Curved space-times in condensed matter physics: from the dynamical Casimir effect in vibrating cavities to Hawking radiation from acoustic black holes

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The collaboration

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gravitational physics
cosmology

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Experimental partners

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expts of acoustic HR in
atomic BECs

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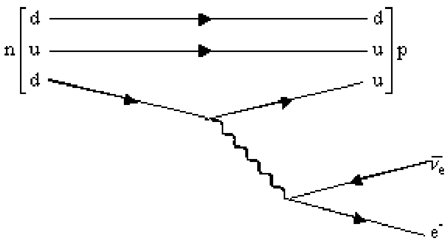
A. Bramati, E. Giacobino
expts of acoustic HR
in exciton-polariton BECs

UAM Madrid
L. Viña, C Tejedor
expts of acoustic HR
in exciton-polariton BECs

Intro - Quantum fields on curved space-times

what is an elementary particle?

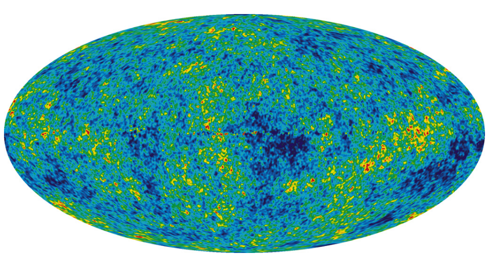


Inertial Lorentzian frames, flat space-time:

- free propagation conserves particle number
- particles only created by some interaction (e.m, weak, strong...)

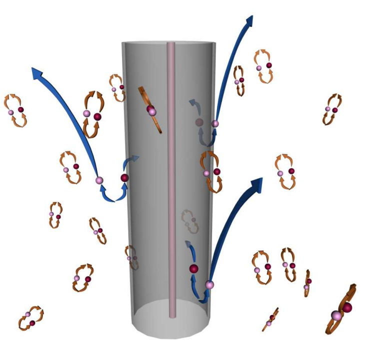
Non-inertial, accelerated frames:

- Unruh effect: accelerated observer observes a temperature $T = h\ a / c\ k_B$

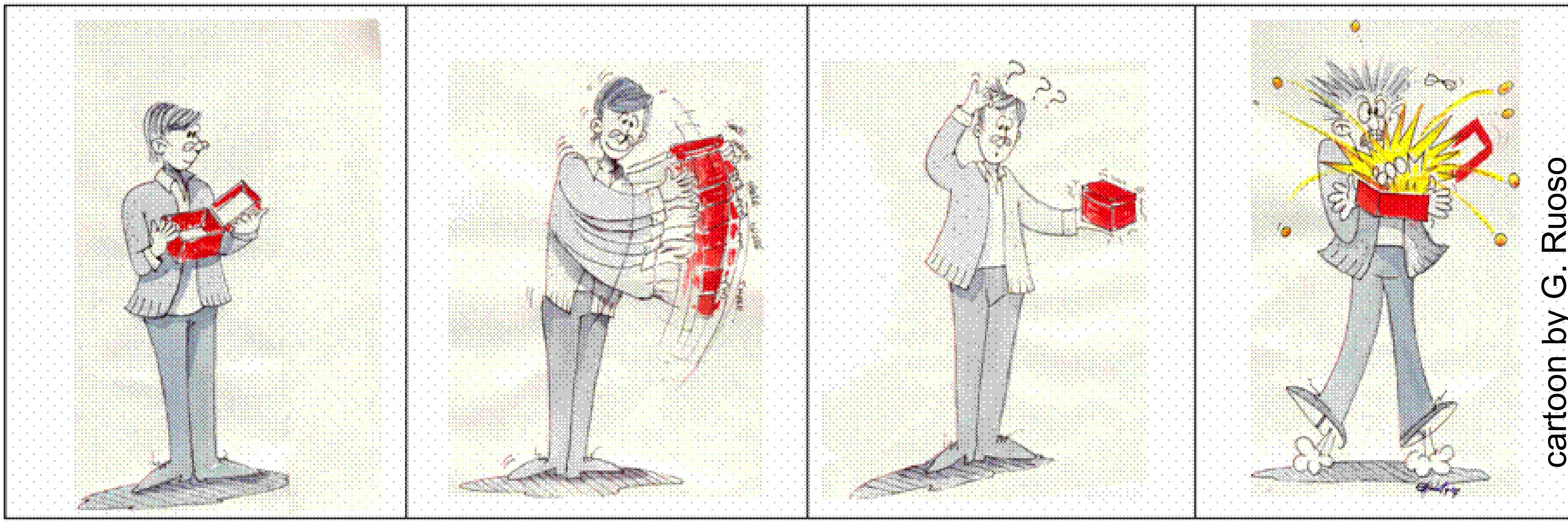


Curved or time-dependent space-time:

- creation of particles off the quantum vacuum
- time-dependent boundary condition: dynamical Casimir effect
- amplification of quantum fluctuations during cosmological inflation, seed for large scale structure of universe
- Hawking radiation from black holes



1 - The dynamical Casimir effect

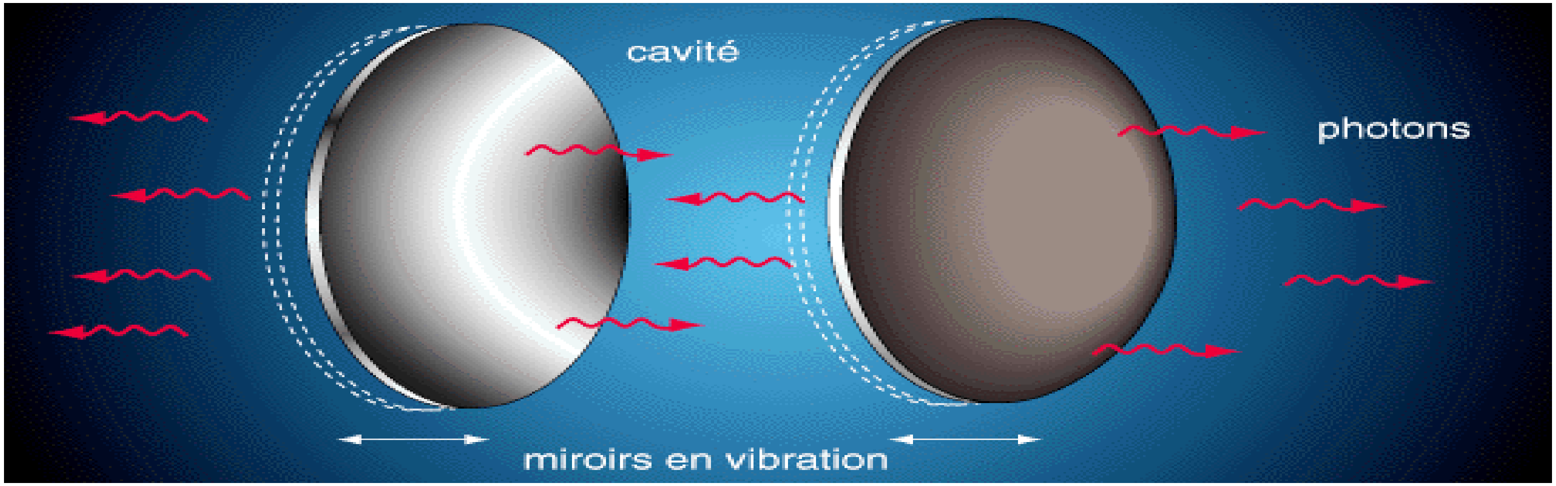


Take an optical cavity
in the e.m. vacuum state

Mechanically shake it
very fast

Beware when you open it again:
(a few) photons may burn you !!

Why experimentally so challenging ?



- Mirrors have to be shaken at twice the cavity frequency
- Hard to do by mechanical motion, even in rf domain
- Hard to distinguish from (parametrically amplified) thermal radiation

Our point of view

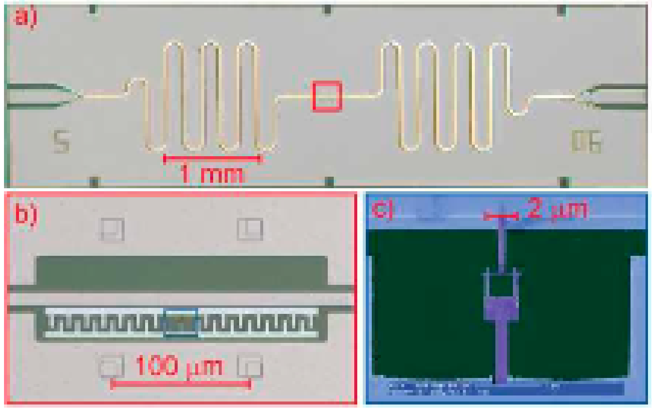
Identify and characterise a simple system that:

- allows for high-frequency modulation of cavity optical length
- coherent modulation to avoid heating and thermal radiation
- intrinsic optical nonlinearity to isolate quantum vacuum radiation

Several candidates :

- ultracold atoms in Mott insulator state in a EIT regime
  (IC, M. Antezza, F. Bariani, S. De Liberato, C. Ciuti, PRA 2008)
- doped quantum wells in semiconductor microcavities
  (S. De Liberato, IC, C. Ciuti, PRA 2005, PRL 2006, PRA 2006)
- Cooper-pair boxes in superconducting strip-line cavities
  (S. De Liberato, D. Gerace, IC, C. Ciuti, to appear)

A candidate (among others)



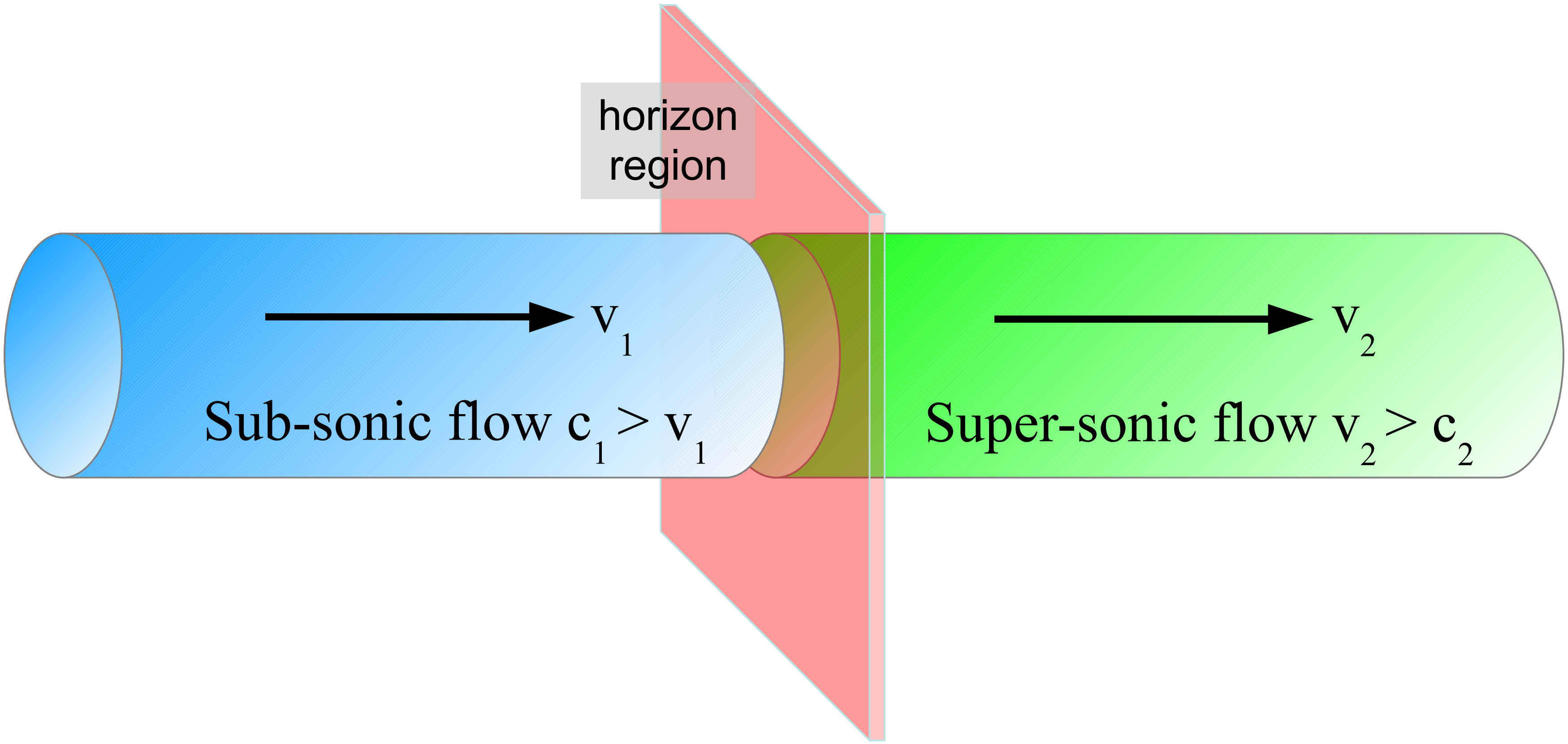
Superconductor Cooper-pair box in microwave stripline cavity :

- Ultra-strong light-matter coupling: quantum vacuum state deformed. Contains finite number of bound photons
- Non-adiabatic modulation releases these photons

- Modulation of optical length via frequency and/or light-matter coupling modulation demonstrated at microwave frequency
- Two level emitter easily saturated: vacuum radiation spectrally isolated

S. De Liberato, D. Gerace, I. Carusotto, C. Ciuti, to appear

2 - Analog Hawking radiation from acoustic black holes



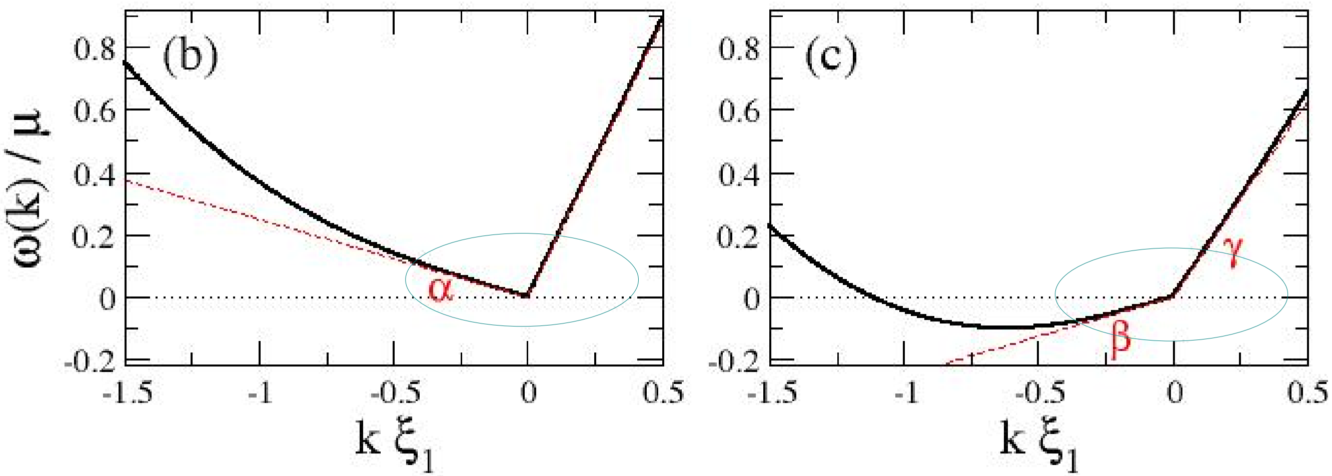
Steady but non-uniform flow

Horizon separates region of sub-sonic and super-sonic flow

No sonic perturbation can propagate back from super-sonic region

W. G. Unruh, PRL **46**, 1351 (1981). *"Artificial Black Holes"*, eds. Novello, Visser, Volovik (2002)

The analogy with QFT in curved space-time



Low-k, hydrodynamic region: linear phonon dispersion $\omega = c_s\,|k| + v\,k$

Mathematical analogy with light propagation in curved metric

$$ds^2 = G_{\mu\nu}\,dx^\mu\,dx^\nu = \frac{n(x)}{c_s(x)}\left[-c_s(x)^2\,dt^2 + (d\vec{x} - \vec{v}(x)\,dt)(d\vec{x} - \vec{v}(x)\,dt)\right]$$

Wave equation for BEC phase $\quad \frac{1}{\sqrt{-G}}\,\partial_\mu\left[\sqrt{-G}\,G^{\mu\nu}\,\partial_\nu\right]\phi(x,t) = 0$

Once quantized → quantum field theory in a curved space time

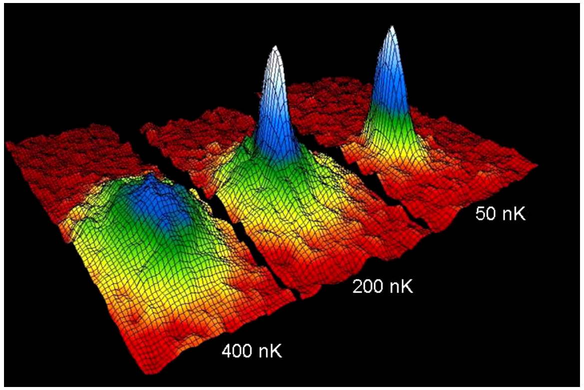
Hawking radiation in black-hole geometries

Astrophysical black-holes

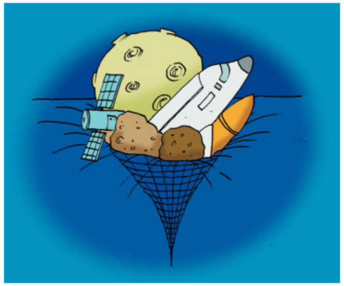
- emit Hawking radiation at $T_H = \frac{\hbar c^3}{8 \pi G M k_B}$
- solar mass BH: $T_H = 0.4\ \mu K$, hardly visible
  if compared to cosmological background at 2.73 K

Acoustic black holes:

- Hawking radiation of phonons at $T_H = \frac{\hbar}{4 \pi k_B c_s} \left[\frac{d}{dx} (c_s^2 - v^2) \right]_H$
- in nK range for μm-sized ultracold atomic BECs
  (not so bad...)



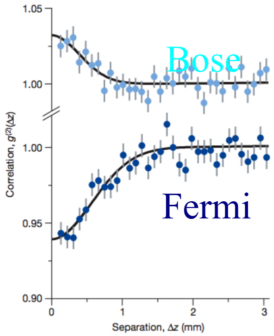
How to detect Hawking radiation?



HR is thermal only if seen from outside

Entanglement between in- and out-going partners

Both accessible w/o irreversible consequences on experimentalist



Jeltes *et al.*, Nature 445, 402 (2007)

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

Prediction of gravitational analogy :

→ entanglement in Hawking pairs gives long-range in/out correlations

$$G_2(x,x') = 1 - \frac{\xi_1\xi_2}{16\pi c_1 c_2}\,\frac{k^2}{\sqrt{n^2\xi_1\xi_2}}\,\frac{c_1c_2}{(c_1-v)(v-c_2)}\,\cosh^{-2}\left[\frac{k}{2}\left(\frac{x}{c_1-v}+\frac{x'}{v-c_2}\right)\right]$$

→ allows to isolate Hawking phonons from incoherent thermal phonons

R. Balbinot, A. Fabbri, S. Fagnocchi, A. Recati, IC, PRA 78, 021603 (2008).

A “numerical experiment”

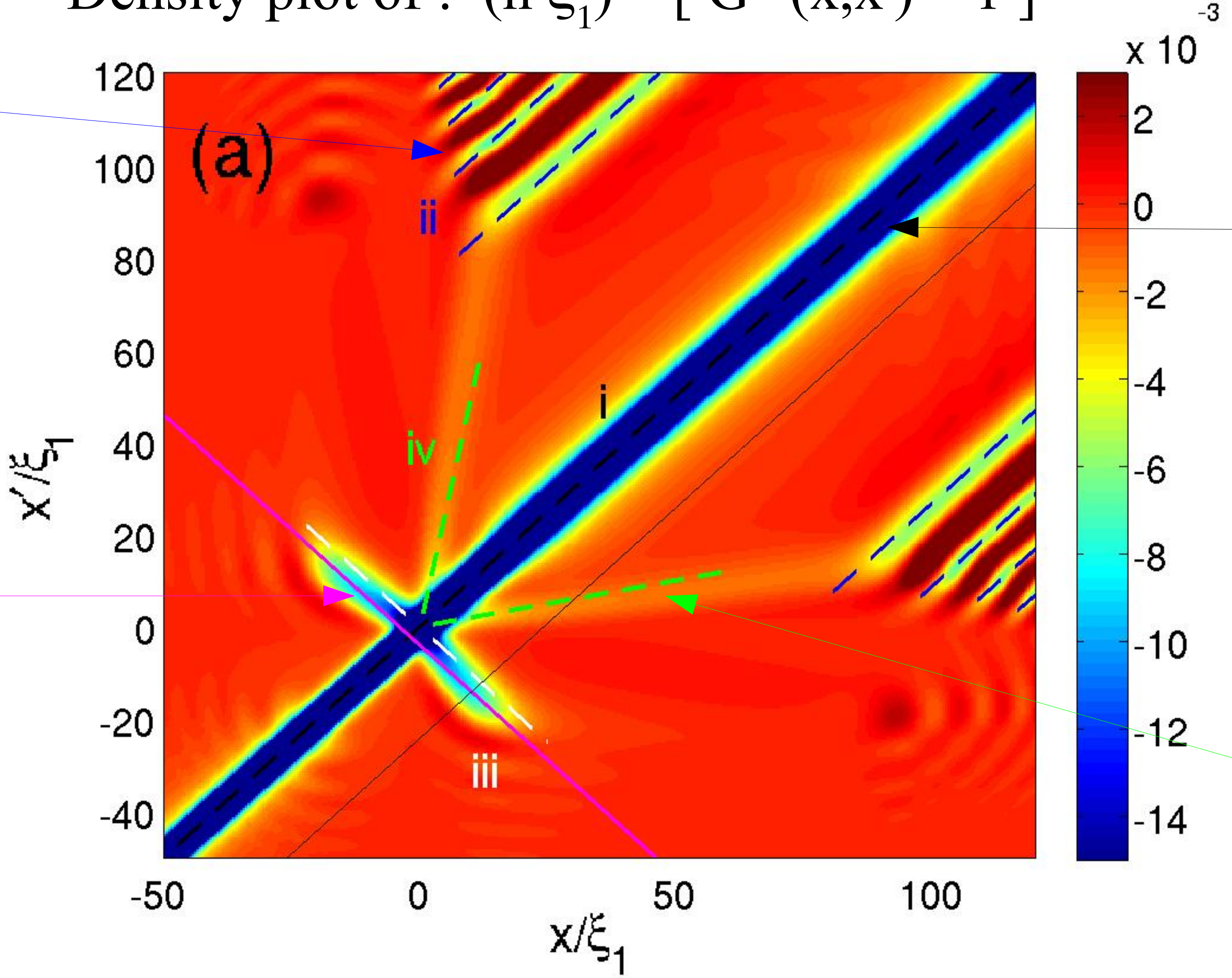
Density plot of : $(n \xi_1) * [G^{(2)}(x,x') - 1]$

(ii) Dynamical Casimir emission

(i) Many-body antibunching

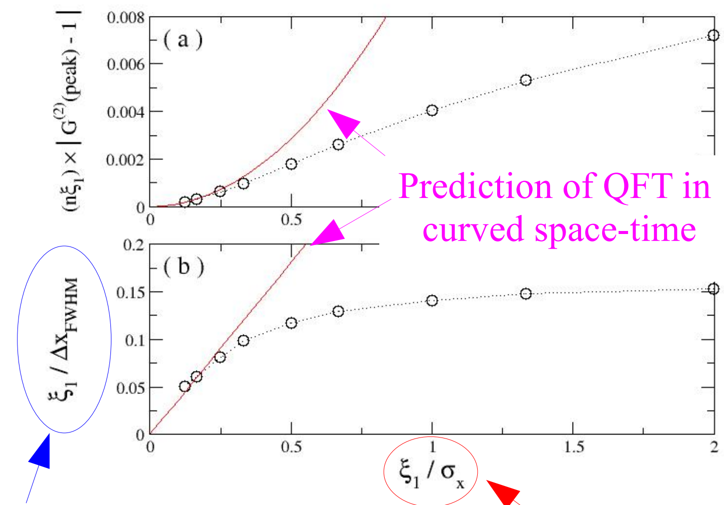
(iii) Hawking in / out

(iv) Hawking in / in



IC, S.Fagnocchi, A.Recati, R.Balbinot, A.Fabbri, New J. Phys. 10, 103001 (2008)

What have we learnt about black holes ?



Standard derivations of Hawking radiation:

- linear dispersion $\omega(k) = c\,|k|$ at all length scales
- infinite blue shift at horizon, relativity and QFT valid up to arbitrary energies

These assumptions violated in analogs:

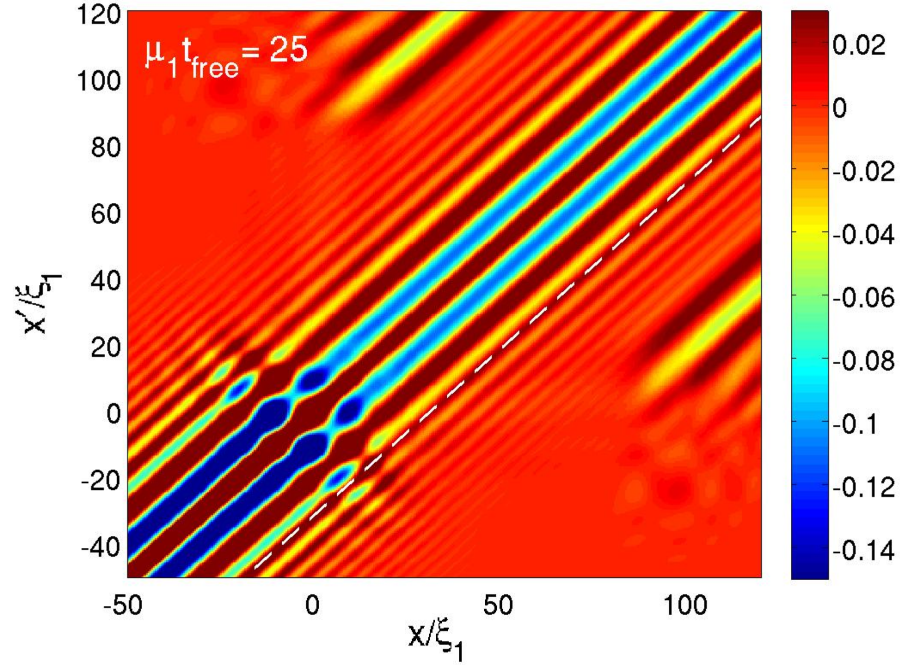
- HR is robust w/r to deviation from hydrodynamics
- but thermal HR spectrum modified by "Planck-scale" physics

Open question:

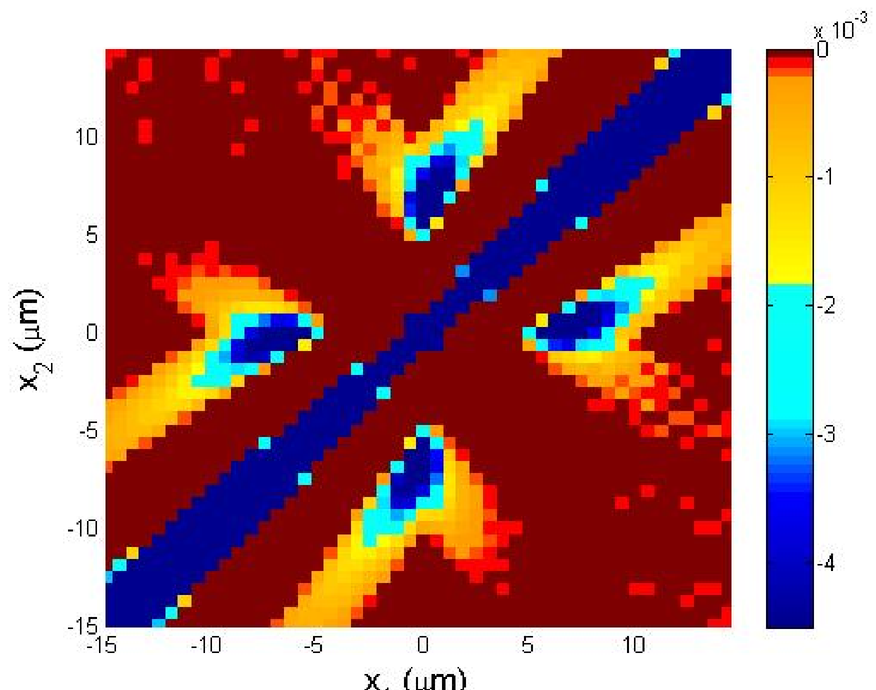
- does this provide new features in BH signal at LHC (and possibly contribute to save the world) ?

from: La Repubblica 11/9/08

Towards the REAL experiment



Eric Cornell's smart trick to reinforce HR signal in atomic BEC experiments



A preliminary snapshot of Davide's investigations on HR in exciton-polariton BECs in semiconductor microcavities

Other research lines of the Quantum Optics team

Non-equilibrium quantum gases in optical devices:

- non-equilibrium BEC vs. lasing
- exotic strong correlation phenomena

Collab: C. Ciuti (Paris 7), M. Wouters (EPFL), A. Imamoglu (ETHZ), D. Gerace (Pavia)
Exp: A. Bramati, E. Giacobino (Paris 6), B. Deveaud (EPFL), L. Viña (UAM)

Slow light physics and applications:

- microscopic diagnostic of strongly correlated phases in ultracold gases

Collab: Y. Castin (LKB), C. Kollath, A. Georges (Ec. Polytechnique)

Opto-mechanical forces in photonic devices:

- atomic BECs in high-Q optical cavities

Exp: T. Esslinger (ETHZ)

- microring solid-state resonators

Exp: M. Ghulinyan (FBK), L. Pavesi (Trento)