Regular PBH constraint from isotropic γ-ray background

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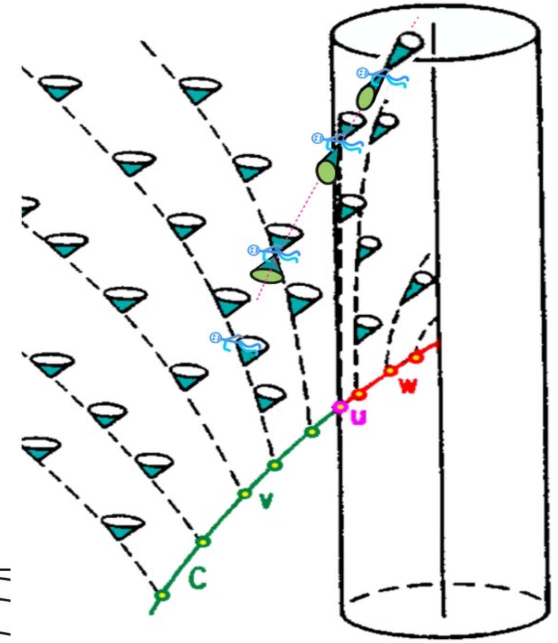
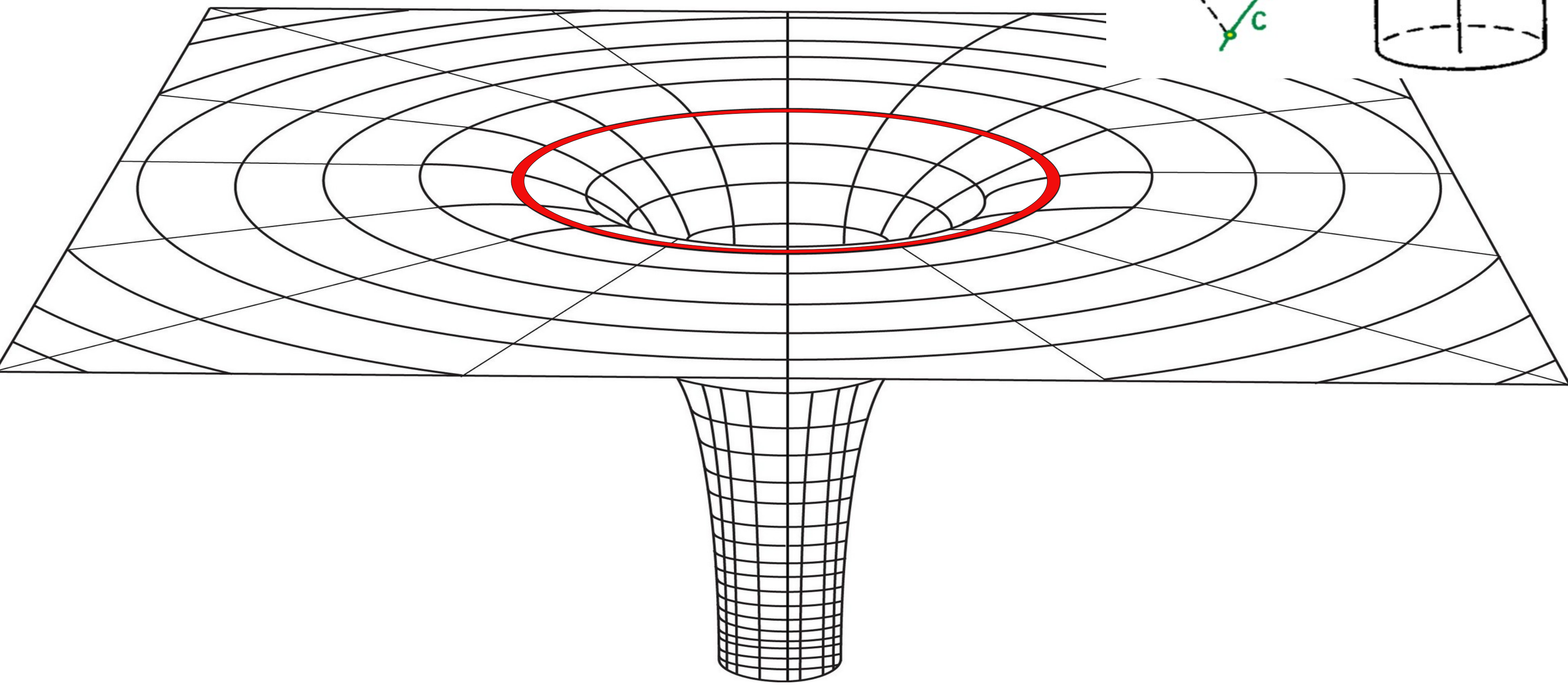
$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2\left(d\theta^2 + \sin^2(\theta)d\phi^2\right)$$

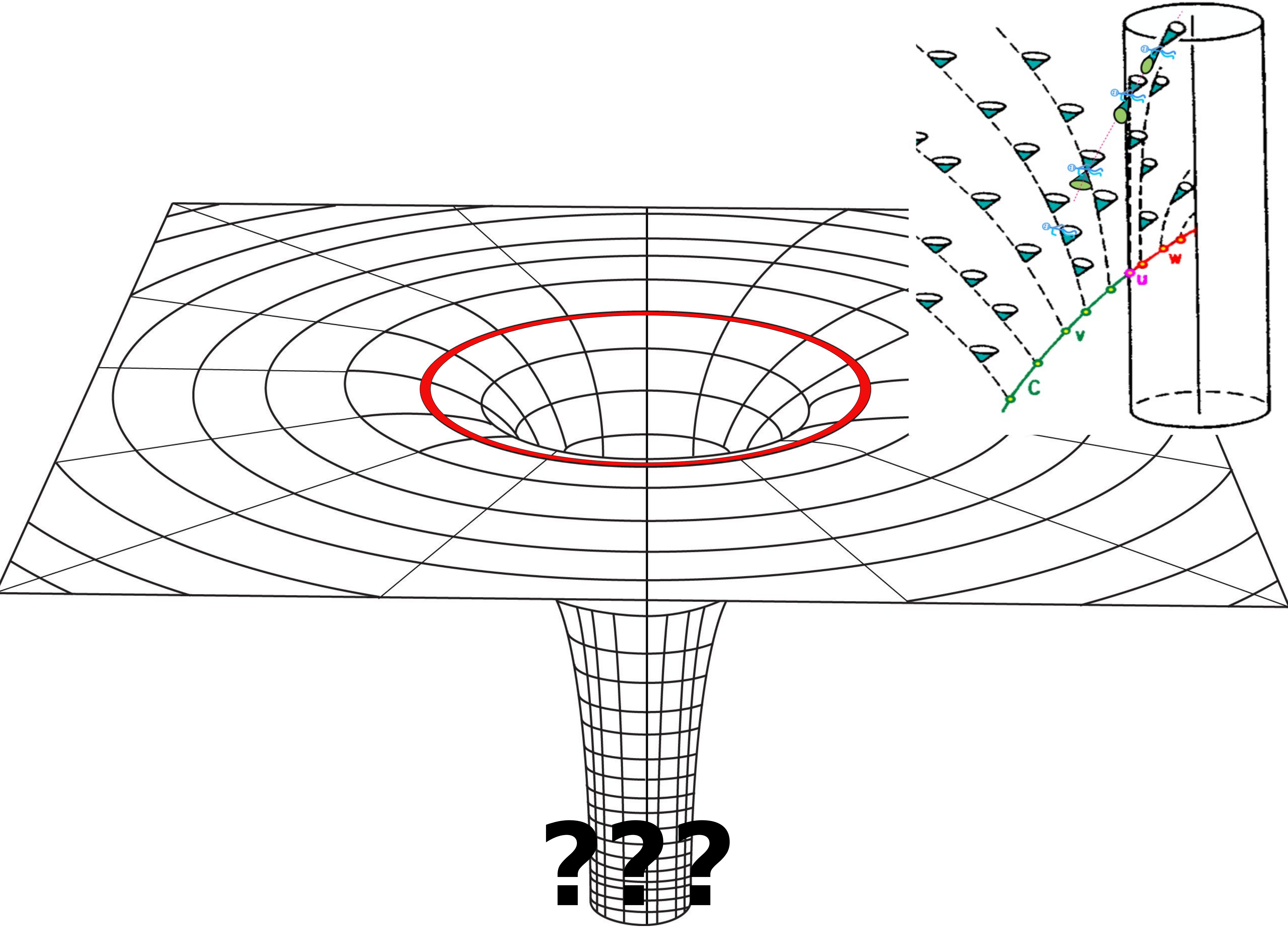


$$\exists \quad r_H \in \mathbb{R}_{++} \quad : \quad f(r_H) = 0 \quad \wedge \quad f'(r_H) > 0$$

Locate a Horizon

$$T = \frac{\kappa}{2\pi} = \frac{f'(r)}{4\pi}\Big|_{r_H}$$




???
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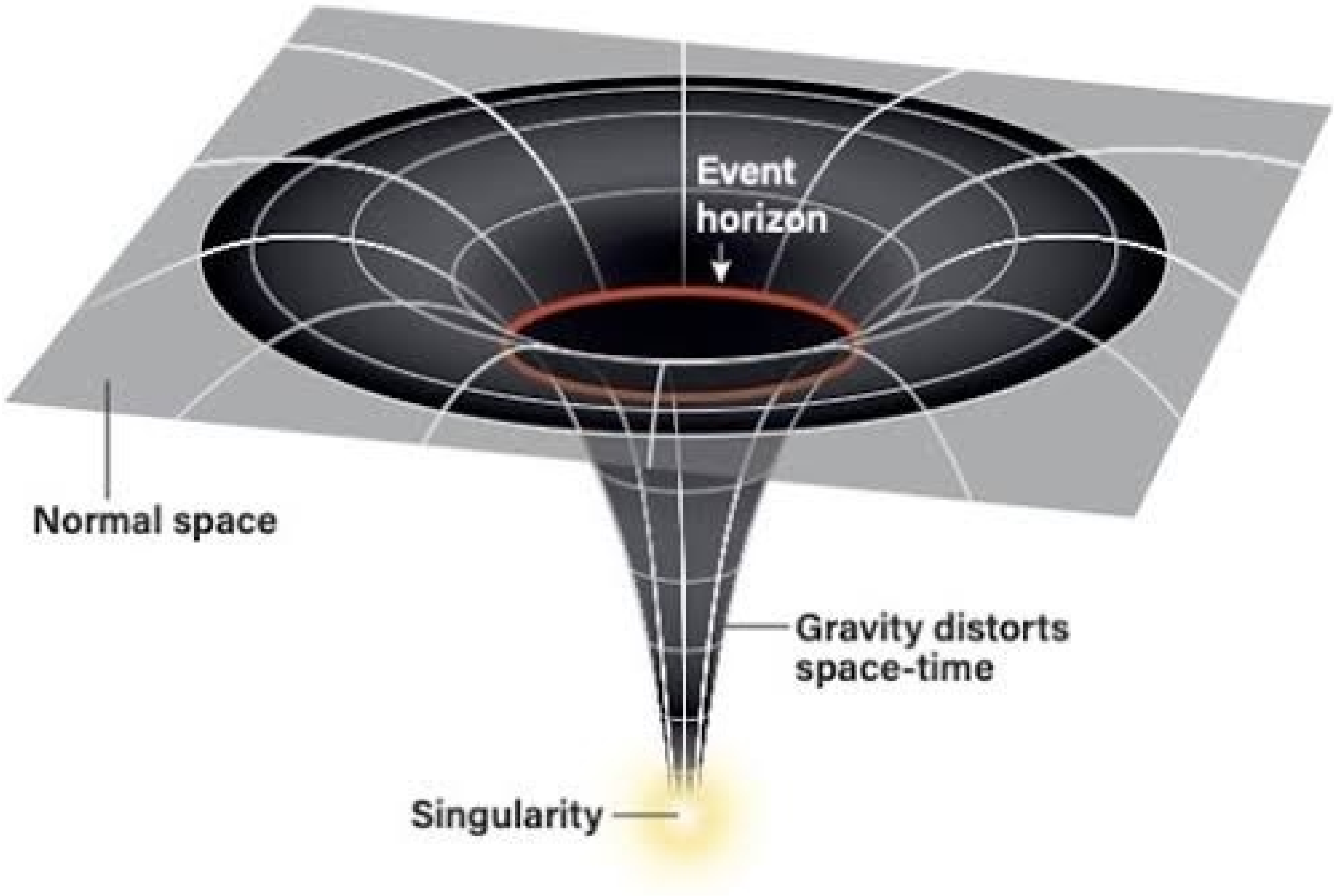
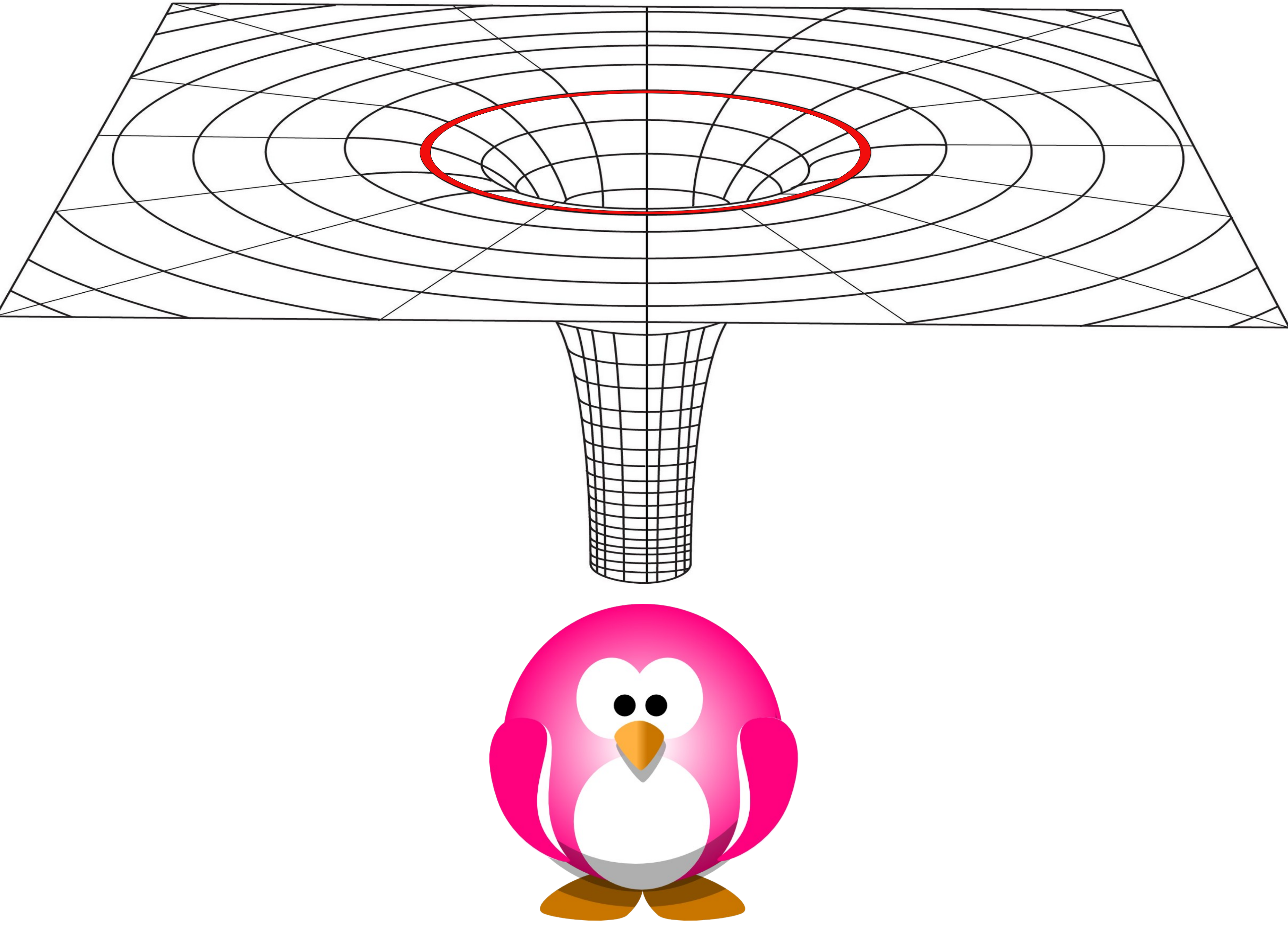
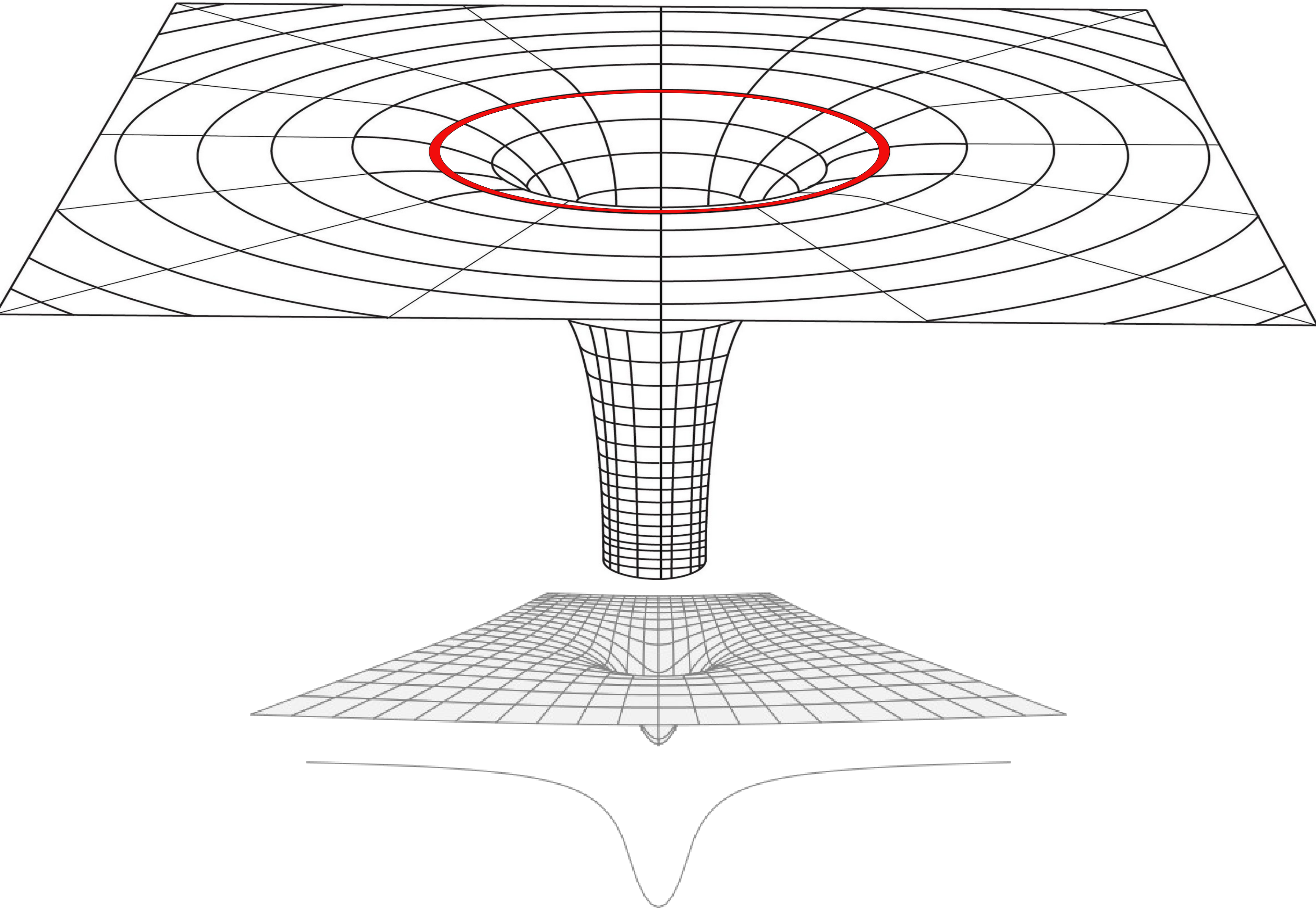

Event
horizon
Normal space
Gravity distorts
space-time
Singularity





Regular BH

$$R \equiv g^{\mu\nu} R_{\mu\nu} \qquad R_{\mu\nu} R^{\mu\nu} \qquad \mathcal{K} \equiv R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}$$

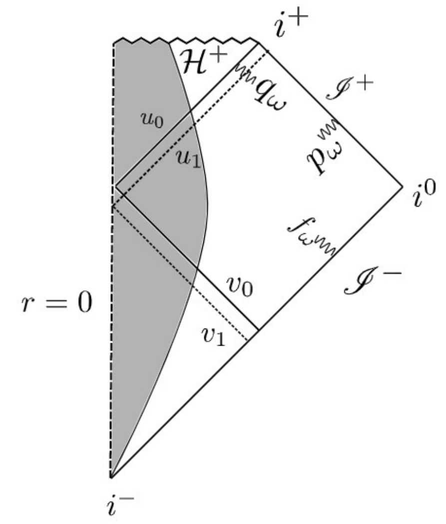
$$f_{\mathrm{B}}(r) = 1 - \frac{2Mr^2}{(r^2 + \ell^2)^{3/2}}$$

$$f_{\mathrm{H}}(r) = 1 - \frac{2Mr^2}{r^3 + 2M\ell^2}$$

$$f_{\mathrm{GCSV}}(r) = 1 - \frac{2M}{r} \exp\left(-\frac{\ell}{r}\right)$$

$$f_{\text{H-l}}(r) = 1 - \frac{2Mr^2}{r^3 + \ell\,(1 - \ell r)}$$

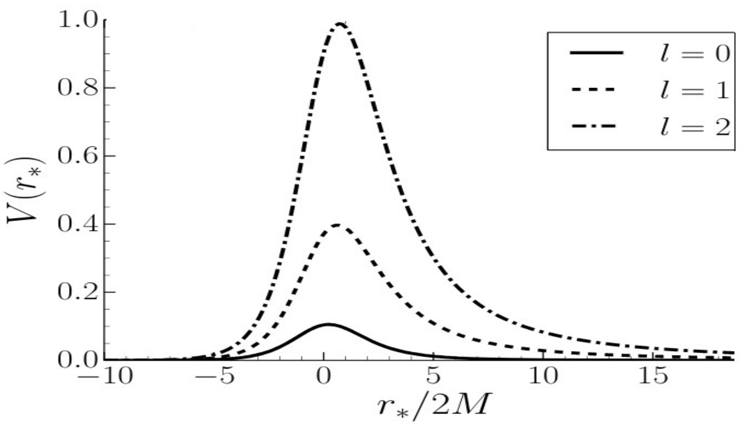
BH Evaporation



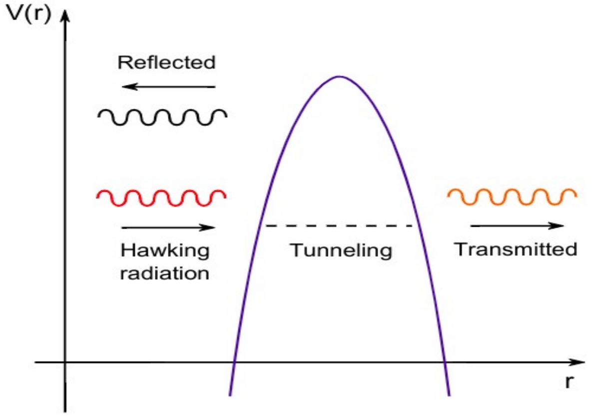
Spacetime before and after the formation of an horizon (Hawking 1975)

In a (1+1)D s-t: $n_\omega = \frac{1}{\left(e^{\frac{2\omega\pi}{\kappa}} - 1\right)}$, $T_H = \frac{\kappa}{2\pi}$

In a 4D s-t: $\nabla^\mu \nabla_\mu \Phi = 0 \;\Rightarrow\; \cdots \;\Rightarrow\; \left(\frac{d^2}{dx^2} + \omega^2 - V(r)\right)\psi(r) = 0$



BH geometry acts as a **potential barrier** that **filters Hawking radiation.**



$n_\omega = \frac{\Gamma(\omega)}{\left(e^{\frac{\omega}{T_H}} - 1\right)}$, $T_H = \frac{\kappa}{2\pi}$

RBH Evaporation

$$\left[-\frac{r^2}{f}\partial_t^2 + s\left(r^2\frac{f'}{f} - 2r\right)\partial_t\right]\Upsilon_s + \left[(s+1)(r^2 f' + 2rf)\partial_r\right]\Upsilon_s$$
$$+\left[\frac{1}{\sin\theta}\partial_\theta(\sin\theta\partial_\theta) + \frac{2is\cot\theta}{\sin\theta}\partial_\phi + \frac{1}{\sin^2\theta}\partial_\phi^2 - s - s^2\cot^2\theta\right]\Upsilon_s + \left[sr^2 f'' + 4srf' + 2sf\right]\Upsilon_s = 0\,.$$

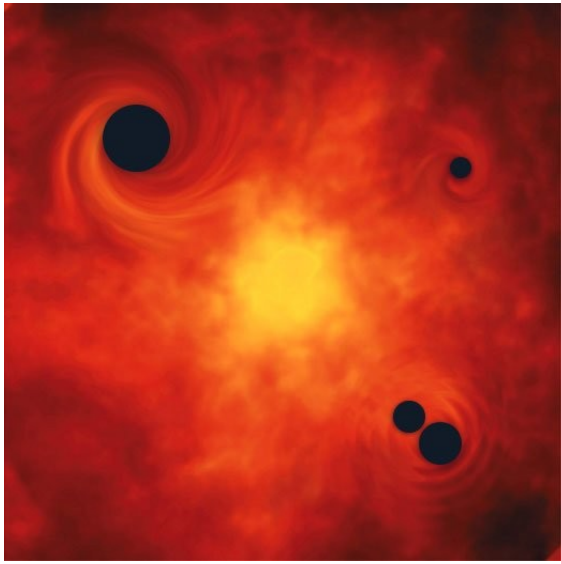
$$\Upsilon_s = \sum_{l,m} e^{-i\omega t} e^{im\phi} S_s^l(\theta) R_s(r)\,,$$

$$\left(\frac{1}{\sin\theta}\partial_\theta(\sin\theta\,\partial_\theta) + \csc^2\theta\,\partial_\phi^2 + \frac{2is\cot\theta}{\sin\theta}\partial_\phi + s - s^2\cot^2\theta + \lambda_l^s\right) S_{l,m}^s = 0\,,$$

$$\frac{1}{\Delta^s}\left(\Delta^{s+1}R_s'\right)' + \left(\frac{\omega^2 r^2}{f} + 2i\omega s r - \frac{is\omega r^2 f'}{f} + s(\Delta'' - 2) - \lambda_l^s\right) R_s = 0\,,$$

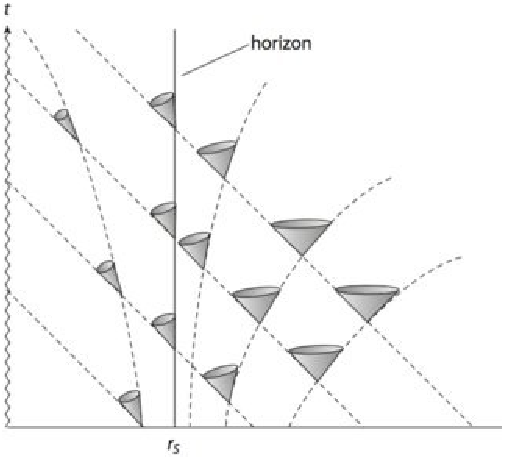
$$R_s \sim R_s^{\text{in}}\frac{e^{-i\omega r^\star}}{r} + R_s^{\text{out}}\frac{e^{i\omega r^\star}}{r^{2s+1}} \qquad (r \to \infty)$$
$$R_s \sim R_s^{\text{hor}}\Delta^{-s}e^{-i\omega r^\star} \qquad (r \to r_H)\,,$$

Primordial BH

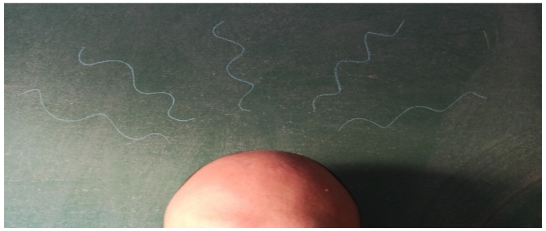


- PBHs are BHs formed in the **early Universe**
- Through the gravitational collapse of **overdensities** in the **cosmic plasma**
- **Masses** can be several orders of magnitude **below** the **solar mass**

So what? Why?



$$M,\ \cancel{a = J/M^2},\ \cancel{Q}\ ,\ \ell$$

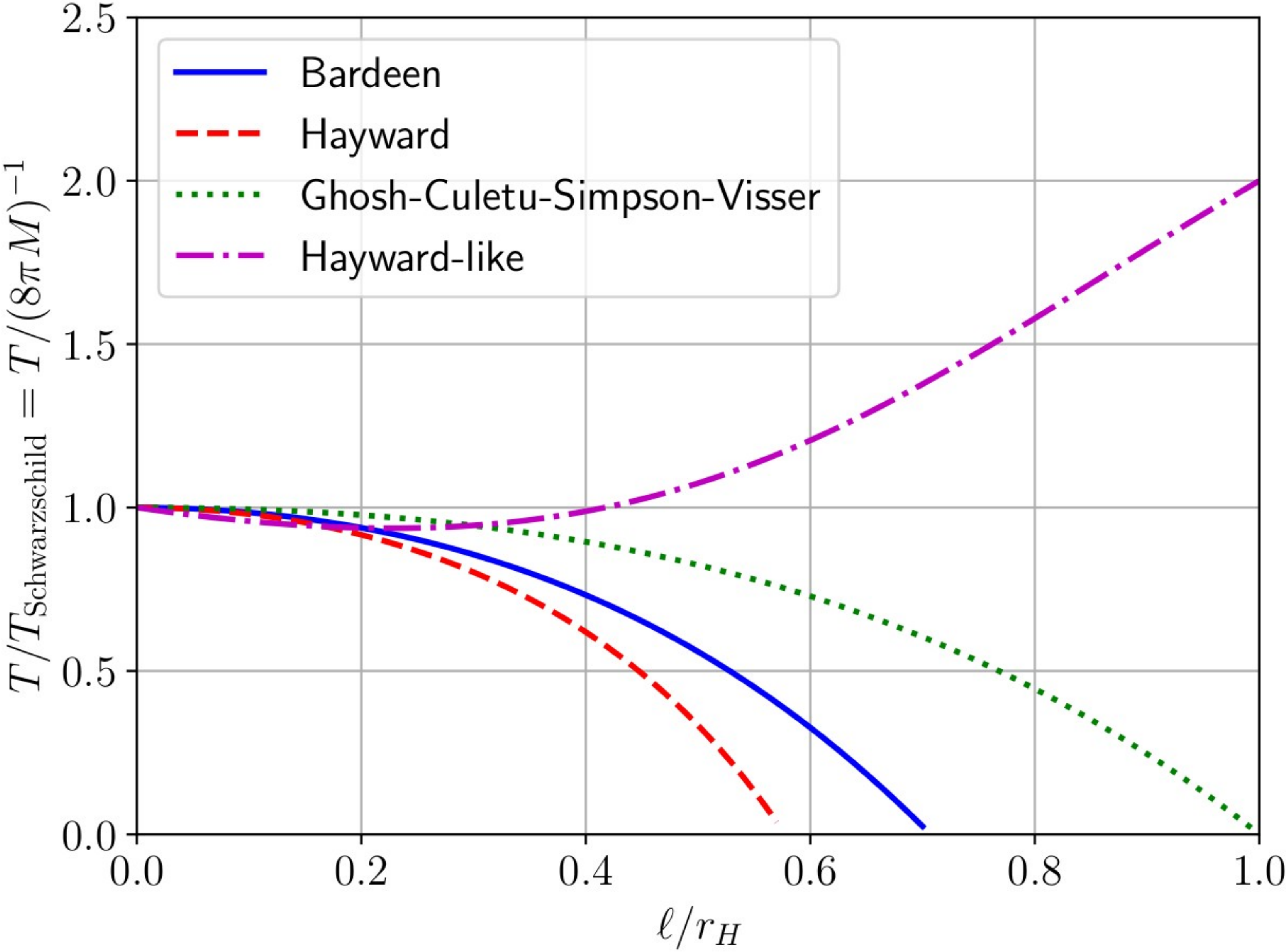


Why Primordial BHs

Masses small enough to emit particles in an interesting manner

$$\boldsymbol{M}\downarrow \; \& \; \boldsymbol{T_H}\uparrow$$

RBHs and Temperature



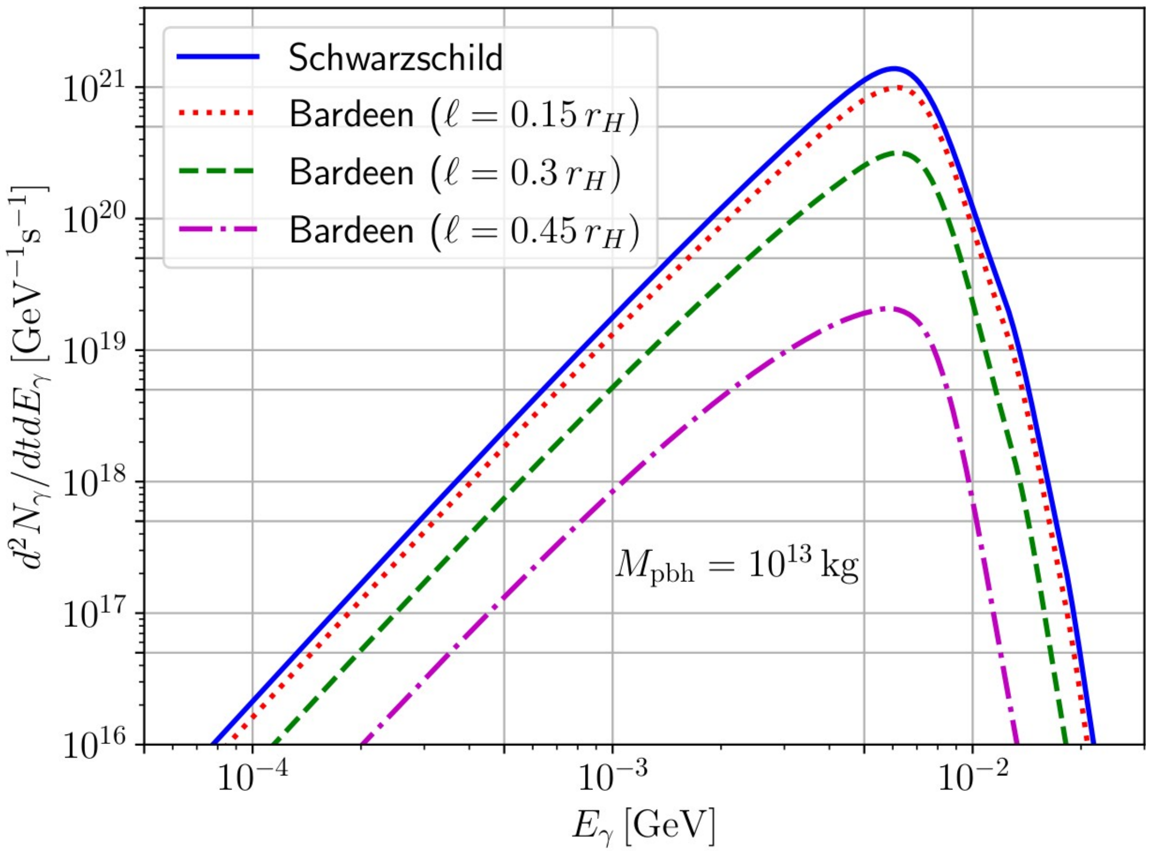
BHs evaporate

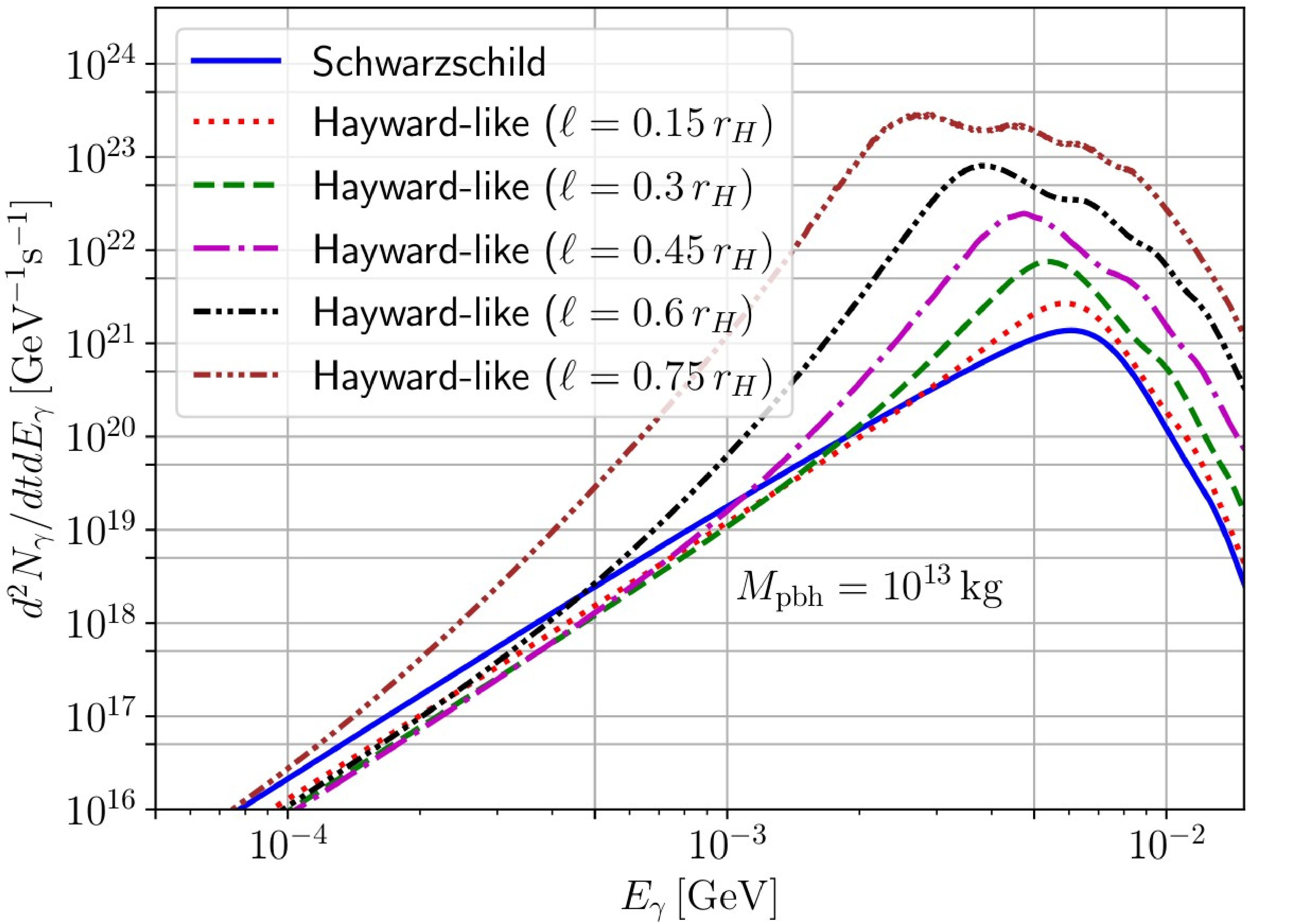
GR

QFT

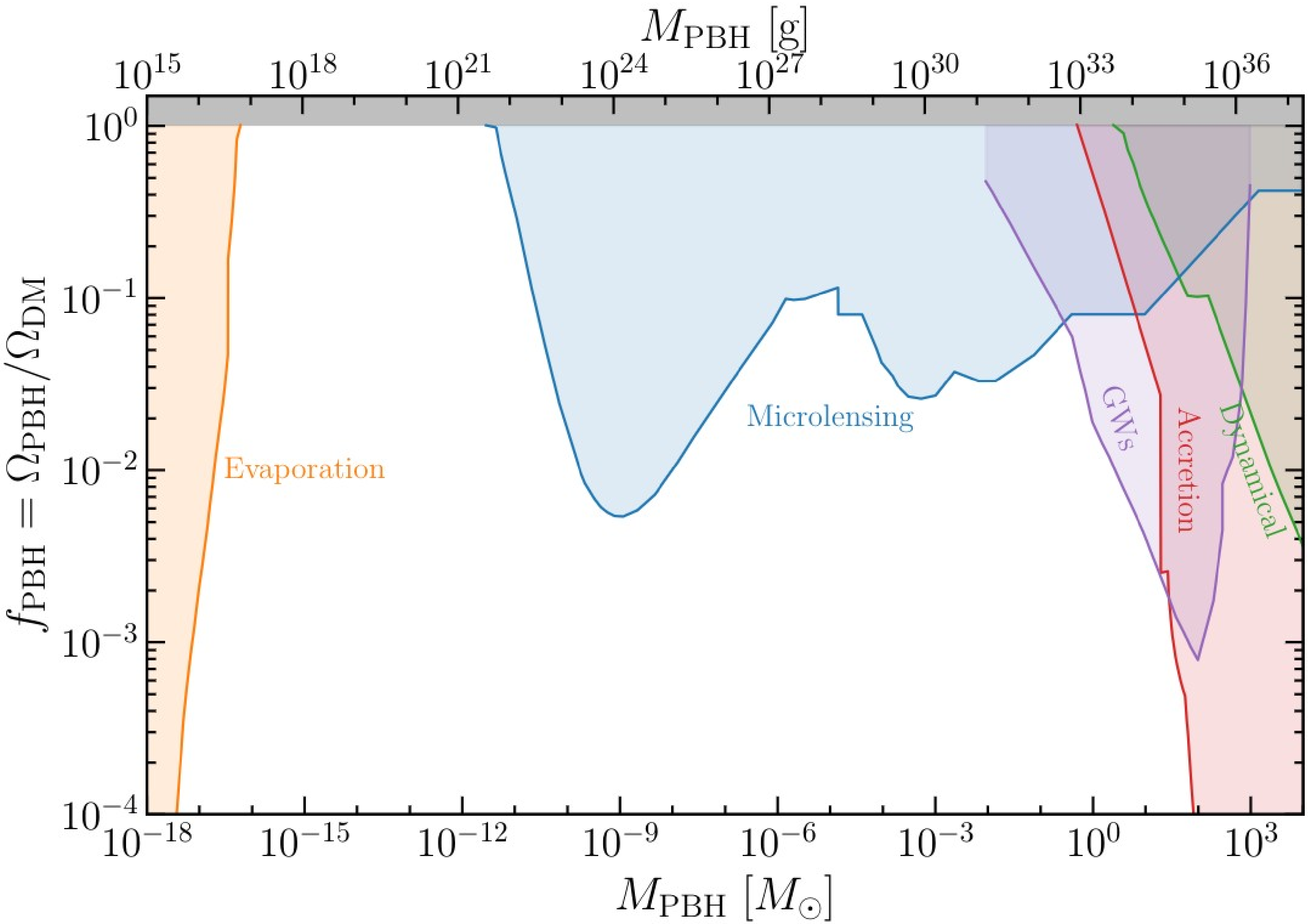
$$\frac{d^2 N_{P,i}}{dt dE_i} = \frac{1}{2\pi} \sum_{l,m} \frac{\Gamma^s_{l,m}(\omega)}{e^{\omega/T} \pm 1}$$

$\boldsymbol{M}\downarrow$ & $\boldsymbol{T_H}\uparrow$




Schwarzschild
Hayward-like ($\ell = 0.15\, r_H$)
Hayward-like ($\ell = 0.3\, r_H$)
Hayward-like ($\ell = 0.45\, r_H$)
Hayward-like ($\ell = 0.6\, r_H$)
Hayward-like ($\ell = 0.75\, r_H$)
$M_{\rm pbh} = 10^{13}\,{\rm kg}$
$d^2 N_\gamma / dt dE_\gamma$ [GeV^{-1}s^{-1}]
E_γ [GeV]
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
10^{23}
10^{24}
10^{-4}
10^{-3}
10^{-2}

PBH as DM fraction

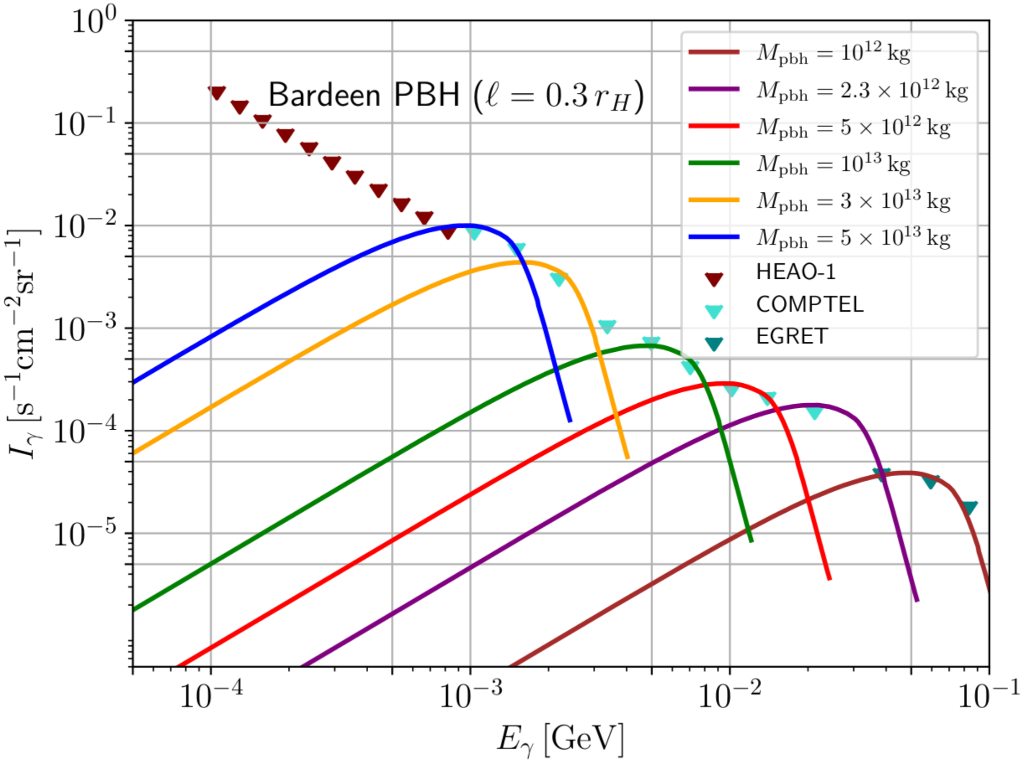


Evaporational constraint

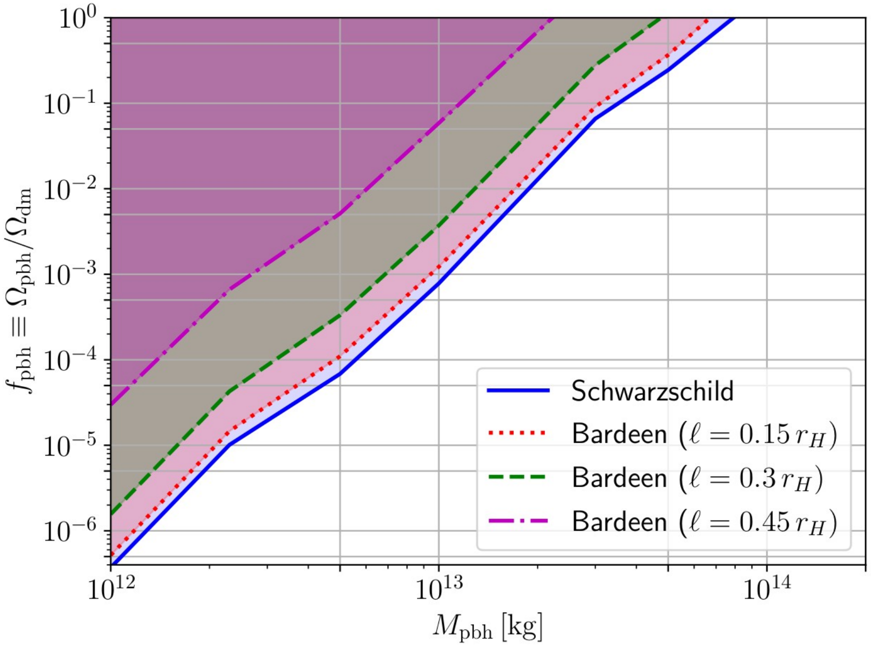
$$\frac{\mathrm{d}n_\gamma}{\mathrm{d}t}(E_\gamma, t) \simeq n_{\mathrm{PBH}}(t)\, E_\gamma\, \frac{\mathrm{d}\dot{N}_\gamma}{\mathrm{d}E_\gamma}(M(t), E_\gamma)\,,$$

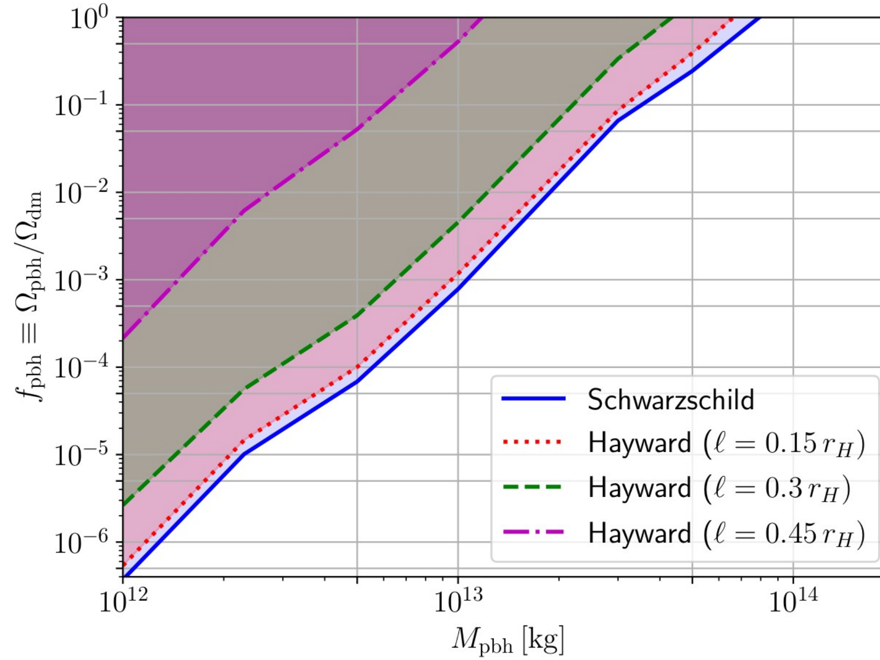
$$n_{\gamma 0}(E_{\gamma 0}) = n_{\mathrm{PBH0}}\, E_{\gamma 0} \int_{t_{\min}}^{\min(t_0,\tau)} \mathrm{d}t\,(1+z)\, \frac{\mathrm{d}\dot{N}_\gamma}{\mathrm{d}E_\gamma}(M(t), (1+z)\, E_{\gamma 0})\,,$$

$$I \equiv \frac{c}{4\pi}\, n_{\gamma 0}\,.$$



Results


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$f_{\rm pbh} \equiv \Omega_{\rm pbh}/\Omega_{\rm dm}$
10^{12}
10^{13}
10^{14}
$M_{\rm pbh}$ [kg]
Schwarzschild
Bardeen ($\ell = 0.15\, r_H$)
Bardeen ($\ell = 0.3\, r_H$)
Bardeen ($\ell = 0.45\, r_H$)


10^0
10^{-1}
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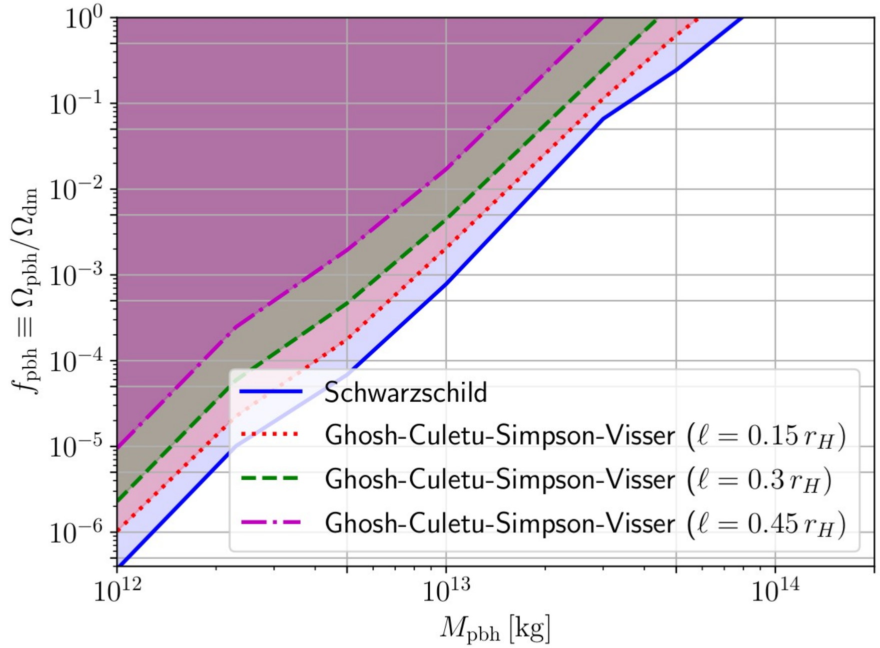
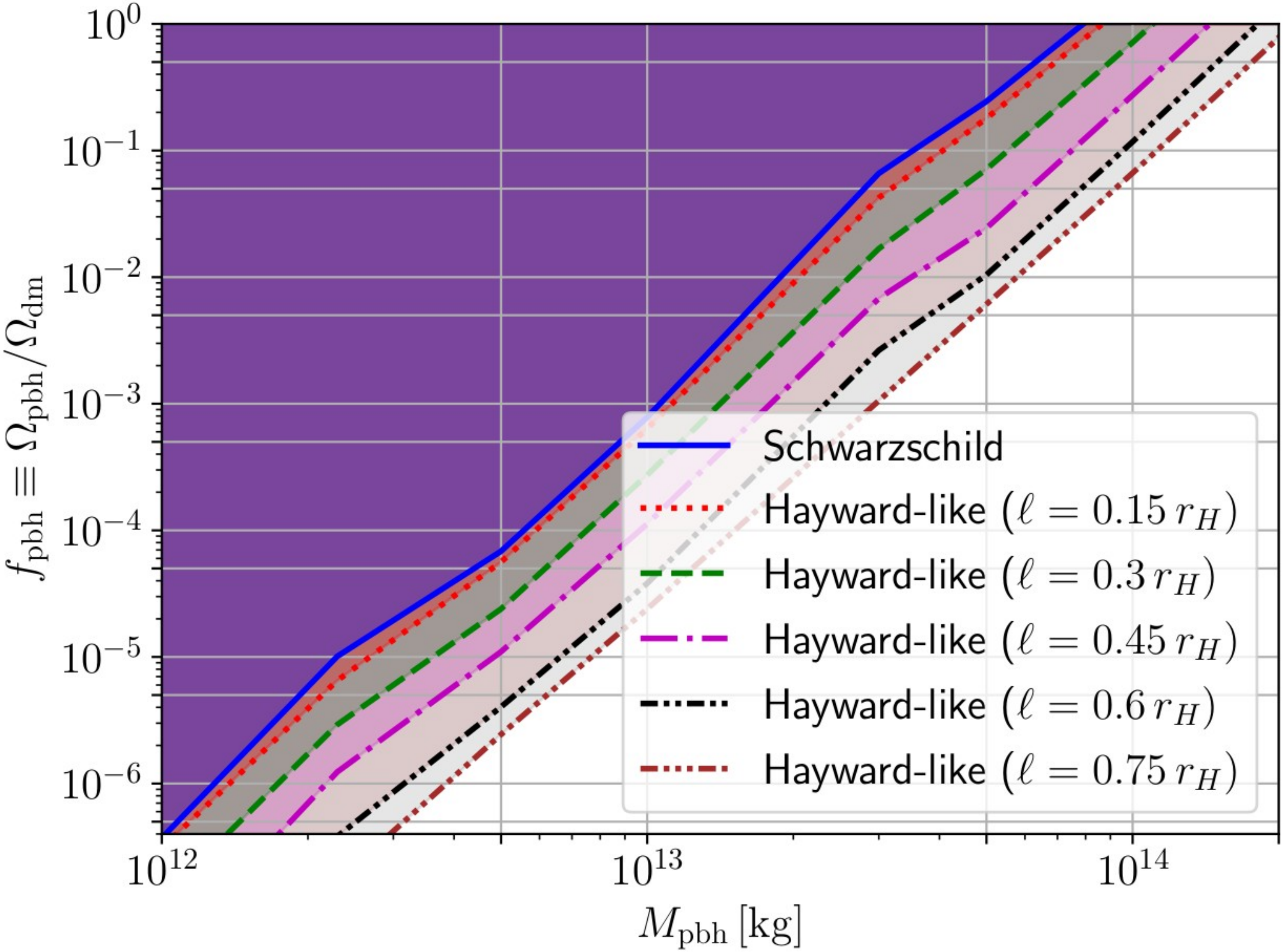
$f_{\rm pbh} \equiv \Omega_{\rm pbh}/\Omega_{\rm dm}$
10^{12}
10^{13}
10^{14}
$M_{\rm pbh}$ [kg]
Schwarzschild
Hayward ($\ell = 0.15\, r_H$)
Hayward ($\ell = 0.3\, r_H$)
Hayward ($\ell = 0.45\, r_H$)


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$f_{\rm pbh} \equiv \Omega_{\rm pbh}/\Omega_{\rm dm}$
10^{12}
10^{13}
10^{14}
$M_{\rm pbh}$ [kg]
Schwarzschild
Ghosh-Culetu-Simpson-Visser ($\ell = 0.15\, r_H$)
Ghosh-Culetu-Simpson-Visser ($\ell = 0.3\, r_H$)
Ghosh-Culetu-Simpson-Visser ($\ell = 0.45\, r_H$)

Results



10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$f_{\rm pbh} \equiv \Omega_{\rm pbh}/\Omega_{\rm dm}$
10^{12}
10^{13}
10^{14}
$M_{\rm pbh}\,[\rm kg]$
Schwarzschild
Hayward-like ($\ell = 0.15\, r_H$)
Hayward-like ($\ell = 0.3\, r_H$)
Hayward-like ($\ell = 0.45\, r_H$)
Hayward-like ($\ell = 0.6\, r_H$)
Hayward-like ($\ell = 0.75\, r_H$)

Conclusion

New Physics = New Constraint

Worth studying since it provides
a rich phenomenology!!!

Thanks for your attention!!!

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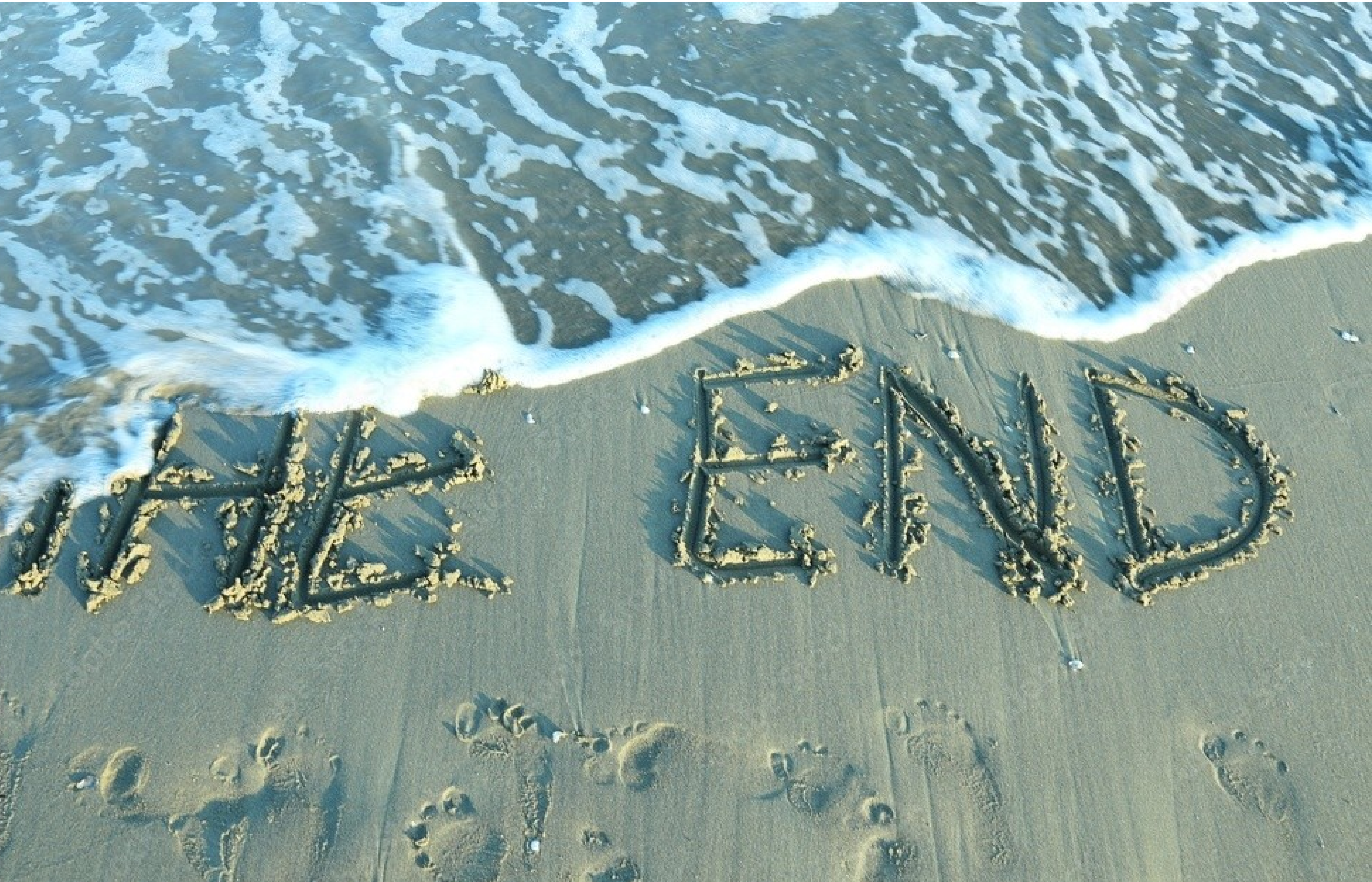
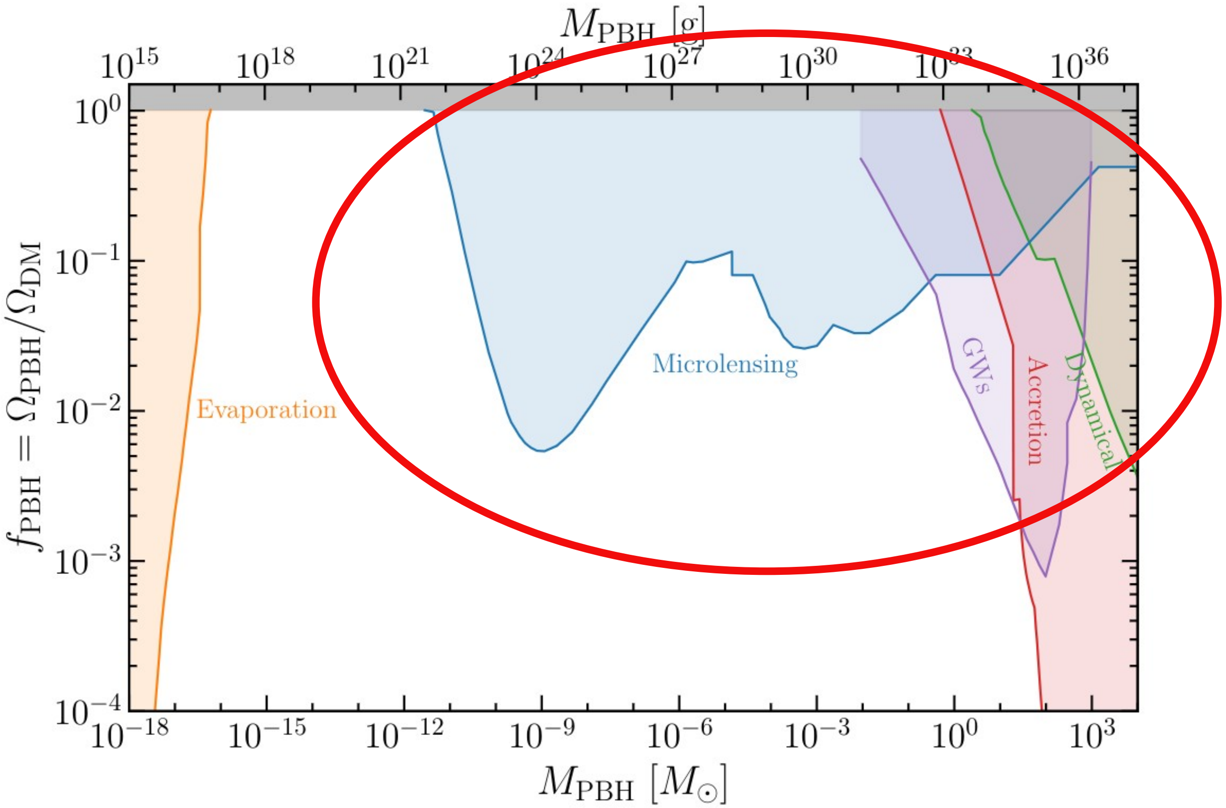


Future Directions

$$ds^2 = -f(r)dt^2 + g(r)^{-1}dr^2 + h(r)d\Omega^2$$



References

https://arxiv.org/pdf/2409.02804

https://arxiv.org/pdf/2409.02807

https://arxiv.org/pdf/XXXX.XXX