Neutrino Signals from Dark Matter Decay

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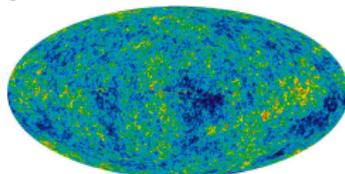
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Why are we interested in decaying dark matter and neutrinos?

Dark matter properties known from cosmological observations:

- Weak-scale (or smaller) interactions
- Non-baryonic
- Cold (maybe warm)
- Very long-lived (not necessarily stable!)

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

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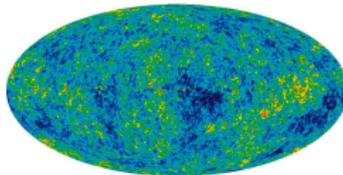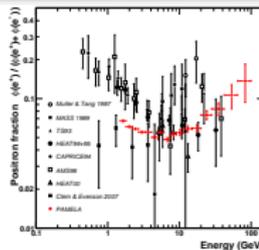- Cold (maybe warm)
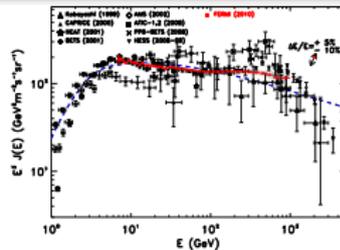- Very long-lived (not necessarily stable!)

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Possible explanations of recently observed cosmic ray anomalies:

- Astrophysical sources (e.g. pulsars)
- Dark matter annihilations
- Dark matter decays

[PAMELA Coll. (2008)]   [Fermi LAT Coll. (2010)]

Decaying dark matter with a lifetime of 10^{26} s is a possible explanation!

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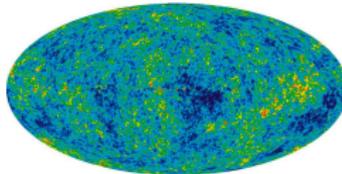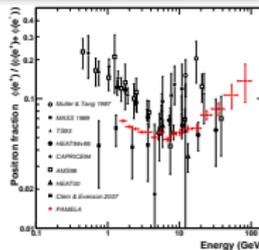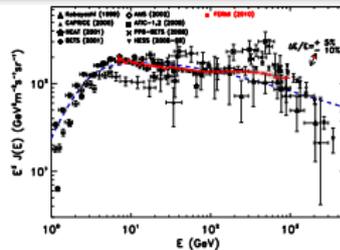- Dark matter annihilations
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Investigate dark matter explanations using collider searches, direct detection experiments and multi-messenger indirect searches:

Study signals in all cosmic ray messengers: gamma rays, antimatter and neutrinos!

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 $U(1)_{hid}$ and $U(1)_Y$.
  [Chen, Takahashi, Yanagida (2008)], [Ibarra, Ringwald, Tran, Weniger (2009)]

What is the Difference of Dark Matter Annihilations and Decays?

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

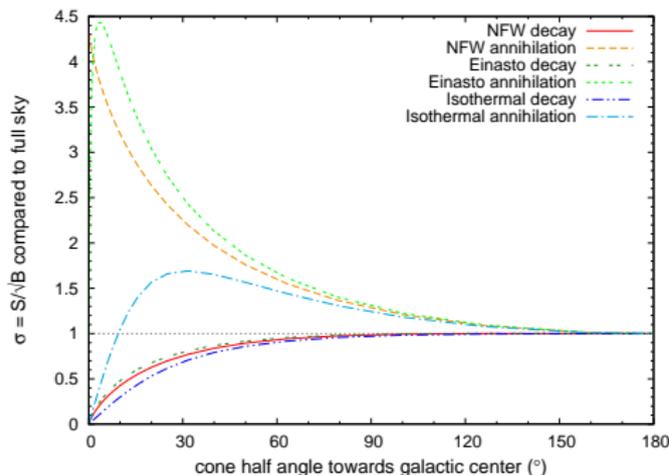<div style="text-align:center">Dark Matter Annihilation</div>

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

particle physics   astrophysics

<div style="text-align:center">Dark Matter Decay</div>

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

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

Different search strategies required!

Neutrino Flux and Atmospheric Background

Decay channels of scalar and fermionic dark matter:

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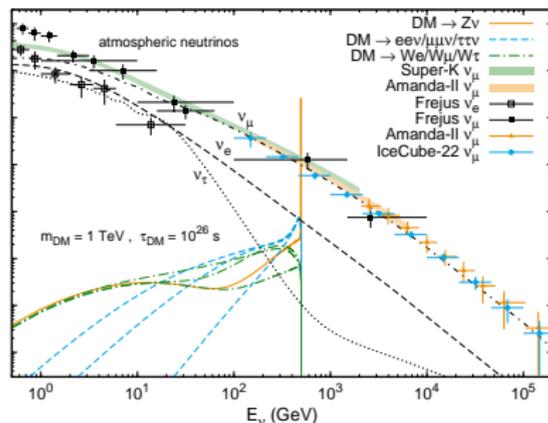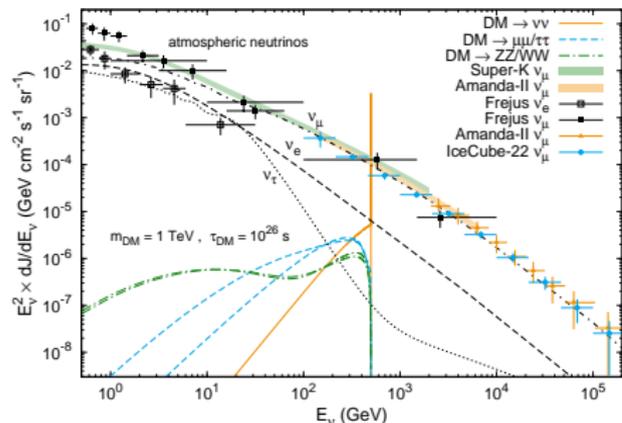
- Triangular tail from extragalactic dark matter decays
- Neutrino oscillations distribute the flux equally into all neutrino flavours
- Atmospheric neutrinos are dominant background for TeV scale decaying dark matter
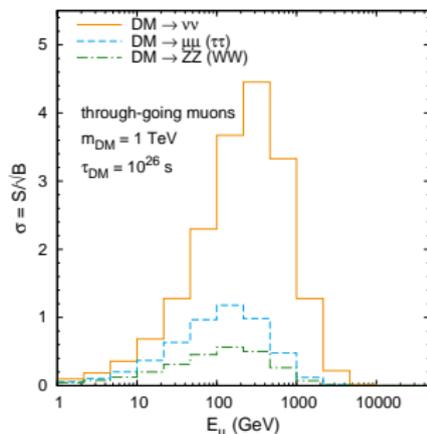
Neutrino Signals I
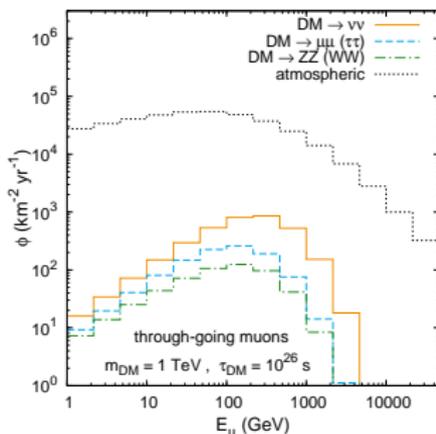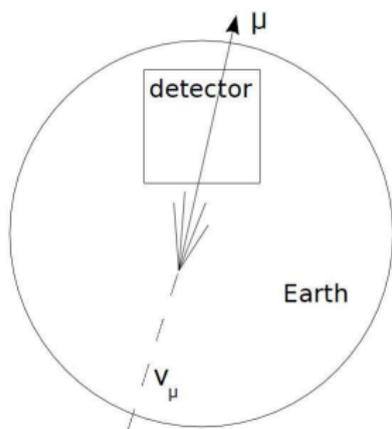## Upward Through-going Muons

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

- $3\times$ larger signal and $3\times$ 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
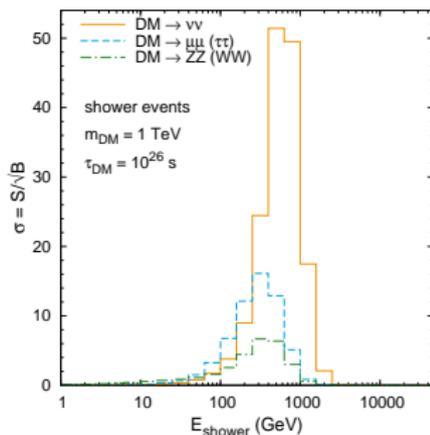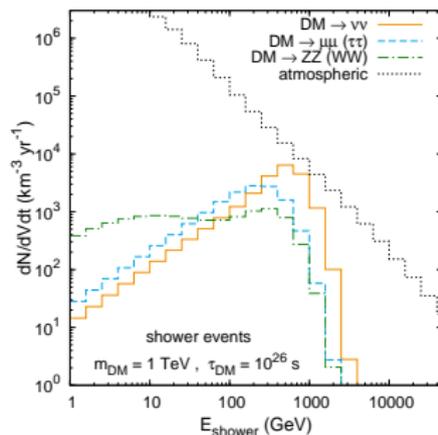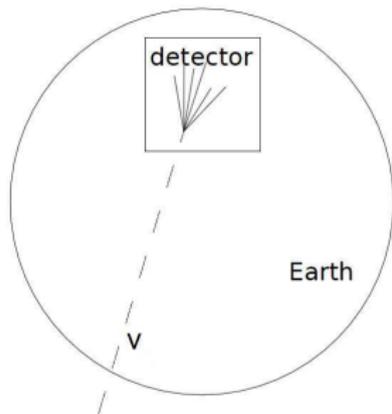
Limits on the Dark Matter Parameter Space

Super-Kamiokande

- Limit on the integrated flux of upward through-going muons

- PAMELA and Fermi LAT preferred regions are not constrained
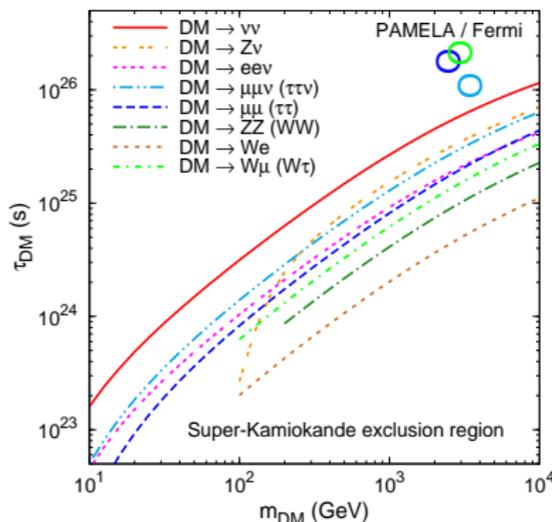
IceCube

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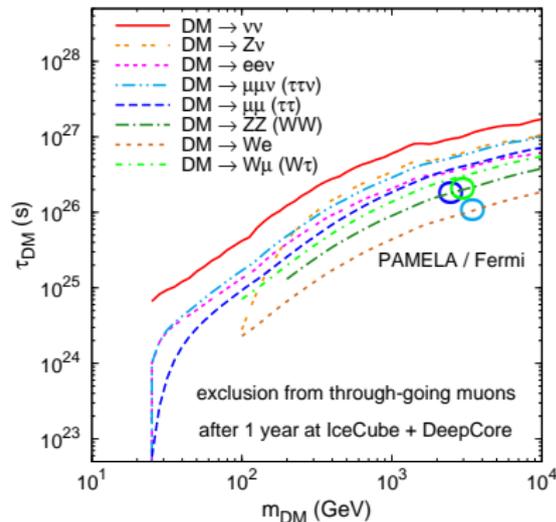
PAMELA and Fermi LAT preferred regions taken from [Ibarra, Tran, Weniger (2009)]

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

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Thanks for your attention!