Dark matter in astrophysics: Direct detections and indirect measurements

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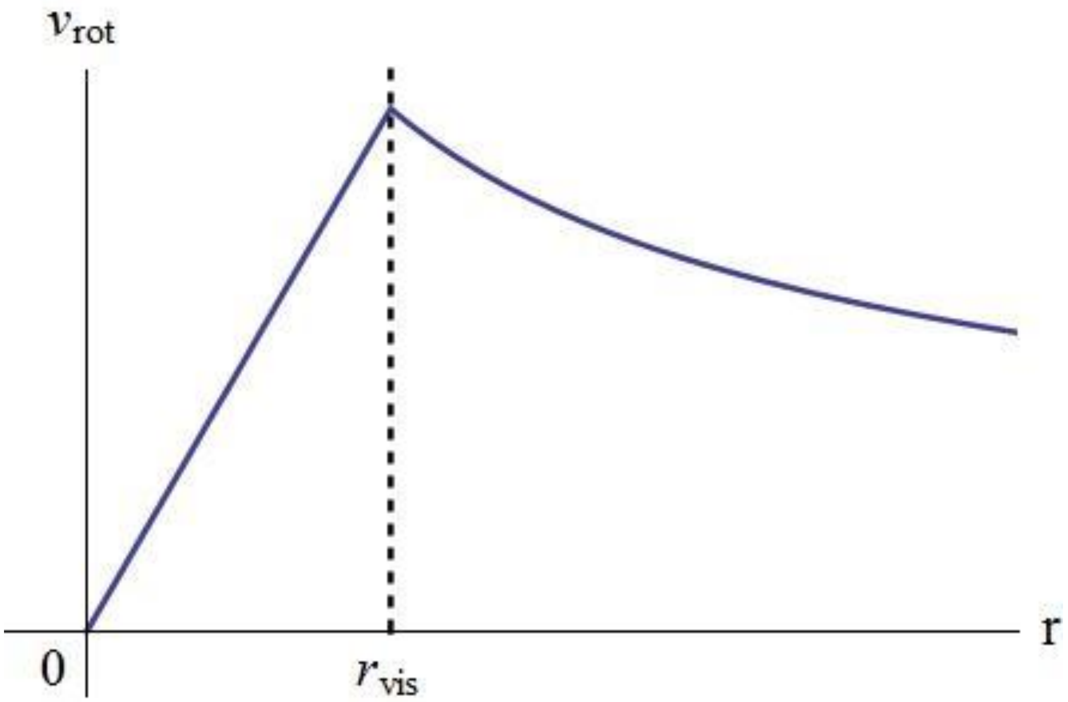
Dark matter in astrophysics: Direct detections and indirect measurements

Chapter 1: Indications for existence of dark matter

Chapter 2: Some dark matter candidates

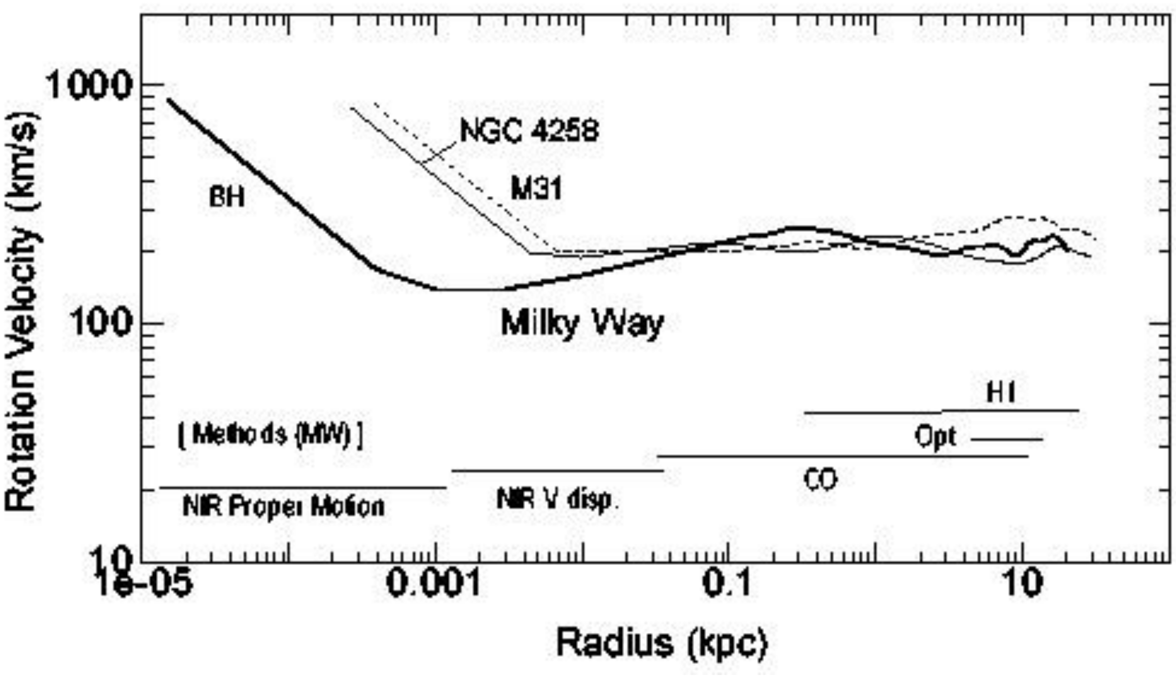
Chapter 3: Dark matter detection

Dark matter: Finding the invisible
Rotational speed of spiral galaxies



From classical mechanics, we would expect a rotational speed that increases linearly with r while we are in the galaxy, and that falls with r-1/2 as soon as we leave it.

Dark matter: Finding the invisible
Rotational speed of spiral galaxies



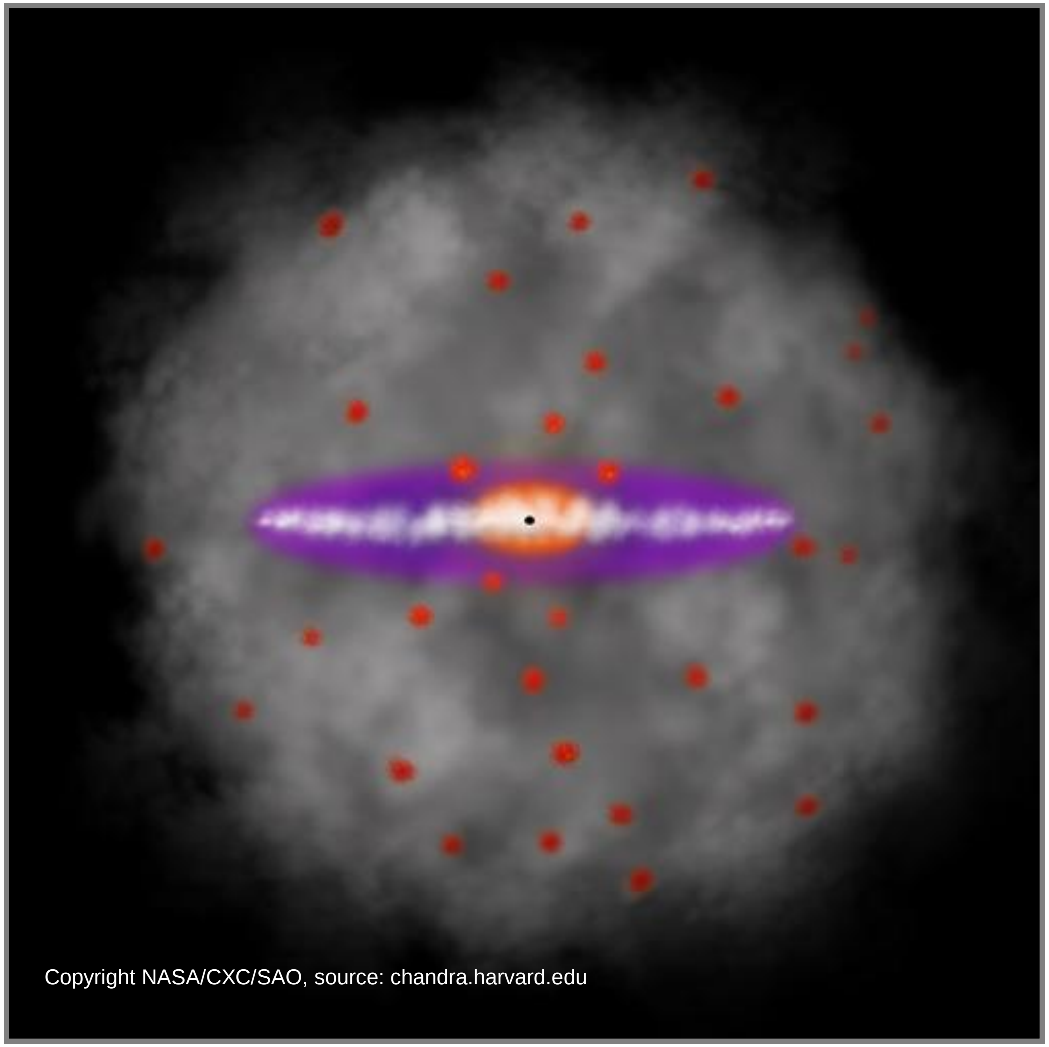
Rubin, Sofue: „Rotation speeds of spiral galaxies“, 2001

In 1975, pioneering physicist Vera Rubin first presented her studies of velocity curves that clearly do not follow the expectations derived from classical mechanics.

Dark matter: Finding the invisible
Astrophysical objects and luminosity

Object, type	M/L in M_{sun}/L_{sun}
Alpha Centauri, globular cluster	2
HGHH92-C11, dwarf galaxy	5.4
Galaxy cluster, average	100
Segue 1, dwarf galaxy satellite to milky way	>1000

Dark matter: Finding the invisible
The dark matter halo


Copyright NASA/CXC/SAO, source: chandra.harvard.edu

In order to explain these measurements, a spherical halo of dark matter was postulated.

The “dark” matter is called “dark” because it does nether absorb light nor radiate. We can only observe gravitational and weak interactions.

The stellar disk is about 100,000 light years in diameter. The dark halo extends to a diameter of at least 600,000 light years.

In our solar system, the local dark matter density is approx.

$\delta_{DM} \sim 0.5\ \mathrm{GeV/cm^3}$

if we assume a homogenous dark matter density.

Dark matter: Finding the invisible
The coma cluster

Optical image of the coma cluster, credit: Kitt Peak , source: chandra.harvard.edu

In his pioneering works, F. Zwicky already discovered signs of dark matter in the coma cluster in 1933.

He found that those galaxies move too quickly compared to expectations from Virial theorem:

$2<E_{kin}> + <E_{pot}> = 0$

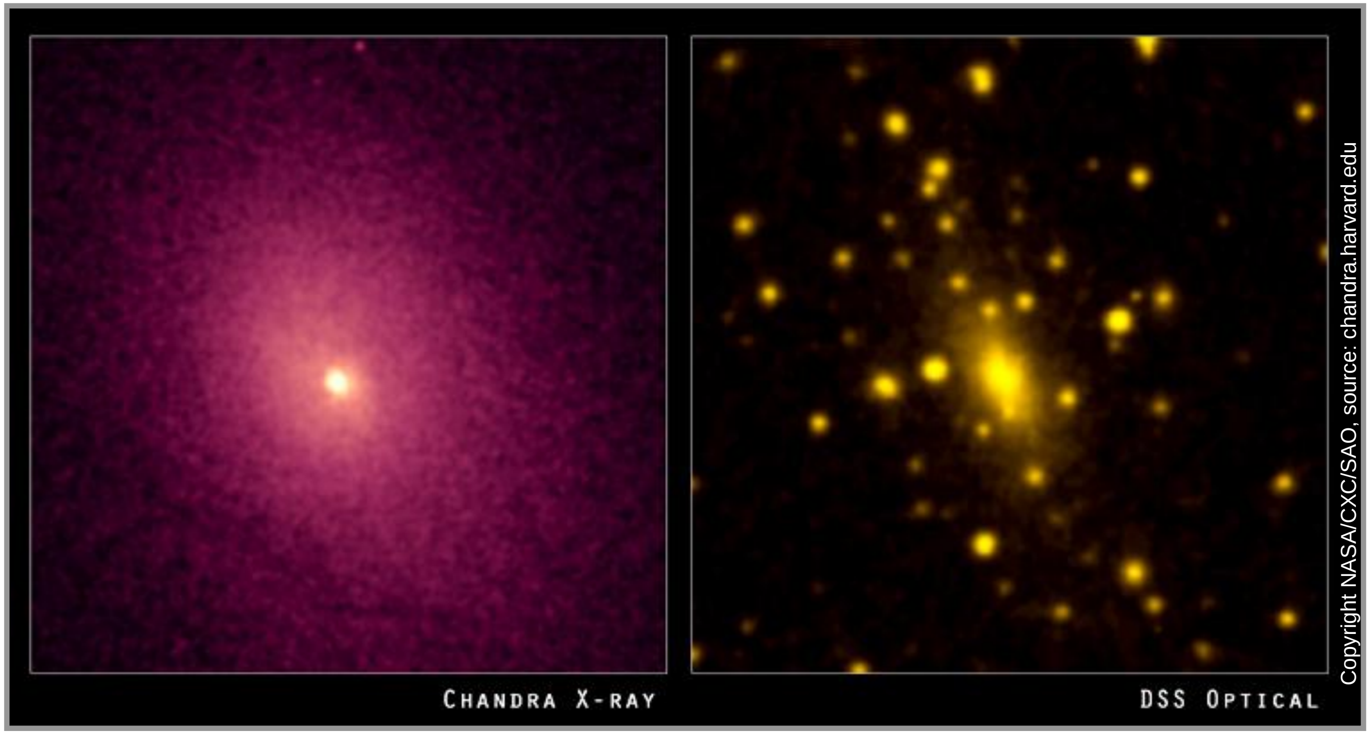
and observed that the mass was 160 times higher than expected from the objects' luminosity.

In fact, in order to explain his results,

$M/L \sim 400\ M_{sun}/ L_{sun}$

would have been necessary.

Dark matter: Finding the invisible
Clouds of hot gas



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Galaxy cluster Abell 2029, dark matter share: 70- 90%

The huge amounts of hot gas (Abell 2029: several million degrees) that can be found in galaxies and galaxy clusters were believed to solve the dark matter mystery.
In fact, they are a confirmation of its existence, as the gas can reach temperatures of several million degrees and would escape without the gravitational impact of dark matter.

Dark matter: Finding the invisible
The bullet cluster (1E 0657-56)

Copyright NASA/CXC/SAO, source: chandra.harvard.edu

X-ray signal: Pink
(Hot gas)

Optical: White/Orange

Lensing Map: Blue

The so-called „Bullet cluster“ which was formed when two galaxy clusters collided.

It is considered a direct proof of the existence of dark matter as the detected mass is clearly not identical with the gas or optical signal.

Dark matter: Finding the invisible
The CMB argument

Cosmic microwave background: electromagnetic “relict“ from the time before the formation of first atoms - approx. the first 300 000 years.

After that, atoms started to form and the universe was not opaque any more.

Today, this radiation can still be detected and gives us valuable information on what the universe looked like in the first stages of its existence.

What makes the cmb interesting for dark matter considerations is the fact that fluctuations of ordinary matter such as those that formed the first objects out of an uniform medium would have left remarkable signals in the cmb.

Dark matter, on the other hand, does not have this kind of coupling. Theories exist that claim that the first structures were in fact formed by dark matter particles and that the “ordinary” particles grouped among them.

In addition, the structure of today’s universe itself s considered a prove for the existence of dark matter.

Dark matter: Finding the invisible
Hot and cold dark matter

Dark matter would have to have a significant effect on the structure formation in the early universe. In a first approach, we differentiate between:

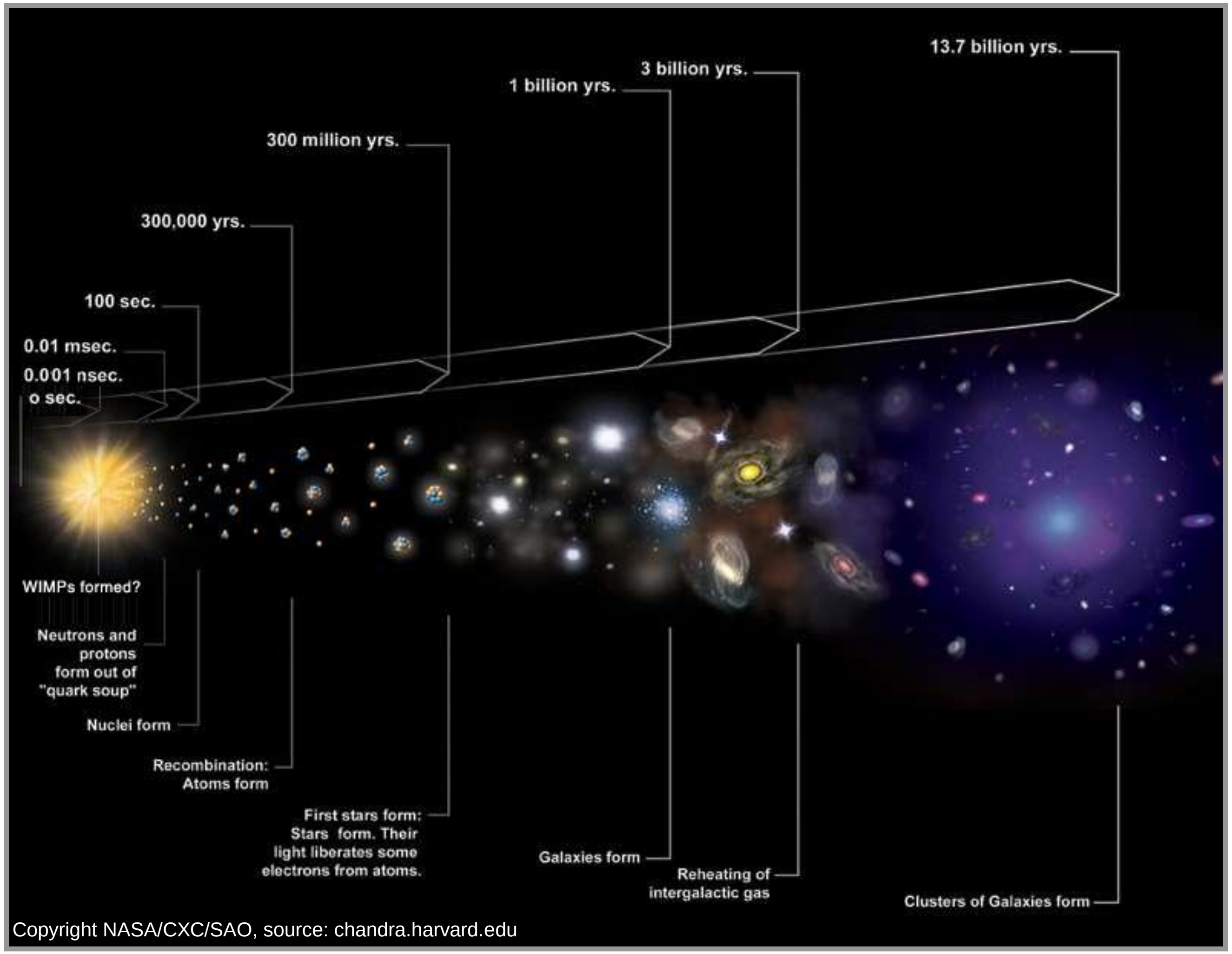
Hot dark matter (particles with relativistic kinetic energies)
Cold dark matter (non- relativistic energies)

Hot dark matter
The hot dark matter would have a strong effect on the instabilities that formed the first cosmological objects during the earliest phase of the universe’s existence: it suggests a top-down scenario, which means that galaxy clusters were formed before the galaxies and stars: instabilities of large scales collapse first ($\lambda_{Jeans} = v_s\, t_{FF} = vs \sqrt{}(3\pi/32G\delta)$ large)

Cold dark matter
The cold dark matter leads to a hierarchic structure formation (λ_{Jeans} small), which is compatible with most theories and measurements.

This arguments leads to the conclusion that only a small fraction of the dark matter is hot (approx. 15%).

Dark matter: Finding the invisible
Hot and cold dark matter- hierarchic structure formation



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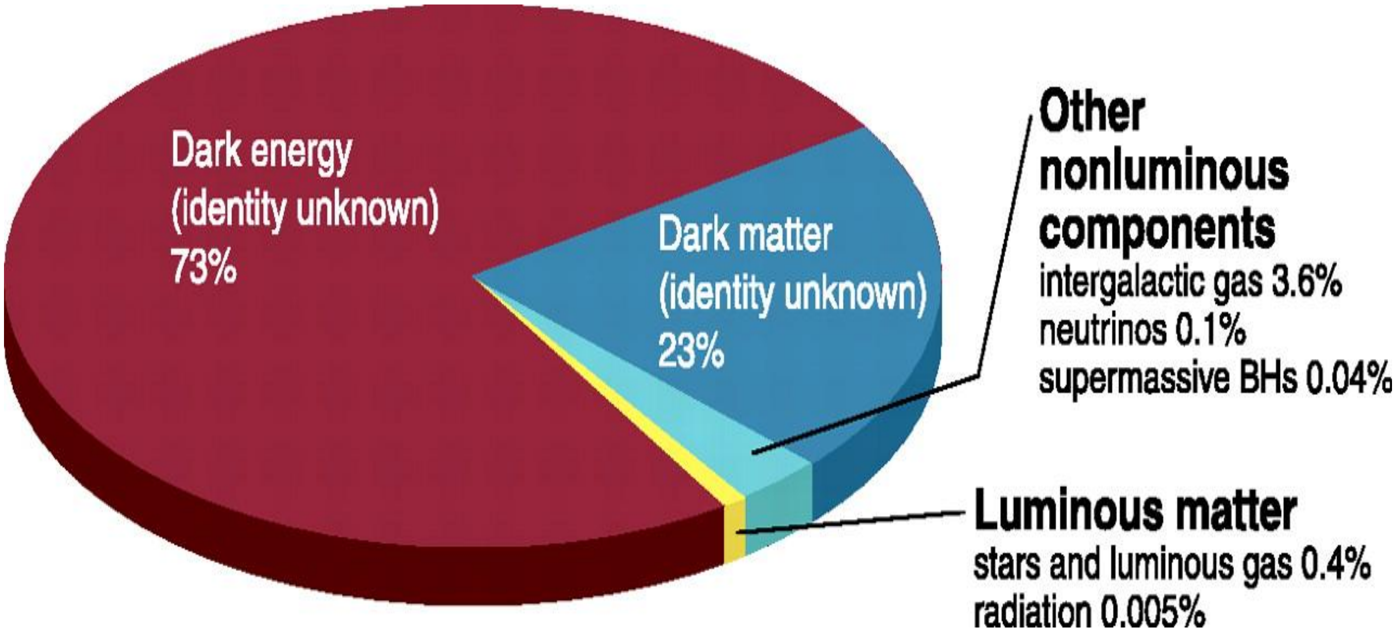
Energy distribution in today's universe



Source: Ostriker, Steinhardt: „New light on dark matter“, Science, 2003

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Alternative explanations

There have been several ideas how measurements such as those of the rotational speeds in spiral galaxies could be explained without introducing dark matter, the most popular ones being :

Alternative gravitational potentials at astrophysical scales

$GM/r \rightarrow GM/r + V(r/r_0)$

Modified Newton dynamics (MOND) theories

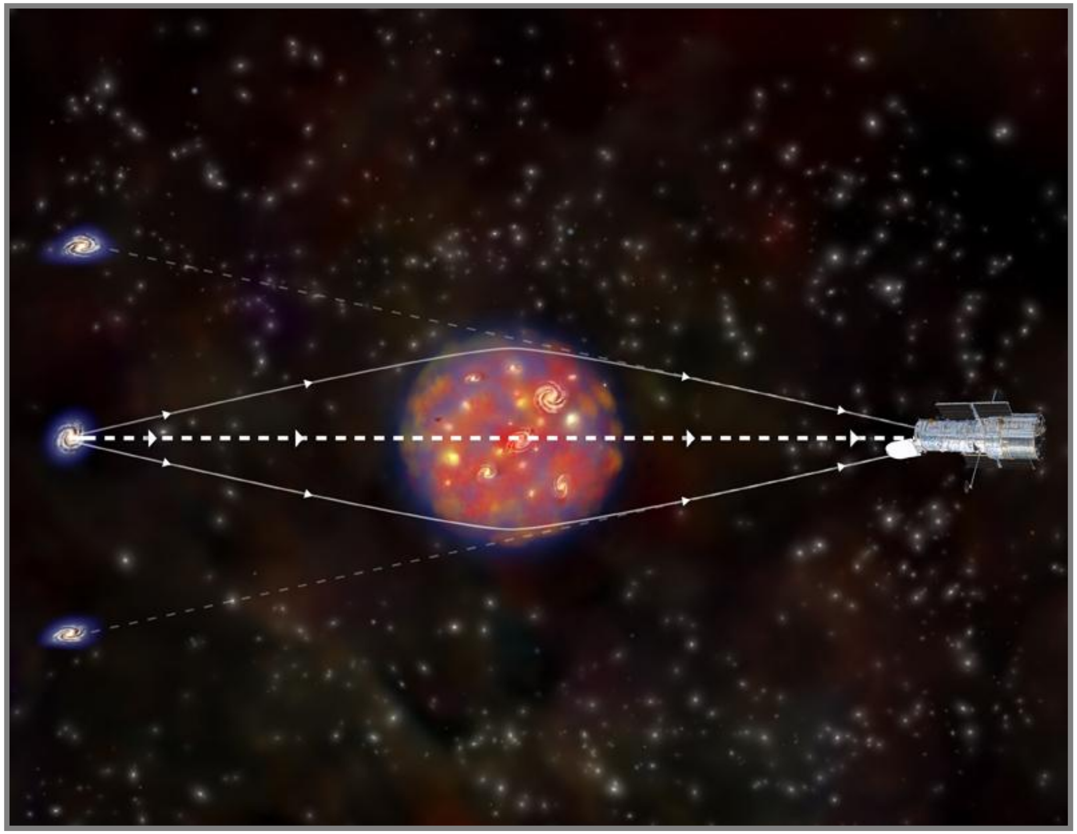
$\vec{F} = m\,\mu(a/a_0)\,\vec{a}$

Whereby a_o is supposed to be a new universal constant and $\mu(x) = 1$ if $x \gg 1$ and $\mu(x) = x$ if $x \ll 1$.

If MOND is applied on the gravitational potential inside a spiral galaxy, it does indeed deliver flat rotational curves.

Both theories do however introduce rather random scales, are difficult to combine with the general theory of relativity and do not explain effects such as the ones in the bullet cluster.

Baryonic dark matter



There are astrophysical objects contribute to the dark matter:

- Neutron stars
- Black holes
- Brown dwarfs

and others.

Several hundreds have been detected with gravitational lensing (called MACHOS = Massive astrophysical compact halo objects).
However, their mass is not sufficient to explain dark matter.

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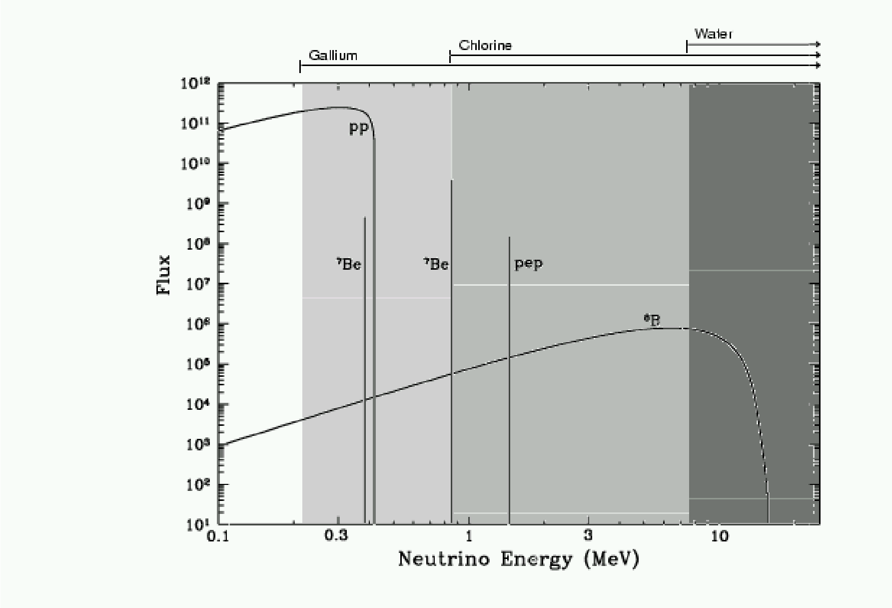
Non- baryonic dark matter
Neutrinos

Neutrinos are prominent dark matter candidates as they only interact weakly and have an extremely low mass (the exact value of the neutrinos’ mass has yet to be measured, but it is clear (neutrino oscillations) that it is not zero as predicted by the standard model.

There are many sources of Neutrinos in the universe, the one being easiest for us to observe is our sun. From the sun, we gain information about the Neutrino mass and flux at the earth’s position.



Non- baryonic dark matter
Neutrinos

Neutrinos can not fully explain the dark matter

-> Neutrinos are hot dark matter and can therefore not be responsible for the majority of the dark matter in our universe

-> The neutrino mass is so small (current experimental upper limits: $m_{ve} < 2.2$ eV) that it could not explain the gravitational effects dark matter is responsible for.

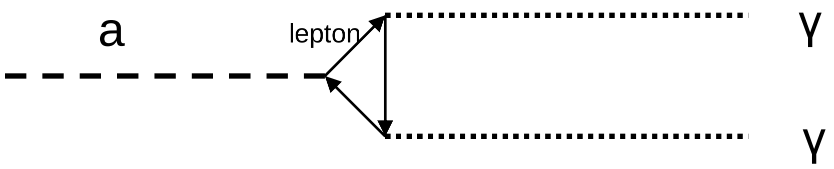
-> However, extremely high-energetic neutrinos are of interest for dark matter search as they are among the secondary particles created in the annihilation of other dark matter candidates.

Non- baryonic dark matter
The Axion

The axion is a Nambu- Goldstone boson that has been predicted theoretically (trying to “fix” the strong CP problem). It is supposed to have an extremely low mass (depending on the model, 10^{-6}… 1 eV)

Its properties are suitable for a dark matter candidate:
- No charge
- Weakly interacting
- Can be created in astrophysical objects with relative ease

Axions are supposed to be created from photons exposed to strong magnetic fields



Due to its unique theoretical nature, the axion is supposed to have been created in the big bang and still be part of the dark matter class.

Non- baryonic dark matter
The WIMPS

WIMP = Weakly interacting massive particle

This class contains a large amount of dark matter candidates which are not predicted by the standard model, such as:

- Supersymmetric particles- e.g. Neutralinos
- Kaluza- Klein particles
- and others

A property they have in common is that they are supposed to be heavy compared to the particles of the standard model (theoretical considerations as well as the fact that they have not yet been detected), interact via the weak interact and gravity only and are stable/ have a lifetime that is at least equal t the age f the universe.

This is why physicists hope to find them with experiments detecting collisions between nuclei and dark matter WIMPs.

Non- baryonic dark matter
The Neutralino

In supersymmetric theories, every „ordinary“ particle of the standard system has a supersymmetric partner whose spin differs by 1/2.

Comparable to the mass eigenvalues in the standard model, supersymmetric particles occur in linear combinations. The lightest possible combination (as an example, there are others) of the Bino B, the Wino W and the Higgsino s is called “the” Neutralino. m_X ~ GeV - TeV

Theories predict that the Neutralino might be a stable particle ($R = (-1)^{L + 3B + 2J}$)

Also, the Neutralino is supposed to be a Majorana particle- its own anti particle.

$$\boxed{X + X \rightarrow \gamma + \gamma}$$

With two X-Ray photons.

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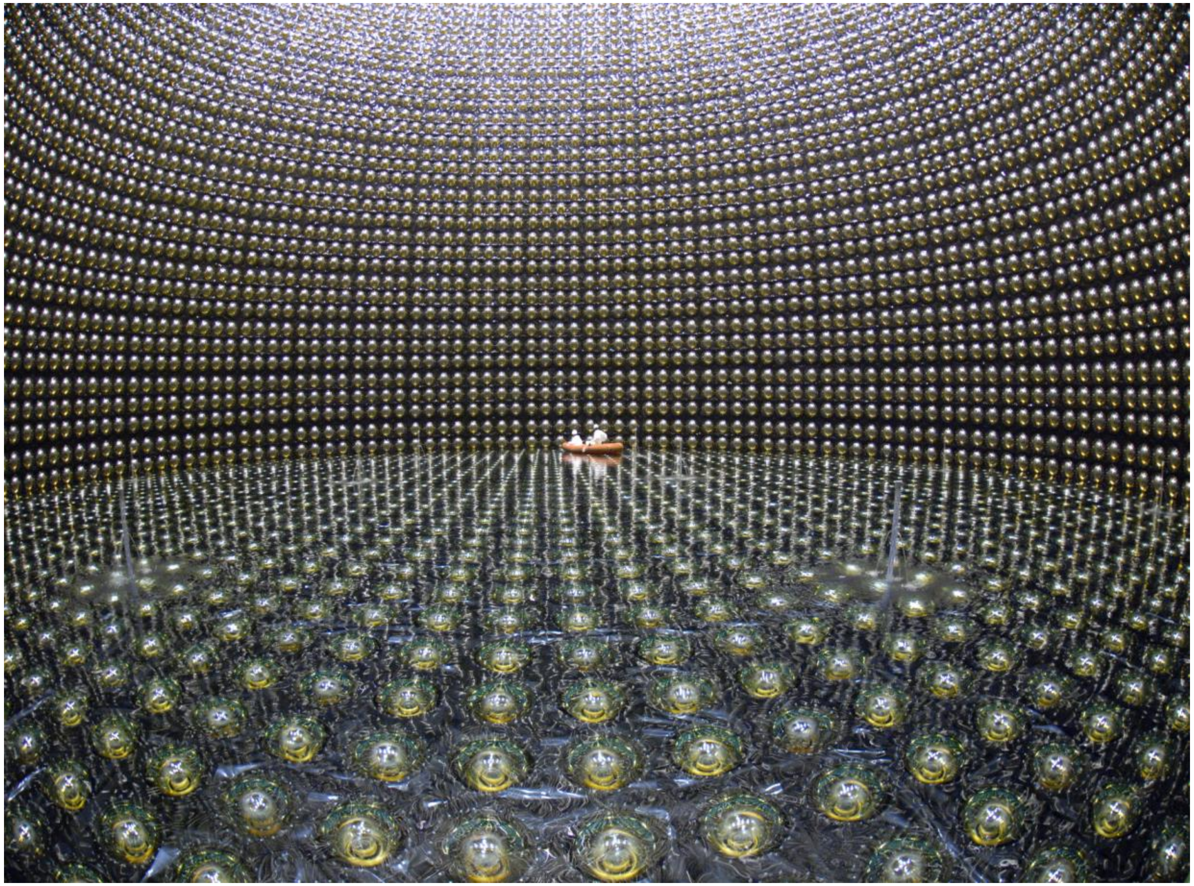
Non-baryonic dark matter
Neutrinos- Super Kamiokande



Source: http://www-sk.icrr.u-tokyo.ac.jp/sk Official Super Kamiokande Homepage

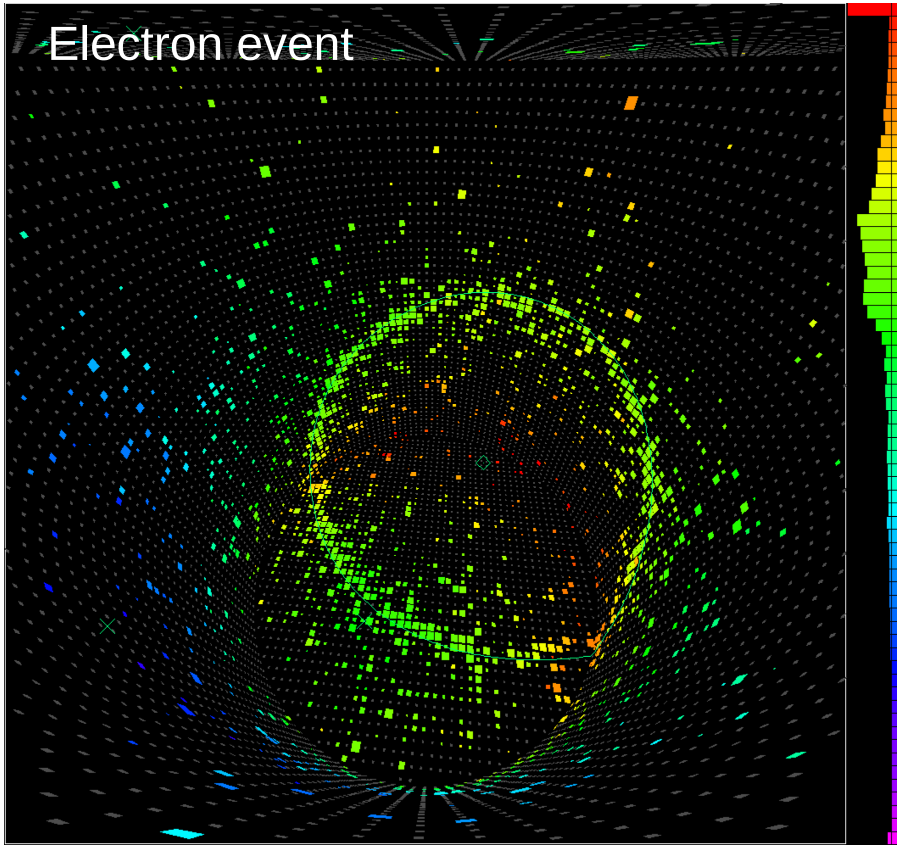
- Water Cerenkov detector
- Filled with 50 kilo tons of water
- The detection channel are:

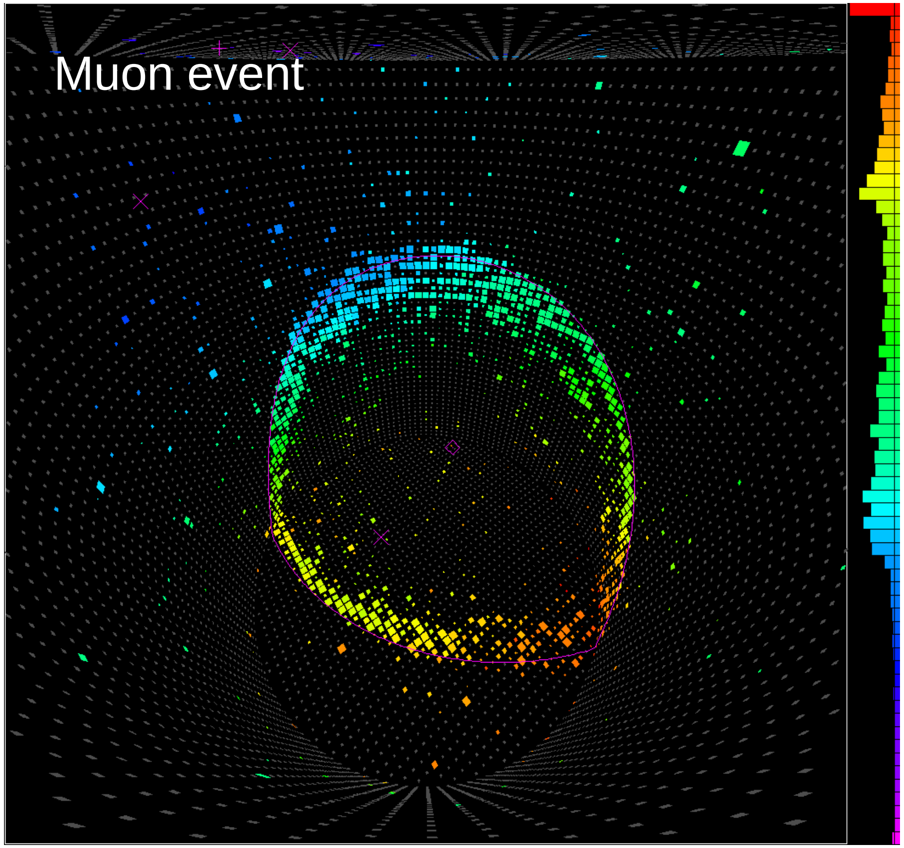
$$\boxed{e^- + v_i -> e^- + v_i}$$

$$\boxed{e^- + \overline{v}_e -> \mu^- + \overline{v}_\mu}$$

- 112000 photo multipliers
- Energy threshold of 5MeV (^{8}B Neutrinos)
- Detected Neutrino current: $\Phi = (2.35 \pm 0.08)\ 10^{-6}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Non- baryonic dark matter
Neutrinos- Super Kamiokande


Electron event


Muon event

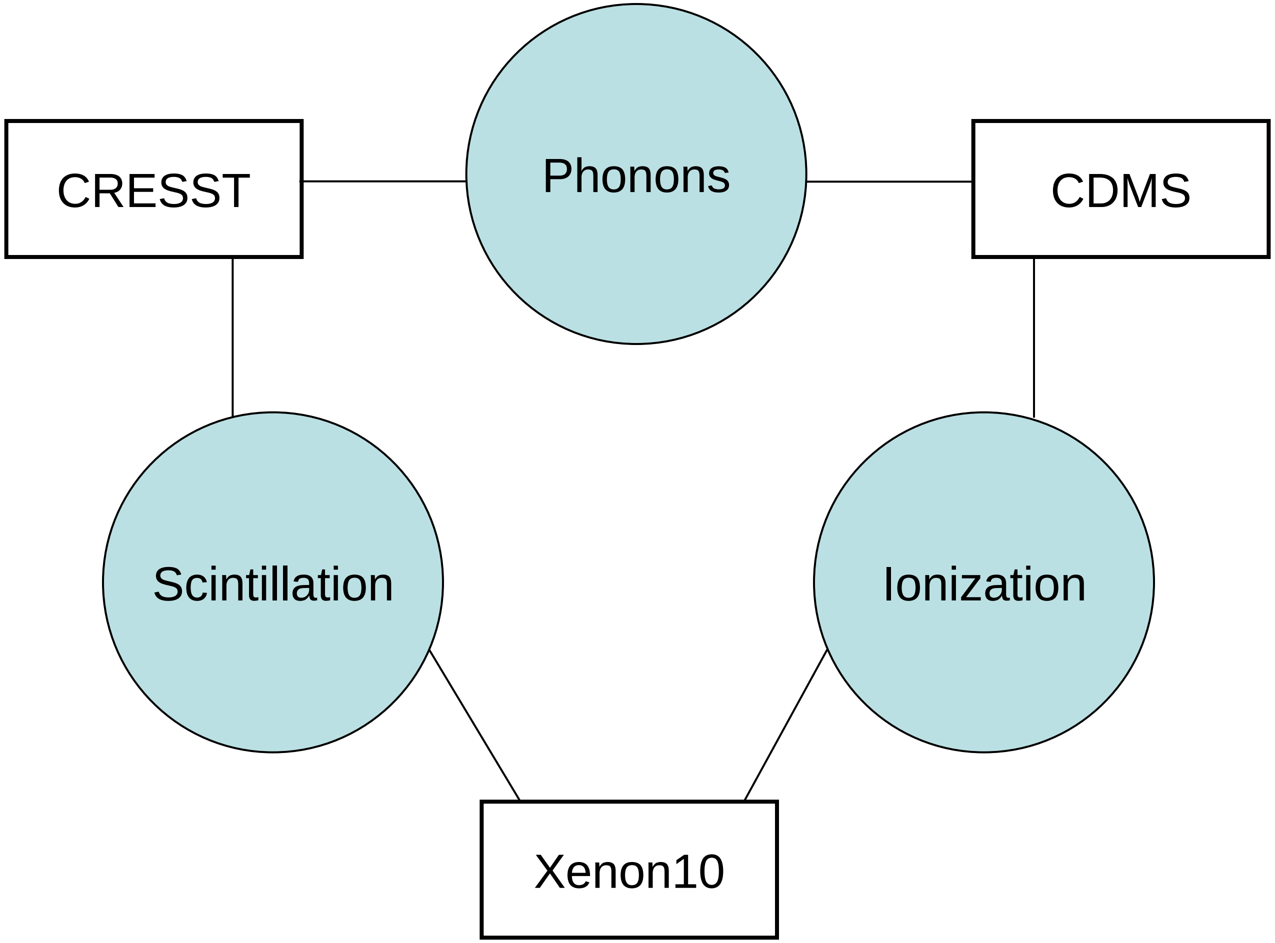
Source: http://www-sk.icrr.u-tokyo.ac.jp/sk Official Super Kamiokande Homepage

Non- baryonic dark matter
The Axion- CAST (CERN Axion Solar Telescope)

Source: http://www.cast.web.cern.ch Official CAST Homepage

So far, no axions have been detected ($m_a < 0.02$ eV)

Non- baryonic dark matter
The WIMPs



CRESST

Phonons

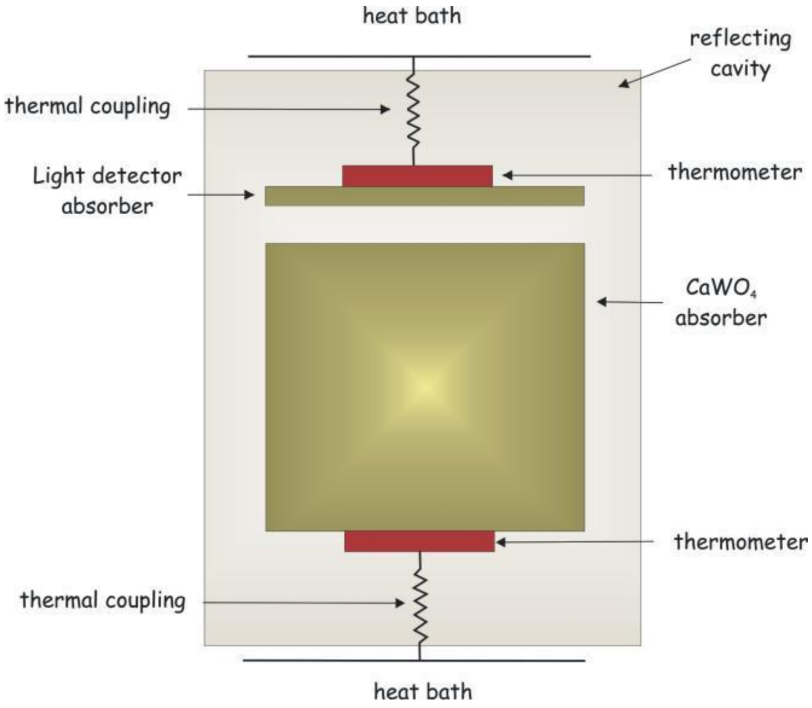
CDMS

Scintillation

Ionization

Xenon10

Non- baryonic dark matter
WIMP detection: CRESST



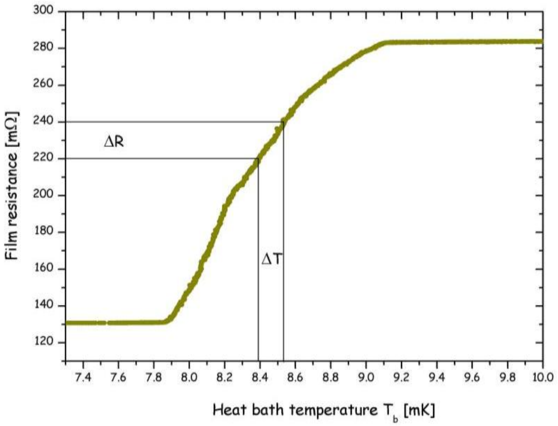
CRESST-II, source: http://www.cresst.de , official CRESST homepage

CRESST is a recoil experiment built in the Gran Sasso massiv, Italy.

Even if the WIMP masses are relatively high, the recoil energy from the elastic scattering which is measured in the form of phonons is extremely small:

~μK

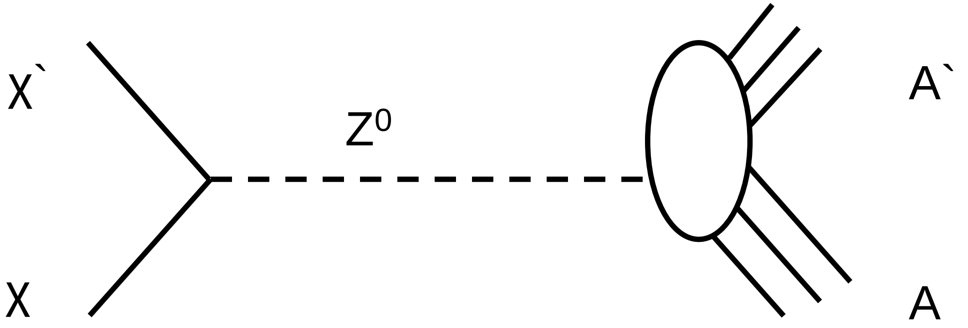
In order to detect this small change in temperature,
superconductors are used (T < 10mK).



Non- baryonic dark matter
WIMP detection: CRESST

In the CRESST experiment, three different elements are used within the detector (Ca, W, O) to improve the background recognition:

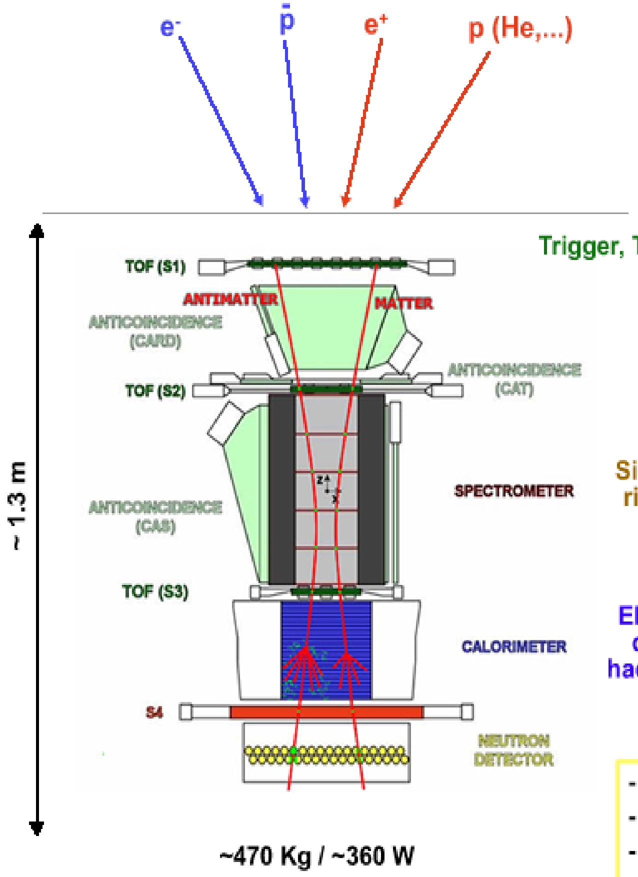
As the elastic scattering between WIMPs and nuclei is a coherent process, it will mainly take place on heavy nuclei (P proportional to $A^{2).}$



Neutrons on the other hand, are a background signal, mainly scatter on lighter nuclei.

Non- baryonic dark matter
The search for antimatter/ PAMELA

PAMELA = Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics



Trigger, ToF, dE/dx

- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

Sign of charge, rigidity, dE/dx

- Permanent magnet, 0.43 T
- 21.5 cm^2 sr
- 6 planes double-sided silicon strip detectors (300 µm)
- 3 µm resolution in bending view → MDR ~800 GV (6 plane) ~500 GV (5 plane)

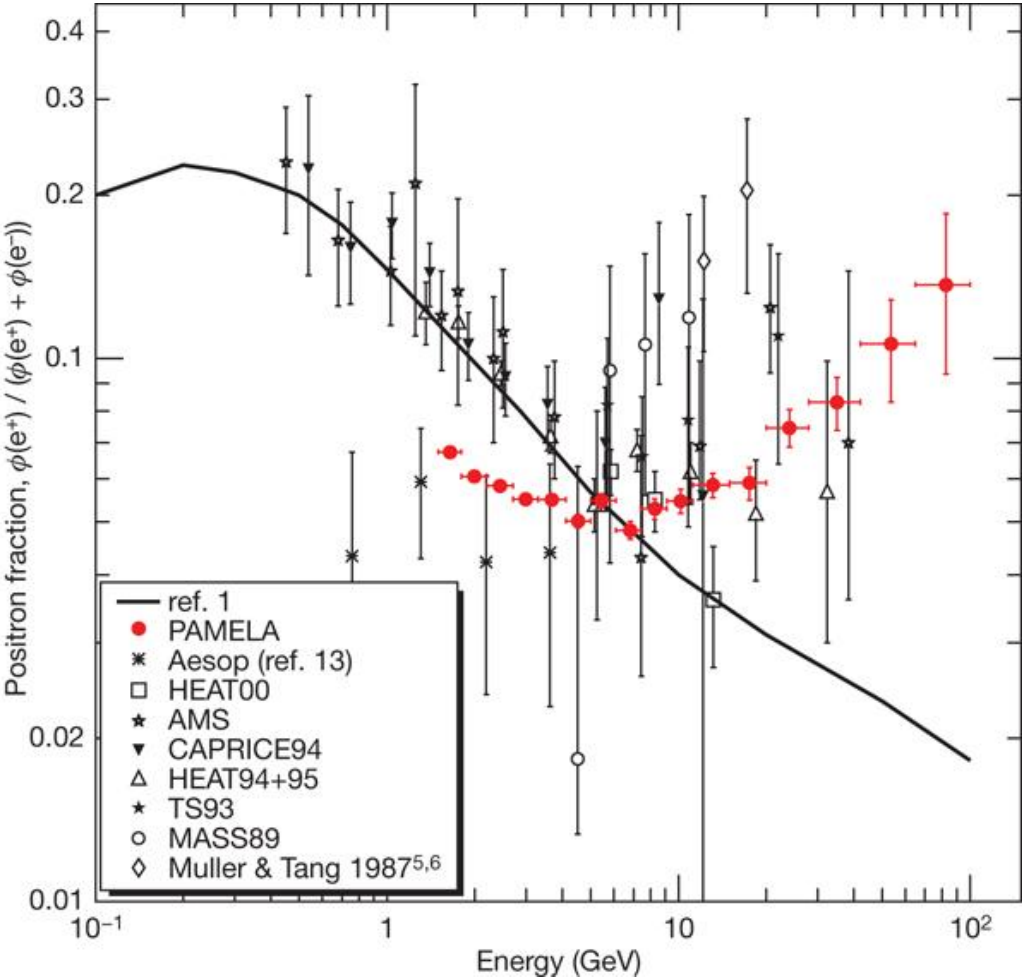
Electron energy, dE/dx, lepton-hadron separation

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm^2 sr

- 36 ^{3}He counters
- ^{3}He(n,p)T; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 µs collection

Source: http://pamela.roma2.infn.it – official PAMELA HP

Non- baryonic dark matter
PAMELA positron signal

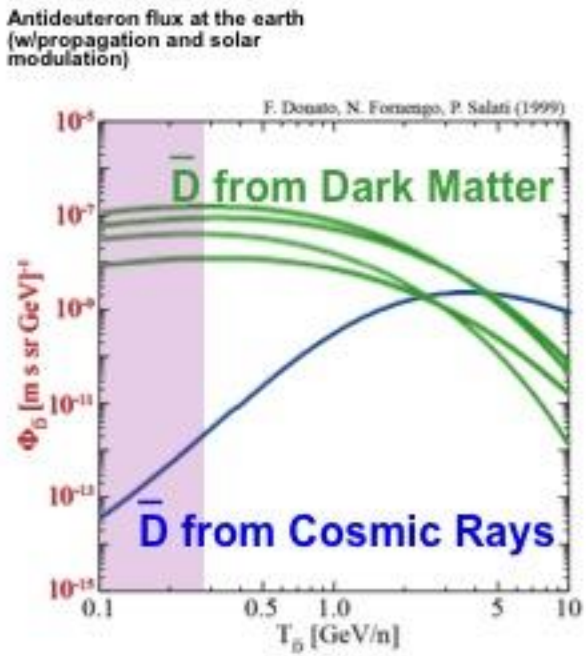


The solid line shows a calculation for pure secondary production of positrons during the propagation of cosmic rays in the Galaxy without reacceleration processes.

Source: „An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV“ O. Adriani et al

Non- baryonic dark matter
The search for antimatter/ GAPS

Antideuteron detection- the future of dark matter research?



GAPS = General antiparticle spectrometer

A balloon experiment that is supposed perform a prototype flight in 2009/2010.

While antiprotons from Neutralino- Neutralino annihilation are hard to separate from antiprotons in cosmic rays, the antideuterons are supposed to be differentiated more easily.

The antiparticles are detected with a time of flight system as well as the record of X-ray and pion signatures that are expected if the particle stops inside the traget. Si(Li) detectors are used:

Energy resolution: 2 keV
Timing: 50 ns

Source: http://pamela.roma2.infn.it – oficial PAMELA HP

Thank you very much for your attention!

Any questions?