An overview of Dark Matter theories and Zoom on the WIMP scenario

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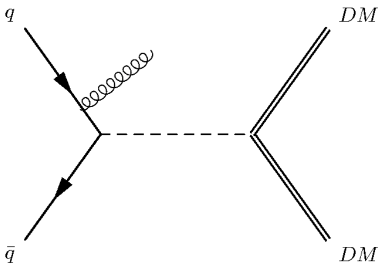


1. Evidence for Dark matter
    - Astrophysical evidence
    - Cosmological history : ΛCDM model
    - Dark Matter properties
2. The particle physics point of view
    - The Standard Model
    - Some Dark Matter condidates
    - The hunt for Dark Matter particles
3. The Supersymmetric WIMP
    - The Supersymmetric Standard Model
    - The WIMP Miracle
    - My thesis

Galactic rotation curves

Observation of star and gas (average) rotation speed in galaxies by Zwicky (1930s) then Rubin (1970s) and more.

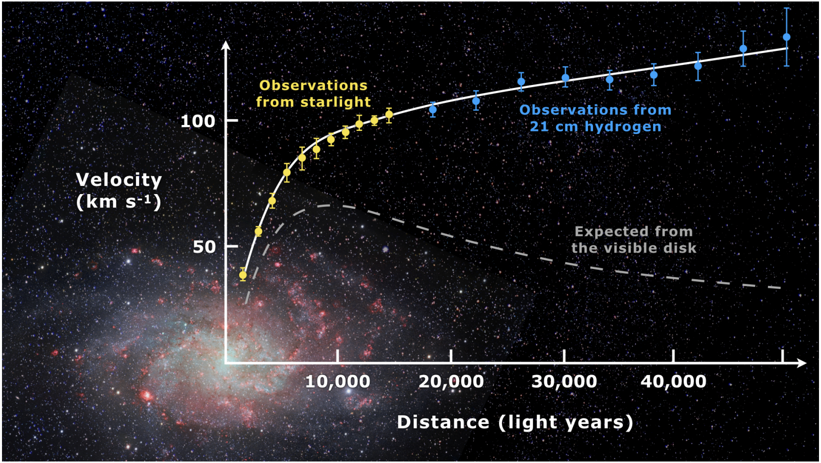
Virial theorem (from Newtonian gravity) states:

$$v(r)^2 \propto \frac{GM(r)}{r} \tag{1}$$

In spiral galaxies, the mass is mostly in the central bulge so we expect:

$$v(r) \propto \frac{1}{\sqrt{r}} \tag{2}$$

Galactic rotation curves



Galaxy M33, Wikipedia image from Corbelli, Salucci, 1999.

Galactic rotation curves

This velocity profile is observed in many more galaxies.
$v(r) \sim cst$ suggests a spherical halo of unseen matter with density

$$\rho(r) \propto \frac{1}{r^2} \tag{3}$$

much larger than the observed stars in the galaxy.

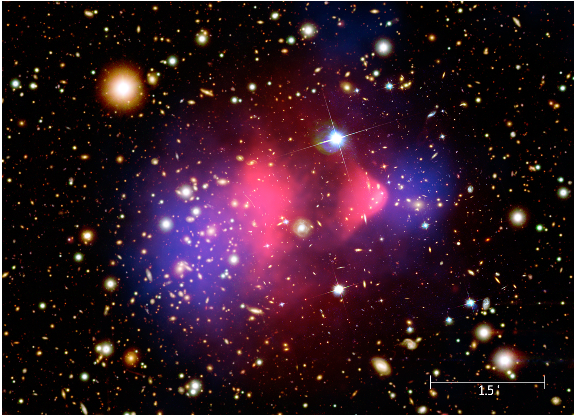
Gravitational lensing

Light propagation is bended by gravitational field (GR). This effect is known as gravitational lensing : used to estimate the mass of a foreground object by observing galaxies in the background.

This can be compared with X-ray observations (that show gas) or rotation curves.

There is a discrepancy of a factor 5 or so between visible matter mass and total mass.

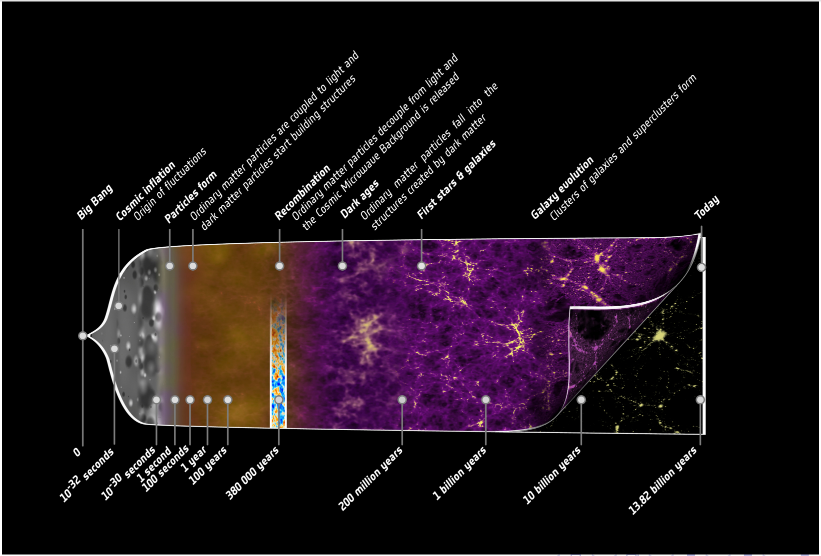
Gravitational lensing



Bullet cluster, composite image from NASA Chandra-X Ray Observatory. Pink : X-Ray image, blue : mass distribution from lensing.

The Big Bang Theory

The Big Bang Theory or ΛCDM model



Timeline of the ΛCDM model

1915 Einstein's theory of General relativity

1922-1927 Friedmann-Lemaitre cosmology

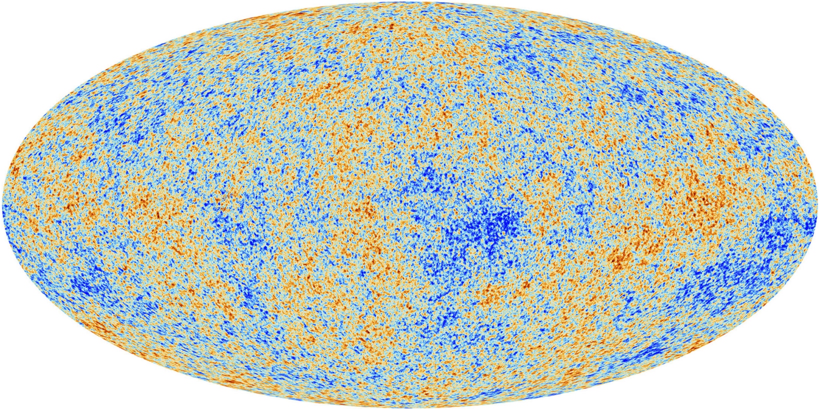
1929 Hubble : expansion of the universe

1965 Discovery of CMB radiation (Penzias and Wilson)

1967 ΛCDM predicts a correct Deuterium and Helium abundance (but lithium problem)

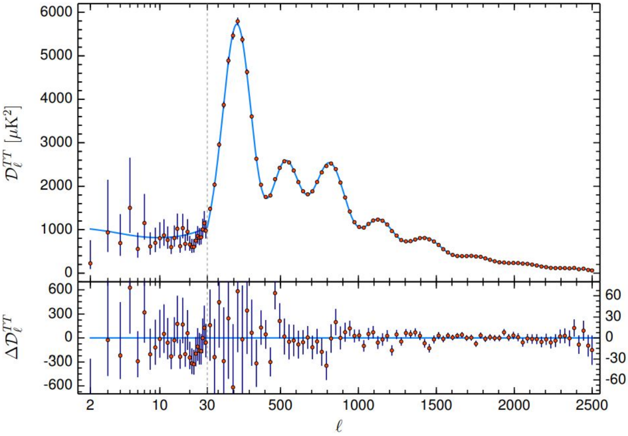
1998 The expansion of the universe is accelerating

The cosmic microwave background



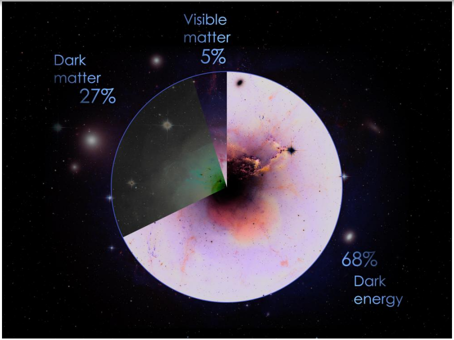
Seen by the Planck satellite (2013).

Planck measurements



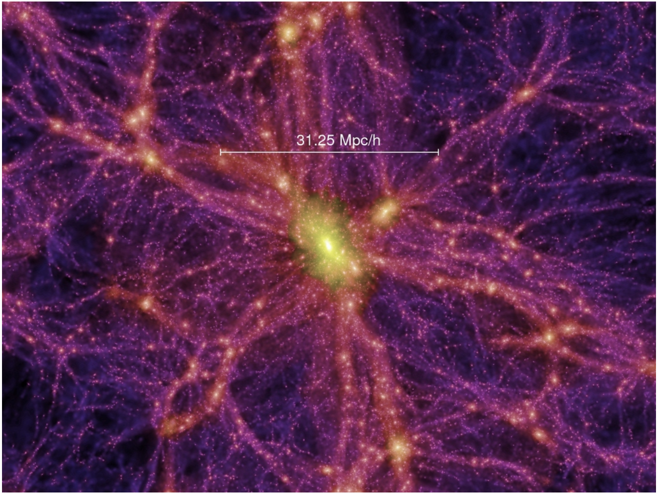
Planck collaboration fit of CMB temperature anisotropies power spectrum (2018) arXiv 1807.06209

Universe content



$$\begin{cases} \Omega_\Lambda = 0.6847 \pm 0.0073 \\ \Omega_{\mathrm{DM}} = 0.2644 \\ \Omega_b = 0.0493 \end{cases} \tag{4}$$

Computer simulations



From Max Planck institute, Millenium Simulation.

Dark Matter profile

Existence of a form of unknown matter with the following properties:

- Massive
- Dark, meaning EM neutral
- Stable on cosmological timescales
- Small self-interaction

Pros: solves the three kinds of observations presented before in one go. Con: what is dark matter?

Some DM candidates

- New unknown particle (the focus of this talk)
- Dark astrophysical objects : dead stars, lone planets, dust clouds...
  Disfavored by CMB data (from early universe).
- Primordial black holes
  Formed in the early universe, in sufficient quantities?

Modified gravity

Another active field of research is to modify the laws of gravity.

Advantages:

- GR is incompatible with particle physics, we know it is incomplete.
- No need to introduce some mysterious dark matter.

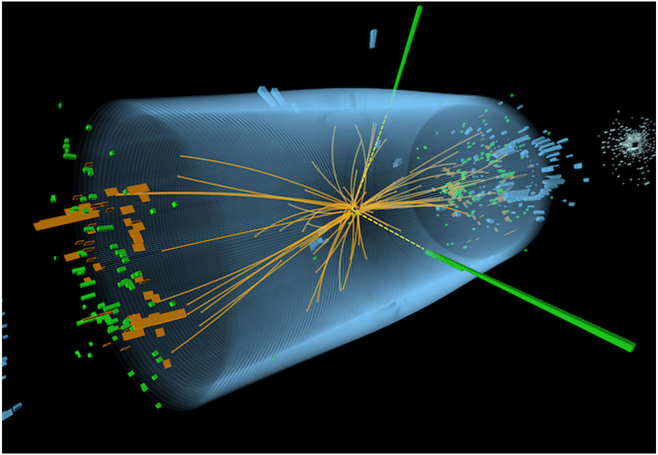
But:

- GR is experimentally very successful in Solar System observations: modifications for large scales only.
- Difficult to solve simultaneously CMB + rotation curves + lensing measurements .

Smashing particles together...

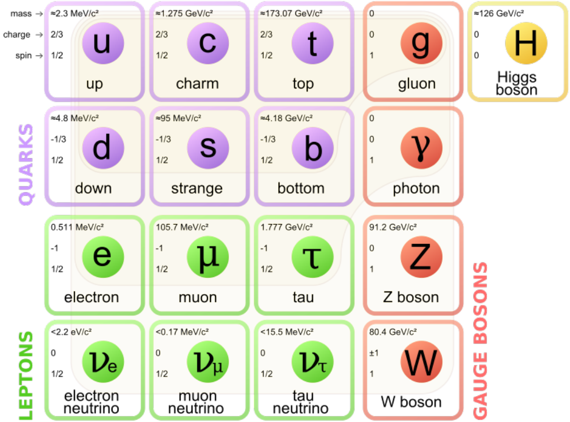
View of the CERN LHC (Switzerland)

... and looking at what comes out



An event seen by the CMS detector

The Standard Model particle content



Timeline of the Standard Model

1900s Beginning of quantum physics (Planck, Einstein)

1925 Schrodinger equation

1927 Dirac equation, positron discovered in 1932

1940s Beginning of quantum field theory (Feynman, Schwinger)

1960s Higgs mechanism, electroweak theory, theory of strong interactions

1973 Prediction of a 3rd generation of quarks, discovery of the bottom (1977) and top (1995)

1998 Neutrino oscillations

2012 Discovery of the Higgs boson at CERN

SM status

Successes of the SM:

- All particles have been discovered since 2012.
- A unified framework that explain (almost) all collider data at low and high energy.
- Precision tests (W mass at 10^{-4}, Z interactions at 10^{-3}...)

Shortcomings of the SM

- There is no Dark Matter candidate in the SM.
- Neutrino masses are absent.
- The Hierarchy Problem.
- Some puzzling discrepancies between measurements and theory: B-decays, muon magnetic moment, proton radius.

Panorama of particle DM models

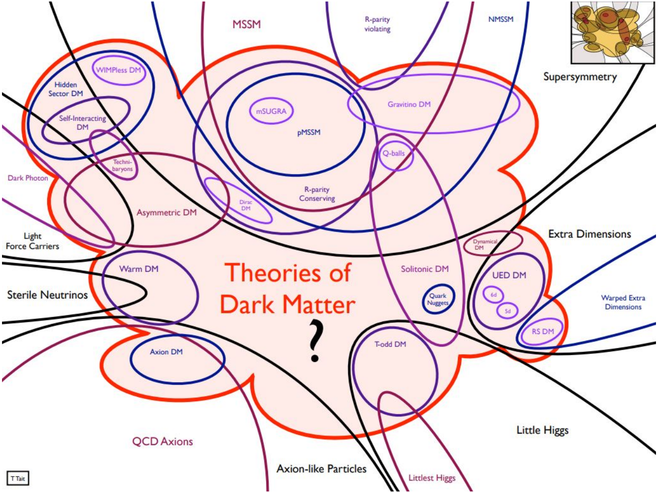


Figure by T. Tait.

Collider searches

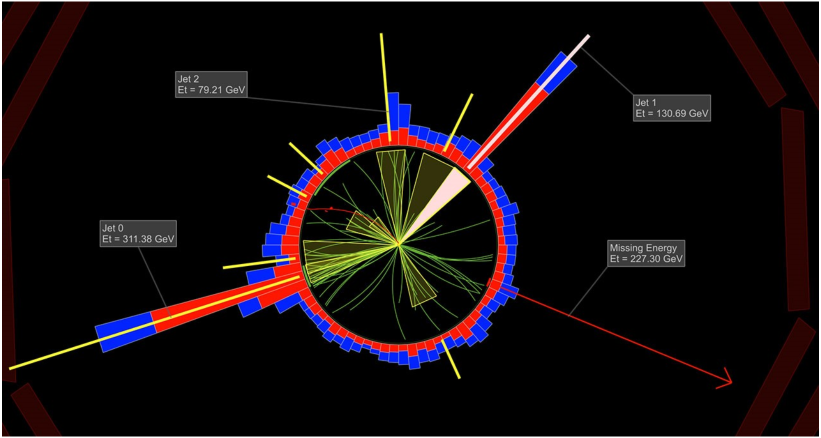
If DM particles (here noted χ) interact with SM particles, one can look for:

$$p + p \to \chi\chi + \text{visible stuff} \tag{5}$$

Possible DM signatures include:

- Missing p_T
- Kinks
- Displaced vertices

Collider searches



Simulated DM event seen by the CMS detector (from CERN website).

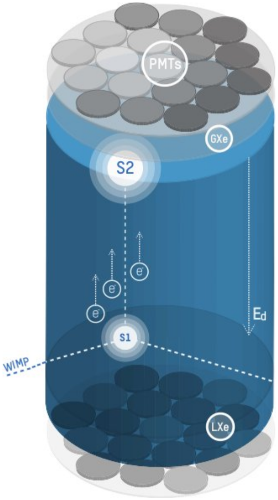
Direct detection

A DM particle from the DM halo surrounding the Earth can collide with an atomic nucleus:

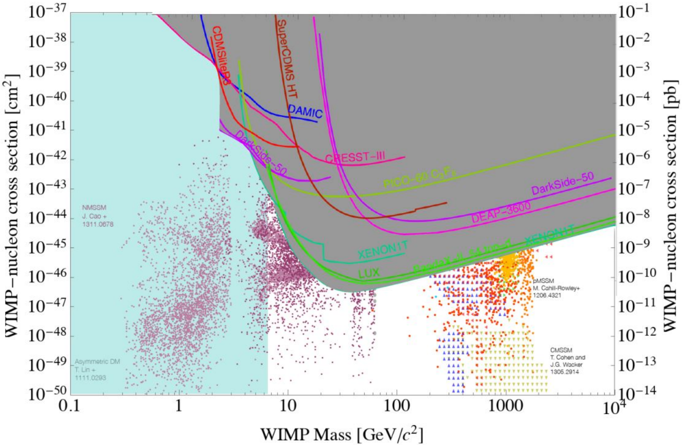
$$\chi + N \to \chi + N^* \tag{6}$$

Example: XENON 1T experiment conducted at Gran Sasso Laboratory (Italy), ended in 2019. It is a tank of liquid Xe surrounded by detectors and buried underground.

Direct detection



Direct detection



Limits from direct detection experiments (figure from Cooley, arXiv 2110.02359).

Indirect detection

DM particles from the galactic halo can annihilate to visible SM particles:

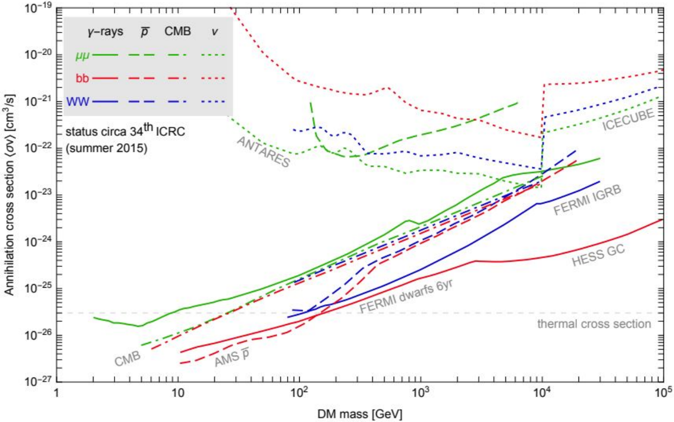
$$\chi + \chi \to \text{visible stuff} \tag{7}$$

By studying flux of particles from the sky, one can look for signals coming from DM.

- γ rays: HESS, CTA, FERMI,...
- Cosmic rays: PAMELA, AMS, AUGER,...
- neutrinos: Ice-Cube, Super-K, KM3-NET,...

But: it requires a very good understanding of astrophysical backgrounds.

Indirect detection



Limits from indirect detection experiments (figure from M. Cirelli ICRC 2015).

My model fits all the observations

Origin of the WIMP model

Supersymmetry was introduced in the 1980s to solve the Hierachy problem (lightness of the Higgs mass). SM extended with supersymmetry has several other attractive features:

- It has a DM candidate, named neutralino, a massive, neutral, stable particle with weak interactions.
- It can fit into a Grand Unification theory.

With drawbacks:

- It doubles the number of particles (new particles are roughly around the Higgs mass).
- The parameter space is very large (not very predictive).

The neutralino falls into the class of WIMP: *Weakly Interacting Massive Particle* where Weak refers to the SM weak interaction.

The Freeze-out Mechanism

After the big bang, the primordial universe is a hot soup of particles.

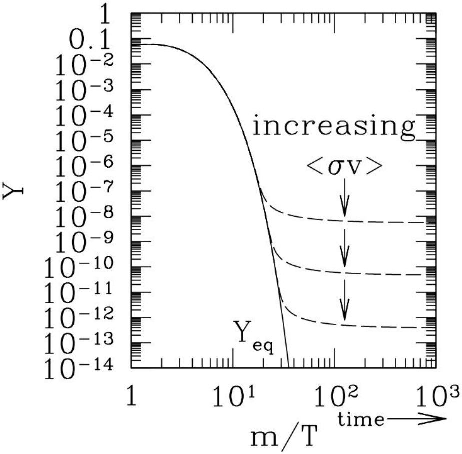
$$\chi + \chi \xleftrightarrow{\sigma} \mathrm{SM} + \mathrm{SM} \tag{8}$$

The density of DM n is given by thermodynamics:

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{\mathrm{eq}}^2 \right) \quad \text{with} \quad n_{\mathrm{eq}} \propto T^{\frac{3}{2}} e^{-\frac{m}{T}} \tag{9}$$

As the universe expands, temperature and density decreases. When $\langle \sigma v \rangle n^2 \ll 3Hn$: *Freeze-out* of n. Then, the DM density ("relic density" only dilutes in the universe expansion.

The Freeze-out Mechanism



Comoving density of DM as function of inverse temperature (figure from Gelmini, Gondolo, 1009.3690).

The WIMP Miracle

If χ interacts with the SM by the weak interaction, one can compute the annihilation cross-section σ. Then in order to reproduce the observed DM density, one finds:

$$m \sim 200\ \mathrm{GeV} \tag{10}$$

close to the Higgs mass (125 GeV). This suggests that DM and the Hierarchy Problem are linked and contributed to the popularity of Supersymmetry.

But with better measurements and more precise calculations:

$$m = 1100 \pm 50\ \mathrm{GeV} \tag{11}$$

in the Higgsino WIMP scenario. The model is still viable (passes collider searches, direct and indirect detection) but its link to the Hierarchy Problem starts being far-fetched.

Including Sommerfeld enhancement in the WIMP model

The DM χ comes with an unstable charged partner χ^+ of mass $m + \delta m$. The mass splitting δm is often neglected in studies but has an effect via Sommerfeld enhancement.

Does varying δm change the properties of the DM particle?

Answer:

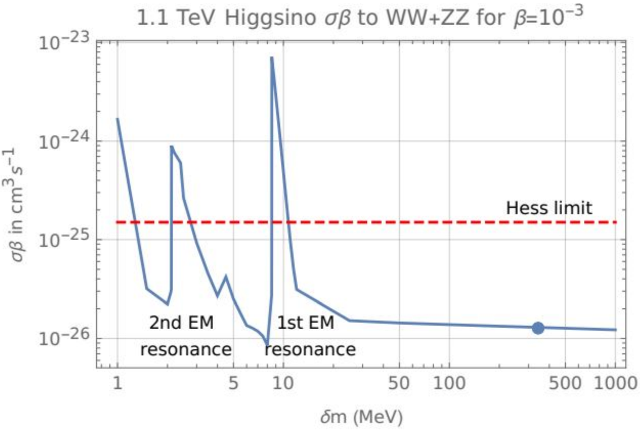
Including Sommerfeld enhancement in the WIMP model

The DM χ comes with an unstable charged partner χ^+ of mass $m + \delta m$. The mass splitting δm is often neglected in studies but has an effect via Sommerfeld enhancement.

Does varying δm change the properties of the DM particle?

Answer: not much, but indirect signals can be very boosted in specific cases.

Including Sommerfeld enhancement in the WIMP model



Indirect signal as function of δm. Note the resonance structures at low δm.

Conclusion

Thank you for your attention.