Toward the observation of Hawking Radiation in a fluid of polaritons

• Kévin Falque, Quentin Glorieux, Maxime Jacquet, Alberto Bramati
Analog Gravity

Unruh PRL 1981: wave equation for acoustic field in a trans-sonic fluid is isomorphic to wave equation for electromagnetic field on black hole spacetime.

Experimental Black-Hole Evaporation?

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It is shown that the same arguments which lead to black-hole evaporation also predict that a thermal spectrum of sound waves should be given off from the sonic horizon in transsonic fluid flow.

which result in an equation for \( \tilde{\psi} \),

\[
\frac{1}{\rho_0} \left[ \frac{\partial}{\partial t} \frac{\rho_0 \tilde{v}}{g'(\xi_0)} \frac{\partial \tilde{\psi}}{\partial t} + \frac{\partial}{\partial t} \frac{\rho_0 \tilde{v}}{g'(\xi_0)} \cdot \nabla \tilde{\psi} + \nabla \left( \frac{\rho_0 \tilde{v}}{g'(\xi_0)} \frac{\partial \tilde{\psi}}{\partial t} \right) - \nabla \cdot \rho_0 \nabla \tilde{\psi} + \nabla \cdot \left( \frac{\tilde{v}}{g'(\xi_0)} \frac{\rho_0}{\nabla \cdot \tilde{v}} \cdot \nabla \tilde{\psi} \right) \right] = 0.
\]

These are precisely the equations for a massless scalar field in a geometry with metric
Unruh PRL 1981: wave equation for acoustic field in a trans-sonic fluid is isomorphic to wave equation for electromagnetic field on black hole spacetime.
Unruh PRL 1981: wave equation for acoustic field in a trans-sonic fluid is isomorphic to wave equation for electromagnetic field on black hole spacetime.

Flow

**Acoustic horizon**

- **Upstream**: subsonic
  - Speed of sound
  - Flow velocity of fluid

- **Downstream**: supersonic
  - Hawking radiation
  - Partner radiation

**Event Horizon**
Acoustic horizon in Quantum fluid of polaritons

Speed of sound
Flow velocity of fluid

Ref:
- Jacquet et al, EPJD 2022
Microcavity polaritons

**Polaritons**: quasi-particles resulting from the strong coupling of cavity photons with quantum wells excitons

**Strong coupling** regime: $\gamma X, \gamma C << \Omega_R$

$\rightarrow$ Photons/Excitons energies anticrossing

**New eigenstates**: Upper Polariton (UP) and Lower Polariton (LP) = half light/ half matter quasi particles

Ref: Quantum fluid of light, 2012 – Carusotto & Ciuti
Microcavity polaritons

Polaritons: quasi-particles resulting from the strong coupling of cavity photons with quantum wells excitons

Dynamics described by the Driven Dissipative Gross Pitaevskii Equation

\[ i\hbar \frac{\partial \psi}{\partial t} = \left( -\frac{\hbar^2 \nabla^2}{2m_{LP}^*} + gn \right) \psi - \frac{i\hbar \gamma}{2} + P(r, t) \]

Driven Dissipative dynamics → Out of Equilibrium system

\( g \): Interaction constant
\( \gamma \): Polariton lifetime (loss rate)
\( P \): Pump term
**Full optical experiment**

**Polaritons**: quasi-particles resulting from the strong coupling of cavity photons with quantum wells excitons

\[ \psi(x, t) = \sqrt{n(x, t)} e^{i\phi_{LP}(x,t)} \]

- density measurement: \[ c_s = \frac{\sqrt{gn}}{m} \]
- phase measurement: \[ \nu = \frac{\hbar \nabla \phi}{m} \]
Full optical experiment

**Polaritons**: quasi-particles resulting from the strong coupling of cavity photons with quantum wells excitons

**Excitation**: Resonant pump

\[
I_{\text{pump}} \Rightarrow n \\
\Phi_{\text{pump}} \Rightarrow \nu
\]

**Detection:**

- **Real space**: \( n \Rightarrow I_{\text{out}} \)
- **Momentum space**: \( \nu \Rightarrow \Phi_{\text{out}} \)

\[
\psi(x, t) = \sqrt{n(x, t)} e^{i\Phi_{LP}(x, t)}
\]

- density measurement: \( c_s = \frac{\sqrt{gm}}{m} \)
- phase measurement: \( \nu = \frac{\hbar \nabla \phi}{m} \)
How to reach the right velocity profile?

Simple analytical model:

\[ c_s = \frac{\sqrt{g \eta}}{m} \]

\[ v = \frac{\hbar \nabla \phi}{m} \]

Simple analytical model:

\[ v(x) = a_1 \cdot \tanh \left( \frac{x-x_1}{w_1} \right) + a_2 \]
How to reach the right velocity profile?

\( \phi_{laser} = \text{gaussian} \)

\( \phi_{laser} = \phi_{SLM}(x) \)

\[
\phi(x) = a_1 \cdot w_1 \ln \left( \cosh \left( \frac{x-x_1}{w_1} \right) \right) + a_2 x
\]

\[
= \int v(x) dx
\]
Wavefront imprinting

Real space image of the fluid

- Pump beam
- Wavefront
- In plane motion of the fluid
- Outcoming field
Experimental creation of an acoustic black hole

Off axis interferometry technique to get phase measurements.

Subsonic vs. supersonic flow.
Hawking effect – Bogoliubov theory

• Gross-Pitaevskii linearization around the steady state solution

\[ \psi(r, t) = \psi_0(r, t) + \delta\psi(r, t) \]

By injecting this expression into the GPE for both \( \psi \) and \( \psi^* \), we obtain:

\[ i\hbar \frac{\partial}{\partial t} \begin{pmatrix} \delta\psi(r, t) \\ \delta\psi^*(r, t) \end{pmatrix} = \mathcal{L}_{Bog} \begin{pmatrix} \delta\psi(r, t) \\ \delta\psi^*(r, t) \end{pmatrix} \]

\[ \mathcal{L}_{Bog} = \begin{bmatrix} \frac{\hbar^2 k^2}{2m} + g|\psi_0|^2 & g|\psi_0|^2 e^{2ik_0x} \\ -g|\psi_0|^2 e^{-2ik_0x} & \frac{\hbar^2 k^2}{2m} - g|\psi_0|^2 \end{bmatrix} \]

Eigenvalues?
Hawking effect – Bogoliubov theory

- Gross-Pitaevskii linearization around the steady state solution

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\[ \omega_{\text{bog}}(k) = \pm \sqrt{\frac{\hbar k^2}{2m} \left( \frac{\hbar k^2}{2m} + 2gn \right)} \]
Moving frame – Doppler shift

\[
\omega_{\text{bog}}(k) = \pm \sqrt{\frac{\hbar^2 k^2}{2m} \left( \frac{\hbar^2 k^2}{2m} + 2gn \right)} \quad \Rightarrow \quad \omega_{\text{bog}}(k) = \mathbf{v} \cdot \mathbf{k} \pm \sqrt{\frac{\hbar(k+k_p)^2}{2m} \left( \frac{\hbar(k+k_p)^2}{2m} + 2gn \right)}
\]

\[
\omega_{\text{bog}}(k) - \omega_{\text{pump}}(k) \text{ [a.u.]} \quad \mathbf{v} = 0
\]
Moving frame – Doppler shift

\[ \omega_{\text{bog}}(k) = \pm \sqrt{\frac{\hbar^2 k^2}{2m} \left( \frac{\hbar^2 k^2}{2m} + 2gn \right)} \]

\[ \Rightarrow \omega_{\text{bog}}(k) = v \cdot k \pm \sqrt{\frac{\hbar(k+k_p)^2}{2m} \left( \frac{\hbar(k+k_p)^2}{2m} + 2gn \right)} \]

\[ \omega_{\text{bog}}(k) - \omega_{\text{pump}}(k) \text{ [a. u.]} \]

\( v = 0 \)

Subsonic: \( c_s > v \)

\[ c_s - v \]

\[ c_s + v \]
Moving frame – Doppler shift

\[ \omega_{bog}(k) = \pm \sqrt{\frac{\hbar^2 k^2}{2m} \left( \frac{\hbar^2 k^2}{2m} + 2gn \right)} \Rightarrow \omega_{bog}(k) = \nu \cdot k \pm \sqrt{\frac{\hbar(k+k_p)^2}{2m} \left( \frac{\hbar(k+k_p)^2}{2m} + 2gn \right)} \]

\[ \omega_{bog}(k) - \omega_{pump}(k) \text{ [a. u.]} \]

\( \nu = 0 \)

Subsonic: \( c_s > \nu \)

Supersonic: \( c_s < \nu \)
Bogoliubov modes on both side of the horizon

Pump/Probe Spectroscopy measurements to get Bogoliubov dispersion on both sides of the horizon.

Ref: Claude et al, PRL 2022
Bogoliubov modes on both side of the horizon

Pump/Probe Spectroscopy measurements to get Bogoliubov dispersion on both sides of the horizon.

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Conclusion

• Microcavity polaritons are a well suited system to perform analog gravity experiments:
  • Optical engineering of the spacetime
  • Optical measurement of the fluid property both in real and momentum space

• Stimulated Hawking effect

• Great platform for the study of Quantum Field on Curved Spacetime

• Correlation between normal and ghost branch

Ref: - Jacquet et al, EPJD 2022
Stimulated Hawking effect - scattering pictures

\[ \omega_{\text{bog}}(k) - \omega_{\text{pump}}(k) \, [\text{a.u.}] \]

**Subsonic:** \( c_s > \nu \)

**Supersonic:** \( c_s < \nu \)

Injected mode
How to reach the right velocity profile?

Simple analytical model:

\[ v_{LP}(x) = a_1 \cdot \tanh \left( \frac{x-x_1}{w_1} \right) + a_2 \quad & \quad \nabla \phi \propto v \]

\[ \phi_{LP}(x) = a_1 \cdot w_1 \cdot \ln \left( \cosh \left( \frac{x-x_1}{w_1} \right) \right) + a_2 x \]
Towards rotating geometries – Giant vortex

\[ \phi_{SLM}(r, \theta) = l \theta - C \ln(r) \]

\[ \nu_{polaritons}(r) = \frac{l}{r} e_{\theta} + \frac{C}{r} e_{r} \]

2 Peculiars boundaries

- Ergoregion: \[ \| \nu_{polaritons}(r) \| > c_s \]
- Event horizon: \[ \| \nu_{polaritons}(r) \cdot e_r \| > c_s \]
Solitons to probe the spacetime

- Mise en place d'un autre set-up avec Cryostat en circuit fermé
- Utilisation de solitons pour sonder l'espace temps
Energy and phase matching possible

Ref: - Jacquet et al, PTRSA 2020
- Jacquet et al, arXiv:2201.02038,

\[ \rightarrow \text{Strong signal} \quad (10^{-4}) \]

4 wave mixing processes for any \( \omega \in [\omega_{\text{min}}, \omega_{\text{max}}] \):

- \((\omega, -\omega) \rightarrow 0\)
- \((k, -k) \rightarrow 0\)
Missions réalisées

• Nice, Quantum Fluid of light **PhoQus** 2021

• Présentation à Rome, Quantum fluid of light **PhoQus** mars 2022

• Edimburgh, Poster **Conference on analog model for gravity** au Higgs Institute, Juin 2022

• Présentation à Lyon, **Journée de la matière condensée**, Aout 2022
Formation réalisées/prévues

• Ecole d'été de Varenne Quantum Fluid of light - Société Italienne de Physique, Varenna ,Italie 1 au 7 Juillet 2022. -30h

• Stage de formation sur les risques liés aux liquides cryogéniques, Septembre 2022– **3h30**

• CdF – Intéractions entre particules dans les gaz quantiques, mars-avril 2023 - Cours de Jean Dalibard – **18h**

• CdF – **Climats extrêmes et analogues actuels : l'Holocène et le Tardiglaciaire** avril-juin 2023 - Cours de Edouard Bard – **20h**
A new feature: Quasi Normal Mode of the black hole

The horizon ($x=0$) is correlated to the whole spacetime: upstream ($x<0$) and downstream ($x>0$).
A new feature: Quasi Normal Mode of the black hole horizon (x=0) is correlated to the whole spacetime: upstream (x<0) and downstream (x>0).

Signature of the black hole ring down, intrinsic to the BH.

The horizon (x=0) is correlated to the whole spacetime: upstream (x<0) and downstream (x>0).
Towards the observation of a stimulated Hawking effect

Injection of the mode $u_{in}$ at $(k_{probe}, \omega_{probe})$

Scattering of the incident mode by the horizon

Detection of transmitted mode $d1_{out}$ at $\omega_{probe}$
Towards the observation of a stimulated Hawking effect

Injection of the mode $u_{in}$ at $(k_{probe}, \omega_{probe})$

Scattering of the incident mode by the horizon

Detection of transmitted mode at $\omega_{probe}$

$u_{in}^*$: 4w mixed signal of $u_{in}$ with the pump at $(-k_{probe}, -\omega_{probe})$

Detection of 4w mixed signal of $d_{out}^*$ with the pump at $-\omega_{probe}$
Bogoliubov dispersion to probe the "space-time"
Experimental Set up