PROCEEDINGS OF SCIENCE

Indirect dark matter searches: A mini-review

Torsten BRINGMANN*
II. Institute for Theoretical Physics, University of Hamburg, Luruper Chausse 149, D-22761 Hamburg, Germany
E-mail: torsten.bringmann@desy.de

Weakly interacting massive particles (WIMPs) still arguably provide the leading hypothesis for the nature of the elusive cosmological dark matter. In astrophysical regions of high dark matter density, these particles would self-annihilate with rather high rates; trying to spot the annihilation products in cosmic rays of various kinds therefore provides a way, in principle, of indirectly detecting dark matter and thereby confirming the particle dark matter hypothesis. Here, I present a short review of the current situation of indirect searches with various messengers and comment on recent theoretical developments in the field. I conclude by advocating that a *dedicated* instrument for indirect dark matter detection, a concept so far familiar only from direct detection experiments, would allow to fully exploit the potential of indirect searches and make them truly complementary to direct and collider searches for dark matter.

The 2011 Europhysics Conference on High Energy Physics-HEP 2011,
July 21-27, 2011
Grenoble, Rhône-Alpes France

---

*Speaker.

PoS(EPS-HEP2011)061

1. Introduction

About eight decades after the existence of dark matter was first conjectured [1], its nature still remains an open issue. Evidence for the very existence of a non-baryonic, cold dark matter (DM) component in the total energy budget of the universe, however, has been accumulating significantly and now spans an impressive range of unrelated cosmological observations of its gravitational effects, covering distance scales from tens of kpc to several Gpc. There is thus indeed very little room for alternative explanations to a DM component which, according to the most recent measurements, contributes $\Omega_\chi = 0.229 \pm 0.015$ to the total energy density on cosmological scales [2].

While in principle there is a whole zoo of possibilities for the nature of DM, weakly Interacting Massive Particles (WIMPs) provide a theoretically particularly appealing and well-motivated class of candidates [3]. These particles usually arise as by-products in models for new physics that are introduced in order to address the shortcomings of the standard model of particle physics (SM) at the electroweak scale, in particular its extreme ultraviolet sensitivity in the scalar sector; as it turns out, WIMPs would be thermally produced in the early universe with a relic density that generically is rather close to the observed DM density today. The lightest supersymmetric neutralino is often taken as a standard template for such a WIMP, but alternative candidates like the lightest Kaluza-Klein photon in theories with universal extra dimensions [4] or the lightest T-odd particle in little Higgs models [5] provide interesting and viable alternatives. WIMPs are not only well-motivated from the point-of-view of particle physics, but have the additional advantage of being, at least in principle, detectable by means other than gravitational: at collider searches for missing transverse energy, in direct detection experiments looking for the recoil of WIMPs off the nuclei of terrestrial detectors or indirectly through the observation of WIMP annihilation products in cosmic rays of various kinds. In fact, it has been argued that the non-observation of any hints for new physics at the CERN LHC may already in the near future start to disfavor the WIMP DM hypothesis [6].

One generic challenge for indirect DM searches is the astrophysical distribution of DM. As it is difficult to constrain directly from kinematic observations – especially in the innermost part of the Milky Way, which is not DM-dominated – one essentially has to rely on the result of N-body simulations. For WIMPs, these consistently find cuspy DM distributions in virialized halos; recent high-resolution simulations [7] tend to somewhat favor the Einasto profile [8]

$$\rho_\chi(r) = \rho_s \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - 1\right)\right] \tag{1.1}$$

over the older, slightly steeper NFW profile [9] with $\rho_\chi \propto r^{-1}$ at small distances r from the center. For quantitative predictions of the expected annihilation flux, however, one unfortunately needs to extrapolate the above scaling behavior several orders of magnitude beyond the actual numerical resolution. Such simulations also do not (fully) include the effect of baryons which are likely to lead to a steeping of the DM profile [10], though one can also make the opposite case [11] (for a discussion of this still ongoing debate, see e.g. Ref. [12]). Also on the observational side, evidence has not yet converged, even for DM-dominated systems, whether there is a clear preference for shallow DM profiles with a central core [13] or full consistency with NFW profiles [14].

While the NFW (or Einasto) profile is a very natural assumption for WIMP DM, in particular useful to *constrain* the annihilation rate, one should keep in mind that the above mentioned uncertainties may induce a considerable uncertainty in the normalization of any signal. A convincing claim of indirect DM *detection* can thus in general only be expected when backed with distinctive spectral signatures that allow a discrimination from astrophysical sources – or simultaneous evidence in several channels that all point to the same, consistent description of DM parameters.

2. Gamma rays from DM annihilation

Gamma rays propagate essentially unperturbed through the galactic halo and therefore directly point back to their sources. The differential gamma-ray flux from a source in the direction ψ, averaged over the opening angle $\Delta\psi$ of the detector, is thus given by

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi) = \frac{\langle\sigma v\rangle_\mathrm{ann}}{4\pi m_\chi^2}\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} \times \frac{1}{2}\int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_\mathrm{l.o.s} d\ell(\psi)\rho^2(\mathbf{r})\,, \tag{2.1}$$

where $\langle\sigma v\rangle_\mathrm{ann}$ is the velocity-weighted annihilation cross section averaged over the line of sight (l.o.s.), m_χ the mass of the DM particle, B_f the branching ratio into channel f and N_γ^f the number of photons per annihilation; the right part counts the number of WIMP pairs along the line of sight.

The existence of clear spectral signatures is one of the great advantages of using gamma rays as detection channel. In general, the following contributions to the spectrum can be distinguished:

- At tree-level, WIMPs annihilate into pairs of quarks, leptons, Higgs and weak gauge bosons. *Secondary photons* are produced in the hadronization and further decay of these primary annihilation products, resulting in a featureless, almost universal spectrum with a rather soft cutoff at $E_\gamma = m_\chi$ [15].

- Photons from *internal bremsstrahlung* (IB) generically dominate at high energies, adding pronounced signatures like a very sharp cutoff at $E_\gamma = m_\chi$ or bump-like features at slightly smaller energies [16, 17] to the spectrum. Electroweak corrections, with a final state W or Z boson instead of a photon, can also give sizable corrections that could visibly effect the spectrum [18], albeit at smaller energies and thus typically in a less pronounced way.

- *Monochromatic γ-ray lines* from DM annihilation into two-body final states containing a photon [19] provide a striking signature. Unfortunately, these processes are loop-supressed and thus usually subdominant, i.e. not actually visible when taking into account realistic detector resolutions [17]; however, examples of particularly strong line signals exist [20].

Dedicated line searches have not reported any signals so far [21]. Extending such searches to IB-induced spectral features, on the other hand, might well be more promising [22] – not only because a signal would immediately provide important hints about the WIMP nature but also because even the resulting constraints on the *total* annihilation cross section may in some cases actually be stronger than those induced by secondary photons.

Traditionally, however, the focus has been on secondary photons since these dominate the spectrum at lower energies and the total number of photons above the detector threshold is a very convenient and simple measure to constrain possible exotic contributions to the observed gamma-ray flux. These constraints are then usually presented in the $\langle\sigma v\rangle$ vs. m_χ plane, assuming that WIMPs annihilate dominantly into $\bar{b}b$.

The currently strongest limits of this kind, for WIMP masses $m_\chi \lesssim 700\,\mathrm{GeV}$, are provided through observations of nearby dwarf galaxies by the Fermi satellite [23] ; for $m_\chi \lesssim 25\,\mathrm{GeV}$, these limits are actually stronger than $\langle\sigma v\rangle \sim 3\cdot 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$, the annihilation rate expected for thermally produced WIMPs in the most simple case (i.e. s-wave annihilation without resonances or co-annihilations [24]). At higher WIMP masses, $m_\chi \gtrsim 700\,\mathrm{GeV}$, the currently strongest limits are presented by the HESS collaboration from observations of the galactic center region [25]; at $m_\chi \sim 1\,\mathrm{TeV}$, these limits are about a factor of 10 weaker than the thermal value (see also Ref. [26, 27] for independent studies of these limits). Galaxy clusters may have an even better discovery potential [28], though current constraints are somewhat less stringent due to the involved astrophysical uncertainties [29]. Also constraints from the extragalactic diffuse gamma-ray background are very interesting, but strongly depend on the adopted model for the distribution of DM subhalos [30].

3. Charged Cosmic Rays from DM annihilation

Unlike gamma-rays, charged cosmic rays interact with both galactic magnetic fields and the interstellar matter and radiation fields. This adds, in general, more complex astrophysical uncertainties to any potential DM-induced component in observed cosmic-ray spectra – not the least because any pronounced spectral feature in the injection spectrum tends to get smeared out. The propagation of cosmic rays in the galaxy is well described by assuming scattering events on randomly distributed magnetic field inhomogeneities, resulting in a diffusion equation for the number density n of cosmic rays as a function of location and momentum p:

$$\frac{\partial}{\partial t}n - \nabla\left(K\nabla - V_c\right)n + \frac{\partial}{\partial p}b_{\mathrm{loss}}n - \frac{\partial}{\partial p}K_{EE}\frac{\partial}{\partial p}n = q_{\mathrm{source}}\,. \tag{3.1}$$

Here, K is the diffusion coefficient (often assumed to scale as a power-law with the particle rigidity, $K \propto \mathscr{R}^\delta$), V_c describes the effect of a convective "wind" (usually taken to transport particles away from the disk, $V_c \propto \hat{\mathbf{e}}_z$), b_{loss} describes all relevant energy losses, q_{source} includes both astrophysical and DM sources and K_{EE} encodes the effect of diffusive re-acceleration by a second order Fermi mechanism (i.e. acceleration due to moving scattering centers). The free parameters of propagation models can generally be very well determined from a fit to a rather small subset of cosmic ray data, in particular the ratio of secondary to primary species like B/C.

For the search of DM signals, one obviously has to concentrate on *antimatter* cosmic rays since these are much less abundant; in WIMP annihilations, on the other hand, CP invariance guarantees that particles and antiparticles are produced in equal amounts. In practice, this means that indirect searches using cosmic rays concentrate on antiprotons, anti-deuterium and positrons.

Antiprotons and Antideuterons

Astrophysical antiprotons are only produced as secondary products, through the spallation of interstellar gas (mostly hydrogen and helium) by impinging cosmic rays. The uncertainties in this background for DM searches are rather small, in particular for energies $T_{\bar{p}} \gtrsim 10\,\mathrm{GeV}$ where the propagation is completely dominated by diffusion – in fact, predictions [31] made on the basis of a B/C analysis [32] in a simple two-zone diffusion model perfectly agree with the subsequent data from BESSpolar [33] and PAMELA [34] in this regime.

The uncertainty in the expected primary antiproton flux from DM annihilations, however, is much larger for two reasons. The first is that the B/C analysis is restricted to sources in the disk; as a result there are strong degeneracies between parameters that do not affect the standard astrophysical background – most importantly between the diffusion constant K and the vertical size L of the diffusive halo of our Galaxy – but may lead to a variation of the expected primary flux (which strongly depends on the total volume probed and thus on L) by about one order of magnitude [35]. The unknown form of the dark matter profile may induce an uncertainty almost as big [31].

A DM-induced excess in the antiproton flux would have a rather featureless form, making a convincing discovery claim extremely difficult. Unlike for gamma rays, it could also not be used to distinguish between DM candidates [31]. Antiprotons may, however, be very efficient in setting constraints [36] – in particular on light DM candidates like those that seem to be compatible with recent claims in direct detection experiments [37]. In this context it is worth noting that the above mentioned degeneracy between the diffusion constant and L can be lifted when considering not only cosmic ray propagation but also synchrotron radiation [38]; the resulting lower bound on L would strengthen the antiproton bound on the DM annihilation rate considerably.

Finally, let us mention the case of antideuterons which have, so far, not been detected in cosmic rays. Since the expected flux at energies $E_{\bar{d}} \lesssim 1\,\mathrm{GeV}$ would be considerably higher from DM annihilations than for the astrophysical background, already the detection of a few antideuterons could be interpreted as a strong indication of a DM signal [39] – even though propagation uncertainties are at least as high as for antiprotons [40].

Positrons

The excess in cosmic-ray positrons at $E_{e^+} \gtrsim 10\,\mathrm{GeV}$ seen by PAMELA [41], as well as in follow-up observations of the electron *and* positron spectrum [42], has triggered a lot of excitement. Relatively soon, however, it became clear that a DM-related origin of the observed excess (as first proposed in Ref. [43]) is by far not the only – let alone the most natural – explanation in view of the fact that many good alternative astrophysical explanations exist (see Ref. [44] for a recent review). Measurements of the anisotropy in the positrons could be one possible way to distinguish between an astrophysical and a DM induced origin of the positron excess [45].

In complete contrast to antiprotons and antideuterons, the propagation of positrons is dominated by energy losses (through synchrotron radiation, inverse Compton scattering and bremsstrahlung emission). The positrons seen at earth are thus mostly produced locally and uncertainties in the propagation parameters have a much smaller effect than for antiprotons [46]. The lesson to be learned from PAMELA, however, is that our knowledge of the local population of *astrophysical sources* is simply not sufficient, at the time of writing, to use positrons as a reliable channel for indirect DM detection. Usually, they cannot even be used to set competitive bounds on the annihilation rate, either, because the predicted flux in standard WIMP models like neutralino DM is actually quite small compared to the expected astrophysical background [47].

4. Multi-wavelength approaches

Electrons and positrons may still be very useful to constrain or even detect the effect of annihilating dark matter. One example are models where annihilation happens predominantly into high-energy leptons, tailored to fit the above mentioned cosmic ray positron excess (like, e.g., [48]); an important effect that needs to be taken into account in this case would be the inverse Compton scattering of high-energy electrons and positrons on microwave background or starlight photons, leading to a potentially large additional gamma-ray component [49].

Electrons and positrons resulting from WIMP annihilations may also produce synchrotron radiation as a result of their interaction with the galactic magnetic field. Comparing this to radio data may indeed lead to rather strong constraints which, however, depend on the galactic magnetic field model adopted [50]. Particularly promising are truly multi-wavelength approaches that try to study the annihilation signal in several wavelengths simultaneously; the combined information from various channels can in this case provide important information and partially reduce systematic uncertainties (see Ref. [51] for a review and Ref. [52] for a recent example).

PoS(EPS-HEP2011)061

5. Neutrinos from DM annihilation

Neutrinos travel unperturbed just like photons. Due to their small interaction rate, however, they are usually not competitive to photons in setting limits on the WIMP annihilation rate when observing targets like the galactic center [53]. WIMPs could, however, become gravitationally trapped by celestial bodies like the sun or the earth and, after many subsequent scattering events, lose enough momentum to fall into the respective gravitational potential well and thus accumulate in the center; in this situation, neutrinos are the only annihilation products that would be visible. For the case of the sun, this actually leads to rather competitive limits [54] in some cases – not on the annihilation, but on the *scattering* rate of WIMPs with nuclei since this determines the rate with which WIMPs are captured and sink to the center of the sun, where they annihilate. These limits can actually be complementary not only to results from direct detection (in particular for spin-dependent scattering rates) but also to results from the LHC (see, e.g., [55]).

6. Conclusions and Outlook

Indirect searches have become very competitive in recent years and start to rule out (part of) the parameter space of well-motivated WIMP DM candidates. When constraining DM models, it is important to consider essentially all indirect detection channels because they probe different aspects of annihilating WIMPs. In terms of potential *signals*, gamma rays are particularly interesting since they carry spectral information which could be used to infer detailed properties of the DM nature, especially when correlated with indirect searches using other messengers or wavelengths.

Having (most likely) not seen any signal so far, a natural question is how far we could hope to get with indirect searches in the future. Space-based gamma-ray telescopes will always be limited by the effective area; ground-based detectors, on the other hand, are multi-purpose experiments dedicated to the physics of extreme objects, with DM only one among many important science goals, so the allocation of observation time will continue to be a critical issue. The main room for improvement thus seems to be in the design of a *dedicated* DM experiment [56] – a concept very familiar so far only from direct searches. In fact, a "Dark Matter Array" (DMA) with an upscaled, CTA-like setup (but optimized for the long observation of a very small number of selected DM sources) could gain almost two orders of magnitude in sensitivity with respect to CTA [56].

While this short review has focussed on indirect searches, it is important to stress the complementary nature of indirect, direct and collider searches: if a signal in more than one of these approaches can be established, it will be much more convincing to claim the (re)discovery of DM and to actually determine its particle properties. On the other hand, one should also keep in mind that the parameter space of well-motivated WIMP DM candidates extends well beyond the reach of *any* of these approaches, both for existing and currently planned experiments. A dedicated DM experiment like DMA would fully exploit the potential of indirect searches and could, even without very optimistic assumptions about the astrophysical distribution of DM, constrain models that are completely out of reach for both direct detection experiments and the LHC.

Acknowledgments

I wish to thank the organizers for inviting me to this conference and gratefully acknowledge support from the German Research Foundation (DFG) through Emmy Noether-grant BR 3954/1-1.

References

[1] F. Zwicky, *Helv. Phys. Acta* **6**, 110 (1933).

[2] E. Komatsu *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **192**, 18 (2011) [arXiv:1001.4538].

[3] for reviews see, e.g., G. Jungman, M. Kamionkowski and K. Griest, *Phys. Rept.* **267**, 195 (1996) [arXiv:hep-ph/9506380]; L. Bergström, *Rept. Prog. Phys.* **63**, 793 (2000) [arXiv:hep-ph/0002126]; G. Bertone, D. Hooper and J. Silk, *Phys. Rept.* **405**, 279 (2005) [arXiv:hep-ph/0404175].

[4] D. Hooper and S. Profumo, *Phys. Rept.* **453**, 29 (2007) [arXiv:hep-ph/0701197].

[5] A. Birkedal *et al.*, *Phys. Rev. D* **74**, 035002 (2006) [arXiv:hep-ph/0603077].

[6] G. Bertone, Nature **468**, 389-393 (2010) [arXiv:1011.3532].

[7] J. Diemand *et al.*, *Nature* **454**, 735 (2008) [arXiv:0805.1244]; V. Springel *et al.*, *MNRAS* **391**, 1685 (2008) [arXiv:0809.0898].

[8] J. Einasto, *Trudy Inst. Astroz. Alma-Ata* **51**, 87 (1965).

[9] J. F. Navarro, C. S. Frenk and S. D. M. White, *Astrophys. J.* **462**, 563 (1996) [arXiv:astro-ph/9508025].

[10] G. R. Blumenthal *et al.*, *Astrophys. J.* **301**, 27 (1986); M. Gustafsson, M. Fairbairn and J. Sommer-Larsen, *Phys. Rev. D* **74**, 123522 (2006) [arXiv:astro-ph/0608634]; J. R. Jardel and J. A. Sellwood, *Astrophys. J.* **691**, 1300 (2009) [arXiv:0808.3449]; D. Ceverino and A. Klypin, *Astrophys. J.* **695**, 292 (2009) [arXiv:0712.3285].

[11] S. Mashchenko, J. Wadsley and H. M. P. Couchman, *Science* **319**, 174 (2008) [arXiv:0711.4803]; S. Peirani, S. Kay and J. Silk, *Astron. Astrophys.* **479**, 123 (2008); T. Goerdt *et al.*, *MNRAS* **368**, 1073 (2006) [arXiv:astro-ph/0601404]; T. Goerdt *et al.*, Astrophys. J. **725**, 1707-1716 (2010) [arXiv:0806.1951]; A. El-Zant, I. Shlosman and Y. Hoffman, *Astrophys. J.* **560**, 636 (2001)

[arXiv:astro-ph/0103386]; C. Tonini *et al.*, Astrophys. J. **638**, L13 (2006) [arXiv:astro-ph/0510577]; E. Romano-Diaz *et al.*, *Astrophys. J.* **685**, L105 [arXiv:0808.0195].

[12] W. J. G. de Blok, arXiv:0910.3538; J. R. Primack, arXiv:0909.2247.

[13] G. Gilmore *et al.*, *Astrophys. J.* **663**, 948 (2007) [arXiv:astro-ph/0703308]; S.-H. Oh *et al..*, *Astronom. J.* **136**, 2761 (2008) [arXiv:0810.2119]; M. Spano *et al.*, *MNRAS* **383**, 297 (2008) [arXiv:0710.1345].

[14] L. E. Strigari, C. S. Frenk and S. D. M. White, arXiv:1003.4268.

[15] see, e.g., J. A. R. Cembranos *et al.*, Phys. Rev. **D83**, 083507 (2011). [arXiv:1009.4936].

[16] A. Birkedal *et al.*, arXiv:hep-ph/0507194.

[17] T. Bringmann, L. Bergström and J. Edsjö, *JHEP* **0801**, 049 (2008) [arXiv:0710.3169].

[18] N. F. Bell *et al.*, *Phys. Rev. D* **78**, 083540 (2008) [arXiv:0805.3423]; M. Kachelriess, P. D. Serpico and M. A. Solberg, *Phys. Rev. D* **80**, 123533 (2009) [arXiv:0911.0001]; P. Ciafaloni and A. Urbano, *Phys. Rev. D* **82**, 043512 (2010) [arXiv:1001.3950]; C. E. Yaguna, *Phys. Rev. D* **81**, 075024 (2010) [arXiv:1003.2730]; P. Ciafaloni *et al.*, JCAP **1103**, 019 (2011) [arXiv:1009.0224]; N. F. Bell *et al.*, Phys. Rev. **D83**, 013001 (2011) [arXiv:1009.2584].

[19] L. Bergström, P. Ullio and J. H. Buckley, *Astropart. Phys.* **9**, 137 (1998) [arXiv:astro-ph/9712318].

[20] see, e.g., M. Gustafsson *et al.*, *Phys. Rev. Lett.* **99**, 041301 (2007) [arXiv:astro-ph/0703512]; E. Dudas *et al.*, JHEP **0908**, 014 (2009) [arXiv:0904.1745]. Y. Mambrini, JCAP **0912**, 005 (2009) [arXiv:0907.2918].

[21] A.A. Pullen, R.R. Chary, M. Kamionkowski, Phys. Rev. D **76** (2007) 063006 [Erratum-ibid. **83** (2011) 029904] [arXiv:astro-ph/0610295]; F. A. Aharonian *et al.* [HEGRA Collaboration], Astron. Astrophys. **400**, 153 (2003) [astro-ph/0302347]; A. A. Abdo *et al.*, Phys. Rev. Lett. **104** (2010) 091302 [arXiv:1001.4836]; G. Vertongen and C. Weniger, JCAP **1105** (2011) 027 [arXiv:1101.2610].

[22] T. Bringmann *et al.*, *Phys. Rev. D* **84**, 103525 (2011) [arXiv:1106.1874].

[23] A. A. Abdo *et al.*, Astrophys. J. **712**, 147-158 (2010) [arXiv:1001.4531]; M. L. Garde *et al.*, [arXiv:1111.0320].

[24] K. Griest, D. Seckel, Phys. Rev. **D43**, 3191-3203 (1991).

[25] A. Abramowski *et al.* [H.E.S.S. Collaboration], Phys. Rev. Lett. **106**, 161301 (2011) [arXiv:1103.3266].

[26] A. Geringer-Sameth, S. M. Koushiappas, [arXiv:1108.2914].

[27] K. N. Abazajian, J. P. Harding, [arXiv:1110.6151].

[28] A. Pinzke, C. Pfrommer, L. Bergström, [arXiv:1105.3240].

[29] A. A. Abdo *et al.*, Astrophys. J. **712**, 147-158 (2010) [arXiv:1001.4531]; X. Huang, G. Vertongen, C. Weniger, [arXiv:1110.1529].

[30] A. A. Abdo *et al.* [Fermi-LAT Collaboration], JCAP **1004**, 014 (2010) [arXiv:1002.4415].

[31] T. Bringmann, P. Salati, Phys. Rev. **D75** (2007) 083006 [arXiv:astro-ph/0612514].

[32] D. Maurin *et al.*, Astrophys. J. **555**, 585-596 (2001) [arXiv:astro-ph/0101231].

[33] K. Abe *et al.*, Phys. Lett. B **670**, 103 (2008) [arXiv:0805.1754].

[34] O. Adriani *et al.* [PAMELA Collaboration], Phys. Rev. Lett. **105**, 121101 (2010) [arXiv:1007.0821].

[35] F. Donato *et al.*, Phys. Rev. D **69**, 063501 (2004) [arXiv:astro-ph/0306207].

[36] L. Bergström, J. Edsjö, P. Ullio, Phys. Rev. **D58**, 083507 (1998) [arXiv:astro-ph/9804050]; L. Bergström *et al.*, JCAP **0605**, 006 (2006) [arXiv:astro-ph/0602632]; F. Donato *et al.*, Phys. Rev. Lett. **102**, 071301 (2009) [arXiv:0810.5292 [astro-ph]].

[37] A. Bottino *et al.*, Phys. Rev. **D58**, 123503 (1998) [arXiv:astro-ph/9804137]; A. Bottino *et al.*, Phys. Rev. **D72**, 083518 (2005) [arXiv:hep-ph/0507086]; J. Lavalle, Phys. Rev. **D82**, 081302 (2010) [arXiv:1007.5253]; C. Evoli *et al.*, [arXiv:1108.0664].

[38] T. Bringmann, F. Donato, R. A. Lineros, [arXiv:1106.4821].

[39] F. Donato, N. Fornengo, P. Salati, Phys. Rev. **D62**, 043003 (2000) [arXiv:hep-ph/9904481].

[40] F. Donato, N. Fornengo, D. Maurin, Phys. Rev. **D78**, 043506 (2008) [arXiv:0803.2640].

[41] O. Adriani *et al.* [PAMELA Collaboration], Nature **458**, 607-609 (2009) [arXiv:0810.4995]; O. Adriani *et al.* [PAMELA Collaboration], Phys. Rev. Lett. **106**, 201101 (2011) [arXiv:1103.2880].

[42] J. Chang *et al.*, Nature **456**, 362-365 (2008); F. Aharonian *et al.* [H.E.S.S. Collaboration], Phys. Rev. Lett. **101**, 261104 (2008) [arXiv:0811.3894]; A. A. Abdo *et al.* [The Fermi LAT Collaboration], Phys. Rev. Lett. **102**, 181101 (2009) [arXiv:0905.0025]; F. Aharonian *et al.* [H.E.S.S. Collaboration], Astron. Astrophys. **508**, 561 (2009) [arXiv:0905.0105]; M. Ackermann *et al.* [Fermi LAT Collaboration], Phys. Rev. **D82**, 092004 (2010) [arXiv:1008.3999].

[43] L. Bergström, T. Bringmann, J. Edsjö, Phys. Rev. **D78**, 103520 (2008) [arXiv:0808.3725].

[44] P. D. Serpico, [arXiv:1108.4827].

[45] I. Cernuda, Astropart. Phys. **34**, 59-69 (2010) [arXiv:0905.1653]; G. Di Bernardo *et al.*, Astropart. Phys. **34**, 528-538 (2011) [arXiv:1010.0174].

[46] T. Delahaye *et al.*, Phys. Rev. **D77**, 063527 (2008) [arXiv:0712.2312]; T. Delahaye *et al.*, Astron. Astrophys. **501**, 821-833 (2009) [arXiv:0809.5268]; T. Delahaye *et al.*, Astron. Astrophys. **524**, A51 (2010) [arXiv:1002.1910].

[47] E. A. Baltz, J. Edsjö, Phys. Rev. **D59**, 023511 (1998) [astro-ph/9808243].

[48] N. Arkani-Hamed *et al.*, Phys. Rev. **D79**, 015014 (2009) [arXiv:0810.0713].

[49] I. Cholis *et al.*, Phys. Rev. **D80**, 123518 (2009) [arXiv:0811.3641]; J. Zhang *et al.*, Phys. Rev. **D80**, 023007 (2009) [arXiv:0812.0522]; M. Cirelli, P. Panci, Nucl. Phys. **B821**, 399-416 (2009) [arXiv:0904.3830]; S. Profumo, T. E. Jeltema, JCAP **0907**, 020 (2009) [arXiv:0906.0001].

[50] e.g. G. Bertone, G. Sigl, J. Silk, Mon. Not. Roy. Astron. Soc. **326**, 799-804 (2001) [astro-ph/0101134] and **337**, 98 (2002) [astro-ph/0203488]; D. Hooper, Phys. Rev. **D77**, 123523 (2008) [arXiv:0801.4378]; P. Grajek *et al.*, [arXiv:0807.1508]; E. Borriello, A. Cuoco, G. Miele, Phys. Rev. **D79**, 023518 (2009) [arXiv:0809.2990]; N. Fornengo *et al.*, [arXiv:1110.4337].

[51] e.g. S. Profumo, P. Ullio, [arXiv:1001.4086].

[52] H. S. Zechlin *et al.*, M. V. Fernandes, D. Elsaesser, D. Horns, [arXiv:1111.3514].

[53] R. Abbasi *et al.* [IceCube Collaboration], Phys. Rev. **D84**, 022004 (2011) [arXiv:1101.3349].

[54] R. Kappl, M. W. Winkler, Nucl. Phys. **B850**, 505-521 (2011) [arXiv:1104.0679]; K. Helbing, f. t. I. Collaboration, [arXiv:1107.5227].

[55] J. Hisano, K. Ishiwata, N. Nagata, [arXiv:1110.3719].

[56] L. Bergström, T. Bringmann, J. Edsjö, Phys. Rev. **D83** (2011) 045024 [arXiv:1011.4514].