# **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

1908

Henrietta Swan Leavitt (1864-1921) 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)

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 extragalactic 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)

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 signature to use these large

#### variations in the velocity of galaxies within

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merknale extrugalaktischer Nichl, zowie der Methoden, welche zur Erforschung derelben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaklieses wichtigen Phänomer aufgesteht worden sind, ver lieses wichtigen Phänomer aufgesteht worden sind, ver Schliesclich wird angedeutet, inwiefern die Rotverschiebung für das Schumm der andelingenden Scahlung von Wichtigkeit zu werden verspricht.

#### The Redshift of Extragalactic Nebulae

by F. Zwicky.

(16.II.33.)

*Contents.* This paper gives a representation of the main characteristics



of autropalactic polylog and of the methods which served their exploration. It is is discussed in the study of the discussed briefly. Finally it will be indid the discussed briefly. Finally it will be indid the discussed briefly. Finally it will be indi-

> if heated (given energy) gas particles are moving faster

and then

§5. Remarks concerning the dispersion



The mass M of the whole system is therefore

 $M \sim 800 \times 10^9 \times 2 \times 10^{33} =$ 

222

This implies for the total potential energy  $\Omega$ :

$$\Omega = -\frac{3}{5}\Gamma \frac{M^2}{R}$$

 $\Gamma =$ Gravitational con

 $\overline{\varepsilon}_p = \Omega/M \sim -64 \times 10^{12}$ 

$$\overline{\varepsilon}_k = \overline{v^2}/2 \sim -\overline{\varepsilon}_p/2 = 32 \times 10^{-1/2}$$
$$\left(\overline{v^2}\right)^{1/2} = 80 \text{ km}/2$$

### Fritz Zwicky was the sinst to understand

#### something of these large variations in the

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merknale erzugskaktischer Nebel, sowie der Metlieden, welche sur Erferschung der elben gedient haben. Insbesondere wird die sog. Retverschiebung extragalaktischer Nebel eingebend diskutiert. Verschiedene Theorien. Hieses wichtigen Phänomer aufgesteht worden sind, ver belless wichtigen Phänomer aufgesteht worden sind, ver Schliesclich wird angedeutet, inwiefern die Rotverschiebung für das bedarum der alle Lingelich Schlung von Wichtigkeit zu werden verspricht.

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"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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and then

or

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total potential energy  $\Omega$ :

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Zwicky was not taken seriously: the problem  $$\times10^{12}$$  was just a "missing luminosity problem"

$$\overline{v}_k = \overline{v^2}/2 \sim -\overline{\varepsilon}_p/2 = 32 \times \overline{\varepsilon}_p/2$$
  
 $\left(\overline{v^2}\right)^{1/2} = 80 \text{ km/s}^2$ 

#### How about Galaxy scales?

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

### speed Kepler's laws distance 84 years 2 years 165 years 30 years 88 225 Jays 88 225 Jays 2 years Jupiter Earth Uranus Mercury Pluto Venus Neptune Mars Saturn

#### All telescopes to Andromeda! Alateleace beata cane roud THE ROTATION OF THE ANDROMEDA NEBULA\* served his PhD een me HORACE W. BABCOCK constant angulatives of 6 from the nucleus. Interesting anomalies in the rom theuryestion curve tak 1e core of the nebula, and the approach to constant angular termina COLEPIOL velocity discovered for the outer spiral arms is hardly to c rotation velecity and car and The Evidence for DM c rotationter cor 1) galaxy rotation curves speed 1) galaxy distance N surement st 5 NCE Q



Hulst).

*Ewen* on his horn telescope

#### revolutionise astronomy



Van de Hulst at Dwingeloo

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

However, **van de Hulst** never stopped and gave the first 21cm map of Andromeda in 1957, showing that the velocities stays constant

the Universe is made of atomic H ul 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 th After the work of Van de Hulst

better understanding of the rotat

difference at has been Mis (Dimanini and Burges of

# Work of Vana dea Hulst, a lot of a measure of the values are increased for a second state of the base of the second state of the values are increased of the second state of the values of the values

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the end of the stand of the stand of the rotation curve. because the Brance is vanishingly small to rotation curve of the ions for R < 6 kpc. With a rotation curve of the ty is immédiately given, based on the assumption m the nucleus. From the calculations of Brandt total mass  $M = 3.7 \times 11^{11} M_{\odot}$ , only 57 percent in the distance of our farthest observed point, the  $= 2.1 \times 11^{11} M_{\odot}$ , close to the value determined

the presently available data, to infer anything the mass density near R = 24 kpc is extremely invering this region, and hence R = 24 kpc; the important question is how soon sion regions were found by Baade beyond R =d by van den Bergh beyond iation beyond this distance, but there are two halysis. First, on the north side of M31 the obradiation from M34 becomes confused with the uth end of the galaxy, the southwest companion tributes to the 21-cm radiation. In the model egative hydrogen density was necessary between mpanion indicating ta cyanishingly small density. eiges chynobser values of the parts of M31 region and the outermost observed point; a in Figures 3 and 4 have been formed, all



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



K.G. Begeman thesis



#### THE 1970s REVOLUTION

the fin vention of the rotation curves of galaxies much above the optical limit.

et and the variation and in the input of the transition of the second term of the term of

poor fit to our observations for R < 6 kpc. With a rotation curve of the e total mass out to infinity is immédiately given, based on the assumption erse-square force far from the nucleus. From the calculations of Brandt it is seen that, of the total mass  $M = 3.7 \times 11^{11} M_{\odot}$ , only 57 percent 24 kpc. Thus, to within the distance of our farthest observed point, the Brandt solution is  $M_{\perp} = 2.1 \times 11^{11} M_{\odot}$ , close to the value determined

appear possible, from the presently available data, to infer anything beyond 24 kpc in 1917, the mass density near R = 24 kpc is extremely shape of the rotation curve in this region, and hence is of low accuracy. he density is low beyond  $R \stackrel{\perp}{=} 24$  kpc; the important question is how soon gible. No optical emission regions were found by Baade beyond R =issociations were found by van den Bergh beyond R = 18 kpc. Radio we detected 21-cm radiation beyond this distance, but there are two which complicate the analysis. First, on the north side of M31 the obs are near zero, so the radiation from M31 becomes confused with the near the Sun. On the south end of the galaxy, the southwest companion r, and Tuve 1964) contributes to the 21-cm radiation. In the model e, Turner, and Tive an egative hydrogen density was necessary between Liandethe southwest company on indicating a vanishingly small density. teil logiciones in ob associations in 1931, as a function of distance from the called 1 to  $10^{-1}$  to 1ass of M31 that mass contained within the outermost observed point; er rotation curves for the data in Figures 3 and 4 have been formed, all even formed, all are solutions, with polynomials of third fourth or sixth order. In Figure 11 (1042) are Autionsequéine outrée procedure adaptede by Wysel and Stayall (1942), re-

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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 The Evidence for DM By the 90s, telescopes were able to test bigger portions of the sky

and study **the distribution** of Galaxies



## LOOKING BACK IN TIME Many people thought the early universe was complex. Or DM But Zel'dovich assumed that it is fundamentally simple, with just gravity at work starting from small density fluctuations at the dawn of time.



## 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



#### LOOKING BACK IN TIME The Evidence for DV 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?

![](_page_30_Figure_1.jpeg)

![](_page_31_Figure_1.jpeg)

![](_page_32_Picture_1.jpeg)

#### The Standard Model of Particle Interactions

Three Generations of Matter

I II III

![](_page_32_Picture_5.jpeg)

![](_page_33_Figure_1.jpeg)

#### 1. neutral

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

#### The Standard Model of Particle Interactions

Three Generations of Matter

![](_page_33_Picture_10.jpeg)

![](_page_34_Figure_1.jpeg)

#### 1. neutral

- 2. stable
- 3. heavy
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#### The Standard Model of Particle Interactions

Three Generations of Matter

![](_page_34_Picture_10.jpeg)

![](_page_35_Figure_1.jpeg)

## neutral stable

- 3. heavy
- 4. 5x more abundant than usual mater
- 5. feeble interactions

#### The Standard Model of Particle Interactions

Three Generations of Matter

![](_page_35_Picture_9.jpeg)

![](_page_36_Figure_1.jpeg)

### 1. neutral

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

→ needs to be a new particle!

#### The Standard Model of Particle Interactions

Three Generations of Matter

![](_page_36_Figure_11.jpeg)

## If dark matter is a new particle...

What is its mass?

How does it interact with 'us'?

![](_page_37_Figure_3.jpeg)

![](_page_38_Figure_0.jpeg)

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

![](_page_38_Figure_3.jpeg)

### THE MOST POPULAR CANDIDATES

![](_page_39_Figure_1.jpeg)

- <u>4. 5x more abundant than usual mater</u>
- 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

![](_page_40_Picture_1.jpeg)

#### axions, axion-like particles, hidden photons ...

## BUT... HOW TO FIND IT?

![](_page_41_Picture_1.jpeg)

# DUT... HOW TO FIND IT?

M LOOO proton eV 1 GeV

![](_page_42_Picture_2.jpeg)

![](_page_42_Picture_3.jpeg)

![](_page_42_Picture_4.jpeg)

![](_page_43_Picture_0.jpeg)

![](_page_44_Picture_0.jpeg)

## DT... HOW TO FIND IT?

M I OOO proton I GeV

![](_page_45_Picture_2.jpeg)

annihilations in halo

### astrophysics:

dark matter  $\chi$ 

![](_page_45_Picture_6.jpeg)

![](_page_45_Picture_7.jpeg)

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**!

![](_page_48_Figure_2.jpeg)

## 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**".

## 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

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

Now ACDM is the Standard Cosmological Model.

Many different observations, including the Cosmic Microwave Background, confirm ACDM 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

![](_page_51_Figure_3.jpeg)

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

![](_page_52_Picture_1.jpeg)

69% dark energy

## THE COSMIC INVENTORY

![](_page_53_Picture_1.jpeg)

Psalter world map, 1260s, British Library

## THE FUTURE?

![](_page_54_Picture_1.jpeg)

... are we here alone?

## EXTRA SLIDES

If receding velocities were *not* proportional to the distance

from our point of view ...

![](_page_56_Figure_3.jpeg)

If receding velocities were *not* proportional to the distance

from our point of view ...

other	US	other	yet
galaxy		galaxy	another

from the point of view of the other galaxy

![](_page_57_Figure_5.jpeg)

hence, not all points in the Universe would be equivalent

If recession velocities are instead proportional to the distance

from our point of view ...

![](_page_58_Figure_3.jpeg)

If recession velocities are instead proportional to the distance

from our point of view ...

other	us	other	yet
galaxy		galaxy	another

from the point of view of the other galaxy

![](_page_59_Figure_5.jpeg)

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

![](_page_60_Figure_2.jpeg)

[Credit: Springel et al. (2005)]

## SUPERNOVAE MEASUREMENTS

#### 1998: First evidence for an accelerated expansion from SNIa

SNIa are **standard candles**.

![](_page_61_Figure_3.jpeg)

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.

![](_page_62_Figure_4.jpeg)

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

![](_page_63_Figure_1.jpeg)

force that is pushing galaxies apart.

## WHY SO SMALL???

![](_page_64_Picture_1.jpeg)

## 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)

![](_page_65_Picture_3.jpeg)