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Primordial black hole probes of heavy neutral leptons

Based on 2405.00124 with A. Tolino and Y. F. Perez-Gonzalez

DSU 2024
Corfu (Greece)
11 September 2024

OUTLINE

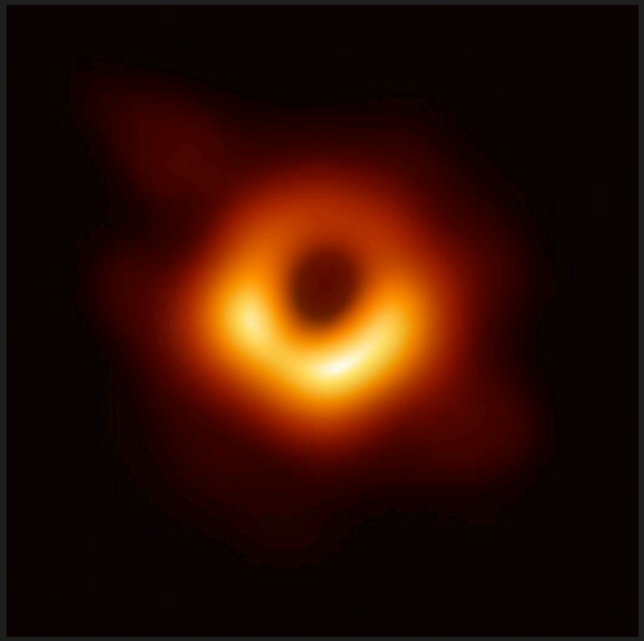
- Primordial black holes: introduction
  - Hawking evaporation
  - PBH explosions
- Exploding PBH signatures: active neutrinos
- BSM case: heavy neutral leptons
  - Theoretical motivation
- Exploding PBH signatures: HNLs
- IceCube sensitivity
- Conclusions

Primordial black holes (PBHs)

Astrophysical black holes

- stellar black holes, relics of massive stars spread throughout galaxies or
- massive black holes inhabiting galaxy centers

Volonteri et al Nature Reviews Physics, Volume 3, Issue 11



Credit: EHT Collaboration

$$M_{\rm ABH} \gtrsim \text{a few } M_\odot$$

Credit: NASA/ESA and G. Bacon (STScI)

Primordial black holes may have formed from the collapse of primordial inhomogeneities in the early Universe, before the BBN epoch.

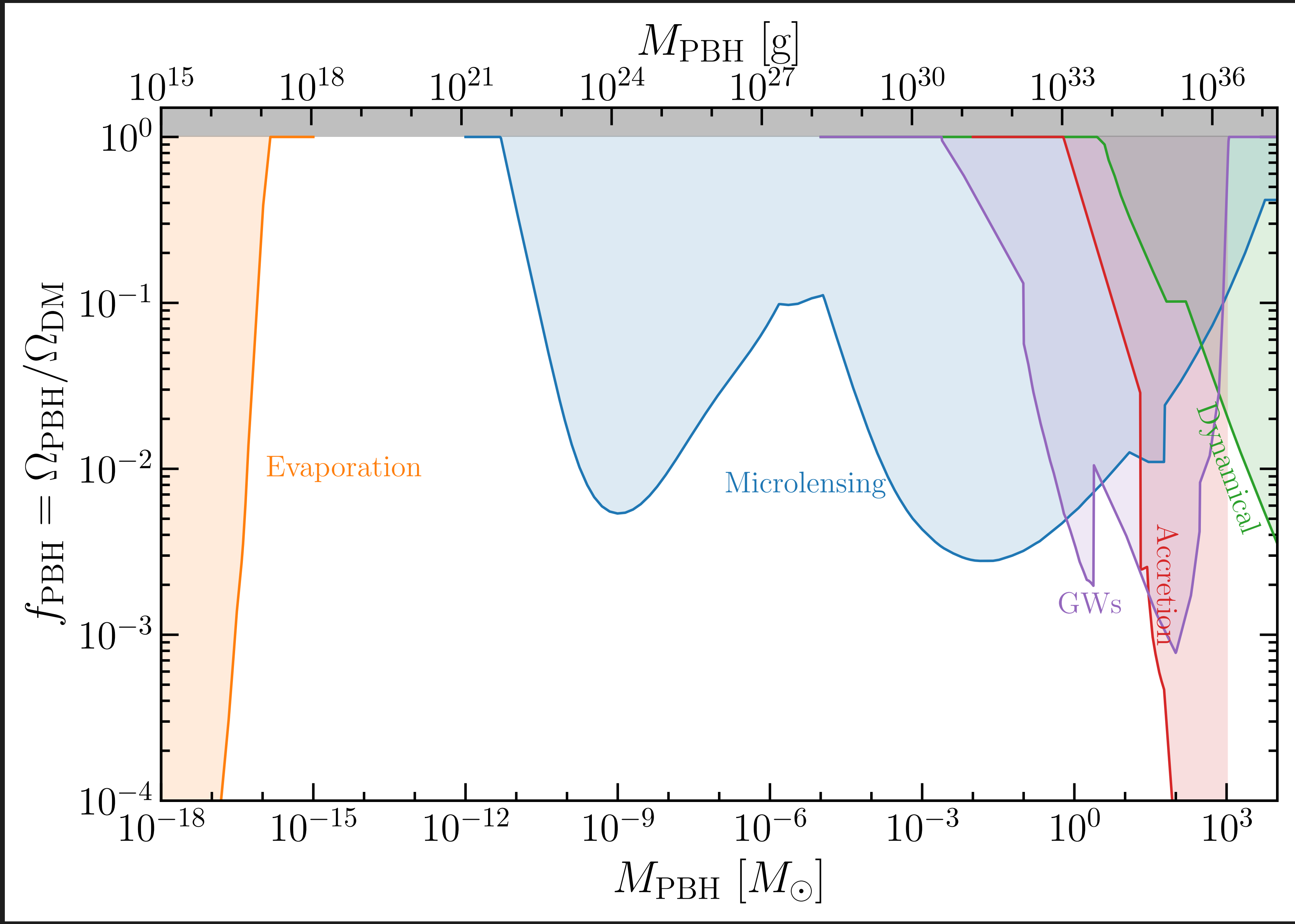
$$M_{\rm PBH} > M_{\rm Planck}$$

Y. B. Zel'dovich and I. D. Novikov, Sov. Astron. 10, 602 (1967)
S. Hawking, MNRAS 152, 75 (1971)

PBHs as dark matter

PBHs constitute one of the earliest proposed and appealing DM candidates.

Hawking (1971), Chapline (1975)



B. J. Kavanagh, “PBH bounds.” https://github.com/bradkav/PBHbounds

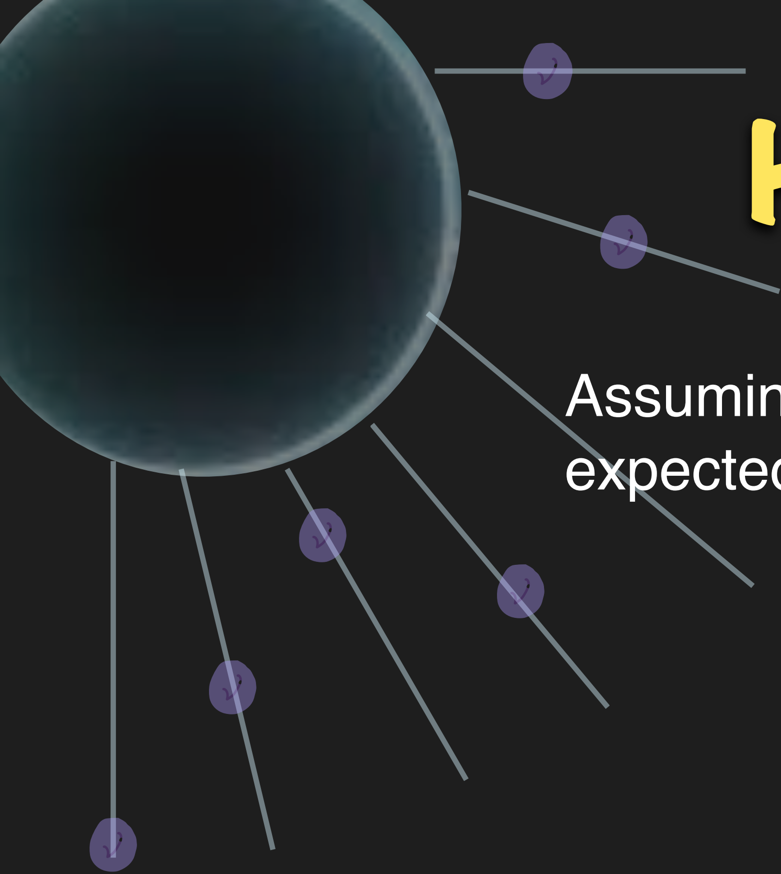
Hawking evaporation

Assuming a semi-classical picture, Hawking showed that a black hole is expected to radiate fundamental particle species at an emission rate of

$$\frac{d^2N_i}{dEdt} = \frac{\Gamma_i(M,E)/2\pi}{e^{8\pi GME} - (-1)^{2s}} n_i$$

(Natural units!)

S.W. Hawking. Nature 248, 30-31 (1974)
S. W. Hawking, Commun. math. Phys., vol. 43, pp. 199–220, 1975



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(Natural units!)

PBH evaporation timescale: $\tau(M) \sim \frac{\hbar c^4}{G^2M^3} \sim 10^{64} \left(\frac{M}{M_\odot}\right)^3 \text{yr}$

PBHs with initial mass M $\sim 10^{15}$g, which formed at 10^{-23}s and had the size of a proton, would be evaporating now.

Evaporation would be suppressed for PBHs heavier than the Earth, ~10^{24}g: they would be cooler than the CMB and so would accrete rather than evaporate.

Hawking evaporation

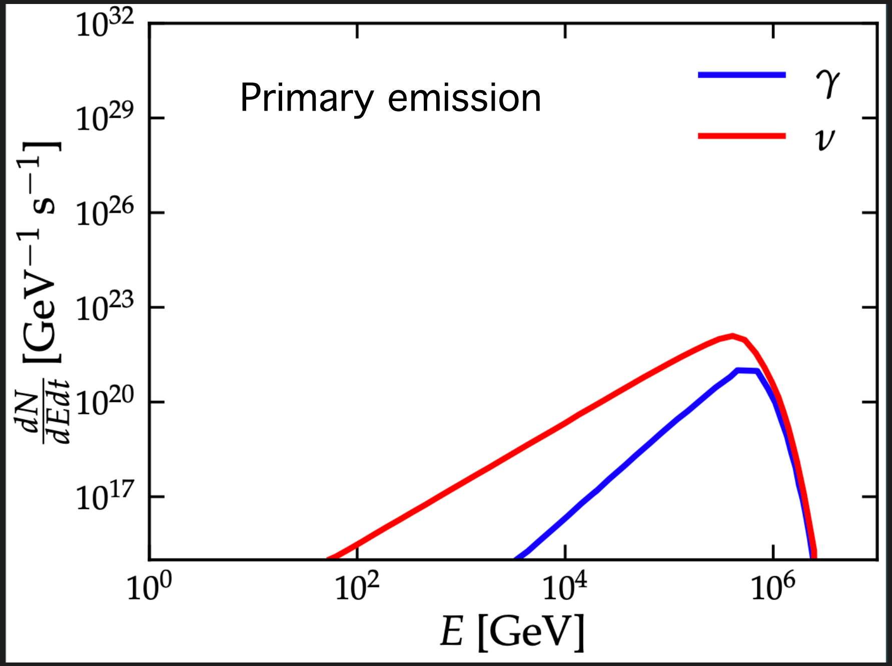
The particle emission rate depends on the black hole instantaneous properties: mass M_{BH}, angular momentum J and charge Q.
Q and J are expected to be depleted in a faster rate than the mass.
PBH reaching the final stages of their lifetime can described uniquely by M.

The emission is approximately black-body, with a temperature that is inversely proportional to the black hole's mass

$$T = \frac{1}{8\pi GM} \sim 1\,\mathrm{TeV}\left(\frac{10^{10}\mathrm{g}}{M}\right)$$

S.W. Hawking. Nature 248, 30-31 (1974)
S. W. Hawking, Commun. math. Phys., vol. 43,1975

The emission of dofs with masses > T is Boltzmann-suppressed.



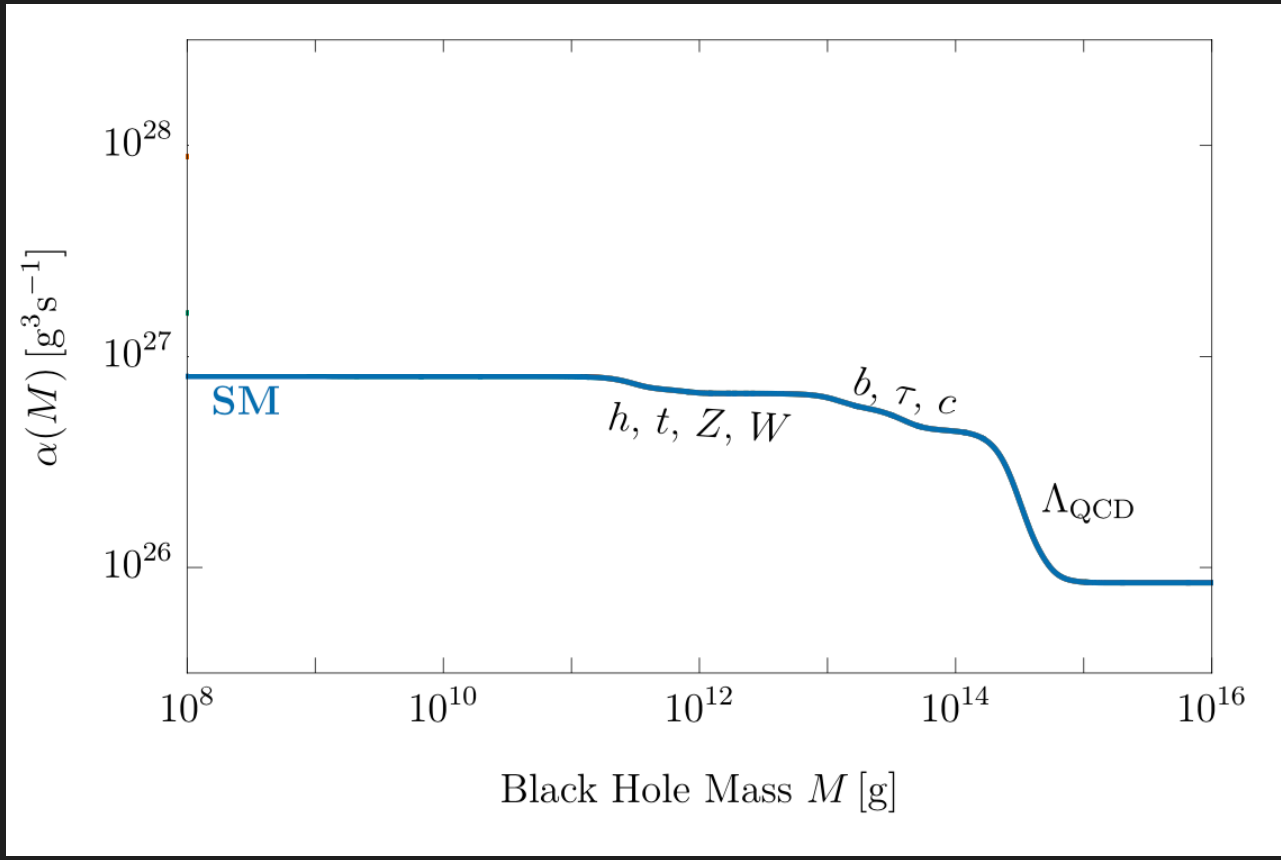
Hawking evaporation

The PBH mass loss rate: $\frac{dM}{dt} = -\frac{\alpha(M)}{M^2}$

D.N. Page, PRD 13 (1976) 198

$$\alpha(M) = M^2 \sum_{i=\text{dofs}} \int_0^\infty \frac{d^2 N_i}{dt dE}(M,E) E dE \qquad x = \frac{E}{T}$$

J. H. MacGibbon+ Phys. Rev. D 41 (1990) 3052–3079
J. H. MacGibbon Phys. Rev. D 44 (1991) 376–392

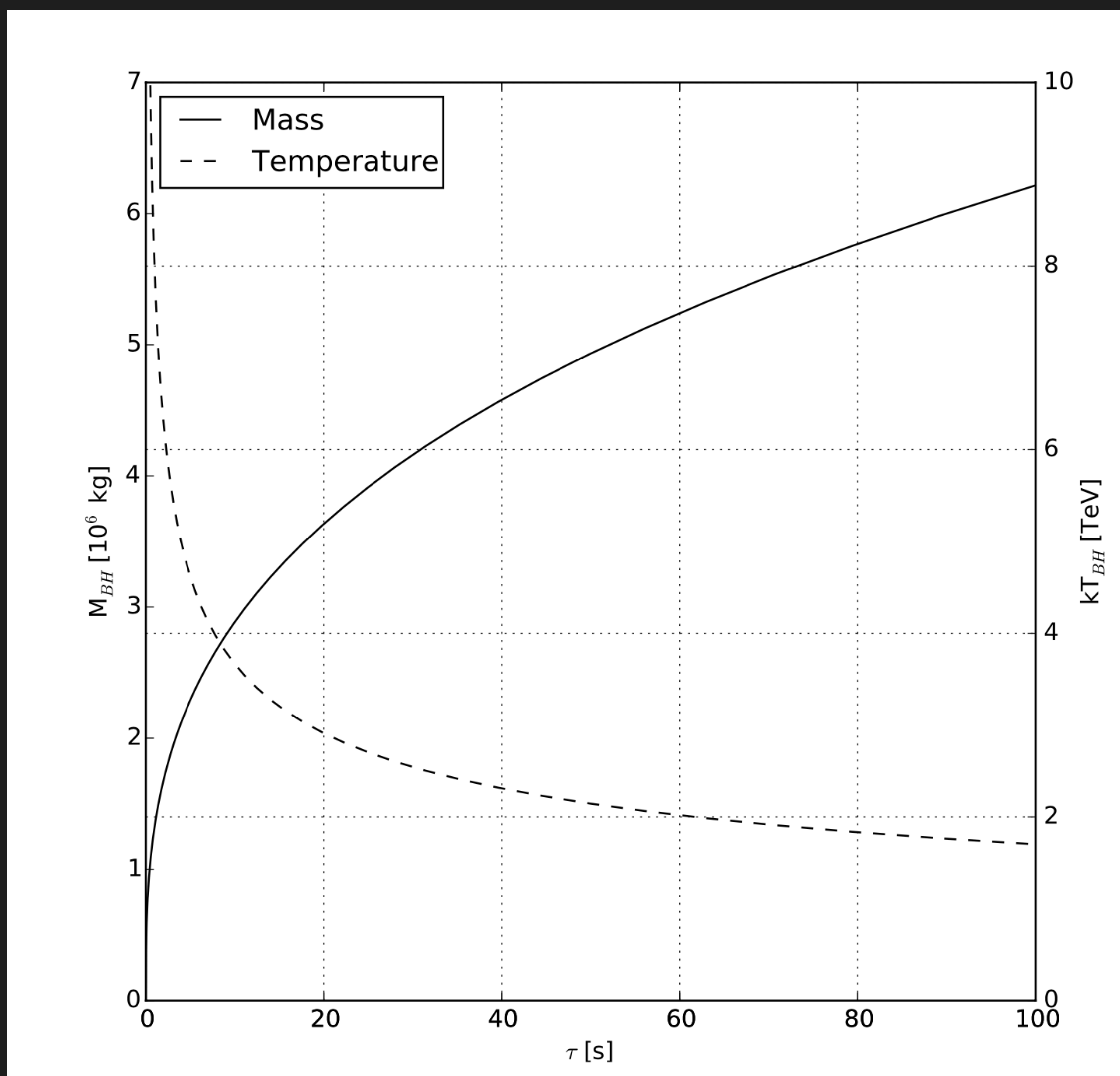


M. J. Baker and A. Thamm SciPost Phys. 12 no. 5, (2022) 150

- α(M) is independent of the particle's non-gravitational interaction strengths.
- Not affected by BSM unless MANY dofs are present.

PBH explosions

When the temperature rises above a particle mass threshold, it can be emitted in evaporation. The black hole loses mass at a faster rate, and the temperature increases at a quicker rate.



Ukwatta+ Astropart. Phys. 80 (2016) 90–114

The evaporation final stage would resemble an explosion emitting a burst of particles (SM and BSM).

Black hole explosions?
S.W. Hawking. Nature 248, 30-31 (1974)

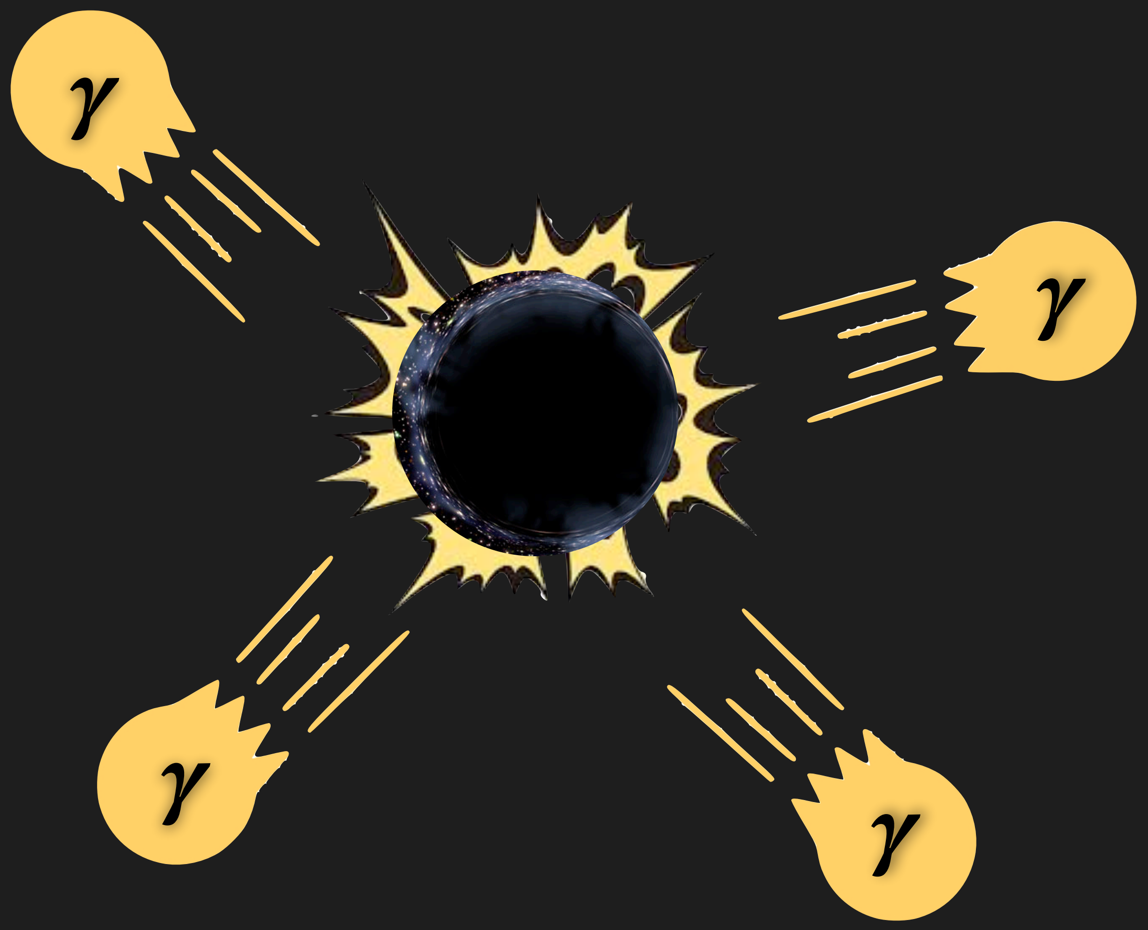
Non-rotating PBHs with masses ~ 10^{15} g would be evaporating now.

D. N. Page Phys. Rev. D 13 (1976) 198–206.
D. N. Page Phys. Rev. D 14 (1976) 3260–3273.
J. H. MacGibbon+ Phys. Rev. D 78 (2008) 064043

How many PBH explosions do we expect?

Photons are a clear signature of exploding PBHs, having strong matches with a gamma-ray burst though with some intrinsic differences.

Capanema+ JCAP 12(2021) 051
Y. F. Perez-Gonzalez PRD 108 8 (2023) 083014
X. Boluna+ JCAP 04 (2024) 024



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Capanema+ JCAP 12(2021) 051
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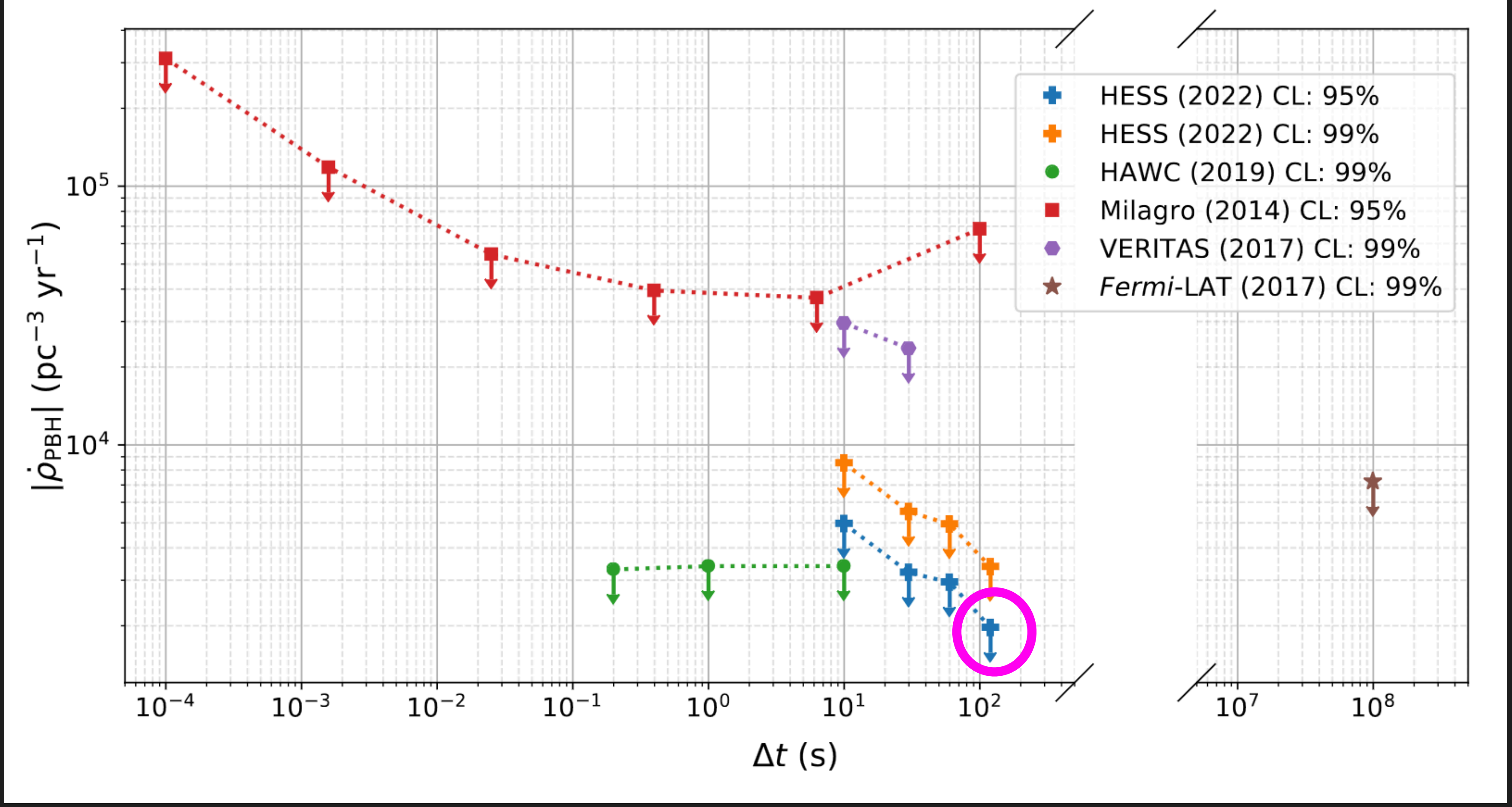
X. Boluna+ JCAP 04 (2024) 024

Facilities like H.E.S.S, Milagro, VERITAS, Fermi-LAT, and HAWC have searched for evaporation bursts of very-high-energy gamma rays. Current strongest direct limit on the rate of exploding PBHs: $\dot{n}_{\rm PBH} < 2000\ {\rm pc}^{-3}\ {\rm yr}^{-1}$ for a burst interval of 120 seconds.



H.E.S.S. JCAP 04 (2023) 040

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

How many PBH explosions do we expect?

We can estimate the number density of PBHs that could exist in the Solar neighborhood, assuming that the ratio of the PBH number density to the entropy density is conserved

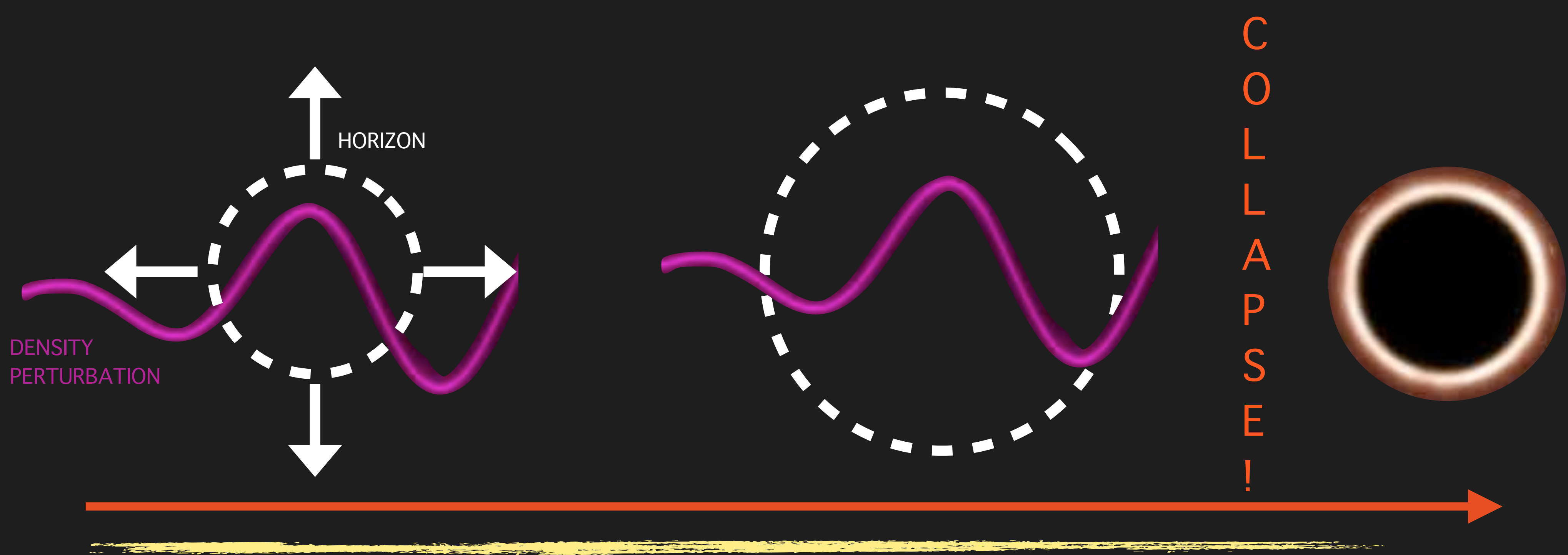
$$n_{\rm PBH} \lesssim 0.35 \left(\frac{\beta'}{10^{-29}}\right)\left(\frac{10^{15}\ {\rm g}}{M_{\rm in}}\right) {\rm pc}^{-3}$$

Carr et al., Rep. Prog. Phys. 84 (2021) 116902
Y. F. Perez-Gonzalez PRD 108 8 (2023) 083014
De Romeri+ 2405.00124

β' encodes the ratio of PBH energy density at formation to the total energy density

$$\beta' \sim 7 \times 10^{-18} \Omega_{\rm PBH} \sqrt{\frac{M^{in}_{\rm PBH}}{10^{15}{\rm g}}}$$

current density parameter of the PBHs: $\Omega_{\rm PBH} = \frac{\rho^{\rm today}_{\rm PBH}}{\rho_c}$



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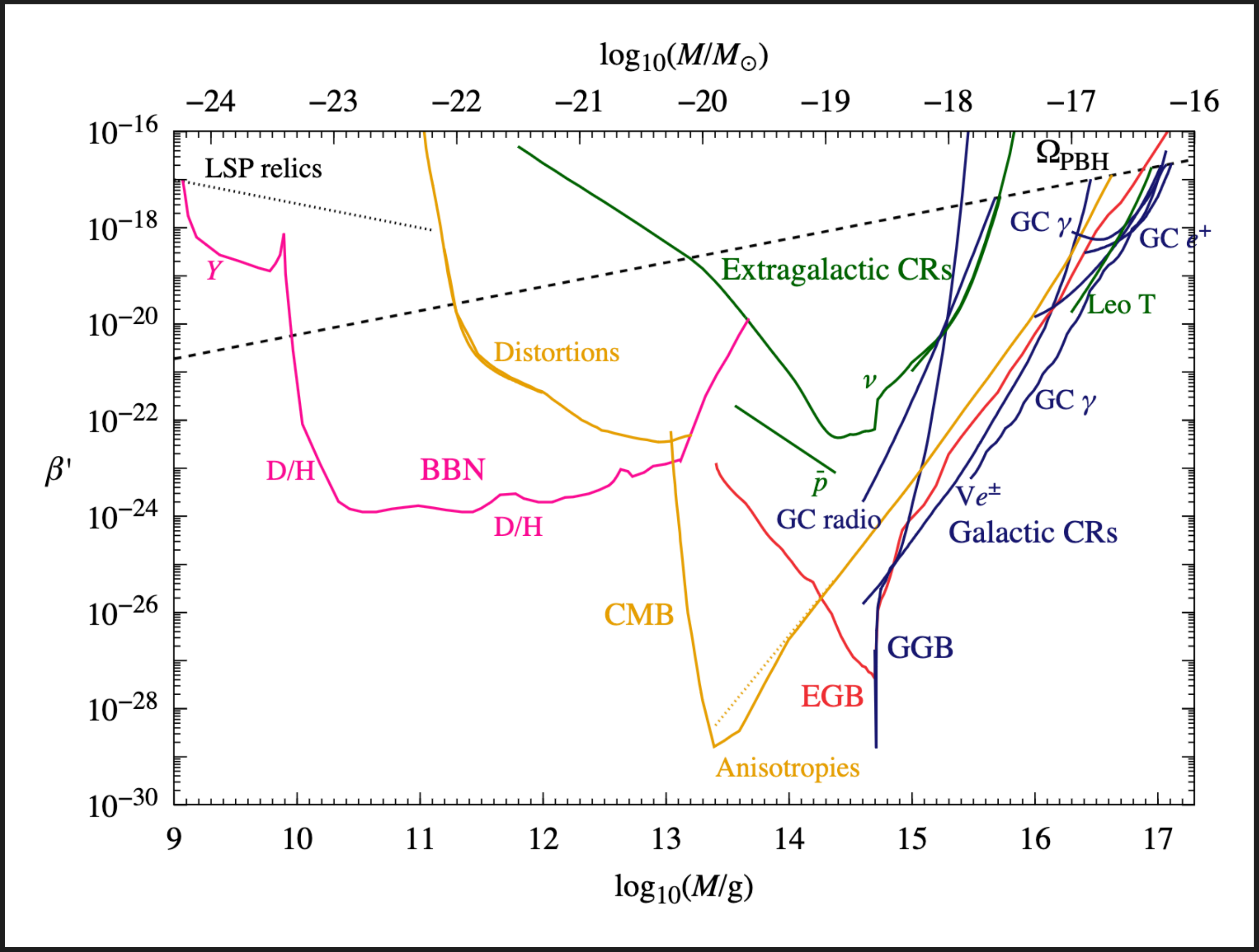
Carr et al., Rep. Prog. Phys. 84 (2021) 116902
Y. F. Perez-Gonzalez PRD 108 8 (2023) 083014
De Romeri+ 2405.00124



Carr et al., Rep. Prog. Phys. 84 (2021) 116902

Galactic γ-ray background
B. J. Carr+ Phys. Rev. D 94, 044029 (2016)

How many PBH explosions do we expect?

We can also estimate the number density of PBHs that could exist in the Solar neighborhood

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

Y. F. Perez-Gonzalez PRD 108 8 (2023) 083014
De Romeri+ 2405.00124

In a spherical volume of a cubic parsec, we can anticipate approximately ~ 1.5 PBHs evaporating presently to align with observations.

PBH lifetime

If the number of dofs is constant during the whole PBH lifetime, the mass lose rate is exactly solvable and the PBH lifetime is given by

$$\tau_d = \frac{M_{\rm in}^3}{3\varepsilon M_p^4} \sim 428\ \mathrm{s} \left(\frac{4.07\times 10^{-3}}{\varepsilon} \right) \left(\frac{M_{\rm in}}{10^{10}\ \mathrm{g}} \right)^3$$

We assume $\varepsilon = 4.07 \times 10^{-3}$ corresponding to the value of the evaporation function for the SM dofs.

We set the initial mass of an exploding PBH to yield a lifetime matching the observation period.

For an observation time of 100 s → $M_{\rm PBH}^{in} = 6.2 \times 10^9$g.

The time-integrate spectrum reads: $$\frac{dN_i}{dE} = \int_0^\tau dt\, \frac{d^2N_i}{dEdt}(M(t))$$

Exploding PBH signatures: active neutrinos

Exploding PBH signatures: active neutrinos

Primary emission

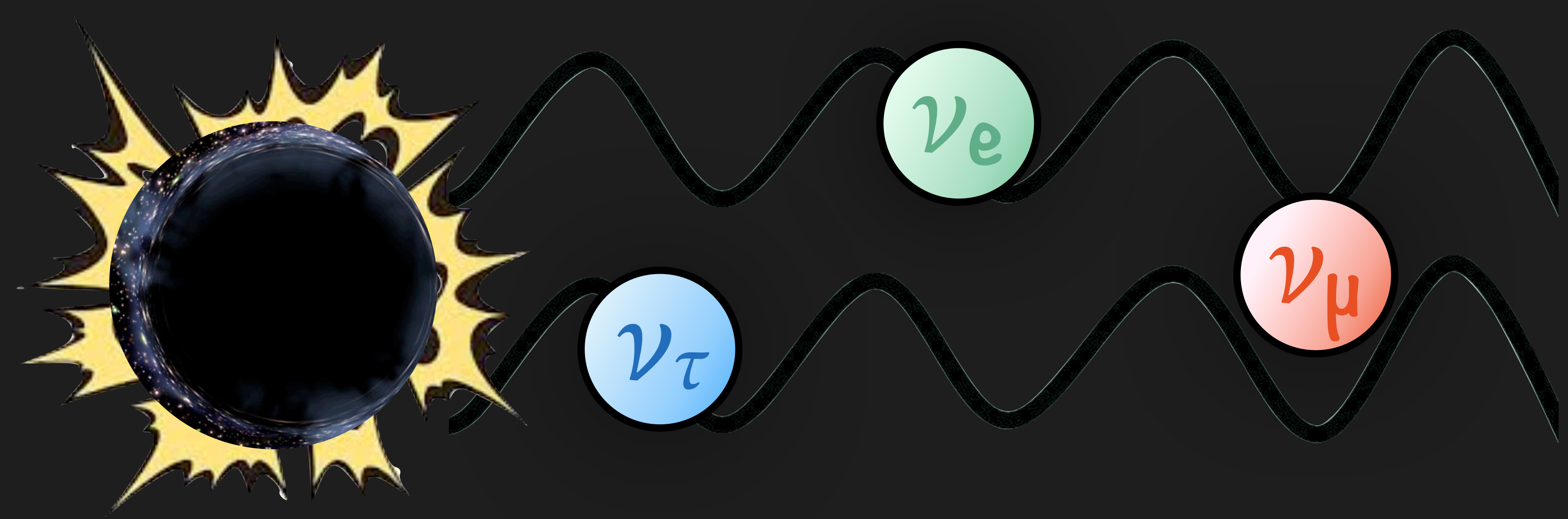
Neutrinos are emitted as mass eigenstates.

Lunardini and Perez-Gonzalez JCAP 08 (2020) 014

The time-integrated spectrum of an observable state with flavour α is obtained by projecting the spectra of the mass eigenstates into the flavour basis

$$\left.\frac{dN_{\nu_\alpha}}{dE}\right|_{\mathrm{pri}} = \sum_{i=1}^{3} |U_{\alpha i}|^2 \frac{dN_{\nu_i}}{dE}$$

The primary emission reflects the thermal spectrum, corrected by the grey-body factors.



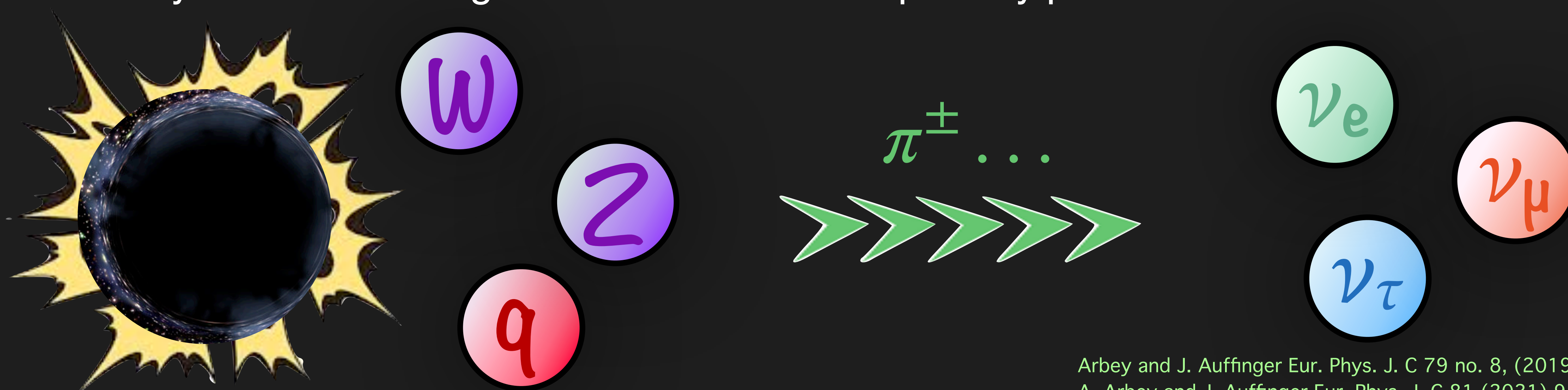
Exploding PBH signatures: active neutrinos

Secondary emission

The largest part of the overall time-integrated spectrum of neutrinos arises from quark hadronization and hadron posterior decays, together with heavy leptons and massive gauge bosons decays

$$\left.\frac{dN^{\nu_\beta}_{\rm PBH}}{dE}\right|_{\rm sec} = \sum_j \int_0^\infty dE_j \frac{dN_j}{dE_j}\frac{dN(j \longrightarrow \nu_\beta)}{dE}(E, E_j)$$

Secondary emission dominates over primary one.
We rely on BlackHawk to evaluate both spectra and HDMSpectra to compute the secondary emission through the hadronization of primary particles.

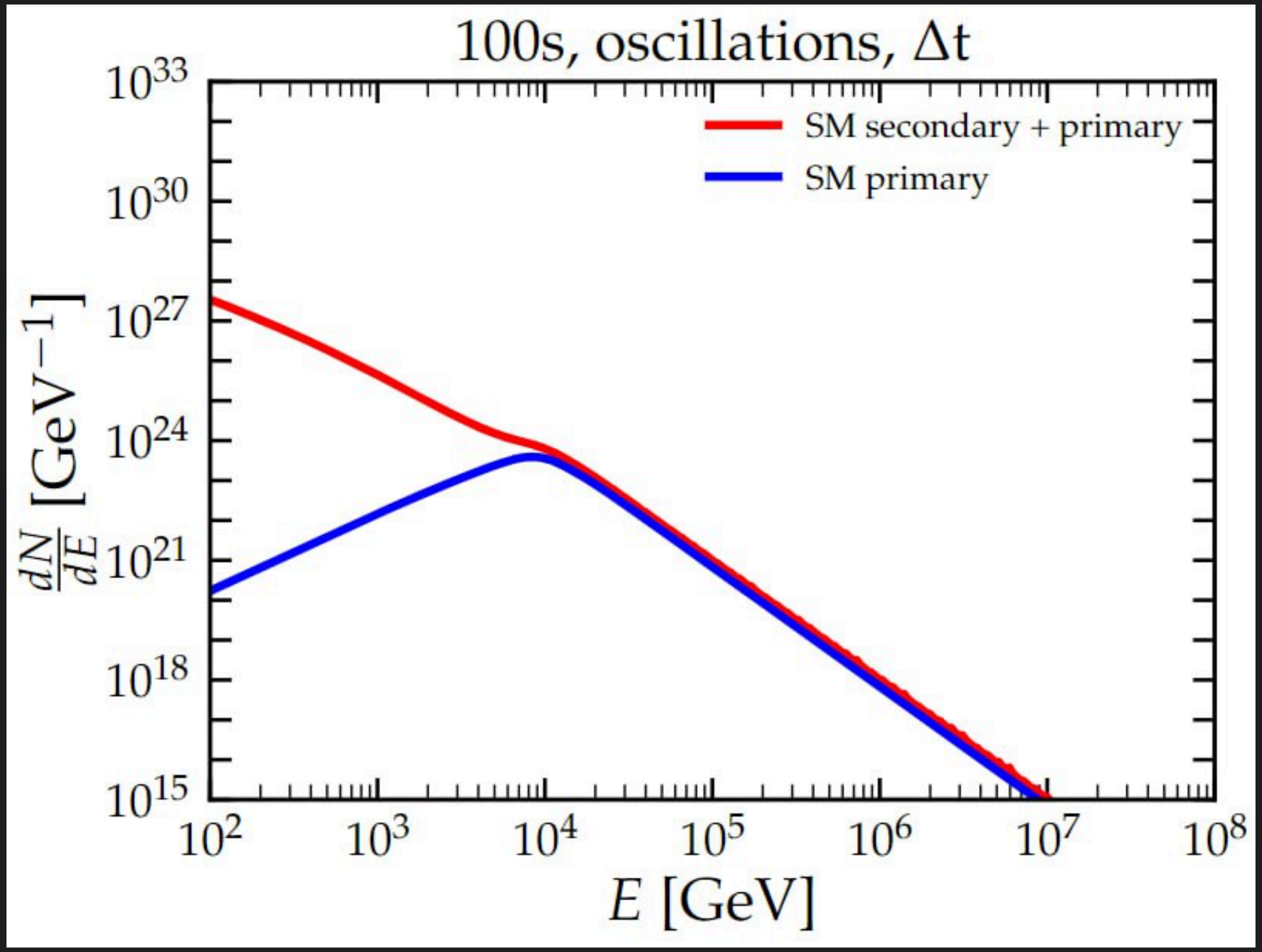


Arbey and J. Auffinger Eur. Phys. J. C 79 no. 8, (2019) 693
A. Arbey and J. Auffinger Eur. Phys. J. C 81 (2021) 910
C. W. Bauer, N. L. Rodd, and B. R. Webber JHEP 06 (2021) 121

Exploding PBH signatures: active neutrinos

Secondary neutrinos are emitted as flavour eigenstates.
Neutrinos undergo oscillations in their route from the PBH to the Earth:

$$\left.\frac{dN_{\nu_\alpha}}{dE}\right|_{\rm sec} = \sum_{\beta=e,\mu,\tau}\sum_{i=1,2,3} |U_{\alpha i}|^2 |U_{\beta i}|^2 \left.\frac{dN^{\nu_\beta}_{\rm PBH}}{dE}\right|_{\rm sec}$$



BSM physics case: heavy neutral leptons

BSM physics case: heavy neutral leptons

Several BSM extensions call upon the introduction of SM-singlet degrees of freedom, dubbed sterile neutrinos or heavy neutral leptons (HNLs), to address neutrino masses and mixings.

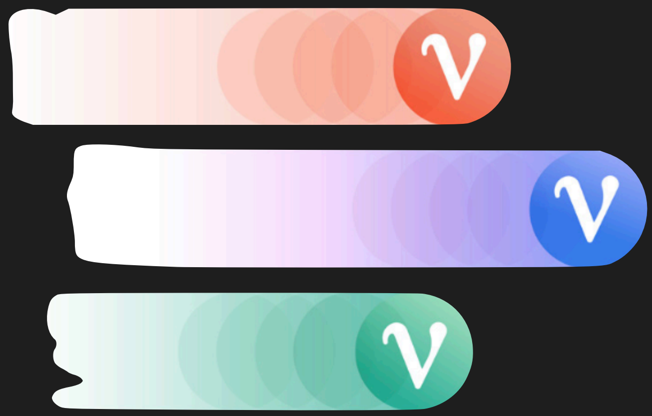
HNLs can have masses that vary over several orders of magnitude, depending on the actual mechanism that originates neutrino masses, and extended phenomenological implications.

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

Most general mass lagrangian for neutrinos

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

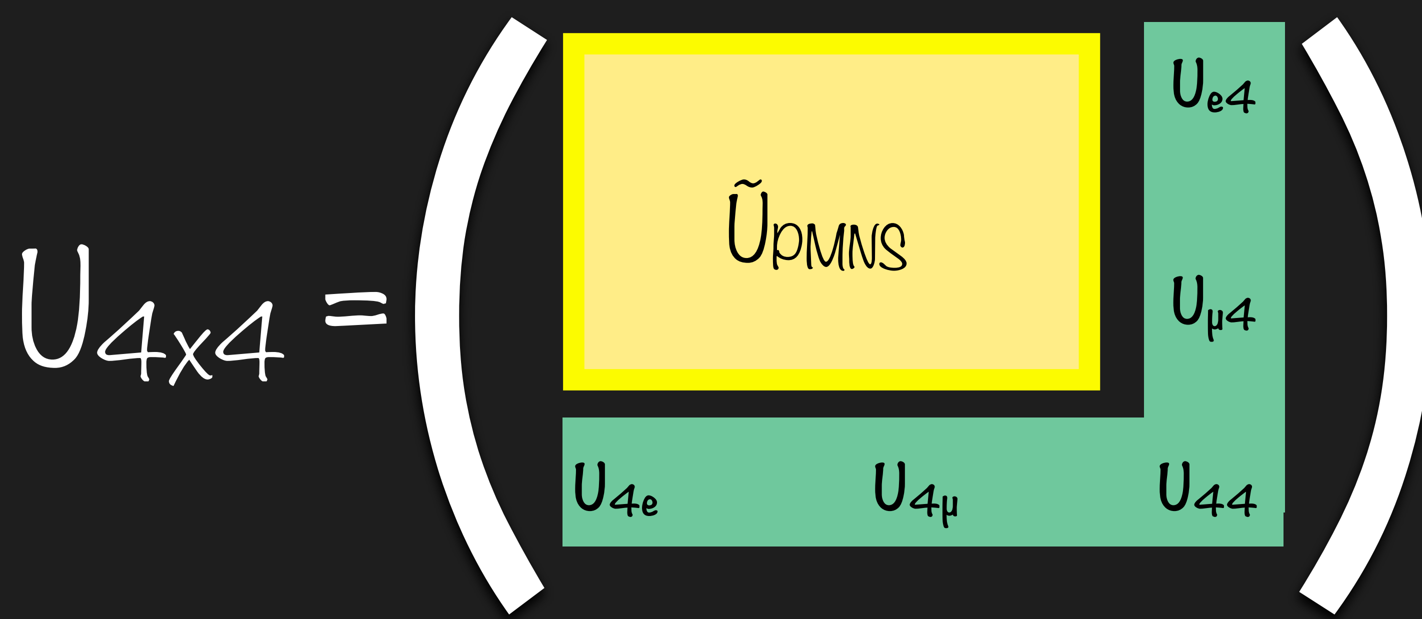
$$\mathcal{N}_L = \begin{pmatrix} \nu_L \\ (N_R)^c \end{pmatrix}, \quad M_\nu = \begin{pmatrix} \mathbf{0}_3 & Yv/\sqrt{2} \\ Y^T v/\sqrt{2} & M_R \end{pmatrix}$$



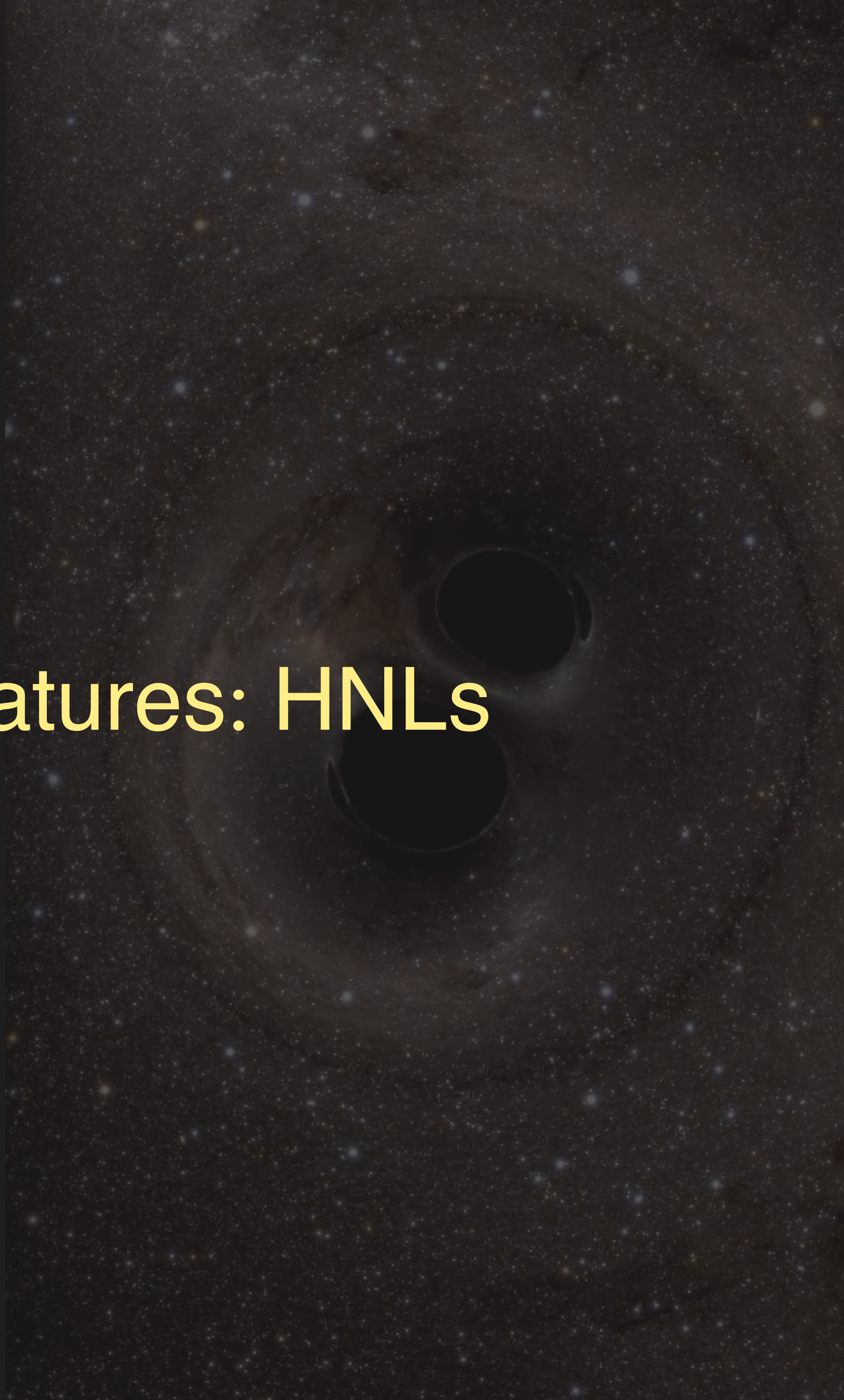
Credit: neutrinos.fnal.gov

BSM physics case: heavy neutral leptons

- We assume the presence of a single HNL state ν4 with a mass m4, which interacts with active neutrinos through the mixing Uα4
- The α = e, μ, τ flavor states can be written as $\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i + U_{\alpha 4}\nu_4$
- The unitarity of the 3×3 sub-block of U is not guaranteed. But holds as long as $|U_{\alpha 4}|^2 \lesssim 10^{-3}$
- We consider different scenarios:
  - 1:0:0: $|U_{e4}|^2 \neq 0, |U_{\mu 4}|^2 = 0, |U_{\tau 4}|^2 = 0$
  - 0:1:0: $|U_{e4}|^2 = 0, |U_{\mu 4}|^2 \neq 0, |U_{\tau 4}|^2 = 0$
  - 0:0:1: $|U_{e4}|^2 = 0, |U_{\mu 4}|^2 = 0, |U_{\tau 4}|^2 \neq 0$

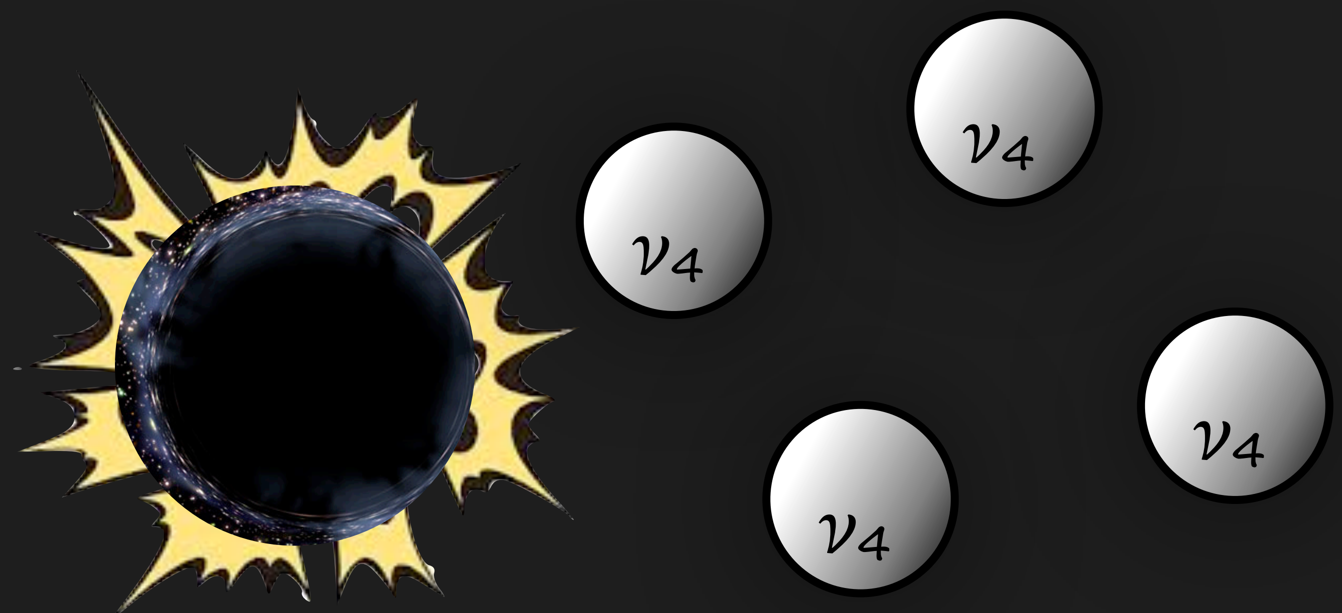


Exploding PBH signatures: HNLs



Exploding PBH signatures: HNLs

- A large ($\gtrsim 10$) number of HNL generations would be required to observe sizeable effects in the primary emission (that is, to change the PBH mass loss rate).
- HNLs lighter than ~ 2 TeV can be produced in the final evaporation of a PBH ($M_{\rm PBH}^{in} = 6.2 \times 10^9$g) and give rise to an observable flux of daughter active neutrinos.
- We consider two mass ranges: a light-mass ($[0.1$-$1]$ GeV) and a heavy-mass ($[0.5$-$2]$ TeV) regime.



Exploding PBH signatures: HNL light-mass regime

HNLs with masses O(100) MeV mainly decay into final states that include one lepton and one meson or three leptons

Atre, T. Han, S. Pascoli, and B. Zhang JHEP 05 (2009) 030
A. M. Abdullahi et al. J. Phys. G 50 no. 2, (2023) 020501

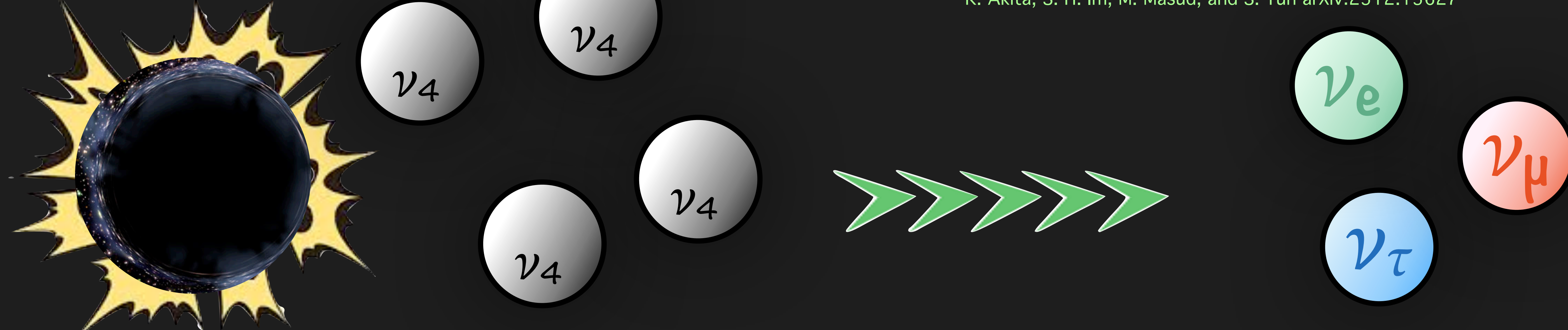
$$\nu_4 \to \nu_\alpha \nu_\ell \bar{\nu}_\ell \quad (\ell = e, \mu, \tau)$$

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

The time-integrated secondary spectrum of neutrinos with flavour α

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

L. Mastrototaro, A. Mirizzi, P. D. Serpico, and A. Esmaili JCAP 01 (2020) 010
K. Akita, S. H. Im, M. Masud, and S. Yun arXiv:2312.13627



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

The time-integrated secondary spectrum of neutrinos with flavour α

Branching ratio

Primary HNL spectrum

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

angle formed between the direction of ν_α in the HNL rest frame and its velocity in the Lab frame

angular and energetic distribution that the active neutrino has in the HNL rest frame

Exploding PBH signatures: HNL heavy-mass regime

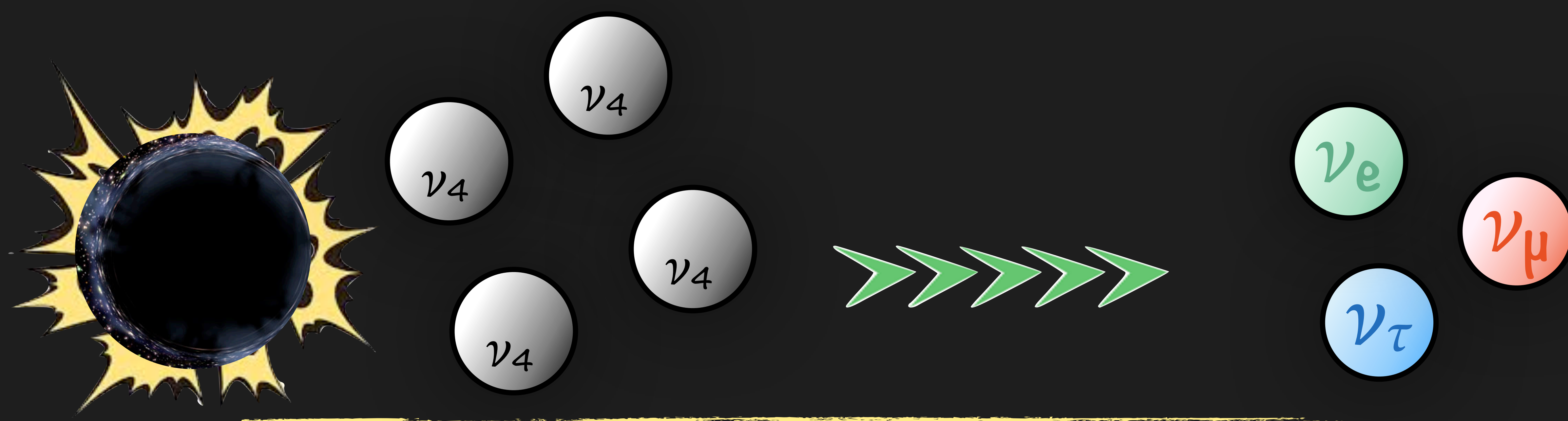
Above the electroweak scale, HNLs mainly decay into bosonic states

$$\nu_4 \to W^{\pm}\mu^{\mp}$$
$$\nu_4 \to Z^0\nu_\mu$$
$$\nu_4 \to H^0\nu_\mu$$

Atre, T. Han, S. Pascoli, and B. Zhang JHEP 05 (2009) 030

The time-integrated secondary spectrum of muonic neutrinos

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



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Atre, T. Han, S. Pascoli, and B. Zhang JHEP 05 (2009) 030

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The time-integrated secondary spectrum of muonic neutrinos

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

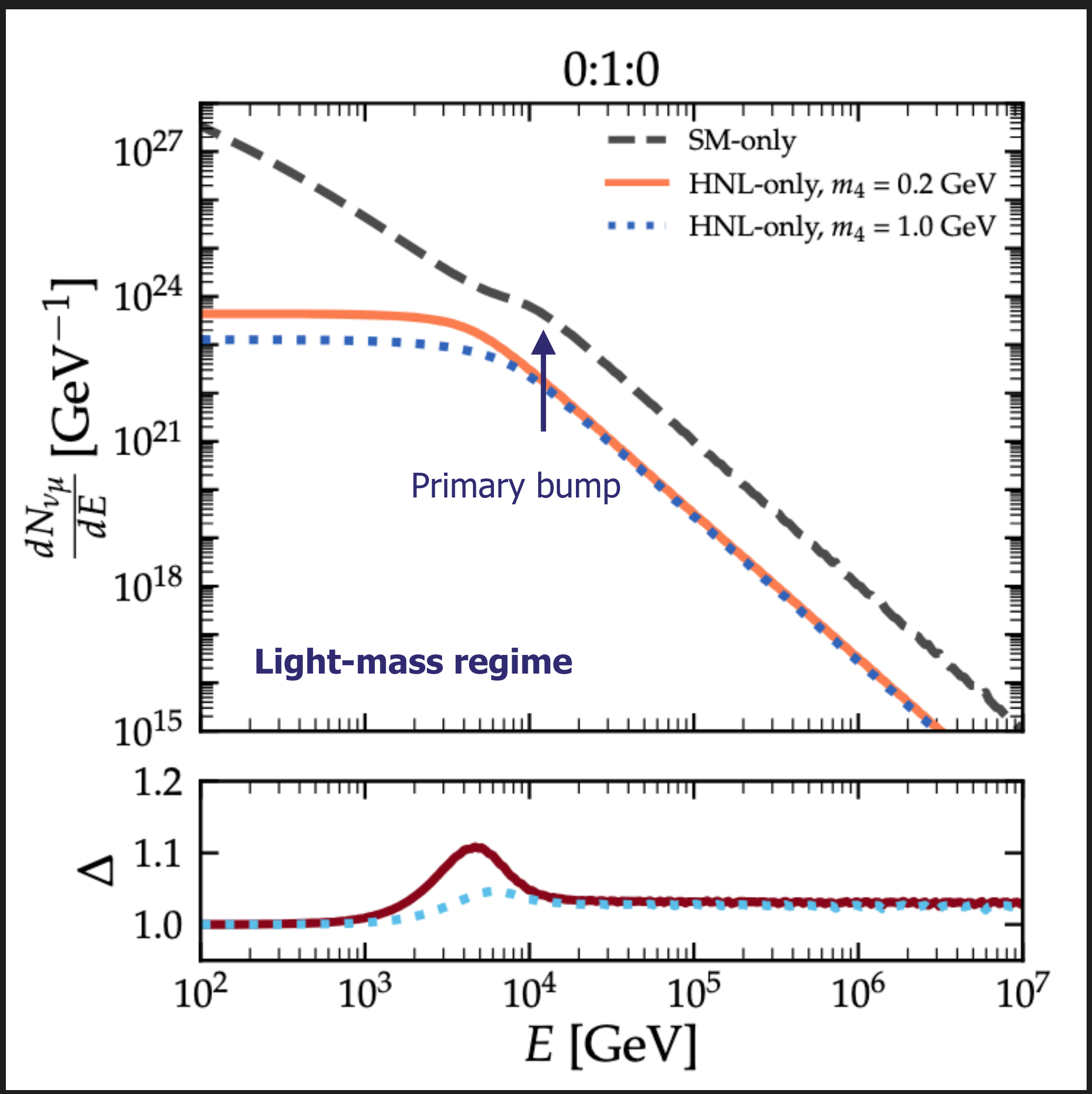
Energetic and angular distribution that the muon neutrino can have in the HNL rest frame, evaluated using PPPC4DMID

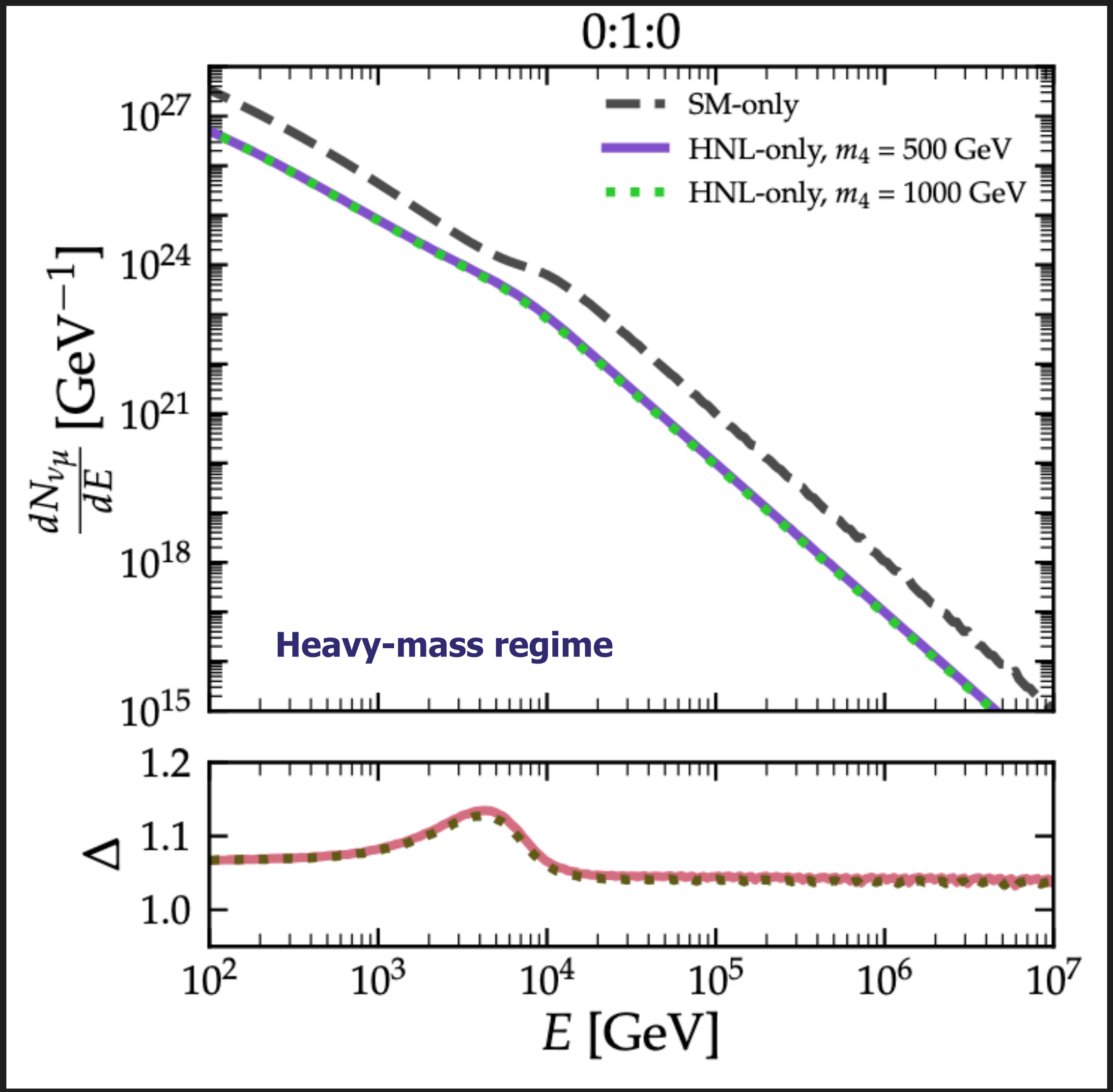
Summary of neutrino spectra

The overall muon neutrino time-integrated spectrum expected from an evaporating PBH will be given by the sum of all SM contributions and the secondary contributions from HNL decays.

Observation time of 100 s.

Only ν_4 mixing with ν_μ is turned on.





VDR, Perez-Gonzalez, Tolino 2405.00124 [hep-ph]

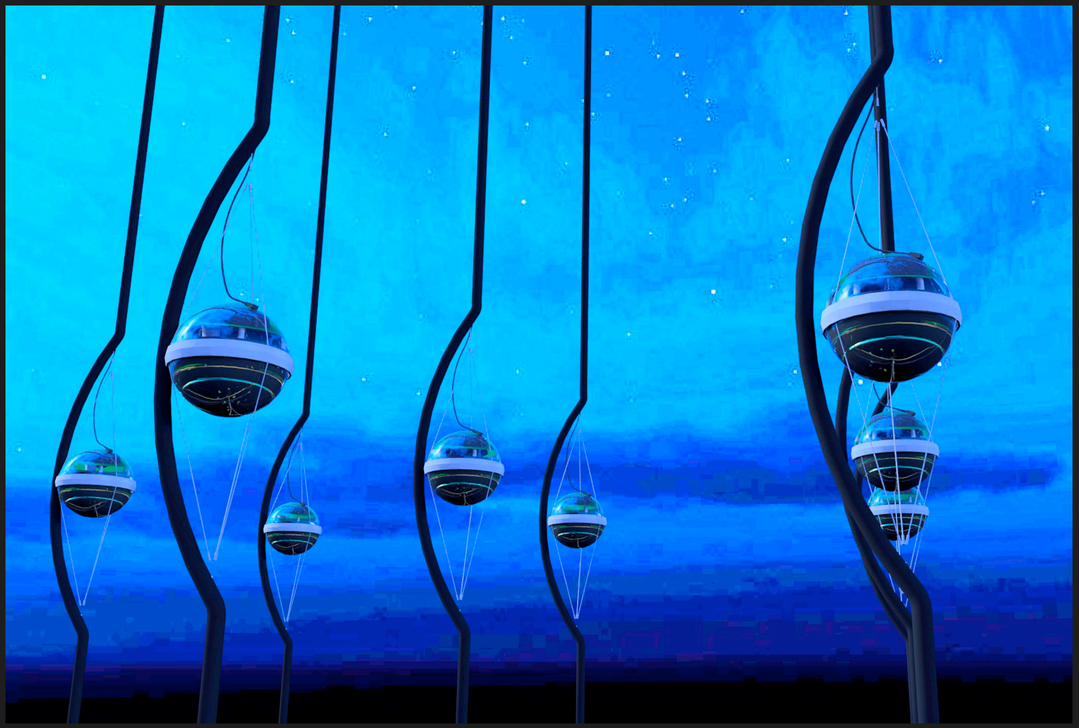
IceCube sensitivity

Neutrinos from PBH explosions at IceCube?

Neutrino telescopes like IceCube may be able to observe exploding PBHs as transient point sources.
Muon-tracks events at IceCube benefit from a high-quality angular resolution that allows to pinpoint with precision the declination angle.

Fluence: $$F_{\nu_\mu}(E) = \frac{1}{4\pi d_{\rm PBH}^2} \left.\frac{dN_{\nu_\mu}}{dE}\right|_{\rm tot}$$

Credit: icecube.wisc.edu/gallery



Credit: icecube.wisc.edu/gallery

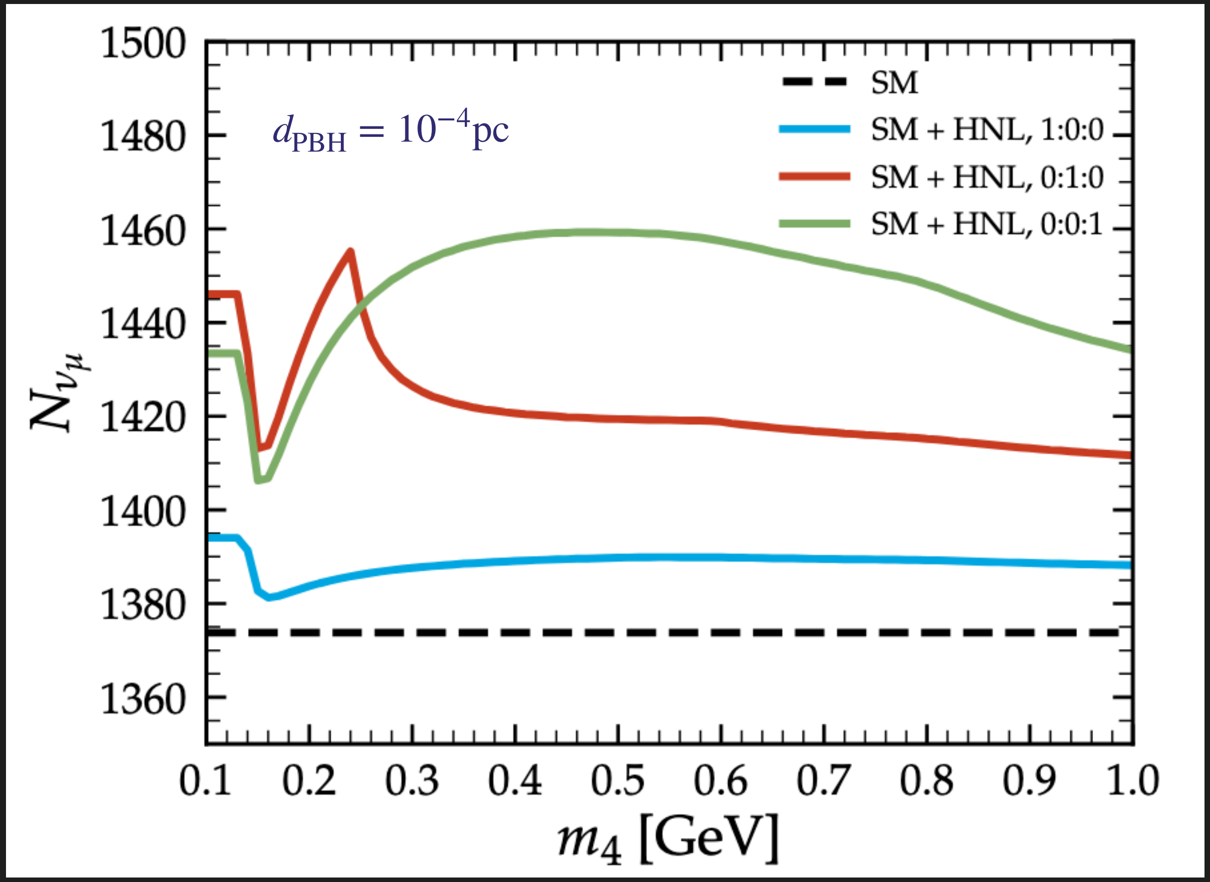
Total number of muon-neutrino events

$$N_{\nu_\mu}(\delta) = \int_{E_{\min}}^{E_{\max}} F_{\nu_\mu}(E)\mathscr{A}_{\text{eff}}(E,\delta)$$

IceCube's effective area indicates the efficiency of observing an astrophysical neutrino flux as a function of energy and declination.

We use the publicly available effective area and we fix the declination angle to be in the range $[30° < \delta < 90°]$.

IceCube Collaboration, M. G. Aartsen et al. Phys. Rev. Lett. 124 no. 5, (2020) 051103



VDR, Perez-Gonzalez, Tolino 2405.00124 [hep-ph]

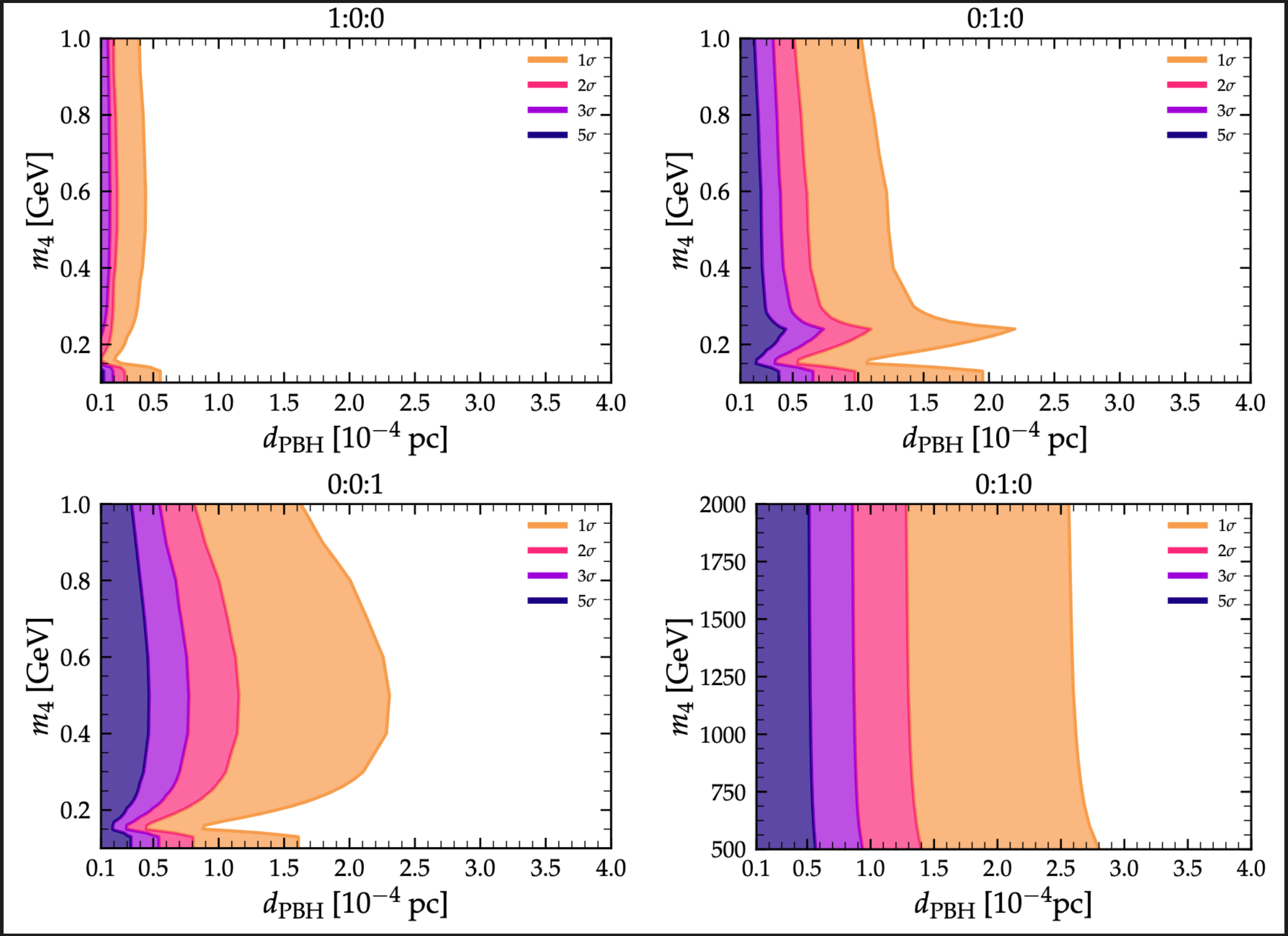
Statistical analysis

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

- Negligible background from high-energy atmospheric neutrino events
- Declination angle from Northern hemisphere
- Nuisance parameter related to uncertainty on PBH distance also negligible

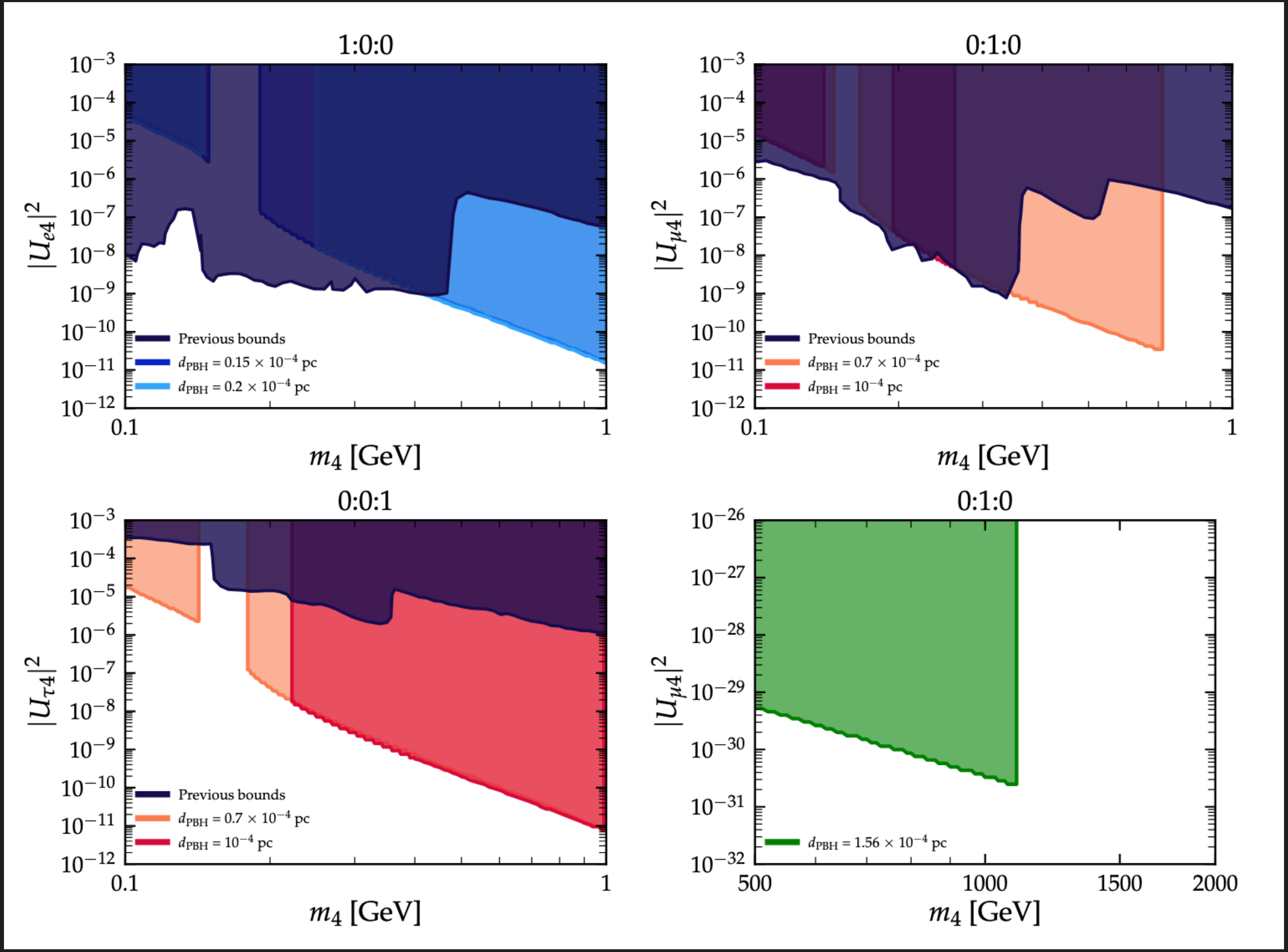
Credit: icecube.wisc.edu/gallery

Results - 1



VDR, Perez-Gonzalez, Tolino 2405.00124 [hep-ph]

Results - 2



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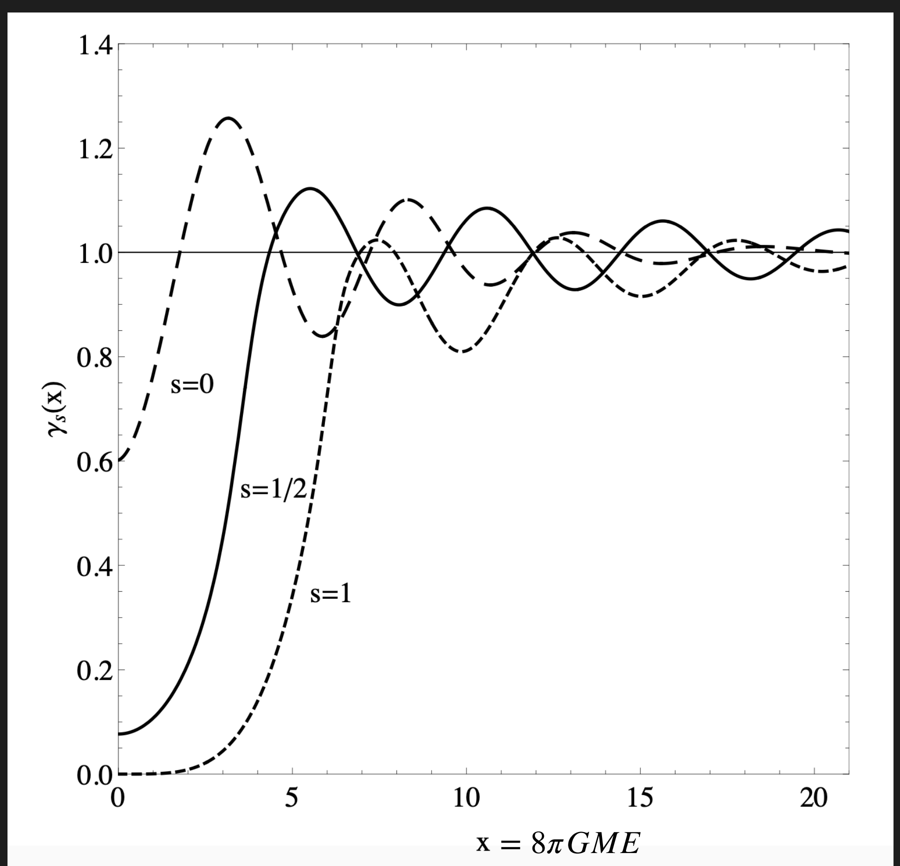
Thank you!

Hawking evaporation

Assuming a semi-classical picture, Hawking showed that a black hole radiates fundamental particle species at an emission rate of

$$\frac{d^2N_i}{dEdt} = \frac{\Gamma_i(M,E)/2\pi}{e^{8\pi GME} - (-1)^{2s}} n_i$$

(Natural units!)



Ukwatta+ Astropart. Phys. 80 (2016) 90–114

n_i: internal dofs associated to the particle species i with spin s_i

Γ_i: indicate the absorption probability (greybody factors), that a (anti-)particle generated by quantum fluctuations at the horizon of a BH escapes to spatial infinity. They are obtained by solving the equations of motion of emitted particles in curved spacetime.

$$\Gamma_i(M,s,E) = 27\,(GME)^2\,\gamma_s$$

S.W. Hawking. Nature 248, 30-31 (1974)
S. W. Hawking, Commun. math. Phys., vol. 43, pp. 199–220, 1975

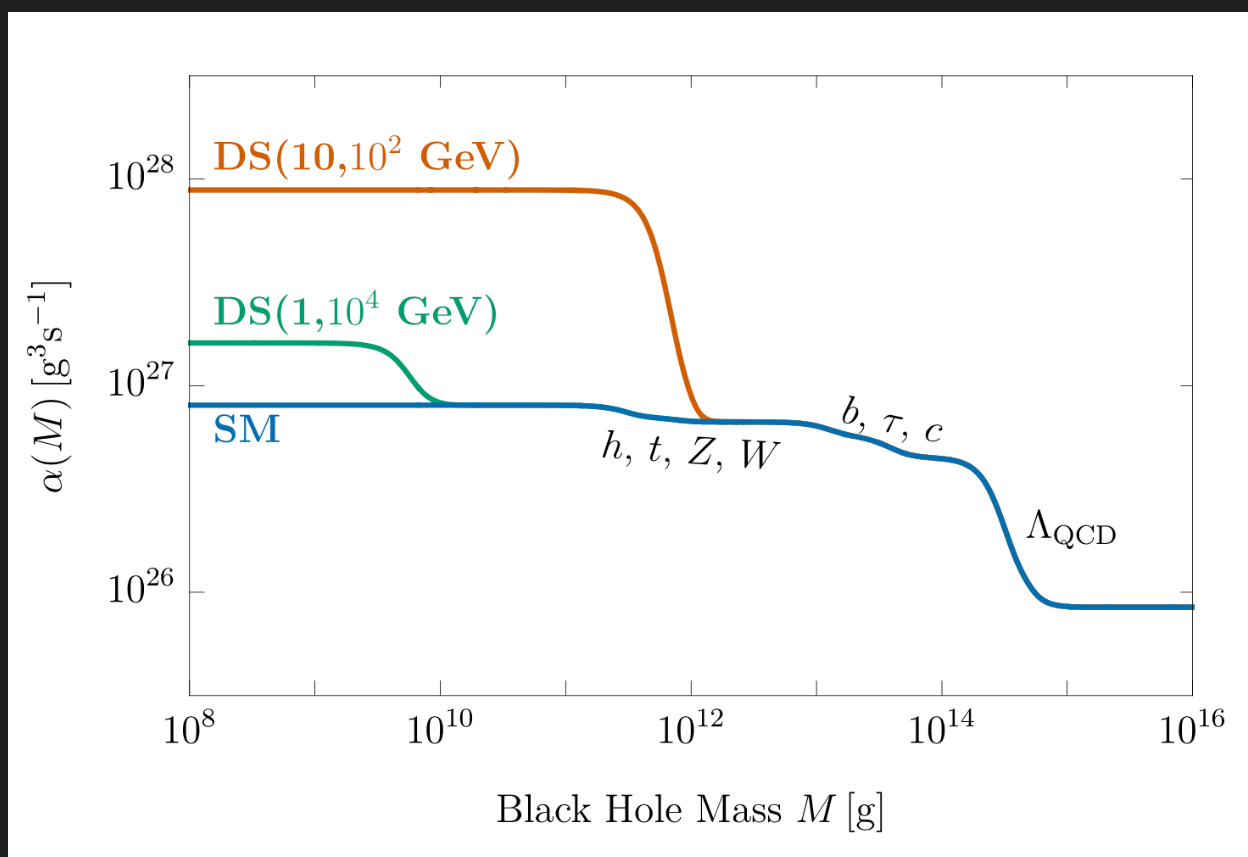
Hawking evaporation

The PBH mass loss rate: $\frac{dM}{dt} = -\frac{\alpha(M)}{M^2}$

D.N. Page, PRD 13 (1976) 198

$$\alpha(M) = M^2 \sum_{i=\text{dofs}} \int_0^\infty \frac{d^2N_i}{dtdE}(M,E)EdE \qquad x = \frac{E}{T}$$

J. H. MacGibbon+ Phys. Rev. D 41 (1990) 3052–3079
J. H. MacGibbon Phys. Rev. D 44 (1991) 376–392



M. J. Baker and A. Thamm SciPost Phys. 12 no. 5, (2022) 150

- All dofs with a de Broglie wavelength of the order of the black hole size are radiated.
- α(M) is independent of the particle's non-gravitational interaction strengths.
- Not affected by BSM unless MANY dofs are present.

PBH lifetime

If the number of dofs is constant during the whole PBH lifetime, the mass lose rate is exactly solvable and the PBH lifetime is given by

$$\tau_d = \frac{M_{\rm in}^3}{3\varepsilon M_p^4} \sim 428 \text{ s} \left(\frac{4.07 \times 10^{-3}}{\varepsilon}\right) \left(\frac{M_{\rm in}}{10^{10}\text{ g}}\right)^3$$

We assume $\varepsilon = 4.07 \times 10^{-3}$ corresponding to the value of the evaporation function for the SM dofs.

$$\varepsilon(M) = \sum_{i=\text{dofs}} \frac{n_i}{128\pi^3} \int_0^\infty \frac{x\Gamma_{s_i}(x)}{exp(x) - (-1)^{2s_i}} dx$$

MacGibbon and B. R. Webber PRD 41 (1990) 3052-3079
MacGibbon PRD 44 (1991) 376-392
Cheek, L. Heurtier, Y. F. Perez-Gonzalez, and J. Turner PRD 105 no. 1, (2022) 015022 and PRD 108 no. 1, (2023) 015005

We set the initial mass of an exploding PBH to yield a lifetime matching the observation period.

For an observation time of 100 s → $M_{\rm PBH}^{in} = 6.2 \times 10^9$g.