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Institut Pascal – Astroparticle Symposium 2023

Primordial Black Holes are True Vacuum Nurseries

King's College London

Durham University

UKRI Science and Technology Facilities Council

In collaboration with

Give him a job!

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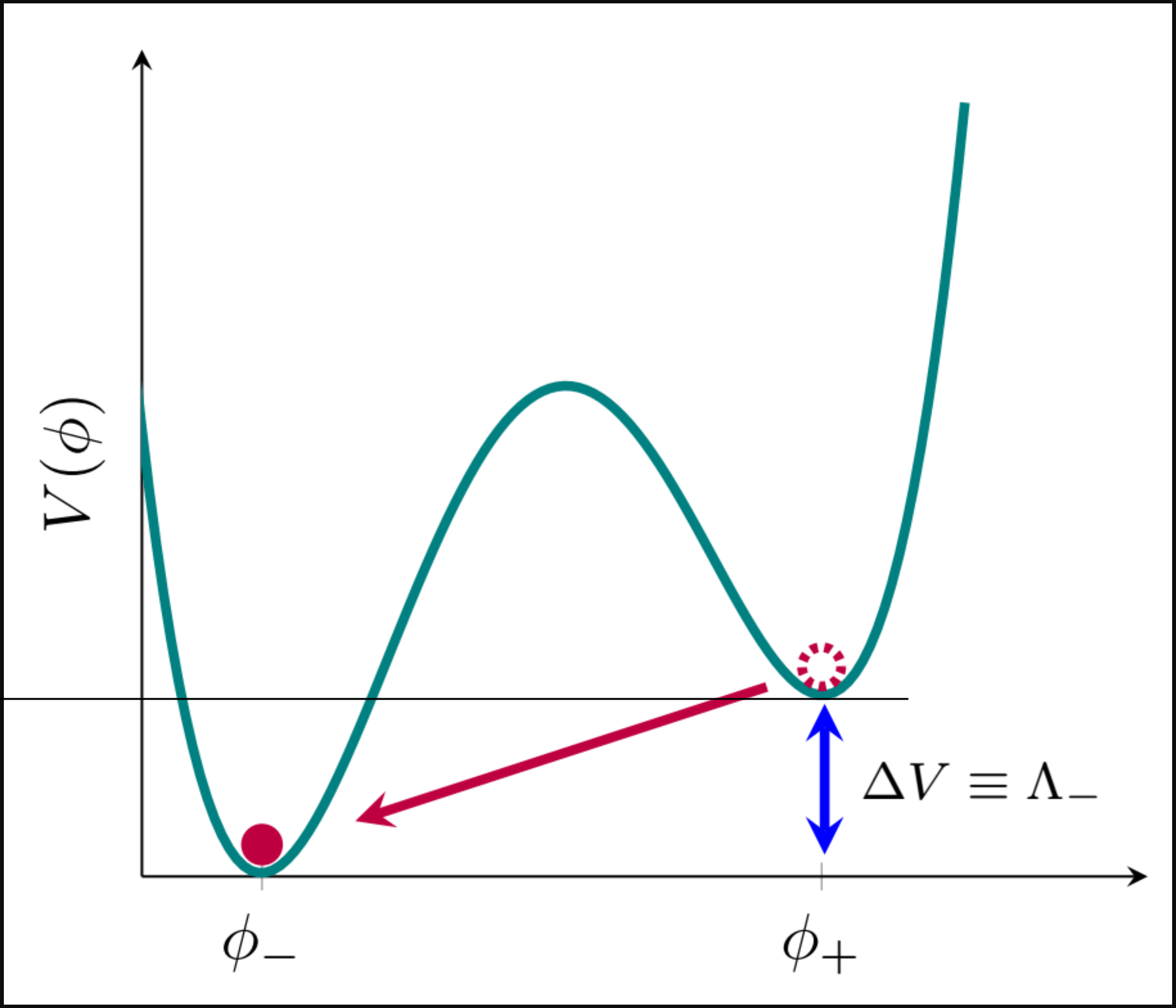
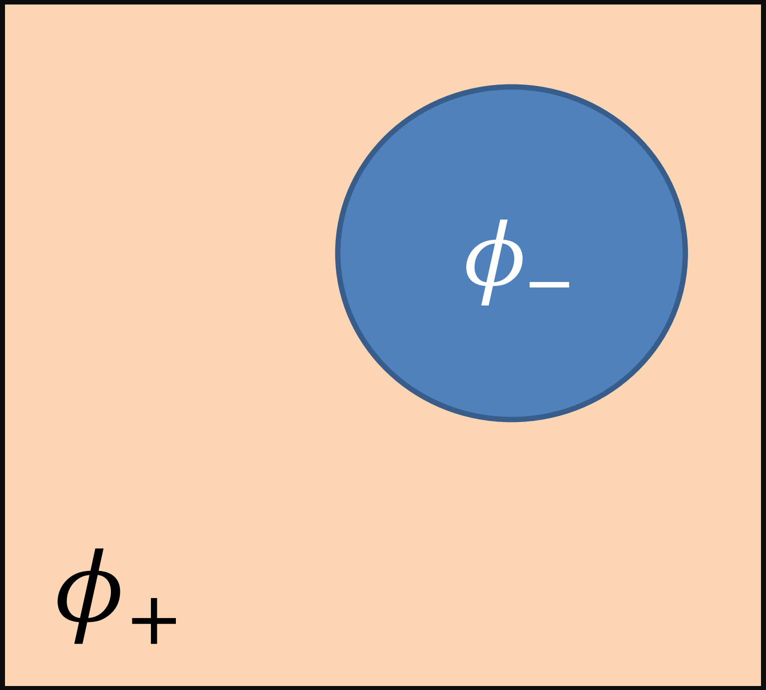
1st-Order Phase Transitions for Dummies



1st-Order Phase Transitions for Dummies



Transition ⟷ Energy Loss

In the vacuum: S. R. Coleman, Phys. Rev. D 15, 2929 (1977)

→ The bubble expands ($O(4)$ symmetric bubble)

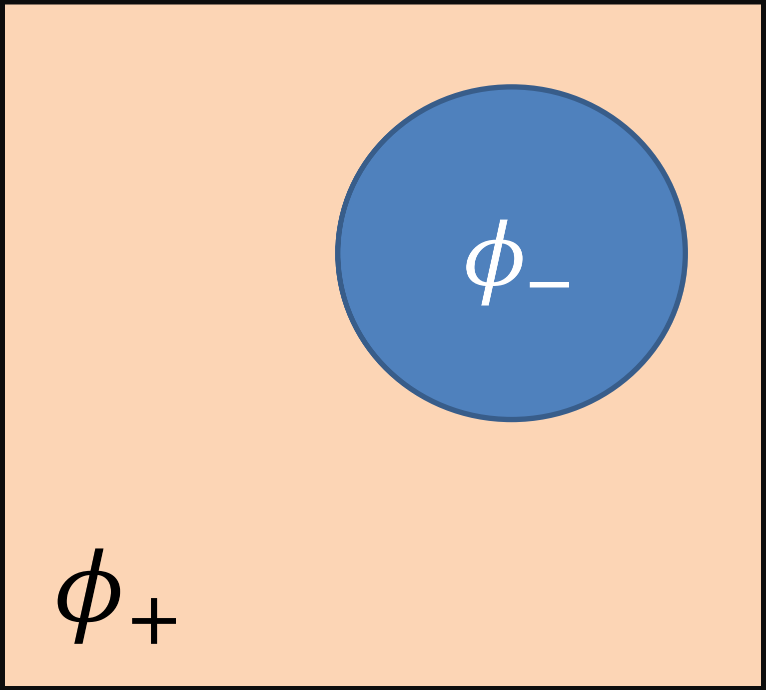
Energy = Kinetic

In a Thermal Bath: A. D. Linde, Phys. Lett. B 100, 37 (1981).

→ The bubble is static ($O(3)$ symmetric bubble)

Energy from Thermostat

1st-Order Phase Transitions for Dummies



Transition ⟷ Energy Loss

In (COLD) GR: Coleman & De Luccia, Phys. Rev. D 21, 3305 (1980).

→ The metric and bubble adjust to conserve energy

Energy = Metric Deformation

Question: What happens around a radiating Black Hole?

1^{ST}-ORDER PHASE TRANSITIONS FOR DUMMIES

QUESTION: What happens around a radiating Black Hole?

SO FAR: Only considered in very extreme situations...

BH radiating in the vacuum (Unruh vacuum)

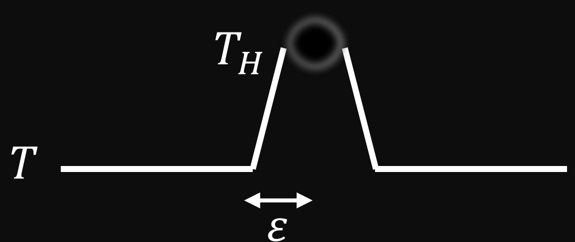
→ No definite answer. Partial results only obtained in 2D.

BH in thermal equilibrium with the plasma (Hartle-Hawking vacuum)

→ The BH and the plasma both behave as thermostats.

$$I_{\rm b}[T] = \beta \int dx^3 \sqrt{-h} \left(-\frac{R}{16\pi G} + \frac{1}{2} h^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + V(\phi) \right)$$

+ Bckgd terms
+ Conical deficit
if $\beta \neq \beta_H$



$$I_{\rm b}[T] = \frac{\mathcal{A}_+}{4G} - \frac{\mathcal{A}_-}{4G} = I_{\rm b}[T_H]$$

Gregory, Moss, and Withers, JHEP 03, 081(2014)

Only used with Hartle-Hawking so far...

1st-Order Phase Transitions for Dummies

Question: What happens around a radiating Black Hole?

So Far: Only considered in very extreme situations...

BH radiating in the vacuum (Unruh vacuum)

→ No definite answer. Partial results only obtained in 2D.

BH in thermal equilibrium with the plasma (Hartle-Hawking vacuum)

→ The BH and the plasma both behave as thermostats.

Reality stands in between the two.

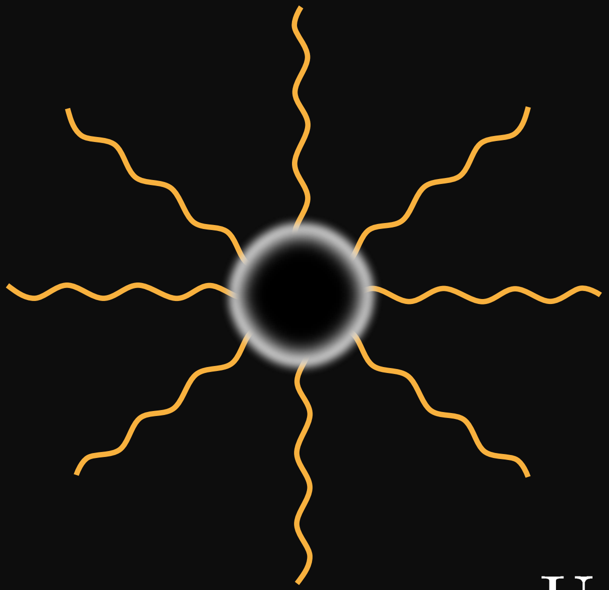
Primordial Black Holes

are

powerful radiators

in

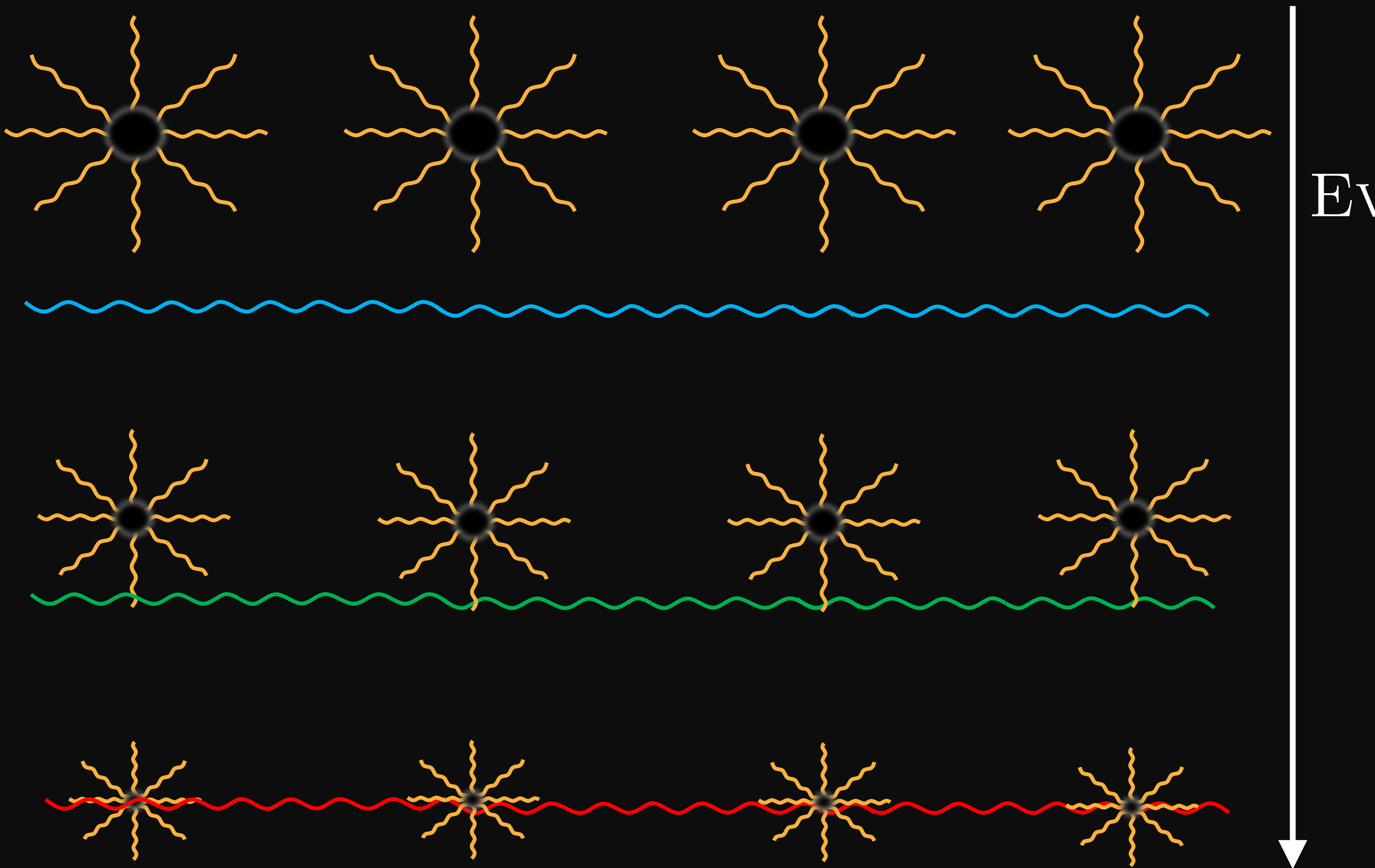
Cosmology



Hawking Radiation $E \sim T_H$

Universe Temperature $T \ll T_H$

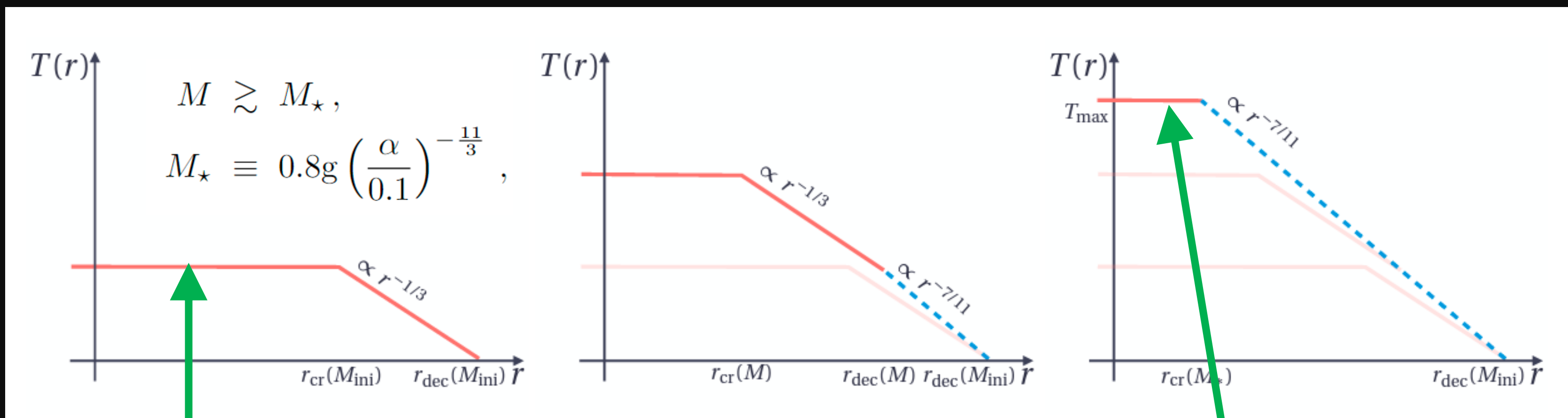
Common Belief



In Reality

Hawking Radiation heats the ambient plasma locally

He et al. *JCAP* 01 (2023) 027



$$T_{\rm plateau} \approx 2\times 10^{-4}\left(\frac{\alpha}{0.1}\right)^{\frac{8}{3}} T_H$$

$$r_{\rm plateau} \approx 7\times 10^{8}\left(\frac{\alpha}{0.1}\right)^{-6} r_H$$

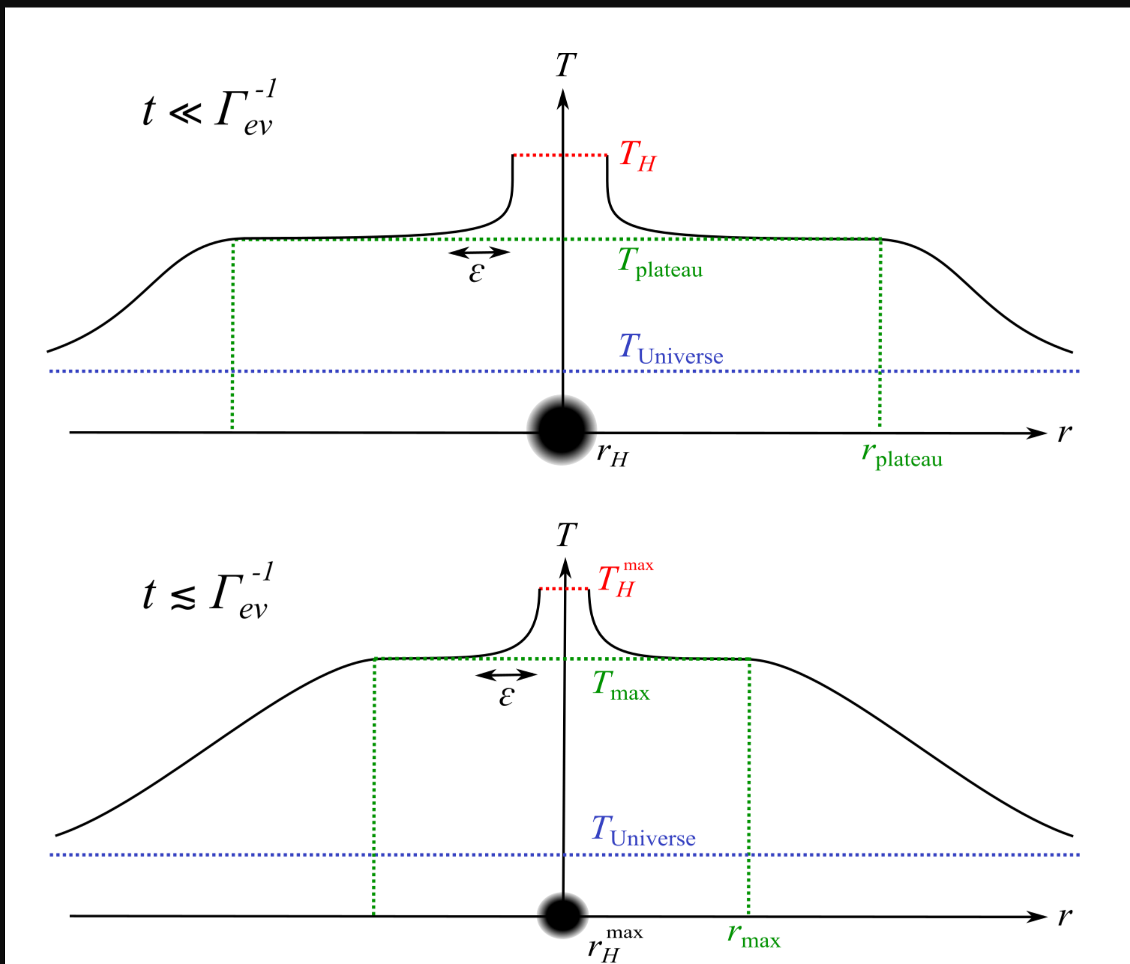
$$T_{\rm max} \approx 2\times 10^{9}\,\text{GeV}\left(\frac{\alpha}{0.1}\right)^{\frac{19}{3}}$$

$$r_{\rm max} = r_{\rm plateau}\Big|_{T_H = T_{\rm max}}$$

In Reality

Hawking Radiation heats the ambient plasma locally

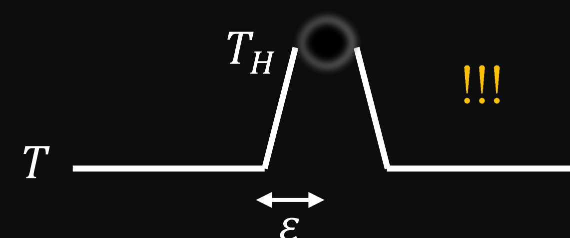
Our best guess:



$$\Gamma(T) \sim \alpha^2 T \sqrt{\frac{T}{T_H}}\,.$$

$$dP \sim \Gamma(T) e^{-(r-r_H)\Gamma(T)} dr$$

Physical realisation of



[Hamaide, Heurtier, Hu, Cheek, to appear]

In Reality

Hawking Radiation heats the ambient plasma locally

→ In the $\varepsilon \to 0$ limit, can use the result

$$I_{\rm b}[T] = \frac{\mathcal{A}_+}{4G} - \frac{\mathcal{A}_-}{4G} = I_{\rm b}[T_H] \quad (*)$$

→ To calculate the rate:

$$\Gamma^{\rm HH}_{\rm FVD} \equiv (GM_+)^{-1} \left(\frac{I_{\rm b}[T_H]}{2\pi}\right)^{1/2} \exp\left(-I_{\rm b}[T_H]\right) .$$

T_H

Linde's result

$$\frac{\Gamma}{V} = T\left(\frac{S_3(\varphi)}{2\pi T}\right)^{3/2} \exp\left[-S_3(\varphi)/T\right]$$

Generalisation to arbitrary T

$$\Gamma_{\rm FVD}(T) \approx T\left(\frac{I_{\rm b}[T]}{2\pi}\right)^{1/2} \exp\left(-I_{\rm b}[T]\right) ,$$

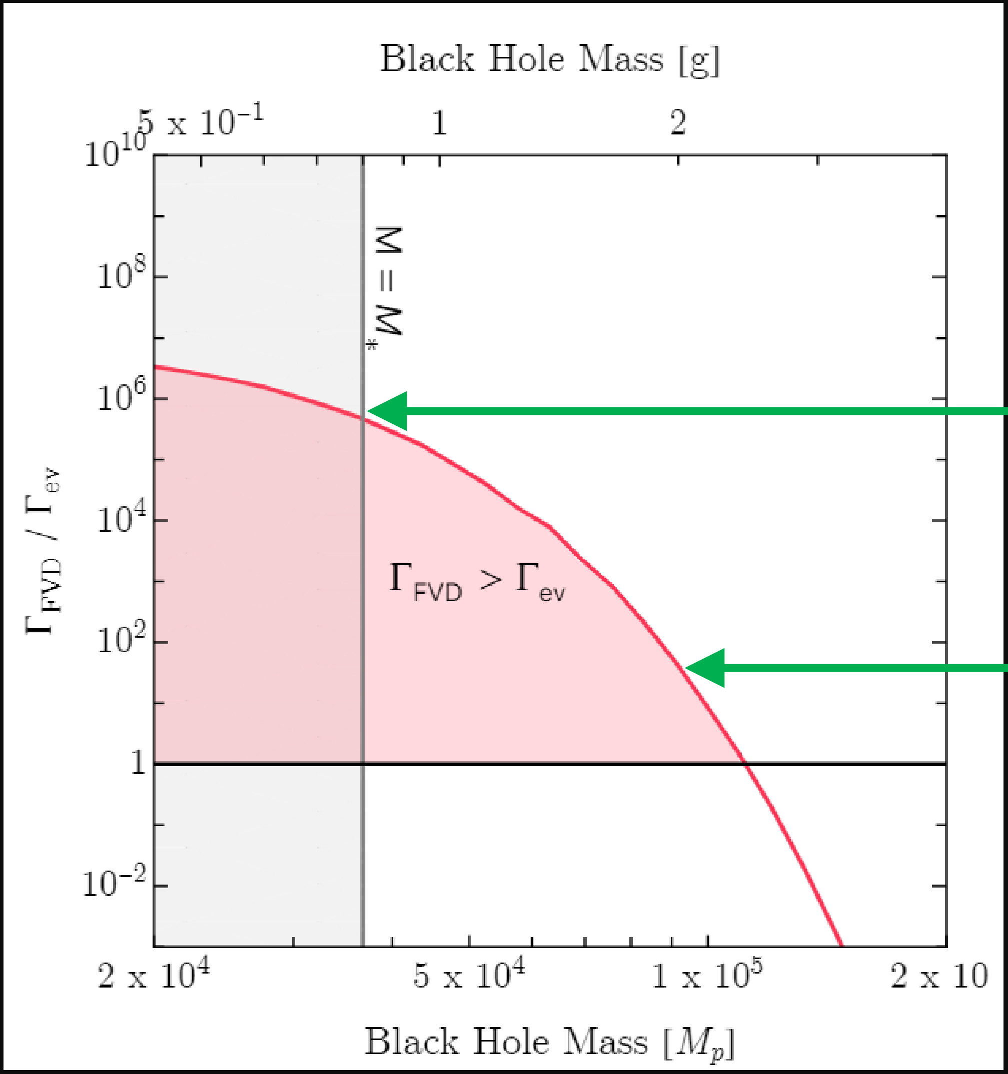
$$\approx T\left(\frac{I_{\rm b}[T_H]}{2\pi}\right)^{1/2} \exp\left(-I_{\rm b}[T_H]\right)$$

$(*)$

Rate to be compared to the evaporation rate...

An example: The EW vacuum

Our Universe may be metastable (at ~2σ)



At $M = M_*$, $T = T_{max}$

Using $T_{plateau}(M)$

[Hamaide, Heurtier, Hu, Cheek, to appear]

An example: The EW vacuum

Our Universe may be metastable (at ~2σ)

$$P_{\rm FVD} \equiv 1 - e^{-\Gamma_{\rm FVD}\Delta t}$$

Using $T_{plateau}(M)$

$$\Delta t \sim \Gamma_{\rm ev}^{-1}$$

$$P_{\rm FVD}(M) = 1 - e^{-\Gamma_{\rm FVD}(T_{\rm plateau})/\Gamma_{\rm ev}}$$

Using T_{max}

$$P_{\rm FVD} \approx 1 \text{ as long as } \Delta t \lesssim 10^{-6} \times \Gamma_{\rm ev}^{-1}$$

Constraint:

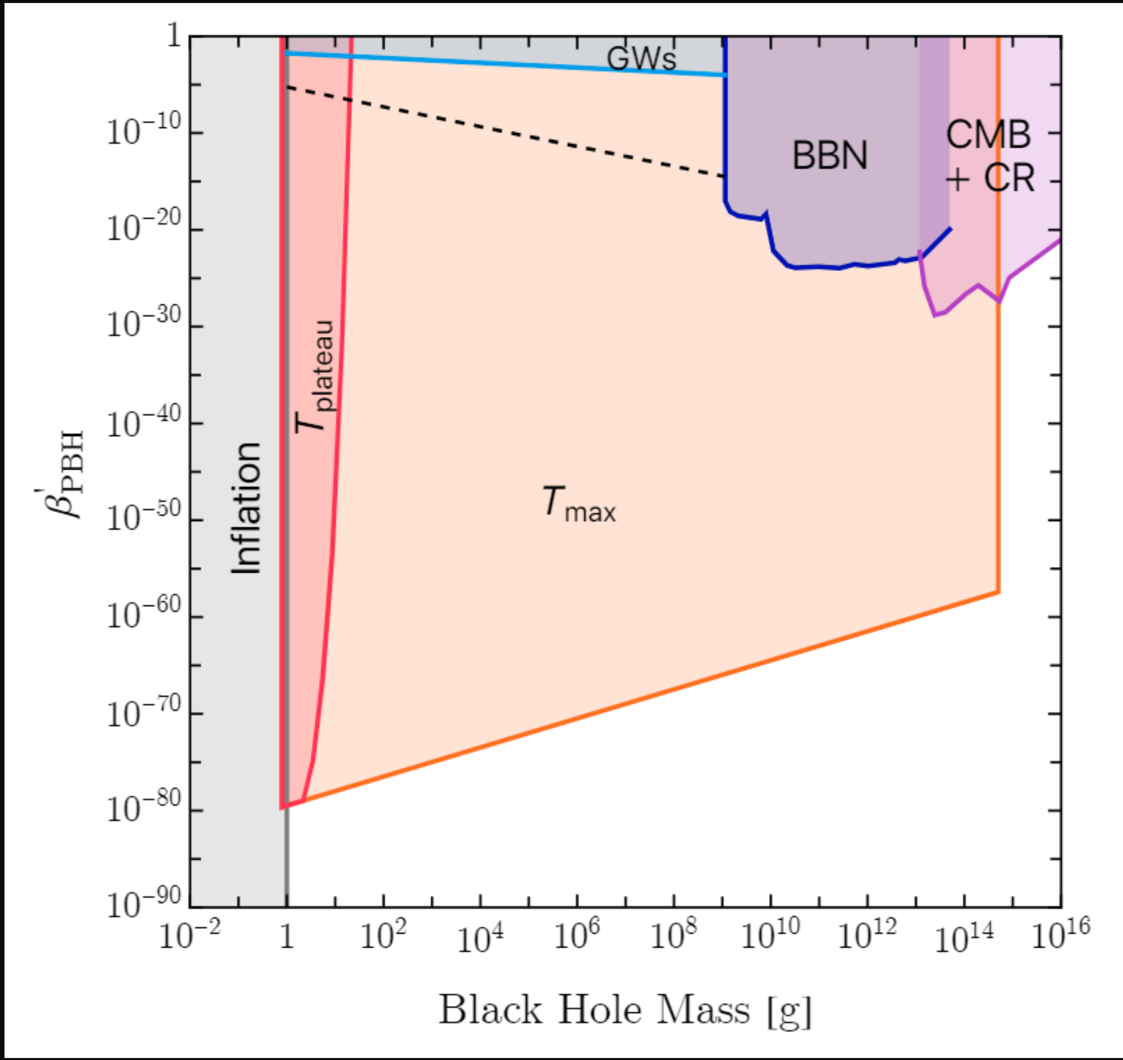
$$\beta_{\rm PBH} = \frac{4}{3}\frac{M N_{\rm PBH} H_0^3}{s_0 T_f} \approx 2 \times 10^{-80} N_{\rm PBH} \left(\frac{M}{M_\star}\right)^{3/2}$$

$$N_{\rm PBH} P_d < 2.7$$

[Hamaide, Heurtier, Hu, Cheek, to appear]

An example: The EW vacuum

Our Universe may be metastable (at ~2σ)



[Hamaide, Heurtier, Hu, Cheek, to appear]

Conclusion

Our Universe may be metastable (at ~2σ)

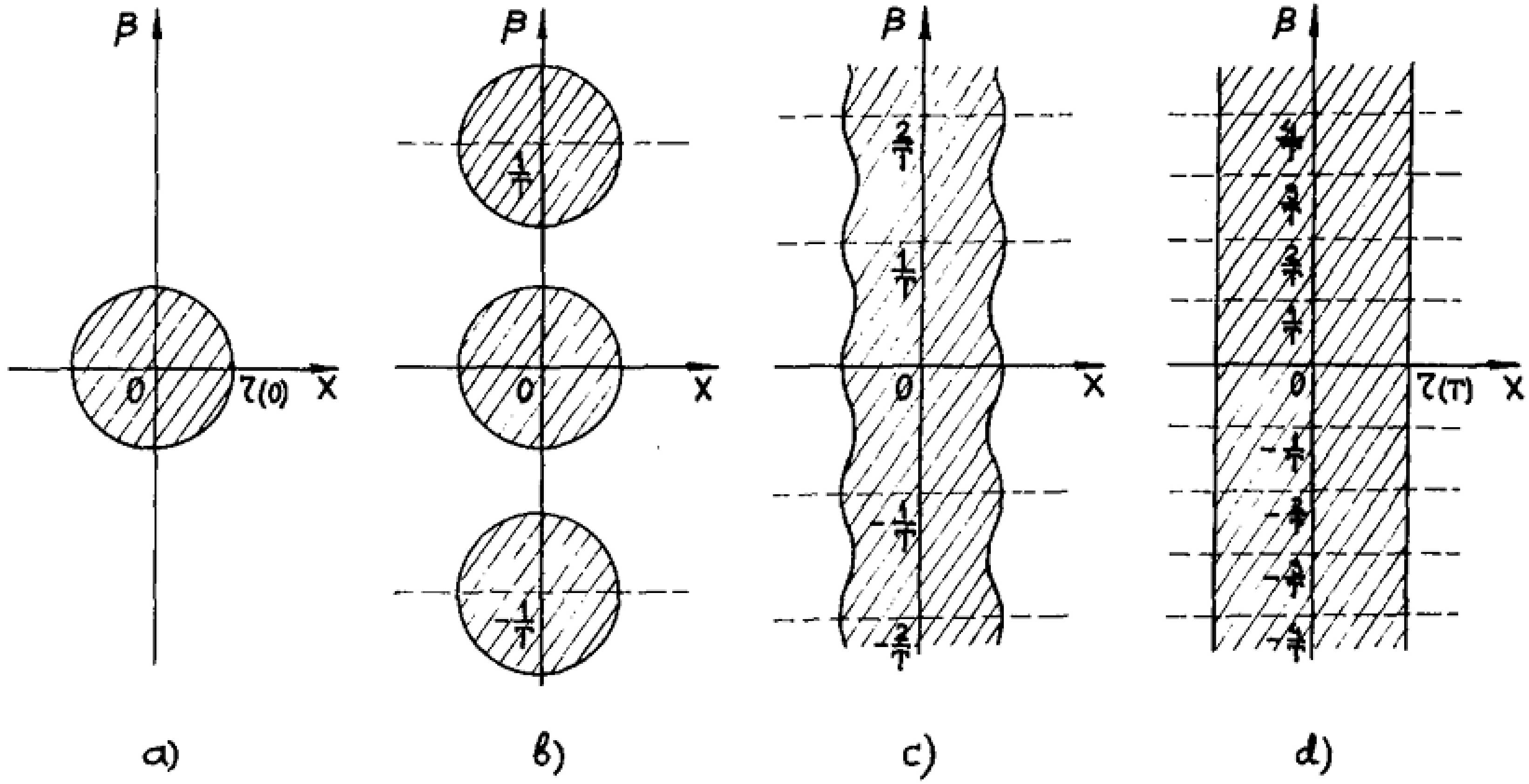
PBHs reheat the Universe locally, leading to a hot spot

The hot-spot temperature can be used to calculate a FVD rate

The rate can be calculated at different times across the hot spot history

Results confirm the validity of the Euclidean formalism

Many refinements needed, but a first step towards a realistic calculation of FVD rates around PBHs...



β
X
0
τ(0)
1/T
−1/T
2/T
−2/T
τ(T)
a)
b)
c)
d)