



# The evolution of galaxies and large-scale structure

*Carlos S. Frenk*  
*Institute for Computational Cosmology,*  
*Durham*



The logo consists of the letters 'I', 'C', 'C', and 'C' in a stylized, bold font. The 'I' is red, and the three 'C's are blue with a red outline. They are set against a light blue rectangular background.

## THE KEY QUESTIONS OF COSMOLOGY

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

Flammarion 1888: tete des etoiles



University of Durham

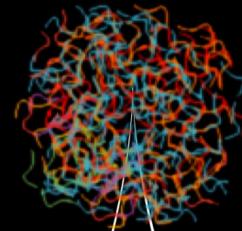
# Recent advances in cosmology

- The contents of our Universe
- The early universe
- The origin of galaxies
- The virtual universe

# The initial conditions

INFLATION

$t=10^{-35}$  sec



QUANTUM  
SPACE-TIME  
FOAM?



$$p = -\rho$$

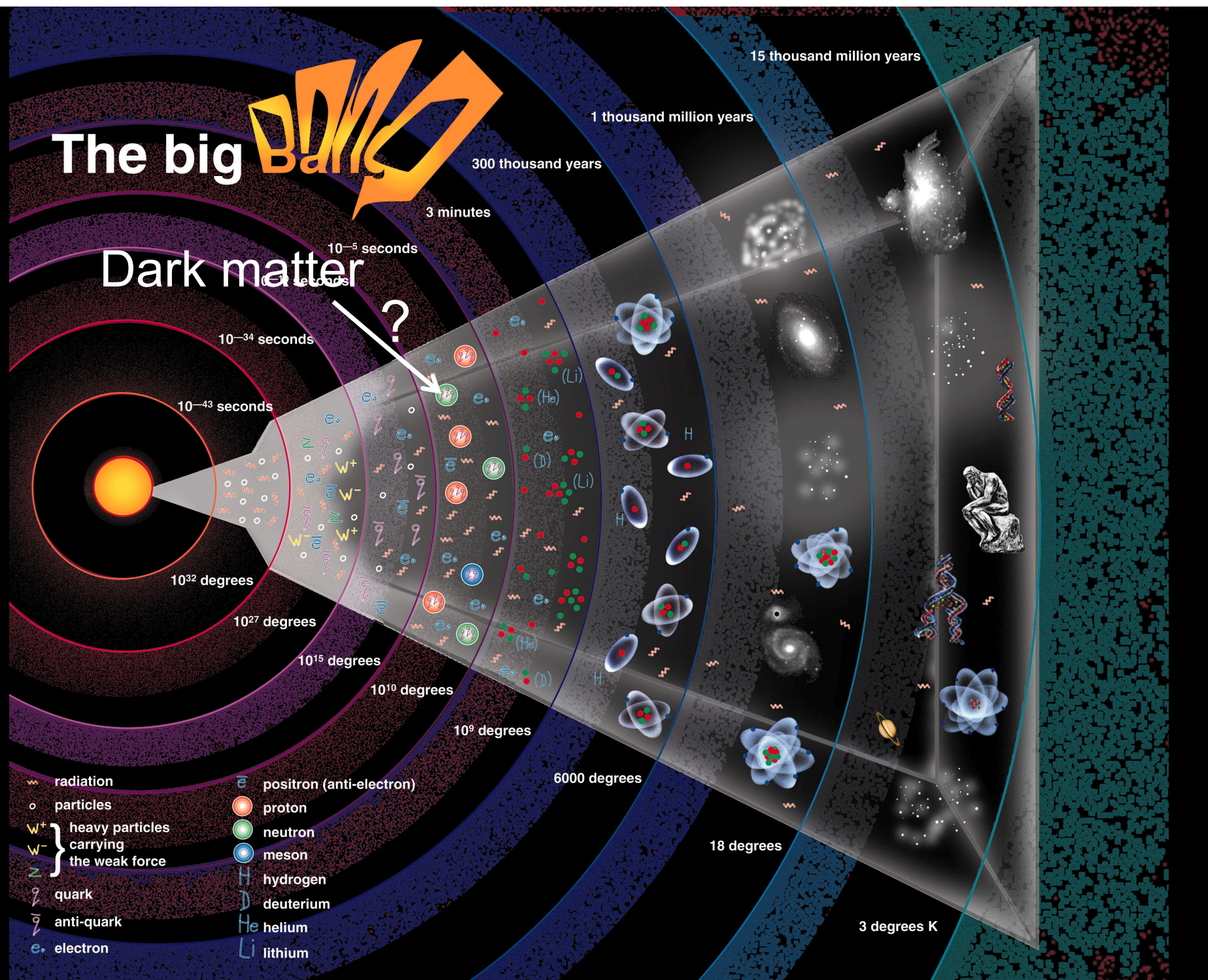
**BLAP!**

THE ENTIRE  
OBSERVABLE  
UNIVERSE!

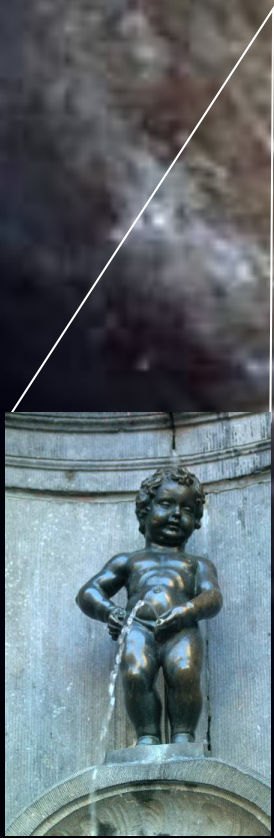
from G. Efstathiou

# The big Bang

## Dark matter



# The building blocks of the Universe



Galaxies are collections of up to a hundred billion stars

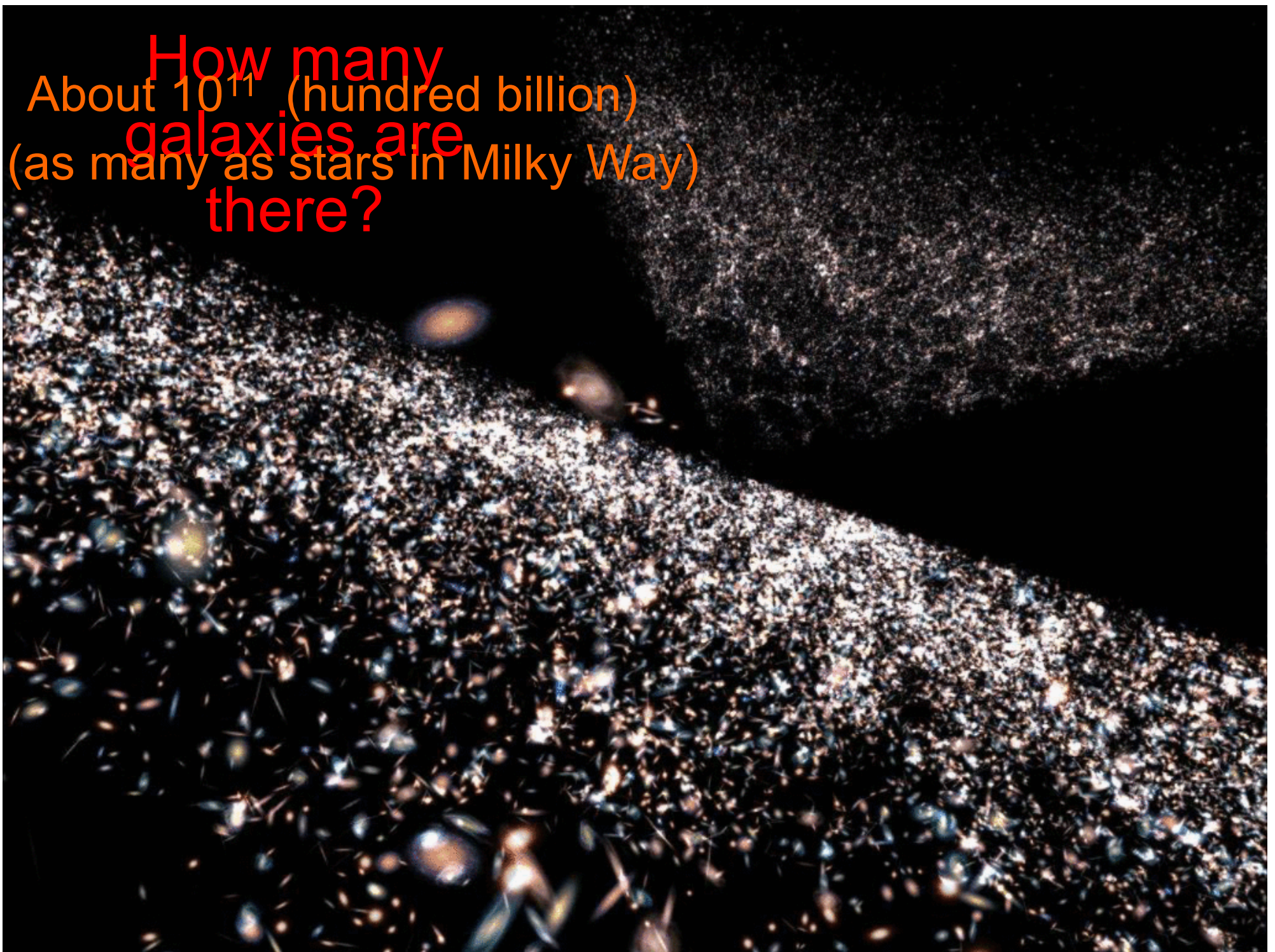
**Virtual Voyage:  
Milky Way to the Virgo Cluster**

**HDTV Visual Excerpt from "Runaway Universe"**

**Courtesy NOVA/WGBH, PBS**

**Tom Lucas Productions**

How many  
About  $10^{11}$  (hundred billion)  
galaxies are  
(as many as stars in Milky Way)  
there?



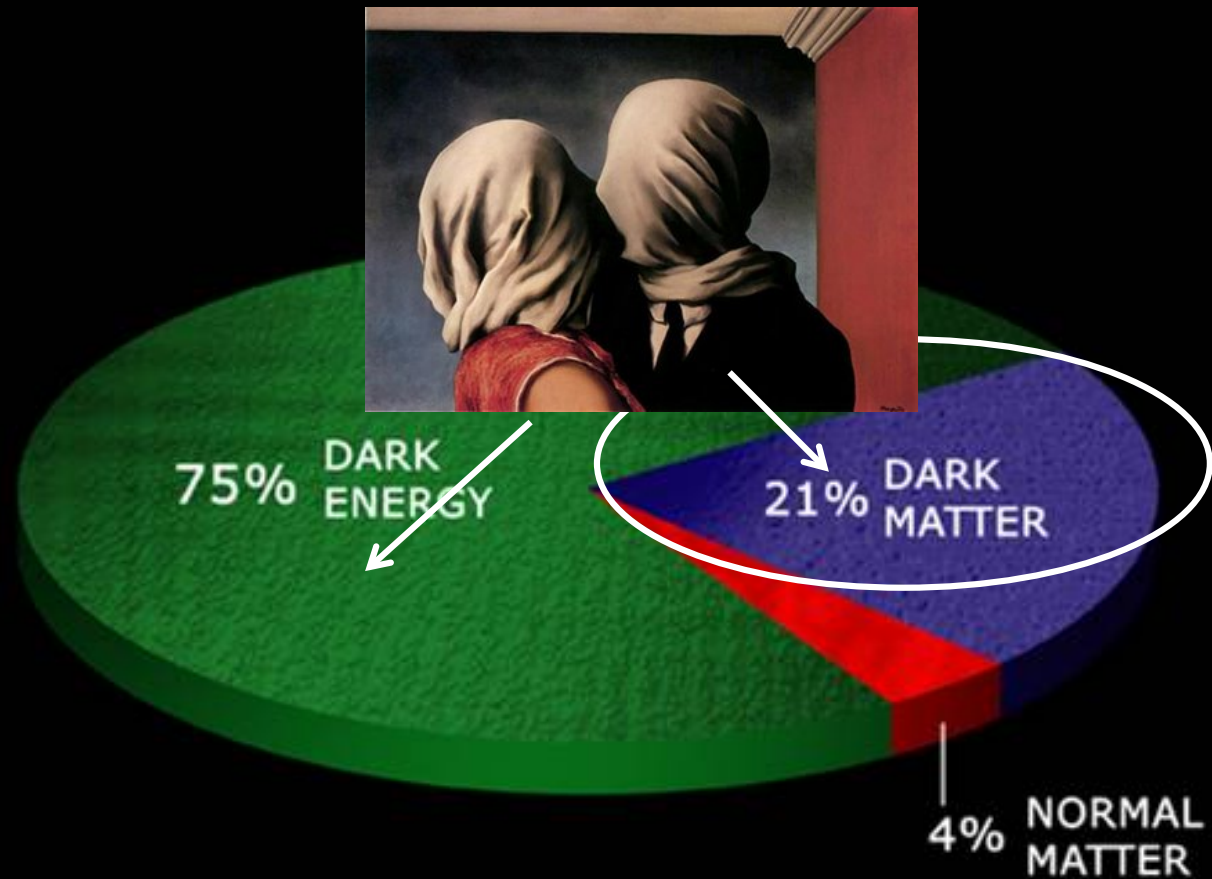


# The content of the Universe



ICC

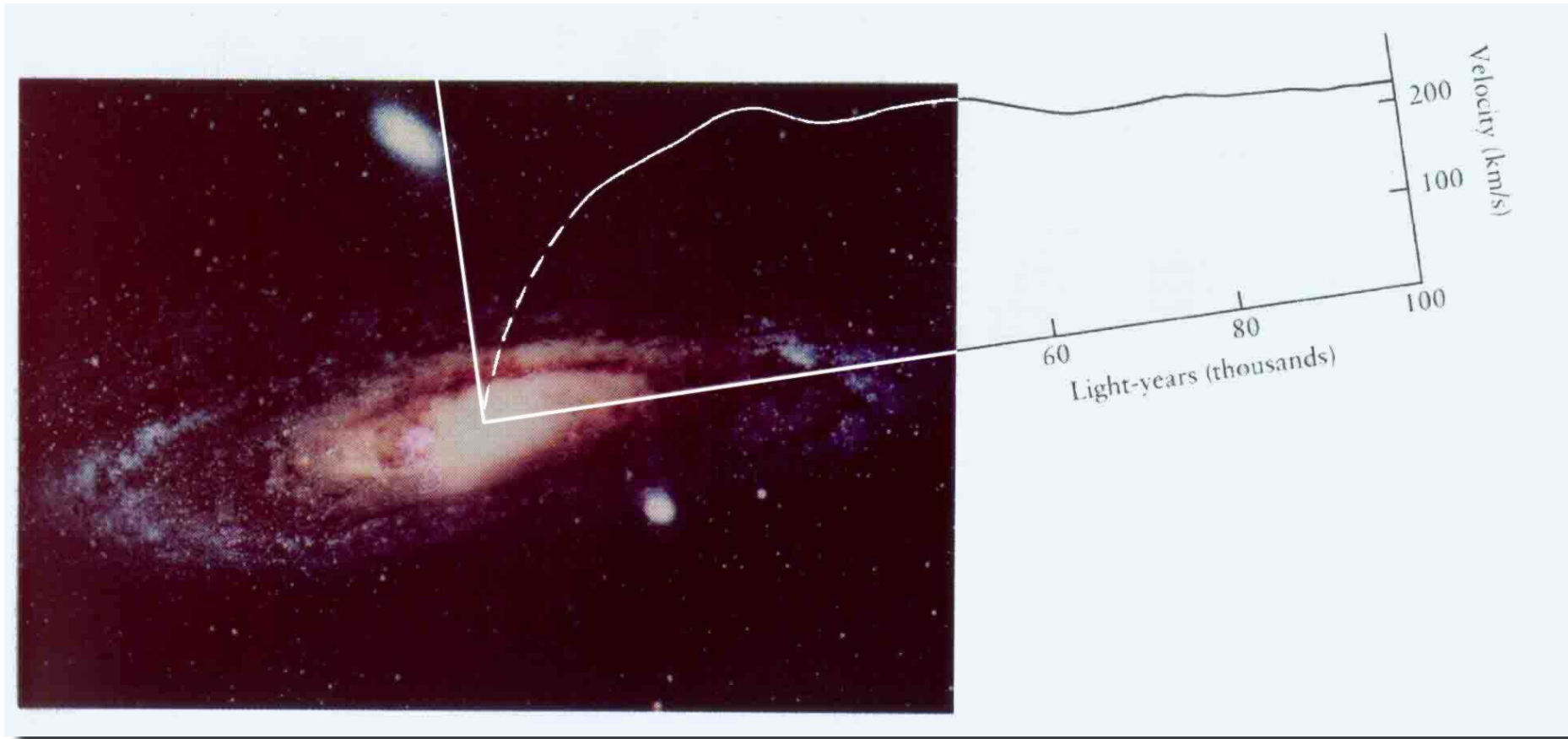
# The content of our universe



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



# Galaxy rotation curves



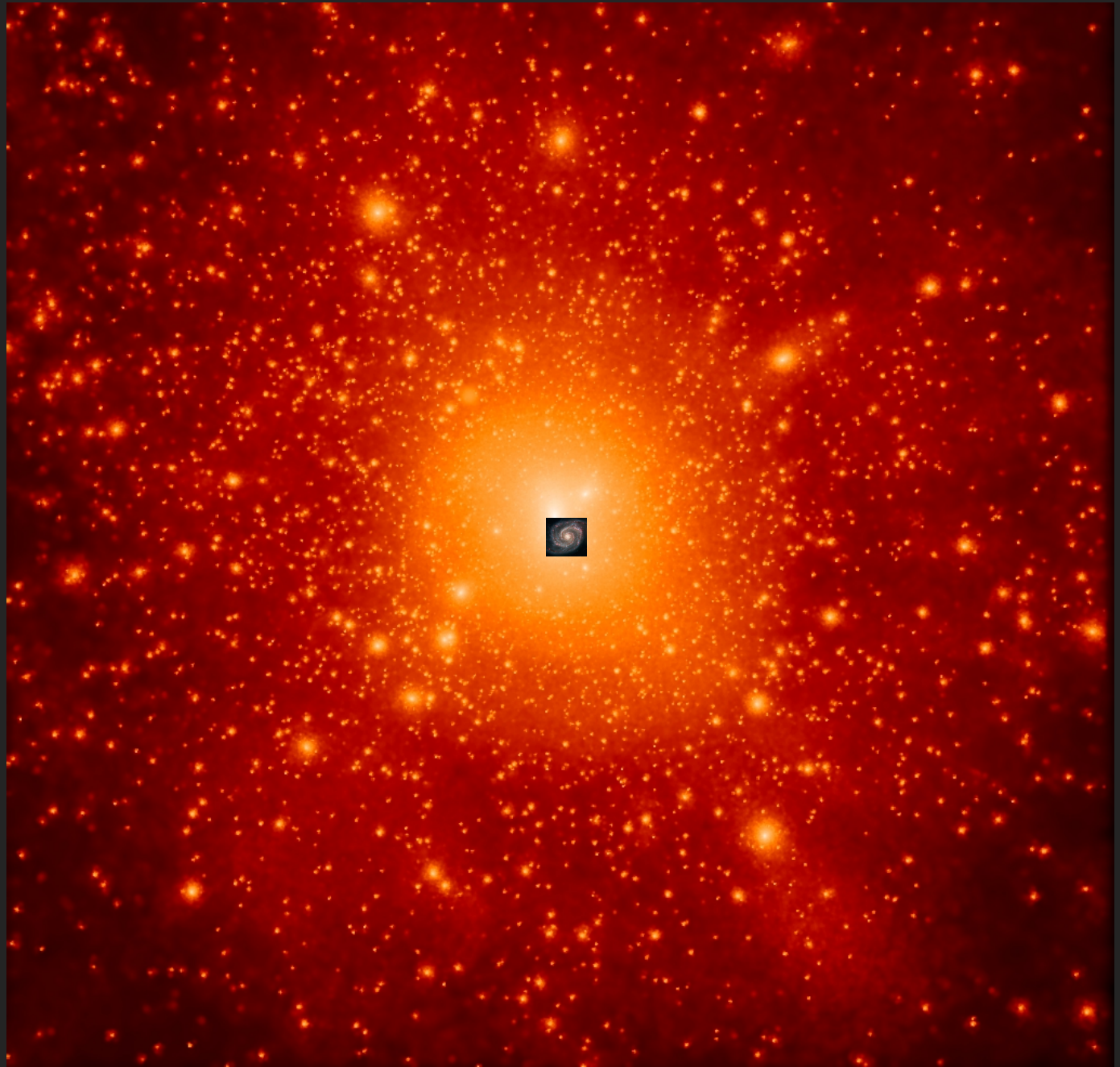
$$V_c^2 = \frac{GM(<r)}{r}$$

Flat  $V_c \rightarrow M(<r) \propto r$  but  $L(<r) = \text{const}$

$\Rightarrow$  dark halos around galaxy

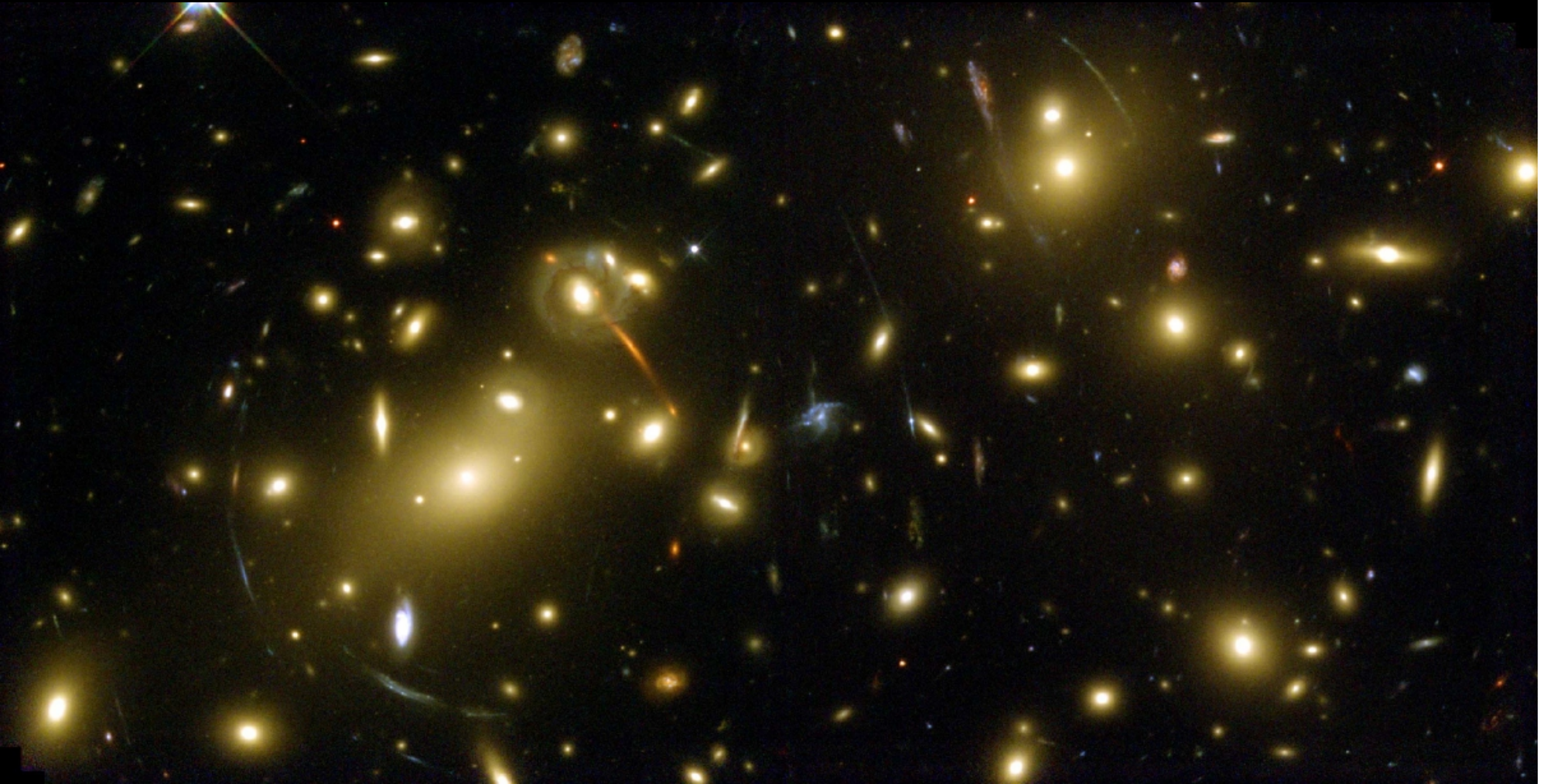
Galaxies are  
embedded in  
huge `halos' of  
dark matter

Computer  
simulation of  
galaxy halo



← 0.5 Mpc/h →

# Gravitational lensing



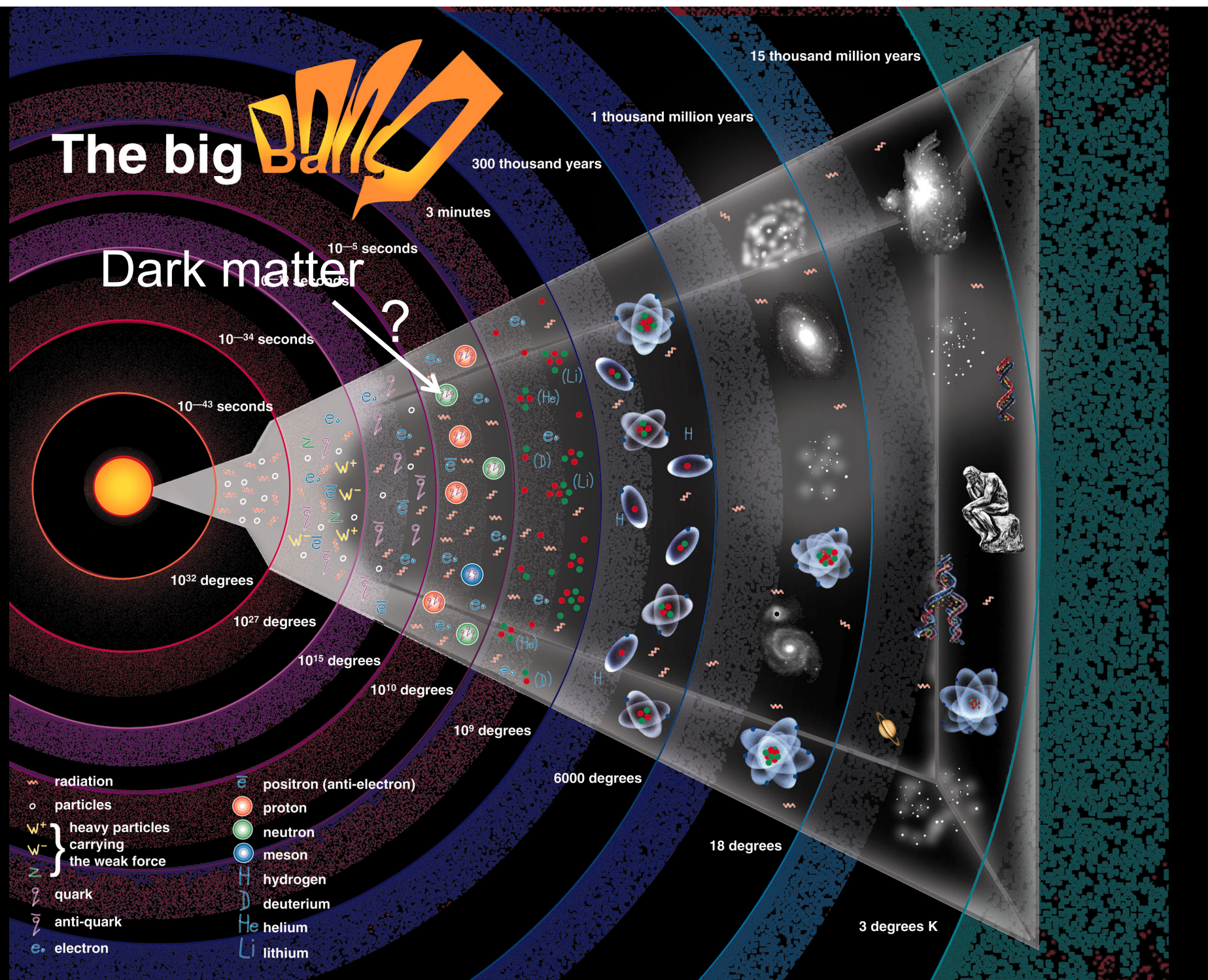
Light from distant galaxies is deflected by dark matter in cluster, distorting the galaxies' images into arcs

# We know dark matter exists because:

- The rotation velocity of stars in galaxies
- The distortion of galaxies behind clusters

# The big Bang

## Dark matter



A simulated galaxy with a dark matter halo. The image shows a dense field of stars in various colors (blue, purple, red, yellow) against a dark background. The stars are concentrated in a central region, with a bright yellow star at the very center. The density of stars decreases as they move away from the center, forming a diffuse, spherical halo. The overall appearance is that of a galaxy with a significant amount of dark matter, which is represented by the diffuse, glowing halo of stars.

# A galactic dark matter halo

Springel, Wang, Volgensberger, Ludlow,  
Jenkins, Helmi, Navarro, Frenk & White '08



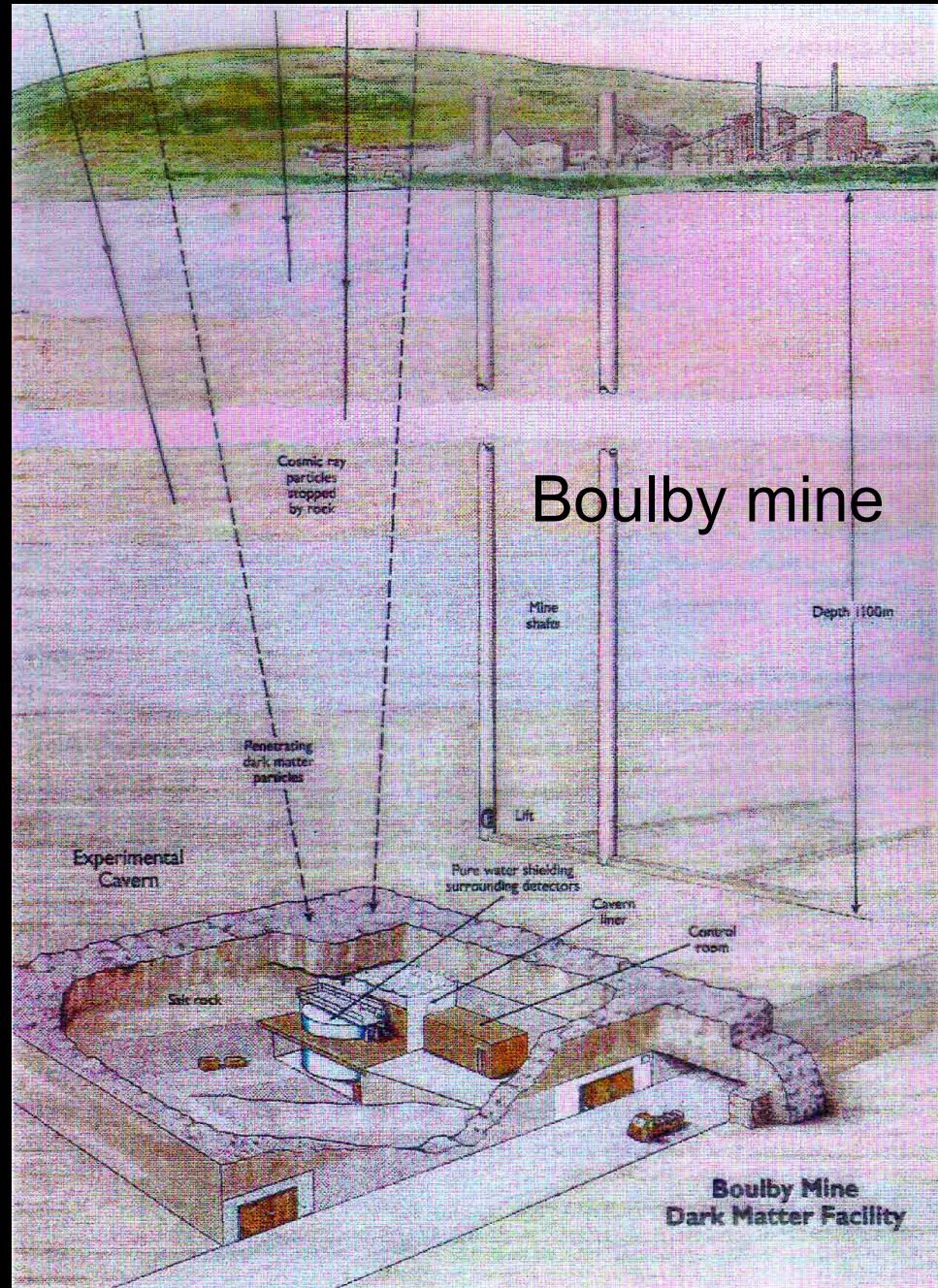
# The search for dark matter

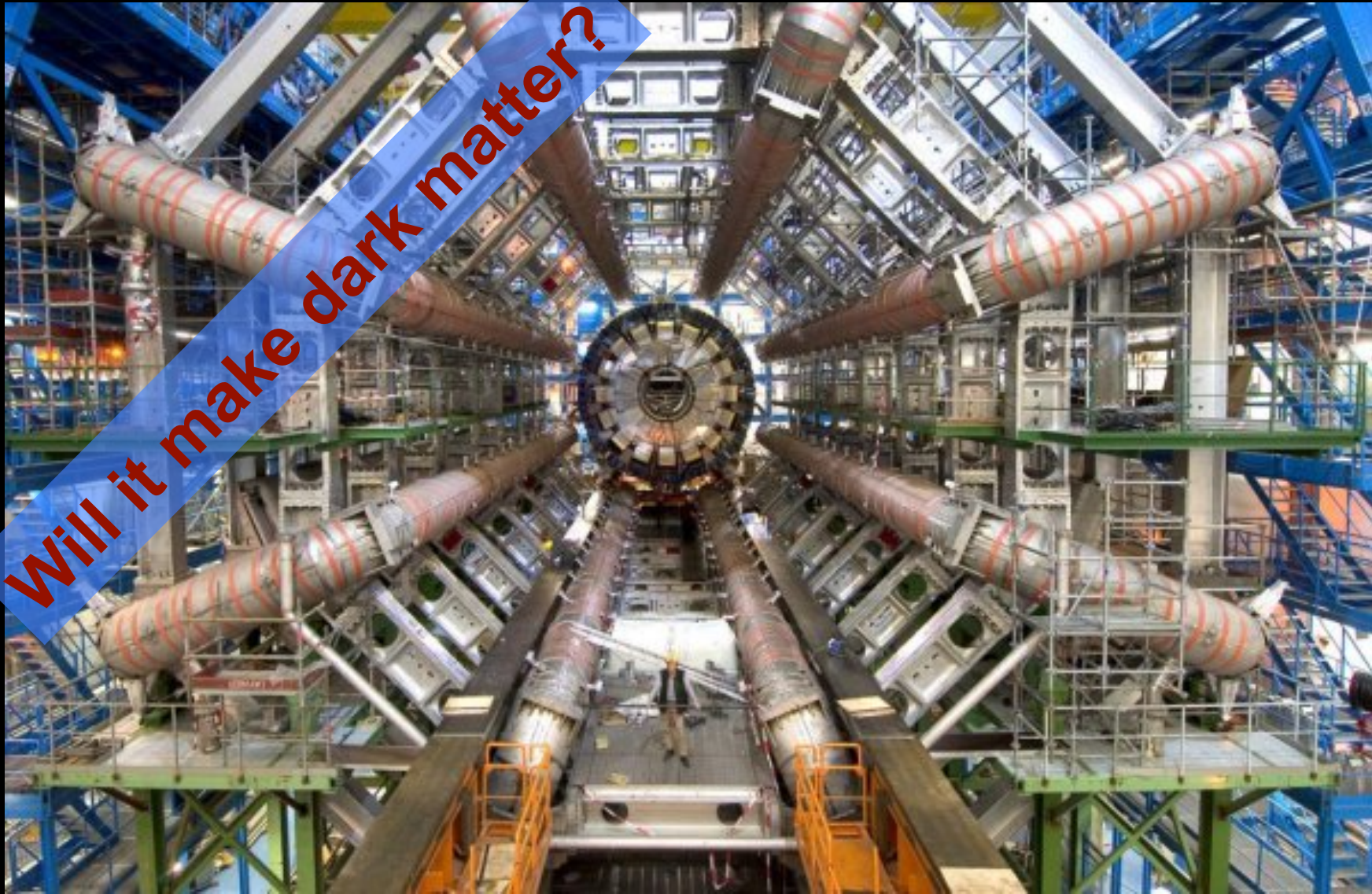
Experimental physics



**UK DM search  
(Boulby mine)**

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





Will it make dark matter?



University of Durham

# Detecting cold dark matter

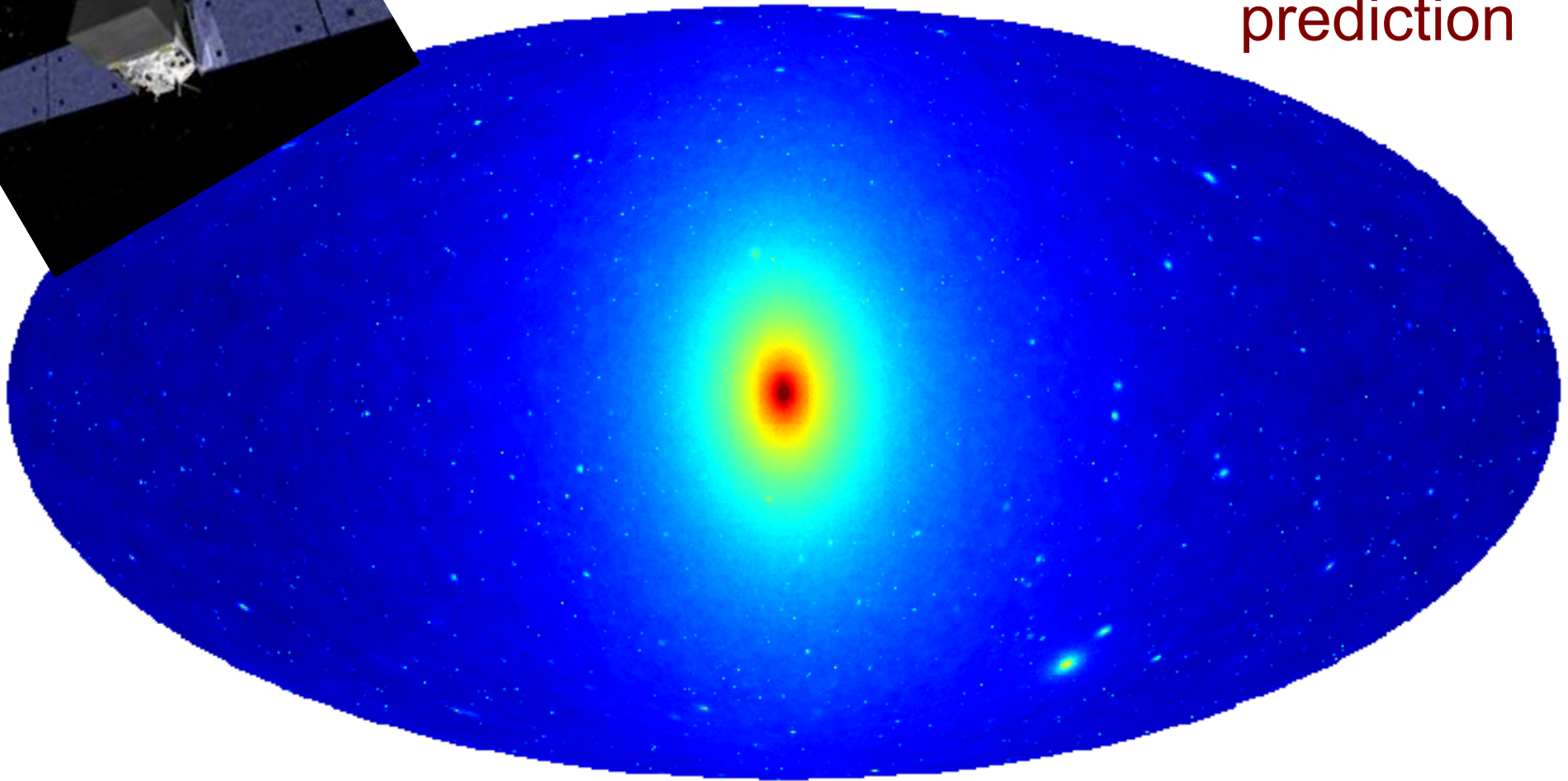
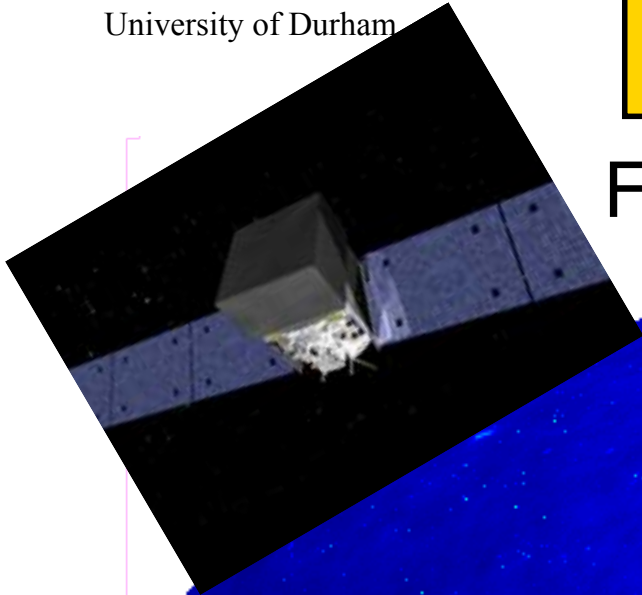
Supersymmetric particles are their own antiparticles

If cold dark matter consists of supersymmetric particle, then under in very high density regions it would annihilate producing  $\gamma$  rays

# Milky Way halo seen in DM annihilation radiation

Fermi satellite

Theoretical prediction

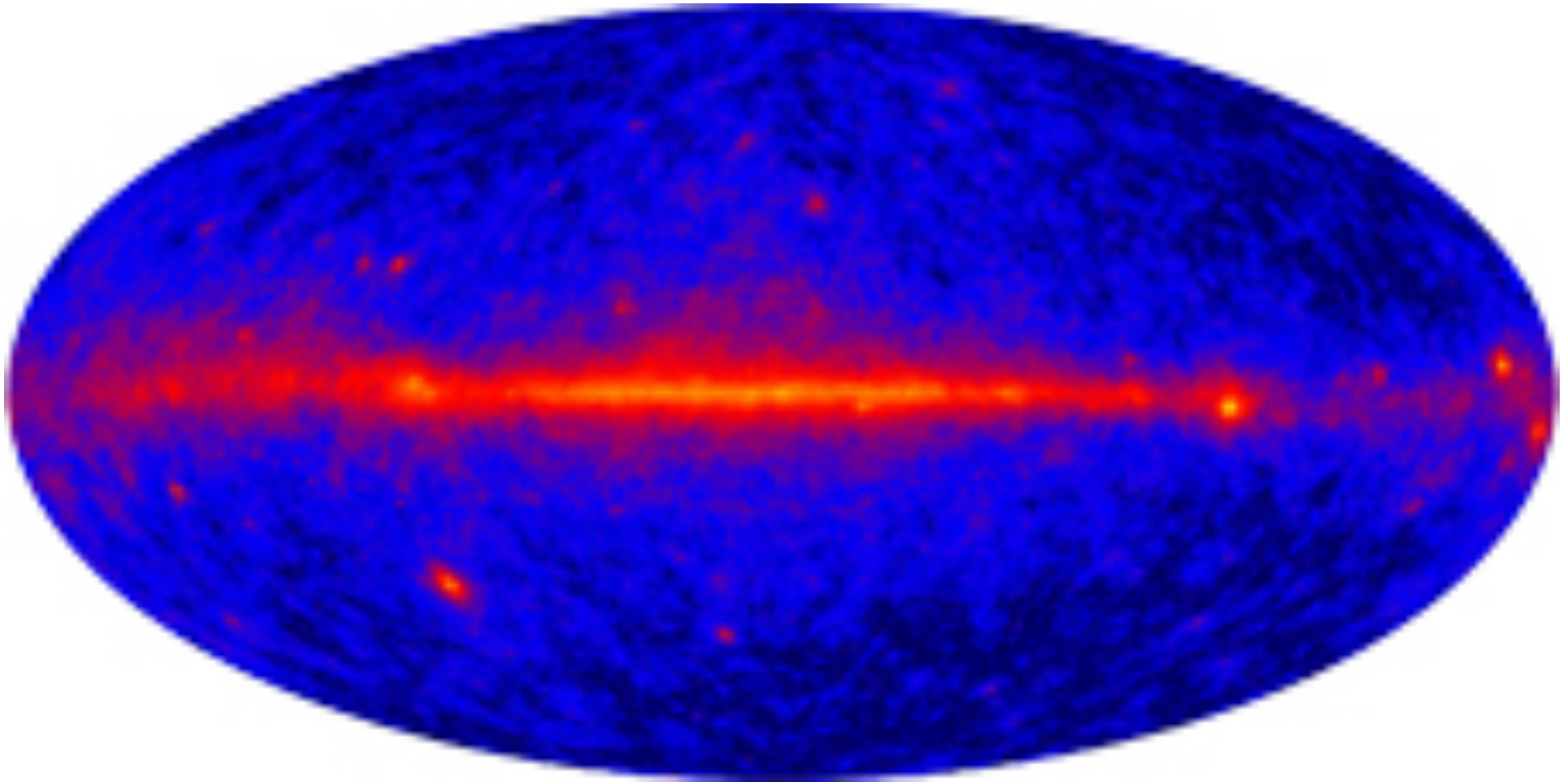


Springel, White, Frenk et al

Nature Nov/08

$18. \text{Log} (M_{\text{sun}}^2 \text{ kpc}^{-5} \text{ sr}^{-1})$

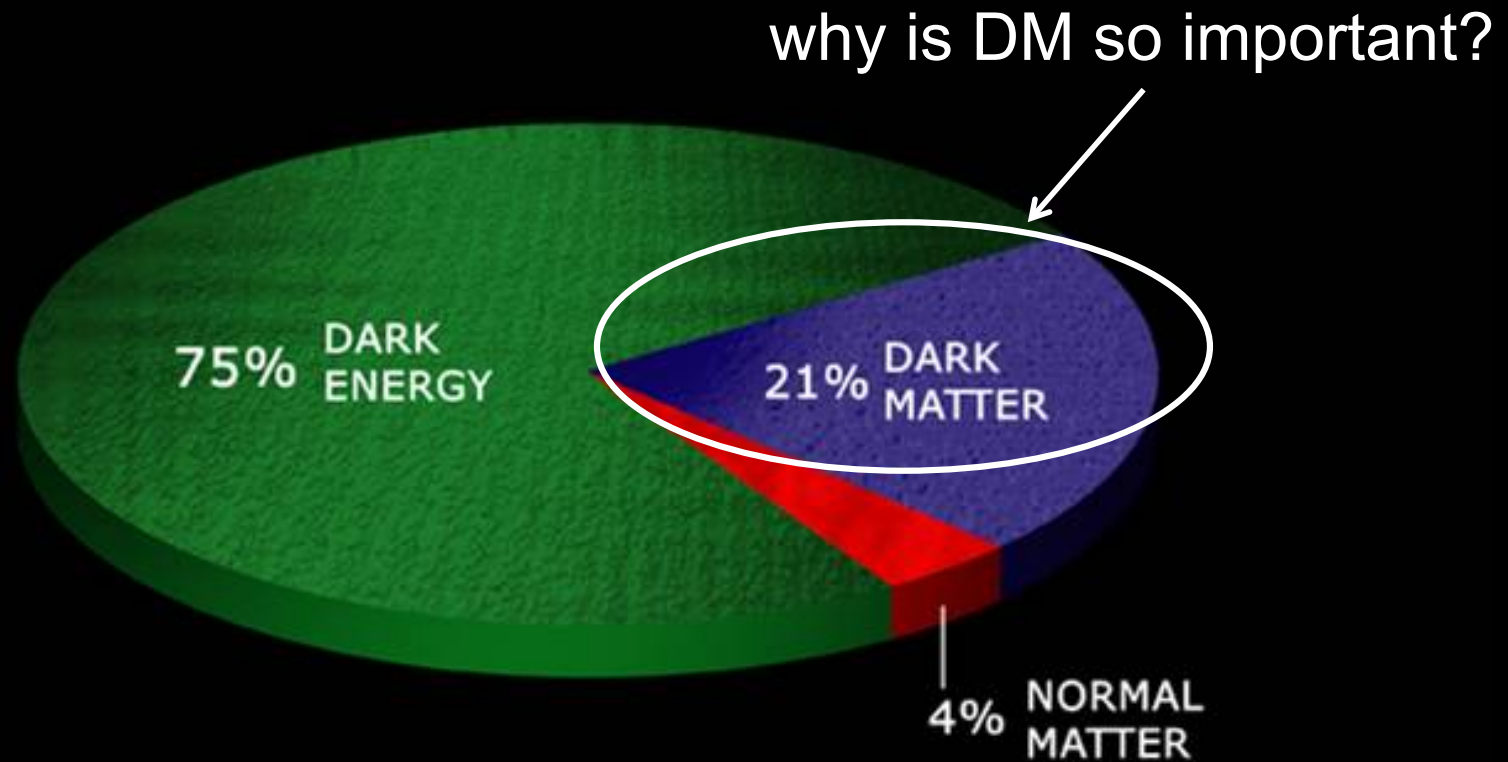
# The first all-sky image from GLAST/Fermi



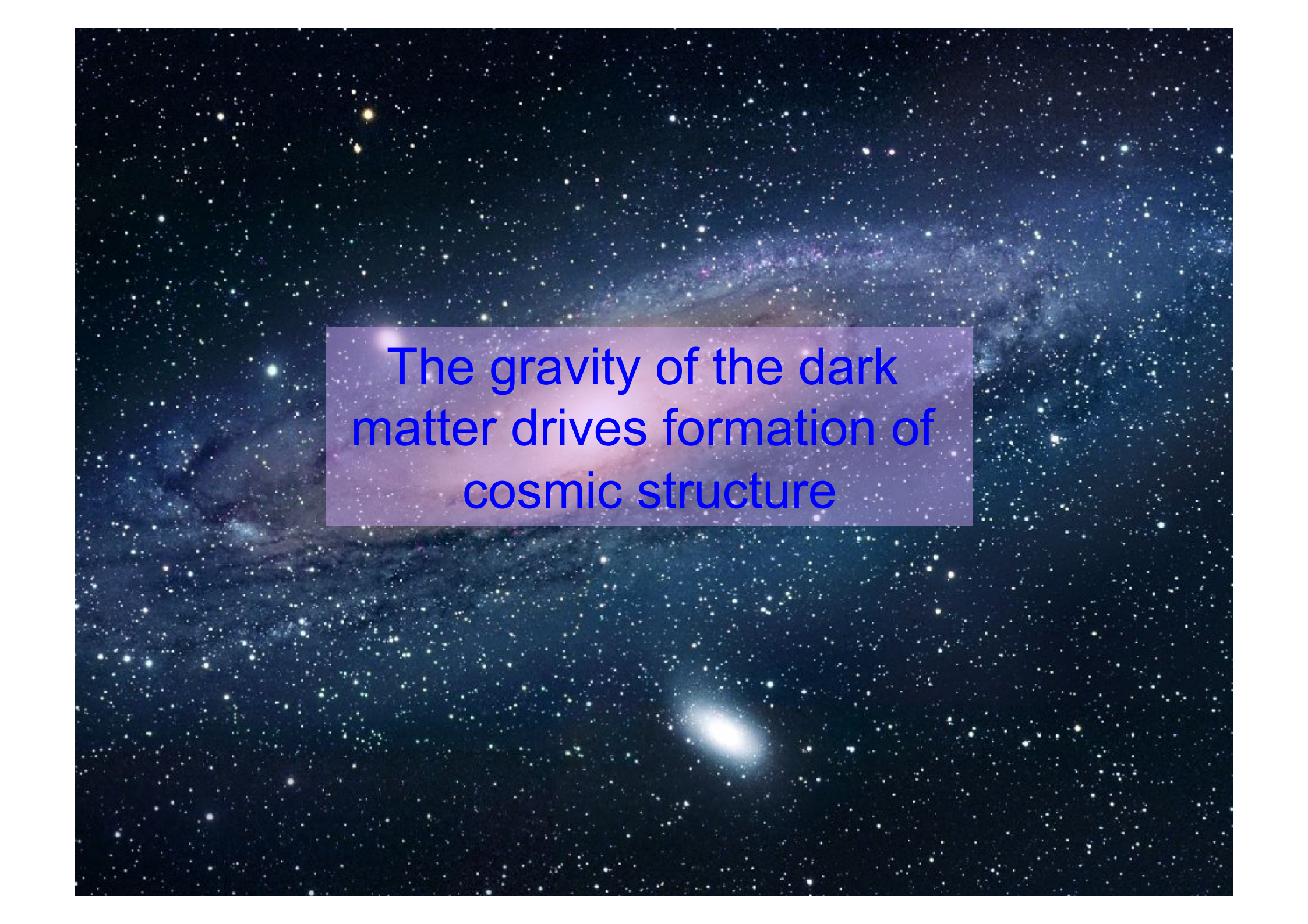


ICC

# The content of our universe



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

A deep space photograph of the Milky Way galaxy, showing a dense field of stars and a bright, glowing region in the foreground. The text is overlaid on a semi-transparent purple box in the center.

The gravity of the dark  
matter drives formation of  
cosmic structure



University of Durham

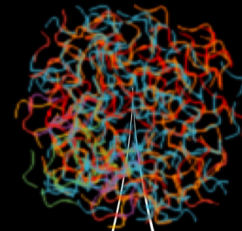
# The progress of physics

But where do galaxies come from?

# The initial conditions

INFLATION

$t=10^{-35}$  sec



QUANTUM  
SPACE-TIME  
FOAM?



$$p = -\rho$$

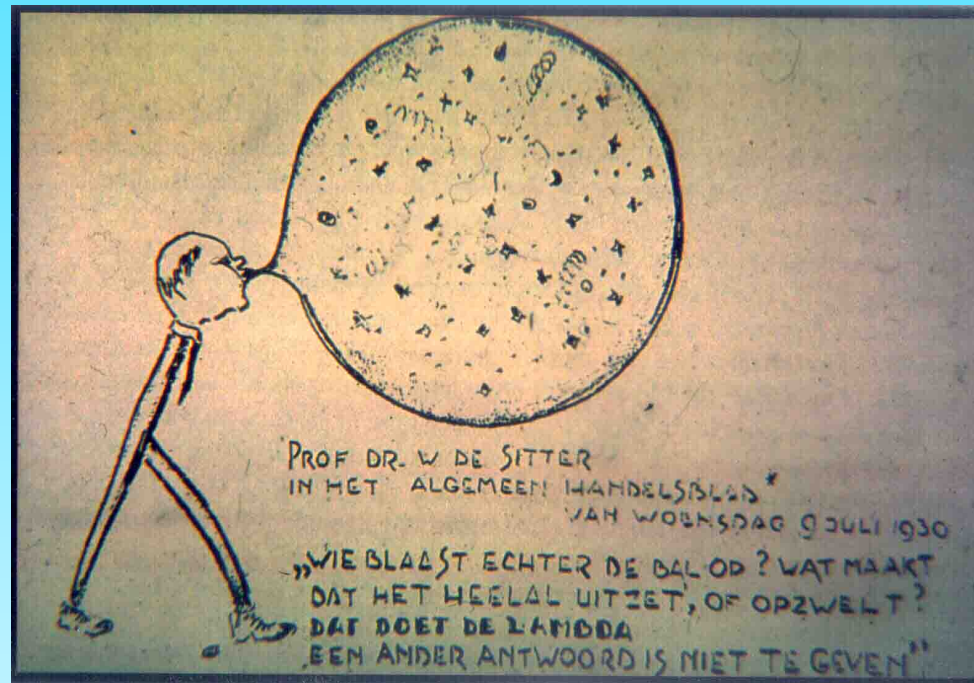
**BLAP!**

THE ENTIRE  
OBSERVABLE  
UNIVERSE!

from G. Efstathiou

# The beginning of the Universe

In 1980, a revolutionary idea was proposed: our universe started off in an unstable state (**vacuum energy**) and as a result expanded very fast in a short period of time → **cosmic inflation**

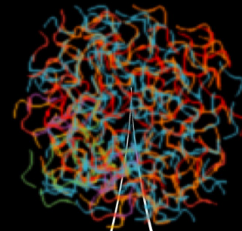


# The initial conditions

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

## INFLATION

$t=10^{-35}$  sec



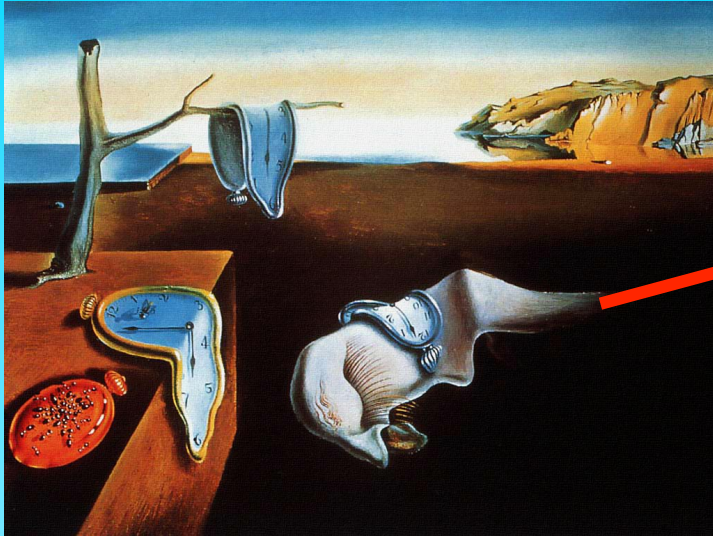
QUANTUM  
SPACE-TIME  
FOAM?

*tiny mass irregularities*

# BLAP!

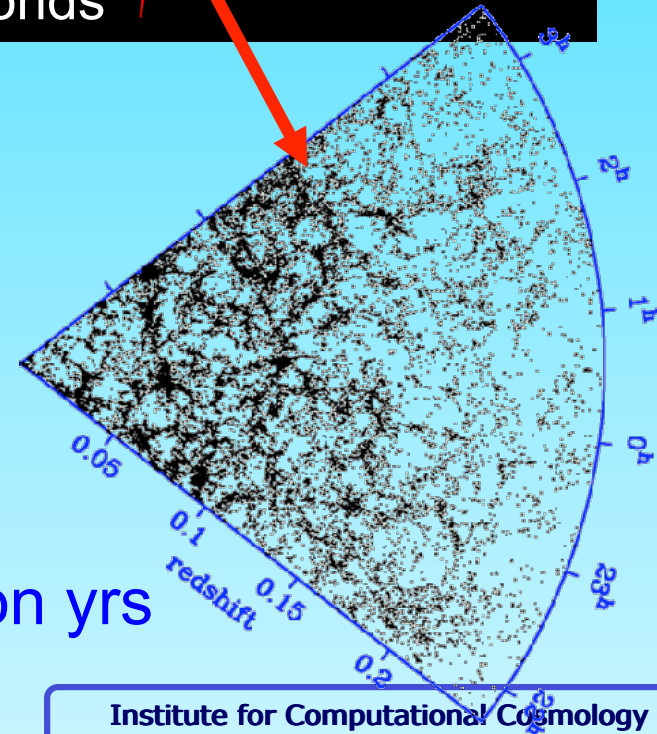
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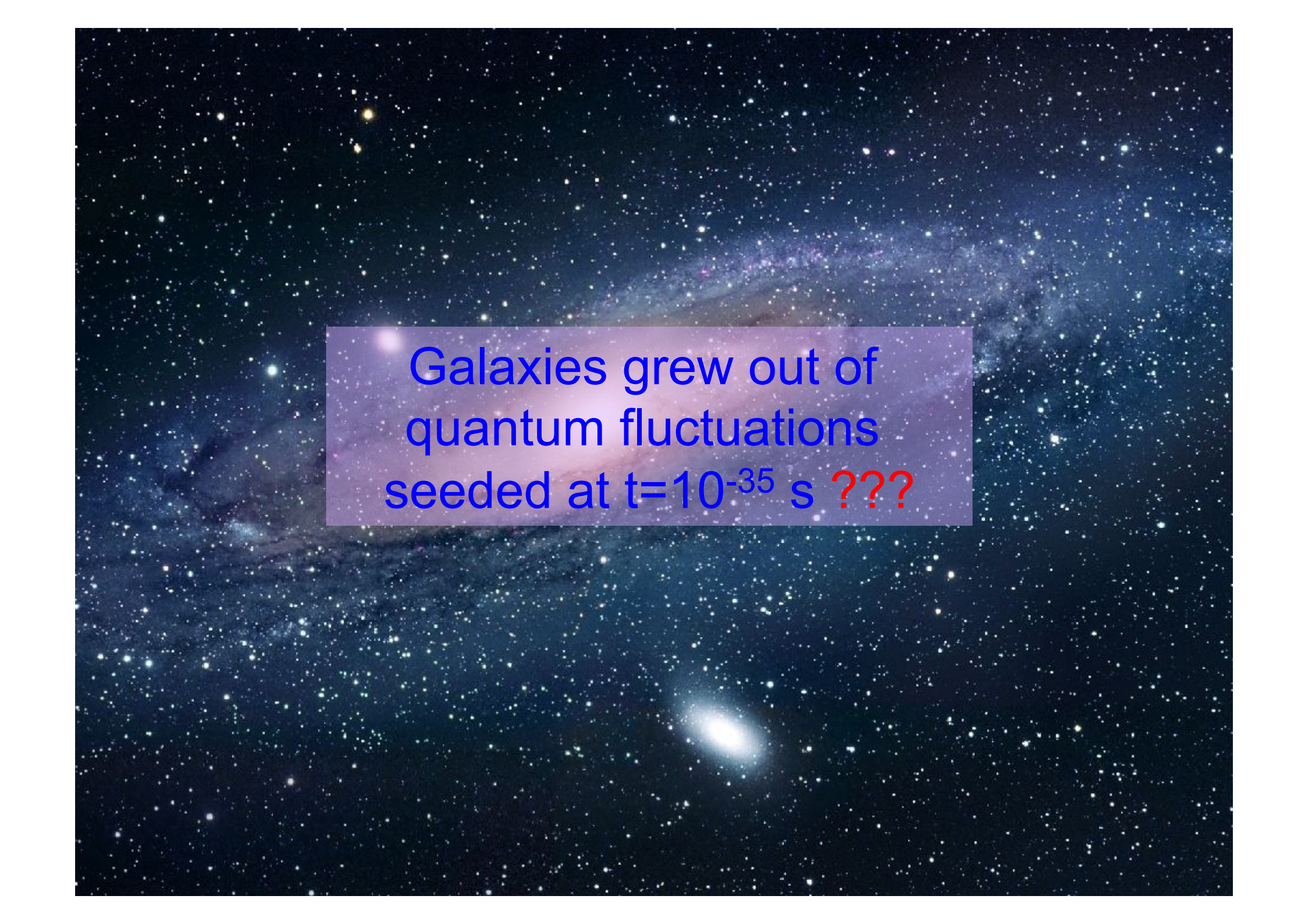
# The growth of cosmic structure



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

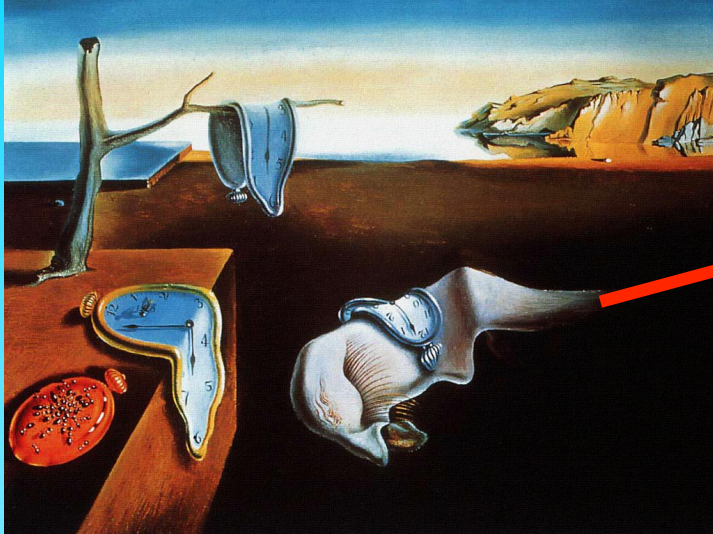
$t=13.8$  billion yrs





Galaxies grew out of  
quantum fluctuations  
seeded at  $t=10^{-35}$  s ???

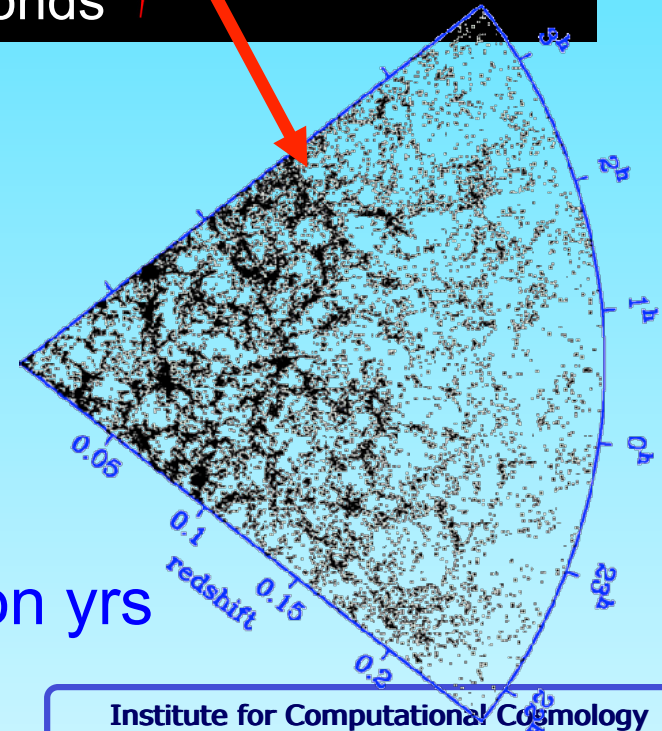
# The growth of cosmic structure



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

How do we test this?

t=13.8 billion yrs



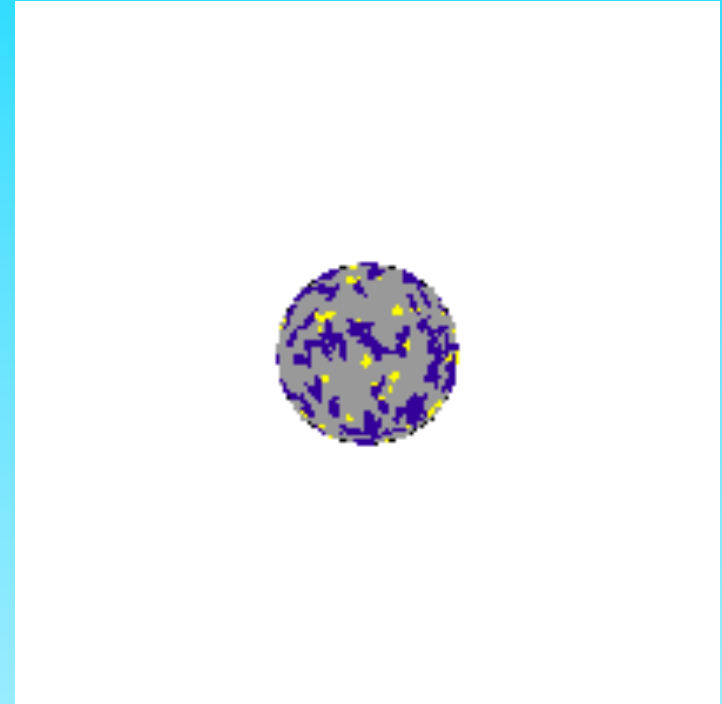


University of Durham

# The Big Bang theory

We know that the  
Universe is expanding today.

Thus, it must have been  
denser in the past.



In the **very distant past**, the Universe would have been **very dense**

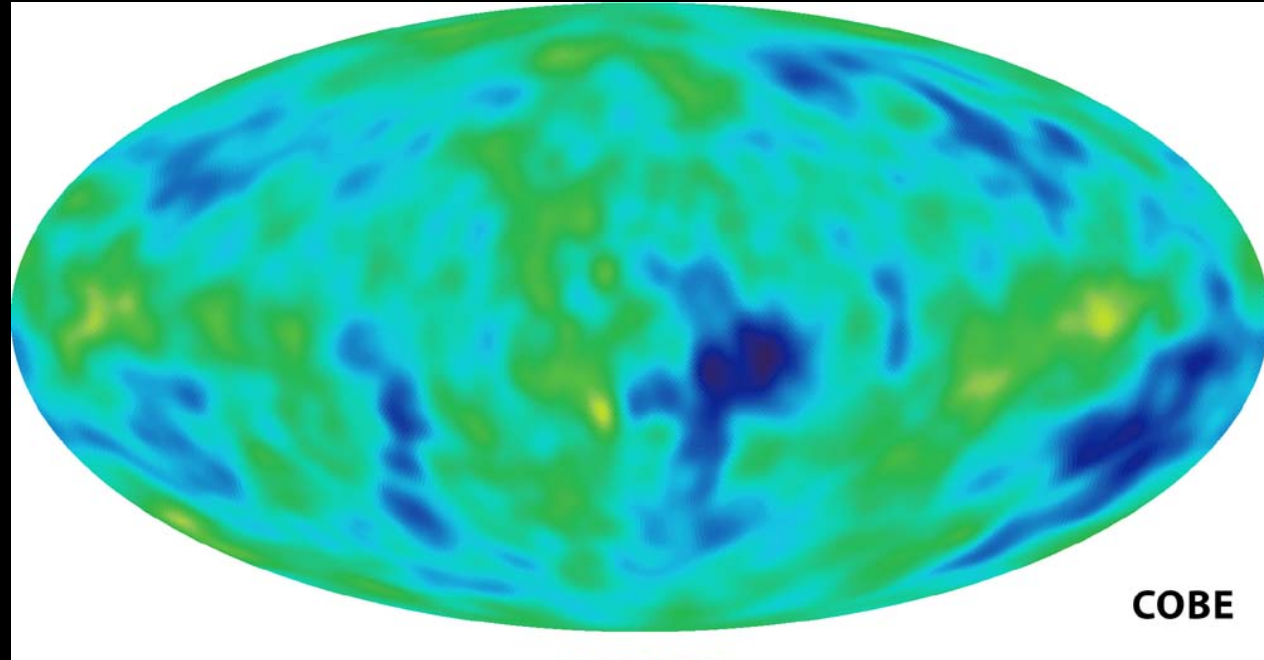
# The echo of the Big Bang

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.



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

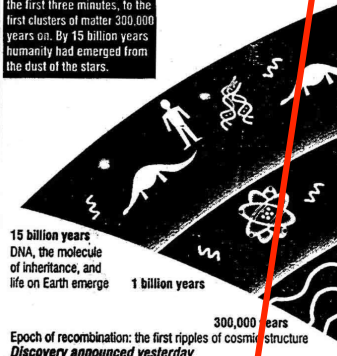
No 1,722

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.



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 now see 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.

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Dr Smoot and colleagues at Berkeley joined researchers from several American research organisations to form the Cobe team. These included the Goddard 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."

Michael 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 would 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<sup>-10</sup> second

10<sup>-33</sup>  
The quark bare particle

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-

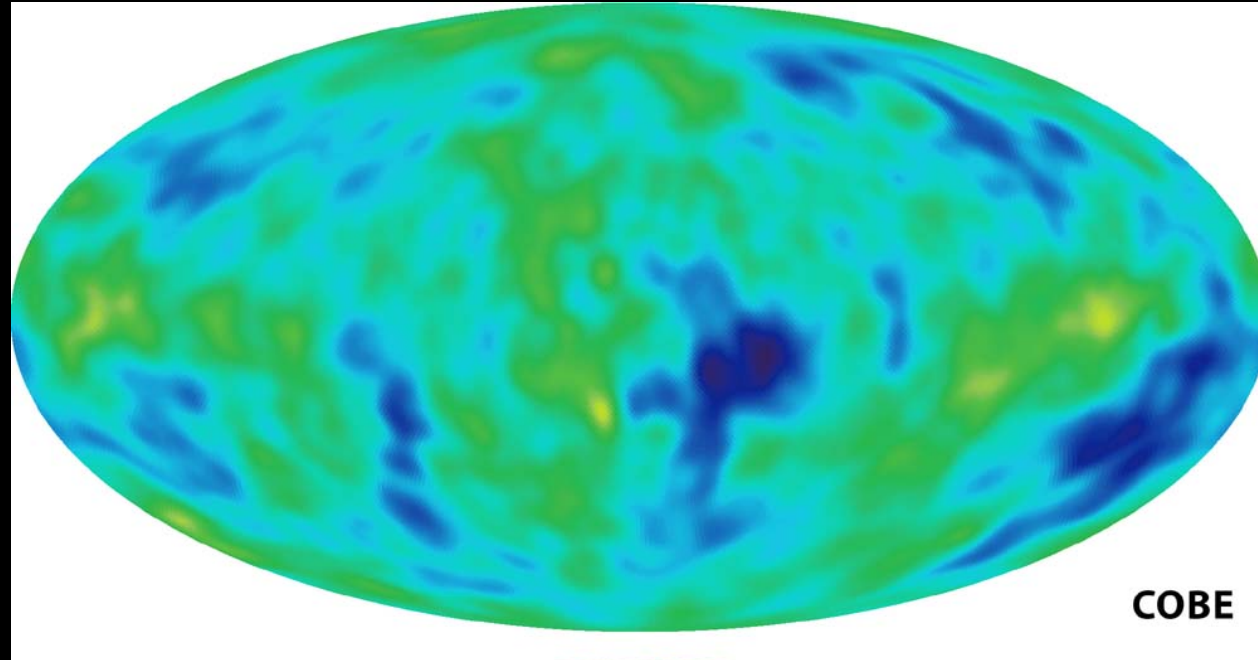
ceptible variations in the temperature of the universe, surrounded by slightly less dense matter. Time when the foggy fireball of radiation cleared and light from these galaxies, re-emitted, reached Earth. Predictions about what the size of the original fog looked like.

Flammarion 1888: tete des etoiles

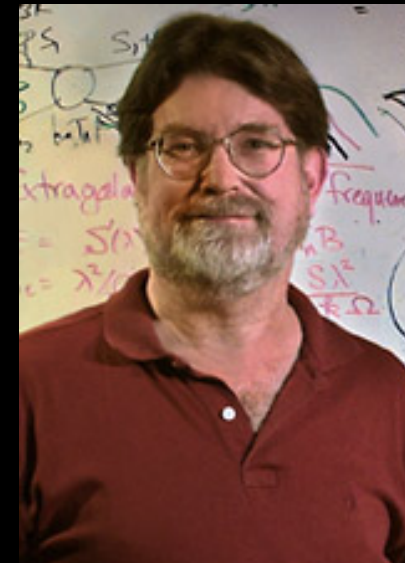
ICC

# The CMB

1992

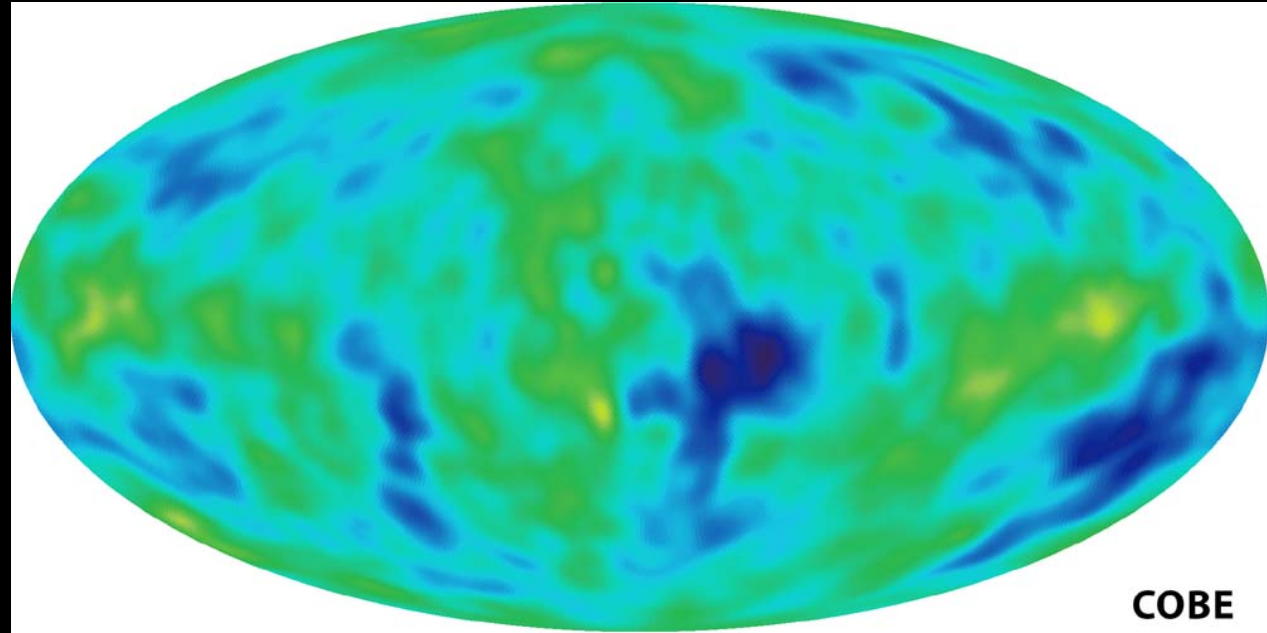


George Smoot - Nobel Prize 2006



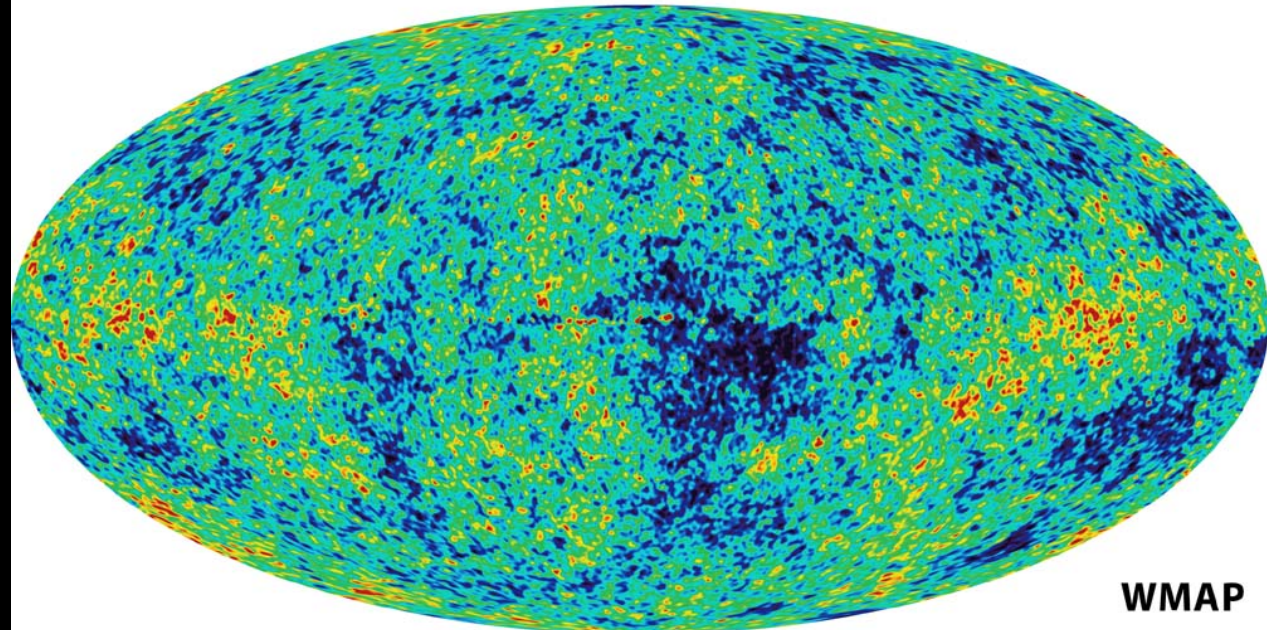
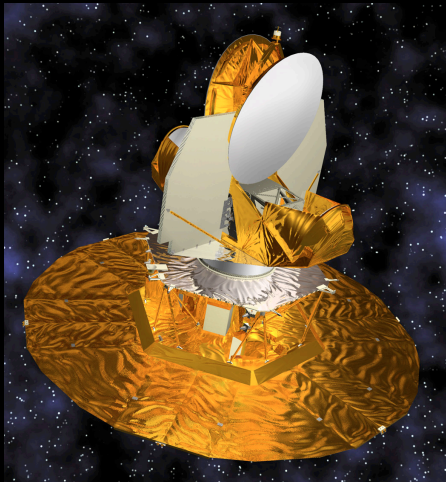
# The CMB

1992



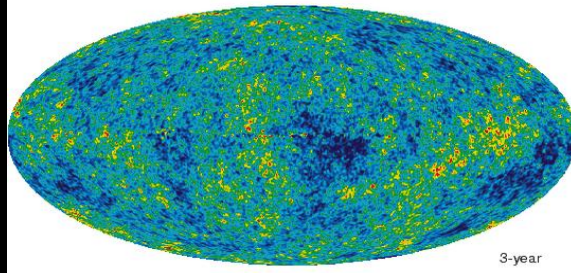
COBE

2003



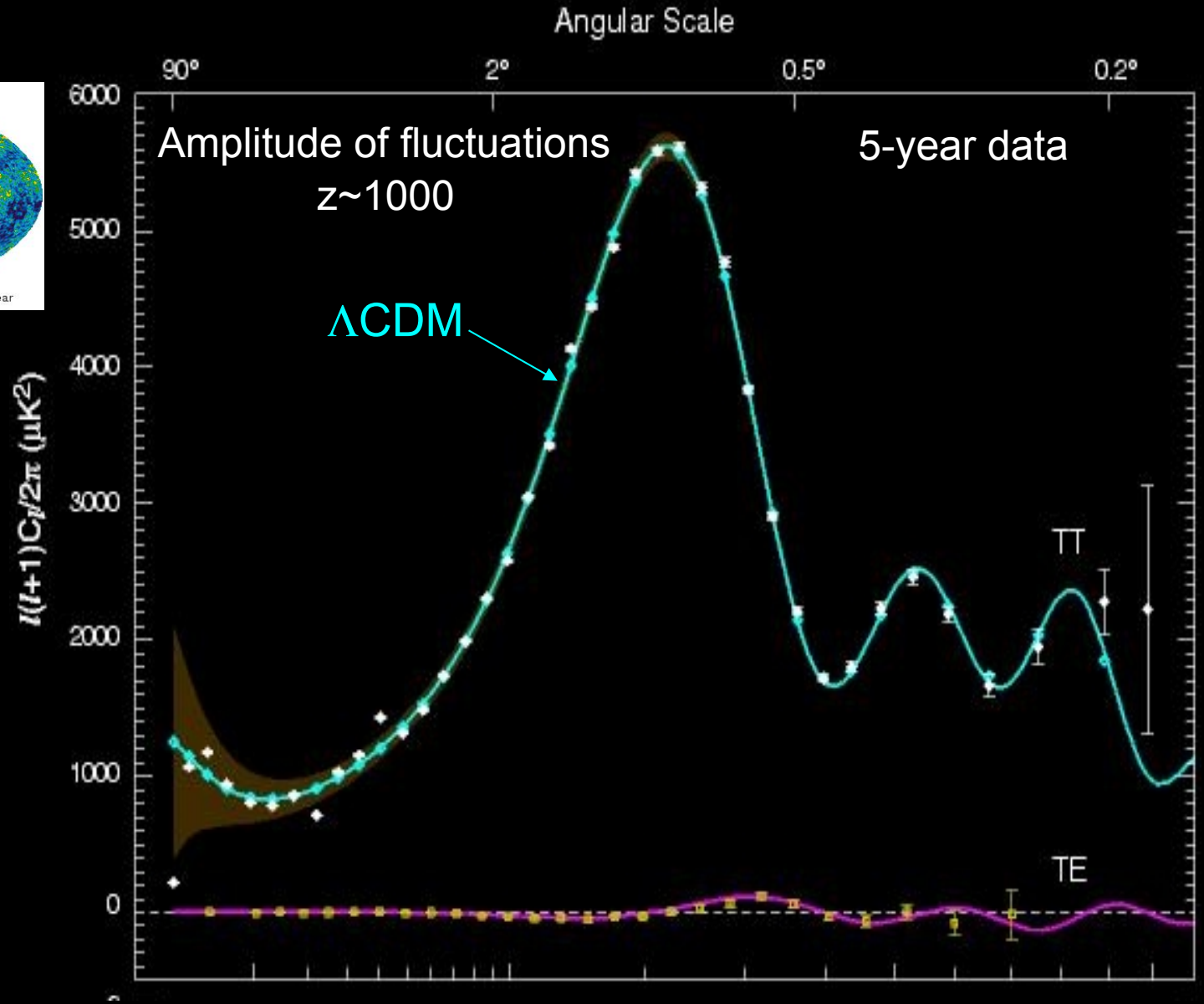
WMAP

# WMAP temp anisotropies in CMB

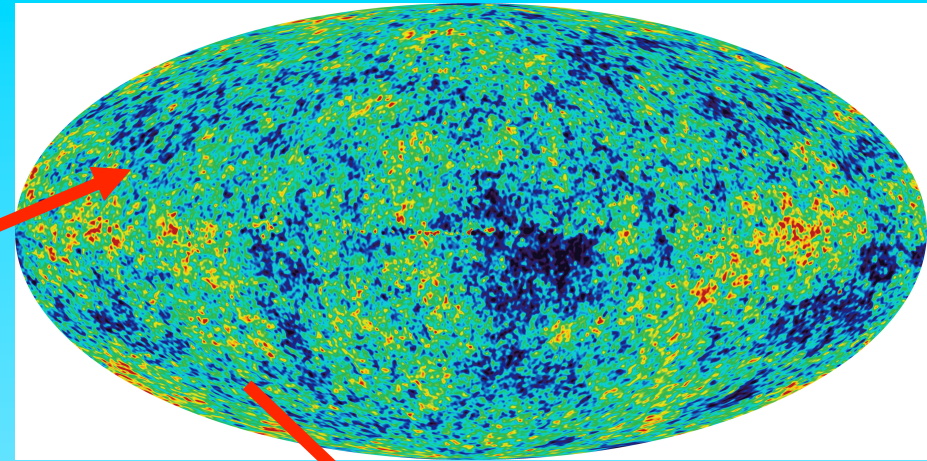
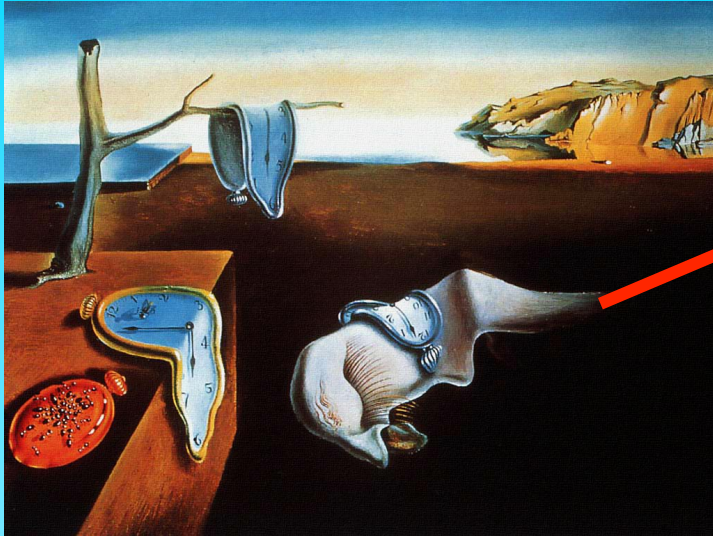


The data confirm the theoretical predictions

Hinshaw et al '06

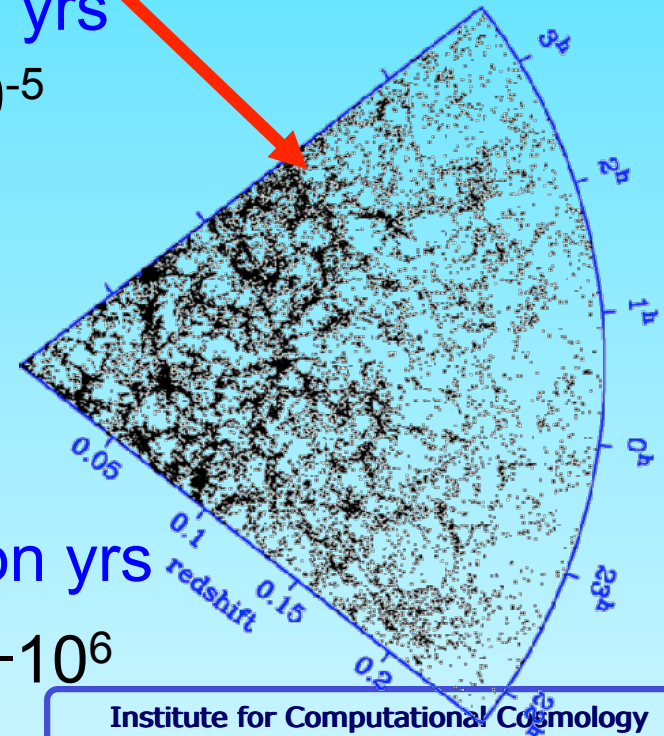


# The growth of cosmic structure



$t=380,000$  yrs

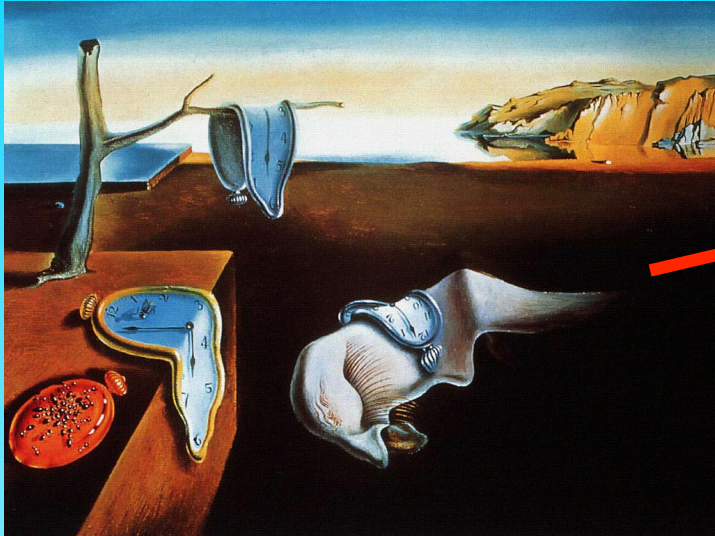
$$\delta\rho/\rho \sim 10^{-5}$$



$t=13.8$  billion yrs

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

# Testing the CDM paradigm



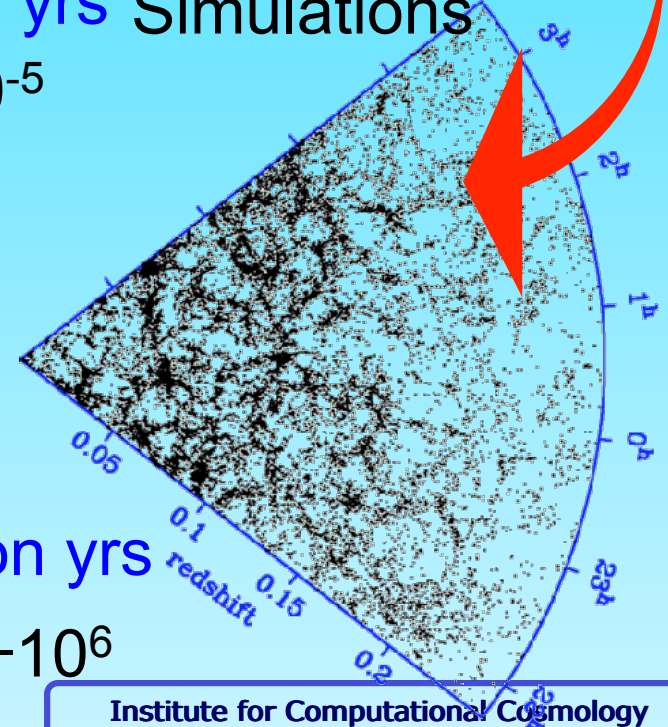
“Cosmology machine”



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

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



# Large Scale Structure

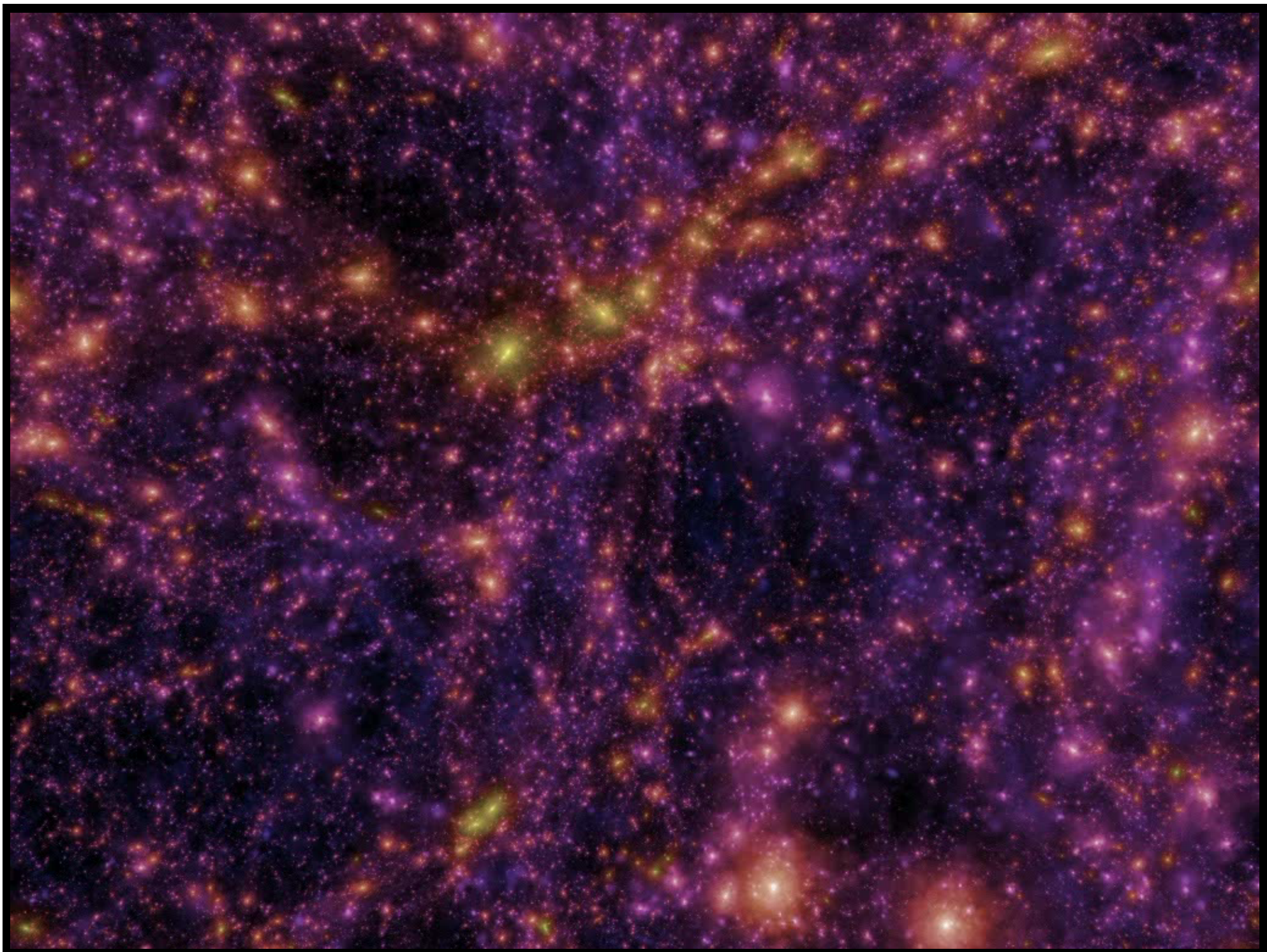
Computer  
simulation

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

500 million light years

$t = 0.06 \text{ Gyr}$





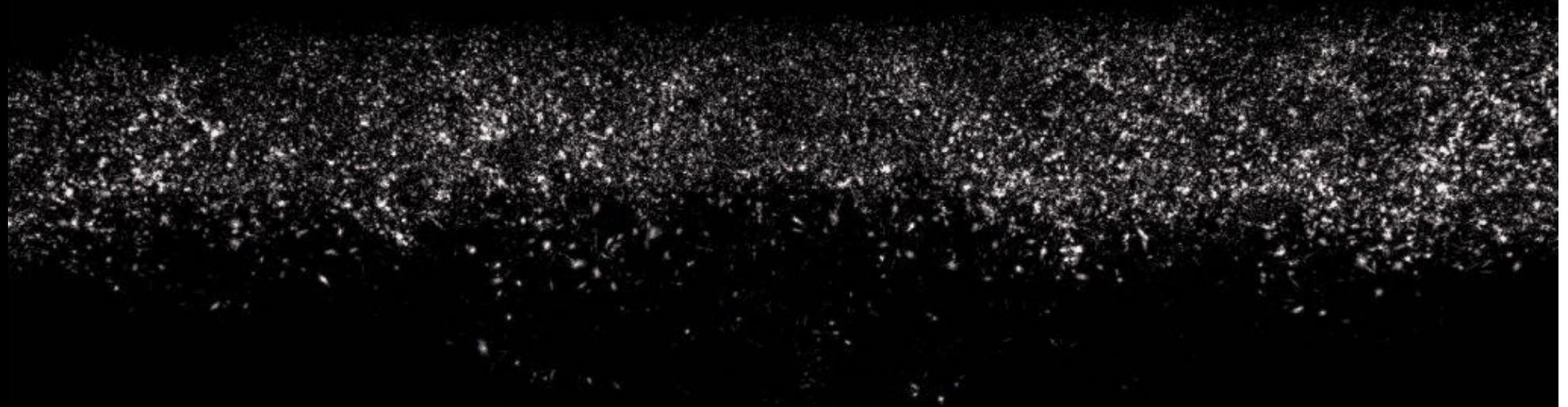
$z = 48.4$

$T = 0.05 \text{ Gyr}$

500 kpc



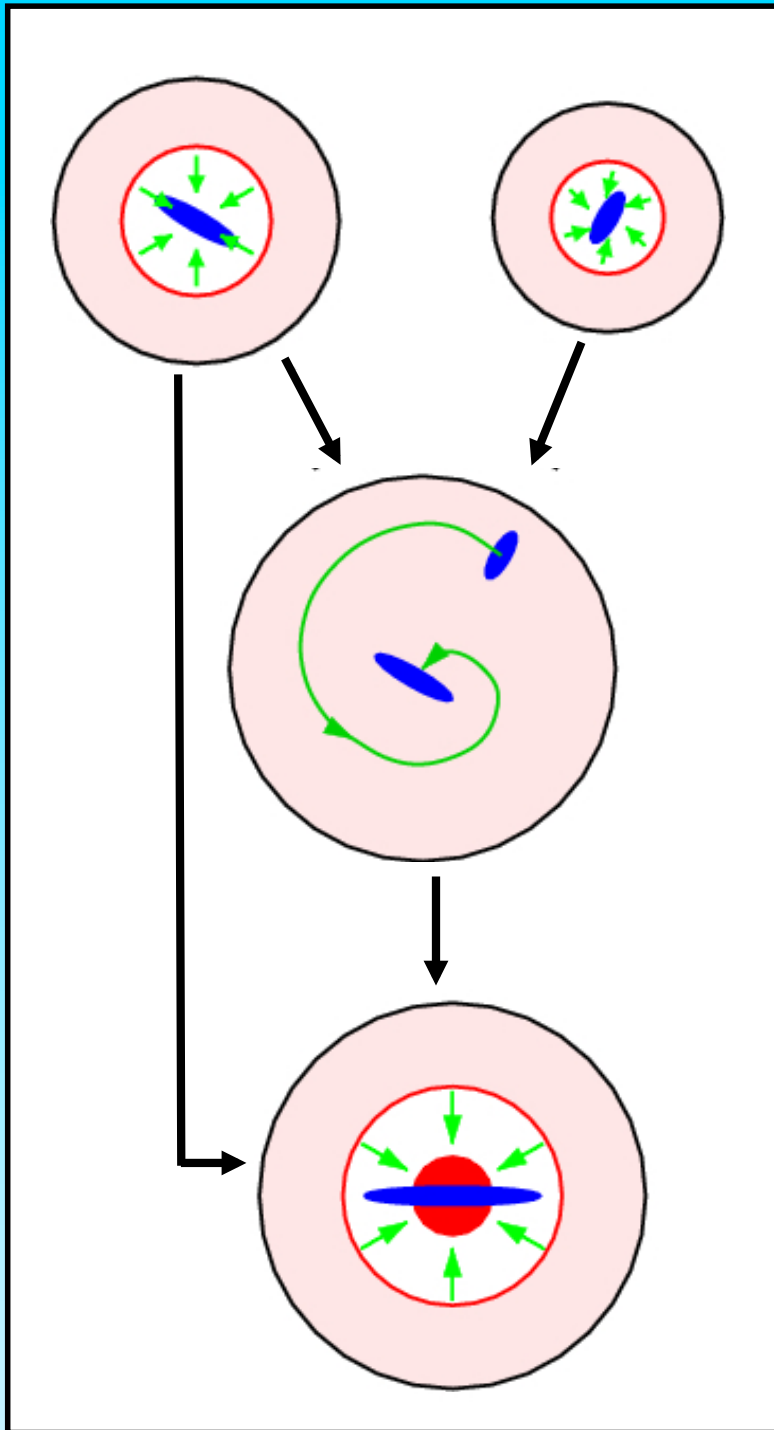
# The 2dF galaxy redshift survey



ICC

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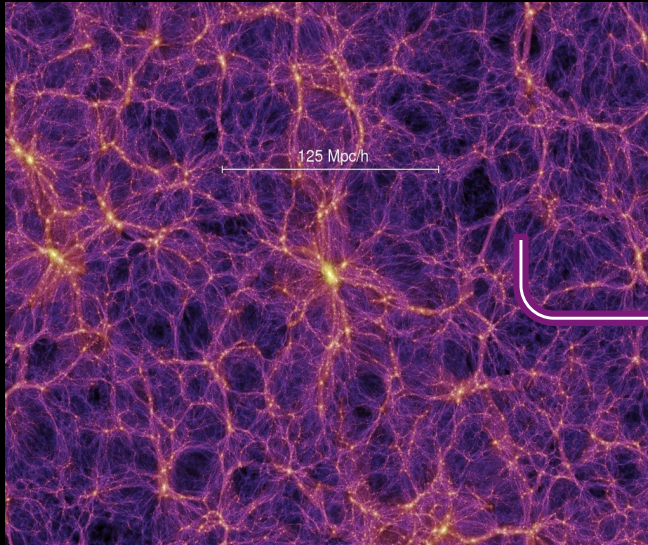
## Galaxy formation: the basics



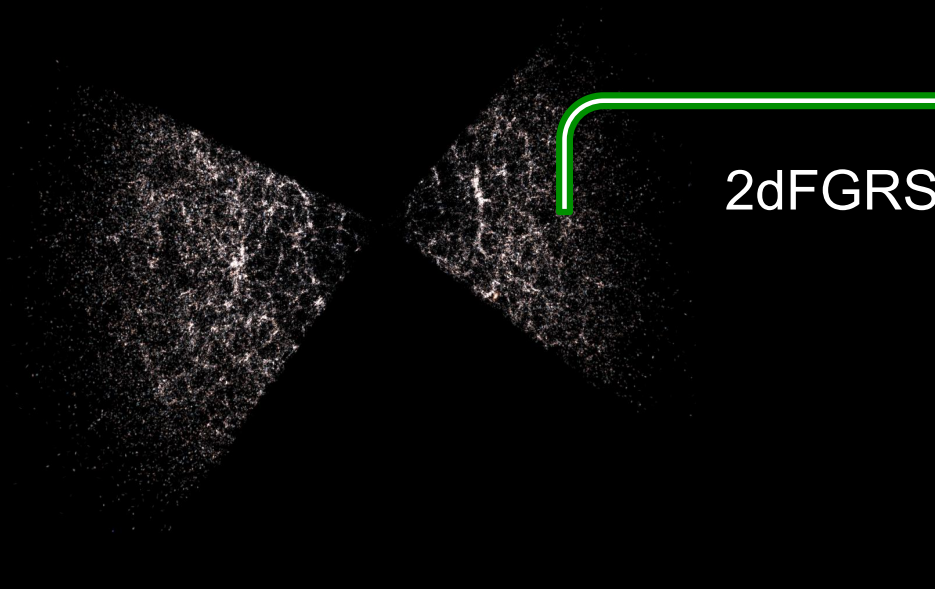
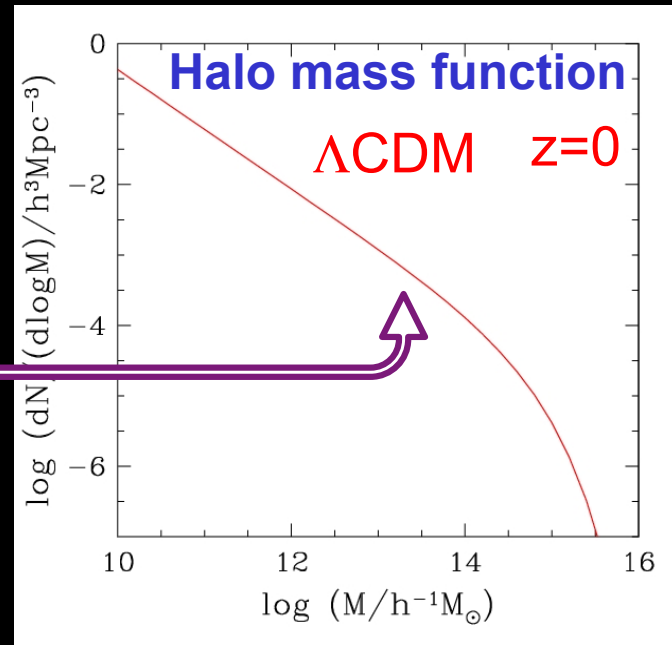
- Infalling gas shock-heated to  $T_{\text{vir}}$
- Gas cools radiatively onto central galaxy and forms **disk**, **conserving  $J$**   
 $\rightarrow r_{\text{disk}} \sim \lambda_{\text{h}} r_{\text{cool}}$
- Stars form in disk
- And give rise to **feedback** effects
- Satellite sinks by **dynamical friction** and merges onto central galaxy
- Mergers trigger central **starburst**
- In major mergers, stellar disks  $\rightarrow$  **spheroids** & **central black hole** grows
- New **disk** may form by gas accretion



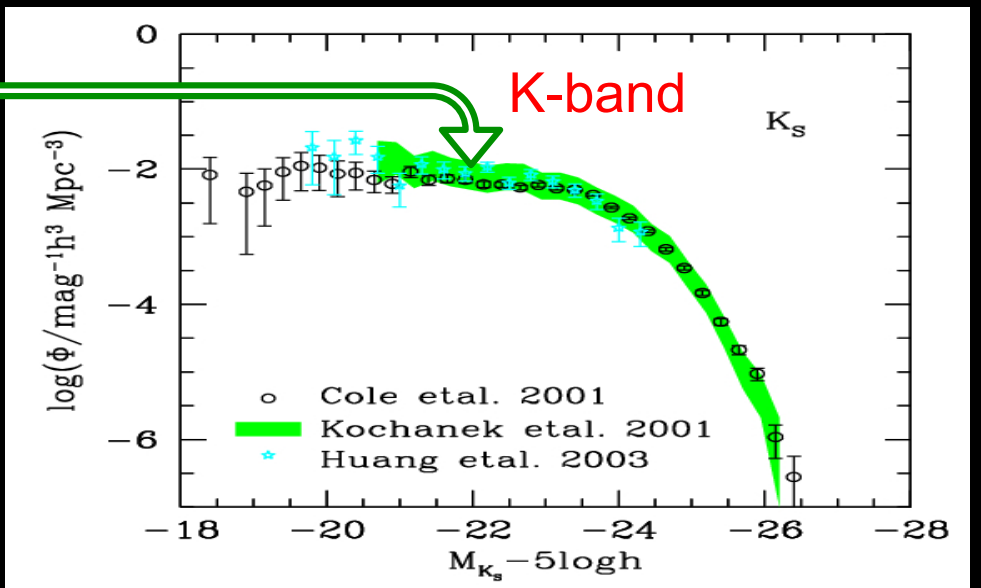
# The abundance of dark halos



Millennium run



2dFGRS



$z = 0$  Dark Matter

Populating the MS with galaxies

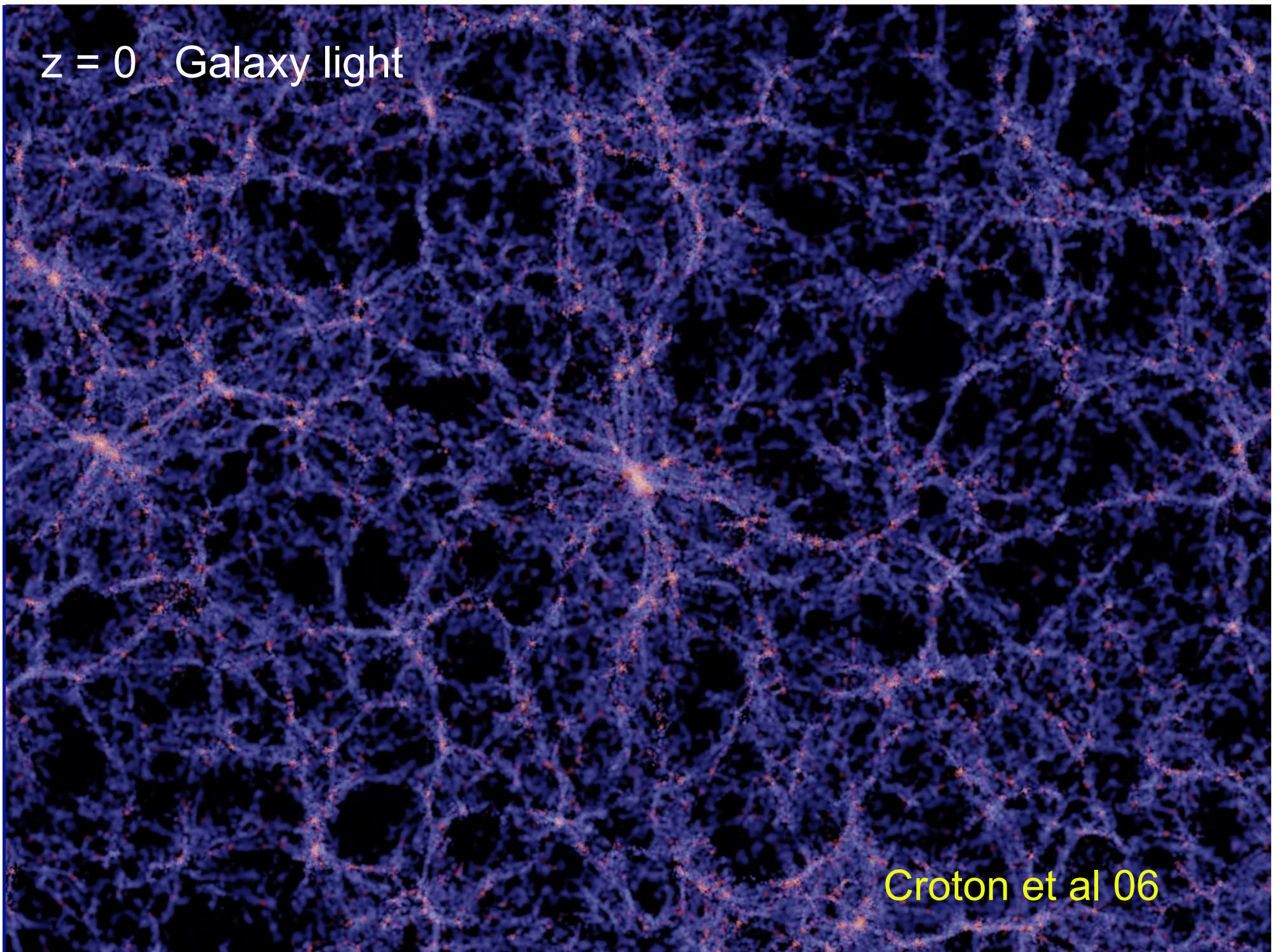
125 Mpc/h

Semi-analytic modelling

- Find dark matter halos
- Construct halo merger trees
- Apply SA model (gas cooling, star formation, feedback)

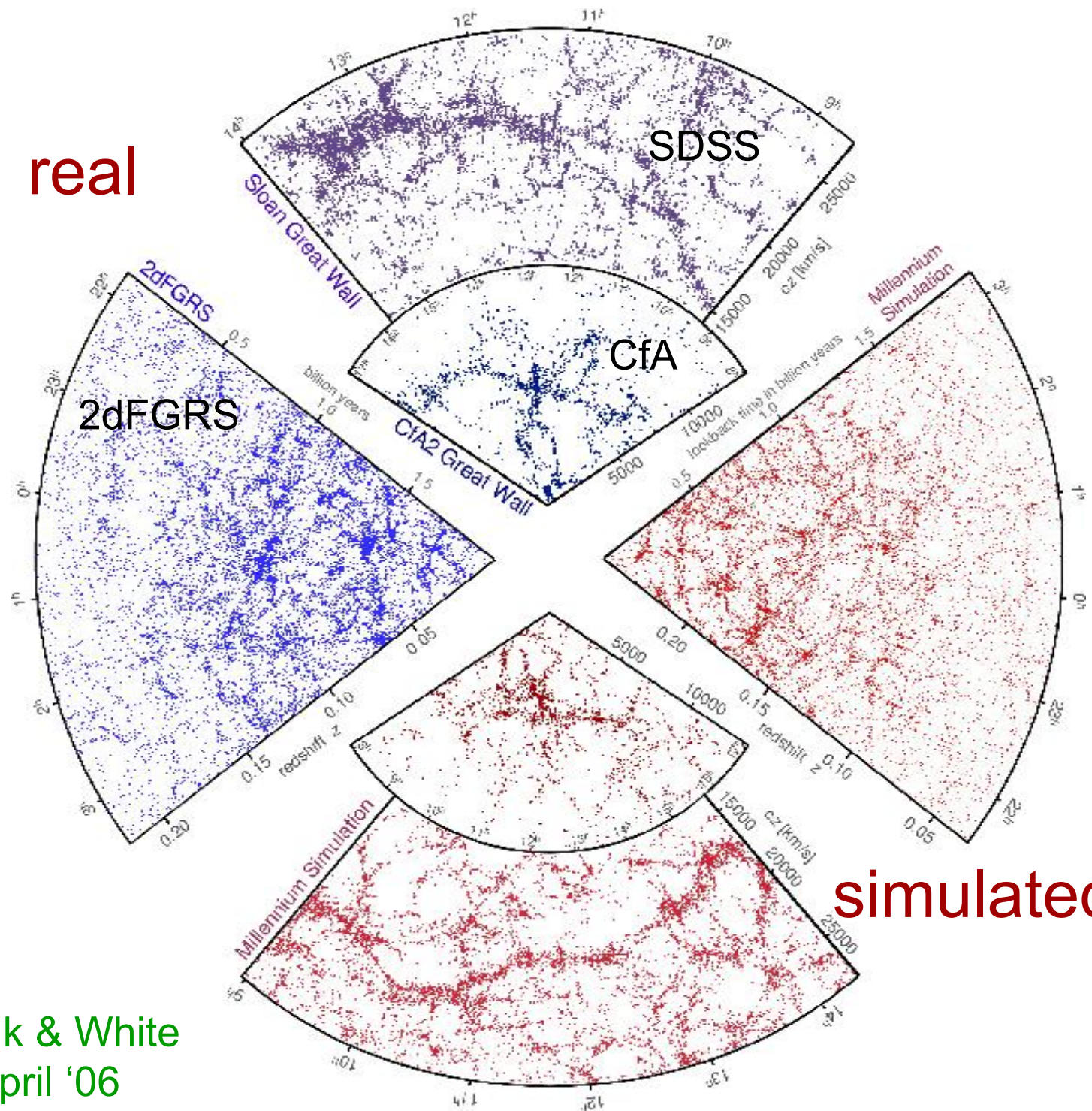
Springel etal 05

$z = 0$  Galaxy light



Croton et al 06

real

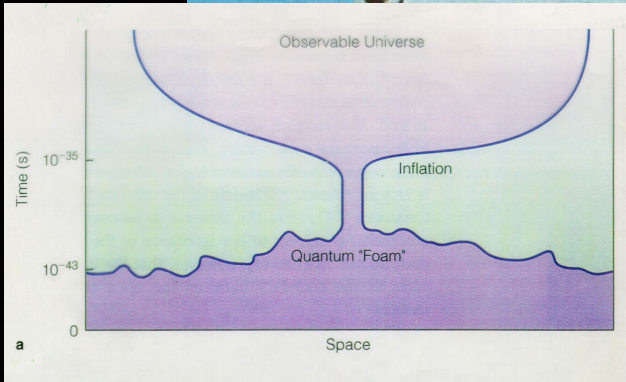


simulated

Springel, Frenk & White  
Nature, April '06

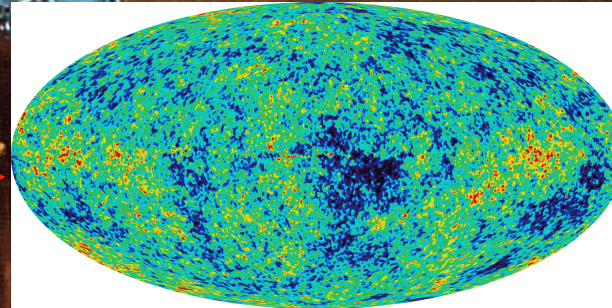
# The origin of cosmic structure

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



1. FLAT geometry:
2. Small (quantum) ripples

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

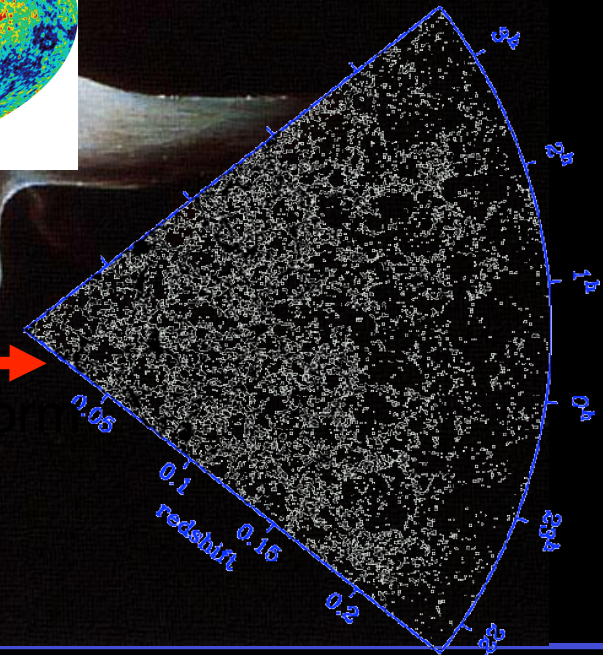


Galaxies  
( $t \sim 13 \times 10^9$  yrs)

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.**

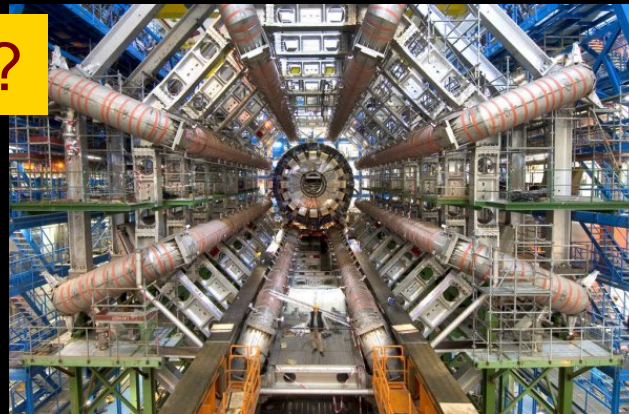


Is this the end of the story?

# Cold dark matter ?

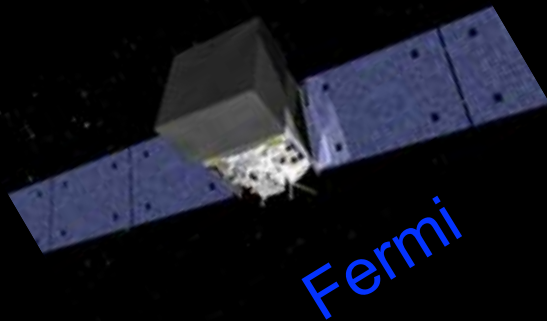
Theory predicts: dark matter is a particle,  
probably a SUSY particle

Dark matter discovery?



LHC – will it make it?

UK DM search  
(Boulby mine)

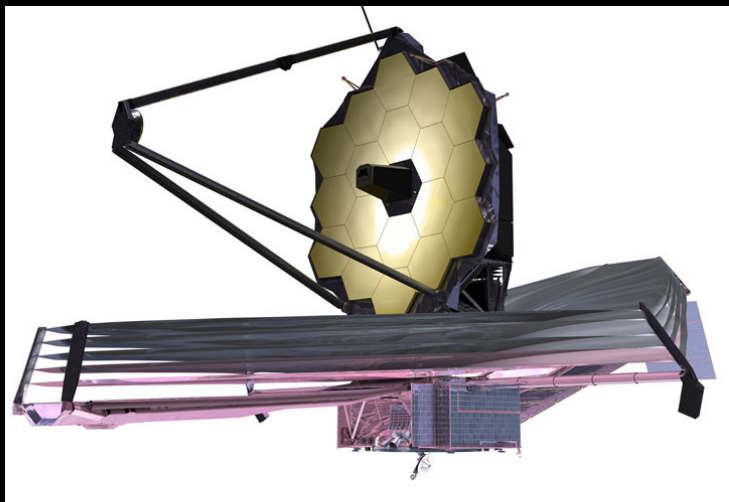


Fermi

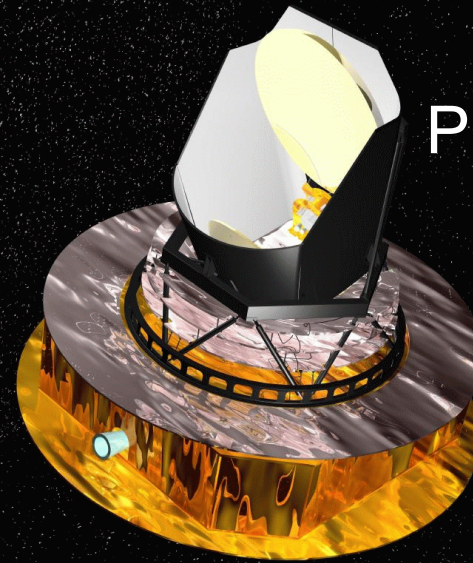


# The future

JWST: the next  
space telescope:



Planck: mapping  
the CMB



Theory, computing and modelling



The “golden” era in cosmology is not over

It has probably just begun!