Hawking Radiation without Lorentz Invariance

Francesco Del Porro

Based on:
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ArXiv:2303.14235
ArXiv:2309.xxxx

In collaboration with:
S. Liberati, M. Herrero-Valea and M. Schneider

Outline

- Lorentz Violating gravity: why and how
- Black Holes in LV gravity
- Hawking radiation in from UH
- The role of KH
- Conclusion

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Lorentz Violating gravity

- A "good way" to break LLI is to assume an inhomogeneous scaling behavior between time and space:

$$\vec{x} \to b\vec{x}, \quad \tau \to b^z \tau$$

- One can introduce a Stueckelberg vector field, <u>the Aether</u>, that parametrizes the time direction:

$$U_\mu = \frac{\partial_\mu \tau}{\sqrt{g^{\alpha\beta}\partial_\alpha \tau \partial_\beta \tau}} \qquad S[g,\tau] = -\frac{1}{16\pi G}\int_{\mathscr{M}} \sqrt{-g}\left(R + c_\theta \theta^2 + c_\omega \omega_{\mu\nu}\omega^{\mu\nu} + c_\alpha a_\mu a^\mu\right)$$

Matter Fields

- The theory allows the presence of higher (spatial) derivative operators:

$$S_m[\phi] = \frac{1}{2}\int_{\mathscr{M}} \sqrt{-g}\ \phi\left[\nabla_\mu \nabla^\mu - \sum_{j=2}^{n} \frac{\alpha_{2j}}{\Lambda^{2j-2}}(\Delta)^j\right]\phi \qquad \Delta = \nabla_\mu \gamma^{\mu\nu} \nabla_\nu$$

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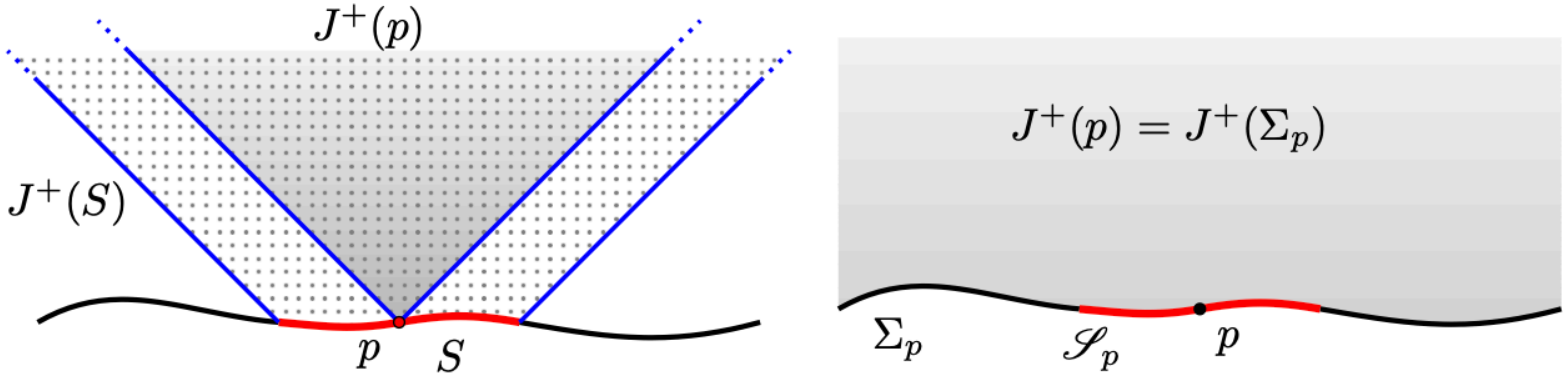
Superluminal particles:

$$\omega^2 = q^2 + \alpha_4 \frac{q^4}{\Lambda^2} + \ldots + \alpha_{2n} \frac{q^{2n}}{\Lambda^{2(n-1)}}$$

Different notion of causality:



J.Bhattacharyya, M.Colombo, T.P. Sotiriou, ArXiv: 1509.01558

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Horizons

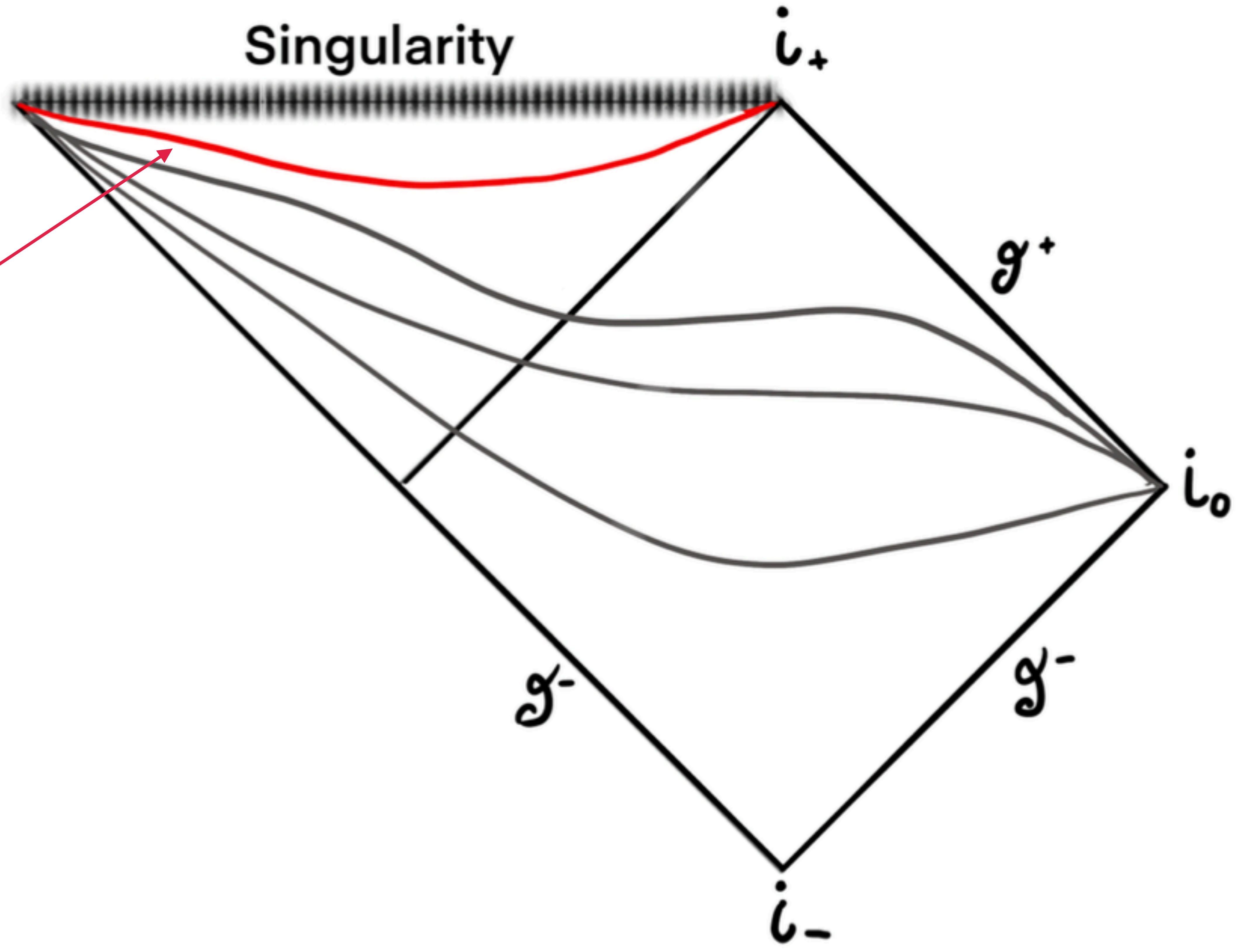
- Killing Horizons are no more causal boundaries! What is a Black Hole?

Horizons

- Killing Horizons are no more causal boundaries! What is a Black Hole?

If U_μ becomes orthogonal to a compact surface, we have a Universal Horizon

$$UH = \{(\chi \cdot U) = 0\,, \quad (\chi \cdot a) \neq 0\}$$



S. Liberati, M. Herrero-Valea, R. Garcia-Santos, ArXiv:2101.00028

UH in Schwarzschild

- We will consider a Schwarzschild solution of the theory:

$$ds^2 = \left(1 - \frac{2M}{r}\right)dt^2 - \frac{dr^2}{1 - \frac{2M}{r}} - r^2 dS_2$$

$$U_\mu dx^\mu = \left(1 - \frac{M}{r}\right)dt + \frac{M}{r - 2M}dr$$

$$\chi^\mu \partial_\mu = \frac{\partial}{\partial t}$$

- The Universal Horizon is located at:

$$UH = \{1 - \frac{M}{r} = 0\} \implies \{r = M\}$$

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Does the UH radiate?

- The derivation of Hawking Radiation is based on the fact that Killing Horizons are causal boundaries. We may expect similar properties from the UH...

- Let us take a massless scalar field on a BH geometry: $$\left[\nabla_\mu \nabla^\mu - \sum_{j=2}^{n} \frac{\alpha_{2j}}{\Lambda^{2j-2}} (\Delta)^j\right] \phi = 0$$

- Solving with a WKB ansatz, and decoupling the angular part, the get the dispersion relation:

$$\phi = \phi_0 e^{i\mathcal{S}_0} = \phi_0 \exp\left[-i \int (\omega\, U_\mu dx^\mu + q\, S_\mu dx^\mu)\right] \implies \omega^2 = q^2 + \sum_{j=2}^{n} \frac{\alpha_{2j}}{\Lambda^{2j-2}} q^{2j}$$

Near-UH Solutions

- Since $[U^\mu \partial_\mu, S^\nu \partial_\nu] \neq 0$, neither ω nor q are conserved quantities. The Killing energy Ω, it is:

$$\Omega = \omega(U \cdot \chi) + q(S \cdot \chi)$$

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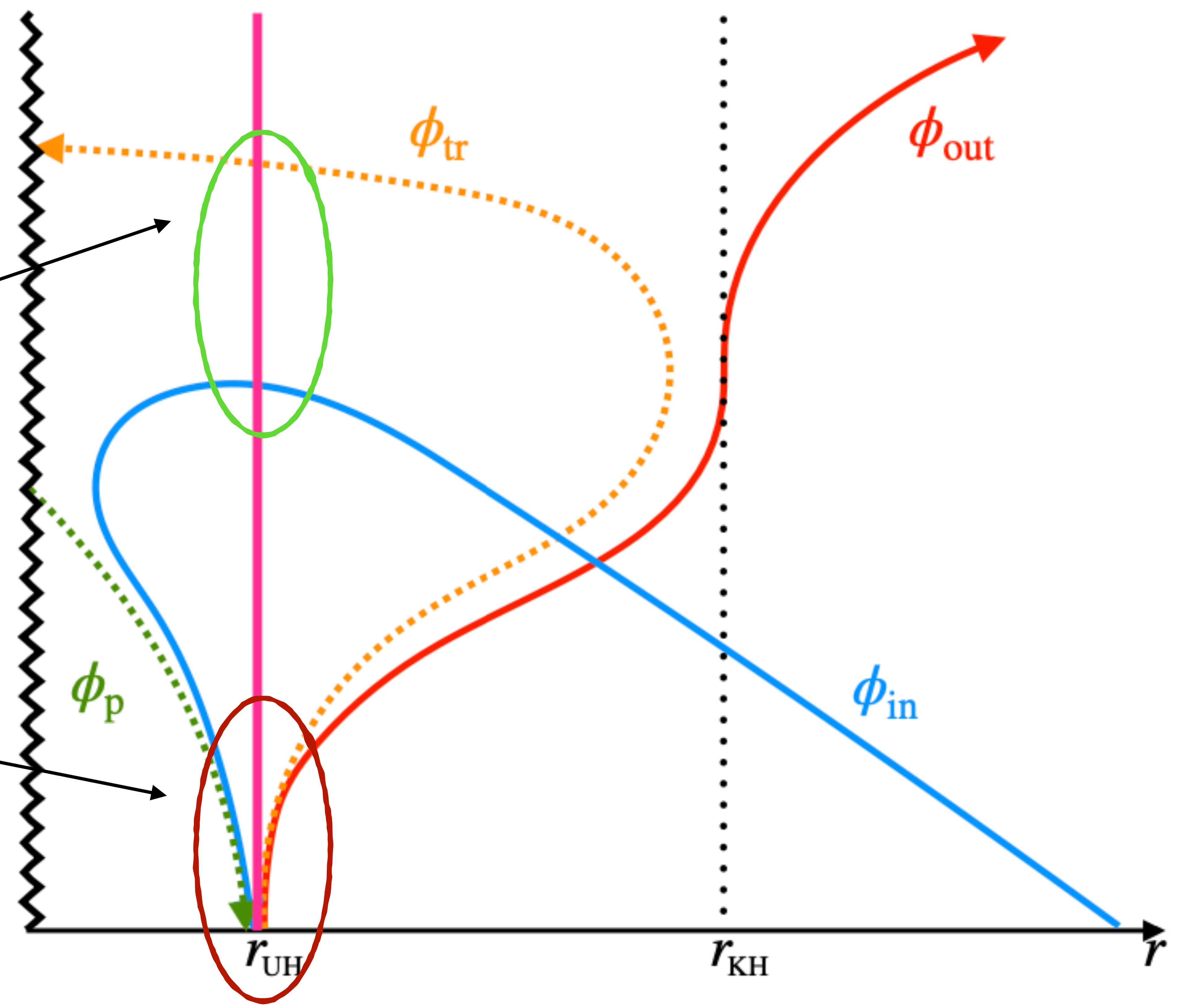
$(U \cdot \chi) \simeq 0$



- $|q|$ is regular at the UH: soft modes
- $|q| \to +\infty$ at the UH: hard modes

FDP, S.Liberati, M.Herrero-Valea, M.Schneider
Phys.Rev.D 106 (2022)

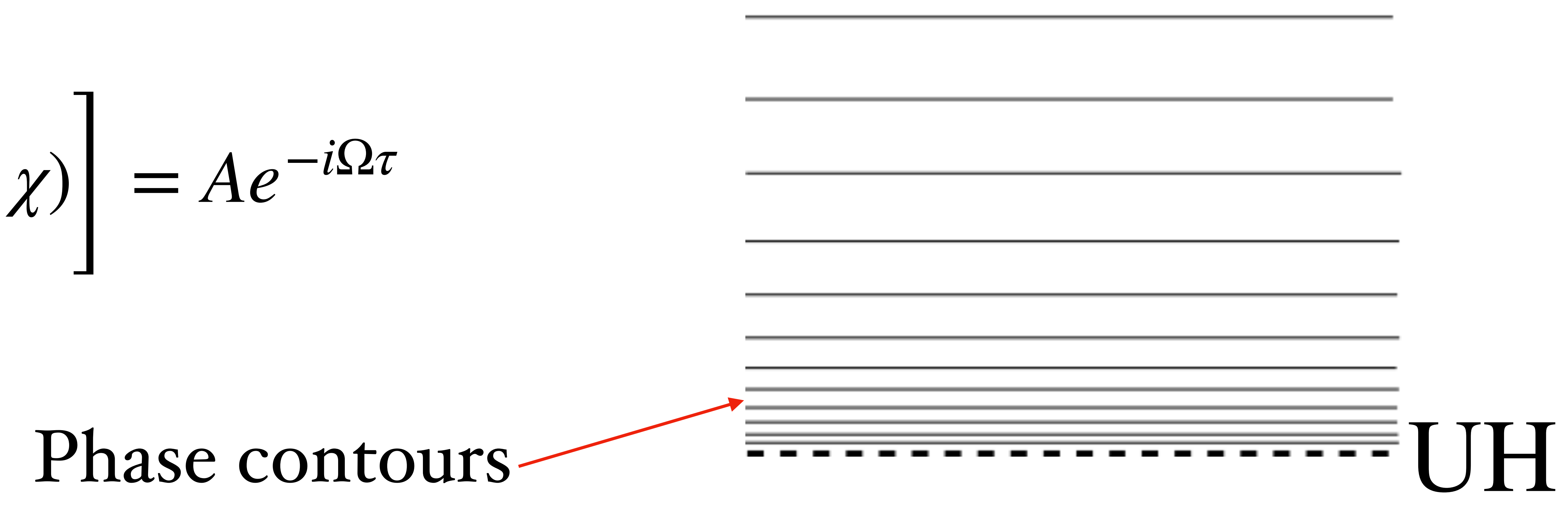
Near-UH Solutions

- We are interested in studying the hard mode which eventually reaches the asymptotic region, for which:

$$|q| \sim \frac{1}{(U \cdot \chi)^{\frac{1}{n-1}}} \qquad |\omega| \sim \frac{1}{(U \cdot \chi)^{\frac{n}{n-1}}}$$

- This gives the form of the outgoing mode, <u>which is non-analytical at the Horizon</u>:

$$\phi_\Omega^{out} = A \exp\left[\frac{i}{2\kappa}\Omega \log(U \cdot \chi)\right] = Ae^{-i\Omega\tau}$$

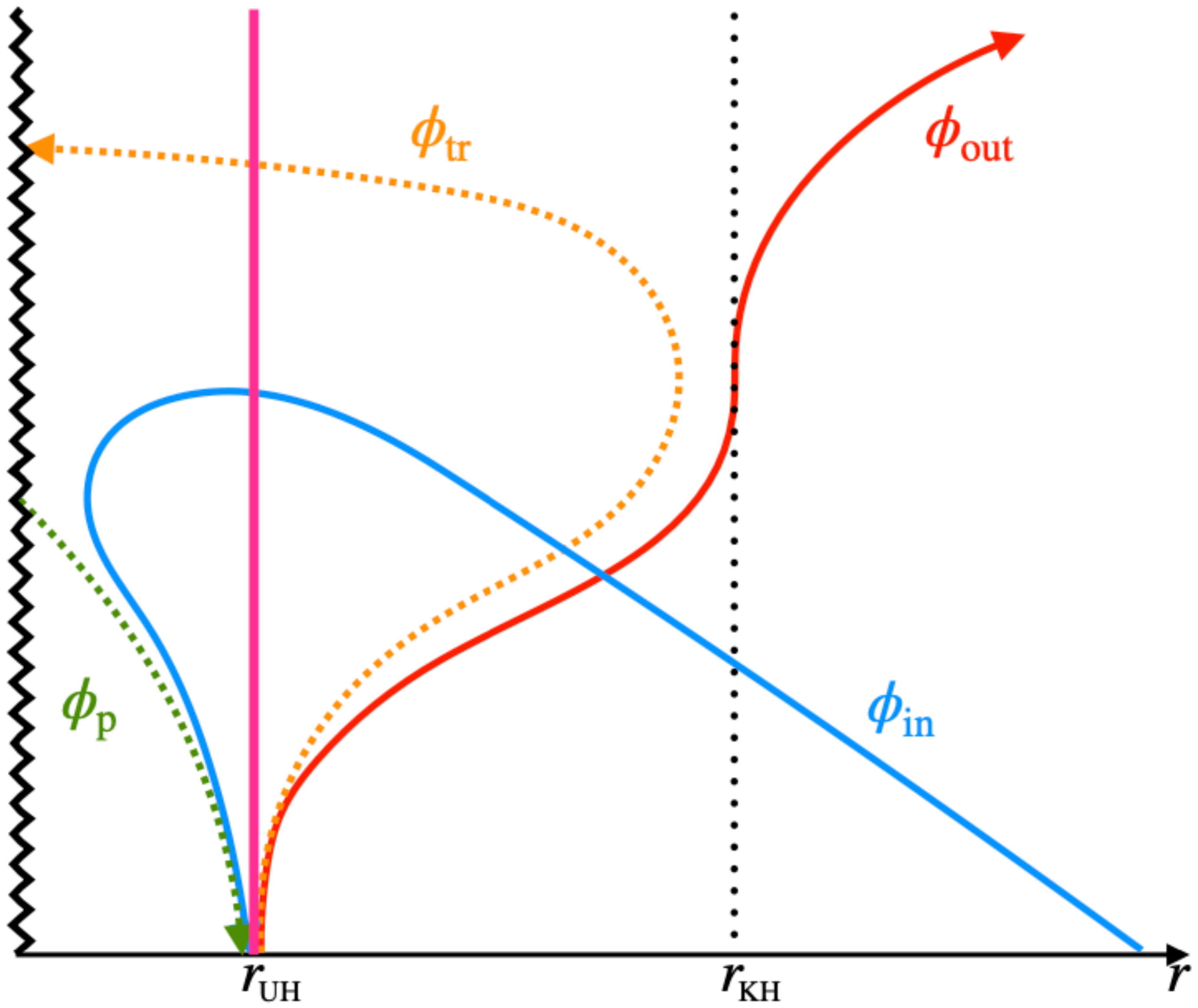


UH temperature

M.Schneider, FDP, M.Herrero-Valea, S.Liberati in ArXiv:2207.08938

- We can evaluate the thermal properties through the tunneling amplitude:

$$\mathrm{Im}\mathcal{S}_0 = \mathrm{Im}\left[-\mathrm{i}\int_{\mathrm{r_{UH}}-\epsilon}^{\mathrm{r_{UH}}+\epsilon}\left(\omega\,\mathrm{U}_\mu \mathrm{dx}^\mu + \mathrm{q}\,\mathrm{S}_\mu \mathrm{dx}^\mu\right)\right]$$



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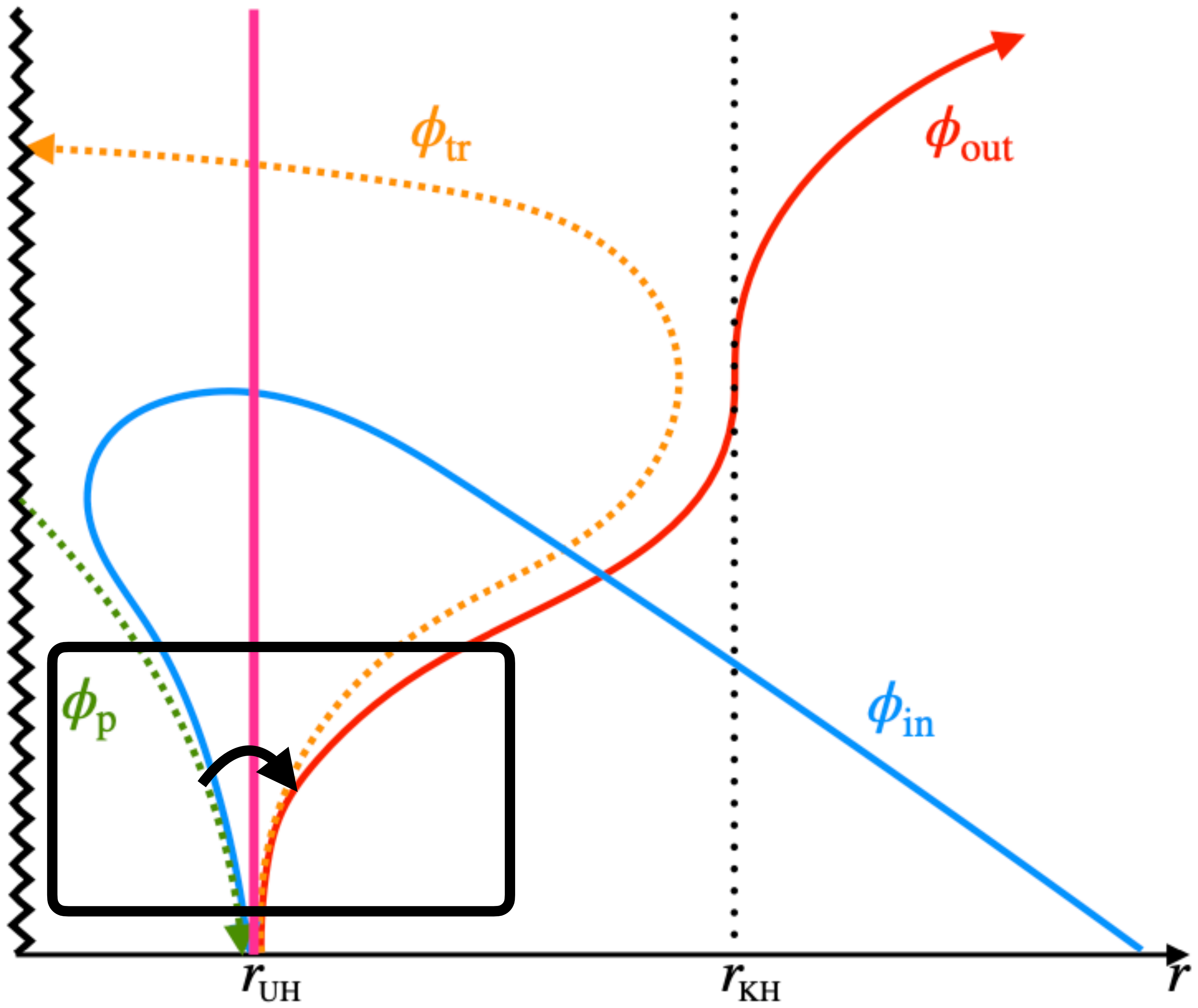
- The amplitude of tunneling out is given by

$$\Gamma = e^{-2\mathrm{Im}\mathcal{S}_0} = e^{-\Omega\pi/\kappa_{\mathrm{UH}}} \implies T_{\mathrm{UH}} = \frac{\kappa_{\mathrm{UH}}}{\pi}$$



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Propagation of the outgoing ray

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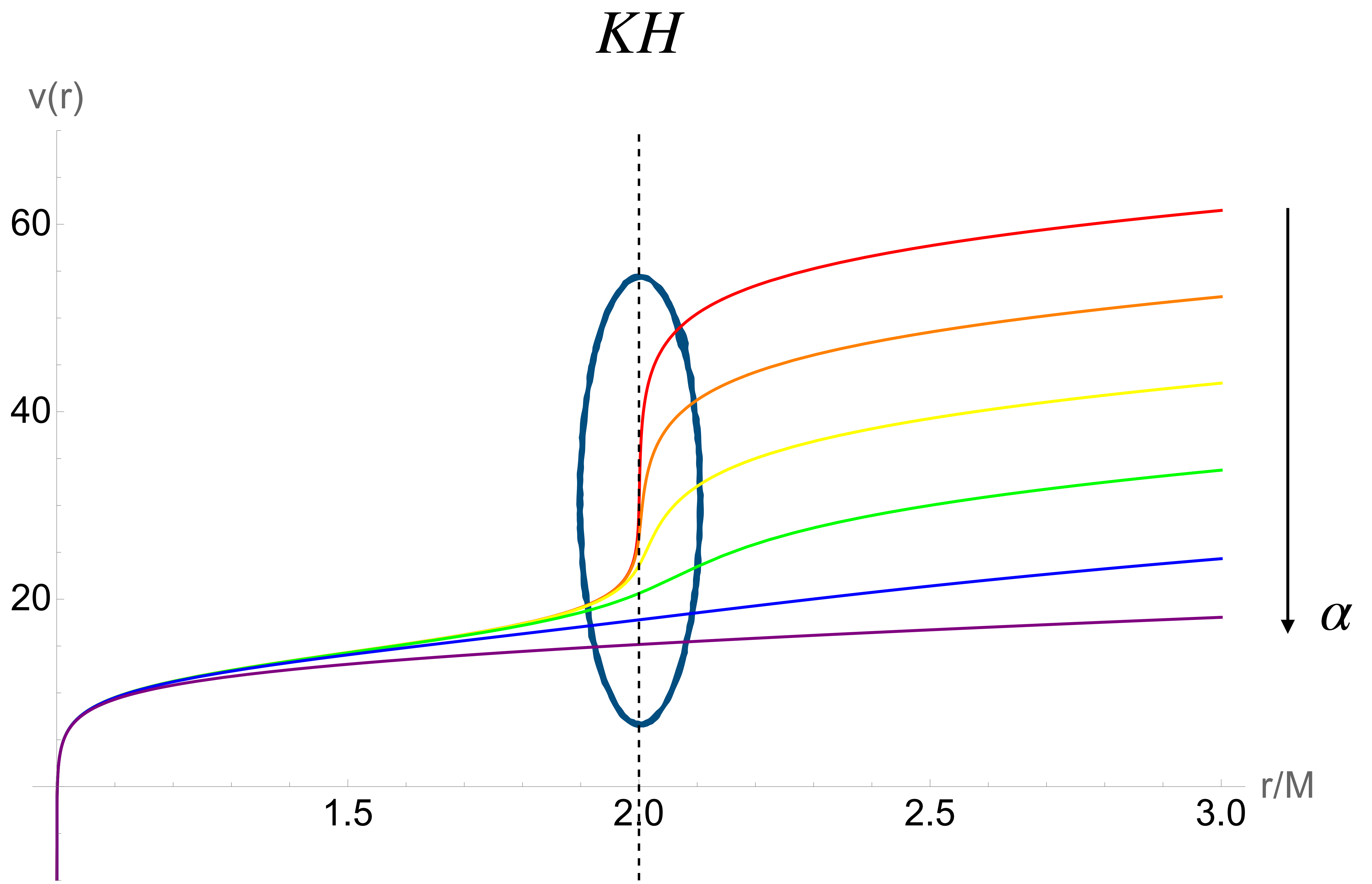
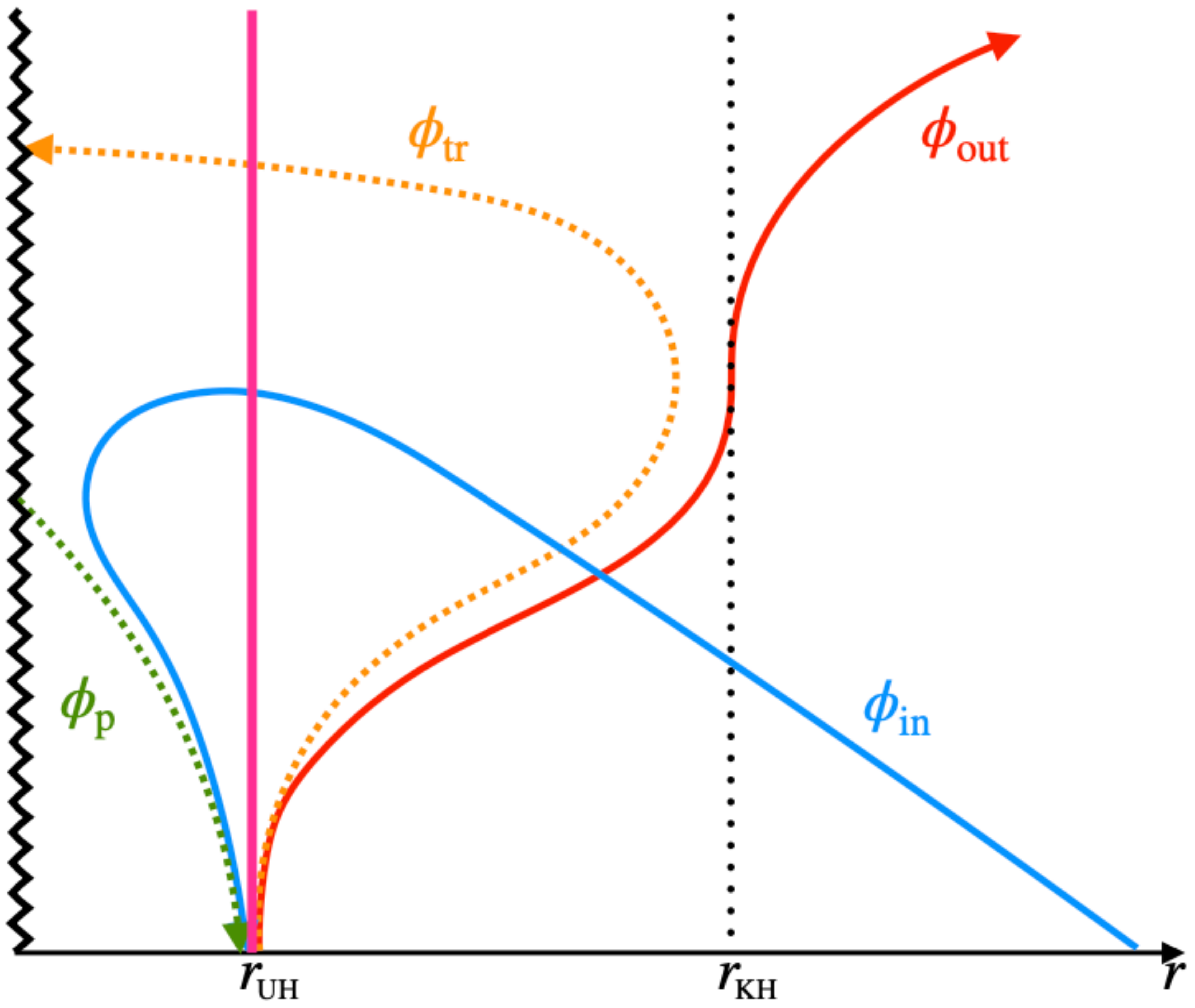
The rays for which $\underline{\alpha = \Omega/\Lambda \ll 1}$ linger at the KH for long time



Thermal spectrum?

- For very <u>low α</u> the red mode and the orange one assume “almost” the relativistic shape



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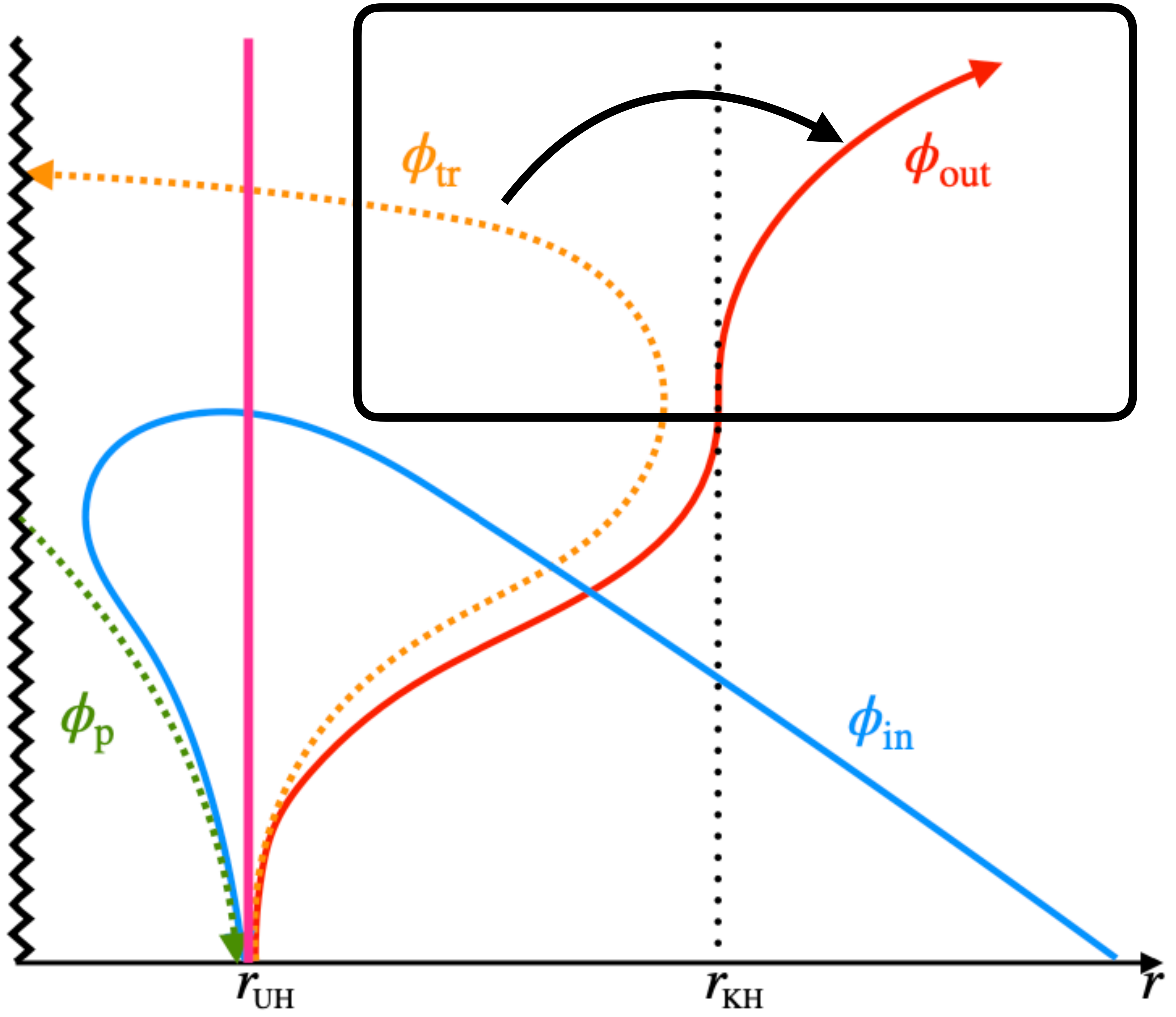

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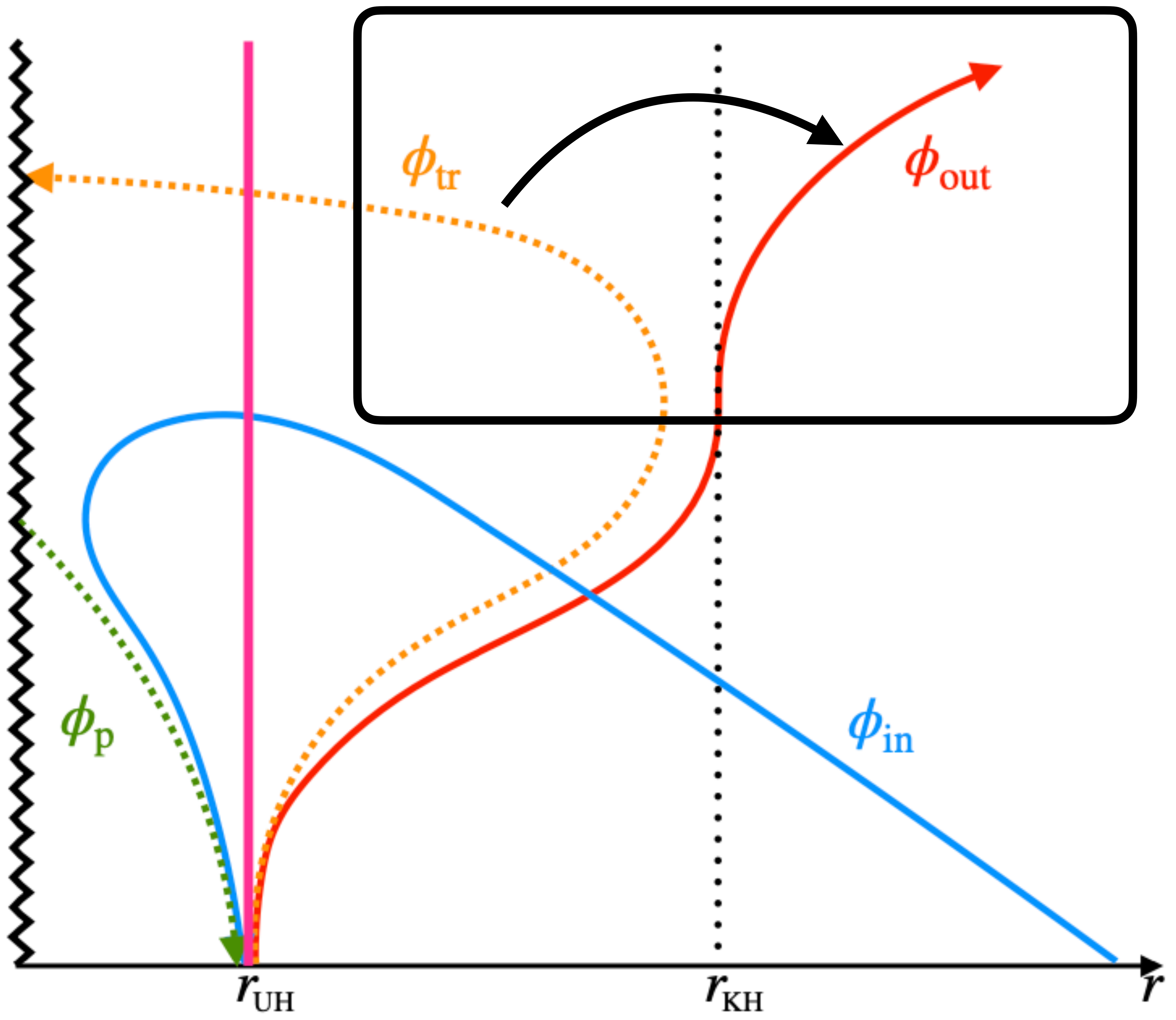

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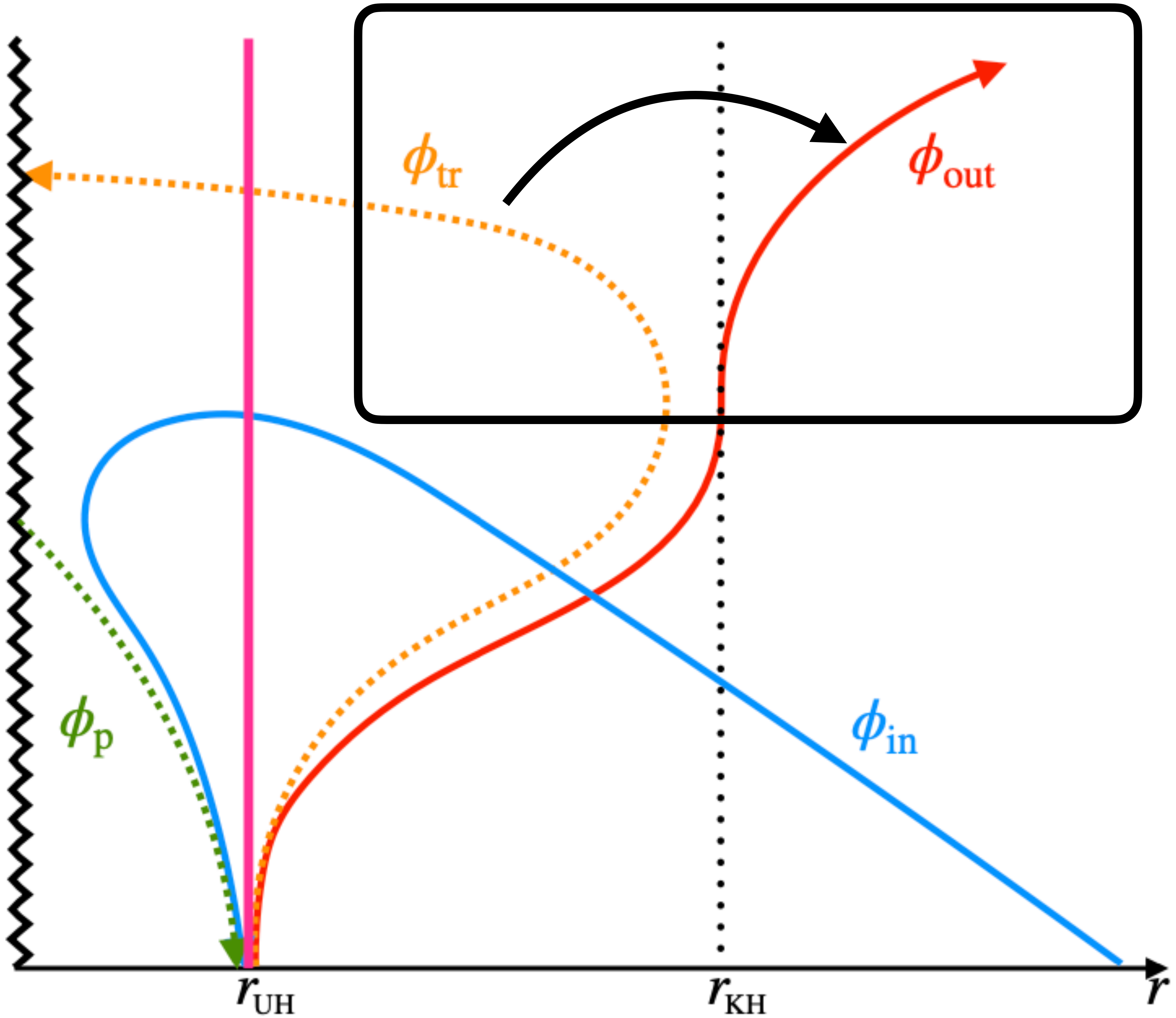
Deviation from thermality!!



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Conclusions and further developments

- LV Black Holes have a causal boundary with similar thermal properties to the GR ones
- Along their propagation, particles feel differently the KH depending on their energies
- Low-energies particles are reprocessed by the KH, recovering the relativistic limit
- Further developments: what arrives at infinity? Is there a global state?

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Thank you!

SIGRAV