Ch. 13
Dark Matter & Dark energy

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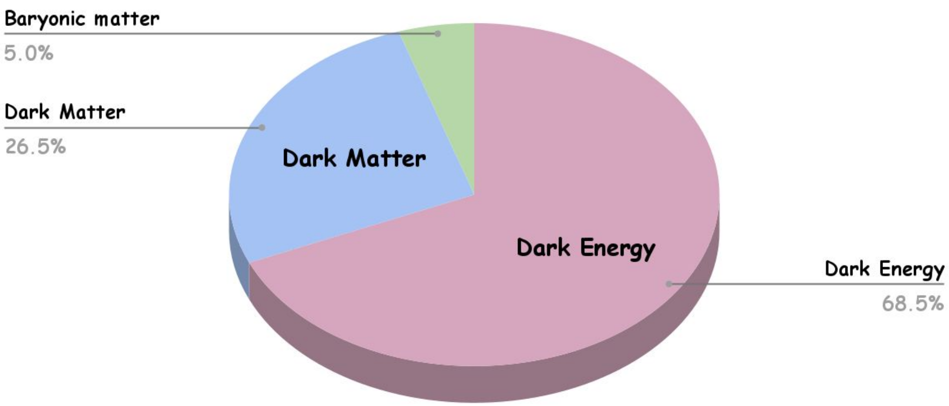
Physics Seminar II
2021. 06. 11

Energy content of the universe

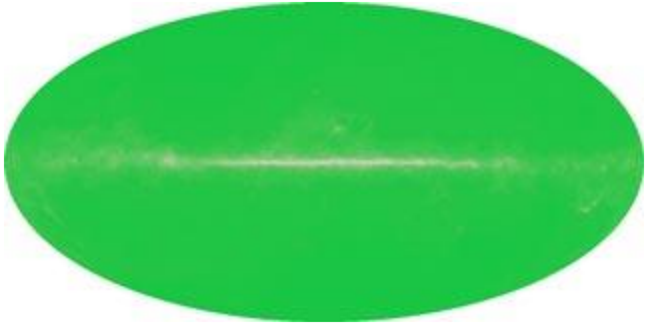
The Contents of the universe



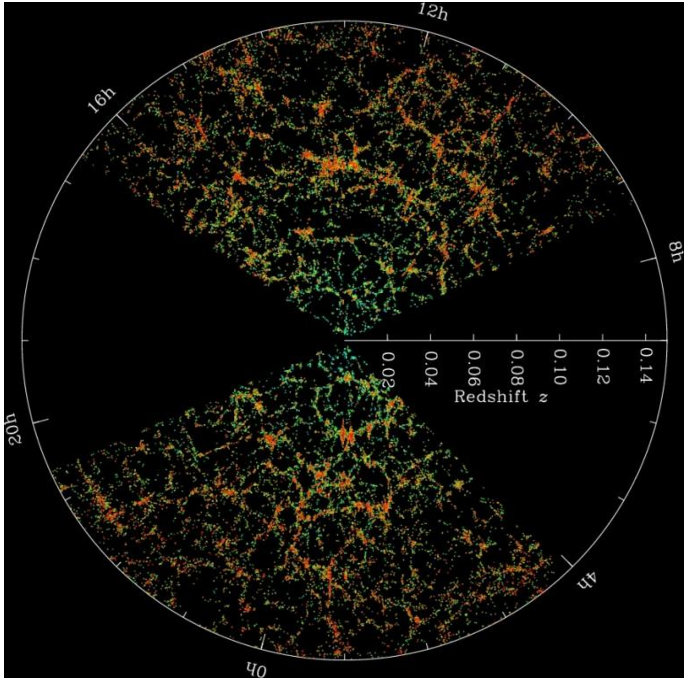
Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age [Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_* [Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag} [Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
k_{eq} [Mpc^{-1}]	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

Ref : Planck 2018 results I.

Large-scale structure of the universe



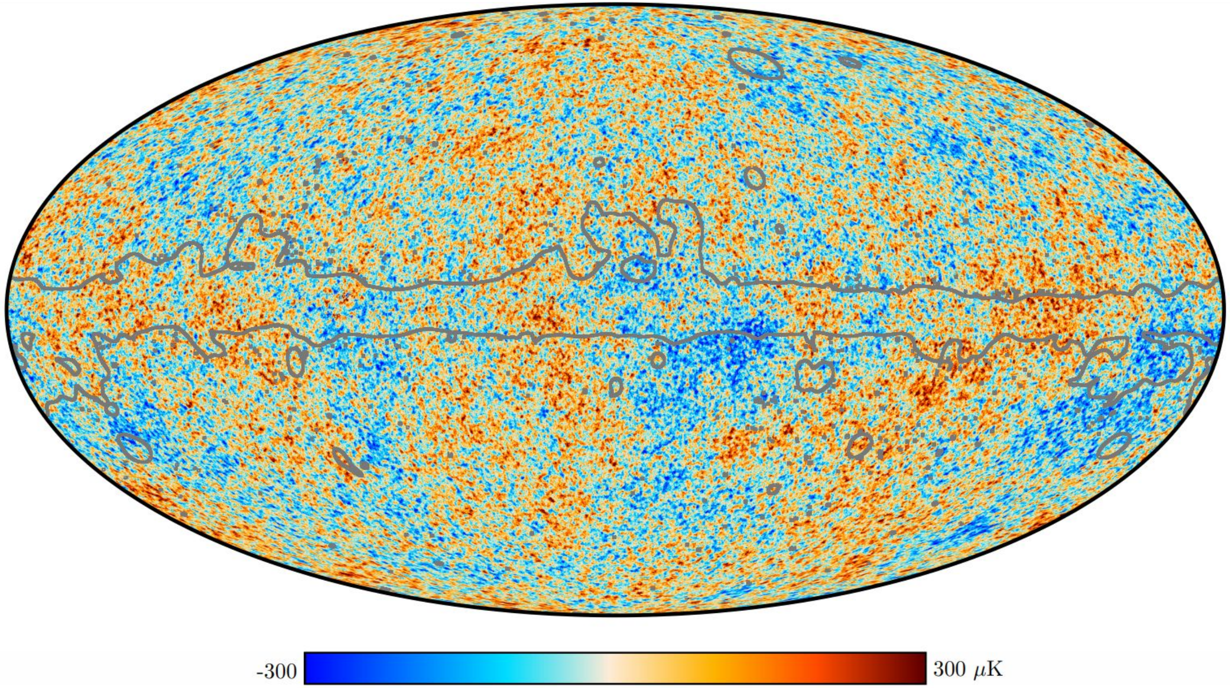
Ref : https://map.gsfc.nasa.gov/media/030635/index.html



Ref : https://www.darkenergysurvey.org/supporting-science/large-scale-structure/

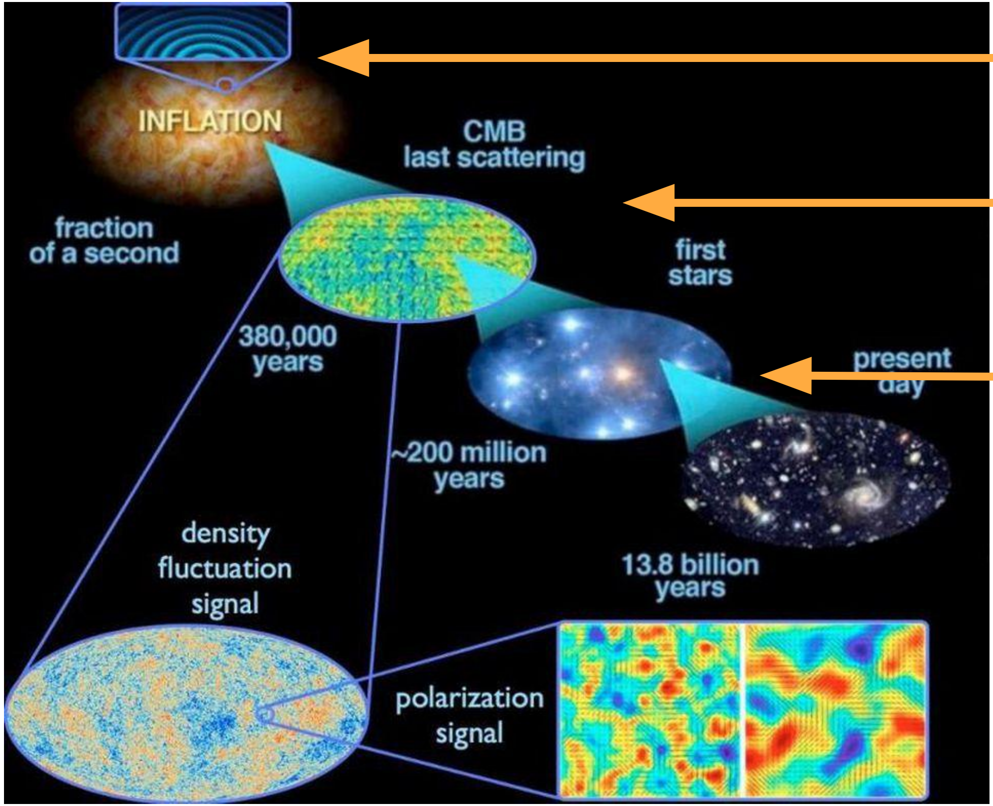
- The universe seems to be isotropy in CMB
- But the distribution of galaxies looks different

Large-scale structure of the universe



Ref : https://www.cosmos.esa.int/web/planck/picture-gallery

Large-scale structure of the universe



quantum fluctuation

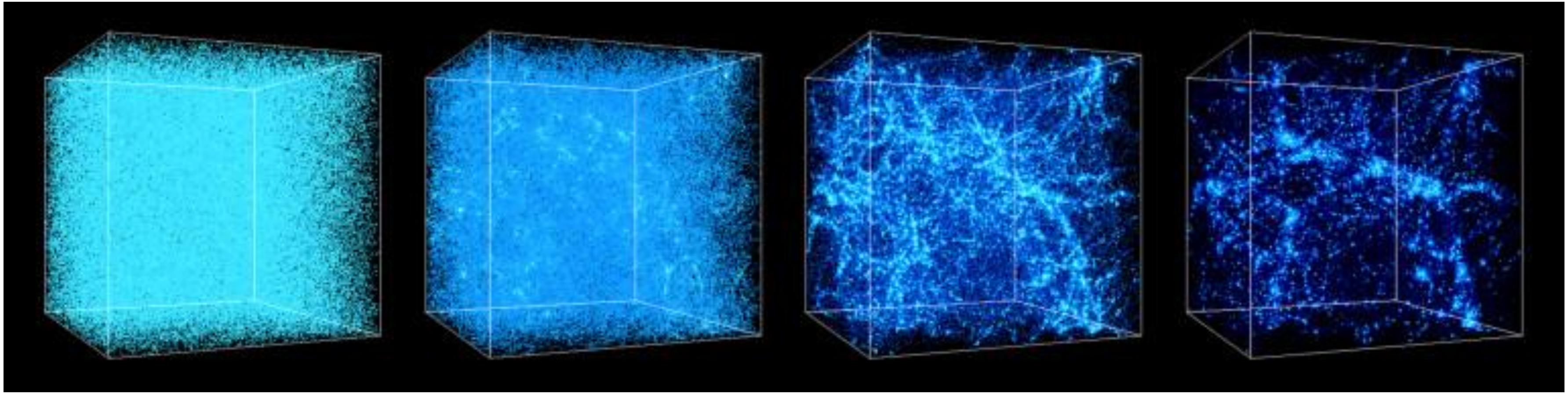
density fluctuation

gravitational instability

formation of stars

Ref : https://www.forbes.com/sites/startswithabang/2019/05/11/ask-ethan-how-well-has-cosmic-inflation-been-verified/?sh=6278dd9d1d07

Large-scale structure of the universe



Ref : https://www.darkenergysurvey.org/supporting-science/large-scale-structure/

Evidence of DM

- Zwicky gave us hint of DM

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

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ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

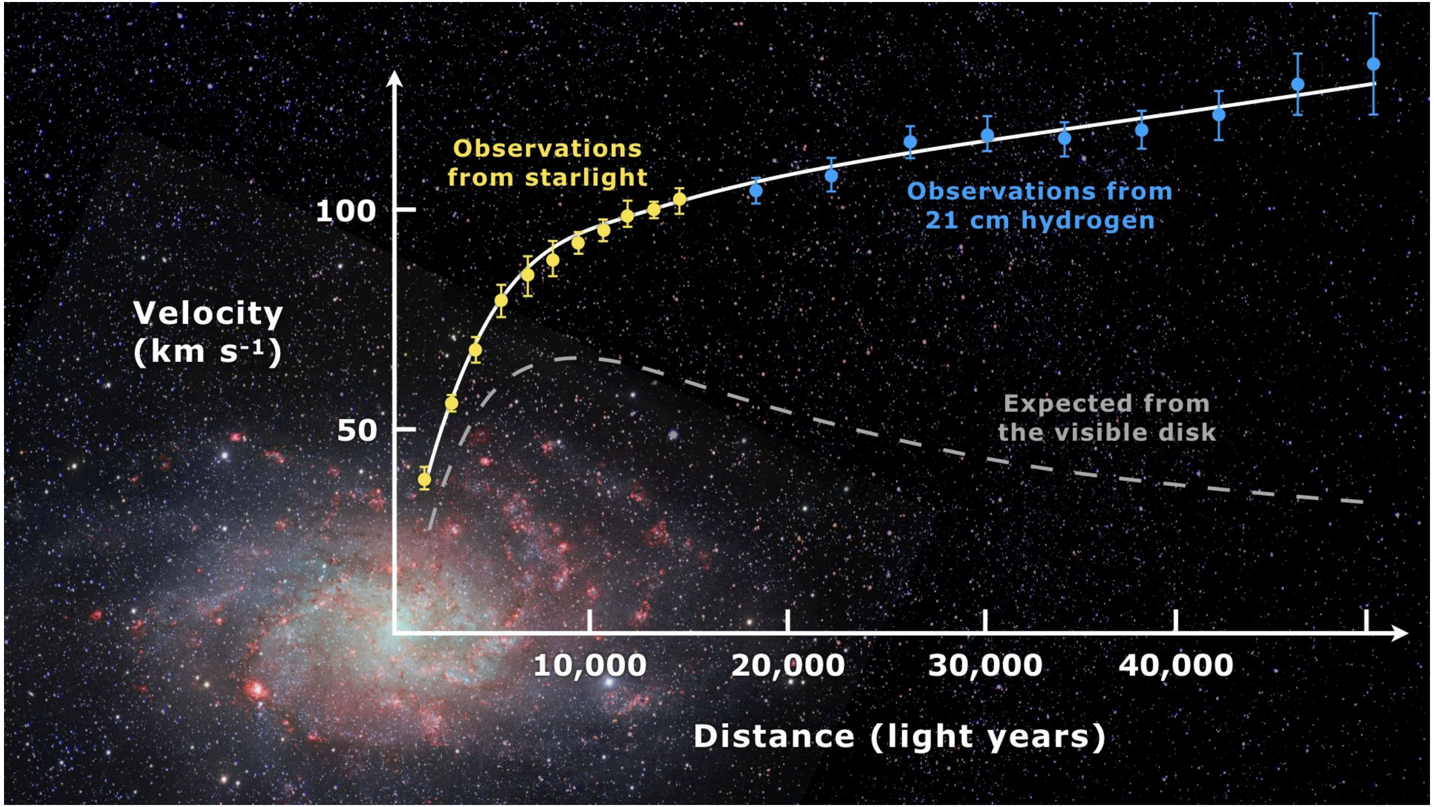
$$\overline{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_{\odot} . \qquad (36)$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathcal{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^{7} suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500 , \qquad (37)$$

as compared with about $\gamma' = 3$ for the local Kapteyn stellar system. This discrepancy is so great that a further analysis of the problem is in order. Parts of the following discussion were published several years ago, when the conclusion expressed in (36) was reached for the first time.[5]

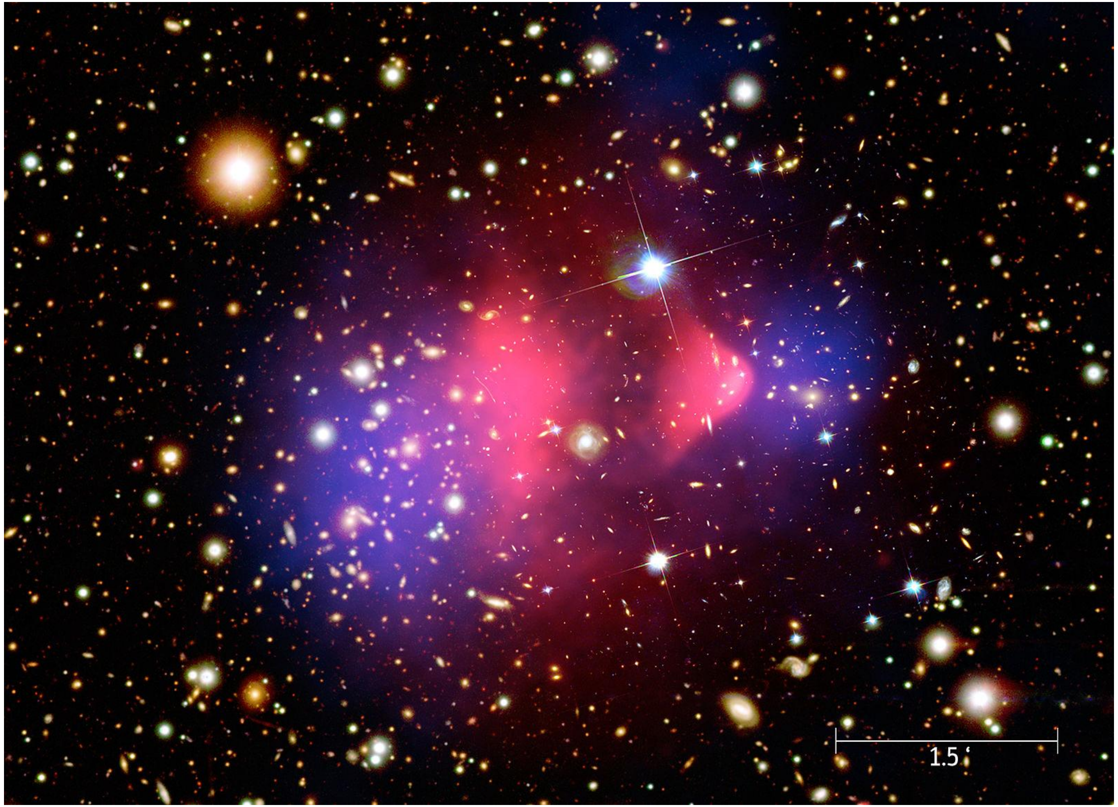
Evidence of DM



$$v \sim \text{Const.}$$

$$v \sim r^{-\frac{1}{2}}$$

Evidence of DM



Ref : https://en.wikipedia.org/wiki/File:1e0657_scale.jpg

Background : Optical from HST

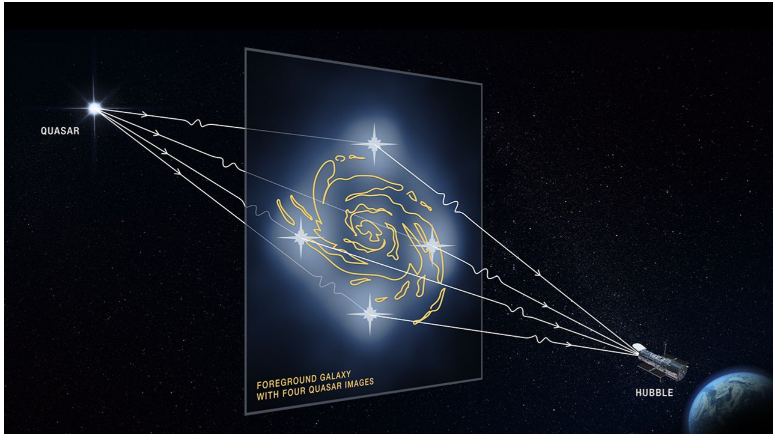
Pink : X-ray from Chandra

Blue : gravitational lensing

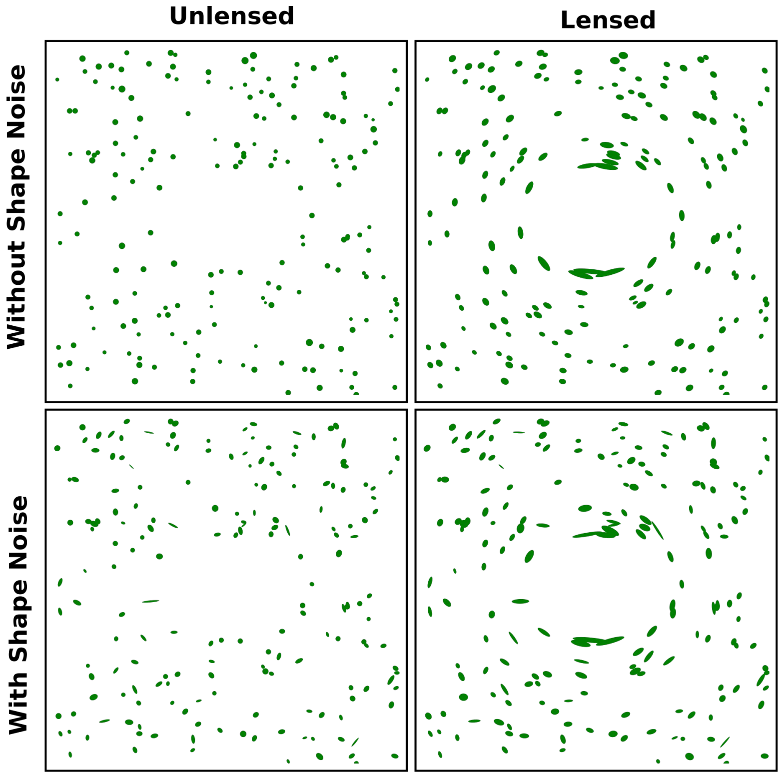
- This was the first clear separation seen between normal and dark matter. (from ESA explanation)

Evidence of DM

- Strong lensing .vs. Weak lensing



Ref : https://hubblesite.org/contents/media/images/2020/05/4617-Image?news=true



Ref : https://en.wikipedia.org/wiki/Weak_gravitational_lensing#/media/File:Shapenoise.svg

Evidence of DM

cmb fluctuations

Evidence of DM - Summary

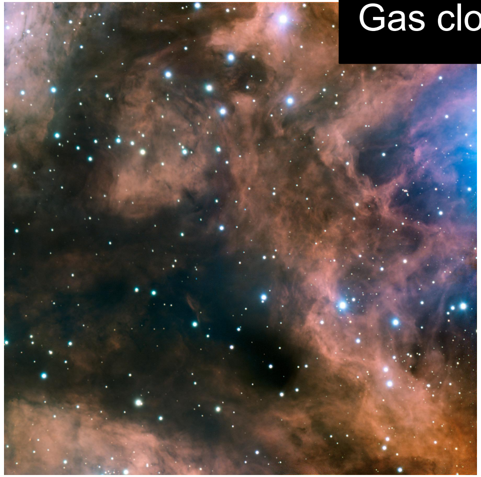
Evidence of DM
Dynamics of galaxies in the cluster
Rotation curve of galaxy
Bullet cluster
Weak lensing
Large scale structure
CMB observation

Contribution of baryonic matter

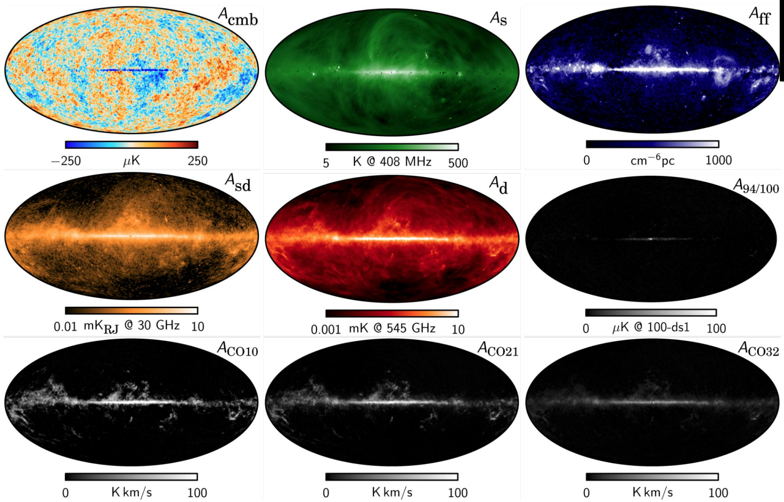
- The visible luminous matter only provide a density of $\Omega_{\mathrm{lum}} < 1\%$

- **So, What is the Dark Matter ?**

DM candidates



Gas cloud?



Galactic dust?

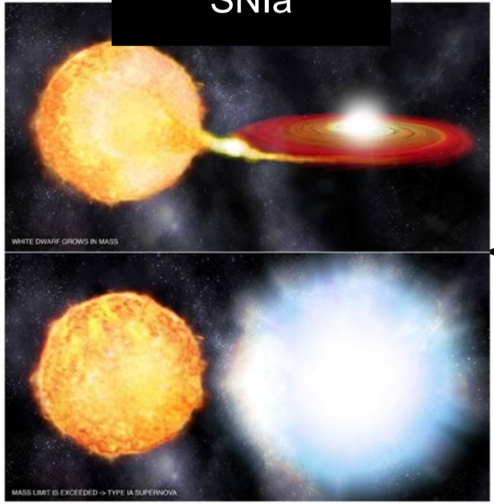
- No, we can find them by their absorption line with spectroscopic observation etc.

Ref :

1. https://en.wikipedia.org/wiki/Interstellar_cloud#/media/File:Carved_by_Massive_Stars.jpg
2. https://www.cosmos.esa.int/documents/387566/425793/2015_FGAmpl/a3cec4dc-7e13-45df-b5d2-01df97905bc0?t=1423087421731

DM candidates

SNIa



Black hole

Neutron star

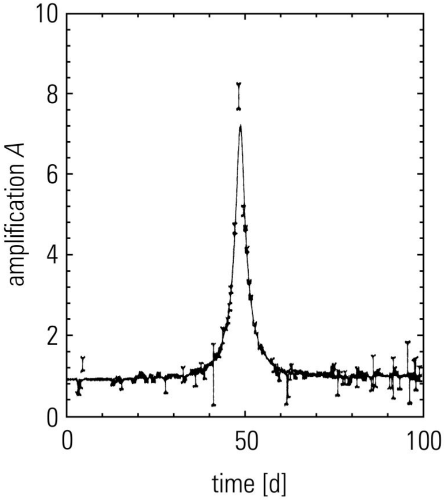
- No, the fraction of SN is too small

Ref : https://phys.org/news/2014-08-ia-supernovae-stem-explosion-white.html

DM candidates

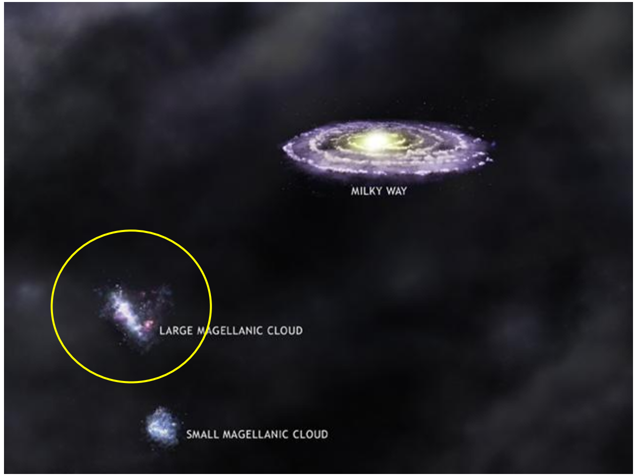
- We need to find **massive** & **non-luminous** object
- MACHO (MAssive Compact Halo Object) : massive and compact and non-luminous object

- The experiments : *MACHO*, *EROS*, *OGLE*
- They found MACHO by using **Microlensing**



DM candidates

- Excellent candidates for such a search are stars in the **LMC** (Large Magellanic Cloud)
- MACHO team found 20% of the halo mass



Ref : https://chandra.harvard.edu/resources/illustrations/milkyWay.html

DM candidates

Other candidates

1. Remote possibility : massive quark star

2. NACHOs (Not Astrophysical Compact Halo Object)

Neutrino as DM

- neutrino were considered a good candidate for DM respecting # density

- direct mass determination :

$$m_{\nu_e} < 3\,\mathrm{eV}$$
$$m_{\nu_\mu} < 190\,\mathrm{keV}$$
$$m_{\nu_\tau} < 18\,\mathrm{MeV}$$

- individual neutrino flavour a mass limit can be derived : $m_\nu \leq 10\,\mathrm{eV}$

Neutrino as DM

- Recent estimates of Ω_ν is $\Omega_\nu < 1.5\%$

- But, LSS can't be understood when it comes to neutrinos
- neutrinos are not considered a good candidate for DM

WIMPs (Weakly Interacting Massive Particles)

- possible a fourth generation of leptons with heavy neutrinos

- From LEP (Large Electron-Positron Collider) :

$$m_{\nu_x} \geq m(Z)/2 \approx 46\,\mathrm{GeV}$$

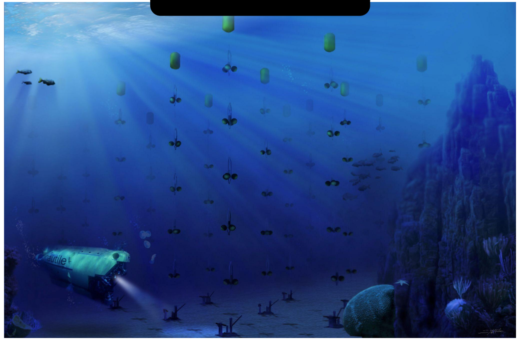
- Alternative to heavy neutrino : WIMPs

WIMPs (Weakly Interacting Massive Particles)

- expected WIMP rate : one event per kilogram target per day

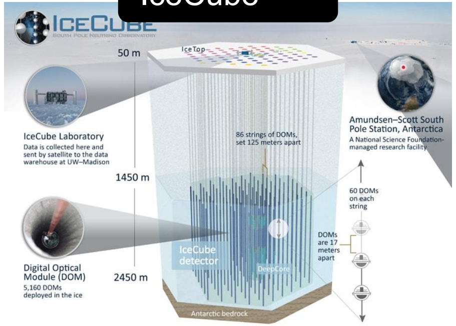
- Detector : ANTARES, IceCube

ANTARES



(c) J. A. Aguilar (2010)

IceCube



Ref : https://icecube.wisc.edu/science/icecube/

Axion

- The possible solution of strong CP problem is Axion

- This is pesudoscalar particle

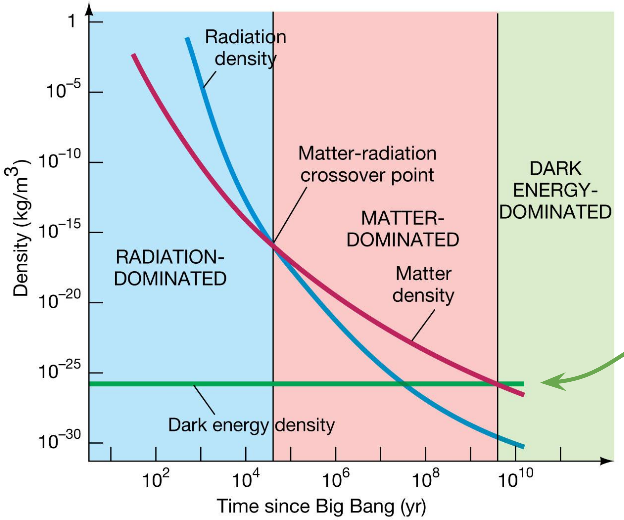
- theoretical axion density : $> \ 10^{10} \ \mathbf{cm}^{-3}$

DM candidates - Summary

DM candidates
MACHO
WIMPs
Axion

The Role of the Vacuum energy density

- Cosmological constant Λ
- 1917, Einstein insert vacuum energy to make static universe
- 1931, Hubble found that galaxies are receding
- 1998, SNIa observation



DE is constant!

Ref : https://pages.uoregon.edu/jimbrau/BraulmNew/Chap27/7th/AT_7e_Figure_27_01.jpg

The Role of the Vacuum energy density

- Λ term in the field equation appears to dominate today
- It results in an accelerated expansion

- Two survey team

1. Supernova Cosmology Project
2. High-z Supernova Search Team

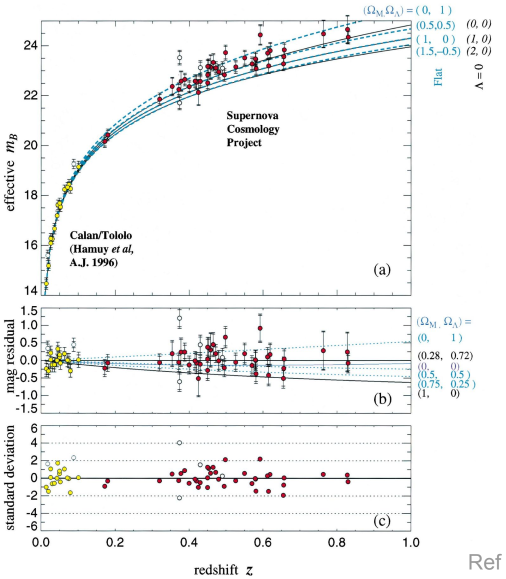
Brian P. Schmidt
(High-z team)

Saul Perlmutter
(Supernova Cosmology project)

Ref : http://cosmicdiary.org/fpatat/2011/10/04/the-nobel-prize-in-physics-2011-goes-to-supernovae/

The Role of the Vacuum energy density

- 1998, High-z Supernova Search Team published
  "*Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant*"
- 1999, Supernova Cosmology Project published
  "Measurements of Ω and Λ from 42 High-Redshift Supernovae"



- The results from SCP team

Ref : Perlmutter et al. 1999

DE candidates

- So, What is the Dark Energy?

DE candidates
Λ, Cosmological constant
$\phi(t)$, Scalar field (Quintessence etc.)
Modified GR

Galaxy Formation

- 18th century,

Thomas Wright hypothesized the Milky Way galaxy was a flattened disk of stars.
Immanuel Kant coined the term Island Universe to describe these ‘nebulae’.

- Today, galaxies evolve via gravitational attraction with DM

- Regarding galaxy formation, there are two type of DM

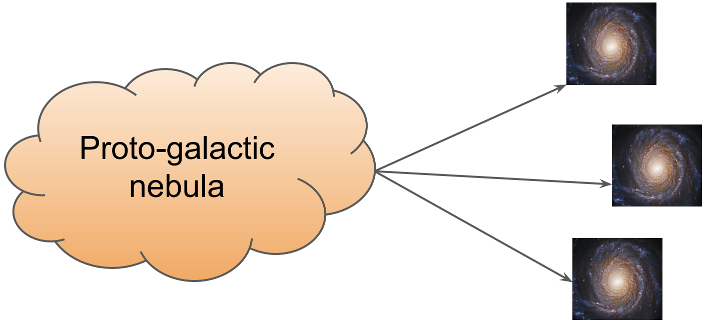
Galaxy Formation

1. Hot DM : Neutrinos

   Relativistic neutrinos could easily escape from mass aggregation

- Top-down scenario : The ELS model (Eggen, Lynden-Bell and Sandage, 1962)

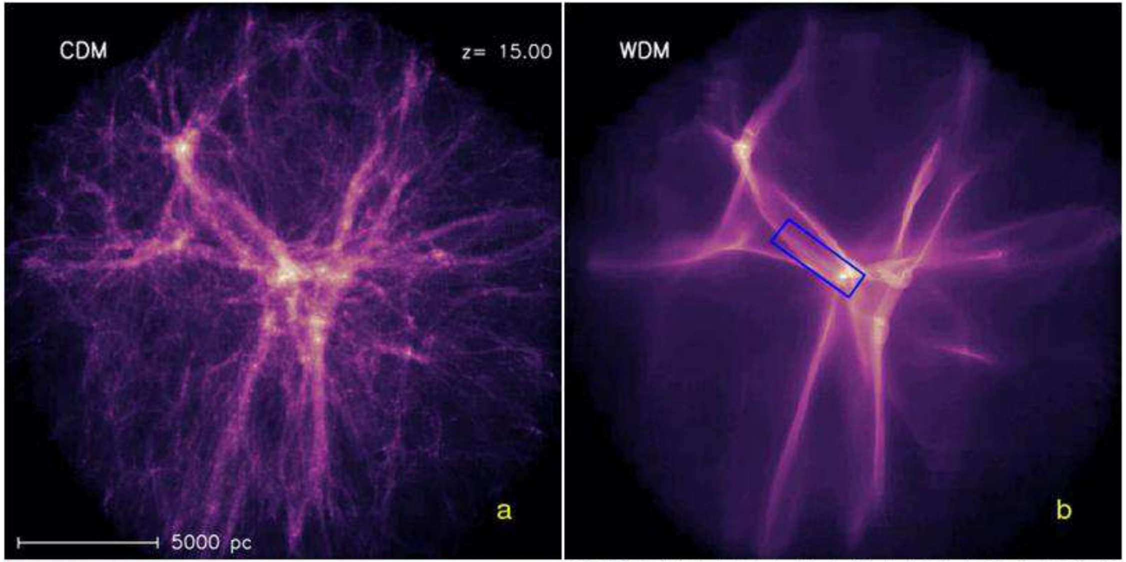
  Large structure -> galaxies



Galaxy formation

2. Cold DM

- Bottom-up scenario : galaxies -> large structure



Ref : Liang & Tom, 2007

Summary

- In general, the density parameter can be presented as a sum of contributions $\Omega = \Omega_{\mathrm{b}} + \Omega_{\mathrm{DM}} + \Omega_{\Lambda}$
- each components $\Omega_{\mathrm{b}} \sim 0.05,\ \Omega_{\mathrm{DM}} \sim 0.265,\ \Omega_{\Lambda} \sim 0.685$

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DM candidates
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