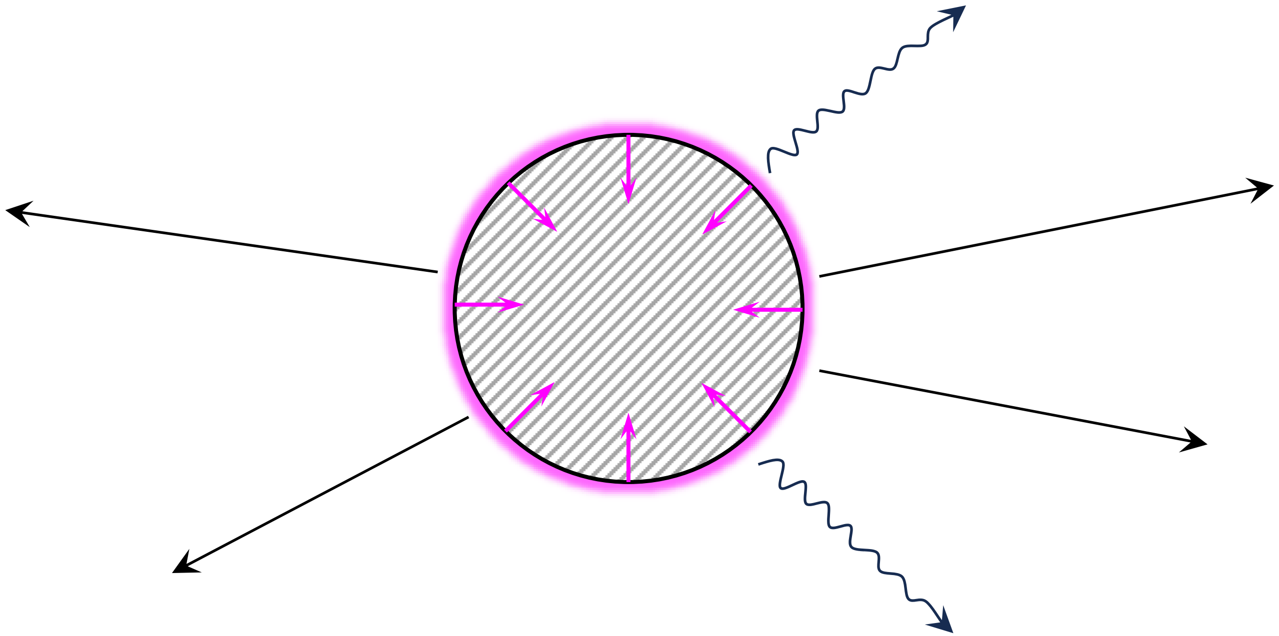
Hawking Radiation into the Electroweak Vacuum



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with Prof. Archil Kobakhidze

The key research question:

Does the nature of the Hawking radiation change qualitatively, accounting for the complicated structure of the vacuum surrounding black holes?

I want to motivate the following discovery:

Correctly accounting for the standard model vacuum results in unequal matter/antimatter production on black hole event horizons.

Contents:

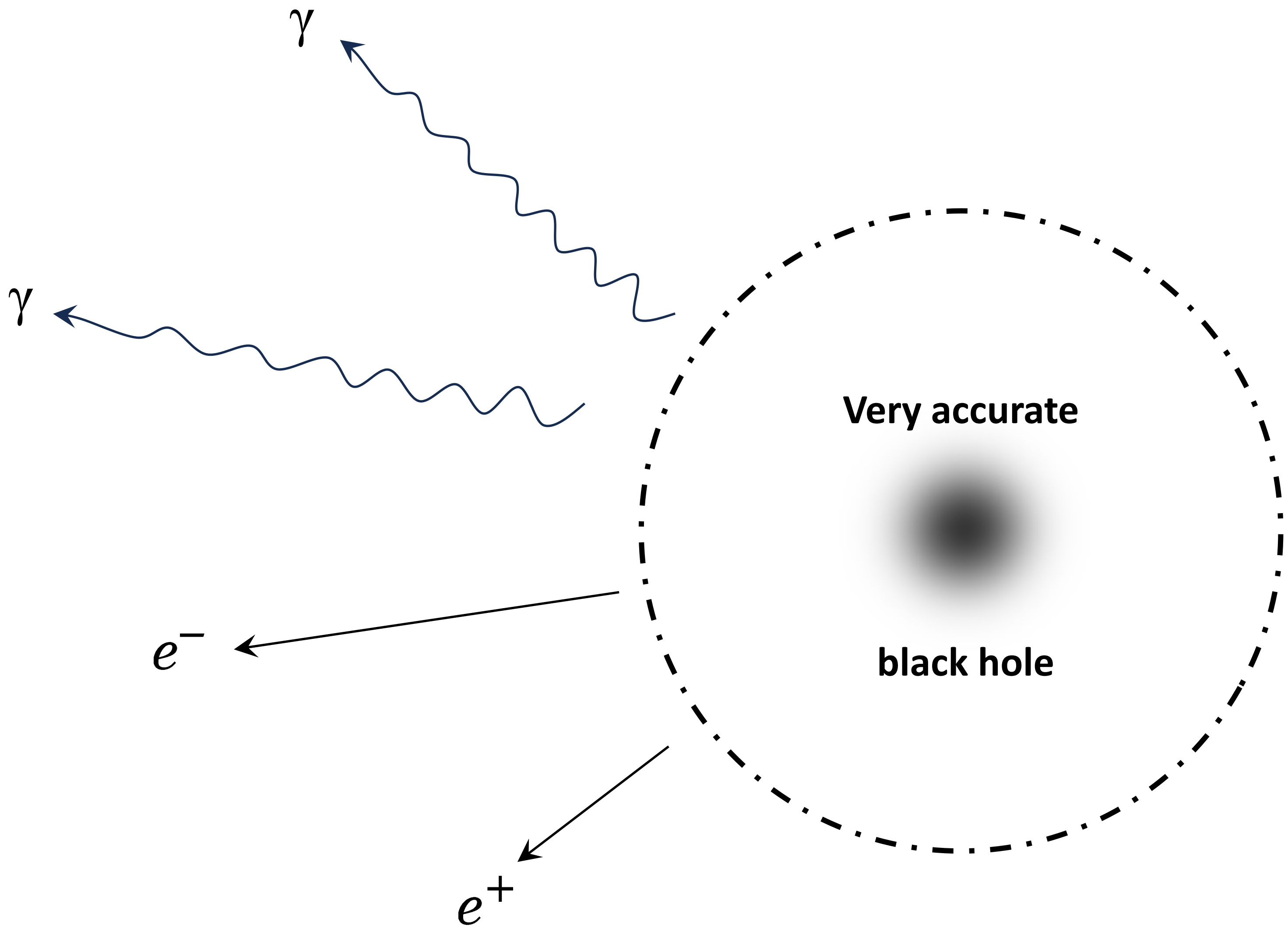
I – Hawking radiation

II – Electroweak instantons & anomaly

III – Asymmetric Hawking radiation (this work)

Part I: Black holes aren’t black

Hawking radiation



Stephen Hawking (1974) tells us that **black holes** ***thermally glow*** due to the quantum vacuum

$$T_{\mathrm{H}} = \frac{1}{8\pi M}$$

Black hole explosions?

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-

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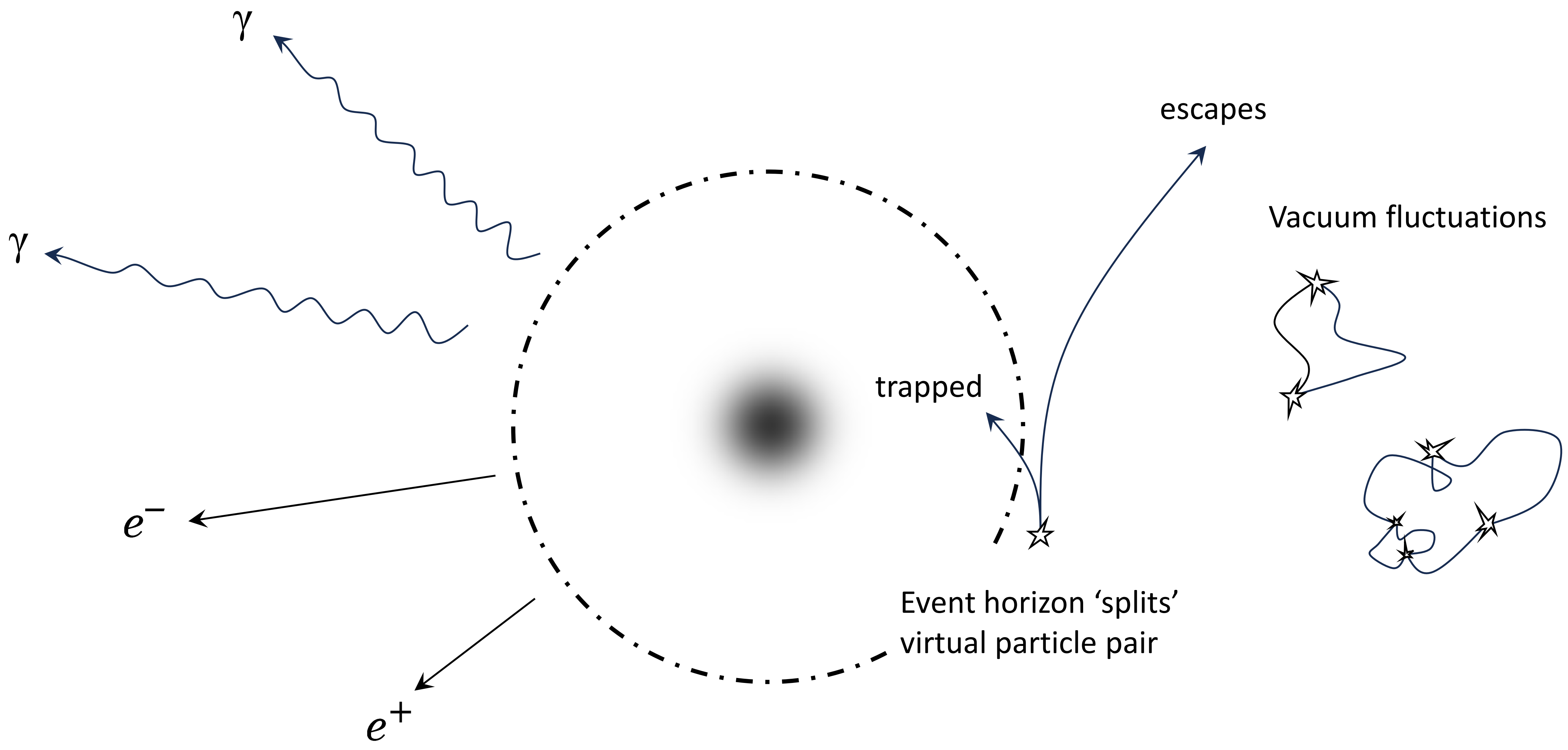
Hawking radiation



Hawking radiation

Thermality:

The ***Boltzmann distribution:***

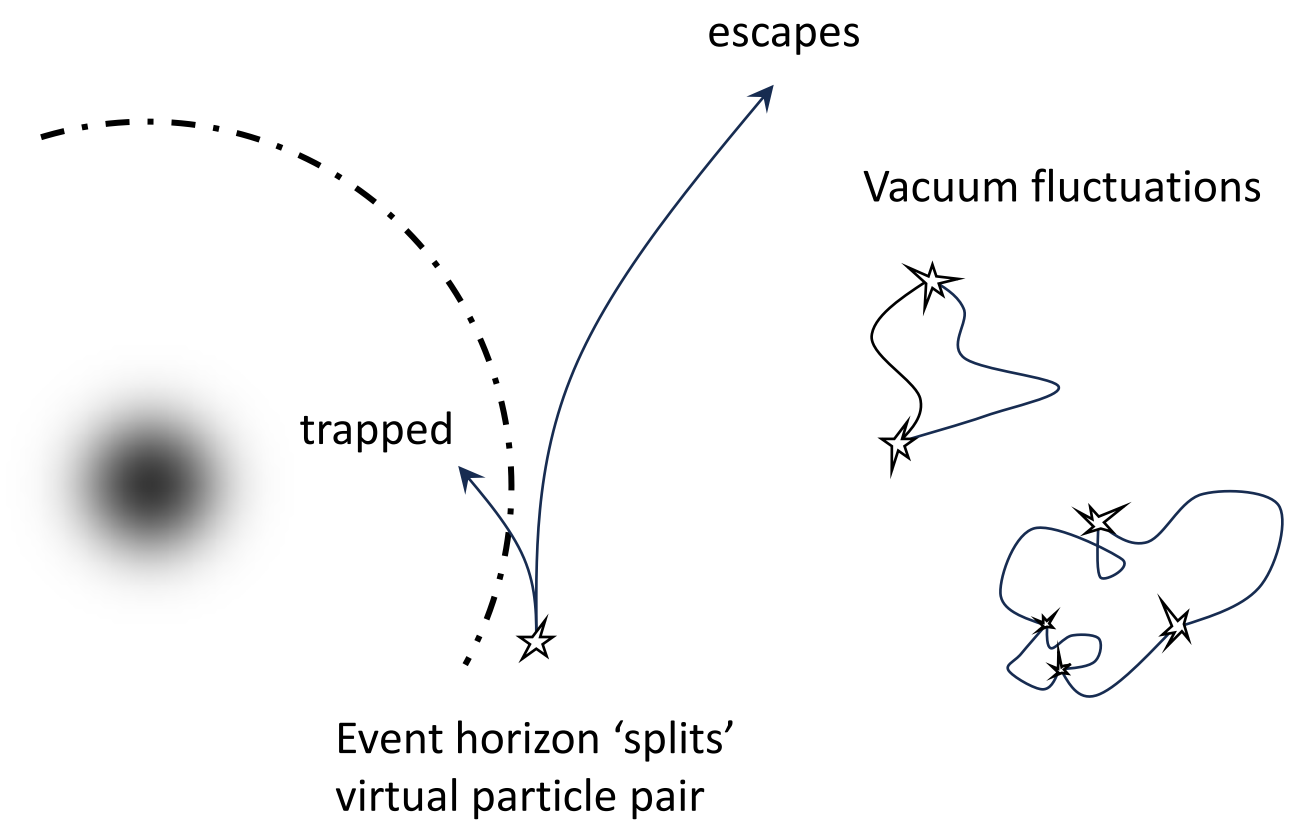
$$P \propto e^{-E/T}$$

does not discriminate matter/antimatter.

e.g. At rest

$$E_{e^-} = m_{e^-}c^2 = m_{e^+}c^2 = E_{e^+}$$

This is a **fundamental symmetry.**



Or is it?

The horizon is subject to a **standard model** (SM) **vacuum**.

Part II: Electroweak instantons & anomaly

The electroweak force

Consider a simplified SU(2) electroweak force (EW), **without U(1)*** or **Higgs****

$$W_a = W_a^k \frac{\sigma^k}{2}$$

σ^k the Pauli matrixes.

$$\mathcal{L}_{\text{EW}} = \mathcal{L}_{\text{matter}} - \frac{1}{2}\text{tr}\, W_{ab}W^{ab}\,, \qquad W_{ab} = \partial_a W_b - \partial_b W_a + ig_{\text{W}}[W_a, W_b]$$

with usual standard model (SM) matter + couplings.

For our purposes…

* *Abelian*, so doesn't participate directly

** Damps effects below EW breaking scale, $\Lambda_{\text{EW}} \sim 10^2\ \text{GeV}$

The electroweak vacuum

By construction, W_a has a **gauge freedom**, for any $U \in \mathrm{SU}(2)$:

$$W_a \longrightarrow U W_a U^\dagger + \frac{i}{g_\mathrm{W}} U(\partial_a U^\dagger)$$

Leaving all observables (and $\mathcal{L}_\mathrm{EW}$) invariant.

What is the vacuum?

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What is the vacuum?

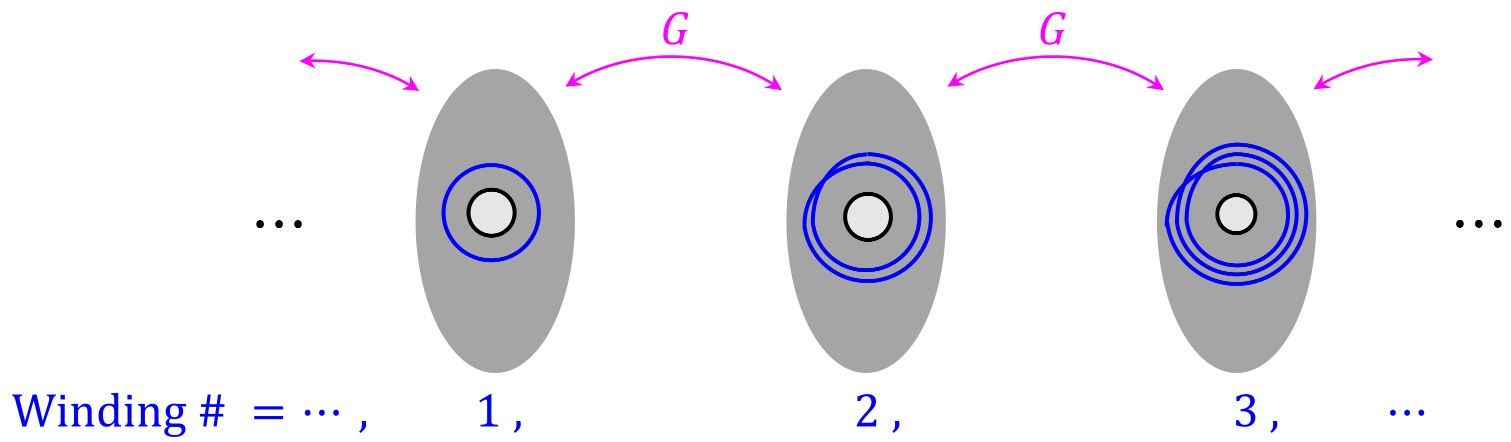
$$W_a = 0 \checkmark$$

also *any* $W_a = \frac{i}{g_\mathrm{W}} U(\partial_a U^\dagger)$

The weak vacuum

$$W_a\Big|_{\text{vac.}} = \frac{i}{g_{\text{W}}} U(\partial_a U^\dagger)$$

Vacuum structure: Islands of gauge equivalence



The weak vacuum

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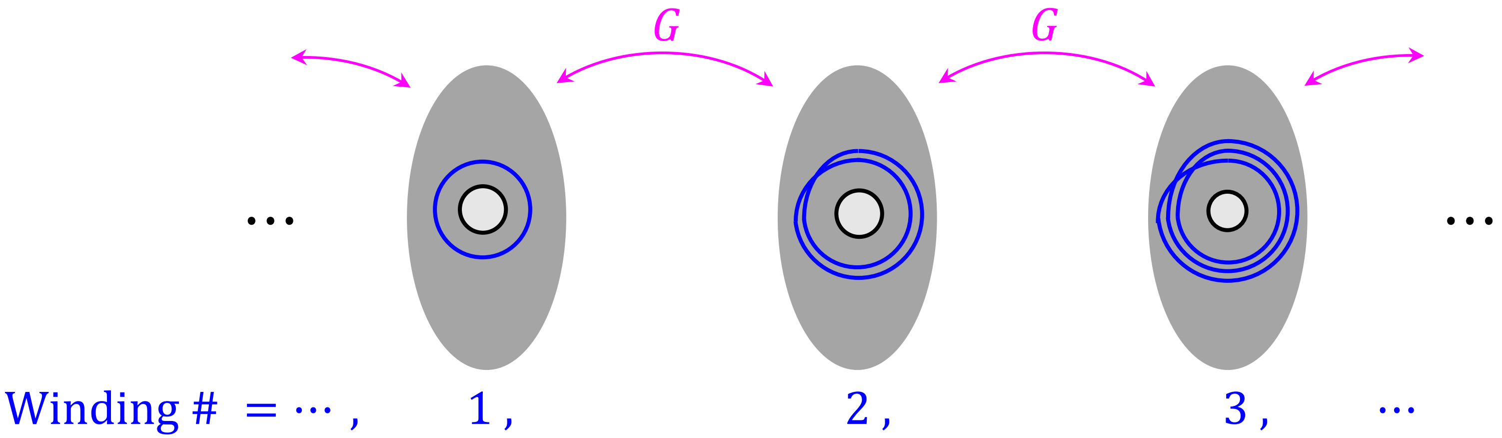
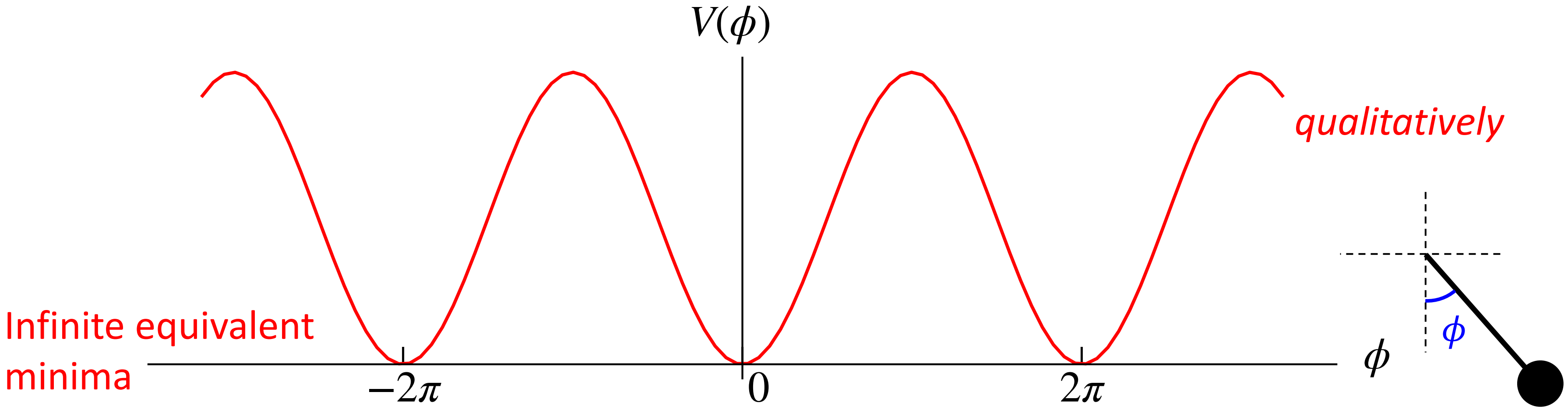




Nontrivial vacuum: *so what?*

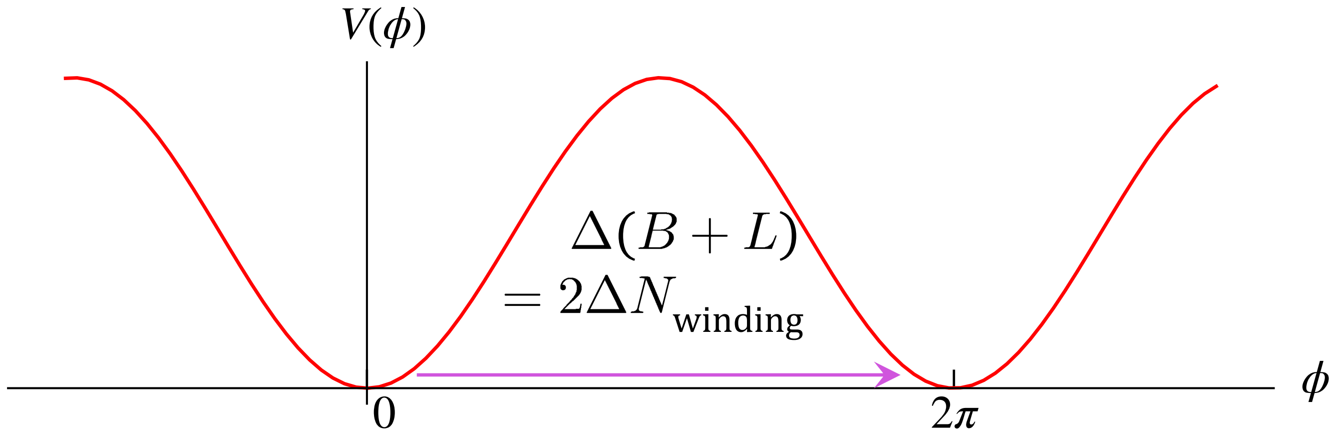
1: Instantons

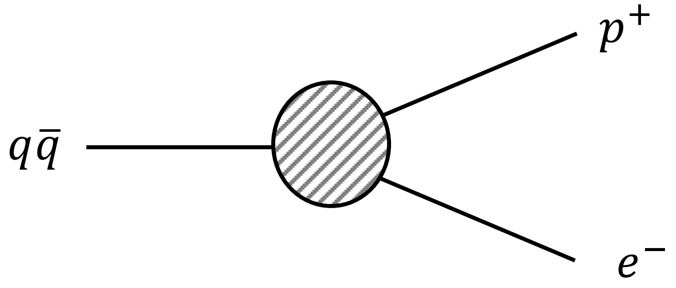
2: θ-Vacuum

Instantons: $B + L$ violation

W_a may tunnel through the potential barrier: an ***instanton***

Instantons in the presence of fermions correspond to a **violation of the baryon + lepton number,** '$B + L$', i.e. ***matter – antimatter***





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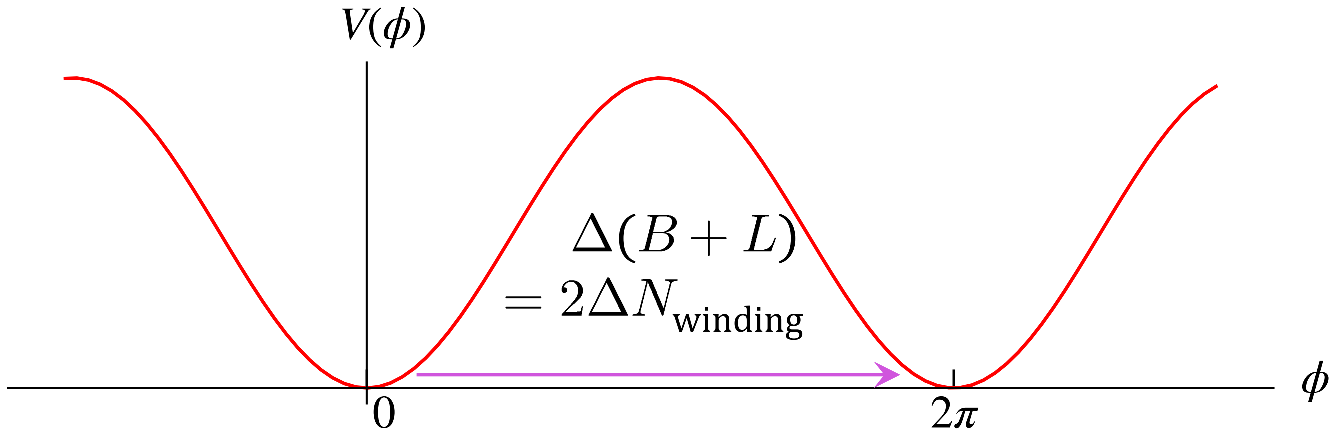
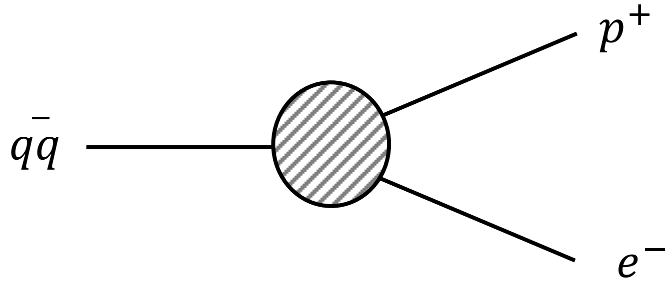




'Quantum anomaly':
when *quantum* effects violate *classical* conservation.

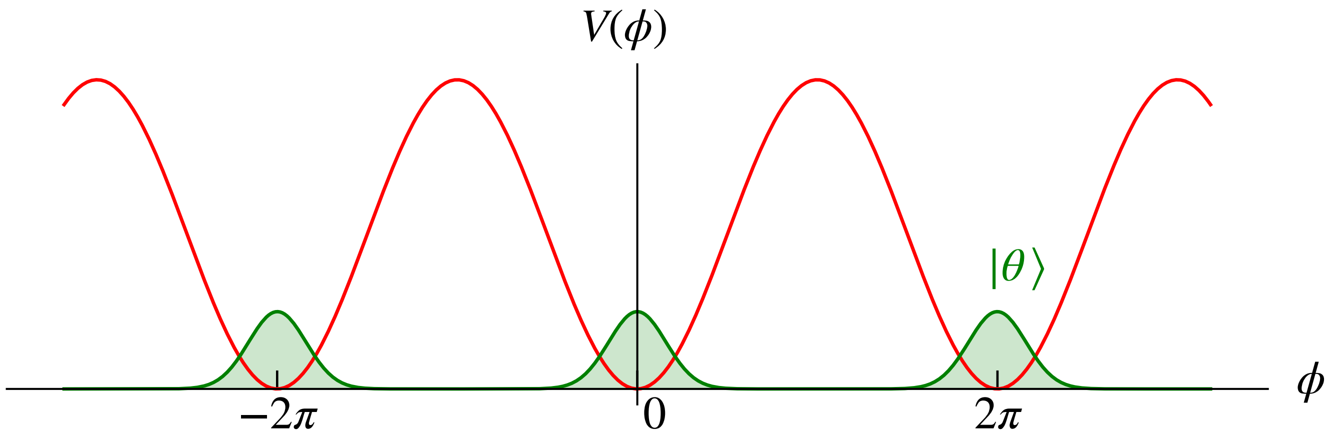
θ-vacuum / θ-term

The perturbative ‘vacua’ must **mix**. The true *quantum* vacuum is:

$$|\theta\rangle = \sum_{n=-\infty}^{\infty} e^{-i\theta n} \, |n\rangle$$

Vacua of each exact winding number n

The *theta vacuum*, $0 \leq \theta < 2\pi$



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Vacua of each exact winding number n

The *theta vacuum*, $0 \leq \theta < 2\pi$

We can fix the $\theta = 0$ vacuum and add to the Lagrangian the ***θ*-term:**

$$\mathcal{L}_\theta = \frac{\theta g_{\mathrm{W}}^2}{16\pi^2} \mathrm{tr}\, W_{ab} \widetilde{W}^{ab}$$

violating CP!
biasing the B+L violation

The θ-term is unphysical

For the electroweak force, a *generalised chiral redefinition* of the fermion fields

$$\psi \to e^{i\theta\gamma^5}\psi \qquad \text{that is} \quad \begin{pmatrix}\psi_{\mathrm{L}} \\ \psi_{\mathrm{R}}\end{pmatrix} \to \exp\left[i\theta\begin{pmatrix}-I & 0 \\ 0 & I\end{pmatrix}\right]\begin{pmatrix}\psi_{\mathrm{L}} \\ \psi_{\mathrm{R}}\end{pmatrix}$$

removes the θ-term

In flat space, the weak θ-term is unphysical

The θ-term *CP* asymmetry always vanishes

The θ-term is unphysical

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removes the θ-term

In **flat** space, the weak θ-term is unphysical

Event horizons forbids this transformation, leaving a residual correction!

Evaporating black hole

We use the Vaidya metric for simplicity:

$$\mathrm{d}s^2 = \left(1 - \frac{2M(u)}{r}\right)\mathrm{d}u^2 + 2\,\mathrm{d}u\,\mathrm{d}r - r^2\,\mathrm{d}\Omega^2$$

for a BH emitting a non-interacting relativistic radiation (‘null dust’).

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$$\mathrm{d}s^2 = \left(1 - \frac{2M(u)}{r}\right)\mathrm{d}u^2 + 2\,\mathrm{d}u\,\mathrm{d}r - r^2\,\mathrm{d}\Omega^2$$

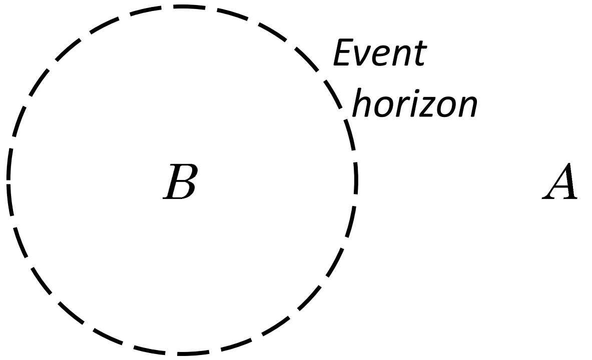
for a BH emitting a non-interacting relativistic radiation (‘null dust’).

We assume vacuum mixing extends from the static (Schwarzschild) limit

Part III: Asymmetric Hawking radiation

My result: corrections on horizons

Take EW theory over black hole spacetime with θ-term:

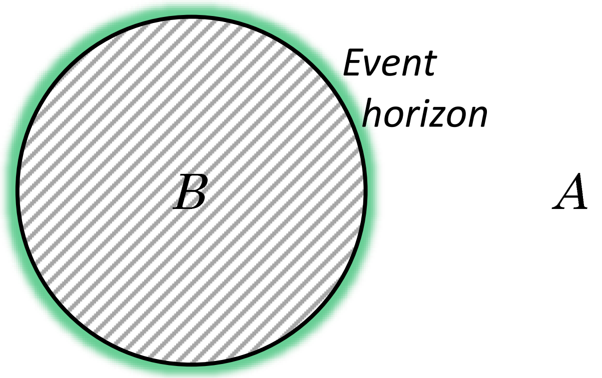


Regions A and B, fields freely varied inside and out

$$S = \int_{A\cup B} \mathrm{d}^4x\sqrt{-g}\left(\mathcal{L}_{\mathrm{EW}} + \frac{\theta g_{\mathrm{W}}^2}{16\pi^2}\,\mathrm{tr}\, W_{ab}\widetilde{W}^{ab}\right)$$

My result: corrections on horizons

Integrate out the interior fields, up to boundary terms.



Regions A fields integrated out

$$S = \int_A \mathrm{d}^4x\sqrt{-g}\left(\mathcal{L}_{\mathrm{EW}} + \frac{\theta g_{\mathrm{W}}^2}{16\pi^2}\mathrm{tr}\, W_{ab}\widetilde{W}^{ab} + \text{boundary terms}\right)$$

My result: corrections on horizons

Effective theory

$+$ boundary terms

$$\mathcal{L}\Big|_{A,\mathrm{eff}} = \sqrt{-g}\left(\mathcal{L}_{\mathrm{EW}} + \frac{\theta g_{\mathrm{W}}^2}{16\pi^2}\,\mathrm{tr}\,W_{ab}\widetilde{W}^{ab} + \mathcal{L}_{\mathcal{M}} + \frac{\theta}{4n_g} n_\mu J^\mu_{B+L}\,\delta(x\in\partial A)\right)$$

Original EW Lagrangian

θ-term outside the horizon

Boundary correction for the current lost over the horizon

Residual θ-term on the horizon

+ Gravitational anomaly contribution

My result: corrections on horizons

Effective theory

$$\mathcal{L}\Big|_{A,\text{eff}} = \sqrt{-g}\left(\mathcal{L}_{\text{EW}} + \frac{\theta g_{\text{W}}^2}{16\pi^2}\text{tr}\, W_{ab}\widetilde{W}^{ab} + \mathcal{L}_{\mathcal{M}} + \frac{\theta}{4n_g} n_\mu J^\mu_{B+L}\delta(x \in \partial A)\right)$$

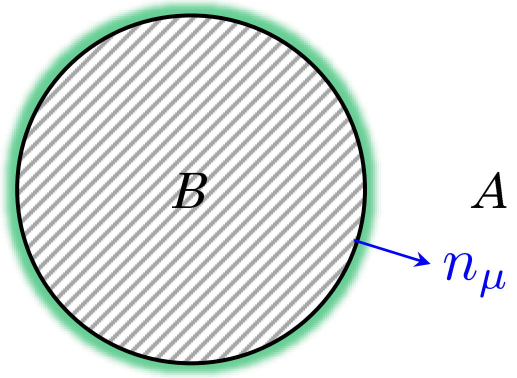
The external θ-term is still unphysical and must vanish.

My result: residual anomaly

Effective theory

$$\mathcal{L}\big|_{A,\mathrm{eff}} = \sqrt{-g}\left(\mathcal{L}_{\mathrm{EW}} + \frac{\theta g_{\mathrm{W}}^2}{16\pi^2}\operatorname{tr} W_{ab}\widetilde{W}^{ab} + \mathcal{L}_{\mathcal{M}} + \frac{\theta}{4n_g} n_\mu J^\mu_{B+L}\,\delta(x \in \partial A)\right)$$

The internal θ-term leaves a residual correction on the boundary.



n_μ = horizon normal covector
n_g = # generations = 3

— *CP* violating coupling to J_{B+L}!

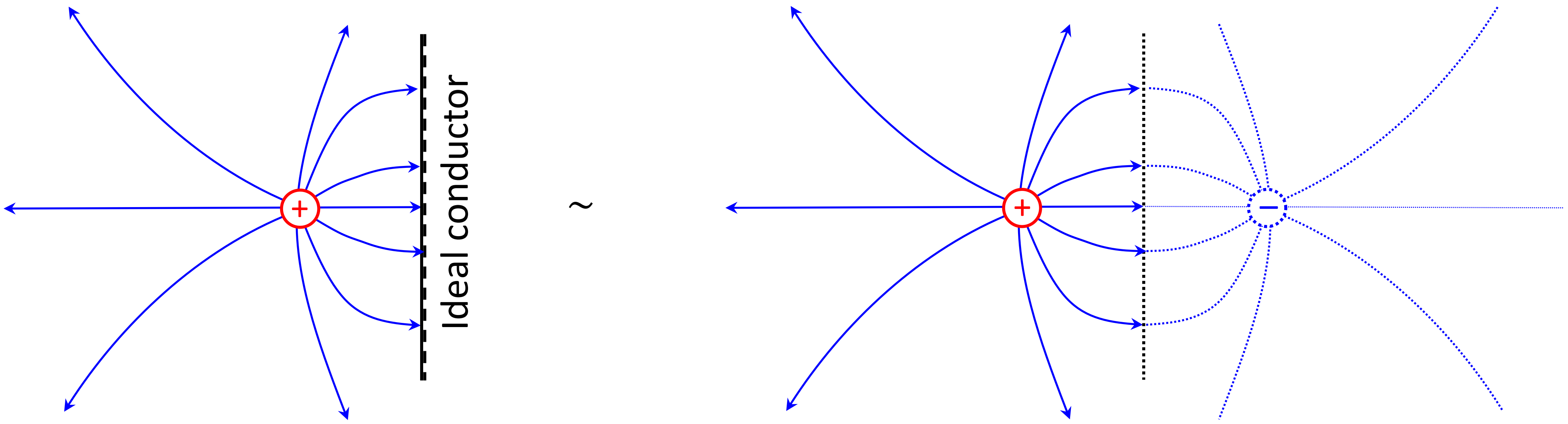
— Proportional to θ (constant of universe? New *axion* DoF??)

— Confined to (just outside) the horizon

— *effective topological charge*

Boundaries and effective charges

In effect, the horizon gains an **effective (topological) charge**, à la **method of images**

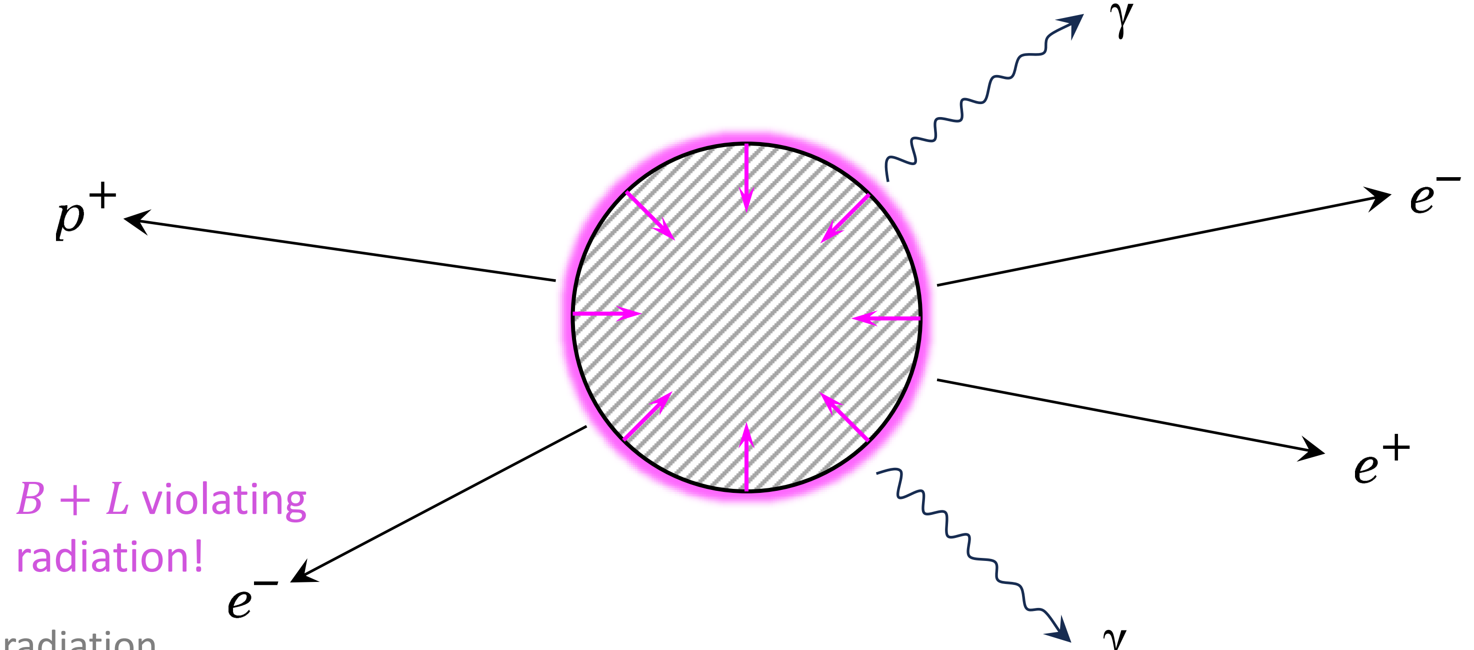


Boundary conditions ~ effective charges

My result: Asymmetric radiation

This contributes a chemical potential violating matter/antimatter symmetry in the Hawking radiation **as the black hole shrinks**!

$$\mu_{B+L} \simeq -\frac{\theta}{4n_g}\frac{\alpha^{1/2}}{M(u)}\delta(r - r_{\mathrm{H}}) = -\frac{2\pi\theta}{n_g}\alpha^{1/2}T_{\mathrm{H}}\delta(r - r_{\mathrm{H}})$$



n_μ = horizon normal covector

n_g = # generations = 3

$\alpha \simeq 3.5 \times 10^{-3}$ parameterises fermionic DoF

Conclusion

We have discovered a new source of matter/antimatter asymmetry in the Hawking radiation of black holes purely in the standard model.

This new effect may have significant implications:

— Dynamics of evaporating black holes

— Generation of matter-antimatter asymmetry in the early universe through the evaporation of *primordial black holes*

↑

(no new physics is required!)

Where next?

(How) does embedding in cosmological spacetime change this?

Effects from de Sitter horizons?

Correspondence with the exact theory?

Quantum gravitational structure of the horizon?

Thanks!

References

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[2] Peskin, M. E. & Schroeder, D. V. *An Introduction to quantum field theory* (Addison-Wesley, Reading, USA, 1995)

[3] Weinberg, E. J. *Classical Solutions in Quantum Field Theory: Solitons and Instantons in High Energy Physics* (Cambridge University Press, 2012).

[4] Astaneh, F. A. & Solodukhin, S. N. Fermions, boundaries and conformal and chiral anomalies in d = 3, 4 and 5 dimensions (2023)

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