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I review prospects for detecting dark matter in space-based experiments, with an emphasis on recent developments. I propose the "Martha Stewart criterion" for identifying dark matter candidates that are particularly worth investigation and focus on three that satisfy it: neutralino dark matter, Kaluza-Klein dark matter, and superWIMP gravitino dark matter.

1. Dark Matter Now

We live in interesting times: we know dark matter exists, and we now know how much. At the same time, we have very little idea what it is, other than that it can't be any known particle. Cosmology therefore provides the long-awaited quantitative evidence for new particle physics. The dark matter problem is arguably our strongest beacon, an unambiguous and fundamental, yet approachable, problem pointing us toward promising directions at the frontier.

As with most frontiers, the dark matter landscape is populated by a variety of colorful characters: axions [1–3], neutralinos [4,5], Q balls [6], wimpzillas [7], axinos [8], self-interacting dark matter [9], fuzzy dark matter [10], annihilating dark matter [11], Kaluza-Klein dark matter [12,13], superWIMP dark matter [14,15], and many others. To bring some order to the following discussion, if not to the field, we therefore need a guiding principle.

2. The Martha Stewart Criterion

The naturalness with which the observed relic density is obtained provides a selection criterion. Any proposal for dark matter must explain the observed relic density, the one piece of rather precise quantitative information we have about dark matter. For many dark matter candidates, the relic density may vary over many orders of magnitude, and the observed relic density is obtained by fine-tuning one or more free parameters. On the other hand, for some dark matter candidates the relic density is automatically in the correct range without the need to introduce and adjust new mass scales.

In the latter category, the most well-known examples are weakly-interacting massive particles (WIMPs). WIMP masses and annihilation cross sections are set by the weak scale, as dictated by particle physics considerations alone. In the early universe, all particles are in thermal equilibrium. As the universe cools, the number of stable, massive particles falls, eventually dropping exponentially with the Boltzmann suppression factor $e^{-m/T}$. Soon after that, however, when the annihilation rate falls below the expansion rate, the number of particles approaches a constant — the particles "freeze out." This behavior is shown in Fig. 1. It is well-known that for WIMPs, the freeze out relic density, a function of only the known energy scales $M_{\text{weak}} \sim 100$ GeV and $M_{\text{Planck}} \sim 10^{19}$ GeV, is naturally near the observed value $\Omega_{\text{DM}} \sim 0.1$.

What are we to make of this fact? Consider an analogous phenomenon that occurred much later in the history of the universe. On 27 December 2001, the American lifestyle guru Martha Stewart sold all of her ImClone stock. The next day, the price of ImClone stock began an exponential drop, eventually freezing out at a price roughly 1/4 its initial value. The ImClone stock price as a function of time is also shown in Fig. 1. Subsequently, Ms. Stewart was accused of insider trad-
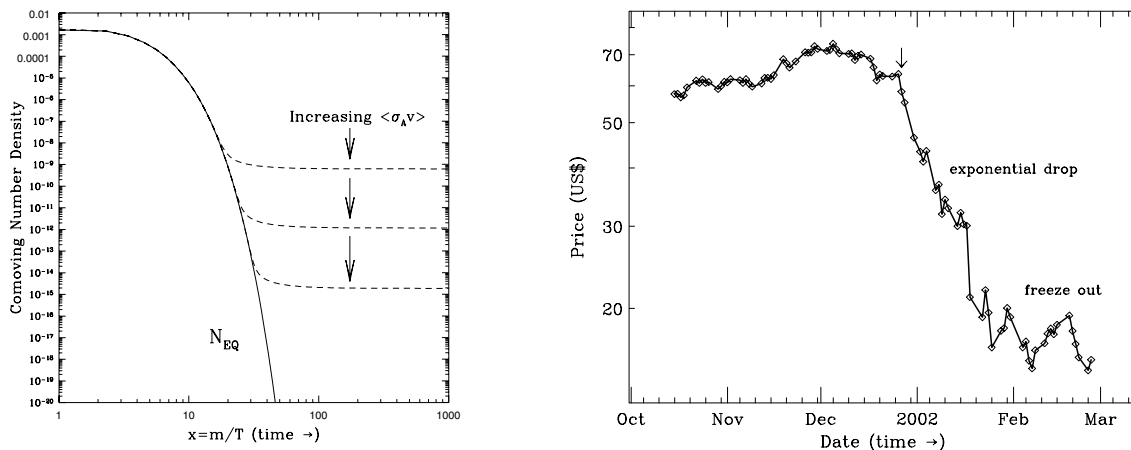
Figure 1. The number density of massive stable particles (left) and the price of ImClone stock (right) as functions of time. In the right panel, the date of Martha Stewart's stock sale is indicated by the arrow.

ing.

Is dark matter made of WIMPs? Is Ms. Stewart guilty? Both cases initially rest on what may simply be coincidences. However, in both cases, these coincidences are so remarkable that they warrant serious investigation. Here we will discuss three dark matter candidates that satisfy the "Martha Stewart criterion": they naturally obtain the observed relic density without the need to introduce and fine-tune new energy scales. There are, of course, other highly-motivated candidates, such as axions. Note, however, that an additional benefit of studying candidates that pass the Martha Stewart criterion is that the absence of completely unknown energy scales makes these scenarios relatively predictive. They are typically open to investigation from many directions, and so may be explored by a rich variety of methods at the interface of particle physics, astrophysics, and cosmology.

3. Neutralinos

Neutralinos χ are the prototypical WIMPs. Neutralinos are in general mixtures of the superpartners of neutral Higgs and gauge bosons. Par-

ticle physics considerations require their mass and interactions to be determined by the weak scale, and so they naturally freeze out with relic density near $\Omega_{\rm DM} \sim 0.1$, as discussed above. Note, however, that although neutralinos have become leading dark matter candidates, they are prototypical, but not typical. Not only are they fermions, which is not a WIMP requirement, but they are Majorana fermions (they are their own anti-particles). The latter property has strong consequences, as we will see.

Neutralinos may be detected directly by looking for scattering in highly sensitive detectors below the Earth's surface. The prospects for direct detection have been reviewed by Konstantin Matchev [16]. Here our focus is on space-based detection. We therefore consider indirect detection in which dark matter particles annihilate with each other somewhere in the universe, and their annihilation products are detected in space.

A leading indirect signal is positrons from $\chi\chi$ annihilation in the galactic halo [17,18]. Hard positrons are the best signal, as the background drops rapidly as positron energy increases, and the background is also better understood at high

energies. The best possible signal, then, would be from $\chi\chi \to e^+e^-$. Unfortunately, because neutralinos are Majorana fermions, the Pauli exclusion principle implies that a pair of neutralinos in an initial S-wave state has total angular momentum $J = 0$. This process is therefore extremely suppressed, either by the P-wave factor $v^2 \sim 10^{-6}$, where v is the average WIMP velocity now, or by $m_e/M_{\mathrm{weak}} \sim 10^{-5}$.

The next best hope for hard positrons if from $\chi\chi \to W^+W^-, ZZ$, followed by gauge boson decay to positrons. In many models, however, the neutralino is Bino-like, that is, it is the superpartner of the U(1) hypercharge gauge boson. In this case, it does not couple to SU(2) gauge bosons, and these modes are also suppressed. For Bino-like neutralinos, then, the leading sources of positrons are processes such as $\chi\chi \to \bar{b}b$, followed by $\bar{b} \to \bar{c}e^+\nu$. These signals are far from ideal, as the 3-body decays produce broad and soft positron energy distributions.

Another prominent indirect signal is photons from neutralino annihilation in the center of our galaxy [19,20]. The best signal is hard photons, but again the best hope, $\chi\chi \to \gamma\gamma$, is highly suppressed, as it is possible only through loop diagrams. The next best signal is $\chi\chi \to W^+W^-, ZZ$ followed by gauge bosons decaying eventually to photons. As noted above, however, in the case of a Bino-like neutralino, this is absent, and one must turn to $\chi\chi \to f\bar{f}$, resulting in relatively soft photons.

These points are nicely illustrated in minimal supergravity, a simple model that incorporates many of the virtues of weak-scale supersymmetry. Minimal supergravity is parametrized by 5 parameters, the most important of which are m_0 and $M_{1/2}$, the unified scalar and gaugino masses at the grand unified scale $M_{\mathrm{GUT}} \simeq 2 \times 10^{16}$ GeV.

A slice of minimal supergravity parameter space is shown in Fig. 2. In each panel, the region with the currently favored range of dark matter density [23,24] is red (dark shaded). This favored region has two branches. The region with $m_0 \lesssim 200$ GeV is known as the "bulk region." Here the neutralino is Bino-like and space-based indirect searches are therefore weak. However, in the cosmologically preferred region with $m_0 \gtrsim 1$ TeV, the "focus point region" [25,26], the neutralino is a Bino-Higgsino mixture, and space-based indirect searches are quite promising. Particularly relevant for the present discussion are the contours labeled Φ_{e^+} and Φ_γ^1, which denote the reaches of AMS and GLAST, respectively.

Given a specific model, such as minimal supergravity, the properties of many supersymmetric particles are correlated, and a broad range of data may have implications for dark matter. In fact, recent progress in particle physics and cosmology now disfavors the bulk region. In particular, the combination of the Higgs boson mass bound $m_h > 115$ GeV, the consistency of $B(b \to s\gamma)$ (and, possibly, $(g - 2)_\mu$) with standard model predictions, and the low value of Ω_{DM} favored by WMAP essentially excludes the bulk region. The focus point region remains as one of the viable alternatives, however. Recent progress therefore enhances the possibility that supersymmetric dark matter may have properties accessible to indirect detection through space-based experiments. Although this discussion has been confined to minimal supergravity, the line of argument is valid more generally and applies to model frameworks beyond minimal supergravity.

4. Kaluza-Klein Dark Matter

Another recent development is the investigation of dark matter candidates in models with extra spatial dimensions. Such models generically predict a tower of Kaluza-Klein (KK) particles for every field that propagates in the extra dimensions. It is natural to attempt to identify one of these KK particles with dark matter.

Of particular interest are models with universal extra dimensions, in which all standard model fields propagate [27]. If the extra dimensions are compactified on circles, such models predict massless states that have not been observed. To eliminate such states, one may compactify the extra dimensions on orbifolds. Such compactifications not only eliminate the unwanted states, but they also preserve a discrete symmetry, called KK-parity, which ensures the stability of the lightest KK particle. Particle physics provides motivations for tying the KK particle masses to the weak
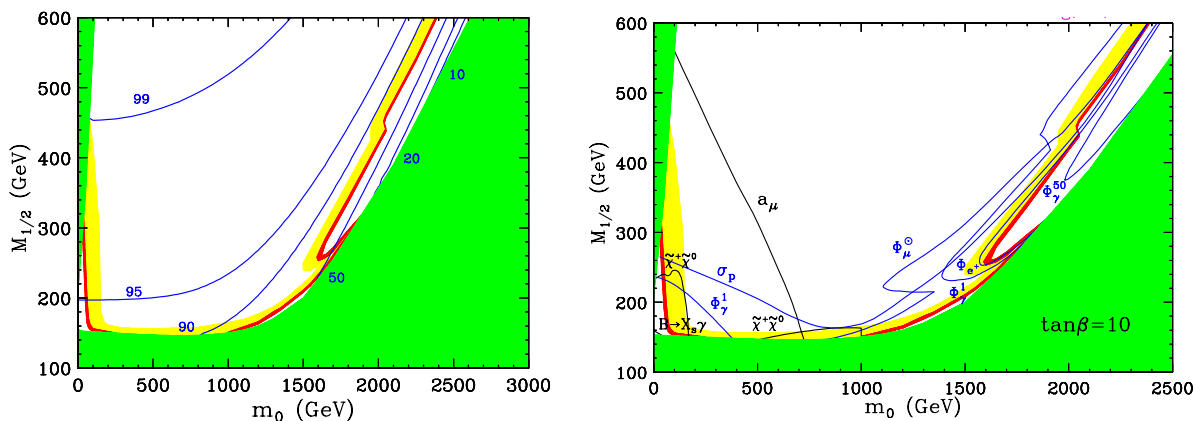
Figure 2. Left: Contours of neutralino gaugino-ness $R_\chi \equiv |a_{\tilde{B}}|^2 + |a_{\tilde{W}}|^2$ in percent, where $\chi = a_{\tilde{B}}(-i\tilde{B}) + a_{\tilde{W}}(-i\tilde{W}) + a_{\tilde{H}_d}\tilde{H}_d + a_{\tilde{H}_u}\tilde{H}_u$, in the $(m_0, M_{1/2})$ plane of minimal supergravity with $A_0 = 0$, $\tan\beta = 10$, and $\mu > 0$ [21]. The green (medium shaded) regions are excluded. In the yellow (light shaded) region, the thermal relic density satisfies the pre-WMAP constraint $0.1 < \Omega_{\mathrm{DM}}h^2 < 0.3$. In the red (dark shaded) region, the neutralino density is in the post-WMAP range $0.094 < \Omega_{\mathrm{DM}}h^2 < 0.129$. Right: Reaches of various high-energy collider and low-energy precision searches (black) and direct and indirect dark matter searches (blue) in the next few years [22]. The experiments probe regions below the contours indicated, and the shaded regions are as in the left panel.

scale, and for expecting the lightest KK particle to be neutral in charge and color [28]. In such models, then, an excellent dark matter candidate naturally emerges — a stable WIMP with relic density naturally in the right range.

Dark matter in universal extra dimension models is similar to dark matter in supersymmetry, with one key difference. In supersymmetry, superpartners differ in spin by $1/2$, but in extra dimensions, the excited KK states have the same spin as their ground state standard model partners. This has profound implications for dark matter. Suppose the lightest KK particle is the B^1 boson, the first excited KK state of the hypercharge gauge boson. Unlike the Bino, the B^1 is a vector particle with spin 1. The suppressions applicable to Majorana fermion dark matter therefore do not apply. For example, the process $B^1B^1 \to e^+e^-$ is unsuppressed, and, in fact, $\sim 20\%$ of B^1 annihilations occur through this channel.

Because the B^1 dark matter is highly non-relativistic now, positrons are therefore produced mono-energetically with energy equal to the dark matter mass. Positron spectra for various B^1 dark matter masses are shown in Fig. 3. The mono-energetic spike is modified by propagation in the galactic halo [29]. Despite this, we see that the positron signal retains a characteristic sharp upper edge. Detection of such a feature by the space-based experiments PAMELA and/or AMS would signal the discovery dark matter. At the same time, it would simultaneously exclude the soft and broad spectra predicted by neutralino dark matter, and would even provide a measurement of the dark matter particle's mass.

5. SuperWIMP Gravitino Dark Matter

Both supersymmetry and extra dimensions predict partner particles for all known particles. Can a partner of the graviton, either the grav-
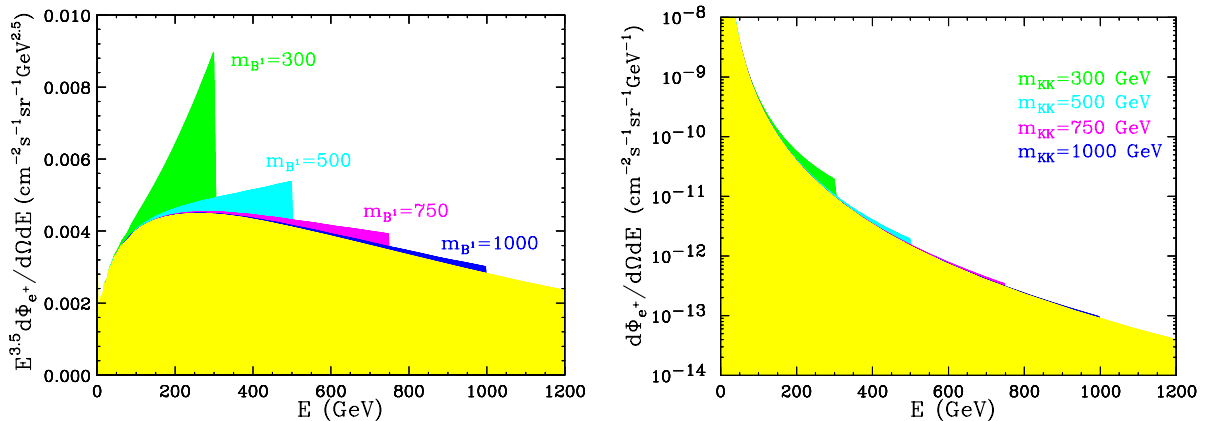
Figure 3. Positron spectra from B^1 dark matter annihilation for various B^1 masses as indicated [22]. The yellow (light shaded) region is the expected background. The differential flux is given in the right panel, and is modified by the factor E^3 in the left panel.

itino or a KK graviton, be the dark matter? Such particles are interesting, as they are minimal dark matter candidates in that they interact only through gravity, the only interaction required of dark matter.

Let us consider the gravitino. We assume it is the lightest supersymmetric particle. Given its extremely weak couplings, it will play no role in the early universe.[2] If the next-lightest supersymmetric particle is a WIMP, it will freeze out with a thermal relic density in the preferred range. However, it eventually decays to the gravitino with lifetime

$$\tau = \Gamma^{-1} \sim M_{\mathrm{Planck}}^2/M_{\mathrm{weak}}^3 \sim \ \mathrm{year} \ . \qquad (1)$$

The gravitino then inherits the desired relic density. As with conventional WIMPs, the gravitino relic density is determined by M_{weak} and M_{Planck} only. This scenario therefore satisfies the Martha Stewart criterion. Note, however,

that the gravitino is not a WIMP; rather it is a *super*weakly-interacting massive particle, or superWIMP.

Decays to gravitino superWIMPs occur long after Big Bang nucleosynthesis (BBN). One might therefore guess that the superWIMP scenario is excluded if one wants to preserve the successful BBN predictions for the light element abundances. The dominant form of visible energy released in decays to superWIMPs is electromagnetic. For such energy, BBN constraints are conveniently given in the $(\tau_{\mathrm{WIMP}}, \zeta_{\mathrm{EM}})$ plane. Here τ_{WIMP} is the WIMP lifetime, the time at which the energy is released, and

$$\zeta_{\mathrm{EM}} \equiv \epsilon_{\mathrm{EM}} Y_{\mathrm{WIMP}} \qquad (2)$$

is a measure of the energy released. In Eq. (2), ϵ_{EM} is the initial electromagnetic energy released in each WIMP decay, and $Y_{\mathrm{WIMP}} \equiv n_{\mathrm{WIMP}}/n_\gamma^{\mathrm{BG}}$ is the WIMP number density before they decay, normalized to the number density of background photons $n_\gamma^{\mathrm{BG}} = 2\zeta(3)T^3/\pi^2$.

The BBN-excluded regions are shaded in Fig. 4, and the predicted values of the superWIMP scenario are given by the grid. We see that BBN excludes some of the parameter space, but leaves

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[2]We assume that primordial number densities are diluted by inflation, and the universe reheats to a low enough temperature that there is no significant regeneration. For gravitinos, this is valid for reheat temperatures $T_{\mathrm{RH}} \lesssim 10^8 - 10^{10}$ GeV [30]; for KK gravitons, it requires $T_{\mathrm{RH}} \lesssim 1 - 100$ TeV [31].
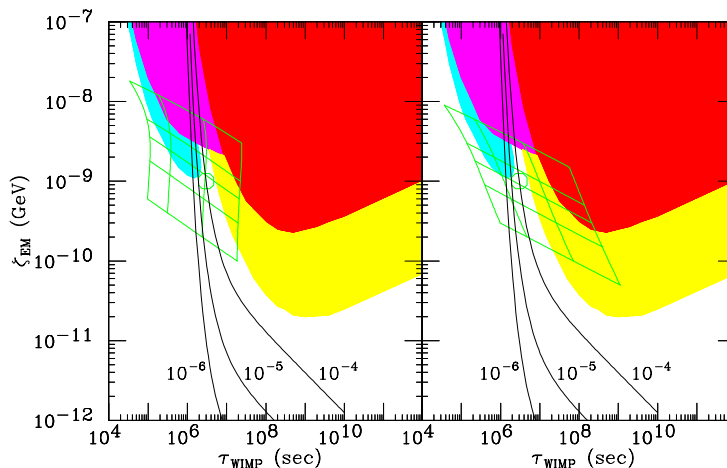
Figure 4. The grid gives predictions in the superWIMP gravitino dark matter scenario for decay time τ_{WIMP} and energy release ζ_{EM} from $\tilde{\gamma} \to \gamma \tilde{G}$ (left) and $\tilde{l} \to l\tilde{G}$ (right). The shaded regions are excluded by BBN, and the contours give values for μ distortions of the CMB [15].

much of it intact. In fact, inconsistencies in the standard BBN picture, notably the prediction of more ^{7}Li than is observed, currently prefer the decay time and energy release indicated by the circles in Fig. 4. SuperWIMP gravitino dark matter may not only pass BBN constraints, but may even resolve the leading current anomaly in standard BBN.

Can such a scenario be verified? In fact, it can — energy release in the early universe may also leave its imprint on the cosmic microwave background (CMB). Parameterizing the CMB spectral shape by

$$f(E) = \frac{1}{e^{E/(kT)+\mu} - 1} \ , \tag{3}$$

electromagnetic energy released at time $\tau \sim$ year cannot be completely thermalized, leading to $\mu > 0$. The predicted size of such "μ distortions" from decays to superWIMPs is given in Fig. 4. At present, the CMB is consistent with a Planckian spectrum; the current bound is $\mu < 9 \times 10^{-5}$. However, the Diffuse Microwave Emission Survey (DIMES), a future space mission, is designed

to probe μ distortions as low as $\mu \sim 10^{-6}$ and may discover μ distortions predicted in the superWIMP dark matter scenario.

If WIMPs and gravitinos are highly degenerate, WIMP decay may be very late. In the case of $\tilde{\gamma} \to \gamma \tilde{G}$, the produced photons may then be observed as bumps in the diffuse photon background. Predicted spectra are shown in Fig. 5. For the parameters indicated, the flux excesses are already excluded, but for other underlying supersymmetry parameters, the fluxes may be reduced to within current uncertainties. The robust prediction, however, is that any excess must occur in the keV to MeV range. Such signals may again by uncovered by space-based experiments, such as INTEGRAL now underway.

6. Summary and Outlook

We have reviewed some recent advances and their implications in the study of neutralino dark matter, Kaluza-Klein dark matter, and superWIMP gravitino dark matter. Space-based experiments, ranging from PAMELA and AMS, to
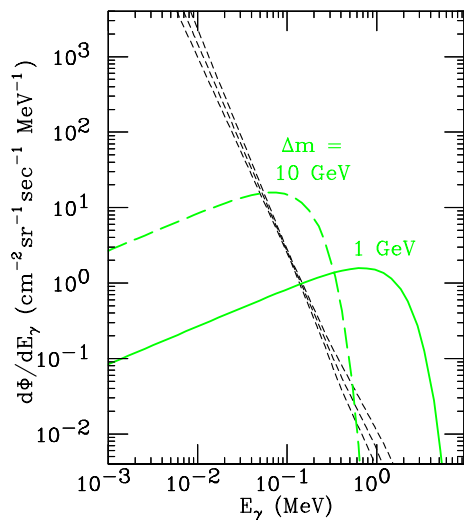
Figure 5. Diffuse photon flux predictions from decays $\tilde{\gamma} \rightarrow \gamma\tilde{G}$ in the superWIMP gravitino dark matter scenario [14]. The straight lines are existing measurements from HEAO, OSSE, and COMPTEL.

GLAST, DIMES, INTEGRAL, and many others, may shed light on these possibilities and, in some cases, may provide information that is impossible or very difficult to obtain in terrestrial experiments. These dark matter candidates satisfy the Martha Stewart criterion. They are therefore especially interesting as they naturally explain the observed dark matter relic density. Of course, there are many other known dark matter candidates and likely also many more to be discovered. Space-based experiments provide a window on many of these other possibilities also.

At the same time, although the importance of space-based experiments has been emphasized here, it is clear that the solution to the dark matter problem, even in the most favorable of circumstances, will require a multi-faceted approach drawing on inputs from particle physics, astrophysics, and cosmology. A schematic picture of how the different pieces might fit together for the case of neutralino dark matter is shown in

Fig. 6. By producing supersymmetric particles in the laboratory, the microscopic properties of neutralinos and other supersymmetric particles will be determined. These will then determine dark matter properties, such as annihilation rates and interaction cross sections. In parallel, astrophysical experiments and cosmological observations will be able to determine the relic density with even greater precision, and also possibly detect dark matter in a variety of ways. Only by combining all of these approaches can we hope to develop a compelling microscopic description of particle dark matter in the coming years.

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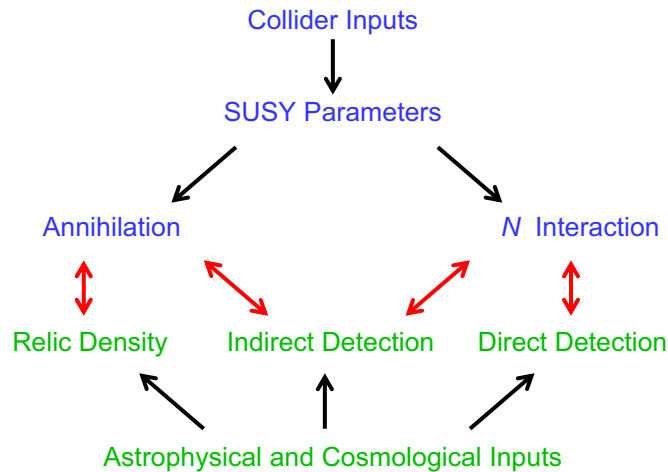13. H. C. Cheng, J. L. Feng and K. T. Matchev, Phys. Rev. Lett. **89**, 211301 (2002) [hep-

Figure 6. A schematic picture of the investigation of neutralino dark matter from the combined approaches of particle physics, astrophysics, and cosmology.

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