Hawking evaporation in LQG

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Joint work with Suddhasattwa Brahma, Martin Bojowald, and Erick Evan Duque [arXiv:2504.11998]

FAU^2 WORKSHOP ON QUANTUM GRAVITY ACROSS SCALES

20-22 May 2025

Motivation

- Black holes and the early universe are among the few probes to study the smoking gun of quantum gravity. The success of LQC in resolving the singularity issue has inspired numerous studies to study the LQG effect on black holes (LQGBH).

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  - Singularity resolution
  - The fate of gravitational collapse
  - The loss paradox

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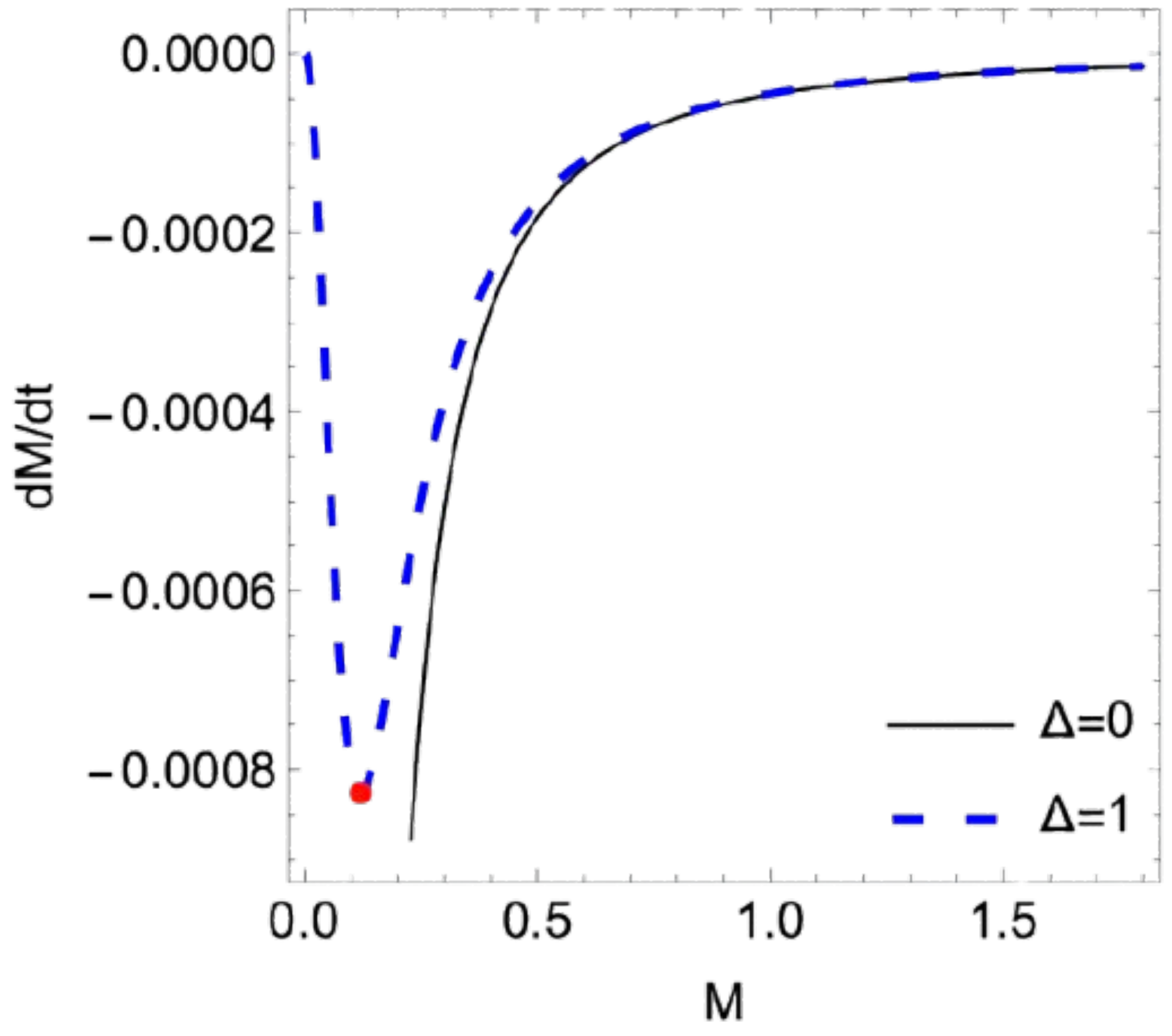
  - Singularity resolution

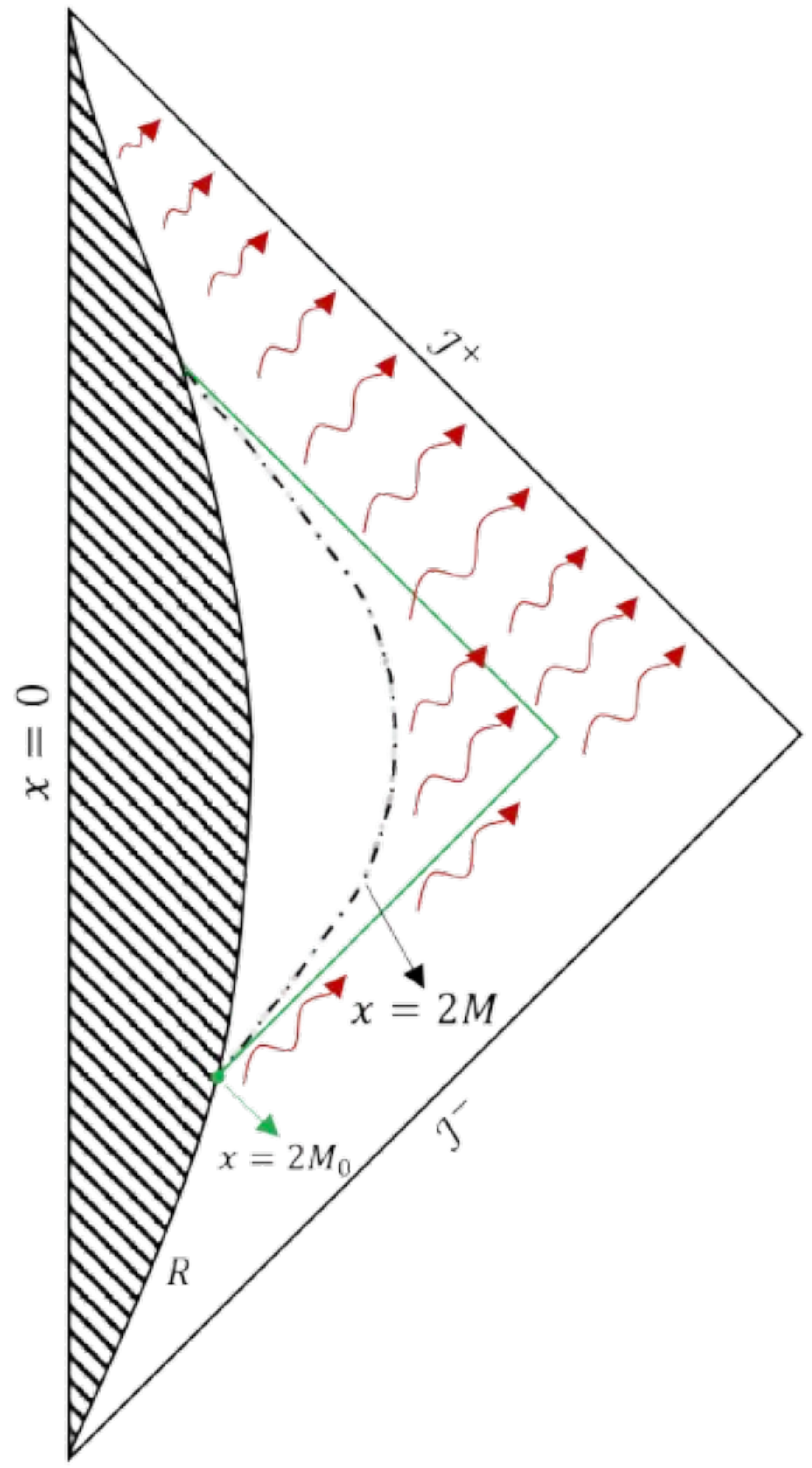
  - The fate of gravitational collapse

  - The loss paradox

- A covariant model for a spherically symmetric system has been proposed [Alonso-Bardaji, Brizuela'21; Bojowald, Duque'23; Alonso-Bardaji, Brizuela'24; Zhang, Lewandowski, Ma, Yang'24].

Takeaways





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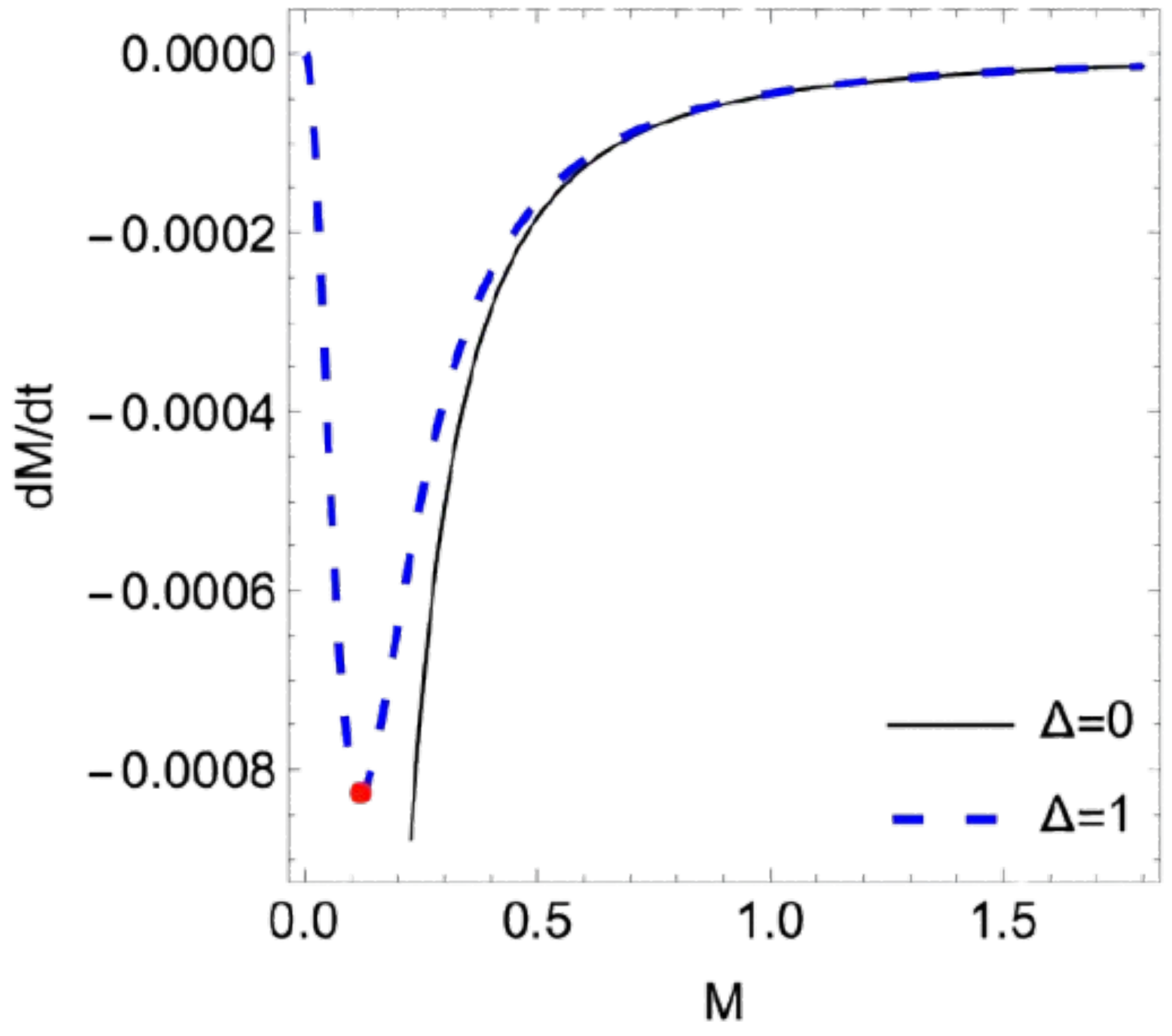

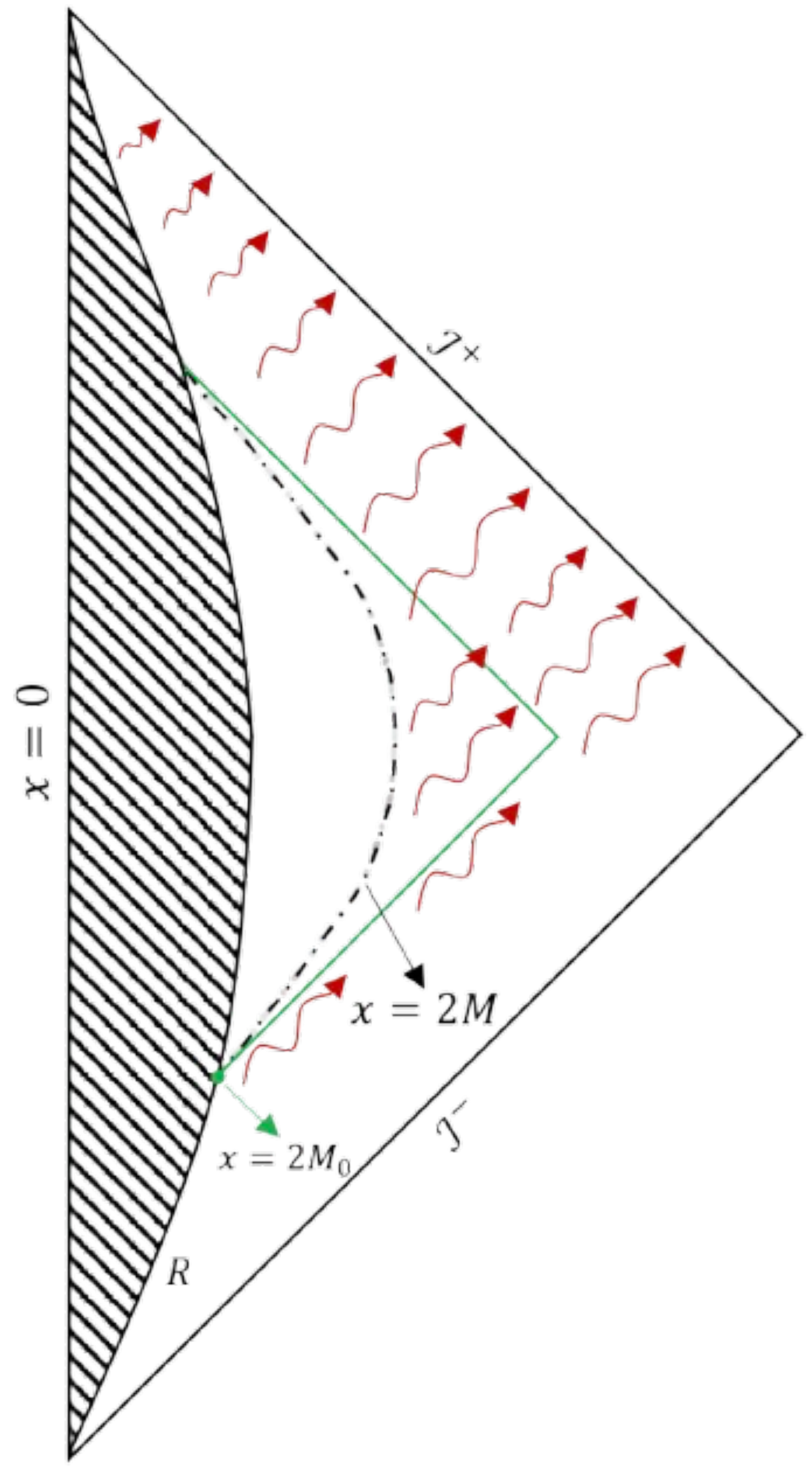

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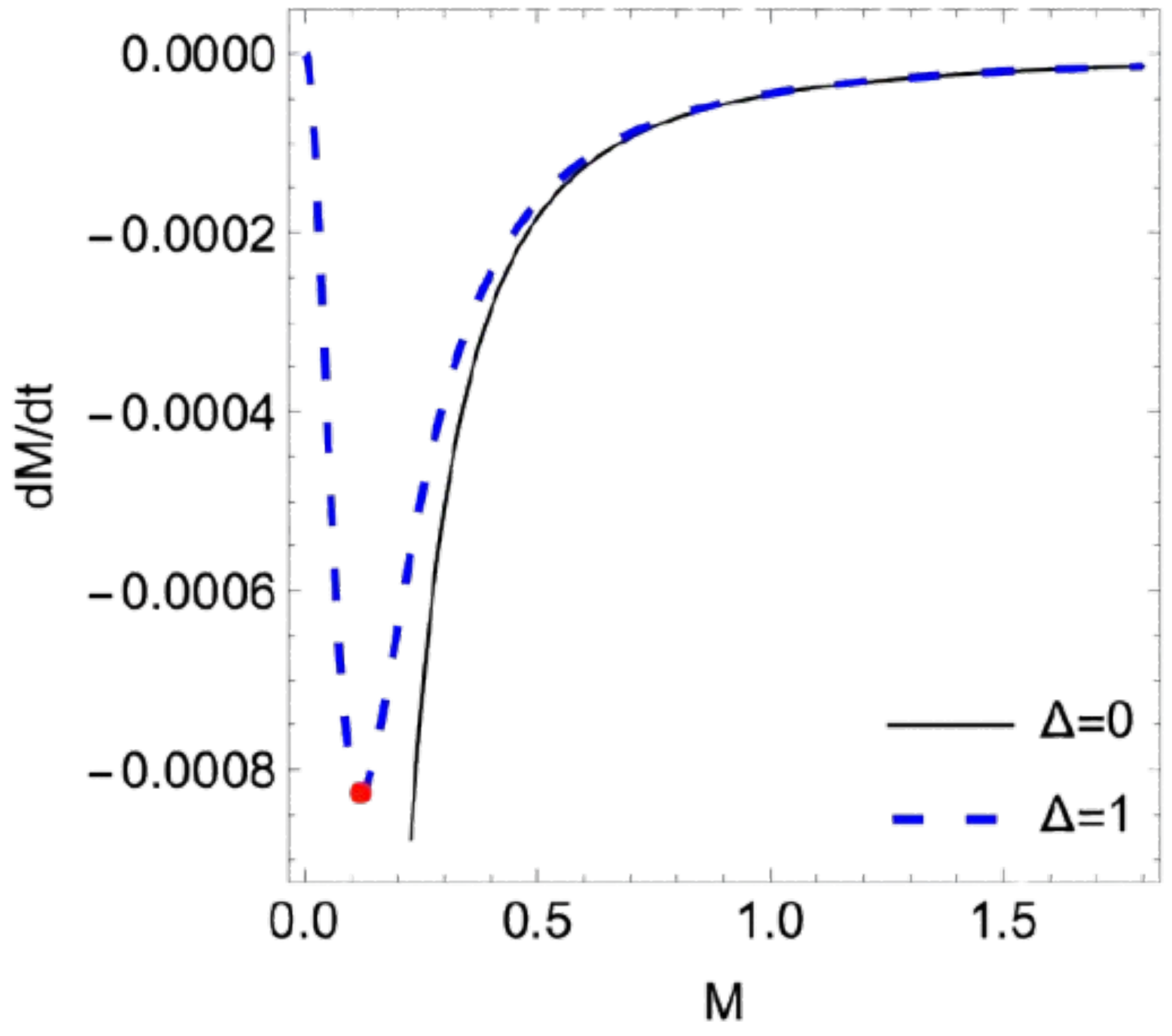

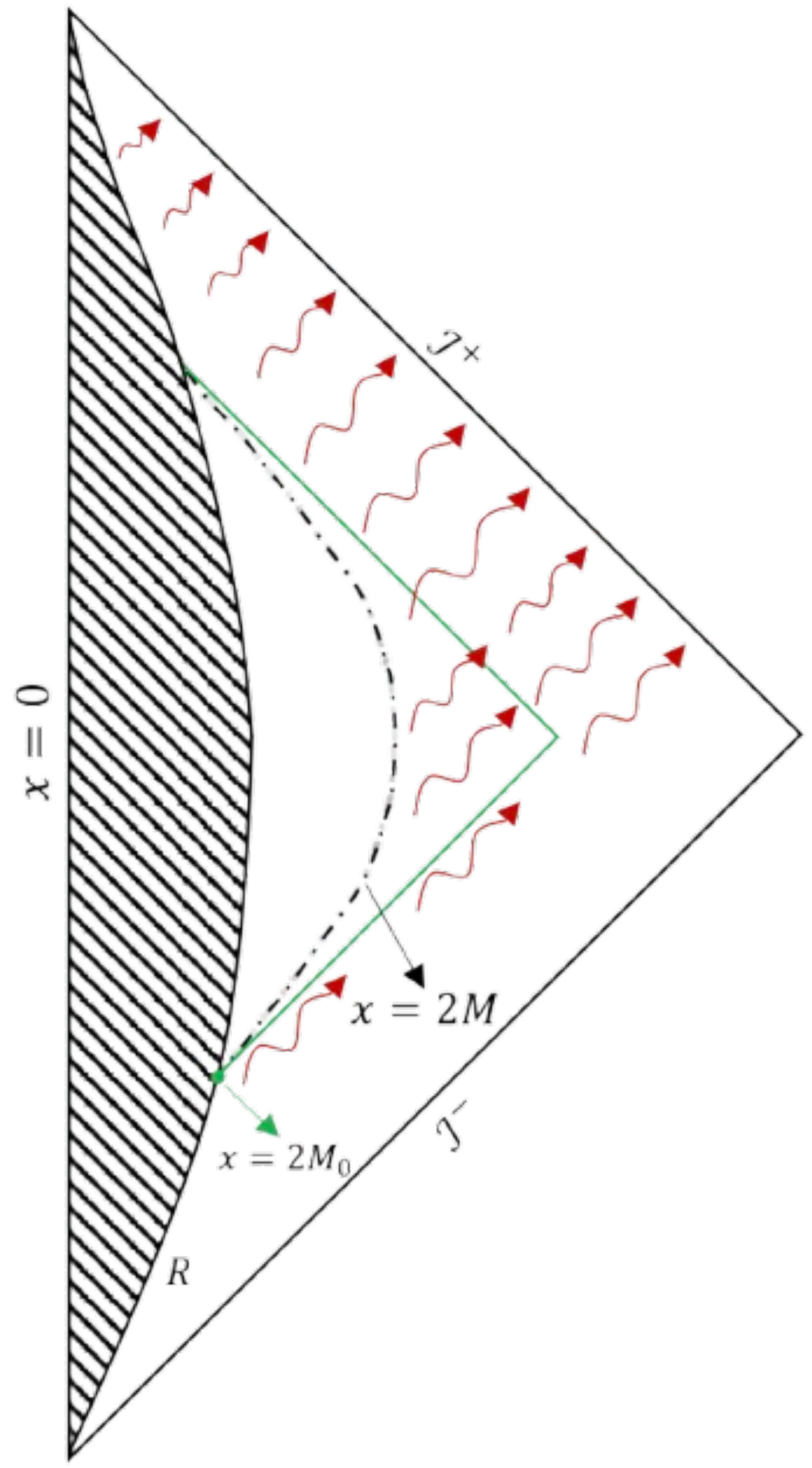

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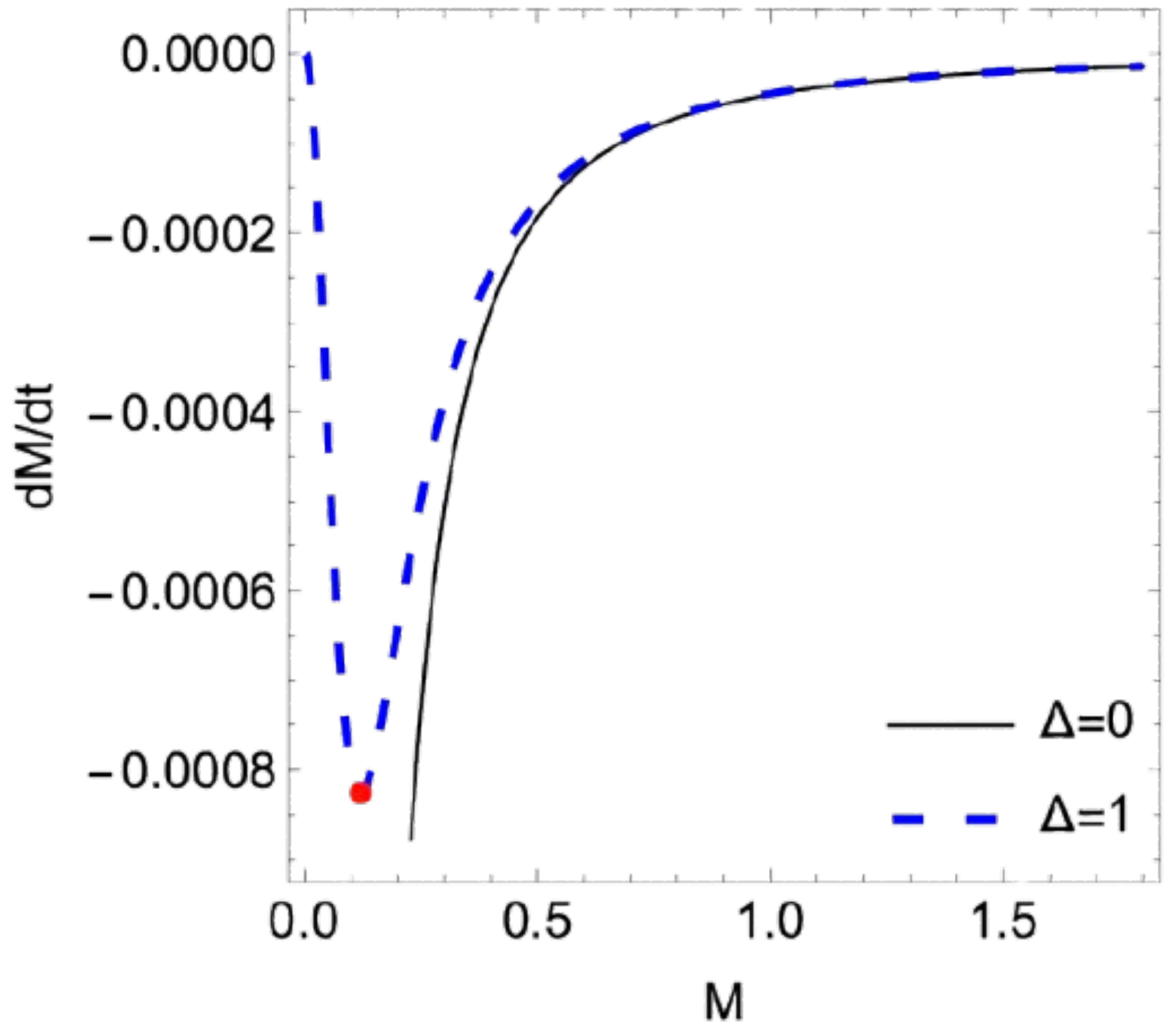

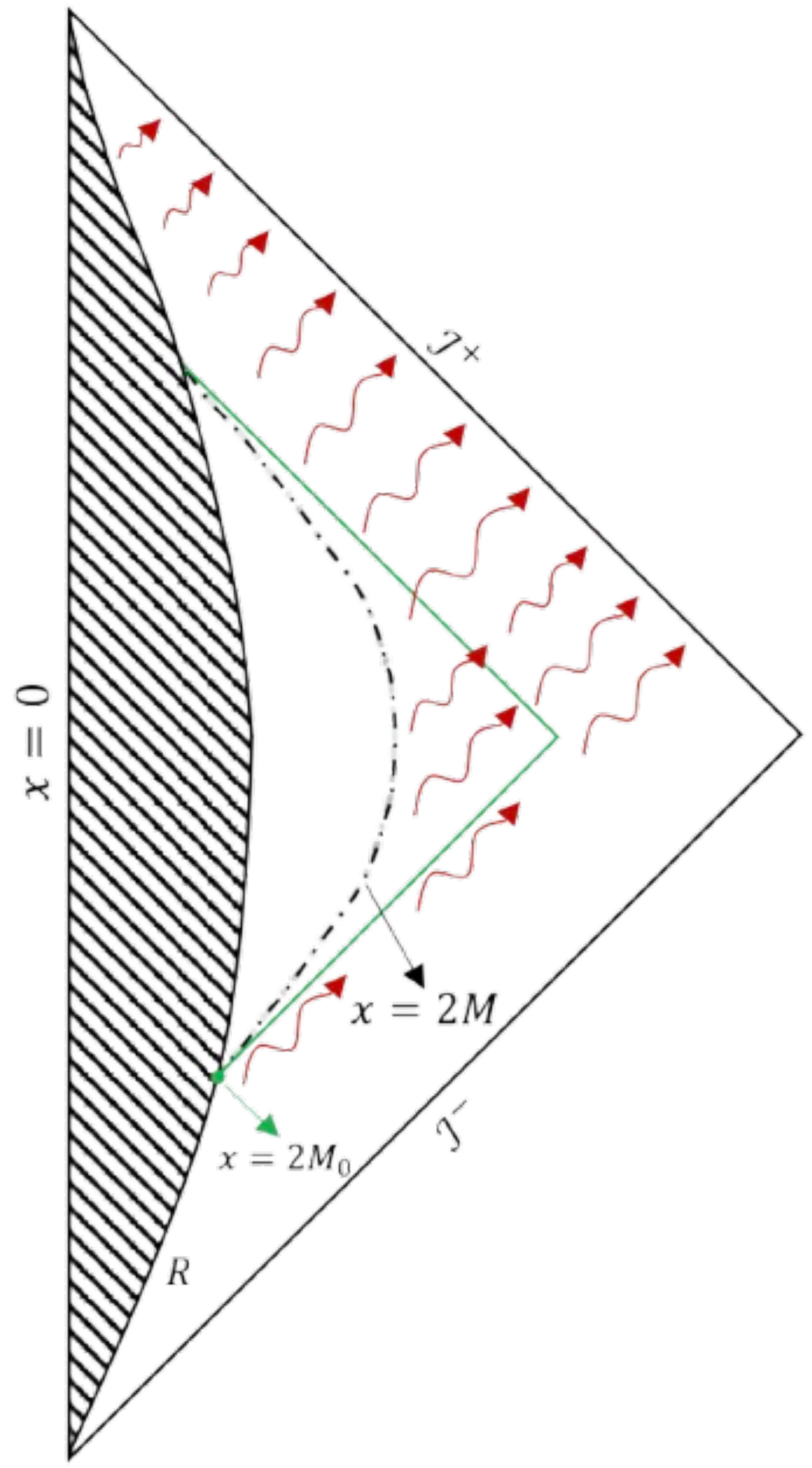

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(2) The universality of black hole absorption rates is preserved.

(3) After the evaporation slows, gravitational instability emerges and prevails, precluding thermal stabilization.

(4) The mass hierarchy favours a black to white hole transition.

Outline

(1) *Framework, vacuum solutions, and scalar field coupling*

(2) *The black hole evaporation*

(3) *Summary and outlook*

Framework, Vacuum Solutions, and Scalar Field Coupling

HDA

$$\{H_x[N_1^x], H_x[N_2^x]\} = H_x\left[N_1^x\left(N_2^x\right)' - N_2^x\left(N_1^x\right)'\right]$$

$$\{H[N_1], H_x[N_2^x]\} = -H[N_2^x N_1']$$

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Geometry from Phase Space

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→

Modified structure function

$$f(E^x, E^\varphi, K_\varphi) = \left[\left(1 + \left(\frac{\tilde{\lambda}\left(E^x\right)'}{2E^\varphi}\right)^2\right)\cos\left(\tilde{\lambda}K_\varphi\right)^2\right]\chi^2\frac{E^x}{(E^\varphi)^2}$$

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Gauge trans. = isometry

$$\delta_\epsilon \tilde{g}_{\mu\nu}\Big|_{\text{O.S.}} = \mathcal{L}_\zeta \tilde{g}_{\mu\nu}\Big|_{\text{O.S.}}$$

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The desired line-element then

$$\mathrm{d}s^2 = -N^2\mathrm{d}t^2 + \frac{1}{f}\left(\mathrm{d}x + N^x\mathrm{d}t\right)^2 + E^x\mathrm{d}\Omega^2$$

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Periodic and non-periodic phase space

- Starting with the most general ansatz for the Hamiltonian constraint containing up to second-order derivatives and quadratic first-order derivative terms [Alonso-Bardaji and Brizuela'22; Bojowald and Duque'24]

$$\tilde{H} = a_0 + ((E^x)')^2 a_{xx} + ((E^\varphi)')^2 a_{\varphi\varphi} + (E^x)'(E^\varphi)' a_{x\varphi} + (E^x)'' a_2 + (K'_\varphi)^2 b_{\varphi\varphi} + (K_\varphi)'' b_2 + (E^x)' K'_\varphi c_{x\varphi} + (E^\varphi)' K'_\varphi c_{\varphi\varphi} + (E^\varphi)'' c_2$$

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Canonically related

Periodic phase space

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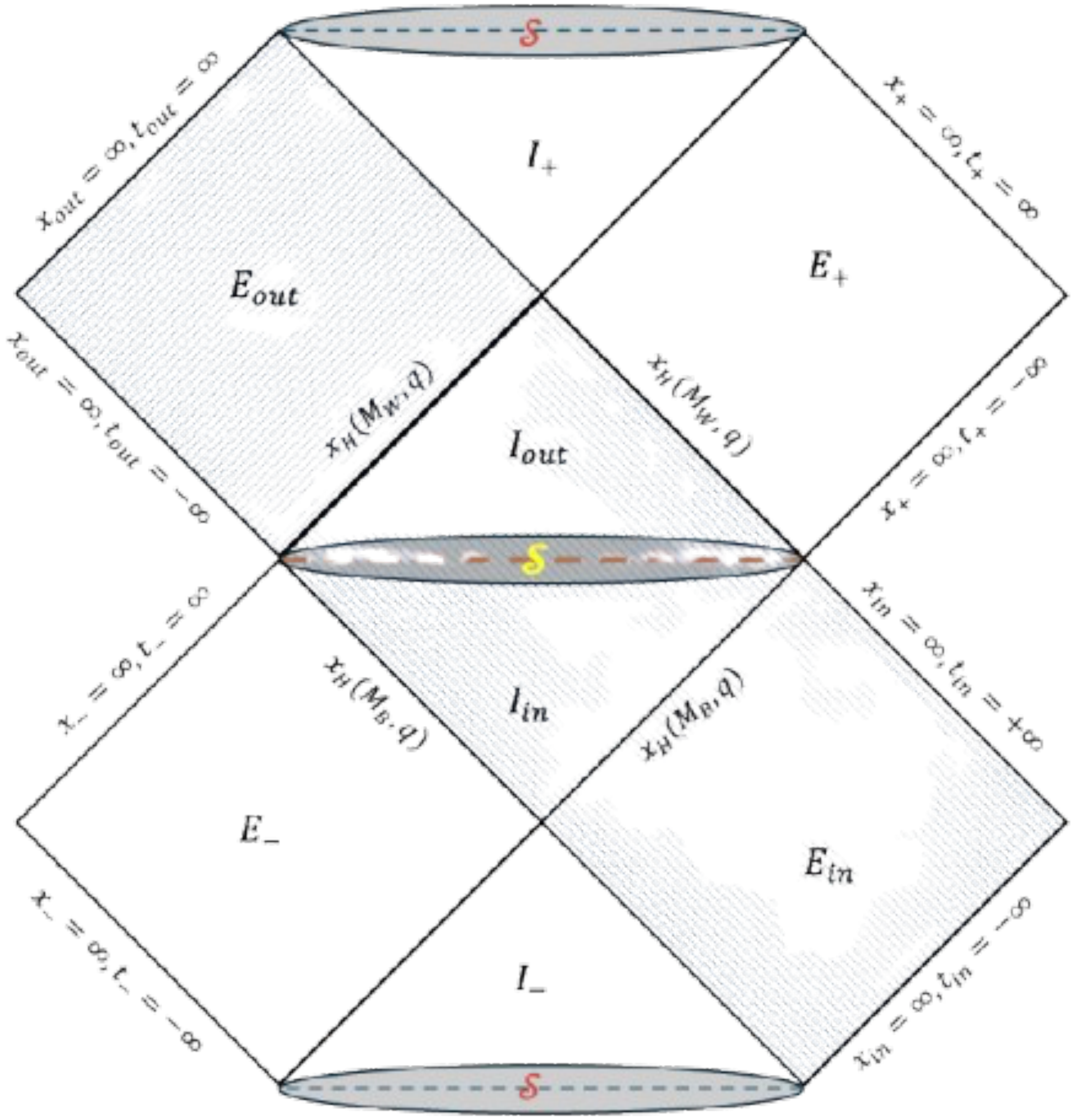
Global structure

Vacuum Schwarzschild solution $\Lambda = 0$



$$ds^2 = -\left(1 - \frac{2M}{x}\right)\frac{dt^2}{\alpha^2\chi^2} + \frac{dx^2}{\chi^2\left(1 - \frac{2M}{x}\right)\left(1 + \lambda^2(x)\left(1 - \frac{2M}{x}\right)\right)} + x^2 d\Omega^2$$

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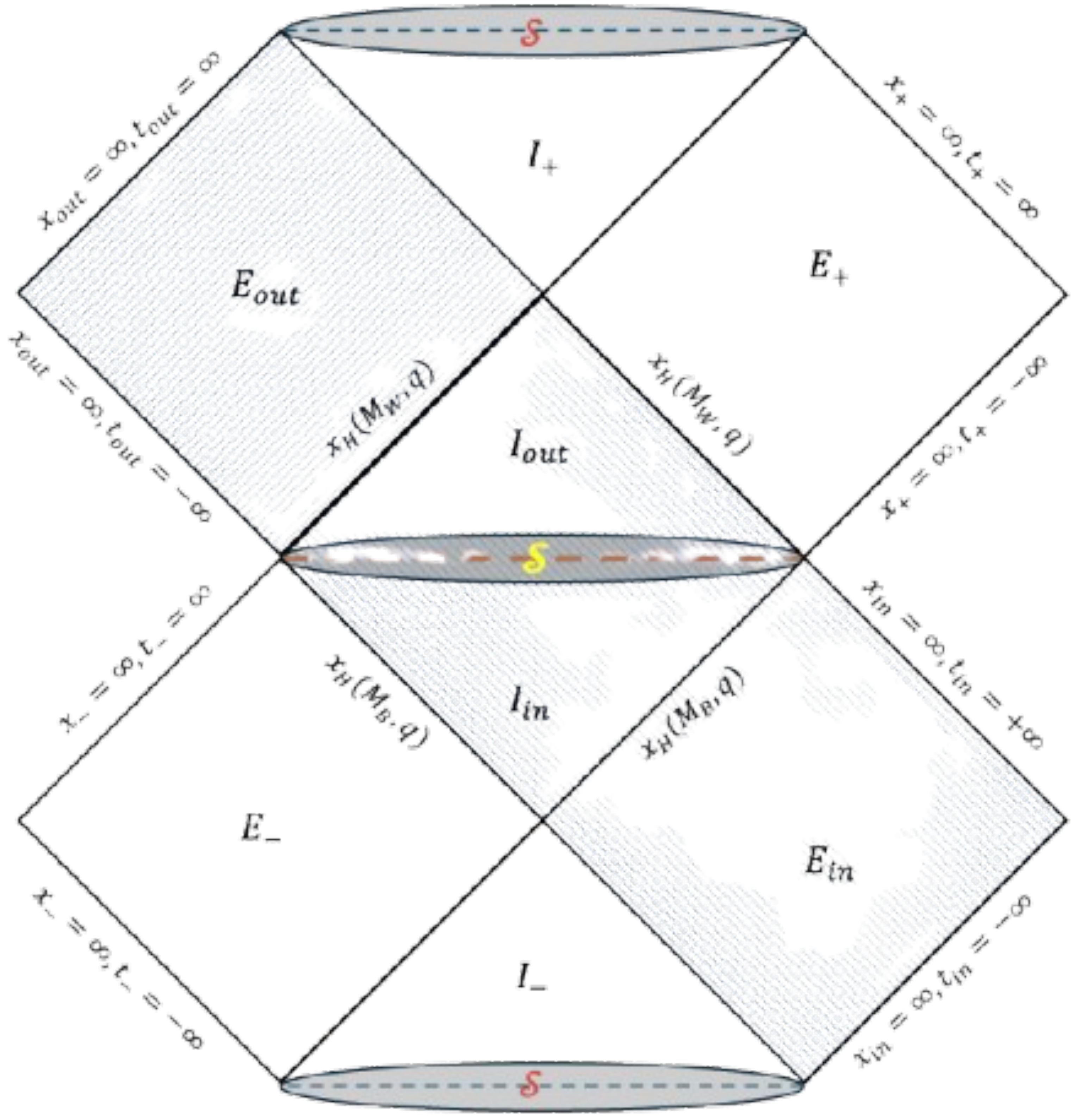

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$$1 + \lambda^2\left(1 - \frac{2M}{\sqrt{E^x}} - \frac{\Lambda}{3}E^x\right) = 0$$

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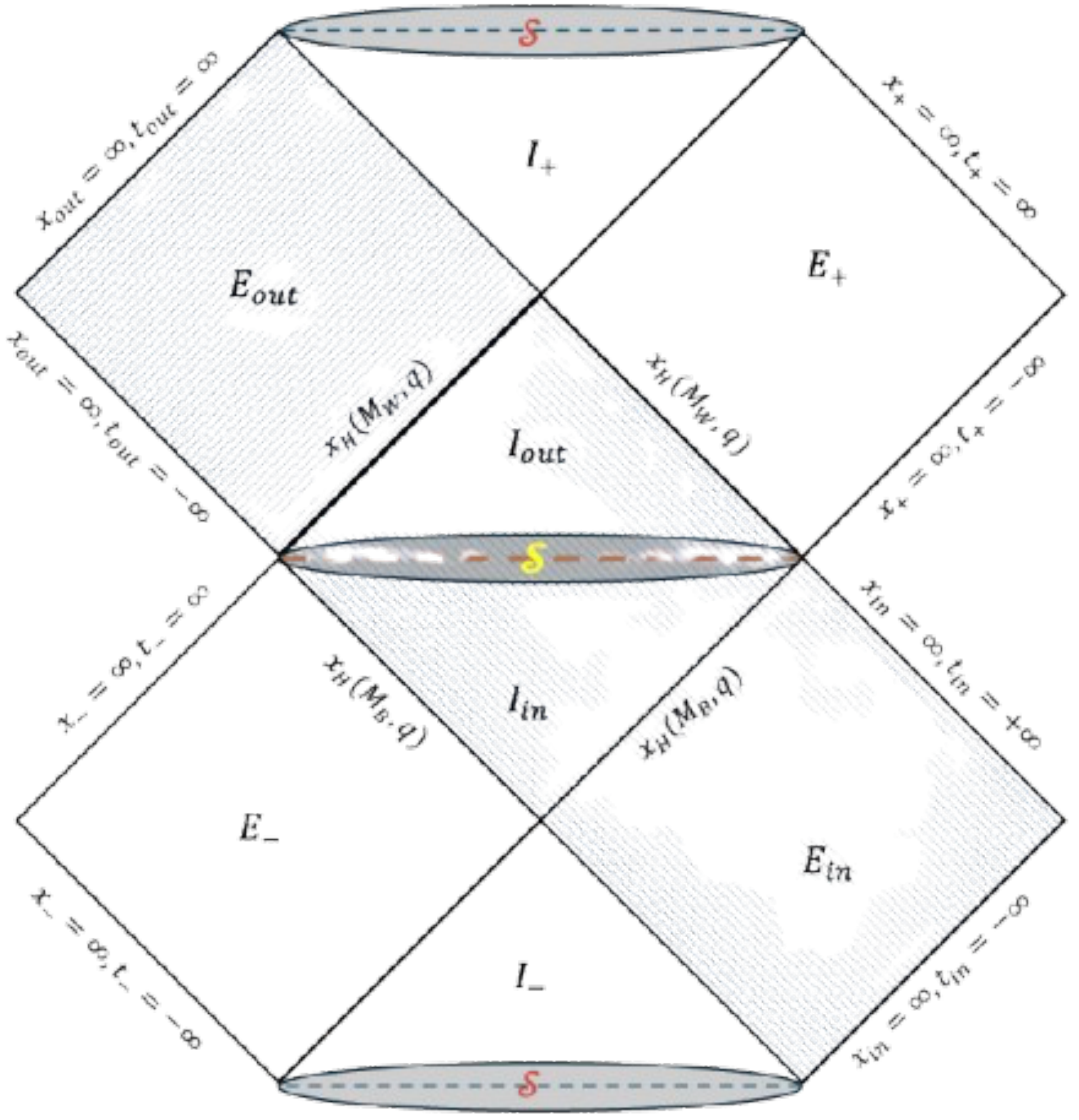

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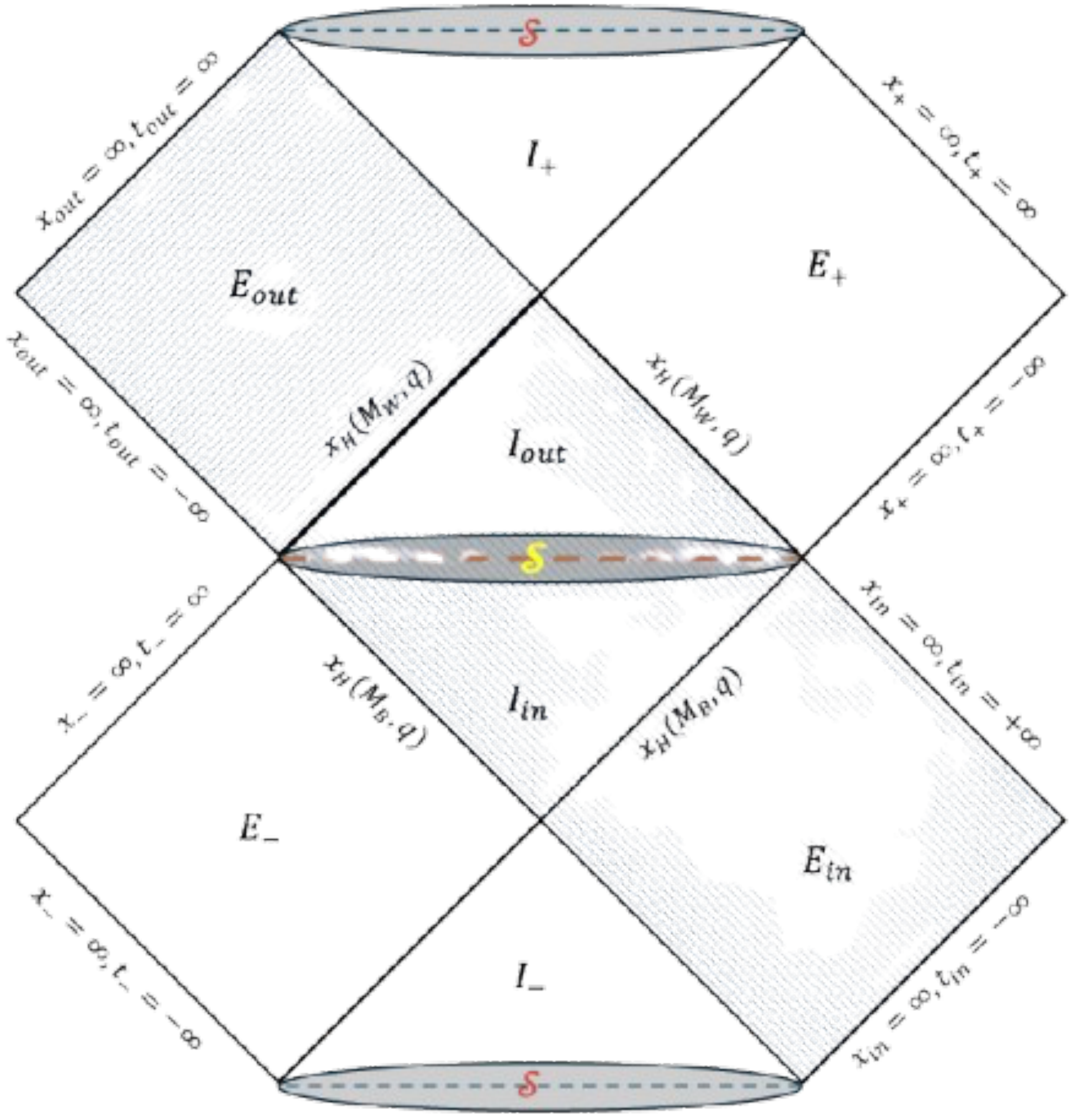

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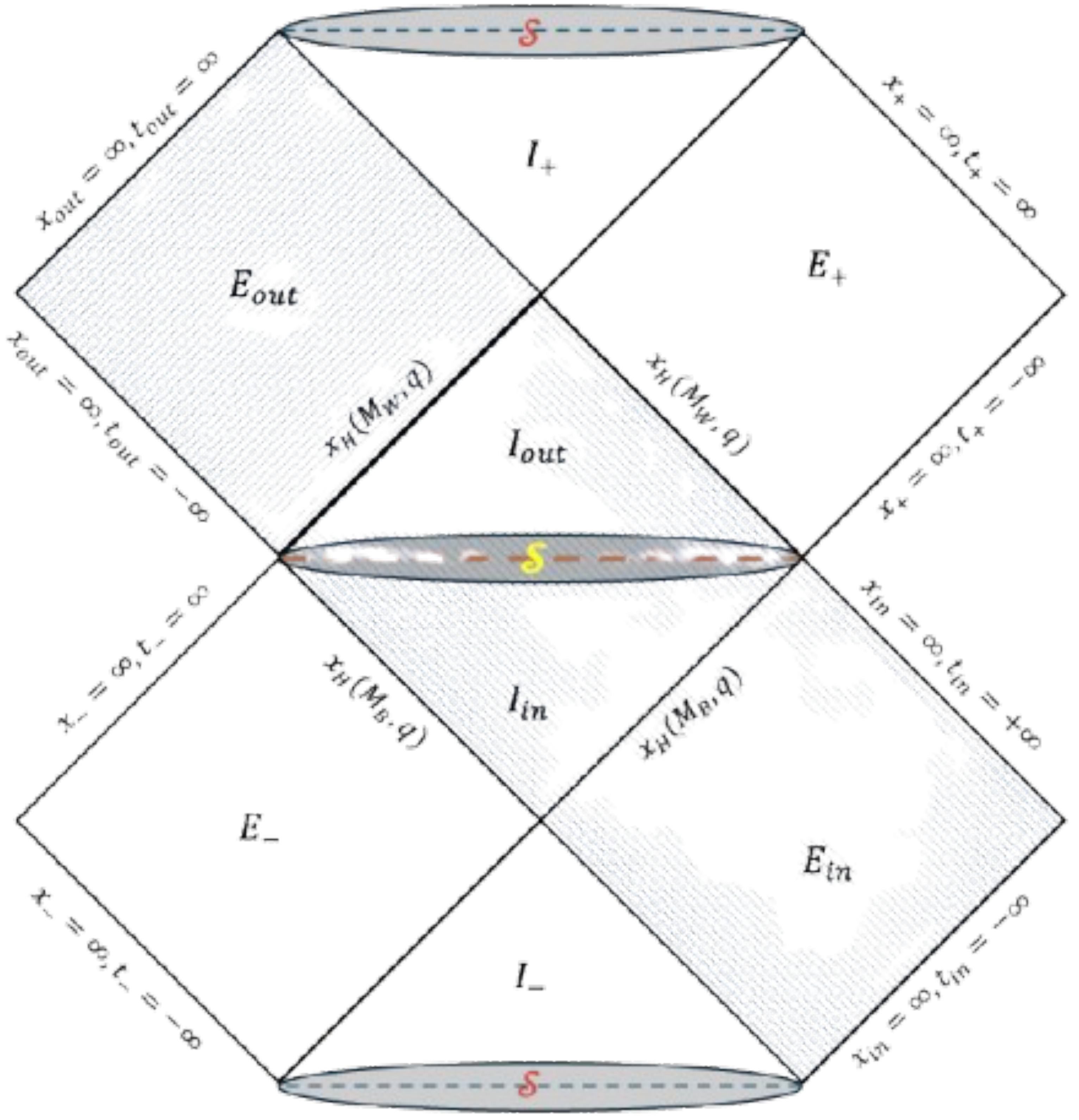
2. **Asymptotic limit ($x \to \infty$):**

$$ds^2 \approx -\frac{dt^2}{\alpha^2\chi(\infty)^2} + \left(1+\lambda(\infty)^2\right)^{-1}\frac{dx^2}{\chi(\infty)^2} + x^2 d\Omega^2 .$$

Requiring asymptotic flatness implies $\alpha = \chi(\infty)^{-1}$ $\chi(\infty) = 1/\sqrt{1+\lambda(\infty)^2}$.

Vacuum Schwarzschild solution $\Lambda = 0$



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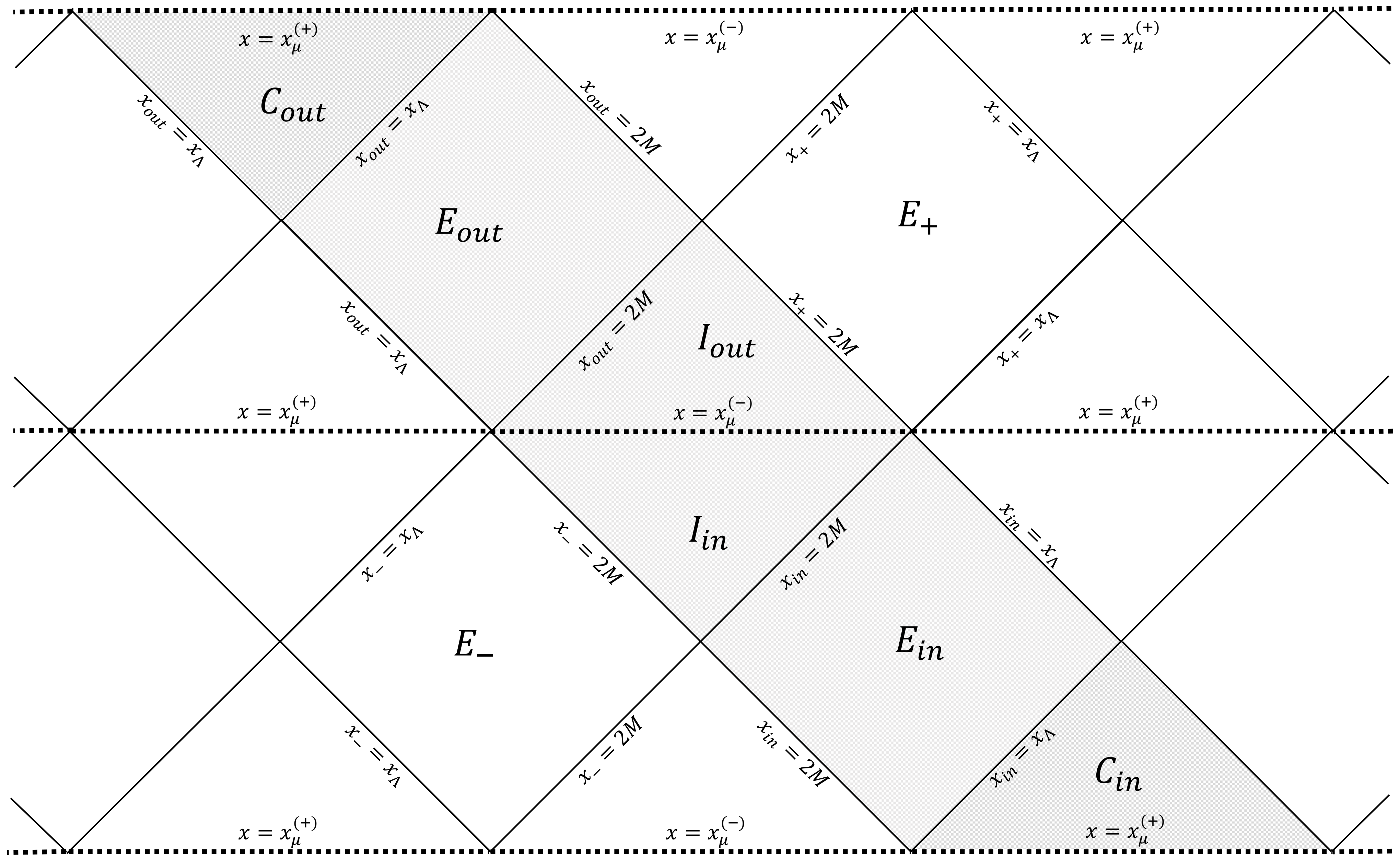
2. **Zero mass limit ($M \to 0$):**

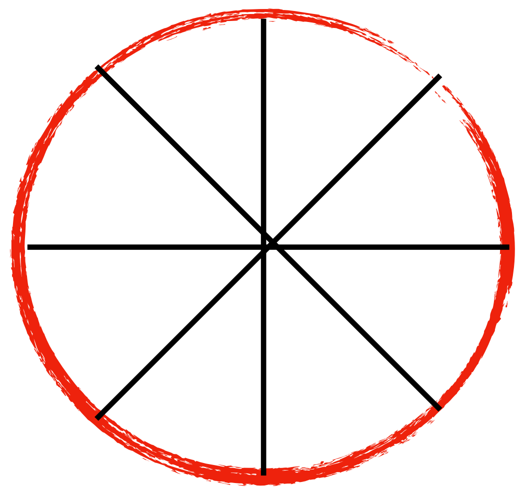
Recovering the flat time attained by $\chi^2 = \alpha^{-2} \equiv \chi_0^2 = \left(1 + \lambda_\infty^2\right)^{-1}$

$$ds^2 = -dt^2 + \frac{1}{\chi_0^2\left(1 + \lambda^2(x)\right)}dx^2 + x^2 d\Omega^2$$

dS-Schwarzschild vacuum with $\lambda(x) = \tilde{\lambda}$



Large x effect



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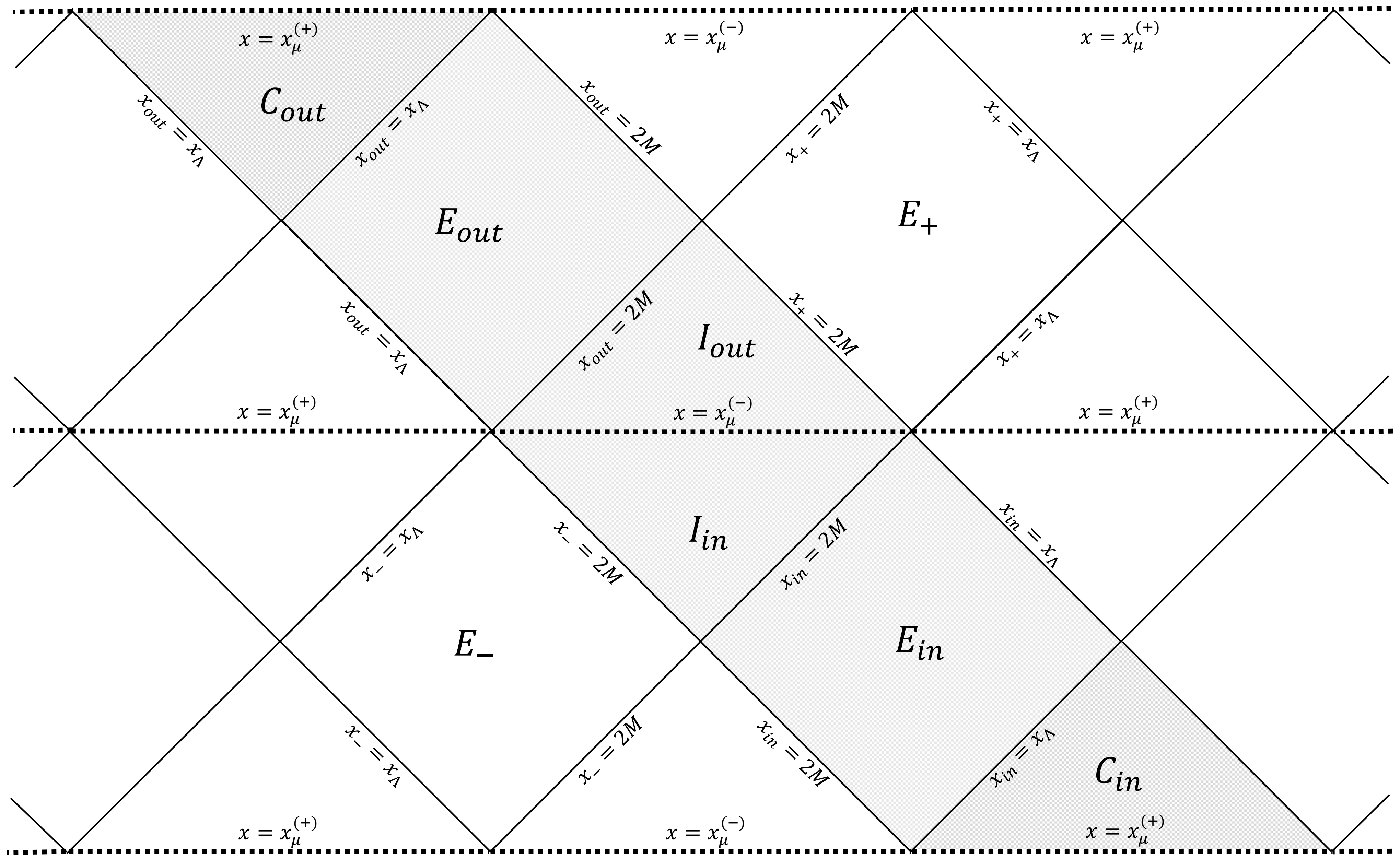

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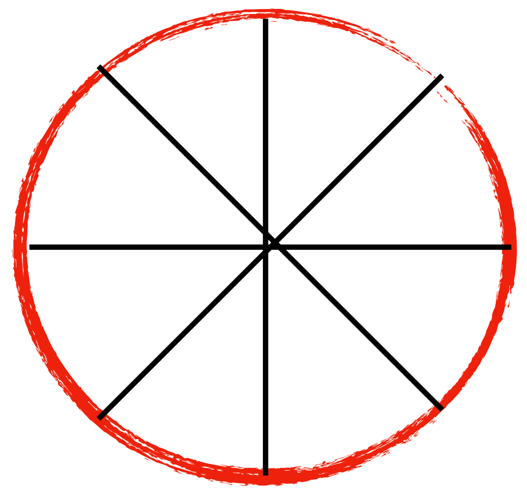
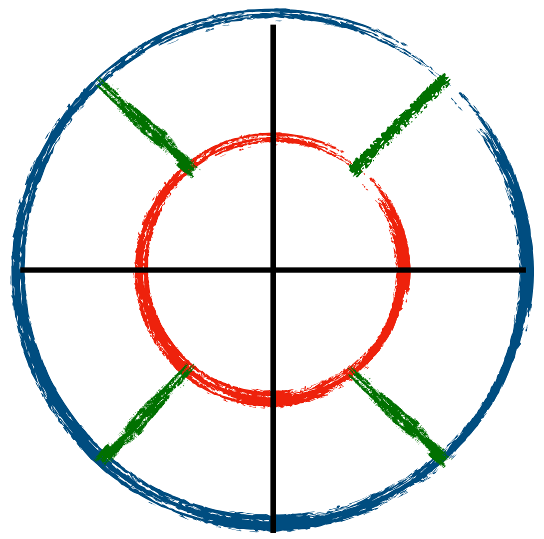
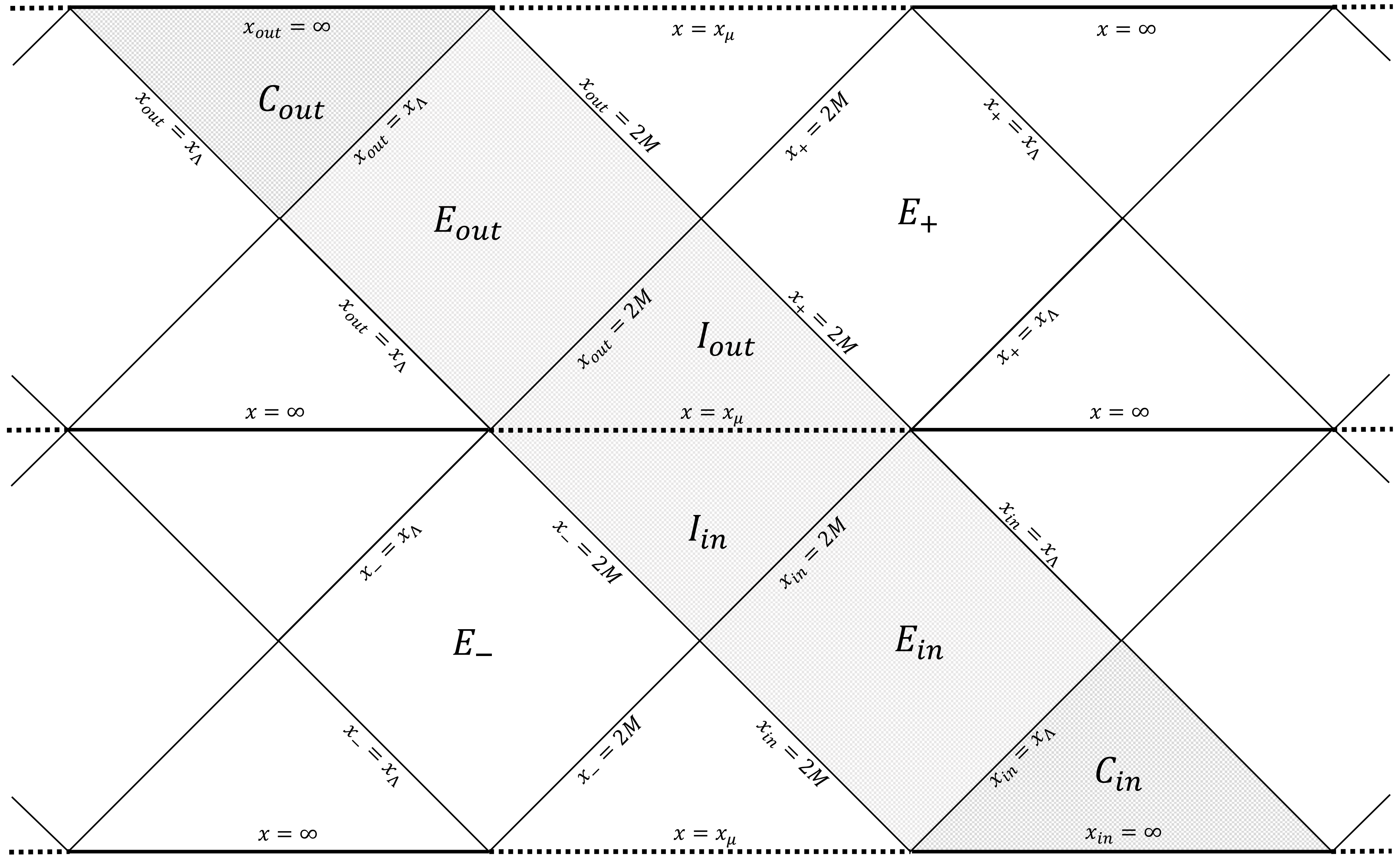




dS-Schwarzschild vacuum with $\lambda(x) = \sqrt{\frac{\tilde{\Delta}}{x^2}}$



No IR effect

Covariance coupling

Hamiltonian constraint of the gravitational degrees of freedom with scalar matter

$$\tilde{H} = \tilde{H}_{\text{grav}} + \tilde{H}_{\phi}$$

The covariance allowed for a variety of coupling schemes [Bojowald and Duque'24]. Two interesting scenarios:

- Minimally coupled scalar field (low-curvature)

$$\tilde{H} = E^x \sqrt{\tilde{q}_{xx}} \left(\frac{P_\phi^2}{2\left(E^x\right)^2 \tilde{q}_{xx}} + \frac{\left(\phi'\right)^2}{2\tilde{q}_{xx}} + V(\phi) \right)$$

- Non-minimally coupled scalar (high-curvature)

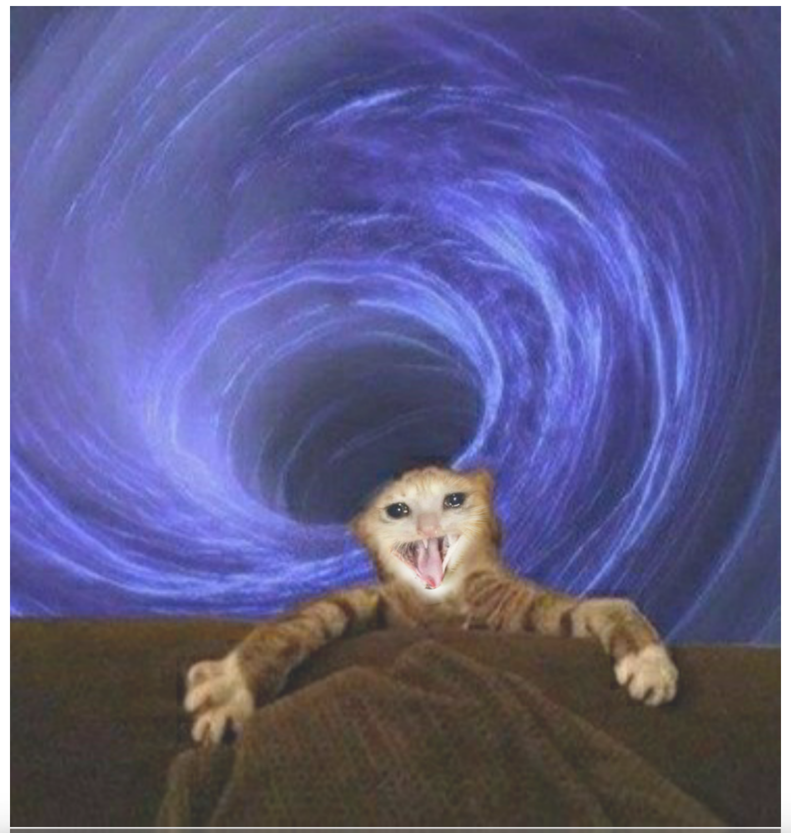
$$\tilde{H} = \chi \frac{\sqrt{E^x}}{2} \left(\frac{P_\phi^2}{E^\varphi E^x} \left(1 + \lambda^2 (E^x) \left(\frac{\left(E^x\right)'}{2E^\varphi} \right)^2 \right) \cos^2(\lambda K_\varphi) + \frac{E^x}{E^\varphi} \left(\phi'\right)^2 + 2E^\varphi V(\phi) \right)$$

THE BLACK HOLE EVAPORATION

Near horizon expansion

- Near-horizon $x = 2M\left(1 + \left(\chi_0\zeta/4M\right)^2\right)$, the line-element can be cast into Rindler line-element

$$ds^2 = -\zeta^2 d\tau^2 + d\zeta^2 \longrightarrow$$ Near horizon temperature $T = \frac{\chi_0}{4\pi}\frac{1}{\sqrt{2Mx(1-2M/x)}}$



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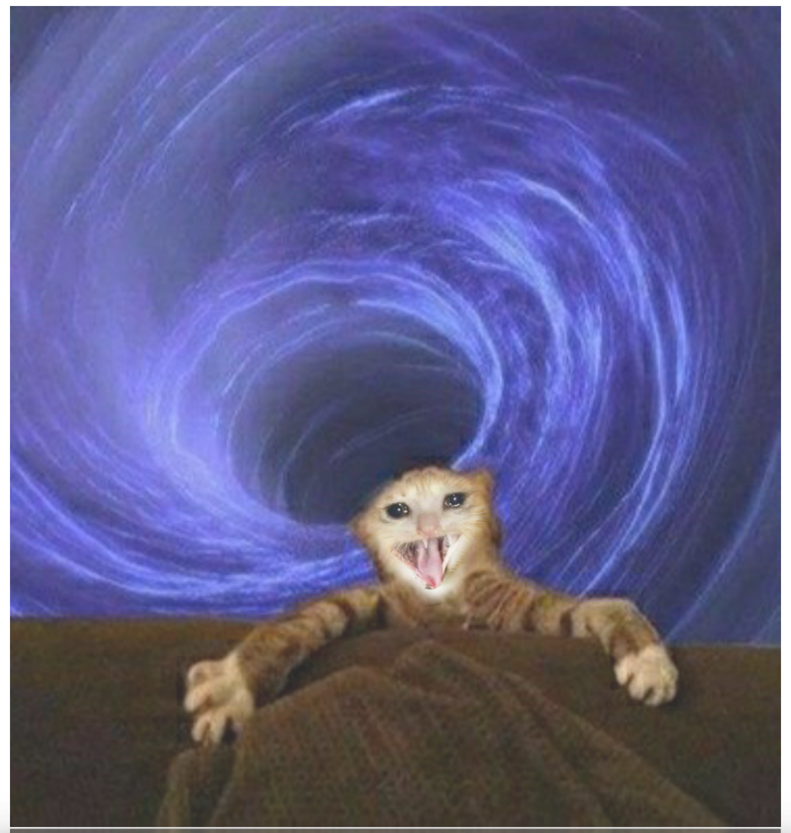

- The temperature at arbitrary $\bar{x} > x$

$$T(\bar{x}) = \frac{\chi_0}{8\pi M}\left(1 - \frac{2M}{\bar{x}}\right)^{-1/2}$$

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Near horizon temperature $T = \frac{\chi_0}{4\pi} \frac{1}{\sqrt{2Mx\left(1 - 2M/x\right)}}$

- The temperature at arbitrary $\bar{x} > x$

$$T(\bar{x}) = \frac{\chi_0}{8\pi M}\left(1 - \frac{2M}{\bar{x}}\right)^{-1/2}$$

- The temperature measured by the asymptotic observer

$$T(\infty) = \frac{1}{8\pi M}\chi_0 = \chi_0 T_H$$

Hawking temperature recovered in the scale-dependent holonomy

A geometric approach

Brown-York quasi-local energy

$$E_{BY}(x) = x\chi_0 \left(\sqrt{1+\lambda^2} - \sqrt{1-\frac{2M}{x}} \sqrt{1+\lambda^2\left(1-\frac{2M}{x}\right)} \right)$$

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An infinitesimal change δM will change the Brown-York quasi-local energy which can be associated with thermodynamics relation $\delta E_{BY} = T\delta S$, which provides:

$$S(x) = \frac{8\pi x^2}{15\lambda^4}\left[\sqrt{1+\lambda^2\left(1-\frac{2M}{x}\right)}\left(3+\lambda^2\left(1+\frac{3M}{x}\right) - 2\lambda^4\left(1+\frac{M}{x}-\frac{6M^2}{x^2}\right)\right) - \sqrt{1+\lambda^2}\,(3+\lambda^2-2\lambda^4)\right]$$

A geometric approach

Brown-York quasi-local energy

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Black hole entropy

A geometric approach

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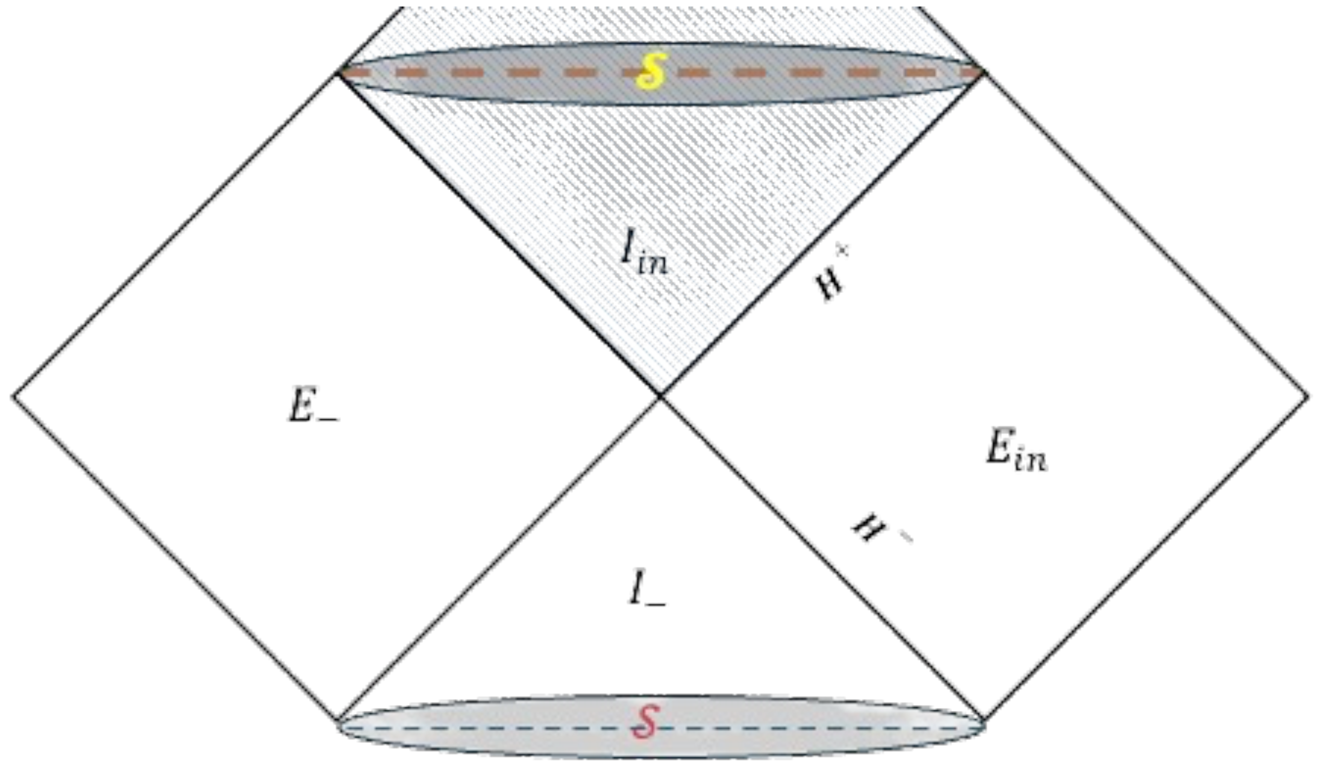
Parikh-Wilczek formalism



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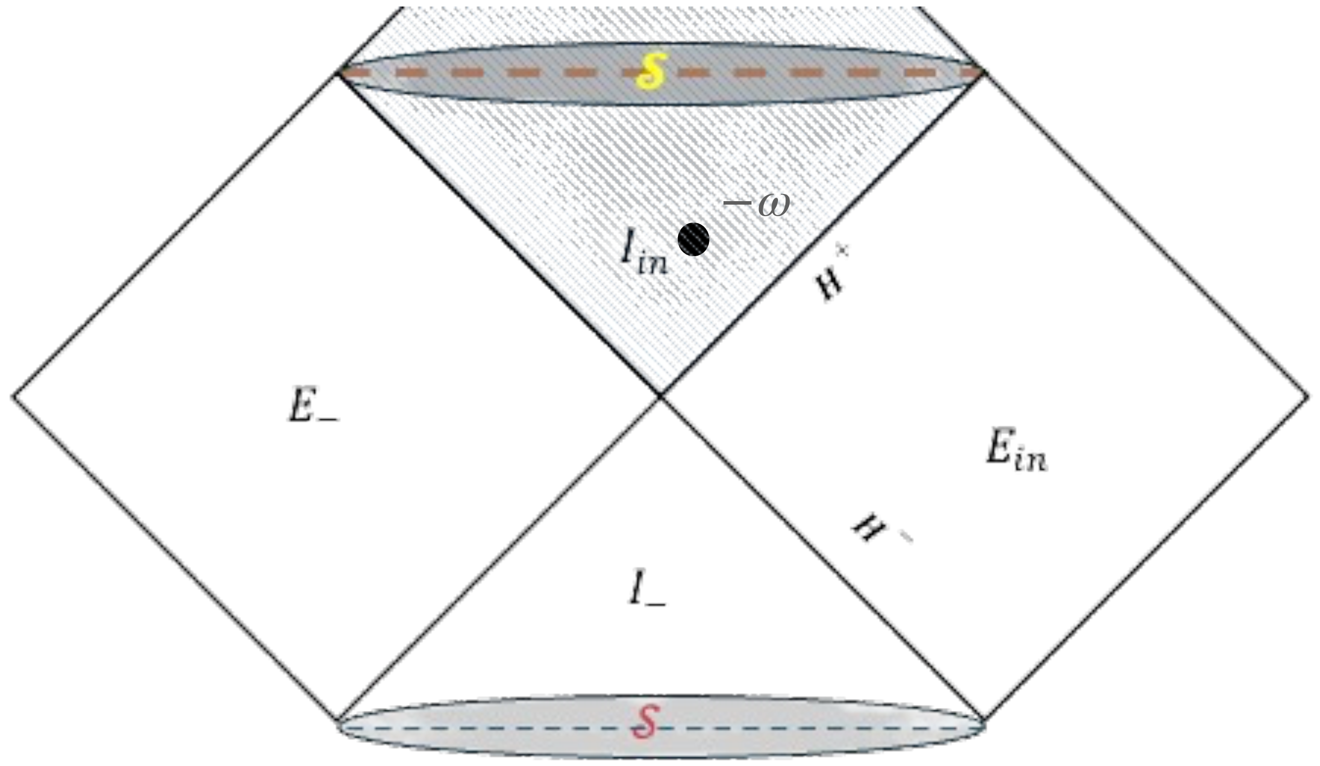
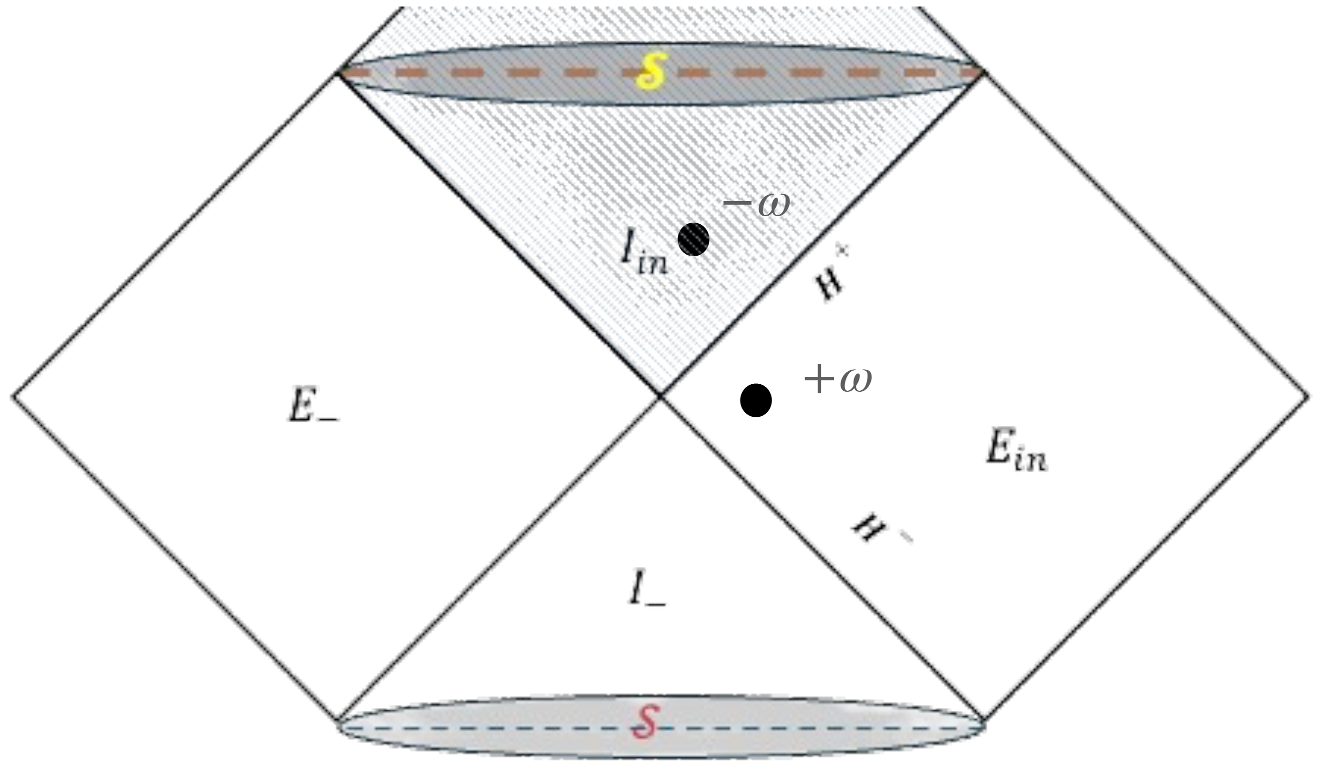
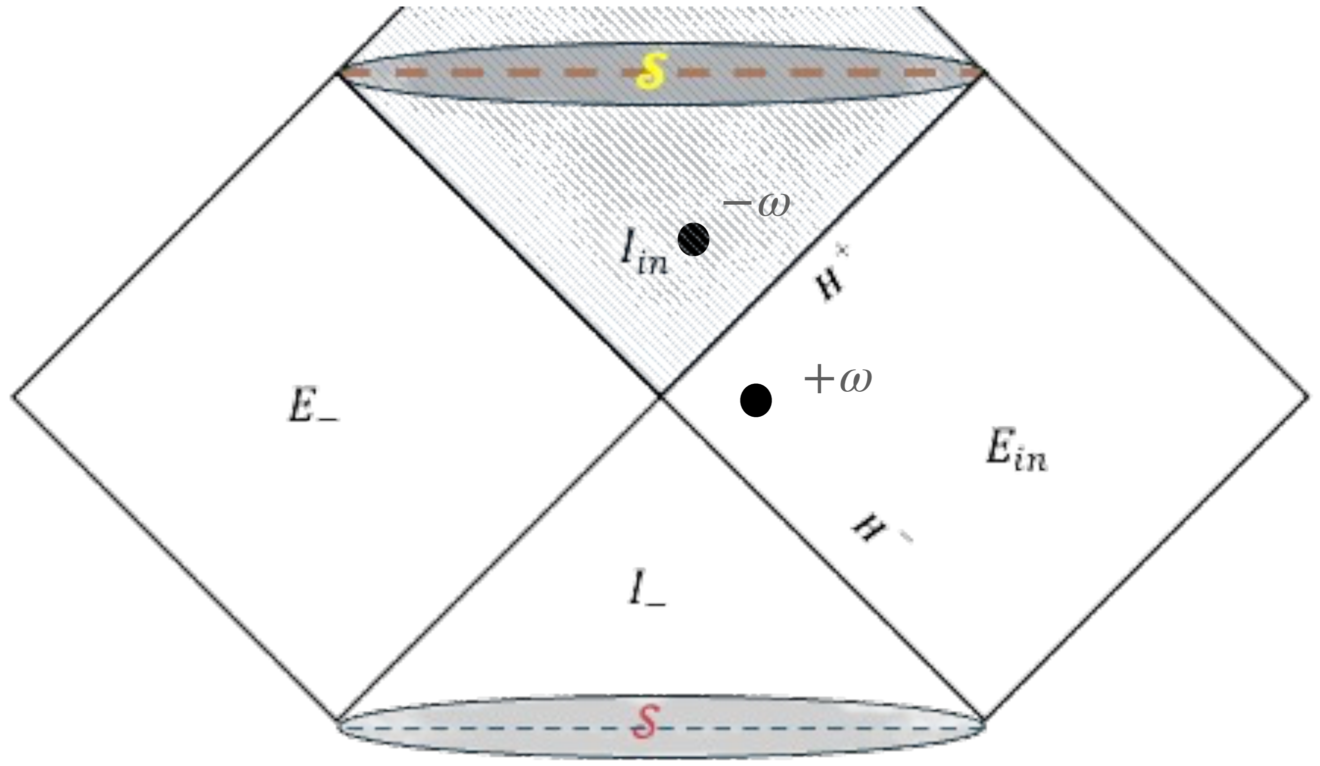
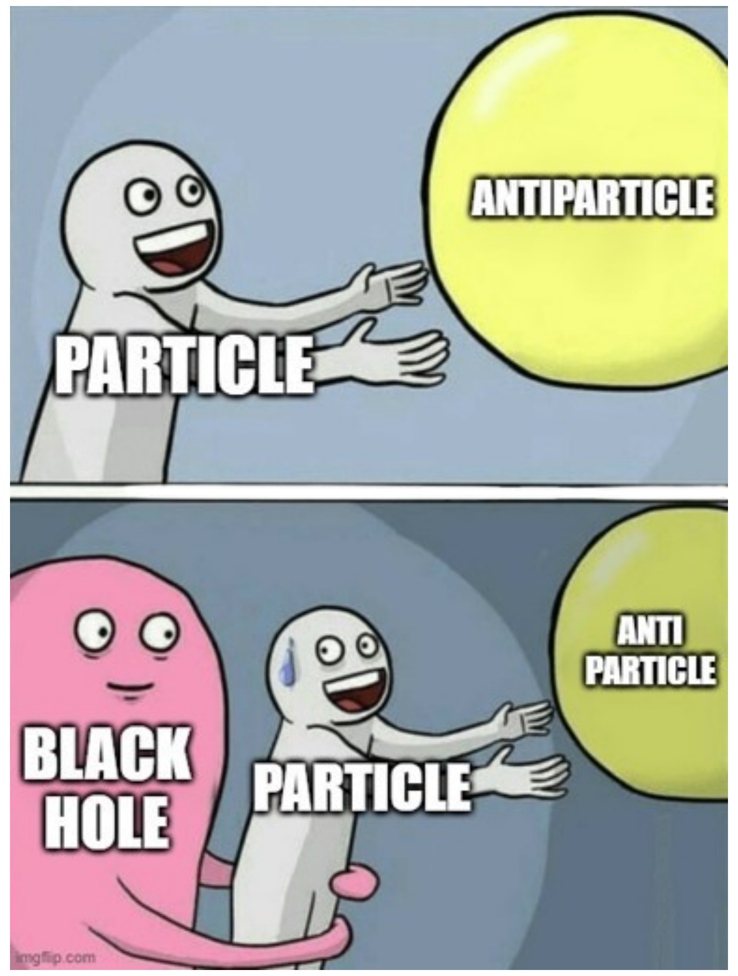




$-\omega$
I_{in}
H^+
$+\omega$
E_-
E_{in}
H^-
I_-





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The ADM mass M_{ADM} is held constant throughout the process

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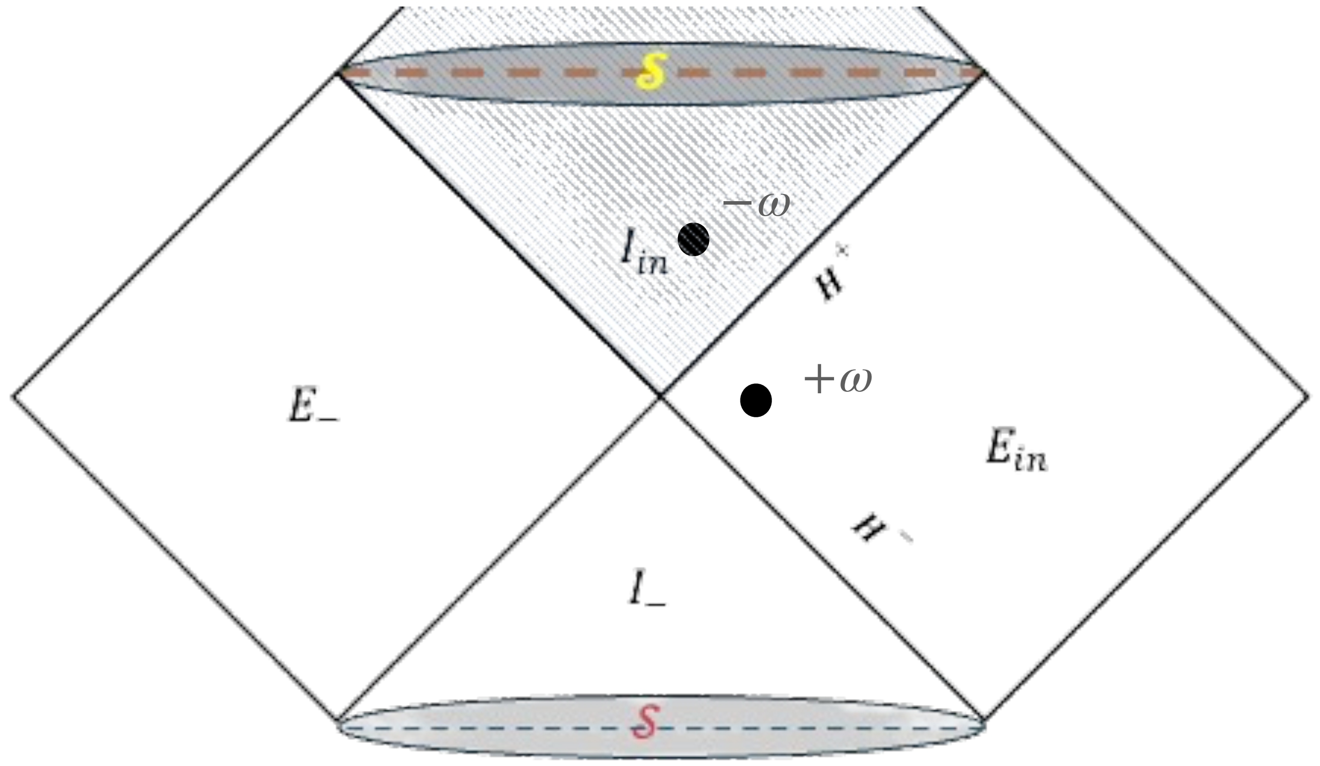

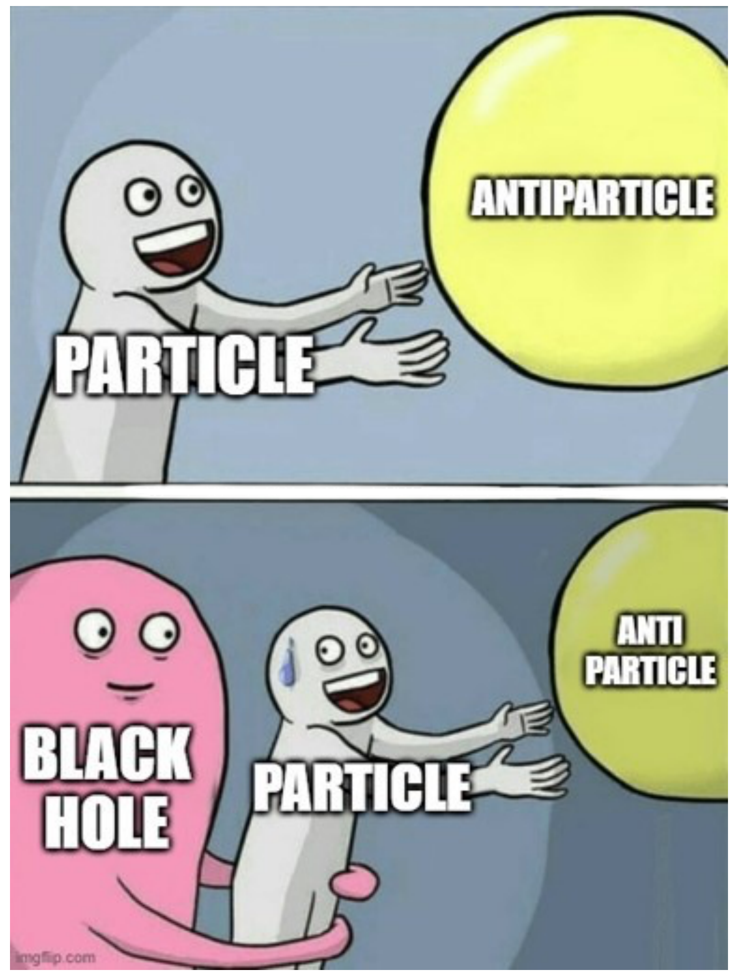

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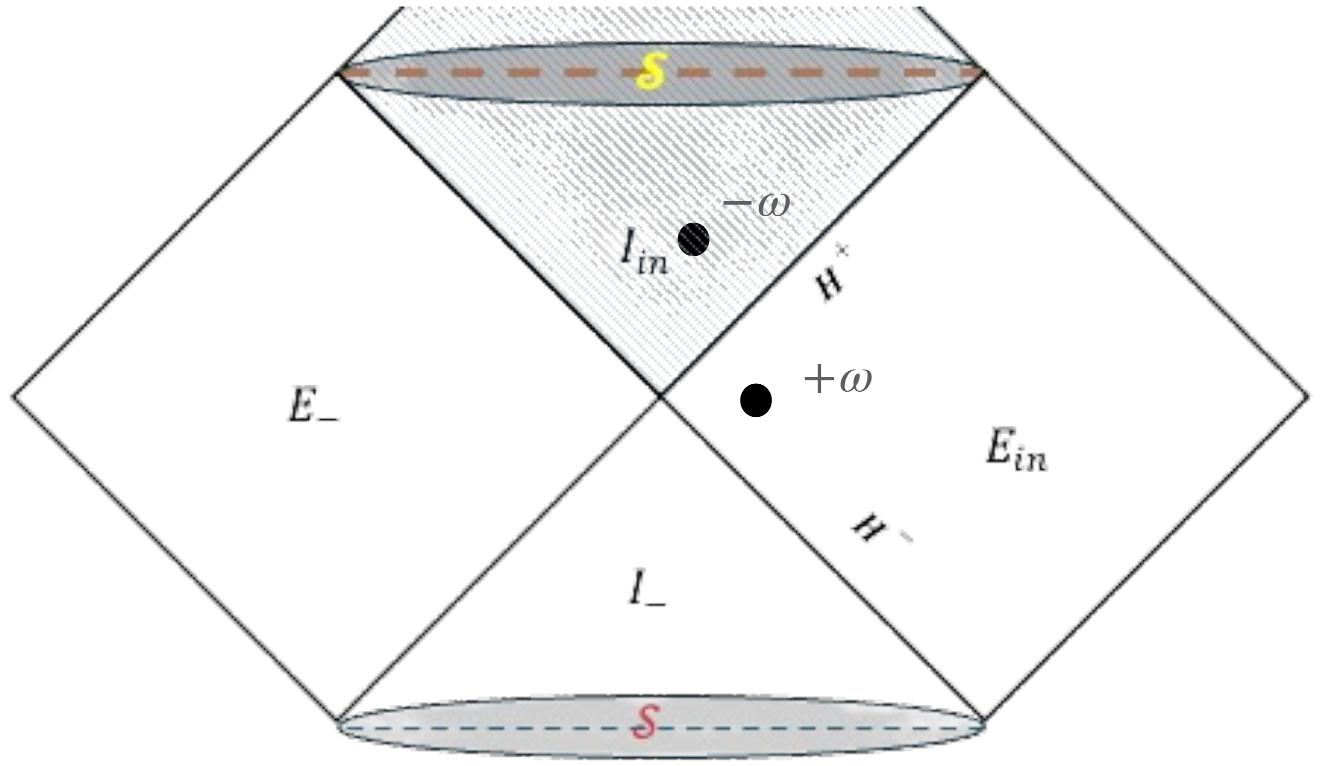

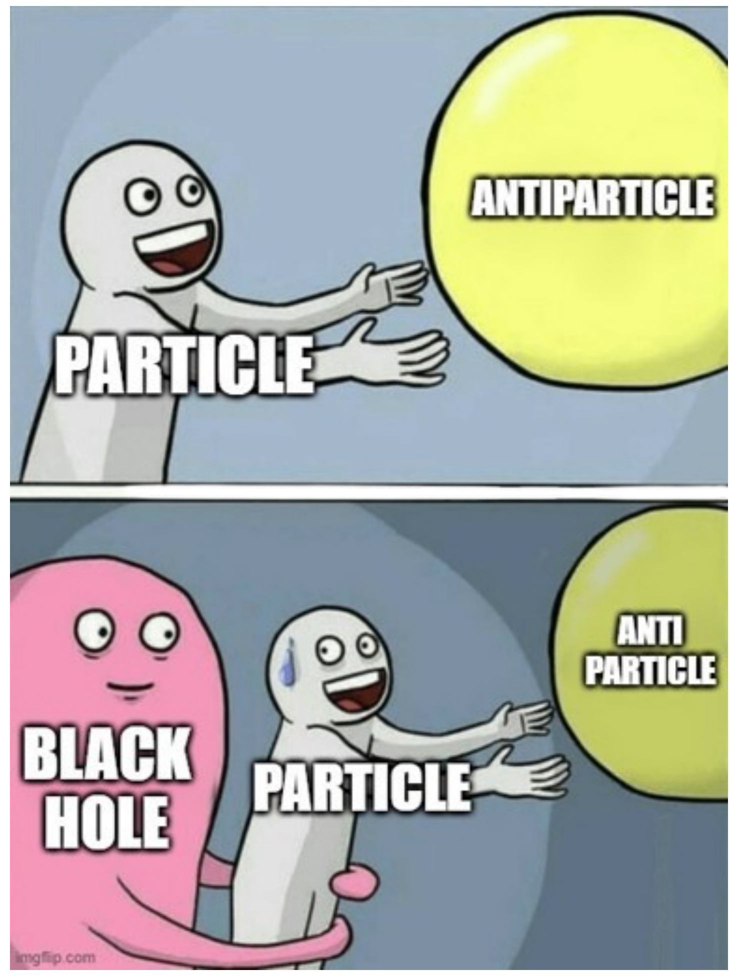

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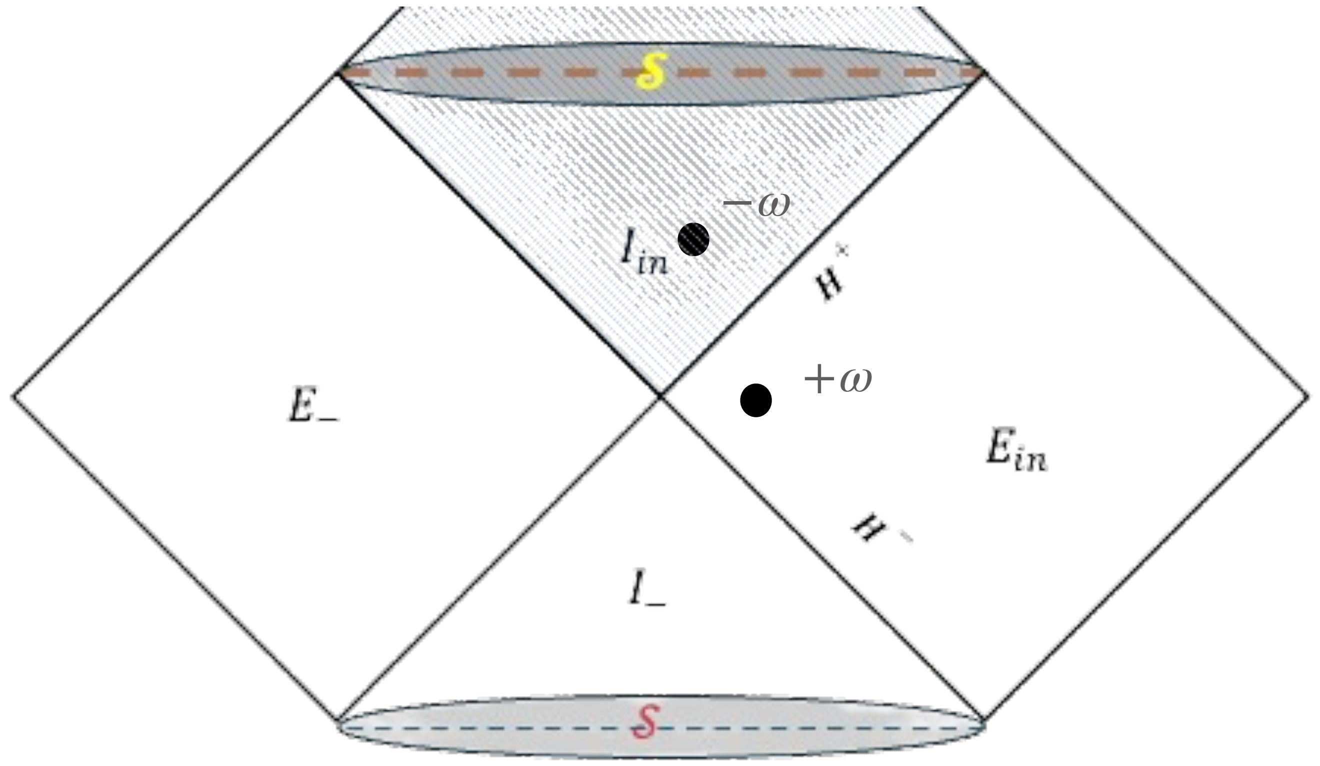

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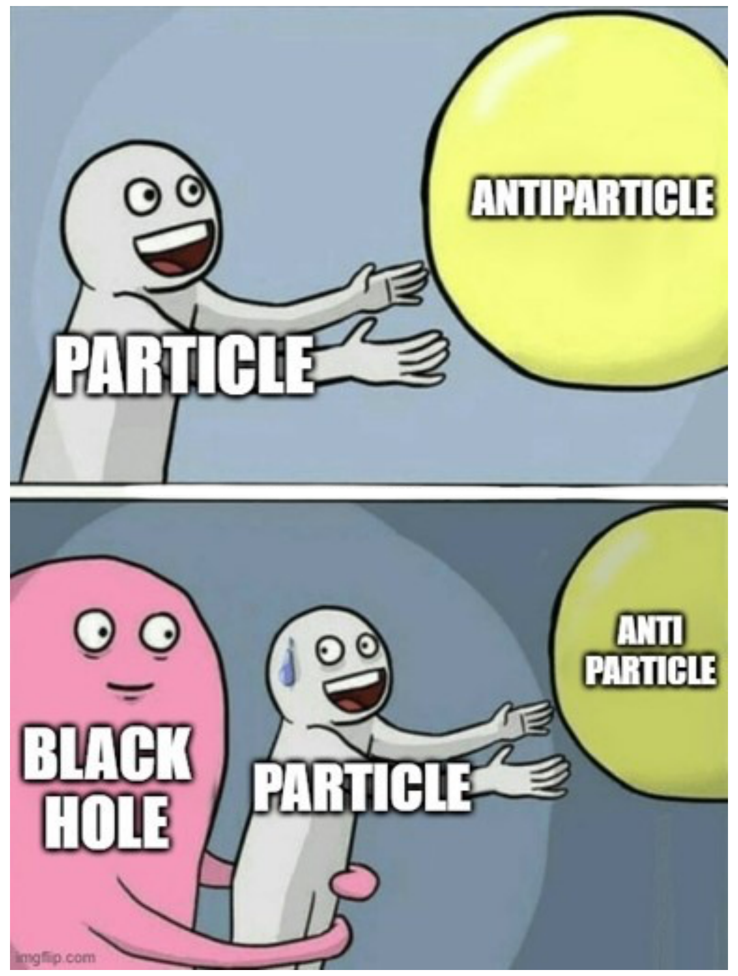

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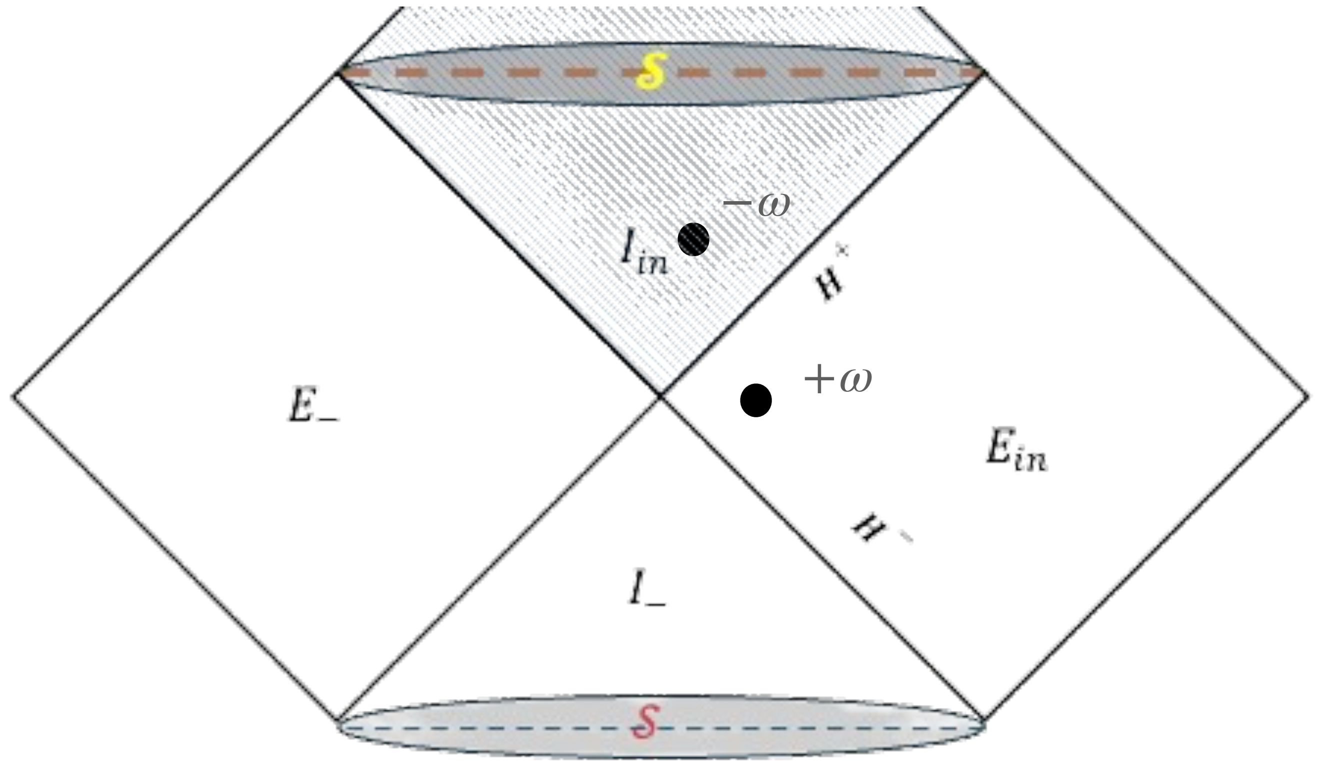

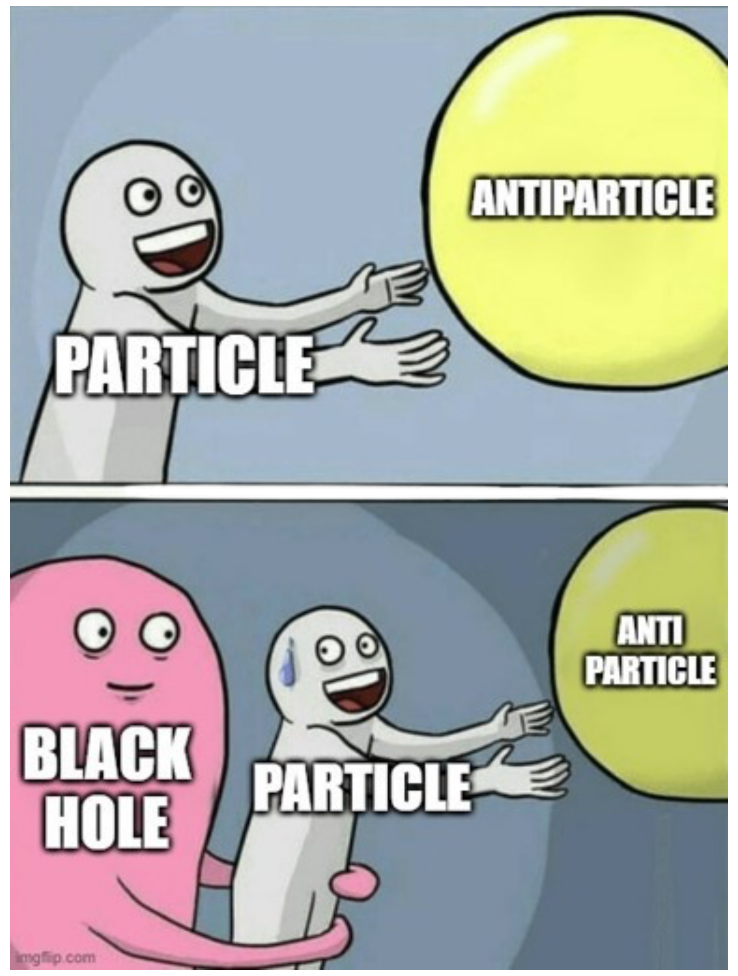

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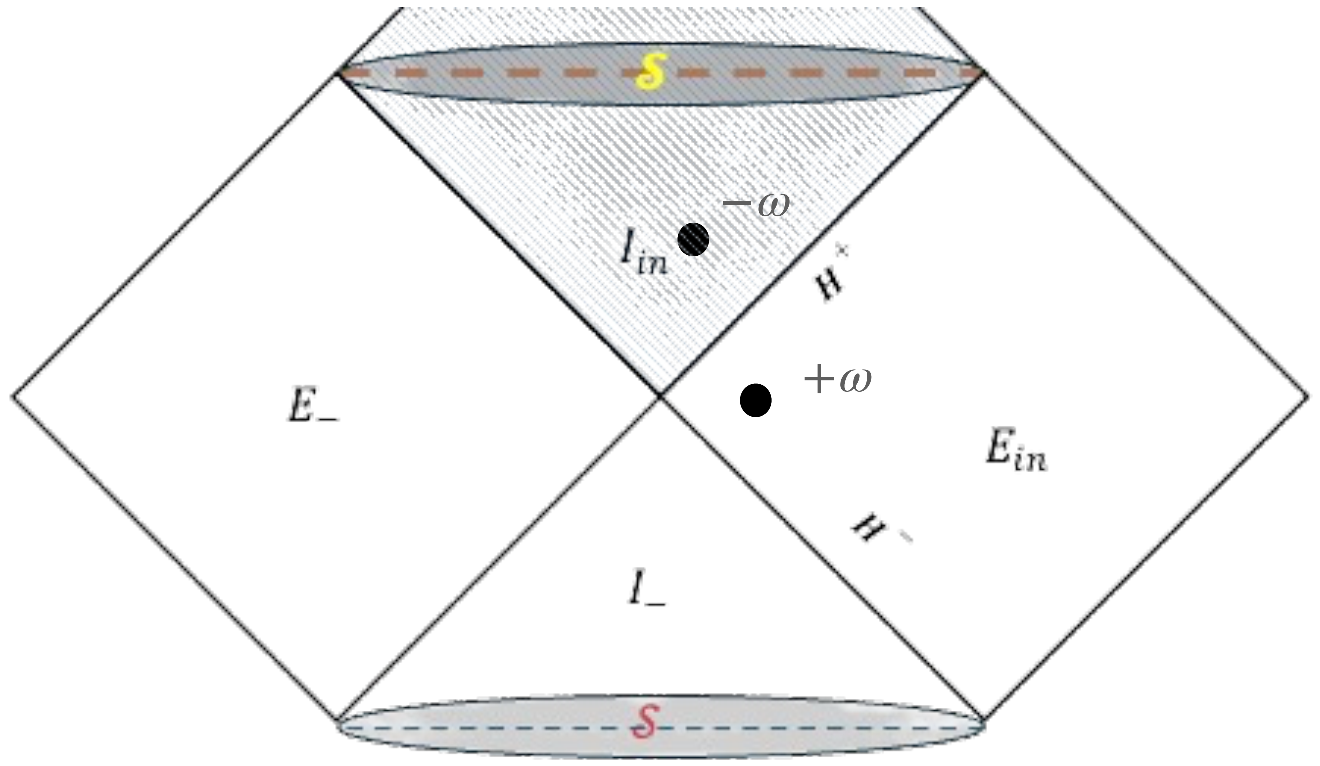

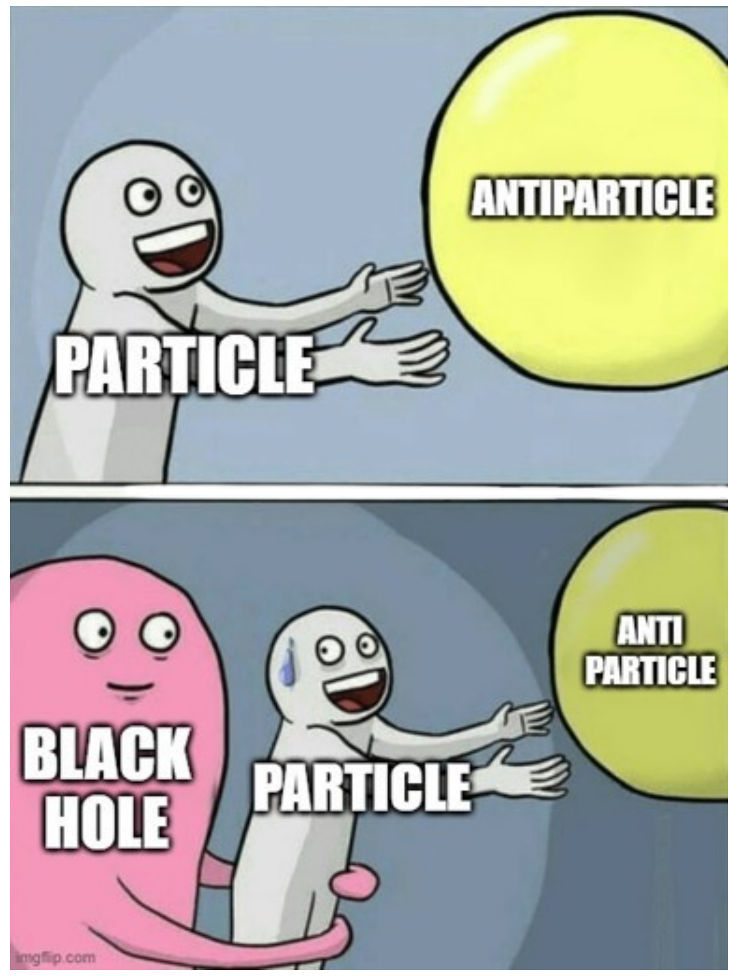

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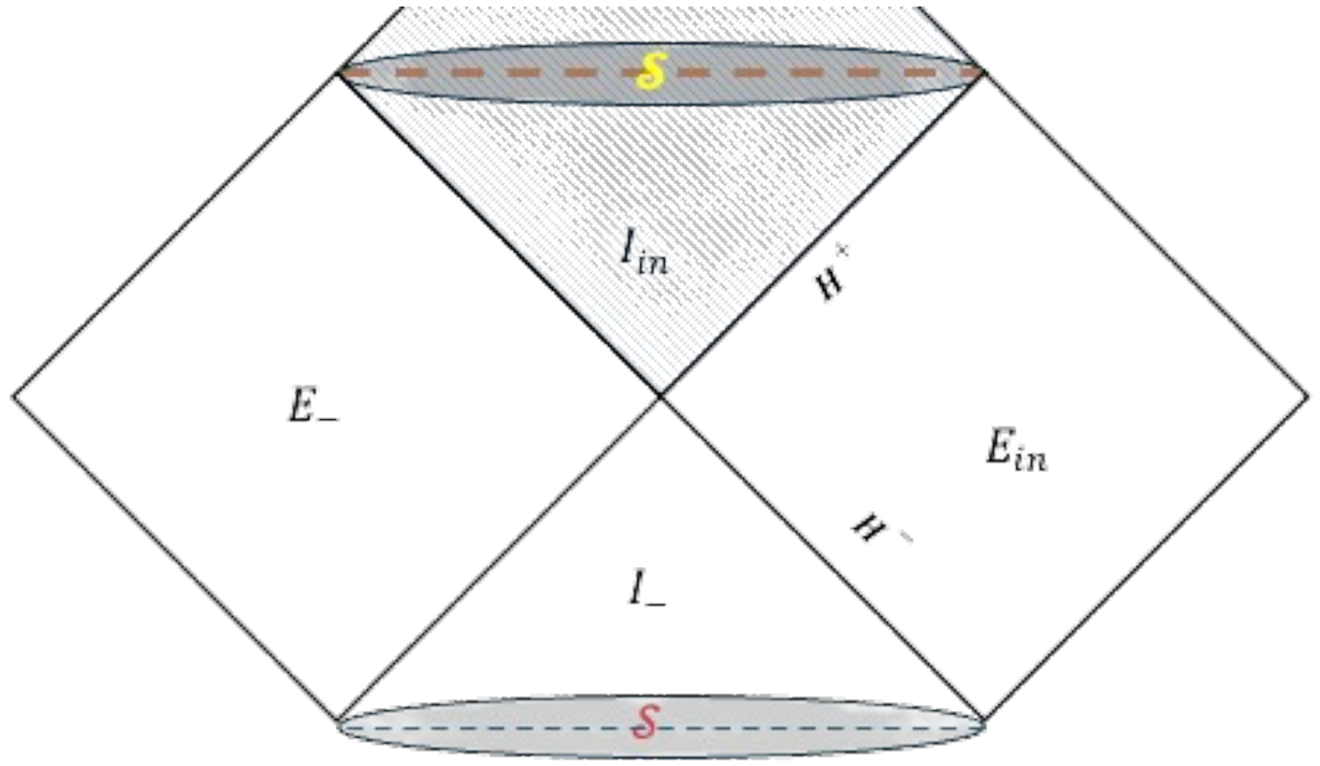
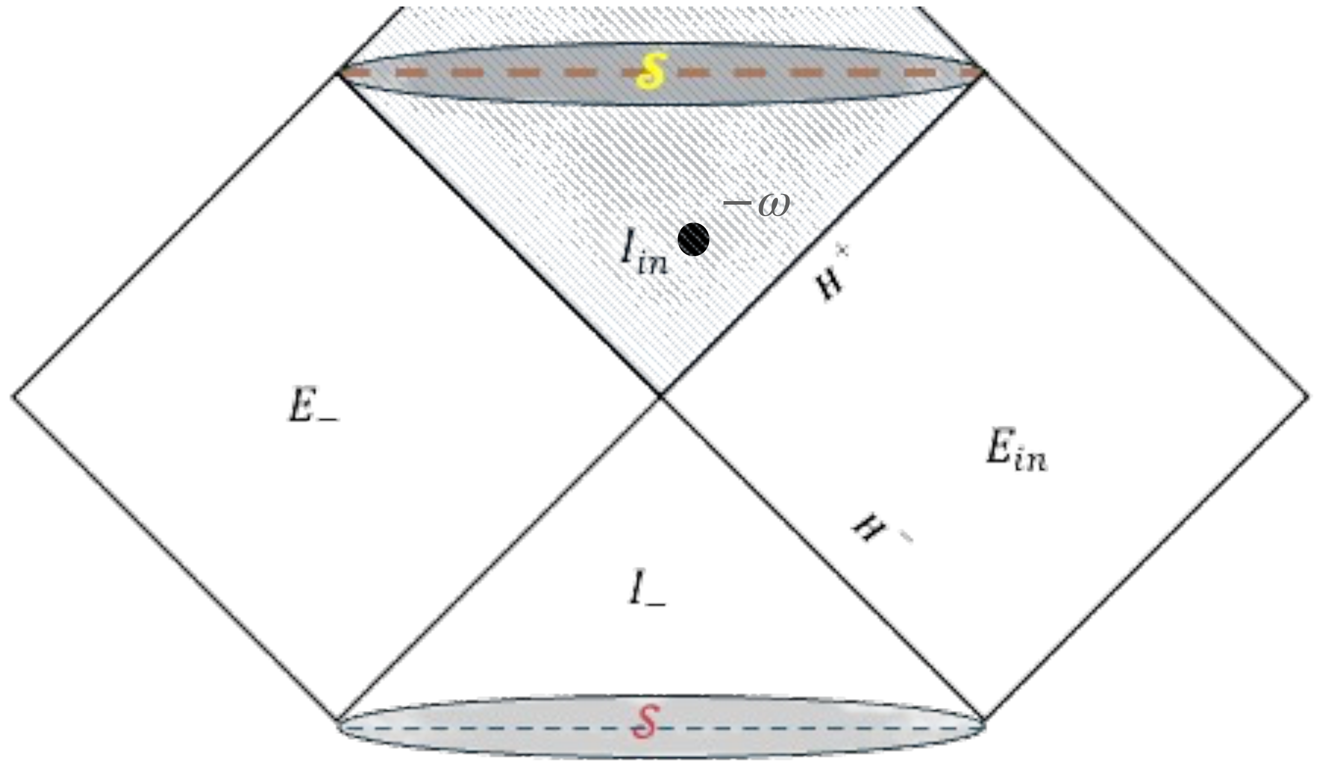
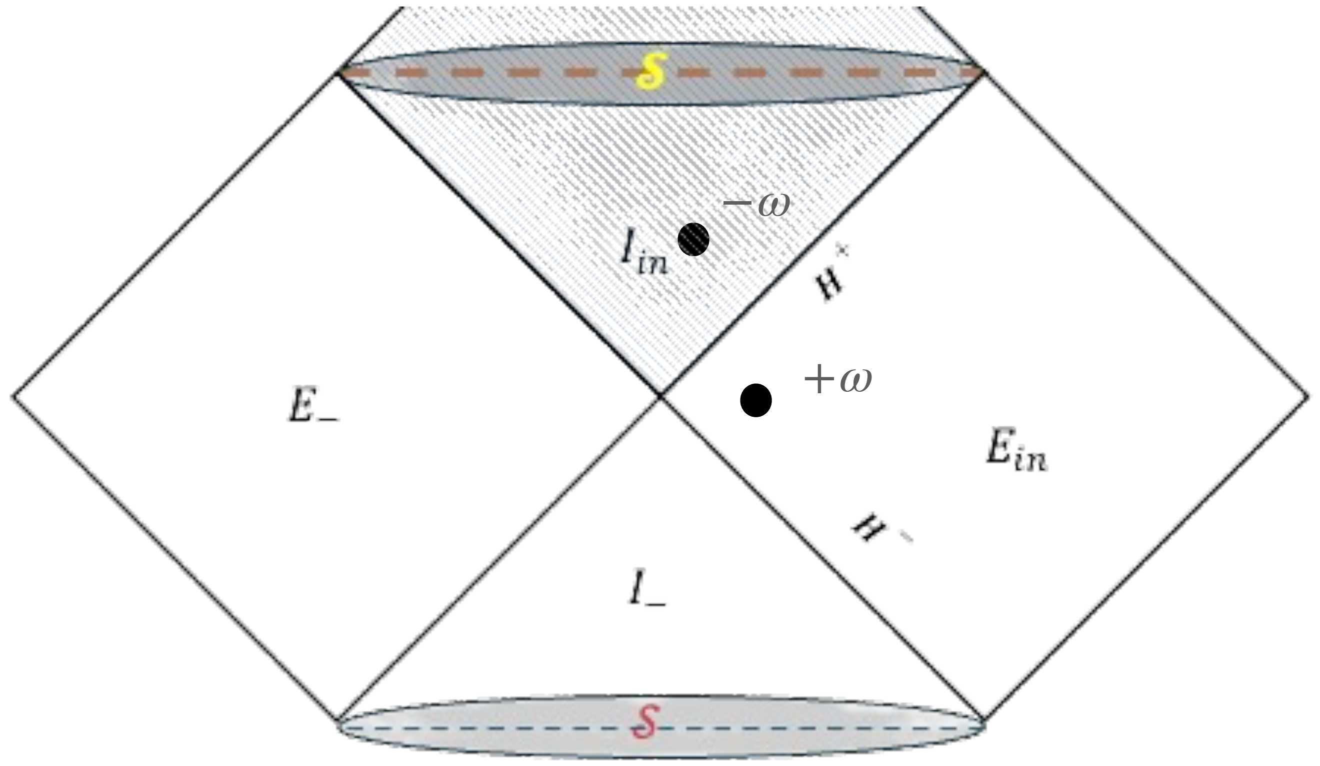
$$S_{\mathrm{BH}} = 4\pi M^2$$

Parikh-Wilczek formalism




S
I_{in}
$-\omega$
H^+
E_-
E_{in}
H^-
I_-
S



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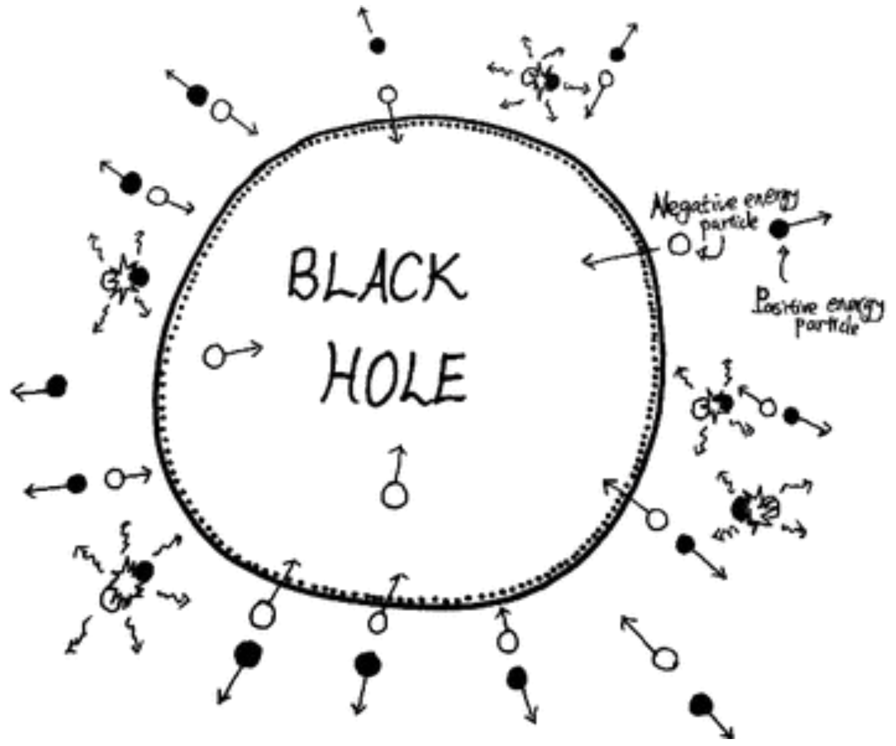

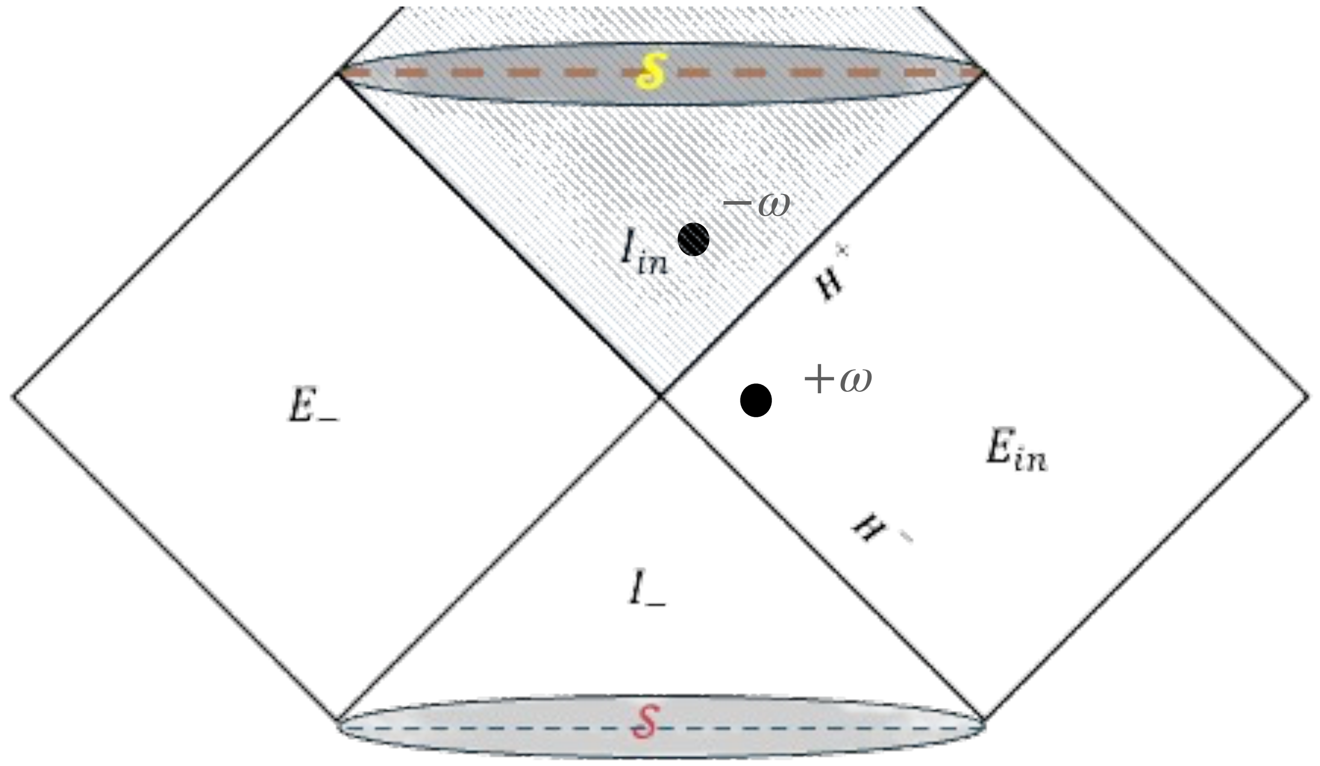

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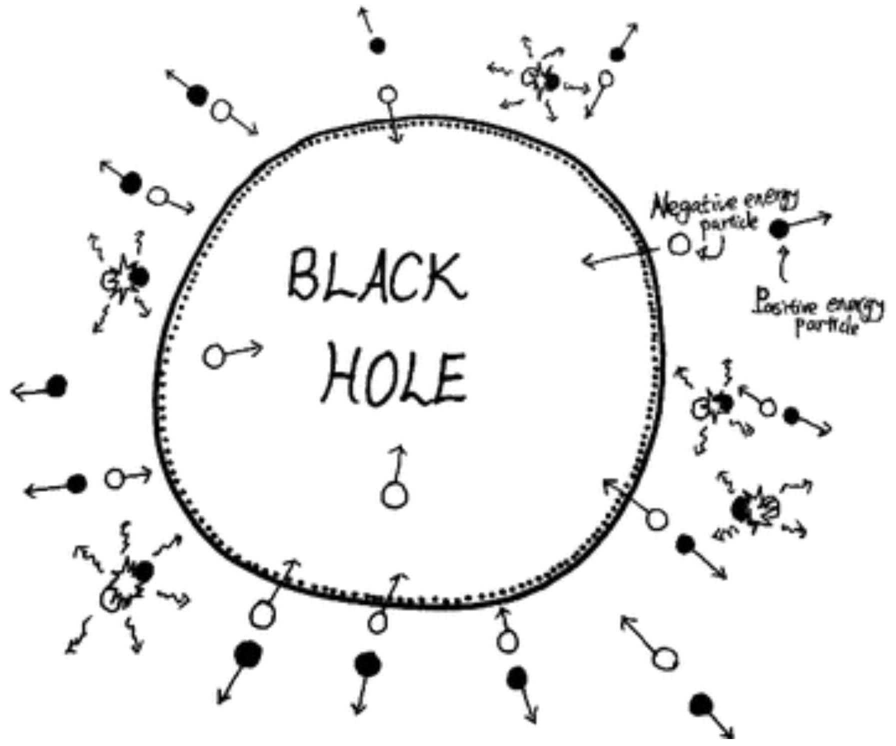

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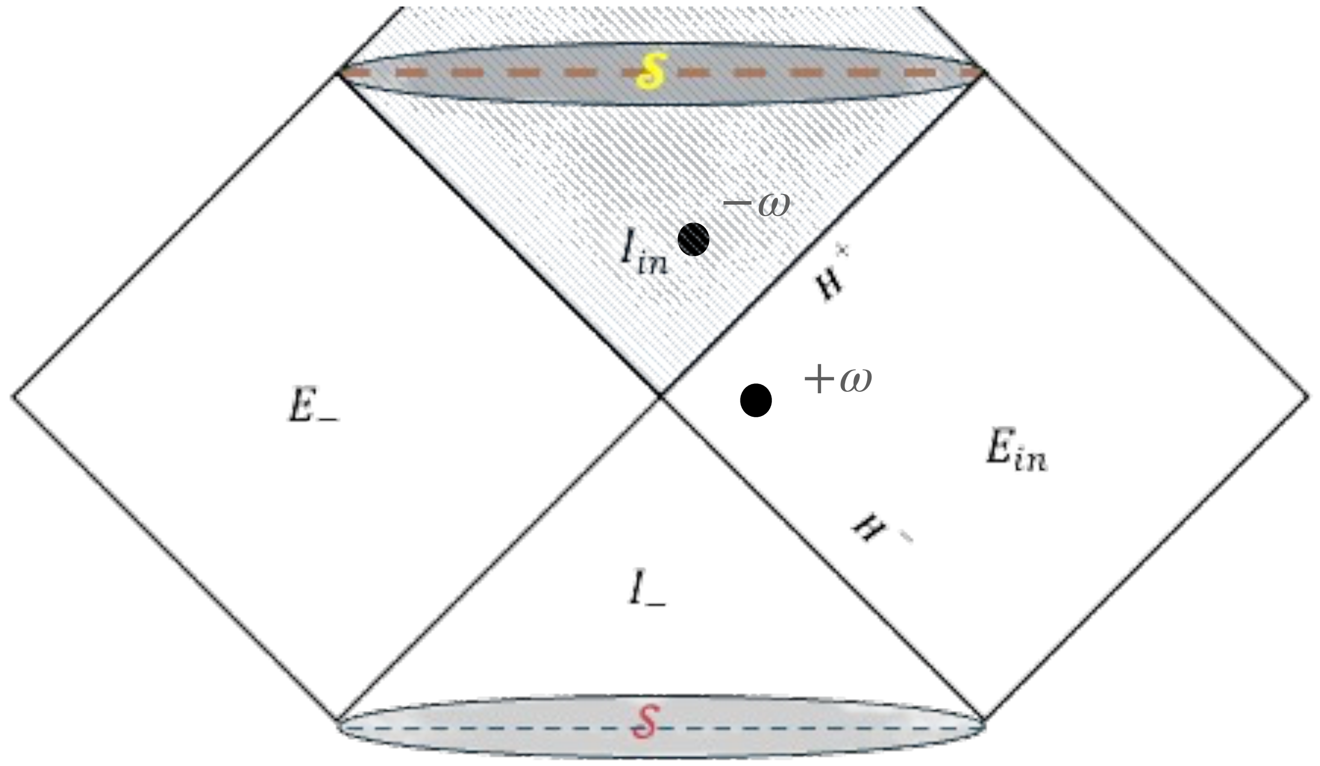

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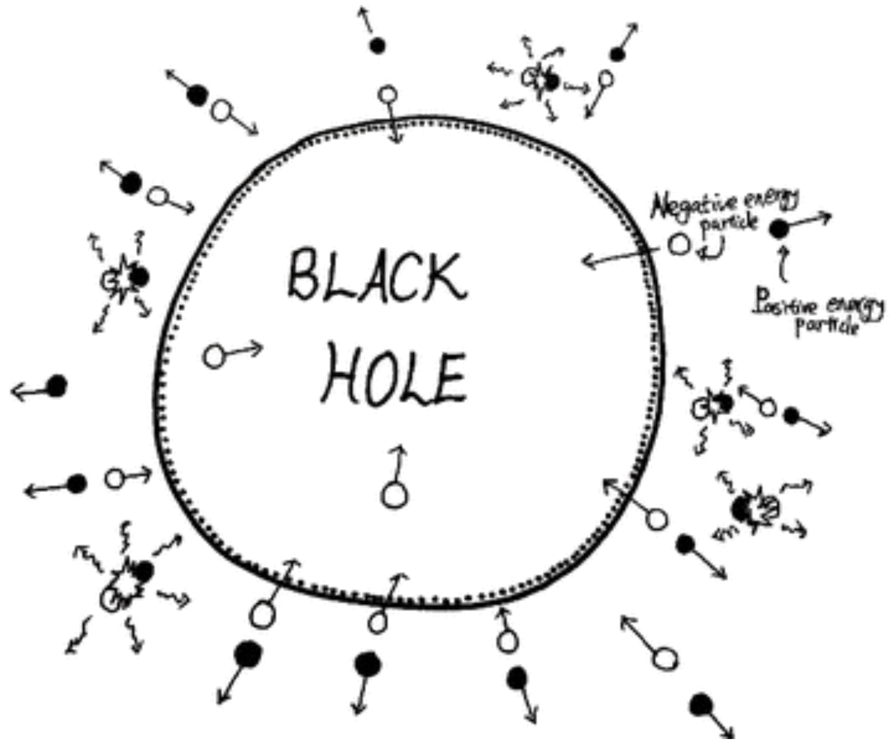

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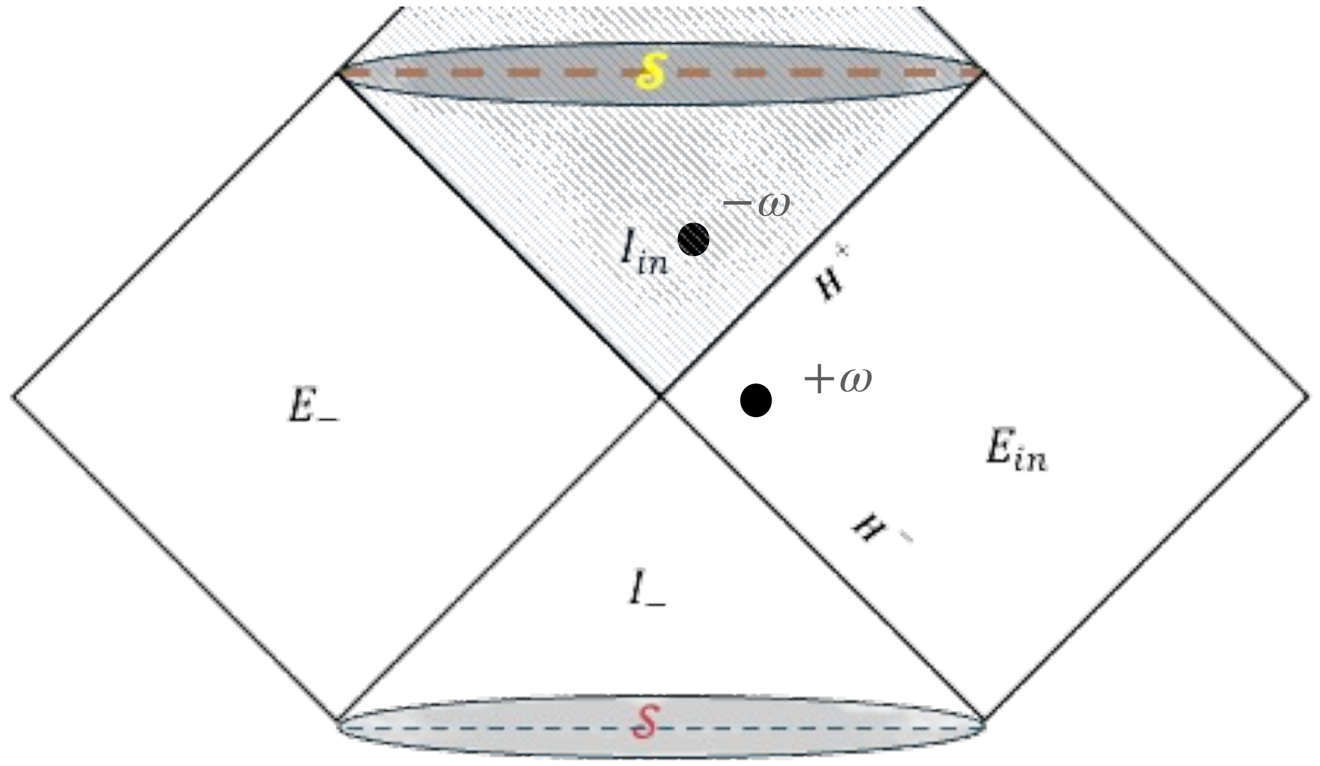

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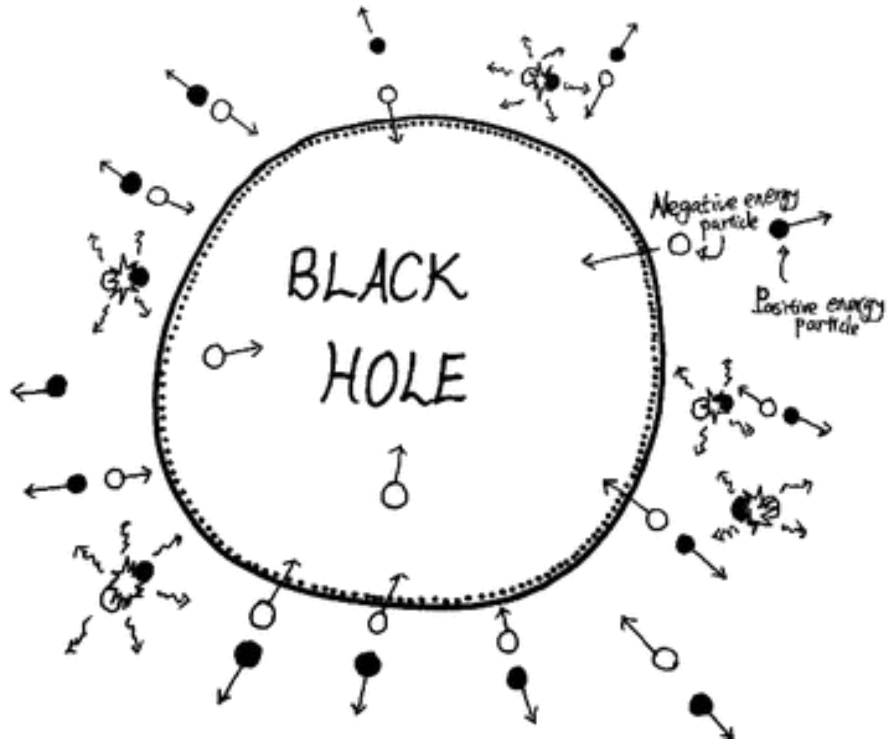

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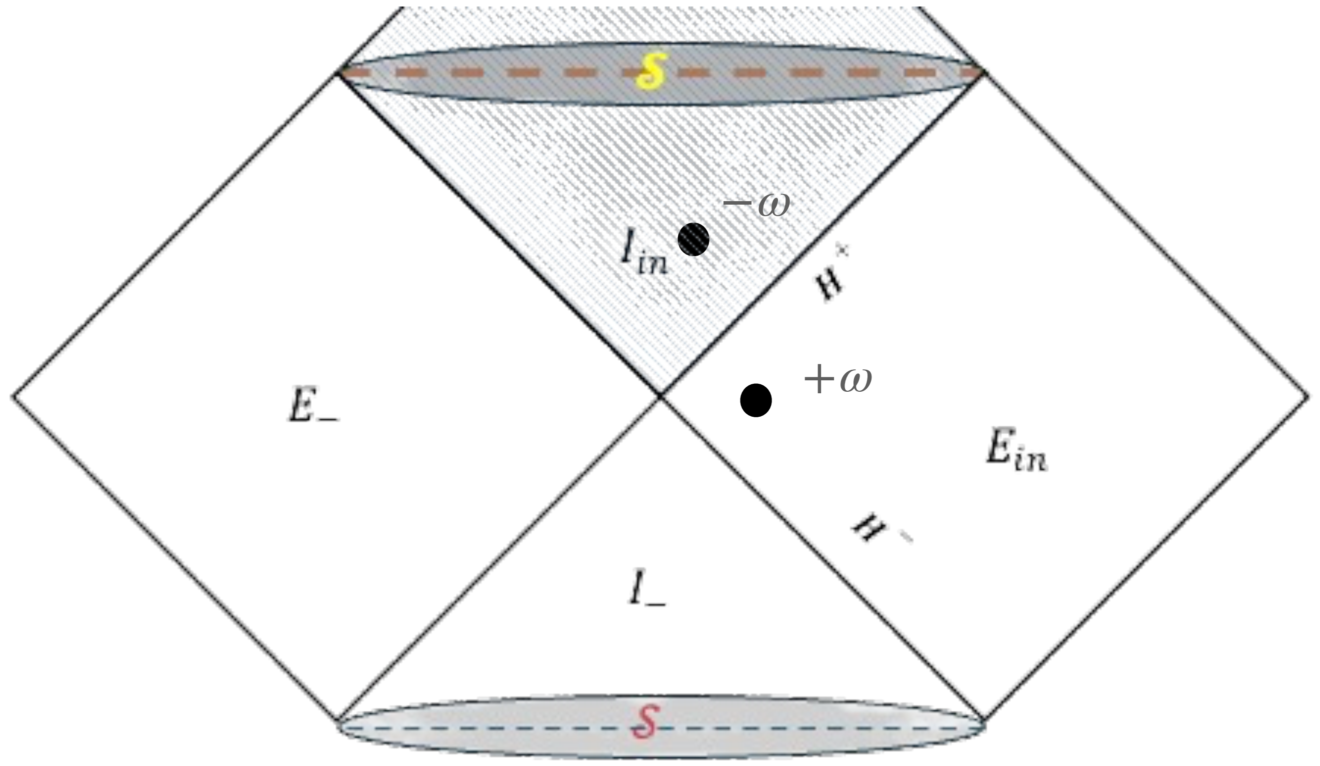

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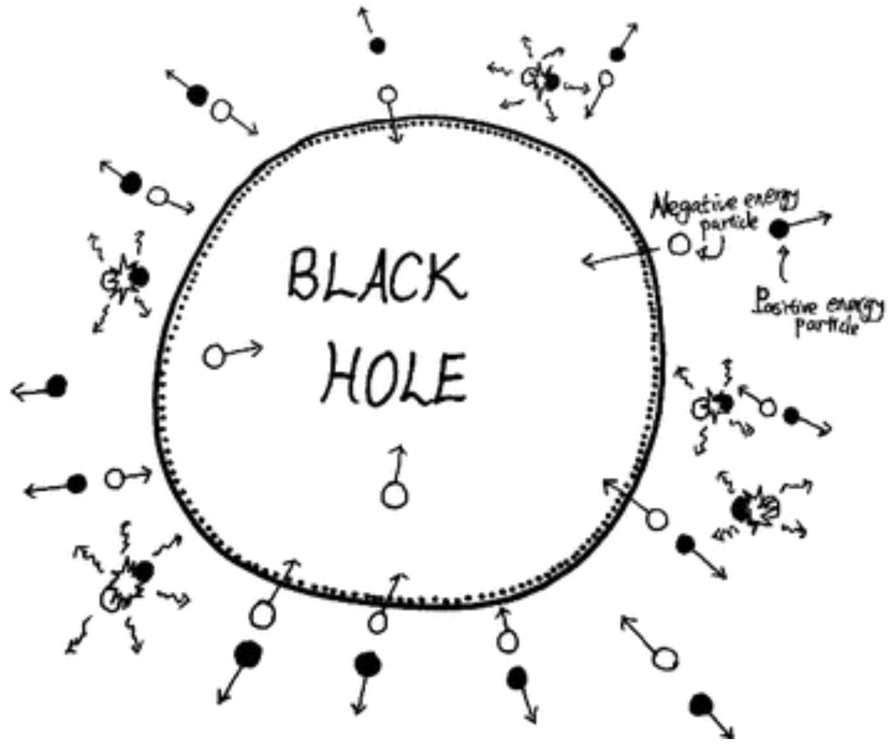

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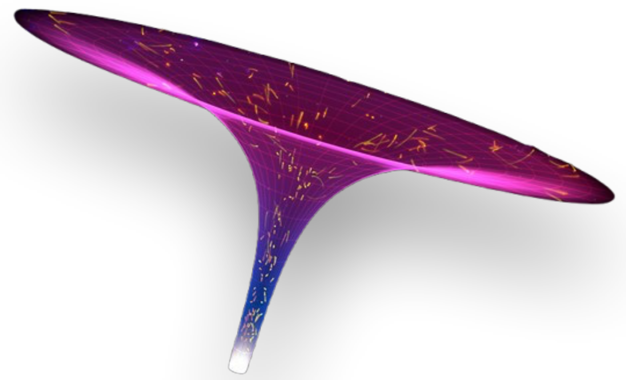
Where $\kappa = \chi_0 / 4M$.



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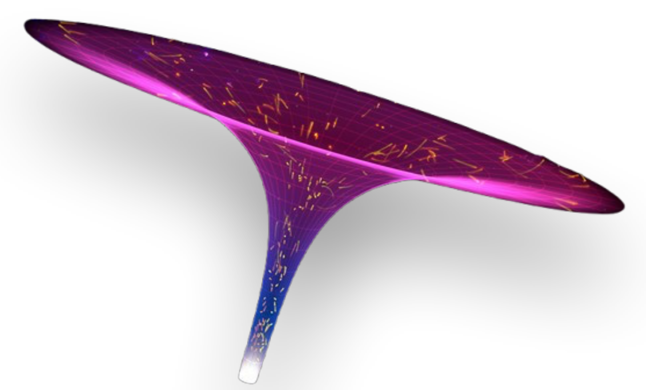

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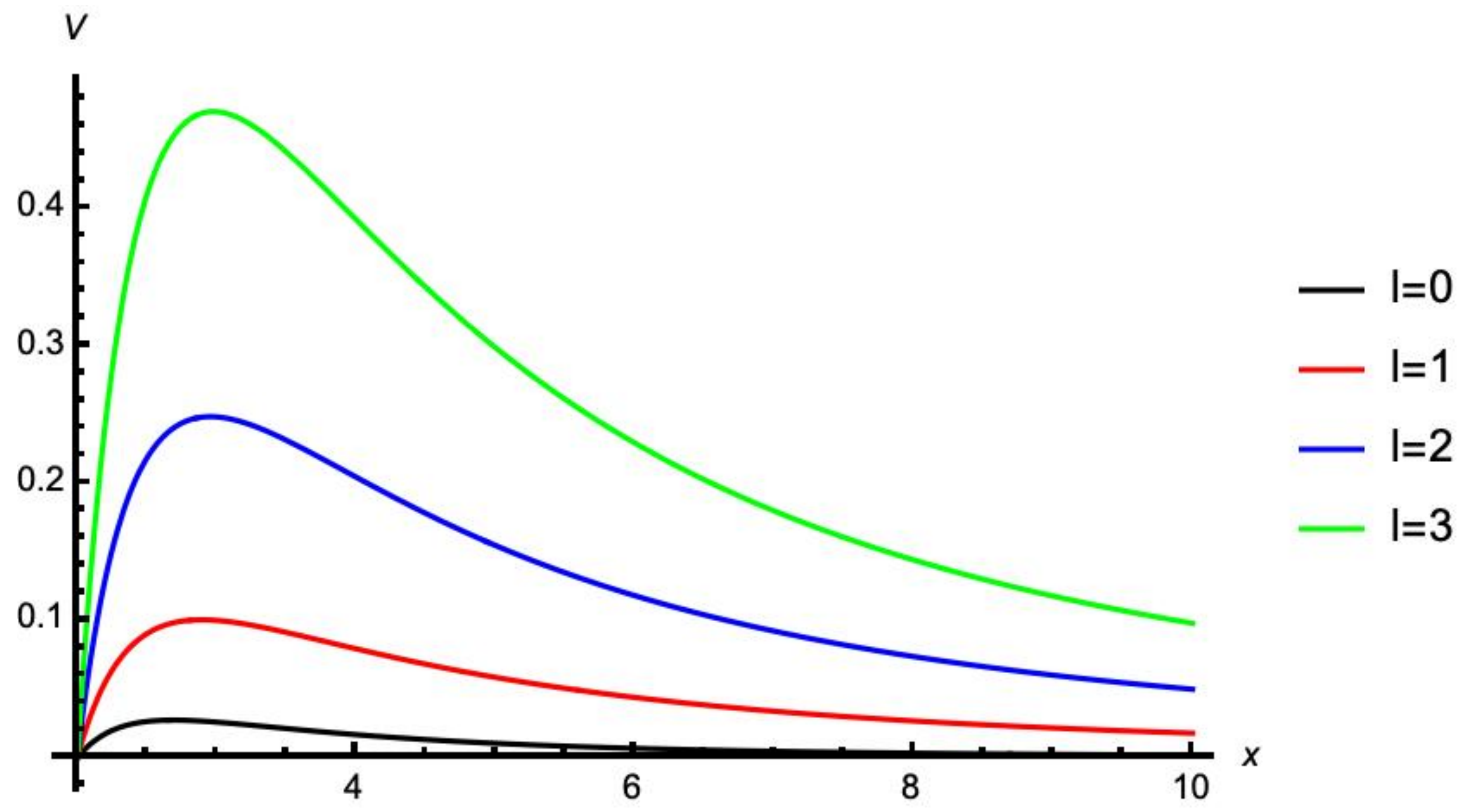
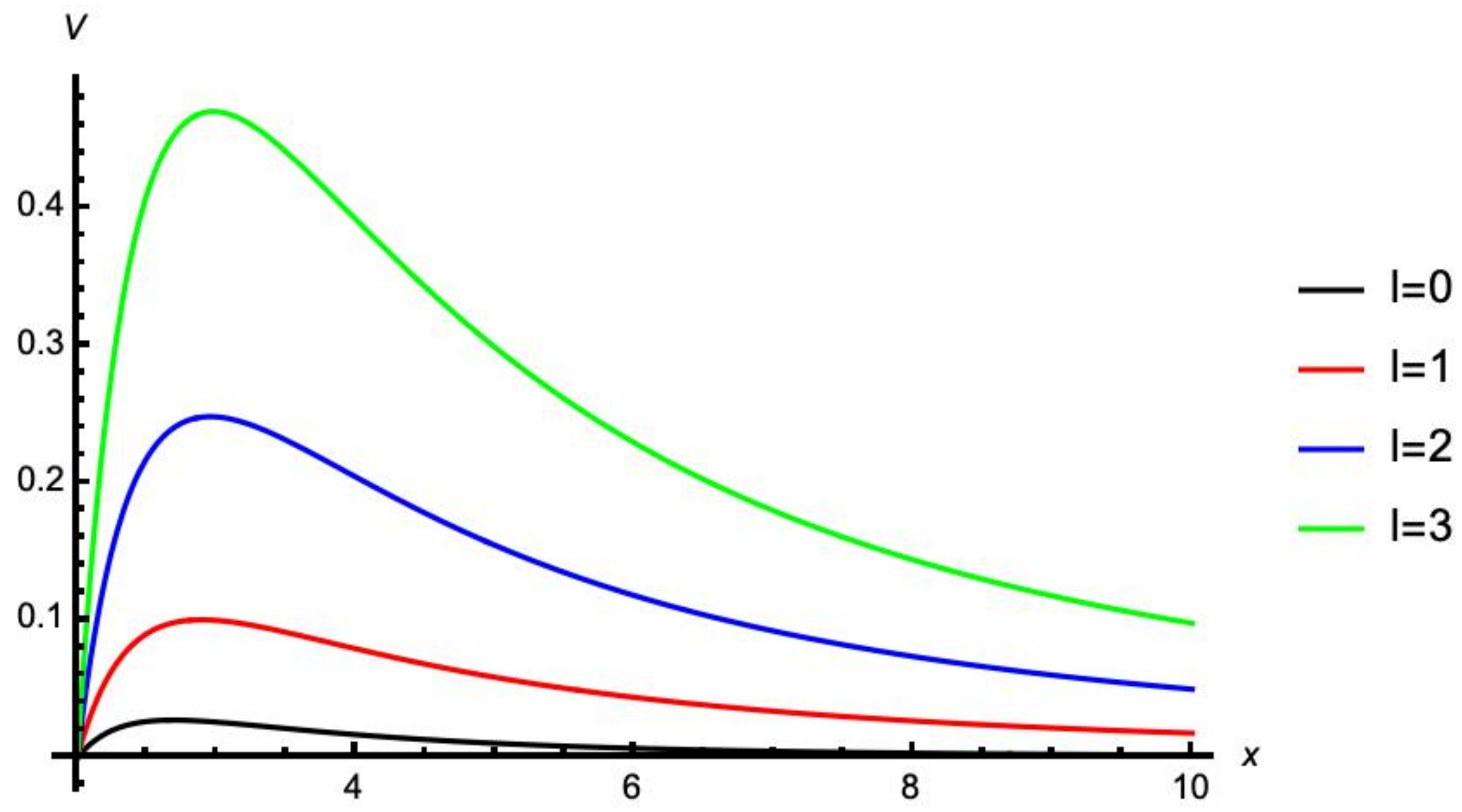
- Low-frequency modes $\omega \ll T_\infty$ ⟶ $M\omega \ll 1$ [Page'76; Unruh'76; Harmark, Natario, Schiappa'10, etc]





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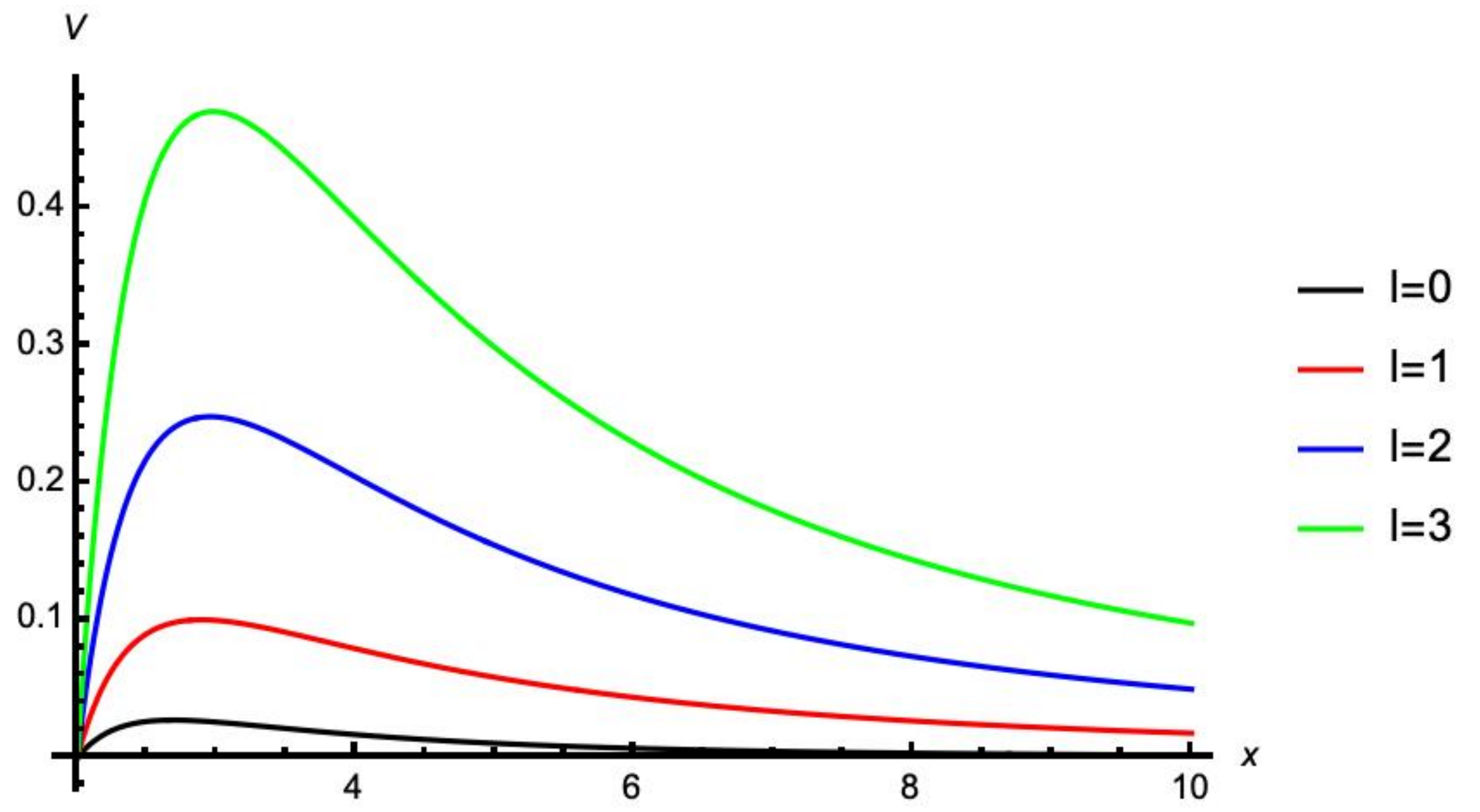

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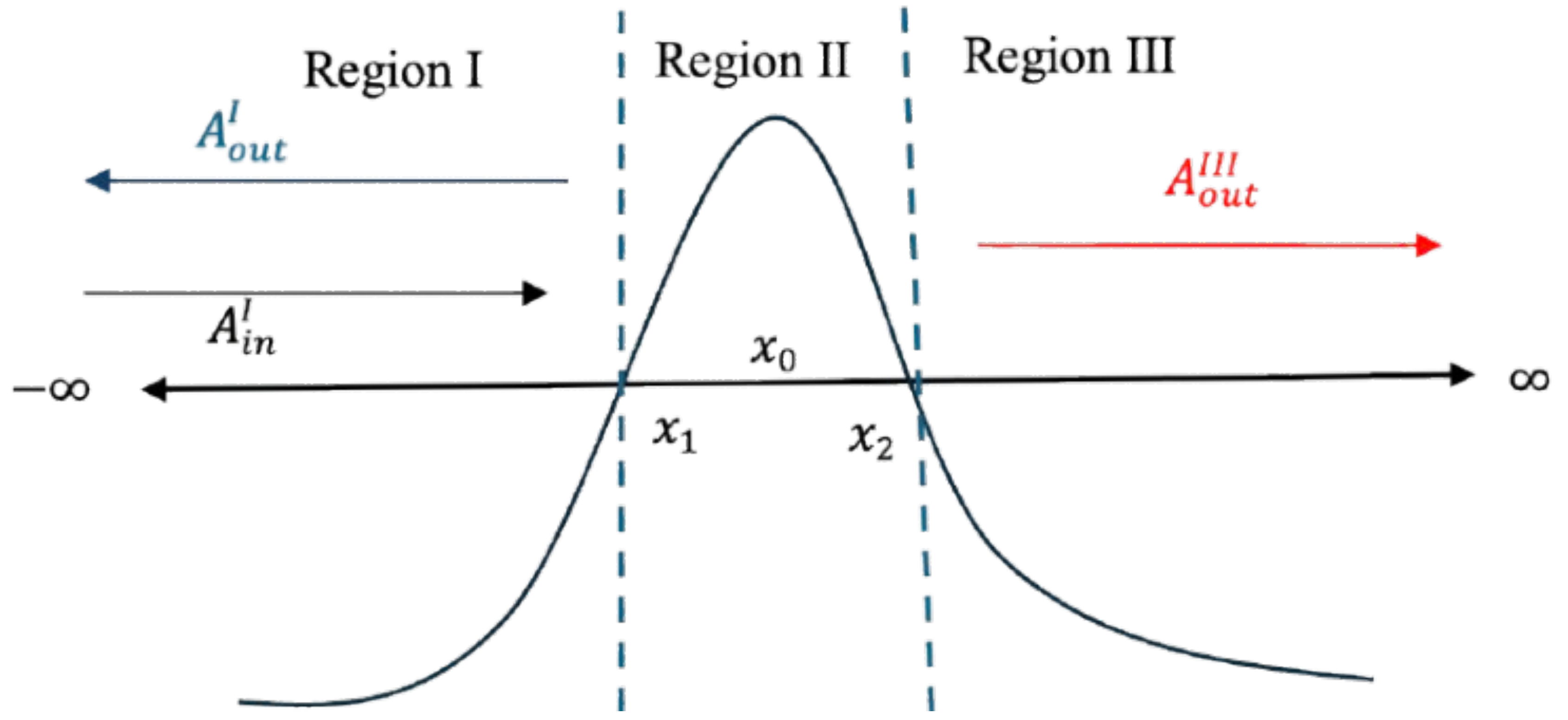

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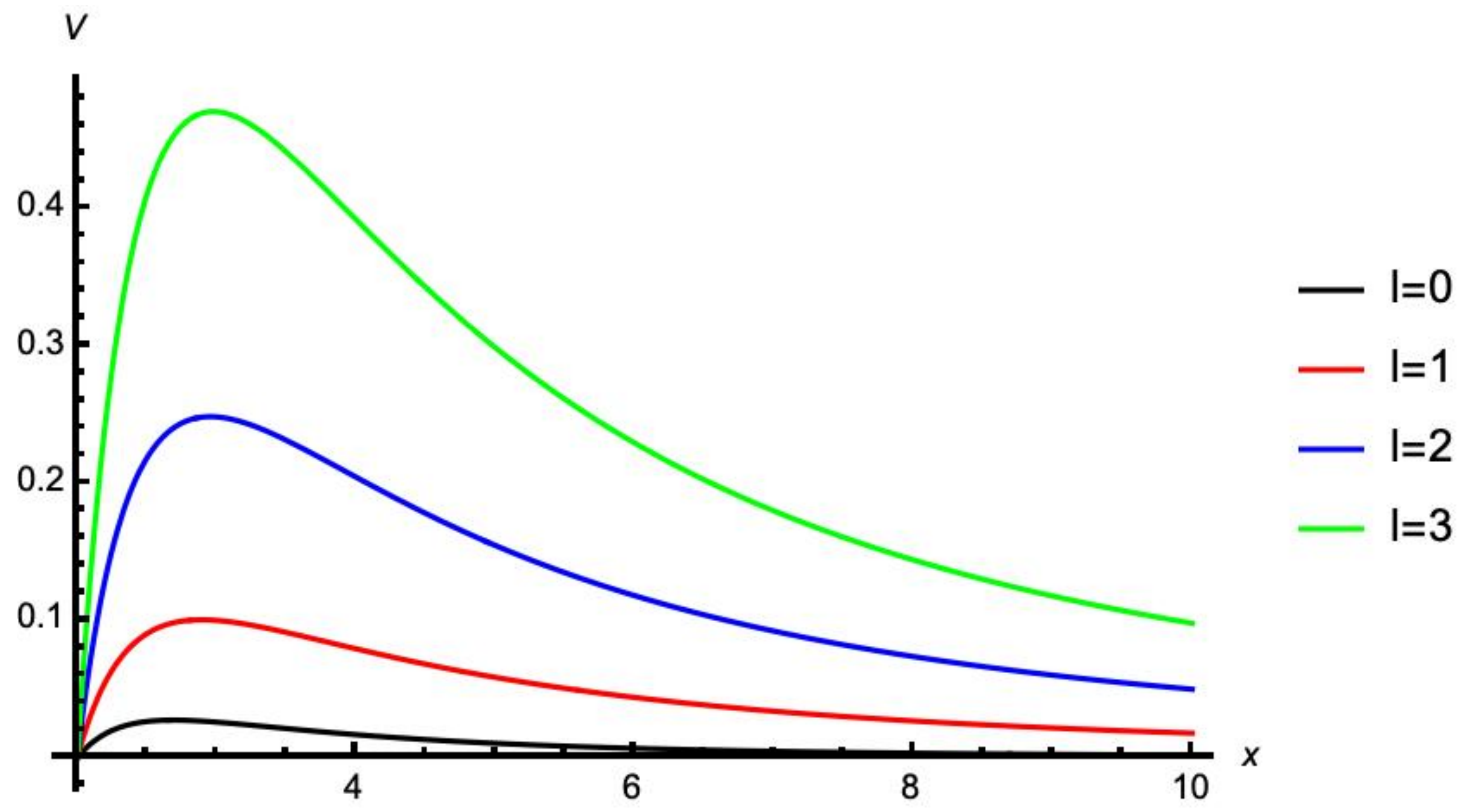

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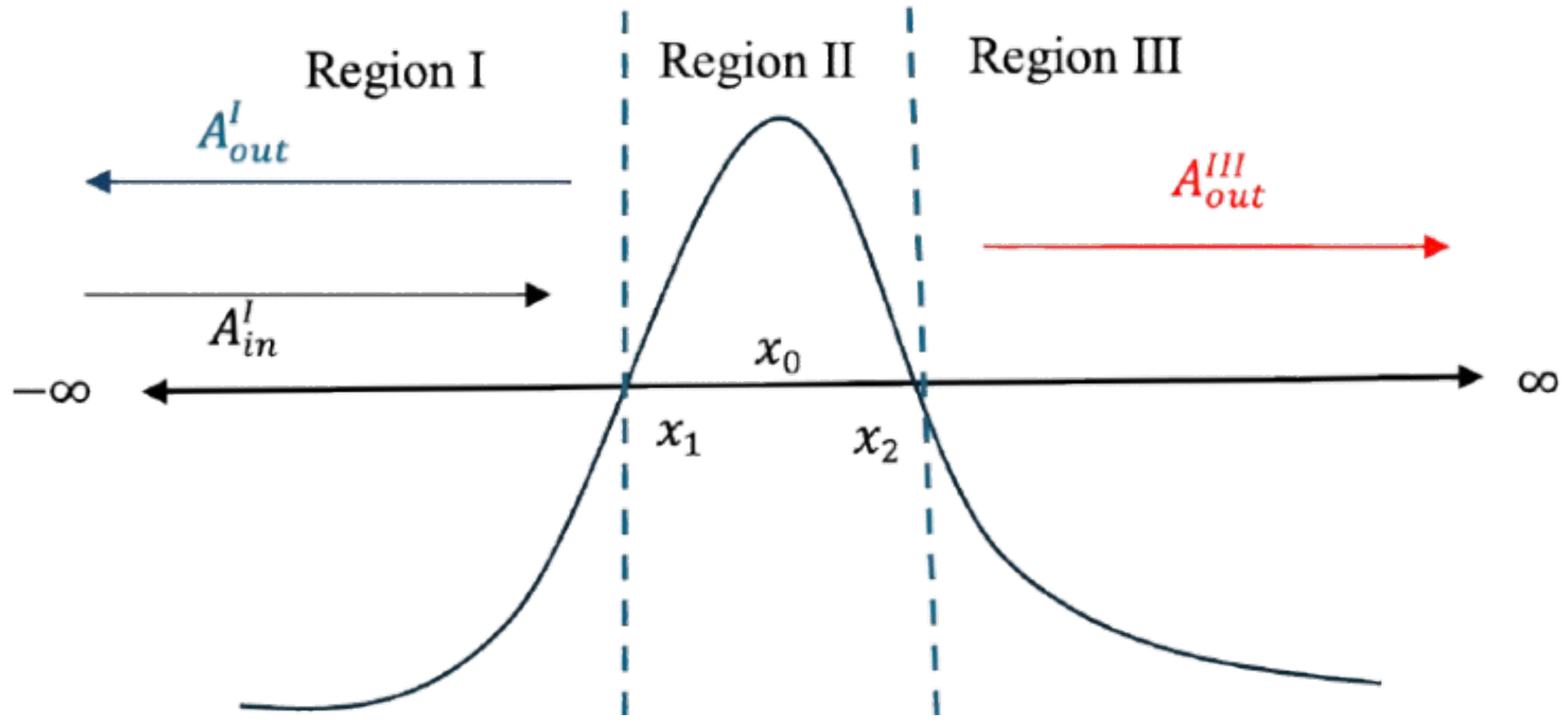

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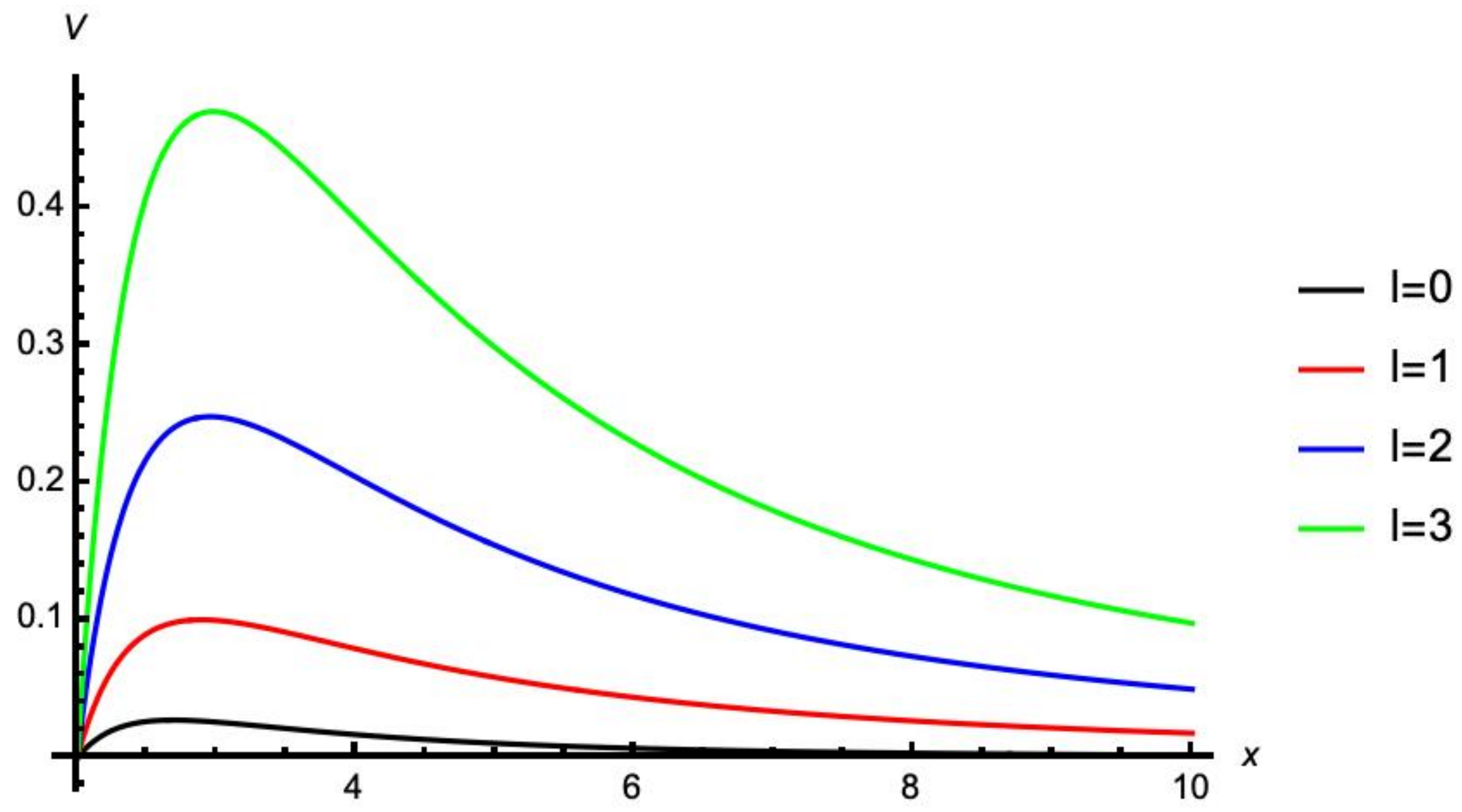

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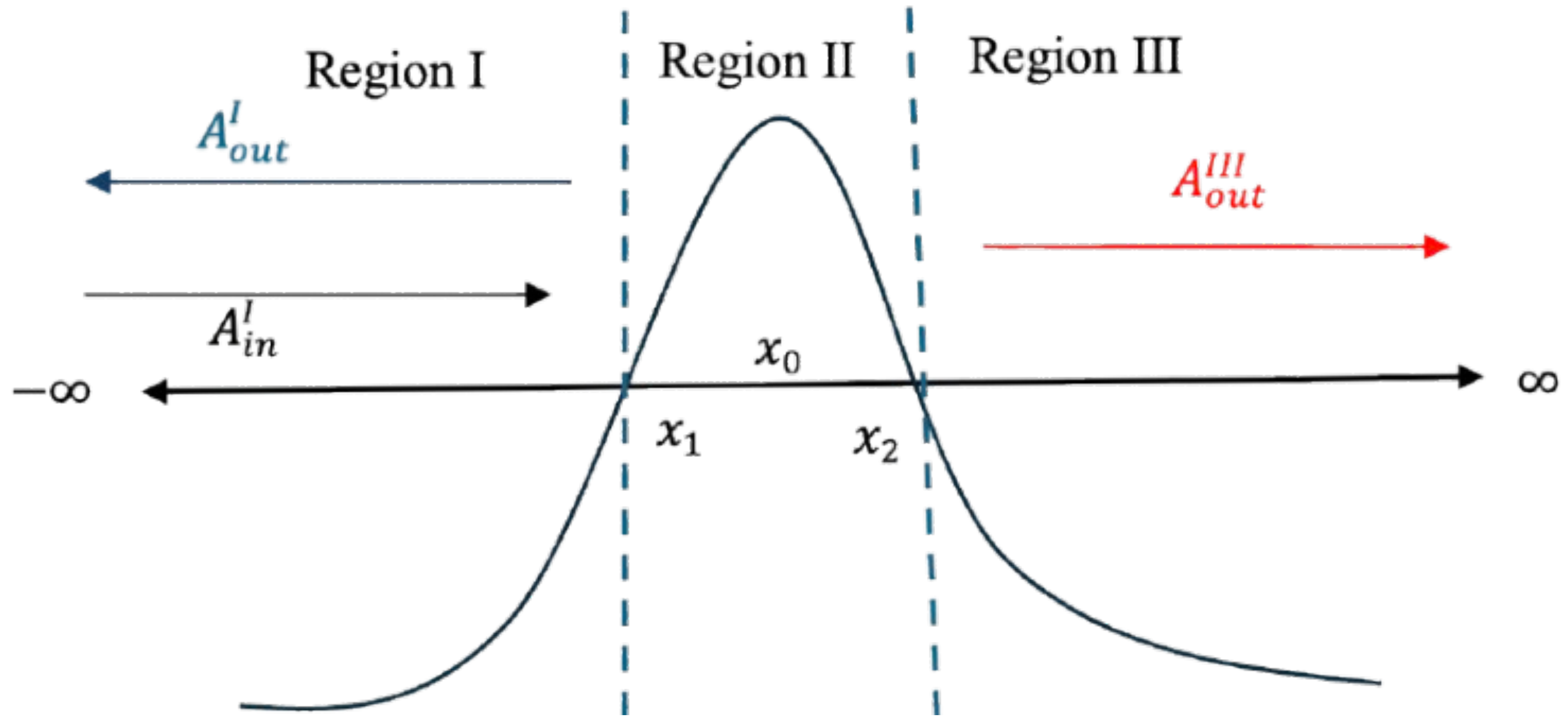

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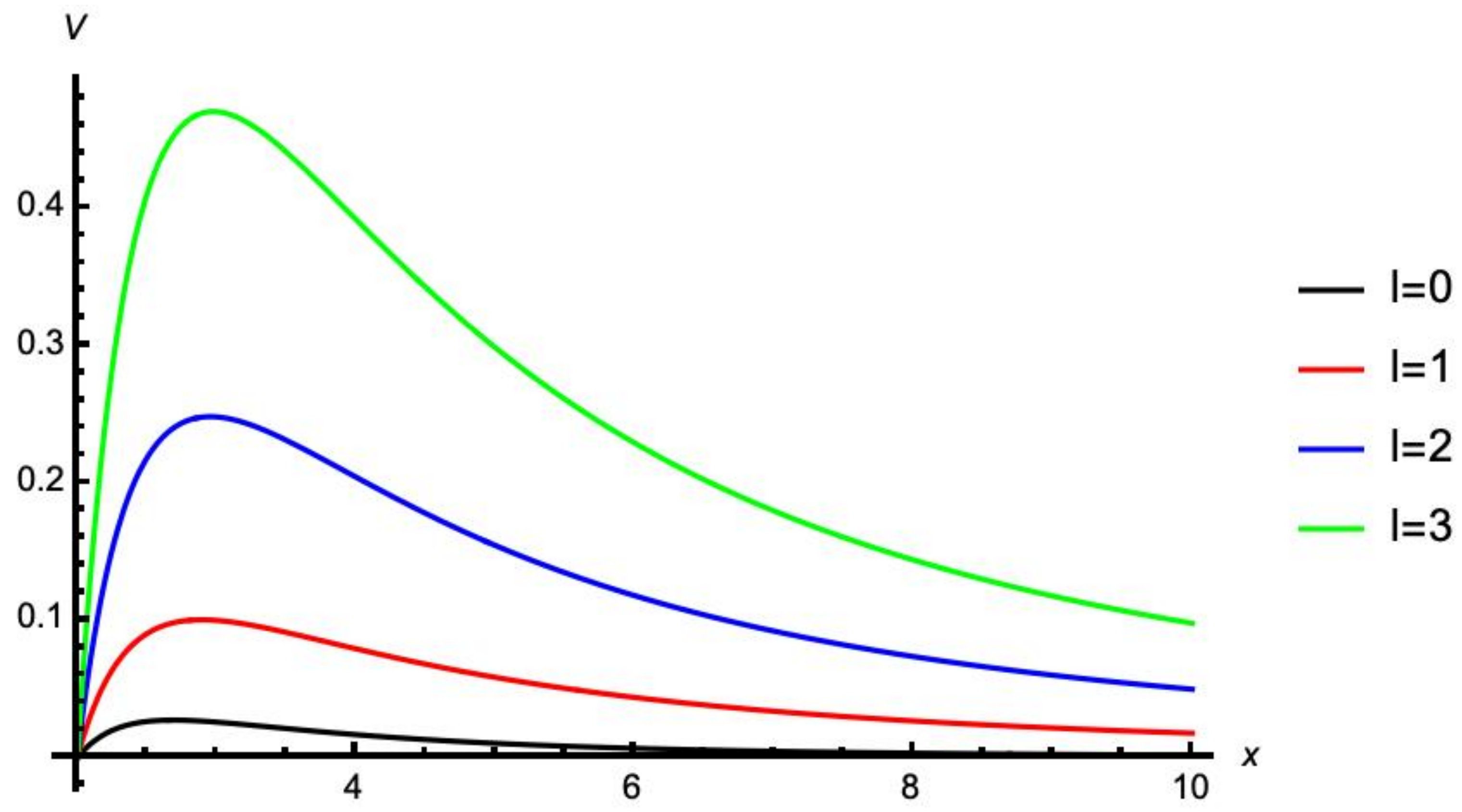

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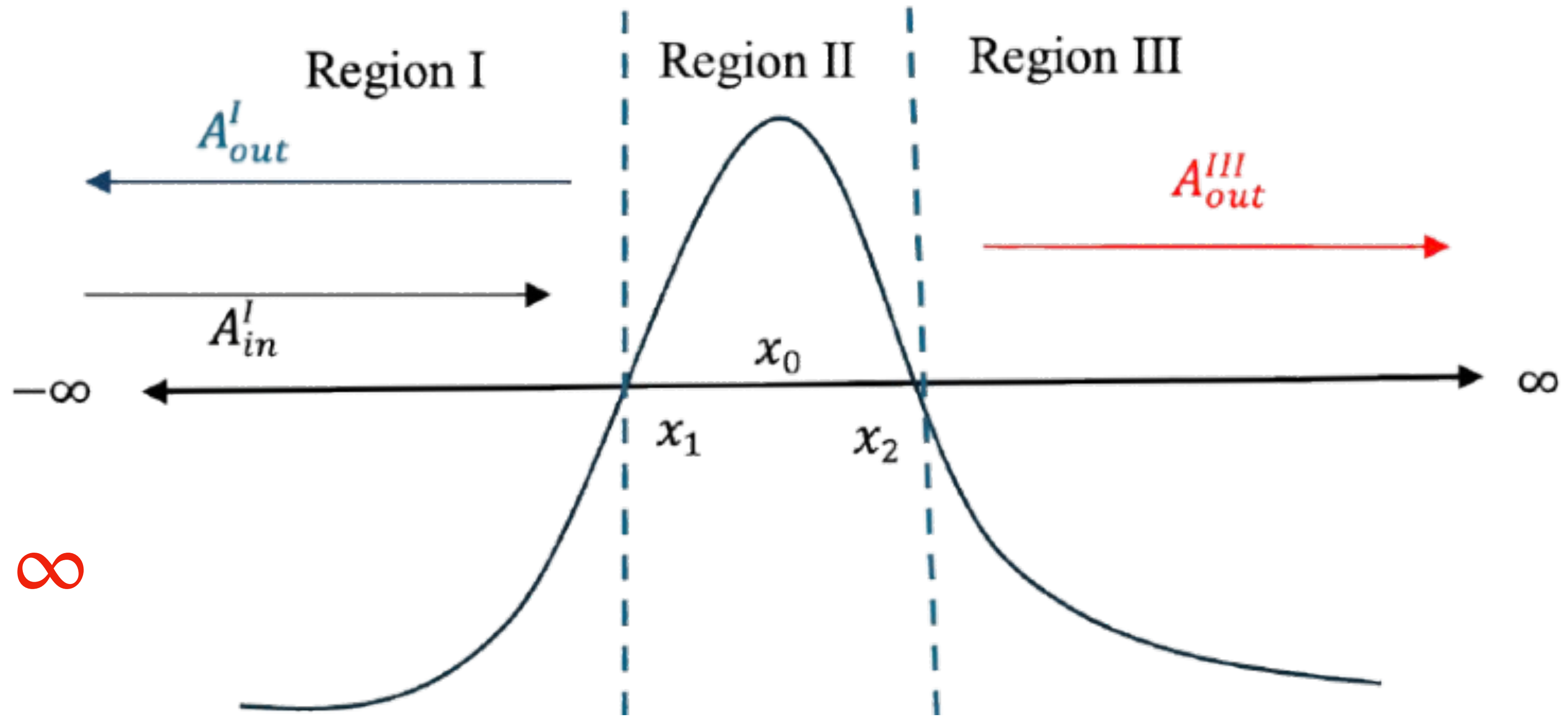

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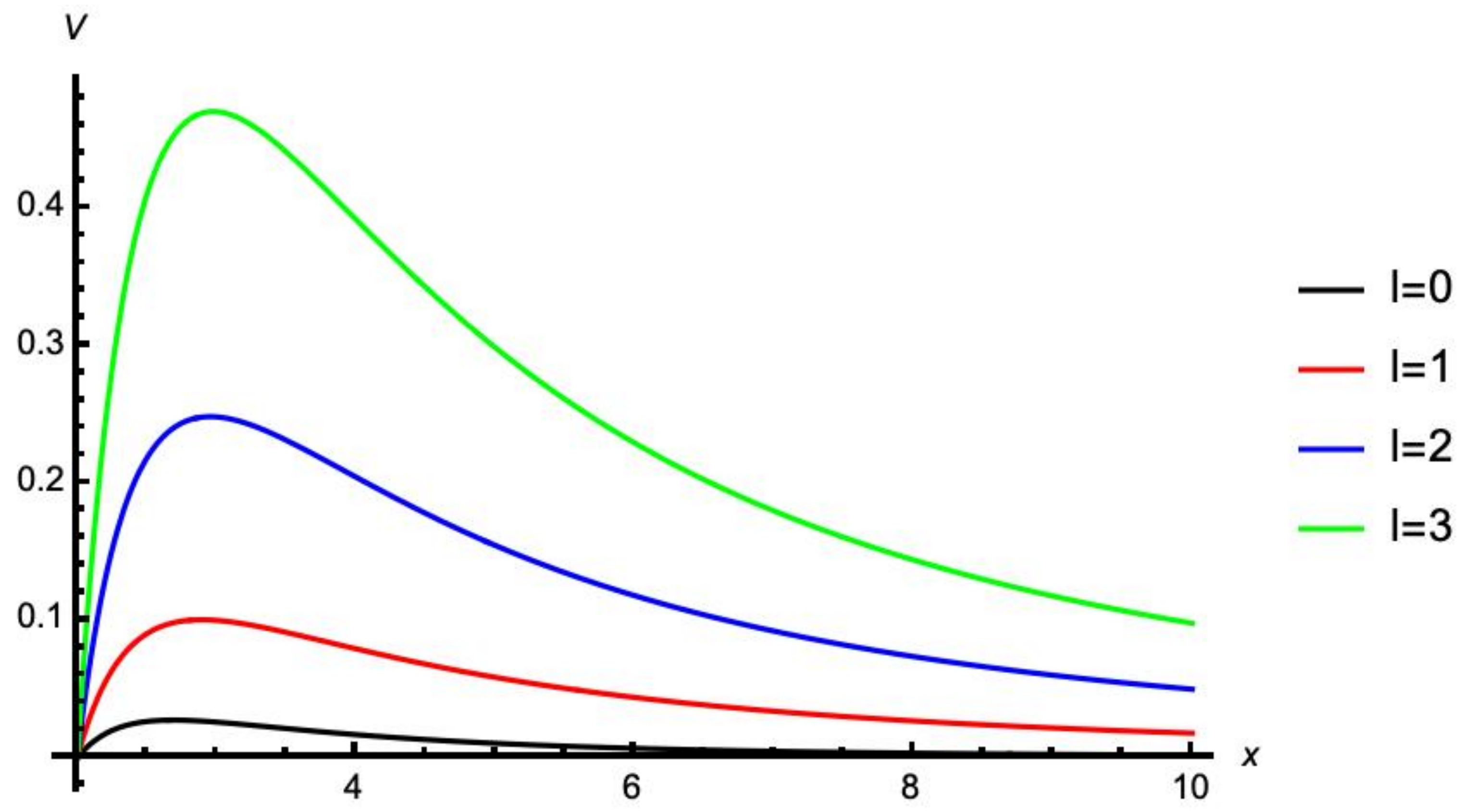

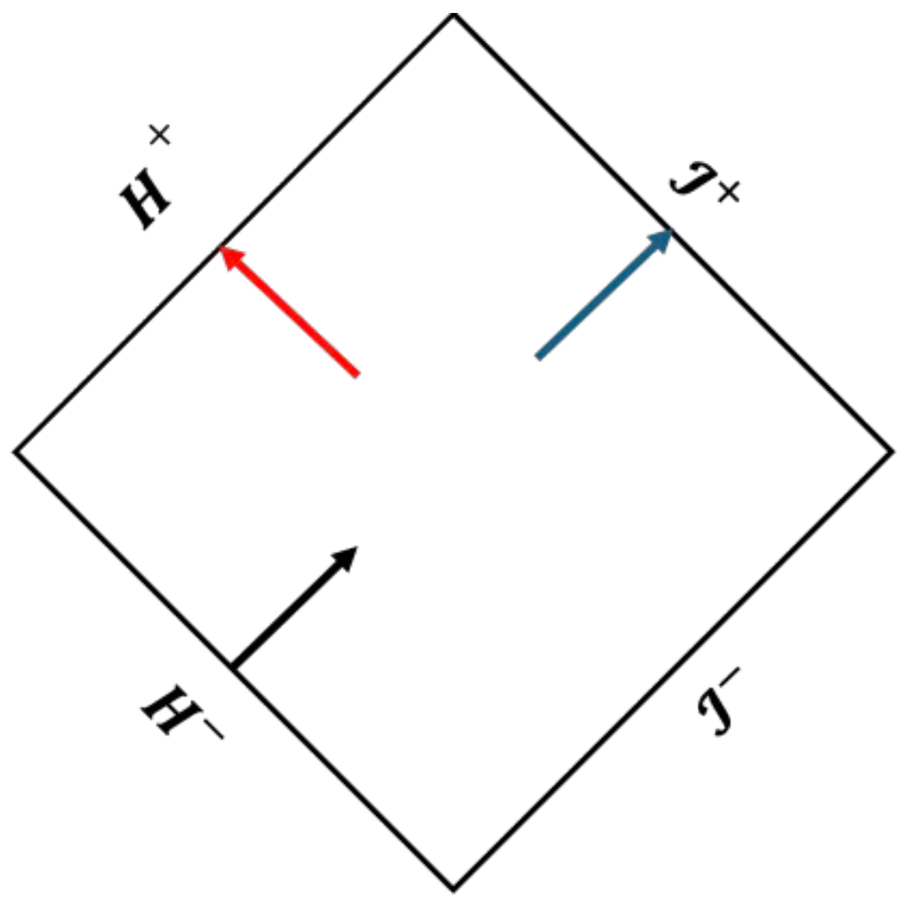

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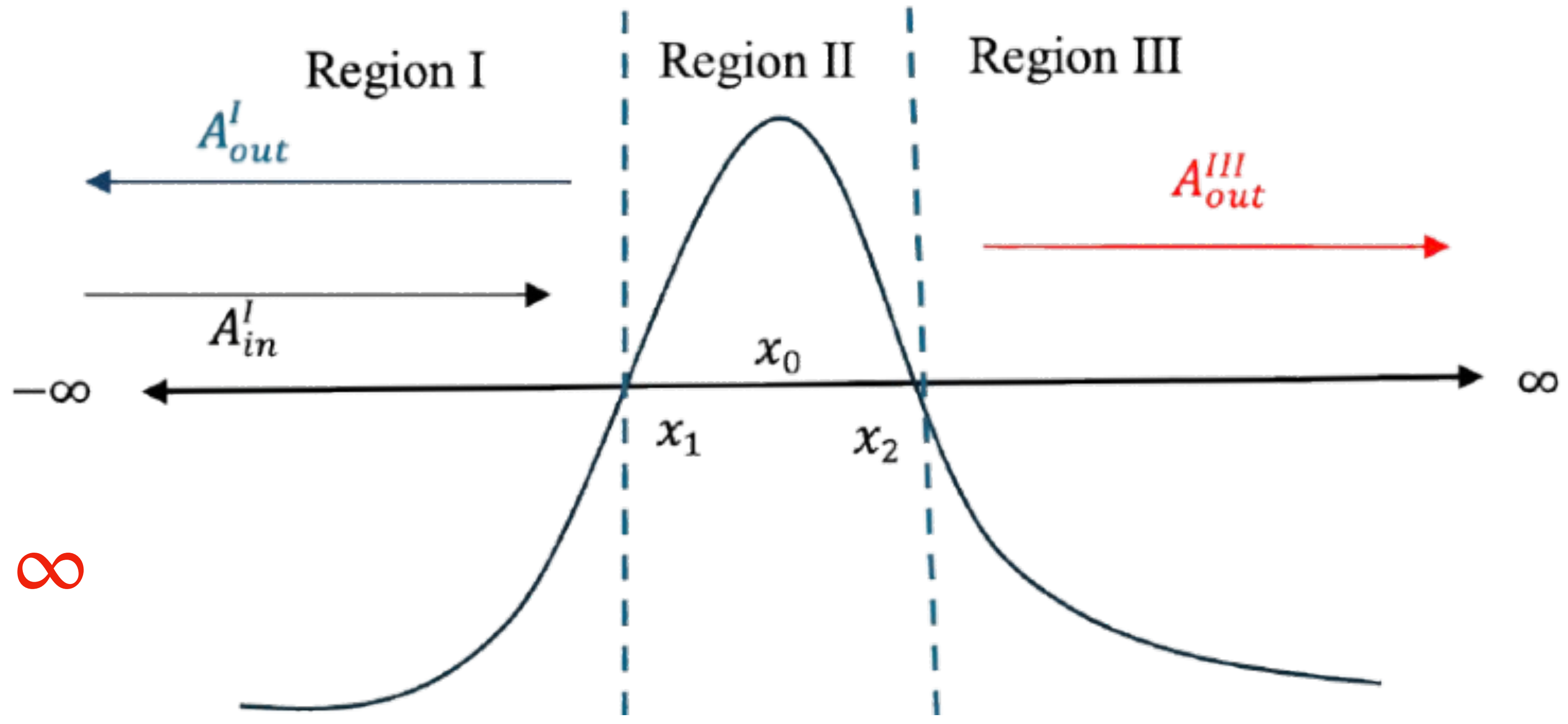

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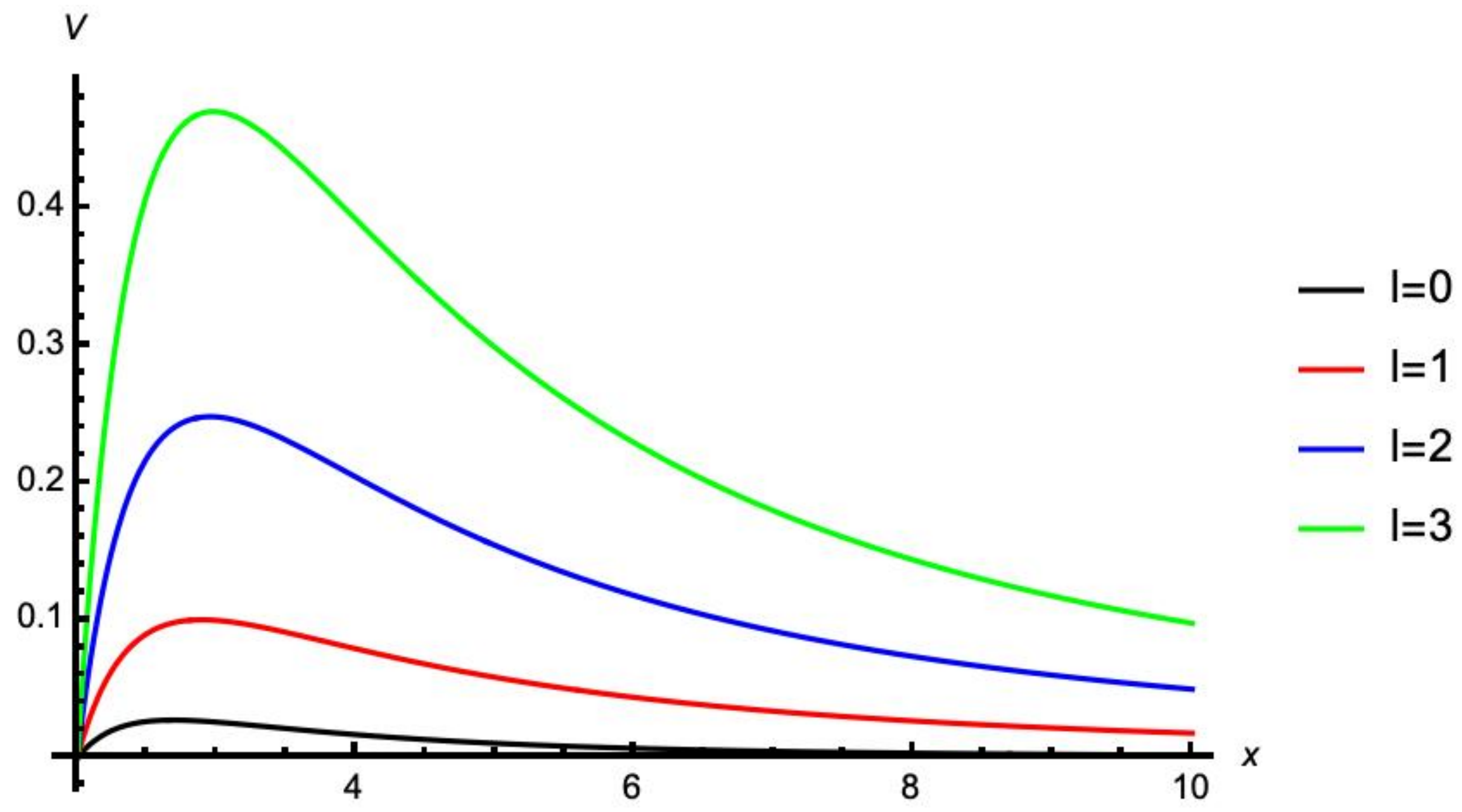

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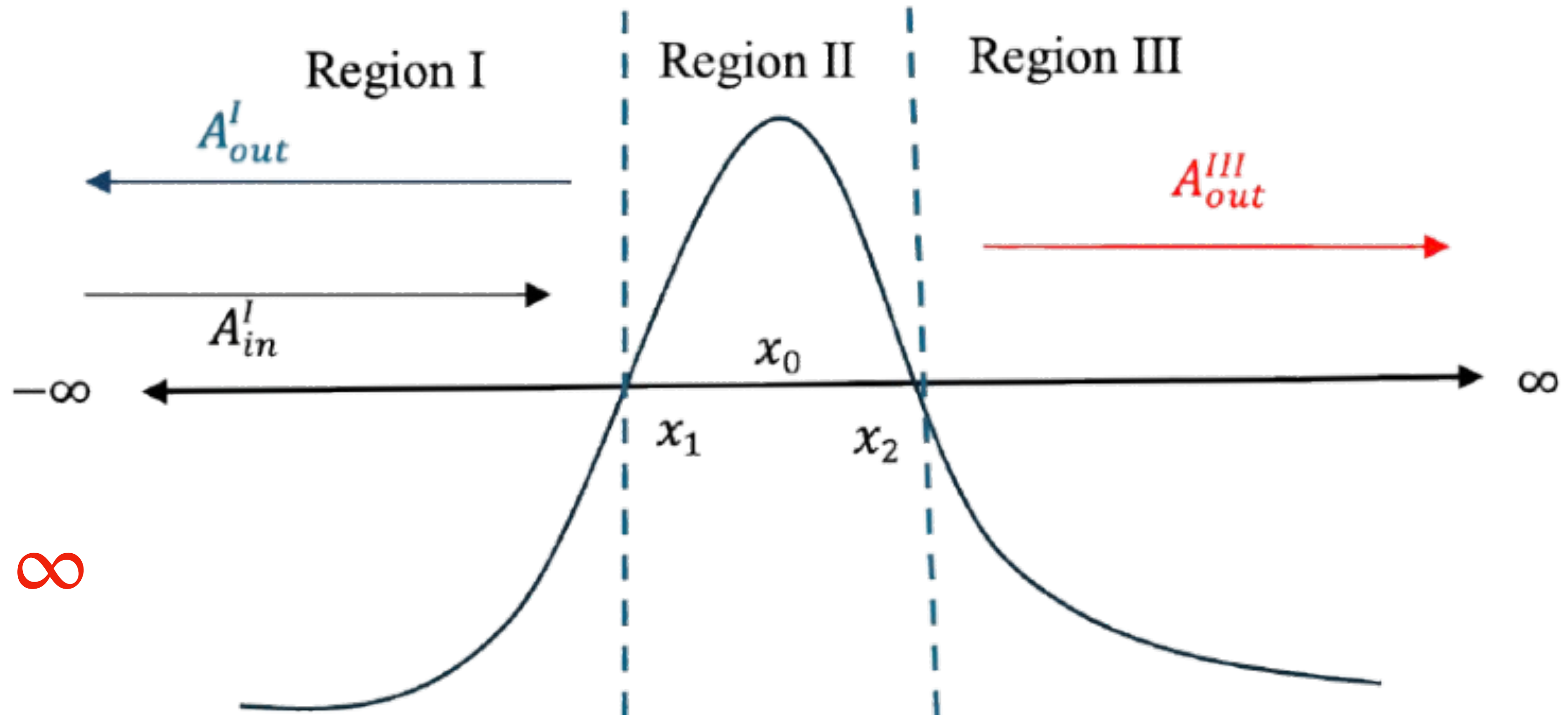
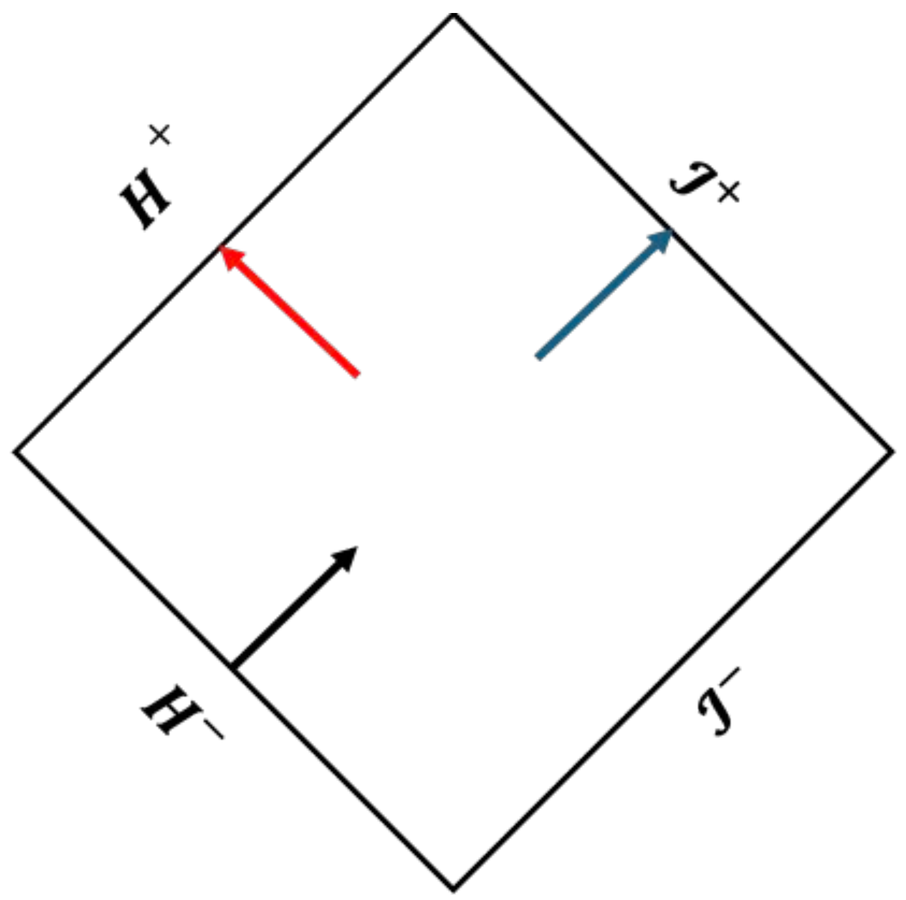




The grey-body factor:

$$T_l(\omega) = \left|\frac{J_{\mathscr{I}^+}}{J_{H^-}}\right|$$

$$\lambda(x) = \sqrt{\Delta/x^2}$$

- Transmission coefficient

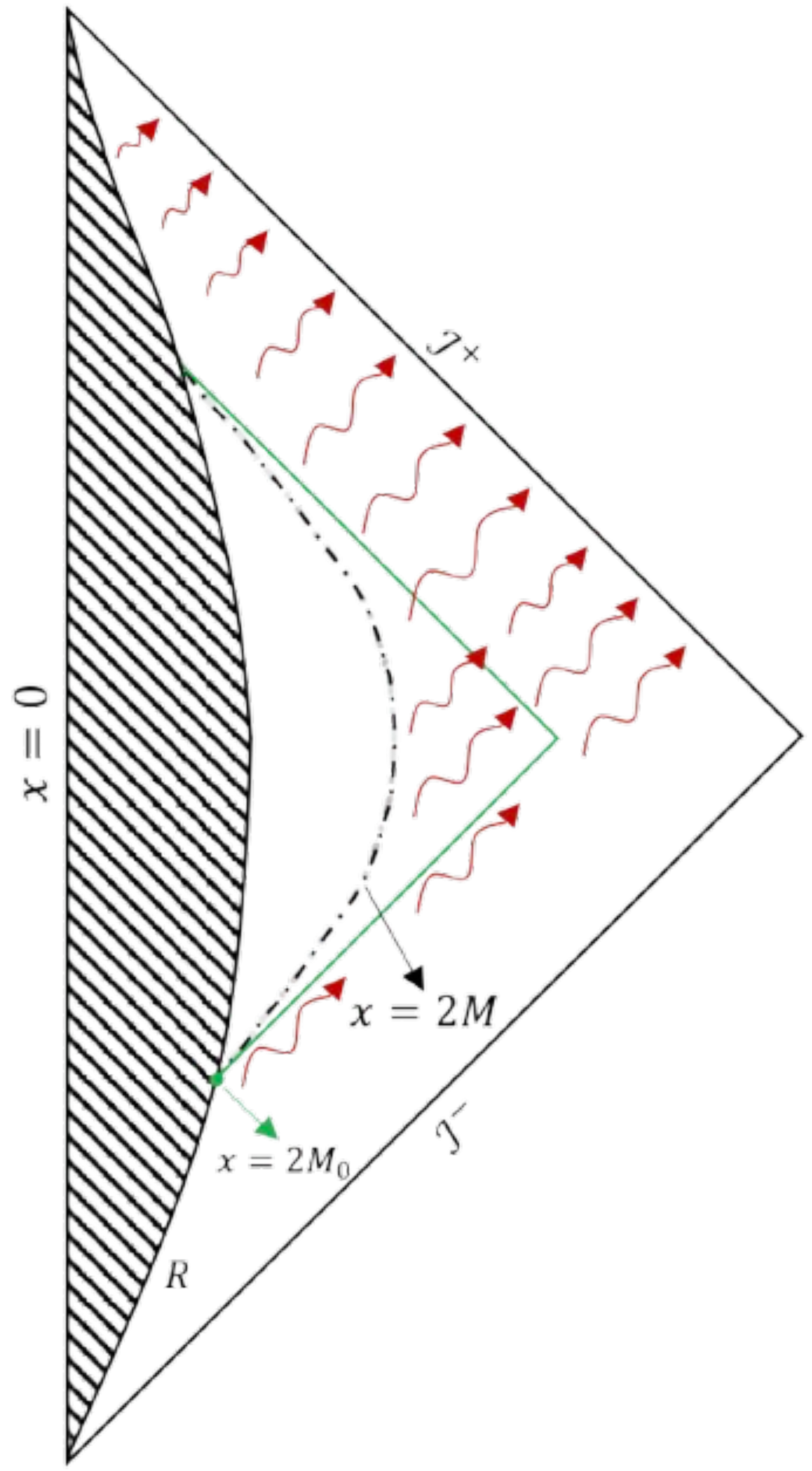
$$T_0(\omega) = \frac{16M^2\omega^2}{\left[\left(1-4M^2\omega^2\right)^2 + \left(\frac{\Delta}{12M^2}\right)^2 (M\omega)^2 \left(1-\frac{3\Delta}{160M^2}\right)^2\right]}$$

- Cross section

$$\sigma = A_{\mathrm{H}}$$

The black hole energy emission can be computed from the expectation value of the momentum energy tensor $\langle T^x_t \rangle$:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{1}{2\pi}\int_0^\infty \mathrm{d}\omega \frac{\omega T_0(\omega)}{\exp(8\pi M\omega\chi_0^{-1}) - 1}$$



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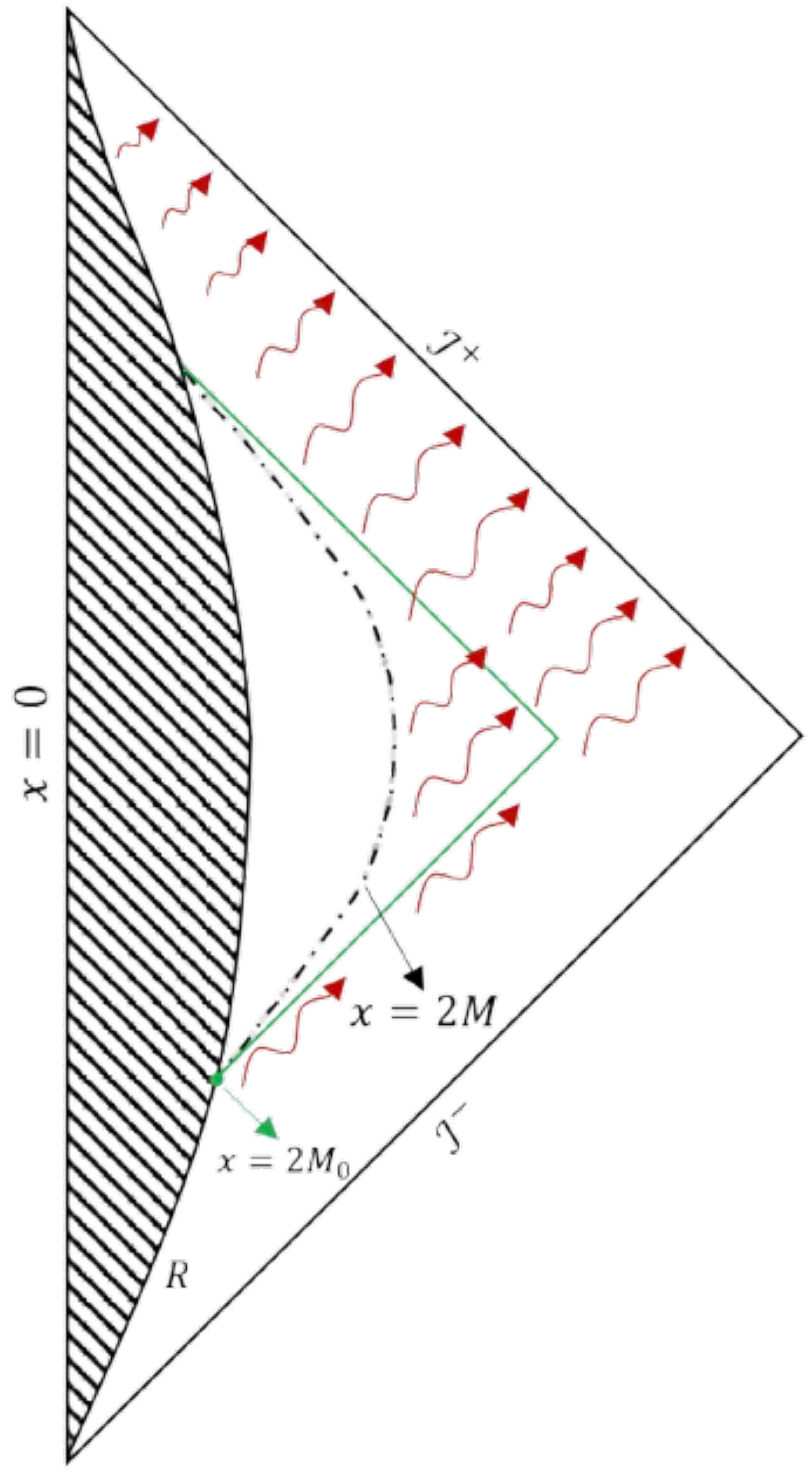

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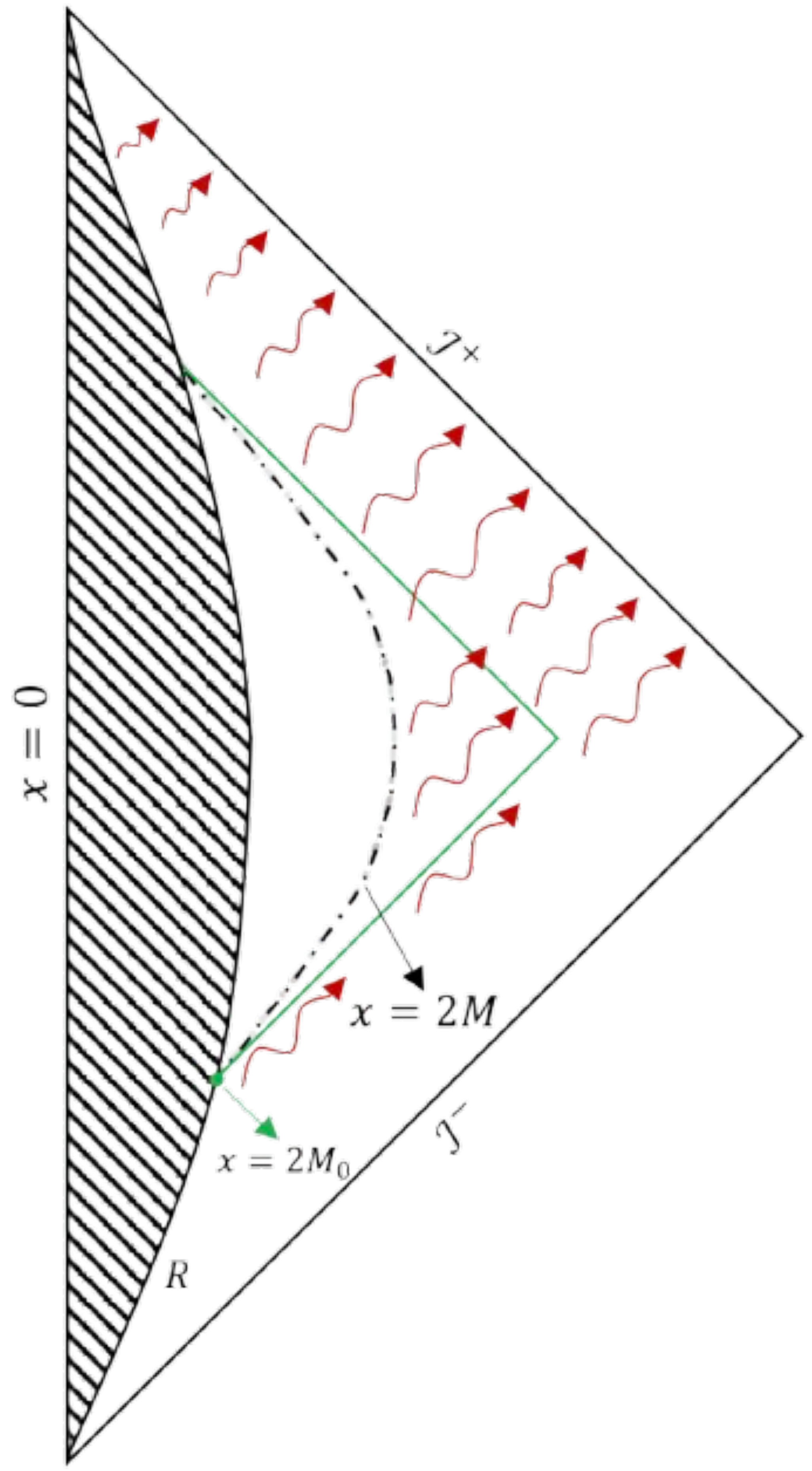

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- Cross section

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- To leading order, universality is preserved [Unruh'76; Das, Gibbons, and Mathur'97].
- The holonomy correction reduces the absorption rates.
- The classical limit is recovered when $\Delta \to 0$.

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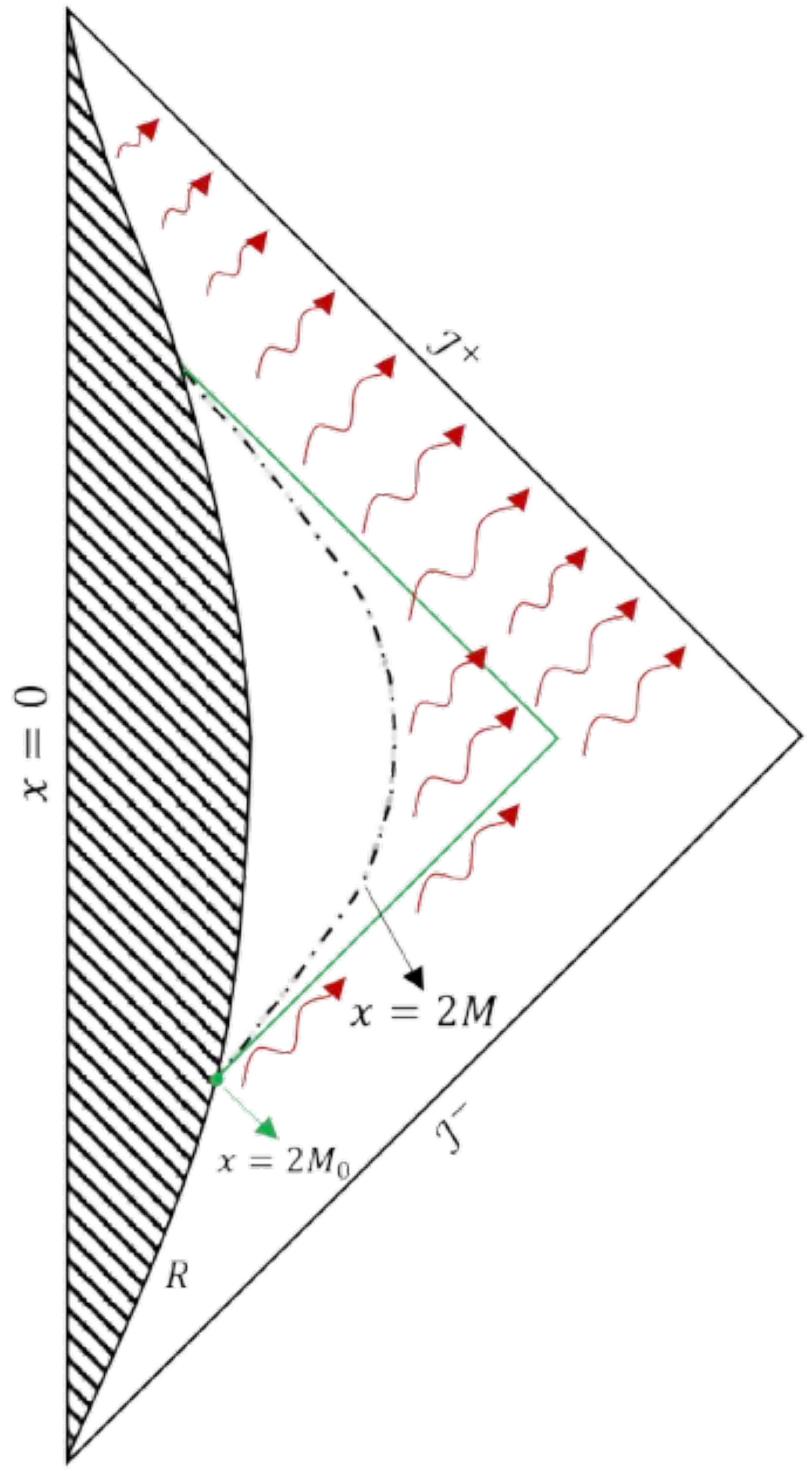


Black to white hole transition

1. Quantum fluctuation dominates $\rightarrow M_f \approx 3.8\sqrt{\Delta}$

   [Parikh & Pereira'24]

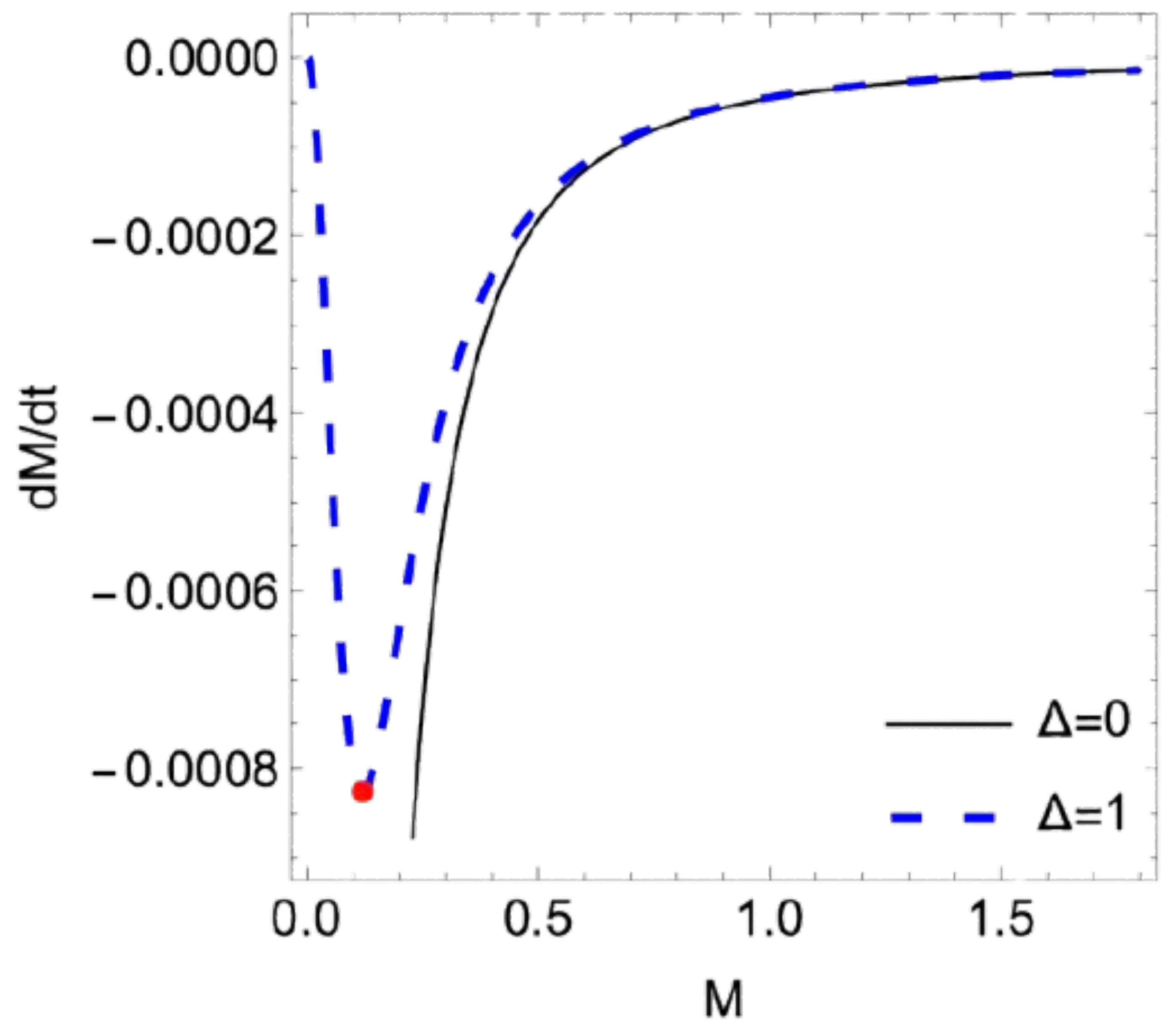
2. Thermal stabilization $\rightarrow M_r \approx 0.15\sqrt{\Delta}$

   [IHB, Bojowald, Brahma, & Duque'25]

3. Gravitational instability $\rightarrow M_c \approx 0.57\sqrt{\Delta}$

   [Bojowald, Duque, & Shankaranarayanan'25]

Mechanism for Black to White Hole transition



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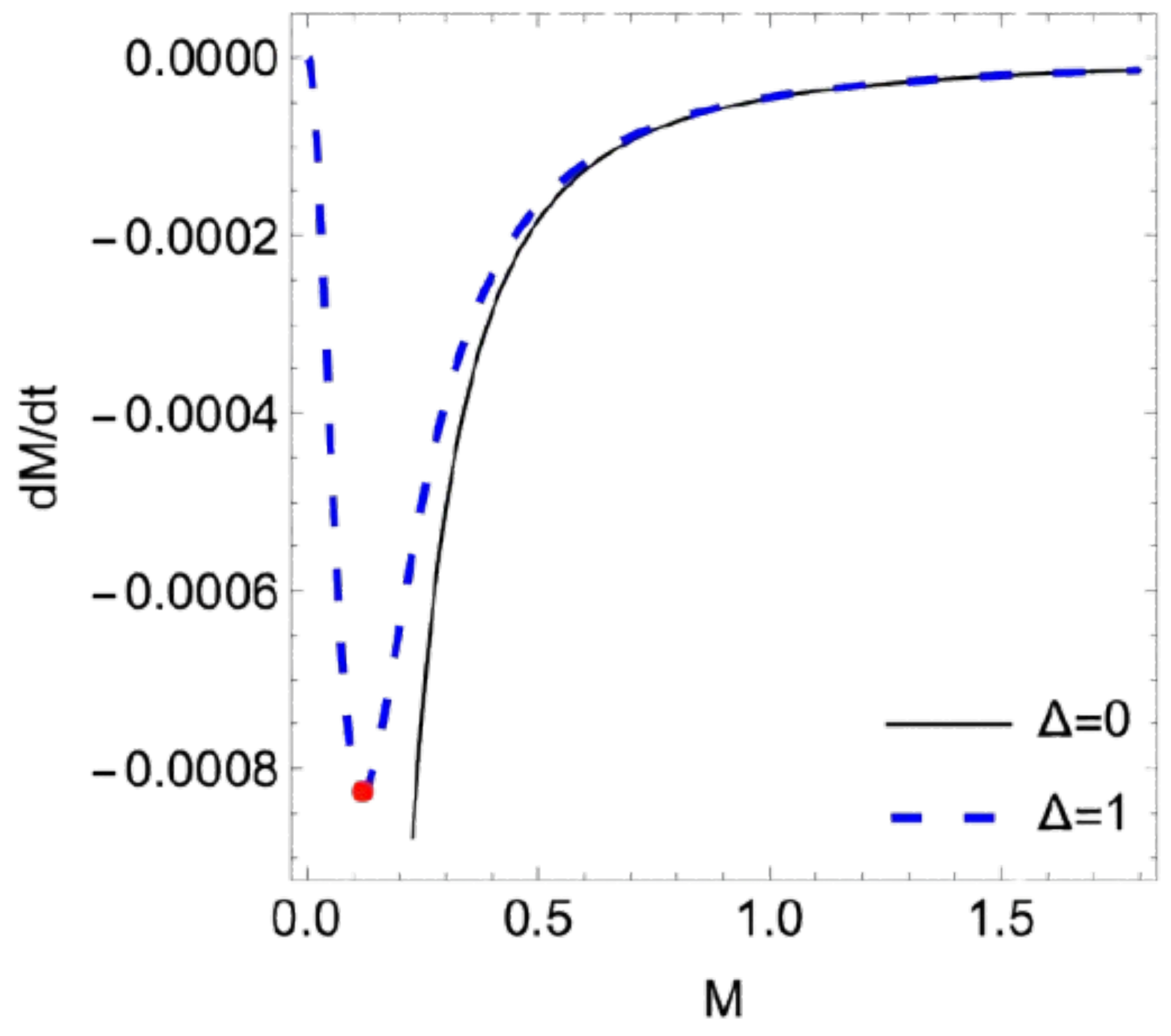

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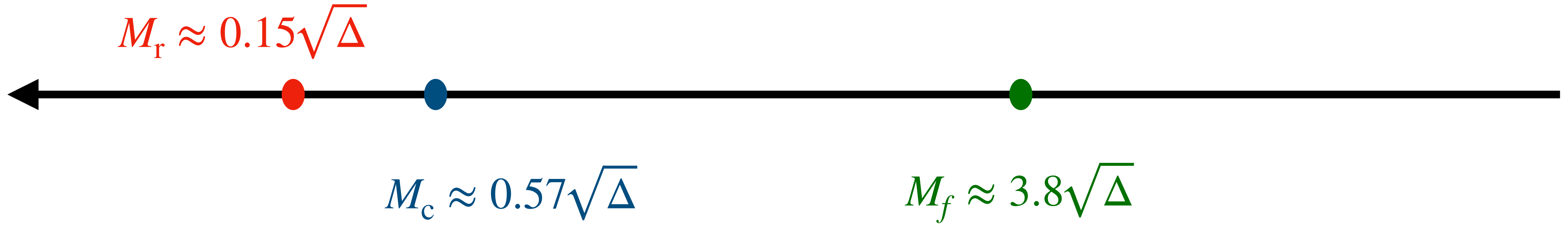

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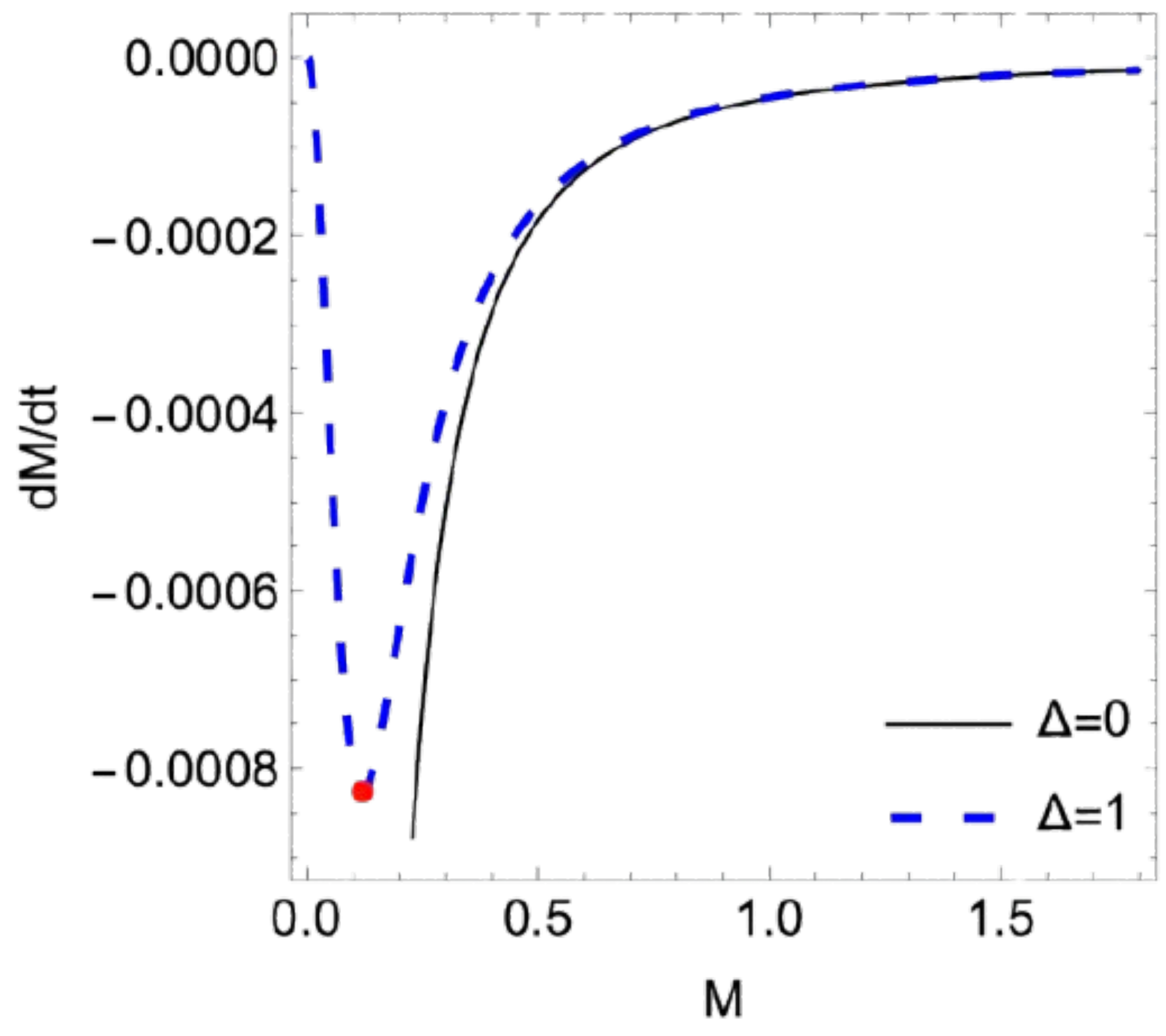
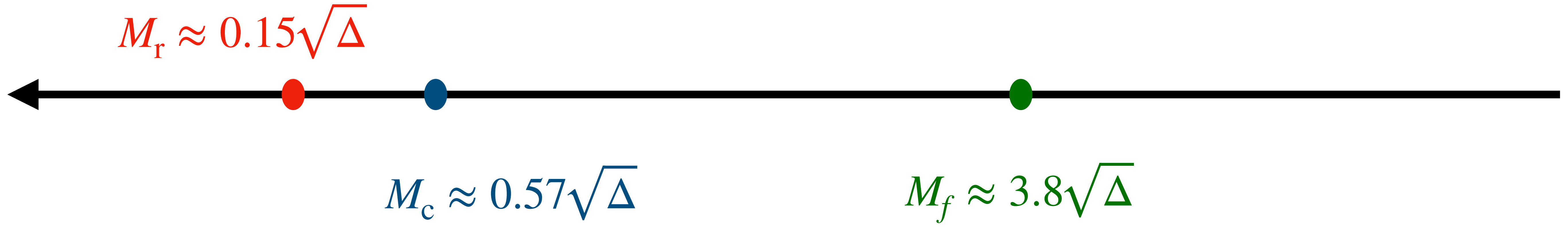


Thermal stabilization is preceded by gravitational destabilization → The repulsive QG effect



CONCLUSION

Summary and outlook

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- Consistent (anomaly-free and covariance) vacuum solution for arbitrary holonomy function $\lambda(x)$.
- We regained the thermal Hasking distribution and universality of black hole absorption rates to leading order.
- The Hawking temperature is recovered only under the condition that $\lambda(x)$ decreases monotonically.
- The Brown–York quasi-local formalism and the tunnelling approach yield consistent results for black hole entropy.
- The black hole evaporation process slows down due to the holonomy correction. The gravitational instability kicks in before reaching a remnant stage, favouring the black to white hole transition according to the hierarchy $M_{\rm f} > M_{\rm c} > M_{\rm r}$.

In progress (coming soon)

- Include backreaction effects consistently and more quantitatively.
- Deformed Minkowski spacetime. → Maximal acceleration