Dark Matter
Indirect Detection

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Summary

1. Indirect dark matter detection: basics.
2. Searches with gamma rays: instruments and targets.
3. Searches with gamma rays: results from different targets.

Q1: Which target gives to the most stringent upper limits on dark matter?

Q2: How will improve the limits from the isotropic diffuse background and the Galactic center?
Today

1. Indirect dark matter detection: basics.
2. Searches with gamma rays: instruments and targets.
3. Searches with gamma rays: results from different targets.
4. Searches with charged cosmic rays and neutrinos.
5. Beyond WIMPs.
Searches with antimatter

- What differences with respect to gamma rays?
- Directional information?
- Why antimatter signal?
Searches with antimatter

- Trajectories are perturbed by magnetic fields and interaction with gas and dust: “cosmic-ray propagation”.
- After propagation no directional information can be inferred.
- Antimatter from astrophysical sources is suppressed (low background).
Summary of CR lectures

- Astrophysical sources can accelerate CR and inject them in the ISM —> Primary CR spectrum
- Secondary CR from interaction with ISM.
- CR propagate in the Galaxy (semi-analytical models, numerical codes).
- We measure local CR fluxes of primary/secondary.
- Antimatter is of secondary origin.

Typically, antimatter from astro less abundant than matter.
CR transport equation

\[ N_j \equiv \frac{dn_j}{dE} \]

CR differential energy density
CR transport equation

\[ N_j \equiv \frac{dn_j}{dE} \]

CR differential energy density

**Source term** of primary cosmic rays

supernova explosions, neutron stars and stellar winds from young hot O/B stars
DM annihilation: a source of primary CR

**Source term** of primary cosmic rays

\[
\frac{\partial N_j}{\partial t} - \nabla \left[ k \nabla N_j(\varepsilon) - \sqrt{c} N_j(\varepsilon) - M_j N_j(\varepsilon) \right] - \frac{\partial}{\partial \varepsilon} \left[ \frac{\partial}{\partial \varepsilon} \left( \frac{\varepsilon^2}{E} N_j(\varepsilon) \right) \right] = \]

\[
= q_0 Q_j^{(E)} + \sum \frac{n_k > m_j}{k} \rho_k N_k(\varepsilon) + \frac{2}{\partial E} \left[ -b(\varepsilon) N_j^{(E)} + b_k^p N_k + \frac{\partial N_j^{(E)}}{\partial \varepsilon} \right] \]

**Dark matter annihilation**

\[
\chi \chi \rightarrow \left\{ ZZ, W^+W^-, \gamma\gamma \right\}
\]

\[
\text{hadronization} \quad \rightarrow \gamma, e^\pm, \mu^\pm, p/\bar{p}, \pi^\pm, \nu/\bar{\nu}, \ldots
\]

Equal amount of matter and antimatter

\[
Q^j_{\text{DM}}(r, z, E) = \langle \sigma v \rangle \frac{dN_j}{dE_j} \left( \frac{\rho_\chi(r, z)}{m_\chi} \right)^2
\]
DM annihilation: a source of primary CR

\[ \chi \chi \rightarrow \left\{ \begin{array}{c} ZZ, W^+W^-, \gamma\gamma \\ q\bar{q}, l^+l^-, \nu\bar{\nu} \end{array} \right\} \]

hadronization

\[ \rightarrow \left\{ \begin{array}{c} \gamma, e^\pm, \mu^\pm, p/\bar{p}, \pi^\pm, \nu/\bar{\nu}, \ldots \end{array} \right\} \]

defects

\[ Q^j_{\text{DM}}(r, z, E) = \langle \sigma v \rangle \frac{dN_j}{dE_j} \left( \frac{\rho_\chi(r, z)}{m_\chi} \right)^2 \]

\[ \begin{array}{c}
e^+ \\
\bar{p} \end{array} \]
Antiproton/proton ratio

Antiproton/proton recent measurements. Antiprotons traditionally well modelled by our CR knowledge —> Useful to set stringent constraints on DM contribution.
Antiproton/proton ratio

However quite some uncertainty affects the prediction of the astro only antiproton signal.
Constraints on DM from antiproton/proton ratio

Annihilation constraints from $\bar{p}/p$

Astrophysical uncertainties on the constraints

Giesen+ JCAP'15
**Discussion of uncertainties in the GeV excess signal + protons & radio constraints.**
The positron fraction

\[ \frac{\Phi(e^+)}{\Phi(e^+) + \Phi(e^-)} \]

**Anomaly**: a rise in the positron fraction for \( E > 10 \text{ GeV} \)

From CR propagation physics, the ratio is expected to decrease for all propagation models.
The positron fraction

e.g. see Lavalle & Salati A&A'09
Primary to secondary ratio

**Primary electrons** are accelerated together with protons
→ spectral index at injection \( \alpha \sim 2.2 \pm 0.1 \)

After propagation:
\[ \Phi_{e^-} \propto \epsilon^{-\alpha - 0.5 - \delta/2} \]
\[ D(E) = D_0 \beta (\mathcal{R}/1\text{GV})^\delta \]

**Secondary positrons** (and electrons) are produced via CR proton – ISM interaction:
\[ p + H \rightarrow X + \pi^\pm \]
\[ \pi^\pm \rightarrow \nu_\mu + \mu^\pm \]
\[ \mu^\pm \rightarrow \nu_\mu + \nu_e + e^\pm \]
→ spectral index at injection softer \( \alpha \sim 2.7 \)

Decrease around \( E^{-0.5} \)
expected in positron fraction, for all propagation models.
Origin of the positron fraction?
What you additionally need to explain the data

Minimal model requires an **extra-component** in the $e^-$ and $e^+$ fluxes:

$$J(e^{\pm}) \propto E^{-\alpha_{\text{extra}}} \exp\left(-E/E_{\text{cut}}\right)$$

→ New common source of $e^-$ and $e^+$
Positron fraction from DM annihilation?

Prediction for typical dark matter channel but…

Dark matter interpretation:
- Annihilation into leptons only
- Quite massive particle
- Very large cross section
The dark matter interpretation of the positron fraction is in tension with other observations!

However:

• Accuracy of AMS02 data starts to exclude channels.
• Annihilation into leptons produces always an Inverse Compton emission, not seen in gamma rays —> Gamma-ray constraints.
• Tension with current constraints from CMB.  

The dark matter interpretation of the positron fraction is in tension with other observations!
Other possible explanations

Primary positrons from pair production in pulsar magnetosphere

How to discriminate dark matter from astrophysics?
Other possible explanations

Primary positrons from pair production in pulsar magnetosphere

How to discriminate dark matter from astrophysics?

a. Shape of the spectrum (challenging)

b. Anisotropy (directional signal)
Searches with neutrinos

- How do they travel?
- How do they interact?
Searches with neutrinos

- Unperturbed propagation, like for photons
- Signal generally suppressed with respect to gamma rays
- Search for an excess of high-energy neutrinos from the Sun and the Earth, signalling the presence of dark matter annihilation.
In the Sun:
- capture of dark matter
- annihilation of dark matter
- escape of high-energy neutrinos

Detection at Earth by e.g. IceCube

WIMPs in the Sun

\[ \rho_X \]  
\[ \chi \]  
velocity distribution

\[ \sigma_{\text{scatt}} \]  

\[ \Gamma_{\text{capture}} \]  

\[ \Gamma_{\text{annihilation}} \]  

\[ \nu_{\mu} \]  

Earth

Detector

oscillations
propagation
Dark matter capture in the Sun
- dark matter particles going through the Sun interact with particles (protons mostly)
  - elastic scattering with protons in the Sun (same process as in direct detection)
  - the dark matter loses energy and its velocity decreases
- if, after the scattering, $v_{\text{DM}} < v_{\text{escape}}$, the dark matter particle is trapped by the Sun gravitational potential
- after multiple scatterings, the dark matter thermalises in the core of the Sun

$$C^\odot \sim \phi_X (M_\odot/m_p) \sigma_{XP}$$

It depends on:
- the local dark matter density and velocity distribution
- the elastic scattering cross section on protons
- element composition in the Sun
Dark matter annihilation in the Sun
- dark matter particles in the Sun might annihilate
  ➡ only neutrinos can escape from the Sun because of low absorption
  ➡ the dark matter annihilation competes with the capture rate

\[
\Gamma_A \propto \langle \sigma v \rangle \cdot N_{DM}^2 \\
\dot{N}_{DM} = C_\odot - 2 \Gamma_A \quad \Rightarrow \quad N_{DM}(t) = \sqrt{\frac{C_\odot}{A_\odot}} \tanh \left( \frac{t}{\tau_{eq}} \right)
\]

\[
\Gamma_A = \frac{1}{2} A_\odot N_{DM}^2
\]

\[
A_\odot = \frac{1}{2} C_\odot
\]

with \( \tau_{eq} := \frac{1}{\sqrt{C_\odot A_\odot}} \propto \frac{1}{\sqrt{\sigma_{SD} \langle \sigma v \rangle}} \) as the equilibration time
WIMPs in the Sun

Dark matter annihilation in the Sun

- Dark matter annihilation in the Sun
- Equilibrium
- Out of equilibrium
- $t_{\odot} \gg \tau_{eq} \propto \frac{1}{\sqrt{\sigma_{SD} \cdot \langle \sigma v \rangle}}$
- Equilibrium
- $t_{\odot} \ll \tau_{eq}$
- Out of equilibrium
- $t_{\odot} \sim 4.5 \times 10^9$ yr

Graph showing annihilation rate $\Gamma_A(t)$ over time $t$.

$m_{DM} = 100$ GeV, $\langle \sigma v \rangle = 3 \cdot 10^{-26}$ cm$^3$/s
WIMPs in the Sun

At equilibrium, dependence only on the scattering x-section (as direct detection)

\[ \sigma_{\text{SD}} = 10^{-41} \text{ cm}^2 \]
\[ \tau_{\text{eq}} = 0.28 \cdot 10^9 \text{ y} \ll t_\odot \]

Equilibrium

\[ \sigma_{\text{SD}} = 10^{-45} \text{ cm}^2 \]
\[ \tau_{\text{eq}} = 28 \cdot 10^9 \text{ y} \gg t_\odot \]

Out of equilibrium

At equilibrium, dependence only on the scattering x-section (as direct detection)
Neutrinos from DM annihilation

\[ \chi \chi \rightarrow \left\{ ZZ, W^+W^-, \gamma\gamma, q\bar{q}, l^+l^-, \nu\bar{\nu} \right\} \text{ hadronization} \rightarrow \gamma, e^\pm, \mu^\pm, p/\bar{p}, \pi^\pm, \nu/\bar{\nu}, \ldots \]

\[ \mathcal{O} \text{ (GeV)} - \mathcal{O} \text{ (TeV)} \quad \text{from dark matter} \]

\[ E_\nu \sim \mathcal{O} \text{ (MeV)} \quad \text{from the Sun (astro)} \]
Neutrinos from DM annihilation

\[ \chi \chi \rightarrow \{ \text{ZZ}, W^+W^-, \gamma\gamma \} \text{ hadronization} \rightarrow \gamma, e^\pm, \mu^\pm, p/\bar{p}, \pi^\pm, \nu/\bar{\nu}, \ldots \]

Example: annihilation into ZZ
Neutrinos from DM annihilation

\[ \chi \chi \rightarrow \left\{ ZZ, W^+ W^-, \gamma \gamma, q\bar{q}, l^+ l^-, \nu \bar{\nu} \right\} \]\(\rightarrow\) hadronization decays \(\gamma, e^\pm, \mu^\pm, p/\bar{p}, \pi^\pm, \nu/\bar{\nu}, \ldots\)

Monochromatic neutrinos from ZZ:

\[
\left( \frac{dN_\nu}{dE_\nu} \right)_{ZZ}^{\text{rest}} = 2\Gamma_{ZZ \rightarrow \nu\nu} \delta(E_\nu - m_Z/2)
\]

Boosted neutrinos from ZZ:

\[
E_\nu \sim m_{DM}
\]

\[
\left( \frac{dN_\nu}{dE_\nu} \right)_{ZZ} = \frac{2\Gamma_{ZZ \rightarrow \nu\nu}}{m_Z \gamma \beta}
\]

\[
\gamma = \frac{m_\chi}{m_Z}
\]
Neutrinos from DM annihilation

\[ \chi \chi \rightarrow \left\{ ZZ, W^+W^-, \gamma\gamma, q\bar{q}, l^+l^-, \nu\bar{\nu} \right\} \xrightarrow{\text{hadronization}} \gamma, e^\pm, \mu^\pm, p/\bar{p}, \pi^\pm, \nu/\bar{\nu}, \ldots \]

\[ E_\nu \ll m_{\text{DM}} \]

“Soft” neutrinos
Neutrinos from DM annihilation

- Oscillations of neutrinos in the dense medium of the Sun
- Scattering with protons, neutrons and electrons (energy losses)

“Soft” neutrinos

courtesy of S. Wild
Neutrino telescopes
• Optical modules in a transparent medium to detect the light emitted by relativistic secondaries produced (Cherenkov effect) in charged-current neutrino-nucleon interactions.

• Large volumes are required because of small cross sections and fluxes.
IceCube

86 strings, 5160 optical modules
86 ice tanks on the surface
~ 50 GeV energy threshold
~ 1° angular resolution
IceCube: muon tracks

\[ \nu_\mu / \bar{\nu}_\mu + N \rightarrow \mu^\pm + N' \]

✓ Very good angular resolution → it is possible to define the \textbf{arrival direction} (Is it the Sun?)
✓ No energy measurement
✓ Background: atmospheric neutrinos, not correlated with the Sun direction

→ \textbf{Is there an excess towards the Sun?}
IceCube: muon tracks

\[ \nu_\mu / \bar{\nu}_\mu + N \rightarrow \mu^\pm + N' \]

✓ Very good angular resolution \( \rightarrow \) it is possible to define the **arrival direction** (Is it the Sun?)
✓ No energy measurement
✓ Background: atmospheric neutrinos, not correlated with the Sun direction

° **Is there an excess towards the Sun?**

IceCube 79-strings results
✓ No significant excess in \( \theta_{\text{sun-}\mu} \lessapprox 5^\circ \)

° **Upper limits on the annihilation rate, i.e. capture rate, i.e. elastic scattering cross section!**
Upper limits on WIMPs

- Same effect from the center of the Earth, but signal not competitive with direct detection (equilibrium typically not yet reached)
- The signal from the Sun leads to competitive limits on the scattering cross section.

** For latest limits on DM spin-dependent cross section with IC79 and an improved event-level likelihood see: IceCube Coll. PRL’13

** For searches for DM in the Milky Way halo and constraints on the annihilation cross section, but not competitive with gamma rays, see: IceCube Coll. EPJC’16
Sterile neutrinos

- Sterile neutrinos can decay to photon + neutrino

- Can search for the photons (X-rays)

other possible dark matter candidate…
An X-ray signal

- Telescope: XMM-Newton
- Target: Galaxy clusters (73)
- Analysis: look for non-atomic spectral lines

Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters

Esra Bulbul, Maxim Markevitch, Adam Foster, Randall K. Smith, Michael Loewenstein, Scott W. Randall

(Submitted on 10 Feb 2014 (v1), last revised 9 Jun 2014 (this version, v2))

+ other papers with similar analysis and debate.. but signal still there!
An X-ray signal

- Telescope: XMM-Newton
- Target: Galaxy clusters (73)
- Analysis: look for non-atomic spectral lines

background lines from thermal plasma

Excess (red points) 4-5 sigma detection
capabilities and subject to significant modeling uncertainties. On the origin of this line, we argue that there should be no atomic transitions in thermal plasma at this energy. An intriguing possibility is the decay of sterile neutrino, a long-sought dark matter particle candidate. Assuming that all dark matter is in sterile neutrinos with \( m_s = 2E = 7.1 \text{ keV} \), our detection in the full sample corresponds to a neutrino decay mixing angle \( \sin^2(2\theta) \approx 7 \times 10^{-11} \), below the previous upper limits. However, based
Summary

1. Indirect dark matter detection: how to look for DM with astro probes.
2. Searches with gamma rays: basics definitions, instruments and targets.
3. Searches with gamma rays: what are the main methods to look for DM with gamma rays, current results from different targets.
4. Searches with charged cosmic rays and neutrinos: what are the pros/cons, why are they important.
5. Beyond WIMPs: you can look for many other DM candidates, not only WIMPs.