Gamma-Ray Lines from Radiative Dark Matter Decay

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Outline

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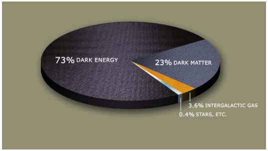
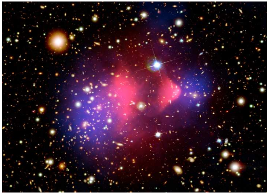
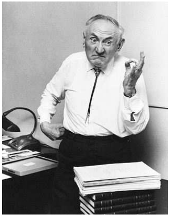
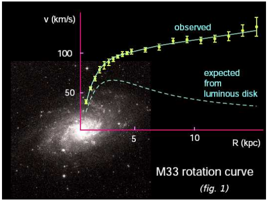
Established Dark Matter Properties





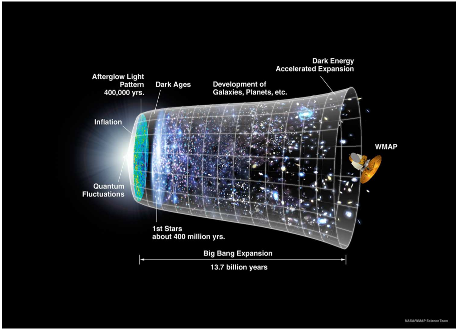




Dark matter clearly exists and is

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

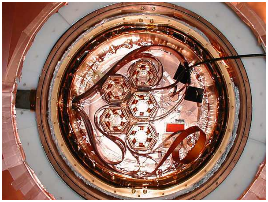
Dark Matter Stability – An Assumption



- 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,

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

Approaches to Non-Gravitational Dark Matter Detection



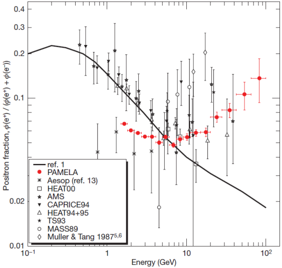
- Collider searches: SM SM $\longrightarrow$ DM X
- Direct detection: DM nucleus $\longrightarrow$ DM nucleus
- Indirect detection: DM DM $\longrightarrow$ SM SM, DM $\longrightarrow$ SM SM

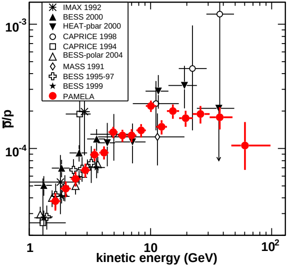
Some Examples of “Weakly” Unstable Dark Matter

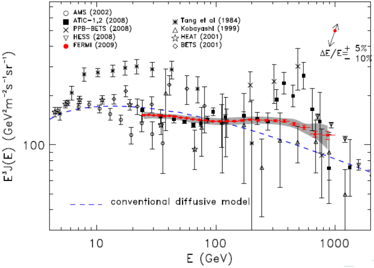
- Gravitino dark matter with R-parity violation
  [Takayama, Yamaguchi '00], [Buchmüller, Covi, Hamaguchi, Ibarra, Yanagida '07]
  [Ibarra, DT '08], [Ishiwata, Matsumoto, Moroi '08]
  [Chen, Ji, Mohapatra, Nussinov, Zhang '08, '09]
  [Buchmüller, Ibarra, Shindou, Takayama, DT '09], [Bomark, Lola, Osland, 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
  [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]

Puzzling Results in Cosmic-Ray Antimatter

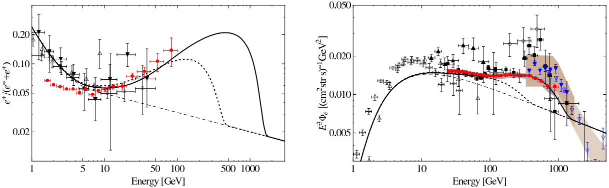
- Several unexpected and puzzling results from telescopes PAMELA, Fermi LAT, ATIC, ... over the last couple of years







A Non-Gravitational Dark Matter Signature?



[Ibarra, DT, Weniger '09]

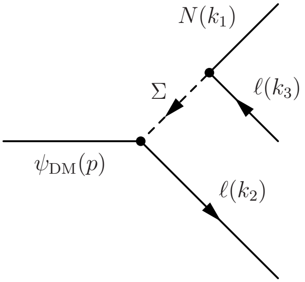
- The unidentified source of primary electrons/positrons must be **local** and capable of producing **highly energetic leptons** $\rightarrow$ dark matter, astrophysics?
- The decay of "leptophilic" DM is a possible interpretation of the cosmic lepton anomalies.
- $\rightarrow$ Motivation to find ways to test leptophilic dark matter.

Outline

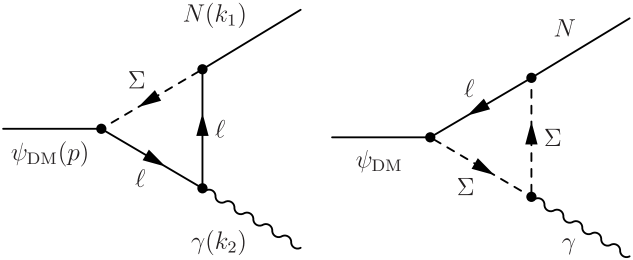
Radiative Dark Matter Effects

- 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 $\rightarrow$ irrelevant?

- 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.
- 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.



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

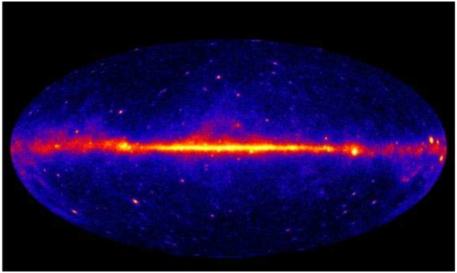


- $\psi_{\text{DM}} \rightarrow \gamma N$: two-body decay creates monochromatic gamma rays at

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

$\rightarrow$ observable in the gamma-ray sky?

Gamma-Ray Lines in the Sky



[Fermi LAT gamma-ray sky map]

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

- 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

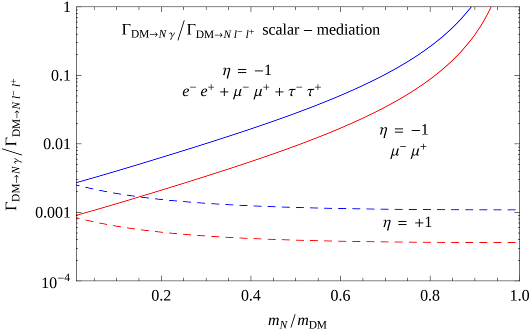
$$\frac{\Gamma(\psi_{\text{DM}} \to \ell^+\ell^- N)}{\Gamma(\psi_{\text{DM}} \to \gamma N)} = \frac{3\alpha_{\text{em}}}{8\pi} \times R \times S$$

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

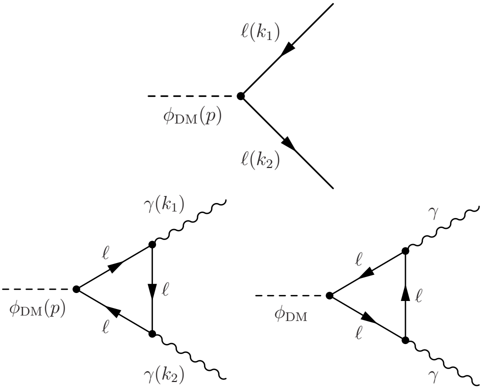
- In this case, if the DM lifetime $\tau_{\text{DM}} \sim 10^{26}\,\text{sec}$, we have

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

Kinematical Enhancement



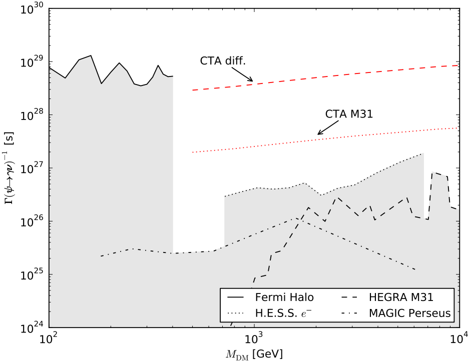
- If ψ_{DM} and N have opposite *CP* parities, the kinematical factor S can lead to significant relative enhancement of the radiative decay mode when the mass of N is comparable to m_{DM}.



- In the case of scalar dark matter, the radiative decay widths are proportional to a factor $m_\ell^2/m_{\phi_{\mathrm{DM}}}^2 \sim 10^{-10}$ due to chirality suppression
  $\rightarrow$ completely unobservable.

Outline

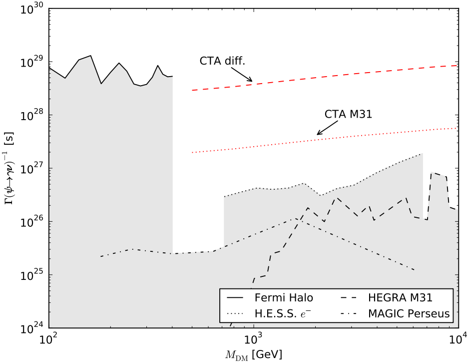
Constraints from Line Searches



[Garny, Ibarra, DT, Weniger '10]

- The negative search for gamma-ray lines by Fermi LAT constrains the partial lifetime $\tau(\mathrm{DM} \to \gamma\nu)$ 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.

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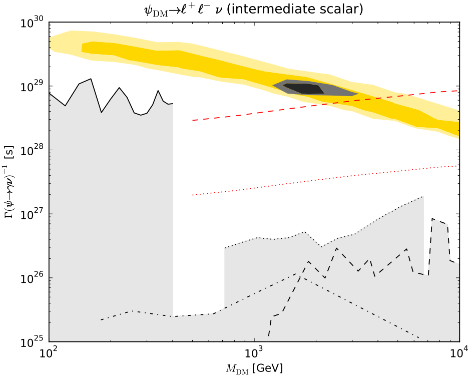

[Garny, Ibarra, DT, Weniger '10]

- Example: The decay $\psi_{\text{DM}} \to \ell^+\ell^-\nu$ can simultaneously reproduce PAMELA and Fermi.
- 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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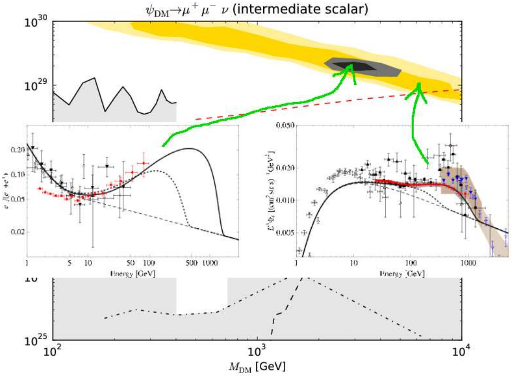

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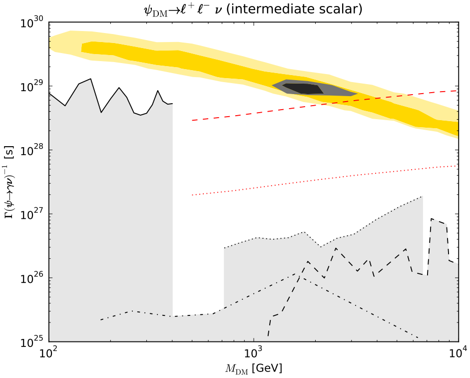

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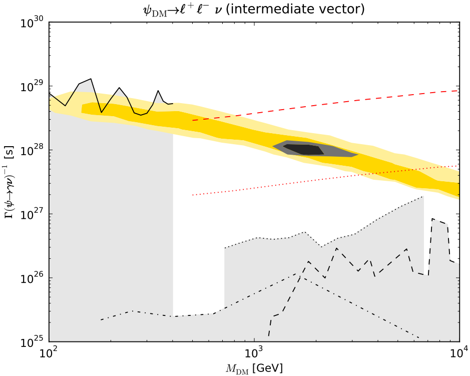
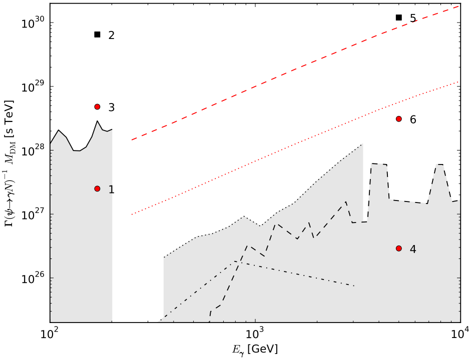


[Garny, Ibarra, DT, Weniger '10]

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

Constraints from Line Searches



[Garny, Ibarra, DT, Weniger '10]

- Using kinematical enhancement, one can construct scenarios where gamma-ray line constraints decide the viability of models which can reproduce the electron/positron measurements and are compatible with antiproton results.

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Conclusions

- Dark matter stability is by no means established, and effects of dark matter decay may be observable in cosmic rays, gamma rays and neutrinos.
- Next-to-leading order decays can have interesting effects: even purely leptophilic models can generate hadrons and monochromatic lines.
- In the case of fermionic dark matter, radiatively induced gamma-ray lines from leptophilic decays may be observable in the future under favorable conditions.
- Some leptophilic models that are currently unconstrained can can be tested using radiatively induced gamma-ray lines.

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Thank you for your attention!