Downward-going tau neutrinos and Dark Matter

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based on N. Fornengo, V. Niro, arXiv:1108.2630
Outline

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2 Neutrino fluxes
   - Dark Matter
   - Backgrounds

3 Contained hadronic events
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Indirect Dark Matter detection

The Dark Matter (DM): 23% of the matter present in the Universe

Indirect detection: look for the products of DM self-annihilation or decay occurring in GH, in EG environment, in celestial bodies, like the Sun and the Earth

Typical way of looking for a neutrino signal: an excess of upward-going muons ⇒
- large conversion area offered by the rock below the detector
- well-established and efficient experimental techniques
- $\nu_\mu$ atmospheric neutrinos are the main source of background

Our proposal: downward-going tau events ⇒
- DM annihilation typically produces similar amount of all neutrino flavors
- atmospheric neutrinos $\nu_\tau$ component is very suppressed
- oscillations is basically inoperative in the downward-going direction for the atmospheric background
- it might be a competitive discovery channel
Dark Matter
The differential neutrino flux from the Sun is:

$$\frac{d\phi_\nu}{dE_\nu} = \sum_f BR_f \frac{\Gamma_\odot}{4\pi d^2} \frac{dN^f_\nu}{dE_\nu}$$

Propagation: oscillation, neutral and charged current interactions
Our examples: i) annihilation into neutrinos with $BR_{\nu_e\bar{\nu}_e} = BR_{\nu_\mu\bar{\nu}_\mu} = BR_{\nu_\tau\bar{\nu}_\tau} = 1/3$
ii) annihilation into tau leptons with $BR_{\tau\bar{\tau}} = 1$

Apparent motion of the Sun for a detector at latitude $\varphi = 36^\circ$
Backgrounds

Sources of background for the $\nu_\tau$ signal from DM annihilation:

- $\nu_\tau$ atmospheric background coming from oscillation of atmospheric $\nu_\mu$
- very small intrinsic $\nu_\tau$ contribution coming from decay of charmed particles
- $\nu_e$ and $\nu_\mu$ neutrinos produced in the solar corona by cosmic-ray collisions → they generate $\nu_\tau$ during their propagation to the Earth
- $\nu_\mu$ produced in cosmic-ray interactions with the interstellar medium → they generate $\nu_\tau$ from the Galactic plane

The atmospheric $\nu_\tau$ background is sizebly reduced for $\cos \theta_Z \geq 0$ and is much smaller than the $\nu_e$ and $\nu_\mu$ fluxes.

Black: solar corona neutrinos
Yellow: galactic contribution


Backgrounds

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

\[ \chi \bar{\chi} \rightarrow \tau \bar{\tau} \]

Black: total downward-going \( \nu_\tau \) fluxes integrated (zenith angles with \( \cos \theta_Z \geq 0 \))
Green: total downward-going \( \nu_\tau \) background fluxes
Red: total downward-going \( \nu_\mu \) background fluxes

⇒ the signal is dominant over the background in the down-going \( \nu_\tau \) channel, especially at high energies where the tau cross section is not suppressed by mass threshold.

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Downward-going \( \nu_\tau \) and DM

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Signals at water Cherenkov detectors

For GeV-TeV energy range: CC $\nu_\tau$ interactions in water Cherenkov detectors lead to multiple Cherenkov rings $\rightarrow$ statistical methods to identify $\nu_\tau$ and hadronic decays of tau leptons ($BR^h_\tau \simeq 64\%$) because of a more spherical topology than the backgrounds.

Backgrounds to $\nu_\tau$ CC events with hadronic tau decay:
- **NC events** from $\nu_e$ and $\nu_\mu$ atmospheric neutrinos
- **CC events** from $\nu_e$ and $\nu_\mu$ atmospheric neutrinos

$\Rightarrow$ The SK Collaboration: number of event selection criteria to reduce these backgrounds; neural network and maximum likelihood techniques to discriminate tau neutrino events.

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>$\nu_e,\nu_\mu$ BKG MC</th>
<th>CC $\nu_\tau$ MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generated in fiducial volume</td>
<td>$-$</td>
<td>17135 (100%)</td>
<td>78.4 (100%)</td>
</tr>
<tr>
<td>$E_{vis} &gt; 1.33$ GeV</td>
<td>2888</td>
<td>2943 (17.2%)</td>
<td>51.5 (65.7%)</td>
</tr>
<tr>
<td>Most energetic ring e-like</td>
<td>1803</td>
<td>1765 (10.3%)</td>
<td>47.1 (60.1%)</td>
</tr>
<tr>
<td>Likelihood $&gt; 0$</td>
<td>649</td>
<td>647 (3.8%)</td>
<td>33.8 (43.1%)</td>
</tr>
<tr>
<td>NN output $&gt; 0.5$</td>
<td>603</td>
<td>577 (3.4%)</td>
<td>30.6 (39.0%)</td>
</tr>
</tbody>
</table>

- **hep-ex/0607059, Tokufumi Kato’s PhD thesis**
Signals at water Cherenkov detectors

The atmospheric $\nu_e$ and $\nu_\mu$ fluxes are usually larger than the DM fluxes $\Rightarrow$ the misidentification has a relevant impact on the actual performance of water Cherenkov detectors in identifying $\nu_\tau$ events.

Our analysis:

- $E_{\text{vis}}^{\text{min}} = 3.5$ GeV as lower limit on the visible energy
  $\rightarrow$ a specific detector should choose the minimal visible energy able to maximize the number of correctly identified tau events with respect to the misidentified ones

- total downward-going events ($\cos \theta_Z \geq 0$)

- favourable situation in which the track events from $\nu_\mu$ CC interactions will always be detected

- as misidentified background events we will only considered NC events from $\nu_e$ and $\nu_\mu$ atmospheric neutrinos and CC events from $\nu_e$ interactions
Signal events from hadronic tau decay

The total number of contained events for charged current $\nu_\tau$ interactions is:

$$N^{CC}_\tau \bigg|_{S,B} = M_{\text{det}} N_y \times \int_{E_{\text{vis}}^{\min}}^{E_{\text{vis}}^{\max}} dE_{\text{vis}} \int d\Omega \frac{dI^{CC}_\tau}{d\Omega dE_{\text{vis}}} \bigg|_{S,B},$$

$M_{\text{det}}$ is the detector mass, $N_y$ the number of years of exposure and $\eta(\theta)$ is the on-source duty factor (we take $\eta(\theta) = 1/2$ for bkg).

The visible energy $E_{\text{vis}}$ is the sum of the energy $E_{h,1}$ of the broken nucleon and the hadronic energy $E_{h,2}$ of the tau decay.

### Hadronic tau decay

$$\frac{dI^{CC}_\tau}{d\Omega dE_{\text{vis}}} \bigg|_{S,B} = \int_{E_{\text{vis}}}^{\infty} dE_{\nu} \int_{E_{\nu}^{\min}}^{E_{\nu}} dE_{\tau} \frac{d\phi_{\nu_\tau}}{d\Omega dE_{\nu}} \bigg|_{S,B} \Sigma^{CC}_\tau (E_{\tau}, E_{\nu}) \frac{1}{E_{\tau}} \frac{dn_{\nu}}{dz_{\nu}}$$

with $\Sigma^{CC}_\tau (E_{\tau}, E_{\nu}) = N_A \left( Z \frac{d\sigma^p_{\nu_\tau}}{dE_{\tau}}(E_{\tau}, E_{\nu}) + N \frac{d\sigma^n_{\nu_\tau}}{dE_{\tau}}(E_{\tau}, E_{\nu}) \right)$,

$E_{\tau}^{\min} = \max[m_\tau, E_{\nu} - E_{\text{vis}}]$ and $z_{\nu} = (E_{\nu} - E_{\text{vis}})/E_{\tau}$. 

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Background events

\( \nu_e \) and \( \nu_\mu \) neutral-current interactions

\[
\left. \frac{dI_{N\text{C}}^{e,\mu}}{d\Omega \ dE_{\text{vis}}} \right|_B = \int_{E_{\text{vis}}}^{\infty} dE_\nu \left. \frac{d\phi_{\nu_e,\nu_\mu}}{d\Omega dE_\nu} \right|_B \sum_{e,\mu}^{N\text{C}} (E_{\text{vis}}, E_\nu)
\]

The visible energy is given by \( E_{\text{vis}} = E_\nu - E'_\nu \), \( E_\nu \) being the initial neutrino energy and \( E'_\nu \) the final ones.

\( \nu_e \) charged-current interactions

\[
\left. \frac{dI_{N\text{C}}^{e,\mu}}{d\Omega \ dE_{\text{vis}}} \right|_B = \left. \frac{d\phi_{\nu_e}}{d\Omega dE_{\text{vis}}} \right|_B \sum_{e,\text{TOT}}^{CC} (E_{\text{vis}})
\]

The visible energy \( E_{\text{vis}} \) is equal to the full initial neutrino energy \( E_\nu \).
Contained hadronic events

Number of signal events expected for $M_{\text{det}} N_y = 1 \text{ Mton} \times \text{year}$: from 1 to 100, depending on $m_\chi$ and $BR_f$. Higher signals in the range from 30 GeV up to 200-300 GeV.

Lower limit on the visible energy:

$E_{\text{vis}}^{\text{min}} = 3.5 \text{ GeV}$,

zenith angles with $\cos \theta_Z \geq 0$,

hadronic tau from $\nu_\tau$ background: small,

$\nu_e$ CC events: the biggest background.

Neutral current + charged current events from atmospheric $\nu_e$ and $\nu_\mu$:

$\Rightarrow$ problem if they are not controlled at a level better than a few percent.

Possible way to reduce the misidentification background could be obtained considering specific tau hadronic decays (multiple pion production) and finding suitable cuts to statistically distinguish these events from the CC/NC.
Statistical significance

\[ \zeta \equiv \frac{S}{\sqrt{S + B}}, \]

with

\[ B = \epsilon_\tau \, N^{CC}_\tau \big|_B + \epsilon_\mu^{\mu} N^{NC}_\mu \big|_B + \epsilon_e^{\mu} \left( N^{NC}_e \big|_B + N^{CC}_e \big|_B \right). \]

We have fixed

\[ \epsilon_\tau = 40\%, \quad \epsilon_e^{\mu} = \epsilon_\mu^{\mu} = 4\%. \]

10 yrs of data taking: 5 \( \sigma \) significance for \( m_\chi \) between 20-300 GeV (60-200 GeV) for annihilation into \( \nu \overline{\nu} \) (\( \tau \overline{\tau} \)).
Misidentification parameters

Dependence of $\zeta$ on $\epsilon^{\text{mis}}_e = \epsilon^{\text{mis}}_\mu$ and $\epsilon_\tau$, for $m_\chi = 100$ GeV, $\sigma_p = 10^{-41}$ cm$^2$ and an exposure $M_{\text{det}} N_y = 1$ Mton$ \times$ year.

for $\nu \bar{\nu}$: an efficiency of tau-events reconstruction $\epsilon_\tau \simeq 50$-60% would allow to a clear signal detection with $\epsilon^{\text{mis}}_e = \epsilon^{\text{mis}}_\mu \simeq 5$-9%. Alternatively, a reduction of $\epsilon^{\text{mis}}_e = \epsilon^{\text{mis}}_\mu \simeq 1$% level would be enough (for this benchmark case) to obtain a 5 $\sigma$ detection with $\epsilon_\tau \simeq 40%$. 
Sensitivity to DM scattering cross section $\sigma_p$

Contours for $\zeta = 1.64$, for a detector with exposure $M_{\text{det}}N_y = 1 \text{ Mton} \times \text{year}$.
Dotted lines: limits without considering misidentification,
solid lines: $\epsilon_\tau = 40\%$ and $\epsilon_e^{\text{mis}} = \epsilon_\mu^{\text{mis}} = 4\%$.

DAMA and CoGeNT direct detection experiments point toward a light DM candidate
with $m_\chi \approx 10 \text{ GeV}$ and $\sigma_p \approx 10^{-42} \text{ cm}^2 - 10^{-40} \text{ cm}^2$:
$\rightarrow \nu\bar{\nu}$: 9 - 900 hadronic events in 10 yrs HK
$\rightarrow \tau\bar{\tau}$: 1 - 50 hadronic events in 10 yrs HK
Conclusions

Possible new channel for DM searches at Cherenkov detectors
⇒ downward-going hadronic tau events:

- the downward-going $\nu_\tau$ background is extremely small
- statistical methods to identify hadronic tau events
- several tens of events per year (depending on $m_\chi/BR_f$) are potentially collectible in a Mton-scale detector, like Hyper-Kamiokande
- the main limitation to the downward-going tau neutrinos signal is the level of misidentification of NC/CC $\nu_\mu e$ and $\nu_e$ events, which need to be kept at level of percent
- a 5 $\sigma$ significance discovery is potentially reachable for $m_\chi$ in the range from 20 to 300 GeV with 10 years of exposure, and for $\sigma_p = 10^{-41}$ cm$^{-2}$ ($\epsilon_\tau = 40\%$, $\epsilon_{mis}^{e} = \epsilon_{mis}^{\mu} = 4\%$)
- a better performance will enlarge the 5 $\sigma$ discovery region in the ($m_\chi, \sigma_p$) plane
BACKUP SLIDES
For a Mton-scale detector, the expected number of down-going $\nu_\tau$ signal events can reach the level of 50 or more, depending on the DM mass. For a prolonged exposure of a decade or more, more than a hundred of signal events is potentially under reach.
Full efficiency for the detection of tau hadronic events ($\epsilon_{\tau} = 100\%$) and no misidentification.
Efficiency of tau hadronic events $\epsilon_\tau = 70\%$ and misidentification of electron and muon events $\epsilon^\text{mis}_e = \epsilon^\text{mis}_\mu = 1\%$. 