SWIFAR Journal Club: Search for the Hawking radiation of primordial black holes: prospective sensitivity of LHAASO.

Yang, Wang, Zhao, Zhang, JCAP 10 (2024) 083 [http://arXiv.org/abs/2408.10897]

Amol Upadhye

November 13, 2024

Hawking radiation's 50th birthday! 生日快乐

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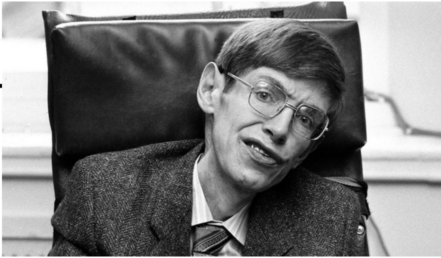
Letter | Published: 01 March 1974

Black hole explosions?

S. W. HAWKING[1]

Nature **248**, 30–31 (1974) | Cite this article



QUANTUM gravitational effects are usually ignored in calculations of the formation and evolution of black holes. The justification for this is that the radius of curvature of space-time outside the event horizon is very large compared to the Planck length $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm, the length scale on which quantum fluctuations of the metric are expected to be of order unity. This means that the energy density of particles created by the gravitational field is small compared to the space-time

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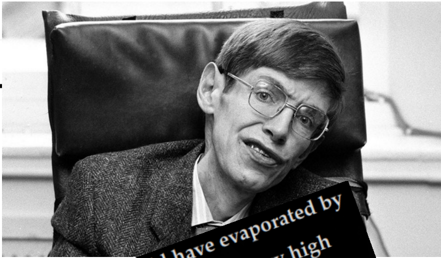
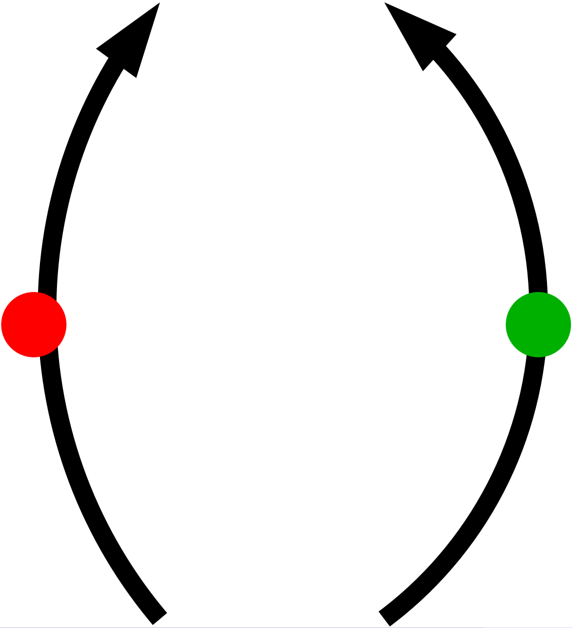


Any such black hole of mass less than 10^{15} g would have evaporated by now. Near the end of its life the rate of emission would be very high and about 10^{30} erg would be released in the last 0.1 s. This is a fairly small explosion by astronomical standards but it is equivalent to about 1 million 1 Mton hydrogen bombs.

Quantum fluctuations near a black hole



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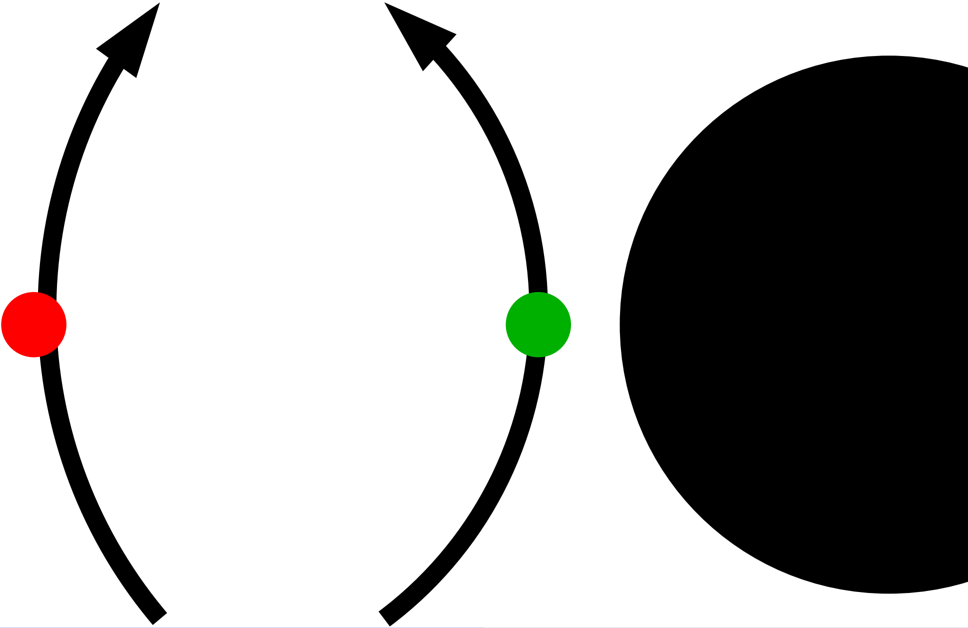

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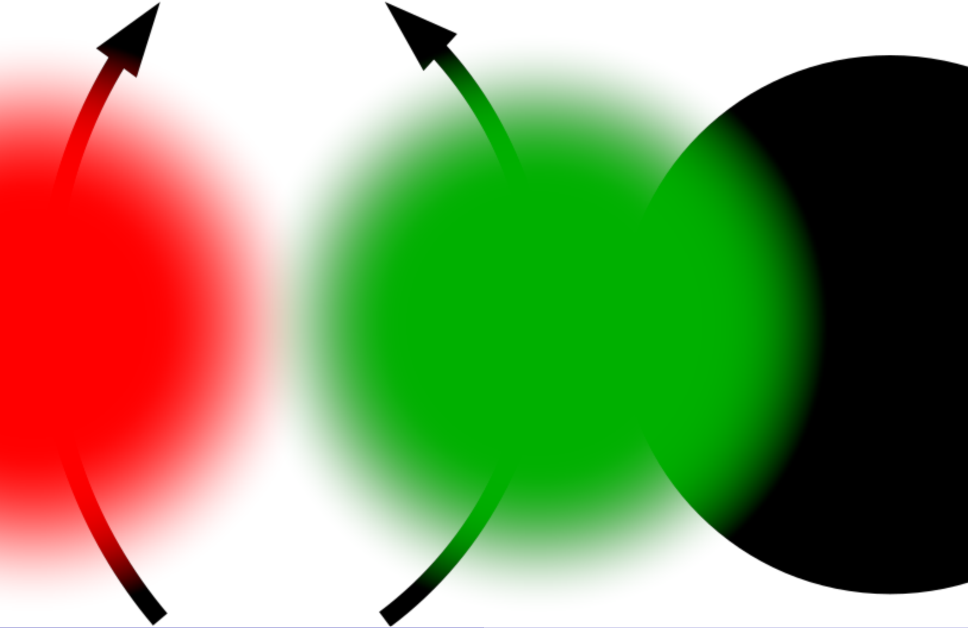

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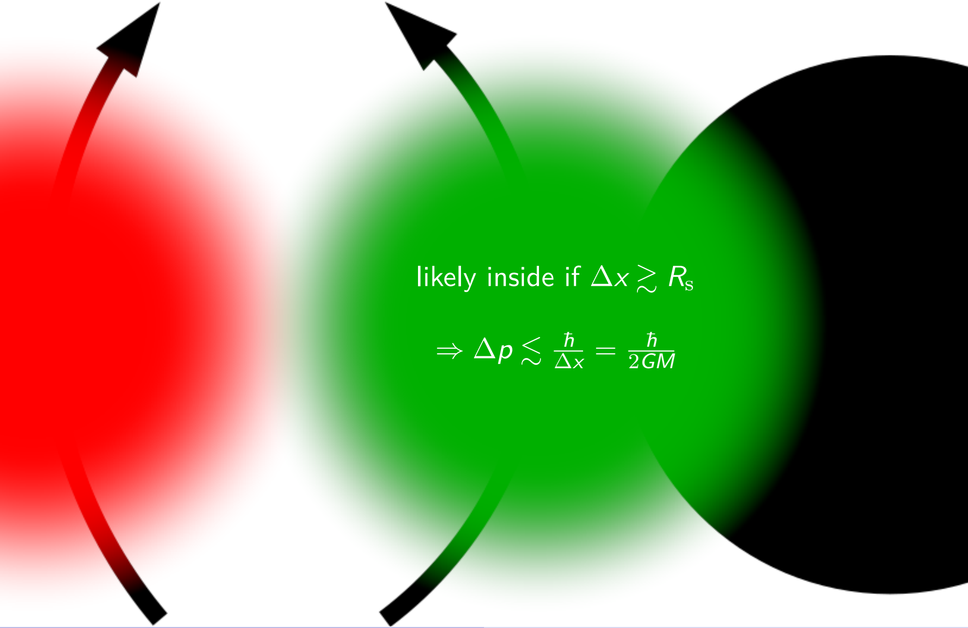
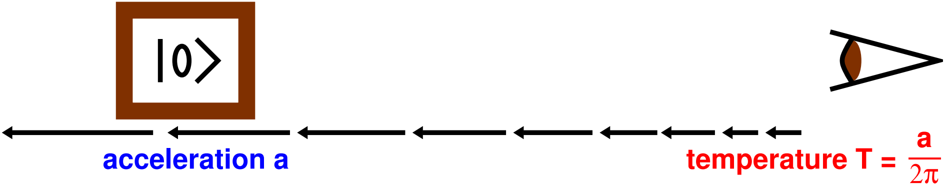


Black hole temperature



- Result from QFT in curved spacetime: a vacuum $|0\rangle$ in an accelerating frame looks like a thermal bath with $T = a/(2\pi)$ in your frame.

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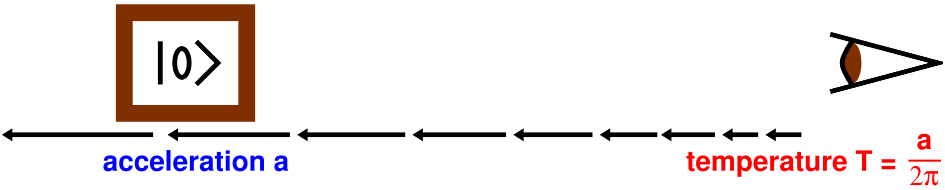

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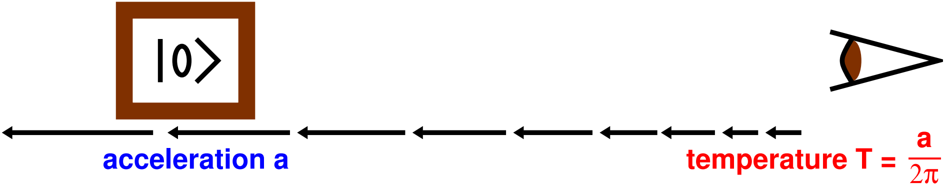

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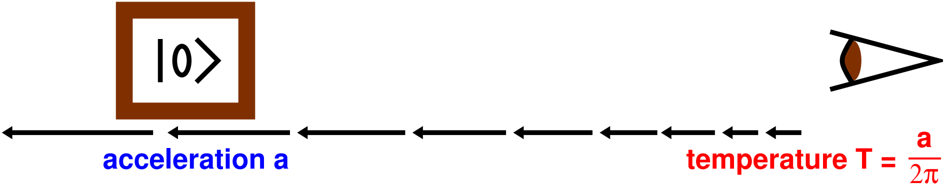

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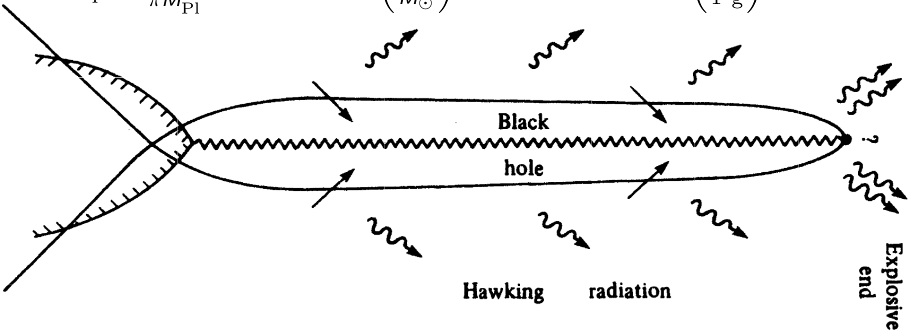
- Intensity $\propto T^4 \Rightarrow$ luminosity $L \propto T^4 R_s^2 \propto 1/M^2$

Explosion by Hawking radiation

The more mass the black hole loses, the hotter it gets, the more luminous it becomes, and the faster it loses mass.

$L \propto \frac{1}{M^2} \Rightarrow \frac{dM}{dt} = -L \propto -\frac{1}{M^2} \Rightarrow$ Explosive end of black hole

$$t_{\rm evap} = \frac{80M^3}{\pi M_{\rm Pl}^4} \approx 2.1 \times 10^{67} \left(\frac{M}{M_\odot}\right)^3 {\rm yr} \approx 3.4 \times 10^{-25} \left(\frac{M}{1\ {\rm g}}\right)^3 {\rm sec}$$



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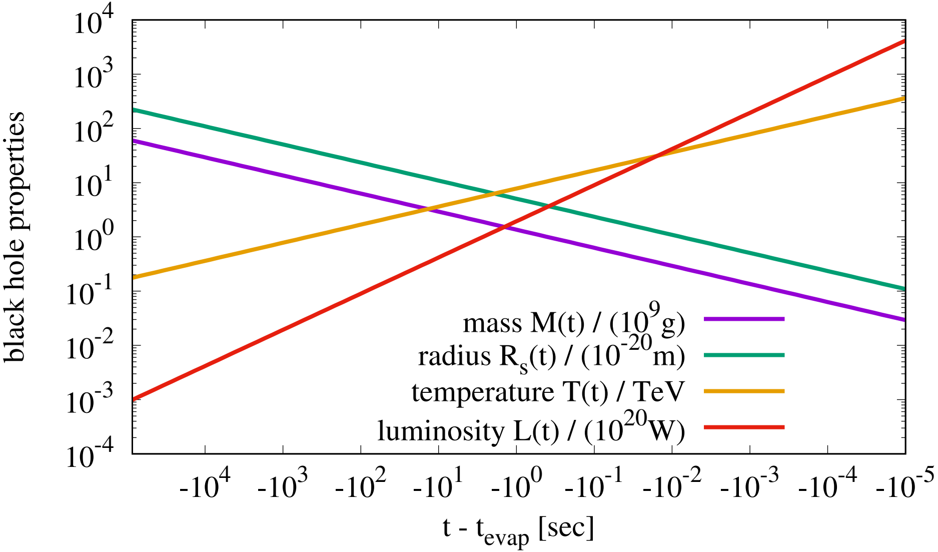
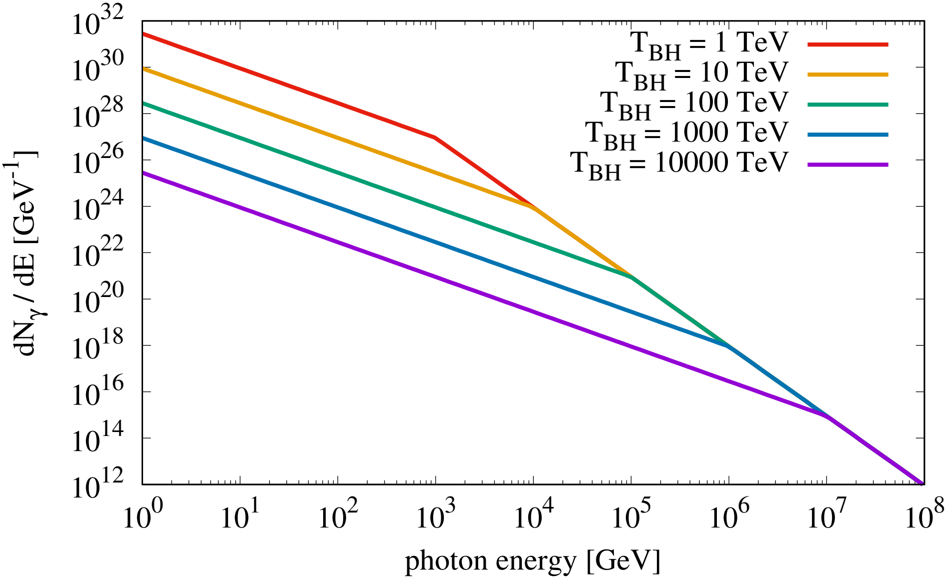
A black hole's last day



Large High-Altitude Air Shower Observatory (LHAASO)

LHAASO Science Book: arxiv.org/abs/1905.02773v4

Photon emission from a black hole



Detectability of black hole explosion

Expected number of photons with $E_1 \leq E \leq E_2$ from a black hole explosion at distance r from Earth:

$$\mu(r, \theta_i) = \int_{E_1}^{E_2} dE \, \frac{dN_\gamma}{dE} \, \frac{A_\gamma(E, \theta_i)}{4\pi r^2}$$

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Maximum distance to detectable explosion:

$$r_{\max}(\theta_i) = \sqrt{\int_{E_1}^{E_2} dE \, \frac{dN_\gamma}{dE} \, \frac{A_\gamma(E,\theta_i)}{4\pi \mu_{\min}(\theta_i)}}$$

where $\mu_{\min}$ is the minimum number of photons needed to detect the explosion to 5σ above the angle-dependent backgrounds (from protons and other cosmic rays).

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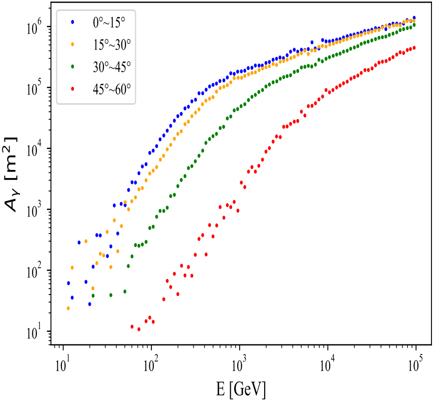
Upper limit (99% CL) on the black hole explosion rate:

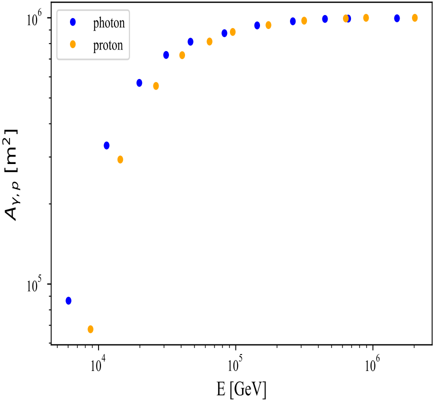
$$UL_{99} = \frac{4.6}{V \times S} \text{ where } V = \sum_i \frac{1}{3} r_{\max}^3 f_{\rm sky}(\theta_i),$$

S is the integration time, and $f_{\rm sky}(\theta_i)$ is the sky fraction observed in angular band i.

Detector areas



Water Cherenkov Detector Array(WCDA)



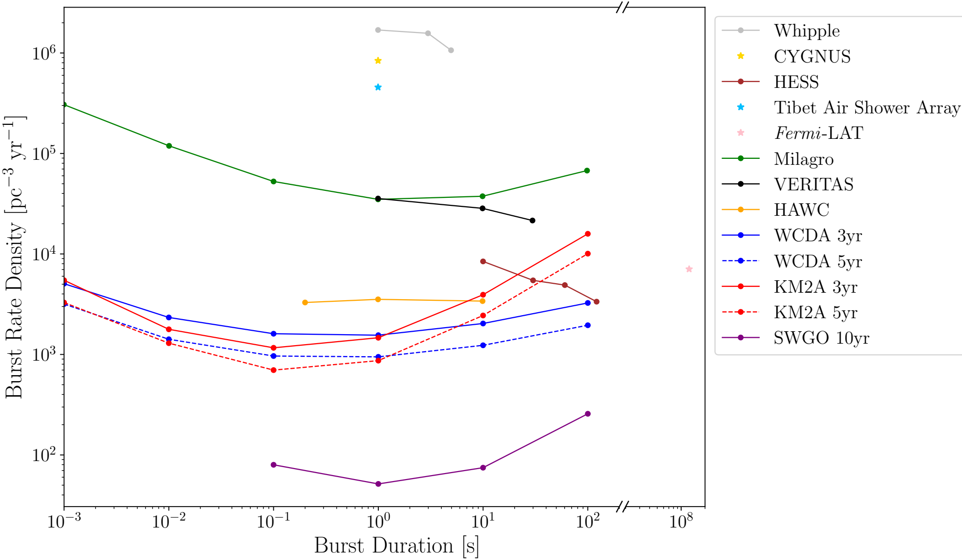
Kilometer Squared Array (KMSA)

Binned constraints on black hole explosion rate

Det.	τ [s]	$r_{\max}$ [pc]	UL_{99} [$\mathrm{pc}^{-3}\mathrm{yr}^{-1}$]
WCDA	10^{-3}	0.09	5100
	10^{-2}	0.11	2300
	10^{-1}	0.12	1600
	1	0.13	1600
	10	0.12	2000
	10^{2}	0.11	3300
KM2A	10^{-3}	0.08	5500
	10^{-2}	0.11	1800
	10^{-1}	0.13	1200
	1	0.12	1400
	10	0.09	4100
	10^{2}	0.05	16000

The 99% confidence level upper limits on the local burst rate density of PBHs, i.e., UL_{99}, for WCDA and KM2A for a 3 year observing run.

Total constraints on black hole explosion rate



Summary

1. Hawking radiation from quantum-mechanical black holes was predicted 50 years ago.
2. Small black holes of mass $M \gtrsim 10^{14}$ g would explode today due to Hawking radiation. Along the way, they will reach higher energies than our particle colliders.
3. Primordial black holes of these masses cannot be ruled out on either experimental (microlensing) or theoretical grounds, and may be candidates for the dark matter.
4. LHAASO will be sensitive to black hole explosions within about 0.1 pc of the Earth and will be able to bound the explosion rate per unit volume.