Hawking radiation and universal horizons

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Hawking radiation in Lorentz-invariant theories

- Hawking radiation $\to$ physical meaning of black hole thermodynamic laws
- Lorentz-invariant theories $\Rightarrow$ Killing horizon separates outgoing modes ; Thermal emission spectrum [1]
- Temperature of the emitted spectrum $=$ thermodynamic temperature

[1] S. W. Hawking. "Particle Creation by Black Holes". In: *Commun. Math. Phys.* 43 (1975), pp. 199–220. DOI: 10.1007/BF02345020, W.G. Unruh. "Notes on black hole evaporation". In: *Phys. Rev. D* 14 (1976), p. 870. DOI: 10.1103/PhysRevD.14.870.

Superluminal dispersion relations

- superluminal motion $\Rightarrow$ Killing horizon can be crossed in both directions
- What becomes of the laws of black hole thermodynamics? of predictability[2]?
- Two routes to address these questions
  $\rightarrow$ analogue gravity (see the previous talks)
  $\rightarrow$ Lorentz-breaking theories of gravity (Hořava gravity, Einstein-æther theory)

[2] T. Jacobson. "Lorentz violation and Hawking radiation". In: (2001). arXiv: gr-qc/0110079 [gr-qc].

Black holes in Lorentz-violating theories

- Generally possess a *universal horizon* $\rightarrow$ solves the predictability issue; first law[3]

- What about the second law?

- Does the universal horizon radiate thermally?

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[3] P. Berglund, J. Bhattacharyya, and D. Mattingly. "Mechanics of universal horizons". In: *Phys. Rev. D* 85 (2012), p. 124019. DOI: 10.1103/PhysRevD.85.124019. arXiv: 1202.4497 [hep-th], P. Hořava et al. "GR 20 parallel session A3: modified gravity". In: *General Relativity and Gravitation* 46.5, 1720 (2014). ISSN: 0001-7701. DOI: 10.1007/s10714-014-1720-4. URL: http://dx.doi.org/10.1007/s10714-014-1720-4.

Black holes in Lorentz-violating theories

- Using one version of the "tunneling formalisme"[4] $\rightarrow$ yes (but doubts about the validity of the procedure)

- Analyzing the characteristics of the modes[5] $\rightarrow$ one can define a surface gravity geometrically (but link with the emission process unclear)

- Full QFT calculation $\rightarrow$ no late-time emission from the UH

[4] P. Berglund, J. Bhattacharyya, and D. Mattingly. "Towards Thermodynamics of Universal Horizons in Einstein-æther Theory". In: *Phys.Rev.Lett.* 110.7 (2013), p. 071301. DOI: 10.1103/PhysRevLett.110.071301. arXiv: 1210.4940 [hep-th].

[5] B. Cropp et al. "Ray tracing Einstein-Æther black holes: Universal versus Killing horizons". In: *Phys.Rev.* D89.6 (2014), p. 064061. DOI: 10.1103/PhysRevD.89.064061. arXiv: 1312.0405 [gr-qc].

Outline

Section 2

The model

The collapsing shell model

- interior: Minkowski metric with non-accelerated æther
- exterior: solution of [6] with $c_{123} = 0$, $r_0 = 2M$, and $r_u = 0$
  $\rightarrow$ Killing horizon at $r = 2M$ (Schwarzschild metric)
  $\rightarrow$ Universal horizon at $r = M$

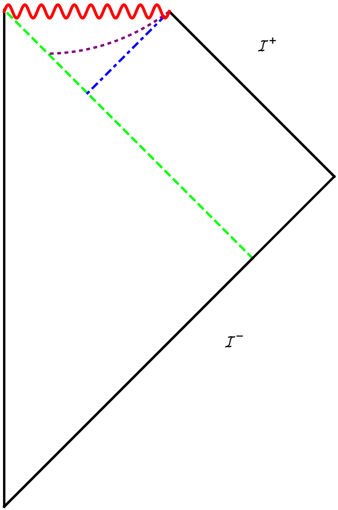
$$u^\mu \partial_\mu = \partial_v - \frac{M}{r}\partial_r$$

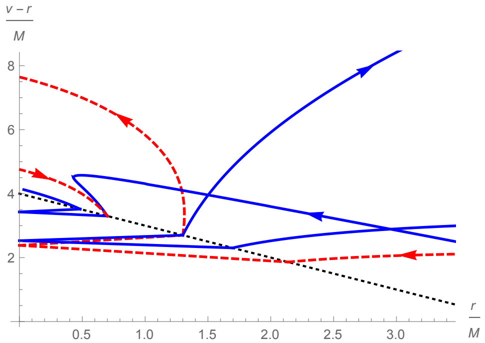
- Real scalar field ϕ with quartic dispersion from coupling to the æther

$$S = \int d^4x \sqrt{-g}\left(\partial_\mu\phi\partial^\mu\phi - \frac{1}{\Lambda^2}\left(\nabla_\mu h^{\mu\nu}\nabla_\nu\phi\right)^2\right)$$
$$h^{\mu\nu} \equiv g^{\mu\nu} - u^\mu u^\nu$$

[6] P. Berglund, J. Bhattacharyya, and D. Mattingly. "Mechanics of universal horizons". In: *Phys. Rev. D* 85 (2012), p. 124019. DOI: 10.1103/PhysRevD.85.124019. arXiv: 1202.4497 [hep-th].

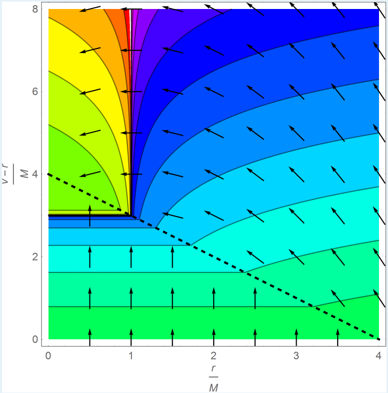
Conformal diagram and characteristics





Preferred time

æther field and preferred time



$$t = \begin{cases} v - r & v < 4M \\ v - r_U^* & v > 4M \wedge r > M \\ \boxed{-\left(v - r_U^*\right)} & v > 4M \wedge r < M \end{cases}$$

$$X = \begin{cases} r, & v < 4M \\ r_U^* & v > 4M \wedge r > M \\ -r_U^* & v > 4M \wedge r < M \end{cases}$$

$$r_U^* = r + M \ln\left|\frac{r}{M} - 1\right|$$

The model: summary

- Collapsing shell $\Rightarrow$ well-defined vacuum state at $t \to -\infty$
- Dispersion from coupling to the æther $\Rightarrow$ maintains causality and a standard Hamiltonian structure
- Exterior solution: exact solution of Einstein-æther for explicit calculation (but main results independent on the details)

Section 3

Scattering coefficients and radiation

WKB modes at fixed frequency

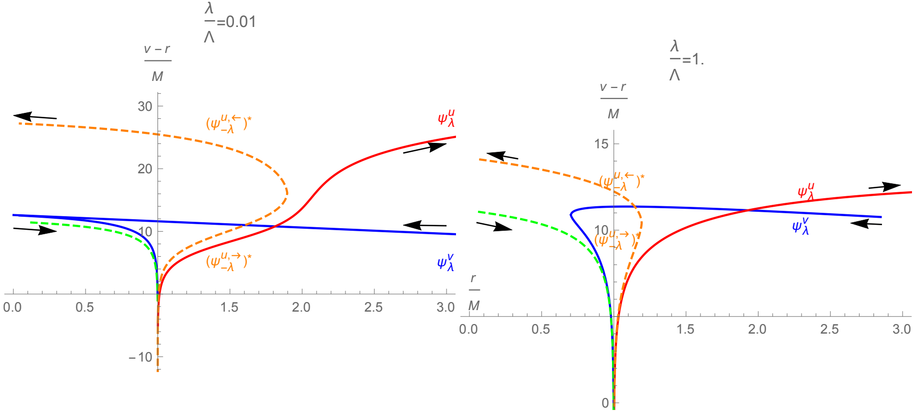
2 modes inside the shell

- ϕ_ω: positive energy, incoming
- ϕ_ω^v: positive energy, outgoing

4 WKB modes close to the universal horizon:

- ψ_λ^u: positive energy, outgoing
- $\left(\psi_{-\lambda}^{u,\rightarrow}\right)^*$: negative energy, outgoing
- ψ_λ^v: positive energy, incoming
- $\left(\psi_{-\lambda}^{u,\leftarrow}\right)^*$: negative energy, incoming

Modes near the universal horizon



Mode expansion near the universal horizon

- Consider radial modes in the near-horizon approximation $(r/M) - 1 \ll 1$
- Mode expansion:

$$\phi_\omega^{u,\,\mathrm{in}} = \int_{-\infty}^{\infty} d\lambda \left(\gamma_{\omega,\lambda} \psi_\lambda^u + \boxed{\delta_{\omega,\lambda}} (\psi_{-\lambda}^u)^* + A_{\omega,\lambda} \psi_\lambda^v + B_{\omega,\lambda} \left(\psi_\lambda^{u,\leftarrow}\right)^* \right)$$

- $\delta_{\omega,\lambda}$ encodes the mixing of positive- and negative-energy modes
- stationary, nonvanishing late-time spectrum requires $|\delta_{\omega,\lambda}|^2 \propto 1/\omega$ for $\omega \to \infty$ R. Brout et al. “A Primer for black hole quantum physics”. In: *Phys. Rept.* 260 (1995), pp. 329–454. DOI: 10.1016/0370-1573(95)00008-5. arXiv: 0710.4345 [gr-qc].

Late-time scattering

- Mode matching along the matter shell trajectory $\to$ Saddle-point approximation $\to$

$$\delta_{\omega,\lambda} \underset{\omega\to\infty}{=} O\left(\frac{\sqrt{M\Lambda}}{\omega}\exp\left(-2M\sqrt{\Lambda\omega}\right)\right)$$

- More general shell trajectory and dispersion relation of order $2N$ give

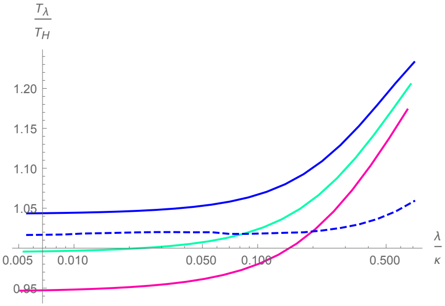
$$\ln\delta_{\omega,\lambda} \underset{\omega\to\infty}{\sim} -A\,\omega^{1/N},\ A>0$$

Global scattering

- Numerical integration including the propagation towards the Killing horizon and beyond → approximately thermal spectrum with temperature

$$T \approx \frac{\kappa_{\text{Killing}}}{2\pi}$$

- expected from known analogue gravity results as the universal horizon does not radiate at late times



Conclusions

Near-UH physics

- Contrary to what was expected using partial arguments, we found no late-time emission from the UH
- Instead, $\ln \delta_{\omega,\lambda} \sim -A\, \omega^{1/N},\ A > 0$

Global scattering

Approximately thermal spectrum from the Killing horizon

Outlook

- Consequences for the black hole thermodynamics laws?
- Fate of the UH? Instability from modes originating from the singularity?
- Analogue model of a UH?

Thank you for your attention!