The problem of Dark Matter searches

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Overwhelming evidence for CDM as building block of all structures in the Universe, from the largest scales down to galactic dynamics:

- CMB
- grav. scaffold
- “Bullet” cluster
- BAO
- galaxies

+ many others:

All point to a single “concordance” model:
Cosmological and astrophysical observations suggest that dark matter is: an optically-dark (i.e., dissipation-less), collision-less, classical fluid with negligible free-streaming effects. This excludes some models, such as, e.g.: Baryonic DM and Hot DM (e.g. SM neutrinos).

From the cosmologist perspective, Non-baryonic Cold DM is the preferred paradigm (i.e., for DM only gravity matters). Not helping much the particle physicist: there are only (weak) upper limits on the DM interaction strength, while other crucial properties (e.g., the mass scale) are missing.

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Baryonic DM

Hot DM
(e.g. SM neutrinos)

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The picture becomes slightly more focussed addressing the question: How was DM generated? The most beaten paths have been:

i) DM as a thermal relic product. (or in connection to thermally produced species);

ii) DM as a condensate, maybe at a phase transition; this usually leads to very light scalar fields;

iii) DM generated at large $T$, most often at the end of (soon after, soon before) inflation; candidates in this scheme are usually supermassive.
**CDM particles as thermal relics**

Let $\chi$ be a stable particle, with mass $M_\chi$, carrying a non-zero charge under the SM gauge group. Processes changing its number density are:

$$\chi \bar{\chi} \leftrightarrow P \bar{P}$$

with $P$ some (lighter) SM state in thermal equilibrium. The evolution of the number density is described by the Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3H n_\chi = -\langle \sigma_A v \rangle_T \left[ (n_\chi)^2 - (n^\text{eq}_\chi)^2 \right]$$

- **dilution by Universe expansion**
- **thermally averaged annihilation cross section**

$\chi$ in thermal equilibrium down to the freeze-out $T_f$, given, as a rule of thumb, by:

$$\Gamma(T_f) = n^\text{eq}_\chi(T_f) \langle \sigma_A v \rangle_{T=T_f} \simeq H(T_f)$$

After freeze-out, when $\Gamma \ll H$, the number density per comoving volume becomes constant. For a species which is non-relativistic at freeze-out:
\[ \Gamma(T_f) \sim H(T_f) \]

\[ \Omega_\chi h^2 \sim \frac{M_\chi s_0 Y^{eq}_\chi(T_f)}{\rho_c/h^2} \]

(freeze-out + entropy conservation)

\[ \sim \frac{M_\chi s_0}{\rho_c/h^2} \frac{H(T_f)}{s(T_f) \langle \sigma_A v \rangle_{T_f}} \]

(standard rad. dominated cosmology)

\[ \sim \frac{M_\chi}{T_f} \frac{g_\chi^*}{g_{\text{eff}}} \frac{1 \cdot 10^{-27} \text{cm}^{-3} \text{s}^{-1}}{\langle \sigma_A v \rangle_{T=T_f}} \]

with: \( M_\chi/T_f \sim 20 \)

The WIMP recipe to embed a dark matter candidate in a SM extension: foresee an extra particle \( \chi \) that is stable (or with lifetime exceeding the age of the Universe), massive (non-relativistic at freeze-out) and weakly interacting.
WIMP dark matter candidates:

A simple recipe in which maybe the most delicate point is the requirement of stability. You can enforce it via a discrete symmetry:

- R-parity in SUSY models
- KK-parity in Universal Extra Dimension models (Servant & Tait, hep-ph/0206071)
- T-parity in Little Higgs models (Bickedal et al., hep-ph/0603077)
- $Z_2$ symmetry in a 2 Higgs doublet SM extension (the “Inert doublet model”, Barbieri et al. hep-ph/0603188)
- Mirror symmetry in 5D models with gauge-Higgs unification (Serone et al., hep-ph/0612286)
- ...

or via an accidental symmetry, such as a quantum number preventing the decay: [Mirror DM], DM in technicolor theories (Gudnason et al., hep-ph/0608055), “minimal” DM (Cirelli et al., hep-ph/0512090), ...

In most of these, DM appears as a by-product from a property considered to understand or protect other features of the theory.
Indirect detection of WIMP dark matter

A chance of detection stems from the WIMP paradigm itself:

Pair annihilations of WIMPs in DM halos (i.e. at $T\equiv 0$)

Focus on: antiprotons, positrons, antideuterons, gamma-rays, (neutrinos)
WIMP coupling to ordinary matter

Halo signals

$\chi$ $\bar{\chi}$

$q$ $\bar{q}$

Annihilation

crossing symmetry

direct detection + capture in sun/earth

Tests at LHC

$q$ $\bar{q}$

$\chi$ $\bar{\chi}$

Production

Neutrino signals from sun/earth

$\chi$ $\bar{\chi}$ $q$ $\bar{q}$

VS
WIMP coupling to ordinary matter ???

Halo signals

SM

???

CP ???

tests at LHC

p

production

neutrino signals from sun/earth

χ

νs

χ

χ

SM

light’’ q

direct detection +
capture in sun/earth

χ

q

scattering

χ

SM

SM

vs

crossing

symmetry ???

χ

χ

χ

χ

χ

χ

χ

χ

χ

χ

χ

χ

χ

q
Indirect detection of WIMP dark matter

A chance of detection stems from the WIMP paradigm itself:

Pair annihilations of WIMPs in DM halos (i.e. at T\(\cong 0\))

Focus on: antiprotons, positrons, antideuterons, gamma-rays, (neutrinos)

- \((\sigma v)_{T\cong 0} \sim \langle \sigma v \rangle_{T=T_f}\)
- final state branching ratios
- \(N_{\chi-\text{pairs}} \propto [\rho_{\chi}(r)]^2 \approx [\rho_{\text{DM}}(r)]^2\)

WIMP DM source function

Dynamical observations (?)/N-body simulations (?)
Indirect detection of WIMP dark matter

A chance of detection stems from the WIMP paradigm itself:

Pair annihilations of WIMPs in DM halos (i.e. at $T=0$)

- Lighter SM particles
- Stable species
- Annihilation into, e.g., a 2-body final state
- Fragmentation and/or decay process

Focus on:
- Antiprotons, positrons, antideuterons, gamma-rays, neutrinos

Search for the species with low or well understood backgrounds from other known astrophysical sources.

For "standard" annihilation rates, final states and DM density profiles, the ratio signal over background is the largest for antiprotons (antideuterons), can be sizable for gamma-rays, is fairly small for positrons and very small for neutrinos.
The $\bar{p}$ measurements are consistent with secondaries:
Antiprotons are generated in the interaction of primary proton and helium cosmic rays with the interstellar gas (hydrogen and helium), e.g., in the process:

\[ p + H \rightarrow 3p + \bar{p} \]

Use the parameter determination from the B/C ratio, to extrapolate the prediction for the $\bar{p}/p$ ratio: excellent agreement for secondaries only!

Predictions obtained with the Dragon propagation code (Evoli et al., 2010); specular results with Galprop, semi-analytic models, ect. ect.
The measured antiproton flux has the spectral shape and normalization as predicted in vanilla secondary models:

Antiproton data are useful to set limits on DM models. These limits will slightly improve with upcoming data on antiproton, but especially with new data on other cosmic ray species, needed to refine propagation models.
Antideuteron fluxes

Possibly a large $\bar{D}$ flux for WIMP models whose $\bar{p}$ flux is consistent with current data. A promising target for future measurements?

NOTE: much cleaner DM signature compared to $\bar{p}$
Steady progresses in the field, with a very rich program upcoming:

**Pamela mission extended**

AMS-02 on the ISS in 2011

BESS Polar II flight a solar min.

GAPS prototype test in 2011
In the last 2-3 years electrons and positrons has gained the rank #1 in cosmic-ray studies:

2008-09: ATIC + PPB-BETS

2009: Fermi GRT

2008: PAMELA

2008-09: HESS
The standard propagation models are wrong: there are extra energy-dependent effects which affect secondary positrons (or primary electrons) but not the secondary to primary ratios for nuclei (at least at the measured energies), e.g.: Piran et al., arXiv:0905.0904; Katz et al., arXiv:0907.1686

There is production of secondary species within the CR sources with a mechanism giving a sufficiently hard spectrum (reacceleration at SN remnants?), e.g.: Blasi, arXiv:0903.2794; Mertsch & Sarkar, arXiv:0905.3152

There are additional astrophysical sources producing primary positrons and electrons: pulsars are the prime candidate in this list, e.g.: Grasso et al., arXiv:0905.0636

There is an exotic extra source of primary positrons and electrons: a dark matter source is the most popular option in this class.
A blind fit of the PAMELA/Fermi/HESS positron/electron data with a generic WIMP model (defined by WIMP mass and dominant annihilation channel), taking into account limits, e.g., from antiproton data, is possible: electrons+positrons

This “solution”:

- a heavy WIMP (mass above 1 TeV), with a large “enhancement factor” in the source function (Sommerfeld effect? non-thermal WIMP? clumps?), annihilating with a hard spectrum into leptons only (leptophilic)!

Anything but a vanilla WIMP model!
Very important caveat: we may have seen a DM signal, but have not seen a DM signature.

The sample fit of the data with a DM signal matches very nicely the signal foreseen more than a decade ago:

Aharonian et al., 1995

The predicted WIMP DM signature (in some cases, not a general feature) was not the rise in the positron fraction, but rather its rise + its sharp decrease at the WIMP mass scale.

Baltz & Edsjö, 1998

WIMP mass (e.g. 100-300 GeV???), hopefully at an energy scale different from the cutoff scale in the electrons.
Learning more about the lepton cosmic-ray puzzle:

- PAMELA keeps taking data and will measure the positron fraction up to 200-300 GeV. Will they see a decrease in the positron ratio?

- Fermi will improve its statistics. Will this allow to identify features in the spectrum to be associated to single sources, say a few nearby pulsars? Will Fermi see a spatial anisotropy, say a 1% effect to be associated to a single nearby source?

- AMS-02 will improve further on statistics and energy coverage.

- Other experiments in R&D phases, e.g.:

PEBS: in 2014, positron fraction up to 2 TeV

CALET: on the ISS in 2013, all electrons up to 20 TeV

+ Cross-correlations of the PAMELA excess with other DM signals!
DM annihilations and gamma-ray fluxes:

Prompt emission of $\gamma$-rays associated to three components:

1) Continuum: i.e. mainly from $f \rightarrow ... \rightarrow \pi^0 \rightarrow 2\gamma$

2) Monochromatic: i.e. the 1-loop induced $\chi\chi \rightarrow 2\gamma$ and $\chi\chi \rightarrow Z^0\gamma$

   (in the MSSM, plus eventually others on other models)

3) Final state radiation (internal Bremsstrahlung), especially relevant for:

   $\chi\chi \rightarrow l^+ l^- \gamma$

For a model for which all three are large (e.g. pure Higgsino):

Bergström et al., astro-ph/0609510
The induced gamma-ray flux can be factorized:

$$\frac{d\Phi_\gamma}{dE_\gamma} (E_\gamma, \theta, \phi) = \frac{1}{4\pi} \langle \sigma v \rangle_T T_0 \sum_f \frac{dN^f_\gamma}{dE_\gamma} B_f \int_{\Delta\Omega(\theta,\phi)} d\Omega' \int_{l.o.s.} dl \, \rho^2_\chi(l)$$

Particle Physics  DM distribution

Targets which have been proposed:

- The Galactic center (largest DM density in the Galaxy)
- The diffuse emission from the full DM Galactic halo
- Dwarf spheroidal satellites of the Milky Way
- Single (nearby?) DM substructures without luminous counterpart
- Galaxy clusters
- The diffuse extragalactic radiation
- ...

All of these are targets for FERMI.
The first upper limits on DM gamma-ray fluxes from Fermi: dwarf satellites

galaxy clusters
diffuse extragalactic

gamma-ray lines
DM annihilations and radiative emission:
The annihilation yields give rise to a multicomponent spectrum:

\[
\chi \bar{\chi} \rightarrow \begin{cases} 
  e^+ e^- \\
  l^+ l^- \text{ or } \phi \phi \rightarrow ... + e^+ e^- \\
  P \bar{P} \rightarrow ... + \pi^\pm \rightarrow ... + e^\pm 
\end{cases}
\]

- Synchrotron
- Inv. Compton
- Bremstrahlung
- Coulomb
- Ionization
- radio
- IR
- X-rays
- γs

For certain DM sources is a very powerful (although model dependent) approach. E.g., the Galactic center (Sgr A*) has a well-measured seed:

significant limits on WIMP models at any wavelength, unlikely the most stringent from the γ-band (even with Fermi)
Looking at a slightly larger angular region, depending on the magnetic fields and models for the distribution of DM, one can extrapolate the limits: Crocker et al., 2010

What will Fermi say about the diffuse emission at the GC? Early reports of an “excess”:

Vitale et al., arXiv:0912.3828

Multi-wavelength tests of an eventual DM component should be rather powerful.
Fermi should also contribute to address the issue of whether the local positron excess is due to primary sources located in the disc or to a leptophilic DM component distributed in a much thicker halo (forgetting now other explanations proposed so far):

Equilibrium number density profile of “all-electrons”, at the local Galacto-centric distance and as a function of height over the disc - a “reference propagation model” for CR in the Galaxy implemented (the old “standard” Galprop)

Primary/secondary sources located in the disc  DM sources extending in the halo
Similar picture for other sample prop. models (thin halo, thick halo, convective, kraichnan, vertically varying D), except if you force the halo to be thin (and with sharp truncation):

solid→ background;  dotted → DM induced component

IC on a 1 μm starlight photon from 100 GeV (1 TeV) electrons gives a gamma-ray of 50 GeV (5 TeV); synchrotron emission on a 1 μG magnetic field 50 GHz (5000 GHz) radiation. Possibly a handle on this from Fermi and Planck.
A prediction for the IC term (plus final state radiation or pion decay terms) for two sample (leptophilic) models fitting the Pamela excess in the positron ratio:

\[ 10^\circ < b < 20^\circ \]

\[ 50^\circ < b < 60^\circ \]

cross checked against Fermi data at intermediate latitudes

a prediction independent on propagation at high latitudes

DM spectral feature at \[ E \geq 100 \text{ GeV} \]

Note also: the prediction is insensitive to the halo model (since it is well away from the GC), and to whether it is related to decaying or annihilating DM (since it is normalized to the locally measured electron/positron flux)
Conclusions:

• The WIMP framework has a very rich phenomenology; it offers definite patterns to link direct and indirect detection, although model independent approaches have some limitations.

• Steady progresses in DM indirect detection from the dramatic improvement in the quality of cosmic-ray data. The DM interpretation of the cosmic lepton puzzle convergences on models with peculiar properties, and it is not the most plausible scenario to explain data at this stage.

• We are learning and will learn a lot from the wealth of data Fermi is delivering; several examples for which the multi-wavelength approach to DM indirect detection is very powerful.

• The cross-correlation among DM signals is the main route to DM identification.