Signatures of Dark Matter in the Diffuse $\gamma$-rays

Pasquale D. Serpico, Center for Particle Astrophysics

Fermilab

Outline

✓ Introduction

✓ Indirect Detection

✓ Galactic vs. Extragalactic
  - Relative Intensity
  - Extragalactic angular features
  - Galactic angular features

✓ Prospects for detection (GLAST)

✓ Conclusions
Introduction
Dark Matter Problem(s), since F. Zwicky, ’33
The accurate Recipe of our Ignorance
✓ It’s cold
✓ It’s dark
✓ Physicists at the most important Labs care for it
✓ It’s non-baryonic! New Physics!

L. Roszkowski
A reasonable bet: WIMPs

✓ The Weakly Interacting Massive Particle "miracle": thermal relic with EW gauge couplings & $m_{\text{wimp}} \approx 0.1\text{–}1 \text{ TeV}$ matches the cosmological abundance requirement, $\Omega_{\text{wimp}} \approx 0.25$

✓ EW symmetry breaking related with DM? Possibly, e.g. neutralino in SUSY, KK states in extra-dimension theories

✓ EW-related candidates interesting experimentally: rich phenomenology, higher chances of detection, many techniques

➢ Warning: keep in mind other possibilities (Axions, SHDM, SuperWIMPS, MeV DM, sterile neutrinos...) Peculiar signatures, ad hoc searches
## WIMP detection techniques

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<th>Interaction</th>
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<td><strong>Direct</strong></td>
<td>Local (crossing Earth surface)</td>
<td>WIMP-nucleus scattering</td>
<td>Phonons</td>
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<td>(CDMS...)</td>
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<td><strong>Indirect</strong></td>
<td>Earth, Sun, Galaxy, Cosmos</td>
<td>WIMP pair annihilation</td>
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<td><strong>Collider</strong></td>
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<td>(LHC,...)</td>
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Advertisement: INFN Napoli is heavily involved in programs in all the three techniques, directly related to DM searches as one of the primary goals (Warp, Pamela) or serendipitously (ARGO, AUGER, NEMO, LHC)

Sector where interplay among experimental and theoretical physicists is crucial
Indirect Detection: shining light on the dark matter via gamma rays
Indirect detection ("Susy in the sky")?

New physics

\[ \chi \rightarrow \pi^+\pi^- \rightarrow e^+, e^-, \nu \]

\[ \rightarrow \text{A few hadrons, } p, \bar{p}, d \]

\[ \rightarrow \pi^0 \rightarrow \gamma \gamma \]

\[ <E_\gamma > \approx 0.1-0.01 \text{ m } \approx 1-100 \text{ GeV} \]

Cosmology

DM density structure (N-body simulations)

New particle Theory (DarkSUSY)

Hadronization (Pythia)

Propagation, Astrophysics (Galprop)

Detector simulation (GEANT 4)
Where to look for Gammas?

<table>
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<tr>
<th>Target</th>
<th>Advantage</th>
<th>Challenges</th>
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<td>Spectral line $E = m_\chi$ anywhere</td>
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<td>Galactic center</td>
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<td>Satellites, $\mu$-halos...</td>
<td>Low background</td>
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<tr>
<td>Diffuse galactic &amp; extragalactic</td>
<td>High statistics</td>
<td>Cosmological uncertainty, astrophysical foregrounds</td>
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angential AND energy information

- Galactic center
- Satellites/mini-spikes / dwarfs
- Galactic halo
- Extra-galactic
The hierarchical structure formation paradigm

Structures in the Universe results from the gravitational amplification of small, primordial density fluctuations. The collapse is driven by cold DM, and smaller and more compact structures form first. They merge to build up bigger galaxies, and bigger galaxies collide and merge to make the largest galaxies... the largest superclusters are the youngest bound structures.

Is this important for DM detection via gammas? Unfortunately, Yes
Why should we care? A simple argument

\[ I_c \propto \rho_c^\kappa l = \bar{\rho}^\kappa \left( \frac{L}{l} \right)^{3\kappa} l = \bar{\rho}^\kappa \left( \frac{L}{l} \right)^{3\kappa-1} L \]

\[ I_c = \bar{I} \left( \frac{L}{l} \right)^{3\kappa-1} \quad J_c = \left( \frac{L}{l} \right)^{3\kappa-3} \quad \bar{J} = \left( \frac{\rho_c}{\bar{\rho}} \right)^{\kappa-1} \bar{J} \]

For annihilating DM, not only the angular pattern, but also the intensity depends on the degree of clumpiness!

\[ \rho_c l^3 = \bar{\rho} L^3 \]
A preliminary question: which diffuse flux dominates the average intensity?
Application to the Galactic case

via lactea 234 million particles  \[ \text{http://www.ucolick.org/~diemand/vl} \]

\[
I_{\text{sm}}(E, \psi) = f_\gamma(E) \frac{\langle \sigma_{\text{ann}} v \rangle}{2 m^2_\chi} \int_{\text{l.o.s.}} ds \frac{\rho^2_{\text{sm}}[r(s, \psi)]}{4\pi},
\]

\[
I_{\text{cl}}(E, \psi) = \frac{f_\gamma(E)}{4\pi} \int_{\text{l.o.s.}} ds \int dM \int dR \ n_{\text{cl}}[r(s, \psi), M, R] \Gamma_{\text{cl}}(M, R)
\]
Application to the Extragalactic Case

\[ I_{\text{ex}}(E) = \frac{c}{4\pi} \frac{\langle \sigma_{\text{ann}} v \rangle}{2 m_{\chi}^2} \int_0^\infty \text{d}z \frac{\rho_{\text{dm}}(z)}{H(z)(1 + z)^3} f_\gamma[E(1 + z)] e^{-\tau(E,z)} \]

\[ H(z) = H_0 \sqrt{\Omega_M (1 + z)^3 + \Omega_\Lambda}. \]
An useful parametrization

\[ \Gamma_{cl}(M, R) = \int_V d^3x \frac{\left< \sigma_{ann} v \right>}{2 m^2_\chi} \rho_{cl}^2(x) \equiv \bar{\rho}_{cl}^2 V S \Pi = \bar{\rho}_{cl} M S \Pi \]

\[ \int dM \int dR n_{cl}[r(s, \psi), M, R] M = \xi \rho_{sm}[r(s, \psi)]. \text{ Ansatz} \]

\[ I_{\text{gal}}(E, \psi) = \frac{1}{4\pi} f_\gamma(E) \Pi \int_\text{1.o.s.} ds \rho_{sm}[r(s, \psi)] \times (\rho_{sm}[r(s, \psi)] + S \xi \bar{\rho}_{cl}) \]

\[ \rho_{dm}^2(z) \equiv \left( \frac{\rho_{dm,0}}{\rho_{c,0}} \right)^2 \rho_{c,0}^2 (1+z)^6 \Delta^2(z) = \Omega_{dm}^2 \left( \frac{3H_0^2}{8\pi G_N} \right)^2 (1+z)^6 \Delta^2(z) \]

\[ \Delta^2(z) = \frac{\Delta^2(0)}{(1+z)^3}. \text{ Ansatz} \]

\[ I_{\text{ex}}(E') = \frac{c}{4\pi} \frac{\left< \sigma_{ann} v \right>}{2 m^2_\chi} \Omega_{dm}^2 \rho_{c,0}^2 \Delta^2(0) \int_0^\infty dz \frac{f_\gamma[E(1+z)] e^{-\tau(E,z)}}{H_0 \sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}} \]
Results

D.Hooper and PS, astro-ph/0702328
Extragalactic dominance Signatures
Cosmological Compton-Getting Effect

✓ The solar system is moving \((u=368 \text{ km/s})\) with respect to the cosmological rest frame, as indicated by the CMB dipole

✓ As long as we collect \(\gamma\)'s from a large number of sources at cosmological distance, sources are on average at rest

A dipole anisotropy should be visible in the HE sky with amplitude

\[
[I(E)=E^2f(E)]
\]

\[
A_{CCG} = \frac{I_{\text{max}}-I_{\text{min}}}{I_{\text{max}}+I_{\text{min}}} = \frac{u/c(2-\frac{d \ln I}{d \ln E})}{2} = 0.5\%
\]

CCG effect for $\gamma$’s

✓ A detection of the CCG effect is well within the reach of GLAST (with the EGRET flux, $O(10^6)$ CGB photons per year at $E>\text{GeV}$)

The signature has been detected in the X-ray background


✓ CCG effect would allow one to extract the truly extragalactic fraction of the CGB, basically in a model independent way

✓ The method is complementary to the traditional one

$$I_{\text{tot}}(E,b,l) = A + B \, I_{\text{Gal}}(E,b,l)$$

✓ Not Peculiar of DM, yet a bound or detection would constrain DM properties
“dark matter annihilation also produces a characteristic anisotropy of the CGB, which provides a powerful tool for testing the origin. [...] As the intensity of photons from annihilation is proportional to the density squared, we show that the predicted shape of the angular power spectrum of gamma rays from dark matter annihilation is different from that due to other astrophysical sources such as blazars.”

Anisotropy at high energy

However, the signature depends on several parameters (Energy spectrum, minimum DM clump mass, cosmological evolution,...). Cosmic variance also prevents to measure the lowest multipoles!

\[
F(E_{\text{cut}}, \hat{n}) \propto \int_0^\infty dz \frac{\rho^\alpha(z, \hat{n})}{H(z)(1+z)^3} W(E_{\text{cut}}, z)
\]

Cumulative photon flux

\[
W(E_{\text{cut}}, z) \equiv \int_{E_{\text{cut}}}^\infty \text{d}E \, g[E(1+z)] e^{-\tau(E_\gamma, z)}
\]

Window function

✓ When the horizon is at \(z << 1\), the signal mostly depends on \(\alpha\) (modulo \(\tau\))

✓ Lower statistics, but more robust predictions: look at \(E > 0.1-1\) TeV!

Other interesting features

- Especially at large scales, the near structures are responsible for the anisotropy pattern.
- A “real” LSS catalogue can be used for predictions
- More modes ($a_{lm}$ vs. $C_l$)
- No cosmic variance limitation
- The relative anisotropy is higher the higher the energy cut. This compensates to some extent the problem of the lower statistics available

\[ a_{lm} \sim \frac{\Delta I_{lm}}{\langle I \rangle} \]
Expectations for GLAST

\[ F_{10}(E_{\text{cut}}, \hat{n}) = \sum_{l=1}^{l_{\text{max}}=10} a_{lm} Y_{lm}(\hat{n}) \]

\[ \sigma_{a_{lm}}^2 = C_l^N = \frac{4\pi f_{\text{sky}}}{N_\gamma} \left( 1 + \frac{N_{\text{CR}}}{N_\gamma} \right) \]

\[ N_\gamma = t \cdot g_{\text{cut}} \cdot DC \cdot \Omega_{\text{fov}} \cdot f_m \cdot \int_{E_\gamma}^{\infty} dE \, A_{\text{eff}}(E) I_\gamma(E) \]
Signatures in the Energy Spectrum

$m_\chi = 500$ GeV

$z = 1, .3, .1, 0$

$E_\gamma (\text{GeV})$

$m_\chi = 500$ GeV

$E_\gamma (\text{GeV})$

D.Hooper and PS, astro-ph/0702328
Galactic dominance Signatures
Offset position in the halo

Cylindrical symmetry in the limit of spherical halo; $O(10\%)$ asphericity expected, yet the symmetry axes of the ellipsoid are unknown
Compton-Getting effect

✓ The baryonic disk of the Galaxy is supported against radial collapse by its angular momentum.

✓ The dark halo is supported by random velocity (a collisionless pressure).

✓ The disk rotates into the rest frame of the DM halo with velocity $u = 220$ km/s. A CG dipole with amplitude of about 0.3% is expected if DM dominates the diffuse flux.

✓ Note that this is a DM-peculiar effect, since astrophysical contamination from the disk would be co-rotating with us, at better than 10%.

D. Hooper and PS, astro-ph/0702328
Prospects for Detection
Prospects for Detection - I

- Astrophysical & DM signals have different angular shapes
- Energy spectra very different

How large must the DM contribution be to be interesting?
Prospects for Detection - II

\[ \langle \sigma_{\text{ann}} \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \quad m_\chi = 100 \text{ GeV} \]
Concluding Remarks
Conclusions

- Unveiling the nature of DM is one of the greatest unresolved mysteries of astrophysics and cosmology, and one of the few arguments in favor of physics beyond the standard model.

- In most models, DM may be detectable in one or more ways (direct, indirect or collider searches). One promising way is via the gamma rays produced via DM annihilation.

- Many candidate sources exist in the Universe. Diffuse fluxes, besides spectral features, have peculiar angular shapes. The large scale ones are robust and deterministic. If the emission is at least at the few percent of the overall diffuse flux, there are good chances of DM detection.

- Small-scale structures encode important statistical information, but extremely model-dependent. In the future, if we are lucky enough we may use gamma-maps to extract information on the clustering properties of matter on relatively small scales.

This field requires combined efforts of particle physicists (theoreticians & accelerator experimentalists), simulation experts, cosmologists, underground lab physicists, astronomers, ν & γ astroparticle physicists...
If you still think it is not worth studying DM...

Remember: the dark side rules the universe!