Title: On the partner particles for black hole evaporation

Date: Aug 14, 2015 04:30 PM

URL: http://pirsa.org/15080037

Abstract: Due to the linearity of the field equations and the resulting bilinear structure of the Hamiltonian, quantum radiation effects such as black hole evaporation or particle creation in an expanding universe are typically described as (squeezing) processes where particles are created in pairs.
Here, we address the following question: given a mode (e.g., wave-packet) corresponding to a created particle (e.g., as part of Hawking radiation), what is its partner, i.e., the other particle of the pair?
After a general derivation of this partner mode, we will discuss some examples such as moving mirror radiation and speculate about possible implications for the black hole information puzzle.

On the partner particles for black-hole evaporation

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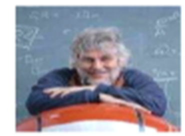
Quantum Radiation

Relativistic quantum fields ($\hbar, c$) in vacuum state $|0\rangle_{\text{in}}$

- Hawking radiation
  $\longrightarrow$ gravitational field

- Sauter-Schwinger effect
  $\longrightarrow$ electric field

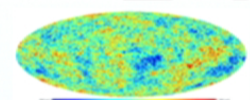
- Unruh radiation
  $\longrightarrow$ acceleration



- Dynamical Casimir effect
  $\longrightarrow$ mirror motion

- Cosmological particle creation
  $\longrightarrow$ expansion

"Particles are created in pairs"



Squeezing

Bogoliubov transformation (linear)

$$\hat{a}_k^{\rm out} = \int dk' \, \alpha^*_{kk'} \hat{a}^{\rm in}_{k'} + \int dk' \, \beta_{kk'} \left(\hat{a}^{\rm in}_{k'}\right)^\dagger$$

Time evolution for bi-linear Hamiltonian

$$\hat{U} = \mathfrak{T}\left[\exp\left\{-i \int dt \, \hat{H}(t)\right\}\right]$$

Generalized squeezing operation

$$|0\rangle_{\rm in} = \exp\left\{\int dk \, dk' \, \xi_{kk'} \left(\hat{a}_k^{\rm out}\right)^\dagger \left(\hat{a}_{k'}^{\rm out}\right)^\dagger - \text{h.c.}\right\} |0\rangle_{\rm out}$$

Creation of particles $\langle 0| \, \hat{n}_k^{\rm out} \, |0\rangle_{\rm in} \neq 0$ in pairs

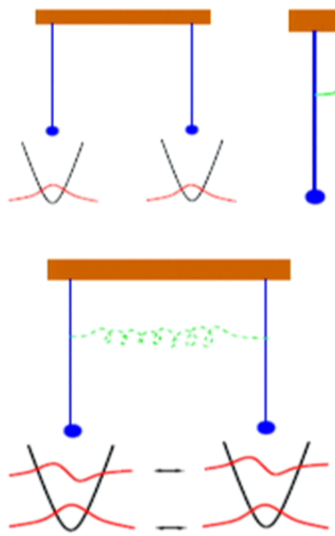
$$|0\rangle_{\rm in} = |0\rangle_{\rm out} + \int dk \, dk' \, \xi_{kk'} \, |k, k'\rangle_{\rm out} + \ldots$$

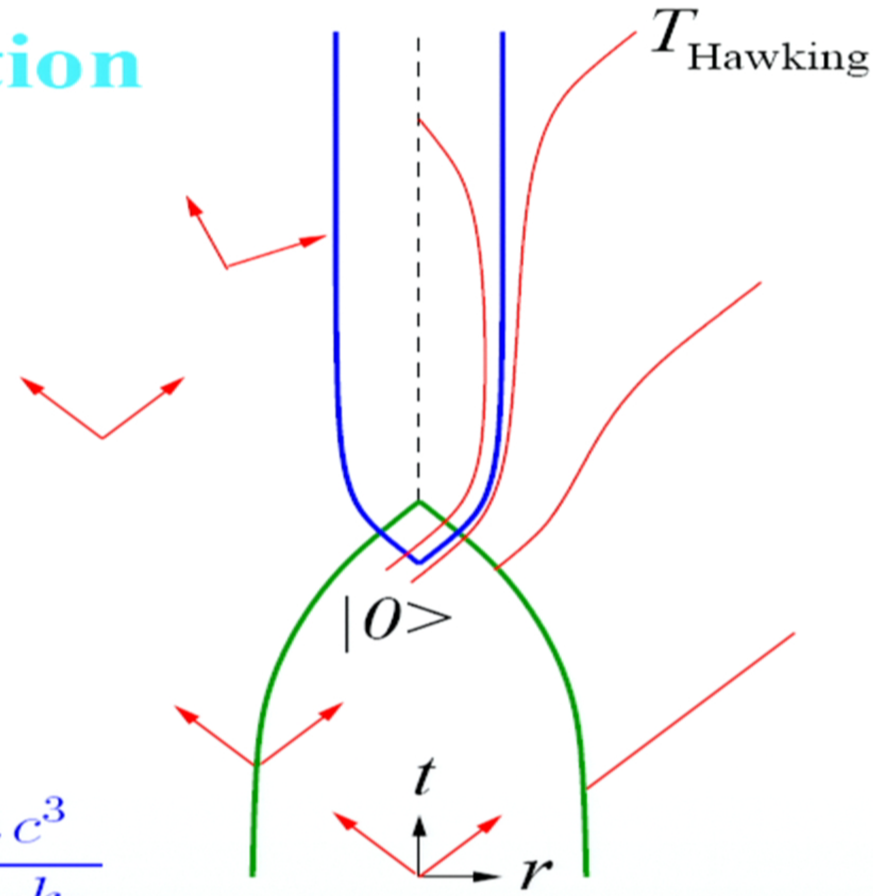
Note: asymptotics. . .

Hawking Radiation

S. W. Hawking, Nature **248**, 30 (1974);

Comm. Math. Phys. **43**, 199 (1975).





$$T_{\text{Hawking}} = \frac{1}{8\pi M}\frac{\hbar\, c^3}{G_{\text{N}} k_{\text{B}}}$$

But: trans-Plankian problem, information puzzle etc.

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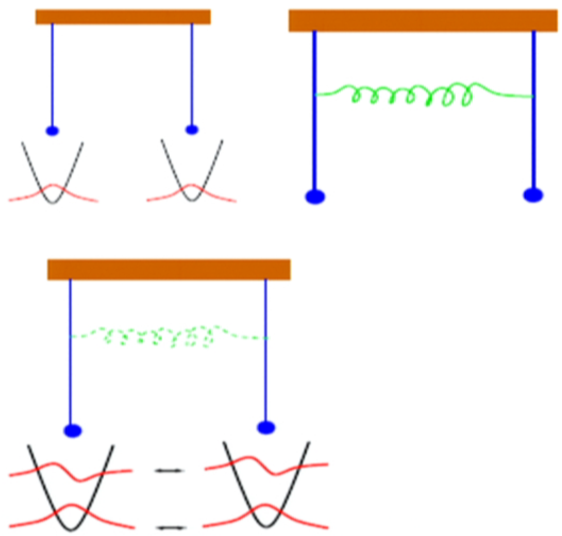

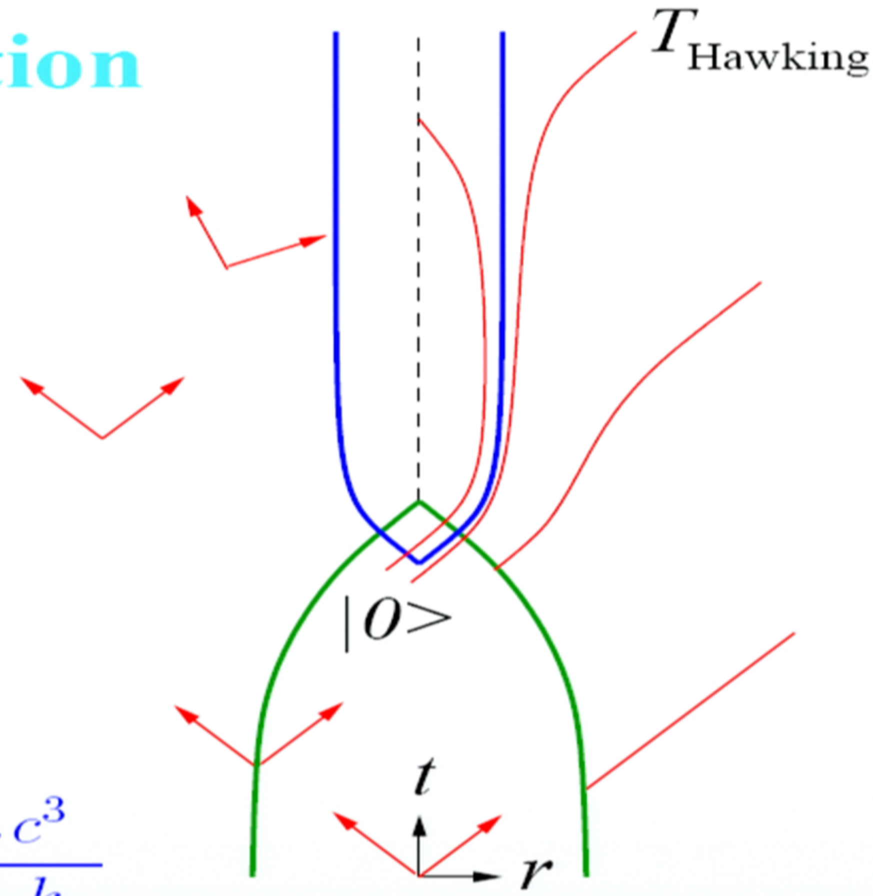

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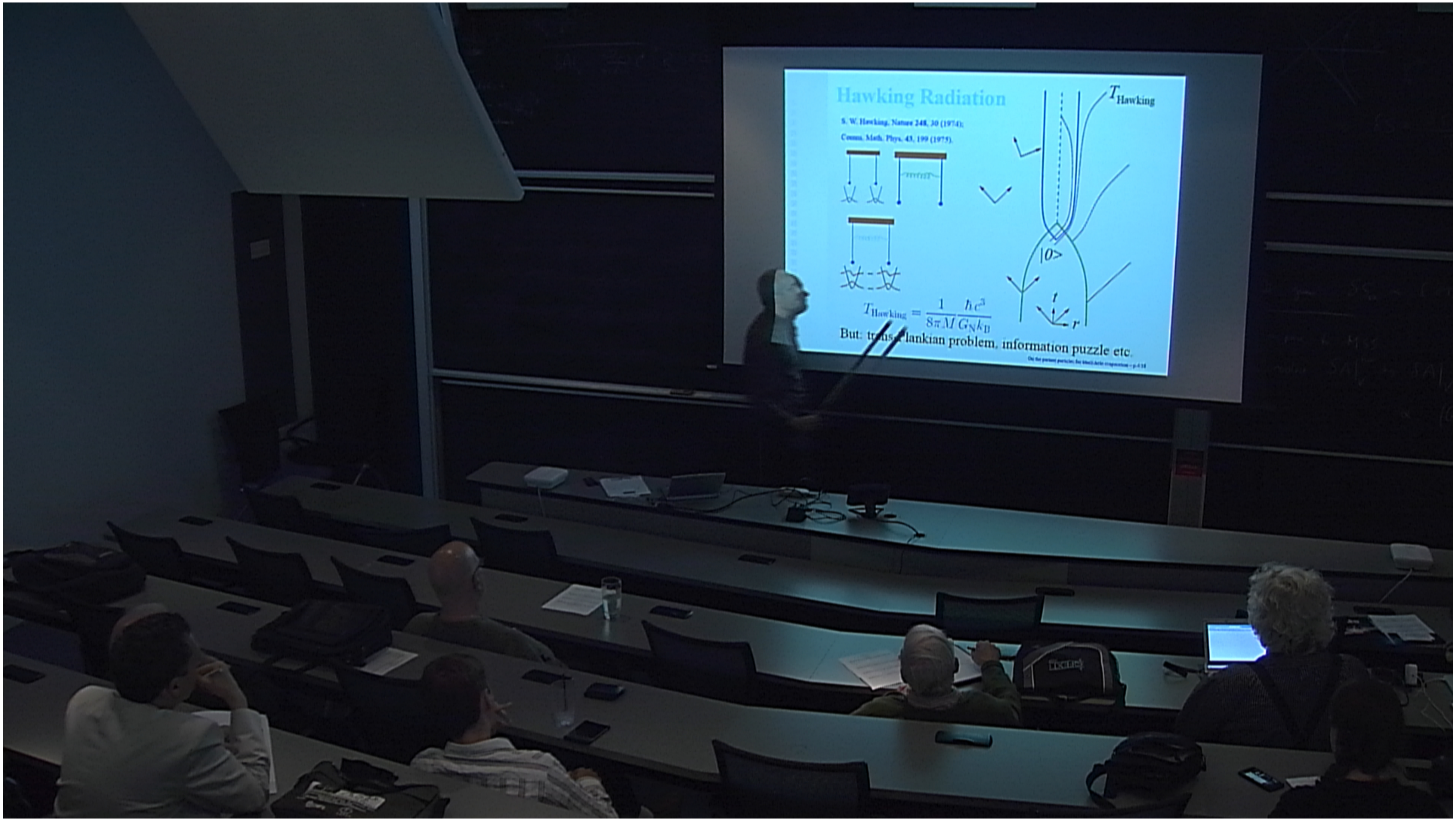
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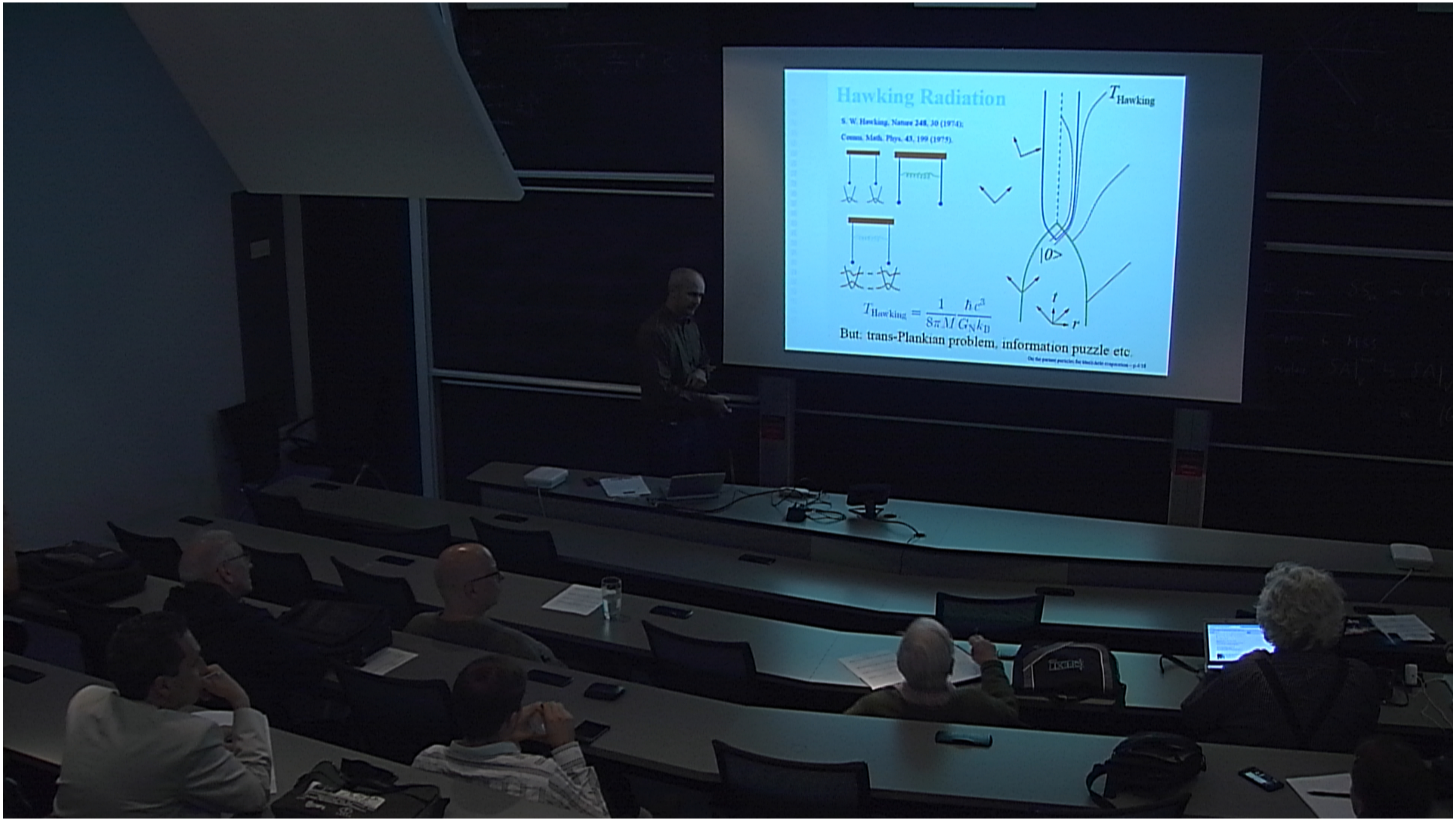
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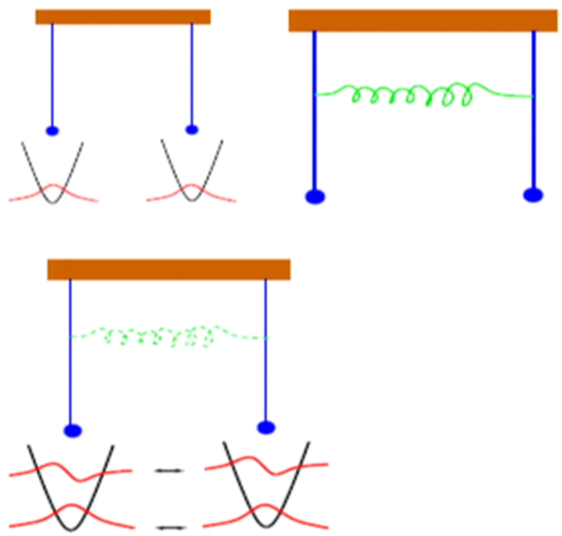

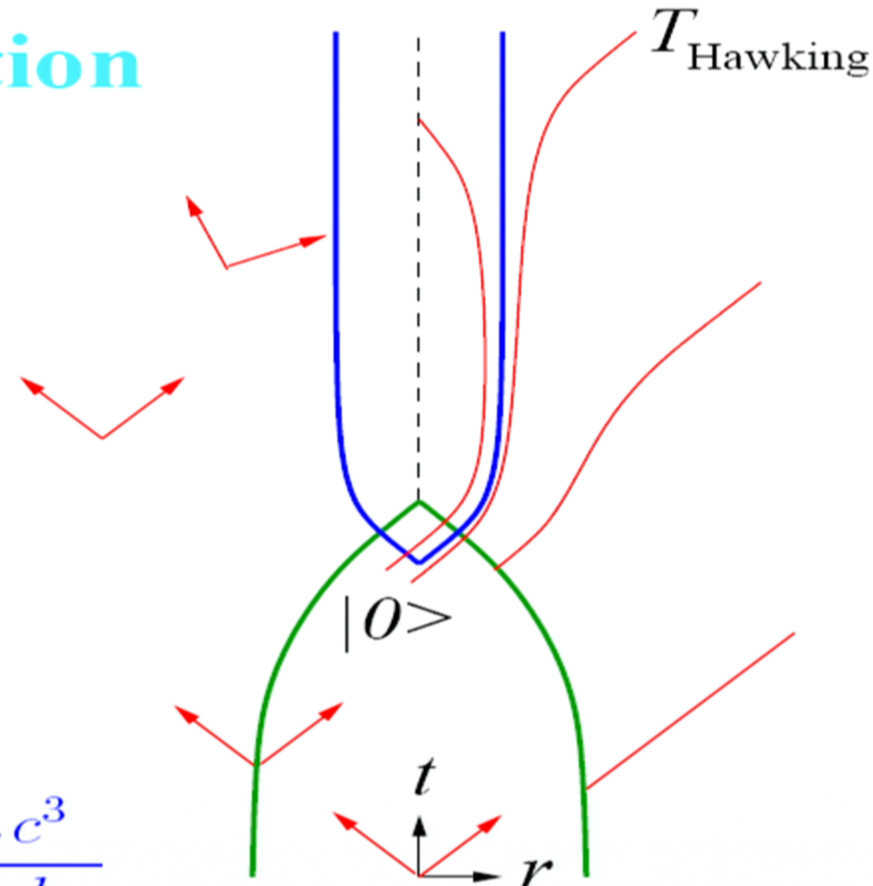

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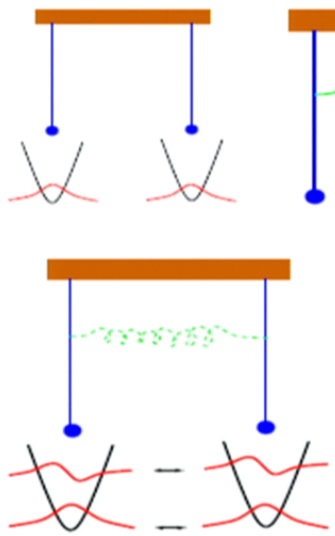

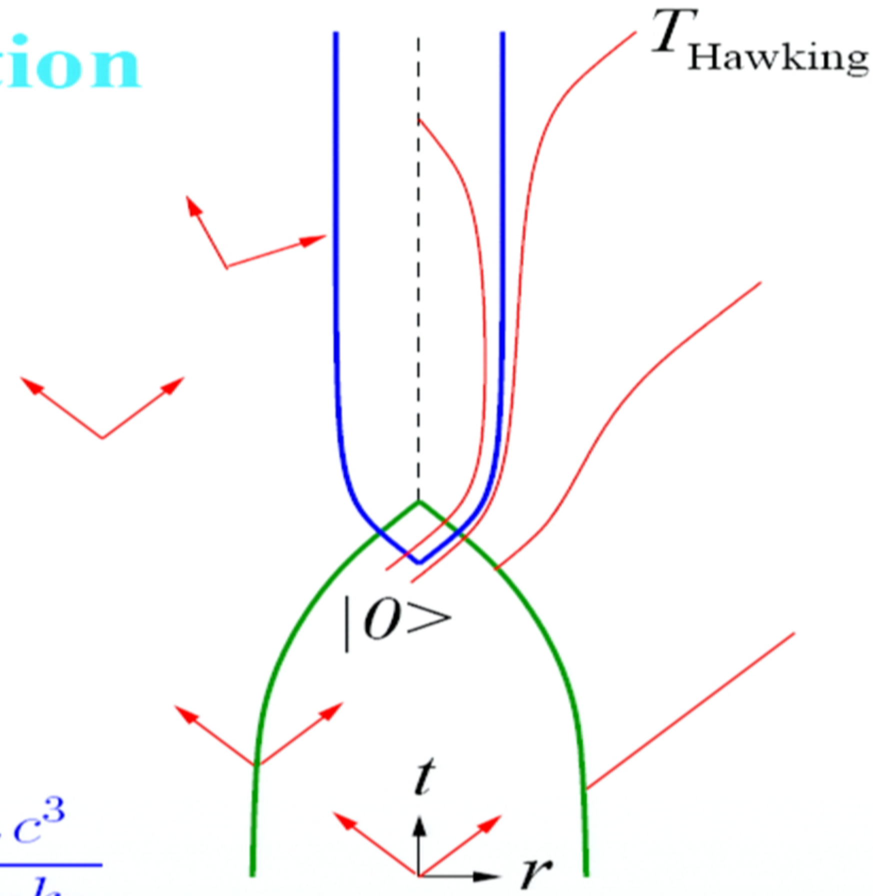

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Moving Mirror in 1+1 D

Toy model for black hole evaporation: accelerated mirror with

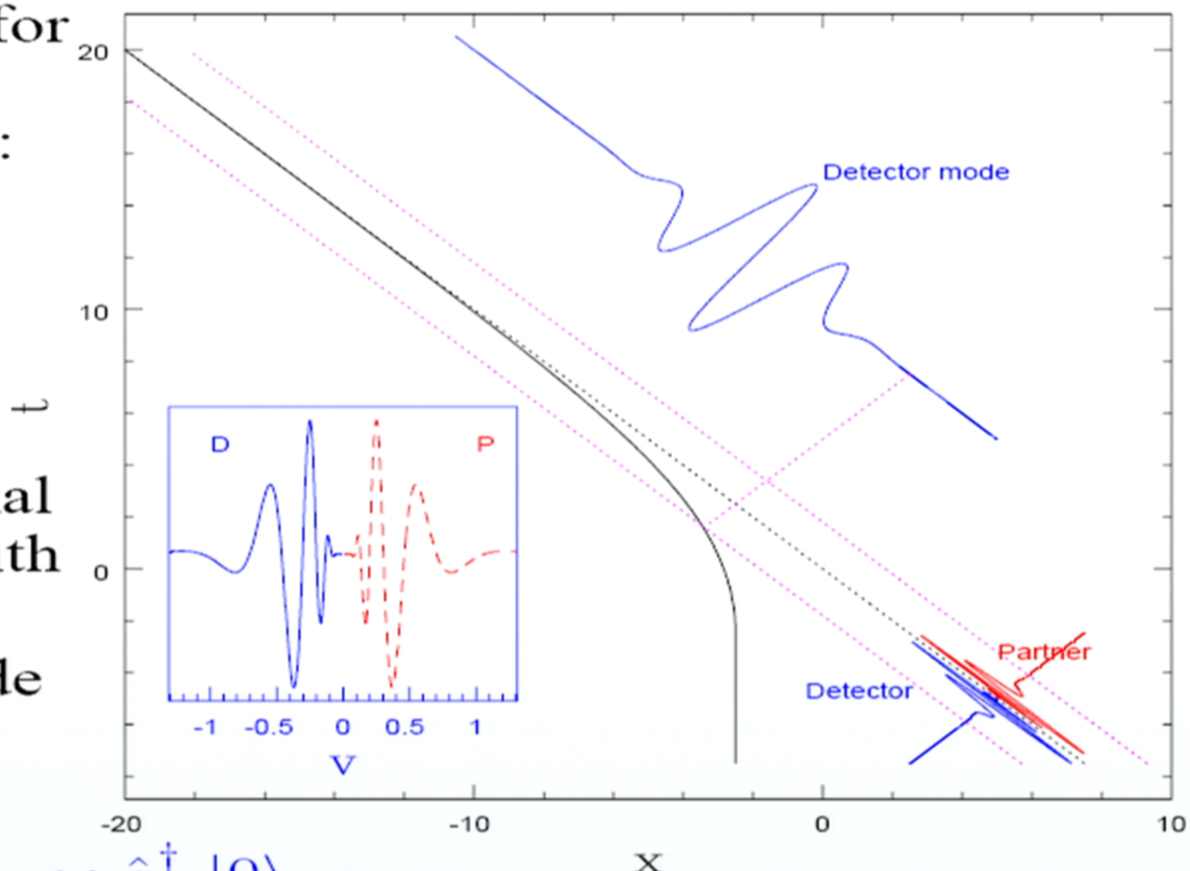
$v = -\frac{e^{-\kappa u}}{\kappa}$

$v = t + x$

$u = t - x$

emits thermal radiation with $T = \frac{\kappa}{2\pi}$

Partner mode in local vacuum!



But: $\hat{a}_{\mathrm{H}} \left|0\right\rangle_{\mathrm{in}} \propto \hat{a}^{\dagger}_{\mathrm{P}} \left|0\right\rangle_{\mathrm{in}}$

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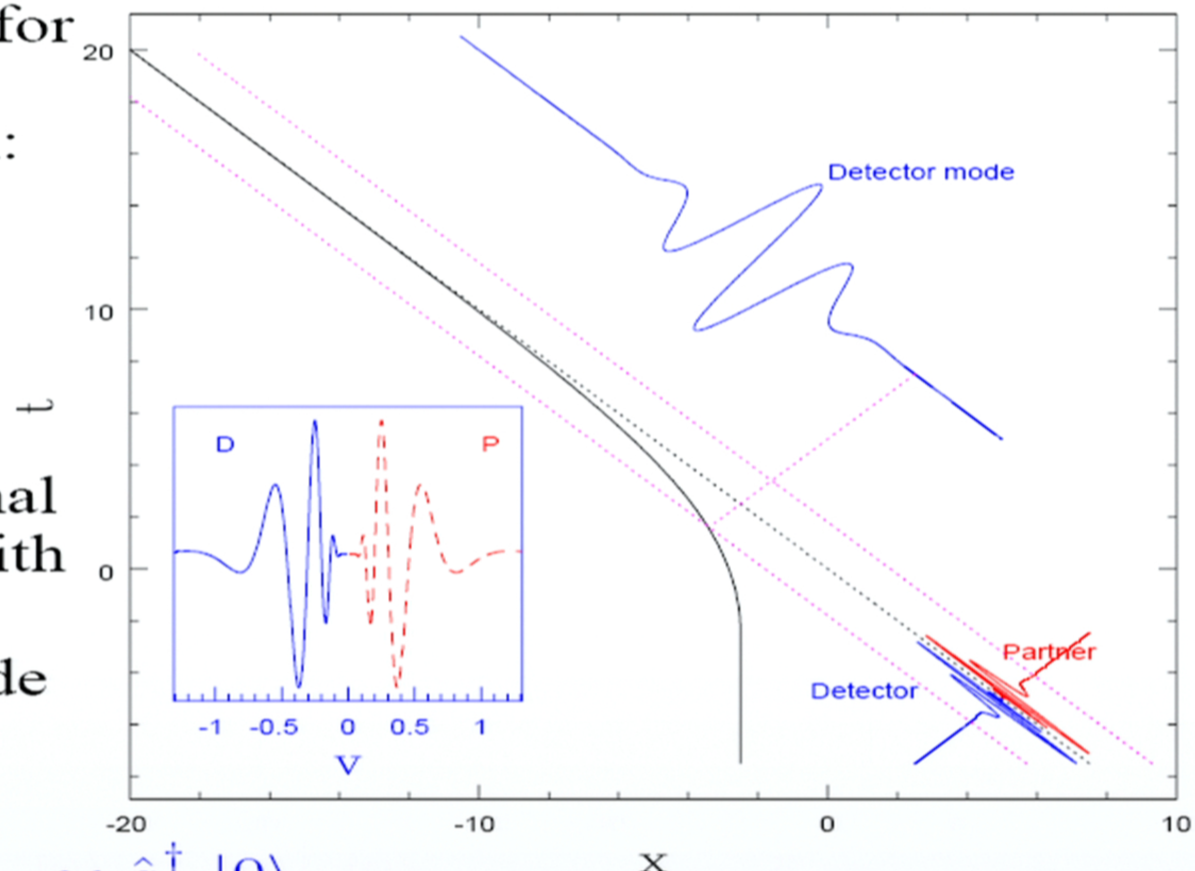

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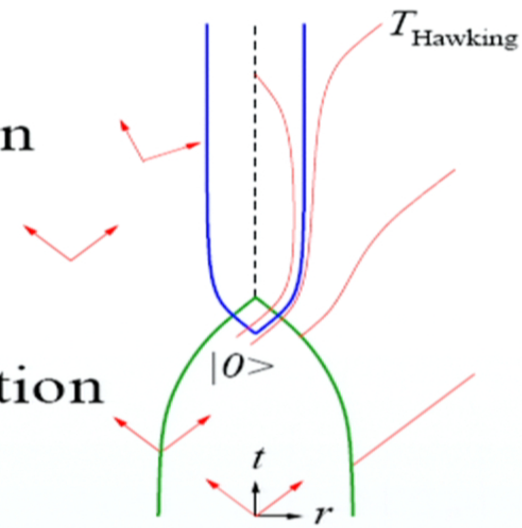
Black Hole Information Puzzle

Is black hole formation $\longrightarrow$ evaporation unitary?

- regularity near horizon ($\longleftrightarrow$ firewall etc.)
- correlations between Hawking particles and vacuum fluctuations falling towards singularity
  - a) information is lost
    $\longrightarrow$ "non-unitarity"?
  - b) singularity stores information
    $\longrightarrow$ black-hole entropy?
    $\longrightarrow$ simple picture:
    one qubit per ℓ^3_{Planck}?
  - c) singularity re-emits information
    $\longrightarrow$ causal structure?
- information $\neq$ energy



Energy vs Entropy...

Toy model: N independent qubits

Ground state: $|0\rangle = |\downarrow\downarrow\downarrow\downarrow \ldots\rangle$

Flip $n \ll N$ qubits with probability $p \lll 1$

Number of permutations (possible states)

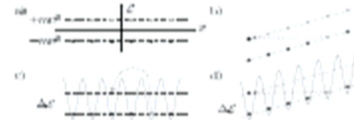
$$\langle E \rangle = p \begin{pmatrix} N \\ n \end{pmatrix} \times \mathcal{O}(n)$$

Entropy of state $\hat{\varrho}$ with $\langle 0 | \hat{\varrho} | 0 \rangle \approx 1$

$$\frac{S}{\langle E \rangle} = \mathcal{O}(\ln N)$$

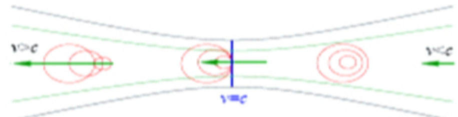
Number N of qubits??? (per volume???)

Laboratory Analogues

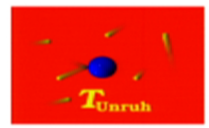


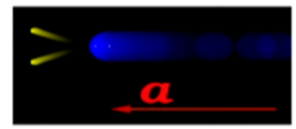

- Sauter-Schwinger effect
  $\longrightarrow$ atoms in optical lattices

  F. Queisser, P. Navez, R. S., Phys. Rev. A **85**, 033625 (2012).




- Hawking radiation
  $\longrightarrow$ trans-sonic fluids



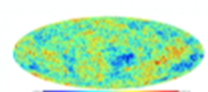
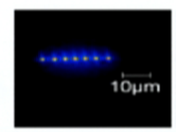


- Unruh effect
  $\longrightarrow$ electrons in lasers

  R. S., G. Schaller, D. Habs, Phys. Rev. Lett. **97**, 121302 (2006); ibid. **100**, 091301 (2008).

- Dynamical Casimir effect
  $\longrightarrow$ wave-guides C.M. Wilson *et al*, Nature **479**, 376 (2011).

  M.Uhlmann, G.Plunien, R.S., G.Soff, Phys. Rev. Lett. **93**, 193601 (2004).

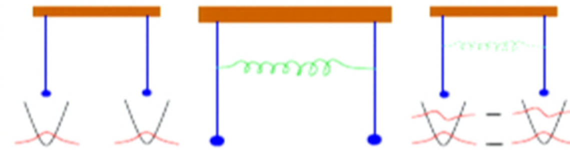
- cosmological particle creation
  $\longrightarrow$ ion traps, condensates

  R. S. *et al.*, Phys. Rev. Lett. **99**, 201301 (2007).
  P.M.Alsing, J.P.Dowling, G.J.Milburn, ibid. **94**, 220401 (2005).

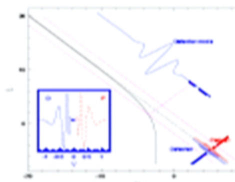
Summary

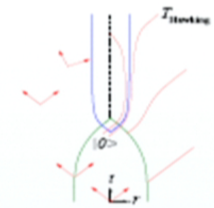
M.Hotta, R.S., W.G.Unruh, Phys. Rev. D **91**, 124060 (2015).

- quantum radiation: “particles in pairs”

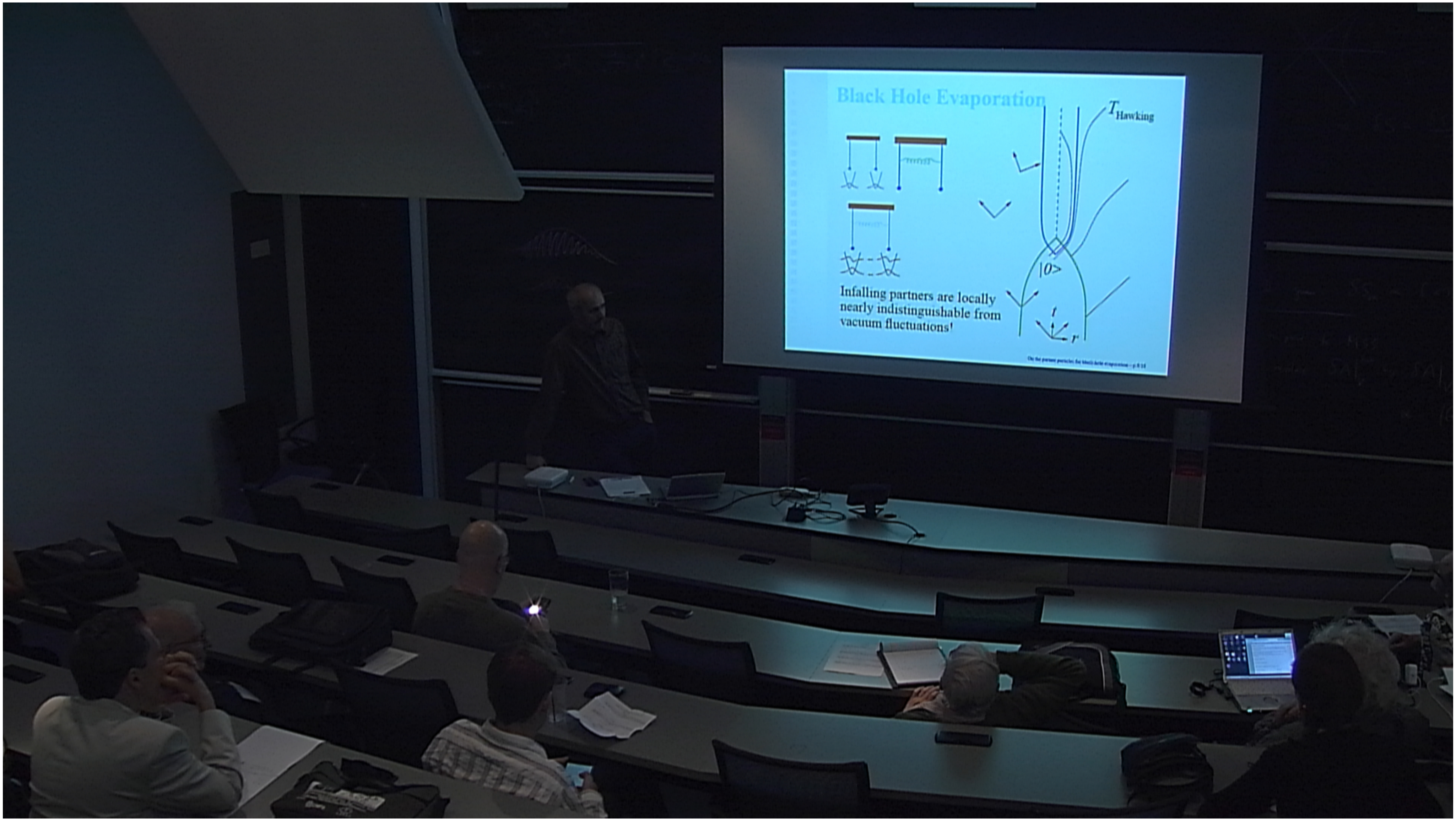


- determination of partner “particle”
- moving mirror and black hole
- partners ≈ vacuum fluctuations
- information ≠ energy
- black hole information puzzle
- laboratory analogues





. . . and Best Wishes


Black Hole Evaporation
THawking
|0>
Infalling partners are locally nearly indistinguishable from vacuum fluctuations!
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