SEVENTH FRAMEWORK PROGRAMME

invisibles

neutrinos, dark matter & dark energy physics

MARIE CURIE ACTIONS

Invisibles is a new European ITN project (FP7-PEOPLE-2011-ITN, PITN-GA-2011-289442-INVISIBLES (April 2012-March 2016)), which focuses on Neutrino and Dark Matter phenomenology and their connection. Experimental and theoretical aspects are also encompassed. The network involves nodes in seven European countries and its associated partners extend to seven non-European countries.

Valentina De Romeri

DARK MATTER

11th June 2014,

ECOLE BILINGUE INTERNATIONALE DE CLERMONT FERRAND

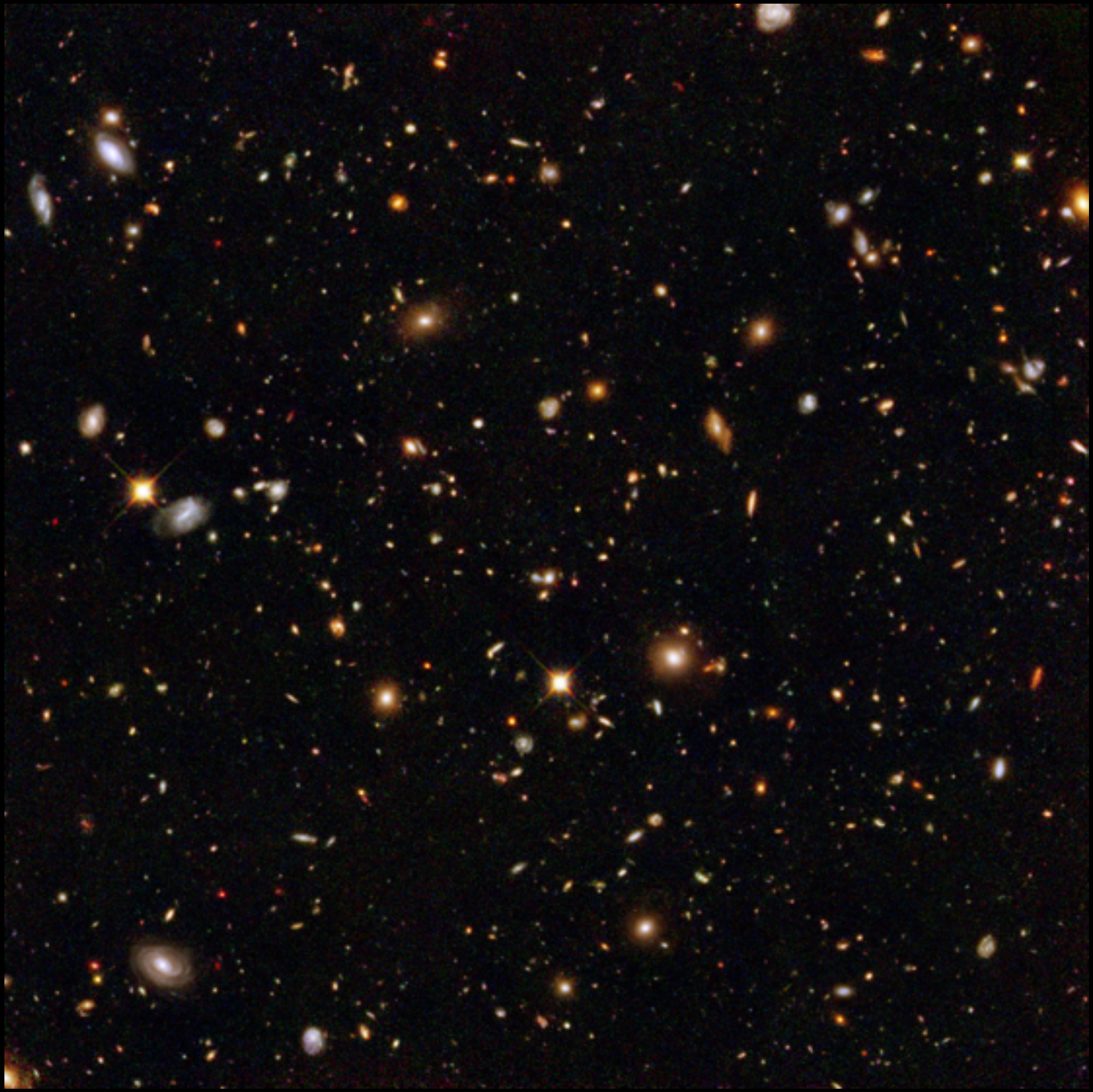
Hot questions about Dark Matter

1. What is dark matter?
2. How do we know that it exists?
3. How much is there?
4. Where is it?
5. Could it be normal stuff?
6. How is it distributed?
7. Why should we care?
8. How to search for dark matter?
9. Then what?

1. What is dark matter?


Galactic
center

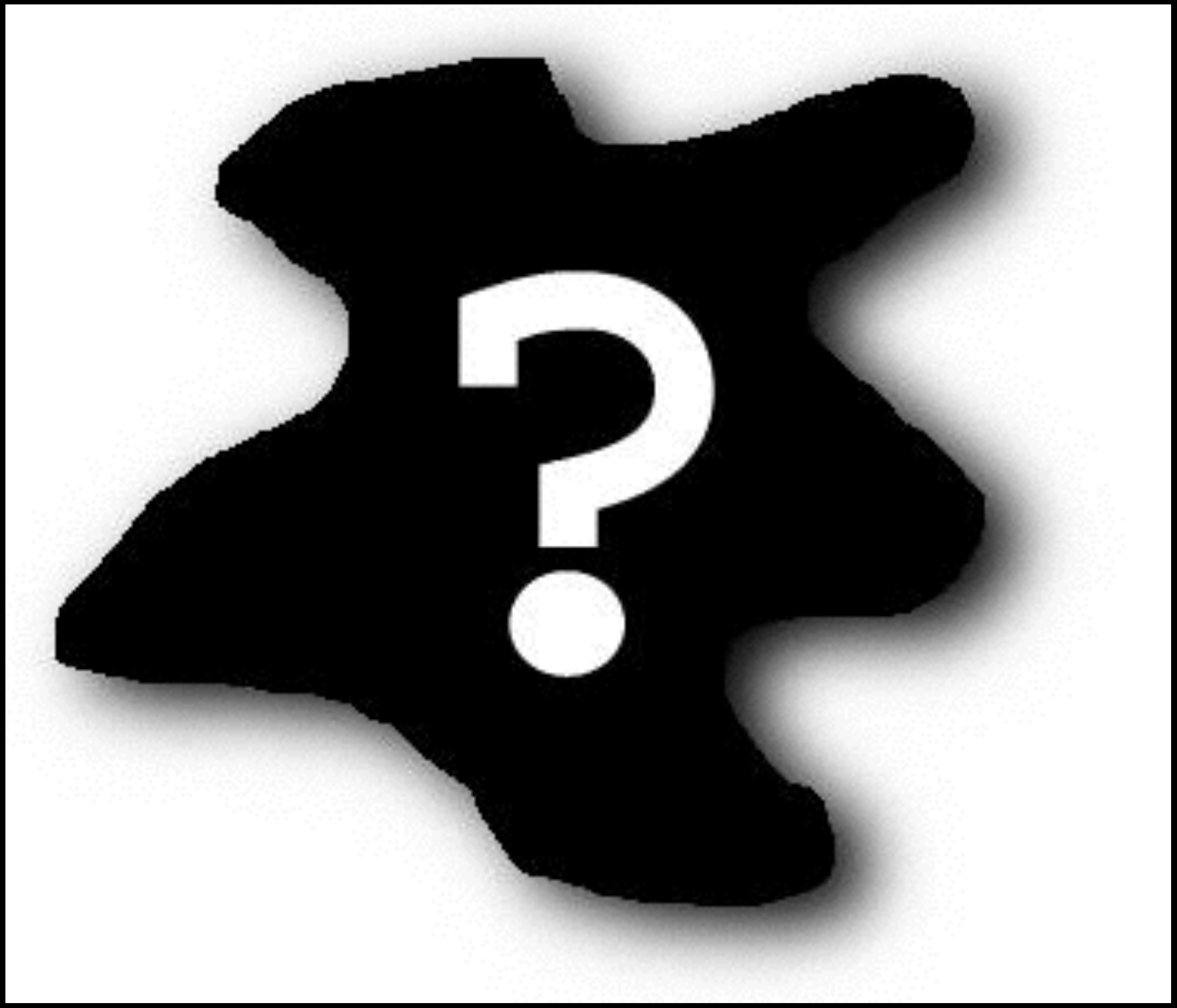
“Empty” portion of sky



Dense region of the Universe

“The world is full of things which nobody by any chance ever observes.”

Sherlock Holmes



Is it something evil...?

Not Dark Matter.

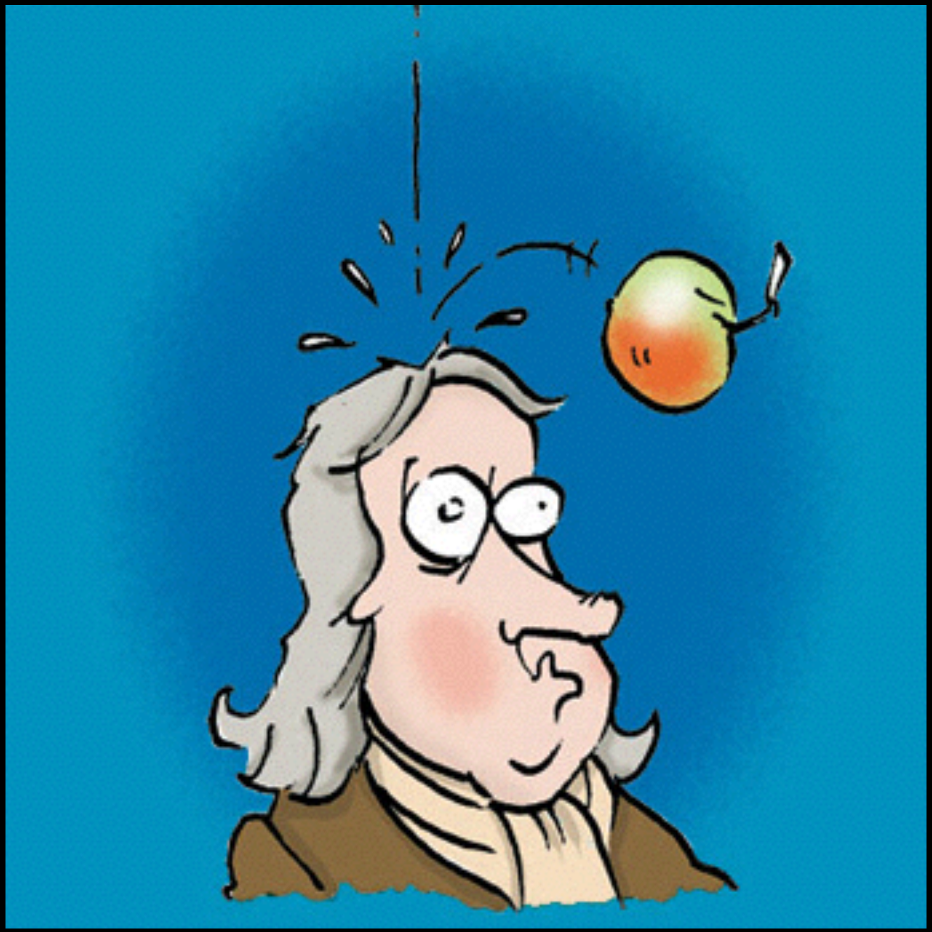
Dark matter.

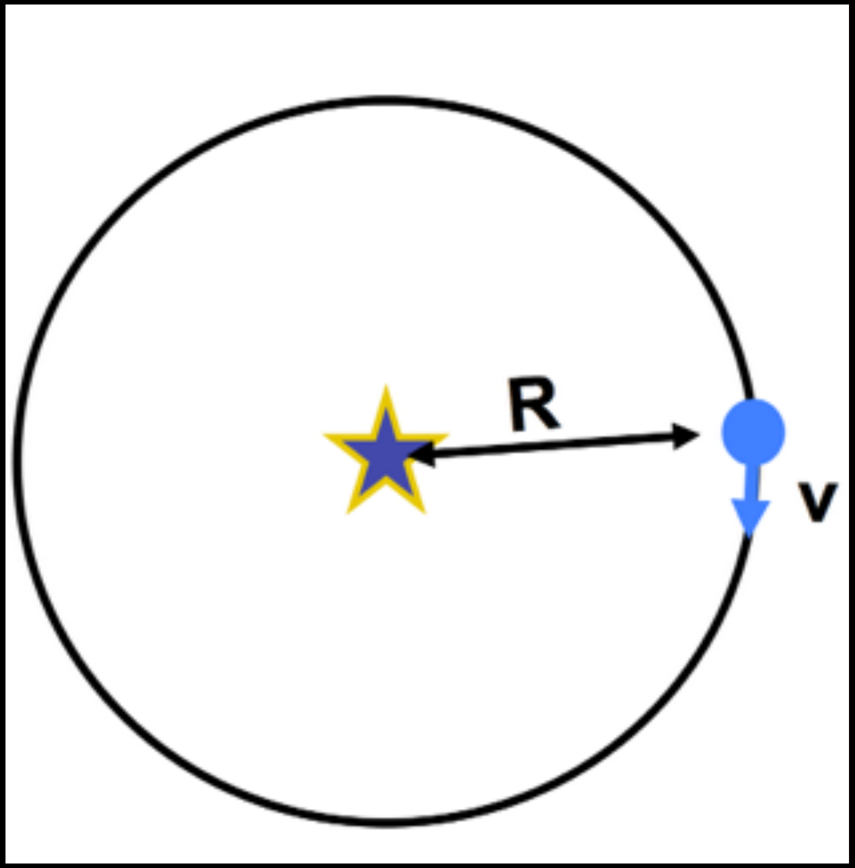
2. How do we know that it exists?

Count up what you see and figure out how much it weighs.

but.... light has not to be in the same place as mass

Use gravity!





$$m_{pl}\frac{v^2}{R} = \frac{GM_{sun}}{R^2}m_{pl}$$

Centrifugal force — Gravitational force

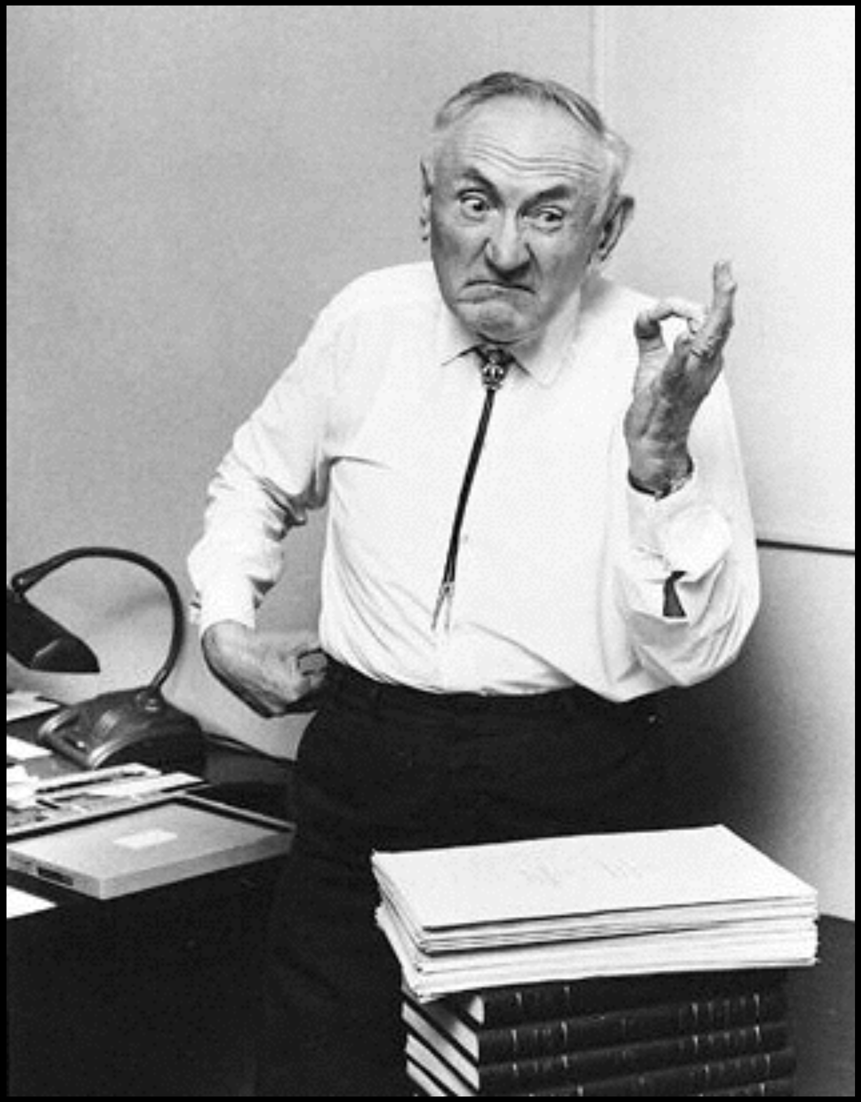
$$v \propto \sqrt{\frac{M_{sun}}{R}}$$

Measure the speed at which planets orbit around the Sun → mass of the Sun

$$\frac{v^2}{R} = \frac{GM_{galaxy}}{R^2}$$

Measure the speeds of stars → determine the mass of their host galaxy

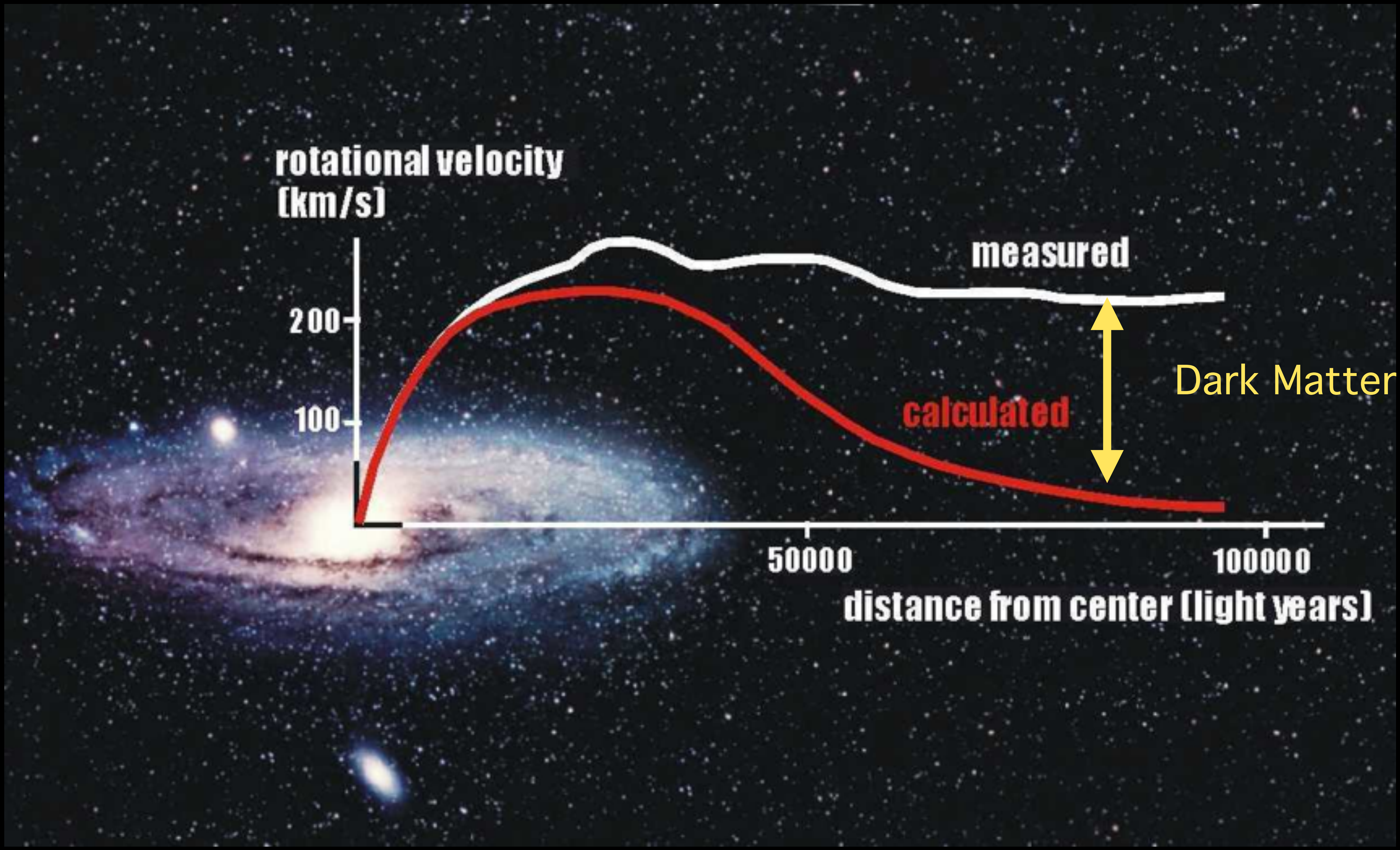
Fritz Zwicky

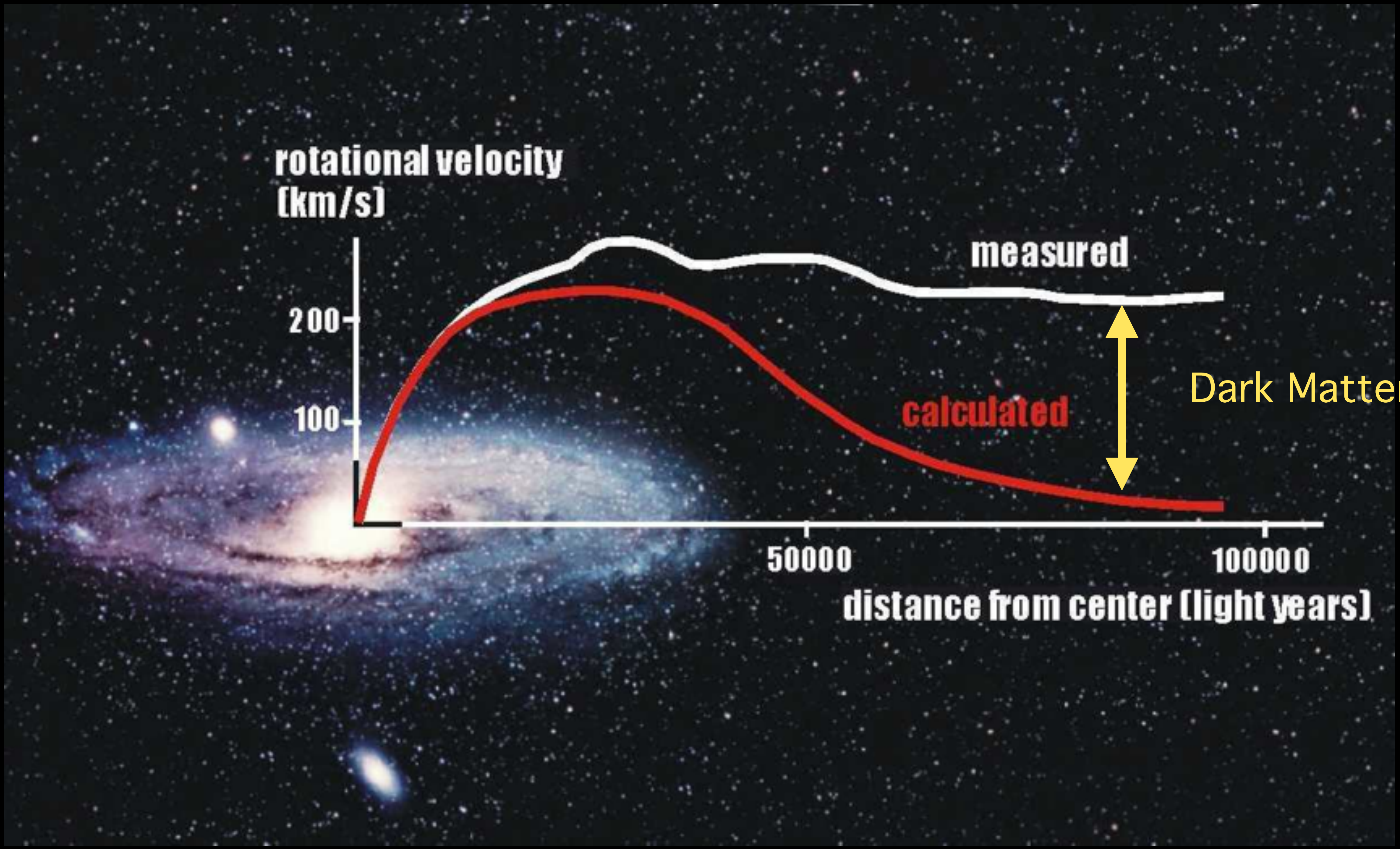


Identified the presence of missing matter (dark matter) in the Coma cluster (1933 & 1937)

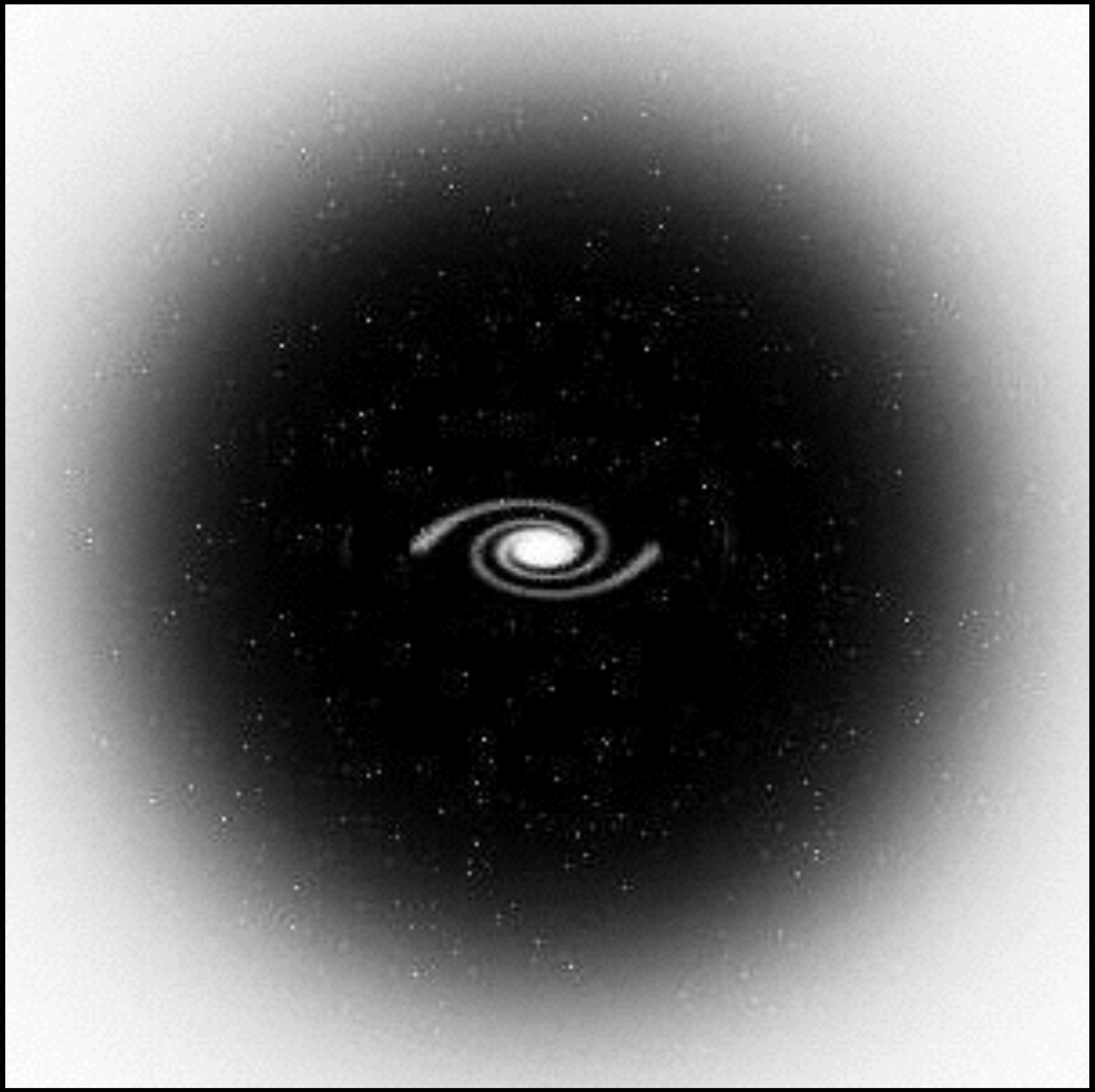
Vera Rubin

Studied the variation of the velocities of stars with distance from the center of the Andromeda galaxy (1970)


rotational velocity
(km/s)
200
100
measured
calculated
Dark Matter
50000
100000
distance from center (light years)



Most of the mass is invisible!

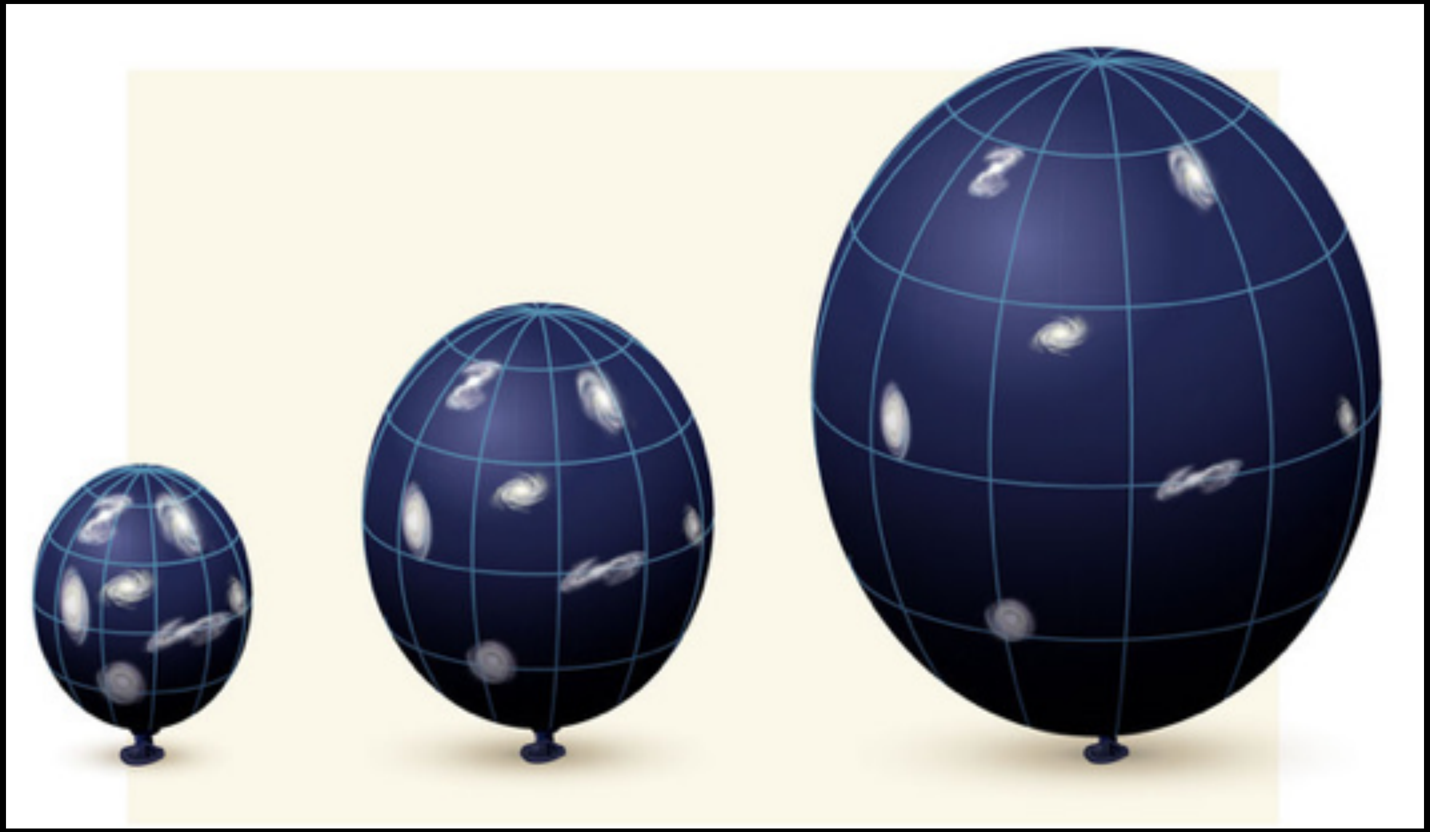


Extra “dark” matter around every galaxy (and cluster of galaxies)

DARK MATTER HALO

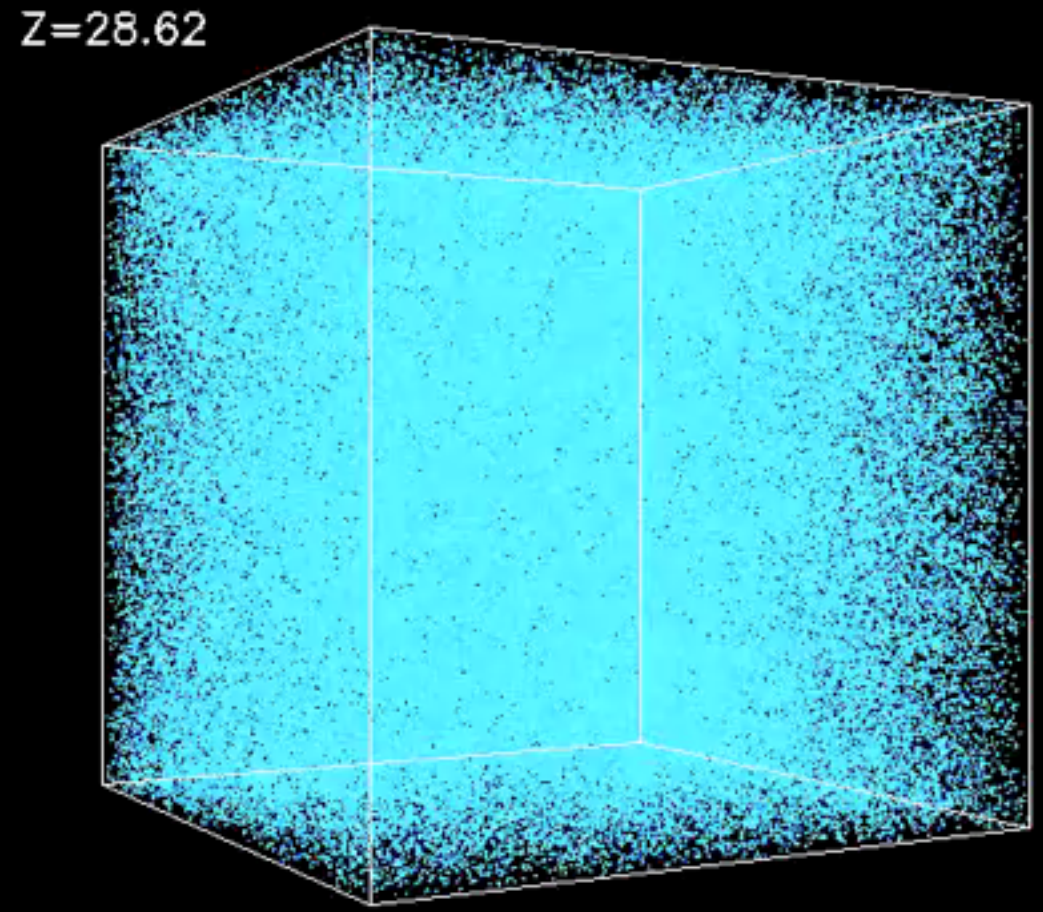
Measure the expansion rate of the Universe

More mass
pulls things together and slows the expansion down



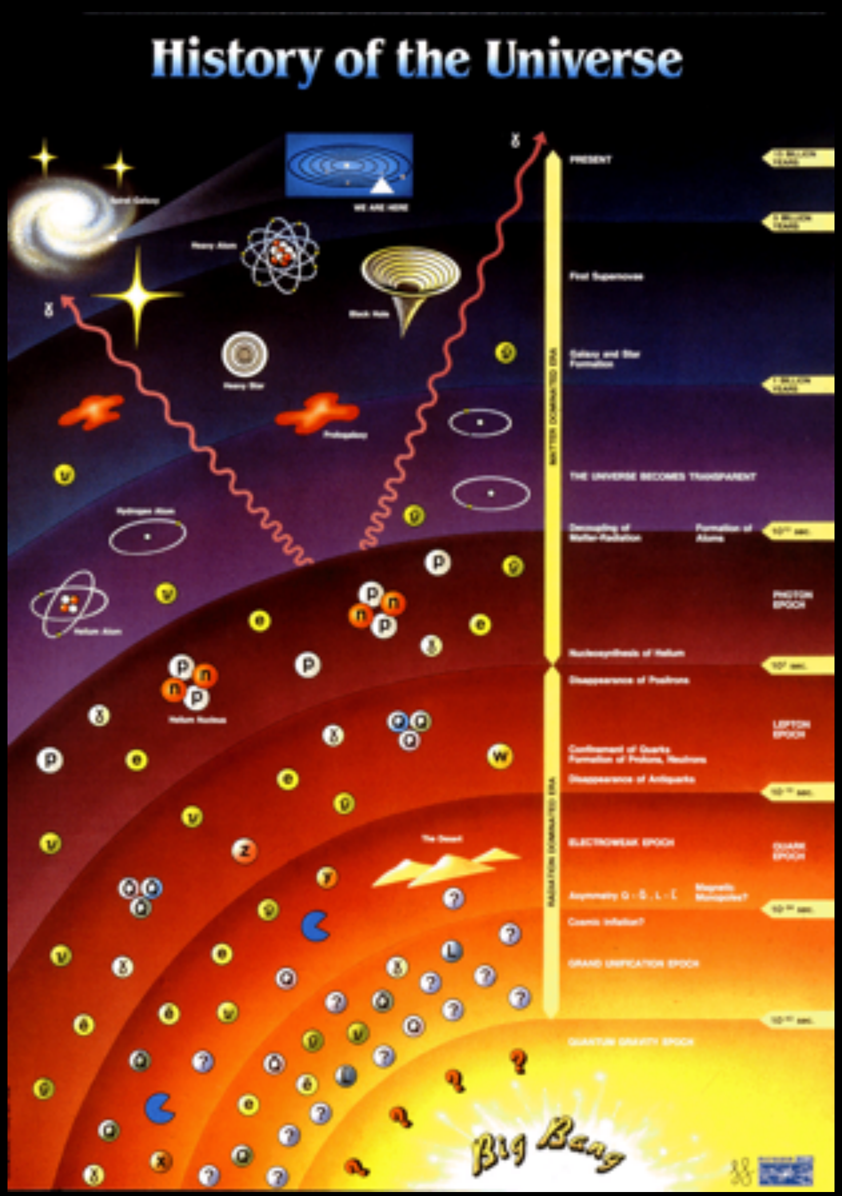
Measure the growth of structures

More mass
pulls things together and makes them clumpier

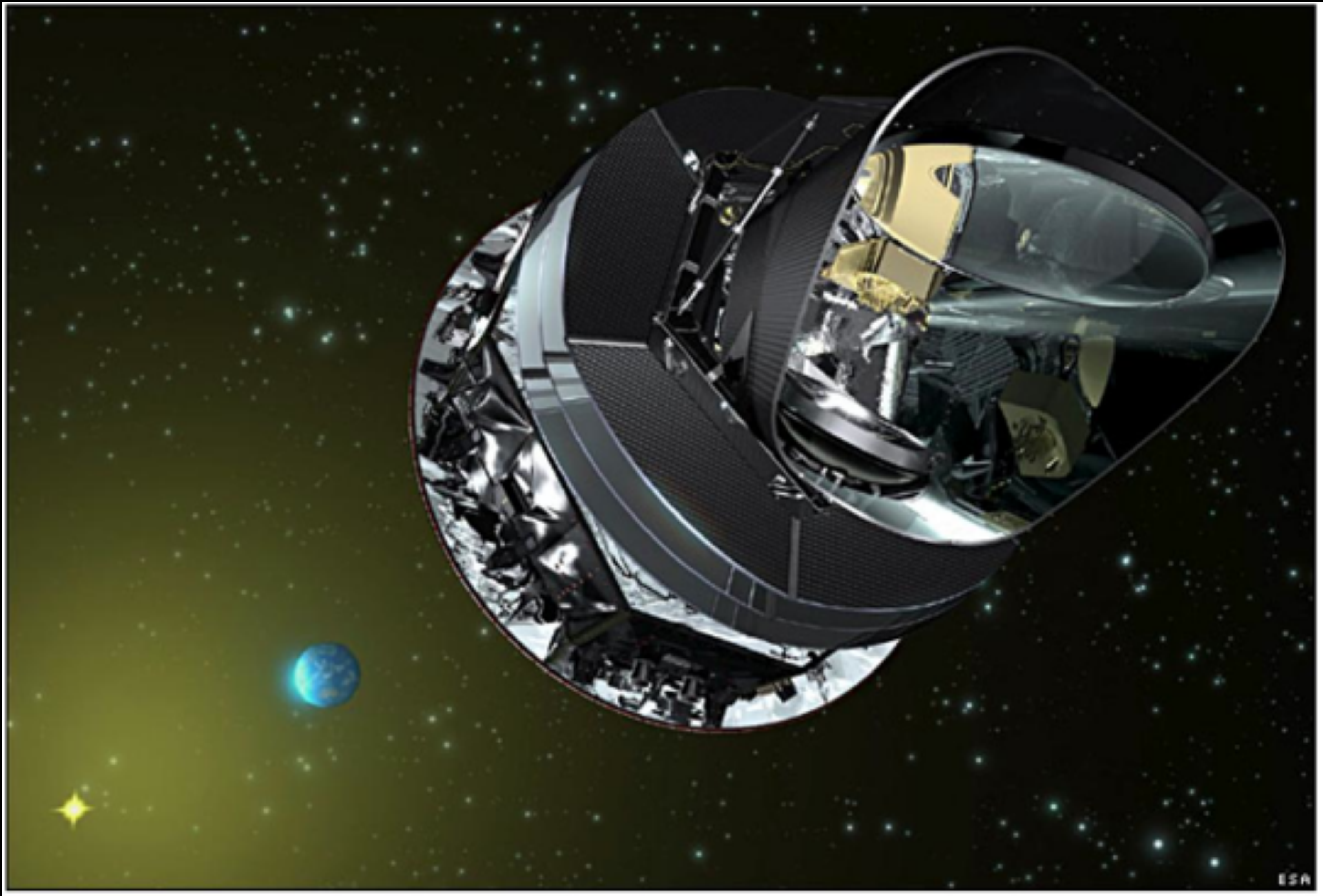


Age of the Universe

The Universe is 13.8 billion years old

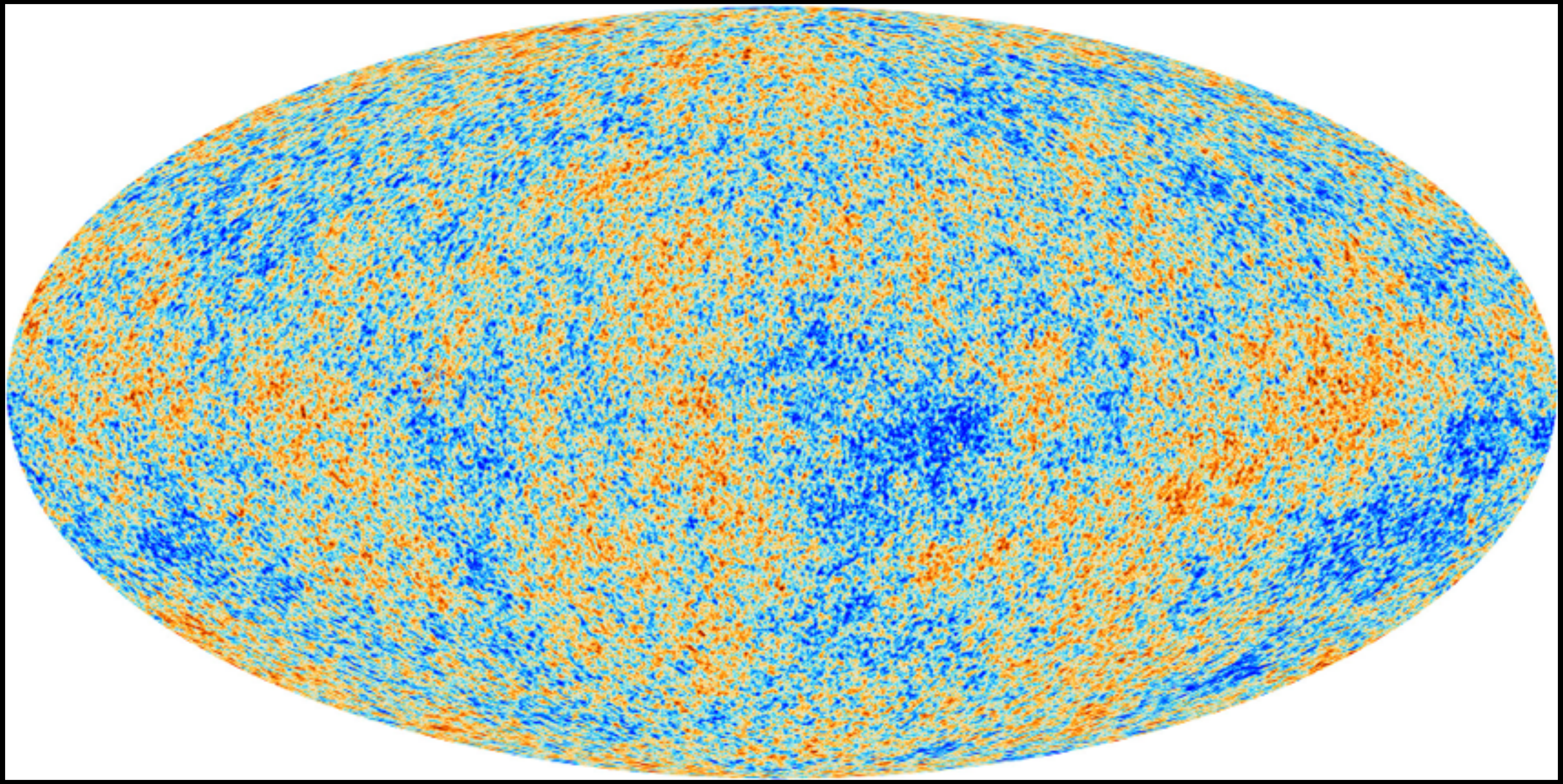


How did the Universe look like in his youth?



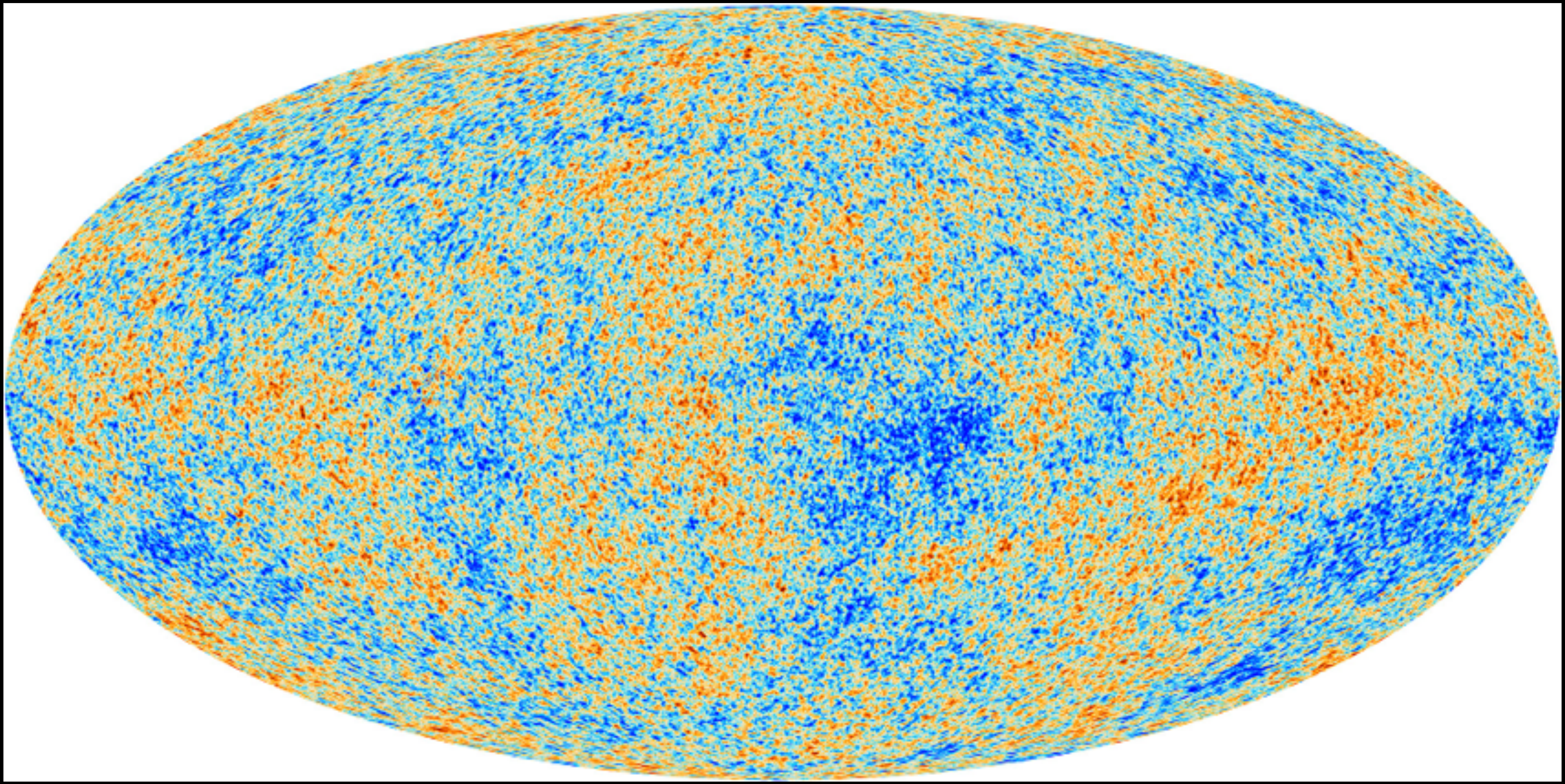
Planck satellite


Physical Map of the World, April 2004
CANADA
UNITED STATES
NORTH PACIFIC OCEAN
NORTH ATLANTIC OCEAN
RUSSIA
CHINA
BRAZIL
SOUTH PACIFIC OCEAN
SOUTH ATLANTIC OCEAN
INDIAN OCEAN
AUSTRALIA
Antarctica



The 380.000 years old Universe
observed by Planck satellite

density fluctuations are 1/100.000



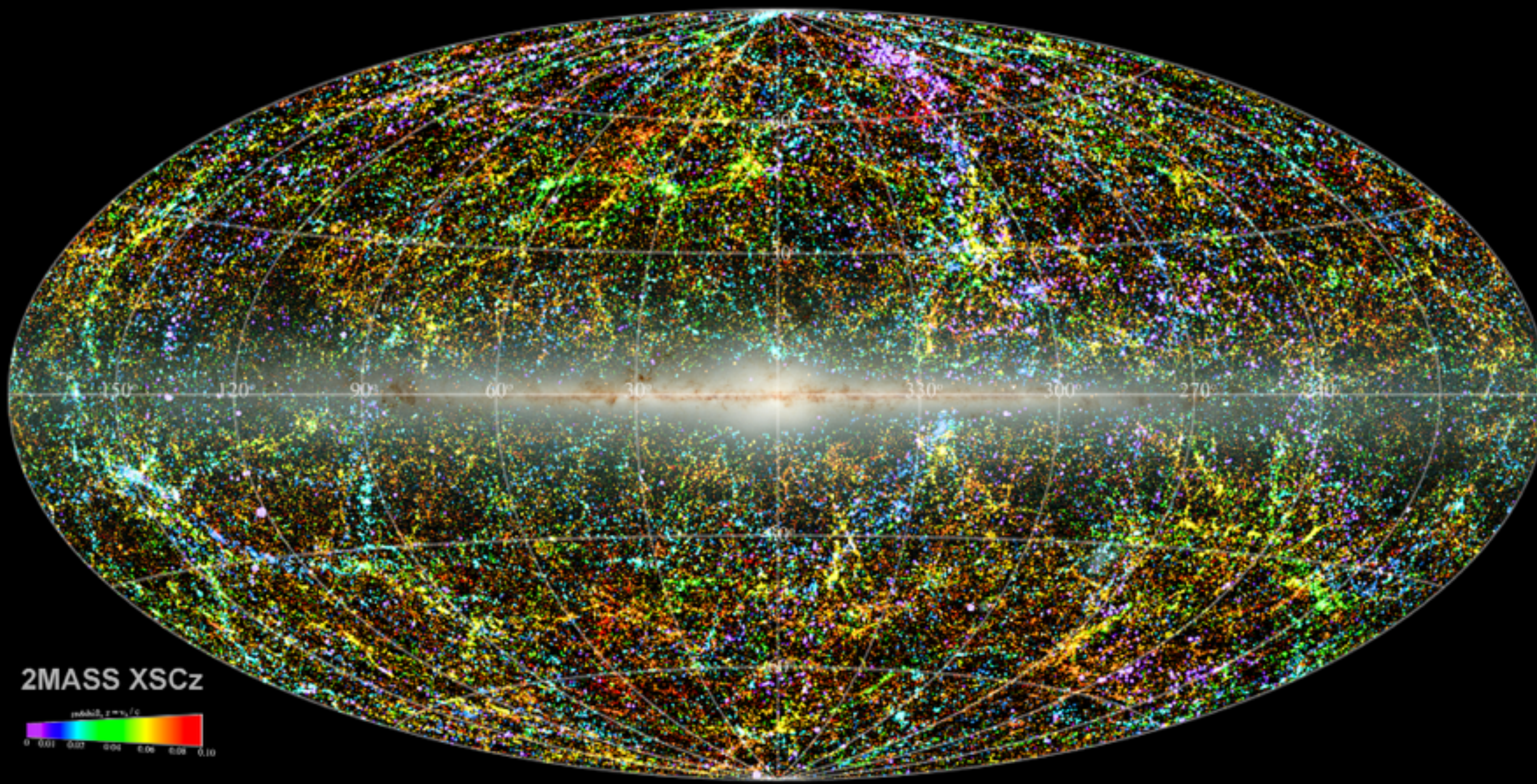
Red color: the Universe was a little bit denser

Blue color: a little less dense

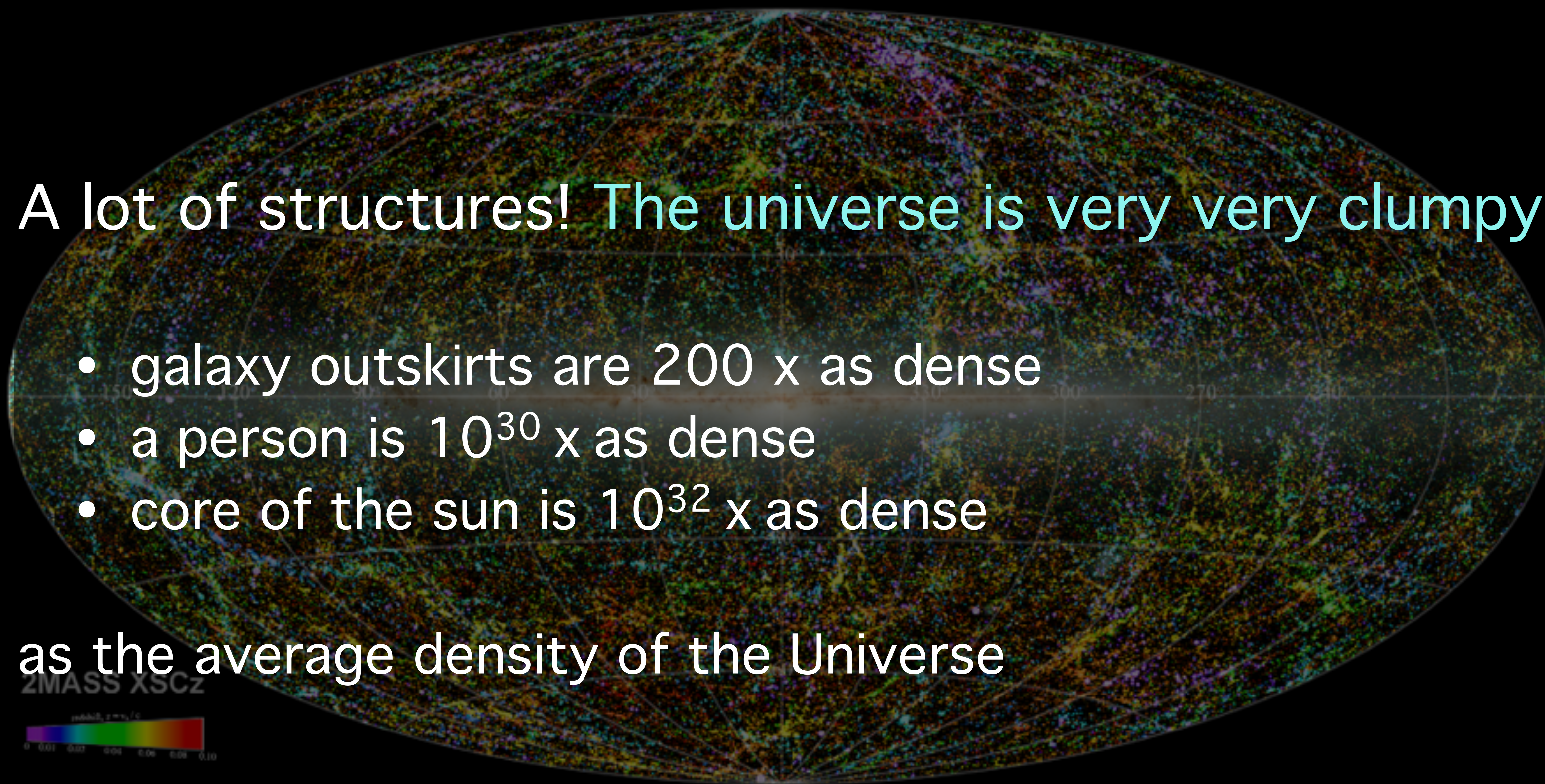
at that time

Very tiny density fluctuations!!

How does the Universe look like today?



How does the Universe look like today?

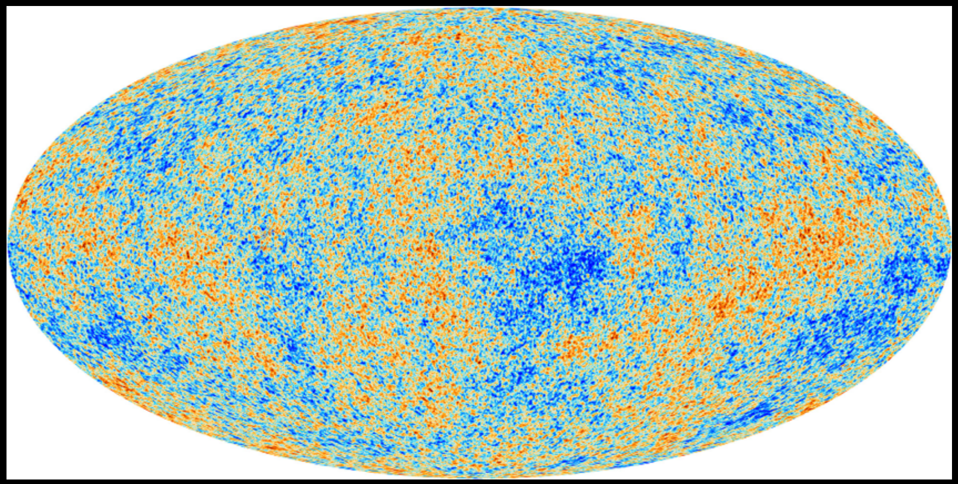


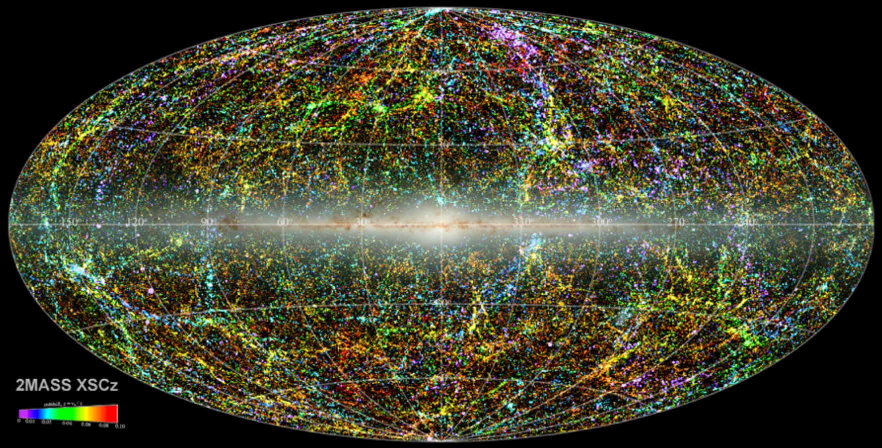
A lot of structures! The universe is very very clumpy

- galaxy outskirts are 200 x as dense
- a person is 10^{30} x as dense
- core of the sun is 10^{32} x as dense

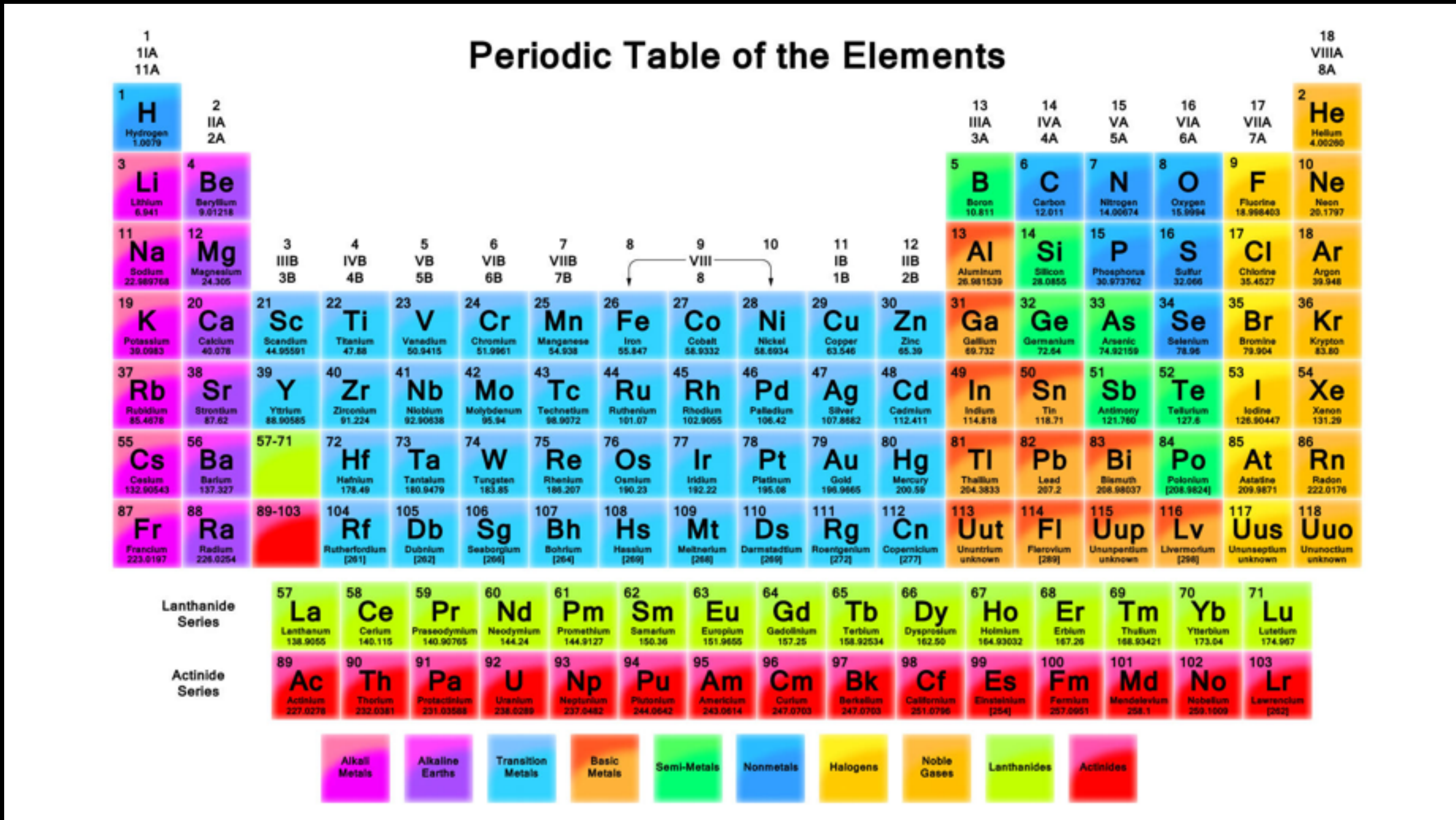
as the average density of the Universe

youth → today

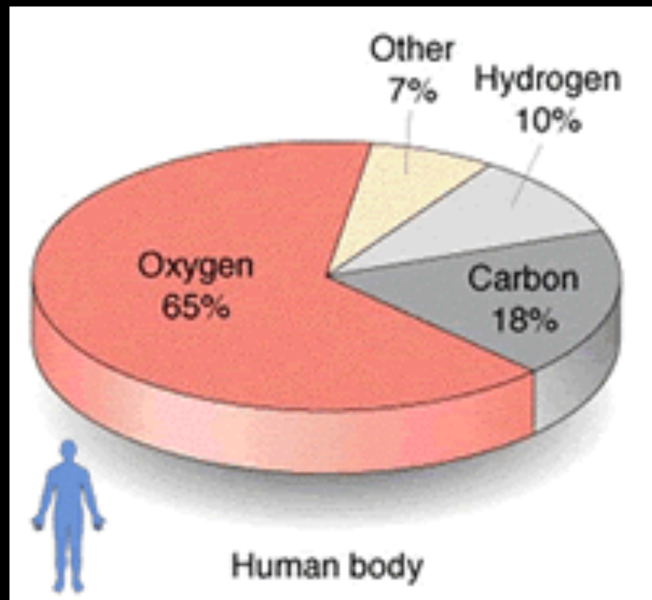




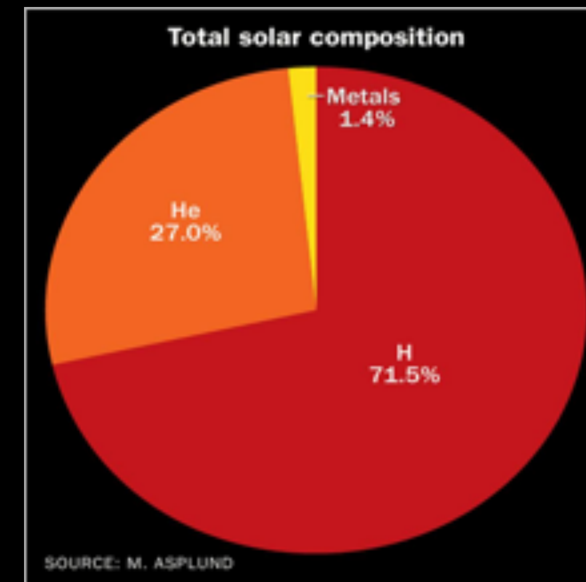
How the Universe evolves depends on what it is made of!

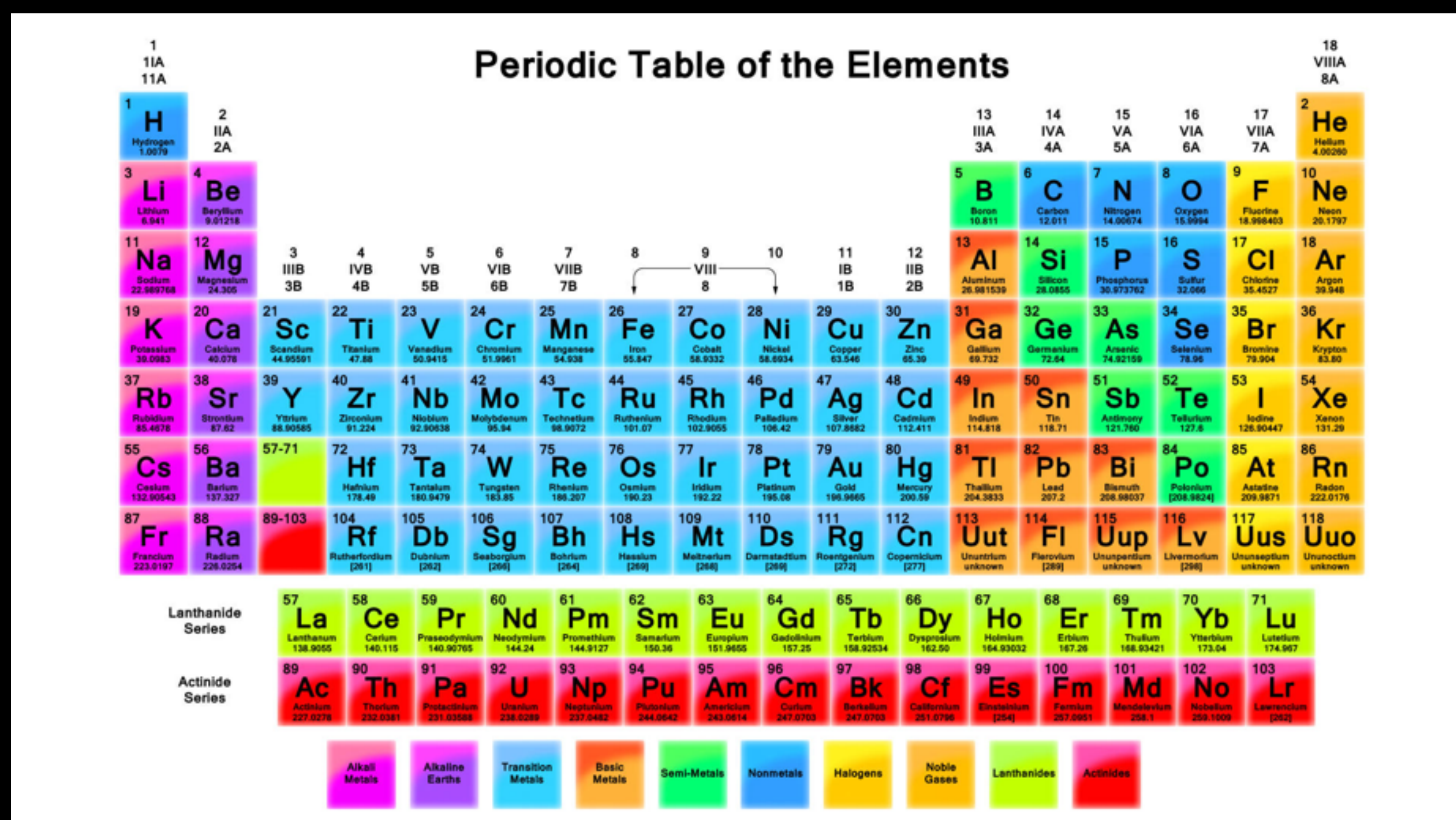

Periodic Table of the Elements
Lanthanide Series
Actinide Series
Alkali Metals
Alkaline Earths
Transition Metals
Basic Metals
Semi-Metals
Nonmetals
Halogens
Noble Gases
Lanthanides
Actinides

Me and you

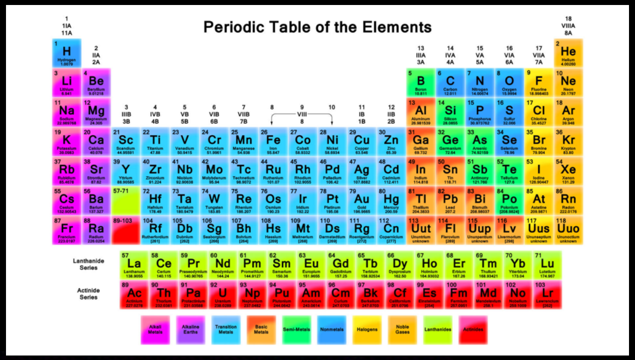


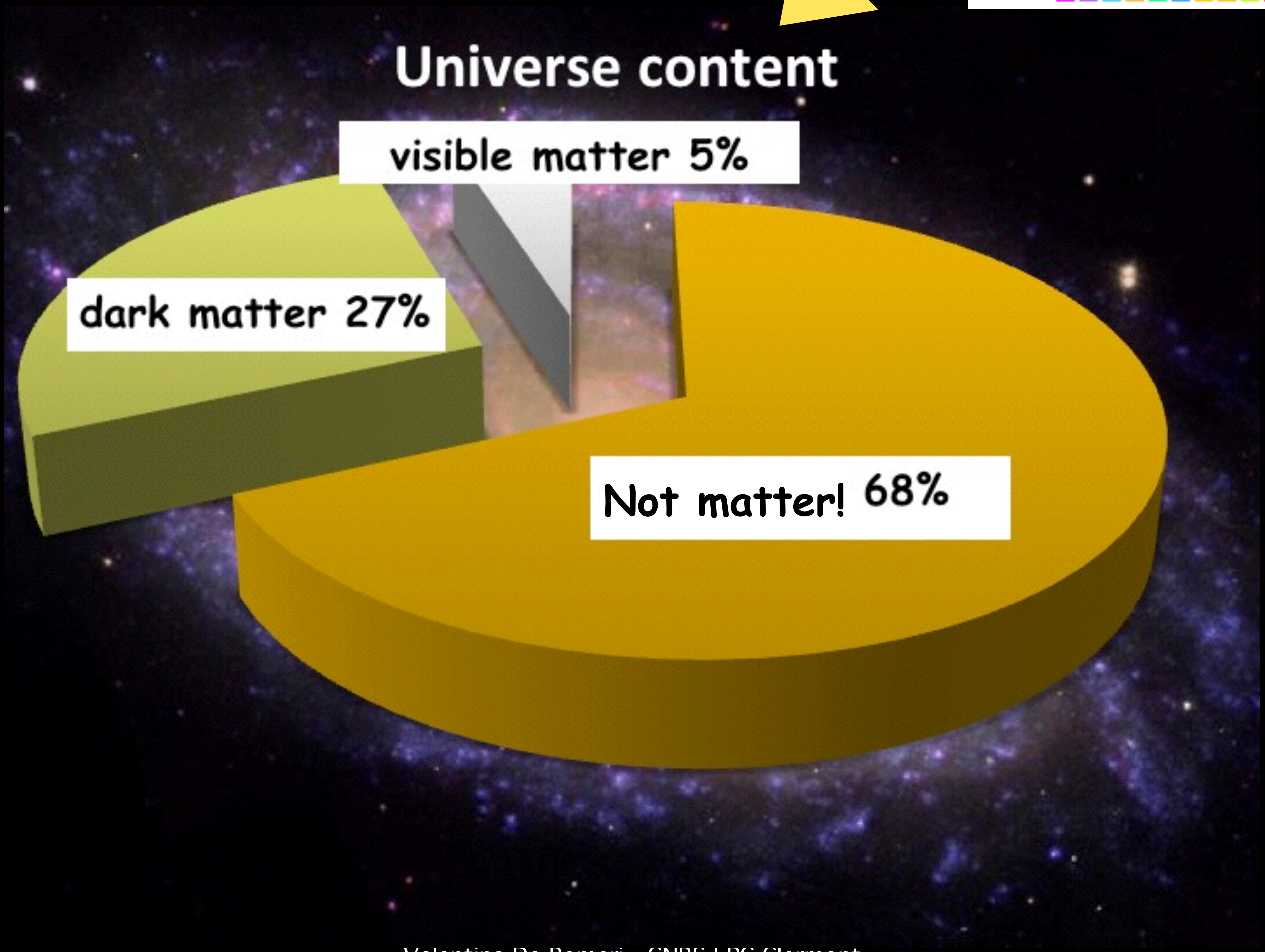
Sun

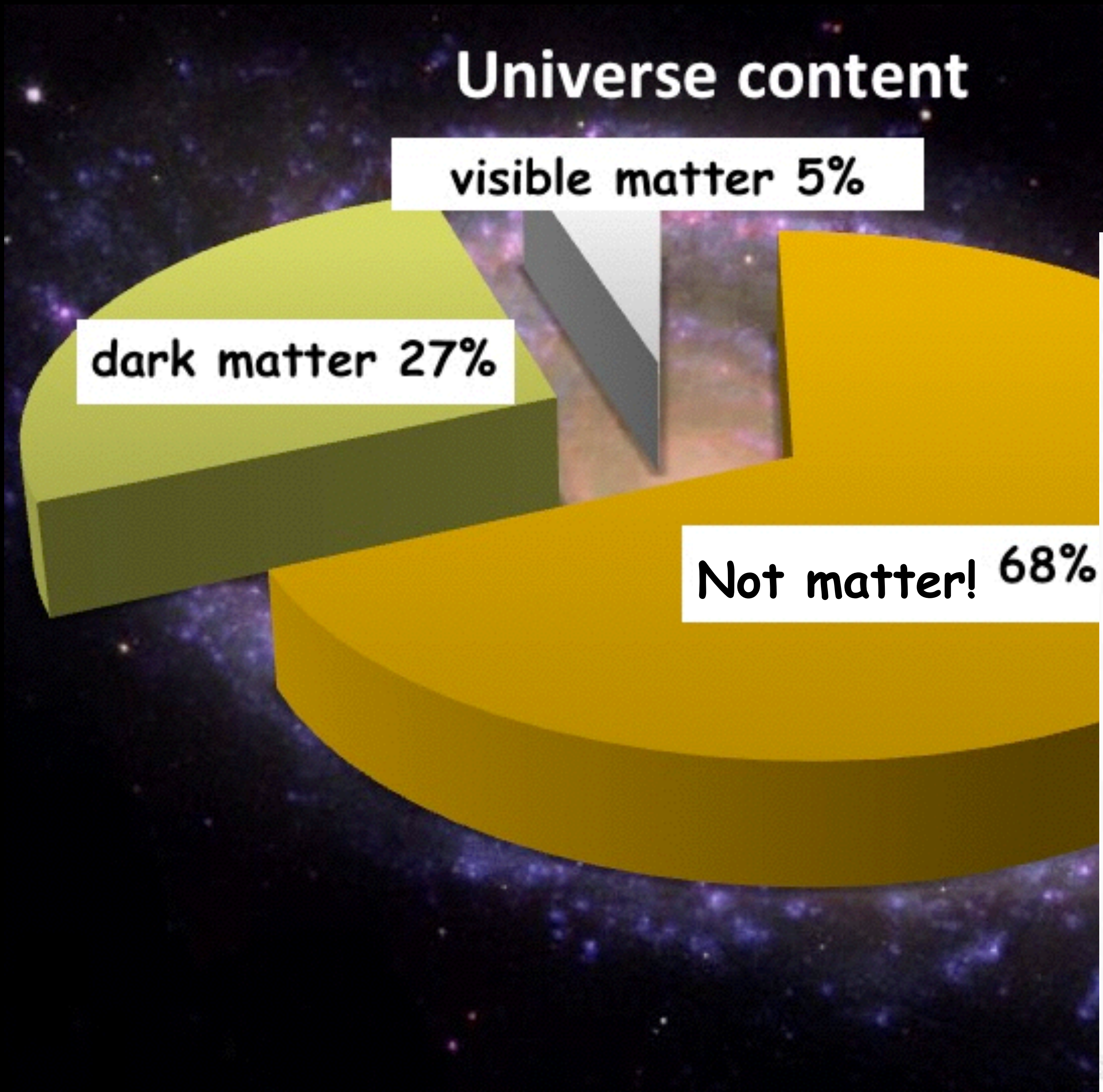


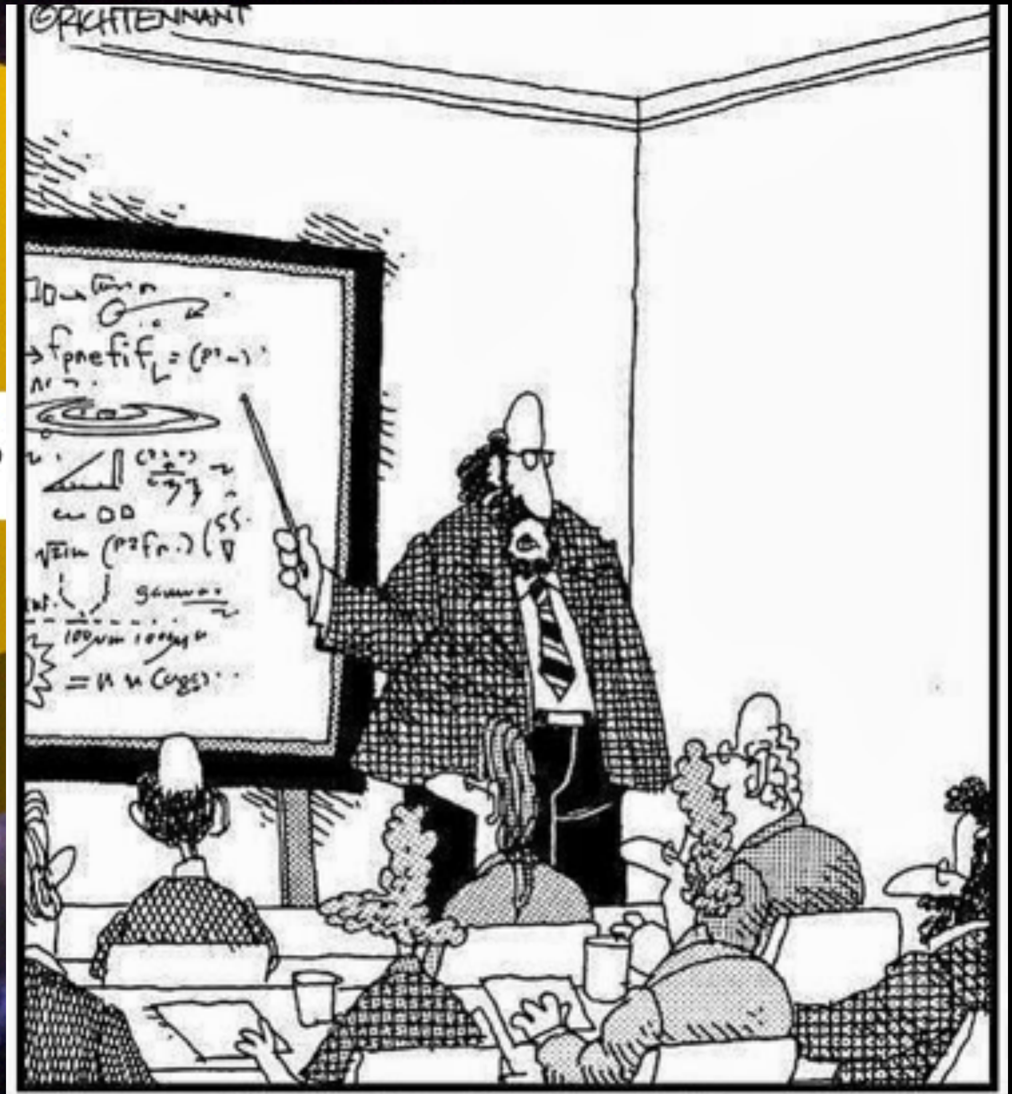


3. How much is there?

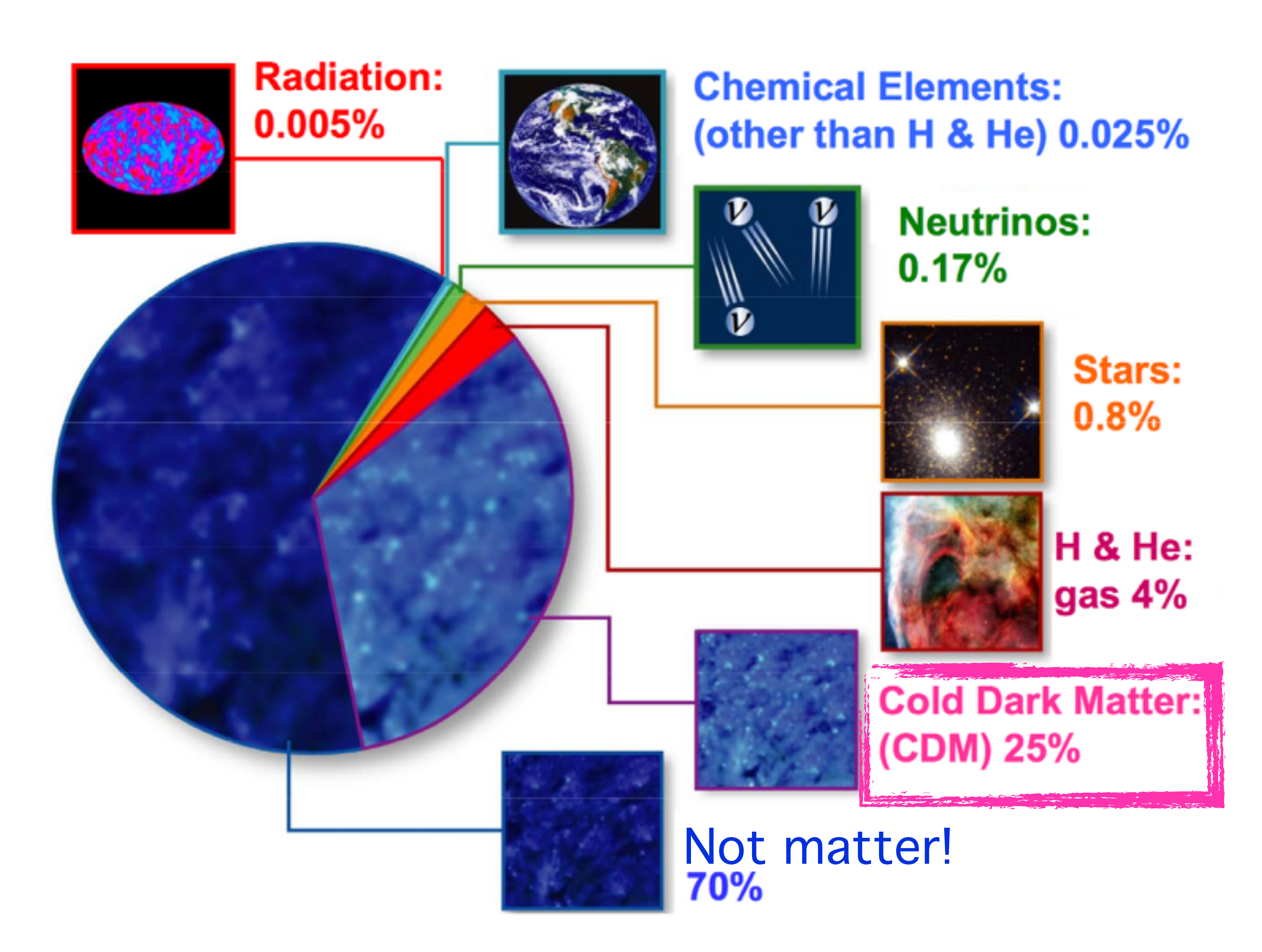

Periodic Table of the Elements


Universe content
visible matter 5%
dark matter 27%
Not matter! 68%





"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.17%
Stars:
0.8%
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
Not matter!
70%

4. Where is it?

95% of the Universe is totally different stuff of the content of the periodic table!

"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T **SEE** THEM."

5. Could it be normal stuff?

3 possibilities:

1) Galaxies are mostly made up of very non-luminous objects (MACHOs: black holes, neutron stars, white dwarf stars, large planets, etc.)

2) We don't understand gravity: Gravity does not work in galaxies and clusters the way it does on Earth or in our Solar System

3) The missing mass consists of some other form of matter

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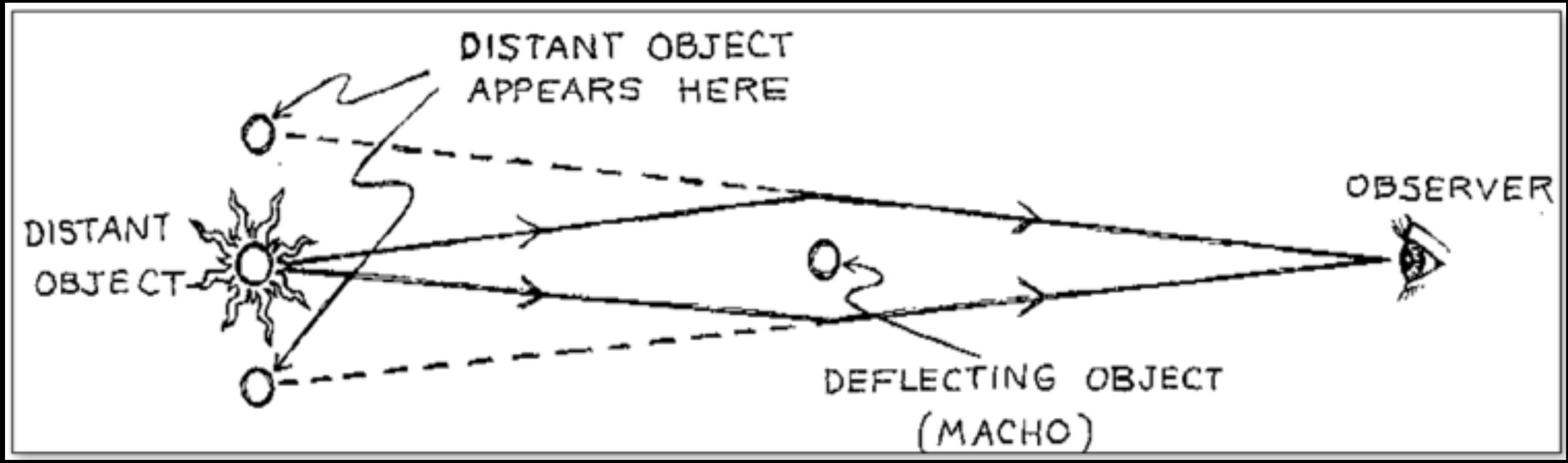
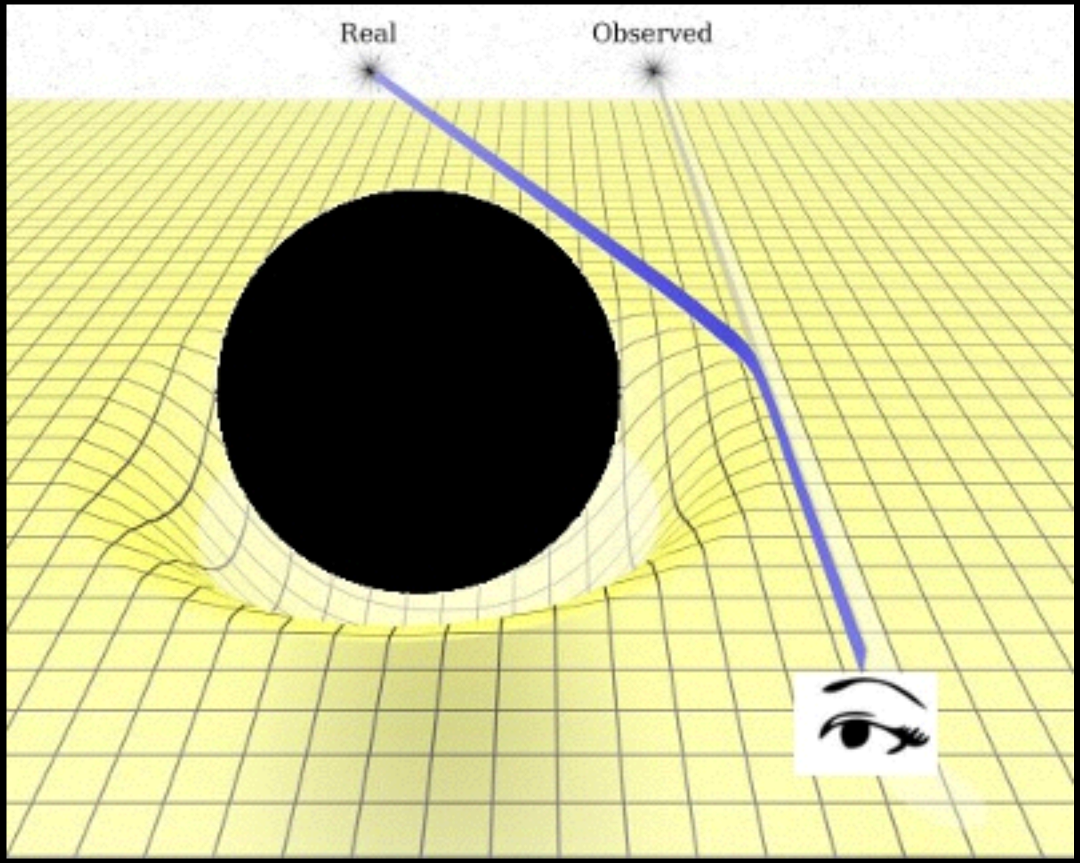
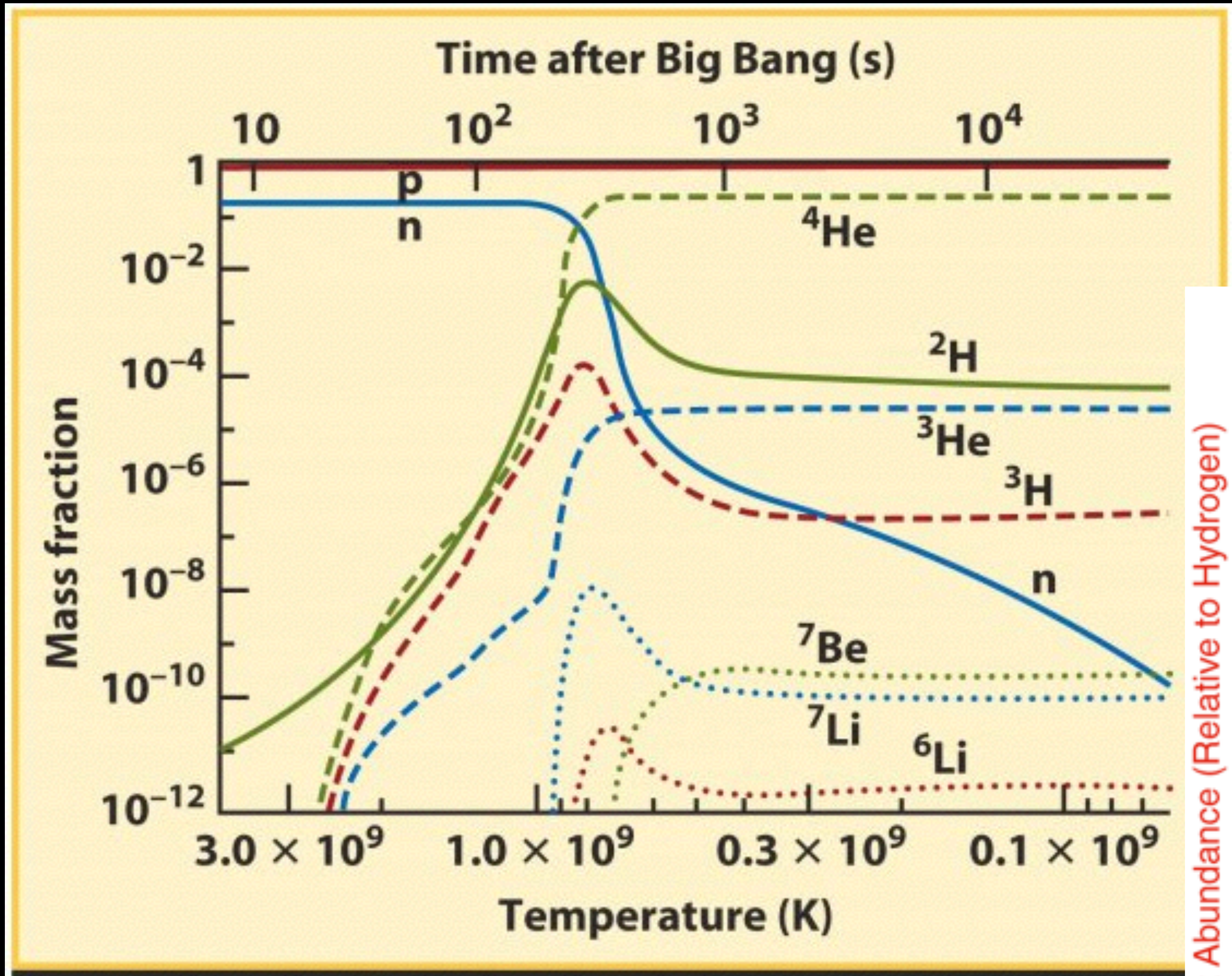
Gravitational lensing

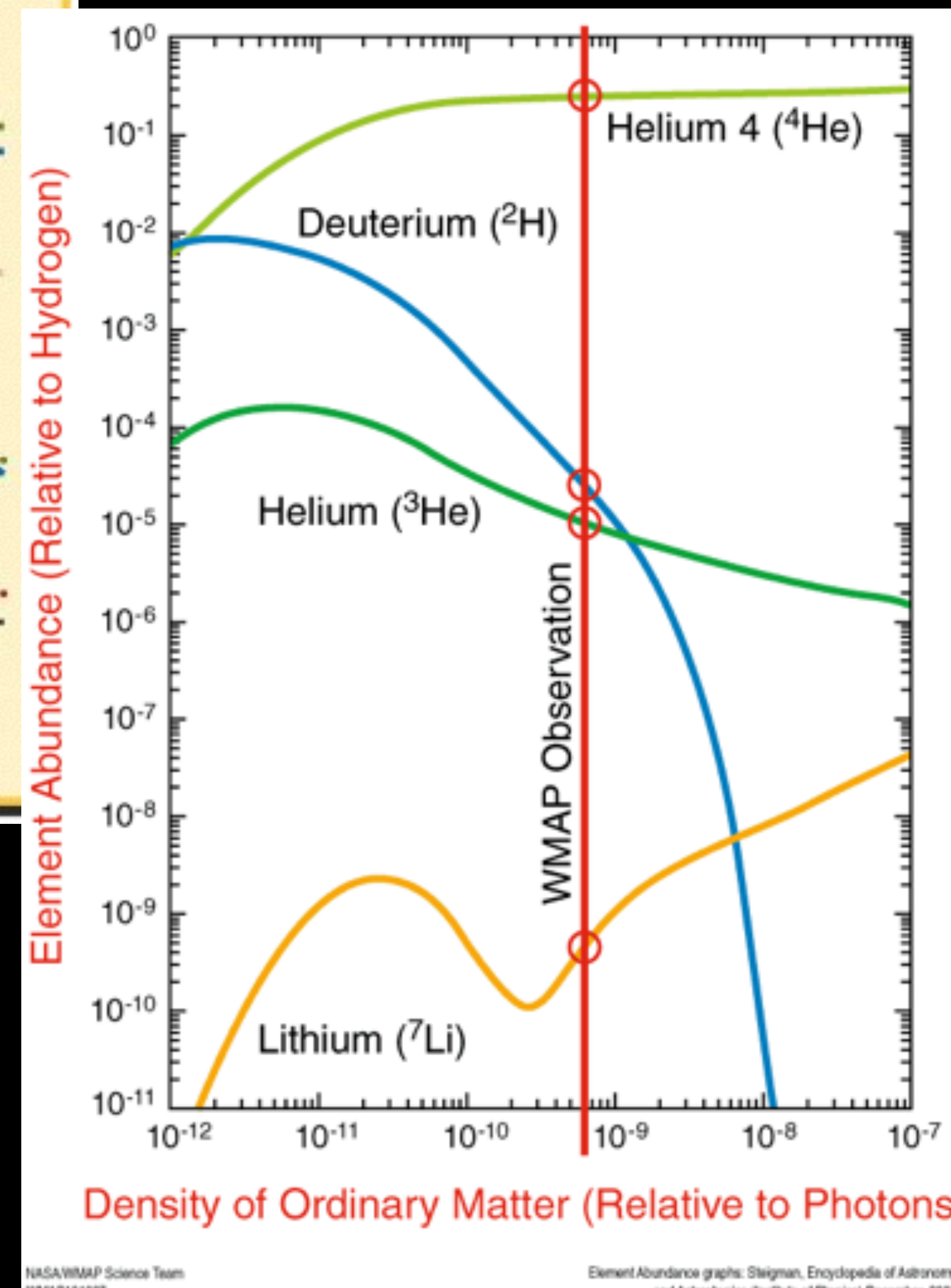


Massive objects can be detected as gravitational lenses, even if they are themselves non-luminous





Time after Big Bang (s)
10
10^2
10^3
10^4
1
p
n
^{4}He
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
^{2}H
^{3}He
^{3}H
n
^{7}Be
^{7}Li
^{6}Li
Mass fraction
3.0×10^9
1.0×10^9
0.3×10^9
0.1×10^9
Temperature (K)



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Helium 4 (^{4}He)
Deuterium (^{2}H)
Helium (^{3}He)
Lithium (^{7}Li)
WMAP Observation
Element Abundance (Relative to Hydrogen)
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
Density of Ordinary Matter (Relative to Photons)
NASA/WMAP Science Team
WMAP101087
Element Abundance graphs: Steigman, Encyclopedia of Astronomy and Astrophysics (Institute of Physics) December, 2000

3 possibilities:

1) Galaxies are mostly made up of very non-luminous objects (MACHOs: black holes, neutron stars, white dwarf stars, large planets, etc.)

2) Gravity does not work in galaxies and clusters the way it does on Earth or in our Solar System

3) The missing mass consists of some other form of matter

MOND fails in explaining the growth of structures
Bullet cluster: evidence for dark matter

3 possibilities:

1) Galaxies are mostly made up of very non-luminous objects (MACHOs: black holes, neutron stars, white dwarf stars, large planets, etc.)

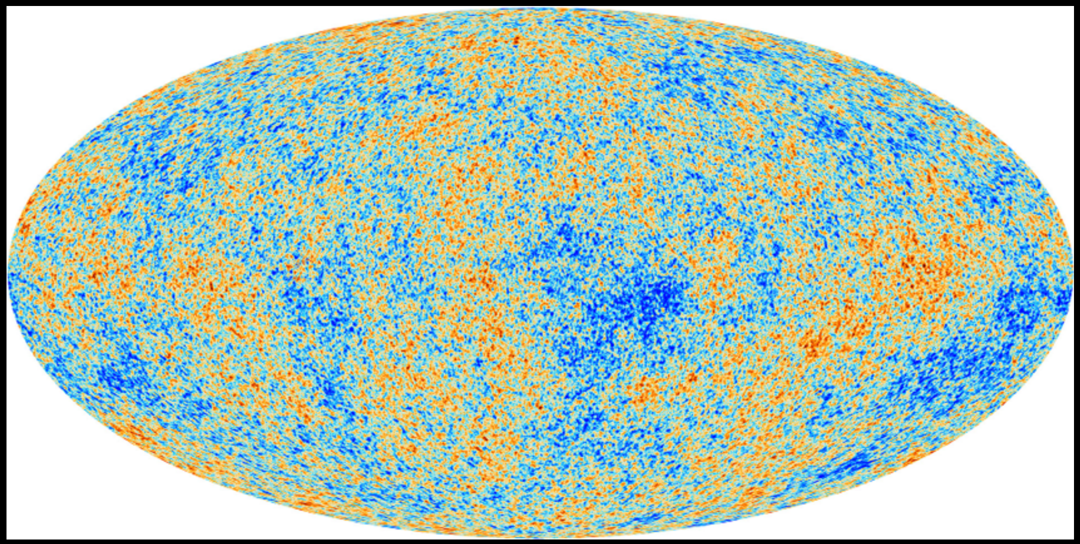
2) Gravity does not work in galaxies and clusters the way it does on Earth or in our Solar System

3) The missing mass consists of some other form of matter

6. How is it distributed?

Structure formation depends on:

- The initial density fluctuations
- The total amount of matter
- The type of matter (how much normal matter and how much dark matter)
- What the dark matter is



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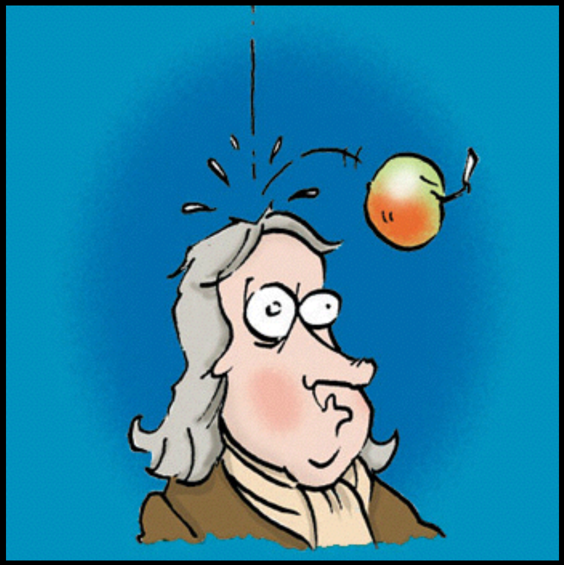
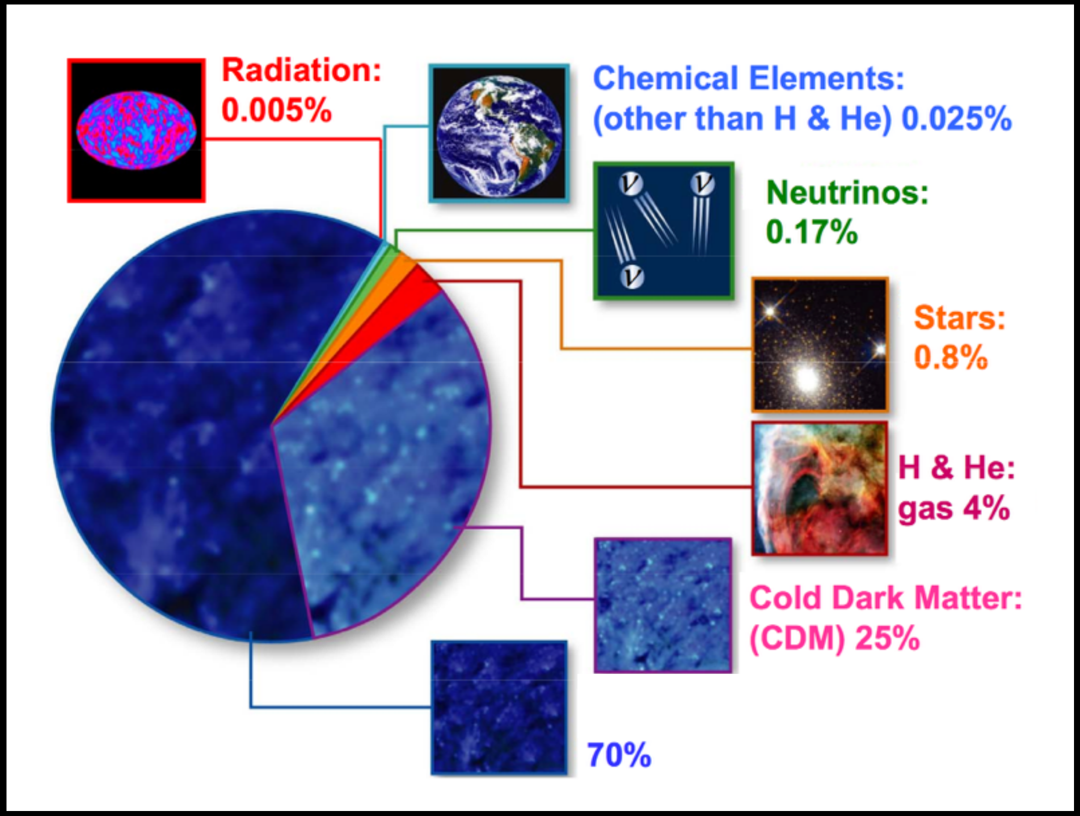


+

+


Radiation:
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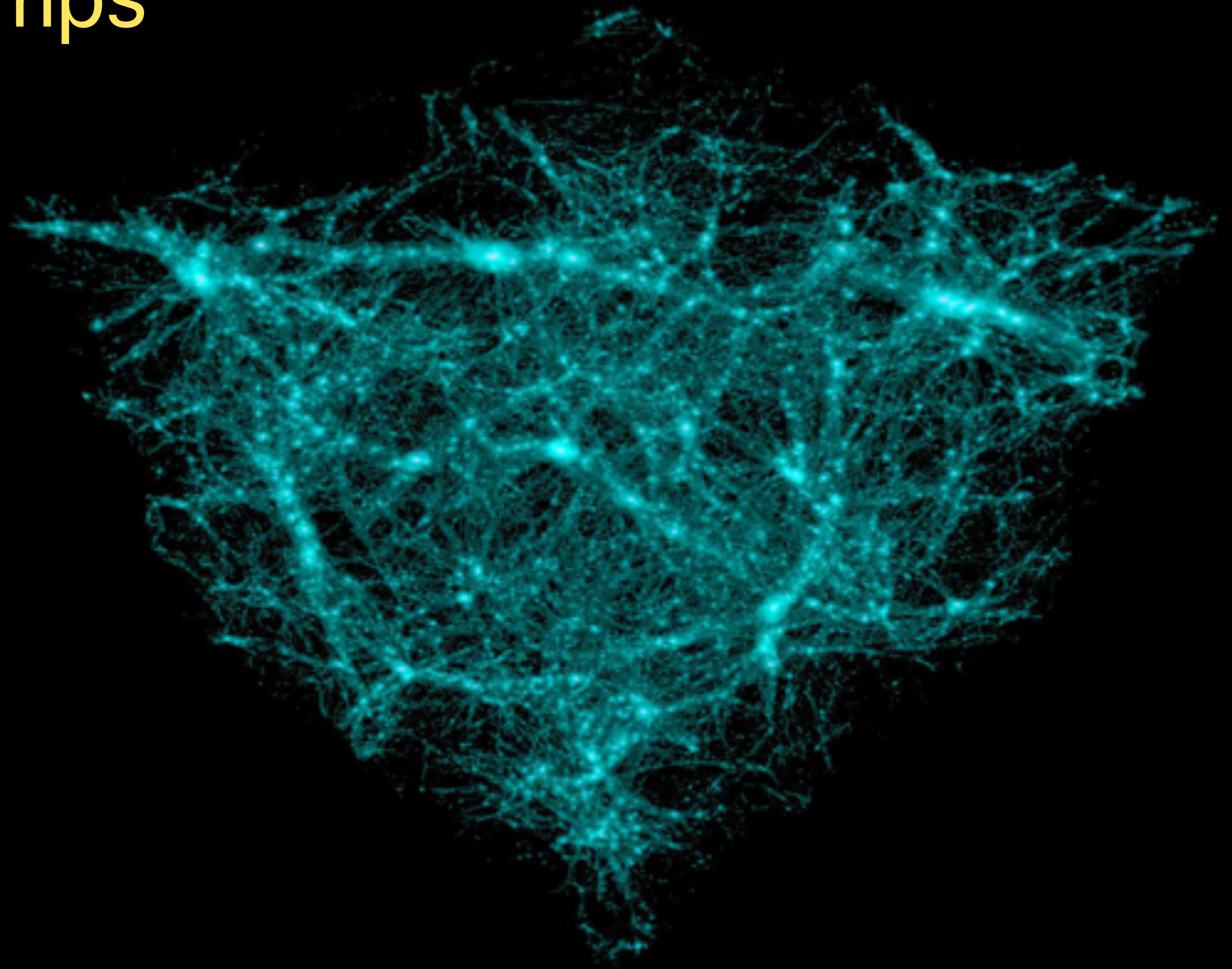
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
70%

Dark matter comes in clumps



Galaxies form by gravity in the regions where we have most dark matter

We can predict where galaxies form in our simulated Universe

7. Why should we care?

From the simulation we have the right amount of clumpiness.

We needed the dark matter to get the structure forming up as we see them.

BUT we also know that the dark matter cannot be made of normal stuff.

What we know so far about dark matter

1) Not made of normal stuff (i.e. baryons: protons, neutrons)

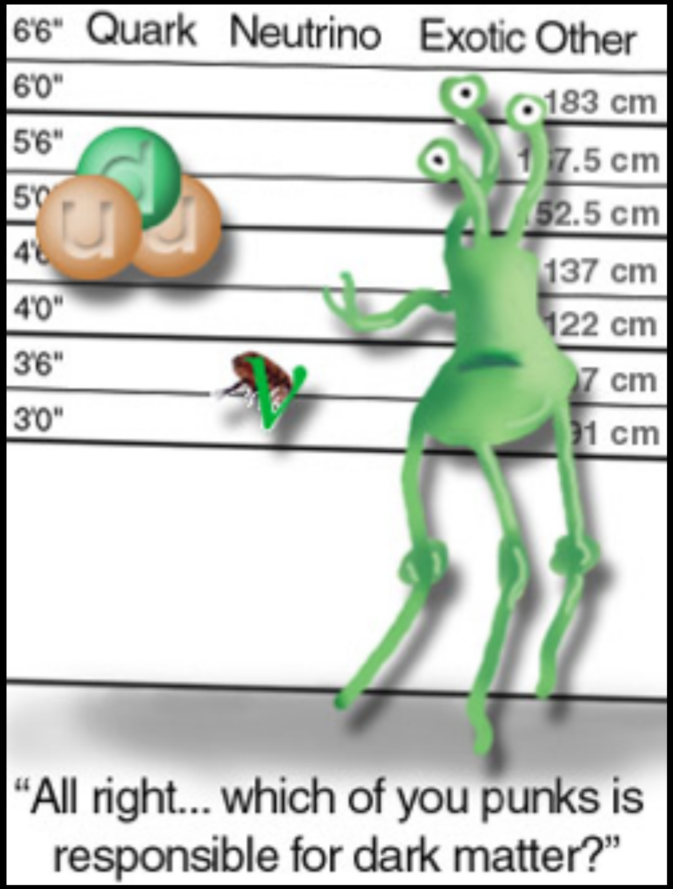
2) Doesn't cool (does not condense to the center of galaxies)

3) Does not significantly emit, reflect, or absorb light (electrically neutral)

4) Stable on cosmological scales (or lifetime >> t_U ~13.7 Gyr)

5) Massive (26% of the energy content of the Universe)

Best idea: it's a subatomic particle
we don't know its mass
we don't know how it interacts with other particles
...



Many candidates have been proposed!

axion

neutralino

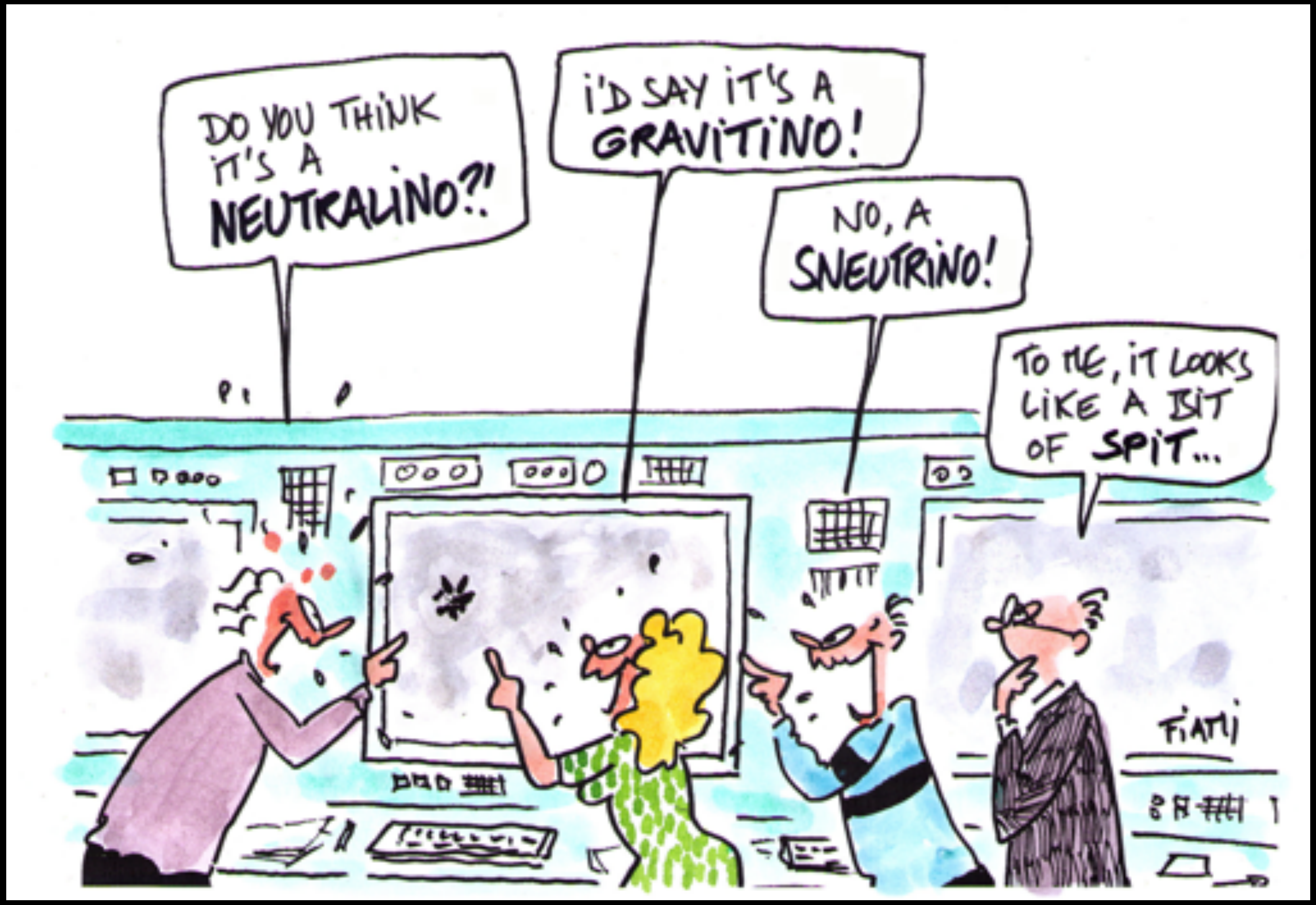
sneutrino

WIMPzillas

gravitino

WIMP

...



But... wait...

Michele just taught us about some interesting particles!

Many candidates have been proposed!

There are known particles with most of the properties required, the neutrinos

axion neutralino

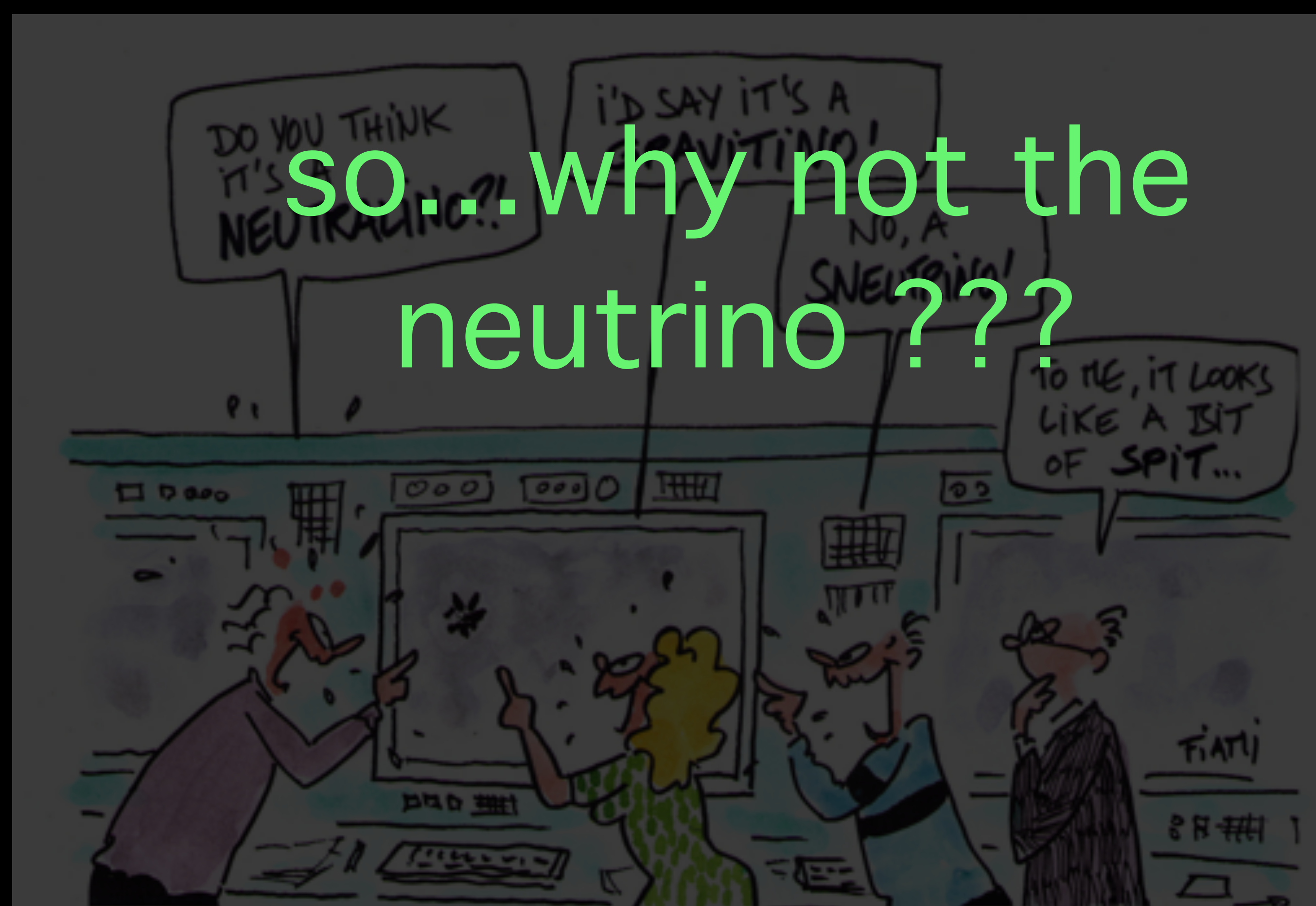
sneutrino

WIMP

WIMPzillas

gravitino

...



so...why not the neutrino ???

A key feature of dark matter particles: how fast they move.

HOT dark matter: particles move very fast in terms of the speed of light
COLD dark matter: particles are much slower than light

Everything we saw about structure formation makes the assumption that the dark matter is COLD

The measurements indicate the neutrinos can only have a small mass. This makes it rather hard for gravity to slow them down.

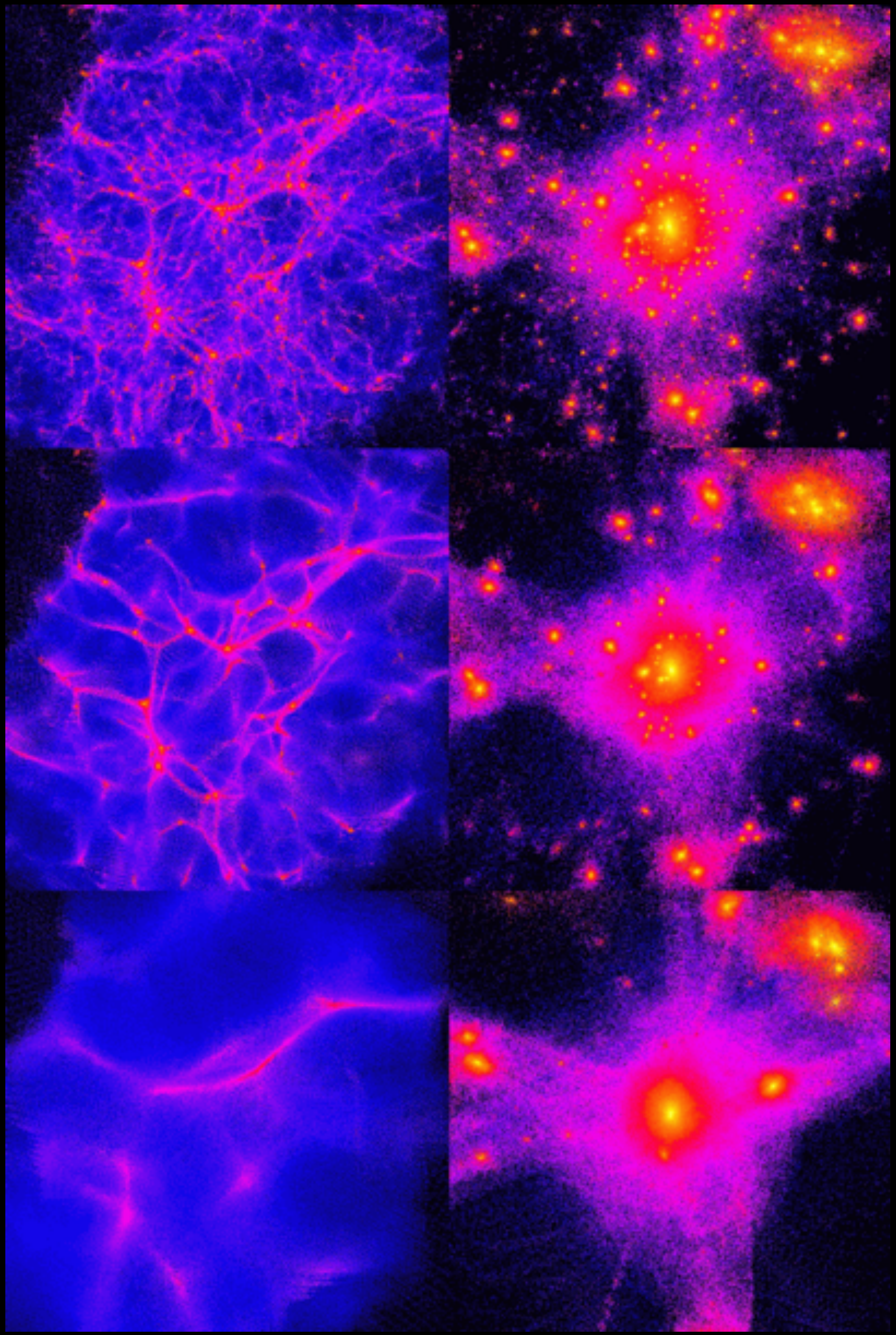
Neutrinos are too light and quick moving to make up the dark matter !!!

In general, particles with near-zero rest masses (including neutrinos) are a constituent of hot dark matter.

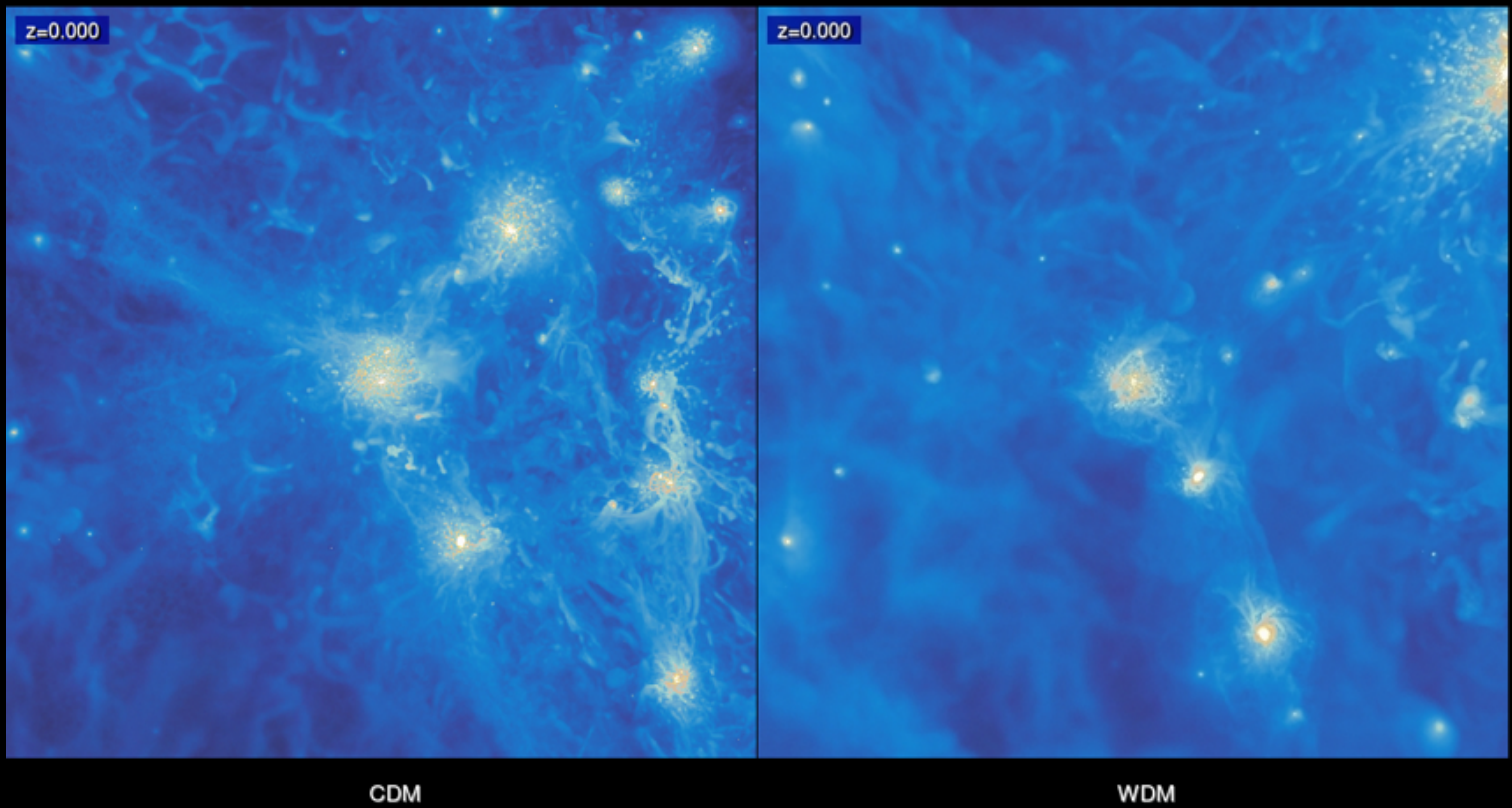
cold

warm

hot

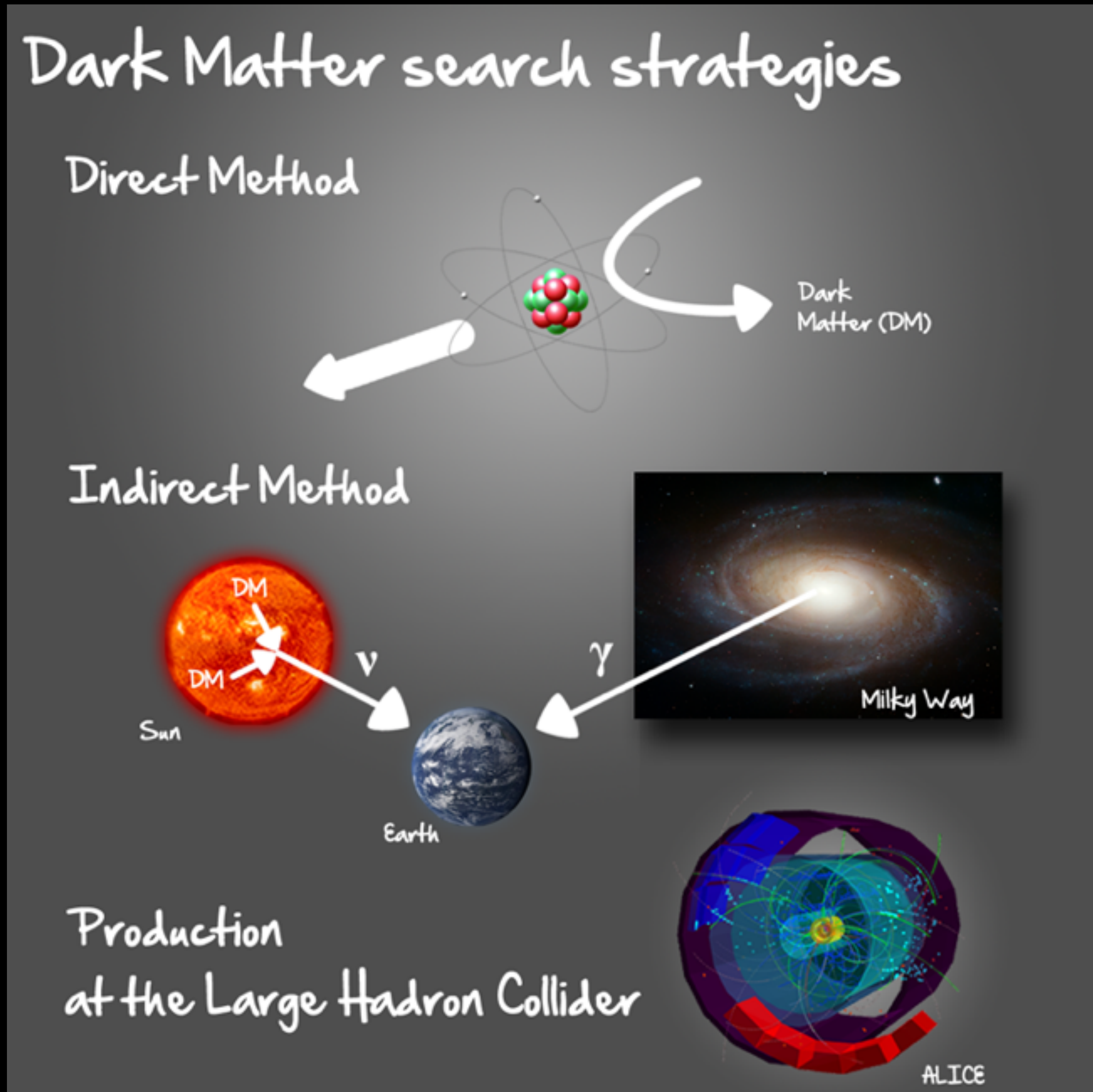


Hot dark matter is ruled out, but dark matter could be a little bit WARM



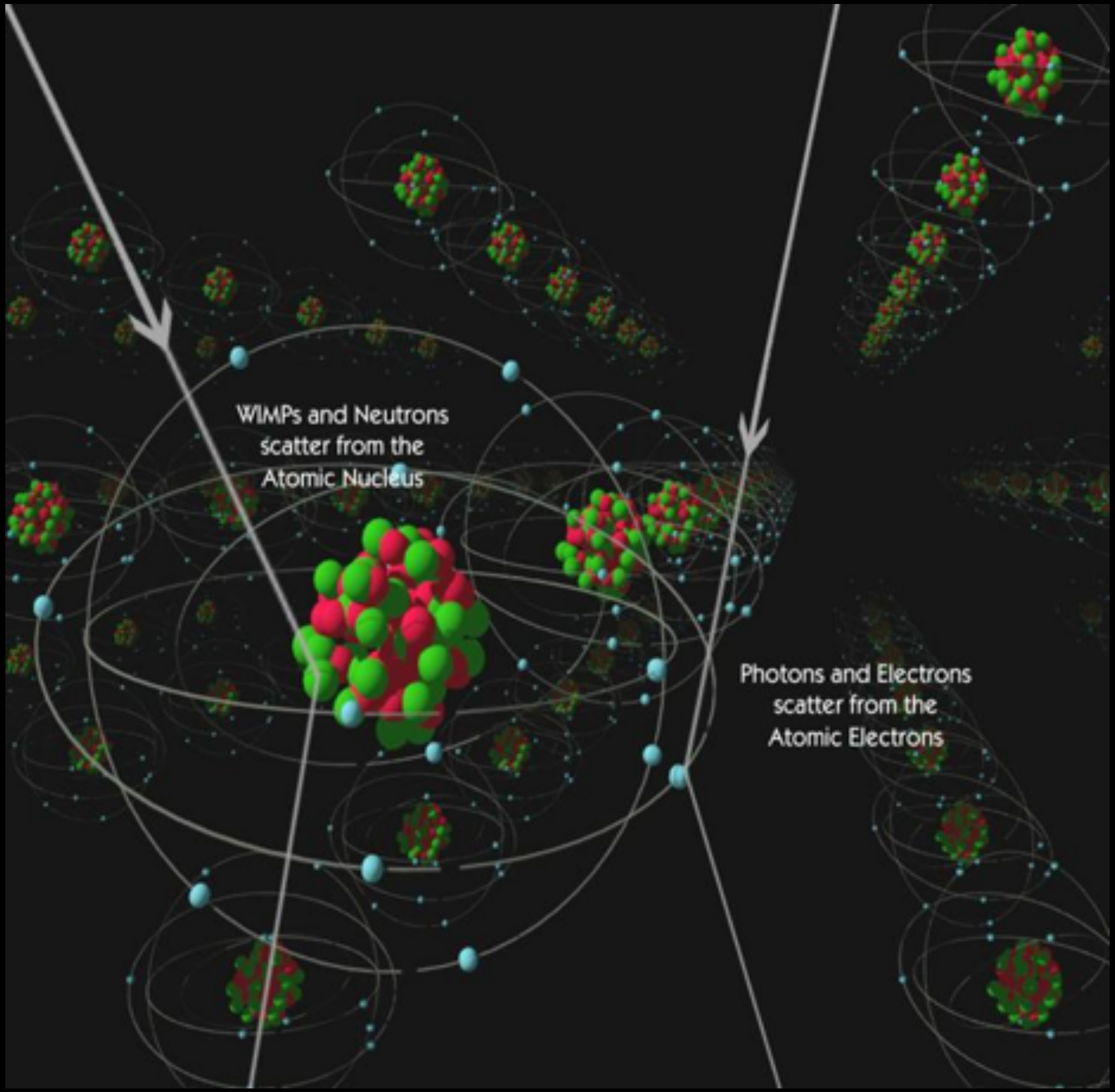
Instead of faint stars, re-imagine the dark matter as a gas of weakly interacting particles, which we will call WIMPs (Weakly Interacting Massive Particles)

8. How to search for WIMPs?


Dark Matter search strategies
Direct Method
Dark Matter (DM)
Indirect Method
DM
DM
Sun
ν
γ
Milky Way
Earth
Production at the Large Hadron Collider
ALICE

Direct detection

1) Go deep underground and wait for WIMPs to hit your detector



Direct detection

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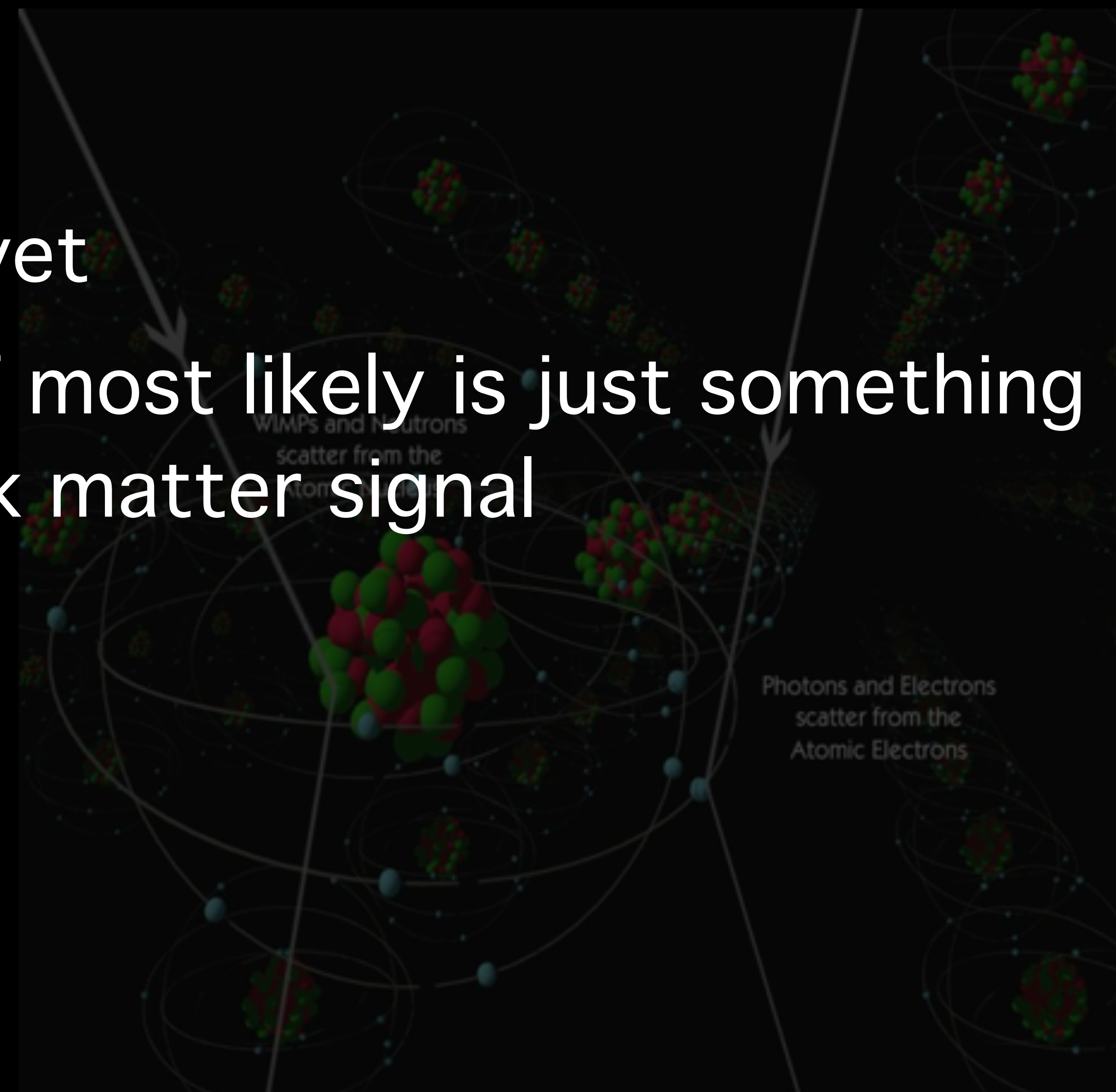
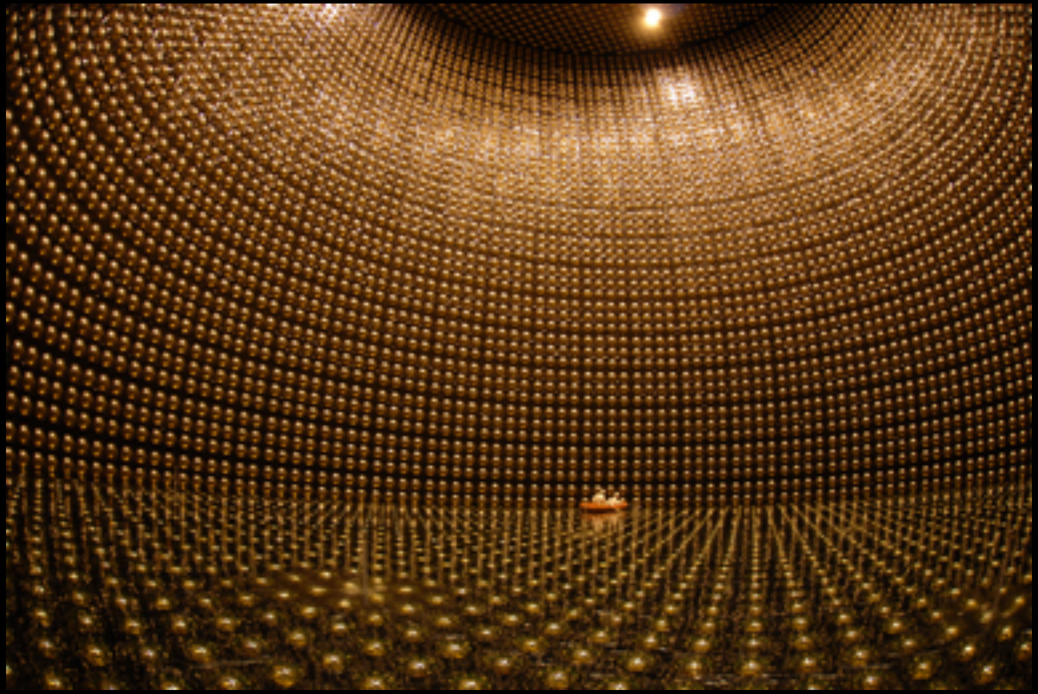


No dark matter candidate yet

Some interesting hints BUT most likely is just something known which mimics a dark matter signal

Indirect detection

2) Use “telescopes” to look for energetic particles that are produced when dark matter particles interact with themselves

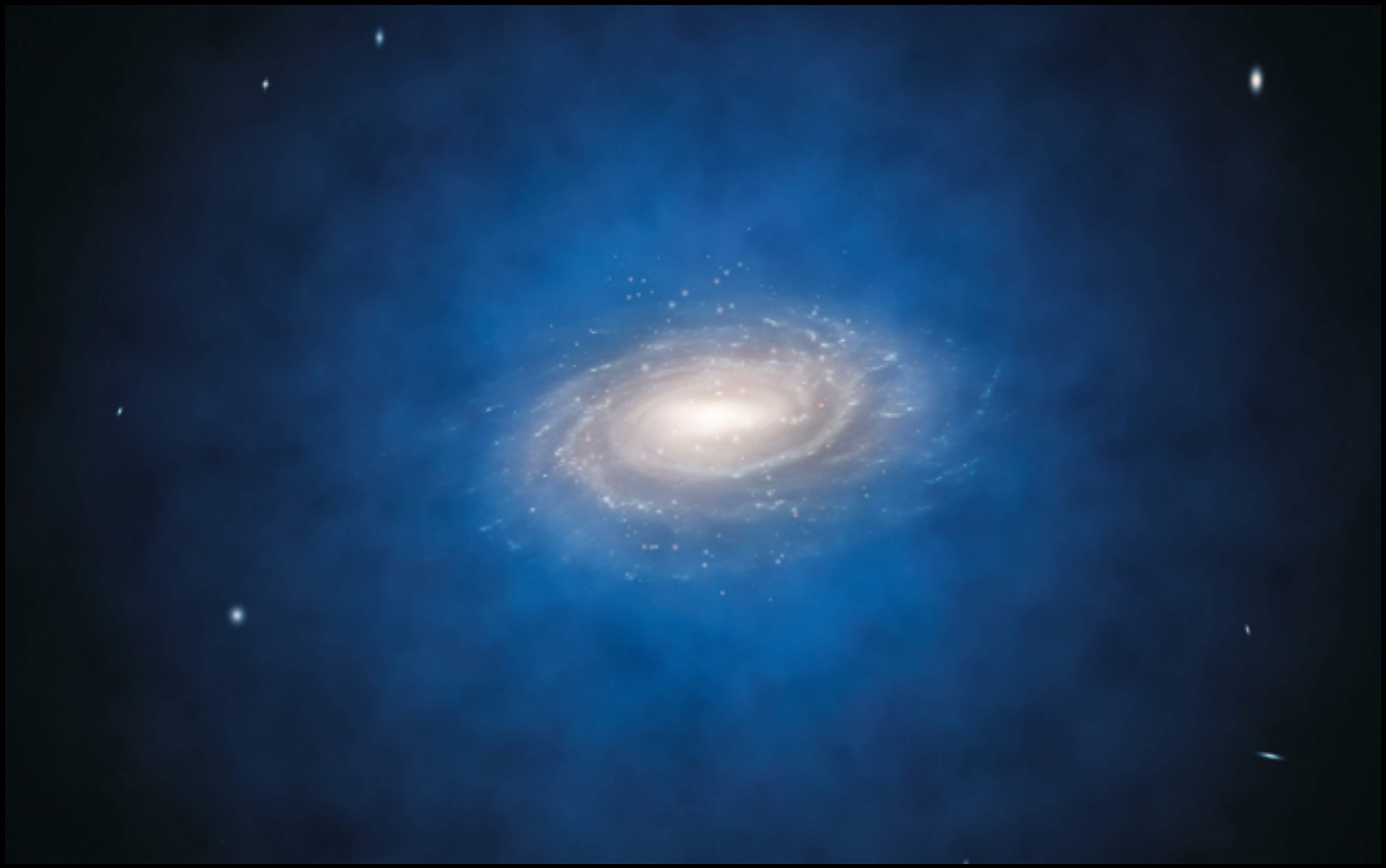


Dark matter might interact with itself and create high energy photons...

Very weakly

Only visible in regions with plenty of dark matter

For instance, look at the centers of galaxies



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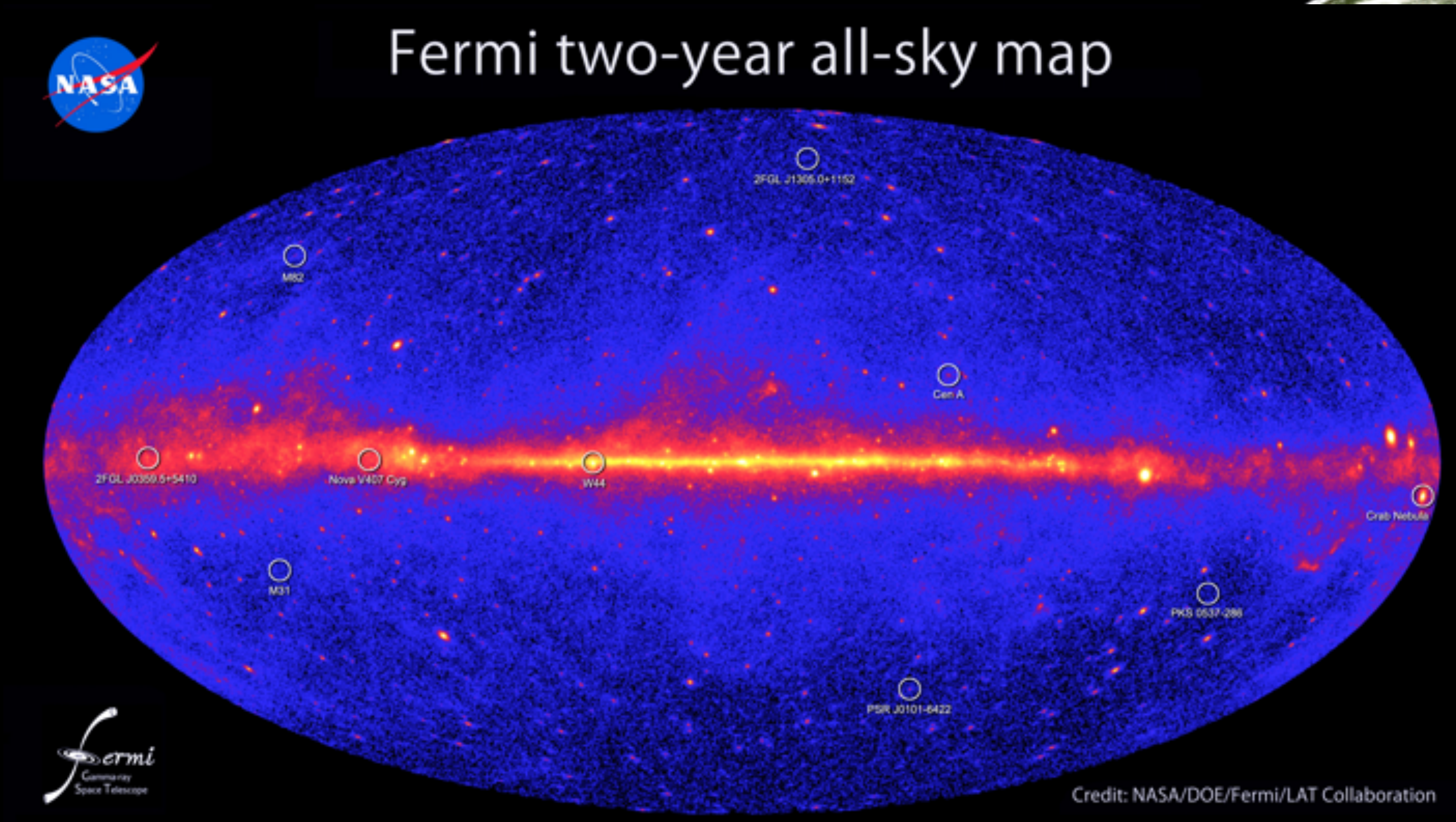


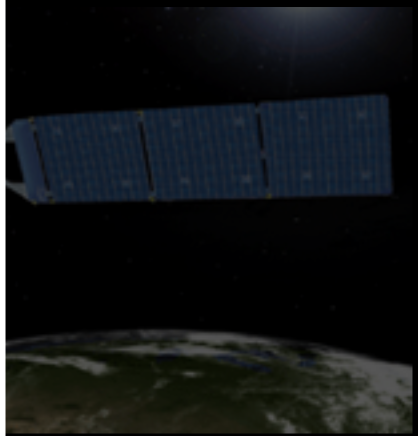
Dark matter might interact … te high energy photons…

Very …

Only …

For i…

My work!



Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 11 February 2014 (MN LaTeX style file v2.2)

γ-ray anisotropies from dark matter in the Milky Way: the role of the radial distribution

F. Calore[1], V. De Romeri[2,3], M. Di Mauro[4,5,6], F. Donato[4,5], J. Herpich[7], A.V. Macciò[7], L. Maccio…[8,9]

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ABSTRACT

The annihilation of dark matter particles in the halo of galaxies may end up into γ-rays, which travel almost unperturbed till to their detection at Earth. This annihilation signal can exhibit an anisotropic behavior quantified by the angular power spectrum, whose properties strongly depend on the dark matter distribution and its clumpiness. We use high resolution pure dark matter N-body simulations to quantify the contribution of different components (main halo and satellites) to the global signal as a function of the analytical profile adopted to describe the numerical results. We find that the smooth main halo dominates the angular power spectrum of the γ-ray signal up to quite large multipoles, where the sub-haloes anisotropy signal starts to

Credit: NASA/DOE/Fermi/LAT Collaboration

Dark matter might interact with itself and create high energy photons...

Very weakly

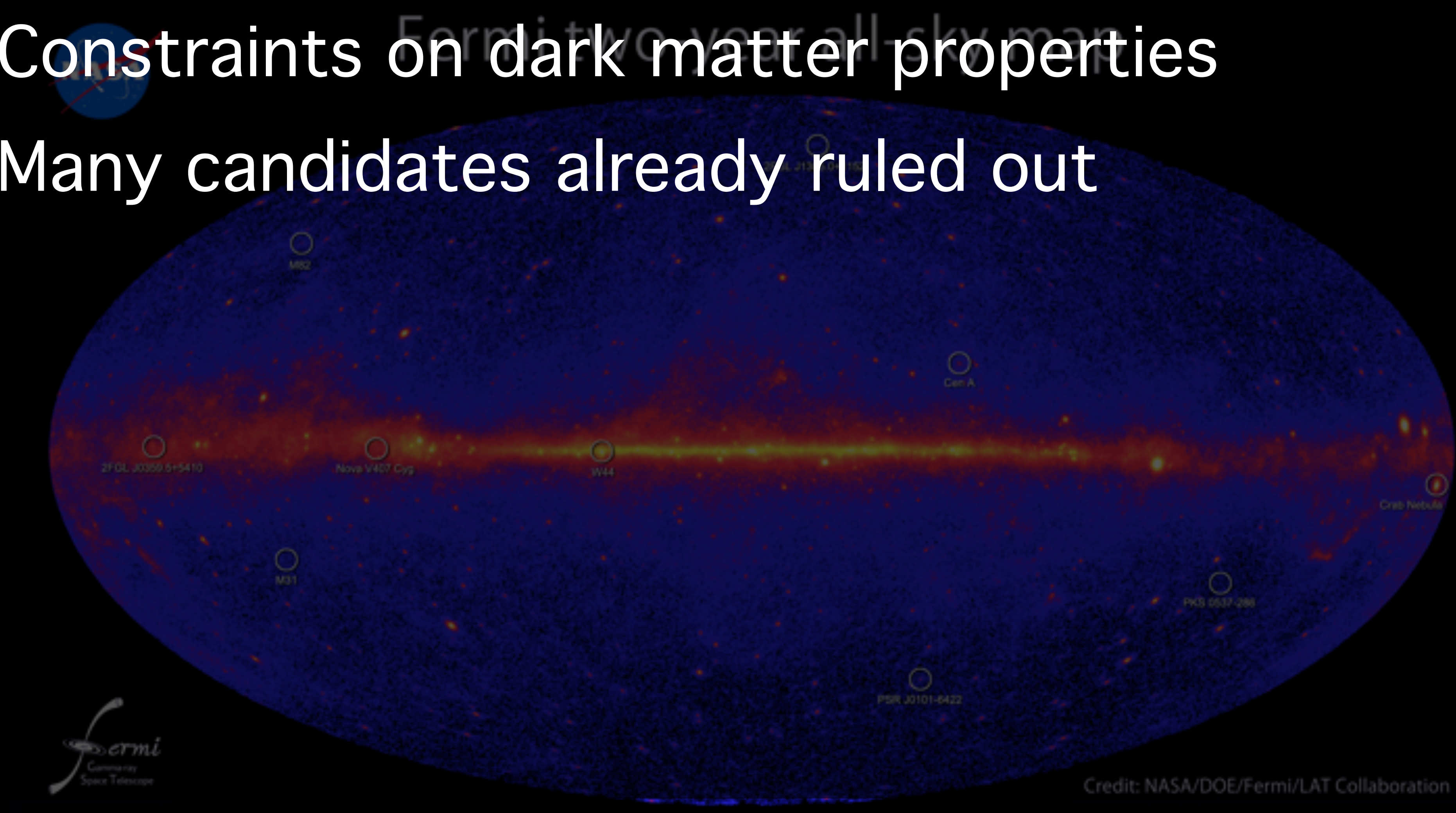
Only visible in regions with plenty of dark matter

For instance, look at the centers of galaxies

No dark matter candidate yet

Constraints on dark matter properties

Many candidates already ruled out



Production at colliders

3) Create it using a particle accelerator

Maybe at very very high energies, dark matter interacts with normal matter.

Accelerators: recreate conditions of primordial Universe

Large Hadron Collider (LHC) @ CERN, Geneva

Production at colliders

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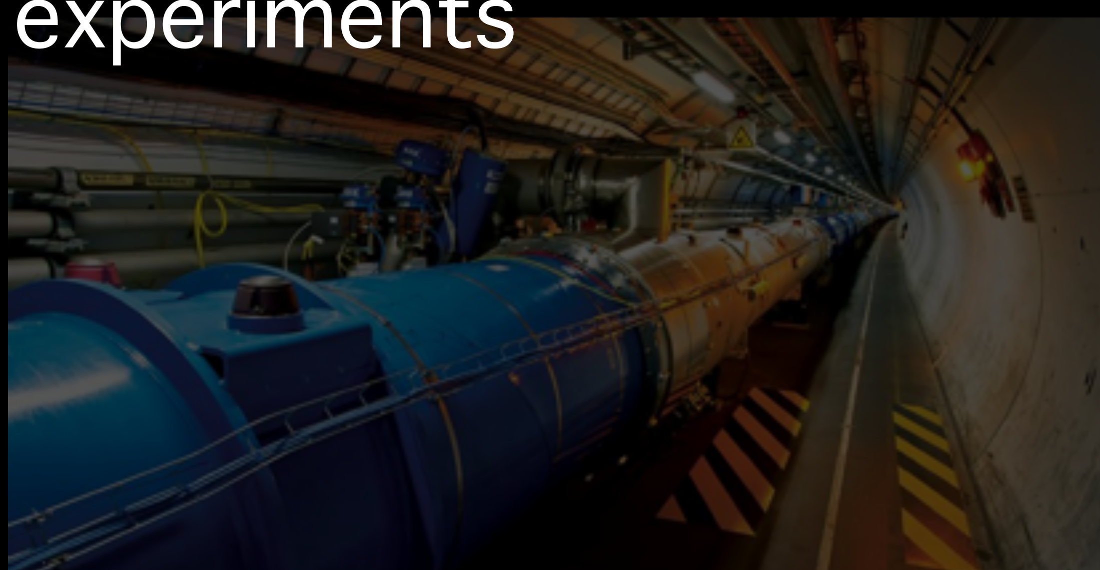
Accelerators: recreate conditions of primordial Universe

So far, "only" the Higgs as been discovered at LHC

No possible candidate for dark matter

Large Hadron Collider (LHC) @ CERN, Geneva

Caveat: even if new particle is discovered, must be cross-checked with direct/indirect detection experiments



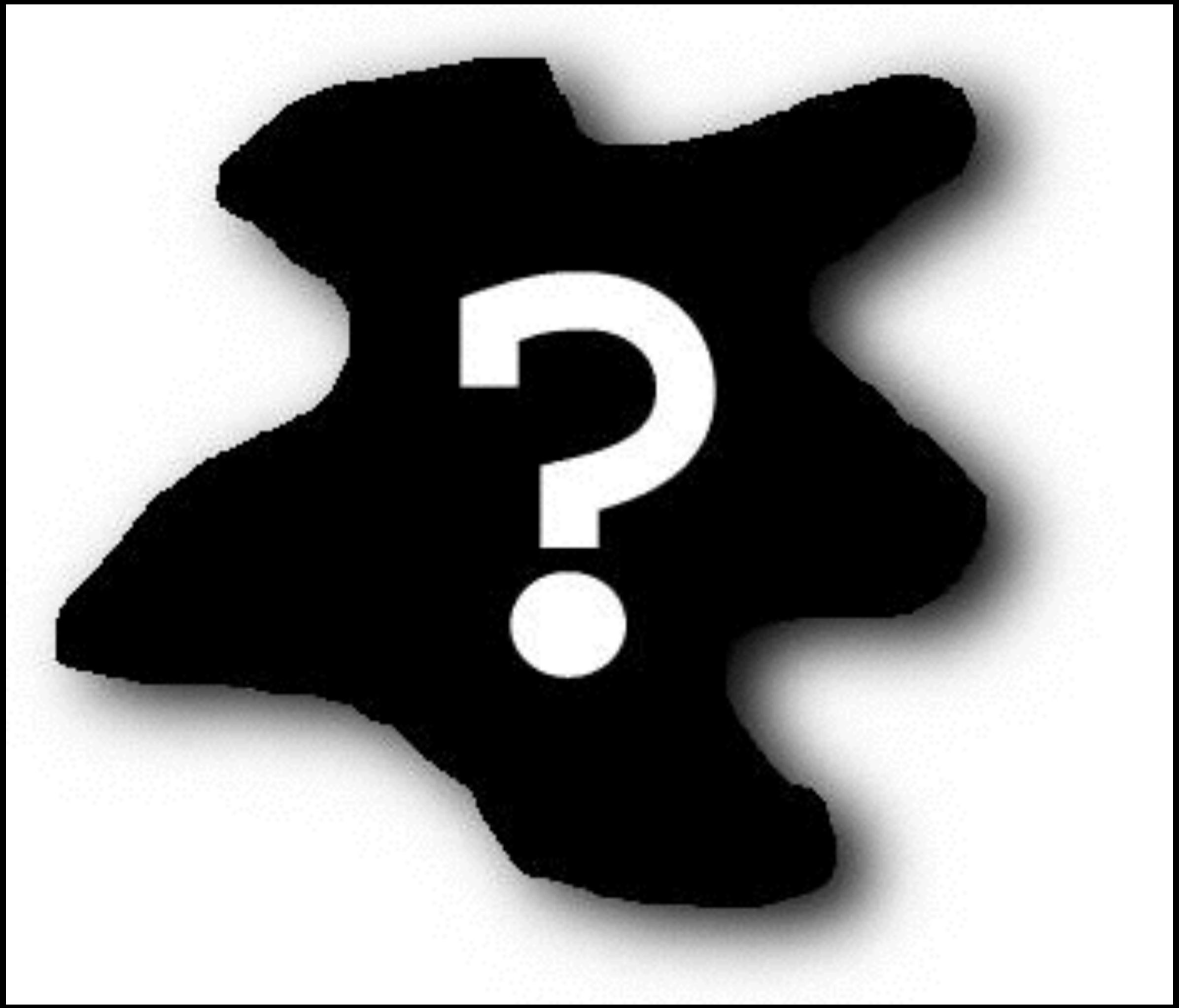

9. ...so, what?

Hot questions about Dark Matter

1. What is dark matter?
   it's something we cannot see; it could be made by "cold" weakly interacting massive particles.
2. How do we know that it exists?
   several compelling cosmological evidences.
3. How much is there?
   around 26 % of the energy content of the Universe!!!
4. Where is it?
   everywhere. Even here in this room.
5. Could it be normal stuff?
   NO.
6. How is it distributed?
   it forms halos and it is very clumpy.
7. Why should we care?
   galaxies would not have formed as they are, we would not be here now.
8. How to search for dark matter?
   direct, indirect detection and production at colliders.
9. Then what?
   good chances of discover it in the next years.

Dark Matter in the XXI century

Dark matter's nature remains a mystery!



Dark Matter in the XXI century