Dark matter at neutrino telescopes

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University Federici II Napoli

In collaboration with
Marco Chianese, Damiano Fiorillo, Gennaro Miele, Ofelia Pisanti
O(100) TeV excess @ neutrino telescopes

• three methods are consistent
• excess cosmic flux < 100 TeV?

Credits: Hanzen IWNT'19 Venice
O(100) TeV excess @ neutrino telescopes

OBSERVATION AND CHARACTERIZATION OF A COSMIC MUON NEUTRINO FLUX FROM THE NORTHERN HEMISPHERE USING SIX YEARS OF ICINGUICE DATA


ABSTRACT

but the field of view is restricted to the Northern Hemisphere. IceCube data from 2009 through 2015 have been analyzed using a likelihood approach based on the reconstructed muon energy and zenith angle. At the highest neutrino energies between 194 TeV and 7.8 PeV a significant astrophysical contribution is observed, excluding a purely atmospheric origin of these events at 5.6σ significance. The data are well described by an isotropic, unbroken power law flux with a normalization at 10 TeV neutrino energy of $(0.90_{-0.27}^{+0.30}) \times 10^{-18}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ and a hard spectral index of $\gamma = 2.13 \pm 0.13$. The observed spectrum is harder in comparison to previous IceCube analyses with lower energy thresholds which may indicate a break in the astrophysical neutrino spectrum of unknown origin. The highest energy event observed has a reconstructed

$$d\Phi_{\text{astro}} \over dE_\nu d\Omega = \Phi^0_{\text{astro}} \left( \frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma_{\text{astro}}}.$$
O(100) TeV excess @ neutrino telescopes

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

Compatible!

Credits: Hanzen IWNT '19 Venice

Neutrino Energy [GeV]

OBSERVATION AND CHARACTERIZATION OF A COSMIC MUON NEUTRINO FLUX FROM THE NORTHERN HEMISPHERE USING SIX YEARS OF ICECUBE DATA


Science 2018
O(100) TeV excess @ neutrino telescopes

Credits: Hanzen IWNT 19 Venice

Chianese, Mele, Miele, Migliozzi, SM, Astro J. (2017)

\[ d\Phi_{astro} / dE_\nu d\Omega = \Phi^0_{astro} \left( \frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma_{astro}} \]

\[ \gamma_{astro} = 2 \]
O(100) TeV excess @ neutrino telescopes

Credits: Hanzen IWNT 19 Venice

• excess cosmic flux < 100 TeV?

- only few sigma (about 2.5 sigma) but...
- depends on the assumed astrophysical source
- 1-component fit with softer spectral index works
O(100) TeV excess @ neutrino telescopes

• excess cosmic flux < 100 TeV?

is it related to the Dark Matter problem?

Credits: Hanzen IWNT 19 Venice
Annihilating dark matter

$$\Gamma_{\text{Events}} \sim V L_{\text{MW}} n_N \sigma_N \left( \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \right)^2 \langle \sigma_{\text{Ann}} v \rangle \lesssim 1 \text{ per few hundred years}$$

\begin{align*}
V &= \text{detector volume} \\
n_N &\sim n_{\text{Ice}} \\
L_{\text{MW}} &= \text{dim of galaxy} \\
\sigma_N &\sim \text{Typical neutrino-nucleon} \\
&\quad \text{Cross section at 1PeV} \\
\sigma_{\text{Ann}} &\leq 4\pi/(m_{\text{DM}}^2 v^2) \quad \text{from unitarity limit}
\end{align*}

Decaying dark matter

$$\Gamma_{\text{Events}} \sim V L_{\text{MW}} n_N \sigma_N \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \Gamma_{\text{DM}} \sim \left( \frac{\lambda}{10^{-29}} \right)^2 / \text{year}$$

Decay seems favorite with respect to annihilation

Possible enhancement
Dark Matter substructure
Zavala, PRD 89 2014
Standard Model particles and dark matter stability: a comment

• photon stable because massless (for gauge symmetry motivation)
• neutrino stable because is lightest fermion (Lorentz invariance)
• electron stable because is lightest charged particle (electric charge conservation)
• proton (?) stable if baryon number exactly conserved

What is the symmetry that stabilize DM?
(R)-parity, mirror world,….but so far no evidence

To have a stable particle on top of SM without any extra symmetry is not automatic even if not impossible…. BUT quite baroque
Decaying Dark Matter and IceCube

Aisati, Gustafsson, Hambye PRD 2015
Chianese, SM, Miele, Vitagliano PLB 2016
Chianese, SM, Miele JCAP 2017
Chianese, SM, Miele PLB 2017
Hirishima, Kitano, Murase, PRD 2018
Sui, Dev, JCAP 18
Chianese, SM, Miele, Peinado, JCAP 2018
Bhattacharya, Esmaili, Ruiz, Sarcevic, arxiv 1903.12623

Feldstein, Kusenko, Matsumoto, Yanagida PRD (2013)
Esmaili, Serpico JCAP 2013
Bai, Lu, Salvado JHEP 2013
Higaki, Kitano, Sato JHEP 2014
Bhattacharya, Gandhi, Gupta JCAP 2015
Murase, Laha, Ando, Ahlers PRL 2015
Esmaili, Kang, Serpico, JCAP 2014
Fong, Minakata, Panes, Funchal JHEP 2015
Cheng, Dev, Soni PRD 2015
Koop, Liu, Wang, JHEP 2015
Anchordoqui et al, PRD 2015
Boucenna, Chianese, Mangano, Miele, SM, Pisanti, JCAP 2015
Ko, Tang PRB 2015
Fiorentin, Niro, Fornengo JHEP 2016
DeV, Kazanas, Mohapatra, Tepliz, Zhang JCAP 2016
Dibari, Ludl, Ruiz, JCAP 2016
Bhattacharya, Esmaili, Ruiz, Sarcevic, JCAP 2017
Kachelriess, Kalashev, Kuznetsov PRD 18
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Sui, Dev, JCAP 18
Chianese, SM, Miele, Peinado, JCAP 2018
Bhattacharya, Esmaili, Ruiz, Sarcevic, arxiv 1903.12623

Search for neutrino from decaying DM with IC

IceCube Collaboration EPJC 2018

Feldstein, Kusenko, Matsumoto, Yanagida PRD (2013)
Esmaili, Serpico JCAP 2013
Bai, Lu, Salvado JHEP 2013
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Dibari, Ludl, Ruiz, JCAP 2016
Bhattacharya, Esmaili, Ruiz, Sarcevic, JCAP 2017
Kachelriess, Kalashev, Kuznetsov PRD18
Neutrino flux at Earth

\[
\frac{d\phi}{dE_\nu d\Omega} = \frac{d\phi^{\text{bkg}}}{dE_\nu d\Omega} + \frac{d\phi^{\text{Astro}}}{dE_\nu d\Omega} + \frac{d\phi^{\text{DM}}}{dE_\nu d\Omega}
\]

three components are assumed:

1) Atmospheric neutrino
   Honda, Kajita, Kasahara, Midorikawa, Sanuki, PRD (2007)
   Enberg, Reno, Sarcevic, PRD (2008)

2) Astrophysical isotropic neutrino flux

\[
\frac{d\Phi_{\text{astro}}}{dE_\nu d\Omega} = \Phi_{\text{astro}}^0 \left( \frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma_{\text{astro}}}
\]

3) Decaying Dark Matter neutrino flux

\[
\frac{d\phi^{\text{DM}}_{\alpha}}{dE_\nu d\Omega} = \sum_\beta P_{\alpha\beta} \left[ \frac{d\phi^{\text{G}}_{\beta}}{dE_\nu d\Omega} + \frac{d\phi^{\text{EG}}_{\beta}}{dE_\nu d\Omega} \right]
\]
Dark Matter Neutrino flux: Galactic and Extra-Galactic contributions

\[
\frac{d\phi_{\alpha}^{DM}}{dE_{\nu}d\Omega} = \sum_{\beta} P_{\alpha\beta} \left[ \frac{d\phi_{\beta}^{G}}{dE_{\nu}d\Omega} + \frac{d\phi_{\beta}^{EG}}{dE_{\nu}d\Omega} \right]
\]

\( P \): flavor conversion due to oscillation

See for instance:

- Mena, Ruiz, Vincent, PRL 2014
- Palladino, Pagliaroli, Villante Vissani, PRL 2015
Dark Matter Neutrino flux: Galactic and Extra-Galactic contributions

\[
\frac{d\phi_{\alpha}^{DM}}{dE_\nu d\Omega} = \sum_\beta P_{\alpha\beta} \left[ \frac{d\phi_{\beta}^{G}}{dE_\nu d\Omega} + \frac{d\phi_{\beta}^{EG}}{dE_\nu d\Omega} \right]
\]

**Extra-Galactic**

\[
\frac{d\phi_{\beta}^{EG}}{dE_\nu d\Omega} = \frac{\Omega_{\chi} \rho_c}{4\pi m_\chi \tau_\chi} \int_0^\infty dz \frac{1}{H(z)} \frac{dN_\beta}{dE_\nu} \bigg|_{E(1+z)}
\]

**Galactic**

\[
\frac{d\phi_{\beta}^{G}}{dE_\nu d\Omega} = \frac{1}{4\pi m_{DM} \tau_{DM}} \frac{dN_\nu}{dE_\nu} \int_0^\infty ds \rho_h [r(s,l,b)]
\]
Dark Matter Neutrino flux: expected angular distribution

\[
\frac{d\phi_{DM}^{\alpha}}{dE^{\alpha}d\Omega} = \sum_{\beta} P_{\alpha\beta} \left[ \frac{d\phi_{\beta}^{G}}{dE^{\beta}d\Omega} + \frac{d\phi_{\beta}^{EG}}{dE^{\beta}d\Omega} \right]
\]

Extra-Galactic

\[
\frac{d\phi_{\beta}^{EG}}{dE^{\beta}d\Omega} = \frac{\Omega_{\chi}\rho_c}{4\pi m_{\chi} \tau_{\chi}} \int_{0}^{\infty} dz \left. \frac{1}{H(z)} \frac{dN_{\beta}}{dE^{\beta}} \right|_{E(1+z)}
\]

Galactic

\[
\frac{d\phi_{\beta}^{G}}{dE^{\beta}d\Omega} = \frac{1}{4\pi m_{DM} \tau_{DM}} \frac{dN_{\nu}}{dE^{\nu}} \int_{0}^{\infty} ds \rho_{h} [r(s,l,b)]
\]

the contributions are comparable but difference in the angular distributions
Finally, the quantity \( \frac{d\phi_{DM}}{dE\nu d\Omega} = \sum_{\beta} P_{\alpha\beta} \left[ \frac{d\phi_{G}^\beta}{dE\nu d\Omega} + \frac{d\phi_{EG}^\beta}{dE\nu d\Omega} \right] \)

### Extra-Galactic

\[
\frac{d\phi_{EG}^\beta}{dE\nu d\Omega} = \frac{\Omega_{\chi} \rho_c}{4\pi m_{\chi} \tau_{\chi}} \int_0^\infty dz \left. \frac{1}{H(z)} \frac{dN_\beta}{dE\nu} \right|_{E(1+z)}
\]

- isotropic

### Galactic

\[
\frac{d\phi_{G}^\beta}{dE\nu d\Omega} = \frac{1}{4\pi m_{DM} \tau_{DM}} \frac{dN_\nu}{dE\nu} \int_0^\infty ds \rho_h [r(s, l, b)]
\]

### Line-of-Sight

\[
r(s, l, b) = \sqrt{s^2 + R_\odot^2 - 2sR_\odot \cos b \cos l}
\]

- larger flux close to galaxy center
\[
\frac{d\phi_{\alpha}^{\text{DM}}}{dE_\nu d\Omega} = \sum_\beta P_{\alpha\beta} \left[ \frac{d\phi_{\beta}^{\text{G}}}{dE_\nu d\Omega} + \frac{d\phi_{\beta}^{\text{EG}}}{dE_\nu d\Omega} \right]
\]

**Galactic**  
**Extra-Galactic**
Dark Matter Neutrino flux: expected angular distribution

\[
\frac{d\phi^{\text{DM}}}{dE_\nu d\Omega} = \sum_{\beta} P_{\alpha\beta} \left[ \frac{d\phi^{\text{G}}}{dE_\nu d\Omega} + \frac{d\phi^{\text{EG}}}{dE_\nu d\Omega} \right]
\]

Galactic Extra-Galactic

Data prefer mildly DM rather than isotropic distribution at 98% CL

Chianese, SM, Miele, Vitagliano PLB 2016

10% p-values, DM scenario can not be excluded

Esmaili, Serpico JCAP 2013

IceCube Preliminary
Dark Matter Neutrino flux: expected angular distribution

\[
\frac{d\phi^\text{DM}_{\alpha}}{dE_{\nu}d\Omega} = \sum_{\beta} P_{\alpha\beta} \left[ \frac{d\phi^G_{\beta}}{dE_{\nu}d\Omega} + \frac{d\phi^\text{EG}_{\beta}}{dE_{\nu}d\Omega} \right]
\]

1. Galactic
2. Extra-Galactic

Esmaili, Serpico JCAP 2013

Data prefer mildly DM rather than isotropic distribution at 98% CL

Chianese, SM, Miele, Vitagliano PLB 2016

10% p-values, DM scenario can not be excluded

Credits: Esmaili, Serpico JCAP 2013

a rigorous evaluation can only be performed within IceCube collaboration
- background
- lack of data

IceCube Preliminary
Neutrino spectrum from DM decay (weak corrections)

\[ \frac{dN_\beta}{dE_\nu} \]

\[ m_{DM} = 2 \text{PeV} \]

\[ \text{IceCube Collaboration EPJC 2018} \]

\[ Z + \nu, W^+ + W^-, H + \nu, \mu^+ + \mu^-, \tau^+ + \tau^- \]

\[ E_\nu / \text{GeV} \]

\[ 10^3, 10^4, 10^5, 10^6 \]

\[ \text{Ciafaloni, Comelli, Riotto, Sala, Strumia, Urbano, JCAP (2011)} \]

\[ \text{PYTHIA 8.2} \]

\[ m_{DM} = 2 \text{PeV} \]

\[ X \rightarrow \tau \tau \]

\[ \text{no Weak Shower, with Weak Shower} \]

\[ E(\text{GeV}) \]

\[ 10^3, 10^4, 10^5, 10^6, 10^7 \]

\[ \text{HESE} \]

\[ \text{only } \nu \text{ and flavor-averaged} \]

\[ m_{DM} = 2 \text{PeV} \]

\[ X \rightarrow \nu_e \nu_\nu \]

\[ \text{with Weak Shower} \]

\[ E(\text{GeV}) \]

\[ 10^3, 10^4, 10^5, 10^6, 10^7 \]
two-years cascade events: all-sky

\[ DM \rightarrow H + \nu \] (cascades)

unbinned

six-years nu-mu track events: North-hemisphere

\[ DM \rightarrow Z + \nu \] (tracks)

<table>
<thead>
<tr>
<th>Tracks</th>
<th>Cascades</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bg.</td>
<td>Bg.</td>
</tr>
<tr>
<td>Signal+Bg.</td>
<td>Signal+Bg.</td>
</tr>
<tr>
<td>( m_{DM} / \text{PeV} )</td>
<td>( - \times 1.3 )</td>
</tr>
<tr>
<td>( \tau_{DM} / 10^{27} \text{s} )</td>
<td>( - \times 22 )</td>
</tr>
<tr>
<td>Astroph. norm.</td>
<td>( 0.97 \times 0.16 )</td>
</tr>
<tr>
<td>Spectr. index</td>
<td>( 2.16 \times 1.99 )</td>
</tr>
<tr>
<td>TS = 2 \times \Delta \text{LLH}</td>
<td>( 6.7 (p = 0.035) )</td>
</tr>
</tbody>
</table>

- the two analysis give very different DM mass
- but not surprising: different data
- p-value above 1%

Although best fit includes a non-zero DM component
the result is not significant, no DM signal
Other analysis 1

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$\tau_{\text{DM}} [10^{-28} \text{ s}]$</th>
<th>$(N_{\text{DM}})$</th>
<th>$m_{\text{DM}}$ [TeV]</th>
<th>$\phi_{\text{astro}} (N_{\text{astro}})$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u\bar{u}$</td>
<td>0.11</td>
<td>(28.4)</td>
<td>1761</td>
<td>0.52 (13.0)</td>
<td>2.34</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>0.07</td>
<td>(26.9)</td>
<td>1103</td>
<td>0.58 (14.3)</td>
<td>2.35</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.11</td>
<td>(28.7)</td>
<td>598</td>
<td>0.45 (12.5)</td>
<td>2.27</td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td>0.37</td>
<td>(28.5)</td>
<td>412</td>
<td>0.47 (12.6)</td>
<td>2.29</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>0.43</td>
<td>(27.8)</td>
<td>407</td>
<td>0.52 (13.3)</td>
<td>2.32</td>
</tr>
<tr>
<td>$hh$</td>
<td>0.12</td>
<td>(28.8)</td>
<td>611</td>
<td>0.45 (12.6)</td>
<td>2.27</td>
</tr>
<tr>
<td>$e^+e^-$</td>
<td>2.20</td>
<td>(4.0)</td>
<td>4160</td>
<td>3.53 (37.3)</td>
<td>3.36</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>9.77</td>
<td>(4.9)</td>
<td>6583</td>
<td>3.51 (36.5)</td>
<td>3.39</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>0.89</td>
<td>(27.4)</td>
<td>472</td>
<td>0.59 (14.3)</td>
<td>2.36</td>
</tr>
<tr>
<td>$\nu_e\bar{\nu}_e$</td>
<td>4.12</td>
<td>(3.6)</td>
<td>4062</td>
<td>3.52 (37.7)</td>
<td>3.33</td>
</tr>
<tr>
<td>$\nu_\mu\bar{\nu}_\mu$</td>
<td>4.63</td>
<td>(5.0)</td>
<td>4196</td>
<td>3.52 (36.4)</td>
<td>3.41</td>
</tr>
<tr>
<td>$\nu_\tau\bar{\nu}_\tau$</td>
<td>0.96</td>
<td>(16.6)</td>
<td>341</td>
<td>1.58 (24.9)</td>
<td>2.74</td>
</tr>
</tbody>
</table>

Bhattacharya, Esmaili, Ruiz, Sarcevic, 1903.12623

DM → $W^+ W^-$

Data

- Total best fit [60 TeV - 10 PeV]
- DM → $W^+ W^-$: $\tau = (412) = 0.37$
- astro v. $\Phi_{\text{astro}} = 0.47 (E_{\nu}/100 \text{ TeV})^{-2.29}$
- atm. $\mu$ best fit [60 TeV - 10 PeV]
- atm. v best fit [60 TeV - 10 PeV]
- Total IC best fit [60 TeV - 10 PeV]

Density plot showing $\tau_{\text{DM}} [10^{-28} \text{ s}]$ vs. $m_{\text{DM}}$ [PeV].
Other analysis 2

Chianese, Miele, M, Peinado, JCAP 2018

mDM = 220 TeV
Life-time vs DM mass: comparing different analysis

Analysis 1

Analysis 2

Analysis IC
Neutrino and gamma: a multimessenger approach

Ahlers, Halzen PPNP 2018

Isotropic γ-ray background (Fermi)

High-energy neutrinos (IceCube)

γ-rays from π⁰ decay

π⁺/π⁰ production

HESE (6yr)

calorimetric limit

proton

γ

ν + ν (8yr)

M. Ahlers (2017)

Murase, Ahlers, Lacki PRD 2013

Murase, Guetta, Ahlers, PRL 2016

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Fermi limits for decaying dark matter

Cohen, Murase, Rodd, Safdi, Soreq, PRL 2017
Clasification of operator with neutrino final state

<table>
<thead>
<tr>
<th>( (R_{SU(2)})_Y )</th>
<th>operator</th>
<th>final states</th>
</tr>
</thead>
<tbody>
<tr>
<td>spin 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0)</td>
<td>( \chi H^1 H )</td>
<td>( hh, Z^0 Z^0, W^+ W^- f\bar{f} )</td>
</tr>
<tr>
<td></td>
<td>( \chi (\mathcal{L}H)^2 )</td>
<td>( \nu\nu h, \nu h Z^0, \nu Z^0 h, \nu e^- W^+ )</td>
</tr>
<tr>
<td></td>
<td>( \chi HLE )</td>
<td>( \nu\nu h, \nu h Z^0, \nu e^- W^+ )</td>
</tr>
<tr>
<td></td>
<td>( \tilde{H} \tilde{Q} \tilde{U}, \phi \tilde{H} \tilde{Q} \tilde{D} )</td>
<td>( h\ell^+ \ell^-, Z^0 \ell^+ \ell^-, W^\pm \ell^\pm, \ell^+ \ell^- )</td>
</tr>
<tr>
<td></td>
<td>( \chi B_{\mu \nu} (\bar{\tau} \tau)_{\mu \nu} )</td>
<td>( h\gamma \gamma, \gamma^2, \gamma Z, ZZ )</td>
</tr>
<tr>
<td></td>
<td>( \chi W_{\mu \nu} \tilde{W}^{\mu \nu} )</td>
<td>( \gamma \gamma, \gamma Z^0, Z^0 W^-, b )</td>
</tr>
<tr>
<td></td>
<td>( \chi G_{\nu \nu} (\gamma G)_{\nu \nu} )</td>
<td>hadrons</td>
</tr>
<tr>
<td></td>
<td>( \chi D_{\mu} H^1 D^{\mu} H )</td>
<td>( hh, Z^0 Z^0, W^+ W^- c )</td>
</tr>
<tr>
<td>(2) ( 1/2 )</td>
<td>( V_\chi [114]^e )</td>
<td>( hhh, h Z^0 Z^0, h W^+ W^- )</td>
</tr>
<tr>
<td></td>
<td>( V_{\phi \tilde{Q} \tilde{U}} [114]^\nu f )</td>
<td>( hh, Z^0 Z^0, W^+ W^- )</td>
</tr>
<tr>
<td></td>
<td>( \phi \tilde{L} \tilde{E} )</td>
<td>( \ell^+ \ell^- )</td>
</tr>
<tr>
<td></td>
<td>( \delta \tilde{Q} \tilde{U}, \phi \tilde{Q} \tilde{D} )</td>
<td>( qq )</td>
</tr>
<tr>
<td>(3)</td>
<td>( \phi^a R^a \sigma H )</td>
<td>( hh, Z^0 Z^0, W^+ W^- f\bar{f} )</td>
</tr>
<tr>
<td></td>
<td>( \phi^a W_{\mu \nu}^a B^{\mu \nu} )</td>
<td>( \gamma \gamma, Z^0 Z^0 )</td>
</tr>
<tr>
<td></td>
<td>( \phi^a \tilde{L} \sigma \mu \nu \sigma \tilde{D} )</td>
<td>( h\ell^+ \ell^-, Z^0 \ell^+ \ell^-, W^\pm \ell^\pm, \ell^+ \ell^- )</td>
</tr>
<tr>
<td></td>
<td>( \phi^a \mathcal{G}<em>{\mu \nu} \phi</em>{\mu \nu} \tilde{Q} \tilde{D} )</td>
<td>( hqq, Z^0 q, W^\pm q, q\bar{q} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( (R_{SU(2)})_Y )</th>
<th>operator</th>
<th>final states</th>
</tr>
</thead>
<tbody>
<tr>
<td>spin 1/2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>( \tilde{H} \tilde{L} \tilde{E} )</td>
<td>( \nu h, \nu Z^0, \ell^\pm W^\mp )</td>
</tr>
<tr>
<td>(2) ( 1/2 )</td>
<td>( \mathcal{H} \mathcal{L} \mathcal{E} )</td>
<td>( \nu h, \nu Z^0, \ell^\pm W^\mp )</td>
</tr>
<tr>
<td></td>
<td>( \nu h, \nu Z^0, \ell^\pm W^\mp )</td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>( \tilde{f} g_\gamma v^\mu f )</td>
<td>( ff )</td>
</tr>
<tr>
<td></td>
<td>( B_{\nu \nu} F^\mu \nu /2 )</td>
<td>( ff )</td>
</tr>
</tbody>
</table>

Cohen, Murase, Rodd, Safdi, Soreq, PRL 2017

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Moreover, we expect that such new data are not going to change substantially our conclusions.

According to the table S2 of ref. \[ \text{our conclusions.} \]

In this paper, we study in more detail the production of a neutrino line from Dark Matter Dark Matter decaying only into neutrinos. Specifically, we focus on a model with the recent IceCube and Fermi-LAT data. Finally, in section 2.2 as benchmark. Hence, we provide the allowed regions of the parameter space of the model in agreement with neutrinos and gamma-rays observations.

In ref. \[ \text{3} \] it has been shown that most of such Dark Matter models, especially the ones with hadronic final states (see also ref.s \[ \text{4} \] \[ \text{5} \] \[ \text{6} \]). Depending on the specific Dark Matter decay channel, through-going muon neutrinos, we consider an astrophysical neutrino flux with spectral index 18.71...2.5. For the same reason, the components of the model with the recent measurements related to the blazar TXS 0506+056 and by the IceCube analysis could alleviate the tension between the HESE and through-going muon neutrino data sampling.

Does not acquire a VEV
Neutrino are Dirac

\[ \begin{array}{c|cccc}
 & L & \ell_R & H & \Delta & \nu_R \\
SU(2)_L & 2 & 1 & 2 & 3 & 1 \\
U(1)_Y & -1/2 & -1 & 1/2 & 1 & 0 \\
U(1)_L & 1 & 1 & 0 & -2 & 1 \\
\end{array} \]

\[ \mathcal{L}_\nu = \frac{1}{2} \lambda_{ij} L_i^T C^{-1} i \tau_2 \Delta L_j + \text{h.c.} \]

\[ \Delta = \sum_{i=1}^{3} \delta_i \tau_i = \begin{pmatrix} \Delta^+ & \sqrt{2} \Delta^{++} \\ \sqrt{2} \Delta^0 & -\Delta^+ \end{pmatrix} \]

\begin{itemize}
  \item Does not acquire a VEV
  \item Neutrino are Dirac
\end{itemize}
Reheating temperature below DM freeze-out temperature

\[ T_F < T_{RH} \]

\[ \Omega_\chi h^2 \simeq 7.3 \times 10^{-11} \frac{1}{g_*^{1/2}(T_{F,\text{std}})} \frac{\text{GeV}^{-2}}{\langle \sigma v \rangle x_{F,\text{std}}^{-1}} \]

\[ x_{F,\text{std}} \simeq \ln \left[ 0.038 \frac{g_\chi m_\chi M_{\text{Pl}} x_{F,\text{std}}^{1/2}}{g_*^{1/2}(T_{F,\text{std}})} \langle \sigma v \rangle \right] \]

\[ T_{F,\text{std}} = m_\chi / x_{F,\text{std}} \]

\[ \langle \sigma v \rangle \simeq 2.8 \times 10^{-26} \text{ cm}^3/\text{s} \quad \text{DM about 2TeV} \]

Larger DM mass overclose Universe

\[ T_{RH} < T_F \]

\[ \Omega_\chi h^2 \simeq 2.3 \times 10^{-11} \frac{g_*^{1/2}(T_{RH})}{g_* (T_{F,\text{rh}})} \frac{T_{RH}^3 \text{GeV}^{-2}}{m_\chi^3 \langle \sigma v \rangle x_{F,\text{rh}}^{-4}} \]

\[ x_{F,\text{rh}} \simeq \ln \left[ 0.015 \frac{g_\chi g_*^{1/2}(T_{RH})}{g_* (T_{F,\text{rh}})} \frac{M_{\text{Pl}} T_{RH}^2 x_{F,\text{rh}}^{5/2}}{m_\chi} \langle \sigma v \rangle \right] \]

Giudice, Kolb, Riotto PRD 2001

Reheating temperature become a free parameter (lower limit from BBN)

\[ T_{RH} \simeq 660 \left( \frac{m_\chi}{100 \text{ TeV}} \right)^{1/2} \text{ GeV} \]
Conclusions

- Astrophysical exces at hundred TeV?
- Decaying (annihilating seems disadvantaged) Dark Matter could be a possible explanation
- Multimessenger analysis can strongly constraint the decay channel
- A rigorous angular distribution (an time) analysis will discriminate DM hypotesis

THANKS