Particle Dark Matter

The problem of the Dark Matter in the Universe may be connected to the physics of CRs.
We will see in a while that hypothetical particles filling up the dark haloes of the Galaxy can constitute a source of PRIMARY CRs.

It is kind of exotic source, since it is based on the hypothesis that the haloes of the Galaxy, and of all the galaxies, is filled by massive particles.

Evidence for the existence of DARK MATTER in the Universe comes from a huge number of experiments performed from sub-galactic to cosmological scales.
All the many evidences are GRAVITATIONAL only.
The most robust results are from the CMB Temperature anisotropies, first by WMAP then by Planck experiments.

These data determine the composition of the Universe:

- Heavy Elements : 0.03 %
- Neutrinos : 0.3 %
- Stars : 0.5 %
- Free H and He : 4 %
- Dark Matter : 25 %
- Dark Energy : 70%

The most of the Universe is made of an unknown kind of matter, or anything with matter gravitational effects, and an even more mysterius dark energy, responsible for the accelerated expansion of the Universe.
Let's here concentrate on the DARK MATTER (DM) pb.
One of the most reliable solutions to the DM problems is the existence of a new (not in the Standard Model of particle physics) particles with some basic properties:

- stable on scales of the Universe $t \sim 10^{10}$ yr
- non baryonic ($\Omega_b h^2 \ll \Omega_m h^2$)
- neutral (or almost neutral)
- massive
- collisionless and weakly interacting with baryons

One major tool to understand the structure and evolution of the Universe is through cosmological SIMULATIONS.
The simulated cosmological structures can then be compared to the actual patterns of structures measured by different surveys. They indicate that, in order to observe the real structures (galaxy clusters, superclusters, ...) the DM must be COLD, i.e. non-relativistic at the time of decoupling from the primordial plasma.

We concentrate here on a generic class of particles that in principle can form the DM in the Universe:
Weakly Interacting Massive Particles (WIMPs).
WIMPs are DM candidates compatible with the cold DM (CDM) required by cosmological numerical simulations to form the haloes of DM surrounding galaxies and clusters of galaxies.

Using the laws of Thermodynamics of the early Universe, it is possible to find a solution for the relic density parameter:

$$\Omega_\chi h^2 \simeq 0.1 \frac{3 \cdot 10^{-26}\, cm^3\, s^{-1}}{\langle \sigma_{ann} v \rangle}.$$

$$\Omega = \frac{\rho_\chi}{\rho_{crit}}$$

$$\rho_{crit} = \frac{3 H_0^2}{8 \pi G} \simeq 10^{-29} \frac{g}{cm^3} \simeq$$

$$\simeq 1.3 \cdot 10^{11} \frac{M_\odot}{Mpc^3} \simeq$$

$$\simeq 5 \cdot 10^{-6} \frac{GeV/c^2}{cm^3} \simeq$$

$$\simeq \text{few} \frac{\text{H atoms}}{m^3}$$

If $\langle \sigma_{ann} v \rangle \simeq 3 \cdot 10^{-26}\, cm^3/s$, $\Omega_\chi h^2 \simeq 0.1$ which is right the value observed by WMAP and Planck.

$$\sigma_{ann} \approx 3 \cdot 10^{-26} \frac{cm^3/s}{10^{-3}\, c} \approx 3 \cdot 10^{-26} \frac{cm^3/s}{3 \cdot 10^{10} \cdot 10^{-3}\, cm/s} \simeq$$

$$\approx 10^{-26-7}\, cm^2 = 10^{-33}\, cm^2 = \text{nbarn}$$

which is the typical size of a weak cross section

⇒ figure e+e− cross section

The dark matter distribution

The ΛCDM (Λ is the cosmological constant, a solution to the dark energy problem) cosmology predicts the existence of DM haloes, from sub-galactic to extra-galactic scales. Numerical collisionless N-body simulations follow the hierarchical structure formation and provide predictions for the DM distribution within virialized haloes. Simulations suggest the existence of a universal DM spatial density profile, $\rho(r)$.
$\rho(r)$ can be generically parametrized as (for the MW):

$$\rho(r) = \rho_\odot \left(\frac{r_\odot}{r}\right)\left[\frac{1+(r_\odot/r_s)^\alpha}{1+(r/r_s)^\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}$$

$r_\odot \simeq 8.5$ kpc is the distance of the Sun from the GC;
$\rho_\odot \simeq 0.4\ \mathrm{GeV/cm^3}$ is the local DM density
r_s is the typical scale length of a halo
$(\alpha, \beta, \gamma) = (1,3,1)$ for Navarro-Frenk-White profile, which is divergent as $r \to 0$;
$= (2,2,0)$ for a cored pseudo-isothermal profile.

The $\rho(r)$ here is for spherically symmetric haloes.

Some valuable simulation suggest an Einasto profile:

$$\rho(r) = \rho_{-2} \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right]\right\}$$

r_{-2} is a radius : $\gamma(r_{-2}) \equiv \left[-d \ln \rho(r) / d \ln(r)\right]_{r_{-2}} = -2$

$\rho_{-2} = \rho(r_{-2})$

α is fitted to simulation data, $\alpha \sim 0.17$.

[Hydro-dynamical simulations.]

Simulations with resolution down to $10^5 M_\odot$ show that haloes and sub-haloes form down to the resolution mass of the simulations.

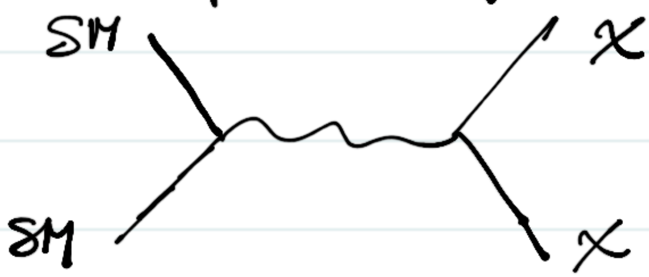
Subhaloes : dwarf galaxies; dark substructures.

⇒ figure with DM profiles

Particle dark matter detection

How can we look for and hopefully detect a signal from a relic (from the Big Bang) dark matter particle?

1) Search for New Physics at colliders.



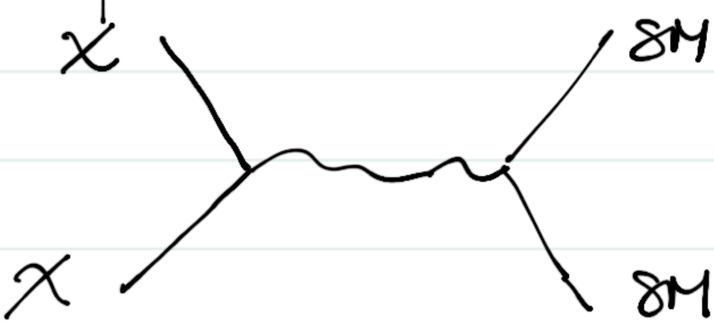
New particles (χ) can be produced from the collision of two Standard Model particles.
Nevertheless, even if a new, neutral, stable, weakly interacting particle was discovered, we could not be sure that Nature has chosen it to form the haloes of galaxies.

2) Direct DM detection.

Measures the recoil of a DM particle scattering off the nucleus of a detector. It is performed in deep underground laboratories.

Typical signatures:
- Recoil energy rate
- annual modulation
- Directionality

3) Indirect detection.
It measures the spectrum of the particles produced in the self-annihilation of two DM particles. The final states are SM particles.



The annihilation takes place in the haloes of structures, in particular in the halo of the MW.

Which particles are we looking for? of course those whose background is the least.

⟹ (figure on the rare CRs

The particles most suitable for indirect DM detection are:

- e^+, $\bar{p}$, $\bar{D}$ $\Rightarrow$ charged, diffuse
- γ-rays, νs $\Rightarrow$ neutral, trace back to sources

In these lectures: e^+, $\bar{p}$, $\bar{D}$; γs.

Neutrinos are so far less sensitive.
They can be observed from celestial bodies such as the Sun or the center of the Earth.

- χ are slowed down by scattering off the nuclei of the macroscopic body;
- χ are accumulated at the center of the body;
- $\chi\chi$ annihilate with ν emission
- ν propagate and convert to μ
- Detection of upgoing muons at ν-telescopes.

The search via νs bases on spin-dep. $\sigma_{\chi p}$.

Dark Matter annihilation spectra.

The differential spectrum for the production of a particle i in a $\chi\chi$ annihilation event is defined as:

$$\frac{dN_i}{dE_i} = \sum_{F,h} B_{\chi h}^{(F)} \frac{dN_i^h}{dE_i}$$

- h is a specific channel for the production of i (i.e. $b\bar{b}$ quarks or gg for $i = \bar{p}$);
- F is the final state leading to h (q and g may either be produced directly or through Higgs or gauge bosons intermediate states);
- $B_{\chi h}^{(F)}$ is the branching ratio for the annihilation of χ pairs to h particles via the F-channel.

* Comment of Branching Ratios

The single production spectra dN_i^h/dE_i are usually evaluated within Monte Carlo simulations of EW annihilation events.

γ-rays from Dark Matter annihilation

The flux of γ-rays $\left[\frac{\text{photons}}{m^2\ s\ sr\ GeV}\right]$ from DM annihilation and from the angular direction ψ is:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \psi) = \frac{1}{4\pi} \frac{\langle \sigma_{ann} v \rangle}{2m_\chi^2} \frac{dN_\gamma}{dE_\gamma} \cdot$$

particle physics

$$\cdot \int_{l.o.s.} \rho^2(r(\lambda, \psi))\ d\lambda\, d\psi$$

cosmology (J-factor)

λ = line of sight between observer and source

ψ is the angle between the l.o.s. and the line pointing to the GC. It is connected to the gal. longitude ℓ and latitude b by $\cos\psi = \cos\ell \cdot \cos b$

$$r = \sqrt{\lambda^2 + r_\odot^2 - 2\lambda r_\odot \cos\psi}$$

Jr is defined the dimensionless function:

$$J(\psi) = \frac{1}{8.5\,\text{kpc}} \left(\frac{1}{\rho_{loc}^2}\right)^2 \int_{l.o.s.} \rho^2(\lambda(\psi))\, d\lambda(\psi)$$

J-factor

also, often the measure occurs over a solid angle $\Delta\Omega$, and:

$$\langle J \rangle_{\Delta\Omega} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} J(\psi)\, d\Omega$$

$\Delta\Omega$ is related to the integration angle α_{int} around ψ:

$$\Delta\Omega = 2\pi\left(1 - \cos(\alpha_{int})\right)$$

The evaluation of the J-factor is a non trivial task, since one should know the DM distribution in that position of the sky. Numerical simulations.

⇒ See figure on J-factors

a DM signal from γ-rays must be searched where the J-factor, the integrated squared density, is higher.

γ-rays: The Fermi-LAT sky

The γ-ray sky is being measured by the Fermi Large Area Telescope (LAT) since June 2008. γ-rays are detected from $E_\gamma \sim 20$ MeV up to more than 300 GeV.
The Fermi observatory operates primarly in an all-sky scanning survey mode. The LAT has a $70°$ half angle field of view, and provides 30 minutes of Overtime on each point of the sky every two orbits (1 orbit takes 1.5 hours).

⇒ Figure: The invaluable γ-ray sky

The γ-ray EMISSION is predicted from:

DIFF. EM.

1. Interactions of CRs (p, He mainly) with the galactic gas (H_I, H_{II}, DNG):

$$CR + GAS \longrightarrow hadrons \rightarrow \pi^0 \rightarrow 2\gamma$$

2. Inverse Compton of CR e^- and the ISRF (VIS, IR, CMB):

$$e^- + \gamma(E) \rightarrow e^- + \gamma(E'), \quad E' > E$$

3. Isotropic, mostly extragalactic, background

4. Point sources.

4FGL, feb. 2019. 5098 sources, 8 years of data.

75 are spatially extended;

1525 have not a plausible counterpart at other wave-lengths (unassociated);

2940 are blazars (AGN class)

241 are pulsars

5. Extended sources

75 in the 4FGL; notably Fermi Bubbles and Loop I, giant structures

6. Residual Earth Limb, negligible for $E \gtrsim 200$ MeV

The GALACTIC DIFFUSE EMISSION dominates over all other components. at $E > 50$ MeV, photons from GDE are 5 times more abundant than photons from point sources. $\gtrsim 50\%$ of total, depending on b.

The Galactic Diffuse Emission

The galactic diffuse emission is due to the interaction of CRs with target photons and gas.

CR	TARGET	γ-ray from
p, He, ...	GAS	$\pi^0 \to 2\gamma$
e^+e^-	photons	IC
e^+e^-	GAS	Bremsstrahlung

ISM - GAS

99 % of the ISM is gas, and 70% of this mass is hydrogen. 90% H, 10% He in number.

H_I : neutral atomic hydrogen

H_{II} : ionized hydrogen

H_2 : molecular hydrogen

Hydrogen, and in general the ISM, may be found at different temperatures.

COLD neutral hydrogen: T: 50 ÷ 100 K

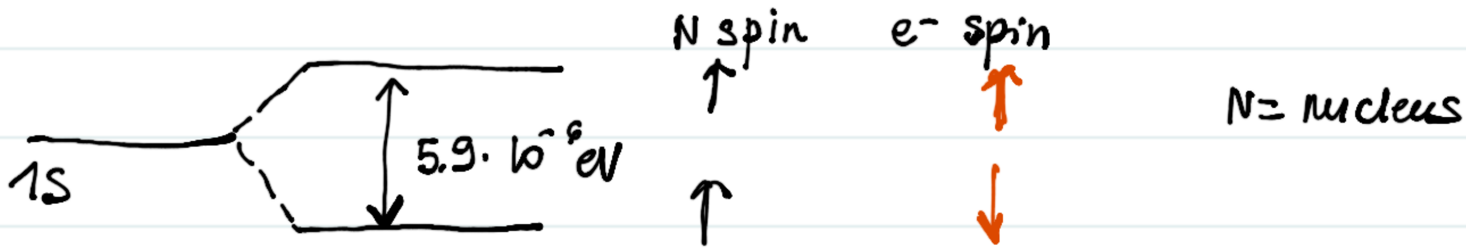
WARM // // : T: $6 \cdot 10^3 \div 10^4$ K

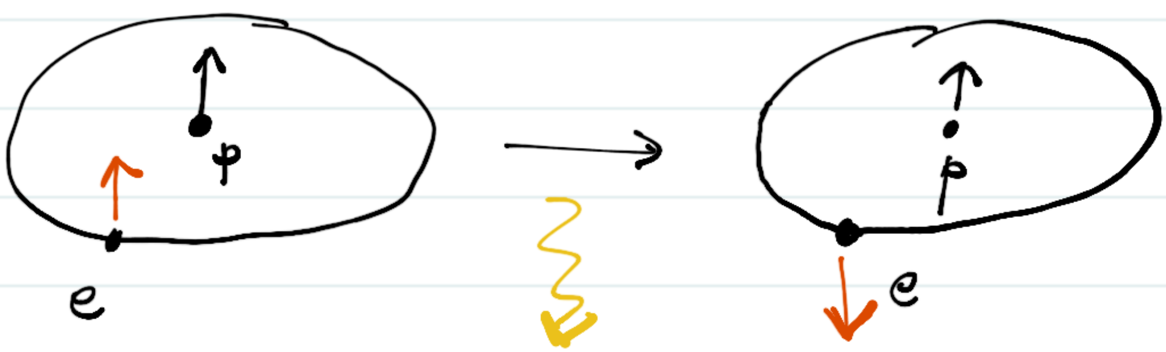
WARM ionized // : T: $8 \cdot 10^3$ K

Molecular clouds ($10^2 \div 10^6$ part/cm^3) are at $T = 10 \div 20 K$.
There is also a hot ionized medium, $T = 10^6 \div 10^7 K$, where one observes X-ray emission, and absorption in the UV.

NOTE. The 21 cm line or HI line.

It is a fundamental tracer in astronomy.
Its emission occurs at the HYPERFINE structure of the H atom. It follows the e^- spin flip.





The spin flip from upper to lower level (aligned → opposite spins) comes with the emission of a photon.
The energy of this photon is $E = 5.9 \cdot 10^{-6}$ eV

The corresponding frequence is

$$\nu = 1.42 \text{ GHz} \Rightarrow \text{radio / Microwave}$$

and the corresponding wavelength is:

$$\lambda = 21 \text{ cm}$$

The 21 cm trace atomic hydrogen HI - It can be emitted or absorbed. Often it is redshifted.

The molecular mass is usually traced by the ^{12}CO emission line. $J = 1 \to 0$ at $\lambda = 2.6$ mm (~ 100 GHz). It traces H_2 since it is CO main collisonal partner, and collisions excite its rotational transitions.

There is also a mixture of dense HI and diffuse H_2 that escapes 21 cm and CO radio surveys because of its optical thickness. This DARK NEUTRAL MEDIUM can indirectly be traced by its dust and CR content.

In order to compute the γ-rays from ISM gas, it is necessary to create column density MAPS for the Galaxy (bar, spiral arms, ...).

N_{HI} (atomic hydrogen column density) $\longrightarrow$ 21 cm

N_{H_2} (molecular " " ") $\longrightarrow$ CO line $\to W_{CO}$

N_{HII} (ionized " " ") $\to$ only indirect infos

N_{DNM} (dark neutral medium // //) → complex (21 cm and CO must be severely corrected), uncertain estimates.

So one has to build up MAPS for these components, consider the CRs in the whole galaxy and compute the emissivity in every point.

For the galactic IC radiation, one needs to know the ISRF at all useful wavelengths (CMB, VIS, IR). See before, this radiation field must be convolved with CR e⁻ in the whole MW.

The GDE is determined by a comparison with the Fermi-LAT data. For this reason, it is necessary to predict <u>all</u> the photons along a l.o.s. (given ℓ, b).

$$N_{pred}(\ell,b,E) = q_{HI}(E)\, N_{HI}(\ell,b) + \quad ⊛$$

$$+\, q_{CO}(E)\, W_{CO}(\ell,b) + \quad ⊛$$

$$+\, q_{DNM}(E)\, N_H^{DNM}(\ell,b) + \quad ⊛$$

$$+\, q_{HI,corr}(E)\, N_{HI}^{corr}(\ell,b) + \quad ⊛$$

$$+ C_{IC}(E)\, I_{IC}(\ell,b,E) +$$

$$+ C_{ext}(E)\, I_{ext}(\ell,b) +$$

$$+ C_{iso}(E)\, I_{iso} +$$

$$+ \Sigma_j\, N_{PS_j}\, \delta(\ell-\ell_j, b-b_j) +$$

$$+ C_{limb}(E)\, I_{limb} + I_{sun,moon}(\ell,b,E).$$

The parameters $q_i(E)$ represent the γ-ray emissivities associated to the column densities N and W. The latter are computed, after fits and comparison to a wealth of data on gases emission. $q_i(E)$ are free parameters, at least in the Fermi approach.

The parameters $C_i(E)$ are normalization factors associated to the respective intensity MAPS.

N_{PS_j} is the total number of photons emitted by each single j point source located at ℓ, b.

Usually $I_{sun,moon}$ are fixed.

All these components are fitted to the γ-ray sky. The fit leads to the determination of the free parameters, hence of the GDE. The GDE is given by the sum of the terms marked by (*) in the previous equation.
Once $q_j(E)$ or $C_j(E)$ are known, one can invert the problem, and derive the fluxes of incoming CRs, once cross sections are fixed.

(Figure: The diffuse emission of the Galaxy