Cosmic-Ray Signatures of Dark Matter Decay

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Outline

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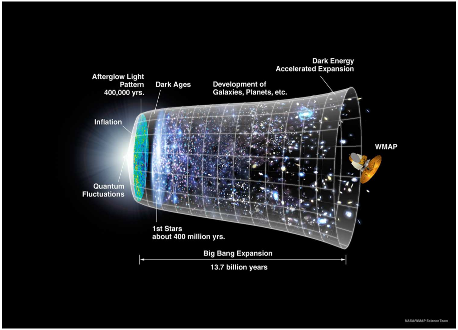
1. Unstable Dark Matter and Indirect Detection
2. Charged Particles from Dark Matter Decay
3. Gamma Rays from Dark Matter Decay
4. Conclusions

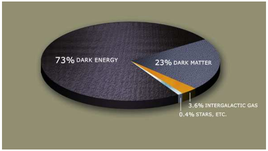
Dark Matter Stability – An Assumption

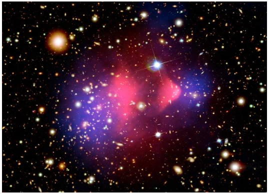


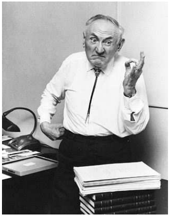
- We do not know whether the dark matter particles are **perfectly** stable – from the presence of dark matter in the Universe today we can only infer stability on a cosmological timescale,

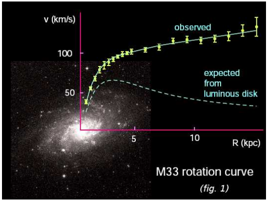
$$\tau_{\mathrm{DM}} > \tau_{\mathrm{universe}} \sim 4 \times 10^{17}\ \mathrm{s}$$

Established Dark Matter Properties









Dark matter clearly exists and is

- massive
- electrically neutral and colorless
- cold
- non-baryonic
- stable

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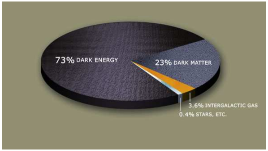
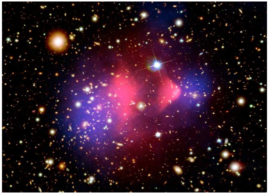
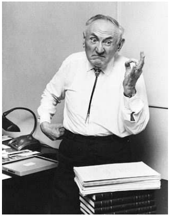
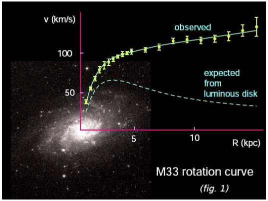




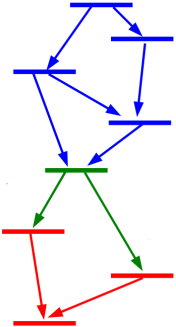




Dark matter clearly exists and is

- massive
- electrically neutral and colorless
- cold
- non-baryonic
- ~~stable~~ very long-lived

Extending the Standard Model...



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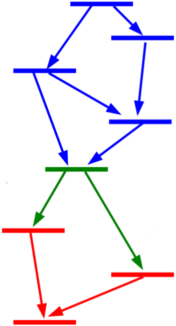

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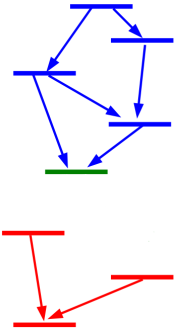

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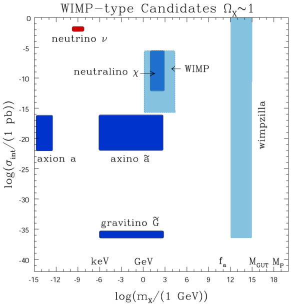
- In SUSY, the lightest neutralino typically has a lifetime of $\tau_\chi \sim 10^{-25}$ s if there is no extra suppression of its decays to the Standard Model → imposing R-parity ensures absolute stability of the LSP

Looking for Dark Matter Candidates



[Roszkowski '05]

- (Supersymmetric) WIMPs are excellent dark matter candidates, but they make up only a part of the parameter space suitable for finding dark matter candidates

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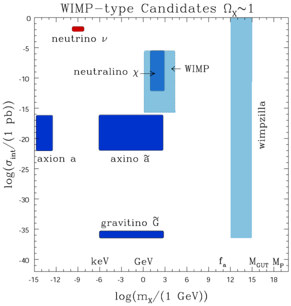
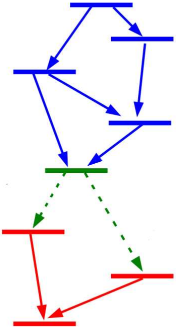


[Roszkowski '05]

- (Supersymmetric) WIMPs are excellent dark matter candidates, but they make up only a part of the parameter space suitable for finding dark matter candidates
- Super-weakly interacting particles like the gravitino are natural candidates for dark matter and typically have long lifetimes

Extending the Standard Model...



- Super-WIMPs only require a moderate suppression of couplings to obtain a lifetime compatible with dark matter
- There are viable dark matter candidates that are unstable, potentially producing detectable cosmic rays via their decays (positrons, antiprotons, gamma rays, neutrinos, antideuterons, ...)

Some Candidates for Decaying Dark Matter

- Gravitino dark matter with broken R-parity
  [Takayama, Yamaguchi '00], [Buchmüller, Covi, Hamaguchi, Ibarra, Yanagida '07]
  [Ibarra, DT '08], [Ishiwata, Matsumoto, Moroi '08]
  [Chen, Ji, Mohapatra, Nussinov, Zhang '08, '09]
  [Buchmüller, Ibarra, Shindou, Takayama, DT '09]
- Hidden sector gauge bosons/gauginos
  [Ibarra, Ringwald, DT, Weniger '08, '09]
  [Chen, Takahashi, Yanagida '08, '09]
- Right-handed sneutrinos in models with Dirac masses
  [Pospelov, Trott '08]
- Hidden sector fermions
  [Hamaguchi, Shirai, Yanagida '08]
  [Arvanitaki, Dimopoulos, Dubovsky, Graham, Harnik, Rajendran '08, '09]
- Bound states of strongly interacting particles
  [Hamaguchi, Nakamura, Shirai, Yanagida '08]
  [Nardi, Sannino, Strumia '08]

Different Approaches to Dark Matter Detection

- Collider searches: SM SM → DM X
- Direct detection: DM nucleus → DM nucleus
- Indirect detection: DM DM → SM SM

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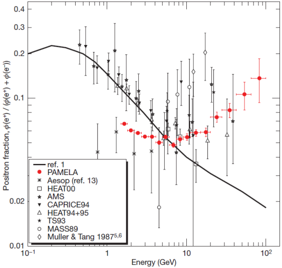
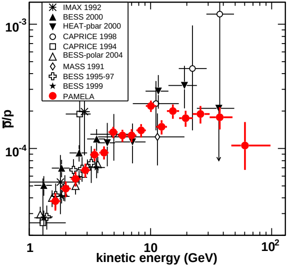
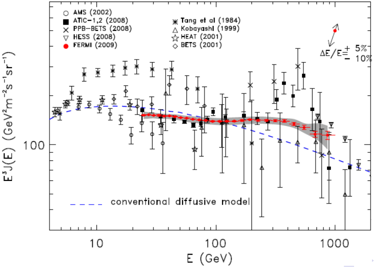
A Wealth of New Data on Charged Cosmic Rays

- New and unexpected results from PAMELA, Fermi, ATIC,... over the last year





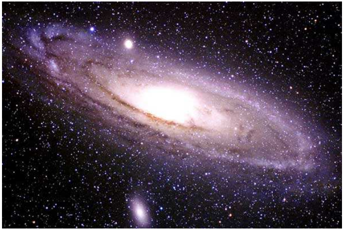


Can This Be Due to Dark Matter Decay?

- The source of electrons/positrons must be **local** and capable of producing leptons with energies of $\mathcal{O}(100\ \text{GeV})$
- Assuming that they are due to dark matter decay, what dark matter properties can we infer from the PAMELA/Fermi electron anomalies?
- Inject various cosmic-ray species all over the dark matter halo and propagate them to our position in the Galaxy

$$0 = \text{source} + \text{diffusion} + \text{energy loss} + \text{convection} + \ldots$$

Solving the Transport Equation

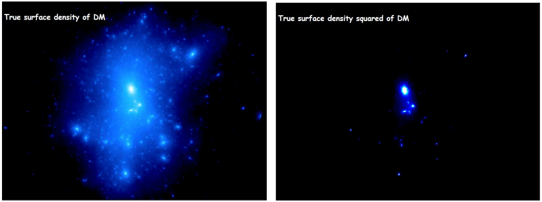


- Assumption: the Milky Way disk is embedded in a diffusive magnetic halo of cylindrical shape
- → Exploit symmetries and make simplifying assumptions to find semi-analytical solutions to the transport equation – the solutions for positrons and antiprotons correspond to limiting cases of the full transport equation [Donato et al.]

  OR

  → Employ a computer code to treat the problem completely numerically: e.g. GALPROP [Moskalenko and Strong]

The Source Term for Cosmic Rays from DM Decay



[Moore et al. '05]

- Annihilating dark matter:
  $Q_i(E,r,z) = \langle \sigma v \rangle \, \rho^2_{\text{DM}}(r,z)/m^2_{\text{DM}} \; dN_i/dE$
- Decaying dark matter:
  $Q_i(E,r,z) = \rho_{\text{DM}}(r,z)/(m_{\text{DM}}\tau_{\text{DM}}) \; dN_i/dE$

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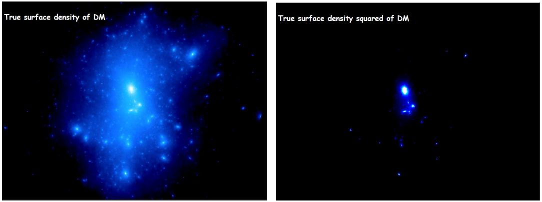

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- Decaying dark matter:
  $Q_i(E,r,z) = \rho_{\mathsf{DM}}(r,z)/(m_{\mathsf{DM}}\tau_{\mathsf{DM}})\ dN_i/dE$
- Important qualitative differences:
  - No signal enhancement from dark matter substructures (no boost factors) → Strategies like looking for annihilation signals from the center of the Galaxy or from the Sun/Earth are not applicable
  - Indirect signatures of dark matter decay are less sensitive to uncertainties in the dark matter distribution

A Model-Independent Look at the PAMELA/Fermi Results

- Assume "model 0" background which fits low-energy electron data fairly well, but leaves a deficit at high energies
- We examined various dark matter decay channels for different masses and lifetimes

For fermionic dark matter particles:

$$\psi_{\text{DM}} \rightarrow Z^0\nu,\ W^{\pm}\ell^{\mp},\ \ell^{\pm}\ell^{\mp}\nu$$

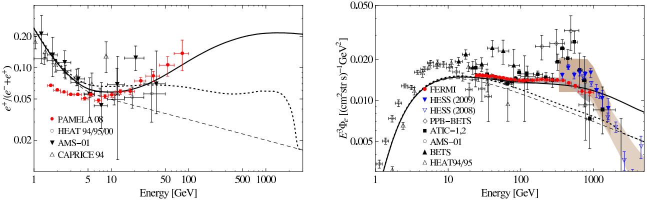
For scalar dark matter particles:

$$\phi_{\text{DM}} \rightarrow Z^0Z^0,\ W^{\pm}W^{\mp},\ \ell^{\pm}\ell^{\mp}$$

- Hadronization was simulated using a Monte Carlo code (PYTHIA 6.4) to obtain the energy spectra dN_i/dE of photons, positrons, antiprotons...

Positrons from Gauge Boson Fragmentation

- Positrons from gauge boson fragmentation can give a sizable contribution to the positron fraction, but are rather soft
- The recent results on the total electron + positron flux from Fermi LAT give additional constraints



[Ibarra, DT, Weniger '09]

- $\psi_{\text{DM}} \rightarrow Z^0\nu$. The positron spectrum from hadronization of gauge bosons is too flat and does not agree well with either PAMELA or Fermi unless the dark matter is extremely heavy (which seems to be in conflict with HESS observations).

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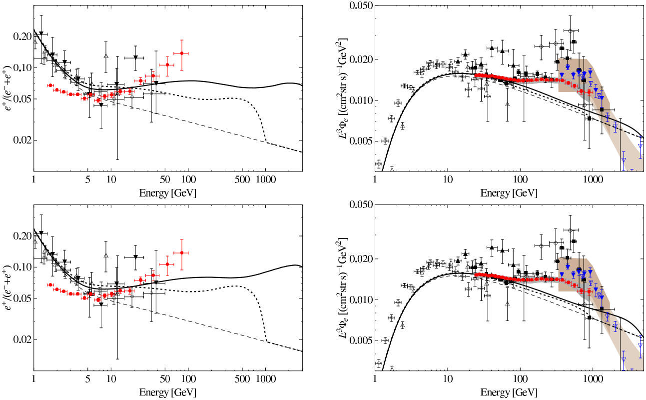
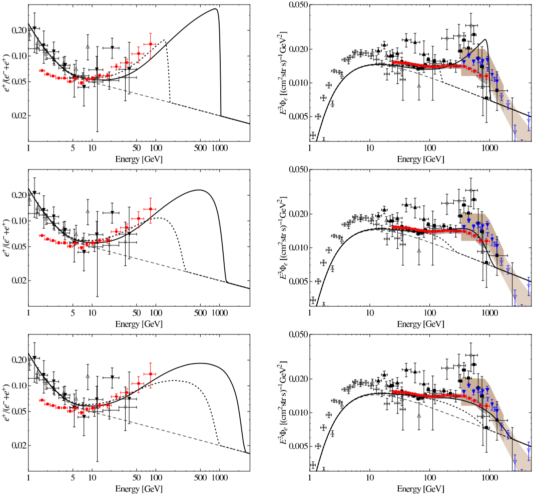


[Ibarra, DT, Weniger '09]

- $\phi_{\text{DM}} \to Z^0Z^0, W^\pm W^\mp$. The spectrum from the hadronization of gauge bosons fails to account for either of the observations due to the softness of the spectrum.

Positrons from Direct Decay into Leptons



[Ibarra, DT, Weniger '09]

- $\phi_{\rm DM} \longrightarrow \ell^\pm\ell^\mp$. Hard leptons from two-body decays reproduce the steep rise in the positron fraction quite well. However, decays into the first generation yield spectral features unobserved by Fermi.

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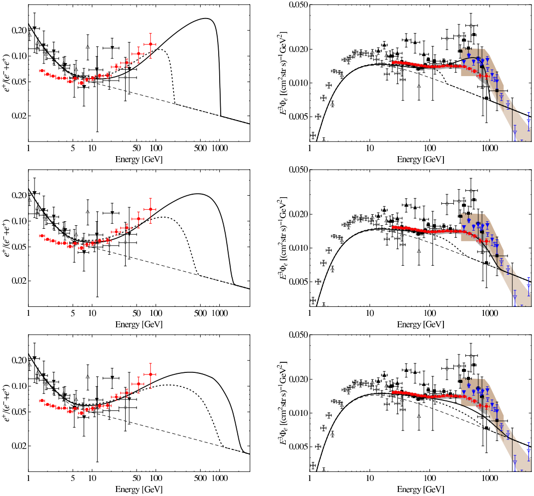

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Decay Channels in Light of the Fermi Results

- The almost perfect power-law behavior $\propto E^{-3.0}$ with no distinct spectral features of the total electron + positron flux observed by Fermi disfavors pure decays into first-generation leptons and requires dark matter masses $\mathcal{O}(1\ \text{TeV})$
- The most promising decay channels to fit both PAMELA and Fermi electron measurements are

$$\begin{aligned}
\psi_{\text{DM}} &\rightarrow \mu^+\mu^-\nu, \quad m_{\text{DM}} = 3.5\ \text{TeV} \\
\psi_{\text{DM}} &\rightarrow \ell^+\ell^-\nu, \quad m_{\text{DM}} = 2.5\ \text{TeV} \\
\psi_{\text{DM}} &\rightarrow W^\pm\mu^\mp, \quad m_{\text{DM}} = 3.0\ \text{TeV} \\
\phi_{\text{DM}} &\rightarrow \mu^+\mu^-, \quad m_{\text{DM}} = 2.5\ \text{TeV} \\
\phi_{\text{DM}} &\rightarrow \tau^+\tau^-, \quad m_{\text{DM}} = 5.0\ \text{TeV}
\end{aligned}$$

with lifetimes $\sim (1\ldots2)\times 10^{26}$ sec

A lifetime of 10^{26} seconds?!

- A possible interpretation: The lifetime of a TeV-mass particle decaying via a dimension-6 operator suppressed by a mass scale M is given by

$$\tau_{\text{DM}} \sim 2 \times 10^{26} \text{ sec} \left(\frac{\text{TeV}}{m_{\text{DM}}}\right)^5 \left(\frac{M}{10^{16} \text{ GeV}}\right)^4$$

- M is remarkably close to the Grand Unification scale $M_{\text{GUT}} = 2 \times 10^{16}$ GeV for lifetimes $\mathcal{O}(10^{26})$ sec

  [Eichler '89]

  [Arvanitaki, Dimopoulos, Dubovsky, Graham, Harnik, Rajendran '08]

  [Hamaguchi, Shirai, Yanagida '08]

- It may be possible to probe the GUT scale via cosmic rays from dark matter decay

An unnaturally large dark matter mass?

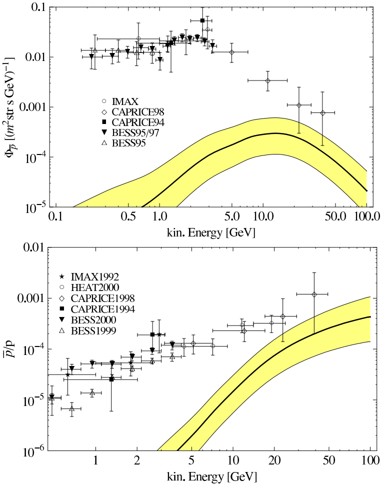
- The flux of cosmic rays from dark matter decay is invariant under a rescaling of abundance/lifetime:

$$\text{Source term} \propto \rho_{\text{DM}}/(m_{\text{DM}}\tau_{\text{DM}})$$

- It is conceivable that the anomalous cosmic-ray signatures are caused by the decay of a subdominant dark matter component into the dominant dark matter component
- The primary dark matter could then be completely stable and possibly detectable in direct dark matter searches

Example: Hidden sector gauginos decaying into dark matter neutralinos via kinetic mixing [Ibarra, Ringwald, DT, Weniger '09]

Antiproton Constraints from PAMELA $\bar{p}/p$



[Ibarra, DT, Weniger '09]

- Measurements of the antiproton-to-proton ratio by PAMELA can exclude otherwise promising decay channels like $\psi_{\text{DM}} \rightarrow W^{\pm}\mu^{\mp}$.

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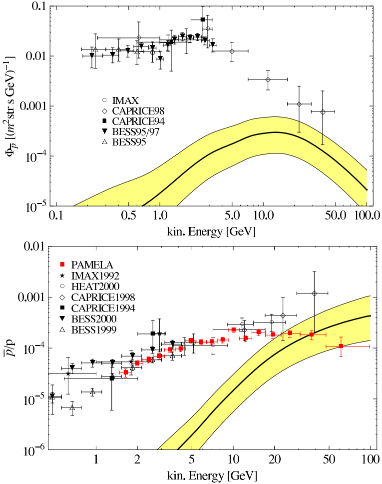

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    - Prompt radiation, e.g.

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$$\text{DM} \rightarrow Z^0 \rightarrow \pi^0 \rightarrow \gamma\gamma$$

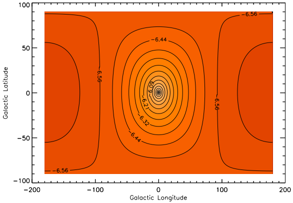
  - Subsequent inverse Compton scattering of energetic $e^\pm$ from DM decay on the interstellar radiation field, e.g.

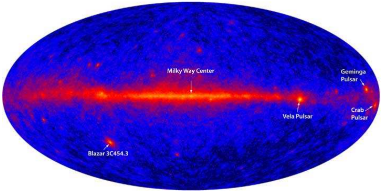
$$\begin{aligned} \text{DM} \quad \rightarrow \quad e^+e^- \quad & \rightarrow \quad \text{... propagation of } e^\pm \text{ ...} \\ & \rightarrow \quad e^\pm\gamma \quad \rightarrow \quad e^\pm\gamma \end{aligned}$$

    Energy loss of high-energy $e^\pm$ → upscattering of low-energy ISRF photons

Gamma Rays from Dark Matter Decay

- We are located far from the center of the Galactic dark matter halo → Prediction of an anisotropic dark matter contribution to the background of “extragalactic” gamma rays due to the decay of dark matter particles in the Milky Way halo

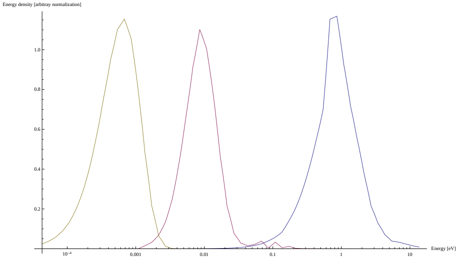




[Bertone, Buchmüller, Covi, Ibarra ’07]

Gamma Rays from Inverse Compton Scattering

- Charged particles interacting with the interstellar radiation field (CMB, dust radiation, starlight) can upscatter photons to gamma-ray energies

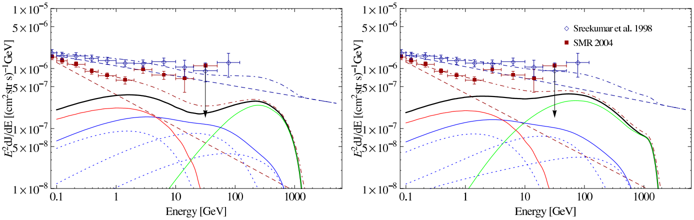


[Porter et al. '05]

- Inverse Compton yields an additional contribution to anisotropies in diffuse gamma rays

Contribution to the Diffuse Gamma-Ray Background

- For dark matter lifetimes $\mathcal{O}(10^{26})$ sec one generally gets an $\mathcal{O}(0.1\ldots1)$ contribution to the diffuse extragalactic background from prompt radiation and inverse Compton
- This can yield a deviation from the expected power-law behavior in the diffuse background, for example in $\psi_{\text{DM}} \to \ell^{\pm}\ell^{\mp}\nu$, $\psi_{\text{DM}} \to W^{\pm}\mu^{\mp}$



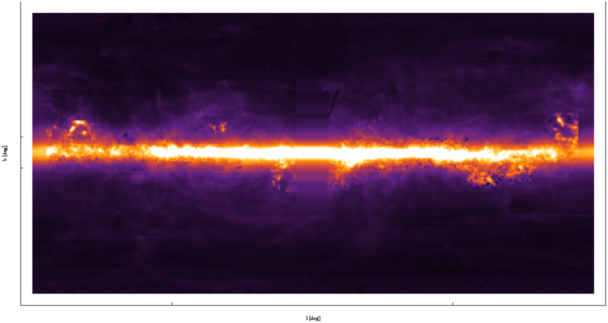
[Ibarra, DT, Weniger '09]

- In addition, two-body dark matter decays could give rise to gamma-ray lines

Gamma-Ray Anisotropies

- Define the anisotropy A as the relative difference in flux from Galactic center (GC) and Galactic anticenter (GAC) hemispheres:

$$A_{b_{\mathrm{min}}:b_{\mathrm{max}}} = \frac{\bar{J}_{\mathrm{GC}} - \bar{J}_{\mathrm{GAC}}}{\bar{J}_{\mathrm{GC}} + \bar{J}_{\mathrm{GAC}}}$$



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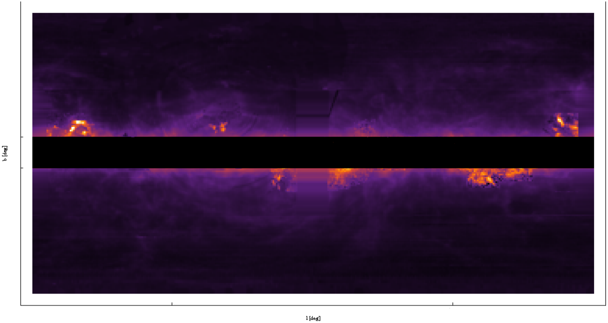

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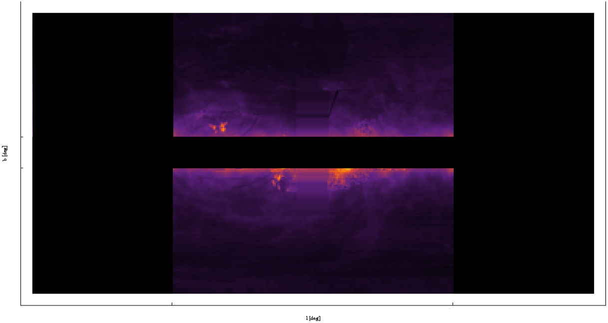

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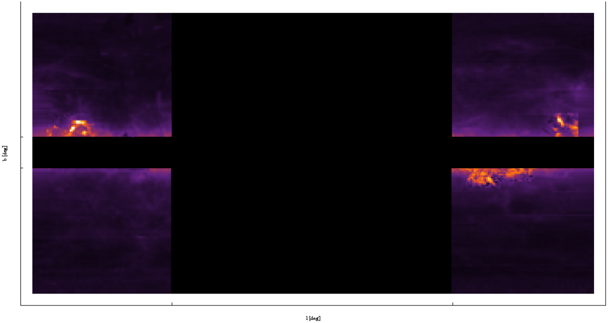
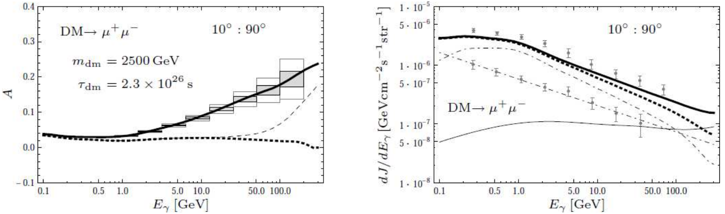


Gamma Rays from Dark Matter Decay

- The anisotropies between Galactic center and anticenter hemispheres can be substantial and should be testable by Fermi.
  Example: $\phi_{\text{DM}} \to \mu^+\mu^-$



[Ibarra, DT, Weniger '09]

- Similarly, sizable anisotropies are predicted for **all** of the decay modes that can reproduce the PAMELA/Fermi electron excesses

Outline

1. Unstable Dark Matter and Indirect Detection
2. Charged Particles from Dark Matter Decay
3. Gamma Rays from Dark Matter Decay
4. Conclusions

Conclusions and Outlook

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- Dark matter decay remains a viable explanation for the observed PAMELA/Fermi anomalies, but requires $m_{\mathrm{DM}} \gtrsim 1$ TeV and leptonic decay modes with lifetimes $\tau_{\mathrm{DM}} \sim 10^{26}$ sec
- There are a number of decay modes that can reproduce the observed electron anomalies, but the combination of PAMELA and Fermi results restrics the possibilities to a few cases
- Whole-sky Fermi LAT results on diffuse gamma rays will put any dark matter interpretations of the electron anomalies to a crucial test

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Thank you for your attention!