NEUTRINOS FROM DARK MATTER ANNIHILATION

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Overview

Motivation

Expected Flux from Dark Matter Annihilation

Theoretical and Experimental Constraints

Experimental Search Strategies and Prospects

Conclusions
Dark Matter Understanding

- **Observational Evidence**
  - Non-baryonic
  - Cold massive
  - Not strongly interacting
  - Stable (long lived)

- **Particle Nature**
  - Mass?
  - Cross-sections?
    - Self-annihilation $<\sigma v>$
    - Interaction with matter
  - Theoretical Model
    - SUSY, LED, ...

![Some Dark Matter Candidate Particles](image)

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Strategies for WIMP Detection

- Direct Detection
  - Recoil effects - WIMP scattering of nucleons

- Indirect Detection
  - Neutrinos – annihilation signals from WIMPs accumulated in the Sun or Earth
  - Photons, Neutrinos – Milky Way Halo, Cosmic Flux, …
  - Anti-matter (e+, D, pbar) – local neighborhood (few kpc)

- Production
  - Tevatron, LHC, ILC, …
## Neutrino Dark Matter Searches

**Solar**
- Neutrino Flux, *Scattering cross-section*
- Muon neutrinos
- Background off-source on-source
- Excess
- $M_{\text{WIMP}} \sim < \text{TeV}$

**Earth**
- Neutrino Flux, *(Scattering cross-sections)*
- Muon neutrinos
- Background simulations
- Excess
- $M_{\text{WIMP}} \sim < 100\text{GeV}$

**Halo**
- Neutrino Flux, *Self-annihilation cross-section*
- Muon neutrinos, *Cascades*
- Background off-source on-source
- Anisotropy, Spectrum
- All $M_{\text{WIMP}}$
Expected Flux

- Annihilation $\sim \rho^2$
- Decay $\sim \rho$
Expected Flux

Line of sight

\[ J(\psi) = \frac{1}{R_{sc} \rho_{sc}^2} \int_{0}^{\ell_{\max}} \rho^2 (\sqrt{R_{sc}^2 - 2l R_{sc} \cos \psi + l^2}) dl \]

Expected differential (neutrino) Flux:

\[ \frac{d\Phi}{dE} = \frac{\langle \sigma_A \nu \rangle}{2} J(\psi) \frac{R_{sc} \rho_{sc}^2 dN}{4\pi m^2_{\chi} dE} \]
Dark Matter self-annihilation products

- Variety of particles generated in annihilation process
- Observed particle spectra may show feature at $E=M_{\text{WIMP}}$
How large can the self-annihilation cross-section $\langle \sigma_A v \rangle$ be?

Theoretical/cosmological constraints
  - “DM annihilation flattens cusp”
- Unitarity bound
- Natural scale
  - If DM is thermal relic of early universe to achieve $\Omega_{DM} = 0.3$

Derived limits/sensitivity:
- BBM - Beacom, Bell, Mack (2008)
  - Cosmic time-integrated annihilation
- MW Halo Isotropic
  - $J(\psi = \pi)$ (immediate neighborhood)
- MW Halo Average
  - Average flux from halo
- MW Halo Angular
  - 30° cone around GC
Primary Sources: $e^-$-accelerated in supernova remnants
Secondary Sources: $e^\pm$ from collisions between cosmic rays & ISM protons

F. Aharonian et al., arXiv:0905.0105.

What can we learn from the anomalous excess?

- Various astrophysical sources may explain observations
  - Most promising candidates
    - Pulsars (Geminga, ...)
    - Supernova Remnants
  - First manifestation of Dark Matter
    - High mass DM (TeV range)
    - Leptophilic final states
    - Non-conventional DM models
    - Unusually large boost factors (enhancement in annihilation rate)
Underlying Message to Neutrino Telescopes

Astrophysical sources could also explain data ... and this might be the most obvious

The Dark Matter might not be what we expected ... model independent approaches

Boost factors certainly would be nice for neutrinos, too
Neutrino Telescopes – Detection Principle

- Muon neutrino interacts in water/rock/ice near/in the detector
- Relativistic muon produces Cherenkov light and suffers radiative losses (track)
- Electron / tau neutrinos interacts in the detector
- Rapid radiative loss (shower)
- Optical sensors detect radiation
- Based on number of photons and arrival time the event can be reconstructed

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<table>
<thead>
<tr>
<th>Location</th>
<th>IceCube</th>
<th>DeepCore</th>
<th>ANTARES</th>
<th>Super K</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Pole (1500m)</td>
<td>South Pole (2000m)</td>
<td>Mediterranean (2100m)</td>
<td>Kamioka (1000m)</td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td>~1GT by 2011</td>
<td>~14MT by 2010</td>
<td>~10 MT</td>
<td>~22.5 KT</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Northern Sky</td>
<td>All Sky (using IceCube as veto)</td>
<td>Southern Sky + large part of Northern Sky</td>
<td>All Sky</td>
</tr>
<tr>
<td>Advantages</td>
<td>Large volume</td>
<td>“Shielded” from atm. muon backgrounds</td>
<td>Good angular resolution</td>
<td>Large dataset, excellent flavor id, well understood detector, …</td>
</tr>
<tr>
<td>Energy</td>
<td>High-energy</td>
<td>10-100GeV</td>
<td>100GeV- …</td>
<td>MeV-GeV-range</td>
</tr>
</tbody>
</table>
Searches Strategies

- Galactic Center
  - Large halo profile uncertainty
  - Other sources?
    - Bengtsson et al. ‘90, Berezinsky et al. ’94, ...

- Milkyway Halo
  - Large scale anisotropy
  - Less profile dependence

- Dwarf Satellite Galaxies
  - High M/L, many within 100kpc
    - Bergstrom ‘06, Profumo ‘06

- ...
Searches in neutrino telescopes: IceCube - Northern Hemisphere

- Muon neutrinos on Northern Hemisphere
- Less dependent on halo profile
- Look for an excess of events in the on-source region with respect to the off-source
- Set limit on the self-annihilation cross section
Searches in neutrino telescopes: SuperK

Upmu flux limit from GC and comparing with Hisano’s model

<table>
<thead>
<tr>
<th>$\theta_{GC}$</th>
<th>Upmu flux limit ($\times 10^{-15} \text{ cm}^2 \text{ sec}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>4.11</td>
</tr>
<tr>
<td>20°</td>
<td>9.99</td>
</tr>
<tr>
<td>30°</td>
<td>11.81</td>
</tr>
</tbody>
</table>

This SK upmu flux limit is compared with the expected upmu flux limit from the Hisano’s model. The WIMP mass and annihilation rate (into lepton pair) which can explain PAMELA excess are estimated in this model. Hisano et.al. Phys.Rev.D79(2009)043516

Some scenario of Hisano’s model such as annihilation into left handed $\tau^+\tau^-$ can be excluded by SK upmu.

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Conclusions

- Neutrino Telescopes can probe Dark Matter self-annihilation cross-section
  - Solar/Earth WIMPs probe WIMP-nucleon scattering cross-section (compare to direct detection experiments)
  - Halo WIMPs compare to γ-ray indirect detection experiments
- Neutrinos can be used to place model independent constraints on the total WIMP self-annihilation cross-section (BBM)
- Observations in lepton channels (if interpreted as DM signals) favor models with high-mass leptophilic WIMPs
  - Neutrinos can test these models
- Neutrinos have a crucial part in obtaining a more complete DM picture

Thanks to John Beacom, Matt Kistler
Backup
How large can the self-annihilation cross-section $\langle \sigma_A v \rangle$ be?

- Most often assumed – “natural scale”
  - $3 \times 10^{-26} \text{ cm}^3/\text{s}$

- **KKT**
  - Cusp profiles

- **Unitarity**
  - Limit from Q.M.
  - The probabilities for elastic and inelastic scattering must sum to 1
  - Unitarity of the scattering matrix

$$\langle \sigma_A v \rangle_{KKT} \simeq 3 \times 10^{-19} \frac{\text{cm}^3}{\text{s}} \left( \frac{m_\chi}{\text{GeV}} \right)$$

$$\langle \sigma_A v \rangle \leq 1.5 \times 10^{-13} \frac{\text{cm}^3}{\text{s}} \left( \frac{\text{GeV}}{m_\chi} \right)^2 \left( \frac{300 \text{ km/s}}{v_{\text{rms}}} \right)$$
Indication for large boost factors?