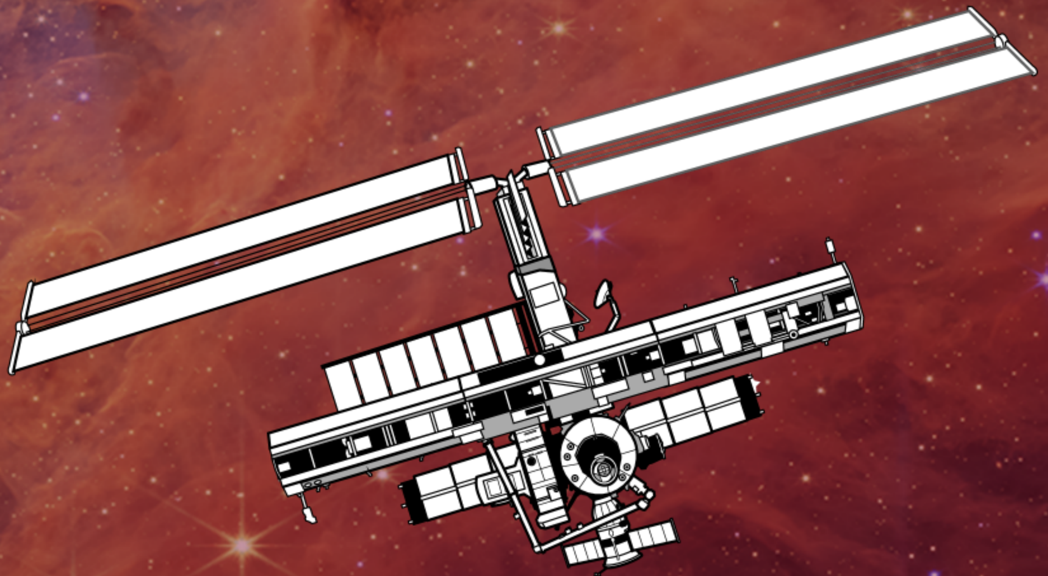
PBH PROBES OF HNLS

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

Agnese Tolino

IFIC (CSIC-UV)

September 26th, 2024



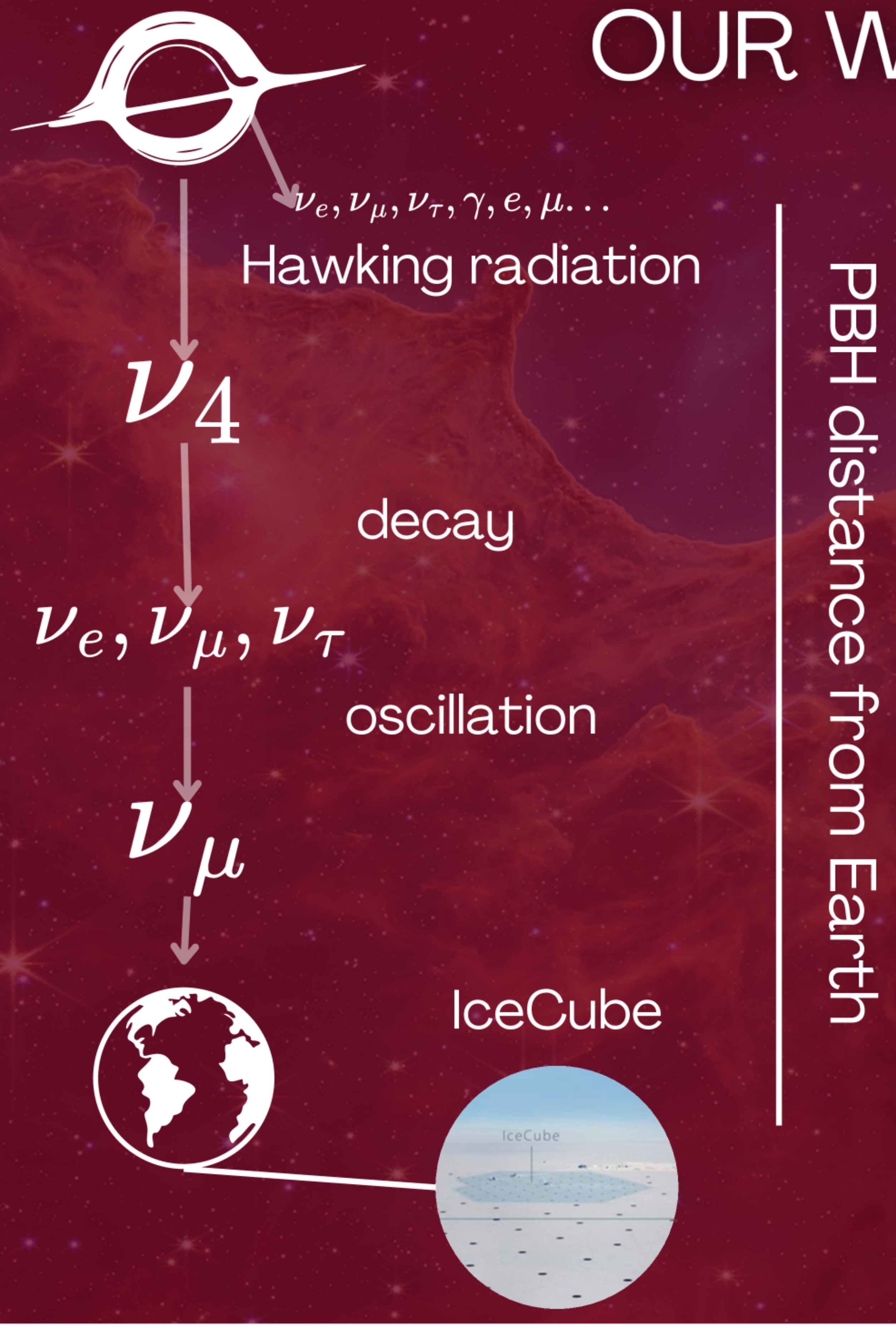
ISAPP School Neutrinos and Dark Matter

OUR WORK … ACCORDING TO CHAT GPT

Generate the following image: "Primordial black hole emitting sterile neutrinos that later decay in muon neutrinos and give a sizeable signature at IceCube"

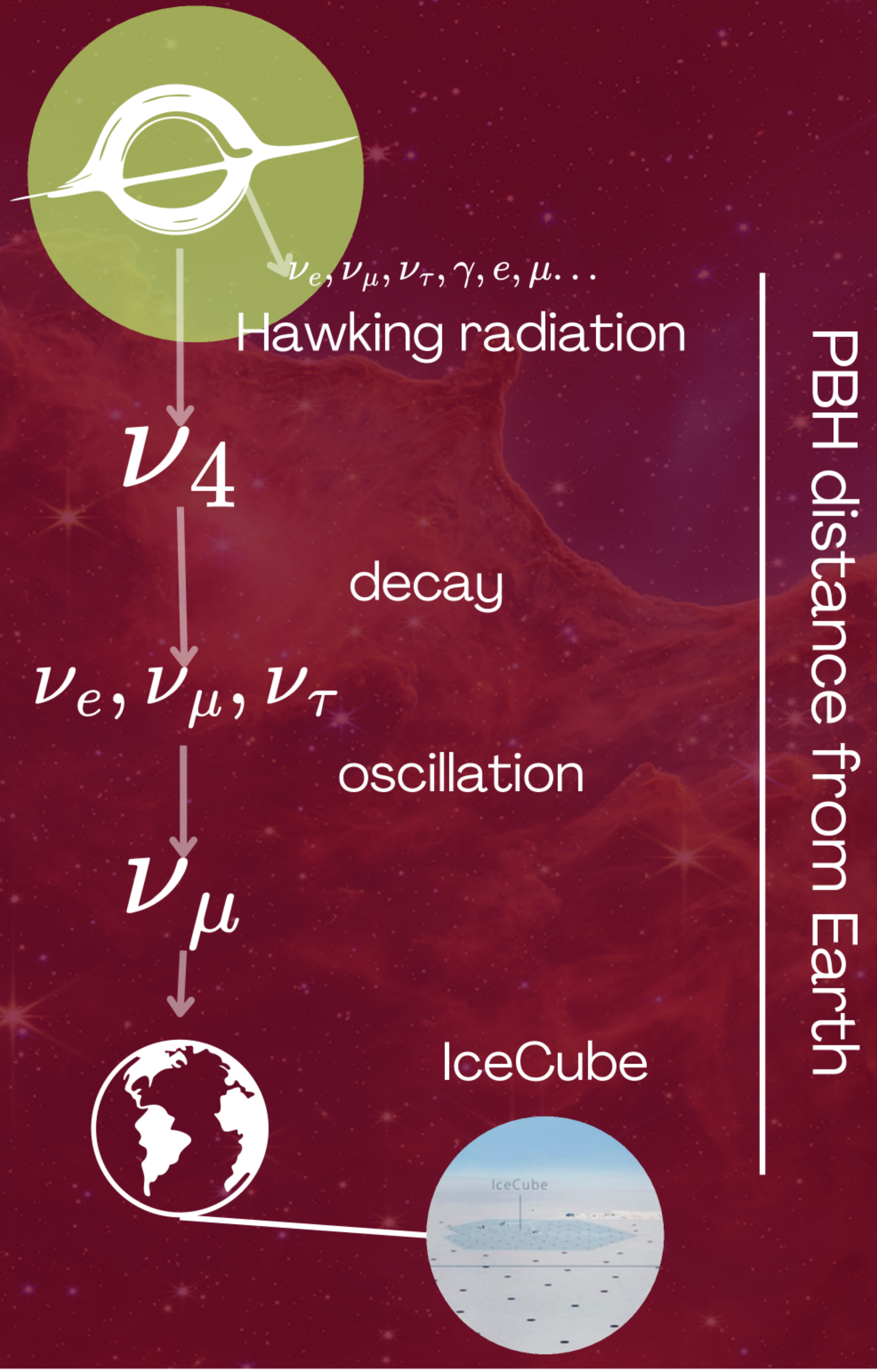
Credit: OpenAI

OUR WORK…ACCORDING TO US



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

IDENTIKIT OF PBHS



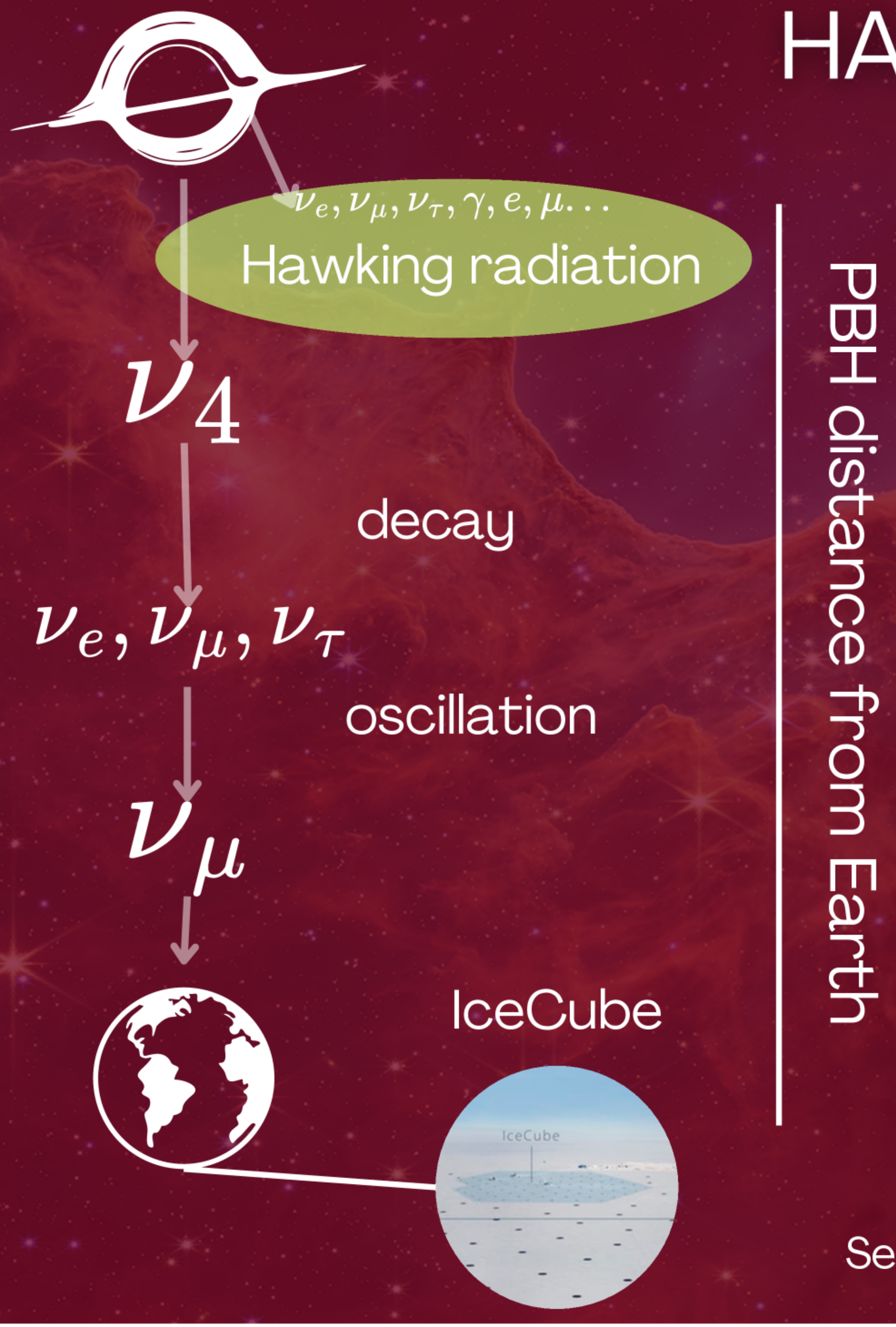
- Might have formed in the Early Universe by the collapse of fluctuations
- Uniquely described by mass, charge and angular momentum
- Masses span from 10^{-5} g to $10^{5} M_\odot$

$$M_{\rm PBH}^{\rm in} = 2 \times 10^{5} \gamma \frac{t}{1s} M_\odot$$

See also lecture from Cirellii

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 BHs **evaporate** with a temperature

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

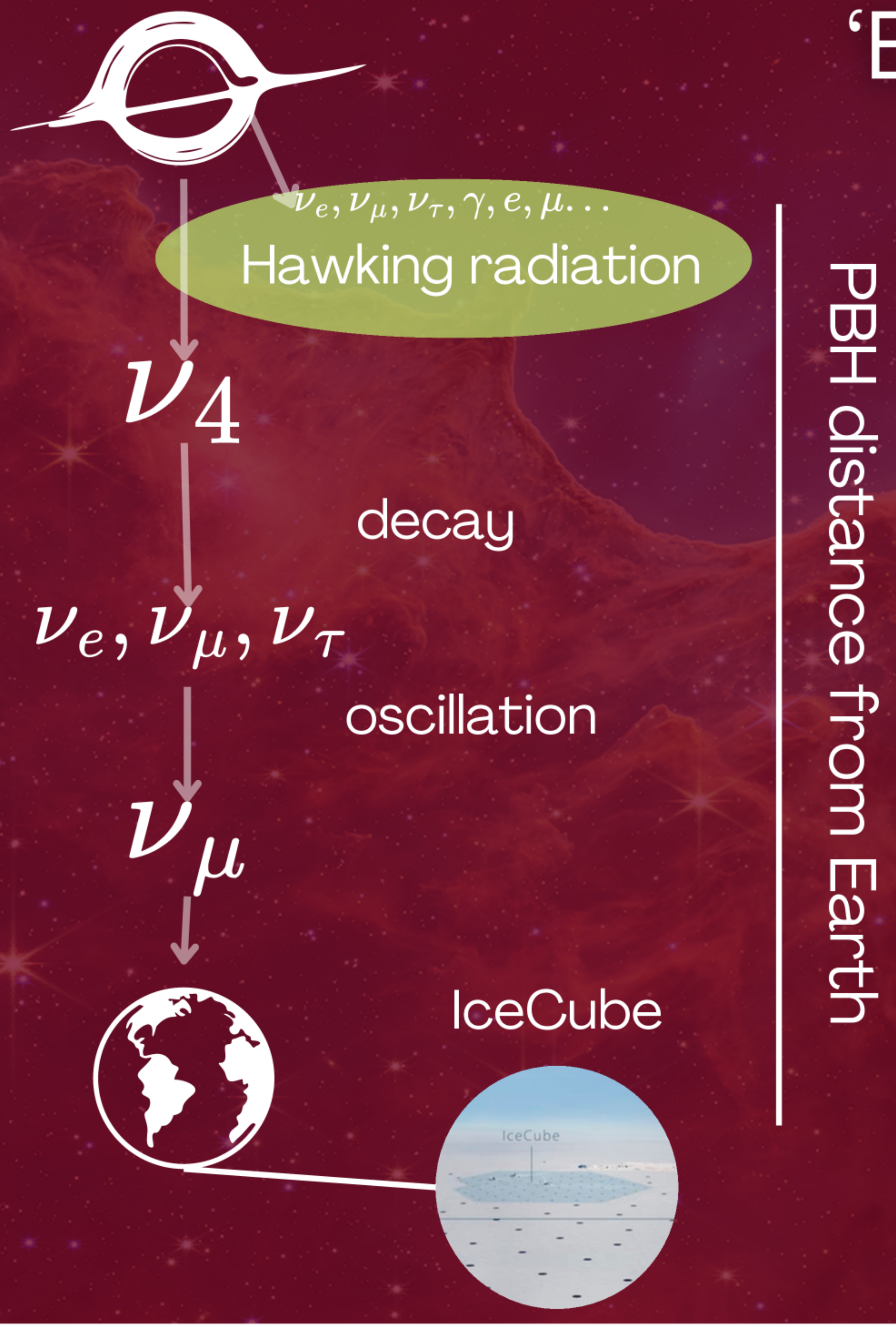
- Mass loss goes as $\frac{dM}{dt} \sim M_{\rm PBH}^{-2}$
- The evaporation corresponds to the emission of particles with a thermal spectrum

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

See also lectures from Cirelli & Pueschel

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 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 $M_{\rm PBH}^{\rm in} \sim 10^{15}{\rm g}$ exploding in a **100s burst**

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
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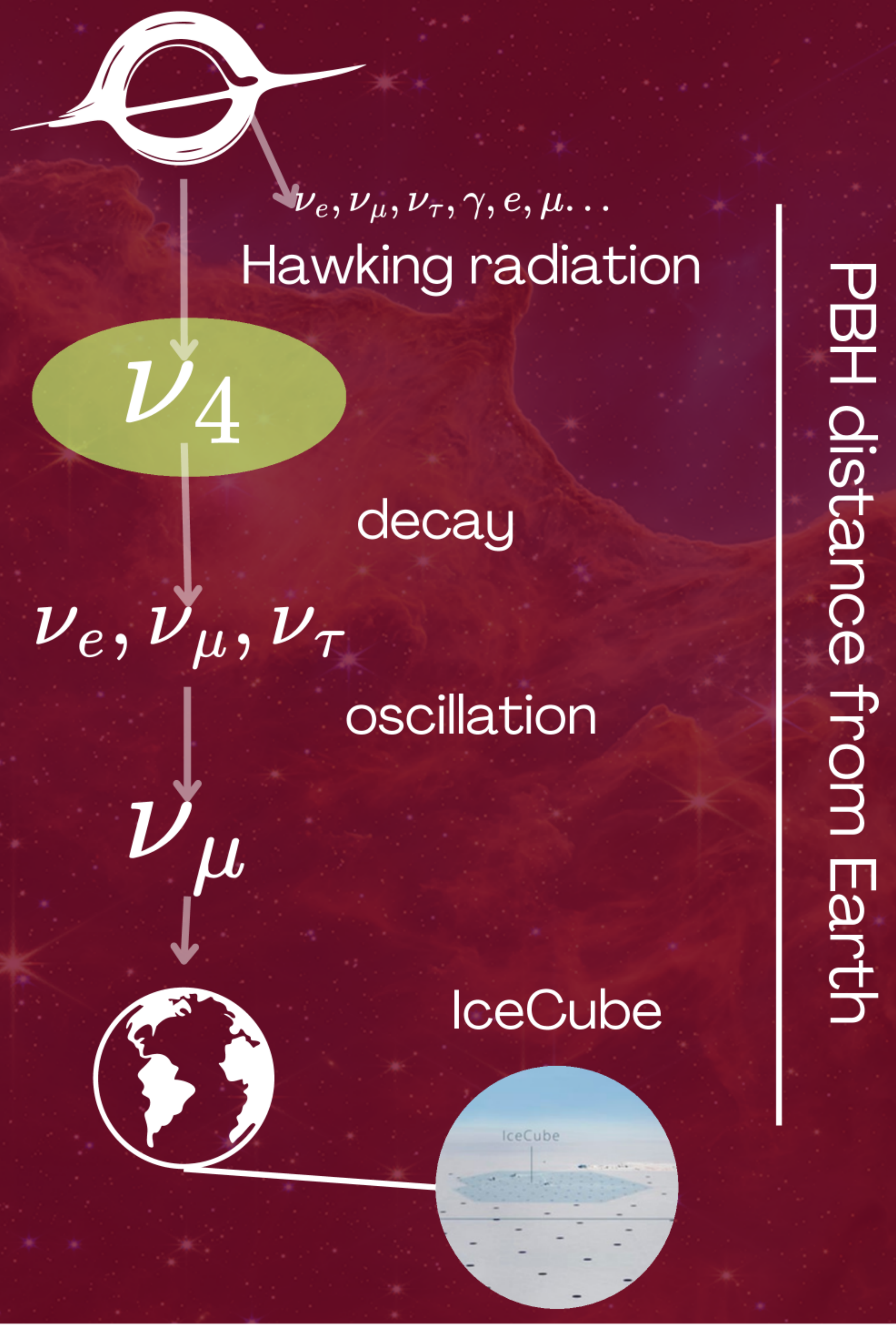
HNLS



- 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:

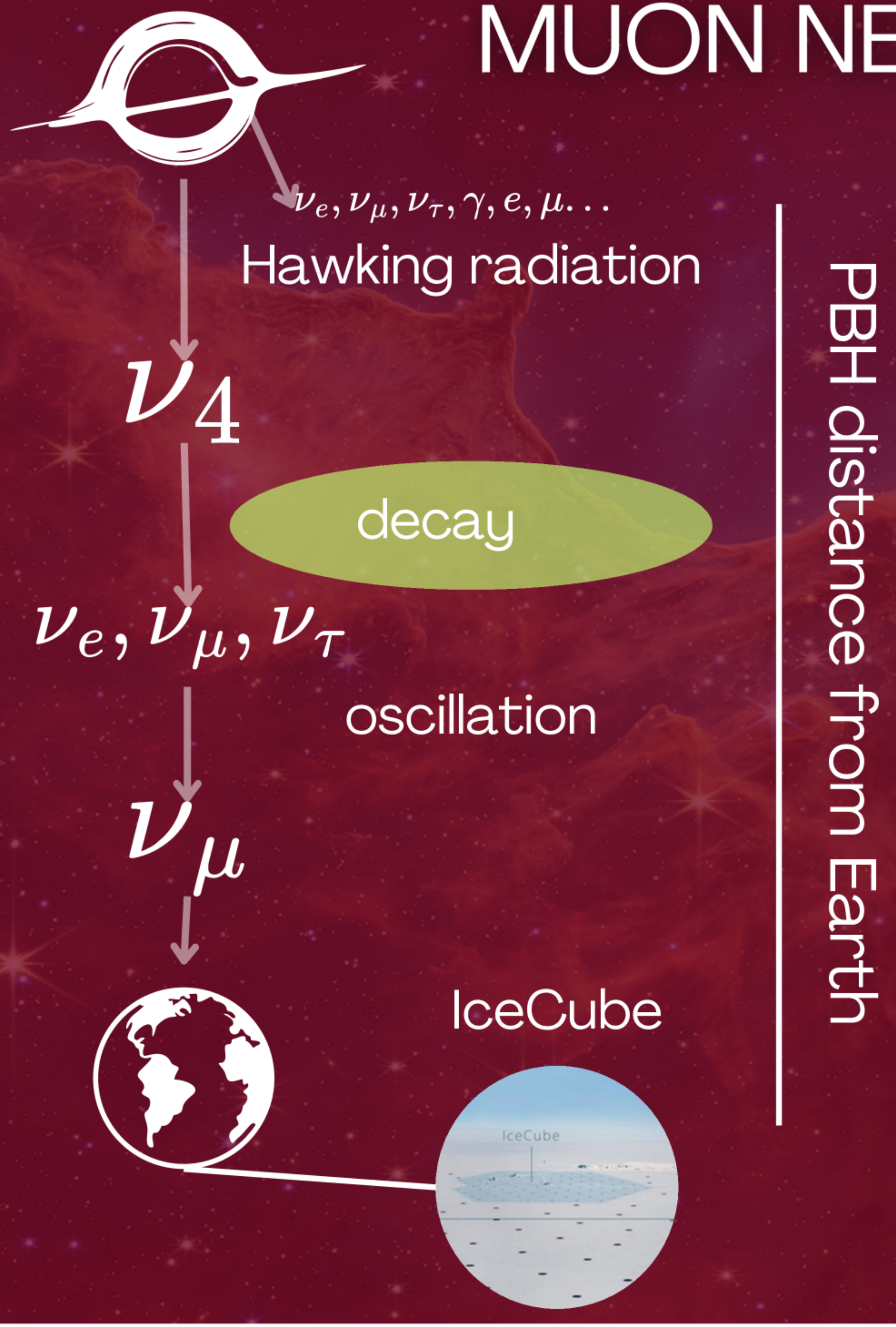
$$|U_{\alpha 4}|^2 \neq 0$$

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

See Kopp & Lasserre lectures

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

MUON NEUTRINO SIGNAL FROM PBHS



Depending on the mass, HNLs decay in different channels:

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

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:2312.1362

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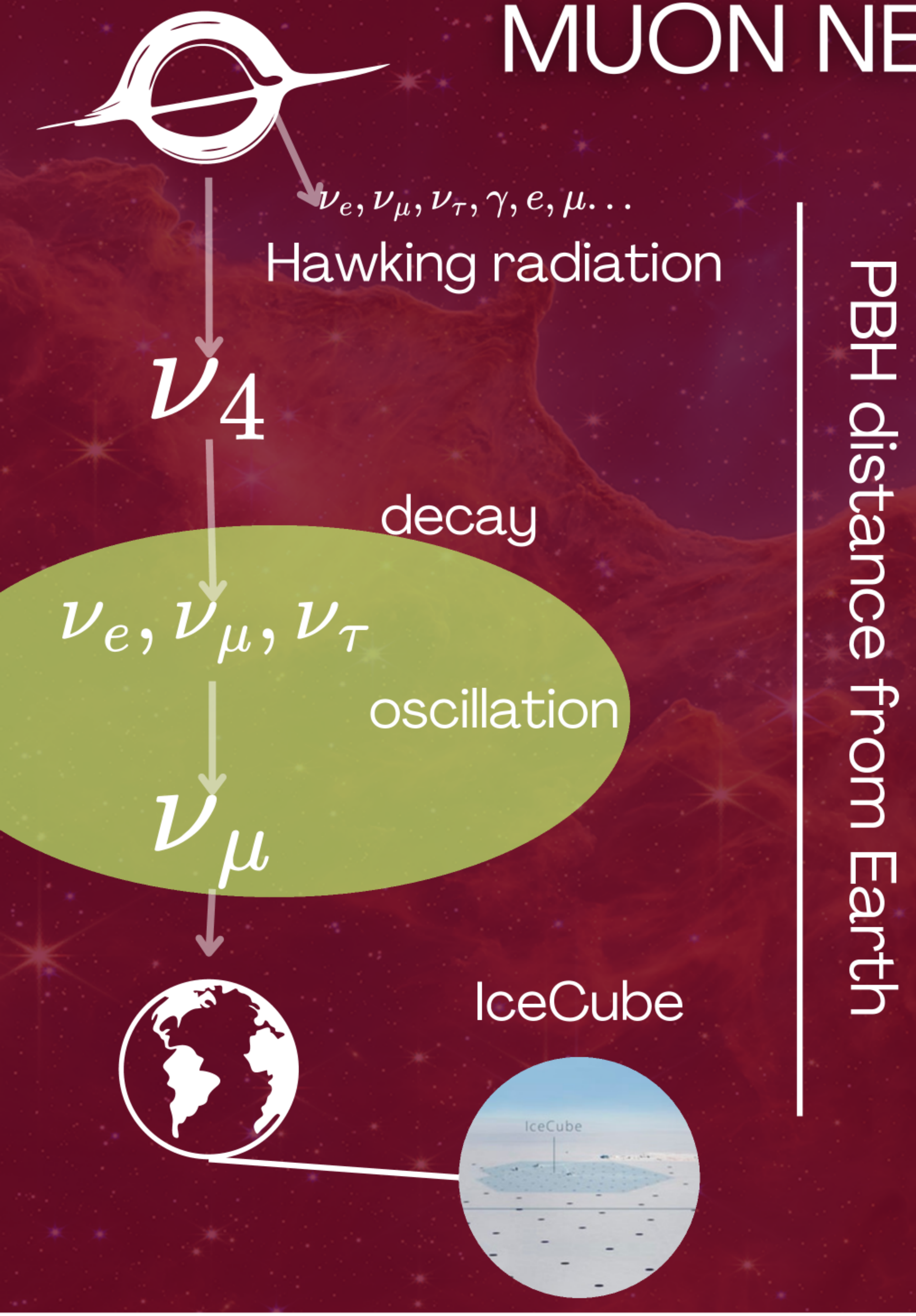

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The active neutrinos oscillate into muon neutrinos

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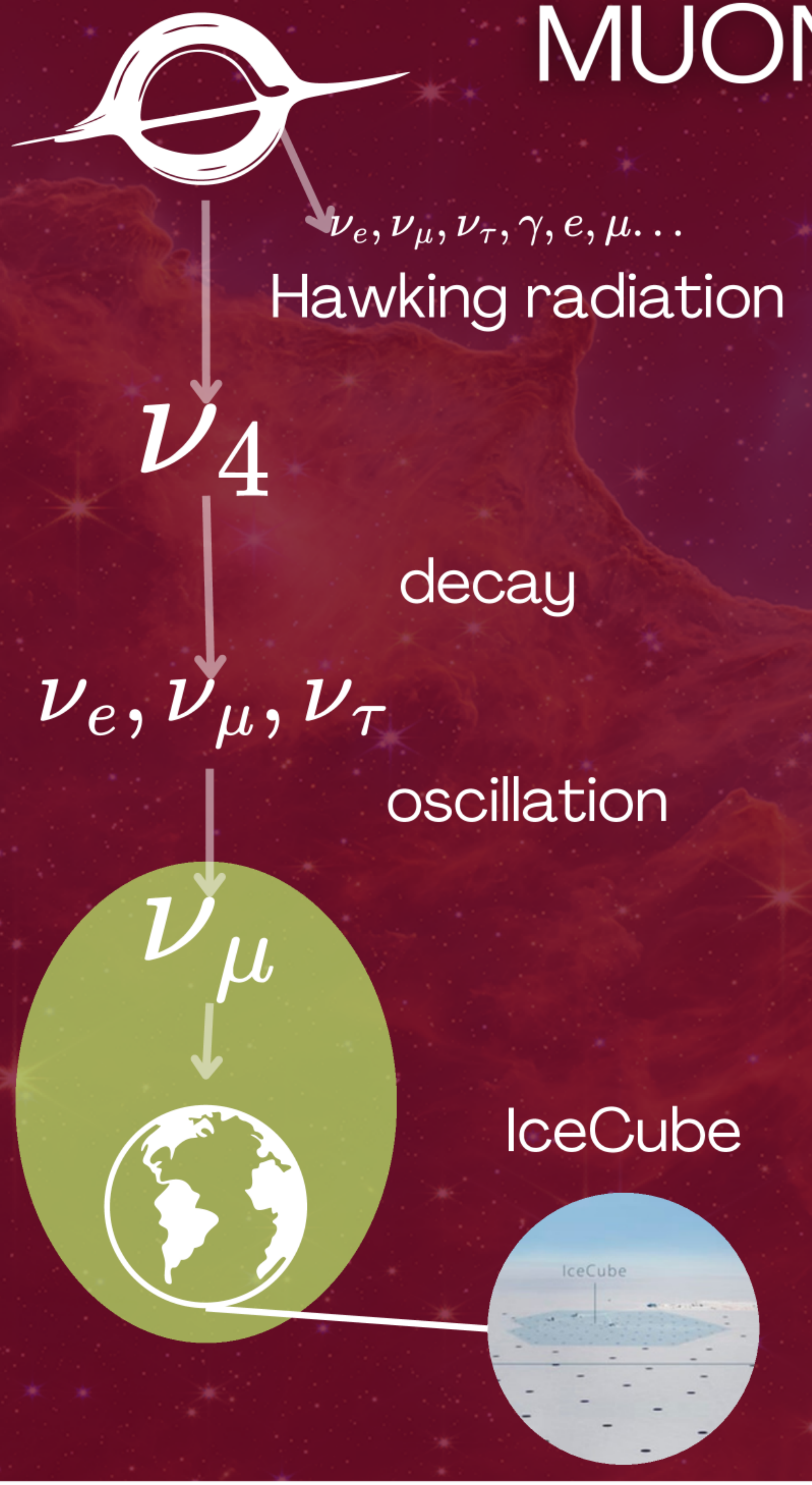

PBH distance from Earth

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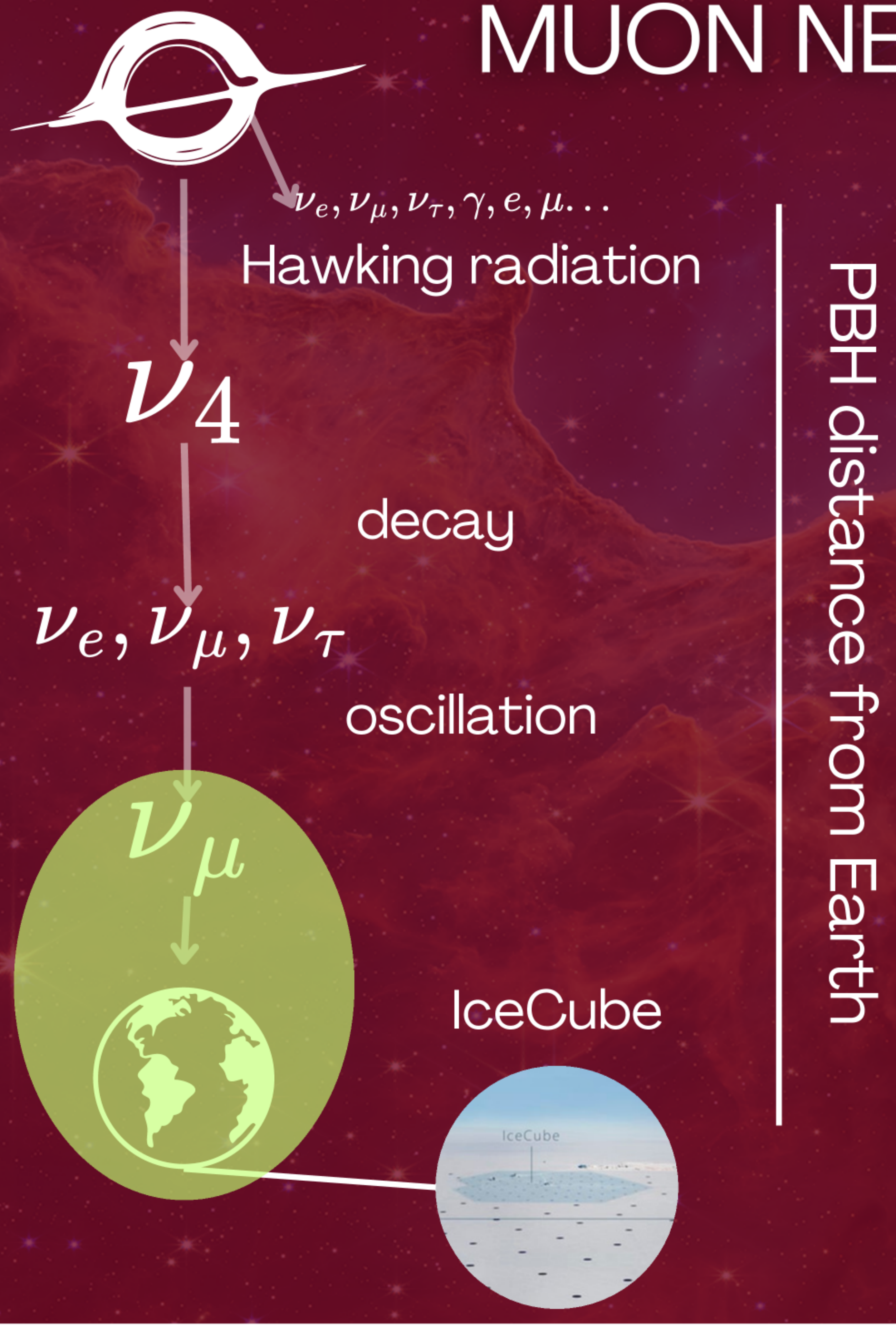
The active neutrinos oscillate into muon neutrinos

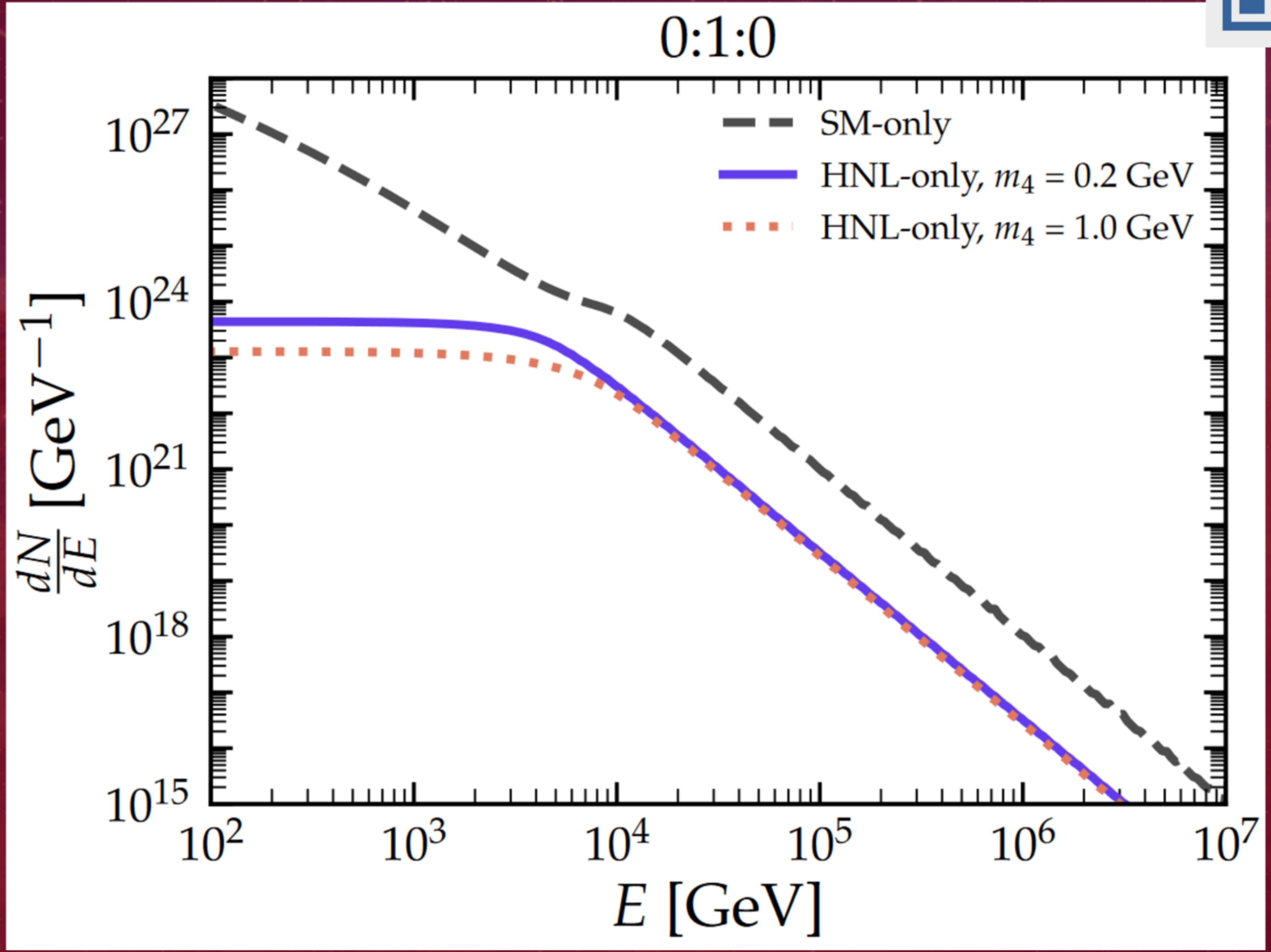
Overall neutrino spectrum at Earth from a 100s PBH burst:

- SM contributions (primary & secondary)
- HNL decay

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

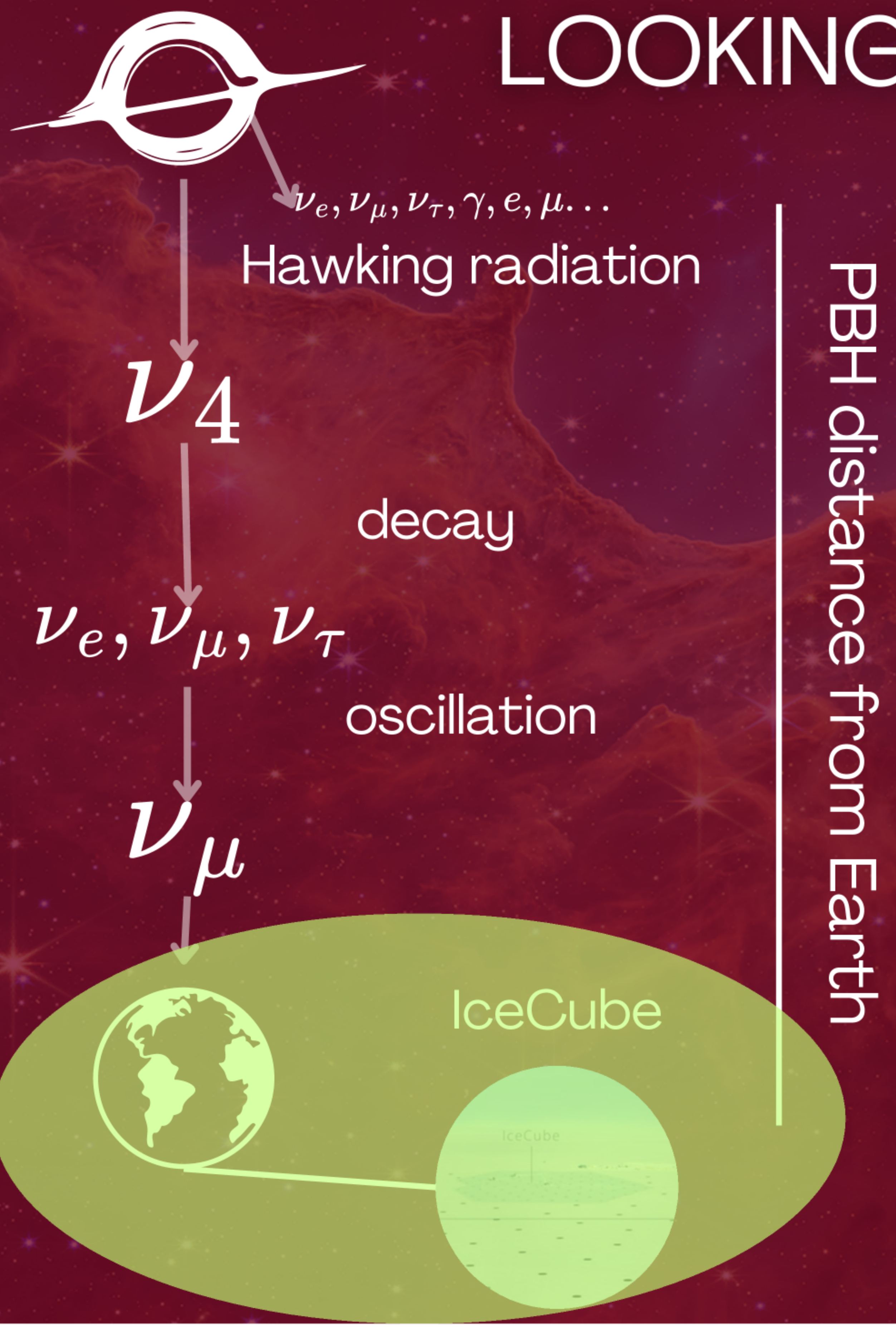
MUON NEUTRINO SIGNAL FROM PBHS





Example of the expected muon neutrino spectrum from HNL decay (color) and SM-only contributions in a 100s PBH burst

LOOKING FOR HNL SIGNATURES AT ICECUBE



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

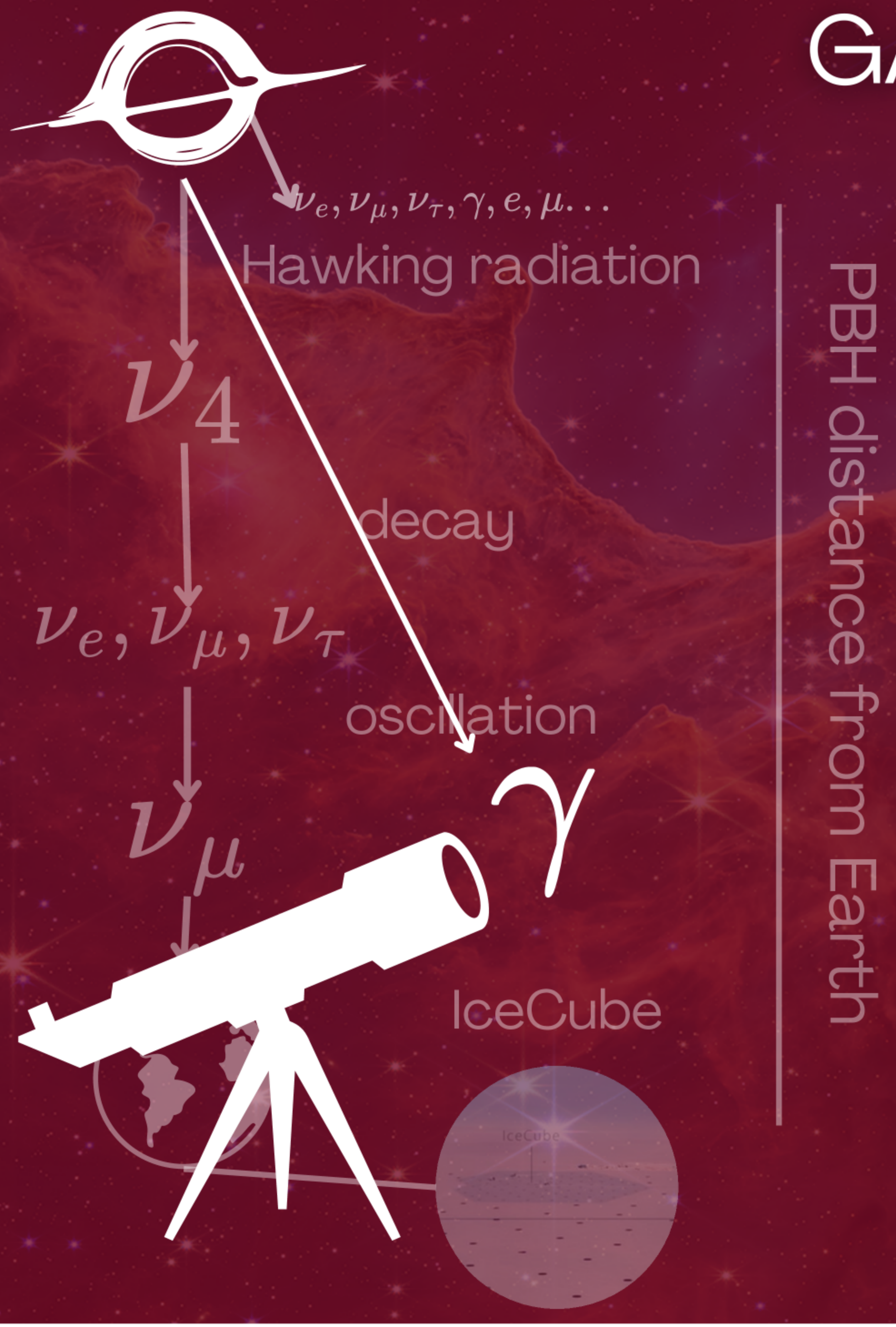
100 GeV - 100 PeV

Signature: excess of muon neutrinos at IceCube due to HNL decay!

See also lectures from Franckowiak on IceCube

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

GAMMA-RAY CONSTRAINTS



- Photons are a smoking gun of PBH burst
- PBH at max 1 pc from us: compatible with **constraints from gamma-ray bursts searches** (strongest: H.E.S.S.) and **overdensities**

See also lectures from Pueschel on gamma-ray constraints

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

ANALYSIS SCHEME

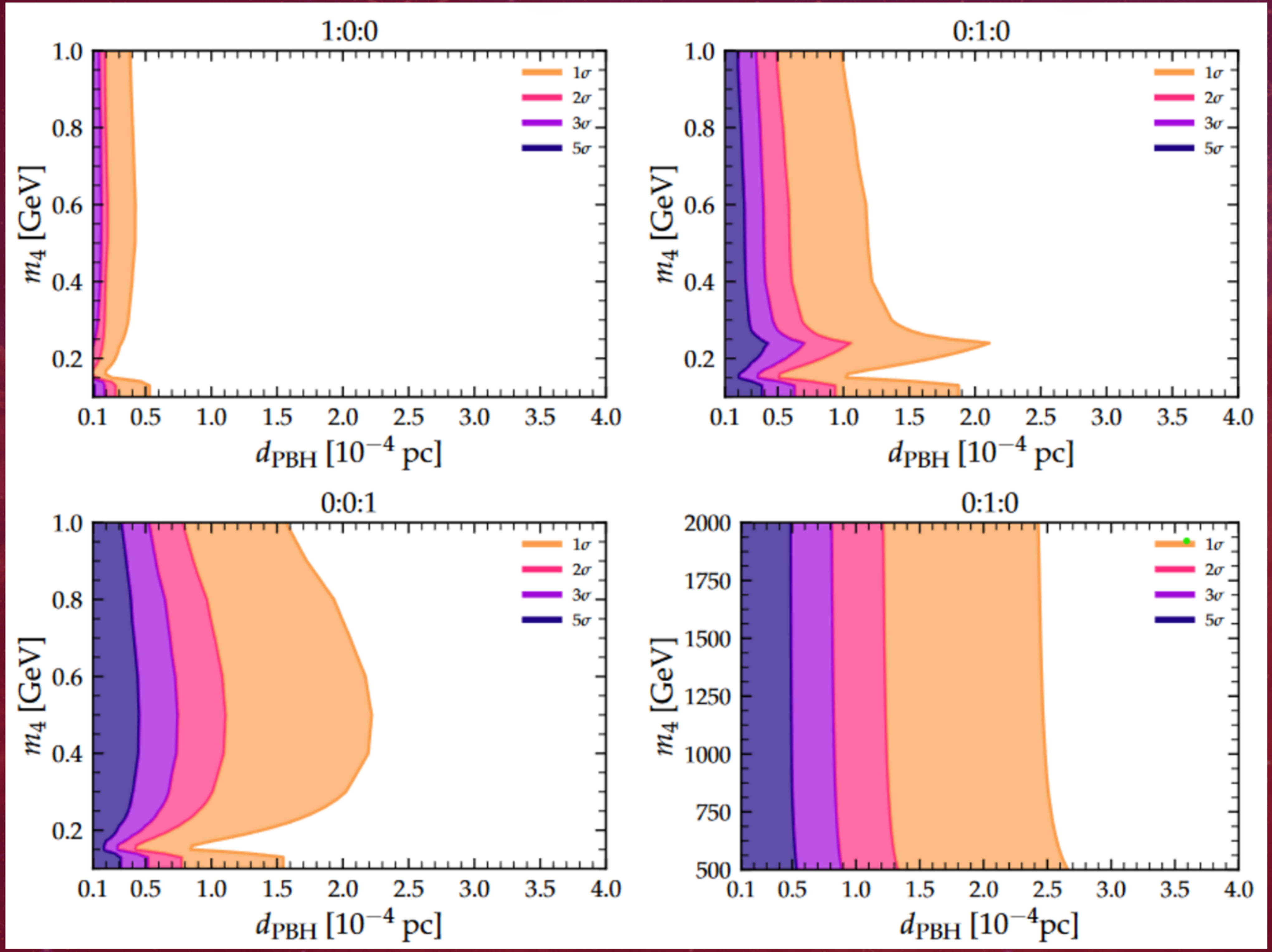
1

Evaluated the expected number of muon ν at IceCube (from northern emisphere) emitted in a **100s PBH burst** considering both **HNL + SM contributions**

2

Estimated the **IceCube sensitivities** to HNL decays with a simple χ2 analysis

RESULTS (A SELECTION)

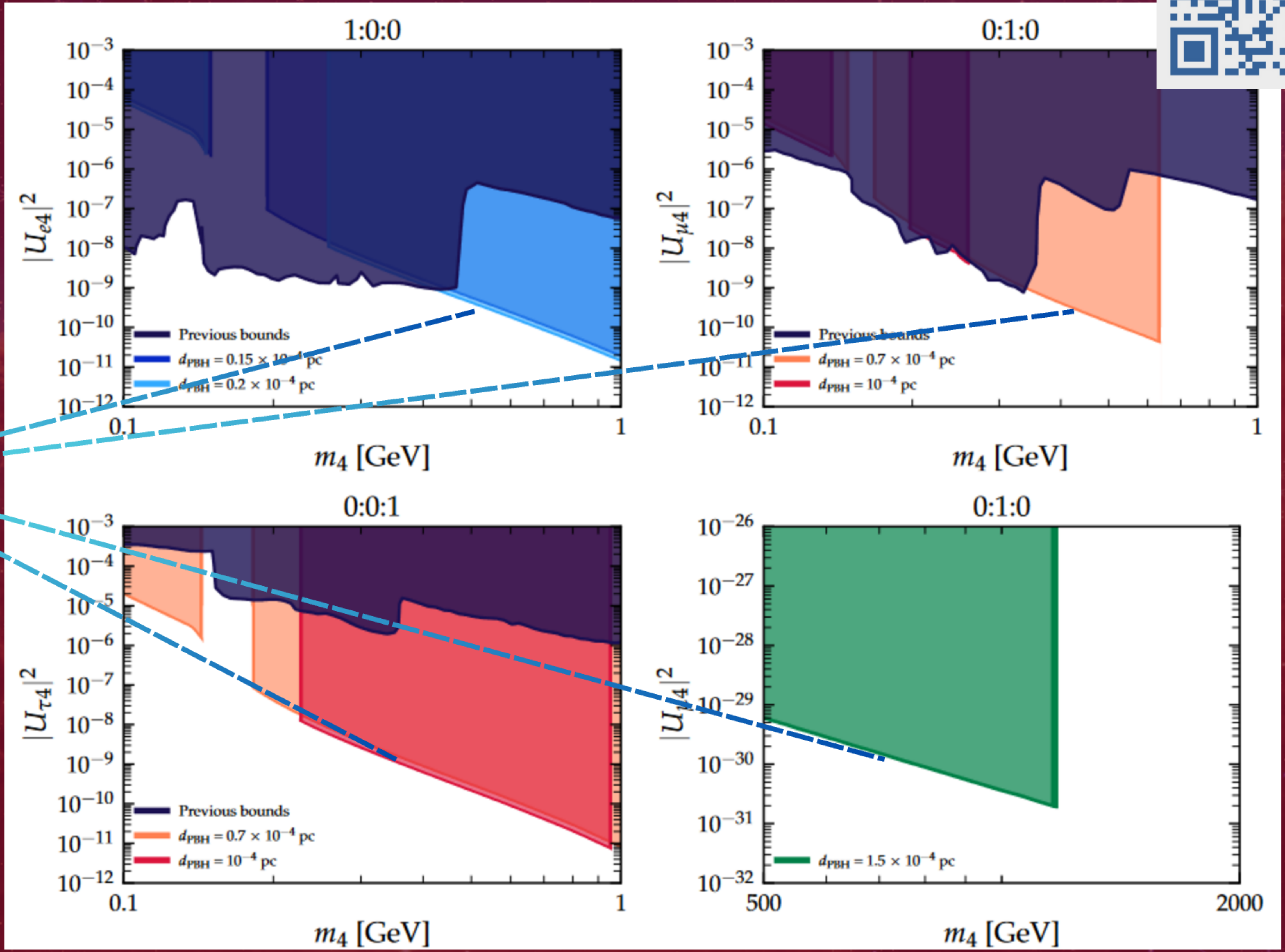


IceCube sensitivity to HNLs from a PBH burst lasting 100s

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

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

Expected IceCube sensitivity at 90% CL for a 100s PBH burst



CONCLUSION

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

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

We found that

- the HNL mass [0.1-1] GeV range could be proved at IceCube if $d_{\rm PBH} \leq 10^{-4}{\rm pc}$ for HNL mixings 0:1:0 and 0:0:1
- the [0.5-2] TeV range even at $d_{\rm PBH} \leq 2.5 \times 10^{-4}{\rm pc}$ for 0:1:0

IceCube would be able to set stringent constraints on HNL mixing and mass!

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