Unstable Dark Matter: Indirect Detection and Constraints

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Theory Seminar
Fermilab

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Outline

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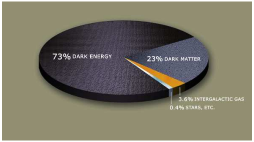
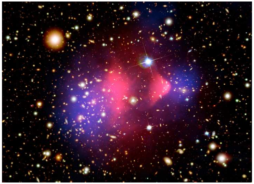
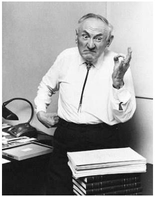
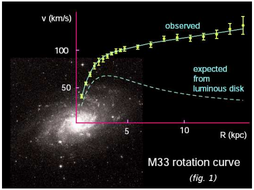
1. Unstable Dark Matter and Indirect Detection
2. Cosmic-Ray Antimatter
3. Neutrino Signals
4. Gamma-Ray Signatures
5. Hadronic Constraints
6. Conclusions

The Dark Universe







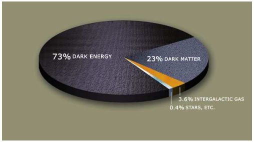


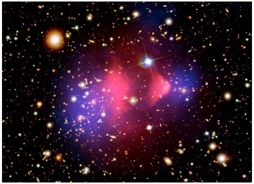
Surprising realization from cosmology and astronomy over the last decades: most of the energy density of the Universe is of an unknown form.

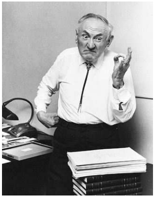
- 73% dark energy
- 23% dark matter
- 4% baryonic matter

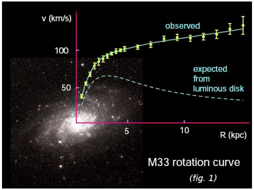
Five times more dark matter than ordinary matter: $\Omega_{\mathrm{DM}}/\Omega_{\mathrm{B}} \simeq 5$.

Dark Matter Exists



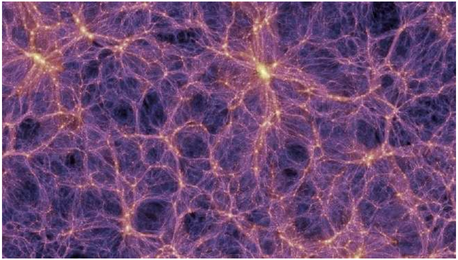






- Rotation curves, cluster dynamics
- Strong and weak gravitational lensing
- Simulations of structure formation
- Intracluster gas
- Cosmic microwave background
- Large-scale structure
- Primordial nucleosynthesis
- Cluster mergers

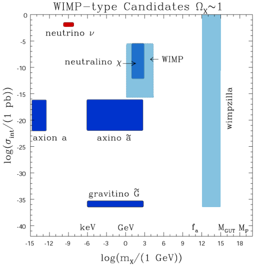
Dark Matter Exists



Dark matter is **required on all scales** from dwarf galaxies to galaxy clusters to superclusters to filaments and voids.

What is the microscopic nature of the dark matter?

Established Dark Matter Properties

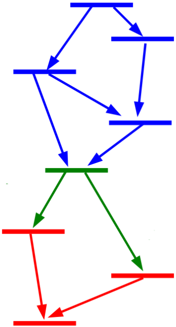


The dark matter is likely composed of unknown elementary particles. We know that it has to be

- massive
- cold
- without electric and color charge
- non-baryonic
- cosmologically stable

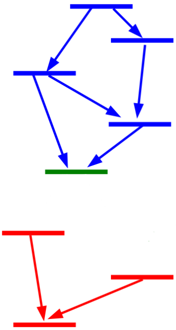
implying that the dark matter **cannot be any of the Standard Model particles**.

Extending the Standard Model...



- Extensions of the Standard Model typically contain new heavy states, the lightest of which may be a viable dark matter candidate
- In SUSY, the lightest neutralino typically has a lifetime of $\tau_\chi \sim 10^{-25}$ s if there is no suppression of its decay to Standard Model particles

Extending the Standard Model...



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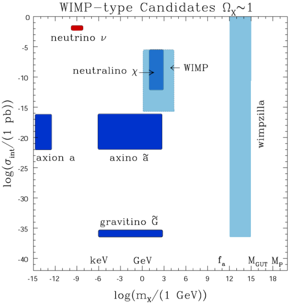
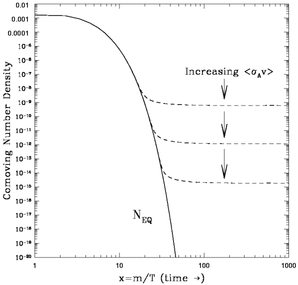
- In SUSY, the lightest neutralino typically has a lifetime of $\tau_\chi \sim 10^{-25}$ s if there is no suppression of its decay to Standard Model particles $\rightarrow$ imposing R-parity ensures absolute stability of the LSP

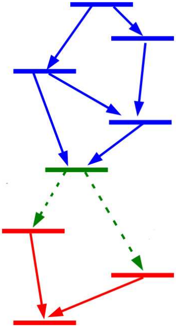
Dark Matter Candidates





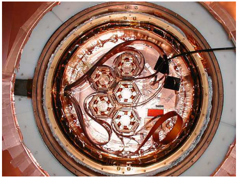
- Weakly interacting massive particles (WIMPs) are the leading candidates because they can be produced via thermal freezeout with the observed relic abundance.
- However, the dark matter might also consist of “super-weakly” interacting massive particles, which naturally have long lifetimes.

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 observable cosmic rays through their late decay

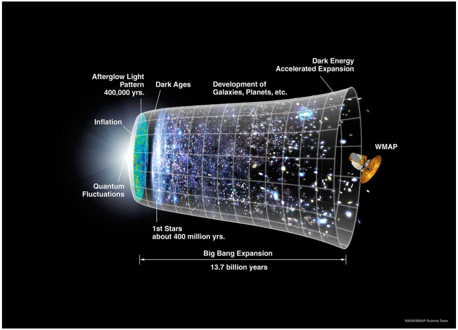
Approaches to Non-Gravitational Dark Matter Detection



A determination of the particle identity of the dark matter is impossible using gravity alone.

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

Dark Matter Stability – An Assumption



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

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

Approaches to Non-Gravitational Dark Matter Detection

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

Some Examples of “Weakly” Unstable Dark Matter

- Gravitino dark matter with R-parity violation

  [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], [Bomark, Lola, Osland, Raklev ’10]
- Hidden sector gauge bosons/gauginos

  [Ibarra, Ringwald, Weniger ’08], [Ibarra, Ringwald, DT, Weniger ’09]

  [Chen, Takahashi, Yanagida ’08, ’09]
- Right-handed sneutrinos in models with Dirac masses

  [Pospelov, Trott ’08]
- Hidden sector fermions/scalars

  [Park, Park ’12], [Kyae, Park ’12], [Hamaguchi, Shirai, Yanagida ’08]

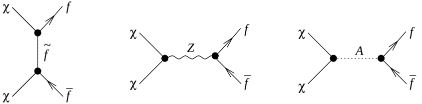
  [Arvanitaki, Dimopoulos, Dubovsky, Graham, Harnik, Rajendran ’08, ’09]
- Hidden SU(2) vectors

  [Arina, Hambye, Ibarra, Weniger ’09]
- Bound states of strongly interacting particles

  [Hamaguchi, Nakamura, Shirai, Yanagida ’08]

  [Nardi, Sannino, Strumia ’08]

Indirect Dark Matter Detection



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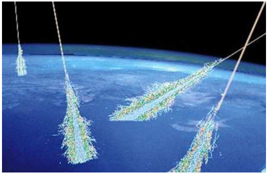
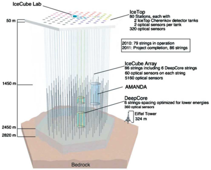


Indirect dark matter detection:

- Late DM annihilation/DM decay processes might be observable today:
  → Look for annihilation/decay products in cosmic radiation in the form of anomalous abundances or spectral features.
- Use low-background, well understood channels:
  - Photons – radio waves, X-rays, γ-rays (multi-wavelength)
  - Cosmic-ray antimatter – positrons, antiprotons, antideuterons
  - Neutrinos

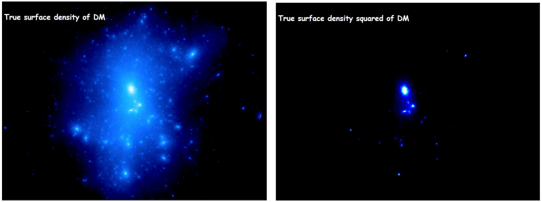
Indirect Dark Matter Detection



The main indirect detection channels for various dark matter decay modes

$$\begin{array}{lll}
\mathrm{DM} \to W^{\pm},\ Z^{0},\ q,\ h & \to \gamma,\ \nu,\ e^{\pm},\ \bar{p},\ \bar{d} & (+\ \text{secondary}\ \gamma) \\
\mathrm{DM} \to e^{\pm} & \to e^{\pm} & (+\ \text{secondary}\ \gamma) \\
\mathrm{DM} \to \mu^{\pm} & \to e^{\pm},\ \nu & (+\ \text{secondary}\ \gamma) \\
\mathrm{DM} \to \tau^{\pm} & \to e^{\pm},\ \gamma,\ \nu & (+\ \text{secondary}\ \gamma) \\
\mathrm{DM} \to \gamma & \to \gamma & \\
\mathrm{DM} \to \nu & \to \nu &
\end{array}$$

The Source of Cosmic Rays from DM Decay



[Moore et al. '05]

- Linear dependence on DM density as opposed to quadratic dependence → important qualitative differences wrt DM annihilation
    - No signal enhancement from dark matter substructures (~~boost factors~~) → regions of high DM density not necessarily the best targets for indirect searches
    - Indirect signatures of DM decay are less sensitive to uncertainties in the DM distribution
    - Milder angular dependence of indirect signals than for annihilating DM
- As a result, constraints on decaying DM are typically less stringent than those on annihilating DM

Computing Indirect Signatures

DM mass, lifetime / annihilation cross section
Branching ratios

↓

Spatial dark matter distribution

↓

Energy spectrum at injection (from `PYTHIA`, `HERWIG`, ...)

↓

Propagation (semi-analytical or numerical)
Astrophysical backgrounds

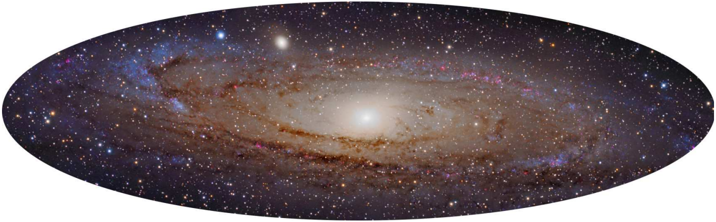
↓

Solar modulation

↓

Energy spectrum observed at Earth

Indirect Dark Matter Detection

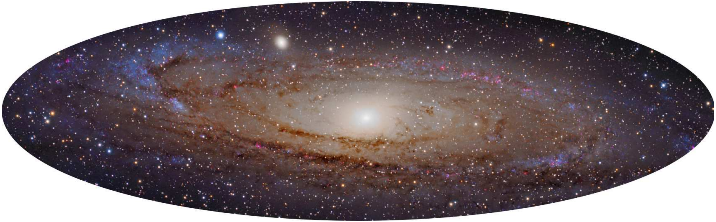


Propagation of decay/annihilation products in the Galaxy:

Simple propagation	Complicated propagation
Photons	Positrons, electrons
Neutrinos	Antiprotons, antideuterons

"model-independent" ↔ (propagation) "model-dependent"

Propagation of Cosmic Rays



- Propagation of charged particles is described in a stationary two-zone diffusion model with cylindrical boundary conditions.
- The Milky Way is embedded in a magnetic halo causing diffusion of cosmic rays.
- Master equation for cosmic-ray transport:

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

- Solve either numerically (e.g., `GALPROP`) or semi-analytically in an idealized setup

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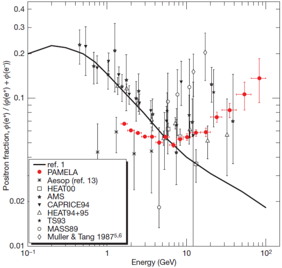
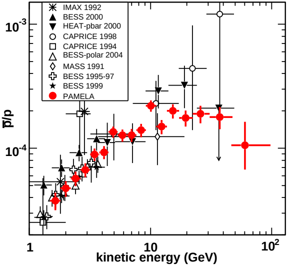
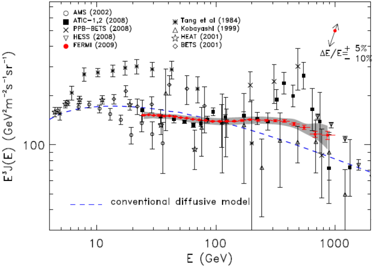
Puzzling Results in Cosmic-Ray Antimatter

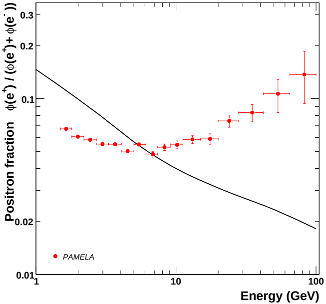
- Several unexpected and puzzling results from telescopes PAMELA, Fermi LAT, ATIC, ... over the last couple of years

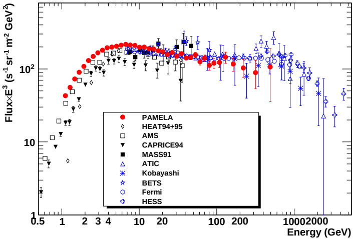






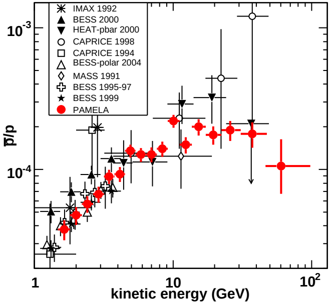
The Cosmic-Ray Anomalies





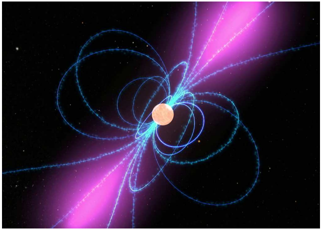
- Very significant deviation between measurement and theoretical expectation above 10 GeV (discrepancy at lower energies is due to solar modulation).
- The fact that the positron fraction **increases** with the energy strongly suggests the presence of primary positrons.
- Electrons lose energy efficiently via inverse Compton scattering, with the highest energy particles coming from the closest distances.

The Cosmic-Ray Anomalies



- At the same time, no excess in antiprotons is observed – consistent with production of secondary antiprotons by cosmic-ray spallation
- Important constraint on dark matter models: low branching fraction into hadrons required
- More on this later!

Astrophysical Explanations

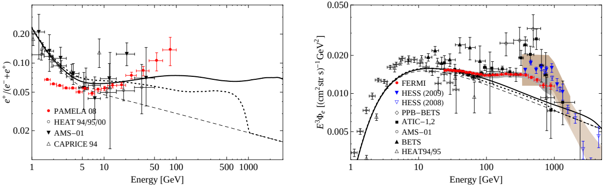


- The unidentified source of primary electrons/positrons must be **local** and capable of producing **highly energetic leptons** → dark matter OR astrophysics?
- Astrophysical explanations include
    - Mature pulsars (nearby or distant)
    - Shock acceleration of secondaries within CR sources
    - Inhomogeneous CR source distribution
    - Nearby supernova explosions
    - ...

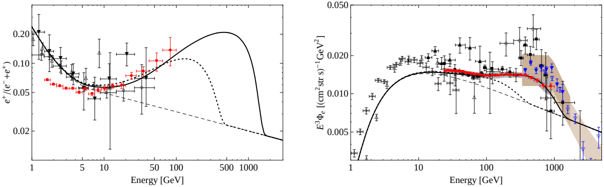
→ be careful about dark matter interpretations.

Charged Leptons from Decaying Dark Matter

$$\psi_{\text{DM}} \to Z^0 \nu$$



$$\psi_{\text{DM}} \to \mu^+ \mu^- \nu$$



[Ibarra, DT, Weniger '09]

- Analyze various dark matter decay modes in a model-independent manner, treating m_{DM} and τ_{DM} as free parameters

Decay Channels in Light of the Fermi Results

- The smooth power-law behavior $\propto E^{-3.0}$ of the total $e^{\pm}$ flux observed by Fermi disfavors pure decays into first-generation leptons and requires dark matter masses $\mathcal{O}(1\text{ TeV})$
- The decay channels that best fit both the PAMELA and Fermi LAT electron measurements are

$$
\begin{aligned}
&\psi_{\mathsf{DM}} \to \mu^+\mu^-\nu, && m_{\mathsf{DM}} = 3.5\text{ TeV}\\
&\psi_{\mathsf{DM}} \to \ell^+\ell^-\nu, && m_{\mathsf{DM}} = 2.5\text{ TeV}\\
&\psi_{\mathsf{DM}} \to W^{\pm}\mu^{\mp}, && m_{\mathsf{DM}} = 3.0\text{ TeV} \quad (\bar{p}\text{ overpr.})\\
&\phi_{\mathsf{DM}} \to \mu^+\mu^-, && m_{\mathsf{DM}} = 2.5\text{ TeV}\\
&\phi_{\mathsf{DM}} \to \tau^+\tau^-, && m_{\mathsf{DM}} = 5.0\text{ TeV}
\end{aligned}
$$

with lifetimes $\tau_{\mathsf{DM}} \sim (1\ldots2)\times10^{26}$ s ($\sim 10^9$ times the age of the Universe)

A Possible Connection to Unification?

- 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

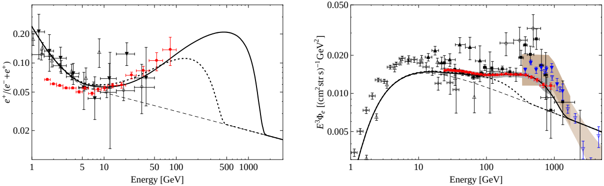
  [Eichler '89]

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

  [Hamaguchi, Shirai, Yanagida '08]

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

Charged Leptons from Decaying Dark Matter



$$\psi_{\text{DM}} \to \mu^+\mu^-\nu$$

[Ibarra, DT, Weniger '09]

- Both from the spectral shape and from the absence of a hadronic excess, leptonic decays are favored
- Leptonically decaying dark matter is a possible interpretation of the cosmic lepton anomalies.
- Fixing the dark matter mass and lifetime by fits to the cosmic-ray anomalies allows to make **testable predictions** for other cosmic-ray, gamma-ray and neutrino fluxes

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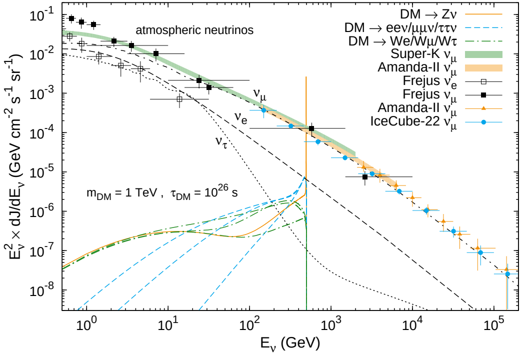
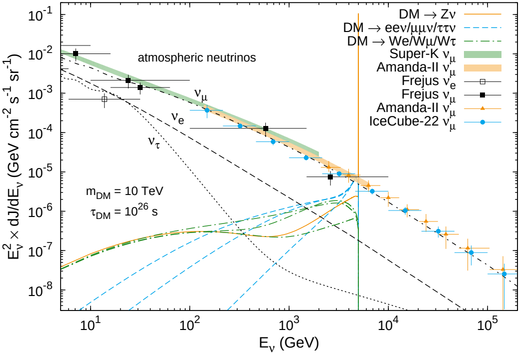
Neutrino Signals



- Neutrinos share many properties and detection strategies with gamma rays
- Neutrinos are difficult to detect due to weak interaction strength and large atmospheric backgrounds
- However, for relatively large ($\gtrsim$ a few TeV) masses, the fluxes become comparable to the backgrounds for lifetimes $\sim 10^{26}$ sec.

Neutrino Signals



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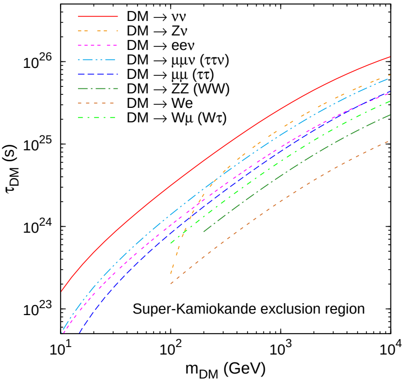
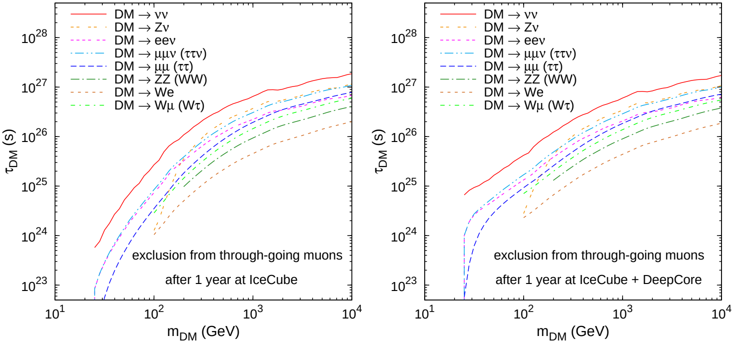


[Covi, Grefe, Ibarra, DT '10]

- Constraints from SuperKamiokande observations are not competitive with those from other indirect detection channels.

Neutrino Signals

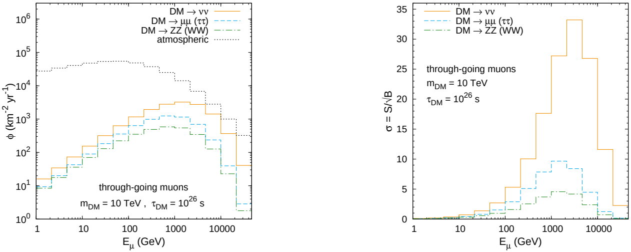


[Covi, Grefe, Ibarra, DT '10]

see also [Buckley, Freese, Hooper, Mandal, Murayama, Spolyar '10]

- The new generation of km^3 sized detectors can constrain the parameter space at the level relevant to the cosmic-ray anomalies.
- Above: exclusion limits for IceCube / IceCube + DeepCore from non-observation of an excess in the rate of through-going muons
- The DeepCore subdetector can lower the threshold at low energies.

Neutrinos from Dark Matter Decay



[Covi, Grefe, Ibarra, DT '10]

- The potential to constrain dark matter interpretations is even stronger when making use of spectral information: a signal could show up with high significance in several energy bins
- Identification of specific decay modes is difficult and requires complementary information: antimatter, gamma rays

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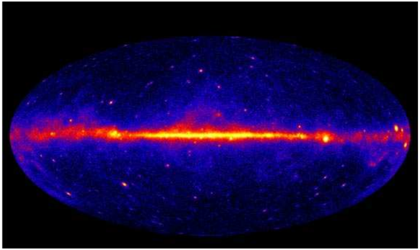
The Gamma-Ray Sky

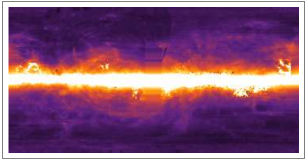


[Fermi LAT gamma-ray sky map]

Gamma rays are probably the most important probe for indirect detection of dark matter in the GeV – TeV mass range because

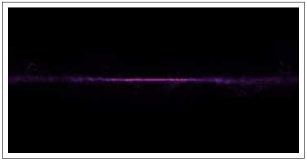
- gamma rays are produced as both primary and secondary products
- spectral and angular information is preserved
- sensitivity to distant sources
- practically no absorption on Galactic scales
- astrophysical backgrounds are relatively well understood

The Gamma-Ray Sky



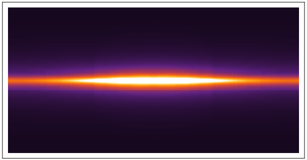
diffuse Galactic emission

$=$



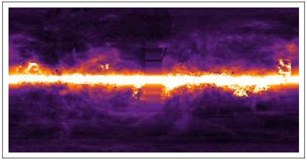
bremsstrahlung

$+$



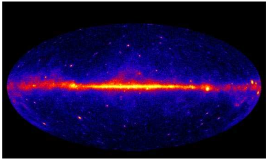
inverse Compton

$+$



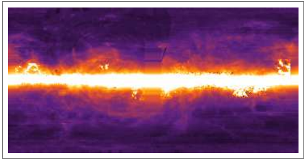
π^0 decay

The Gamma-Ray Sky



Observed emission

$-$



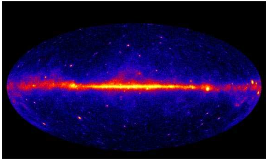
diffuse Galactic

$-$ sources

$=$

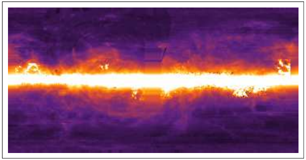
diffuse extragalactic

The Gamma-Ray Sky



Observed emission

−



diffuse Galactic

− sources

=

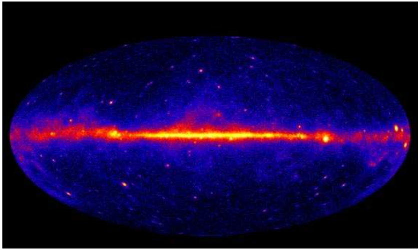
diffuse extragalactic

+

dark matter emission?

→ gamma rays from dark matter may be misidentified as extragalactic emission!

The Gamma-Ray Sky

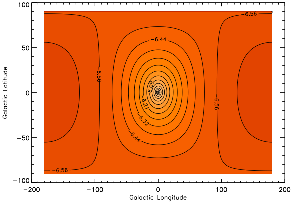


[Fermi LAT gamma-ray sky map]

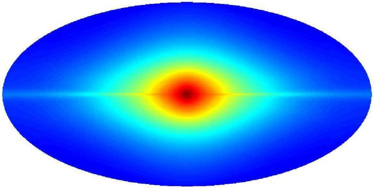
A gamma-ray signal from dark matter decay may be identified in several different ways:

- A contribution to the diffuse extragalactic gamma-ray background (which presumably follows a power law)
- A large-scale anisotropy in the overall gamma-ray flux
- A distinct spectral feature or monochromatic line in the diffuse flux or in sources (galaxies, clusters)

Dark Matter Emission



[Bertone et al. '07]



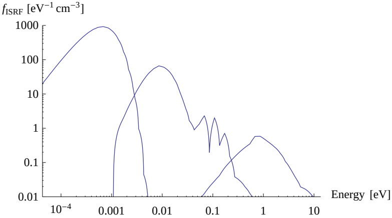
[Zhang et al. '10]

The gamma-ray emission from dark matter decay has two distinct components:

- a prompt component from the decay process itself
- a secondary component from inverse Compton scattering of electrons and positrons

with each of these receiving contributions from dark matter in the Galactic halo and at cosmological distances.

Inverse Compton Scattering



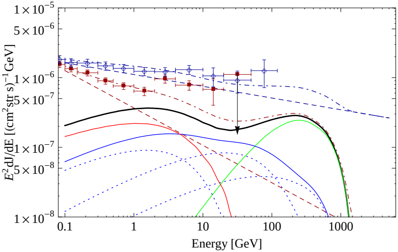
[Porter, Strong '05]

Energetic electrons and positrons can upscatter low-energy photons in the interstellar radiation field to gamma-ray energies

- Primary energy loss mechanism for $e^{\pm}$
- Generates a secondary gamma-ray signature indicating the presence of a $e^{\pm}$ population

$$\text{electron/positron propagation} \quad \overset{\text{ICS}}{\longleftrightarrow} \quad \text{gamma-ray emission}$$

Gamma Rays from Dark Matter Decay

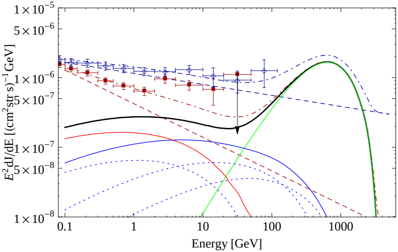


$$\psi_{\text{DM}} \to \ell^+ \ell^- \nu$$

[Ibarra, DT, Weniger '09]

- Gamma-ray flux for DM mass and lifetime matched to the electron/positron data, including prompt emission and inverse Compton radiation.
- The shape of the combined flux depends on the index and normalization of the truly extragalactic component from active galactic nuclei etc., which presumably follows a power law

Gamma Rays from Dark Matter Decay



$$\phi_{\text{DM}} \rightarrow \tau^+\tau^-$$

[Ibarra, DT, Weniger '09]

- Gamma-ray flux for DM mass and lifetime matched to the electron/positron data, including prompt emission and inverse Compton radiation.
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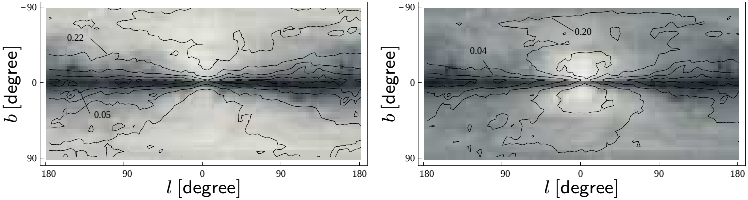
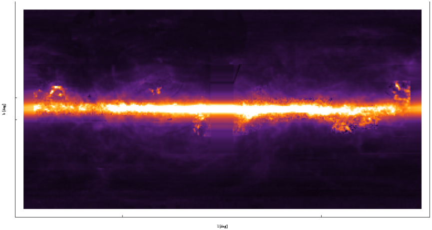
Morphology of the Gamma-Ray Emission



[Ibarra, DT, Weniger '09]

- The tentative gamma-ray signal from dark matter is hidden under several layers of astrophysics → difficult to identify and map.
- However, the morphology of the gamma-ray emission from dark matter and astrophysics is different.
- Clean method: look for large-scale anisotropies in the **overall** gamma-ray flux instead of trying to precisely extract a signal, which depends on the adopted foreground model.

Large-Scale Anisotropies

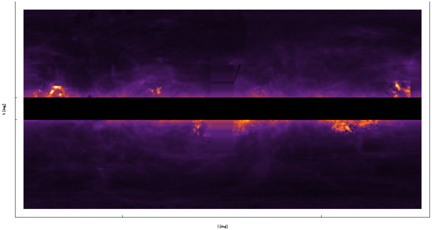


- When the Galactic disk is masked, the remaining diffuse emission is remarkbly isotropic.
- After masking the disk, define the anisotropy parameter

$$A = \frac{J_{\mathsf{GC}} - J_{\mathsf{GAC}}}{J_{\mathsf{GC}} + J_{\mathsf{GAC}}}$$

to quantify the anisotropy between different hemispheres in the sky.

Large-Scale Anisotropies



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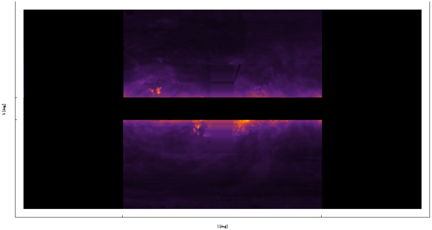

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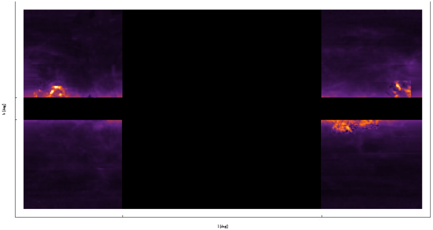

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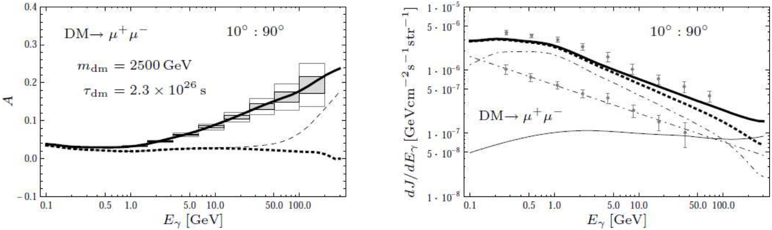
Large-Scale Anisotropies



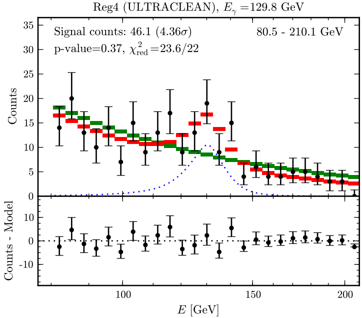
[Ibarra, DT, Weniger '09]

- Anisotropies can be sizable: up to $\sim 20\%$ and increasing with the energy → behavior very different from the Galactic emission.
- Large anisotropies are predicted for a priori foreground models for **all** decay modes that fit the leptonic cosmic-ray anomalies.
- Statistically, anisotropies should be detectable; however, large systematic uncertainties exist.

Radiative Dark Matter Decay

- Radiative effects can have interesting effects, e.g. electroweak bremsstrahlung [Berezinsky, Kachelriess, Ostapchenko '02], [Ciafaloni, Comelli, Riotto, Sala, Strumia, Urbano '10] or "internal bremsstrahlung" for WIMP annihilation [Bergström '89], [Bergström, Bringmann, Edsjö '08].
- Even leptophilic DM models unavoidably generate hadrons at the quantum level due to SU(2) invariance.
- In addition, radiative two-body dark matter decays may give rise to gamma-ray lines.
- However, radiative effects usually suppressed compared to leading-order processes by loop factors and powers of couplings

Gamma-Ray Lines in the Sky

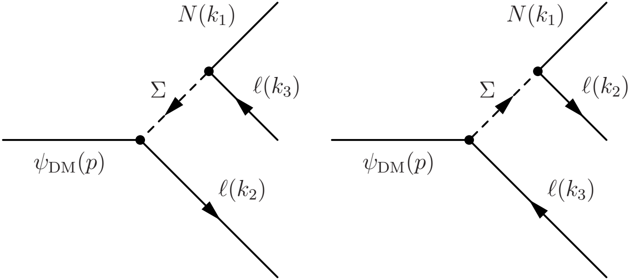


[Weniger '12]

- Lines constitute a well-defined signature and are relatively straightforward to search for.
- There is **no** background of monochromatic gamma rays from astrophysical processes → "smoking gun" signature of dark matter.
- Therefore, the discovery of a line would be compelling evidence for underlying fundamental particle physics process.

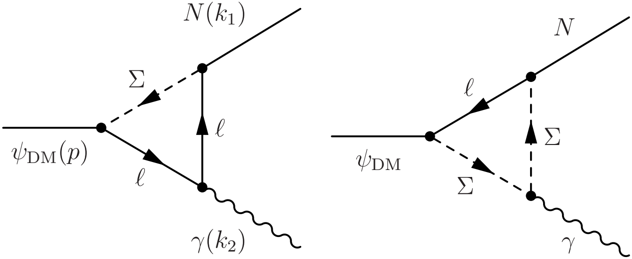
Gamma-Ray Lines from Fermionic Dark Matter

- If the dark matter particles carry spin-1/2 and decay mostly into charged leptons, the simplest decay mode is $\psi_{\text{DM}} \to \ell^+\ell^- N$, where N is a neutral fermion. (See also [Cheng, Huang, Low, Shaughnessy '12])
- Assume that this is the **only** decay mode at leading order: simple leptophilic toy model where the three-body decay is mediated by a charged scalar Σ or a charged vector V.



Gamma-Ray Lines from Fermionic Dark Matter

- At next-to-leading order, radiative two body-decays are induced by closing the external charged lepton lines into a loop.



- $\psi_{\mathsf{DM}} \to \gamma N$: two-body decay creates monochromatic gamma rays at

$$E_\gamma = \frac{m_{\psi_{\mathsf{DM}}}}{2}\left(1 - \frac{m_N^2}{m_{\psi_{\mathsf{DM}}}^2}\right)$$

→ observable in the gamma-ray sky?

Gamma-Ray Lines from Fermionic Dark Matter

- What is the relative intensity of the radiative two-body decays?
- For an intermediate scalar and chiral DM couplings, the ratio between three- and two-body decay processes can be expressed as

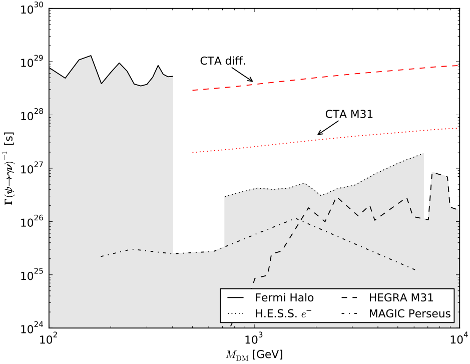
$$\frac{\Gamma(\psi_{\mathsf{DM}} \to \ell^+\ell^- N)}{\Gamma(\psi_{\mathsf{DM}} \to \gamma N)} = \frac{3\alpha_{\mathsf{em}}}{8\pi} \times R \times S$$

  with $3\alpha_{\mathsf{em}}/(8\pi) \simeq 10^{-3}$ and R, S typically $\mathcal{O}(1)$.

- In this case, if the DM lifetime $\tau_{\mathsf{DM}} \sim 10^{26}\,$sec, we have

$$\begin{aligned} \Gamma^{-1}(\psi_{\mathsf{DM}} \to \ell^+\ell^- N) &\sim 10^{26}\,\text{sec} \\ \Rightarrow \Gamma^{-1}(\psi_{\mathsf{DM}} \to \gamma N) &\sim 10^{29}\,\text{sec.} \end{aligned}$$

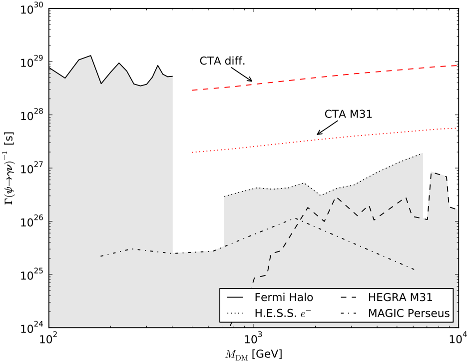
Constraints from Line Searches



[Garny, Ibarra, DT, Weniger '11]

- The negative search for gamma-ray lines by Fermi LAT constrains the partial lifetime $\tau(\text{DM} \to \gamma\nu)$ at $\mathcal{O}(10^{29}$ sec$)$ (!) for gamma-ray energies up to a couple hundred GeV. [Abdo et al. '10]

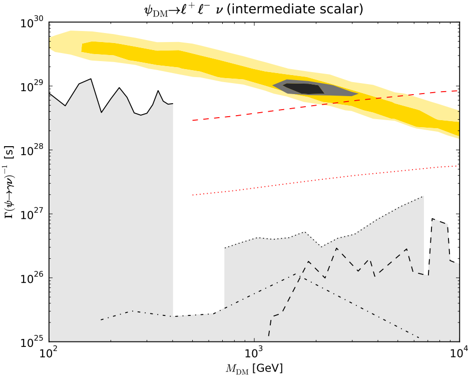
Constraints from Line Searches



[Garny, Ibarra, DT, Weniger '11]

- Imaging air Cherenkov telescopes can provide information at higher energies from observations of sources (galaxies, clusters) or the diffuse flux of electrons + gamma-rays.

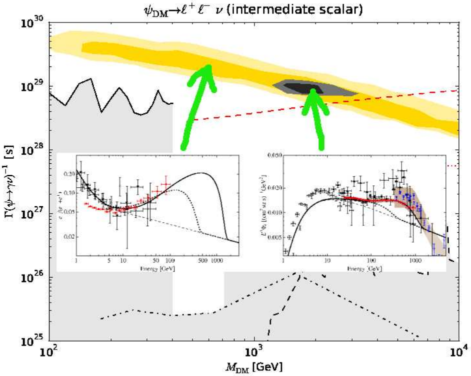
Constraints from Line Searches



[Garny, Ibarra, DT, Weniger '11]

- Example: The decay $\psi_{\text{DM}} \to \ell^+\ell^-\nu$ can simultaneously reproduce the PAMELA and Fermi electron data.
- Under favorable conditions, the preferred region of the parameter space is not far from the observational limits for lower DM masses.

Constraints from Line Searches



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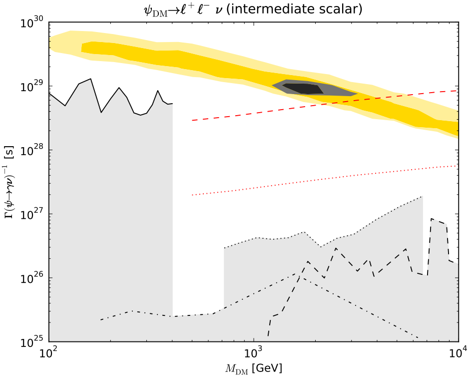

[Garny, Ibarra, DT, Weniger ’11]

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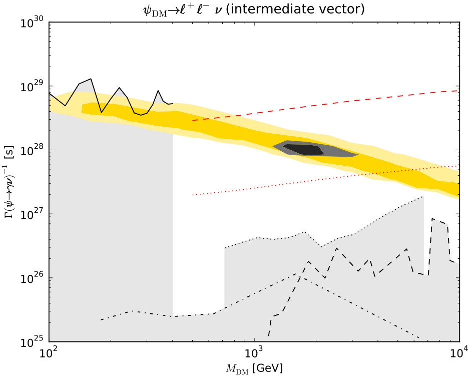
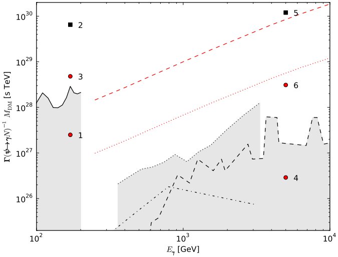


[Garny, Ibarra, DT, Weniger '11]

- Relative intensity of the radiative decay can be enhanced by an order of magnitude if the decay is mediated by a vector.
- Present and future observations can constrain a relevant part of the parameter space.

Kinematic Enhancement



[Garny, Ibarra, DT, Weniger '11]

- If $\psi_{\rm DM}$ and N have opposite *CP* parities, there can be a significant enhancement of the radiative decay mode as $m_N \to m_{\rm DM}$,

$$\mathrm{BR}(\psi_{\rm DM} \to \gamma\nu) \propto \left(1 - \frac{m_N}{m_{\rm DM}}\right)^{-2}$$

- Potentially very strong enhancement of the line when the masses of $\psi_{\rm DM}$ and N become near-degenerate

Outline

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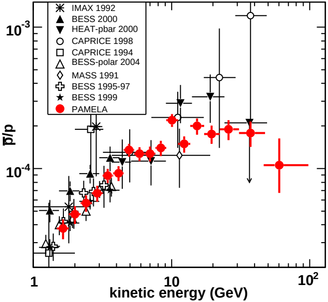
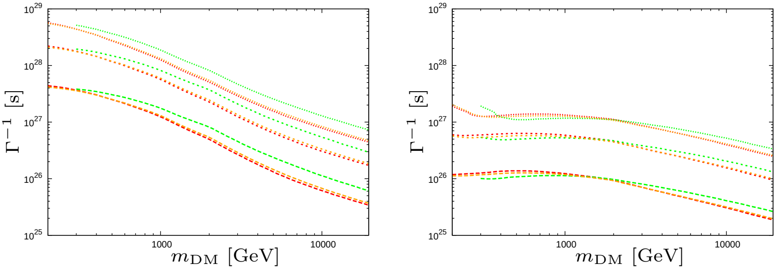
5. Hadronic Constraints
6. Conclusions

Hadronic Constraints



- No excess in antiprotons observed → important constraint on unstable dark matter
- We perform a scan over $m_{\mathrm{DM}} - \tau_{\mathrm{DM}}$ parameter space over several orders of magnitude in mass and lifetime
- Huge uncertainty in antiproton propagation due to degeneracy in determination of parameters from secondary/primary measurements

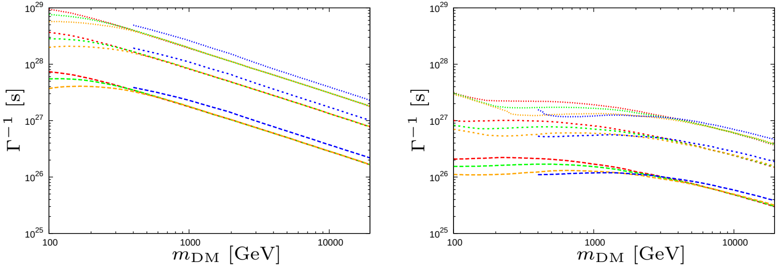
Hadronic Constraints on Scalar DM



[Garny, Ibarra, DT '12]

- Perform scan over $m_{\text{DM}} - \tau_{\text{DM}}$ parameter space over several orders of magnitude
- Demand that $\bar{p}/p$ ratio does not exceed observations at 95% C.L.
- $\phi_{\text{DM}} \to W^+W^-$, $\phi_{\text{DM}} \to Z^0Z^0$, $\phi_{\text{DM}} \to h^0h^0$

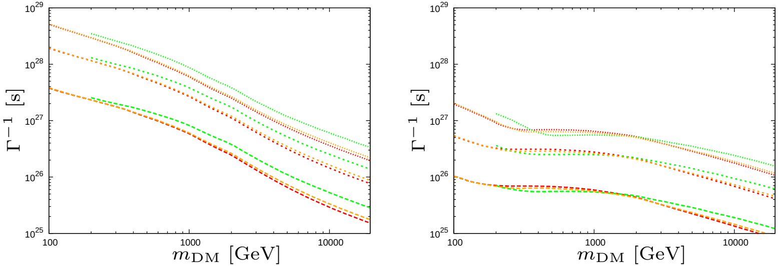
Hadronic Constraints on Scalar DM



[Garny, Ibarra, DT '12]

- Perform scan over $m_{\text{DM}} - \tau_{\text{DM}}$ parameter space over several orders of magnitude
- Demand that $\bar{p}/p$ ratio does not exceed observations at 95% C.L.
- $\phi_{\text{DM}} \to d\bar{d}$, $\phi_{\text{DM}} \to c\bar{c}$, $\phi_{\text{DM}} \to s\bar{s}$, $\phi_{\text{DM}} \to t\bar{t}$

Hadronic Constraints on Fermionic DM



[Garny, Ibarra, DT '12]

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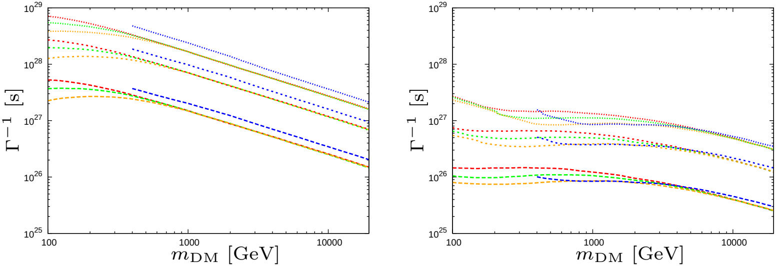
Hadronic Constraints on Fermionic DM



[Garny, Ibarra, DT '12]

- Perform scan over $m_{\mathsf{DM}} - \tau_{\mathsf{DM}}$ parameter space over several orders of magnitude
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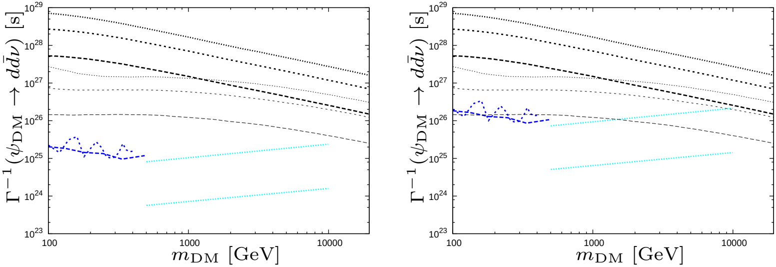
- $\psi_{\mathsf{DM}} \to d\bar{d}\nu$, $\psi_{\mathsf{DM}} \to c\bar{c}\nu$, $\psi_{\mathsf{DM}} \to s\bar{s}\nu$, $\psi_{\mathsf{DM}} \to t\bar{t}\nu$

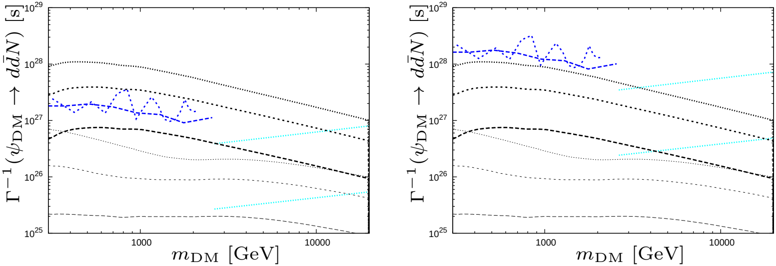
Gamma-Ray Lines vs. Cosmic-Ray Constraints



[Garny, Ibarra, DT '12]

- Monochromatic photons can be radiated from quark loops, just as in the case of charged leptons
- Constraints from gamma-ray lines for $\psi_{\rm DM} \to d\bar{d}\nu$ vs. constraints from $\bar{p}/p$ fraction

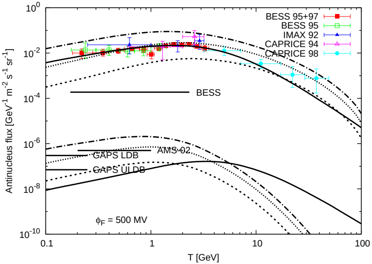
Gamma-Ray Lines vs. Cosmic-Ray Constraints



[Garny, Ibarra, DT '12]

- Monochromatic photons can be radiated from quark loops, just as in the case of charged leptons
- Constraints from gamma-ray lines for $\psi_{\rm DM} \to d\bar{d}N$ vs. constraints from $\bar{p}/p$ fraction, with $m_N = 0.9\, m_{\rm DM}$ (*left:* scalar, *right:* vector)

Antideuterons as a DM Signature



[Ibarra, DT '09]

- Antideuteron production from DM necessarily accompanies antiproton production
- Antideuterons could be a striking signature of hadronic DM annihilation/decay due to the extremely low astrophysical background
- The primary antideuteron flux can significantly exceed the background even if the antiproton flux is negligible

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Summary

- Constraints on the DM lifetime can be derived from observations of charged cosmic rays, gamma rays and neutrinos.
- Anomalous lepton abundances in cosmic rays can be interpreted as leptophilic dark matter decay.
- This interpretation predicts the presence of secondary gamma rays and neutrinos which can be searched for.
- Gamma rays from dark matter decay could be detected as contributions to the extragalactic background light, as large-scale anisotropies in the overall flux, or as narrow lines.
- Radiative effects can be relevant and lead to interesting interplay between leptonic/hadronic and gamma-ray constraints.
- We have presented general lifetime bounds on hadronic dark matter decay modes.

Thank you for your interest!