Dark Matter

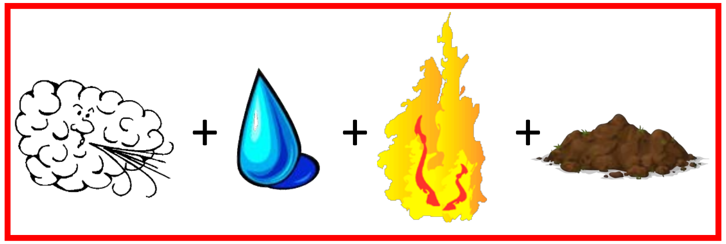
The modern quintessence of the universe

Paola Gianotti
INFN-LNF

Quintessence

It was Aristotle who first introduced this concept

Ancient Greeks believed that nature was made by 4 elements: earth, air, fire and water
The «fifth element» the **ether** was, according to Aristotle, the constituent of the celestial world.

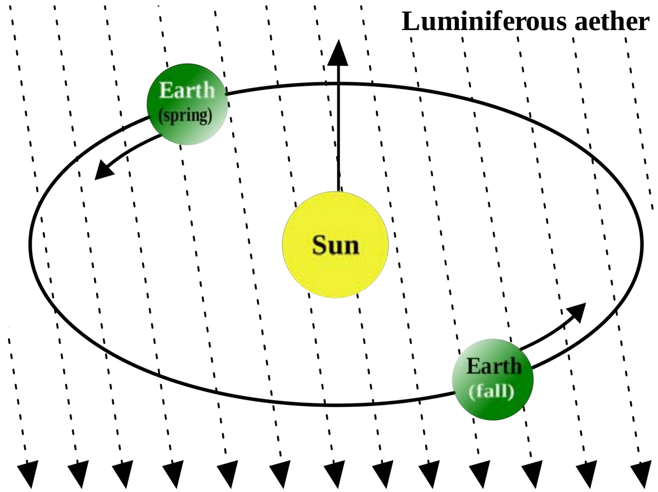


The idea of an invisible matter that pervades the universe has resurfaced in the history of science.

Ether and relativity

After the discovery of the electromagnetic waves, scientists were looking for the element through which electromagnetic waves propagate.

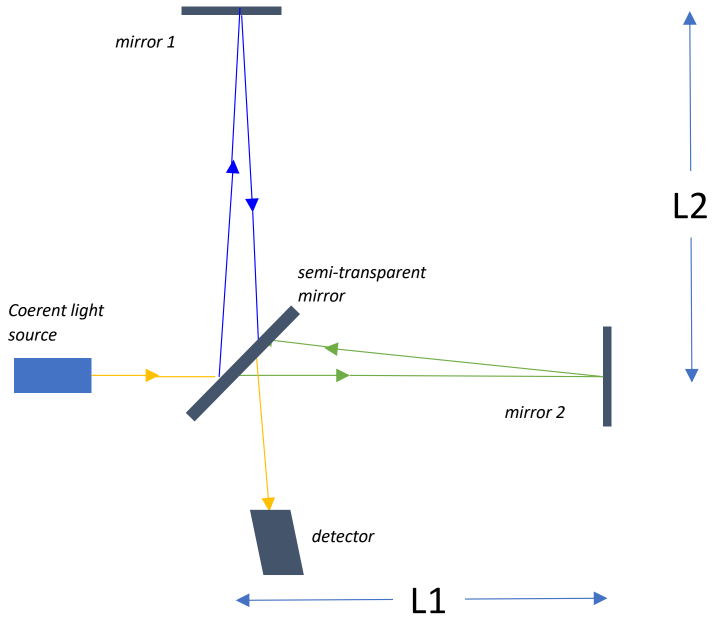
It was believed that electromagnetic waves **could not propagate in vacuum** and the **existence of the ether** was dusted off: **a substance that permeated the universe allowing electromagnetic waves to travel**.



Michelson and Morley experiment

In 1887 Albert Michelson and Edward Morley concieved an experiment to demonstrate ether existence.

They thought that if ether was pervading the whole space, it would have been possible to measure the earth motion with respect to it.



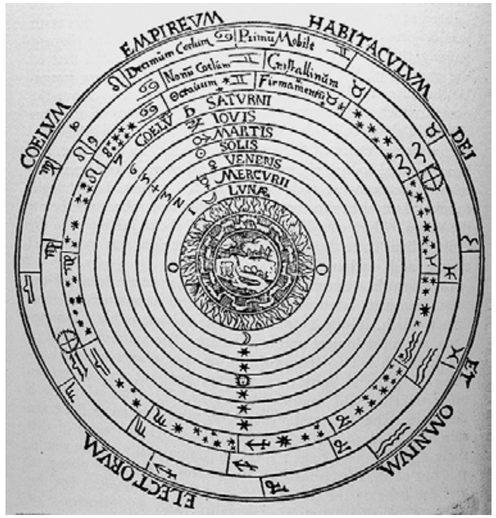
The experiment was not providing the expected results.
The two light rays were always arriving intime independently of the direction of motion.

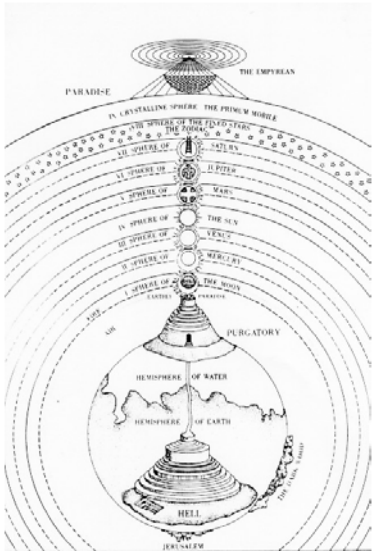
History of cosmology

Cosmology is the study of the Universe, its constituents, how it formed and evolves. Cosmology was born with man often related to religion.

In eastern countries, the geocentric Ptolemaic system (200 A.C.) was the first scientific theory trying to classify and predict the position of celestial bodies.

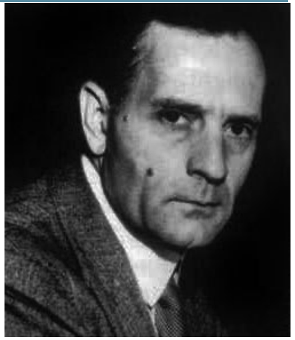
There were also helio-centric theories (Aristarchus 270 B.C.)





Adopted by the Catholic Church with some modifications, the Ptolemaic idea was in vogue up to 1600.

Modern Cosmology



Edwin Hubble
1889 –1953

Modern cosmology was born between 1915 and 1929:

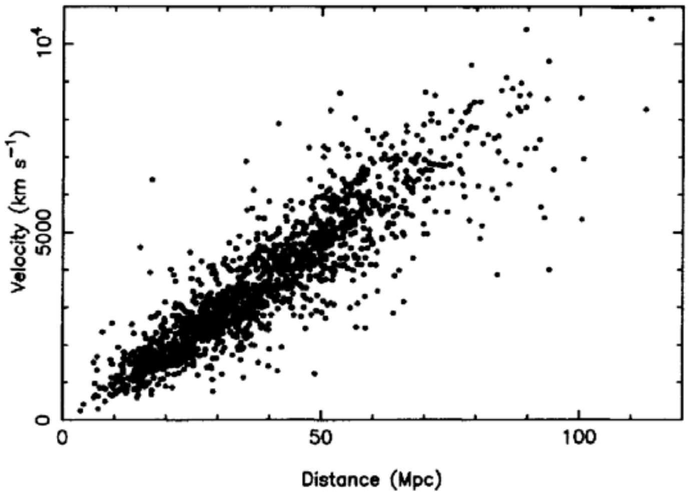
- 1915 Einstein publishes general relativity theory;
- 1927 Lemaître e Friedman solved Einstein equations and determined the universe expansion;
- 1929 Hubble discovered red-shift of galaxies, proving that Universe is expanding.

$$v = H_0 D$$

Departure speed is proportional to distance

Red-shift is the shift of some known transitions towards lower frequencies.

$$z = \frac{f_{emis} - f_{obs}}{f_{obs}}$$



Departure velocity of 1355 galaxies

Doppler effect

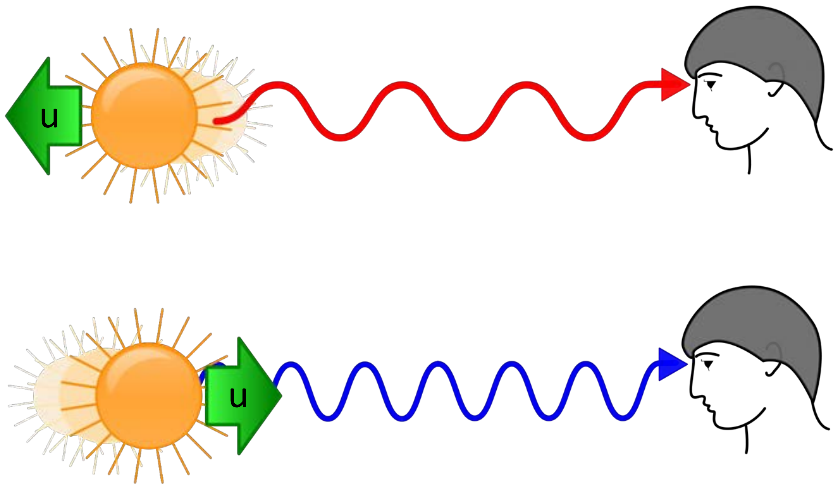
It is a physical phenomenon consisting in the **changing**, with respect to the original value, **of the frequency of a wave** measured by an observer moving with respect to the source.

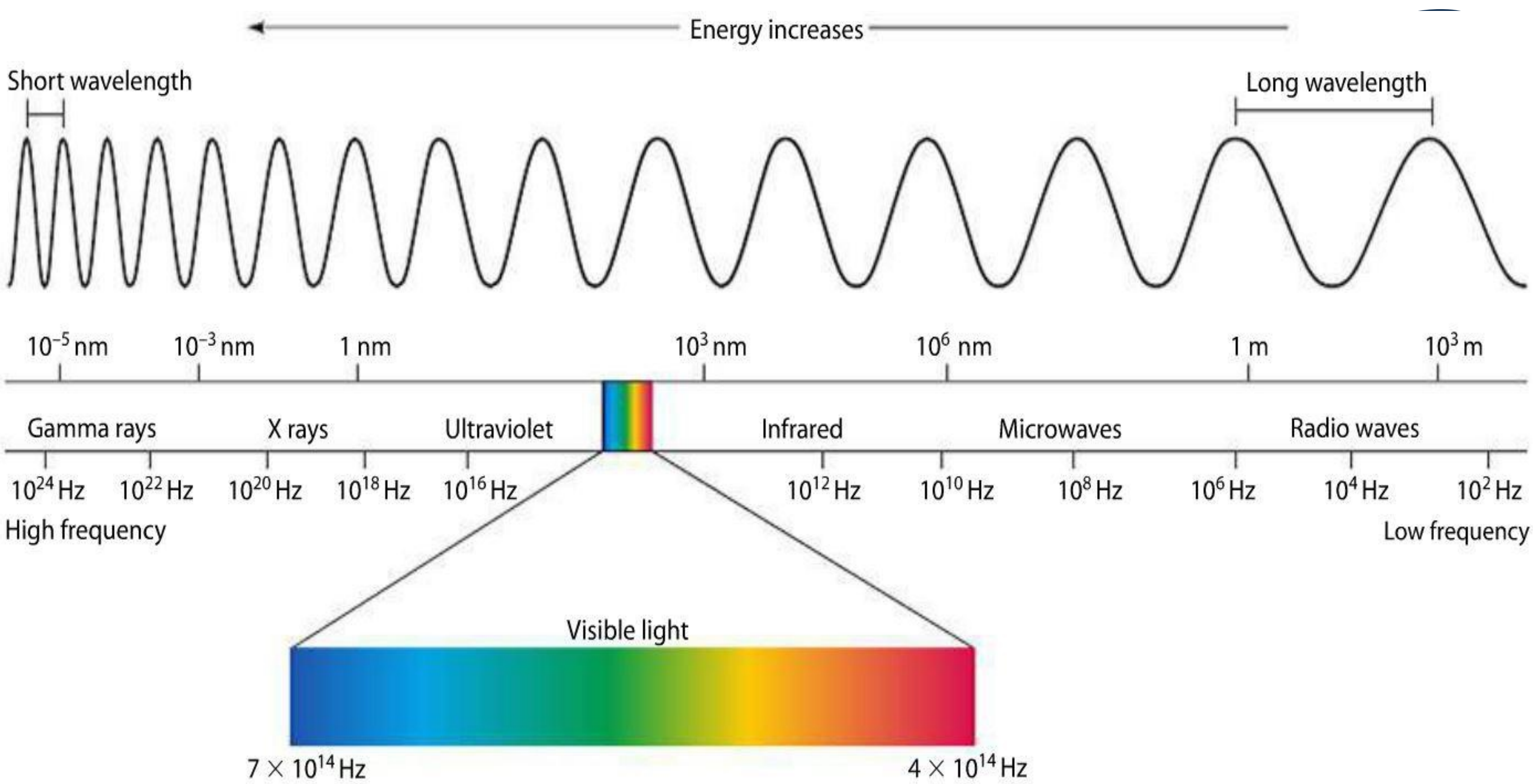
If the source is moving with respect to the observer, the measured frequency is:

$$f_1 = f \frac{1}{1 \mp \frac{u}{v}}$$

for a e.m. wave

- if the source is moving away from the observer, a lower frequency is received, red-shifted (for visible light)
- if the source is moving toward the observer, a highe frequency is received, blue-shifted.



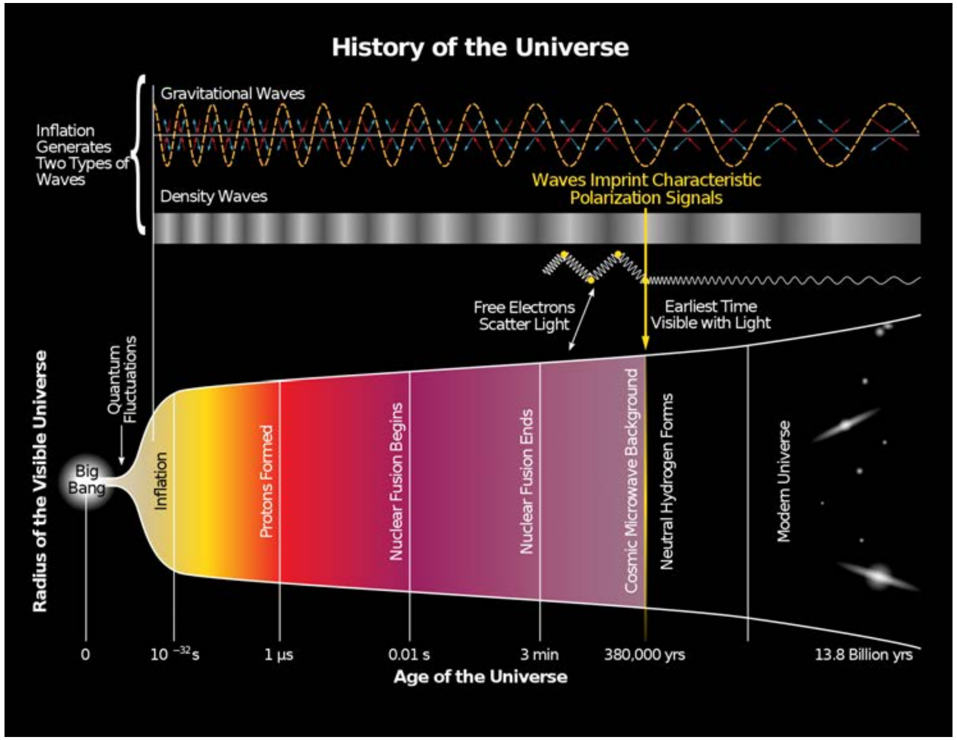


Energy increases
Short wavelength
Long wavelength
10⁻⁵ nm
10⁻³ nm
1 nm
10³ nm
10⁶ nm
1 m
10³ m
Gamma rays
X rays
Ultraviolet
Infrared
Microwaves
Radio waves
10²⁴ Hz
10²² Hz
10²⁰ Hz
10¹⁸ Hz
10¹⁶ Hz
10¹² Hz
10¹⁰ Hz
10⁸ Hz
10⁶ Hz
10⁴ Hz
10² Hz
High frequency
Low frequency
Visible light
7 × 10¹⁴ Hz
4 × 10¹⁴ Hz

History of the Universe 1

The theory of Big Bang tells us that the universe was born 13.7 billions years ago.

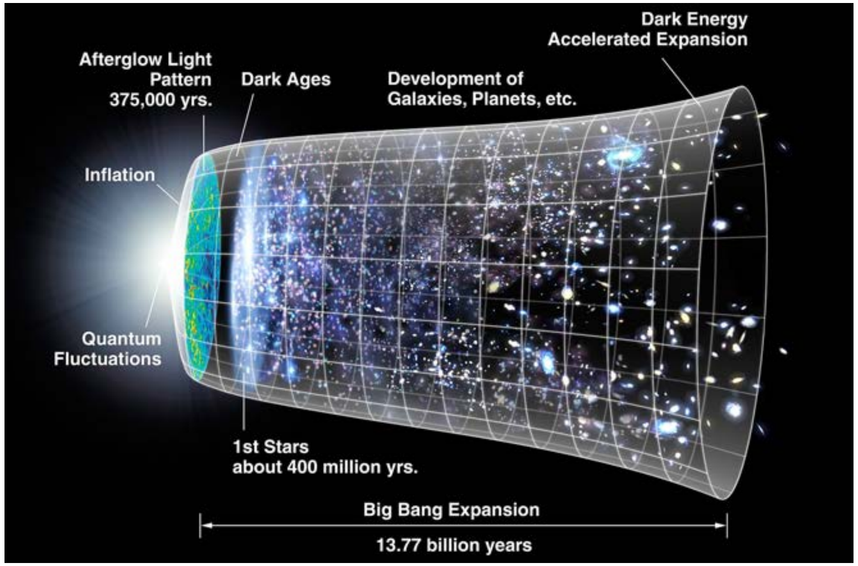
- After the singularity at 10^{-43} s the universe was in a state where the 4 known forces had the same intensity. They were unified (Planck Era).
- Then space-time is formed, the gravity decouples from the other forces (Grand-unification Era).
- At 10^{-35} s inflation era started. The universe started expanding and the Higgs field create particle-antiparticle pairs.
- At 10^{-9} s electroweak force decouple.
- Hadron's era starts. Quark e antiquark start to bound. We are at 10^{-6} s .



History of the Universe 2

After fundamental particles formation, they start interacting and bounding.

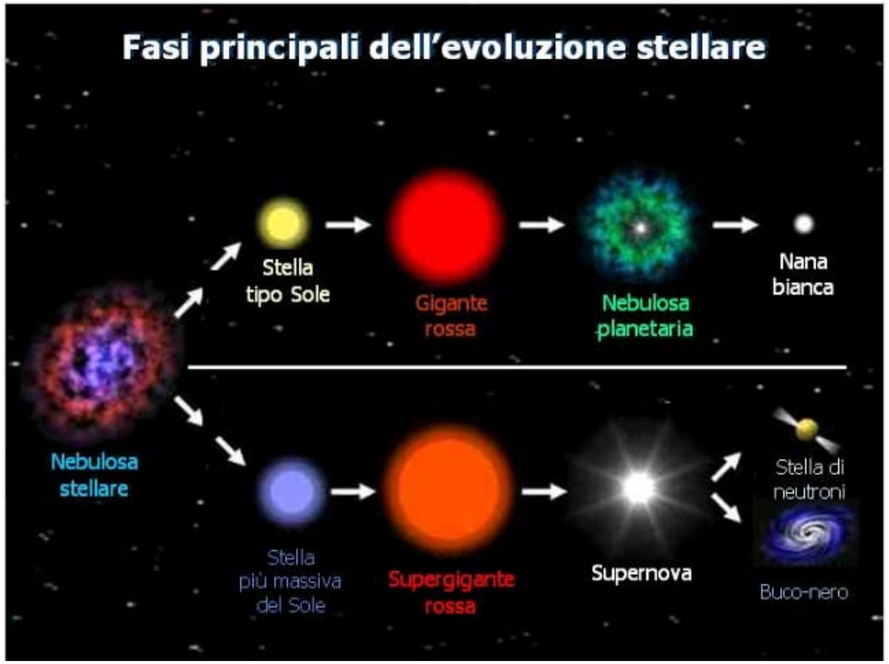
- **Nucleo-synthesis era**: protons and neutrons form first nuclei;
- **Opacity era**: temperature lowers and e.m. interaction starts decoupling. From now on the photons travel faster (200 s after BB);
- **Matter era**: when atoms are formed ~ 300.000 anni.

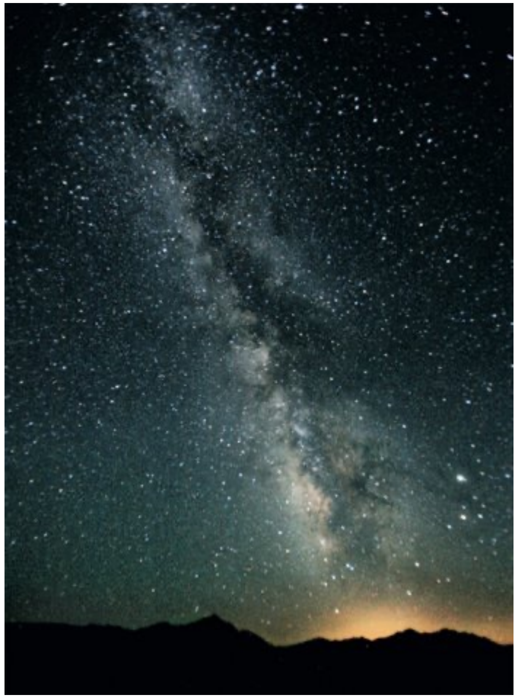


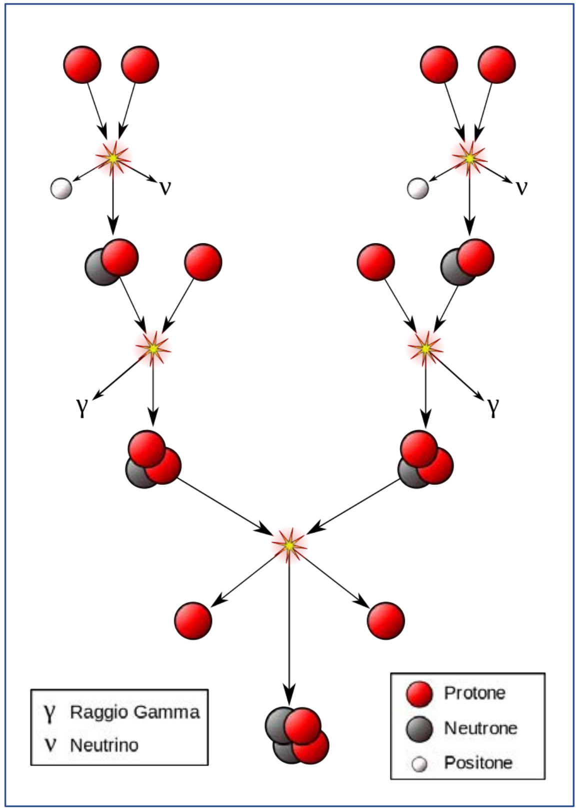
La galaxy M101

Stars and Galaxies

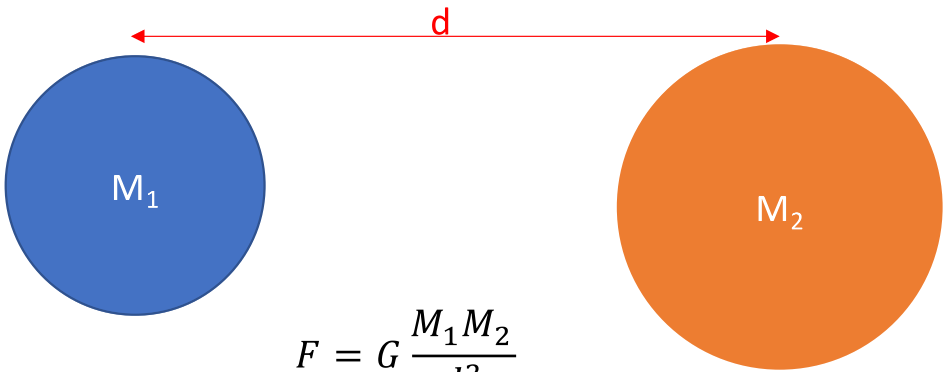
Light coming from stars is due to nuclear fusion reactions.



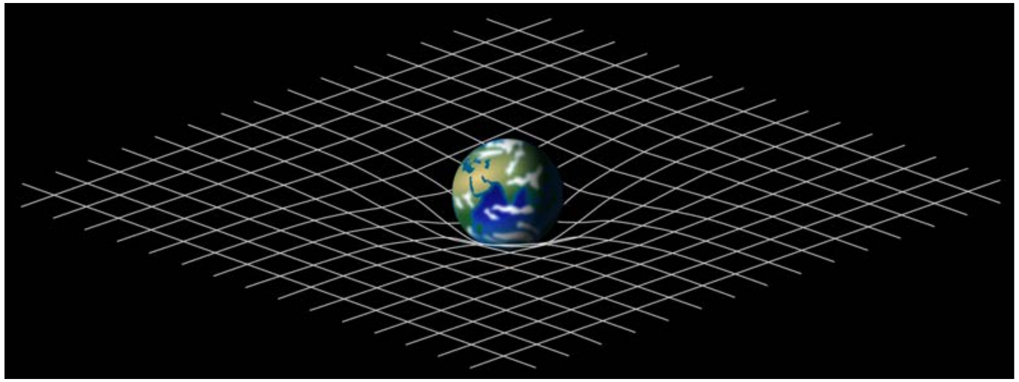




Newtonian Gravity – Einstenian Gravity



$$F = G\frac{M_1 M_2}{d^2}$$

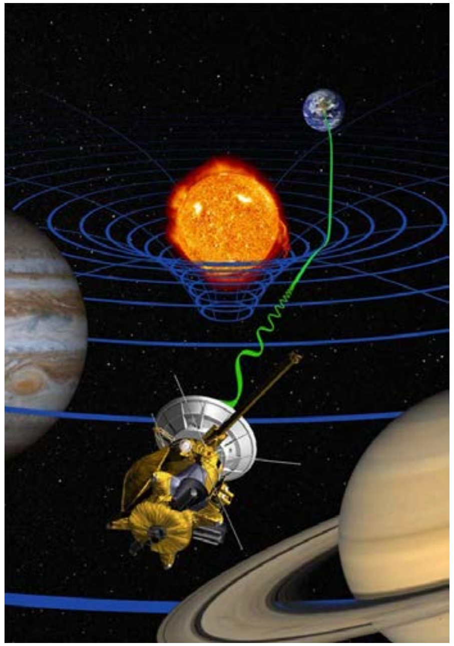


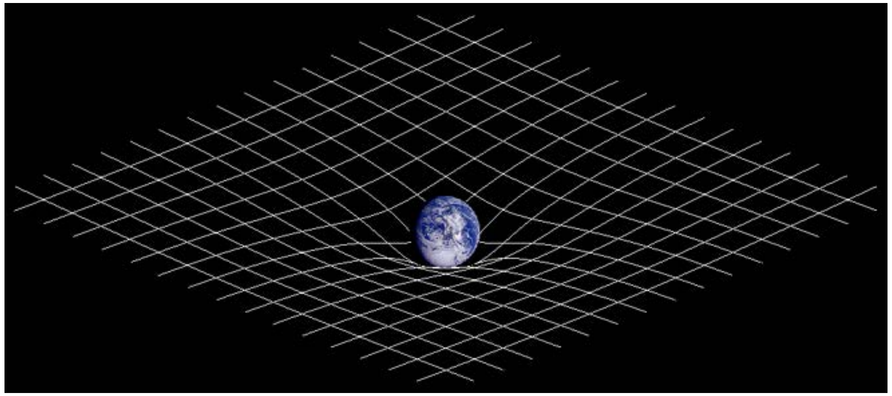
$$R_{\mu\nu} - \frac{1}{2} + Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$G = 6.673 \times 10^{-11}\ N\ m^2/kg^2$

Lensing Effect

Thanks to the **theory of general relativity,** new models of the universe were built.
Gravity is no longer see as an action between object with mass, but as the **effect of a physics law that create the curvature of the space-time.**

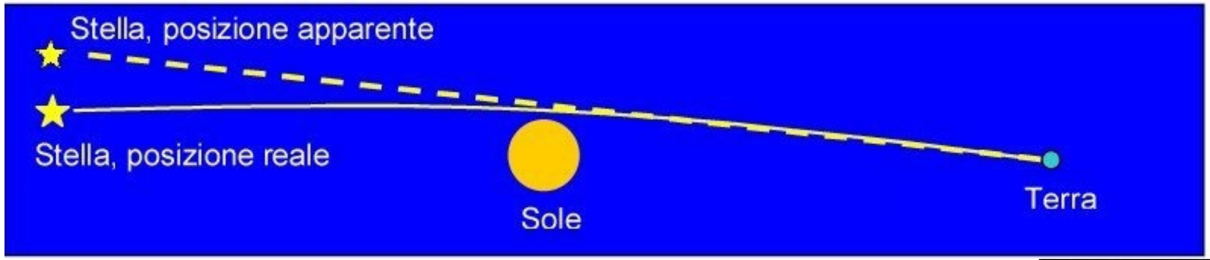


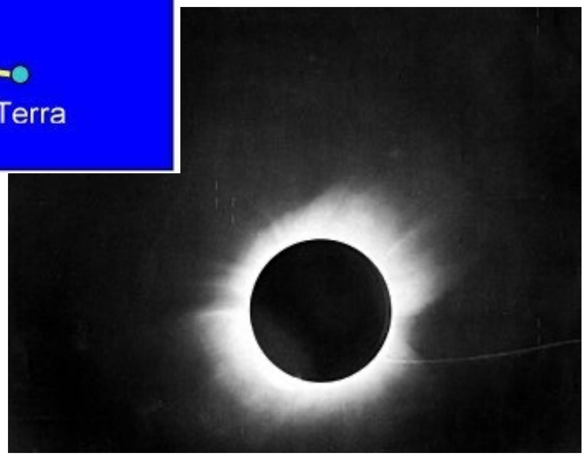


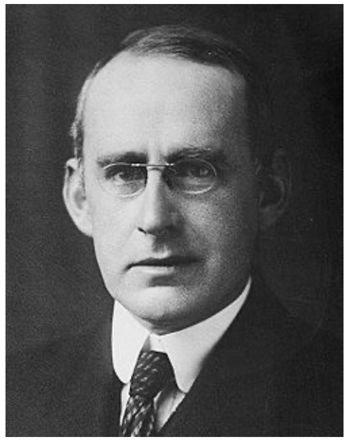
This interpretation implies that not only **massive objects** but also those **without a mass**, as light, **feel gravitational effect** when they pass through a space deformation.

Experimental test

Light ray deflection was observed for the first time in 1919 by Eddington during a solar eclipse. Even if the measurement was not very accurate, it was possible to observe stars close to the solar edge, that in reality should have been behind. Stars positions on the taken pictures were compared with nominal positions in standard conditions:
a deviation of about 1.98 ” of the light coming from these stars was measured. In good agreement with Einstein General Relativity predictions.






Arthur Eddington
1882 – 1944

Cosmos observation

Observing galaxies, we see that they are **more brilliant in the center** than in the periphery.

This implies that the majority of the stars are in the center.

If this would be the case, the speed of peripheral celestial bodies should be lower.

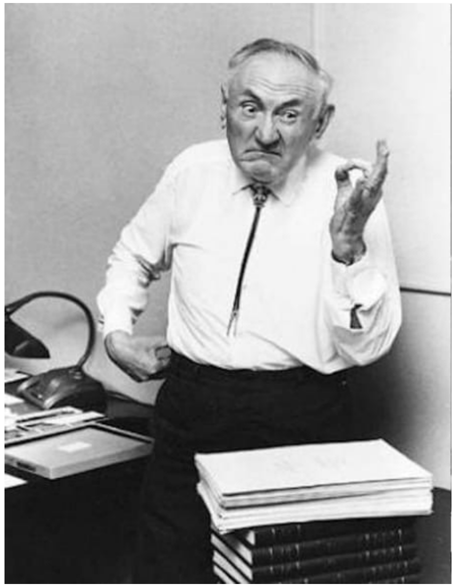
$$v_r(r) = \sqrt{\frac{G_N M(r)}{r}}$$

Dark Matter

In 1933 Fritz Zwicky was studying galaxy clusters motion. He evaluated the mass of the galaxies and of the clusters from **their luminosity**. Summing up he determined the total mass.

To have a second independent measurement, he evaluated the dispersion of velocities of galaxies in the clusters.

The two estimates differ by 400! The second measurement was tremendously bigger.



Fritz Zwicky
1898 – 1974

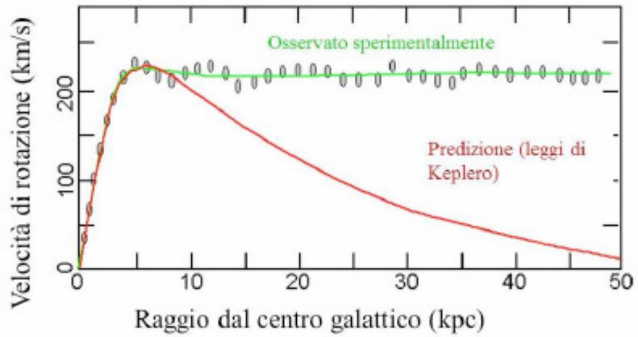
He concluded that some «*dunkel materie*» should exist to reconcile the difference between the two measurements.

Vera Rubin and galaxies rotation

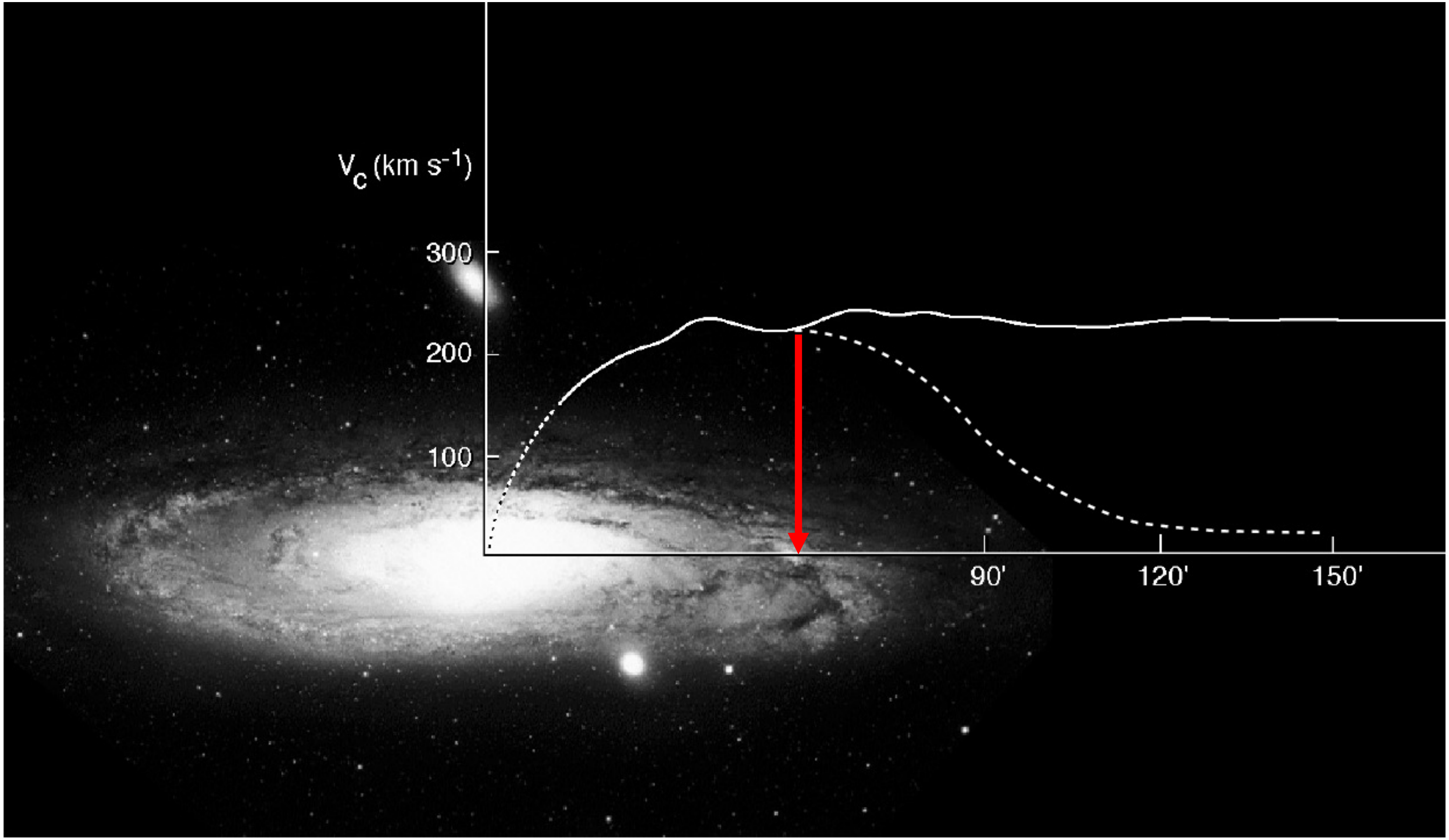
In the ’70s, thanks to radio-telescopes, it became possible to measure the rotation speed of celestial bodies as a function of their distance from the center of the galaxy, and not only making calculations as Zwicky did.
The measurement was done using Doppler effect of a known transition of Hydrogen.

Vera Rubin
1928 – 2016

Vera Rubin studied spiral galaxies rotation. These contain a huge number of stars on almost circular concentric orbits centered on the galactic center.
Following Kepler second law stars with larger orbits should have had lower orbital speed.



To justify the experimental measurements an explanation could be that some extra mass should surround the galaxies.

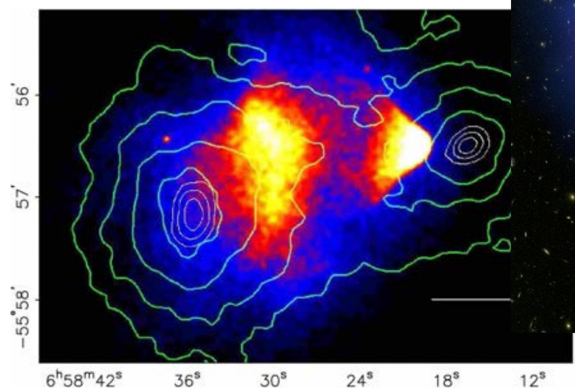


V_c (km s^{-1})
300
200
100
90'
120'
150'

Another clue of Dark Matter

Observing the «Bullet Cluster» with optical and X-ray telescopes and studying gravitational lensing phenomena on radiations, we see effects that can be explained only introducing some **dark matter**.

In practice the visible matter do not justify the lensing phenomena we observe.



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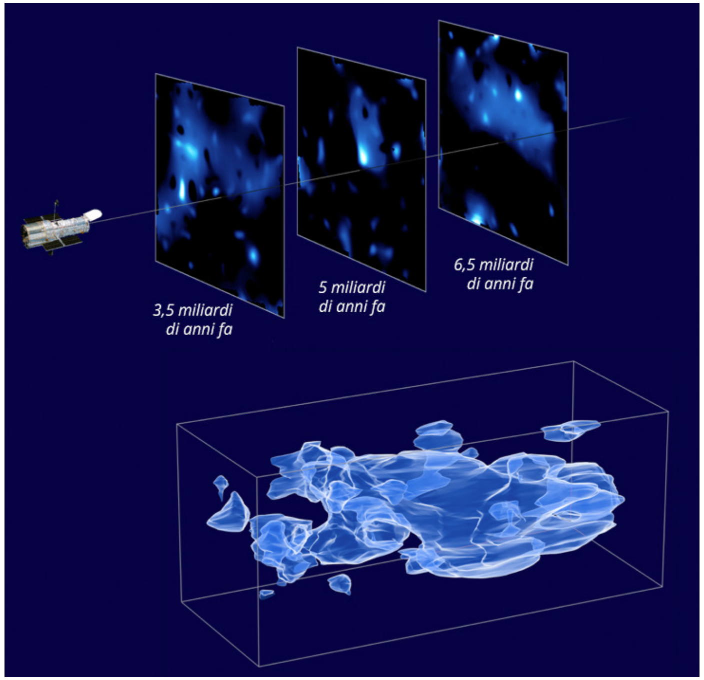
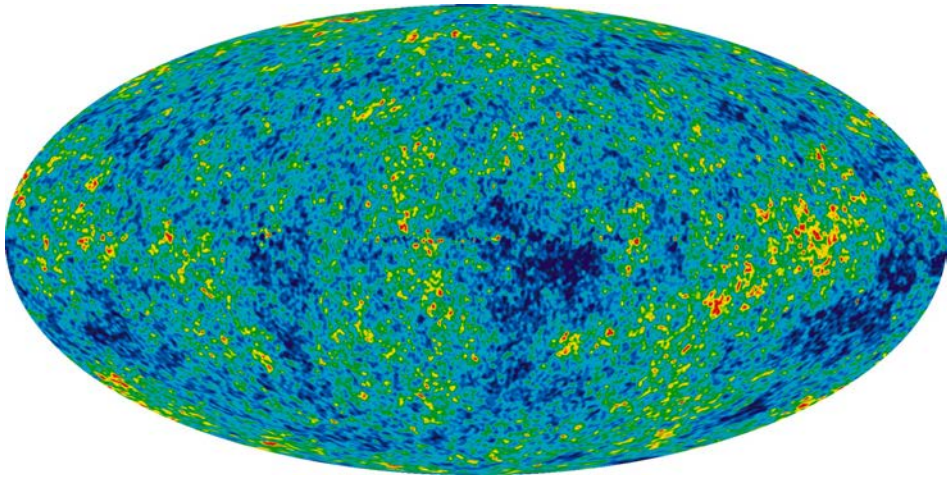
Light deflection due to gravity produces an effect similar to that of lenses: it modify the image of the light source creating distortions or producing multiple images.
These similarities with optic justify the name **gravitational lens**, or *lensing.*

Dark Matter the new quintessence



Dark matter distribution measured by survey HST Cosmos studying gravitational lensing phenomena.

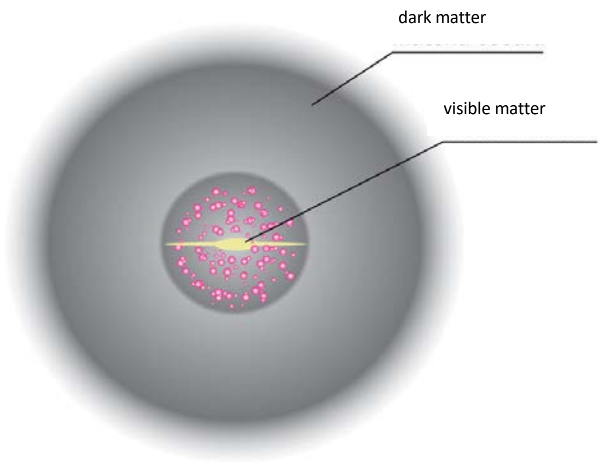
- We started speaking about **dark matter** around '30s to solve the problem of missing mass in galaxies clusters.
- In the '70s we understood that only admitting a new form of matter we could explain cosmic anomalies.
- Recently, development of cosmological models based on general relativity and multi-messenger studies, allowed to define better the characteristics of this form of matter that is dominant on cosmic scale.

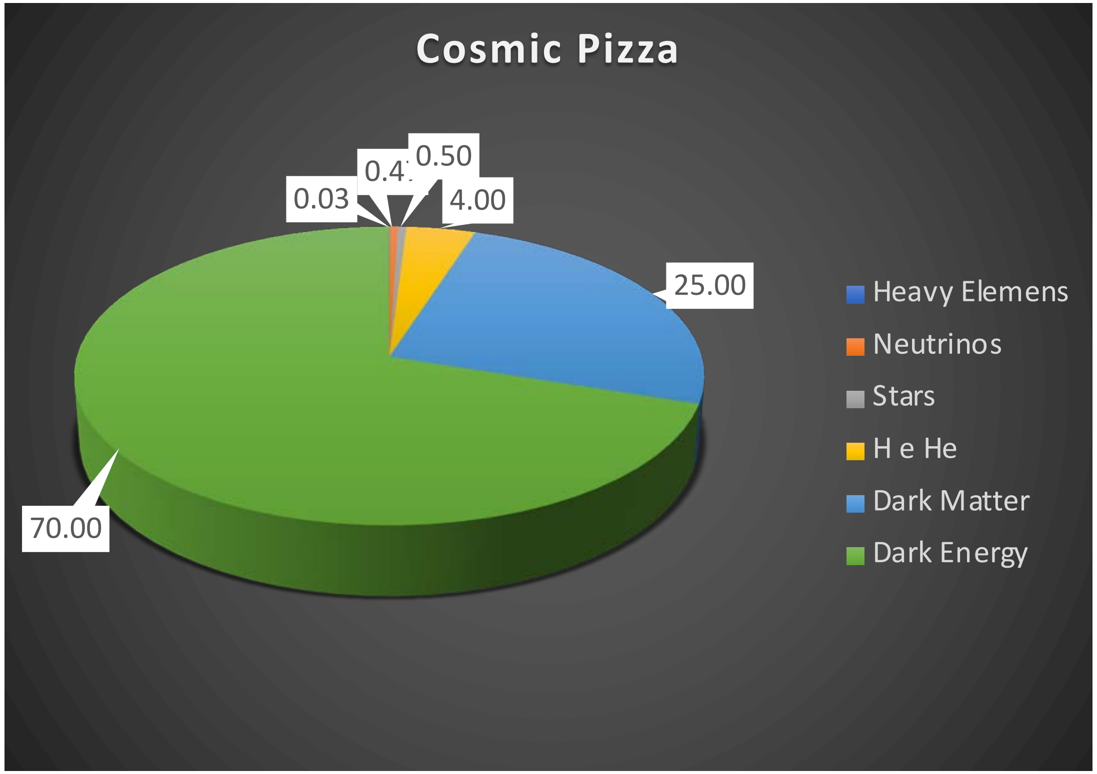


What is Dark Matter?

We know better what dark matter is not than what it is:

- dark matter is dark
- It is not «ordinary matter»
- dark matter is not antimatter
- is not represented by Black Holes
- neutrinos are not responsible for dark matter





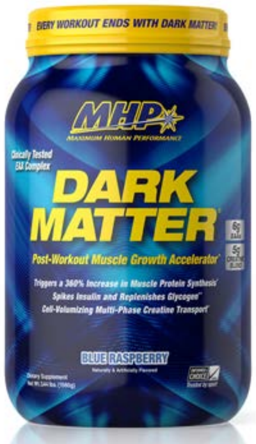
How to imagine Dark Matter

A priori, all the theories can be good. In general, we give more credit to those able to interpret also other unexplained phenomena in the Standard Model.

Among the open problems we have:

- Matter-Antimatter asymmetry
- Neutrinos masses and their hierarchy
- CP conservation of Strong Interaction
- Existence of new particles beyond the Standard Model
- Extra space dimensions
- …..

DM inspired



dietary supplement

Fishing wire

Liquor

Beer

Face mask


Nail polish

Some hypotheses on Dark Matter

Two classes of hypotheses: DM is composed by High Energy particles (HDM), or they are slow and low energy (CDM).
Under the assumption of HDM, particles should be very light, easy to accelerate.
Vice versa for CDM we expect more massive particles.

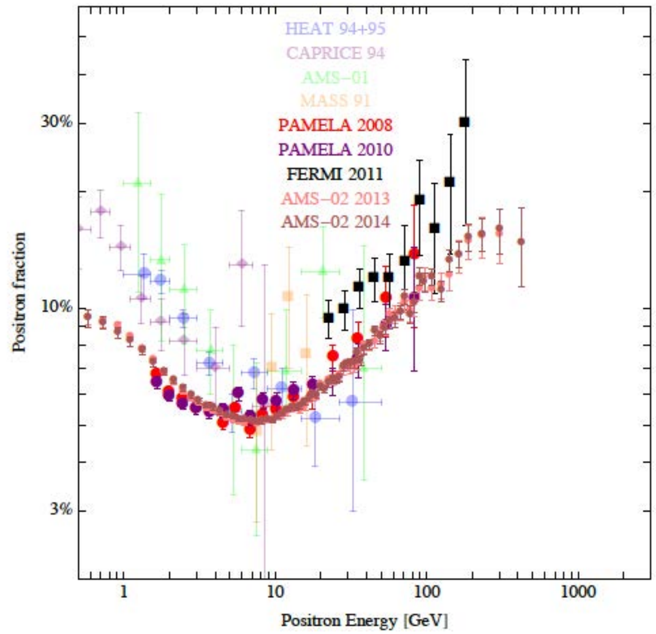
Weakly Interacting Massive Particles, o «WIMPs». This is a new class of particles exhibiting only gravitational interaction or in the end a new very week force. They must be produced in the Big Bang and being ubiquitous in the universe. Something similar is predicted by Super-Symmetric Theories.

Axions. These should be very light and slow weakly interacting with ordinary matter. They are foreseen «decaying» in photon pairs through which we can detect them. They will also explain the absence of CP-violation of strong interaction.

MACHO, Massive Astrophysical Compact Halo Objects. They were the first proposed dark matter candidates. These should be cosmic objects (neutrons stars, white and brown dwarfs) compound of ordinary matter, but with very high densities.

A wind of Dark Matter

To have ordinary matter gravitationally stable, we must admit the presence of a **dark matter halo**.
The Earth, in its motion around the Sun, is traversing the dark matter halo of Milky Way and should be possible to detect interactions between dark matter particles and ordinary particles.



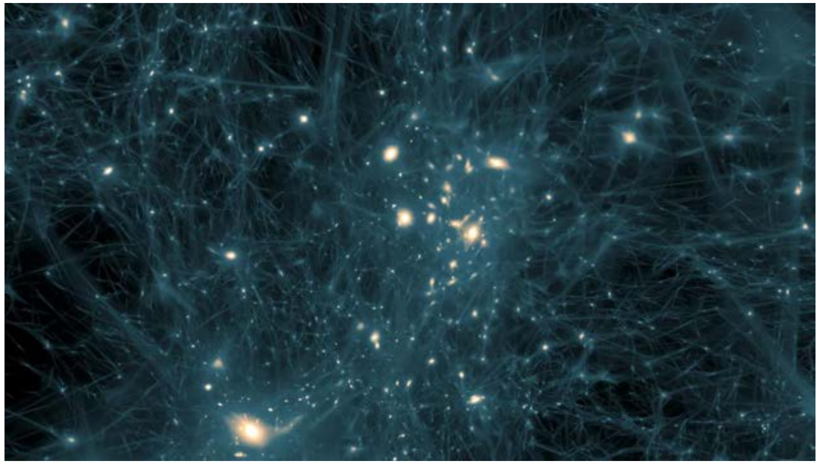
Some models propose that dark matter can interact producing particles of ordinary matter.

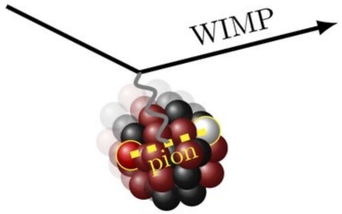
To try to detect dark matter, different kind of approaches are used:

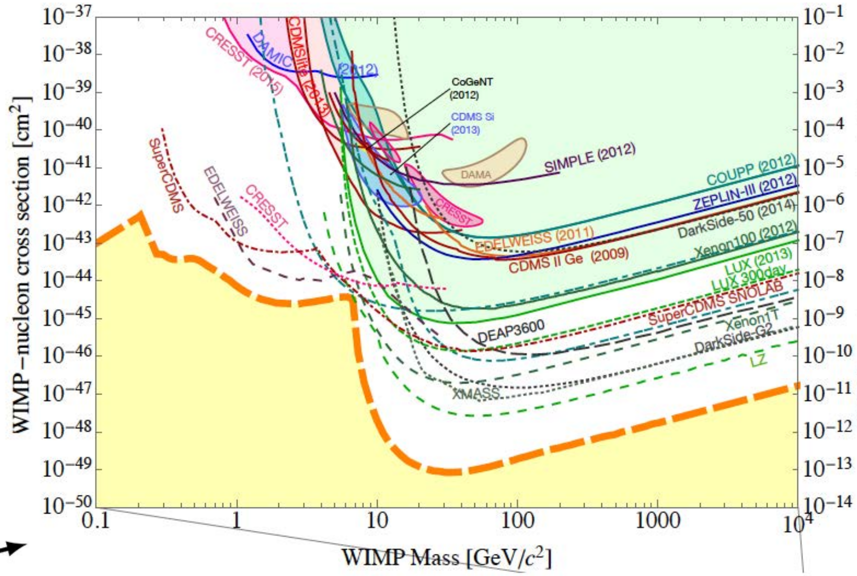
- looking for anomalies in the cosmic ray flux;
- looking for anomalous sources of gamma-rays or of neutrinos.

Weakly Interactive Massive Particles

In the primordial universe, WIMPs should have been produced as the other particles. Up to when density allowed, they interacted among each other disappearing-reappearing via annihilation processes. When expansion arrive to a point that their density became such that interactions were no more possible, they kept on living and the quantity of dark matter in the universe freeze-out.

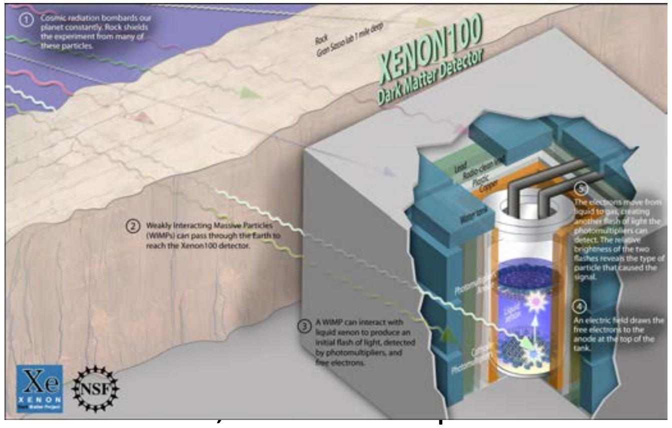






To detect WIMPs an indirect technique is used. The recoil energy of a heavy nucleus is measured.

Weakly Interactive Massive Particles



They feebly interact with ordinary matter, something like neutrinos that can cross planets without being perturbed.

In spite of neutrinos, that are practically massless, WIMPs should have a high mass (~1000 times proton mass) to give reason to the 25% of universe «missing mass».

Hunt take place in:

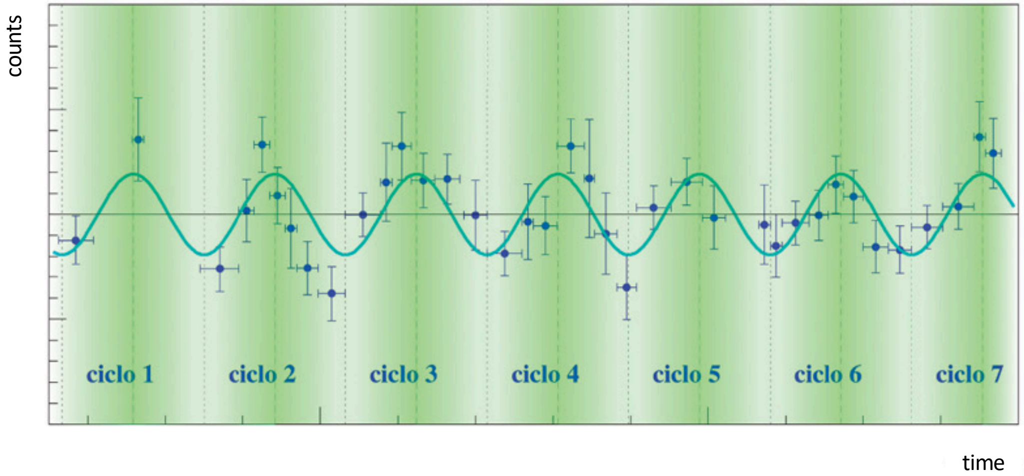
- **outer space** on satellite detectors – as for AMS-02, installed on the ISS;
- **or in deep underground** waiting for WIMPs interacting in gigantic detectors. Being underground all other particles are almost totally absorbed reducing backgrounds.

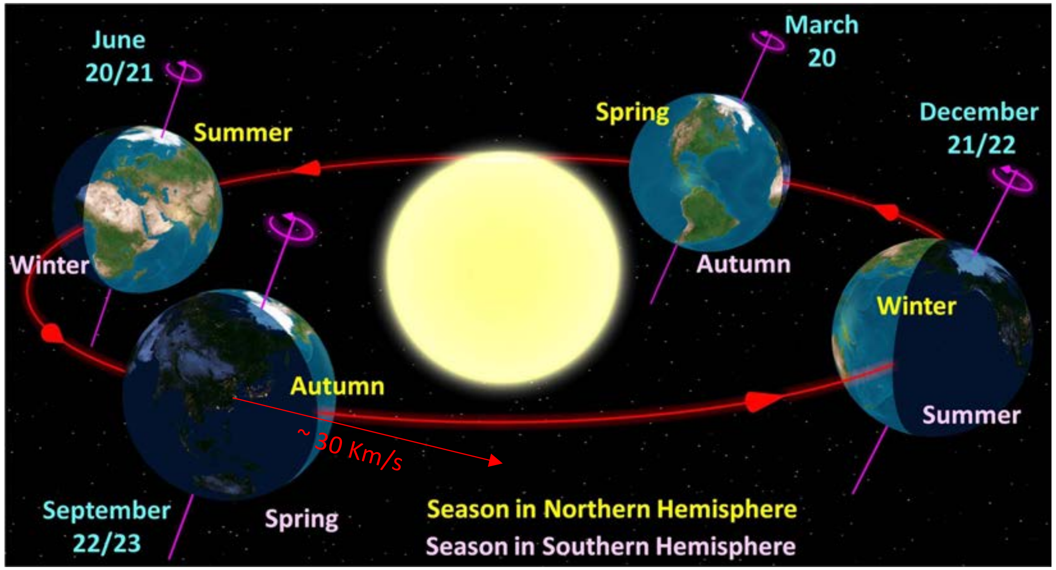
At INFN Gran Sasso Laboratories, several international collaborations are searching for WIMPs signals – XENON has released las week a new more stringent limit.

DAMA Experiment

To be honest an experiment that has seen a signal exist: DAMA
This is a detector made of hyper-pure NaI crystals (100 Kg) taking data since 2002 at LNGS. The goal is to detect WIMPs interactions.

The annual modulation measured by DAMA is compatible with the «wind» of dark matter particles foreseen for the Milky Way.



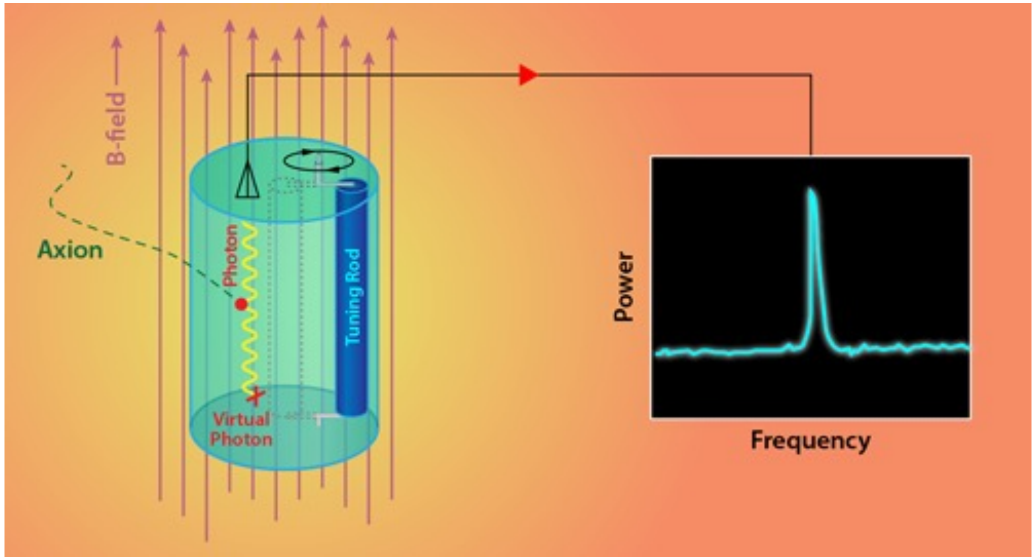


Axions

Axions stand in an intermediate position between HDM and CDM. They are light particles (~μeV) produced when the universe was hot and dense, that following gravitational interactions slowed down. They could have formed the halos that we «observe» in galaxies periphery.

Contrary to WIMPs the mass rage allowed is narrow.

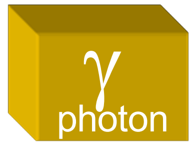
Axions detection tries to stimulate their conversion into photons via the interaction with a strong magnetic field.
To increase the interaction probability resonant cavities are used. The expected frequencies are in the micro-wave range.

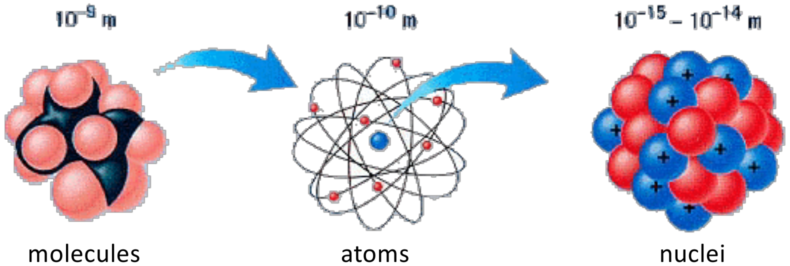


Up to know the reached value is ~ 650 MHz

Forces of Nature

force	*intensity*	*effect*
Gravitational	1	*Keeps you seated*
Weak	10^{29}	*Decays:* $n \rightarrow p + e^{-} + n$
Elettromagnetic	10^{40}	*Binds atoms*
Strong	10^{43}	*Binds nuclei*

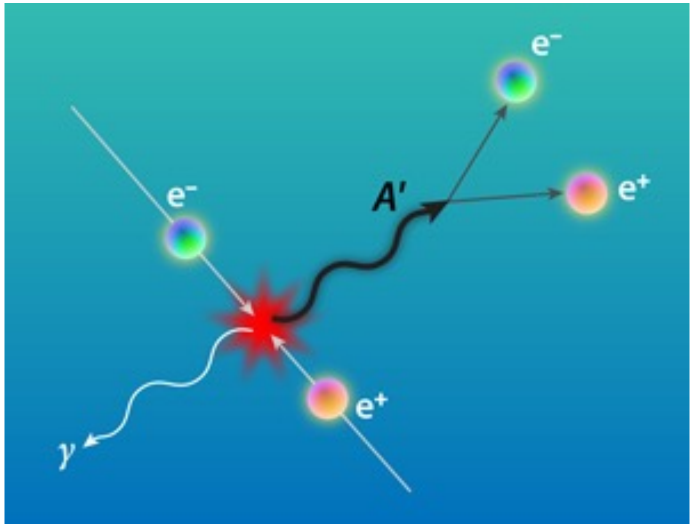


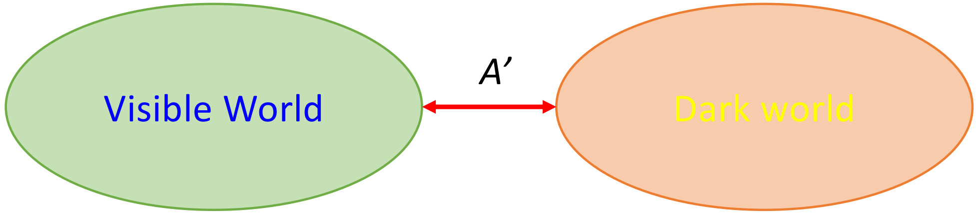


What about a new force?

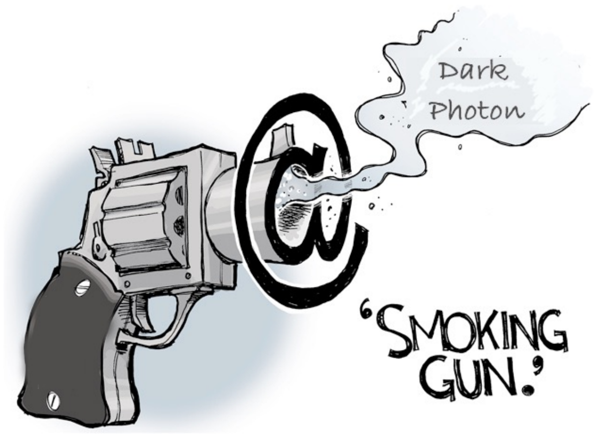
Some theorists made the hypothesis that a new **fifth force** could exist. This should be characterized by a new mediator usually labelled *A'*.

This **dark photon** could interact with those of SM and represent the contact point between our and the dark world.

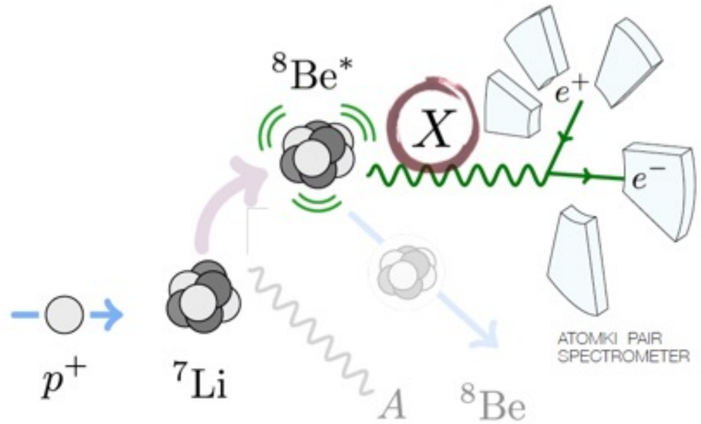


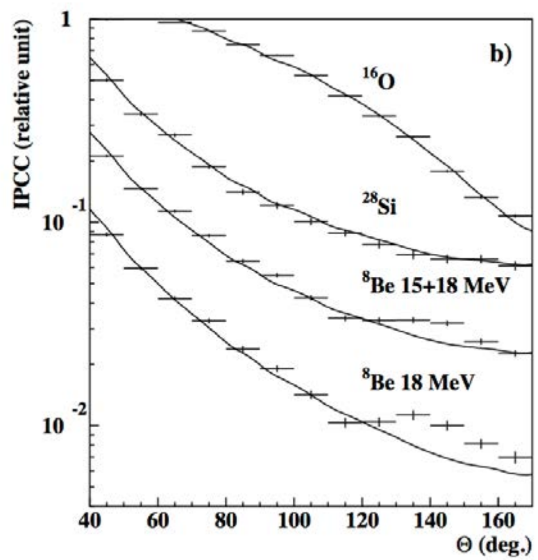


Other Phenomena

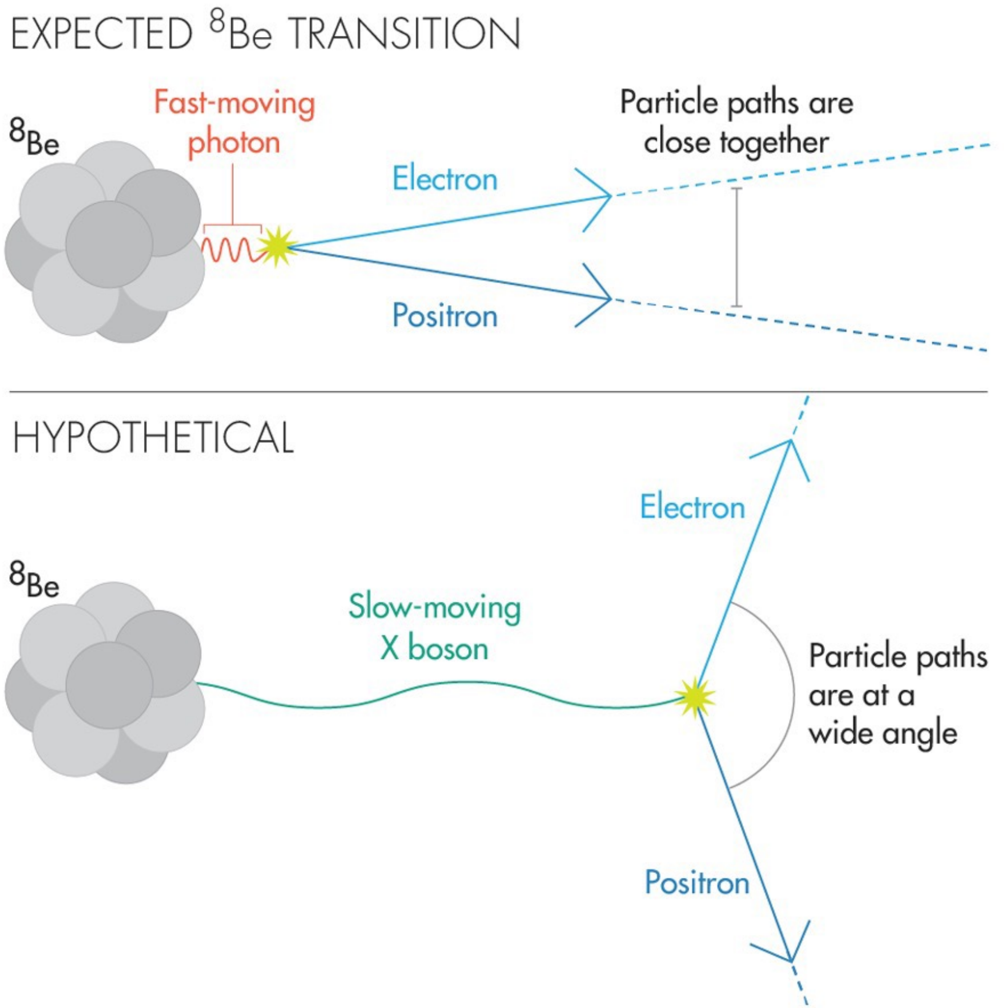


The idea of a **dark photon** would also allow to explain the anomalies in the positrons observations of AMS-2 experiment and the result of a recent nuclear physics experiment done in Hungary.



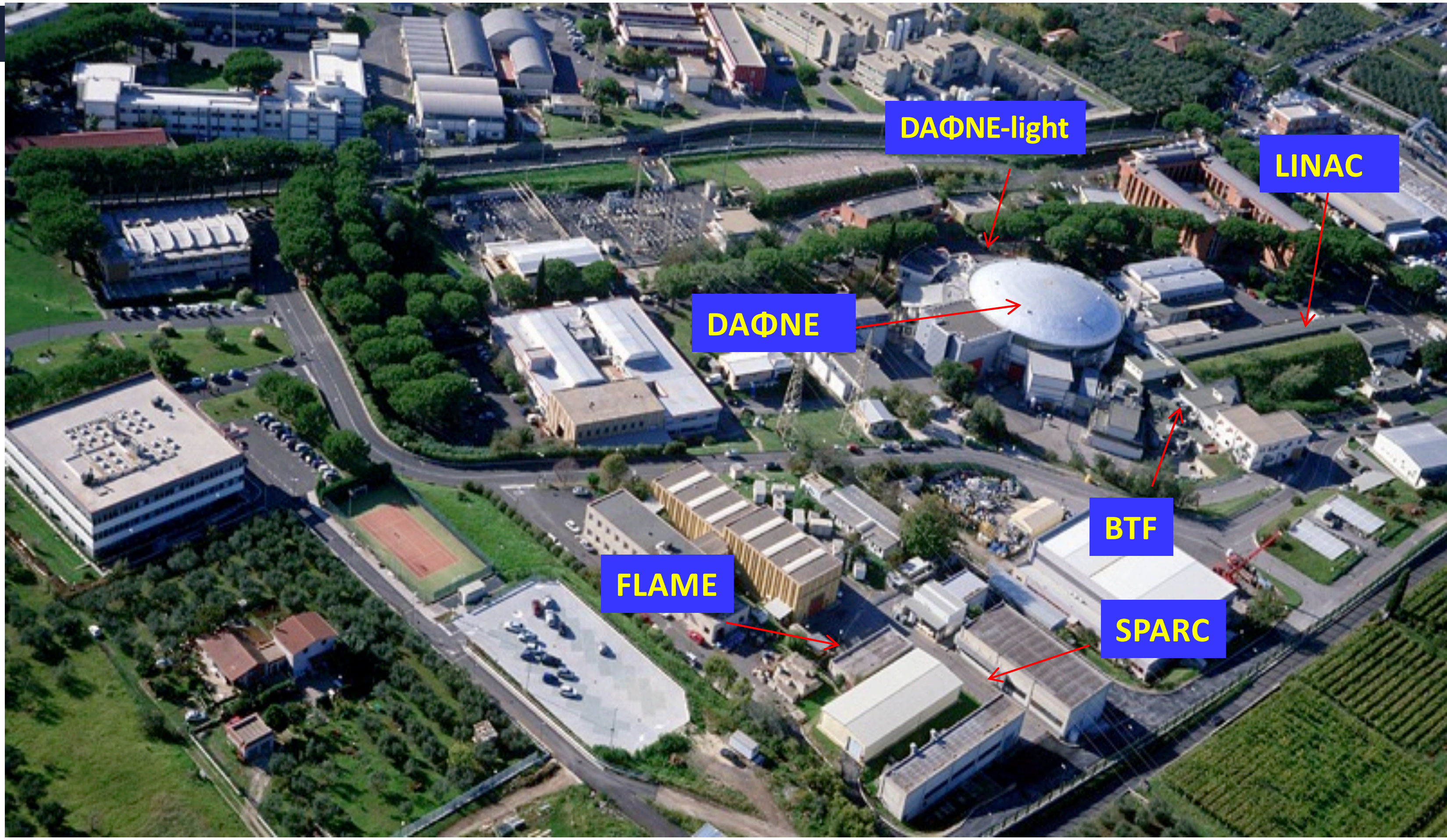


Researchers of Debrecen observed an anomaly in the de-excitation via electron-positron emission, of ^{8}Be, ^{4}He e ^{12}C nuclei. This anomaly shows the characteristics of a light **dark photon**.


EXPECTED 8Be TRANSITION
8Be
Fast-moving photon
Electron
Positron
Particle paths are close together
HYPOTHETICAL
8Be
Slow-moving X boson
Electron
Positron
Particle paths are at a wide angle

Dark Photon Hunting

Frascati National Laboratory of INFN



PADME experiment

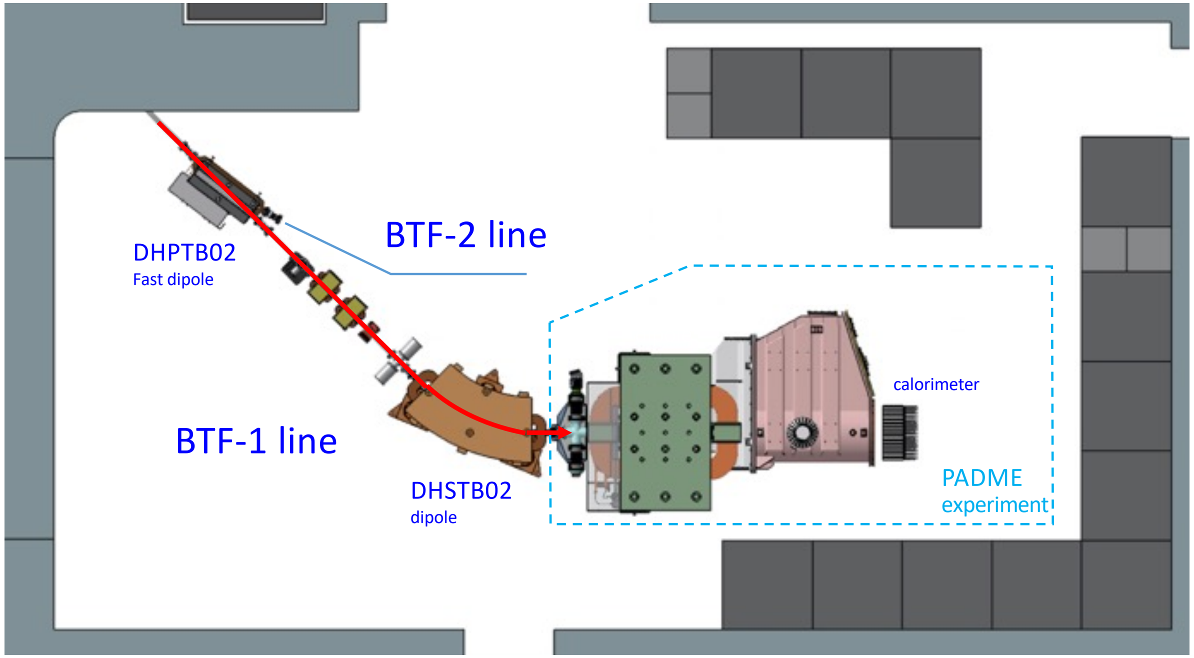
Positron **A**nnihilation into **D**ark **M**atter **E**xperiment, for friends PADME

The main goal of the experiment is to test the hypothesis that dark matter is secluded in a parallel world whose unique contact with ours is via gravitation and eventually a new force mediated by a **dark photon**.

The **dark photon** may hide among ordinary photons (we call this phenomenon «kinetic mixing») and only looking carefully we could try to detect it.

The low coupling might also explain why it has not been observed up to now.

PADME Technique



Positrons form LNF LINAC are accelerated up to an energy ~ 500 MeV and then fired on a thin diamond target (100 µm).

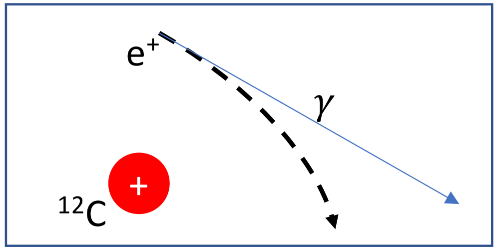
The true target are the electrons of Carbon atoms since the reaction expected is:

$$e^+ + e^- \rightarrow A' + \gamma$$

This must be searched for in the huge number of

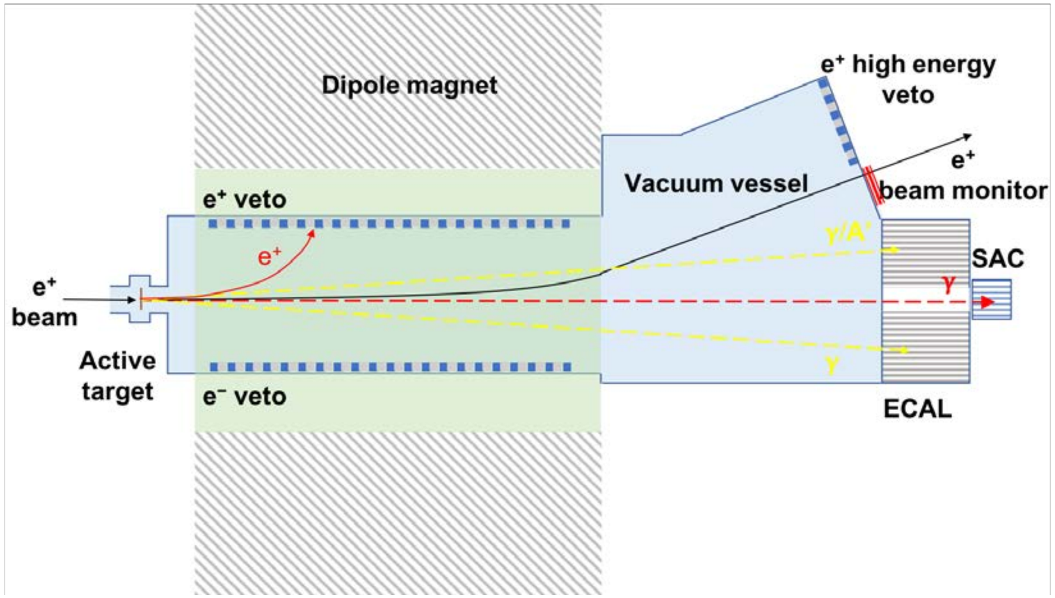
$$e^+ + e^- \rightarrow \gamma + \gamma$$

$$e^+ + {}^{12}C \rightarrow e^+ + {}^{12}C + \gamma$$



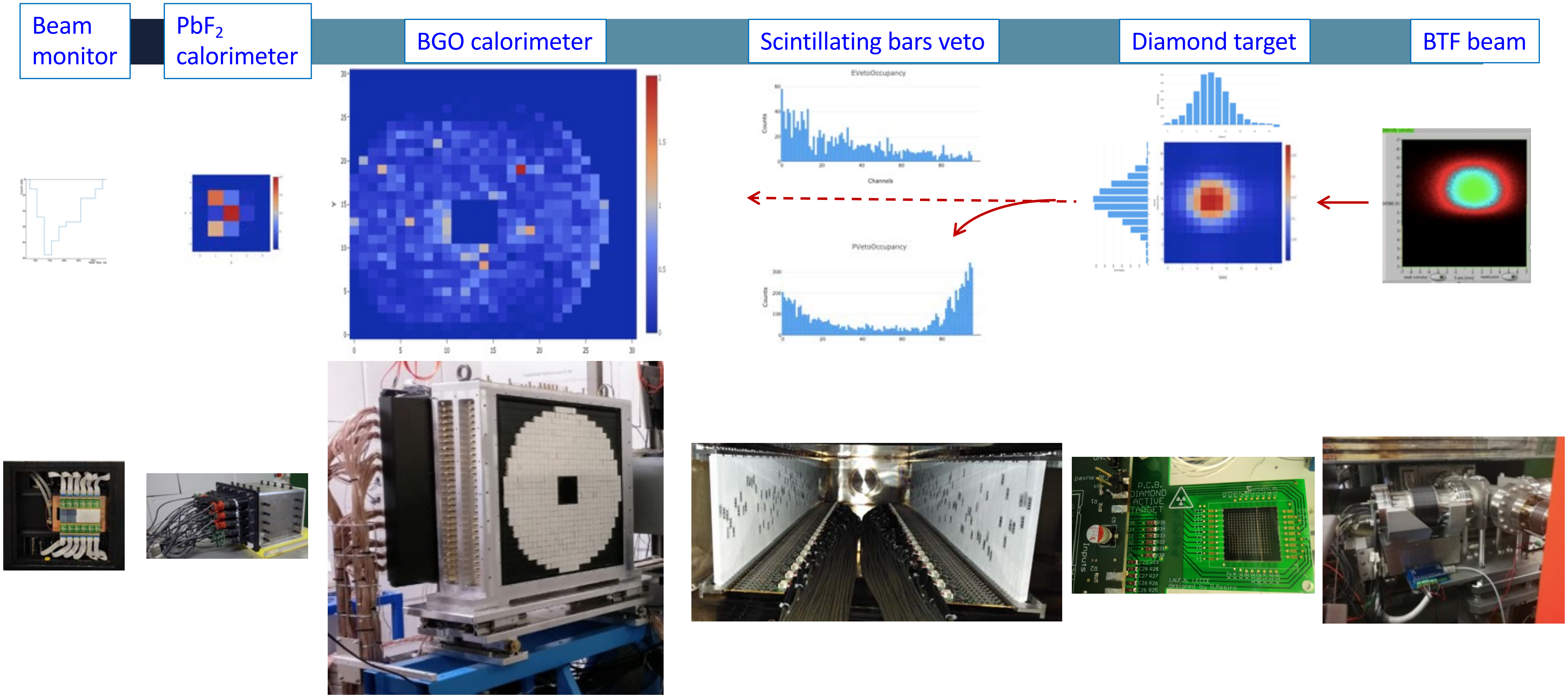
Bremsstrahlung

The experimental setup



$$\frac{\sigma(e^+e^- \to U\gamma)}{\sigma(e^+e^- \to \gamma\gamma)} = \frac{N(U\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(U\gamma)} = \epsilon^2 * \delta,$$

PADME Technique

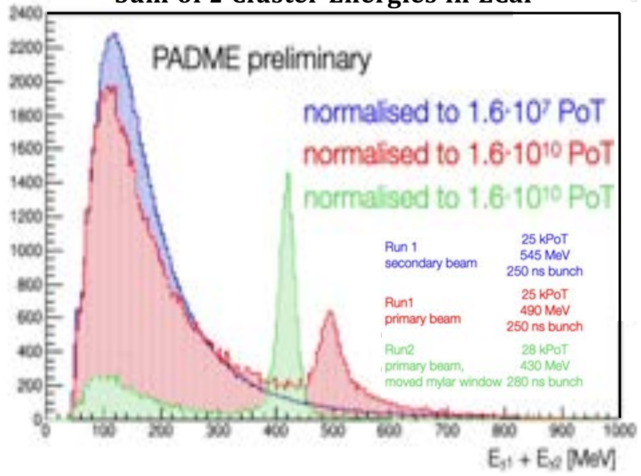


PADME status

PADME had up to now 3 data taking period:

- Run I (2019): detector calibration and beam line commissioning;
- Run II (2020): final tuning and first physics measurements;
- Run III (2022): with a slightly modified setup we performed an energy scan to confirm/disprove the particle nature of the Hungarian anomaly.

Sum of 2 Cluster Energies in ECal



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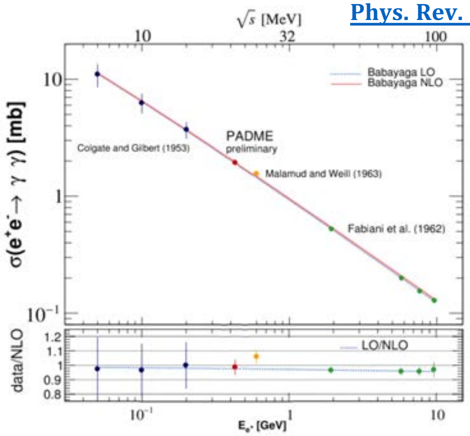

$\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)) = 1.930 \pm 0.029\,(stat) \pm 0.057\,(syst) \pm 0.020\,(target) \pm 0.079\,(lumi)\,mb$

QED @NLO $\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)) = 1.9573 \pm 0.0005\,(stat) \pm 0.0020\,(syst)\,mb$

Conclusions

- Since Ptolemy decreed that the Earth was the center of the Universe, our knowledge of the cosmos changed a lot.
- Copernicus, Kepler and Newton moved the center to the Sun, and in the centuries to come we understood that also this star is nothing special in the Universe.
- Today we know that our place in the Universe is nothing special. We are in the periphery of a galaxy that has nothing special compared to others.
- But the most surprising discovery is that we are made of a type of matter that is not even the dominant one.
- Since we don't know what the Universe is mainly made of, we are trying our best to datermine.
- The idea of a «Parallel World» made up of Dark Matter is undoubtedly fascinating and many experimental evidences lead us to believe in this hypothesis.