Hawking radiation in laboratory analogues

Scott Robertson

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- C. Barceló, S. Liberati and M. Visser, *Living Rev. Relativity* **14**, 3 (2011)
- S. Robertson, *J. Phys. B* **45**, 163001 (2012)

Hawking Radiation

Hawking (1974, *Nature* **248**, 30):

QFT in black hole spacetime → Black holes emit thermal radiation

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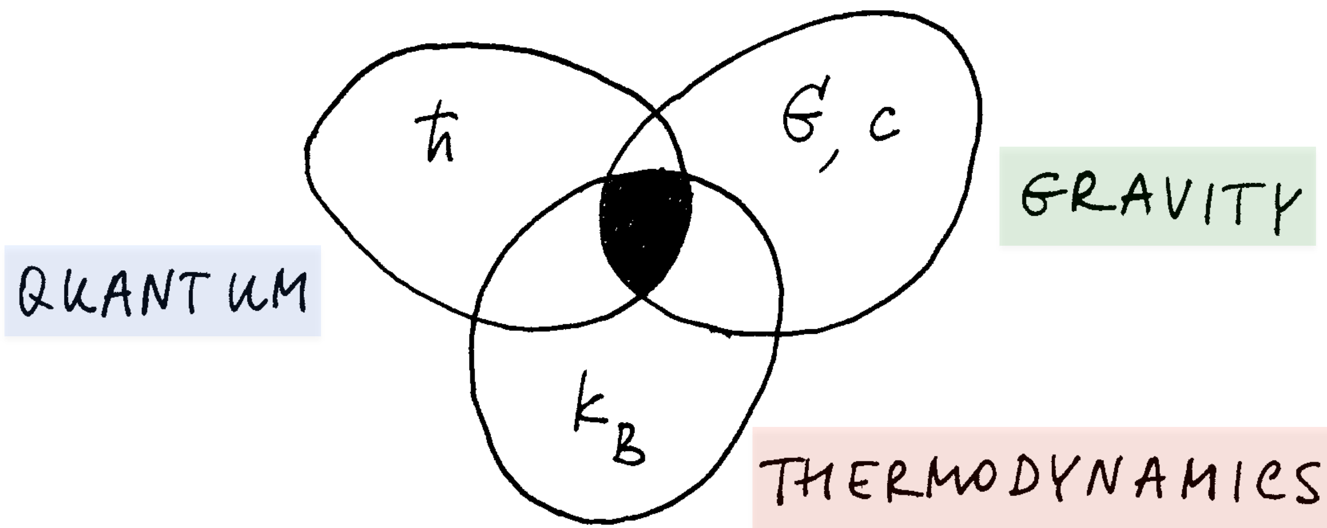

Picture courtesy of Ulf Leonhardt

Hawking Radiation

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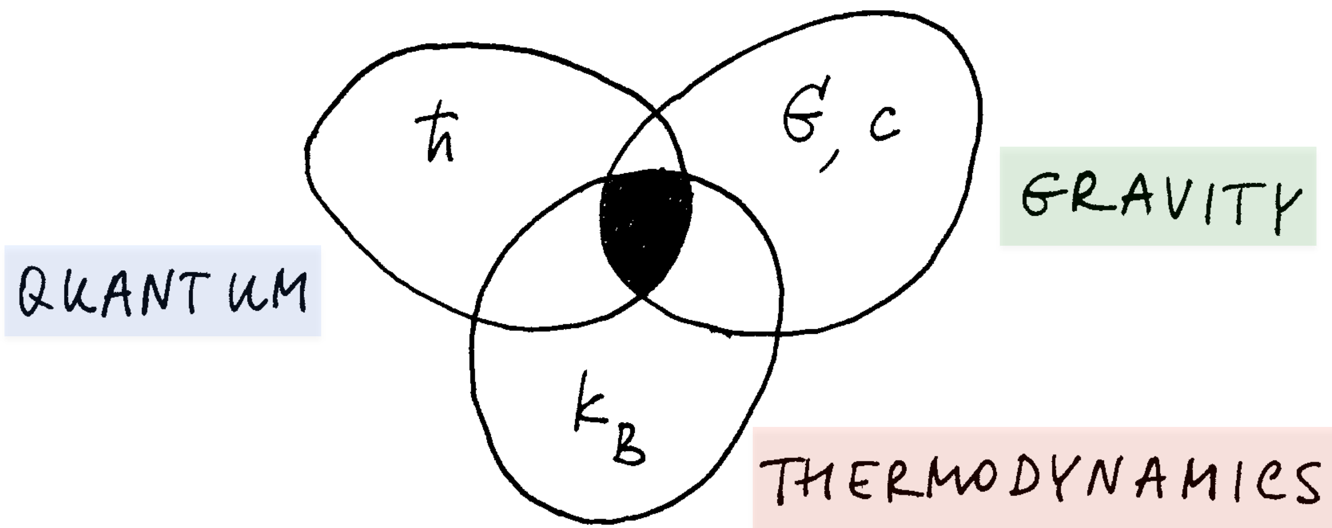
→

$$M \approx M_{\text{Sun}}$$
$$T \approx 10^{-7}\, K \quad << \quad T_{\text{CMB}}$$



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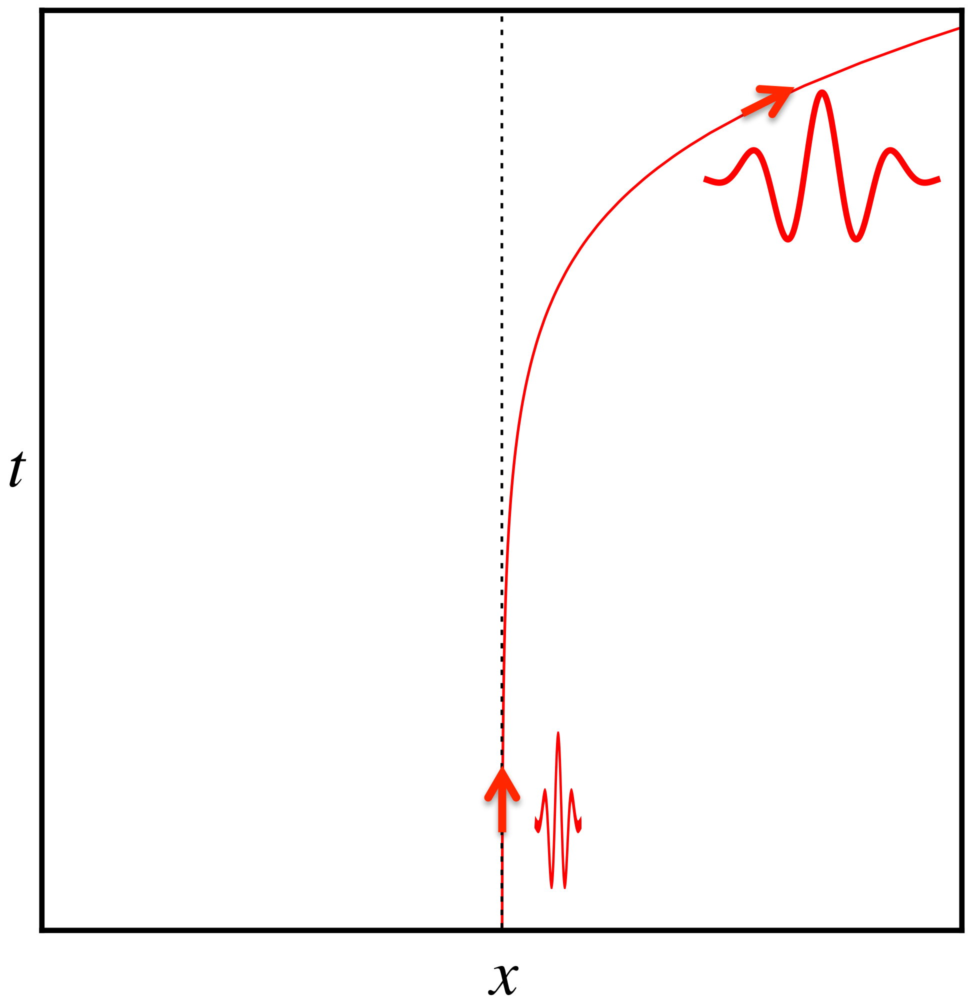
Trans-Planckian problem



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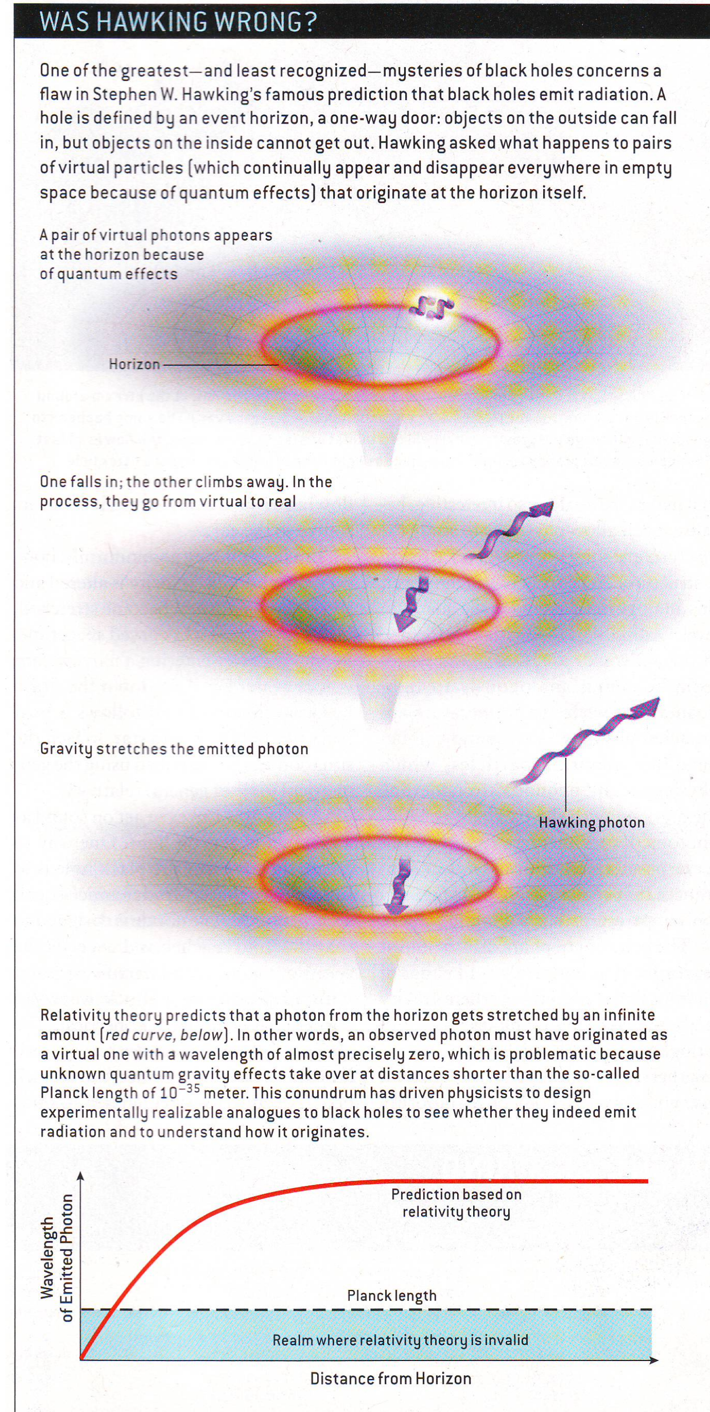


WAS HAWKING WRONG?

One of the greatest—and least recognized—mysteries of black holes concerns a flaw in Stephen W. Hawking's famous prediction that black holes emit radiation. A hole is defined by an event horizon, a one-way door: objects on the outside can fall in, but objects on the inside cannot get out. Hawking asked what happens to pairs of virtual particles (which continually appear and disappear everywhere in empty space because of quantum effects) that originate at the horizon itself.

A pair of virtual photons appears at the horizon because of quantum effects

Horizon

One falls in; the other climbs away. In the process, they go from virtual to real

Gravity stretches the emitted photon

Hawking photon

Relativity theory predicts that a photon from the horizon gets stretched by an infinite amount (*red curve, below*). In other words, an observed photon must have originated as a virtual one with a wavelength of almost precisely zero, which is problematic because unknown quantum gravity effects take over at distances shorter than the so-called Planck length of 10^{-35} meter. This conundrum has driven physicists to design experimentally realizable analogues to black holes to see whether they indeed emit radiation and to understand how it originates.

Prediction based on relativity theory

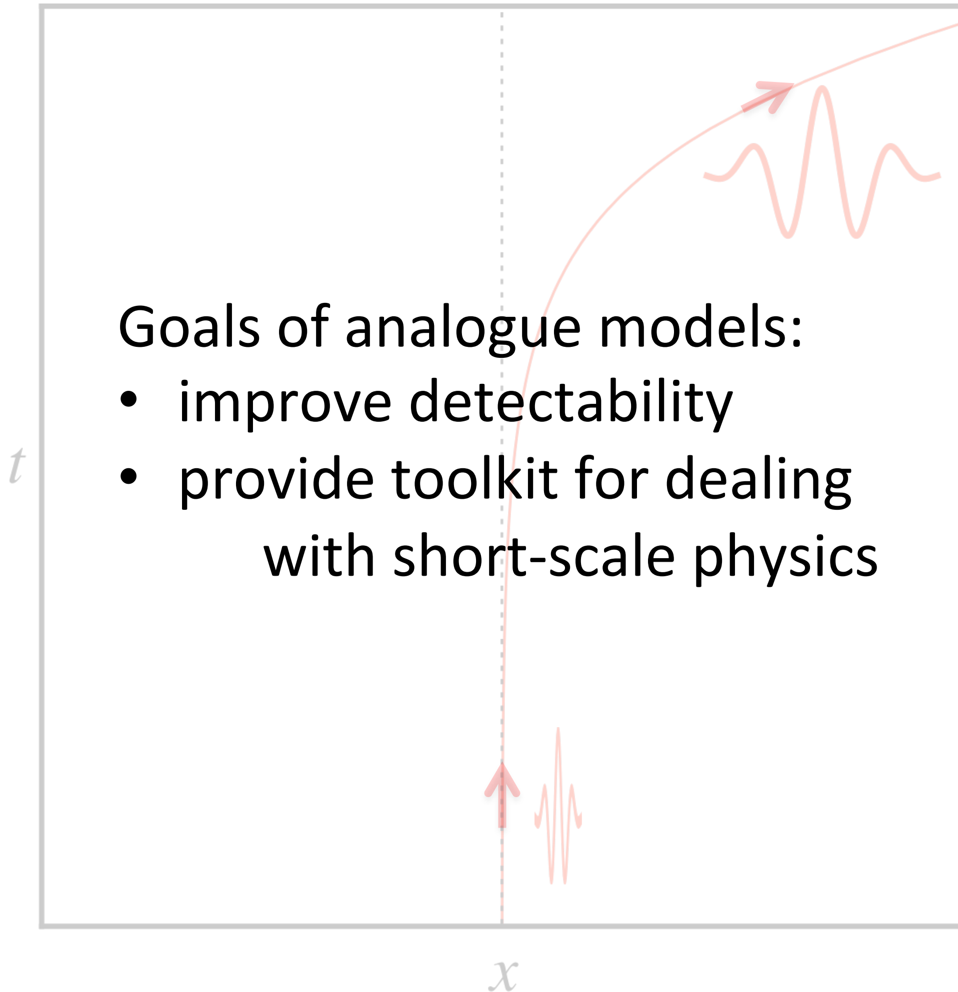
Wavelength of Emitted Photon

Planck length

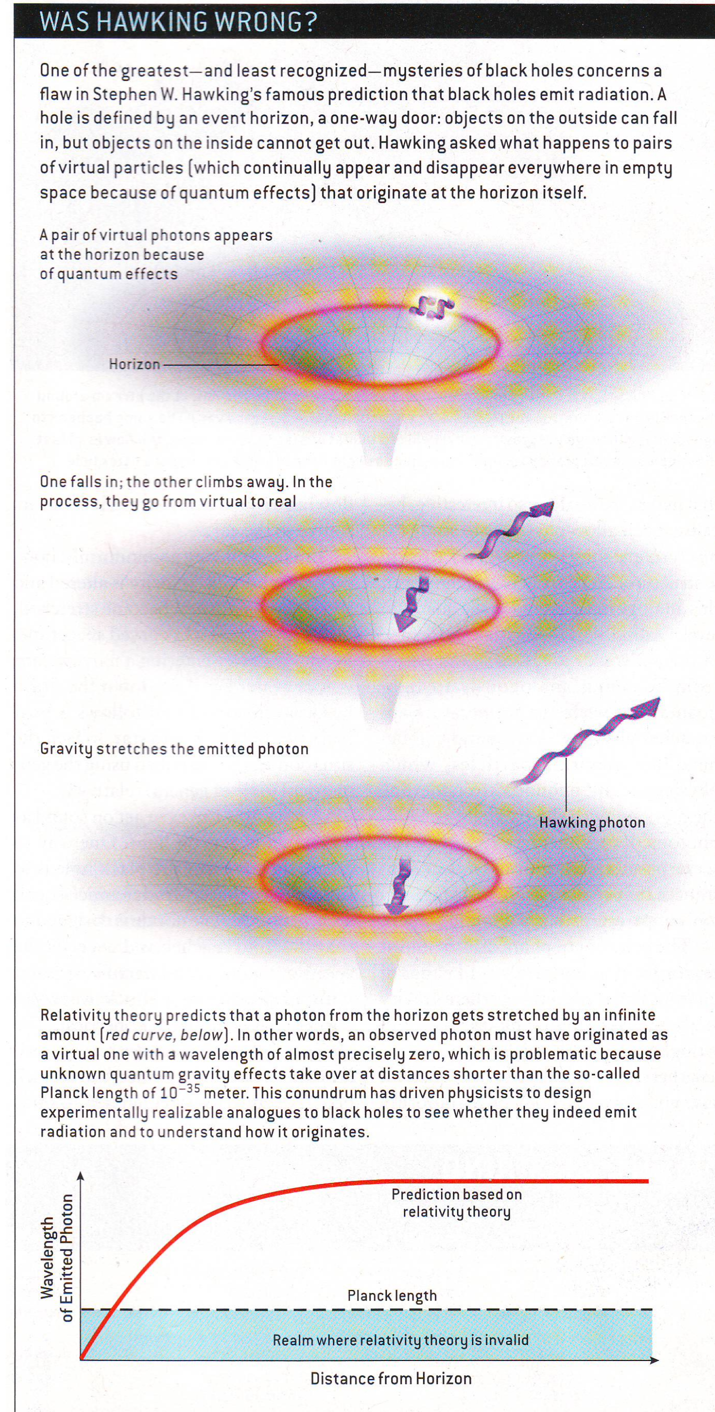
Realm where relativity theory is invalid

Distance from Horizon

Trans-Planckian problem



Goals of analogue models:
- improve detectability
- provide toolkit for dealing with short-scale physics



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Analogue models

Unruh (1981, *Phys. Rev. Lett.* **46**, 1351):

Sound waves in moving fluid ⟷ Scalar field in spacetime

$$g_{\mu\nu}dx^{\mu}dx^{\nu} = c^2dt^2 - \left(dr - v(r)dt\right)^2 - r^2d\Omega^2$$

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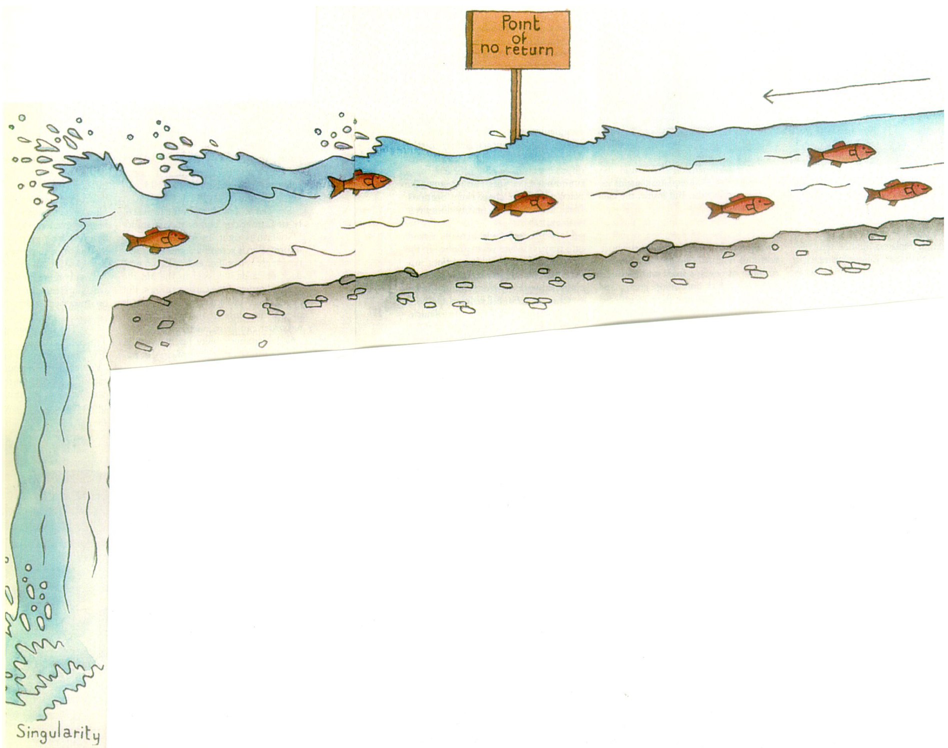

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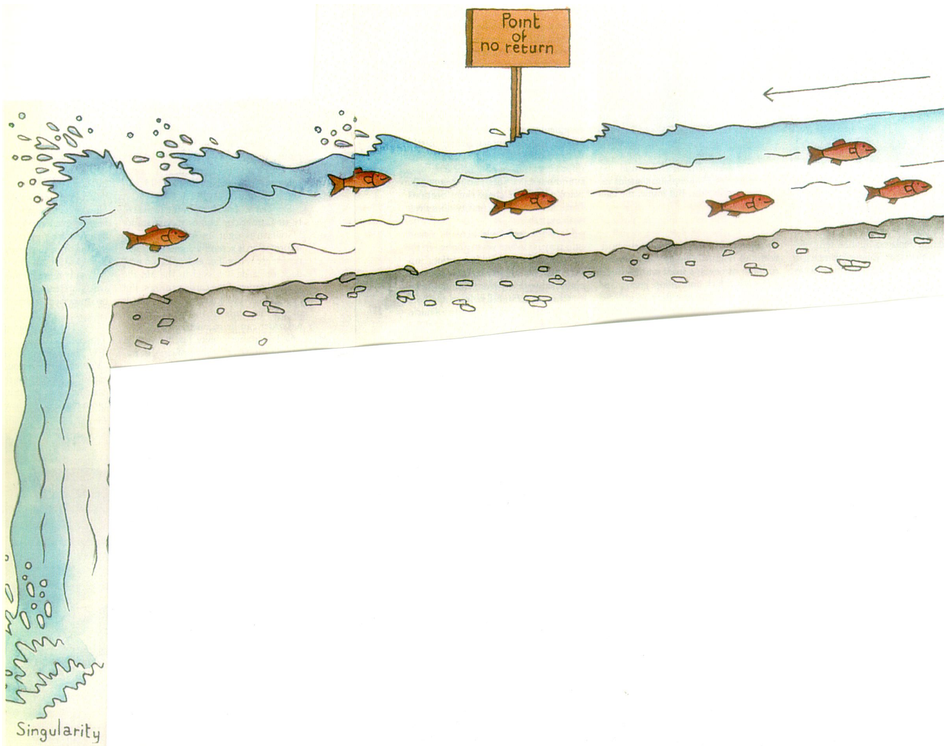

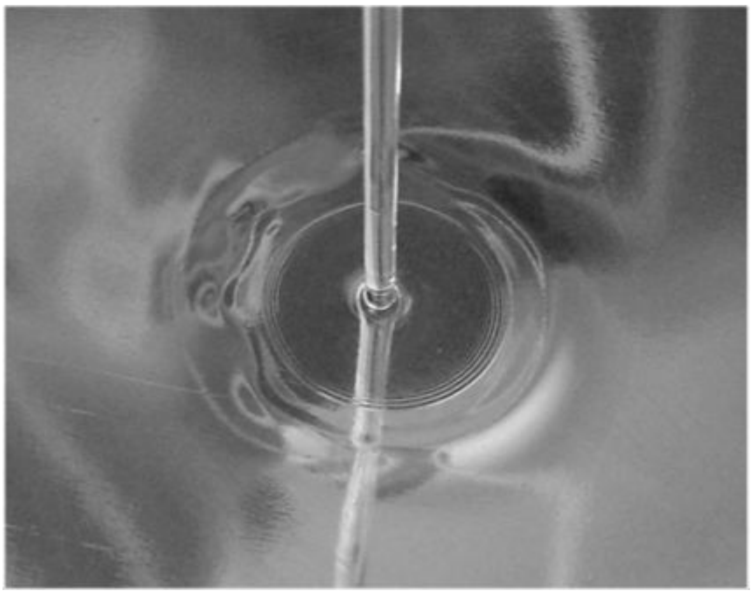

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If event horizon where $|v| = c$

→ Sound waves emitted as thermal spectrum

$$k_B T = \frac{\hbar\kappa}{2\pi}$$

where

$$\kappa = \left.\frac{dv}{dr}\right|_{\text{horizon}}$$

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$$k_BT = \frac{\hbar\kappa}{2\pi}$$

where

$$\kappa = \left.\frac{dv}{dr}\right|_{\text{horizon}}$$

$$v(r) = -\sqrt{\frac{r_S}{r}}$$

Black hole in Painlevé-Gullstrand coordinates

Dispersion

Jacobson (1991, *Phys. Rev. D* **44**, 1731):

Short-distance behaviour gives rise to dispersion

→ alters ancestry of outgoing modes

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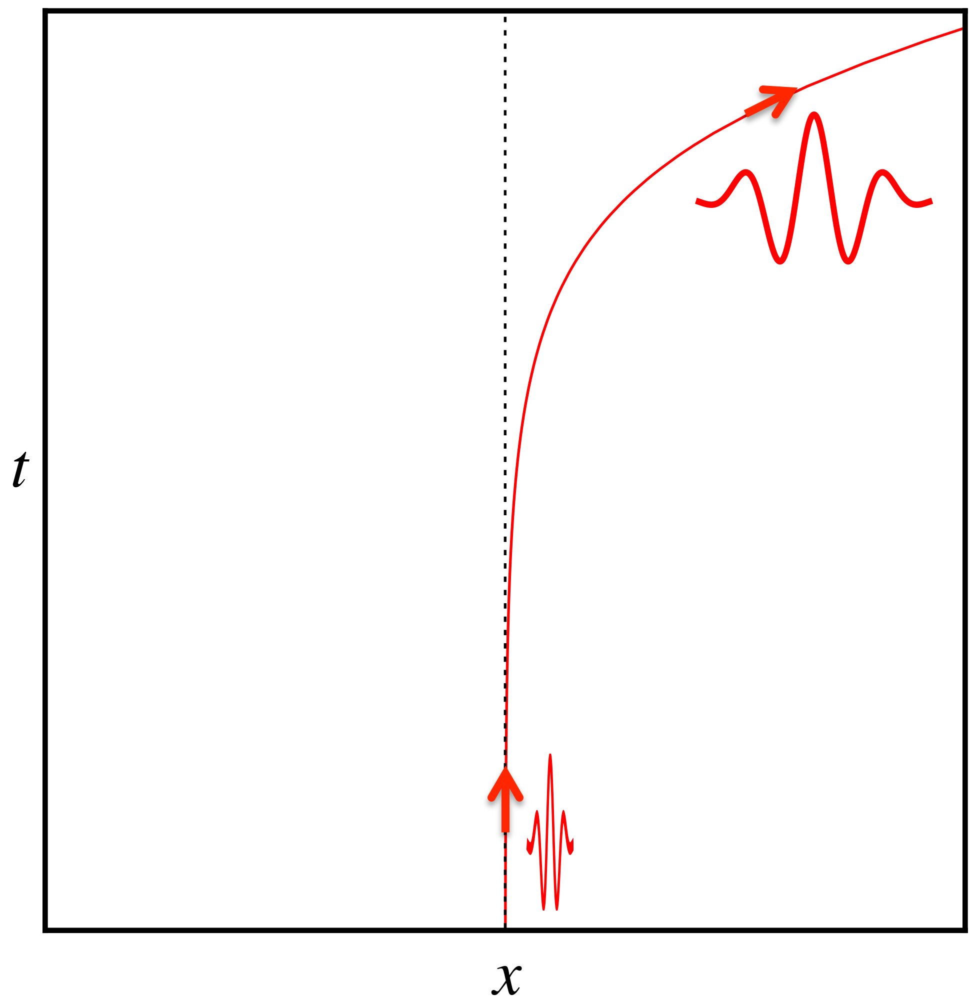
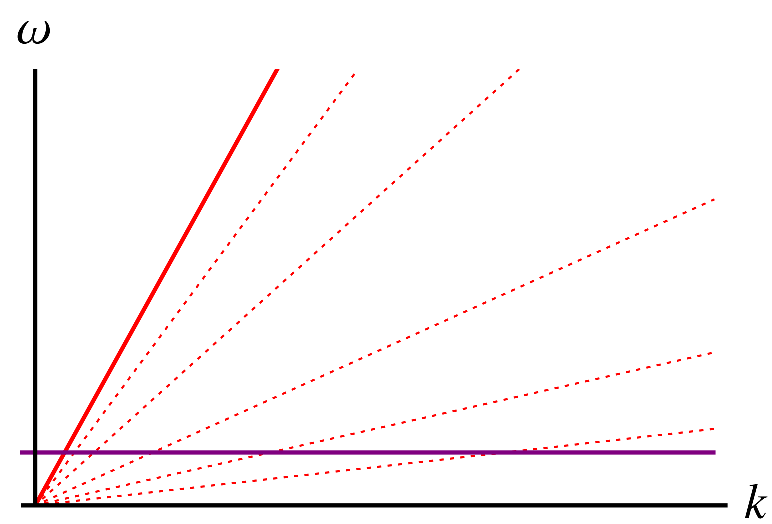


$$\omega = \left(c + v\right)k$$



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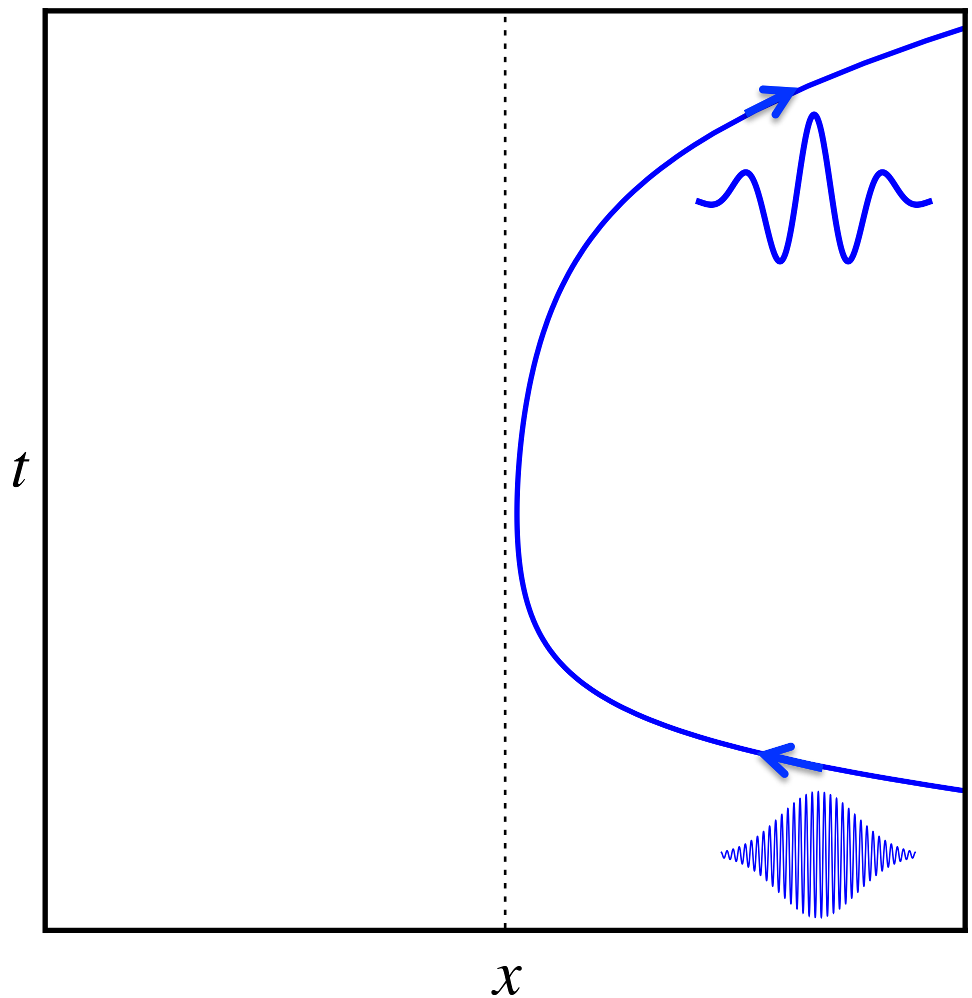
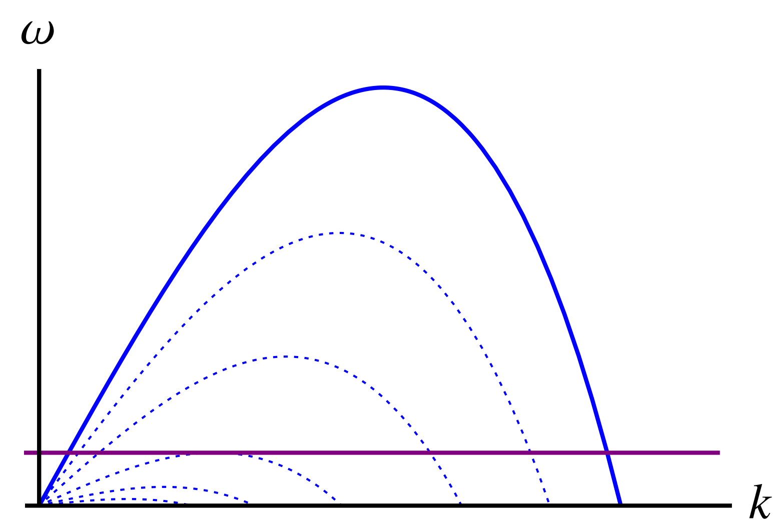


$$\omega = \left(c(k) + v\right)k$$



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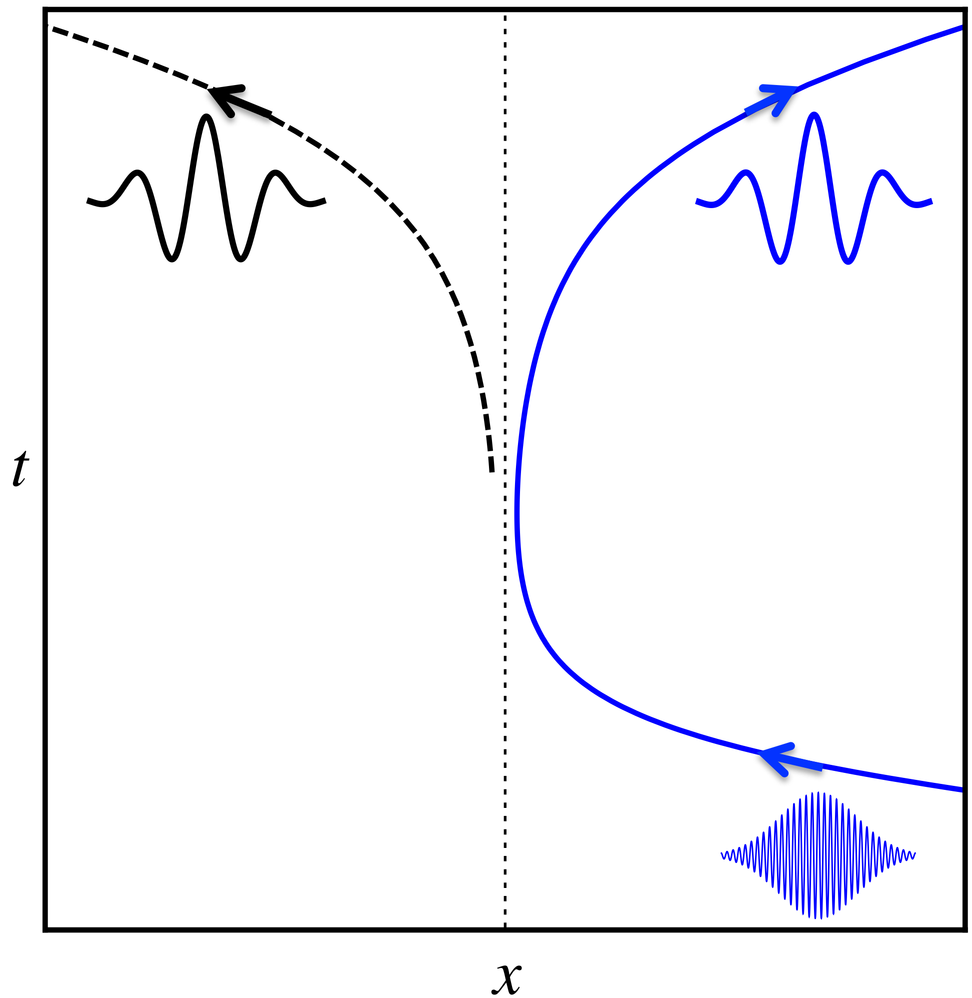

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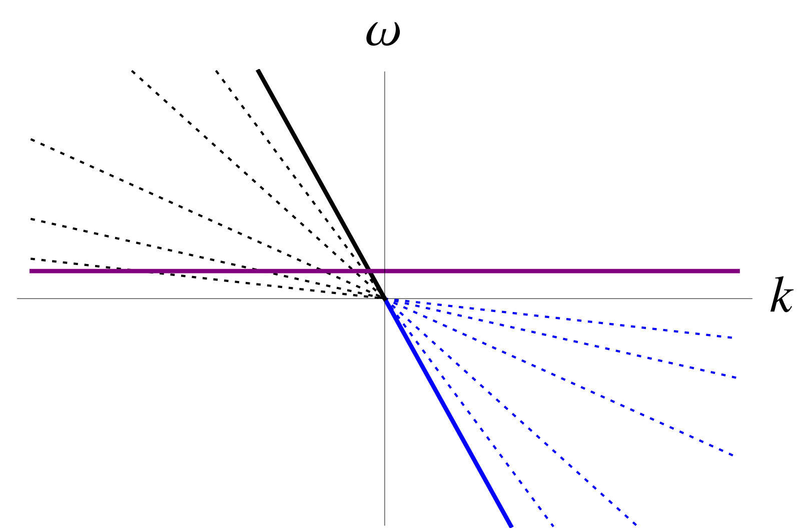


Positive and negative norm

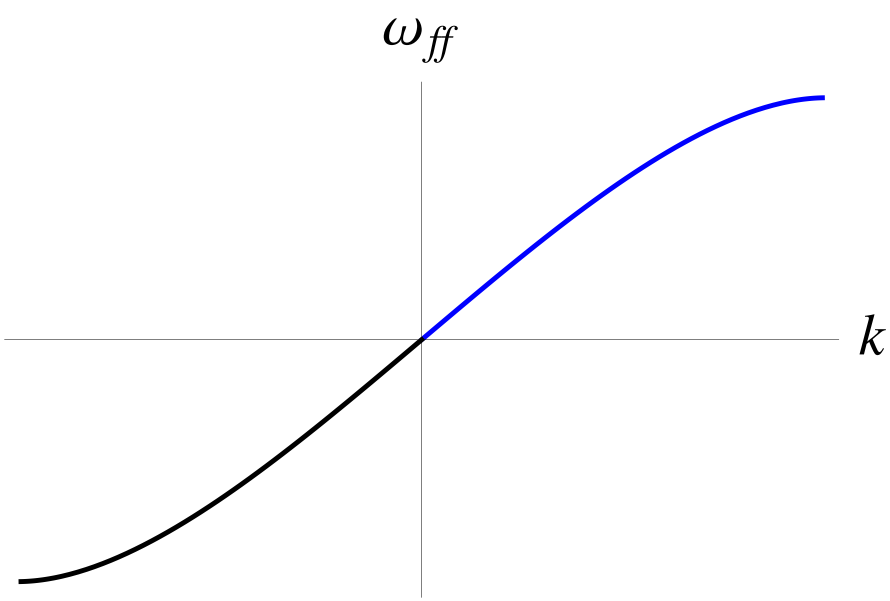
Conserved norm:

$$(\phi,\phi) = i\int\left(\phi^*\left(\partial_t + v\partial_x\right)\phi - \phi\left(\partial_t + v\partial_x\right)\phi^*\right) dx$$

Sign of norm is fixed **=** sign of ω_{ff}

= sign of k

(on counter-propagating branch)

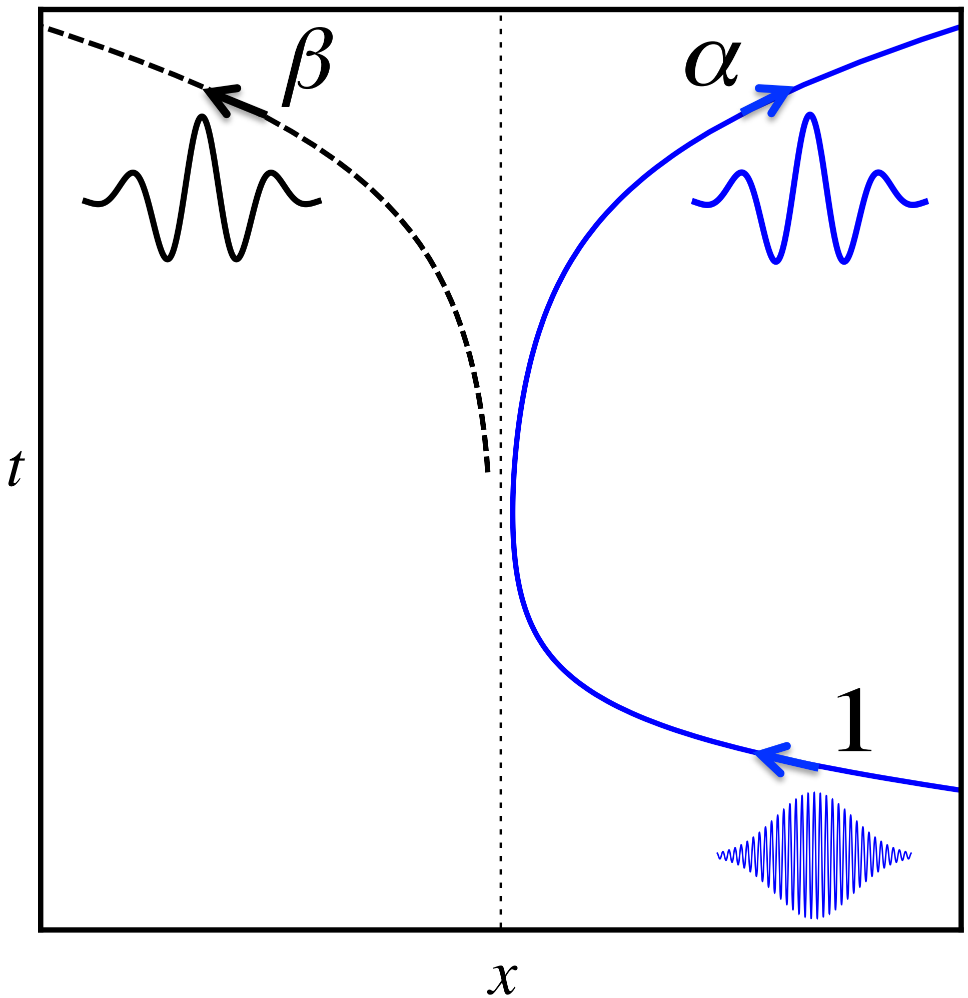


$$\omega_{ff} = c(k)k$$

Hawking radiation

Mixing of positive- and negative-norm modes

→ Amplification of incident wave



$$|\alpha|^2 - |\beta|^2 = 1$$

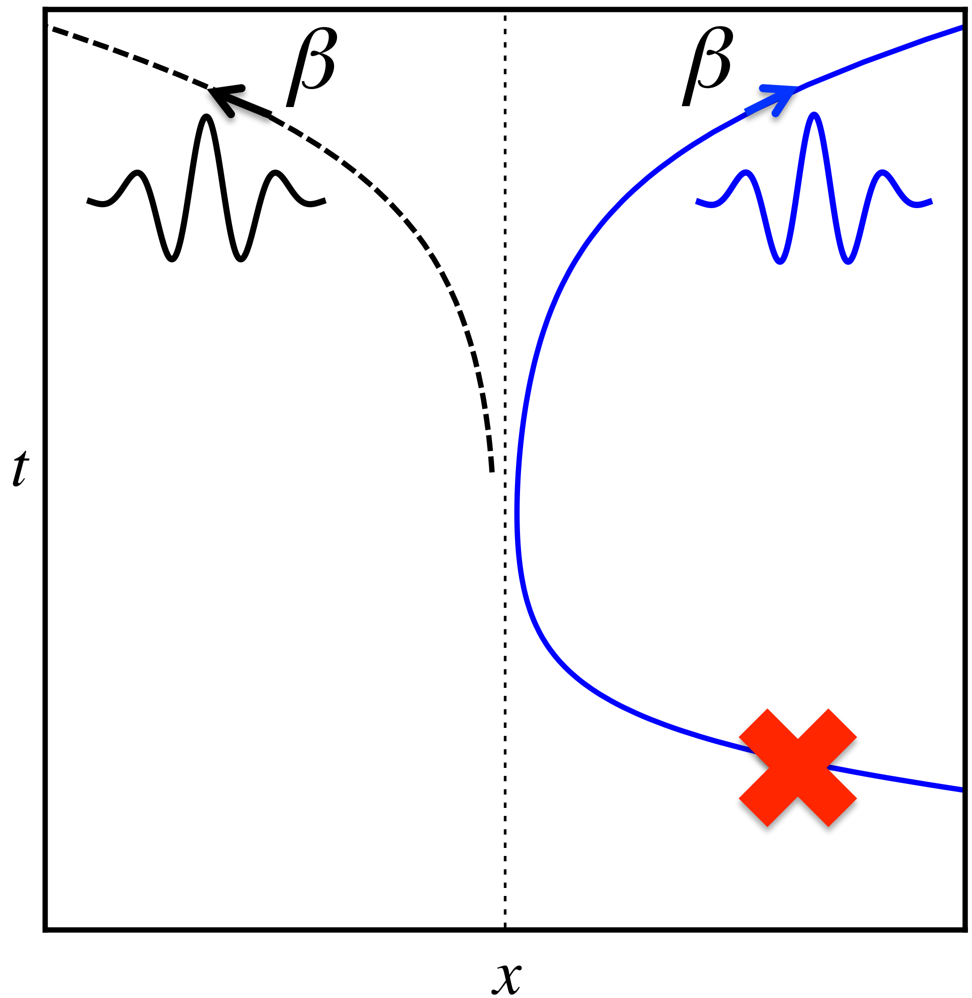
Hawking radiation

Mixing of positive- and negative-norm modes

→ Amplification of incident wave

→ Quantum noise when input is vacuum

Caves (1982, *PRD* **26**, 1817)



$$|\alpha|^2 - |\beta|^2 = 1$$

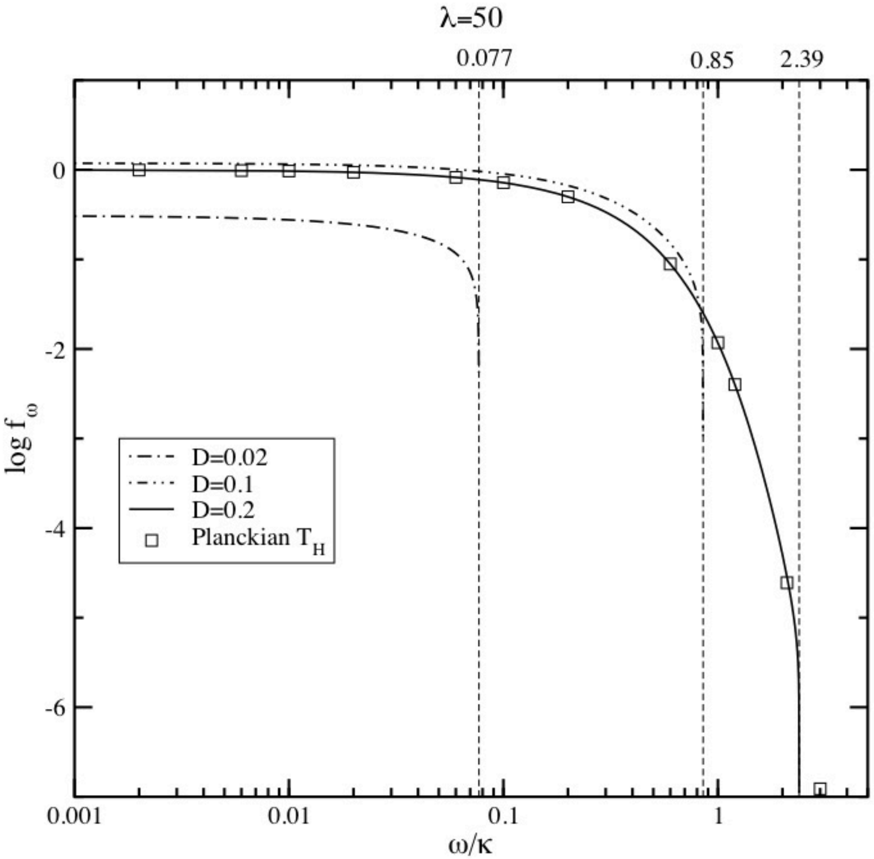
↓

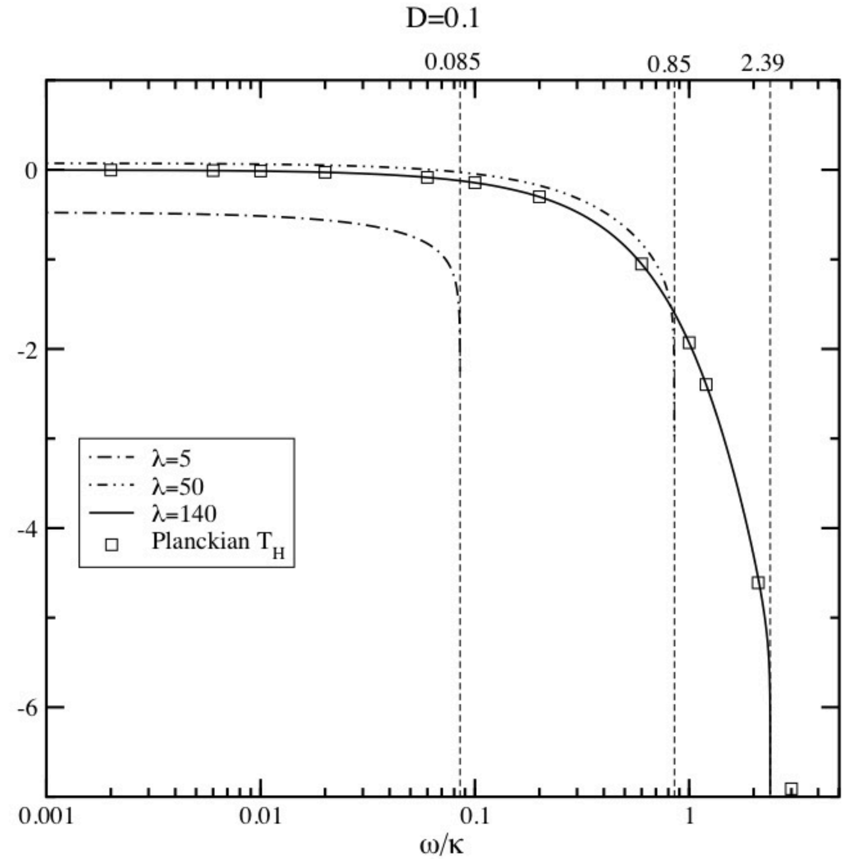
$$|\mathrm{vac}_{\mathrm{in}}\rangle \neq |\mathrm{vac}_{\mathrm{out}}\rangle$$

↓

Particle creation

Numerical results



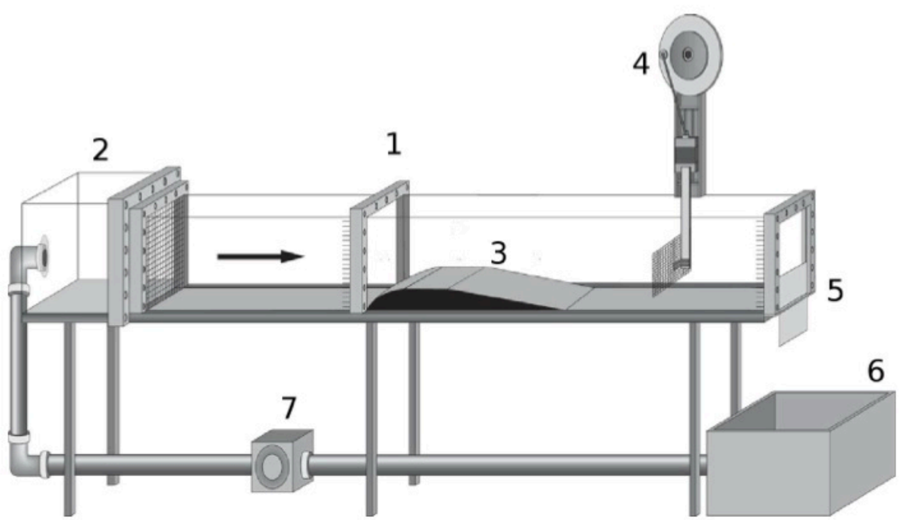


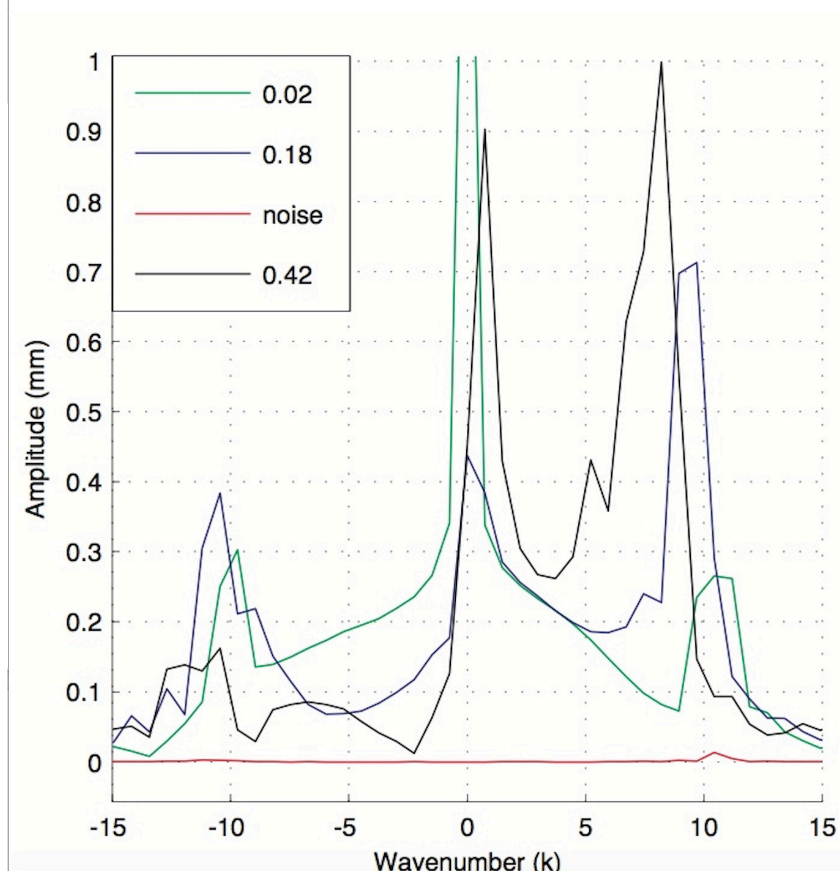
J. Macher and R. Parentani, *Phys. Rev. D* **79**, 124008 (2009)

Analogue models: Advantages

Stimulated Hawking effect

→ Can probe horizon with incident wave



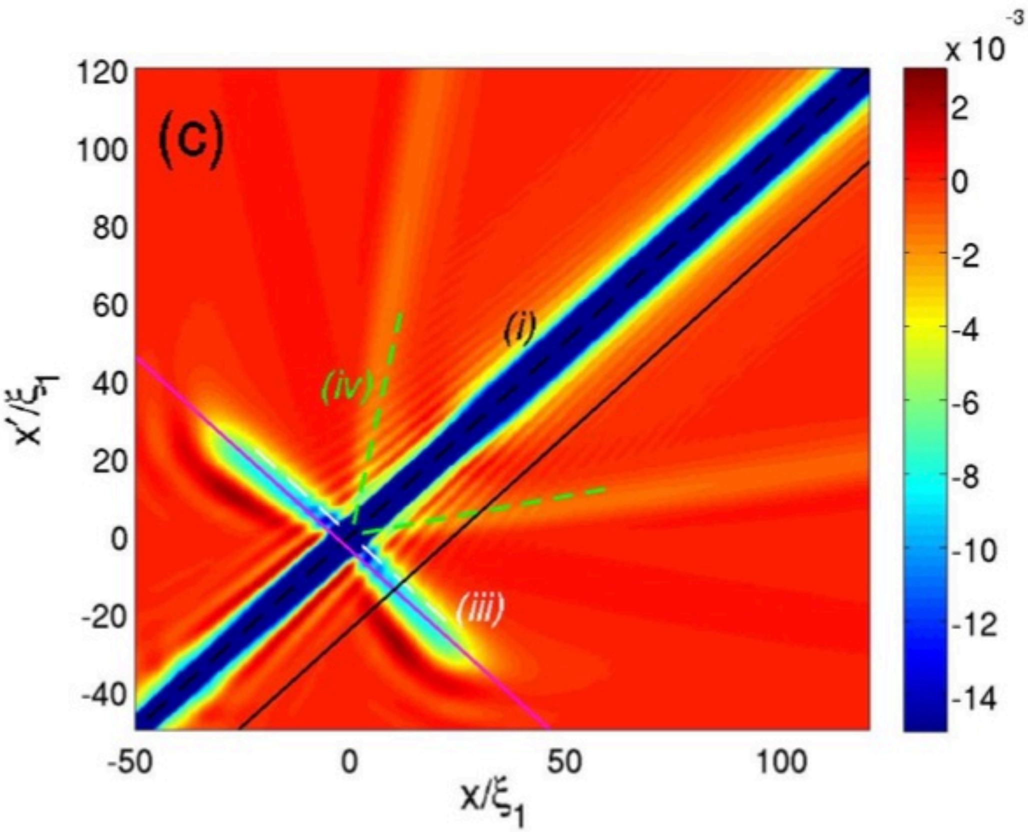


S. Weinfurtner *et al.*, *PRL* **106** 021302 (2011)

L.-P. Euvé *et al.*, arXiv:1409.3830 (2014)

Analogue models: Advantages

Access to both Hawking partners
→ Can measure correlations



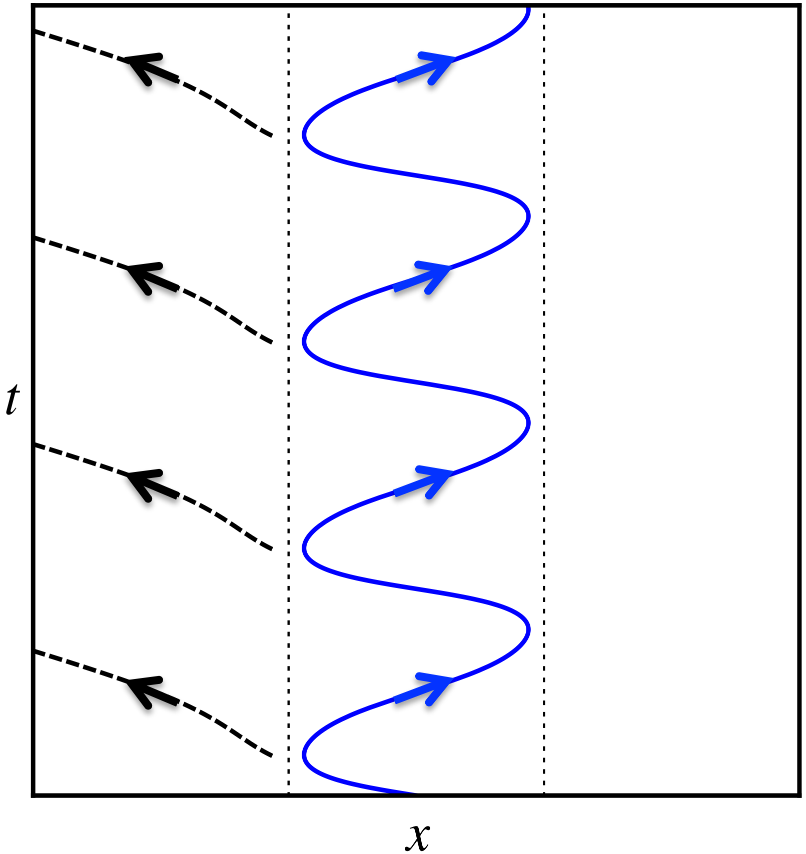
$$G^{(2)}(x,x') = \frac{\langle :n(x)n(x'):\rangle}{\langle n(x)\rangle\langle n(x')\rangle}$$

I. Carusotto *et al.*, *New J. Phys*. **10** 103001 (2008)

Analogue models: Advantages

Modes trapped between two horizons

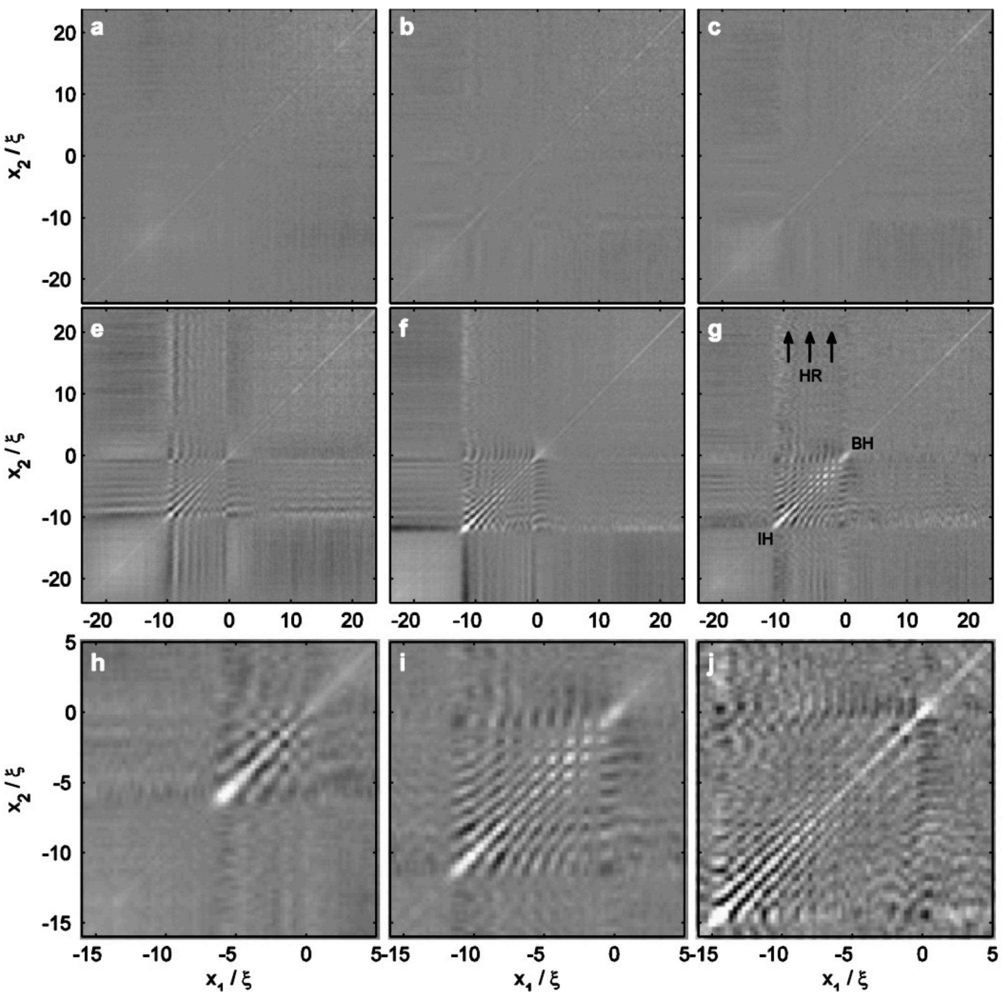
→ Leads to Black Hole Laser effect



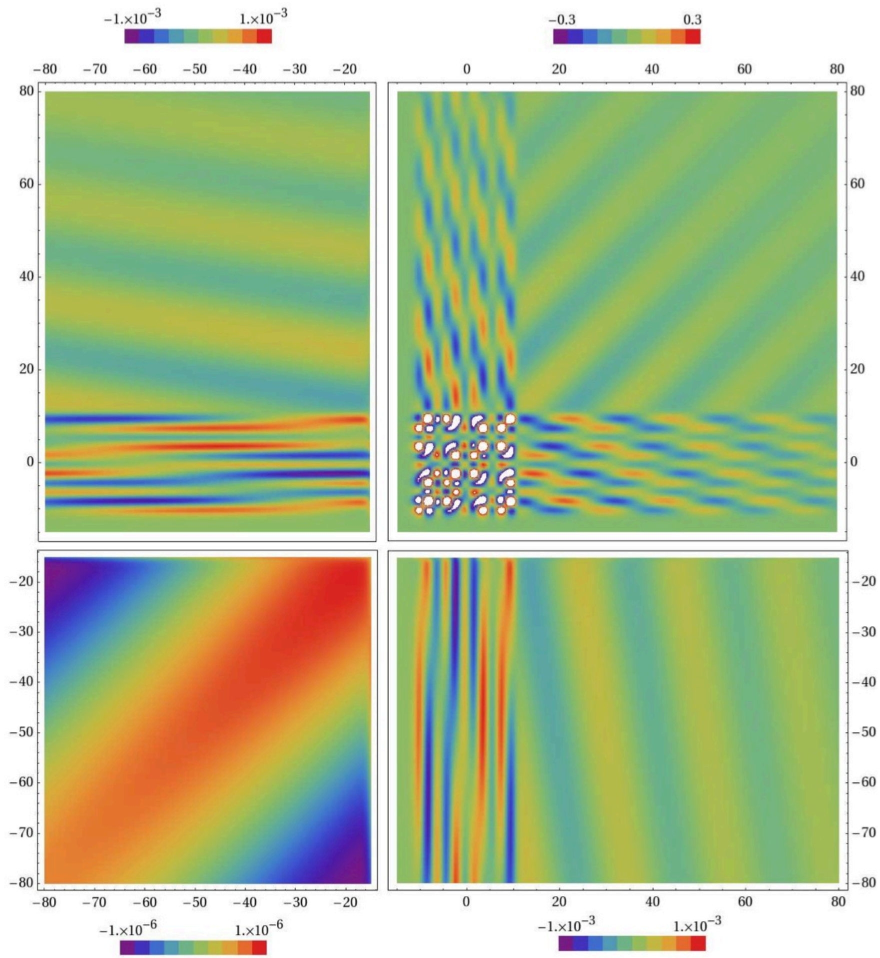
- S. Corley and T. Jacobson, *PRD* **59** 124001 (1999)
- U. Leonhardt and T. G. Philbin, arXiv:0803.0669 (2008)

Analogue models: Advantages

J. Steinhauer, *Nature Physics* **10**, 864 (2014)



S. Finazzi and R. Parentani,
New J. Phys. **12** 095015 (2010)



Summary

- Waves in moving media mimic fields in spacetime
  → Analogue black holes and Hawking radiation

- Short-distance physics modifies dispersion relation
  → Waves incident from infinity

- Black hole mixes positive- and negative-norm modes
  → Acts as an amplifier with HR as quantum noise

Advantages:

- Stimulated (classical) Hawking effect
- Correlations between partners measurable
- Laser effect can be exploited