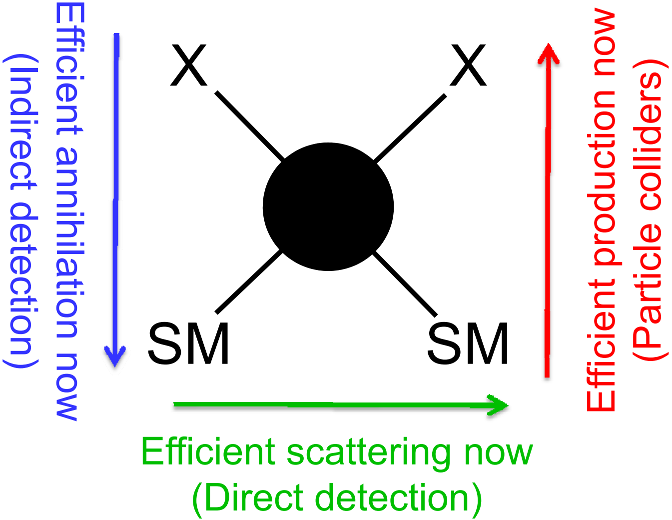
Indirect Detection of Dark Matter

Shruti Patel

Summer Term 2019: From the Largest to the Smallest Scales

Outline

1. Introduction, Motivation, Challenges
2. Estimates for Annihilations and Decay
3. Astrophysical Probes for DM searches
   3.1 Gamma Rays
   3.2 Solar Neutrinos
   3.3 Charged Cosmic Rays
4. Conclusions



[J.Feng, astro-ph:1211.3116]

Indirect Detection

- **Basic Principle**: Detection of Standard Model particle debris from Dark Matter interactions in the Universe
  - DM $\rightarrow$ quarks, leptons, bosons
  - these are or will produce cosmic rays, that we can detect on Earth $\rightarrow \gamma, \nu, e^{+}, \bar{p} \ \cdots$

Key Processes

- Pair annihilation of DM: $\chi + \chi \rightarrow$ SM
- Decay of DM: $\chi \rightarrow$ SM

Indirect Detection of WIMPs

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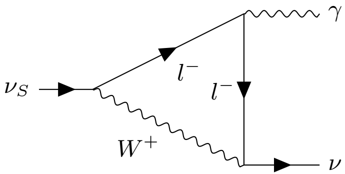
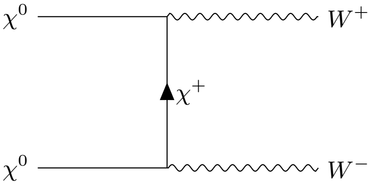
Caveats to this search paradigm

- $\chi + \chi \rightarrow$ SM can be highly suppressed if loop-induced
- $\chi \rightarrow$ SM may not occur at all in models where DM stability is protected by a symmetry (eg. a $\mathbb{Z}_2$ symmetry in the scalar sector, $\mathbb{R}$ parity in SUSY)



Diagrams for radiative decay of a sterile neutrino, to a photon and a neutrino.



Tree-level annihilation of a supersymmetric wino χ^0 to W bosons, through exchange of a chargino χ^+.

Advantages, Challenges and Motivations

Advantages

- Indirect detection benefits from huge amount of ambient DM in the Universe
- Existence of telescopes which provide access of exotic sources of DM particles over a large energy range

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Motivations

Indirect detection can probe questions not accessible in DD and collider searches

1. Is DM perfectly stable?
2. What is the explanation for the observed abundance of DM?

Estimates for Indirect Searches: Decaying DM

Considerations and Constraints

- Stable DM desirable to explain the large amount of DM in the Universe today, **without** resorting to enormous abundance at recombination $\leftarrow$ violates CMB limits!
- DM-Lifetime τ must be longer than age of the Universe:$\tau \gg$ few $\times 10^{17} s$

- Symmetries of a low-energy theory can be broken by high-scale physics

  $\Longrightarrow$ Symmetry-breaking operators suppressed at low energies
  $\Longrightarrow$ Timescale of decay via these operators can be sufficiently long

- Consider an $\mathcal{O}$(TeV) DM decaying through a Dim-6 operator suppressed by M_{GUT} $\sim 2 \times 10^{16}$ GeV
  - $\Gamma \sim m_\chi^5 \cos^4\theta$ ($\cos\theta$: mixing angle establishing the coupling to any intermediate channel)
  - Lifetime $\tau \sim M_{\mathsf{GUT}}^4 / m_\chi^5 \sim (2 \times 10^{16}\ \text{Gev})^4 / (10^3\ \text{Gev})^5 \sim 10^{26} s$

Estimates for Decaying DM

Would a decaying DM be observable? Let's make a back-of-the-envelope estimate

- Particle detection estimate for our local halo:

  with a volume element dV at distance r from Earth, with DM number density n, lifetime τ and detector area A

$$\frac{dN}{dt} = \frac{A}{4\pi r^2} \times n \frac{dV}{\tau} = A \times n(\vec{r}) \times \frac{d\Omega}{4\pi} \times \frac{dr}{\tau}$$

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- If $n(\vec{r})$ is the number density of DM within a 1 kpc distance of Earth we get

$$\text{counts/unit time} = \frac{A \cdot n \cdot r}{\tau} = \frac{A \cdot \rho \cdot r}{m_\chi \tau} = \frac{A \cdot (0.4\,\text{GeV/cm}^3) \cdot 1\text{kpc}}{m_\chi \tau}$$

  with $\rho \sim 0.4\,\text{GeV/cm}^3$ being the local DM density in the neighbourhood of the Earth

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- Using $m_\chi = 1$ TeV, $\tau = 10^{26} s$, and $A = 1$ m^2

$$\frac{dN}{dt} = 10^{-4}/s \sim \text{few 1000 events per year}$$

- Benhchmark detector: **AMS-02**: The Alpha Magnetic Spectrometer `[www.ams02.org]`

"Thermal relic" scenario

- If DM self-annihilates and was once in thermal equilibrium with the SM, late-time relic abundance can be entirely determined by the annihilation cross section σ_{ann}
- Measuring σ_{ann} at late times by observing the annihilation products would give direct insight into the mechanism governing DM abundance
- Annihilation rate per unit volume per unit time, for number densities n is $\sigma v_{\text{rel}} n^2/2$
- Annihilation rate scales as $n^2 \equiv \rho^2/m_\chi^2$ for fixed σ
  $\Longrightarrow$ limits on annihilation signals become weaker as the DM mass increases

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Detectability of thermal relic DM:

$$\frac{dN}{dt} = \frac{A\langle\sigma v_{\text{rel}}\rangle}{2}(1\,\text{kpc})\frac{\rho^2}{m_\chi^2} \sim 10^{-26}\text{cm}^3/\text{s} \times A \times (1\text{kpc}) \times \left(\frac{0.4\text{GeV}}{m_\chi}\right)^2 \text{cm}^{-6}$$

For $m_\chi = 100$ GeV, $\frac{dN}{dt} \sim 100$ events per year

Astrophysical Probes of DM

DM gravitationally trapped in celestial bodies fuels steady rate of annihilation/decay

Astrophysical Searches can be divided into two categories

1. Not-So-Indirect/Neutral searches:
   Probes can identify a source direction
   $\implies$ ν and γ rays mainly travelling in more-or-less straight lines

2. Indirect/Charged searches:
   Probes that do not "trace back" to the annihilation/decay event
   $\implies$ trajectories are bent as particles propagate

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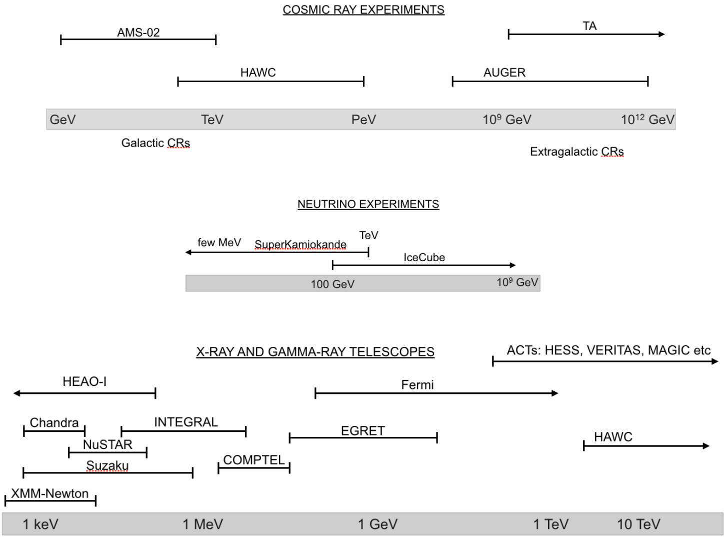
Current experiments consist of

- Cosmic-ray detectors, neutrino telescopes, photon telescopes in the radio and microwave bands
- photon telescopes in the hard UV, X-ray and gamma-ray bands

Astrophysical Probes of DM

[1710:05137]



Astrophysical Probes of DM

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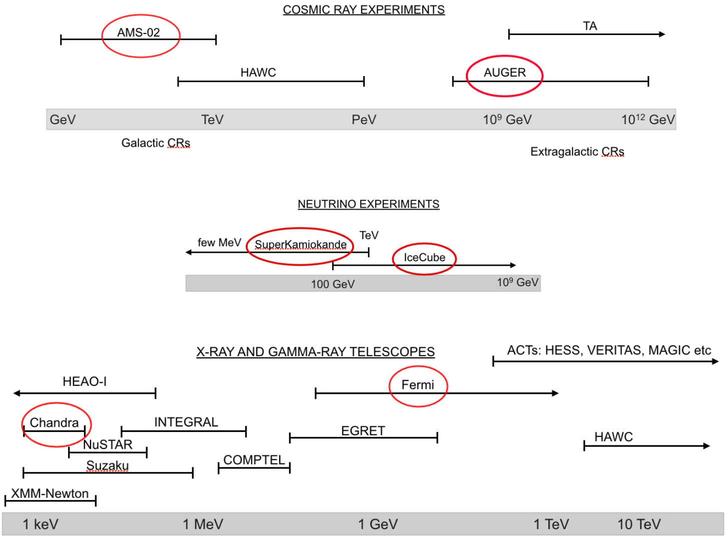

Detection of Neutral Particles: Ingredients

- γ rays and νs travel through space undisturbed, the resulting flux with R no. of particles:

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$$P = \frac{\langle \sigma v_{\text{rel}} \rangle}{2m_\chi^2} \cdot \sum_i BR_i \frac{dN_\gamma^i}{dE_i}\,,$$

BR_i= branching fraction to different annihilation channels
$\frac{dN_\gamma^i}{dE_i}$ = particle spectrum as function of energy, determines spectral shape of the signal

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- $J(\Delta\Omega)$ = DM Density Profile $\equiv$ **Astrophysical Input**

$$(\Delta\Omega) \propto \int_{\Delta\Omega} \int_{l=0}^{\infty} dl\, d\Omega \rho_\chi^2(l)$$

$J(\Delta\Omega)$ characterizes DM mass density, determined by gravitational probes or N-body simulations

Particle Physics Input: γ/ν Spectrum

Search strategy depends on the photon/neutrino spectrum per annihilation/decay

Three possible spectral categories for photons[1]:

1. Hadronic / photon-rich continuum:
   - $\chi\chi \to \{q, l, V\} \to \pi^{\pm}, \pi^0$
   - $\pi^0 \to \gamma\gamma$ has 99% branching ratio $\implies$ broad spectrum of γ produced along with $e^{\pm}$ from $\pi^{\pm}$ decays

2. Leptonic / photon-poor:
   - $\chi\chi \to \{e, \mu\}$
   - γ produced directly only as part of 3-body final states, by final state radiation or internal bremsstrahlung $\implies$ suppressed rate for γ production

3. Lines:
   - $\chi\chi \to \gamma\gamma$ (or $\bar{\nu}\nu$ in the neutrino case)
   - Allows for "bump hunts", a clear detection of a gamma-ray spectral line a **smoking gun for DM annihilation**
   - DM is neutral $\implies$ process is only induced via a loop

[1] Qualitatively similar for neutrinos except in the leptonic case

Three standard density profiles

1. **Navarro-Frenk-White (NFW) profile**

$$\rho_{\mathsf{NFW}}(r) = \frac{\rho_\odot}{\left(\frac{r}{R}\right)^\gamma \left(1+\frac{r}{R}\right)^{3-\gamma}} \stackrel{\gamma=1}{\equiv} \frac{\rho_\odot}{\frac{r}{R}\left(1+\frac{r}{R}\right)^2} \,,$$

   with r the distance from the galactic center, $R = 20$ kpc, $\rho_\odot = 0.4\mathrm{GeV/cm}^3$ at $r_\odot = 8.5$ kpc

2. **Einasto profile** (It fits micro-lensing and star velocity data best)

$$\rho_{\mathsf{Einasto}}(r) = \rho_\odot \;\exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{R}\right)^\alpha - 1\right)\right] \,,$$

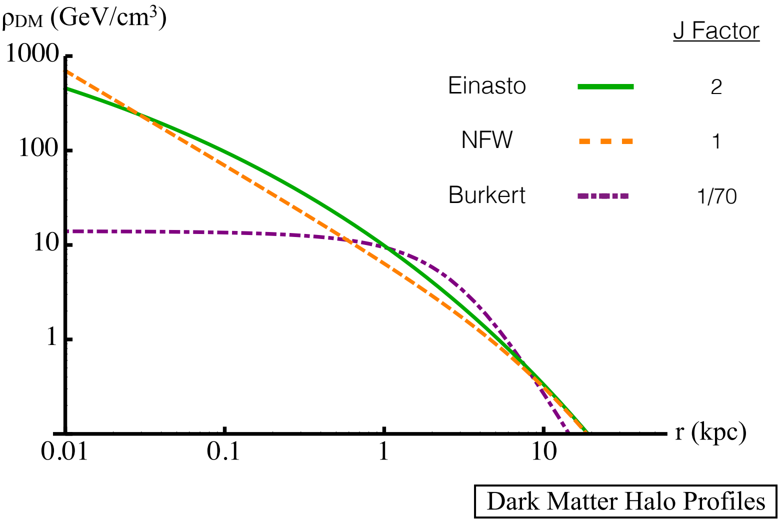
   with $\alpha = 0.17$ and $R = 20$ kpc

3. **Burkert profile**

$$\rho_{\mathsf{Burkert}}(r) = \frac{\rho_\odot}{\left(1+\frac{r}{R}\right)\left(1+\frac{r^2}{R^2}\right)}$$

   where we assume $R = 3$ kpc

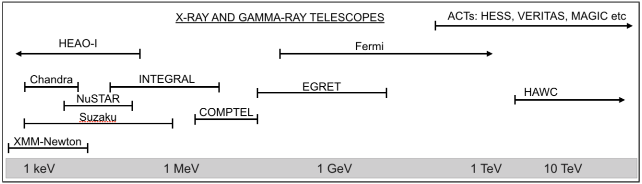
[Plehn: 1705.01987]

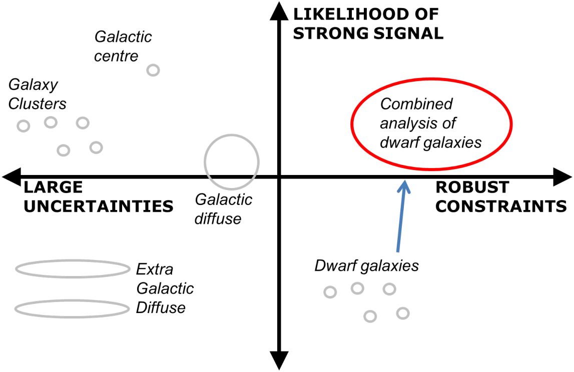


J-factors contribute significantly to the uncertainty in interpretation of signal

γ-Ray Probes: Galaxy Targets and Detectors

[1411.1925]





[PhD Thesis: G. Giesen]

target region	advantages	inconveniences
Galactic Center	high concentration of DM close proximity $\rightarrow$ spectral features as smoking gun	uncertainty on the DM profile important population of γ-ray sources diffuse emission from cosmic rays
dSph	no γ-ray point sources no intrinsic diffuse emission no substructures	"ultra-faint" satellites recently reevaluated uncertainties on DM distribution
Dark satellites	smoking gun confirmation of ΛCDM	not found yet
Clusters	DM dominated bright sources	unknown substructures uncertainty on the mass profile
Galactic diffuse emission	spectral and spatial distribution can be used	astrophysical diffuse emission
Isotropic background	spectral and spatial distribution can be used	halo and subhalo abundance as a function of redshift to be modeled contribution of astrophysical sources

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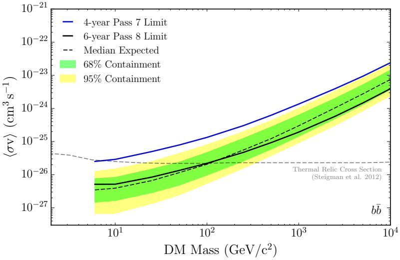
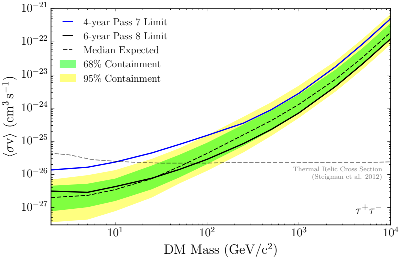
γ-Ray Probes: Constraints from Fermi-LAT



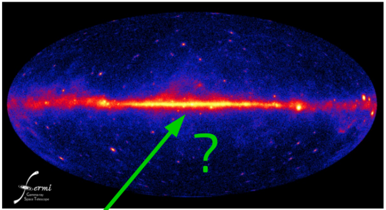


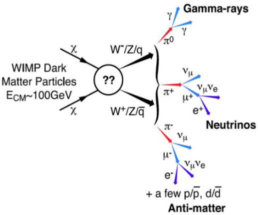
Constraints on DM from a combined analysis of 15 dSph using 4- and 6-years of Fermi-LAT data

[Christoph Weniger, GRAPPA, Presented at 13th Recontres du Vietnam]

The Fermi Galactic center/bulge GeV excess

Five years of
Fermi LAT data
> 1 GeV





- Initial claims by Goodenough & Hooper (2009) (see also Vitale & Morselli (2009))
- Approved by Fermi LAT collaboration in 2015
- Controversial discussion about origin continuous

Is this a dark matter annihilation signal?

Neutrinos give a handle on Direct Detection cross-sections

- The main edge for ν-telescopes is Solar Neutrinos
- WIMPs scatter against Hydrogen in the Sun and subsequently annihilate $\Longrightarrow$ ν searches from the Sun sensitive to **spin-dependent** (SD) WIMP-nucleon cross-section

- Capture rate for DM in the Sun for SD scattering [Hooper, Kribs: hep-ph/0208261]

$$C^{\odot}_{\mathrm{SD}} \simeq 3.35 \times 10^{18}\,\mathrm{s}^{-1} \left(\frac{\rho_{\mathrm{local}}}{0.3\,\mathrm{GeV/cm}^3}\right) \left(\frac{270\,\mathrm{km/s}}{\bar{v}_{\mathrm{local}}}\right)^3 \left(\frac{\sigma_{\mathrm{H,SD}}}{10^{-6}\,\mathrm{pb}}\right) \left(\frac{1000\,\mathrm{GeV}}{m_\chi}\right)^2$$

- Analogous formula for the capture rate from spin-independent (scalar) scattering

$$C^{\odot}_{\mathrm{SI}} \simeq 1.24 \times 10^{18}\,\mathrm{s}^{-1} \left(\frac{\rho_{\mathrm{local}}}{0.3\,\mathrm{GeV/cm}^3}\right) \left(\frac{270\,\mathrm{km/s}}{\bar{v}_{\mathrm{local}}}\right)^3 \left(\frac{2.6\,\sigma_{\mathrm{H,SI}} + 0.175\,\sigma_{\mathrm{He,SI}}}{10^{-6}\,\mathrm{pb}}\right) \left(\frac{1000\,\mathrm{GeV}}{m_\chi}\right)^2$$

- Factors of 2.6 and 0.175 from solar abundances of elements, dynamical factors, form factor suppression
- **Spin-dependent cross section 3 or 4x larger than spin-independent cross section**

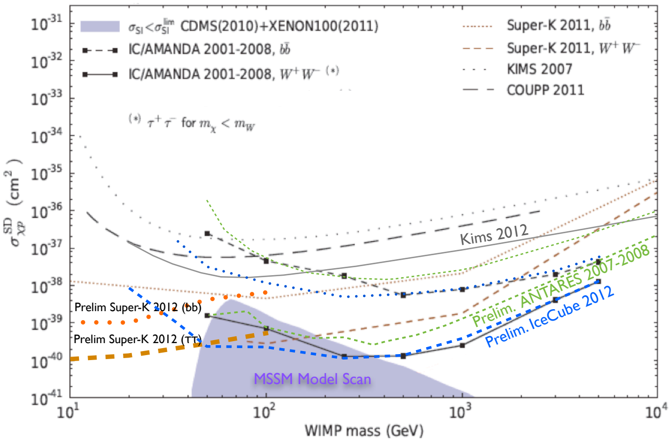
ν Probes: Direct Detection In Disguise

If the capture and annihilation cross sections are high, the Sun reaches equilibrium between these processes.

- For N WIMPs in the Sun, the rate of change is
$$\dot{N} = C^{\odot} - A^{\odot} N^2$$
with Annihilation Rate $A^{\odot} = \frac{\langle \sigma v \rangle}{V_{\rm eff}}$
- $V_{\rm eff}$ is effective volume of the core $\rightarrow$ determined by matching core temperature with the gravitational potential energy of a single WIMP at core radius
- Solving the diff. equation gives the annihilation rate in the Sun
$$\Gamma = \frac{1}{2} A^{\odot} N^2 = \frac{1}{2} C^{\odot} \tanh^2 \left(\sqrt{C^{\odot} A^{\odot}}\, t_{\odot} \right)$$
- $t_{\odot} \simeq 4.5$ billion years+ $\rightarrow$ age of the solar system.
- $A^{\odot}$ maximized when it reaches equilibrium with $C^{\odot}$
$$\sqrt{C^{\odot} A^{\odot}} t_{\odot} \gg 1$$
- At equilibrium $\Gamma \simeq \frac{C^{\odot}}{2}$ and resulting ν flux is
$$\frac{dN_{\nu_f}}{dE_{\nu_f}} = \frac{C^{\odot}}{8\pi (D^{\odot})^2} \left(\frac{dN_{\nu_f}}{dE_{\nu_f}} \right)_{\rm inj} \implies \text{Limits on } \sigma_{\rm H,DS}$$

ν Probes: Direct Detection In Disguise

[Feng, astro-ph:1211.3116]

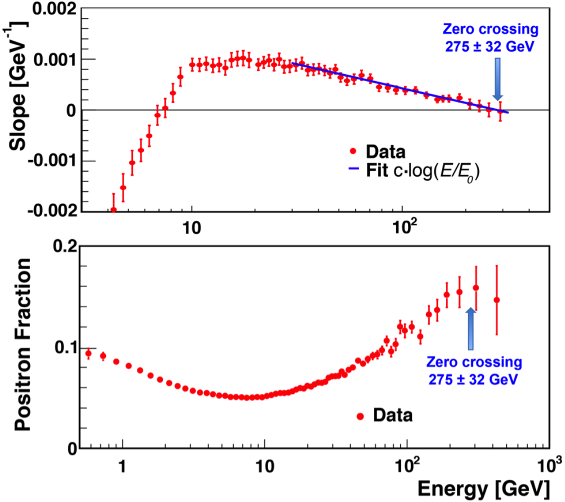


Limits on SD scattering cross section from **COUPP** - The Chicagoland Observatory for Underground Particle Physics, **KIMS**- Korea Invisible Mass Search, **Super-K** and **AMANDA**- Antarctic Muon And Neutrino Detector Array

A Quick Word on Charged Cosmic Rays

- Main signature for DM in charged cosmic rays is in the anti-proton and positron channel
- Anti-particles rarely produced in secondary processes
- Even a small addition of anti-particles produced in WIMP-annihilation could give detectable signal
- Signal takes form of rise in $\frac{e^+}{e^-}$ or $\frac{\bar{p}}{p}$ ratio
- Smoking Gun signature provided by **anti-deuteron** $\rightarrow$ Expected signal 4x larger than background for energies < 1GeV/n

[Accardo et al, AMS COLLABORATION]

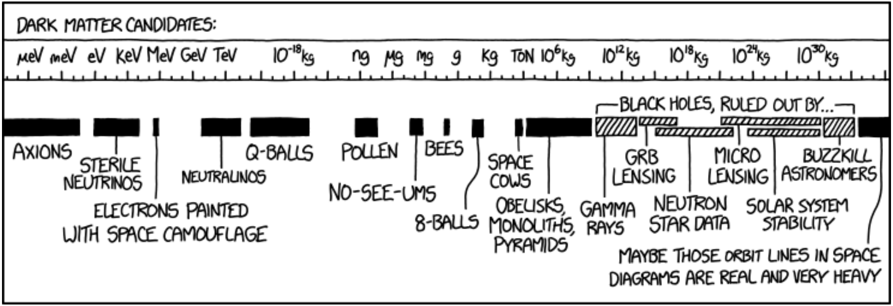


Slope parameter and positron fraction as measured by AMS

Summary

1. Indirect Searches for DM complementary to Direct and Collider searches
2. We can get insights to questions that cannot be answered by other searches
   - DM Stability
   - Explanation for Relic Abundance
3. Indirect Detection is divided into searches for Neutral and Charged Cosmic Rays
4. Hints of an excess at the galactic center and in the positron/electron fraction in the earth's atmosphere not fully resolved but point to exciting developments to come

Thank you for your attention!



[Randall Munroe: XKCD]

References

1. Title Picture: Astronomy Picture of the Day (nasa.gov)
2. TASI Lectures on Indirect Detection of Dark Matter by Tracy R. Slatyer
3. Indirect Detection of WIMP Dark Matter: a compact review by Jan Conrad
4. An Introduction to Particle Dark Matter by Stefano Profumo
5. Conclusion Picture: Randall Munroe (xkcd.com/2035/)