Dark Matter - intro

Our story start at the beginning of the XX century when ‘the big question’ was…

… are we here alone?

Astronomers used telescopes (since XVII) to study the stars and their motion. In late XIX century '*astrophotography*', thanks to long exposure times, made clear that some objects are extended.

The first photograph of M31, the Andromeda **nebula**
(Isaac Roberts, 1899)

Progress at the end of the XIX century

"Computers" at Harvard , ca. 1890
classification of stars in photographs by comparing with old catalogs

Progress at the end of the XIX century

Cepheids variable stars

relationship between period and luminosity

⇨ a new distance measure

"Computers" at Harvard , ca. 1890

Henrietta
Swan Leavitt
(1864-1921)

1908

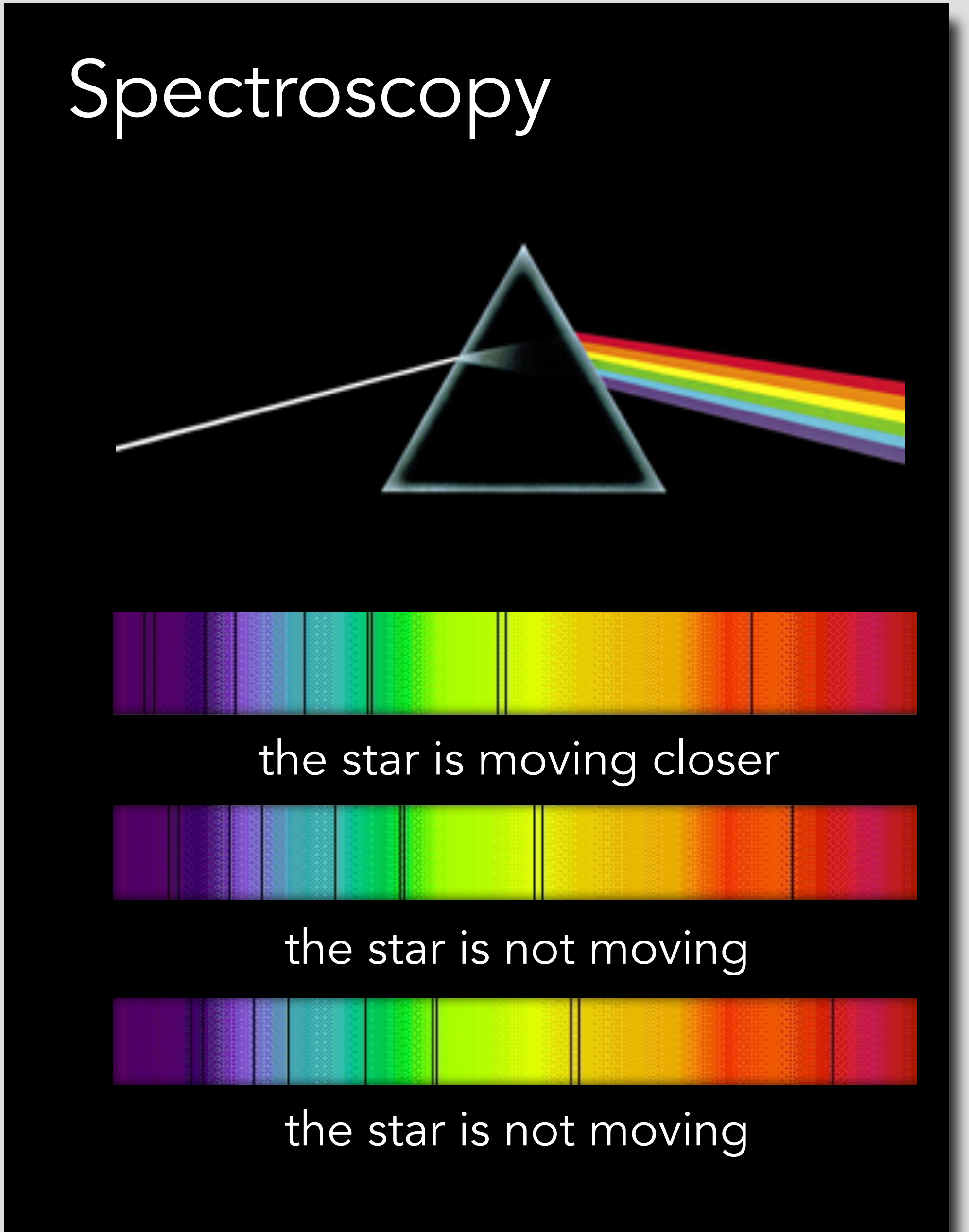
1777 VARIABLES IN THE MAGELLANIC CLOUDS.

By Henrietta S. Leavitt.

In the spring of 1904, a comparison of two photographs of the Small Magellanic Cloud, taken with the 24-inch Bruce Telescope, led to the discovery of a number of faint variable stars. As the region appeared to be interesting, other plates were examined, and although the quality of most of these was below the usual high standard of excellence of the later plates, 57 new variables were found, and announced

"Computers" at NASA ,
(before the arrival of an IBM in 1964)
From the movie *Hidden Figures*, 2017

Progress at the beginning of the XX century



Vesto Slipher
(1875-1969)

Around 1917 it became clear that the mysterious nebulae are moving away from us ....

April 20th, 1920: the great debate

Harlow Shapley
(1885-1972)

How large is the Milky Way?

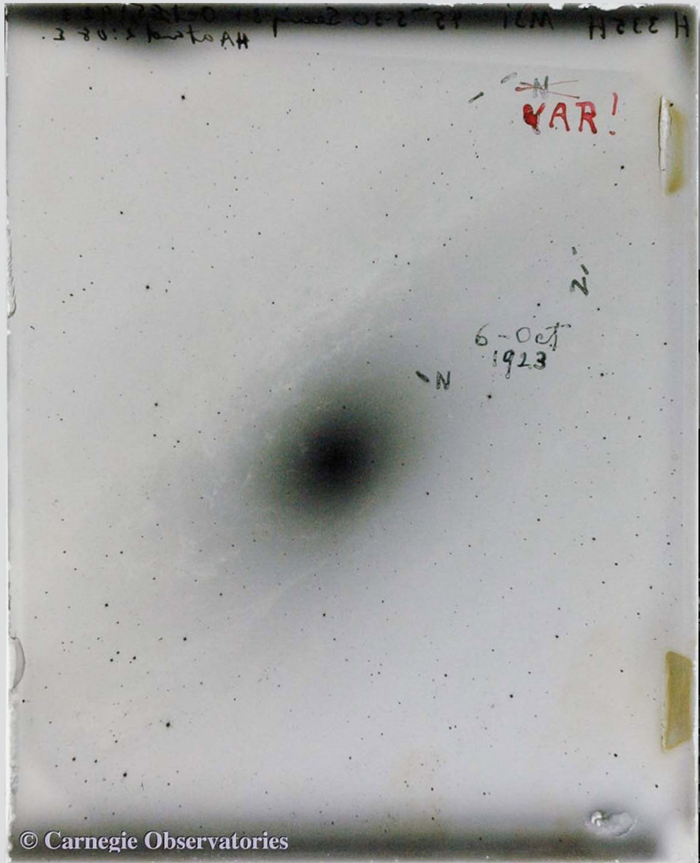
Are nebulae extra-galactic objects?

Heber Curtis
(1872-1942)

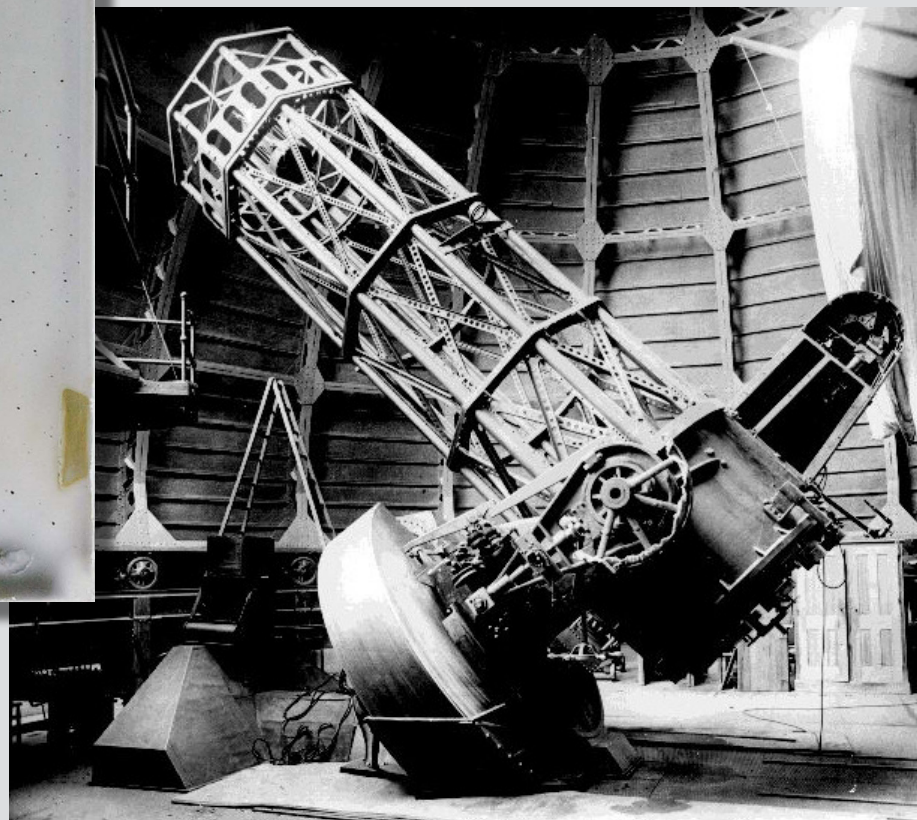
Baird Auditorium, Smithsonian National Museum of Natural History, Washington D.C.

1924: Hubble finds a variable Cepheid star in the Andromeda nebula:
extragalactic astronomy begins!

Edwin Hubble
(1889-1953)

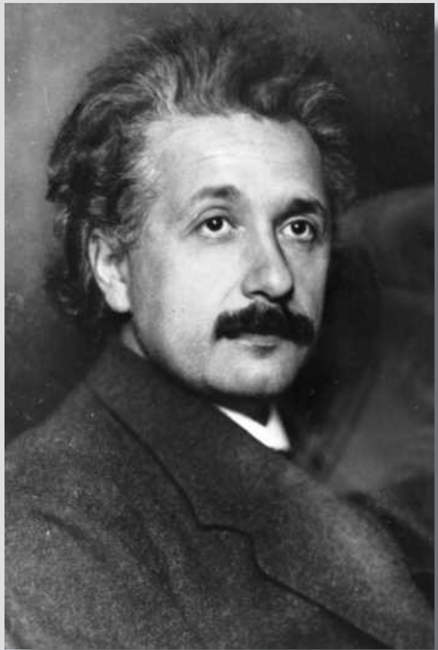


Andromeda nebula becomes Andromeda ***galaxy***!



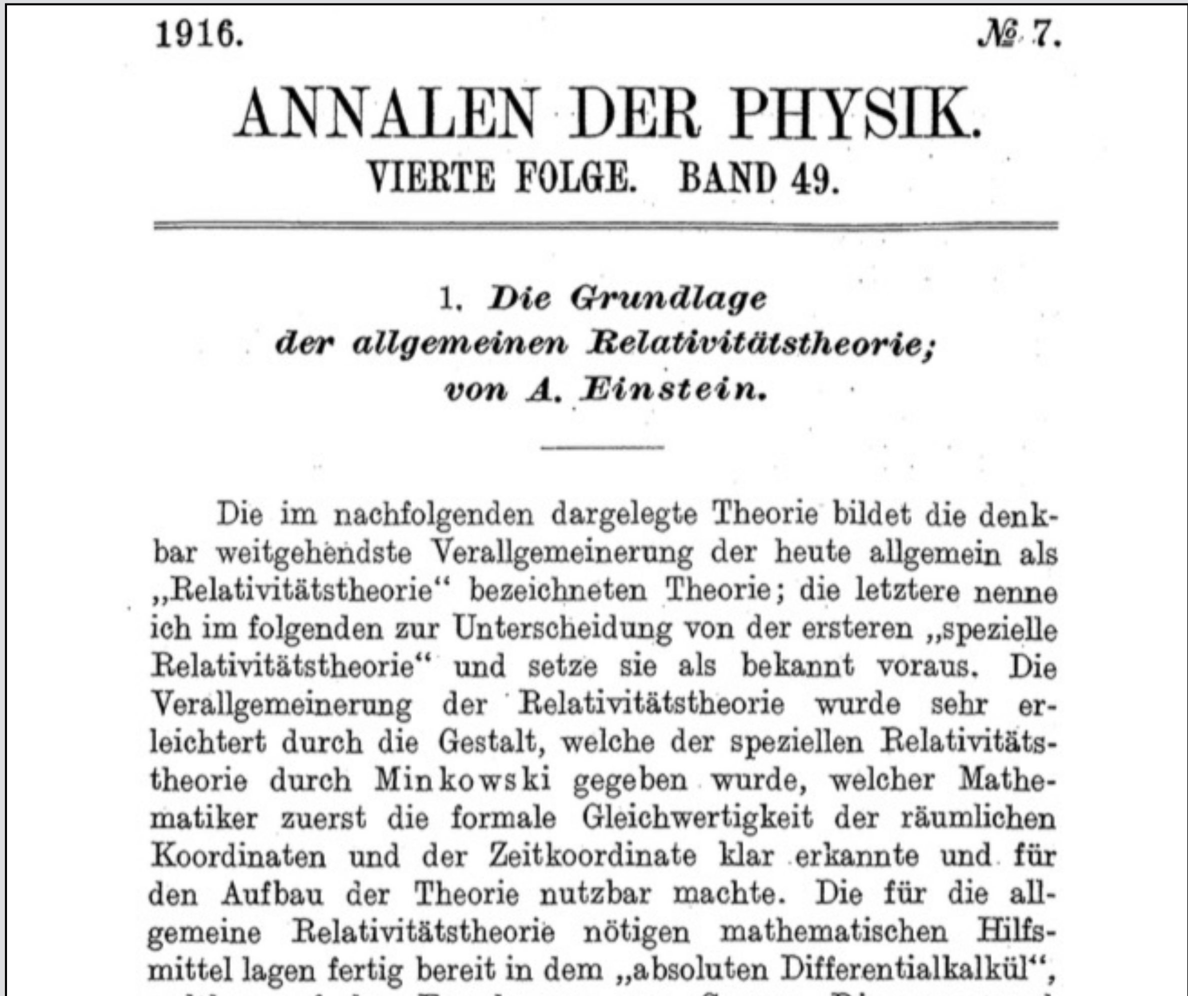
Hooker telescope, Mt. Wilson, California

Meanwhile, in Europe …



Albert Einstein
(1879-1955)

… Einstein publishes, in 1915,
the **theory of general relativity**



1916. № 7.

ANNALEN DER PHYSIK.

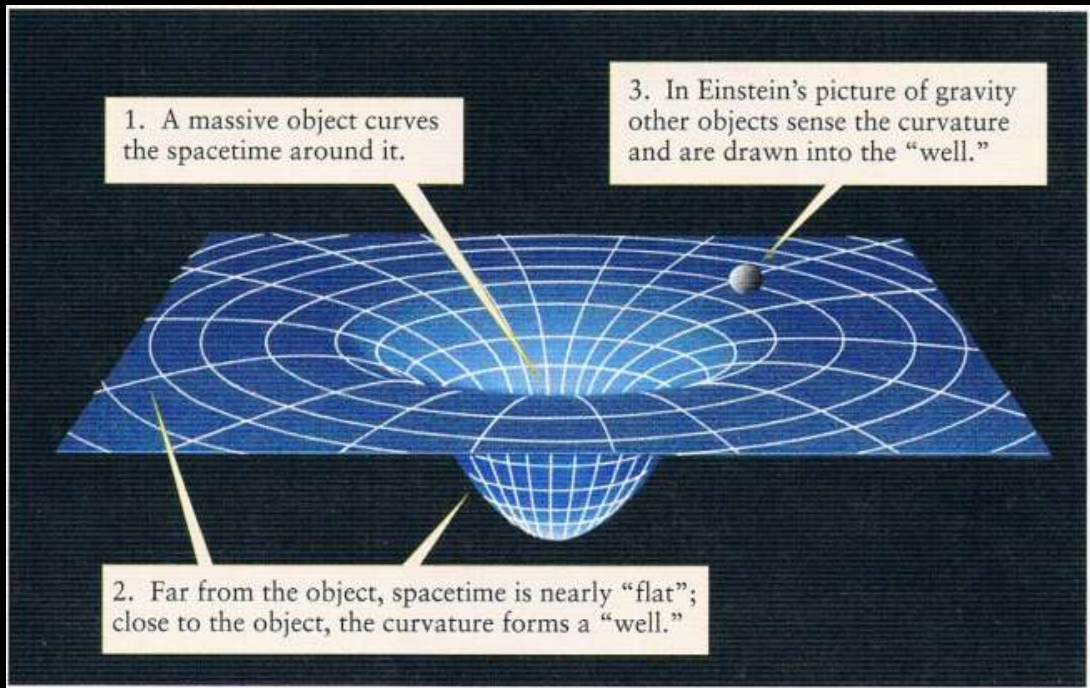
VIERTE FOLGE. BAND 49.

1. ***Die Grundlage der allgemeinen Relativitätstheorie;***
von A. Einstein.

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül",

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\,\pi\, G\, T_{\mu\nu}$$

geometry (space-time) energy (mass) density



The expansion of the Universe … predicted!

Alexander Friedmann
(1888-1925)

Georges Lemaître
(1894-1966)

Thanks to **general relativity** and to the **cosmological principle**
(that is imagining a very simple Universe)
Friedmann in 1922 and Lemaître in 1927 *predict* that the
Universe might be expanding!

(but nobody notices)

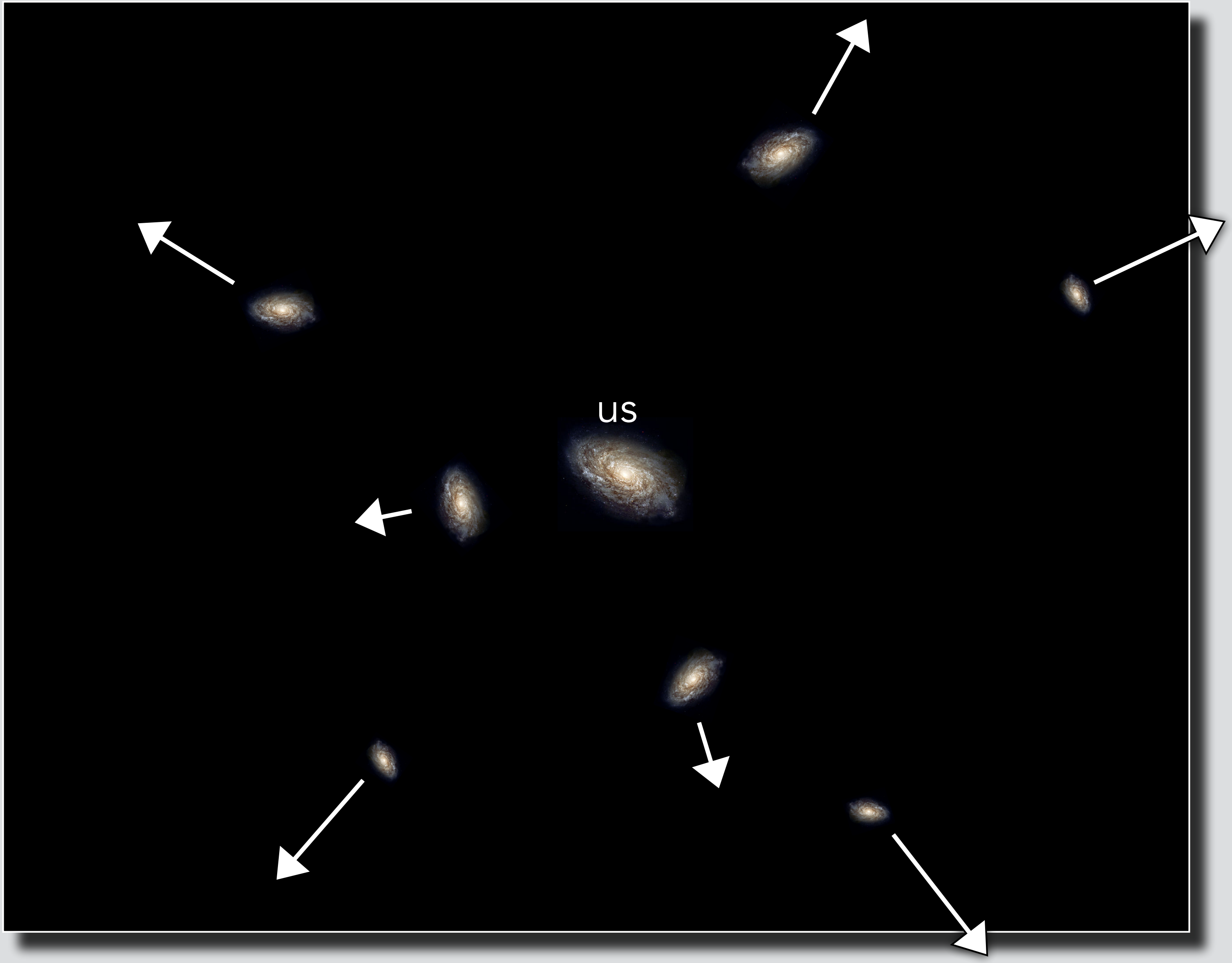
What Is The Universe Expanding Into?

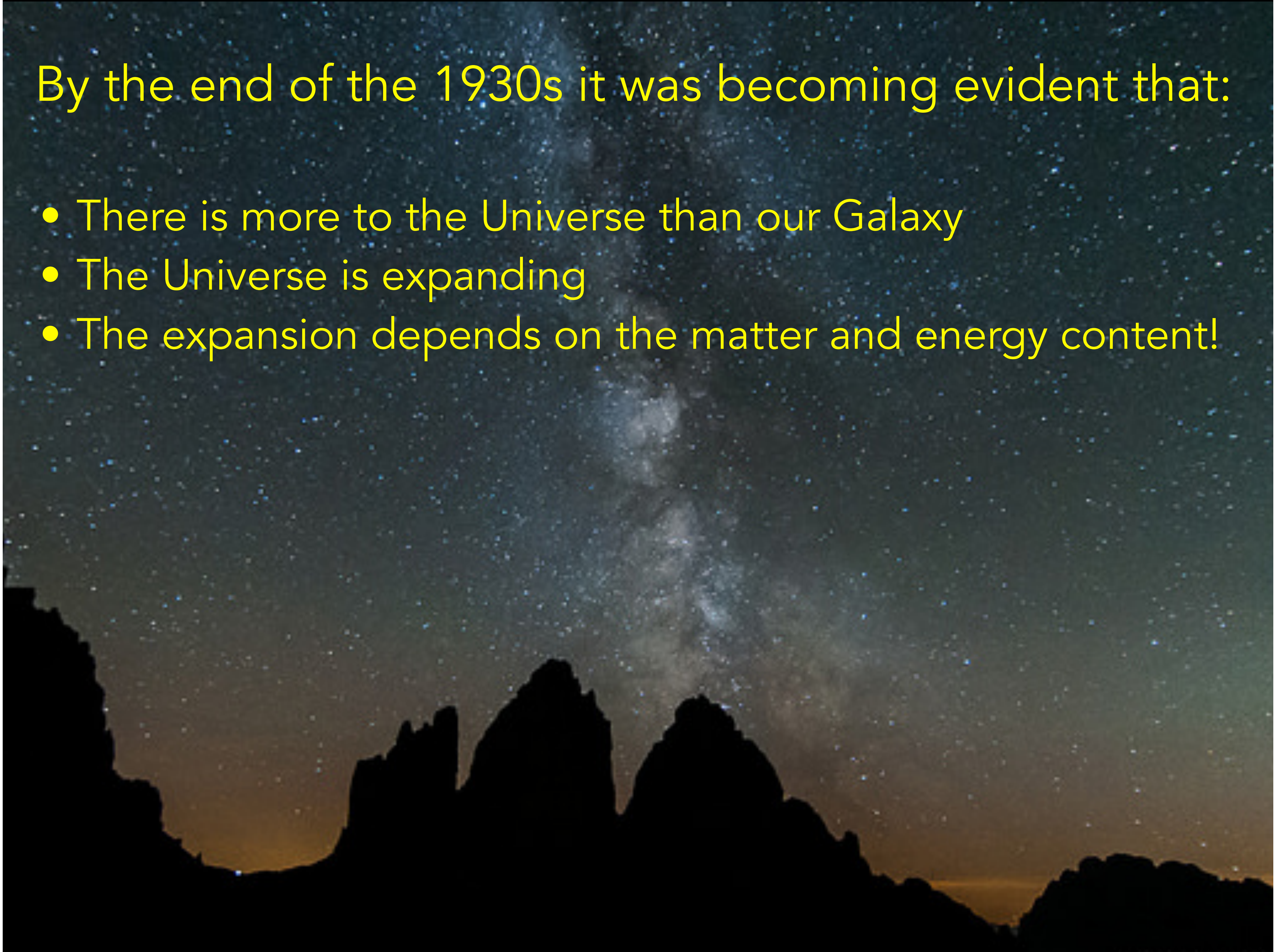
Image Credit: LIFE magazine

Like a surface of the balloon (2D)
— space itself is being "expanded"
— there is no "centre" of the expansion (on the surface)

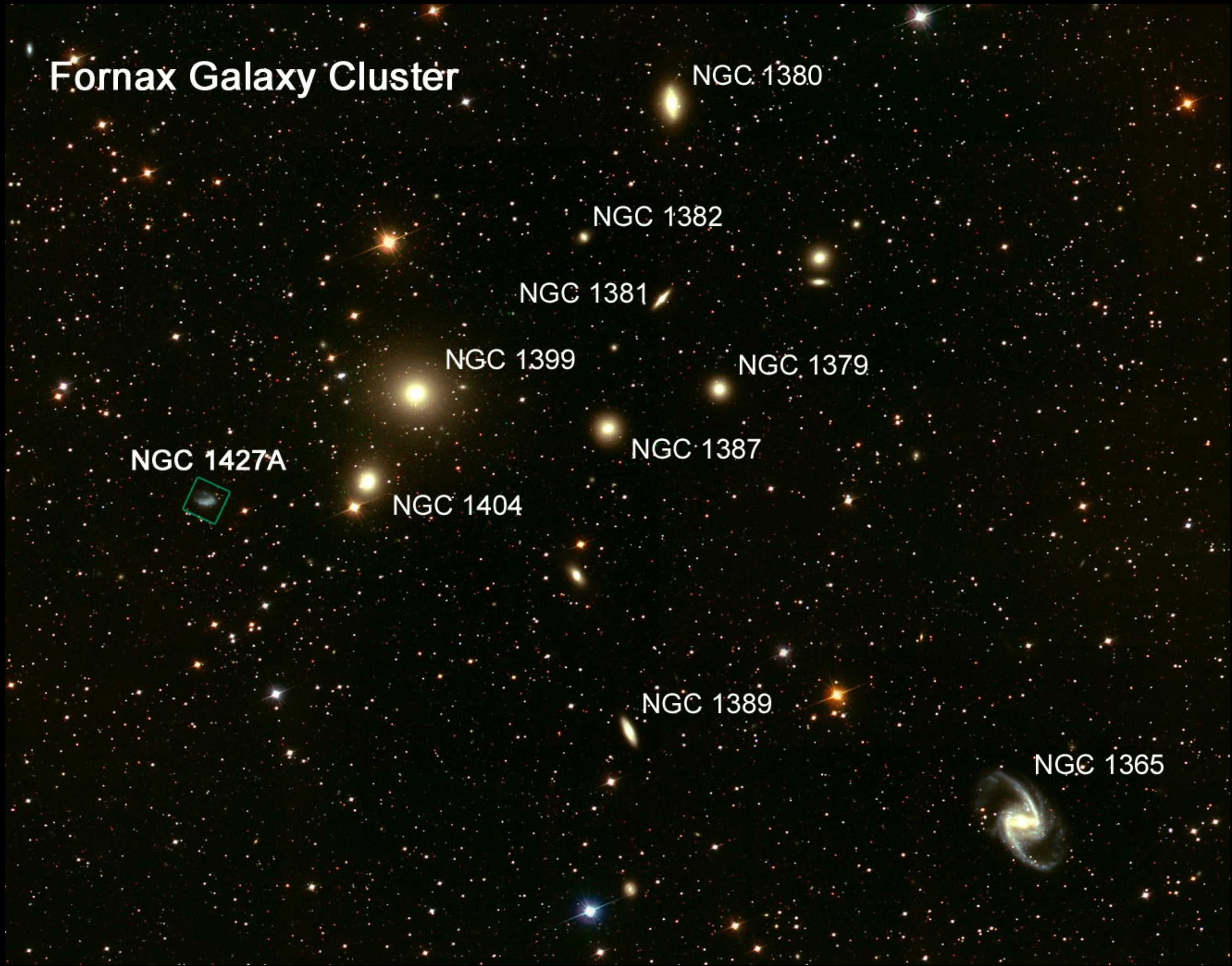
1929: Hubble finds that galaxies are moving away from us *faster* the *further away* they are.
The Universe is indeed expanding!

Edwin Hubble
(1889-1953)




By the end of the 1930s it was becoming evident that:
• There is more to the Universe than our Galaxy
• The Universe is expanding
• The expansion depends on the matter and energy content!

After Hubble's discovery, astronomers begun to study intensively distances and velocities of many astronomical objects.
Big **clusters of galaxies** were a prime target.



Hubble & Humason published redshifts of several galaxy clusters in 1931.
They noticed large variations in velocities within the Coma Cluster.

Fritz Zwicky was the first to apply viral theorem to the large variations in the velocity of galaxies within galaxy clusters: **is this telling us something about the cluster itself?**

The Redshift of Extragalactic Nebulae

by F. Zwicky.

(16.II.33.)

Contents. This paper gives a representation of the main characteristics of extragalactic nebulae and of the methods which served their exploration. In particular, the so called redshift of extragalactic nebulae is discussed in detail. Different theories which have been worked out in order to explain this important phenomenon will be discussed briefly. Finally it will be indicated to what degree the redshift promises to be important for the study of penetrating radiation.

For an isolated self-gravitating system,

$$2K + U = 0$$

$$K = \frac{1}{2} M \langle v^2 \rangle \qquad U = -\frac{\alpha G M^2}{\mathcal{R}}$$

$$M = \frac{\langle v^2 \rangle \mathcal{R}}{\alpha G}$$

$$\mathcal{M} > 9 \times 10^{46} \text{gr}$$

Fritz Zwicky was the first to understand something of these large variations in the velocity of galaxies within galaxy clusters: **is this telling us something about the cluster itself?**

The Redshift of Extragalactic Nebulae

by F. Zwicky.

(16.II.33.)

"In order to obtain the observed value of (velocity), the average density in the Coma system would have to be at least 400 times larger than that derived on the grounds of observations of luminous matter. If this would be confirmed **we would get the surprising result that *dark matter* is present in much greater amount than luminous matter** "

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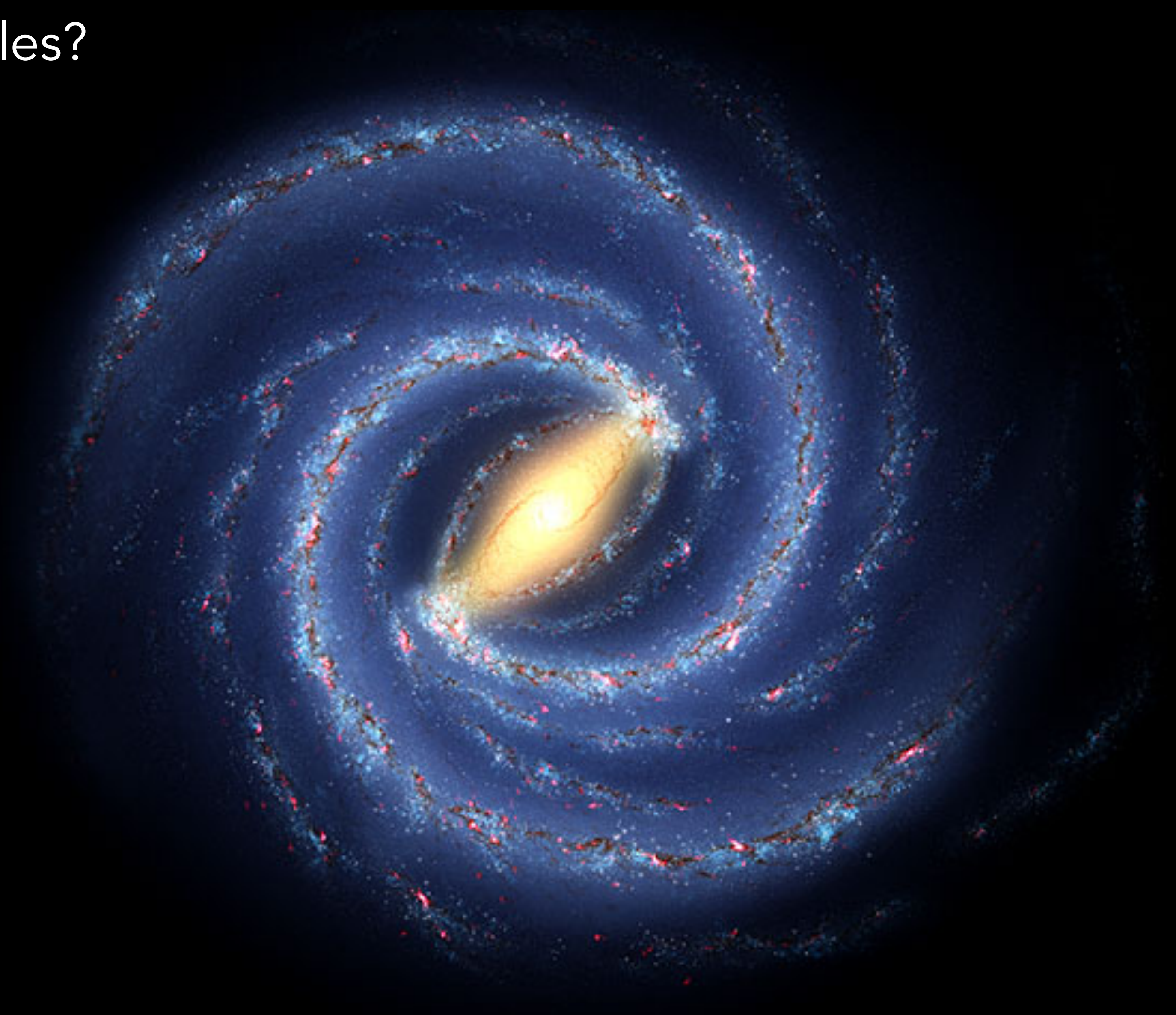
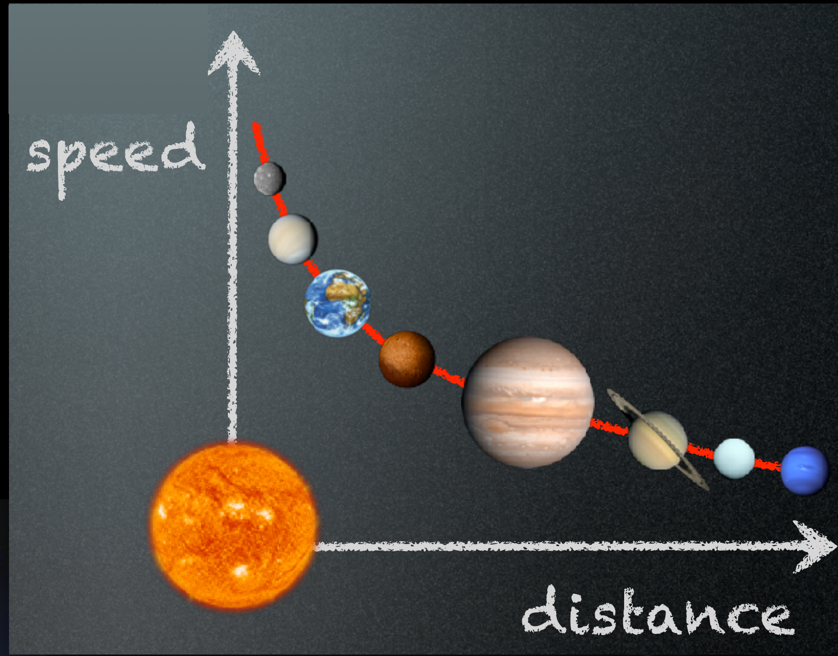
Zwicky was not taken seriously: the problem was just a "missing luminosity problem"

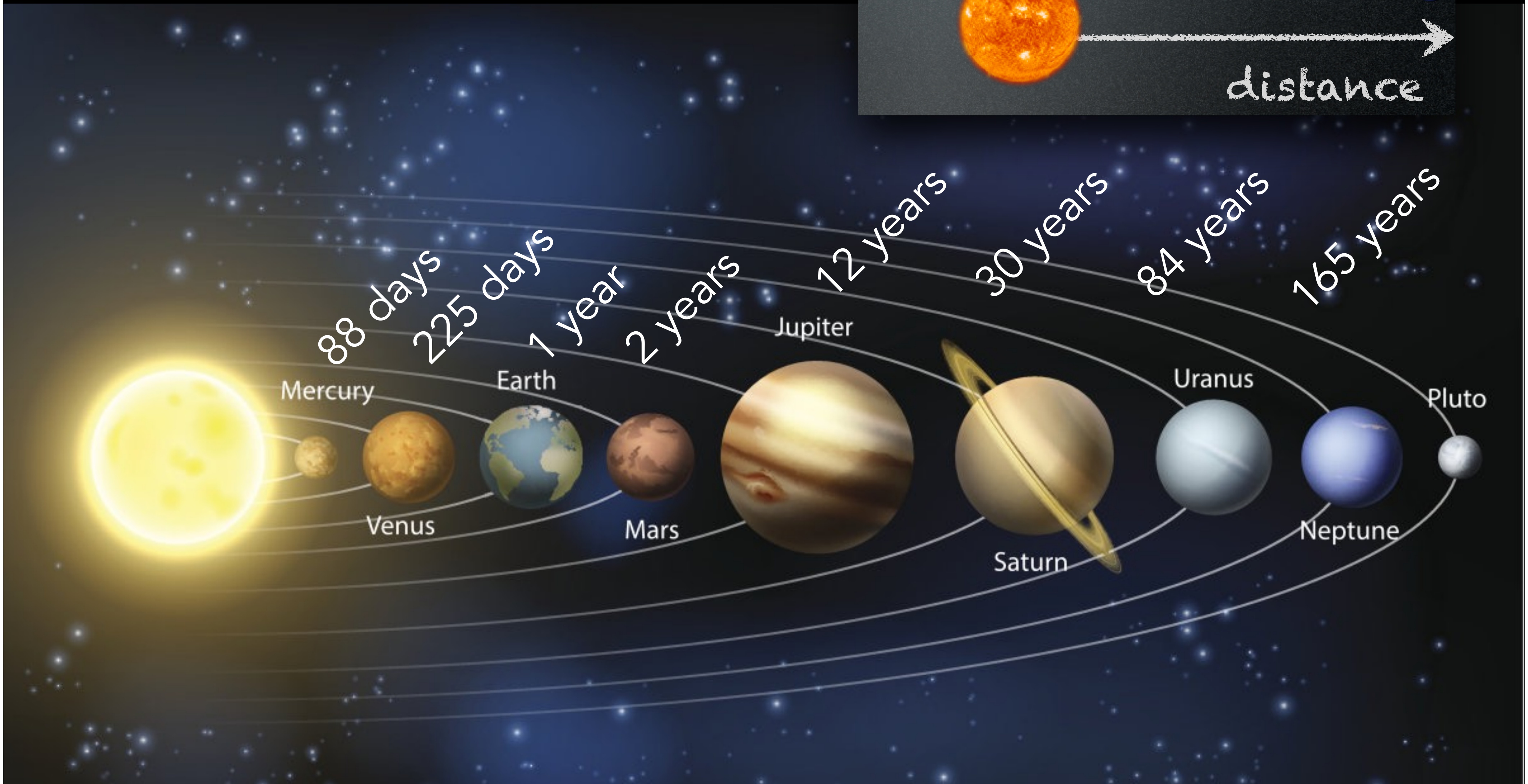
How about Galaxy scales?



While galaxies in a cluster move randomly, stars within galaxies exhibit **rotational** motion, similarly to the Solar System.

Kepler’s laws





All telescopes to Andromeda!

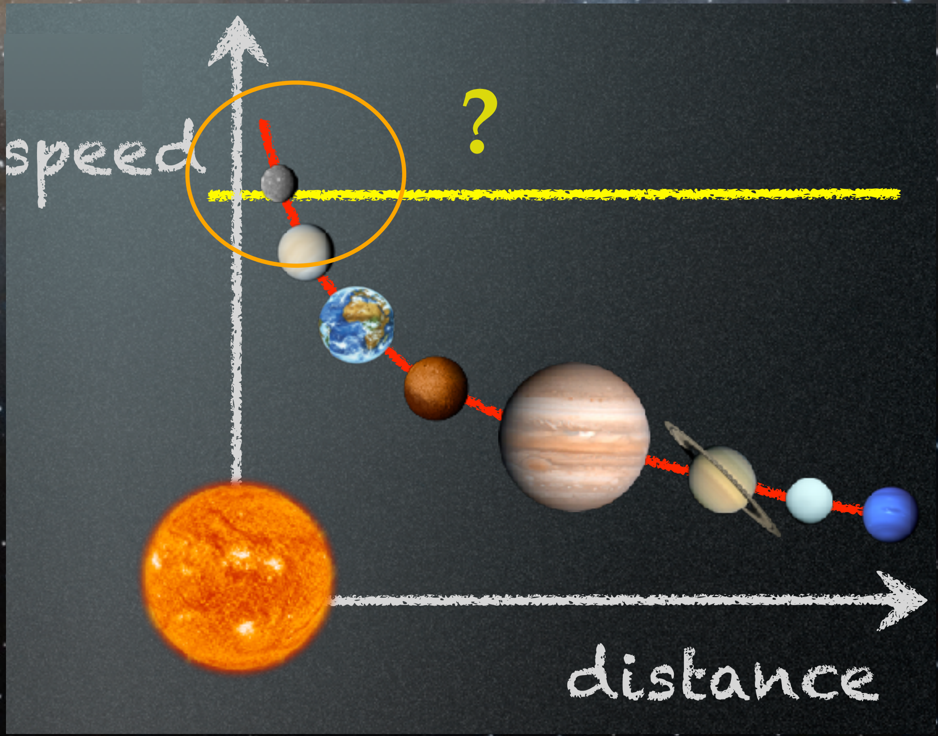
In 1939 Horace Babcock measures the rotation curves for Andromeda measuring a **constant angular velocity**!

THE ROTATION OF THE ANDROMEDA NEBULA*

BY

HORACE W. BABCOCK

core of the nebula, and the approach to constant angular velocity discovered for the outer spiral arms is hardly to be anticipated from current theories of galactic rotation.



Measurement still not precise enough and performed only close-by the centre of Andromeda.

After the II word war, left-over radars help revolutionise astronomy

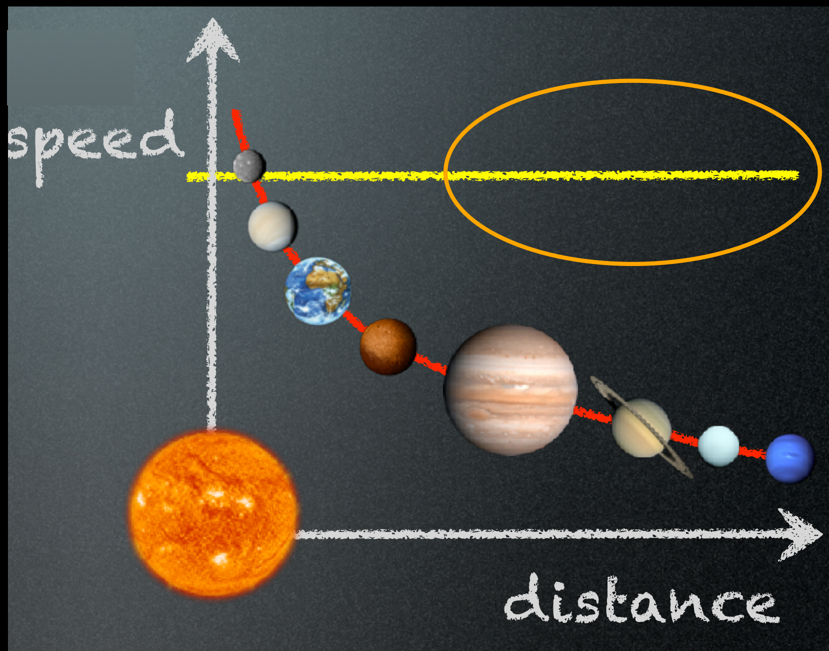
Van de Hulst at Dwingeloo

Hydrogen atoms emit a **21-cm radio signal**.

Most of the gas in the Universe is made of atomic H — 21cm a powerful probe!

That meant that one could measure gas velocity accurately and much farther from the centre of Andromeda!

Van de Hulst gave the first 21cm map of Andromeda in **1957** showing that the velocities stays constant much far away from the visible region.



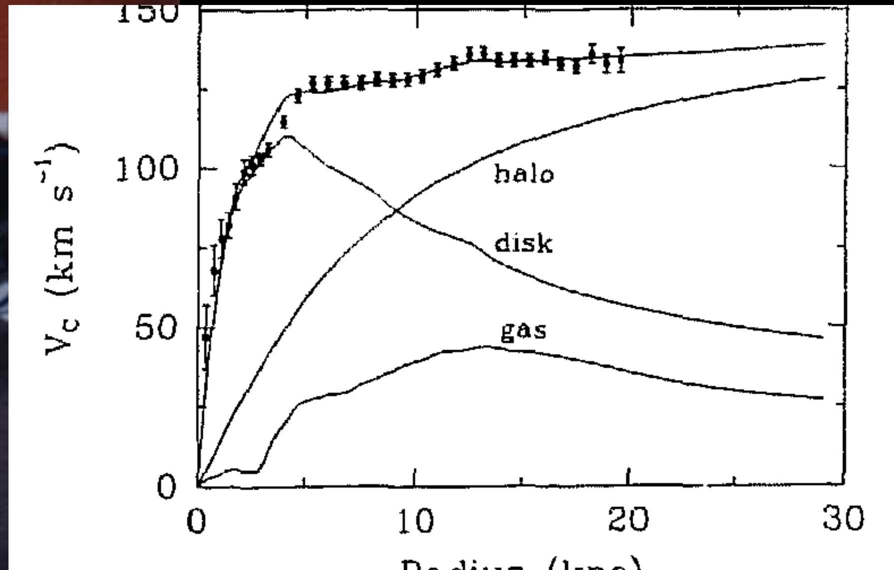
THE 1970s REVOLUTION

the invention of spectrograph by Kent Ford in the 1960s

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

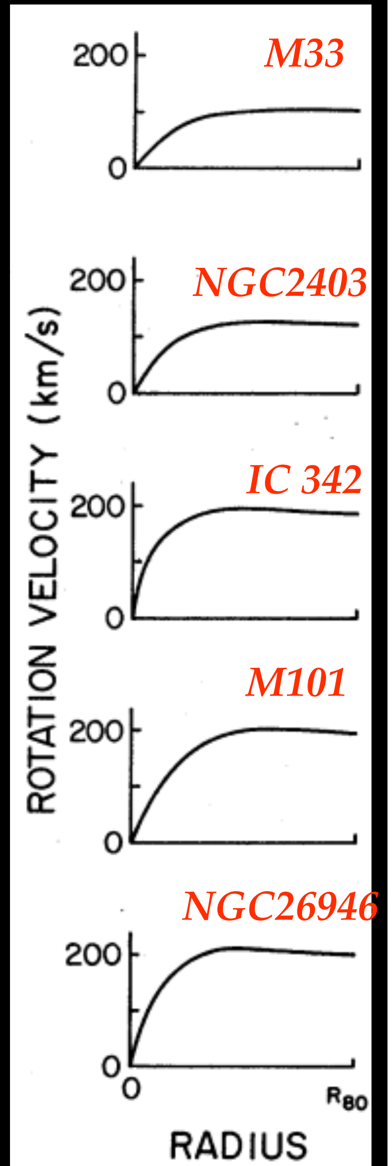
VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

Received 1969 July 7; revised 1969 August 21



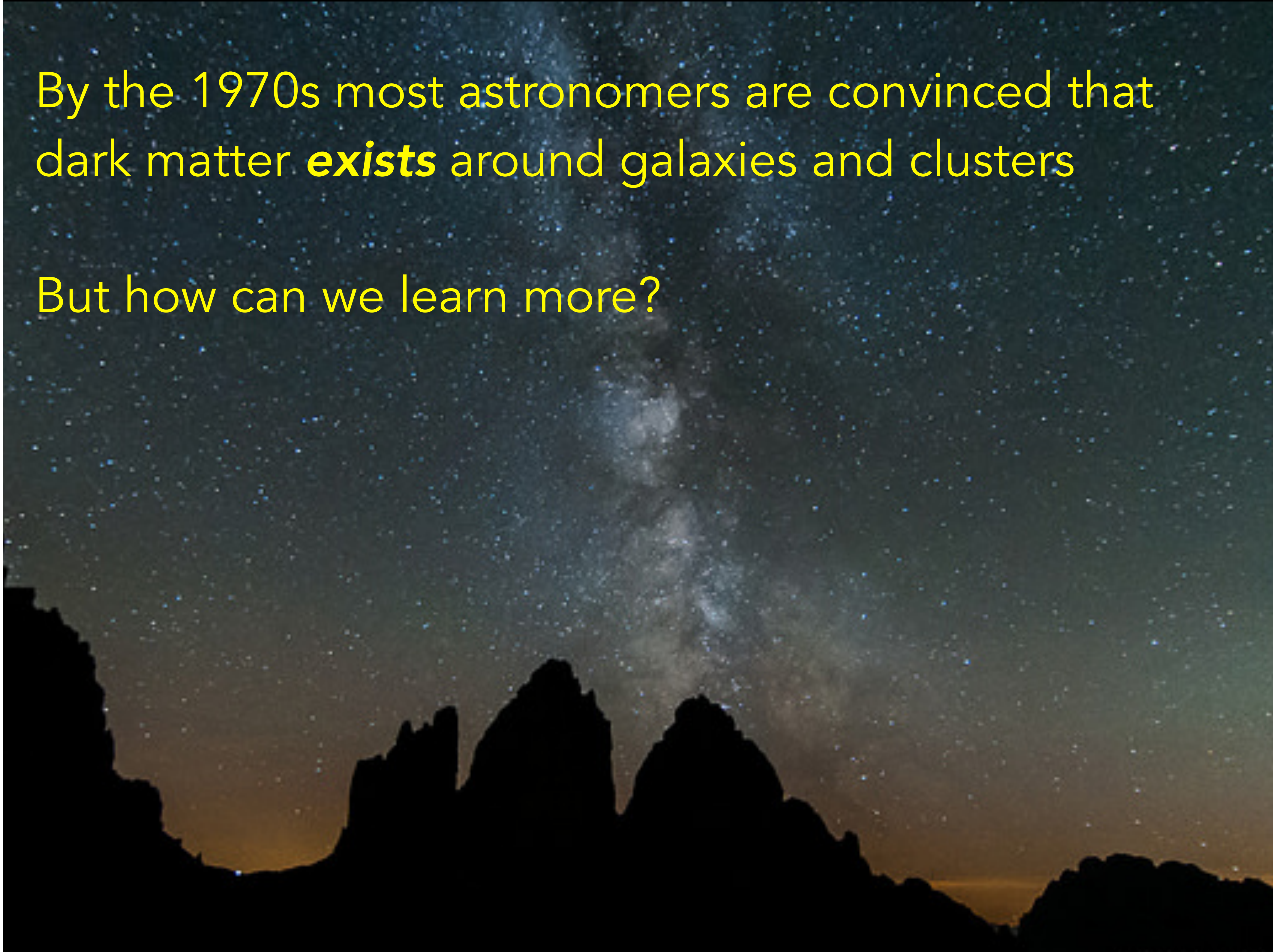
K.G. Begeman thesis

Flat rotation curves began to emerge clearly from 21 cm observations.
Five galaxies as obtained by Rogstad and Shostak in 1972.



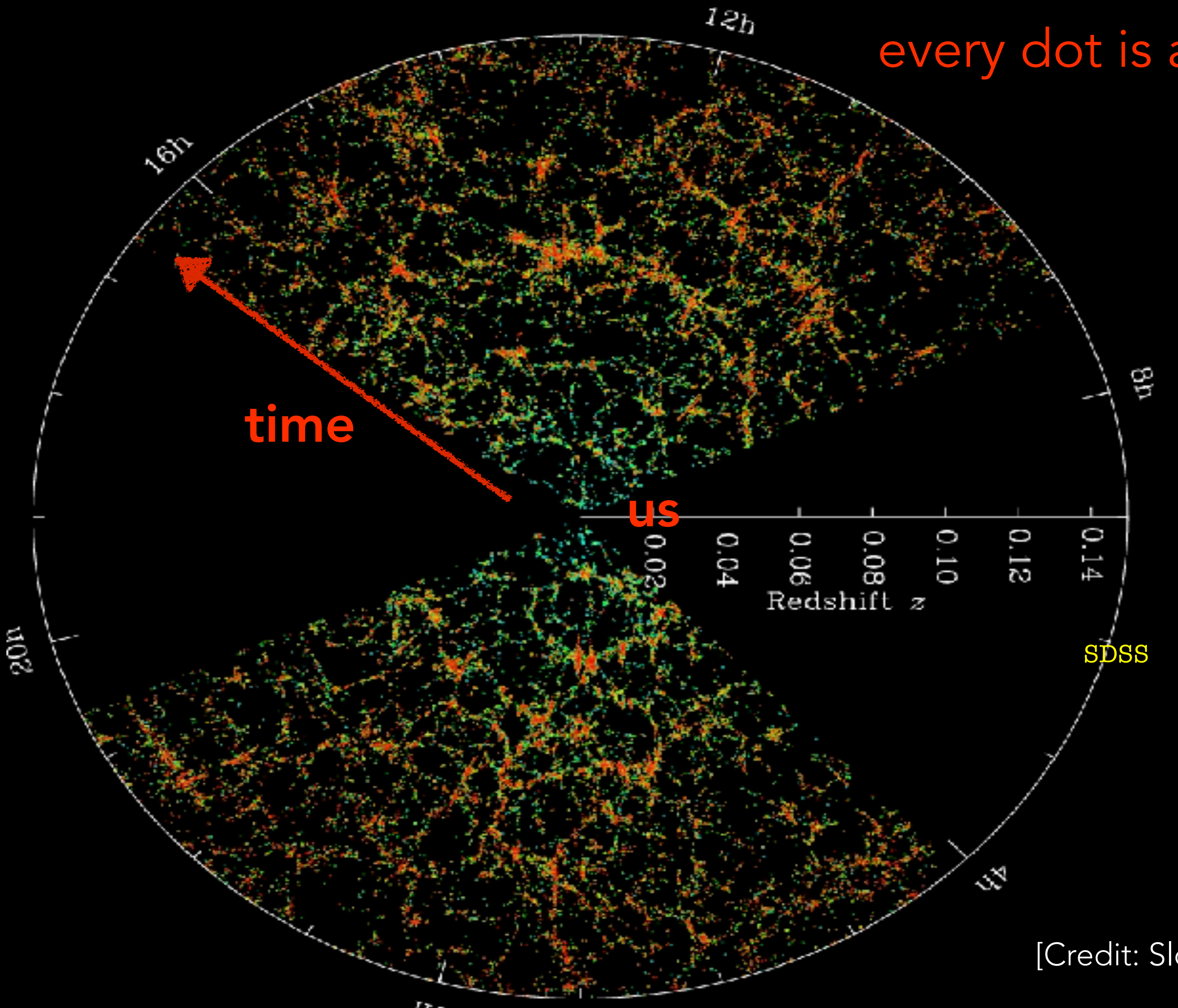
By the 1970s most astronomers are convinced that dark matter ***exists*** around galaxies and clusters

But how can we learn more?



LOOKING BACK IN TIME

By the 90s, telescopes were able to test bigger portions of the sky and study ***the distribution*** of Galaxies

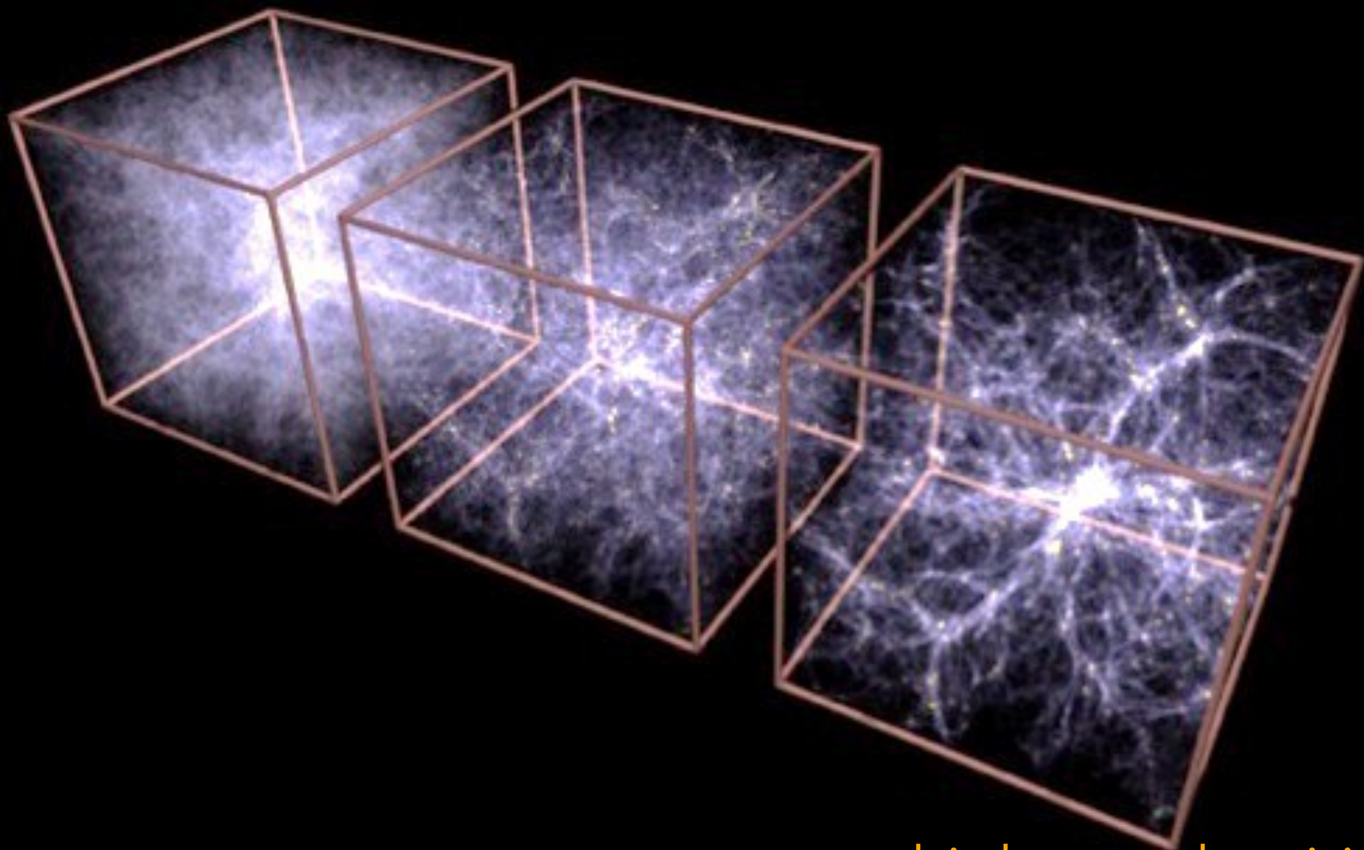


[Credit: Sloan digital sky survey]

LOOKING BACK IN TIME

Many people thought the early universe was complex.
But Zel'dovich assumed that it is fundamentally simple, with just gravity at work starting from small inhomogeneities at the dawn of time.

homogenous
early universe

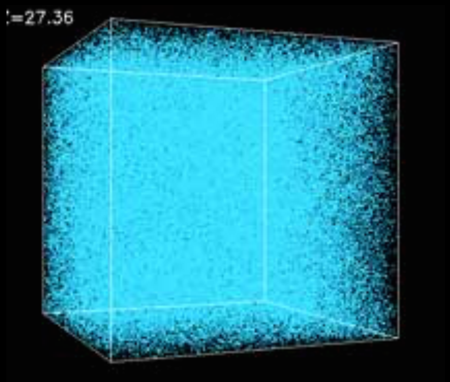


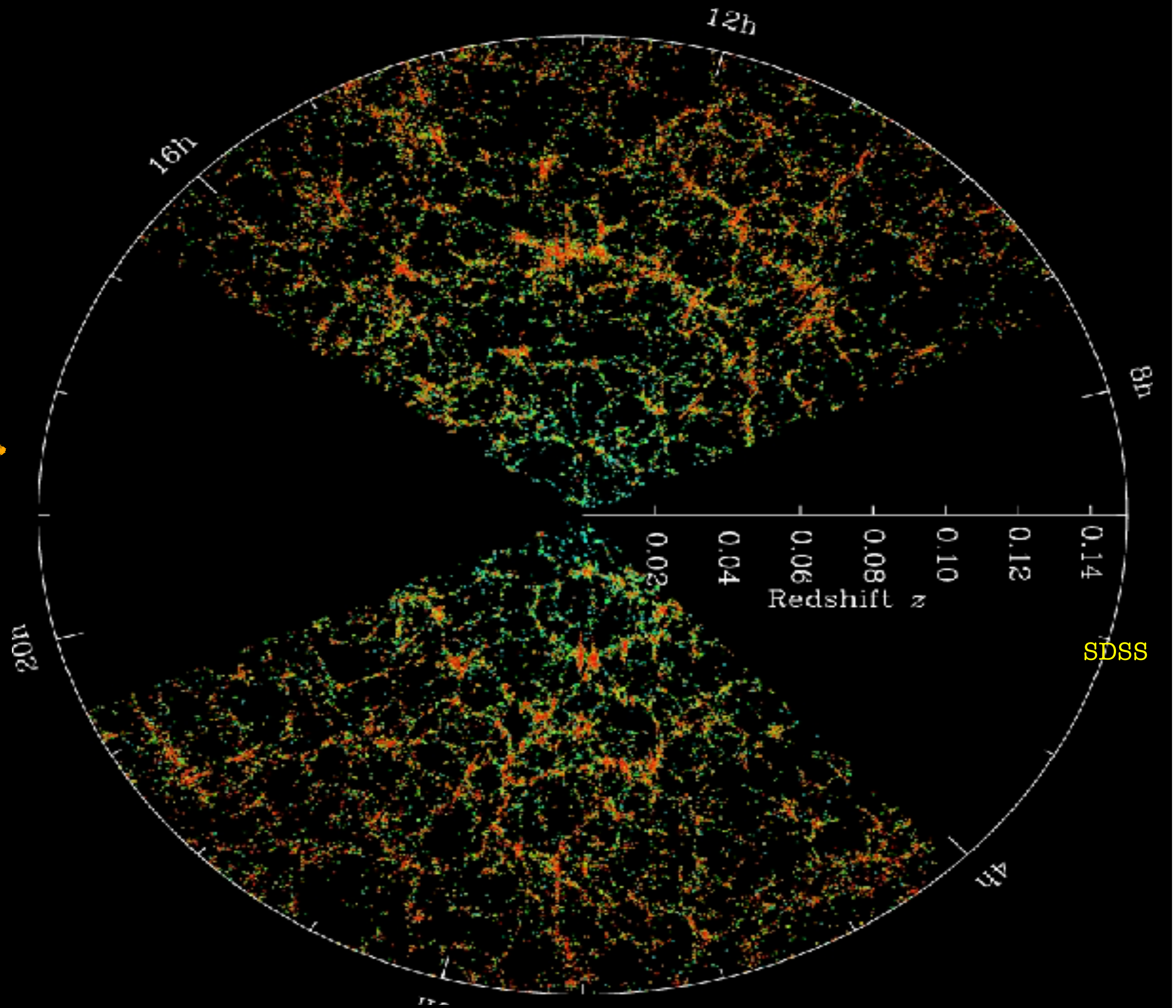
high overdensities
@present day

LOOKING BACK IN TIME

In time, we were able to test this conjecture as computers got powerful enough to simulate the formation of structures starting from the early Universe

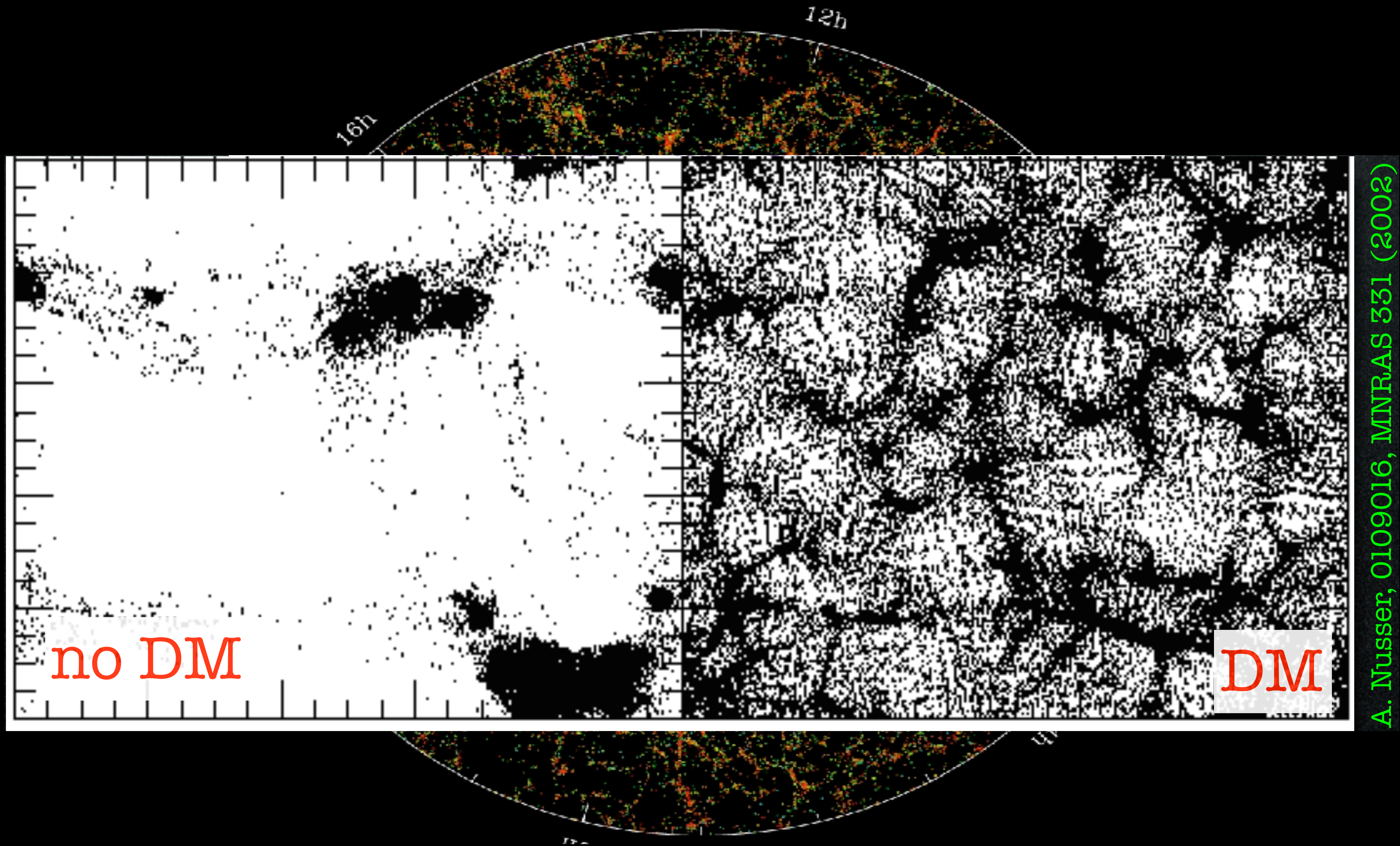
homogenous
early universe





LOOKING BACK IN TIME

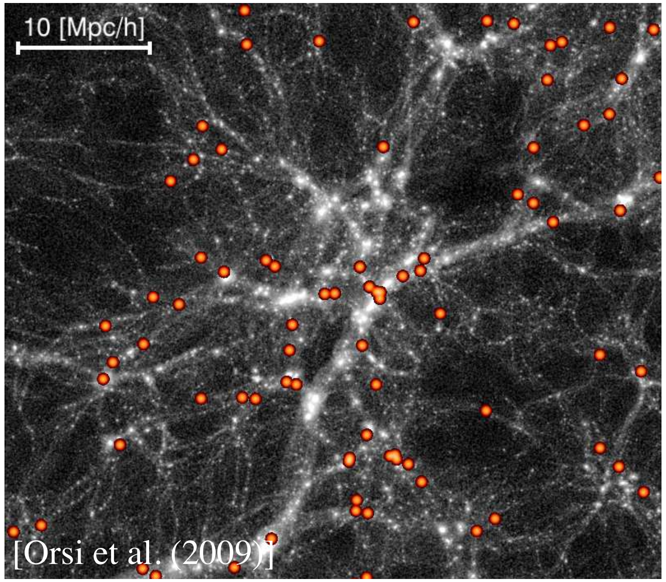
At the beginning of 2000s this ‘precision cosmology’ spectacularly confirmed that dark matter makes up majority of the mass in our Universe!



Summary:

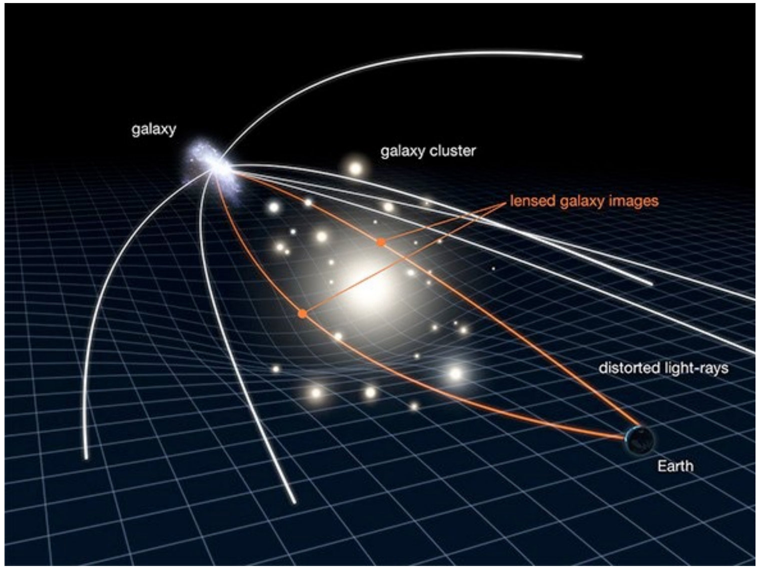
- evidence on a wide range of scales
- and throughout the history of the Universe

large scale structures



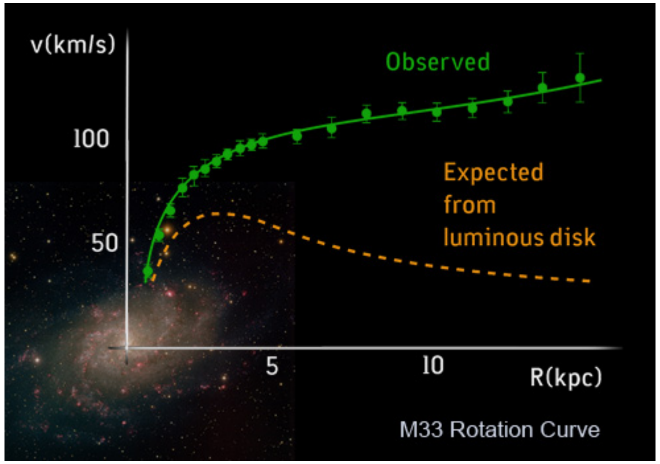
10s Mpc

clusters of galaxies



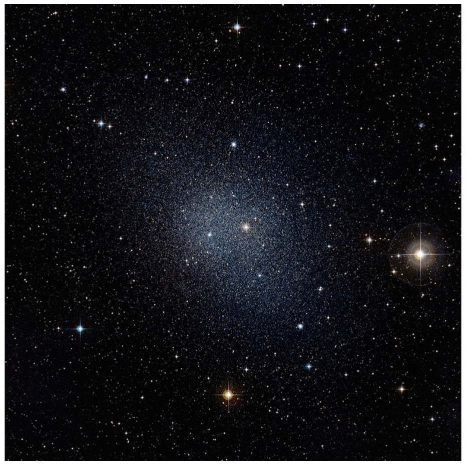
Mpc

Milky Way-sized galaxies



10s kpc

dwarf galaxies

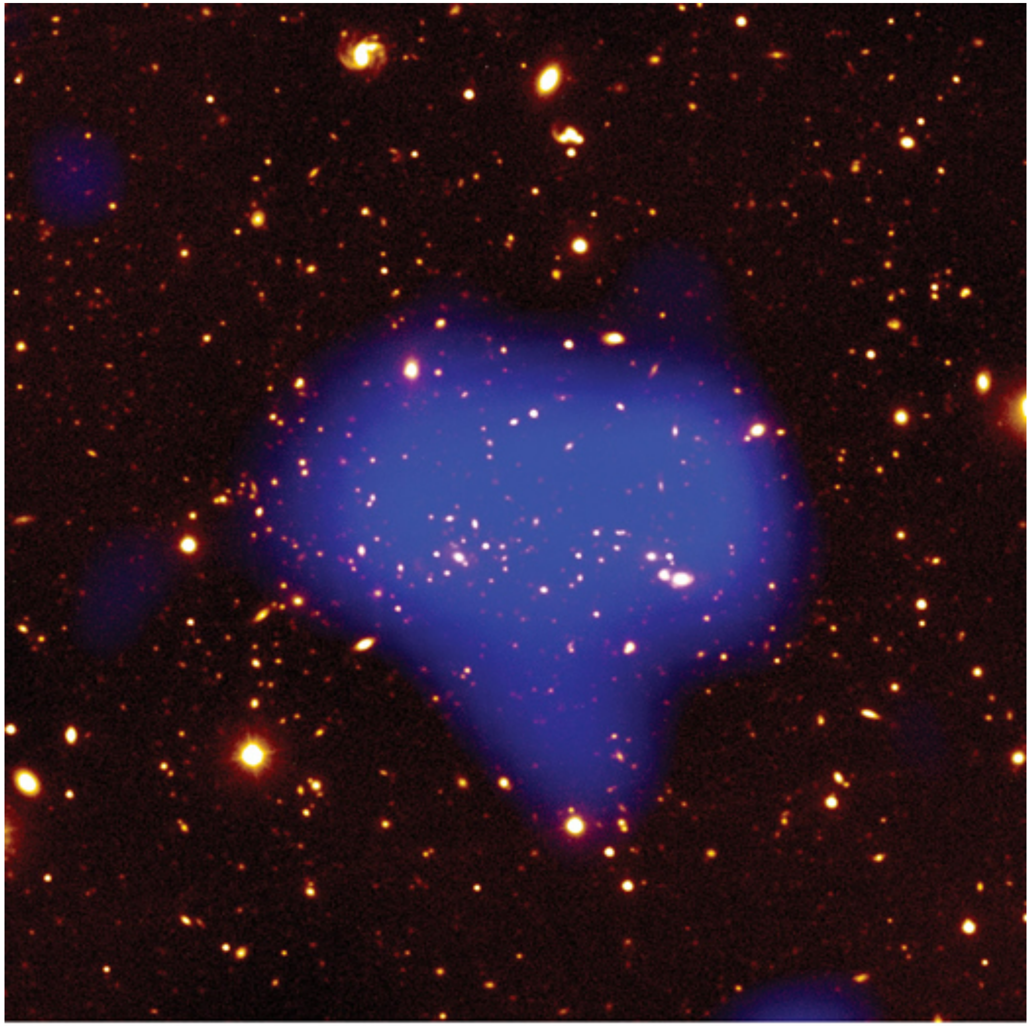


<~ kpc

Evidence for DM presence:

- velocity dispersion in galaxy clusters
- rotational curves in spiral galaxies
- properties of large scale galaxy distribution
- weak lensing in galaxy clusters
- CMB

- Further evidence from Galaxy clusters: 02) temperature of the hot gas

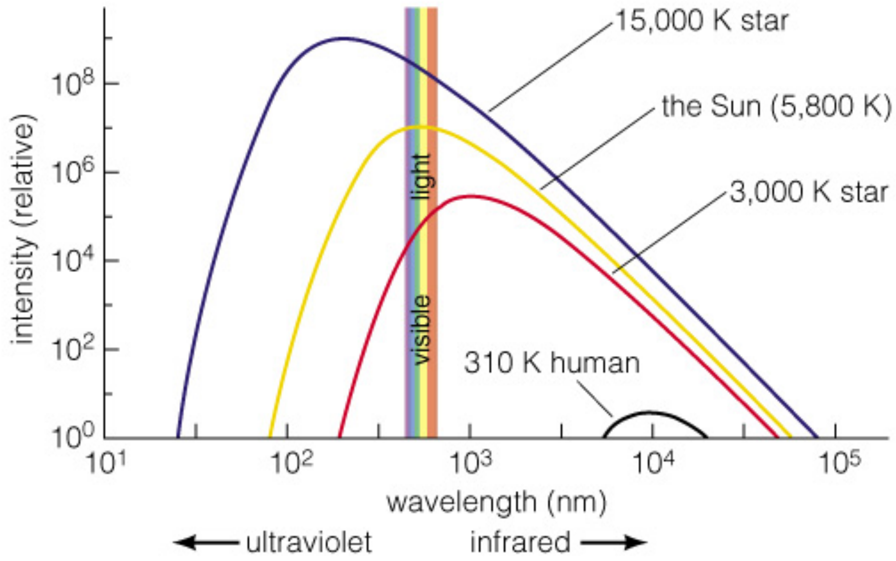


A distant cluster of Galaxies in both, visible, and X-ray light (the blue overlay).

2) Clusters contain large amounts of gas. The gas is extremely hot (100 million Kelvin) and it therefore emits very energetic, X ray photons:

- Further evidence from Galaxy clusters: 02) temperature of the hot gas

Radiation of a hot gas tells us cluster mass. How does that work:



Thermal radiation spectrum

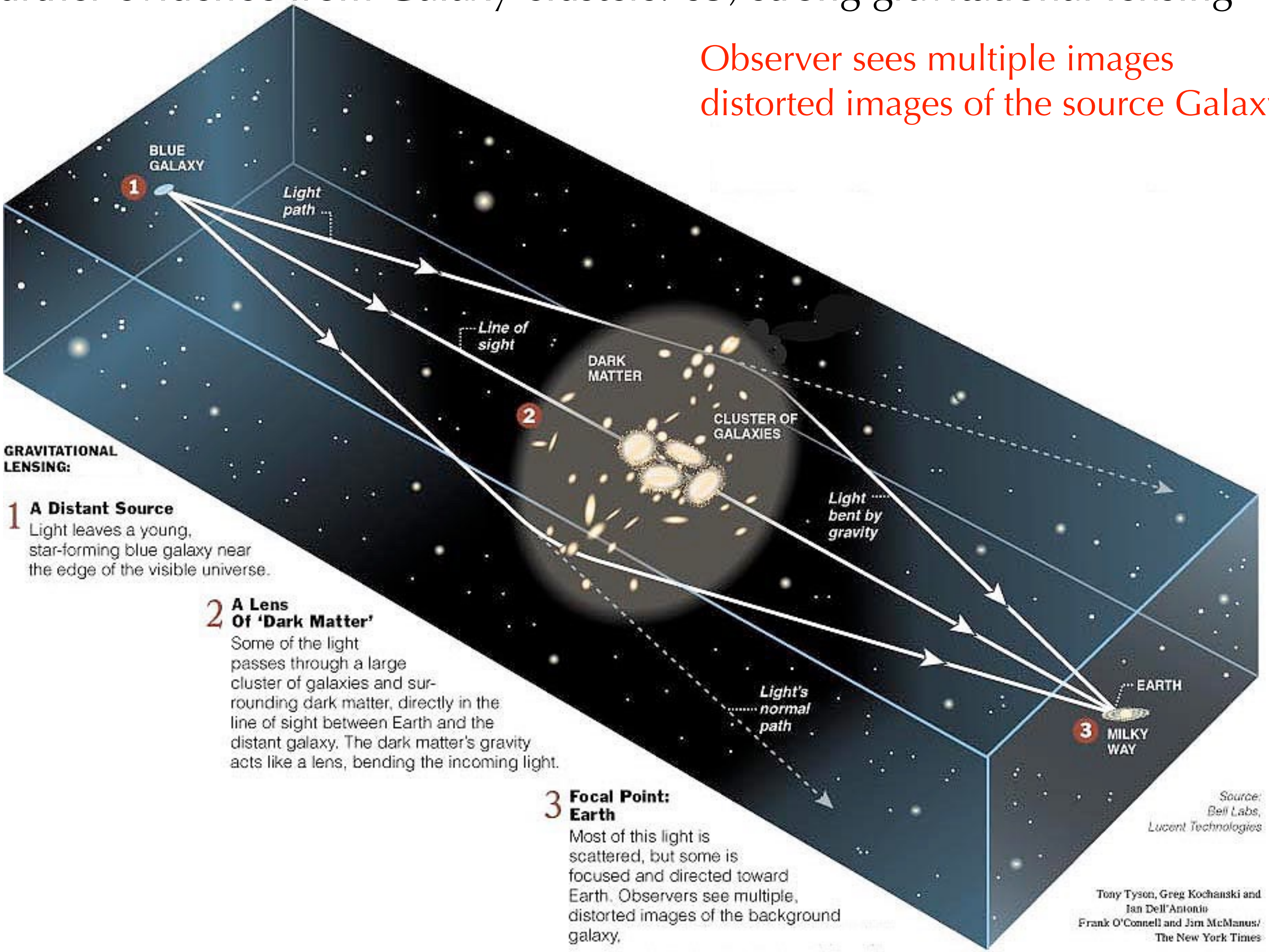
How fast molecules of gas are moving is connected to the amount of gravity they feel: ***stronger the gravity, faster the gas is moving and hotter it is.***

And, we can measure its *temperature* by measuring the *spectrum of photons* the gas emits!

And again, it turns out, dark matter has to be around.

- Further evidence from Galaxy clusters: 03) strong gravitational lensing

Observer sees multiple images
distorted images of the source Galaxy.



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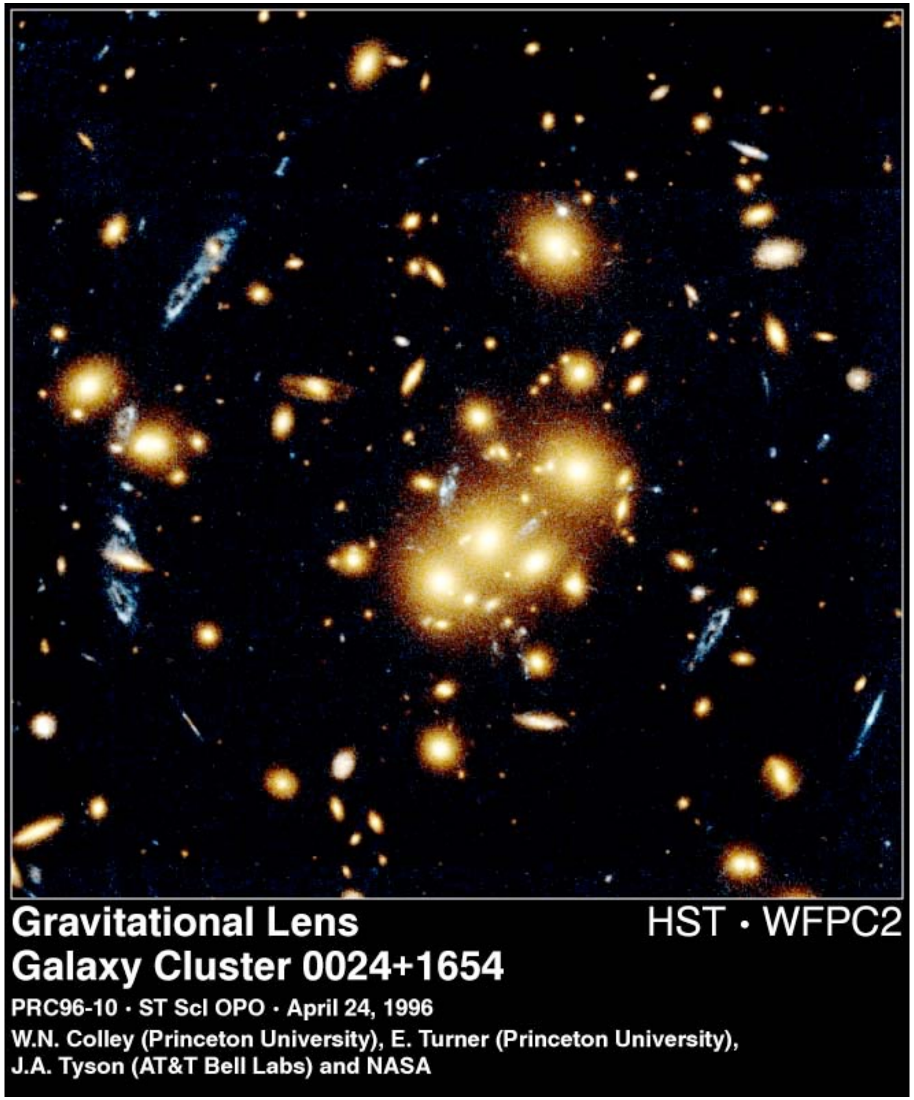


The cluster galaxies are the yellowish ones.

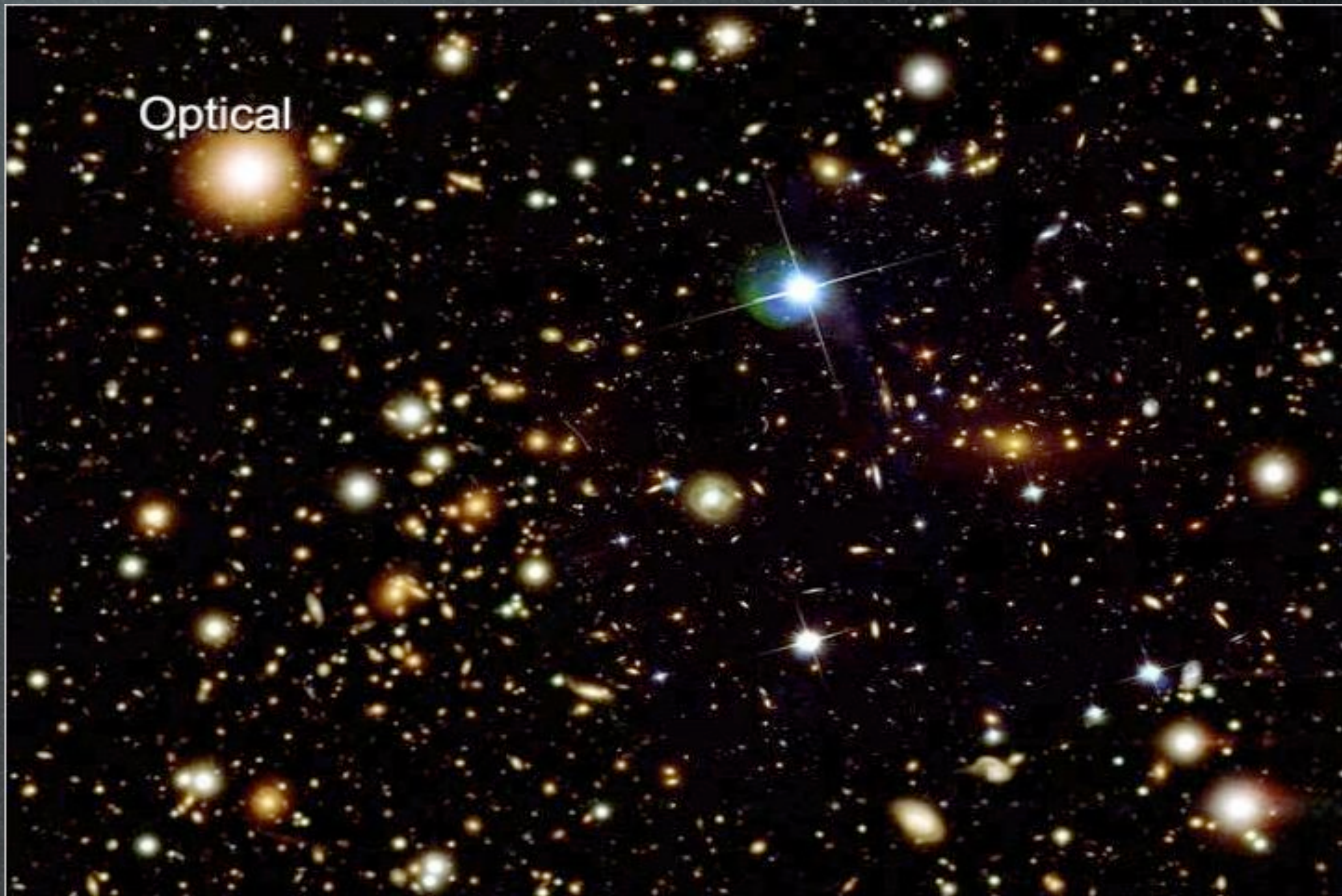
The faint blue galaxies are distant high-redshift galaxies that are lensed by the cluster (this radiation is redshifted to appear blue to us).

Four multiple images of a Blue Source Galaxy!

The mass of stars and hot gas in these clusters is too small to bend the light from the background galaxies so much.

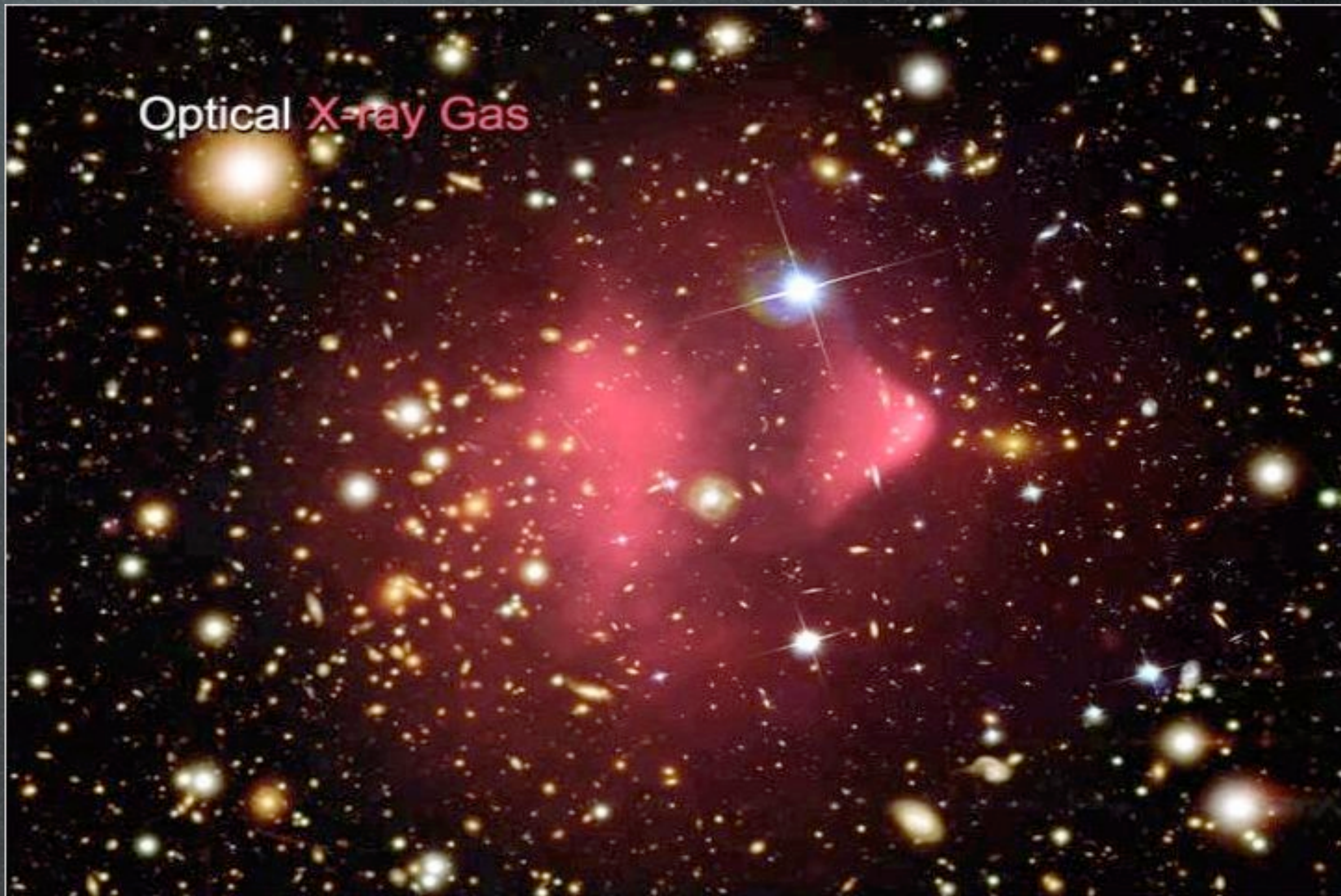
A great concentration of dark matter in the cluster centers is required to give these dramatic lensing events.

- Further evidence from Galaxy clusters: bullet cluster



“bullet cluster” - NASA
astro-ph/0608247

- Further evidence from Galaxy clusters: bullet cluster



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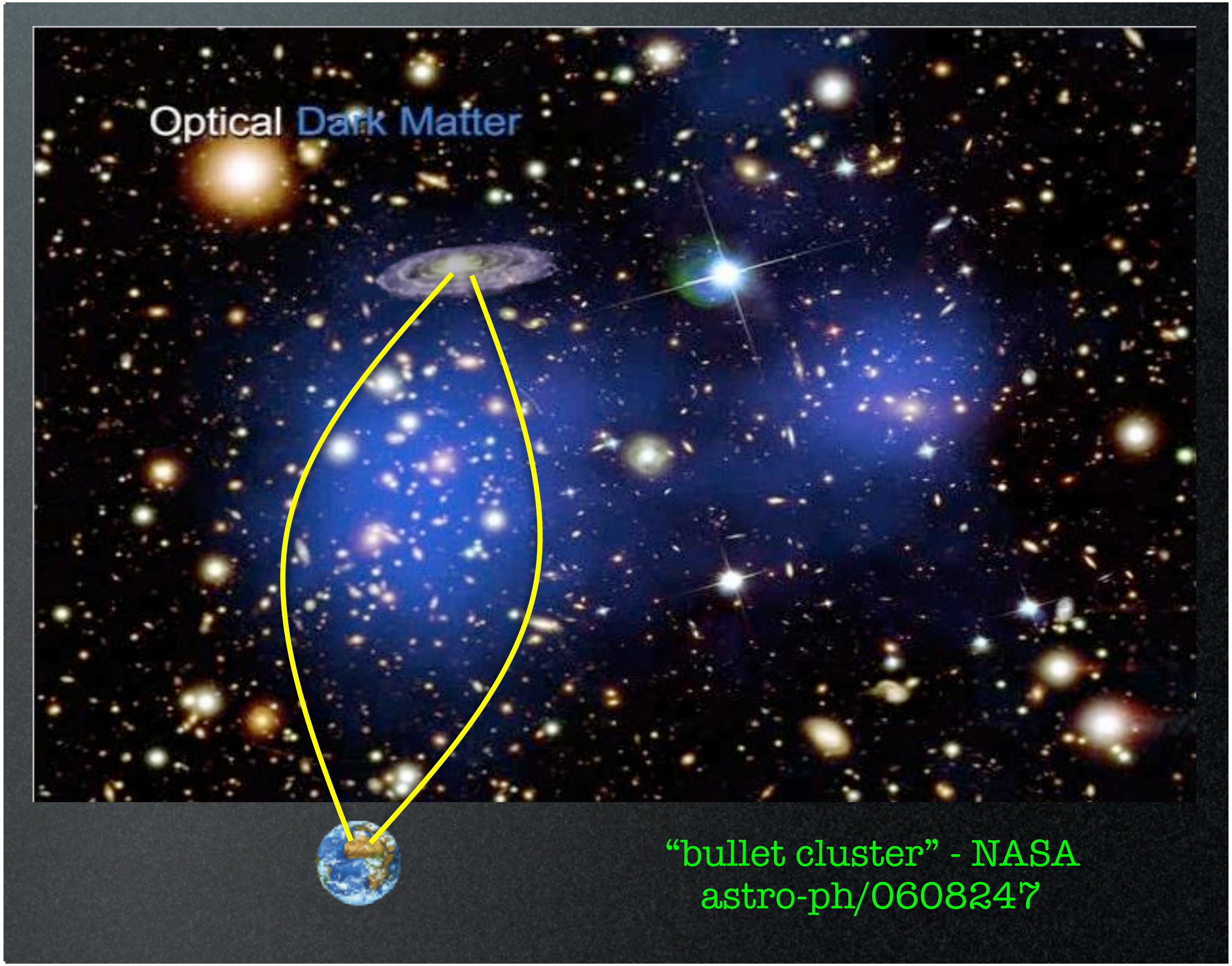


• Further evidence from Galaxy clusters: bullet cluster

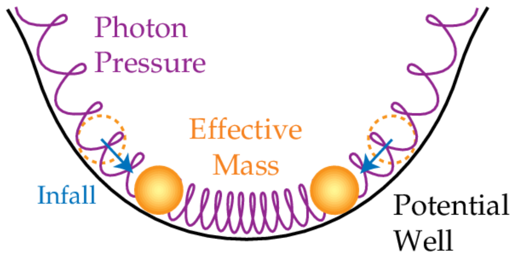
"bullet cluster" - NASA
astro-ph/0608247

[further developments]

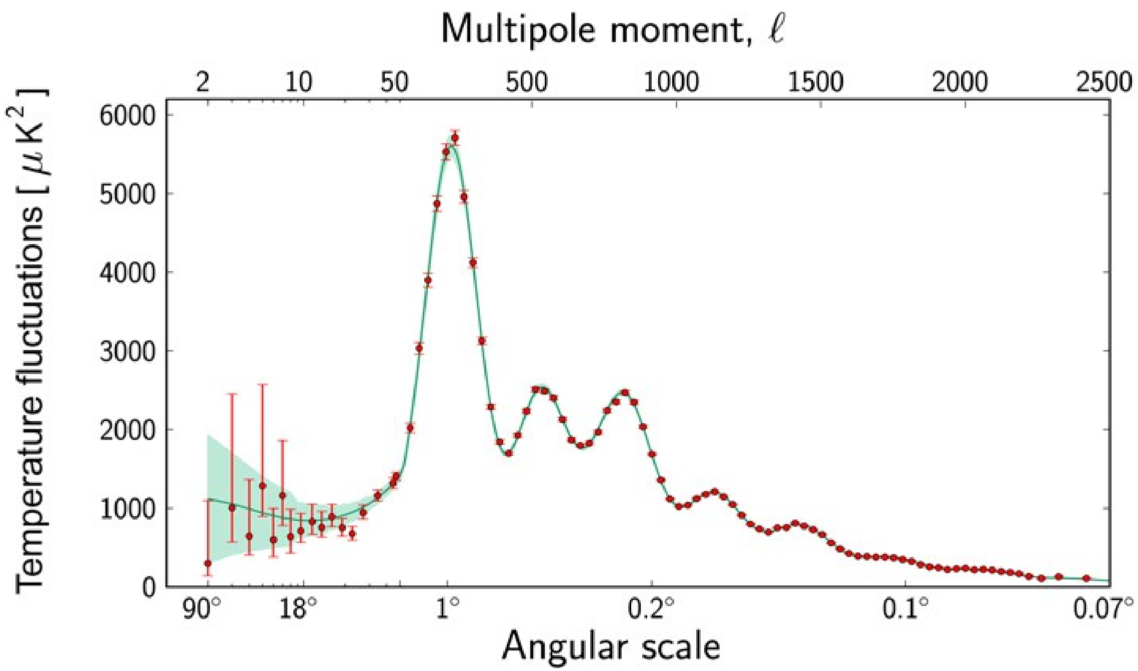
Summary:

- evidence for presence on a wide range of scales: from dwarf galaxies (106 Msol) to clusters (10^15 Msol) -- local Universe.
- and throughout the history of the Universe of matter on large scales.

CMB
angular power spectrum

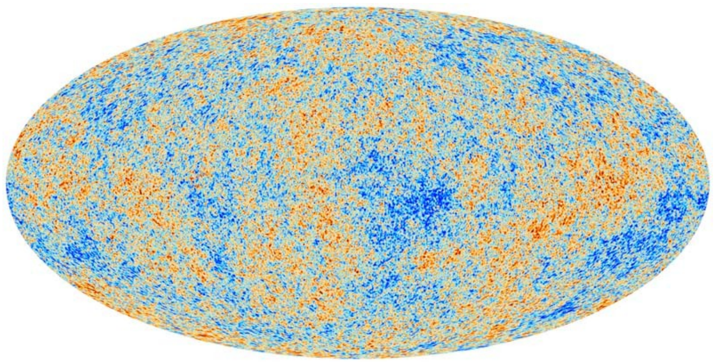


Credit: Wayne Hu



Planck Mission

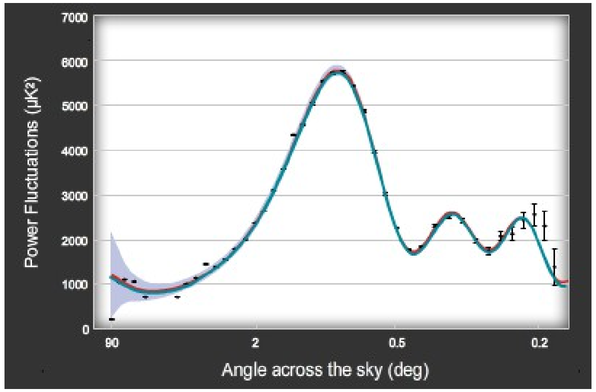
Cosmic microwave background anisotropies

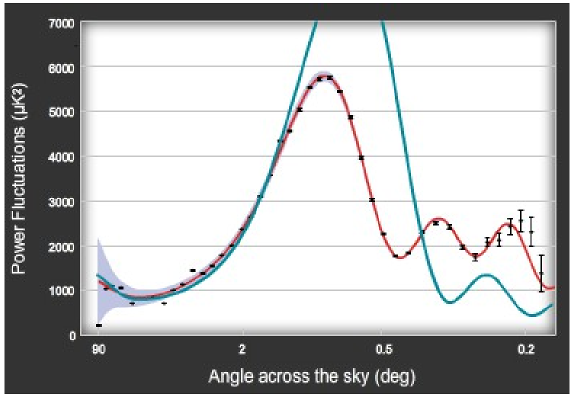


Planck Mission

- but the story holds together only if dark matter is also present. The story works and it has been tested by observing the spectra of i) both the CMB

http://lambda.gsfc.nasa.gov/education/cmb_plotter/

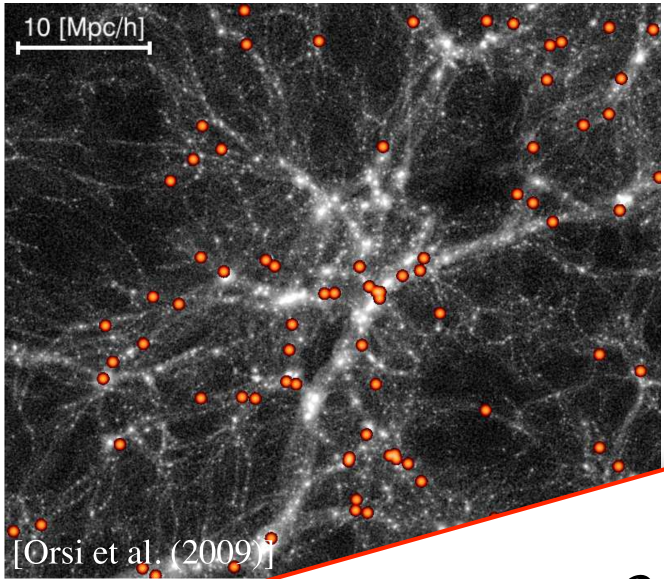




Dark matter is out there!

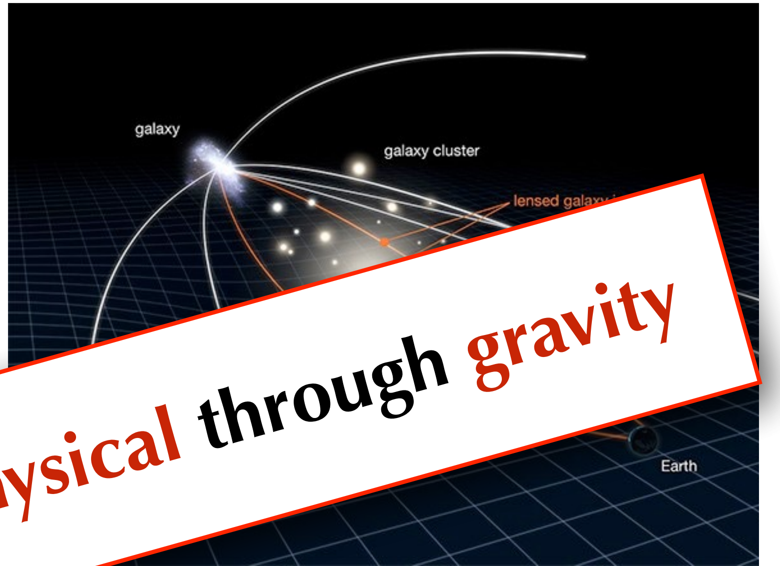
an essential building block of the Standard Model of Cosmology

large scale structures



10s Mpc

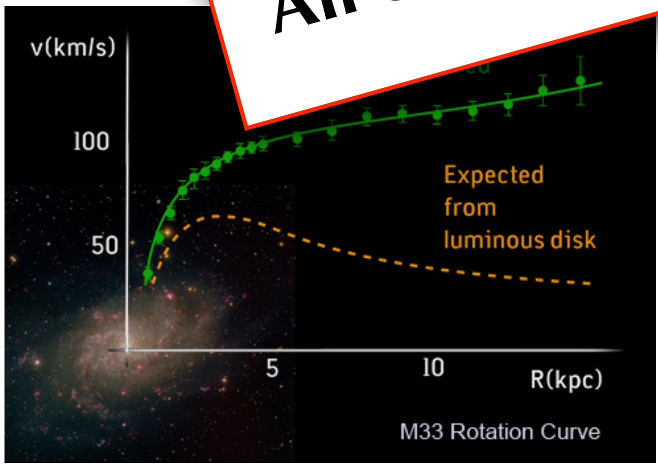
clusters of galaxies



Mpc

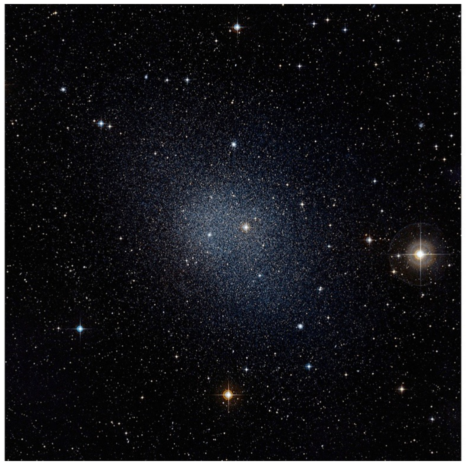
All evidence is astrophysical through gravity

Milky W



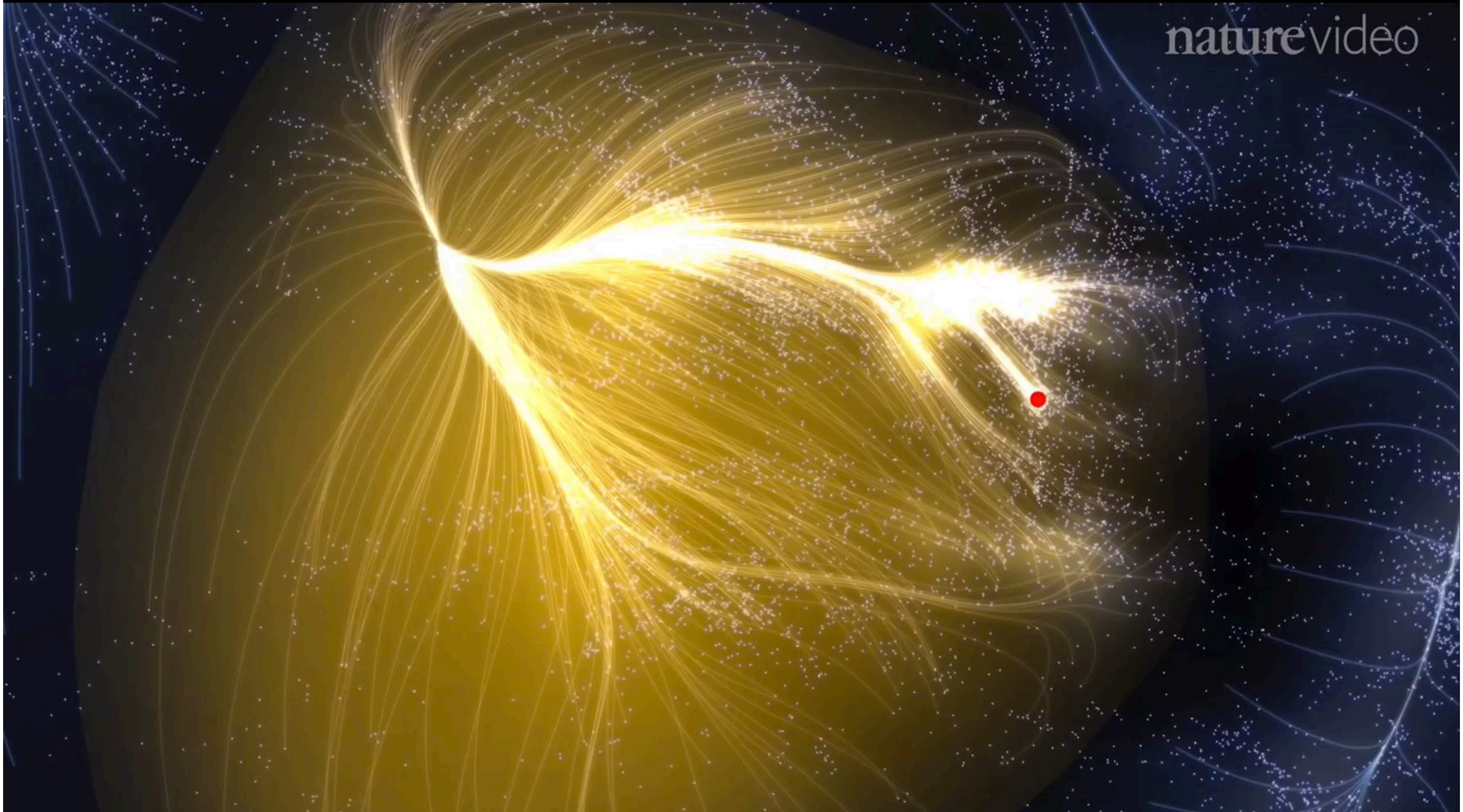
10s kpc

dwarf galaxies

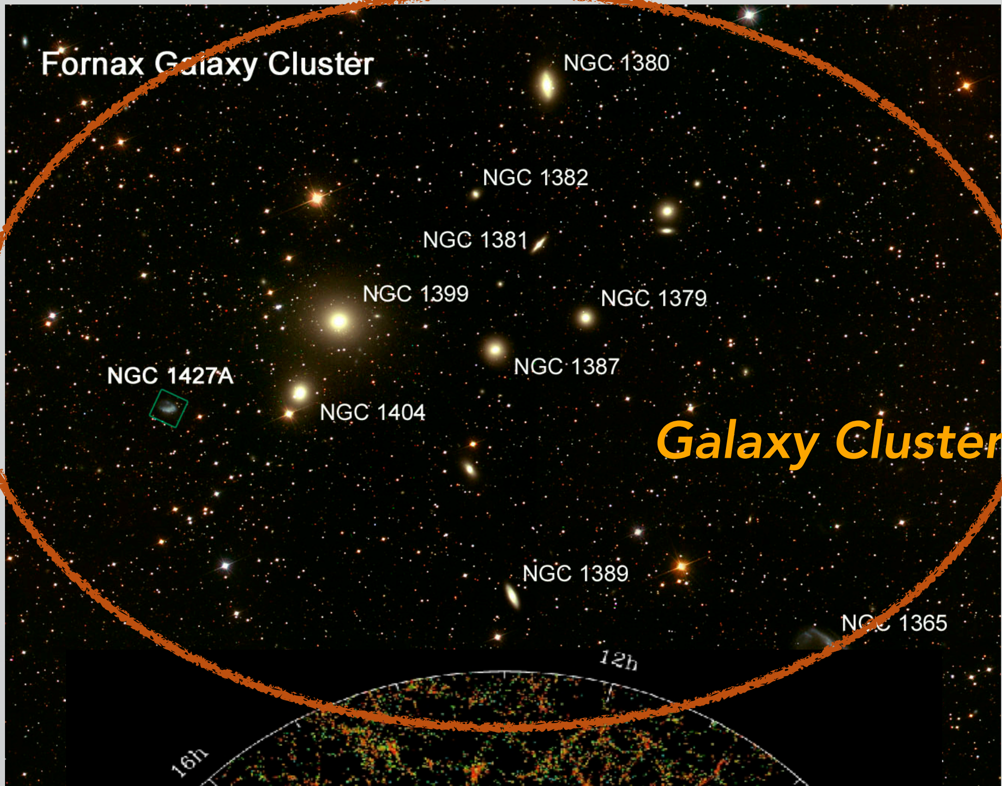


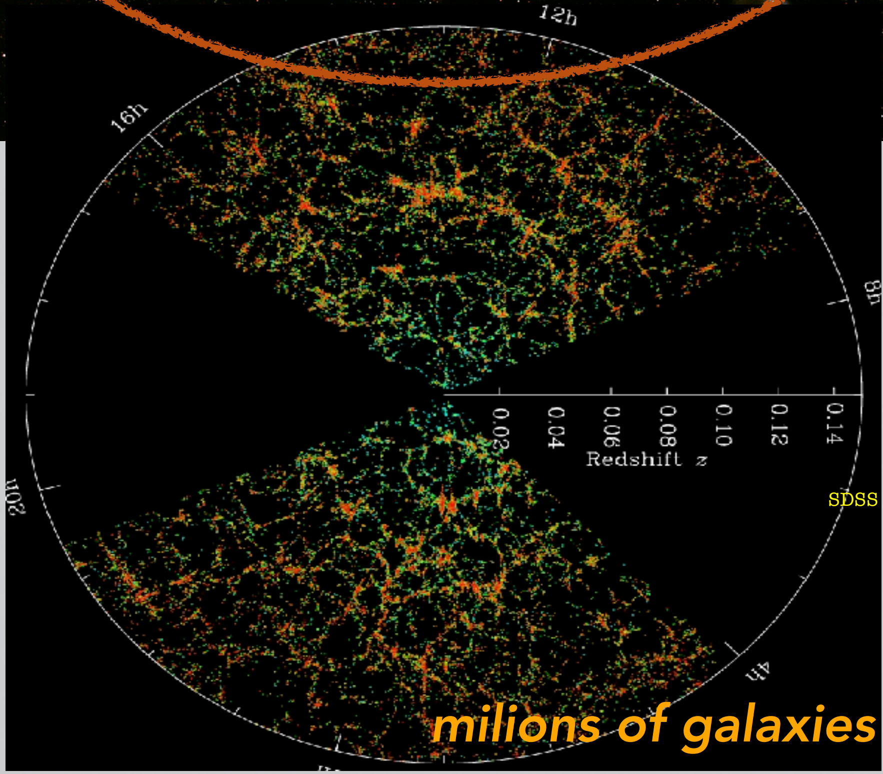
<~ kpc

Lanieakea - "immeasurable heaven"



WHAT DO WE KNOW SO FAR?





'see through' ➜ **neutral**!

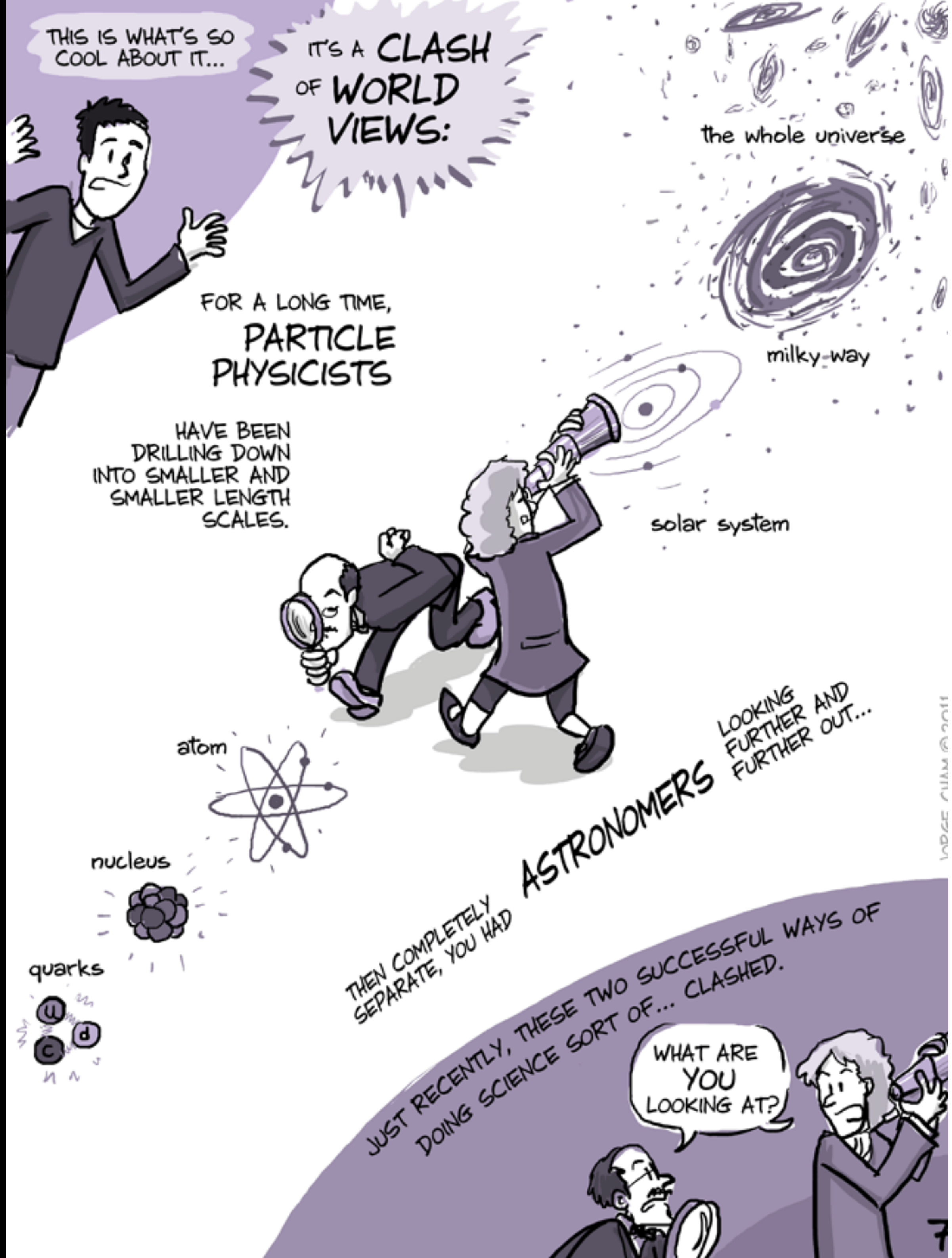
stable ➜ it was present throughout history of Universe

+ not observed at Earth ➜ only **feeble interactions**

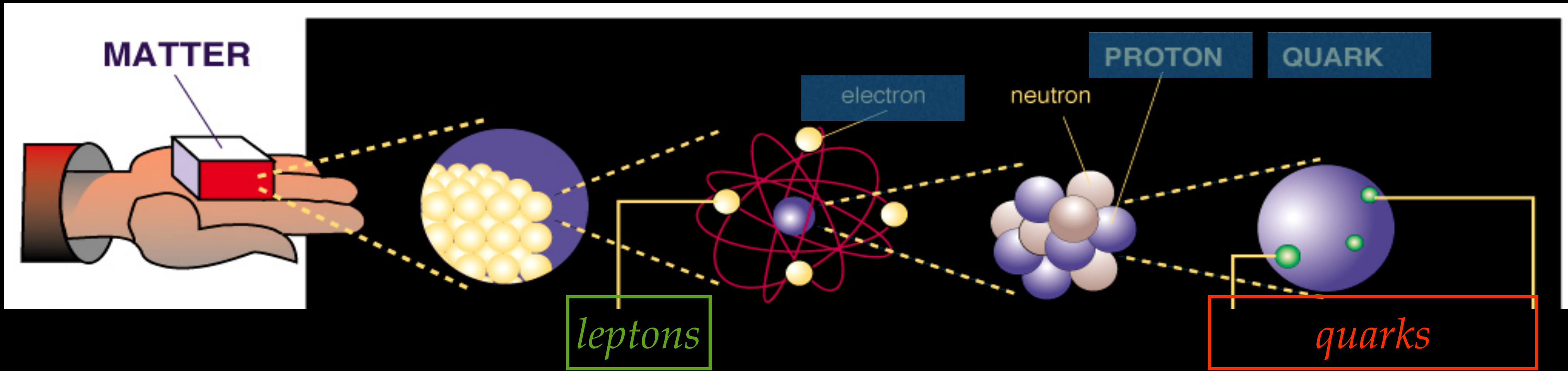
slow moving ➜ **heavy**

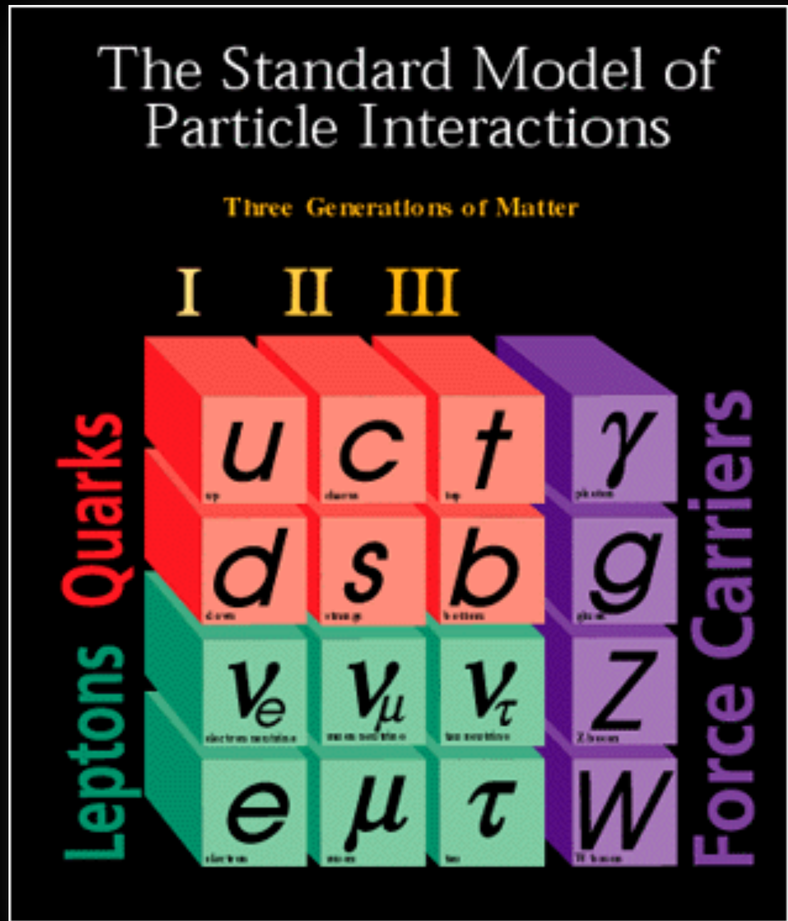
5-6 times more abundant than usual matter

COULD IT BE SOME PARTICLE WE KNOW?



COULD IT BE SOME PARTICLE WE KNOW?





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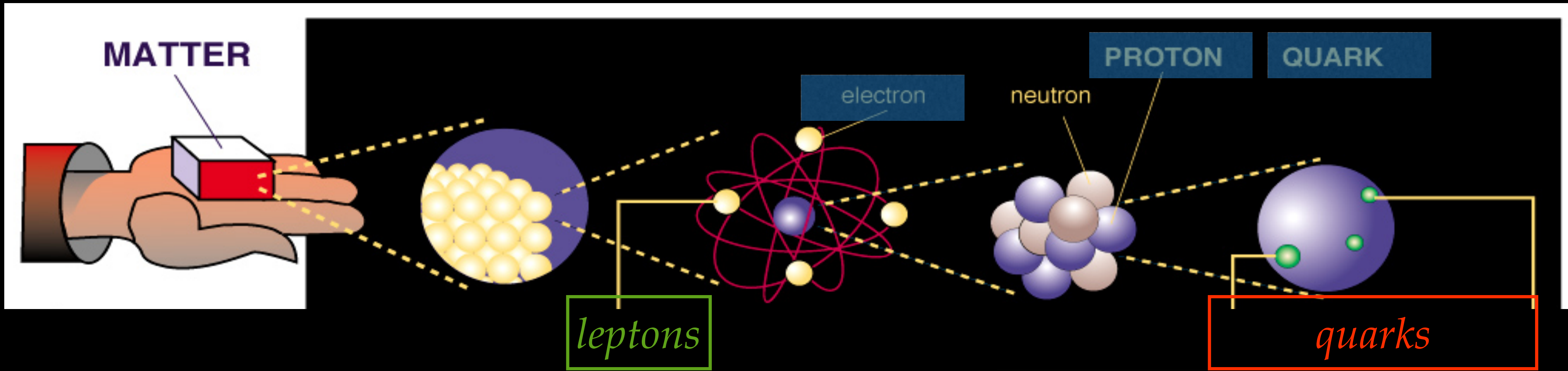
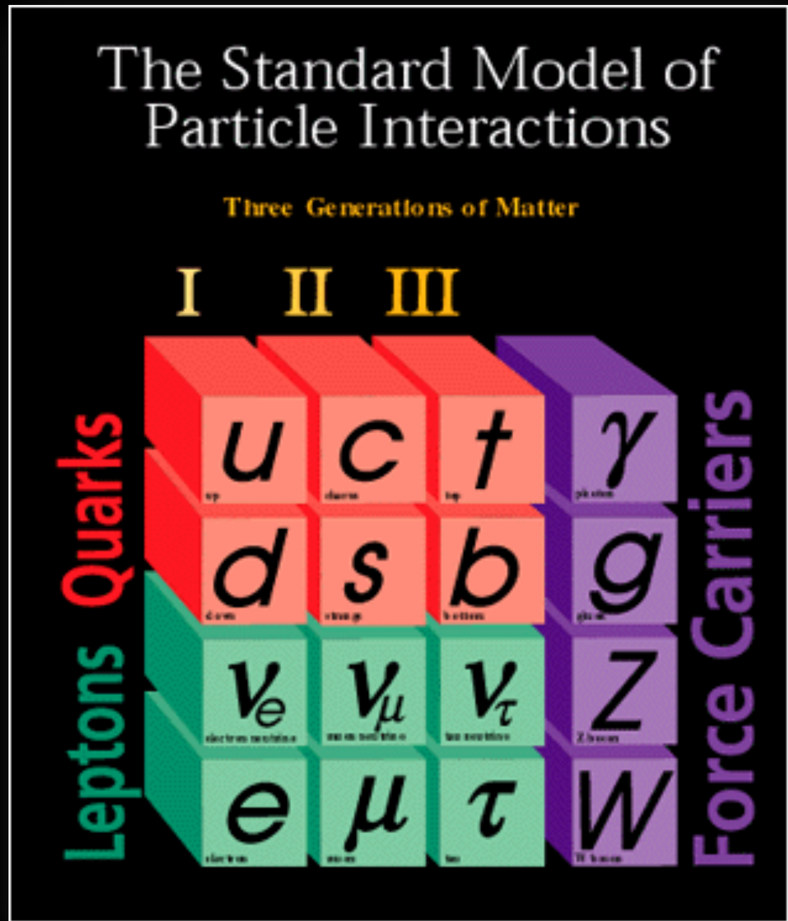


1. neutral
2. stable
3. heavy
4. 5x more abundant than usual mater
5. feeble interactions



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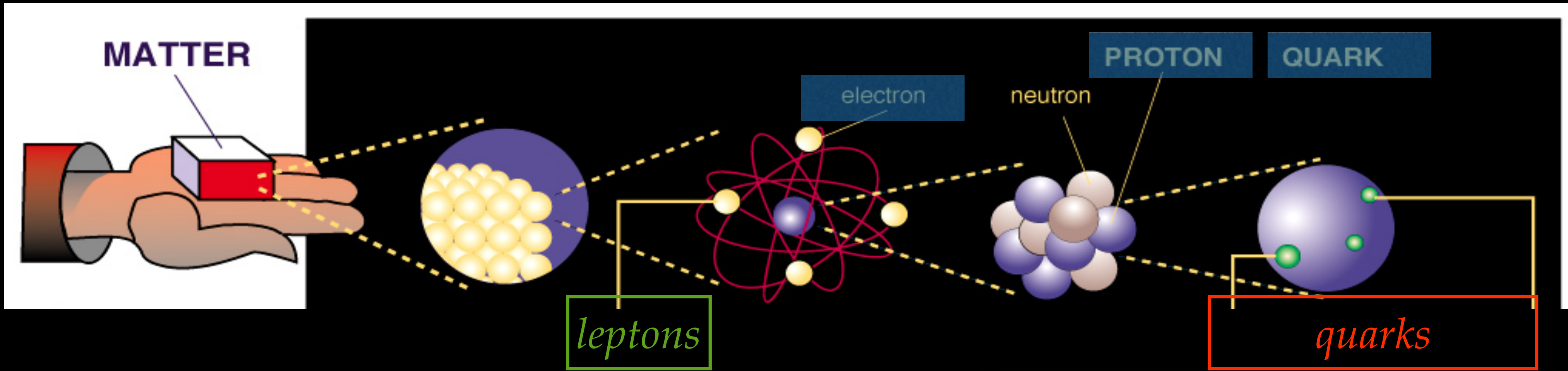

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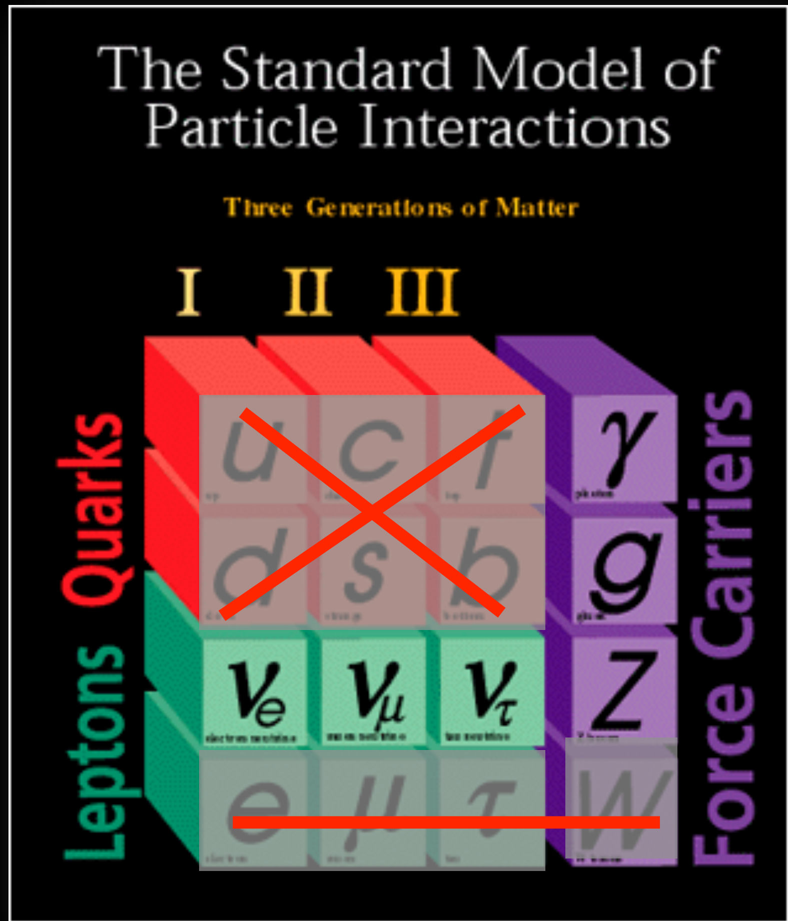

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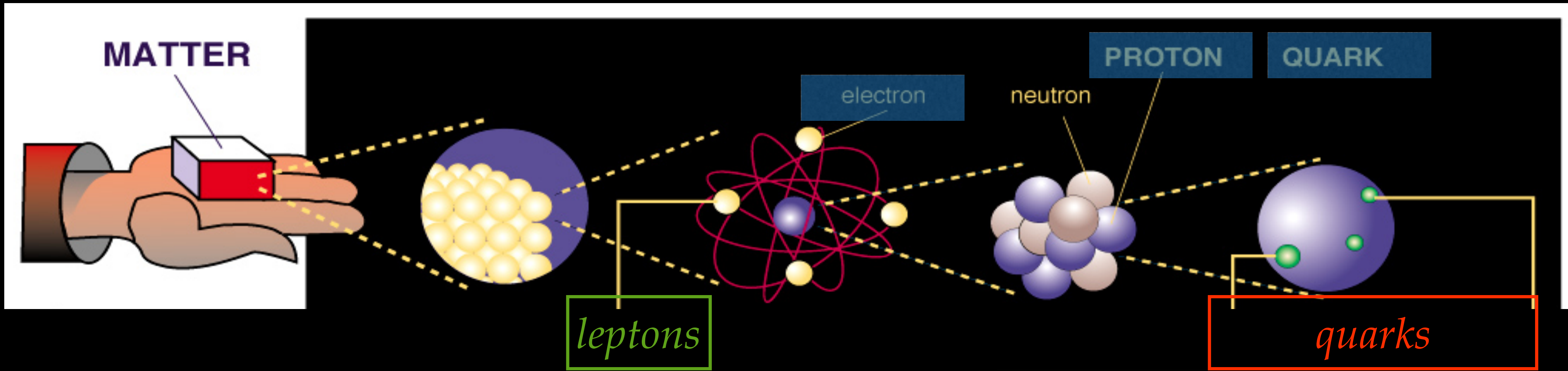

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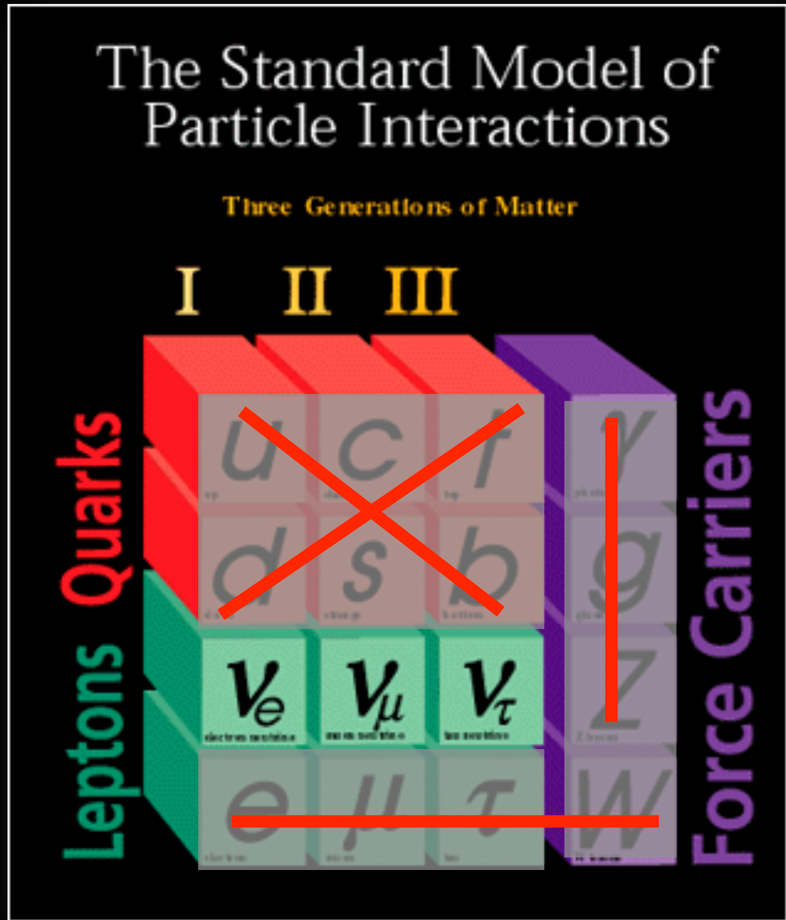

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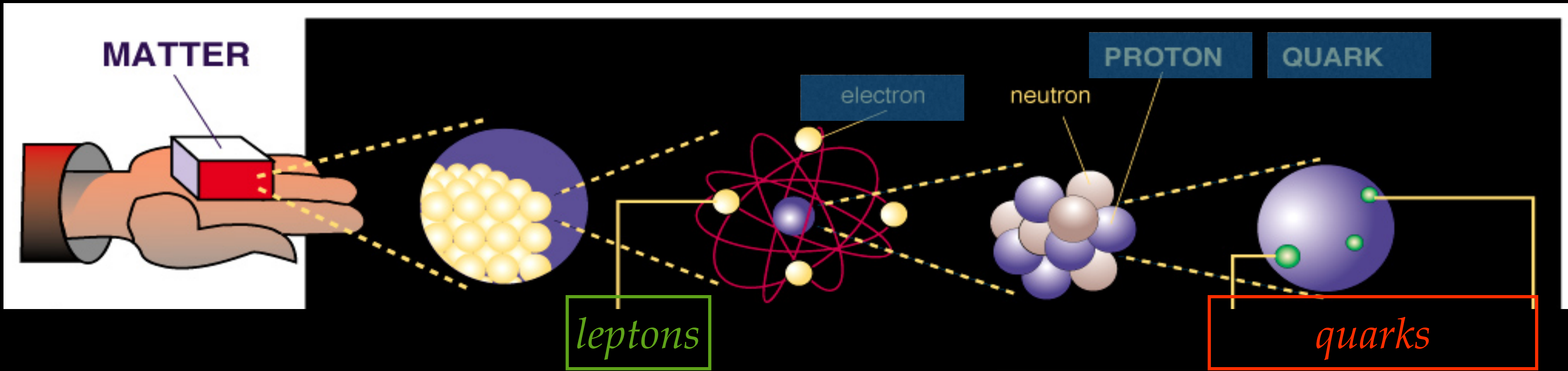

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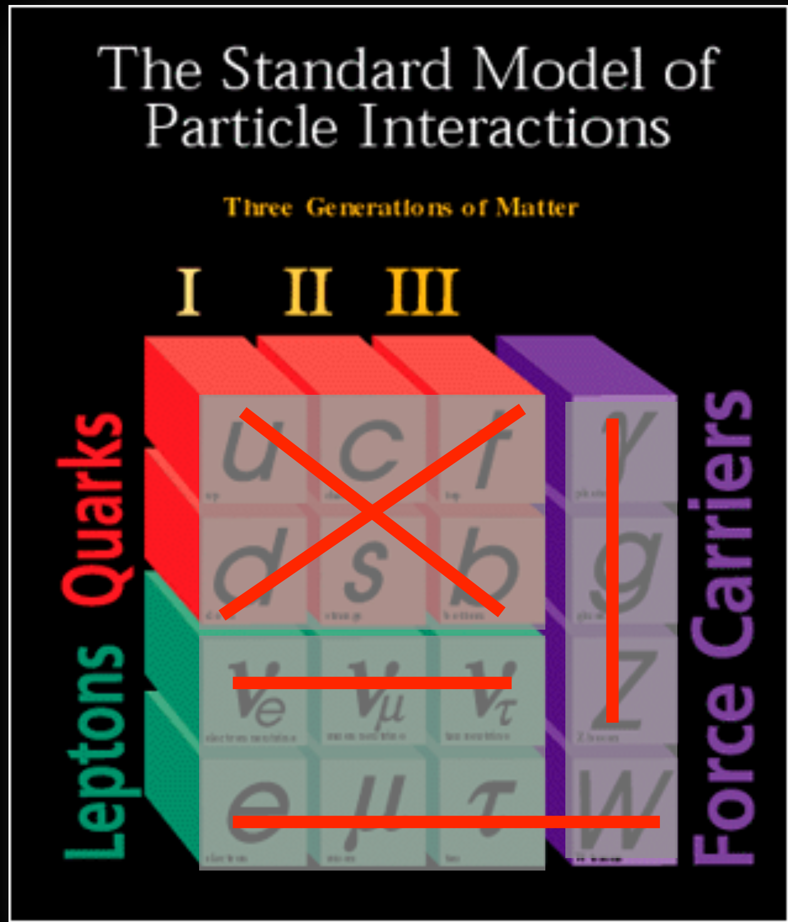
→ needs to be a new particle!



What are the options?

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THE MOST POPULAR CANDIDATES

"Weakly Interacting Massive Particles"

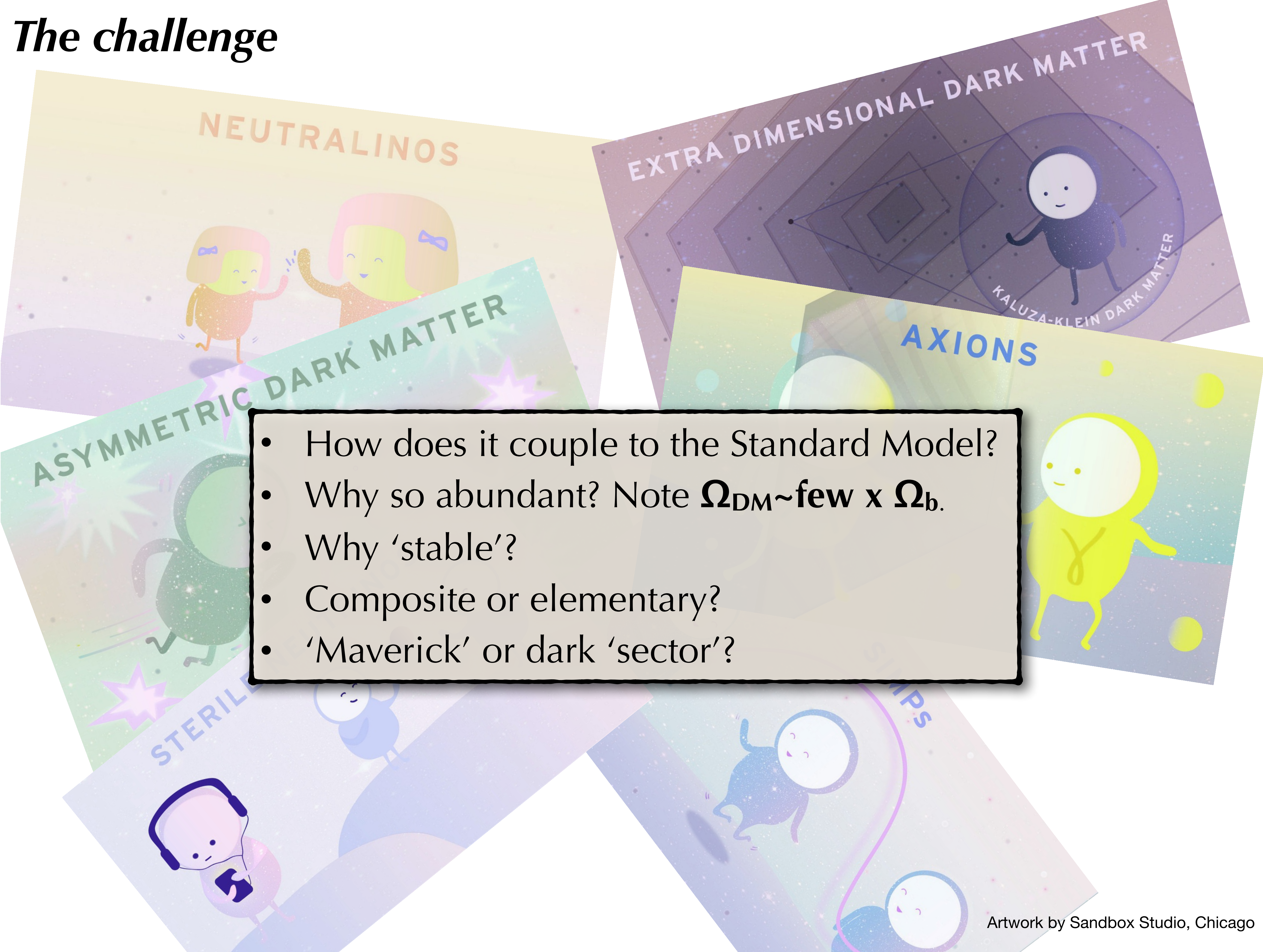
It means simply:

1. neutral
2. stable
3. heavy
4. 5x more abundant than usual mater
5. feeble interacting

Typically particles 10-100 times heavier than proton, as there are many models in which such particles could complete the missing link in our Standard model of particle physics.

"a simple, elegant, compelling explanation for a complex physical phenomenon" (R. Kolb)

The challenge



- How does it couple to the Standard Model?
- Why so abundant? Note $\mathbf{\Omega_{DM} \sim few \times \Omega_b}$.
- Why 'stable'?
- Composite or elementary?
- 'Maverick' or dark 'sector'?

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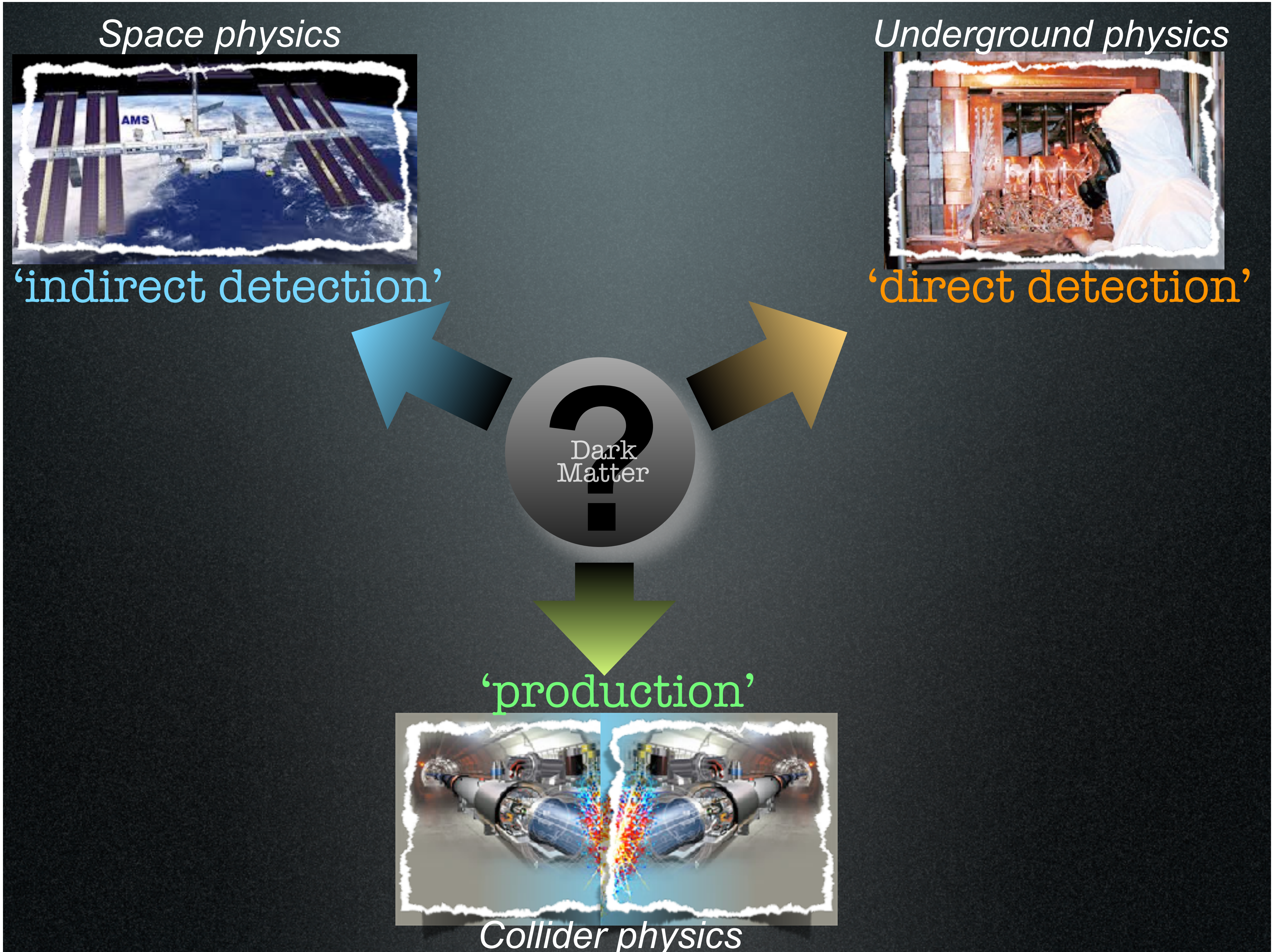
How to probe its particle physics nature?



The course programme and requirements

1. **Intro (2 classes)**

Material: Book "B. Gianfranco: Particle Dark Matter"chapter 1

Method: journal club

2. **The growth of cosmic structures: (5 classes)**
    - why Dark matter is distributed in the way we observe?
    - where do the 'seeds' of this distribution originate?
    - what can we learn from the measured distribution

Material: Cosmology lectures by Roman Scoccimarro — lectures 10-15

Method: Black board

3. **Going beyond gravity — how can we 'search' for the particle physics nature of dark matter? (10-13 classes)**
    - production: chapter 7
    - small scale dark matter clustering - N-body simulations - chapters 2&3
    - 'indirect' searches: chapter 24-29
    - 'direct' searches: chapter 17
    - 'collider' searches: chapter 13

Material: Book "B. Gianfranco: Particle Dark Matter"

Method: journal club