Five Lectures on Dark Matter

First Lecture

Università degli Studi di Padova

INFN Istituto Nazionale di Fisica Nucleare Sezione di Padova

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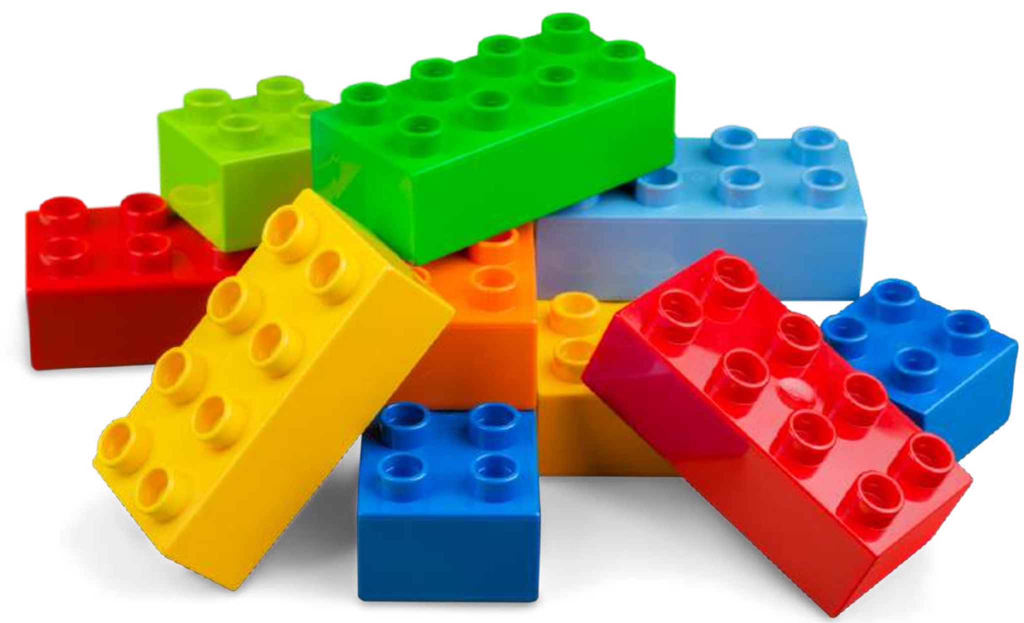
II Joint ICTP-Trieste/ICTP-SAIFR School on Particle Physics (June 22 — July 3, 2020)

The Big Question

What are the building blocks of our Universe?



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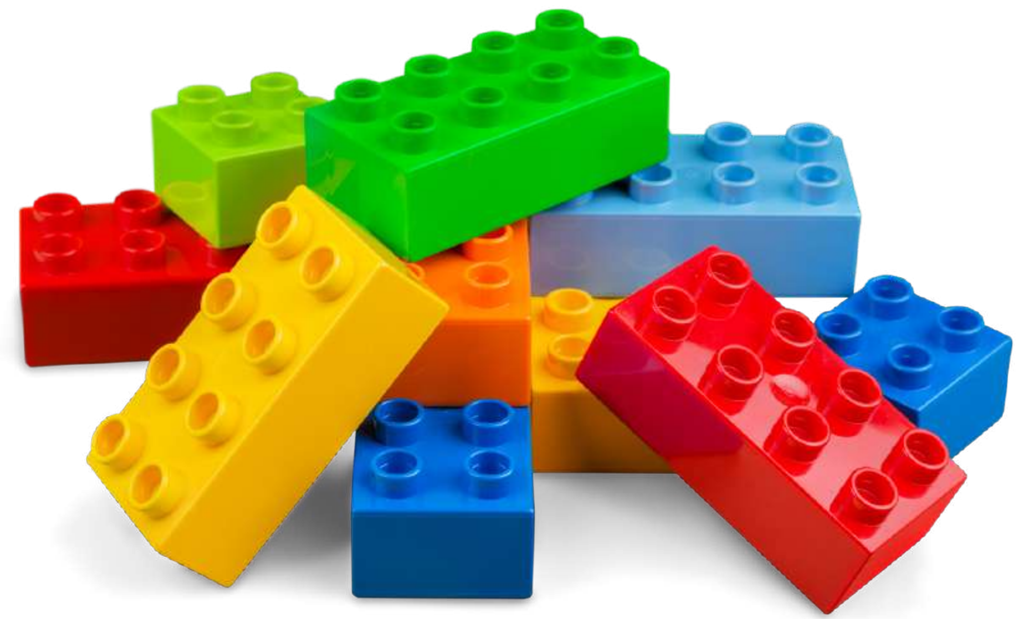
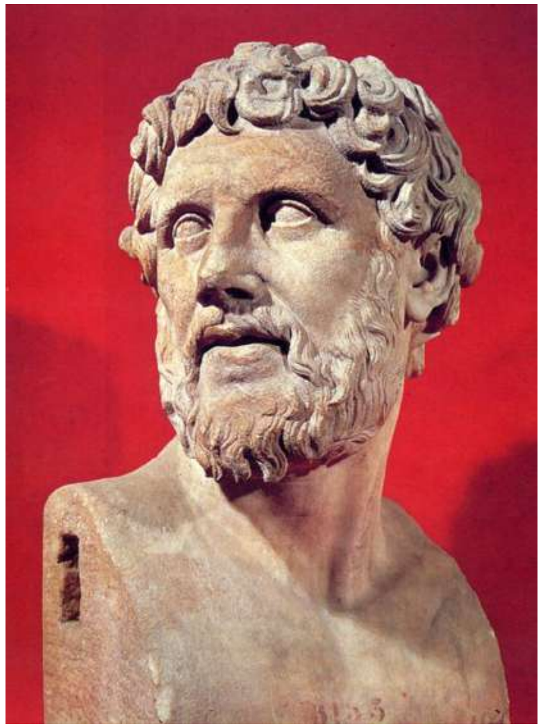
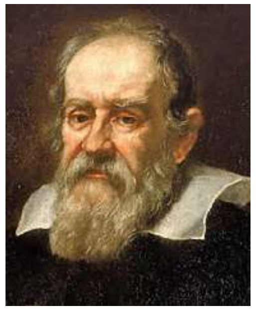


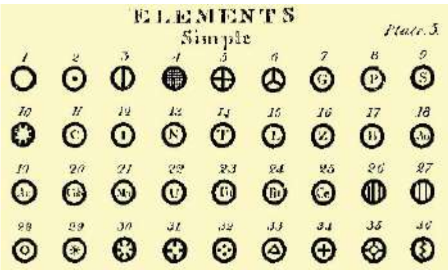


Atomic theory by Democritus (400 BC)

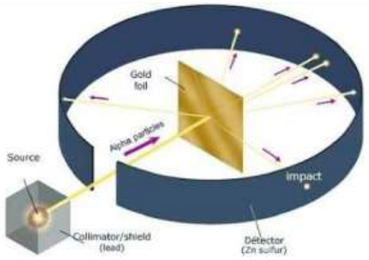
This question has been around for a while!

A Very Slow Progress

1600's  Scientific method by G. Galilei

1800 Experimental evidence for atoms by J. Dalton 

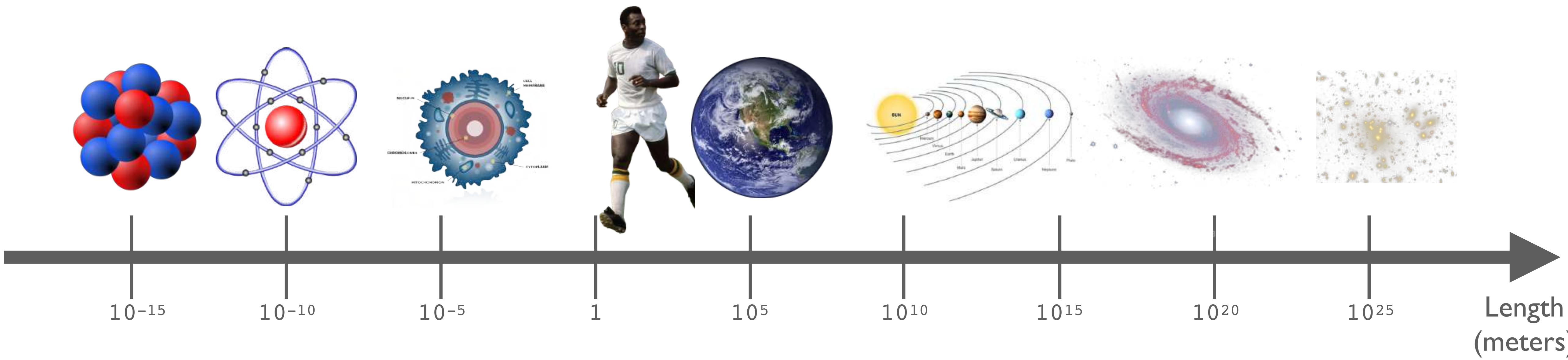
1897  Electron discovery by J. J. Thomson (atom <u>not</u> invisible!)

1911 Discovery of the nucleus by E. Rutherford 

1970's Zoo of elementary particles and the Standard Model

2012  Higgs boson discovery
(Standard Model is complete!)

A Magnificent Unified Description



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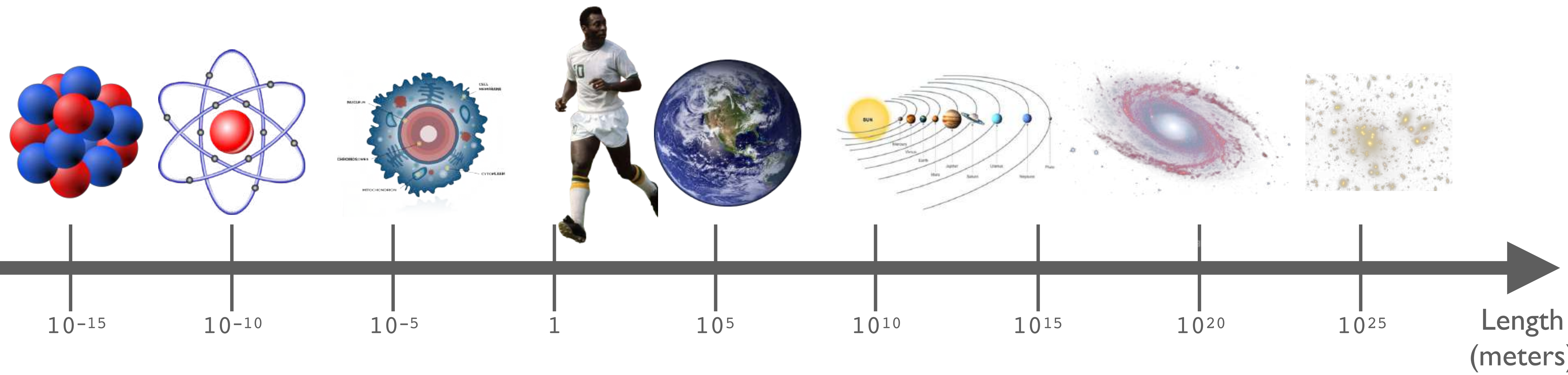

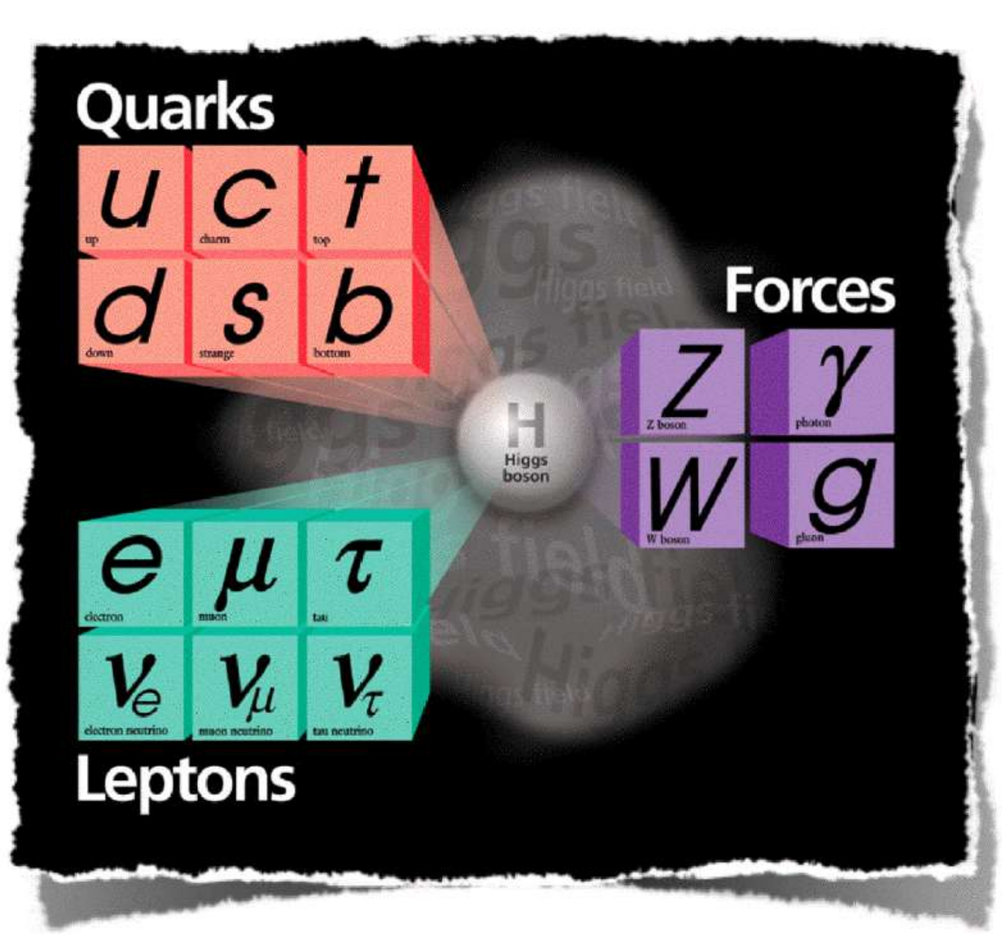

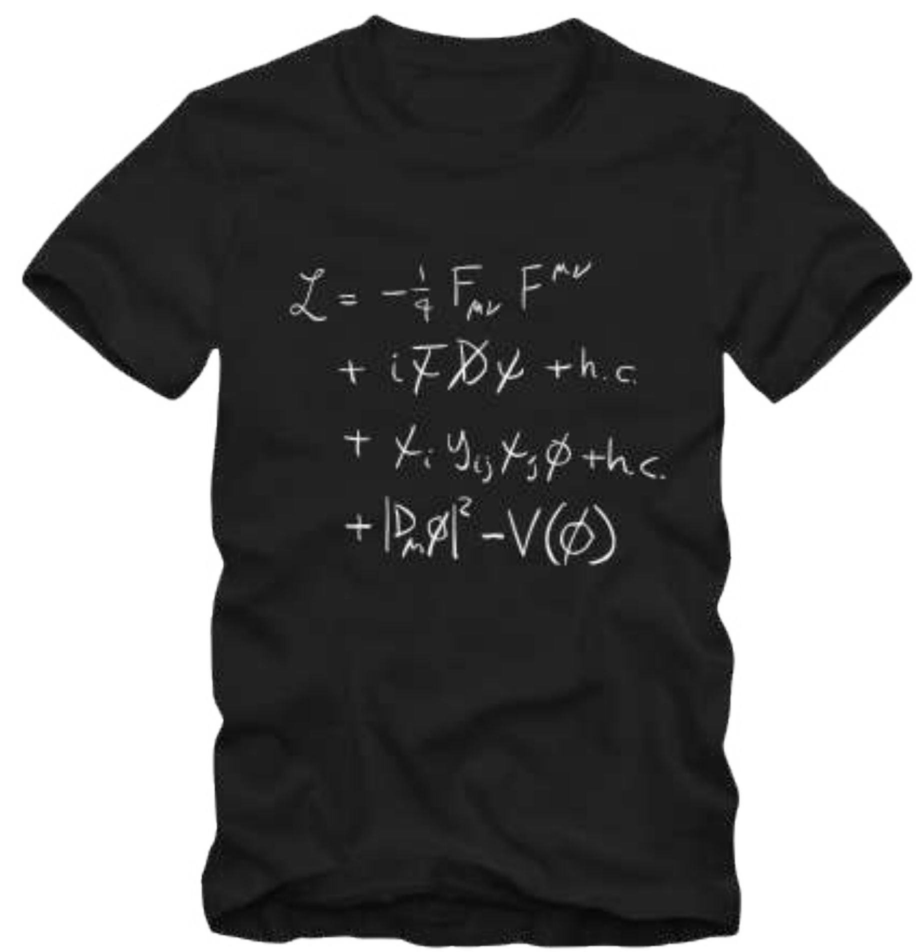

Is the Game Over?

Have we finally found an answer to the question asked by Democritus more than 2000 years ago?

Can we declare victory?

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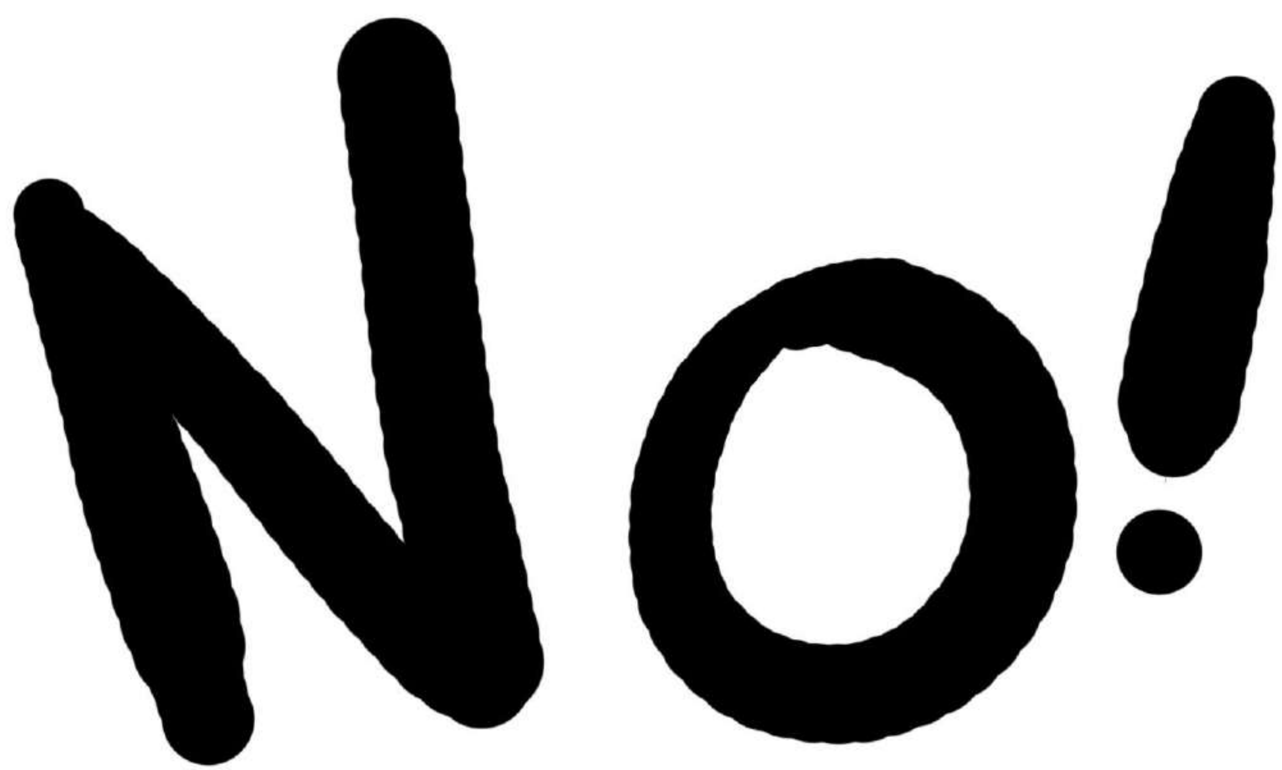
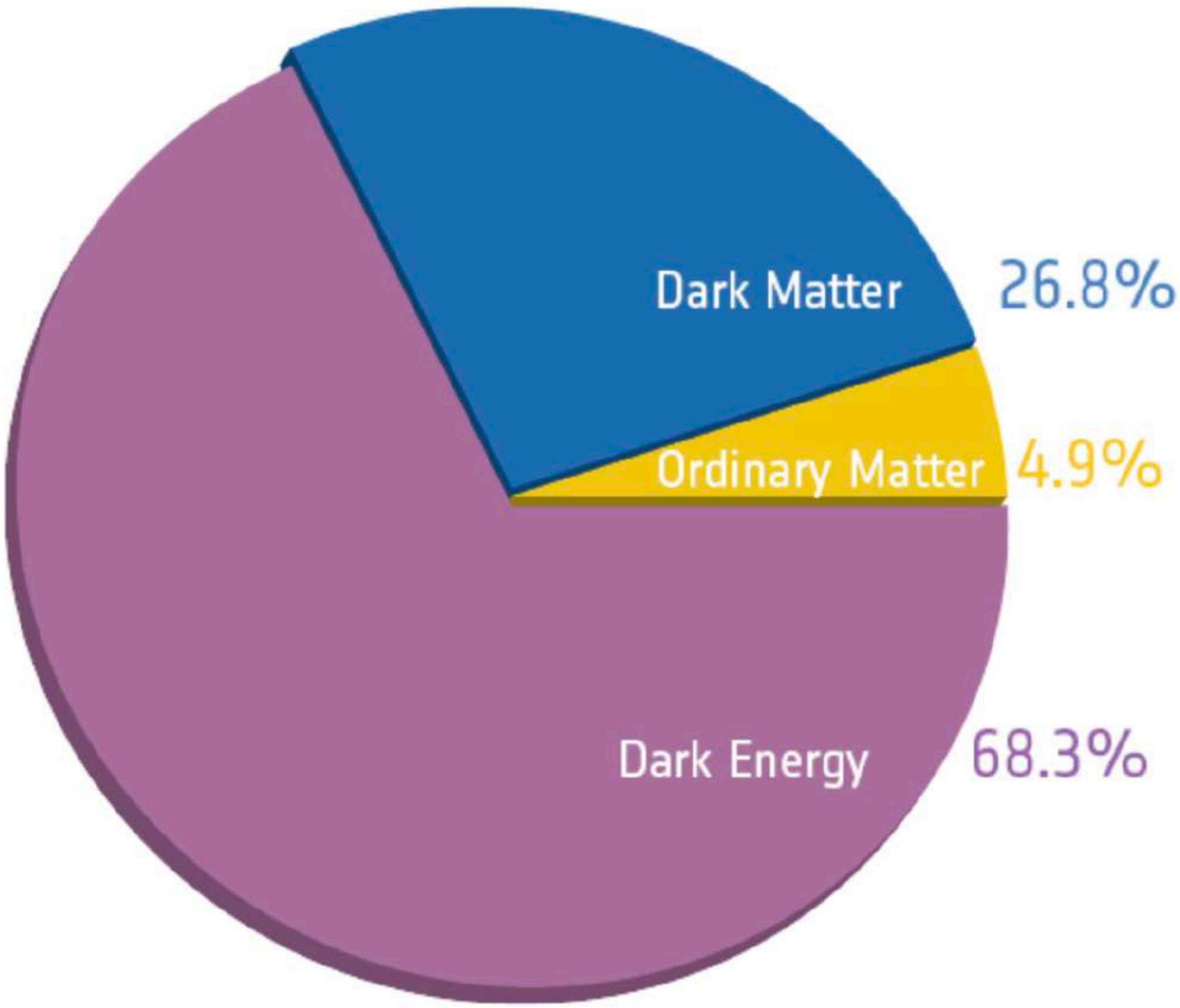


Dark Matter

Standard Model matter: approximately 5% of the current energy budget



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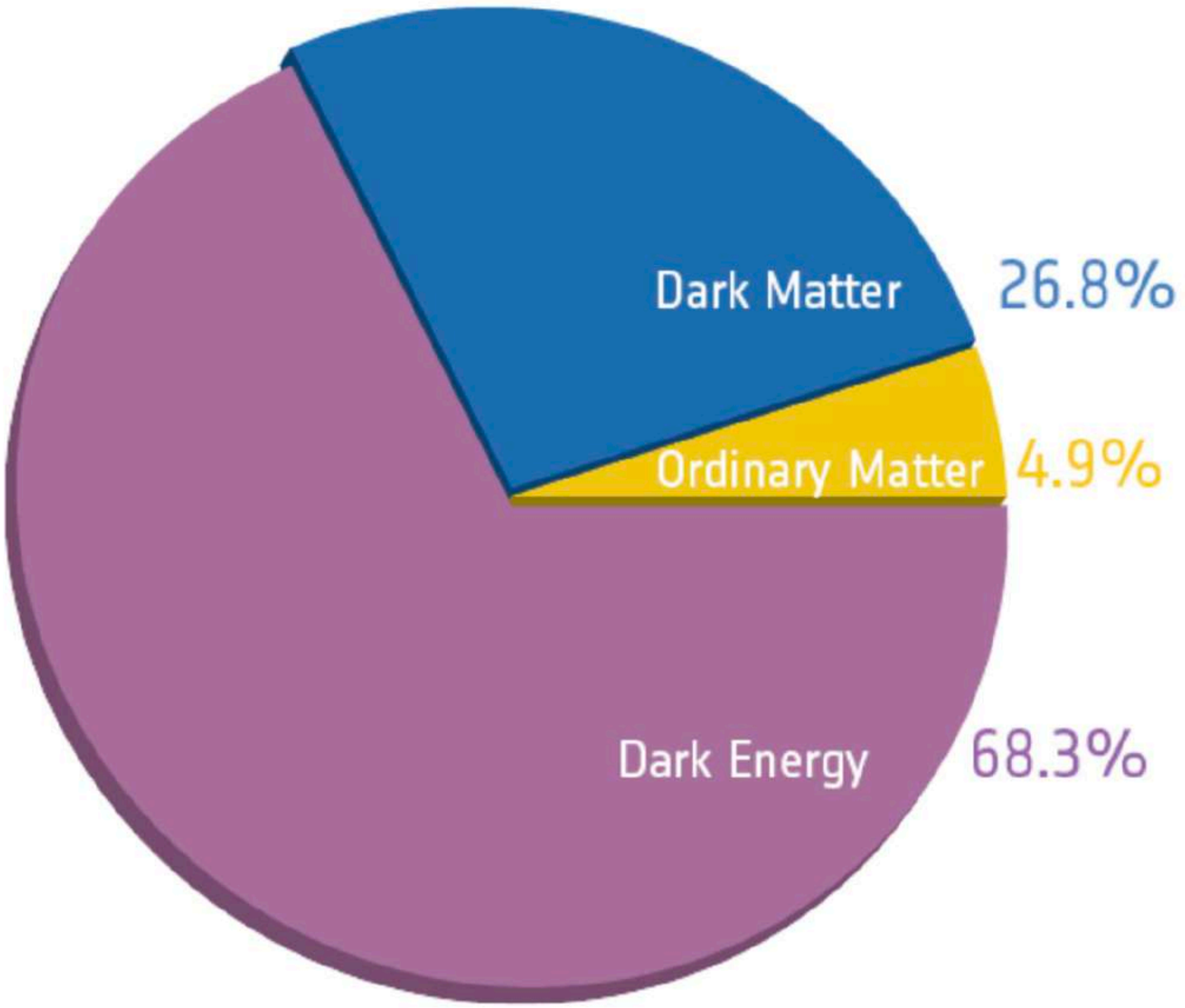

In this five lectures we deal with <u>dark matter</u>

We will review its evidence,
theories and experimental searches

Looking at the Invisible?

How can we be sure that dark matter exists?

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Observe very carefully the motion of visible objects

Using laws of gravity we find the gravitational potential Φ

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How can we be sure that dark matter exists?

Observe very carefully the motion of visible objects

Using laws of gravity we find the gravitational potential Φ

Infer <u>total</u> amount of matter (visible and invisible)

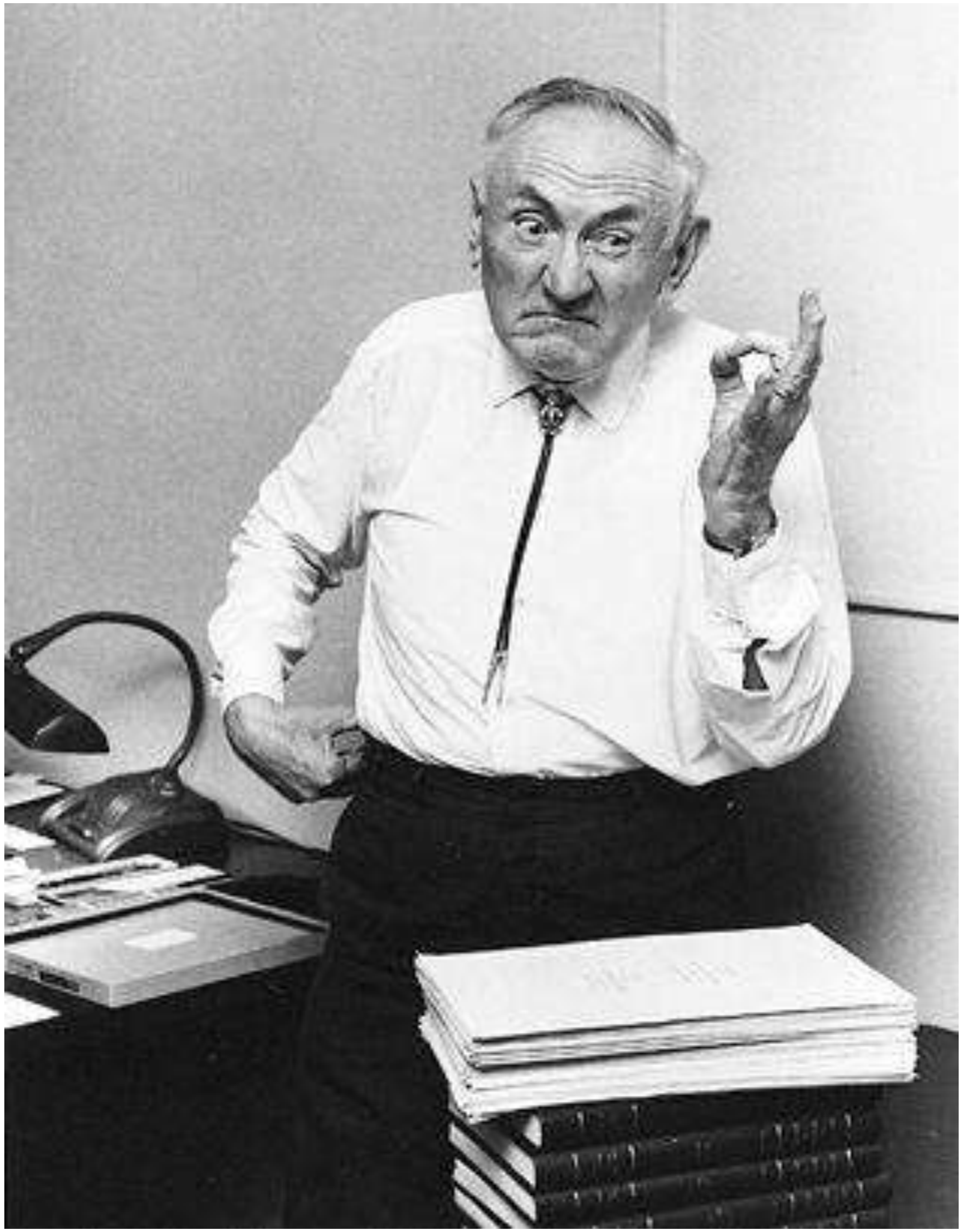
$$\nabla^2 \Phi = -4\pi G_N \rho$$

Zwicky and the Coma Cluster

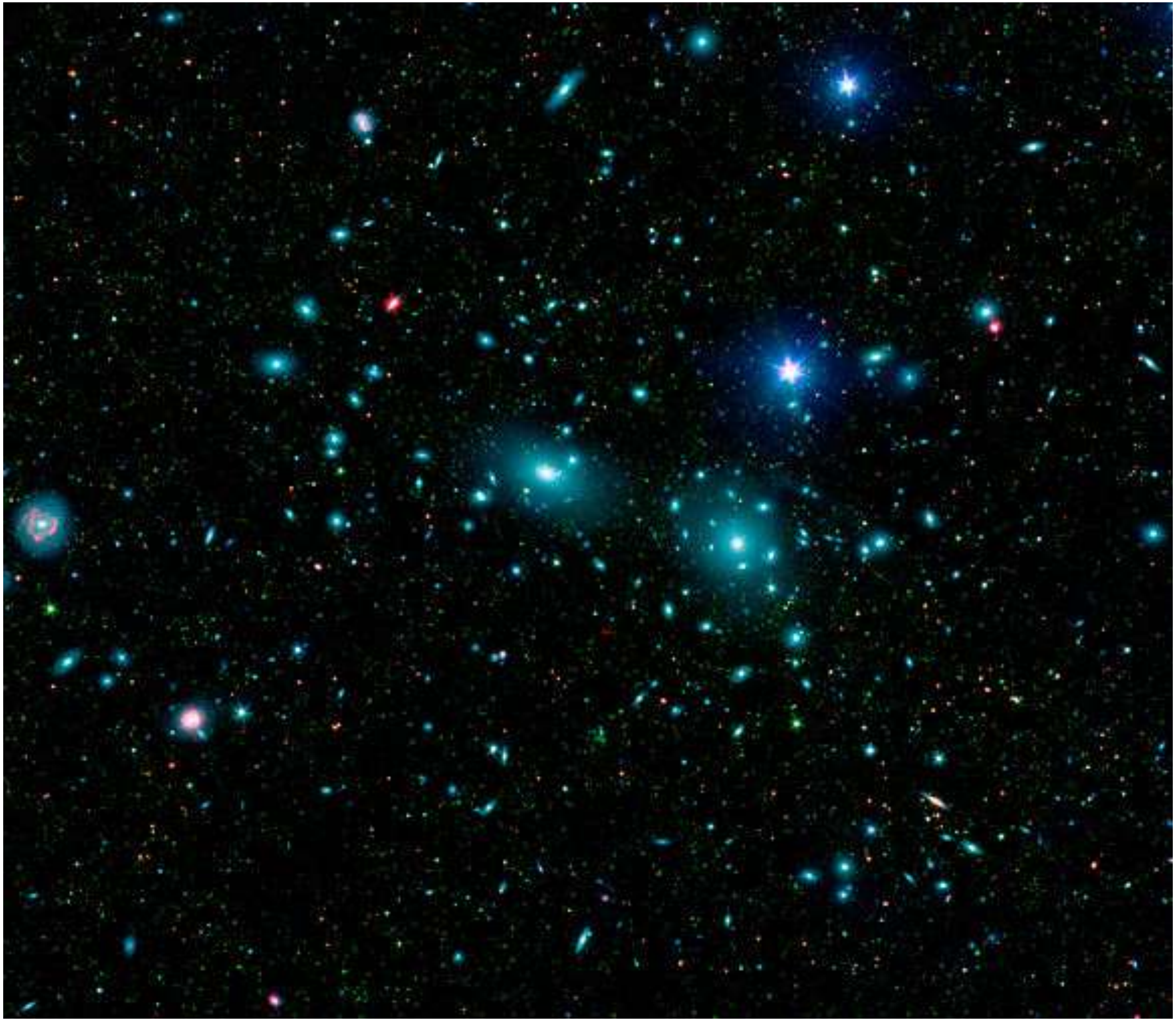
<u>Fritz Zwicky (1930's)</u>

Careful observation of galaxies within the Coma Cluster

Two independent measurement of the cluster mass… surprise!



Zwicky and the Coma Cluster



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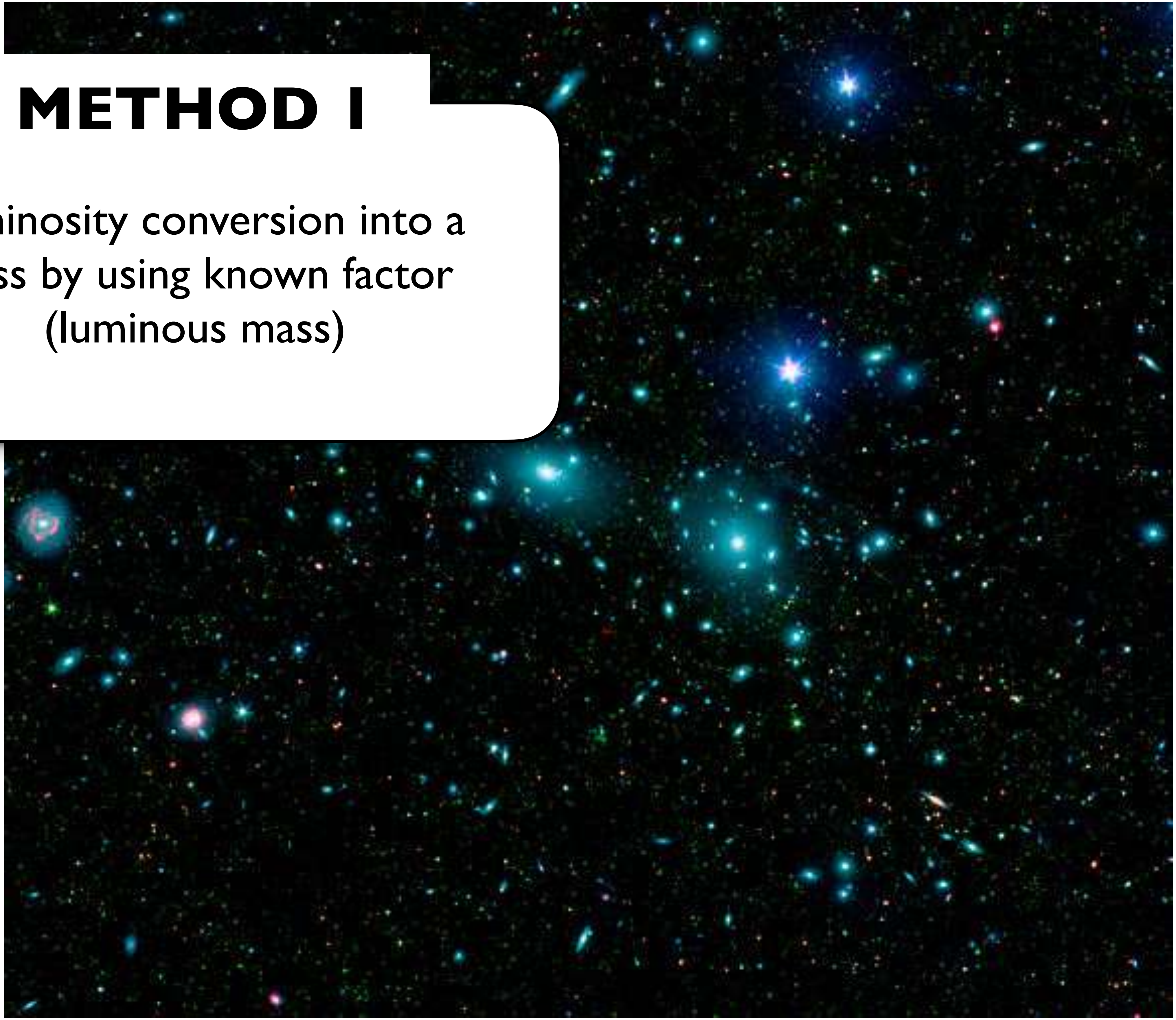
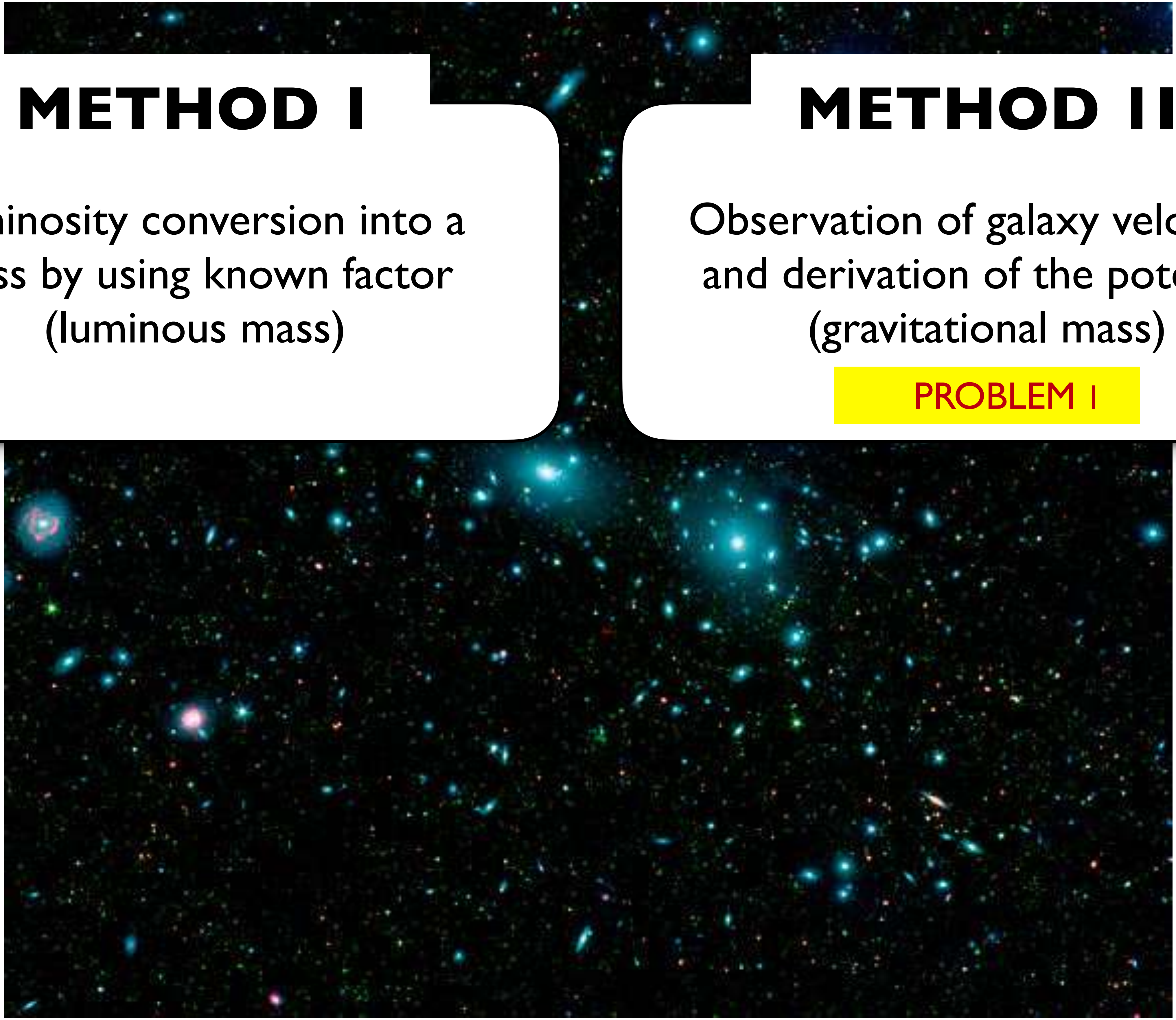


METHOD I

Luminosity conversion into a mass by using known factor (luminous mass)

Zwicky and the Coma Cluster



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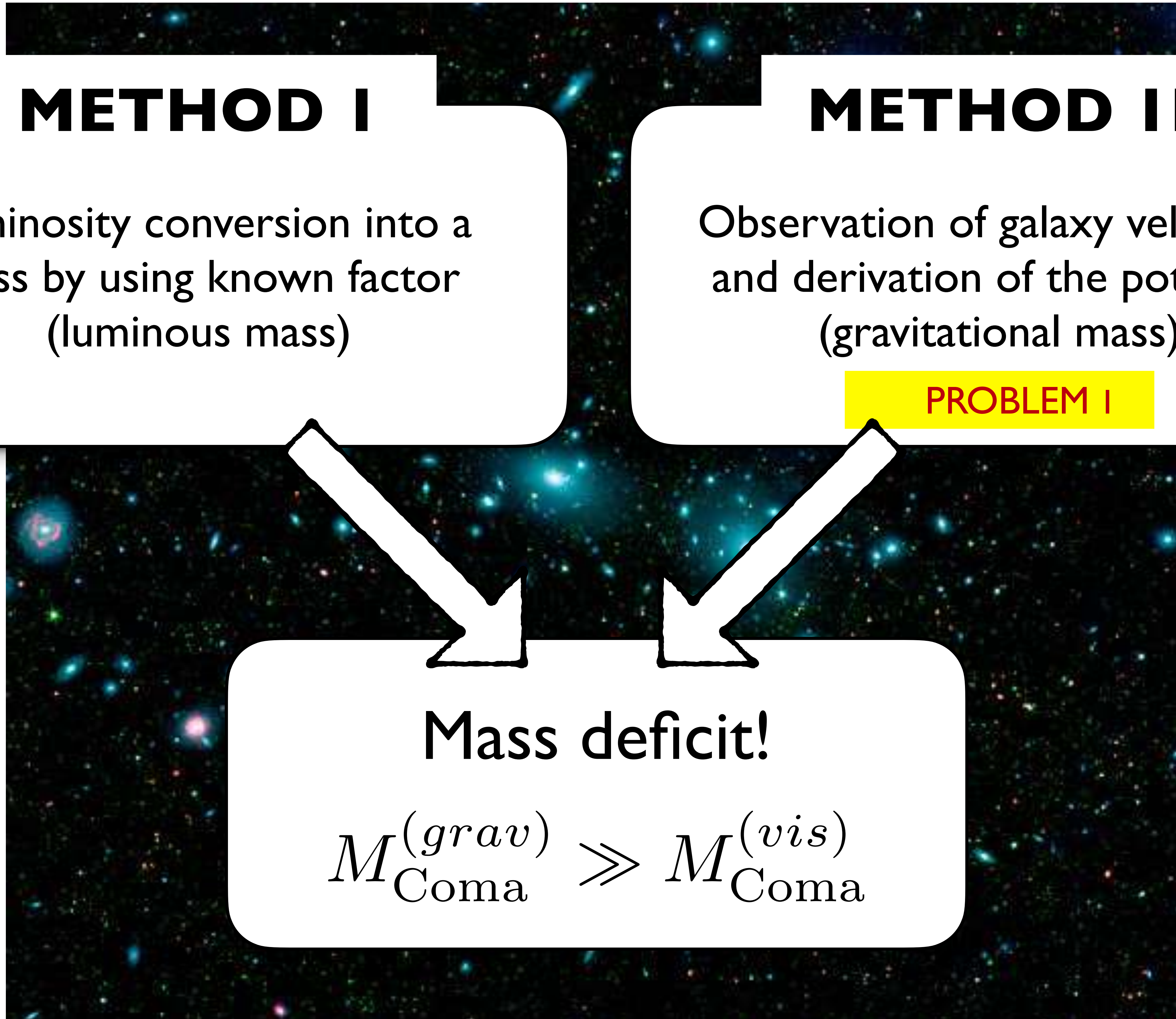
Luminosity conversion into a mass by using known factor (luminous mass)

METHOD II

Observation of galaxy velocities and derivation of the potential (gravitational mass)

PROBLEM 1

Zwicky and the Coma Cluster



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Luminosity conversion into a mass by using known factor (luminous mass)

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Observation of galaxy velocities and derivation of the potential (gravitational mass)

PROBLEM 1

Mass deficit!

$$M^{(grav)}_{\mathrm{Coma}} \gg M^{(vis)}_{\mathrm{Coma}}$$

Galactic Rotation Curves

<u>Vera Rubin (1970's)</u>

Careful observation of stellar motion within spiral galaxies

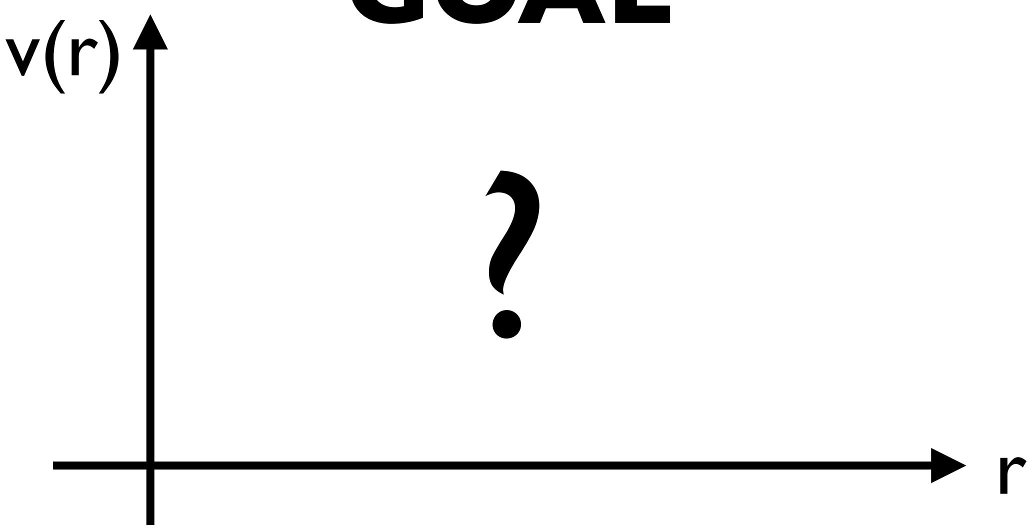
Comparison with expectation based on visible mass… surprise!

Galactic Rotation Curves

Galactic Rotation Curves

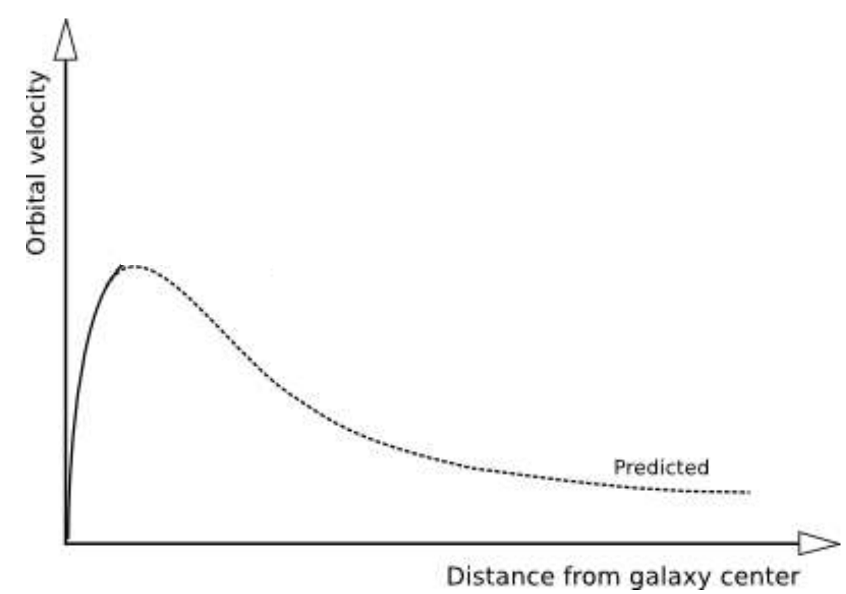
Galactic Rotation Curves

GOAL



PREDICTION

$$v(r) \propto \begin{cases} r & r \ll r_c \\ r^{-1/2} & r \gg r_c \end{cases}$$



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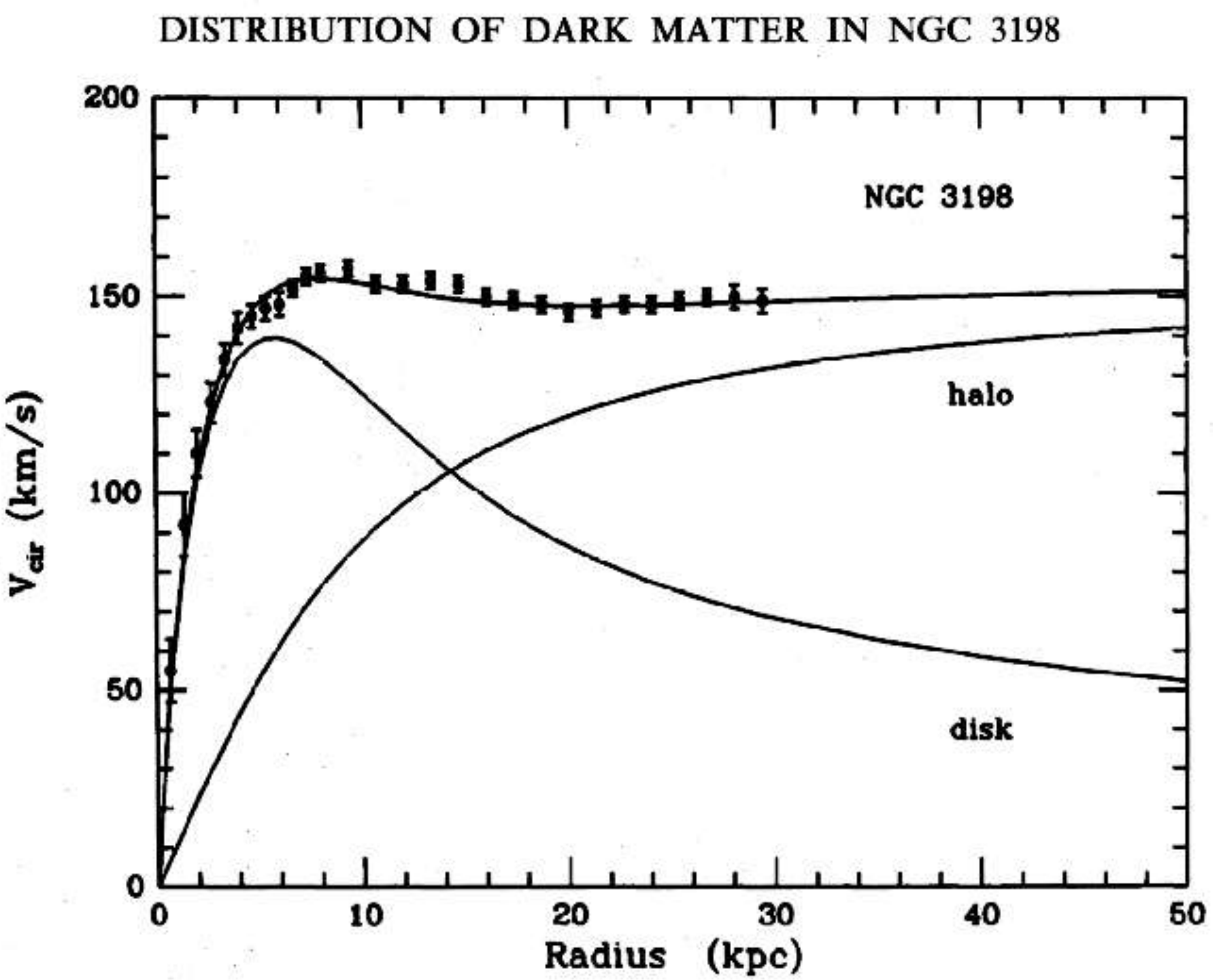
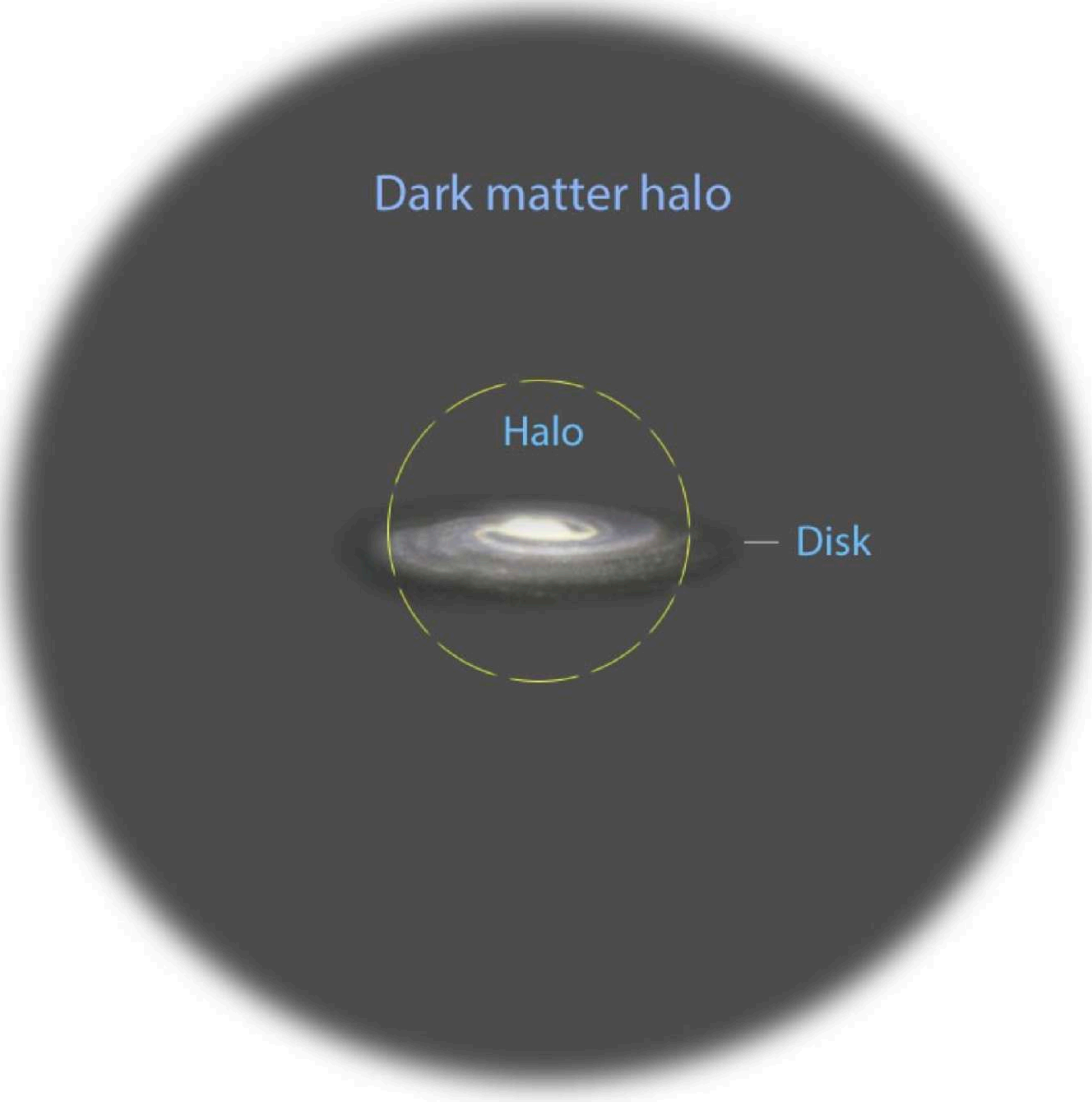
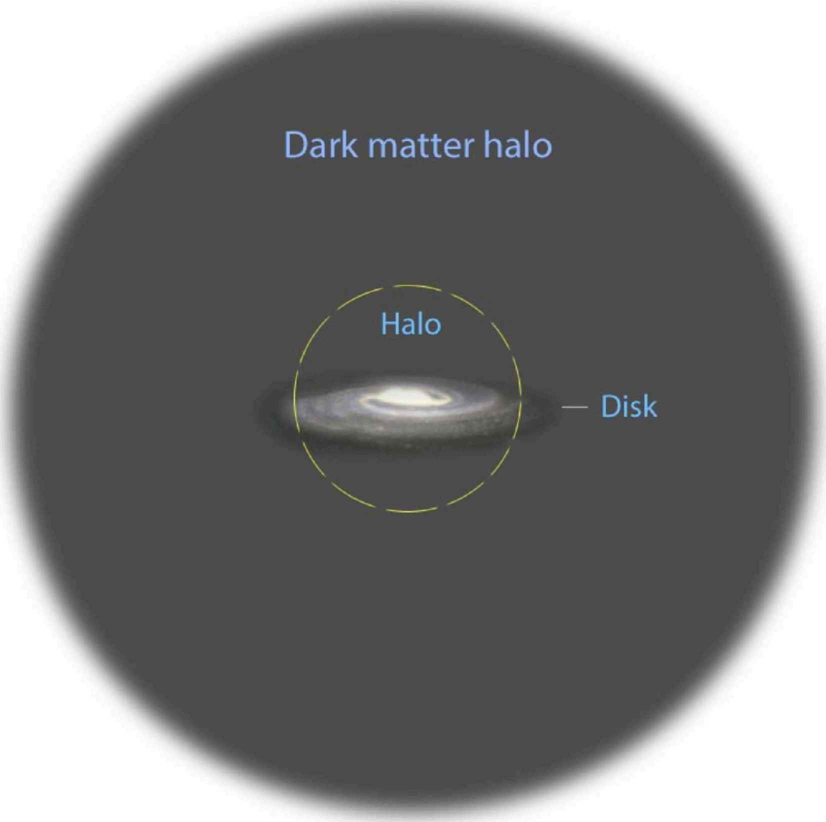


A Dark Matter Halo



A Dark Matter Halo

$$m\frac{v^2(r)}{r} = \frac{G_N M(r) m}{r^2} \quad \Rightarrow \quad \rho_{\text{halo}} \propto r^{-2}$$



A Dark Matter Halo

$$m\frac{v^2(r)}{r} = \frac{G_N M(r) m}{r^2} \quad \Rightarrow \quad \rho_{\rm halo} \propto r^{-2}$$

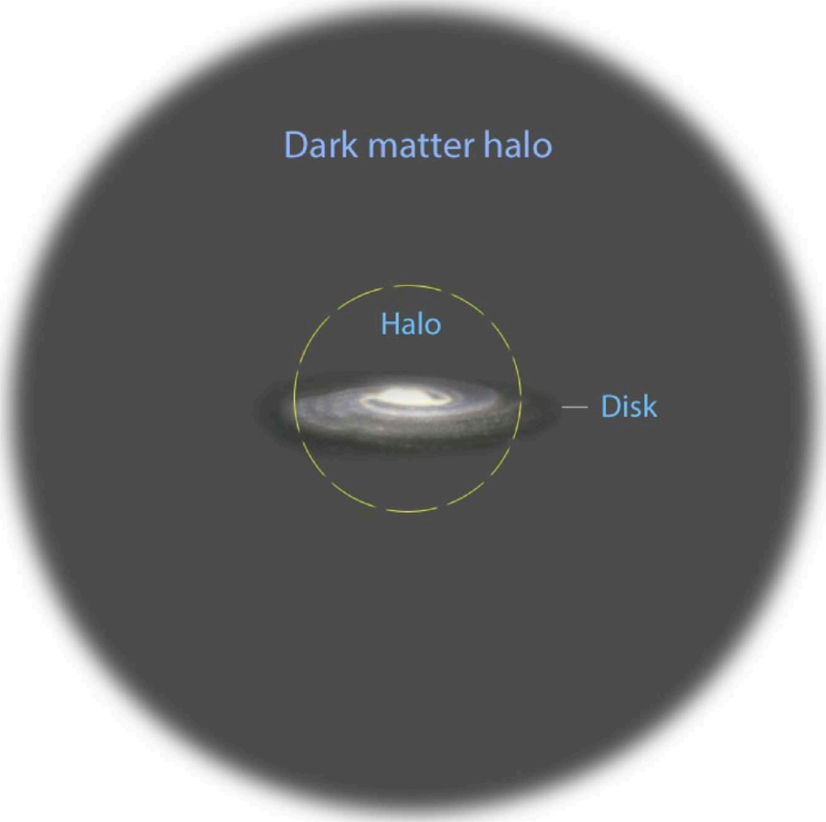
N-body simulations

Isothermal: $\rho_{\rm DM}^{\rm isothermal}(r) = \dfrac{\rho_0}{1+(r/r_c)^2}$

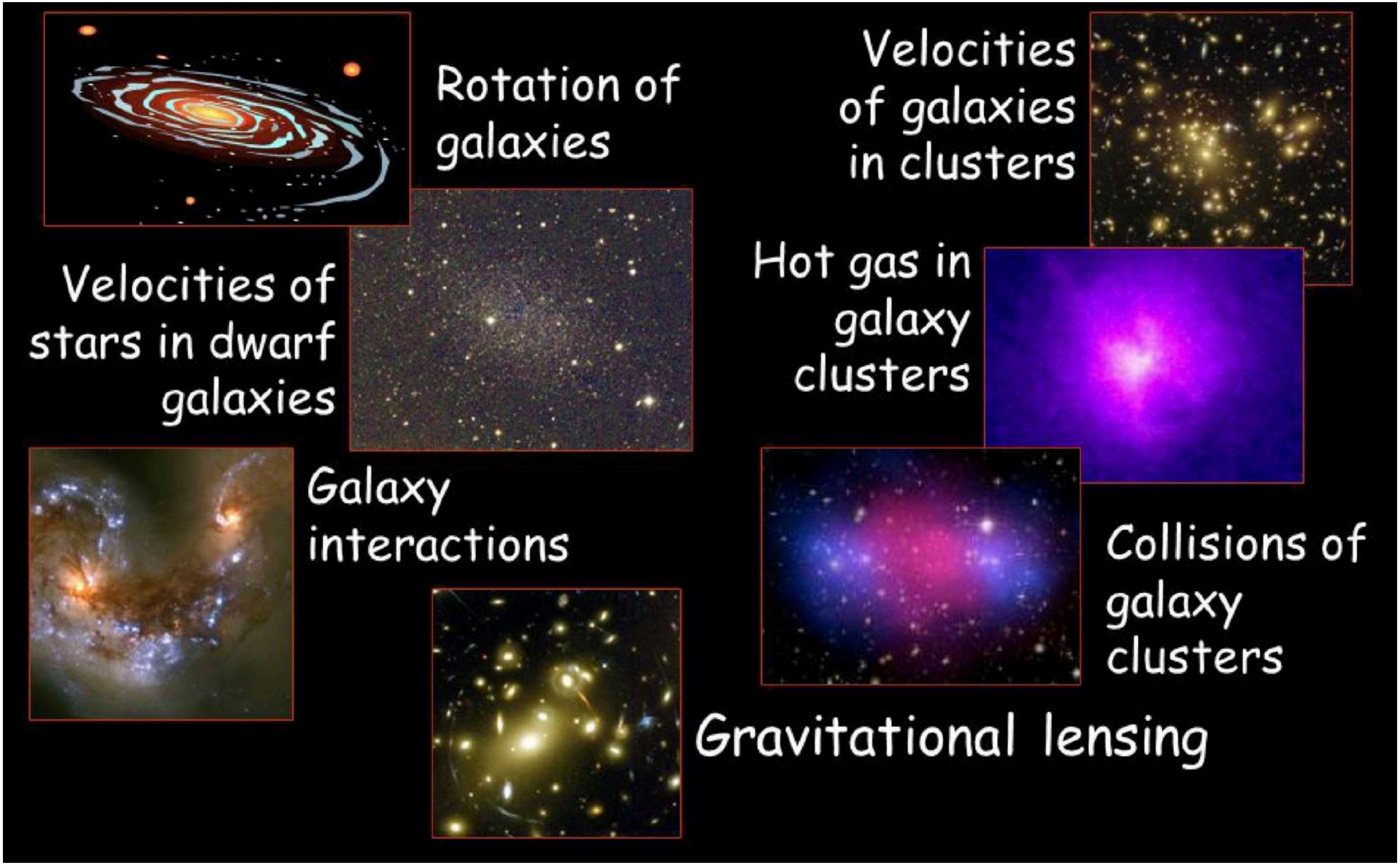
NFW: $\rho_{\rm DM}^{\rm NFW}(r) = \dfrac{\rho_s}{(r/r_s)\,(1+r/r_s)^2}$

Einasto: $\rho_{\rm DM}^{\rm Einasto}(r) = \rho_E \exp\left[-\dfrac{2}{\alpha}(r/r_E)^{\alpha} - 1\right]$

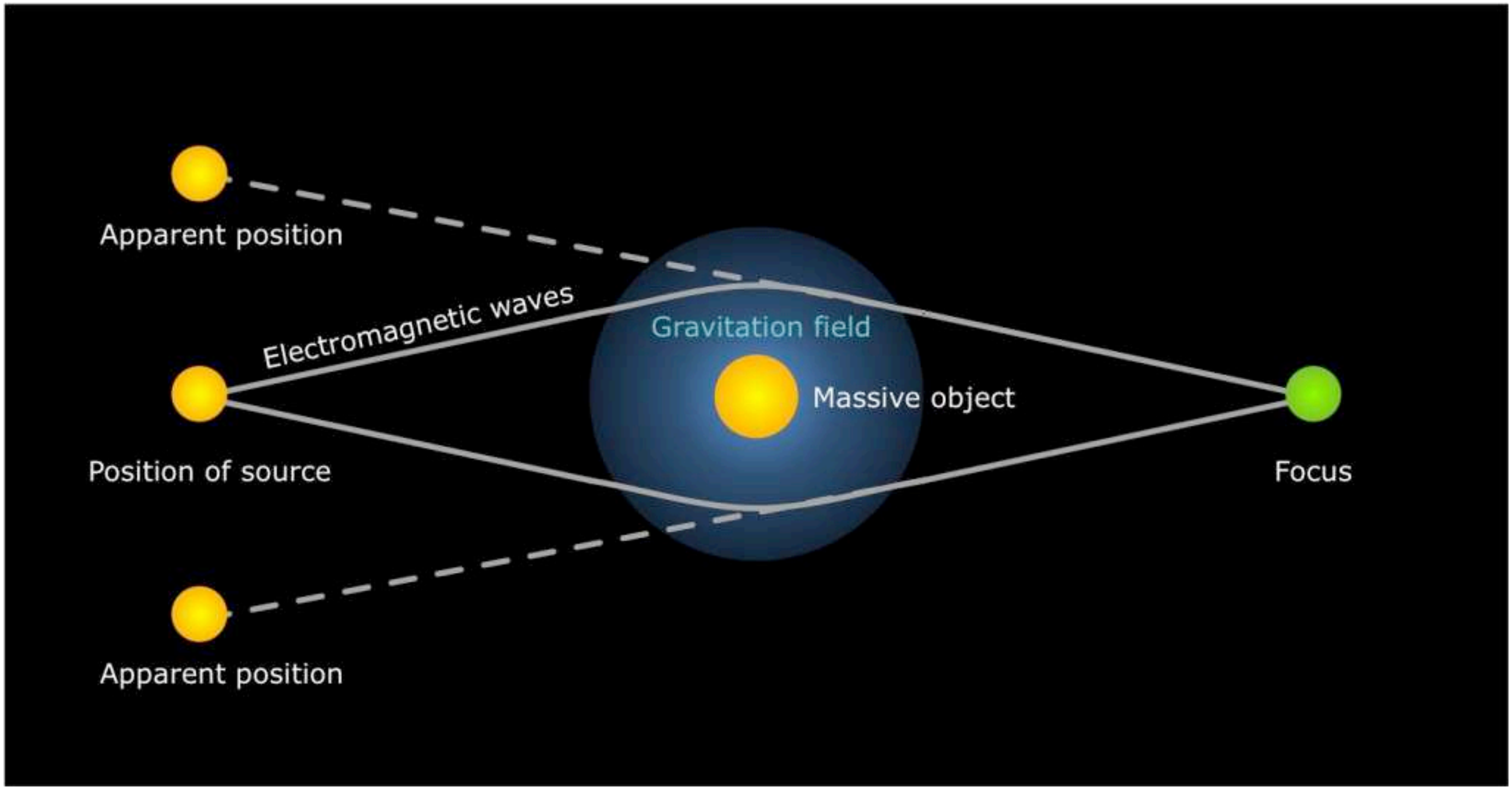
Halo density profile for the Milky Way very important for indirect searches (later)



Firm evidence over decades

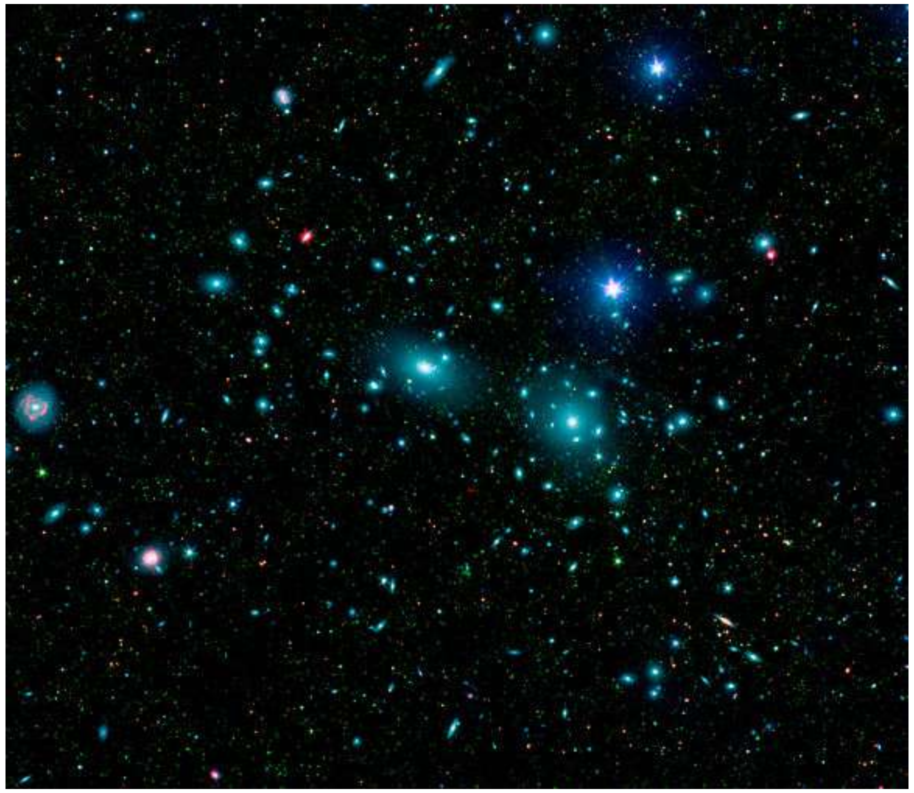


Gravitational Lensing



We can find evidence for dark matter even beyond the visible galactic disk

Hot gas in galaxy clusters



Clusters are filled with hot gas that does not fall within galaxies

We observe its X-ray emission

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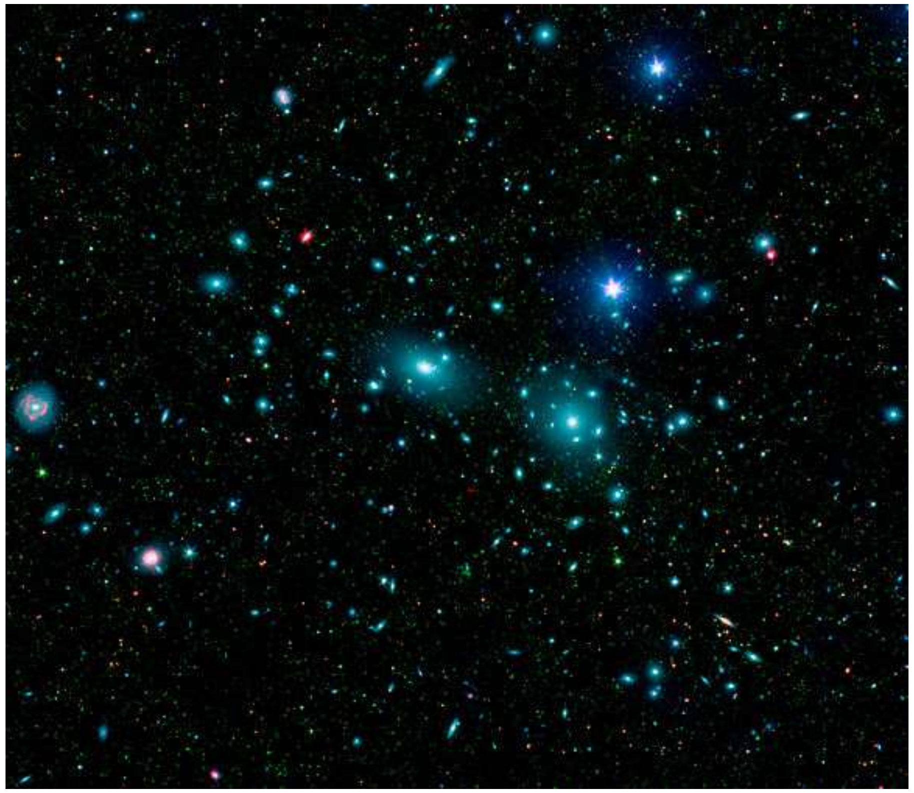
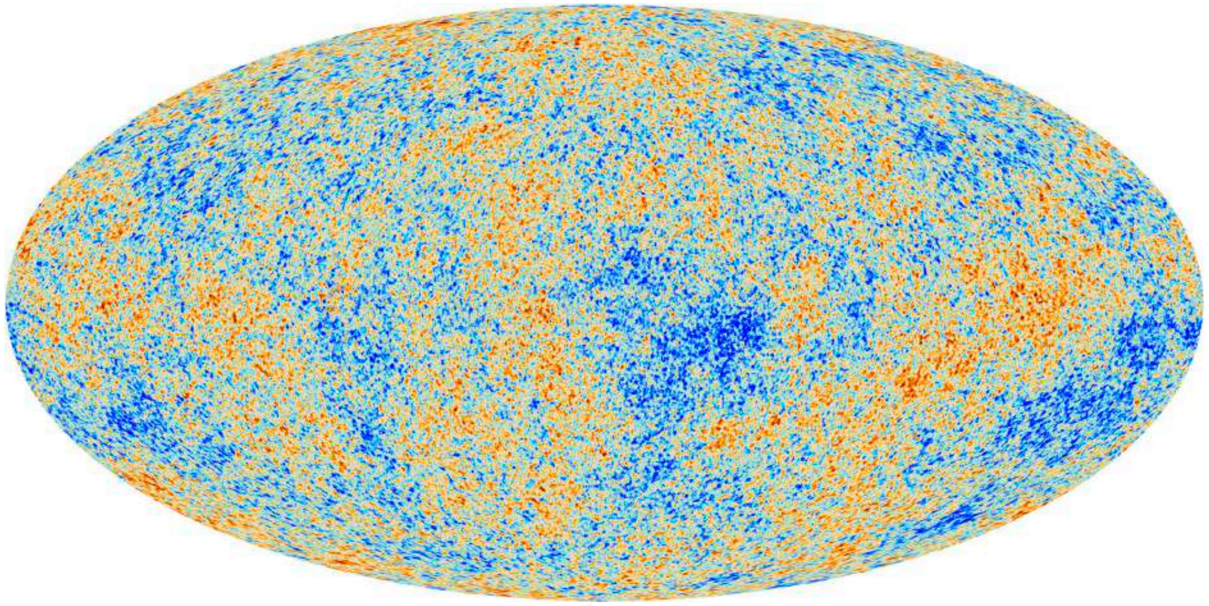


$$\boxed{\frac{dp(r)}{dr} = -\frac{G_N M(r)\rho(r)}{r^2}}$$

Hydrostatic equilibrium:
we can infer the distribution of gravitational mass

Cosmic Microwave Background

Universe 380,000 yrs old,
Temperature 0.3 eV,
Tiny density fluctuations



Species present @ CMB formation:
photons, neutrinos, electrons, protons, dark matter

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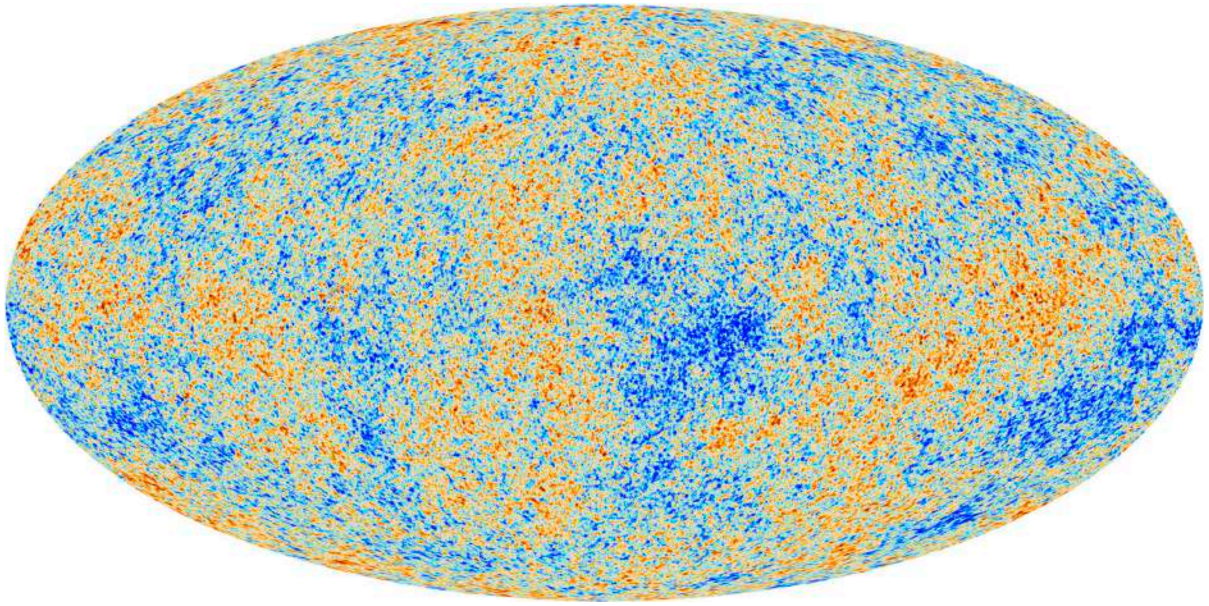

Species present @ CMB formation:
photons, neutrinos, electrons, protons, dark matter

$p \quad e^- \quad \gamma$

Coulomb and Thomson scattering, bound plasma

Sound waves

gravity

χ

Free to collapse under its own gravity

Cosmic Microwave Background

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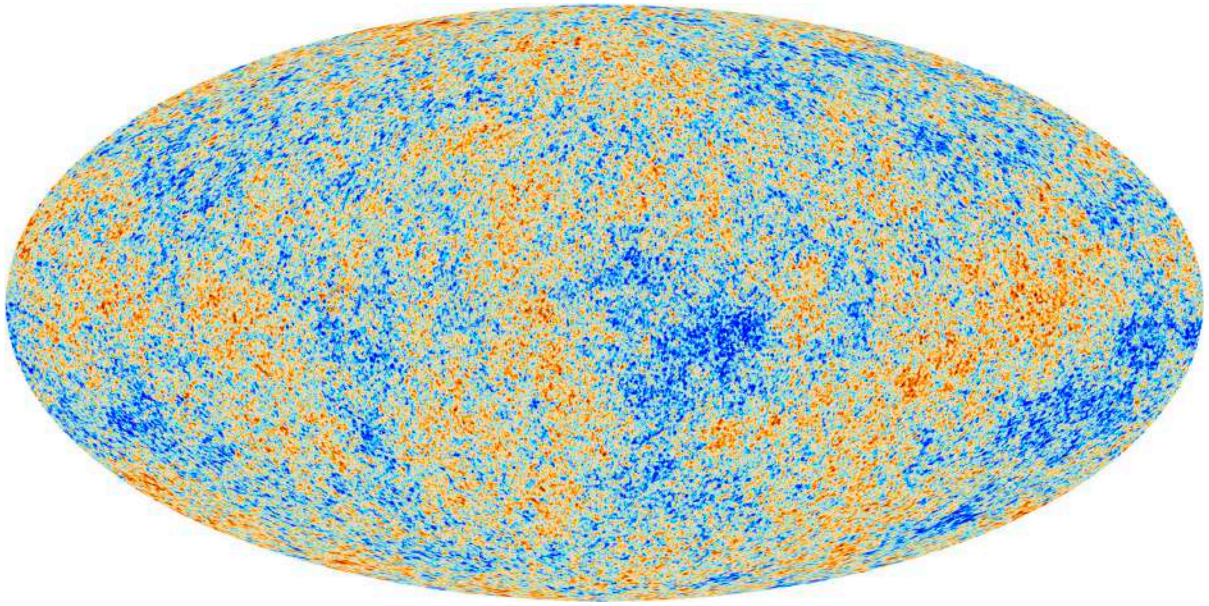
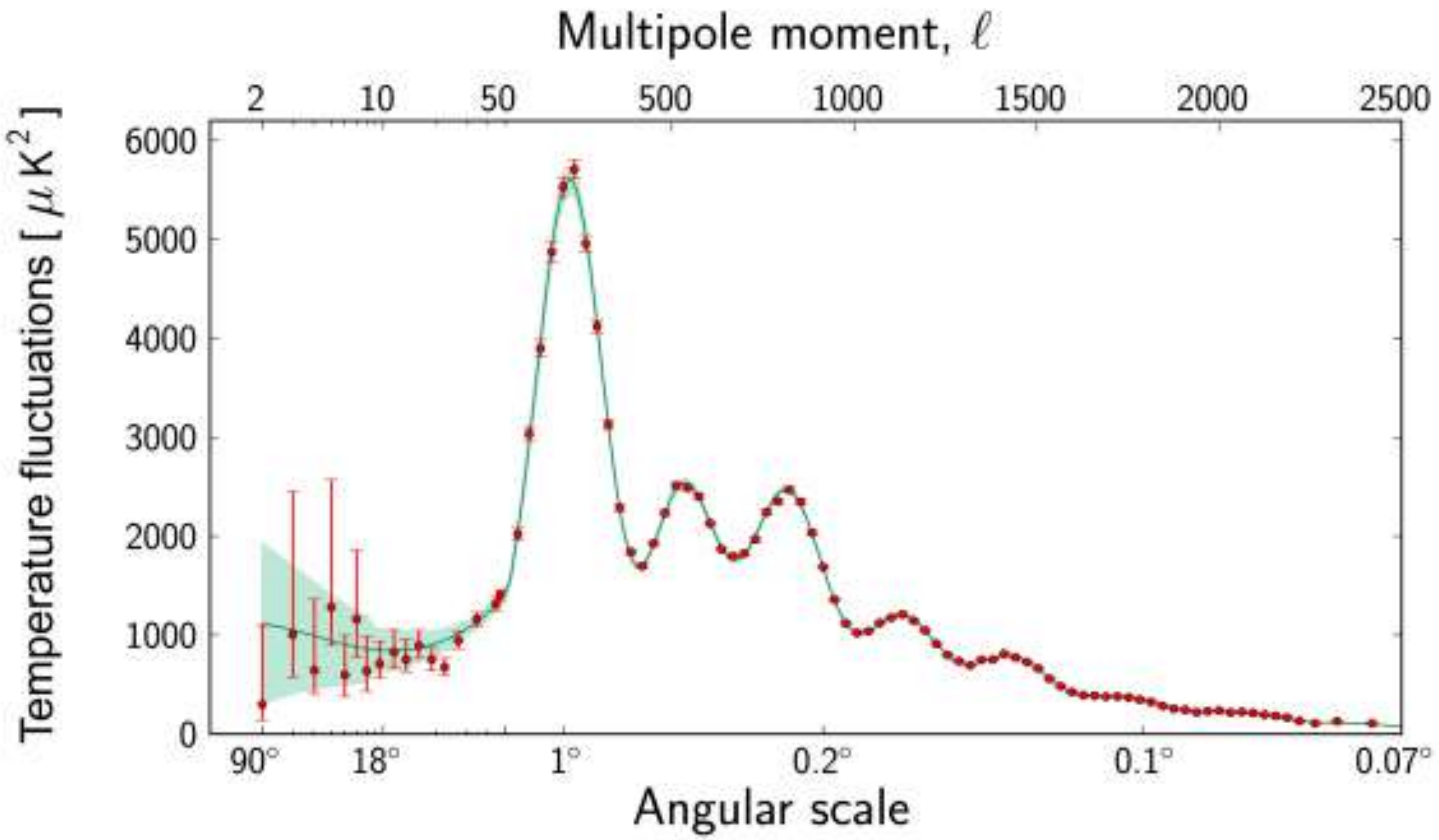


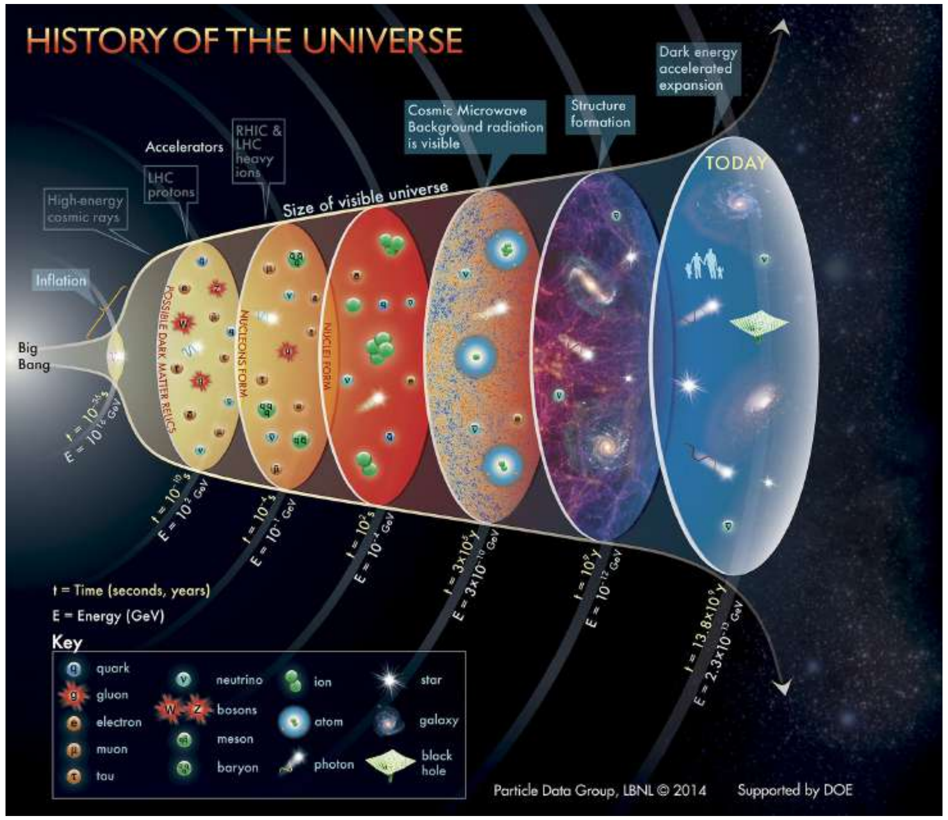


$$\rho_{\rm DM} \simeq 5\,\rho_B$$

Dark matter must be non-baryonic!

Structure Formation

How did we go from a highly homogeneous and isotropic universe to galaxies and clusters?



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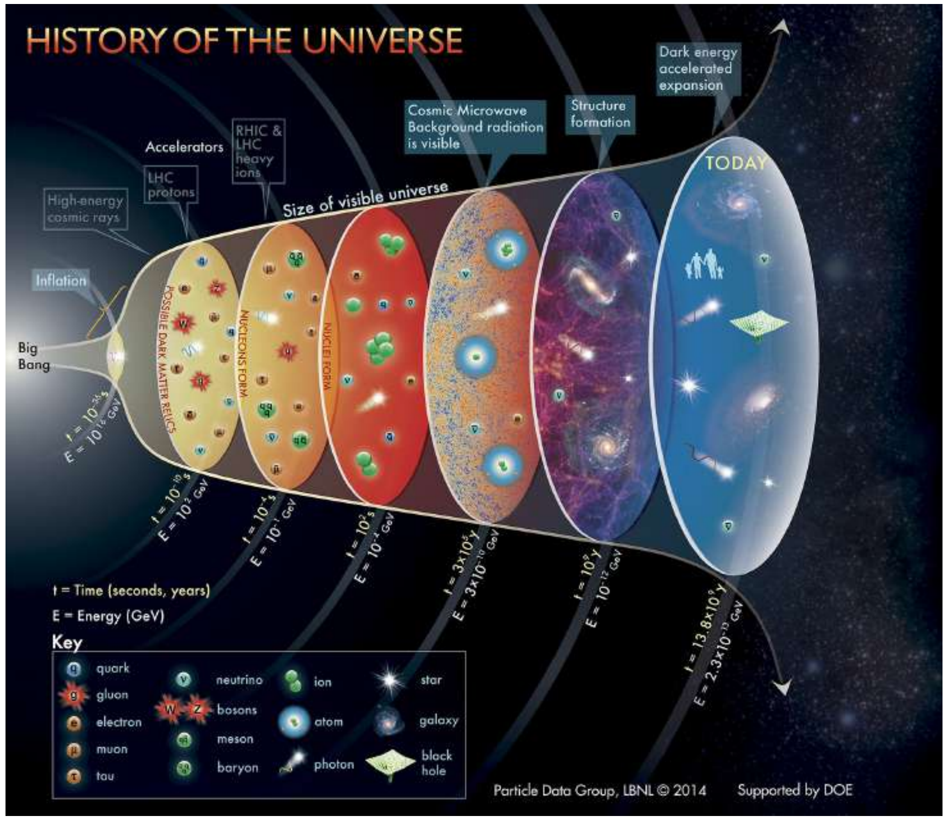

GRAVITATIONAL COLLAPSE

$$\frac{\delta\rho}{\rho} \propto \begin{cases} \ln(a) & \text{RD} \\ a & \text{MD} \end{cases}$$

Structure Formation

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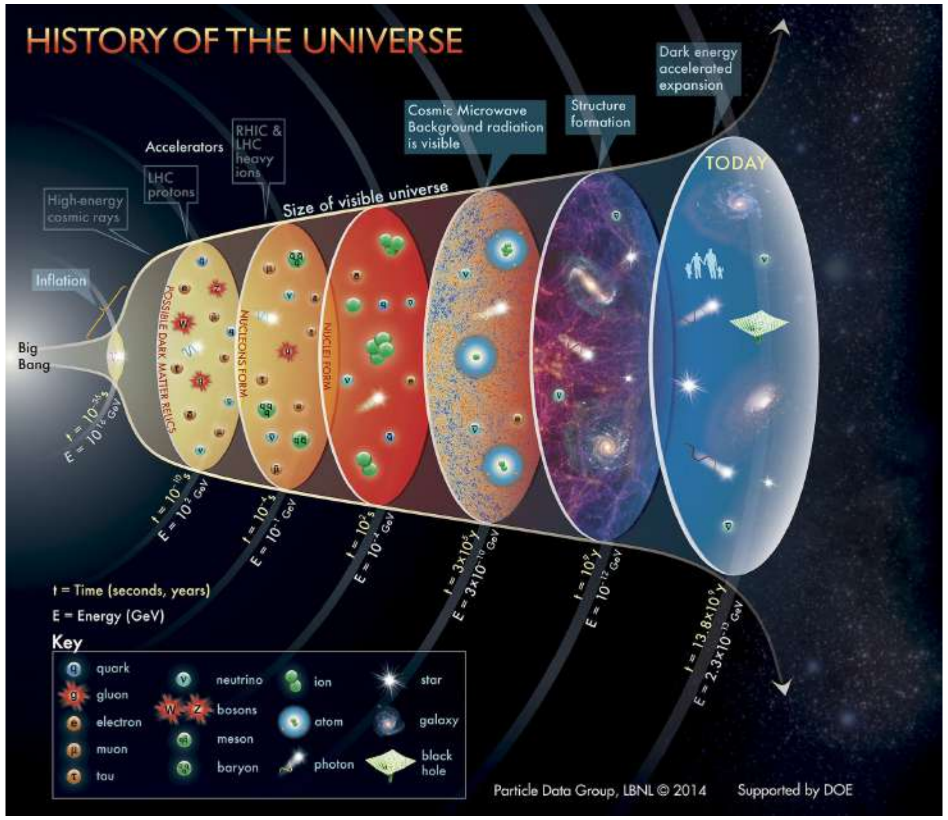
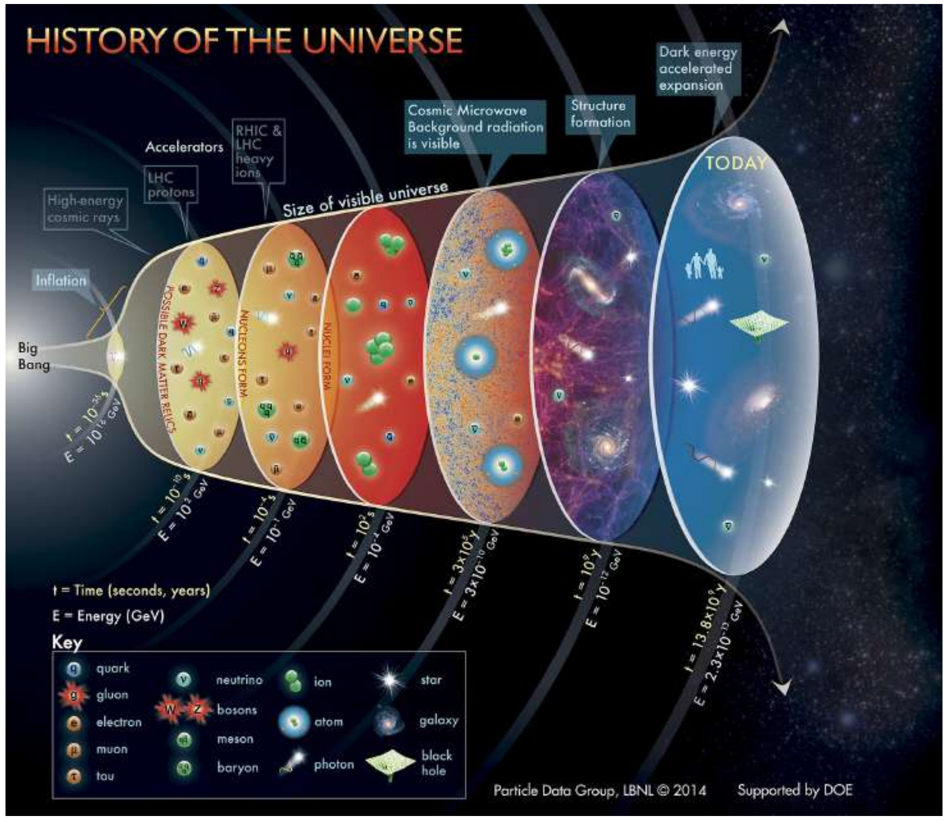


BARYONS ONLY

$$\left.\frac{\delta\rho}{\rho}\right|_{\rm today} \simeq \left.\frac{\delta\rho}{\rho}\right|_{\rm CMB} \frac{a_0}{a_{\rm rec}} \simeq 10^{-5} \times 10^{3} \simeq 10^{-2}$$

Structure Formation



How did we go from a highly homogeneous and isotropic universe to galaxies and clusters?

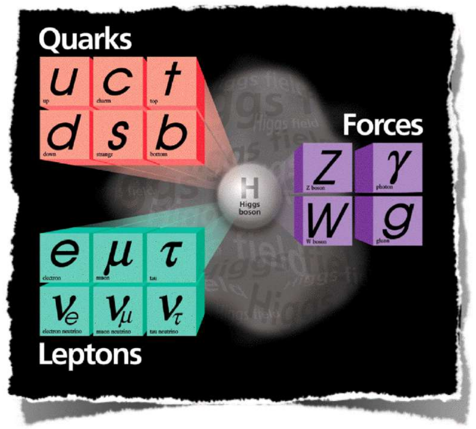
Structure formation can reach the non-linear regime only if there is dark matter!

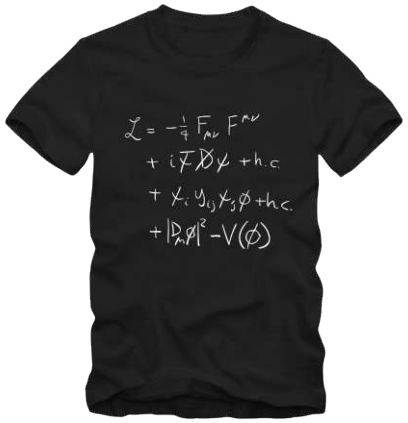
The Big Question in 2020

What is the dark matter made of?

The Big Question in 2020

Standard Model



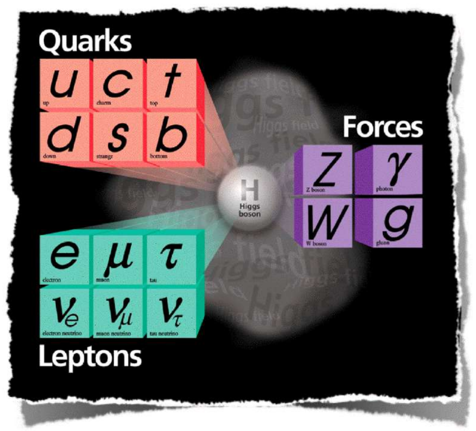


gravity

Dark Matter

The Big Question in 2020

Standard Model



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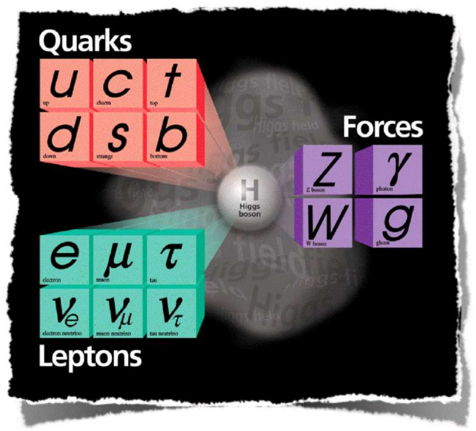

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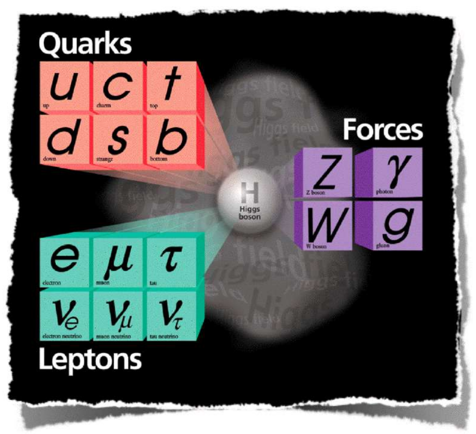
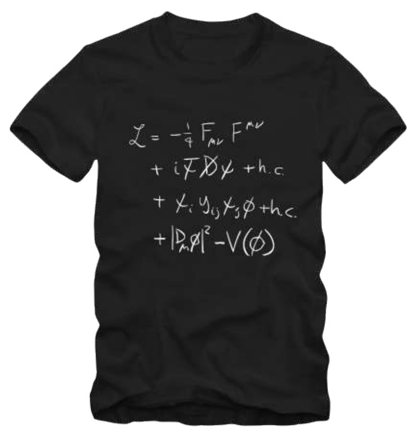




In these lectures I will tell you about possible ideas that could end up in that t-shirt

We cannot put anything we want:
solid bounds from dark matter searches

What dark matter cannot be

RELIC DENSITY

$$\Omega_{DM}(t_0)h^2 = \frac{\rho_{DM}}{\rho_{\rm crit}/h^2} = 0.1198 \pm 0.0012$$

What dark matter cannot be

RELIC DENSITY

$$\xi_{DM} = \frac{\rho_{DM}}{s(t_0)} = \frac{m_{DM} n_{DM}}{s(t_0)} = m_{DM} Y_{DM} \simeq 4.35 \times 10^{-10}\,\mathrm{GeV}$$

What dark matter cannot be

Reproduce the relic density

MASS BOUNDS

BOSON DM:

de Broglie wavelength smaller than dwarf galaxies size

$$\lambda_{DM} = \frac{h}{p} \simeq \left(\frac{1\,\mathrm{eV}}{m_{DM}}\right) 2.3 \times 10^{-3}\,\mathrm{m}$$

$$m_{DM} \gtrsim 10^{-22}\,\mathrm{eV}$$

What dark matter cannot be

Reproduce the relic density

MASS BOUNDS

FERMION DM:

Tremaine-Gunn bound
(Pauli exclusion principle)

$$m_{\rm DM} \gtrsim \left(\frac{9\pi}{4\sqrt{2}\, g} \frac{1}{\sqrt{M G^3 R^3}} \right)^{1/4}$$
$$\gtrsim (10 - 100)\,{\rm eV}$$

PROBLEM 2

What dark matter cannot be

Reproduce the relic density

"Statistical" bounds on the mass

CHARGE NEUTRAL

Searches for DM-electron bound states

$$q_{\mathrm{DM}} \lesssim \begin{cases} 10^{-6} & m_{\mathrm{DM}} = 10\,\mathrm{GeV} \\ 10^{-4} & m_{\mathrm{DM}} = 10\,\mathrm{TeV} \end{cases}$$

What dark matter cannot be

Reproduce the relic density

"Statistical" bounds on the mass

Charge neutrality

COLDNESS

Cosmological structures study:

DM particles must have been non-relativistic when the universe had a temperature T ~ 1 keV

This excludes hot relics (next lecture)

What dark matter cannot be

Reproduce the relic density

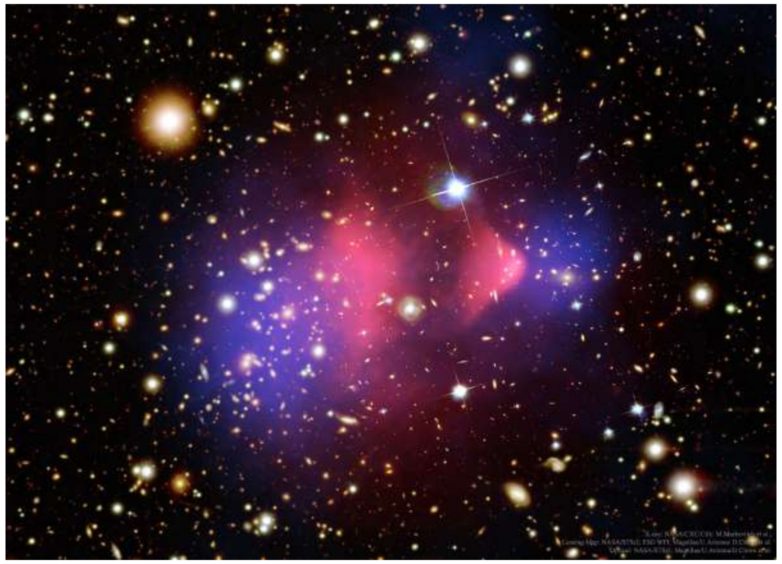
“Statistical” bounds on the mass

Charge neutrality

Cold relics

Self-Interactions

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



What dark matter cannot be

Reproduce the relic density

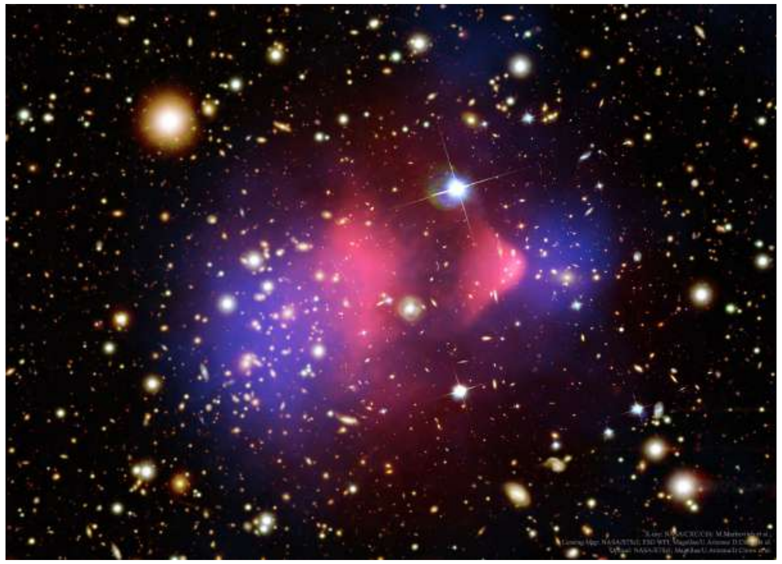
"Statistical" bounds on the mass

Charge neutrality

Cold relics

Self-Interactions

$$\frac{\sigma_{\rm self}}{m} \lesssim 10^{-24}{\rm cm}^2\,{\rm TeV}^{-1}$$



What dark matter cannot be

Reproduce the relic density

"Statistical" bounds on the mass

Charge neutrality

Cold relics

Not too-much self-interacting

Stability

Invisible decays alter expansion history $\tau_{\rm DM} \gtrsim 5 \times 10^{18}\,{\rm sec}$

Visible decays impact CMB spectra $\tau_{\rm DM} \gtrsim 10^{25-29}\,{\rm sec}$

$$\tau_H \simeq 4 \times 10^{17}\,{\rm sec}$$

What dark matter cannot be

Reproduce the relic density

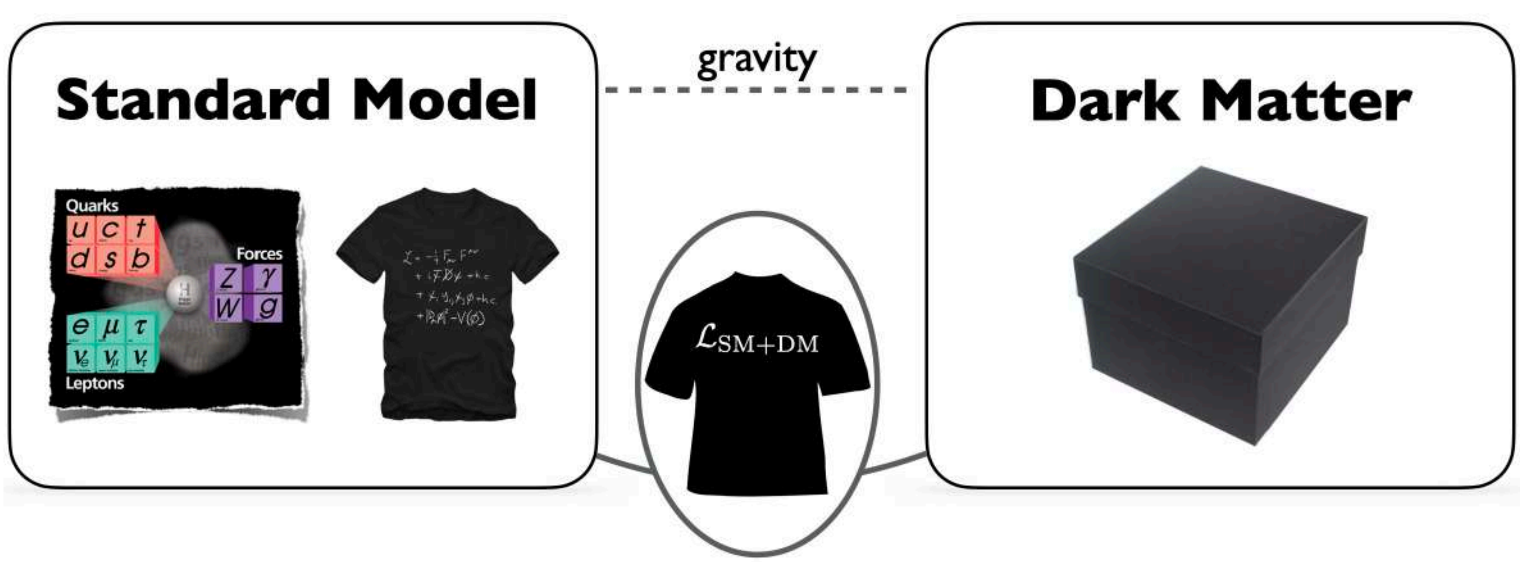
“Statistical” bounds on the mass

Charge neutrality

Cold relics

Not too-much self-interacting

Enough long-lived



We will see plausible options this week