Cosmic-Ray and Gamma-Ray Constraints on Dark Matter Stability

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Outline

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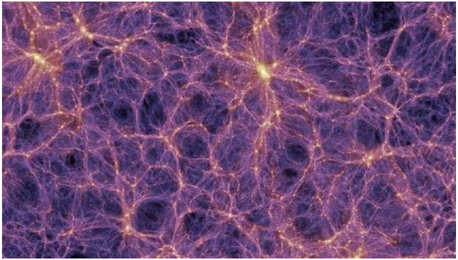
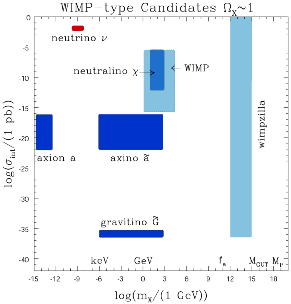
Dark Matter Exists



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

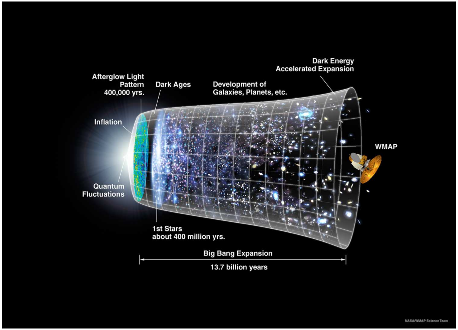


The dark matter is most likely some kind of undiscovered elementary particle. We know that it has to be

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

implying that it **cannot be a Standard Model particle**.

Dark Matter Stability – An Assumption

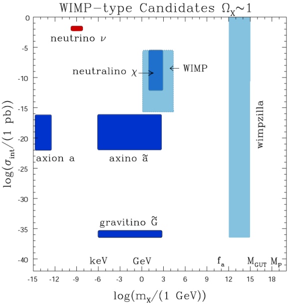


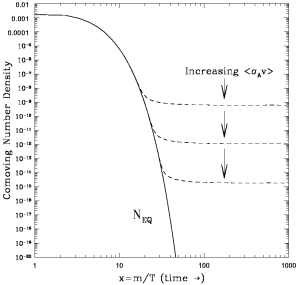
- We do not know whether the dark matter particles are **perfectly** stable – from the presence of dark matter in the Universe today we can only infer stability on a cosmological timescale,

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

- No fundamental reason for perfect dark matter stability

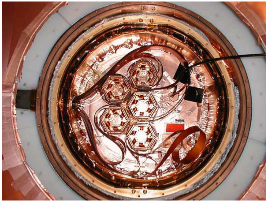
Established Dark Matter Properties



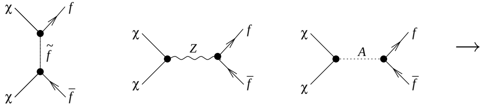


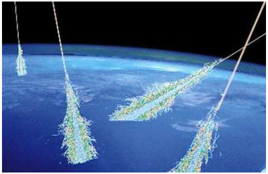
- Weakly interacting massive particles (WIMPs) are the leading candidates because they can plausibly be produced as thermal relics with the observed abundance.
- Other viable possibilities exist, such as "super-weakly" interacting massive particles, which may be unstable.
- A determination of the particle identity of the dark matter is impossible using gravity alone.

Approaches to Non-Gravitational Dark Matter Detection



- Collider searches: SM SM $\rightarrow$ DM X
- Direct detection: DM nucleus $\rightarrow$ DM nucleus
- Indirect detection: DM DM $\rightarrow$ SM SM, DM $\rightarrow$ SM SM

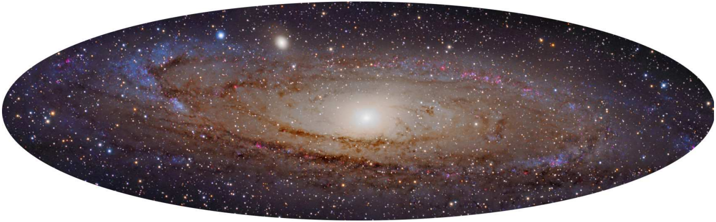




Indirect dark matter detection:

- DM annihilation/DM decay might still occur today at a significant rate.
- Look for annihilation/decay products in cosmic radiation in the form of anomalous abundances or spectral features.
- Ideally use low-background, well understood channels:
    - Photons
    - Cosmic-ray antimatter
    - Neutrinos

Indirect Dark Matter Detection

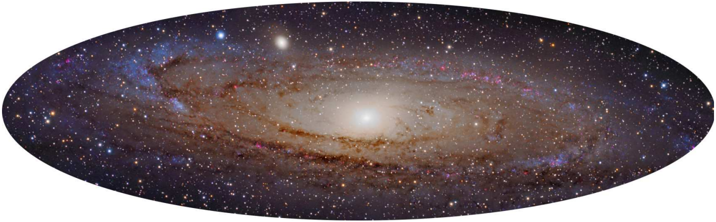


Propagation of decay/annihilation products in the Galaxy:

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

model-independent $\leftrightarrow$ 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.
- Transport equation for cosmic rays (schematically):

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

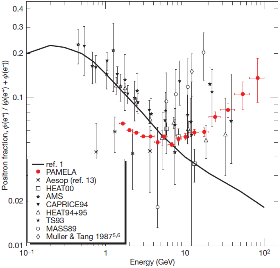
- Solve either numerically (`GALPROP`, ...) or semi-analytically in an idealized setup

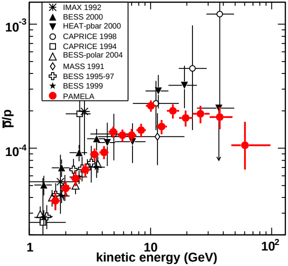
Indirect Dark Matter Detection

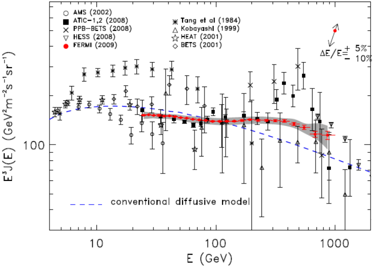
DM mass, lifetime / annihilation cross section
Branching ratios
$\downarrow$
Energy spectrum at injection (from `PYTHIA`, `HERWIG`, ...)
$\downarrow$
Spatial dark matter distribution
$\downarrow$
Propagation (semi-analytical or numerical)
Astrophysical backgrounds
$\downarrow$
Locally observed spectrum

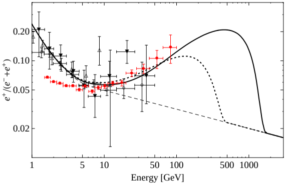
Outline

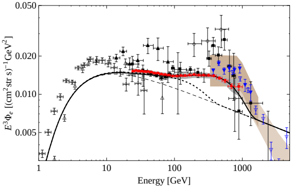
- Several unexpected and puzzling results from telescopes PAMELA, Fermi LAT, ATIC, ... over the last couple of years









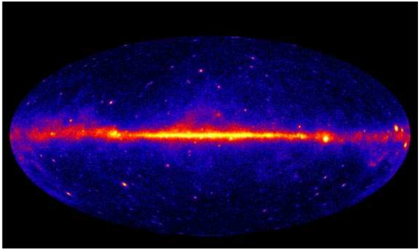


[Ibarra, DT, Weniger '09]

- Both spectrally 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 us to make testable predictions in other channels.

Outline

The Gamma-Ray Sky

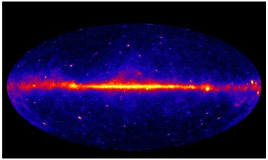


[Fermi LAT gamma-ray sky map]

A gamma-ray signal from dark matter decay may show up in several ways:

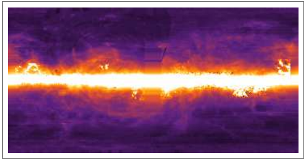
- A contribution to the diffuse extragalactic background (which presumably follows a power law)
- A large-scale anisotropy in the overall flux
- A monochromatic line in the diffuse flux or in sources (galaxies, clusters)

The Gamma-Ray Sky



Observed emission

−



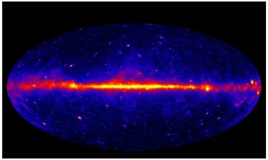
diffuse Galactic

− sources

=

diffuse extragalactic

The Gamma-Ray Sky



Observed emission

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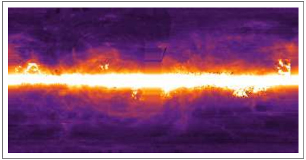


diffuse Galactic

$-$ sources

$=$

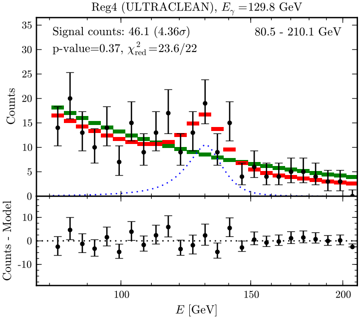
diffuse extragalactic

$+$

dark matter emission?

$\rightarrow$ gamma rays from dark matter may be misidentified as extragalactic emission!

Gamma-Ray Lines in the Sky

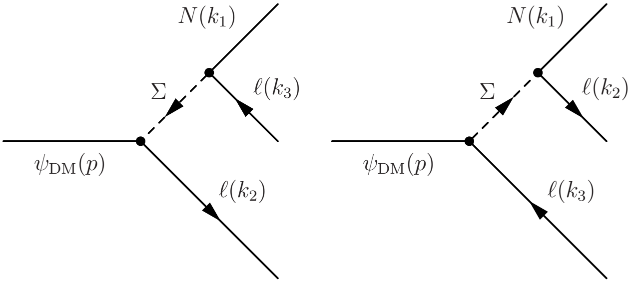


[Weniger '12]

- 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.

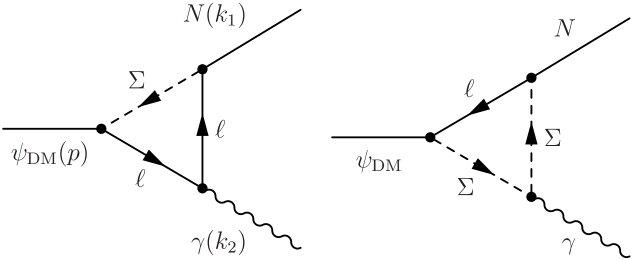
Gamma-Ray Lines from Fermionic Dark Matter

- If the dark matter particles carry spin-1/2 and decay mostly into charged leptons, the simplest decay mode is $\psi_{\rm DM} \to \ell^+\ell^- N$, 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

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

$\longrightarrow$ 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

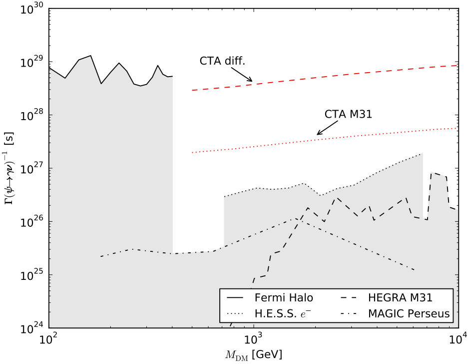
$$\frac{\Gamma(\psi_{\text{DM}} \to \ell^+\ell^- N)}{\Gamma(\psi_{\text{DM}} \to \gamma N)} = \frac{3\alpha_{\text{em}}}{8\pi} \times R \times S$$

  with $3\alpha_{\text{em}}/(8\pi) \simeq 10^{-3}$ and R, S typically $\mathcal{O}(1)$.
- In this case, if the DM lifetime $\tau_{\text{DM}} \sim 10^{26}\,\text{sec}$, we have

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

- For scalar dark matter, the radiative decays are helicity-suppressed and thus unobservable.

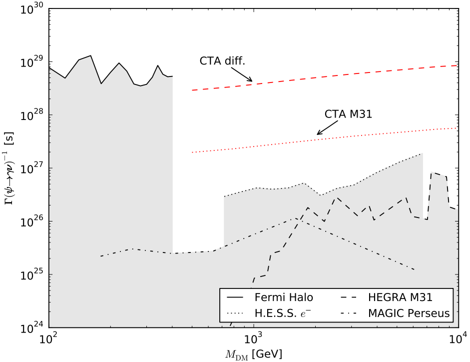
Constraints from Line Searches



[Garny, Ibarra, DT, Weniger '10]

- 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]

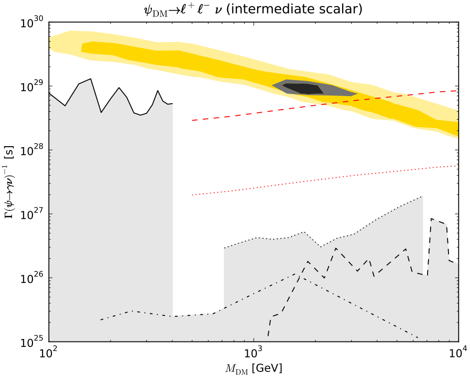
Constraints from Line Searches



[Garny, Ibarra, DT, Weniger '10]

- 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 '10]

- 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.

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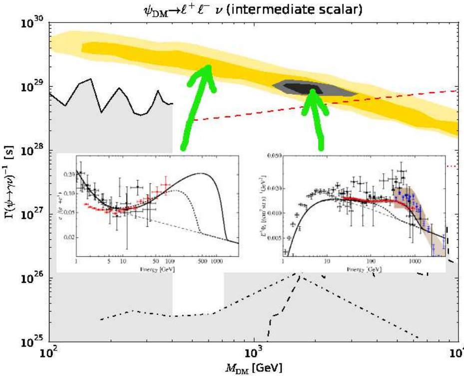

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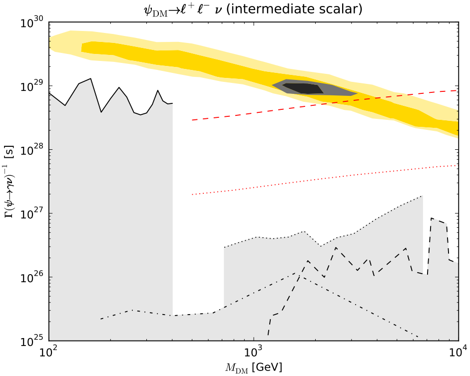

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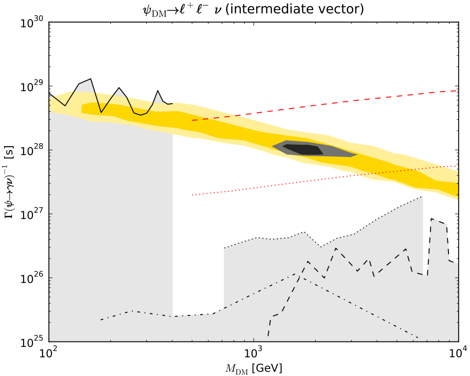
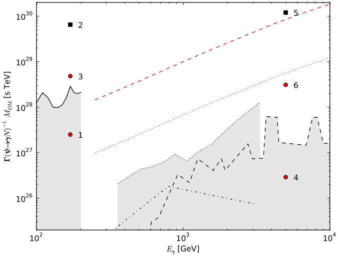


[Garny, Ibarra, DT, Weniger '10]

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

Kinematic Enhancement



[Garny, Ibarra, DT, Weniger '10]

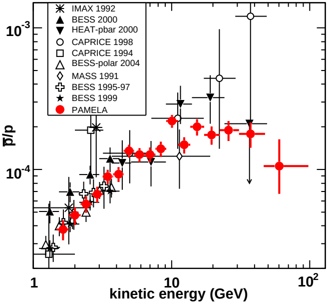
- If $\psi_{\rm DM}$ and N have opposite *CP* parities, there can be a significant enhancement of the radiative decay mode as $m_N \to m_{\rm DM}$,

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

- Potentially very strong enhancement of the line when the masses of $\psi_{\rm DM}$ and N are of similar size

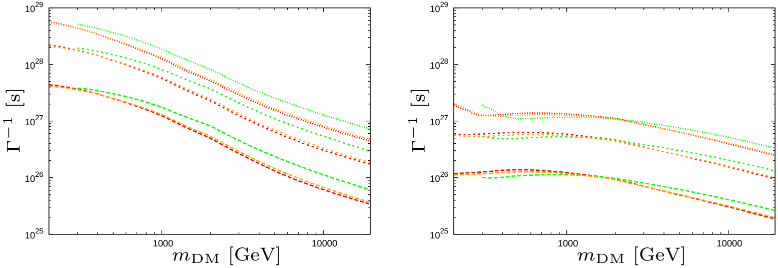
Outline

Hadronic Constraints



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

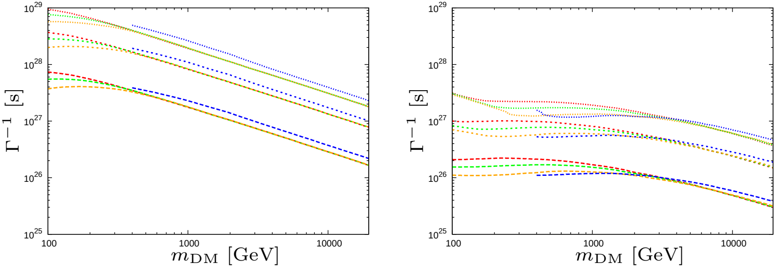
Hadronic Constraints on Scalar DM



[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.
- $\phi_{\text{DM}} \rightarrow W^+W^-$, $\phi_{\text{DM}} \rightarrow Z^0Z^0$, $\phi_{\text{DM}} \rightarrow h^0h^0$

Hadronic Constraints on Scalar DM



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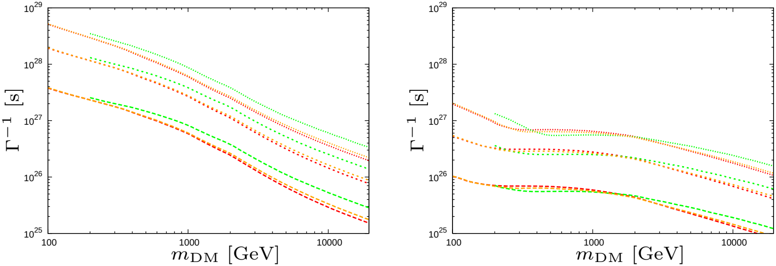
- $\phi_{\mathsf{DM}} \to d\bar{d}$, $\phi_{\mathsf{DM}} \to c\bar{c}$, $\phi_{\mathsf{DM}} \to s\bar{s}$, $\phi_{\mathsf{DM}} \to t\bar{t}$

Hadronic Constraints on Fermionic DM



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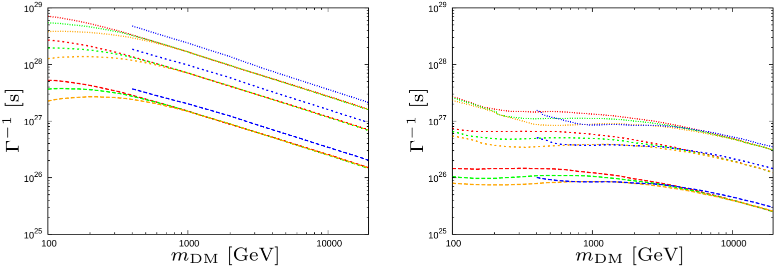
Hadronic Constraints on Fermionic DM



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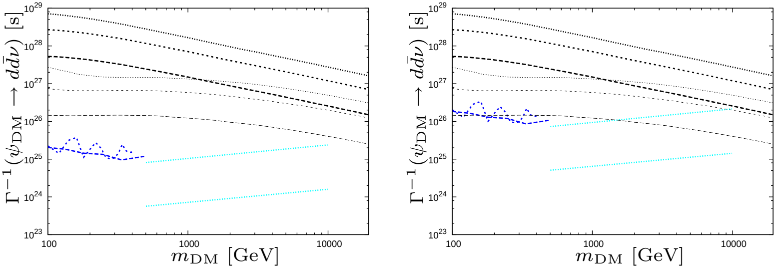
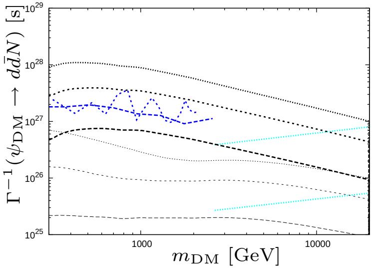
- Demand that $\bar{p}/p$ ratio does not exceed observations at 95% C.L.
- $\psi_{\text{DM}} \to d\bar{d}\nu$, $\psi_{\text{DM}} \to c\bar{c}\nu$, $\psi_{\text{DM}} \to s\bar{s}\nu$, $\psi_{\text{DM}} \to t\bar{t}\nu$

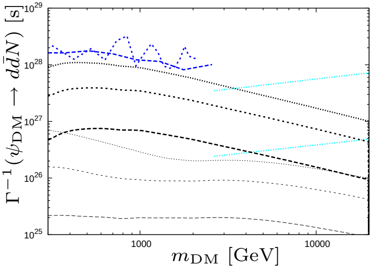
Gamma-Ray Lines vs. Cosmic-Ray Constraints



- 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





- 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)

Outline

Conclusions

- Dark matter stability is by no means established. Observations of charged cosmic rays, gamma rays and neutrinos can yield lower bounds on the DM lifetime.
- Interpretation of cosmic-ray anomalies in terms of DM decay predicts fluxes of gamma rays and hadrons.
- Radiative effects can be important $\longrightarrow$ interesting interplay between charged cosmic rays and gamma rays.
- Line searches can be competitive with cosmic-ray constraints in some situations.
- We have presented general constraints on hadronic decays.

Thank you for your interest!