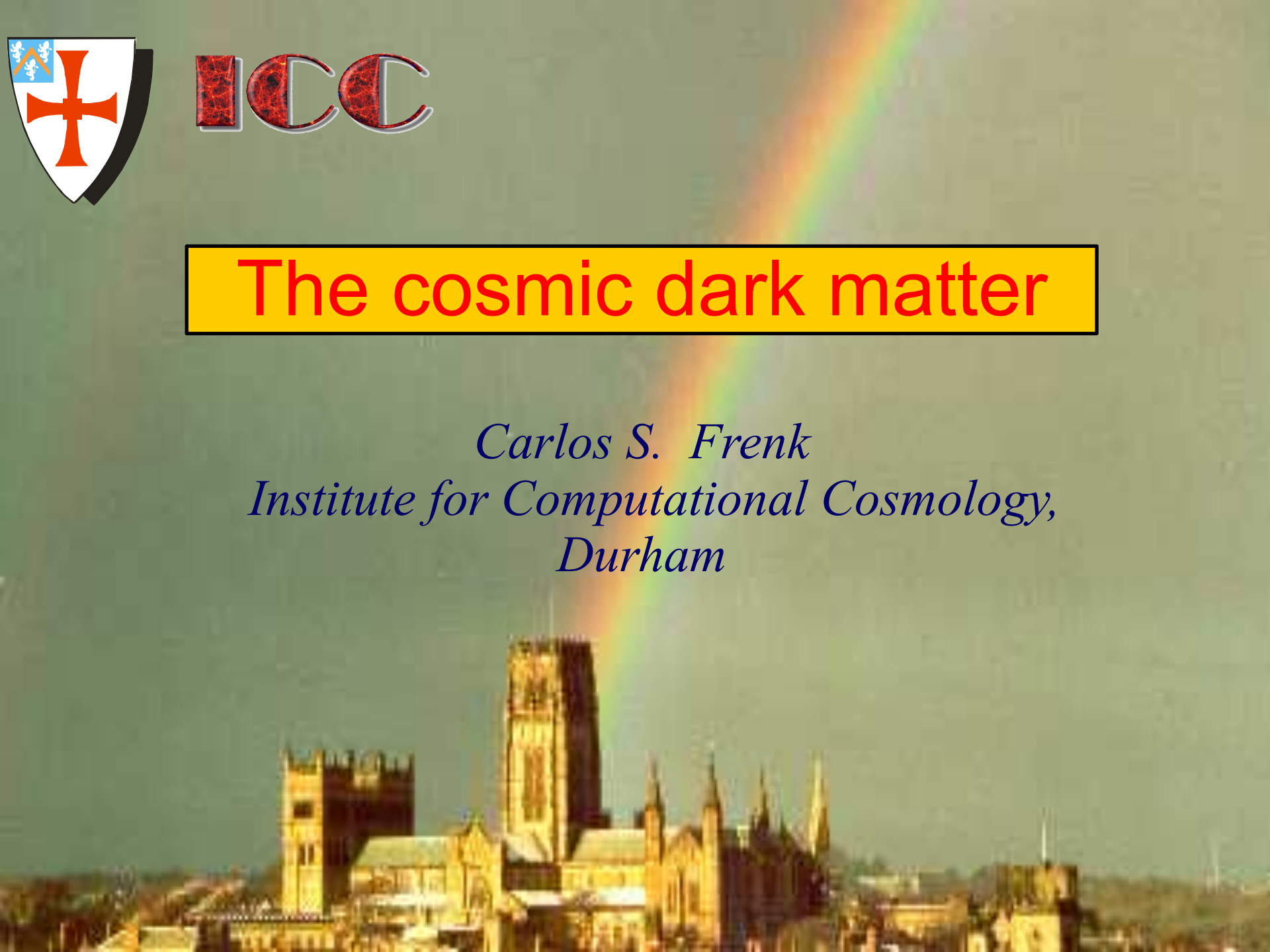


The cosmic dark matter

Carlos S. Frenk
Institute for Computational Cosmology, Durham

ICC
University of Durham

Where and what is it?

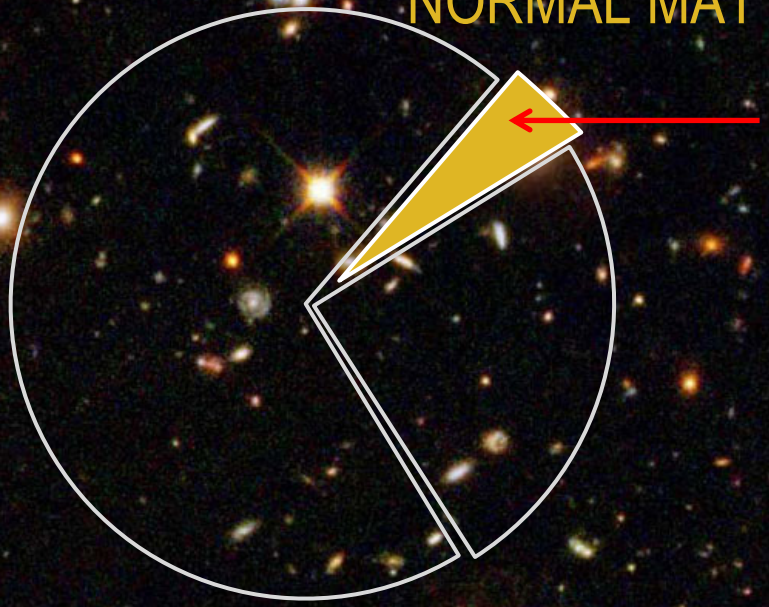
What is the Universe made of?

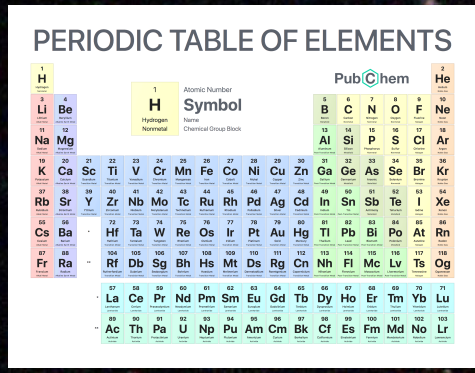
The (bizarre) contents of our Universe

The content of our universe

4%

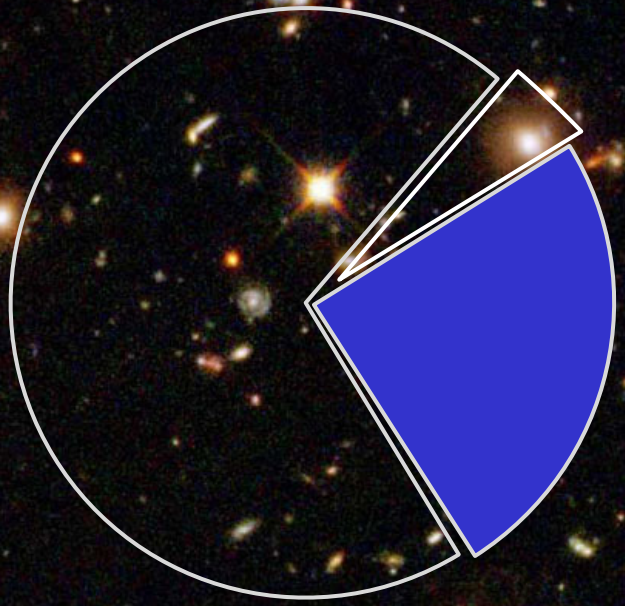
NORMAL MATTER





Normal matter ≡ matter made of ordinary atoms

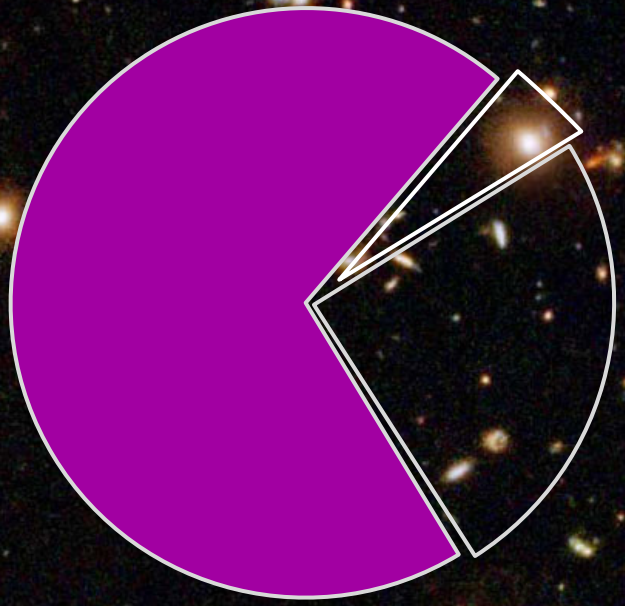
The content of our universe



24%
DARK MATTER

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

The content of our universe



71%

DARK ENERGY

Dark energy ≡ mysterious form of energy which opposes gravity and is causing the cosmic expansion to accelerate

The content of our universe

71%
DARK ENERGY

24%
DARK MATTER

The content of our universe

24%
DARK MATTER

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

We can’t see the dark matter

How do we know it exists?

The force of gravity

Issac Newton:

matter → gravity → motion

$$F = ma = \frac{GmM}{r^2}$$

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

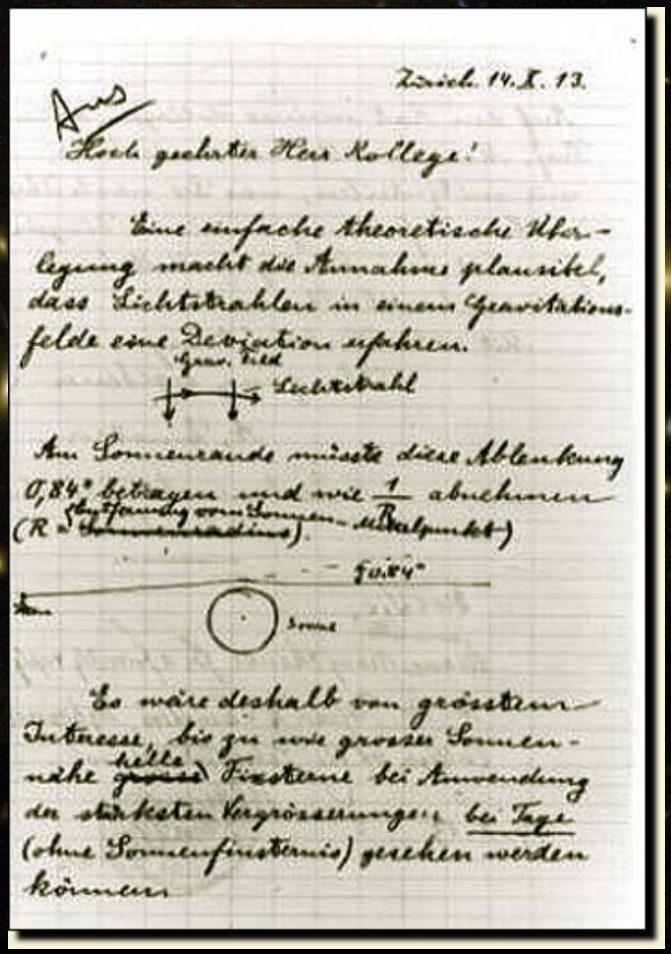
Stars rotate too fast to be held in place by gravity of visible mass

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

Clumps of dark matter: dark halos

→ dark matter keeps galaxy in place

Gravitational lensing: mapping the dark matter



Zürich, 14.X.13.

Hoch geehrter Herr Kollege!

Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.

Grav. field — Lichtstrahl

Am Sonnenrande müsste diese Ablenkung 0,84" betragen und wie $\frac{1}{R}$ abnehmen (R = Abstand vom Sonnen-Mittelpunkt).

0.84"

Sonne

Es wäre deshalb von grösstem Interesse, bis zu wie grossen Sonnennähe helle Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.

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

Institute for Computational Cosmology

Gravitational lensing: Hubble space telescope

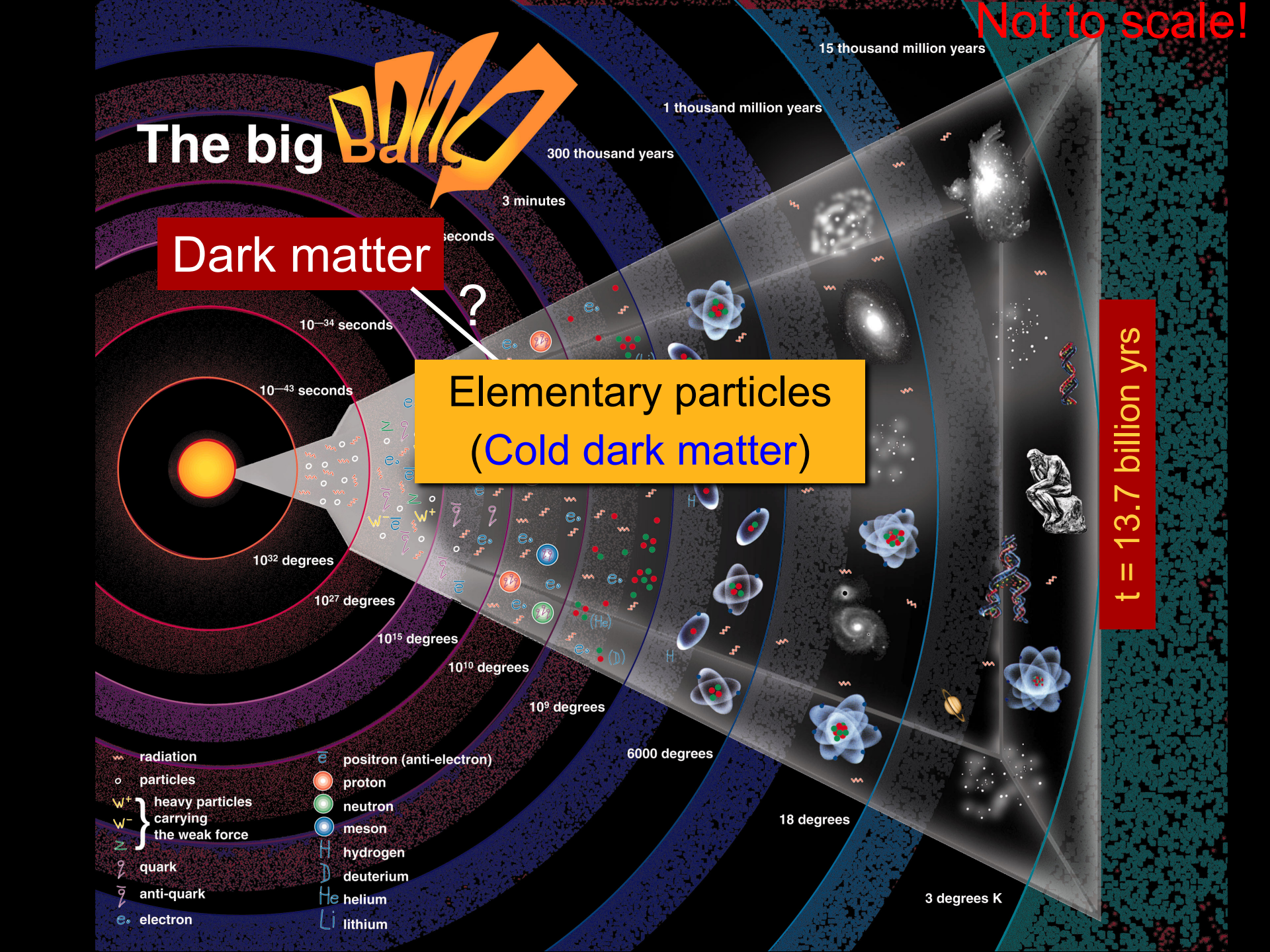
Can use gravitational lensing to "weigh" galaxy clusters → there is about 10 times more dark than visible mass

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

We know dark matter exists because:

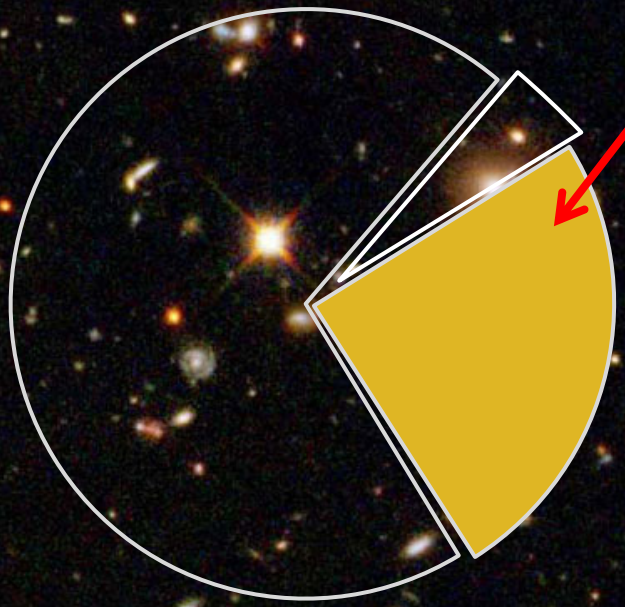
- The rotation velocity of stars in galaxies
- The distortion of galaxy images behind clusters

What is the dark matter?


Not to scale!
The big Bang
Dark matter
?
Elementary particles
(Cold dark matter)
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
t = 13.7 billion yrs
radiation
particles
W+ W− Z heavy particles carrying the weak force
quark
anti-quark
e electron
positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium
Li lithium

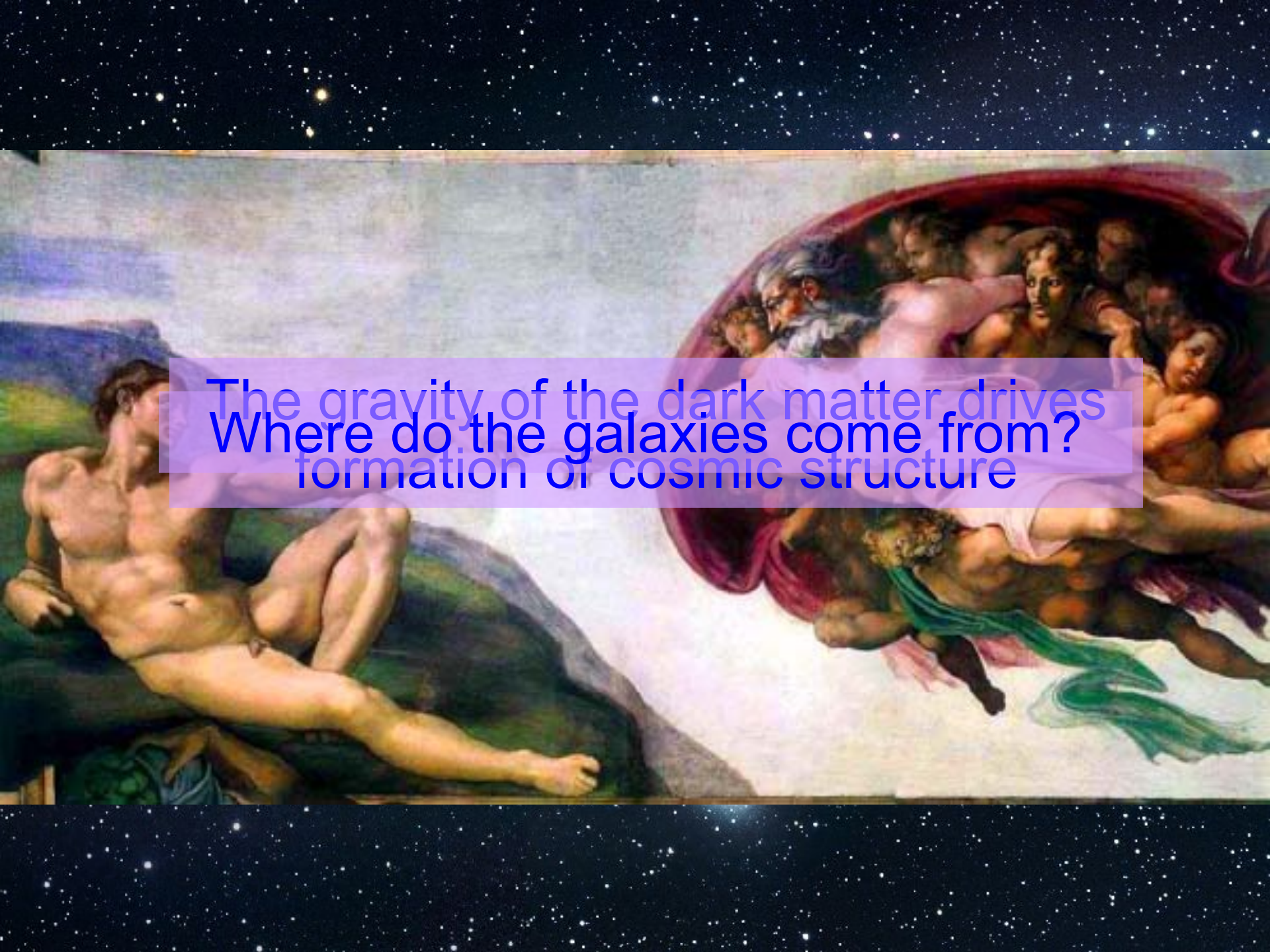
The content of our universe

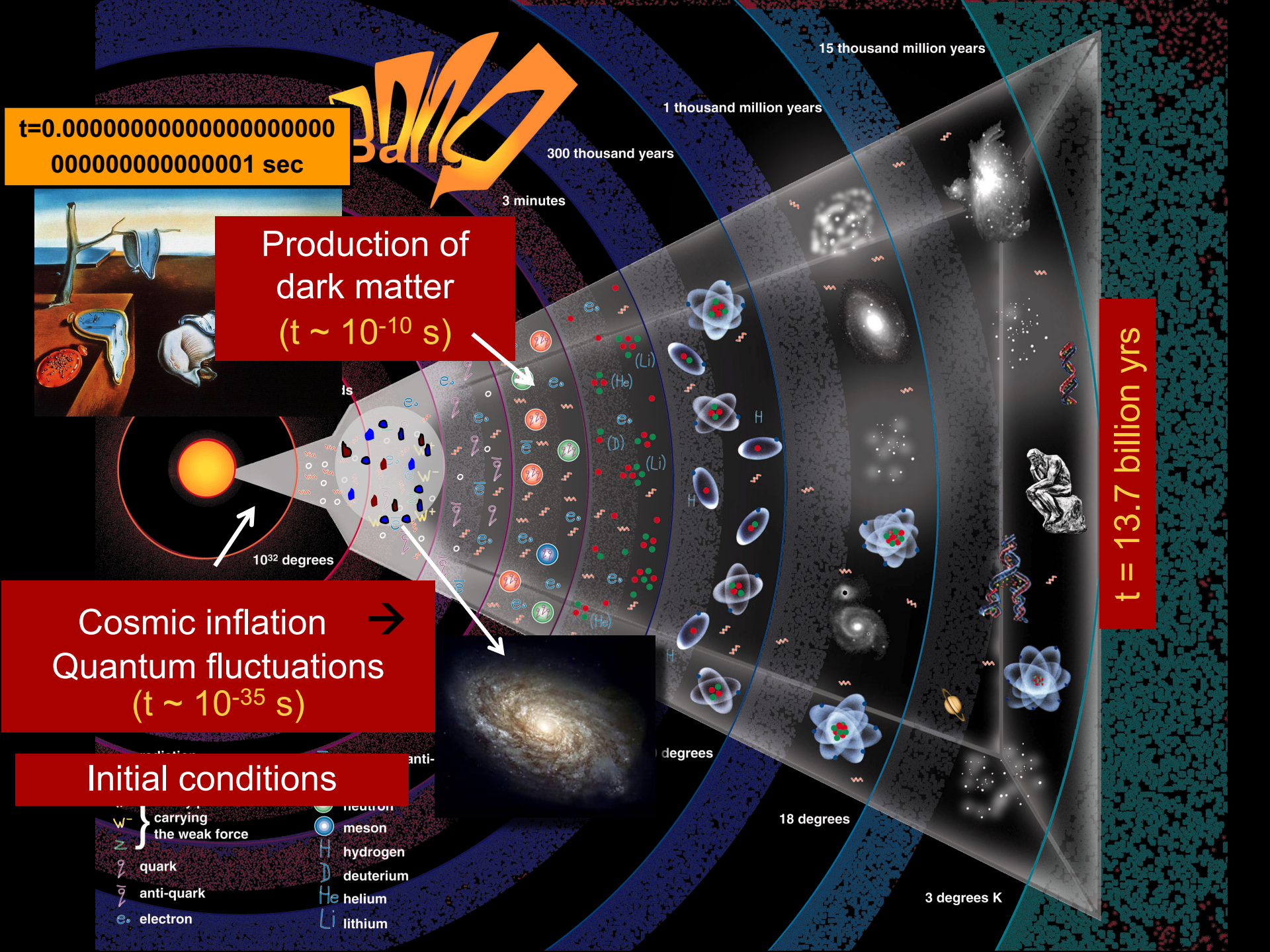
Why is DM so important?

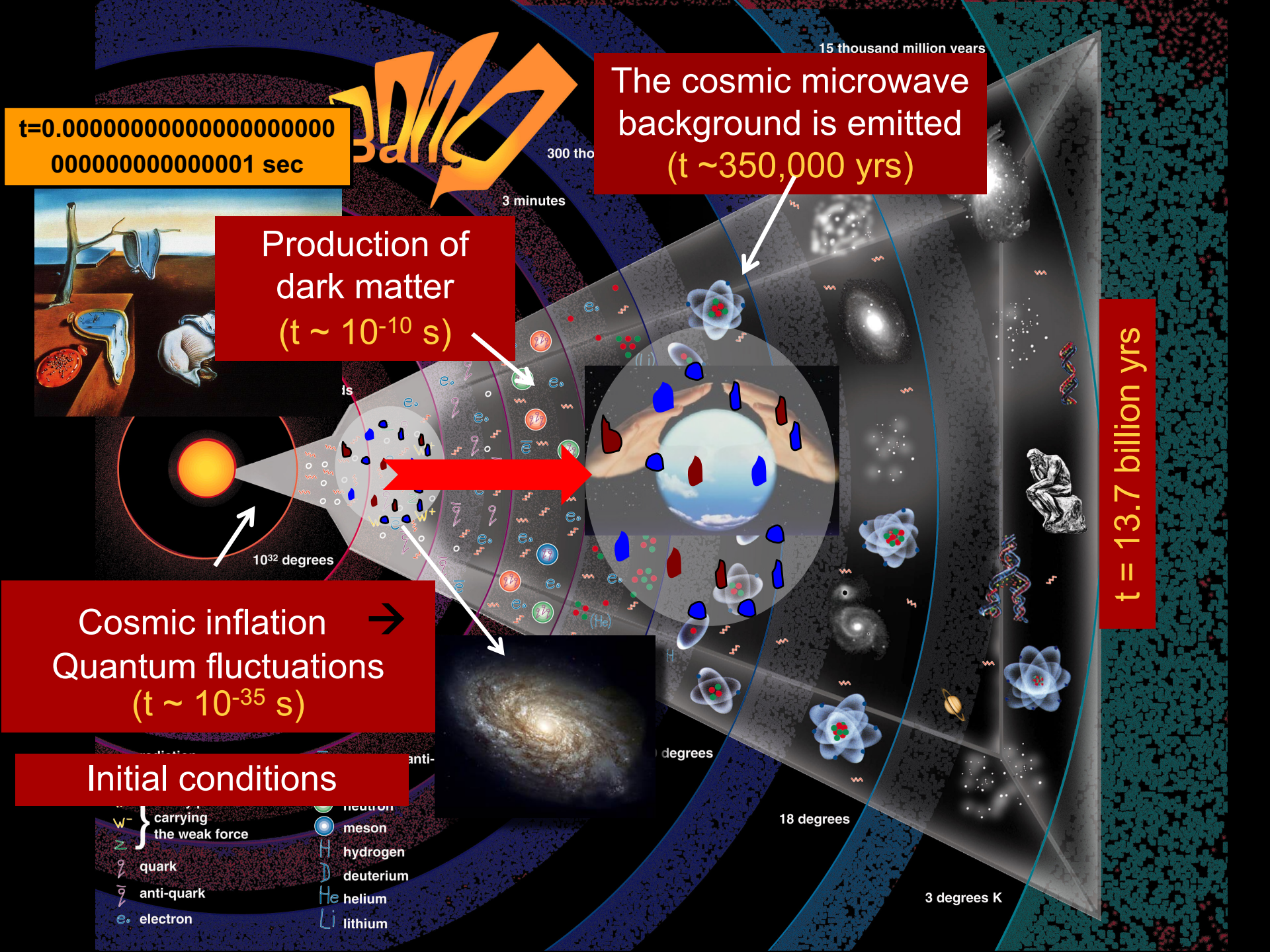


24%
DARK MATTER

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


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


t=0.00000000000000000000000000000001 sec
Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
Production of dark matter (t ~ 10-10 s)
10^32 degrees
Cosmic inflation
Quantum fluctuations
(t ~ 10-35 s)
Initial conditions
degrees
18 degrees
3 degrees K
t = 13.7 billion yrs
carrying the weak force
quark
anti-quark
electron
meson
hydrogen
deuterium
helium
lithium


t=0.00000000000000000000000000000001 sec
Big Bang
300 tho
3 minutes
15 thousand million years
The cosmic microwave background is emitted (t ~350,000 yrs)
Production of dark matter (t ~ 10-10 s)
10^32 degrees
Cosmic inflation
Quantum fluctuations
(t ~ 10-35 s)
Initial conditions
degrees
18 degrees
3 degrees K
t = 13.7 billion yrs
carrying the weak force
quark
anti-quark
electron
meson
hydrogen
deuterium
helium
lithium

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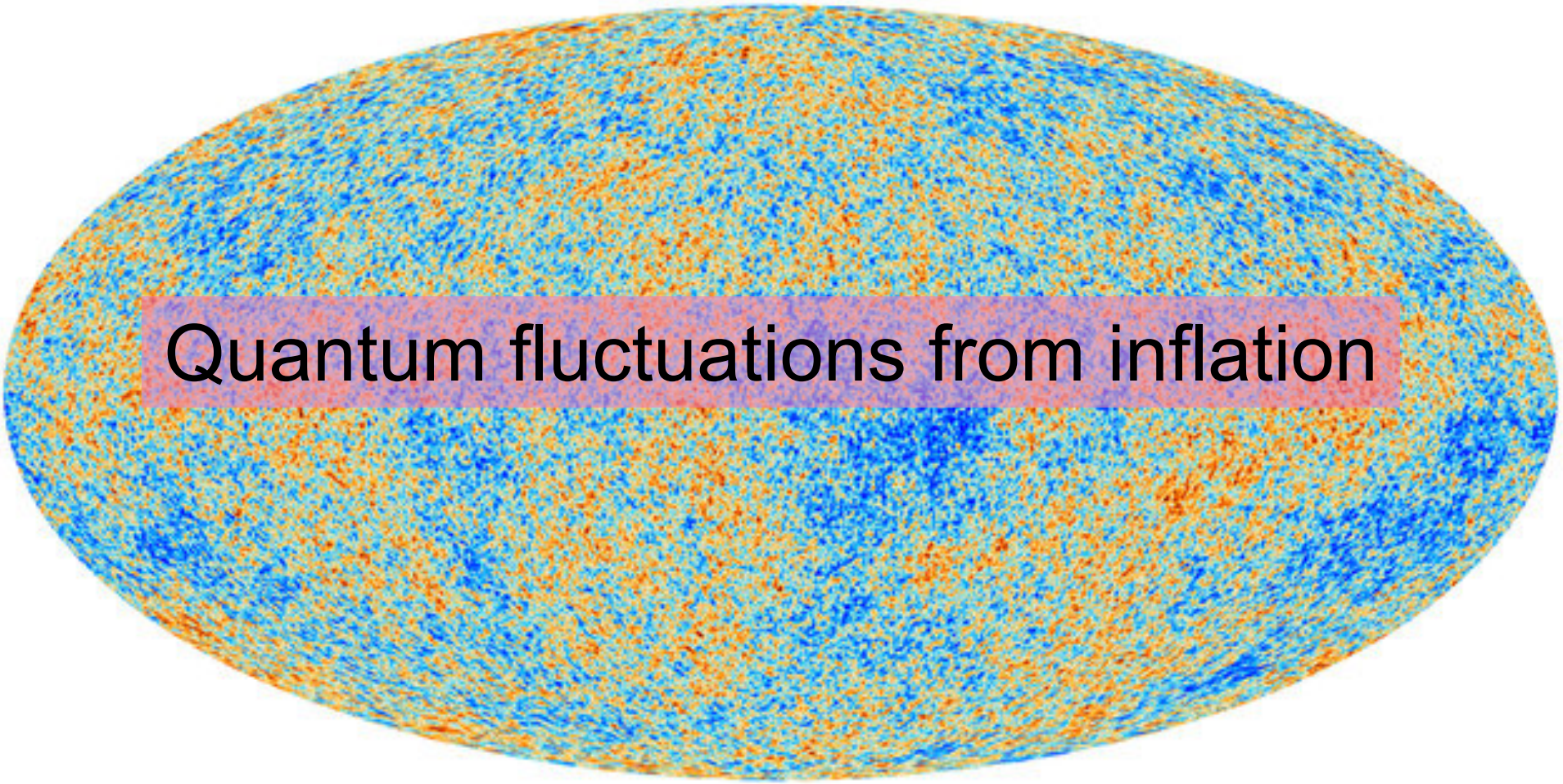
The initial conditions for galaxy formation



Planck collaboration '13

Institute for Computational Cosmology

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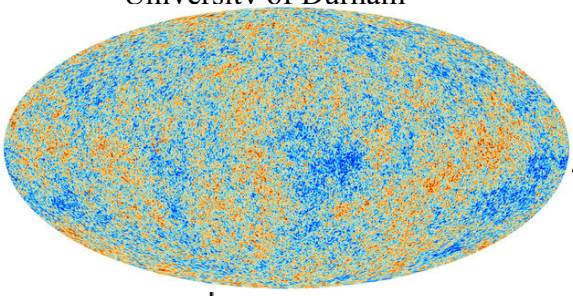
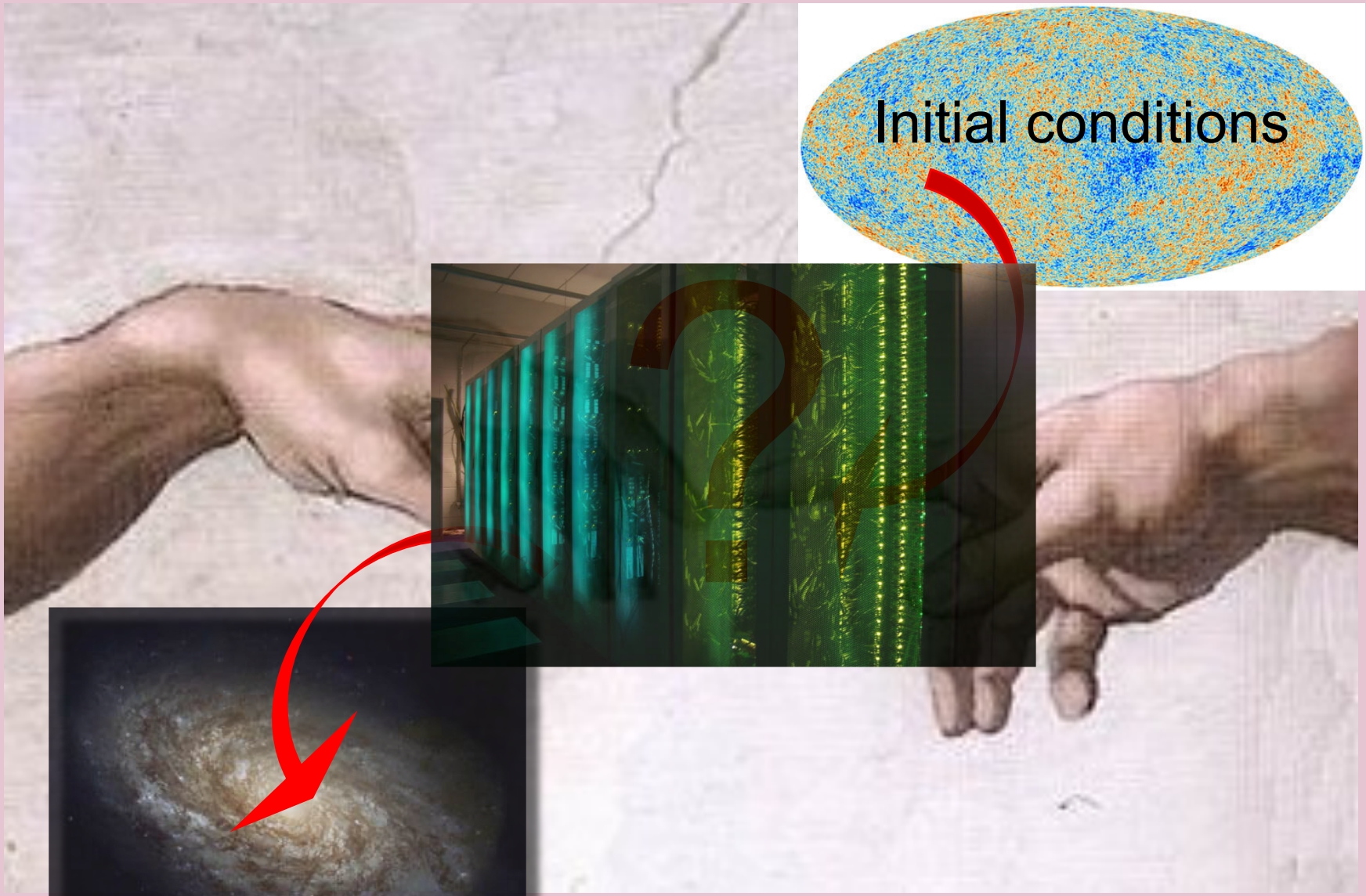
Planck: CMB temperature anisotropies



Planck coll. 2015

The formation of galaxies



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How to make a virtual universe

Initial conditions + assumption about content of Universe

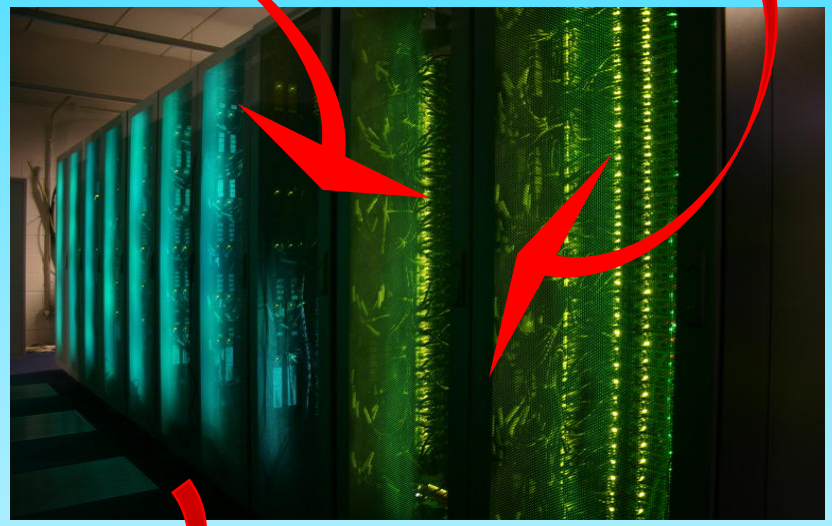
Equations of physics:

General Relativity

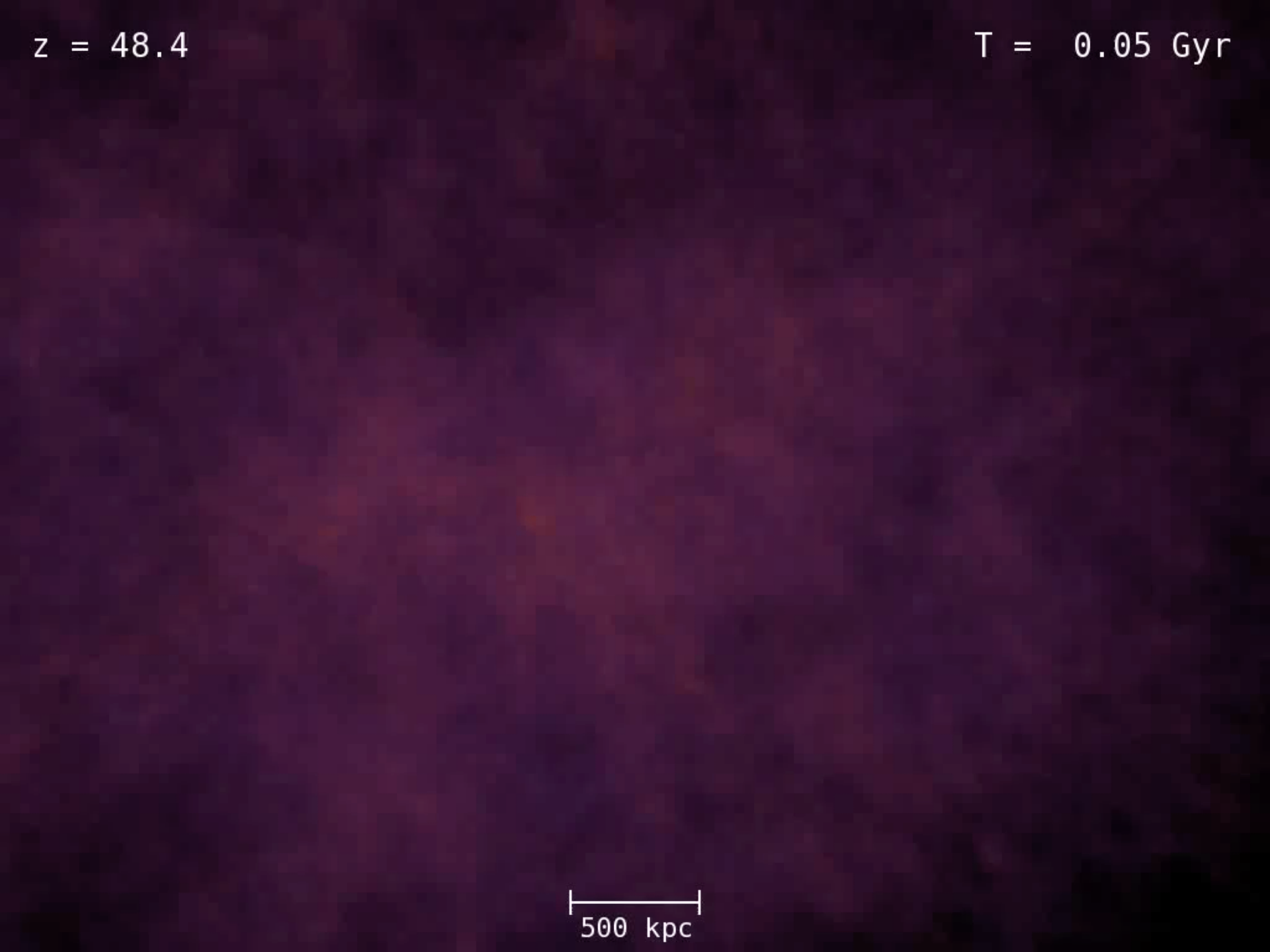
Mechanics

Radiative hydrodynamics

Atomic physics, etc



Institute for Computational Cosmology

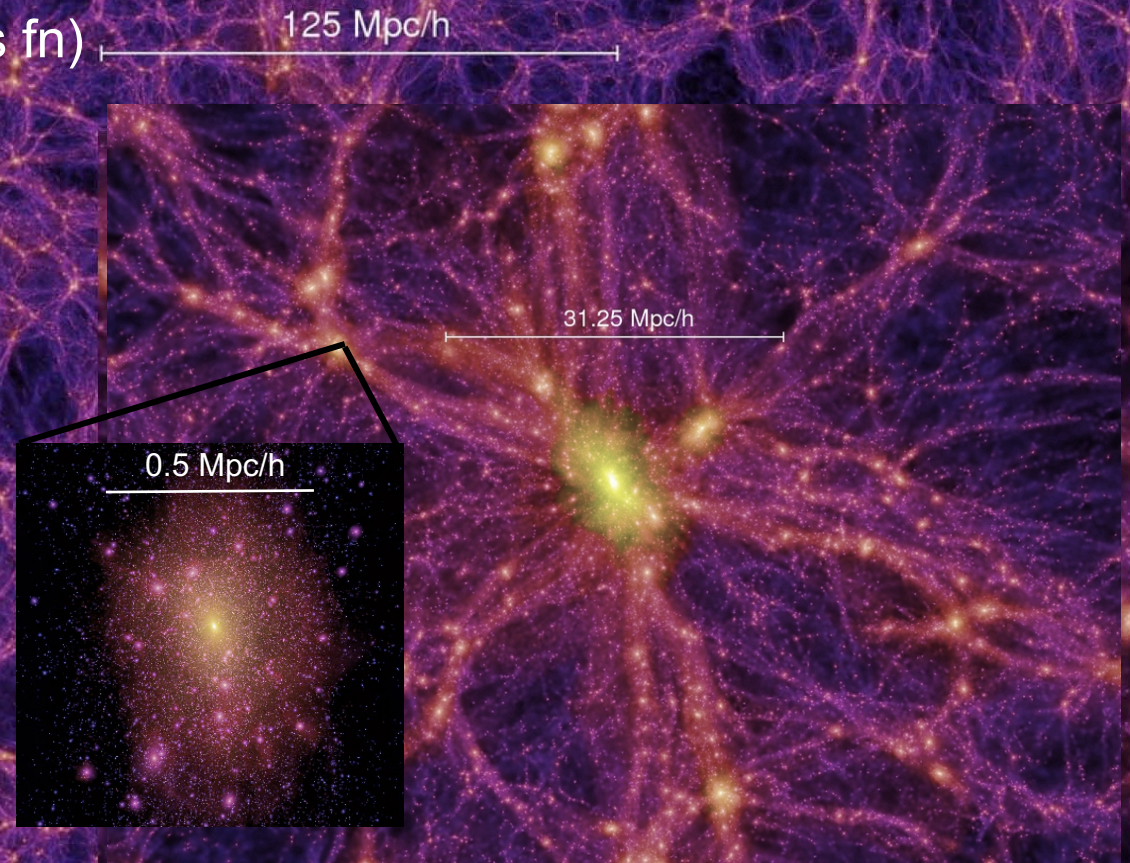

z = 48.4
T = 0.05 Gyr
500 kpc


Where is the dark matter?

Cosmological simulations of dark matter evolution

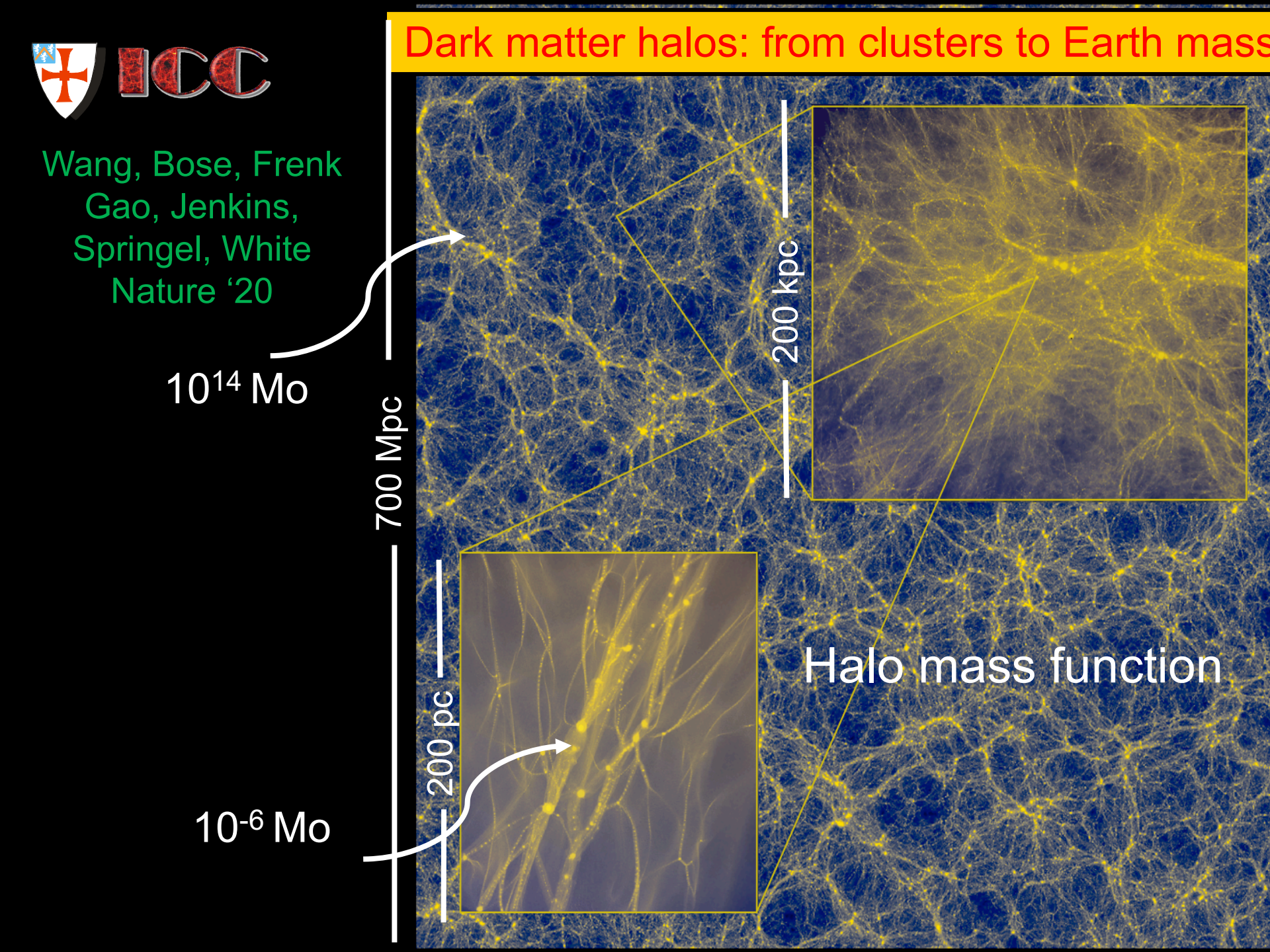
The properties of the dark matter distribution on all scales is a solved problem in CDM

- The distribution of dark matter
- The abundance of halos (mass fn)
- The structure of halos

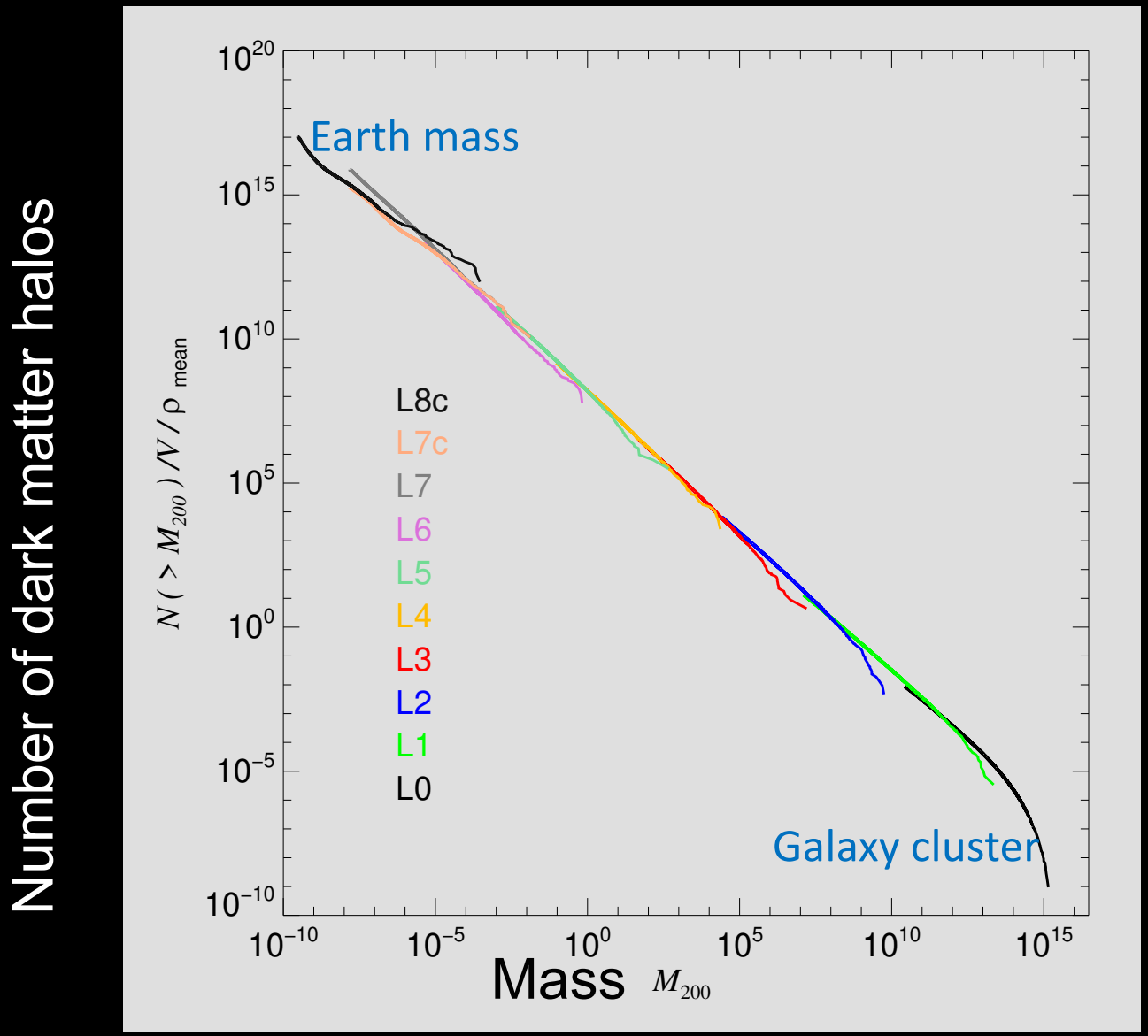


Springel et al ‘05, ’08,
Gao et al ‘11

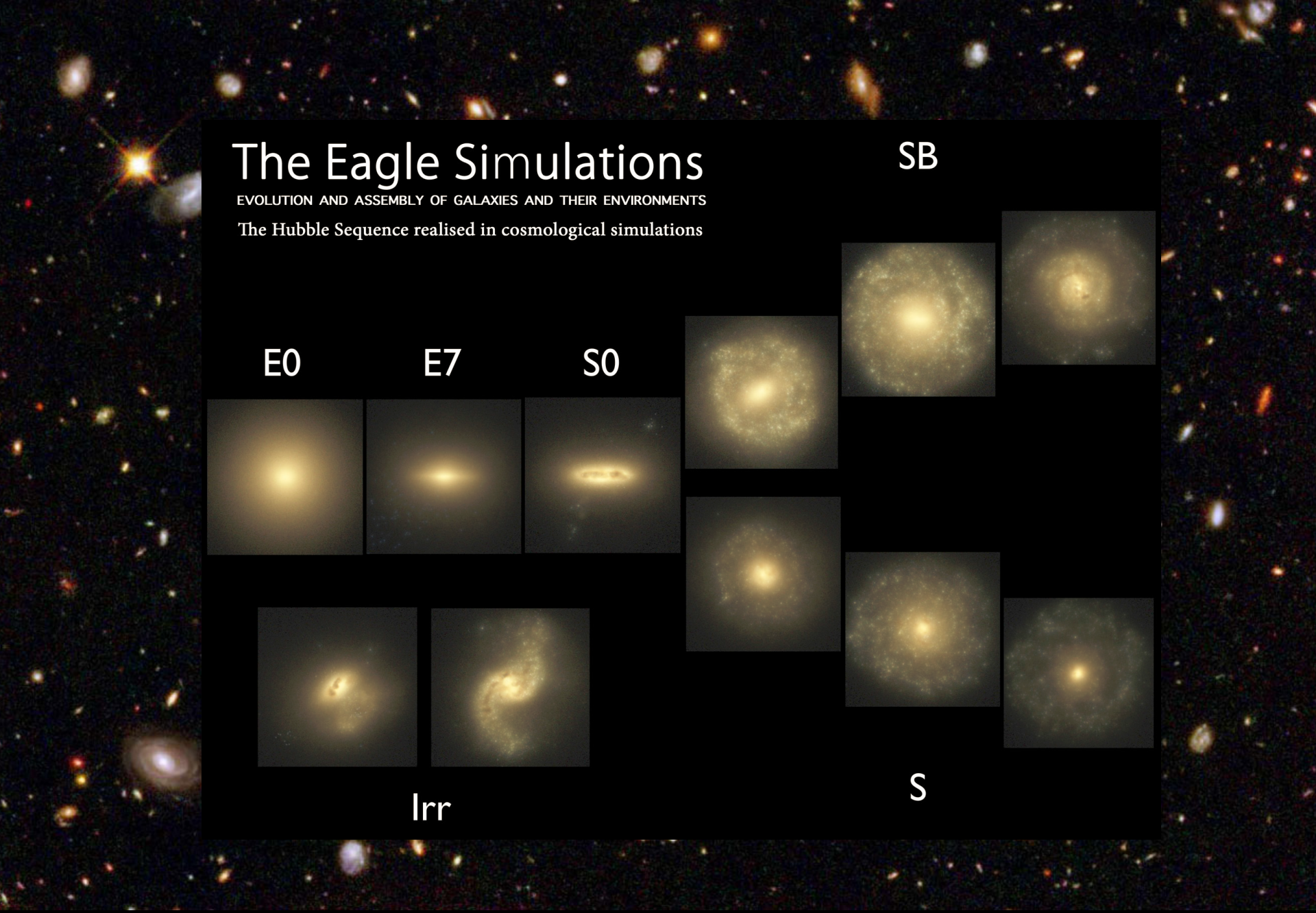
Dark matter halos: from clusters to Earth mass



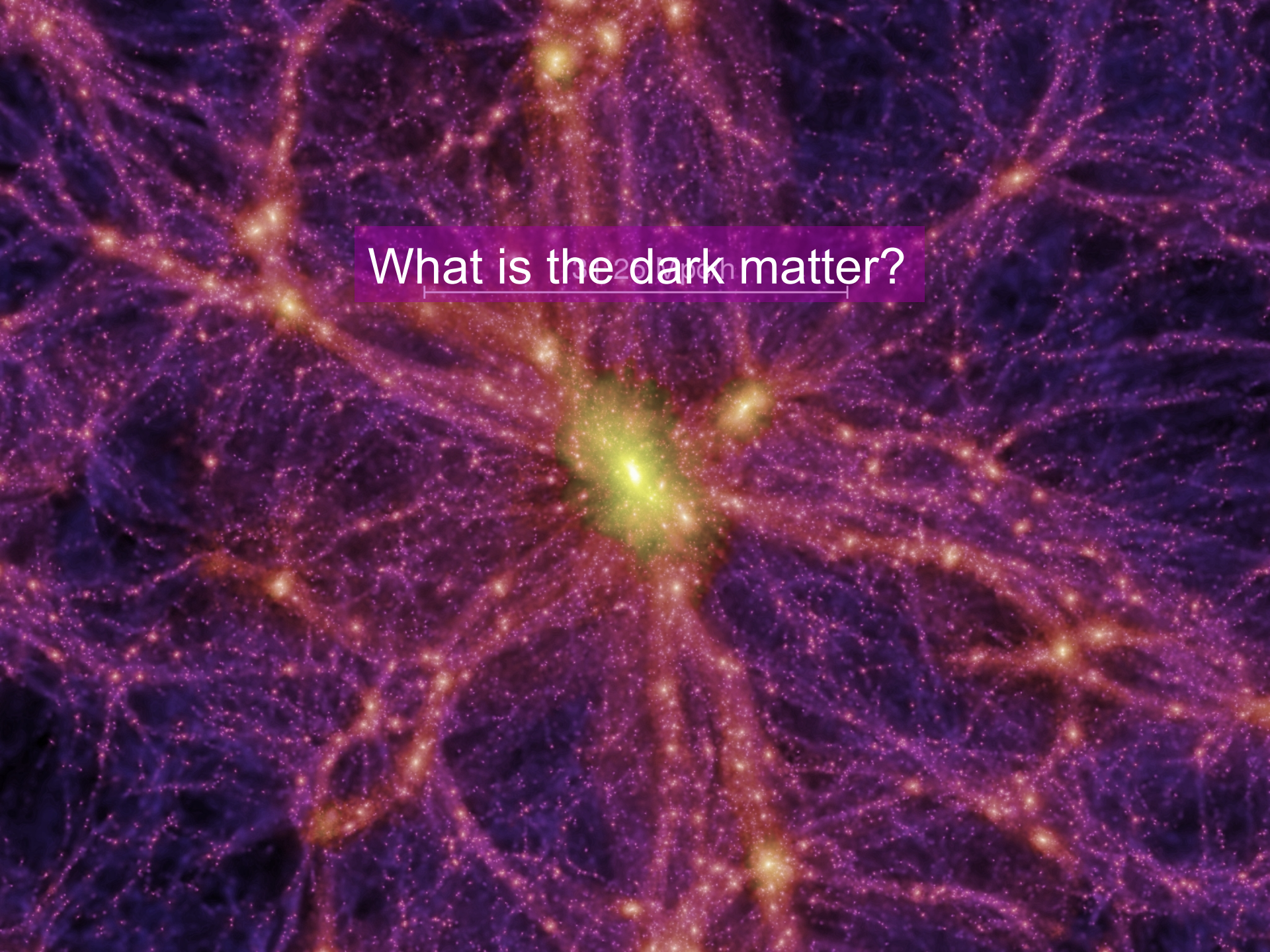
The mass function of cold dark matter halos




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

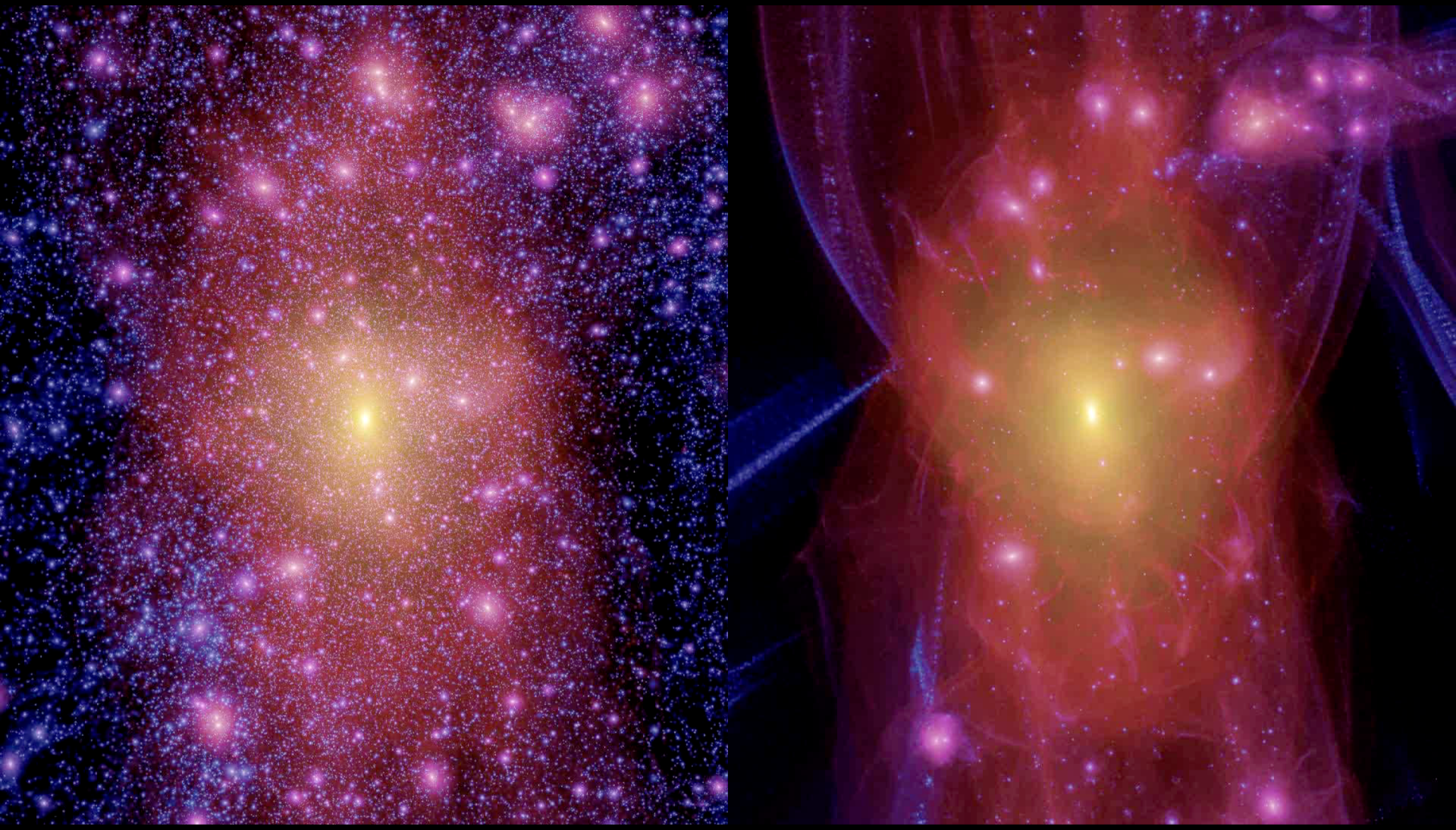


Trayford et al ‘15


What is the dark matter?

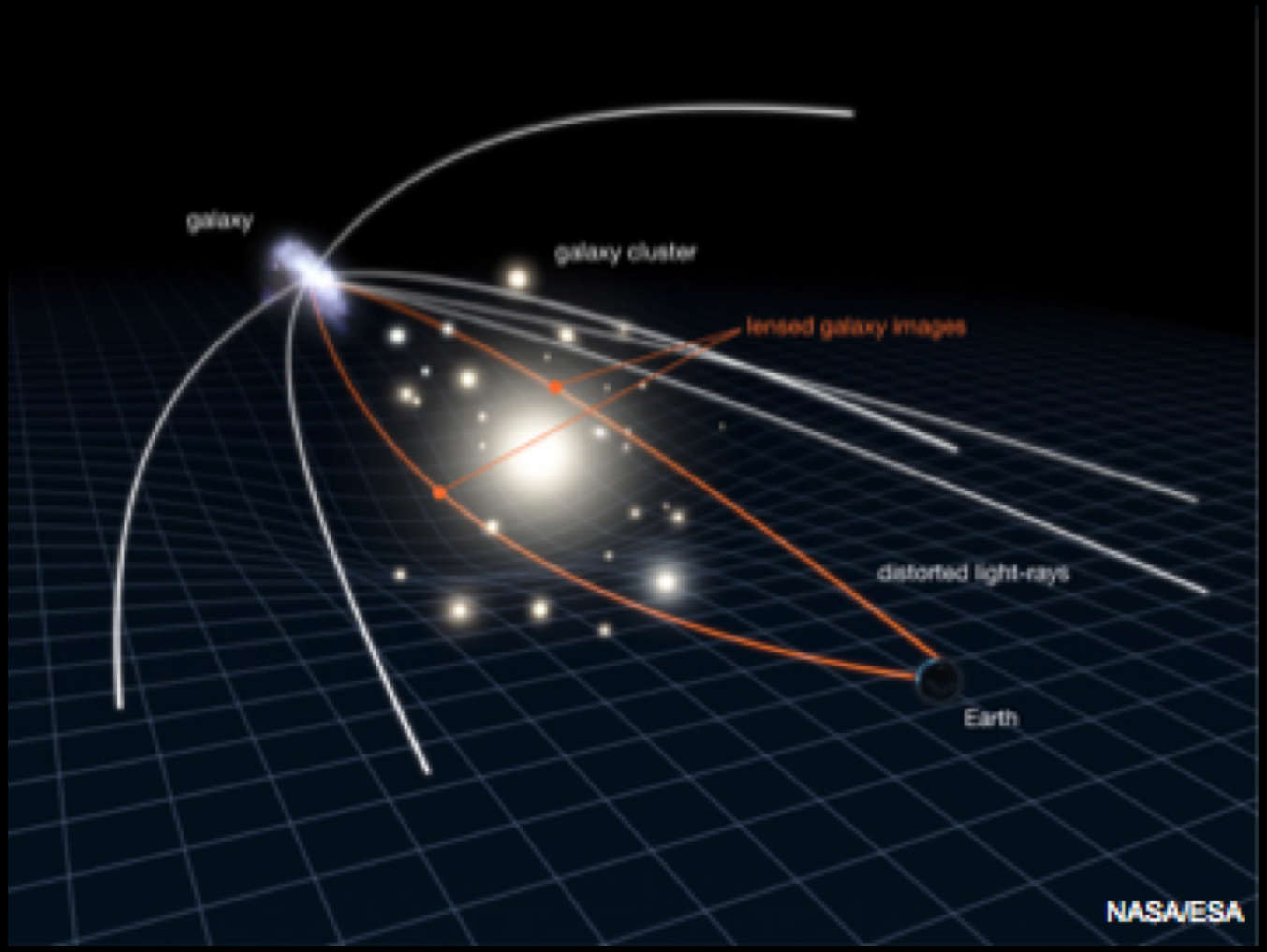
cold dark matter

warm dark matter



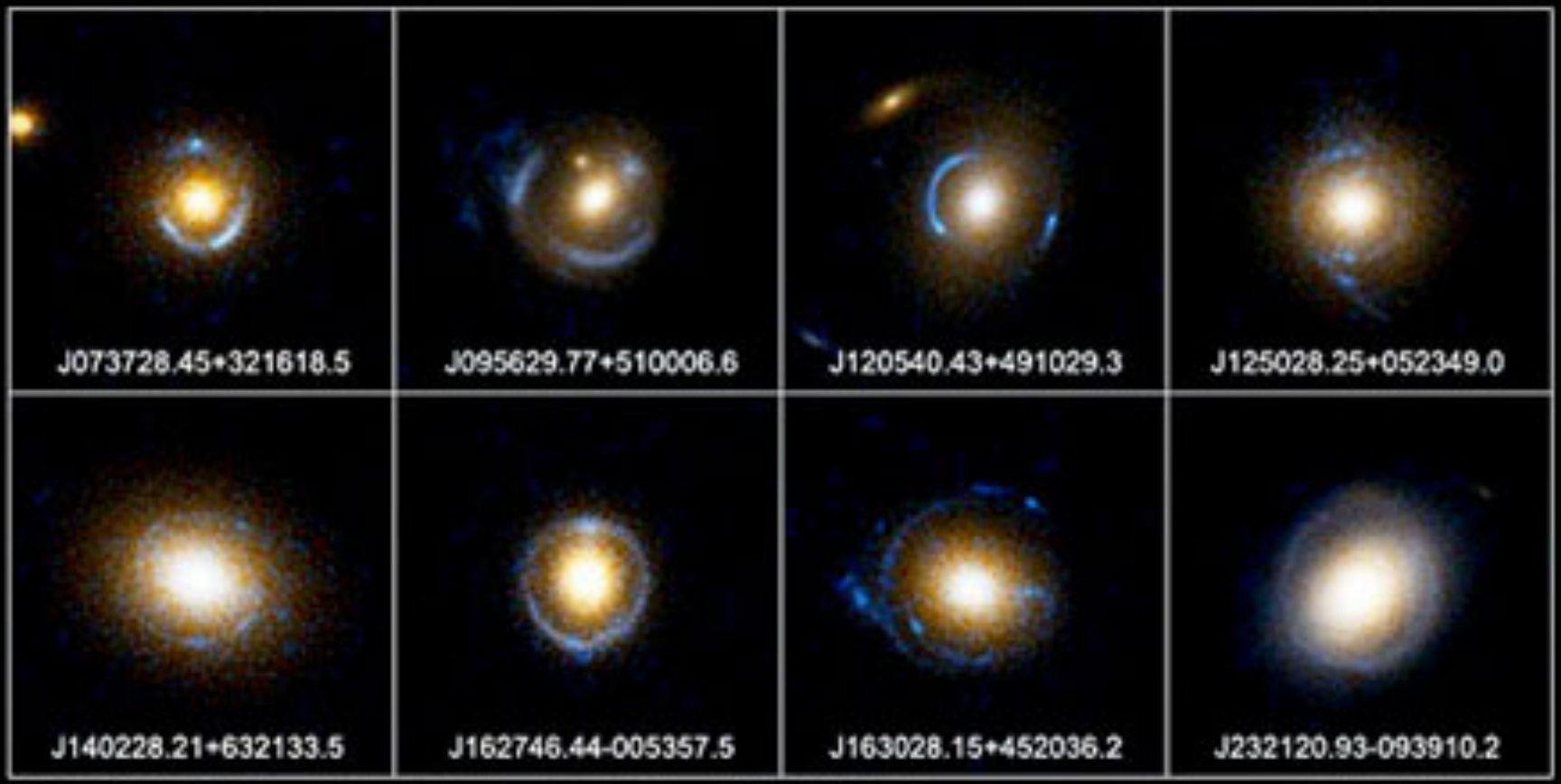
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12

Gravitational lensing: Einstein rings

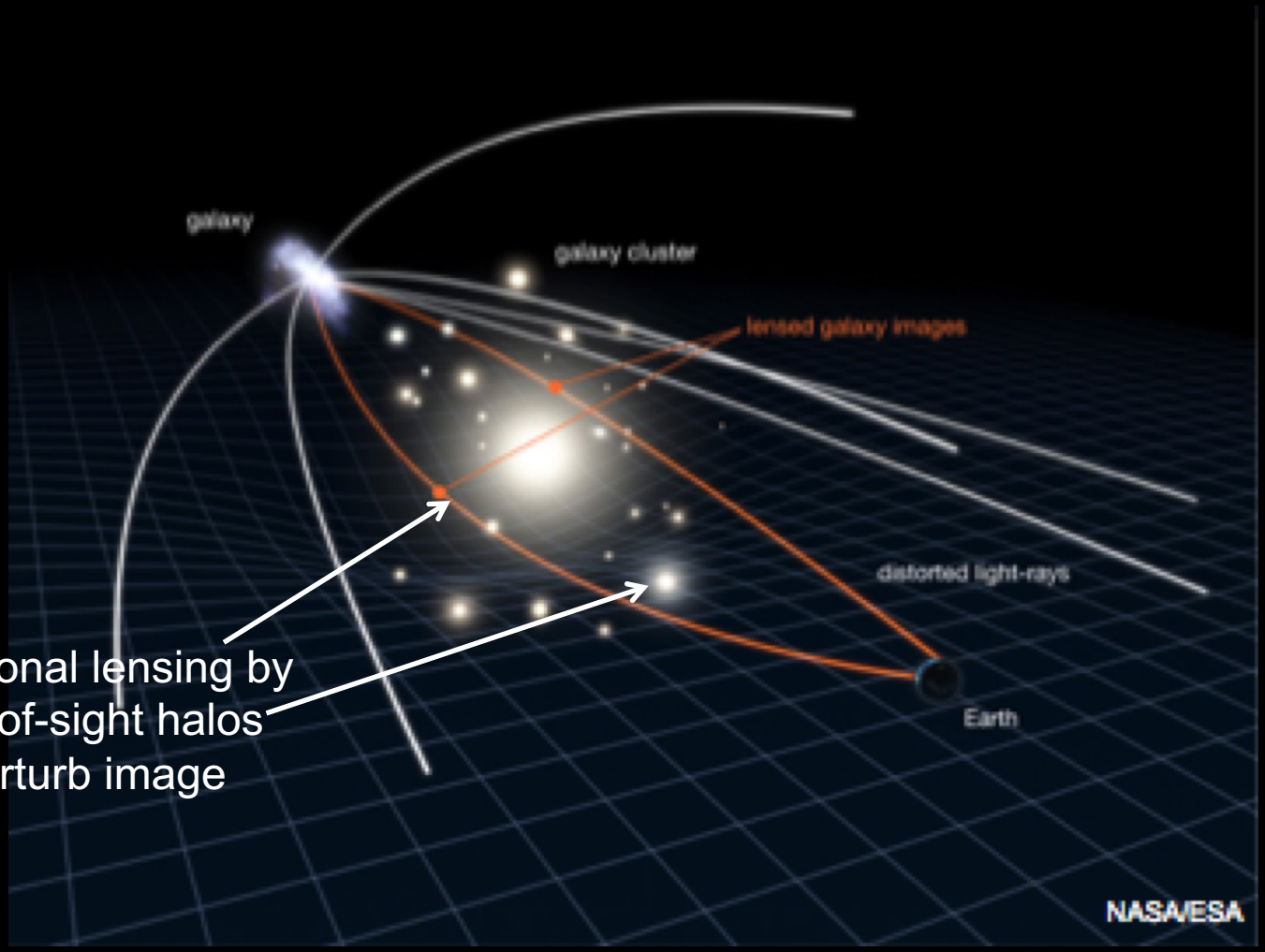


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



Gravitational lensing: Einstein rings

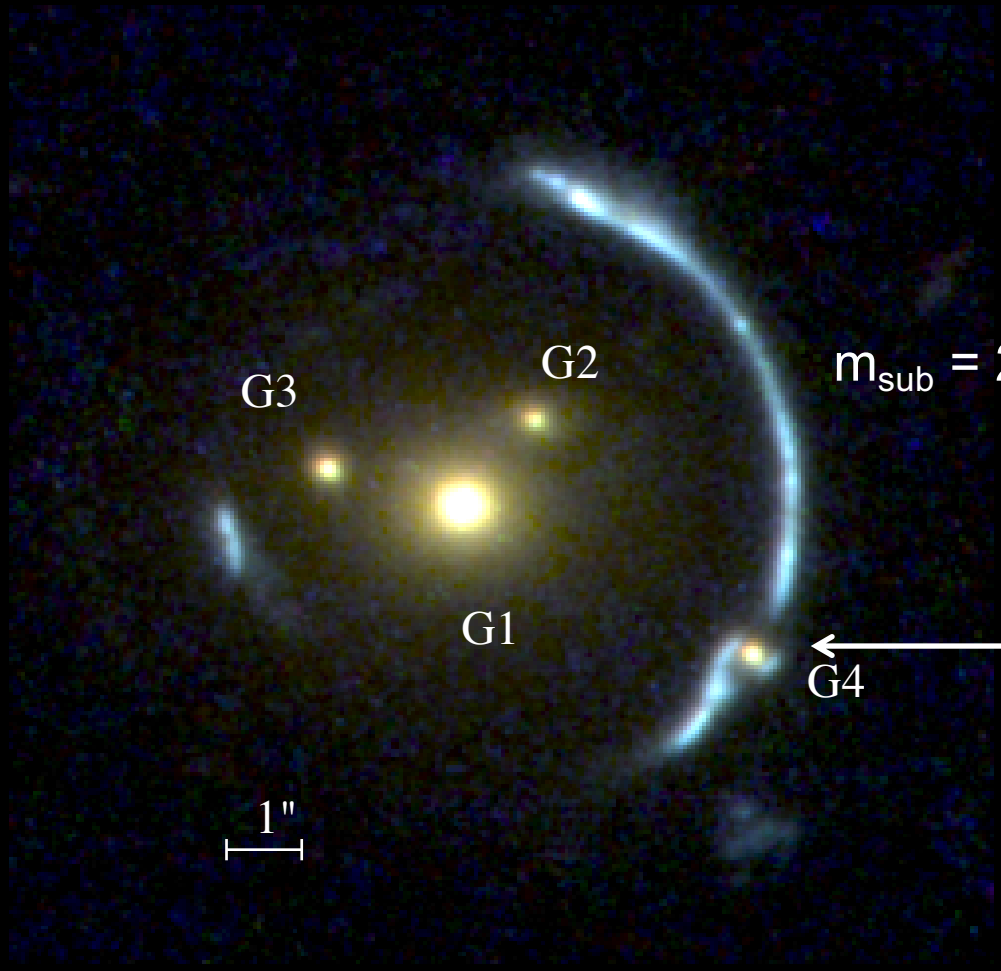


Additional lensing by line-of-sight halos perturb image

When the source and the lens are well aligned → strong arc or an Einstein ring

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



Vegetti et al ‘10

The search for dark matter

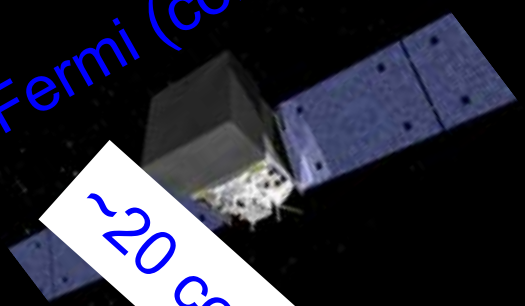
Experimental physics

The search for dark matter

Cold dark matter ?

Theory predicts: dark matter is an elementary particle

Fermi (cold DM)



~20 countries

69 countries

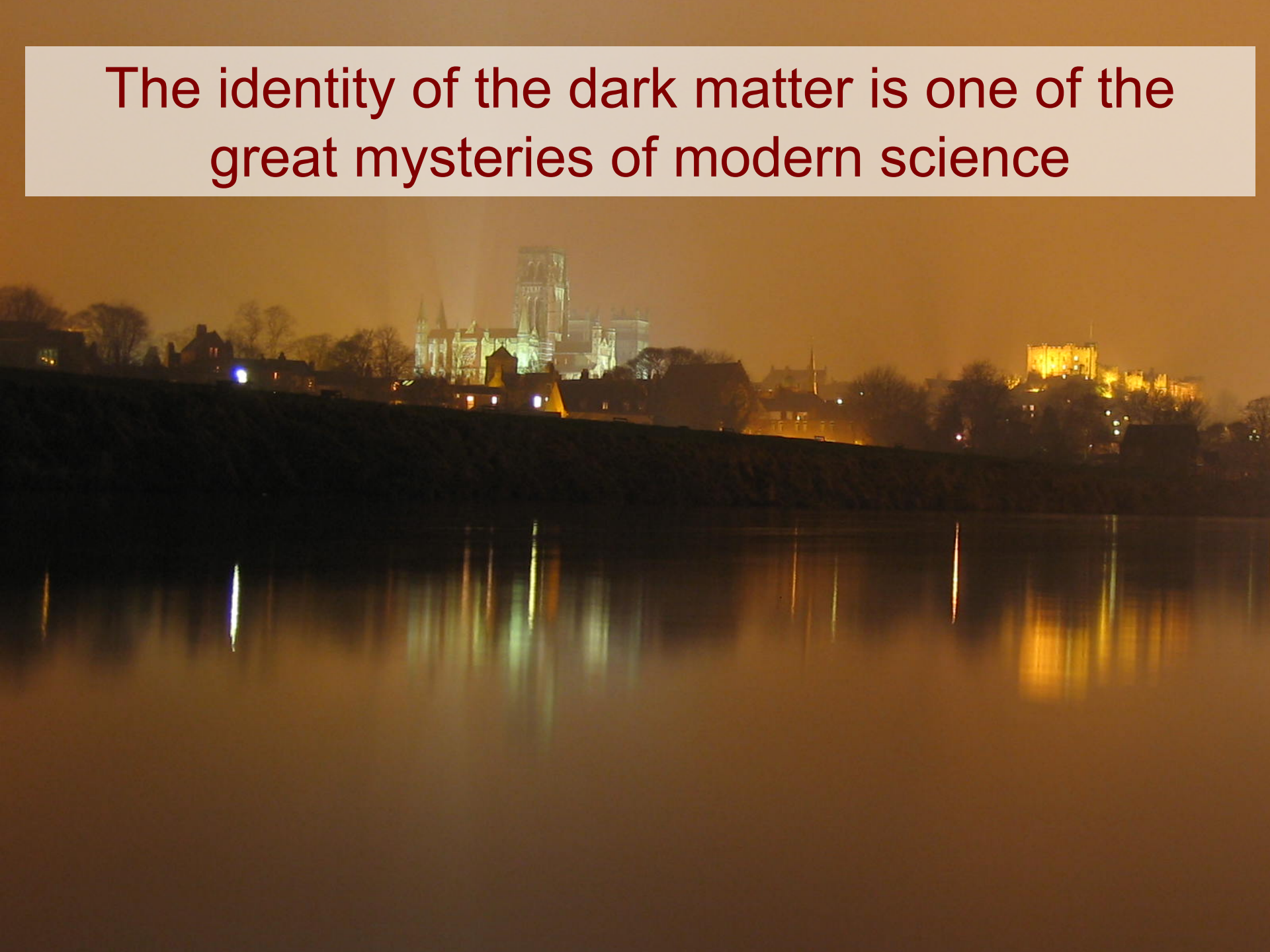
LHC – will it make it?

XMM (warm DM)

Direct detection

~15 countries

The identity of the dark matter is one of the great mysteries of modern science



Ogden question 1 – The cosmic dark matter: where and what is it?

Not yet solved but we have made great progress