



Bach, the Universe and everything: the origin of galaxies

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Cosmology



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?

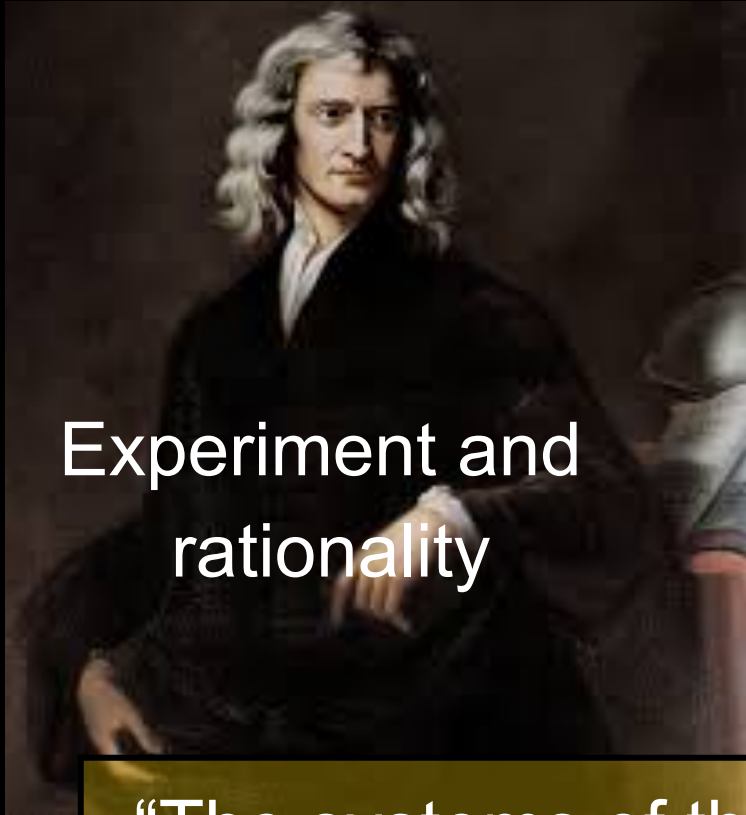
The science of the Universe

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 (?)

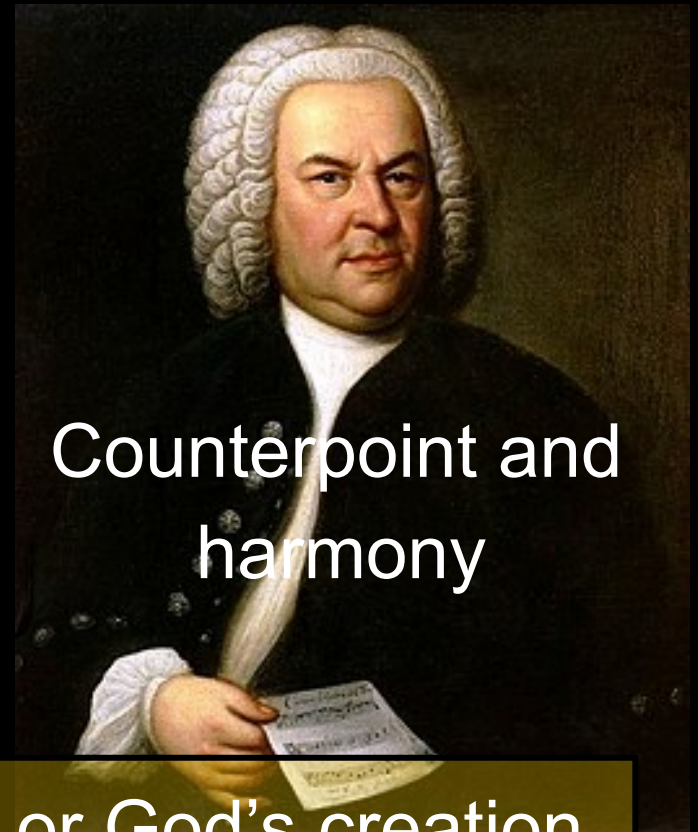
The age of enlightenment (1680 – 1789)



Experiment and
rationality

1642 - 1726

Truth



Counterpoint and
harmony

1685 - 1750

“The systems of the World” or God’s creation

Virtual Voyage: Milky Way to the Virgo Cluster

HDTV Visual Excerpt from "Runaway Universe"

Courtesy NOVA/WGBH, PBS

Tom Lucas Productions

Landmark moments in the early Universe

The dark matter is almost certainly
made of exotic elementary particles

It makes up 80 percent of all matter

We know dark matter exists because



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

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





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

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To be Physics, it must be testable!

The heat from the Big Bang



By today, the radiation from the Big Bang has cooled to 2.7 degrees

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

15 thousand million years

The temperature of this radiation should show small irregularities

Production of dark matter
($t \sim 10^{-10}$ s)

300 thousand years

3 minutes

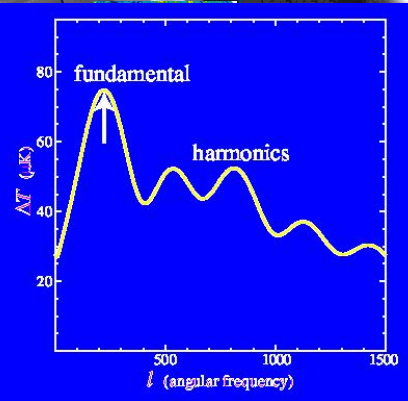
10^{-43} seconds

10^{32} degrees

10^{27} degrees

10^{15} degrees

Cosmic inflation
(initial conditions)
($t \sim 10^{-35}$ s)



$t = 13.7$ billion yrs

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

1 degrees

18 degrees

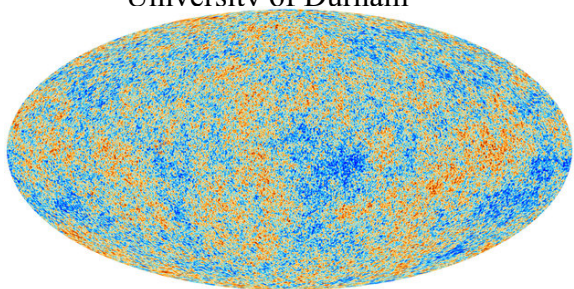
3 degrees K

The initial conditions for galaxy formation



Quantum fluctuations from inflation

Planck: CMB temperature anisotropies



Angular scale

1°

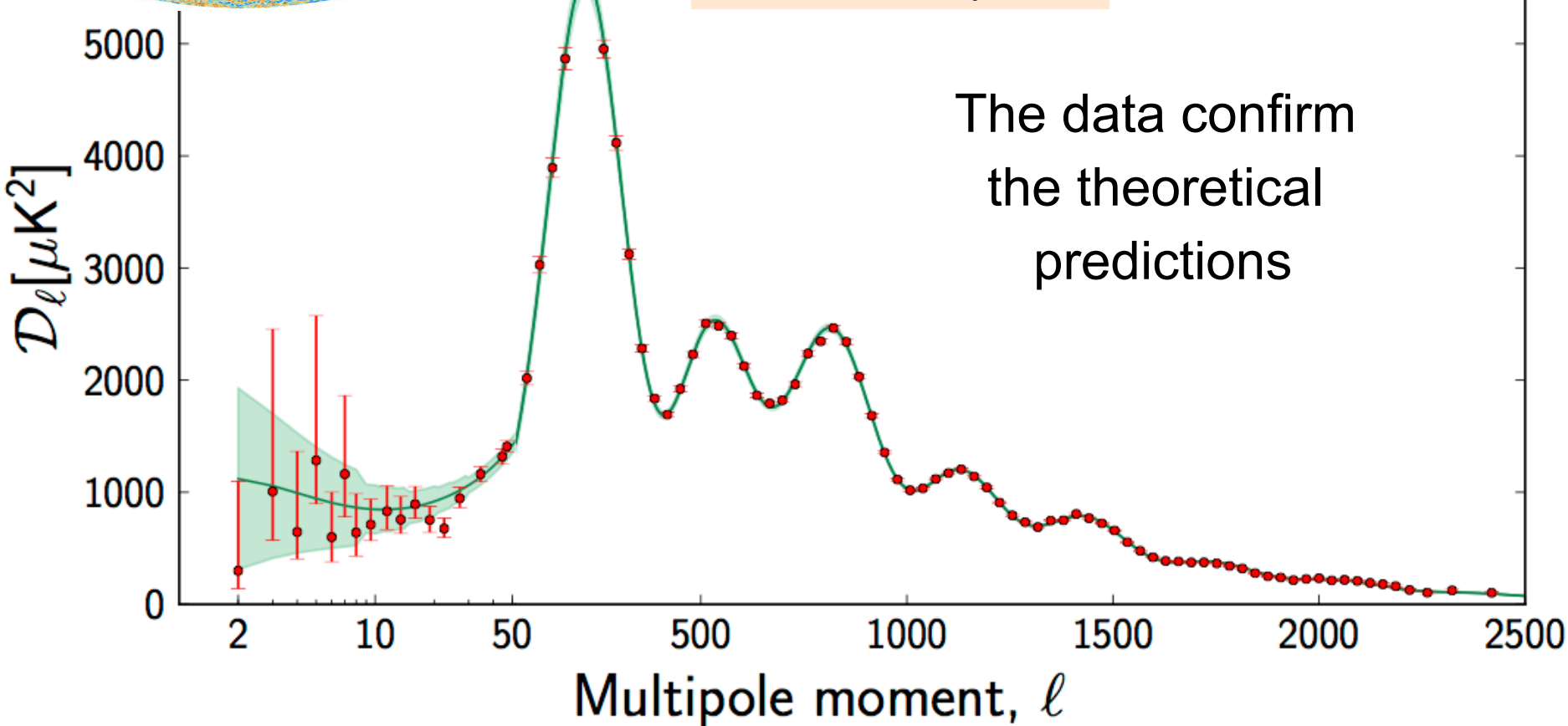
0.2°

0.1°

0.07°

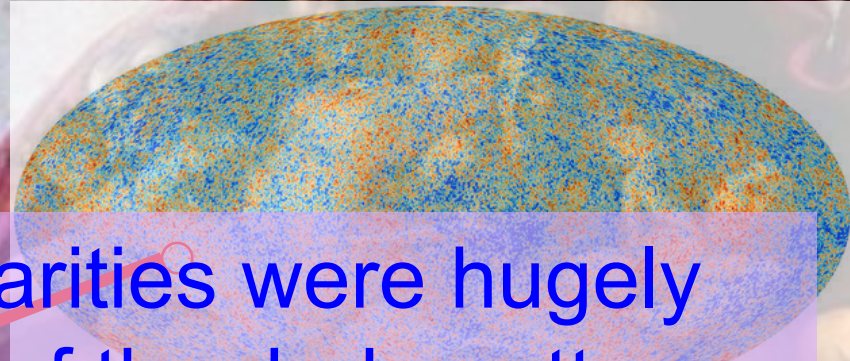
Fluctuation amplitude

The data confirm
the theoretical
predictions

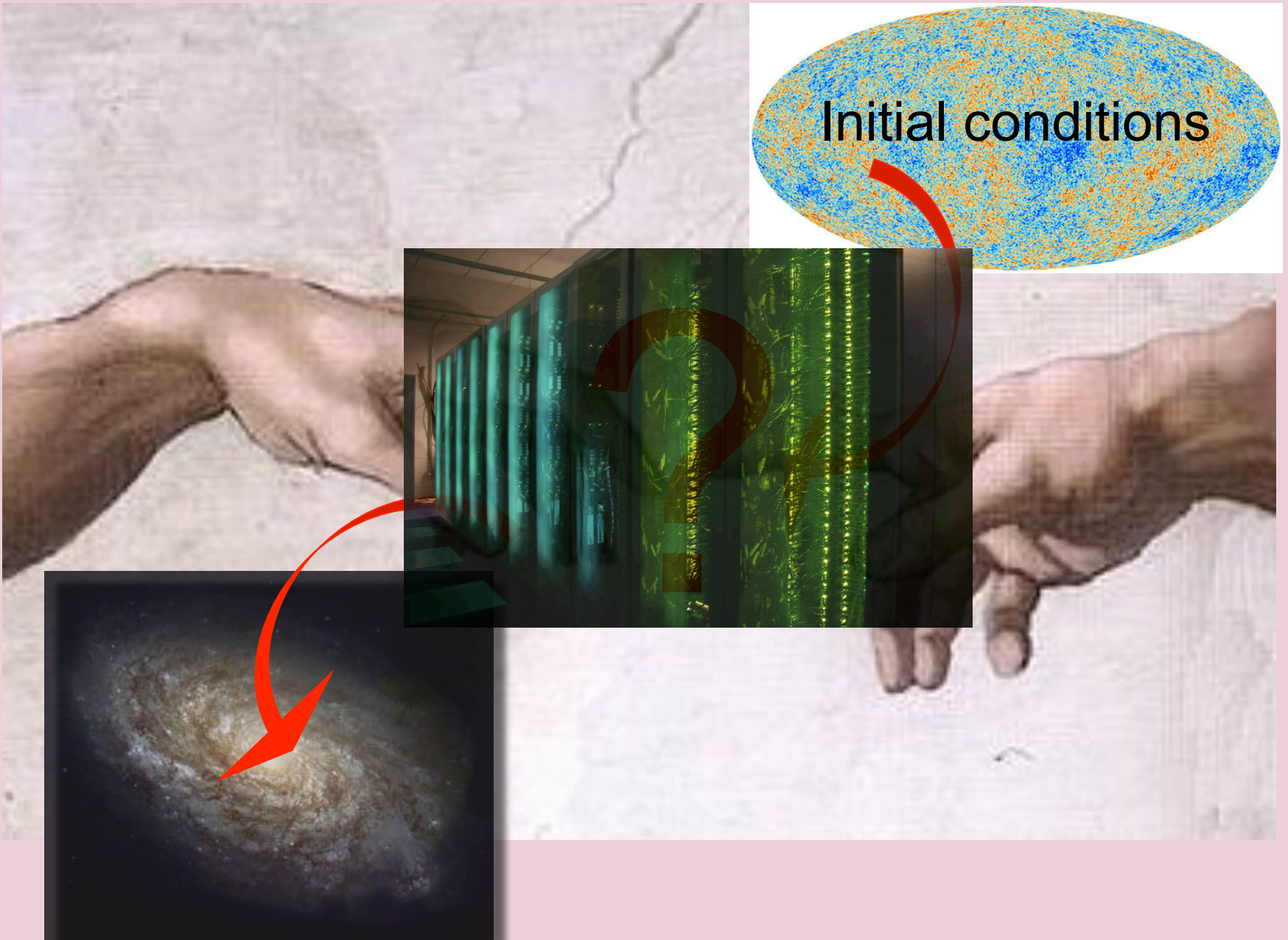


How did galaxies form?

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



The formation of galaxies



How to make a virtual universe

Initial conditions + assumption about content of Universe

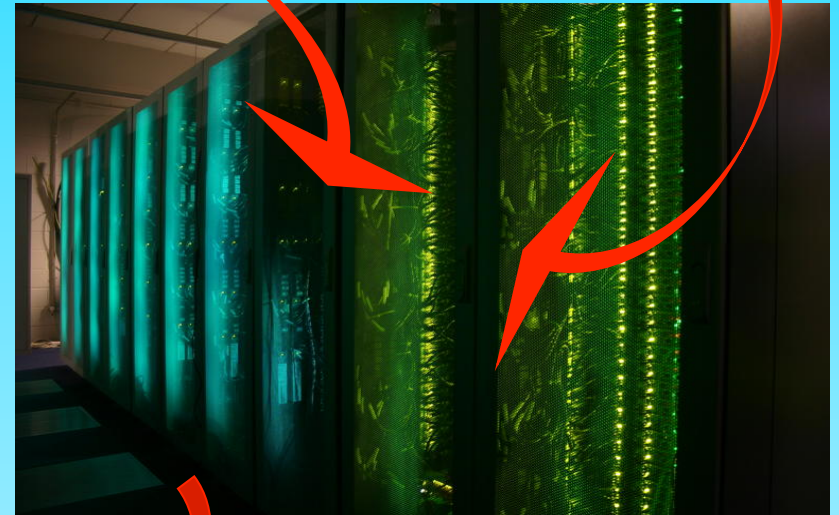
Equations of physics:

General Relativity

Mechanics

Radiative hydrodynamics

Atomic physics, etc

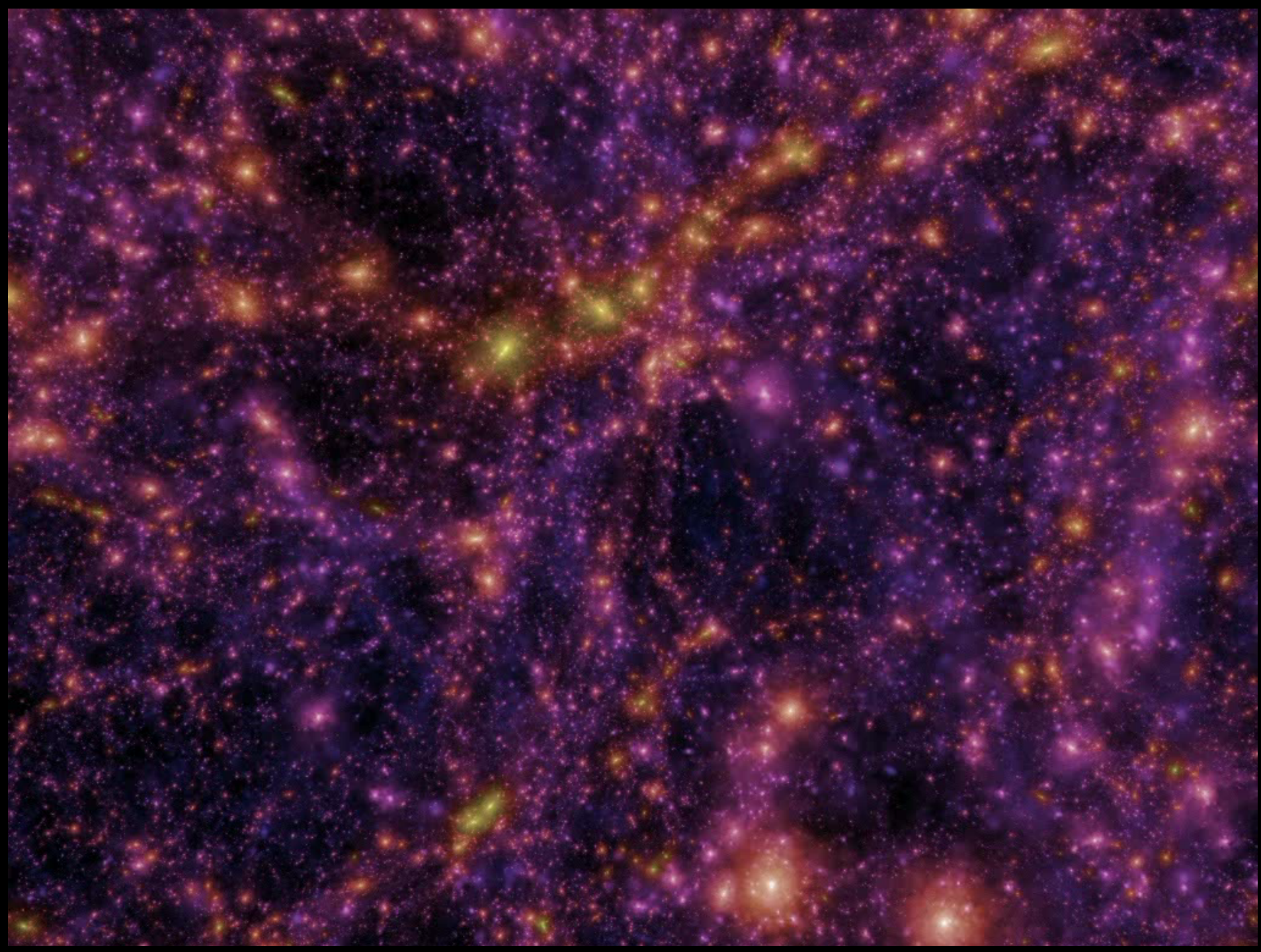


$z = 48.4$

$T = 0.05 \text{ Gyr}$

500 kpc

A visualization of a cosmic structure, likely a simulation of a galaxy cluster or a large-scale filament, at a redshift of $z = 48.4$ and a time of $T = 0.05 \text{ Gyr}$. The image shows a complex, filamentary network of matter, with a central region of higher density and a surrounding, more diffuse structure. The color scale is not explicitly defined, but the image appears to be a grayscale or a very low-contrast color map. A scale bar at the bottom indicates a length of 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

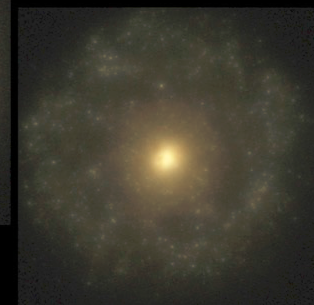
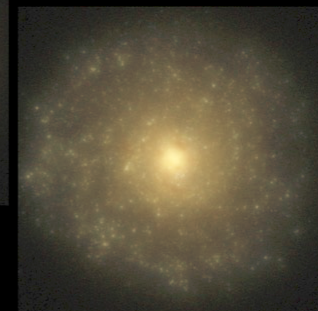
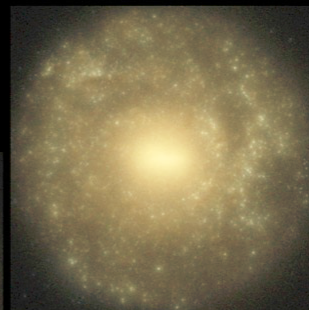
The Hubble Sequence realised in cosmological simulations

SB

E0

E7

S0



S

Irr

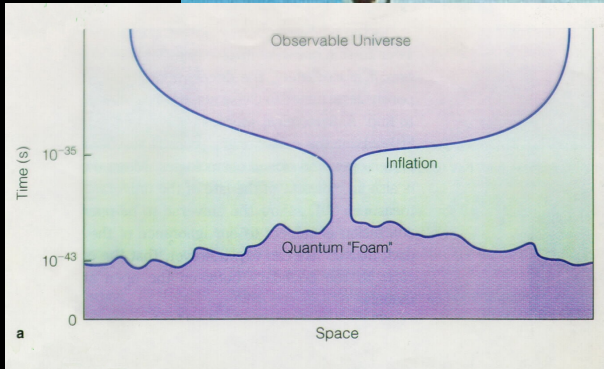


Trayford et al '15



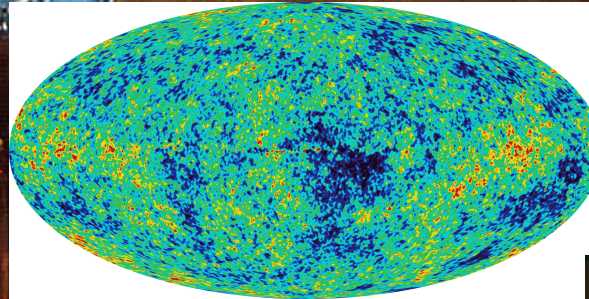
The origin of cosmic structure

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

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



The Universe seems to conform to “rational”
mathematical laws (that can be reproduced in a
computer)

... just like Bach's harmony and counterpoint

It seems to have been made to please both
Newton and Bach