Evolving view on the Universe and discovery of its dark components

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Our story 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*' (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

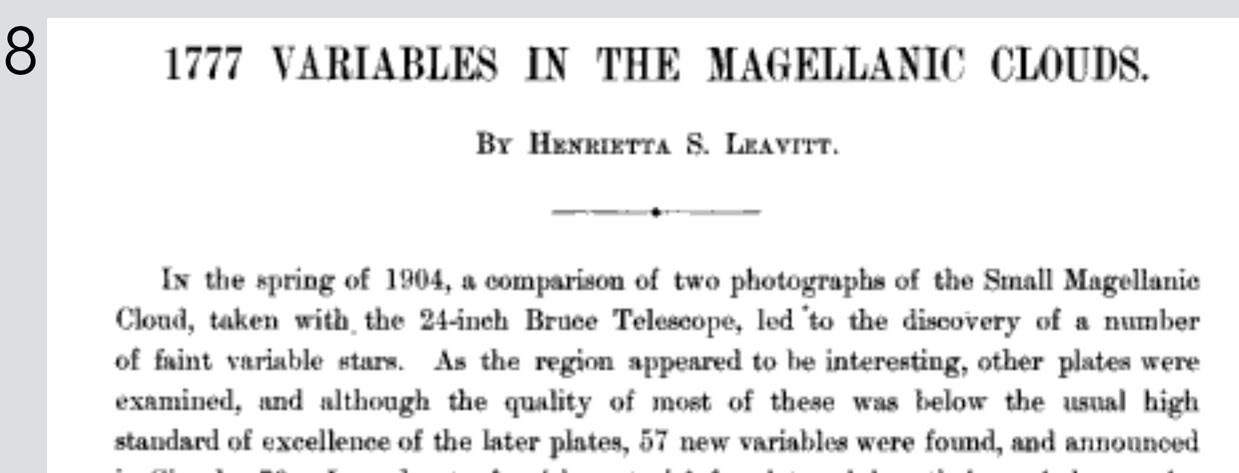
relationship between period and luminosity

⇨ 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

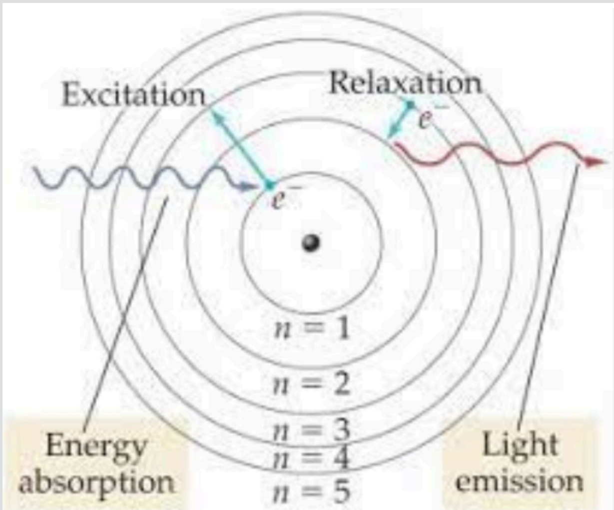
Progress at the beginning of the XX century

Spectroscopy

the star is moving closer

the star is not moving

the star is not moving



Vesto Slipher
(1875-1969)

Astronomers started using spectroscopy to measure motions of stars and planets. Around 1917 it became clear that the mysterious nebulae are moving away from us ….

April 20th, 1920: the great debate

Harlow Shapley
(1885-1972)

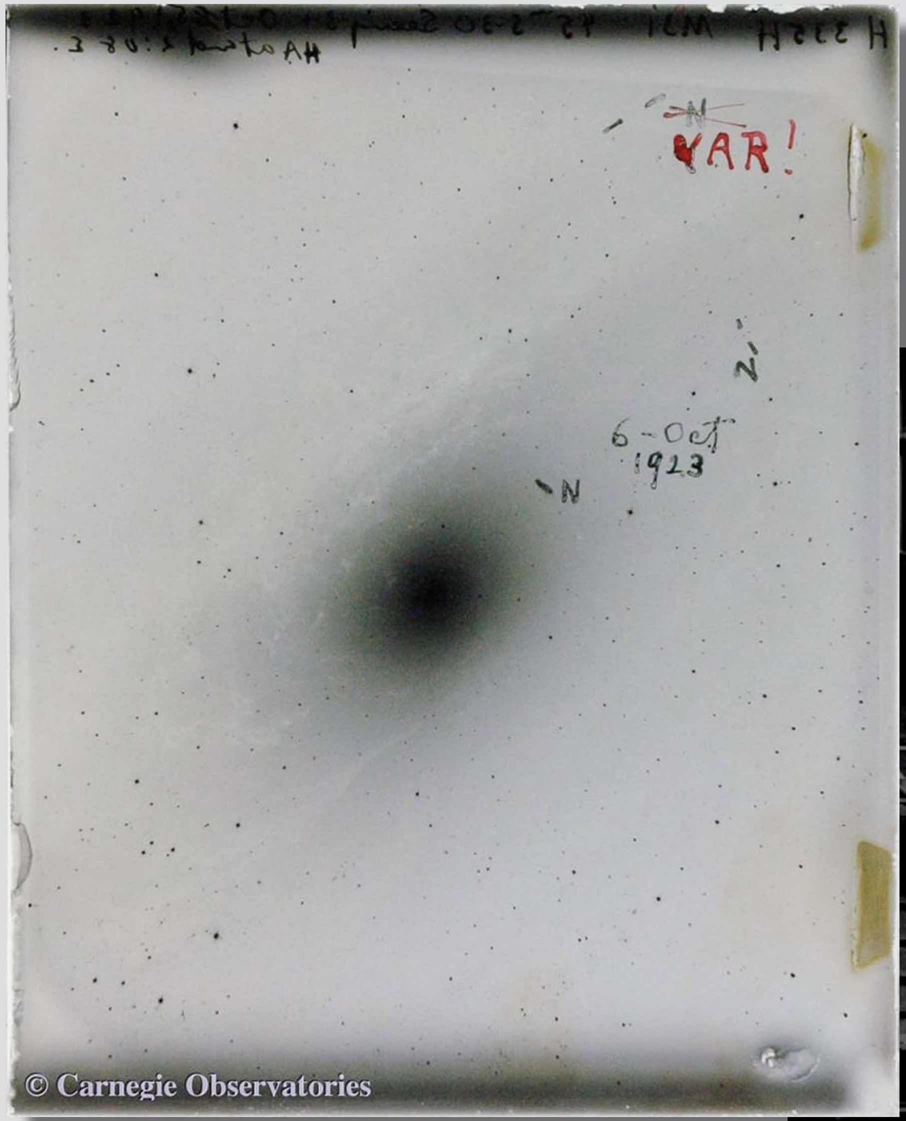
Are nebulae extra-galactic objects (island Universes)? How large is the Universe?

Heber Curtis
(1872-1942)

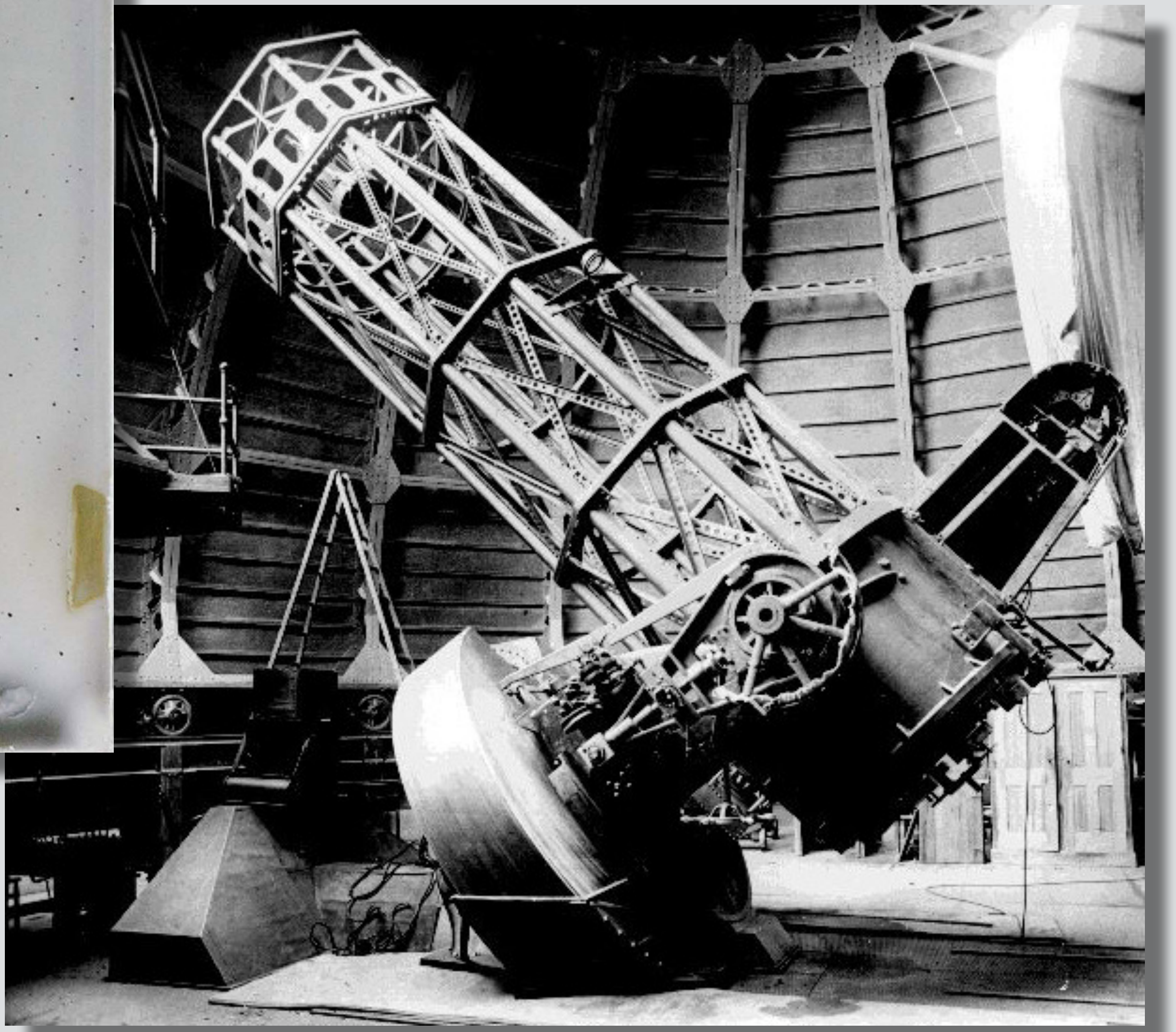
Baird Auditorium, Smithsonian National Museum of Natural History, Washington D.C.

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

Edwin Hubble
(1889-1953)

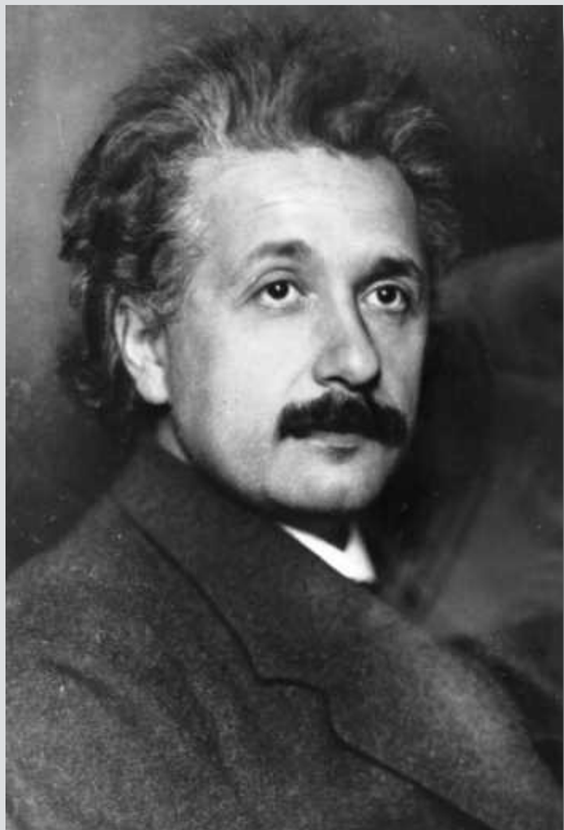


Andromeda nebula becomes Andromeda ***galaxy***!



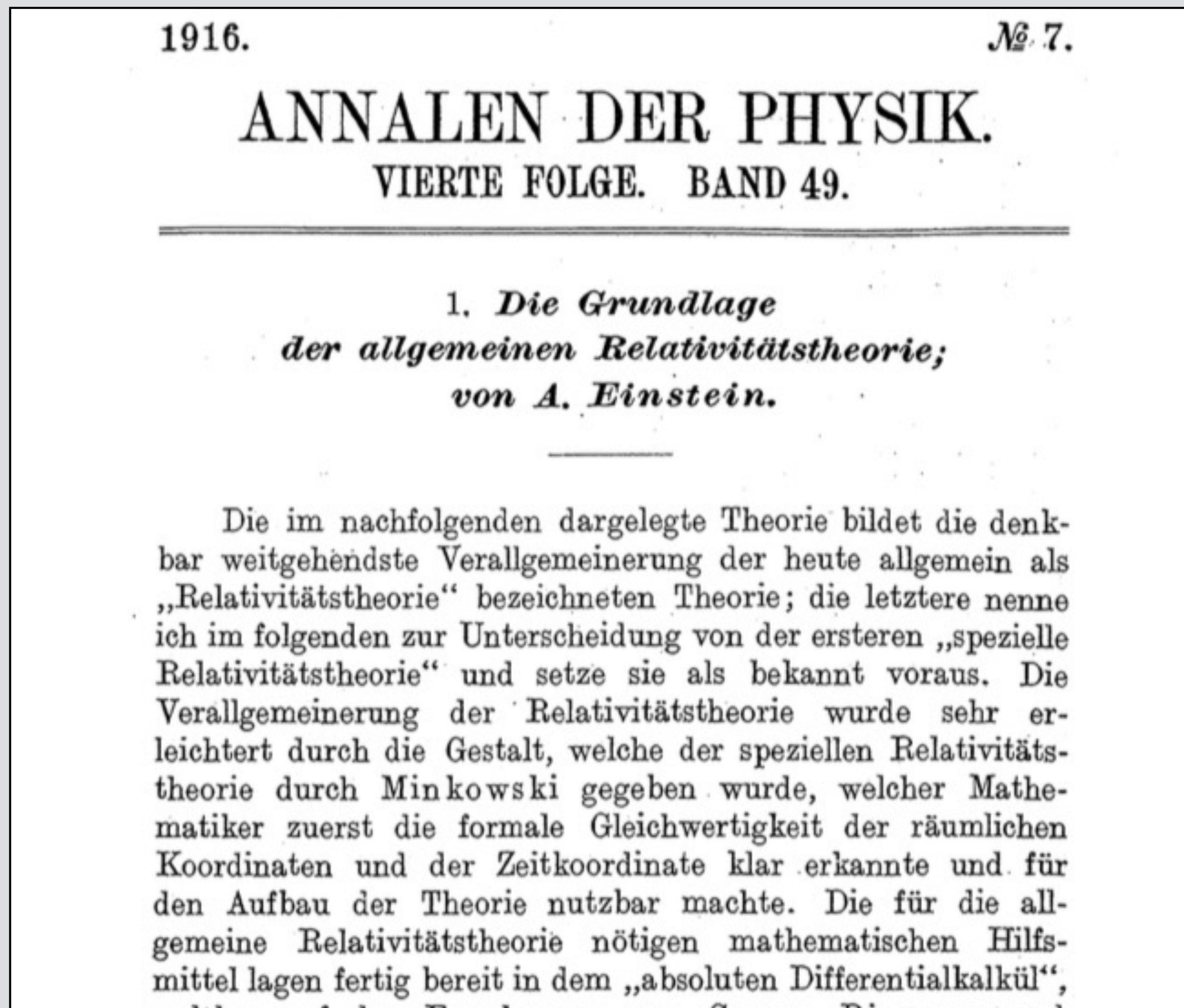
Hooker telescope, Mt. Wilson, California (1917)

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.

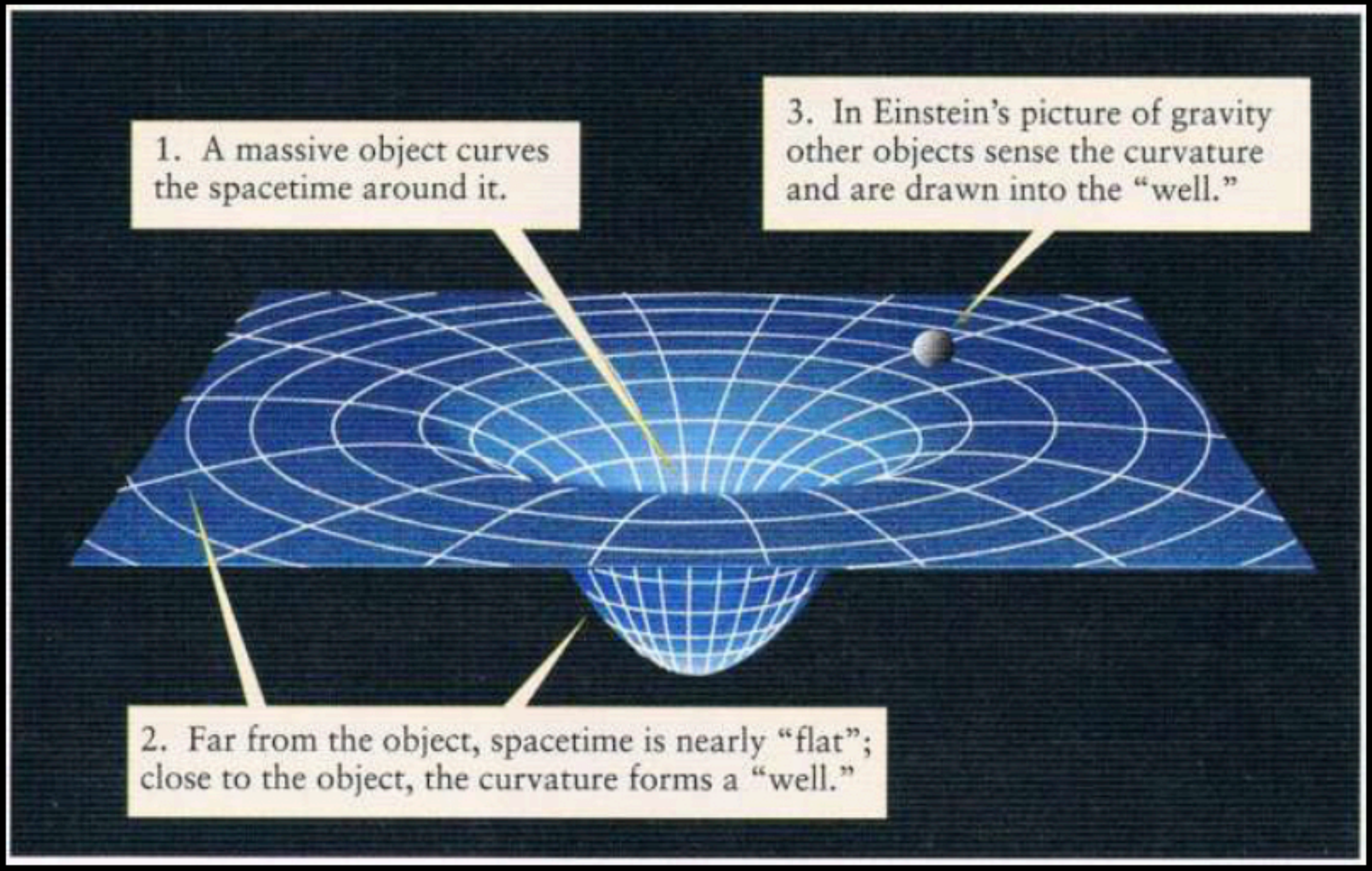
1. *Die Grundlage der allgemeinen Relativitätstheorie;*
von A. Einstein.

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

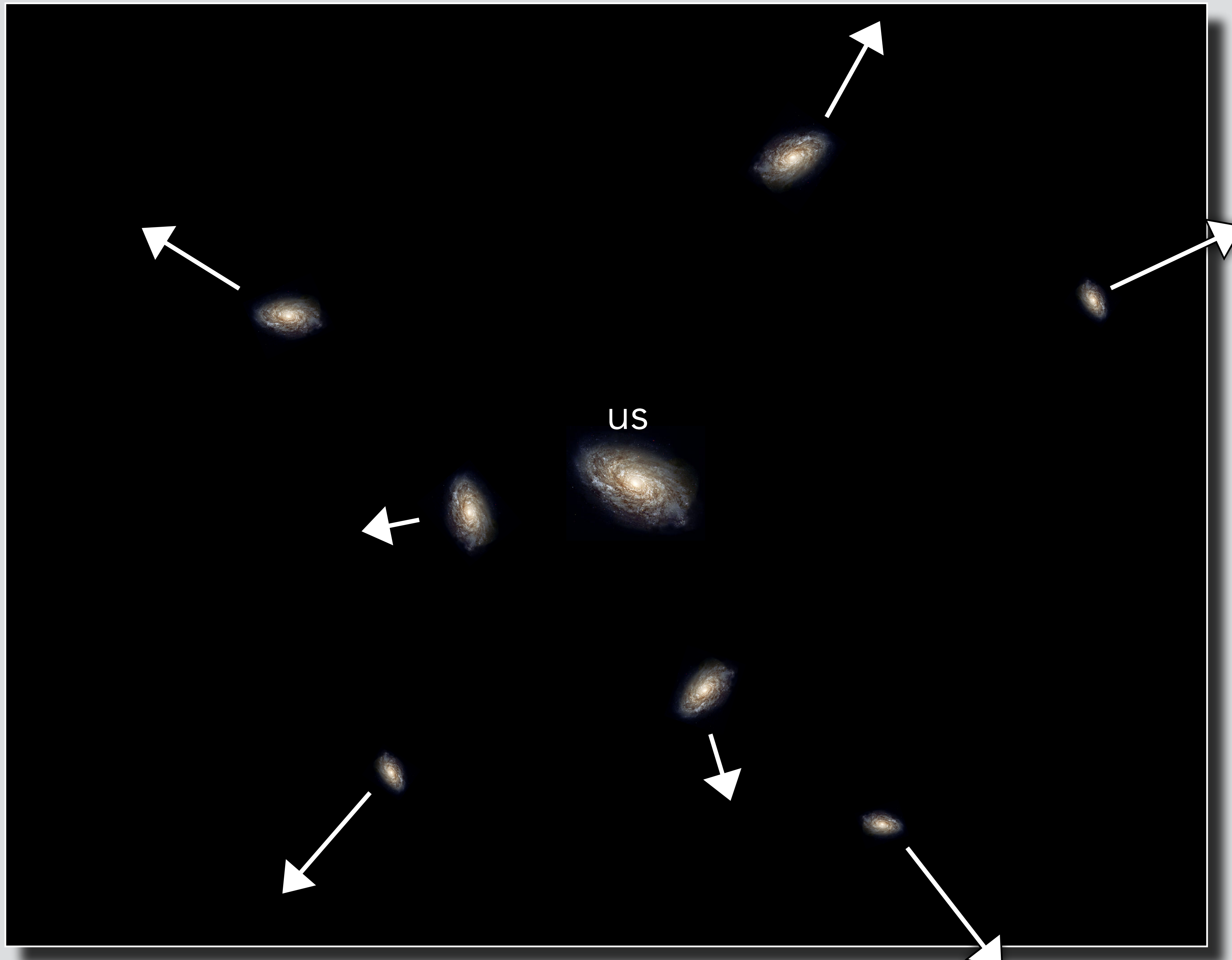
Like a surface of the balloon (2D)

— 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)

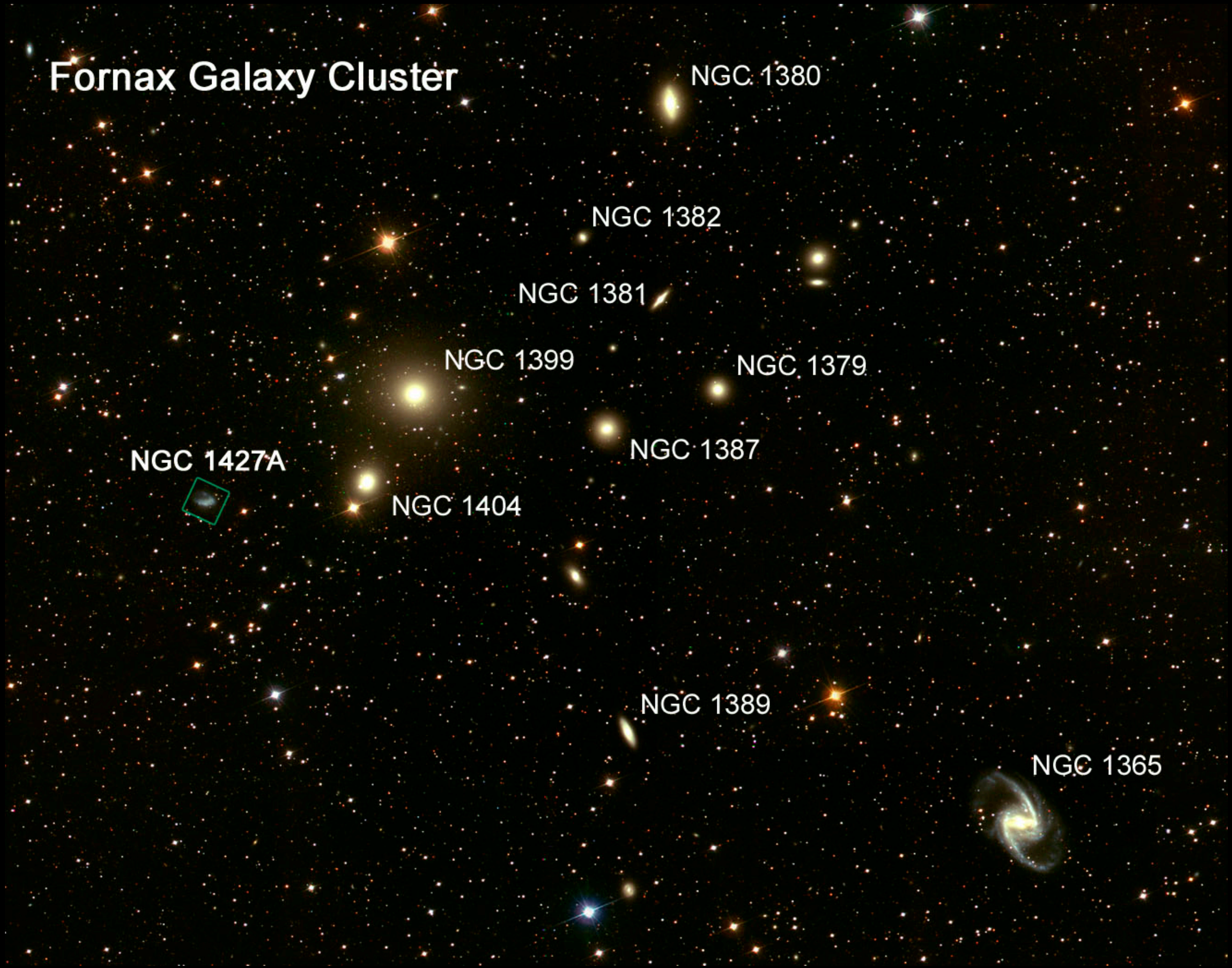


By the end of the 1930s it was becoming evident that:

- 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.

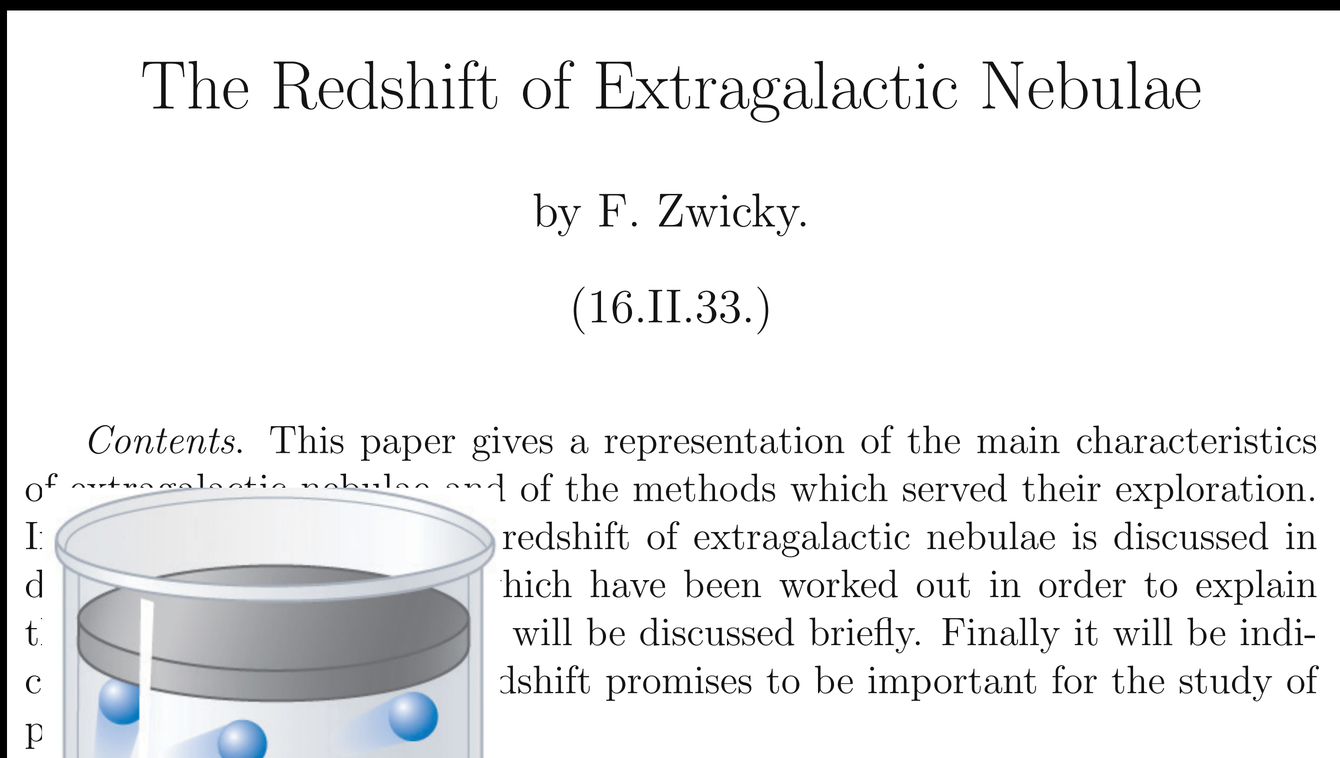


Hubble & Humason published distances of several galaxy clusters in 1931.

They noticed large variations in velocities within the Coma Cluster.

Fritz Zwicky was the first to use these large variations in the velocity of galaxies within galaxy clusters to ask:

is this telling us something about the cluster itself?

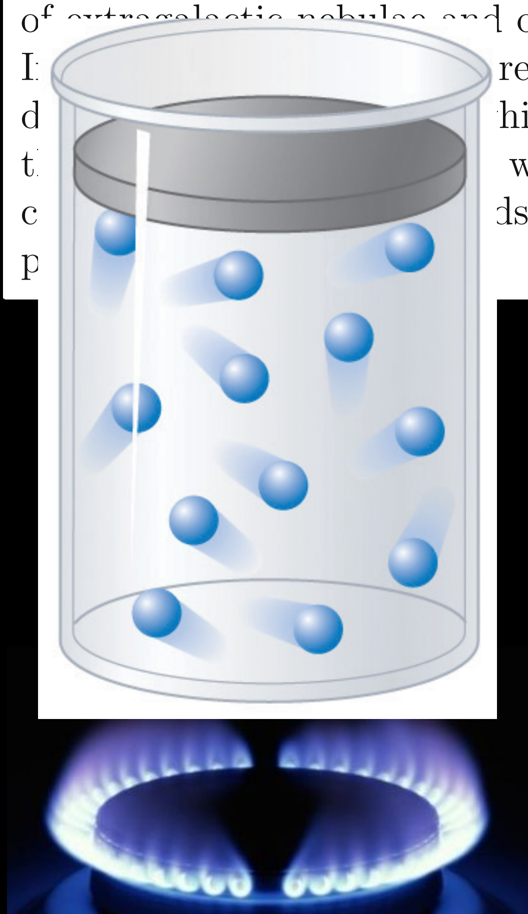


The Redshift of Extragalactic Nebulae

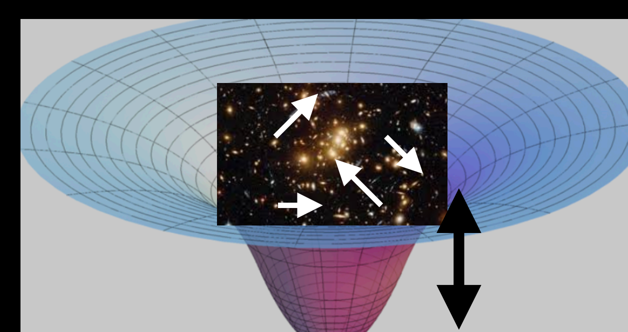
by F. Zwicky.

(16.II.33.)

Contents. This paper gives a representation of the main characteristics of ... of the methods which served their exploration. I... redshift of extragalactic nebulae is discussed in d... hich have been worked out in order to explain t... will be discussed briefly. Finally it will be indi- c... dshift promises to be important for the study of p...



if heated (given energy)
gas particles are moving faster



is high velocity "dispersion" for galaxies in a cluster a sign of a *strong gravitational* energy in the cluster?

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** " —> DARK MATTER

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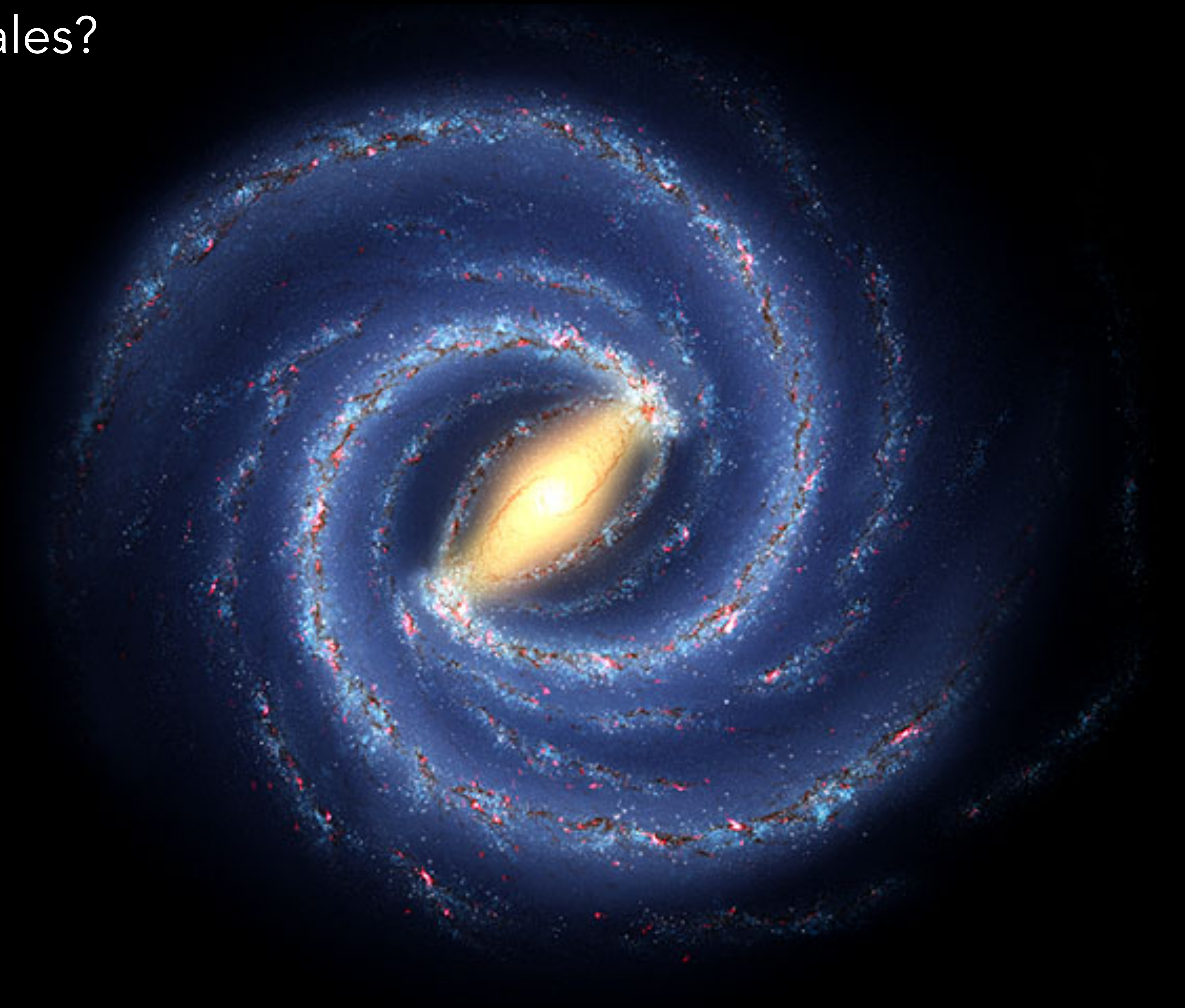
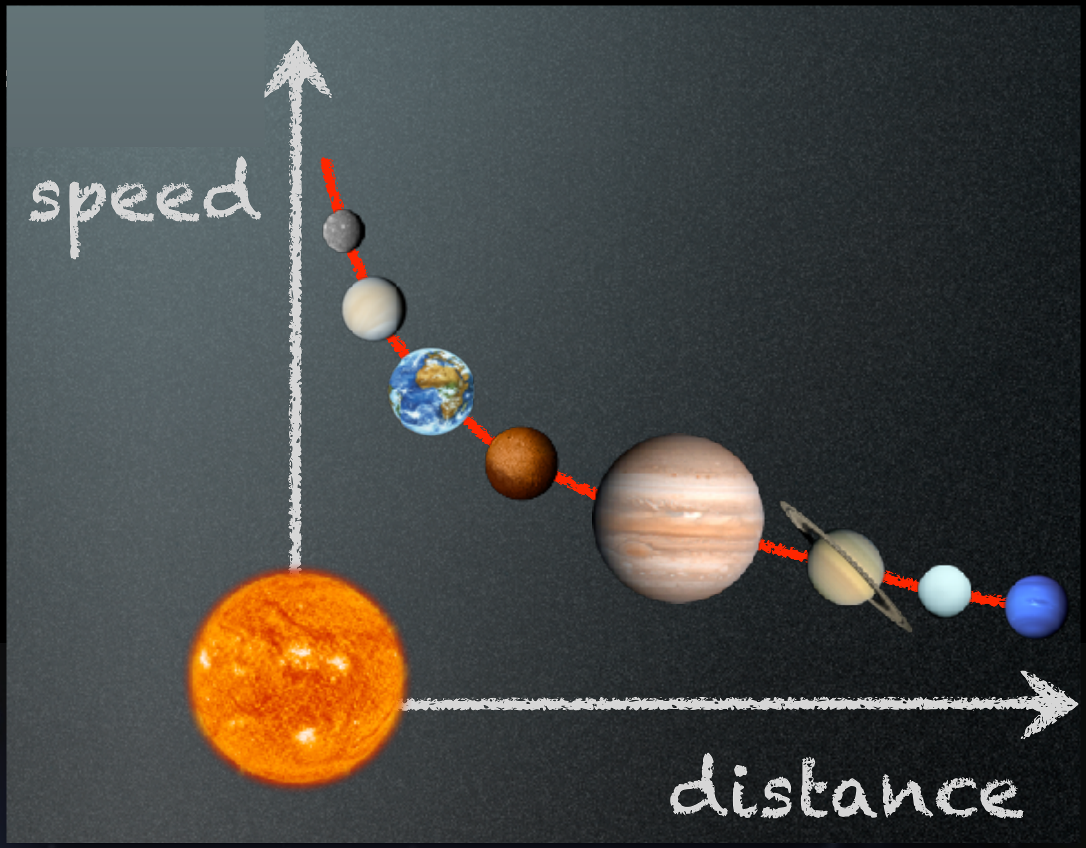
Zwicky was not taken seriously: the problem was just a "missing luminosity problem"

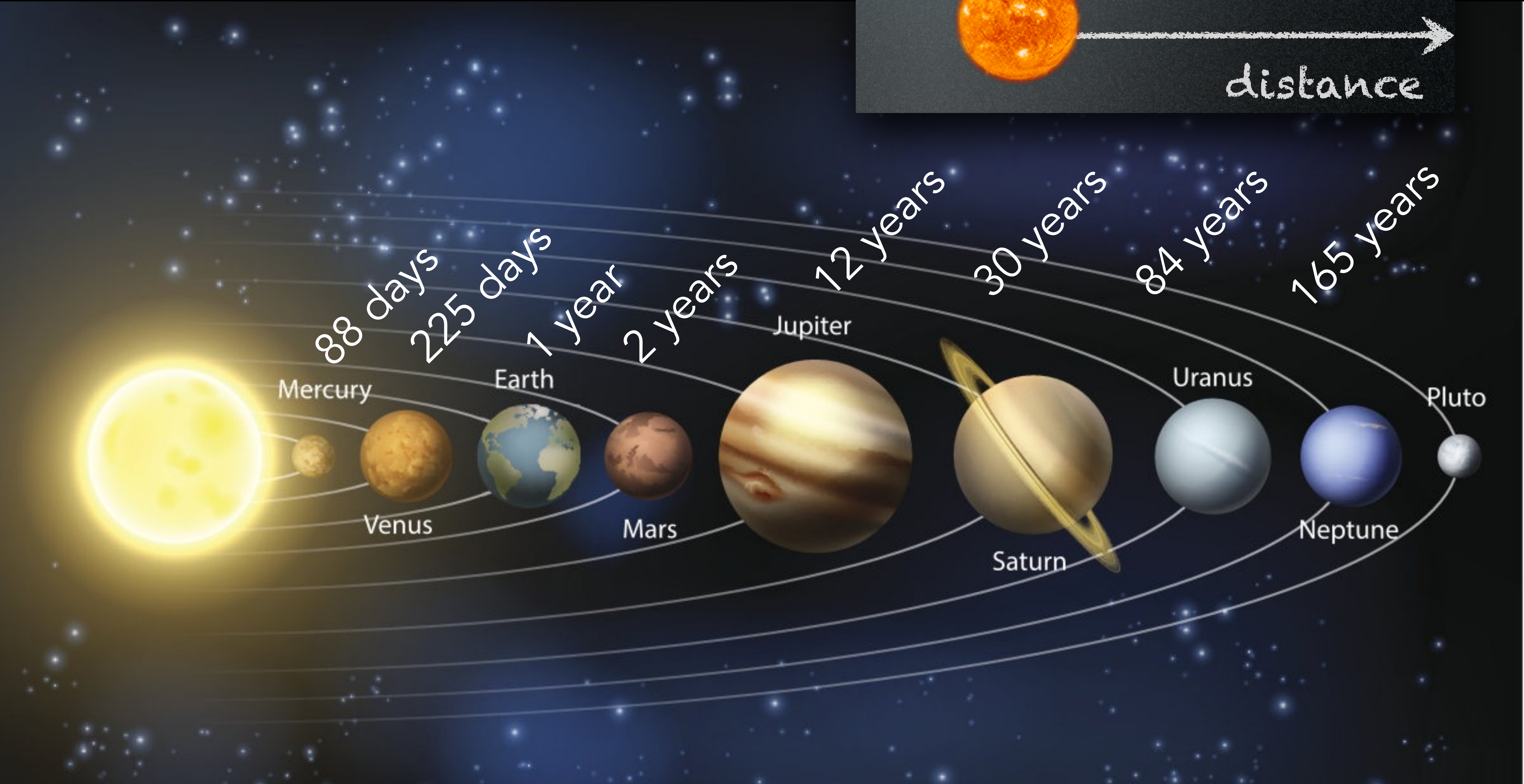
How about Galaxy scales?



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!

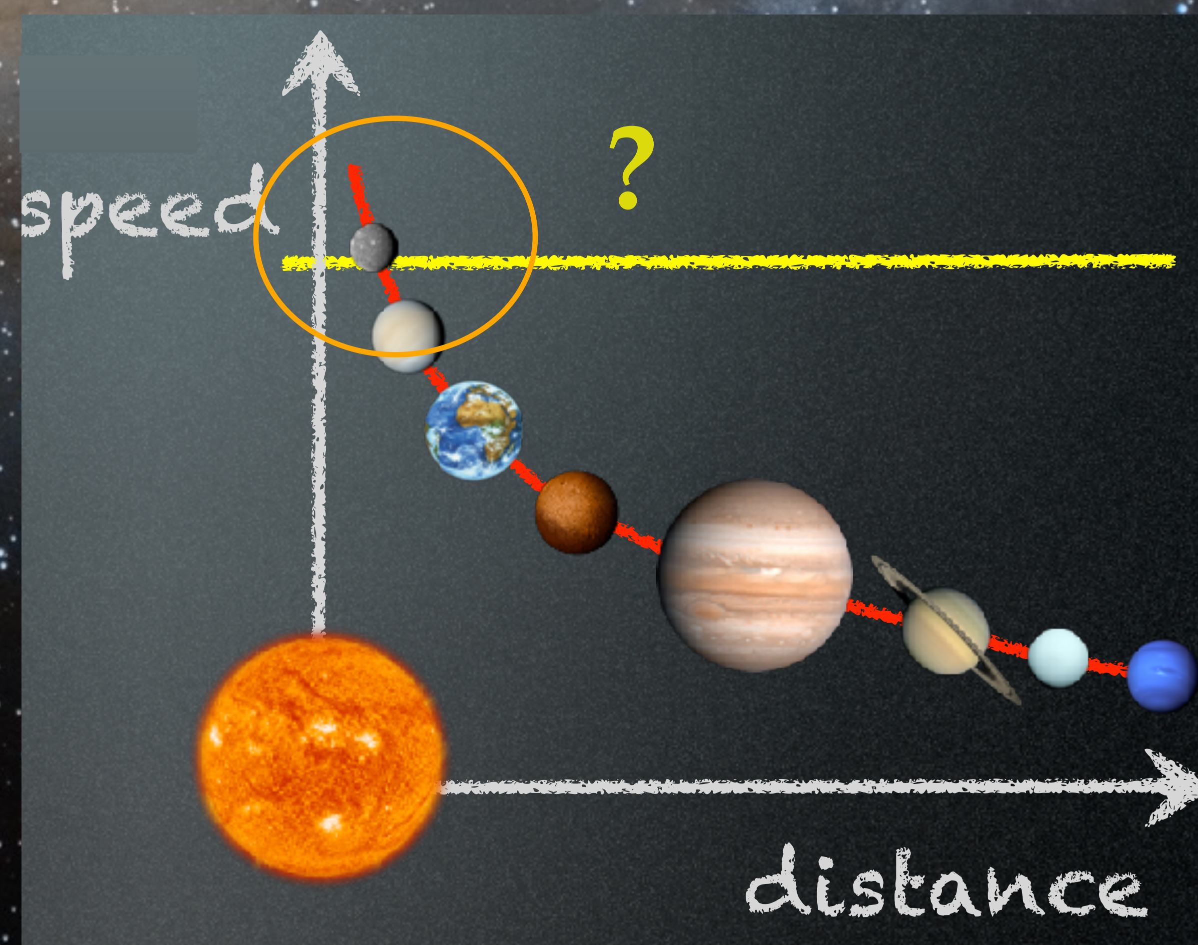
In 1939 Horace Babcock measures the rotation curves for Andromeda measuring a **constant angular velocity**!

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

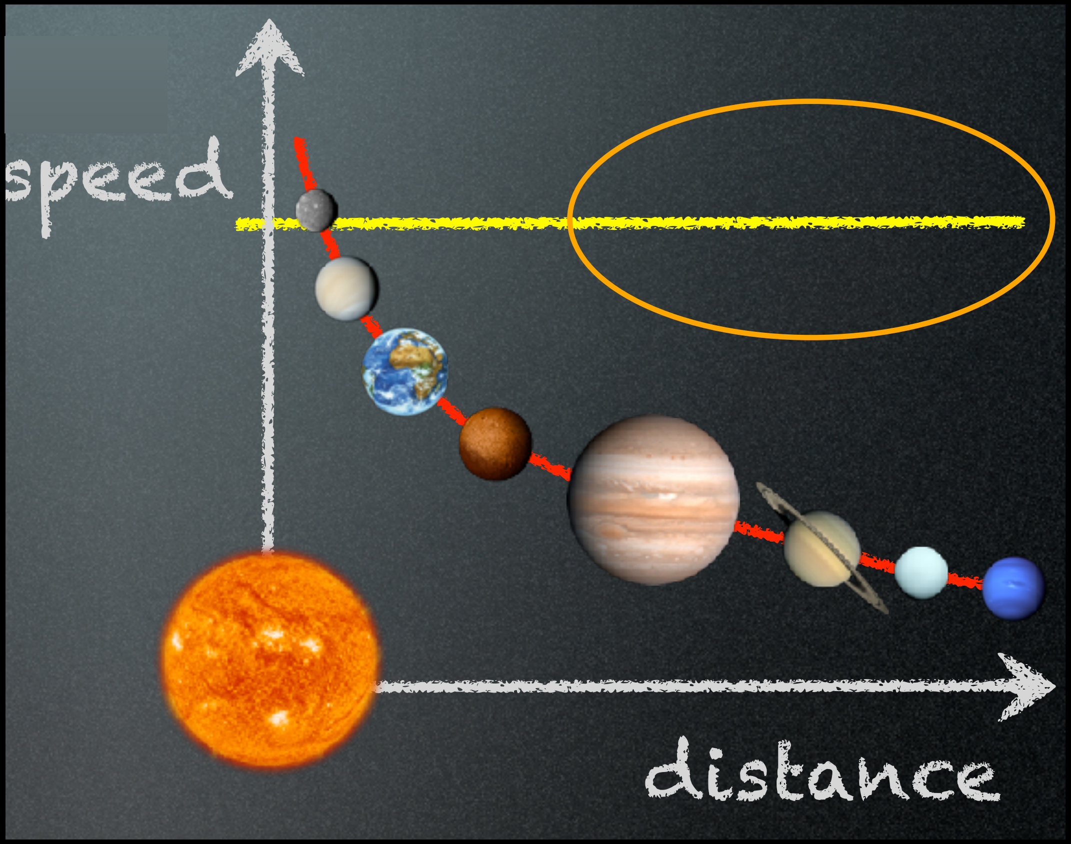
***Van de Hulst** at Dwingeloo*

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

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

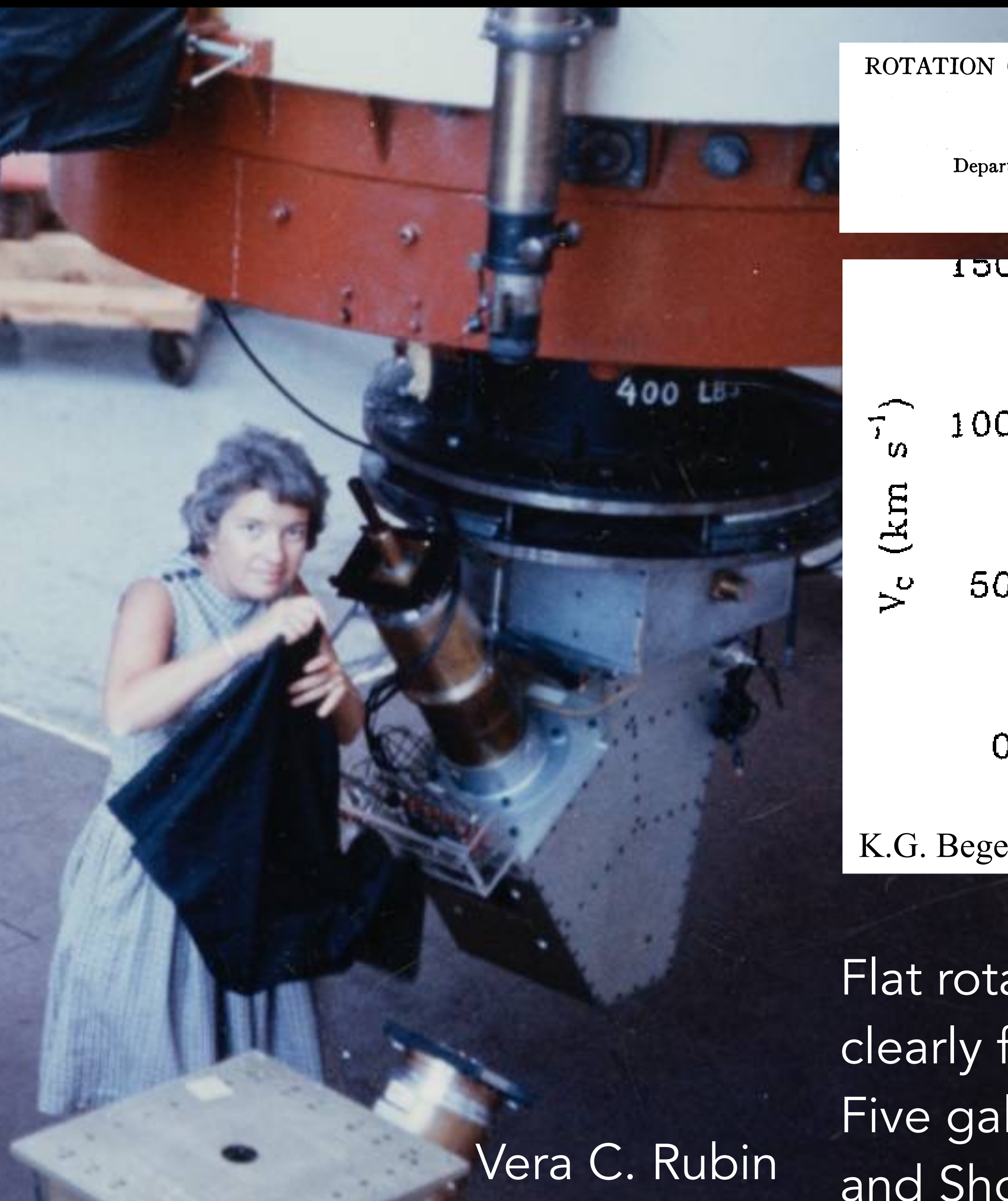
That meant that one could measure gas velocity accurately and much farther from the centre of Andromeda!

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



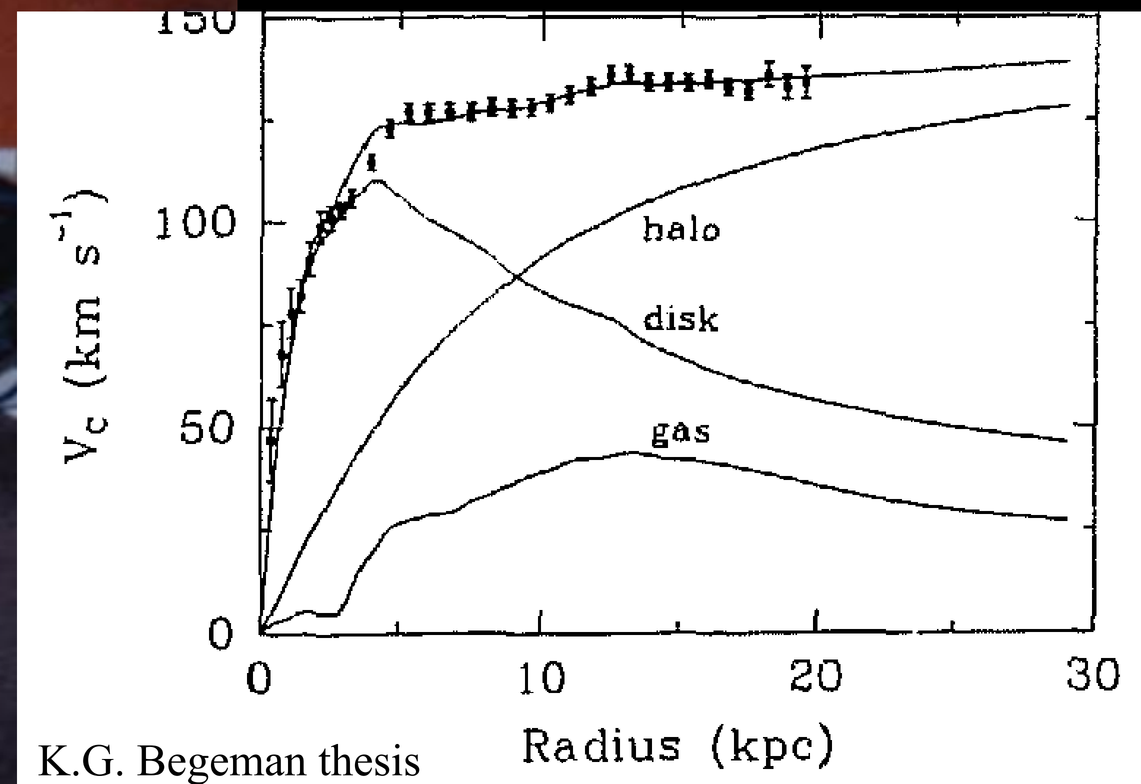
Vera C. Rubin

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

VERA C. RUBIN† AND W. KENT FORD, JR.†

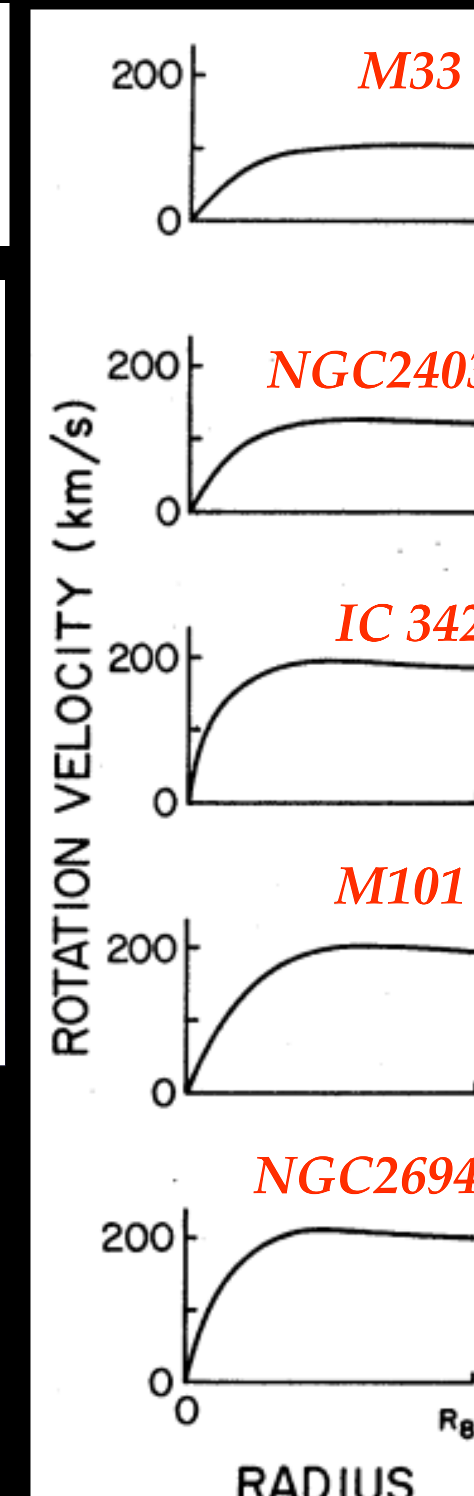
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

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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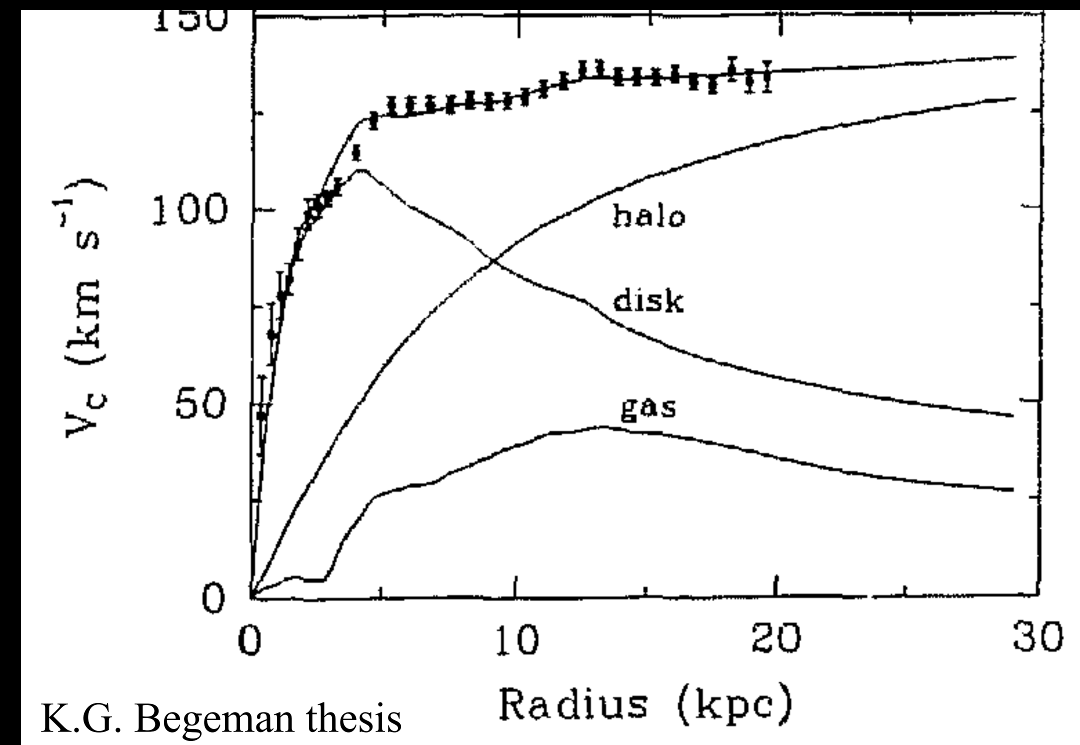
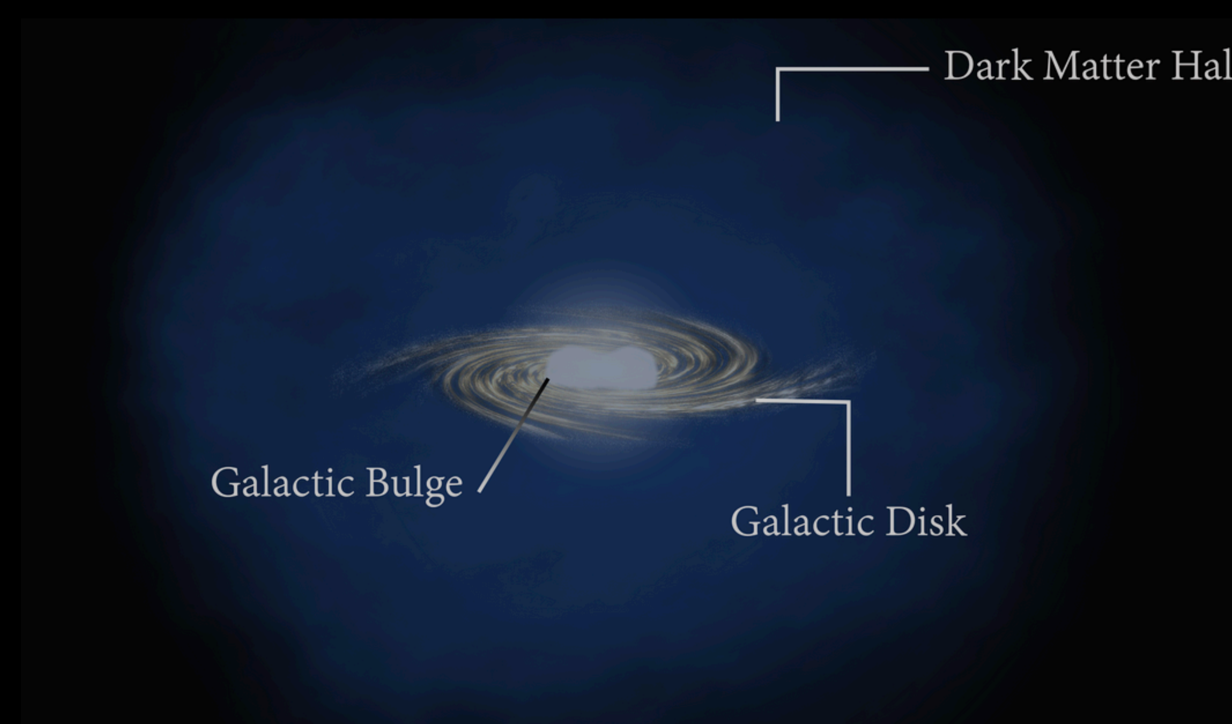




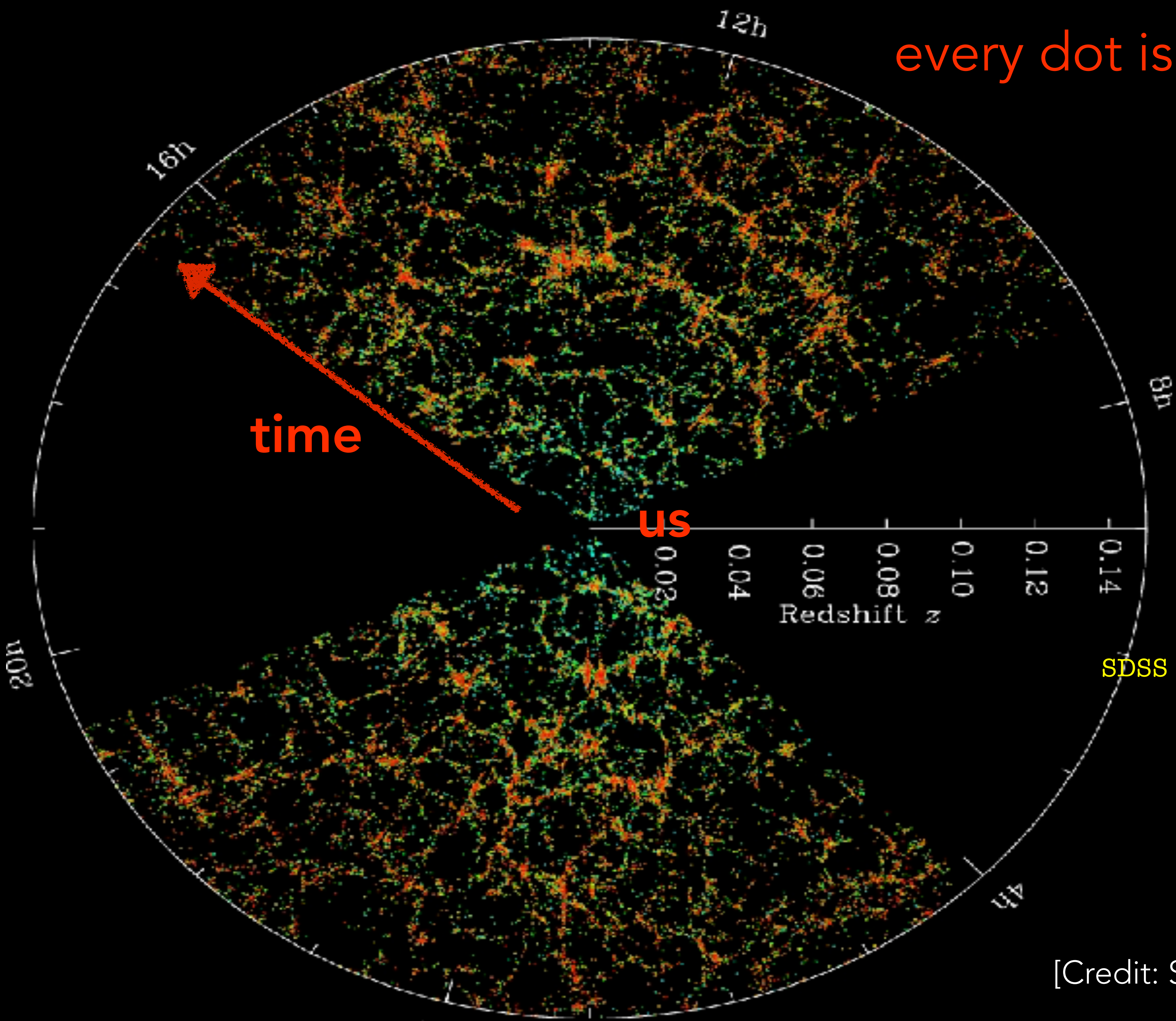
By the 1970s most astronomers are convinced that dark matter ***exists*** around galaxies and clusters

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

every dot is a galaxy!

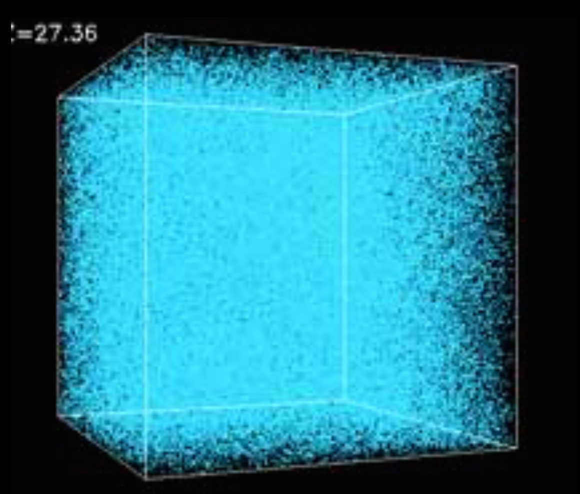


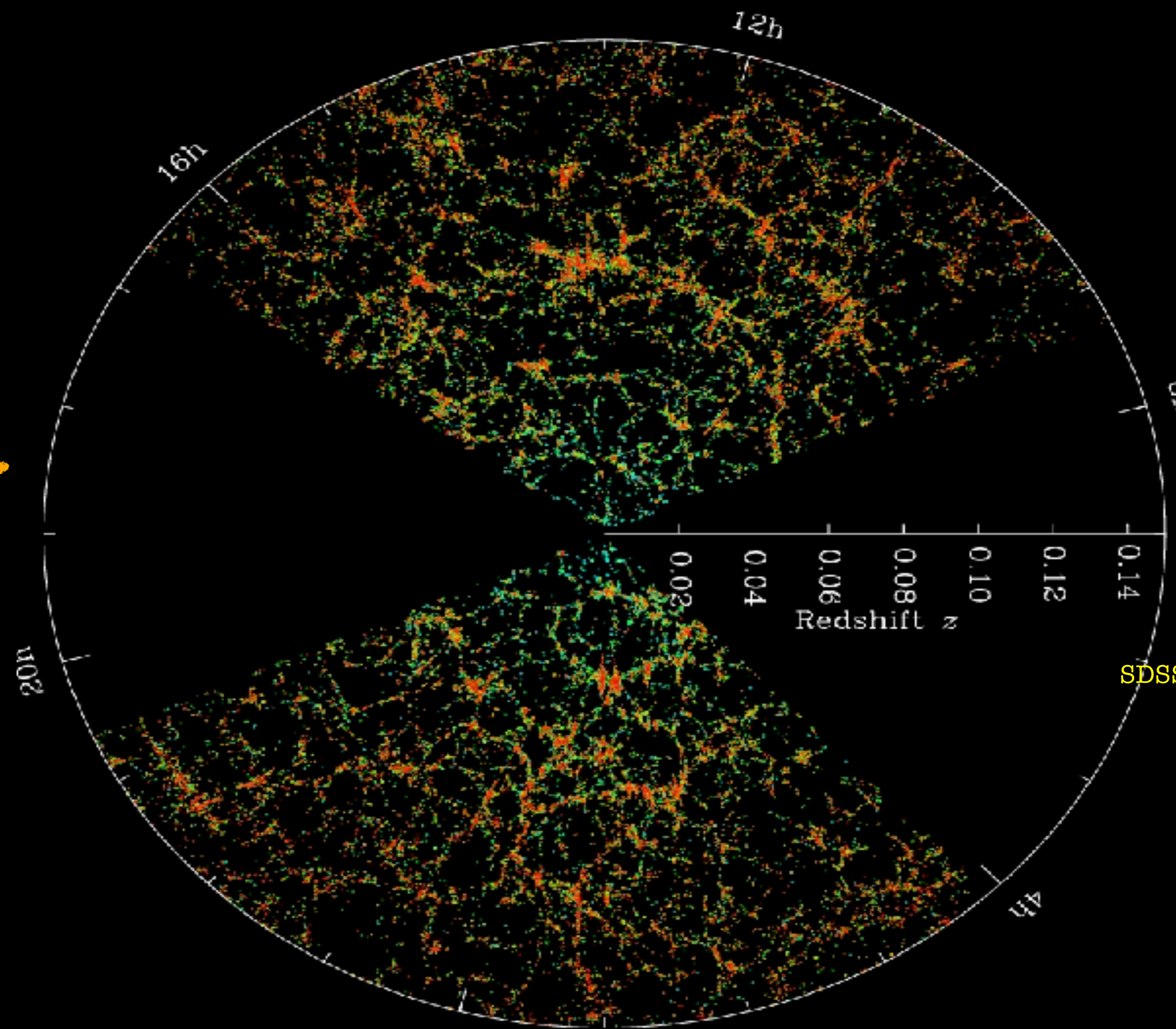
[Credit: Sloan digital sky survey]

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 density fluctuations at the dawn of time.

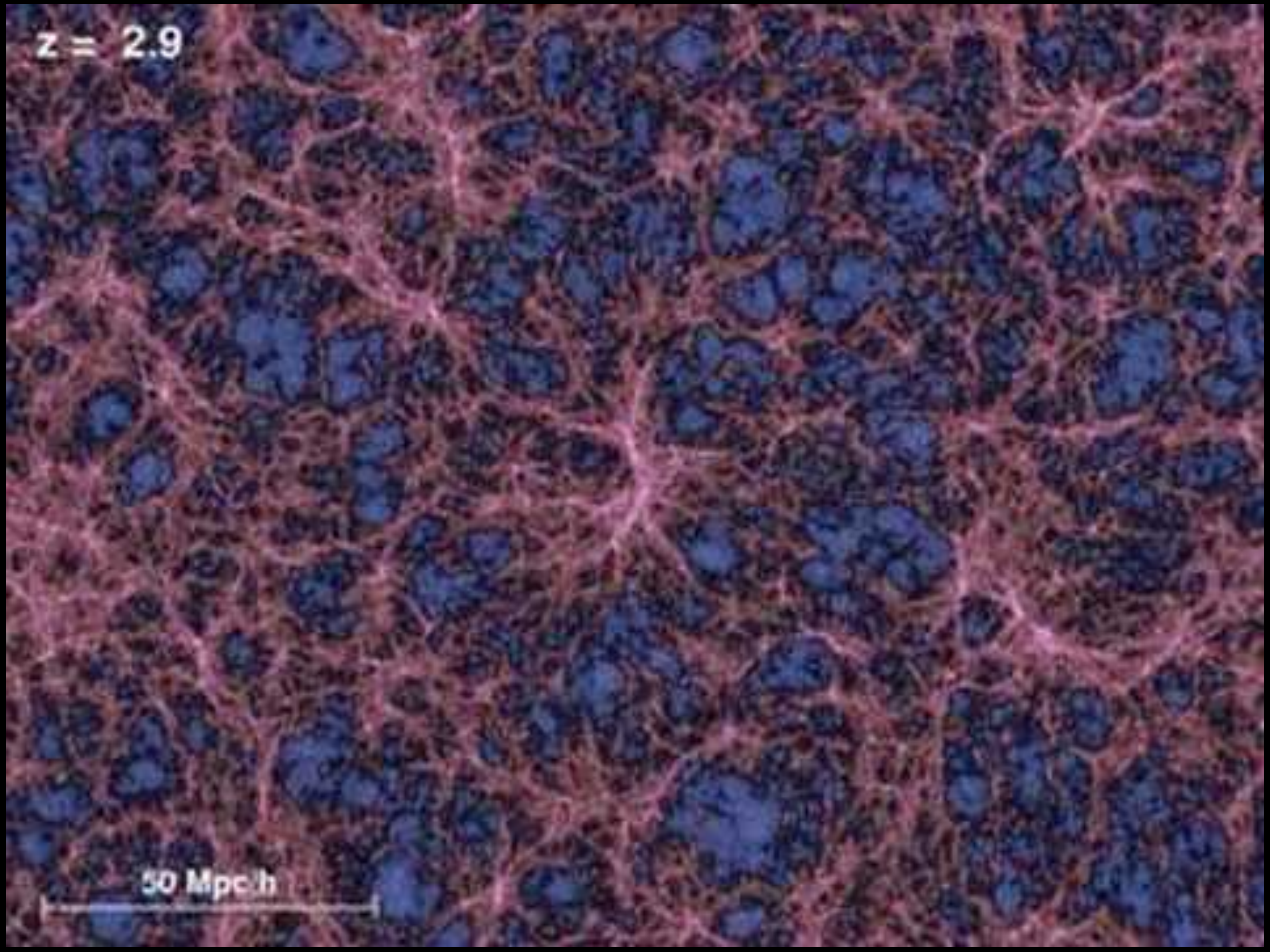
homogenous
early universe





LOOKING BACK IN TIME

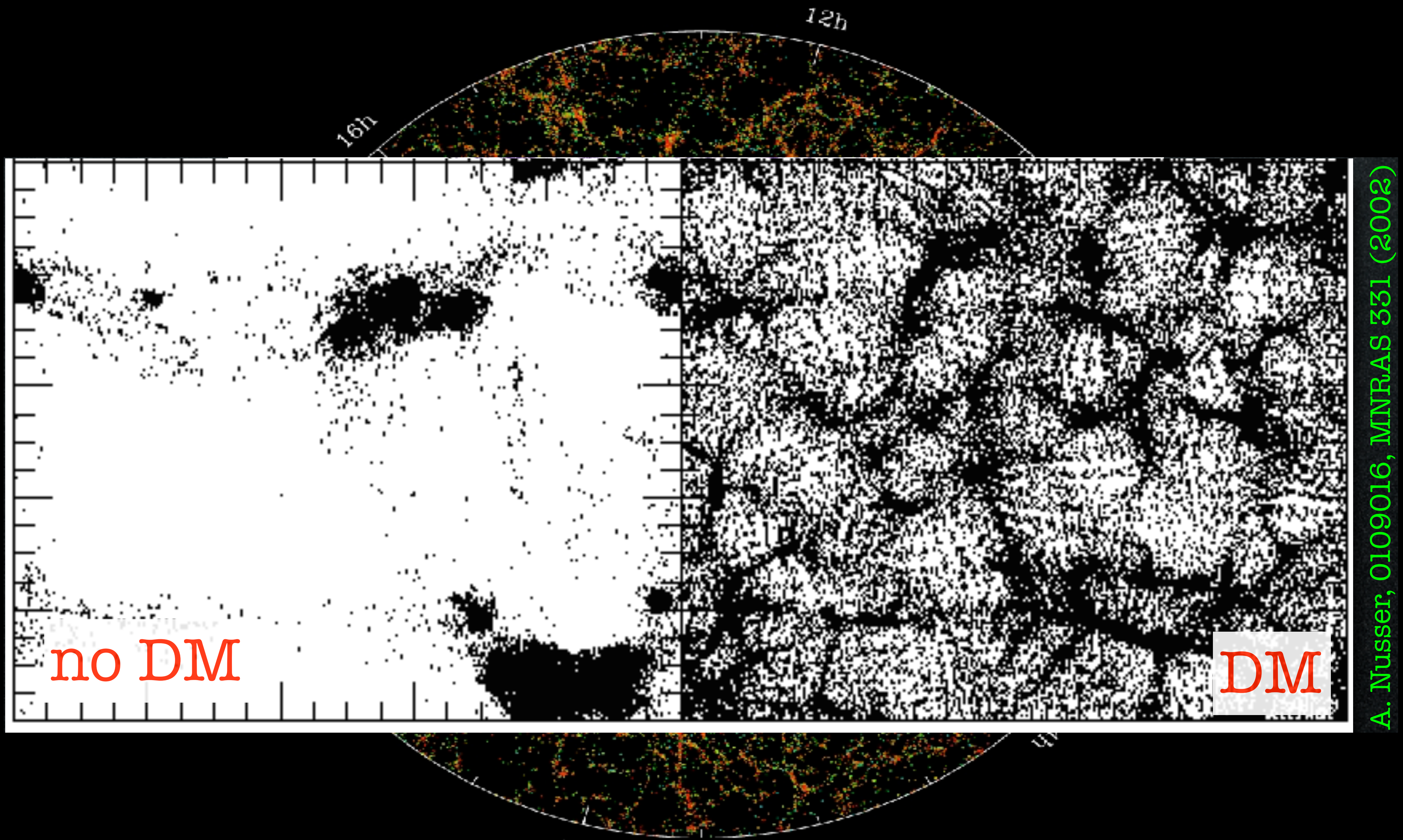
In time, we were able to test this conjecture as computers got powerful enough to simulate the formation of structures starting from the early Universe



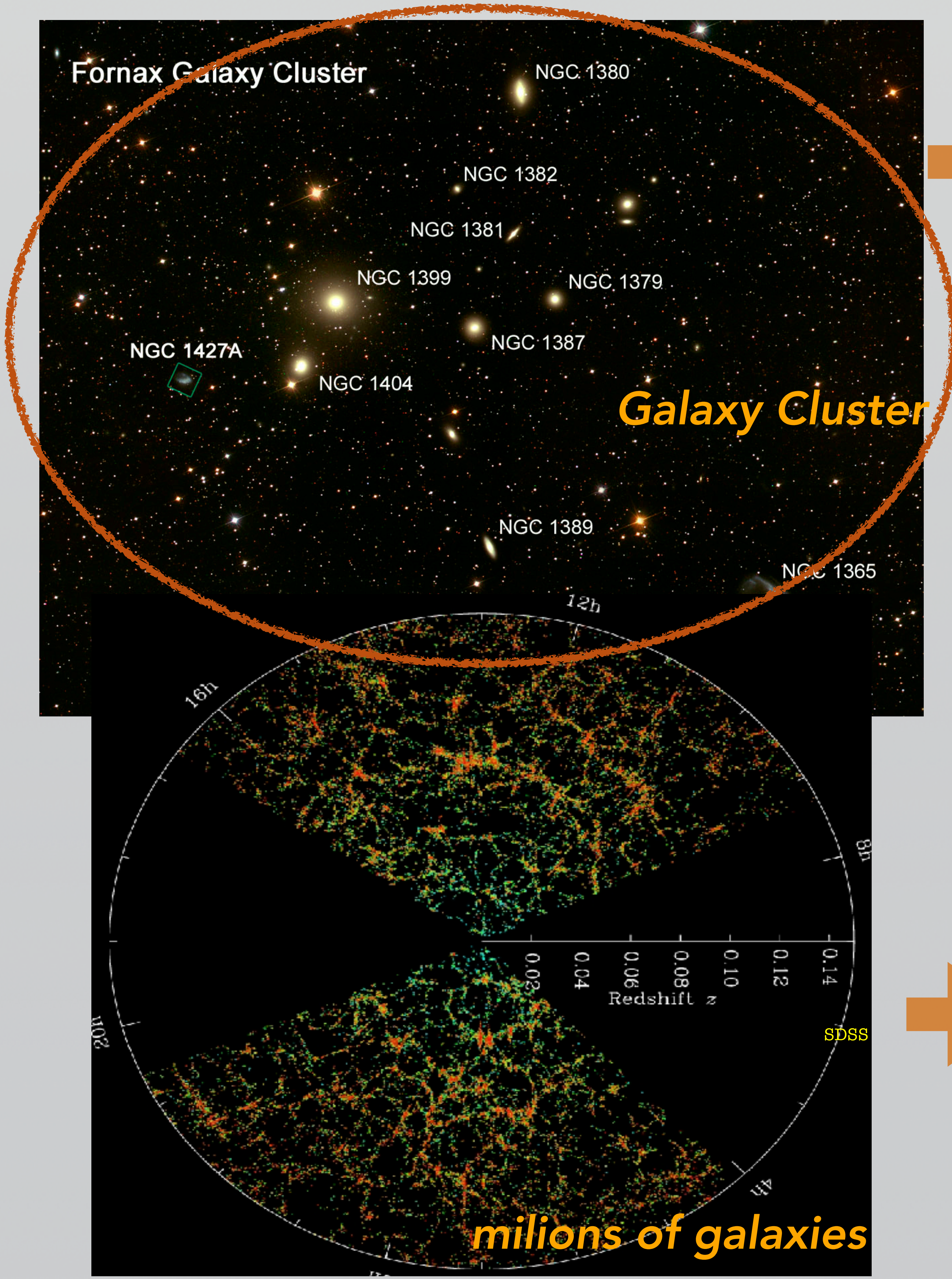
[Credit: Springel et al. (2005)]

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!



WHAT DO WE KNOW SO FAR?



'see through' ➜ **neutral**!

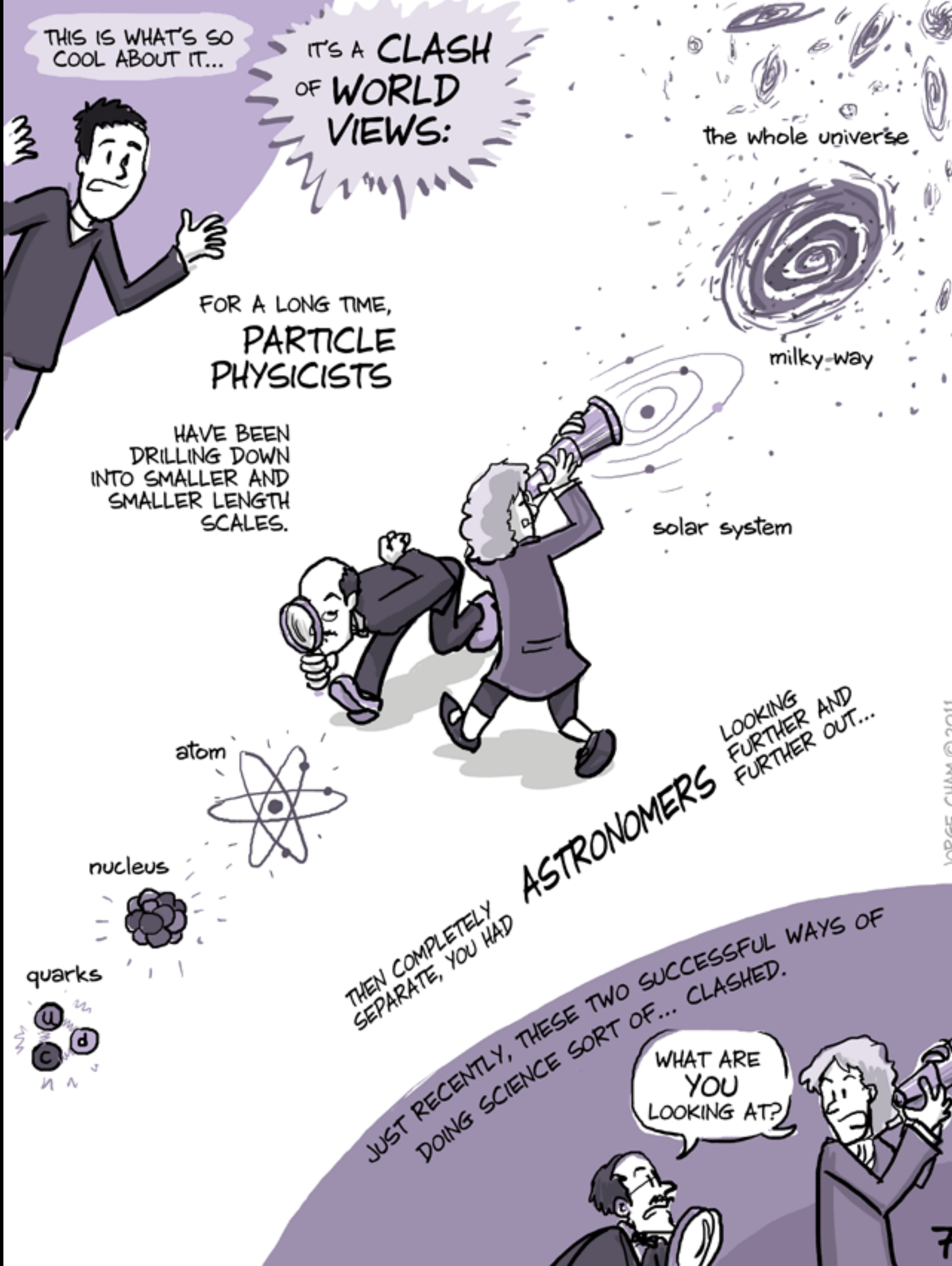
stable ➜ it was present throughout history of Universe

+ 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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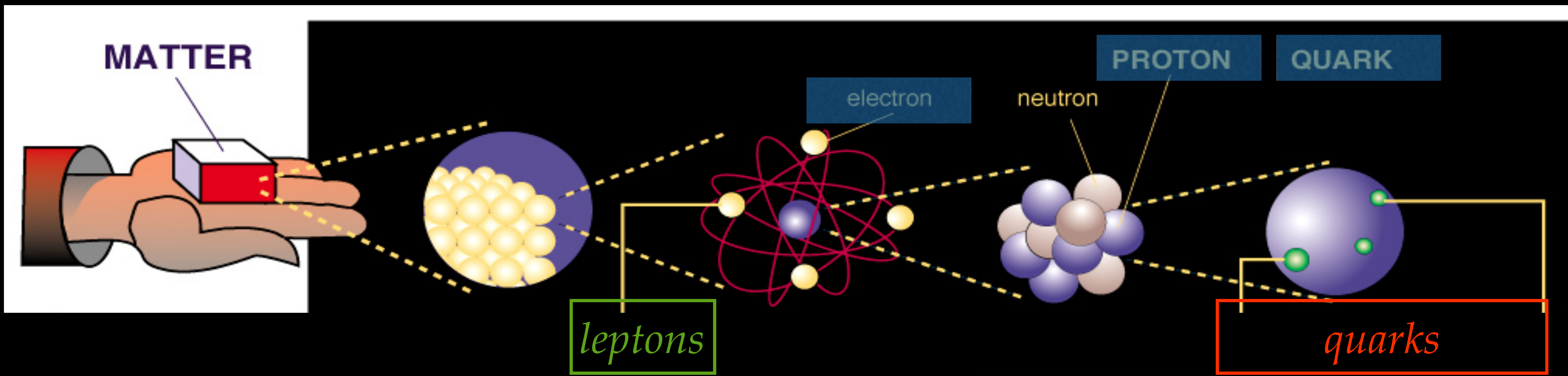

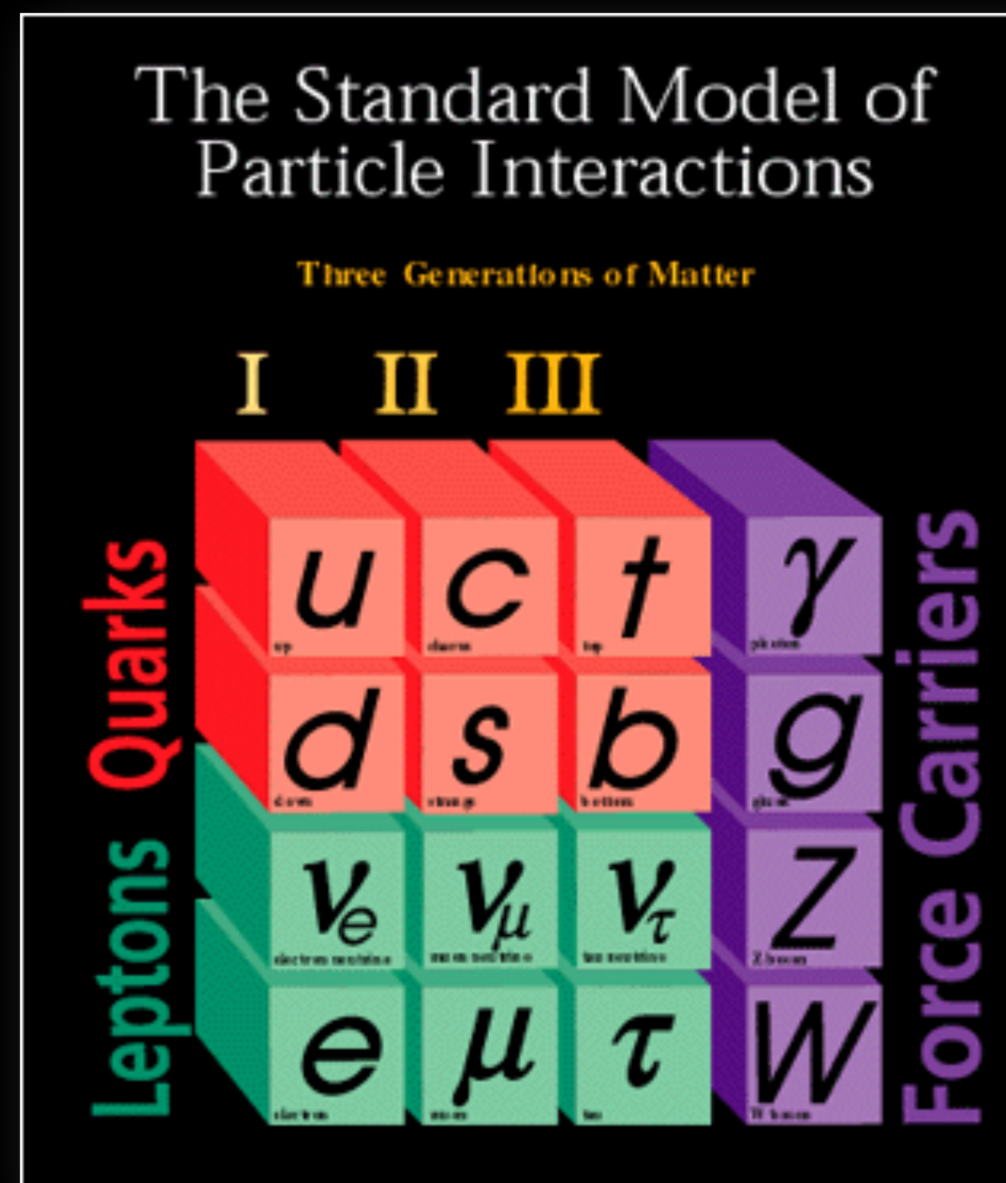

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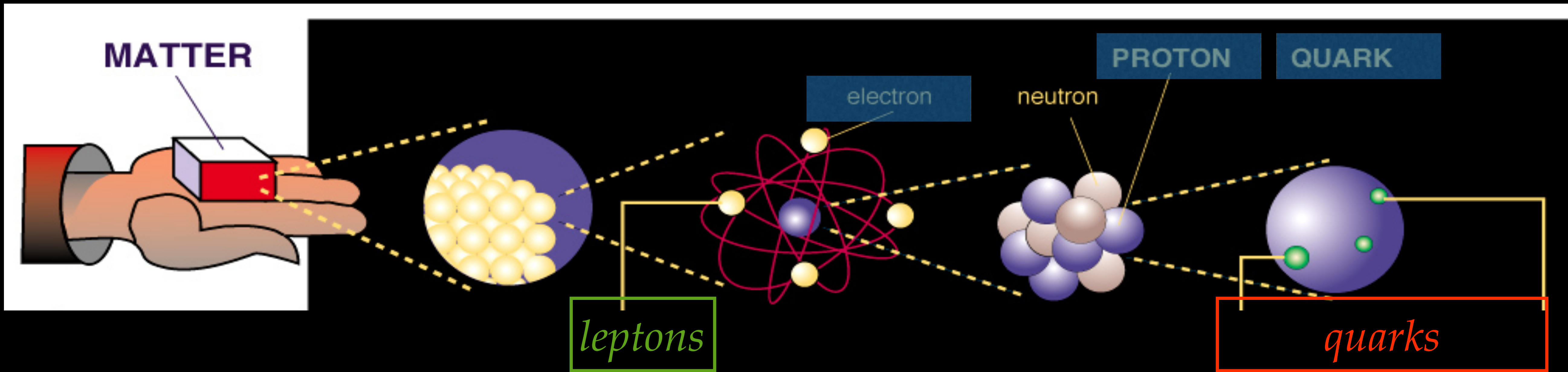
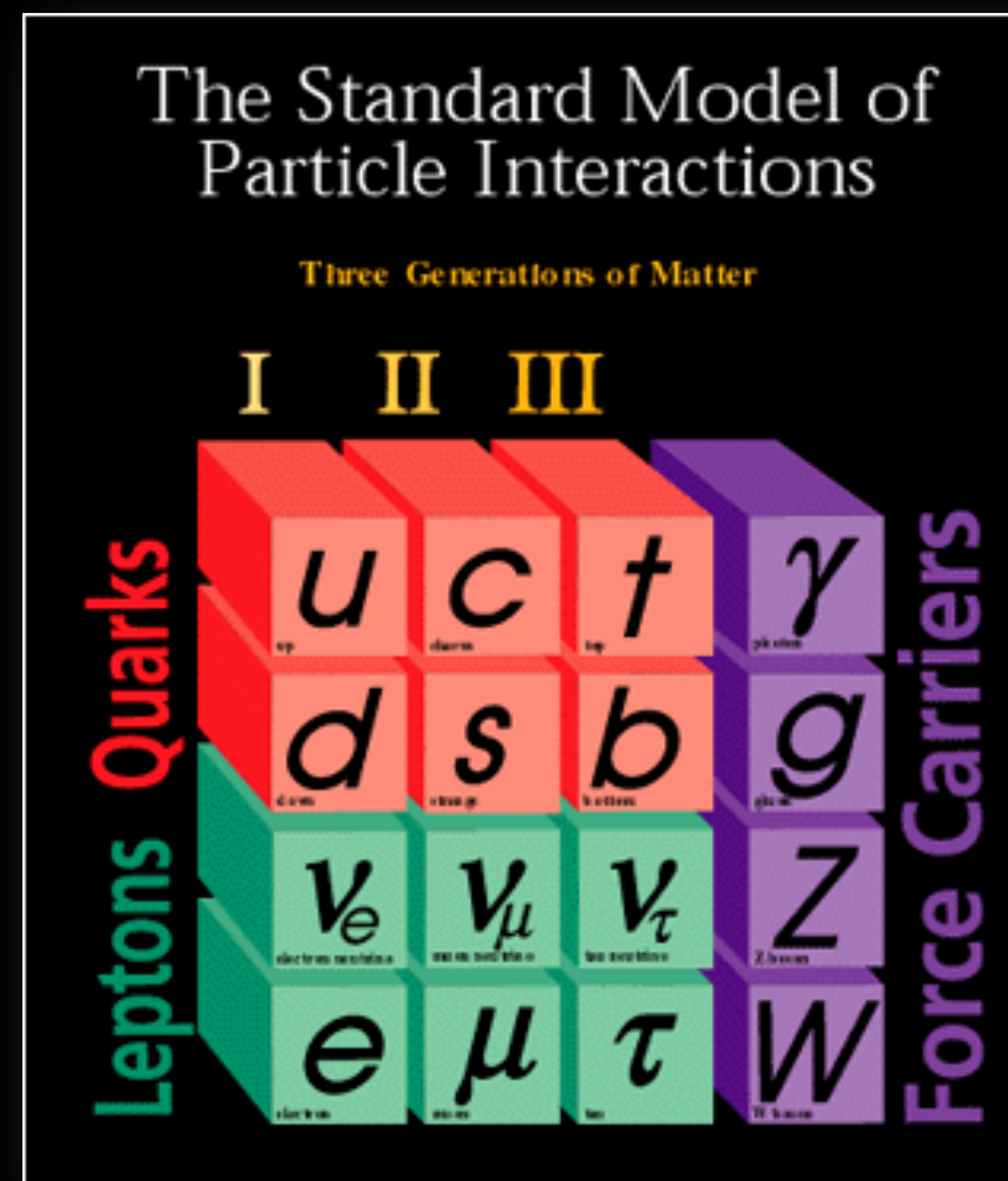


1. neutral
2. stable
3. heavy
4. 5x more abundant than usual mater
5. feeble interactions



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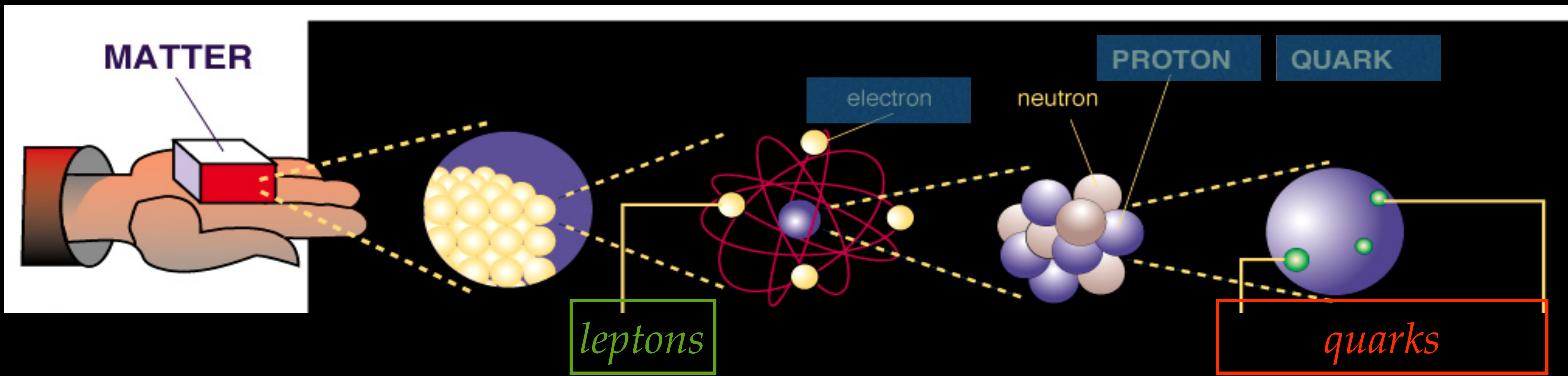

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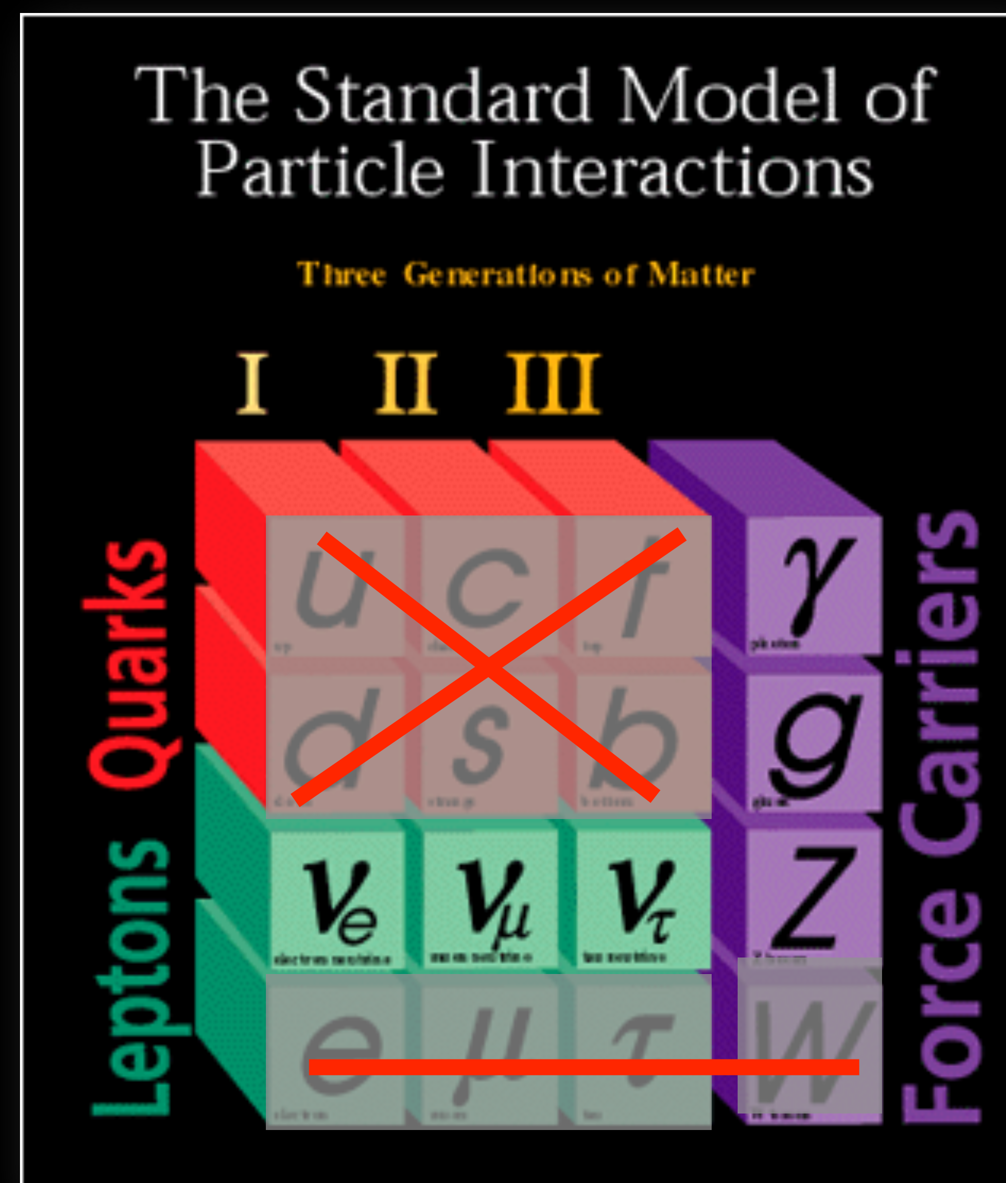

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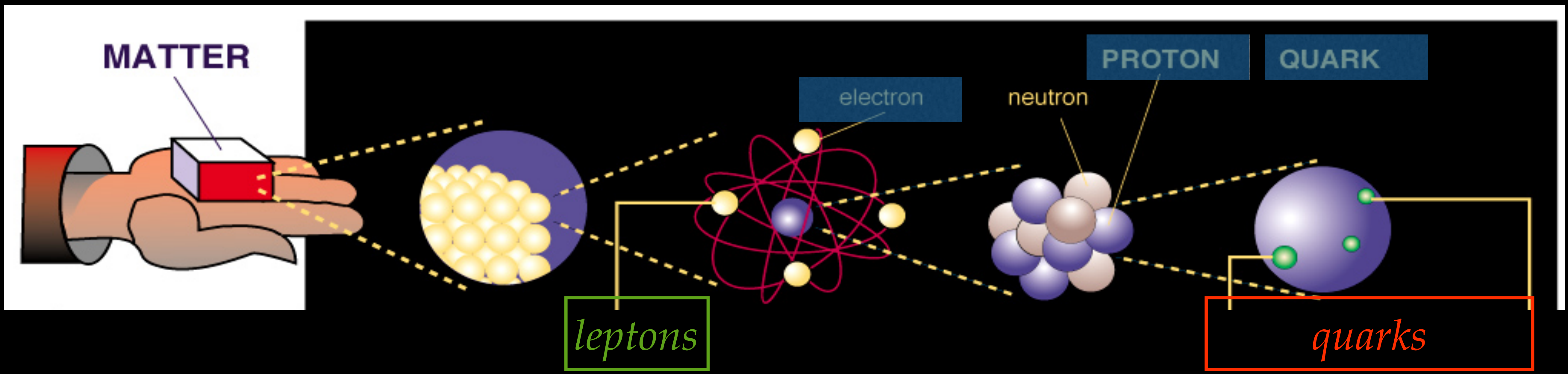

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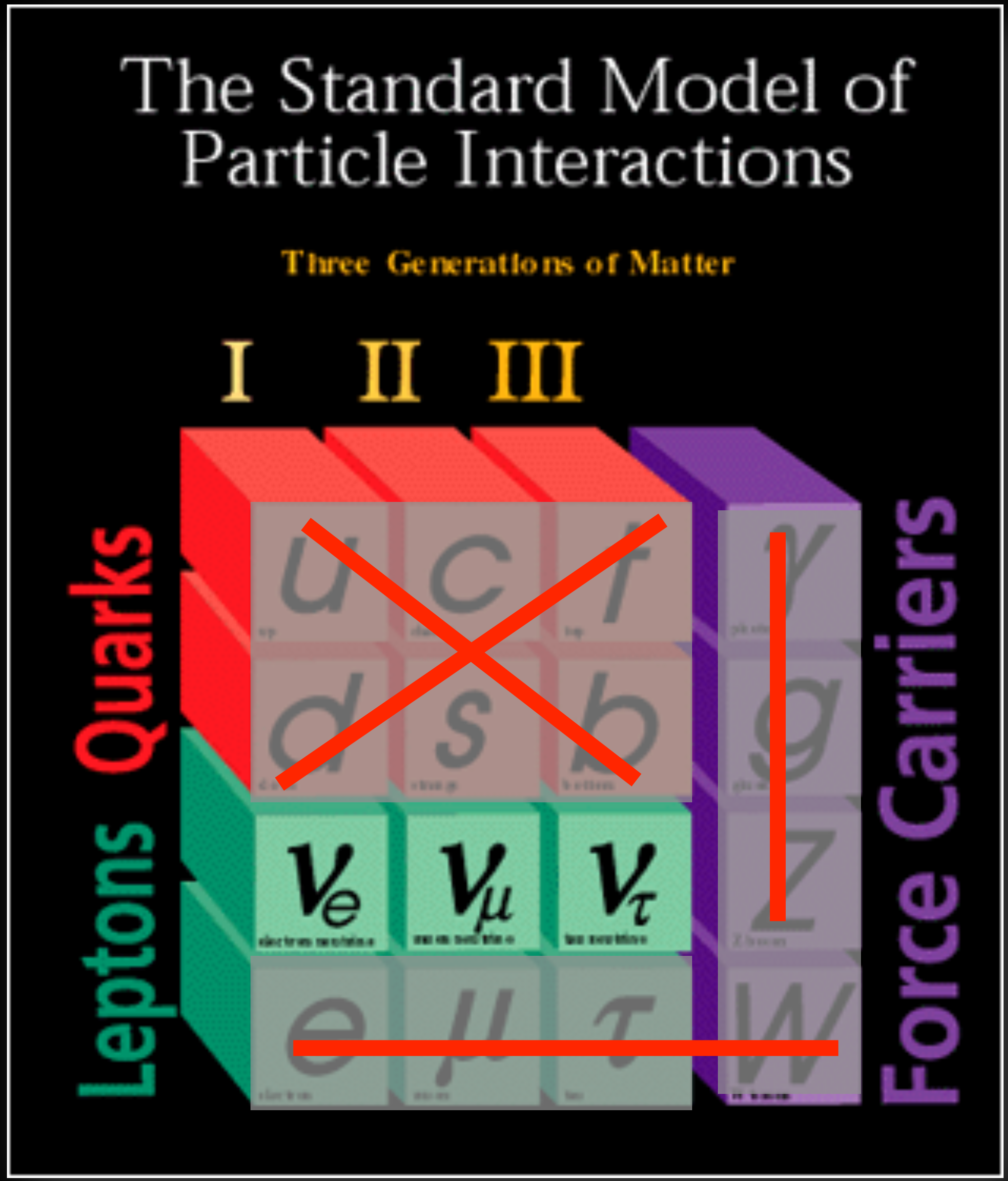

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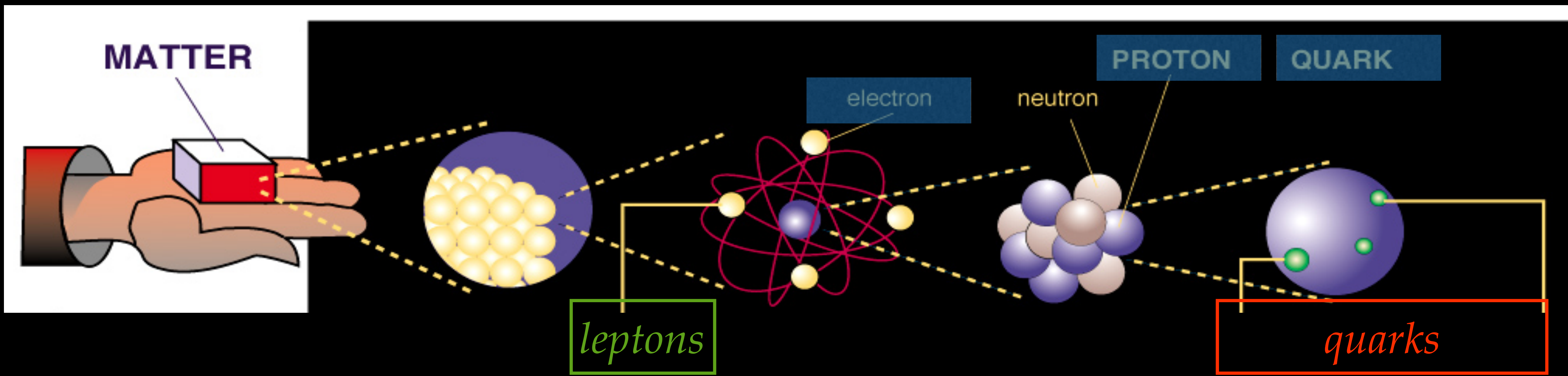
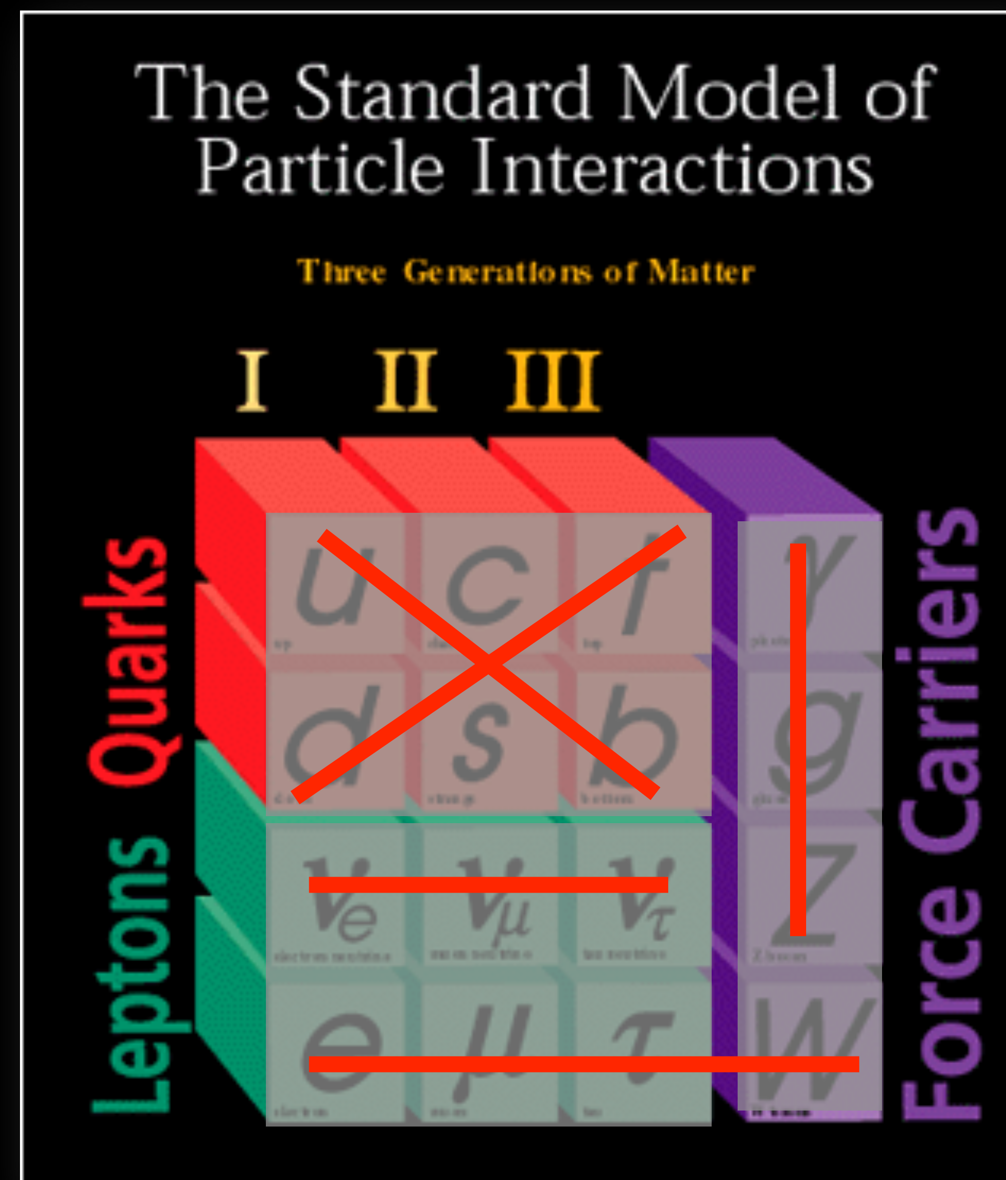


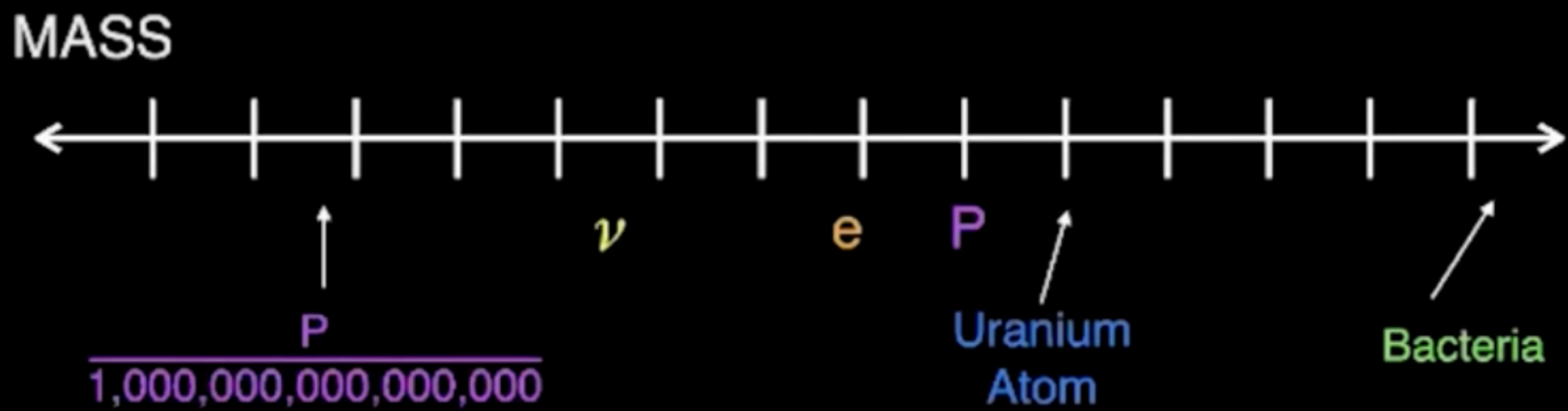
1. **neutral**
2. **stable**
3. **heavy**
4. 5x more abundant than usual mater
5. feeble interactions

➜ needs to be a new particle!



If dark matter is a new particle…

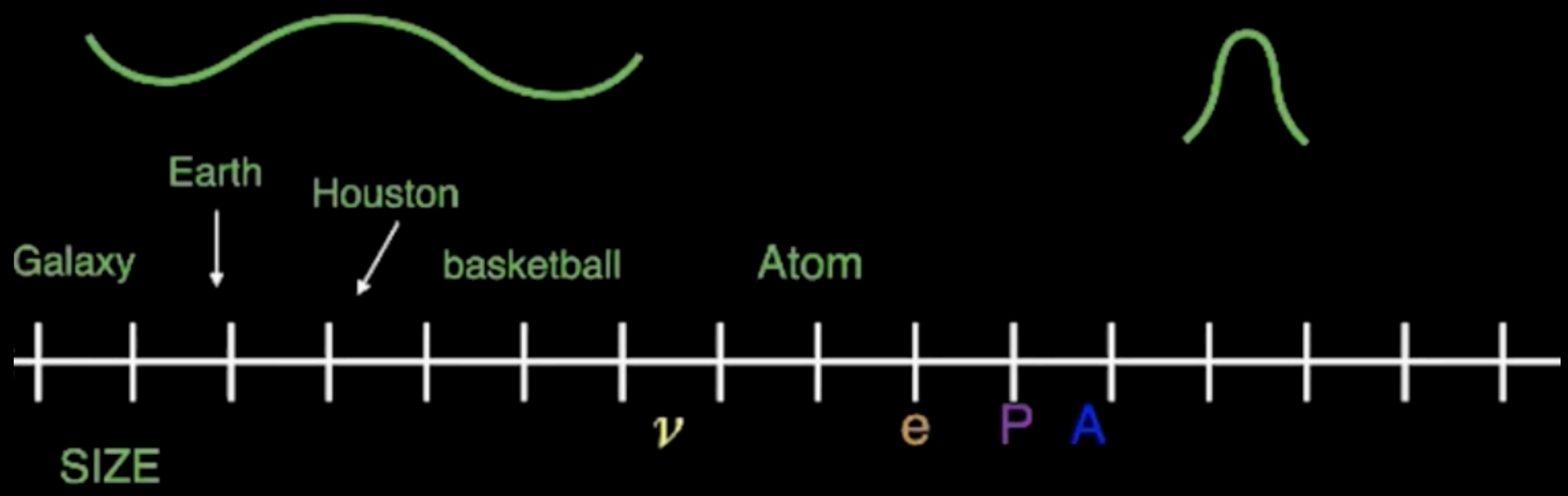
- What is its mass?
- How does it interact with 'us'?



[Credit: D. Kaplan]

Light particles are waves

- The size of the particle is its wavelength.
- The lighter it is, the bigger it gets.



[Credit: D. Kaplan]

THE MOST POPULAR CANDIDATES

"Weakly Interacting Massive Particles"

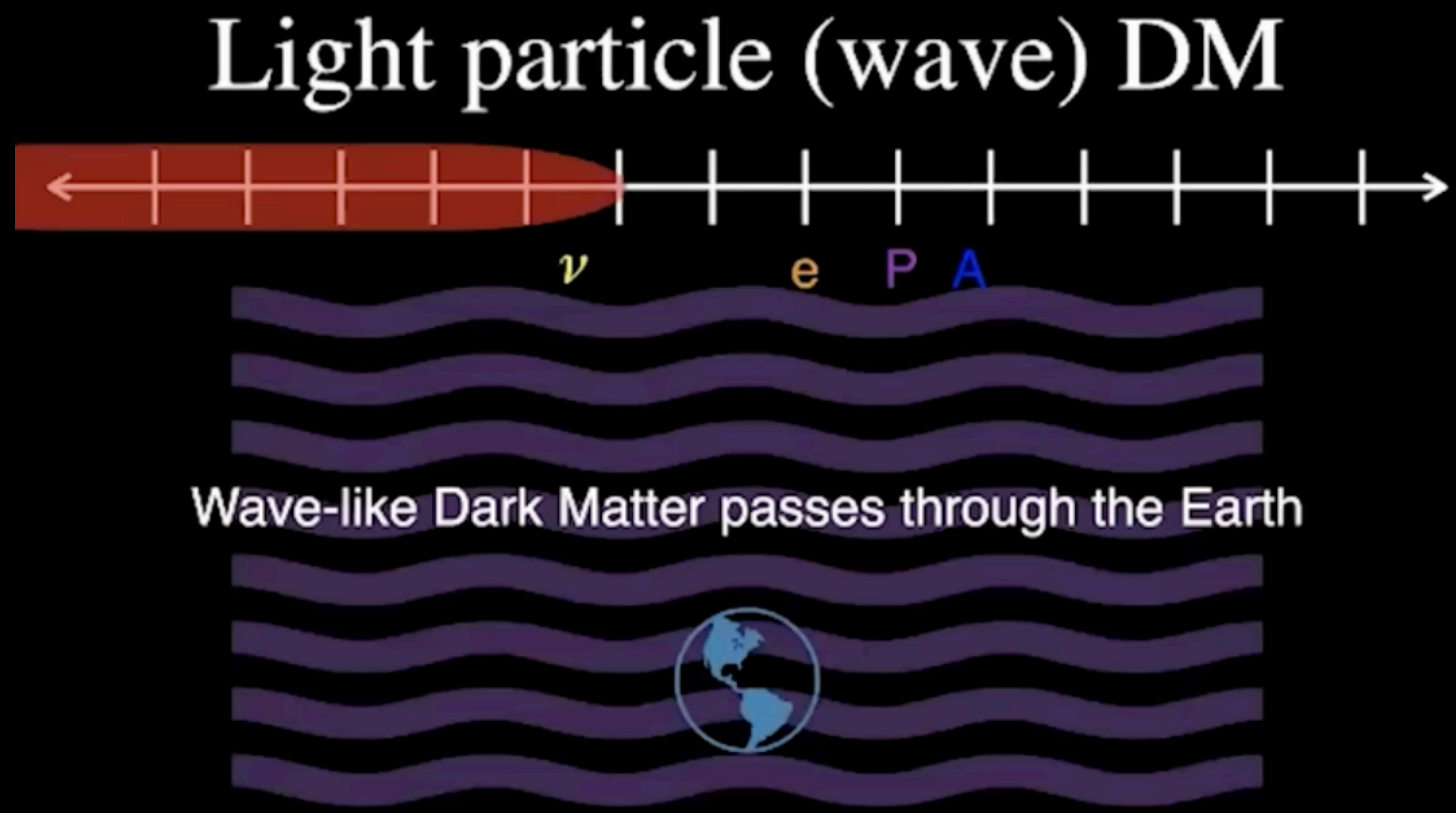
It means simply:

1. neutral
2. stable
3. slow moving (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 MOST POPULAR CANDIDATES

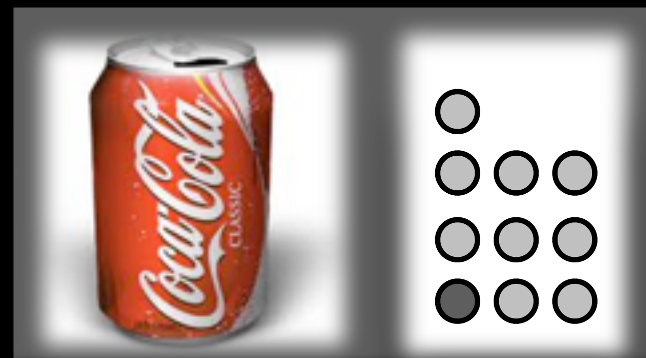


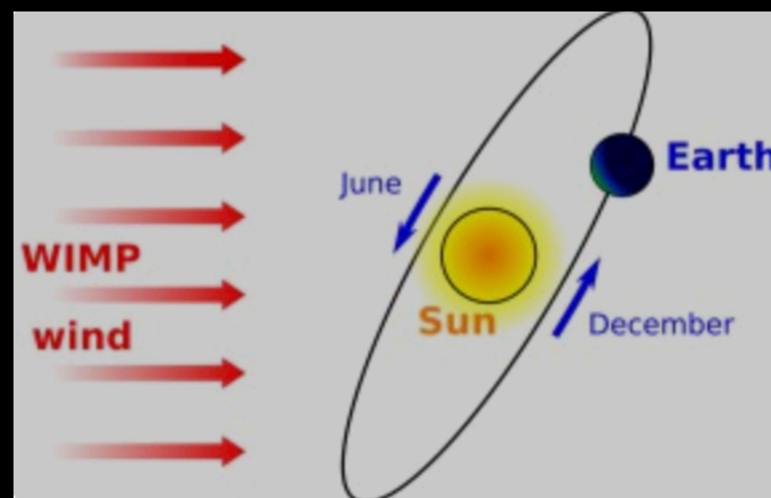
axions, axion-like particles, hidden photons …

BUT… HOW TO FIND IT?

BUT... HOW TO FIND IT?

lab:





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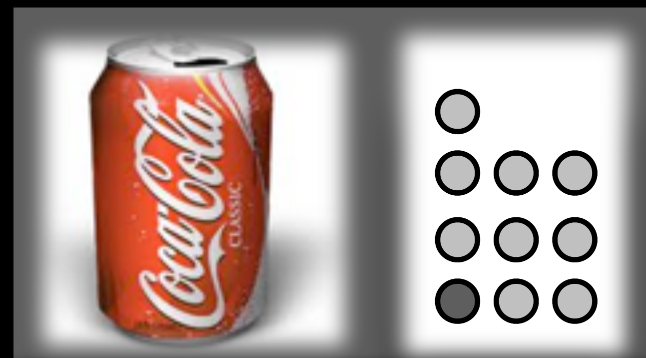

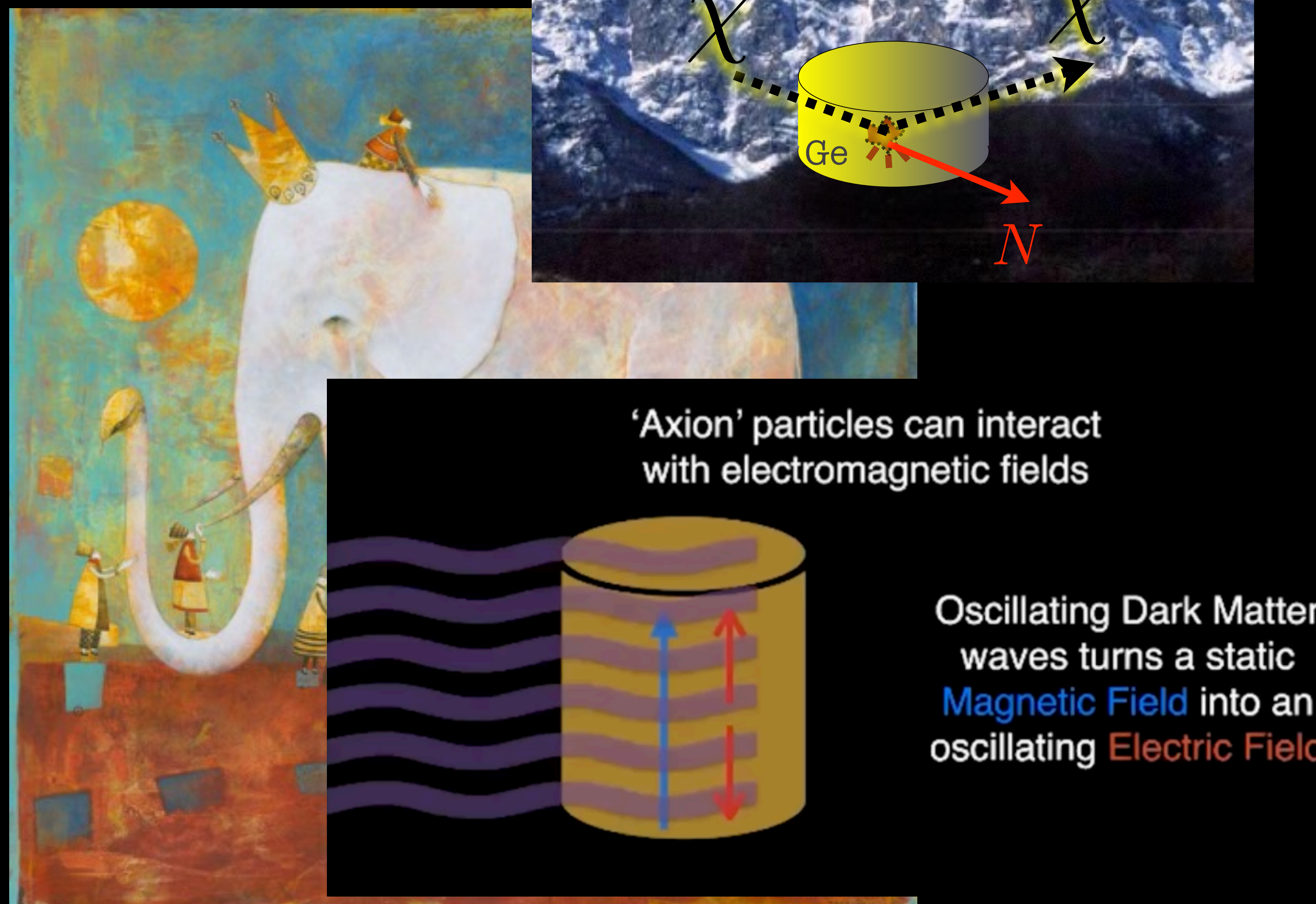

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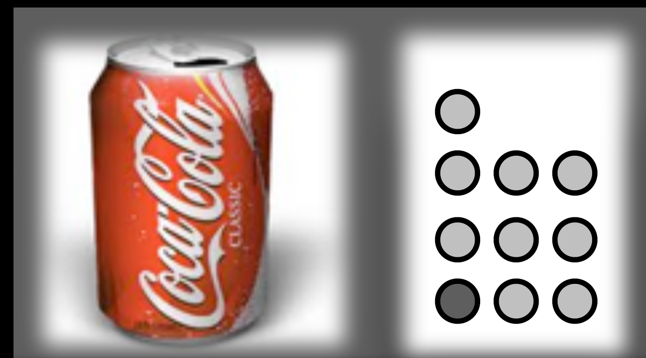
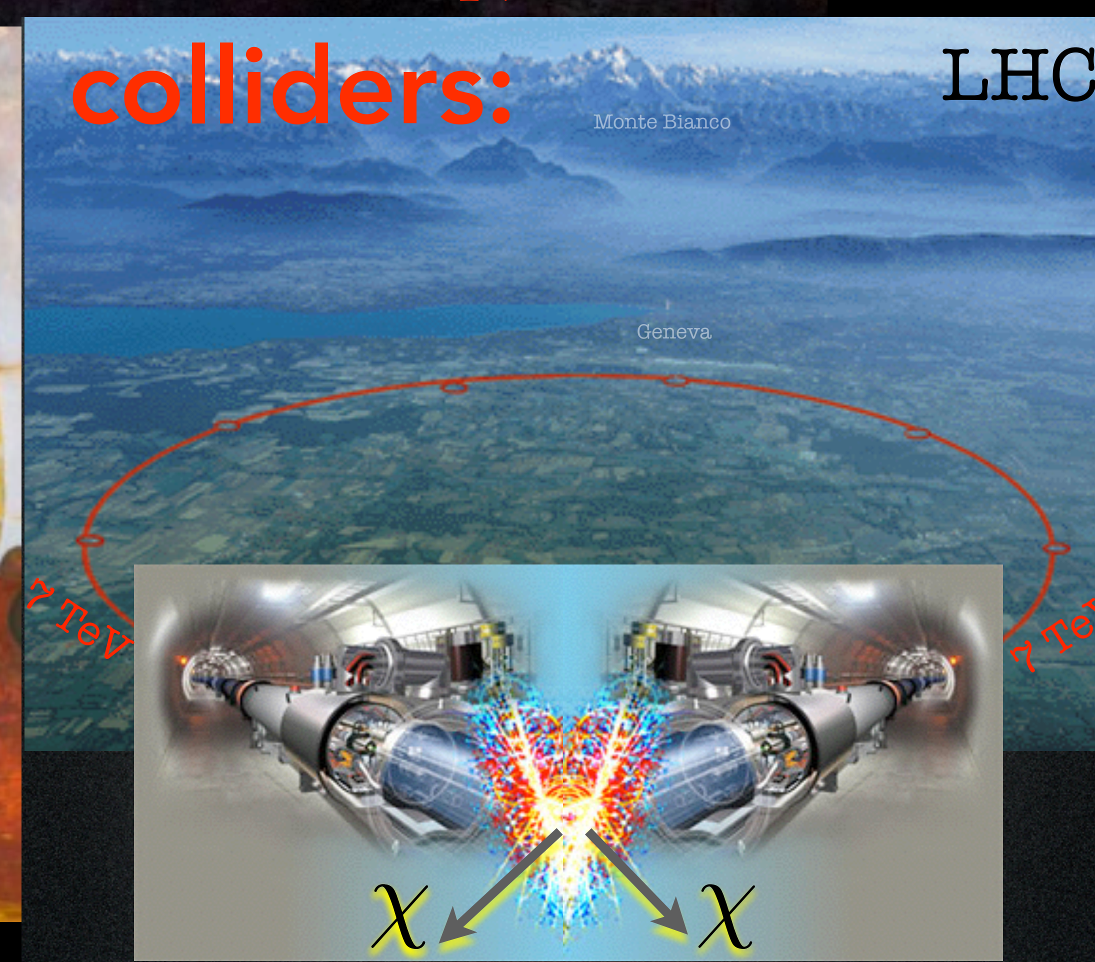
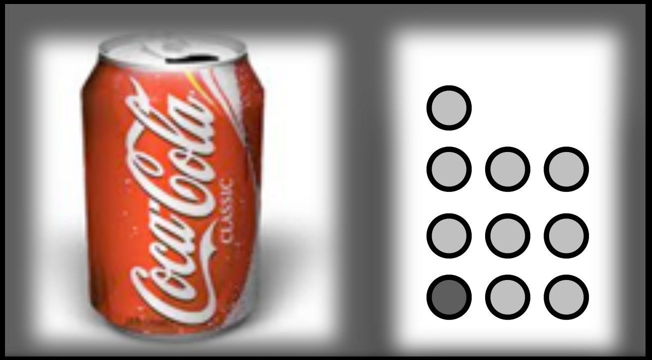
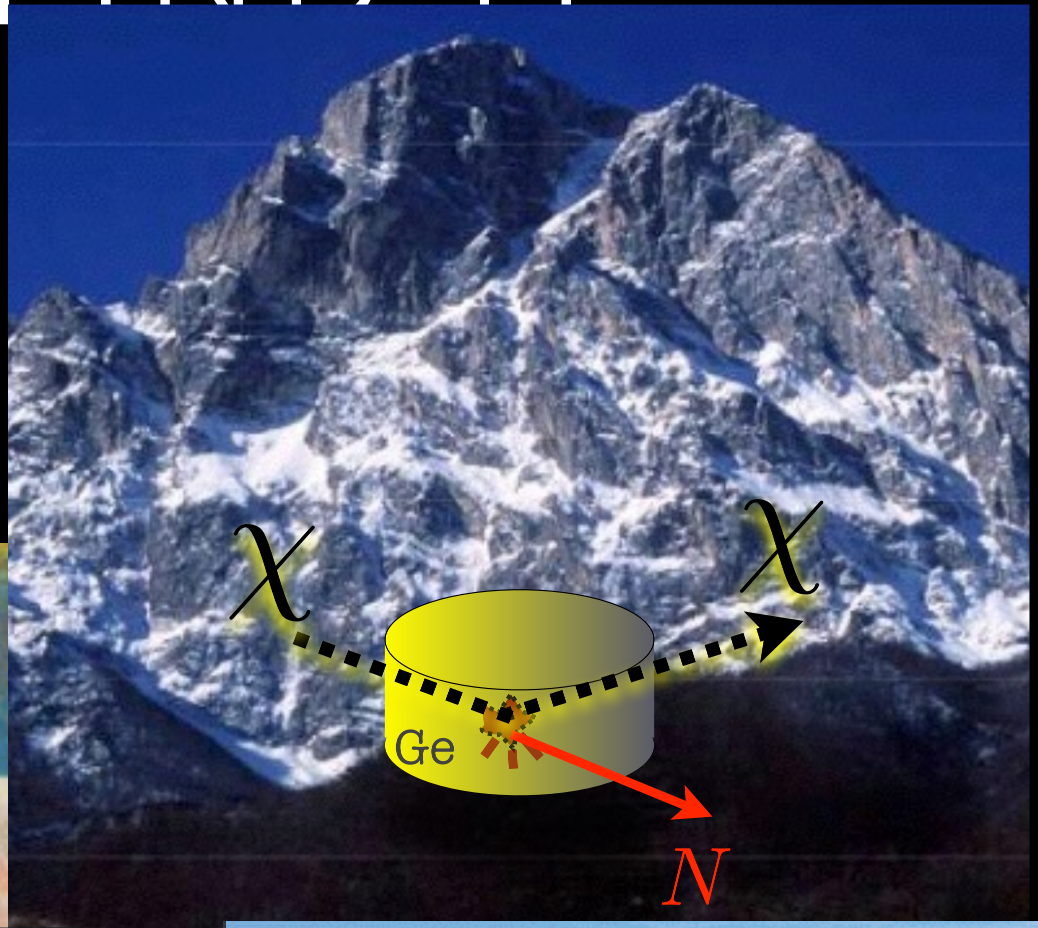


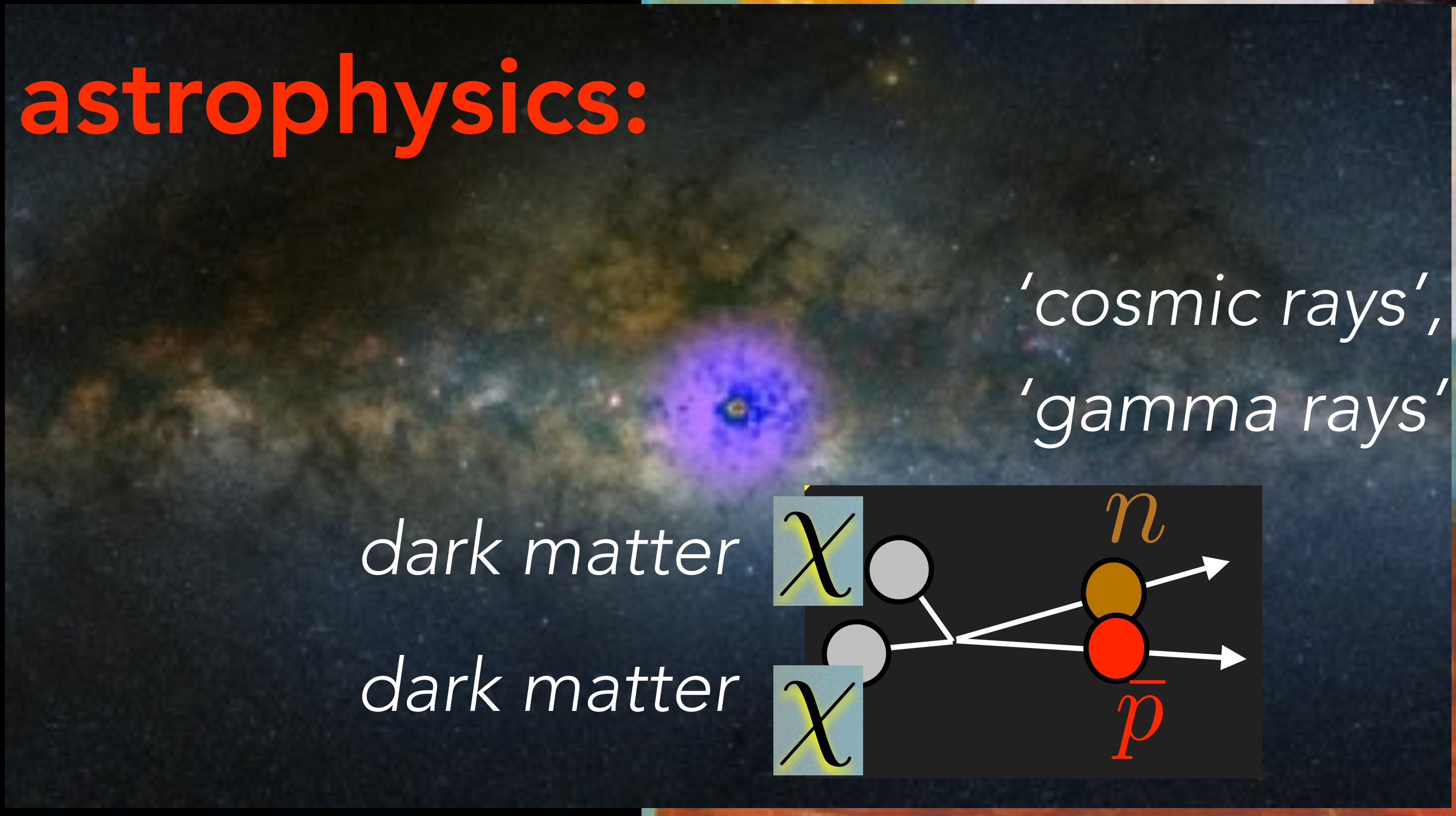


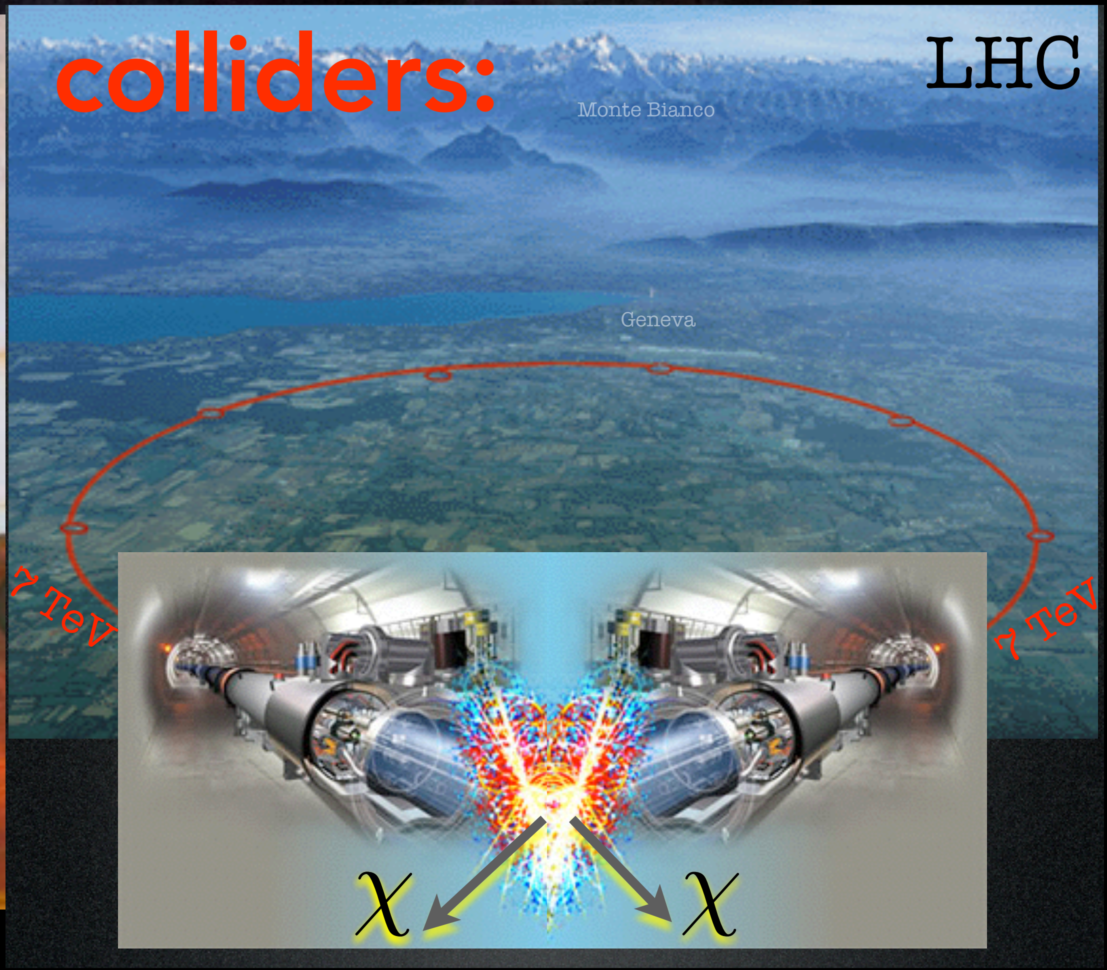
BUT... HOW TO FIND IT?

lab:









Exciting times!

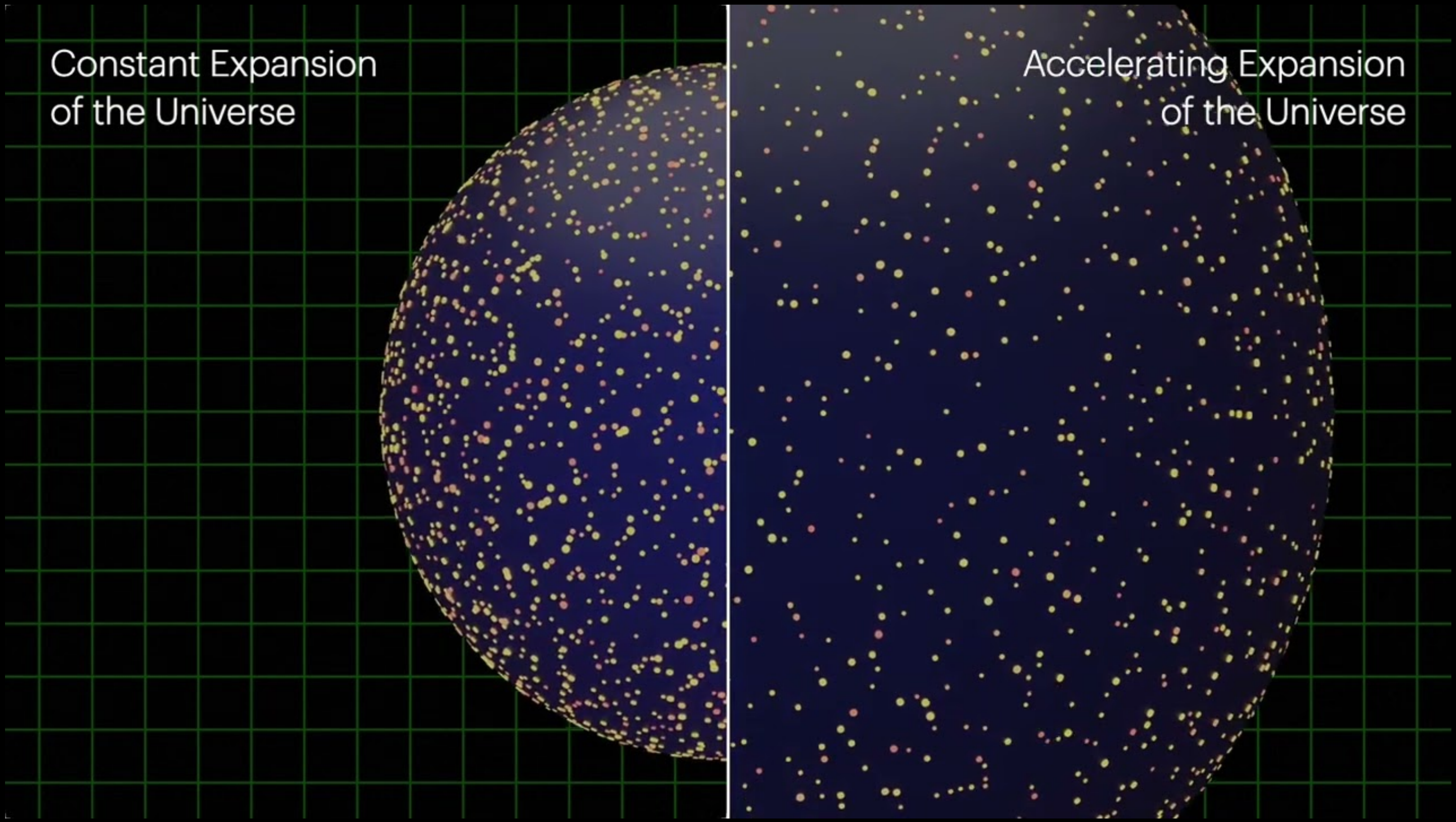
The tools are here and with the right sensitivity

'It is difficult to look for a black cat in a dark room, specially when there is no cat' (Confucius, credit G. Bertone)

In parallel to the studies on the nature of dark matter particle, detailed measurements of the expansion of the Universe progressed

Hubble measurements showed that Universe was expanding.

Since 1998 we know that this expansion is in fact **accelerating**!



THE CURIOUS CASE OF THE COSMOLOGICAL CONSTANT

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

geometry (space-time) energy (mass) density cosmological constant

Einstein added it to … *stop* the expansion!
Then retracted it as his "biggest blunder"

However, it came back with the vengeance! An accelerating expansion can be accounted for by a positive value of the cosmological constant, equivalent to the presence of a vacuum energy, dubbed "**dark energy**".

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Dark energy: the most important property is that it has ***negative pressure*** which is everywhere in space.

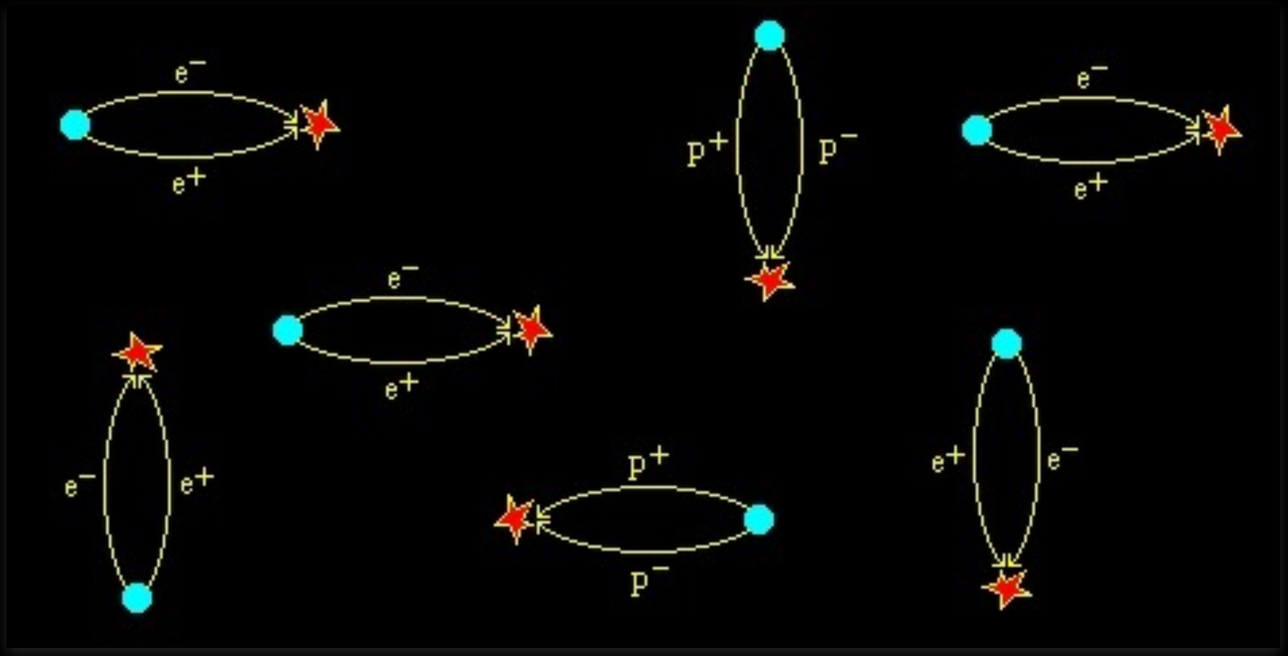
Now ΛCDM is the Standard Cosmological Model.

Many different observations, including the Cosmic Microwave Background, confirm ΛCDM predictions

WHAT IT COULD BE

Vacuum energy is an underlying background energy that exists in *empty* space throughout the entire Universe

According to quantum mechanics space is filled with virtual particle pairs that blink into existence and then annihilate in a timespan too short to observe



The cosmological constant problem: discrepancy between the measured small value of vacuum energy, to theoretical predictions ranges **from 40 to more than 100 orders of magnitude** …
… "the worst theoretical prediction in the history of physics"!

THE COSMIC INVENTORY

THE COSMIC INVENTORY

Psalter world map, 1260s, British Library

THE FUTURE?

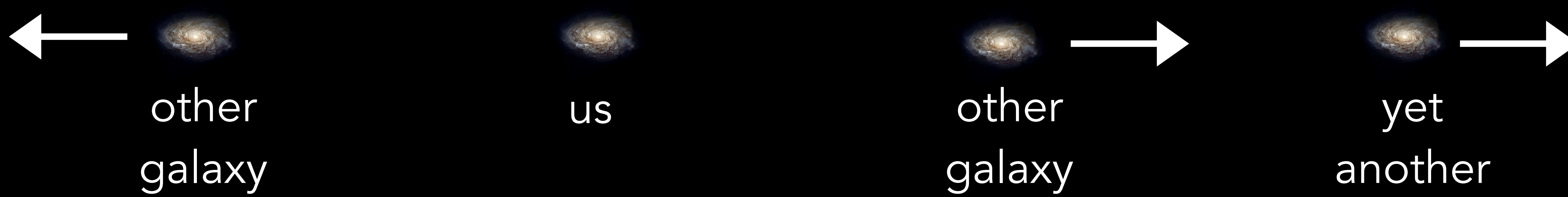
… are we here alone?

EXTRA SLIDES

Hubble's law and the cosmological principle

If receding velocities were *not* proportional to the distance

from our point of view …



Hubble's law and the cosmological principle

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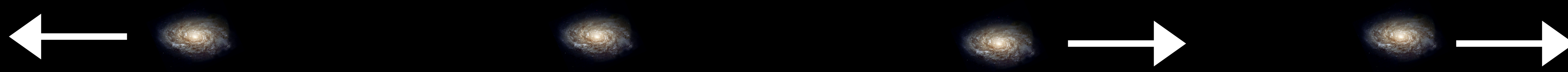


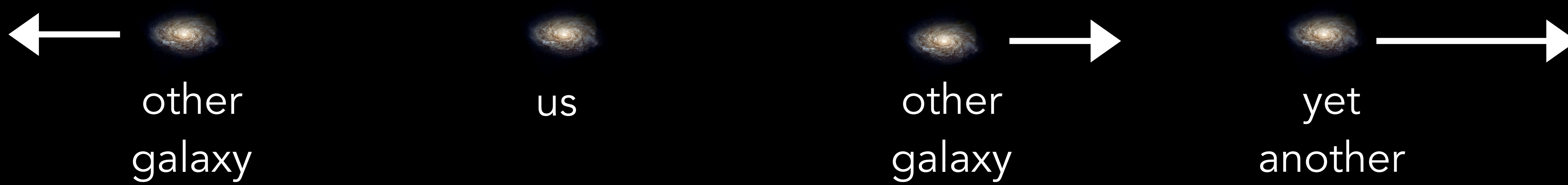
from the point of view of the *other galaxy*

hence, not all points in the Universe would be equivalent

Hubble's law and the cosmological principle

If recession velocities *are* instead proportional to the distance

from our point of view …



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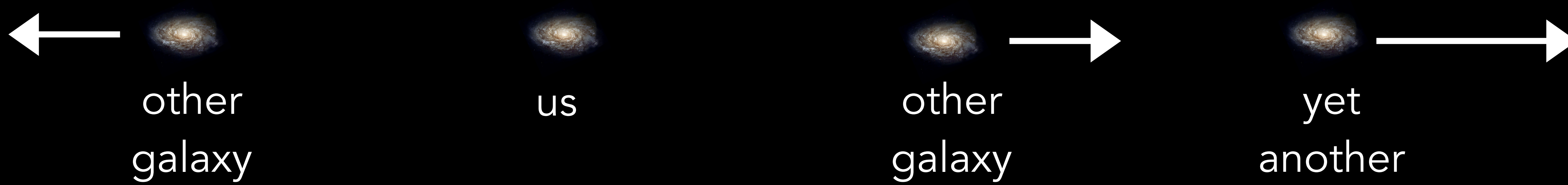

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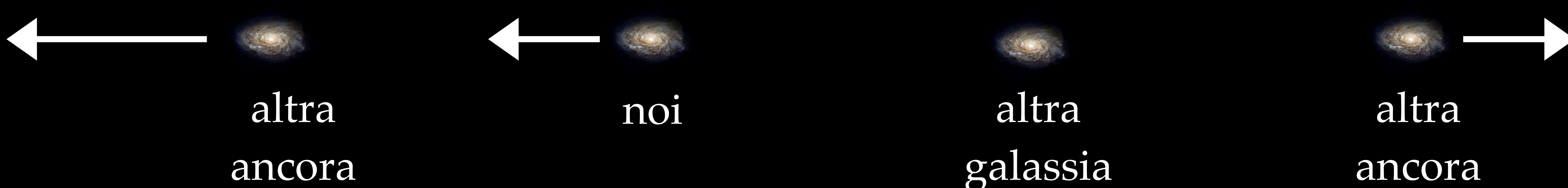
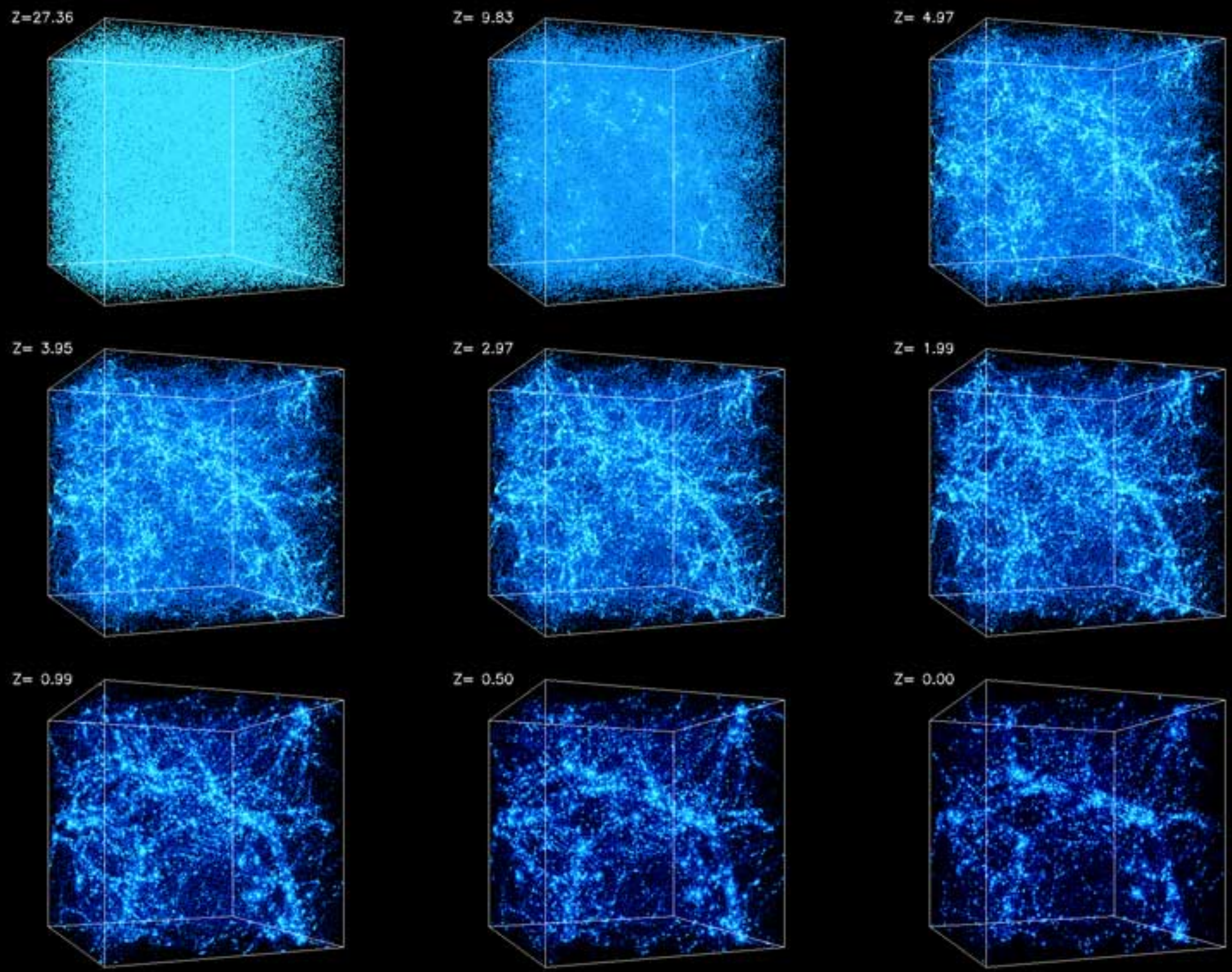


all points would then be equivalent!

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

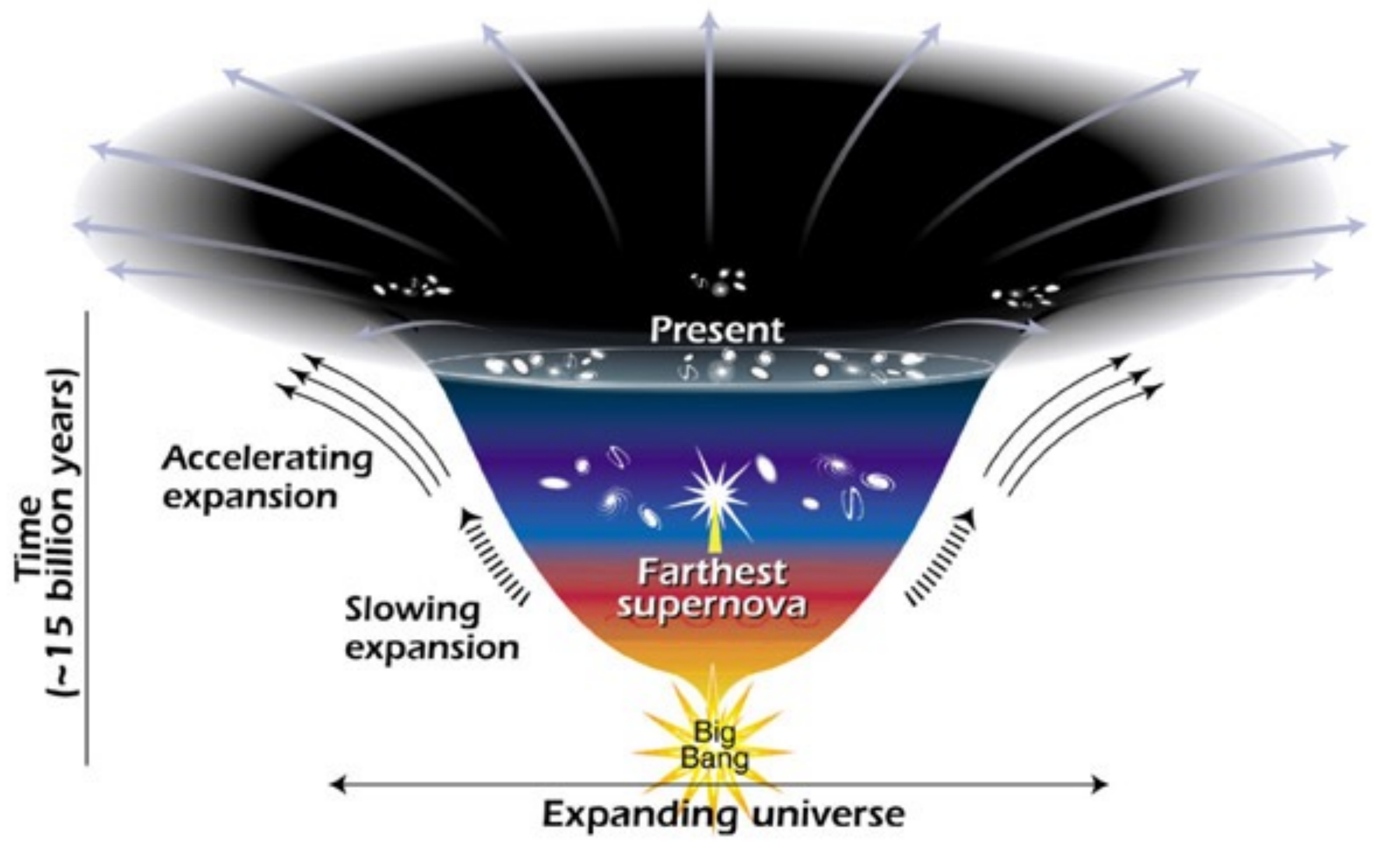


[Credit: Springel et al. (2005)]

SUPERNOVAE MEASUREMENTS

1998: First evidence for an accelerated expansion from SNIa

SNIa are ***standard candles***.



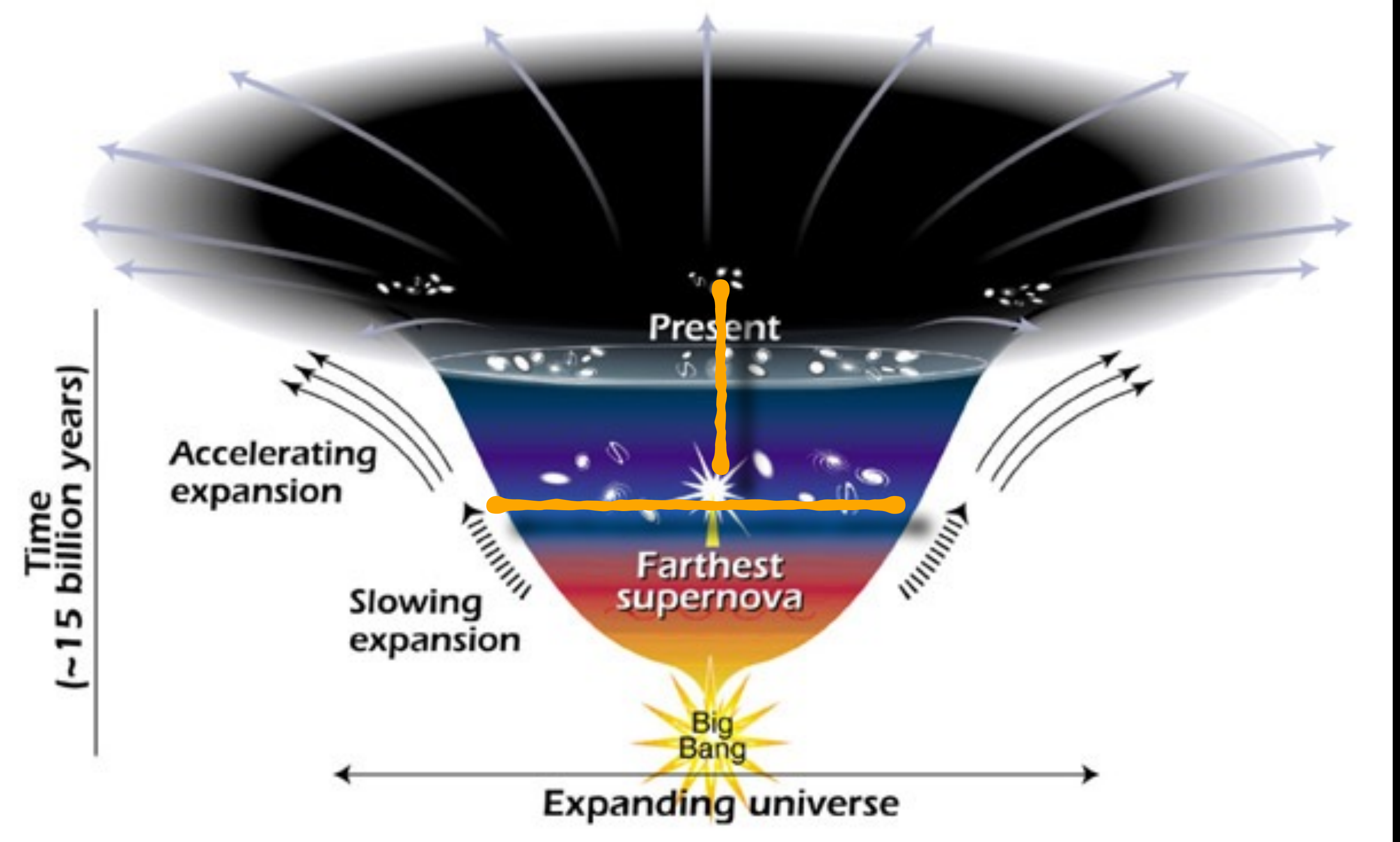
This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.

SUPERNOVAE MEASUREMENTS

1998: First evidence for an accelerated expansion from SNIa

SNIa are ***standard candles***.

Since we know how bright they shine we can estimate how distant they are.
We can also measure their redshift and determine how much the Universe expanded since the explosion.



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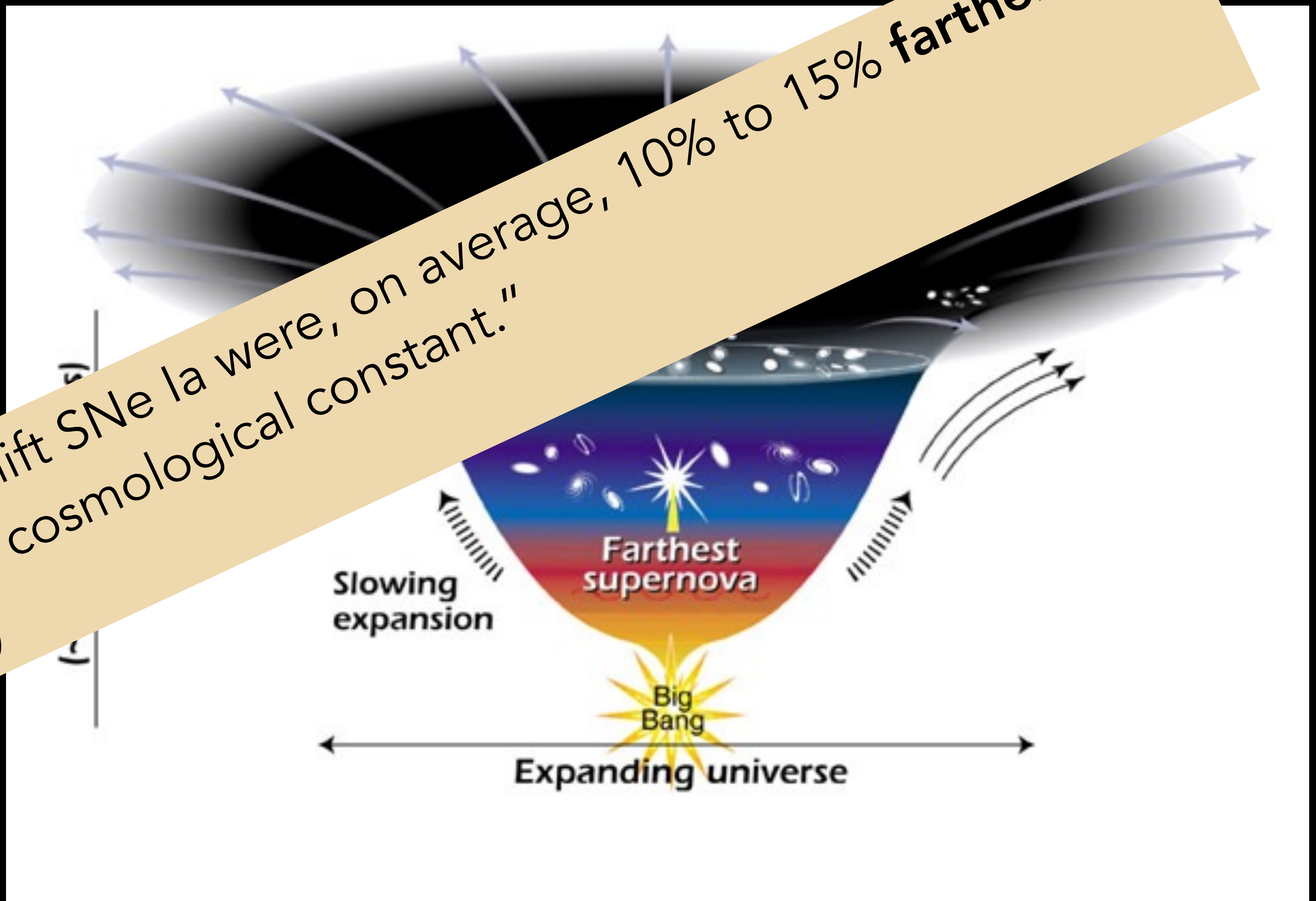
"...the distances of the high-redshift SNe Ia were, on average, 10% to 15% **farther** than expected in a universe without a cosmological constant." Adam Riess (Nobel Prize, 2011)



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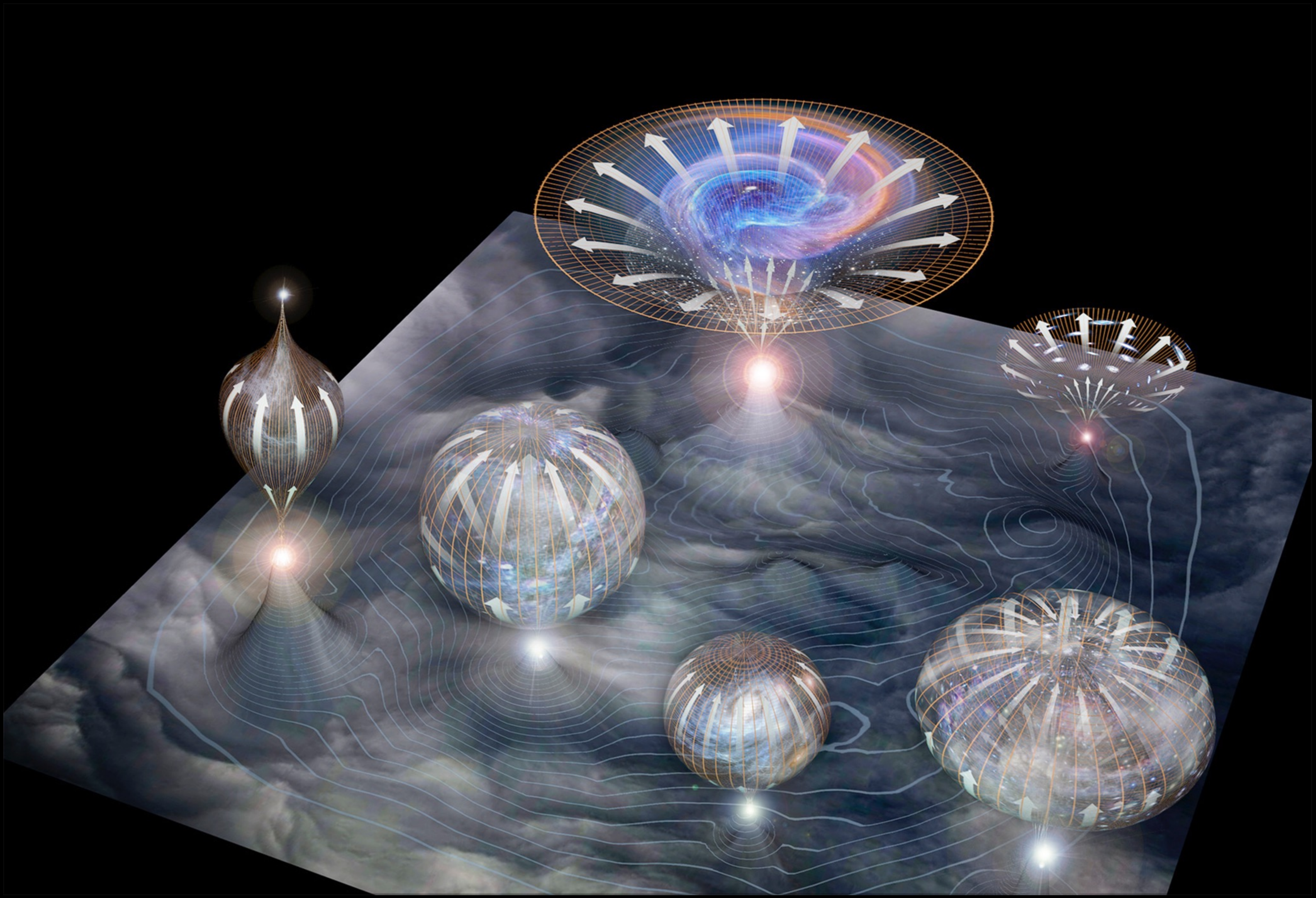
WHY SO SMALL???



WHY SO SMALL???

We do have an anthropic explanation why the planet on which we live is in the narrow range of distances from the sun… this would not be a satisfying explanation if the earth were the only planet in the universe… But with vast numbers of planets in the rest of the universe, at different distances from their respective stars, this sort of anthropic explanation is just common sense.

(Steven Weinberg)