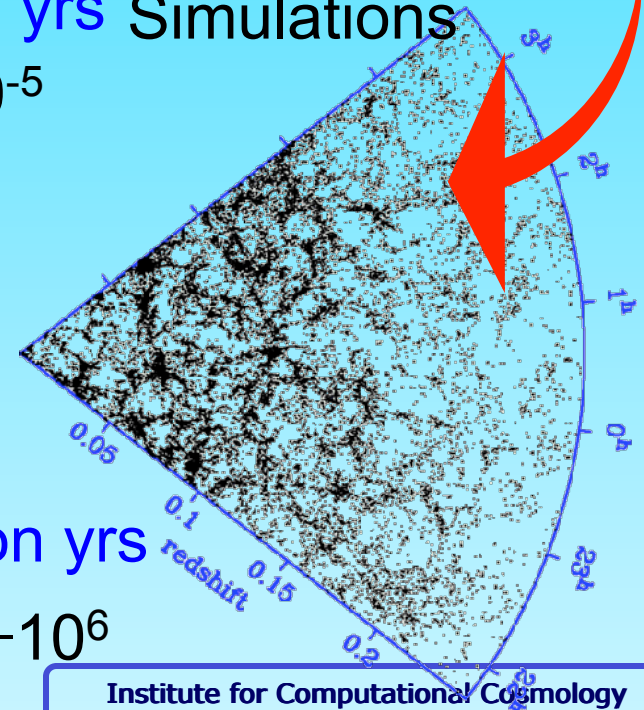
“Cosmology machine”



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



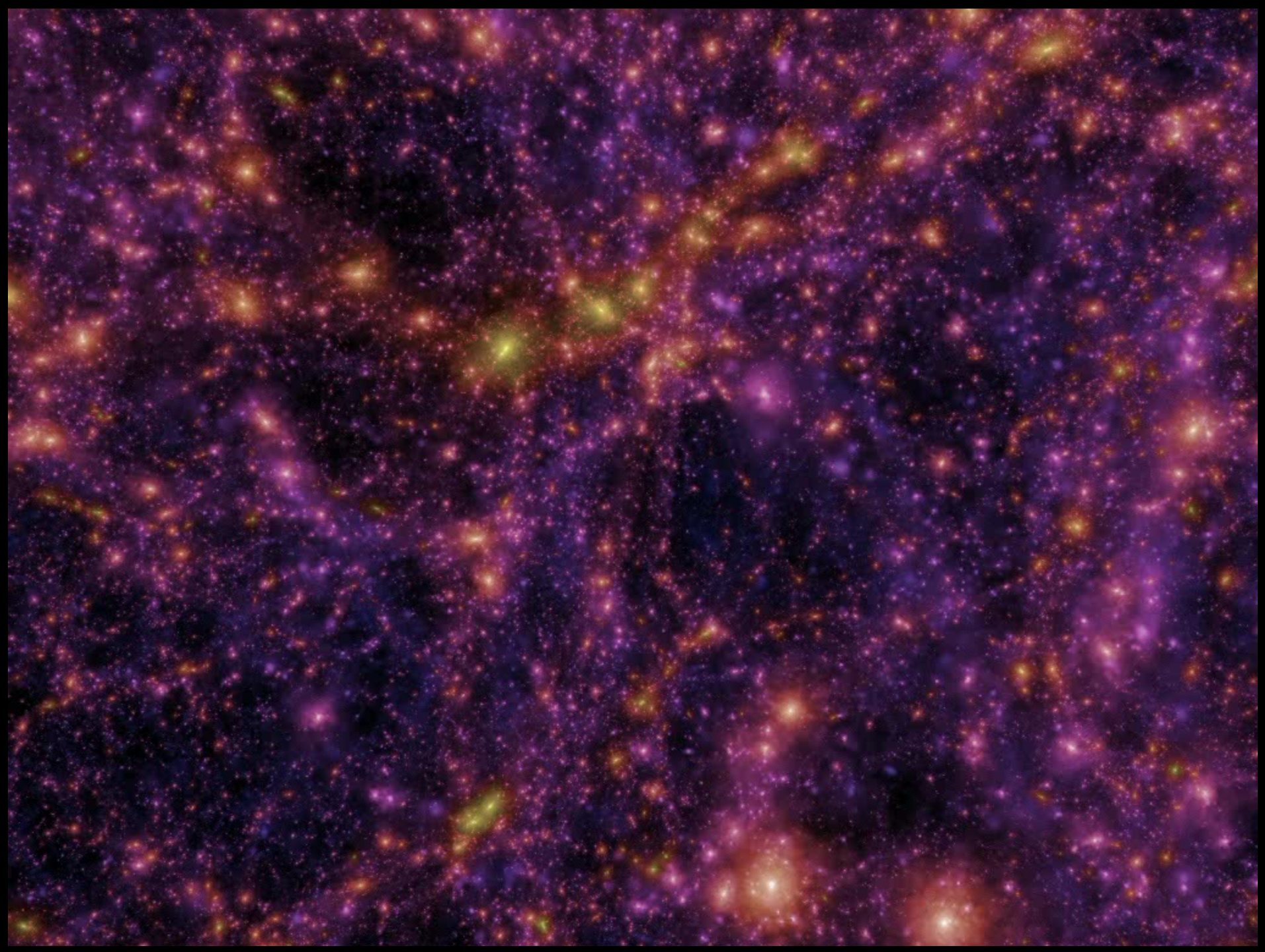
t=13.8 billion yrs

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

$z = 48.4$

$T = 0.05 \text{ Gyr}$

500 kpc



The EAGLE simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

A project of the Virgo consortium

$z = 19.9$

$L = 25.0 \text{ cMpc}$

Visible components:

CDM

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

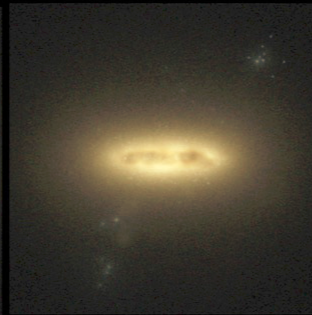
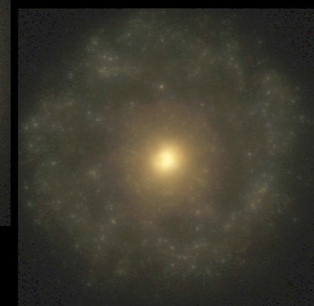
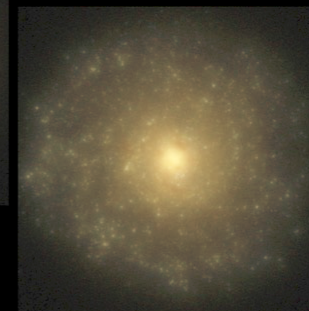
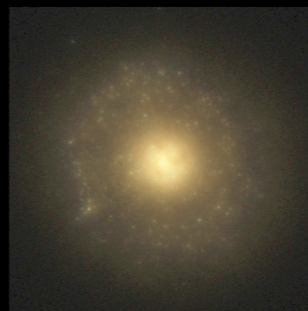
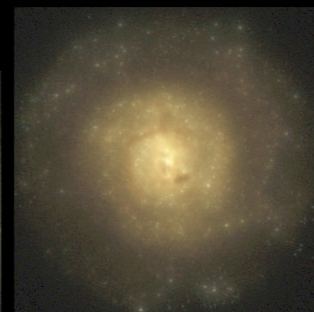
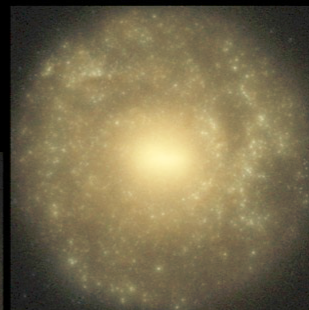
The Hubble Sequence realised in cosmological simulations

SB

E0

E7

S0



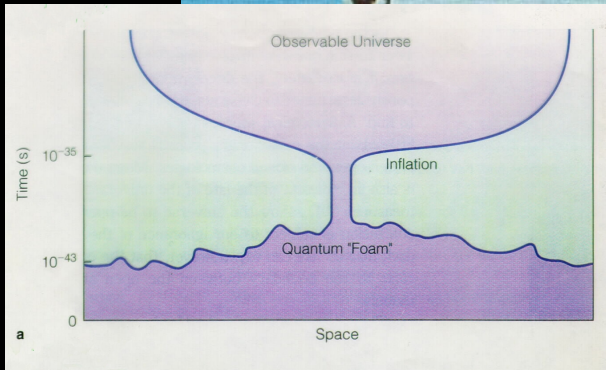
Irr

S

Trayford et al '15

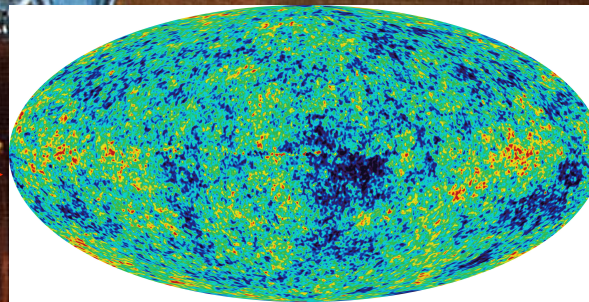
The origin of cosmic structure

Inflation ($t \sim 10^{-35}$ s)



Small (quantum) ripples

CMB ($t \sim 3 \times 10^5$ yrs)

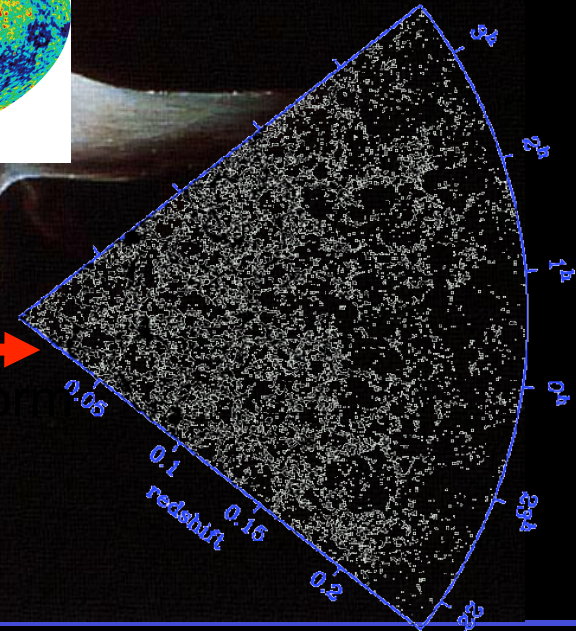


Galaxies ($t \sim 13 \times 10^9$ yrs)

Cold dark matter

Ripples seen as hot & cold spots in cosmic radiation

Galaxies



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

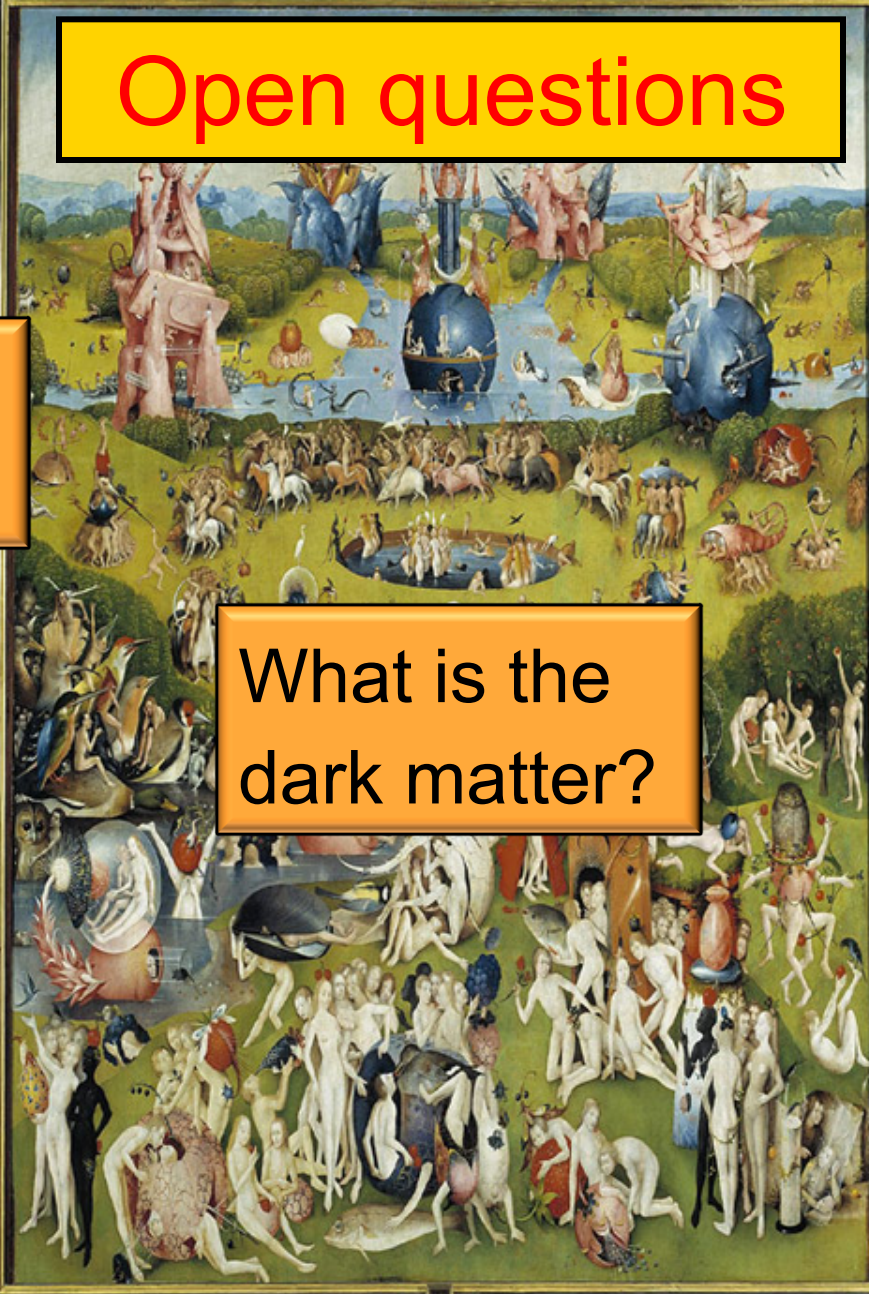
Is this the end of the story?



How did the universe begin?



Open questions



What is the dark matter?

What is the dark energy?



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

A nighttime photograph of a city skyline reflected in a body of water. The city lights are visible, including a prominent cathedral with a tall spire. The water is dark, and the lights create a shimmering reflection. A semi-transparent white box with blue text is overlaid on the bottom part of the image.

... but the best is still to come