Neutrino Signals from Dark Matter Decay

Michael Grefe

Deutsches Elektronen-Synchrotron
DESY, Hamburg, Germany

Presentation Skills Seminar
DESY Hamburg – 18 January 2011

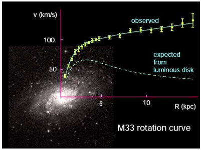
Based on work in collaboration with Laura Covi, Alejandro Ibarra and David Tran: JCAP **1004** (2010) 017

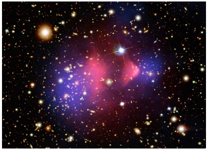
Outline

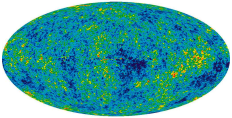
- Motivation
  - Why are we studying cosmic ray signals in the context of dark matter searches?
- Neutrino Signals and Neutrino Detection
  - What neutrino signal from dark matter decay can be observed at Earth?
  - How will these signals look in a neutrino detector?
- Neutrino Constraints on Decaying Dark Matter
  - How useful are neutrinos to detect or to constrain decaying dark matter?
- Conclusion

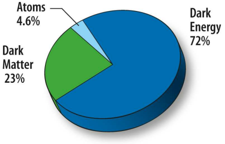
What do we know about dark matter?

- Dark matter is observed on various scales through its gravitational interaction
- Dark matter contributes significantly to the energy density of the universe





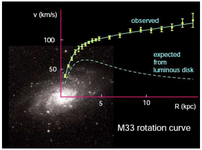


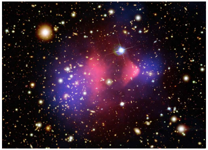


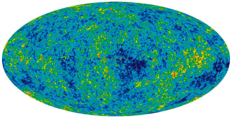
- Dark matter properties known from cosmological observations:
  - No electromagnetic interactions (dark)
  - Weak-scale (or smaller) interactions
  - Non-baryonic
  - Cold (maybe warm)
  - Very long-lived (but not necessarily stable!)

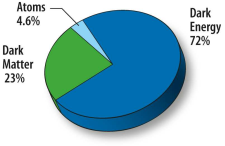
What do we know about dark matter?

- Dark matter is observed on various scales through its gravitational interaction
- Dark matter contributes significantly to the energy density of the universe







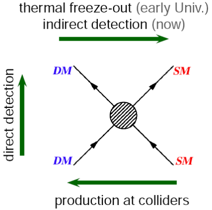


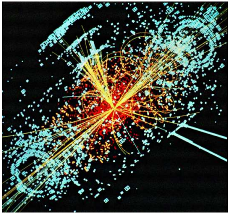
- Dark matter properties known from cosmological observations:
  - No electromagnetic interactions (dark)
  - Weak-scale (or smaller) interactions
  - Non-baryonic
  - Cold (maybe warm)
  - Very long-lived (but not necessarily stable!)

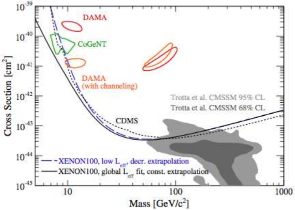
Particle dark matter could be a (super)WIMP with lifetime $\gg$ age of the Universe!

How can we unveil the nature of dark matter?

- There are three strategies for detecting dark matter based on non-gravitational interactions:
  - Production of dark matter particles at colliders
  - Direct detection of dark matter in the scattering off nuclei
  - Indirect detection of dark matter in cosmic ray signatures



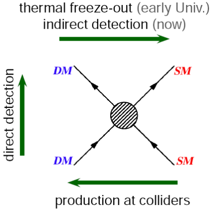


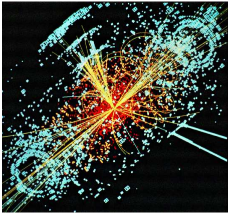


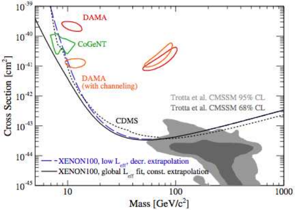
How can we unveil the nature of dark matter?

► There are three strategies for detecting dark matter based on non-gravitational interactions:

- Production of dark matter particles at colliders
- Direct detection of dark matter in the scattering off nuclei
- Indirect detection of dark matter in cosmic ray signatures



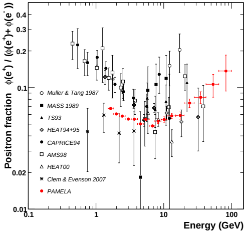




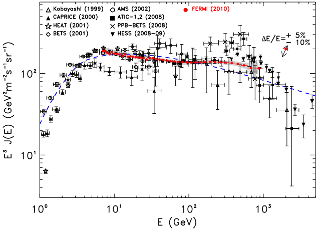
A combination of these search strategies will be necessary to reliably identify the particle nature of the dark matter!

Why are we interested in neutrino signals?

- Recently, anomalies were observed in the cosmic ray positron and electron spectra



[PAMELA Coll. (2008)]



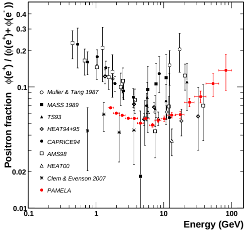
[Fermi LAT Coll. (2010)]

- New sources of positrons and electrons are needed to explain the spectra:
  - Astrophysical sources (e.g. pulsars)
  - Dark matter annihilations
  - Dark matter decays (typically a lifetime 10^{26} s is needed)

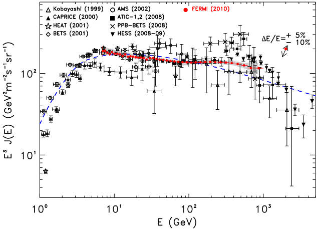
- To obtain a consistent dark matter explanation, a multi-messenger approach that includes all cosmic ray channels will be necessary: This includes gamma rays, positrons, antiprotons, antideuterons, and neutrinos!

Why are we interested in neutrino signals?

- Recently, anomalies were observed in the cosmic ray positron and electron spectra



[PAMELA Coll. (2008)]



[Fermi LAT Coll. (2010)]

- New sources of positrons and electrons are needed to explain the spectra:
  - Astrophysical sources (e.g. pulsars)
  - Dark matter annihilations
  - Dark matter decays (typically a lifetime 10^{26} s is needed)

- To obtain a consistent dark matter explanation, a multi-messenger approach that includes all cosmic ray channels will be necessary: This includes gamma rays, positrons, antiprotons, antideuterons, and neutrinos!

Neutrinos are an important complementary channel for indirect dark matter detection!

What is the Difference of Dark Matter Annihilations and Decays?

- Different angular distribution of the gamma-ray/neutrino flux from the galactic halo:

Dark Matter Annihilation

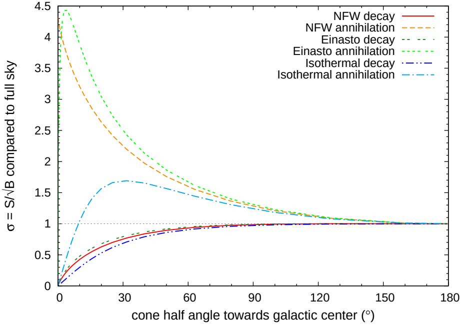
$$\frac{dJ_{\text{halo}}}{dE} = \frac{\langle\sigma v\rangle_{\text{DM}}}{8\pi\, m_{\text{DM}}^2} \frac{dN}{dE} \int_{\text{l.o.s.}} \rho_{\text{halo}}^2(\vec{l})\, d\vec{l}$$

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

- Less sensitive to the halo model
- Best statistical significance for full-sky observation

What is the Difference of Dark Matter Annihilations and Decays?

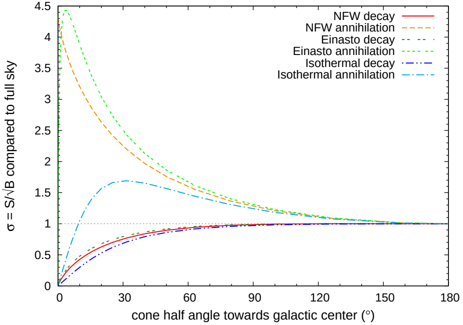
- Different angular distribution of the gamma-ray/neutrino flux from the galactic halo:

Dark Matter Annihilation

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

Dark Matter Decay

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



Annihilation

- Strong signal from peaked structures
- Enhancement of cross section needed
- Best statistical significance for small cone around galactic centre

Decay

- Less sensitive to the halo model
- Best statistical significance for full-sky observation

Different search strategies required!

Models of Decaying Dark Matter

- A non-exhaustive list of models predicting decaying dark matter includes:
  - **Gravitino dark matter with R-parity violation**

    Decay rate suppressed by Planck scale and small R-parity violation.

    [Takayama, Yamaguchi (2000)], [Buchmüller, Covi, Hamaguchi, Ibarra, Yanagida (2007)], [Chen, Mohapatra, Nussinov, Zhang (2009)]
  - **Sterile neutrinos**

    Decay rate suppressed by small Majorana mass of the sterile neutrino

    [Asaka, Blanchet, Shaposhnikov (2005)]
  - **Right-handed Dirac sneutrinos**

    Decay rate suppressed by small neutrino Yukawa couplings

    [Pospelov, Trott (2008)]
  - **Bound state of strongly interacting particles**

    Decay via GUT-scale or Planck-suppressed higher-dimensional operators.

    [Hamaguchi, Nakamura, Shirai, Yanagida (2008)], [Nardi, Sannino, Strumia (2008)]
  - **Hidden sector fermions**

    Decay via GUT-scale suppressed dimension-6 operators.

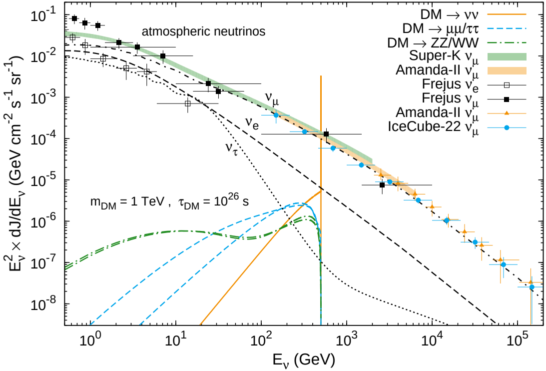
    [Hamaguchi, Shirai, Yanagida (2008)], [Arvanitaki, Dimopoulos, Dubovsky, Graham, Harnik, Rajendran (2008)]
  - **Hidden sector gauge bosons and gauginos**

    Decay rate suppressed by tiny kinetic mixing between $U(1)_{\text{hid}}$ and $U(1)_Y$.

    [Chen, Takahashi, Yanagida (2008)], [Ibarra, Ringwald, Tran, Weniger (2009)]

Neutrino Flux and Atmospheric Background

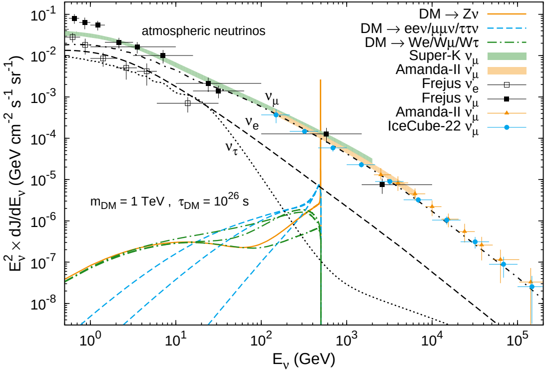
- Decay channels of a scalar dark matter particle:
  - DM $\rightarrow \nu\nu$: two-body decay with monoenergetic line at $E = m_{DM}/2$
  - DM $\rightarrow \ell^+\ell^-$: soft spectrum from lepton decay (no neutrinos for e^+e^-)
  - DM $\rightarrow Z^0Z^0/W^+W^-$: low-energy tail from gauge boson fragmentation



- 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 dark matter

Neutrino Flux and Atmospheric Background

- Decay channels of a fermionic dark matter particle:
  - DM $\rightarrow Z^0\nu$: narrow line near $E = m_{DM}/2$ and tail from Z^0 fragmentation
  - DM $\rightarrow \ell^+\ell^-\nu$: hard prompt neutrino spectrum and soft spectrum from lepton decay
  - DM $\rightarrow W^\pm\ell^\mp$: soft spectrum from $W^\pm$ fragmentation and lepton decay



- 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 dark matter

Neutrino Signals I

Upward Through-going Muons

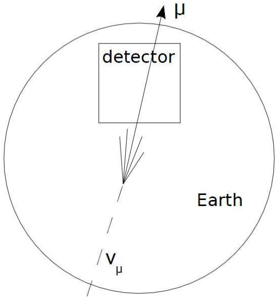
- Muon tracks from CC DIS of muon neutrinos off nuclei outside the detector

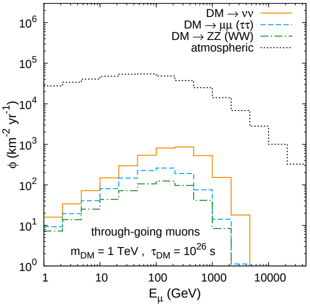
Advantages

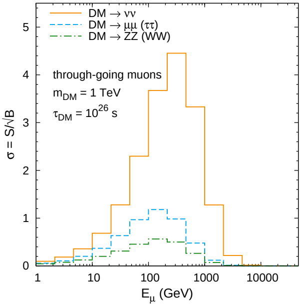
- Muon track reconstruction is well-understood at neutrino telescopes

Disadvantages

- Neutrino–nucleon DIS and propagation energy losses shift muon spectrum to lower energies
- Bad energy resolution (0.3 in $\log_{10} E$) smears out cutoff energy







Neutrino Signals II

Improvements using Showers

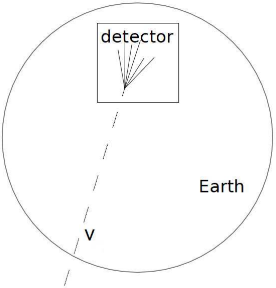
▶ Hadronic and electromagnetic showers from CC DIS of electron and tau neutrinos and NC interactions of all neutrino flavours inside the detector

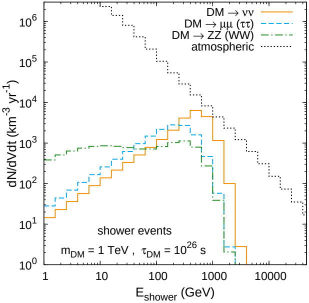
Disadvantages

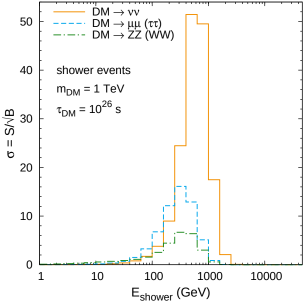
- TeV-scale shower reconstruction is not yet well understood

Advantages

- 3× larger signal and 3× lower background compared to other channels
- Better energy resolution (0.18 in $\log_{10} E$) helps to distinguish spectral features
- Potentially best channel for dark matter searches







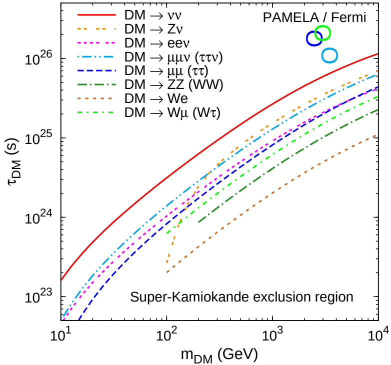
Limits on the Dark Matter Parameter Space

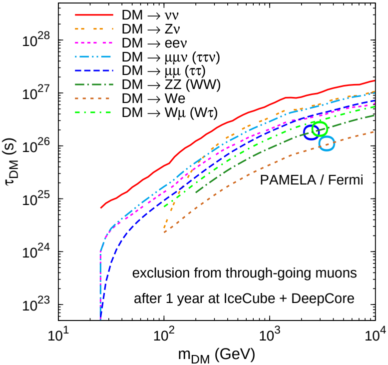
Super-Kamiokande

- Limit on the integrated flux of upward through-going muons
- PAMELA and Fermi LAT preferred regions are not constrained

IceCube

- Observation of the integrated flux of upward through-going muons will soon test the PAMELA and Fermi LAT preferred regions
- Use of spectral information and new detection channels like showers will allow to greatly improve the sensitivity





PAMELA and Fermi LAT preferred regions taken from [Ibarra, Tran, Weniger (2009)]

Conclusion

- The determination of the nature of particle dark matter via indirect detections requires a multi-messenger approach – including neutrinos
- Results from Super-Kamiokande do not constrain the dark matter parameter range fitting the PAMELA and Fermi LAT observations
- Present and future neutrino experiments like IceCube have the capability to detect dark matter signals, in particular at large masses

  Use of new detection channels like showers and use of spectral information will allow to greatly improve the sensitivity of these experiments
- After detection, directional observation with gamma rays and neutrinos will allow to distinguish between annihilating and decaying dark matter
- Then, the neutrino channel will give important additional information about the dark matter decay modes and hence about the nature of dark matter

Conclusion

- The determination of the nature of particle dark matter via indirect detections requires a multi-messenger approach – including neutrinos
- Results from Super-Kamiokande do not constrain the dark matter parameter range fitting the PAMELA and Fermi LAT observations
- Present and future neutrino experiments like IceCube have the capability to detect dark matter signals, in particular at large masses

  Use of new detection channels like showers and use of spectral information will allow to greatly improve the sensitivity of these experiments
- After detection, directional observation with gamma rays and neutrinos will allow to distinguish between annihilating and decaying dark matter
- Then, the neutrino channel will give important additional information about the dark matter decay modes and hence about the nature of dark matter

Thanks for your attention!