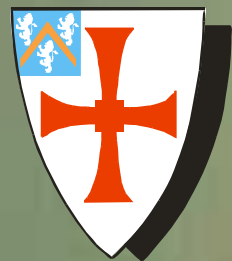


ICC





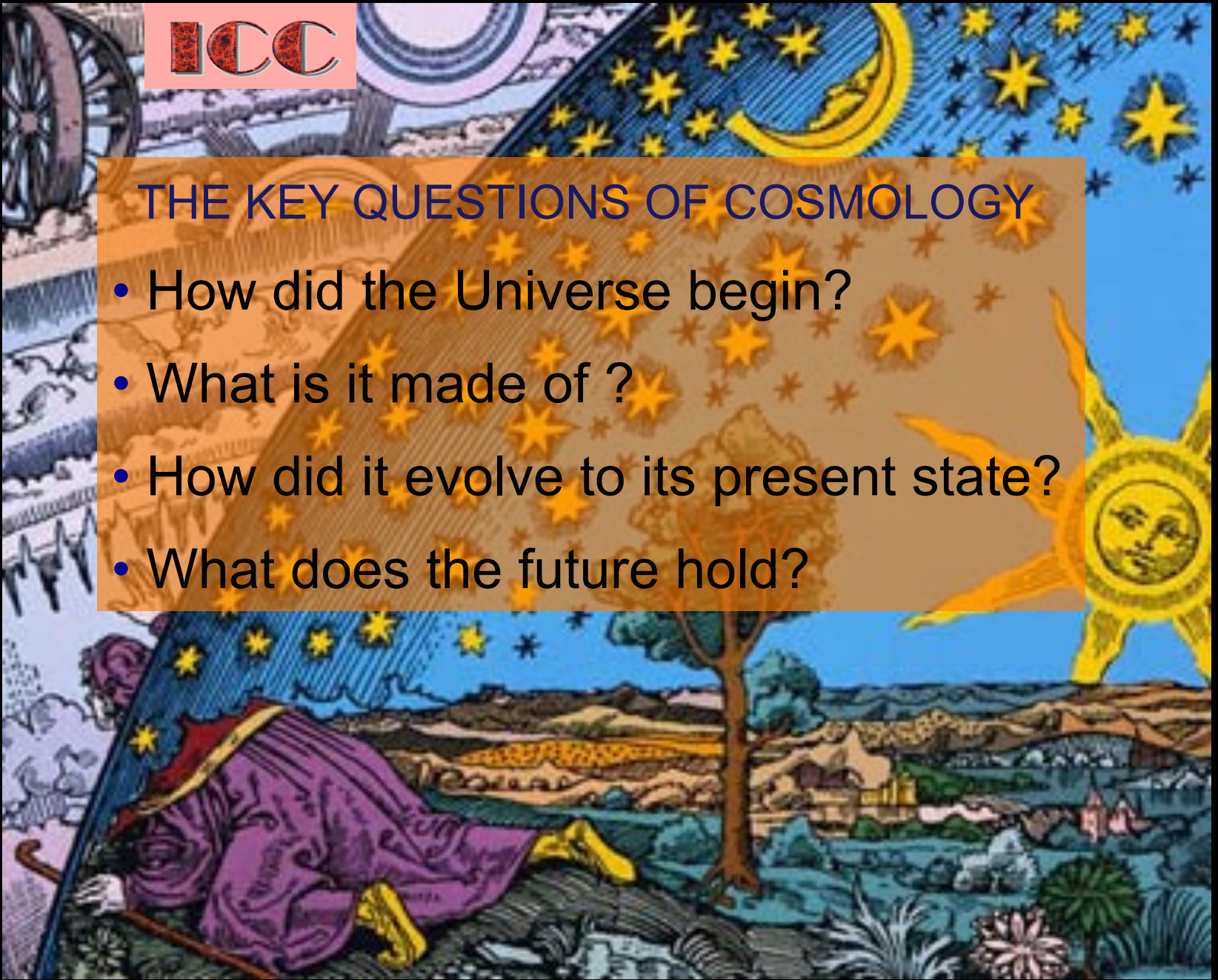
Everything from nothing: or how our Universe was made

Carlos S. Frenk
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 (?)

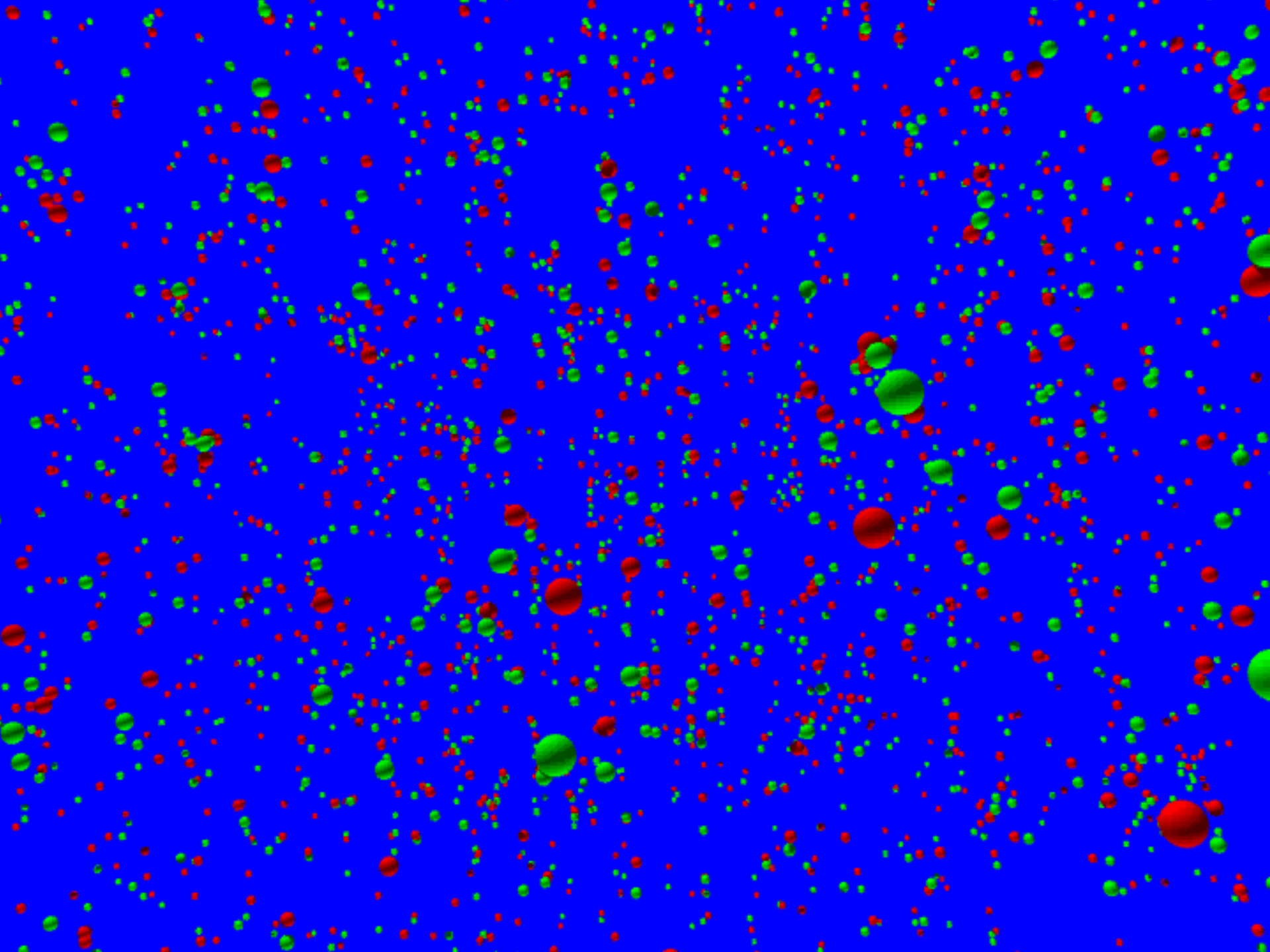
Cosmic history is a story about
nothing

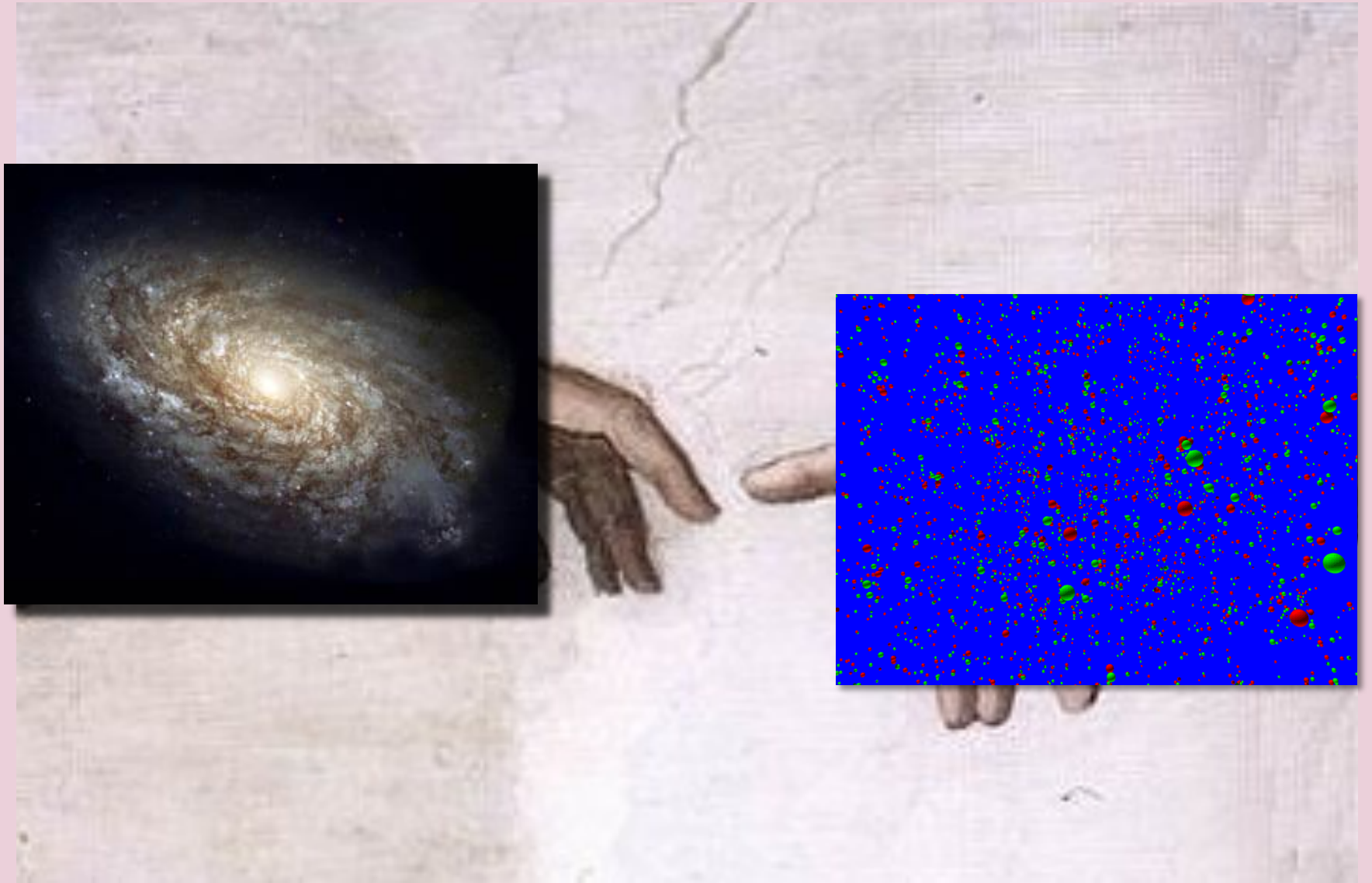
... or rather of how nothing became
everything

Nothing?

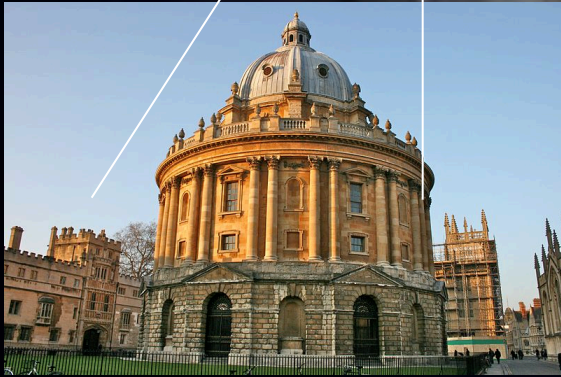
In physics “nothing” is called
the “vacuum”

... and the vacuum is full of energy ...
... the vacuum energy





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"

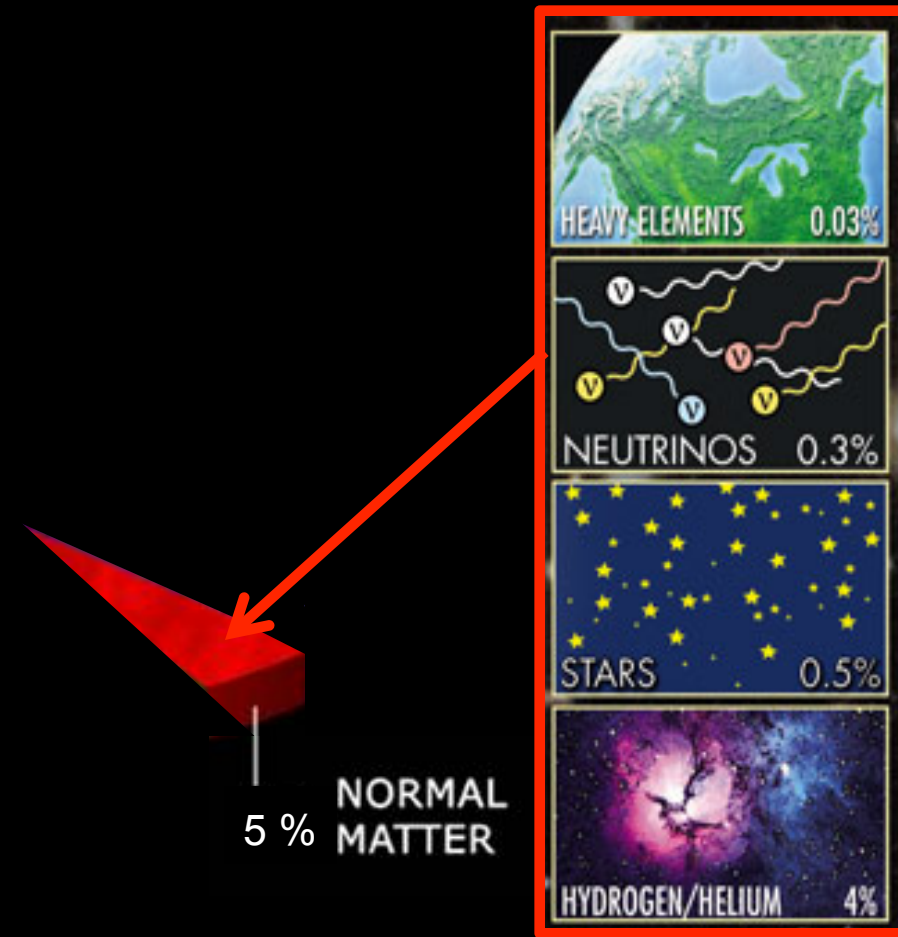
Courtesy NOVA/WGBH, PBS

Tom Lucas Productions



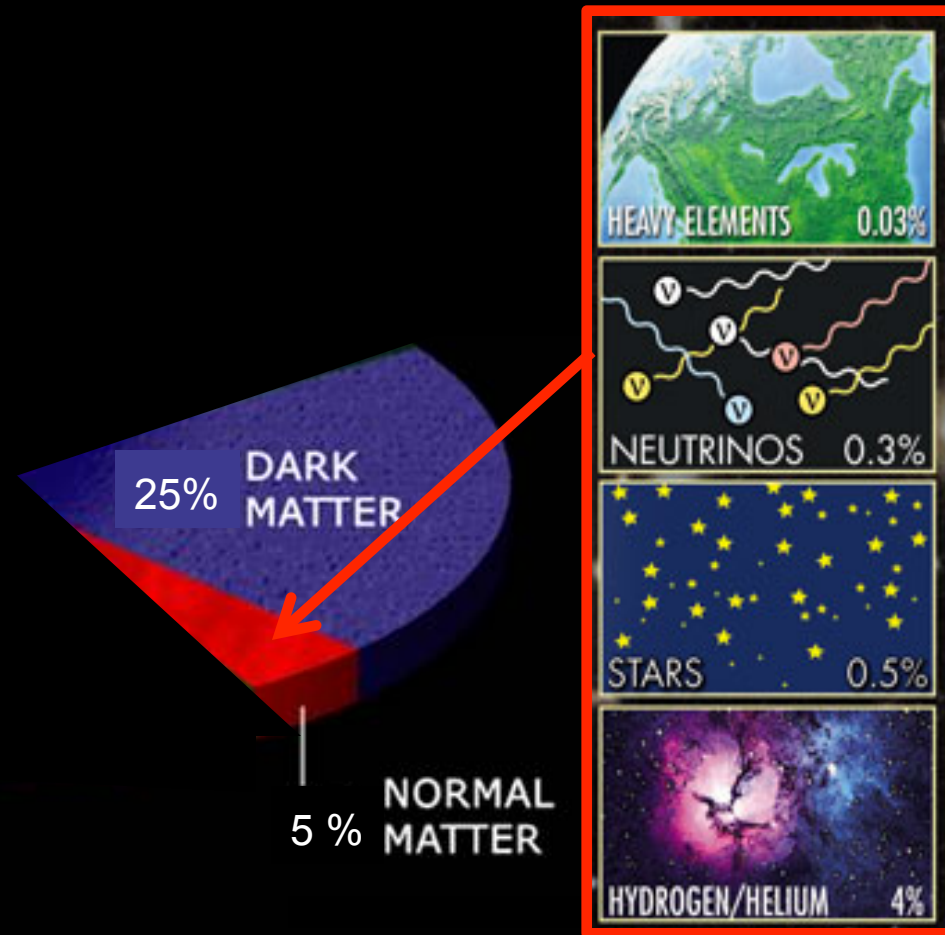
The content of the Universe

The content of our universe



Normal matter \equiv matter made of ordinary atoms

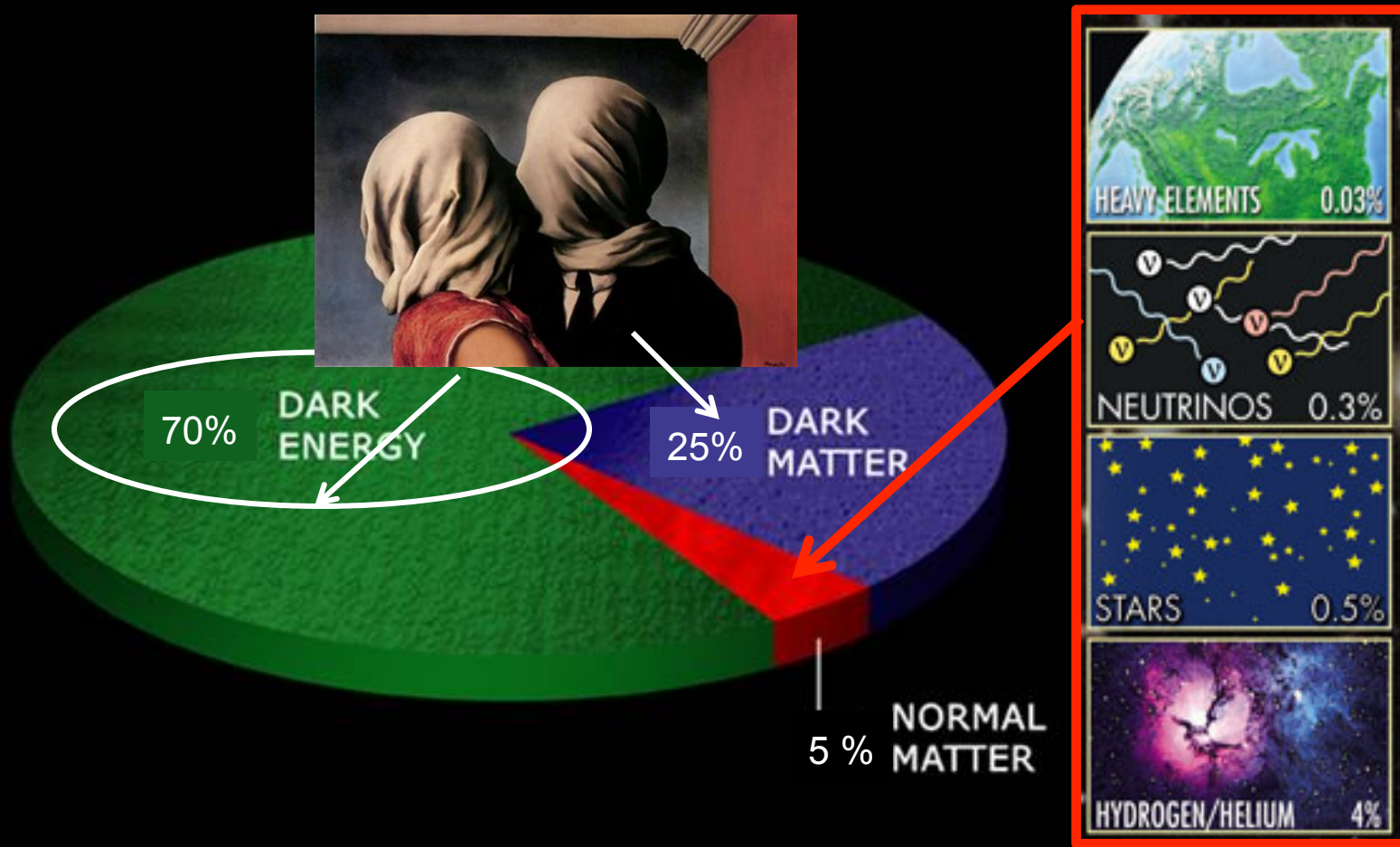
The content of our universe



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

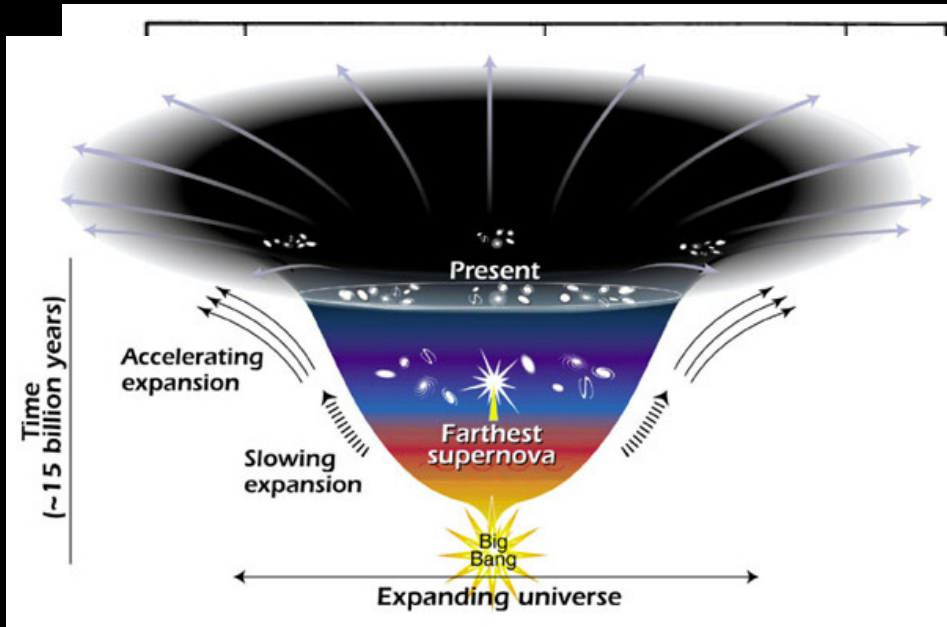
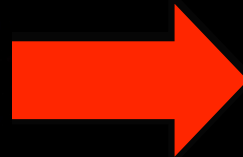
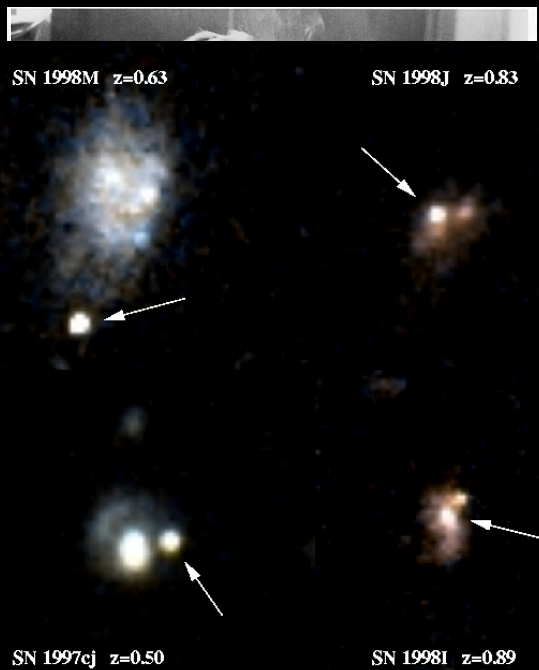


The content of our universe



Dark energy \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

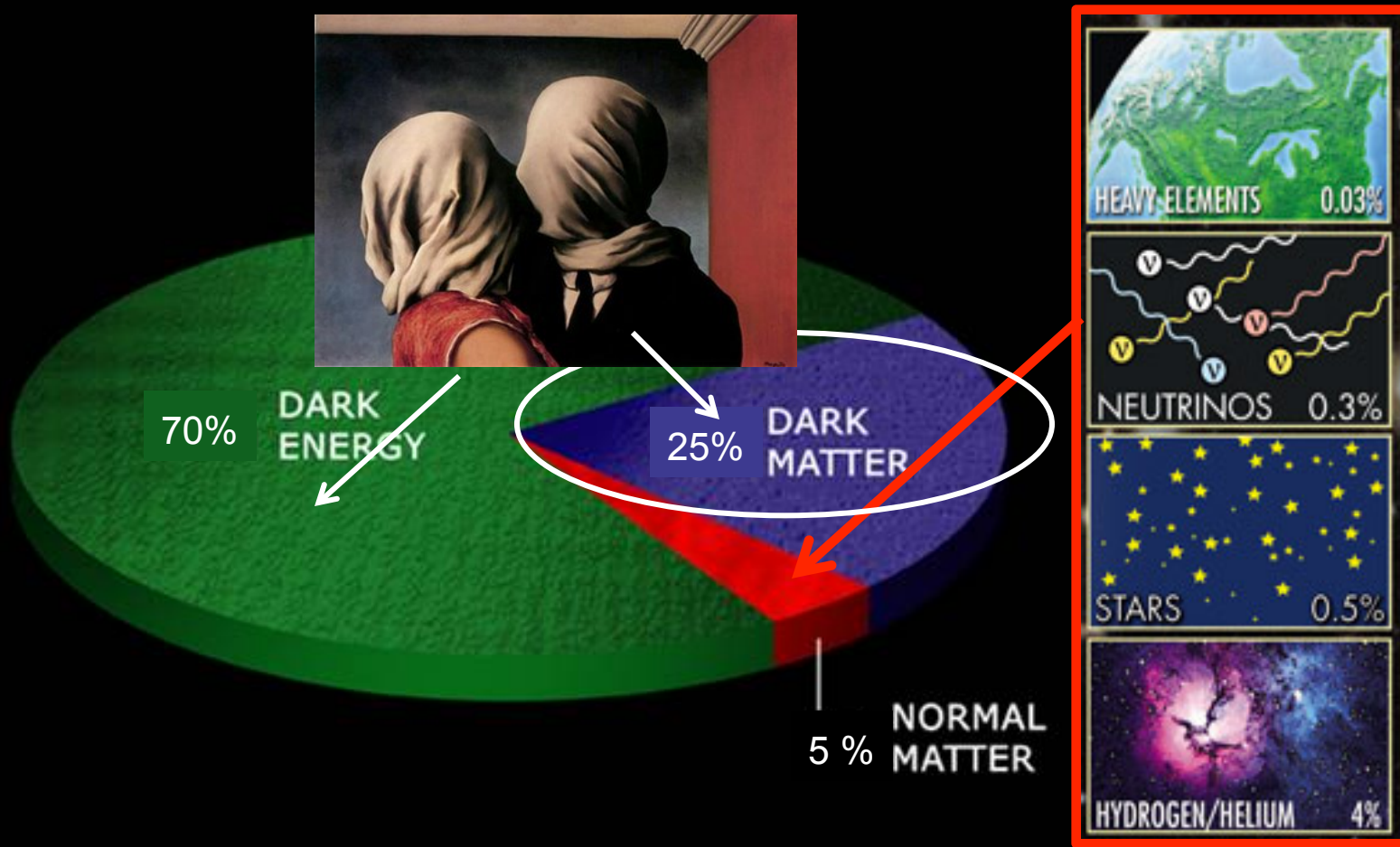
What is the cosmic dark energy?

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



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



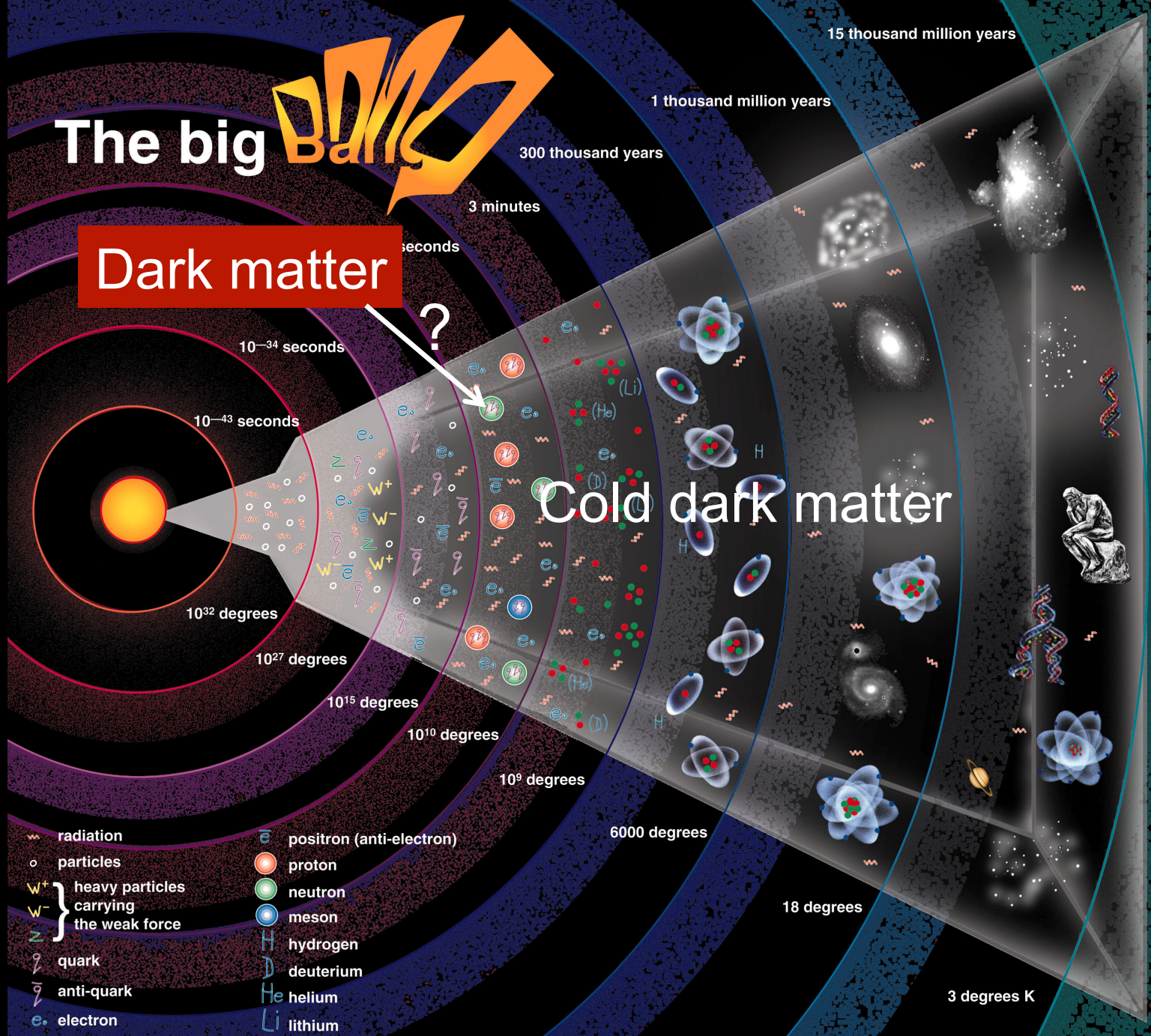
What is the dark matter?

The big Bang



Dark matter

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

15 thousand million years

1 thousand million years

300 thousand years

3 minutes

seconds

10^{-34} seconds

10^{-43} seconds

10^{32} degrees

10^{27} degrees

10^{15} degrees

10^{10} degrees

10^9 degrees

6000 degrees

18 degrees

3 degrees K

Key assumption: the dark matter is an elementary particle formed in the early universe, different from particles in ordinary atoms



The search for dark matter

Experimental physics



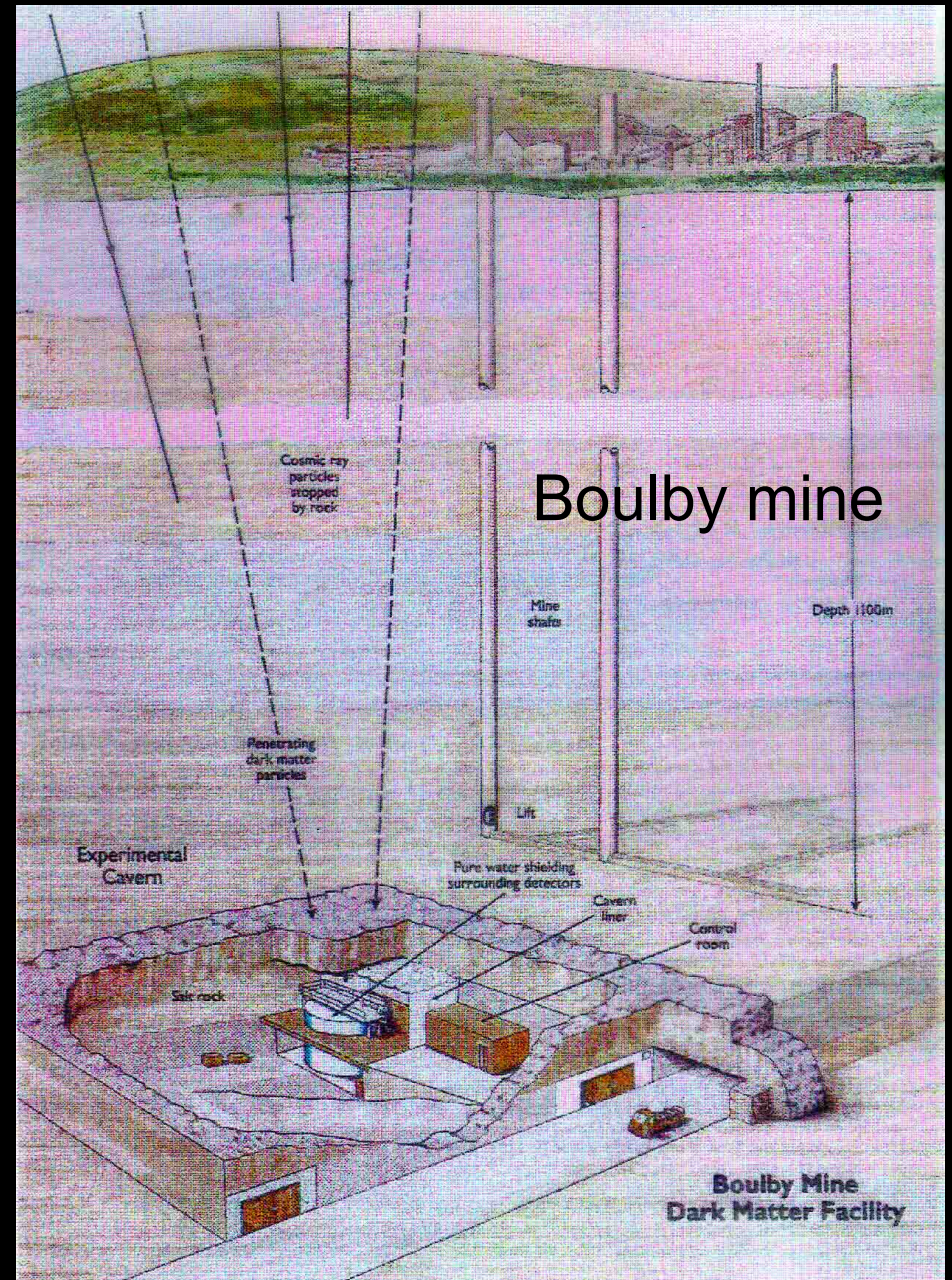
The search for dark matter



Searching for the dark matter ?



**UK DM search
(Boulby mine)**



Looking for dark matter ...
down the mine
(where cosmic rays can't
penetrate)



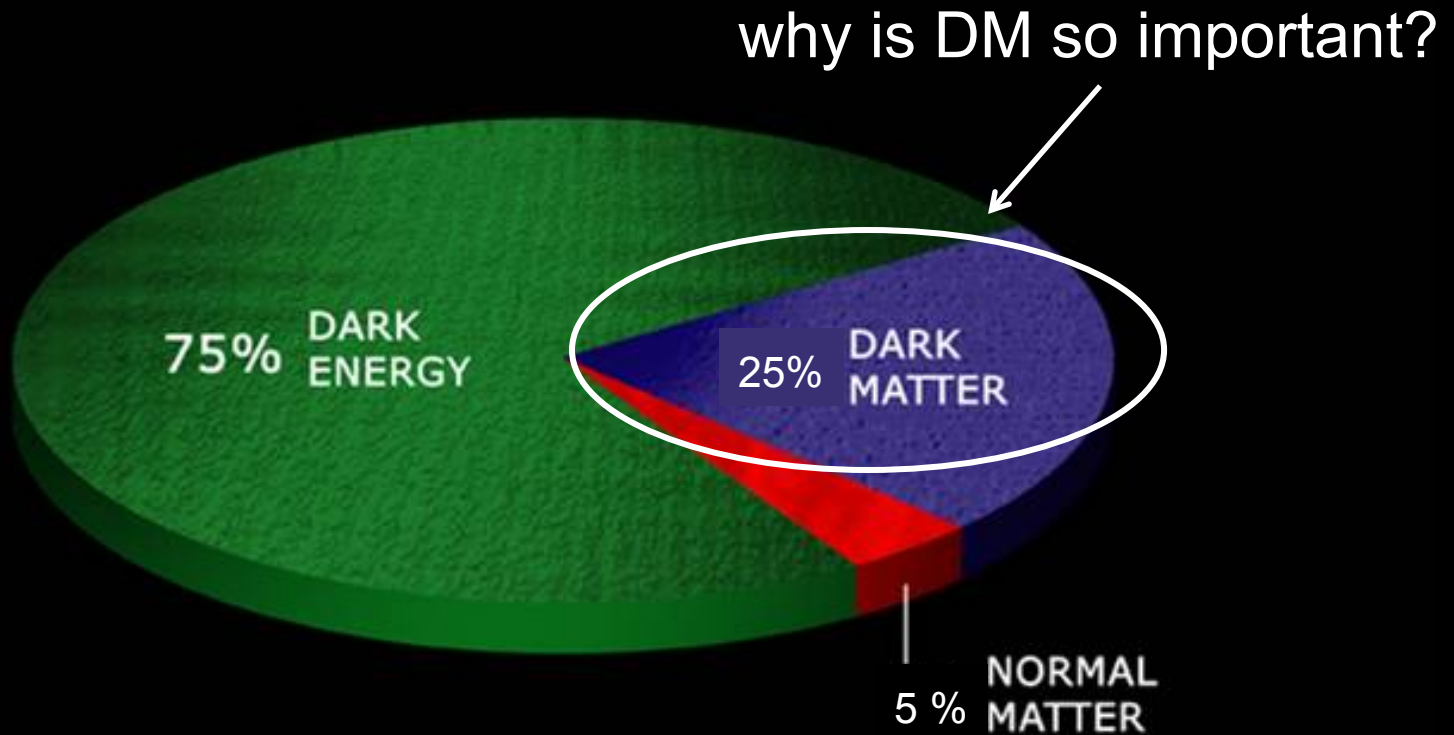
FIRE EXTINGUISHER
KEEP CLEAR

THE GREAT WALL
AGREEMENT
1985-1986

44

38

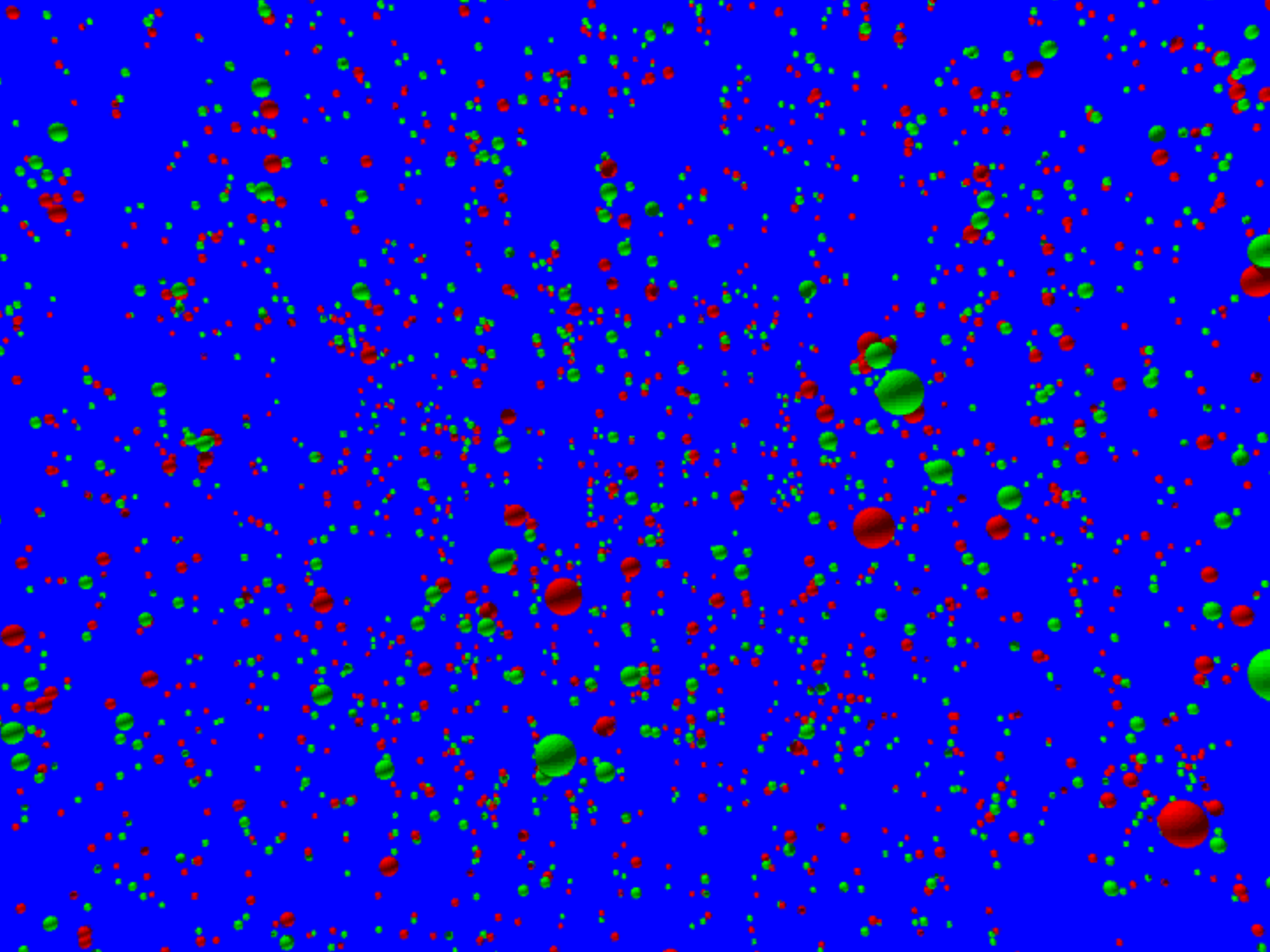
The content of our universe



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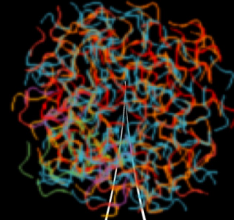
The gravity of the dark matter drives
Where do the galaxies come from?
formation of cosmic structure



The initial conditions

INFLATION

$t=10^{-35}$ sec

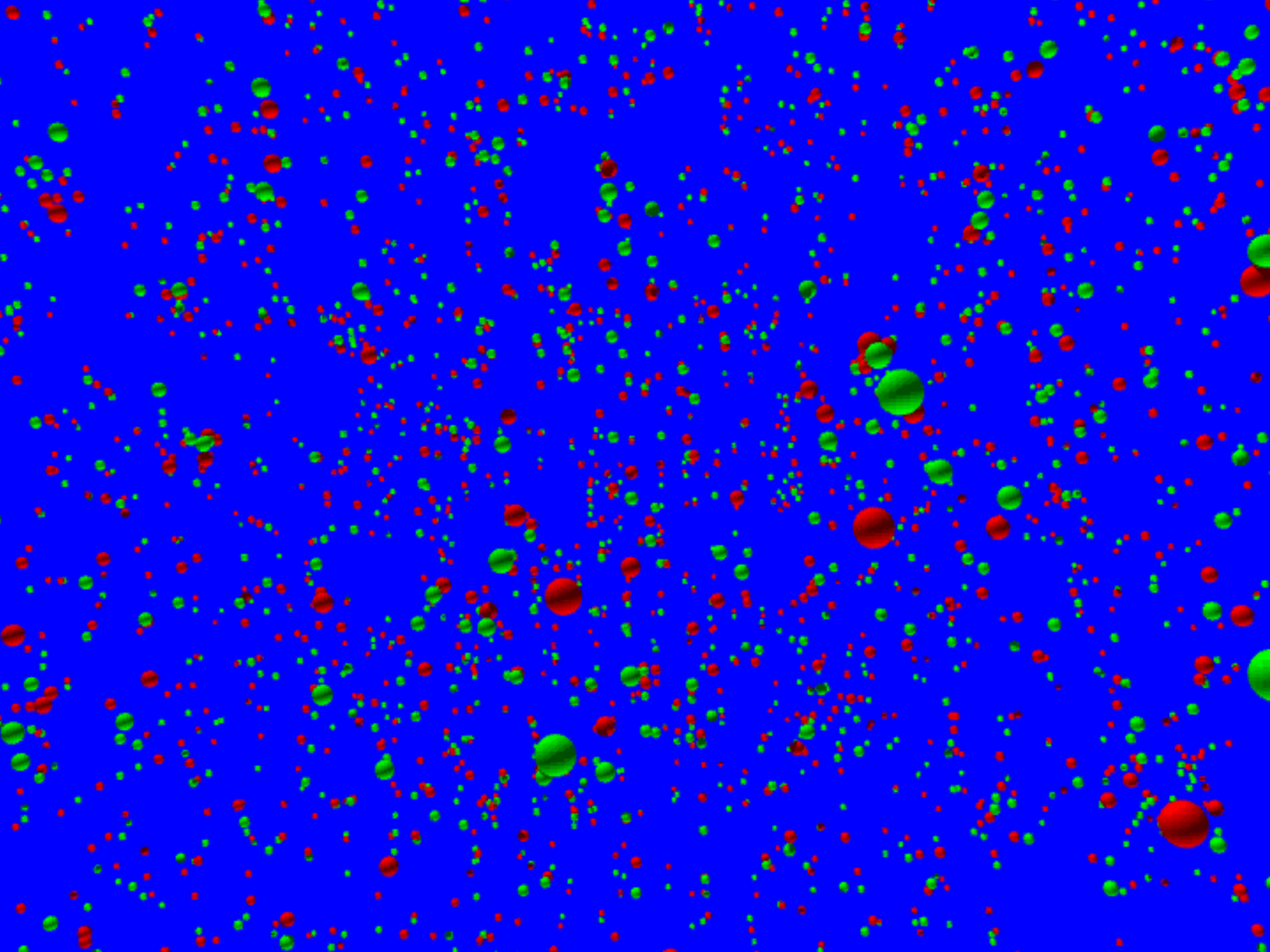


QUANTUM
SPACE-TIME
FOAM?

BLAP!

**THE ENTIRE
OBSERVABLE
UNIVERSE!**

from G. Efstathiou

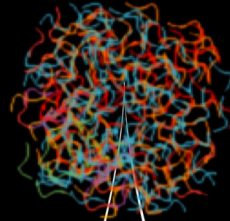


The initial conditions

INFLATION

$t=10^{-35}$ sec

Inflation theory predicts early universe seeded by tiny fluctuations in mass produced by quantum processes



QUANTUM SPACE-TIME FOAM?

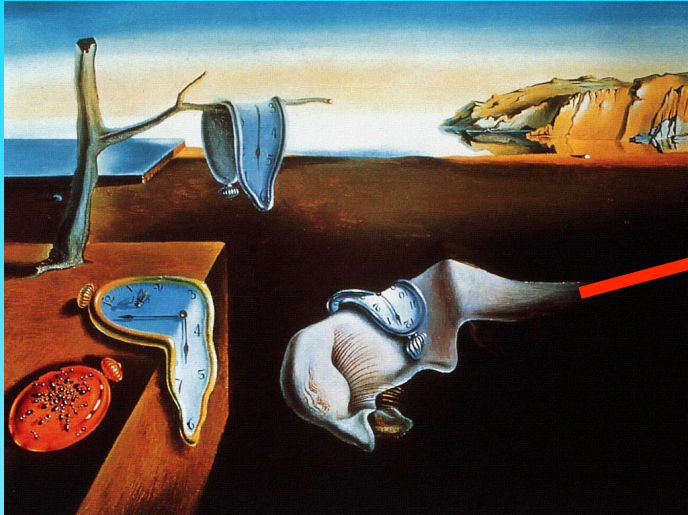
tiny mass irregularities

BLAP!

THE ENTIRE OBSERVABLE UNIVERSE!

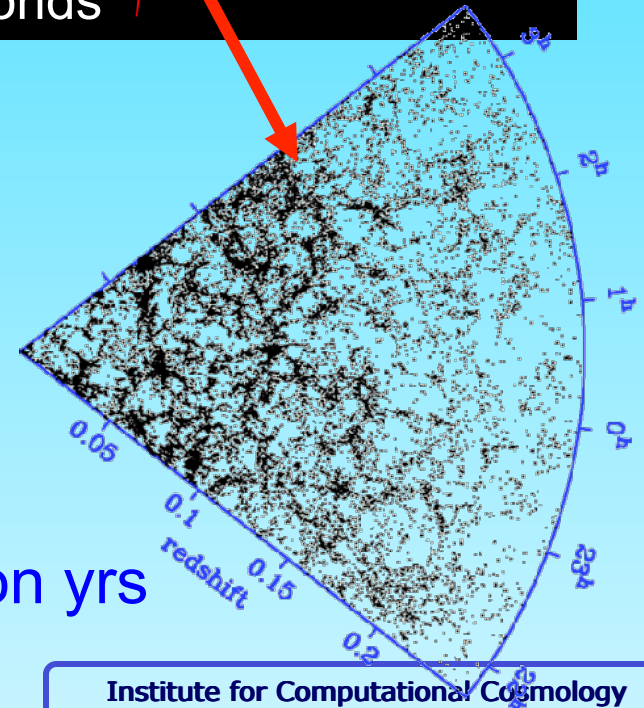


The growth of cosmic structure



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

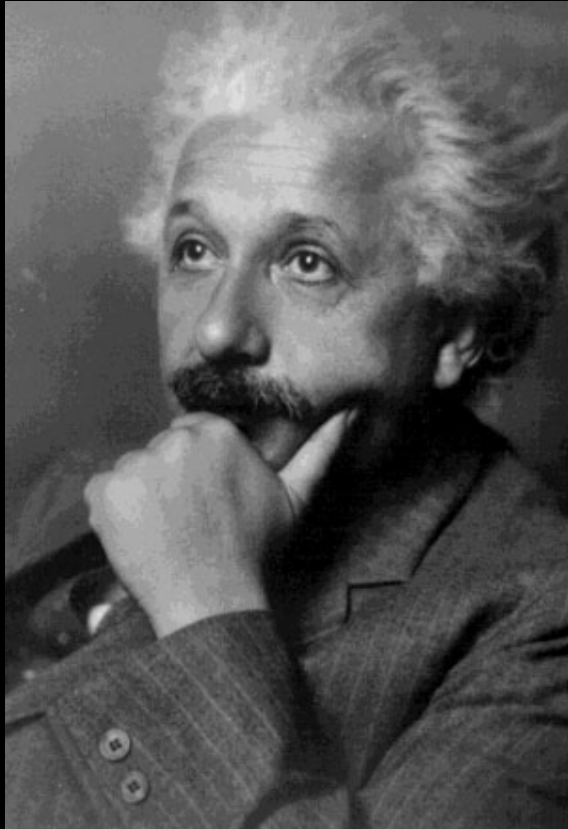
*Small irregularities
in the early universe
grow under the
action of gravity:*

500 million light years

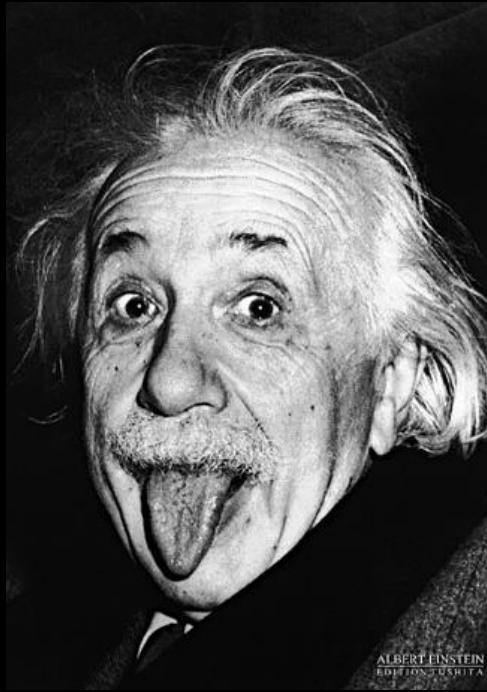
$t = 0.06 \text{ Gyr}$



The force of gravity



The force of gravity



The science of the Universe

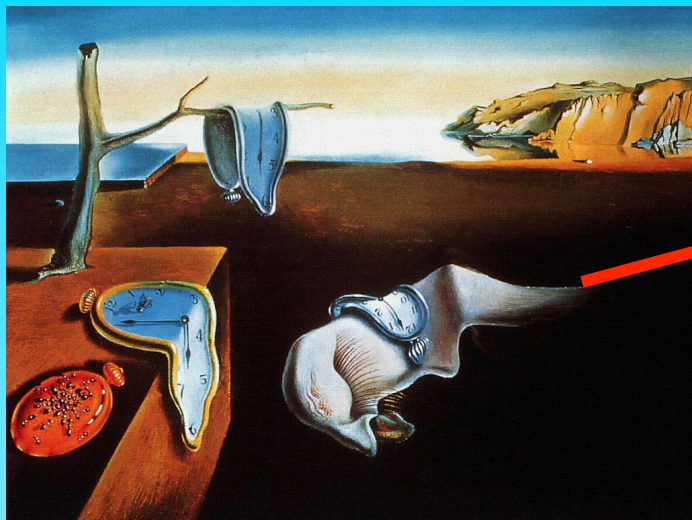
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The laws of Physics: general rules about natural phenomena, derived empirically and expressed mathematically, e.g. Newton's law of gravitation, Boyle's gas law, quantum mechanics, relativity

- Experimentally verified on Earth
- Universal

To be Physics, it must be testable!

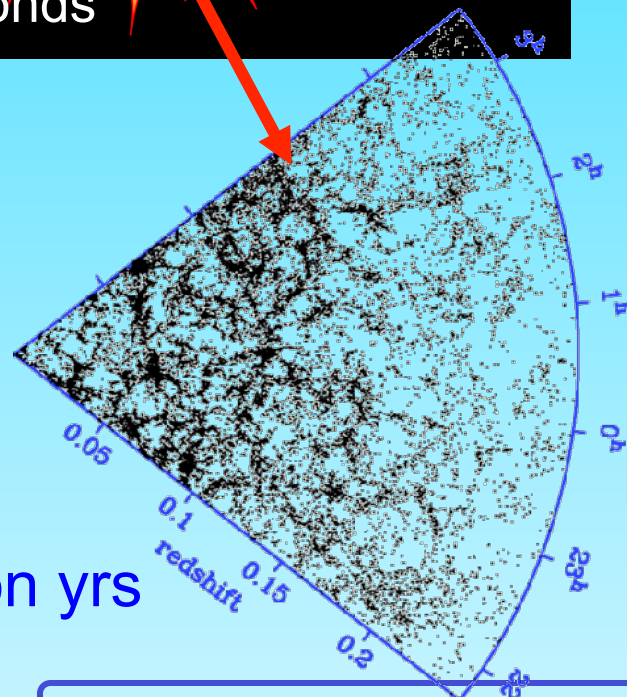
The growth of cosmic structure



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

How do we test this?

$t=13.8$ billion yrs





Need to be able to look into the past!



We can because light travels at a finite speed
(300,000 km/s)

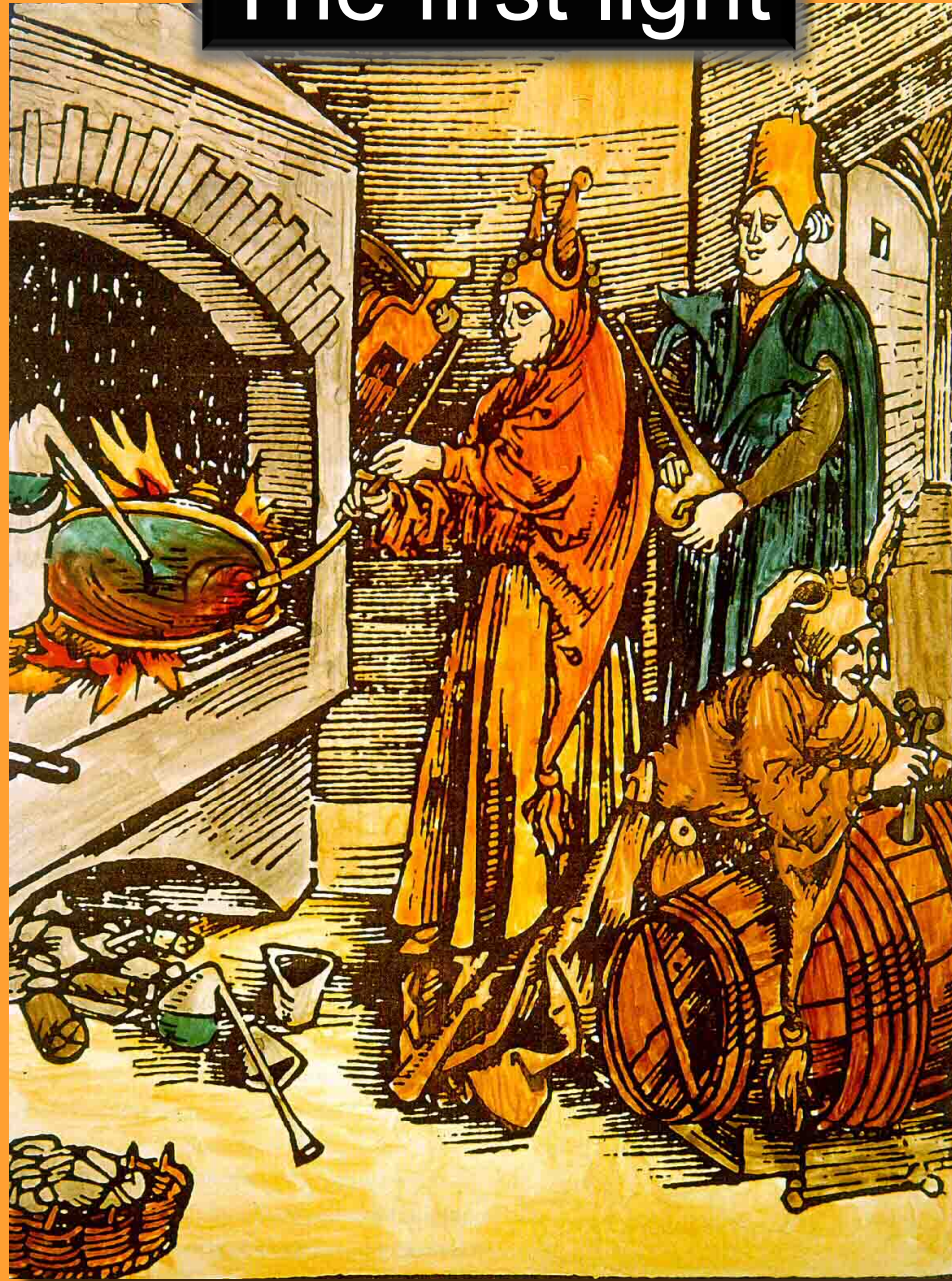


Need to be able to look into the past!



The farther away an object is, the longer its light has been travelling and the farther into the past we can see

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 thousand years

3 minutes

10^{-5} seconds

10^{-10} seconds

10³²

The early universe was foggy

10^{32} degrees

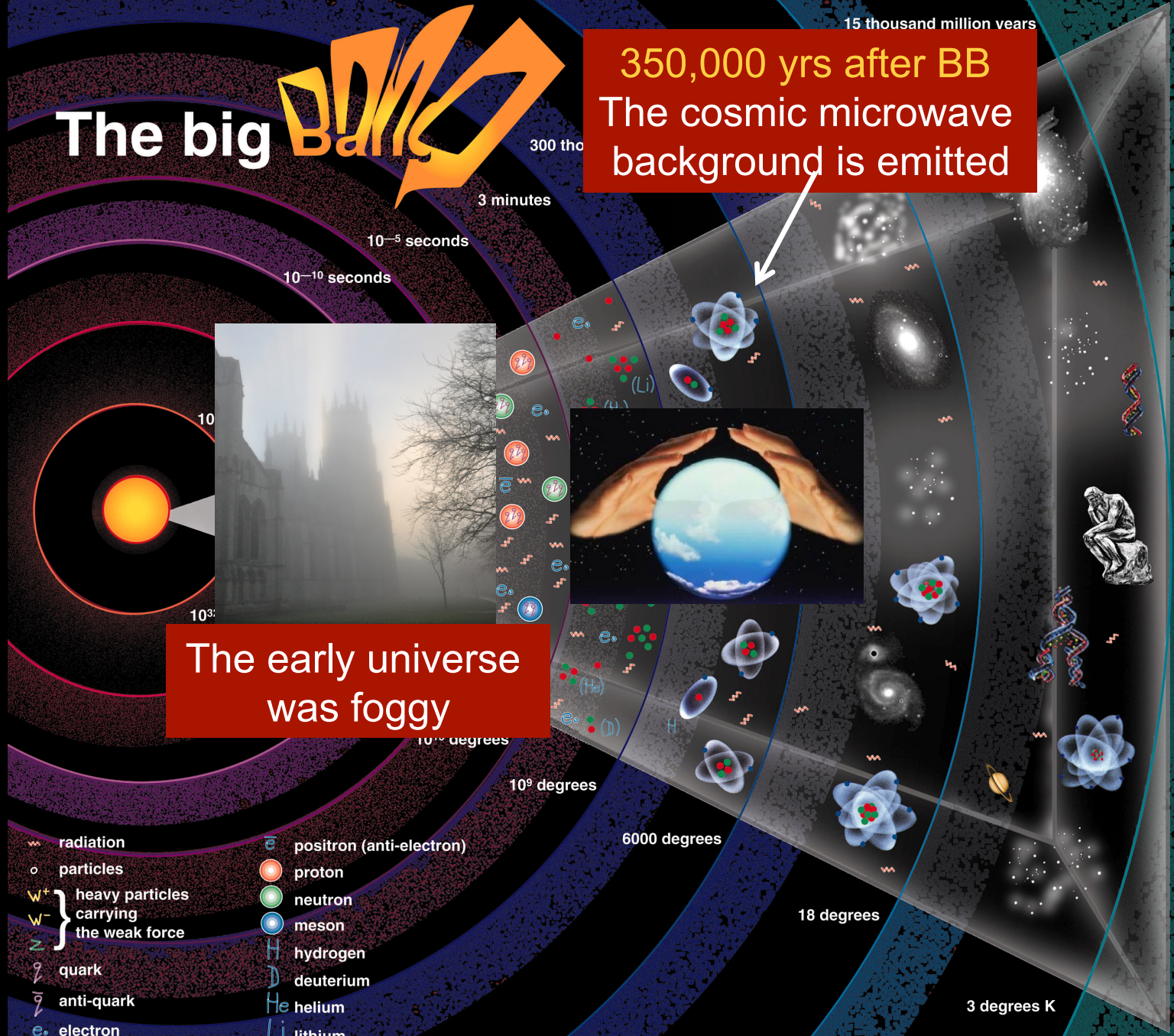
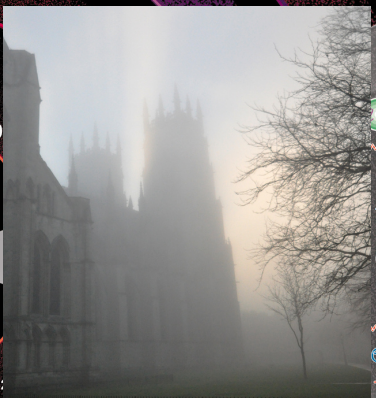
10⁹ degrees

6000 degrees

18 degrees

3 degrees K

- ⌚ radiation
- particles
- W⁺ heavy particles carrying the weak force
- W⁻ heavy particles carrying the weak force
- Z heavy particles carrying the weak force
- q quark
- q̄ anti-quark
- e⁻ electron
- e⁺ positron (anti-electron)
- p proton
- n neutron
- m meson
- H hydrogen
- D deuterium
- 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.

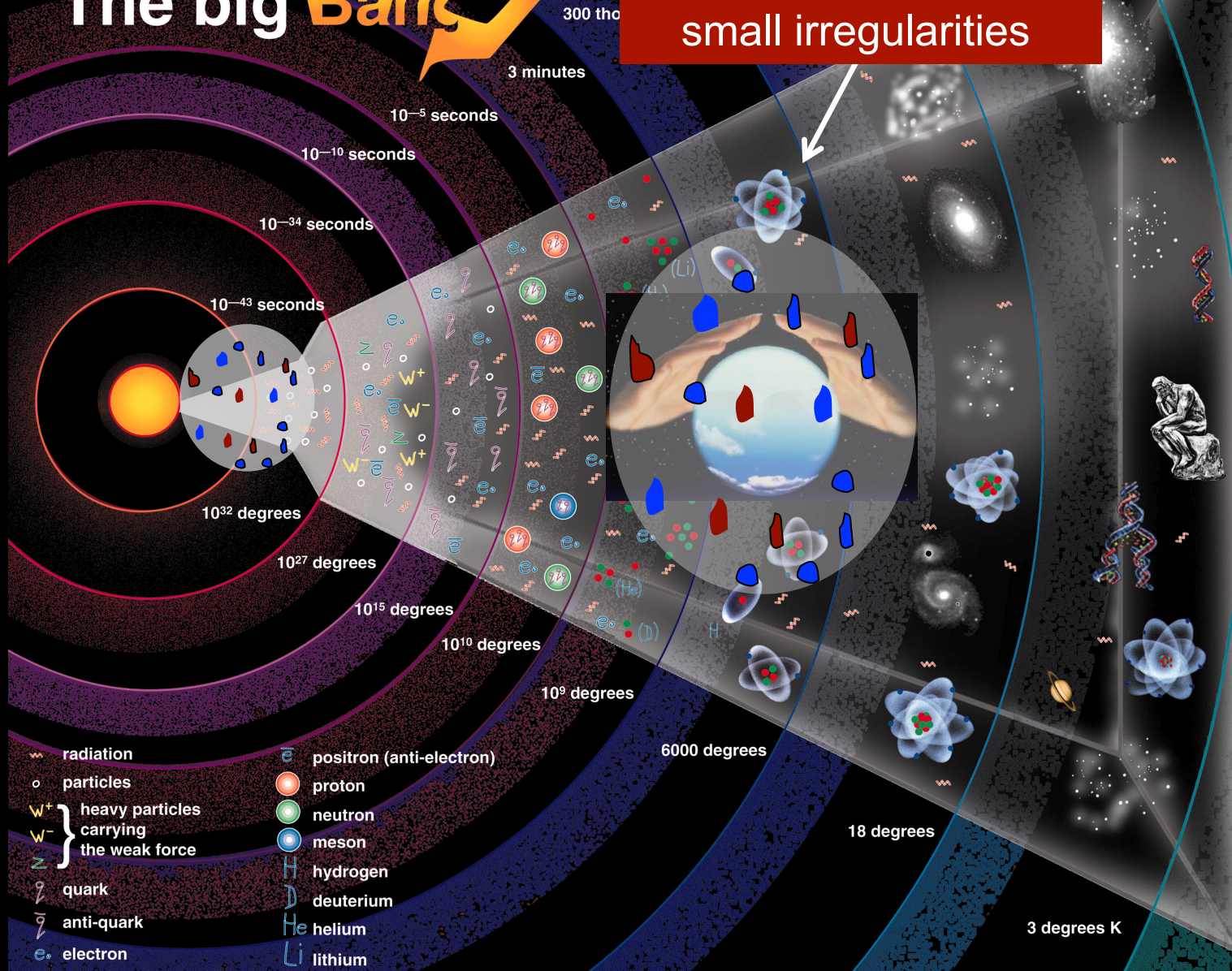


The big Bang



The temperature of this radiation should show small irregularities

15 thousand million years



- radiation
- particles
- W^+ heavy particles carrying the weak force
- W^- heavy particles carrying the weak force
- Z heavy particles carrying the weak force
- q quark
- \bar{q} anti-quark
- e^- electron
- e^+ positron (anti-electron)
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The big Bang



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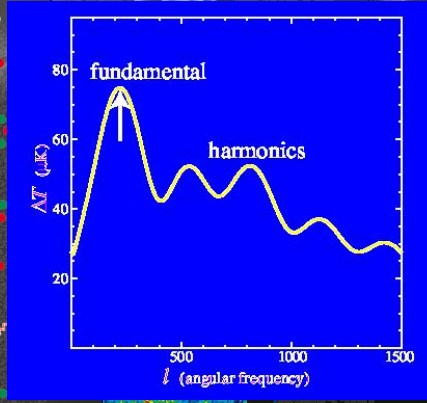
10^{10} degrees

10^9 degrees

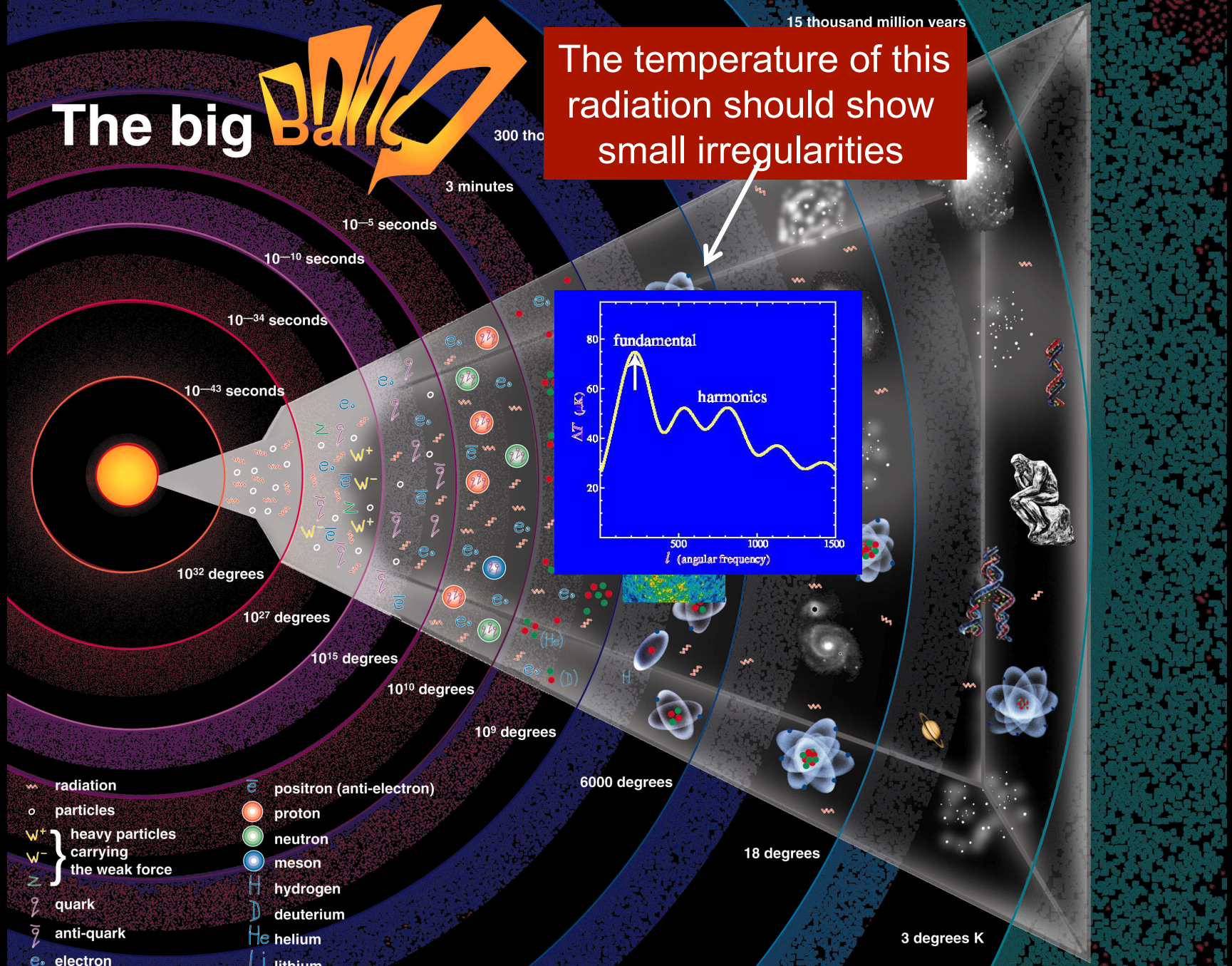
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18 degrees

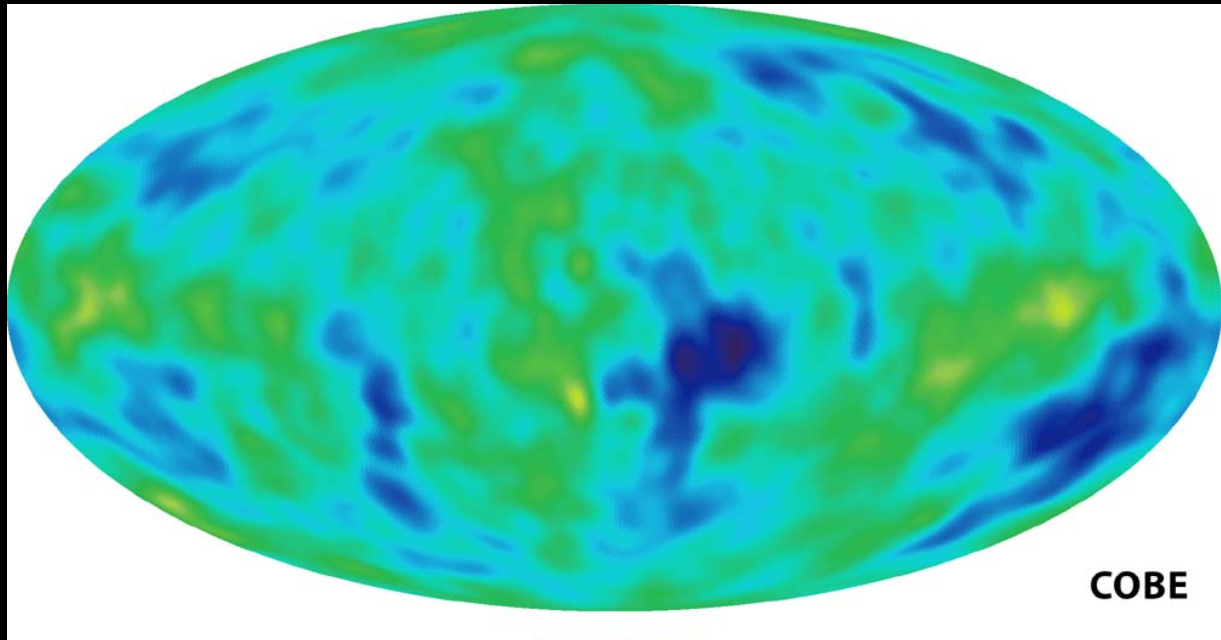
3 degrees K



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- Li lithium



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 confirmed, "it's one of the major discoveries of the century. In fact, it's one of the major discoveries of science."

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 towards 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.

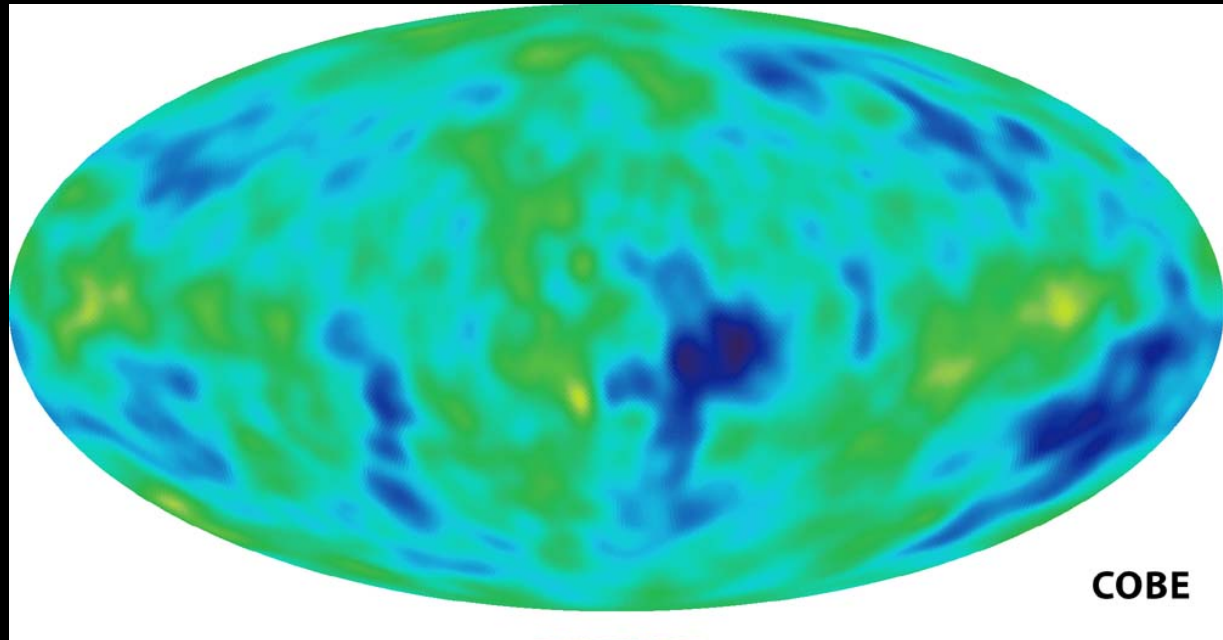
A remnant glow from the Big Bang is still around today, in the form of microwave radiation that has bathed the universe for the billions of years since the explosion. Galaxies must have formed by growing gravitational forces bringing matter together. To produce a "lumpy" universe, radiation from the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

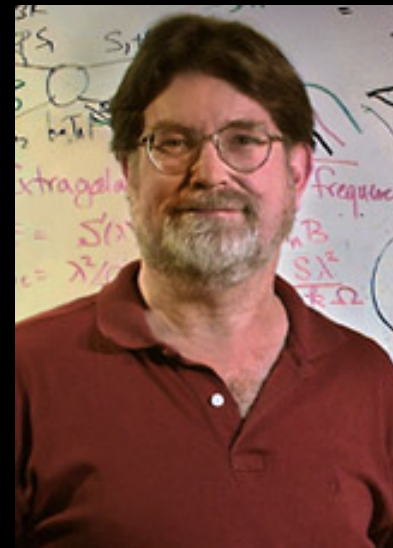
Cobe detected almost imperceptible variations in the tem-

ceptible variations in the tem- surrounded by slightly less dense time when the foggy fireball of ra- and light from these galaxies, re- predictions about what the size of the original fog lifted."

1992

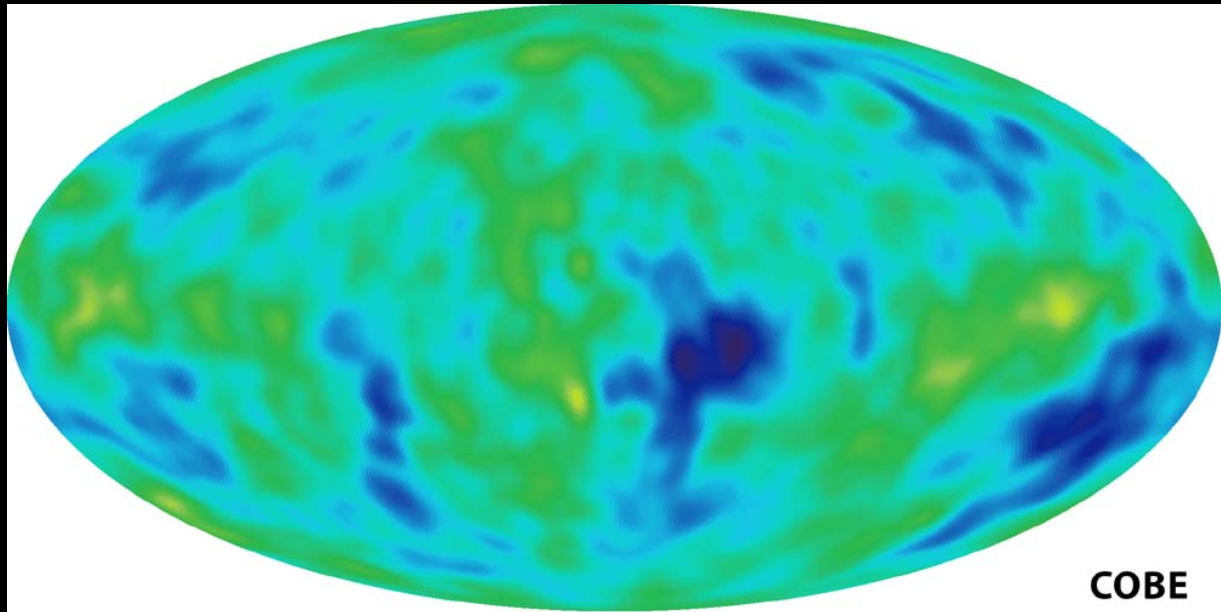


George Smoot - Nobel Prize 2006



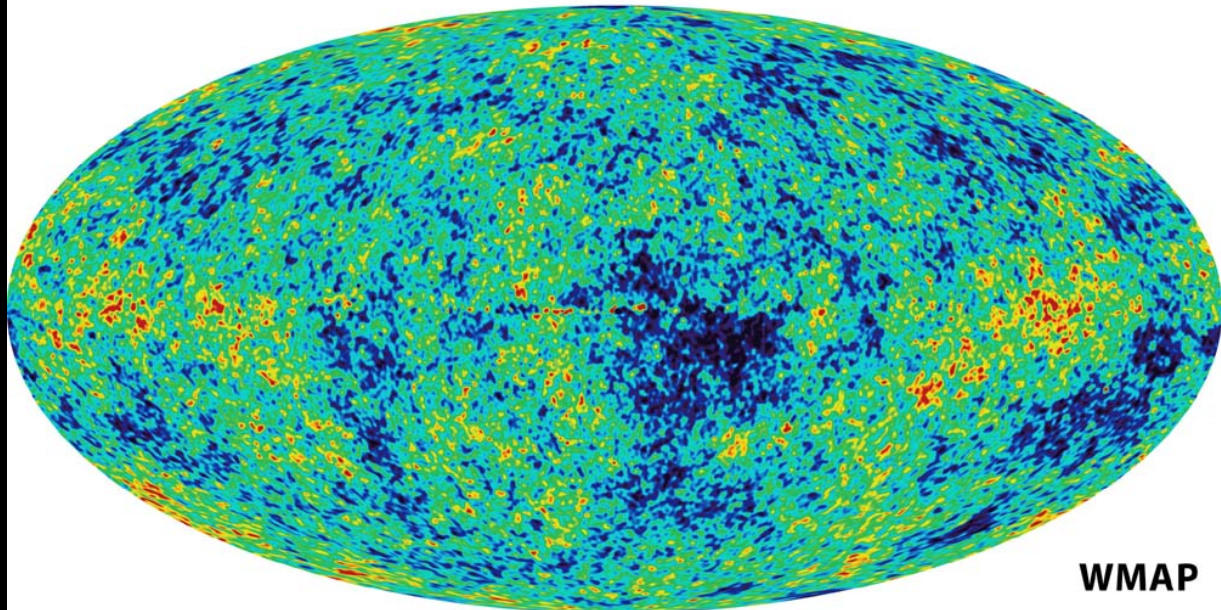
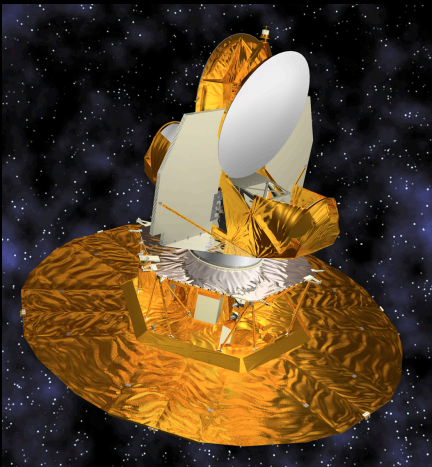
The CMB

1992



COBE

2003

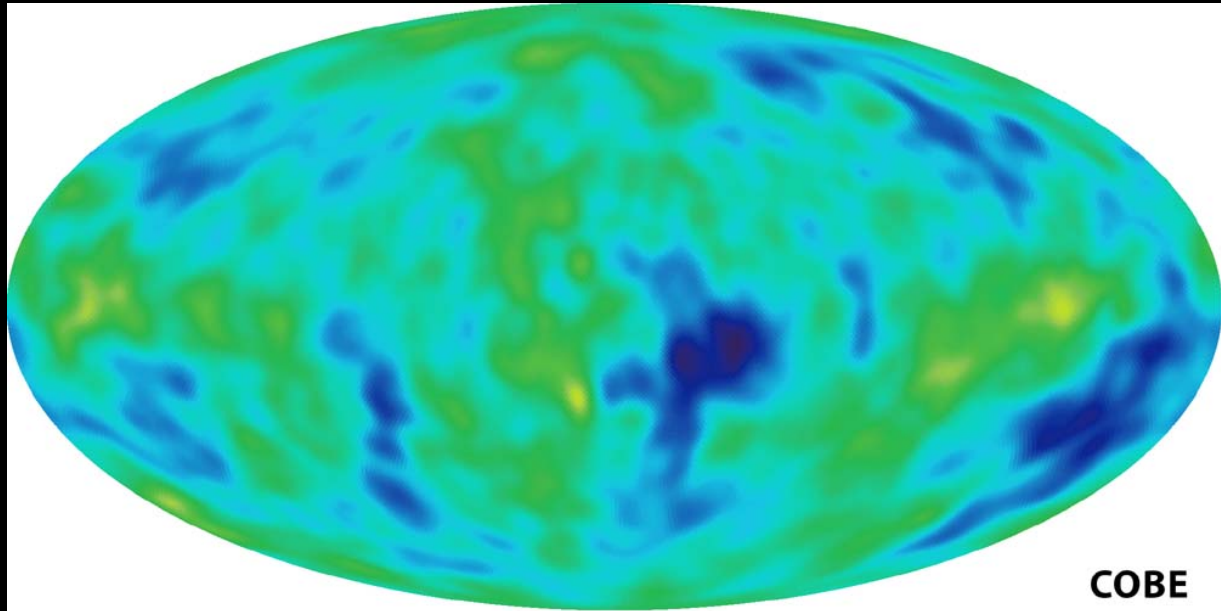


WMAP

ICC

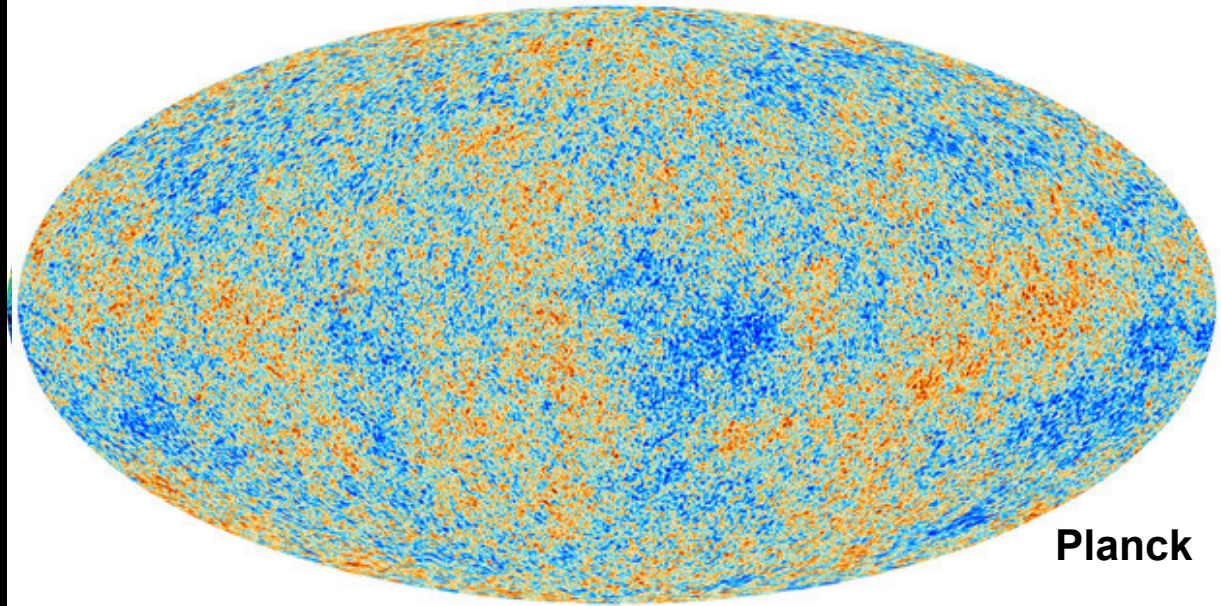
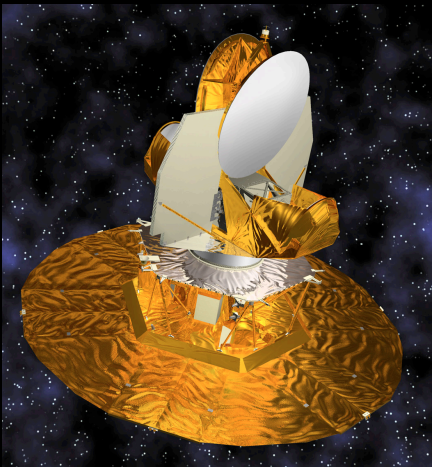
The CMB

1992



COBE

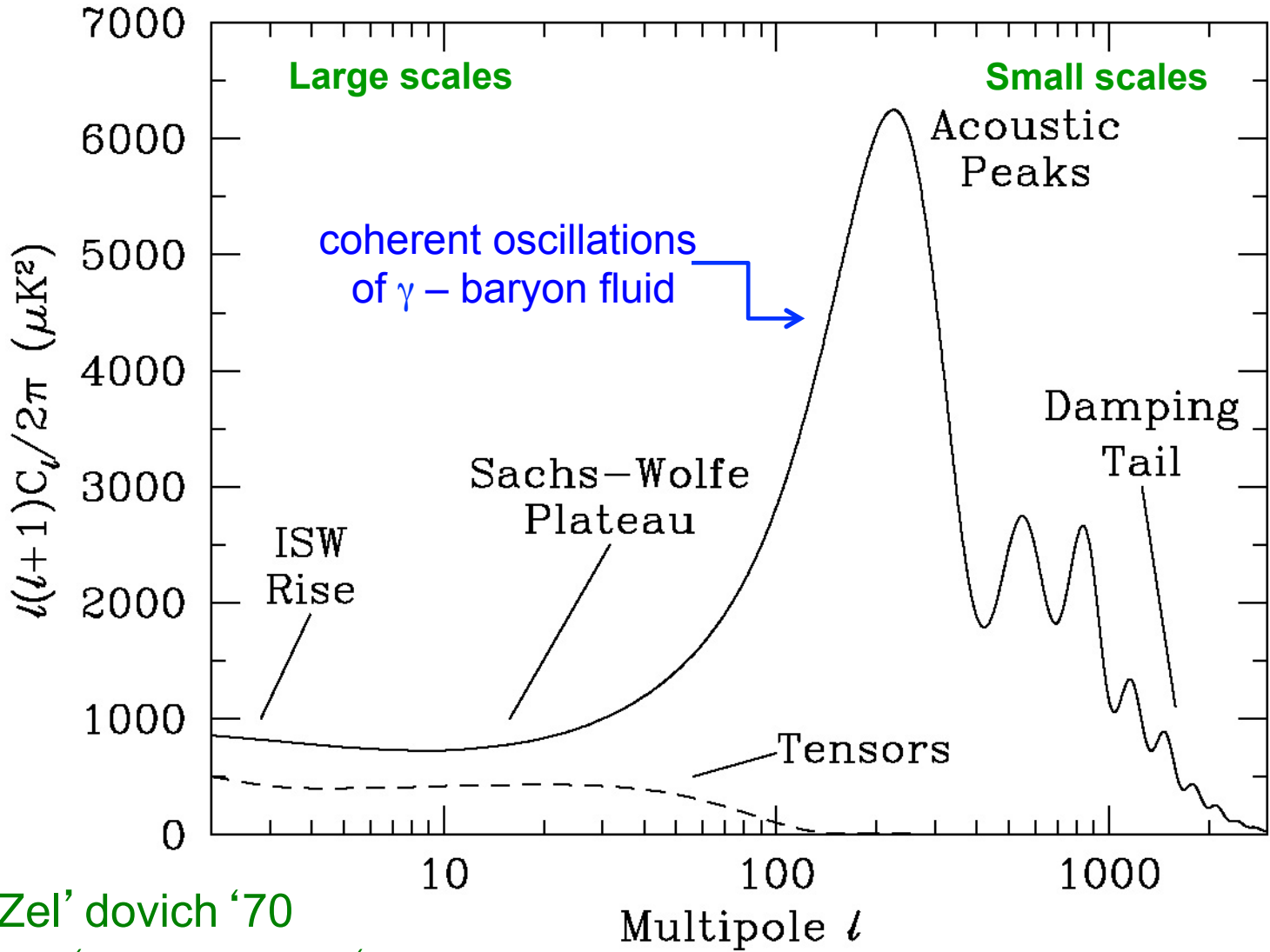
2012



Planck

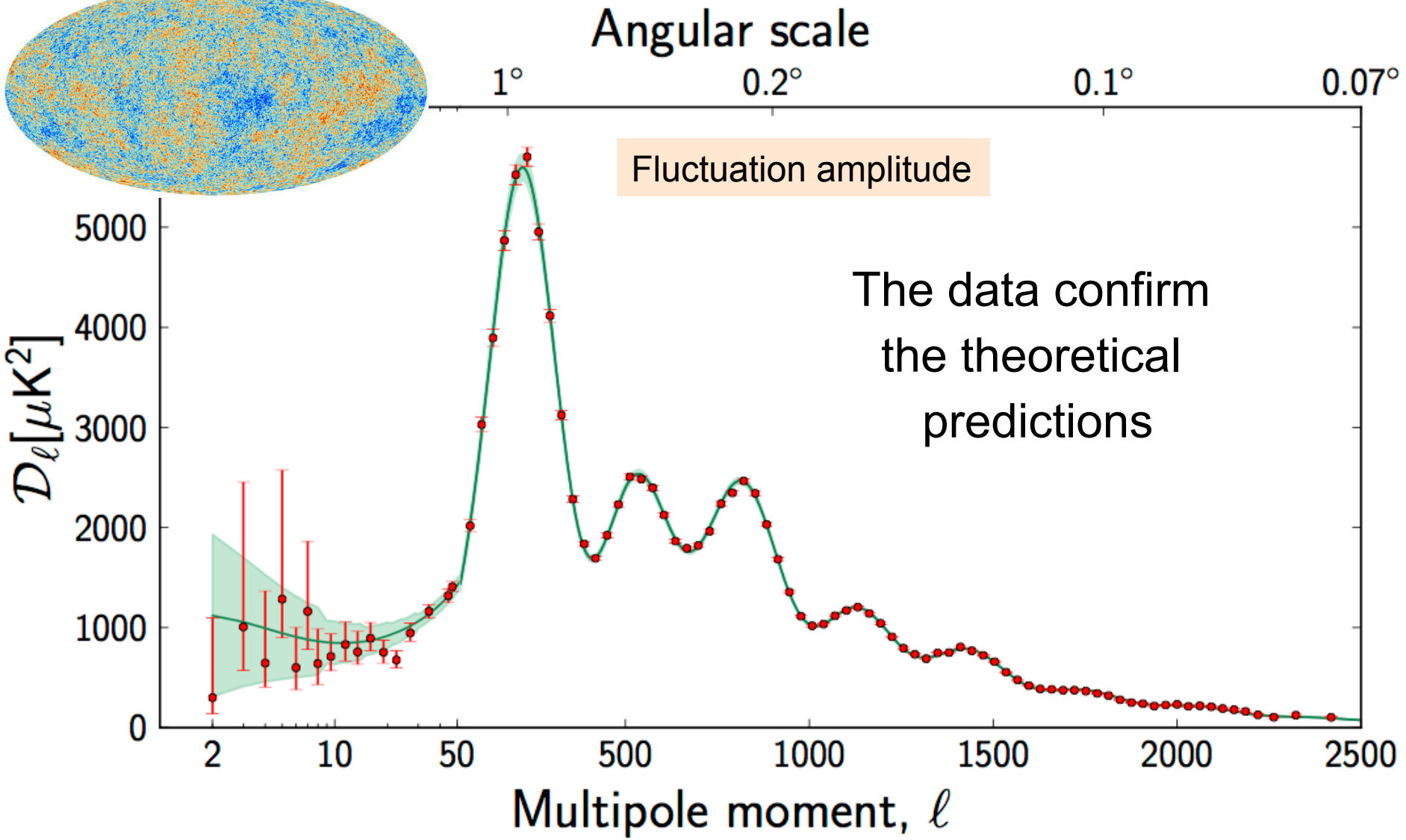
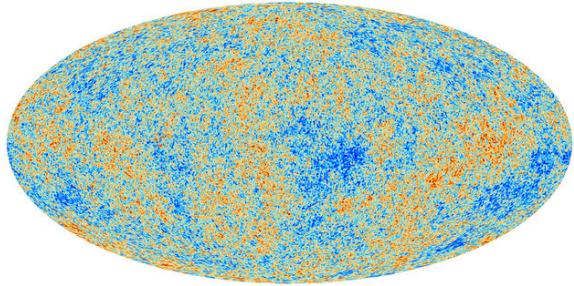
Temperature anisotropies in CMB

2D power spectrum

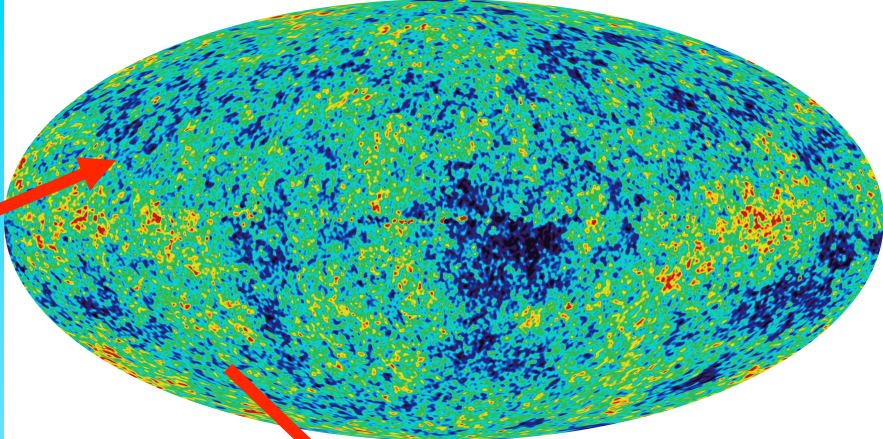
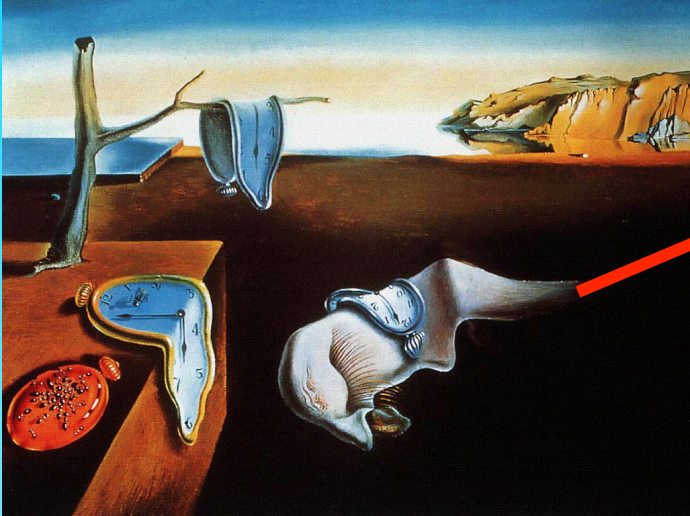


Sunyaev & Zel'dovich '70
 Peebles & Yu '70; Peebles '82

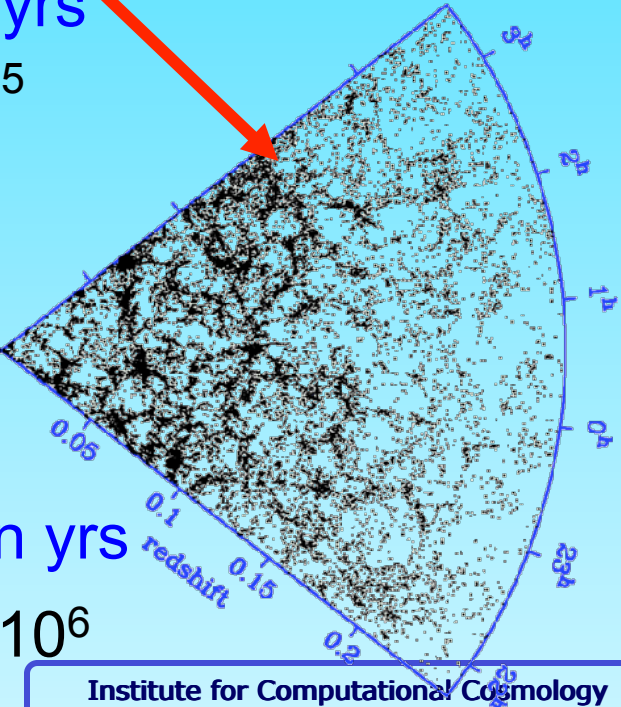
Planck: CMB temperature anisotropies



The growth of cosmic structure



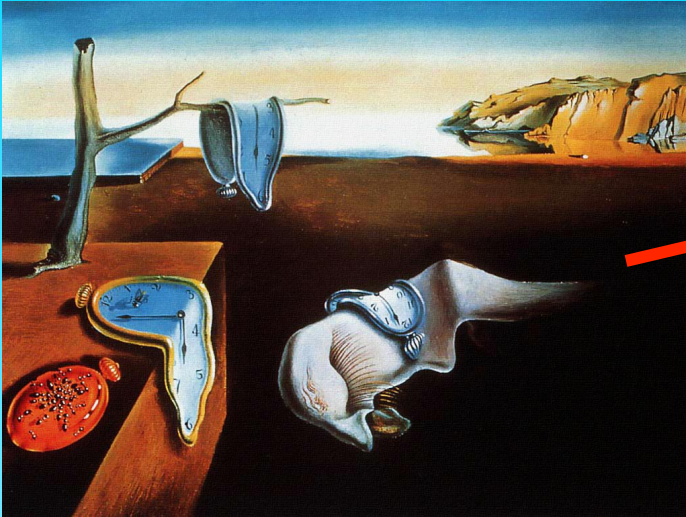
$t=380,000$ yrs
 $\delta\rho/\rho \sim 10^{-5}$



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

Testing the cold dark matter paradigm

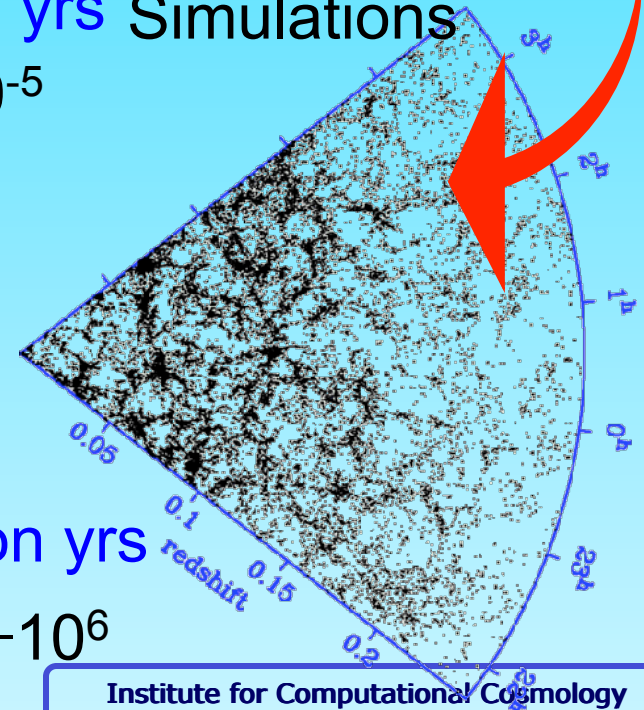
“Cosmology machine”



$t=380,000$ 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



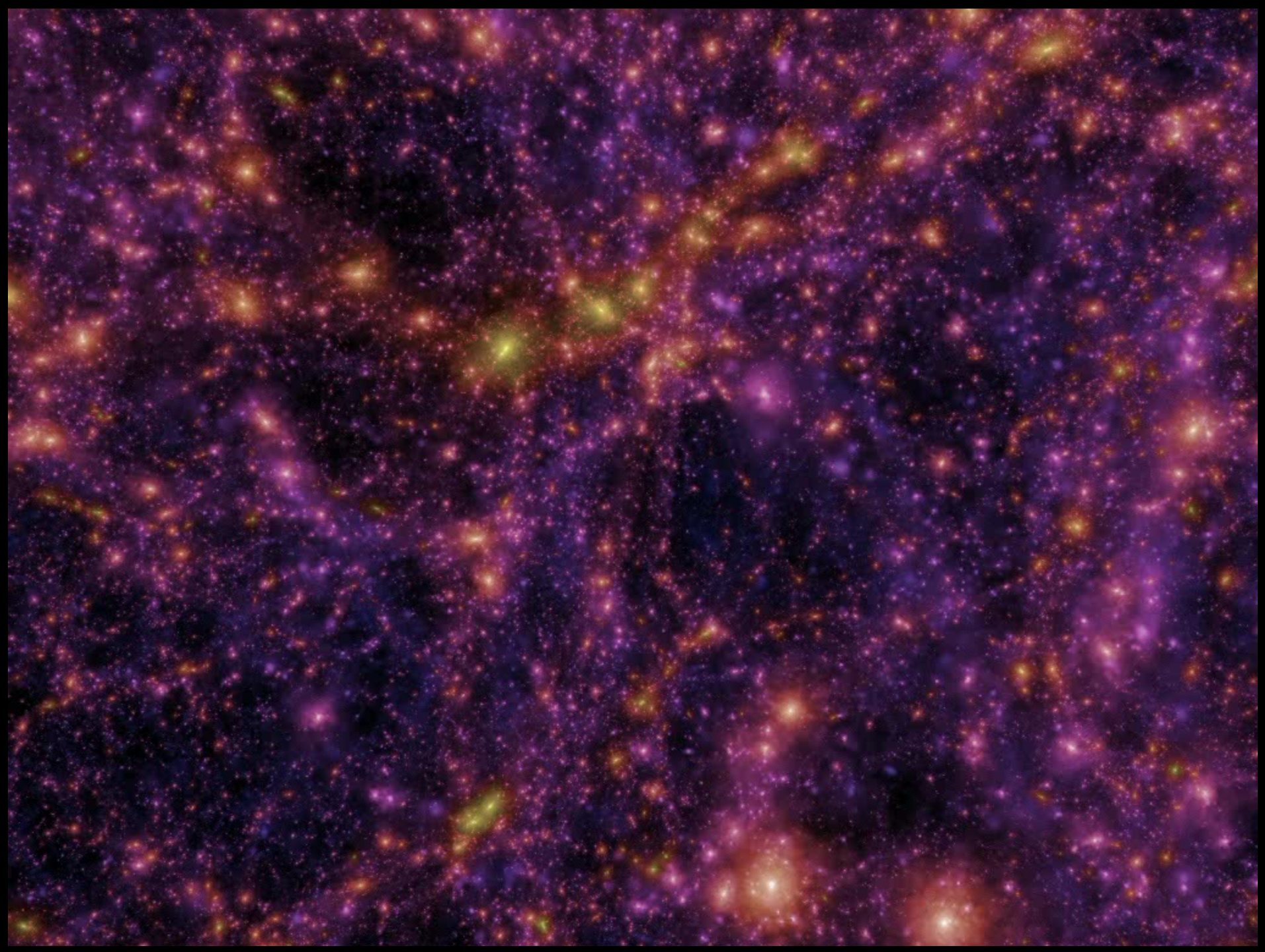
$t=13.8$ billion yrs

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

$z = 48.4$

$T = 0.05 \text{ Gyr}$

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

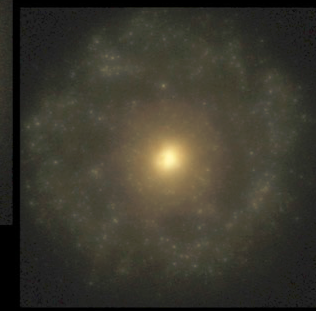
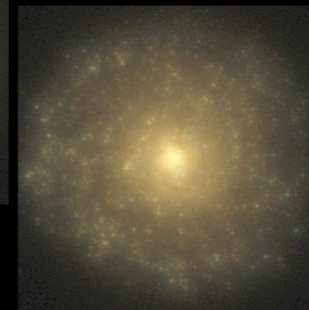
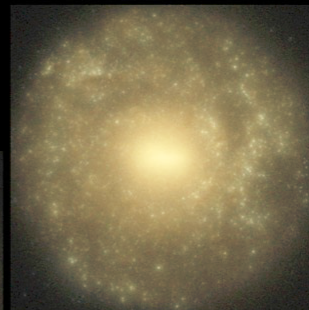
The Hubble Sequence realised in cosmological simulations

SB

E0

E7

S0



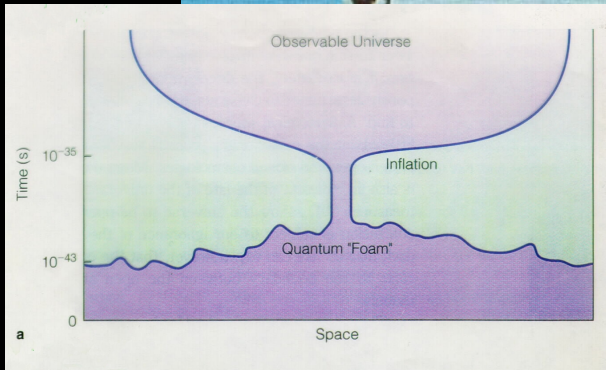
Irr

S

Trayford et al '15

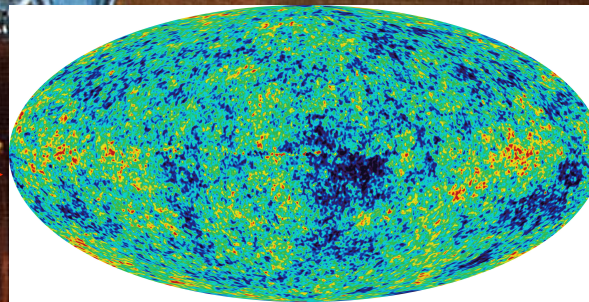
The origin of cosmic structure

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



Small (quantum) ripples

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

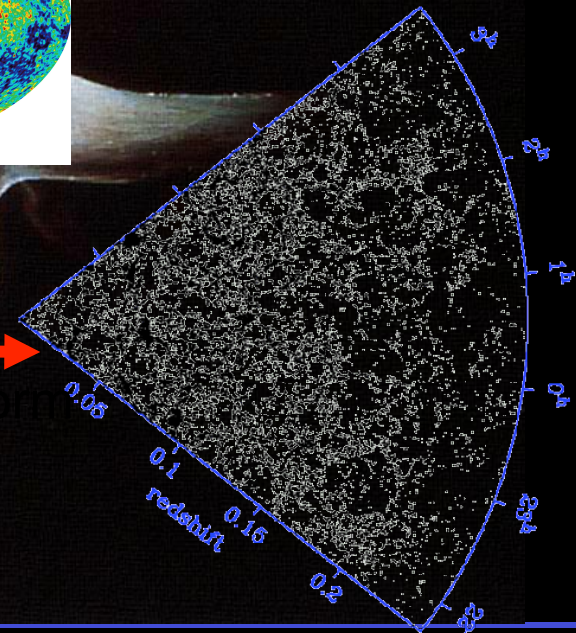


Galaxies ($t \sim 13 \times 10^9$ yrs)

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.**



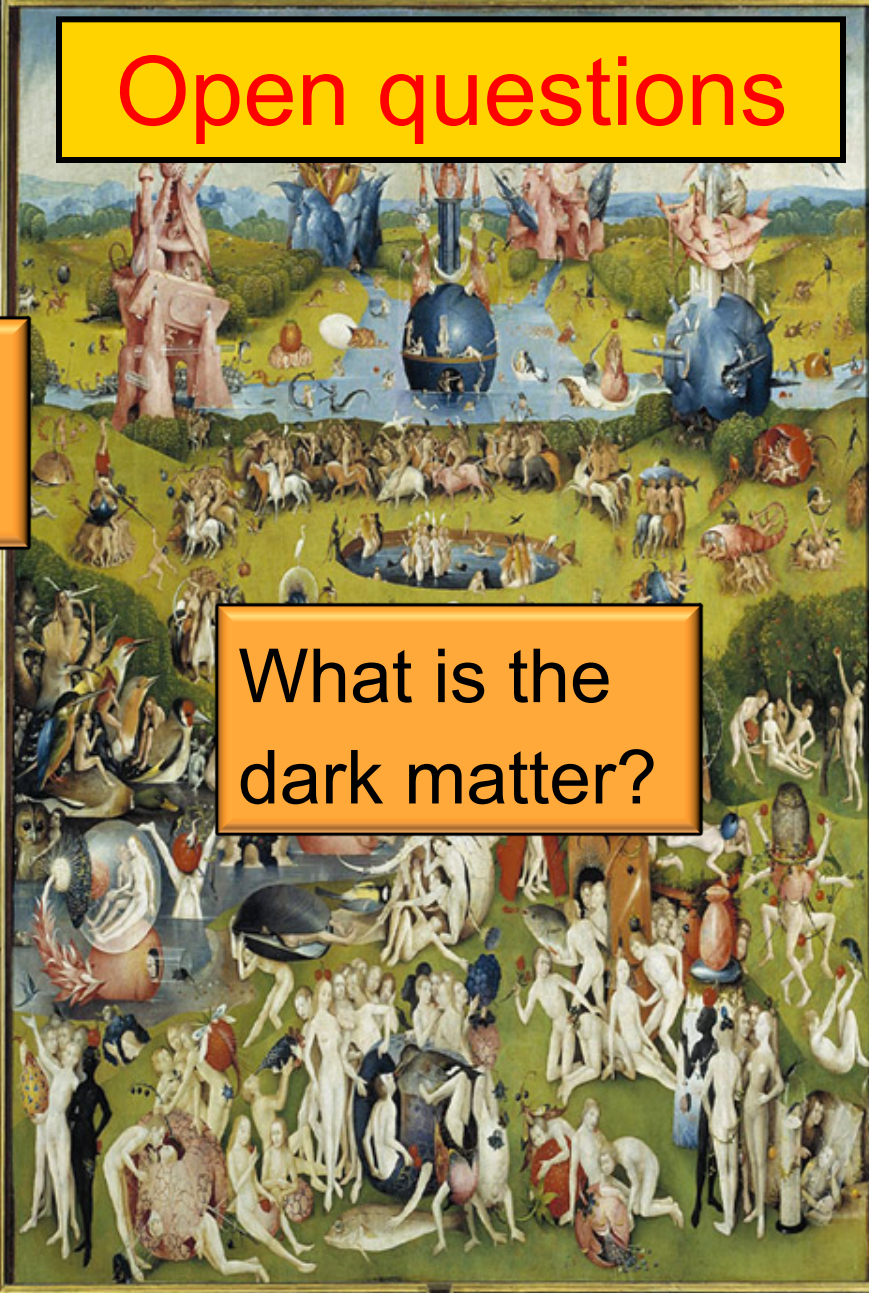
Is this the end of the story?



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



... and there is still a lot more to come