From Neutrino Astronomy to Dark Matter-Neutrino Interactions

Part 2

Marco Chianese

Università degli Studi di Napoli Federico II - INFN

IMPRS Young Scientists Workshop
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JCAP 1512 (arXiv:1507.01000)
PL B757 (arXiv:1601.02934)
Two components
Two components

\[ E^{-2.6} \]
Two components

\[ E^{-2.0} \]

Events per 1347 Days

Deposited EM-Equivalent Energy in Detector (TeV)

- Background Atmospheric Muon Flux
- Bkg. Atmospheric Neutrinos ($\pi/K$)
- Background Uncertainties
- Atmospheric Neutrinos (90% CL Charm Limit)
- Bkg.+Signal Best-Fit Astrophysical (best-fit slope $E^{-2.58}$)
- Bkg.+Signal Best-Fit Astrophysical (fixed slope $E^{-2}$)

IceCube Preliminary
What is the origin of PeV neutrinos?
Our assumption

Boucenna, CHIANESE, Mangano, Miele, Morisi, Pisanti, VITAGLIANO, JCAP 1502

Standard atmospheric background

Decaying Leptophilic Dark Matter

Some astrophysical source (SuperNova Remnants)
Dark Matter at IceCube

For PeV DM the annihilation is negligible with respect to decay

\[ \Gamma_{\text{Events}} \propto \left( \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \right)^2 \langle \sigma_{\text{Ann}} v \rangle \lesssim 1 \text{ per few hundred years} \]

\[ \Gamma_{\text{Events}} \propto \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \Gamma_{\text{DM}} \sim \left( \frac{\lambda}{10^{-29}} \right)^2 / \text{year} \]

Feldstein et al., PR D88 (2013)
Decaying Dark Matter

In literature it has been argued that a very heavy decaying DM can explain the IceCube neutrino spectrum.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Year(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feldstein et al., PR D88 (2013)</td>
<td></td>
</tr>
<tr>
<td>Esmaili, Serpico, JCAP 1311</td>
<td></td>
</tr>
<tr>
<td>Bai et al., arXiv:1311.5864</td>
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<tr>
<td>Ema et al., PL B733 (2014)</td>
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<tr>
<td>Bhattacharya et al., JHEP 1406</td>
<td></td>
</tr>
<tr>
<td>Higaki et al., JHEP 1407</td>
<td></td>
</tr>
<tr>
<td>Ema et al., JHEP 1410</td>
<td></td>
</tr>
</tbody>
</table>

For a gauge-singlet fermionic DM the simplest operator is the renormalizable SM-DM coupling.

\[ \mathcal{L} \supset g \bar{L} H^c \chi \]

This coupling yields to a 2 bodies DM decay with some channels producing one primary neutrino.
2 bodies decay

\[ \mathcal{L} \supset g \bar{L} H^c \chi \]

\[ \chi \to l^\pm W^\mp \]
\[ \chi \to \nu_l Z \]
\[ \chi \to \nu_l h \]

\[ g = \mathcal{O} \left( 10^{-30} \right) \]
We consider a SM-DM coupling with the following characteristics:

- non-renormalizable

\[
\frac{y}{M^n_{Pl}} \chi \ldots
\]
We consider a SM-DM coupling with the following characteristics:

- non-renormalizable
- direct coupling with neutrino

```
y
Mⁿ
M_P¹
χ...
```

"natural" small coupling

primary ν flux
We consider a SM-DM coupling with the following characteristics:

- non-renormalizable
- direct coupling with neutrino
- multi body final state

"natural" small coupling

\[ \frac{y}{M_{Pl}^n} \chi \cdots \]

primary $\nu$ flux

spread $\nu$ flux
We consider a SM-DM coupling with the following characteristics:

- non-renormalizable
- direct coupling with neutrino
- multi body final state
- leptophilic (no quarks)

\[
\frac{y}{M_{Pl}^{n}} \chi \ldots
\]

- "natural" small coupling
- primary $\nu$ flux
- spread $\nu$ flux
- negligible contribution at low energy
Decaying Leptophilic Dark Matter

There exists only one operator with those characteristics.

*Haba et al., PL B695 (2011)*

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>DM decay operators</th>
</tr>
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<tbody>
<tr>
<td>4</td>
<td>$\bar{L}H^c X$</td>
</tr>
<tr>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>6</td>
<td>$\bar{L}E\bar{L} X$, $H^+ H L H^c X$, $(H^c)^t D_\mu H^c \bar{E}\gamma^\mu X$, $\bar{Q}D\bar{L} X$, $\bar{U}Q\bar{L} X$, $\bar{L}D\bar{Q} X$, $\bar{U}\gamma_\mu D\bar{E}\gamma^\mu X$, $D^\mu H^c D_\mu \bar{L} X$, $D^\mu D_\mu H^c \bar{L} X$, $B_{\mu\nu}\bar{L}\sigma^{\mu\nu} H^c X$, $W^a_{\mu\nu}\bar{L}\sigma^{\mu\nu} \tau^a H^c X$</td>
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Haba et al., PL B695 (2011)

“natural” small coupling multi body decay
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“natural” small coupling
multi body decay
primary $\nu$ flux

*Haba et al., PL B695 (2011)*
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</tr>
</tbody>
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Symmetries and Models

Allowed

\[
\frac{y_{\alpha \beta \gamma}}{M^2_{\text{Pl}}} \left( \overline{L_\alpha} \ell_\beta \right) \left( \overline{L_\gamma} \chi \right)
\]

- We can use Abelian U(1) symmetry:

<table>
<thead>
<tr>
<th>(L_e, \ell_e)</th>
<th>(L_\mu, \ell_\mu)</th>
<th>(L_\tau, \ell_\tau)</th>
<th>(H)</th>
<th>(\chi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U(1)</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

- We can use non-Abelian symmetries like \(A_4\):

<table>
<thead>
<tr>
<th>(L)</th>
<th>(\ell)</th>
<th>(H)</th>
<th>(\chi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A_4)</td>
<td>3</td>
<td>3</td>
<td>1, 1', 1''</td>
</tr>
</tbody>
</table>

Forbidden

\[
\overline{L} H^c \chi + \text{h.c.}
\]

U(1) flavour indices

\{\mu, e, \tau\} + \{\tau, e, \mu\} + \{e, \mu, e\}

\(A_4\) flavour indices

\{e, \mu, \tau\} + \text{cyclic permutations}
Neutrino flux from DM

The differential neutrino flux from decaying DM has two components

\[
\frac{dJ^G_\chi}{dE_\nu}(E_\nu) = \frac{1}{4\pi} \int d\Omega \left( \frac{dJ^G_\chi}{dE_\nu}(E_\nu, l, b) + \frac{dJ^{EG}_\chi}{dE_\nu}(E_\nu) \right)
\]

where

\[
\frac{dJ^G_\chi}{dE_\nu}(E_\nu, l, b) = \frac{1}{4\pi M_\chi \tau_\chi} \sum_{\alpha=e,\mu,\tau} \frac{dN^{\alpha}_{\nu+\bar{\nu}}}{dE_\nu}(E_\nu) \int_0^\infty ds \rho_\chi(r(s, l, b))
\]

\[
\frac{dJ^{EG}_\chi}{dE_\nu}(E_\nu) = \frac{\Omega_\chi \rho_{cr}}{4\pi M_\chi \tau_\chi} \int_0^\infty dz \frac{1}{H(z)} \sum_{\alpha=e,\mu,\tau} \frac{dN^{\alpha}_{\nu+\bar{\nu}}}{dE_\nu}((1+z)E_\nu)
\]
Neutrino events

- Knowing the total differential neutrino flux

\[
\frac{dJ}{dE_\nu} (E_\nu) = \frac{dJ_{\chi}}{dE_\nu} (E_\nu) + \frac{dJ_{\text{Ast}}}{dE_\nu} (E_\nu)
\]

where

**Unbroken Power Law**

\[
E_\nu^2 \frac{dJ_{\text{Ast}}}{dE_\nu} (E_\nu) = J_0 \left( \frac{E_\nu}{100 \text{ TeV}} \right)^{2-\gamma} \exp \left( -\frac{E_\nu}{E_0} \right)
\]

**Broken Power Law**

- Then, the number of neutrinos in a given energy bin \([E_i, E_{i+1}]\) is equal to

\[
N_i = 4\pi \Delta t \int_{E_i}^{E_{i+1}} dE \sum_{\alpha=e,\mu,\tau} \frac{dJ^\alpha_{\nu+\bar{\nu}}}{dE} A_{\alpha} (E)
\]

Exposure time \(\Delta t = 988\) days

Effective IceCube area

*IceCube, Science 342 (2013)*
Unbroken Power Law

Boucenna, CHIANESE, Mangano, Miele, Morisi, Pisanti, VITAGLIANO, JCAP 1502

\[ \chi^2 / \text{d.o.f.} = 10.3 / 12 \]

\[ M_{DM} = 5.0 \text{ PeV} \]

\[ \gamma = 3.0 \]

Assumption

\[ |Y_{\mu e\tau} - Y_{\tau e\mu}| = |Y_{e\mu e}| \equiv y \]
Broken Power Law

\[ \chi^2 / \text{d.o.f.} = 9.2 / 12 \]

\[ M_{\text{DM}} = 5.0 \, \text{PeV} \]

\[ \gamma = 2.0 \]

\[ |Y_{\mu e\tau} - Y_{\tau e\mu}| = |Y_{e\mu e}| \equiv y \]
Low energy neutrinos

Low energy neutrino excess
The latest IceCube data show a 2-sigma excess in the energy range 60-100 TeV with respect to a power-law having spectral index 2.
Low energy excess

The 2-sigma excess is with respect to the sum of:

- atmospheric neutrinos and muons
- astrophysical component described by a power-law

\[ \phi^\text{Astro}_\nu \propto E^{-2} \]
Origin of the excess

Assuming that such an excess has a genuine physical origin, it is of interest to pursue a study in order to unveil its nature.

We perform statistical tests of hypothesis on the angular distribution in the arrival direction of neutrinos in 60-100 TeV.

- astrophysical galactic sources (galactic plane)
- astrophysical extragalactic sources (isotropic distribution)
- decaying Dark Matter
- annihilating Dark Matter

Due to the low statistics, we consider just one additional component to the neutrino background at a time.
Angular distributions

In case of astrophysical scenarios, the expected angular distributions in the arrival directions are

\[ p_{\text{gal}}(\sin b, l) = \frac{\Theta(\sin b + \sin b_{\text{gal}}) - \Theta(\sin b - \sin b_{\text{gal}})}{4\pi \sin b_{\text{gal}}} \]

Galactic latitude

Angular size of Galactic Plane

\[ b_{\text{gal}} \in [2^\circ, 4^\circ] \]

\[ p_{\text{iso}}(\sin b, l) = \frac{1}{4\pi} \]

*Fermi-LAT, APJ 750 (2012)*
Angular distributions

In case of Dark Matter scenarios, we have

\[
p^{\text{dec}}(\cos \theta) \propto \int_0^\infty \rho_h[r(s, \cos \theta)]ds + \Omega_{\text{DM}}\rho_c \beta
\]

\[
p^{\text{ann}}(\cos \theta) \propto \int_0^\infty \rho_h^2[r(s, \cos \theta)]ds + (\Omega_{\text{DM}}\rho_c)^2 \Delta_0^2 \beta
\]

where

\[
\beta = \int_0^{\frac{100}{60} - 1} \frac{dz}{H(z)} = \frac{0.56}{H_0}
\]

\[
\cos \theta = \cos b \cos l
\]
Analysis

We perform two different non-parametric statistical tests:

- Kolmogorov-Smirnov (KS)
- Anderson-Darling (AD)

In the energy range 60-100 TeV, IceCube has detected 12 events but 5 events are background.

We also consider the angular uncertainty affecting the reconstruction of the arrival direction.

\[
\frac{12!}{5!7!} \times 100 \times \frac{1}{\text{different combinations}}
\]

Montecarlo on experimental error

Averaged on background combinations
Background averaged range of $p$-values for all the cases.

**CHIANESE, Miele, Morisi, Vitagliano, PL B757 (2016)**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>KS</th>
<th>AD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astrophysics</td>
<td>Gal. plane $0.007 - 0.008$</td>
<td>not defined</td>
</tr>
<tr>
<td></td>
<td>Iso. dist. $0.20 - 0.55$</td>
<td>$0.17 - 0.54$</td>
</tr>
<tr>
<td>DM decay</td>
<td>NFW $0.06 - 0.16$</td>
<td>$0.03 - 0.14$</td>
</tr>
<tr>
<td></td>
<td>Isoth. $0.08 - 0.22$</td>
<td>$0.05 - 0.19$</td>
</tr>
<tr>
<td>DM annih. $\Delta_0^2 = 10^4$</td>
<td>NFW $(0.3 - 0.9) \times 10^{-4}$</td>
<td>$(0.3 - 3.8) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>Isoth. $(0.9 - 2.8) \times 10^{-3}$</td>
<td>$(1.0 - 5.0) \times 10^{-3}$</td>
</tr>
<tr>
<td>DM annih. $\Delta_0^2 = 10^6$</td>
<td>NFW $0.02 - 0.05$</td>
<td>$0.02 - 0.07$</td>
</tr>
<tr>
<td></td>
<td>Isoth. $0.10 - 0.28$</td>
<td>$0.08 - 0.29$</td>
</tr>
<tr>
<td>DM annih. $\Delta_0^2 = 10^8$</td>
<td>NFW $0.19 - 0.54$</td>
<td>$0.17 - 0.53$</td>
</tr>
<tr>
<td></td>
<td>Isoth. $0.20 - 0.55$</td>
<td>$0.17 - 0.54$</td>
</tr>
</tbody>
</table>
Forecast analysis

Number of signal events required to distinguish the decaying DM angular distribution from isotropic one.

CHIANESE, Miele, Morisi, VITAGLIANO, PL B757 (2016)
Number of signal events required to distinguish the annihilating DM angular distribution from isotropic one.

\[ \Delta_0^2 = 10^6 \]

Annihilation

CHIANESE, Miele, Morisi, VITAGLIANO, PL B757 (2016)
Conclusions

We had the first observation of extraterrestrial high energy neutrinos at IceCube.

IceCube events could be related to the Dark Matter problem, in particular:

- PeV neutrinos could be originated by a leptophilic decaying Dark Matter
- the 2-sigma excess in the energy range 60-100 TeV could be related to a Dark Matter scenario

IceCube can provide important information and give indications on the direction for future DM experiments.

The need of more statistics at low and high energy emphasizes the importance of future Neutrino Telescope (IceCube-2gen and KM3NeT).
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Thanks for your attention
Deposited and neutrino energies

To statistically estimate the ratio between the deposited and neutrino energies a MonteCarlo simulation of the apparatus is required.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Signature</th>
<th>$E_{vis}/E_\nu; E_\nu$ = 1 TeV</th>
<th>$E_\nu = 10$ TeV</th>
<th>$E_\nu = 100$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e + N \rightarrow e +$ had.</td>
<td>Cascade</td>
<td>94%</td>
<td>95%</td>
<td>97%</td>
</tr>
<tr>
<td>$\nu_\mu + N \rightarrow \mu +$ had.</td>
<td>Track (+ Cascade)</td>
<td>94%</td>
<td>95%</td>
<td>97%</td>
</tr>
<tr>
<td>$\nu_\tau + N \rightarrow \tau +$ had. $\rightarrow$ had.</td>
<td>Cascade/Double Bang</td>
<td>&lt; 94%</td>
<td>&lt; 95%</td>
<td>&lt; 97%</td>
</tr>
<tr>
<td>$\nu_\tau + N \rightarrow \tau +$ had. $\rightarrow$ $\mu +$ had.</td>
<td>Cascade + Track</td>
<td>&lt; 94%</td>
<td>&lt; 95%</td>
<td>&lt; 97%</td>
</tr>
<tr>
<td>$\nu_l + N \rightarrow \nu_l +$ had.</td>
<td>Cascade</td>
<td>33%</td>
<td>30%</td>
<td>23%</td>
</tr>
</tbody>
</table>

IceCube, JINST 9 (2014)

When for a bin of the deposited energy a significant statistics is collected one could apply the average ratio

$$\frac{E_{dep}}{E_\nu} = \frac{97\% \sigma^{CC} + 23\% \sigma^{NC}}{\sigma^{CC} + \sigma^{NC}} \approx 75\%$$
Dark Matter density profiles

Navarro-Frenk-White: \[ \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r} \left( 1 + \frac{r}{r_s} \right)^{-2} \]

Isothermal: \[ \rho_{\text{Iso}}(r) = \frac{\rho_s}{1 + (r/r_s)^2} \]

*Cirelli et al., JCAP 1103*
To evaluate the neturino energy specturm $dN_\nu/dE_\nu$, we have developed a MonteCarlo in *Mathematica*.

There are 6 decay channels with the same Branching Ratio.

\[
\text{Br} \left( \chi \rightarrow e^\pm \mu^\mp \nu_\tau \right) = \text{Br} \left( \chi \rightarrow \mu^\pm \tau^\mp \nu_e \right) = \text{Br} \left( \chi \rightarrow \tau^\pm e^\mp \nu_\mu \right) = \frac{1}{6}
\]

We take into all the secondary neutrinos.

<table>
<thead>
<tr>
<th>$\mu \rightarrow e + \nu_e + \nu_\mu \sim 100%$</th>
<th>$\tau \rightarrow e + \nu_e + \nu_\tau \sim 17.8%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu + \nu_\mu + \nu_\tau \sim 17.4%$</td>
<td>$\tau \rightarrow \pi + \nu_\tau \sim 10.8%$</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi + \pi^0 + \nu_\tau \sim 25.5%$</td>
<td>$\tau \rightarrow \pi + \pi^0 + \pi^0 + \nu_\tau \sim 9.3%$</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi + \pi^+ + \pi^- + \nu_\tau \sim 9.0%$</td>
<td></td>
</tr>
</tbody>
</table>

- **2 neutrinos**
- **3 neutrinos**
- **$\gamma$-rays**

**constraint from FERMI**
Isotropy

- The observed IceCube flux is isotropic.

*IceCube, PRL 113 (2014)*

Prompt neutrinos cannot explain the IceCube data!

*See also: Halzen, Wille, 1601.03044*