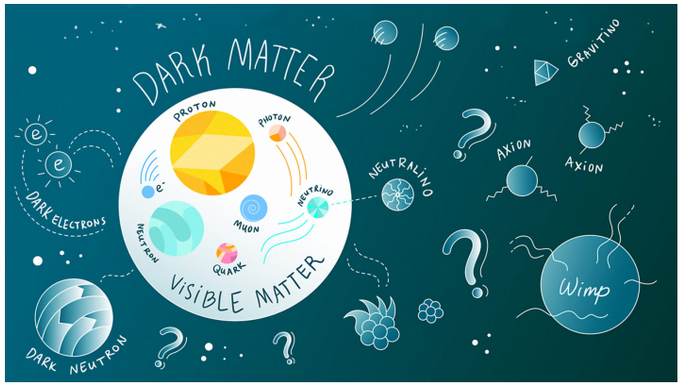


KIAS 입자물리 여름학교 2023

Dark Matter

전북대학교
JEONBUK NATIONAL UNIVERSITY

Seodong Shin

Department of Physics

Contents

1. Evidence of Dark Matter in our Universe

- Introduction
- Motion and Distribution of visible matter
- History of our Universe: Cosmic Microwave Background

2. Properties of Dark Matter

- Astrophysical properties
- Particle physics properties
- Weakly Interacting Massive Particle (WIMP)

Contents

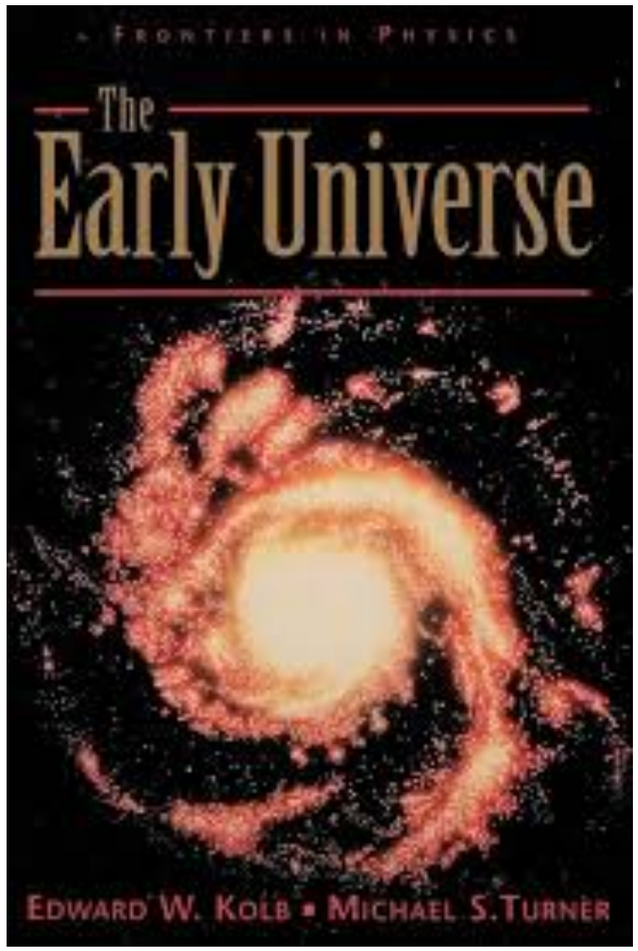
3. Experimental Probes of Dark Matter

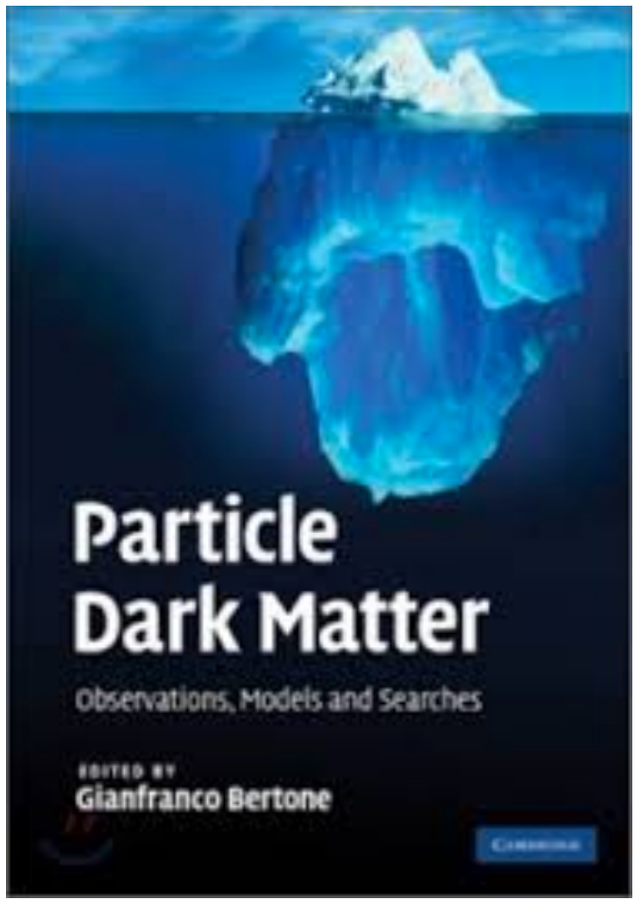
- Direct detection
- Indirect detection
- Collider search

4. Future Direction of Dark Matter Research

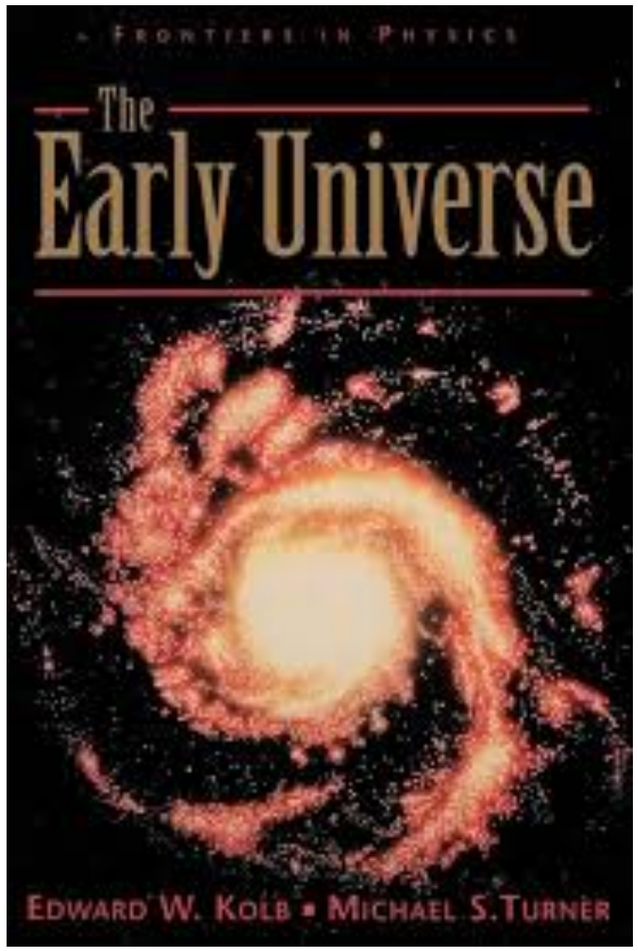
- Short discussion

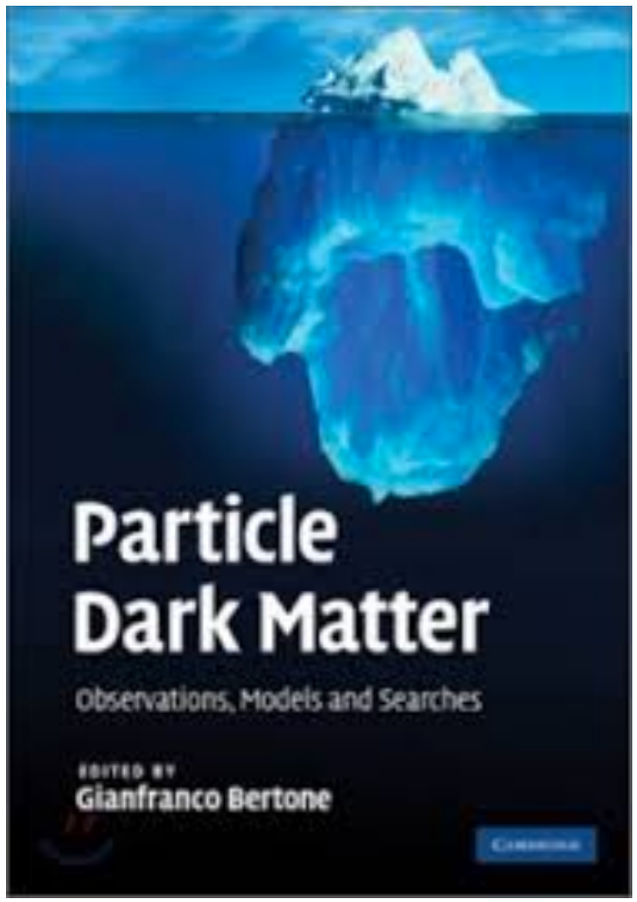
References


Frontiers in Physics
The
Early Universe
Edward W. Kolb • Michael S. Turner


Particle
Dark Matter
Observations, Models and Searches
Edited by
Gianfranco Bertone

References



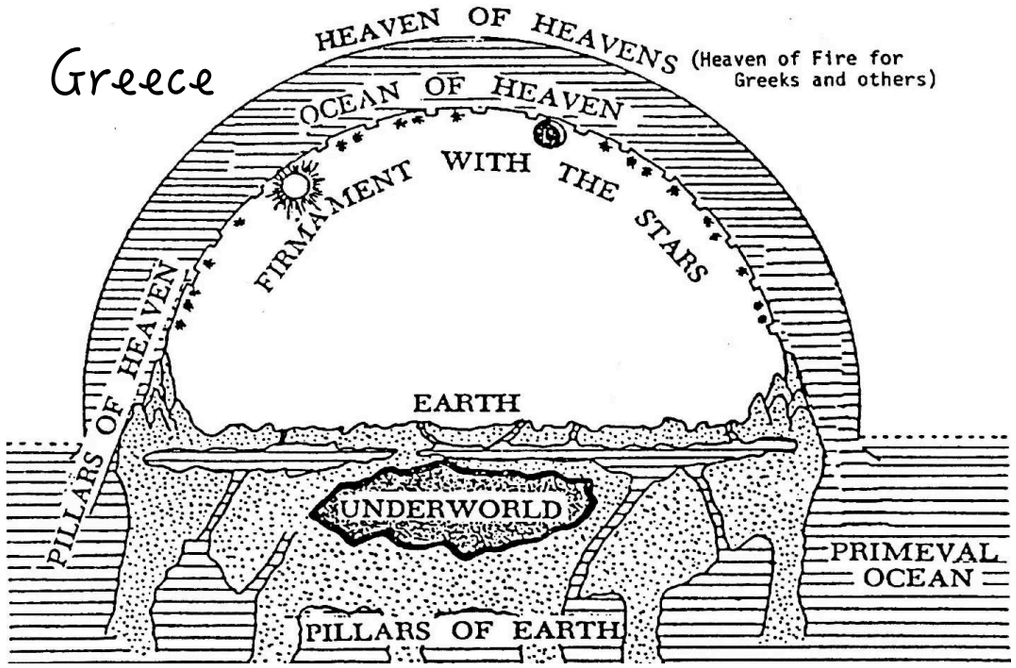


+ TASI or Les Houches lecture notes
(e.g., Profumo 2013, Gelmini 2015, Lisanti 2016, Slatyer 2017, Lin 2019, … and their review papers)

What is Universe?

What is Universe?

Structure of Universe (imagined by ancient people)



Myths and Folklore Wiki



조경철, 프레시안 2009.12.28

고대 인도인의 우주구조의 구상

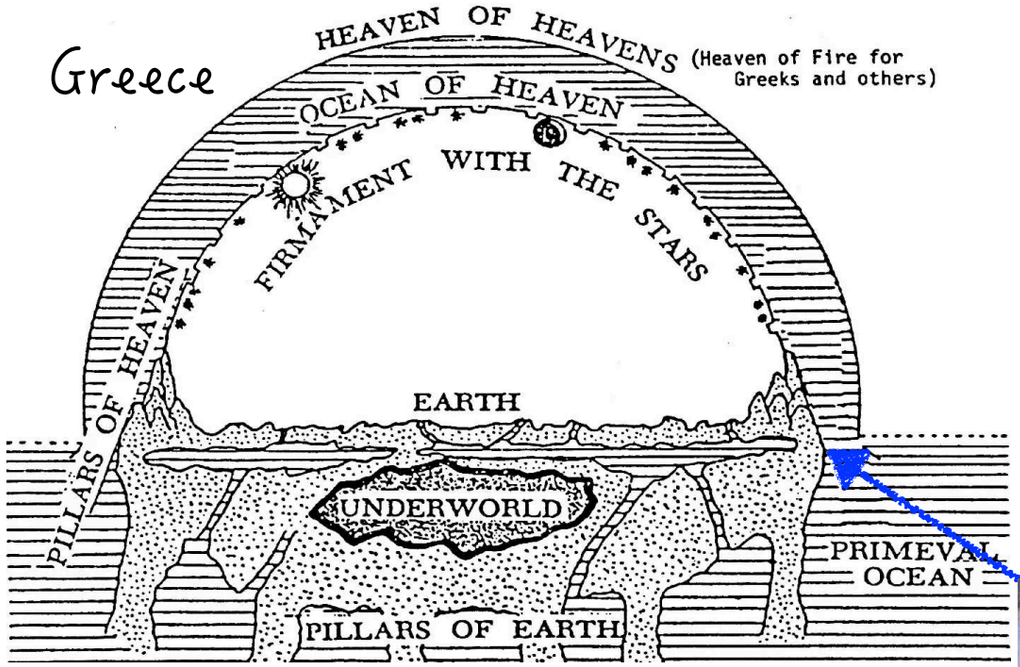


Egypt

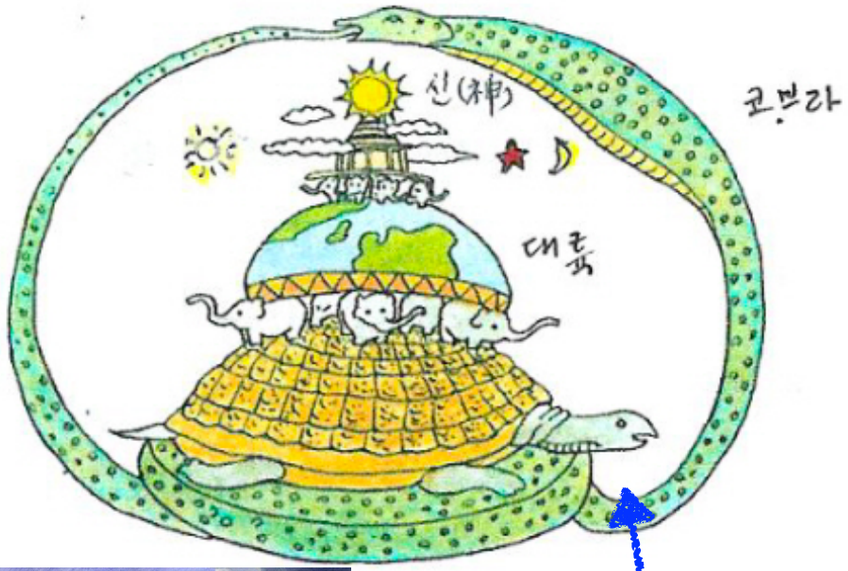
https://www.ancienthistorylists.com/egypt-history/top-10-worshipped-ancient-egyptian-gods/

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Myths and Folklore Wiki



경철, 프레시

의 우주관





Egypt

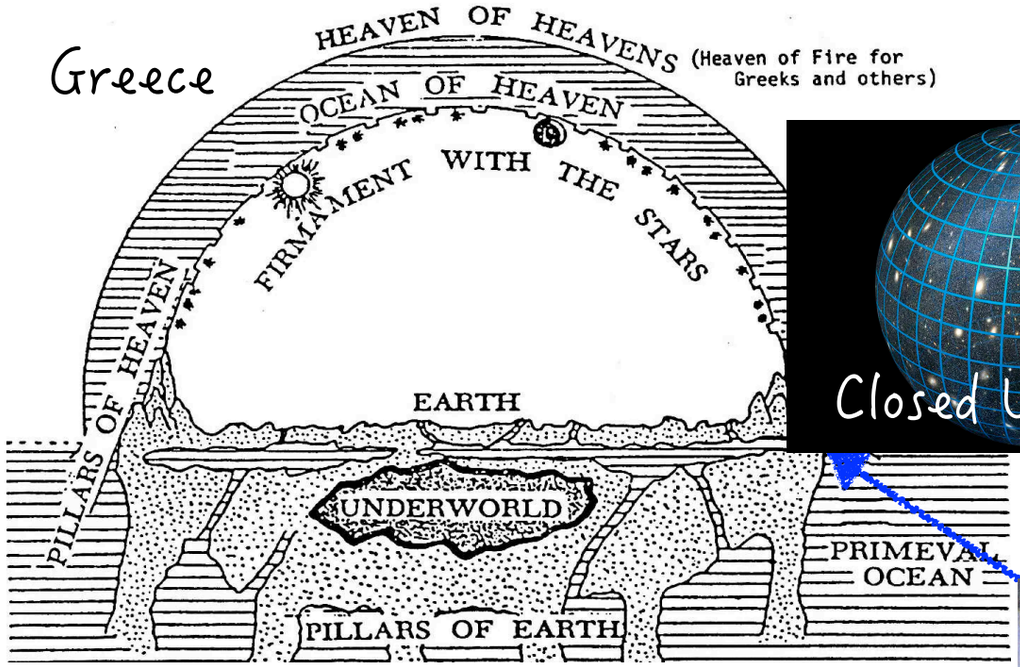


Gods

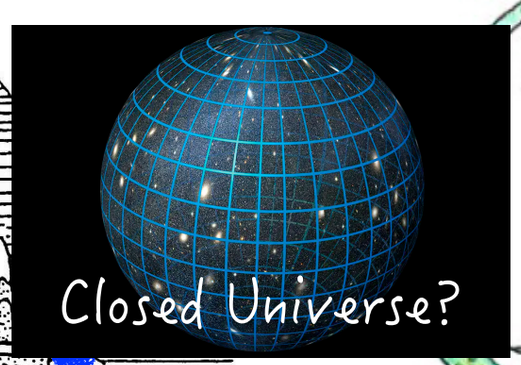
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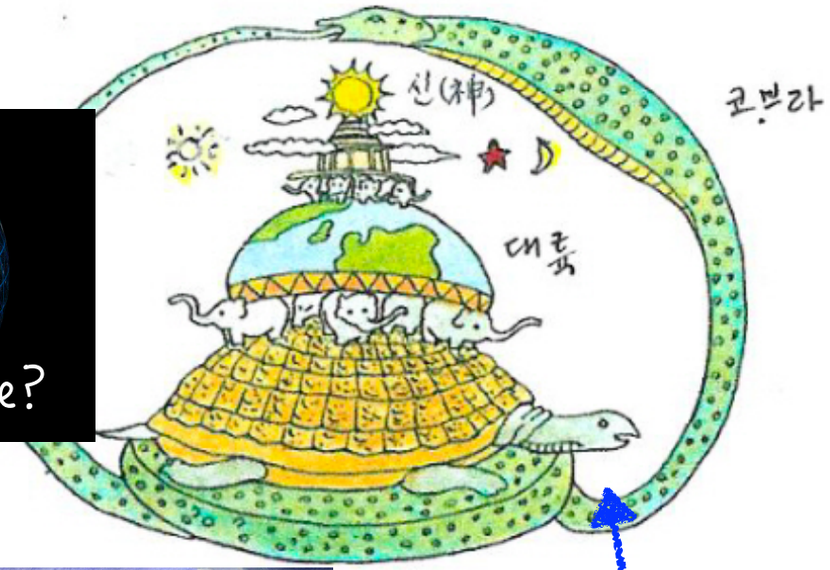
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Myths and Folklore Wiki





경철, 프레시

의 우주관





Egypt

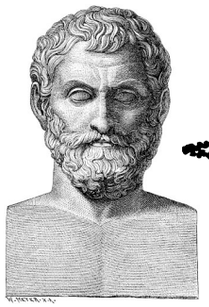


Gods

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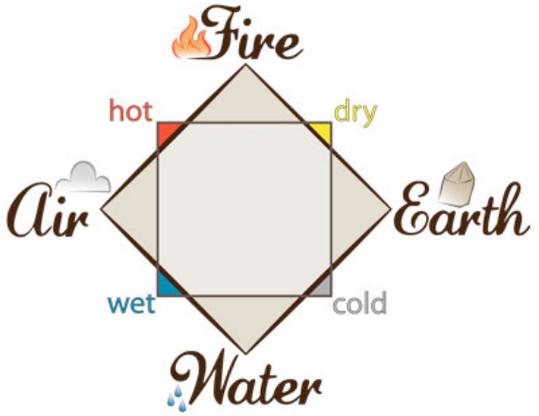
What is Universe?

Structure of Universe (systematically explained with philosophy)



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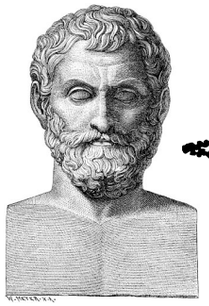
Thales



https://www.patheos.com/blogs/agora/2014/03/seekers-and-guides-an-elemental-journey/

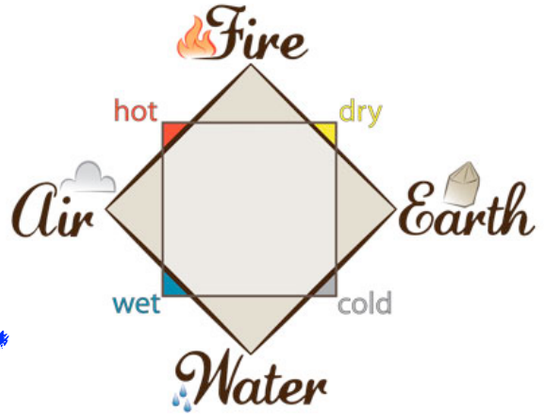
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Structure of Universe (systematically explained with philosophy)

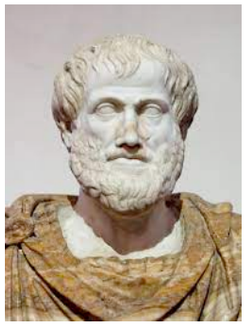


만물의 근원은 물

Thales



https://www.patheos.com/blogs/agora/2014/03/seekers-and-guides-an-elemental-journey/



Aristotle

\+

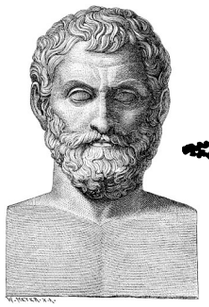
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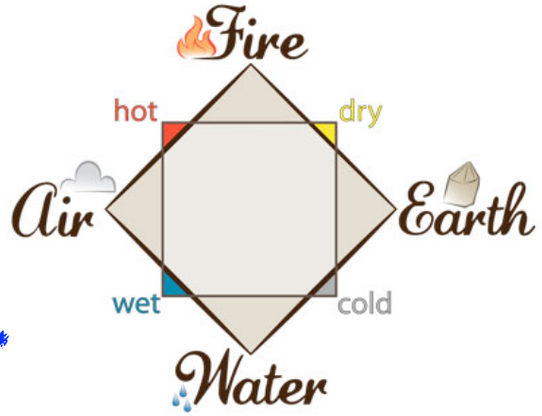
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Aristotle

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Aether



https://elementsunearthed.com/tag/aristotle/

Structure of Universe (large scale) is explained by the fundamental elements (small scale)!

What is Universe?

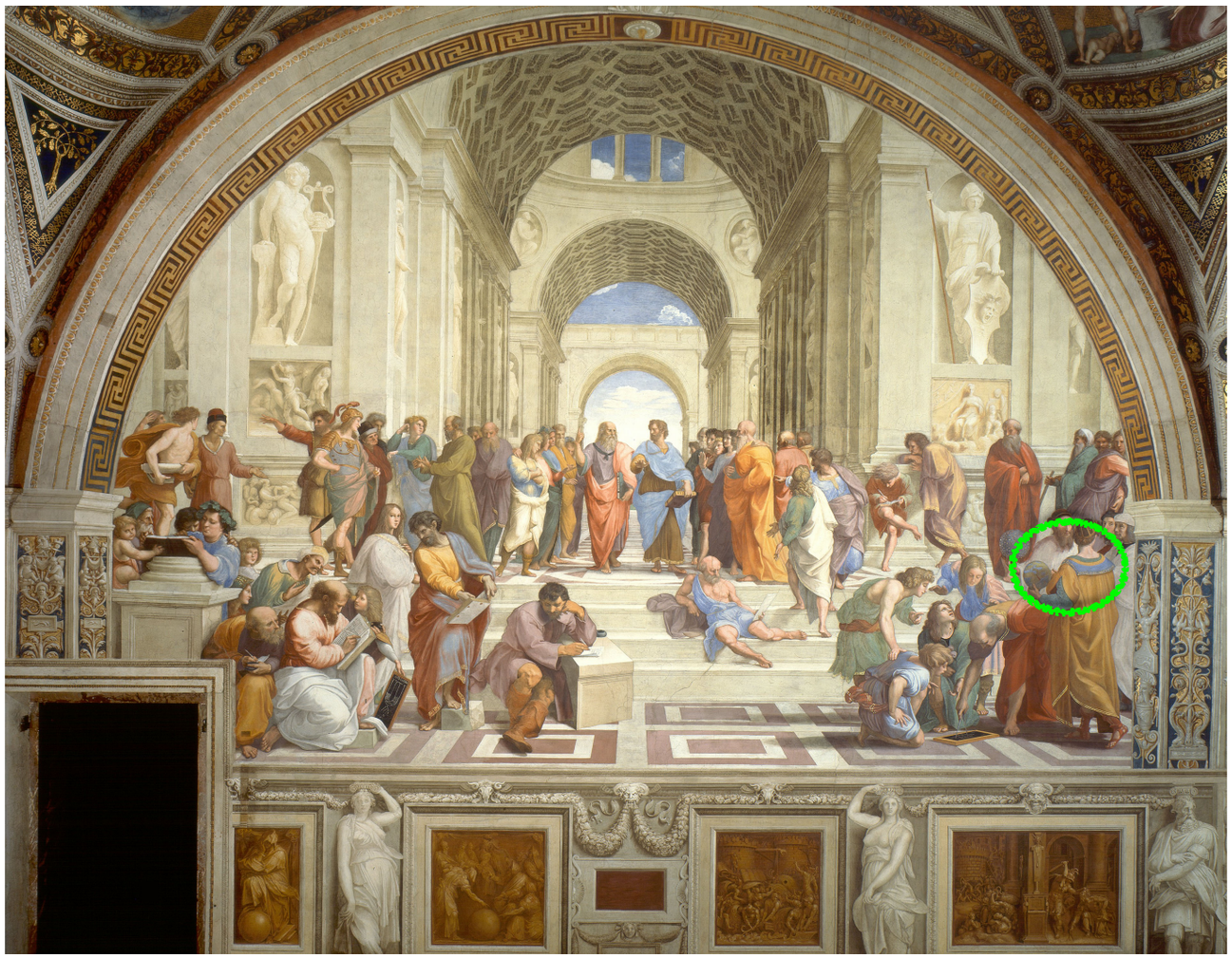
Structure of Universe (systematically explained with philosophy)



라파엘로, 아테네학당

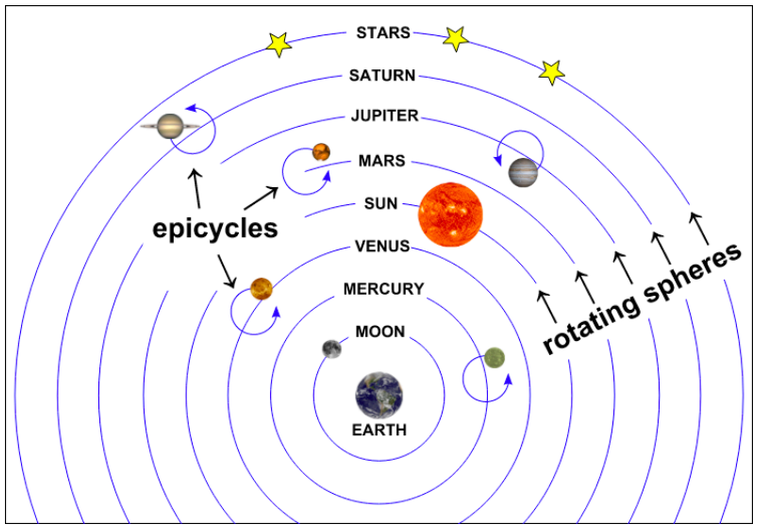
What is Universe?

Structure of Universe (systematically explained with philosophy)



라파엘로, 아테네학당

Geocentric model

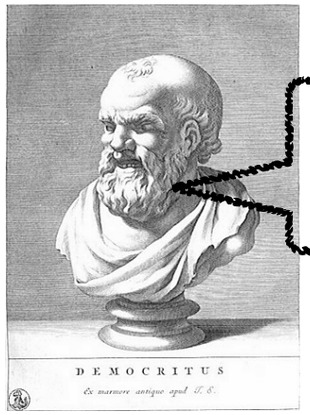


Faithful Science

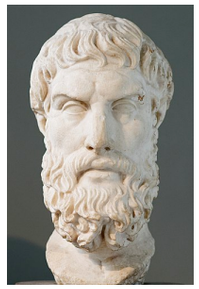
Ptolemy

What is Universe?

Structure of Universe (systematically explained with philosophy)

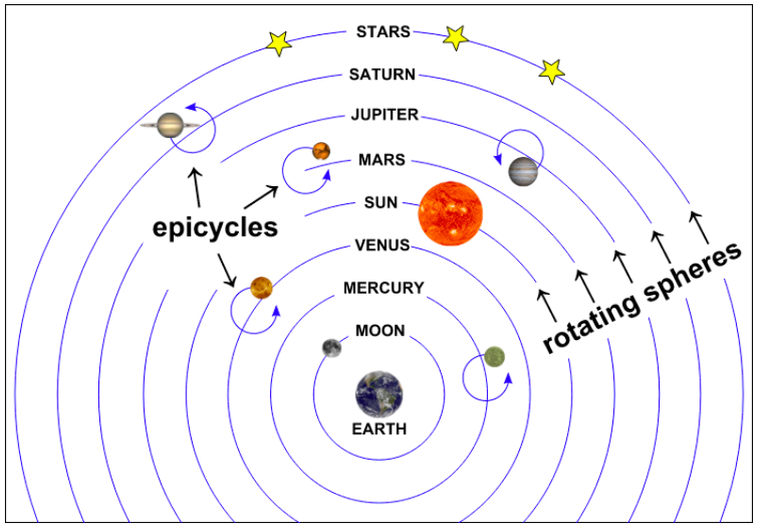


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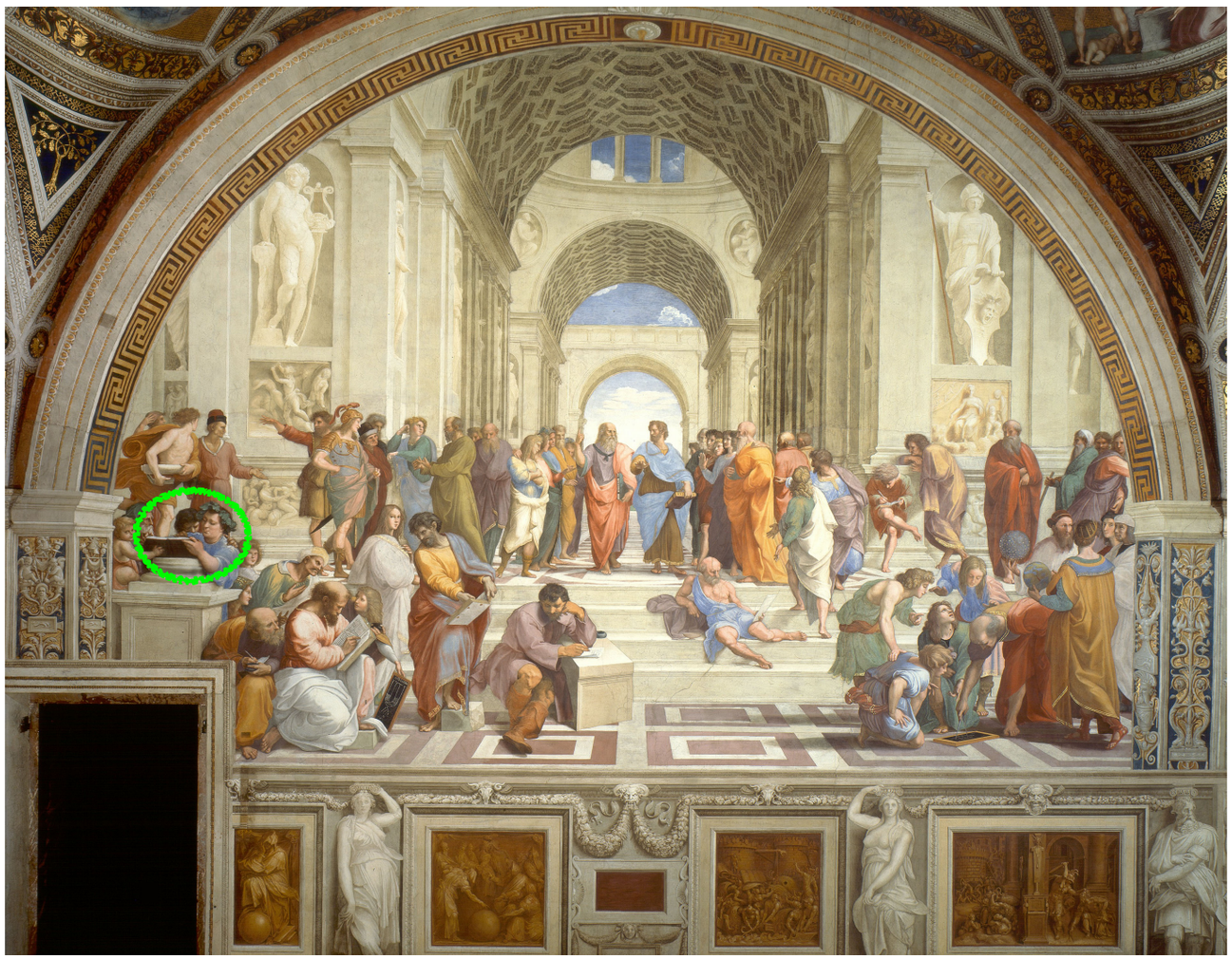
or Epicurus?

Geocentric model



Faithful Science

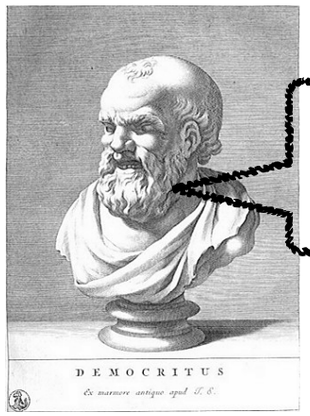
Ptolemy



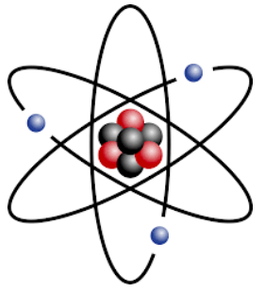
라파엘로, 아테네학당

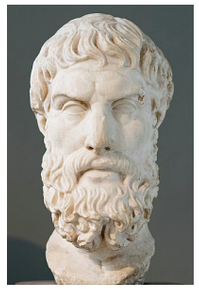
What is Universe?

Structure of Universe (systematically explained with philosophy)



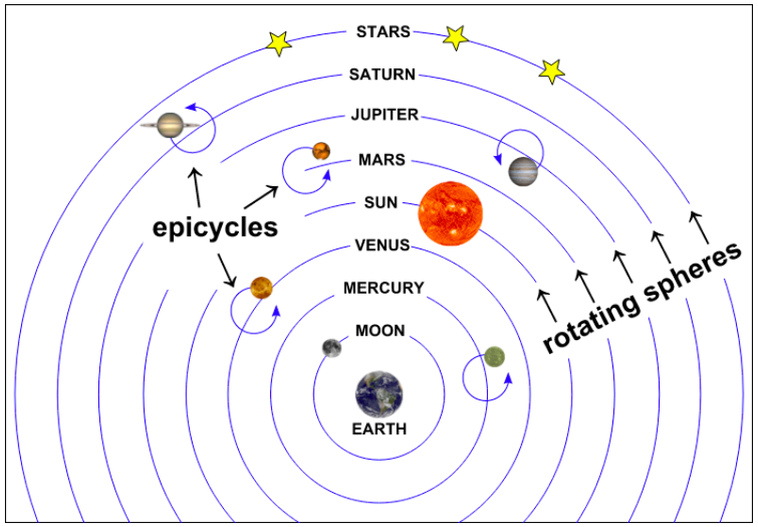
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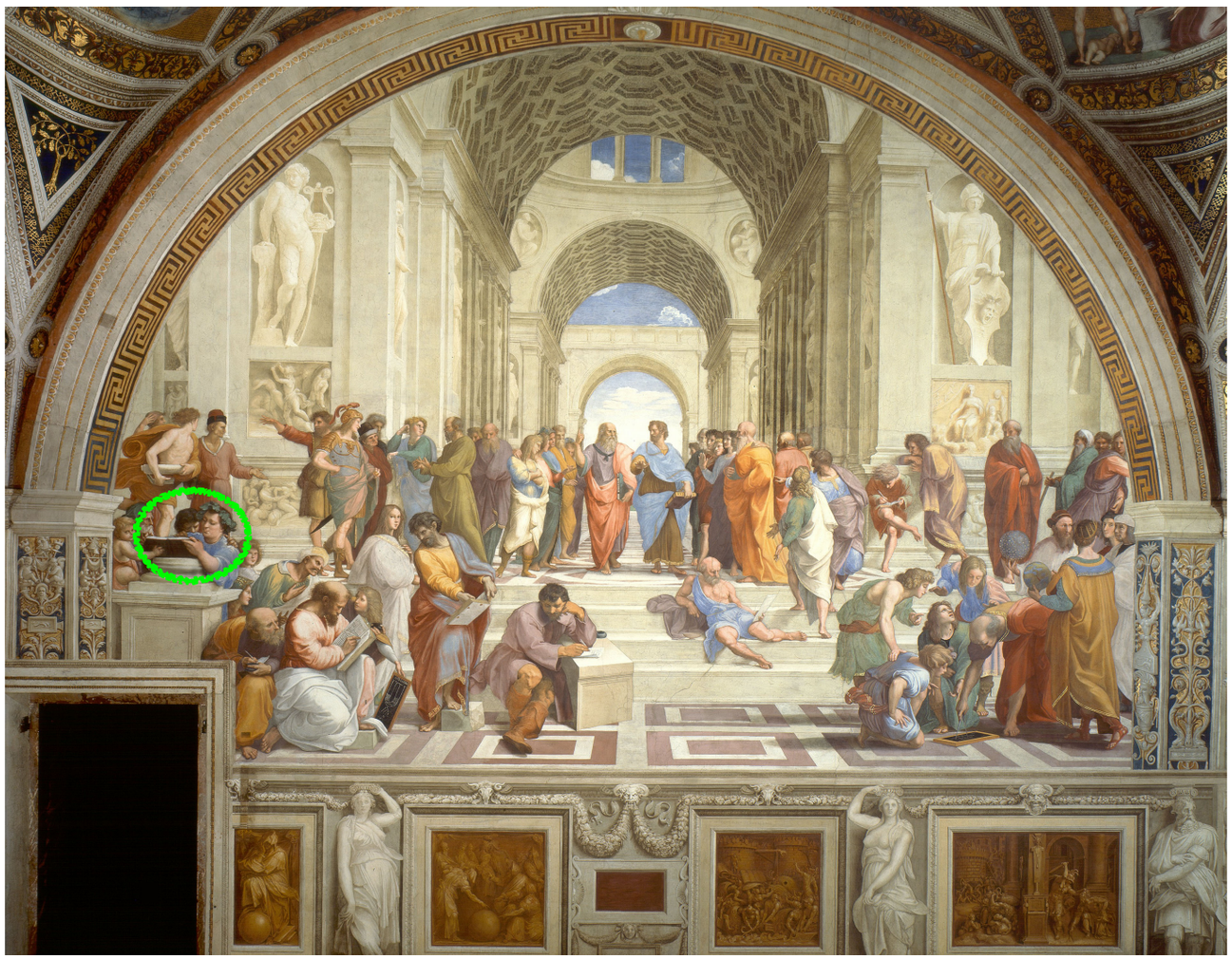
or Epicurus?

Geocentric model



Faithful Science

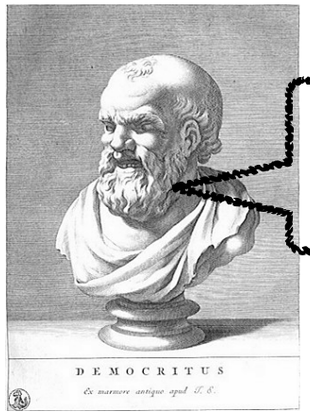
Ptolemy



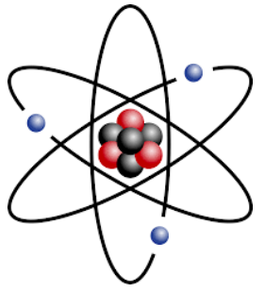
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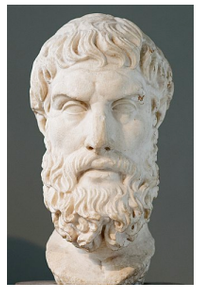
What is Universe?

Structure of Universe (systematically explained with philosophy)



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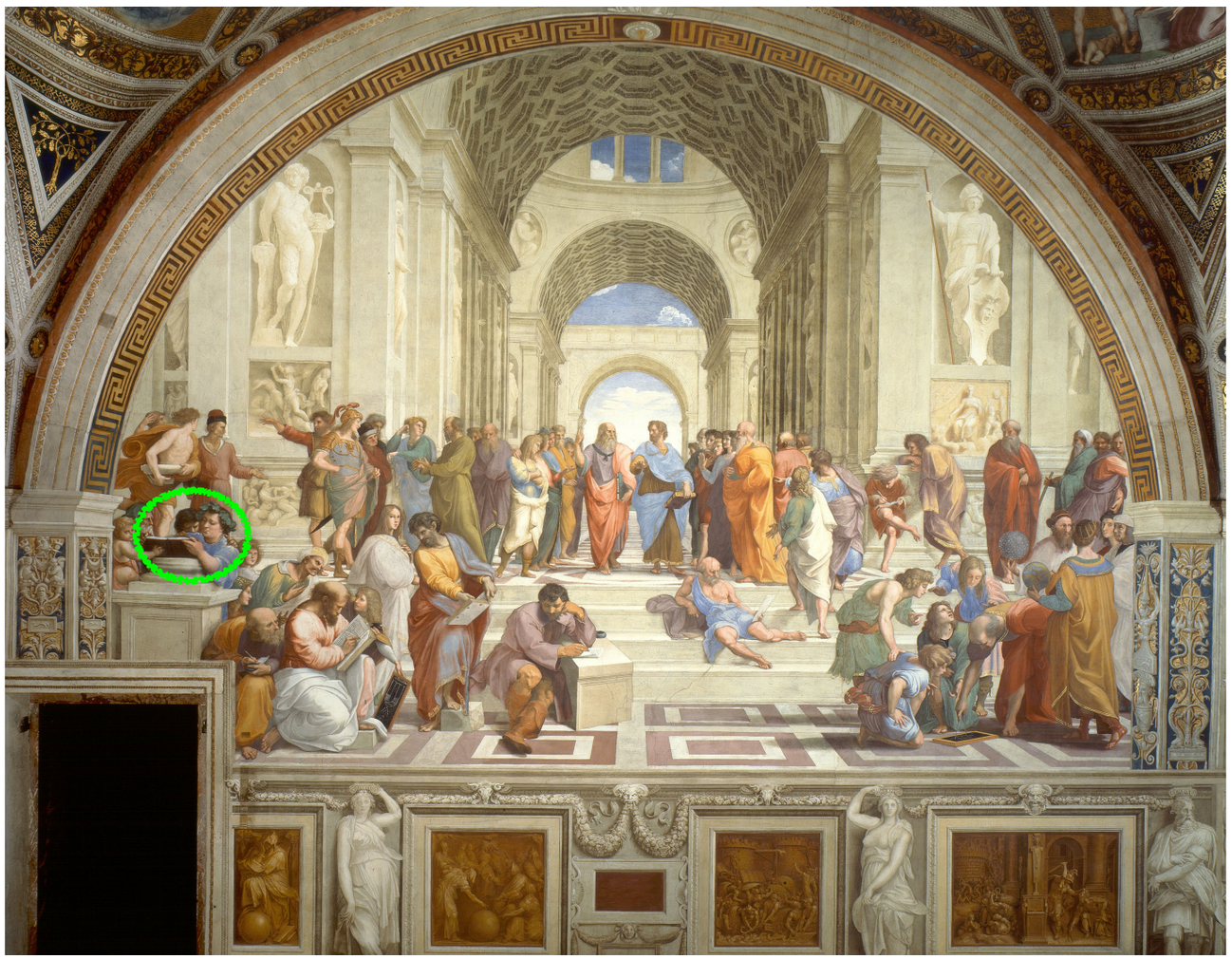


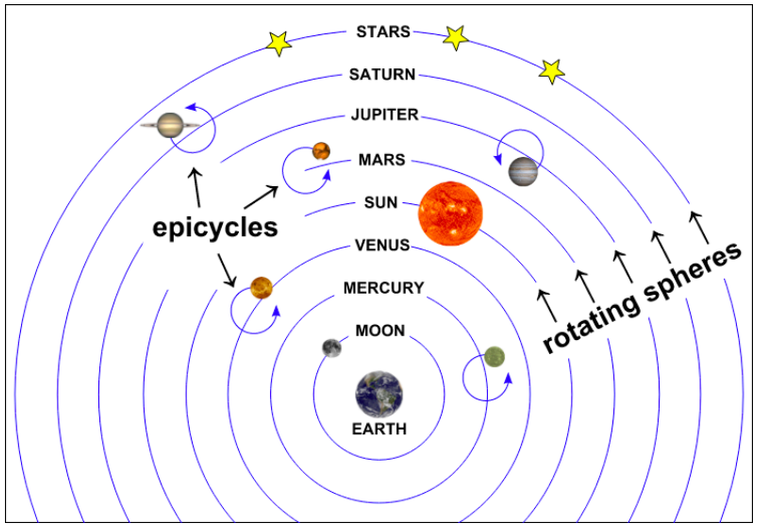


or Epicurus?

Universe is infinite
(not a closed space)

Geocentric model



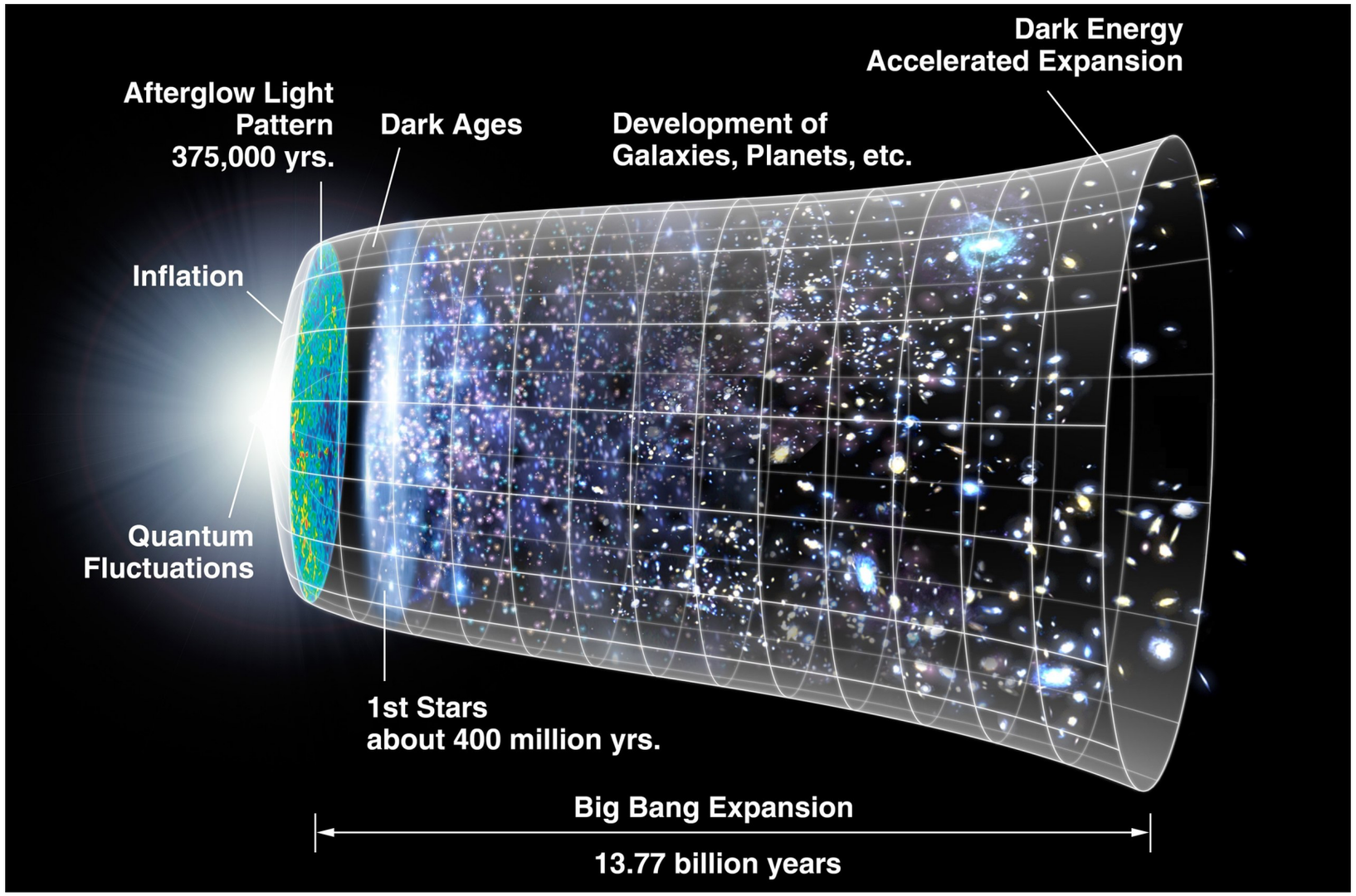


Faithful Science

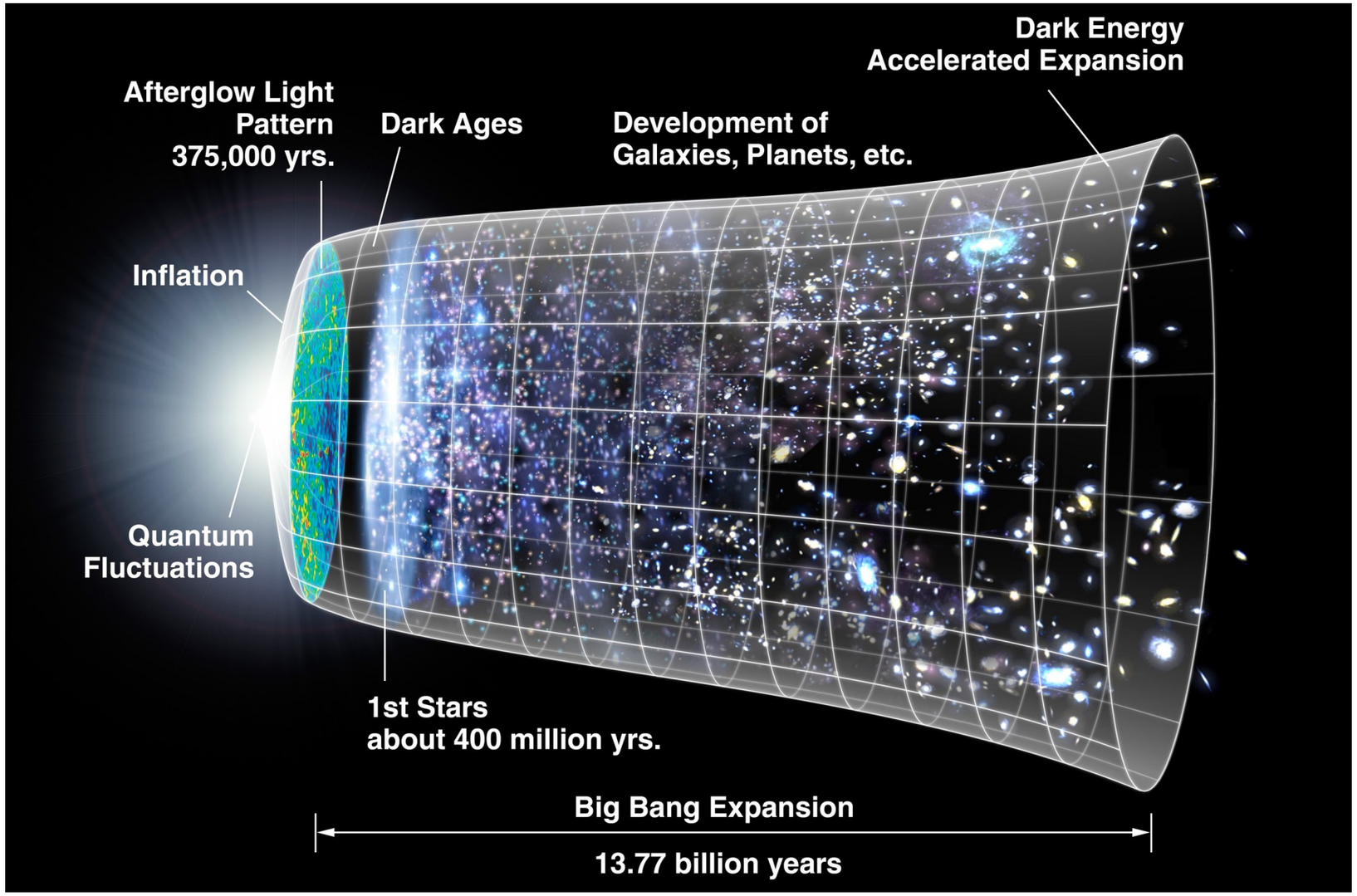
Ptolemy

라파엘로, 아테네학당

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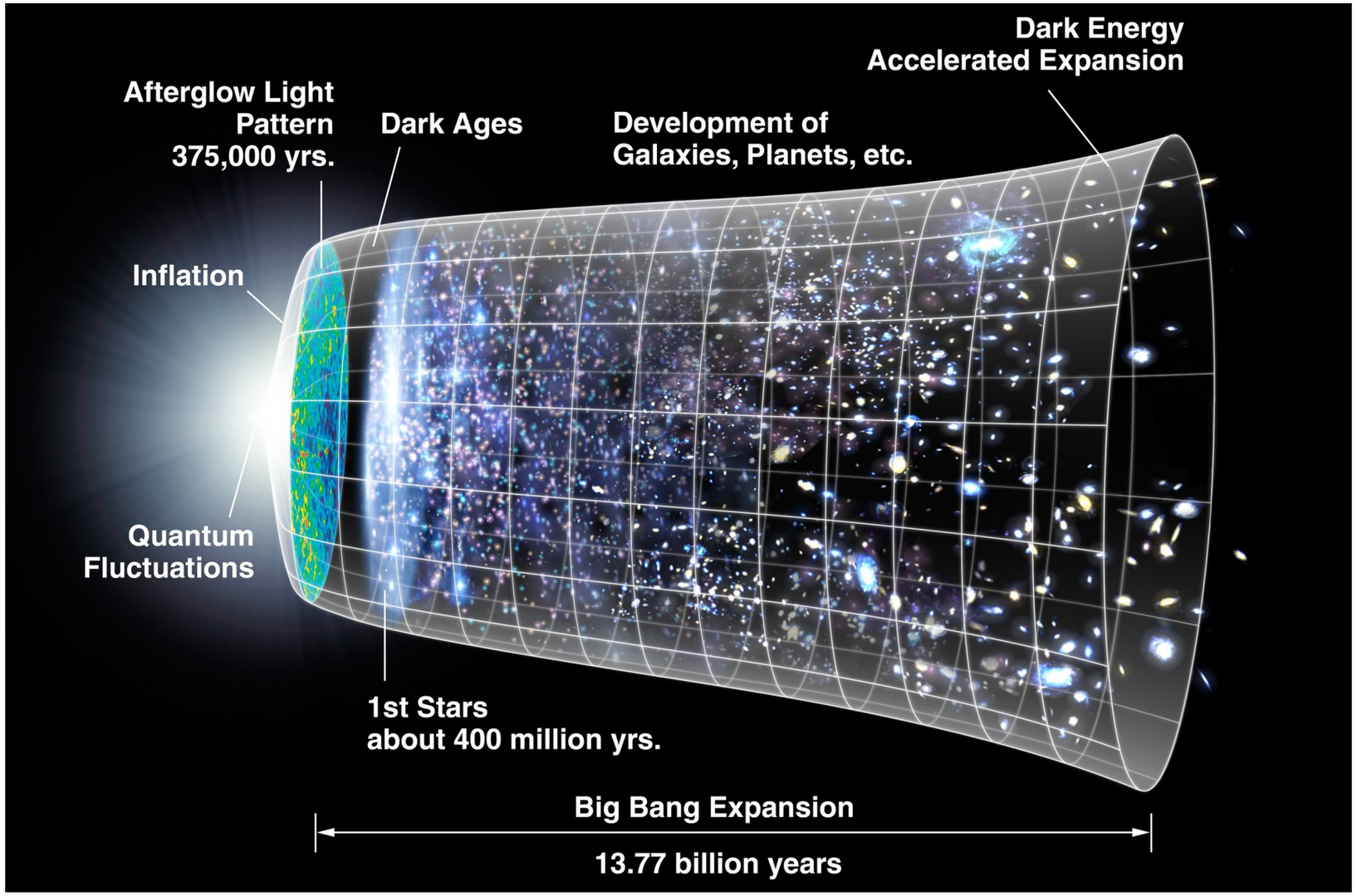


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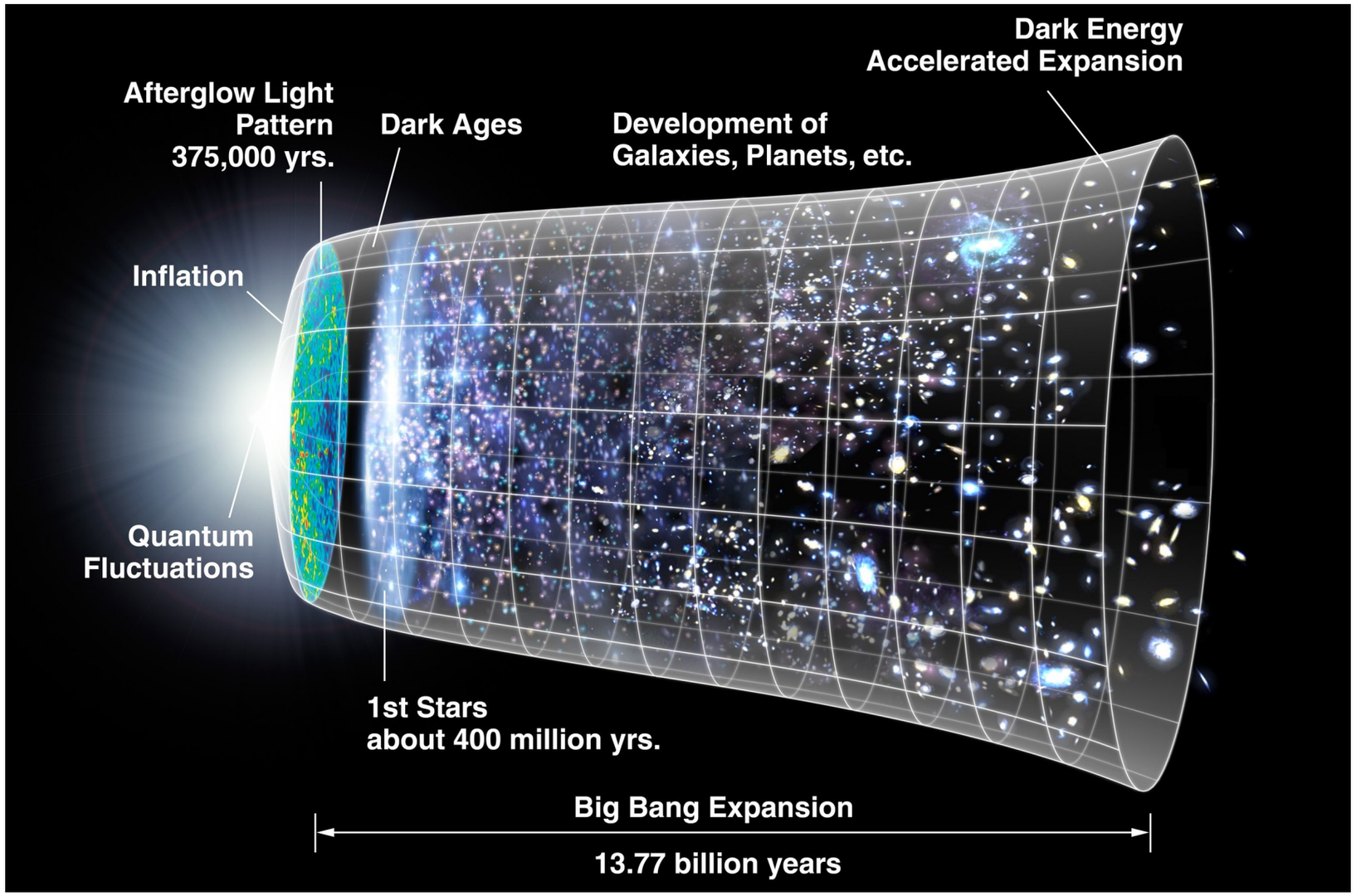
- What is it made of?
- How does it change?

What is Universe?



- What is it made of? Elementary particles
- How does it change?

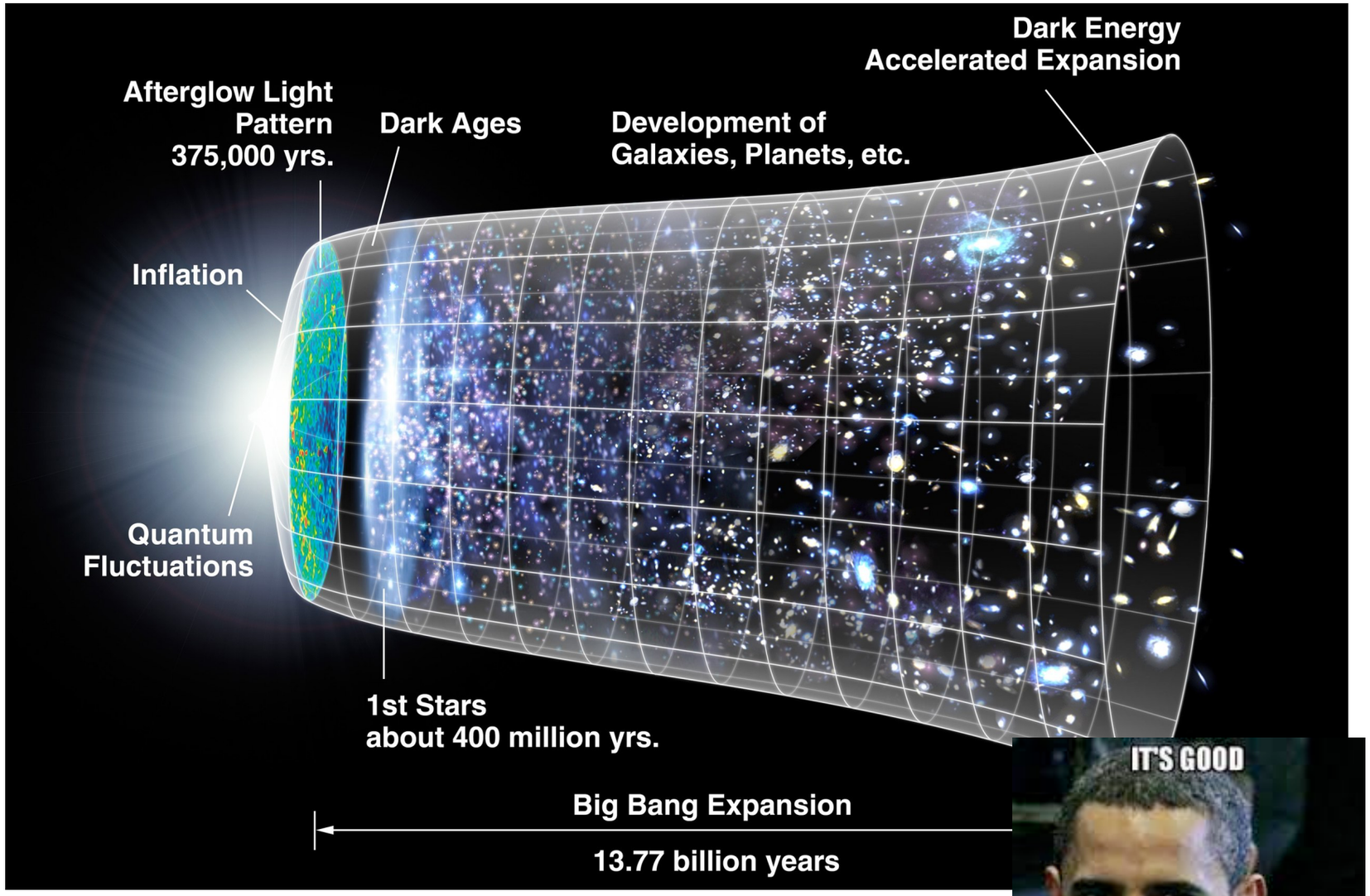
What is Universe?



- What is it made of? Elementary particles
- How does it change? General Relativity

  Fundamental interactions among the particles

What is Universe?



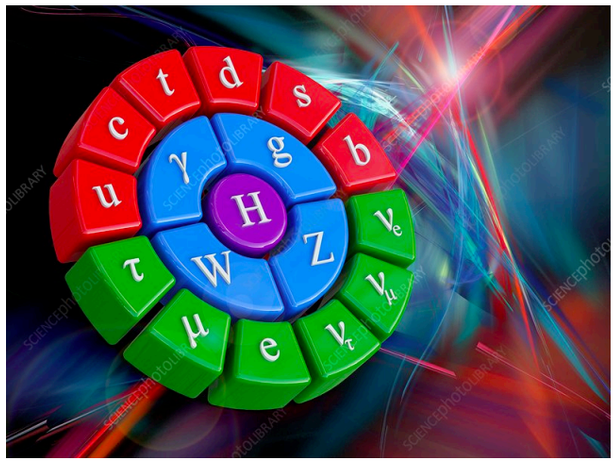


- What is it made of? Elementary particles
- How does it change? General Relativity

  Fundamental interactions among the particles

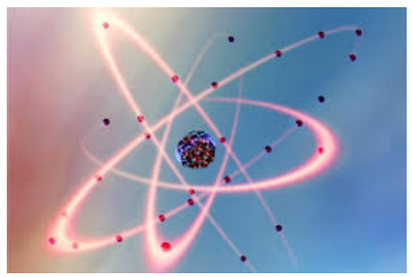
What is Universe?

Standard Model

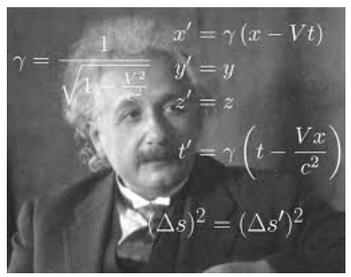


SU(3)×SU(2)×U(1)

Prof. K.S. Jeong's lecture



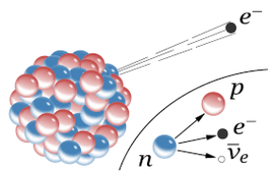
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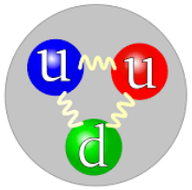
Quantum Field Theory



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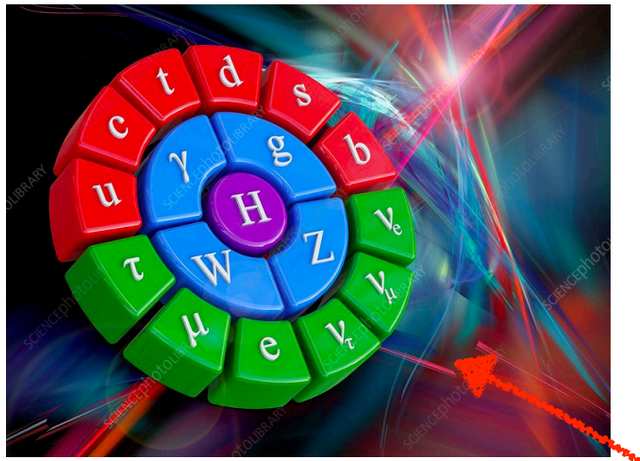


- What is it made of? Elementary particles
- How does it change? General Relativity

  Fundamental interactions among the particles

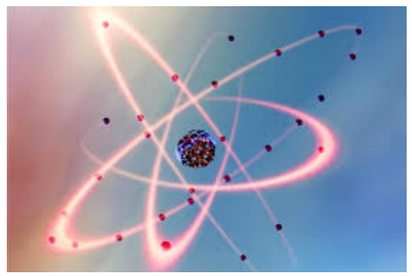
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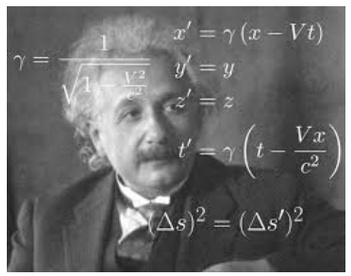


SU(3)×SU(2)×U(1)

Prof. K.S. Jeong's lecture



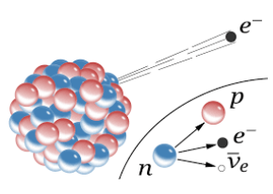
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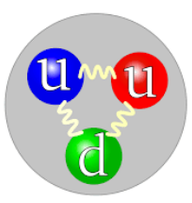
Quantum Field Theory



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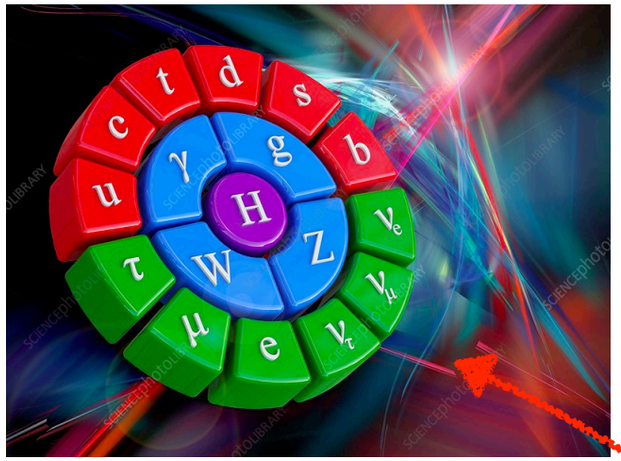


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- How does it change? General Relativity

  Fundamental interactions among the particles

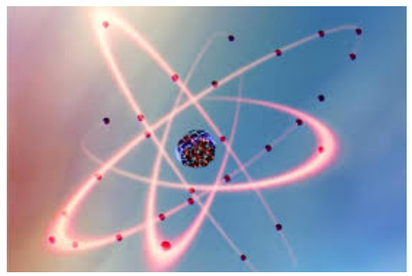
What is Universe?

Standard Model

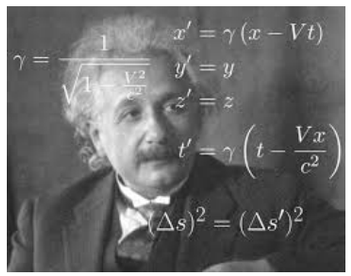


SU(3)×SU(2)×U(1)

Prof. K.S. Jeong's lecture



+



Quantum Field Theory

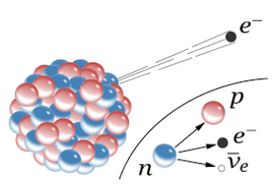
Symmetry: the tool understanding Universe



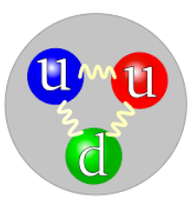
Emmy Noether



+



+

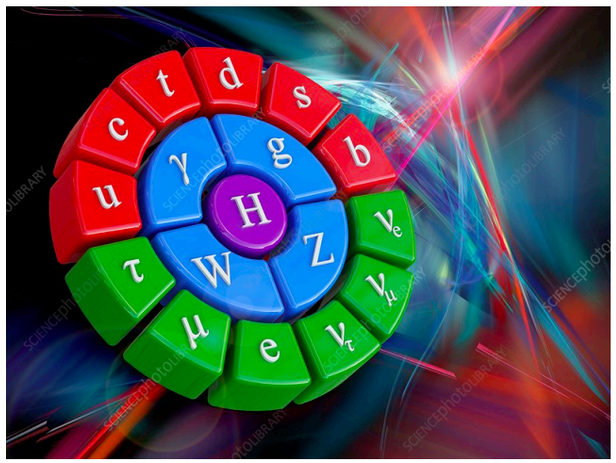


- What is it made of? Elementary particles
- How does it change? General Relativity

Fundamental interactions among the particles

What is Universe?

Standard Model + GR is not the theory of everything.



SU(3)×SU(2)×U(1)

Prof. K.S. Jeong's lecture

- Theoretical reason for $m_H \ll m_P$, m_{GUT}?

  Hierarchy problem

- Unification of the symmetries into a single larger symmetry?

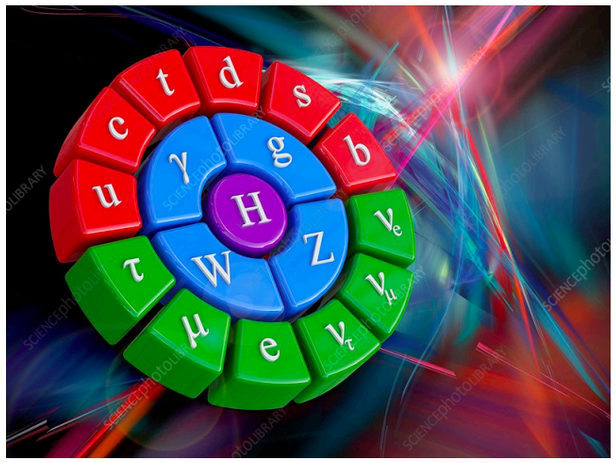
- Quantization of gravity?

- What is it made of? Elementary particles
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Prof. K.S. Jeong's lecture

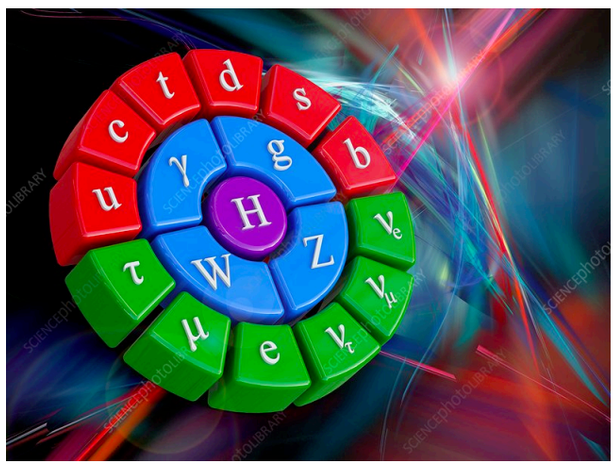
- Oscillation of the neutrinos?
- Asymmetry between matter - antimatter?
- Cosmological constant: a ground state energy of quantum fluctuations of everything in Universe is about 10^{-120} small?
- Why is Universe same everywhere and every direction?

- What is it made of? Elementary particles
- How does it change? General Relativity

  Fundamental interactions among the particles

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Standard Model + GR is not describing Universe correctly.



The existence of Dark Matter
and Dark Energy

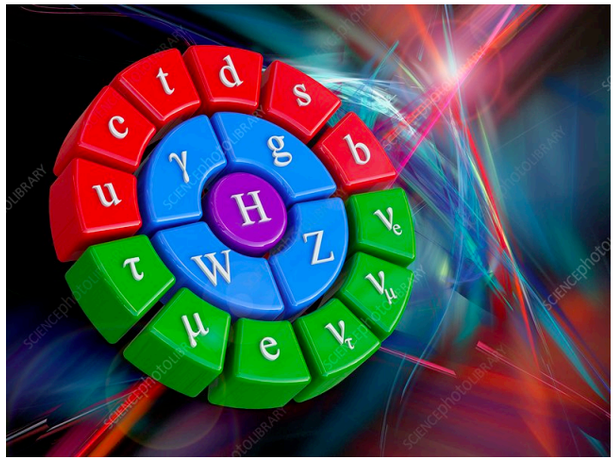
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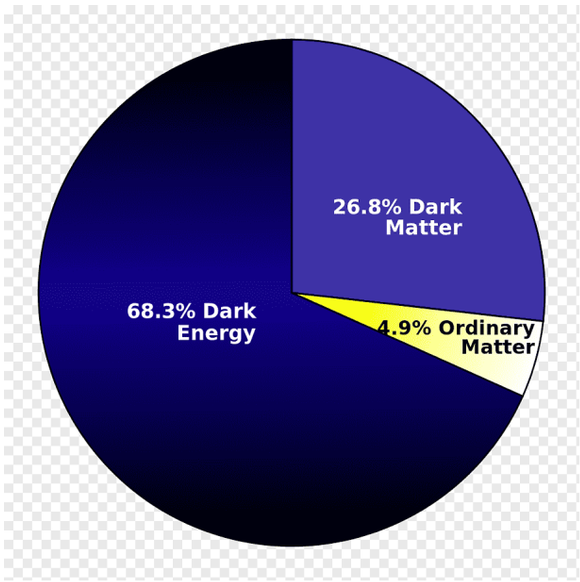
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SU(3)×SU(2)×U(1)

95%

The existence of Dark Matter and Dark Energy

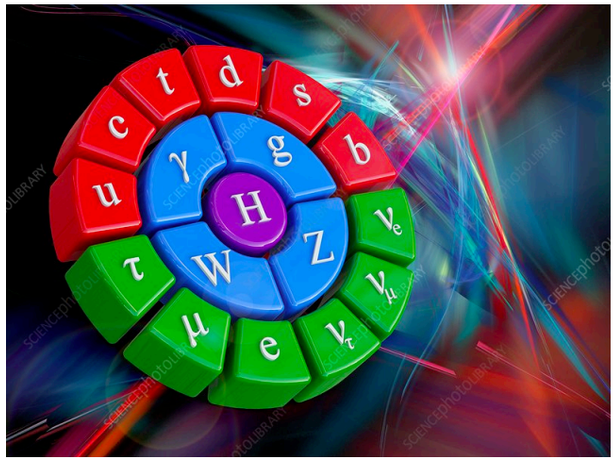


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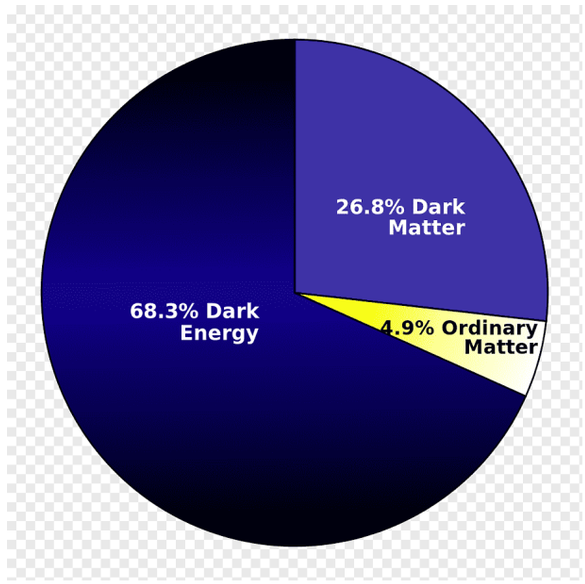
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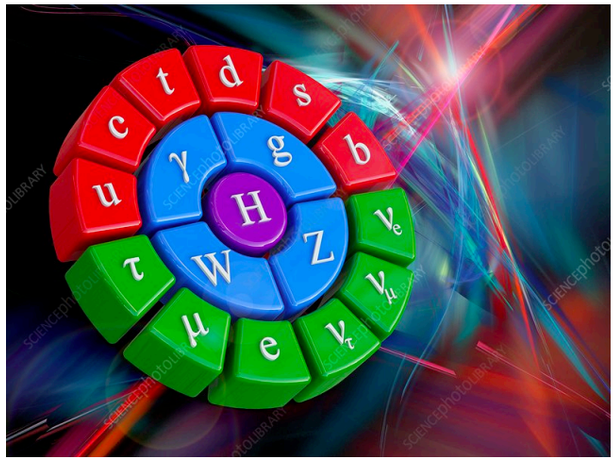


Evolution of Universe

- What is it made of? Elementary particles
- How does it change? ~~General Relativity~~ Fundamental interactions among the particles

What is Universe?

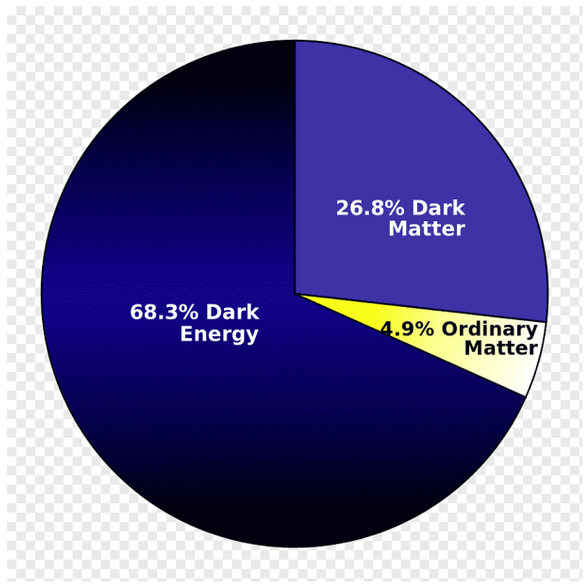
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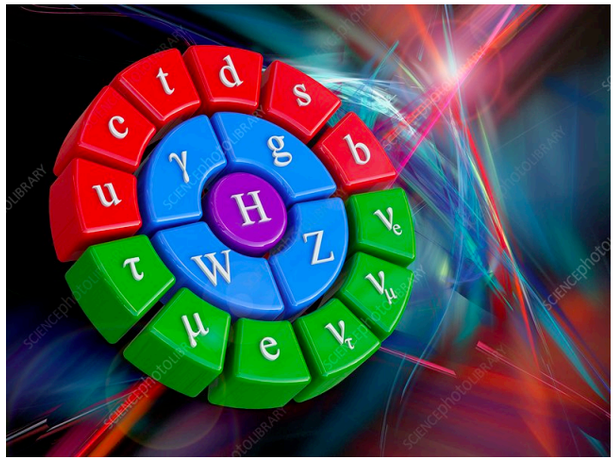


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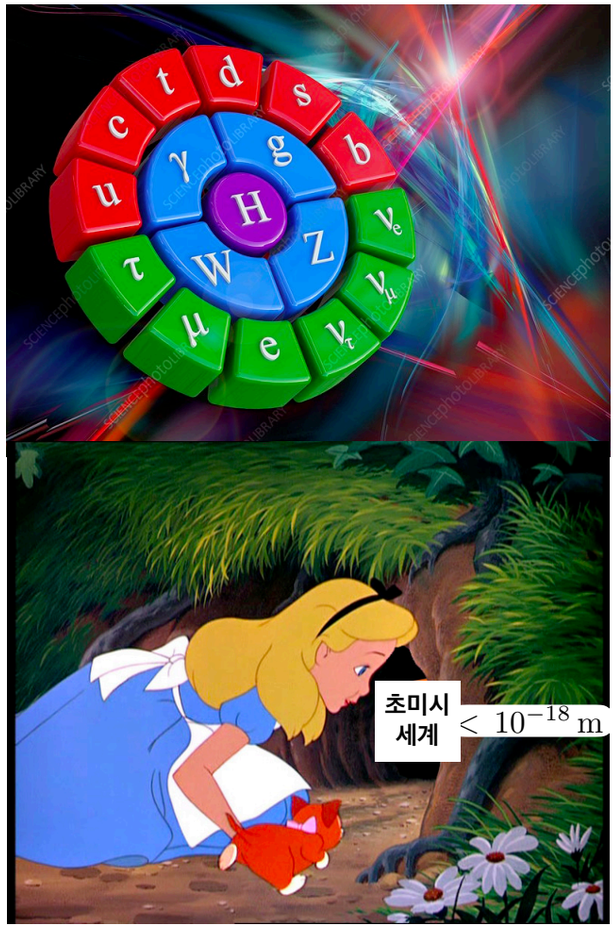
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Standard Model



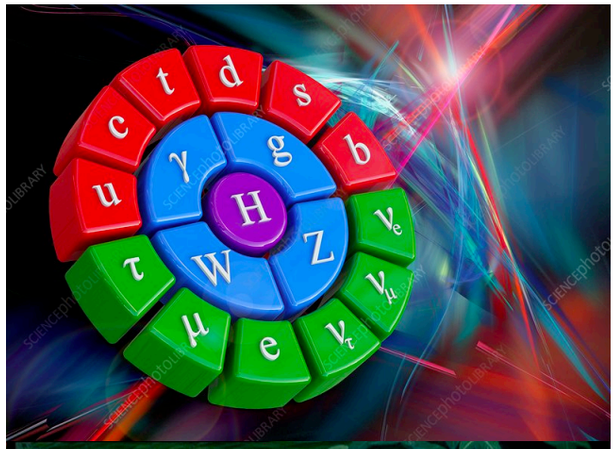
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Standard Model



What is Universe?

Standard Model



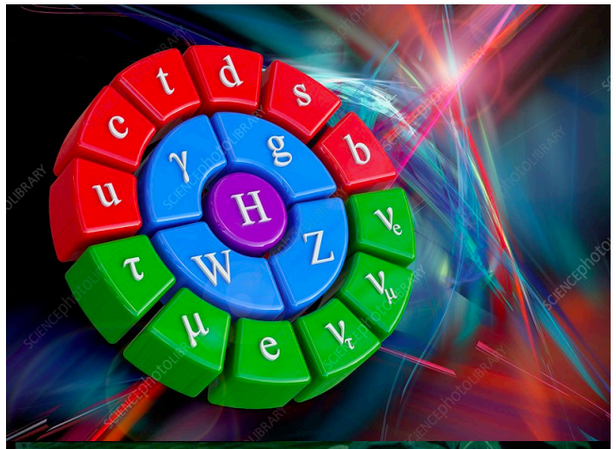


New Physics beyond the Standard Model



What is Universe?

Standard Model

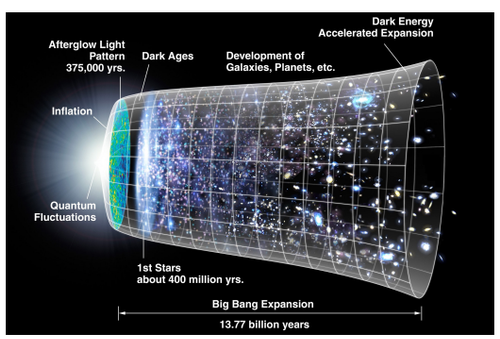




New Physics beyond the Standard Model

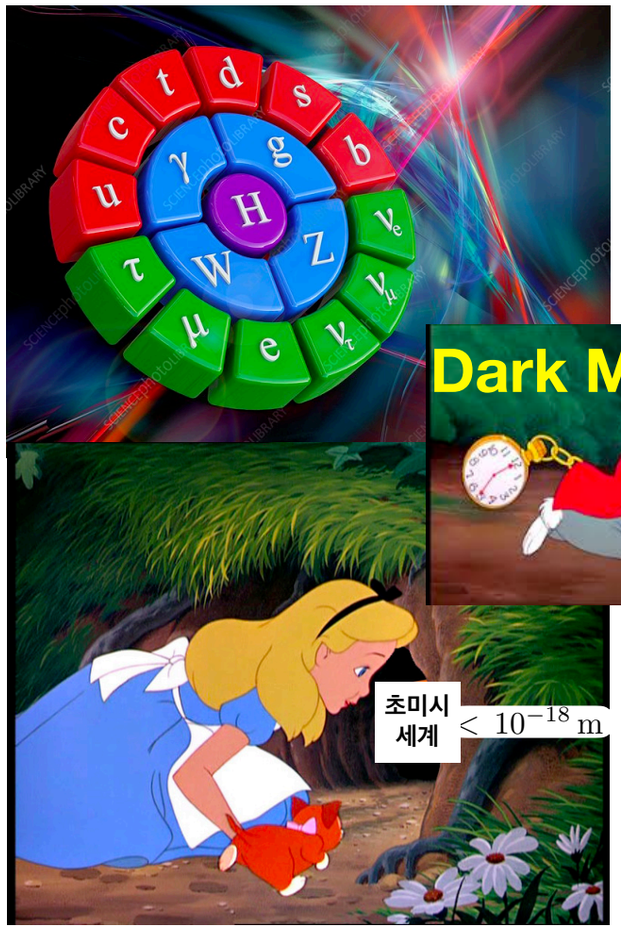


- What is it made of? — New particles
- How does it change? — New symmetries



What is Universe?

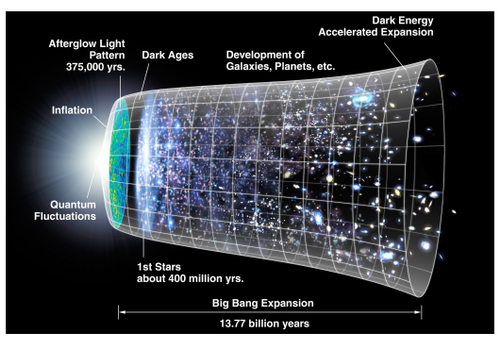
Standard Model



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Dark matter and structure of Universe

What is Dark Matter?

Dark matter and structure of Universe

What is Dark Matter?

- Invisible: transparent for lights with any wavelengths
- Massive: gravitational interaction
- Cold (or slightly warmer): much slower than the light
- A lot: 5 times more than the ordinary matter
- Cosmologically stable

Dark matter and structure of Universe

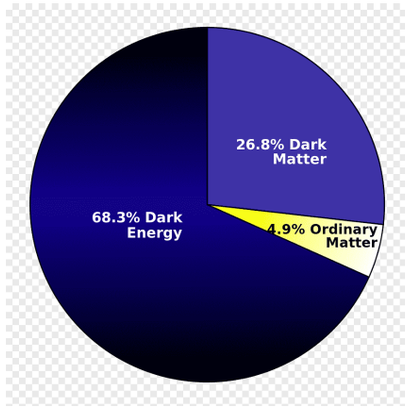
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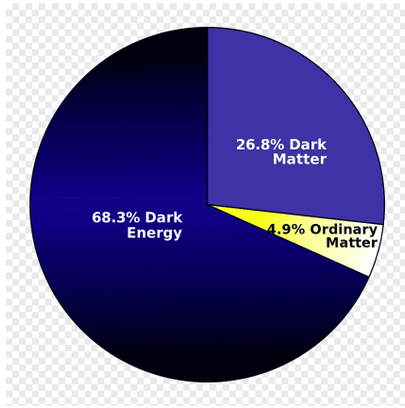
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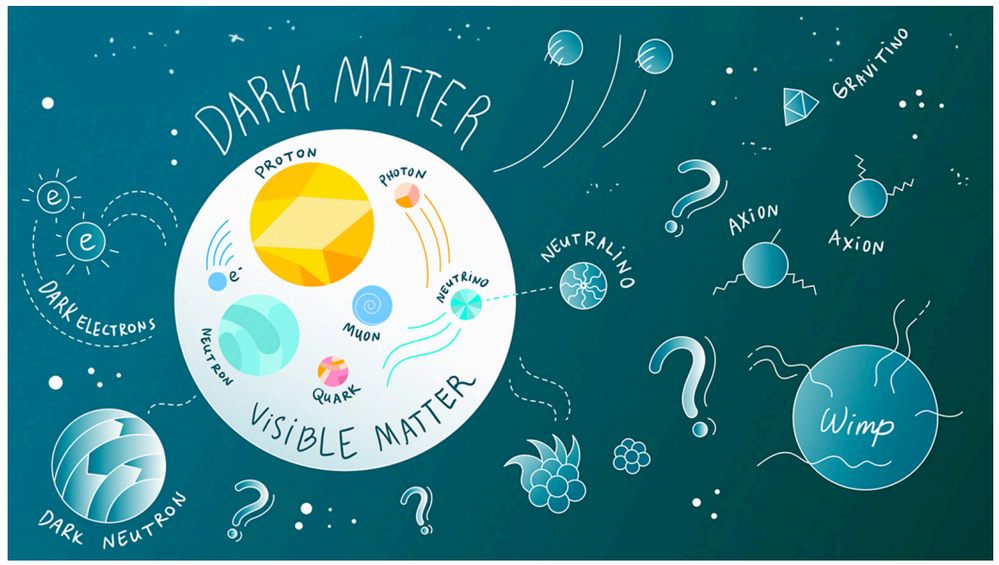
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Nobody knows
what it is exactly.



Symmetry magazine

Evidence of Dark Matter in our Universe (gravitational interaction)

- Motion of visible matter
- Distribution of visible matter
- History of our Universe (observed by light)

Natural unit

Normalized to the physical constants such as

e: electric charge

c: speed of light

$\hbar$: (reduced) Planck constant

k_B: Boltzmann constant

....

$$\hbar = c = k_B = 1$$

$$E = \sqrt{m^2c^4 + p^2c^2} = \sqrt{m^2 + p^2}$$

eV: kinetic **energy** of an electron accelerated (from rest) by an electric potential difference 1 volt

Prof. K.S. Jeong's lecture

Energy, momentum, mass, length

De Broglie wavelength $\lambda = h/p = [h/(E/c)] = (2\pi)[\hbar c/E]$

Length 1 eV^{-1} $1.97 \times 10^{-7}\,\mathrm{m} = \dfrac{\hbar c}{1\,\mathrm{eV}}$

Mass 1 eV $1.78 \times 10^{-36}\,\mathrm{kg} = \dfrac{1\,\mathrm{eV}}{c^2}$

$0.197\,\mathrm{GeV} \cdot \mathrm{fm} = 1$

$3 \times 10^8 m/s = 1$

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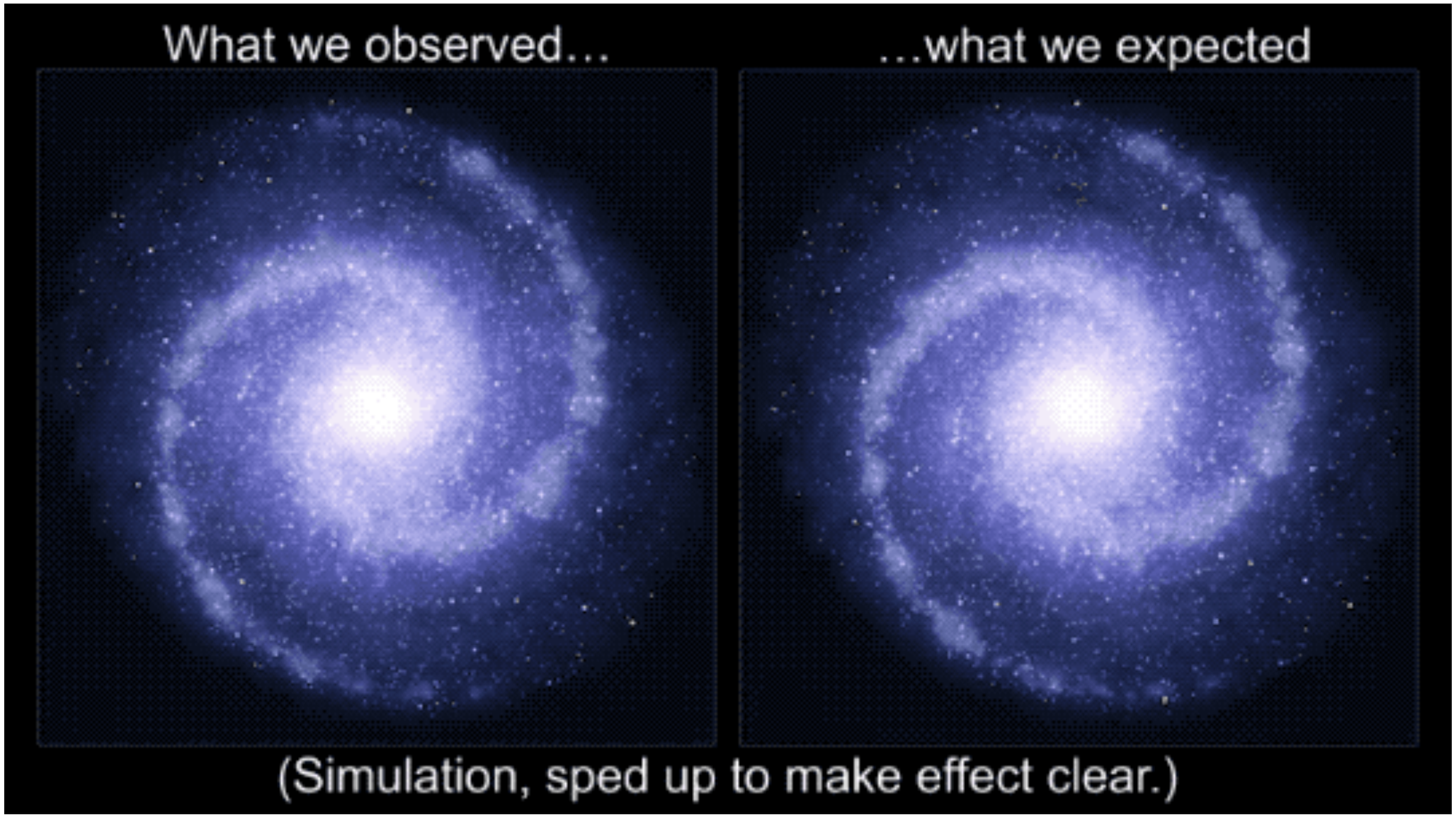
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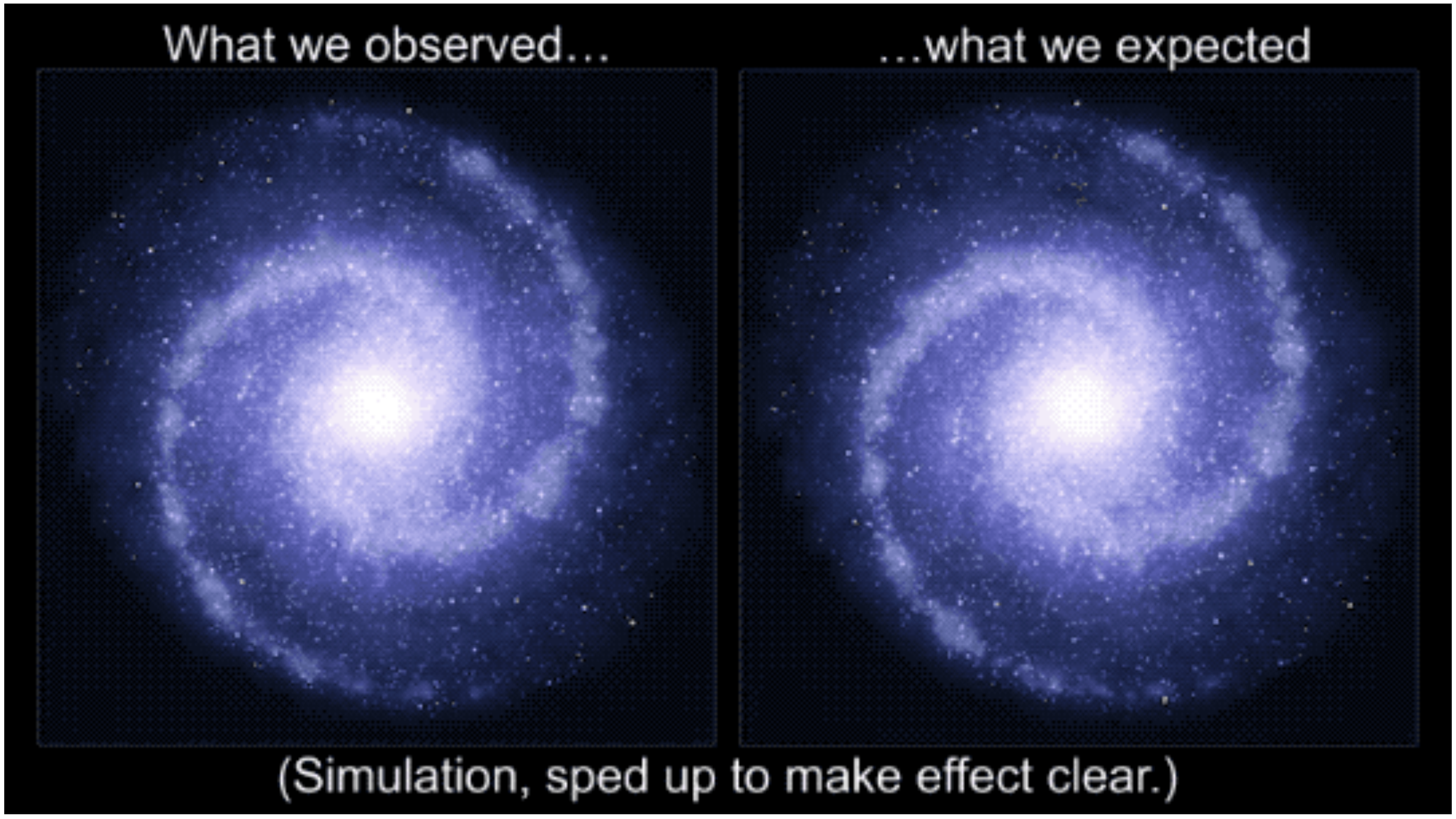
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Motion of visible matter



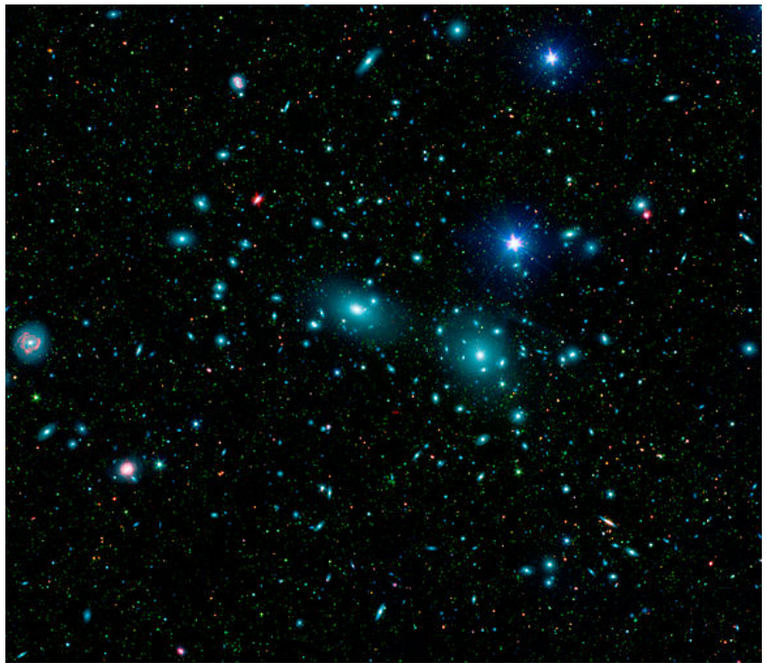
NASA, https://nasa.tumblr.com/post/180859237809/dark-matter-101-looking-for-the-missing-mass

Motion of visible matter



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Motion of visible matter: Coma cluster



Coma cluster

(머리털자리 은하단, Abel 1656)

100 Mpc from our galaxy



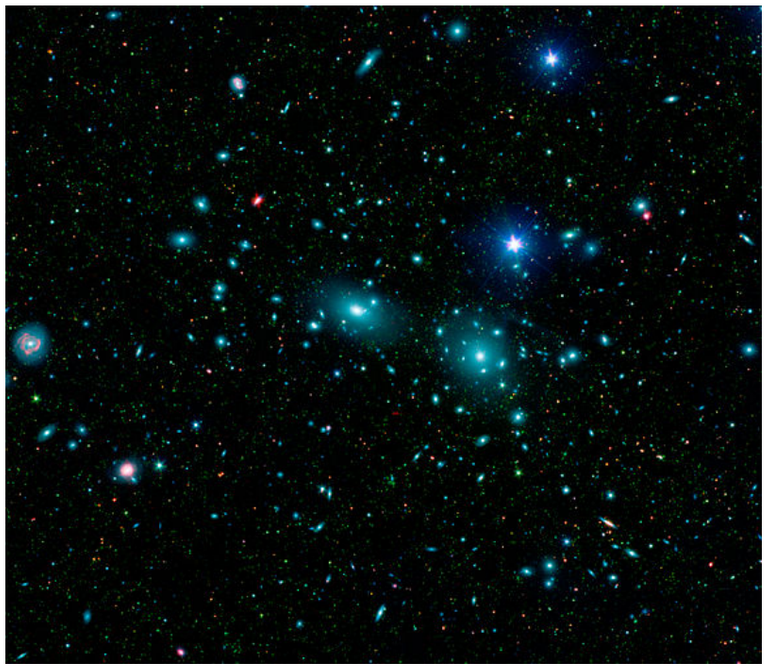
1933, Fritz Zwicky

Zwicky, Helv. Phys. Acta 6, 110 (1933)

Rotate!

Get mass by observing the rotation.

Motion of visible matter: Coma cluster



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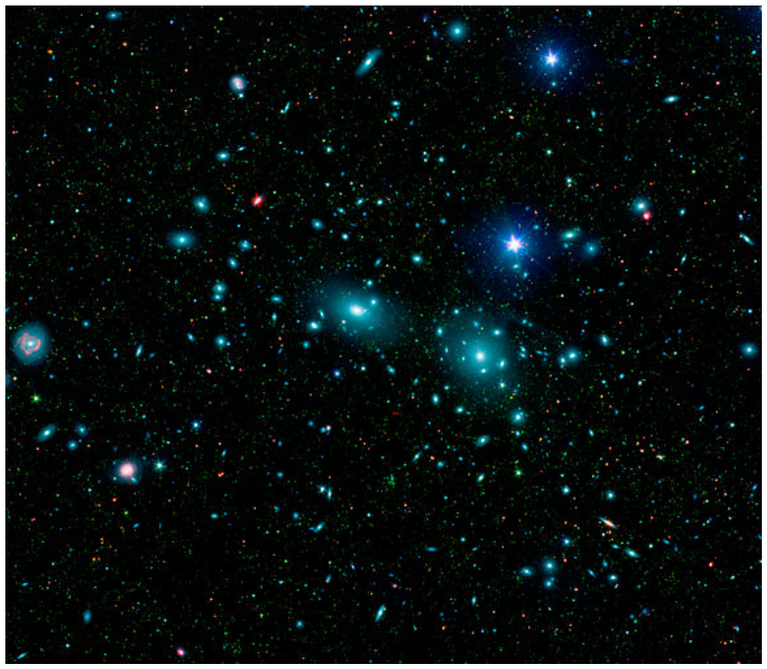
Virial theorem

|Gravitational potential energy|
= 2 × kinetic energy

$$-\langle U \rangle = 2\langle K \rangle$$

Coma cluster is virialized: no longer expanding nor contracting

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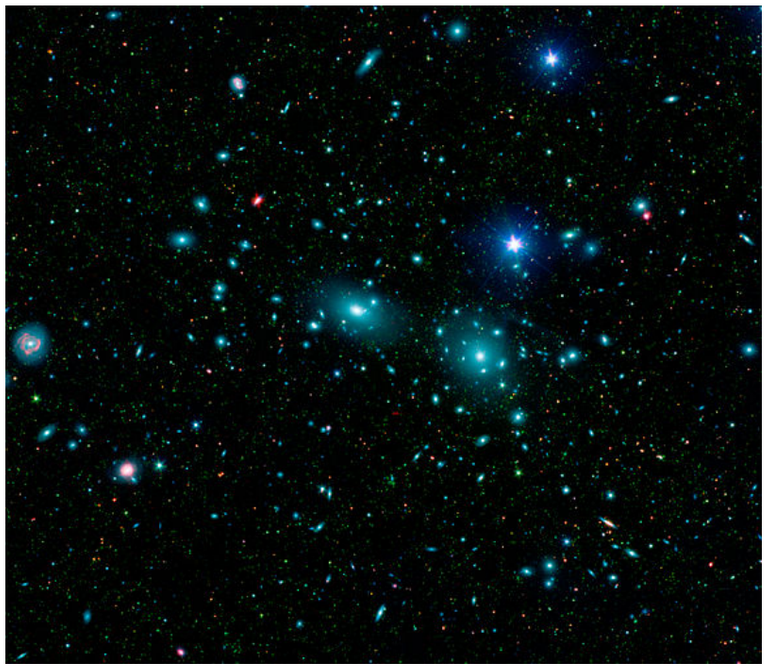
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$$K = \frac{1}{2}\sum_i m_i |\dot{\mathbf{x}}_i|^2 = \frac{1}{2} M \langle v^2 \rangle$$

$$\langle v^2 \rangle \equiv \frac{1}{M}\sum_i m_i |\dot{\mathbf{x}}|^2$$

$$U = -\frac{1}{2} G \sum_{i \neq j} \frac{m_i m_j}{|\mathbf{x}_i - \mathbf{x}_j|}$$

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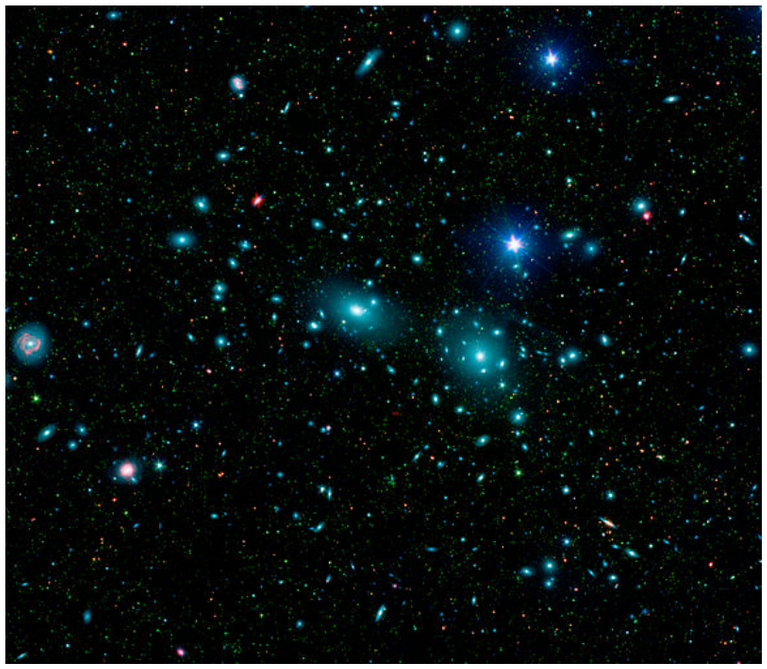
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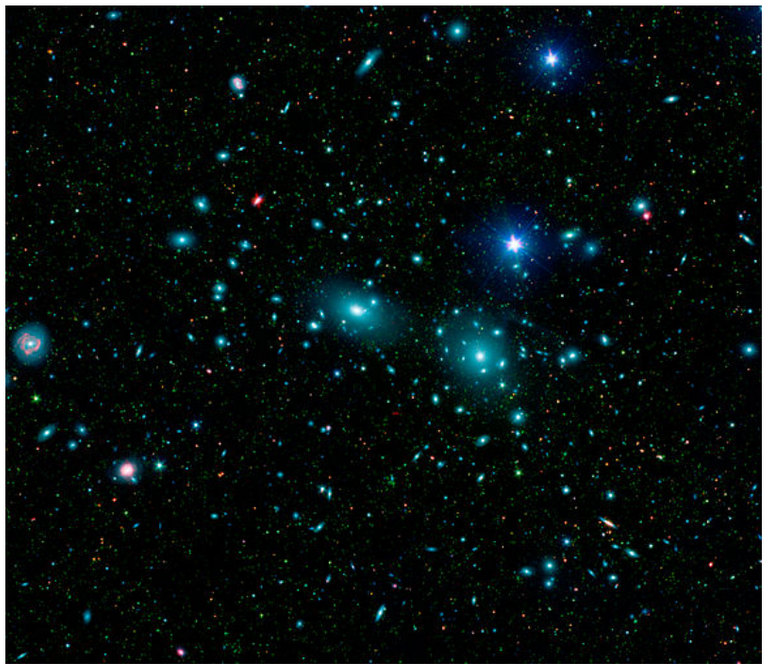
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Motion of visible matter: Coma cluster

Complementary approach: temperature measurements

Motion of visible matter: Coma cluster

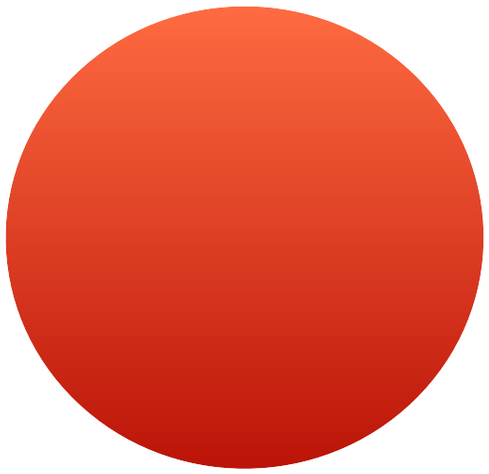
Complementary approach: temperature measurements

- Consider a dense star, whose gravitational field requires a large pressure gradient to make it stable.

Motion of visible matter: Coma cluster

Complementary approach: temperature measurements

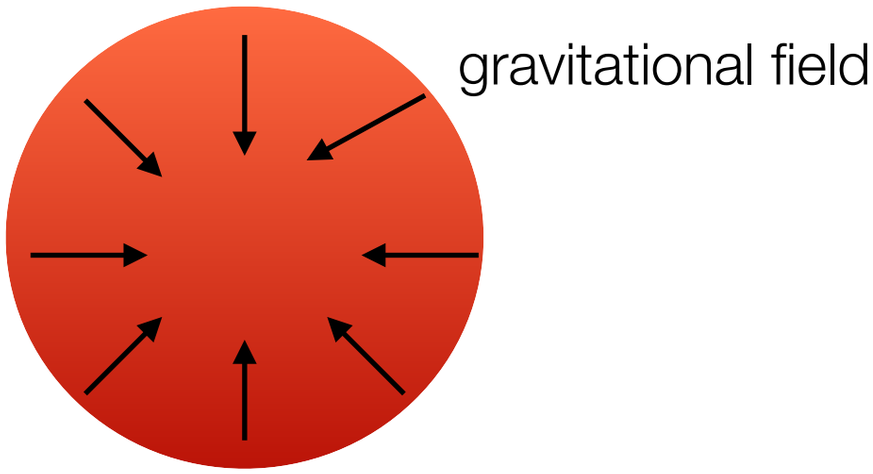
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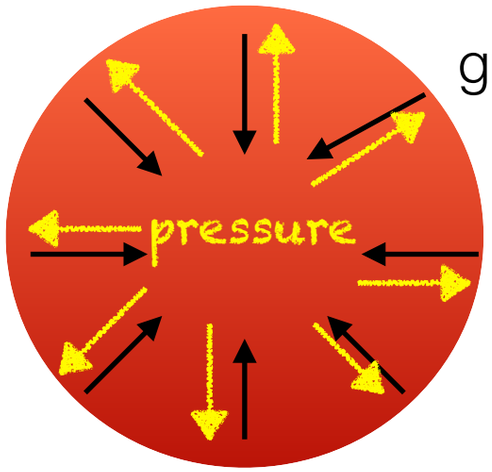
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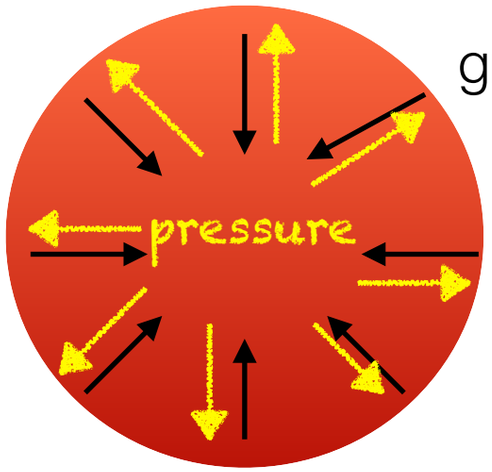
gravitational field

Motion of visible matter: Coma cluster

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Hydrostatic equilibrium



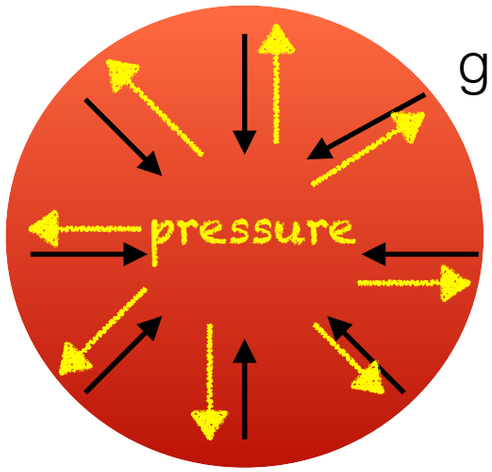
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Hydrostatic equilibrium



gravitational field

$$\rho \mathbf{a} + \nabla P = 0$$

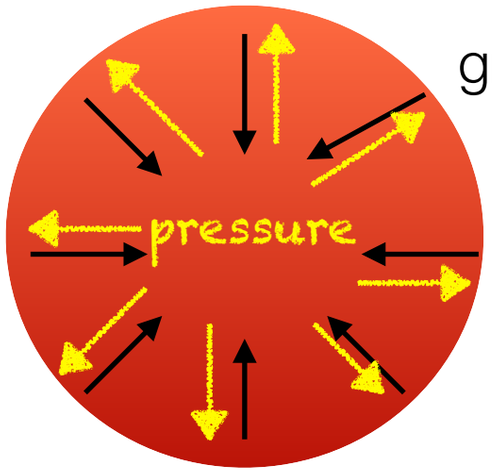
Navier-Stokes equation

Motion of visible matter: Coma cluster

Complementary approach: temperature measurements

- Consider a dense star, whose gravitational field requires a large pressure gradient to make it stable.

Hydrostatic equilibrium



gravitational field

$$\rho \mathbf{a} + \nabla P = 0$$

Navier-Stokes equation

- Remind in the general relativity class, in MCRF,

$$(\rho + P) a_i + P_{,i} = 0$$

pressure-gradient force

$\mathbf{F} = m\mathbf{a}$

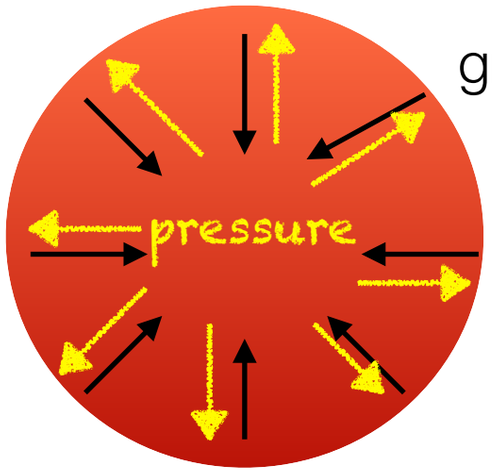
$\rho + P$: inertial mass density

Motion of visible matter: Coma cluster

Complementary approach: temperature measurements

- Consider a dense star, whose gravitational field requires a large pressure gradient to make it stable.

Hydrostatic equilibrium



gravitational field

$$\rho \mathbf{a} + \nabla P = 0$$

Navier-Stokes equation

- Remind in the general relativity class, in MCRF,



$$(\rho + P) a_i + P_{,i} = 0$$

pressure-gradient force

$\mathbf{F} = m\mathbf{a}$

$\rho + \boldsymbol{P}$: inertial mass density

$$-a_i = \frac{P_{,i}}{\rho + P}$$

Since $\rho + \boldsymbol{P}$ is greater than ρ, the gradient must be larger in relativity.

Larger $\boldsymbol{P}$ → larger $\mathbf{T}$ → larger gravity → ⋯→ gravitational collapse.

Motion of visible matter: Coma cluster

- The classical feature is applied in the scales of galaxy clusters.

- If the gas in the inner cluster region has pressure against the gravitational fall of the outer galaxies, it is in hydrostatic equilibrium:

$$\frac{dP}{dr} = -\rho(r) G \frac{M(r)}{r^2}$$

$\rho(r)$: density of the gas

$M(r)$: total mass inside a sphere or radius r

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- For an ideal gas, $$P = \frac{N k_B T}{V} = n k_B T = \frac{\rho k_B T}{\mu m_p}$$

μ: mean molecular weight, m_p: proton mass

Inside a star, the average mass per particle is $\langle m \rangle = \mu m_H$

$\mu \simeq 0.6$ for a fully ionized plasma of solar composition.

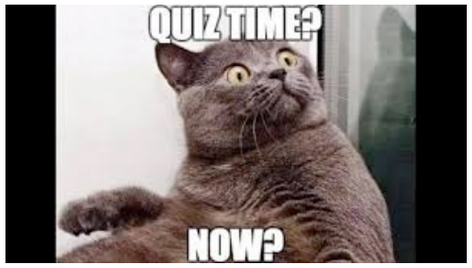
Motion of visible matter: Coma cluster

$$P = \frac{\rho k_B T}{\mu m_p} \longrightarrow M(r) = -\frac{k_B T r}{G \mu m_p} \left(\frac{d \log \rho}{d \log r} + \frac{d \log T}{d \log r} \right)$$

Motion of visible matter: Coma cluster

Quiz

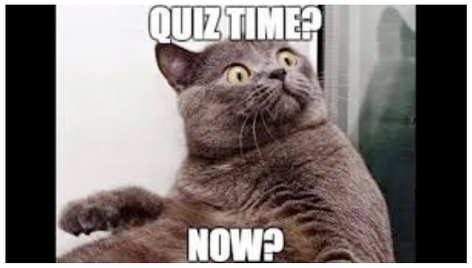
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Motion of visible matter: Coma cluster

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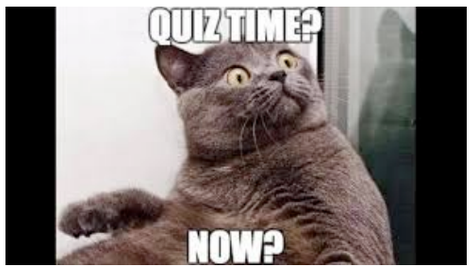
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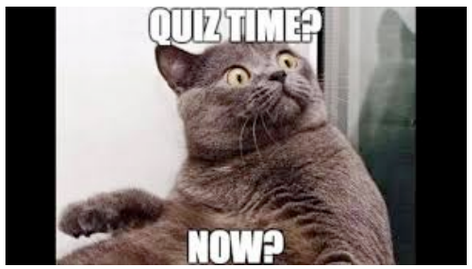
- T : roughly constant outside the core, ρ : roughly $r^{-2} \sim r^{-1.5}$,
  μ: composition of the cluster gas

$$k_B T \approx (1.3 - 1.8)\,\mathrm{keV} \left(\frac{M(r)}{10^{14} M_\odot} \right) \left(\frac{1\,\mathrm{Mpc}}{r} \right)$$

Motion of visible matter: Coma cluster

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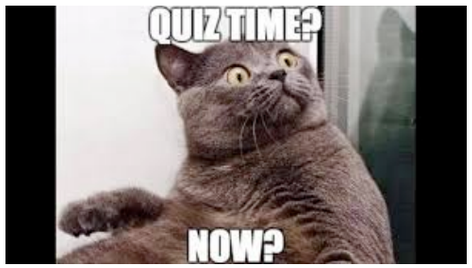
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Motion of visible matter: Coma cluster

Quiz

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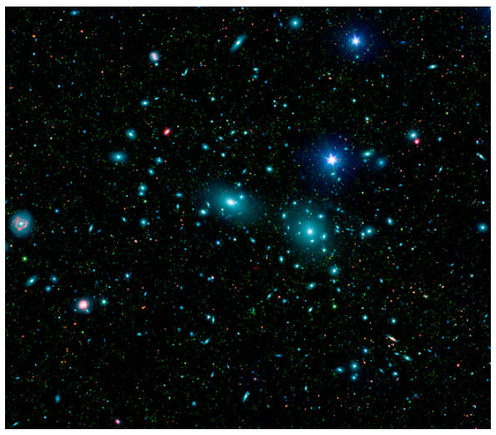


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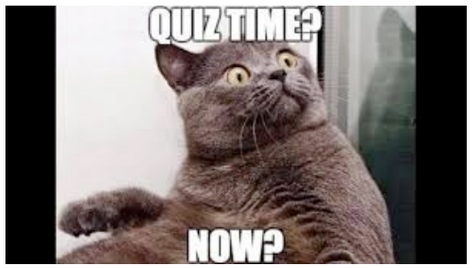


Chandra X-ray observatory webpage

Motion of visible matter: Coma cluster

Quiz

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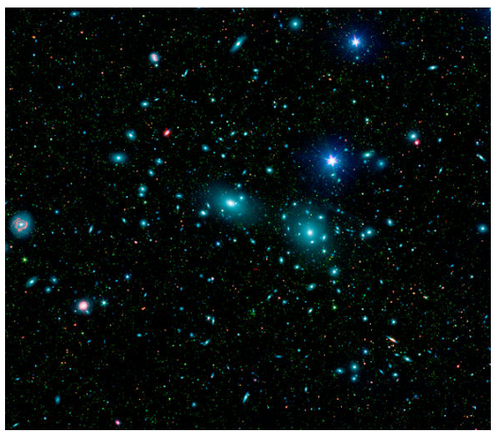
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$$M_{\mathrm{vir}} \sim 1.7 \times 10^{15}\, M_\odot \left(\frac{\sigma_r}{1000\,\mathrm{km/s}} \right)^2 \left(\frac{r_h}{1\,\mathrm{Mpc}} \right)$$

Consistent!





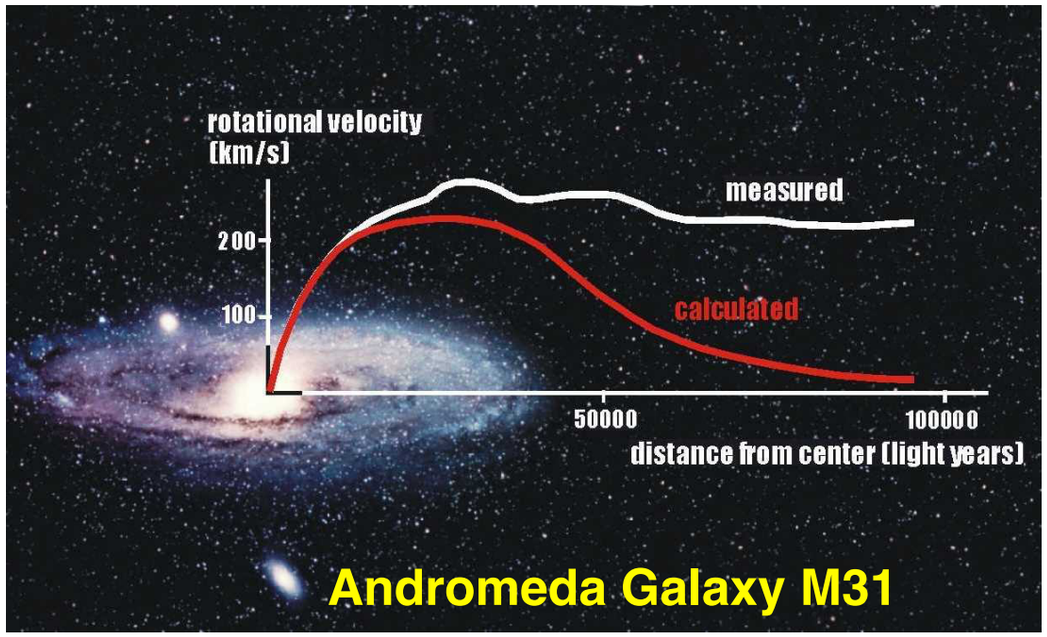
Chandra X-ray observatory webpage

Motion of visible matter: Galaxy rotation

Galactic Rotation Curve



1970s, Vera Rubin, Kent Ford, …

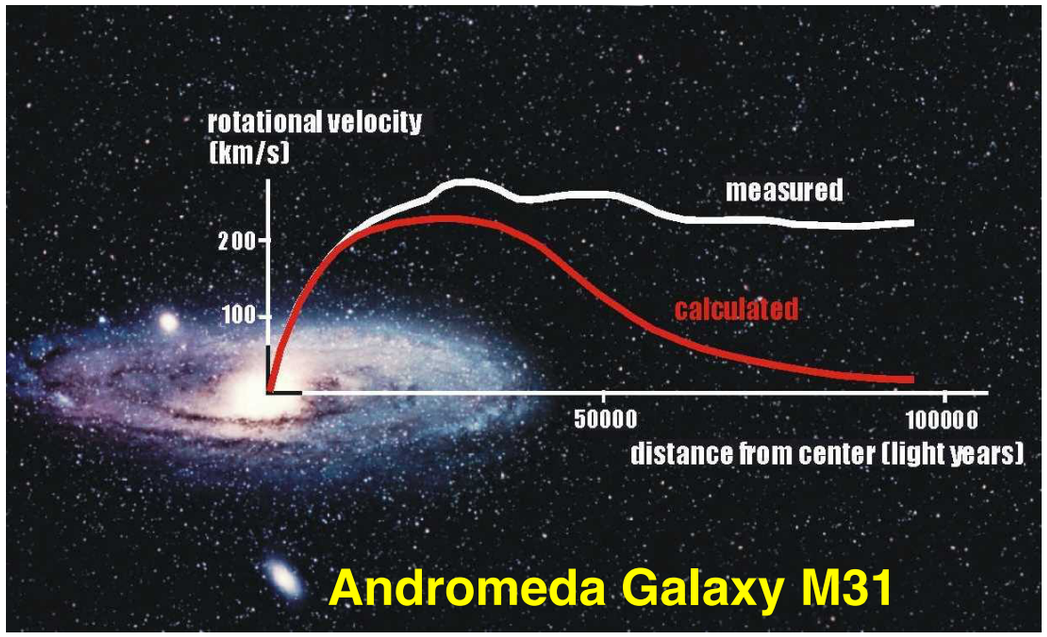


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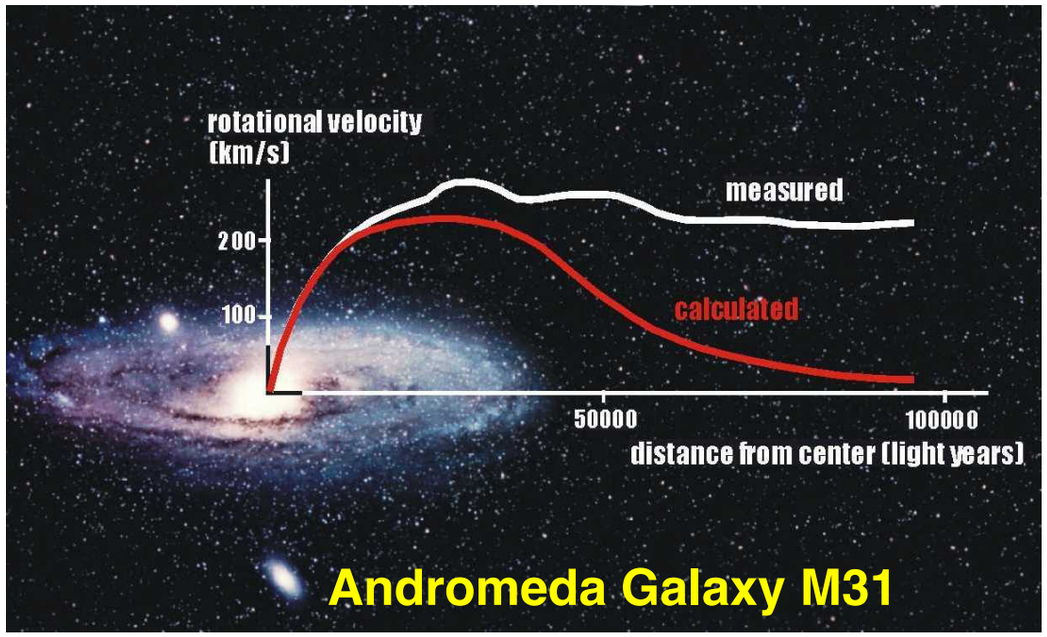
Gauss's theorem in gravitation

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Gauss's theorem in gravitation

$$\nabla \cdot \vec{g} = -4\pi G\rho \longrightarrow \oint_{\partial V} \vec{g} \cdot d\vec{A} = -4\pi G \int_V \rho \, dV \longrightarrow \vec{g}(r) = -\frac{GM(r)}{r^2}\hat{r}$$

$$\vec{F} = m\vec{g} = -m\frac{v^2}{r}\hat{r} \longrightarrow \frac{GM(r)}{r^2} = \frac{v^2}{r} \longrightarrow v = \sqrt{\frac{GM(r)}{r}}$$

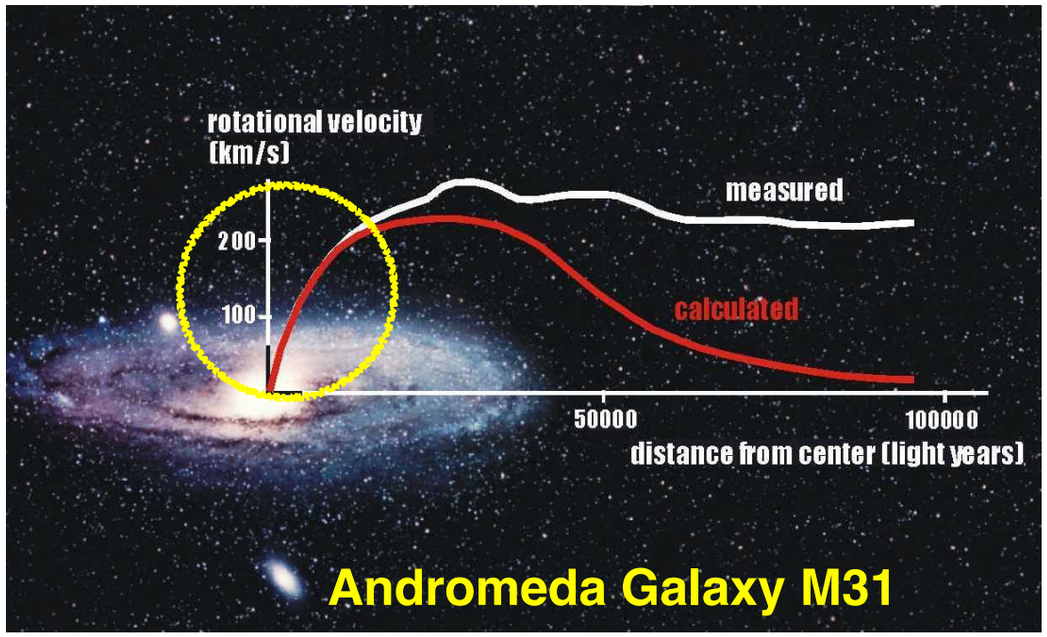
$\boldsymbol{M(r)}$: mass up to $\boldsymbol{r}$, we can assume a point-like particle mass at $\boldsymbol{r}$ = 0.

Motion of visible matter: Galaxy rotation

Galactic Rotation Curve: inner region



1970s, Vera Rubin, Kent Ford, …



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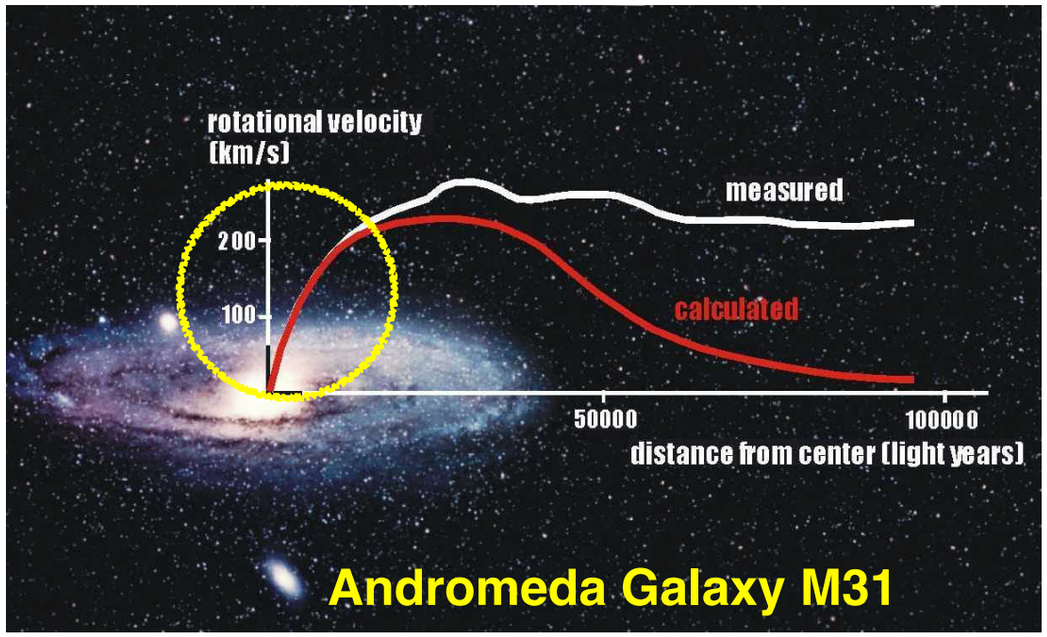
For a constant ρ, $M(r) \propto r^3$.

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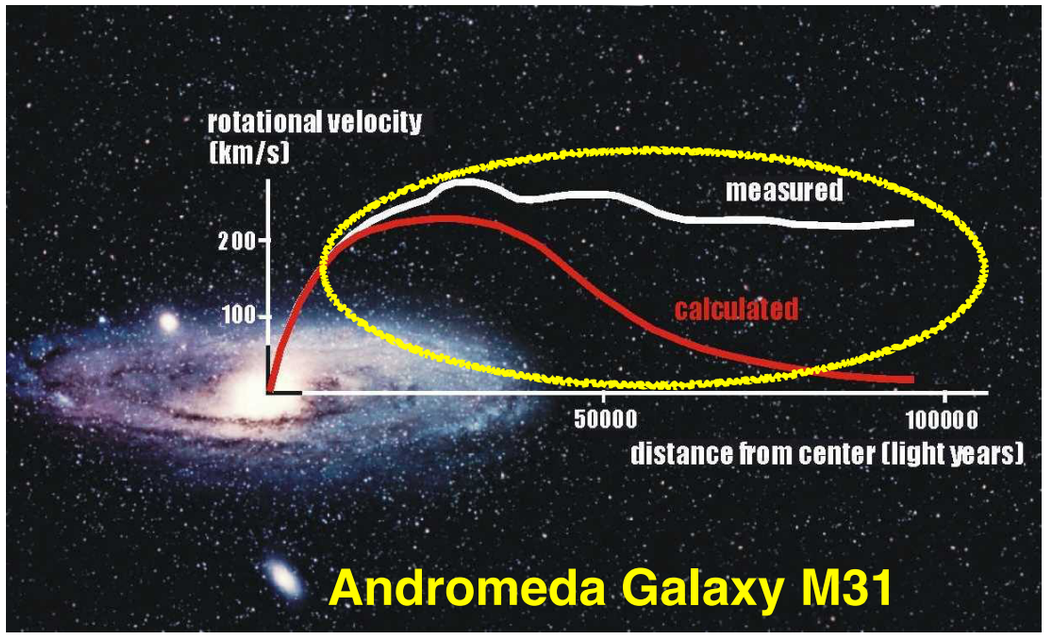
For a constant ρ, $M(r) \propto r^3$. $\longrightarrow$ $v \propto \sqrt{\frac{r^3}{r}} = r$

Motion of visible matter: Galaxy rotation

Galactic Rotation Curve: outer region



1970s, Vera Rubin, Kent Ford, …

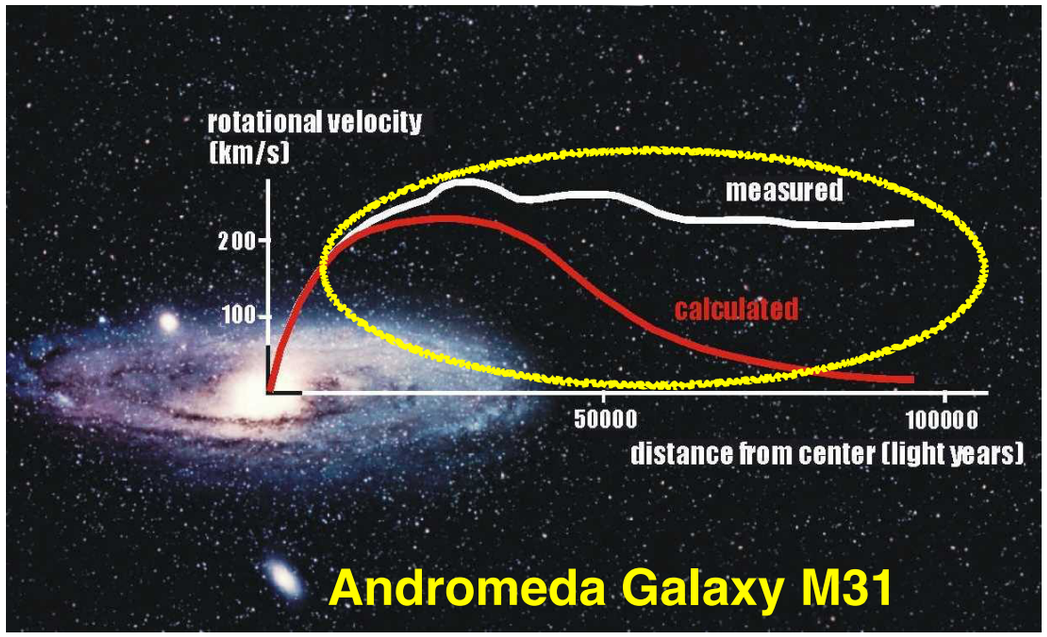


Motion of visible matter: Galaxy rotation

Galactic Rotation Curve: outer region



1970s, Vera Rubin, Kent Ford, …



Gauss's theorem in gravitation

Expected $$v = \sqrt{\frac{GM(r)}{r}} = \sqrt{\frac{GM}{r}} \propto \sqrt{\frac{1}{r}}$$

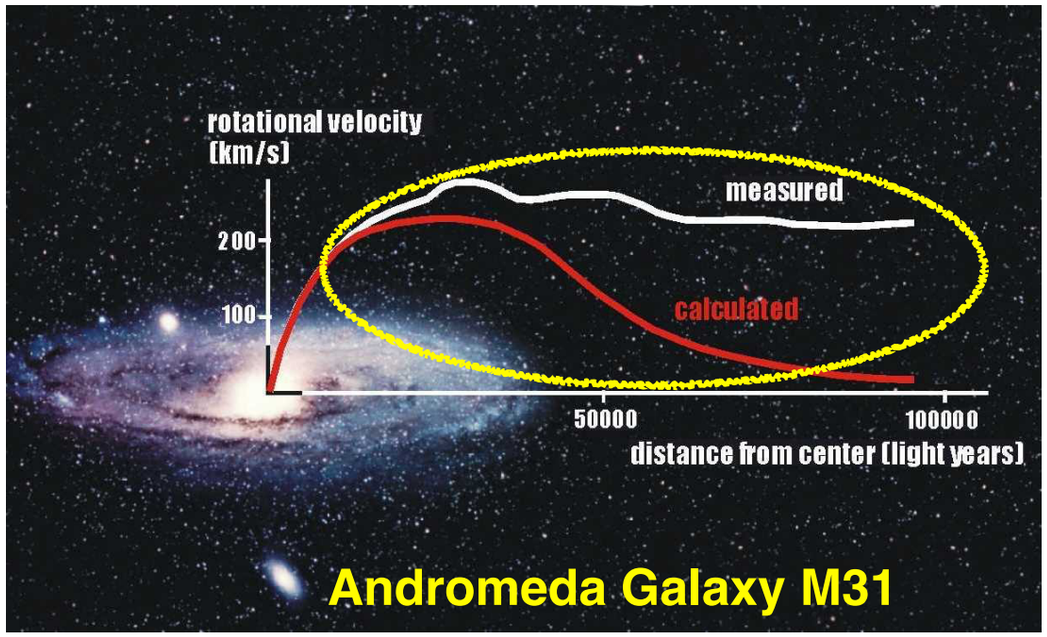
For $r > R_{\text{disk}} \sim O(10\text{kpc})$, $M(r) \approx$ constant → $\rho \propto 1/r^3$.

Motion of visible matter: Galaxy rotation

Galactic Rotation Curve: outer region



1970s, Vera Rubin, Kent Ford, …



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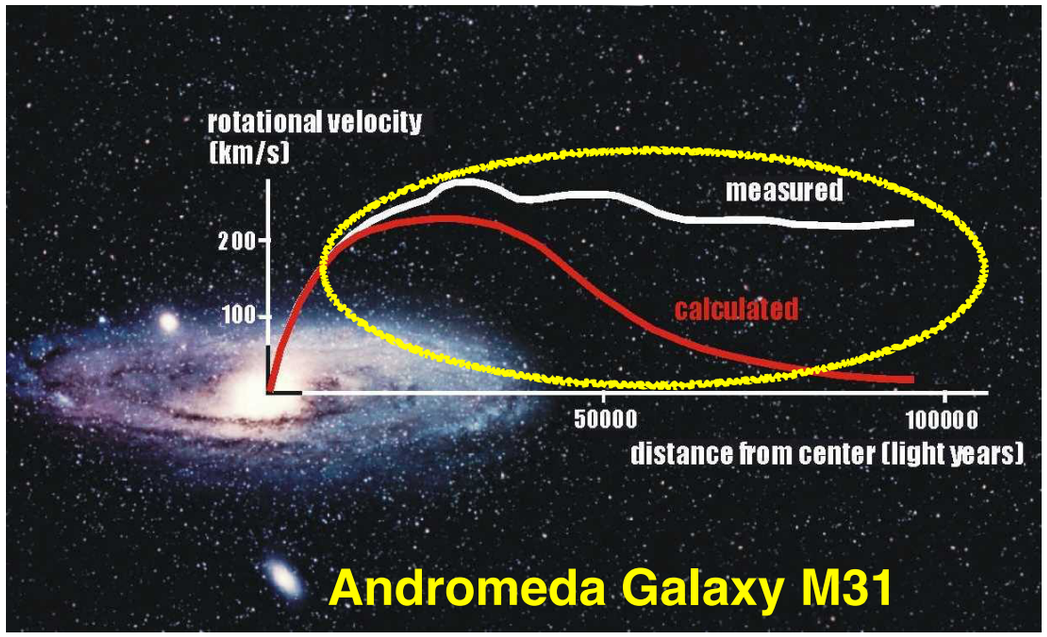
Assume: spherical distribution

Motion of visible matter: Galaxy rotation

Galactic Rotation Curve: outer region



1970s, Vera Rubin, Kent Ford, …



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Non-luminous massive objects even for $r > R_{disk}$

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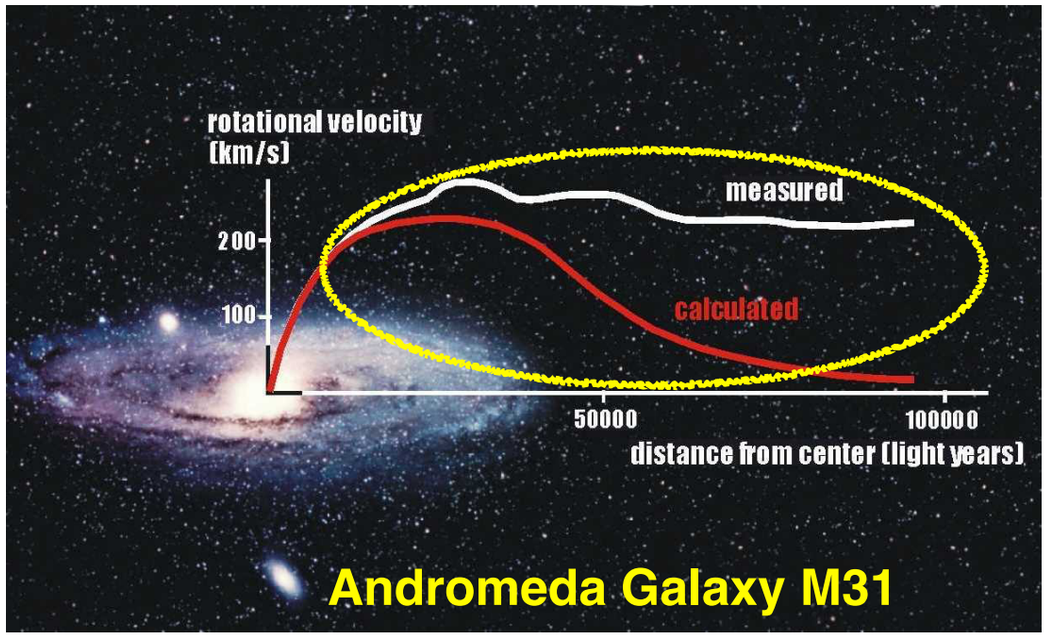
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Motion of visible matter: Galaxy rotation

Galactic Rotation Curve: outer region



1970s, Vera Rubin, Kent Ford, …



Interstellar medium (mostly H or H_2)?

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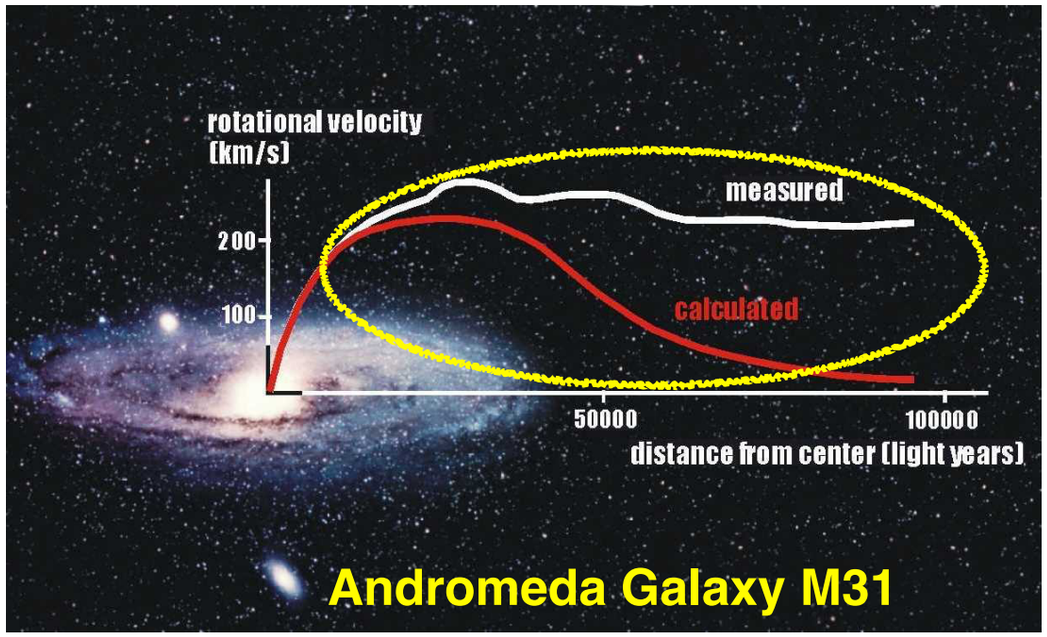
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Motion of visible matter: Galaxy rotation

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1970s, Vera Rubin, Kent Ford, …



Interstellar medium (mostly H or H_2)?

→ Baryonic DM?: Just about 10-20% of the total stellar mass in our galaxy or M31!!!

Non-luminous massive objects even for $r > R_{disk}$

Measured $\quad v = \text{constant} \longrightarrow M(r) \propto r \longrightarrow \rho(r) \propto \dfrac{M(r)}{r^3} \propto \dfrac{1}{r^2}$

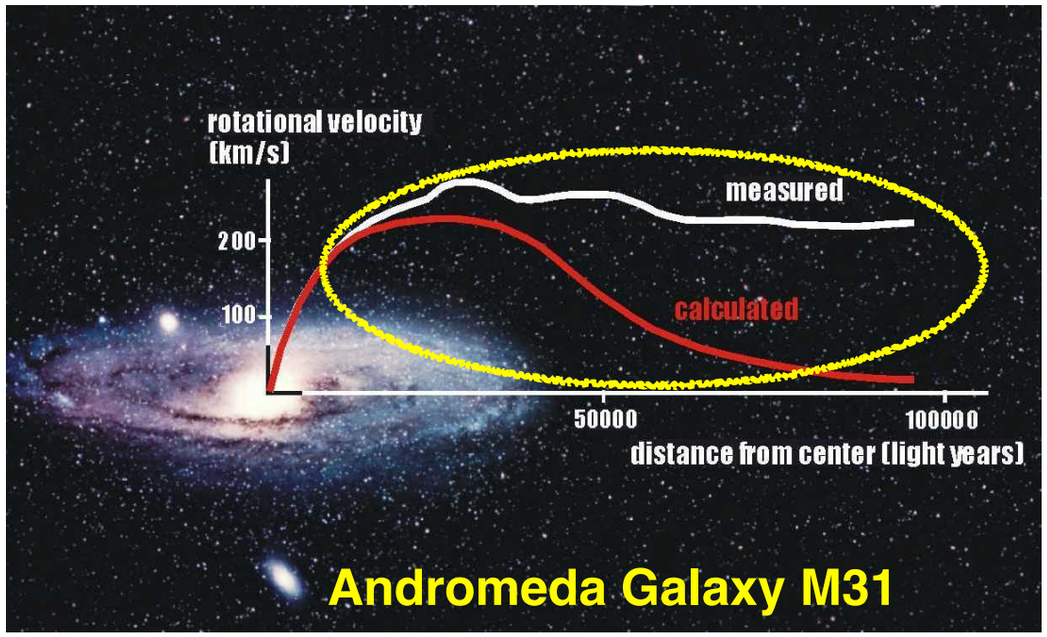
Assume: spherical distribution

Motion of visible matter: Galaxy rotation

Galactic Rotation Curve: outer region



1970s, Vera Rubin, Kent Ford, …



Non-baryonic Dark Matter dominates for $r > R_{\text{disk}}$



Non-luminous massive objects even for $r > R_{disk}$

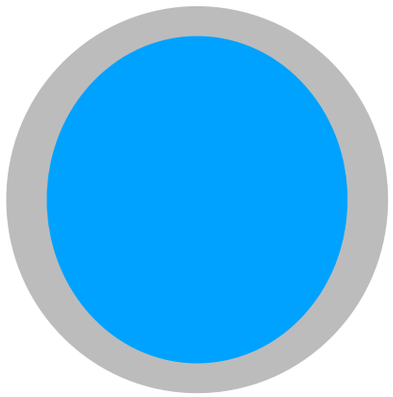
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Formation of Dark Halo

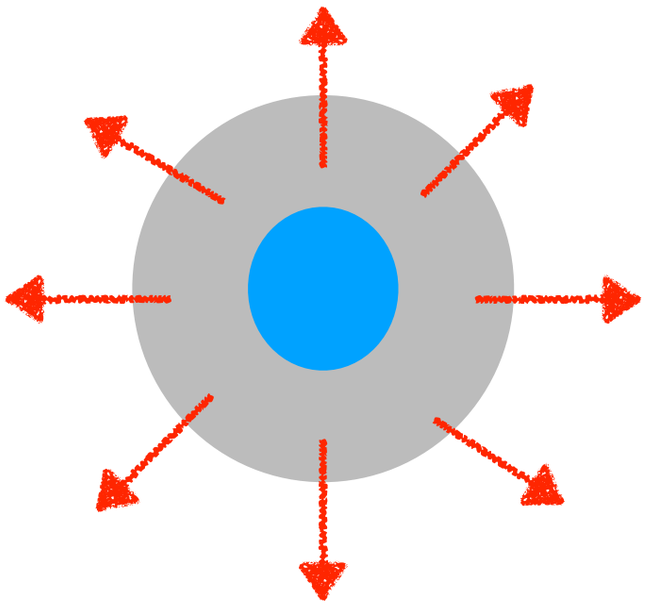
Formation of Dark Halo

Visible matter + DM (just after structure formation)



Formation of Dark Halo

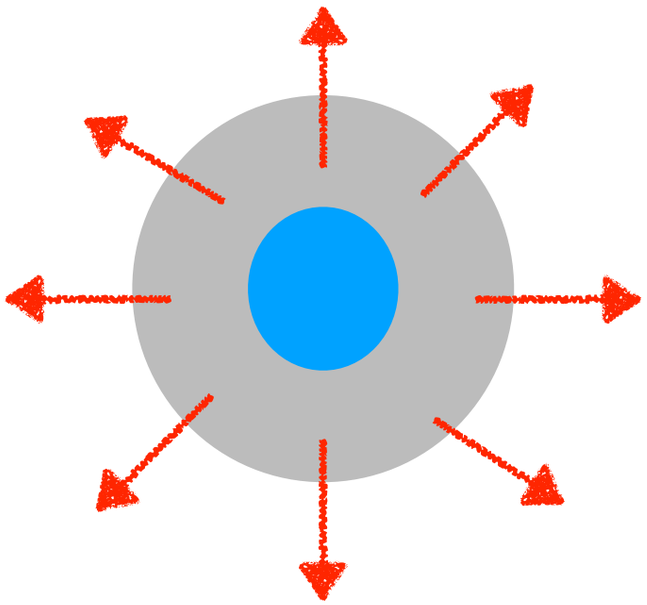
Visible matter + DM (just after structure formation)



Kinetic energy dissipation by
EM radiation
(irreversible process, isotropic)

Formation of Dark Halo

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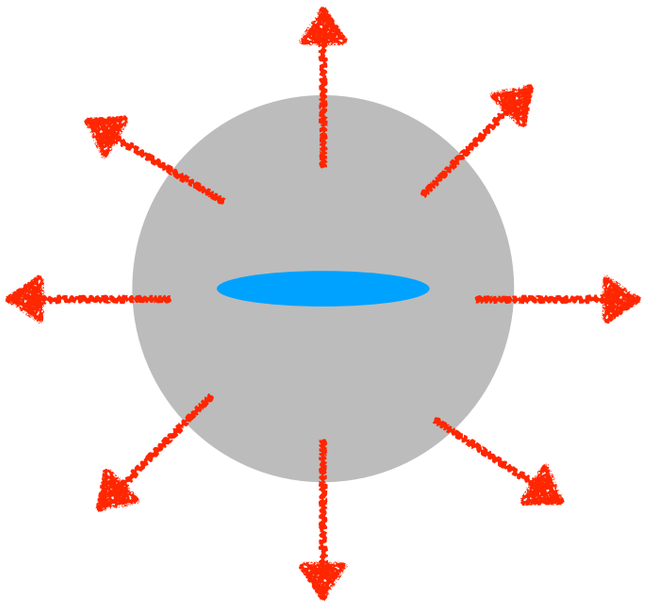


Kinetic energy dissipation by
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Initial angular
momentum conserved

Formation of Dark Halo

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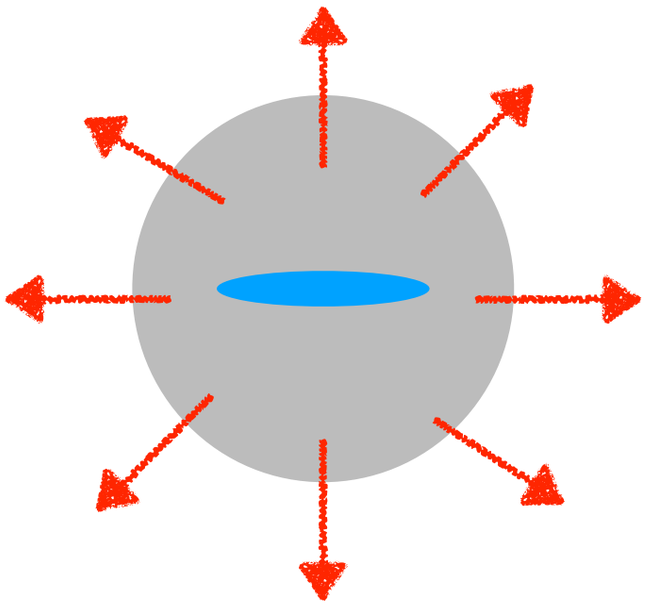
Initial angular
momentum conserved

- Angular speed increases as it collapses to the center (much faster than DM).

  + baryons can interact strongly → Visible matter now forms a disk

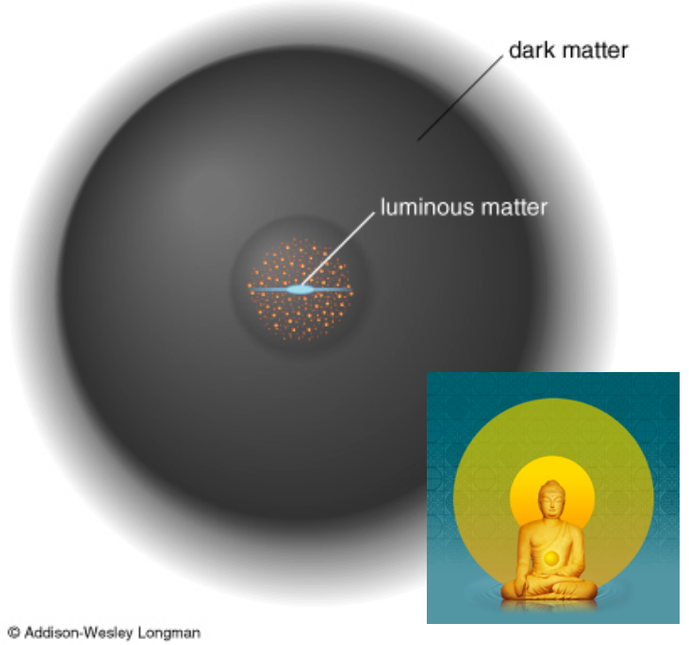
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Kinetic energy dissipation by
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(irreversible process, isotropic)

Initial angular
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- Angular speed increases as it collapses to the center (much faster than DM).

  \+ baryons can interact strongly → Visible matter now forms a disk

- Dark matter is nearly “dissipationless” and forms a **dark halo**.

  Otherwise, the size of dark halo should not be extended over $r > R_{disk}$.

Formation of Dark Halo

- Dissipation of the visible matter (small fraction of the entire galaxy) does not disrupt the stability of the dark halo.

Formation of Dark Halo

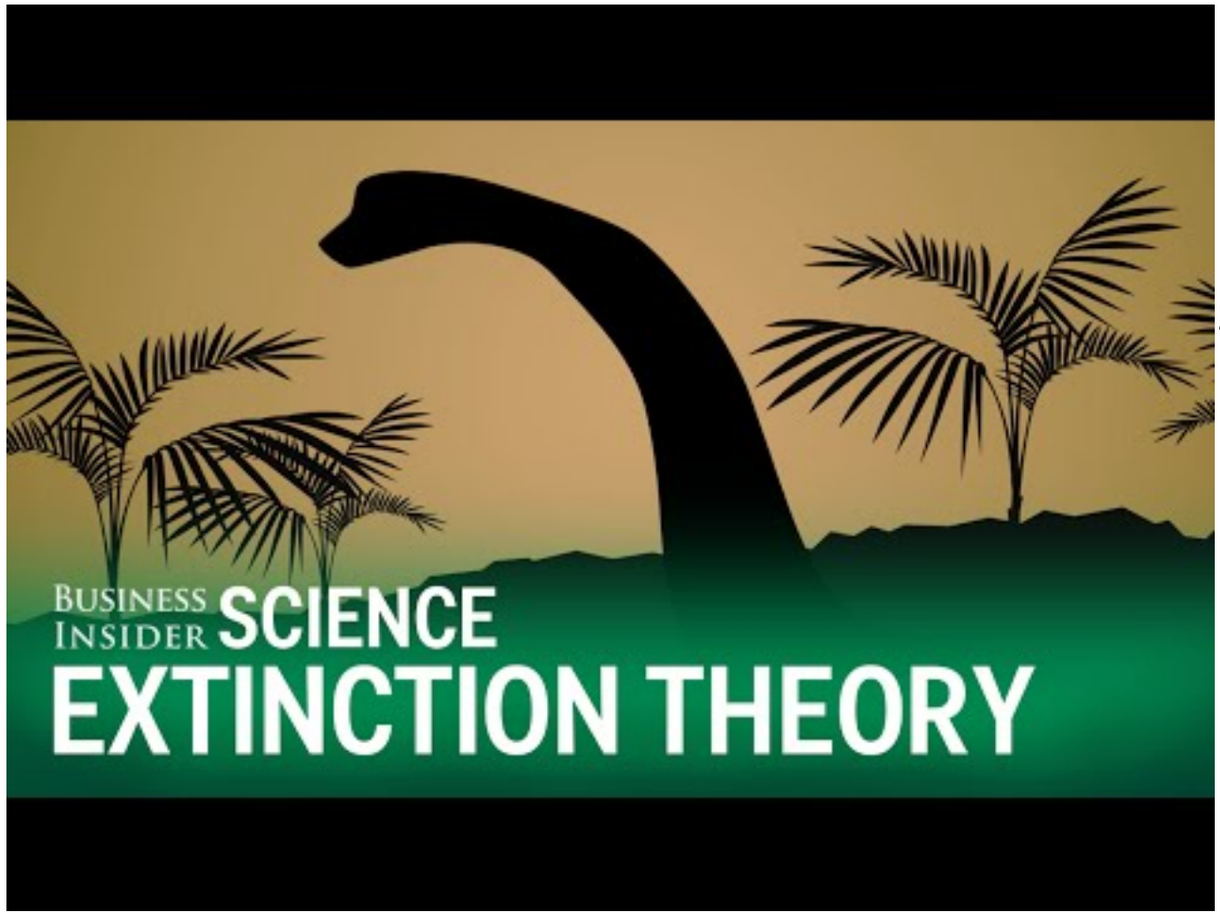
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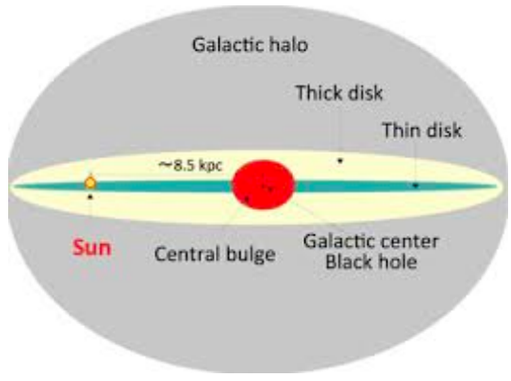
- Dissipation of a small fraction of dark matter does not disrupt the stability of the dark halo.

Formation of Dark Halo

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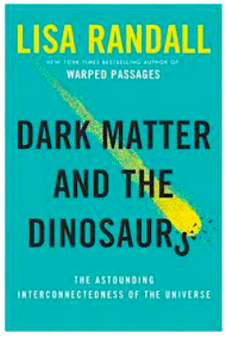




5-10% of DM (sub-component DM) can be dissipative and form a Dark Disk (Double Disk Dark Matter)

Fan, Katz, Randall, Reece,
Dark Universe 2, 139 (2013)
PRL 100, 211302 (2013)

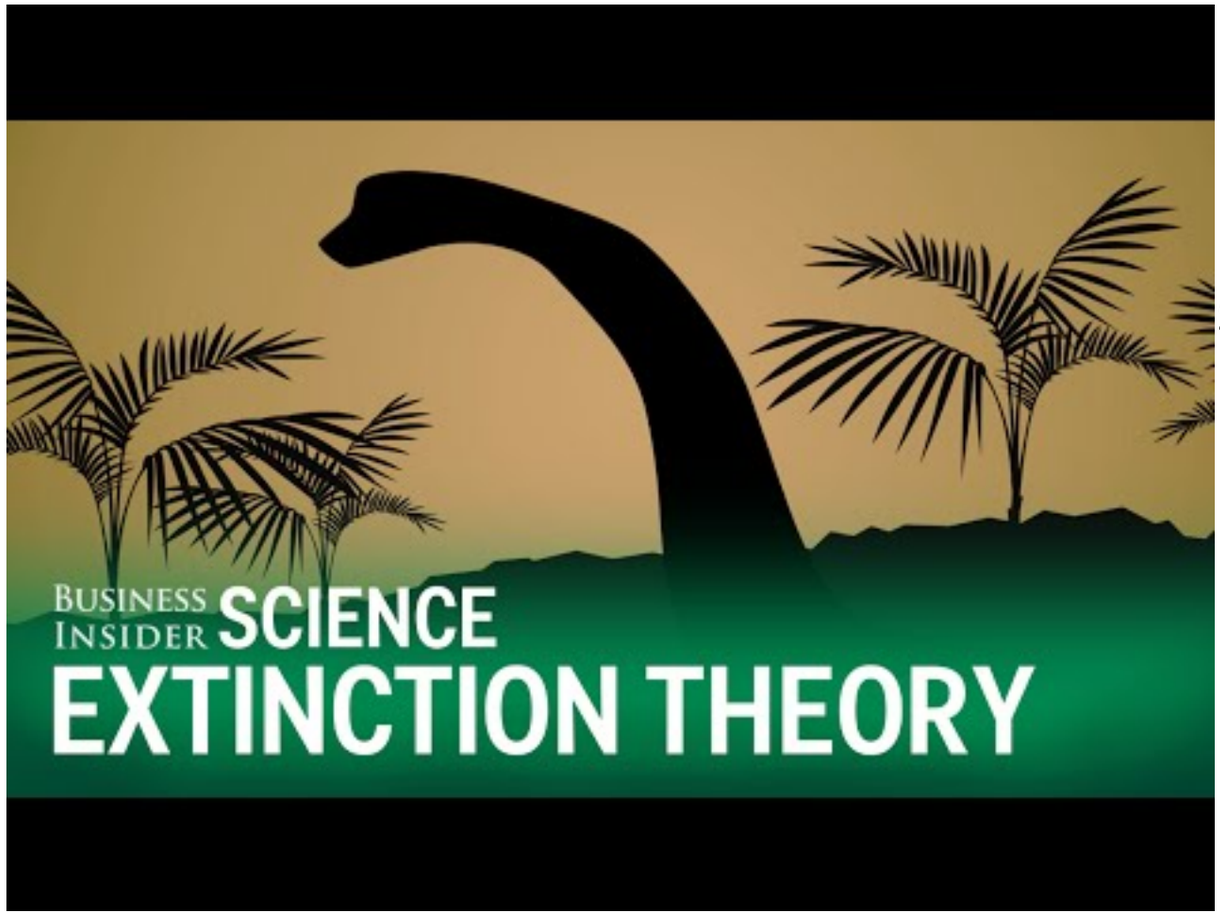


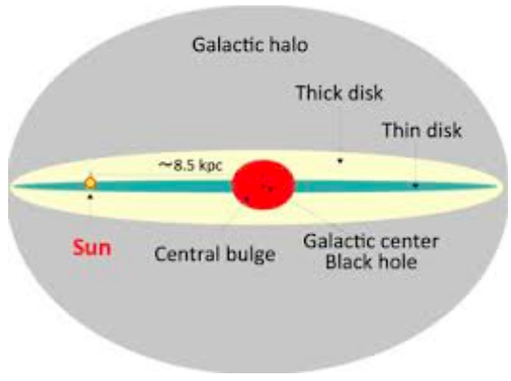


Formation of Dark Halo

• Dissipation of the visible matter (small fraction of the entire galaxy) does not disrupt the stability of the dark halo.

• Dissipation of a small fraction of dark matter does not disrupt the stability of the dark halo.

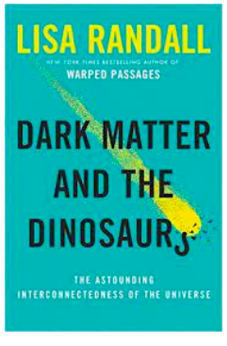




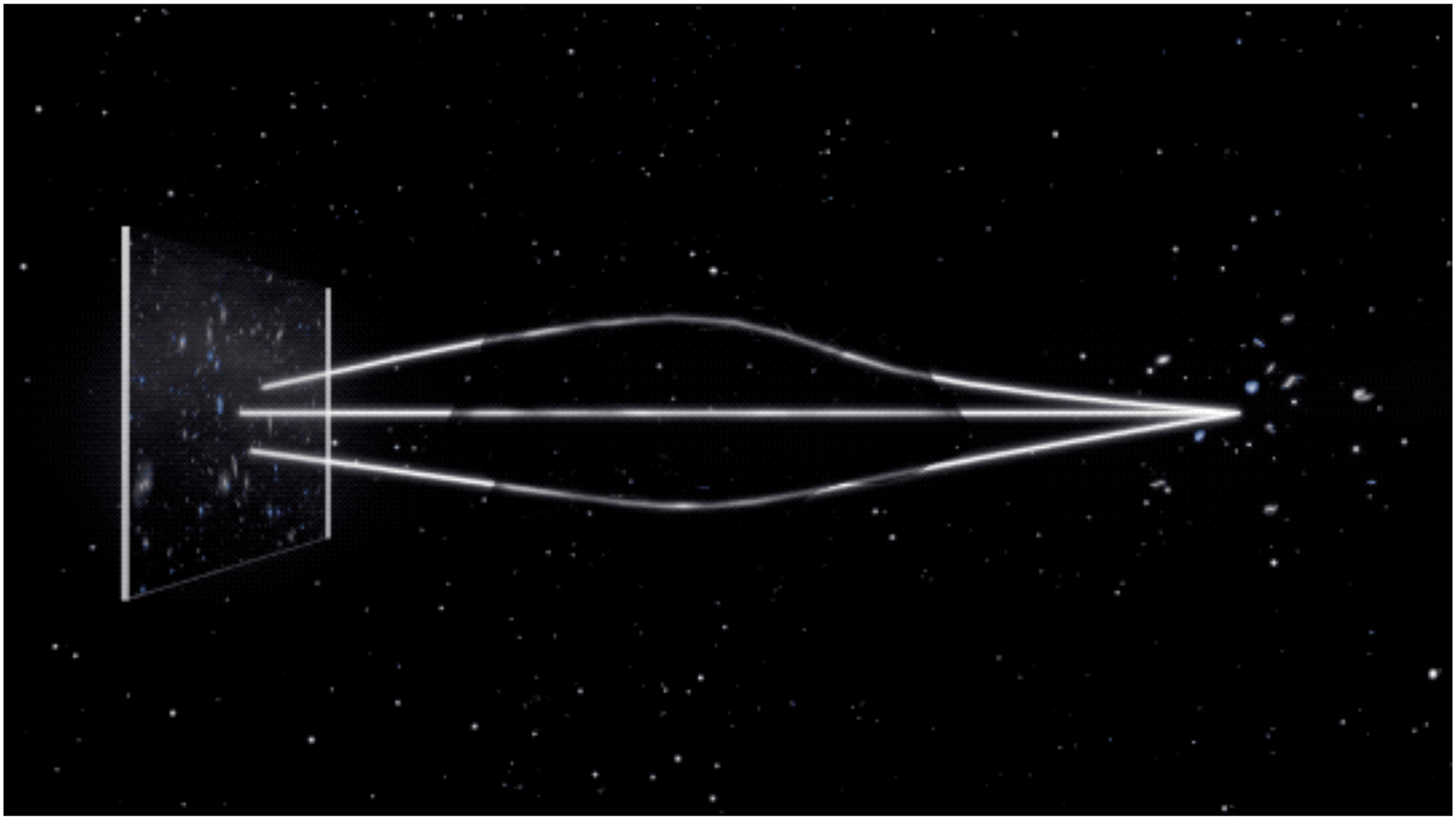
5-10% of DM (sub-component DM) can be dissipative and form a Dark Disk (Double Disk Dark Matter)

Fan, Katz, Randall, Reece,
Dark Universe 2, 139 (2013)
PRL 100, 211302 (2013)



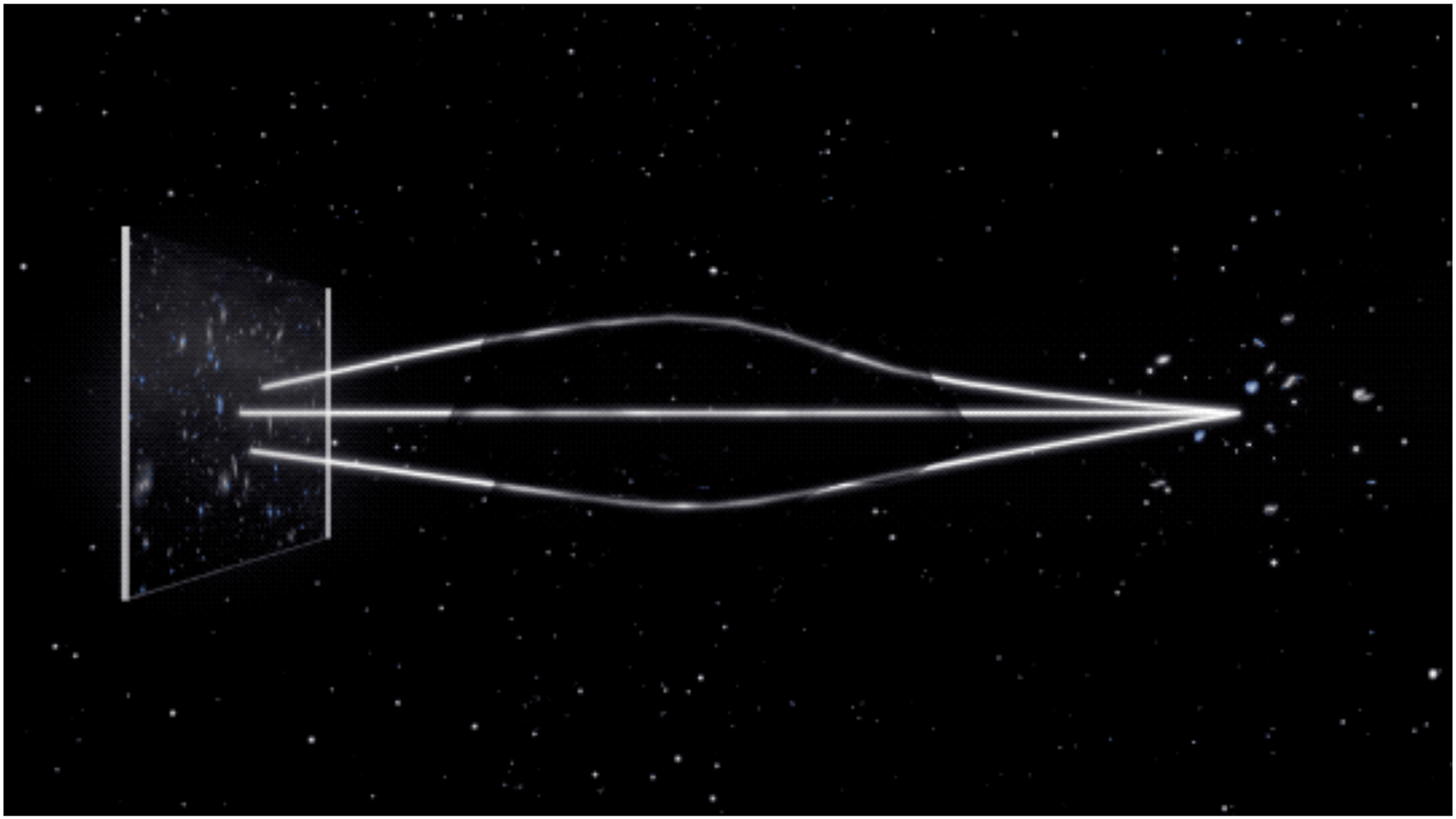


Distribution of visible matter



NASA, https://nasa.tumblr.com/post/180859237809/dark-matter-101-looking-for-the-missing-mass

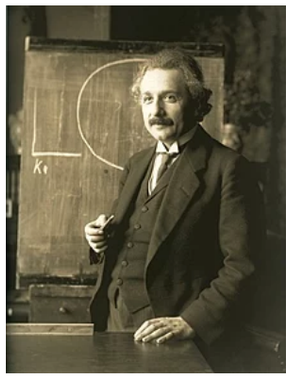
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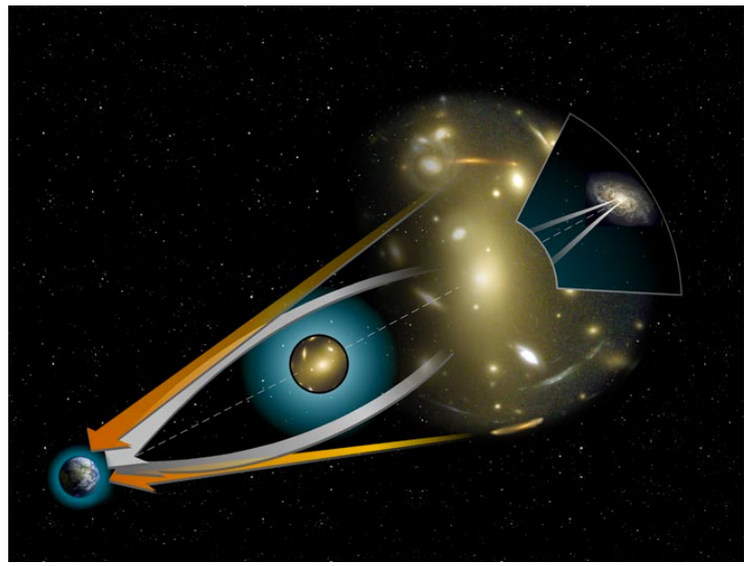
Distribution of visible matter: Lensing

Gravitational Lensing

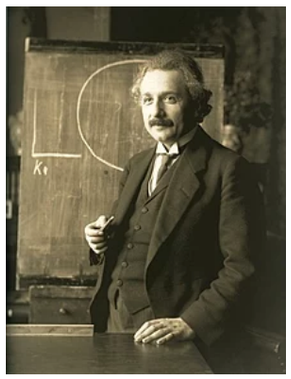


General Theory of Relativity $G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$

Gravity: Curvature of Spacetime Geometry



Distribution of visible matter: Lensing

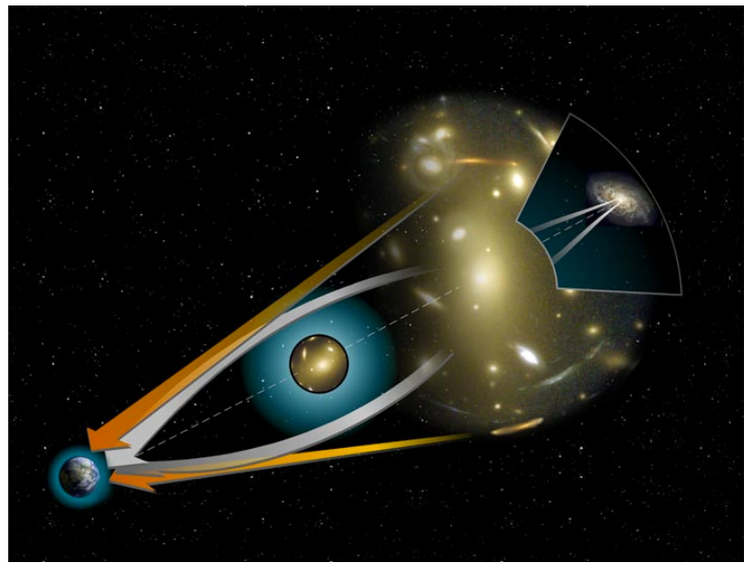


Gravitational Lensing

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Gravity: Curvature of Spacetime Geometry

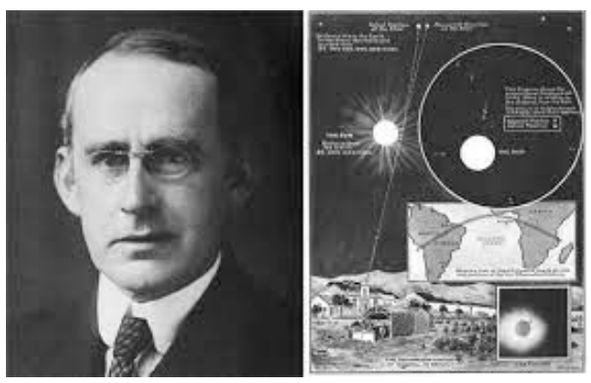
Cambridge cosmology lecture

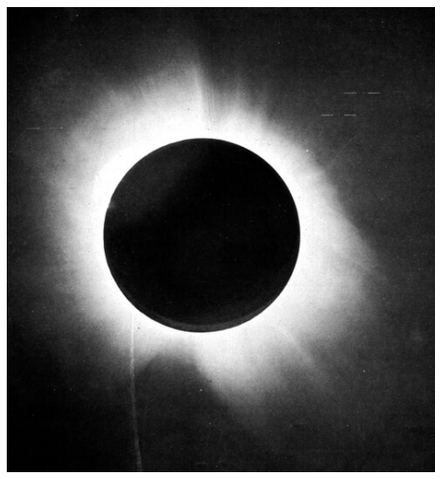


- Einstein's calculation in 1919:

$$\alpha = \frac{4GM_\odot}{c^2 R_\odot} = 1.7\,\text{arcsec}$$

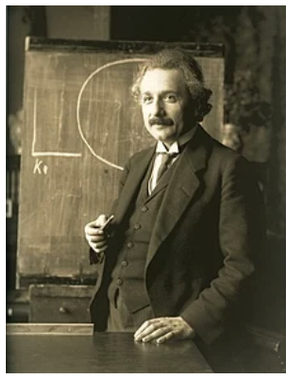
- Arthur Eddington confirmed the prediction with an accuracy of ±30% during the solar eclipse of May 29, 1919





Distribution of visible matter: Lensing

Gravitational Lensing

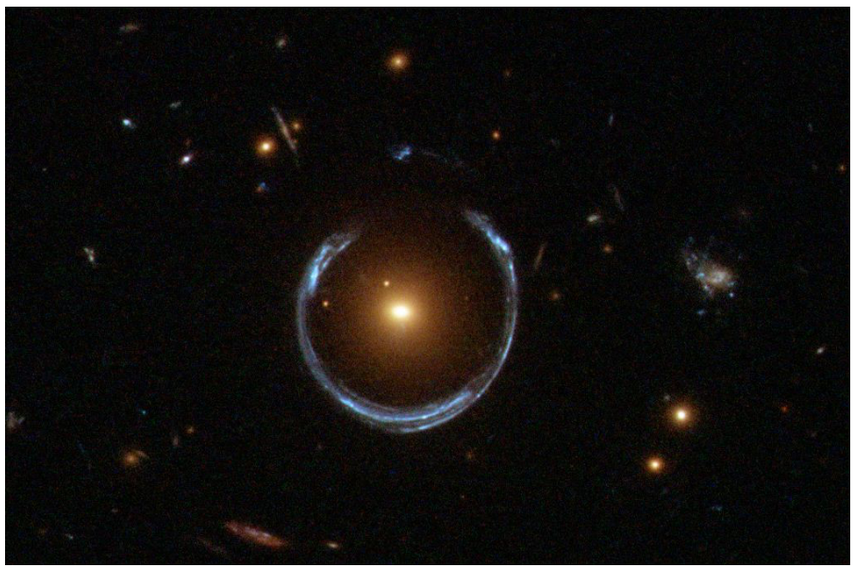


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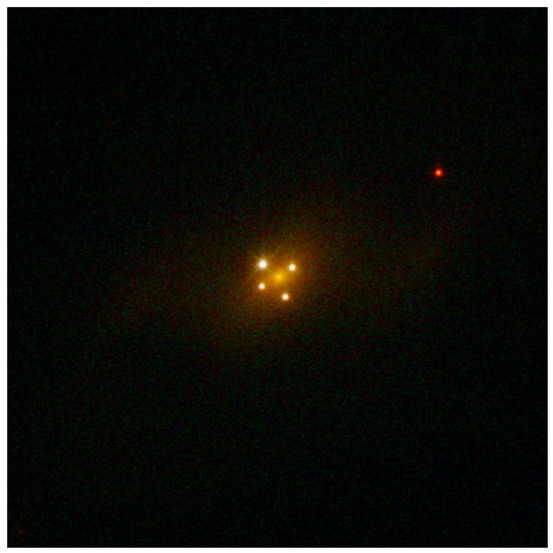
- Einstein rings, multiple images, highly distorted images and arcs are all examples of strong lensing by either individual massive galaxies or the complex mass distribution of rich clusters of galaxies.

Hubble space telescope: cosmic horseshoe, a star-forming galaxy at z = 0.444



Wikipedia: Einstein Ring

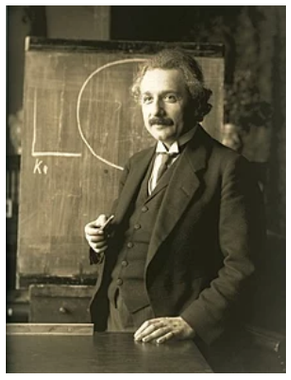
Hubble space telescope: Einstein cross



Wikipedia: Einstein Cross

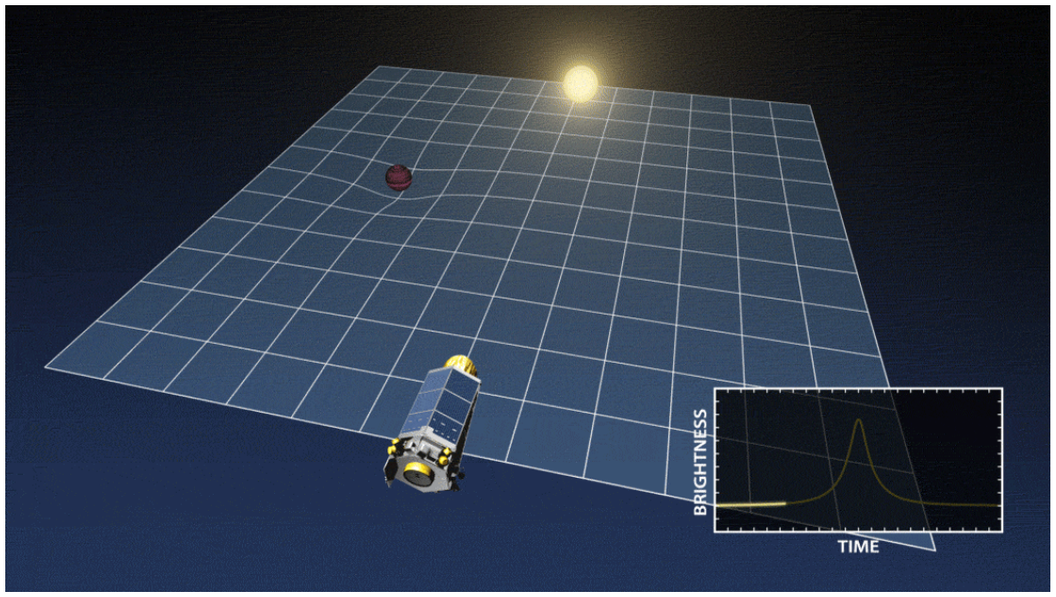
Distribution of visible matter: Lensing

Gravitational Lensing

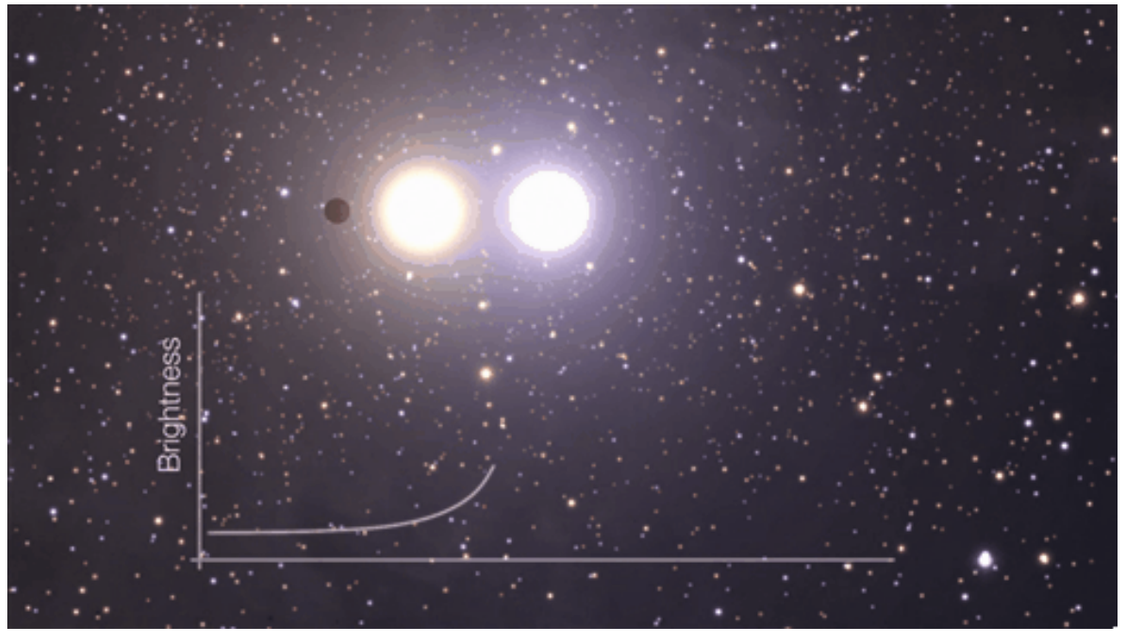


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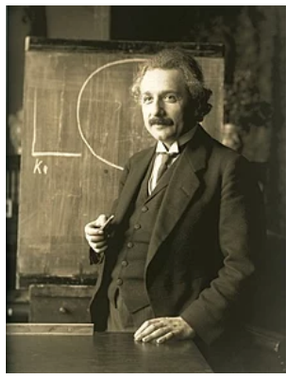
NASA Ames/JPL-Caltech/T. Pyle - https://www.jpl.nasa.gov/news/news.php?feature=6314



https://supernova.eso.org/exhibition/videos/eso50microlensingexo/

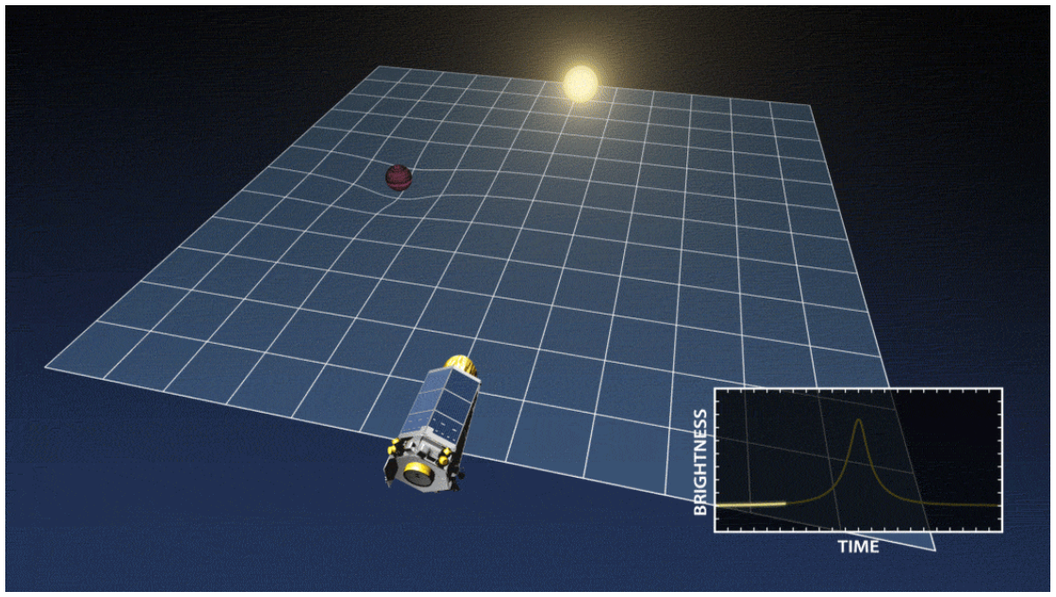
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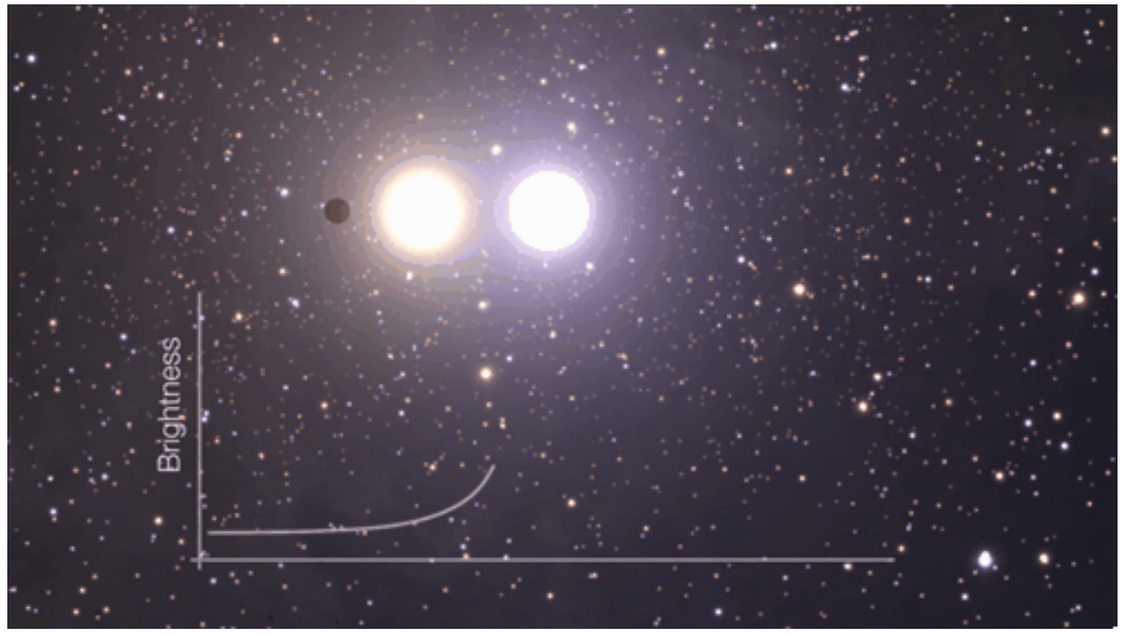


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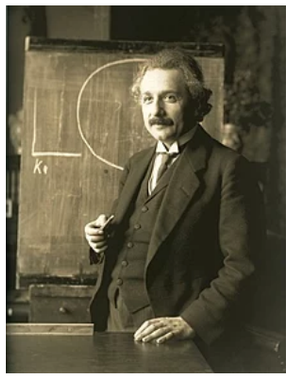
NASA Ames/JPL-Caltech/T. Pyle - https://www.jpl.nasa.gov/news/news.php?feature=6314



https://supernova.eso.org/exhibition/videos/eso50microlensingexo/

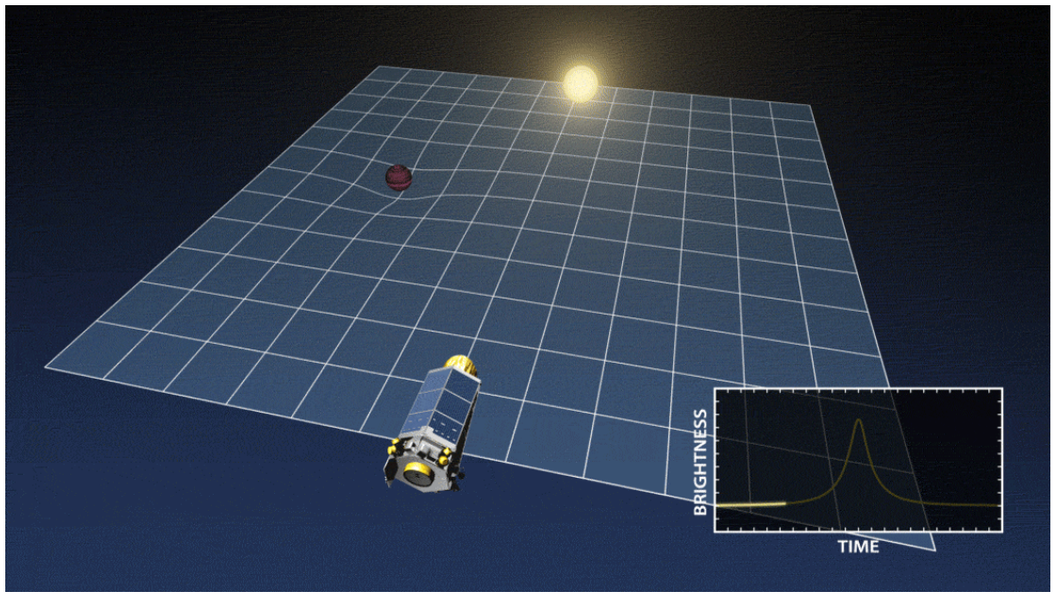
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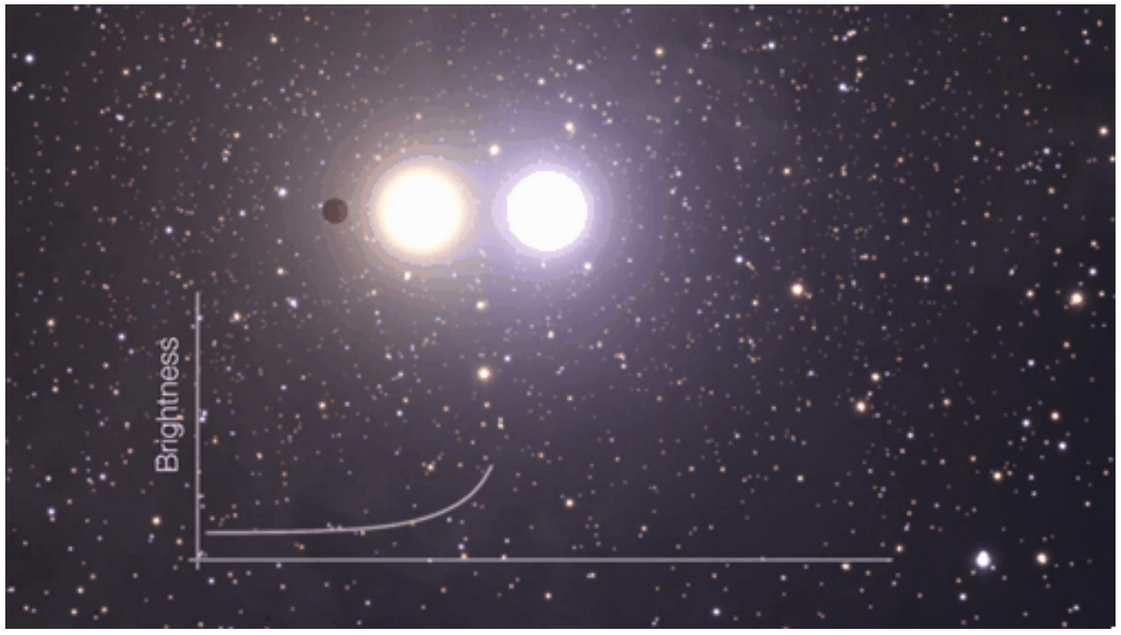


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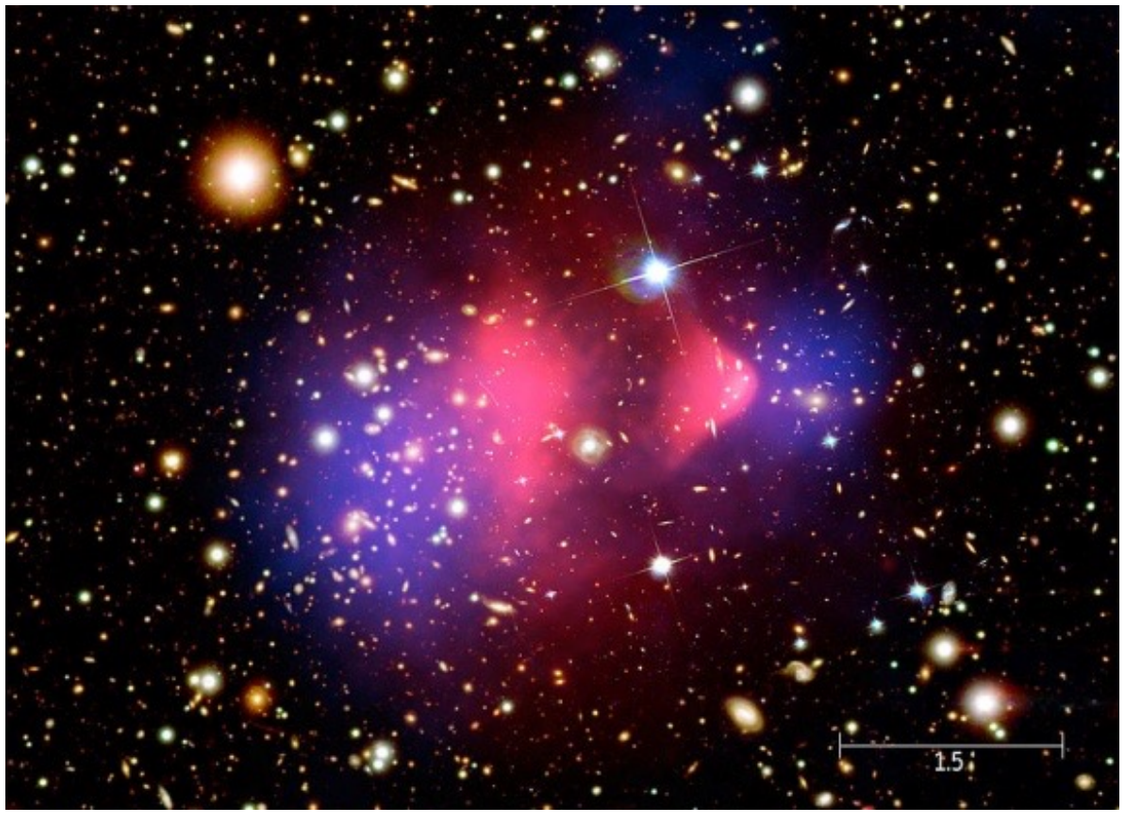
NASA Ames/JPL-Caltech/T. Pyle - https://www.jpl.nasa.gov/news/news.php?feature=6314



https://supernova.eso.org/exhibition/videos/eso50microlensingexo/

Distribution of visible matter: Bullet cluster

1E 0657-558

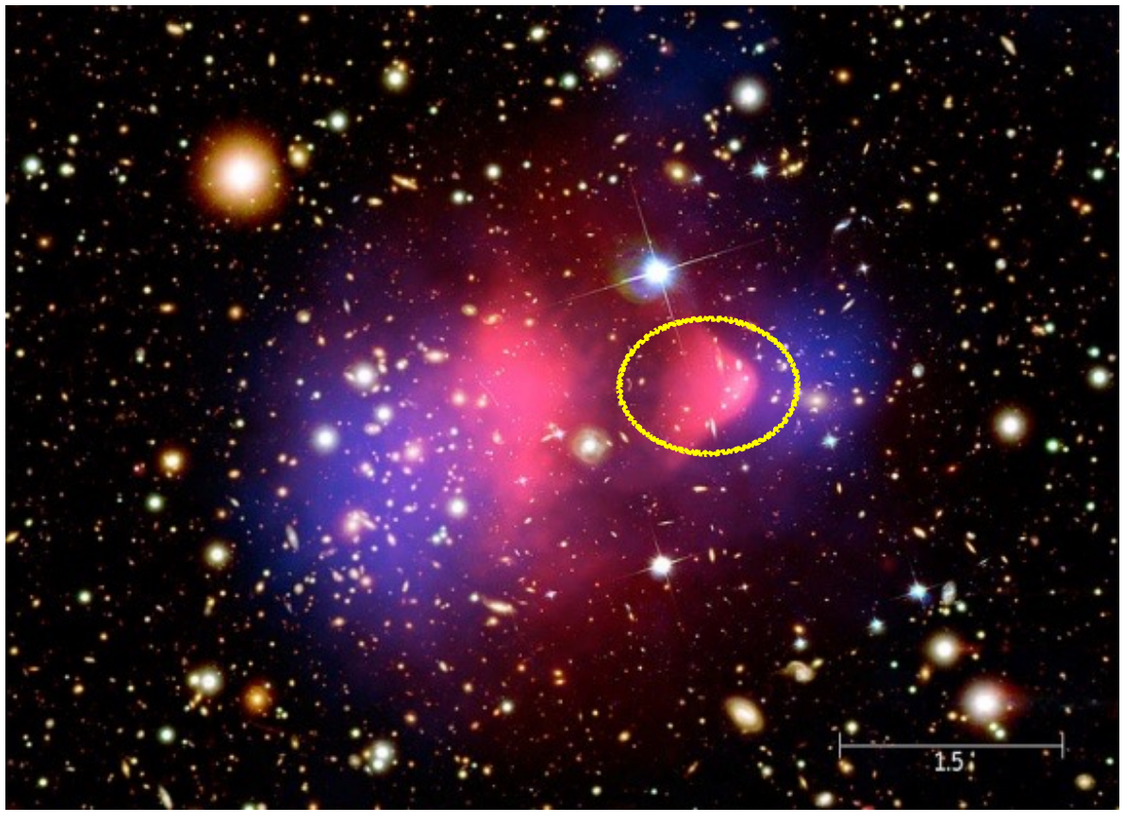


Red: X-ray emitting hot gas
(baryonic matter)

Blue: non-luminous matter observed
by gravitational lensing (dark matter)

Distribution of visible matter: Bullet cluster

1E 0657-558



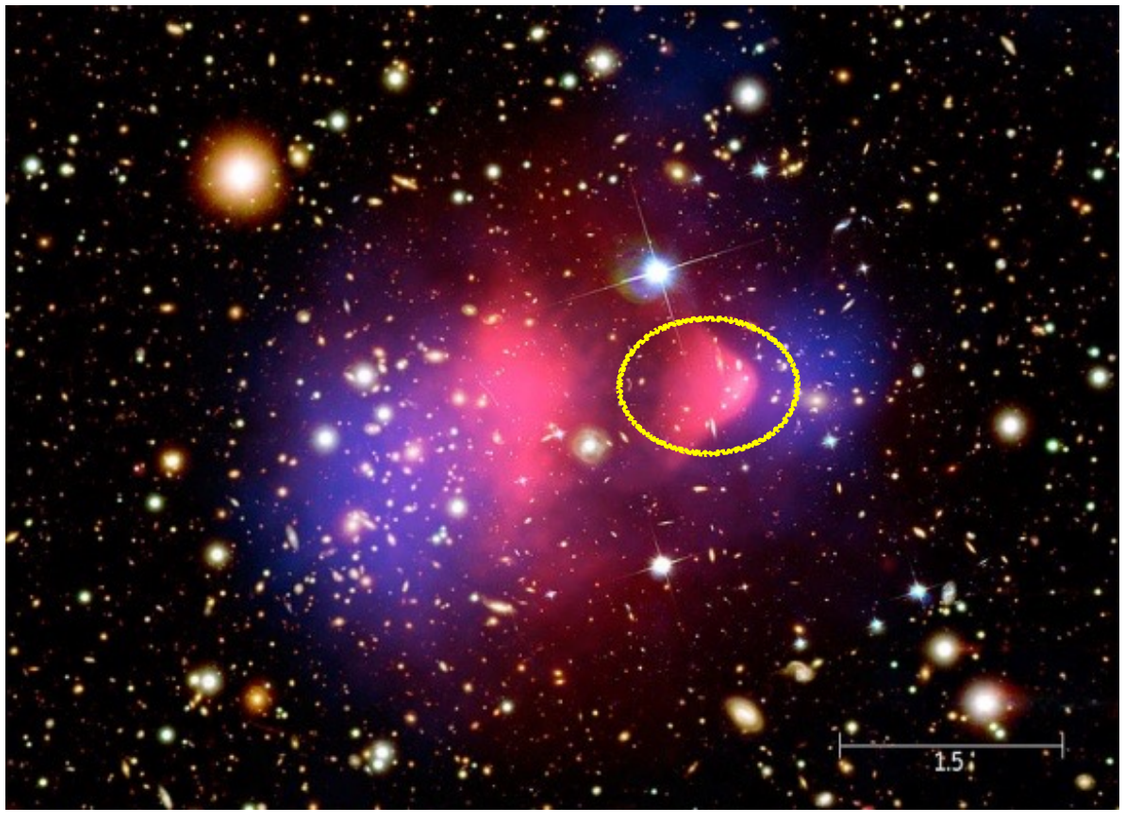
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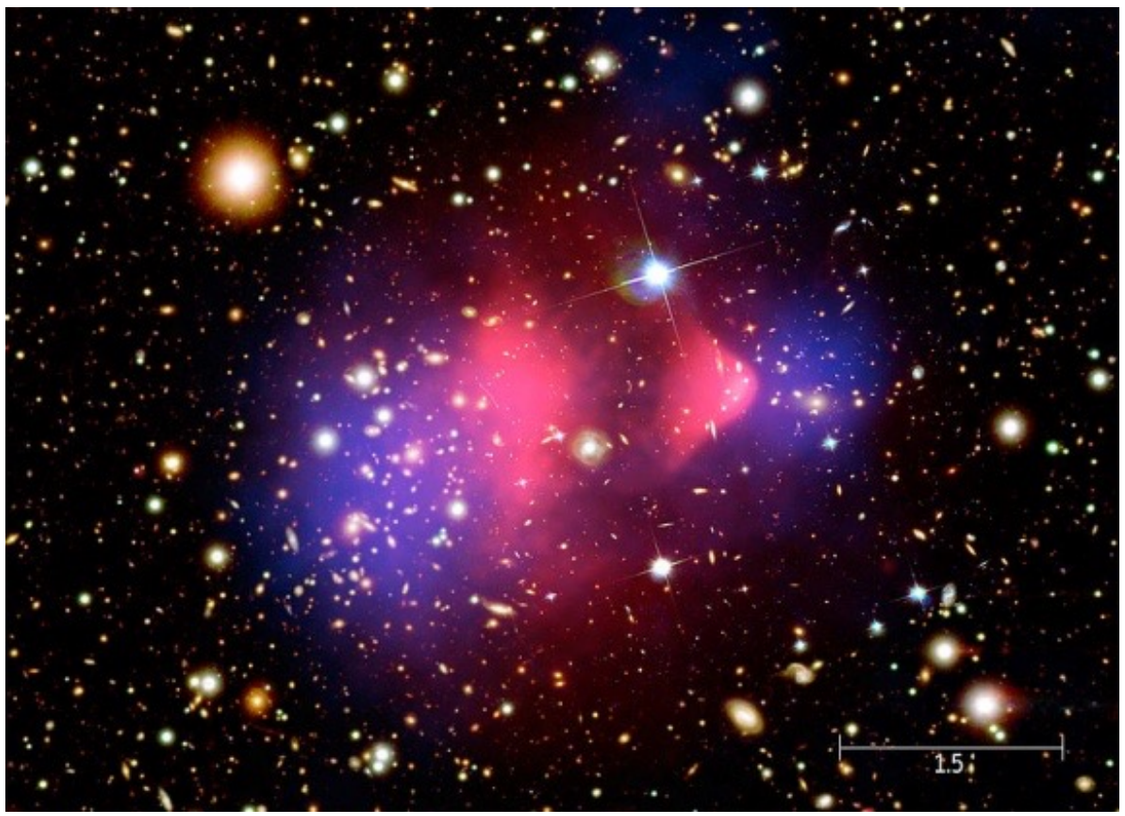
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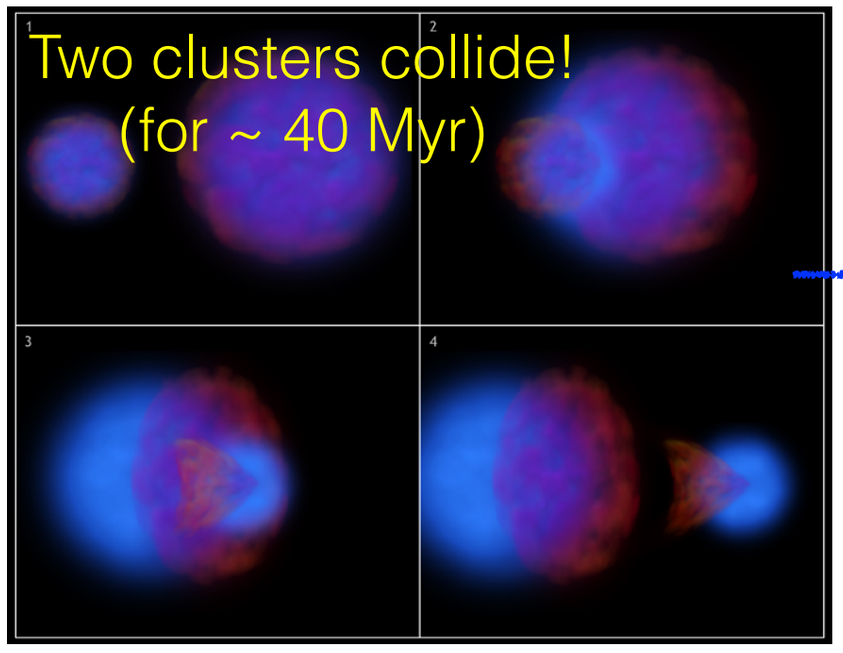
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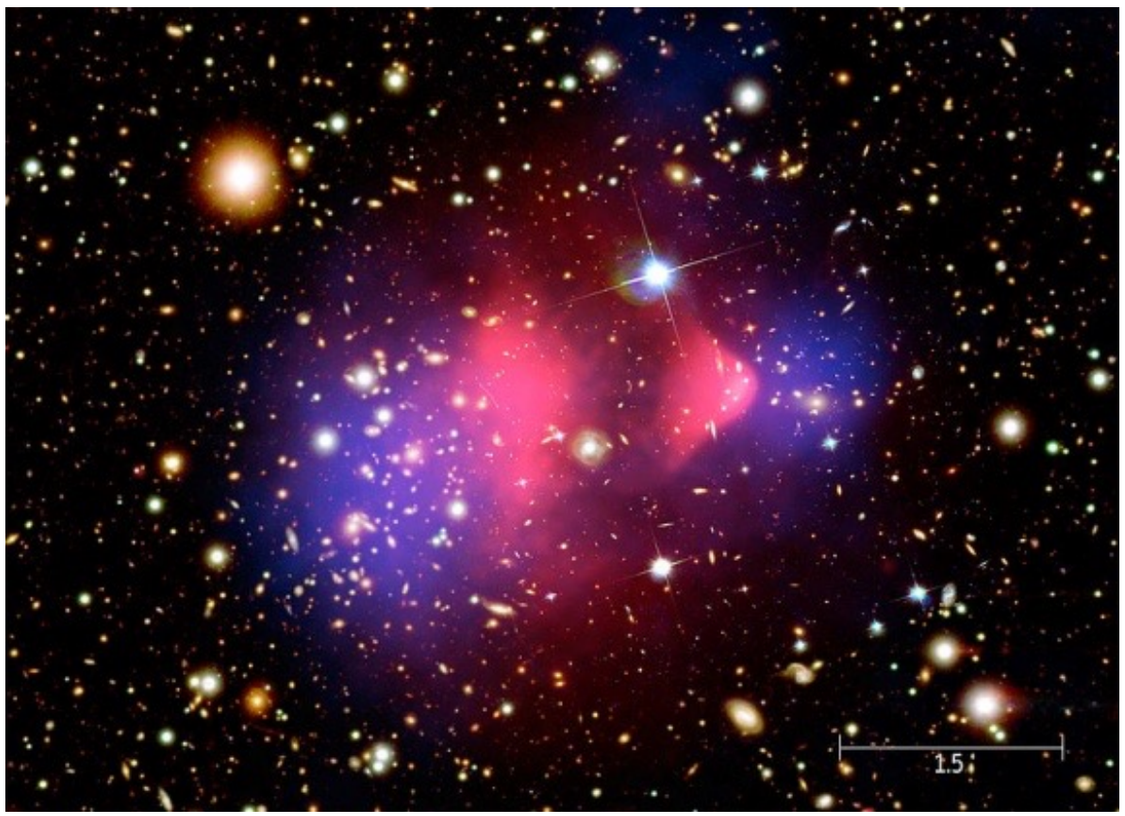


Baryonic particles interact strongly
(EM int.) among themselves and gather.

Dark Matter just pass by but
in a gravitational potential.

Distribution of visible matter: Bullet cluster

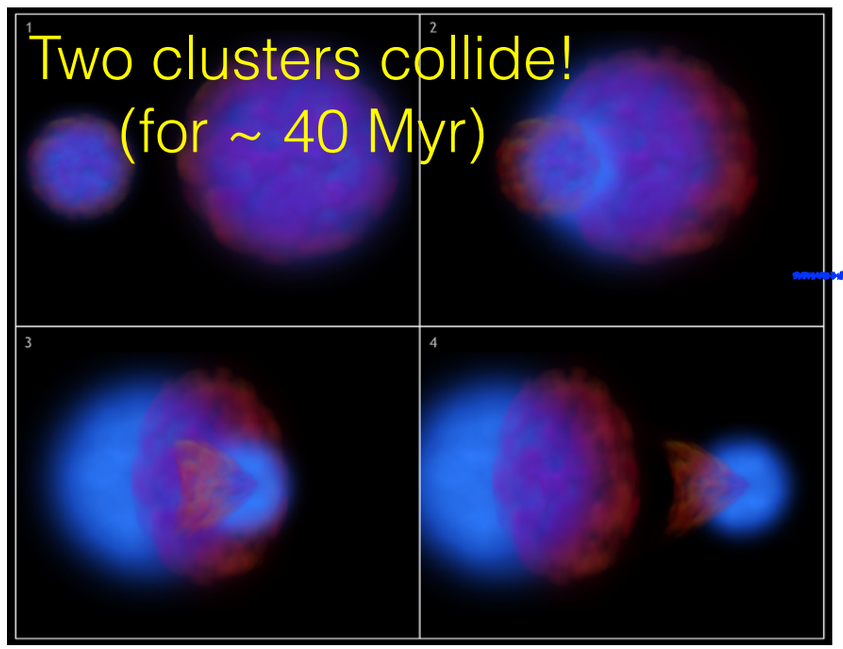
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$$\frac{\sigma_{\rm SI}}{m} \lesssim 1\,{\rm cm}^2/{\rm g}$$

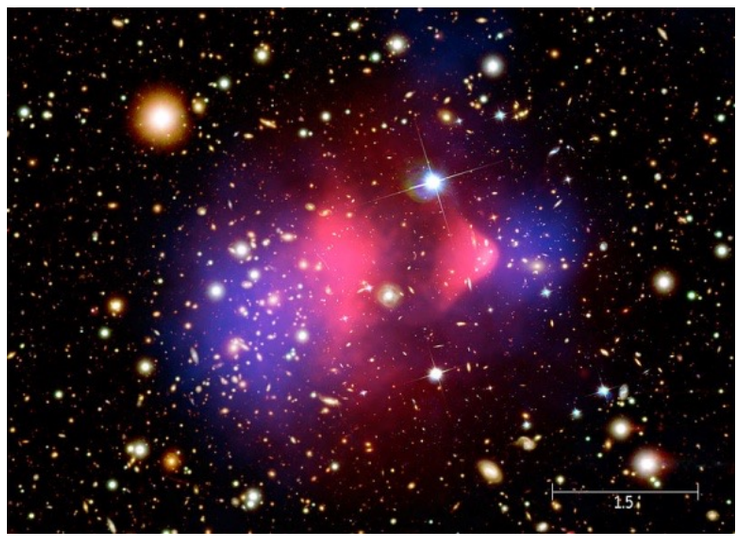


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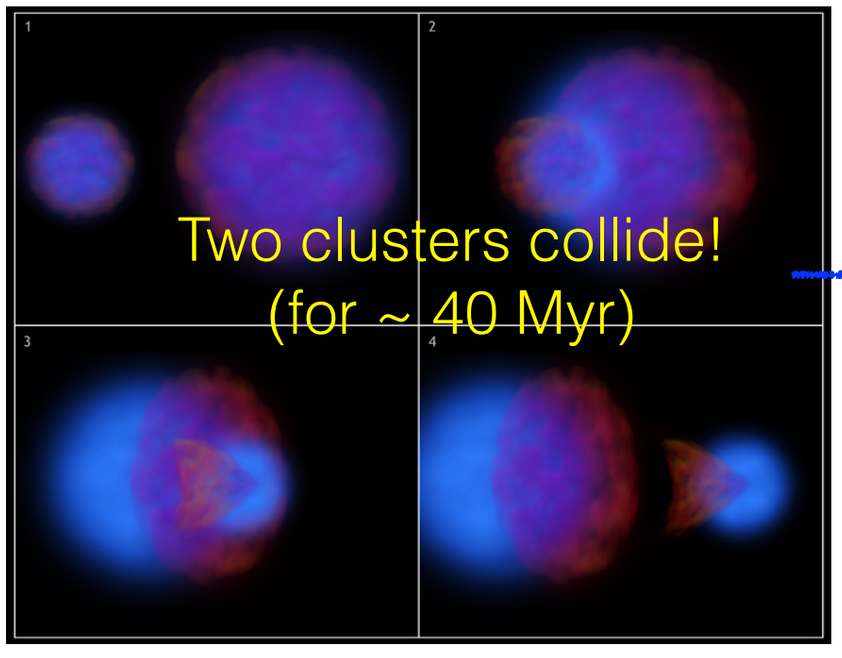
Distribution of visible matter: Bullet cluster

Bullet cluster



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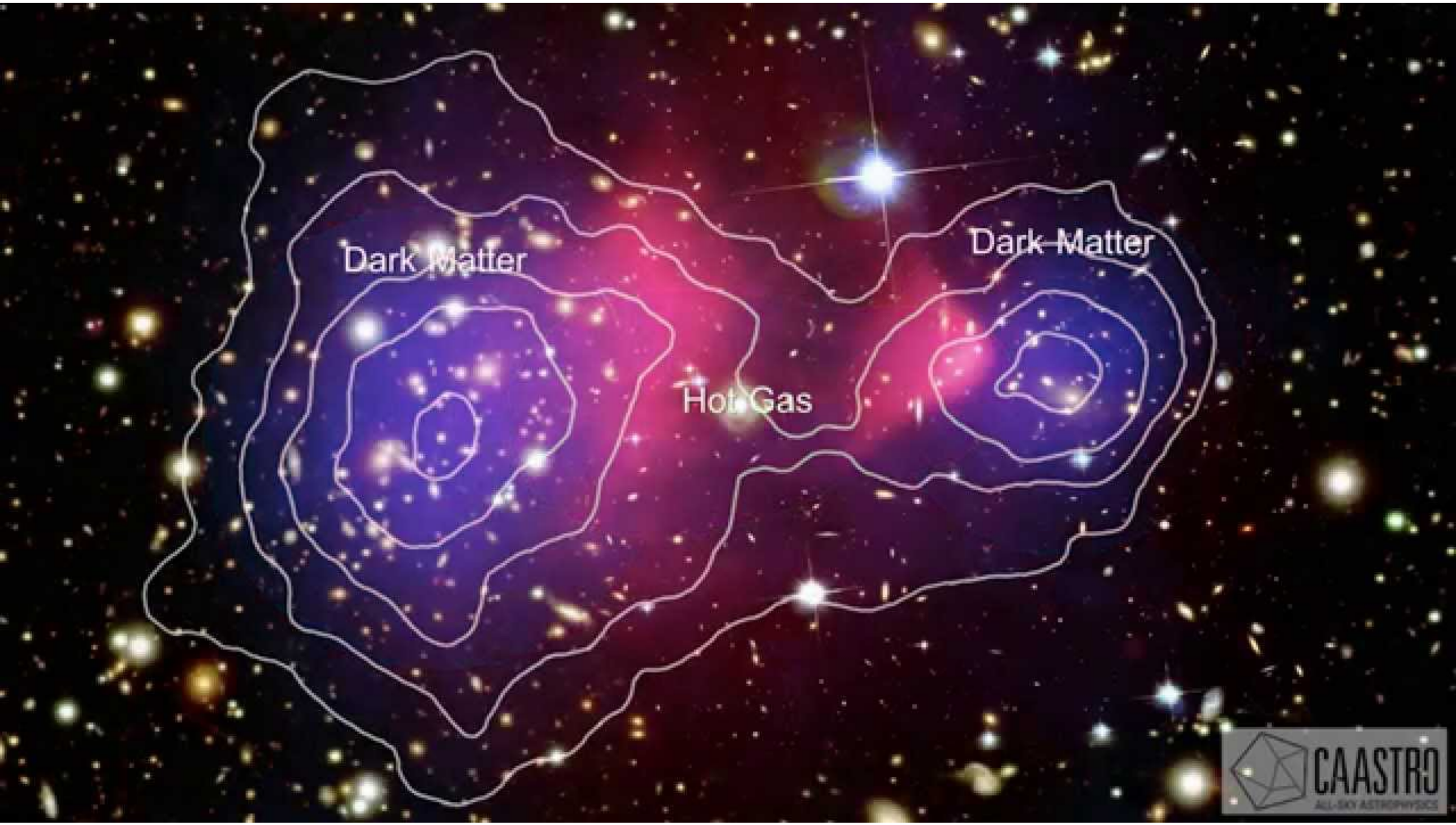
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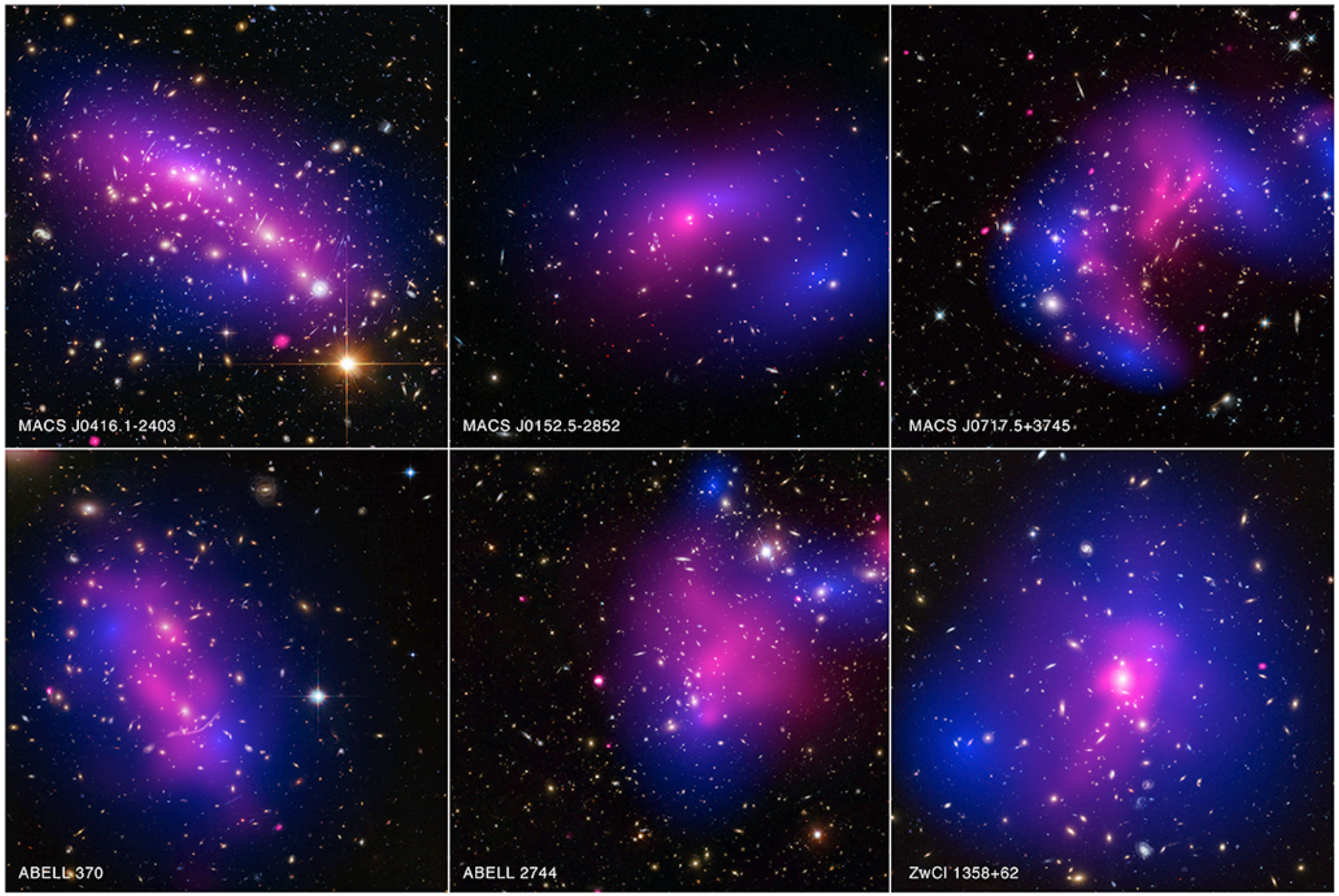
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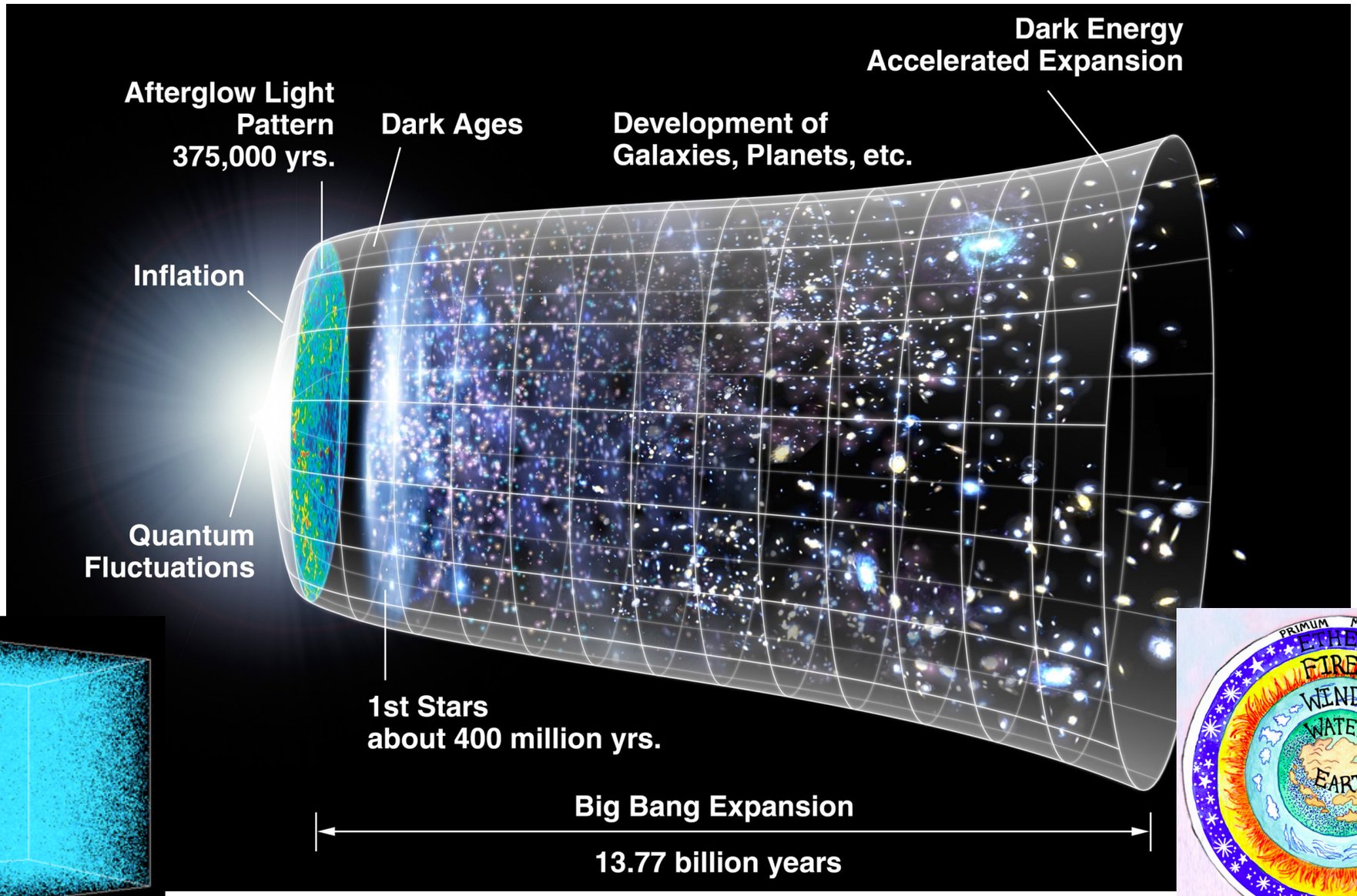
Distribution of visible matter: Bullet cluster

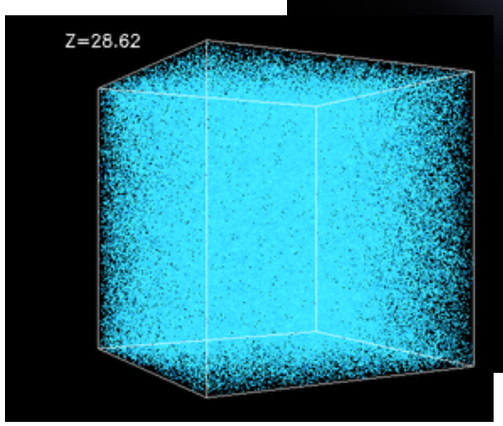


Distribution of visible matter: Bullet cluster



History of our Universe

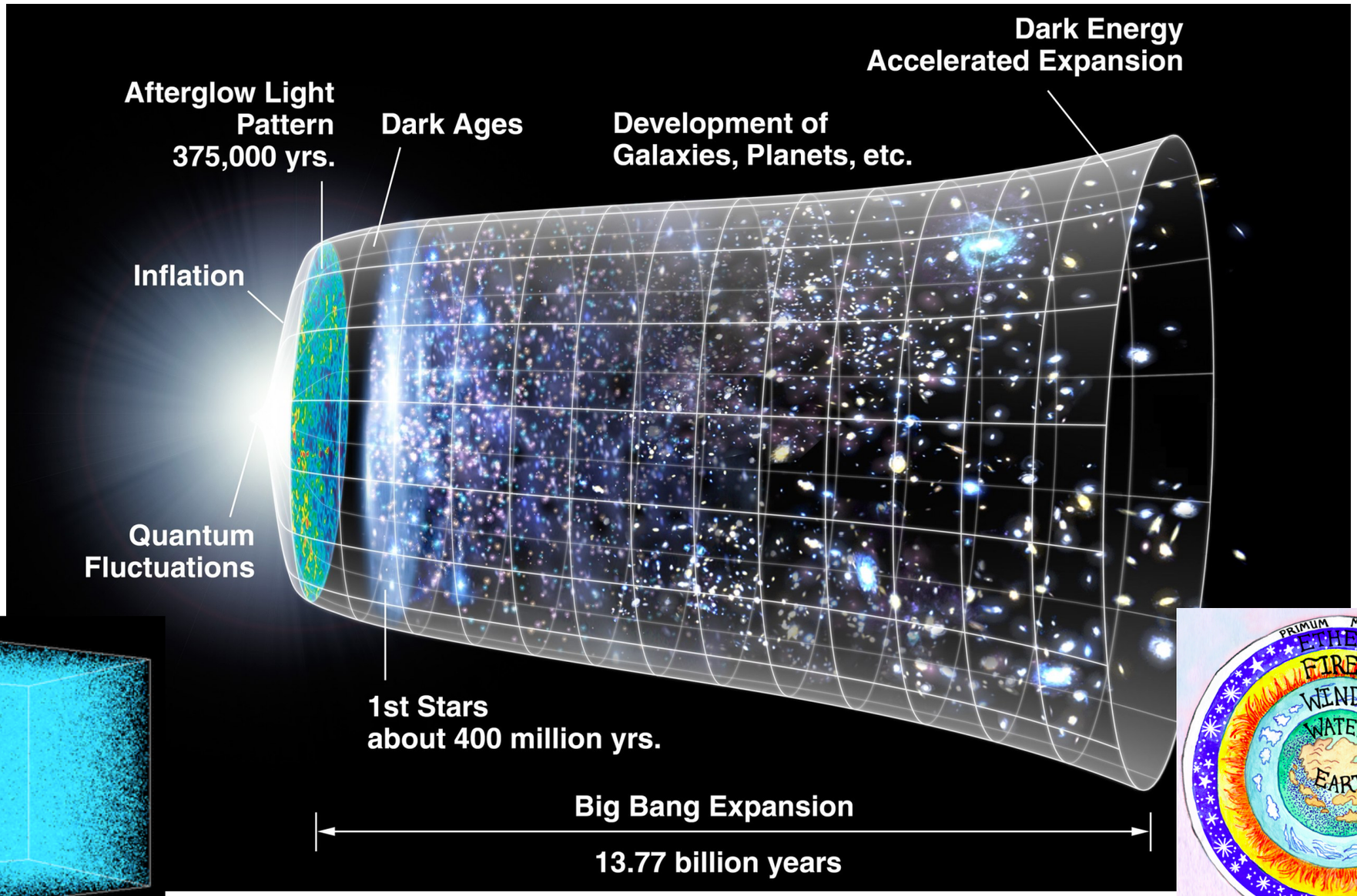


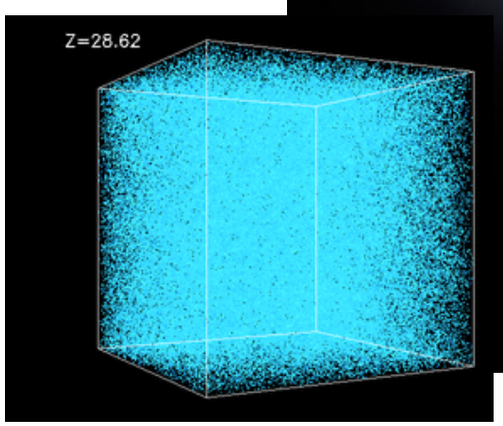




Very important in constructing our Universe!

History of our Universe







Very important in constructing our Universe!

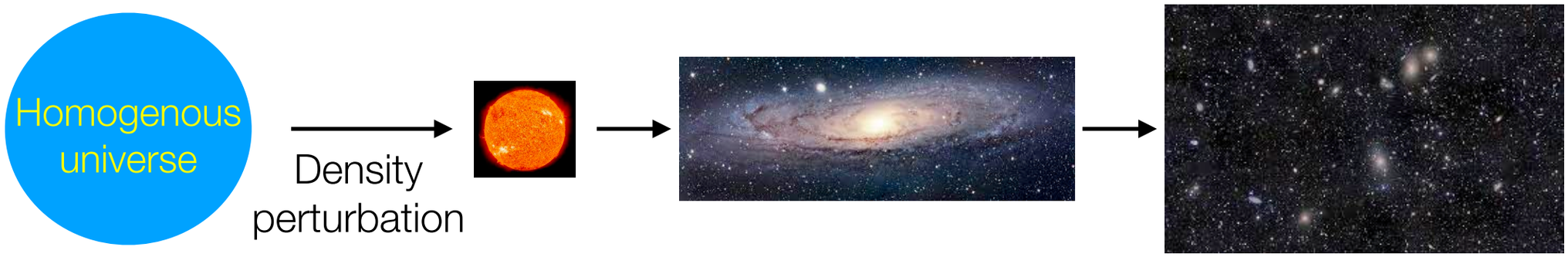
Dark matter and structure of Universe

Dark Matter is a key element in the structure of Universe

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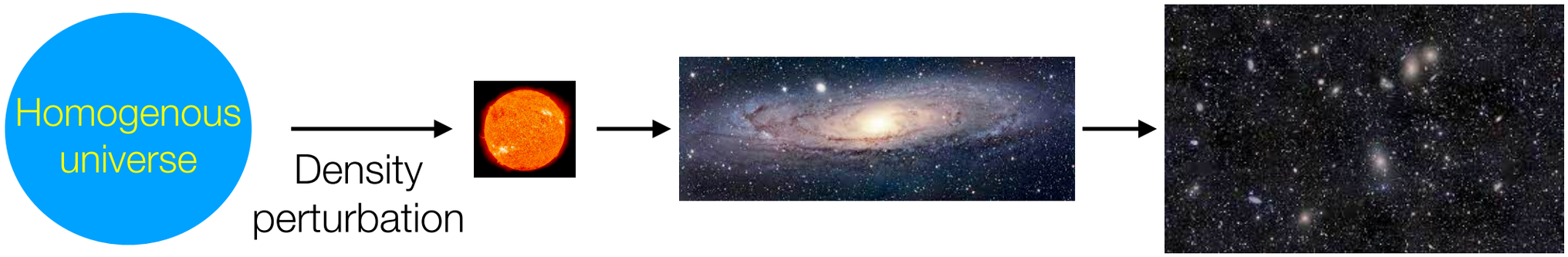
Structure formation



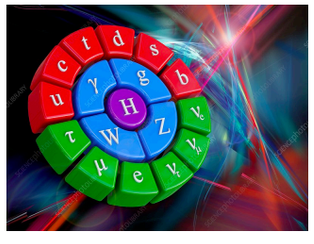
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Dark Matter is a key element in the structure of Universe

Structure formation



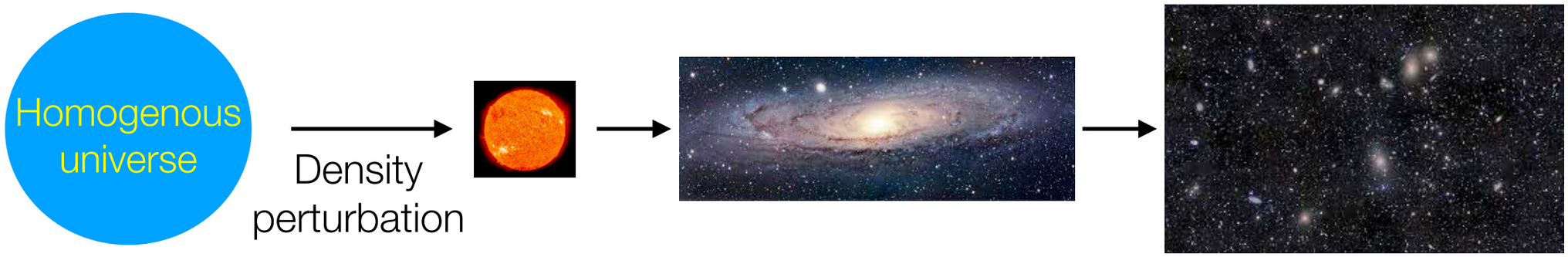
Impossible only with



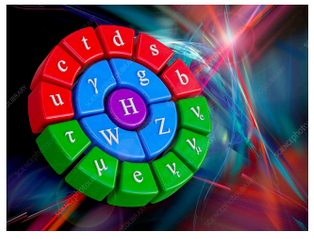
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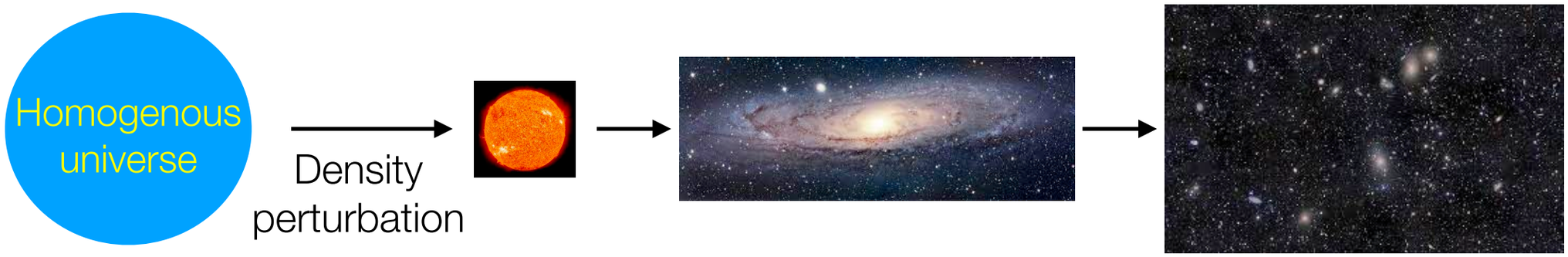
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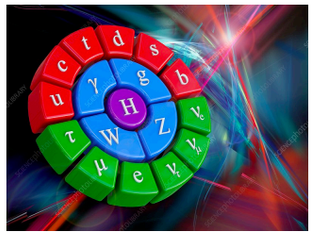
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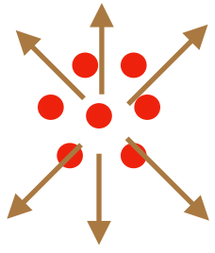
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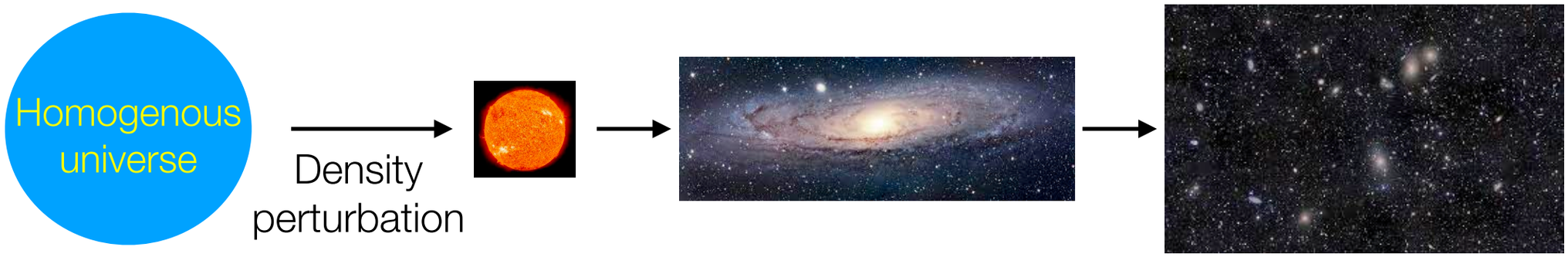
Radiation pressure



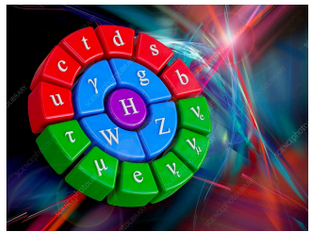
Dark matter and structure of Universe

Dark Matter is a key element in the structure of Universe

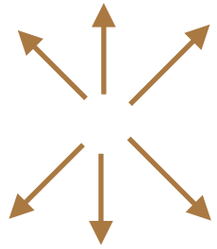
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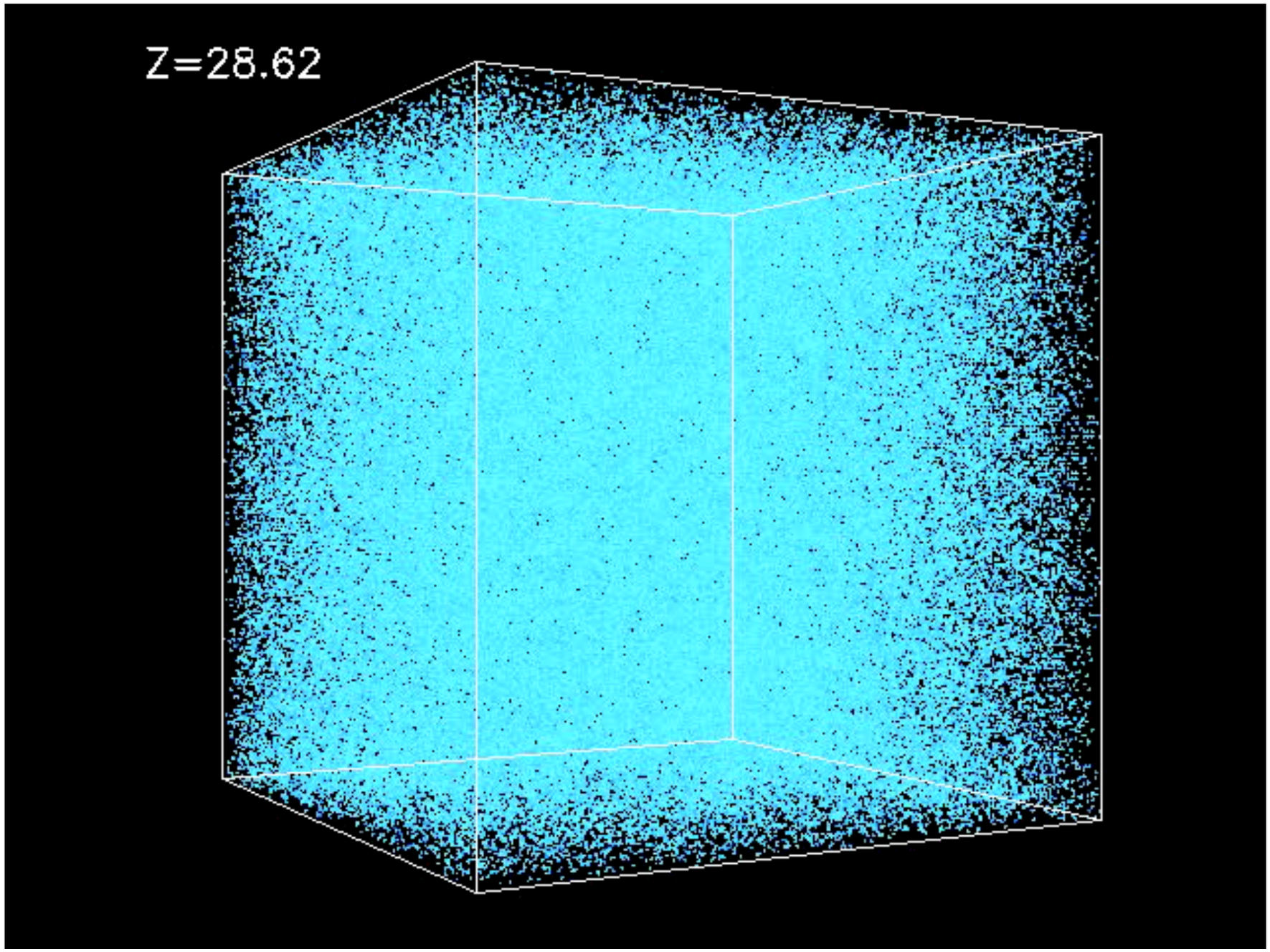
Radiation pressure



Structure is washed out by radiation. (Not enough time)

Dark matter and structure of Universe

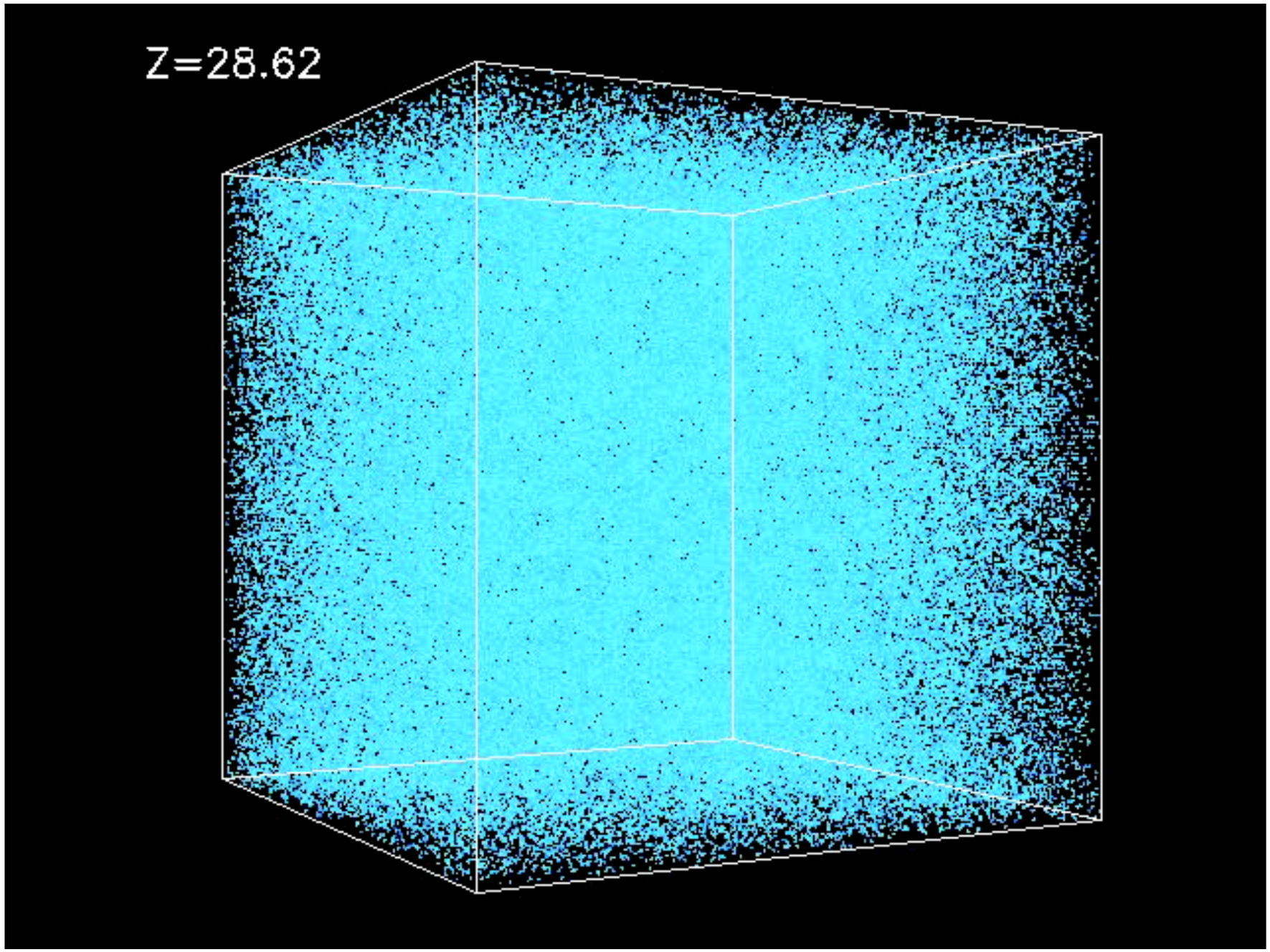
DM: cold fluid with density perturbation and velocity distribution



http://cosmicweb.uchicago.edu/filaments.html

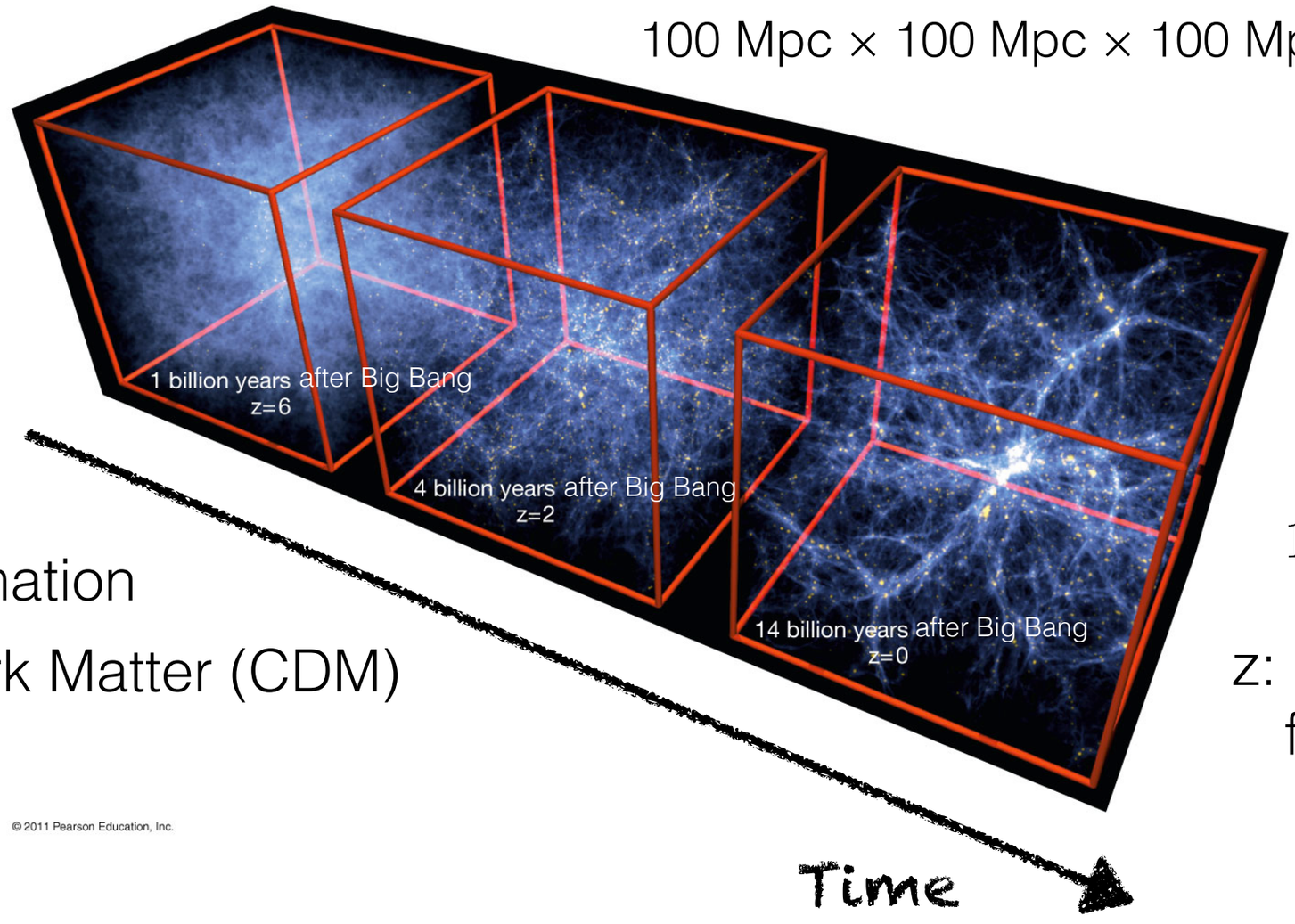
Dark matter and structure of Universe

DM: cold fluid with density perturbation and velocity distribution



http://cosmicweb.uchicago.edu/filaments.html

Dark matter and structure of Universe



© 2011 Pearson Education, Inc.

Structure formation

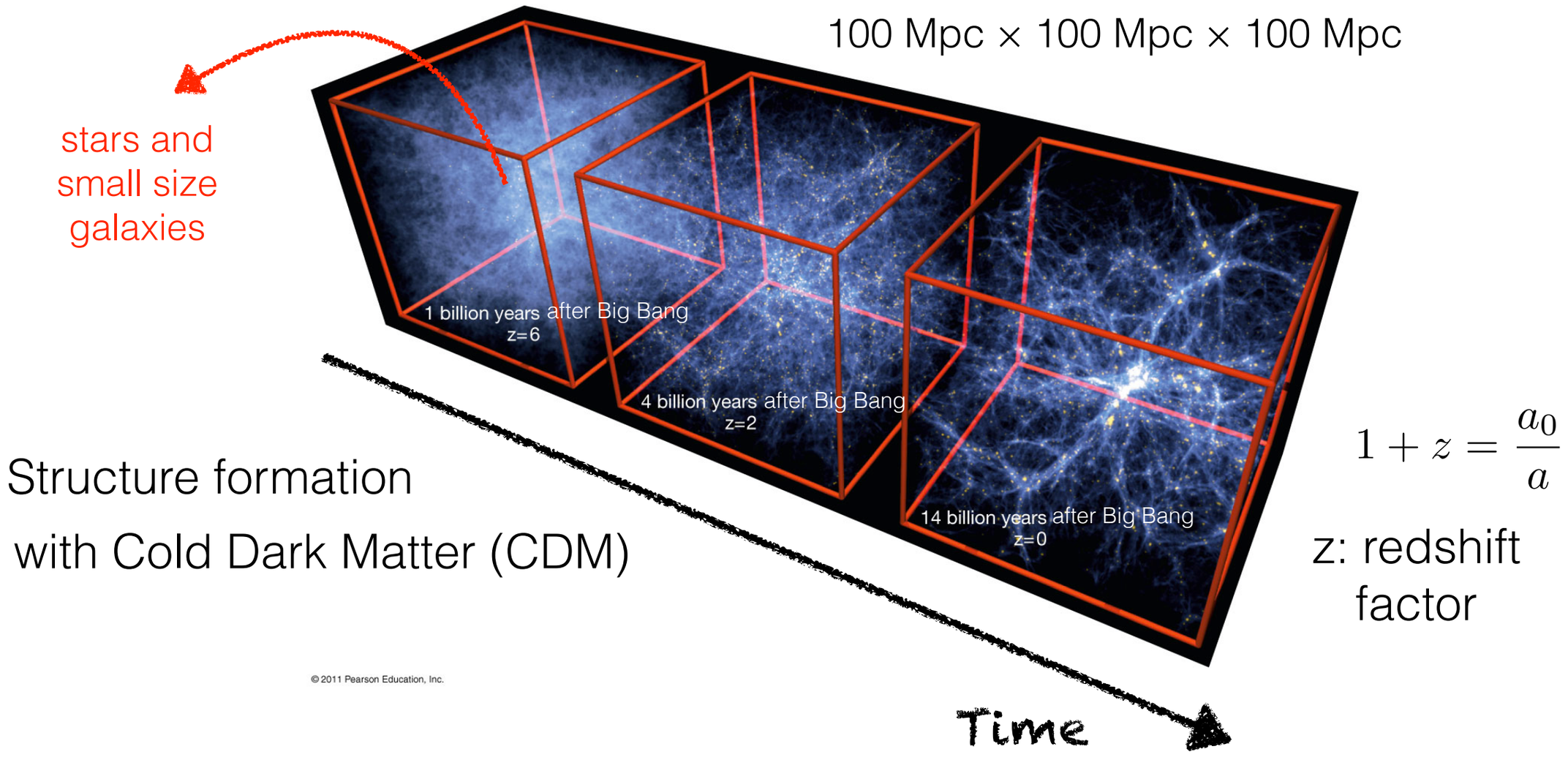
with Cold Dark Matter (CDM)

$$1 + z = \frac{a_0}{a}$$

z: redshift

factor

Dark matter and structure of Universe



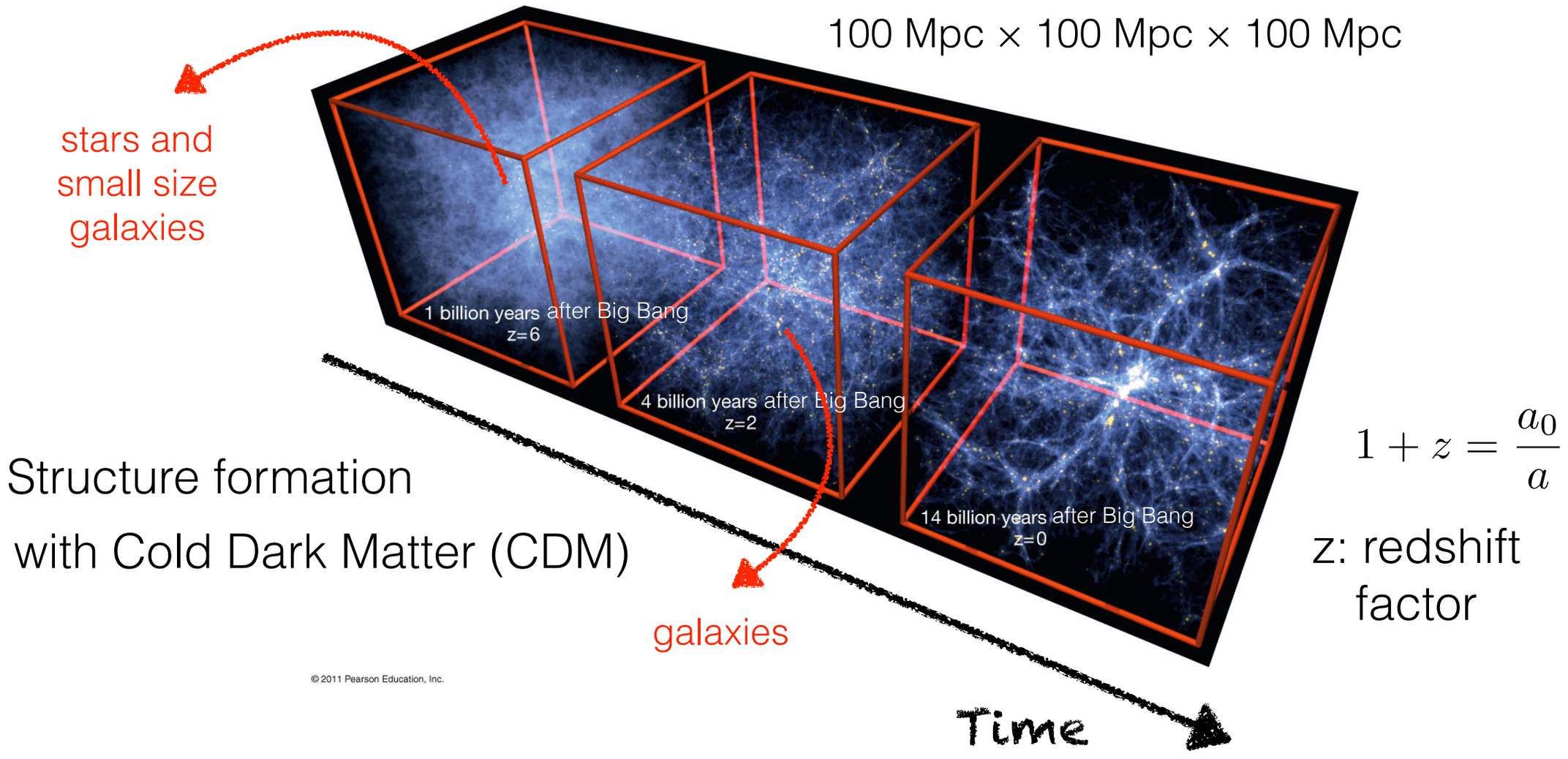
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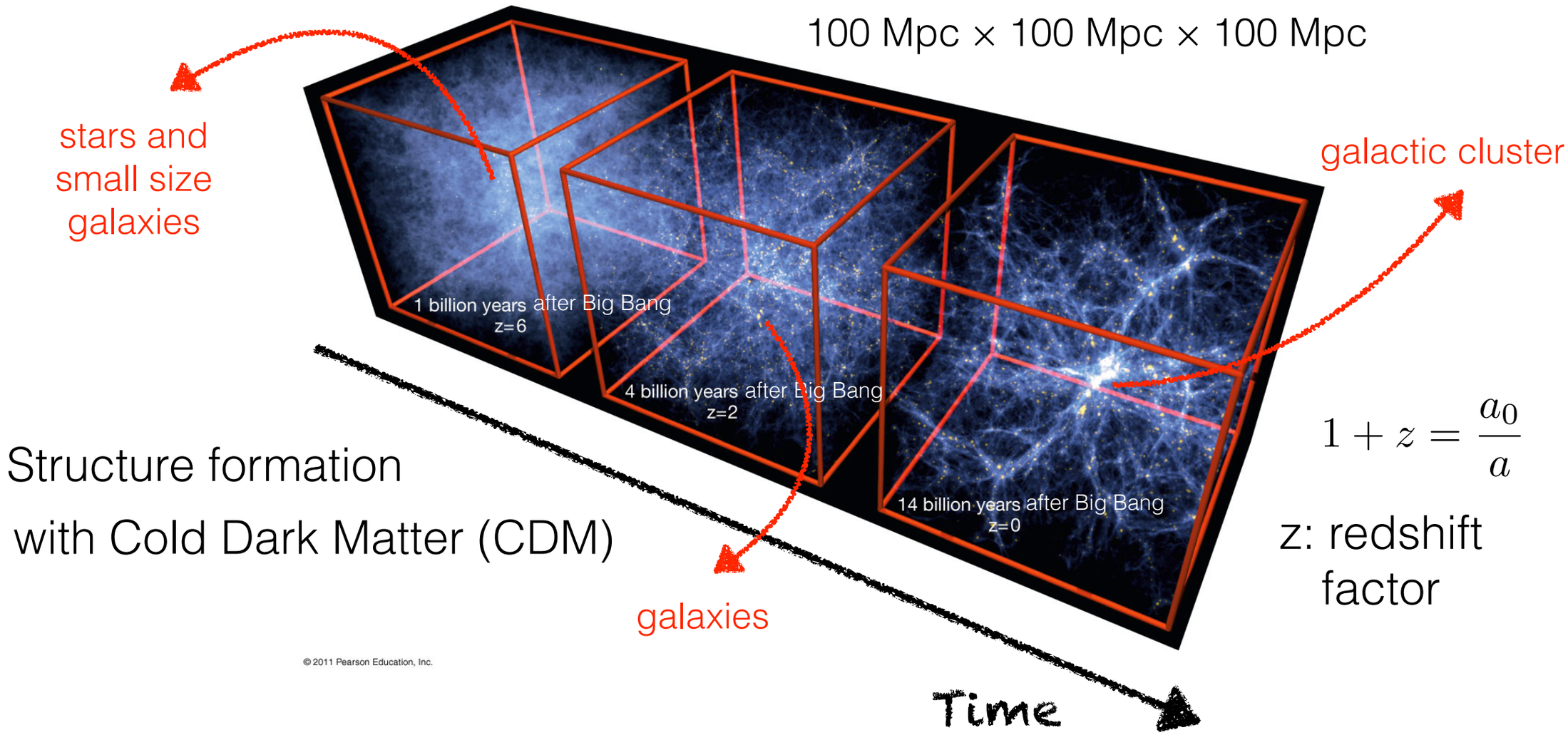
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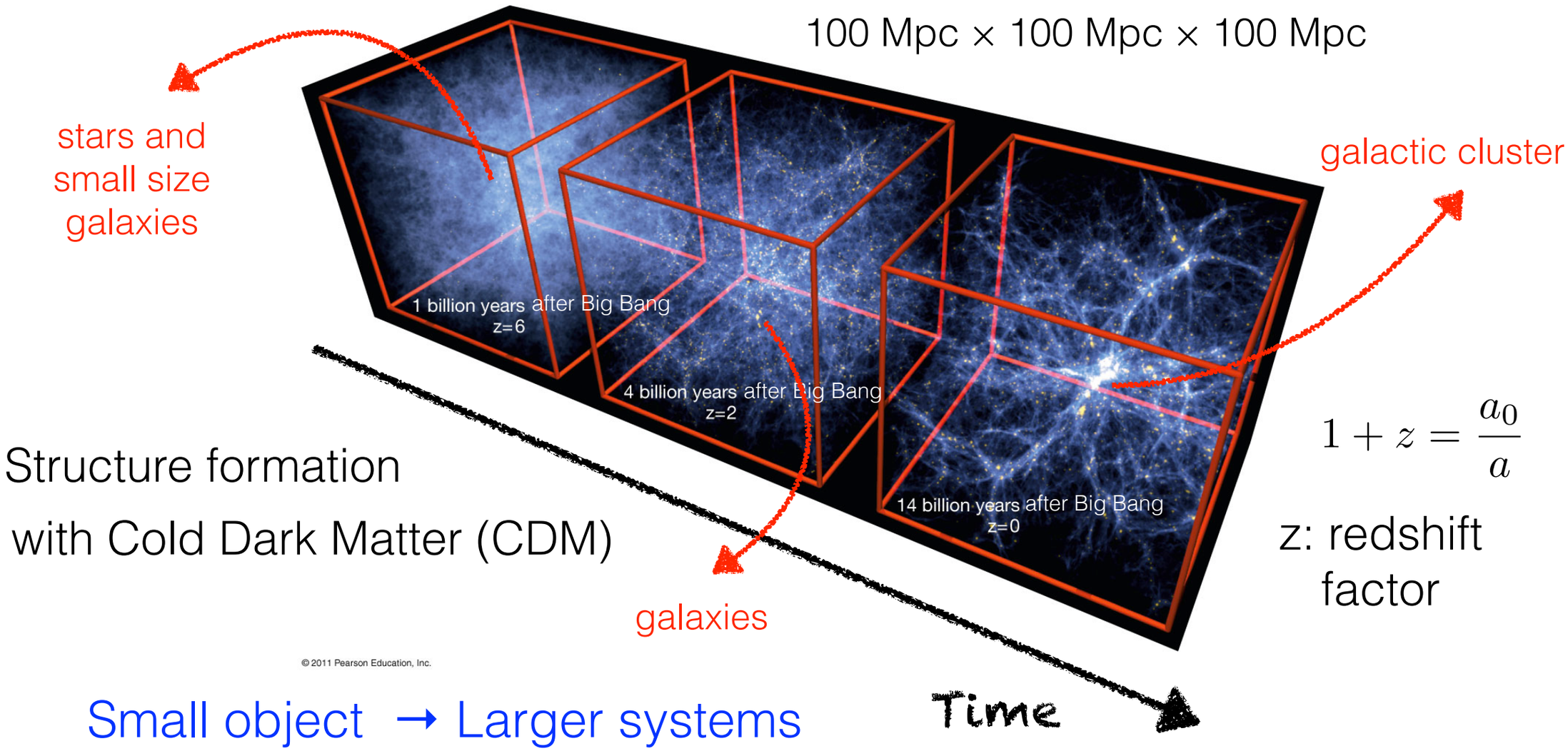
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Structure formation

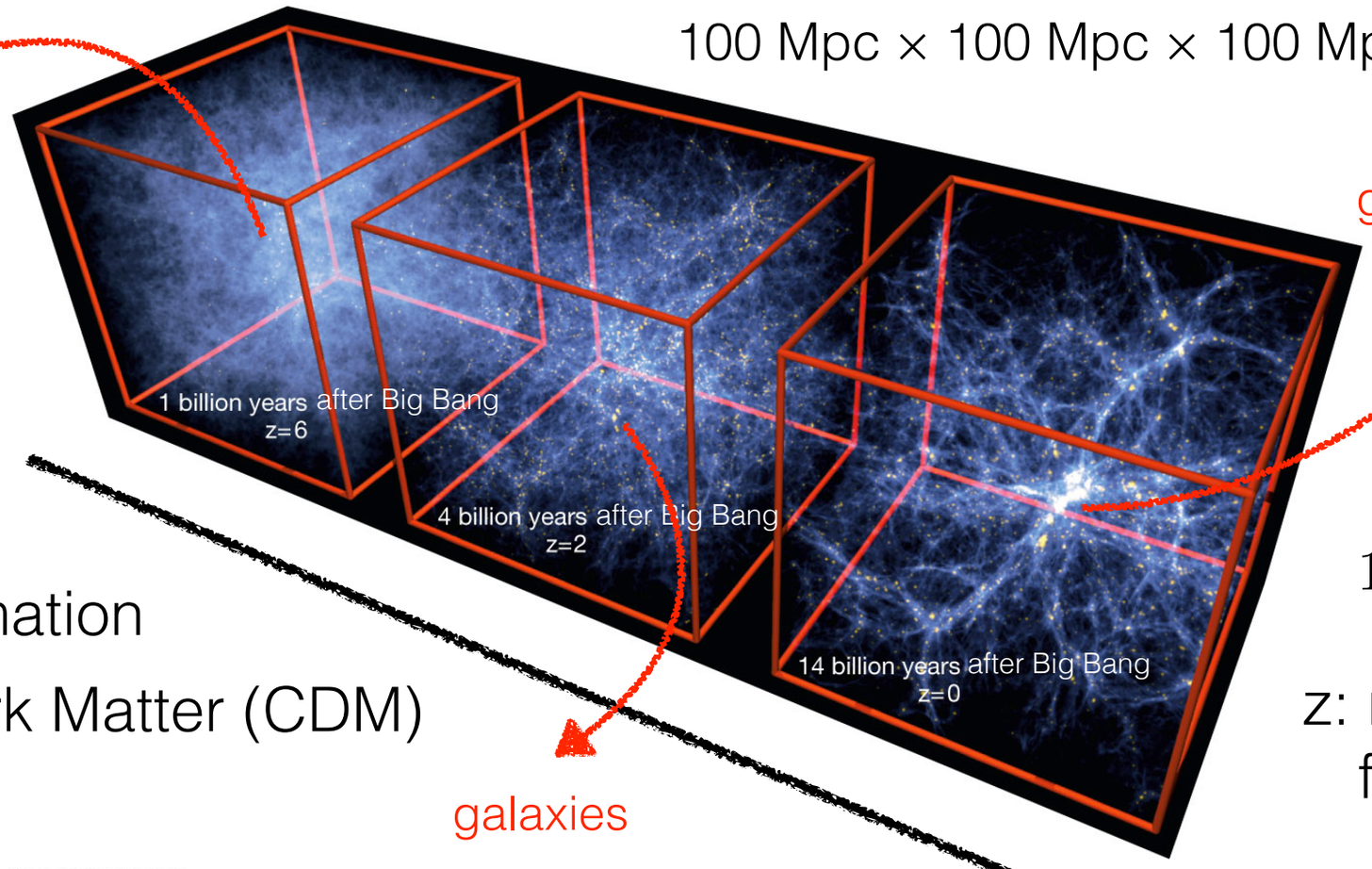
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Small object → Larger systems

Dark matter and structure of Universe



Structure formation

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$$1 + z = \frac{a_0}{a}$$

z: redshift factor

Small object → Larger systems

Confirmed by observation of

690 million years after Big Bang (z = 7.085)



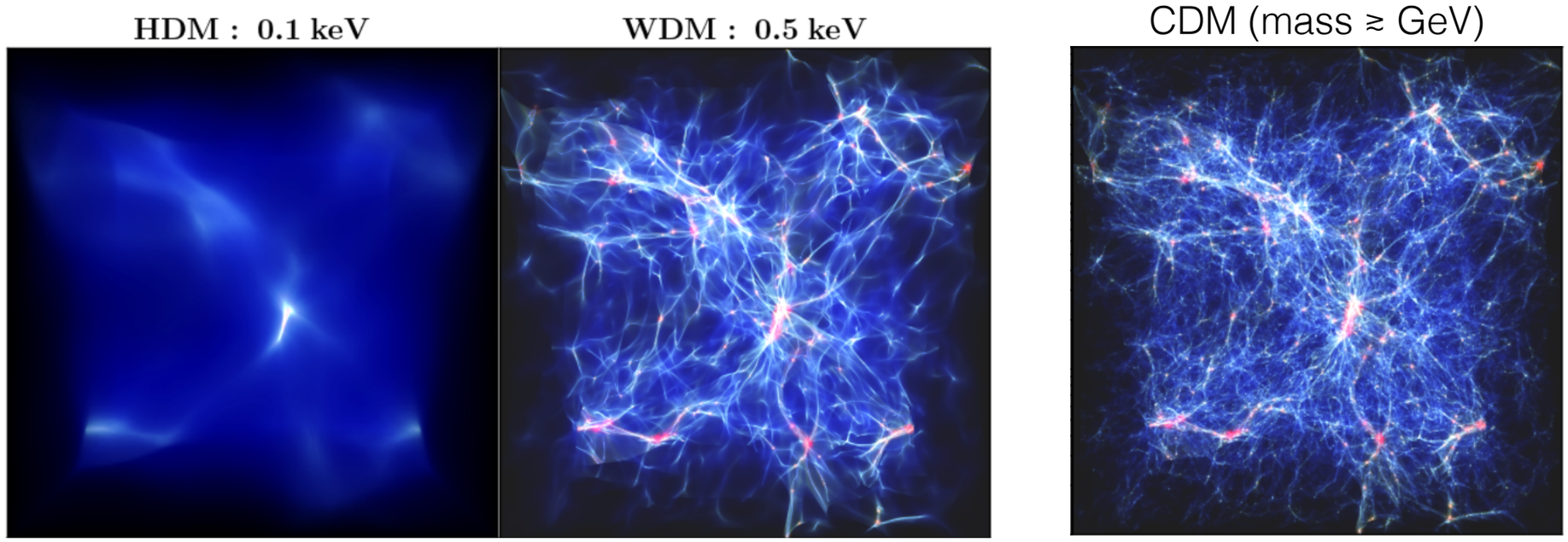
Quasi stellar-Object

Extremely luminous AGN

(size < solar system)

by super massive black hole

Dark matter and structure of Universe



Bauer et al., 1512.01981

z = 2.5

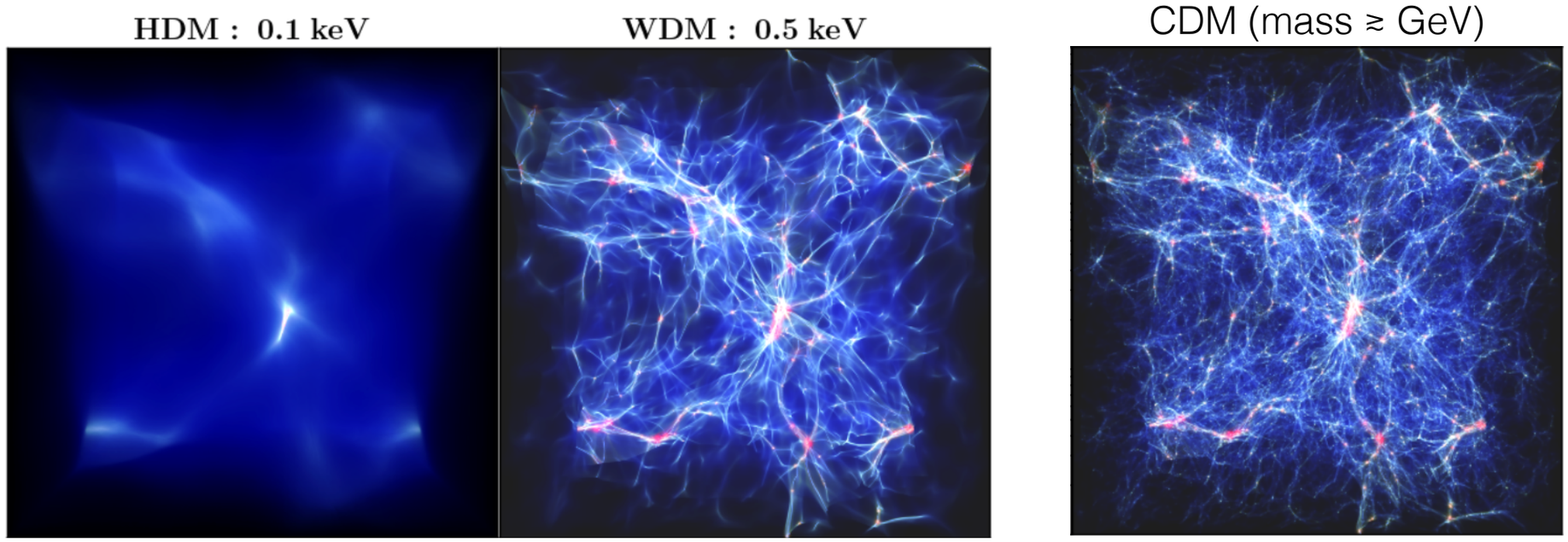
25 h^{-1} Mpc box (galactic cluster size)

- Hot Dark Matter (HDM): large velocity dispersion, wash out the structure

- Warm Dark Matter (WDM): intermediate velocity dispersion
  Not bad, but constrained from Lyman-α (H around quasars) so mass ≳ O(keV)

- Cold Dark Matter (CDM): vanishing velocity dispersion, behaves like points

Dark matter and structure of Universe



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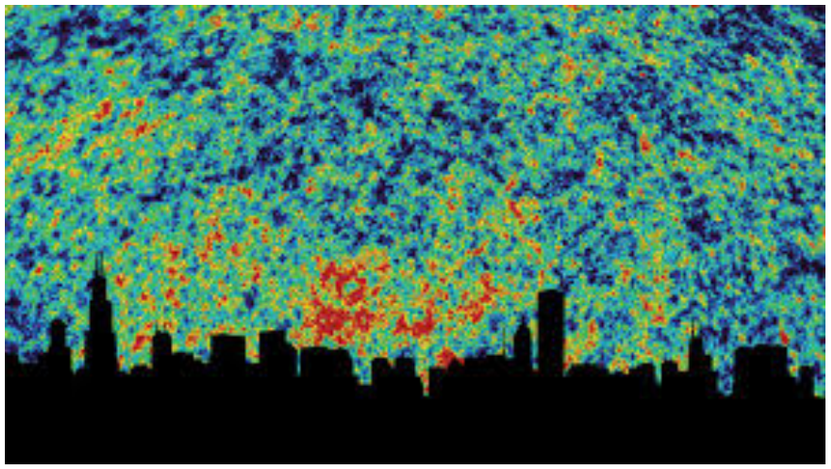
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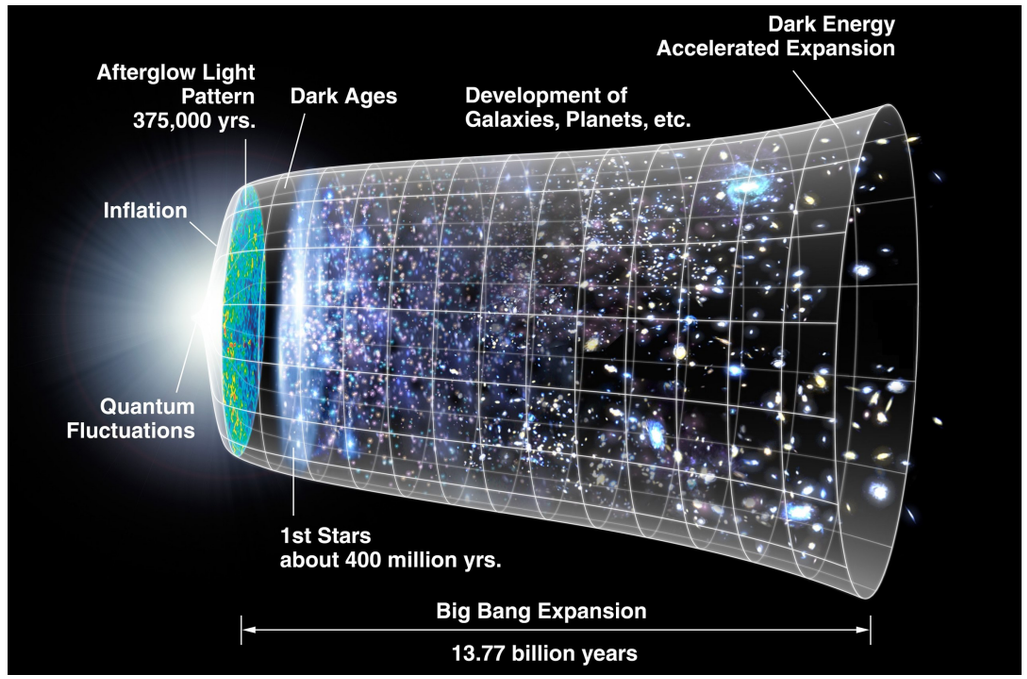
Temperature in the early universe or simply mass (in many cases)

History: Cosmic Microwave Background

1 mm - 1 m EM radiation (not μm), 300MHz - 300GHz

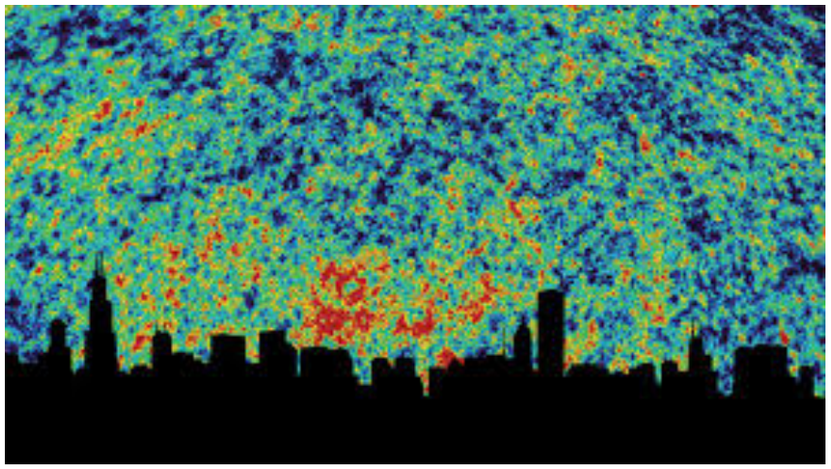


Prof. K.-Y. Choi's lecture

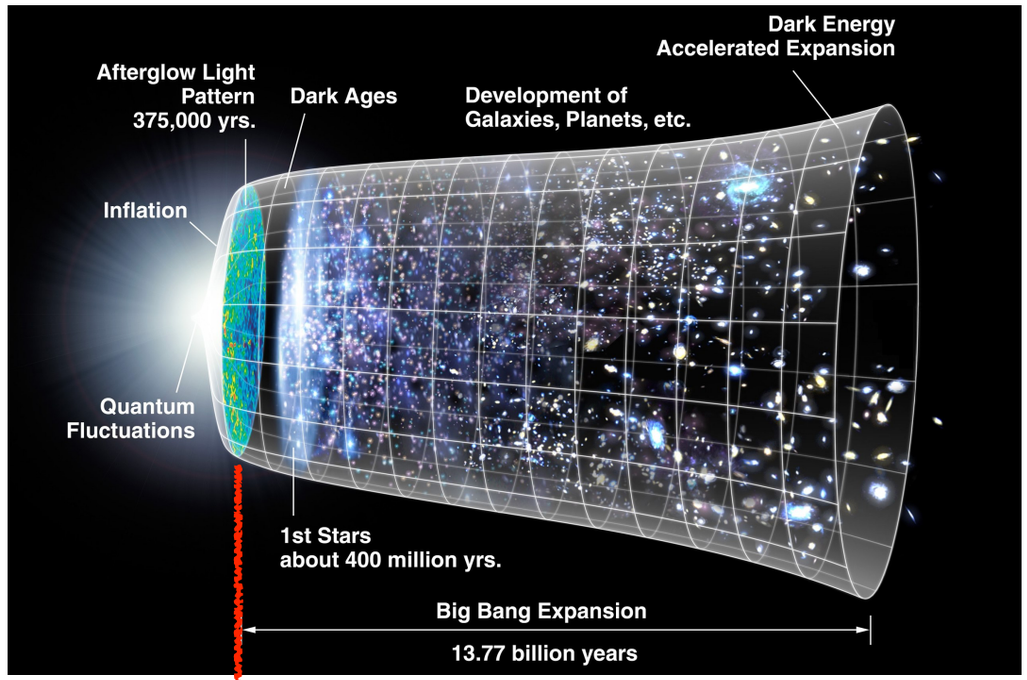


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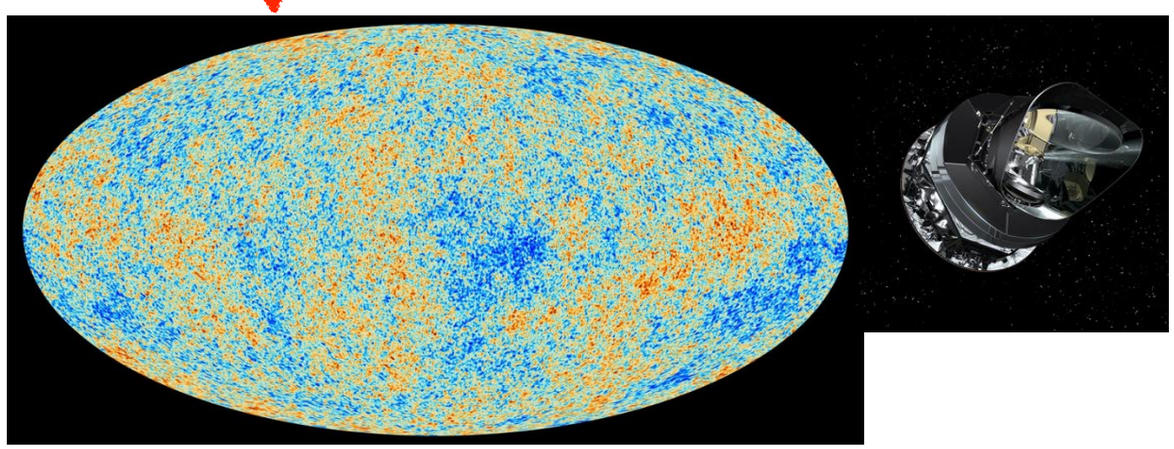
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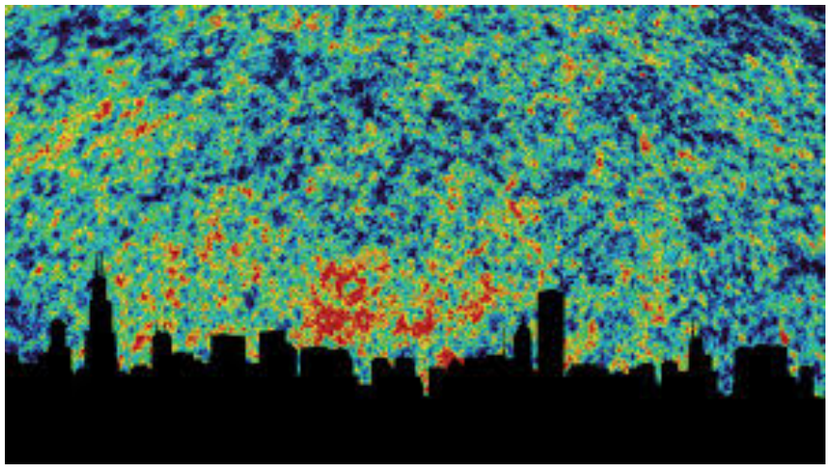


photon decouples from plasma of e, p (recombination)

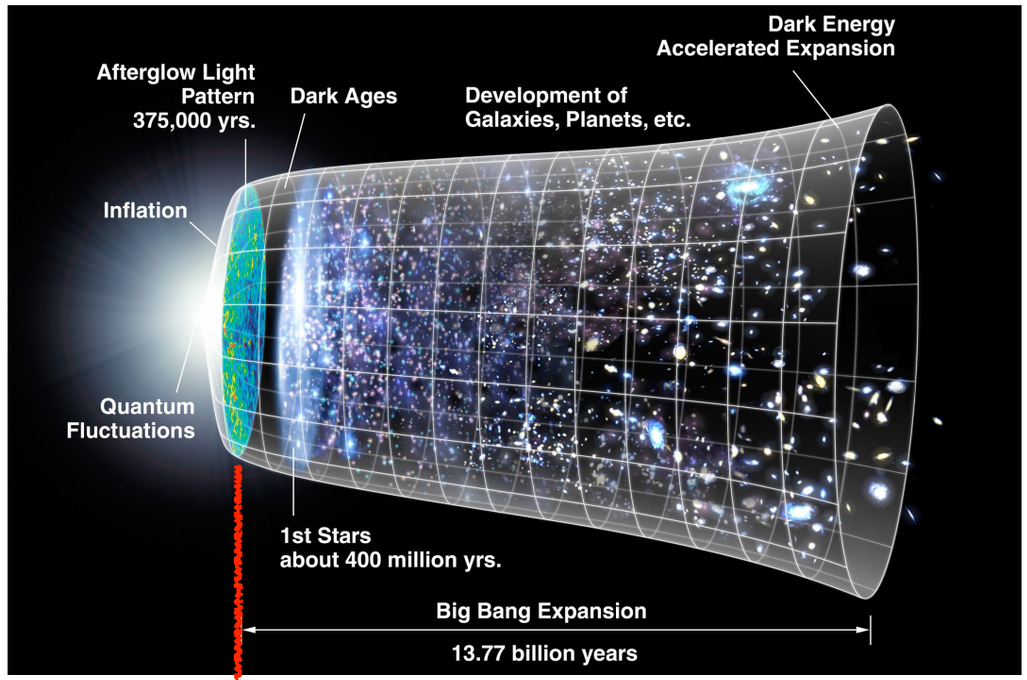


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Prof. K.-Y. Choi's lecture

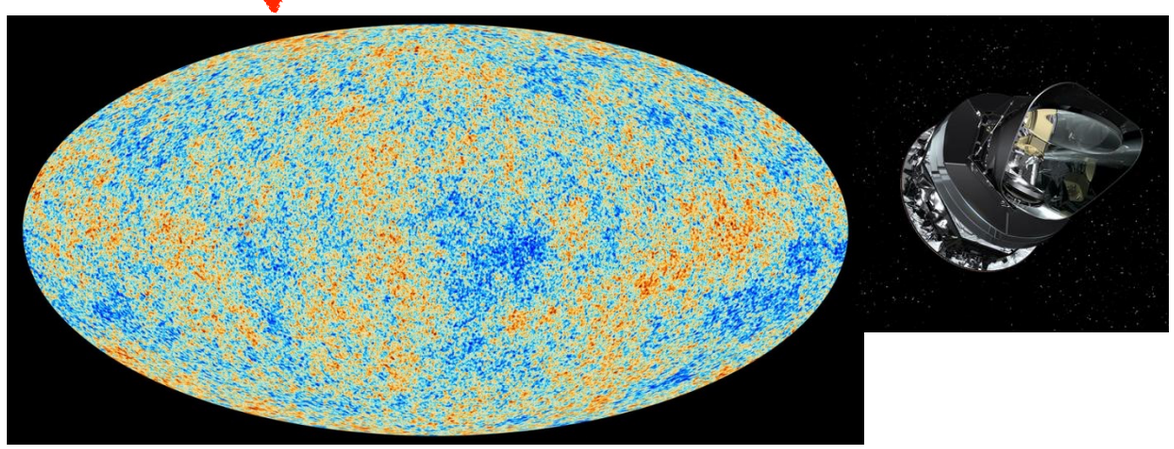


Black body spectrum at T = 2.725 K

Uniform but 10^{-5} ~ 10^{-4} level anisotropy

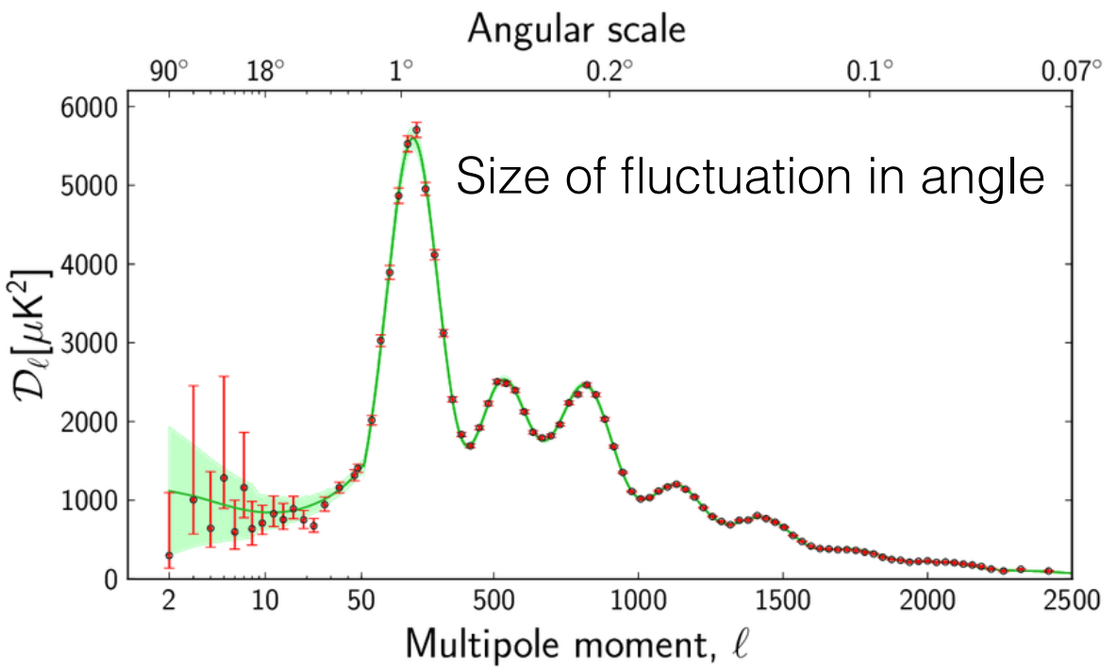
CMB shows the hints of the history before it decouples!

photon decouples from plasma of e, p (recombination)



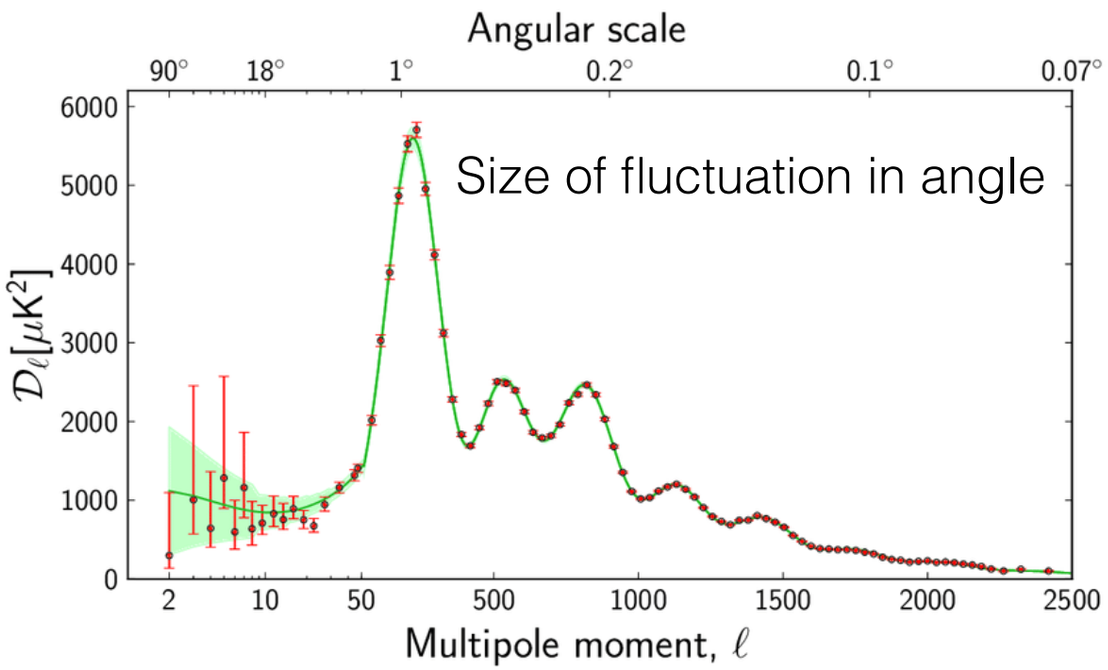
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Prof. K.-Y. Choi's lecture



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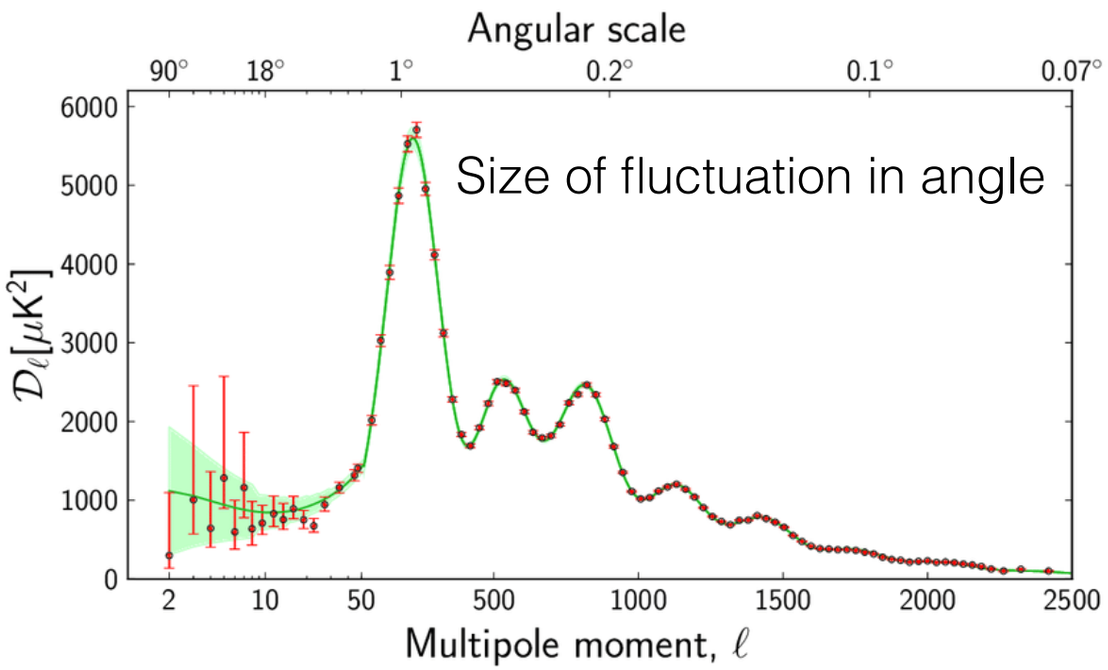


photon - baryon plasma

↓ erase anisotropies

↓ form overdensities (gravitation)

History: Cosmic Microwave Background



Prof. K.-Y. Choi's lecture

Spring: photon

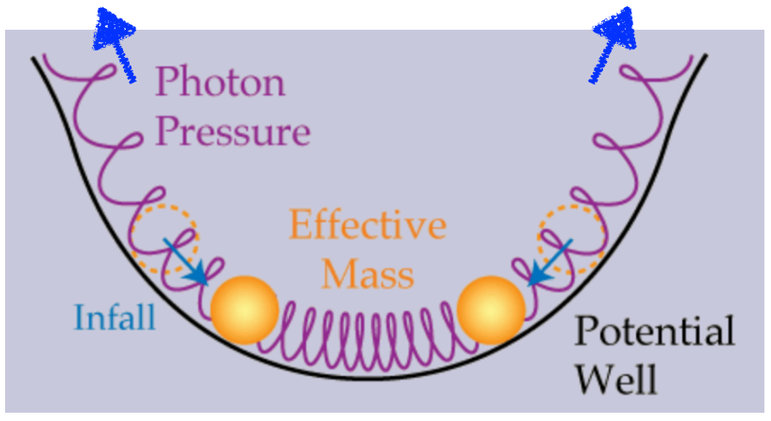
Ball: gravity by baryon

Potential Well: Dark Matter
(not connected to
photon: spring)

photon - baryon plasma

erase anisotropies

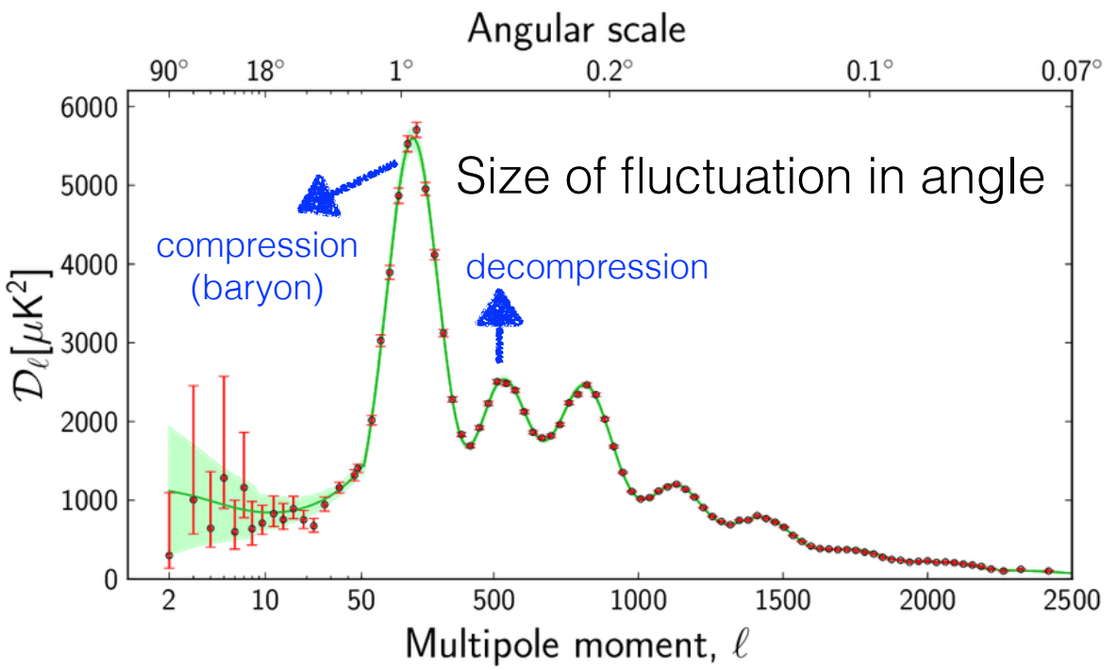
form overdensities (gravitation)



background.uchicago.edu

acoustic ocsillations
(compression - decompression)

History: Cosmic Microwave Background



Prof. K.-Y. Choi's lecture

Spring: photon

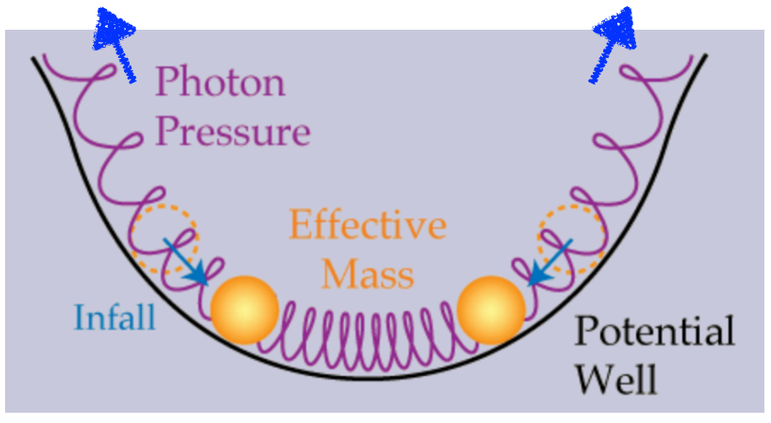
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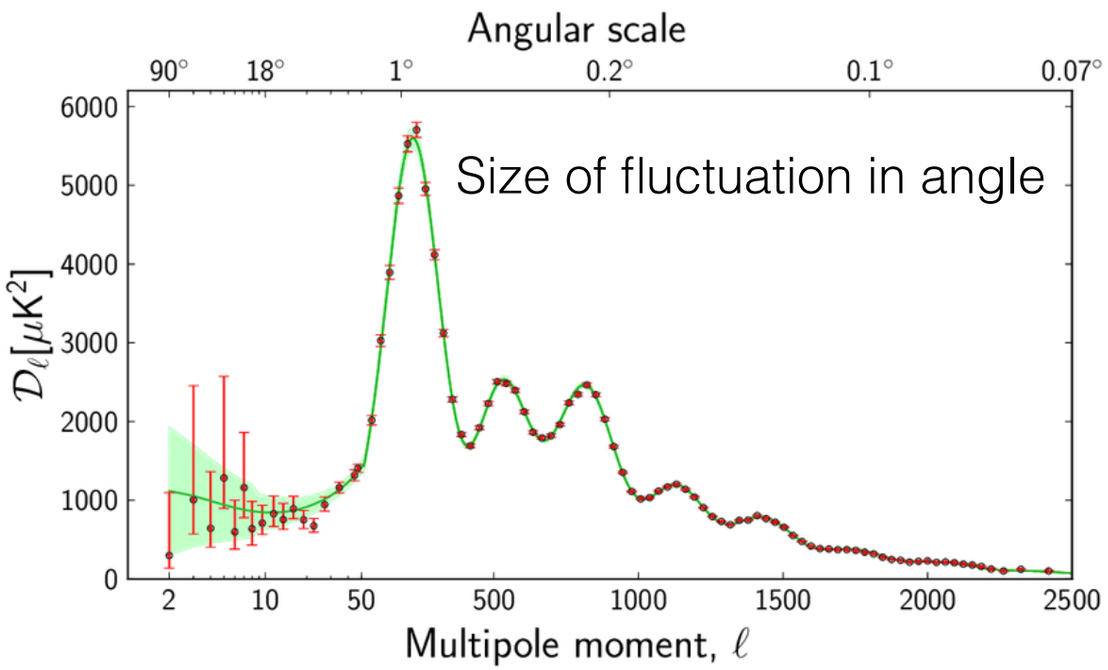


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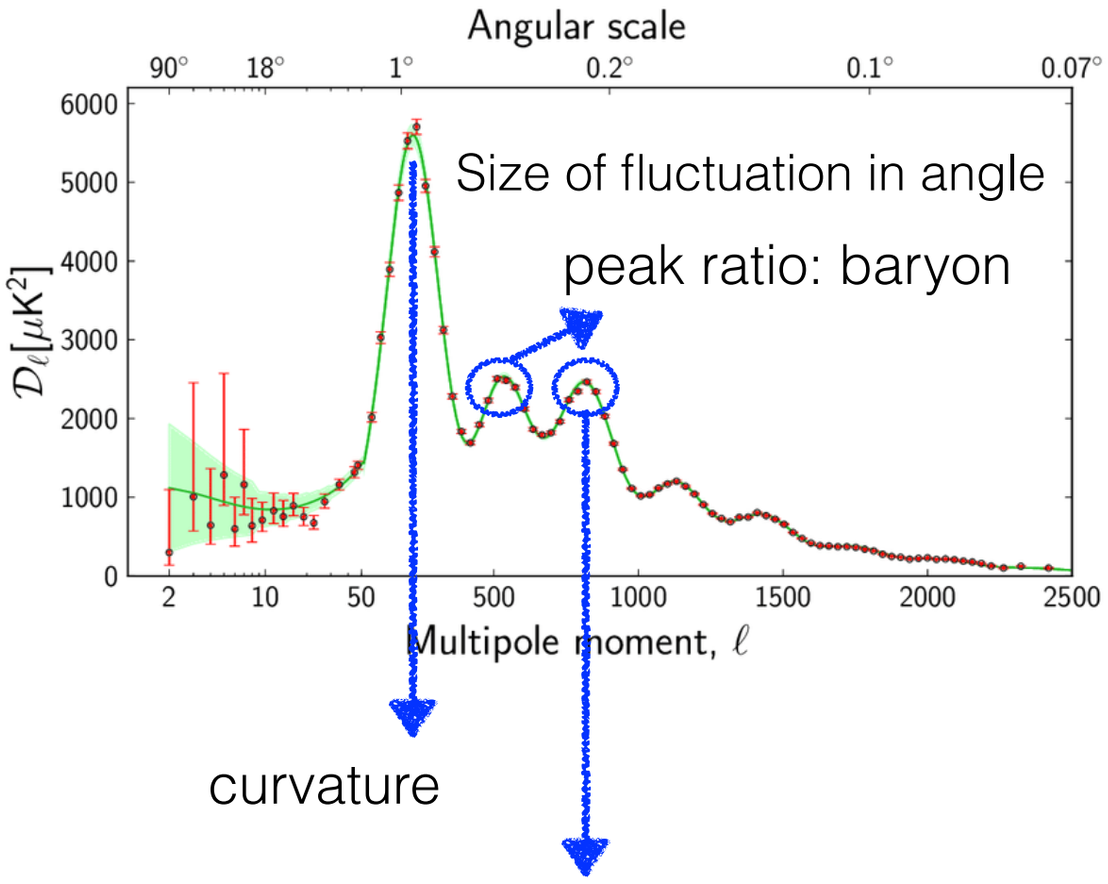
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Prof. K.-Y. Choi's lecture

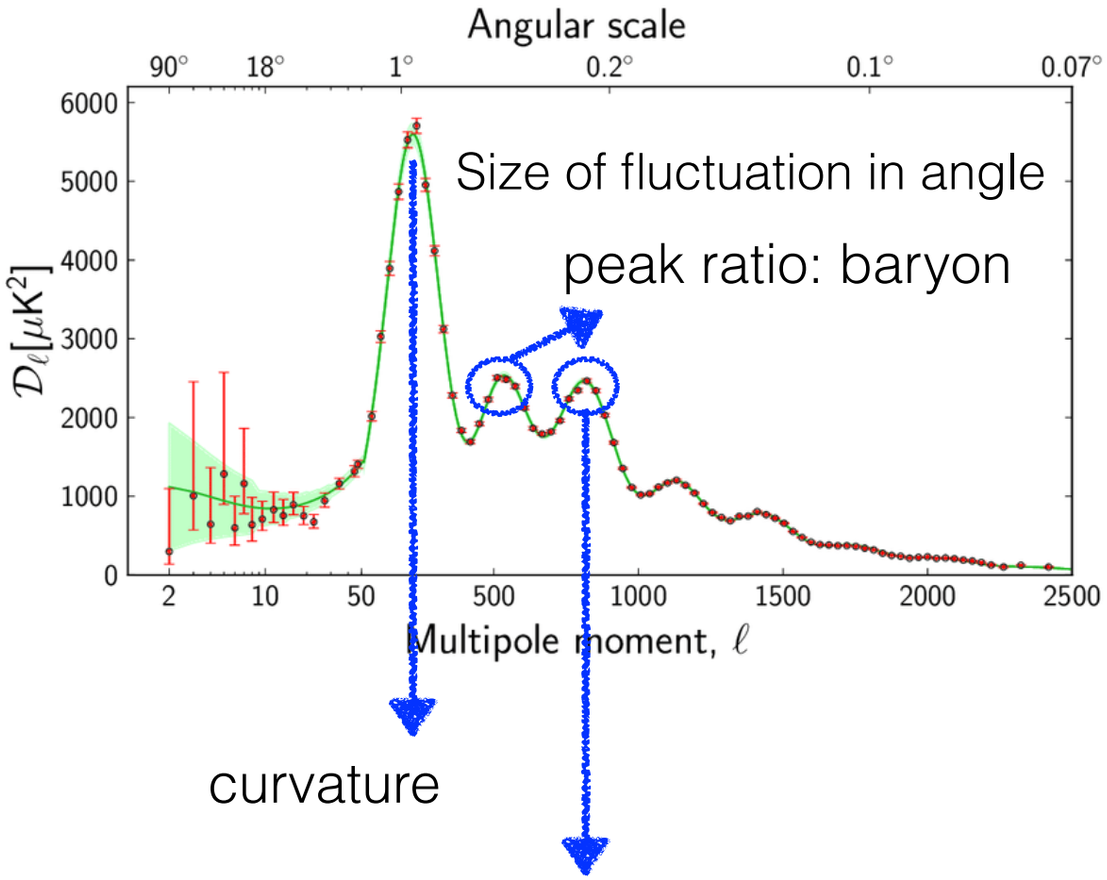


History: Cosmic Microwave Background

Prof. K.-Y. Choi's lecture



History: Cosmic Microwave Background



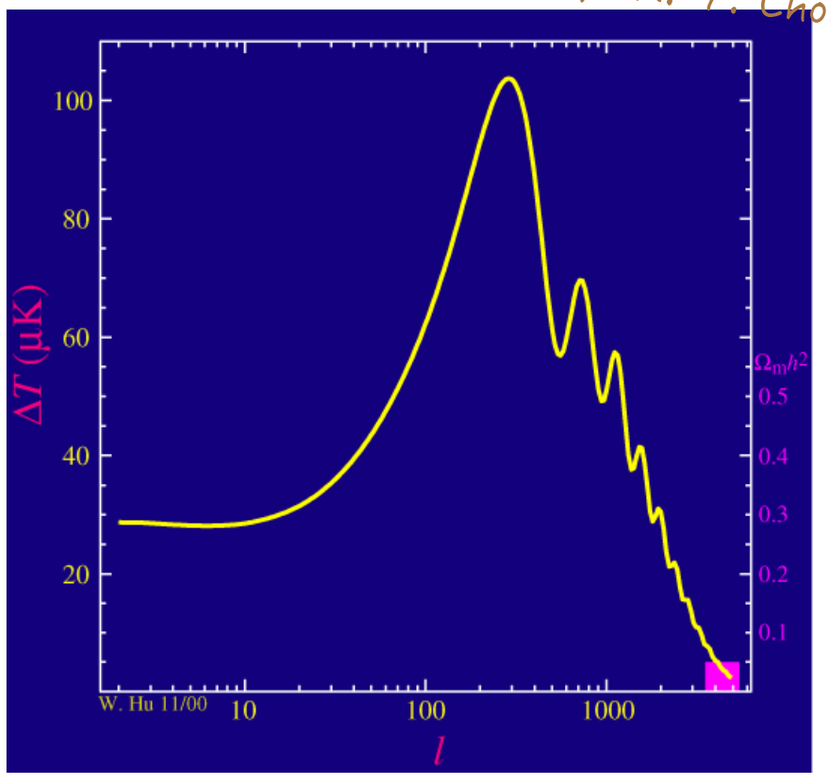
Size of fluctuation in angle

peak ratio: baryon

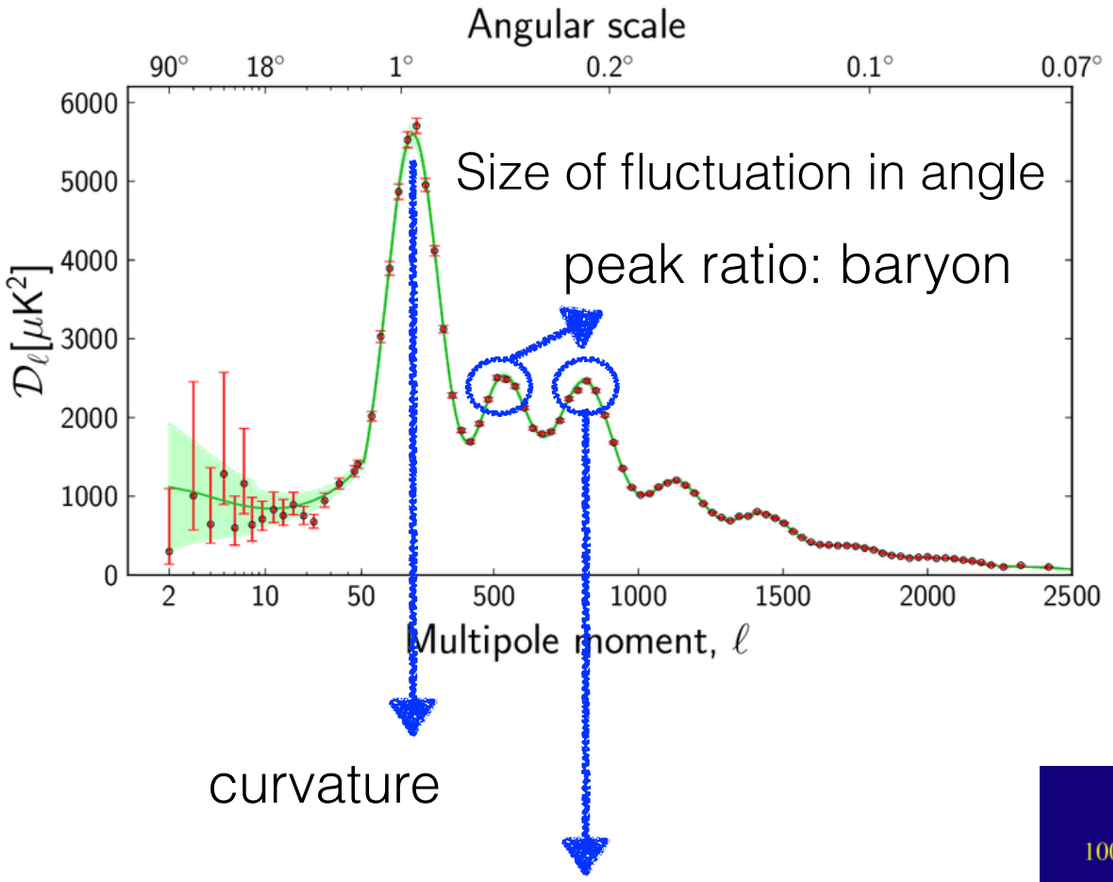
curvature

Effect of Dark Matter
(gravitational potential)

Prof. K.-Y. Choi's lecture



History: Cosmic Microwave Background



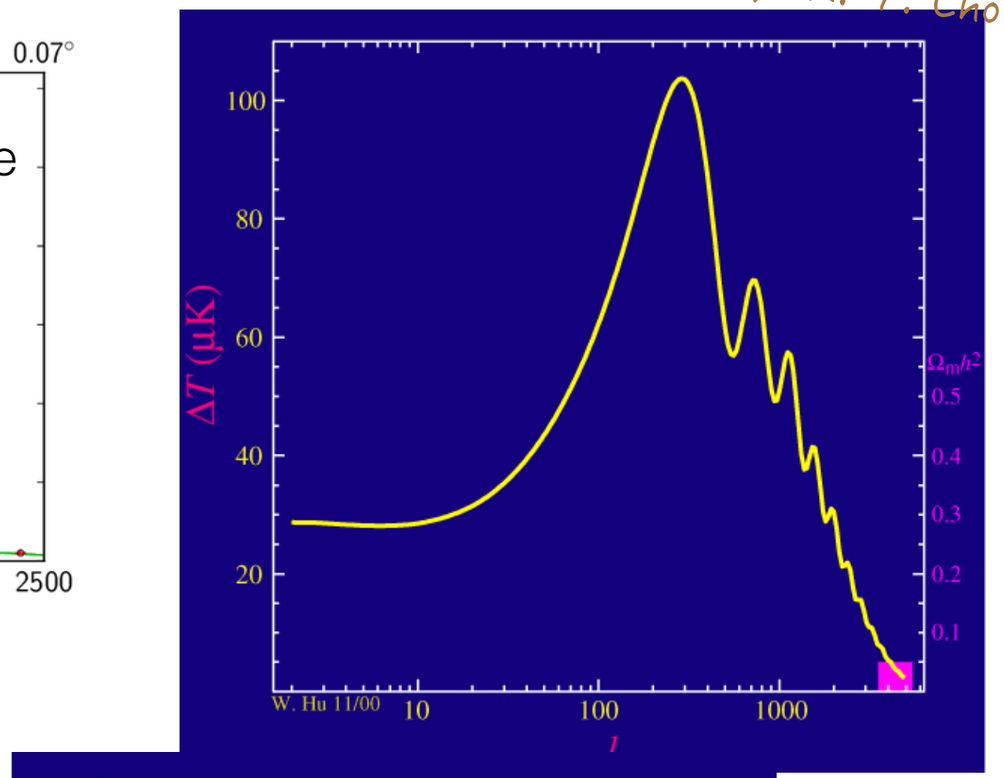
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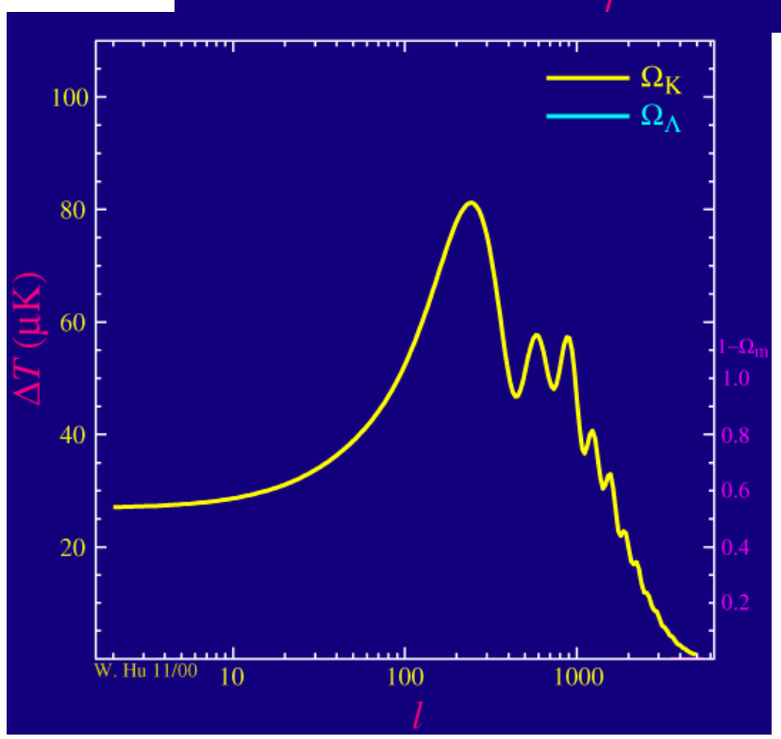
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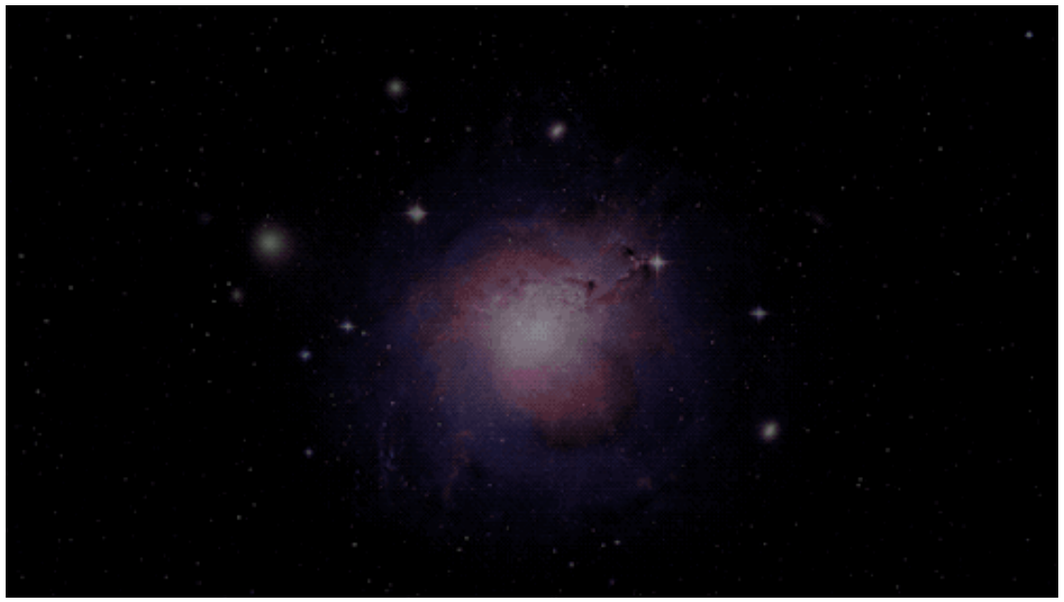
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Prof. K.-Y. Choi's lecture

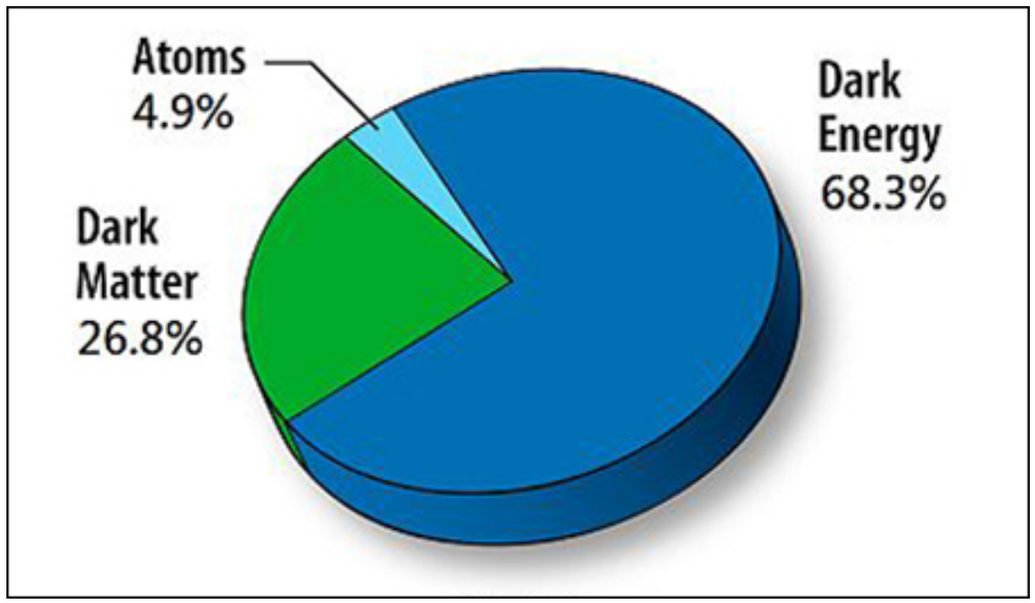




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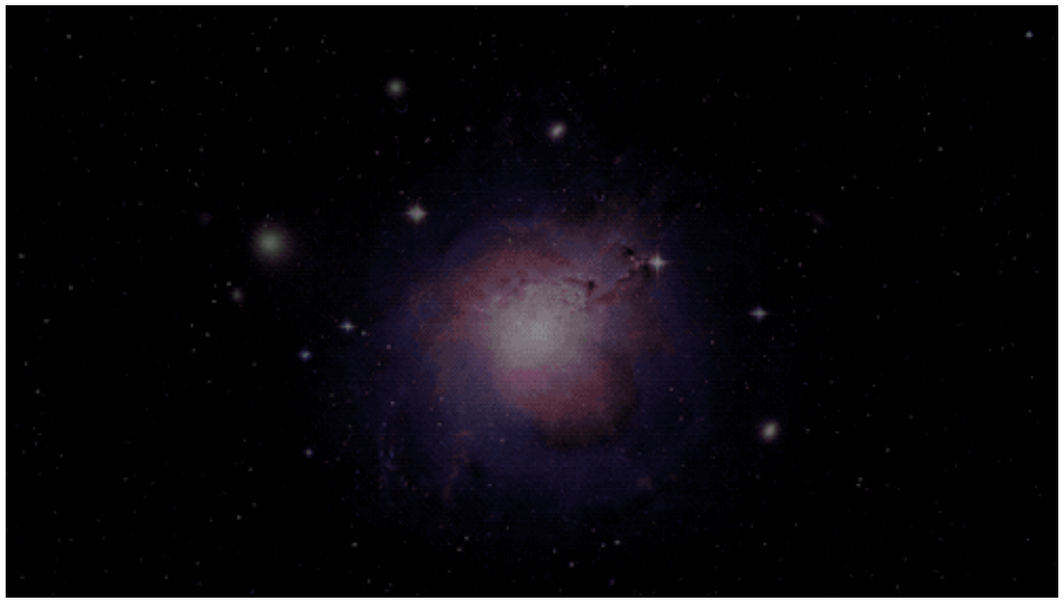


NASA

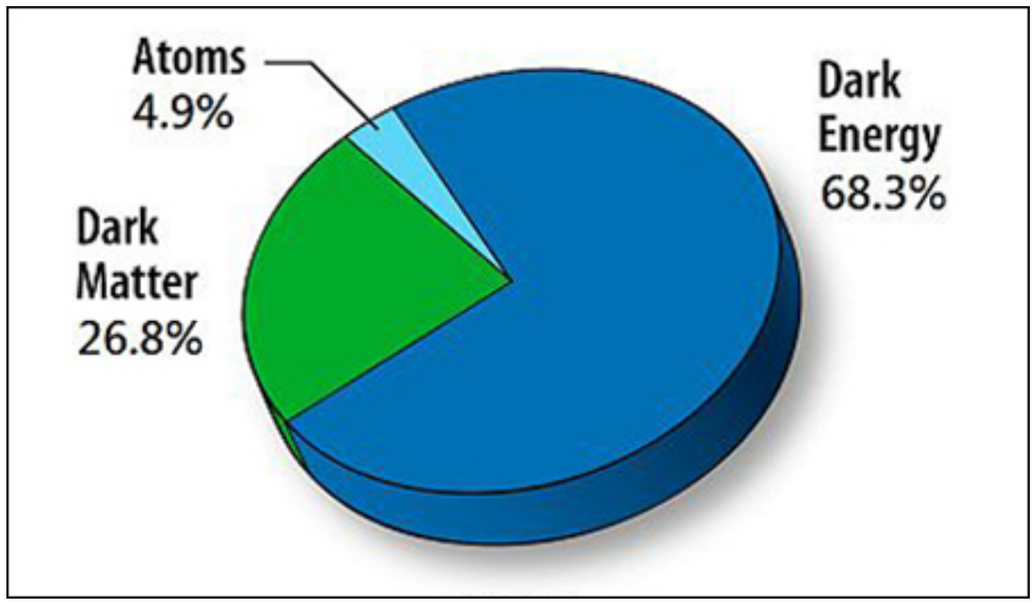


- 85% of the matter (27% of the total energy density of our universe)
- 5 times larger than the particles discovered so far (SM particles)

History: Cosmic Microwave Background

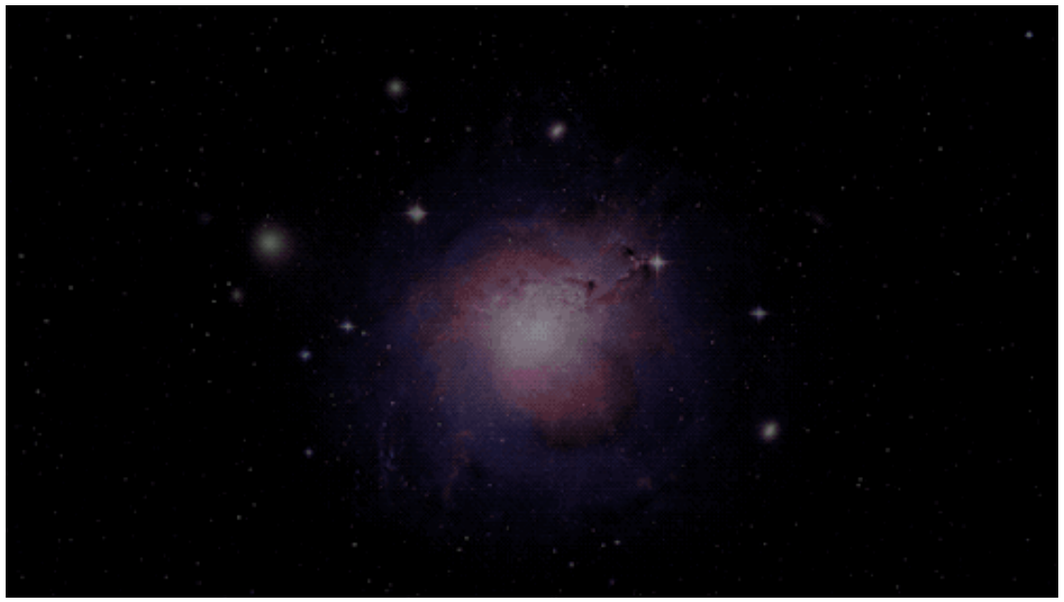


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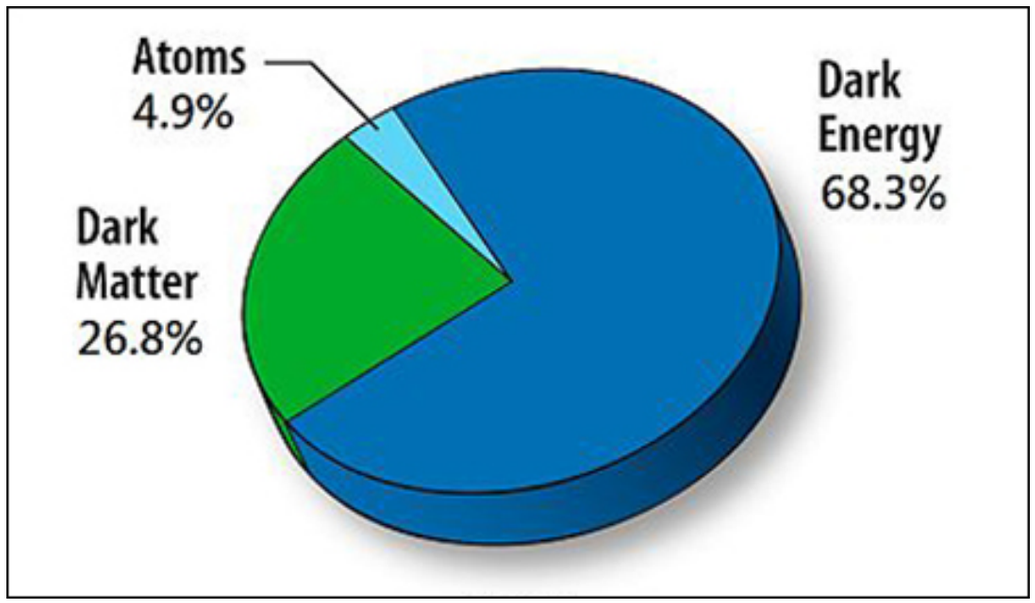


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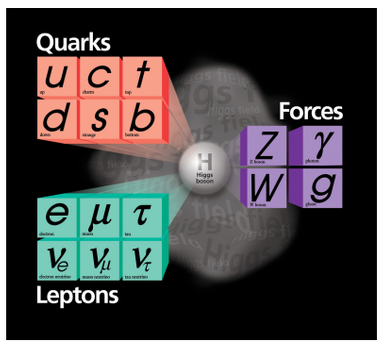
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New Physics beyond the SM

DM +



Properties of Dark Matter

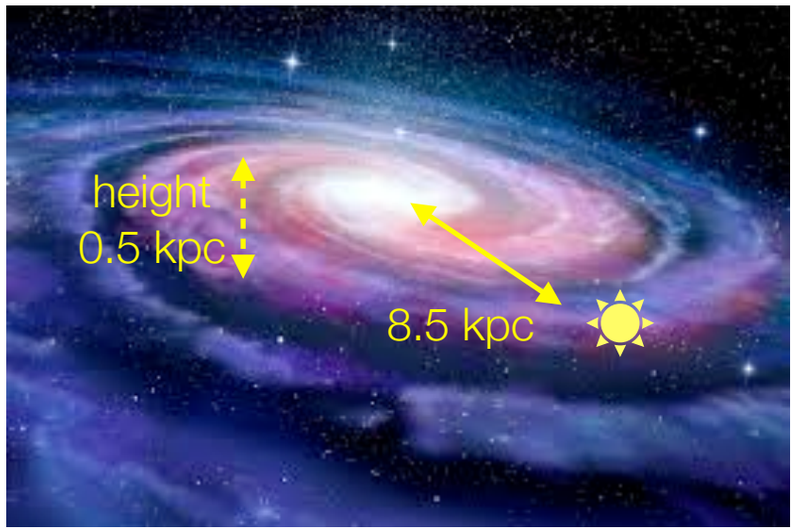
- Astrophysical properties (distribution)
- Particle physics properties
- Weakly Interacting Massive Particle (WIMP)

Astrophysical properties



CERN courier

Astrophysical properties: Our Milky Way

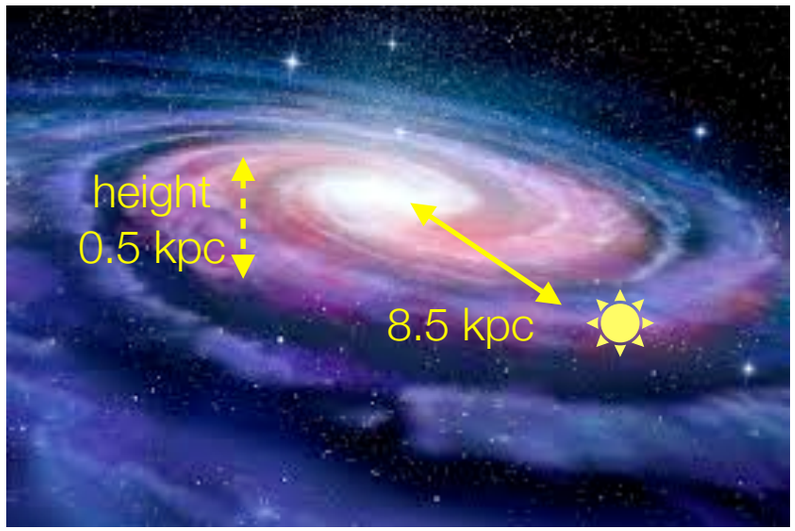


Radius of the Galactic disk (most stars) ~ 10 kpc

10^{11} stars with total (stellar) mass ~ $5 \times 10^{10}\, M_\odot$

Solar mass $M_\odot \sim 2 \times 10^{30}\,\mathrm{kg}$

Astrophysical properties: Our Milky Way

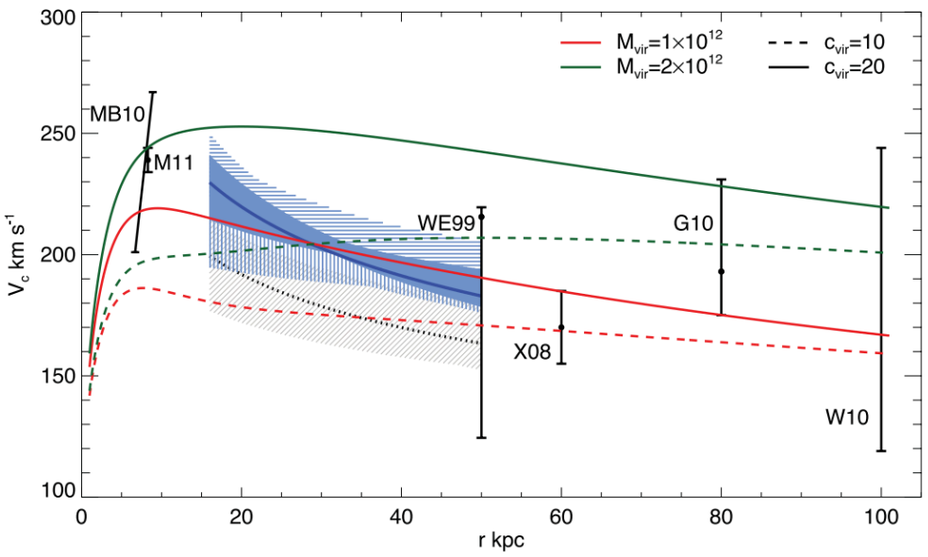


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$$M(R)_{\mathrm{MW}} = 9.6 \times 10^{10}\, M_\odot \left(\frac{v}{220\,\mathrm{km/s}}\right)\left(\frac{R}{8.5\,\mathrm{kpc}}\right)$$



Deason, Belokurov, Evans, An
MNRAS: Letters 424, 1 (2012)

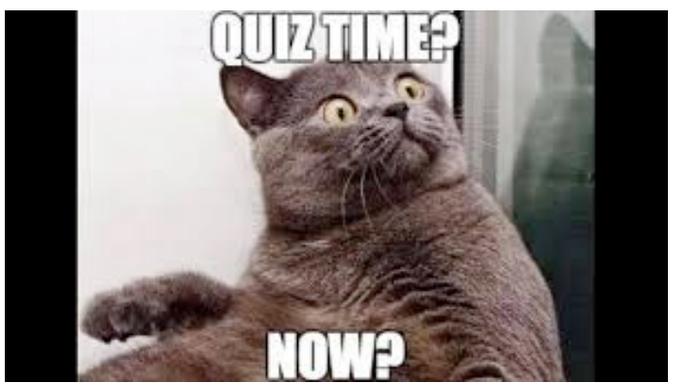
MW halo observation with stellar orbits up to 50 kpc

Motions of satellite galaxies (with large uncertainties) for larger distances

→ Good fit for $M_{\mathrm{MW}} \simeq 10^{12} M_\odot$

Halo extends up to ~ 100 kpc

Astrophysical properties: Our Milky Way



Prove that

Quiz

$$R_{\rm halo} \sim 100\,{\rm kpc} \gg R_{\rm disk}$$

from $M_{\rm halo} \sim 10^{12} M_\odot$

$\rho_0 \sim 0.3\,{\rm GeV/cm^3}$

Assume $\rho(r) \propto \dfrac{1}{r^2}$

Density and velocity distribution

- The DM density and velocity are related through the gravitational potential.

  (Boltzmann equation & Poisson equation)

- Remind that the constant rotational velocity is obtained:

$$v = \text{constant} \longrightarrow M(r) \propto r \longrightarrow \rho(r) \propto \frac{M(r)}{r^3} \propto \frac{1}{r^2}$$

Isotropic halo in steady state *Isothermal sphere*

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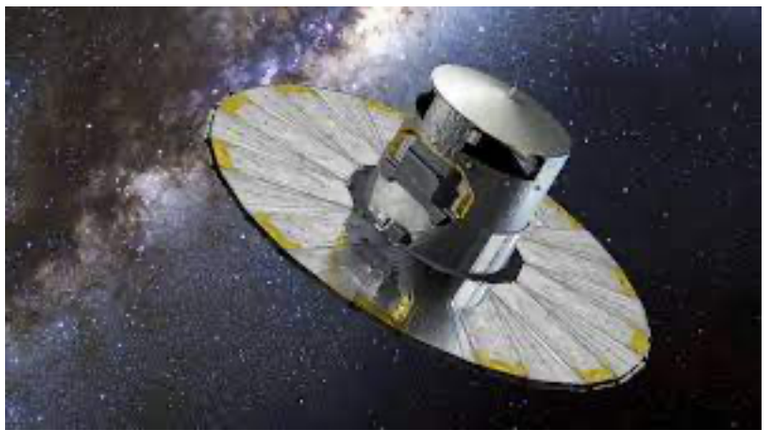
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Isotropic halo in steady state Isothermal sphere

- The observations of star velocities in our galaxy will give the information of ρ.



→ THE EUROPEAN SPACE AGENCY

The mission

Gaia is creating an extraordinarily precise three-dimensional map of more than a thousand million stars throughout our Milky Way galaxy and beyond, mapping their motions, luminosity, temperature and composition. This huge stellar census will provide the data needed to tackle an enormous range of important questions related to the origin, structure and evolutionary history of our galaxy.

Density and velocity distribution

- The most widely used model is the Navarro-Frenk-White (NFW) profile:

Navaro, Frenk, White, Astrophys. J. 462, 563 (1996)

$$\rho_{\rm NFW}(r) = \frac{\rho_\odot}{r/r_s(1+r/r_s)^2}$$

r_s = 20 kpc: scale radius

Very important in experiments

$$\rho_\odot = 0.3 \pm 0.1\,{\rm GeV/cm^3} = 0.008 \pm 0.003\,M_\odot\,{\rm pc}^{-3}$$

Bovy, Tremaine, Astrophys. J. 756, 89 (2012)

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From GAIA using ML

Lim, Putney, Buckley, Shih, 2023

$$0.47 \pm 0.05\,\mathrm{GeV/cm^3}$$

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Lim, Putney, Buckley, Shih, 2023

$$\rho_{\rm NFW}(r) = \frac{\rho_\odot}{r/r_s(1+r/r_s)^2}$$

Different from $\rho_{\rm IsoThermal}(r) \propto 1/r^2$

$0.47 \pm 0.05\,{\rm GeV/cm^3}$

r_s = 20 kpc: scale radius

Very important in experiments

$$\rho_\odot = 0.3 \pm 0.1\,{\rm GeV/cm^3} = 0.008 \pm 0.003\,M_\odot\,{\rm pc^{-3}}$$

Bovy, Tremaine, Astrophys. J. 756, 89 (2012)

- The general NFW profile:

$$\rho_{\rm Gen.NFW}(r) = \rho_s \frac{(r/r_s)^{-\gamma}}{(1+r/r_s)^{3-\gamma}}$$

e.g., γ = 1.2

γ = 1 (NFW)

ρ_s : scale density by requiring $\rho_{\rm Gen.NFW}(r_\odot) = \rho_0$

Density and velocity distribution

- The Einasto profile:

Einasto, Trudy Inst. Astrofiz. Alma-Ata 5, 87 (1965)

$$\rho_{\rm Ein}(r) = \rho_\odot \exp\left[-\frac{2}{\gamma}\left(\left(\frac{r}{r_s}\right)^\gamma - 1\right)\right] \quad \gamma = 0.17$$

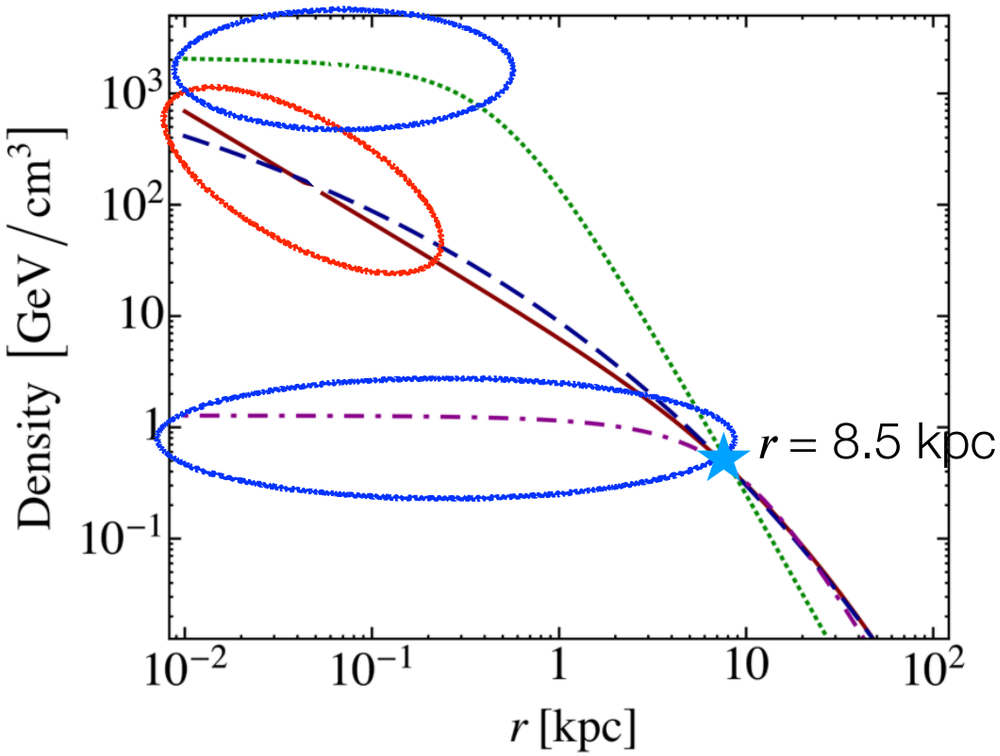
- The Burkert profile: more cored (flatter slope) than the NFW and Einasto

Burkert, IAU Symp. 171, 175 (1996)

$$\rho_{\rm Burk}(r) = \frac{\rho_\odot}{(1 + r/r_s)\,(1 + (r/r_s)^2)}$$

r_s: core radius ≠ scale radius

Density and velocity distribution



Cohen, Lisanti, Pierce, Slatyer, JCAP 1310, 061 (2013)

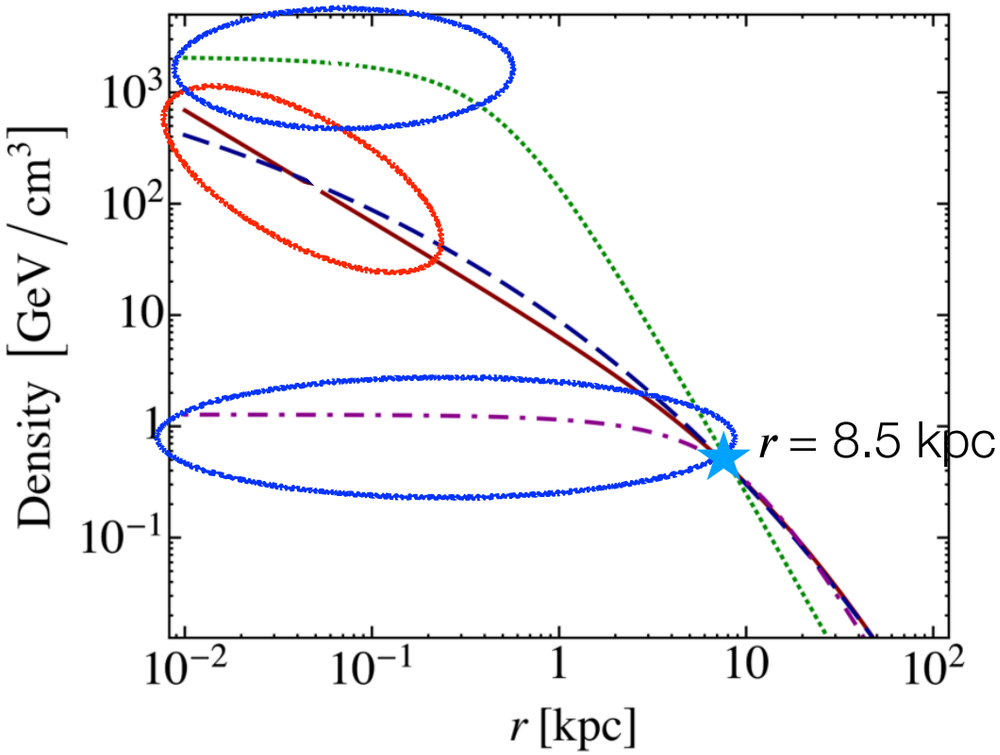
- ✔ Red solid: NFW
- ✔ Blue dashed: Einasto

Cuspy

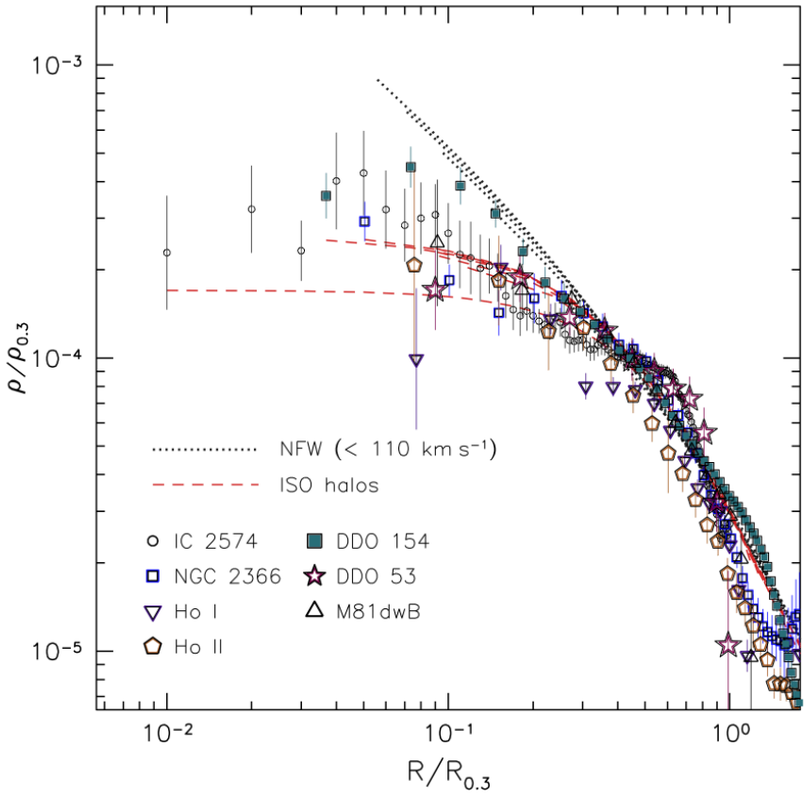
- ✔ Green dotted: Burkert r_s = 0.5 kpc
- ✔ Purple dot-dashed: Burkert r_s = 10 kpc

Cored

Density and velocity distribution



Cohen, Lisanti, Pierce, Slatyer, JCAP 1310, 061 (2013)



Oh, de Blok, Brinks, Walter, Kennicutt, Astrophys. J. 141, 6 (2011)

- ✔ Red solid: NFW
- ✔ Blue dashed: Einasto

Cuspy

- ✔ Green dotted: Burkert r_s = 0.5 kpc
- ✔ Purple dot-dashed: Burkert r_s = 10 kpc

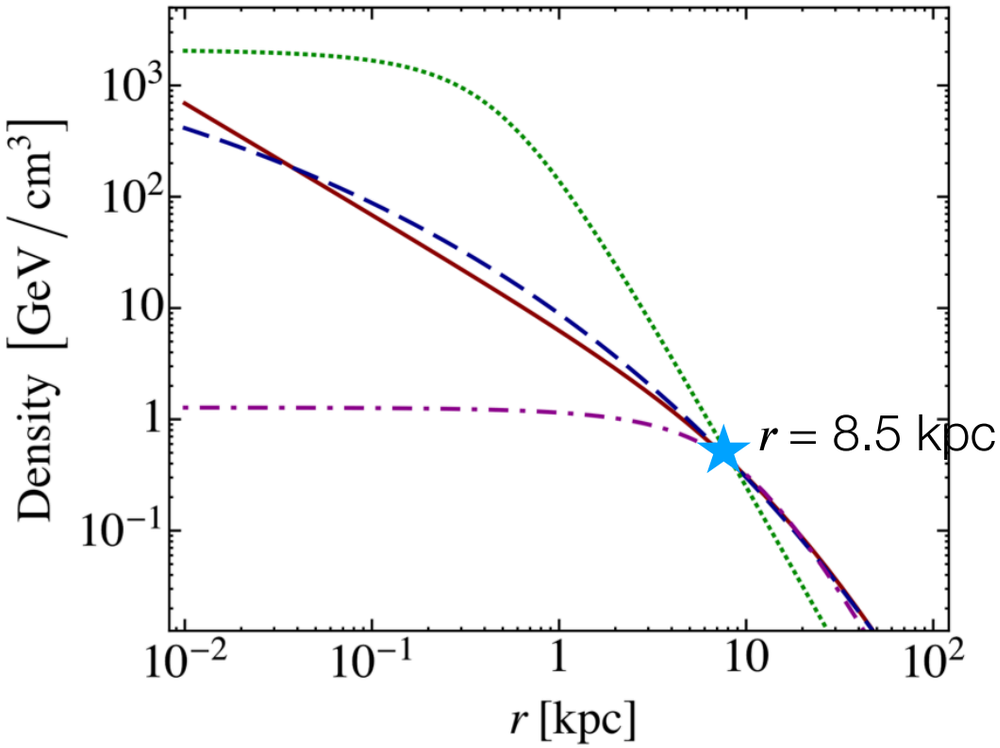
Cored

$$\rho_{\rm pseudo-iso} = \frac{\rho_C}{1+(r/r_s)^2}$$

ρ_C: core density

r_s: core radius

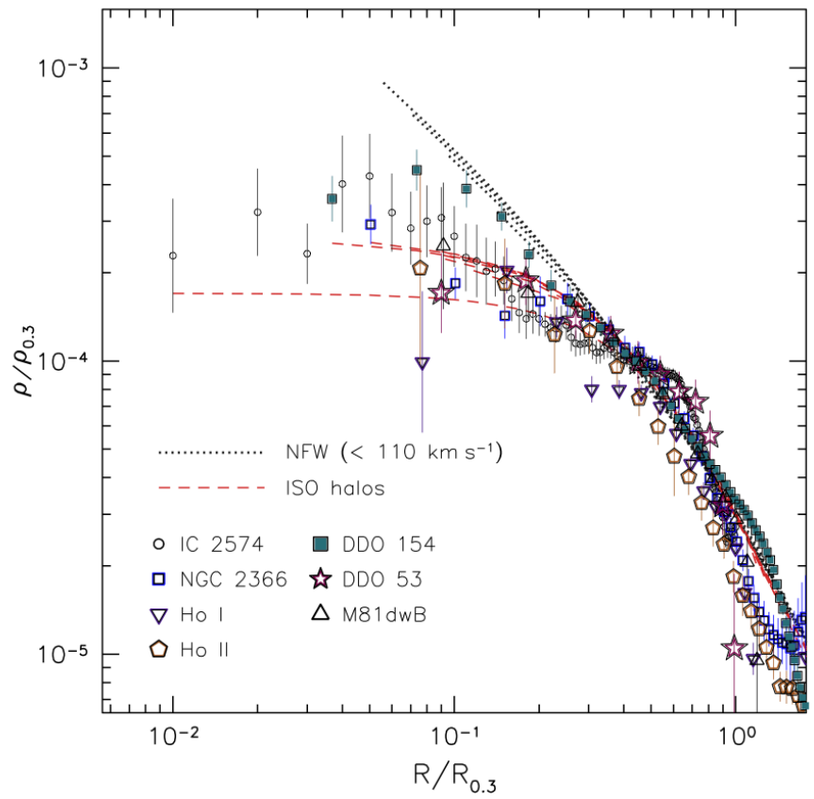
Density and velocity distribution



Cohen, Lisanti, Pierce, Slatyer, JCAP 1310, 061 (2013)

Core-cusp problem

Solutions?



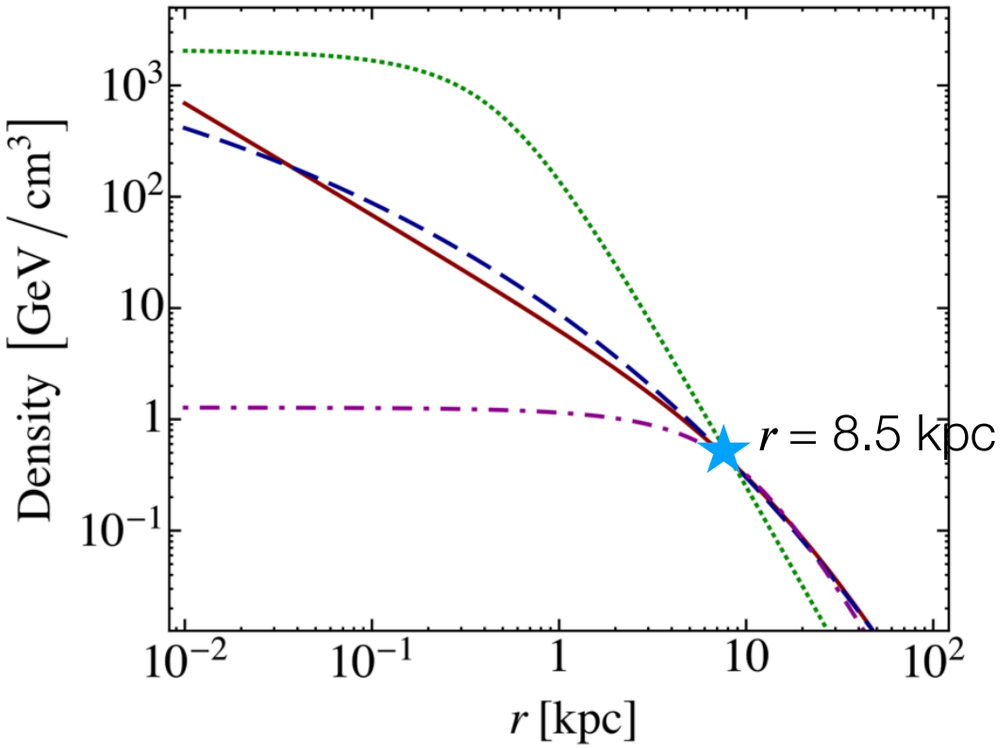
Oh, de Blok, Brinks, Walter, Kennicutt, Astrophys. J. 141, 6 (2011)

$$\rho_{\rm pseudo-iso} = \frac{\rho_C}{1+(r/r_s)^2}$$

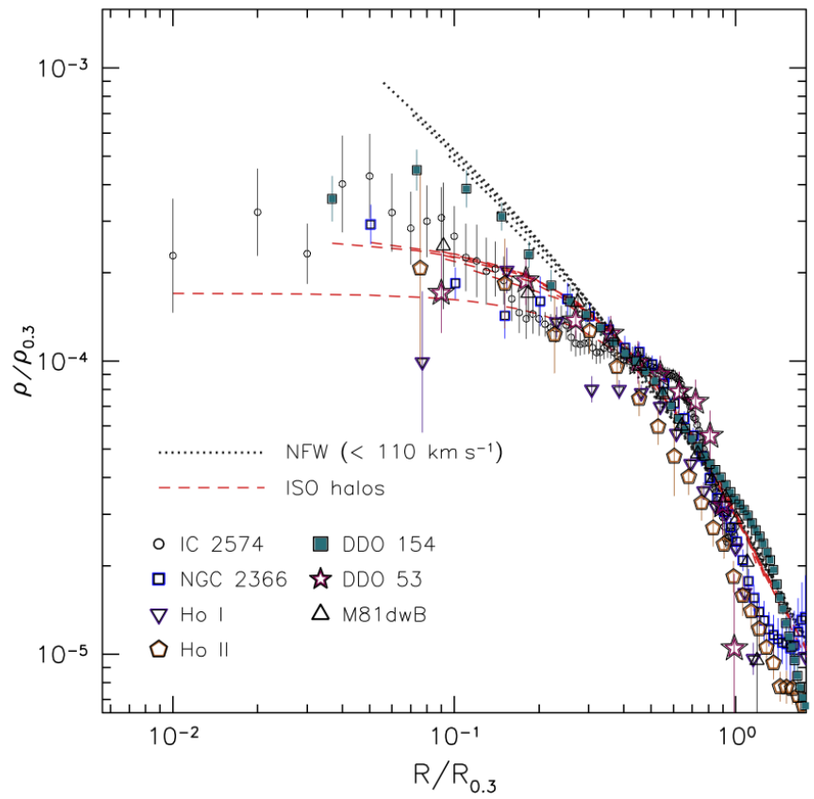
ρ_C: core density

r_s: core radius

Density and velocity distribution



Cohen, Lisanti, Pierce, Slatyer, JCAP 1310, 061 (2013)



Oh, de Blok, Brinks, Walter, Kennicutt, Astrophys. J. 141, 6 (2011)

Core-cusp problem

Solutions?

$$\rho_{\rm pseudo-iso} = \frac{\rho_C}{1+(r/r_s)^2}$$

ρ_C: core density

r_s: core radius

- Inclusion of baryons & resolutions of the simulations
- Non-trivial DM model: Self-Interacting DM (SIDM)
- Warm DM (but the core size is too small to avoid bounds)

Maccio, Paduroiu, Anderhalden, Schneider, Moore, Mon. Not Roy. Astron. Soc. 424, 1105 (2012)

Density and velocity distribution

The most widely used distribution: the truncated Maxwellian

$$f(\mathbf{v}) = \begin{cases} \frac{1}{N_{\rm esc}} \left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2} e^{-3\mathbf{v}^2/2\sigma_v^2} & |\mathbf{v}| < v_{\rm esc} \\ 0 & \text{otherwise} \end{cases}$$

$f(\mathbf{v}) = f(v_i)$ for $i = 1, 2, 3$ $\quad$ σ_v: rms velocity dispersion $\quad$ $N_{\rm esc} = \mathrm{erf}(z) - 2\pi^{-1/2} z e^{-z^2}$

The most probable speed $\quad v_0 = \sqrt{2/3}\sigma_v \approx 235\,\mathrm{km/s}$ $\quad$ $z \equiv v_{\rm esc}/v_0$