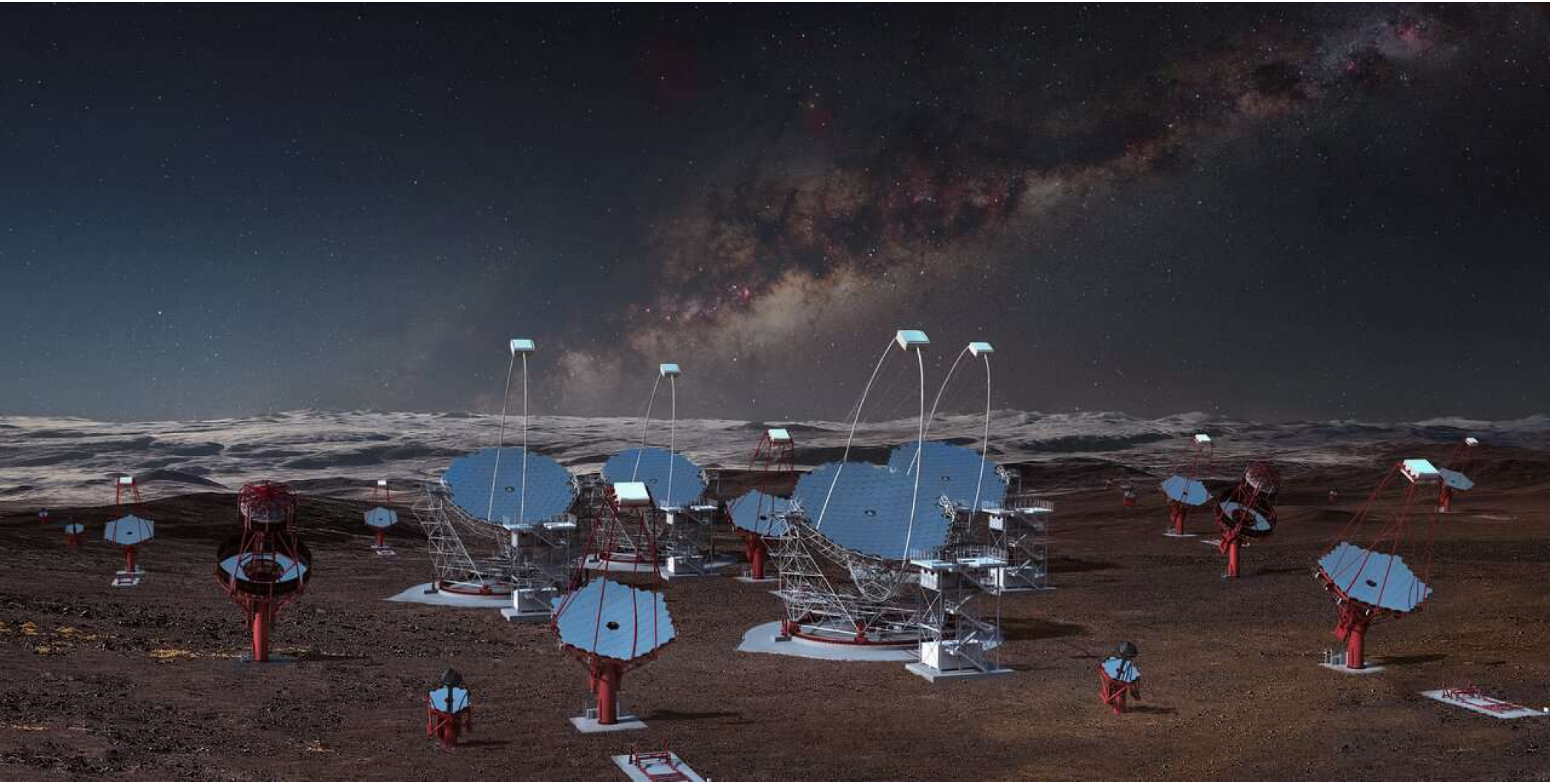


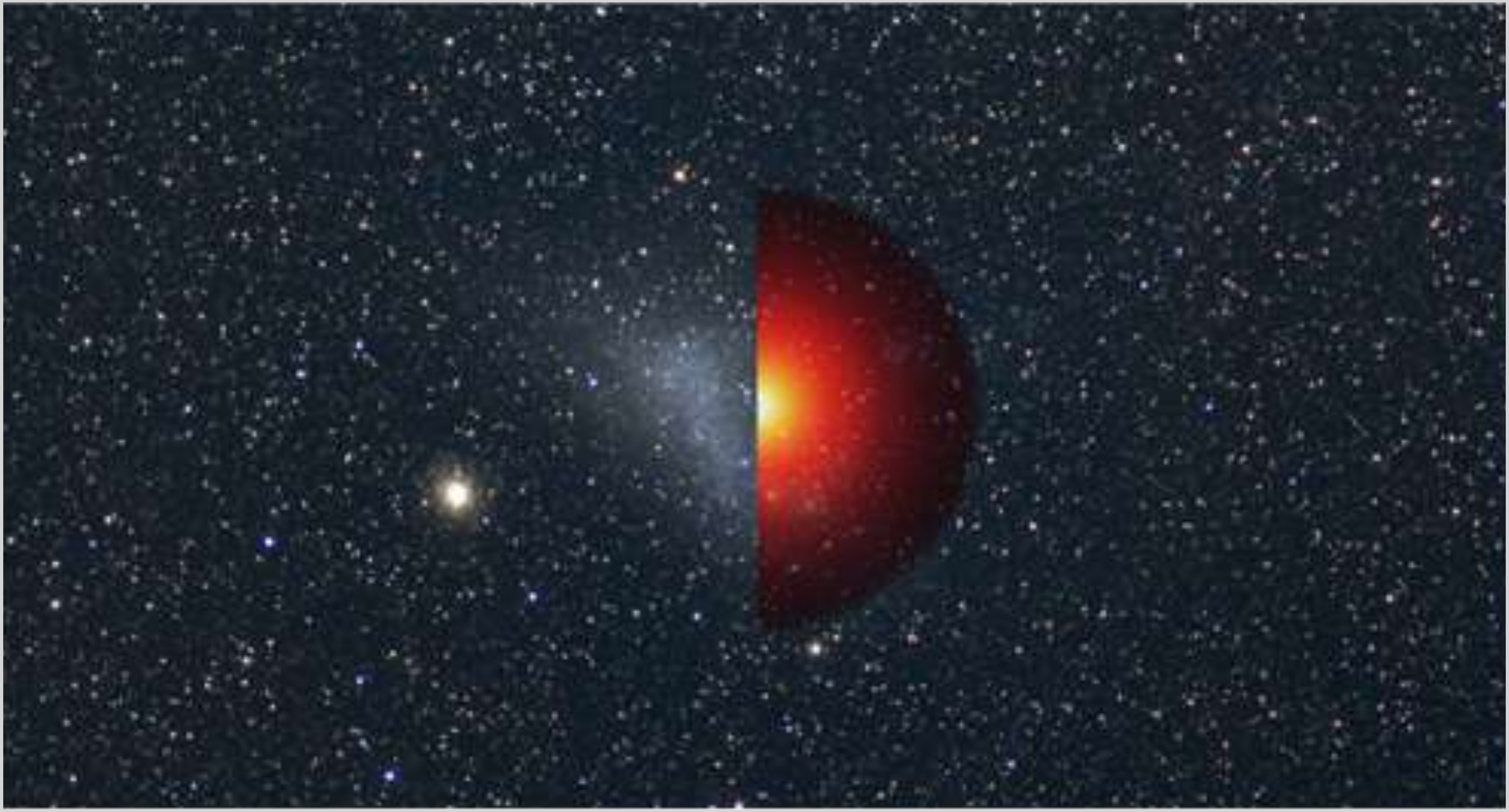
Latin-American School on CTA Science

March 27-31, 2023

São Paulo, Brazil

ICTP-SAIFR/IFT-UNESP

Dark matter - evidence



Gabrijela Zaharijas

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

Outline

1. Pre history *a detour*
2. (gravitational) evidence for dark matter
3. DM candidates
4. Experiments
5. Signal & Targets
6. The gamma-ray sky (astro ‘backgrounds’)
7. Data Analysis strategy
8. Examples of search in particular targets (WIMPs)
   - Galactic center
   - dSphs
   - Galaxy clusters

Today

On Wed

Our pre-history lecture starts 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

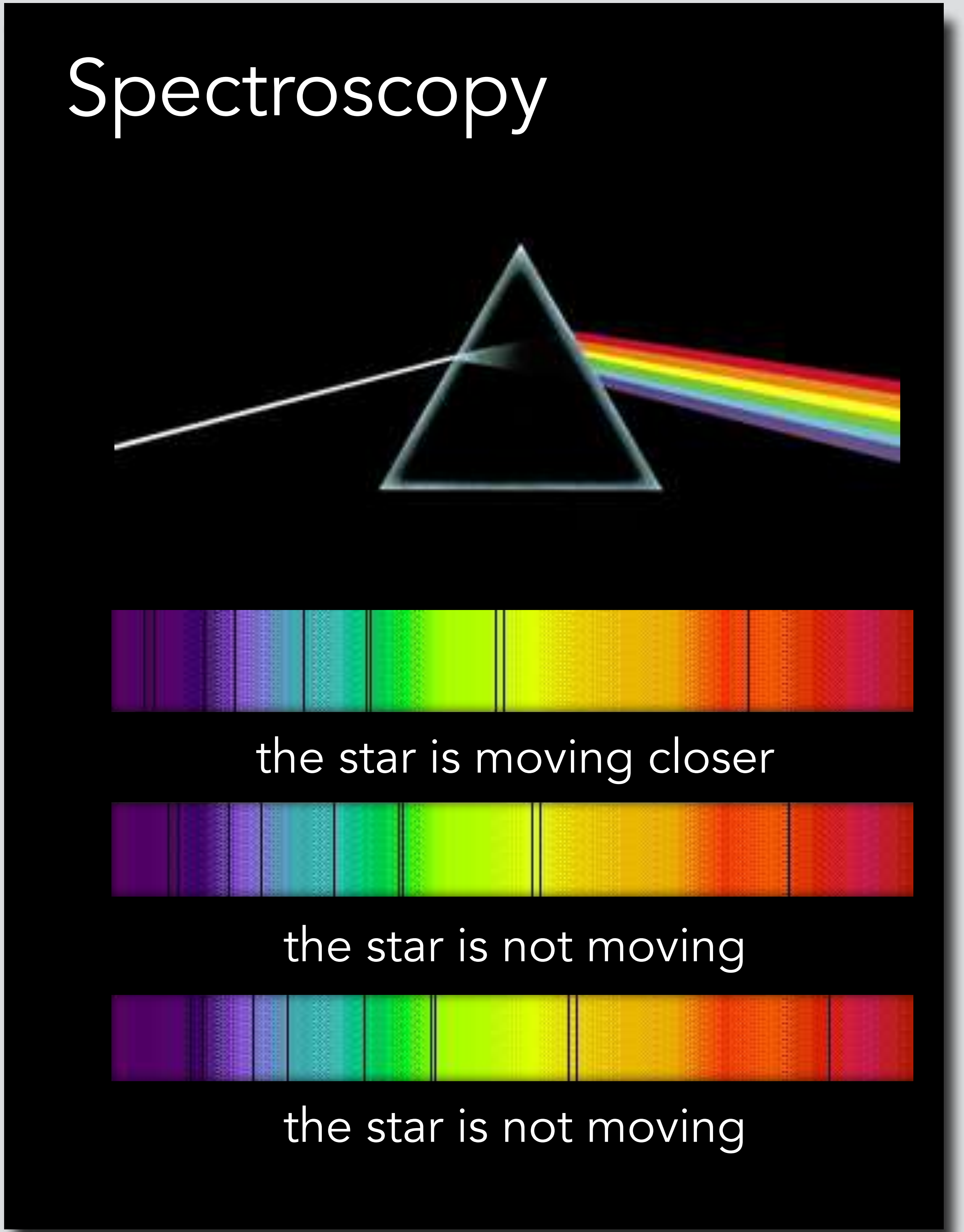
1777 VARIABLES IN THE MAGELLANIC CLOUDS.

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?

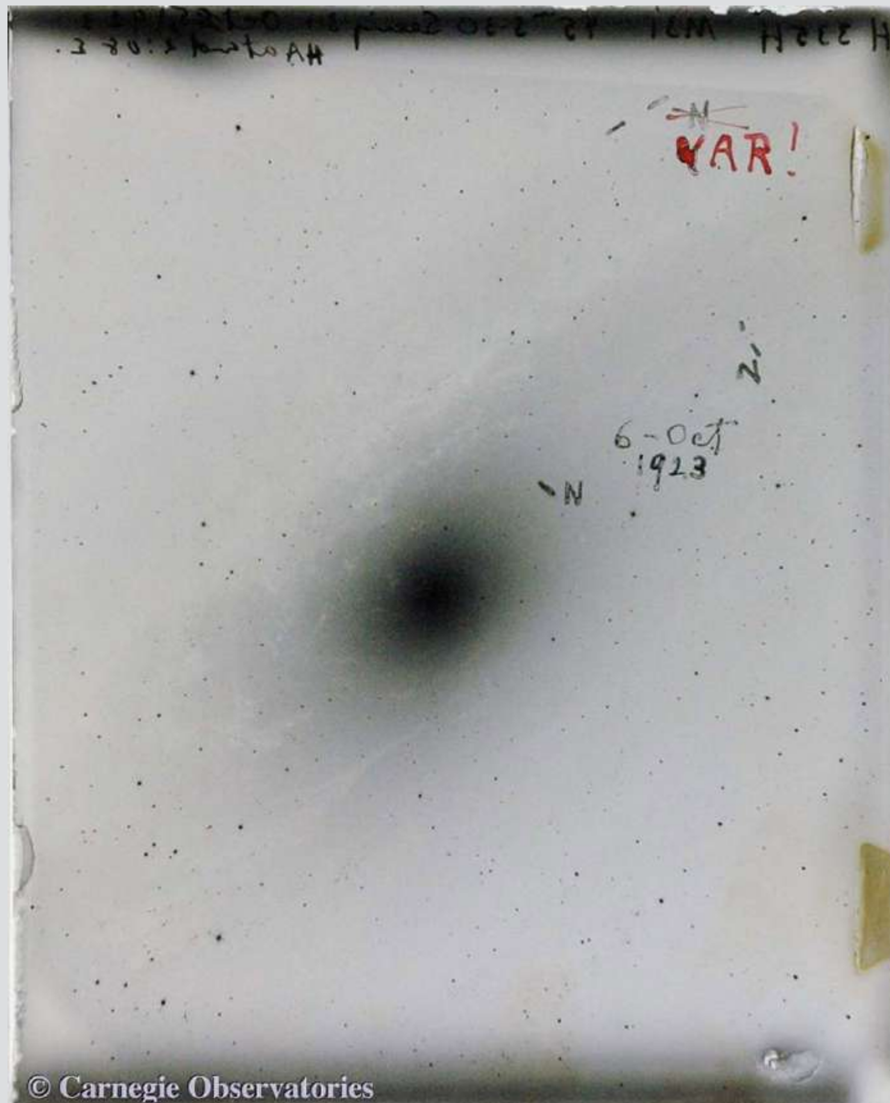
Are nebulae extra-galactic objects?

Heber Curtis
(1872-1942)

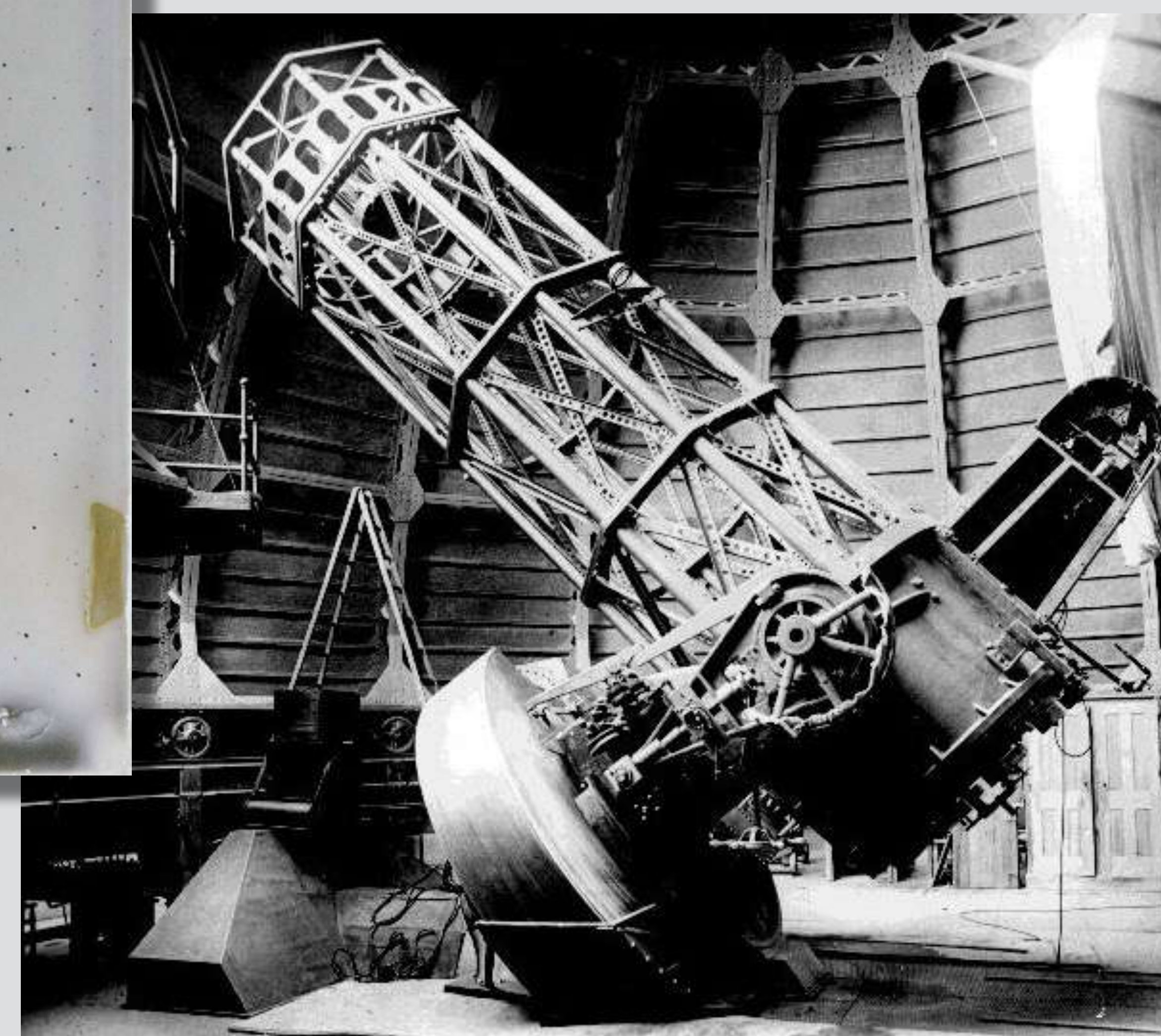
Baird Auditorium, Smithsonian National Museum of Natural History, Washington D.C.

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

Edwin Hubble
(1889-1953)

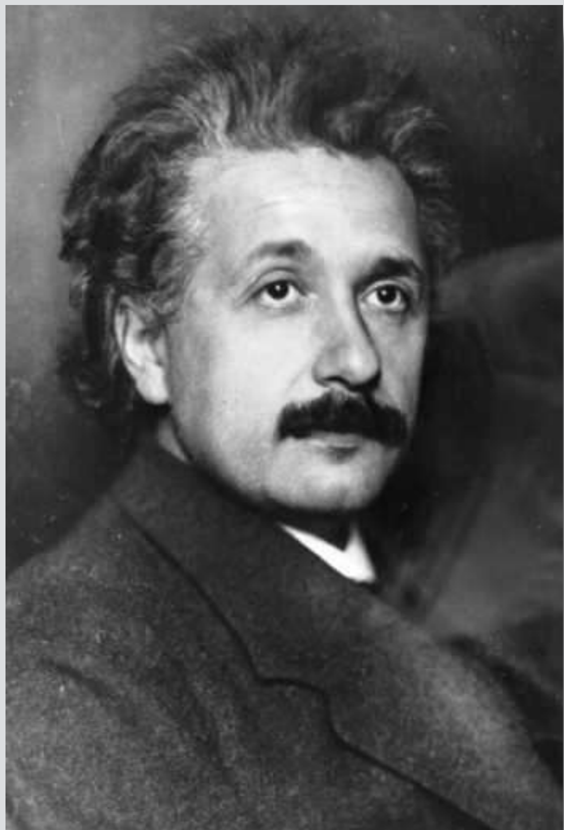


Andromeda nebula becomes Andromeda ***galaxy***!



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.

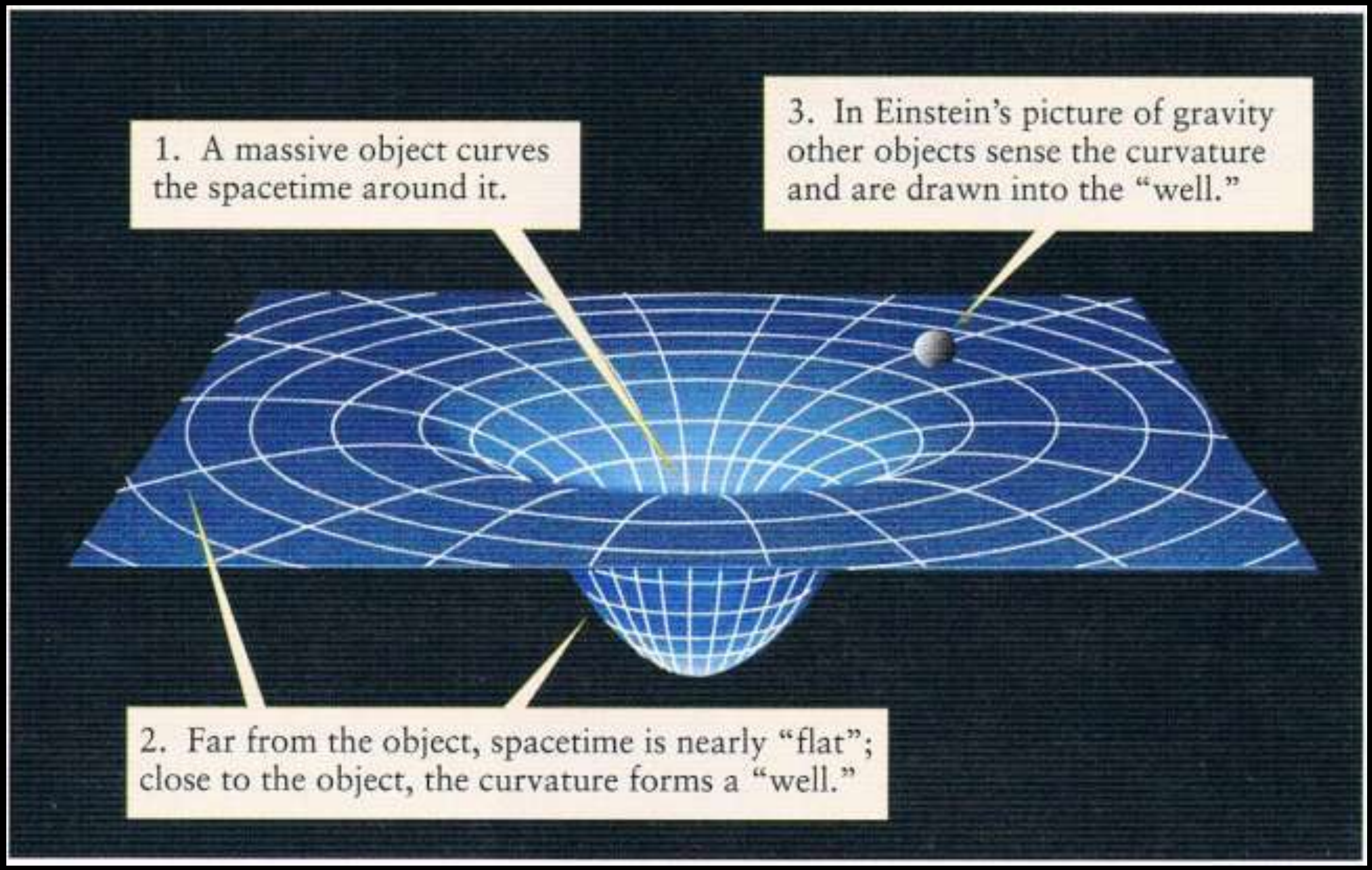
1. ***Die Grundlage der allgemeinen Relativitätstheorie; von A. Einstein.***

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)

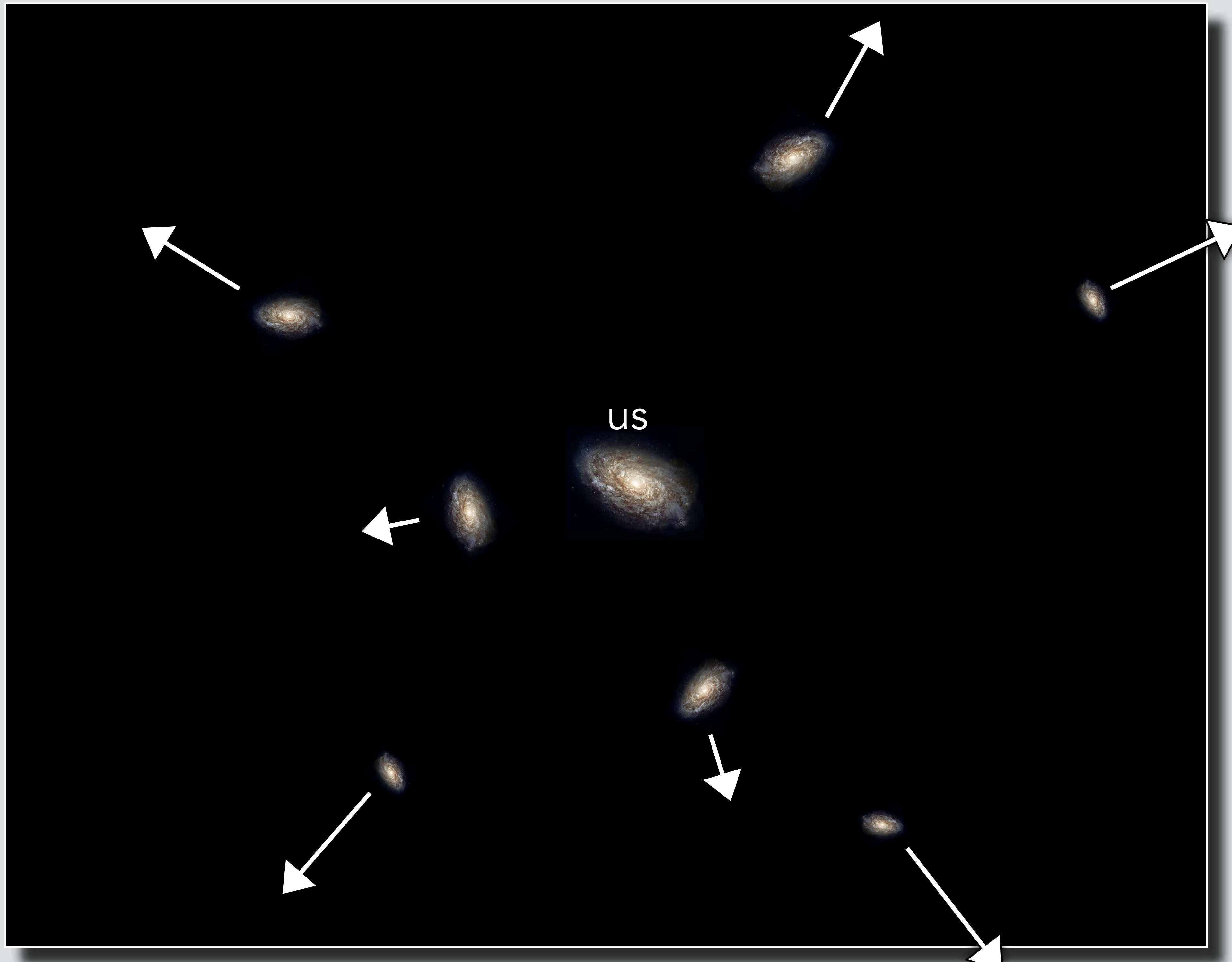
Georges Lemaître
(1894-1966)

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)

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

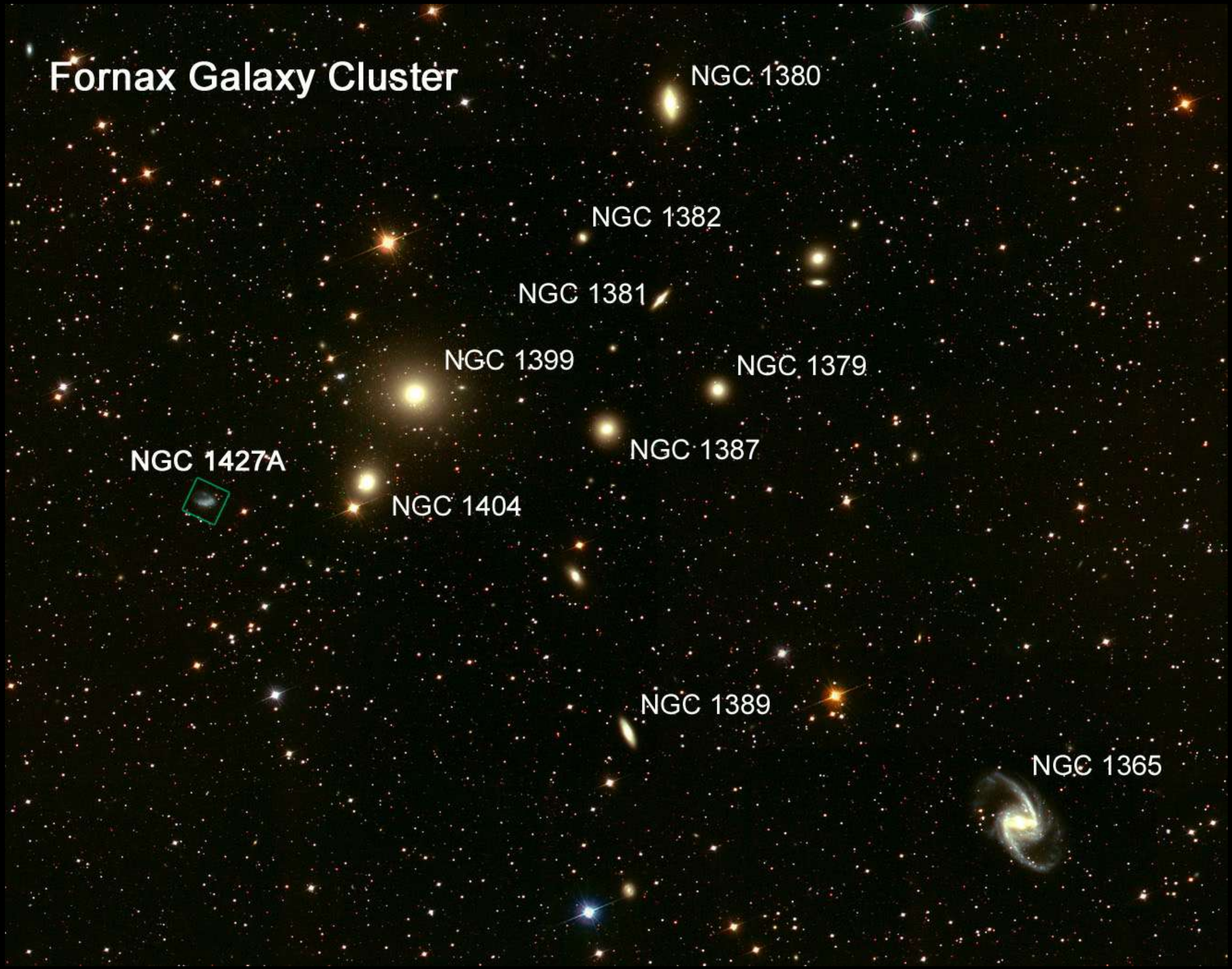
Edwin Hubble
(1889-1953)



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,

$$2K + U = 0$$

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

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

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

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

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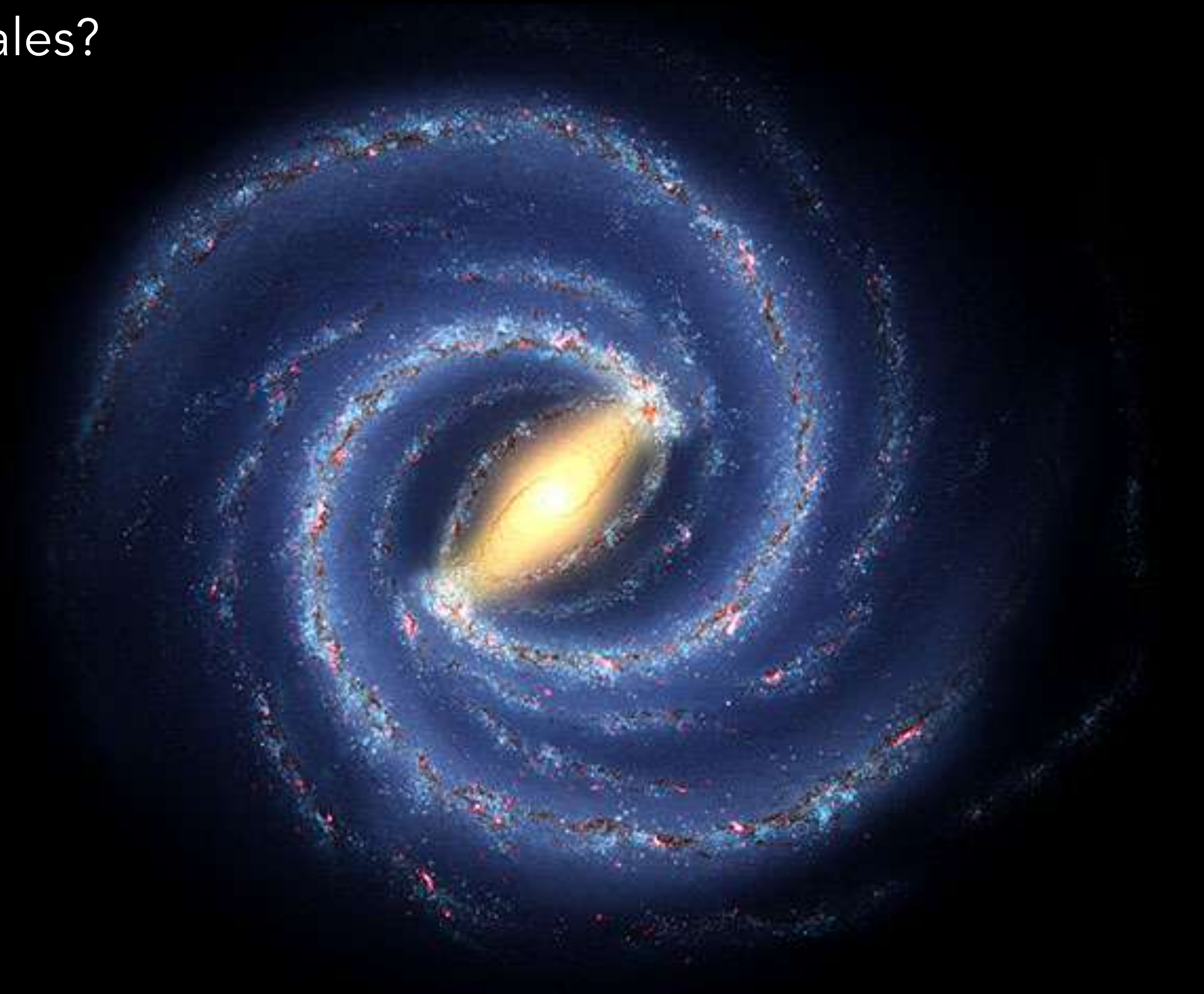
Zwicky was not taken seriously: the problem was just a "missing luminosity problem"

How about Galaxy scales?

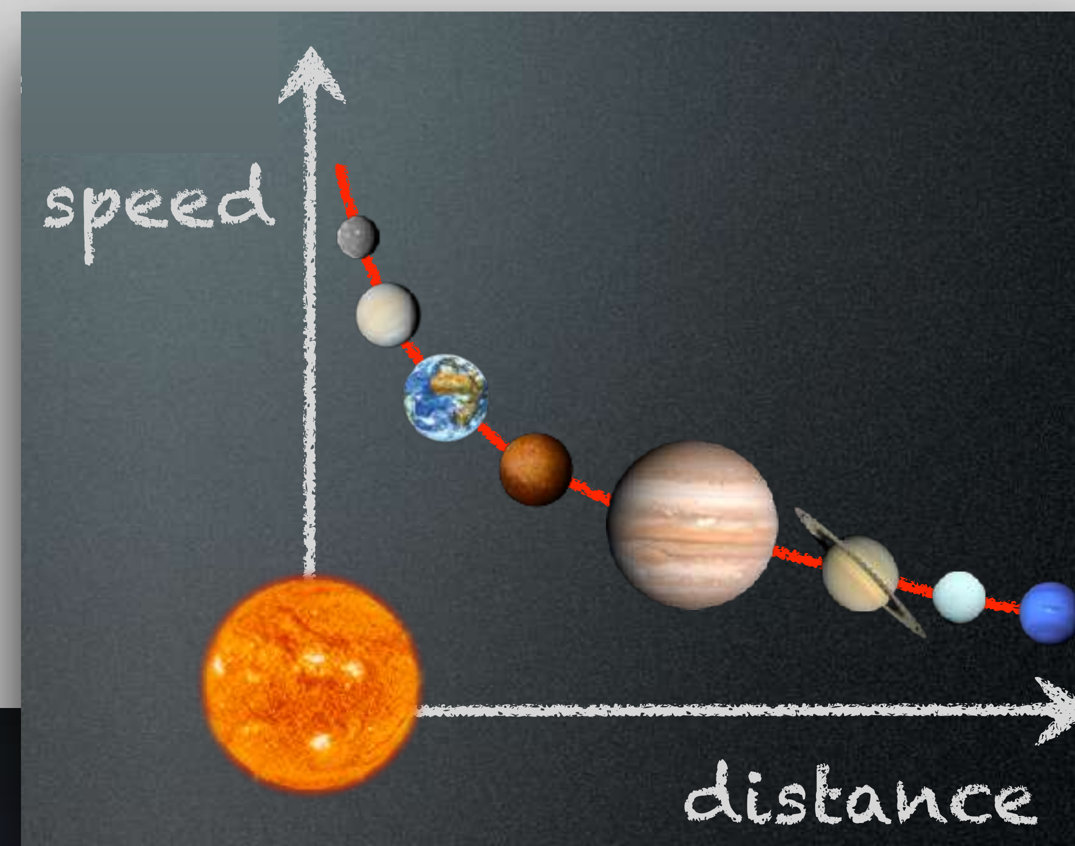


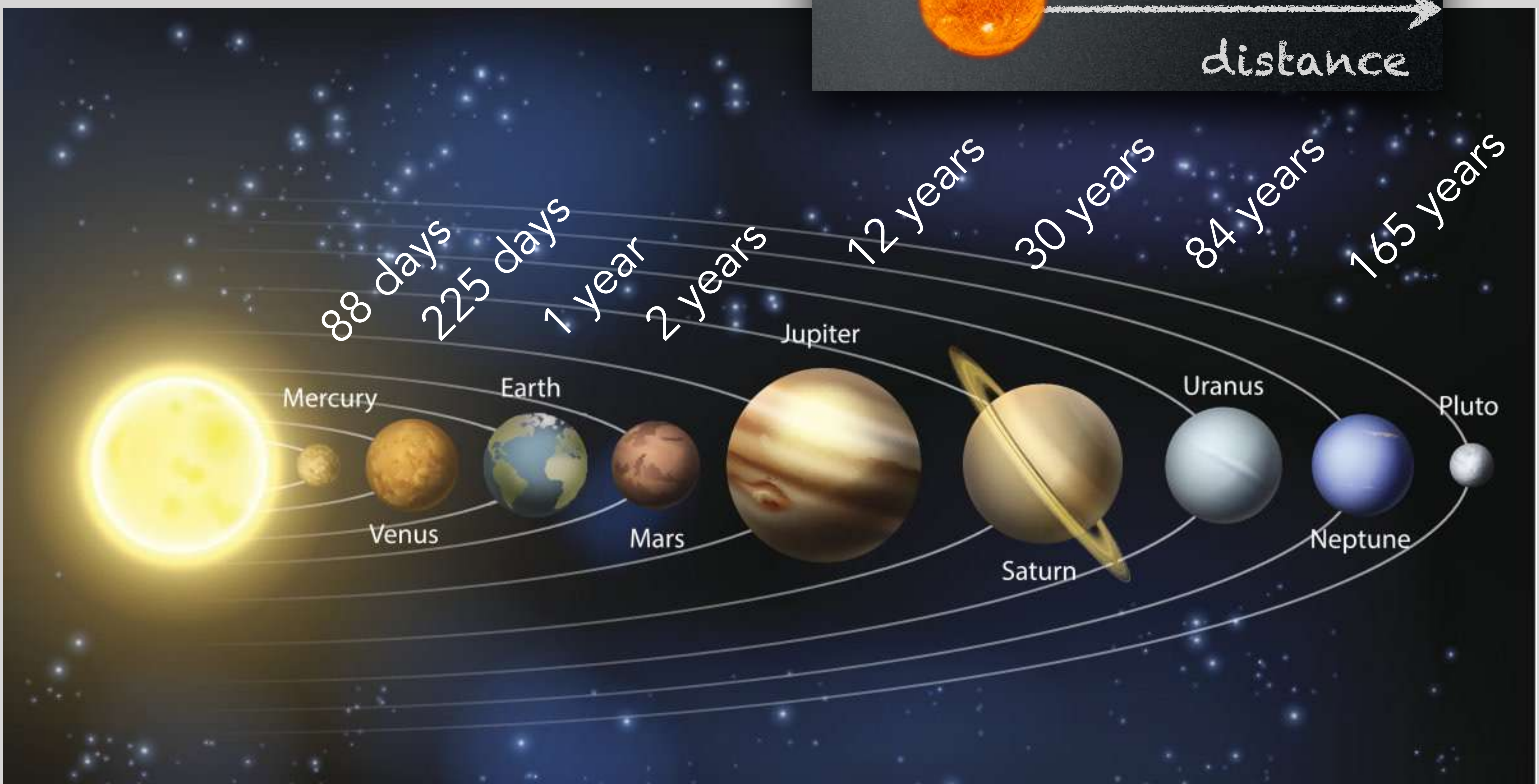
While galaxies in a cluster move randomly,
stars within galaxies exhibit **rotational** motion,
similarly to the Solar System.

Kepler's laws

$$\frac{v^2}{r} = \frac{GM(r)}{r^2}$$

$$M(r) = M \Rightarrow v \propto \frac{1}{\sqrt{r}}$$





All telescopes to Andromeda!

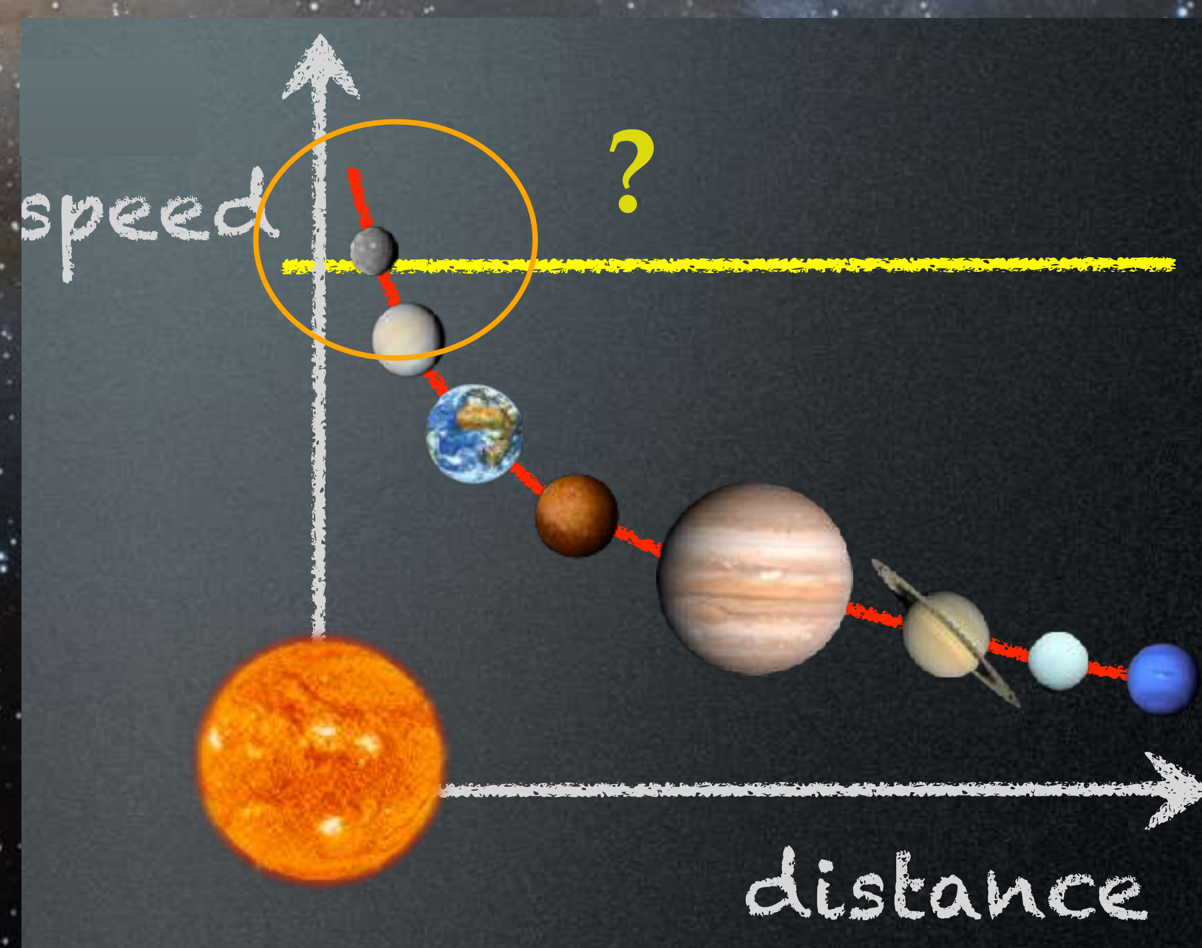
In 1939 Horace Babcock measures the rotation curves for Andromeda measuring a **constant angular velocity**!

THE ROTATION OF THE ANDROMEDA NEBULA*

BY

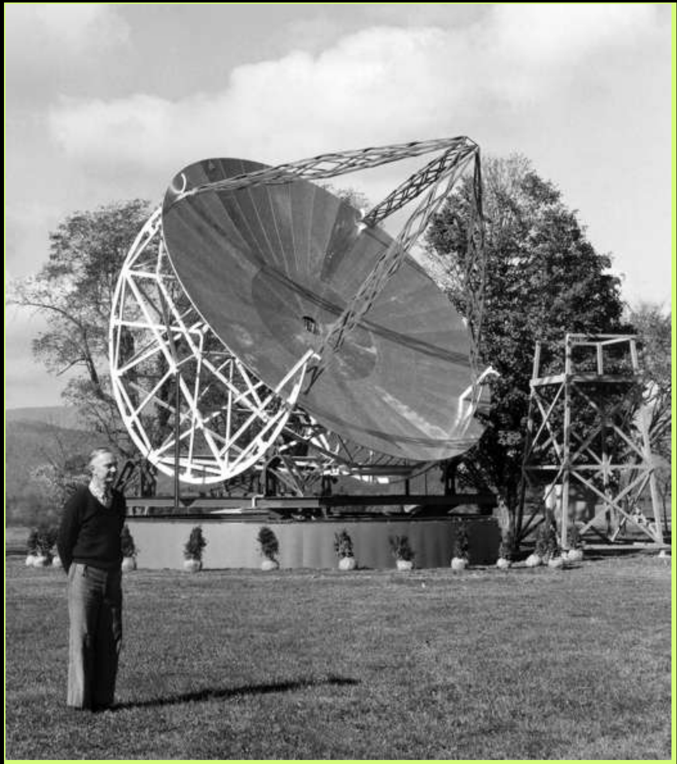
HORACE W. BABCOCK

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



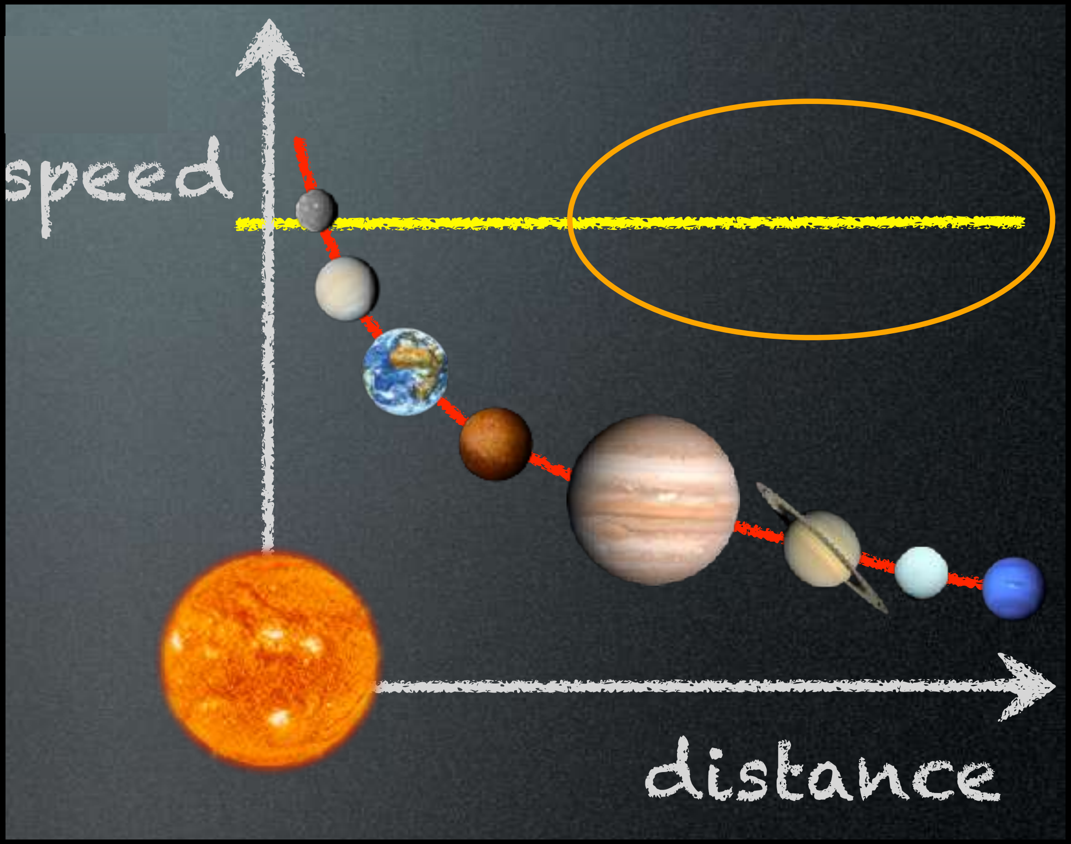
Van de Hulst at Dwingeloo

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.



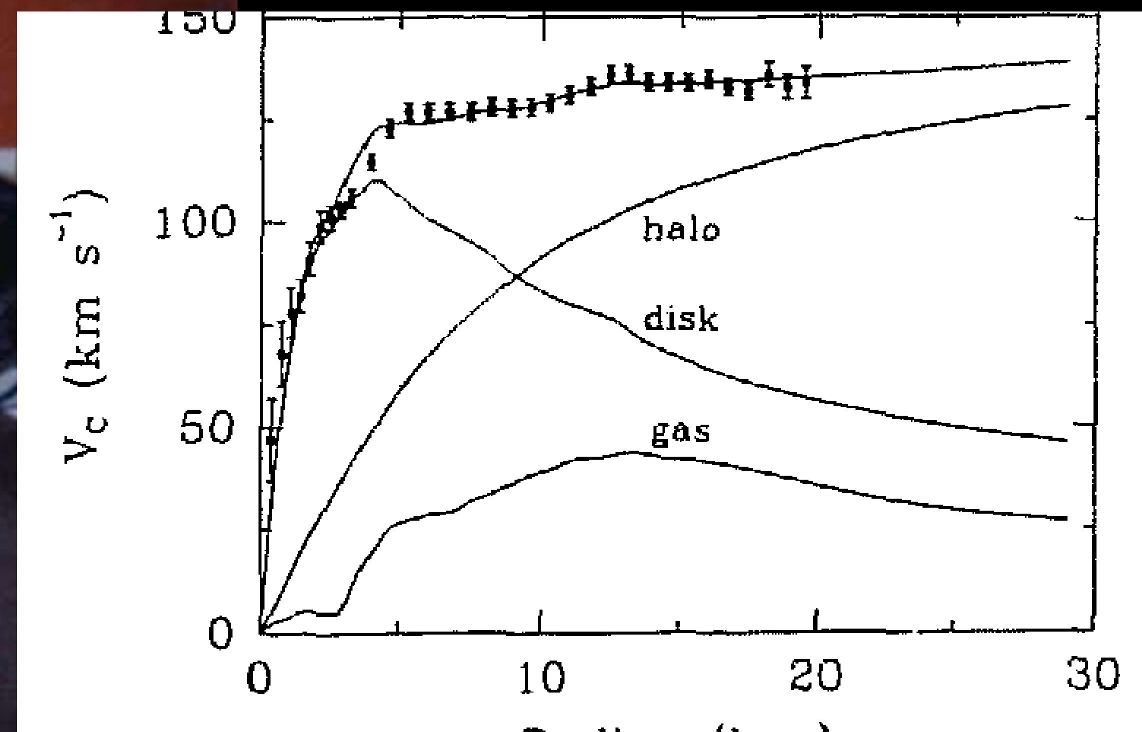
THE 1970s REVOLUTION

the invention of spectrograph by Kent Ford in the 1960s

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

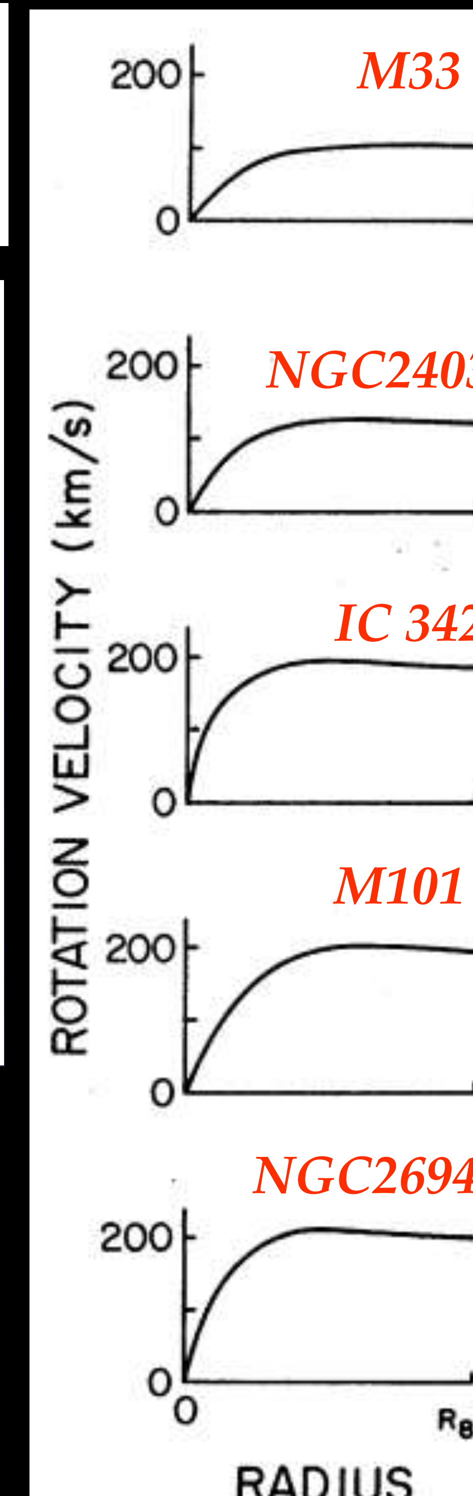
VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

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.



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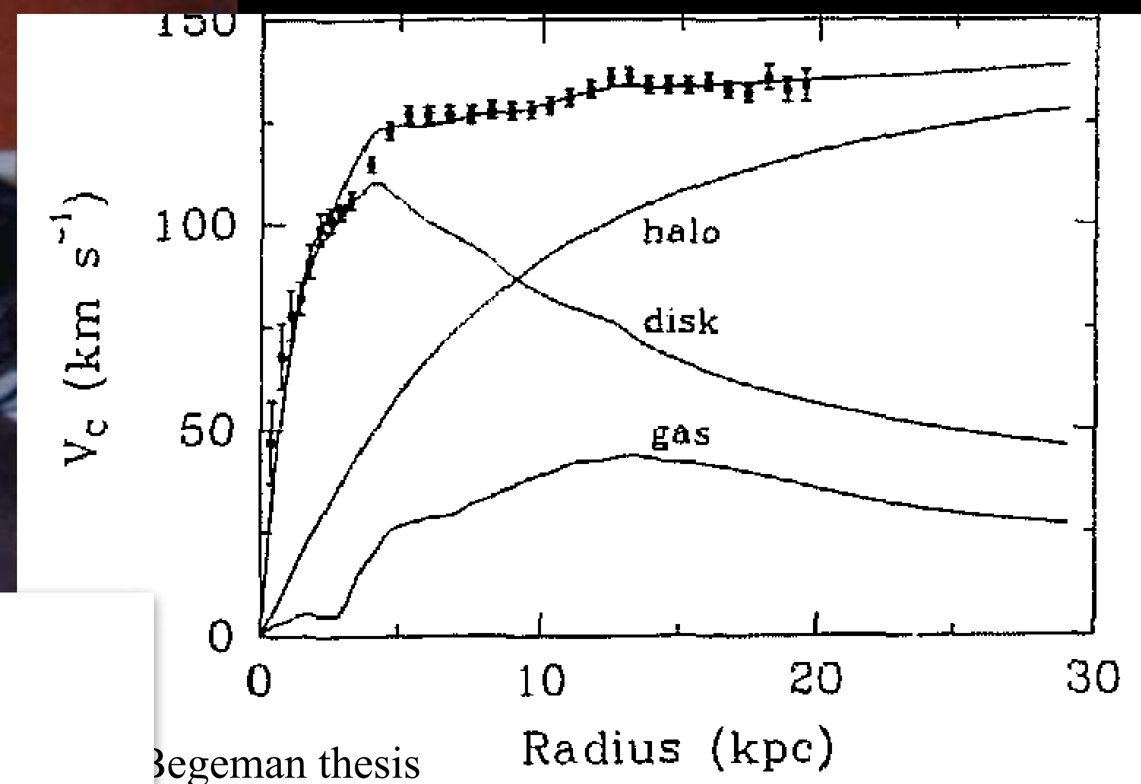
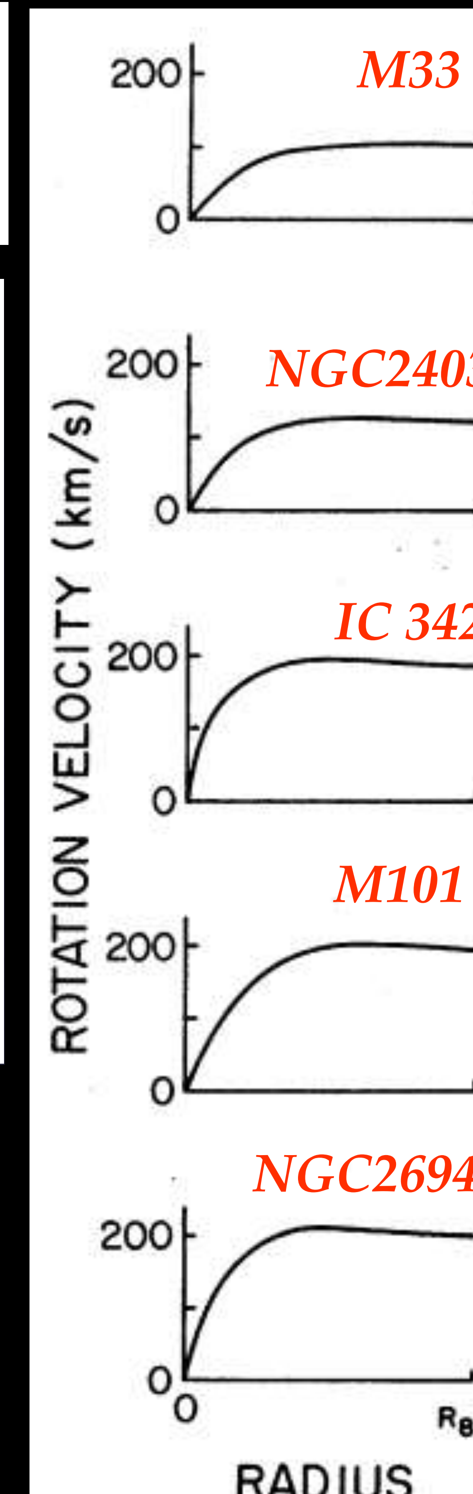


Begeman thesis



$$\frac{v^2}{r} = \frac{GM(r)}{r^2}$$

$$M(r) = M \Rightarrow v \propto \frac{1}{\sqrt{r}}$$

$$M(r) \propto r \Rightarrow v \,\text{constant}$$

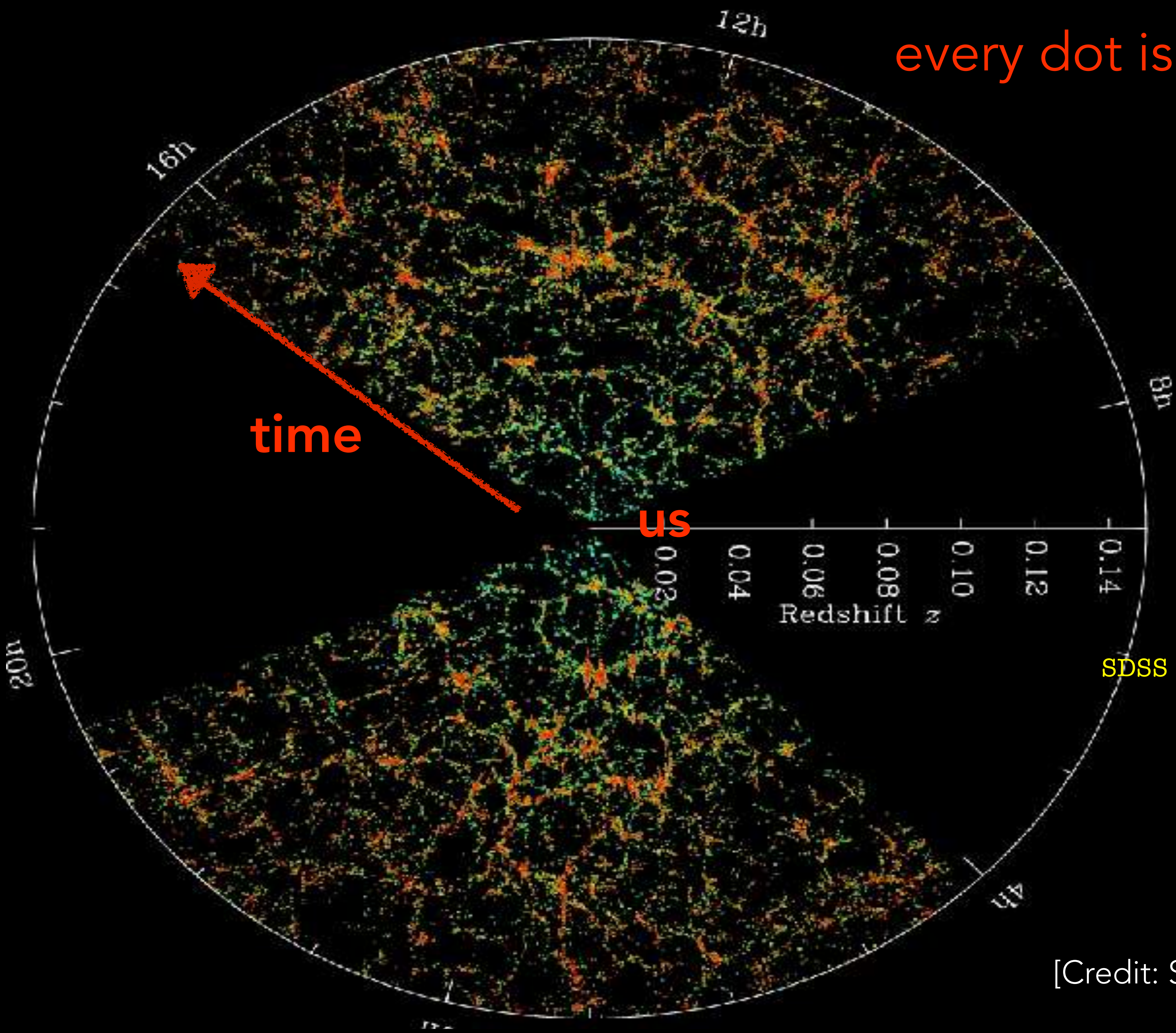
otation curves began to emerge
ly from 21 cm observations.
galaxies as obtained by Rogstad
Shostak in 1972.

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

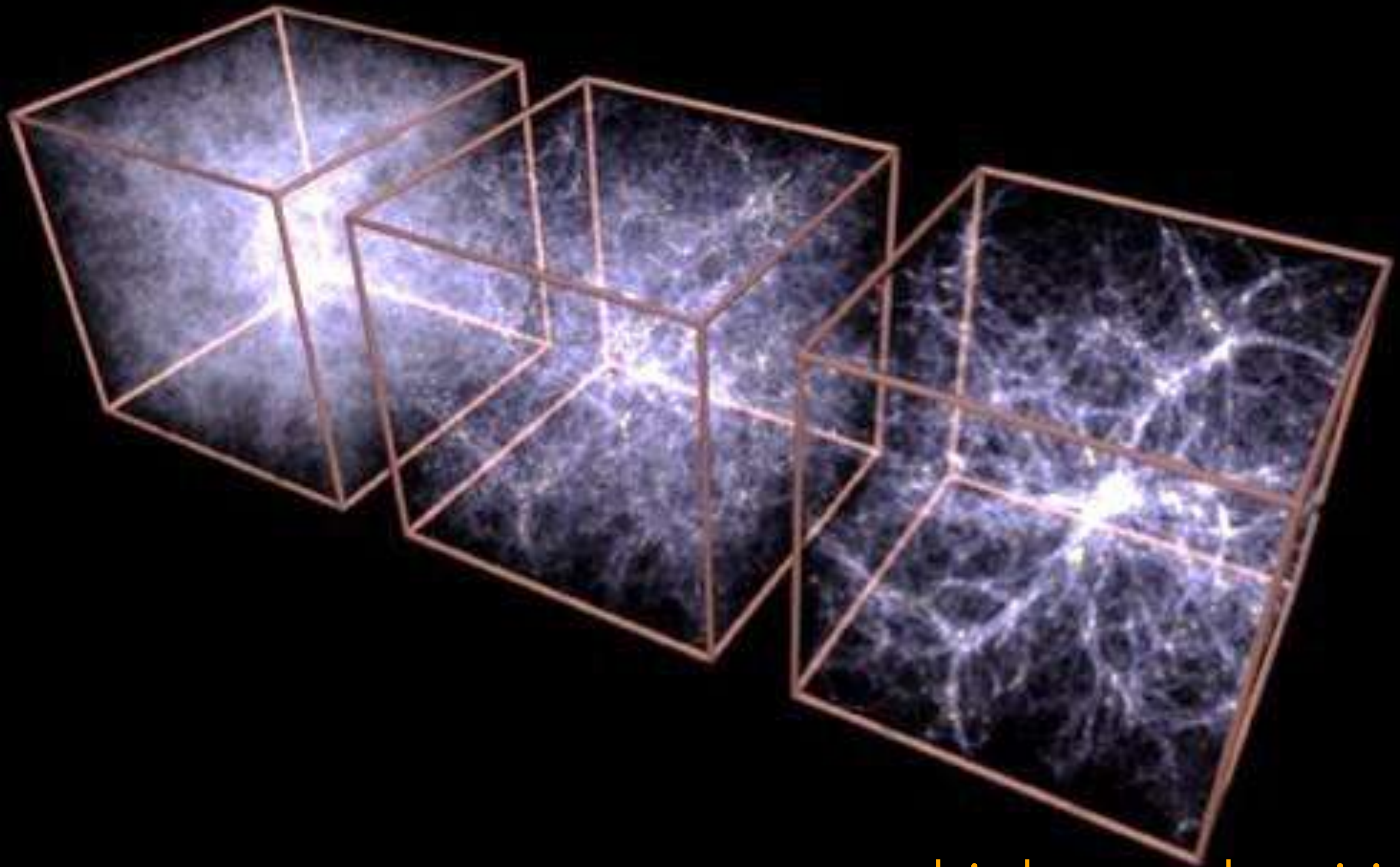


[Credit: Sloan digital sky survey]

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

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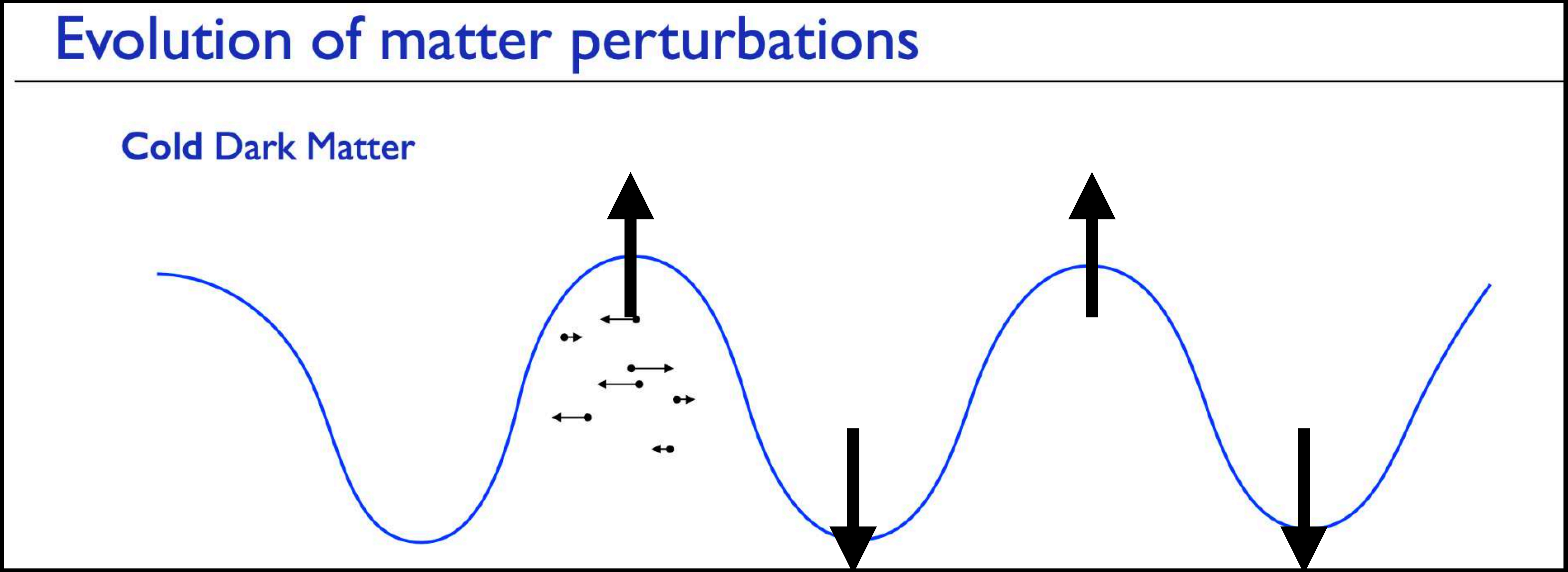
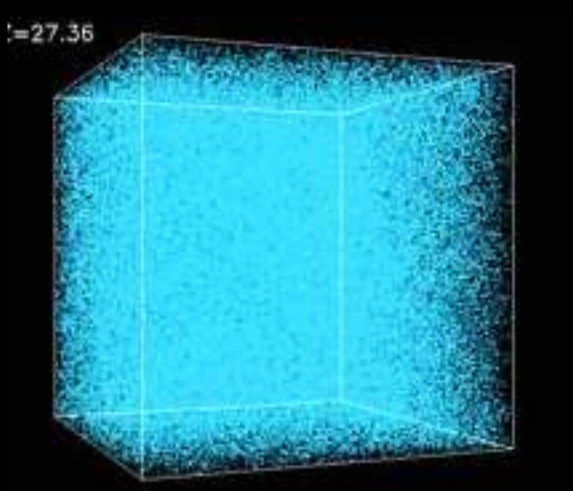
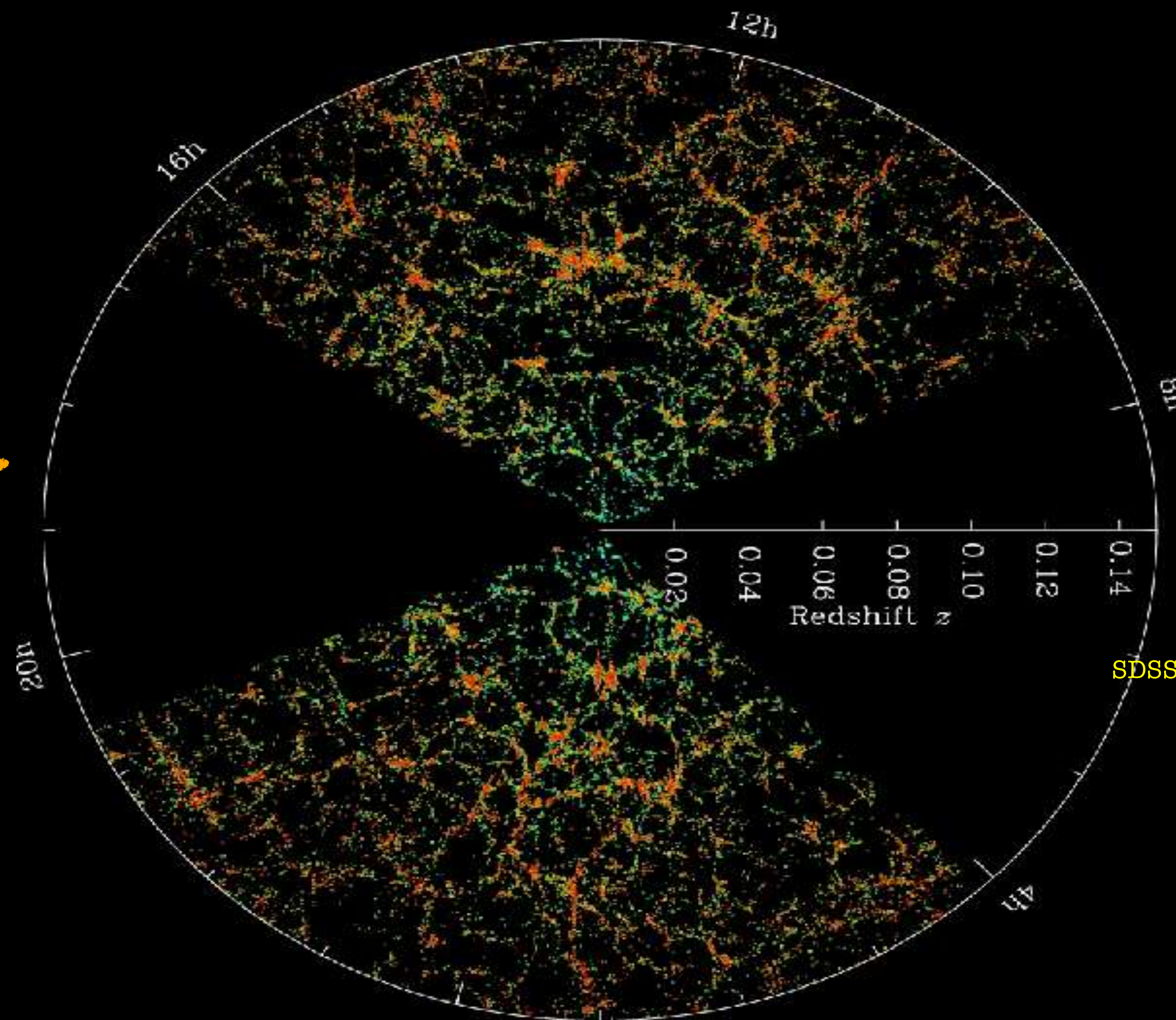


LOOKING BACK IN TIME

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.
Sky survey (Sloan) allowed us to map the distribution of Galaxies in pur neighbourhood.

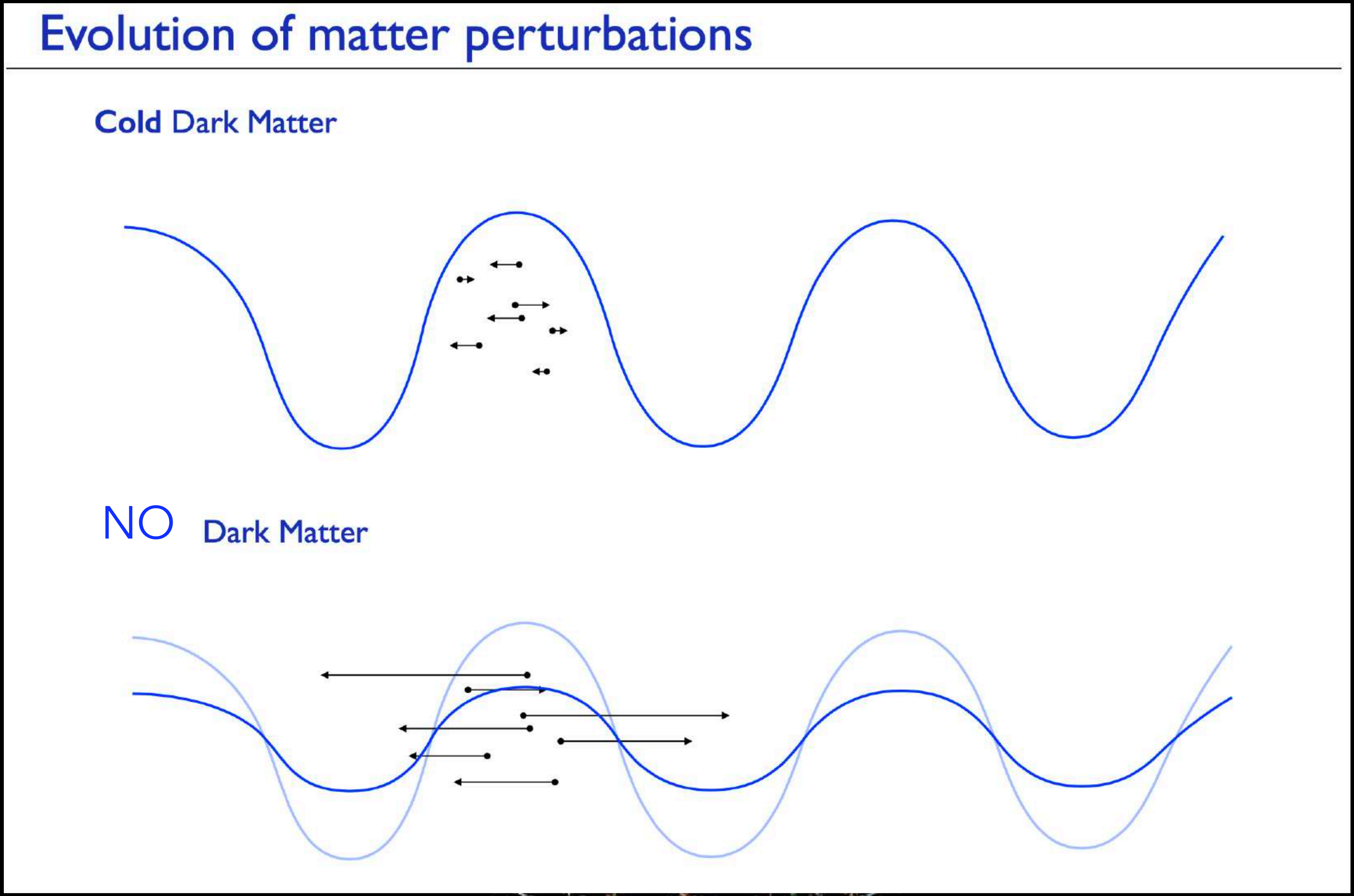
homogenous
early universe





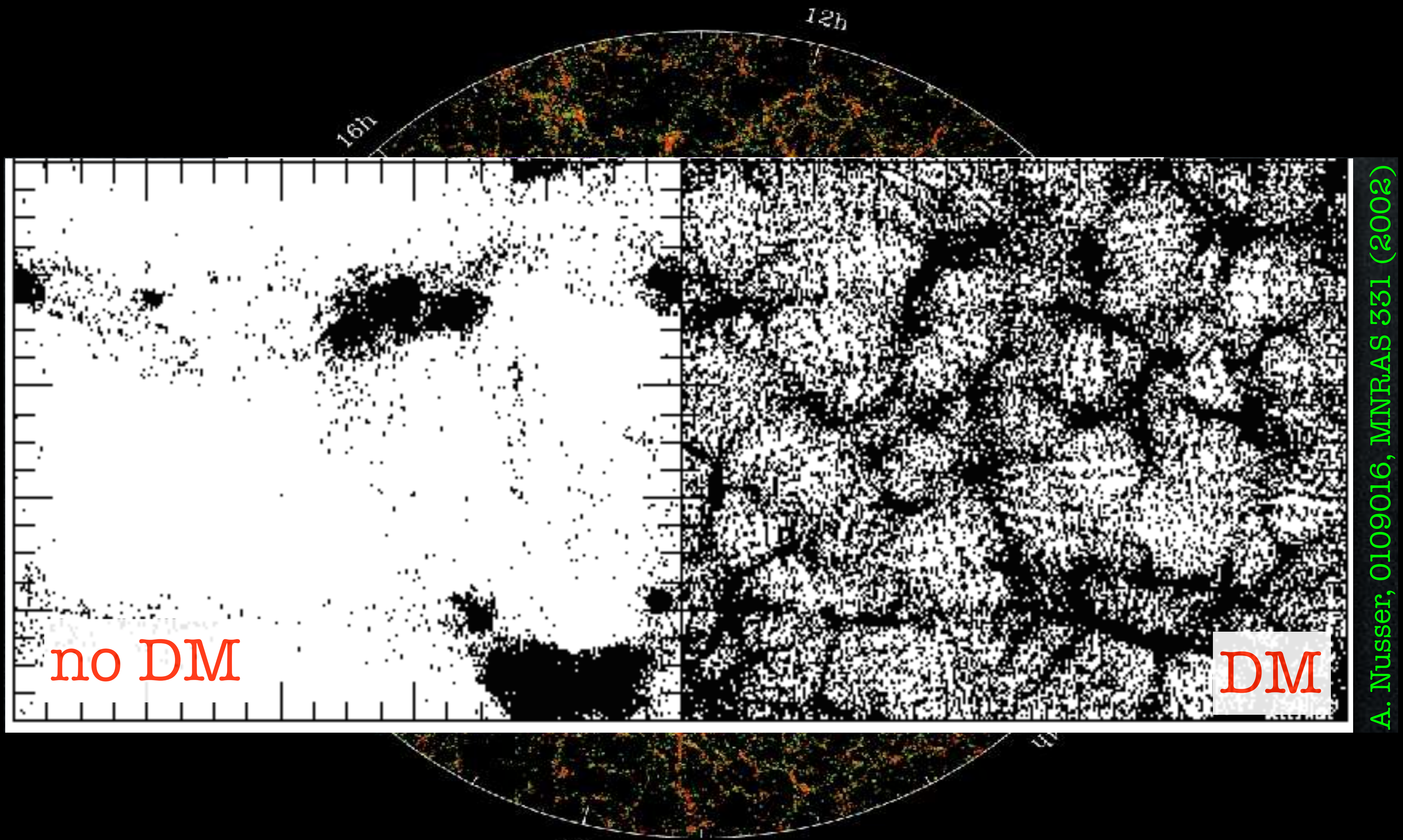
LOOKING BACK IN TIME

The prediction

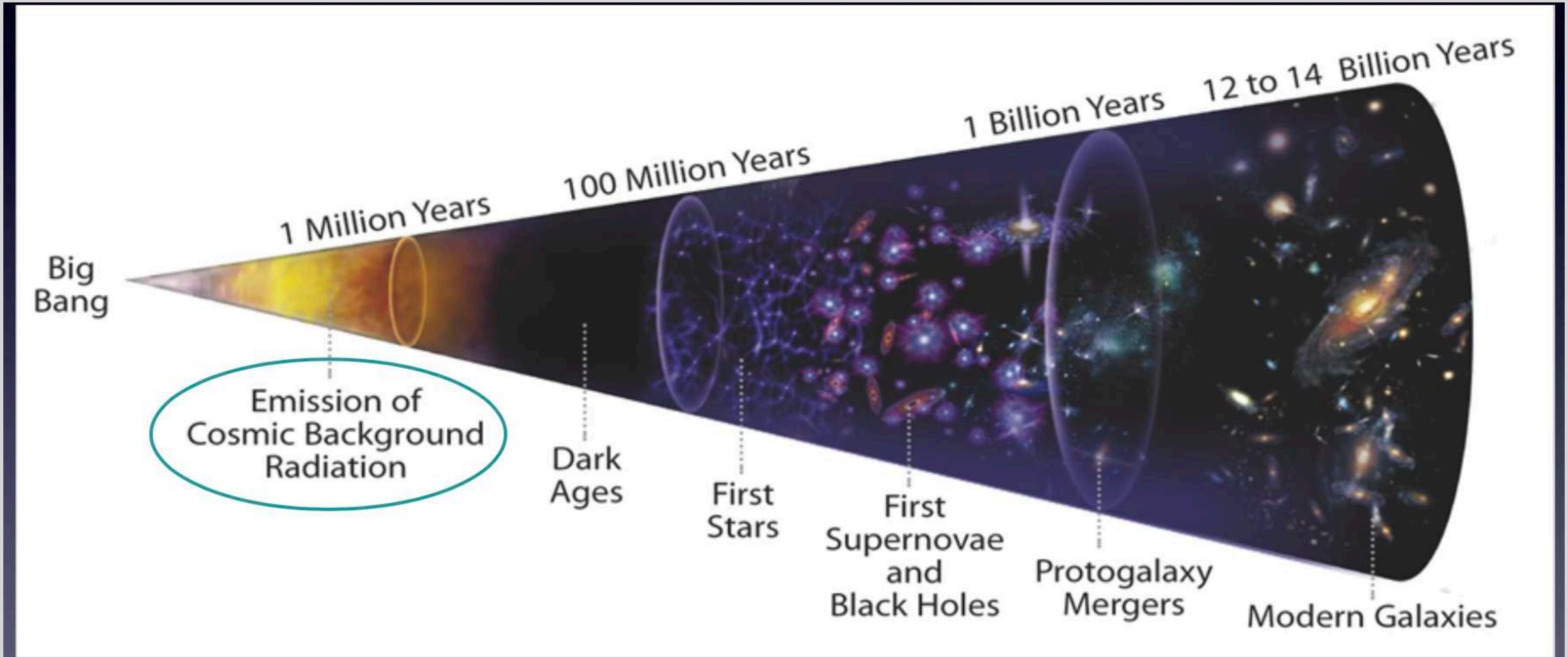


LOOKING BACK IN TIME

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



Further probes: Cosmic Microwave Background (CMB)



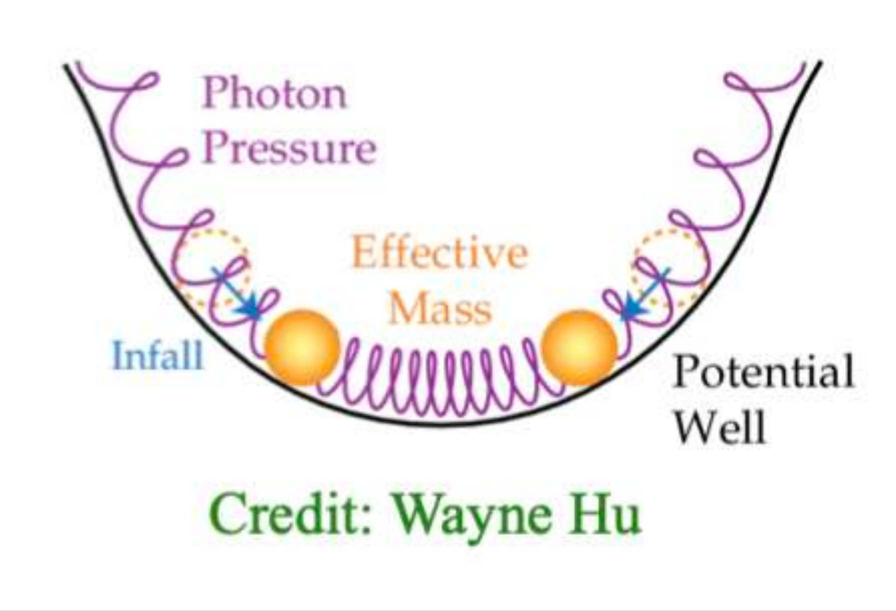
- When the universe was ~400 000 years old (redshift ~ 1000), H gas became largely neutral, universe transparent to microwave photons.
- Cosmic microwave background (CMB) radiation was last scattered at that time. We can measure that light now.
- Gives us a snapshot of the universe very early in its history.

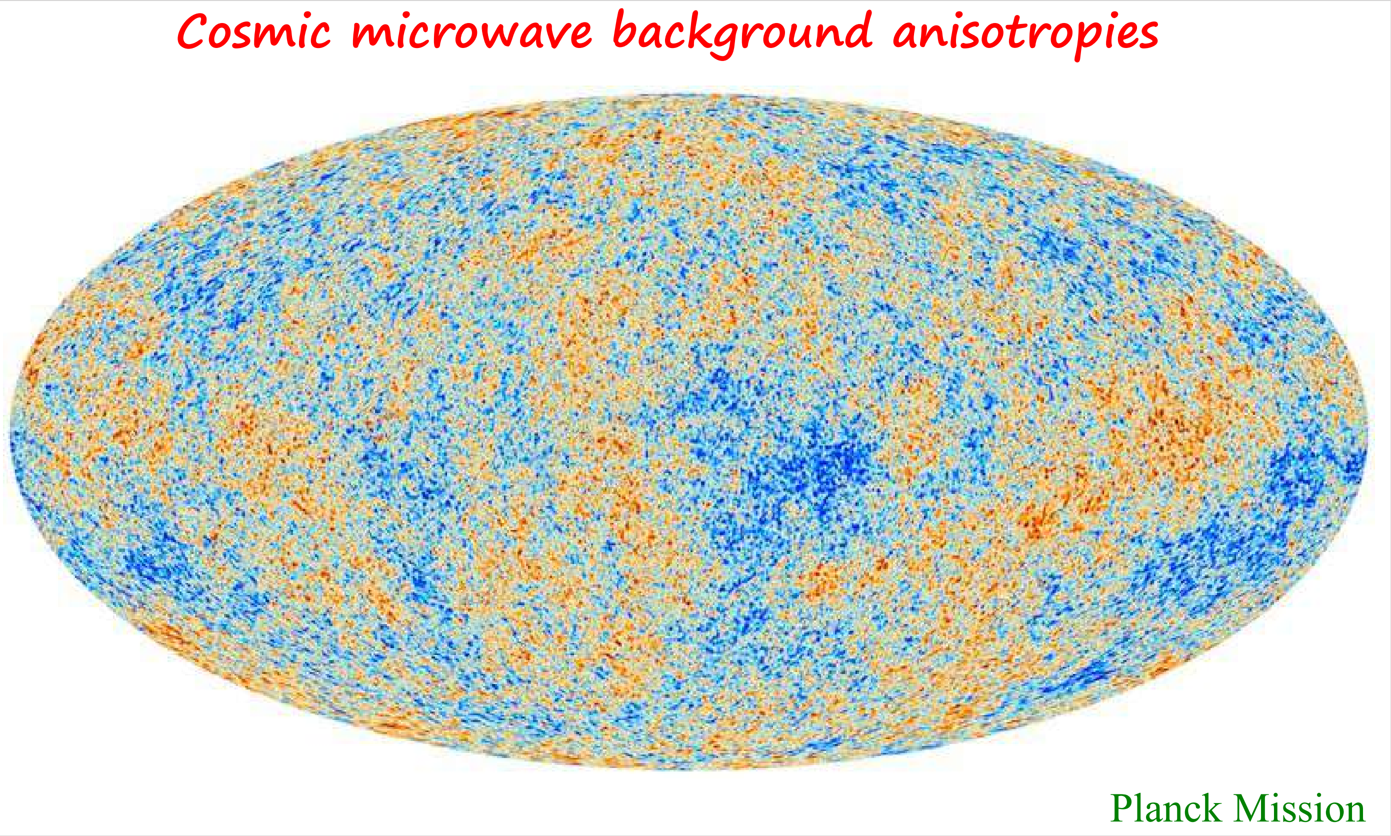
Cosmic Microwave Background (CMB)

- Universe at z~1000 was a hot, nearly perfectly homogeneous soup of light and atoms.

Acoustic oscillations:

- Gravity tries to compress the fluid in potential wells.
- Photon pressure resists compression resulting in acoustic oscillations
- **Each initial overdensity (in dark matter & gas) is an overpressure that launches a spherical sound wave.**





Pattern of **sound imprinted in the temperature** of CMB

- **Compressed regions hotter**
- **Rarefied regions colder**

Cosmic Microwave Background (CMB)

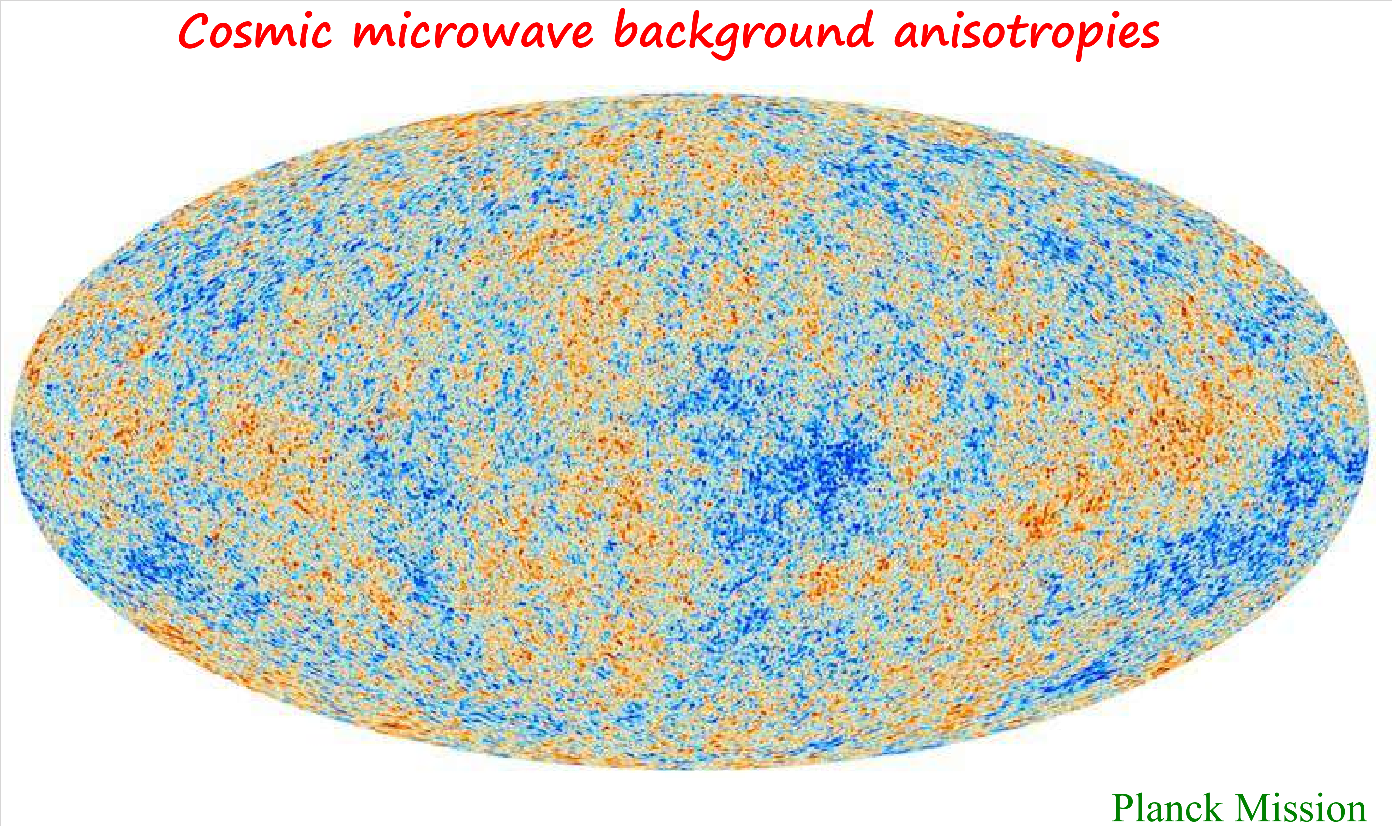
Although there are fluctuations on all scales, there is a characteristic angular scale, ~ 1 degree on the sky, set by the distance sound waves in the photon-baryon fluid can travel just before recombination

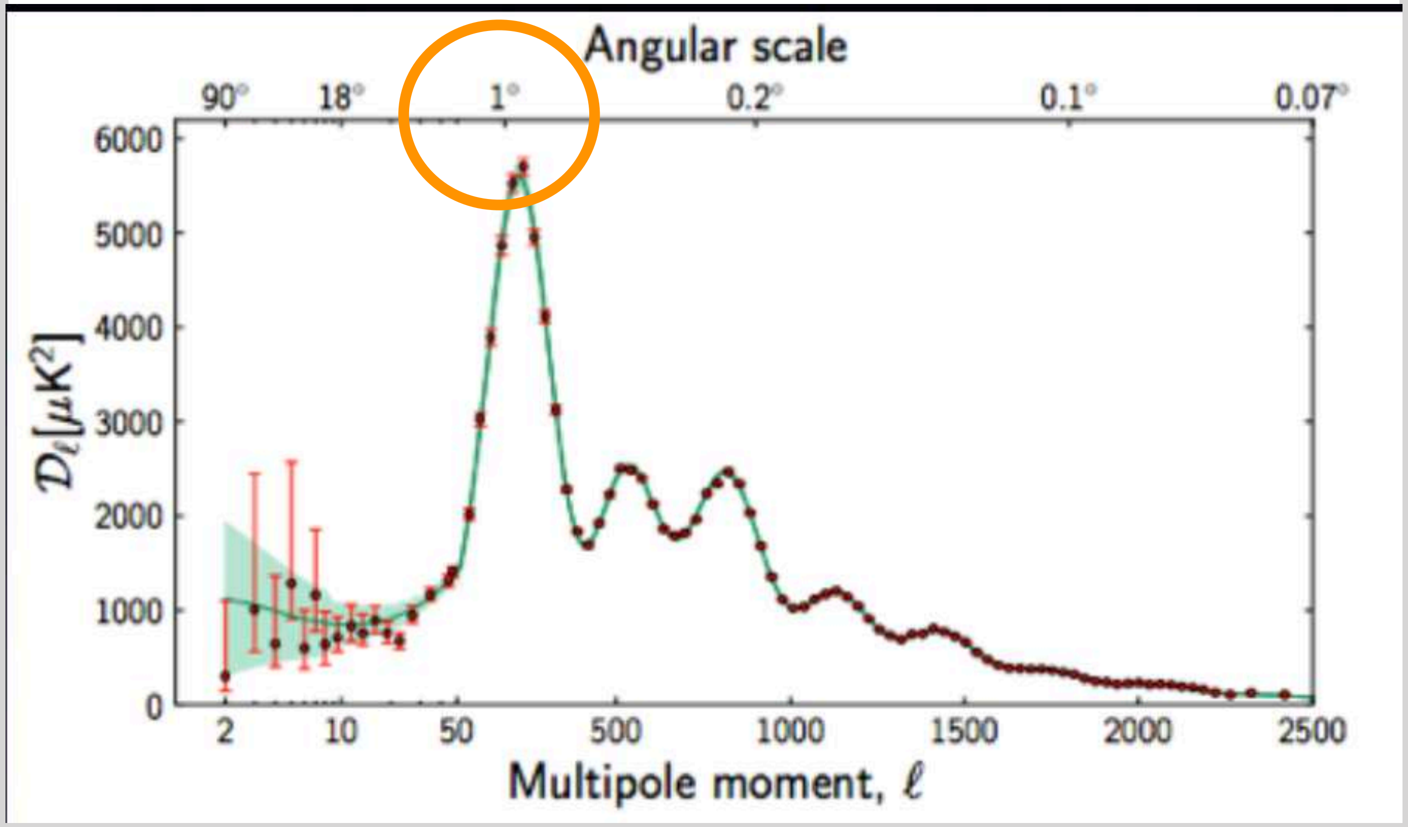
Oscillations are frozen in at recombination

– Baryon-to-photon ratio (through c_s)

$$c_s = [3(1 + 3\rho_b/4\rho_\gamma)]^{-1/2}$$

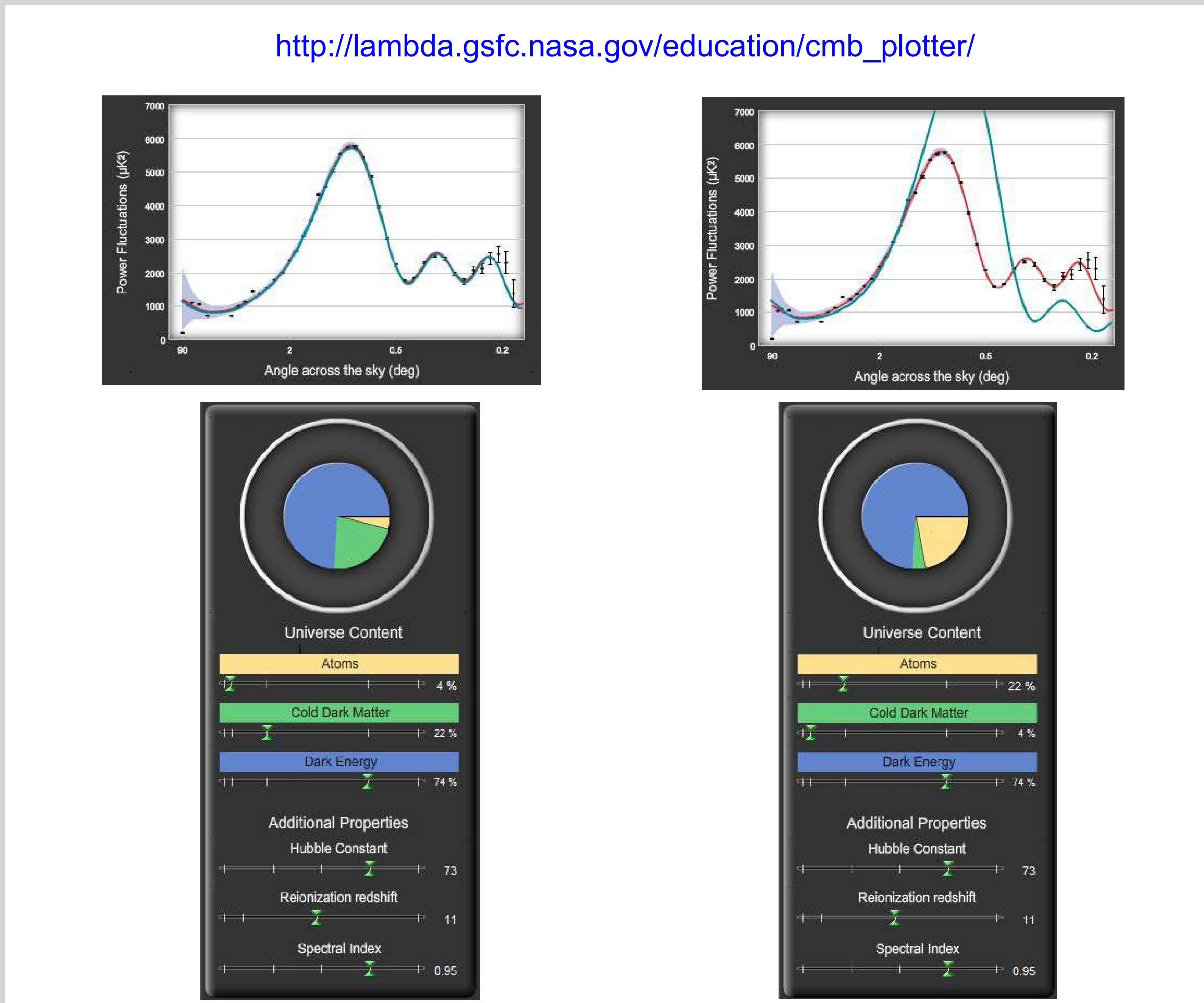
Photon density is known exquisitely well from CMB spectrum.





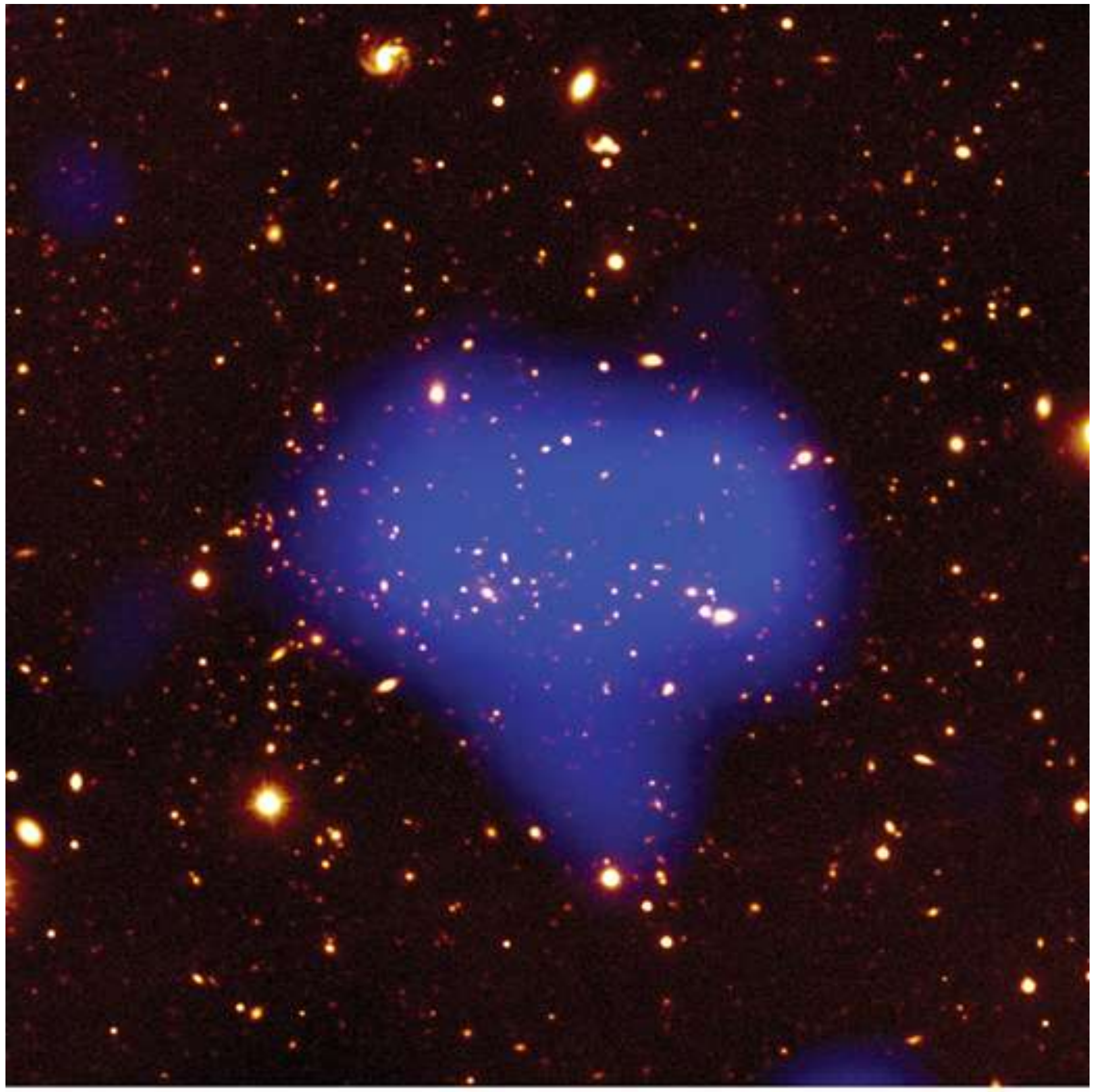
Cosmic Microwave Background (CMB)

Dark component: does not experience radiation pressure, effects on oscillation can be separated from that of baryons.
Result: this simple model fits the data well with a dark matter component about **5x more abundant than baryonic matter**



Lets focus now on Galaxy clusters, which are a multi-pronged probe of DM

- 02) **temperature of the hot gas**

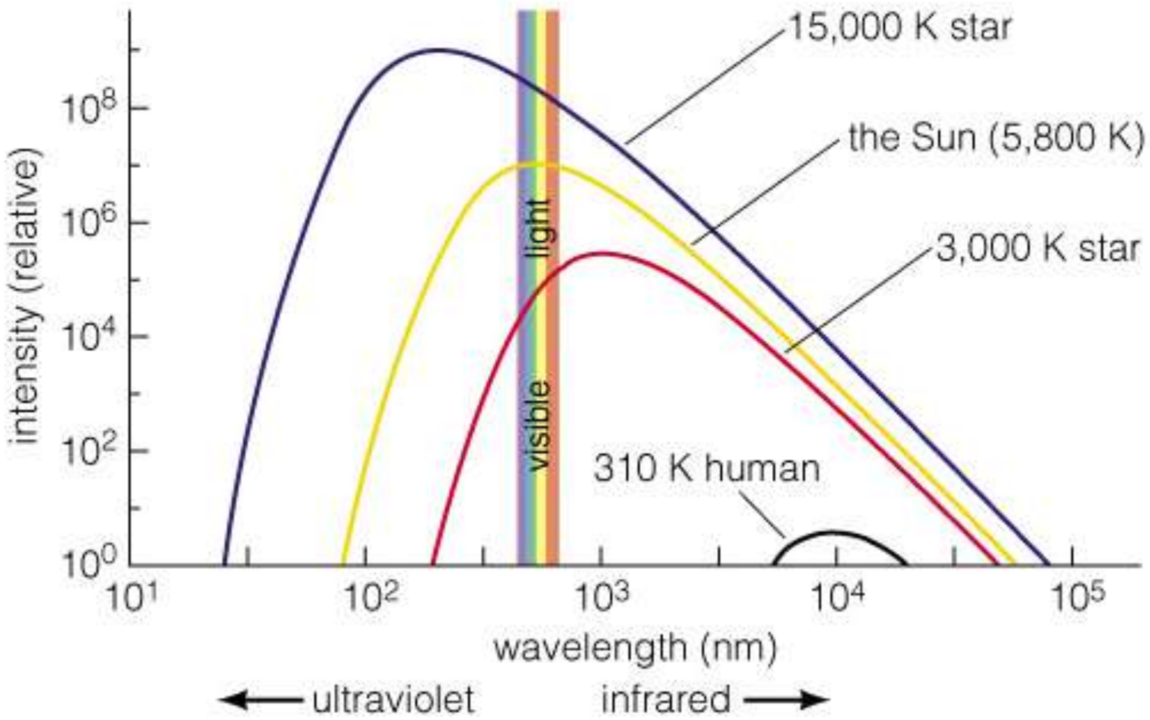


A distant cluster of Galaxies in both, visible, and X-ray light (the blue overlay).

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:

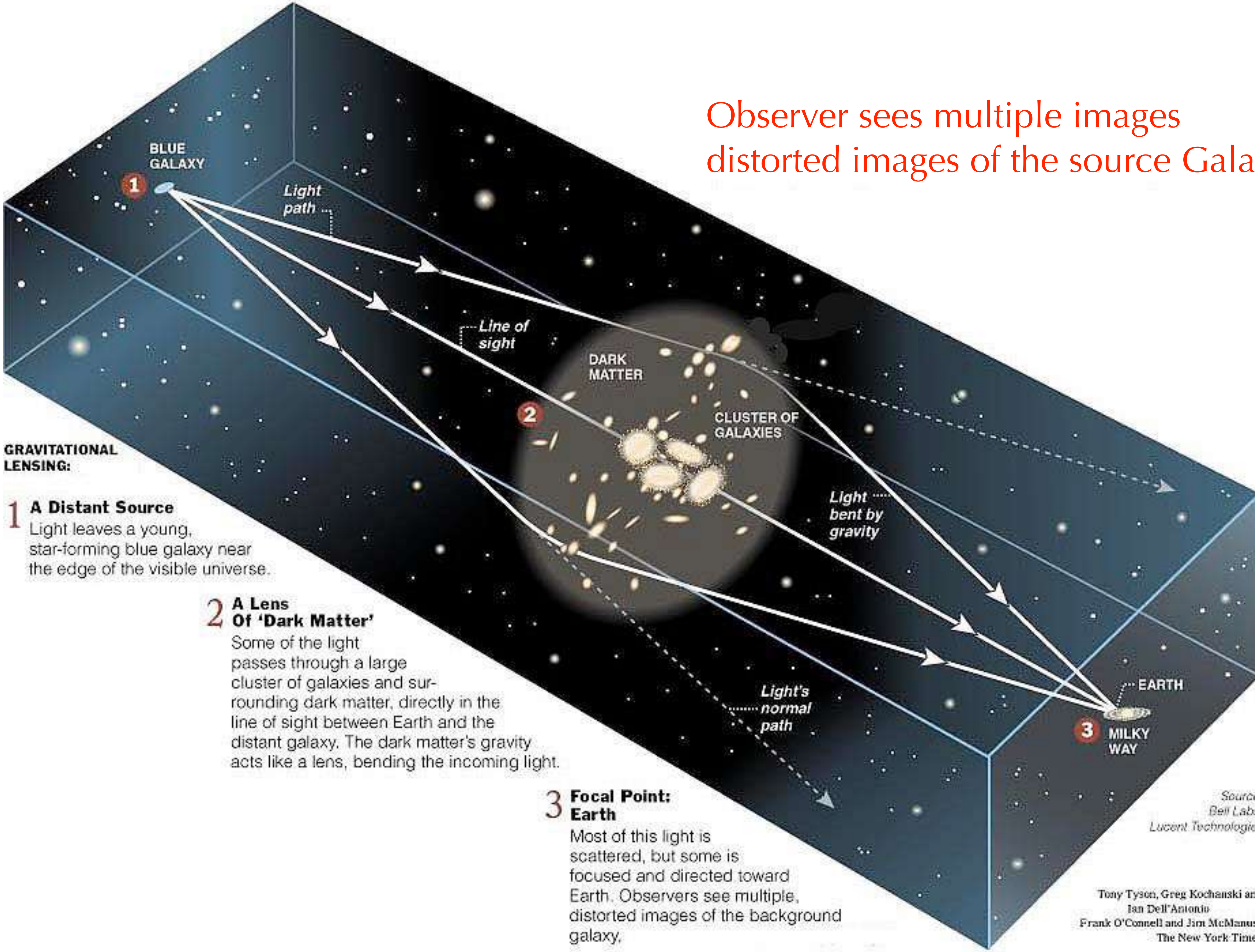


Thermal radiation spectrum

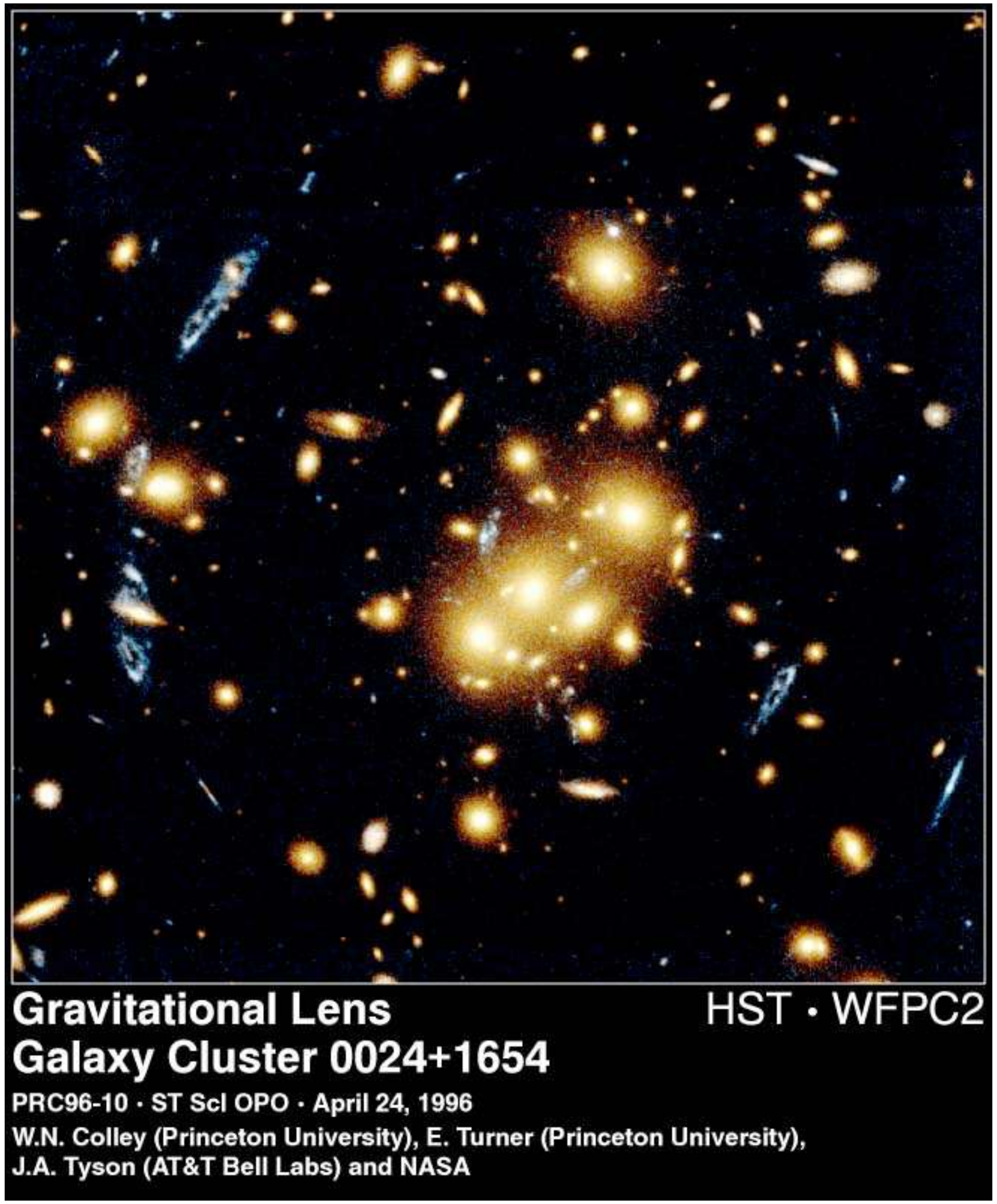
How fast molecules of gas are moving is connected to the amount of gravity they feel: ***stronger the gravity, faster the gas is moving and hotter it is.***
And, we can measure its *temperature* by measuring the *spectrum of photons* the gas emits!
And again, it turns out, dark matter has to be around.

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

Observer sees multiple images distorted images of the source Galaxy.



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

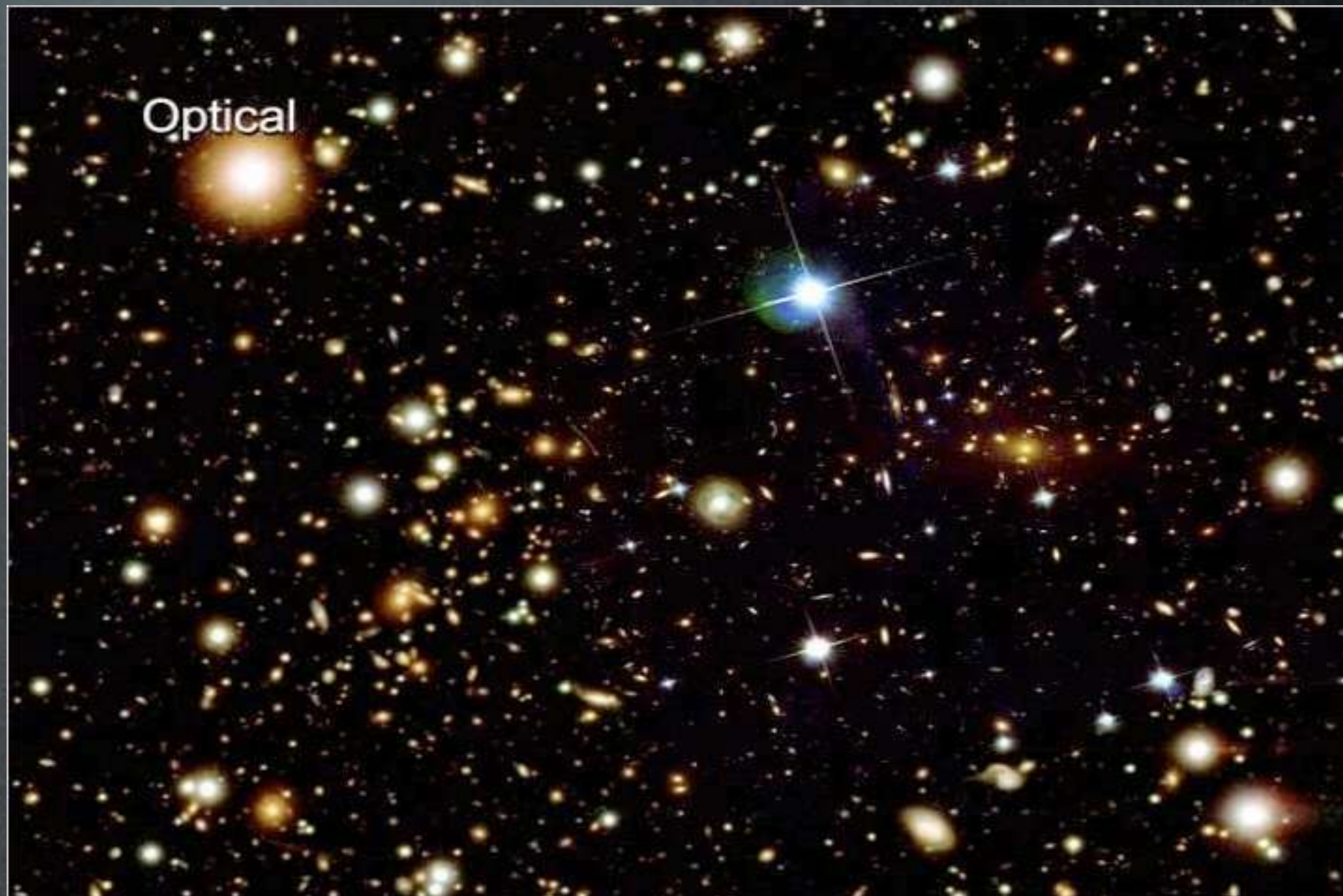


The cluster galaxies are the yellowish ones.

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

We see four multiple images of a Blue Source Galaxy - a significant concentration of dark matter in the cluster centers is required to give these dramatic lensing events.

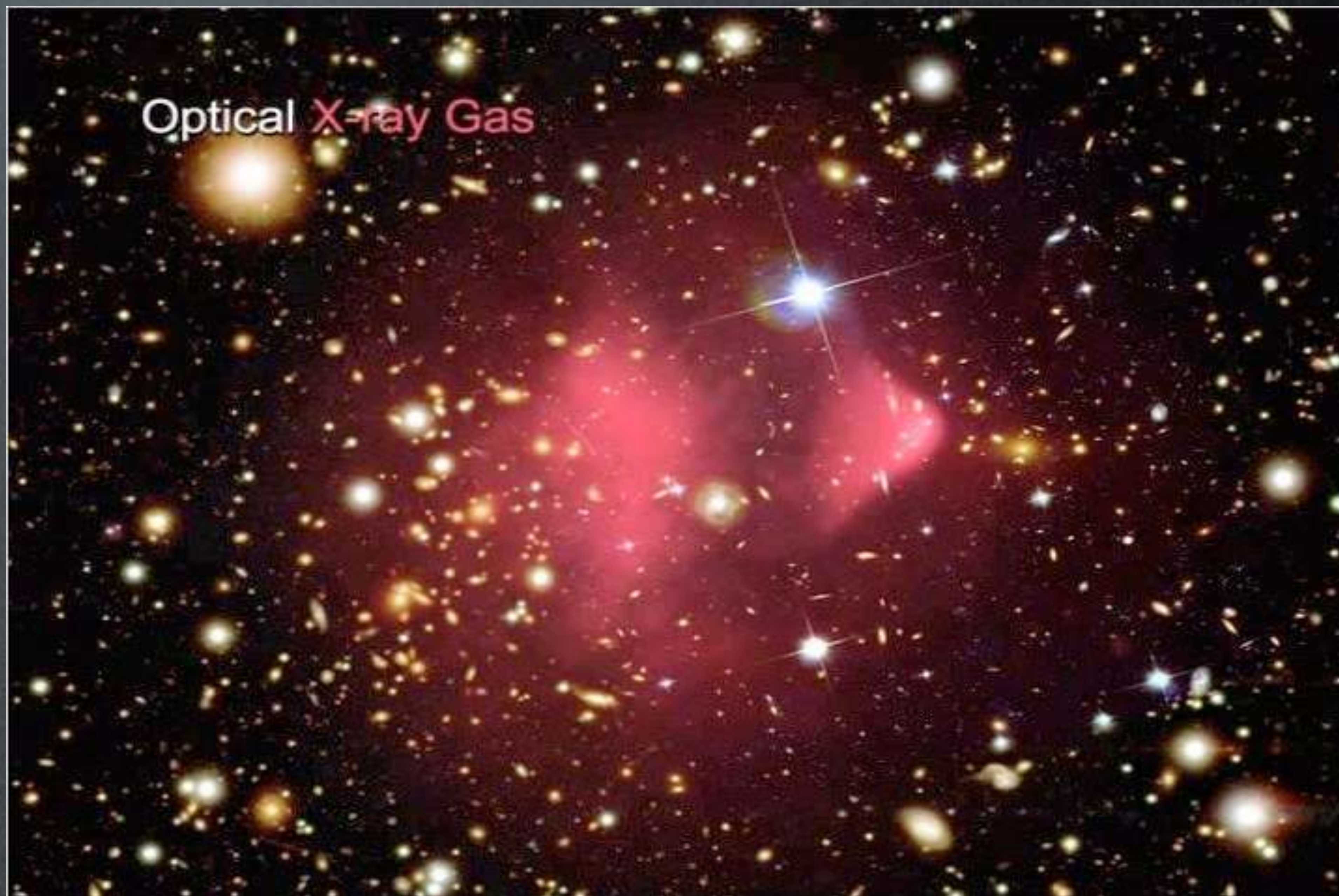
- Further evidence from ***merging*** Galaxy clusters: bullet cluster



Clowe et al 2006

“bullet cluster” - NASA
astro-ph/0608247

- Further evidence from ***merging*** Galaxy clusters: bullet cluster



Clowe et al 2006

“bullet cluster” - NASA
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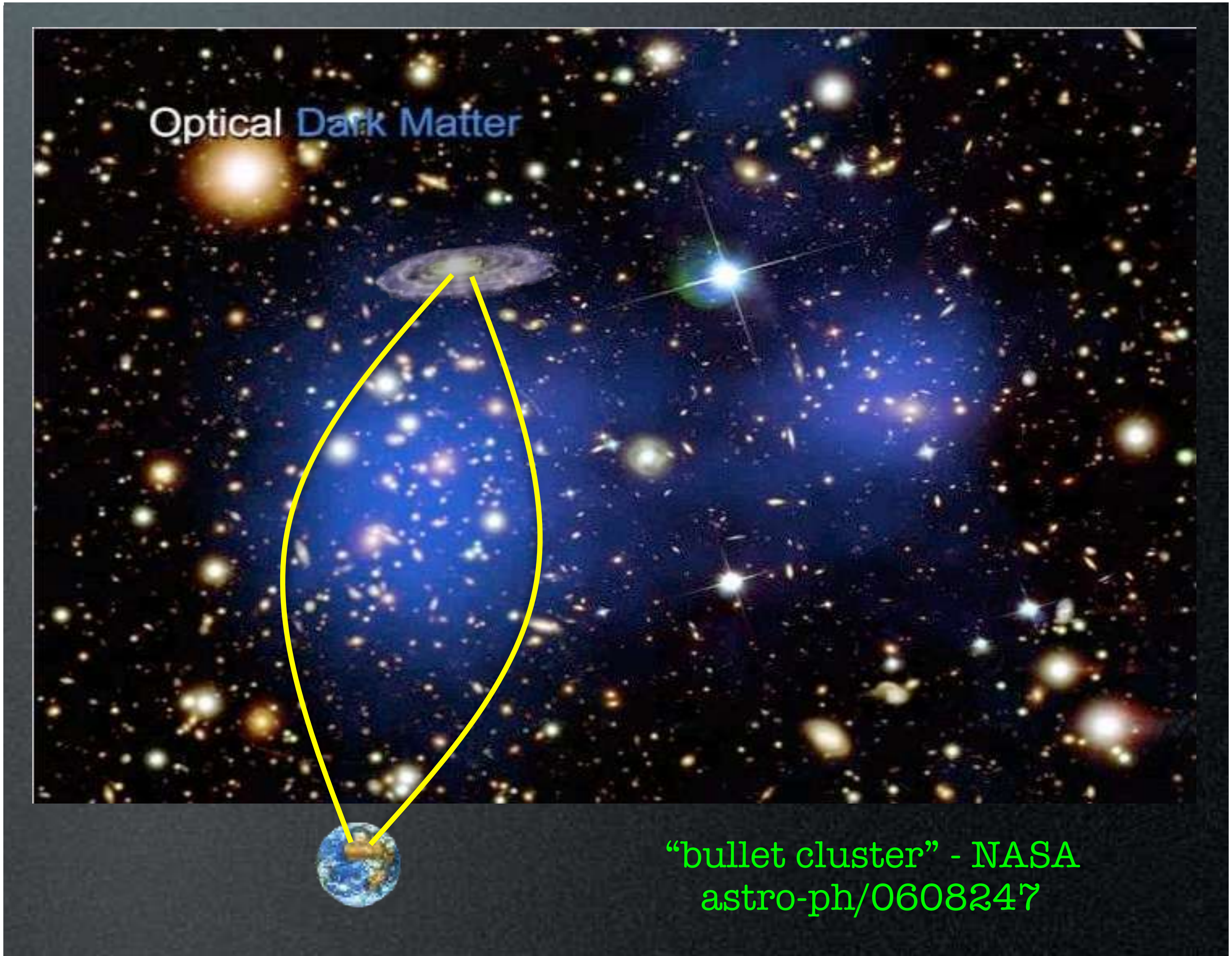
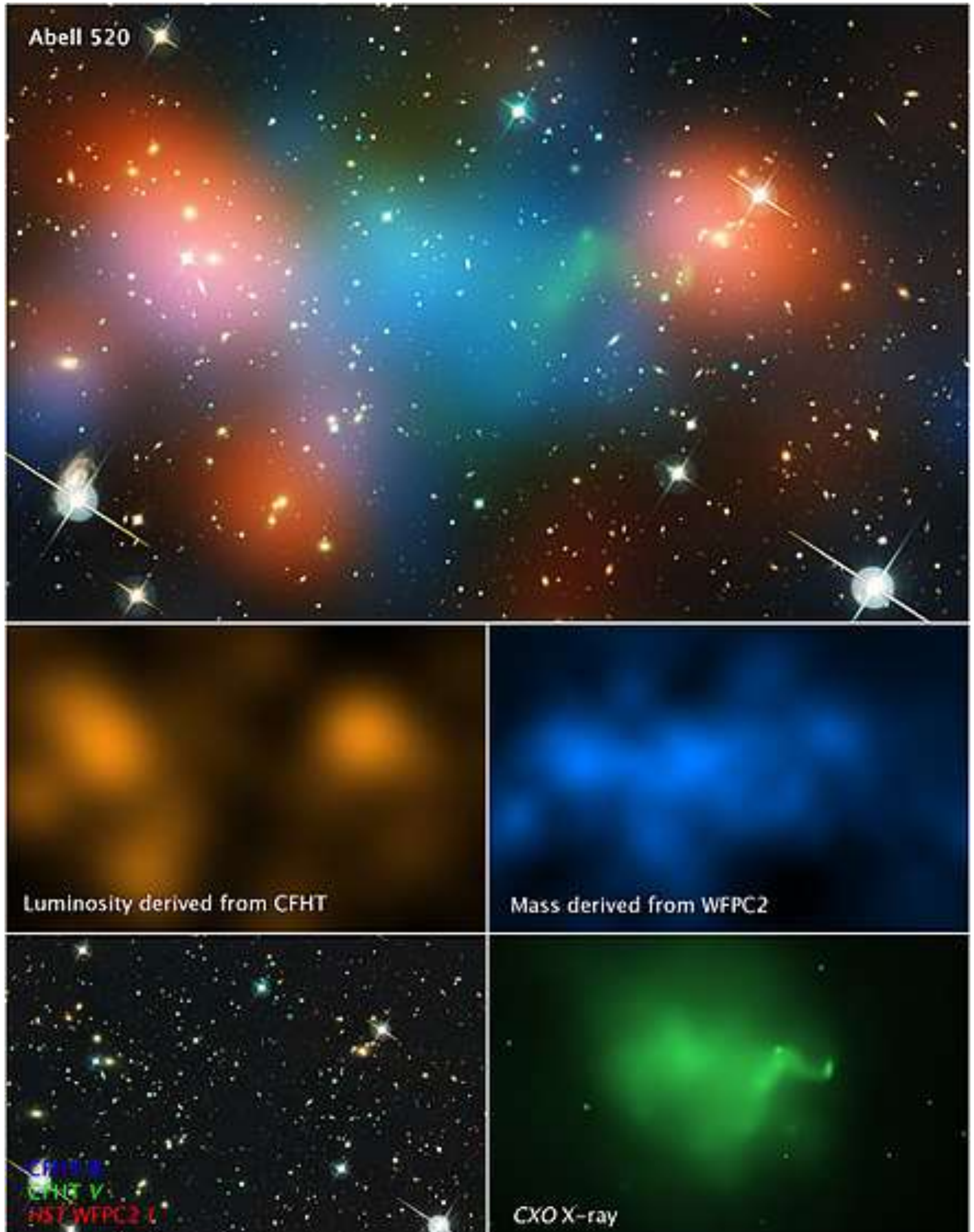
- Further evidence from ***merging*** Galaxy clusters: bullet cluster

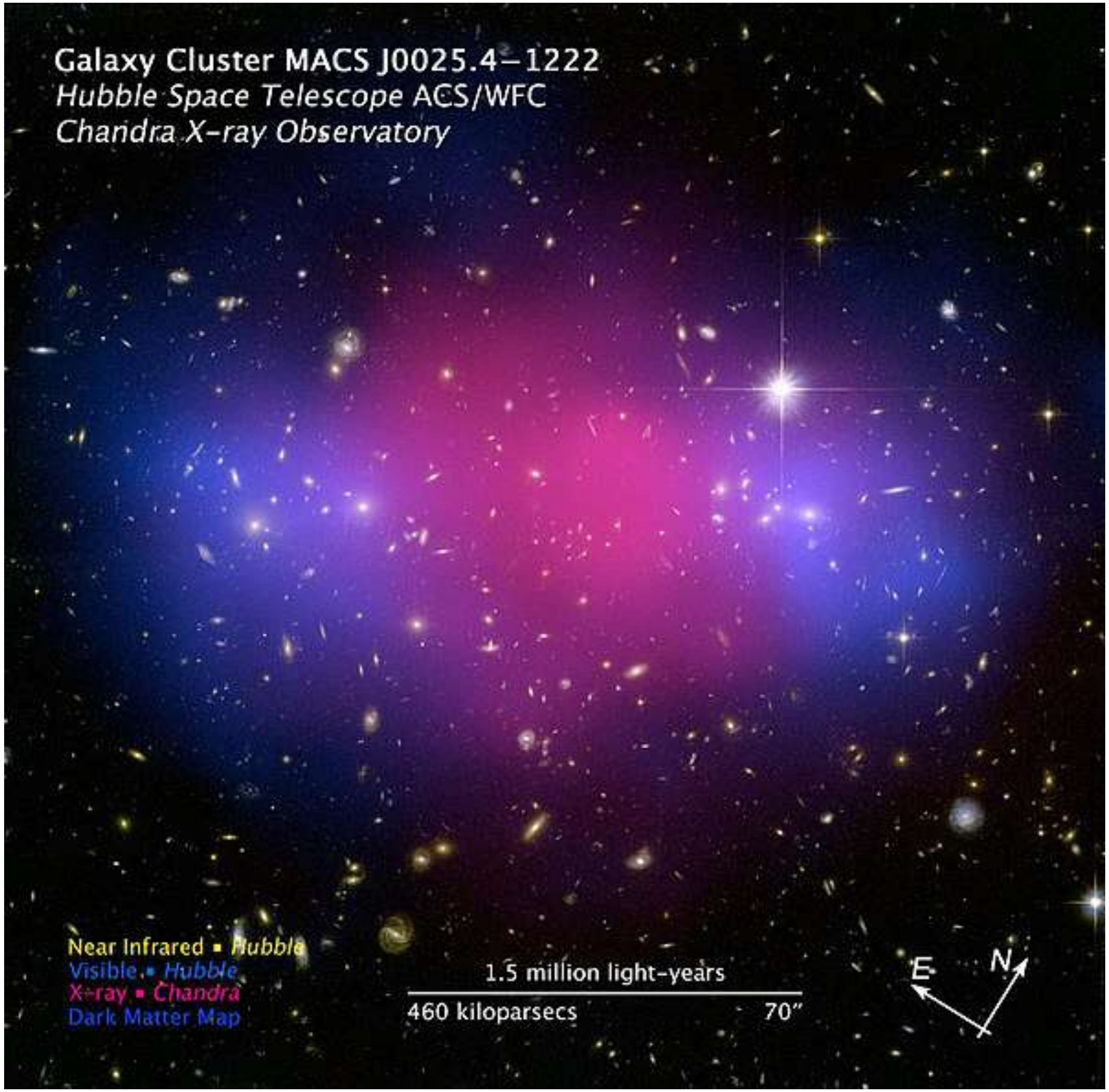


- Further evidence from ***merging*** Galaxy clusters: bullet cluster

Clowe et al 2006

"bullet cluster" - NASA
astro-ph/0608247
[further developments]

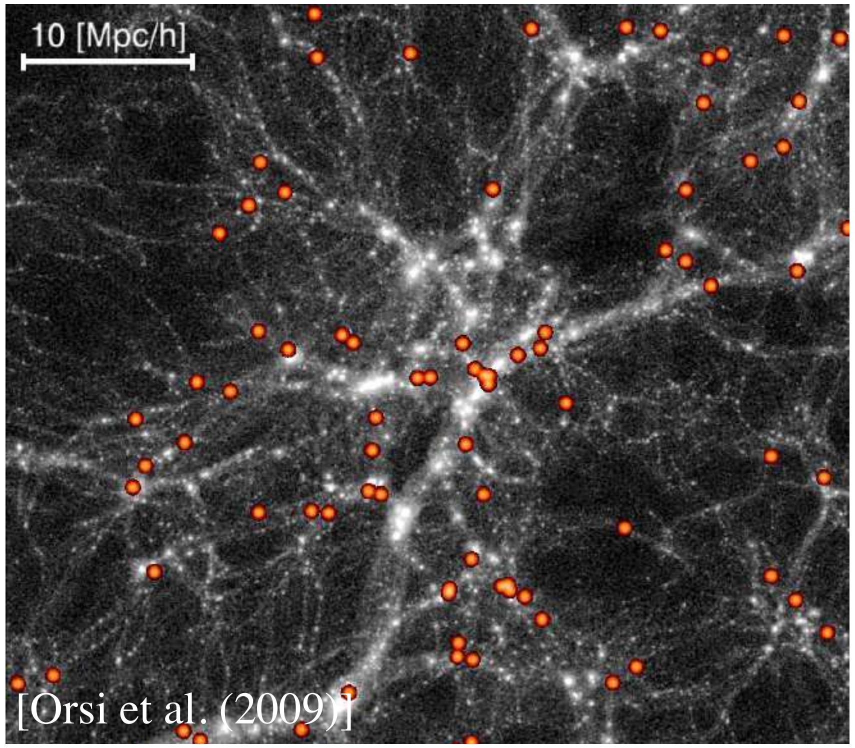

Abell 520
Luminosity derived from CFHT
Mass derived from WFPC2
CFHT V
HST WFPC2 I
CXO X-ray


Galaxy Cluster MACS J0025.4−1222
Hubble Space Telescope ACS/WFC
Chandra X-ray Observatory
Near Infrared ▪ Hubble
Visible ▪ Hubble
X-ray ▪ Chandra
Dark Matter Map
1.5 million light-years
460 kiloparsecs
70″
E
N

Summary:

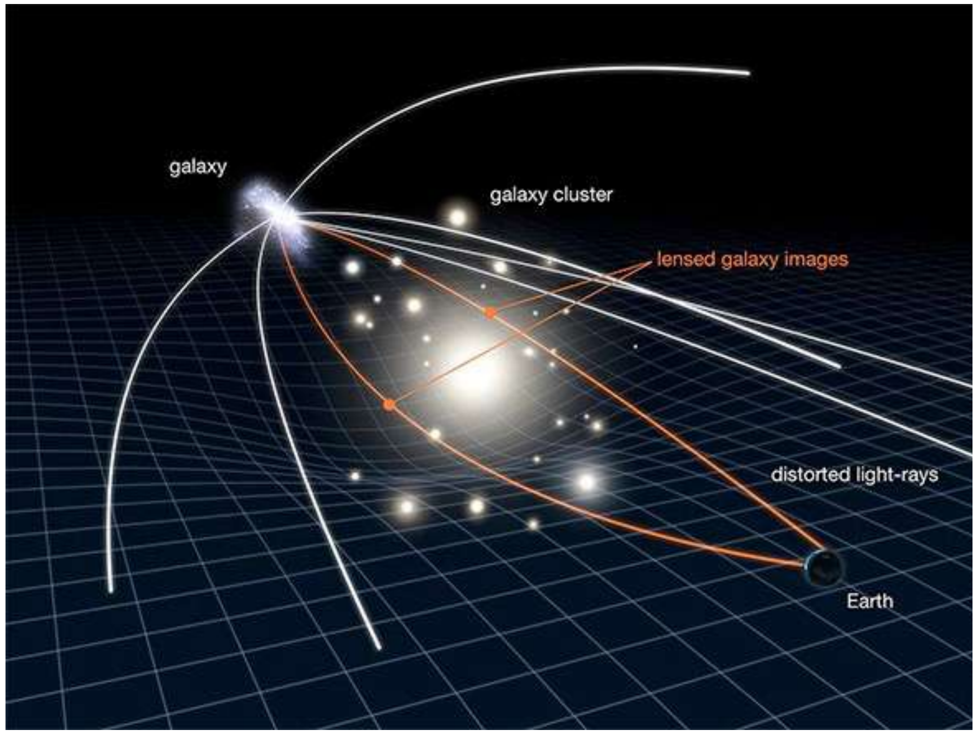
- evidence for DM exists on a wide range of scales
- and throughout the history of the Universe

large scale structures



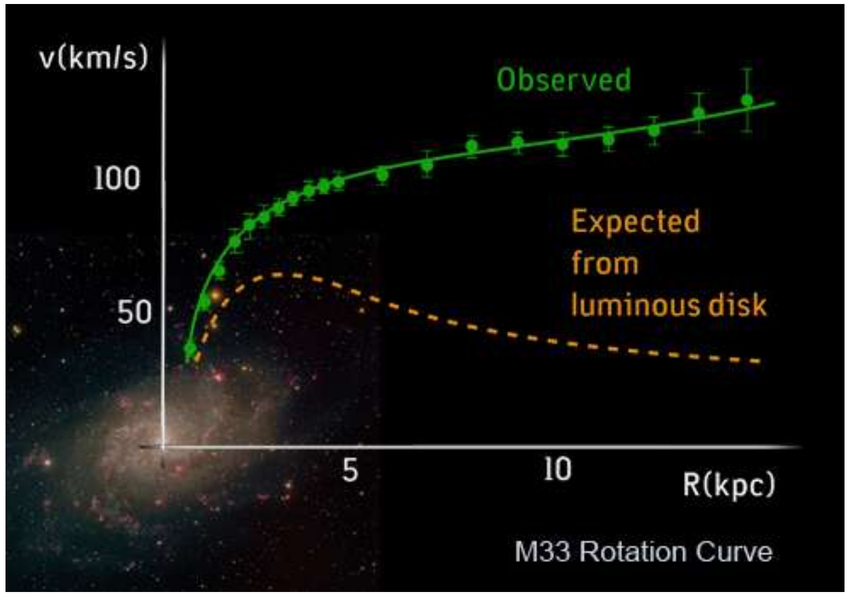
10s Mpc

clusters of galaxies



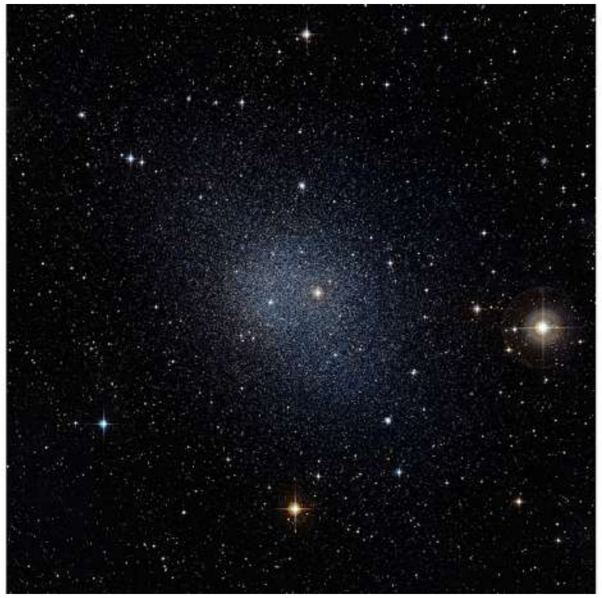
Mpc

Milky Way-sized galaxies



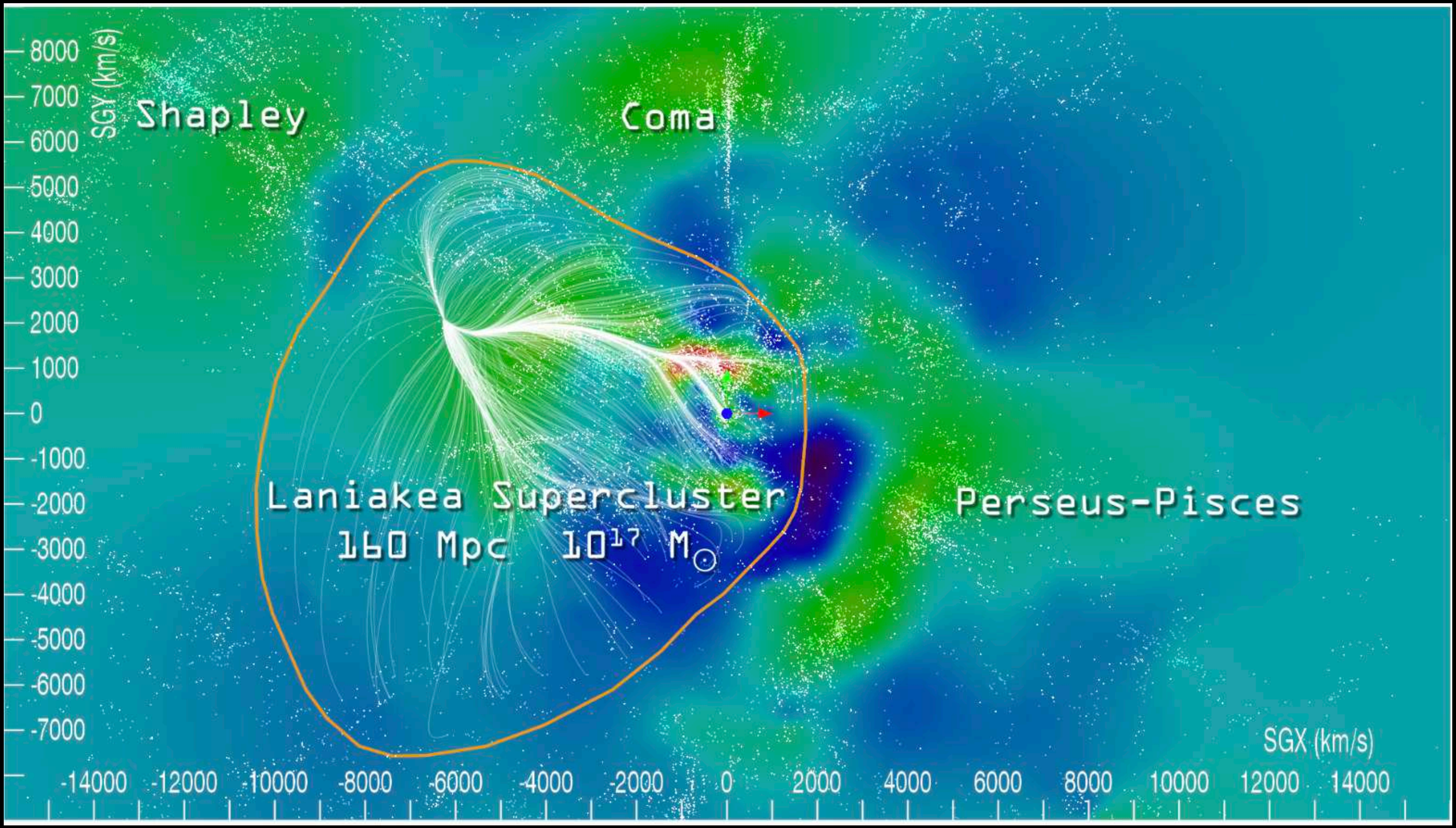
10s kpc

dwarf galaxies



<~ kpc

Lanieakea - "immeasurable heaven" our local supercluster



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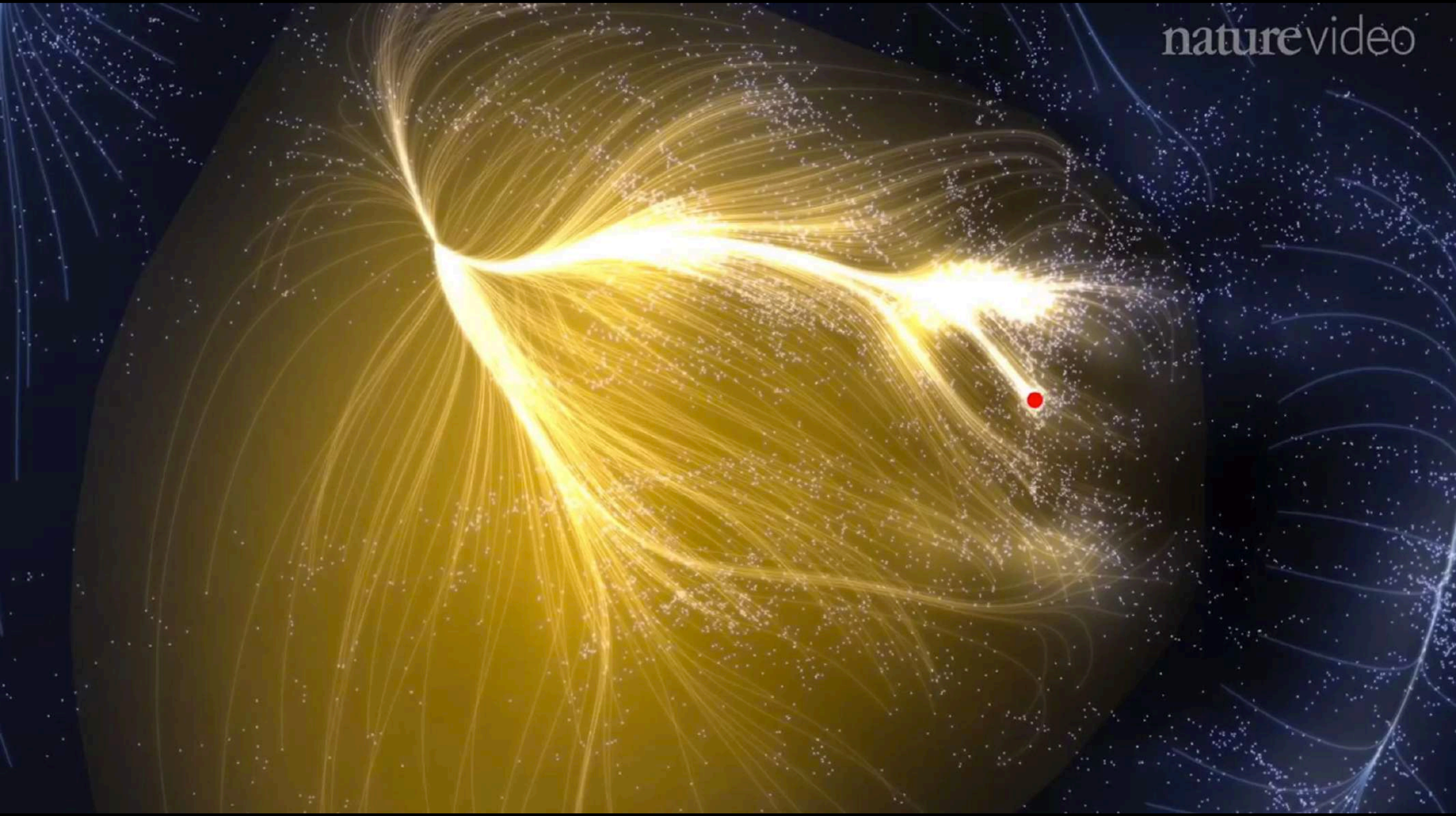
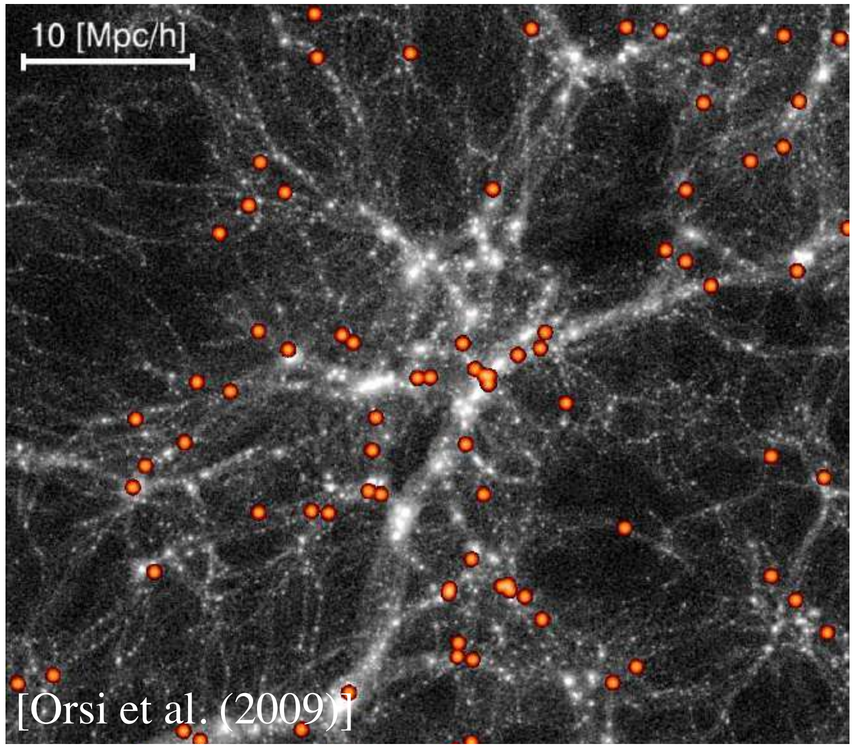


Short summary

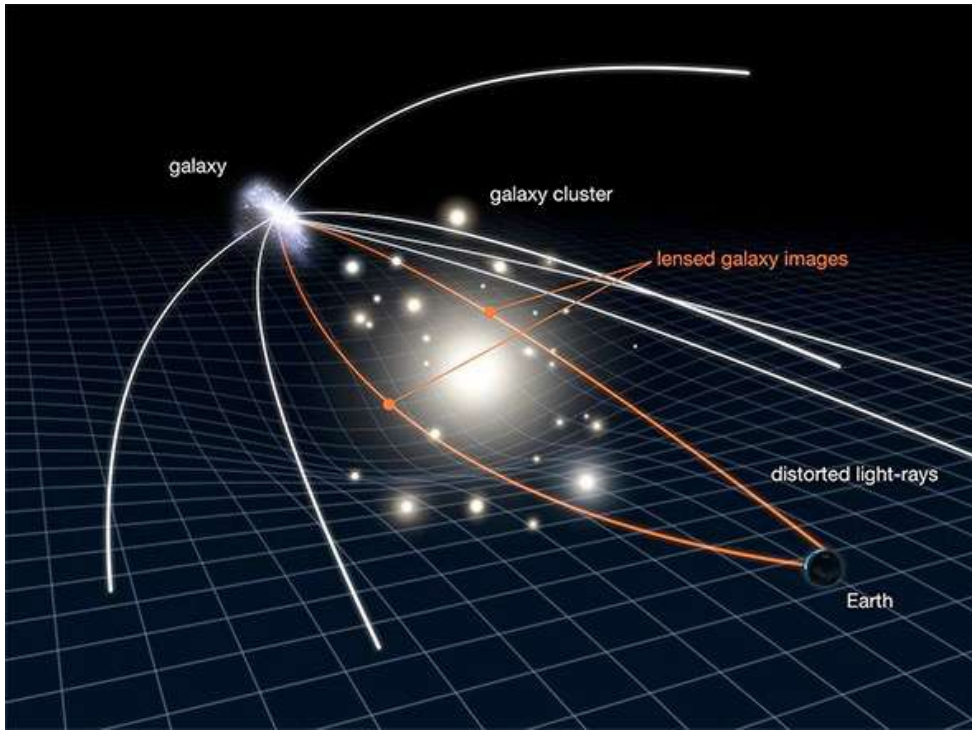
Dark matter is an essential building block of the Standard Model of Cosmology

large scale structures



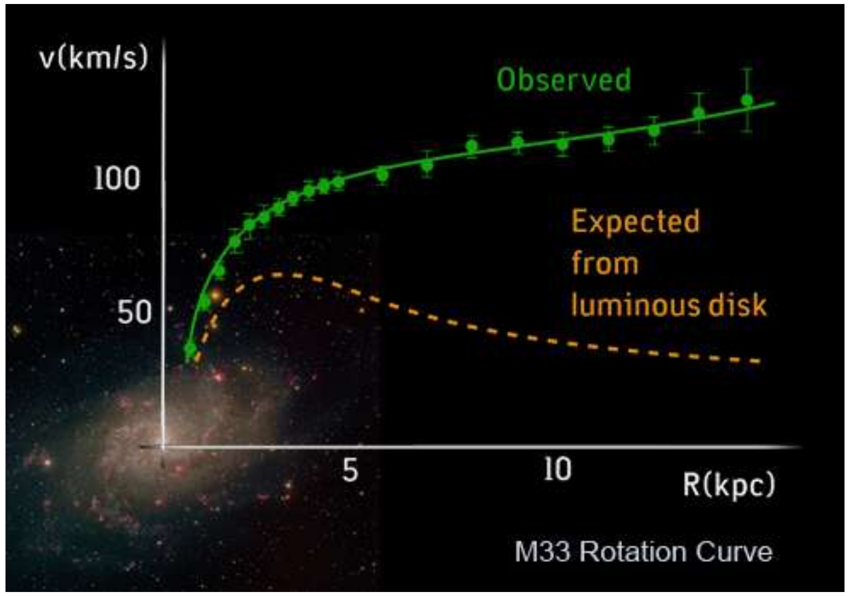
10s Mpc

clusters of galaxies



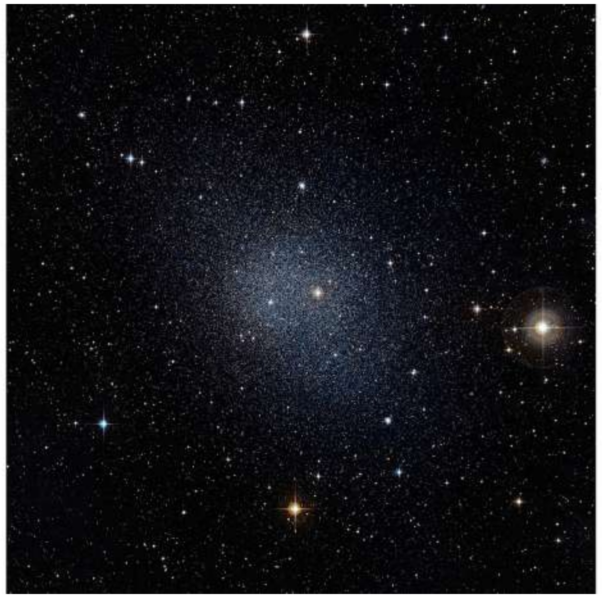
Mpc

Milky Way-sized galaxies



10s kpc

dwarf galaxies



<~ kpc

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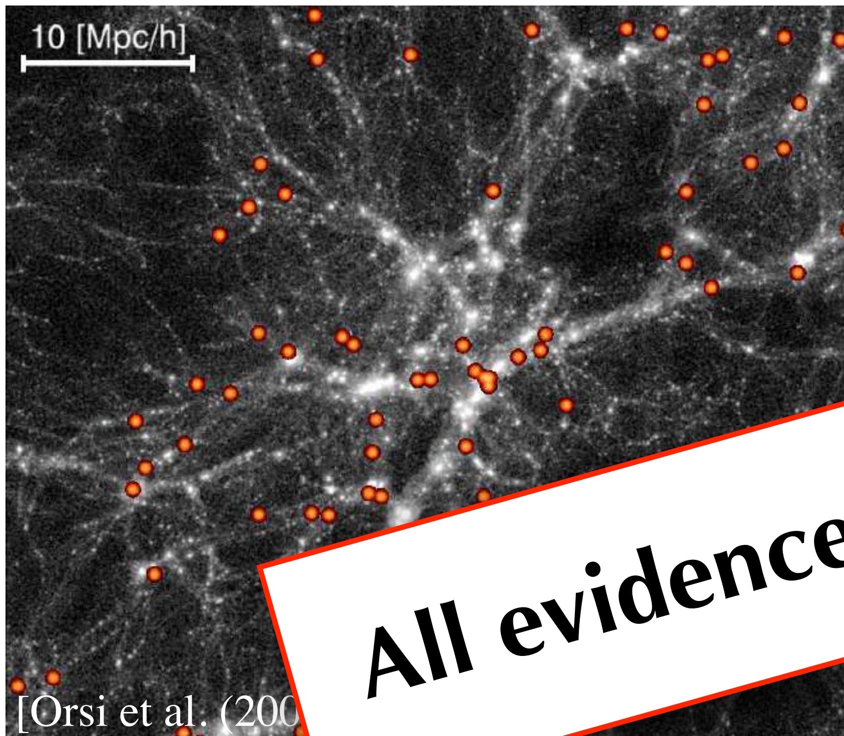
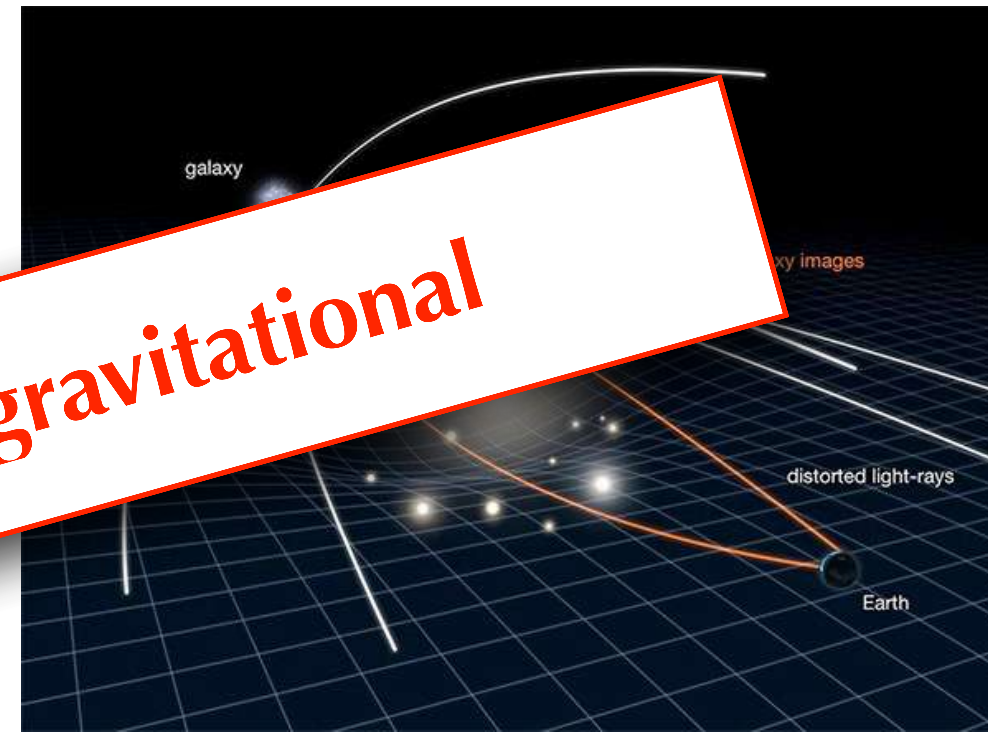
large scale structures

10s Mpc



clusters of galaxies

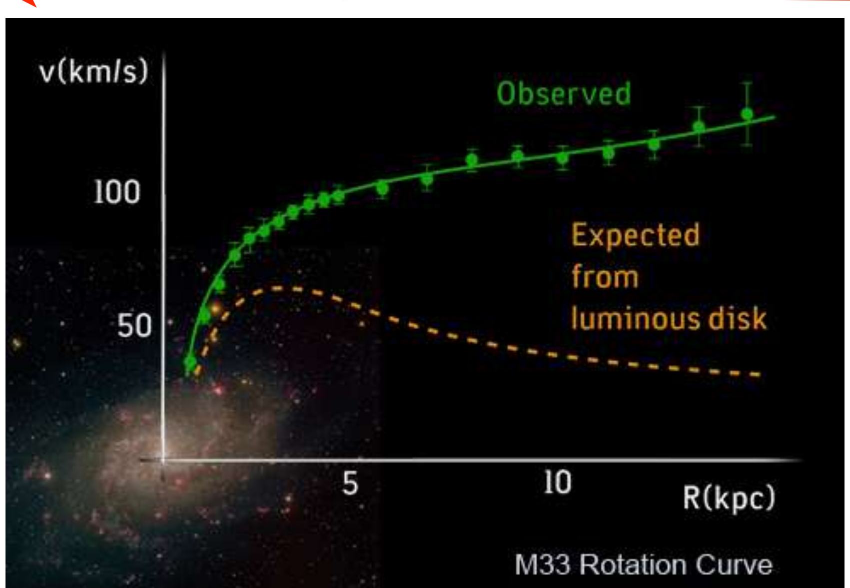
Mpc



All evidence so far is gravitational

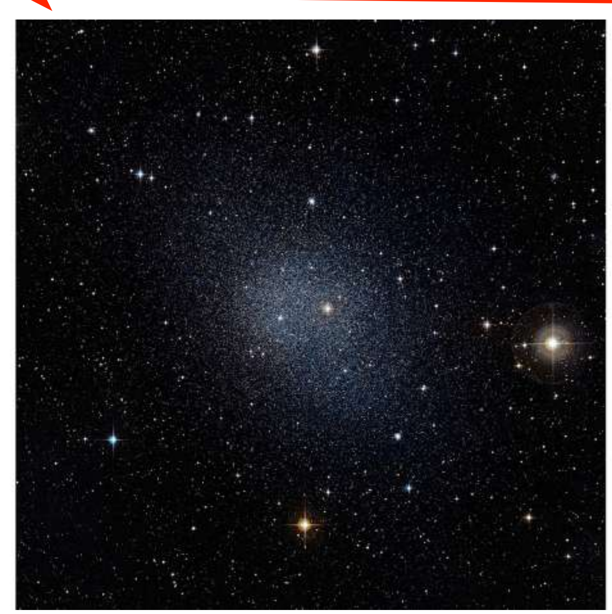
Milky Way-sized galaxies

10s kpc



dwarf galaxies

<~ kpc



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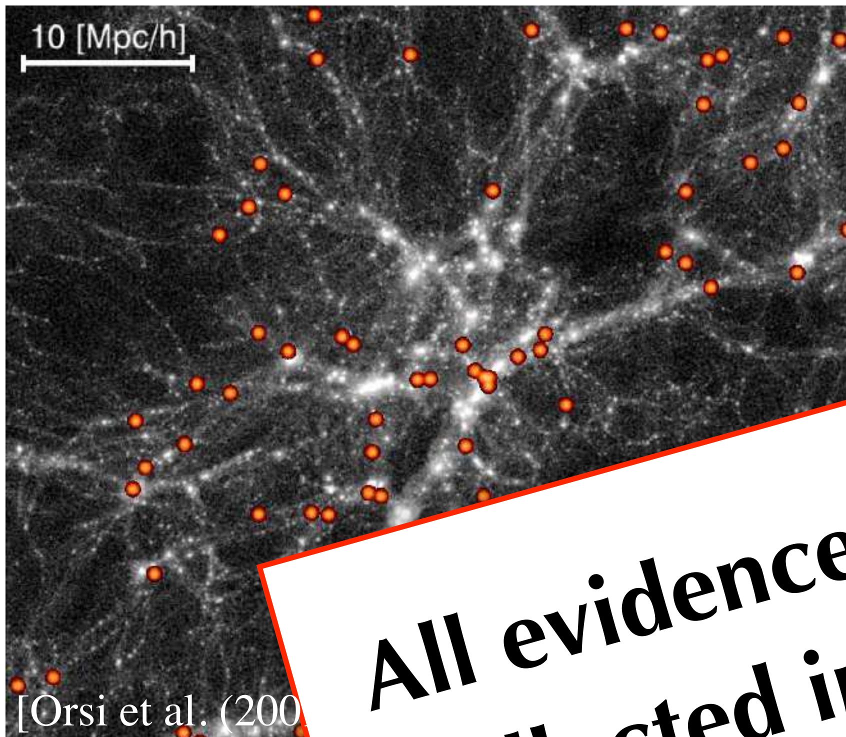


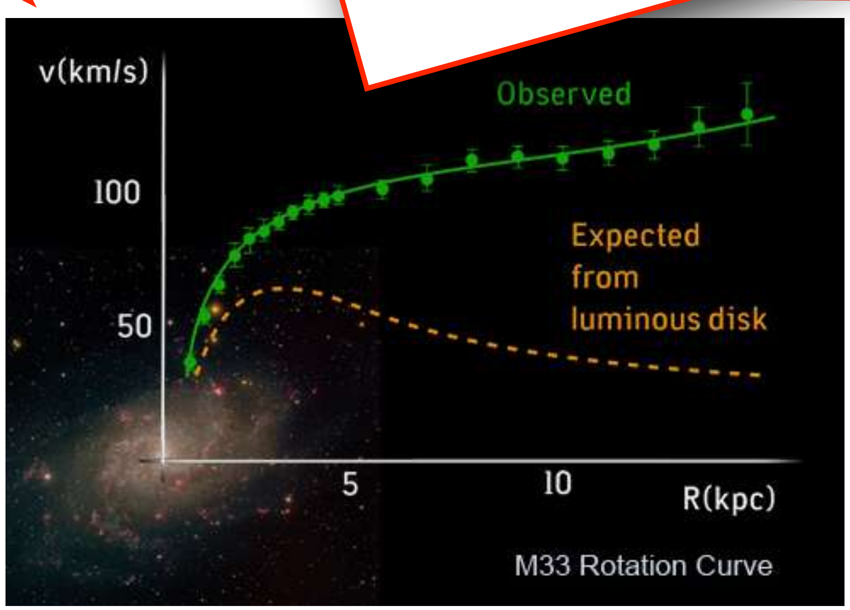
10s Mpc

clusters of galaxies

Mpc

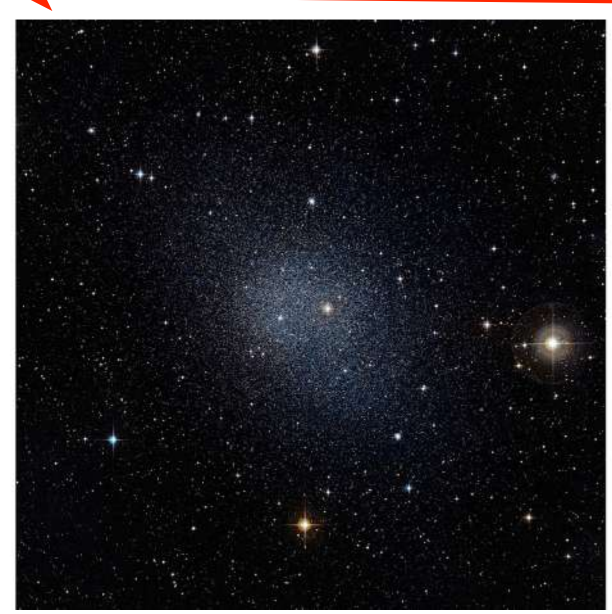
All evidence so far is gravitational
Collected in astrophysical systems

Milky Wa



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

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

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

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

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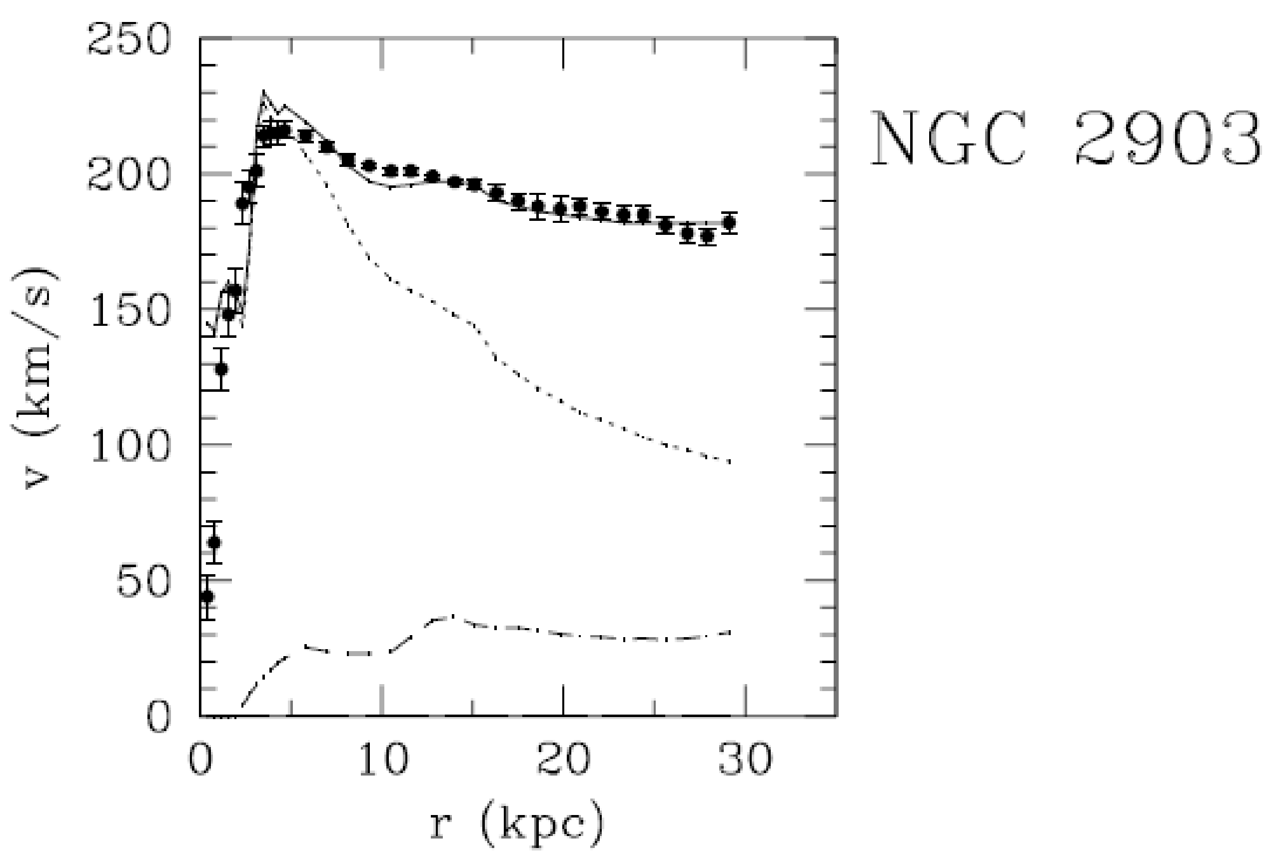
$$v = \sqrt[4]{GMa_0}$$

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



- However, evidence for DM collected on a large span of scales! The toy model cannot explain that with a single constant

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

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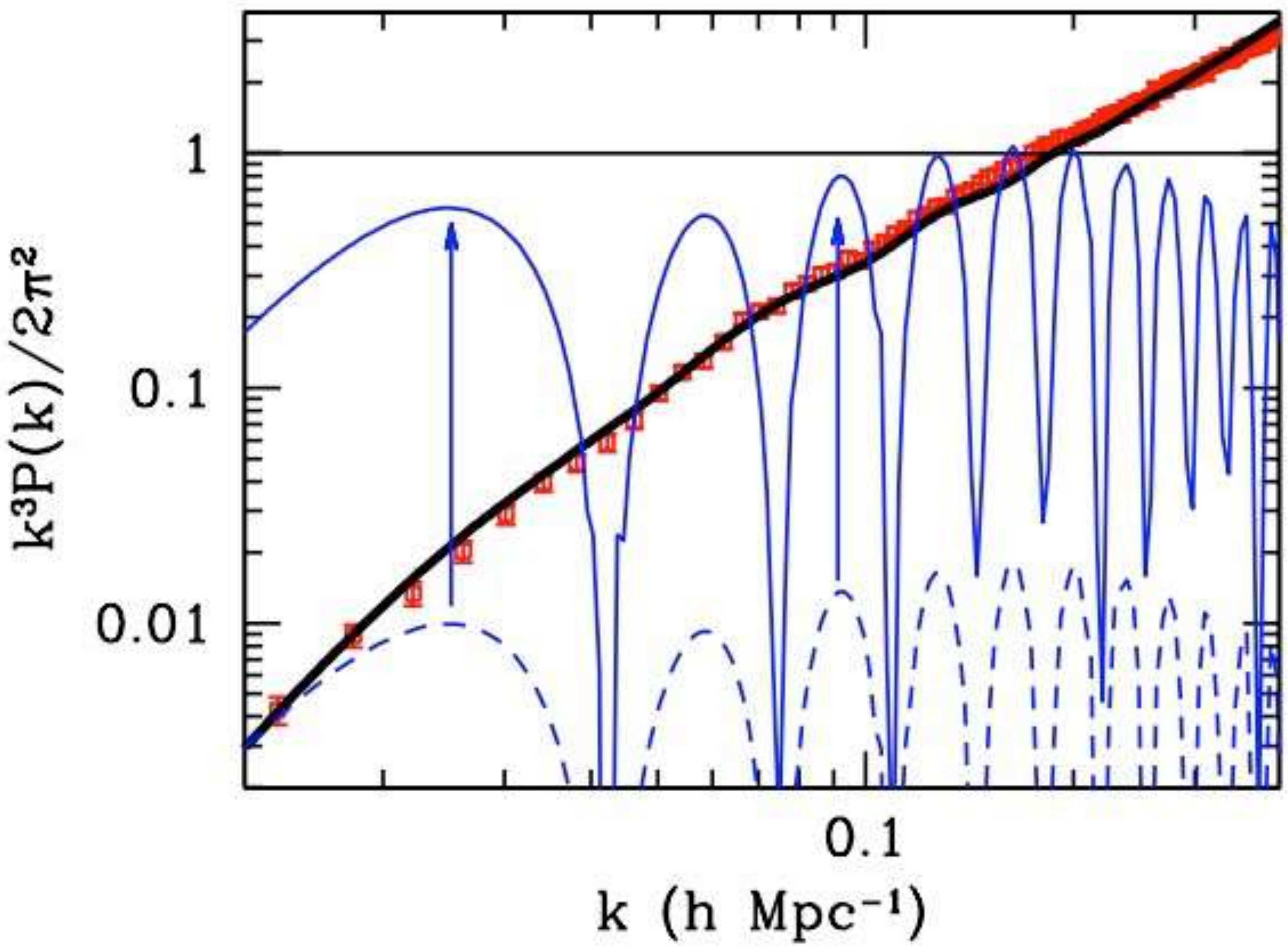
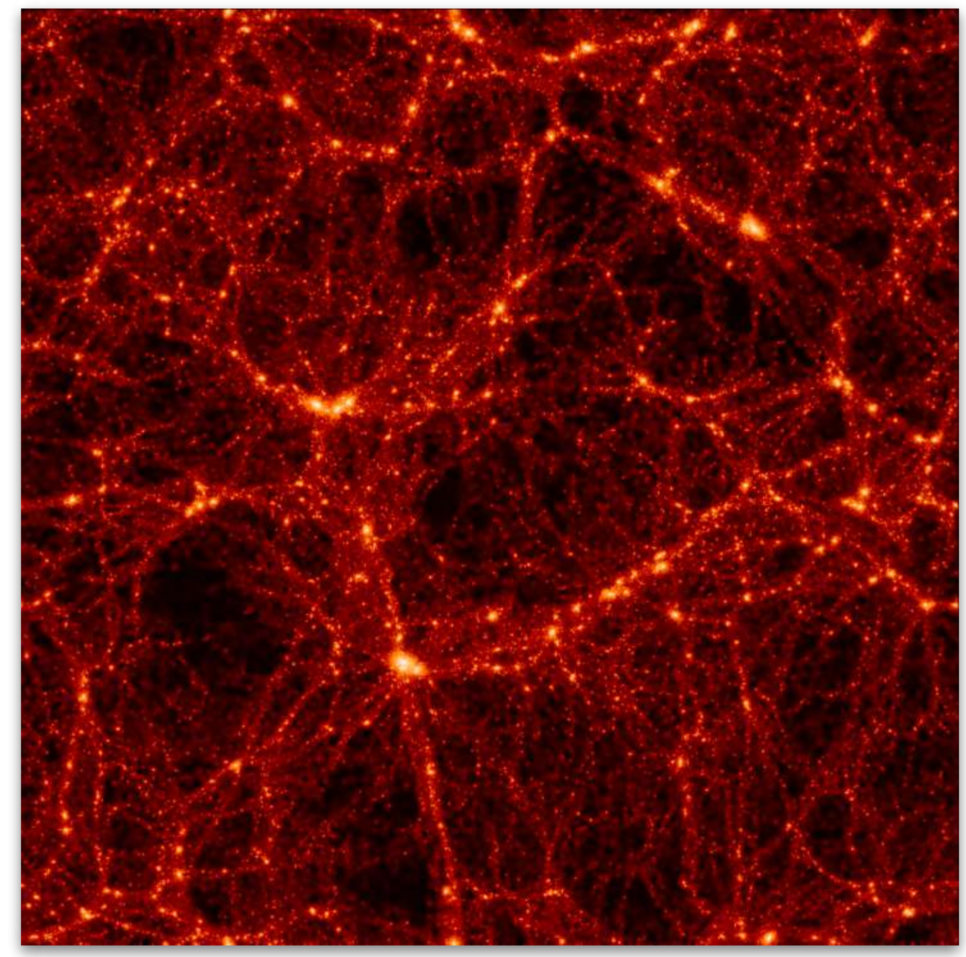
Draft version June 1, 2010

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!

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