Review of indirect detection of dark matter with neutrinos

— Neutrino 2016, London UK —
Matthias Danninger, University of British Columbia
2016-07-09
In a nutshell

Dark Matter distributions

Dark Matter interactions
& Primary decay or annihilation products

Propagation

Detection

Interpretation:
- Testing beyond SM models
- Comparison between searches
Dark Matter Candidates — Why look at $\nu$?

- Overwhelming evidence for particle dark matter
- Still very little knowledge about the properties:
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• Still very little knowledge about the properties:
  • Mass
  • Interaction cross-section with nuclei
Dark Matter Candidates — Why look at $\nu$?

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  - Lifetime
    $\to O$(age of the Universe)
Dark Matter Candidates — Why look at $\nu$?

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  - Mass
  - Interaction cross-section with nuclei
  - Annihilation cross-section into SM particles
  - Lifetime
    $\rightarrow \mathcal{O}(\text{age of the Universe})$

We can probe all these properties with neutrino telescopes!!
Neutrinos from Dark Matter

Indirect detection

DM \rightarrow W^{\pm}, Z, q, h, l^{\pm}, \nu, \gamma

Annihilation products
Indirect detection

DM

Annihilation products

$W^\pm, Z, q, h, l^\pm, \nu, \gamma$

Decay

$W^\pm, Z, q, h, l^\pm, \nu, \gamma$
Neutrinos from Dark Matter

Annihilation products

\[ W^\pm, Z, q, h, l^\pm, \nu, \gamma \]

\[ e^\pm, p, D, \ldots, \nu, \gamma \]

\[ \text{Indirect detection} \]

\[ \text{DM} \rightarrow \text{DM} \]

\[ \nu \rightarrow \text{Annihilation} \rightarrow \text{Decay} \rightarrow \text{Final messenger} \]

- Annihilation rate \( \sim \rho^2 \)
- Decay rate \( \sim \rho \)
Neutrinos from Dark Matter

Annihilation products: $W^\pm, Z, q, h, l^\pm, \nu, \gamma$

Decay: $e^\pm, p, D, \ldots, \nu, \gamma$

Final messenger

- Annihilation rate $\sim \rho^2$
- Decay rate $\sim \rho$

Direct detection

Indirect detection

Collider searches
• Look for potential sources that are well defined and have low or understood astrophysical backgrounds
Clusters of Galaxies
Dwarf spheroidal Galaxies

- Look for potential sources that are well defined and have low or understood astrophysical backgrounds
Indirect Dark Matter searches — Where to look?

- Look for potential sources that are well defined and have low or understood astrophysical backgrounds

Clusters of Galaxies
Dwarf spheroidal Galaxies

(Image: M.Strassler)
Indirect Dark Matter searches — Where to look?

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Clusters of Galaxies
Dwarf spheroidal Galaxies

Analyses performed:
• Source stacking
• Point source analysis
• Large-scale anisotropy measurement
• Extended source searches
The experiments & analysis techniques
The Instruments

**IceCube/DeepCore**

**ANTARES**

**Super-K**

**Baksan**

See talks earlier this week for more details on all neutrino telescopes/detectors

<table>
<thead>
<tr>
<th>Instrument</th>
<th>$E_\nu$-range (GeV)</th>
<th>Instrumented volume (ton)</th>
<th>$\bar{\Theta}$ ($^\circ$) at $E_\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceCube</td>
<td>$\gtrsim 10^5$</td>
<td>~1 Gton</td>
<td>13/3.2/1.3</td>
</tr>
<tr>
<td>ANTARES</td>
<td>$\gtrsim 10^4$</td>
<td>~20 Mton</td>
<td>6/3.5/1.6</td>
</tr>
<tr>
<td>Super-K</td>
<td>$\gtrsim 10^3$</td>
<td>~50 kton</td>
<td>1-1.4</td>
</tr>
<tr>
<td>Baksan</td>
<td>$\gtrsim 10^2$</td>
<td>~3 kton</td>
<td>1.5 (tracks $&gt;$ 7 m)</td>
</tr>
</tbody>
</table>

$^\dagger$ Values are given at muon level ($E_\mu$); $\bar{\Theta}$ dominated by kinematic scattering angle.
Improvements in analysis method and strategy

Few years back:
- Single region analyses using on/off-source counting method

Today:
- Many topological event categories target wide range of DM masses
- Stringent $\mu_{\text{atm.}}$ vetoes allow down-going event selections
- Inclusion of $\nu_e$ channel $\rightarrow$ particle identification
- Statistical analyses including directional and energy information
- Better understanding of systematic uncertainties

Super-K:
- Signal acceptance for $bb$-channel at 10 GeV increased by factor 47

IceCube/DeepCore:
- Veto techniques make Galactic Centre searches possible

No excess over exp. background yet in $\nu$:
- All limits presented at the 90% CL
Results from Searches for Dark Matter annihilations in the Galaxy

Constraining $<\sigma_{AV}>$
Neutrinos from Dark Matter annihilations

Flux measurement

\[
\frac{d\phi_\nu}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{1}{4\pi m_\chi^2} J_a(\psi) \frac{dN_\nu}{dE}
\]
Neutrinos from Dark Matter annihilations

Flux measurement

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Parameter of Interest
Neutrinos from Dark Matter annihilations

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Parameter of Interest
Limits on the annihilation cross-section

- Assume annihilation into $\nu\nu, \tau\tau, \mu\mu, bb, WW$
- Models motivated by increase in positron fraction can be tested
- IceCube: GC located above horizon
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- ANTARES: ~60% of time below horizon
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- Assume annihilation into $\nu\nu$, $\tau\tau$, $\mu\mu$, $bb$, $WW$
- Models motivated by increase in positron fraction can be tested
- IceCube: GC located above horizon
- ANTARES: 
  \~60\% of time below horizon
- Super-K extending to 1\,GeV in $m_\chi$
Including weak corrections is important!

- $\nu$ final states also give rise to a $\gamma$-ray emission
- More stringent limits for masses $> 200$ GeV
- Only $\nu$-telescopes can “truly” discriminate a $\nu$-line
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- More stringent limits for masses > 200 GeV
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The picture might have changed!!
Heavy Dark Matter Decays

- Example of $\text{DM} \rightarrow \nu + \gamma$ (e.g. Gravitino)
- Using published IceCube data (*Atmospheric and astrophysical neutrinos above 1 TeV*)
- $\nu$-telescopes remain the most promising instruments

*Dedicated IceCube analysis on-going!*

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**PRD 92, 123515 (2015)**
Results from Searches for Dark Matter annihilations in the Sun
Solar Dark Matter searches

- All processes depend on WIMP mass
- Annihilation channel (branching ratios)
- At equilibrium ($\Gamma_A = \frac{1}{2} \Gamma_C$) ν-flux does not depend on self-annihilation cross-section
- Capture (scattering) $\rightarrow$ Scattering cross-sections (SI & SD)

$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N$$
Limits on the interaction cross-section (SD)

- Most stringent SD cross-section limit for most models
- Complementary to direct detection efforts
- Different astrophysical & nuclear form-factor uncertainties
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- Different astrophysical & nuclear form-factor uncertainties
Limits on the interaction cross-section (SI)

- SI cross-section limit dominated by direct detection
- Complementary but significantly weaker
- Different astrophysical & nuclear form-factor uncertainties
Complementarity to Collider Searches

- DM is “stable” —> Missing energy at LHC
- Mono-X searches
  —> Rely on the detection of accompanying particles/jets
- Effective theory (was) typically assumed
- Move towards simplified models (still few parameters, but more assumptions)
  —> $m_{DM}$, $m_{med}$, 2 couplings

JHEP06(2016)059 (ATLAS Mono-photon search)
IceCube limits: JCAP 04 (2016) 022

IceCube ($\nu$)
Super-K($\bar{\nu}$)

Atlas/CMS Dark Matter Forum Simplified models arXiv/1507.00966
LHC DM WG Recommendations arXiv/1603.04156
Results from Searches for Dark Matter annihilations in the Earth
Results for Dark Matter Searches from the Earth

- Dark Matter could be captured in the Earth
- Signature: Vertically up-going excess $\nu$-flux
- Experimentally challenging — no off-source data expectation

Future Prospects for neutrino telescopes & conclusions
Future prospects & Conclusions (1/2)

Dark Matter in the Sun

- Discovery channel for Dark Matter
- Most stringent SD cross-section limit for most models
- Sensitivity will continue to improve with current detectors!!
- Publishing data and detector responses is important! —> allows inclusion into explicit model scans Future detectors will further improve limits at low DM masses
- Inclusion of cascade channel will further improve limits

JCAP 04 (2016) 022
[code at: http://nulike.hepforge.org/]
Future prospects & Conclusions (2/2)

Galactic halo, Galactic center, Dwarf spheriodals, Cluster of Galaxies, ...

- Gamma-rays much more competitive for low WIMP masses
- High masses (>1TeV) - neutrinos are more competitive than gamma-rays!
- Exciting prospects for ARCA and IceCube Gen2 high-energy extensions
Thank you!!
Backup
Solar Dark Matter searches

- All processes depend on WIMP mass
- Annihilation channel (branching ratios)
- At equilibrium ($\Gamma_A = 1/2\Gamma_C$) v-flux does not depend on self-annihilation cross-section
- Capture (scattering) $\rightarrow$ Scattering cross-sections (SI & SD)

\[
\frac{dN}{dt} = C_C - C_A N^2 - C_E N
\]
Impact of Astrophysical uncertainties

- Halo model: SMH vs. Mao et al.
- Local Sun velocity (km s⁻¹): 220 vs. 260
- Local DM density (ρ₀): 0.3 vs. 0.4
- Dark-disk fraction (ρ₅₃/ρ₀): 0 vs. 0.3
Impact of Astrophysical uncertainties

- Example for $\sigma_{SD}$
- IceCube results & PINGU sens. from 2014
- Not included: Solar composition & nuclear form-factor uncertainties
Impact of Astrophysical uncertainties

- Example for $\sigma_{SD}$
- IceCube results & PINGU sens. from 2014
- Not included: Solar composition & nuclear form-factor uncertainties
Neutrinos and current experimental excesses

Two interesting experimental excesses that could be linked to DM

- **ATLAS/CMS** —> Possible new resonance in di-photon spectrum (750GeV)
  - Could give rise to neutrino fluxes in some models (new resonance acts as the mediator)
    —> very low neutrino flux predictions —> prospects are not promising (arXiv:1603.05592)
- **Fermi**: Gamma ray excess in the galactic centre (GeV range)
  - Energy range is challenging for neutrino telescopes —> not sensitive to proposed signal scenarios
Weak corrections for neutrino lines

\( b\bar{b} \) channel

\[ \langle \sigma v \rangle \left[ \text{cm}^3 \text{s}^{-1} \right] \]

- LAT: dSphs
- LAT: Unid. (Berlin+ 2013)
- LAT: Isotropic
- HESS: GC
- HESS: dSphs
- MAGIC: Segue I
- Veritas: Segue I
- HAWC: dSphs
- AMS: antiproton (Giesen+ 2015)
- AMS: antiproton (Hooper+ 2014)

Thermal Relic Cross Section (Steigman+ 2012)

\[ M_\chi \text{ [GeV]} \]

K. Bechtol (TeVPA15)
Weak corrections for neutrino lines

\[ M_{DM} = 3 \text{ TeV} \]

\[ E_\gamma \frac{dN}{dE_\gamma} \]

\[ \sigma v \text{ [cm}^3\text{s}^{-1}] \]

\[ \chi \chi \rightarrow \nu \bar{\nu}_\alpha \alpha \]

\[ \alpha = e, \mu, \tau \]

\[ \text{Dark Matter Mass [TeV]} \]

2016-07-09 | Matthias Danninger | Review of indirect detection of dark matter with neutrinos
Limits on the interaction cross-section
Limits on the interaction cross-section

**Neutrino telescope likelihoods:** \texttt{nulike}

Unbinned $\nu$ telescope likelihood $\implies$ full event-level angular and energy info

$$L_{\text{unbin}} \equiv L_{\text{num}}(n_{\text{tot}}, \theta_{\text{tot}}) \prod_{i=1}^{n_{\text{tot}}} (f_S L_{S,i} + f_{BG} L_{BG,i})$$

Strategy: precompute partial likelihoods for each event, then reweight with the $\nu$ spectrum at Earth for each model

- precompute step uses \texttt{nusigma} with CTEQ6-DIS PDFs to get charged current $\nu - n$ and $\nu - p$ cross-sections as function of $x$ and $y$
- like step input: neutrino spectrum at Earth (from DarkSUSY or whatever else you want to use)
- like step output: num predicted events, likelihood
- $\rightarrow$ fully model-independent = future-proof for global fits
Complementarity

Cahill-Rowley et al. 2015, Phys. Rev. D, 91, 055011

Review of indirect detection of dark matter with neutrinos
Results for Dark Matter Searches from the Earth

- **IC86-I Earth limit**: \( m_\chi = 1 \text{TeV}, \chi \chi \rightarrow W^+ W^- \)
- **IC86-I Earth limit**: \( m_\chi = 50 \text{GeV}, \chi \chi \rightarrow \tau^+ \tau^- \)

### Graphical Information

- **Graph Legend**:
  - Blue lines: \( \tau^+ \tau^- \) channel, Pink lines: \( b \bar{b} \) channel, Green lines: \( W^+ W^- \) channel

### Data Points

- **LUX limit**:
  - \( m_\chi = 1 \text{TeV} \)
  - \( m_\chi = 50 \text{GeV} \)