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Dark Matter and Indirect Detection in Cosmic Rays

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Abstract. In the early years, cosmic rays contributed essentially to particle physics through the discovery of new particles. Will history repeat itself? As with the discovery of the charged pion, the recent discovery of a Higgs-like boson may portend a rich new set of particles within reach of current and near future experiments. These may be discovered and studied by cosmic rays through the indirect detection of dark matter.

Keywords: Dark matter, cosmic rays

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WILL HISTORY REPEAT ITSELF?

At this conference, we are celebrating 100 years of cosmic rays and looking to the future. As has been recounted here, the early years of cosmic rays were a glorious period, in part because cosmic rays contributed to the birth of particle physics through the discovery of new particles, including the positron, the muon, and the pion.

These discoveries were in some cases serendipitous, but let me focus on one that was not — the discovery of the charged pion, whose existence was predicted well in advance of its discovery. The history surrounding this discovery is well-known and fascinating and may be very briefly summarized as follows:

- 1935: To explain the strong nuclear force, Yukawa postulates new particle physics at the 100 MeV mass scale [1].
- 1947: A boson is discovered in this mass range, associated with a broken (global) symmetry: the charged pion [2].
- The next 20 years: Many accompanying particles are discovered and studied by both cosmic rays and particle accelerators.

Is a similar story developing in physics today? We have just witnessed another discovery of extraordinary importance, which may play out with striking similarities:

- 1934: To explain the weak nuclear force, Fermi postulates new particle physics at the 100 GeV mass scale [3].
- 2012: A boson is discovered in this mass range, associated with a broken (gauge) symmetry: the Higgs boson [4, 5].
- The next 20 years: Many accompanying particles are discovered and studied in both cosmic rays and particle accelerators.

Of course, the last point is still somewhat uncertain (for nitpickers, even the penultimate point requires confirmation), but there are good reasons to expect additional new particles at the weak scale. The Higgs boson mass is highly fine-tuned. All attempts to explain this fine-tuning predict new particles at the weak scale. This motivation may be viewed as an aesthetic one, but it is buttressed by another: the need for dark matter. Although there are many dark matter candidates, some particles with mass at the 100 GeV scale, the so-called weakly-interacting massive particles (WIMPs), have a privileged position. If one assumes a new particle X that was initially in thermal equilibrium in the early Universe, its relic density is determined by its annihilation cross section σ_A . The relation is remarkably simple:

$$\Omega_X \propto \frac{1}{\langle \sigma_A v \rangle} \sim \frac{m_X^2}{g_X^4}. \quad (1)$$

The last expression is simply the result of dimensional analysis, where m_X is the dark matter's mass, and g_X is the characteristic coupling that enters the dominant annihilation processes. If one assumes $g_X \sim 1$ and includes the neglected dimensionless parameters in (1), one finds that

$$\Omega_X \sim 0.1 \Rightarrow m_X \sim 100 \text{ GeV} ; \quad (2)$$

that is, requiring the new particle to have the right relic density to be dark matter requires its mass to be near the weak scale. This remarkable coincidence, the “WIMP miracle,” implies that particle physics and cosmology independently point to the weak scale as a promising place to look for new particles.

WIMP DARK MATTER DETECTION

The WIMP miracle not only motivates a class of dark matter candidates, it also tells us how to look for them. As illustrated in Fig. 1, the WIMP miracle requires efficient annihilation in the early Universe. Assuming annihilation is dominantly to known particles, this implies a four-particle X - X -SM-SM interaction, where SM denotes a standard model particle. This in turn implies that dark matter can be discovered through present day annihilation $XX \rightarrow \text{SM SM}$ (indirect detection), through scattering $X \text{ SM} \rightarrow X \text{ SM}$ (direct detection), and by producing it at colliders through $\text{SM SM} \rightarrow XX$ (provided the final state dark matter particles are accompanied by some visible particles).

In fact, not only does the WIMP miracle tell us how to look for dark matter, it also tells us (roughly) when to give up. Although we know little about dark matter, we do know that there cannot be too much of it. In the WIMP paradigm, this implies the four point interactions of Fig. 1 cannot be too weak, providing a floor to the most motivated annihilation, scattering, and production cross sections.

Here we will focus on indirect detection. The experimental program in this field may be summarized as attempts to fill in the following sentence in promising ways:

WIMPs annihilate in $\langle a \text{ place} \rangle$ to $\langle \text{particles} \rangle$ that are detected by $\langle \text{an experiment} \rangle$.

There are many ways to complete this sentence, and the indirect detection of dark matter is an extremely diverse, active, and exciting field. In the following, I will outline just three of the many possible directions being explored at present.

FIGURE 1. Dark Matter complementarity: For WIMPs to have the right relic density to be dark matter, they must annihilate efficiently in the early Universe. This implies efficient annihilation now and signals for indirect detection experiments, efficient scattering now and signals for direct detection experiments, and efficient production now at particle colliders.

INDIRECT DETECTION IN POSITRONS

WIMP dark matter may annihilate in the galactic halo to positrons that are detected by satellites and balloon-borne experiments. Following earlier measurements from HEAT [6] and AMS-01 [7] of the positron spectrum up to energies of ~ 10 GeV, this field has been re-animated with results from PAMELA [8] up to energies ~ 100 GeV that show positron fractions that increase with energy. This result has been confirmed recently by a clever analysis from Fermi-LAT [9] (See Fig. 2.) This increase is in conflict with standard expectations for astrophysical background [10], leading some to explore the possibility that the excess is a signal of dark matter annihilation.

Unfortunately, the signal is far larger than expected in the WIMP paradigm. As noted above, the requirement that WIMPs have the correct thermal relic density implies a characteristic annihilation cross section. The annihilation cross section required to reproduce the signal is 100 to 1000 times bigger, and so requires enhancements from particle physics that exploit the different kinematics of dark matter annihilation in the early universe and now. Alternatively, one may sacrifice the WIMP miracle, and dark matter may have a completely different production mechanism. In the meantime, researchers have recalled that pulsars may enhance the positron fraction with excesses that are of the required size [12, 13, 14, 15]. At present, pulsars appear to be by far the more natural and conservative explanation. Further progress awaits data from AMS-02 and proposed experiments, such as CALET.

FIGURE 2. The positron fraction as a function of energy as recently measured by PAMELA [8] and Fermi-LAT [9] up to energies of ~ 100 GeV. The lower dotted curves are the expectation from standard astrophysical background [10], and the higher solid and dashed curves include possible contributions from pulsars or dark matter annihilation [11].

INDIRECT DETECTION IN NEUTRINOS

WIMP dark matter may also annihilate in the center of the Sun to neutrinos that are detected by neutrino telescopes. A WIMP is captured by the Sun when it scatters off normal matter in the Sun and its velocity is reduced below escape velocity. This process implies that WIMPs build up in the Sun, providing a relatively large and nearby overdensity that enhances the annihilation signal.

For most WIMP candidates, the WIMP population in the Sun has reached equilibrium. The annihilation and capture rates are therefore equal, implying a relation between the annihilation and scattering cross sections. Indirect detection bounds may therefore be compared to direct detection bounds.

Preliminary bounds on spin-dependent WIMP-proton scattering from SuperKamiokande [16], ANTARES [17], and IceCube [18] are shown in Fig. 3. These limits are compared to direct detection bounds, and also to the expectations for neutralino dark matter [19, 20]. The indirect searches are seen to be the most stringent at present, and are probing the parameter space of well-motivated WIMP models. Remarkably, spin-independent probes from indirect detection are also becoming competitive with direct detection. The prospects for improved sensitivity are excellent as experiments continue to gather data, and new developments, such as the proposed in-fill array PINGU at IceCube, may greatly improve the experimental sensitivity to dark matter.

FIGURE 3. Limits on the WIMP-proton spin-dependent scattering cross section from searches for WIMPs annihilating to neutrinos in the Sun from the neutrino telescopes SuperKamiokande [16], ANTARES [17], and IceCube [18]. These indirect search limits assume that annihilation is dominantly to bottom quarks, τ leptons, and W bosons, as indicated, and are compared to the direct search limits from the KIMS and COUPP experiments.

INDIRECT DETECTION IN GAMMA RAYS

Last, WIMPs may annihilate in the galactic center or in dwarf galaxies to photons that are detected by space-based and balloon-borne experiments or by ground-based atmospheric Cherenkov telescopes. Traditionally the galactic center has been the favorite target for such sources, given its large overdensity, but the recent discovery of many dwarf galaxies has made them another prime target, with the lower dark matter densities compensated by the promise of reduced and better understood background.

Photon signals are of two kinds: continuum signals from dark matter annihilation to other particles with a radiated photon, and line signals from dark matter annihilating directly to γX , where most typically $X = \gamma, Z, h$. The continuum signal has a smooth energy distribution, but the expected continuum flux in most models is typically far larger than the line signal. Current bounds on dark matter annihilation cross sections from Fermi-LAT [21, 22] and HESS [23] are given in Fig. 4. Also shown for reference is the annihilation cross section $\langle \sigma_A v \rangle \simeq 3 \times 10^{-26} \text{ cm}^3/\text{s}$, which is what is required for dark matter to have the right relic density if it annihilates through s -channel processes. Some well-known dark matter candidates, such as the Kaluza-Klein photon [24, 25] in extra dimensional theories are s -channel annihilators, but some, such as the neutralino [19, 20] from supersymmetry, are not and predict reduced values of $\langle \sigma_A v \rangle$ now. However, the fact that current bounds are approaching this important reference value is a measure of the promise for these experiments to probe viable thermal relic models.

The line signal is in principle much easier to distinguish from backgrounds, but since dark matter does not couple directly to photons, the line signal is typically expected to

FIGURE 4. Bounds on dark matter annihilation cross sections from limits on continuum gamma ray fluxes from dwarf galaxies and the galactic center [26].

proceed only through loops in the Feynman diagram, and so is typically highly suppressed. At present, much activity and excitement surrounds a tentative line signal at $E_\gamma \simeq 135$ GeV [27]. The required annihilation cross section to explain this signal is very large, but models with such large signals existed even before the anomaly was reported [28, 29], and, of course, many more have been constructed since. Further progress to determine if the line signal is real and to improve sensitivities for both continuum and line searches is sure to come from continued running of existing experiments and upcoming experiments, including HESS-2, HAWC, CTA, DAMPE, GAMMA-400, HERD, as well as AMS-02 and CALET.

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REFERENCES

1. H. Yukawa, *Proc.Phys.Math.Soc.Jap.* **17**, 48–57 (1935).
2. C. Lattes, H. Muirhead, G. Occhialini, and C. Powell, *Nature* **159**, 694–697 (1947).
3. E. Fermi, *Z.Phys.* **88**, 161–177 (1934).
4. G. Aad, et al., *Phys.Lett.* **B716**, 1–29 (2012), 1207.7214.
5. S. Chatrchyan, et al., *Phys.Lett.* **B716**, 30–61 (2012), 1207.7235.
6. S. Barwick, et al., *Astrophys.J.* **482**, L191–L194 (1997), astro-ph/9703192.
7. M. Aguilar, et al., *Phys.Lett.* **B646**, 145–154 (2007), astro-ph/0703154.

8. O. Adriani, G. Barbarino, G. Bazilevskaya, R. Bellotti, M. Boezio, et al., *Astropart.Phys.* **34**, 1–11 (2010), 1001.3522.
9. M. Ackermann, et al., *Phys.Rev.Lett.* **108**, 011103 (2012), 1109.0521.
10. I. Moskalenko, and A. Strong, *Astrophys.J.* **493**, 694–707 (1998), astro-ph/9710124.
11. D. Grasso, and D. Gaggero (2011), 1110.2591.
12. A. K. Harding, and R. Ramaty, “The Pulsar Contribution to Galactic Cosmic Ray Positrons,” in *International Cosmic Ray Conference*, 1987, vol. 2 of *International Cosmic Ray Conference*, p. 92.
13. A. Boulares, *Astrophys. J.* **342**, 807–813 (1989).
14. F. A. Aharonian, A. M. Atoyan, and H. J. Voelk, *Astron. Astrophys.* **294**, L41–L44 (1995).
15. L. Zhang, and K. S. Cheng, *Astron. Astrophys.* **368**, 1063–1070 (2001).
16. T. Tanaka, et al., *Astrophys.J.* **742**, 78 (2011), 1108.3384.
17. V. Bertin, *J.Phys.Conf.Ser.* **375**, 012033 (2012).
18. C. Rott (2012), 1210.4161.
19. H. Goldberg, *Phys. Rev. Lett.* **50**, 1419 (1983).
20. J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. A. Olive, and M. Srednicki, *Nucl. Phys.* **B238**, 453–476 (1984).
21. A. Geringer-Sameth, and S. M. Koushiappas, *Phys.Rev.Lett.* **107**, 241303 (2011), 1108.2914.
22. M. Ackermann, et al., *Phys.Rev.Lett.* **107**, 241302 (2011), 1108.3546.
23. A. Abramowski, et al., *Phys.Rev.Lett.* **106**, 161301 (2011), 1103.3266.
24. G. Servant, and T. M. Tait, *Nucl.Phys.* **B650**, 391–419 (2003), hep-ph/0206071.
25. H.-C. Cheng, J. L. Feng, and K. T. Matchev, *Phys.Rev.Lett.* **89**, 211301 (2002), hep-ph/0207125.
26. K. N. Abazajian, and J. P. Harding, *JCAP* **1201**, 041 (2012), 1110.6151.
27. C. Weniger, *JCAP* **1208**, 007 (2012), 1204.2797.
28. E. Baltz, and L. Bergstrom, *Phys.Rev.* **D67**, 043516 (2003), hep-ph/0211325.
29. C. Jackson, G. Servant, G. Shaughnessy, T. M. Tait, and M. Taoso, *JCAP* **1004**, 004 (2010), 0912.0004.