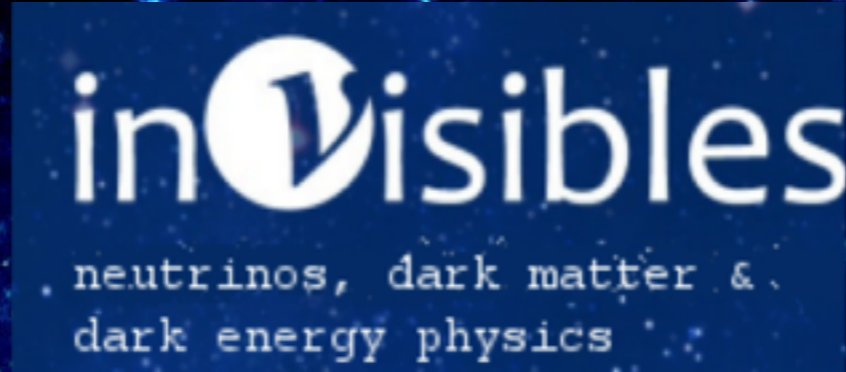




Invisibles is a new European ITN project (FP7-PEOPLE-2011-ITN, PITN-GA-2011-289442-INVISIBLES (April 2012-March 2016)), which focuses on Neutrino and Dark Matter phenomenology and their connection. Experimental and theoretical aspects are also encompassed. The network involves nodes in seven European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



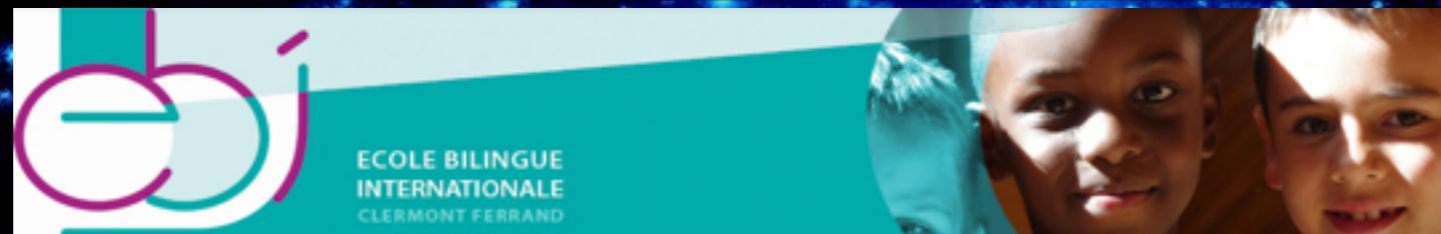
Valentina De Romeri - CNRS LPC Clermont



Valentina De Romeri

# DARK MATTER

11th June 2014,  
ECOLE BILINGUE INTERNATIONALE DE  
CLERMONT FERRAND



# Hot questions about Dark Matter

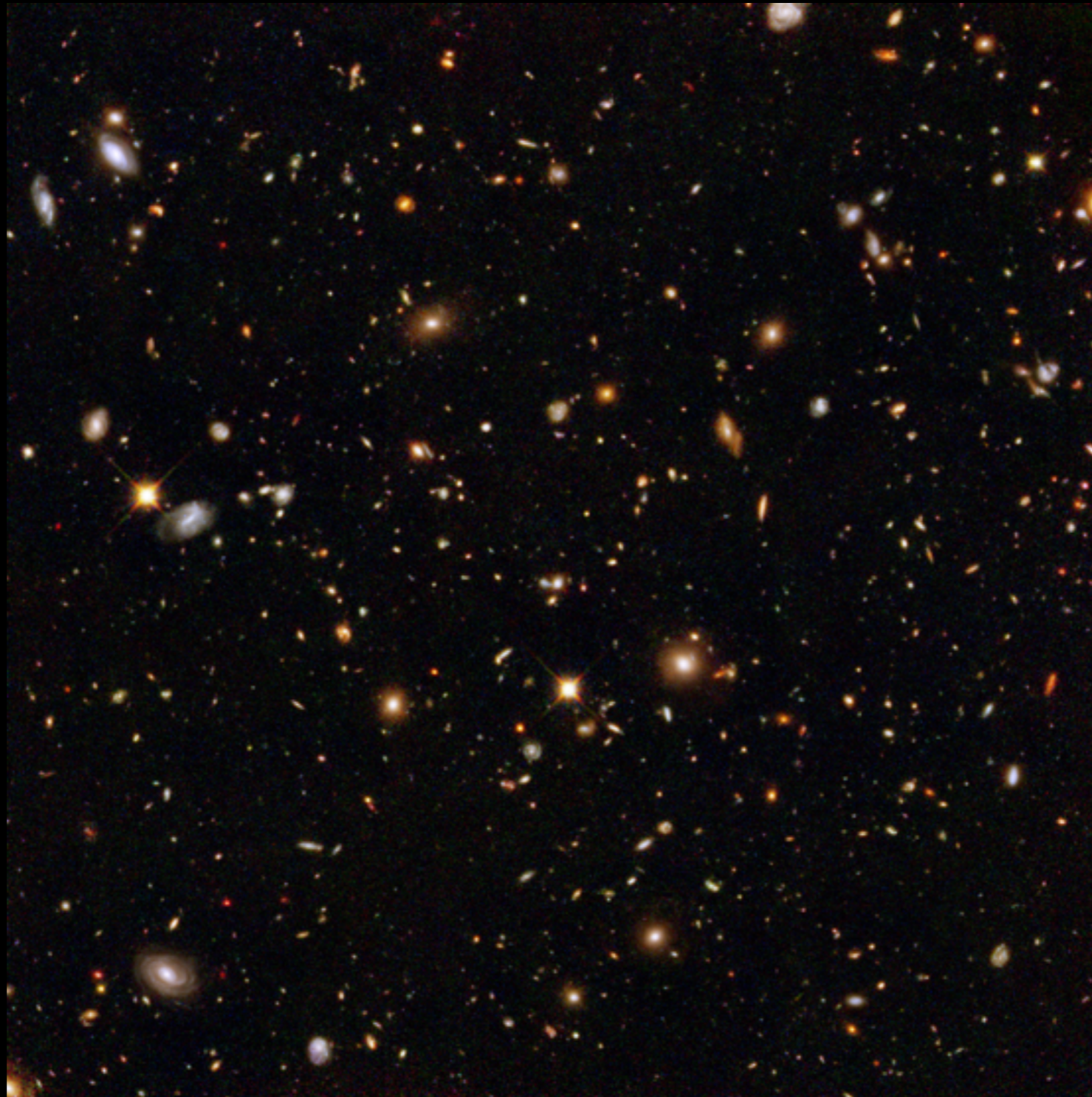
1. What is dark matter?
2. How do we know that it exists?
3. How much is there?
4. Where is it?
5. Could it be normal stuff?
6. How is it distributed?
7. Why should we care?
8. How to search for dark matter?
9. Then what?



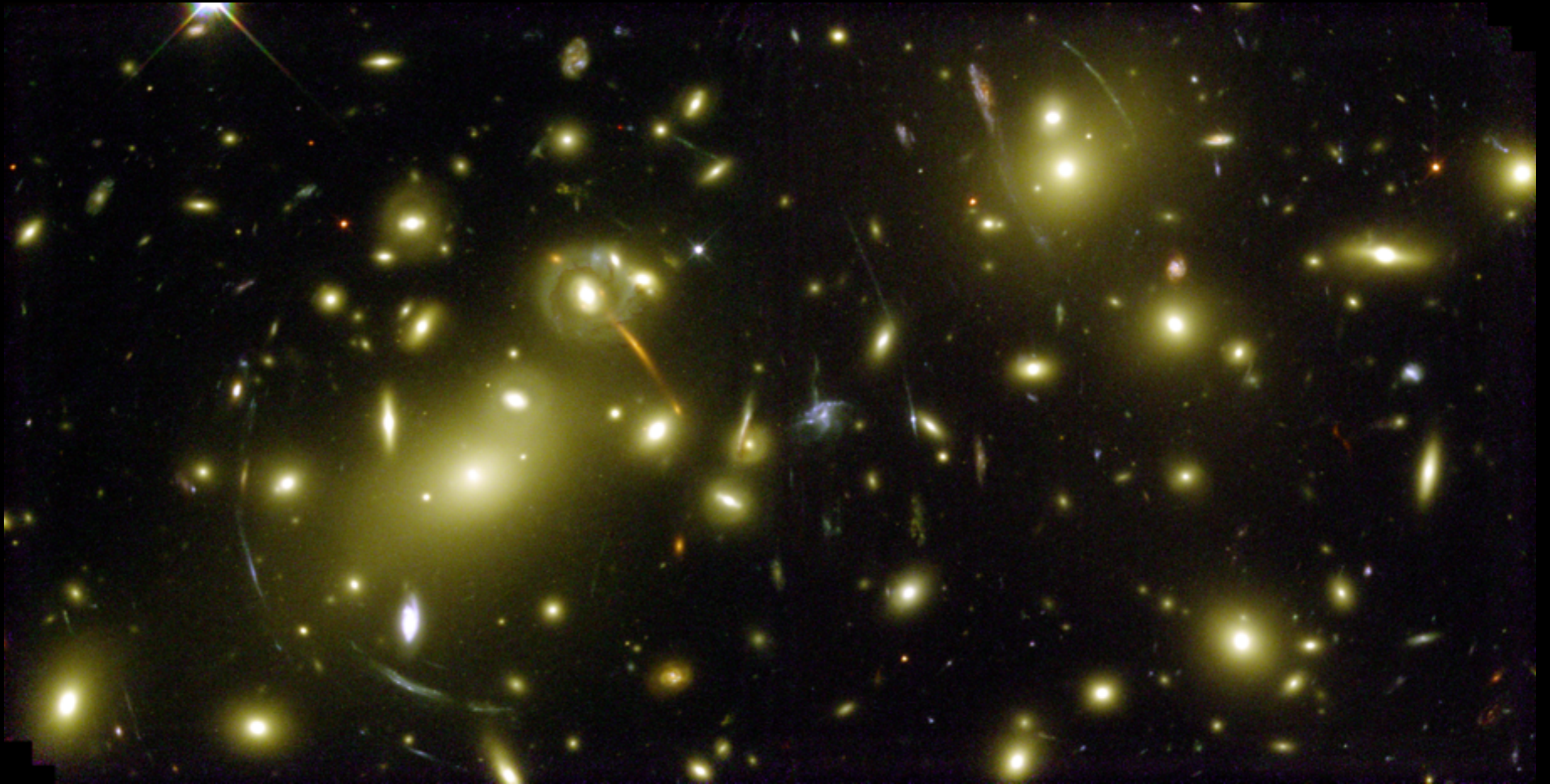
# 1. What is dark matter?



# “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.

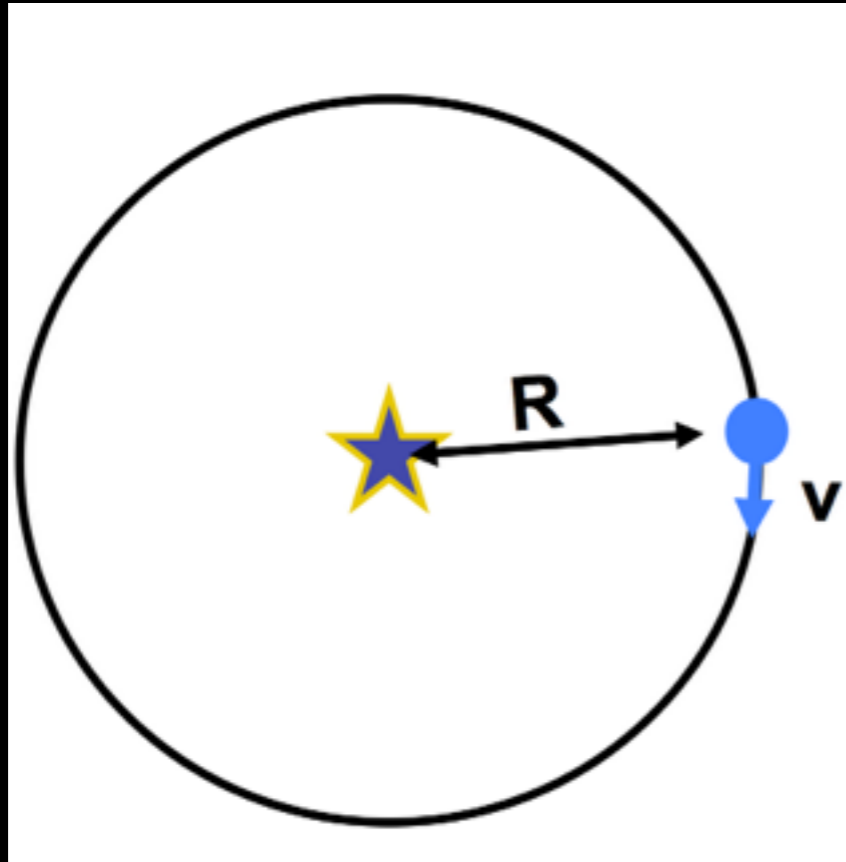
but.... light has not to be in the same place as mass





# Use gravity!





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

Centrifugal force = Gravitational force

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

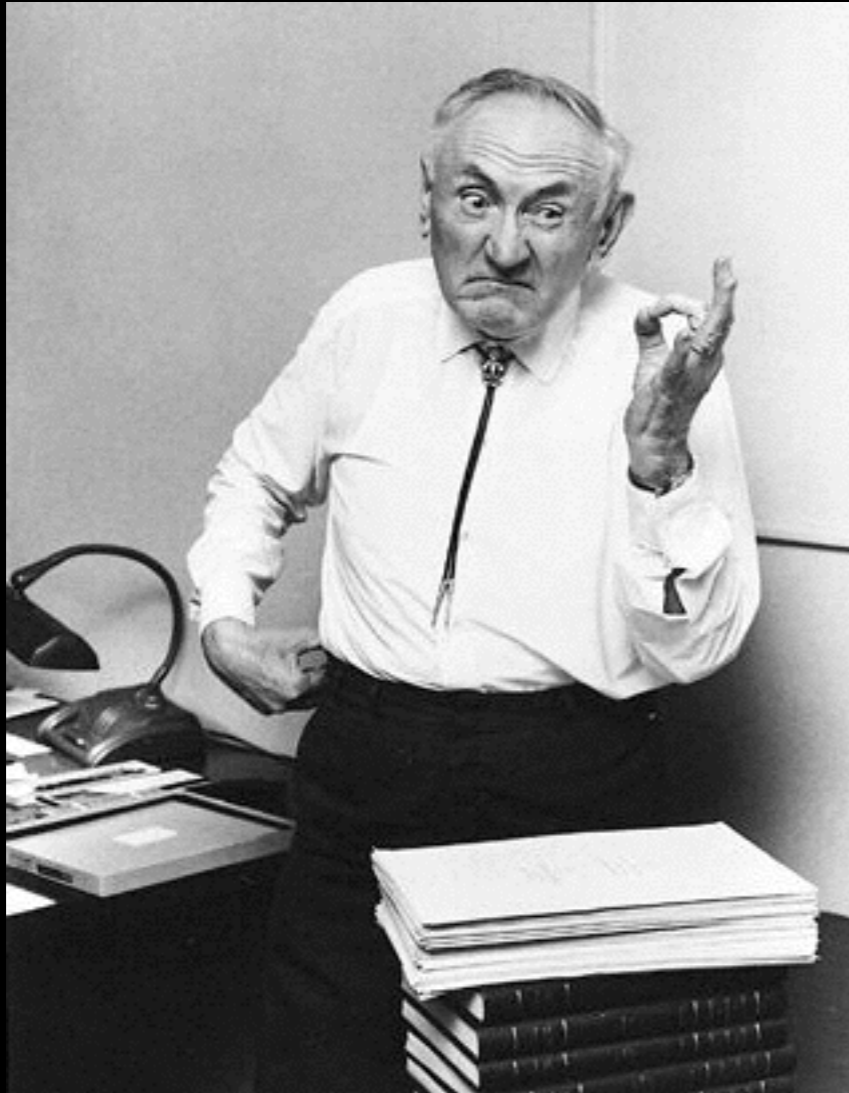
Measure the speed at which planets orbit around the Sun  $\longrightarrow$  mass of the Sun



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

Measure the speeds of stars  $\longrightarrow$  determine the mass of their host galaxy

Fritz Zwicky

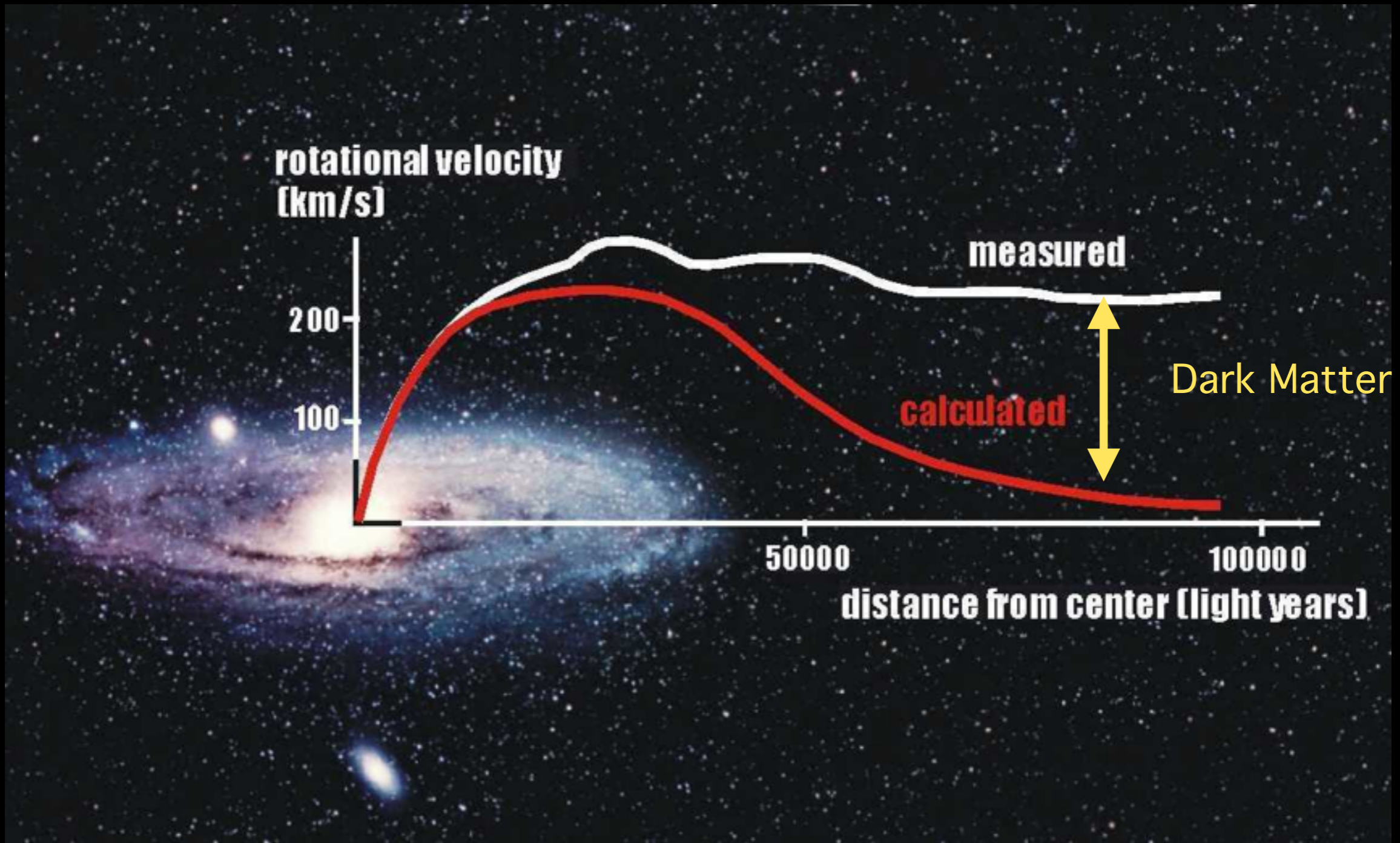


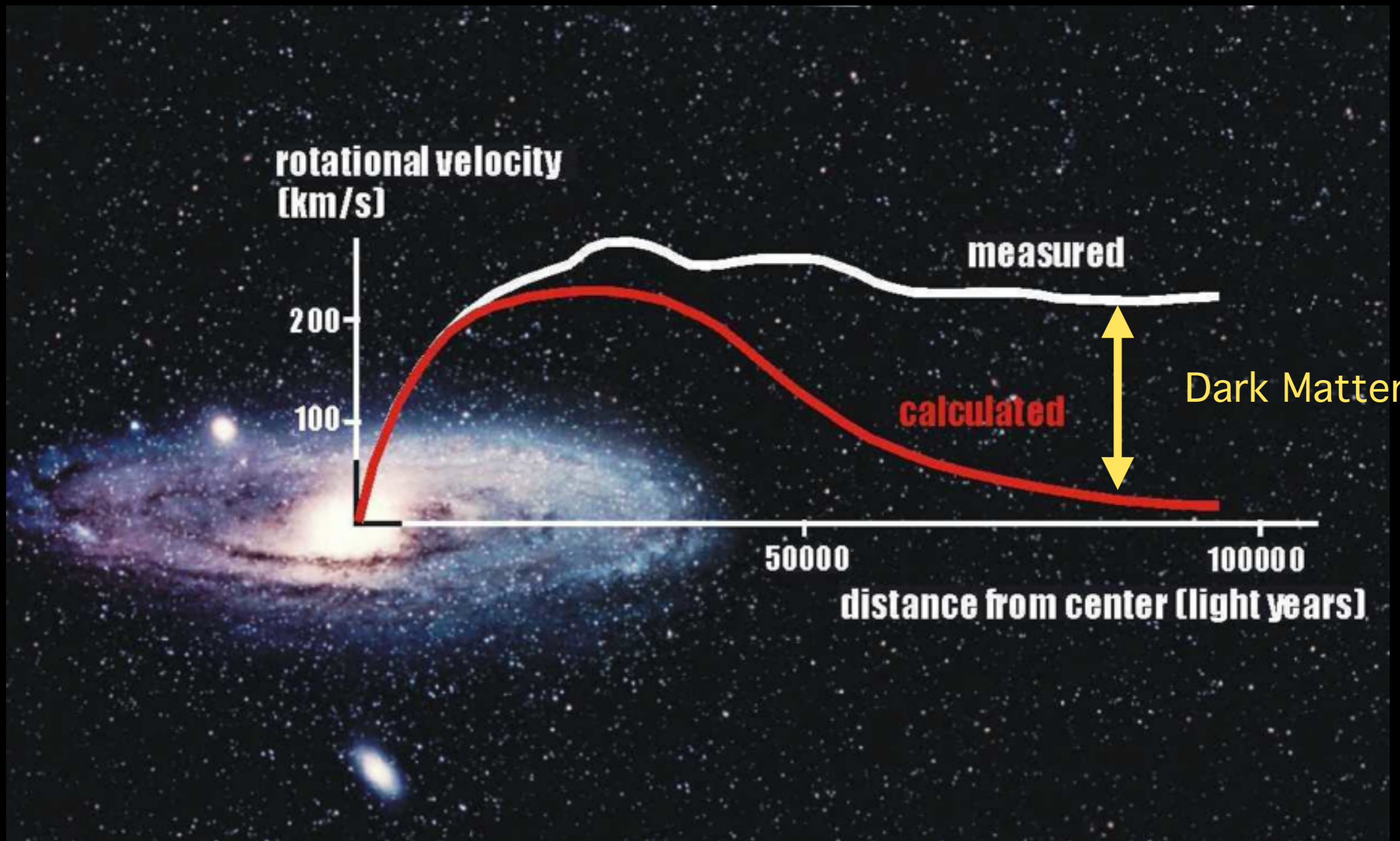
Identified the presence of missing matter (dark matter) in the Coma cluster (1933 & 1937)

Vera Rubin

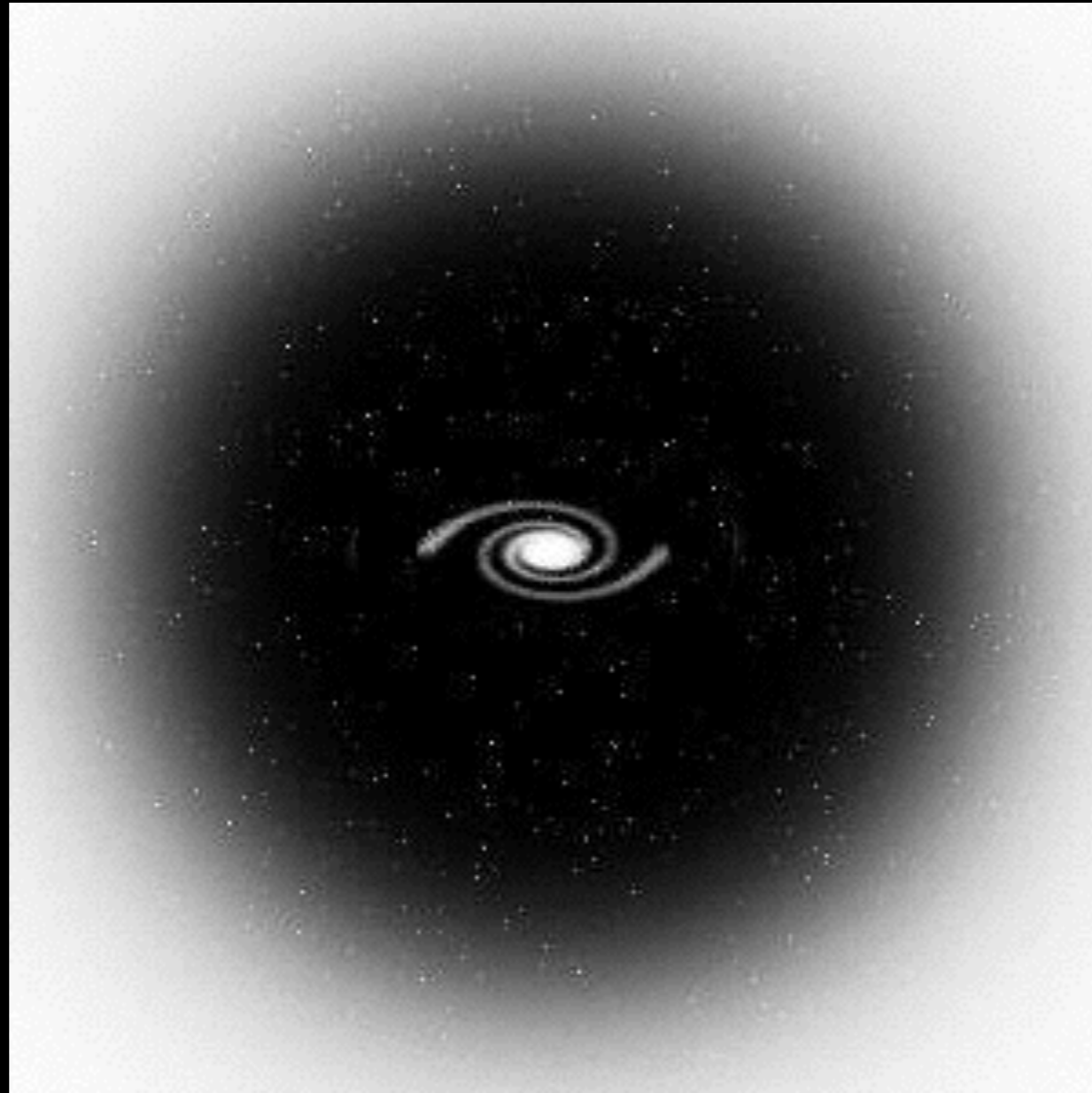


Studied the variation of the velocities of stars with distance from the center of the Andromeda galaxy (1970)





**Most of the mass is invisible!**

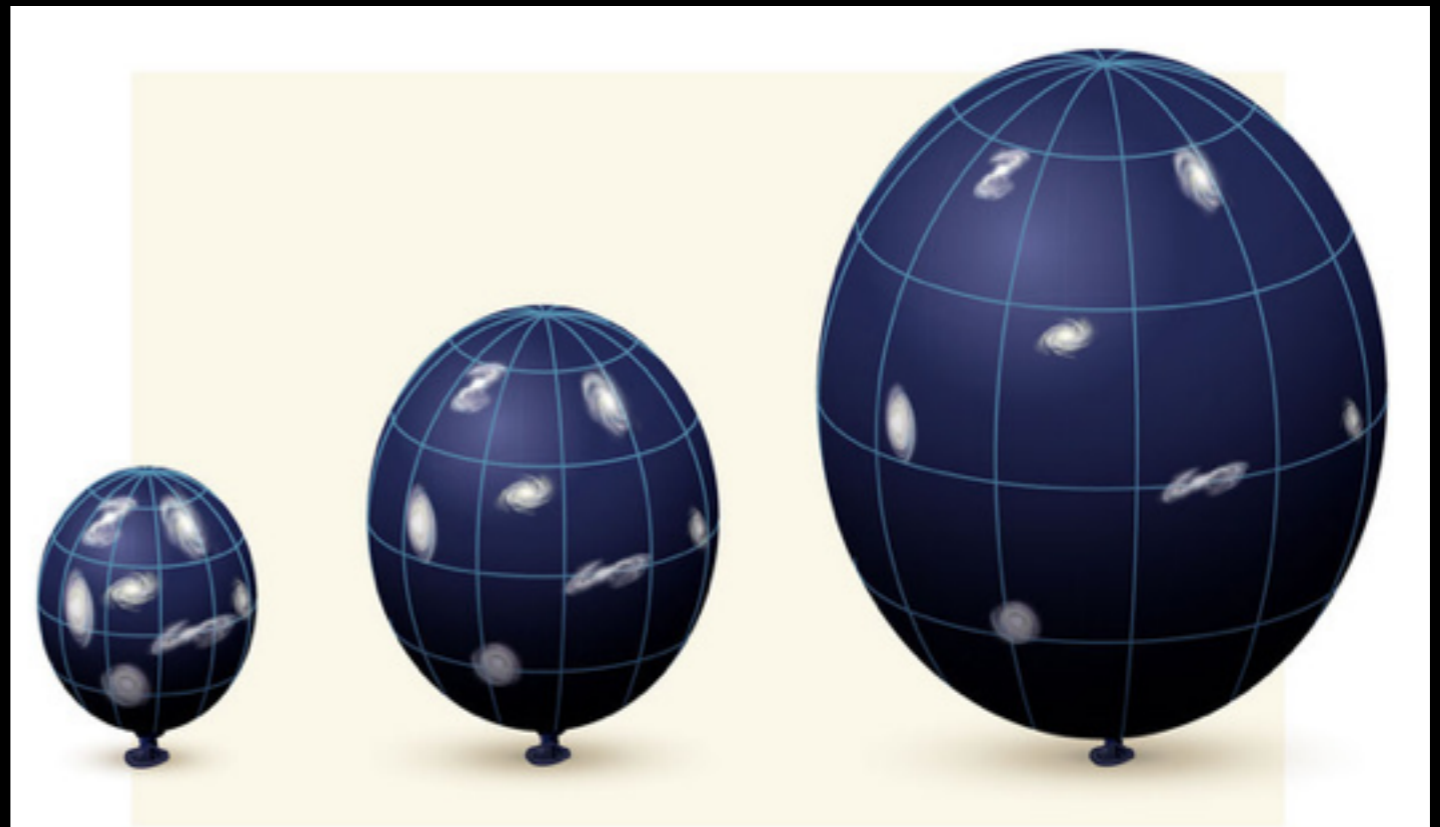


Extra “dark” matter around every galaxy (and cluster of galaxies)

## DARK MATTER HALO

# Measure the expansion rate of the Universe

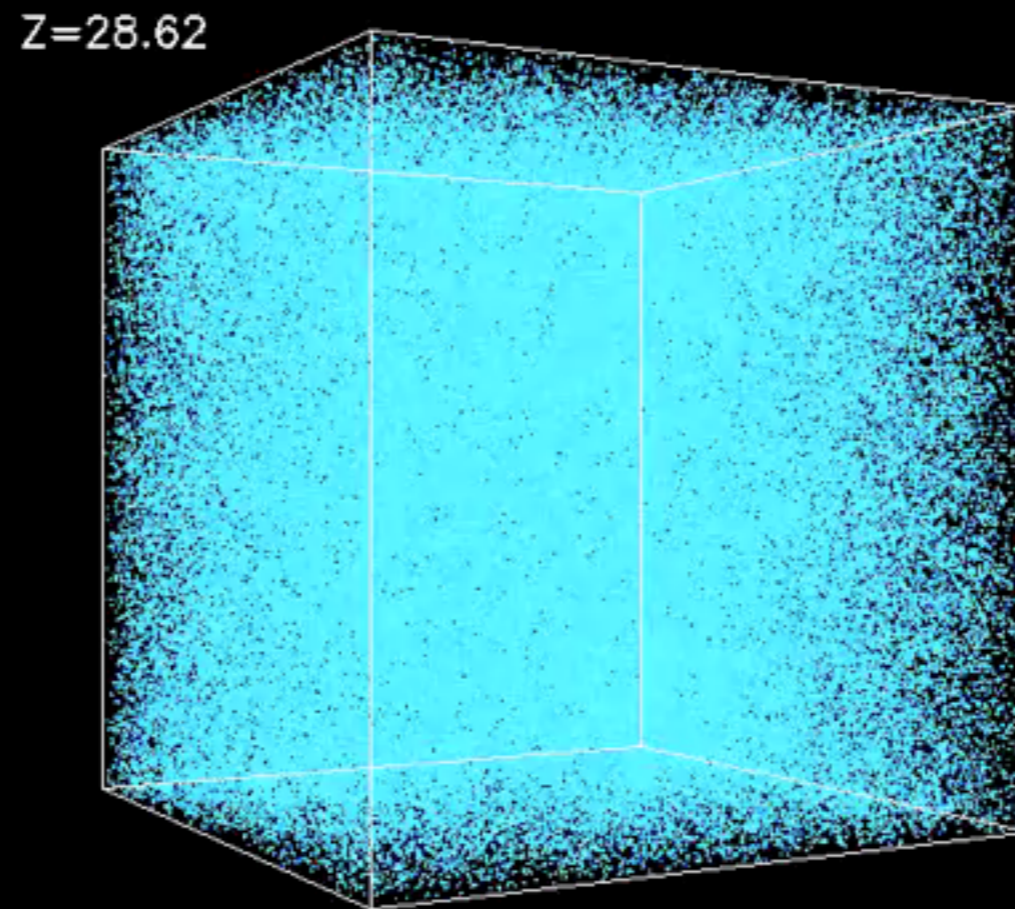
More mass  
pulls things together and slows the expansion down





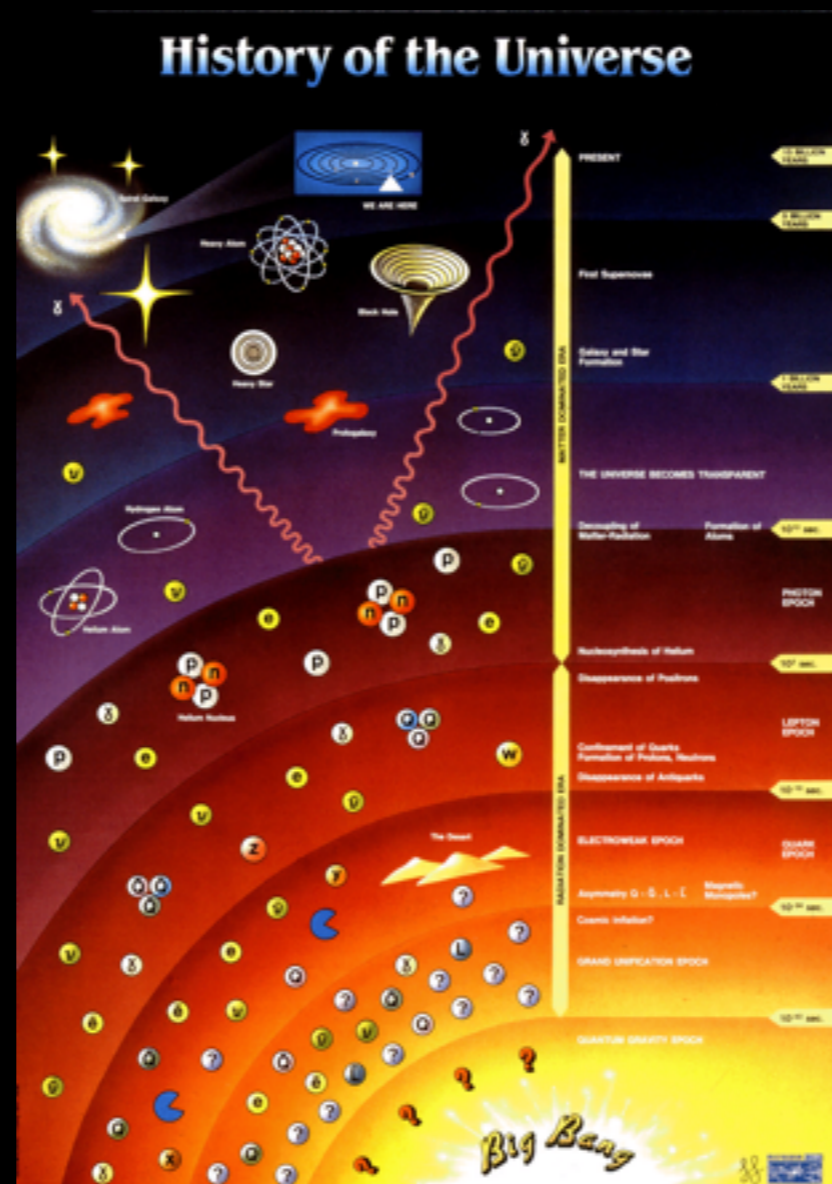
# Measure the growth of structures

More mass  
pulls things together and makes them clumpier

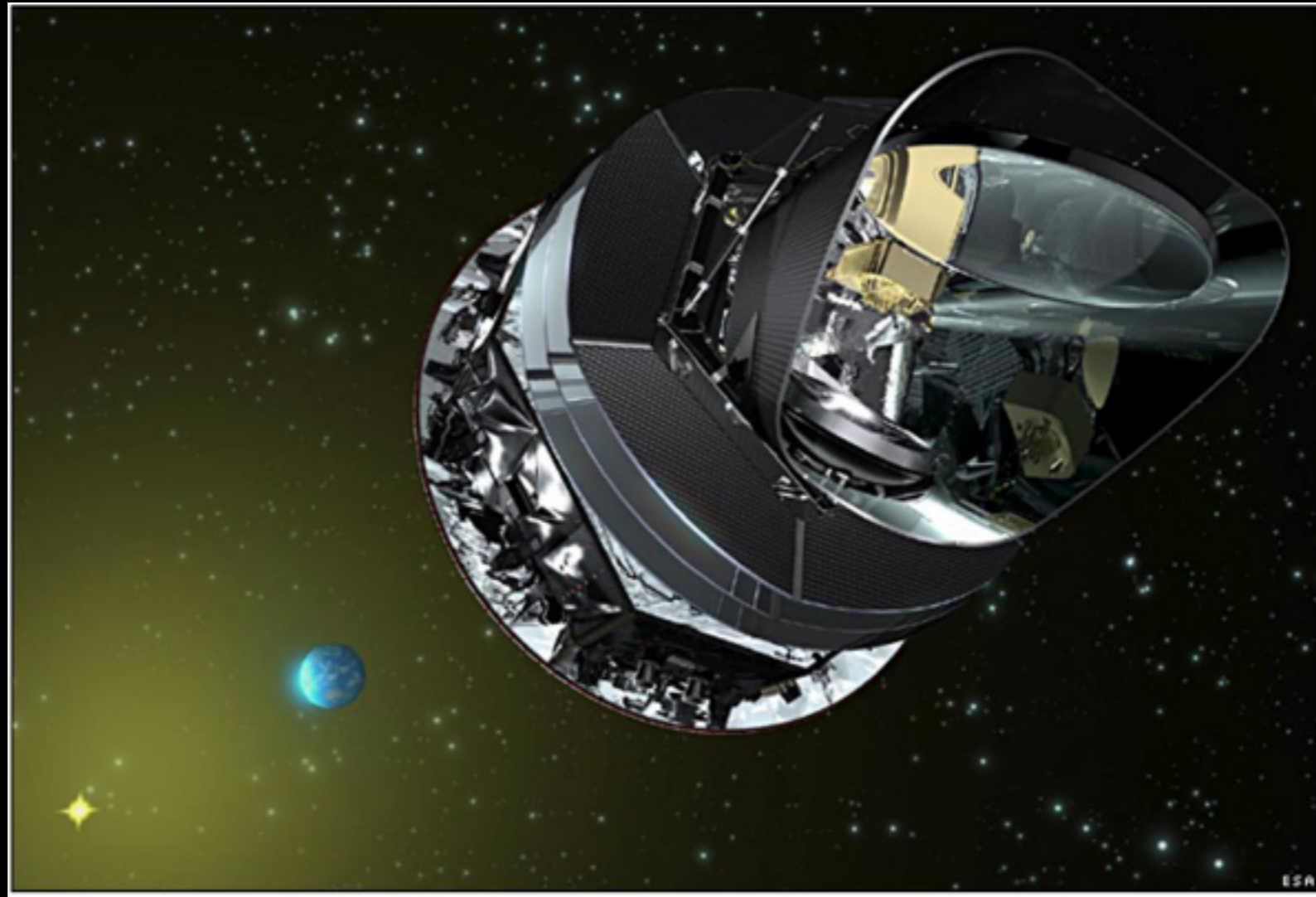


# Age of the Universe

The Universe is 13.8 billion years old



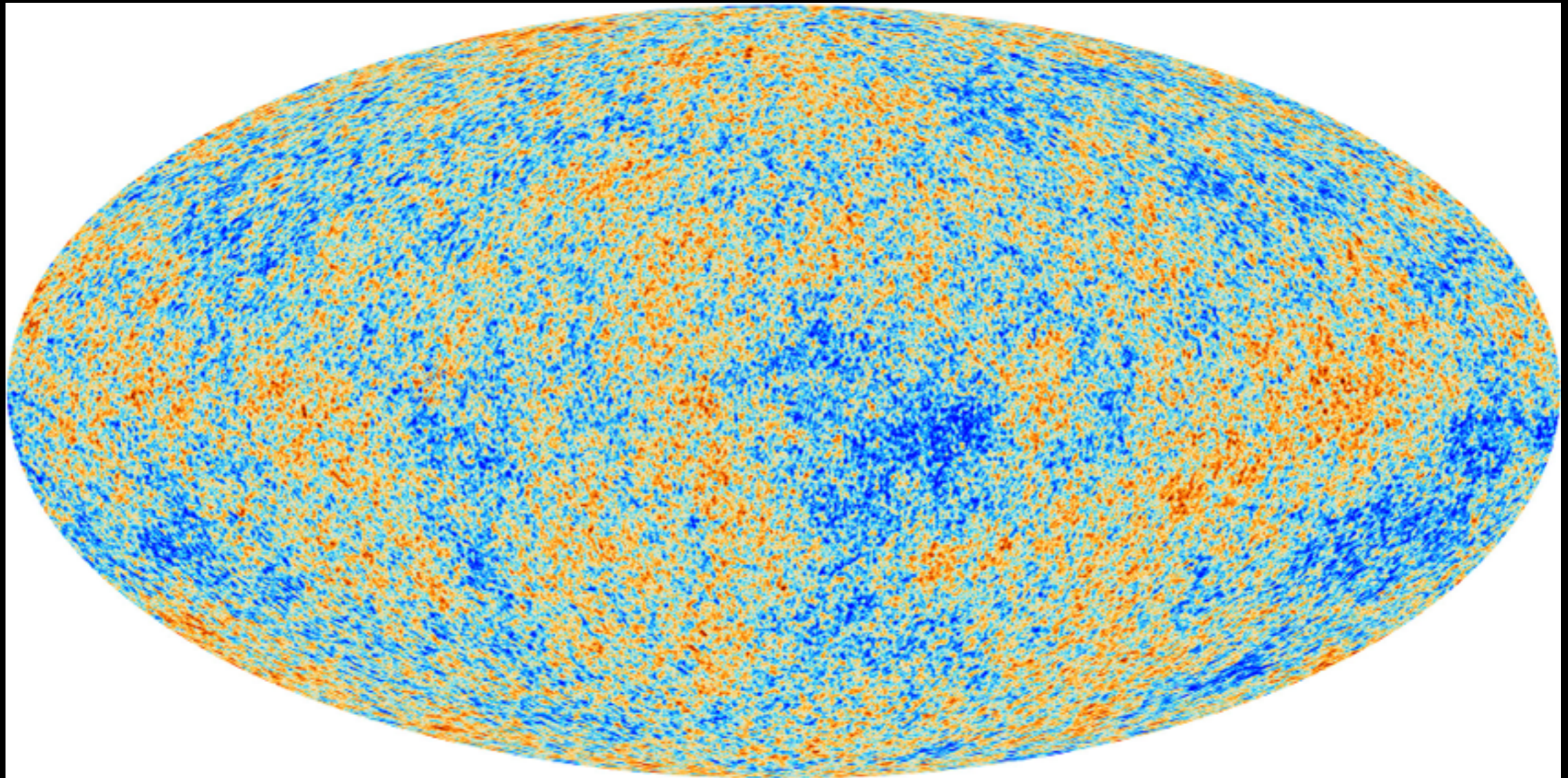
# How did the Universe look like in his youth?



Planck satellite

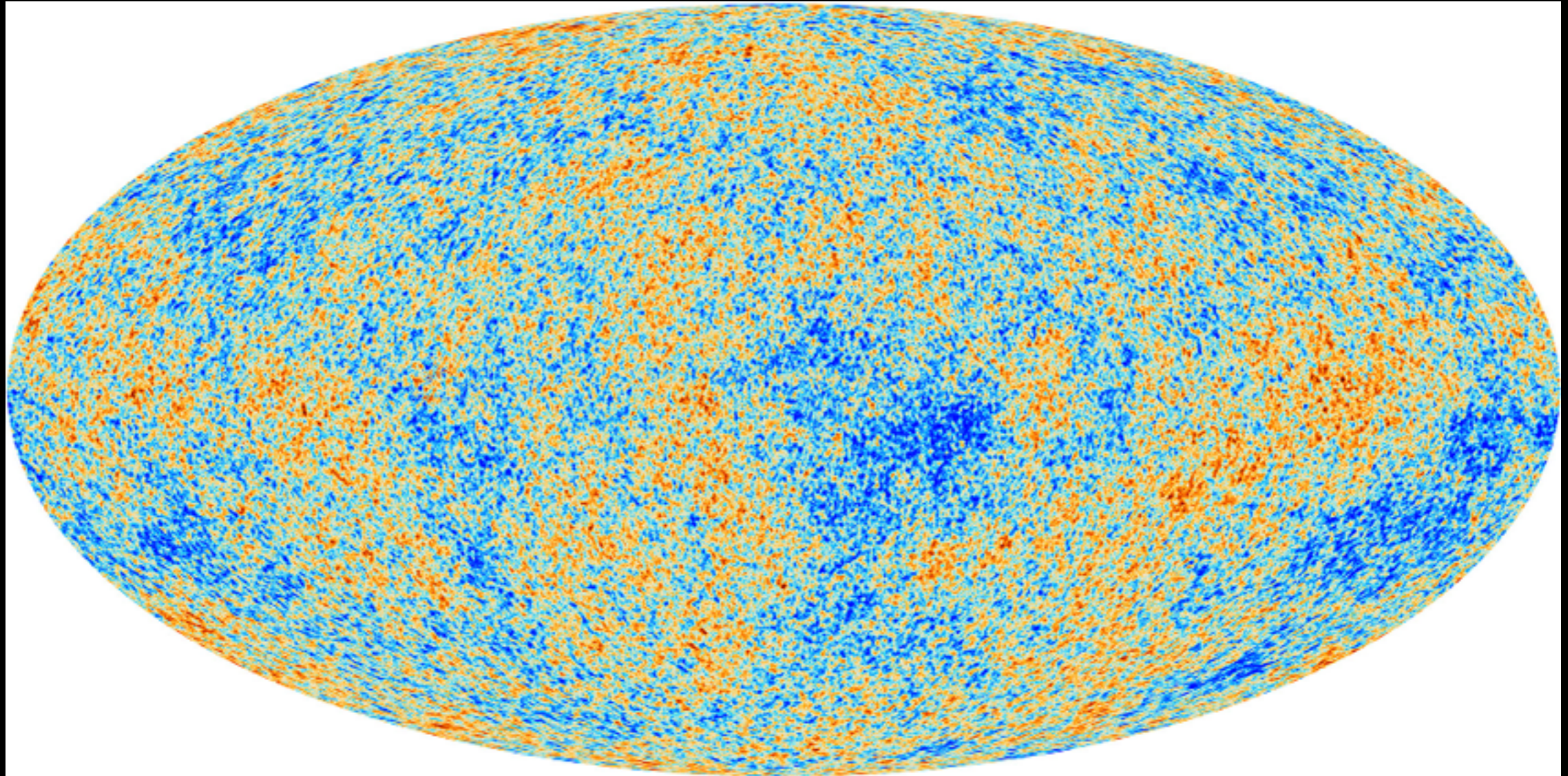
Physical Map of the World, April 2004





The 380.000 years old Universe  
observed by Planck satellite

density fluctuations are  $1/100.000$



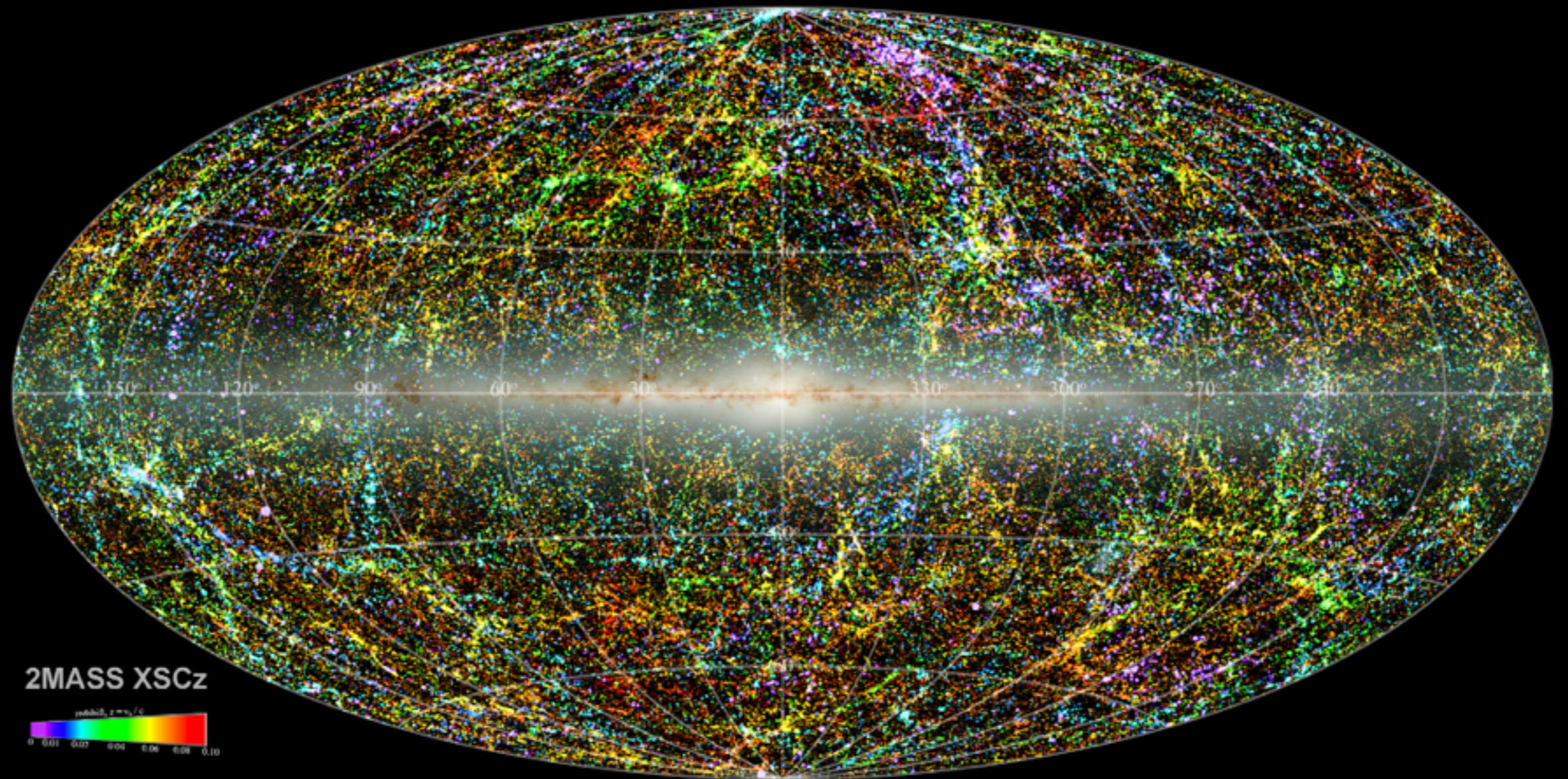
**Red color:** the Universe was a little bit denser

**Blue color:** a little less dense

at that time

**Very tiny density fluctuations!!**

# How does the Universe look like today?

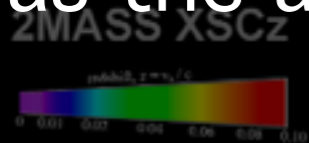


# How does the Universe look like today?

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

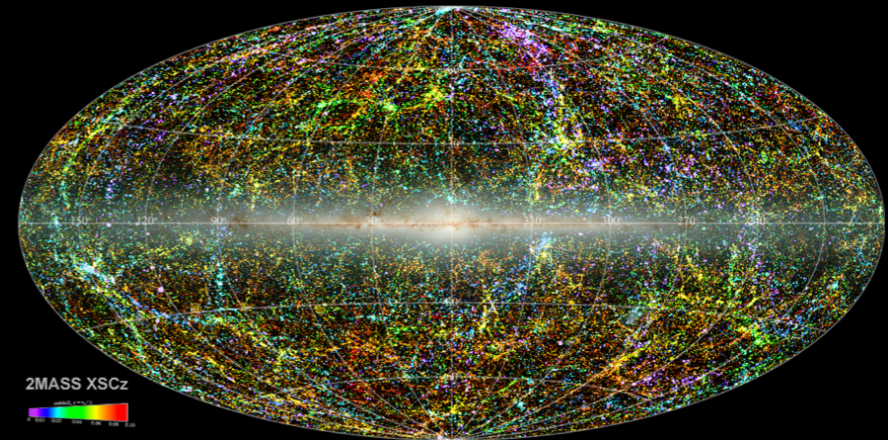
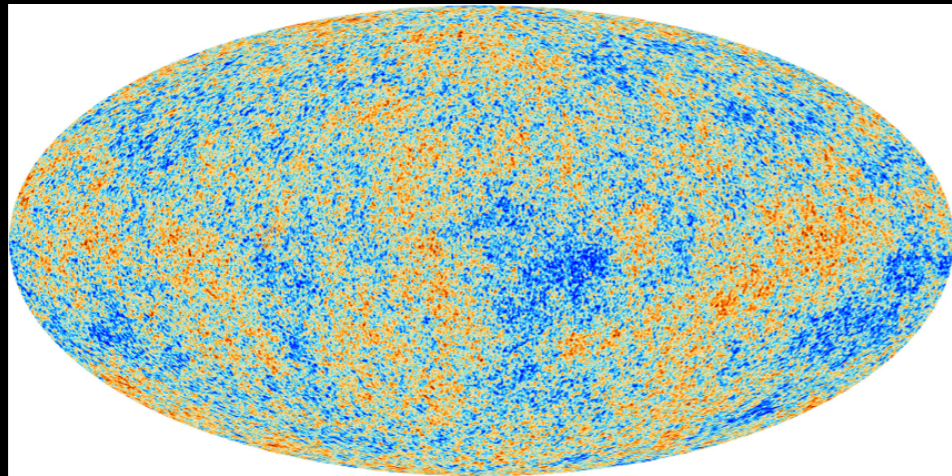




youth



today

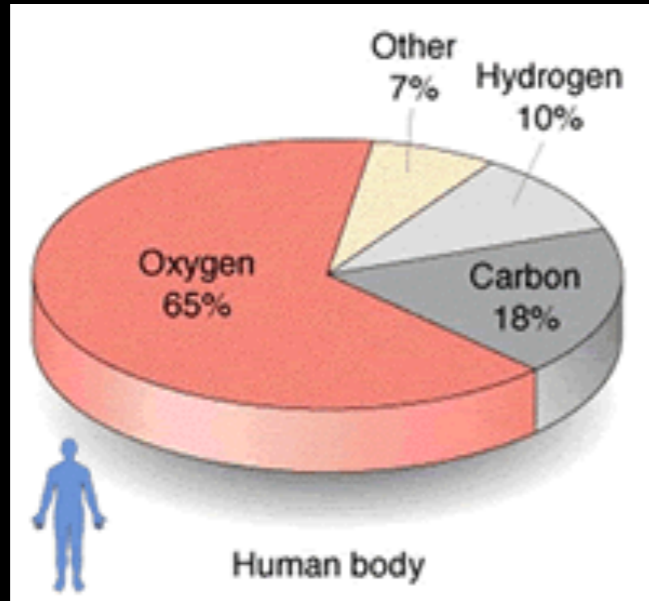


How the Universe evolves depends on what it is made of!

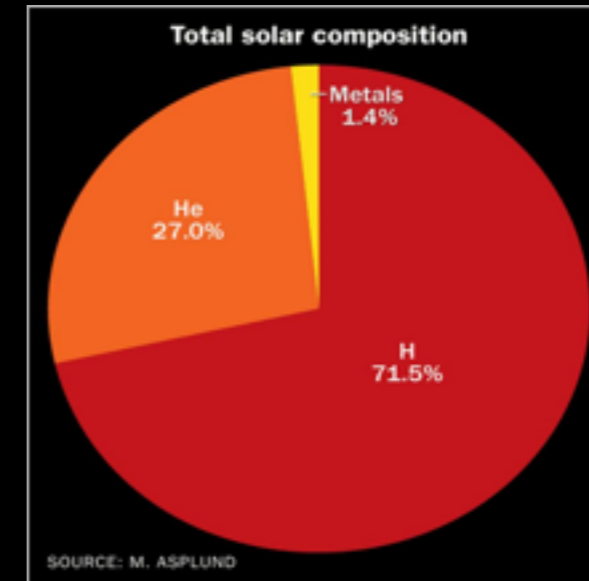
# Periodic Table of the Elements

1 1IA 11A																	18 VIII A 8A			
1 <b>H</b> Hydrogen 1.0079	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2 <b>He</b> Helium 4.00260			
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.01218											5 <b>B</b> Boron 10.811	6 <b>C</b> Carbon 12.011	7 <b>N</b> Nitrogen 14.00674	8 <b>O</b> Oxygen 15.9994	9 <b>F</b> Fluorine 18.998403	10 <b>Ne</b> Neon 20.1797			
11 <b>Na</b> Sodium 22.989768	12 <b>Mg</b> Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 <b>Al</b> Aluminum 26.981539	14 <b>Si</b> Silicon 28.0855	15 <b>P</b> Phosphorus 30.973762	16 <b>S</b> Sulfur 32.066	17 <b>Cl</b> Chlorine 35.4527	18 <b>Ar</b> Argon 39.948			
19 <b>K</b> Potassium 39.0983	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.95591	22 <b>Ti</b> Titanium 47.88	23 <b>V</b> Vanadium 50.9415	24 <b>Cr</b> Chromium 51.9961	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.847	27 <b>Co</b> Cobalt 58.9332	28 <b>Ni</b> Nickel 58.6934	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.723	32 <b>Ge</b> Germanium 72.64	33 <b>As</b> Arsenic 74.92159	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.80			
37 <b>Rb</b> Rubidium 85.4678	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.90585	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.90638	42 <b>Mo</b> Molybdenum 95.94	43 <b>Tc</b> Technetium 98.9072	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.9055	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.8682	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.71	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.6	53 <b>I</b> Iodine 126.90447	54 <b>Xe</b> Xenon 131.29			
55 <b>Cs</b> Cesium 132.90543	56 <b>Ba</b> Barium 137.327	57-71	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.9479	74 <b>W</b> Tungsten 183.85	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.22	78 <b>Pt</b> Platinum 195.08	79 <b>Au</b> Gold 196.9665	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.3833	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.98037	84 <b>Po</b> Polonium [208.9824]	85 <b>At</b> Astatine 209.9871	86 <b>Rn</b> Radon 222.0176			
87 <b>Fr</b> Francium 223.0197	88 <b>Ra</b> Radium 226.0254	89-103	104 <b>Rf</b> Rutherfordium [261]	105 <b>Db</b> Dubnium [262]	106 <b>Sg</b> Seaborgium [266]	107 <b>Bh</b> Bohrium [264]	108 <b>Hs</b> Hassium [269]	109 <b>Mt</b> Meitnerium [268]	110 <b>Ds</b> Darmstadtium [269]	111 <b>Rg</b> Roentgenium [272]	112 <b>Cn</b> Copernicium [277]	113 <b>Uut</b> Ununtrium unknown	114 <b>F1</b> Flerovium [289]	115 <b>Uup</b> Ununpentium unknown	116 <b>Lv</b> Livermorium [293]	117 <b>Uus</b> Ununseptium unknown	118 <b>Uuo</b> Ununoctium unknown			
Lanthanide Series		57 <b>La</b> Lanthanum 138.9055	58 <b>Ce</b> Cerium 140.115	59 <b>Pr</b> Praseodymium 140.90765	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium 144.9127	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.9655	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.92534	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.93032	68 <b>Er</b> Erbium 167.26	69 <b>Tm</b> Thulium 168.93421	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.967				
Actinide Series		89 <b>Ac</b> Actinium 227.0278	90 <b>Th</b> Thorium 232.0381	91 <b>Pa</b> Protactinium 231.03588	92 <b>U</b> Uranium 238.0289	93 <b>Np</b> Neptunium 237.0482	94 <b>Pu</b> Plutonium 244.0642	95 <b>Am</b> Americium 243.0614	96 <b>Cm</b> Curium 247.0703	97 <b>Bk</b> Berkelium 247.0703	98 <b>Cf</b> Californium 251.0796	99 <b>Es</b> Einsteinium [254]	100 <b>Fm</b> Fermium 257.0951	101 <b>Md</b> Mendelevium 258.1	102 <b>No</b> Nobelium 259.1009	103 <b>Lr</b> Lawrencium [262]				
Alkali Metals		Alkaline Earths		Transition Metals			Basic Metals		Semi-Metals		Nonmetals		Halogens		Noble Gases		Lanthanides		Actinides	

# Me and you



# Sun



### Periodic Table of the Elements

1 1IA 11A																		18 VIII 8A																	
1 H Hydrogen 1.0079																	2 He Helium 4.00260																		
3 Li Lithium 6.941	4 Be Beryllium 9.01218											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.0074	8 O Oxygen 15.9994	9 F Fluorine 18.998403	10 Ne Neon 20.1797																		
11 Na Sodium 22.989768	12 Mg Magnesium 24.305	3 Al Aluminum 26.981539	4 Si Silicon 28.0855	5 P Phosphorus 30.973762	6 S Sulfur 32.059	7 Cl Chlorine 35.4527	8 Ar Argon 39.948											13 Ga Gallium 69.723	14 Ge Germanium 72.64	15 As Arsenic 74.92159	16 Se Selenium 78.96	17 Br Bromine 79.904	18 Kr Krypton 83.80												
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95591	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92159	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80																		
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9062	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.90447	54 Xe Xenon 131.29																		
55 Cs Cesium 132.90543	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.9665	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium [209]	85 At Astatine [209]	86 Rn Radon 222.0176																		
87 Fr Francium 223.0197	88 Ra Radium 226.0254	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [293]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown																		
		57 La Lanthanum 138.9055	58 Ce Cerium 140.115	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium 144.9127	62 Sm Samarium 150.36	63 Eu Europium 151.9655	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967																			
		89 Ac Actinium 227.0278	90 Th Thorium 232.0381	91 Pa Protactinium 231.03688	92 U Uranium 238.0289	93 Np Neptunium 237.0482	94 Pu Plutonium 244.0642	95 Am Americium 243.0614	96 Cm Curium 247.0703	97 Bk Berkelium 247.0703	98 Cf Californium 251.0796	99 Es Einsteinium [254]	100 Fm Fermium 257.0951	101 Md Mendelevium 258.1	102 No Nobelium 259.1059	103 Lr Lawrencium [262]																			

Alkali Metals
Alkaline Earths
Transition Metals
Basic Metals
Semi-Metals
Nonmetals
Halogens
Noble Gases
Lanthanides
Actinides



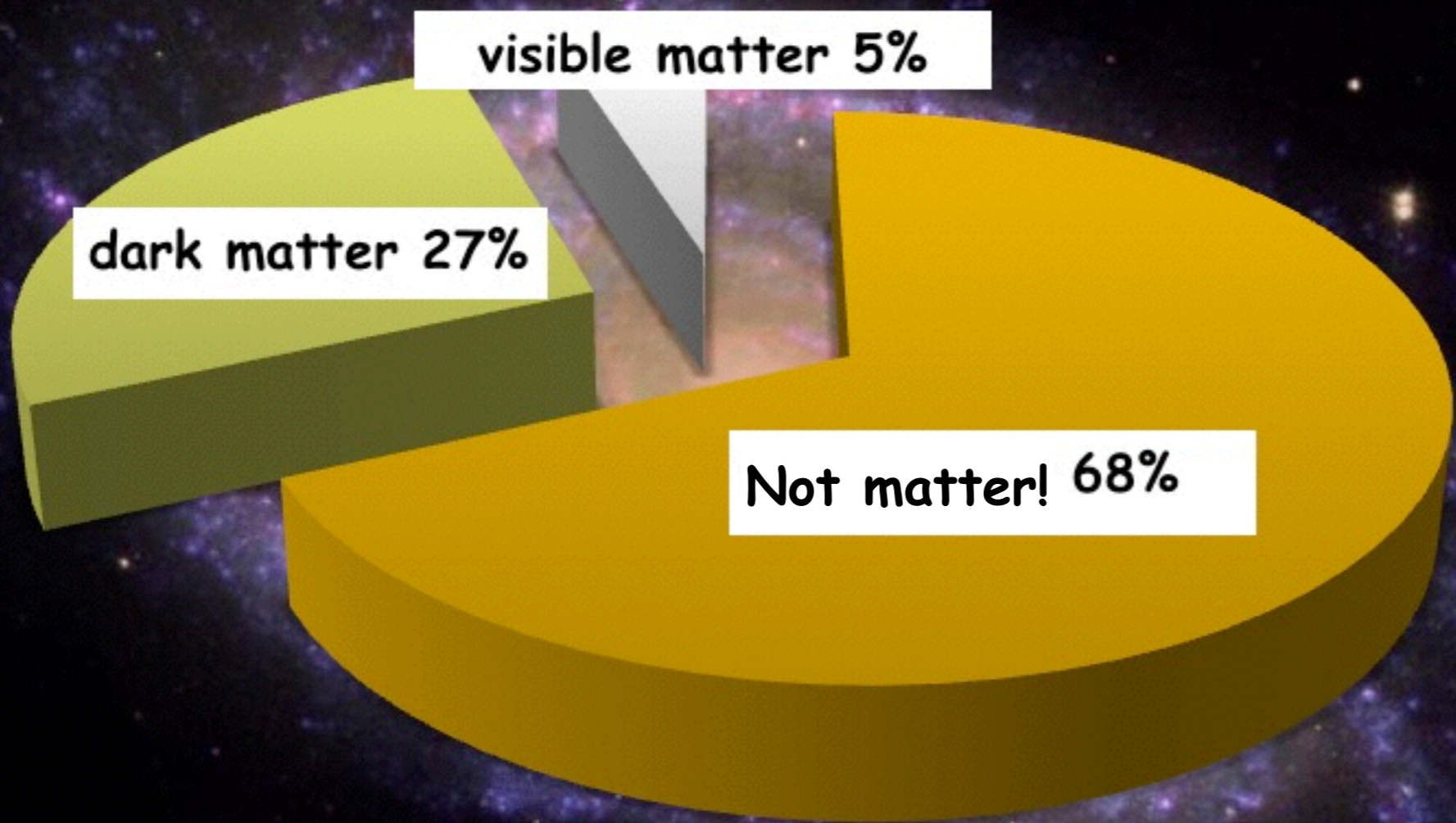
### 3. How much is there?

Periodic Table of the Elements

1 H	2 He																	18 Ar	19 K	20 Ca											36 Kr	37 Rb	38 Sr											54 Xe	55 Cs	56 Ba											86 Rn	87 Fr	88 Ra											118 Og													
3 Li	4 Be																	10 Ne	11 Na	12 Mg											18 Ar	19 K	20 Ca											36 Kr	37 Rb	38 Sr											54 Xe	55 Cs	56 Ba											86 Rn	87 Fr	88 Ra											118 Og
5 B	6 C	7 N	8 O	9 F																	17 Cl	18 Ar	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	55 Cs	56 Ba											86 Rn	87 Fr	88 Ra											118 Og																			
13 Al	14 Si	15 P	16 S	17 Cl	18 Ar																	35 Br	36 Kr	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	87 Fr	88 Ra											118 Og																	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	87 Fr	88 Ra											118 Og																							
39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	55 Cs	56 Ba											86 Rn	87 Fr	88 Ra											118 Og																																										
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	87 Fr	88 Ra											118 Og																																									
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og	87 Fr	88 Ra											118 Og																																									



# Universe content

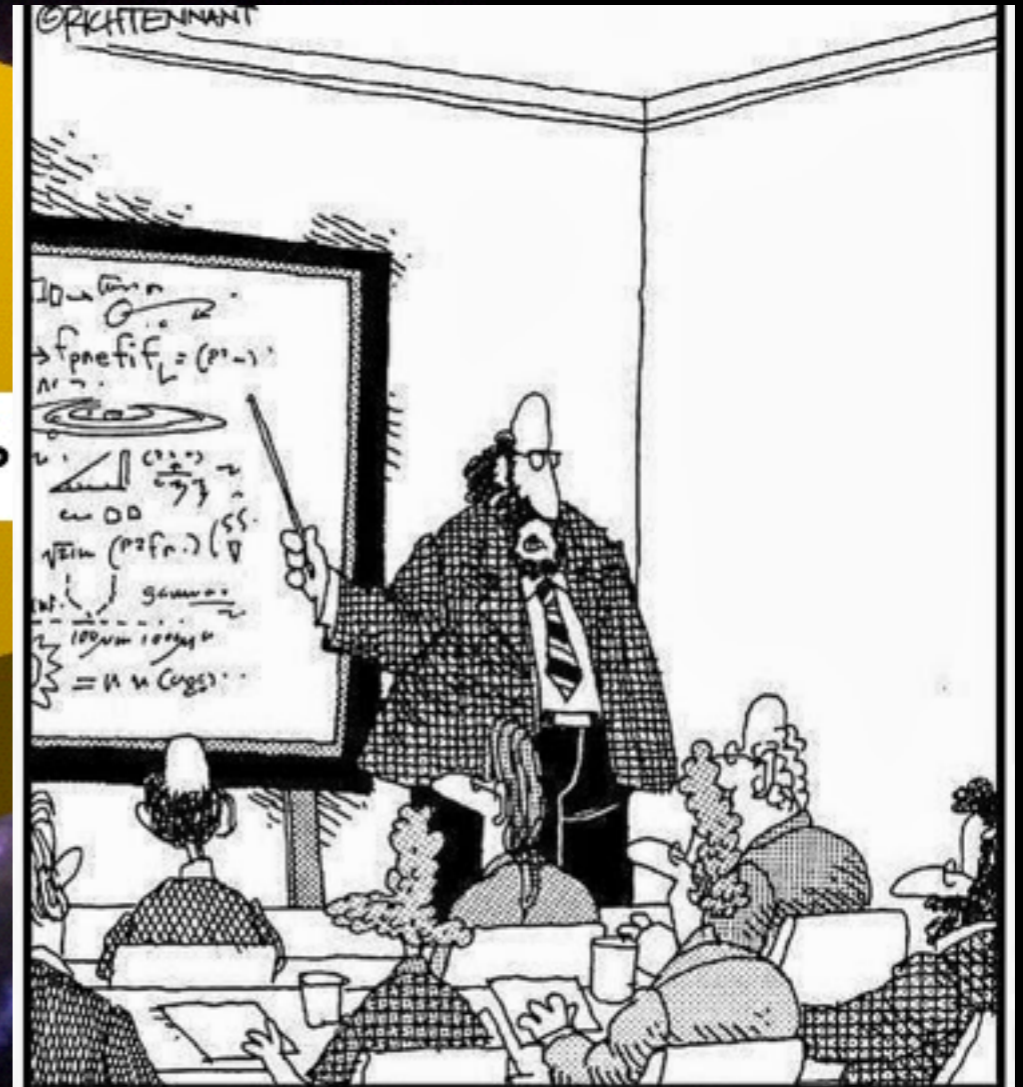


# Universe content

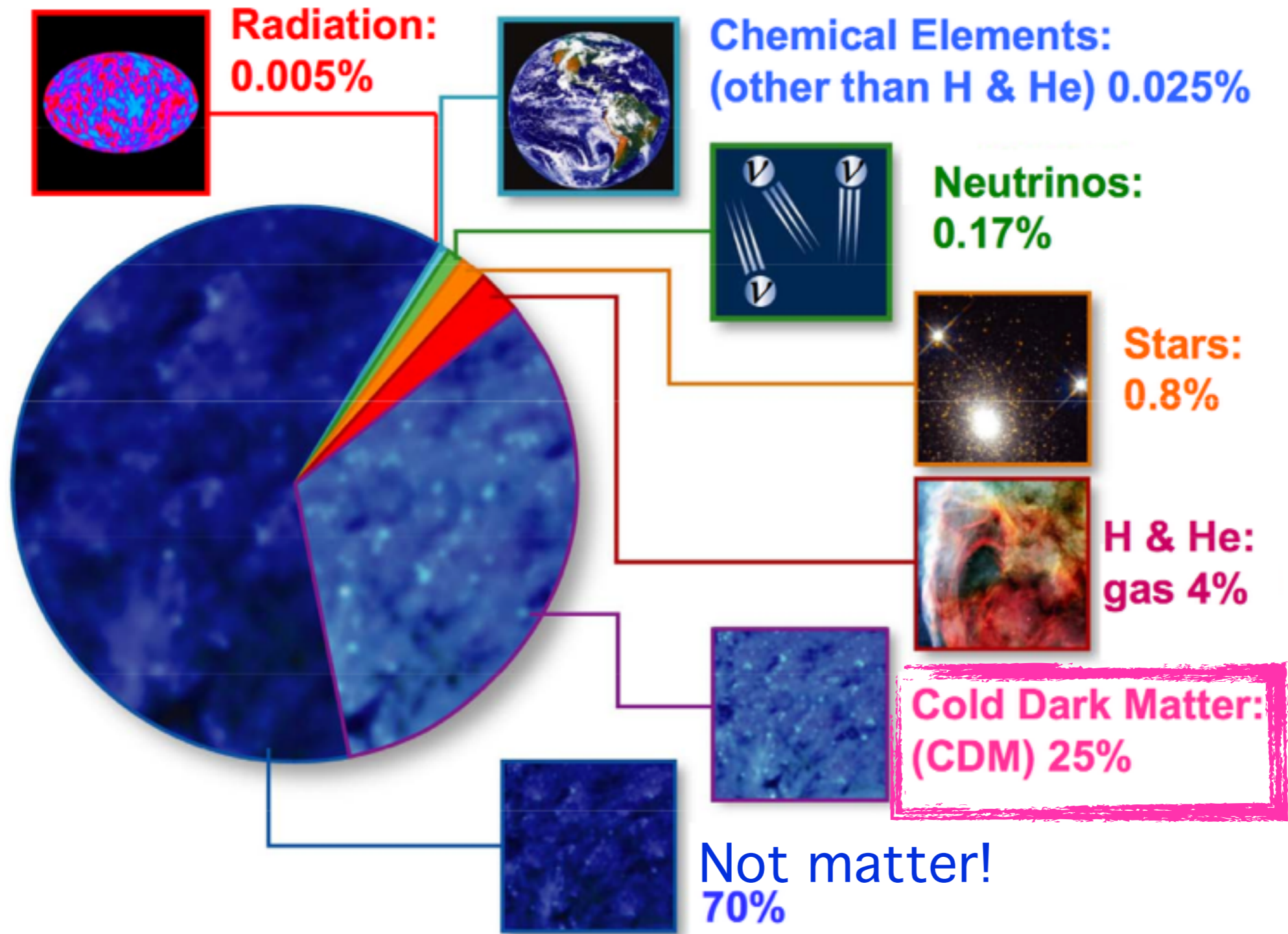
visible matter 5%

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.”





## 4. Where is it?



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





## 5. Could it be normal stuff?

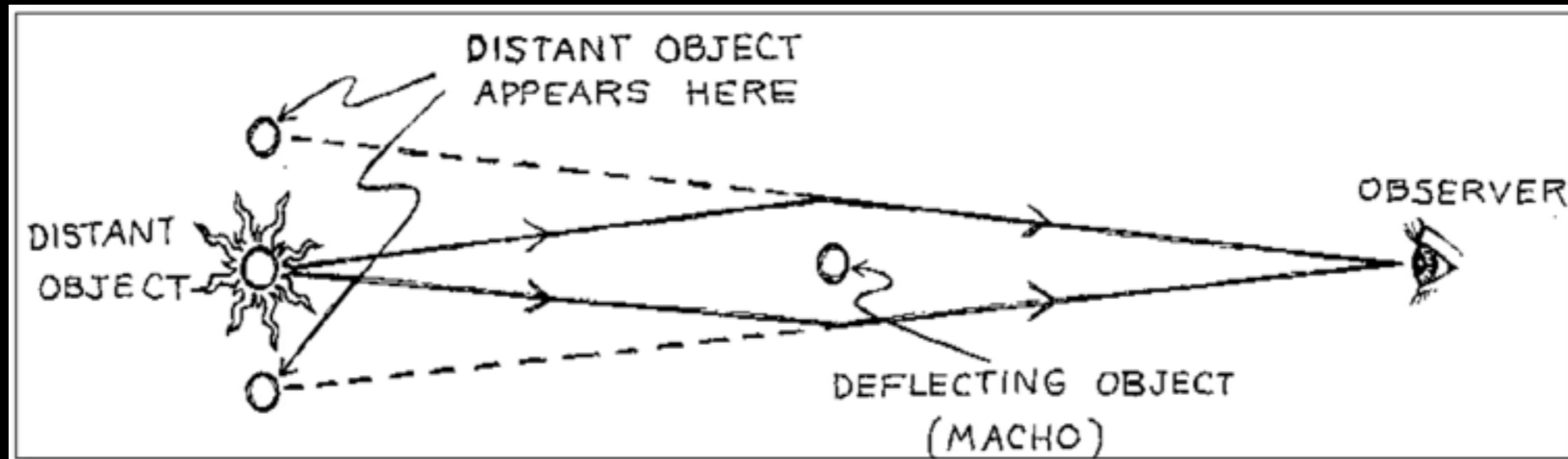
# 3 possibilities:

- 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**

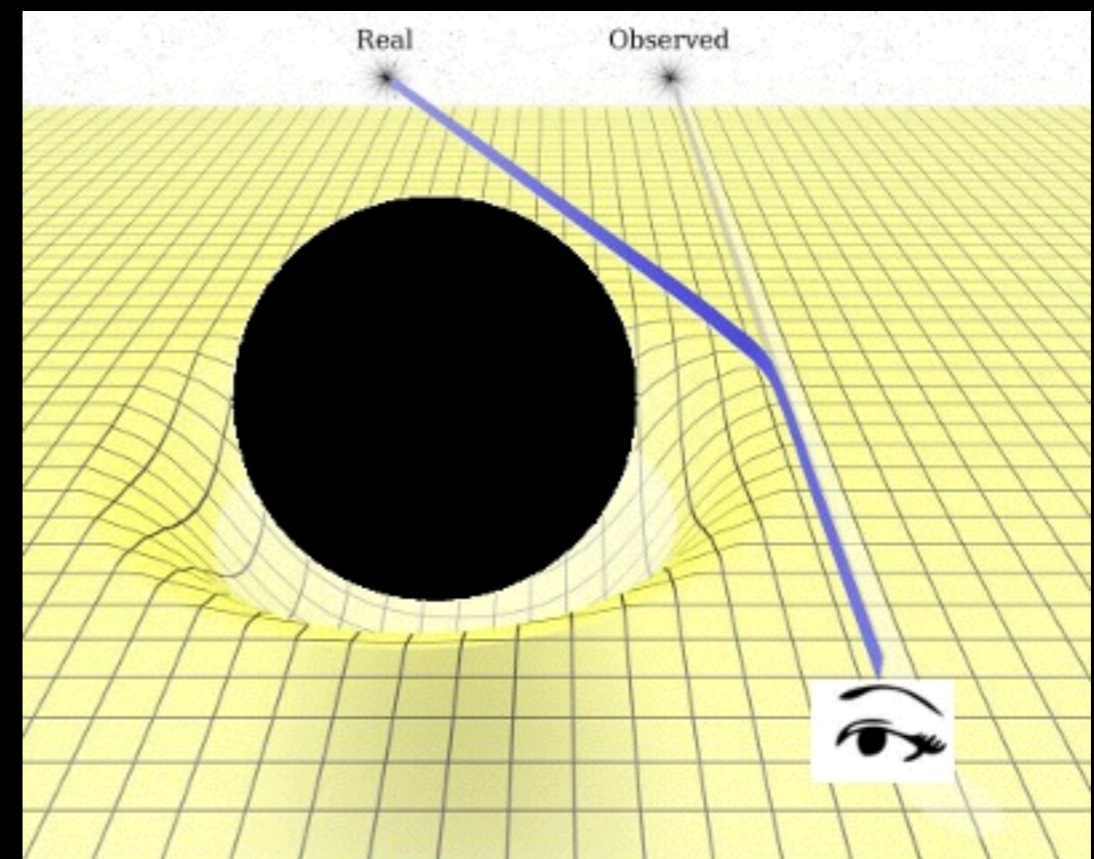
# 3 possibilities:

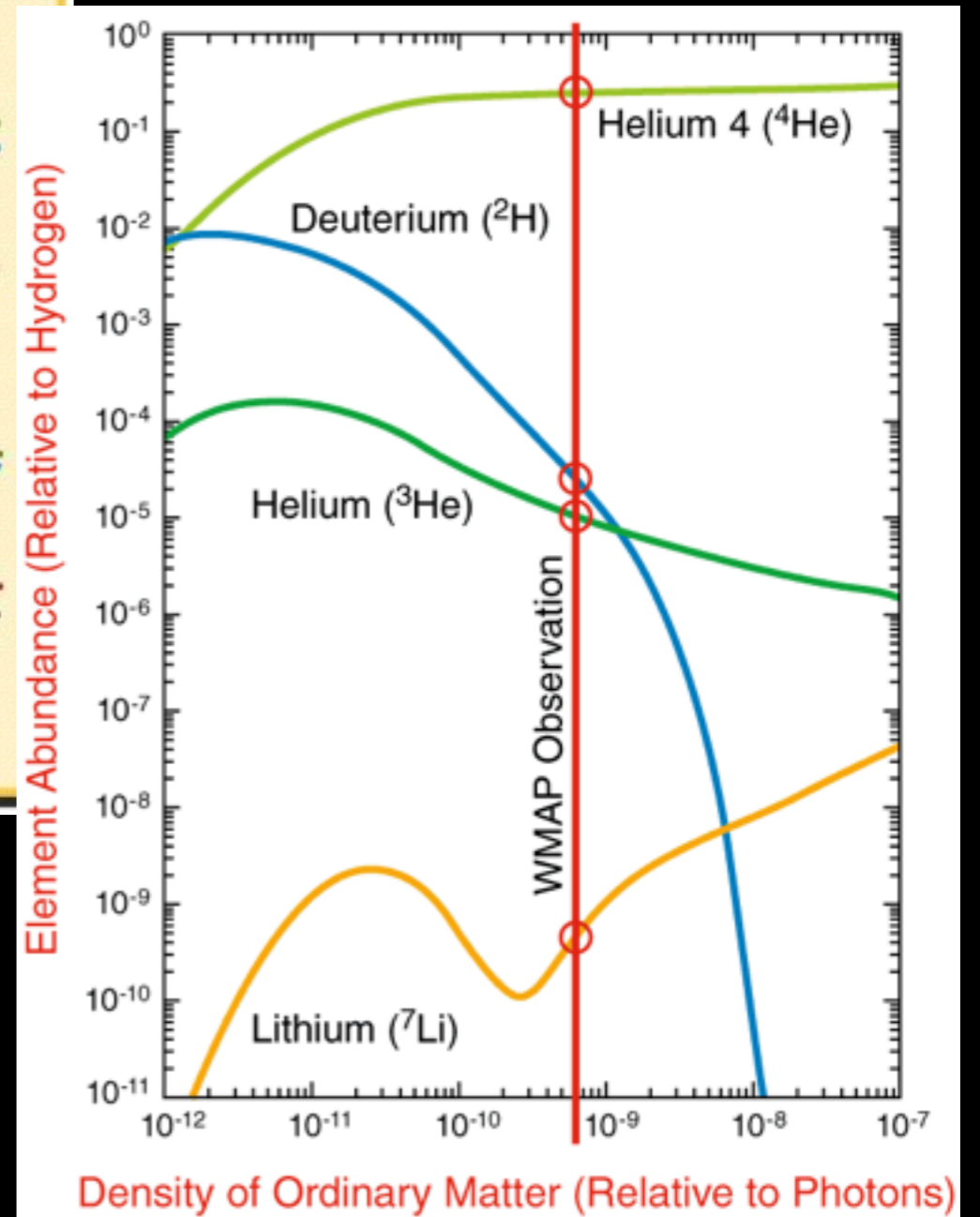
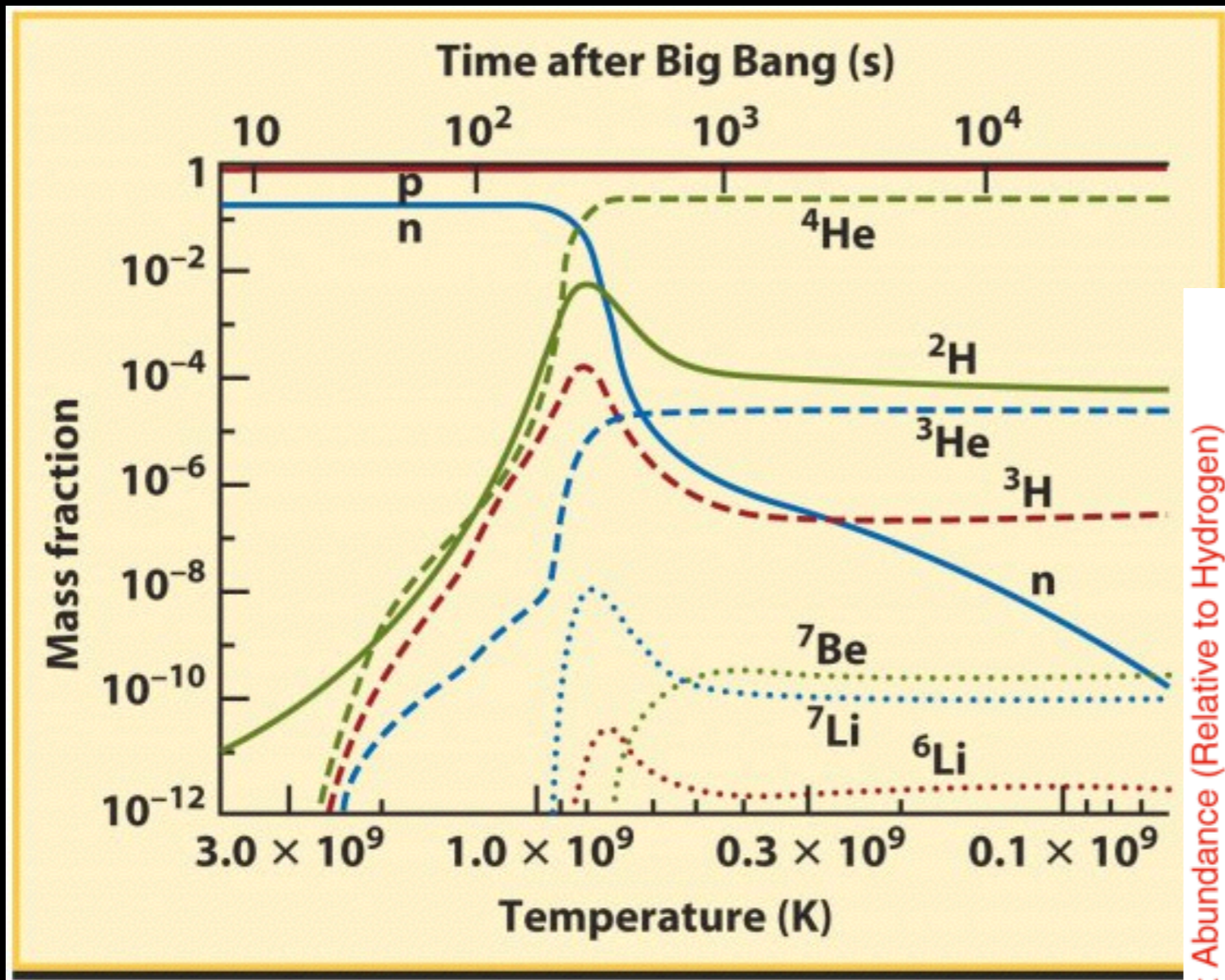
- 1) Galaxies are mostly made up of very **non-luminous objects** (MACHOs: black holes, neutron stars, white dwarf stars, large planets, etc.)
- 2) Gravity does not work in galaxies and clusters the way it does on Earth or in our Solar System
- 3) The missing mass consists of some other form of matter

# Gravitational lensing



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





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~~

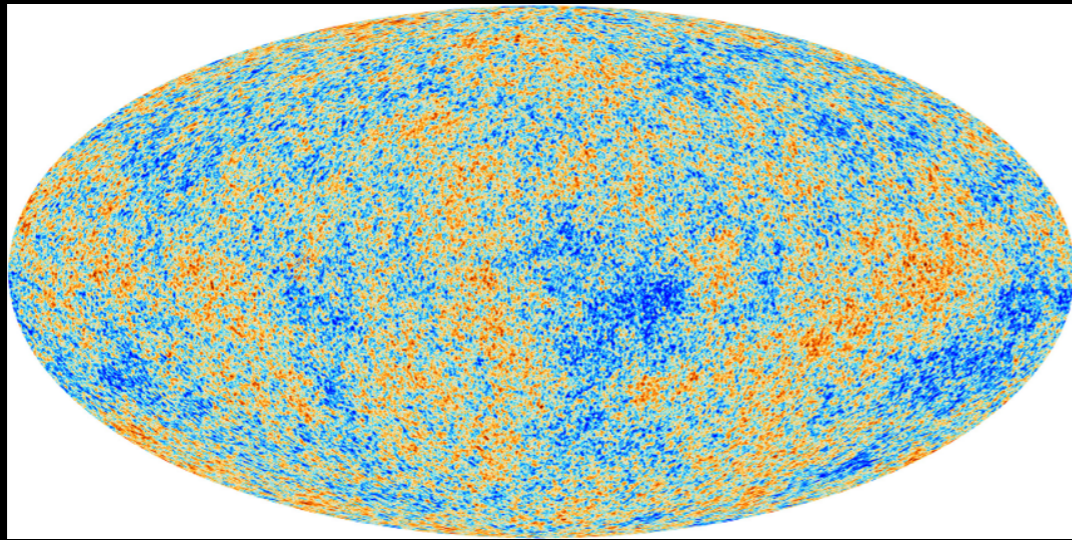
3) The missing mass consists of **some other form of matter**



## 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

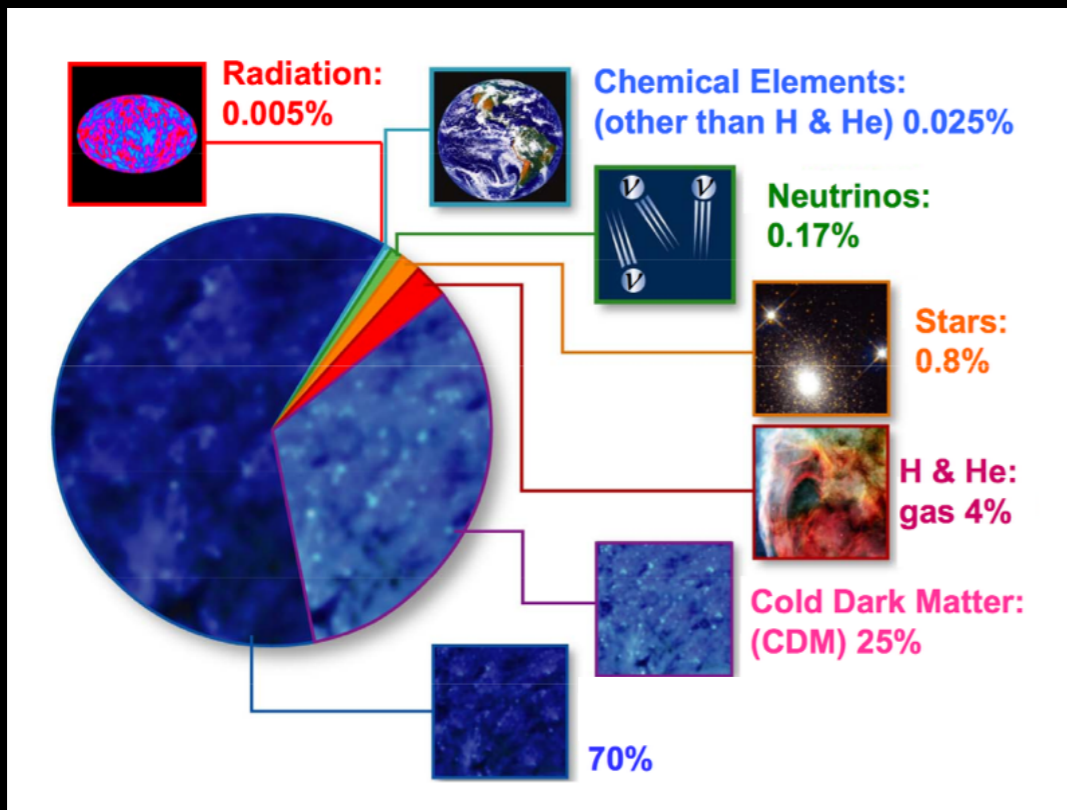


+



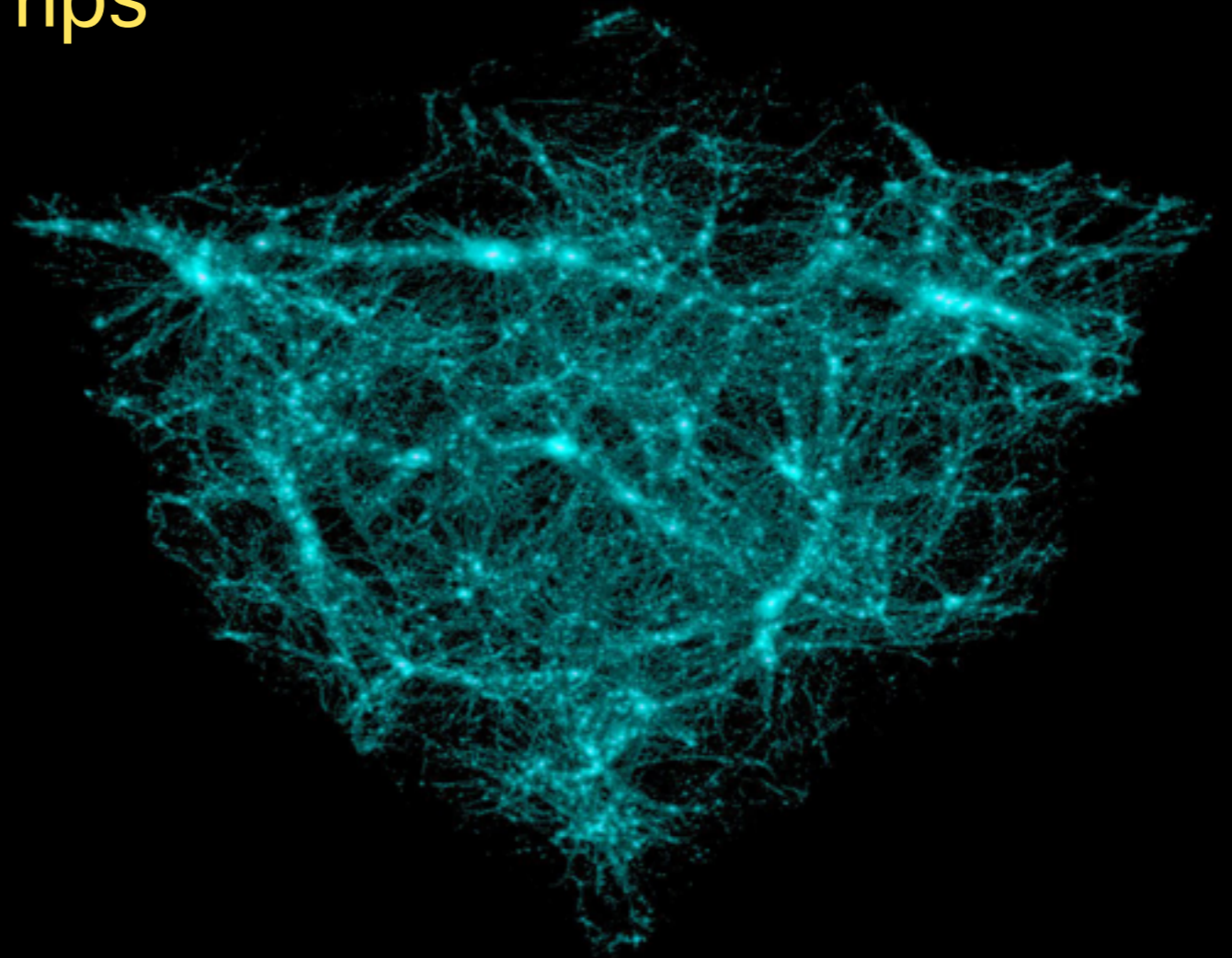
+

+





# 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

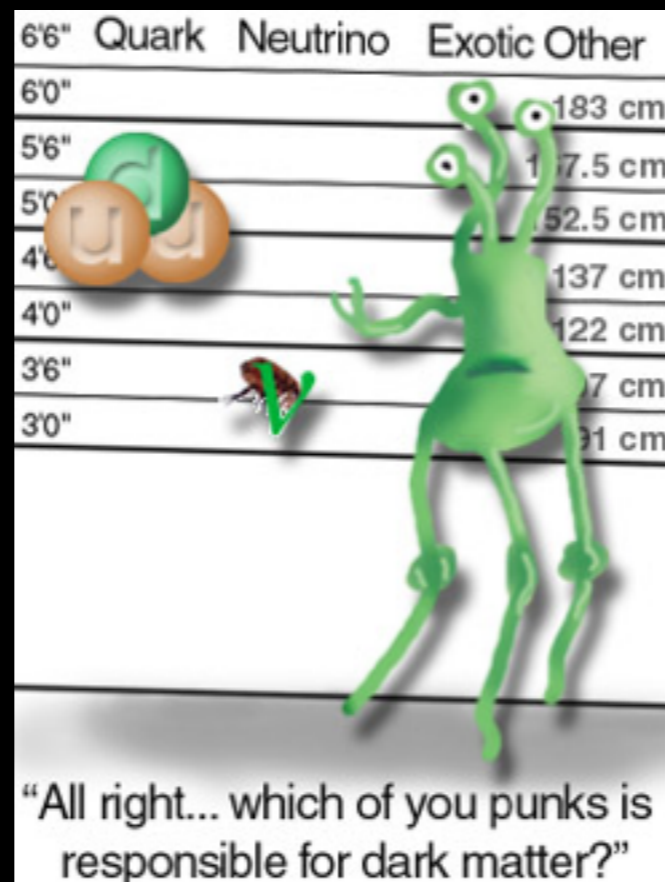
- 1) **Not** made of **normal stuff** (i.e. baryons: protons, neutrons)
- 2) **Doesn't cool** (does not condense to the center of galaxies)
- 3) Does not significantly emit, reflect, or absorb light (**electrically neutral**)
- 4) **Stable** on cosmological scales (or lifetime  $\gg t_U \sim 13.7$  Gyr)
- 5) **Massive** (26% of the energy content of the Universe)



Claudio Munoz

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

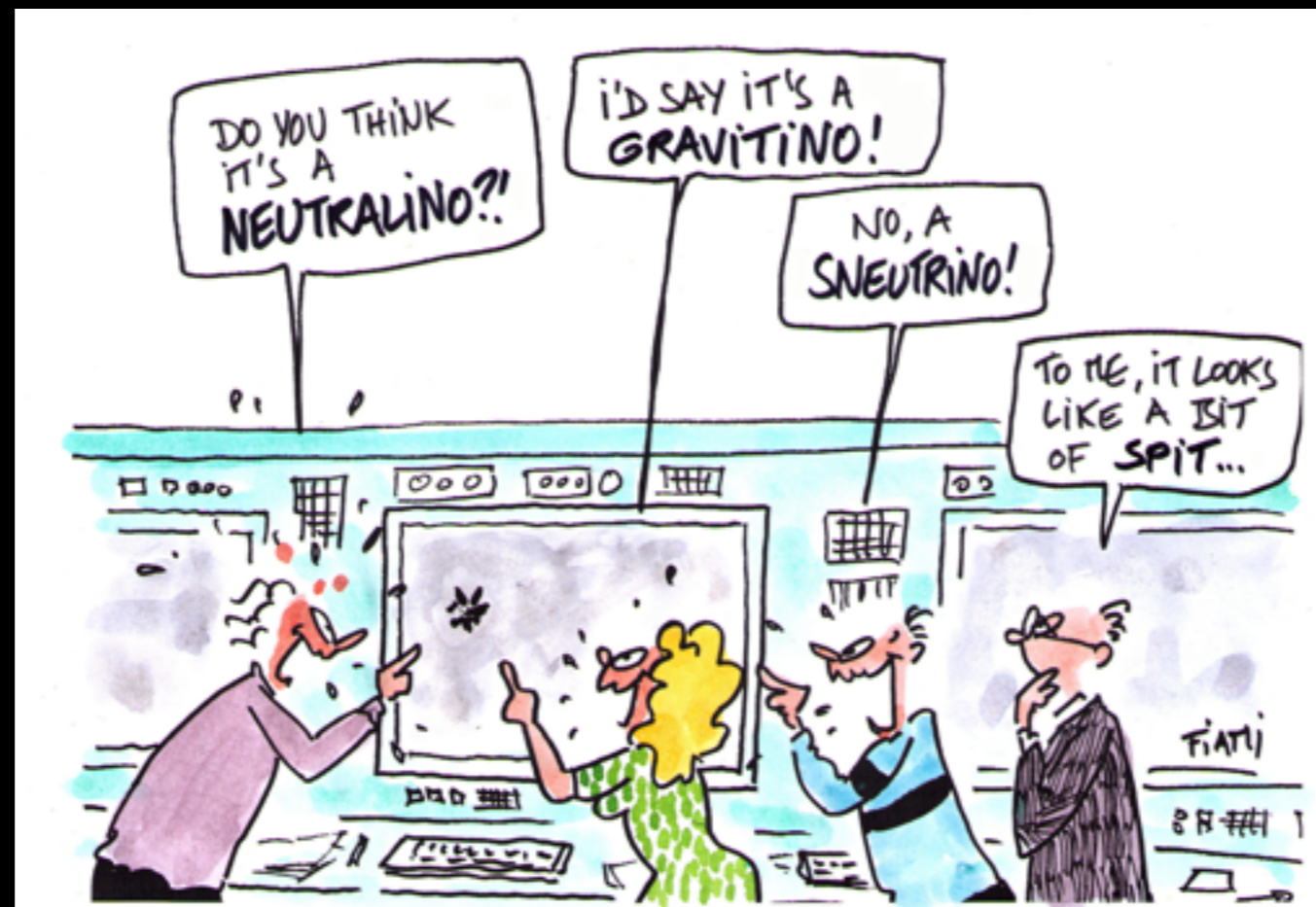
sneutrino

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**

sneutrino

gravitino

WIMP

WIMPzillas

...



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



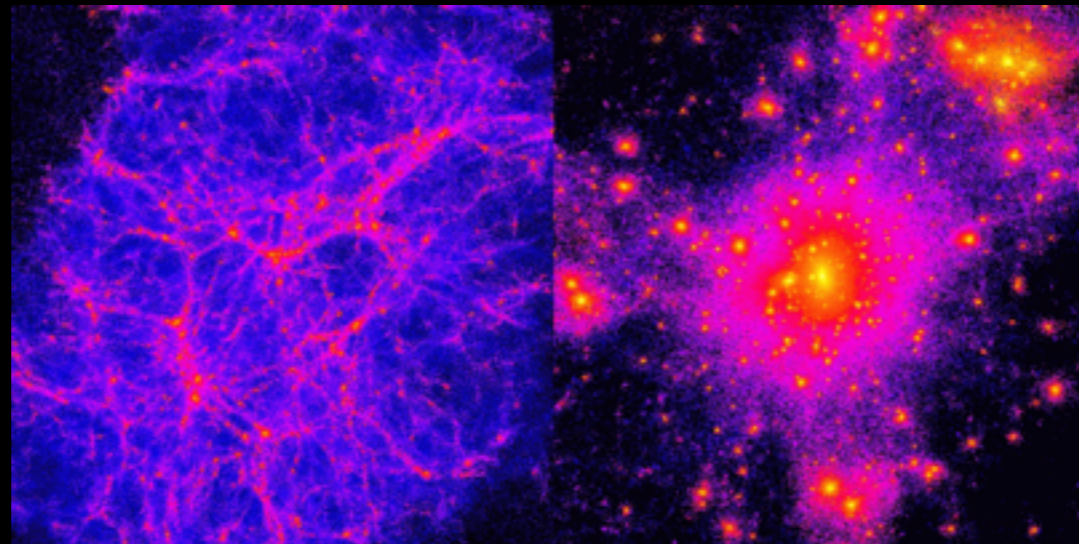
Everything we saw about structure formation makes the assumption that the **dark matter is COLD**

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

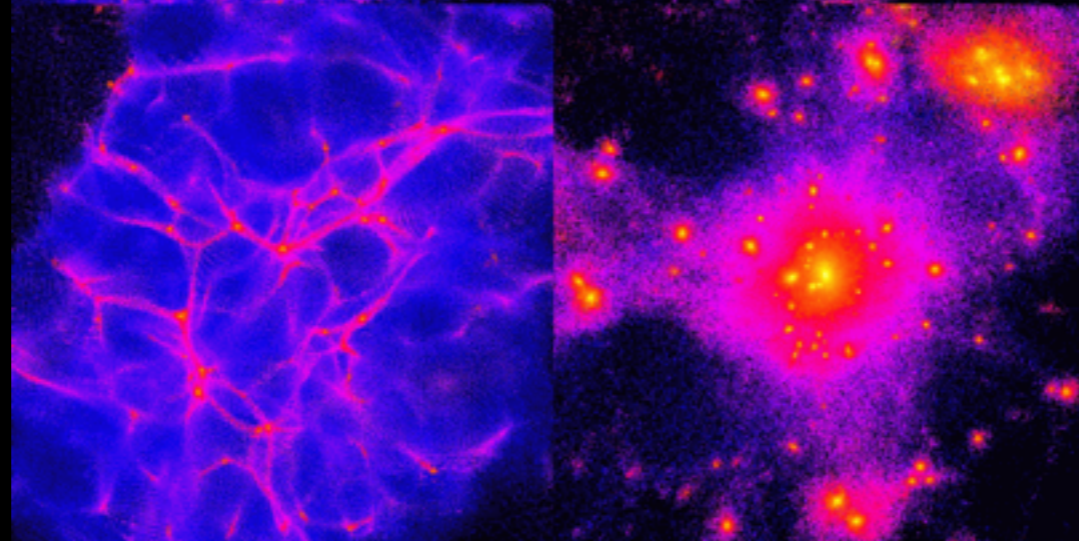
**Neutrinos are too light and quick moving to make up the dark matter !!!**

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

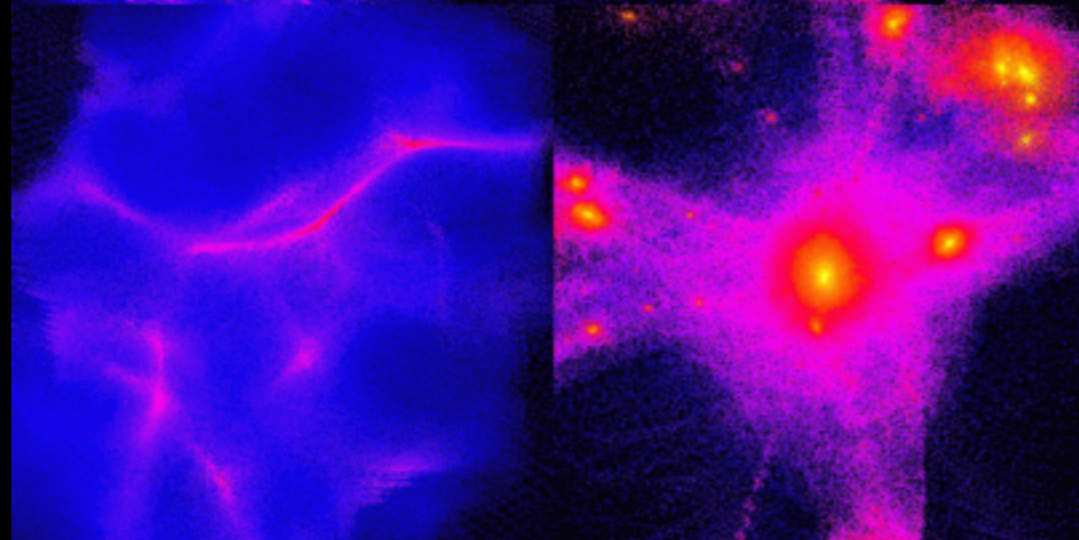
**cold**



**warm**

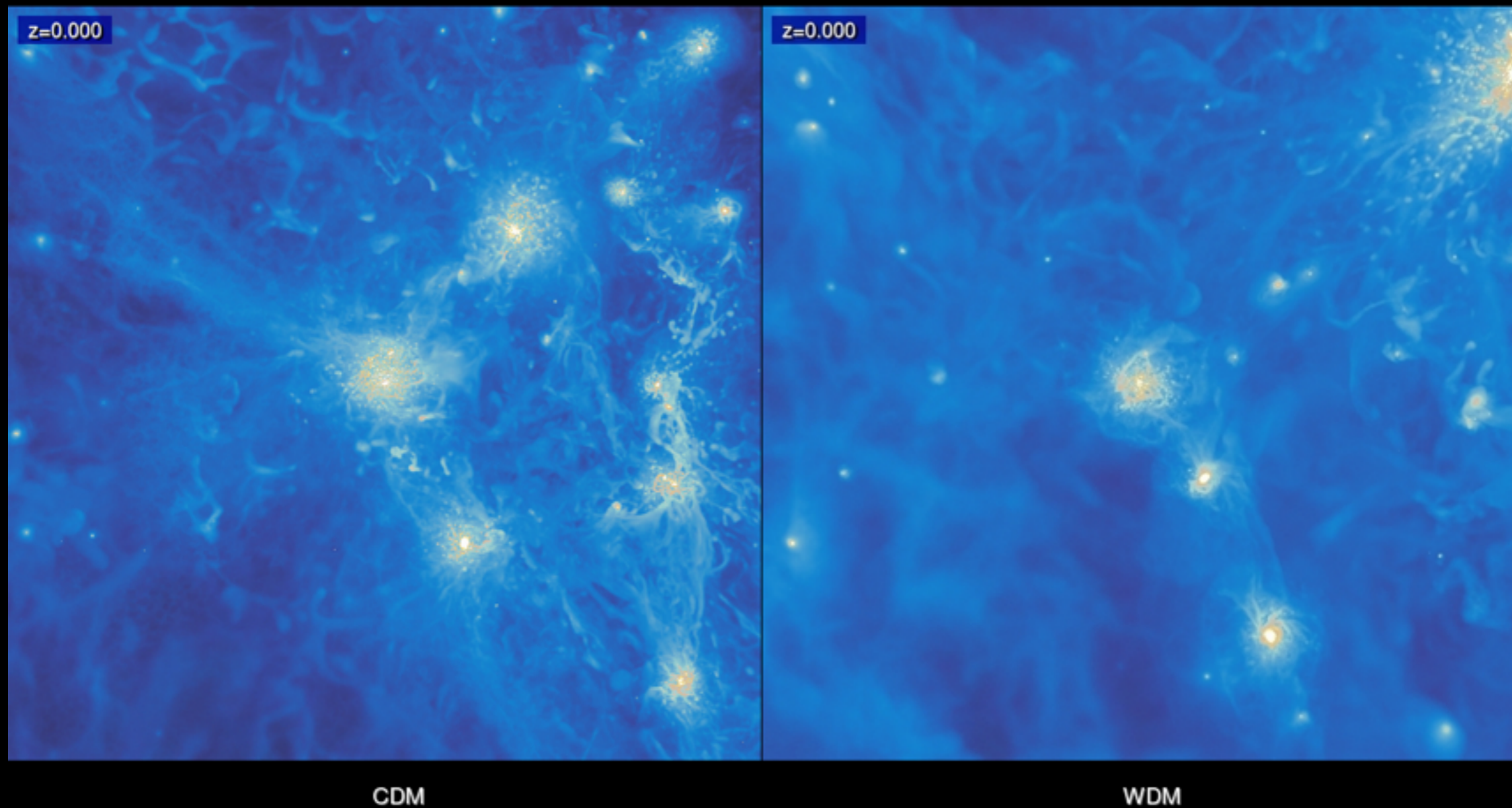


**hot**





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



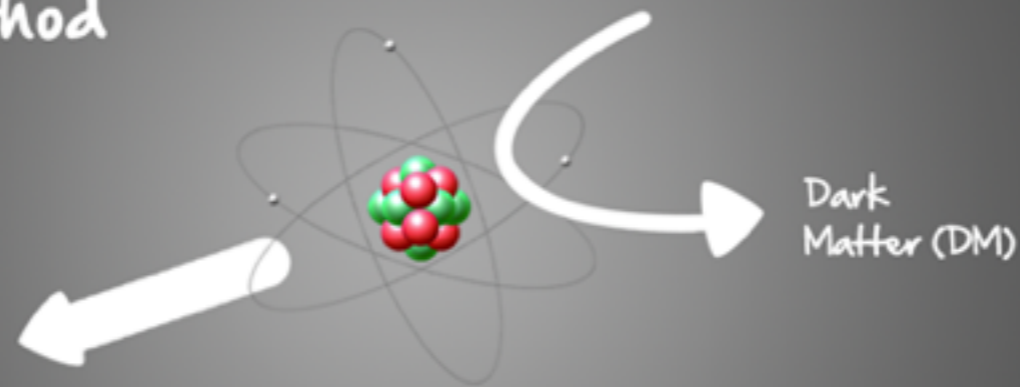
Instead of faint stars, re-imagine the dark matter as a gas of weakly interacting particles, which we will call **WIMPs (Weakly Interacting Massive Particles)**

# 8. How to search for WIMPs?

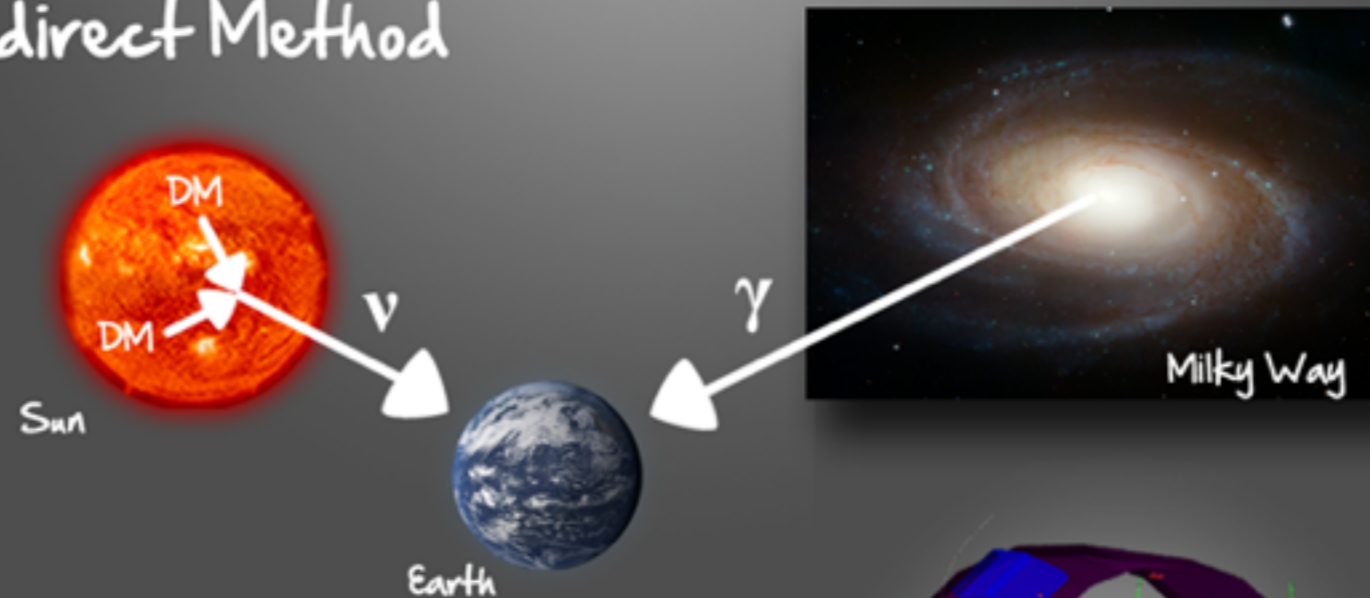


# Dark Matter search strategies

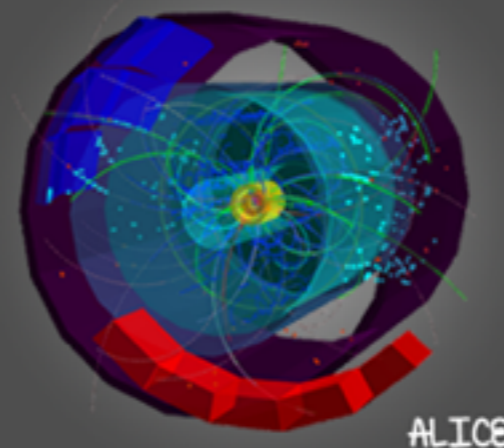
## Direct Method



## Indirect Method

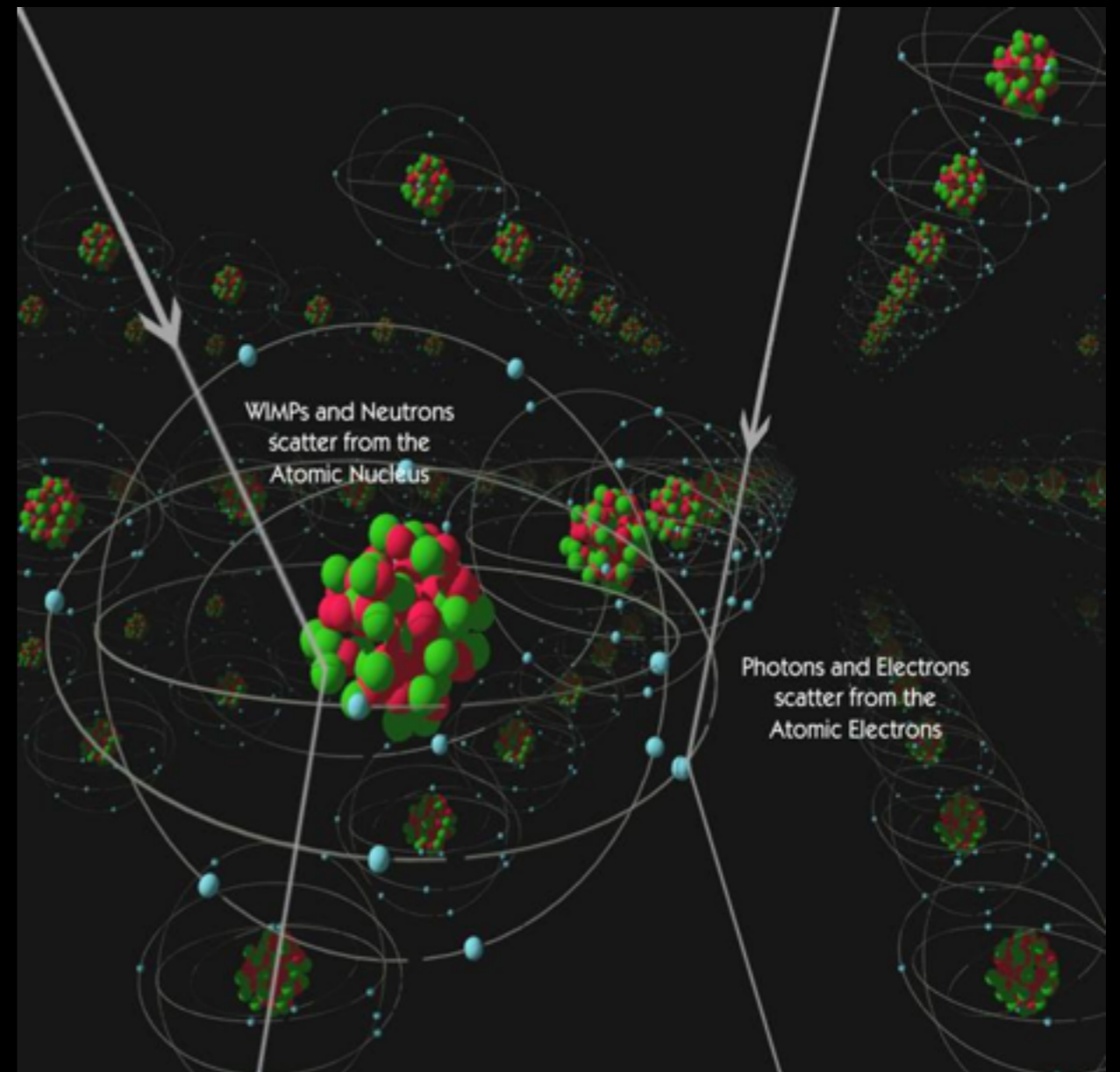


## Production at the Large Hadron Collider



# Direct detection

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

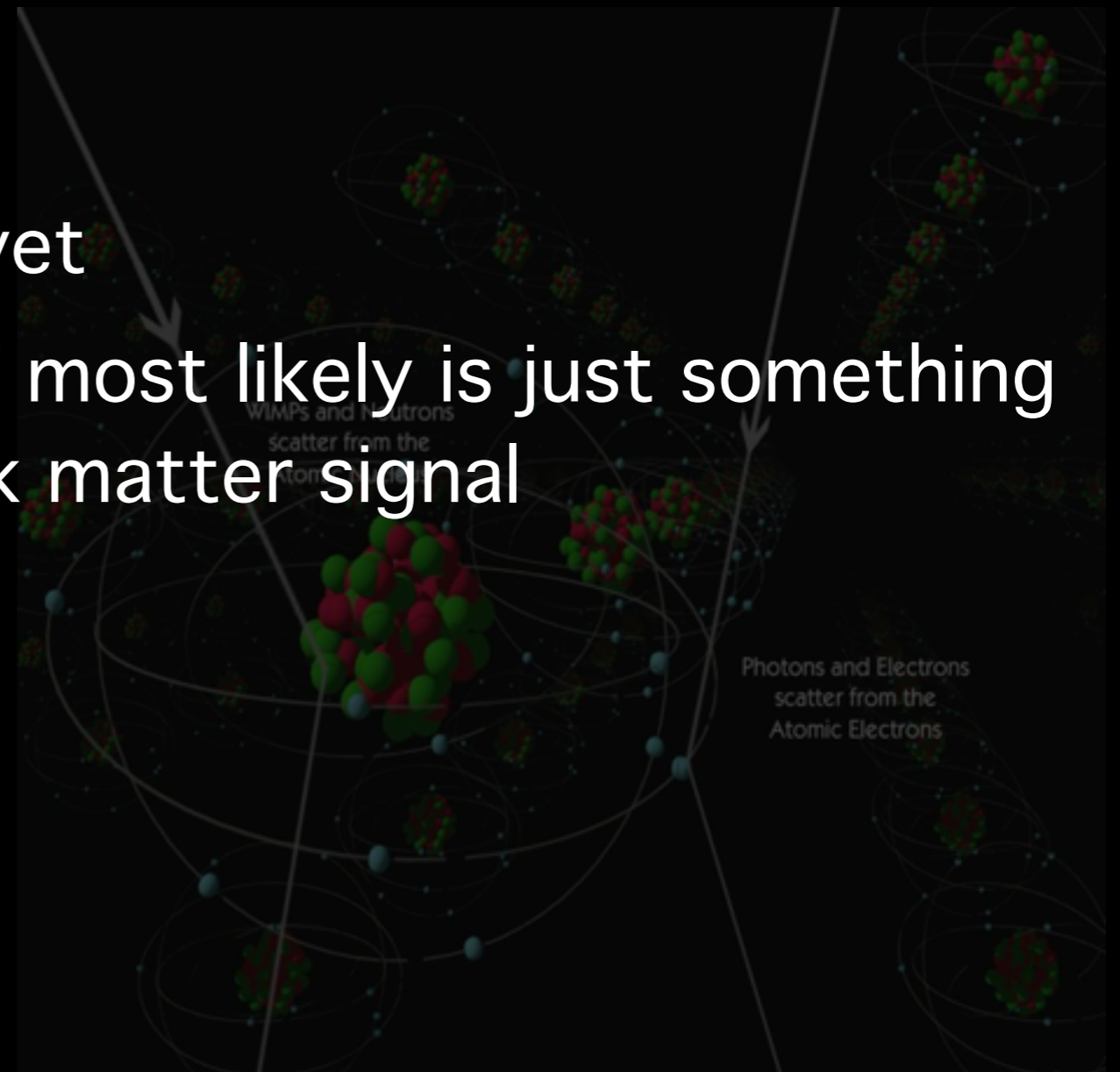


# Direct detection

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

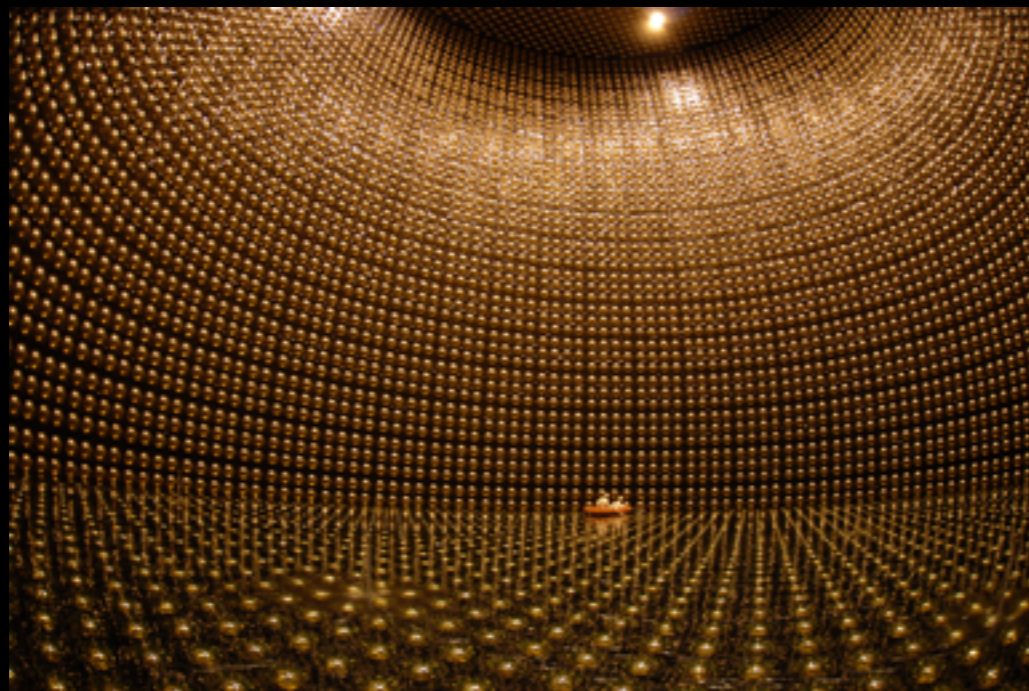
No dark matter candidate yet

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





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

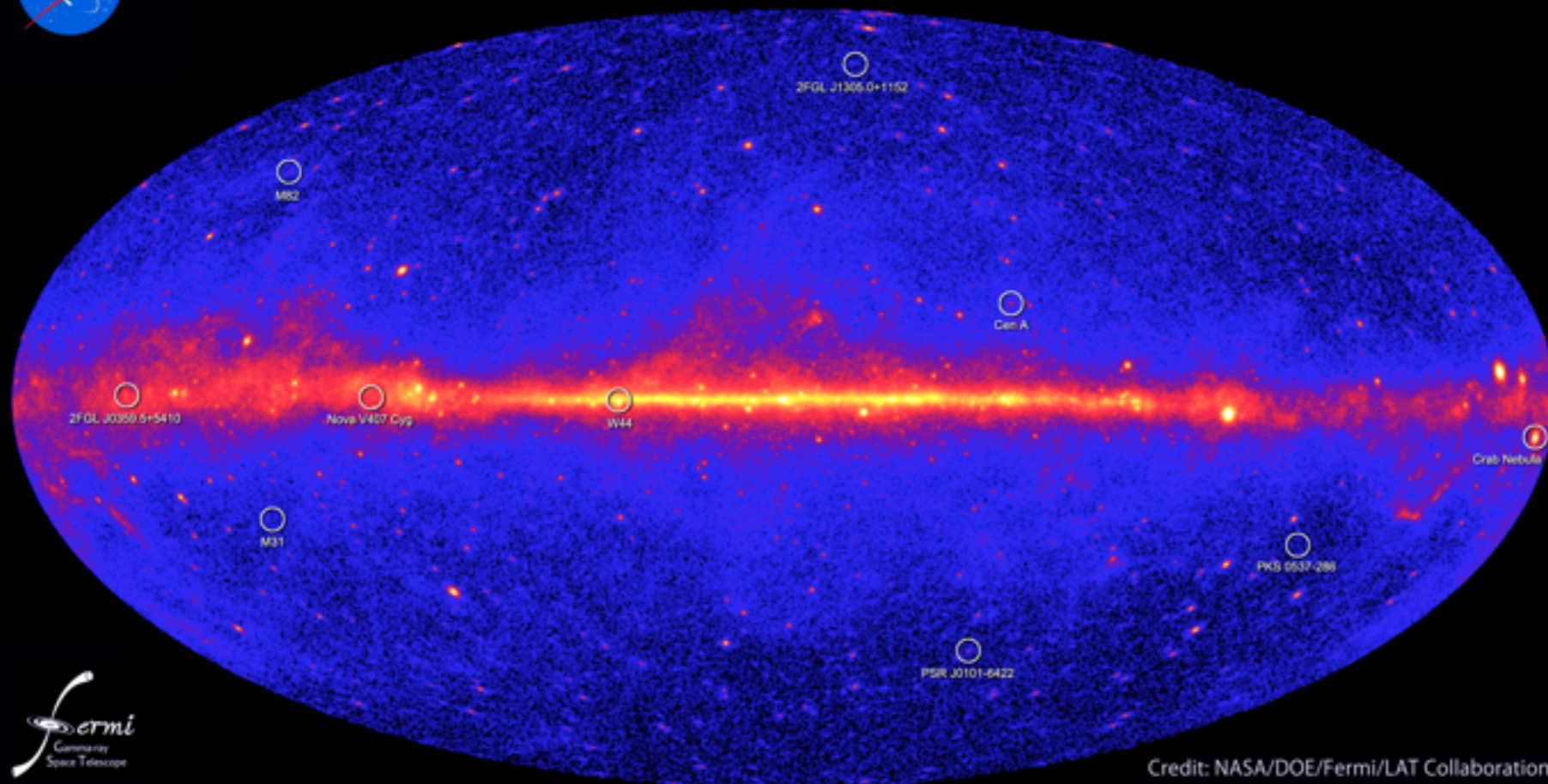
Very weakly

Only visible in regions with plenty of dark matter

For instance, look at the centers of galaxies



Fermi two-year all-sky map





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

Very  
Only  
For it

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

## $\gamma$ -ray anisotropies from dark matter in the Milky Way: the role of the radial distribution

F. Calore<sup>1</sup>, V. De Romeri<sup>2,3</sup>, M. Di Mauro<sup>4,5,6</sup>, F. Donato<sup>4,5</sup>, J. Herpich<sup>7</sup>, A.V. Macciò<sup>7</sup>, L. Maccio<sup>8,9</sup>

<sup>1</sup> GRAPPA Institute, University of Amsterdam, Science Park 904, 1090 GL Amsterdam, The Netherlands

<sup>2</sup> AHEP Group, IFIC - C.S.I.C./Universitat de València, Edificio de Institutos de Paterna, Apartado 22085, E-46071 València, Spain

<sup>3</sup> Address since 1st November 2013: Laboratoire de Physique Corpusculaire, CNRS/IN2P3 - UMR 6533, Campus des Cézeaux, 24 Av. des Landais, F-63177 Aubière Cedex, France

<sup>4</sup> Dipartimento di Fisica, Università di Torino, via Giuria 1, I-10125 Torino, Italy

<sup>5</sup> INFN, Sezione di Torino, I-10125 Torino, Italy

<sup>6</sup> Laboratoire d'Annecy-le-Vieux de Physique Théorique (LAPTh), Univ. de Savoie, CNRS, B.P.110, Annecy-le-Vieux F-74941, France

<sup>7</sup> Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

<sup>8</sup> Ludwig-Maximilians-Universität, Theresienstraße 37, D-80333 München, Germany and

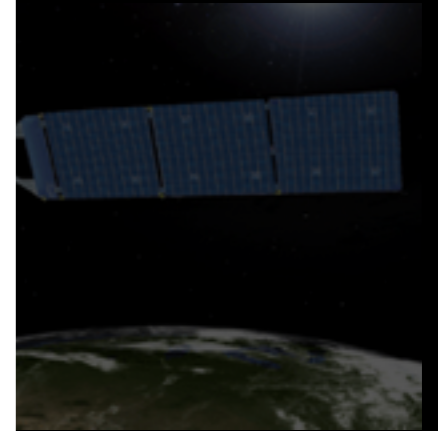
<sup>9</sup> Max-Planck-Institut für Physik (Werner Heisenberg Institut), Föhringer Ring 6, D-80805 München, Germany

LAPTH-009/14, PCCF RI 14-03

### ABSTRACT

The annihilation of dark matter particles in the halo of galaxies may end up into  $\gamma$ -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  $\gamma$ -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

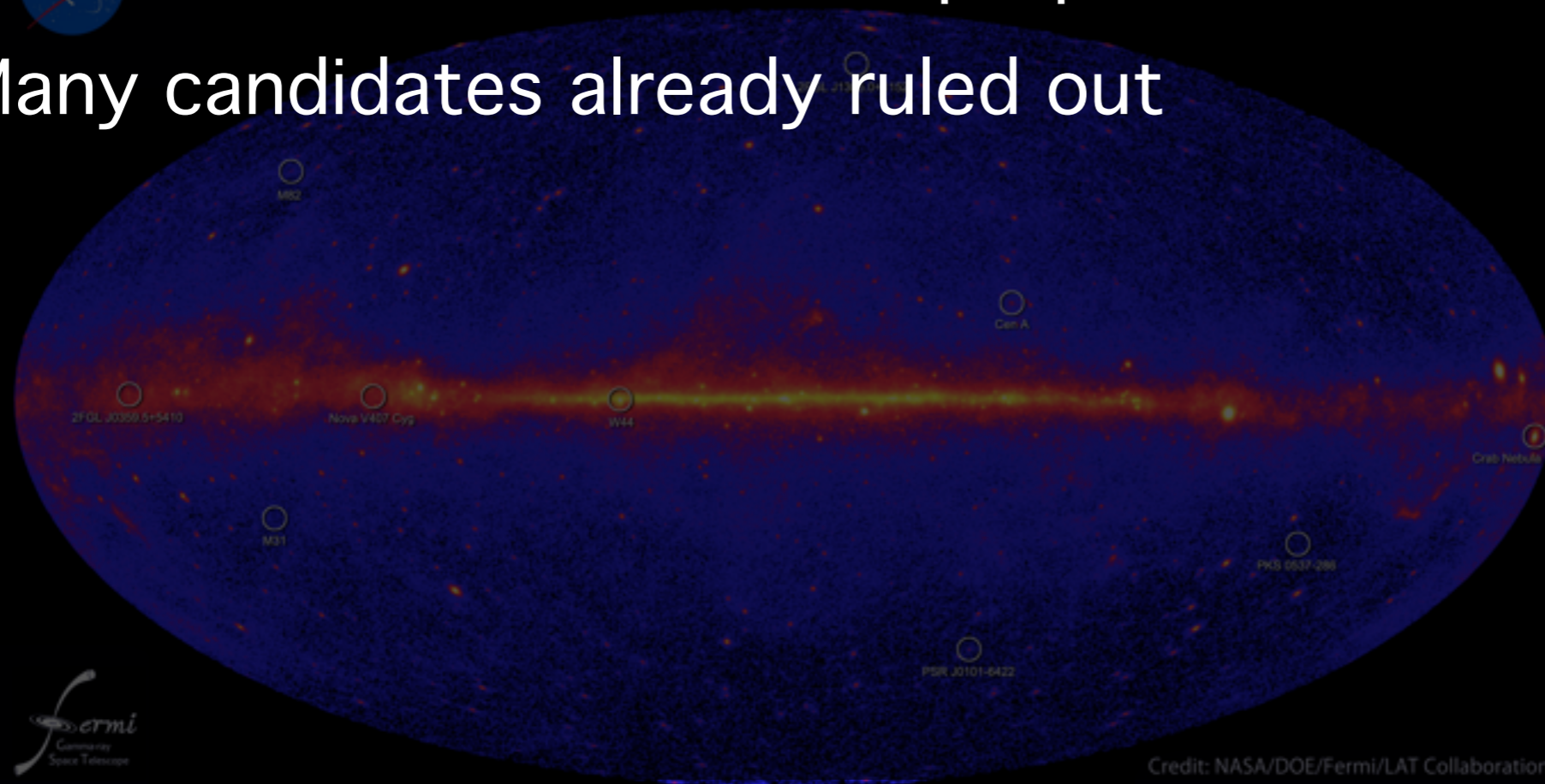
For instance, look at the centers of galaxies



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

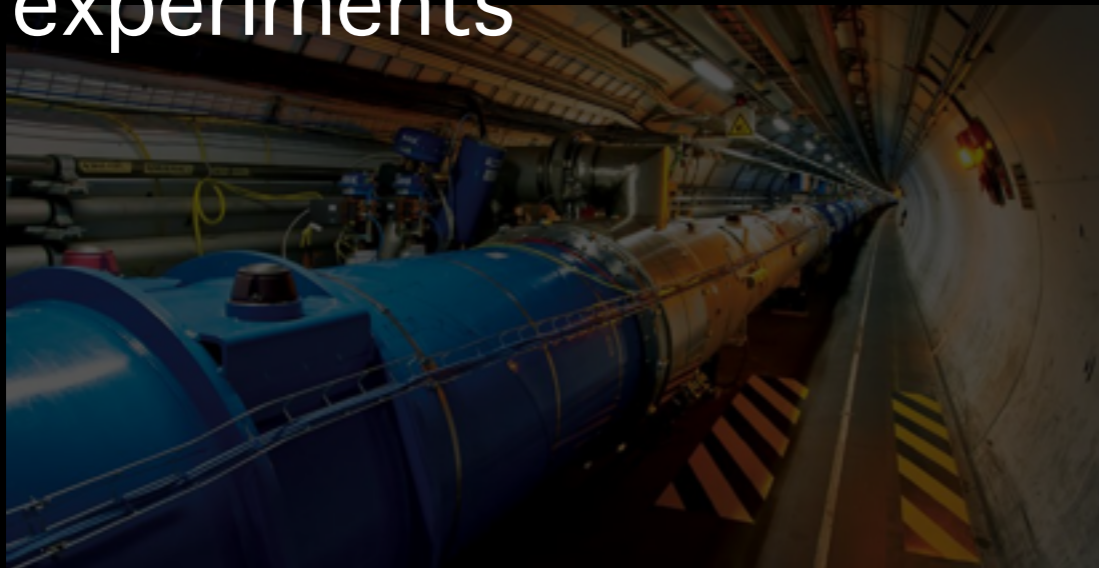
3) Create it using a particle accelerator

Maybe at very very high energies, dark matter interacts with normal matter.  
Accelerators: recreate conditions of primordial Universe

So far, “only” the Higgs has been discovered at LHC

No possible candidate for dark matter

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

## DARK MATTER



**DARK MATTER** is the name given to material in the Universe that does not emit or reflect light but is necessary to explain observed gravitational effects in galaxies and stars. Dark matter, along with dark energy, totals 96% of the Universe, yet it remains a mystery as to what exactly it *is*.

*Acrylic felt, wool felt, and fleece with gravel fill for maximum mass.*

*Packaged in a black opaque bag designed for concealing contents.*



**\$10.49** PLUS SHIPPING

GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON UP Q  
NEUTRON DOWN QUARK TAU GLUON **DARK MATTER** NEUTRINO TACHYON ELECTRON UP QUARK DO  
NEUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON PHOTON NEUTRINO TACHY  
UP QUARK DOWN QUARK TAU NEUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLU  
NEUTRON DOWN QUARK TAU GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEU  
UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON PHOTON NEUTRINO TACHYON ELECTRON UP

The **PARTICLE ZOO**