MULTICHANNEL SEARCHES FOR DARK MATTER

NICOLAO FORNENGO

Department of Theoretical Physics, University of Torino and Istituto Nazionale di Fisica Nucleare (INFN) – Torino Italy



fornengo@to.infn.it nicolao.fornengo@unito.it

www.to.infn.it/~fornengo www.astroparticle.to.infn.it



Workshop on "Next Generation Space Experiments" Dipartimento di Fisica e INFN, Pisa – 8.05.2014

Galactic dark matter signals



Extragalactic/cosmological signals



Extragalactic signals

Photons: gamma, X, radio Neutrínos

Sunyaev-Zeldovich effect on CMB

Optical depth of the Universe

DM DISTRIBUTION > IN CLUSTERS > IN GALAXIES > IN SUBSTRUCTURES

Indirect astrophysical signals



 $\sqrt{s} = 2 m_{\rm DM}$ $\sqrt{s} = m_{\rm DM}$ Annihilation (or decay) $E_{\rm max} = m_{\rm DM}$ $E_{\rm max} = m_{\rm DM}/2$

Relevant particle physics properties:

- 1. Annihilation cross section ^(*) (or decay rate)
- 2. Mass of the DM particle
- 3. BR in the different final states

1+2: Size of the signal 2+3: Spectral features $\begin{array}{c|c} \Phi \\ \hline \\ \langle \sigma v \rangle \\ \Gamma \end{array} \end{array} \xrightarrow{P} E \\ E_{\text{max}} \end{array}$

^(*) Determines also the cosmological relic abundance (for a thermal DM) $\Omega h^2 = 0.11 \iff \langle \sigma_{\rm ann} v \rangle = 2.3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$

ANTIPROTONS



Antiproton source spectra
$$q(r, z, E) = \frac{1}{2} \langle \sigma v \rangle \frac{dN}{dE} \left(\frac{\rho(r, z)}{m_{\chi}} \right)^{2}$$



F. Donato, N. Fornengo, D. Maurín, P. Salatí, R. Taillet, PRD 69 (2004) 0603501

Effect of MC generators



PYTHIA: solid HERWIG: dashed

Cirellí, Corcella, Hektor, Hutsi, Kadastík, Panci, Raídal, Sala, Strumia, JCAP 1103 (2011) 051

Galactic transport

$$\phi(E; r = r_{\odot}, z = 0) = \frac{\beta}{4\pi} \left(\frac{\rho_{\odot}}{m_{\chi}}\right)^2 R(E) \frac{1}{2} \langle \sigma v \rangle \frac{dN}{dE}$$





(1) F. Donato, N. Fornengo, D. Maurín, P. Salatí, R. Taillet, PRD *69* (2004) 0603501

(2) D. Maurín et al. Astron. Astrophys. 381 (2002) 539

case	δ	K_0	L	V_c	V_A	$\chi^2_{\rm B/C}$
		$(\rm kpc^2/Myr)$	(kpc)	$(\rm km/sec)$	$(\rm km/sec)$,
max	0.46	0.0765	15	5	117.6	39.98
med	0.70	0.0112	4	12	52.9	25.68
min	0.85	0.0016	1	13.5	22.4	39.02

Effect of propagation on secondaries



Model	z_t	δ	D_0	η	v_A	γ	dv_c/dz	Φ	Color
	(kpc)		$(10^{28} {\rm cm}^2 {\rm /s})$		(km/s)		$(\rm km/s/kpc)$	(GV)	
KRA	4	0.50	2.64	-0.39	14.2	2.35	0	0.67	Red
KOL	4	0.33	4.46	1.	36.	1.78/2.45	0	0.36	Blue
THN	0.5	0.50	0.31	-0.27	11.6	2.35	0	0.70	Green
THK	10	0.50	4.75	-0.15	14.1	2.35	0	0.69	Orange
CON	4	0.6	0.97	1.	38.1	1.62/2.35	50	0.21	Gray

Evoli, Cholis, Grasso, Maccione, Ullio, PRD 85 (2012) 123511

Effect of modelling on the DM signal



Evolí, Cholis, Grasso, Maccione, Ullio, PRD 85 (2012) 123511

Dependence on height of diffusive halo



- L determines the extension of the confinement region:
 - > For small L, only the sources very close to the solar neighborhood can contribute
 - > As L increases, confinement is more efficient and more sources contribute



- The galactic wind blows the particles away from the disk (convection), leading to an effective size of the diffusive halo of the order of $r_{\rm W}$
- There is a competition between L and r_W :
 - > For large L, the evolution is driven by r_w
 - For small r_w all curves converge, independently of L, because the CR are convected away before being able to reach the boundaries of the diffusion region



- At low energies particles are destroyed more easily, since the probability to cross the disk (and therefore to interact with matter) increases relatively to escape (diffusive or convective)
- There is a competition between L , r_W and r_{SP} :
 - > The effect of r_{sP} is milder: the cut-off due to spallation is less efficient than diffusion or convection to prevent particles coming from faraway from reaching us



Transport in the heliosphere

Propagation in the heliosphere



 $\Phi_{\bar{p}}(r,z,T_{\bar{p}})$

LIS

 $\rightarrow \Phi_{\bar{p}}(\hat{T}_{\bar{p}})|_{\text{Earth}}$

CR transport in the heliosphere is typically treated with a "force-field" approximation

 $\frac{\Phi_{\bar{p}}(T_{\bar{p}})}{p_{\bar{p}}^2} = \frac{\Phi_{\bar{p}}(\hat{T}_{\bar{p}})}{\hat{p}_{\bar{p}}^2} \qquad \qquad T_{\bar{p}} = \hat{T}_{\bar{p}} + \Delta$

More refined treatment adopts e.g. a "stochastic equation" technique: - phase space density sampled and evolved according to a random walk set by the diffusion properties of the heliosphere

Model parameters and geometry: Solar magnetic field: Parker spiral Tilt angle of the current-sheet α Mean free path $\lambda_{\parallel} = \lambda_0 (\rho/1 \text{ GeV})^{\gamma} (B_{\bigoplus}/B)$ Polarity (changes every 11 yr)

Secondary antiprotons



Theoretical uncertainty band includes uncertainty on: primary proton flux nuclear uncertainty in the antiproton production cross section

Antiproton bounds on DM properties



(*) Donato, Maurín, Brun, Delahaye, Salatí, PRL 102 (2009) 071301 (+) Adríaní et al. (PAMELA Collab.), PRL 105 (2010) 121101



Caveat: the bounds are reported (as is usual) under the hypothesis that the DM candidate is the dominant DM component, regardless of its thermal properties in the early Universe

Antiproton bounds



Dependence on the DM halo profile

Dependence on solar modulation

Signals for heavier DM



A specific model: wino DM



Projected AMS-02 sensitivity



Projected AMS-02 sensitivity



Fornengo, Maccione, Vittino, JCAP 1404 (2014) 003



Cirelli, Giesen, JCAP 1304 (2013) 015

Assessment on the antiP signal

- Injection spectra: well under control up to about TeV - what about above? Are MC OK? Impact of NP?
- <u>DM halo shape</u>: < 30% uncertainty
- <u>Transport</u>:

- about a factor of "10" up/down, still - refine from B/C needed (might not solve all, but will help)
- Background:
- with AMS-02, theoretical error now dominant
- necessary to reduce also nuclear-physics uncertainties
- <u>Multí TeV DM</u>:
- background expected to drop significantly - DM signal might have harder features, but normalization drops too $(1/m_{DM} \text{ or } 1/m_{DM}^2)$

ANTIDEUTERONS





$$\frac{dN_{\bar{d}}}{dT_{\bar{d}}} = (4\pi E_{\bar{d}} k_{\bar{d}}) F_{\bar{d}}(\sqrt{s}, \vec{k}_{\bar{d}})$$

$$F_{\bar{d}}(\sqrt{s},\vec{k}_{\bar{d}}) \ d^{3}\vec{k}_{\bar{d}} = \int F_{(\bar{p}\bar{n})}(\sqrt{s},\vec{k}_{\bar{p}},\vec{k}_{\bar{n}}) \ C(\vec{\Delta}) \ \delta^{3}(\vec{k}_{\bar{d}}-\vec{k}_{\bar{p}}-\vec{k}_{\bar{n}}) \ d^{3}\vec{k}_{\bar{n}} \ d^{3}\vec{k}_{\bar{n}} \ d^{3}\vec{k}_{\bar{n}} \ d^{3}\vec{k}_{\bar{n}}$$
coalescence function

Coalescence process

• "Old model": uncorrelated, independent and isotropic (p,n) production

• "MC model": event-by-event coalescence, correlations may be present

(1)
$$F_{(\bar{p}\bar{n})}(\sqrt{s}, \vec{k}_{\bar{p}}, \vec{k}_{\bar{n}}) \longrightarrow F_{(\bar{p}\bar{n})}^{\mathrm{MC}}(\sqrt{s}, \vec{k}_{\bar{p}}, \vec{k}_{\bar{n}})$$
$$\Delta = |\Delta \vec{p}| < p_0$$

Used in: Kadastik, Raidal, Strumia, Phys. Lett. B 683 (2010) 248-254 Dal, Kachelriess, Phys. Rev. D 86 (2012) 103536

(II)

$$F_{(\bar{p}\bar{n})}(\sqrt{s}, \vec{k}_{\bar{p}}, \vec{k}_{\bar{n}}) \longrightarrow F_{(\bar{p}\bar{n})}^{\mathrm{MC}}(\sqrt{s}, \vec{k}_{\bar{p}}, \vec{k}_{\bar{n}})$$

$$\Delta = |\Delta \vec{p}| < p_{0}$$

$$L = |\Delta \vec{r}| < R_{\star} \quad \text{antideuteron "radius"}$$

Used in: Fornengo, Maccione, Vittino, JCAP 09 (2013) 031

Coalescence momentum

Coalescence momentum fixed on ALEPH data on antiD production $p_0 = (195 \pm 22) \text{ MeV}$ 10^{-5} ≟ 5x10⁻⁶ $\begin{array}{l} \mathsf{MC}(\Delta \mathsf{p} + \Delta \mathsf{r}) \\ \mathsf{MC}(\Delta \mathsf{p}) \end{array}$ old model 2×10^{-6} 0.1 0.12 0.14 0.16 0.18 0.2 0.22 p₀ [GeV]

Fornengo, Maccione, Vittino, JCAP 09 (2013) 031

Coalescence process



Transport in the galactic medium



Transport in the heliosphere



TOA Background



Detection prospects





DM configurations allowed by antiproton bounds Relevant detection prospects for Dbar energies <u>below few Gev/n</u>, where dependence on solar modulation modeling can have an impact on the DM signal up to a factor of 2

Fornengo, Maccione, Vittino, JCAP 1309 (2013) 031

Detection prospects: heavier DM



Dependence on coalescence momentum



 $p_0 = (195 \pm 22) \text{ MeV}$

Fornengo, Maccione, Vittino, JCAP 1309 (2013) 031

Dependence on galactic transport



DM configurations allowed by antiproton bounds

Fornengo, Maccione, Vittino, JCAP 1309 (2013) 031

Events expected in GAPS and AMS



For GAPS LDB+ setup

For AMS nominal sensitivity

DM configurations allowed by antiproton bounds

Fornengo, Maccione, Vittino, JCAP 1309 (2013) 031

Detection reachability at 3σ C.L.



Example for GAPS LDB+ setup 3σ detection : $N_{crit} = 1$ events

Fornengo, Maccione, Vittino, JCAP 1309 (2013) 031

Comparison of MC generators

Detector range No cuts, Herwig++, $p_0 = 110$ MeV After angular cut, Herwig++, $p_0 = 110$ MeV No cuts, Pythia 8, $p_0 = 160$ MeV After angular cut, Pythia 8, $p_0 = 160$ MeV 10³ . . . 10^{2} 10^{1}

e+e- antideuteron spectrum at Z resonance



Effect of MC generators



Dal, Kachelriess, PRD 86 (2012) 103536

Assessment on the antiD signal

- Injection spectra: similar to antiP
- <u>Coalescence</u>:
- modeling not well understood at relevant energies - not many relevant data to fix the models: - background: $s^{1/2} = 10-100 \text{ GeV}$ - DM signal: $s^{1/2} = m_{DM}$ (but LHC is hadronic)
- <u>DM halo shape</u>:
 - símilar to antíP
- <u>Transport</u>:
- similar to antiP
- <u>Background</u>:
- similar to antiP, but here the background is very suppressed (especially at low T), and there is room for discovery potential
- Multí TeV DM: similar to antiP

Assessment on the antiP signal

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ANTI HELIUM



Anti ³Helium

$$\begin{array}{rcl} \chi\chi & \longrightarrow & (...) & \longrightarrow & (\bar{p},\bar{n},\bar{n}) & \longrightarrow & {}^{3}\overline{H} & \longrightarrow & {}^{3}\overline{He} \\ & & (\bar{p},\bar{p},\bar{n}) & \longrightarrow & {}^{3}\overline{He} \\ & & (\bar{p},\bar{p},\bar{n},\bar{n}) & \longrightarrow & {}^{4}\overline{He} \end{array}$$



F. Spada et al (AMS Collab), ICHEP 2008

Anti ³Helium



Cosmic structures and gamma-rays

The same Dark Matter structures that act as lenses can themselves emit light at various wavelengths, including the gamma-ray range

- From astrophysical sources hosted by DM halos (SFG, AGN)
- From DM itself (annihilation/decay)



Gamma-rays emitted by DM may exhibit strong correlation with lensing signal

Extragalactic Gamma Rays Background

Most recent measurement comes from Fermí-LAT

EGB obtained by subtracting resolved sources and (modeled) galactic foreground

Unresolved sources (blazars, SFG, radío galaxíes) contribute too

DM may contribute di EGB (very likely subdominantly)



Abdo et al. (Fermí), Phys. Rev. Lett. 104 (2010) 101101

Gamma-rays auto-correlation

Auto-correlation in the gamma-rays emission has been reported For I > 100 galactic foreground can be negleted: EGB contribution Features of the signal (energy and multipole independent) point toward interpretation in terms of blazars

DM plays here a (even more) subdominant role



Gamma-rays vs shear correlation

Proposal: look at the correlation between the observable that directly traces the presence of DM (weak lensing: shear) and the obervable that is a manifestation of the particle physics nature of DM (gamma-rays)



Camera, Fornasa, Fornengo, Regís, Astrophys.J. 771 (2013) L5

Correlation functions

Source Intensity $I_g(\vec{n}) = \int d\chi \, g(\chi, \vec{n}) \, \tilde{W}(\chi)$ Density field of the source

Cross-correlation angular power spectrum

$$C_{\ell}^{(ij)} = \frac{1}{\langle I_i \rangle \langle I_j \rangle} \int \frac{d\chi}{\chi^2} W_i(\chi) W_j(\chi) P_{ij}(k = \ell/\chi, \chi)$$

$$\langle \hat{f}_{g_i}(\chi, \mathbf{k}) \hat{f}_{g_j}^*(\chi', \mathbf{k}') \rangle = (2\pi)^3 \delta^3(\mathbf{k} - \mathbf{k}') P_{ij}(k, \chi, \chi')$$

$$f_g \equiv [g(\mathbf{x}|m, z)/\bar{g}(z) - 1]$$

$$\hat{f}_g : \text{Fourier tranform}$$

Window functions



Astrophysical sources

$$W^{\gamma_S}(E_{\gamma}, z) = \frac{A_S(z) \langle g_S(z) \rangle}{4\pi E_0^2} \int_{E_{\gamma}}^{\infty} dE \left(\frac{E}{E_0}\right)^{-\alpha} e^{-\tau(E, z)}$$

Window functions



Cross-correlation predictions



Fermi-LAT/5-yr with DES

Fermi-LAT/5-yr with Euclid



Reshift information in shear: can be used to separate lensing sources Energy spectrum of gamma-rays: can help in DM-mass reconstruction

Discovery potential



Cross-correlation forecasts



Fermi-LAT/5-yr with DES ("Fermi-enhanced" with Euclid under investigaton)

Camera, Fornasa, Fornengo, Regis, to appear

Auto and Cross Correlations



Cross-correlation of gamma-rays with gravitational probes and other wavelengths can act as a sort of filter and help to isolate a WIMP signature

Fornengo, Regis, Front. Physics 2 (2014) 6



Ando, Benoit-Levy, Komatsu, arXiv:1312.4403

Cross correlation signals

- <u>Gamma-rays</u>
- angular and energy resolution are both relevant
- statistics is important, too, otherwise resolutions are pointless
- sky coverage is another important issue

• <u>Cosmic-shear</u>

DES
0.3 < z < 1.5
13.3 gal / arcmín2
5000 squared degrees
2012-2017

Euclid 0 < z < 2.5 $30 \text{ gal} / \operatorname{arcmin2}$ 20000 squared degrees2020-2026

• <u>LSS</u>

- galaxy surveys under way

• <u>Radío</u>

- SKA and precursors, Lofar, ...