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ASTROPARTICLES
Astroparticles and High Energy Physics Group
GENERALITAT VALENCIANA
Conselleria de Educación, Cultura, Universidades y Empleo

PBH PROBES OF HNLS

based on JCAP 04 (2025) 018

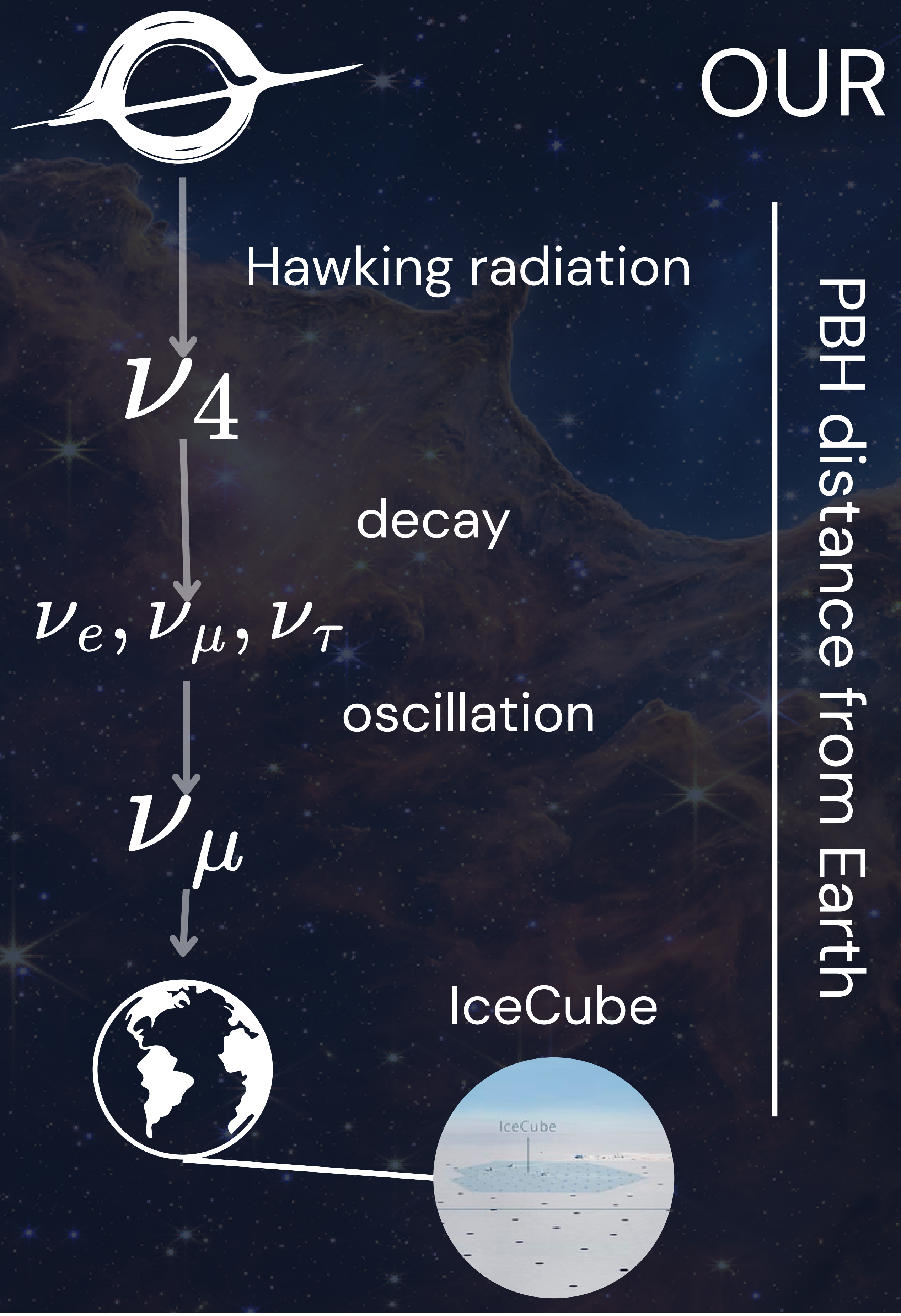
in collaboration with Y.F. Perez-Gonzalez & V. De Romeri

Agnese Tolino
IFIC (CSIC-UV)

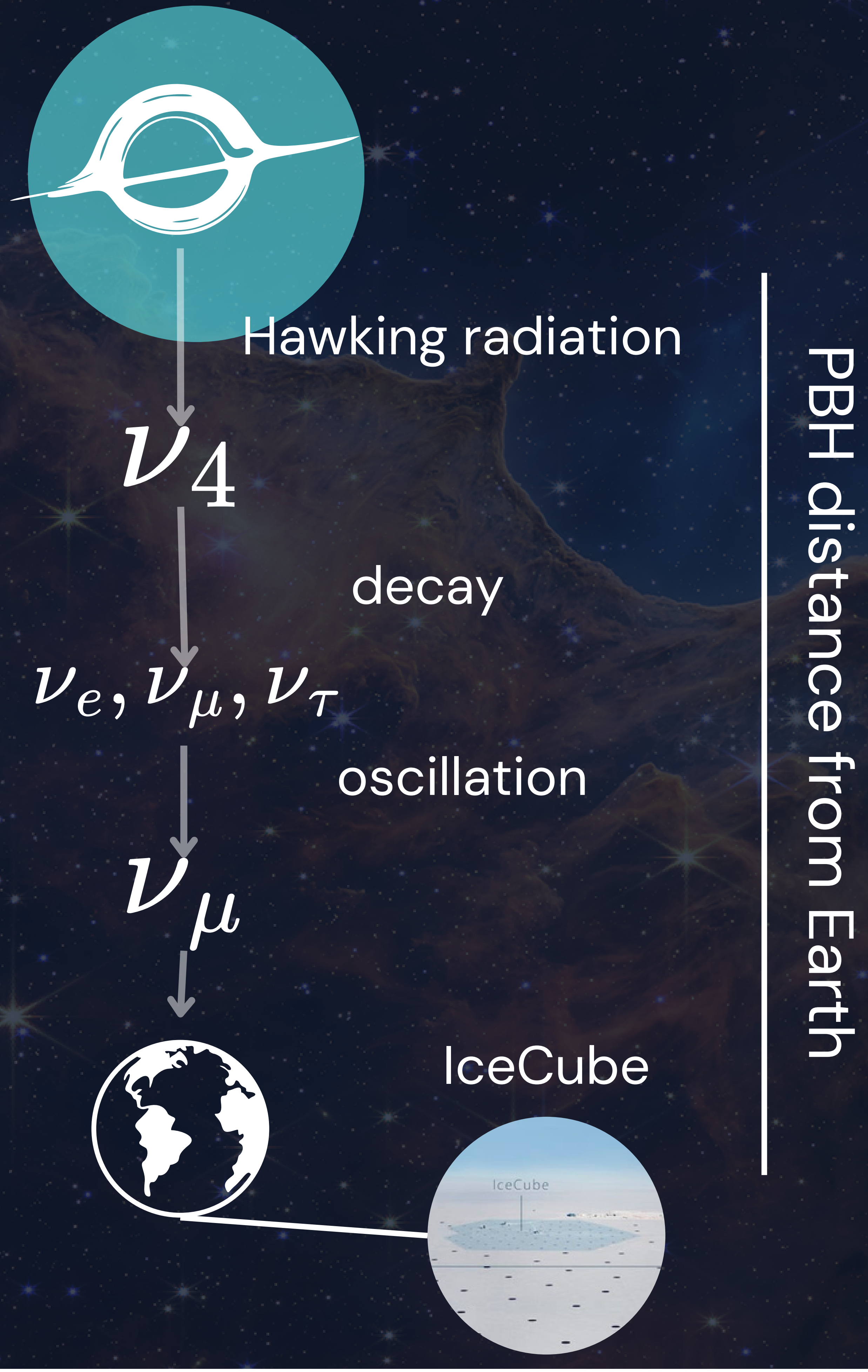
November 6th, 2025

TeVPA, Valencia

OUR WORK… IN A NUTSHELL



In JCAP 04 (2025) 018,
we estimated the combined **sensitivities**
of **IceCube & HAWK**
to Heavy Neutral Leptons (**HNLs**) decays
from a 100s
Primordial Black Hole (**PBH**) **burst**

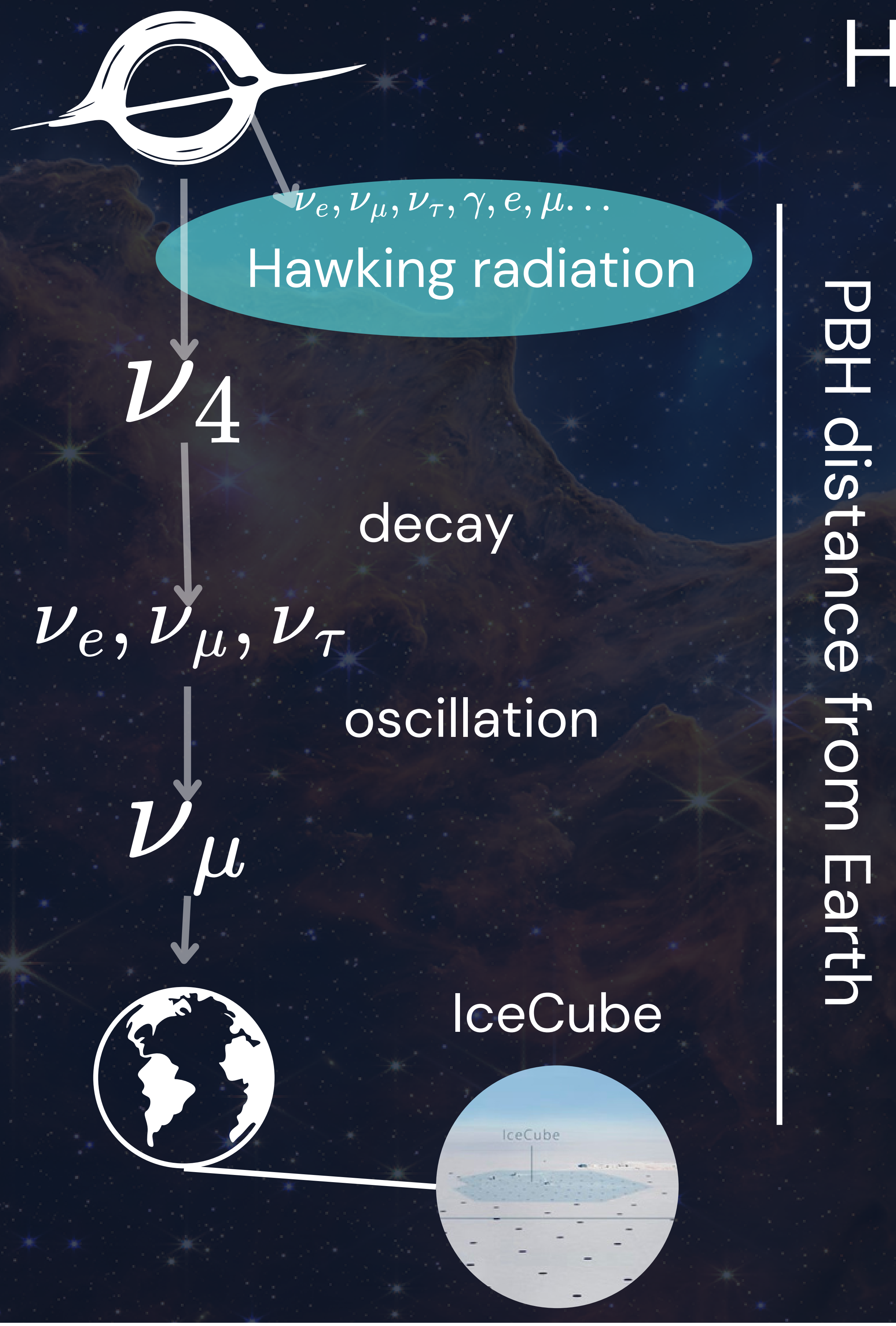


IDENTIKIT OF PBHS

- Might have formed in the Early Universe by the collapse of **overdensities**
- **Schwarzschild** (i.e. non-rotating & uncharged) PBHs are uniquely described by their **mass**
- Masses span from 10^{-5} g to $10^{5} M_{\odot}$

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

HAWKING RADIATION



- Hawking predicted that PBHs **evaporate** with a temperature

$$T = \frac{1}{8\pi G M_{\rm PBH}}$$

- Mass loss goes as $\frac{dM}{dt} \sim M_{\rm PBH}^{-2}$
- The evaporation corresponds to the emission of particles with a semi-thermal spectrum

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

Hawking, Nature 248 (1974) 30-31
Carr et al., Ann. Rev. Nucl. Part. Sci. 70 (2020)
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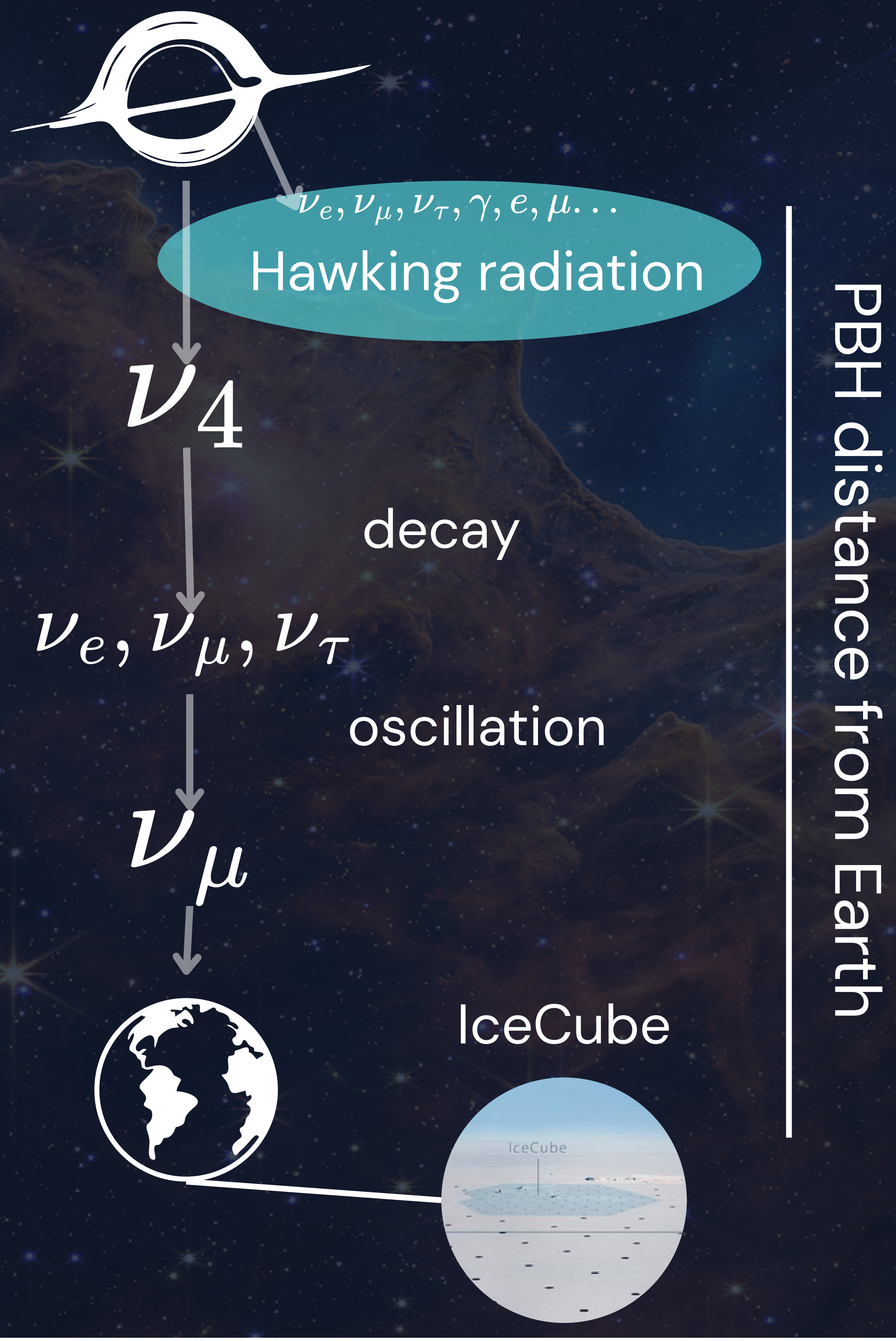
Arbey et al., Eur. Phys. J. C 79 no. 8, (2019) 693

'EXPLODING' PBHS



- In the final stage of evaporation, the PBH quickly becomes **hotter** and emits a **burst of particles**
- Particles with a mass up to $m_i \sim T_{\rm PBH}$ can be emitted, **even BSM particles as HNLs!**

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

- Our work: **1 PBH** with $M_{\rm PBH}^{\rm in} \sim 10^{15}$ g exploding in a **100s burst**

Hawking, Nature 248 (1974) 30-31
Carr et al., Ann. Rev. Nucl. Part. Sci. 70 (2020)
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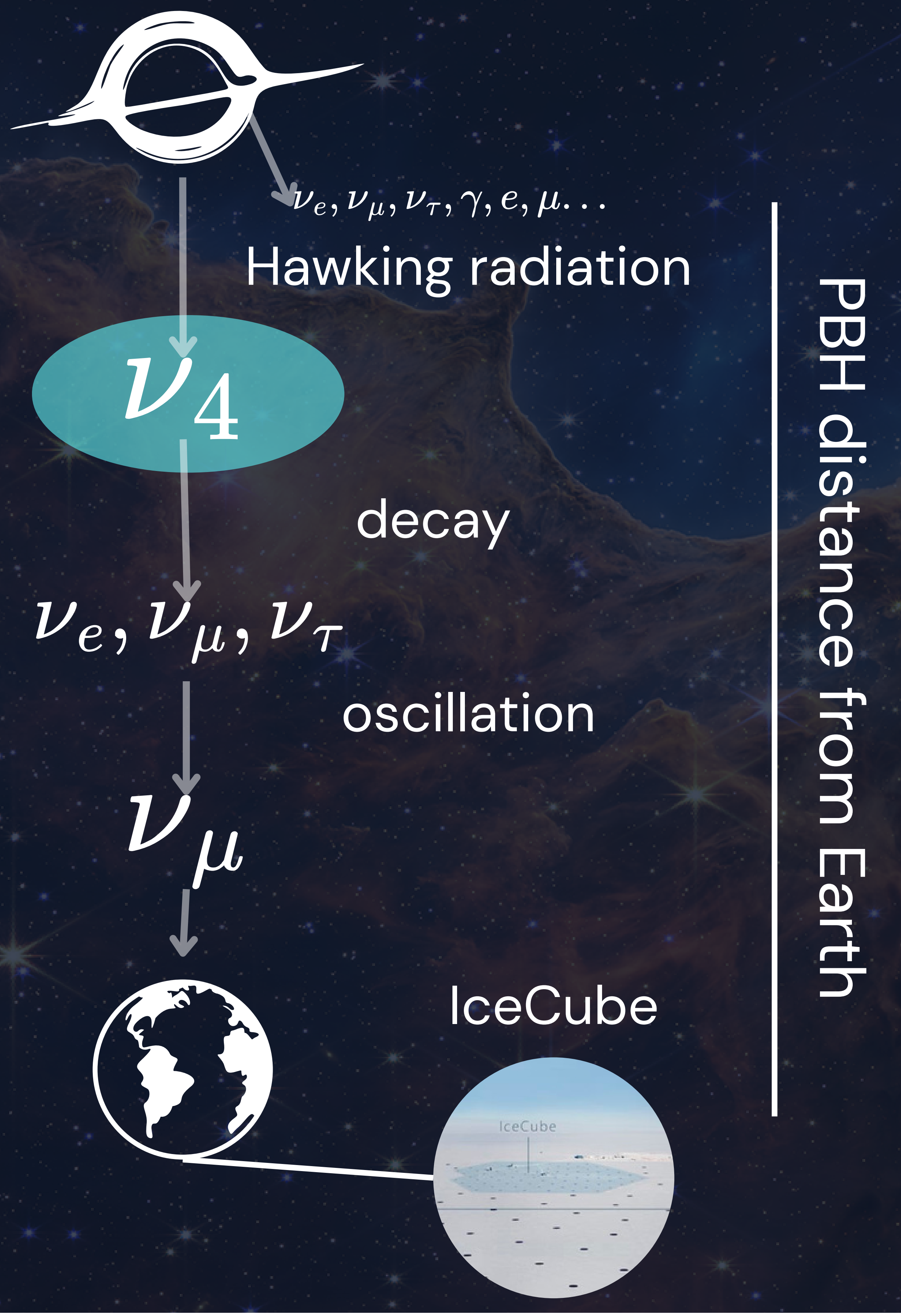
HNLS



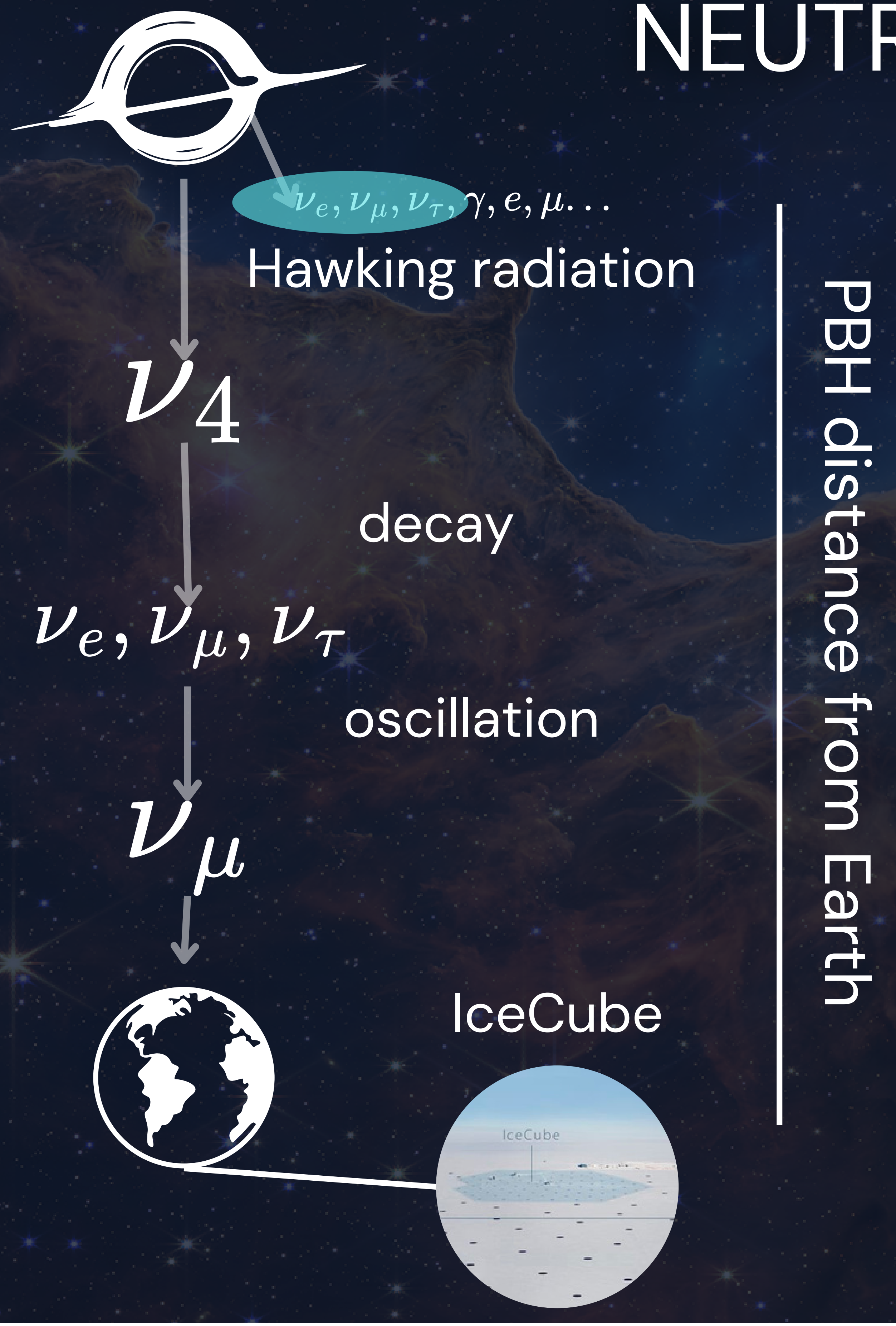
- Introduced to explain neutrino masses in SM extensions
- Phenomenological study: 1 HNL
- Considered the case in which only 1 active neutrino $\alpha = e, \mu, \tau$ at time mixes with the HNL:

$$|U_{\alpha 4}|^2 \neq 0$$

(So 1:0:0 : only electron neutrino mixing, and so on)

Abdullahi et al., J. Phys. G 50 no. 2, (2023) 0205013

NEUTRINO SIGNALS FROM PBHS



- SM neutrinos are directly emitted by the PBH

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:2312.1362

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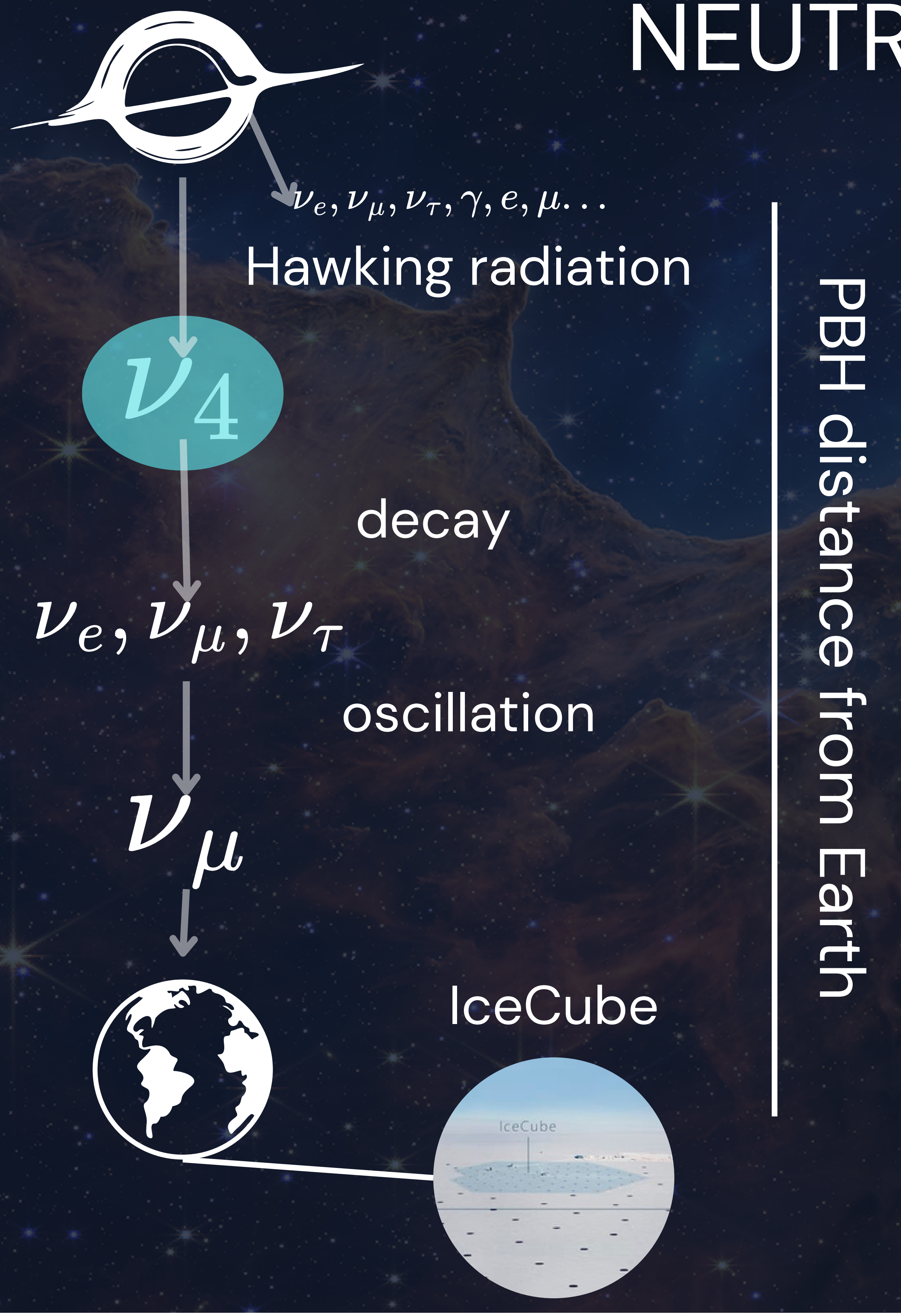

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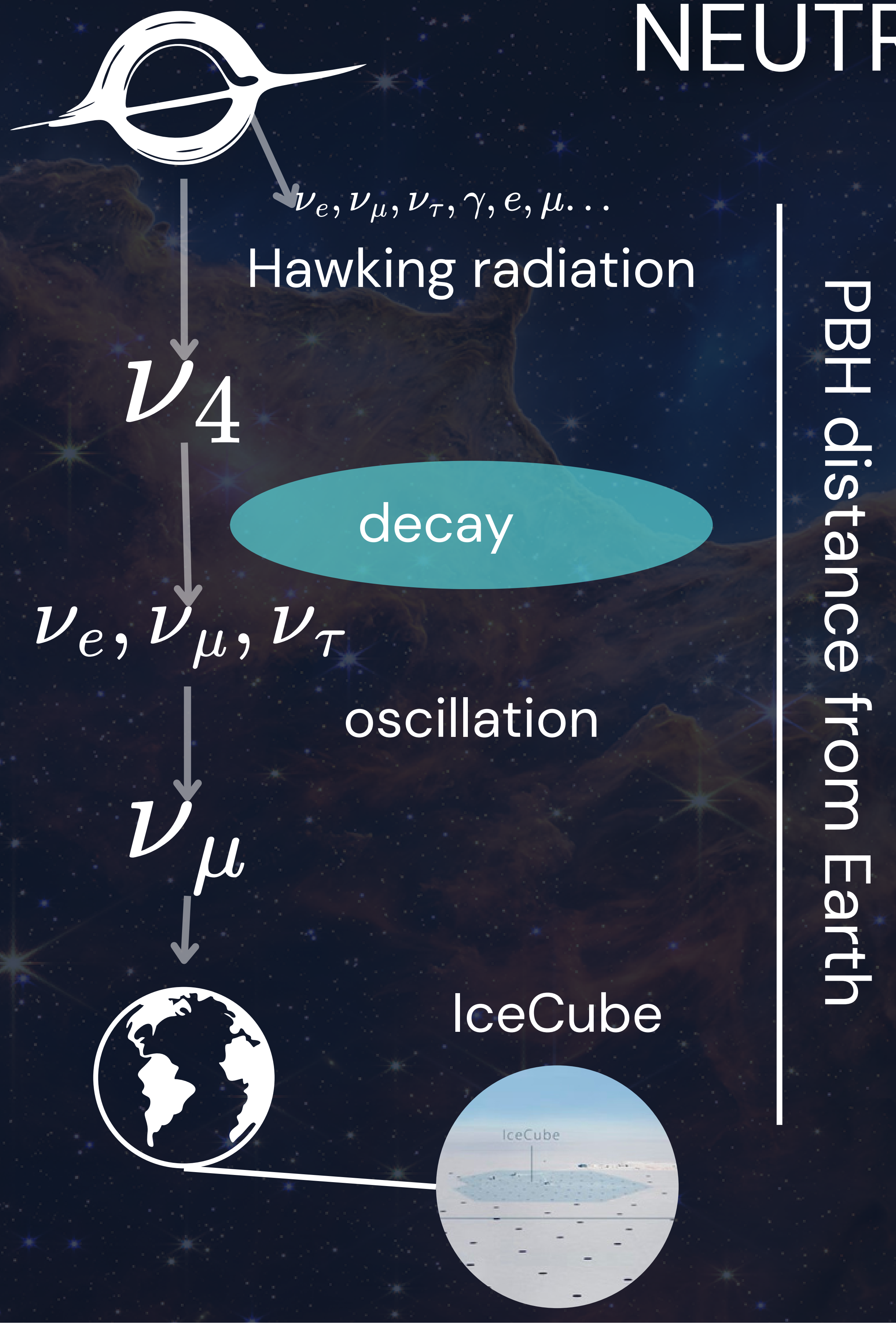

- SM neutrinos **& HNLs** are directly emitted by the PBH
- Depending on the mass, HNLs might decay into active neutrinos:

$$\begin{cases} \nu_4 \to \nu\nu\nu \;\; \& \;\; \nu_4 \to \nu\pi, & \text{if } m_4 \in [0.1, 1]\,\text{GeV} \\ \nu_4 \to H/Z\nu \to \nu \;\; \& \;\; \nu_4 \to W\mu \to \nu, & \text{if } m_4 \in [0.5, 2]\,\text{TeV} \end{cases}$$

Light mass regime
Heavy mass regime

Atre et al., JHEP 05 (2009) 030
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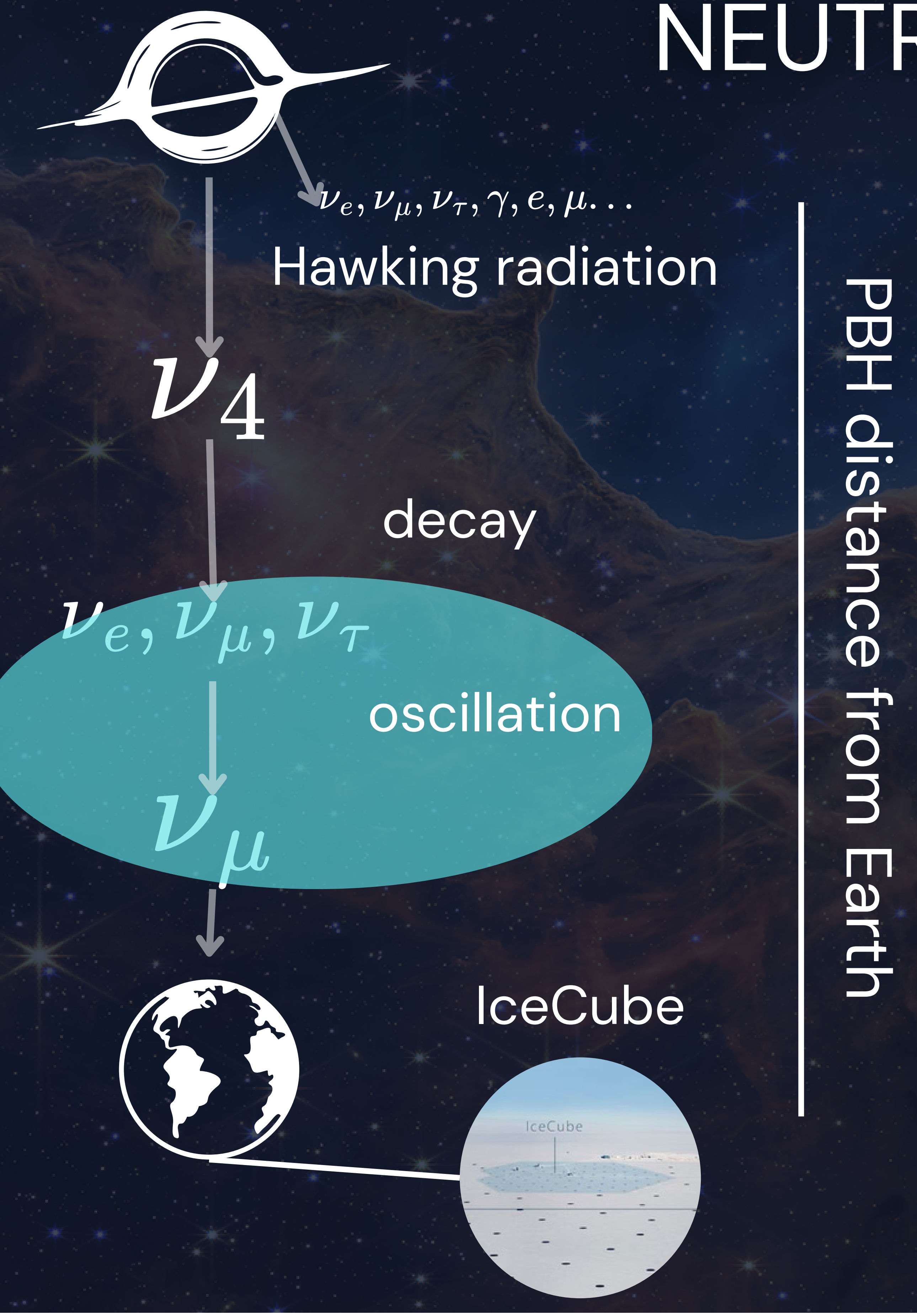

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Light mass regime
Heavy mass regime

- The active neutrinos oscillate into muon neutrinos

Atre et al., JHEP 05 (2009) 030
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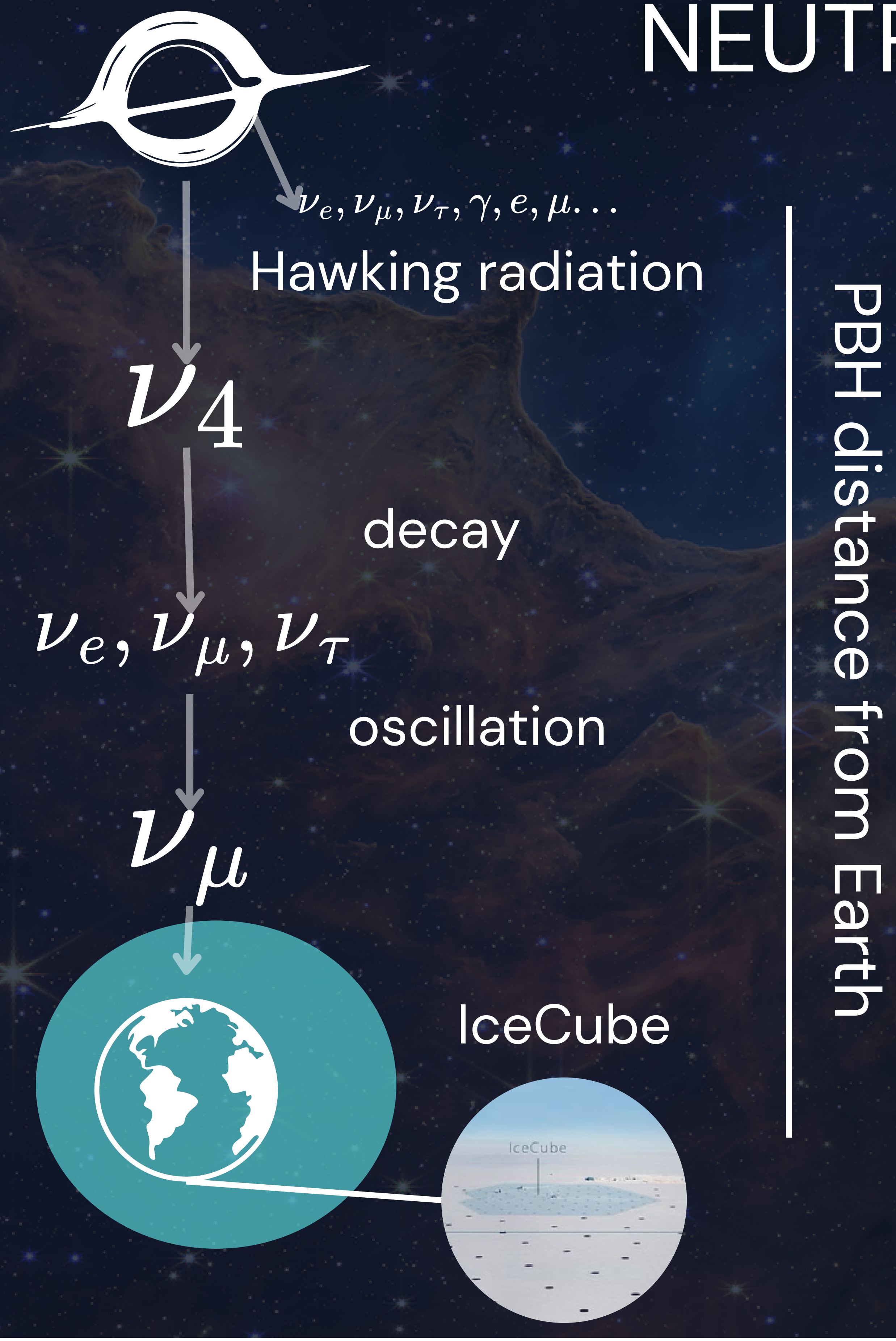

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Light mass regime
Heavy mass regime

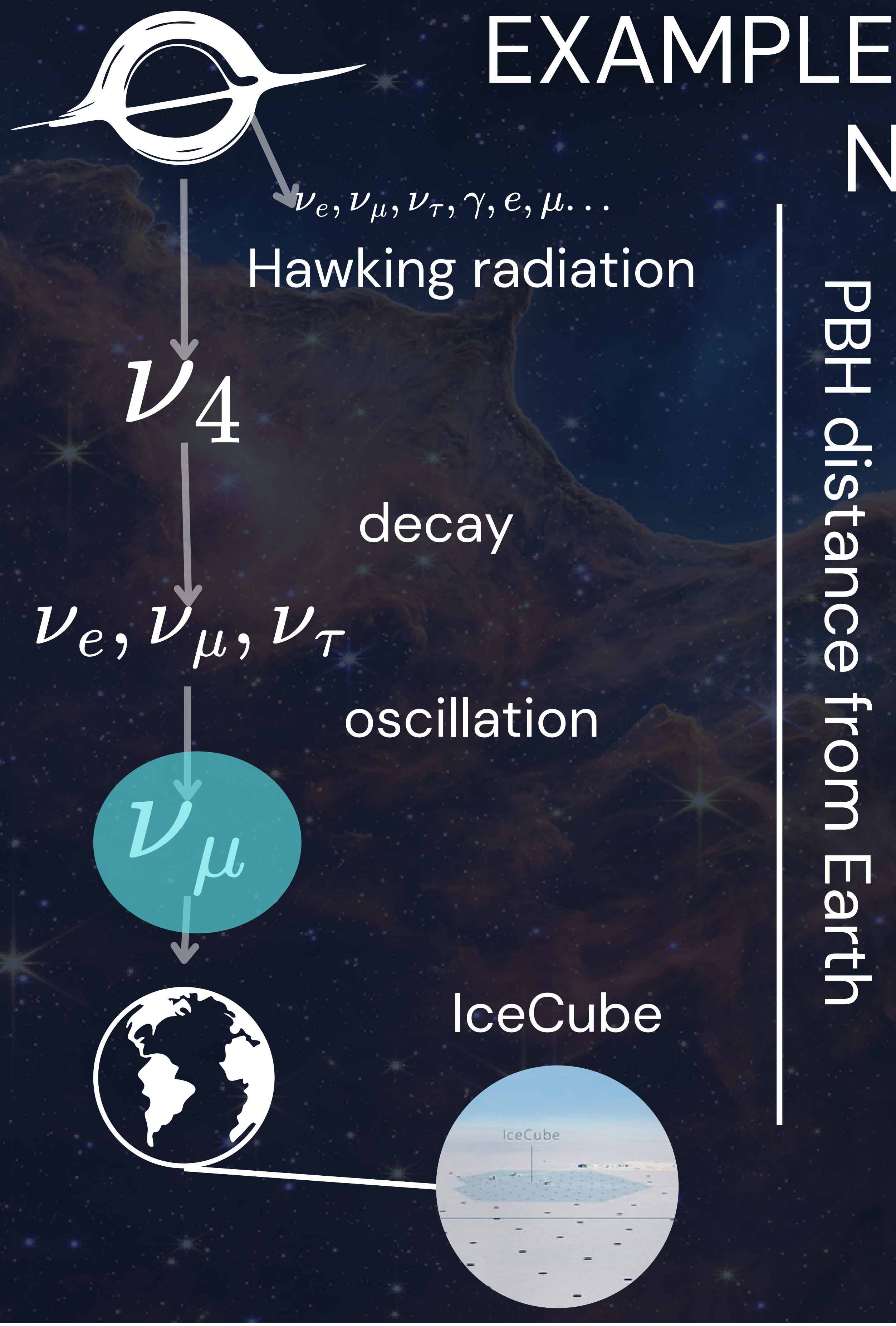
- The active neutrinos oscillate into muon neutrinos
- Overall neutrino spectrum at Earth from a 100s PBH burst:

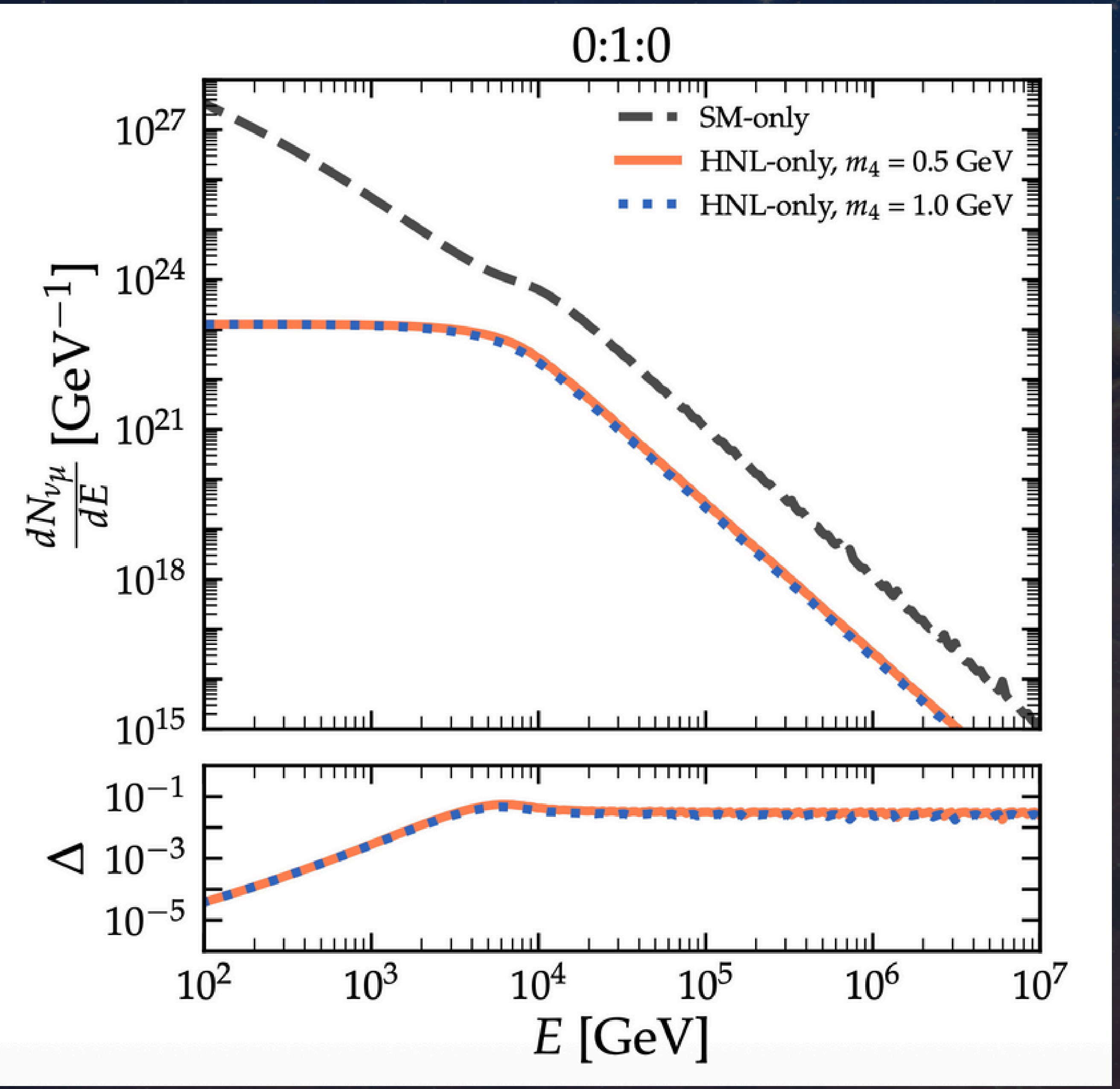
SM-only + HNL-decay contributions

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:2312.1362

Arbey et al., Eur. Phys. J. C81 (2021) 910
Arbey et al., Eur. Phys. J. C 79 no. 8, (2019) 693
Bauer et al., JHEP06(2021) 121

EXAMPLE OF SM-ONLY + HNL-ONLY NEUTRINO SPECTRA





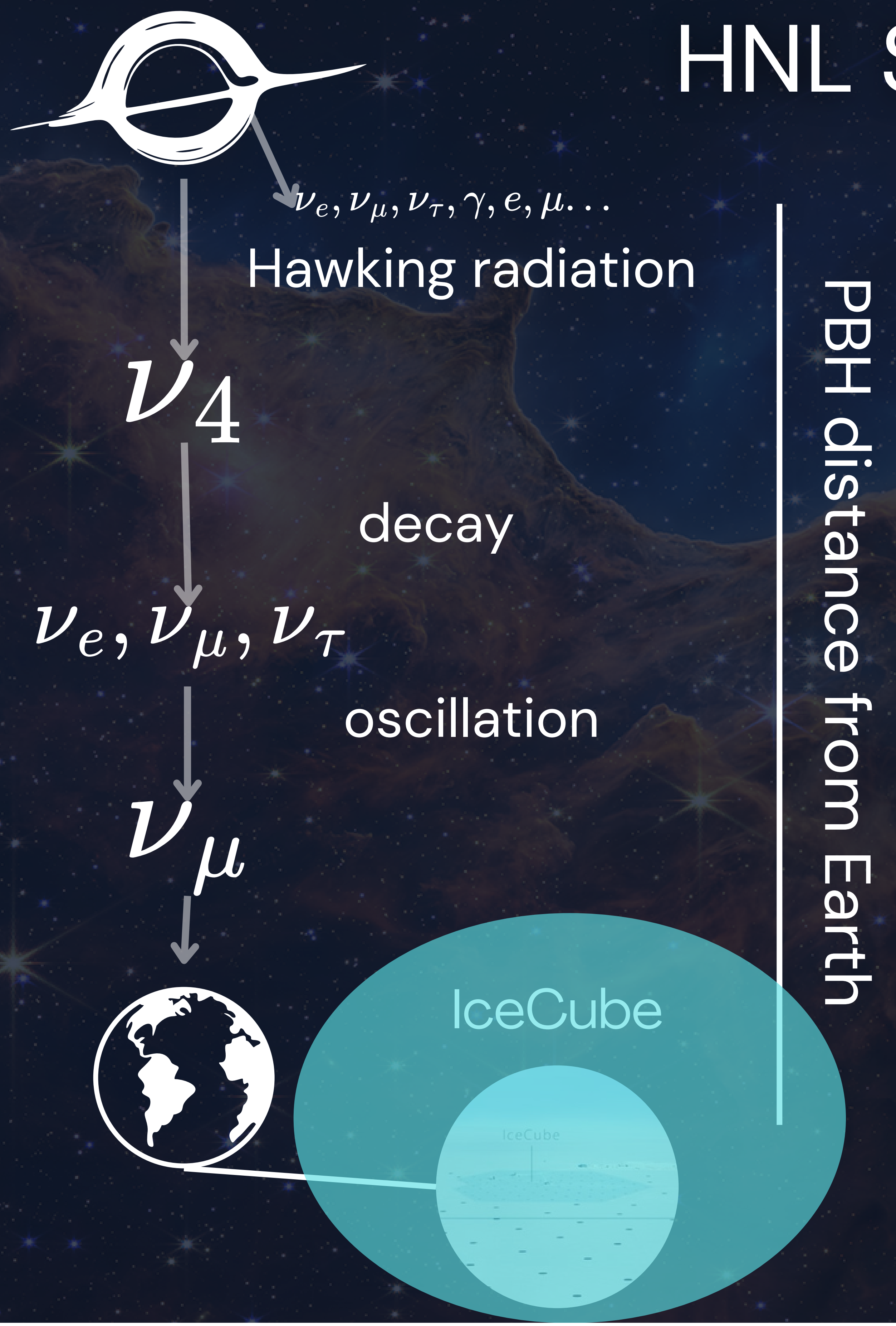
Expected muon neutrino spectrum from HNL-only (color) and SM-only (grey) contributions in a 100s PBH burst

$$\frac{dN_{\nu_\mu}}{dE} \propto B_\alpha(\text{channel})$$

Note that if only one active neutrino mixes with the heavy, the branching ratio, and hence the spectrum, will not depend on the mixing!

The spectra are obtained through BlackHawk + HDMSpectra

HNL SIGNATURES AT ICECUBE



- ν_μ directly emitted by the PBH & through HNL decay are extremely boosted
- IceCube would be able to detect them, as it is sensitive to the right energy range :

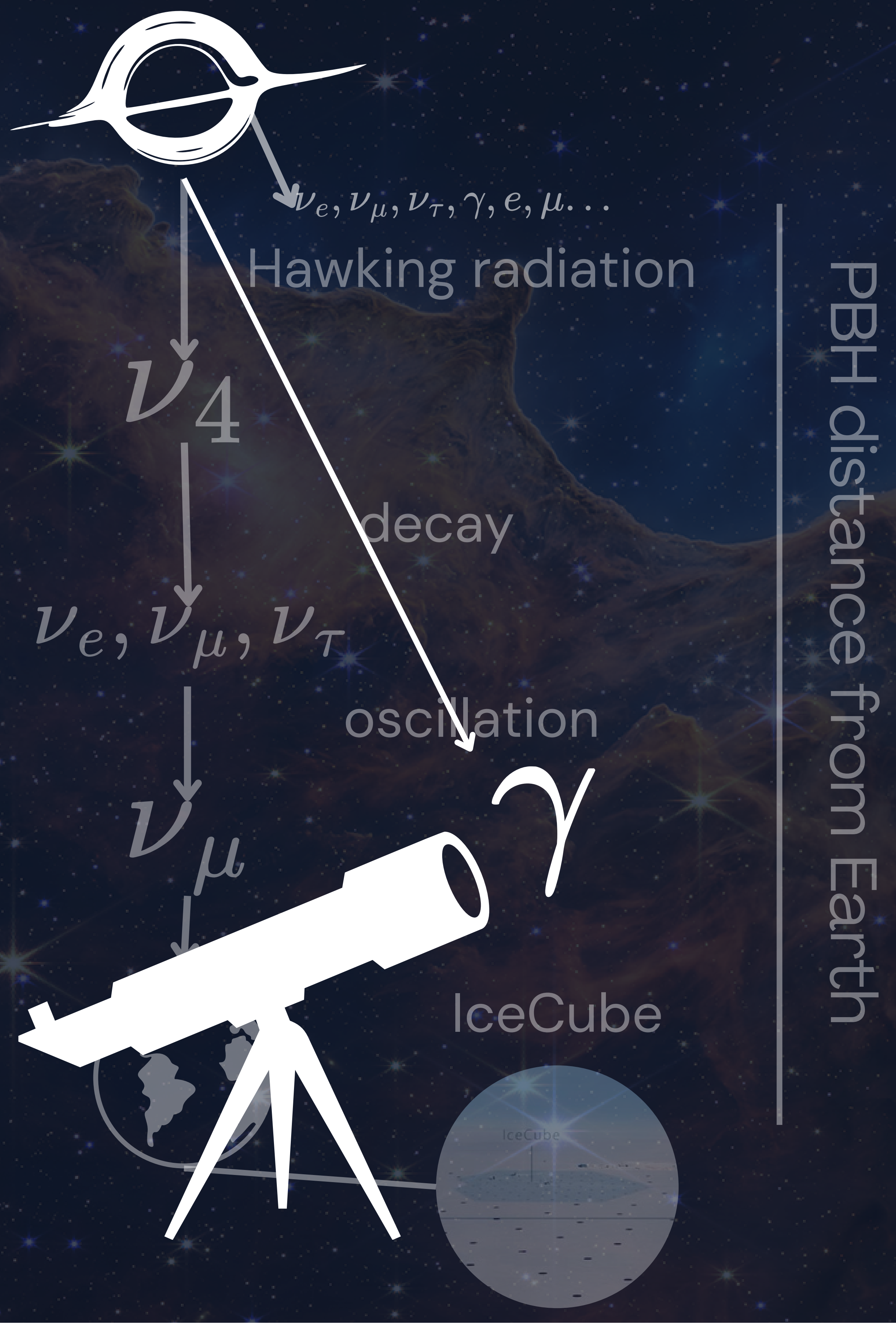
100 GeV – 100 PeV

Signature: excess of muon neutrinos (with respect to the SM-only case) **from the PBH burst @IceCube due to HNL decay!**

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

H.E.S.S. Collab., ICRC2013, p. 0930. 7 (2013)
Milagro et al., Astropart. Phys. 64 (2015) 4-12
HAWC Collaboration, JCAP, 04 (2020) 026
Fermi-LAT Collab., Astrophys. J., 857, no. 1, (2018) 49
VERITAS Collab., 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. Collab., JCAP 04 (2023) 040

... AND PHOTONS



- Photons are a smoking gun of PBH burst and can be produced in HNL decays as well
- Strongest constraints from H.E.S.S. & overdensities allow 1 exploding PBH at max 1 pc from us
- A combined $\nu + \gamma$ analysis is necessary to erase the **degeneracy** between the PBH position and the HNL contribution!

→ Photons @Hawk included in the statistical analysis

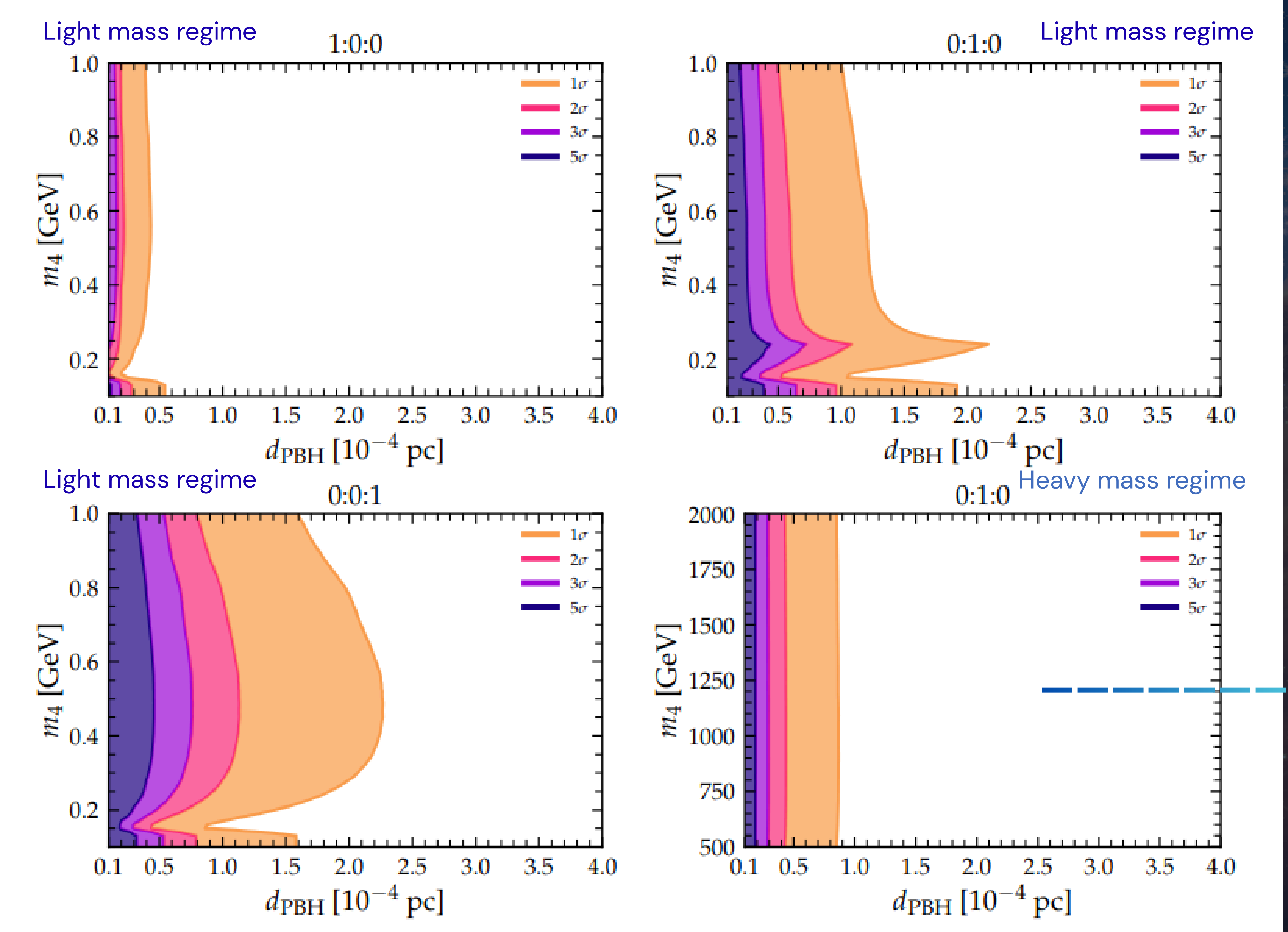
ANALYSIS SCHEME

Evaluated the expected number of muon ν at IceCube and γ at HAWK from northern hemisphere emitted in a **100s PBH burst** considering both **HNL + SM contributions**

Estimated the **IceCube & HAWK sensitivities** to HNL decays with a χ^2 analysis **including** the **uncertainty** over the **PBH distance** from Earth

SELECTED RESULTS

ICECUBE & HAWK SENSITIVITIES



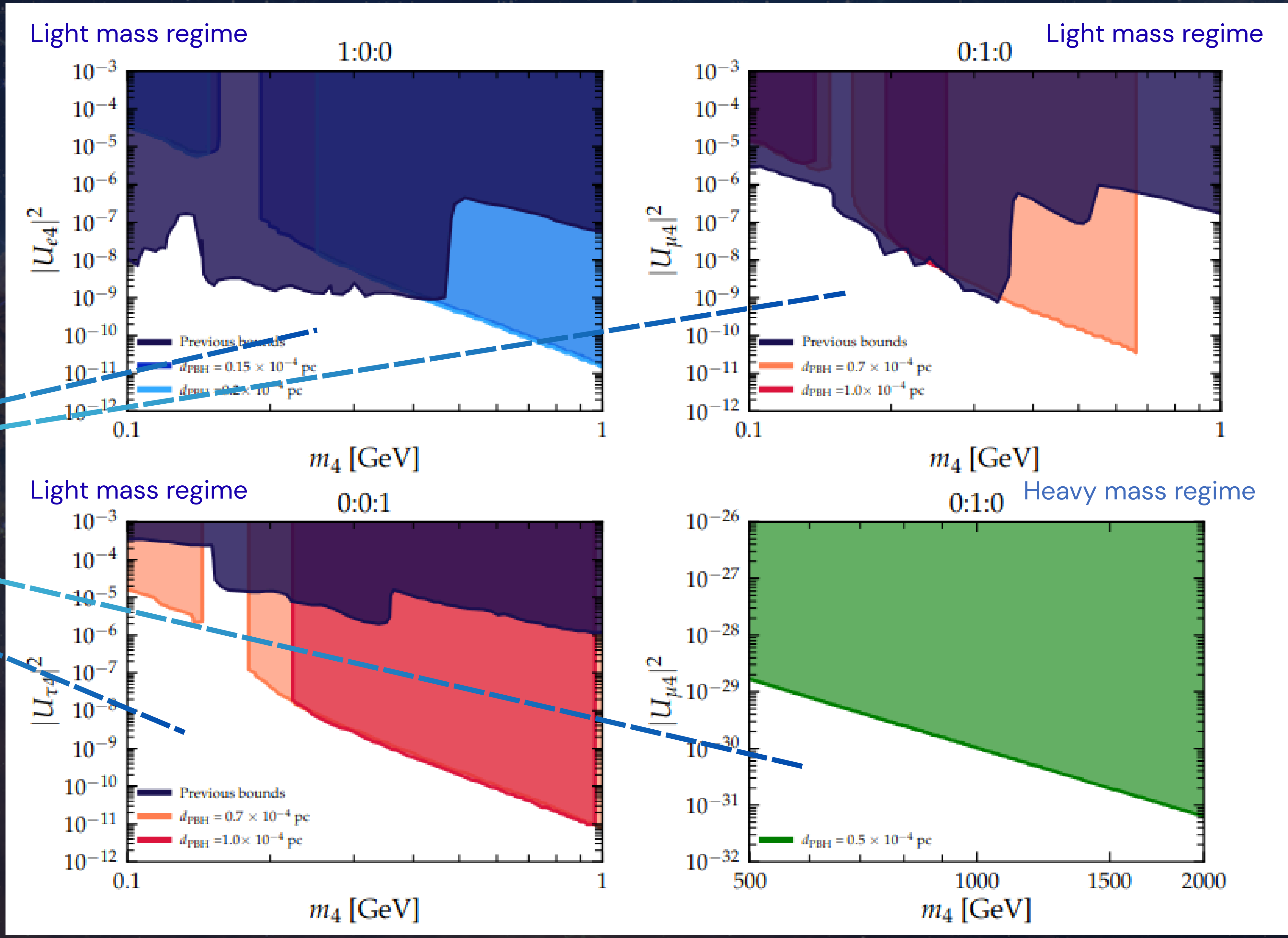
Photon contribution is important → need the PBH to be nearer to pinpoint its distance

Combined IceCube & HAWK sensitivities to HNLs from a PBH burst lasting 100s

Same results can be casted in the HNL mixing - mass plane

$$d_{\text{decay}} \leq d_{\text{PBH}}$$

Expected IceCube & HAWK sensitivities at 90% CL for a 100s PBH burst



CONCLUSIONS

1

We evaluated the muon ν signal at IceCube and γ at HAWK from 100s PBH burst

- included HNL decays
- considered for HNLs 2 mass ranges & 3 mixing scenarios

2

In the statistical analysis, we included both neutrinos @IceCube & photons @HAWK to break the degeneracy between the HNL contribution and the PBH position

3

We found that

- the HNL mass [0.1-1] GeV range could be proved at IceCube and Hawk if $d_{\mathrm{PBH}} \sim 10^{-4}\mathrm{pc}$ for HNL mixings 0:1:0 and 0:0:1
- the [0.5-2] TeV range at $d_{\mathrm{PBH}} \leq 10^{-4}\mathrm{pc}$ for 0:1:0

TAKE-HOME MESSAGE

Joint analyses between IceCube and gamma-ray observatories like HAWK would provide stringent limits on HNL masses and mixings!

TAKE-HOME MESSAGE

Joint analyses between IceCube and gamma-ray observatories like HAWK would provide stringent limits on HNL masses and mixings!

THANK YOU FOR YOUR ATTENTION!

QUESTIONS?

BACKUP SLIDES

PBH EVAPORATION

A PBH that is exploding now had at the time of its formation (during radiation domination) a mass equal to 10^{15} g

At the start of the 100s of the burst, i.e. the last 100s of its life, the PBH has a mass of 6.2×10^9 g

So we compute the time-integrated spectra with BlackHawk for a PBH that has an initial mass of 6.2×10^9 g, as we are interested only in the last 100s of its life:

$$\frac{dN_i}{dE} = \int_0^{\tau} dt \, \frac{d^2 N_i}{dEdt}(M(t)) \, .$$

NEUTRINO SPECTRA FROM HNL DECAYS

[0.1 – 1] GeV:

$$\nu_4 \to \nu_\alpha \pi^0 ,$$
$$\nu_4 \to \nu_\alpha \nu_\ell \bar{\nu}_\ell \quad (\ell = e, \mu, \tau) ,$$

[0.5 – 2] TeV

$$\nu_4 \to W^\pm \mu^\mp ,$$
$$\nu_4 \to Z^0 \nu_\mu ,$$
$$\nu_4 \to H^0 \nu_\mu .$$

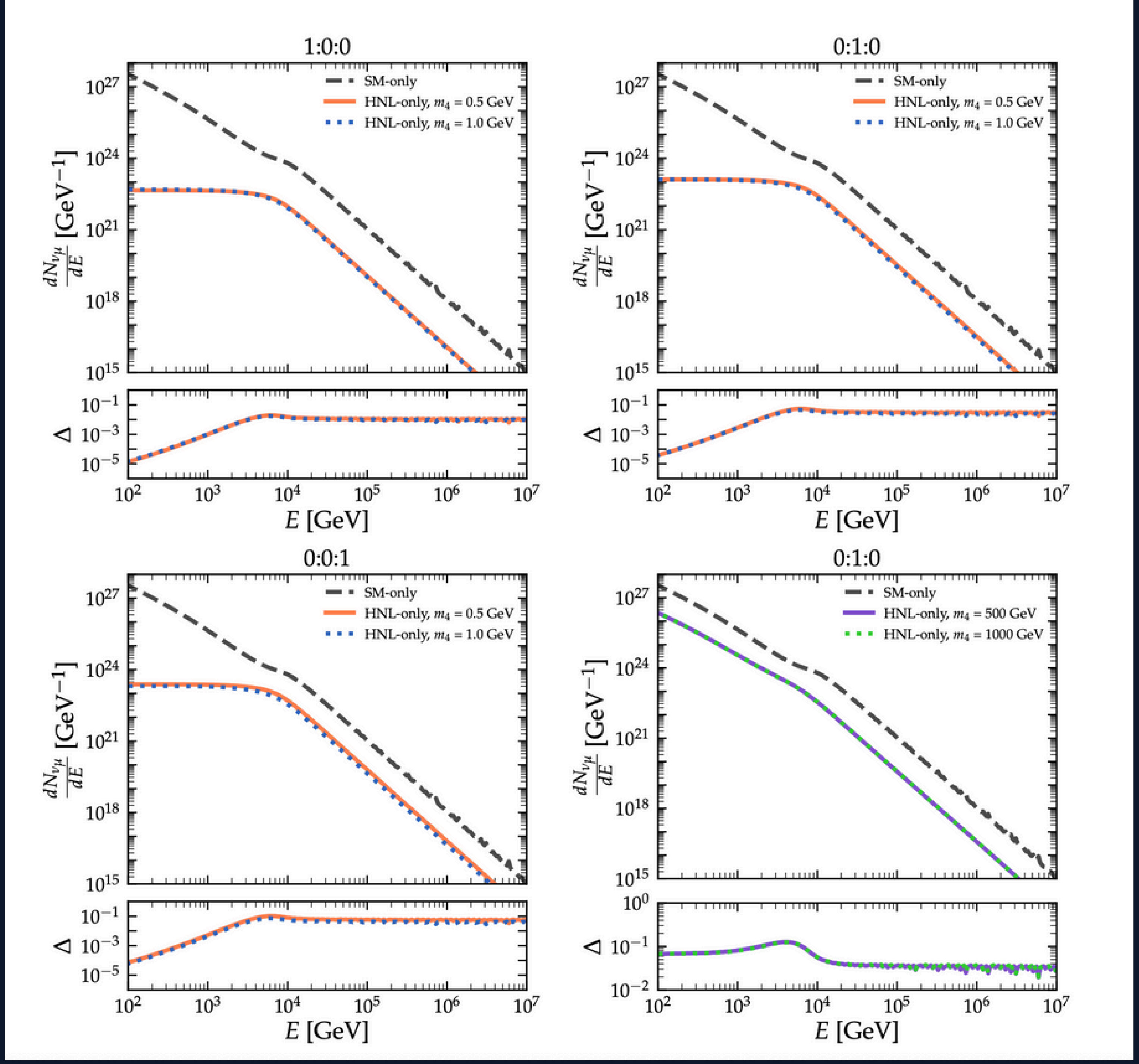
+ charge-conjugated channels

Time-integrated spectra of active neutrinos from an HNL decay:

$$\frac{dN_\alpha}{dE} = \mathcal{B}_a \int d\cos\theta \int_{E_{s,\min}}^{E_{s,\max}} dE_s \frac{1}{\gamma_s (1 + \beta_s \cos\theta)} \frac{dN_s}{dE_s} \mathcal{F}_\alpha \left[\frac{E}{\gamma_s (1 + \beta_s \cos\theta)}, \cos\theta \right] , \quad (20)$$

If only one active neutrino mixes with the HNL, the branching ratio does not depend on the mixing

NEUTRINO SPECTRA FROM HNL DECAYS



Expected muon neutrino spectrum from HNL-only (color) and SM-only (grey) contributions in a 100s PBH burst

Light mass regime:
Angular distributions depend only on the neutrino energy in the HNL rest frame → contribution peaks near the primary bump.

Heavy mass regime:
Angular distributions arise from multiple secondary processes → spectrum resembles the SM-like shape.

PHOTON SPECTRA

[0.1 – 1] GeV

$$\nu_4 \to \pi^0 \nu_\alpha \to \gamma\gamma\nu_\alpha .$$

$$\left.\frac{dN_\gamma}{dE}\right|_{\rm HNL} = 2\int_{E_{\rm min}}^{\infty} dE_{\pi^0} \frac{dN_{\pi^0}}{dE_{\pi^0}} \frac{1}{p_{\pi^0}} ,$$

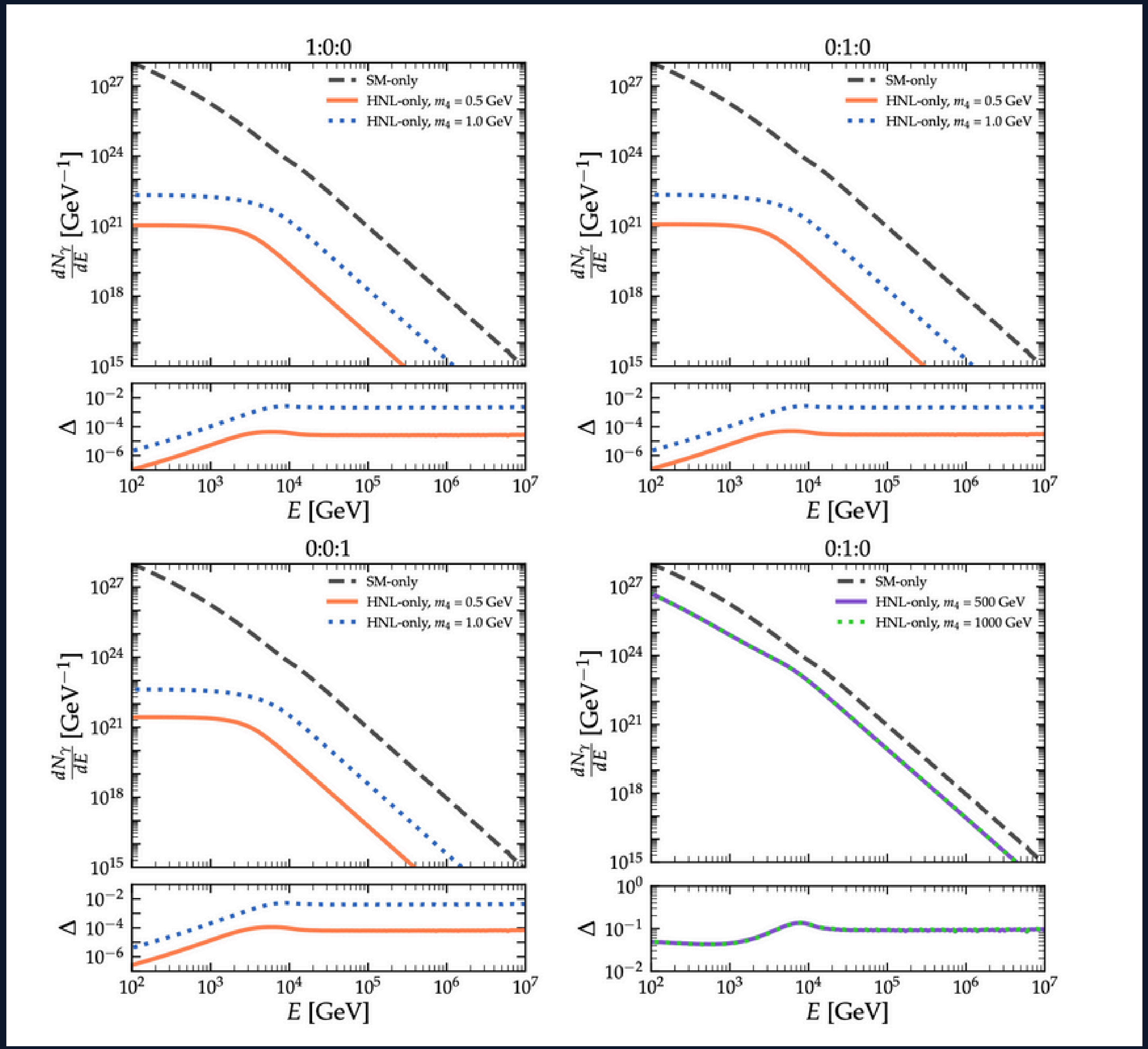
where the pion spectra is

$$\frac{dN_{\pi^0}}{dE} = \frac{1}{2}\mathcal{B}\left(\nu_4 \to \pi^0\nu_\alpha\right) \int dE_s \left(\frac{E\overline{E} - \gamma_s m_{\pi^0}^2}{\gamma_s \beta_s \overline{p}^3}\right) \frac{\overline{p}}{\gamma_s(\overline{p} - \overline{E}) + E} \frac{dN_s}{dE_s} ,$$

[0.5 – 2] TeV

as in the neutrino case

PHOTON SPECTRA



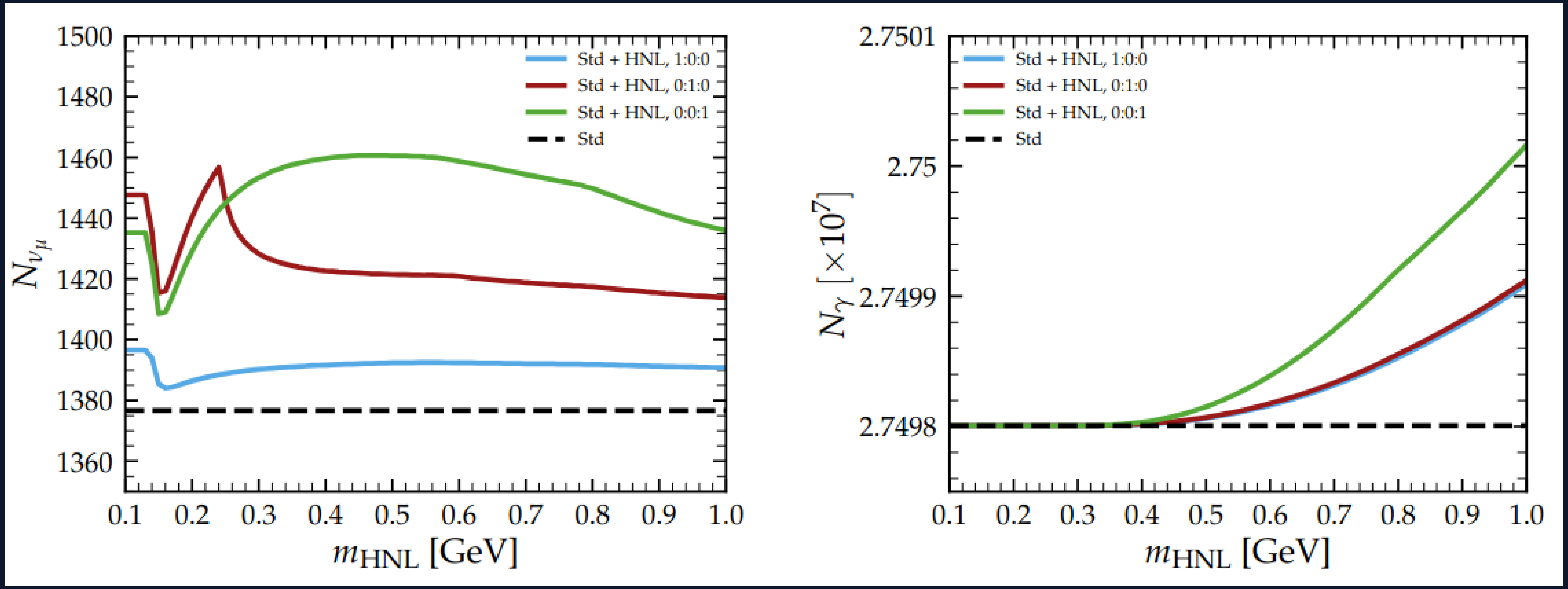
Expected photon neutrino spectrum from HNL-only (color) and SM-only (grey) contributions in a 100s PBH burst

Light mass regime:
As in the neutrino case, the angular distribution of the photons that come from the pion decay only depend on the pion energy distribution, which depends only on its energy in the HNL rest frame.

Heavy mass regime:
As in the neutrino case, the angular distributions arise from multiple secondary processes → SM-like shape.

NUMBER OF EVENTS

[0.1 - 1] GeV regime



Expected muon-neutrino events at IceCube (left panel) and photon events at HAWC (right panel) as a function of the HNL mass. We assume a 100 s burst and a PBH at 0.0001 pc from Earth located in the north emisphere (declination angle [30° < δ < 90°] for IceCube, zenith angles [0° < ζ < 26°] for HAWK).

NUMBER OF EVENTS

[0.5 - 2] TeV regime

We predict around 1470 neutrino events from both SM and HNL decays, independently of the HNL mass

In the same way, we predict 2.87×10^7 events at HAWK regardless of the HNL mass

ANALYSIS

To estimate the combined sensitivity at IceCube and HAWC we rely on the χ2 test statistics

$$\chi^2\left(d_{\rm PBH}, m_4\right) = \min_\alpha \left\{ \frac{\left[N_\gamma^{\rm SM+HNL}(m_4, d_{\rm PBH}(1+\alpha)) - N_\gamma^{\rm SM}(d_{\rm PBH})\right]^2}{\sigma_\gamma^2} + \frac{\left[N_{\nu_\mu}^{\rm SM+HNL}(m_4, d_{\rm PBH}(1+\alpha)) - N_{\nu_\mu}^{\rm SM}(d_{\rm PBH})\right]^2}{\sigma_{\nu_\mu}^2} \right\}, \tag{49}$$

that we minimize over the nuisance parameter α

We find α 10^{-7} - 10^{-5} in the light-mass regime, α 10^{-2} in the high-mass regime