Primordial black hole probes of heavy neutral leptons

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IFIC (CSIC-UV)

Based on arXiv:2405.00124,
in collaboration with Yuber F. Perez-Gonzalez and Valentina De Romeri

GGI Neutrino Frontiers, Arcetri

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MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
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AGENCIA ESTATAL DE INVESTIGACIÓN
GENERALITAT VALENCIANA Conselleria d'Educació, Universitats i Ocupació
IFIC INSTITUT DE FÍSICA CORPUSCULAR
CSIC
VNIVERSITAT DE VALÈNCIA
ASTROPARTICLES Astroparticles and High Energy Physics Group

Our work in a nutshell

In arXiv:2405.00124, we estimated the **sensitivity of IceCube** to **Heavy Neutral Leptons** (HNLs) decays from a 100s **Primordial Black Hole** (PBH) **burst**

Theoretical framework

Identikit of a Primordial Black Hole

- **Primordial Black Holes (PBHs)** might have formed in the Early Universe from the collapse of **primordial fluctuations**

Hawking, Nature 248 (1974) 30-31
Carr et al., Ann. Rev. Nucl. Part. Sci. 70 (2020)
Carr et al., Rept. Prog. Phys. 84 (2021) 11, 116902

Identikit of a Primordial Black Hole

- **Primordial Black Holes (PBHs)** might have formed in the Early Universe from the collapse of **primordial fluctuations**
- They can be uniquely described by **mass** M_{PBH}, **angular momentum** J and **charge** Q

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- **Primordial Black Holes (PBHs)** might have formed in the Early Universe from the collapse of **primordial fluctuations**
- They can be uniquely described by **mass** $M_{\rm PBH}$, **angular momentum** J and **charge** Q
- Initial masses from $M_{\rm P} \sim 10^{-5}$g to $10^5 M_\odot$ depending on the formation time

$$M_{\rm PBH}^{\rm in} \sim 2\ 10^5 \gamma \left(\frac{t}{1s}\right) M_\odot$$

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PBH evaporation and particle emission

❑ Hawking discovered that PBHs lose mass, i.e. **evaporate**, with temperature

$$T_{\mathrm{PBH}} = \frac{1}{8\pi G M_{\mathrm{PBH}}} \sim 1 \ \mathrm{TeV} \left(\frac{10^{10} \ \mathrm{g}}{M_{\mathrm{PBH}}} \right)$$

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$$T_{\rm PBH} = \frac{1}{8\pi G M_{\rm PBH}} \sim 1\ {\rm TeV}\left(\frac{10^{10}\ {\rm g}}{M_{\rm PBH}}\right)$$

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- PBHs lose mass throughout time, with a rate $\sim M_{\rm PBH}^{-2}$

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- PBHs lose mass throughout time, with a rate $\sim M_{\mathrm{PBH}}^{-2}$
- The radiated particles will hence have a **semi-thermal spectrum**:

$$\left.\frac{dN^i}{dEdt}\right|_{\mathrm{prim}} = \frac{g_i \Gamma\left(M_{\mathrm{PBH}}, E_i\right)}{2\pi\left(\exp\left\{\frac{E_i}{T_{\mathrm{PBH}}}\right\} - (-1)^{2s_i}\right)}$$

where g_i are the particle's dofs, s_i its spin, E_i its energy, Γ the reabsorption coefficient

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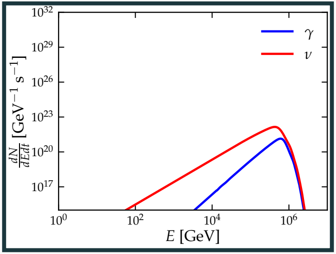

Figure 1: Primary spectrum of γ and ν from a 10^8 g PBH ($T_{\rm PBH} \sim 10^5$ GeV) with BlackHawk v2.3 (Arbey&al.2019)

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Exploding PBHs

- In the final stage of evaporation, the PBH quickly becomes **hotter** and hence emits a **burst of particles**

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➙ also BSM particles, as **Heavy Neutral Leptons (HNLs)**!

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- **1 PBH** with $M^{in}_{\rm PBH} \sim 10^{15}{\rm g}$, exploding now in a 100s burst ($M^{now}_{\rm PBH} \sim 6.2 \times 10^9 {\rm g}$)

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The heavy neutral leptons (HNLs)

- Sterile neutrinos or **Heavy Neutral Leptons (HNLs)** appear in several motivated extensions of the SM to accommodate neutrino masses

Abdullahi et al., J. Phys. G 50 no. 2, (2023) 020501

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- 1 $|U_{\alpha 4}|^2 \neq 0$ at time: 1:0:0, 0:1:0, 0:0:1

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Looking for HNLs signatures at IceCube

- **Photons** are a smoking gun of PBH burst

H.E.S.S. Collaboration, ICRC2013, p. 0930. 7 (2013)
Milagro et al., Astropart. Phys. 64 (2015) 4-12
HAWC Collaboration, JCAP, 04 (2020) 026
Fermi-LAT Collaboration, Astrophys. J., 857, no. 1, (2018) 49
VERITAS Collaboration, PoS ICRC2017, (2018) 691
Carr et al., Rep., Prog. Phys. 84, 116902 (2021)
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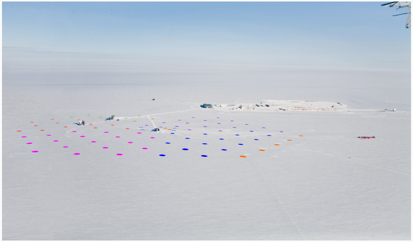

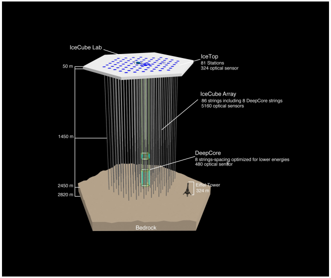

Figure 2: IceCube Neutrino Observatory. Credits: the IceCube collaboration

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- Another signature of the burst: **neutrinos**
- **IceCube** could detect **muonic neutrinos** ν_μ from the burst
  - Right energy range: 100 - 10^8 GeV
- **HNLs decay** into muonic neutrino might produce a **visible excess** at IceCube

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Analysis and Results

The expected spectrum from HNL decay

The **expected spectrum** at IceCube from a 100s PBH burst will receive contributions from SM processes and HNL decays:

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The expected spectrum from HNL decay

Quick **example** of expected signal $\left.\frac{dN_{\nu_\mu}}{dE}\right|_{\mathrm{SM+HNL}}$

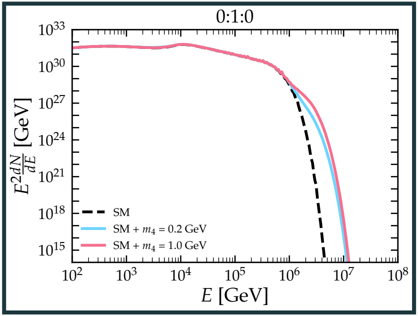

Figure 2: Total time-integrated spectrum (HNL + SM) of ν_μ at the Earth for $\tau = 100$s for two test-masses and 0:1:0; arXiv:2405.00124

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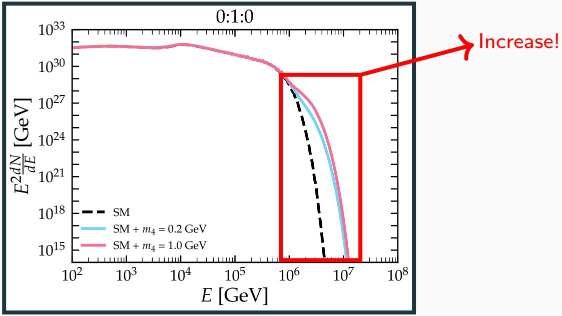

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Sensitivities at IceCube - the analysis

- We evaluated the **expected number of** ν_μ at IceCube emitted in a 100s PBH burst from HNL + SM

IceCube Collaboration, PRL, 124 no. 5, (2020) 051103

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- We estimated the **IceCube sensitivities** to HNL decays from a 100s PBH burst with a simple χ^2 analysis

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Sensitivities at IceCube - Results - I

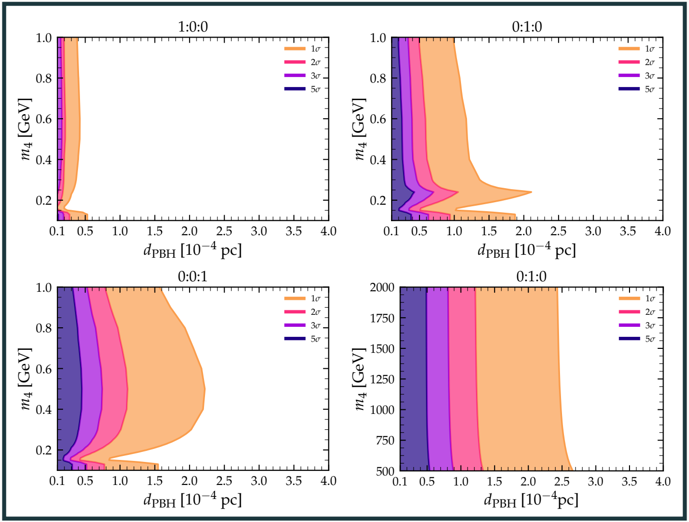

Figure 3: IceCube sensitivity to HNLs from a PBH burst lasting 100s; arXiv:2405.00124

Sensitivities at IceCube - Results - II

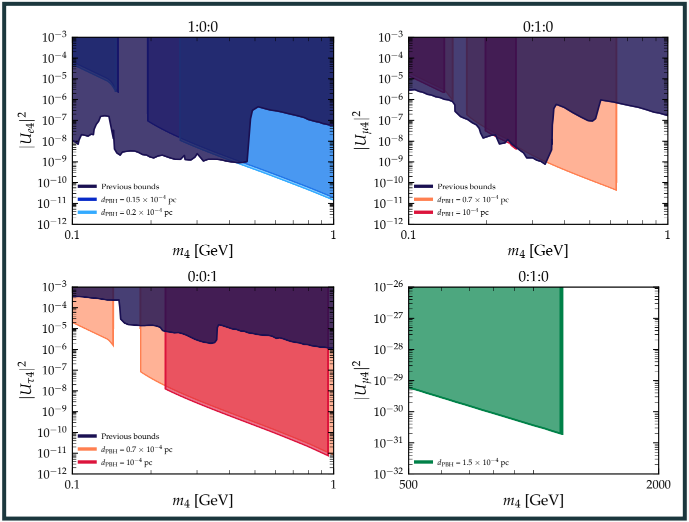

Figure 4: Expected IceCube sensitivity at 90% CL for a 100s PBH burst; arXiv:2405.00124

Conclusions

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- We evaluated the ν_μ signal at IceCube from the decay of HNLs emitted in a 100s PBH burst
  - Two HNL mass ranges: [0.1-1] GeV and [0.5-2] TeV
  - Three mixing scenarios: ν_e, ν_μ or ν_τ mixing with ν_4, i.e. 1:0:0, 0:1:0, 0:0:1

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- In the [0.5-2] TeV range, 0:1:0 even at 2.5×10^{-4} pc
- IceCube would be able to set stringent constraints on m_4 and $|U_{\alpha 4}|^2$

Thanks for your attention!

Questions?

Backup slides

Bounds on exploding PBHs - I

- **Photons** are a smoking gun of exploding PBHs
  - constraints on searches for gamma-ray bursts from H.E.S.S., Milagro, VERITAS, Fermi-LAT, HAWK

- Strongest constraint on the **PBH burst rate** from H.E.S.S. collaboration

$$\dot{n}_{\rm PBH} \sim 2000 {\rm pc}^{-3} {\rm yr}^{-1}$$

- Bounds on **overdensities** (Carr&al.2021 + Perez-Gonzalez2023):

$$n_{\rm PBH} \lesssim 0.35 \left(\frac{\beta'}{10^{-29}}\right)\left(\frac{10^{15}\ {\rm g}}{M_{\rm PBH}^{\rm in}}\right) {\rm pc}^{-3},$$

  In 1pc^3 for $\beta' \leq 10^{-29}$ we expect ~ 1.5 exploding PBH

- Hence, expecting **1 PBH** at $d_{\rm PBH} \leq 1$ pc from Earth is compatible with bounds

H.E.S.S. Collaboration, ICRC2013, p. 0930. 7 (2013)
Milagro et al., Astropart. Phys. 64 (2015) 4-12
HAWC Collaboration, JCAP, 04 (2020) 026
Fermi-LAT Collaboration, Astrophys. J., 857, no. 1, (2018) 49
VERITAS Collaboration, PoS ICRC2017, (2018) 691
Carr et al., Rep., Prog. Phys. 84, 116902 (2021)
Perez-Gonzalez, PRD 108 no. 8, (2023) 083014
H.E.S.S. Collaboration, JCAP 04 (2023) 040

Bounds on exploding PBHs - II

$$\beta' \sim 10^{-9} \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \left(\frac{M_{\rm PBH}^{\rm in}}{M_\odot} \right)^{1/2}$$

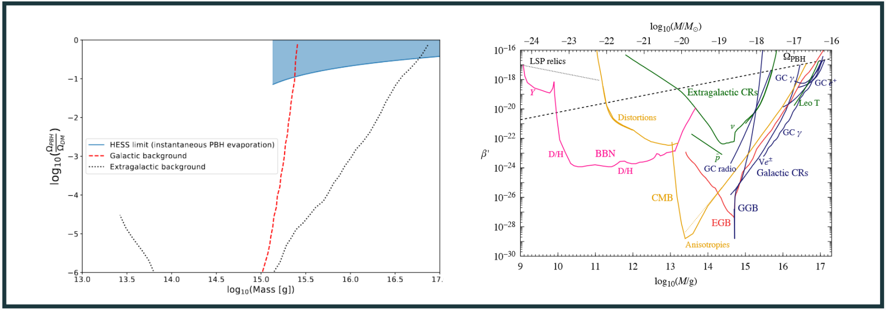

Figure 5: Bounds on β' and $\frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$. Left: from H.E.S.S. 2023, right from Carr 2021.

Carr et al., Rep. Prog. Phys. 84 (2021) 116902
H.E.S.S. Collaboration,JCAP 04 (2023) 040

Other results - I

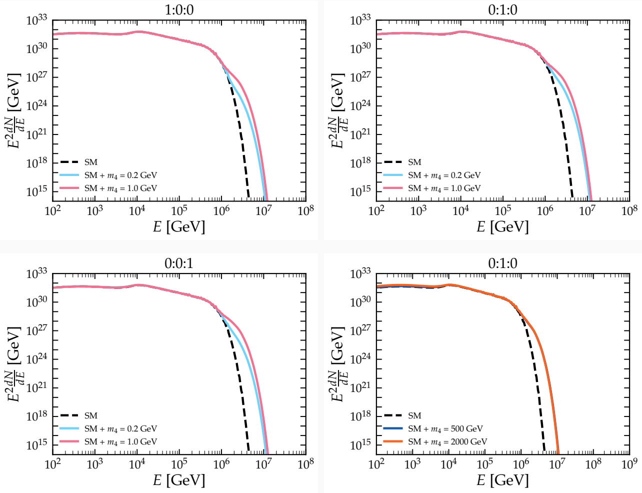

Figure 6: Total time-integrated spectrum of muon neutrinos expected at the Earth from the evaporation of a PBH multiplied by squared-energy, for an observation time of $\tau = 100$ s. In each panel, we show the SM-only contribution (black, dashed) and the SM + HNL spectrum for different HNL benchmark masses (solid, color) and mixings.

Other results - II

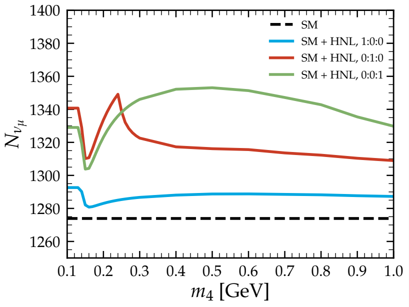

Figure 7: Expected number of muon-neutrino events at IceCube as a function of the HNL mass, from the last stages (100 s) of an evaporating PBH located at a distance $d_{\rm PBH} = 10^{-4}$ pc from Earth and at a declination angle $[30^\circ < \delta < 90^\circ]$. The black dashed curve corresponds to the SM-only case.

List of bounds in the m_4 $|U_{\alpha 4}|^2$ plane

List of bounds of Fig.4:

- ❏ 1:0:0: NA62, T2K, PiENU, BEBC and PS191
- ❏ 0:1:0: T2K, MicroBooNE, NuTeV, E949
- ❏ 0:0:1: T2K, CHARM and constraints from IceCube looking for low-energy "double-bang" events

$+$ SN 1987A detection bounds, not shown for space limits, up to O(100MeV)

NA62 Collaboration, Phys. Lett. B 807 (2020) 135599
T2K Collaboration, Phys. Rev. D 100 no. 5, (2019) 052006
PIENU Collaboration, Phys. Rev. D 97 no. 7, (2018) 072012
Barouki et al., SciPost Phys. 13 (2022) 118, arXiv:2208.00416
Bernardi et al. Phys. Lett. B 203 (1988) 332-334
MicroBooNE Collaboration, Phys. Rev. D 101 no. 5, (2020) 052001
NuTeV, E815 Collaboration, Phys. Rev. Lett. 83 (1999) 4943-4946
E949 Collaboration, Phys. Rev. D 91 no. 5, (2015) 052001
CHARM II Collaboration, Phys. Lett. B 343 (1995) 453-458
Coloma et al., Phys. Rev. Lett. 119 no. 20, (2017) 201804
Carenza et al., Phys. Rev. D 109 no. 6, (2024) 063010

The neutrino mass matrix

- The most general mass term for neutrinos can be written as

$$\begin{aligned}\mathscr{L}^m_{\text{RHN}} &= -Y_{\alpha i}\overline{L}_\alpha \widetilde{H} N_i - \frac{1}{2} M_R^{ij}\overline{N_i^c} N_j + \text{h.c.} \\ &= \frac{1}{2}\overline{\mathcal{N}_L^c} M_\nu \mathcal{N}_L + \text{h.c.}\end{aligned}$$

- After EW symmetry breaking $\mathscr{L}^m_{\text{RHN}}$ becomes

$$\mathscr{L}^m_{\text{RHN}} = -\frac{1}{2}\overline{\mathcal{N}_L^c} M_\nu \mathcal{N}_L + \text{h.c.},$$

with

$$\mathcal{N}_L = \begin{pmatrix} \nu_L \\ (N_R)^c \end{pmatrix}, \quad M_\nu = \begin{pmatrix} \mathbf{0}_{3\times 3} & Yv/\sqrt{2} \\ Y^T v/\sqrt{2} & M_R \end{pmatrix}$$

R. N. Mohapatra et al., Phys. Rev. D 34 (1986) 1642

Mixing in the lepton sector

❏ By diagonalizing the mass matrix $M_\nu = \mathcal{U}_\nu M_\nu^{\mathrm{diag}} \mathcal{U}_\nu{}^T$ $(\mathcal{U}_\nu{}^T \mathcal{U}_\nu = 1)$, $\mathscr{L}^m_{\mathsf{RHN}}$ is written in terms of the neutrino mass states:

$$\mathcal{N}_L^m = \mathcal{U}_\nu{}^T \mathcal{N}_L$$

where $\mathcal{U}_\nu$ is the unitary $(3+n) \times (3+n)$ diagonalizing mass matrix

❏ The CC lepton mixing matrix is the top $(3+n) \times 3$ submatrix of $\mathcal{U}_\nu$ $(\mathcal{U}_l \sim \mathbb{1}_{3\times 3})$:

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \dots & U_{en} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \dots & U_{\mu n} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \dots & U_{\tau n} \end{pmatrix}$$

R. N. Mohapatra et al., Phys. Rev. D 34 (1986) 1642

Details of the spectrum computation - I

Below 1 GeV, the following two channels dominate

$$\begin{aligned} \nu_4 &\rightarrow \nu_\alpha \pi^0 , \\ \nu_4 &\rightarrow \nu_\alpha \nu_\ell \bar{\nu}_\ell \quad (\ell = e, \mu, \tau) , \end{aligned}$$

where α indicates the neutrino flavor that mixes with ν_4

The partial decay widths are

$$\Gamma_\alpha \left(\nu_4 \rightarrow \nu_\alpha \pi^0 \right) = 2 \frac{G_F^2 m_4^3}{32\pi} f_\pi^2 |U_{\alpha 4}|^2 \left[1 - \left(\frac{m_{\pi_0}}{m_4} \right)^2 \right]^2 ,$$

$$\Gamma_\alpha \left(\nu_4 \rightarrow \nu_\alpha \sum_\ell \nu_\ell \bar{\nu}_\ell \right) = \sum_\ell \left[\Gamma \left(\nu_4 \rightarrow \nu_\alpha \nu_\ell \bar{\nu}_\ell \right) + \left(\nu_4 \rightarrow \bar{\nu}_\alpha \nu_\ell \bar{\nu}_\ell \right) \right] = 2 \frac{G_F^2 m_4^5}{64\pi^3} |U_{\alpha 4}|^2 .$$

where ν_α is the neutrino flavour that mixes with ν_4

A. Atre et al., JHEP 05 (2009) 030

Details of the spectrum computation - II

The neutrino spectrum from HNL decay can be computed as

$$\frac{dN_\alpha}{dE} = \mathcal{B}_a \int d\cos\theta \int_{E_{s,\min}}^{E_{s,\max}} dE_s \frac{1}{\gamma_s\left(1+\beta_s\cos\theta\right)} \frac{dN_s}{dE_s} \mathcal{F}_\alpha\left[\frac{E}{\gamma_s\left(1+\beta_s\cos\theta\right)}, \cos\theta\right]$$

- E, E_s are the energies of ν_α and the HNL in the laboratory frame;
- θ is the angle formed between ν_α in the HNL rest frame and its velocity in the laboratory frame;
- $\mathcal{B}_\alpha = \Gamma_\alpha/\Gamma_{\rm tot}$ indicates the branching ratio of the decay process;
- $\frac{dN_s}{dE_s}$ is the total primary spectrum of HNLs;
- $\mathcal{F}_a$ is the angular and energetic distribution of the resulting ν_a in the HNL frame

The primary HNL spectra have been evaluated with BlackHawk, as the SM neutrino spectra

Mastrototaro et al., Phys. Rev. D 104 no. 1, (2021) 016026
Arbey et al., Eur. Phys. J. C 81 (2021) 910

Details of the spectrum computation - III

Light-mass regime [0.1-1] GeV

- 2-body

$$\left.\frac{dN_\alpha}{dE}\right|^{2\mathrm{b}} = \frac{\mathcal{B}_\alpha m_4^2}{m_4^2 - m_{\pi^0}^2} \int_{E_{s,\min}}^{E_{s,\max}} dE_s \frac{1}{p_s} \frac{dN_s}{dE_s} \, .$$

  as $\mathcal{F}_a$ is a Dirac delta

- 3-body

$$\mathcal{F}^{3\mathrm{b}}_{\mathrm{I},\alpha}\left(E'\right) = \left.\frac{dN_\alpha}{dE' d\cos\theta}\right|^{3\mathrm{b}}_{\mathrm{I}} = \frac{1}{2} 16 \frac{E'^2}{m_4^3}\left(3 - 4\frac{E'}{m_4}\right) ,$$

$$\mathcal{F}^{3\mathrm{b}}_{\mathrm{II},\alpha}\left(E'\right) = \left.\frac{dN_\alpha}{dE' d\cos\theta}\right|^{3\mathrm{b}}_{\mathrm{II}} = \frac{1}{2} 96 \frac{E'^2}{m_4^3}\left(1 - 2\frac{E'}{m_4}\right) .$$

  If the neutrino mixes with ν_4

$$\mathcal{F}^{3\mathrm{b}}_{\alpha}\left(E'\right) = \frac{1}{4}\left(3\mathcal{F}^{3\mathrm{b}}_{\mathrm{I}} + \mathcal{F}^{3\mathrm{b}}_{\mathrm{II}}\right) .$$

$$\left.\frac{dN_{\alpha(\ell)}}{dE}\right|^{3\mathrm{b}} = \mathcal{B}_\alpha m_4 \int_{E_s,\min}^{E_s,\max} dE_s \frac{1}{p_s}\frac{dN_s}{dE_s} \int_{E'_{\min}}^{E'_{\max}} dE' \frac{1}{E'} \mathcal{F}^{3\mathrm{b}}_{\alpha(\ell)}\left(E'\right) ,$$

Mastrototaro et al., Phys. Rev. D 104 no. 1, (2021) 016026

Details of the spectrum computation - IV

If only ν_μ mixes with ν_4, three HNL decay channels are relevant in the [0.5-2] TeV mass range

$$\begin{aligned}
\nu_4 &\rightarrow W^\pm \mu^\mp \,, \\
\nu_4 &\rightarrow Z^0 \nu_\mu \,, \\
\nu_4 &\rightarrow H^0 \nu_\mu \,.
\end{aligned}$$

with partial decay widths

$$\Gamma\left(\nu_4 \to \mu W_L\right) = 2\frac{g^2}{64\pi M_W^2}|U_{\mu 4}|^2 m_4^3 \left[1 - \left(\frac{M_W}{m_4}\right)^2\right]^2 \,,$$

$$\Gamma\left(\nu_4 \to \mu W_T\right) = 2\frac{g^2}{32\pi}|U_{\mu 4}|^2 m_4 \left[1 - \left(\frac{M_W}{m_4}\right)^2\right]^2 \,,$$

$$\Gamma\left(\nu_4 \to \nu_\mu Z_L^0\right) = \frac{g^2}{64\pi M_Z^2}|U_{\mu 4}|^2 m_4^3 \left[1 - \left(\frac{M_Z}{m_4}\right)^2\right]^2 \,,$$

$$\Gamma\left(\nu_4 \to \nu_\mu Z_T^0\right) = \frac{g^2}{32\pi \cos^2\theta_W}|U_{\mu 4}|^2 m_4 \left[1 - \left(\frac{M_Z}{m_4}\right)^2\right]^2 \,,$$

$$\Gamma\left(\nu_4 \to \nu_\mu H^0\right) = \frac{g^2}{64\pi M_H^2}|U_{\mu 4}|^2 m_4^3 \left[1 - \left(\frac{M_H}{m_4}\right)^2\right]^2$$

Details of the spectrum computation - V

The resulting spectrum will be

$$\frac{dN_{\nu_\mu}}{dE} = \sum_{i.s.} \mathcal{B}(\nu_4 \to i.s.)\ m_4 \int_{E_s,\mathrm{min}}^{E_s,\mathrm{max}} dE_s \frac{1}{p_s} \frac{dN_s}{dE_s} \int_{E'_\mathrm{min}}^{E'_\mathrm{max}} dE' \frac{1}{E'} \frac{dN}{dE'} \left(\nu_4 \to i.s. \to \nu_\mu\right)\ ,$$

where PPPC4DM has been employed to evaluate $\frac{dN}{dE'}$

Mastrototaro et al., Phys. Rev. D 104 no. 1, (2021) 016026
A. Atre et al., JHEP 05 (2009) 030
Cirelli et al., JCAP 03 (2011) 051

Details of the χ^2 analysis

- The expected N_{ν_μ} at IceCube depends on the **declination angle** δ and the **effective area** $\mathcal{A}_{\rm eff}$:

$$N_{\nu_\mu}(\delta) = \frac{1}{4\pi d_{\rm PBH}^2} \int dE \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\rm HNL+SM} \mathcal{A}_{\rm eff}(E, \delta)$$

- Little atmospheric background for ν_μ from the northern hemisphere (if $\tau_{\rm obs} \sim$ 100s)
    - ➙ set $\delta \in [30\,\text{deg}, 90\,\text{deg}]$

- Sensitivity at IceCube estimated with χ^2 test statistics :

$$\chi^2 = \frac{\left(N_{\nu_\mu}^{\rm HNL+SM} - N_{\nu_\mu}^{\rm SM}\right)^2}{N_{\nu_\mu}^{\rm SM}}$$

(negligible background and $d_{\rm PBH}$ nuisance)

IceCube Collaboration, PRL, 124 no. 5, (2020) 051103