Primordial black hole probes of heavy neutral leptons

Agnese Tolino

IFIC (CSIC-UV)

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

TeV Particle Astrophysics 2024, Chicago

August 27th, 2024

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Financiado por la Unión Europea NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
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

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** $M_{\rm PBH}$, **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

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

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** $M_{\rm PBH}$, **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

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

(See Jessica Turner's plenary talk on Thursday!)

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

PBH evaporation and particle emission

- Hawking predicted that PBHs may lose mass, i.e. **evaporate**, with temperature

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

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
Arbey et al., Eur. Phys. J. C 79 no. 8, (2019) 693

PBH evaporation and particle emission

- Hawking predicted that PBHs may lose mass, i.e. **evaporate**, with temperature

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

- $T_{\mathrm{PBH}} \sim (M_{\mathrm{PBH}})^{-1}$: the smaller the mass, the **hotter** the PBH!

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
Arbey et al., Eur. Phys. J. C 79 no. 8, (2019) 693

PBH evaporation and particle emission

- ❑ Hawking predicted that PBHs may lose mass, i.e. **evaporate**, with temperature

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

- ❑ $T_{\rm PBH} \sim (M_{\rm PBH})^{-1}$: the smaller the mass, the **hotter** the PBH!

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

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
Arbey et al., Eur. Phys. J. C 79 no. 8, (2019) 693

PBH evaporation and particle emission

- Hawking predicted that PBHs may lose mass, i.e. **evaporate**, with temperature

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

- $T_{\rm PBH} \sim (M_{\rm PBH})^{-1}$: the smaller the mass, the **hotter** the PBH!
- PBHs lose mass throughout time, with a rate $\sim M_{\rm PBH}^{-2}$
- The radiated particles will hence have a **semi-thermal spectrum**:

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

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

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
Arbey et al., Eur. Phys. J. C 79 no. 8, (2019) 693

PBH evaporation and particle emission

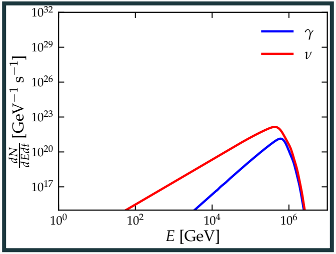

Figure 1: Primary spectrum of γ and ν from a 10^8 g PBH ($T_{\rm PBH} \sim 10^5$ GeV) with BlackHawk v2.3 (Arbey&al.2019)

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
Arbey et al., Eur. Phys. J. C 79 no. 8, (2019) 693

Exploding PBHs

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

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
Arbey et al., Eur. Phys. J. C 79 no. 8, (2019) 693

Exploding PBHs

- In the final stage of evaporation, the PBH quickly becomes **hotter** and hence emits a **burst of particles**
- Very massive particles i can be emitted, up to $m_i \sim T_{\rm PBH}$:

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

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

Arbey et al., Eur. Phys. J. C 79 no. 8, (2019) 693

Exploding PBHs

- In the final stage of evaporation, the PBH quickly becomes **hotter** and hence emits a **burst of particles**
- Very massive particles i can be emitted, up to $m_i \sim T_{\rm PBH}$:

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

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

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
Arbey et al., Eur. Phys. J. C 79 no. 8, (2019) 693

Exploding PBHs

- In the final stage of evaporation, the PBH quickly becomes **hotter** and hence emits a **burst of particles**
- Very massive particles i can be emitted, up to $m_i \sim T_{\rm PBH}$:

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

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

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

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
Arbey et al., Eur. Phys. J. C 79 no. 8, (2019) 693

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

The heavy neutral leptons (HNLs)

- Sterile neutrinos or **Heavy Neutral Leptons (HNLs)** appear in several motivated extensions of the SM to accommodate neutrino masses
- Phenomenological study: **1 HNL**

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

The heavy neutral leptons (HNLs)

- Sterile neutrinos or **Heavy Neutral Leptons (HNLs)** appear in several motivated extensions of the SM to accommodate neutrino masses
- Phenomenological study: **1 HNL**
- Lepton mixing matrix:

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

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

The heavy neutral leptons (HNLs)

- Sterile neutrinos or **Heavy Neutral Leptons (HNLs)** appear in several motivated extensions of the SM to accommodate neutrino masses
- Phenomenological study: **1 HNL**
- Lepton mixing matrix:

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \end{pmatrix} \Rightarrow |U_{\alpha 4}|^2 \text{ mixing between } \nu_e,\ \nu_\mu,\ \nu_\tau \text{ and } \nu_4$$

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

The heavy neutral leptons (HNLs)

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

- Phenomenological study: **1 HNL**

- Lepton mixing matrix:

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \end{pmatrix} \Rightarrow |U_{\alpha 4}|^2 \text{ mixing between } \nu_e,\ \nu_\mu,\ \nu_\tau \text{ and } \nu_4$$

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

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

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)
Perez-Gonzalez, PRD 108 no. 8, (2023) 083014
H.E.S.S. Collaboration, JCAP 04 (2023) 040
IceCube Collaboration, PRD, 99 no. 3, (2019) 032004
IceCube Collaboration, PRL, 124 no. 5, (2020) 051103

Looking for HNLs signatures at IceCube

- **Photons** are a smoking gun of PBH burst
  - **1 PBH at $d_{\mathrm{PBH}} \leq 1$ pc compatible with constraints** from gamma-ray bursts searches (H.E.S.S., Milagro, VERITAS...) and overdensities (Carr&al.2021 and Perez-Gonzalez2023)

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
IceCube Collaboration, PRD, 99 no. 3, (2019) 032004
IceCube Collaboration, PRL, 124 no. 5, (2020) 051103

Looking for HNLs signatures at IceCube

- **Photons** are a smoking gun of PBH burst
  - **1 PBH at $d_{\rm PBH} \leq 1$ pc compatible with constraints** from gamma-ray bursts searches (H.E.S.S., Milagro, VERITAS...) and overdensities (Carr&al.2021 and Perez-Gonzalez2023)
- Another signature of the burst: very energetic **neutrinos**

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
IceCube Collaboration, PRD, 99 no. 3, (2019) 032004
IceCube Collaboration, PRL, 124 no. 5, (2020) 051103

Looking for HNLs signatures at IceCube

- **Photons** are a smoking gun of PBH burst
  - **1 PBH at $d_{\rm PBH} \leq$ 1 pc compatible with constraints** from gamma-ray bursts searches (H.E.S.S., Milagro, VERITAS...) and overdensities (Carr&al.2021 and Perez-Gonzalez2023)
- Another signature of the burst: very energetic **neutrinos**
- **IceCube** could detect **muonic neutrinos** ν_μ from the burst
  - Right energy range: 100 - 10^8 GeV

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
IceCube Collaboration, PRD, 99 no. 3, (2019) 032004
IceCube Collaboration, PRL, 124 no. 5, (2020) 051103

Looking for HNLs signatures at IceCube

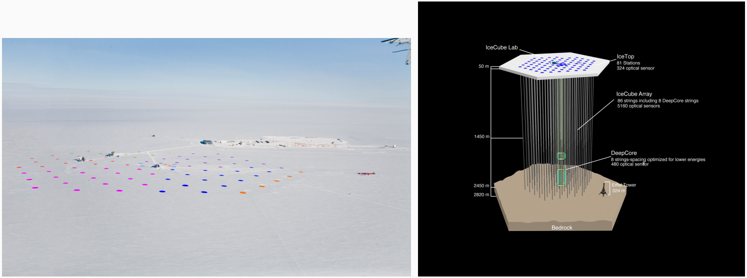

Figure 2: IceCube Neutrino Observatory. Credits: the IceCube collaboration

Looking for HNLs signatures at IceCube

- **Photons** are a smoking gun of PBH burst
  - **1 PBH at $d_{\rm PBH} \leq$ 1 pc compatible with constraints** from gamma-ray bursts searches (H.E.S.S., Milagro, VERITAS...) and overdensities (Carr&al.2021 and Perez-Gonzalez2023)
- Another signature of the burst: very energetic **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

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
IceCube Collaboration, PRD, 99 no. 3, (2019) 032004
IceCube Collaboration, PRL, 124 no. 5, (2020) 051103

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:

Atre et al., JHEP 05 (2009) 030
Mastrototaro et al., JCAP 01 (2020) 010
Coloma et al., Phys. J. C 81 no. 1, (2021) 78
Akita et al., arXiv:2312.13627

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:

$$\left.\frac{dN_{\nu_\mu}}{dE}\right|_{\rm SM} = \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\rm prim} + \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\rm sec}$$

Atre et al., JHEP 05 (2009) 030
Mastrototaro et al., JCAP 01 (2020) 010
Coloma et al., Phys. J. C 81 no. 1, (2021) 78
Akita et al., arXiv:2312.13627

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:

$$\left.\frac{dN_{\nu_\mu}}{dE}\right|_{\mathrm{SM}} = \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\mathrm{prim}} + \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\mathrm{sec}}$$

$$\left.\frac{dN_{\nu_\mu}}{dE}\right|_{\mathsf{HNL}} = \begin{cases} \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\nu_4\to\nu\nu\nu} + \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\nu_4\to\nu\pi}, & \text{if } m_4 \in [0.1, 1]\,\text{GeV} \\ \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\nu_4\to H/Z\nu} + \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\nu_4\to W\mu}, & \text{if } m_4 \in [0.5, 2]\,\text{TeV} \end{cases}$$

Atre et al., JHEP 05 (2009) 030
Mastrototaro et al., JCAP 01 (2020) 010
Coloma et al., Phys. J. C 81 no. 1, (2021) 78
Akita et al., arXiv:2312.13627

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:

$$\left.\frac{dN_{\nu_\mu}}{dE}\right|_{\mathrm{SM}} = \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\mathrm{prim}} + \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\mathrm{sec}}$$

$$\left.\frac{dN_{\nu_\mu}}{dE}\right|_{\mathsf{HNL}} = \begin{cases} \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\nu_4\to\nu\nu\nu} + \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\nu_4\to\nu\pi}, & \text{if } m_4 \in [0.1, 1]\,\text{GeV} \\ \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\nu_4\to H/Z\nu} + \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\nu_4\to W\mu}, & \text{if } m_4 \in [0.5, 2]\,\text{TeV} \end{cases}$$

Atre et al., JHEP 05 (2009) 030
Mastrototaro et al., JCAP 01 (2020) 010
Coloma et al., Phys. J. C 81 no. 1, (2021) 78
Akita et al., arXiv:2312.13627

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:

$$\frac{dN_{\nu_\mu}}{dE}\bigg|_{\mathrm{SM}} = \frac{dN_{\nu_\mu}}{dE}\bigg|_{\mathrm{prim}} + \frac{dN_{\nu_\mu}}{dE}\bigg|_{\mathrm{sec}}$$

$$\frac{dN_{\nu_\mu}}{dE}\bigg|_{\mathsf{HNL}} = \begin{cases} \frac{dN_{\nu_\mu}}{dE}\Big|_{\nu_4\to\nu\nu\nu} + \frac{dN_{\nu_\mu}}{dE}\Big|_{\nu_4\to\nu\pi}, & \text{if } m_4 \in [0.1, 1]\,\text{GeV} \\ \frac{dN_{\nu_\mu}}{dE}\Big|_{\nu_4\to H/Z\nu} + \frac{dN_{\nu_\mu}}{dE}\Big|_{\nu_4\to W\mu}, & \text{if } m_4 \in [0.5, 2]\,\text{TeV} \end{cases}$$

Atre et al., JHEP 05 (2009) 030
Mastrototaro et al., JCAP 01 (2020) 010
Coloma et al., Phys. J. C 81 no. 1, (2021) 78
Akita et al., arXiv:2312.13627

The expected spectrum from HNL decay

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

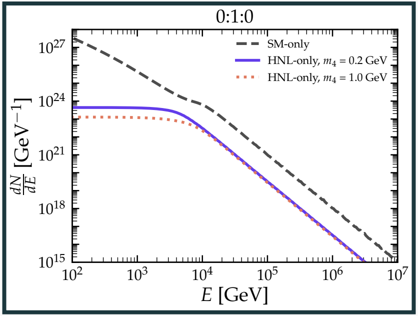

Figure 2: SM-only and HNL-only time-integrated spectrum of ν_μ at Earth for $\tau = 100$s for two test-masses and 0:1:0

Atre et al., JHEP 05 (2009) 030
Mastrototaro et al., JCAP 01 (2020) 010
Coloma et al., Phys. J. C 81 no. 1, (2021) 78
Akita et al., arXiv:2312.13627

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

- We evaluated the **expected number of** ν_μ at IceCube emitted in a 100s PBH burst from HNL + SM
- We focused on ν_μ arriving to the **northern emisphere** to minimize atmospheric background

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

Sensitivities at IceCube - the analysis

- We evaluated the **expected number of** ν_μ at IceCube emitted in a 100s PBH burst from HNL + SM
- We focused on ν_μ arriving to the **northern emisphere** to minimize atmospheric background
- We estimated the **IceCube sensitivities** to HNL decays from a 100s PBH burst with a simple χ^2 analysis

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

Sensitivities at IceCube - Results - I

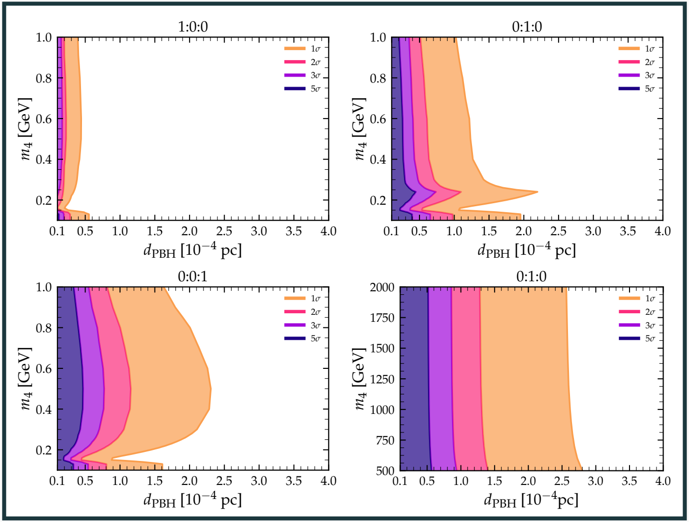

Figure 3: IceCube sensitivity to HNLs from a PBH burst lasting 100s; correction to arXiv:2405.00124

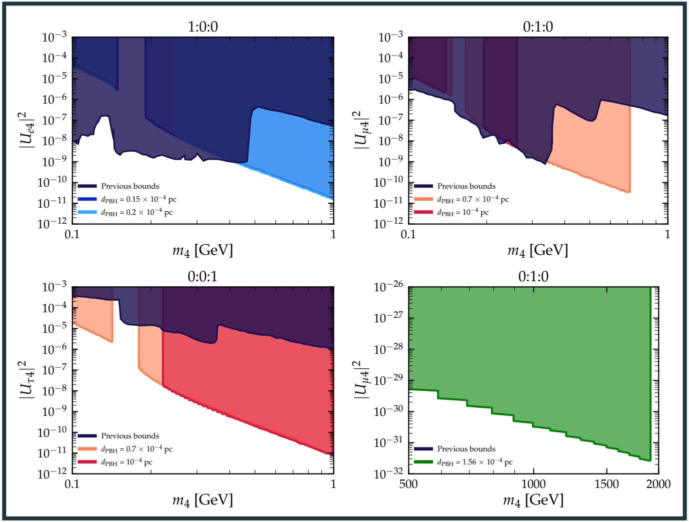

Figure 4: Expected IceCube sensitivity at 90% CL for a 100s PBH burst; correction to arXiv:2405.00124

Conclusions

Conclusions

- 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
- We found that in [0.1-1] GeV, 0:1:0 and 0:0:1 would give visible signals if the PBH burst occurs at 10^{-4} pc
- The [0.5-2] TeV range, 0:1:0, accesible 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

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

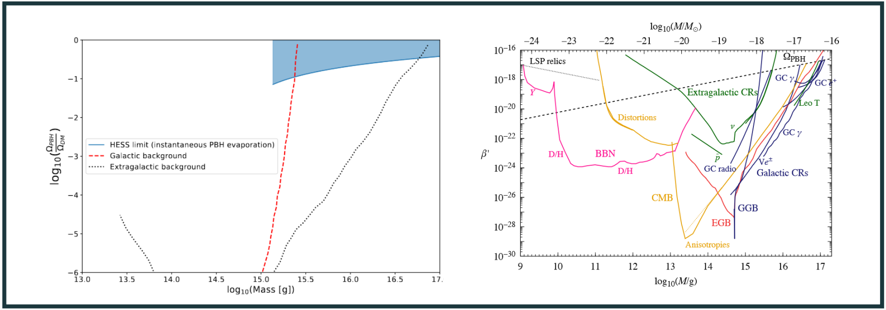

Figure 5: Bounds on β' and $\frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$. Left: from H.E.S.S. 2023, right from Carr 2021.

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

Other results - I

$$\Delta = \left.\frac{dN}{dE}\right|_{SM+HNL} \Big/ \left.\frac{dN}{dE}\right|_{SM}$$

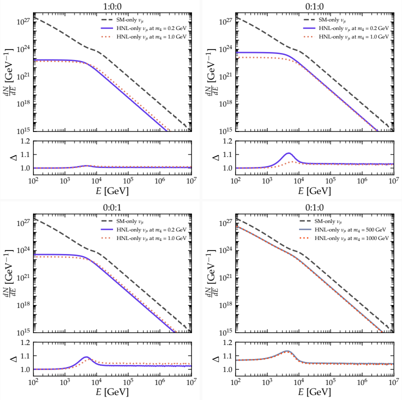

Figure 6: Total time-integrated spectrum of muon neutrinos expected at the Earth from the evaporation of a PBH for an observation time of $\tau = 100$ s. In each panel, we show the SM-only contribution (black, dashed) and the HNL-only contribution for different HNL benchmark masses (solid/dotted, color) and mixings. The smaller panels below each figure depict the relative difference in the spectral shapes between the total (SM + HNL) and SM-only contributions Δ.

Other results - II

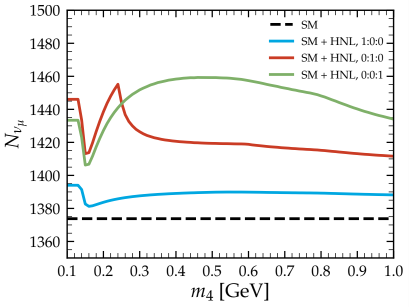

Figure 7: Expected number of muon-neutrino events at IceCube as a function of the HNL mass, from the last stages (100 s) of an evaporating PBH located at a distance $d_{\rm PBH} = 10^{-4}$ pc from Earth and at a declination angle $[30^\circ < \delta < 90^\circ]$. The black dashed curve corresponds to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

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

- 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 $M_\nu = \mathcal{U}_\nu M_\nu^{\rm diag} \mathcal{U}_\nu{}^T$ $(\mathcal{U}_\nu{}^T \mathcal{U}_\nu = 1)$, $\mathscr{L}^m_{\rm RHN}$ 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 $\mathcal{U}_\nu$ $(\mathcal{U}_l \sim \not{1}_{3\times 3})$:

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

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

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

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

- 3-body

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

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

If the neutrino mixes with ν_4

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

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

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

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

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

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

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

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

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** $\mathcal{A}_{\rm eff}$:

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

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

- 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