Neutrino Signals from Decaying Dark Matter[1]

Michael Grefe

Deutsches Elektronen-Synchrotron DESY, Hamburg

The Dark Matter Connection: Theory and Experiment
GGI Firenze – 18 May 2010

[1]Based on work in collaboration with Laura Covi, Alejandro Ibarra and David Tran: JCAP **0901** (2009) 029 & JCAP **1004** (2010) 017

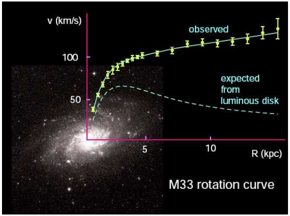
Outline

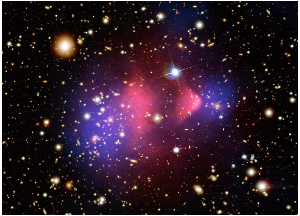
1. Motivation
2. Decaying Gravitino Dark Matter
3. Neutrino Detection
4. Neutrino Constraints on Decaying Dark Matter

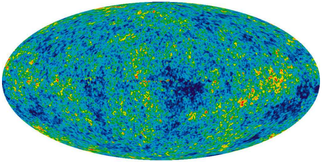
The Quest for Dark Matter I

Cosmological Evidence

- Assuming standard general relativity, the existence dark matter is firmly established from gravitational observations on various scales







- Dark Matter Properties:
  - Weak-scale (or smaller) interactions
  - Cold (maybe warm)
  - Very long-lived (not necessarily stable!)

Particle dark matter can be a (super)WIMP with lifetime $\gg$ age of the Universe!

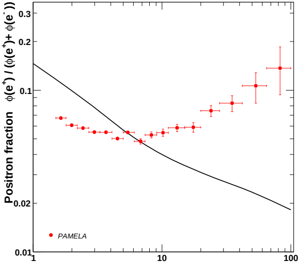
The Quest for Dark Matter II

Why are we interested in Cosmic-Ray Signatures?

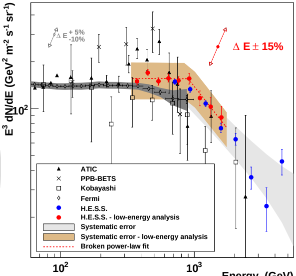
- Complementary method to direct dark matter searches and searches at colliders
- Recent observations:
  - *PAMELA*:
    Steep rise in the positron fraction above 10 GeV
  - *Fermi LAT*:
    Hardening of the electron spectrum around 100 GeV
  - *H.E.S.S.*:
    Change of slope in the electron spectrum at 1 TeV
- In conflict with expectations from secondary production and standard propagation models
- Could be explained by nearby astrophysical sources (pulsars are a source for e^+e^--pairs)

Signature of dark matter annihilation/decay?

- Further observations in different cosmic-ray channels needed to discriminate possibilities



[Adriani et al. (2008)]



[Aharonian et al. (2009)]

Annihilating vs Decaying Dark Matter

Why are we interested in Decaying Dark Matter?

- Flux from the galactic halo:

Dark Matter Annihilation

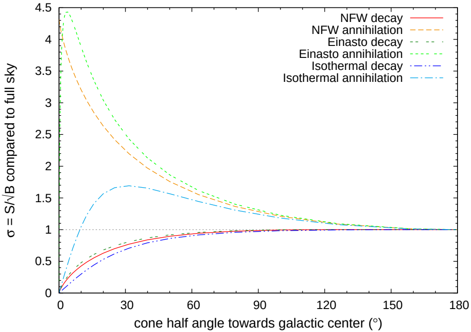
$$\frac{dJ_{\text{halo}}}{dE} = \frac{\langle \sigma v \rangle_{\text{DM}}}{8\pi\, m_{\text{DM}}^2} \frac{dN}{dE} \int_{\text{l.o.s.}} \rho_{\text{halo}}^2(\vec{l})\, d\vec{l}$$

particle physics — astrophysics

Dark Matter Decay

$$\frac{dJ_{\text{halo}}}{dE} = \frac{1}{4\pi\, \tau_{\text{DM}}\, m_{\text{DM}}} \frac{dN}{dE} \int_{\text{l.o.s.}} \rho_{\text{halo}}(\vec{l})\, d\vec{l}$$

particle physics — astrophysics



- Annihilation:
  - Strong signal from peaked structures
  - Enhancement of cross section needed
  - Best statistical significance for small cone around galactic centre
- Decay:
  - Milder angular dependence
  - Less constrained and less studied
  - Best statistical significance for full-sky observation

Annihilating and decaying dark matter require different strategies for observation!

Outline

Decaying Gravitino Dark Matter I

Motivation from the early Universe

- Gravitino arises naturally as the spin-3/2 superpartner of the graviton
- Thermal production: $\Omega_{3/2}h^2 \simeq 0.27 \left(\frac{T_R}{10^{10}\,\text{GeV}}\right) \left(\frac{100\,\text{GeV}}{m_{3/2}}\right) \left(\frac{m_{\tilde{g}}}{1\,\text{TeV}}\right)^2$

  [Bolz et al. (2001)]
- Thermal leptogenesis: $T_R \gtrsim 10^9\,\text{GeV} \;\Rightarrow\; m_{3/2} \gtrsim \mathcal{O}(10)\,\text{GeV}$ favored
- Correct relic density for typical leptogenesis and supergravity parameters
- Problem: Late gravitino decays are in conflict with BBN predictions!
- Gravitino LSP is a natural candidate for cold dark matter
- Problem: Late NLSP decays usually spoil BBN predictions!

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Possible solution: *R*-parity not exactly conserved!

Decaying Gravitino Dark Matter II

Bilinear R-Parity Violation

- Renormalisable R-parity violating terms in the superpotential:

$$W_{\not R_p} = \mu_i L_i H_u + \lambda L L E^c + \lambda' L Q D^c + \lambda'' U^c D^c D^c$$

- Proton stability guaranteed if λ'' vanishes
- We concentrate on bilinear R-parity breaking:
  - μ_i, λ, λ' related by field redefinitions
  - λ'' remains absent
- Bounds on $\not R_p$-couplings:
  - NLSP decays before BBN: Lower bound on $\not R_p$-couplings
  - Lepton/baryon asymmetry not washed out: Upper bound on $\not R_p$-couplings
- Gravitino couplings suppressed by the Planck mass and the small $\not R_p$-couplings
- Gravitino unstable but very long-lived: $\tau_{3/2} \approx \mathcal{O}(10^{23} - 10^{37})$ s

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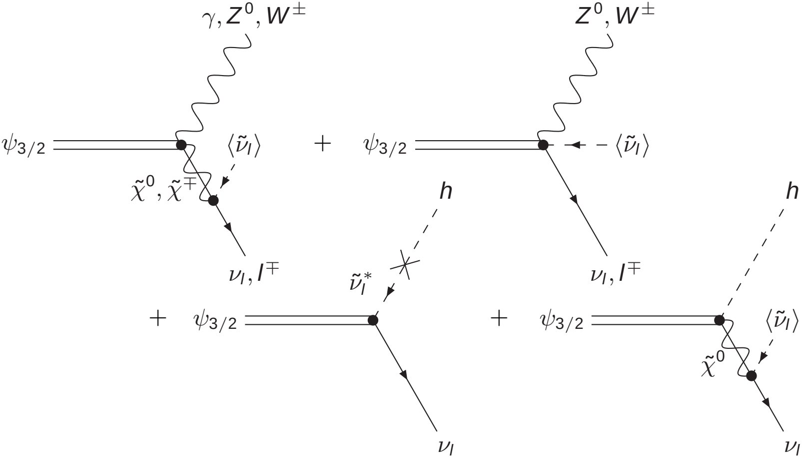
The gravitino is a viable decaying dark matter candidate!

Decaying Gravitino Dark Matter III

Gravitino Decay Channels

- R-parity breaking treated in terms of a non-vanishing sneutrino VEV

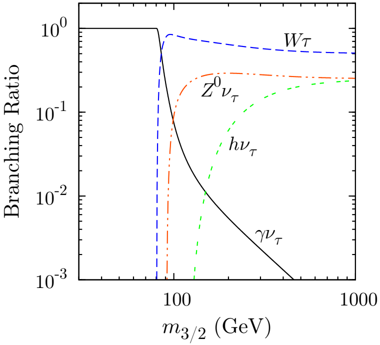


- Observable cosmic rays are created from direct production, gauge/Higgs boson fragmentation and lepton decays

Decaying Gravitino Dark Matter IV

Indirect Detection

- Gravitino branching ratios:
  - Independent of sneutrino VEV
  - Dominant dependence on gravitino mass
  - Large branching ratio into a neutrino line
- Smoking gun signature in neutrinos!



- Gravitino parameters constrained by antiproton observations due to hadronic decays
- Gravitino decays cannot fit PAMELA and Fermi LAT with these parameters

[Buchmüller et al. (2009)]

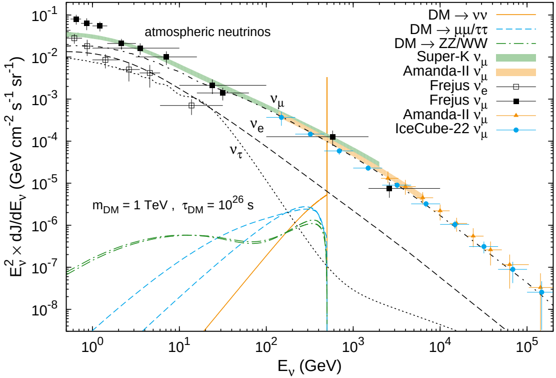
Decaying gravitino dark matter cannot account for the PAMELA and Fermi LAT excesses without additional astrophysical sources

Outline

Neutrino Flux and Atmospheric Background I

Scalar Dark Matter Candidate

- Scalar dark matter decay channels:
  - DM $\to \nu\nu$: two-body decay with monoenergetic line at $E = m_{DM}/2$
  - DM $\to \ell^+\ell^-$: soft spectrum from lepton decay (no neutrinos for e^+e^-)
  - DM $\to Z^0Z^0/W^+W^-$: low-energy tail from gauge boson fragmentation
- Triangular tail from extragalactic dark matter decays
- Neutrino oscillations distribute the flux equally into all neutrino flavours
- Atmospheric neutrinos are dominant background for TeV scale decaying DM



Neutrino Flux and Atmospheric Background II

Fermionic Dark Matter Candidate

- Fermionic dark matter decay channels:
  - DM $\to Z^0\nu$: narrow line near $E = m_{DM}/2$ and tail from Z^0 fragmentation
  - DM $\to \ell^+\ell^-\nu$: hard prompt neutrino spectrum and soft spectrum from lepton decay
  - DM $\to W^\pm\ell^\mp$: soft spectrum from $W^\pm$ fragmentation and lepton decay
- Triangular tail from extragalactic dark matter decays
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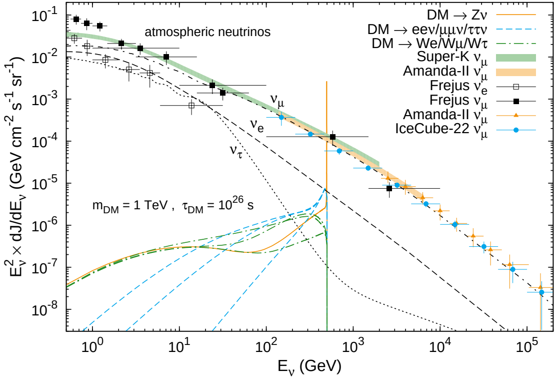
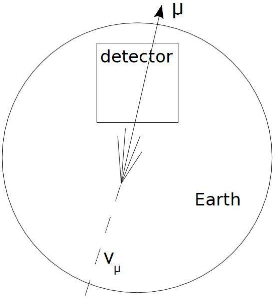
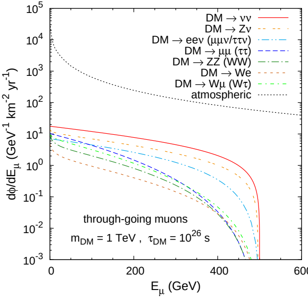


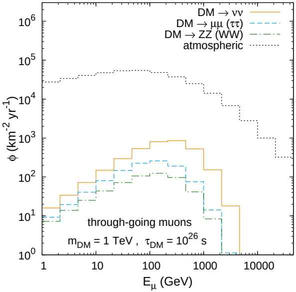
Neutrino Signals I

Upward Through-going Muons

- Muon track from charged-current deep inelastic scattering of a muon neutrino off a nucleon outside the detector
- Deep inelastic neutrino–nucleon scattering and propagation energy loss shifts muon spectrum to lower energies
- Bad energy resolution (0.3 in $\log_{10} E$) smears out cutoff energy
- Muon track reconstruction is the best-understood method at neutrino telescopes



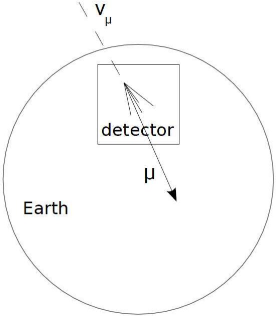


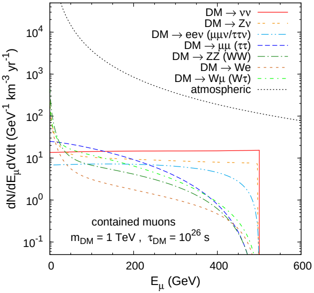


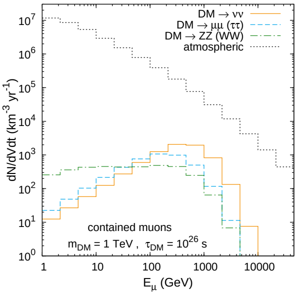
Neutrino Signals II

Contained Muons

- Muon track and hadronic shower from charged-current deep inelastic scattering of a muon neutrino off a nucleon inside the detector
- Deep inelastic neutrino–nucleon scattering shifts muon spectrum to lower energies
- Bad energy resolution (0.3 in $\log_{10} E$) smears out cutoff energy
- If the shower can be used for analysis, reconstruction of initial neutrino energy possible



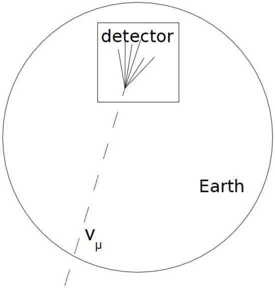


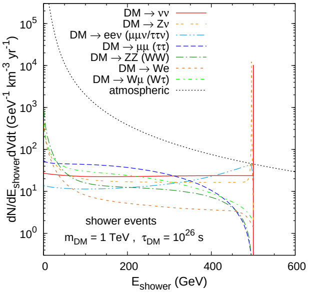


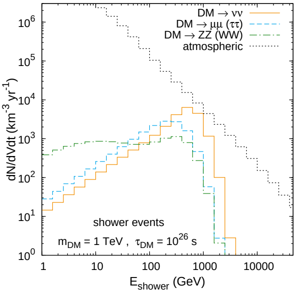
Neutrino Signals III

Showers

- Hadronic and electromagnetic showers from charged-current deep inelastic scattering of electron and tau neutrinos and neutral-current interactions of all neutrino flavours inside the detector
- Potentially best channel for dark matter searches:
  - Better energy resolution (0.18 in $\log_{10} E$) helps to distinguish spectral features
  - $3\times$ larger signal and $3\times$ lower background compared to other channels
- Problem: TeV-scale shower reconstruction is not yet well understood





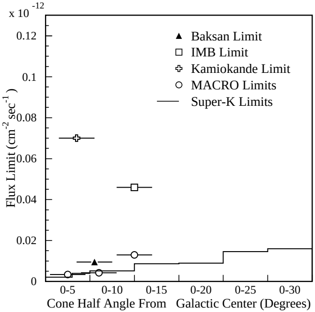


Outline

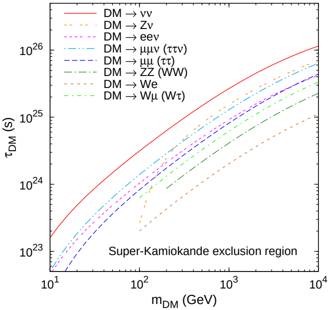
Limits on the Dark Matter Parameter Space I

Limits from Super-Kamiokande

- Limit on integrated upward through-going muon flux from the Super-Kamiokande collaboration
  - As expected, strongest limit from the largest cone around the galactic centre
  - Stronger limits for larger dark matter masses due to increasing neutrino–nucleon cross section and increasing muon range although the neutrino flux decreases with increasing dark matter mass
  - Stronger limits for harder spectra
- Super-Kamiokande does not constrain the parameter region that fits PAMELA and Fermi LAT



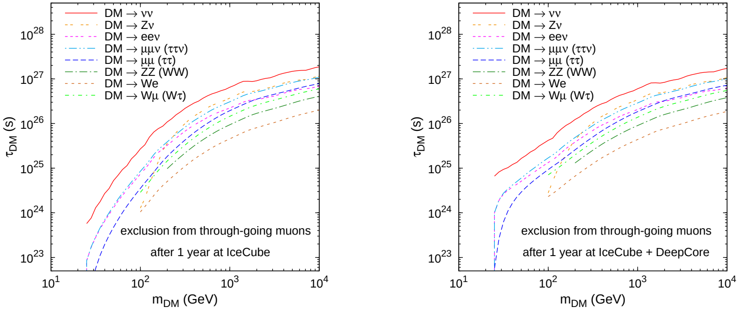
[Desai et al. (2004)]



Limits on the Dark Matter Parameter Space II

Sensitivity of IceCube

- Many orders of magnitude larger than Super-Kamiokande
- Larger volume gives higher events rates and more sensitivity to small fluxes
- DeepCore extension allows to set stronger constraints at lower masses
- Use of spectral information will greatly improve the limits
- Use of different detection channels allows additional improvement
- PAMELA and Fermi LAT preferred regions will be tested



Conclusion

- In contrast to the concentration on peaked structures in the case of annihilation it will be a better strategy to look at spectral features in full-sky observations for a first signal of decaying dark matter
- Directional observation with gamma rays and neutrinos will allow to decide between annihilating and decaying dark matter or astrophysical sources
- Decaying gravitino dark matter is a well-motivated candidate but probably cannot accomodate the Fermi results without astrophysical sources
- Neutrinos are an important complementary channel for indirect dark matter searches
  - Neutrino telescopes will provide strong constraints on the dark matter parameters, in particular at large masses
  - In case of detection the neutrino channel will give additional information about dark matter decay modes and branching ratios

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Thanks for your attention!