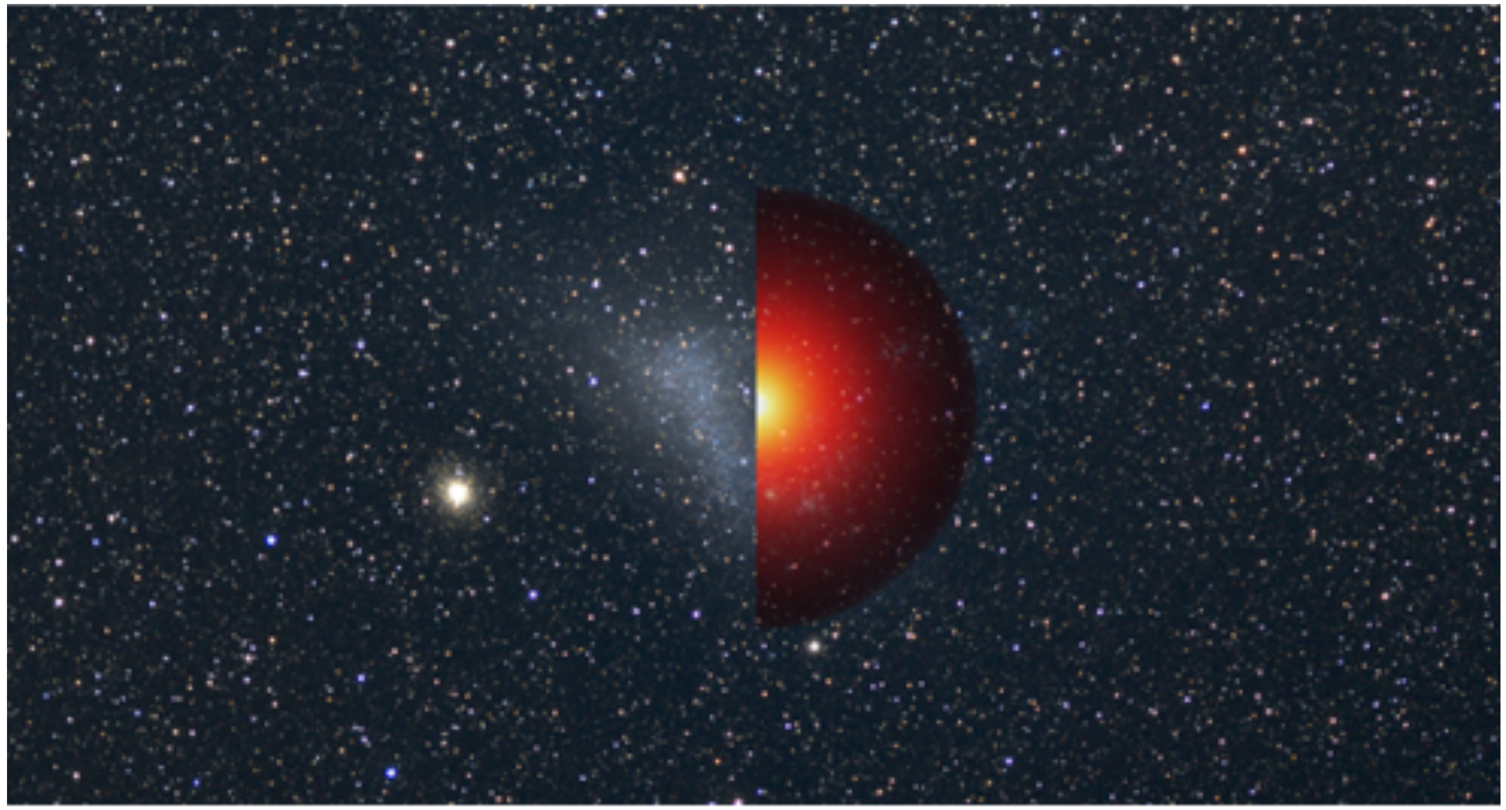


Astrophysical searches for Dark Matter

Gabrijela Zaharijas
Centre for Astrophysics and Cosmology,
University of Nova Gorica, Slovenia

The Plan

- Lecture 1: Astrophysical (gravitational) evidence for dark matter
- Lecture 2: Properties and Candidates
- Lecture 3: Search for particle dark matter: Direct detection and colliders
- Lecture 4: Search for particle dark matter: Astrophysical (indirect) searches

Additional material, e.g:

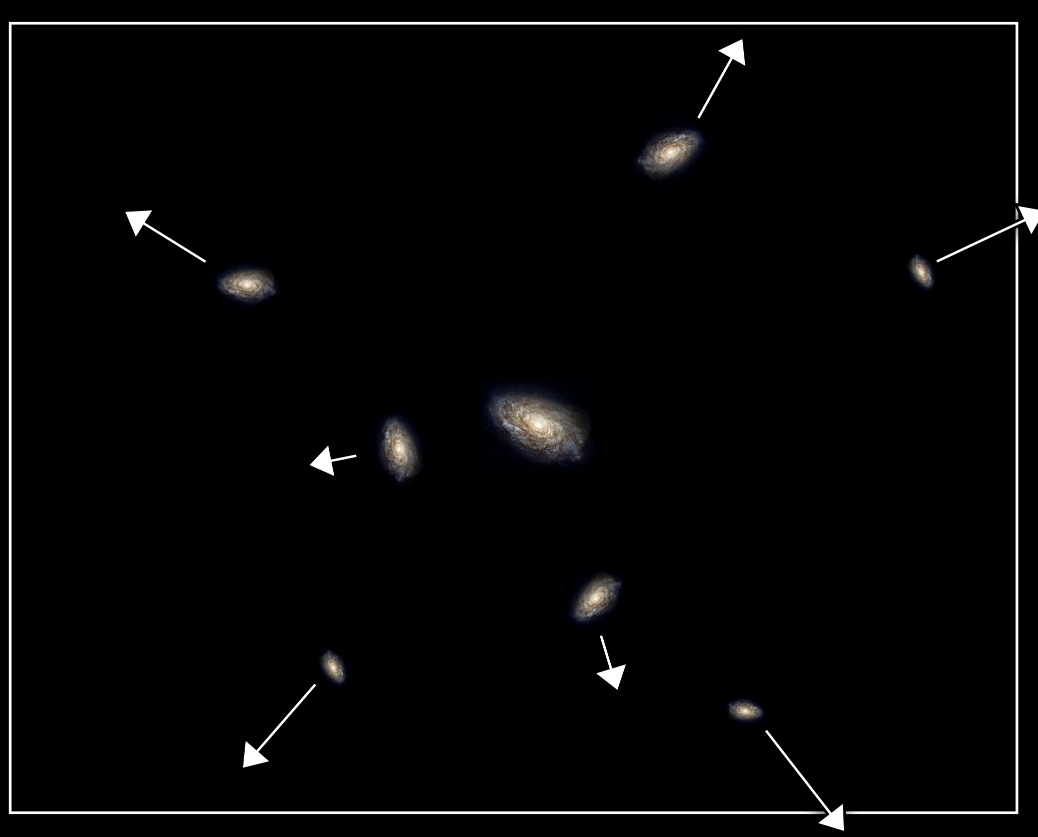
- Marco Cirelli, 2016, lectures@ IDPASC School, Vipava, Slovenia, https://www.idpasc.lip.pt/LIP/events/2016_idpasc_school/
- Tracy Slatyer, 2016, lectures@ ISCT School, http://indico.ictp.it/event/7626/

brief 'pre-' history: 1900- ~1930

- ~1900 'astrophotography' revealed that some objects (M31 - Andromeda galaxy) are extended — 'nebulae'
- 1917 invention of spectrography -> nebulae are moving away from us
- 1920 the 'Big debate' — are nebulae extragalactic or galactic?
- 1924 — Hubble finds a Cepheid star in M31 - extragalactic astronomy begins

- in parallel, on the 'theory side' 1915, Einstein theory of general relativity
- 1922 Friedman - Universe might be expanding!

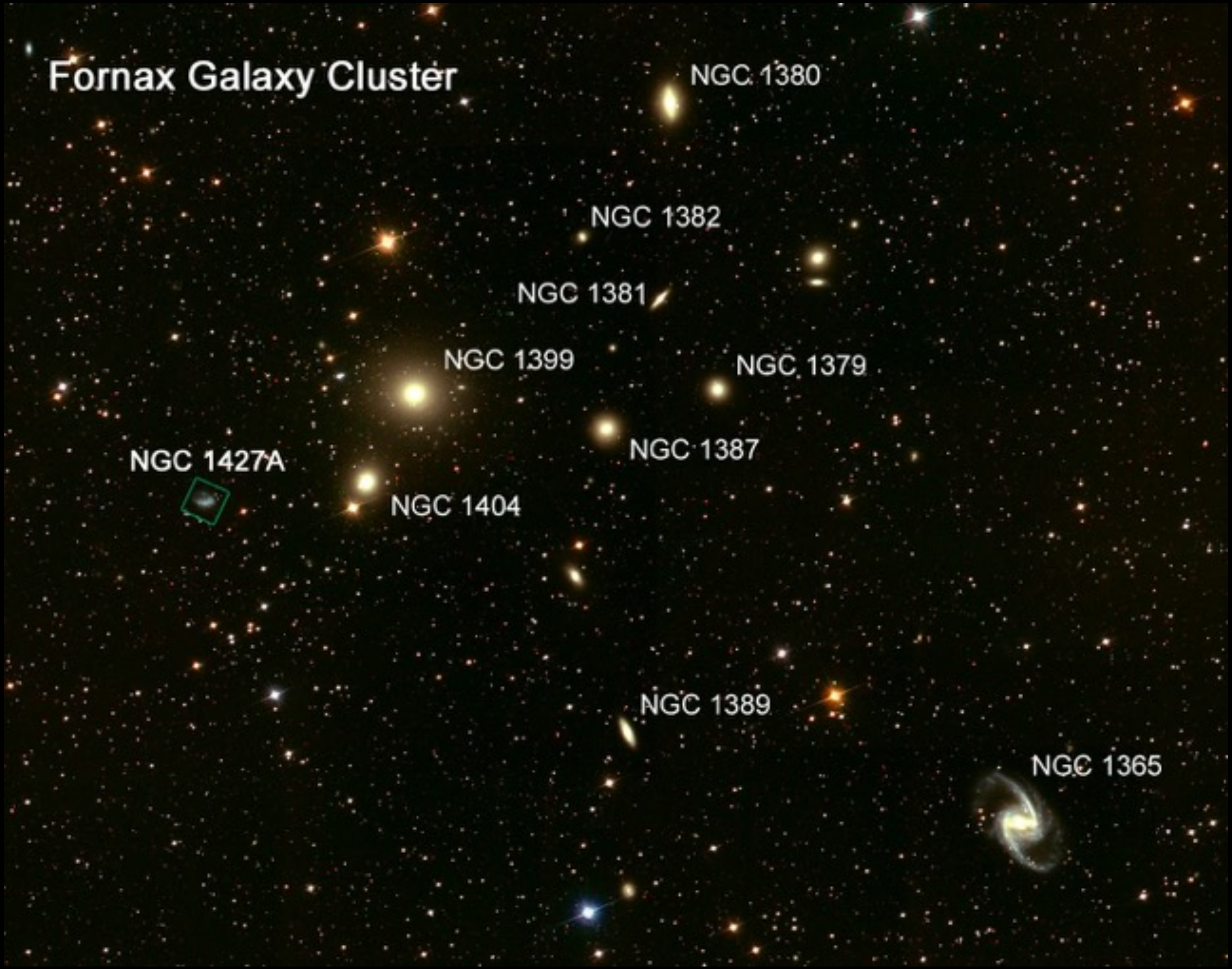
- 1929 — indeed! The Hubble law.



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,

$$2K + U = 0$$

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

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

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

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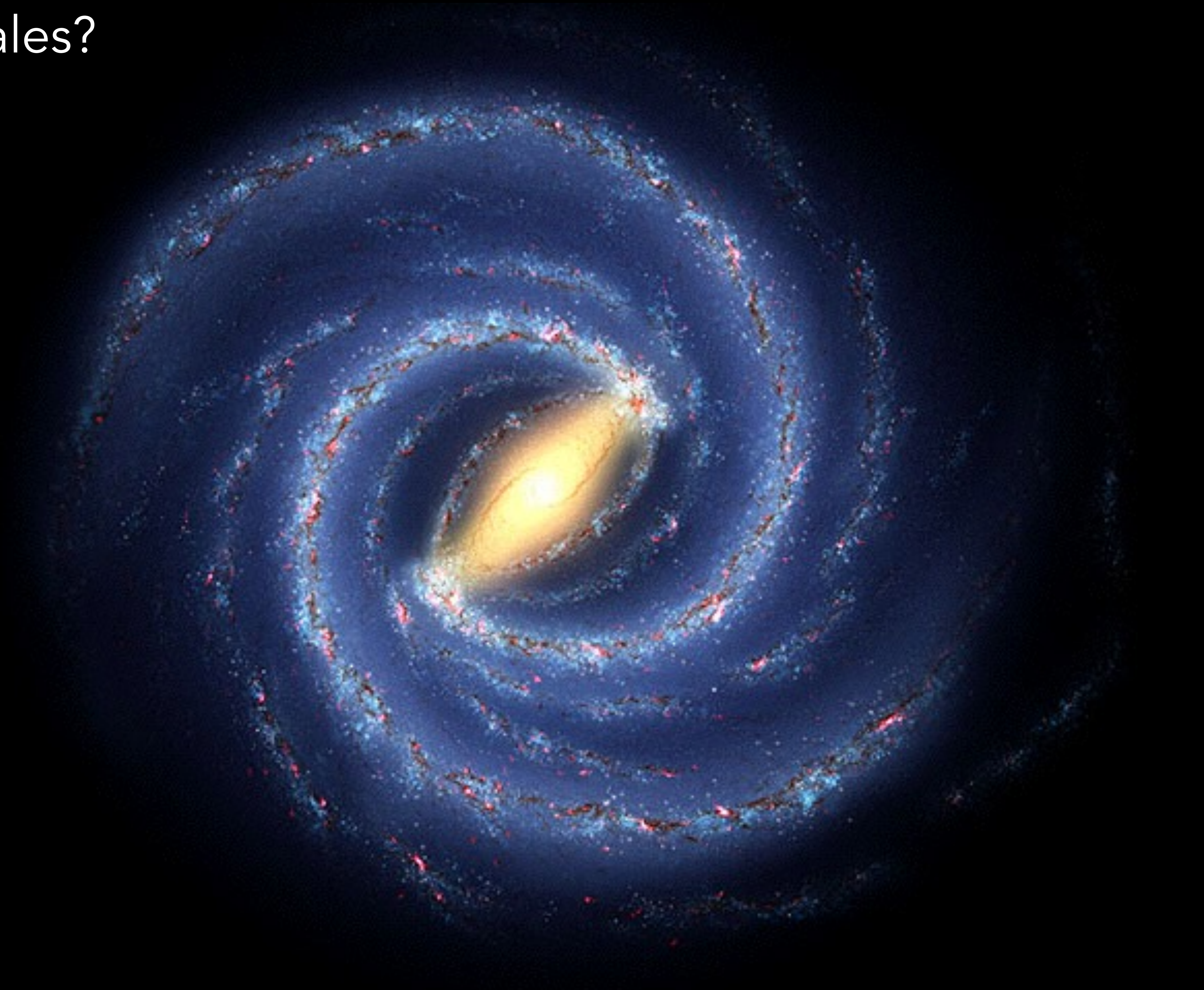
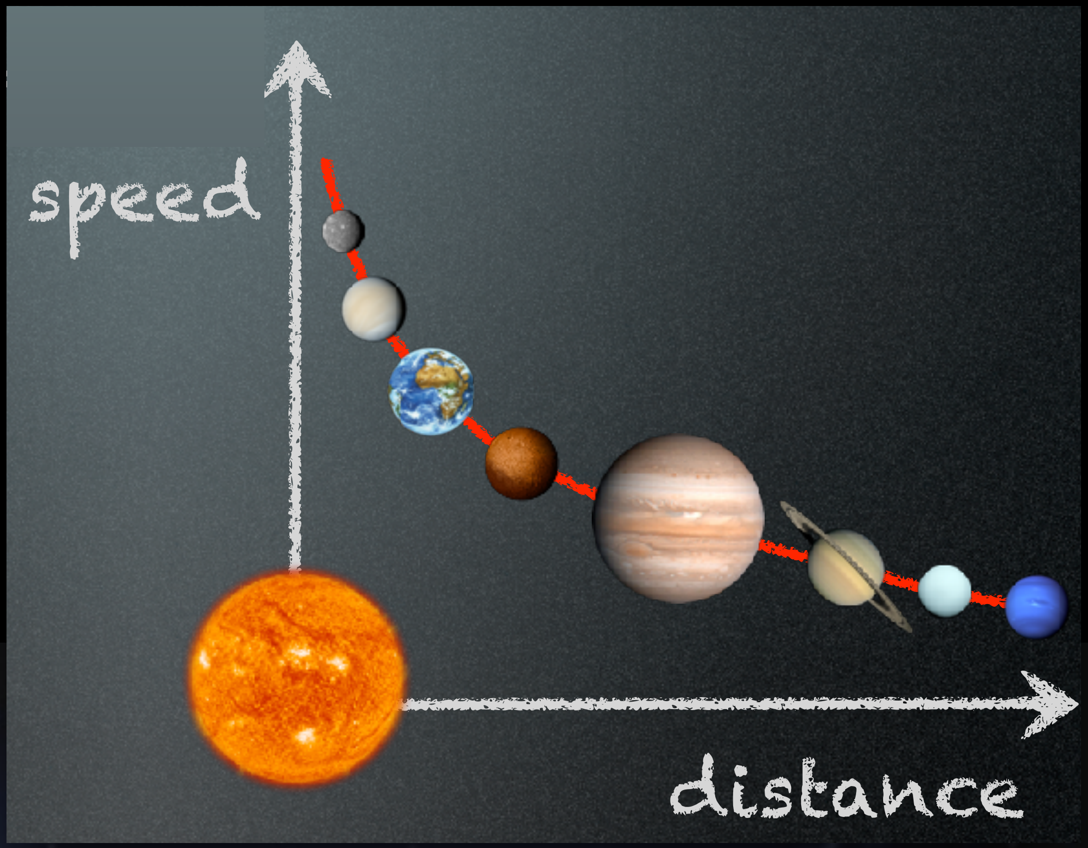
Zwicky was not taken seriously: the problem was just a "missing luminosity problem"

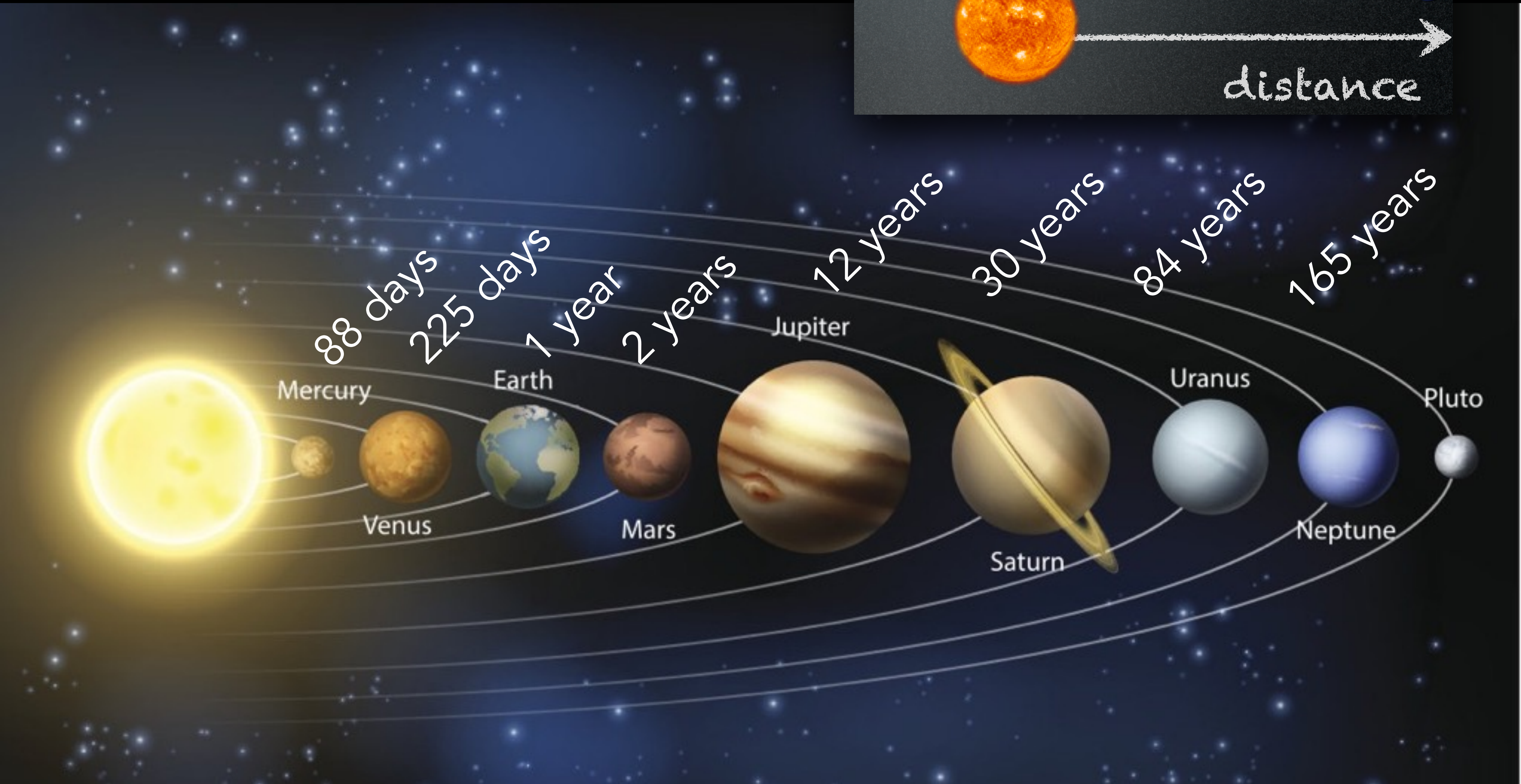
How about Galaxy scales?



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!

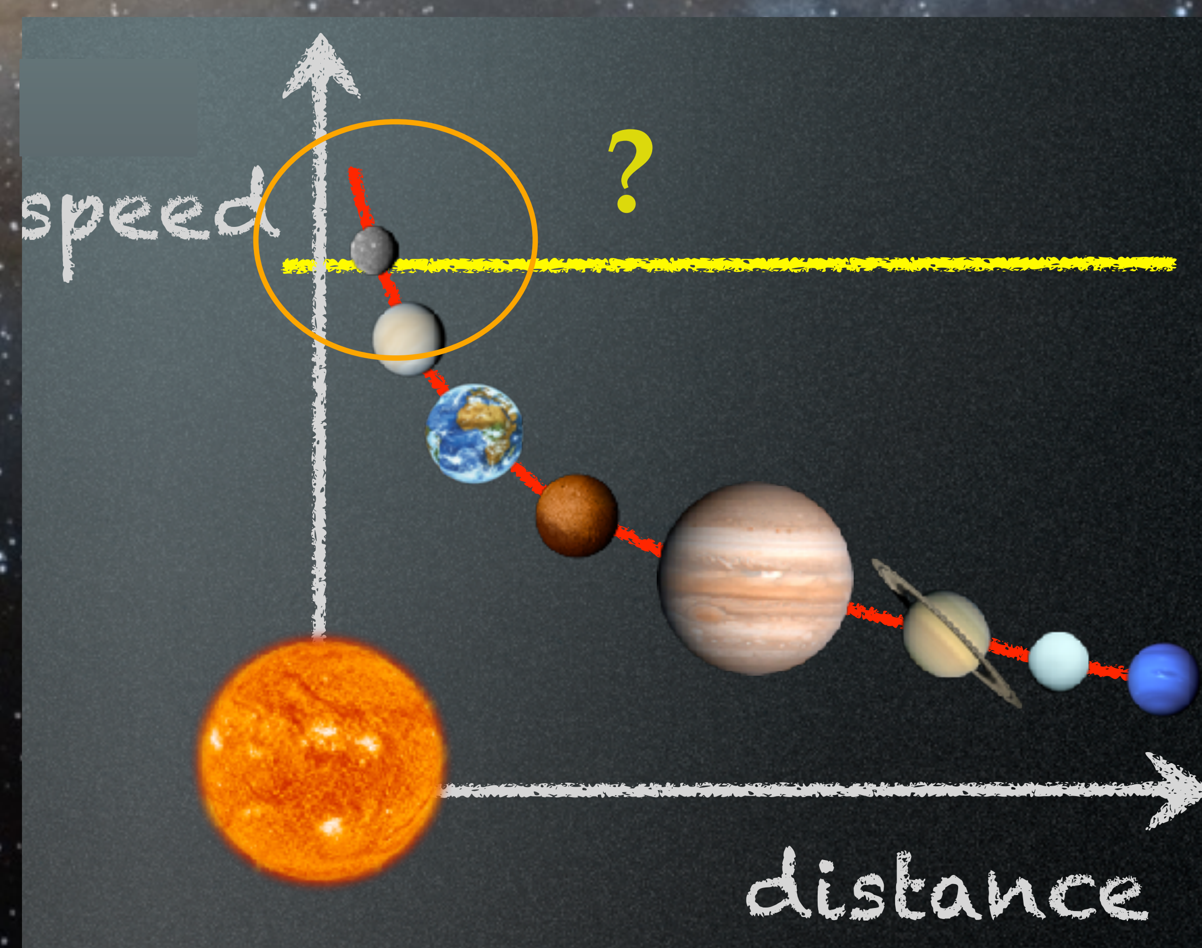
In 1939 Horace Babcock measures the rotation curves for Andromeda measuring a **constant angular velocity**!

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

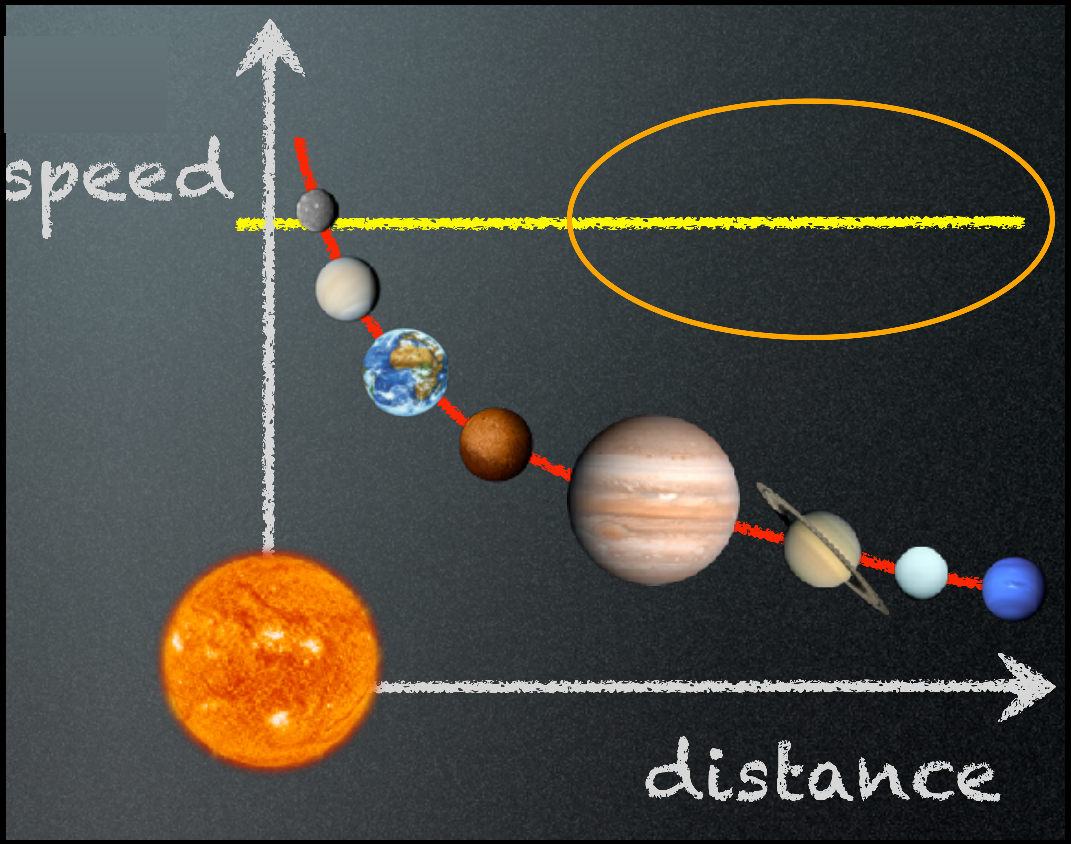
***Van de Hulst** at Dwingeloo*

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

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

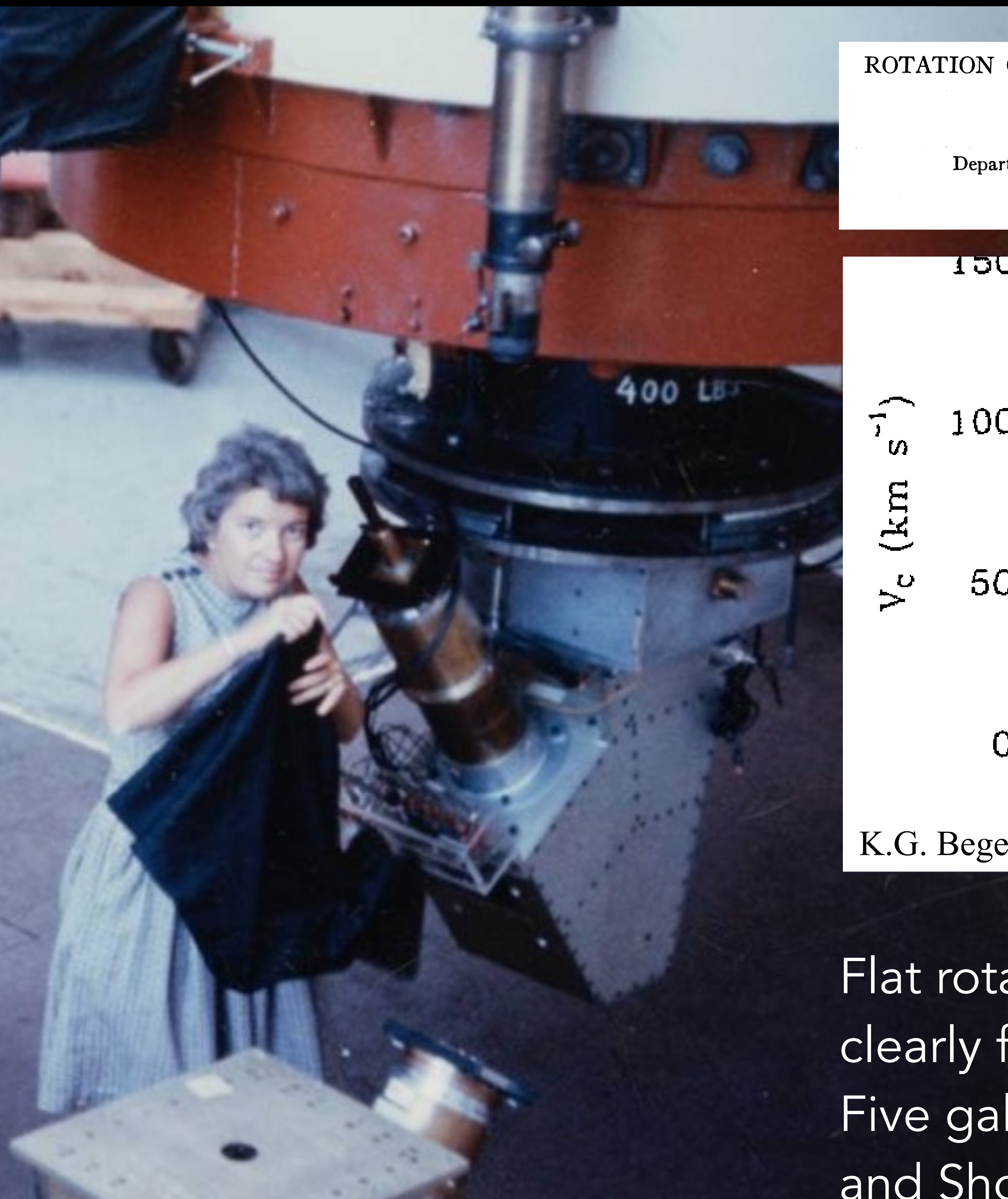
That meant that one could measure gas velocity accurately and much farther from the centre of Andromeda!

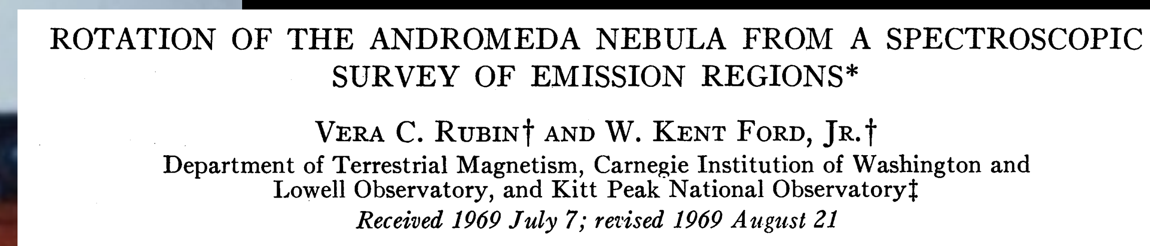
Van de Hulst gave the first 21cm map of Andromeda in **1957** showing that the velocities stays constant much far away from the visible region.



THE 1970s REVOLUTION

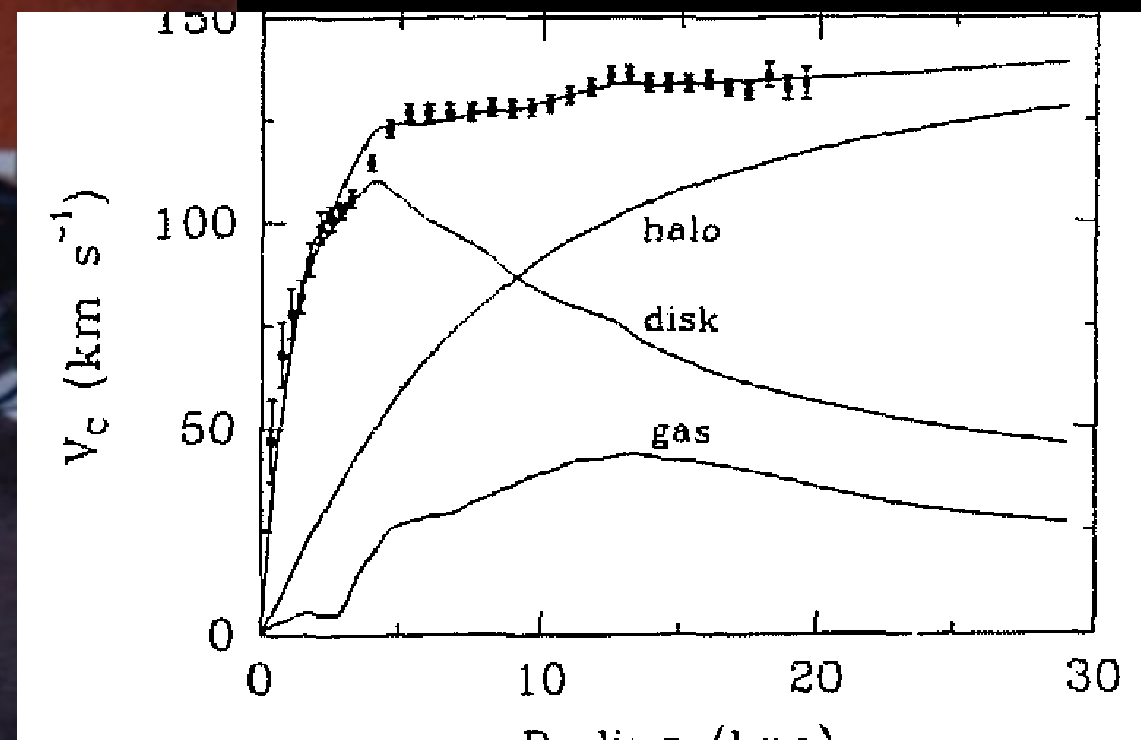
the invention of spectrograph by Kent Ford in the 1960s





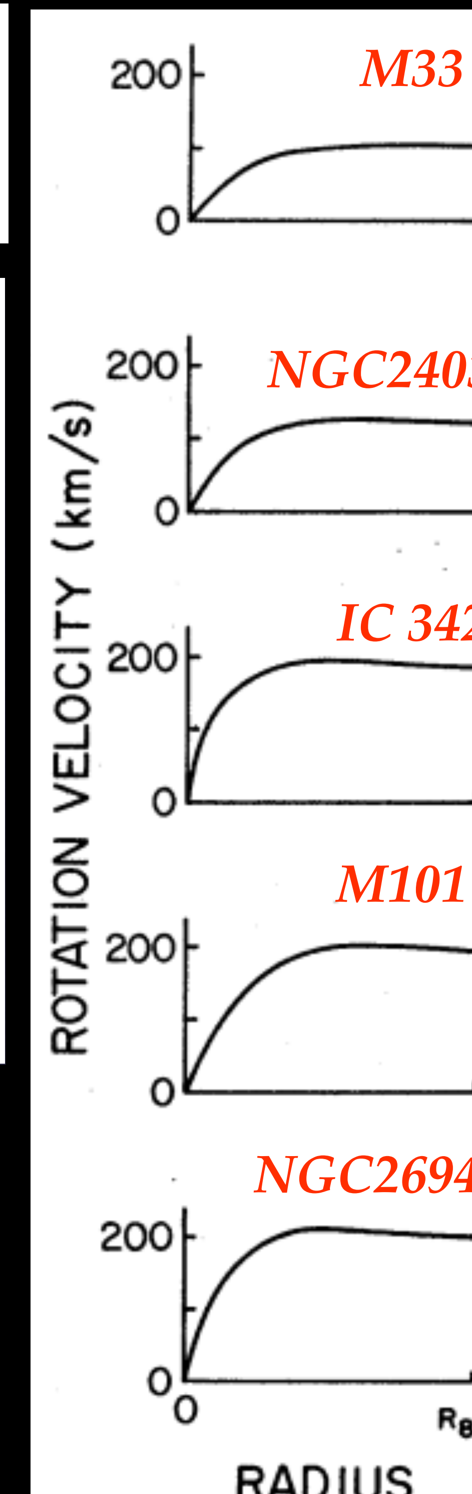
ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

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.

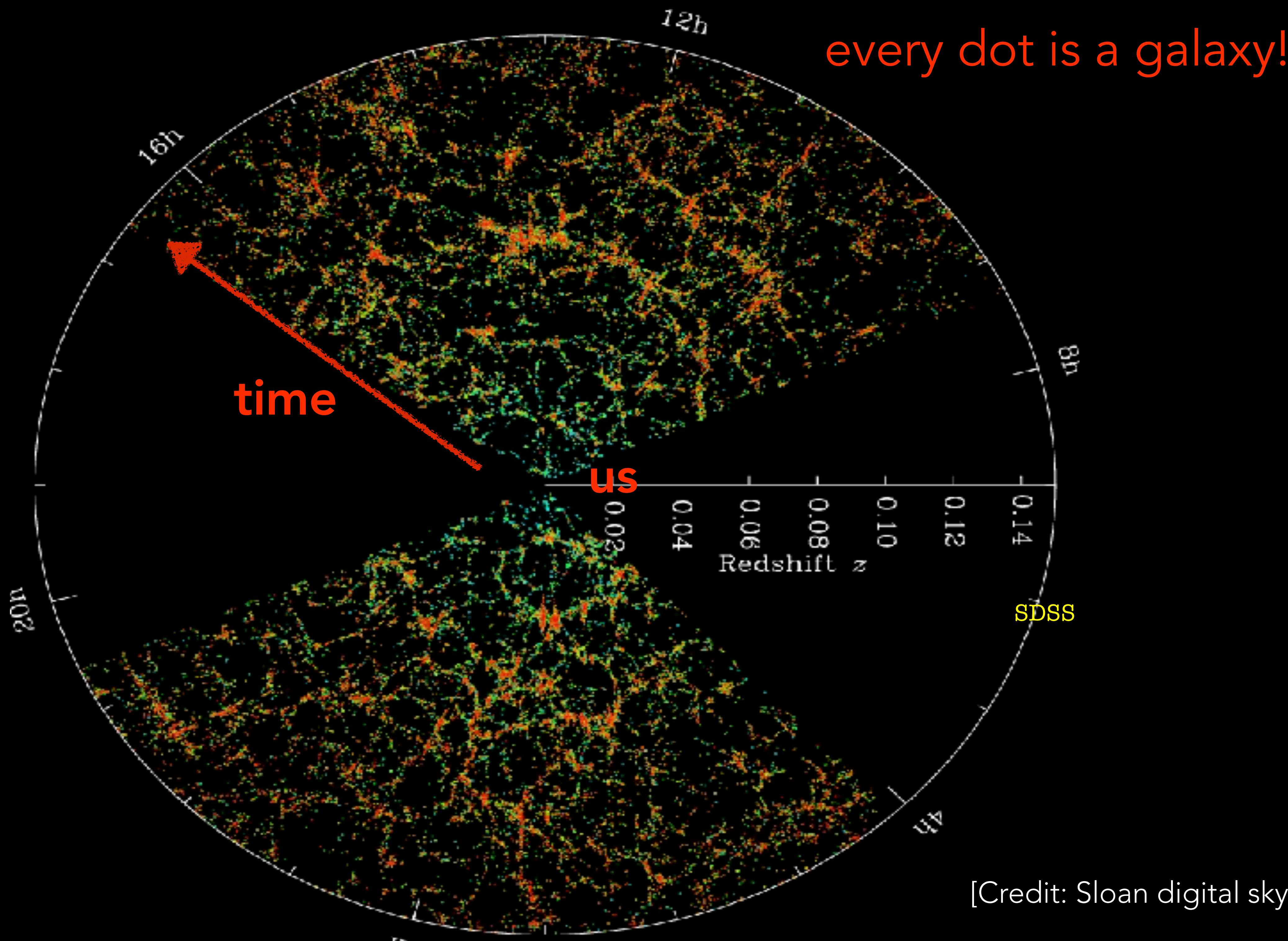


By the 1970s most astronomers are convinced that dark matter ***exists*** around galaxies and clusters

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

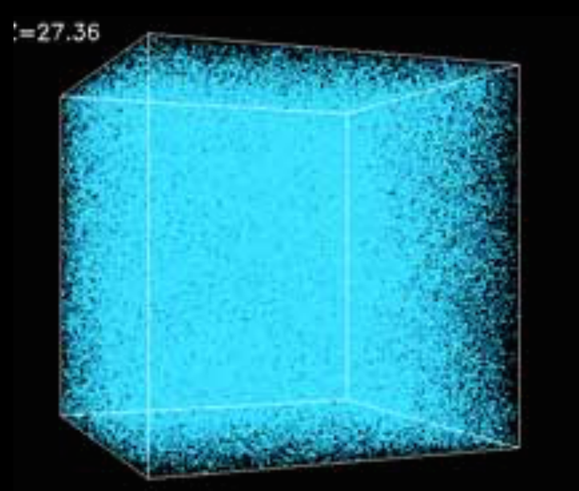


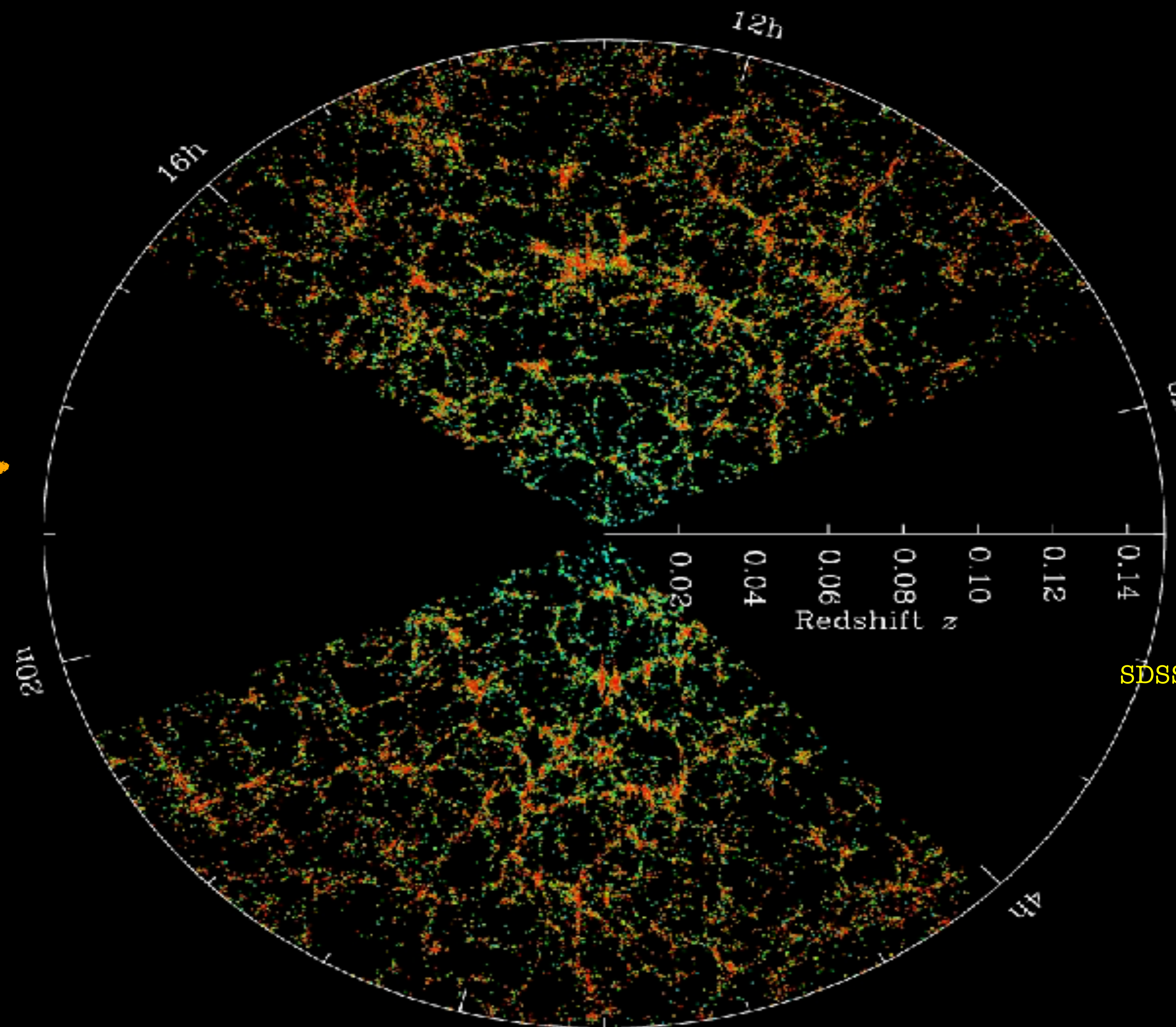
[Credit: Sloan digital sky survey]

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





LOOKING BACK IN TIME

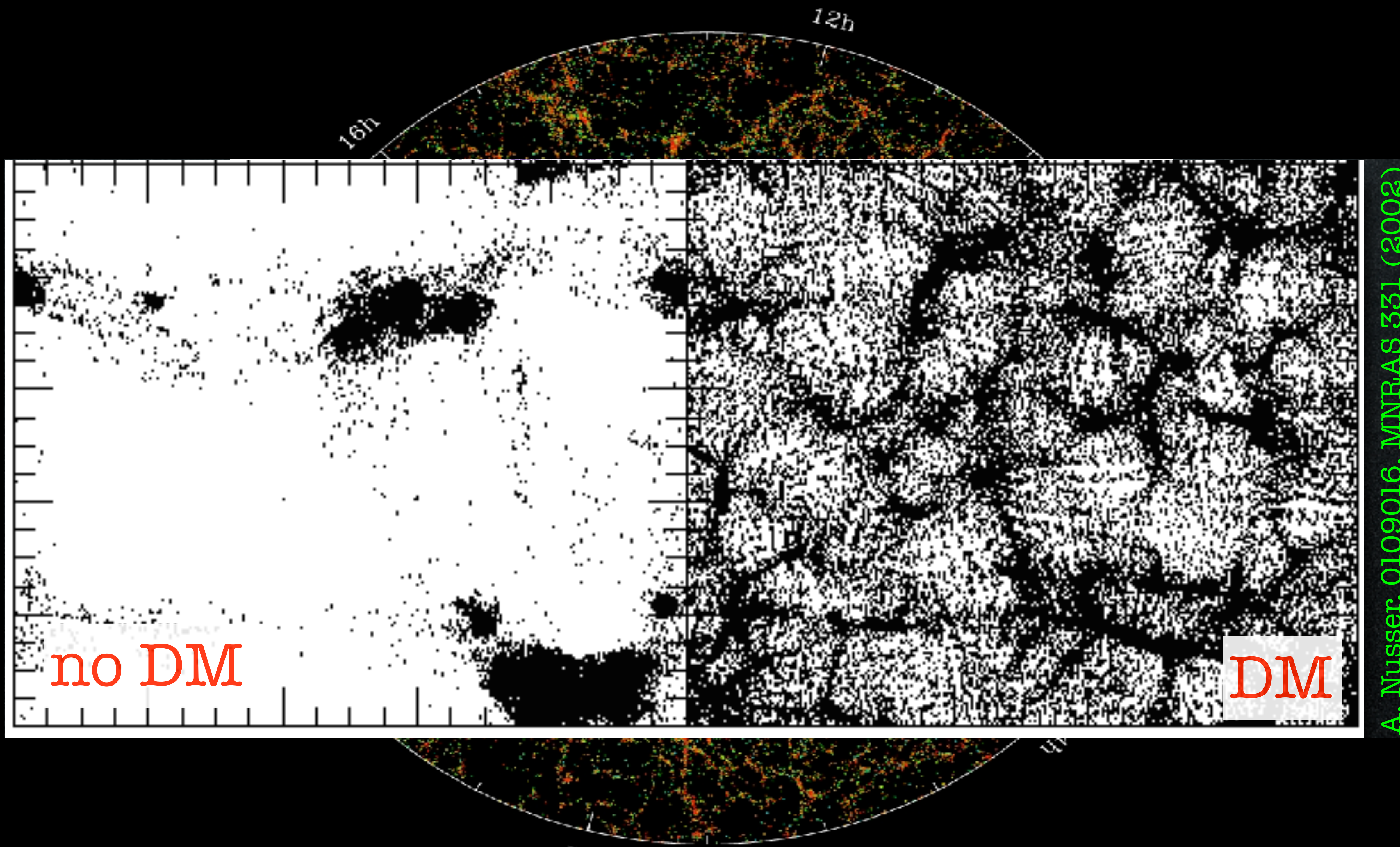
In time, we were able to test this conjecture as computers got powerful enough to simulate the formation of structures starting from the early Universe

[movie]

[Credit: Springel et al. (2005)]

LOOKING BACK IN TIME

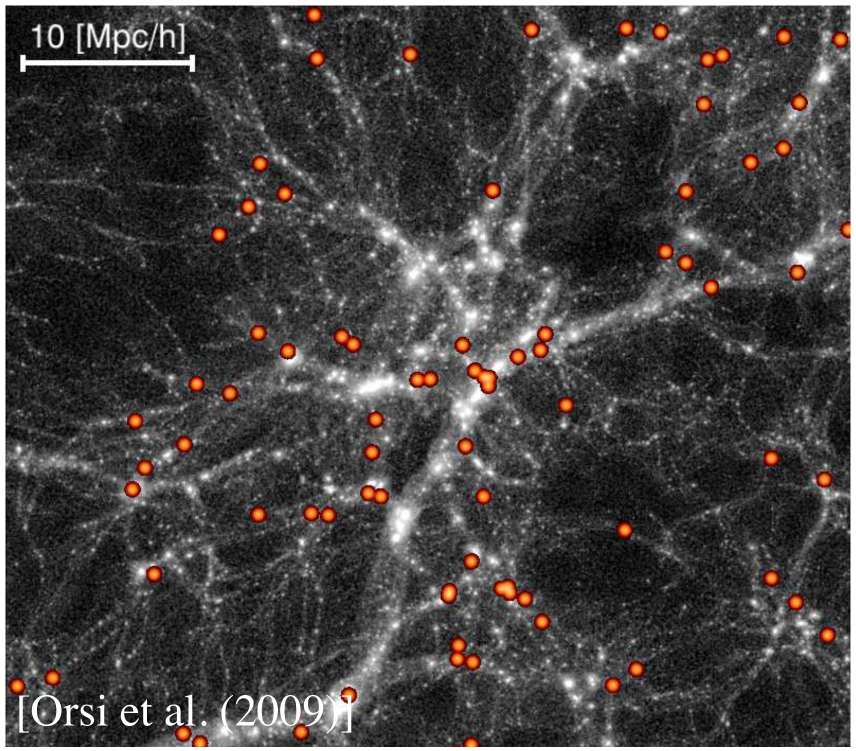
At the beginning of 2000s this ‘precision cosmology’ spectacularly confirmed that dark matter makes up majority of the mass in our Universe!



Summary:

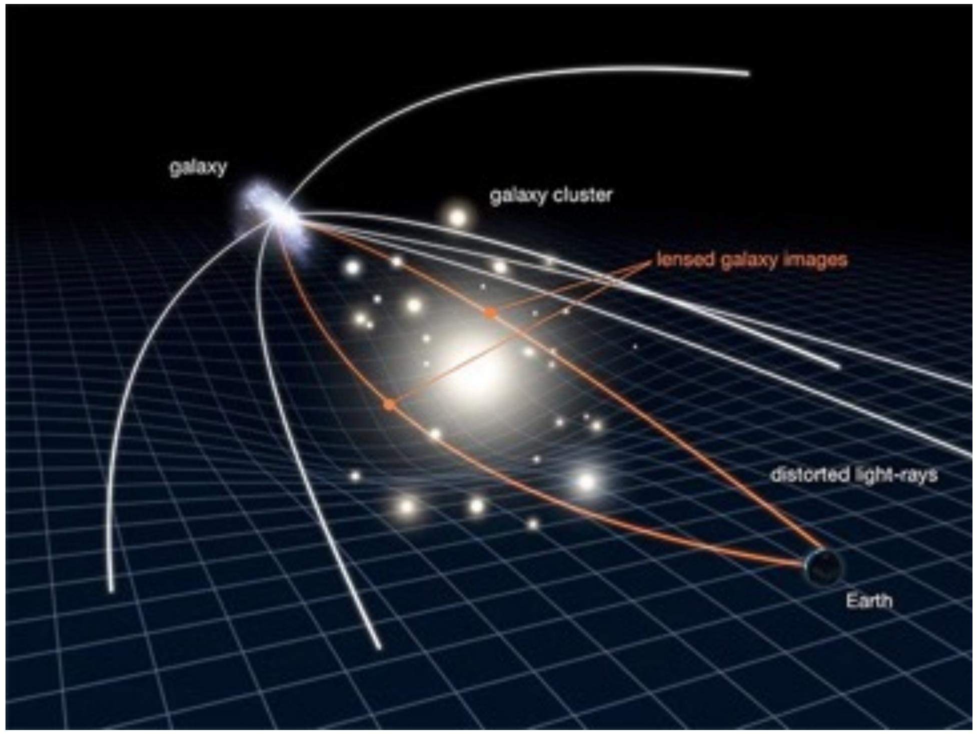
- evidence on a wide range of scales
- and throughout the history of the Universe

large scale structures



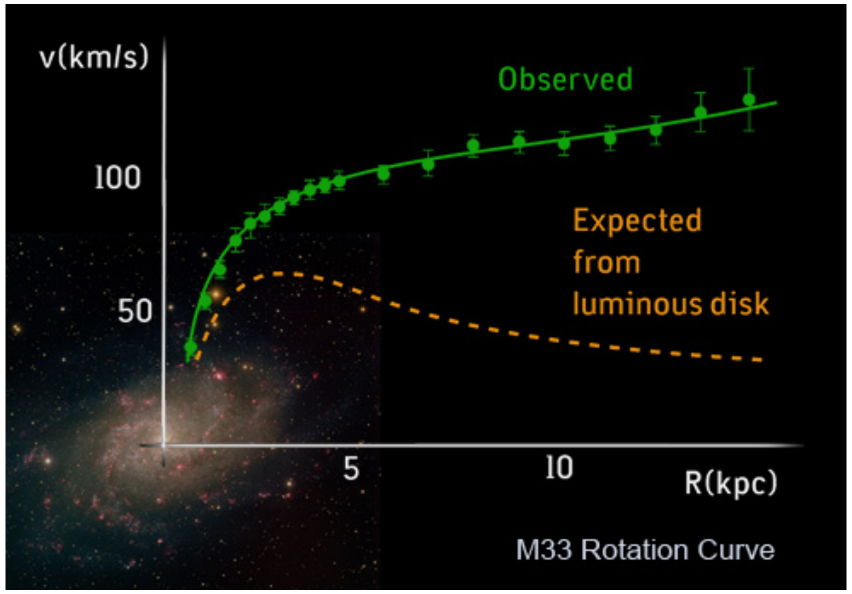
10s Mpc

clusters of galaxies



Mpc

Milky Way-sized galaxies



10s kpc

dwarf galaxies

<~ kpc

Our options

1. Dark matter really exists, and we are observing the effects of its gravitational attraction

2. Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter

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Dark Matter
or MOND?
(MOdified Newtonian Dynamics)
or MOG or the relativistic TeVeS?
(scalar-vector-tensor MOdified Gravity)

- proposed in the 80's to explain the galaxy rotation problem
- Milgrom noted that Newton's law for gravitational force has been verified only where gravitational acceleration is large, and suggested that for extremely small accelerations the theory may not hold.

THE ASTROPHYSICAL JOURNAL, **270**:365–370, 1983 July 15

A MODIFICATION OF THE NEWTONIAN DYNAMICS AS A POSSIBLE ALTERNATIVE TO THE HIDDEN MASS HYPOTHESIS[1]

M. MILGROM
Department of Physics, The Weizmann Institute of Science, Rehovot, Israel; and The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

I have considered the possibility that Newton's second law does not describe the motion of objects under the conditions which prevail in galaxies and systems of galaxies. In particular I allowed for the inertia term not to be proportional to the acceleration of the object but rather be a more general function of it. With some simplifying assumptions I was led to the form

$$m_g \mu(a/a_0)\boldsymbol{a} = \boldsymbol{F}, \tag{1}$$

$$\mu(x \gg 1) \approx 1, \qquad \mu(x \ll 1) \approx x,$$

replacing $m_g \boldsymbol{a} = \boldsymbol{F}$.

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$$\mu(x \gg 1) \approx 1, \qquad \mu(x \ll 1) \approx x,$$

replacing $m_g \boldsymbol{a} = \boldsymbol{F}$.

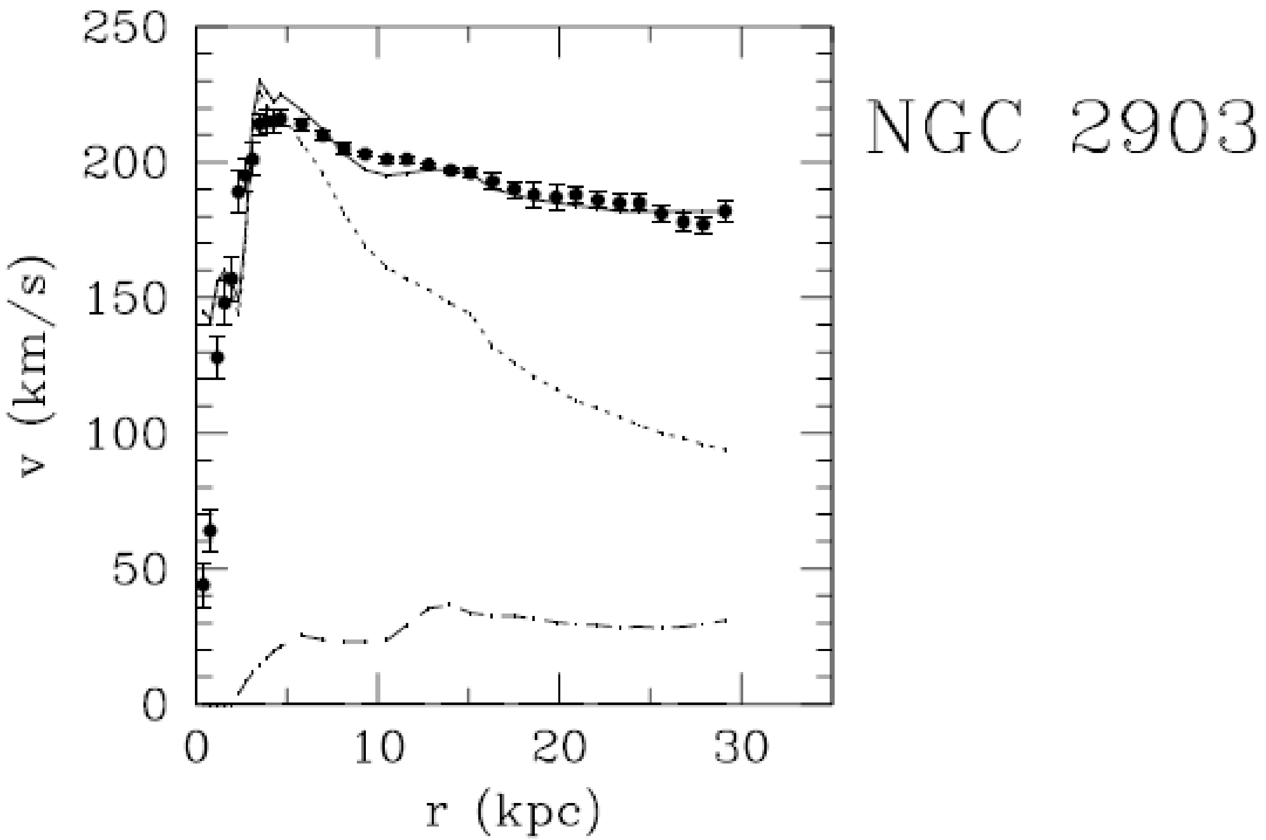
$$\frac{GM}{r^2} = \frac{a^2}{a_0}$$

$$a = \frac{v^2}{r} = \frac{\sqrt{GMa_0}}{r}$$

- proposed in the 80's to explain the galaxy rotation problem
- Milgrom noted that Newton's law for gravitational force has been verified only where gravitational acceleration is large, and suggested that for extremely small accelerations the theory may not hold.

$$v = \sqrt[4]{GMa_0}$$

$$\boxed{a_0 \simeq 10^{-8}\ \mathrm{cm\,s^{-2}}}$$



- However, evidence for DM collected on a large span of scales!
- at small scales MOND fails.

TESTING MODIFIED NEWTONIAN DYNAMICS WITH ROTATION CURVES OF DWARF AND LOW SURFACE BRIGHTNESS GALAXIES

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Department of Astronomy, University of Maryland, College Park, MD 20742-2421

R. H. SANDERS
Kapteyn Institute, P.O. Box 800, 9700 AV Groningen, the Netherlands

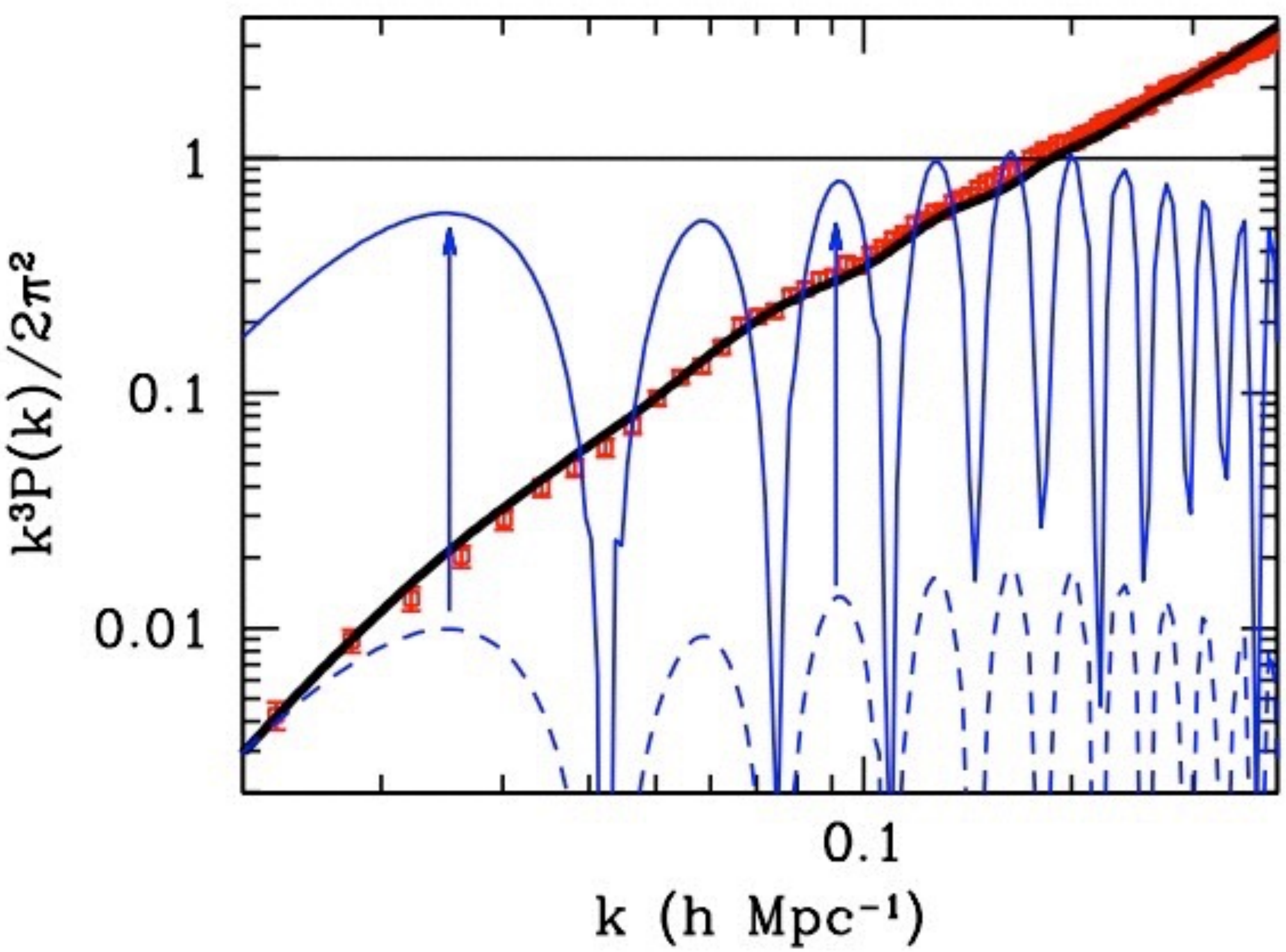
S. S. MCGAUGH
Department of Astronomy, University of Maryland, College Park, MD 20742-2421

Draft version June 1, 2010

ABSTRACT

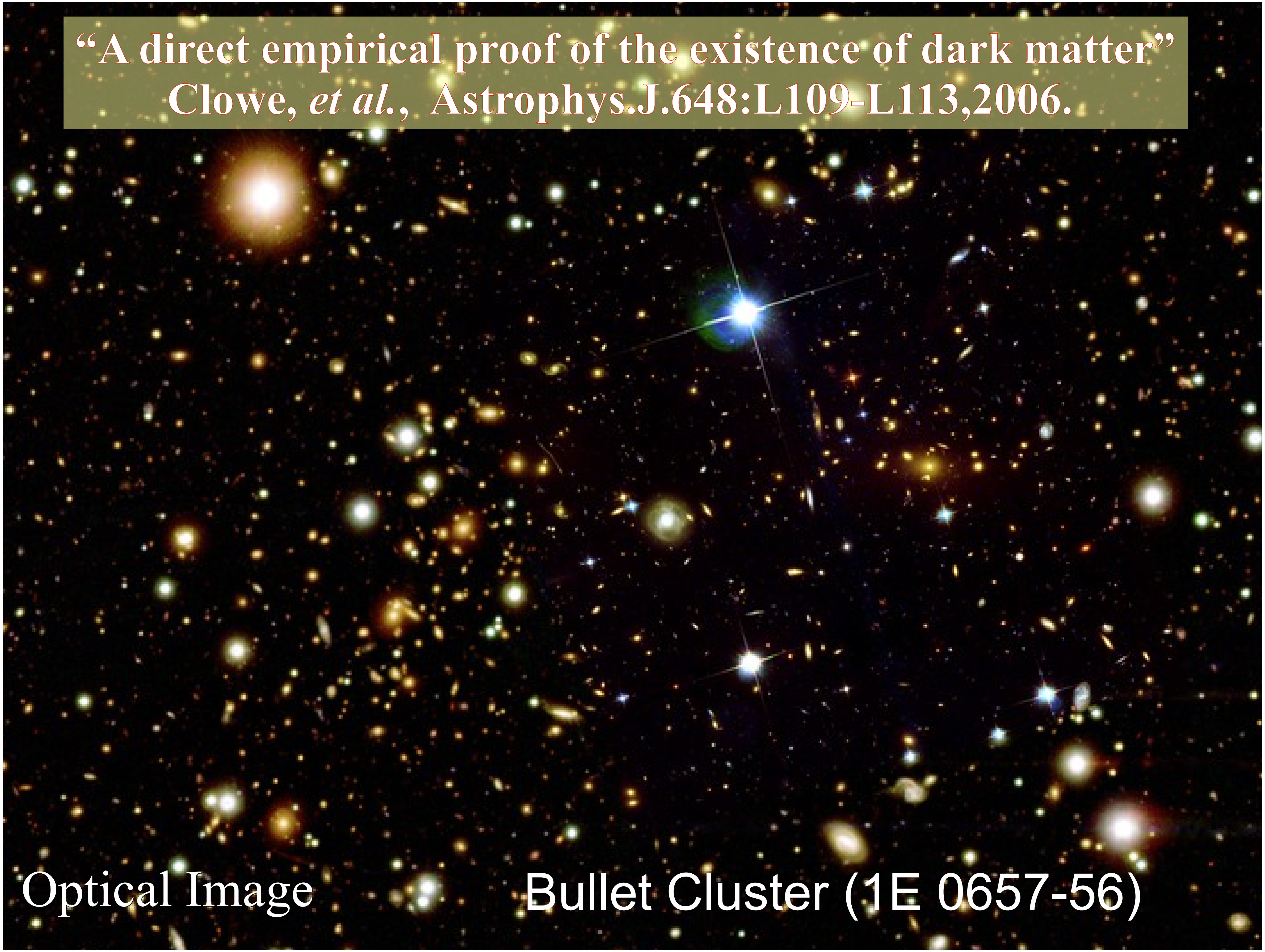
Dwarf and low surface brightness galaxies are ideal objects to test modified Newtonian dynamics (MOND), because in most of these galaxies the accelerations fall below the threshold below where MOND supposedly applies. We have selected from the literature a sample of 27 dwarf and low surface brightness galaxies. MOND is successful in explaining the general shape of the observed rotation curves for roughly three quarters of the galaxies in the sample presented here. However, for the remaining quarter, MOND does not adequately explain the observed rotation curves. Considering the uncertainties in distances and inclinations for the galaxies in our sample, a small fraction of poor MOND predictions is expected and is not necessarily a problem for MOND.

- DM naturally predicts a scale free power spectrum!
- MOND generically cannot achieve that



- Scott Dodelson, from http://arxiv.org/abs/1112.1320.

- en plus, the Bullet cluster!



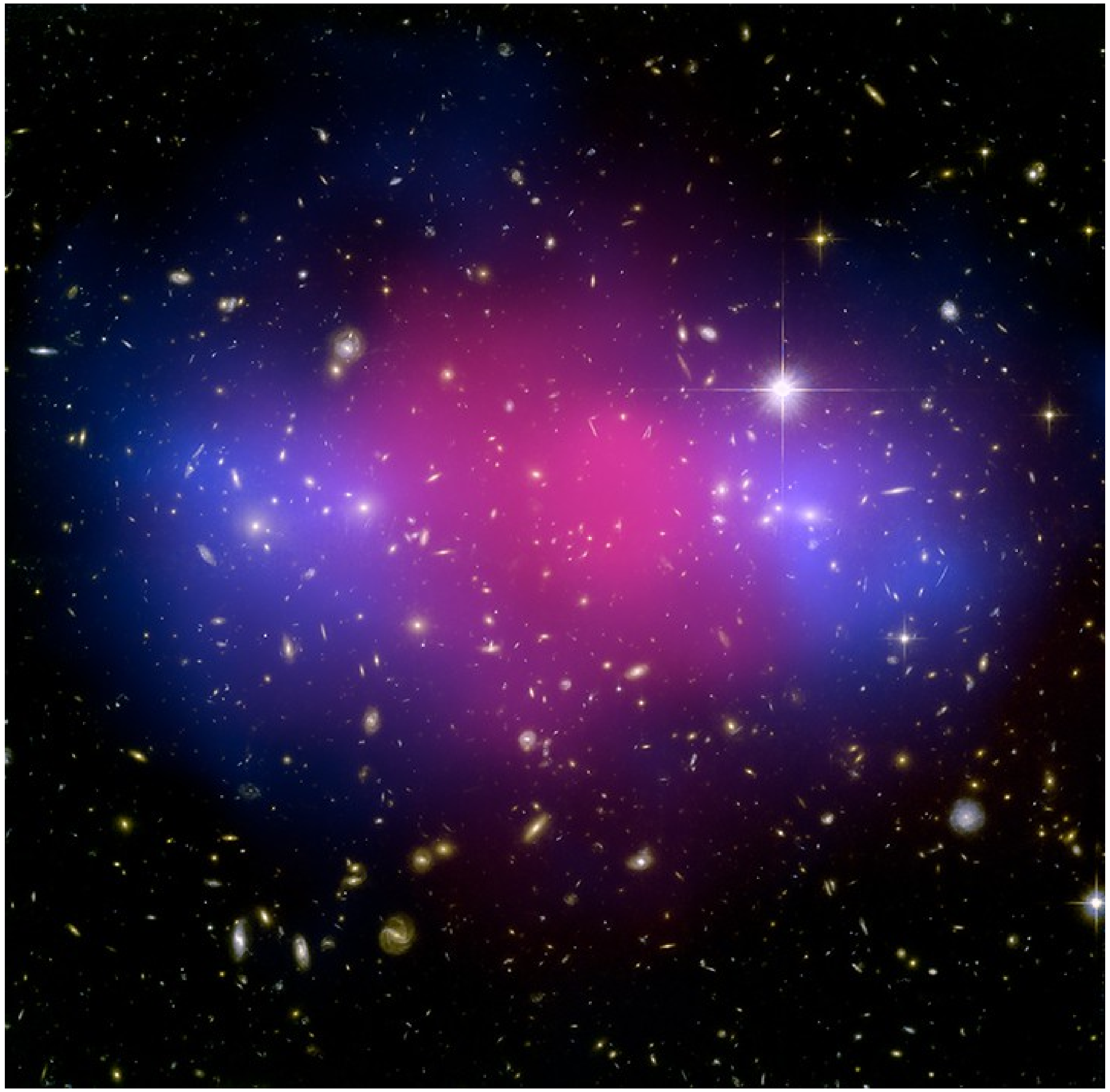
- en plus, the Bullet cluster!

- en plus, the Bullet cluster!

- Chandra X-ray telescope observation of shocked gaseous atoms: bow shock wave in the gas of the smaller Bullet cluster (pink on right), allowed determination of the velocity of the cluster (4500 km/s) and its direction of motion.

- en plus, the Bullet cluster!

- dark matter didn't experience the drag of the collision! The critical evidence is that the (pink) gas clouds are not centered with cluster masses as would be expected if the clusters were composed of ordinary atoms and other standard matter!



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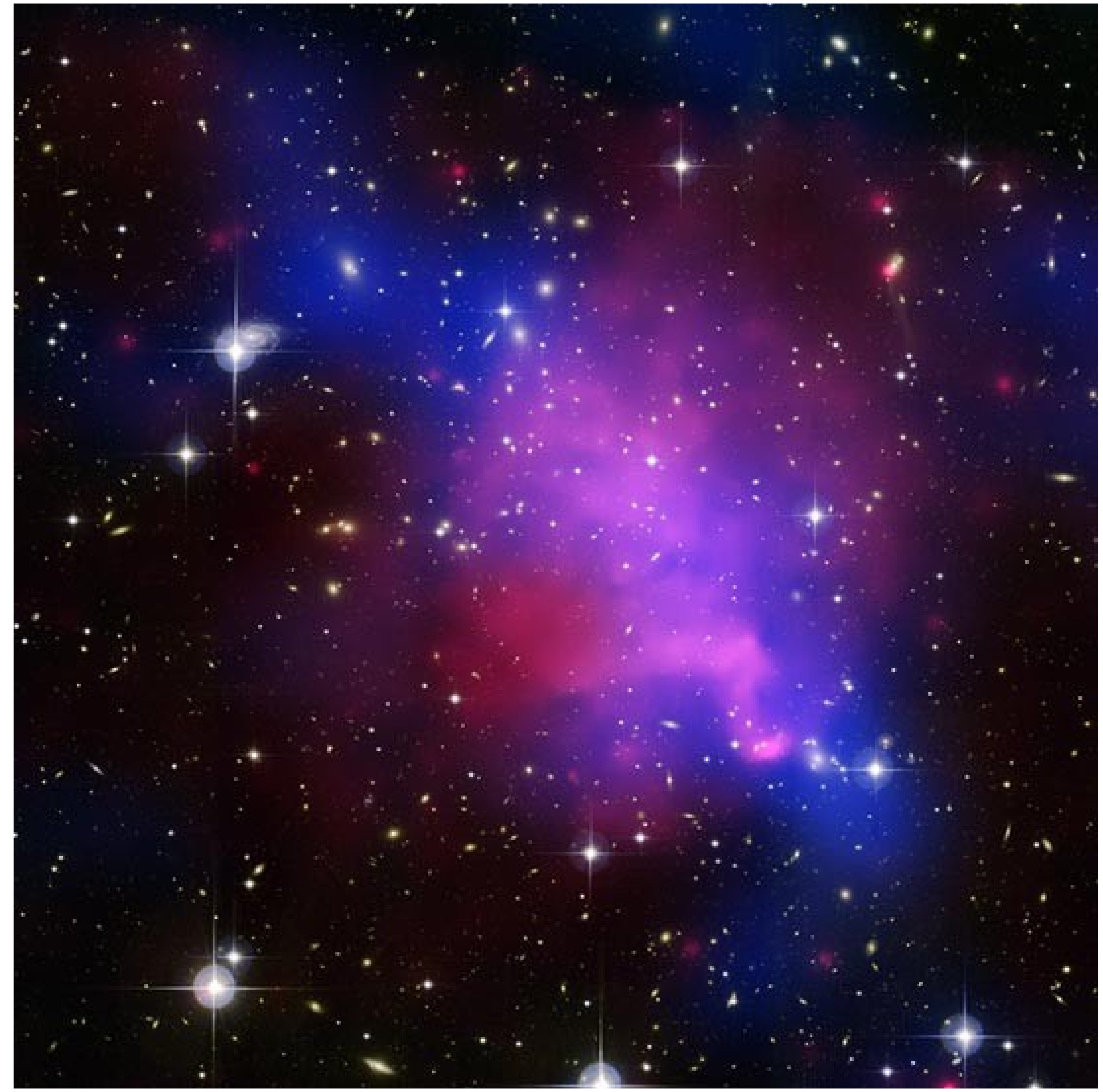
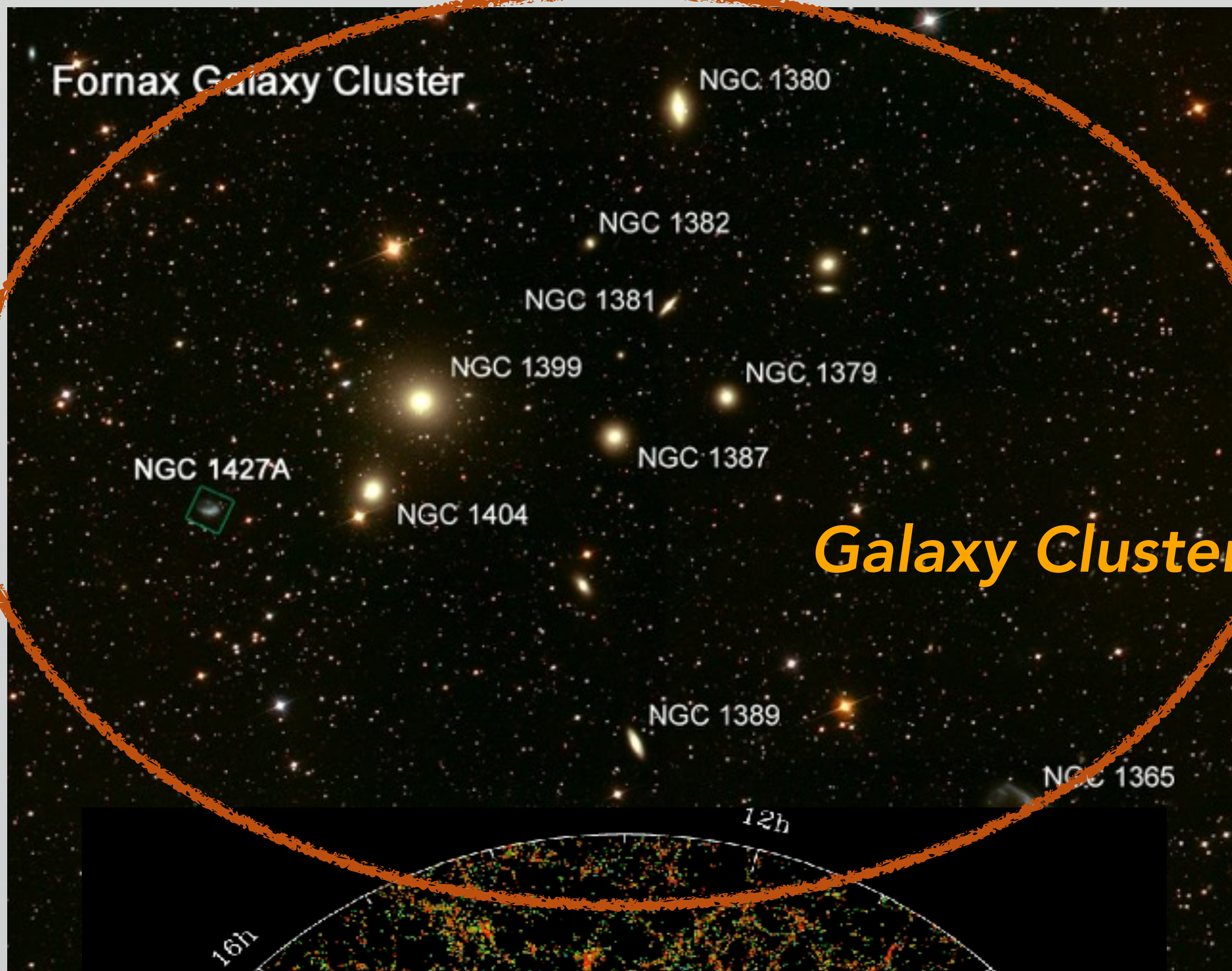
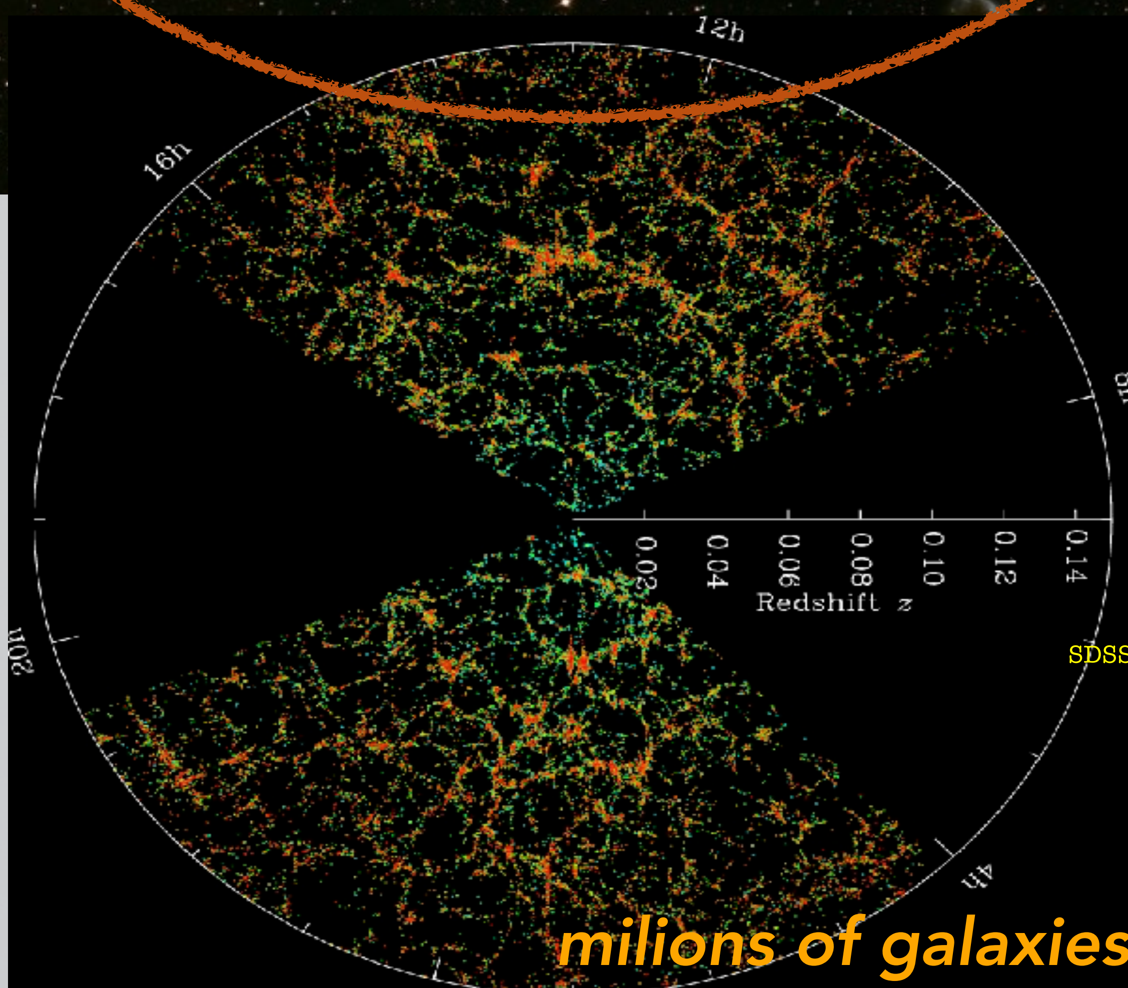


Abell 520

WHAT DO WE KNOW SO FAR?





'see through' ➜ **neutral**!

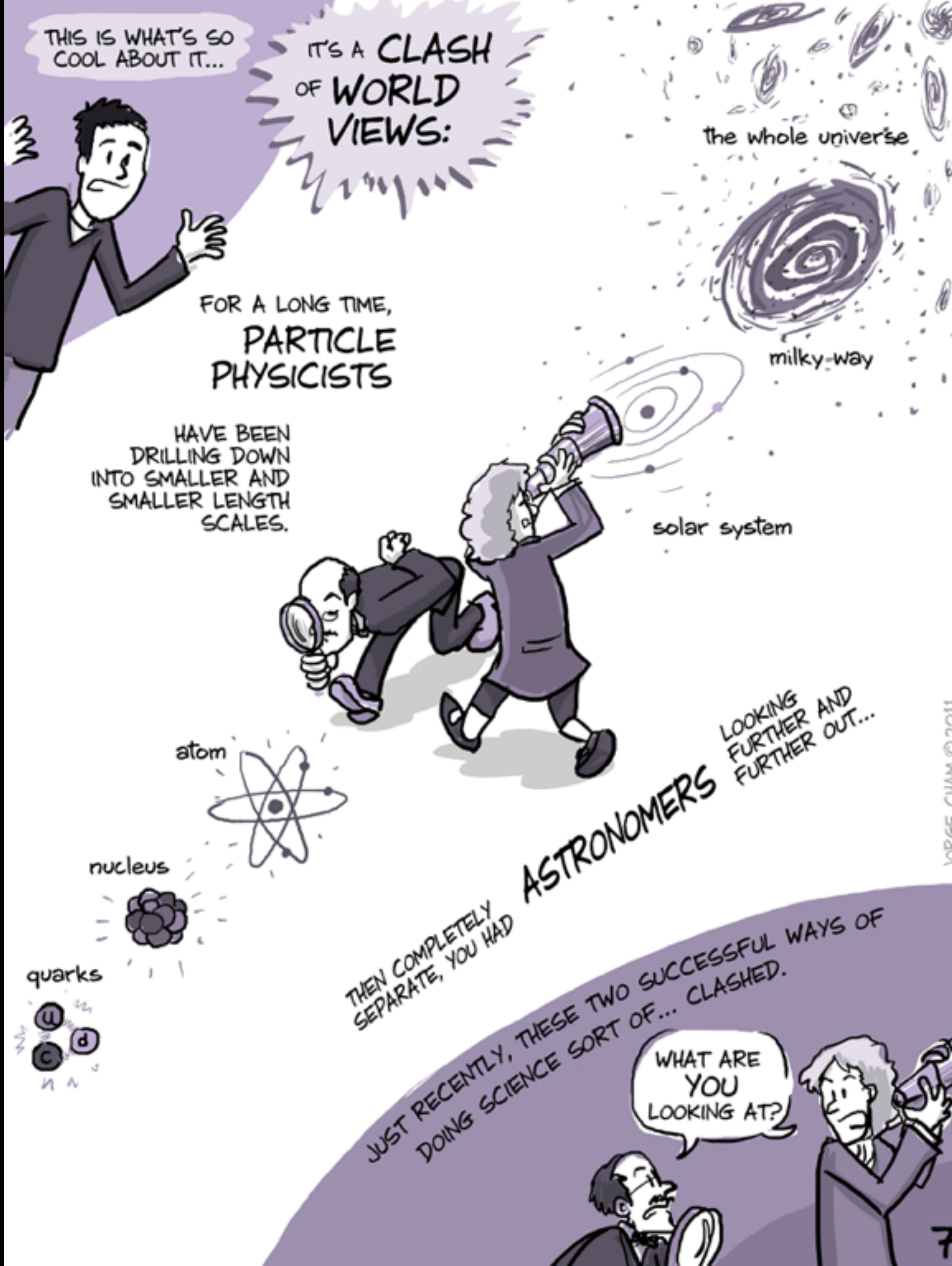
stable ➜ it was present throughout history of Universe

+ 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?



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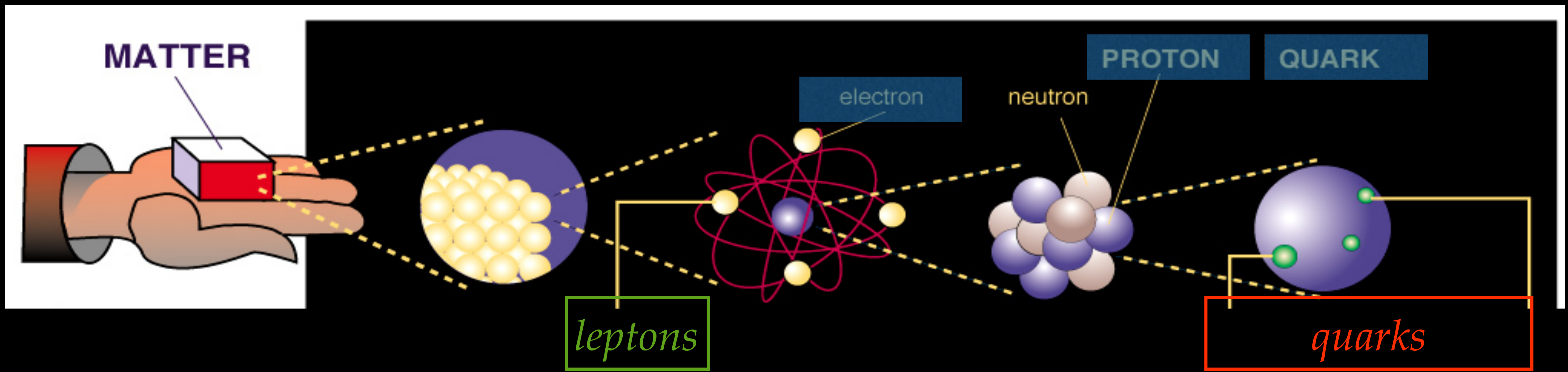

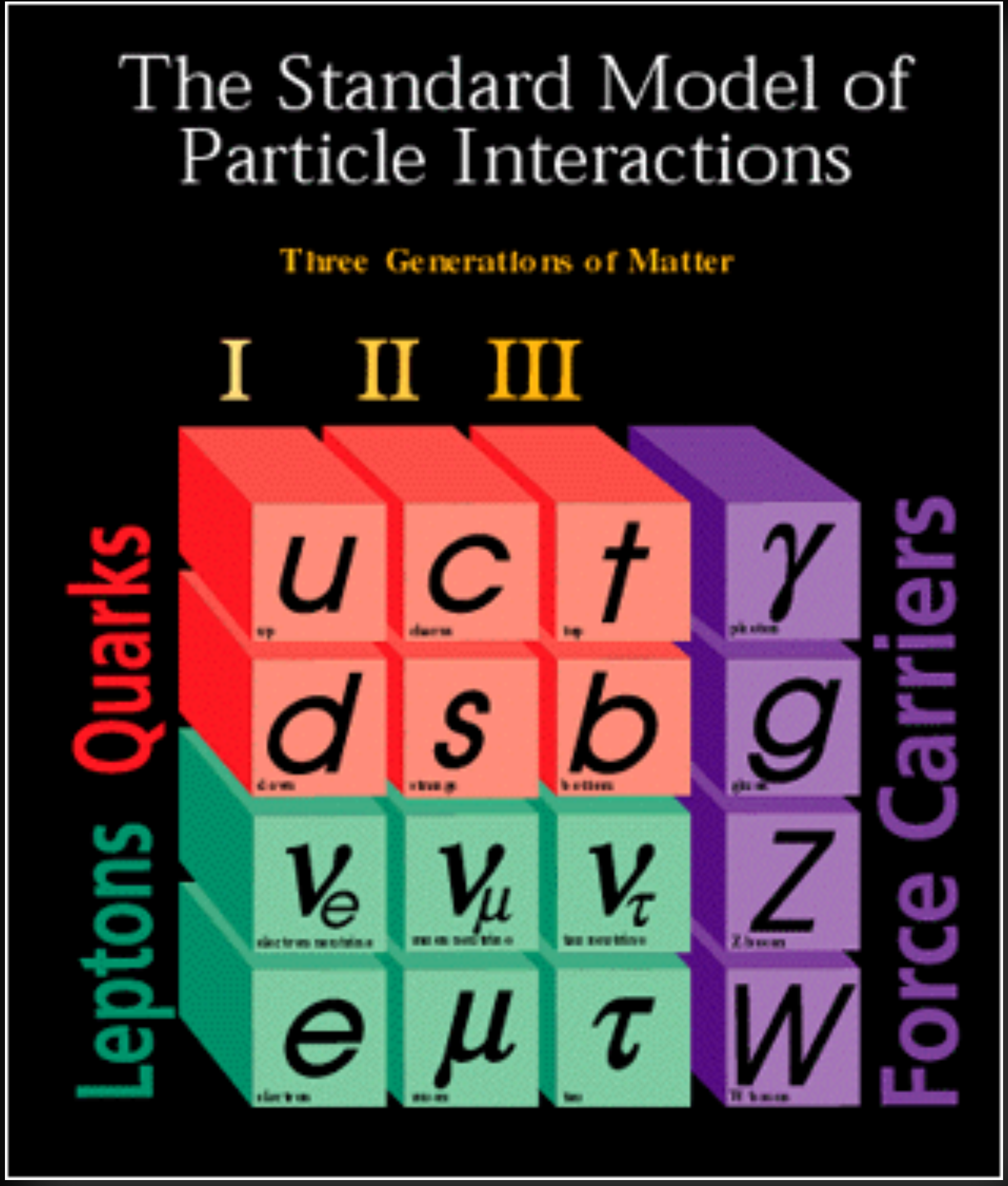

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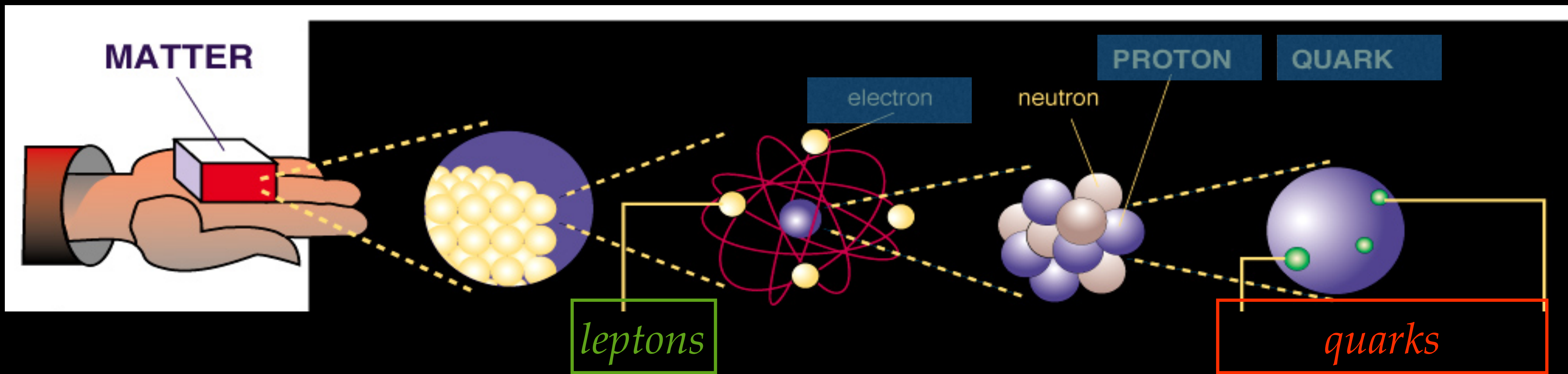
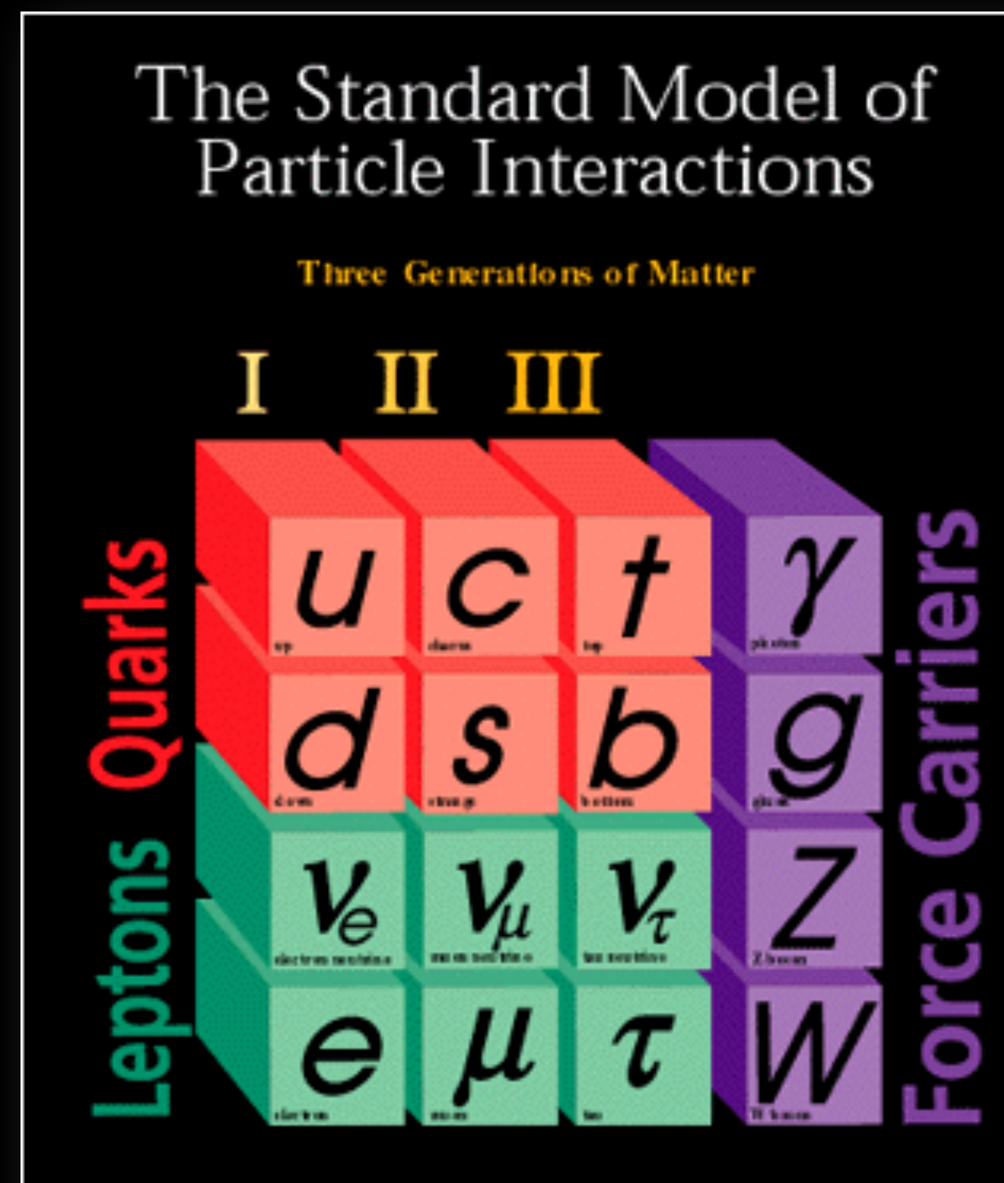


1. neutral
2. stable
3. heavy
4. 5x more abundant than usual mater
5. feeble interactions



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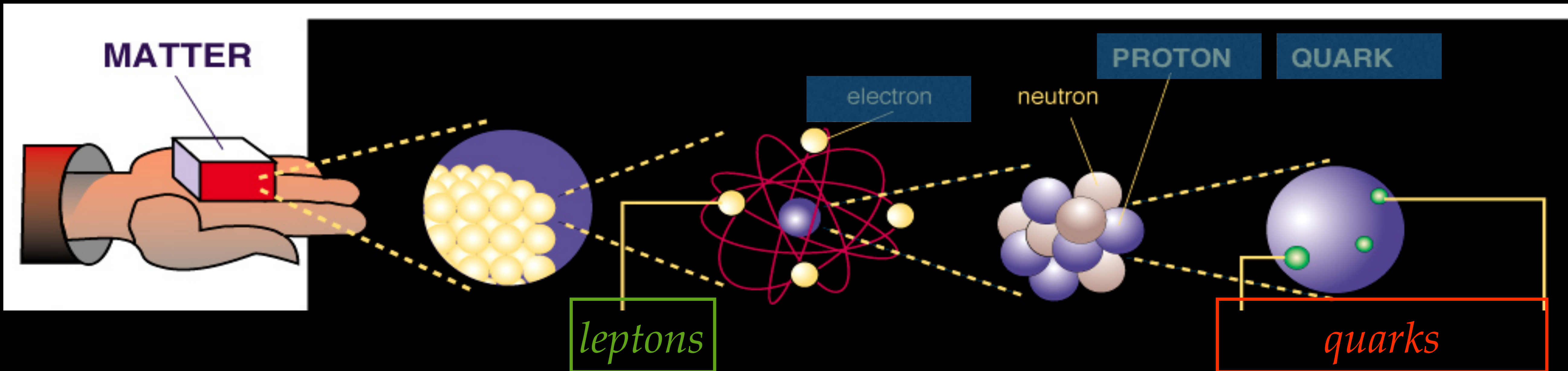

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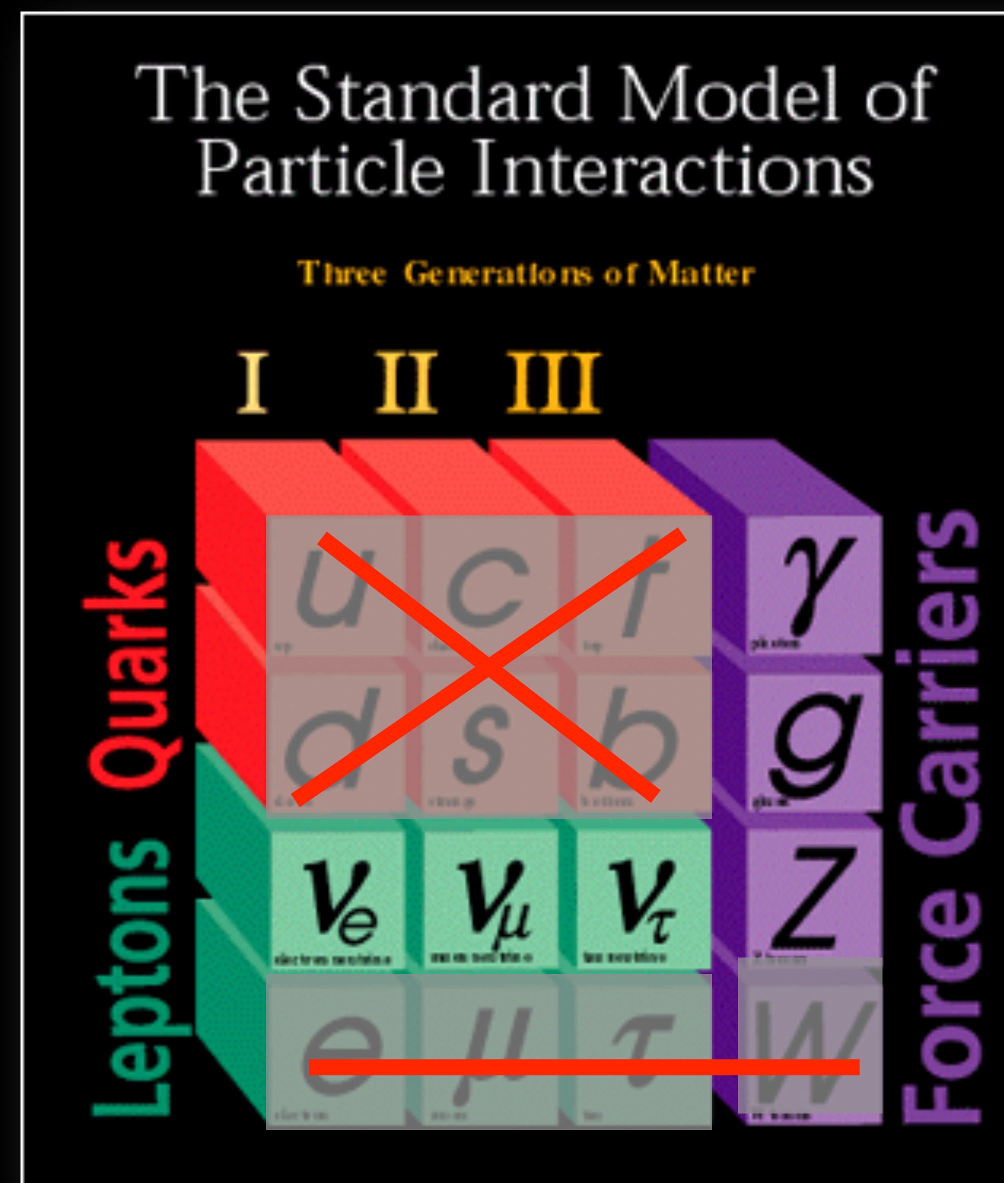

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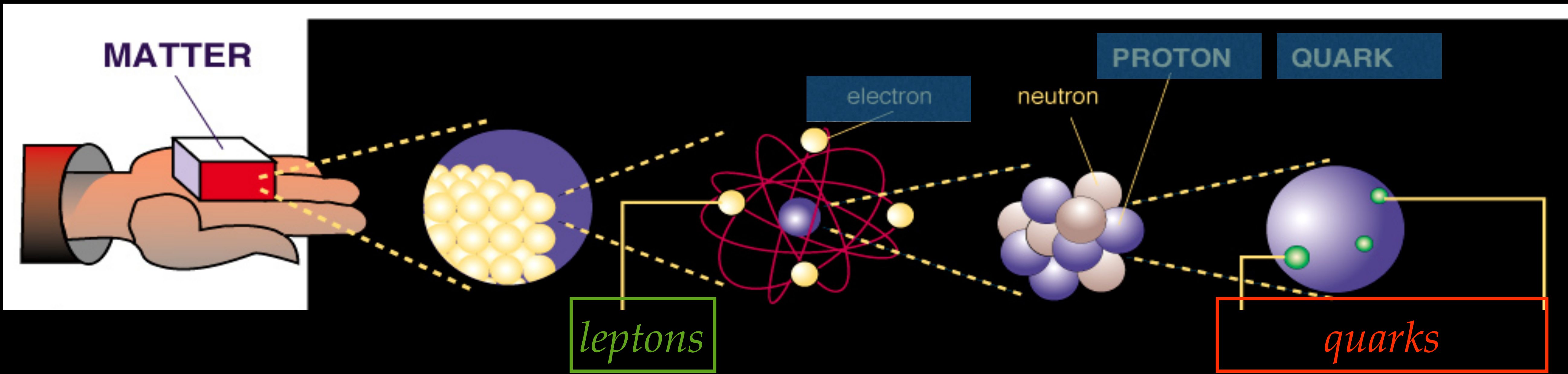

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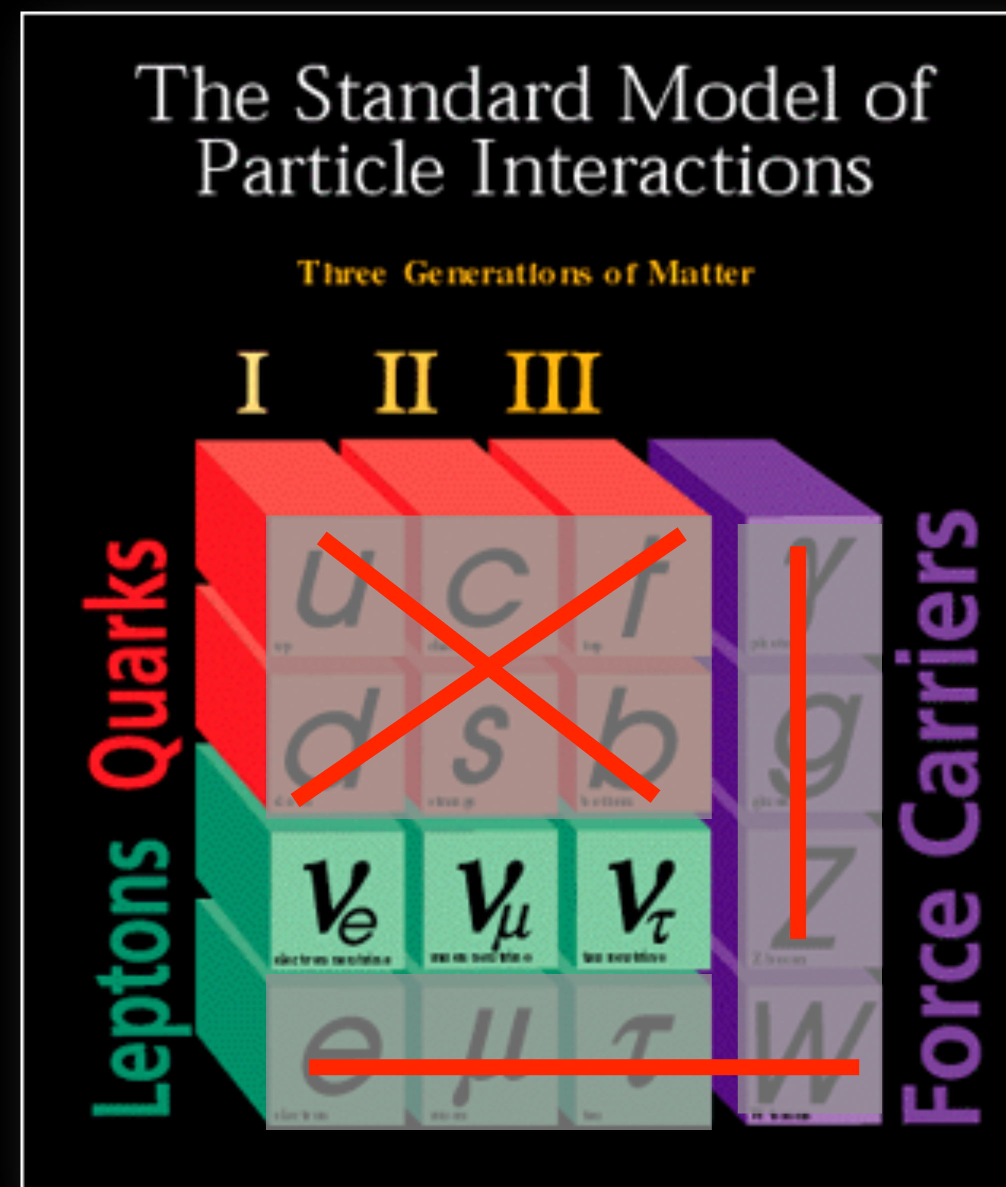

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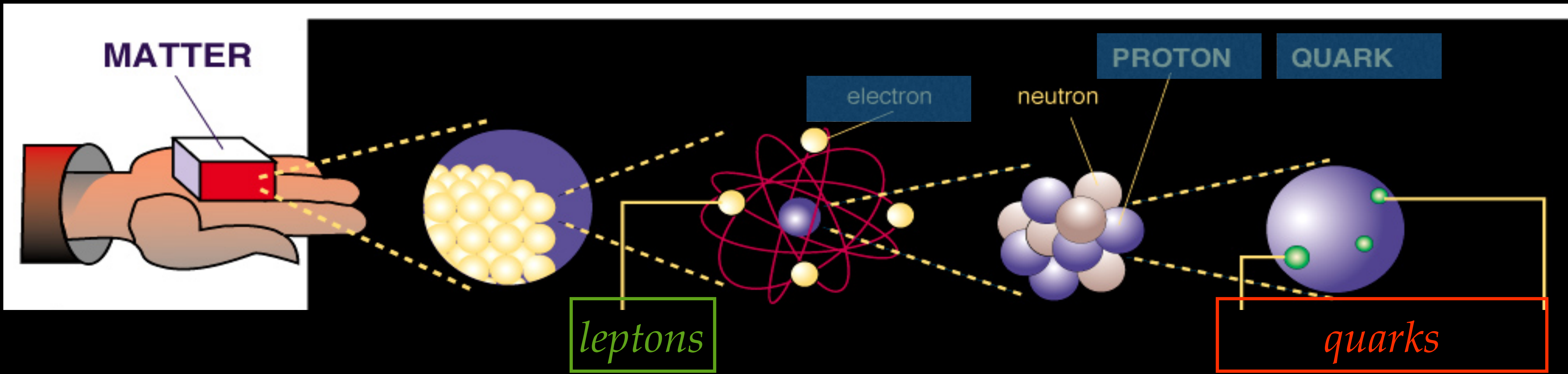
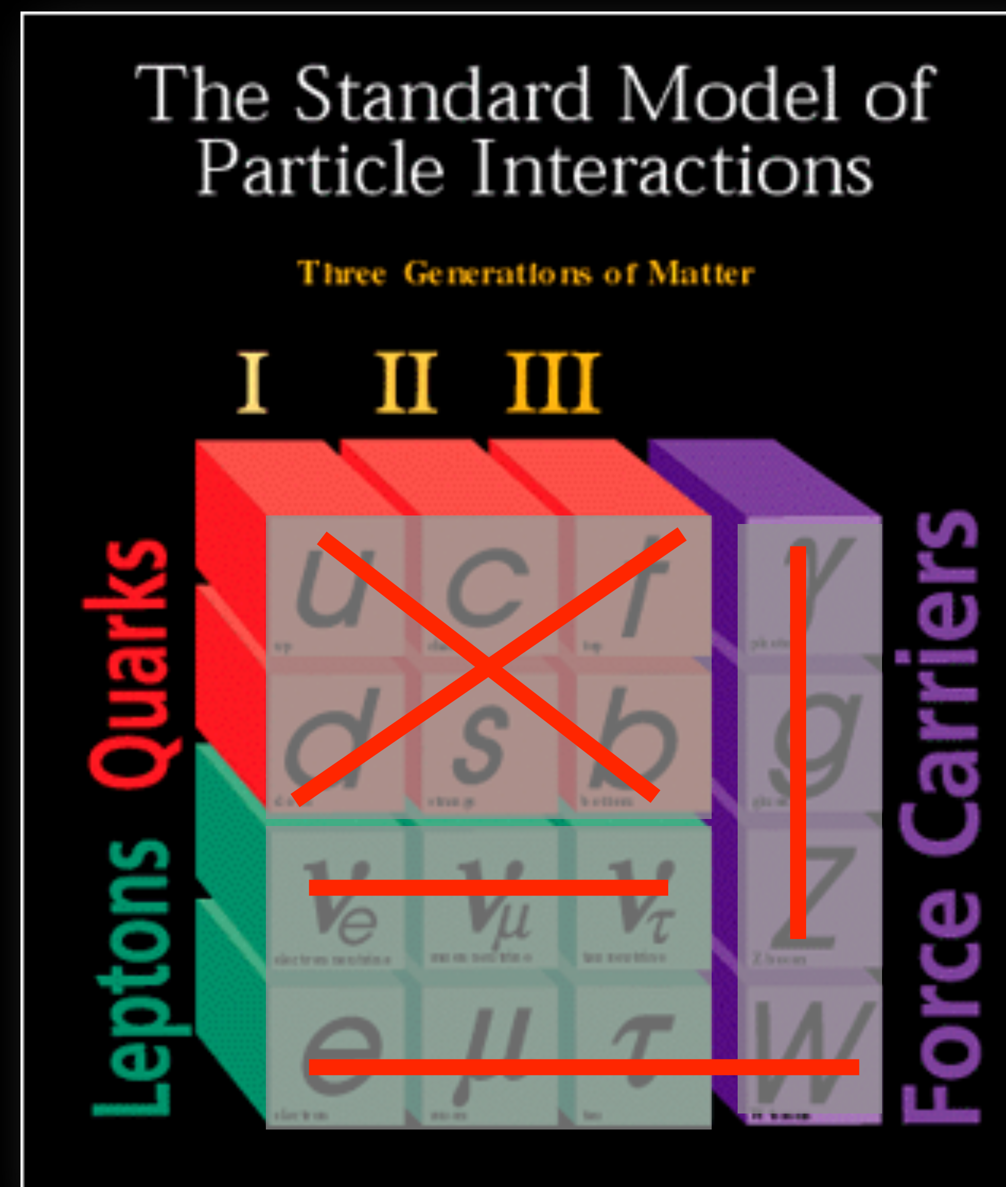


1. **neutral**
2. **stable**
3. **heavy**
4. 5x more abundant than usual mater
5. feeble interactions

→ needs to be a new particle!



THE MOST POPULAR CANDIDATES

"Weakly Interacting Massive Particles"

It means simply:

1. neutral
2. stable
3. heavy (~100x proton mass)
4. 5x more abundant than usual mater
5. feeble interacting

+ decoupled thermally!

THE MOST POPULAR CANDIDATES

Thermal decoupling:

The history of the Early Universe is *'thermal'*.
—> particles are in ***thermal equilibrium in the Early universe plasma***, and 'decouple' when their interaction rate becomes slower then the expansion rate of the Universe.

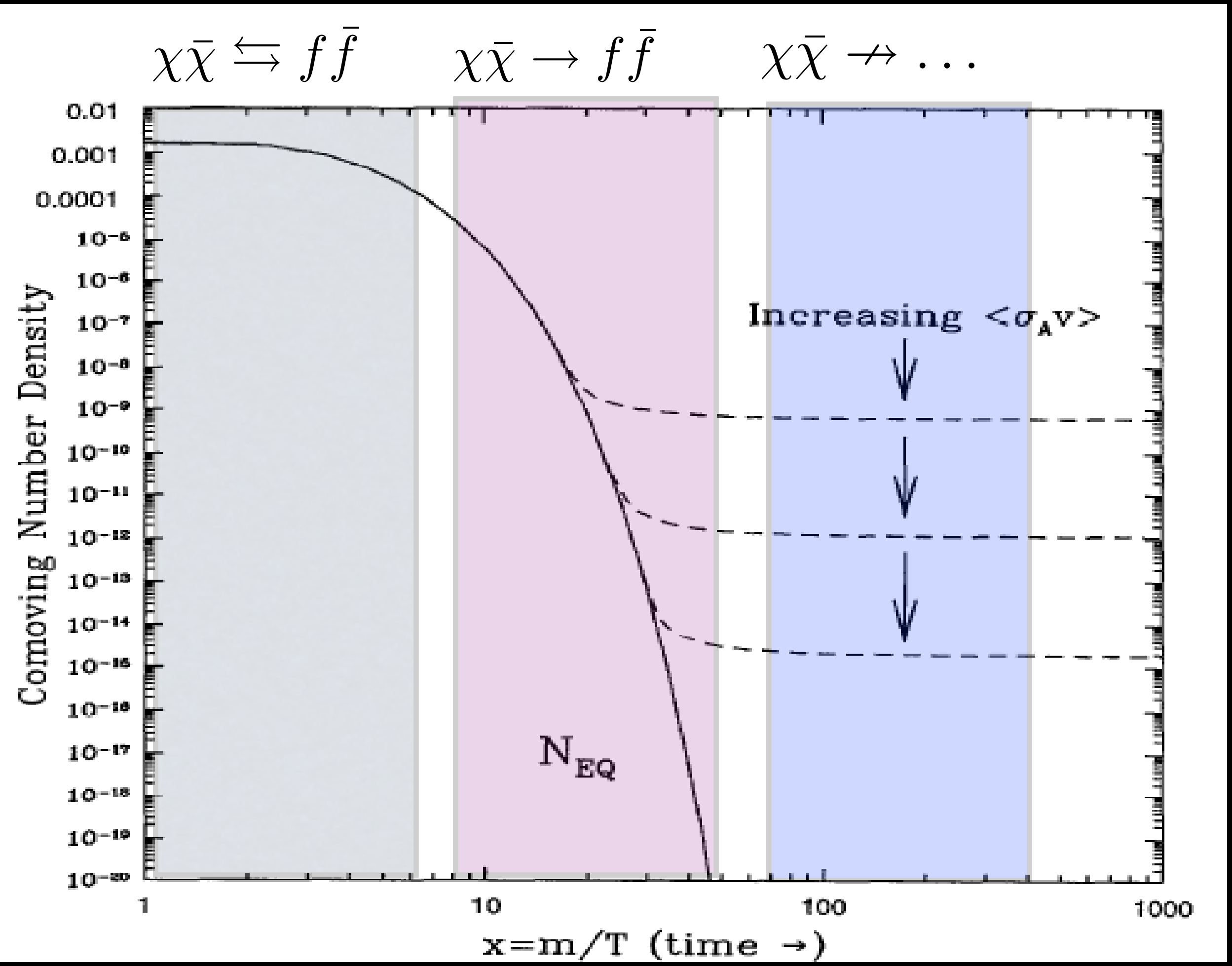
Thermal equilibrium arguments verified by the photon (CMB) & neutrino backgrounds, nucleosynthesis etc.

THE MOST POPULAR CANDIDATES

Thermal decoupling:

$\Omega_{DM} \leftrightarrow$ *thermal decoupling (WIMPs)*:

- initially DM is in equilibrium with thermal plasma;
- as the Universe expands
  → DM interaction rates drops below the expansion rate of the Universe,
  → DM decouples, setting Ω_{DM}.



- IF THE INTERACTION RATE IS WEAK-like and mass >~GeV
  Ω_{DM} depends mainly on $<\sigma v>$!
  The WIMP miracle

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It means simply:

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2. stable
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4. 5x more abundant than usual mater
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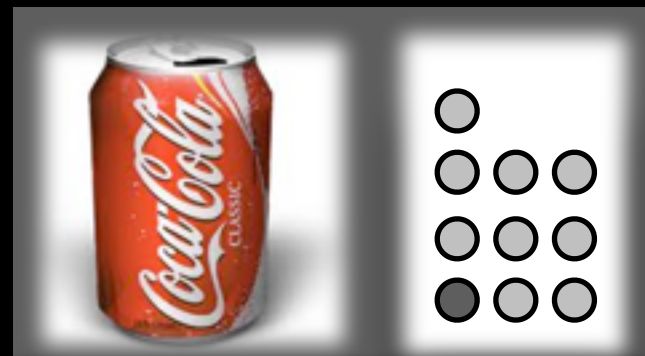
+ decoupled thermally!

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

BUT… HOW TO FIND IT?

BUT... HOW TO FIND IT?

lab:



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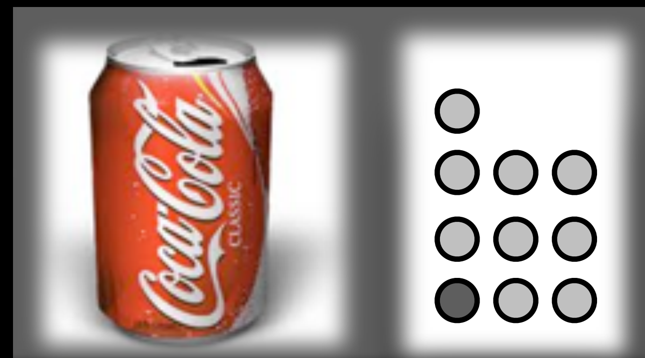
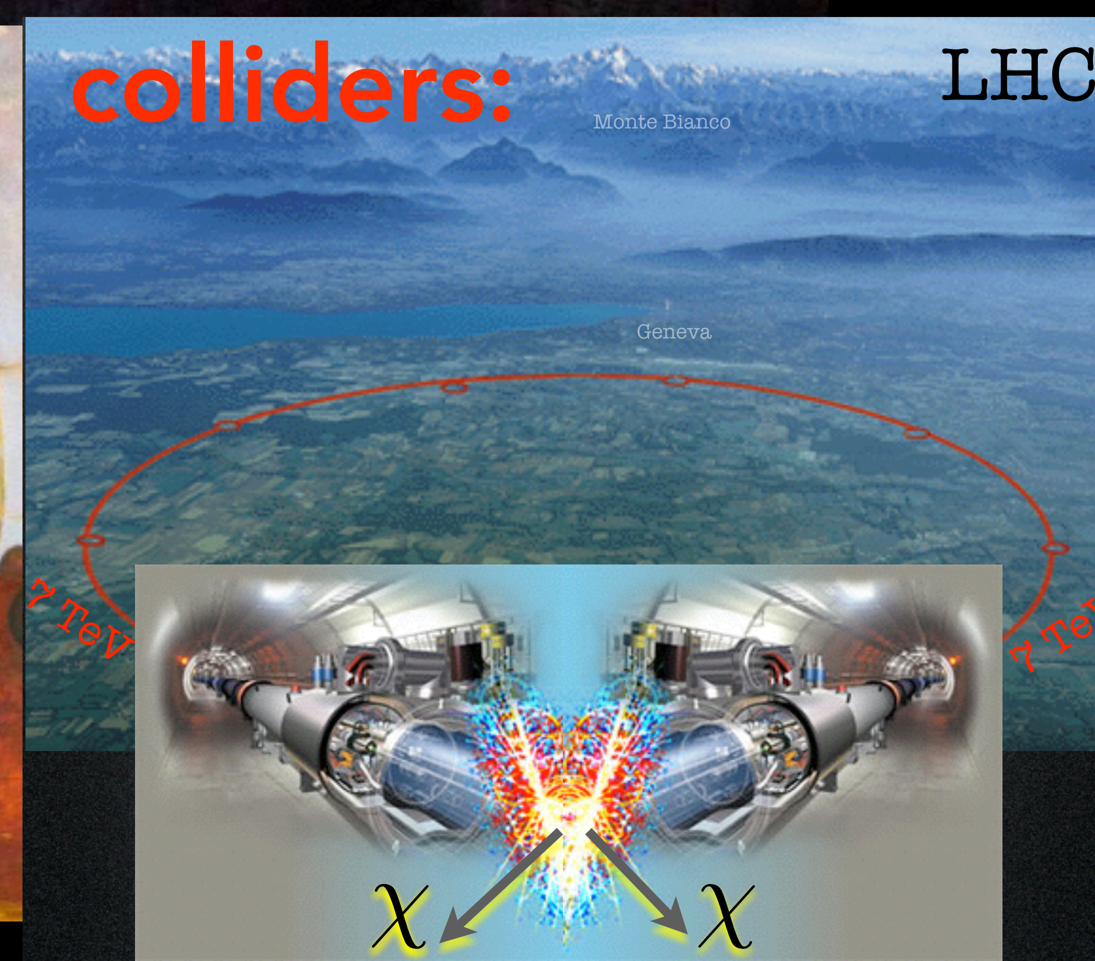
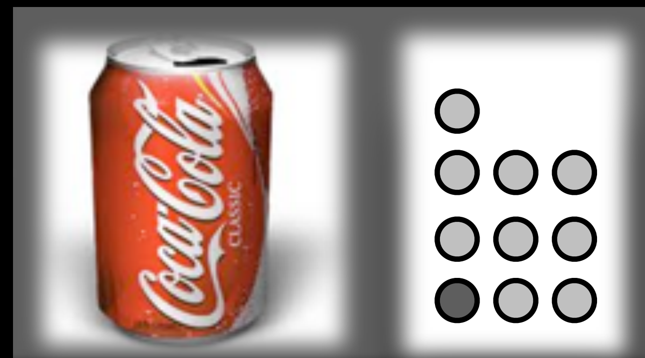
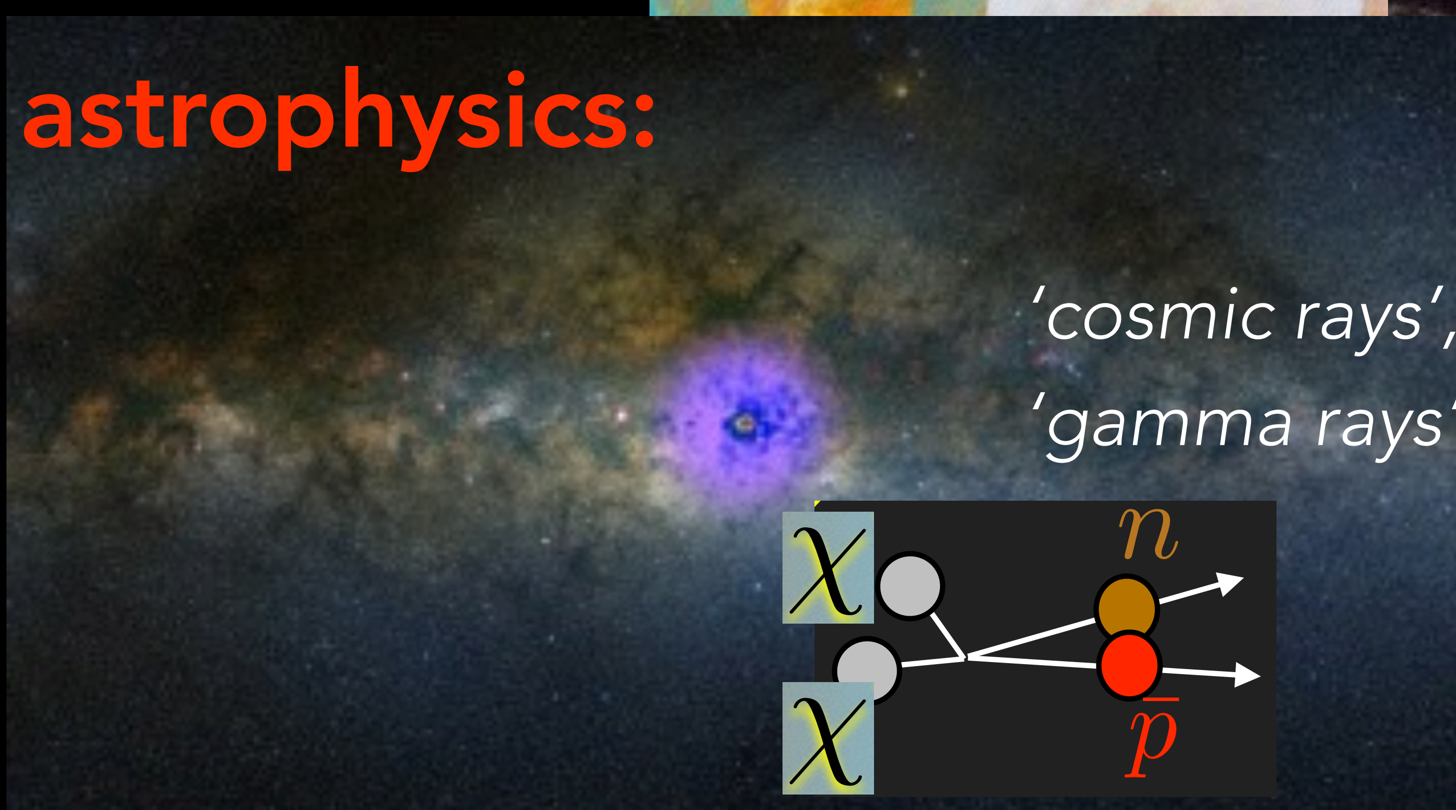


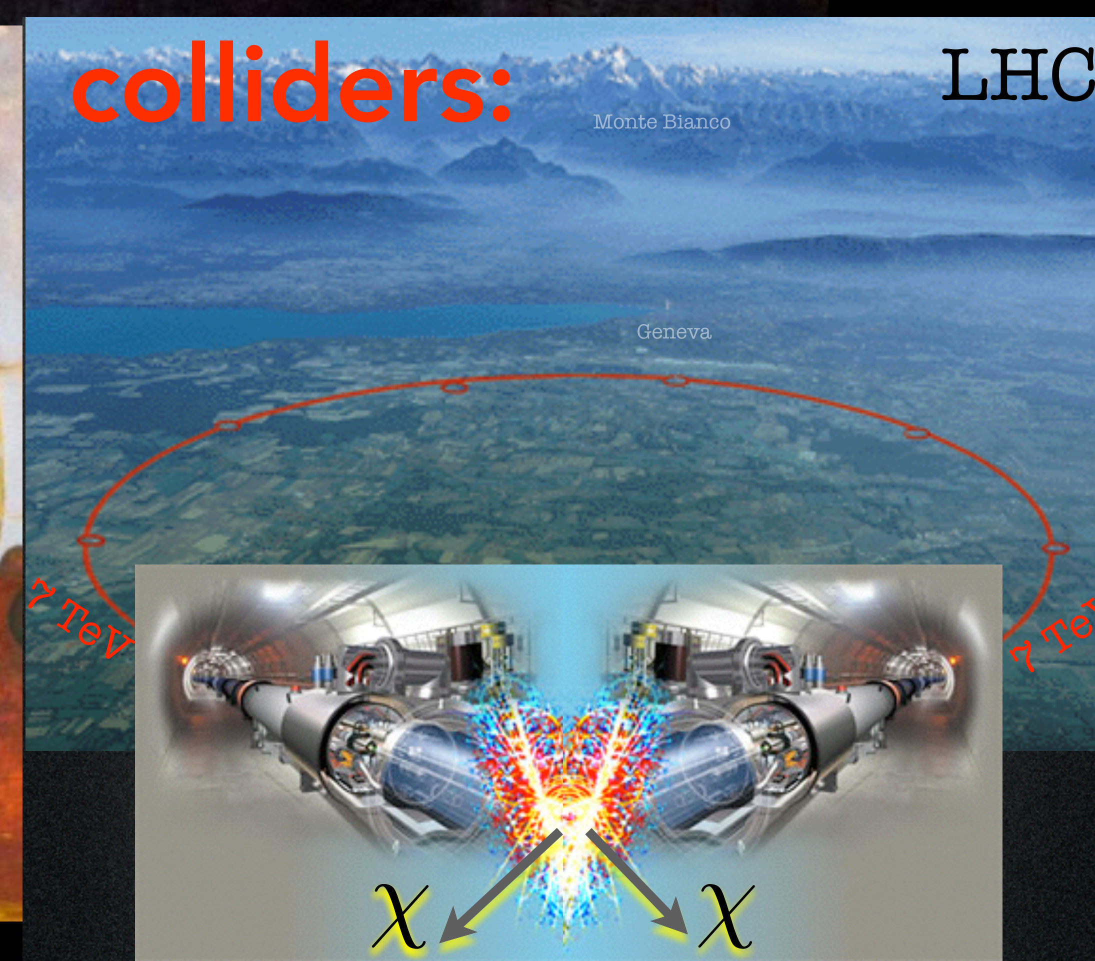


BUT... HOW TO FIND IT?

lab:







Extra Slides

What is Dark Matter?

- Dark matter is fundamentally different from normal matter. It is invisible using modern telescopes because it gives off no light or heat, and it appears to interact with other matter only gravitationally. In contrast, luminous matter is everything commonly associated with the universe: the galaxies, stars, gas and planets.

What do we mean by dark matter and dark energy?

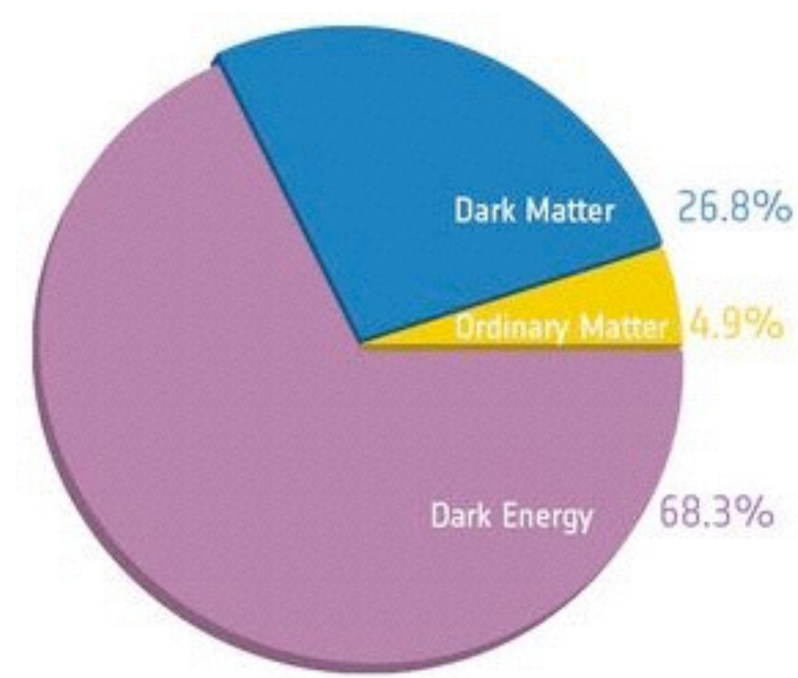
Dark matter and dark energy have *never been directly observed*, but they *seem to be the simplest way to explain **observed motions** in the Universe.*

•Dark matter is the name given to the **invisible** mass which **surrounds galaxies** and whose **gravity governs the observed motions of stars and gas**.

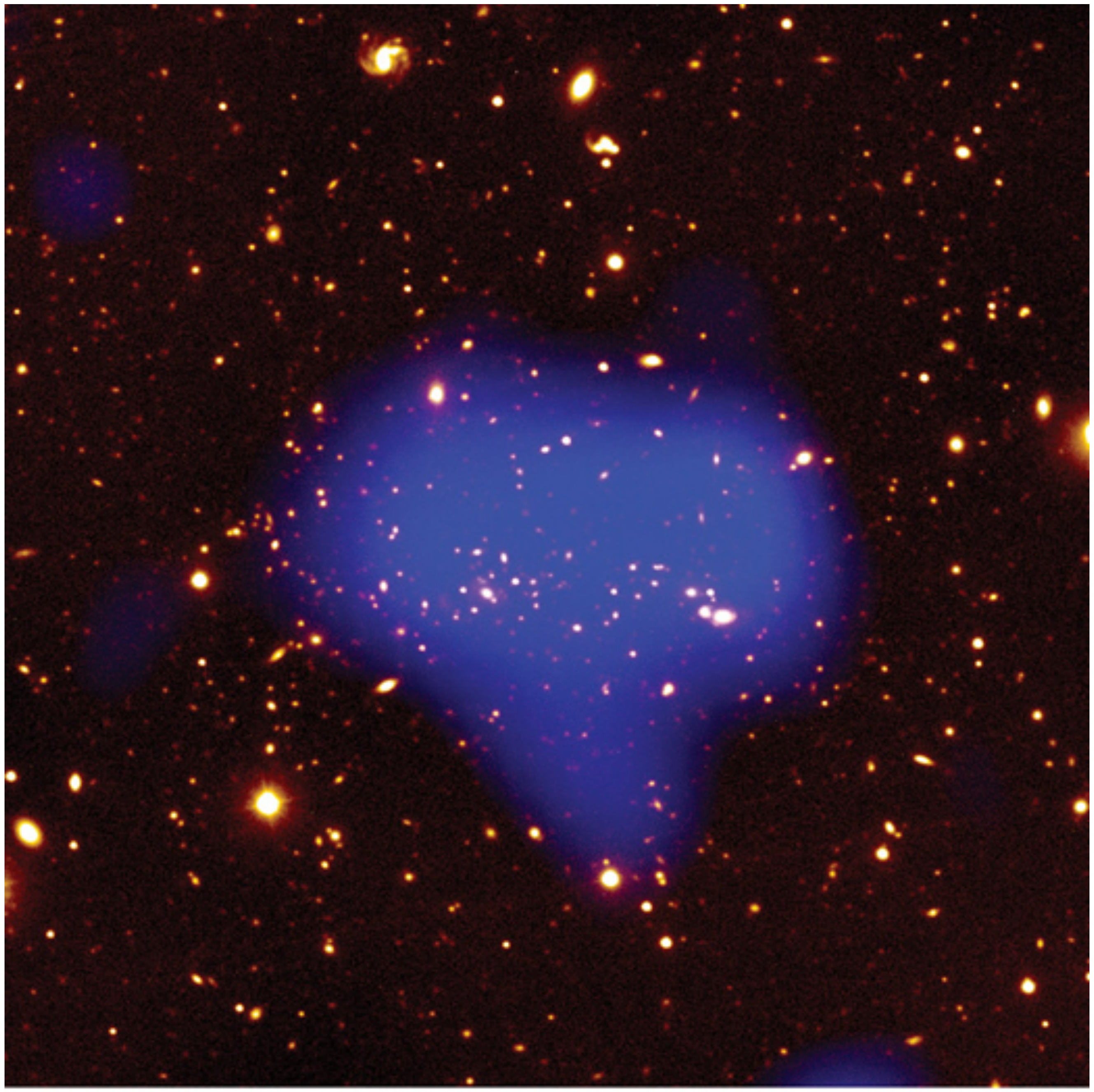
•Dark energy is whatever is causing the expansion of the universe to **accelerate**.

'Dark' -- just means that we do not know what makes ~95% of the Universe.

Gravity is universal... we cannot yet pinpoint the (particle physics) nature of DM.



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

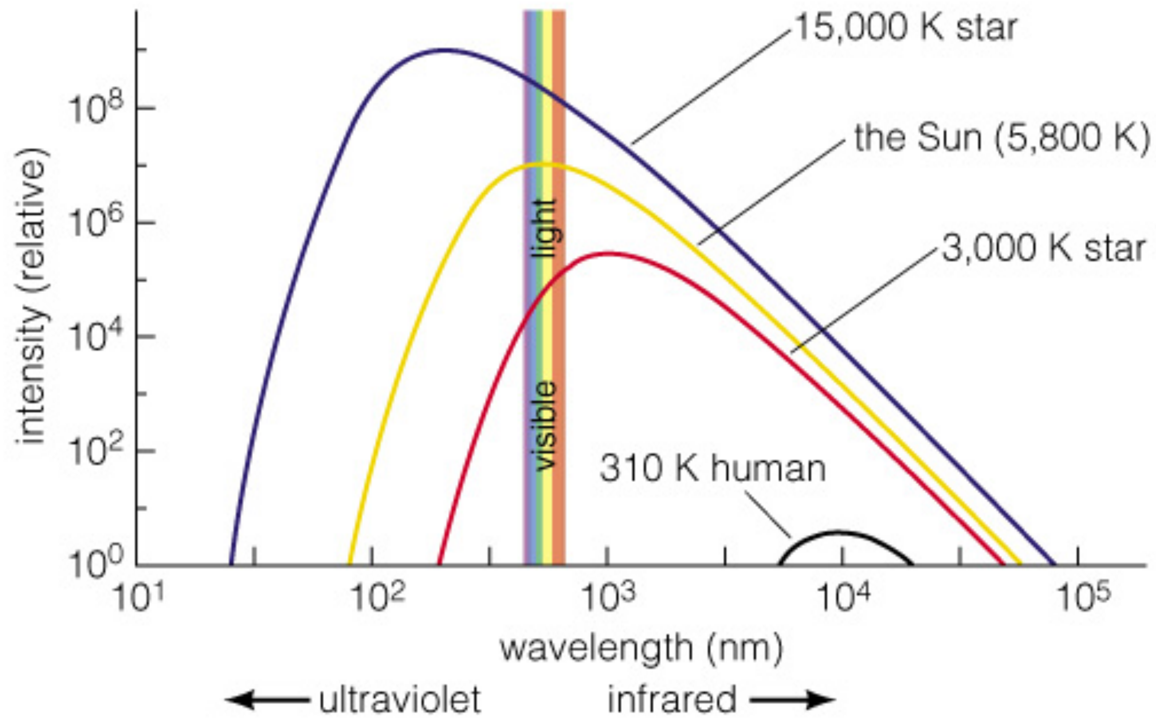


2) Clusters contain large amounts of gas. The gas is extremely hot (100 million Kelvin) and it therefore emits very energetic, X ray photons:

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

- 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

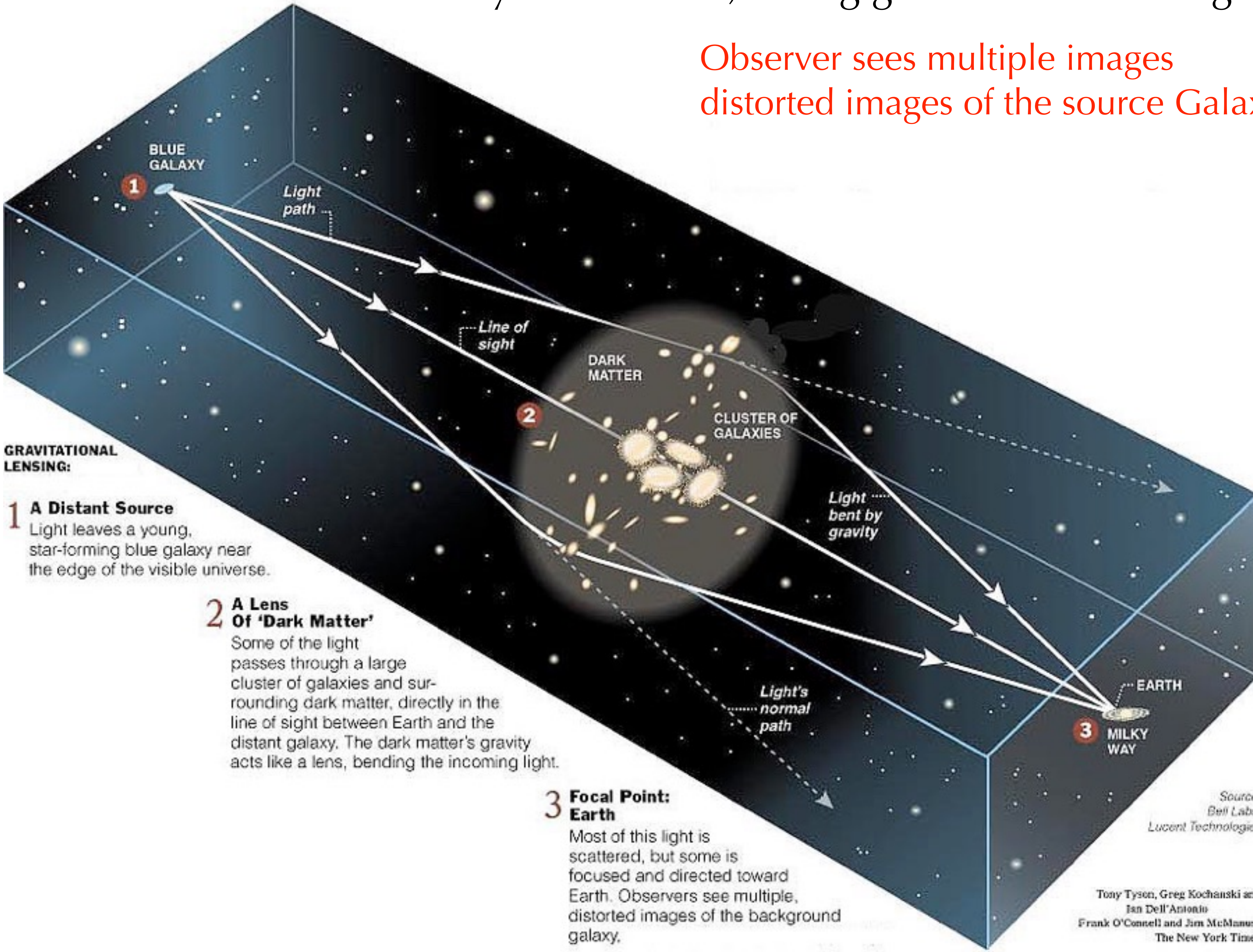
How fast molecules of gas are moving is connected to the amount of gravity they feel: ***stronger the gravity, faster the gas is moving and hotter it is.***

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

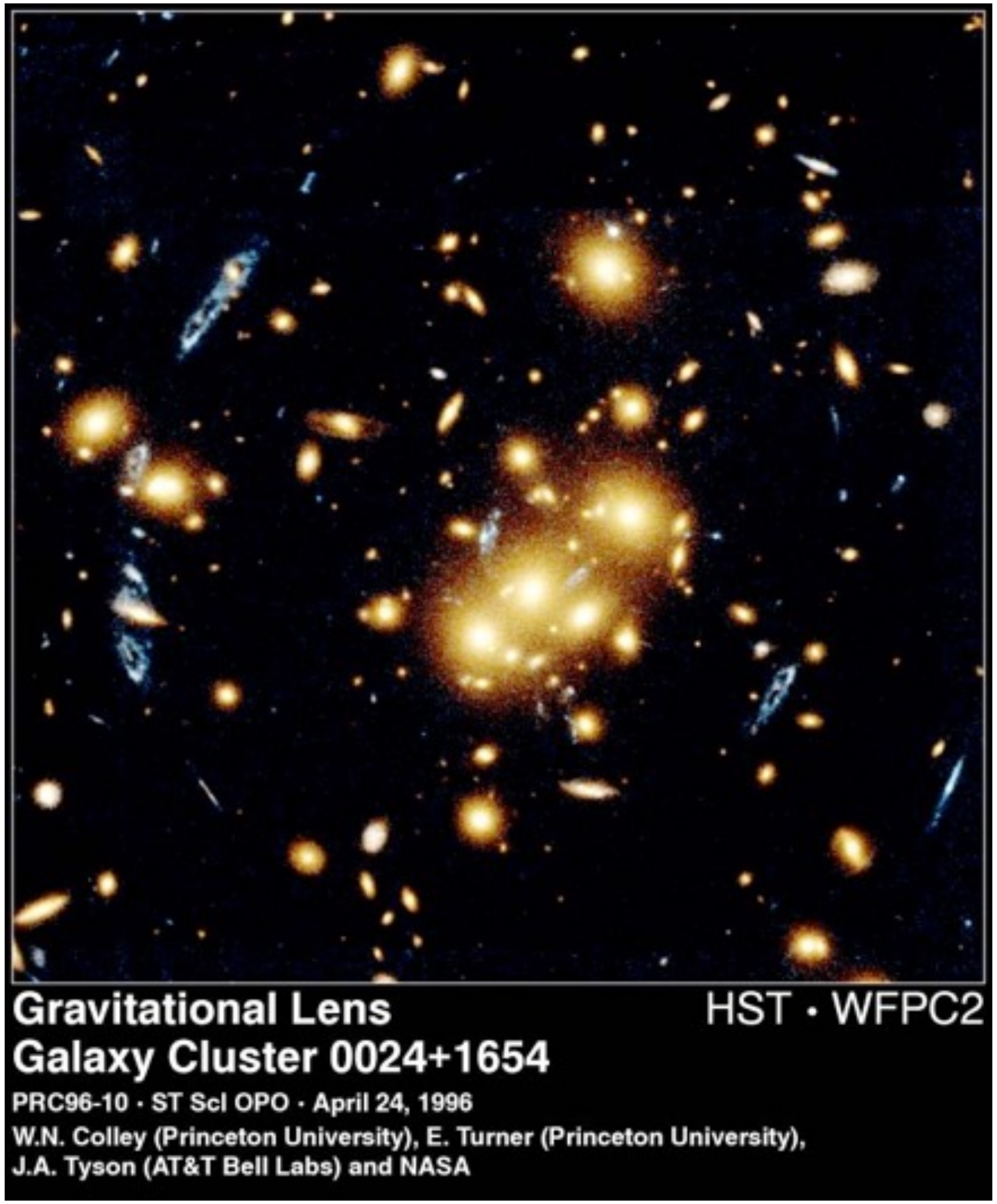
And again, it turns out, dark matter has to be around.

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

Observer sees multiple images distorted images of the source Galaxy.



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



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.