BEC
BOSE EINSTEIN CONDENSATION

The exciting adventure of condensed-matter and optical analogs of gravitational systems

The tale of Navier and Stokes meeting Heisenberg at Hawking's place

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- Dario Gerace (Università di Pavia, Italy)
- Hai-Son Nguyen, Alberto Amo, Jacqueline Bloch (LPN-CNRS, Marcoussis, France)
- M. Tettamanti, A. Parola, S. Cacciatori (Univ. Insubria, Como, Italy)

Acoustic (and fishic) black hole horizon

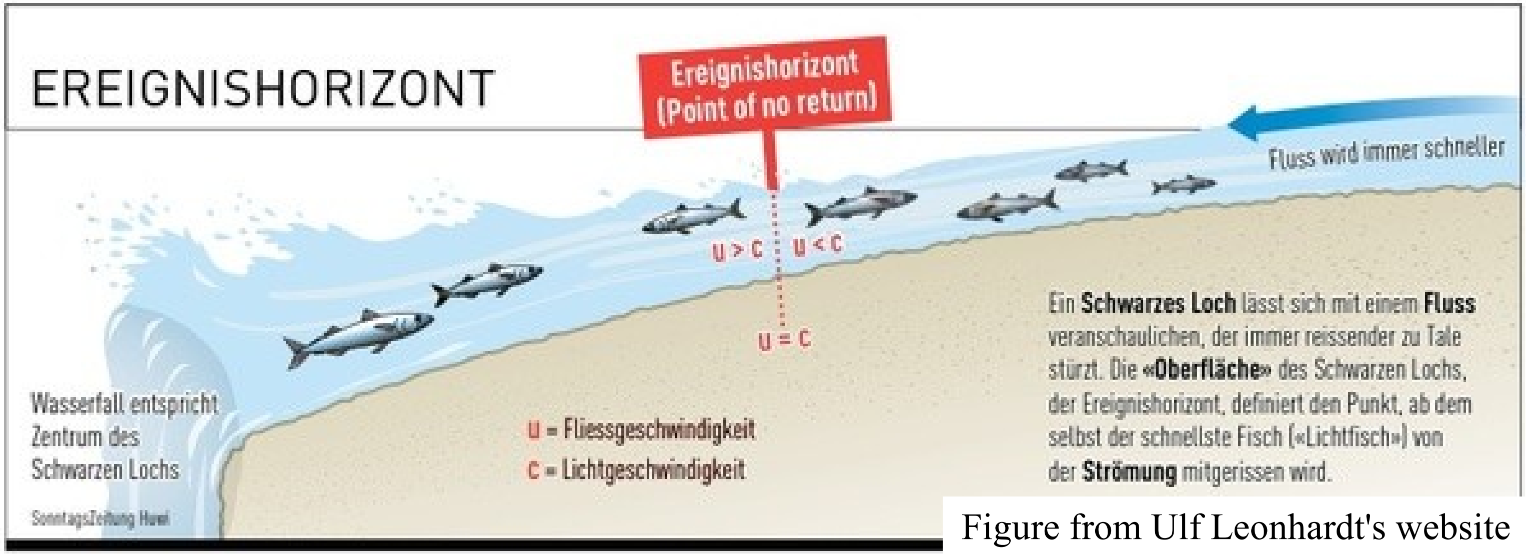


Figure from Ulf Leonhardt's website

Excitations (i.e. fish) propagate (i.e swim) at $v=c_s \pm v_{flow}$

- Horizon region separating sub-sonic (i.e. sub-fishic) flow (upstream) from super-sonic (i.e. sub-fishic) flow (downstream)
- Excitations (i.e. fish) in super-sonic (i.e. super-fishic) region can not travel (i.e. swim) back through horizon

} Behavior analogous to astrophysical black hole horizon

- What happens with quantum fishes ? Hawking radiation ?

Unruh, PRL 1981; Barceló, Liberati, Visser, Liv. Rev. Relativity **14**, 3 (2011)

Mathematical framework

Sonic dispersion of phonons in superfluid → relativistic eq for BEC phase

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

mathematically equivalent to light propagation in curved space-time metric

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

Once quantized → quantum field theory in a curved space time

Simplest analog black hole geometry:

- one-dimensional geometry, flow in the +x direction
- $v(x)/c(x)$ increases along +x direction; horizon where $v(x_H)$ / $c(x_H)$ =1

As in astrophysical black holes → Hawking emission at $T_H=\dfrac{\hbar c^3}{8\pi k_B G M}$

What happens in analogs ?

Some examples of analog models

- Surface waves on flowing classical fluids, e.g. in water tanks
- Nonlinear optical systems:
  moving refractive index perturbations created by strong optical pump
- Other systems:
  - Ion chains in ring traps
  - Arrays of circuit-QED cavities
- Quantum fluids:
  - BECs of ultra-cold atoms
  - quantum fluids of light, e.g. gas of (dressed) photons in microcavity
  - propagating light in bulk nonlinear media → see Victor's talk later on

1 - Surface waves on a classical fluid

G. Rousseaux

Phase and group velocities of surface waves $c_s = \sqrt{gh}$
Flow speed v also varies with h

→ both modulated by tank bottom profile

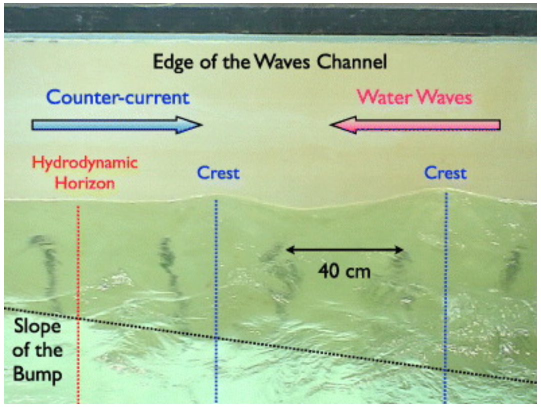
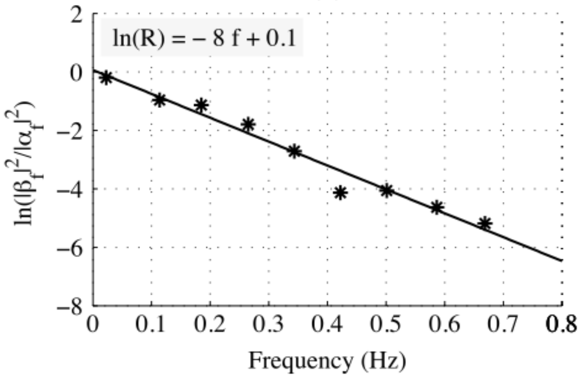


Figure: Rousseaux et al., NJP 2010

Classical Hawking processes:

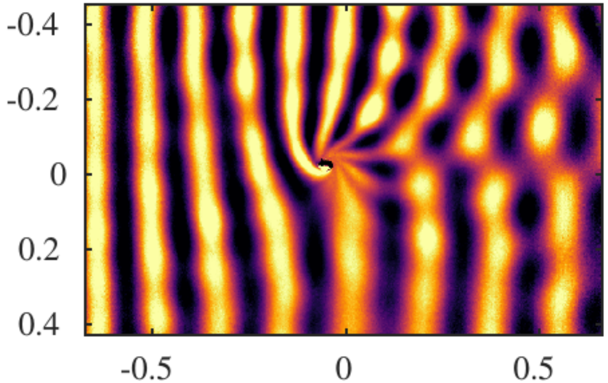
- positive to negative mode conversion
- conversion amplitude claimed to follow thermal law
- Serious concerns in L.-P. Euvé's PhD thesis (Poitiers 2017)
  See also arXiv:1409.3830 (with Parentani's group)

Limited hope of detecting quantum features



Classical Hawking processes reported in Weinfurtner *et al*. PRL 2011.

Correlation expts in arXiv:1511.08145



Torres et al., Nat. Phys. 2017
Expt. observ. of superradiant scattering from rotating BH

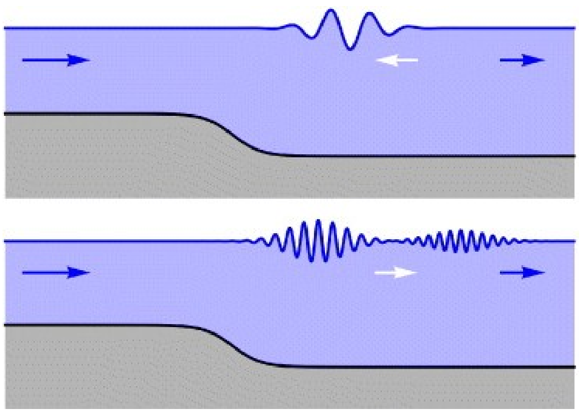


Figure: Leonhardt, Robertson, NJP 2012

2 – Nonlinear optical systems

The idea

(Philbin et al., Science 2008)

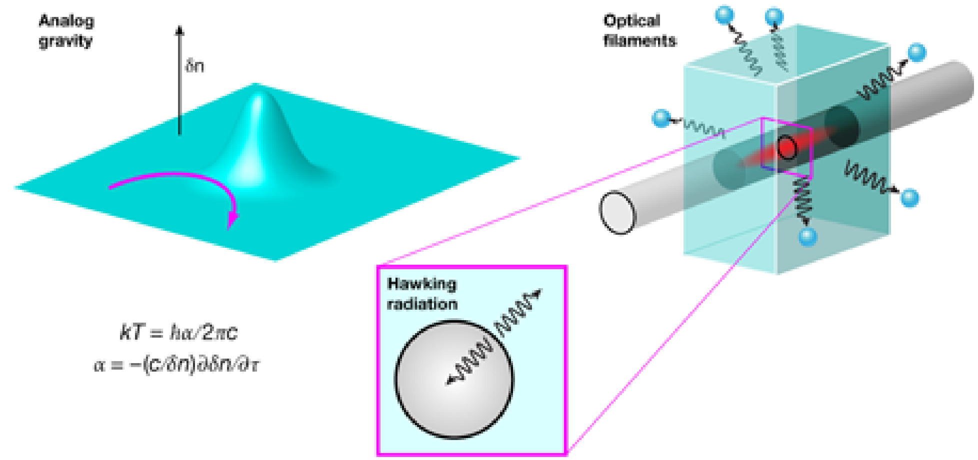


Figure adapted from Belgiorno et al. PRL 2010

Strong optical pulse in nonlinear crystal:

- propagates at v_g
- optical $\chi^{(3)}$ of medium modifies $n \rightarrow n+\delta n$

If $c/n > v_g > c/(n+\delta n)$

- other frequencies feel horizon
- quantum fluctuations → analog HR

Experimental claim of HR from Como group

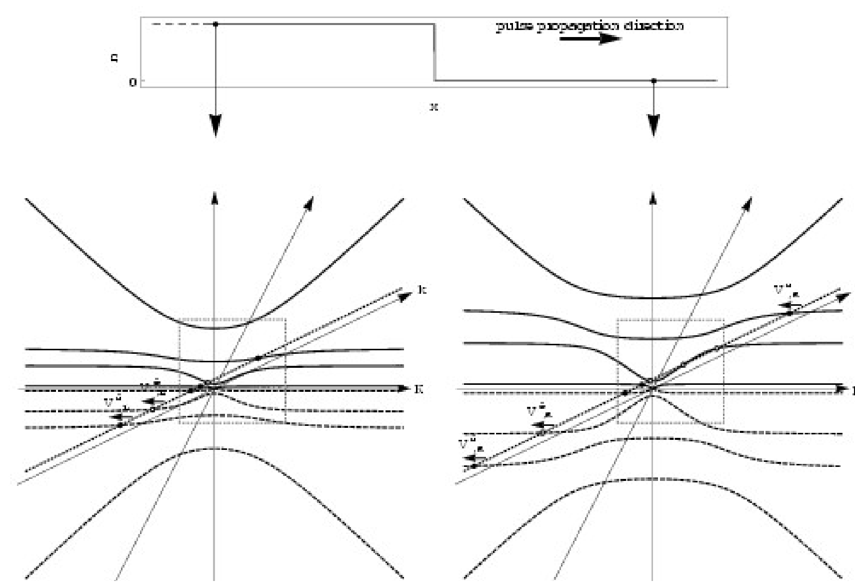
(Belgiorno et al. PRL 2010)

Not yet full consensus on interpretation:

- Dispersion $n(\omega)$ of silica very complicate
- Other emission processes present...

  ...with not too different spectral features

Is observed emission really Hawking?

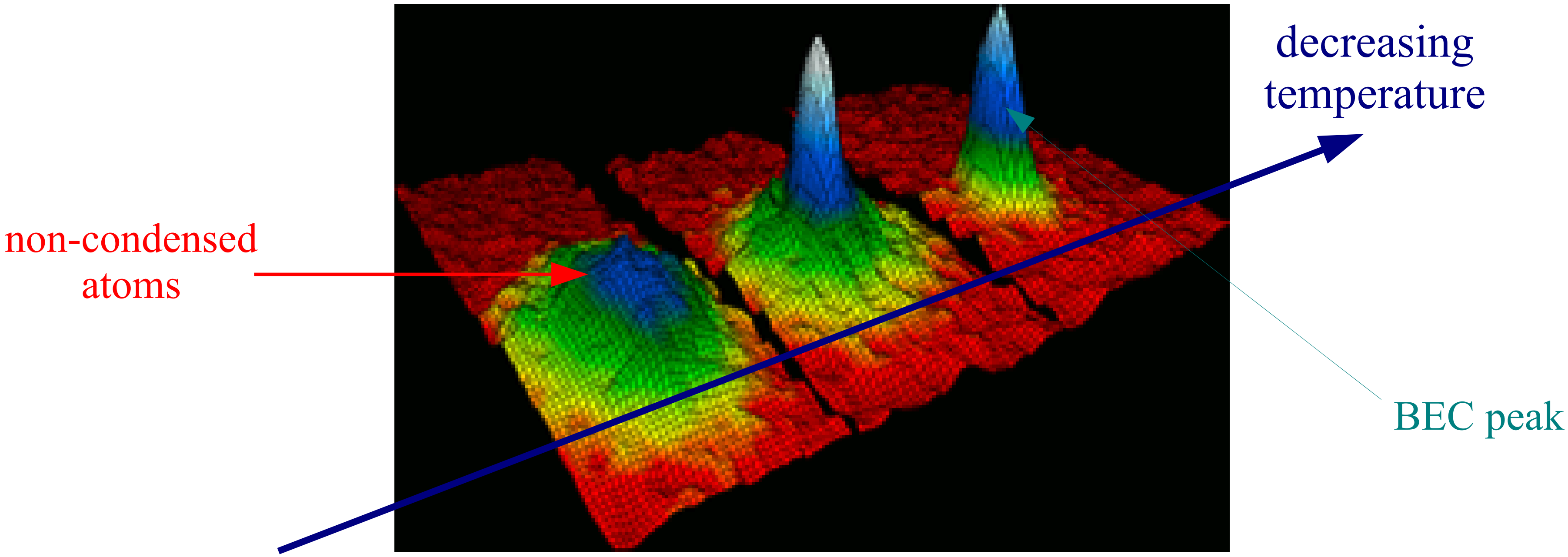


Finazzi & IC, *Spontaneous quantum emission from analog white holes in a nonlinear optical medium*, PRA 89, 053807 (2014)

Part 1:

Superfluid ultracold atomic gases

What are superfluid ultracold atomic gases?



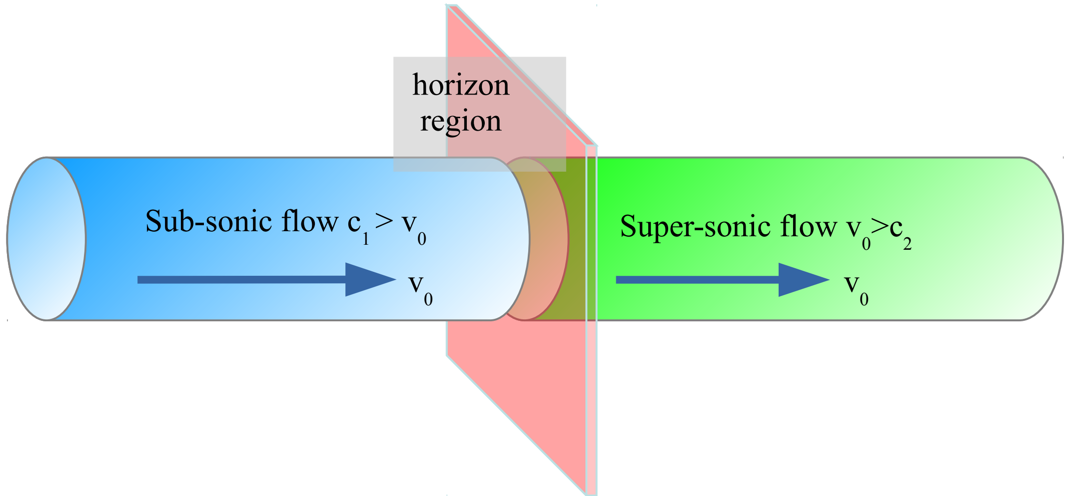
BEC in Rb atomic cloud via momentum distribution images
Figure from JILA group

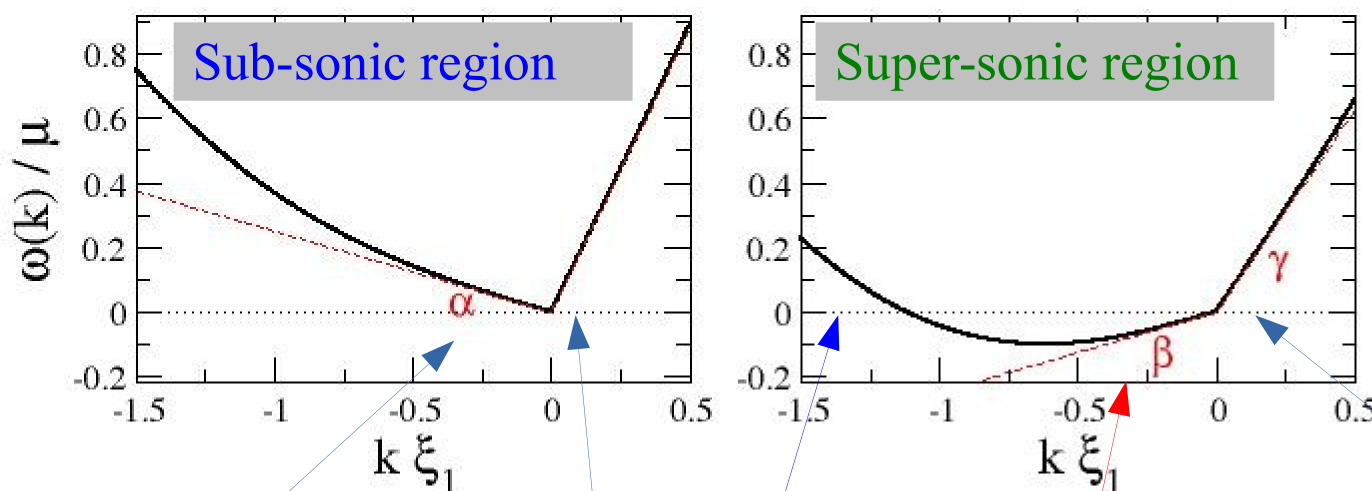
At nano-K temperatures of laser + evaporation cooled atomic clouds:

- Bose-Einstein condensate with macroscopic occupation of k=0 orbital
- superfluid features with phonon mode with sonic dispersion
- Ultra-low temperature: long-lived quantum coherence of excitations
- Trans-sonic flow -> Hawking T_H in nK range for μm-size clouds

$$T_H = \frac{\hbar}{4\pi k_B c_s} \left[\frac{d}{dx} (c_s^2 - v^2) \right]_H$$

A significant detail...





$v_g = v_0 - c_1 < 0$

$v_g = v_0 + c_1 > 0$

$v_g = v_0 - c_2 > 0$

Sound can not propagate back !

$v_g = v_0 + c_2 > 0$

New feature of atomic BEC: single particle excitations **can emerge** from black hole !!

This raises interesting fundamental questions...

Standard derivations of Hawking radiation often assume:

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

These assumptions violated in BEC-based analogs:

- is HR robust w/r to deviation from hydrodynamic dispersion?
- what is role of single particle nature of high-k excitations?
- at closer look: microscopic mechanism of HR completely different...

Some open questions:

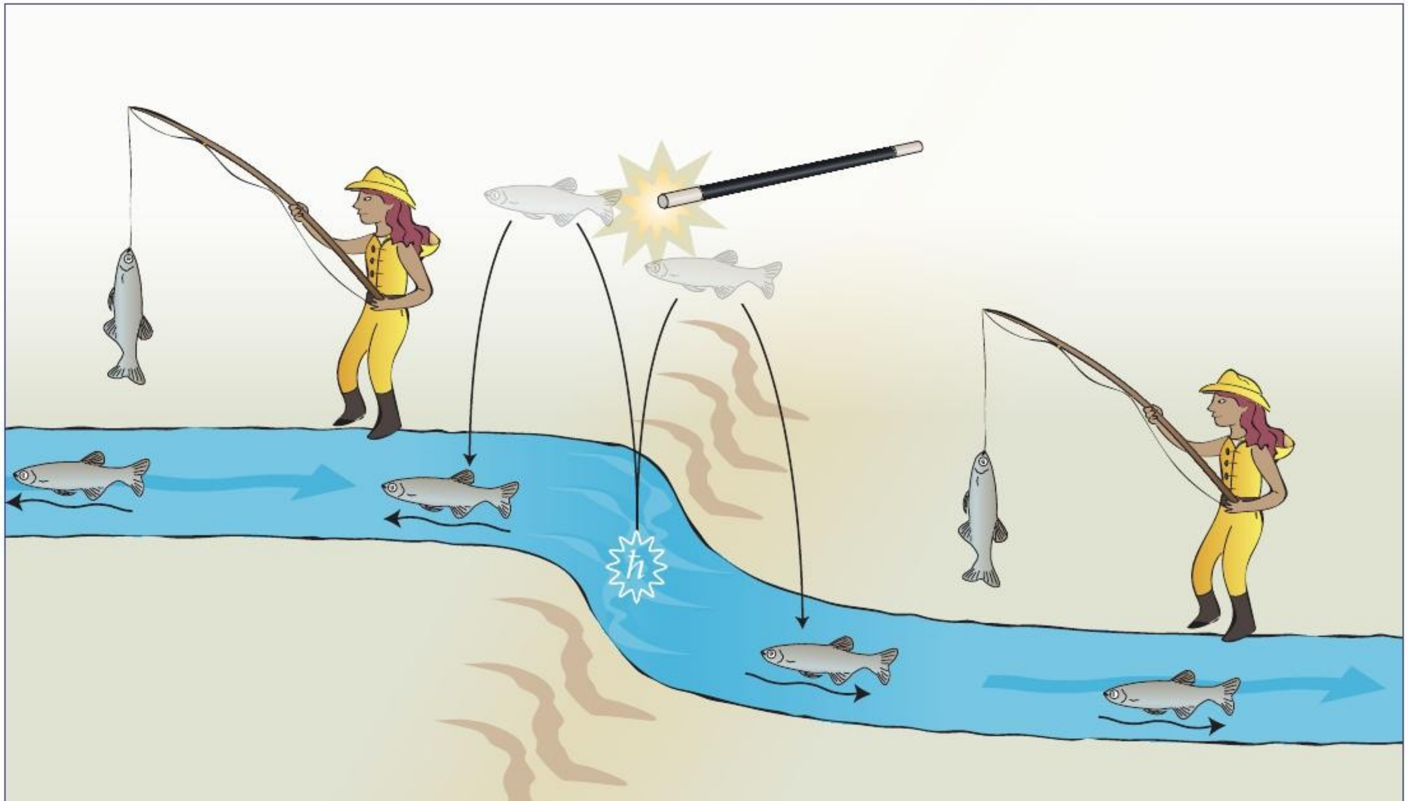
→ thermal HR spectrum modified by "Planck-scale" physics?

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

W. G. Unruh, Phys. Rev. D 51, 2827 (1995); R. Brout et al., Phys. Rev. D 52, 4559 (1995)
T. A. Jacobson and R. Parentani, *An echo of Black Holes*, Scientific American, Dec. 2005.

pseudo-La Repubblica 11/9/08

How to detect Hawking radiation in atomic gases?



Picture from IC-Balbinot, Nat. Phys. N&V, Aug. 2016

- Hawking radiation → correlated pairs generated simultaneously at the horizon
- HR isolated from background of thermal and noise phonons by measuring correlations on opposite sides of horizon
- <u>In the picture:</u> Hawking fish are caught simultaneously by the two fisherwomen!

This idea put into formulas...

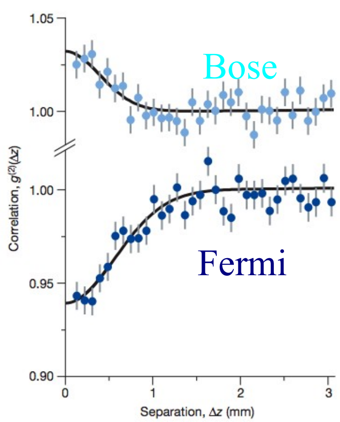
Density-density correlation function $G_2(x,x') = \dfrac{\langle : \delta n(x)\, \delta n(x') : \rangle}{\langle n(x) \rangle \langle n(x') \rangle}$

Prediction of gravitational analogy (Balbinot *et al.* PRA 2008):

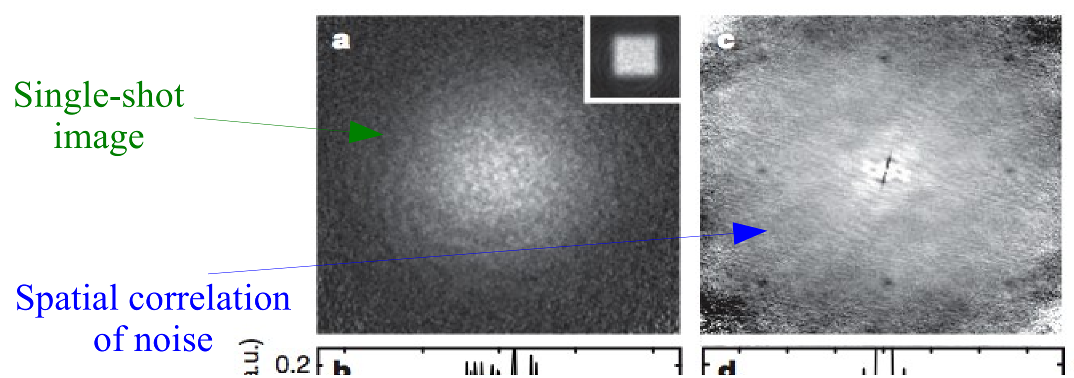
→ entanglement in Hawking pairs gives long-range in/out correlations

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

→ allows to isolate Hawking phonons from background of incoherent thermal phonons



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



Rom *et al.*, Nature 444, 733 (2006)

Measurement of density correlations experimentally demonstrated:

- Atomic HB-T: positive correlation due to thermal Bose atoms (negative for fermions)
- Noise correlations in TOF picture after expansion from lattice

Ab initio numerics: Wigner-Monte Carlo

At t=0, homogeneous system:

- Condensate wavefunction in plane-wave state
- Quantum + thermal fluctuations in plane wave Bogoliubov modes
- Gaussian α_k, variance $<|\alpha_k|^2> = [2 \tanh(E_k / 2k_B T)]^{-1} \rightarrow ½$ for $T \rightarrow 0$.

$$\psi(x, t=0) = e^{i k_0 x}\left[\sqrt{n_0} + \sum_k \left(u_k e^{i k x} \alpha_k + v_k e^{-i k x} \alpha_k^*\right)\right]$$

At later times: conservative (for atoms!) evolution under GPE

$$i\hbar\, \partial_t \psi(x) = -\frac{\hbar^2}{2\mathrm{m}}\, \partial_x^2 \psi(x) + V(x)\psi(x) + g(x)\, |\psi(x)|^2 \psi(x)$$

Expectation values of observables:

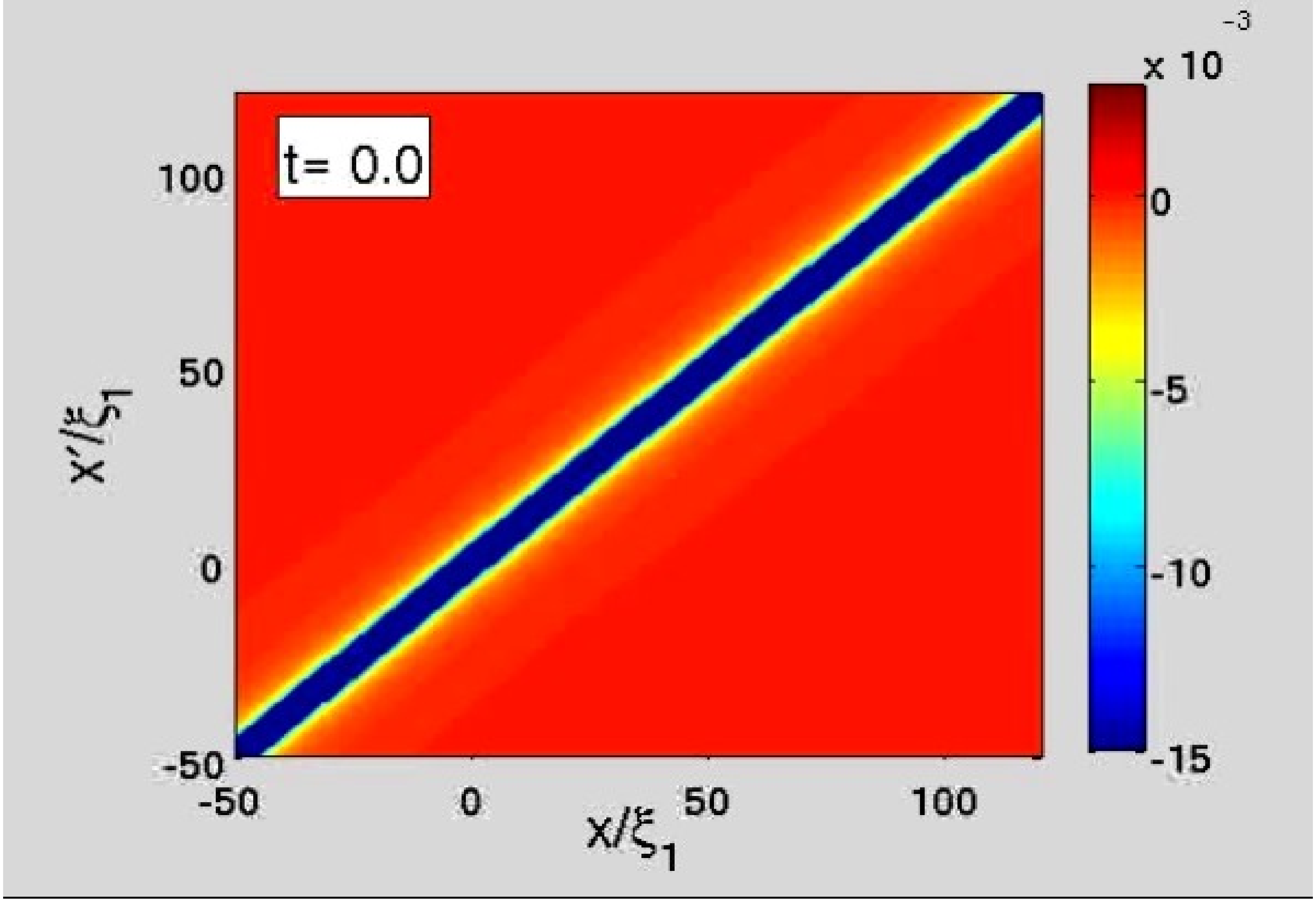
- Average over noise provides symmetrically-ordered observables

$$\langle \psi^*(x)\ \psi(x')\rangle_W = \frac{1}{2}\langle \hat{\psi}^\dagger(x)\ \hat{\psi}(x') + \hat{\psi}(x')\ \hat{\psi}^\dagger(x)\rangle_Q$$

Equivalent to Bogoliubov, but can explore longer-time dynamics

A. Sinatra, C. Lobo, Y. Castin, J. Phys. B 35, 3599 (2002)

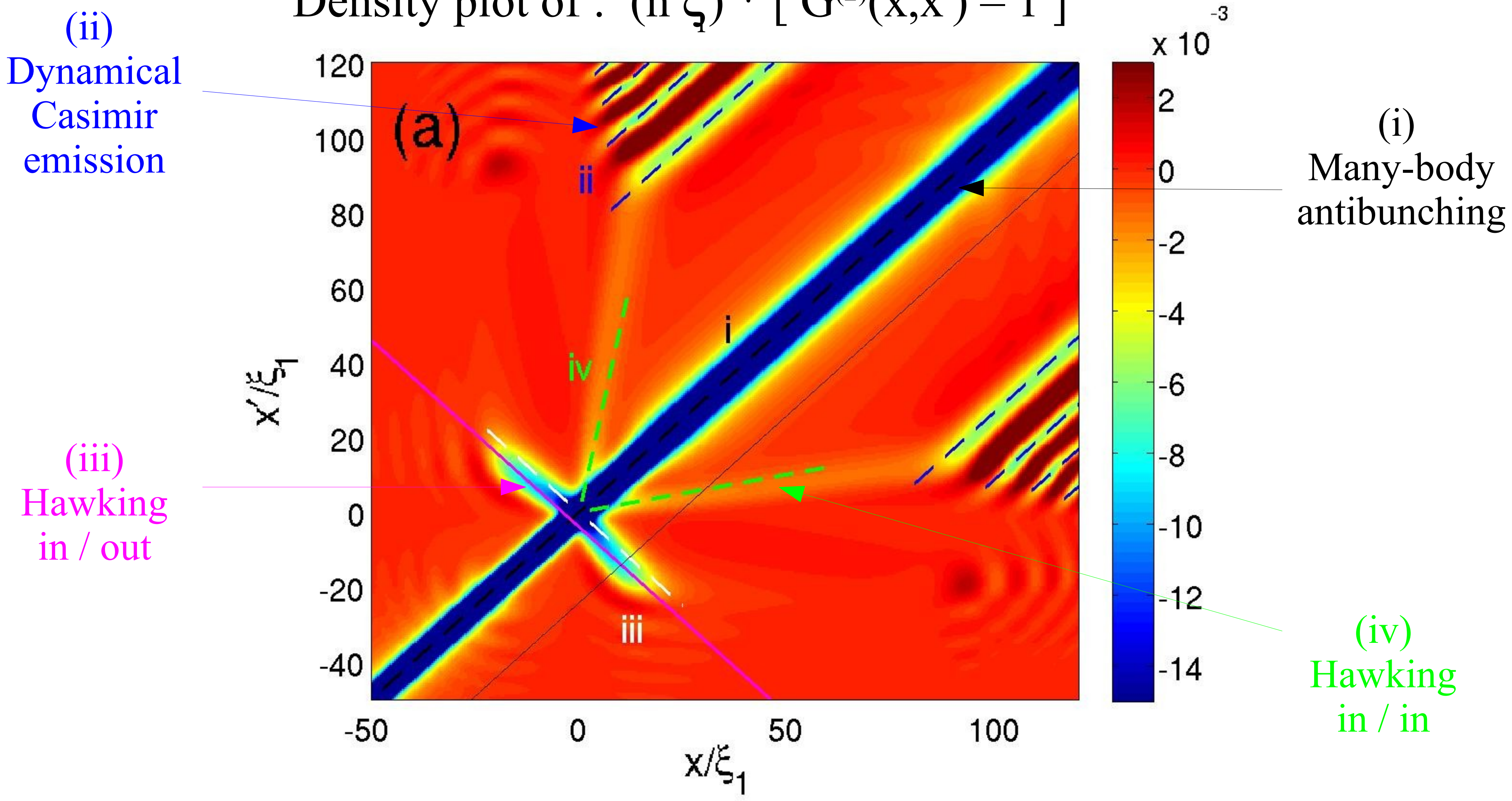
Density correlations: the movie



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

A snapshot of density correlations

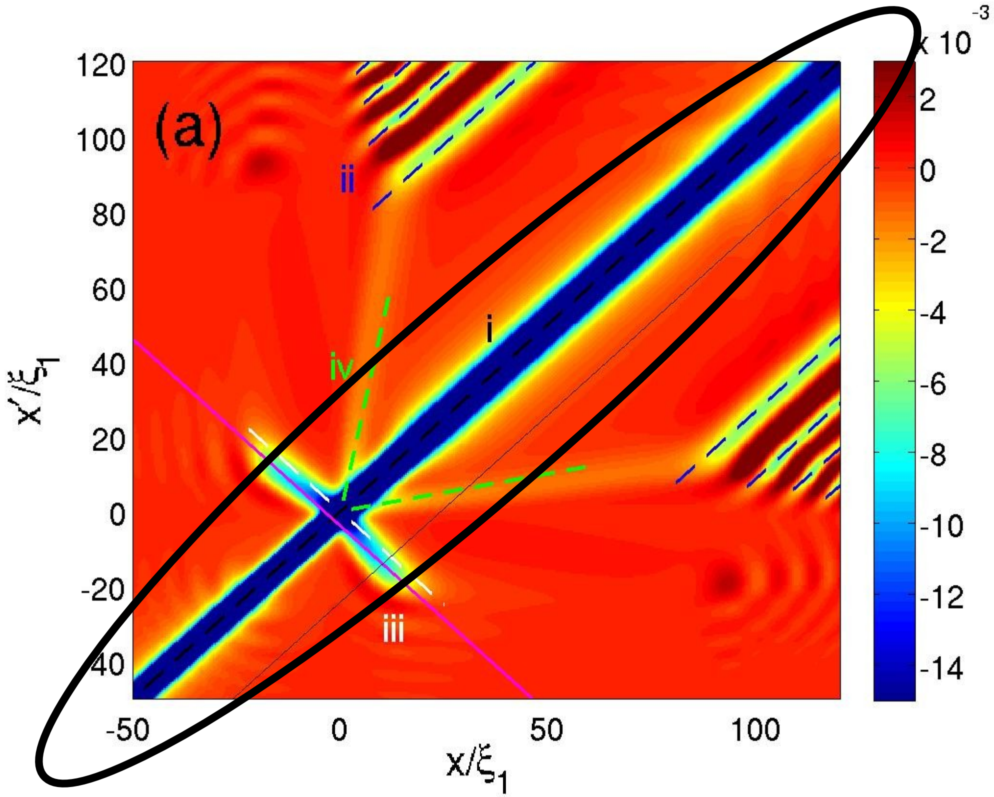
Density plot of : $(n\,\xi) * [\,G^{(2)}(x,x') - 1\,]$



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

Feature (i) : Many-body antibunching

- present at all times
- due to repulsive interactions
- almost unaffected by flow

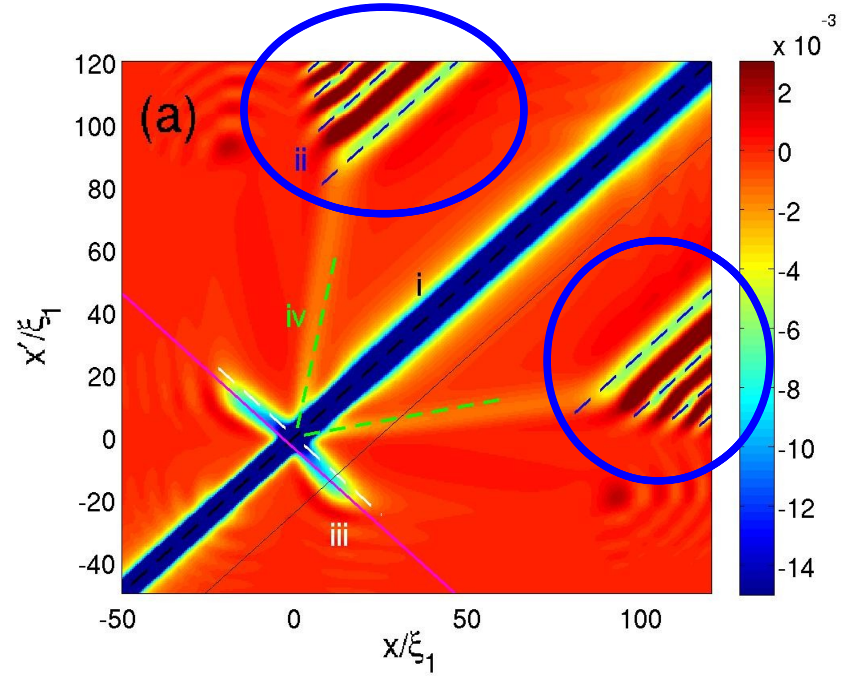


See e.g.: M. Naraschewski and R. J. Glauber, PRA 59, 4595 (1999)

Feature (ii): Dynamical Casimir emission of phonons

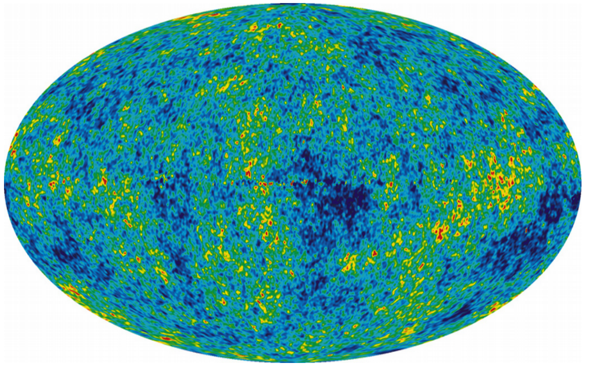
Fringes parallel to main diagonal

- intensity depends on speed of switch-on
- only in x>0 region, move away in time
- do not depend on flow pattern,
  also present in homogeneous system



Physical interpretation:

- in x>0 region $g_1 \rightarrow g_2$ within short time σ_t :
  non-adiabatic modulation of Bogoliubov vacuum
- fringes depend on |x-x'|: counter-propagating correlated pairs emitted at t=0 at all points x>0
- density correlations propagate away at speed $\geq 2c_s$.
- model of amplification of metric fluctuations
  during cosmological inflation period

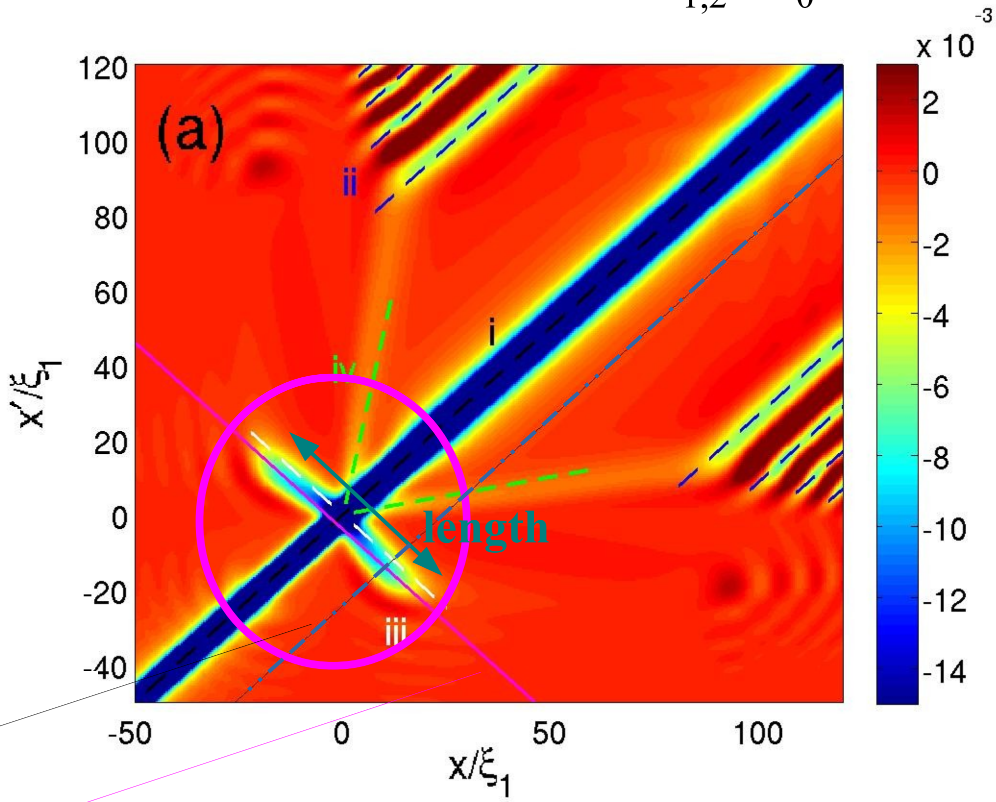


IC, R. Balbinot, A. Fabbri, A. Recati, Eur. Phys. J. D **56**, 391 (2010)
For fluids of light, see: Koghee, Wouters PRL 2014.

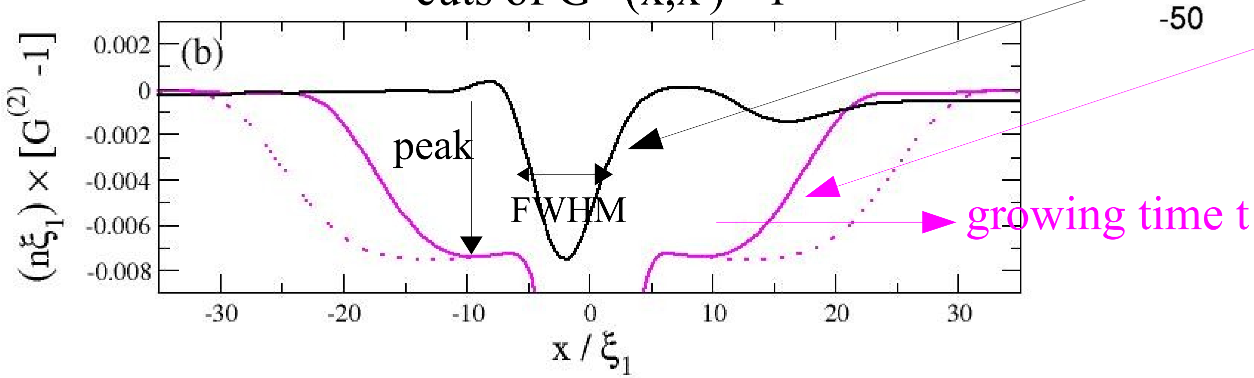
Feature (iii) : The Hawking signal

Negative correlation tongue extending from the horizon x=x'=0

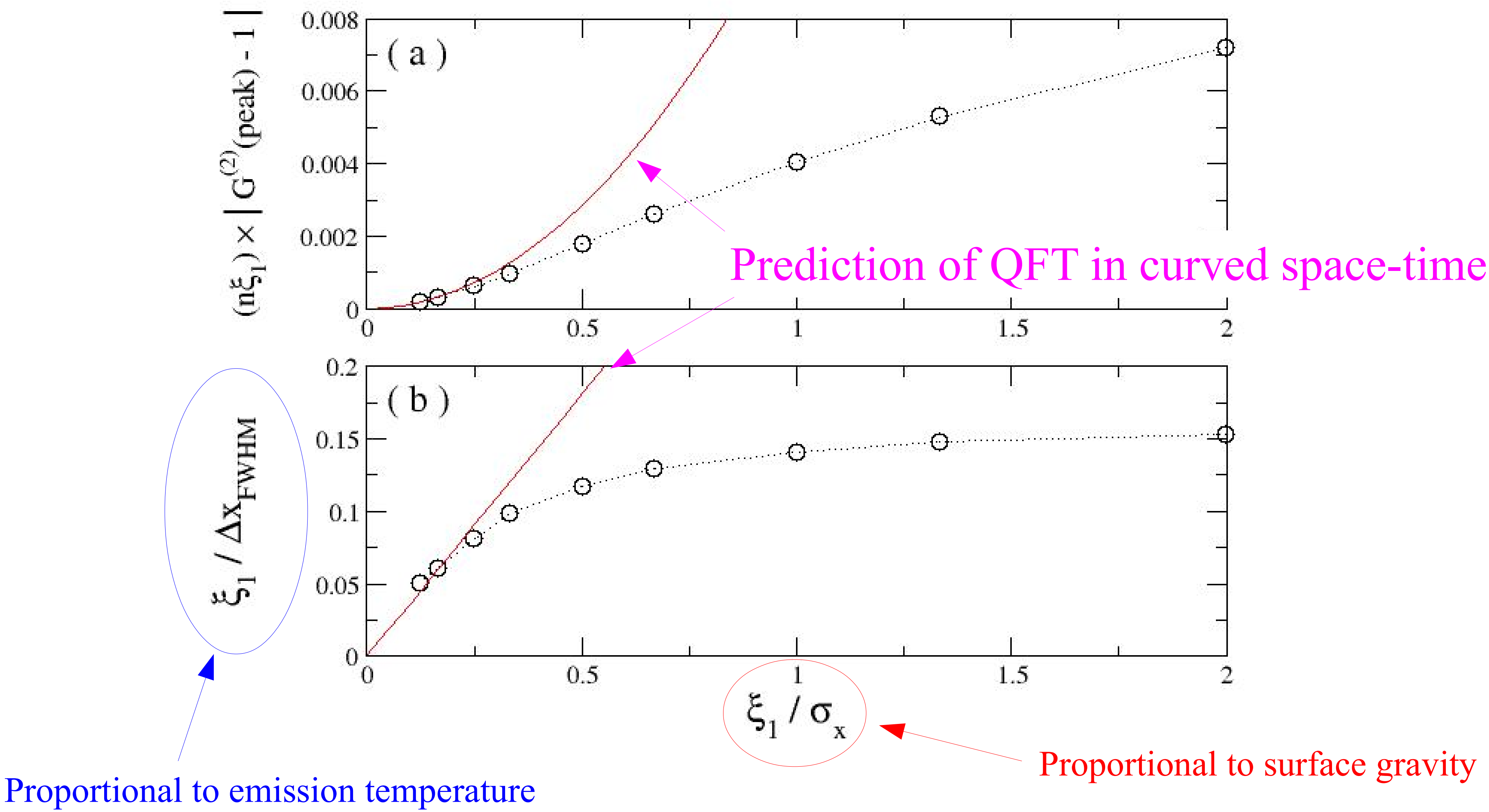
- long-range in/out density correlation which disappears if both $c_{1,2}<v_0$
- length grows linearly in t
- peak height, FWHM constant in t
- slope $\frac{v_0-c_2}{v_0-c_1}$ agrees with theory
  - pairs emitted at all t from horizon
  - propagate at sound speed



cuts of G(2)(x,x') - 1



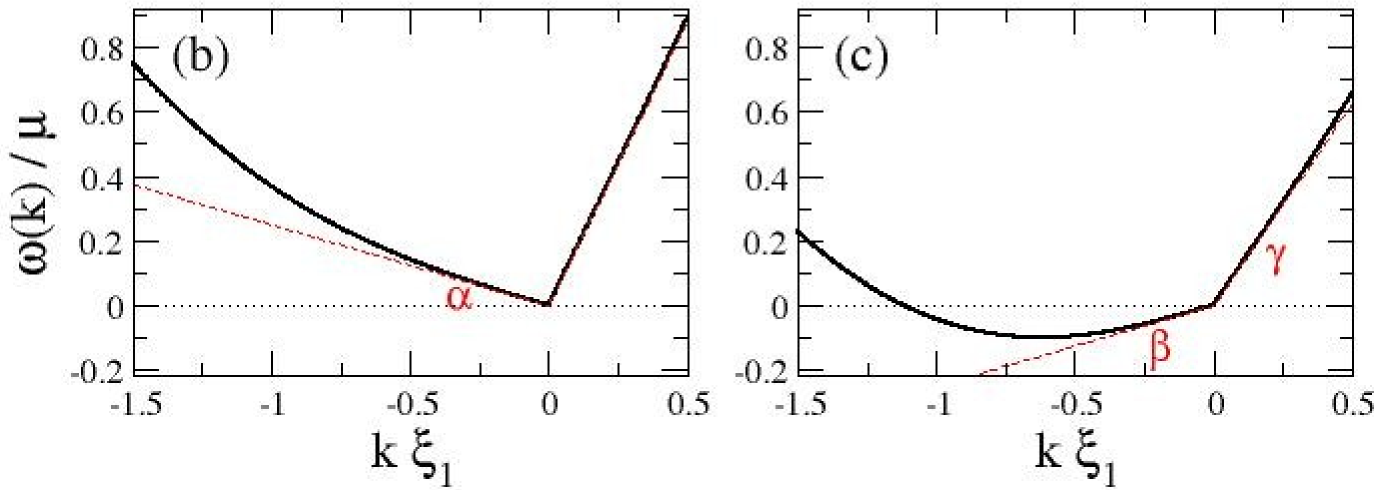
Quantitative analysis



Analog model prediction quantitatively correct in hydrodynamic limit $\xi_1 / \sigma_x \ll 1$

Significant discrepancies for strong surface gravity

Effect of UV dispersion



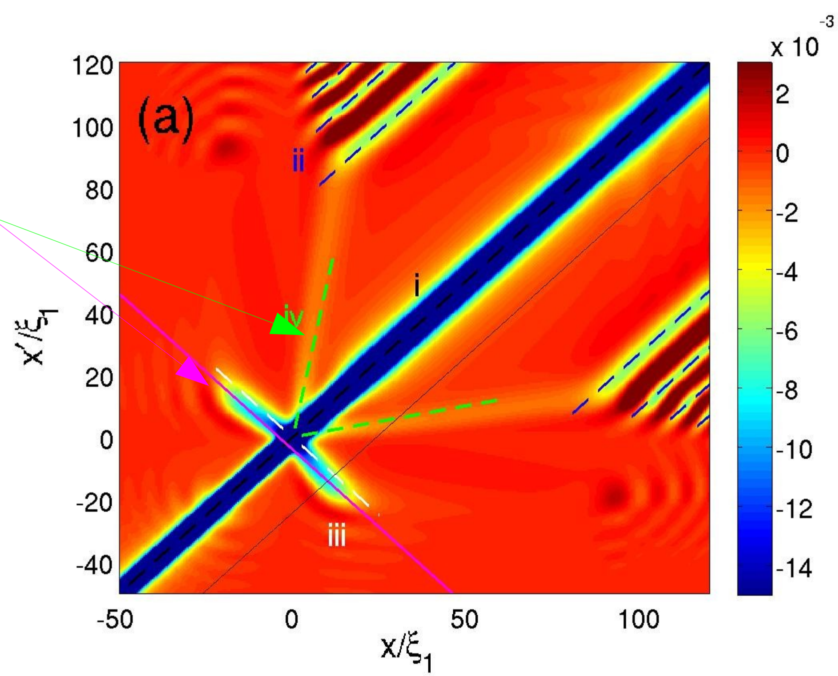
Two parametric "Hawking" processes:

- in/out: vacuum → α + β (feature iii)
- in/in: vacuum → β + γ (feature iv)
- third tongue α-γ hardly visible here

Energy conserved only if sub/super-sonic

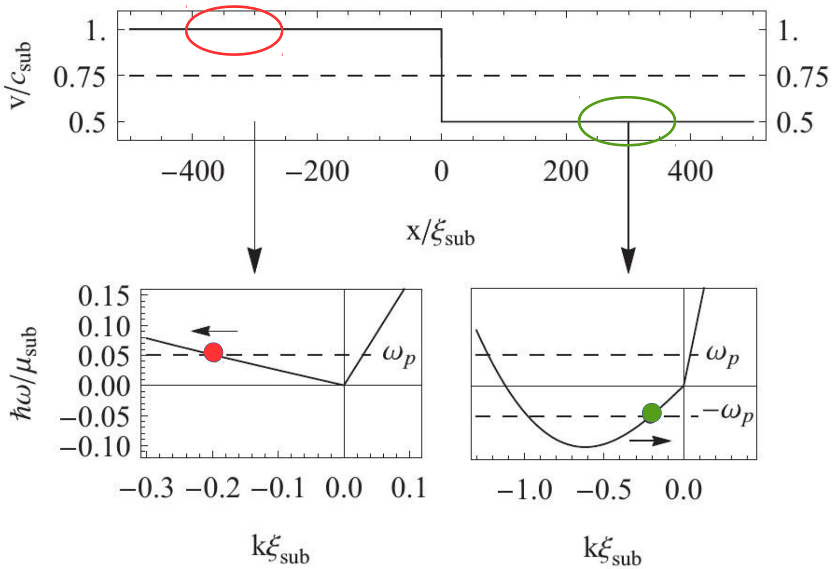
Momentum provided by horizon

Slope of tongues $\frac{v_0 - c_2}{v_0 - c_1} \simeq -1$, $\frac{v_0 - c_2}{v_0 + c_2} \simeq \frac{1}{5}$



How to assess quantum nature of HR in atomic gas ?

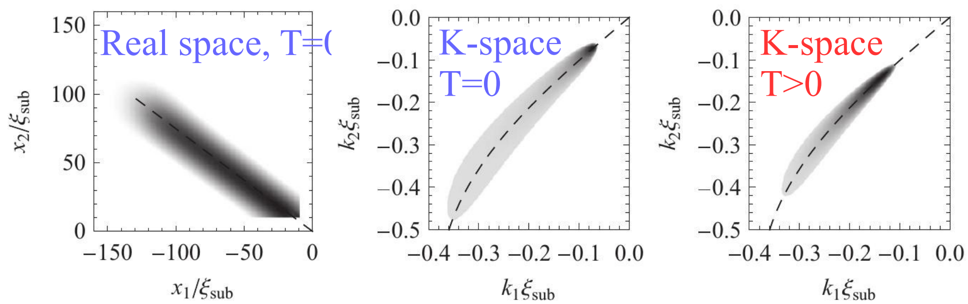
- Signal in density/intensity correlations reinforced at finite T by stimulated Hawking emission.
  → Not a signature of quantum origin of emission



- Peres-Horodecki criterion for entanglement in bipartite systems
  → correlations of quadratures of phonon operators on either side of the horizon

- Phonon wavepacket operators localized in real- and momentum spaces

- Need to measure both phonon quadratures with spatial and spectral selectivity (or make stromg assumptions on the correlation function)



Finazzi, IC, *Entangled phonons in atomic Bose-Einstein condensates,* PRA 2014

Part 1-b:

<u>The recent experiments</u>

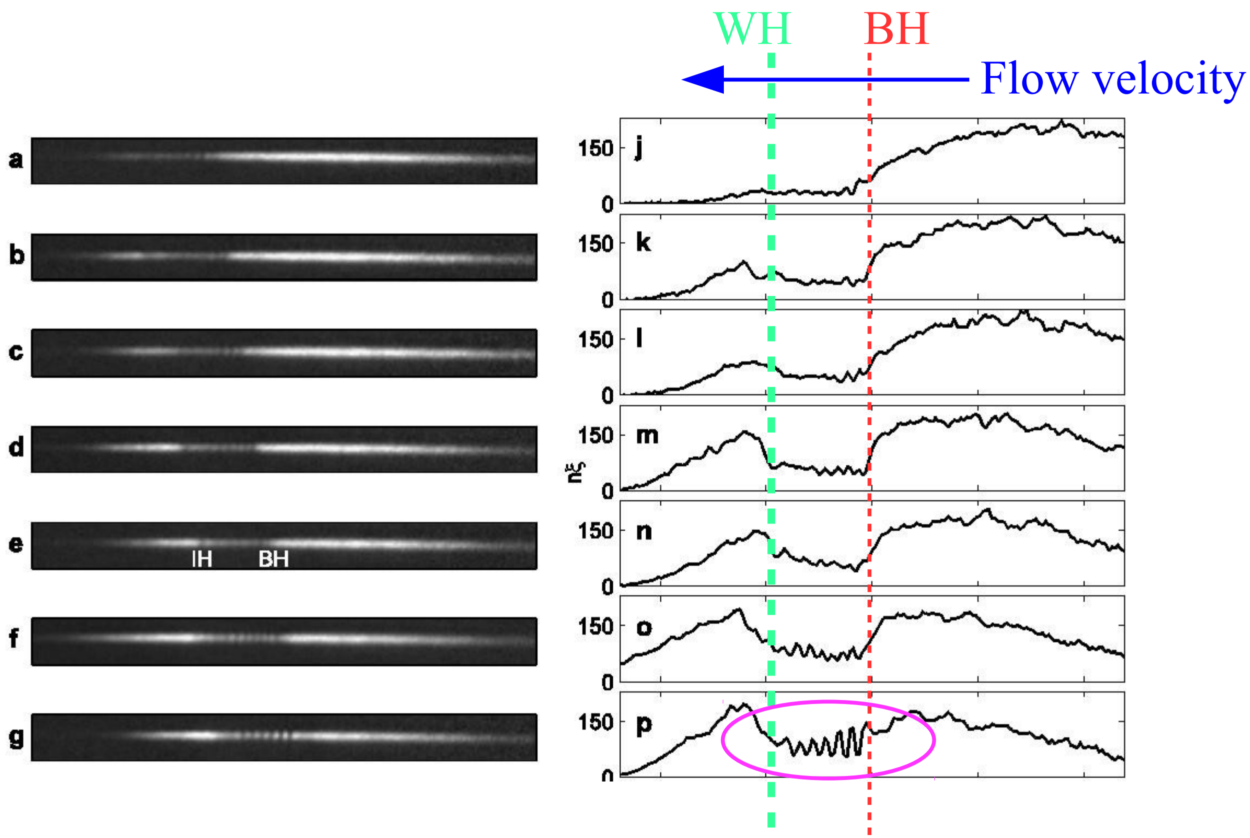
1- Black hole lasing (2014)

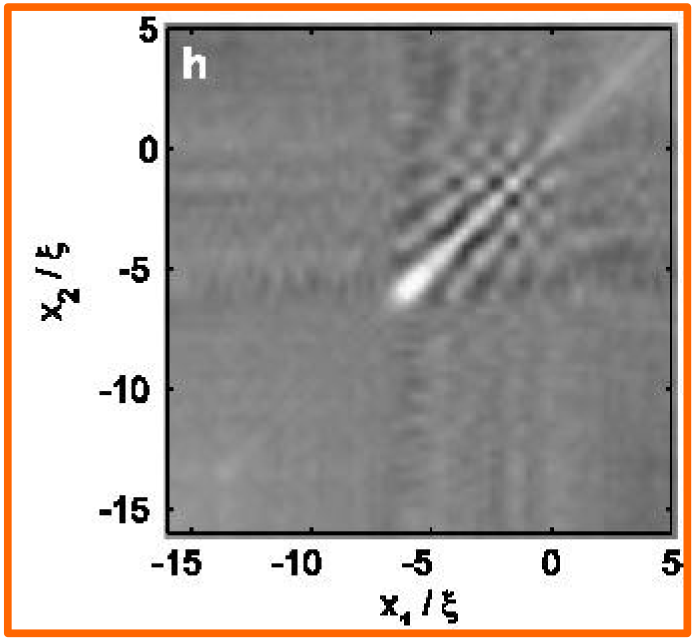
ARTICLES
PUBLISHED ONLINE: 12 OCTOBER 2014 | DOI: 10.1038/NPHYS3104
nature physics

Observation of self-amplifying Hawking radiation in an analogue black-hole laser

Jeff Steinhauer

By a combination of quantum field theory and general relativity, black holes have been predicted to emit Hawking radiation. Observation from an actual black hole is, however, probably extremely difficult, so attention has turned to analogue systems in the search for such radiation. Here, we create a narrow, low density, very low temperature atomic Bose–Einstein condensate, containing an analogue black-hole horizon and an inner horizon, as in a charged black hole. We report the observation of Hawking radiation emitted by this black-hole analogue, which is the output of the black-hole laser formed between the horizons. We also observe the exponential growth of a standing wave between the horizons, which results from interference between the negative-energy partners of the Hawking radiation and the negative-energy particles reflected from the inner horizon. We thus observe self-amplifying Hawking radiation.





Pair of BH/WH horizons in flowing BEC against a waterfall+harmonic potential:

- BH horizon at potential edge. WH horizon further downstream by growing harmonic potential.
- Black hole lasing instability → exponential growth of density modulation: "self-amplifying HR"
- Checkerboard/striped pattern in correlation function of density fluctuations

- Open questions: is initial seed classical or quantum ? What is precise mechanism for amplification?

J. Steinhauer, *Observation of self-amplifying Hawking radiation in an analog black hole laser*, Nature Physics 10, 864 (2014)

Numerical analysis of experiment

GPE simulation with experimental parameters

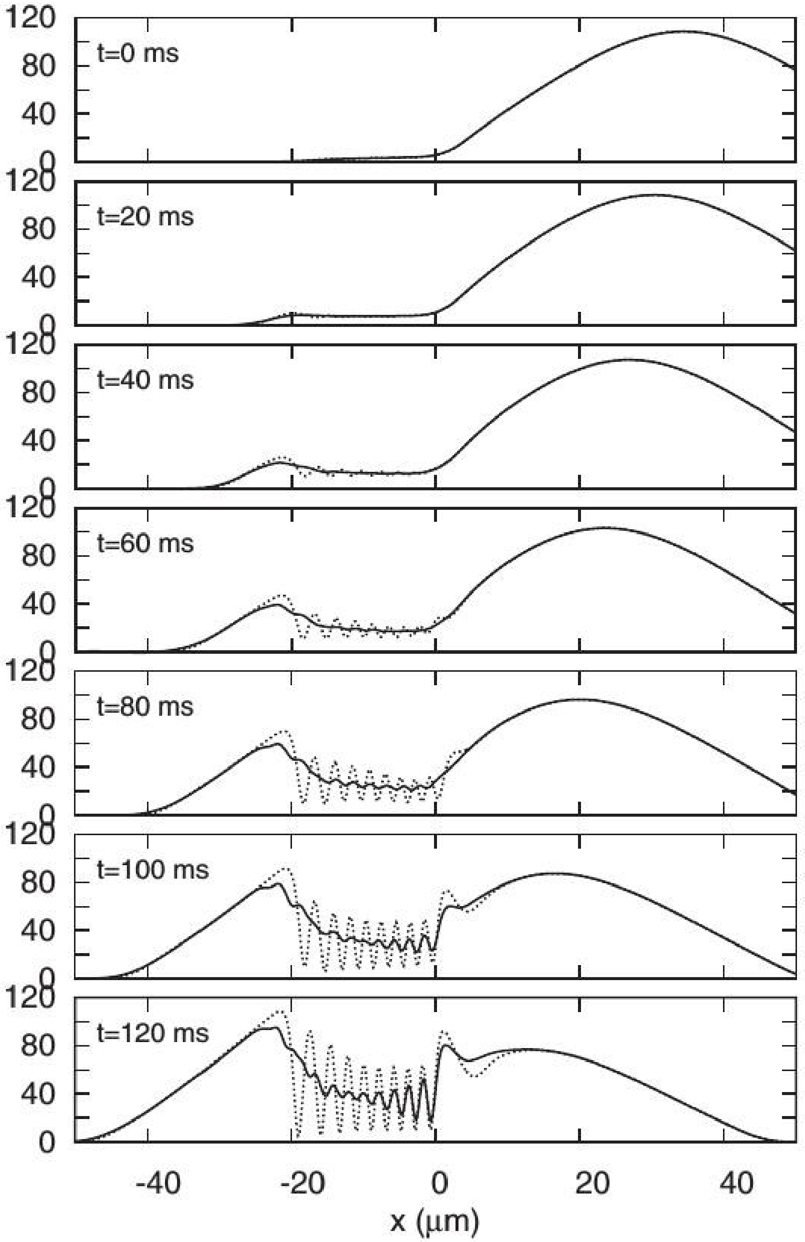
(Tettamanti et al., EPL 2016)

Reproduces quantitatively experimental features

- Observed effect appears to be classical
- Quantum fluctuations don't play crucial role

Further Maryland's concerns about BH lasing mechanism, Jacobson-Clark's group, PRA 96, 023616 (2017):

- WH region emits Cherenkov-Bogoliubov waves
- Amplitude of CB grows in time following atomic density at WH
- Interpretation validated by our numerics



Tettamanti et al., EPL (2016)

2- Hawking radiation (2016)

nature physics

ARTICLES

PUBLISHED ONLINE: 15 AUGUST 2016 | DOI: 10.1038/NPHYS3863

Observation of quantum Hawking radiation and its entanglement in an analogue black hole

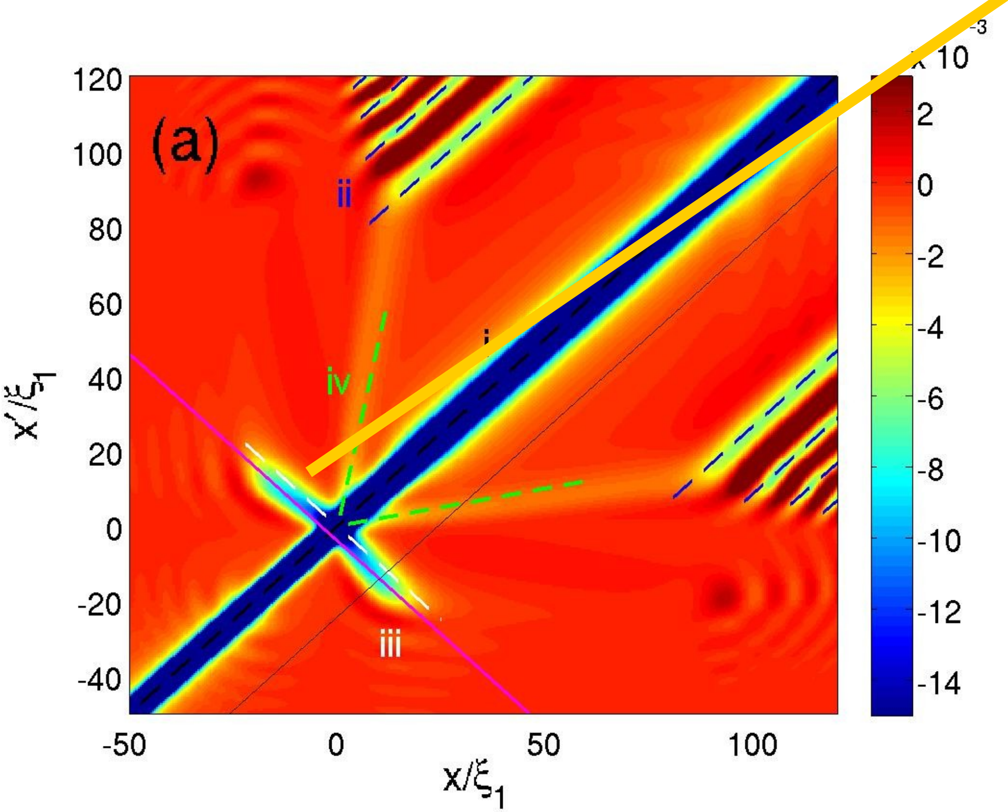
Jeff Steinhauer

We observe spontaneous Hawking radiation, stimulated by quantum vacuum fluctuations, emanating from an analogue black hole in an atomic Bose–Einstein condensate. Correlations are observed between the Hawking particles outside the black hole and the partner particles inside. These correlations indicate an approximately thermal distribution of Hawking radiation. We find that the high-energy pairs are entangled, while the low-energy pairs are not, within the reasonable assumption that excitations with different frequencies are not correlated. The entanglement verifies the quantum nature of the Hawking radiation. The results are consistent with a driven oscillation experiment and a numerical simulation.

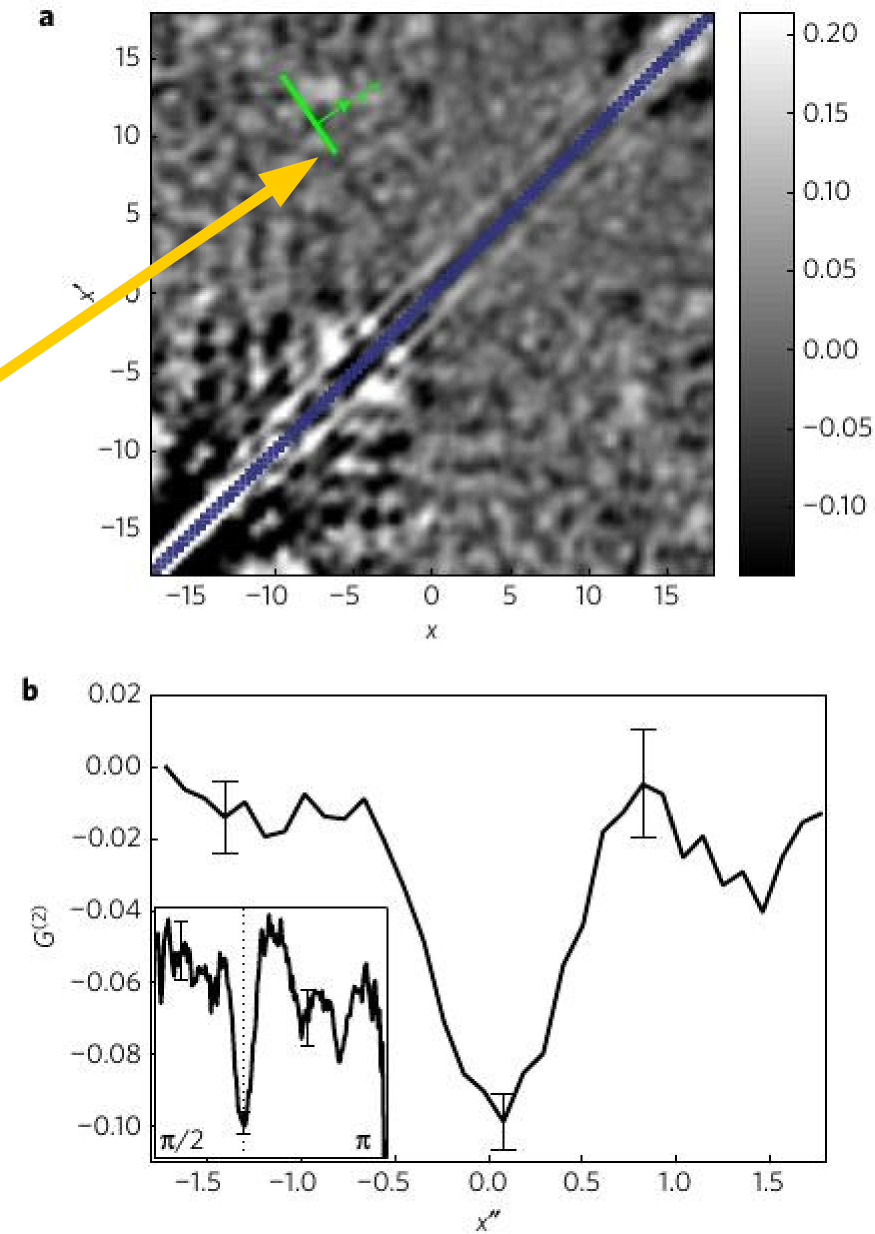
Analog Hawking radiation detected

Analog black hole configuration obtained by sending 1D atomic BEC against optical potential

Experimental evidence of HR based on Balbinot-Fabbri moustache in correlation function of density fluctuations



Theory: IC et al., NJP 2008



Expt: Steinhauer Nat. Phys. '16

Experimental evidence of entanglement

Peres-Horodecki criterion for non-separability

$$\Delta \equiv \langle \hat{b}^{\dagger}_{k_{\mathrm{HR}}} \hat{b}_{k_{\mathrm{HR}}} \rangle \langle \hat{b}^{\dagger}_{k_{\mathrm{P}}} \hat{b}_{k_{\mathrm{P}}} \rangle - |\langle \hat{b}_{k_{\mathrm{HR}}} \hat{b}_{k_{\mathrm{P}}} \rangle|^2 < 0$$

Population Anomalous correlation

Assumption of uncorrelated initial fluctuations
→ simplified Finazzi-IC protocol to
extract anom. corr. from density fluct.

Entanglement visible in intermediate k-range
→ HR from zero-point fluctuations
→ produces entangled phonon pairs

Are data statistically significant?
No other possible explanation?

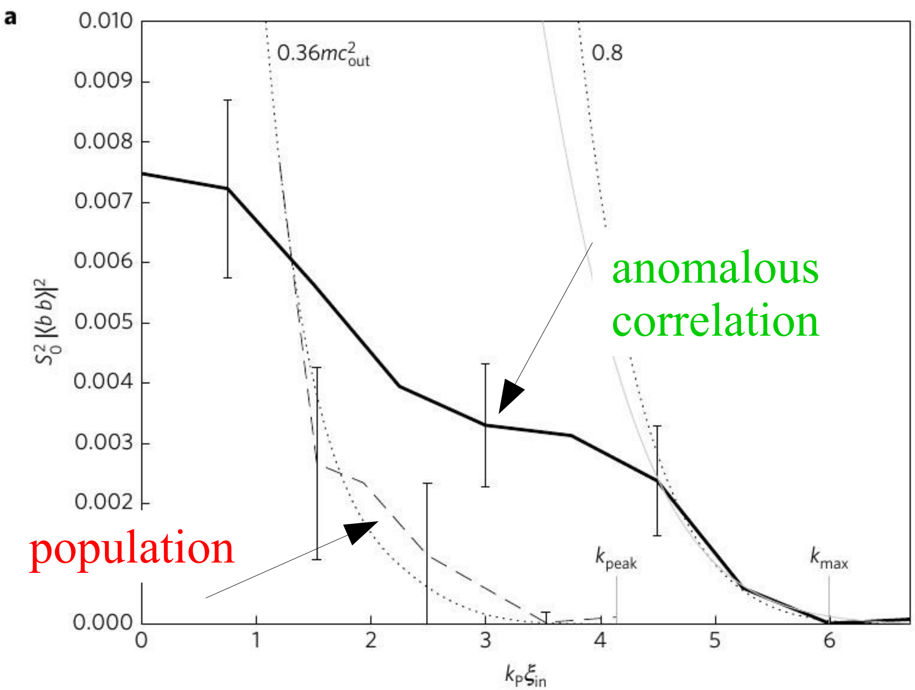


Figure from Steinhauer, Nat. Phys. '16

Long-term perspectives

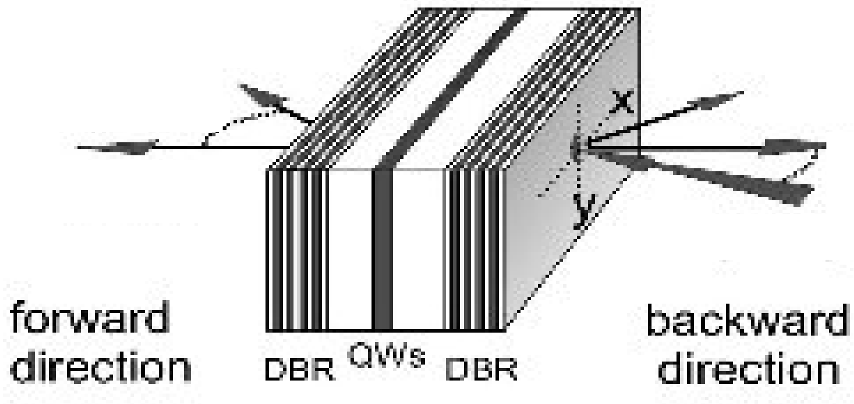
- Quantum Hydrodynamics: Navier-Stokes eqs. with hats on macroscopic hydrodynamic variables
- Entangled states of a macroscopic fluid

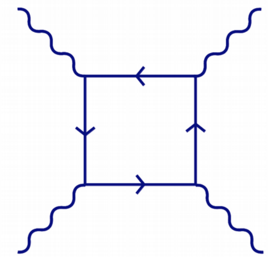
Much more theoretical work by de Nova, Sols, Parentani, Bruschi, Fuentes, etc.

Part 2:

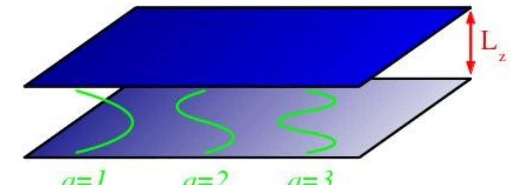
Quantum fluids of light

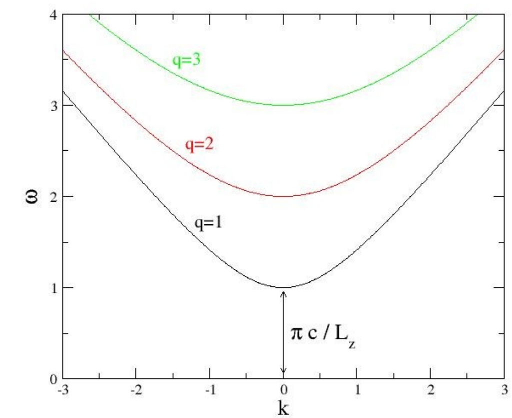
What are quantum fluids of light?





$$\sigma \sim \alpha^4 \frac{\hbar^2}{m^2 c^2} \left(\frac{\hbar \omega}{mc^2} \right)^6$$





- Photons confined to propagate along microcavity plane
- Spatial confinement along z provides photon mass

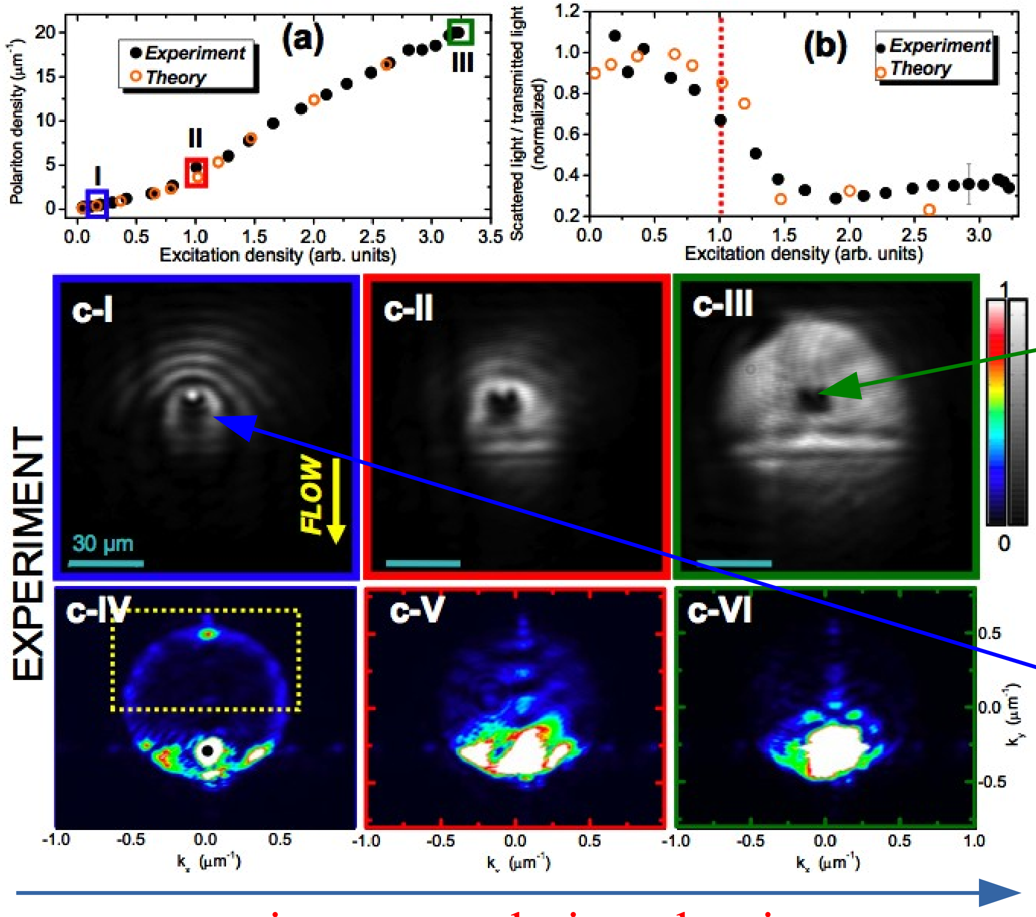
- $\chi^{(3)}$ optical nonlinearity (due to excitonic component) provides binary interactions

- Laser pump coherently injects photons:
  - → radiative losses determine non equilibrium steady state
  - → coherence of polariton fluid guaranteed by coherent pump
- All properties of in-cavity photon fluid transferred to secondary emitted light

- Alternative platform: propagating light in bulk nonlinear media → see Victor's talk later on

IC and C. Ciuti, *Quantum fluids of light*, RMP **85**, 299 (2013)

Experimental observation of superfluid behaviour



superfluid flow

scattering
on weak defect

increase polariton density

Figure from LKB-P6 group:
A.Amo, J.Lefrère, S.Pigeon, C.Adrados, C.Ciuti, IC, R. Houdré, E.Giacobino, A.Bramati, *Observation of Superfluidity of Polaritons in Semiconductor Microcavities*, Nature Phys. **5**, 805 (2009)

Theory: IC and C. Ciuti, PRL **93**, 166401 (2004)

Acoustic horizons in fluid of light

Polariton-polariton interactions

- Bogoliubov phonon dispersion
  on top of polariton condensate

Pump at an angle

- finite in-plane wavevector,
  so condensate is flowing

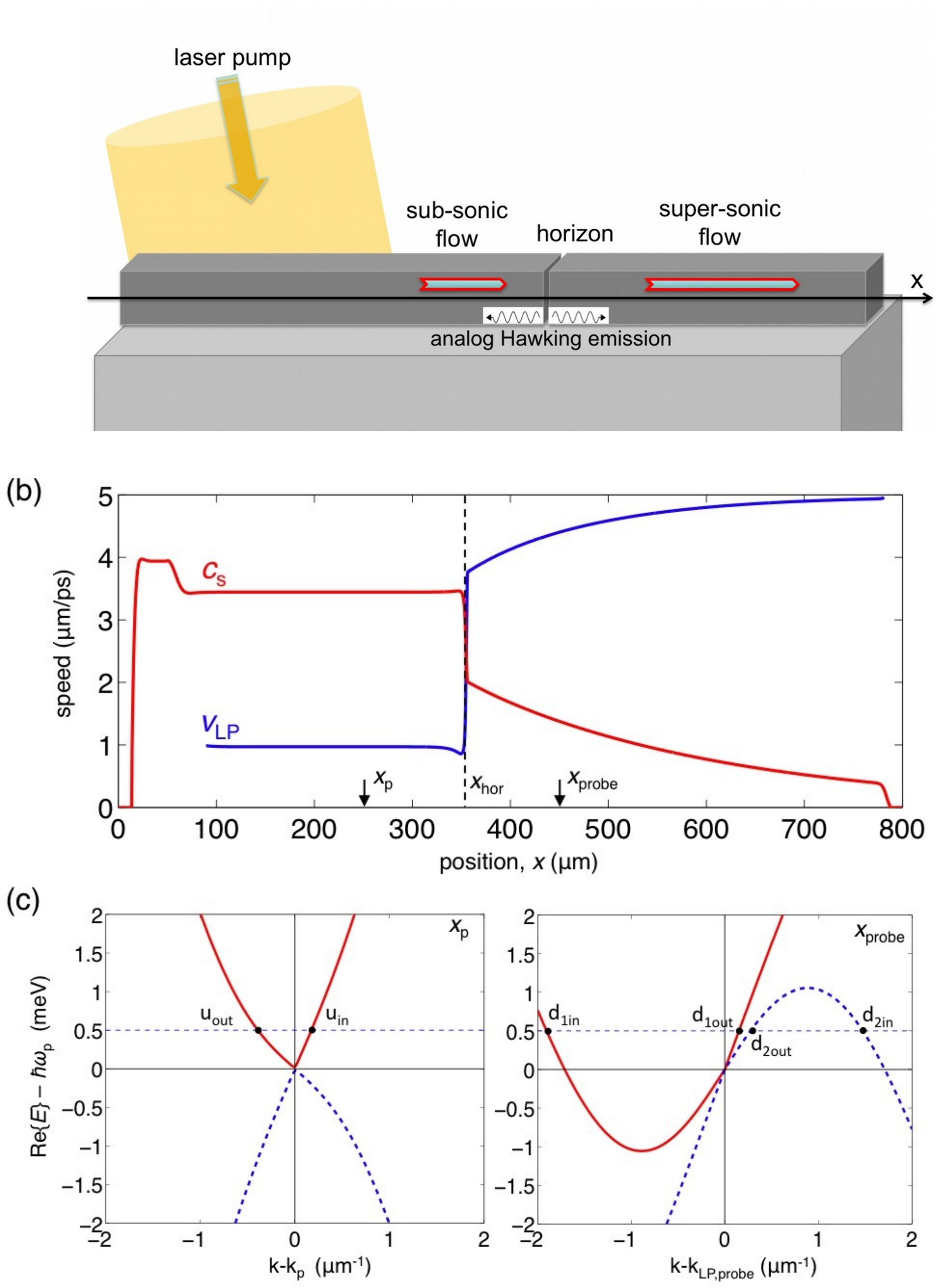
Tailored pump spot + Defect

➔ Horizon with large surface gravity

Hawking emission

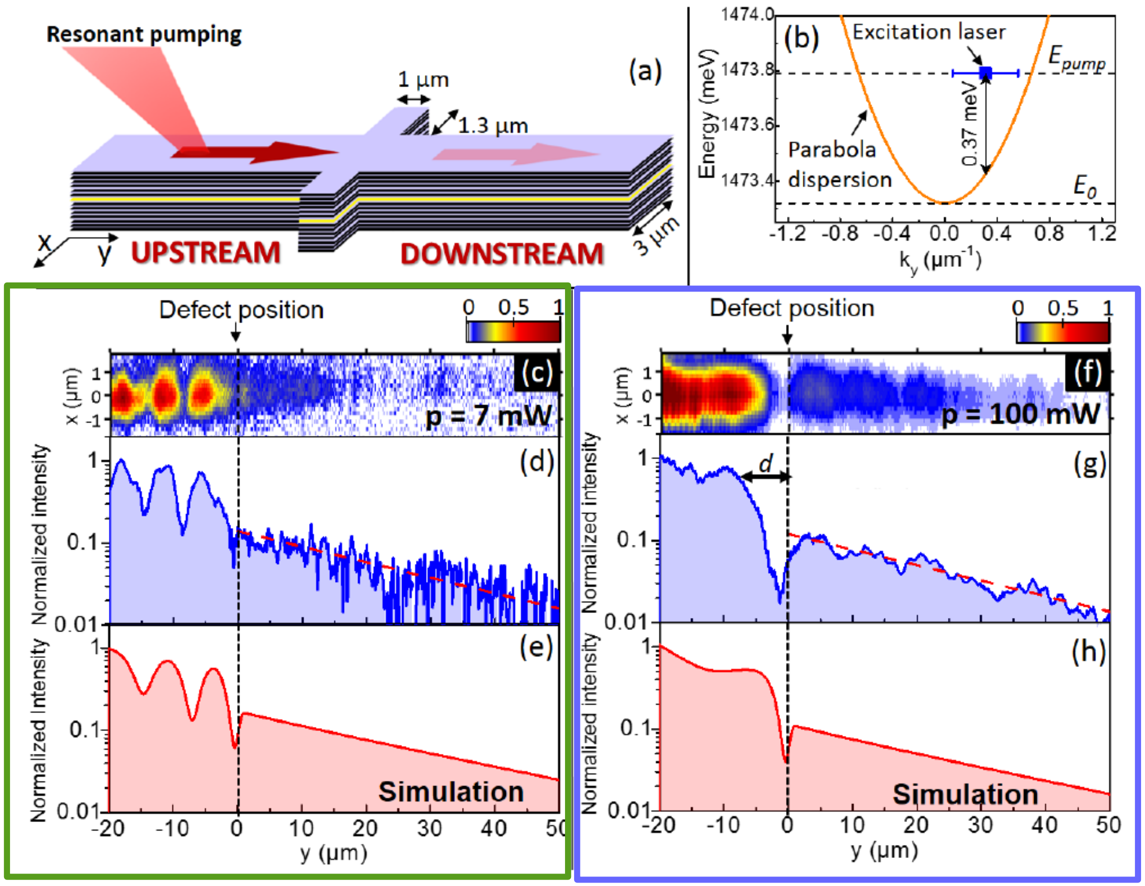
- phonons on photon fluid
- correlations of emitted light
- much higher T_H thanks to small photon mas

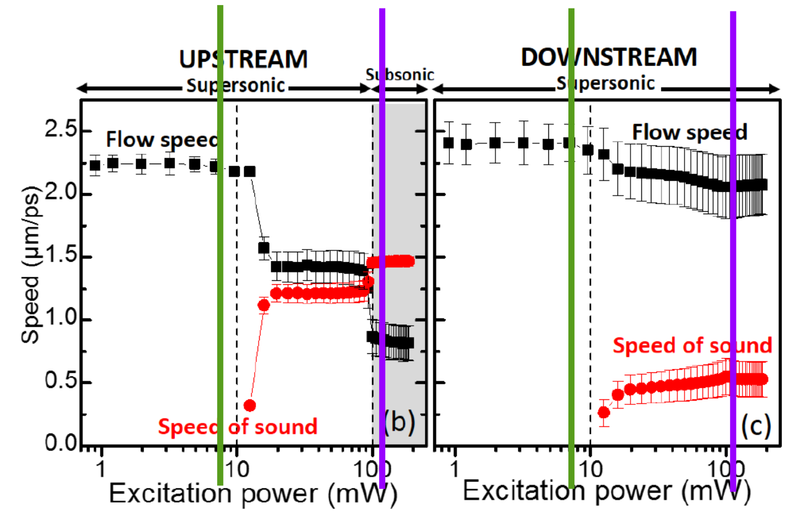
first proposed by F. Marino, PRA **78**, 063804 (2008)



D. Gerace and IC, PRB **86**, 144505 (2012)

Experimental results @ LPN





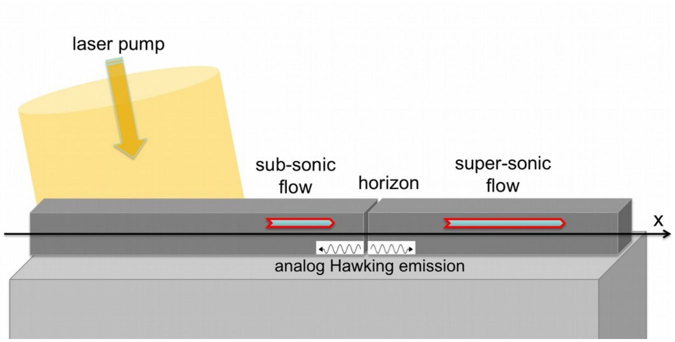
BH created!

The hunt for
Hawking radiation
is now open!!

H.-S. Nguyen, Gerace, IC, *et al.,* PRL **114**, 036402 (2015)

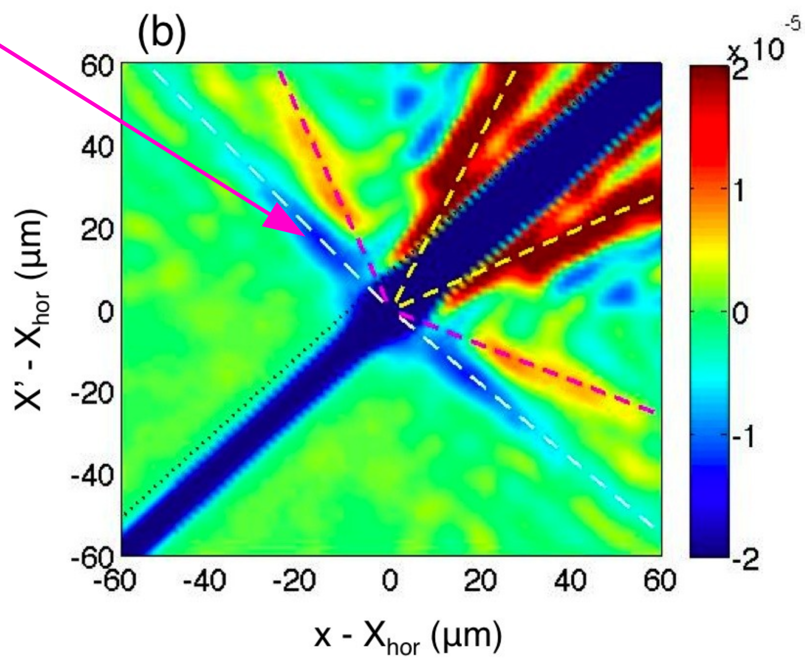
Hawking emission in dissipative photon fluids

- Wigner-MC simulation with driving/losses: $i\,dE = \left\{ \omega_o - \frac{\hbar \nabla^2}{2m} + V_{ext} + g|E|^2 - \frac{i}{2}\gamma \right\} E\; dt + F_{ext}(x,t)\; dt + dW$



- Near-field emission pattern from wire :
  Correlation function of intensity noise
  at different positions (x,x')

- Signature of Hawking radiation processes:
  "Balbinot-Fabbri" correlation tongues
  Conversion of zero-point fluctuations
  into correlated pairs of Bogoliubov phonons
  propagating away from horizon



- In optics language:
  parametric emission of entangled photons
  flow+horizon play role of pump
  photons dressed by fluid into phonons

- Proposed experiment (in progress):
  - steady state under cw pumping
  - collect near-field emission
  - measure intensity noise
  - integrate over long time to extract signal out of shot noise

D. Gerace and IC, PRB **86**, 144505 (2012); P. Grisins, H.-S. Nguyen, J. Bloch, A. Amo and IC, PRB **94**, 144518 (2016).

Conclusions and perspectives

Push forward experiments with artificial black holes in atoms and polaritons:

- Confirm presence of instability in atomic experiment (Steinhauer, Nat. Phys. 2014)
- Describe quantitatively and understand Hawking emission experiment (Steinhauer, Nat. Phys. 2016)
- HR in spinor condensates → promising to highlight back-reaction (Butera, Ohberg, IC, PRA 2017)

- (In progress) Pump/probe stimulated Hawking radiation in microcavity photons system (Nguyen et al., PRL 15, Grisins et al., PRB 16)
- (Longer run: theory+experiments) Assess quantum origin of spontaneous HR from zero-point fluctuations at the horizon

- Explore conceptually new strategy: propagating fluids of light
  - → Theory: conservative dynamics under z/t mapping (Fouxon, Fleurov et al., EPL 2010; Larré, IC, PRA 2015)
  - → Experiments @ Heriot-Watt (Faccio) and @ Tel Aviv (Bar Ad & Fleurov)

- Investigate more complex geometries
  - Black hole lasing in BH/WH configurations
  - Vortex configurations: Superradiance, ergoregions around rotating BHs (quantum features unaccessible to surface-wave experiments)

→ quantum simulator for curved-space-time QFT, give insight on high-energy questions

The future:

Back-reaction effects

(towards BH evaporation)

The little I understand about back-reaction in astrophysics & quantum gravity

What is the long-term fate of a BH?

HR carries away energy, so horizon must (very slowly) shrinks to conserve energy/mass

According to some theories, BH horizon may eventually disappear

- What is left once BH has disappeared ?
- Is there any remnant of what has fallen into the BH ?

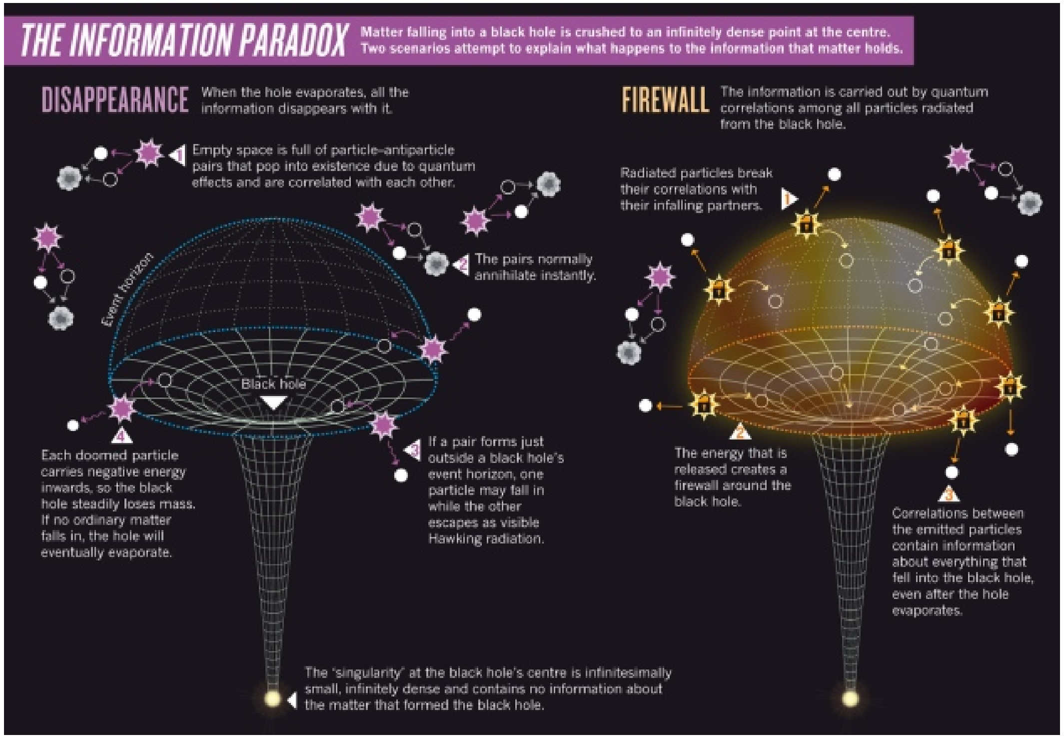


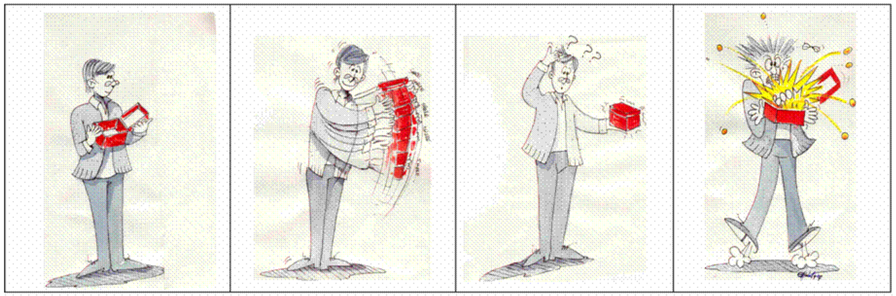
Figure from Nature, 496 (2013)

Our approach:

- Analog models simulate well QFT on curved space-time...
- ...but Einstein eqs. (coupling of matter/energy to metric) not implemented

Still, any hint from higher order couplings of quantum fluctuations to macroscopic flow?
What can a quantum optician's point of view teach on this physics?

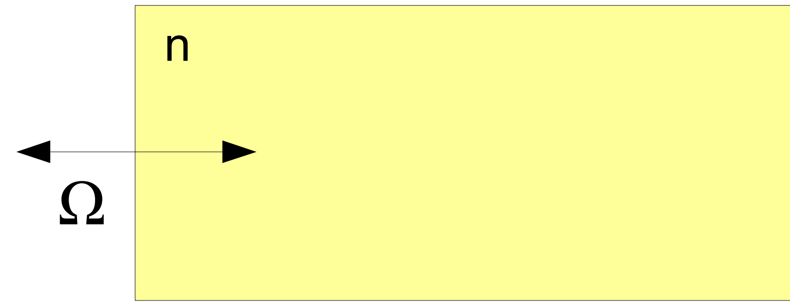
My favourite toy model
Back-reaction effect of dynamical Casimir emission



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 !!



Simplest configuration:

- Half-space slab of refractive index n and mass M
- Mechanically oscillating at frequency Ω

- Prediction for the dissipated energy within 1D scalar model:

$$Q^{-1}=\frac{\tau}{2\pi E_{osc}}\frac{dE_{diss}}{dt}=\frac{1}{6}\left(\frac{n-1}{n}\right)^2\frac{\hbar\Omega}{Mc^2}$$

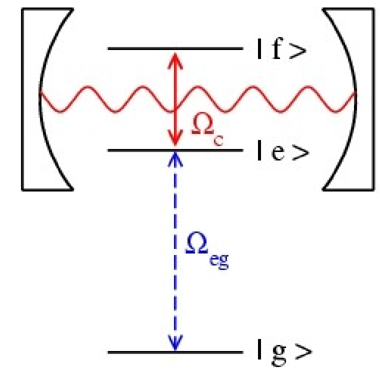
(from Barton and Eberlein, Ann. Phys. 227, 222 (1993))

→ value is ridiculously small

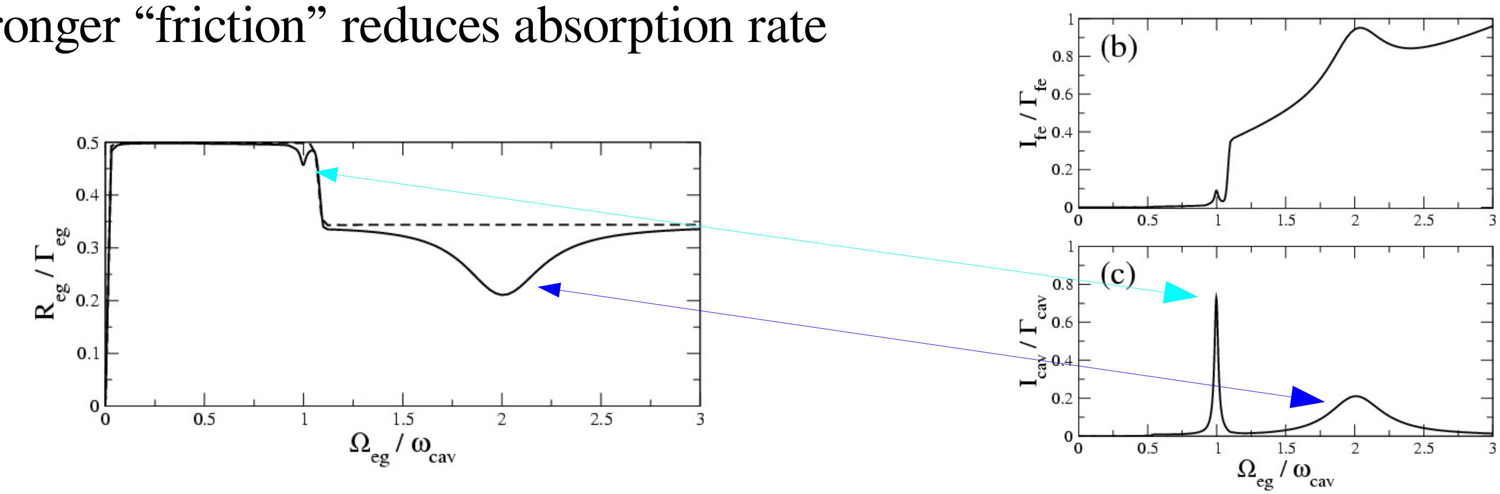
→ hopeless experimental observation by mechanical means, but...

All-optical back-reaction effect

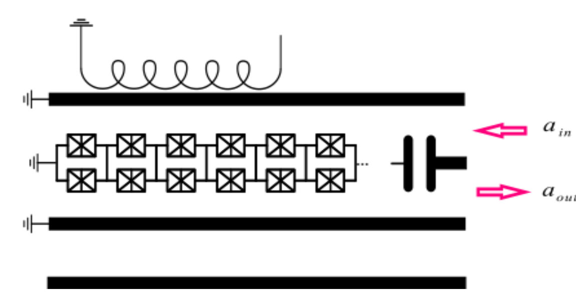
Coherently-driven three-level emitter embedded in optical cavity



- Drive laser on g ↔ e transition experiences absorption
- Absorbed energy $R_{eg} = 2\Omega_{eg}\,\mathrm{Im}\{\mathrm{Tr}[\hat{c}^{\dagger}_{eg}\,\rho_{ss}]\}.$
- Peaks in DCE give dip in absorption:
  stronger “friction” reduces absorption rate



- “Easily” observed with optical or μ-wave
  (circuit-QED) techniques
- Theoretical challenge: extend to analog BH’s!



IC, S. De Liberato, D. Gerace, C. Ciuti, *Back-reaction effects of quantum vacuum in cavity-QED*, PRA **85**, 023805 (2012)

If you wish to know more...

Living Reviews in Relativity

December 2011, 14:3 | Cite as

Analogue Gravity

Authors | Authors and affiliations

Carlos Barceló, Stefano Liberati, Matt Visser

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First Online: 11 May 2011

Nat. Phys., Aug.15h, 2016

news & views

QUANTUM HYDRODYNAMICS

Acoustic Hawking radiation

A milestone for quantum hydrodynamics may have been reached, with experiments on a black hole-like event horizon for sound waves providing strong evidence for a sonic analogue of Hawking radiation.

Iacopo Carusotto and Roberto Balbinot

REVIEWS OF MODERN PHYSICS, VOLUME 85, JANUARY–MARCH 2013

Quantum fluids of light

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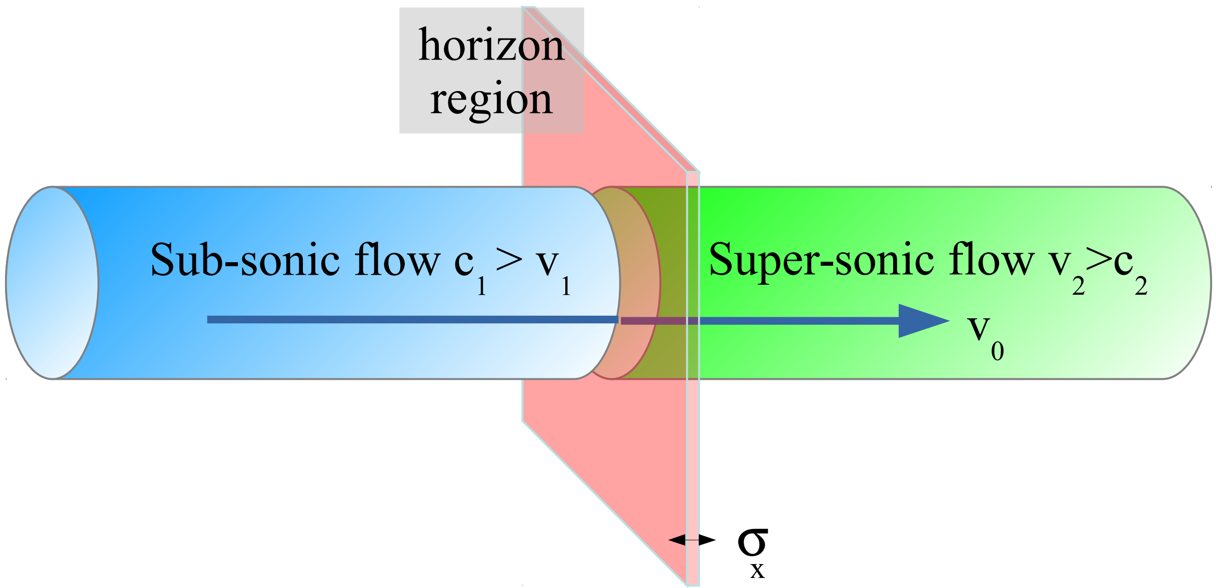
(published 21 February 2013)

I. Carusotto and C. Ciuti, Reviews of Modern Physics **85**, 299 (2013)

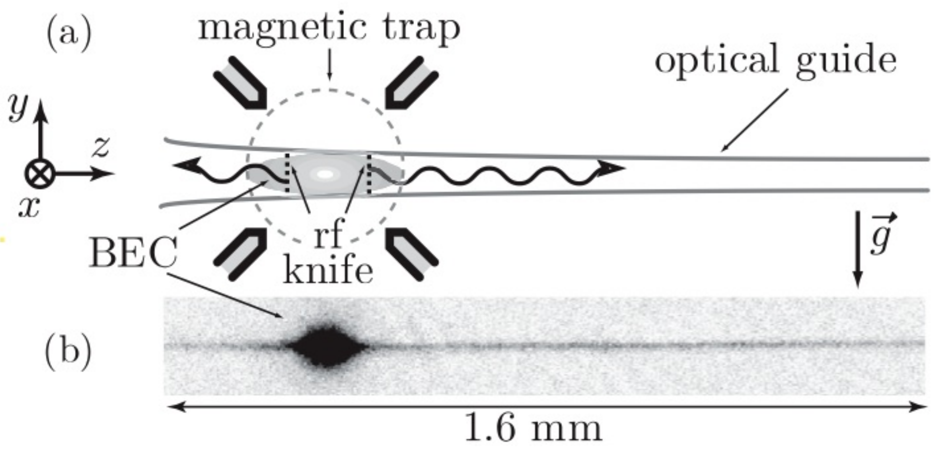
Come and visit us in Trento!

How to generate and study an acoustic black hole ?

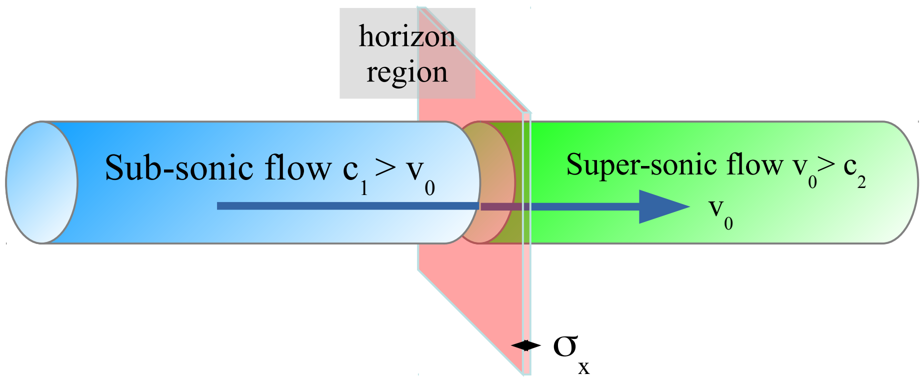


- start from some uniform flow
- switch on horizon at t=0 and go to black-hole regime $c_1 > v_1$, $v_2 > c_2$
  - minimize deterministic disturbances, e.g. Landau processes (in super-sonic region) and soliton shedding during and after switch-on
- concentrate on quantum fluctuations
  - isolate (thermal) Hawking emission from background phonons (also thermal)

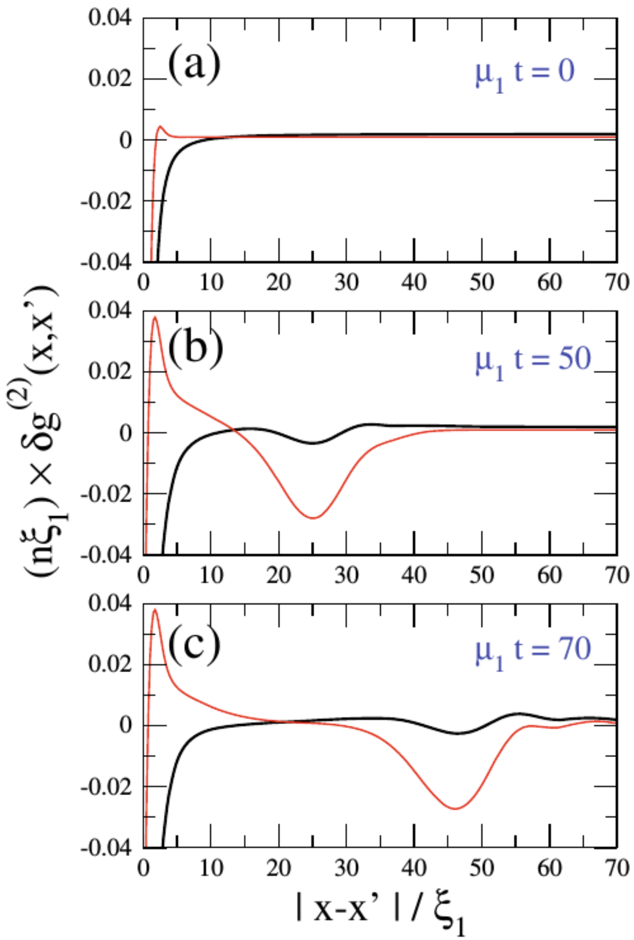
Space-dependent Feshbach resonance



From: W. Guerin *et al*., PRL **97**, 200402 (2006)

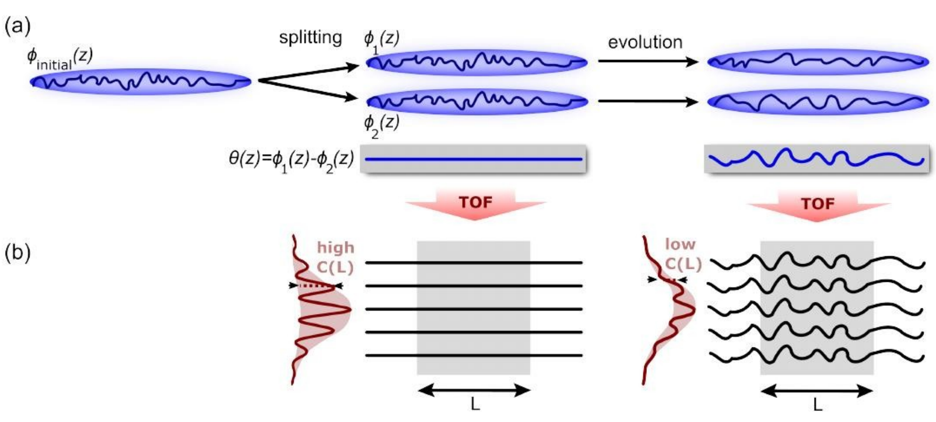


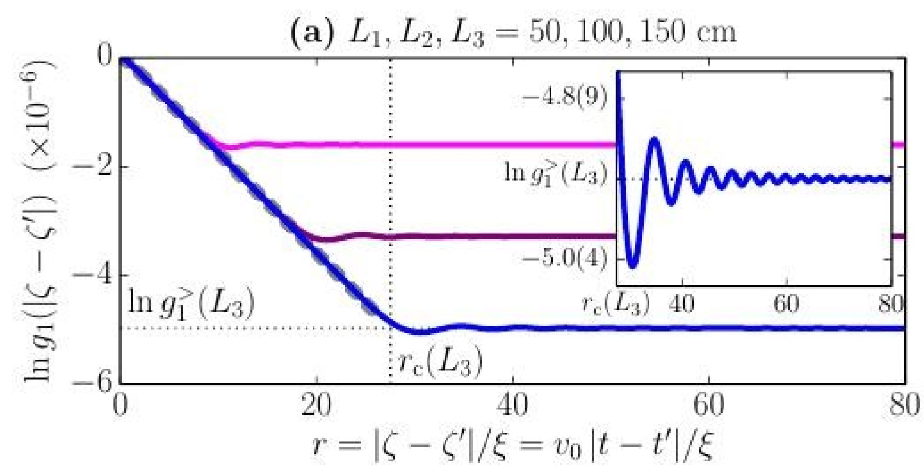
- Out-coupled atom laser beam: uniform density and velocity v_0
- Atom-atom interaction constant initially uniform and equal to g_1
- Within σ_x around t=0: modulation $g_1 \rightarrow g_2$ and $V_1 \rightarrow V_2$ in x>0 region only
  via: Feshbach resonance (g depends on applied B) or modify transverse confinement
- Step in nonlinear coupling constant g → step in sound speed c.
- Black-hole formed if $c_1 > v_0 > c_2$. Arbitrarily large surface gravity via thickness σ_x of crossover region
- Chemical potential jump to be compensated by external potential $V_1 + ng_1 = V_2 + ng_2$
  allows to avoid Cerenkov-Landau phonon emission, soliton shedding
- Experiments in Steinhauer, Nat. Phys. 10, 864 (2014) → slightly different geometry w/o Feshbach.
  Upper bound in surface gravity?



Dynamical Casimir signal on $g^{(2)}(x-x')$:

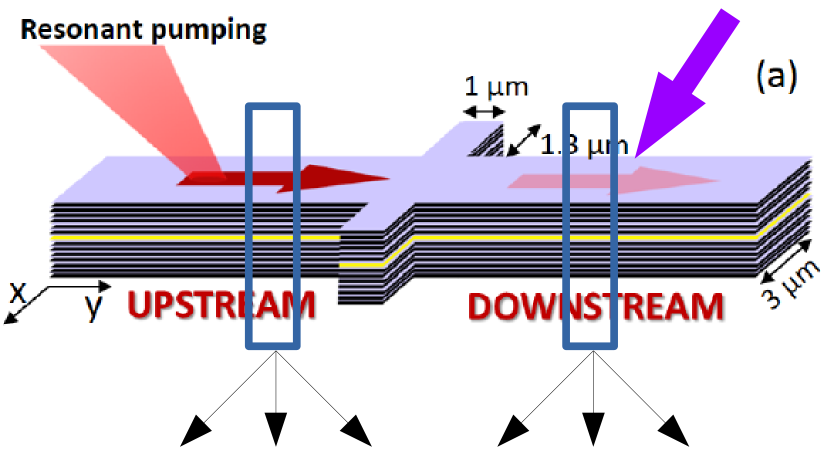
- density counterpart of phase decoherence in split atomic BEC's
- continuity eq. $\partial_x v+\partial_t n=\partial_x(i\partial_x\theta)+\partial_t n=0$ links dip in $g^{(2)}(x-x')$ to sharp corner in $g^{(1)}(x)$ (within hydrodynamic limit)

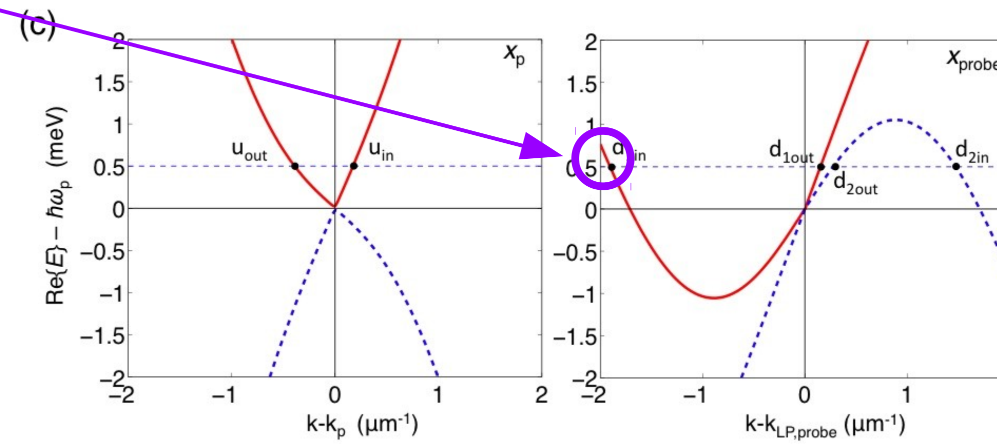




Pump-probe detection of (classical) HR

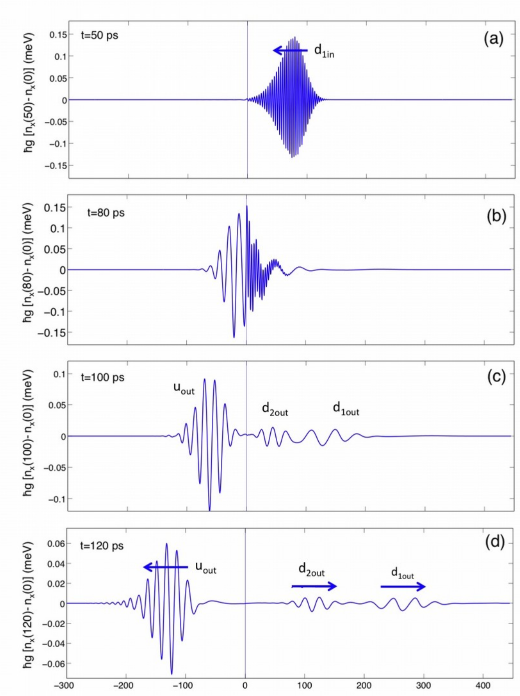
CW probe beam





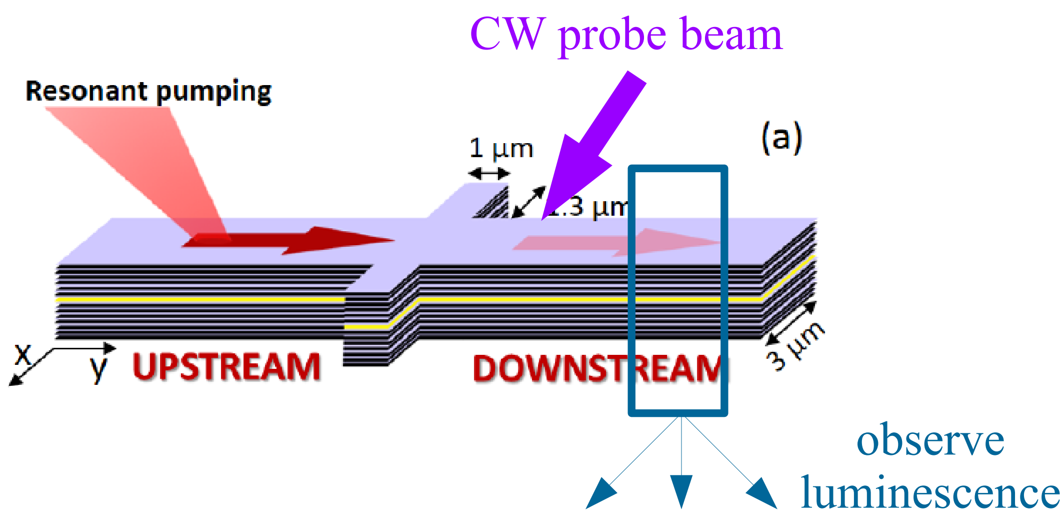
- CW probe at ω_{probe} , frequency resolved detect at ω_{probe} and FWM signal @ $2\omega_{pump}$-ω_{probe}
- Stimulated Hawking on mode d_{2out} → peak in angular distribution
- Scattering matrix S(ω) → signature of thermal Hawking emiss.
- In contrast to pulse expt, no need for temporal resolution

Expt with surface waves on water (Weinfurtner, Unruh, PRL 2010) appears not conclusive as no horizon present, new expt in progress (Rousseaux)

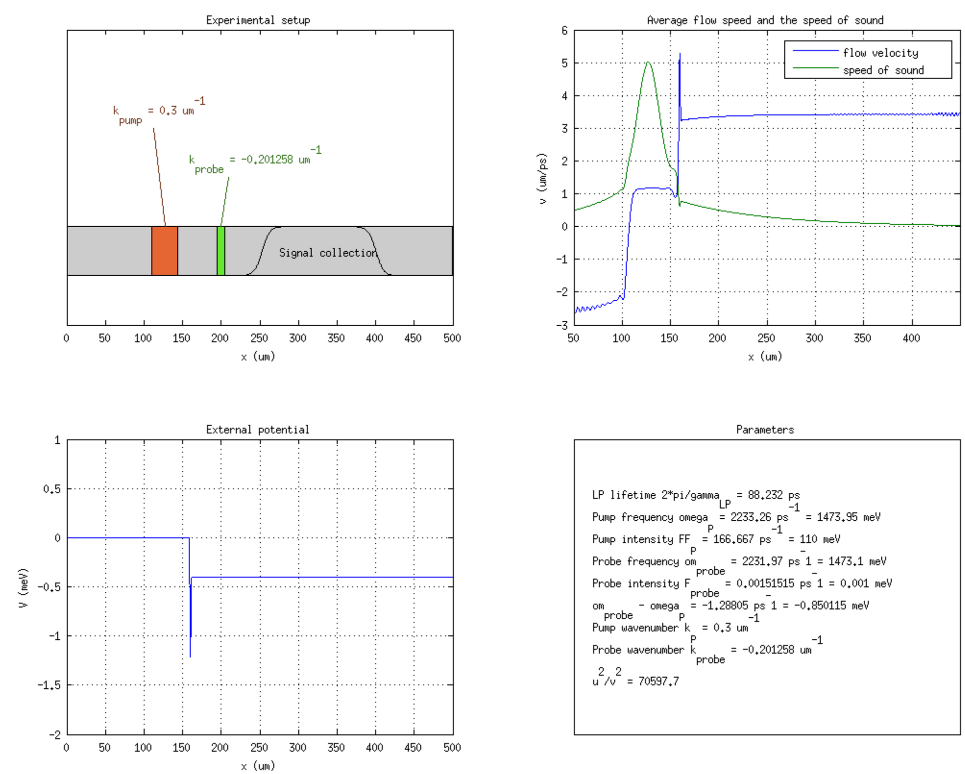


Gerace, IC, PRB 2012

Numerical simulations



- Parameters extracted from LPN experiment
- Add "waterfall" potential downstream of defect to facilitate HR observation
- Sample under fabrication @ LPN



P. Grisins et al., arXiv: 1606.02277 (2016)

Classical Hawking signal

Collected frequency-selected momentum distribution:

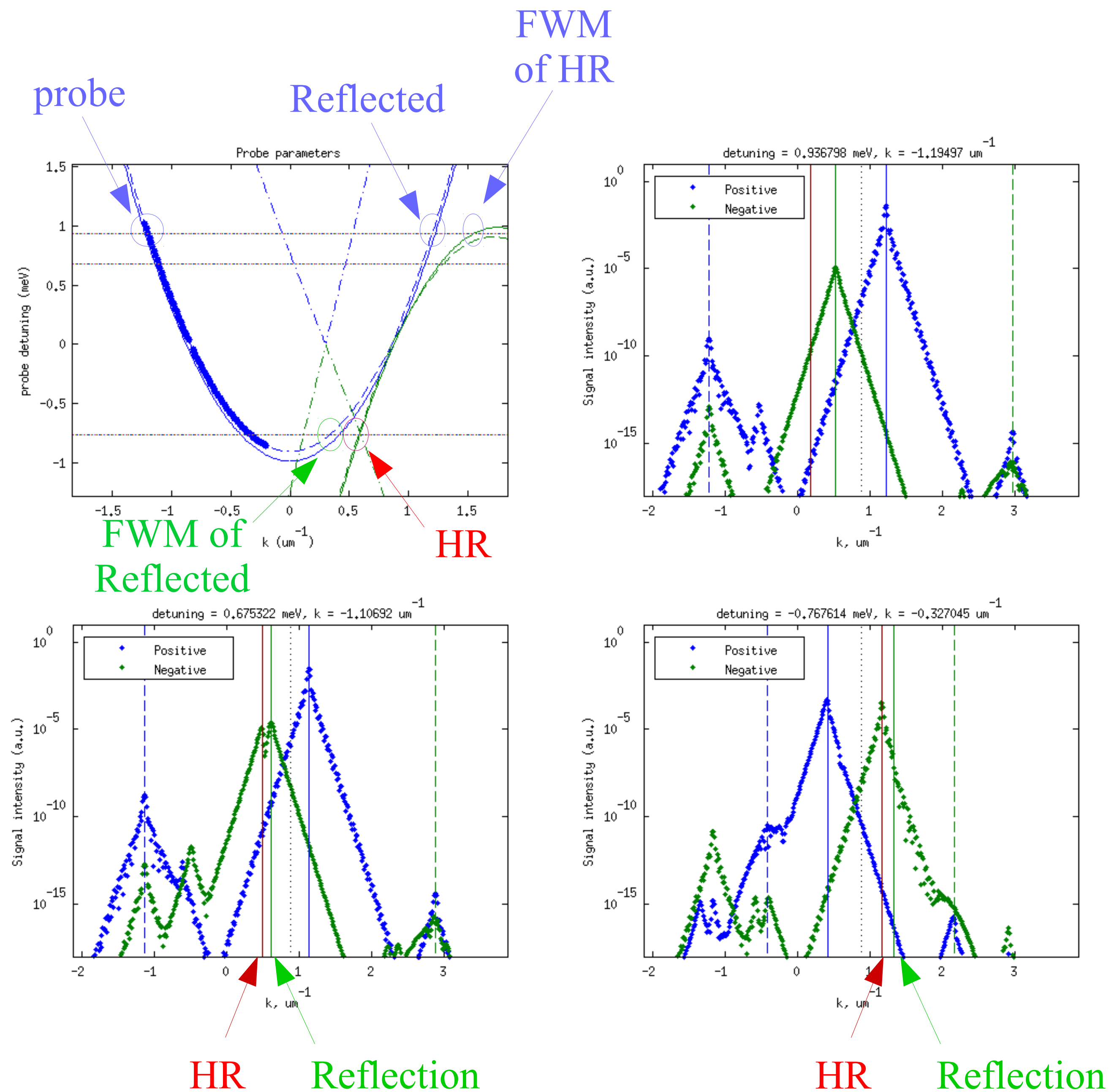
- Probe frequency ω_{pr} (Blue)
- FWM frequency $\omega_{FWM}=2\omega_{pump}-\omega_{pr}$ (Green)

Hawking processes:
→ additional scattering channel

Reflected signal dominates @ ω_{pr}

HR comparable to FWM of reflection @ ω_{FWM}

HR dominates for $\omega_{pr}<\omega_{pump}$

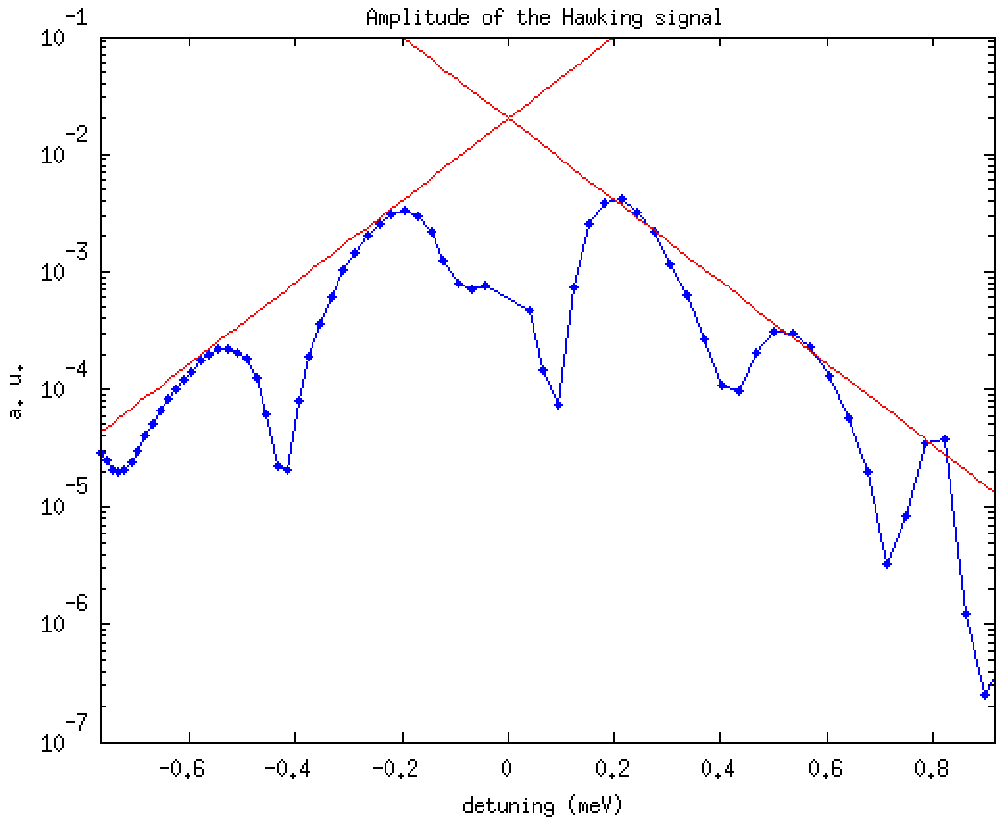


P. Grisins et al., arXiv: 1606.02277 (2016)

Estimated Hawking temperature

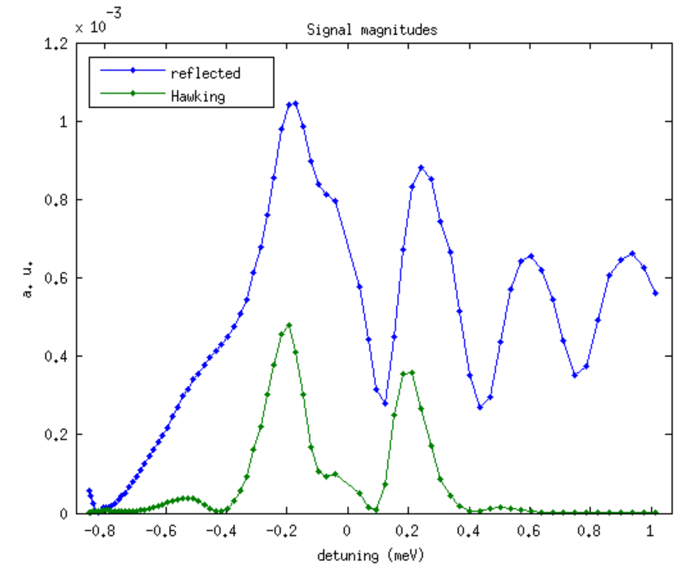
ω_{pr} dependence of Hawking peak
→ thermal tail @ T_H

- Numerical → T_H~1.4 K
  (after correcting for propagating losses)
- Not far from theoretical prediction T_H~1 K
  from gravitational analogy



P. Grisins et al., arXiv: 1606.02277 (2016)

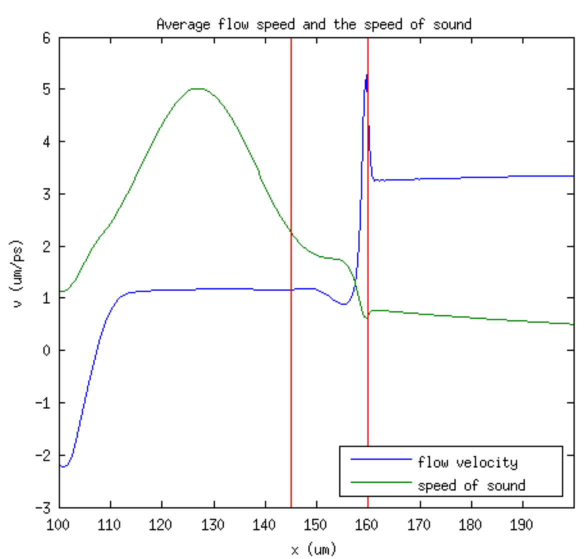
Why oscillations?

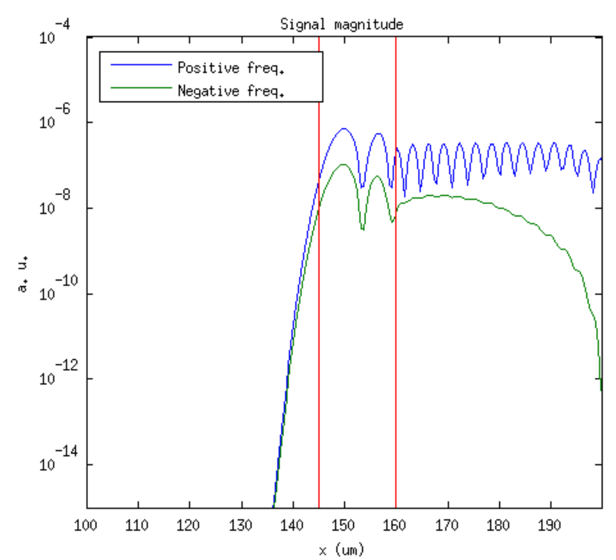


BH horizon and strong pump form cavity for phonons

Reflected and Hawking signals oscillate with ω_{pr}

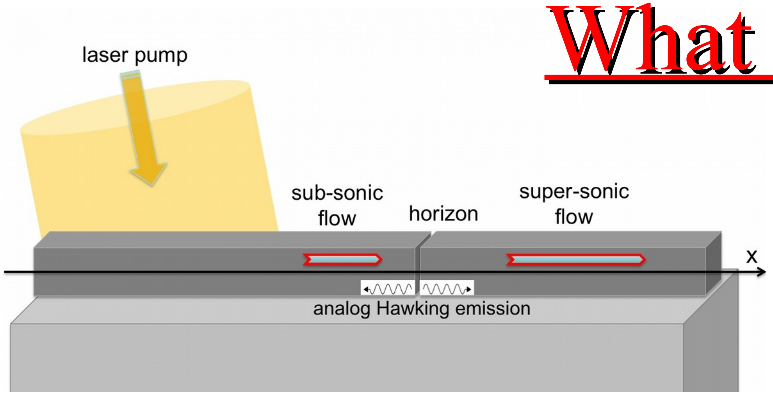
Optical analogs of "eternal BHs" in thermal equilibrium with environment, e.g. with mirror right above horizon

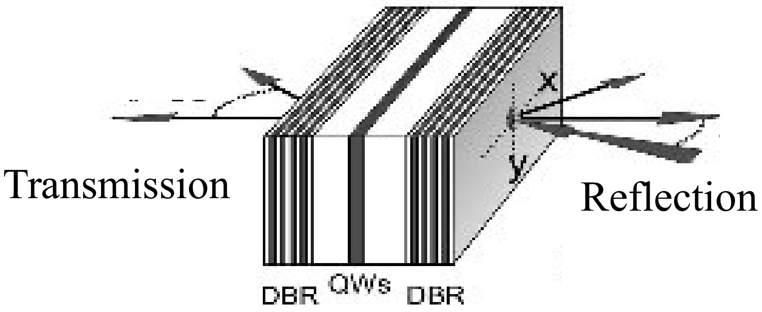




P. Grisins et al., arXiv: 1606.02277 (2016)

What about dissipation?





Light fluid in cavity coupled to dissipation baths:

- radiative emission → photon decay at rate γ; used to observe field, compensated by pump
- description in terms of master equation for density matrix ρ

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] + \frac{\gamma}{2}\int dr \left[2\psi(r)\,\rho\,\psi^\dagger(r) - \psi^\dagger(r)\,\psi(r)\,\rho - \rho\,\psi^\dagger(r)\,\psi(r)\right]$$

$$H = \int dr \left[\psi^\dagger(r)\left(\omega_o - \frac{\hbar\nabla^2}{2m}\right)\psi(r) + \frac{g}{2}\psi^\dagger(r)\,\psi^\dagger(r)\,\psi(r)\,\psi(r) + F(r,t)\,\psi^\dagger(r) + F^*(r,t)\,\psi(r)\right]$$

Fluctuation-dissipation theorem:

- quantum noise acts back onto quantum field
- accurate description in terms of classical field eqs. + stochastic noise

Properties of photon fluid affected by non-equilibrium nature:

- richer dispersion of Bogoliubov excitations; condensation at $k \neq 0$; …
- steady-state population of Bogoliubov modes

IC and C. Ciuti, *Quantum fluids of light*, RMP **85**, 299 (2013)

What about acoustic horizons in fluids of light?

Polariton-polariton interactions

- Bogoliubov phonon dispersion
  on top of polariton condensate

Pump at an angle

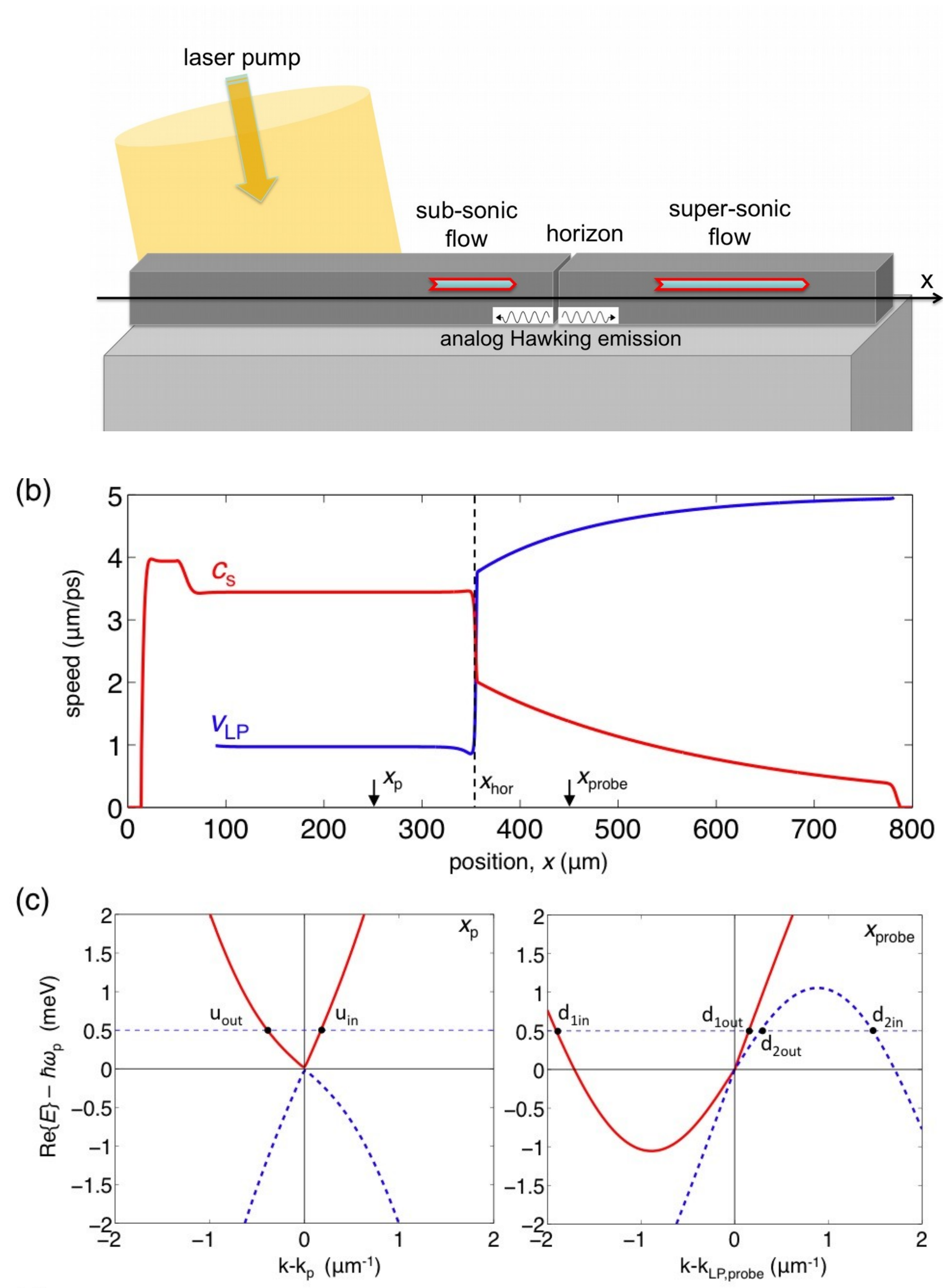
- finite in-plane wavevector,
  so condensate is flowing

Tailored pump spot + Defect

➔ Horizon with large surface gravity

Hawking emission

- phonons on photon fluid
- correlations of emitted light



D. Gerace and IC, PRB **86**, 144505 (2012); similar results in Solnyshkov et. al., PRB 84, 233405 (2011)

Is HR in microcavities a quantum process?

Unavoidable losses of microcavity device generate excitations in the fluid:
lost photon → creates hole → Bogoliubov excitation

Spurious excitations up to $\omega \sim gn$, comparable to T_H

X.Busch, R.Parentani, IC, *Spectrum and entanglement of phonons in quantum fluids of light*, PRA 2014

Might be tamed by tayloring ω-dependent reflectivity of cavity mirror
(as it is likely occurring in atom outcoupling from trap)

Stimulate Hawking processes giving rise to "thermal" Hawking signal:

- Density correlation signal reinforced
- Quantum entanglement still present ?
  - How to detect it ?
  - Hong-Ou-Mandel on emitted light spatially + wavevector-selected ?