Testing Hawking particle creation by black holes through correlation measurements

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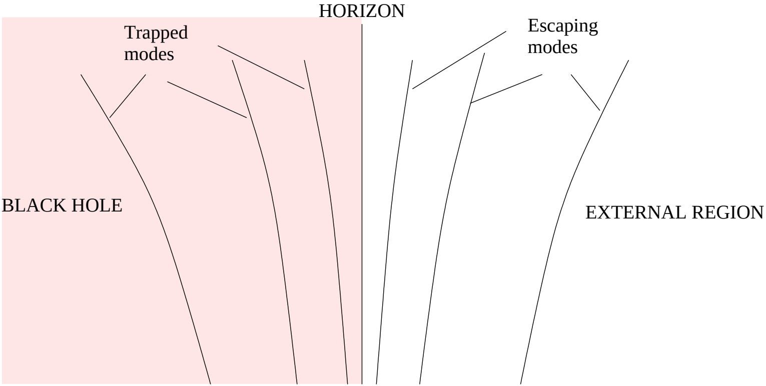
Black Holes

Our understanding of black holes is in the context of gravity

- Mitchell (1784) and Laplace (1795) predicted the existence of newtonian dark stars, compact objects with an escape velocity $\geq c$ (and size $r \leq \frac{2GM}{c^2} \equiv r_G$)
- A general relativistic treatment of light propagation in a gravitational field excludes the existence of dark stars, but confirms the crucial role played by $r = r_G$, the event horizon, separating two causally disconnected regions: the exterior (EXT) and the black hole (BH)

Horizons

The typical feature of horizons that we will use is here described:



The future history of two nearby outgoing light rays initially situated on both sides of the horizon takes them completely apart

Hawking radiation

Black holes are not 'black' when quantum mechanics is taken into account

- The initial vacuum state $|0\rangle_{in}$ of a quantum field in the dynamical background of a collapsing star forming a black hole appears at late times, after horizon formation, as

$$|0\rangle_{in} \propto \exp\Big(\sum_{\omega} e^{-\frac{\pi c \omega}{\kappa_B \kappa}} a_{\omega}^{\dagger(ext)} a_{\omega}^{\dagger(bh)}\Big)|0\rangle_{ext} \otimes |0\rangle_{bh} \ , \qquad (1)$$

  where κ ($= c^4/4GM$ for Schwarzschild) is the horizon's surface gravity.
- Hawking '74: In the exterior region, where the BH degrees of freedom are integrated out, one finds that the black hole behaves as a blackbody emitting thermal radiation at the temperature

$$T_{\rm H} = \frac{\hbar \kappa}{2\pi k_B c} \ . \qquad (2)$$

Experimental detection

Can we observe Hawking radiation??

- In the universe, unfortunately, many orders of magnitude separate T_H ($\sim 10^{-7}\ K$ for a solar mass bh) and T_{CMB}
- No observational evidence, so far, of an excess X-ray radiation due to mini bhs ($10^{15}\ gr$) formed in the early universe (Carr '75)
- Planck scale might be lowered down to the TeV due to extra dimensions, allowing the formation of minibhs at LHC (Arkani-Hamed, Dimopoulos, Dvali '98; Randall and Sundrum '99; ...)

Unruh's breakthrough

Hawking radiation in condensed matter systems

- The Hawking effect is kinematical, i.e. it just depends on the details of mode propagation in a black-hole like geometry, and not on the underlying dynamics
- In '81 Unruh used the mathematical equivalence (gravitational analogy)

  scalar field in a curved spacetime $\leftrightarrow$ sound in inhomogeneous eulerian fluids

  and predicted the production of a thermal flux of phonons (analog Hawking radiation) whenever an acoustic horizon forms

Does Hawking radiation really exist?

The transplanckian problem

- Jacobson '91: Hawking and Unruh analysis seem to rely on the propagation of very short wavelength modes (subplanckian and smaller than the intermolecular distance) in the horizon region
- In gravity we do not know how to properly deal with this problem, but in the fluid case a microscopic description of the system is often available
- In this context we can then investigate the existence of Hawking radiation at a fundamental level and test the theoretical predictions in the lab

Bose-Einstein condensates

The case for BECS (1)

- Among the many systems proposed (Jacobson and Volovik '98; Giovanazzi '05; Leonhardt and Piwnicki '00; Unruh and Schutzhold '05; Rousseaux, Mathis, Maissa, Philbin and Leonhardt '08), acoustic black holes realised in atomic BECs appear particularly attractive (Garay, Cirac, Anglin, Zoller '00)
- The huge difference between T_H and that of the background can be here dramatically reduced (Barcelo, Liberati and Visser '03)
- Still, it is difficult to separate the Hawking-Unruh flux from the thermal phonons at temperature T_C $(> T_H)$

Hawking radiation in correlations

An alternative signature

- In the Hawking effect particles are created in pairs, one reaching infinity (Hawking quanta) and the other trapped inside the black hole (the partner) (Brout, Massar, Parentani, Spindel '95)
- The initial vacuum state $|0\rangle_{in}$ contains local correlations which are transferred, in the course of the time evolution, to nonlocal correlations between the BH and EXT regions: these have a typical form that characterizes the Hawking effect
- Unlike in gravity, in condensed matter systems the acoustic nature of the horizon does not forbid correlation measurements of this type

The case for BECs (2)

Balbinot, Fabbri, Fagnocchi, Recati, Carusotto '08: Our proposal

- We consider a one-dimensional condensate with constant density n and velocity v (< 0), the only nontrivial quantity being the speed of sound c
- c is tuned in such a way that for $x > 0$ the condensate is subsonic $(c_r > |v|)$, while it is supersonic for $x < 0$ $(c_l < |v|)$. This realizes an acoustic black hole, with horizon at $x = 0$ and surface gravity $\kappa = c\frac{dc}{dx}|_{x=0}$
- The one-time density-density correlations between the BH $(x < 0)$ and EXT $(x' > 0)$ regions are easily calculated in the hydrodynamic approximation:

$$G^{(2)} \simeq \frac{\kappa^2 \xi_l \xi_r}{16\pi c_l c_r \sqrt{(n\xi_l)(n\xi_r)}} \frac{c_r c_l}{(c_l + v)(v + c_r)} \cosh^{-2}[\frac{\kappa}{2}(\frac{x}{c_l + v} - \frac{x'}{v + c_r})] , \tag{3}$$

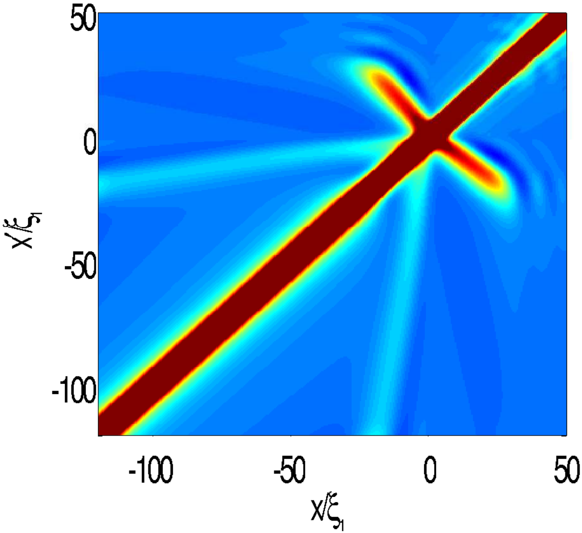
whose stationary peak identifies pairs of quanta created just inside and just outside the horizon and traveling in opposite directions

Hawking radiation in atomic BECs

An ‘ab initio’ calculation

Carusotto, Fagnocchi, Recati, Balbinot, Fabbri ’08: Numerical observation

- A numerical analysis with the full microscopic theory confirms the presence of the Hawking peak: this is the first proof of the existence of Hawking radiation
- When the scale of variation of c is sufficiently larger than the healing length ξ the quantitative comparison with the hydrodynamic prediction is excellent
- The effect is still present and clearly visible (actually, strengthened) in the presence of a thermal background with $T > T_H$
- Inserting numbers for realistic experiments one anticipates correlations of order 10^{-3}, not far from the sensitivity of actual experiments, that could be amplified (Cornell ’09)


50
0
-50
-100
x'/ξ1
-100
-50
0
50
x/ξ1

Final comments

- Density correlation measurements are the most promising way for an experimental verification of the Hawking-Unruh effect in the near future
- Our results make us confident that Hawking radiation exists in gravity as well, and that the semiclassical results are valid up to scales of the order of the Planck length
- Provided black holes evaporate according to unitary rules, we may be able to measure peculiar correlations between particle emitted at early and late times for instance from minibhs at LHC...