Black Hole Metamorphosis: What Happens after Half Evaporation?

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Work[1] with Gia Dvali, Lukas Eisemann and Marco Michel

EPS-HEP2021

28^{th} July 2021

[1] G. D., L. E., M. M., S. Z., *Black hole metamorphosis and stabilization by memory burden*, Phys. Rev. D **102** (2020) , `arXiv:2006.00011`.

Outline

What happens to a black hole after losing half of its mass?

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1. Why it is an open question
2. A proposal: slowdown

Hawking evaporation

- Geometry

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- Entropy[2]

$$S = \hbar^{-1} r_g M$$

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- Hawking particle production:[3] $\frac{\mathrm{d}E}{\mathrm{d}t} \sim \frac{\hbar r_g^{-1}}{r_g}$

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- Hawking particle production:[3] $\frac{\mathrm{d}E}{\mathrm{d}t} \sim \frac{\hbar r_g^{-1}}{r_g}$
- Half evaporation

$$t_{1/2} \sim r_g S$$

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Semi-classical approximation

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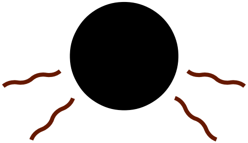
- Quantum fields in fixed metric: black hole mass constant
- No statement about backreaction
- Open question: What does black hole evolve to?

No self-similarity?



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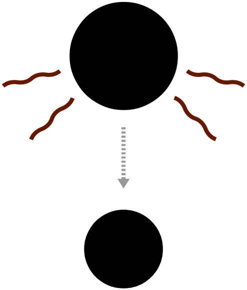

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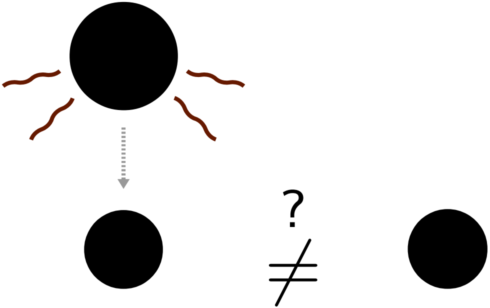

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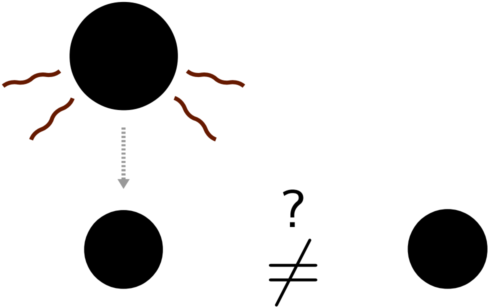

After losing significant fraction of mass:
full deviation from Hawking evaporation possible

Black hole metamorphosis

$$t_{1/2} \sim r_g S$$

$$\downarrow$$

half evaporation: metamorphosis

Black hole metamorphosis

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↓

half evaporation: metamorphosis

↙

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slowdown

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Hawking continues

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↓

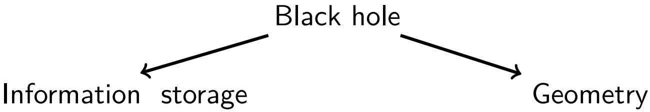
half evaporation: metamorphosis

$t_{2/2} \sim r_g S^2$	$t_{2/2} \sim r_g S$	$t_{2/2} \sim r_g$
slowdown	Hawking continues	classical instability

Outline

What happens to a black hole after losing half of its mass?

Analogue quantum systems



Analogue quantum systems

Black hole

Information storage

Geometry

Analogue quantum systems

Black hole

Information storage — Geometry

- Key property: large entropy S

Analogue quantum systems

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Analogue quantum systems

Black hole

Information storage ← Black hole → Geometry

- Key property: large entropy S
- Number of microstates: e^S
- Requirement: similar energy

Prototype model[4]

- Use S modes $\hat{a}_1^\dagger, \ldots, \hat{a}_S^\dagger$

$$\frac{\hat{\mathcal{H}}_S}{r_g^{-1}} = \sqrt{S} \sum_{k=1}^{S} \underbrace{\hat{n}_k}_{\hat{a}_k^\dagger \hat{a}_k}$$

[4] G. Dvali, *A Microscopic Model of Holography: Survival by the Burden of Memory*, arXiv:1810.02336.

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- Dictionary

$\hat{n}_0$: carries mass

$\langle \hat{n}_0 \rangle = S$: black hole state

$\hat{n}_k$: carry entropy

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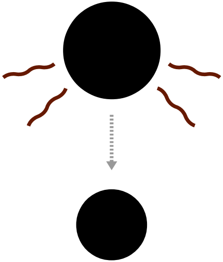

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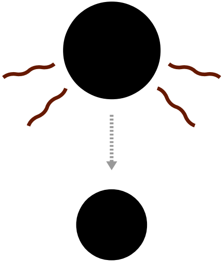

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- Finding:[5] transition slow

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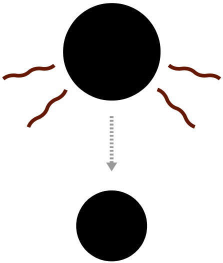

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- Finding:[5] transition slow
- Slowdown at the latest after half evaporation

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slowdown	Hawking continues	classical instability

Primordial black holes as dark matter

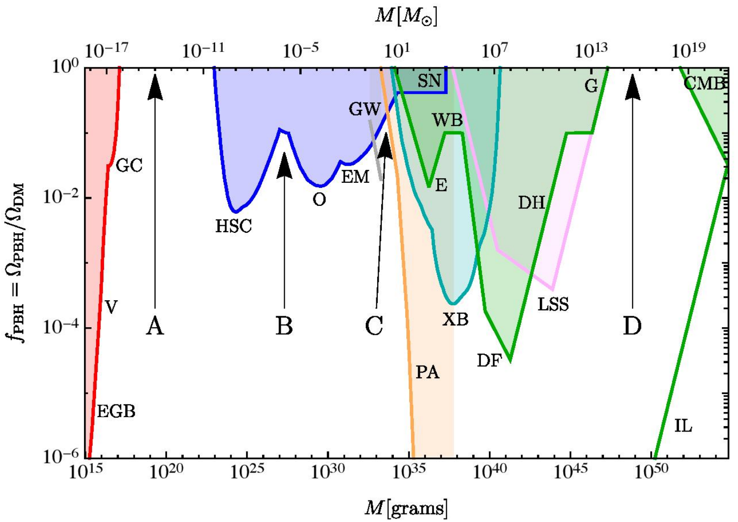

Figure from: B. Carr, F. Kühnel, *Primordial Black Holes as Dark Matter: Recent Developments*, `arXiv:2006.02838`.

Primordial black holes as dark matter

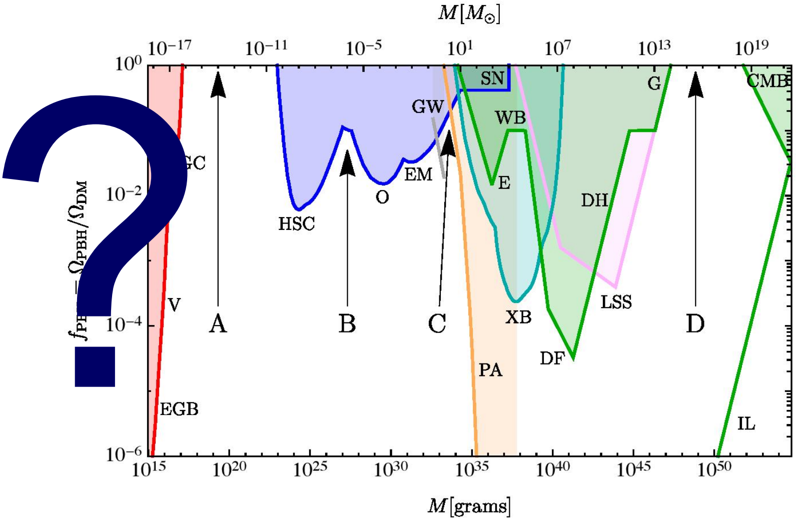

Figure from: B. Carr, F. Kühnel, *Primordial Black Holes as Dark Matter: Recent Developments*, arXiv:2006.02838.

Conclusions

- After black hole has lost half of its mass:
  full deviation from Hawking evaporation possible
- Analogue model: indications for slowdown
- Small primordial black holes as dark matter candidates

Semiclassical correction to Hawking evaporation[6]

- Temperature

$$T = \frac{1}{r_g} = \frac{1}{GM^2}$$

[6] G. Dvali, *Non-Thermal Corrections to Hawking Radiation Versus the Information Paradox*, arXiv:1509.04645.

Semiclassical correction to Hawking evaporation[6]

- Temperature

$$T = \frac{1}{r_g} = \frac{1}{GM^2}$$

- Change of mass

$$\dot{M} = \frac{\Delta M}{\Delta t} \sim r_g^{-2} = T^2$$

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$$\dot{T} = \frac{\dot{M}}{M} T \sim \frac{T^3}{M} \Leftrightarrow \frac{\dot{T}}{T^2} \sim \frac{1}{S}$$

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- Correction of order 1 after

$$t_{\text{Hawking}} \sim r_g S$$

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Full model

- Hamiltonian

$$\hat{H} = \epsilon_0 \hat{n}_0 + \epsilon_0 \hat{b}_0^\dagger \hat{b}_0 + \left(1 - \frac{\hat{n}_0}{N_c}\right) \sum_{k=1}^{K} \epsilon_k \hat{n}_k + C_0 \left(\hat{a}_0^\dagger \hat{b}_0 + \hat{b}_0^\dagger \hat{a}_0\right)$$
$$+ \left(1 - \frac{\hat{n}_0}{N_c - \Delta N}\right) \sum_{k'=1}^{K'} \epsilon_{k'} \hat{n}'_{k'} + \sum_{k=1}^{K} \sum_{k'=1}^{K'} C_{k,k'} \left(\hat{a}_k^\dagger \hat{a}'_{k'} + \text{h.c.}\right)$$
$$+ \sum_{k=1}^{K} \sum_{\substack{l=1 \\ l \neq k}}^{K} \tilde{C}_{k,l} \left(\hat{a}_k^\dagger \hat{a}_l + \text{h.c.}\right) + \sum_{k'=1}^{K'} \sum_{\substack{l'=1 \\ l' \neq k'}}^{K'} \tilde{C}_{k',l'} \left(\hat{a}'^\dagger_{k'} \hat{a}'_{l'} + \text{h.c.}\right)$$

- Initial state

$$|\text{in}\rangle = |\underbrace{N_c}_{n_0}, 0, n_1, \ldots, n_K, \underbrace{0}_{n'_1}, \ldots, \underbrace{0}_{n'_{K'}}\rangle$$

- Final state

$$|\text{out}\rangle = |N_c - \Delta N, \Delta N, 0, \ldots, 0, n'_1, \ldots, n'_{K'}\rangle$$

Time evolution