Gamma-Ray and Neutrino Signatures of Unstable Dark Matter

David Tran
Technical University of Munich

In collaboration with
Laura Covi, Michael Grefe, Alejandro Ibarra and Christoph Weniger

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Outline

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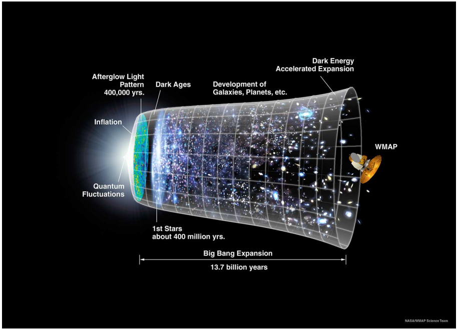
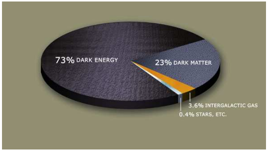
Dark Matter Stability – An Assumption

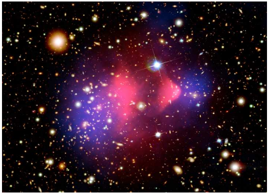


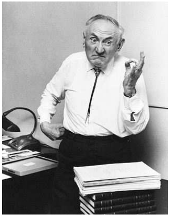
- We do not know whether the dark matter particles are **perfectly** stable – from the presence of dark matter in the Universe today we can only infer stability on a cosmological timescale,

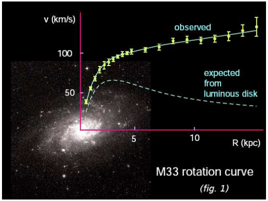
$$\tau_{\mathrm{DM}} > \tau_{\mathrm{universe}} \sim 4 \times 10^{17}\ \mathrm{s}$$

Established Dark Matter Properties







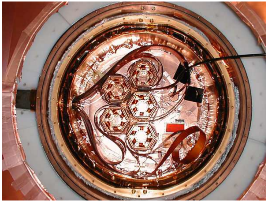


Dark matter clearly exists and is

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

Some Examples of Unstable Dark Matter

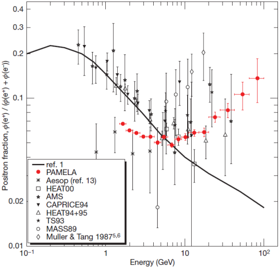
- Gravitino dark matter with R-parity violation
  [Takayama, Yamaguchi '00], [Buchmüller, Covi, Hamaguchi, Ibarra, Yanagida '07]
  [Ibarra, DT '08], [Ishiwata, Matsumoto, Moroi '08]
  [Chen, Ji, Mohapatra, Nussinov, Zhang '08, '09]
  [Buchmüller, Ibarra, Shindou, Takayama, DT '09], [Bomark, Lola, Osland,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

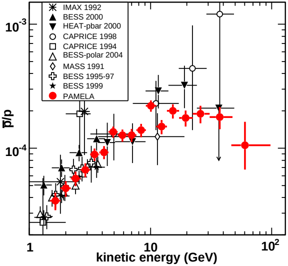


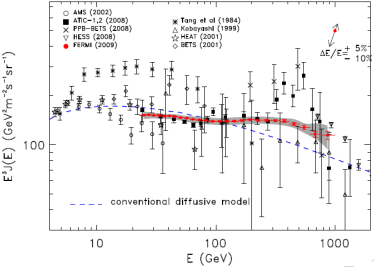
- Collider searches: SM SM $\rightarrow$ DM X
- Direct detection: DM nucleus $\rightarrow$ DM nucleus
- Indirect detection: DM DM $\rightarrow$ SM SM, DM $\rightarrow$ SM SM

A Wealth of New Data on Charged Cosmic Rays

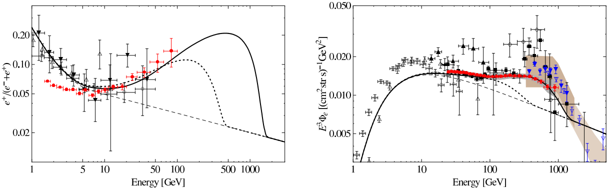
- Several new and unexpected results from PAMELA, Fermi LAT, ATIC, ... over the last years







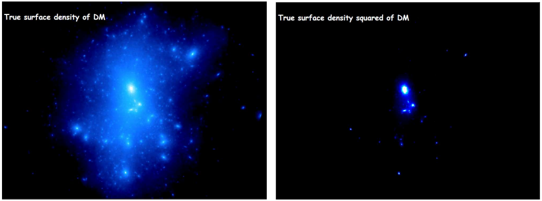
A possible scale for the DM mass and lifetime?



[Ibarra, DT, Weniger '09]

- The unidentified source of primary electrons/positrons must actually **exist**, be **local** and capable of producing **highly energetic leptons** $\rightarrow$ dark matter?
- The decay of "leptophilic" DM is a viable interpretation of the cosmic lepton anomalies (at least on a basic level)
- The PAMELA and Fermi lepton anomalies then suggest a scale for the DM mass and lifetime: $m_{\text{DM}} \sim$ a few TeV, $\tau_{\text{DM}} \sim 10^{26}$ sec.
- Even though this lifetime far exceeds the age of the Universe, it is in the testable range! $\rightarrow$ Look for ways to constrain or exclude decaying DM interpretations

The Source of Cosmic Rays from DM Decay

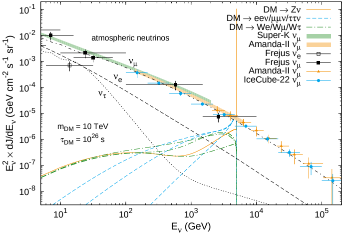


[Moore et al. '05]

- Linear dependence on DM density $\longrightarrow$ important qualitative differences:
  - No signal enhancement from dark matter substructures (~~boost factors~~) $\longrightarrow$ 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
  - Less directional dependence of signals than for DM annihilation
- As a result, it is more difficult to exclude decaying DM interpretations

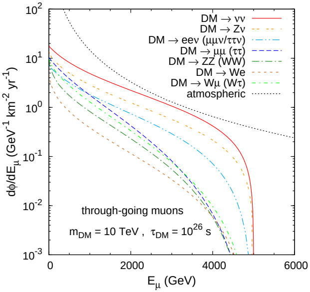
Outline

Neutrinos from Dark Matter Decay



[Covi, Grefe, Ibarra, DT '10]

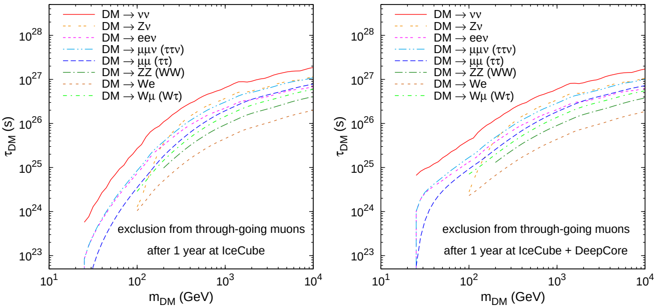
- Neutrinos can be generated directly in DM decays, e.g. DM $\longrightarrow \ell^+\ell^-\nu$, or in the subsequent decay of leptons / hadrons
- Flavor information is essentially erased due to neutrino propagation over Galactic scales
- Large atmospheric backgrounds and low signal fluxes make detection of a signal very challenging
- The best significance, $\sigma = S/\sqrt{B}$, is obtained for a full-sky observation



[Covi, Grefe, Ibarra, DT '10]

- Neutrino energies in the ∼ GeV – TeV range → regard deep-inelastic scattering of neutrinos with nucleons
- Calculate rates of neutrino-induced muon events to derive constraints on exotic neutrino flux
- Interesting range of parameters remains unconstrained by current experiments (SuperKamiokande)

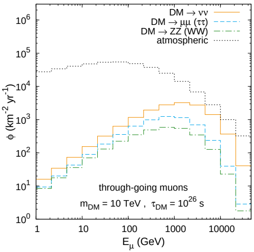
Neutrinos from Dark Matter Decay

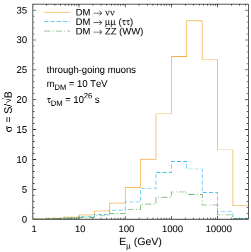


[Covi, Grefe, Ibarra, DT '10]

- Above: exclusion limits for IceCube / IceCube + DeepCore from non-observation of an excess in the rate of through-going muons
- Near-future experiments of km^3 dimensions should be able to constrain leptonic DM decay at the level associated with the lepton anomalies

Neutrinos from Dark Matter Decay





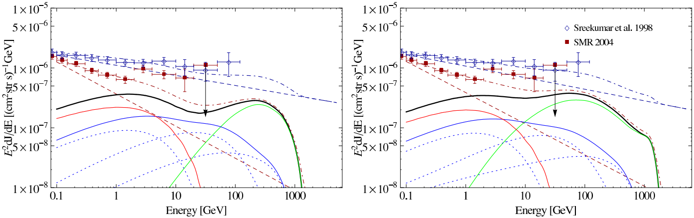
[Covi, Grefe, Ibarra, DT '10]

- 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

Outline

Gamma Rays from Dark Matter Decay

- For dark matter lifetimes $\mathcal{O}(10^{26})$ sec one generally gets an $\mathcal{O}(0.1-1)$ contribution to the "extragalactic background" from prompt radiation and inverse Compton
- This can yield a deviation from the expected power-law behavior in the background radiation, as shown below for $\psi_{\text{DM}} \to \ell^{\pm}\ell^{\mp}\nu$, $\psi_{\text{DM}} \to W^{\pm}\mu^{\mp}$. However, no deviation from a power law observed by Fermi [Abdo et al. '10]!

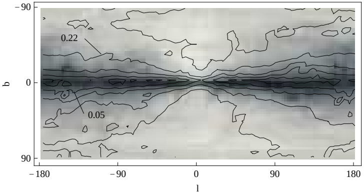


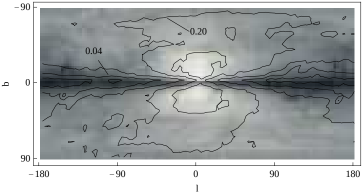
[Ibarra, DT, Weniger '09]

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

Gamma Rays from Dark Matter Decay

- We are located far off-center in the Galactic dark matter halo $\longrightarrow$ anisotropic dark matter contribution to the background of "extragalactic" gamma rays due to prompt radiation from decay of DM particles
- This contribution is distinguishable from the extragalactic one by its angular dependence: substantial DM-induced prompt signal at high Galactic latitudes





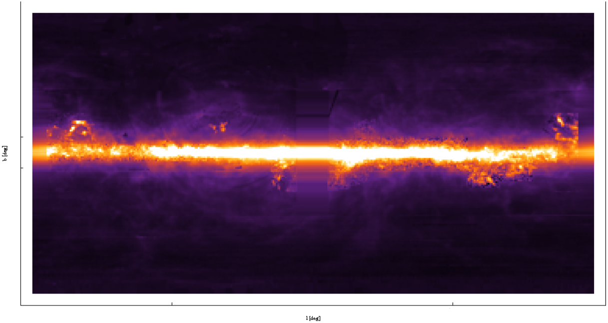
[Ibarra, DT, Weniger '09]

- Above: signal-to-background ratio of DM signal. Left: prompt radiation at 100 GeV, right: inverse Compton at 10 GeV

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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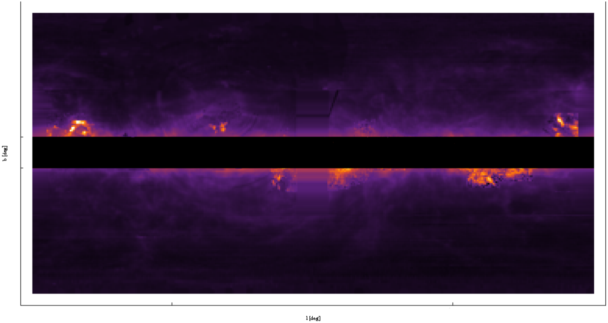

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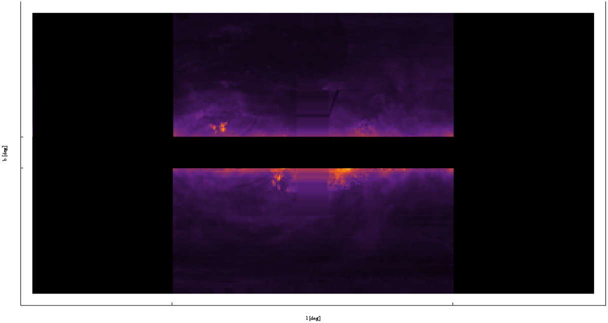

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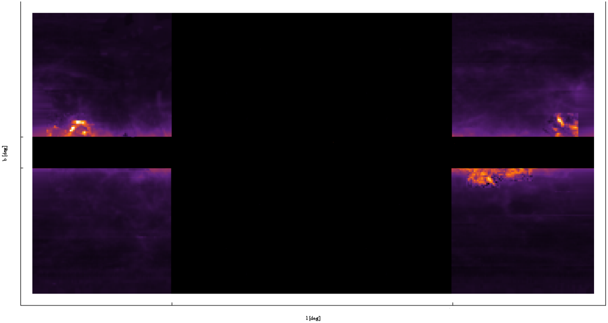
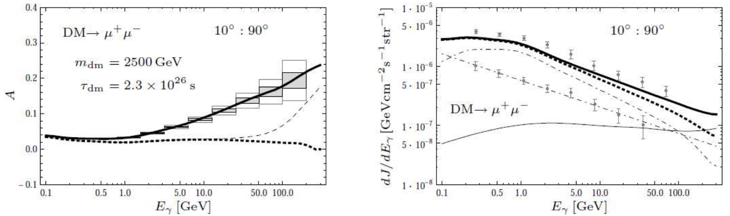


Gamma Rays from Dark Matter Decay

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

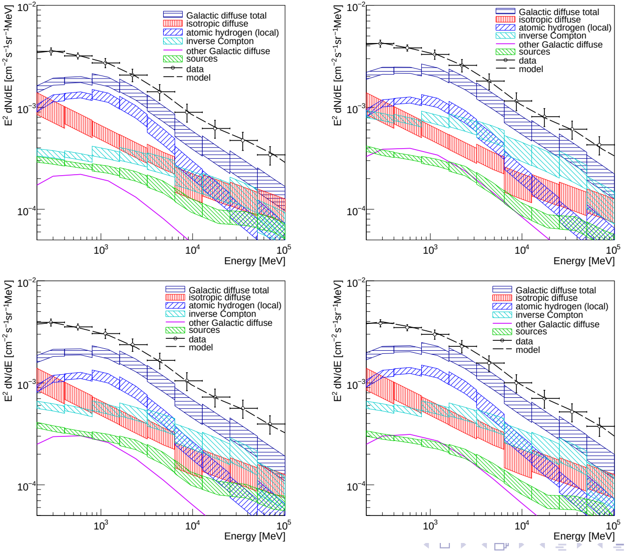


[Ibarra, DT, Weniger '09]

- Similarly, sizable center–anticenter anisotropies are predicted for **all** of the decay modes that can reproduce the PAMELA/Fermi electron excesses
- No anisotropy expected between northern and southern hemisphere
- NB: Not a "smoking gun," but an important test!

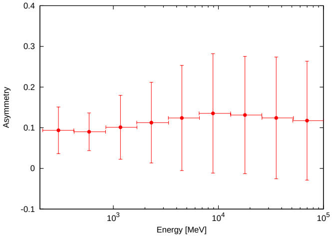
The Diffuse Spectrum as Measured by Fermi LAT

- Results from Fermi LAT on isotropic (?) diffuse gamma-ray emission [Abdo et al. '10]

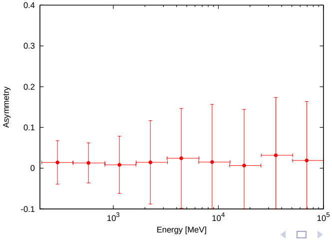


The Diffuse Spectrum as Measured by Fermi LAT

- We make use of the results from Fermi LAT on hemispheric fluxes:
- Center–anticenter anisotropy: around 10% (larger than expected), **but** without discernible energy dependence



- North–south anisotropy: close to zero



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Conclusions

- Unstable dark matter is an interesting scenario with some important differences in indirect detection strategies with respect to dark matter annihilation.
- Next-generation neutrino telescopes can yield important constraints on leptonic dark matter decay modes.
- Prompt gamma-radiation from DM decay exhibits a dipole-like anisotropy at high Galactic latitudes. If decaying DM interpretation of lepton anomalies is correct, a sizable anisotropy in the overall flux is predicted for *a priori* foregrounds.
- Present data indicates an anisotropy larger than expected from astrophysics, but with no discernible energy dependence. However, large uncertainties remain.

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Thank you for your attention!