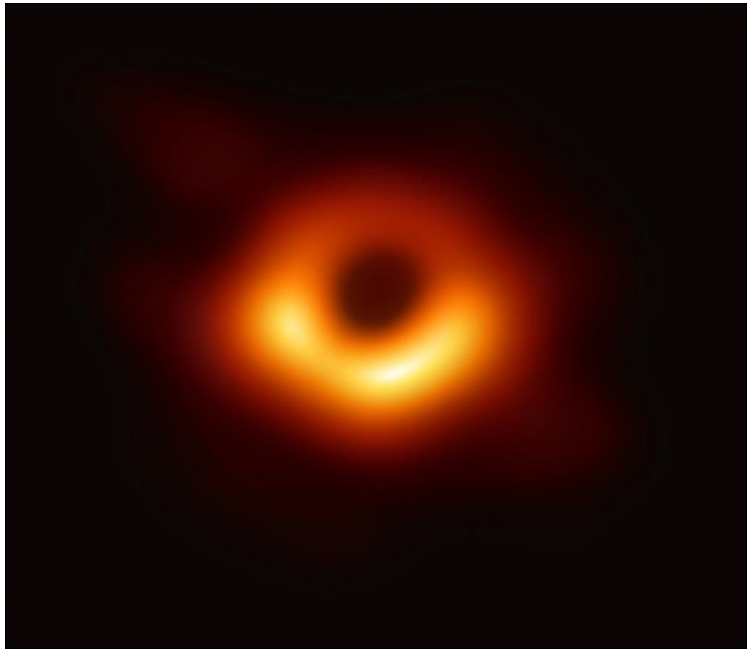


Sagittarius A* imaged by the Event Horizon Telescope, 2017.

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.

VOLUME 46 25 MAY 1981 NUMBER 21

Experimental Black-Hole Evaporation?

W. G. Unruh
Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada
(Received 8 December 1980)

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 out from the sonic horizon in transsonic fluid flow.

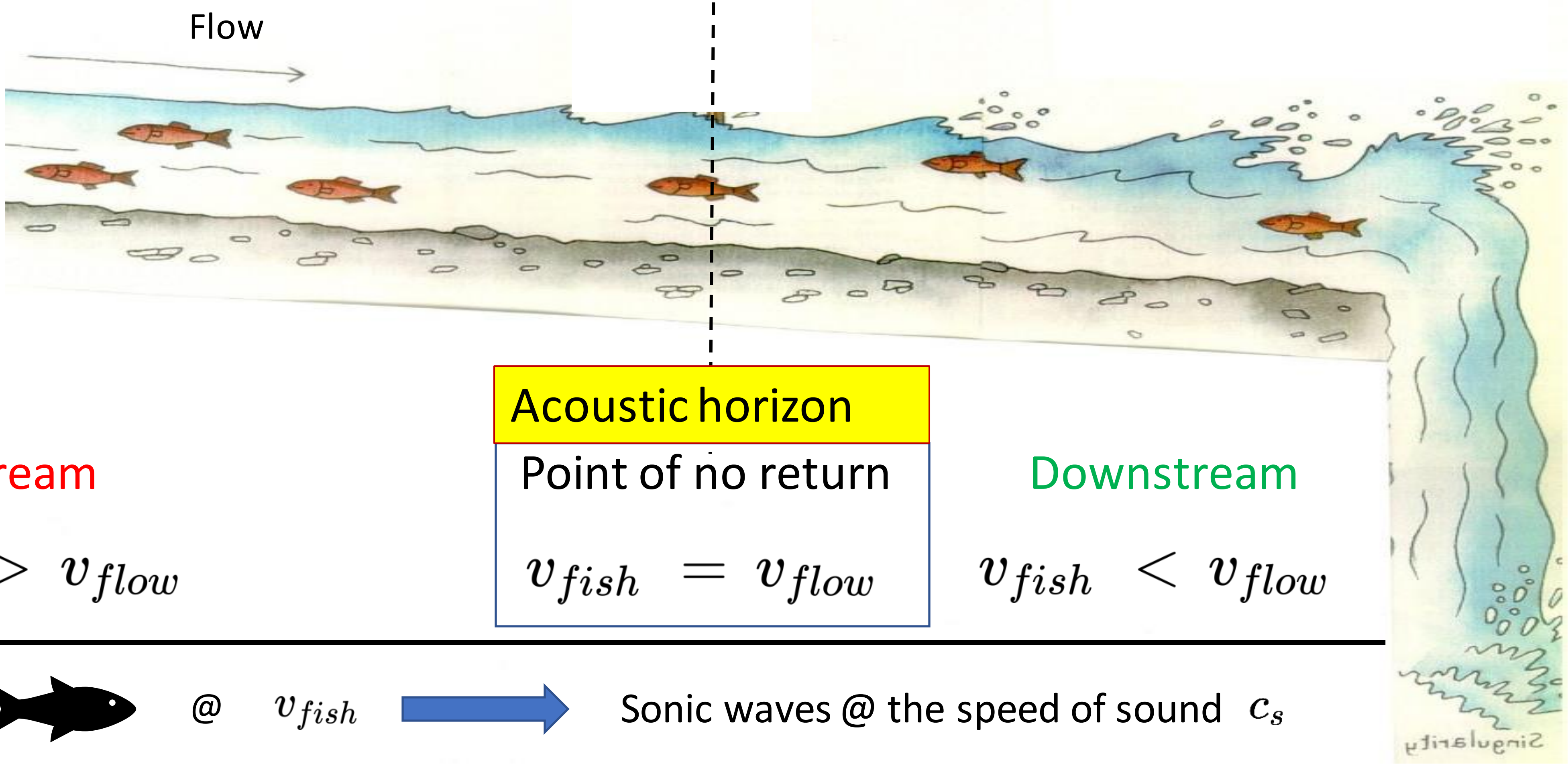
which result in an equation for $\tilde{\psi}$,

$$\frac{1}{\rho_0}\left[\frac{\partial}{\partial t}\frac{\rho_0}{g'(\xi_0)}\frac{\partial\tilde{\psi}}{\partial t}+\frac{\partial}{\partial t}\frac{\rho_0\vec{v}_0}{g'(\xi_0)}\cdot\nabla\tilde{\psi}+\nabla\cdot\left(\frac{\rho_0\vec{v}}{g'(\xi_0)}\frac{\partial\tilde{\psi}}{\partial t}\right)-\nabla\cdot\rho_0\nabla\tilde{\psi}+\nabla\cdot\left(\vec{v}\frac{\rho_0}{g'(\xi_0)}\vec{v}\cdot\nabla\tilde{\psi}\right)\right]=0\,.$$

These are precisely the equations for a massless scalar field in a geometry with metric

Transonic flow → Acoustic horizon

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.



Acoustic horizon

Point of no return

$v_{fish} = v_{flow}$

Upstream

$v_{fish} > v_{flow}$

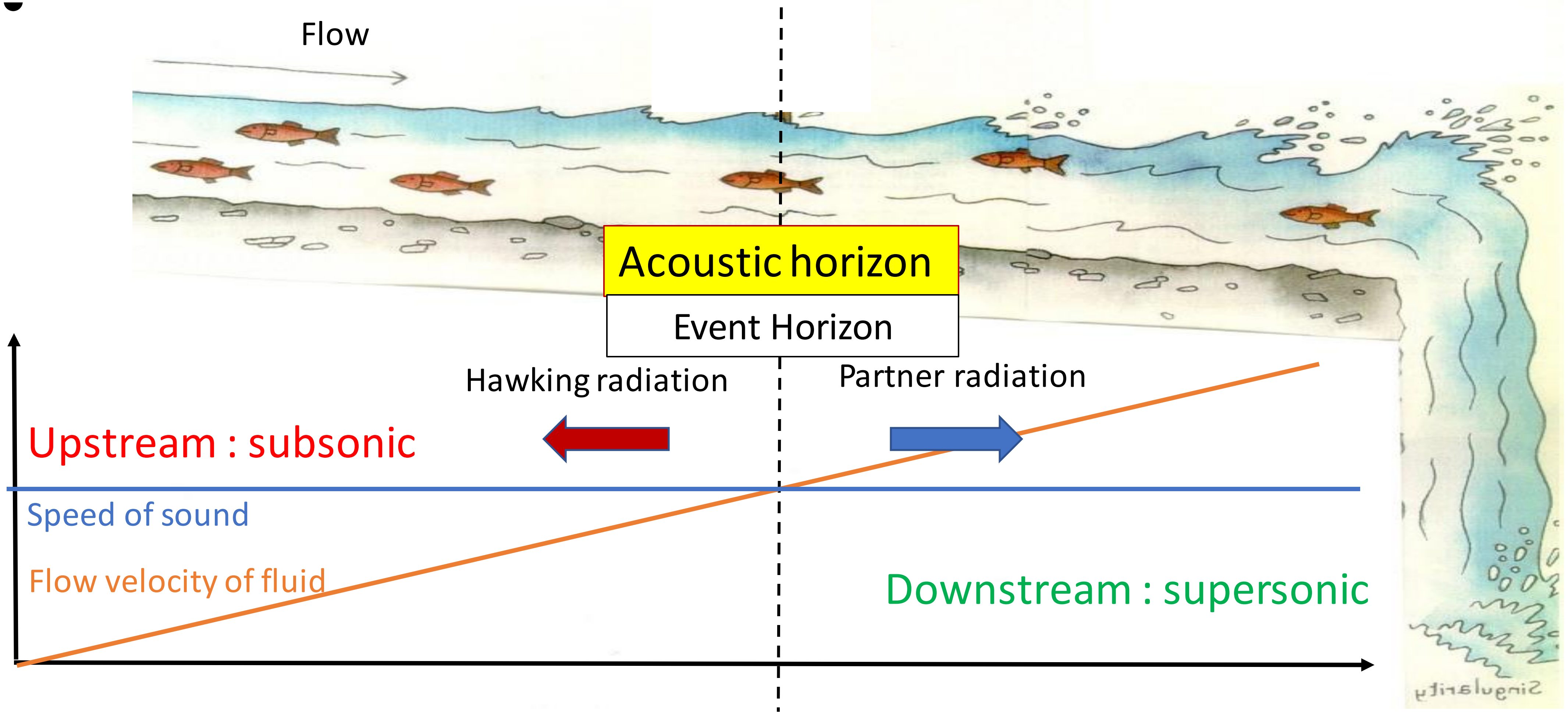
Downstream

$v_{fish} < v_{flow}$

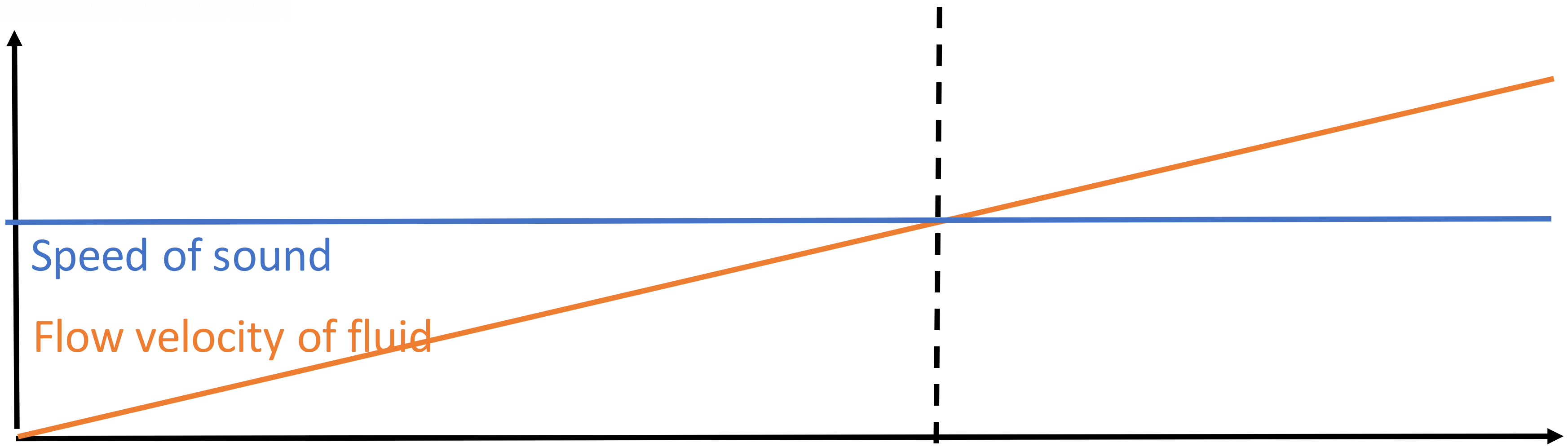
@ v_{fish} → Sonic waves @ the speed of sound c_s

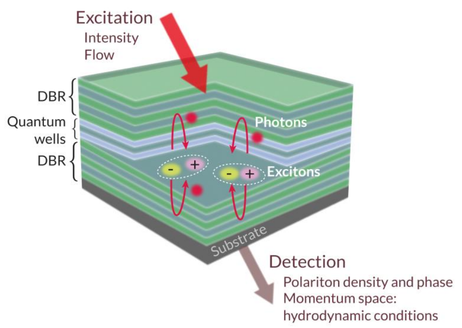
Transonic flow → Acoustic horizon

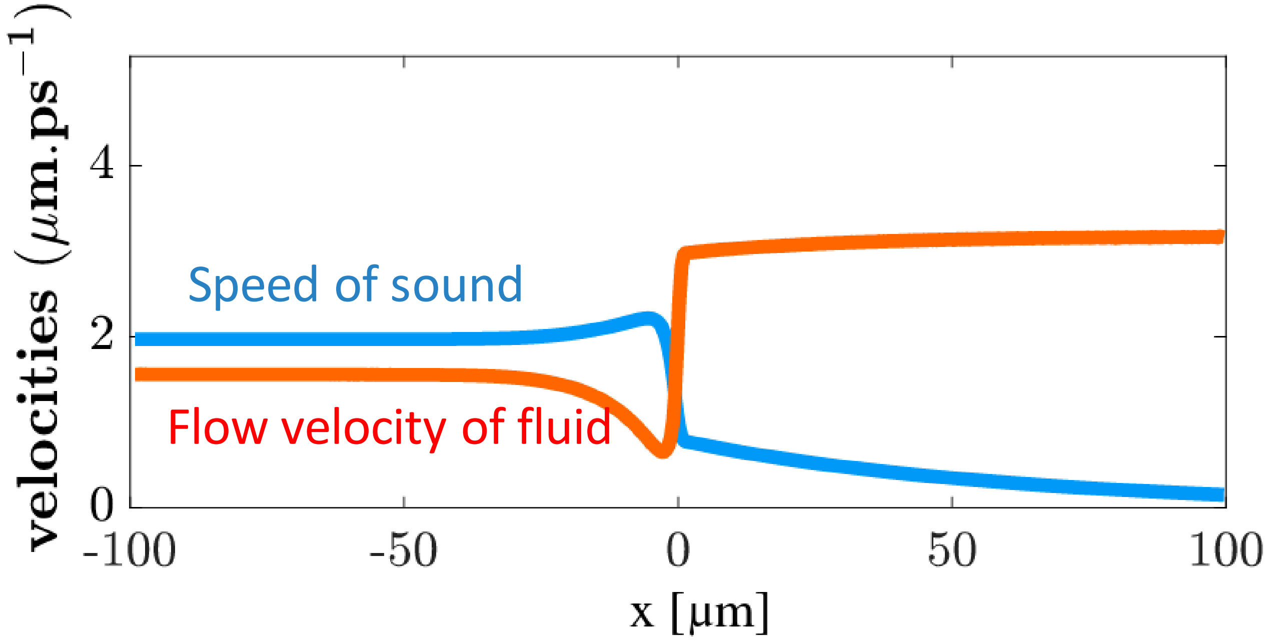
Unruh PRL 1981 : wave equation for acoustic field in a trans-sonic fluid is isomorphic to wave equation for electromagnetic field on black hole spacetime.



Acoustic horizon in Quantum fluid of polaritons





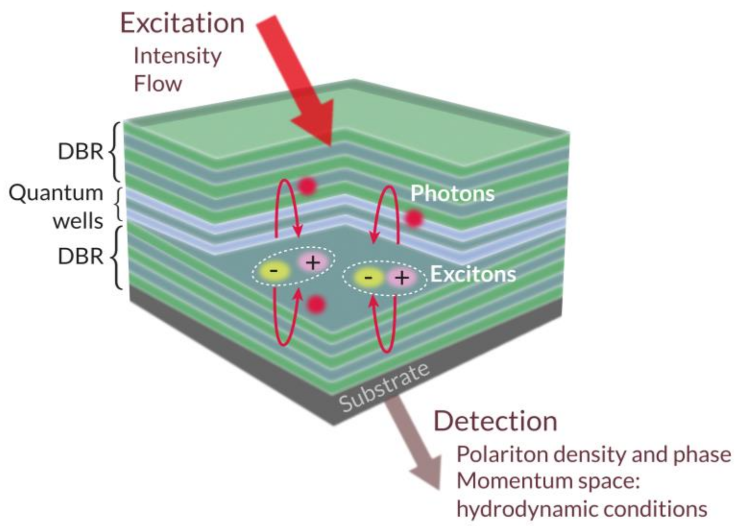


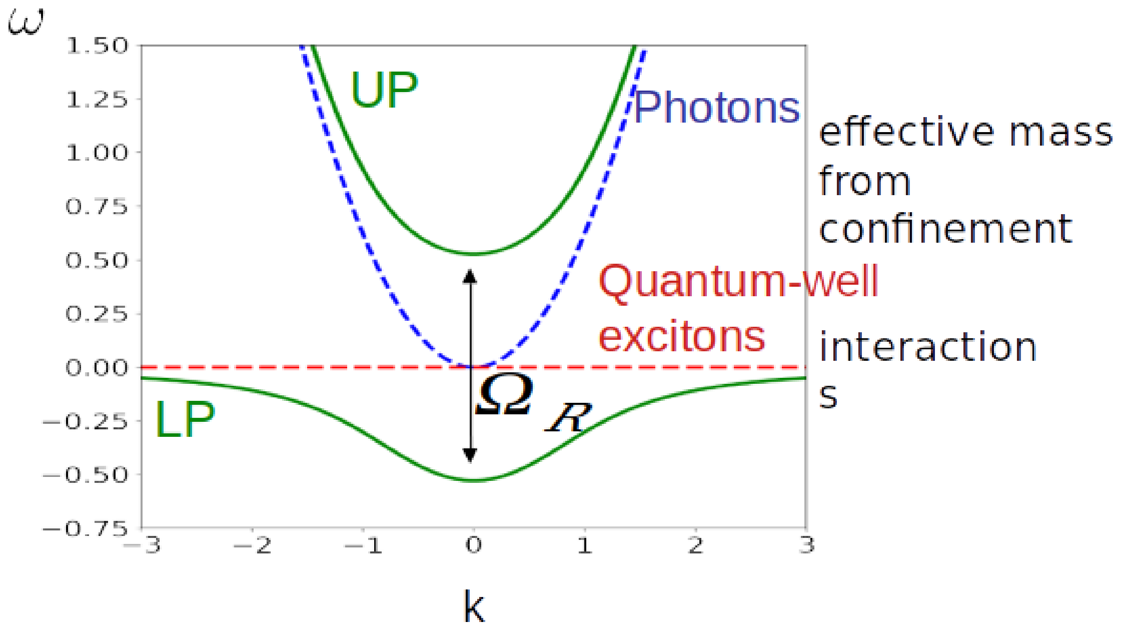
Ref :

- Jacquet et al, EPJD 2022
- H. S. Nguyen et al Phys. Rev. Lett. **114**, 036402 (2015)

Microcavity polaritons

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





Strong coupling regime : $\gamma_X , \gamma_C << \Omega_r$

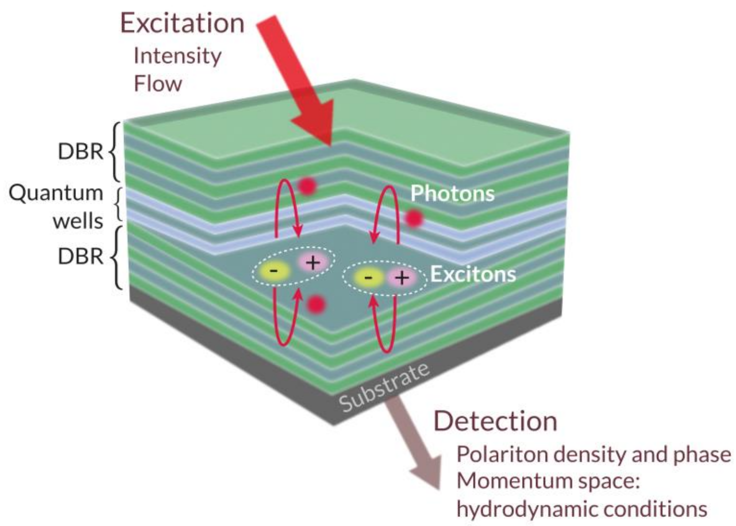
→ Photons/Excitons energies anticrossing

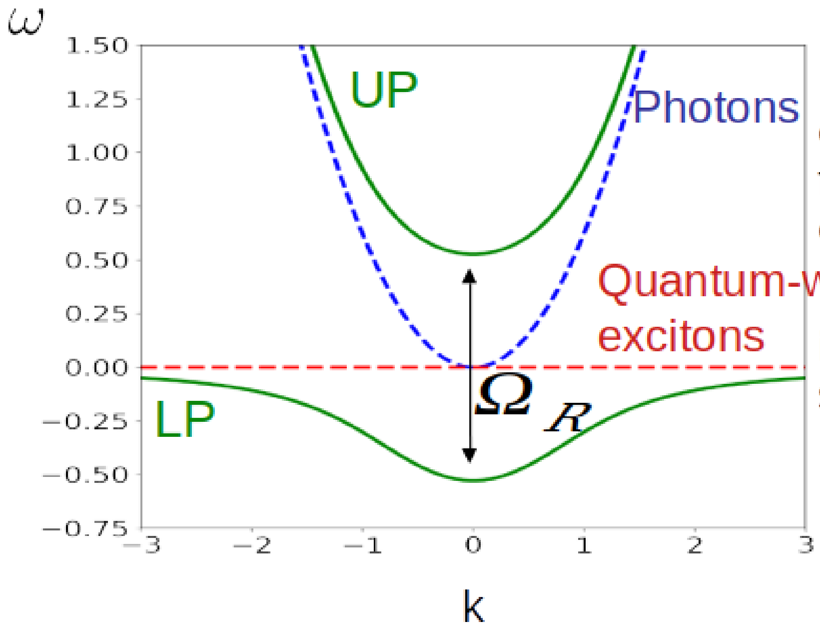
New eigenstates : Upper Polariton (UP) and Lower Polariton (LP) = half light/ half matter quasi particles

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**





effective mass from confinement

interactions

Dynamics described by the Driven Dissipative Gross Pitaevskii Equation

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

g : Interaction constant

γ : Polariton lifetime (loss rate)

P : Pump term

Driven Dissipative dynamics → **Out of Equilibrium system**

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 : $v = \frac{\hbar \nabla \phi}{m}$

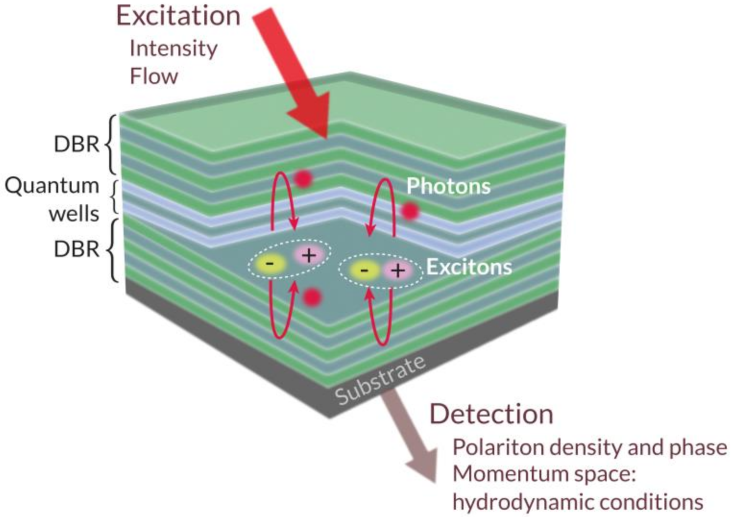
Full optical experiment

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

Excitation : Resonant pump

$$I_{pump} \Rightarrow n$$

$$\phi_{pump} \Rightarrow v$$



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

- density measurement : $c_s = \frac{\sqrt{gn}}{m}$

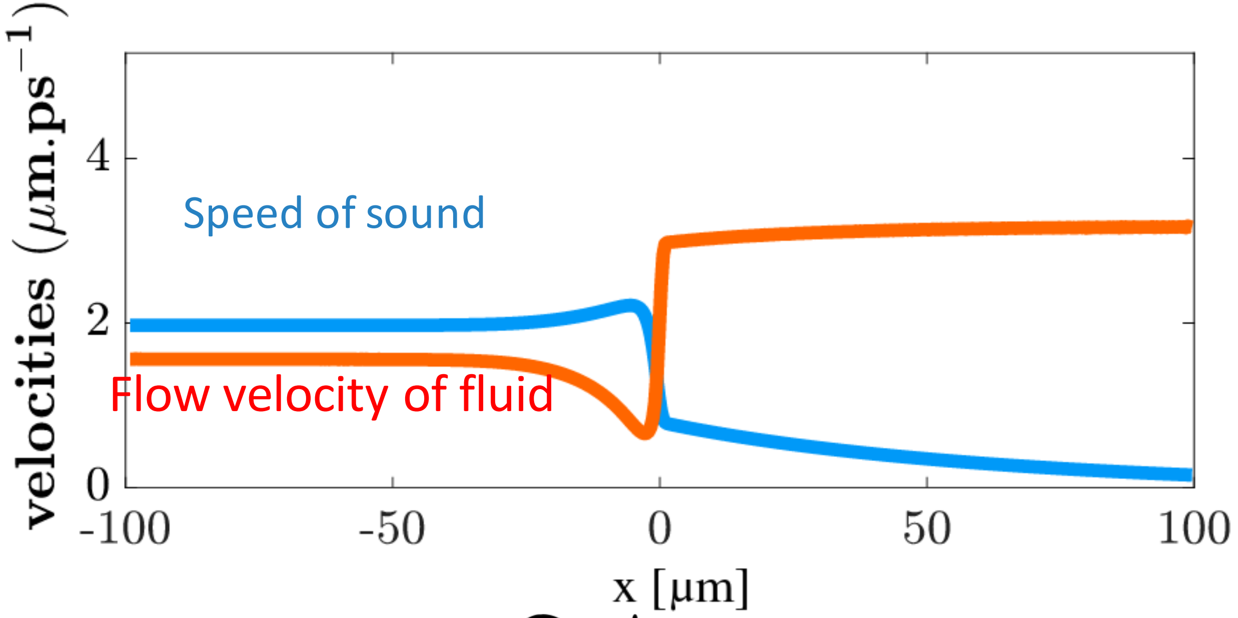
-phase measurement : $v = \frac{\hbar \nabla \phi}{m}$

Detection:

Real space : $n \Rightarrow I_{out}$

Momentum space : $v \Rightarrow \phi_{out}$

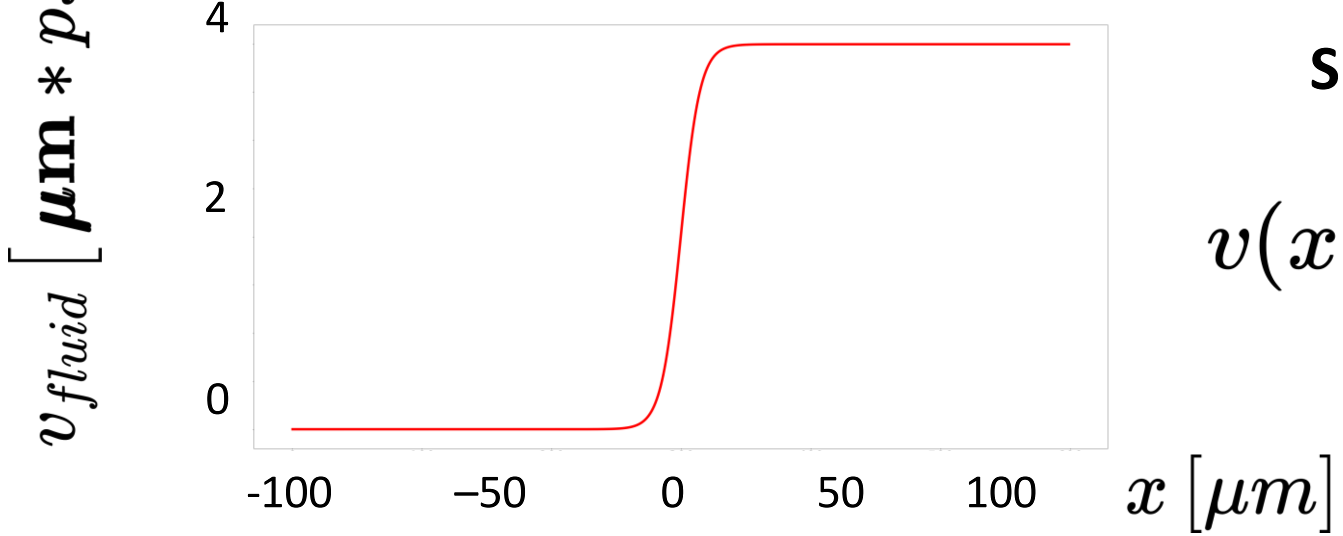
How to reach the right velocity profile ?



$$c_s = \frac{\sqrt{gn}}{m}$$

$$v = \frac{\hbar \nabla \phi}{m}$$

$$\approx$$

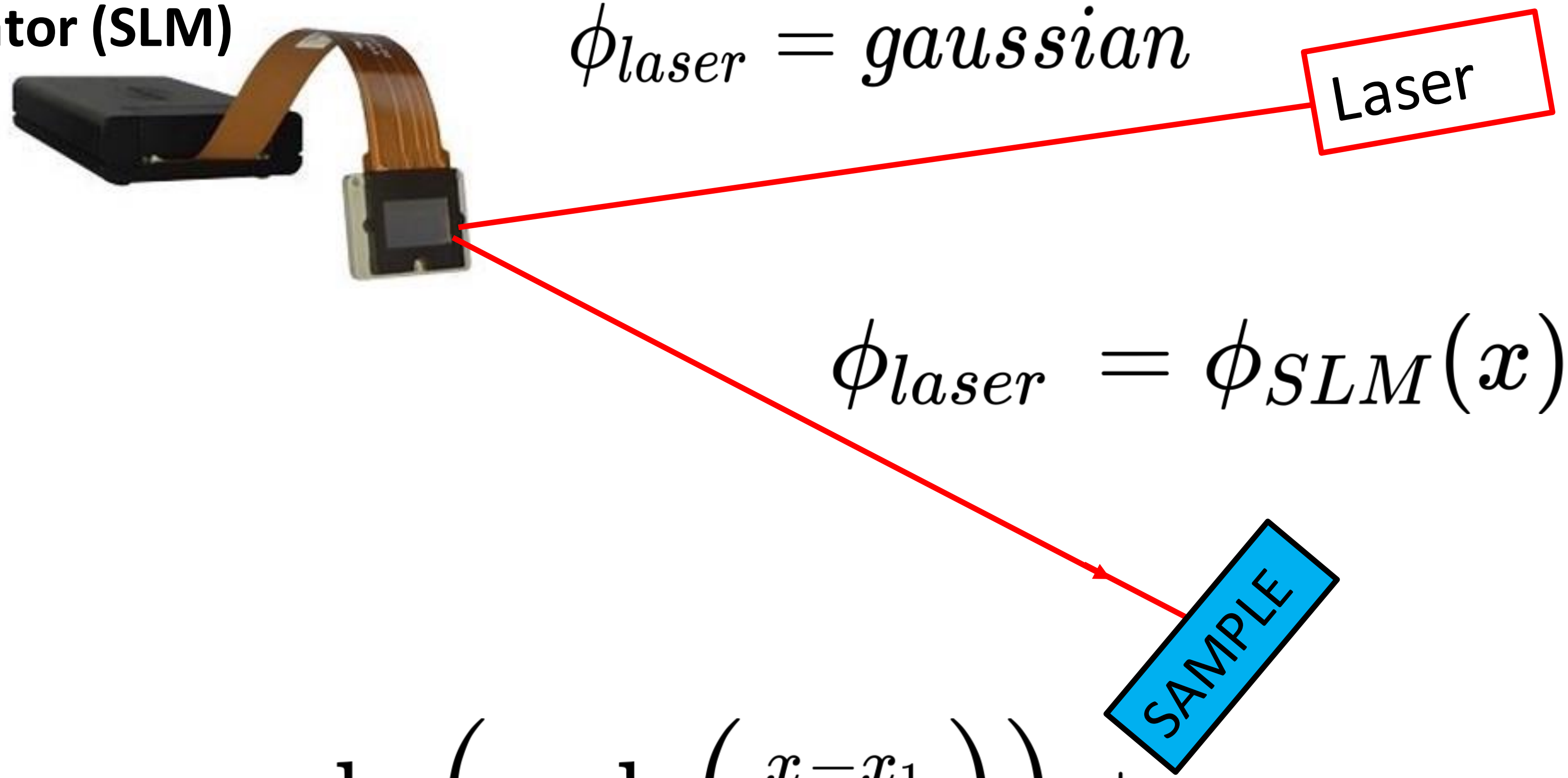


Simple analitycal model :

$$v(x) = a_1 \cdot \tanh\left(\frac{x - x_1}{w_1}\right) + a_2$$

How to reach the right velocity profile ?

Spatial Light Modulator (SLM)



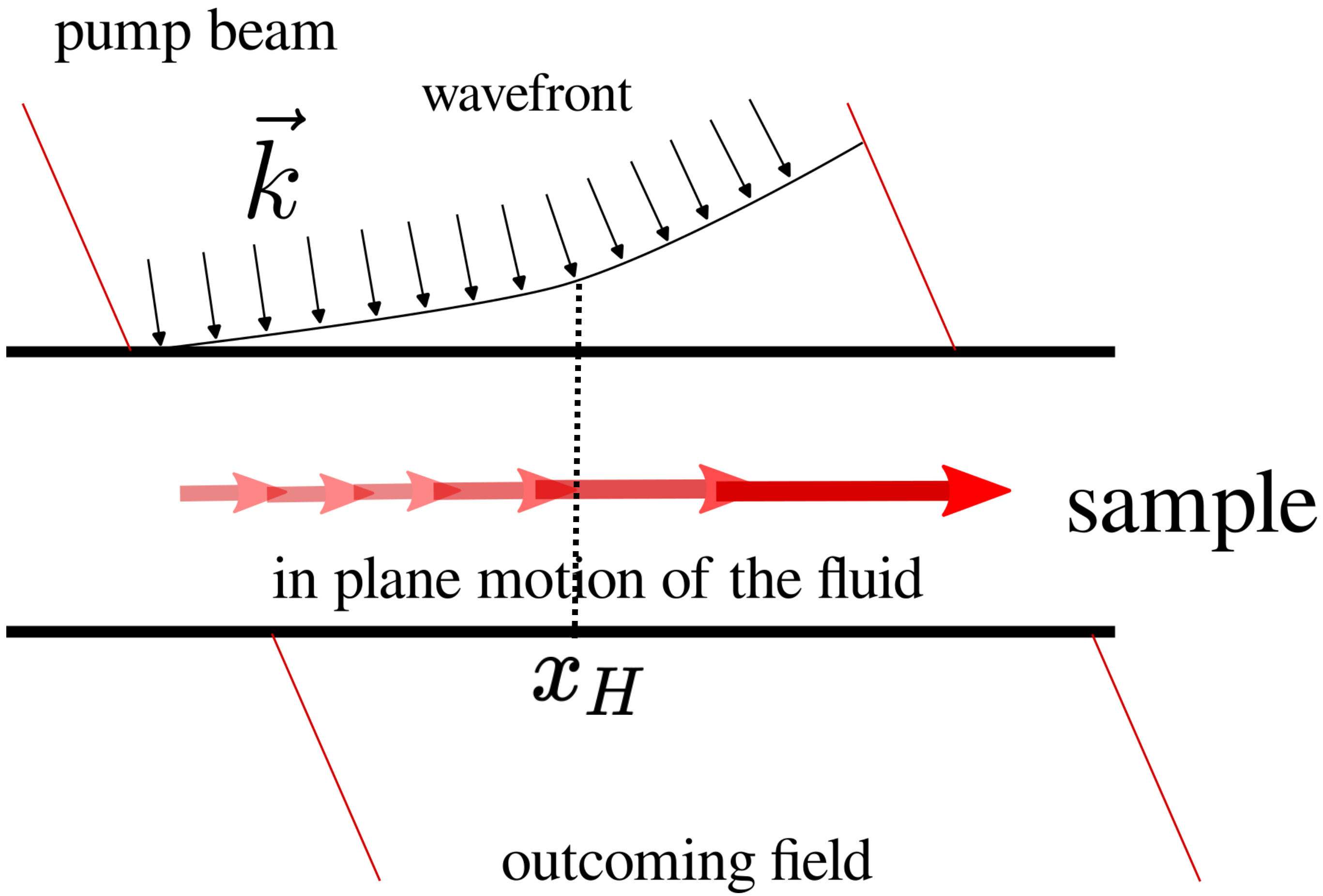
$$\phi_{laser} = gaussian$$

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

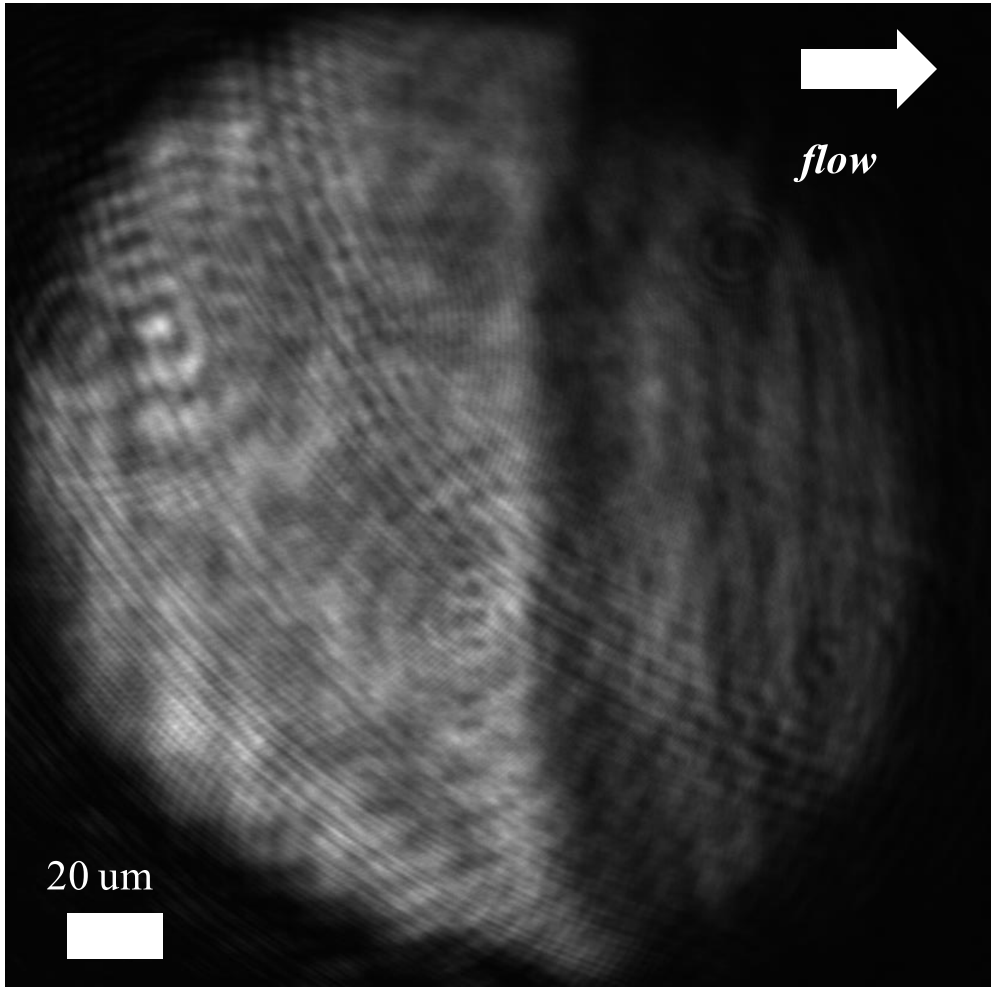
$$\phi(x) = a_1 \cdot w_1 \ln\left(\cosh\left(\frac{x-x_1}{w_1}\right)\right) + a_2 x$$

$$= \int v(x)dx$$

Wavefront imprinting

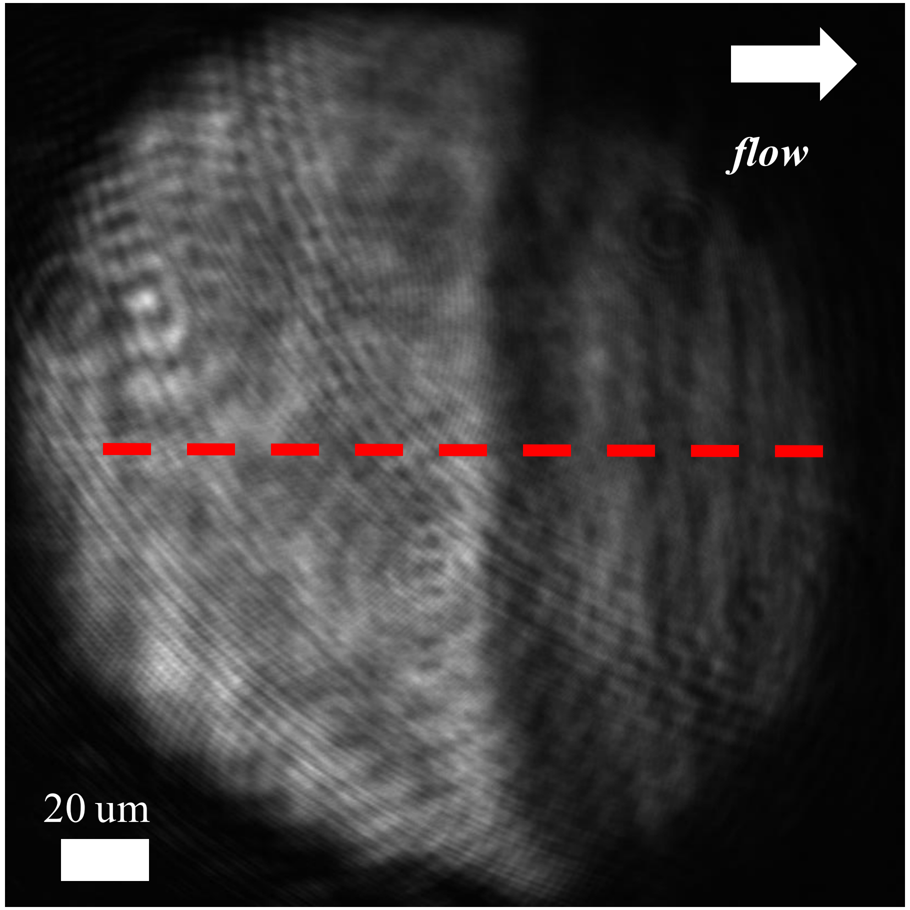


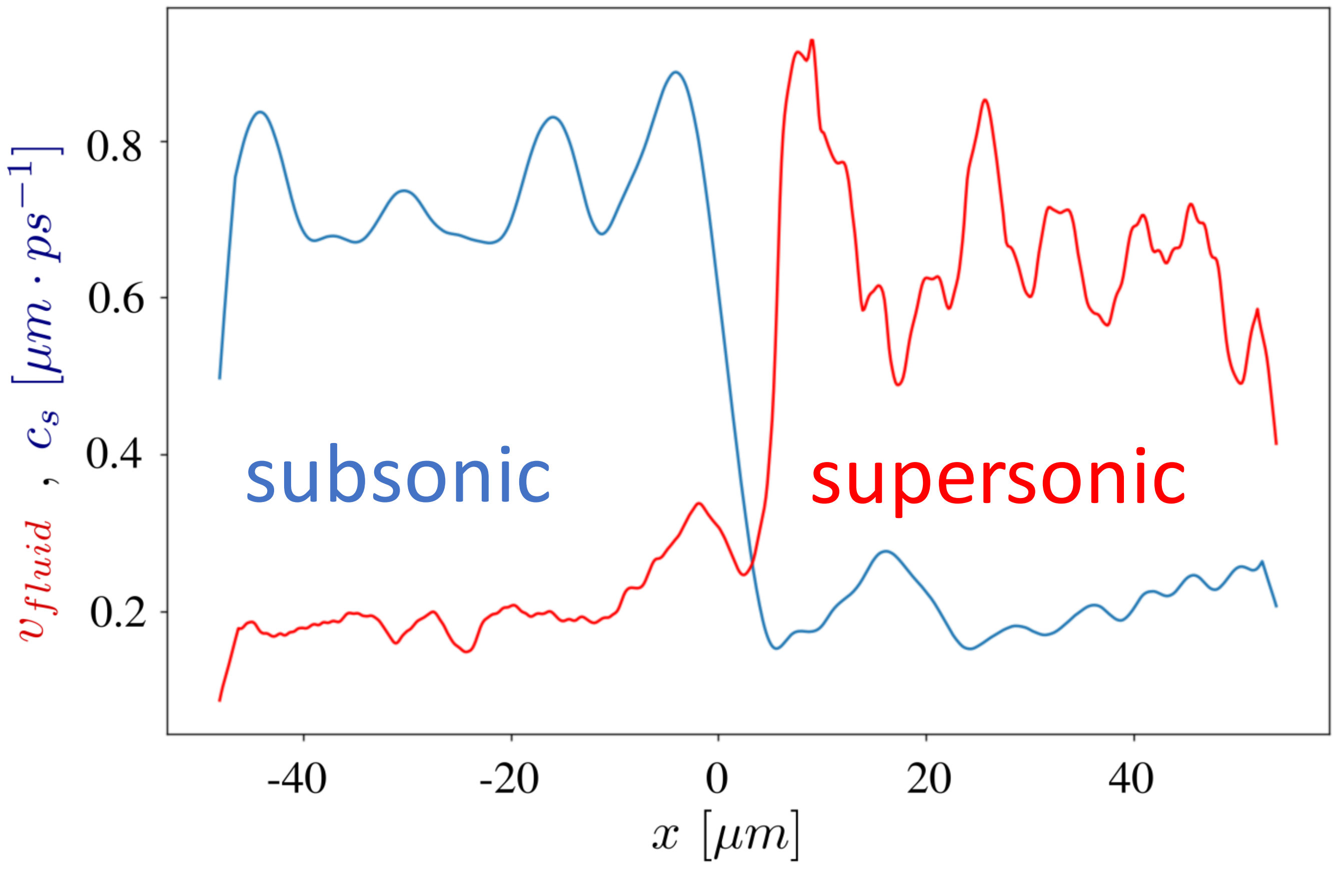
Real space image of the fluid



Experimental creation of an acoustic black hole

Off axis interferometry technique to get phase measurements.





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 ψ and ψ^* we obtain :

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

$$\mathcal{L}_{Bog} = \begin{bmatrix} \frac{\hbar^2 k^2}{2m} + g|\psi_0|^2 & g|\psi_0|^2 e^{2ik_0 x} \\ -g|\psi_0|^2 e^{-2ik_0 x} & -\frac{\hbar^2 k^2}{2m} - g|\psi_0|^2 \end{bmatrix}$$

Eigenvalues ?

Hawking effect – Bogoliubov theory

• **Gross-Pitaevskii linearization around the steady state solution**

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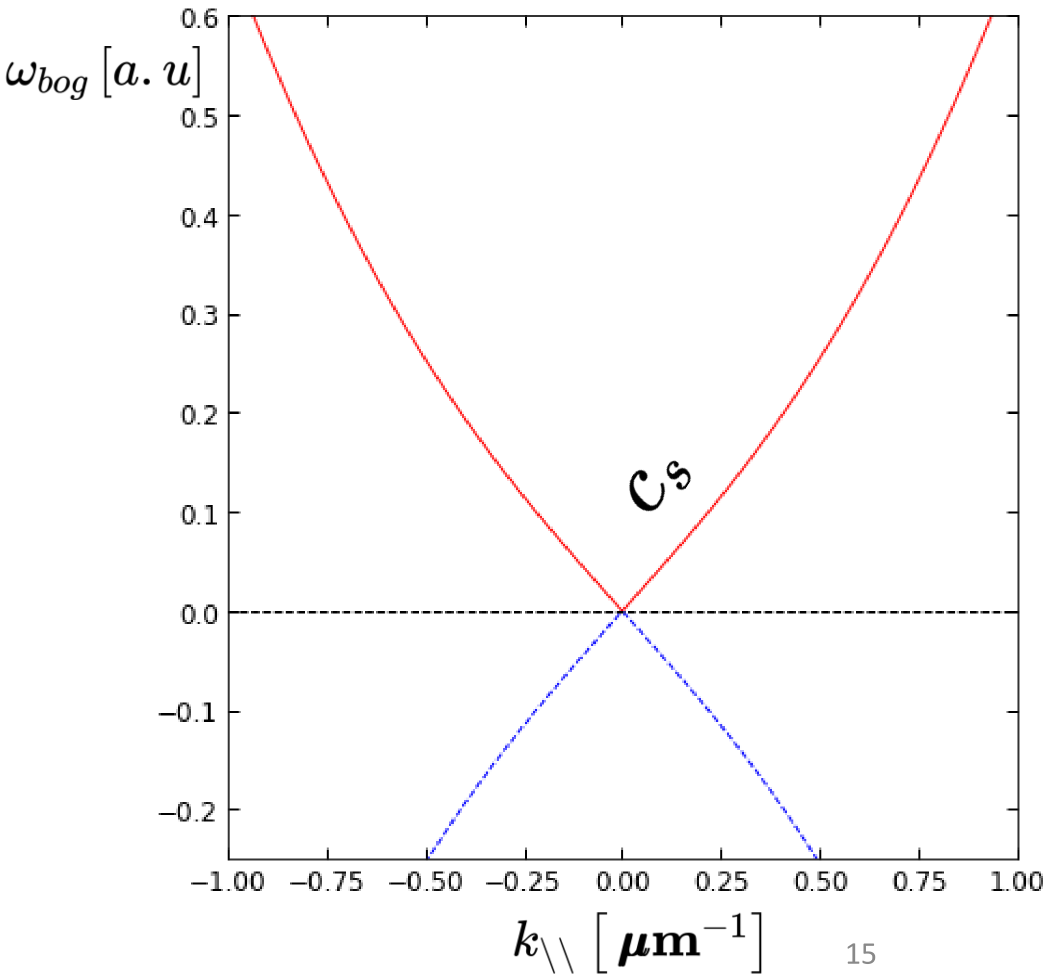
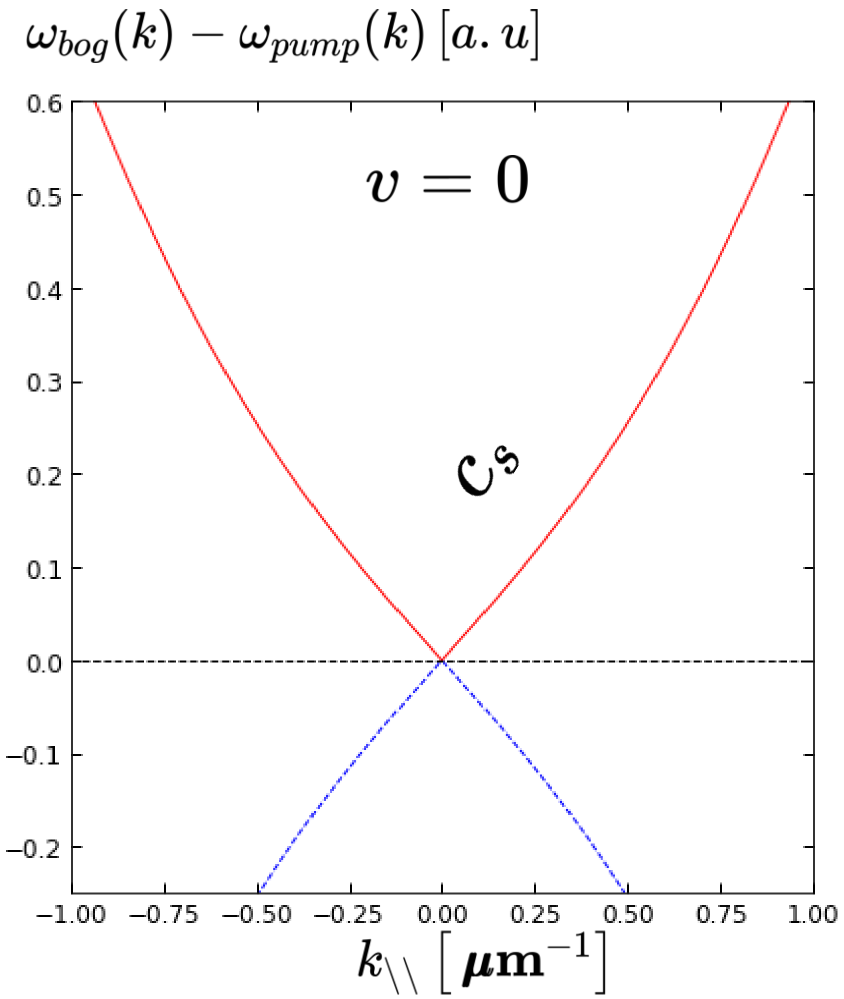
$$\omega_{bog}(k) = \pm\sqrt{\frac{\hbar\ k^2}{2m}\left(\frac{\hbar\ k^2}{2m} + 2gn\right)}$$



Moving frame – Doppler shift

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



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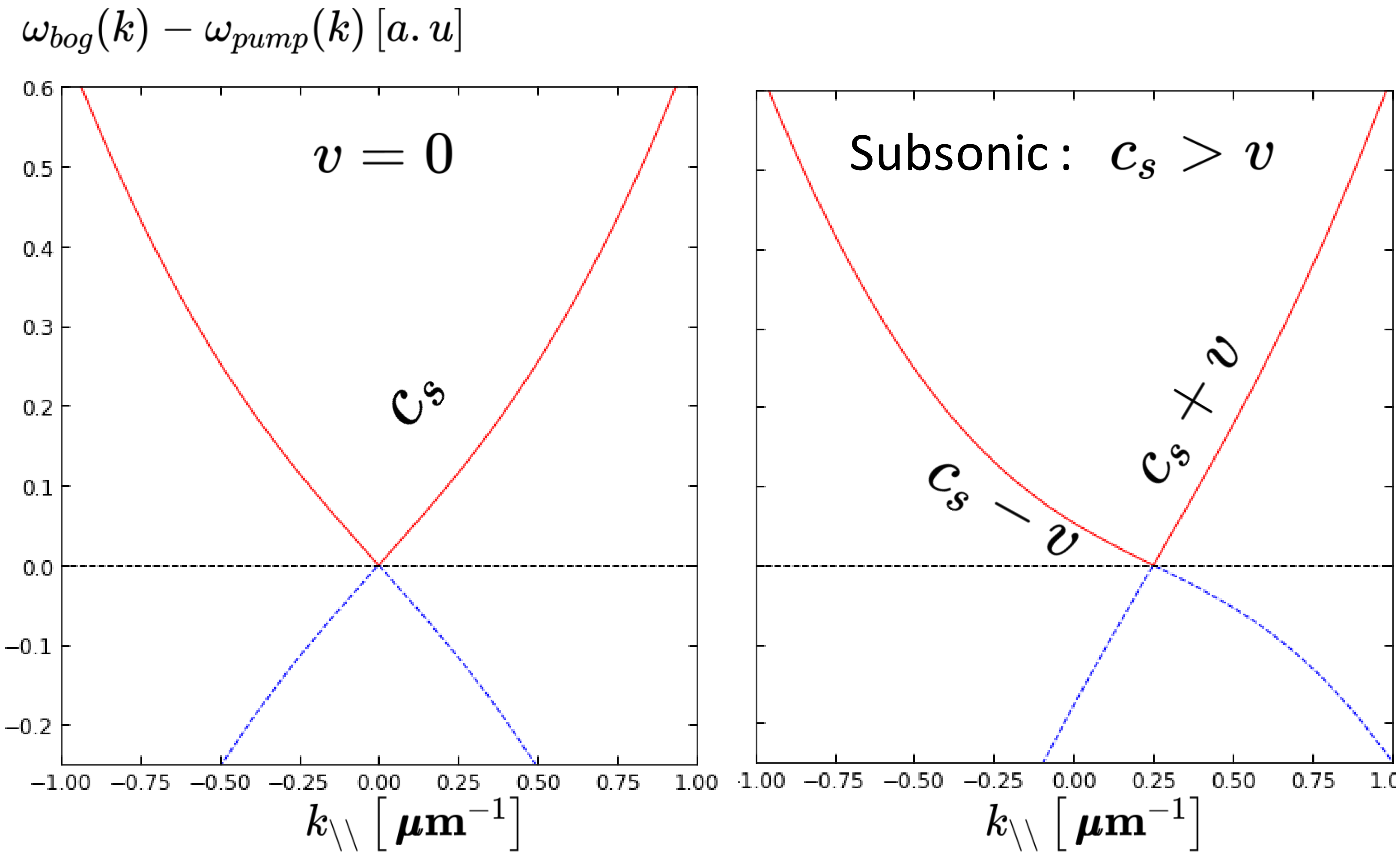

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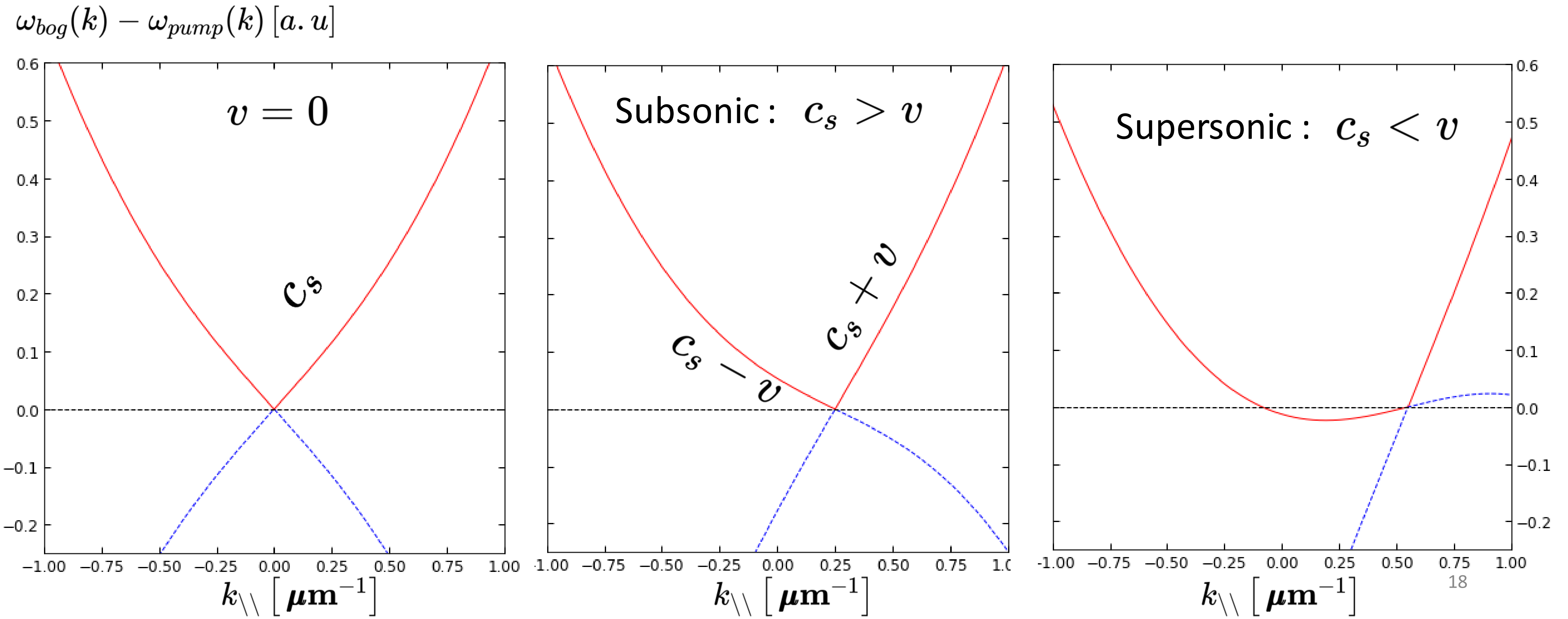
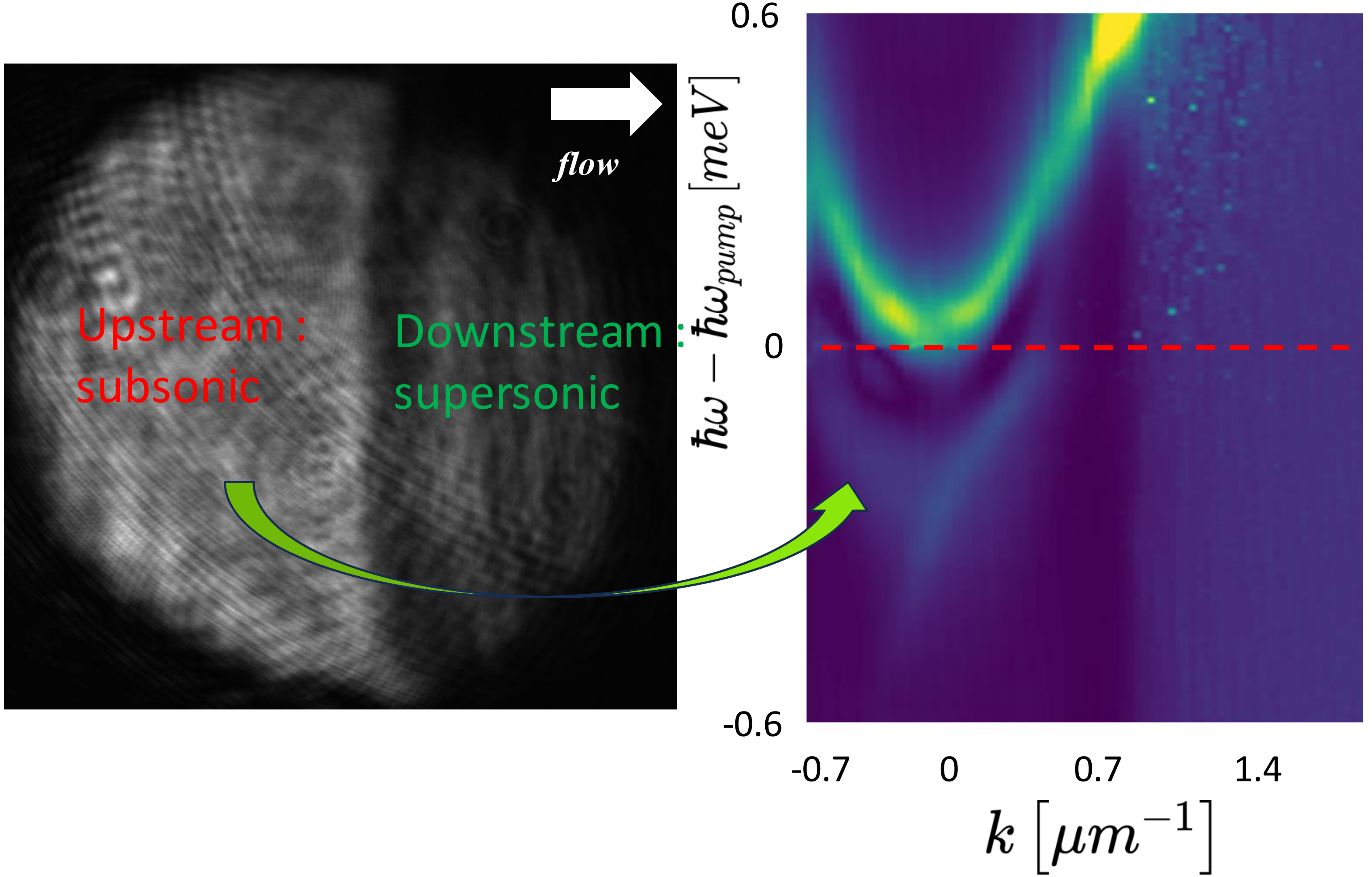


Bogoliubov modes on both side of the horizon

Ref : Claude et al, PRL 2022

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



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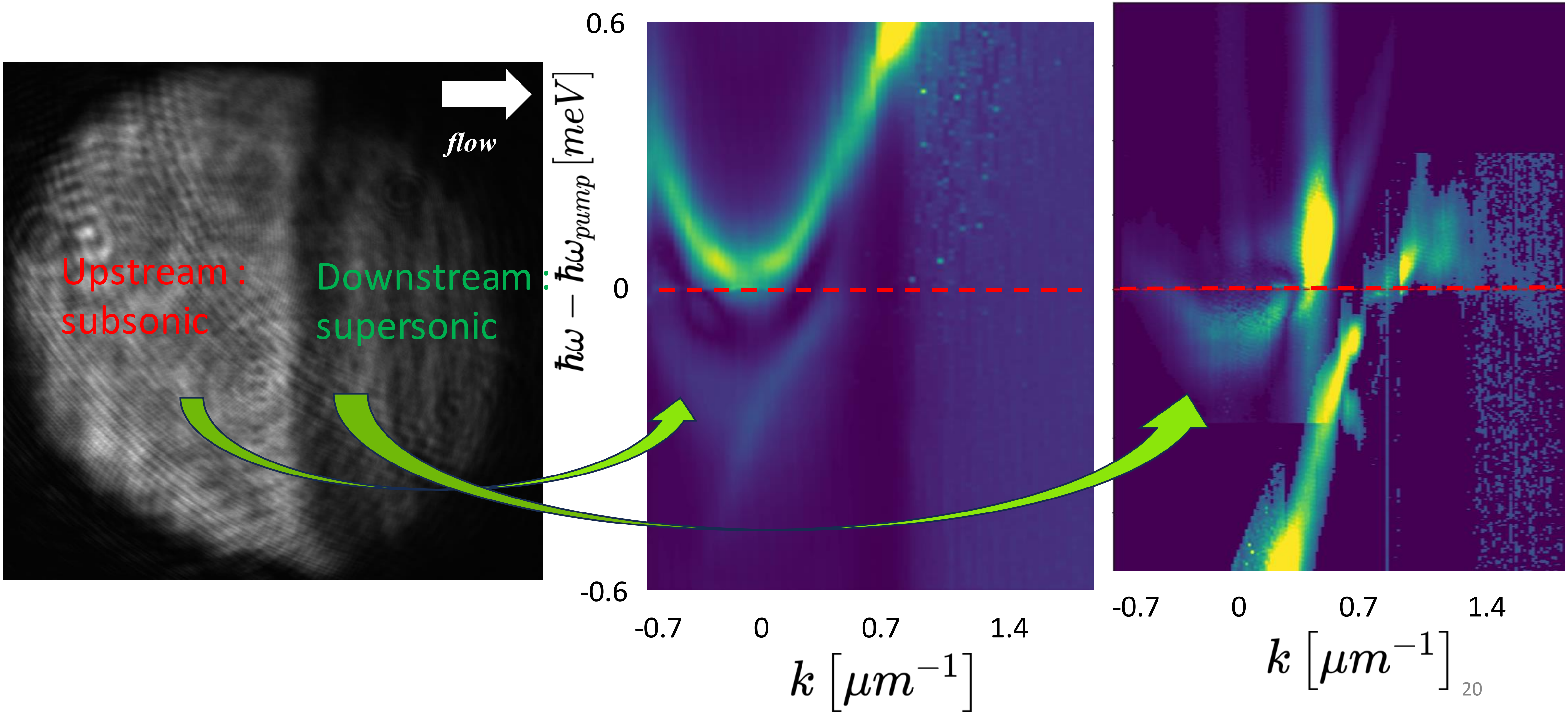
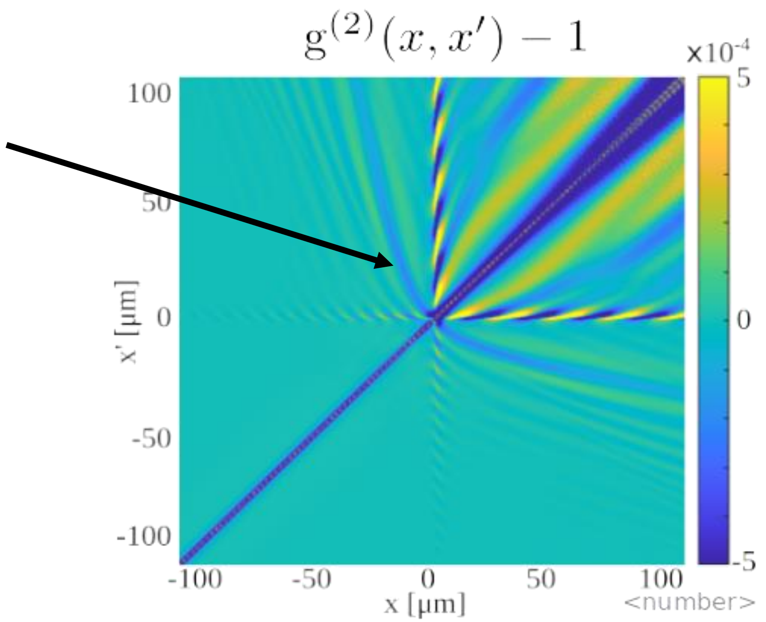


Conclusion

- 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

Ref : -Jacquet et al, EPJD 2022

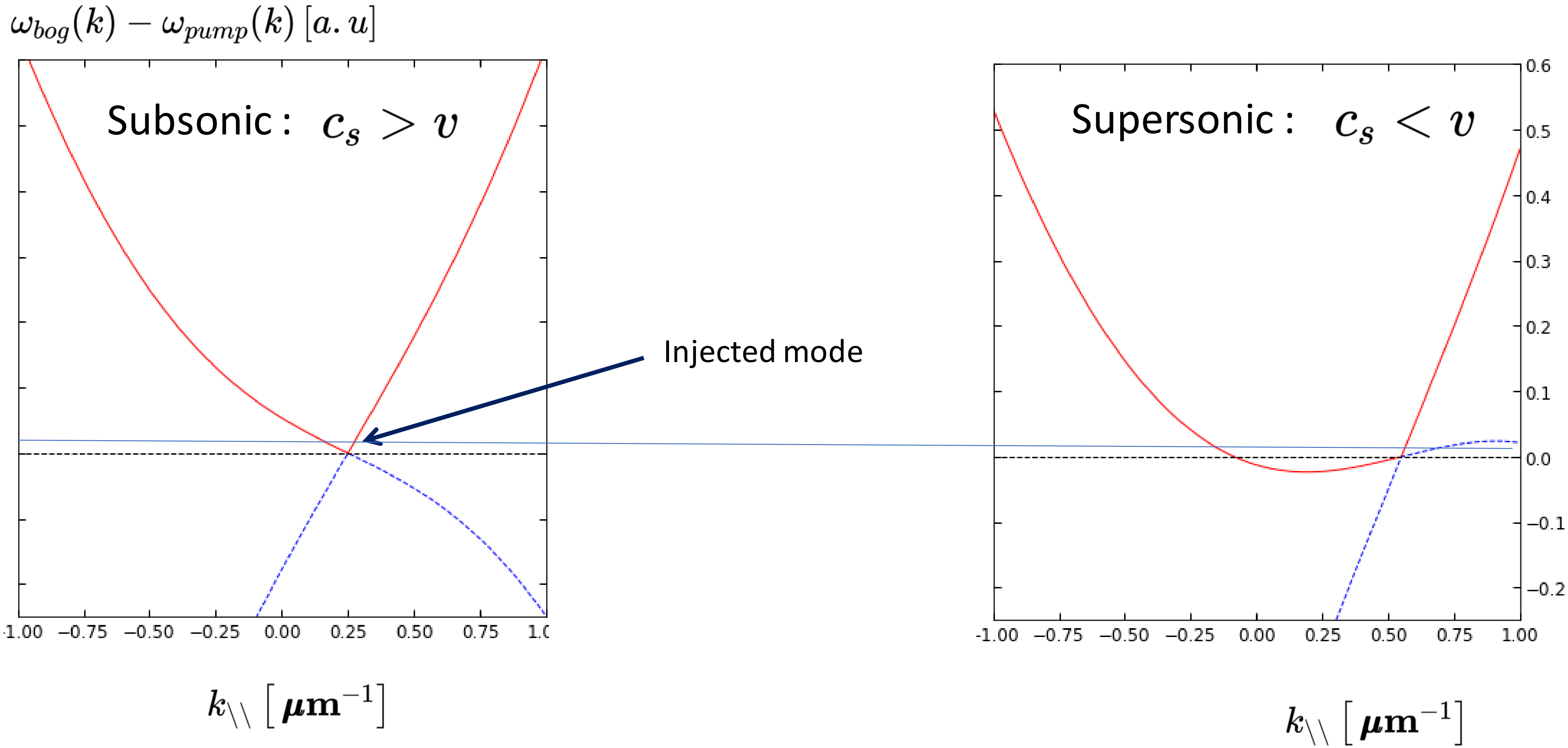
- Stimulated Hawking effect



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

- Correlation between normal and ghost branch

Stimulated Hawking effect - scattering pictures



How to reach the right velocity profile ?

Simple analitycal model :

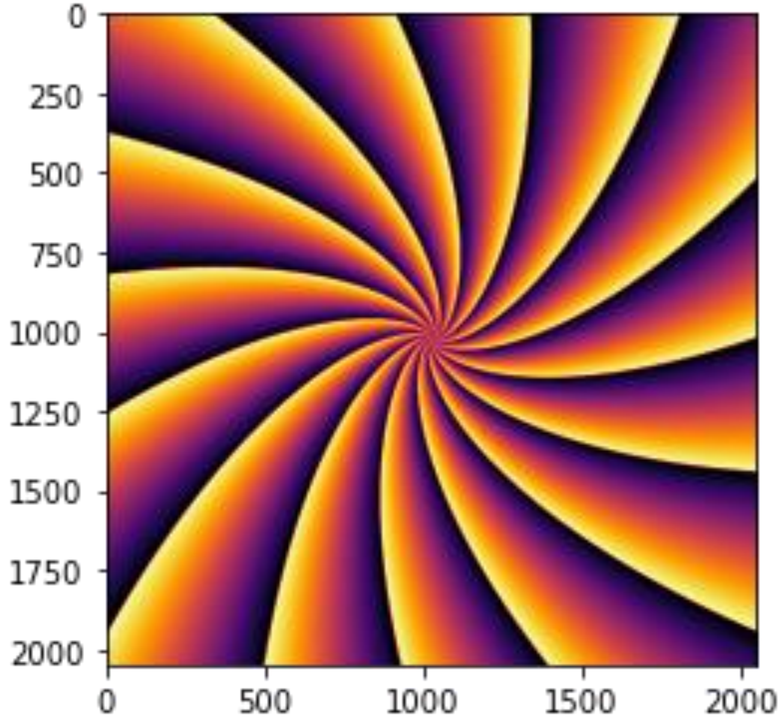
$$v_{LP}(x) = a_1 \cdot \tanh\left(\frac{x - x_1}{w_1}\right) + a_2 \quad \& \quad \nabla\phi \propto v$$

$$\int$$

$$\phi_{LP}(x) = a_1 \cdot w_1 \cdot \ln\left(\cosh\left(\frac{x - x_1}{w_1}\right)\right) + a_2 x$$

Towards rotating geometries – Giant vortex

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

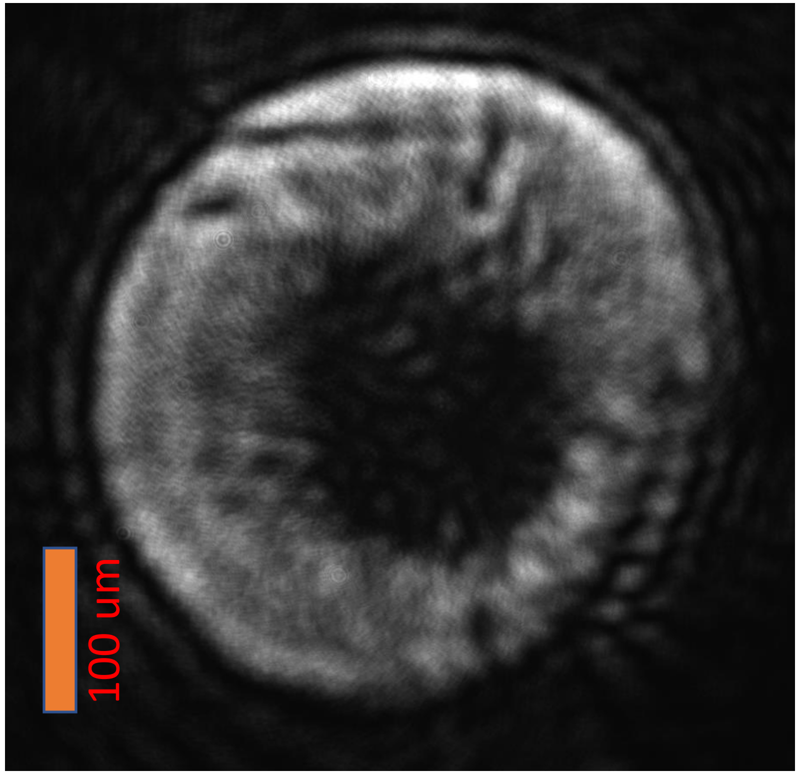


$$v_{polaritons}(r) = \frac{l}{r}\,e_\theta + \frac{C}{r}\,e_r$$

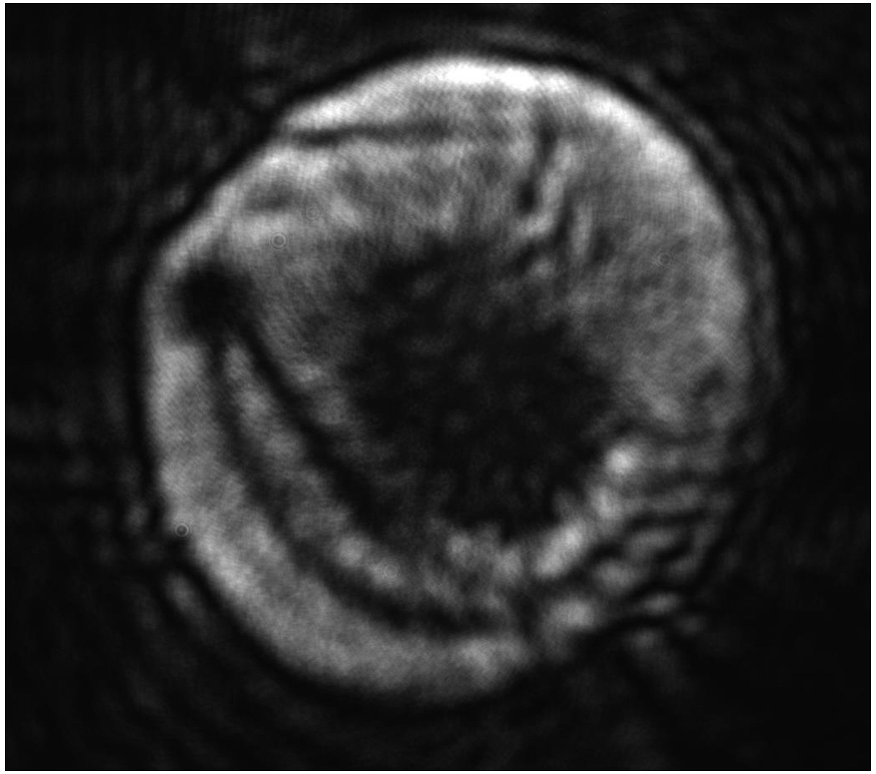
2 Peculiars boundaries

- Ergoregion : $||v_{polaritons}(r)|| > c_s$
- Event horizon : $||v_{polaritons}(r).\, e_r|| > c_s$

Solitons to probe the spacetime



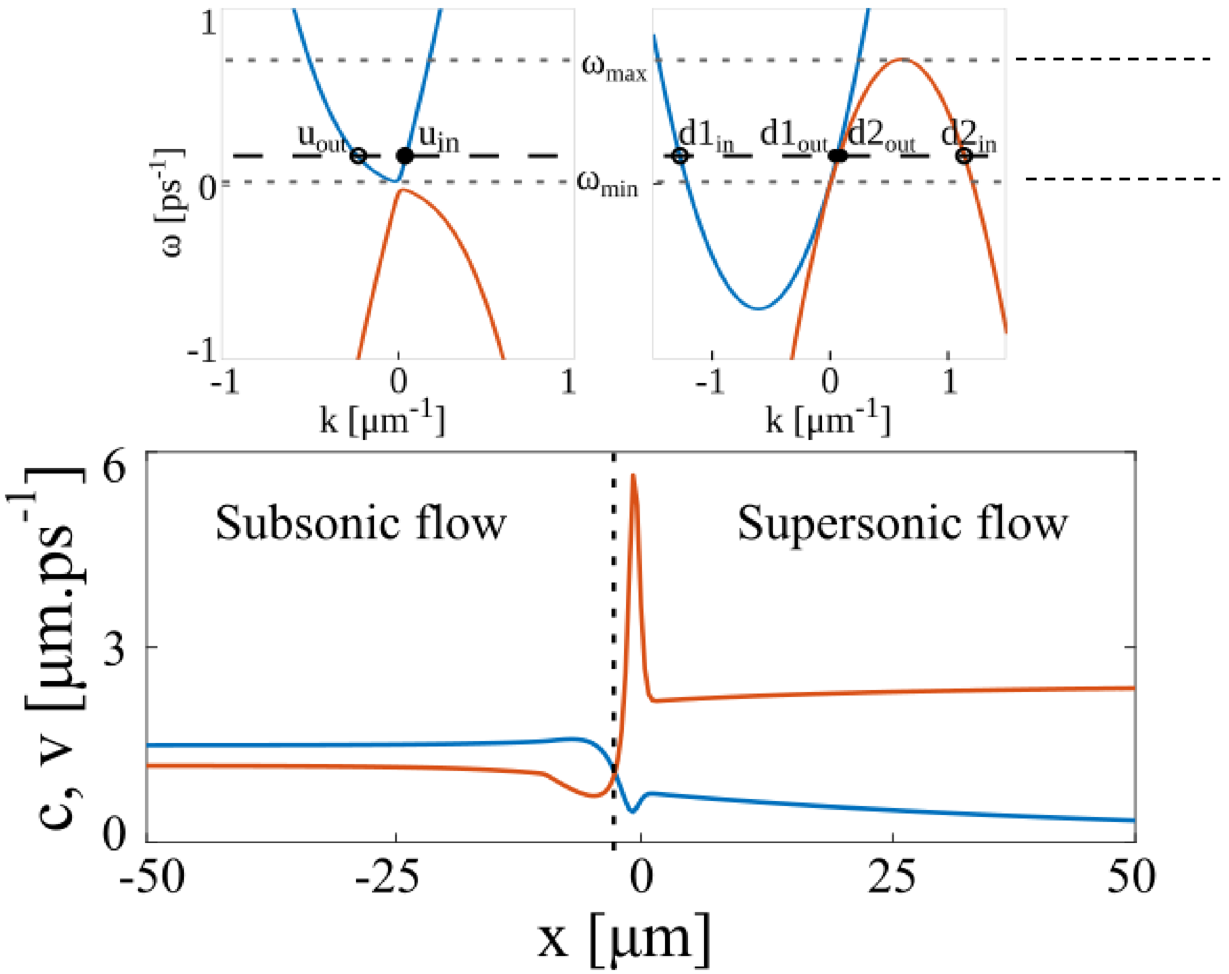
Polariton density without defect



Polariton density with defect

- **Mise en place d'un autre set-up avec Cryostat en circuit fermé**
- **Utilisation de solitons pour sonder l'espace temps**

Ref : -Jacquet et al, PTRSA 2020
-Jacquet et al, arXiv:2201.02038,
--> **Strong signal** (10^{-4})



Energy and phase matching possible

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

- $(\omega, \; -\omega) \rightarrow 0$
- $(k, \; -k) \rightarrow 0$

Missions réalisées

- Nice, Quantum Fluid of light **PhoQus** 2021
- Présentation à Rome, Quantum fluid of light **PhoQus** mars 2022
- Edimuburgh, Poster **Conference on analog model for gravity** au Higgs Institute, Juin 2022
- Présentation à Lyon, **Journée de la matière condensée**, Aout 2022

Formation realisées/prévues

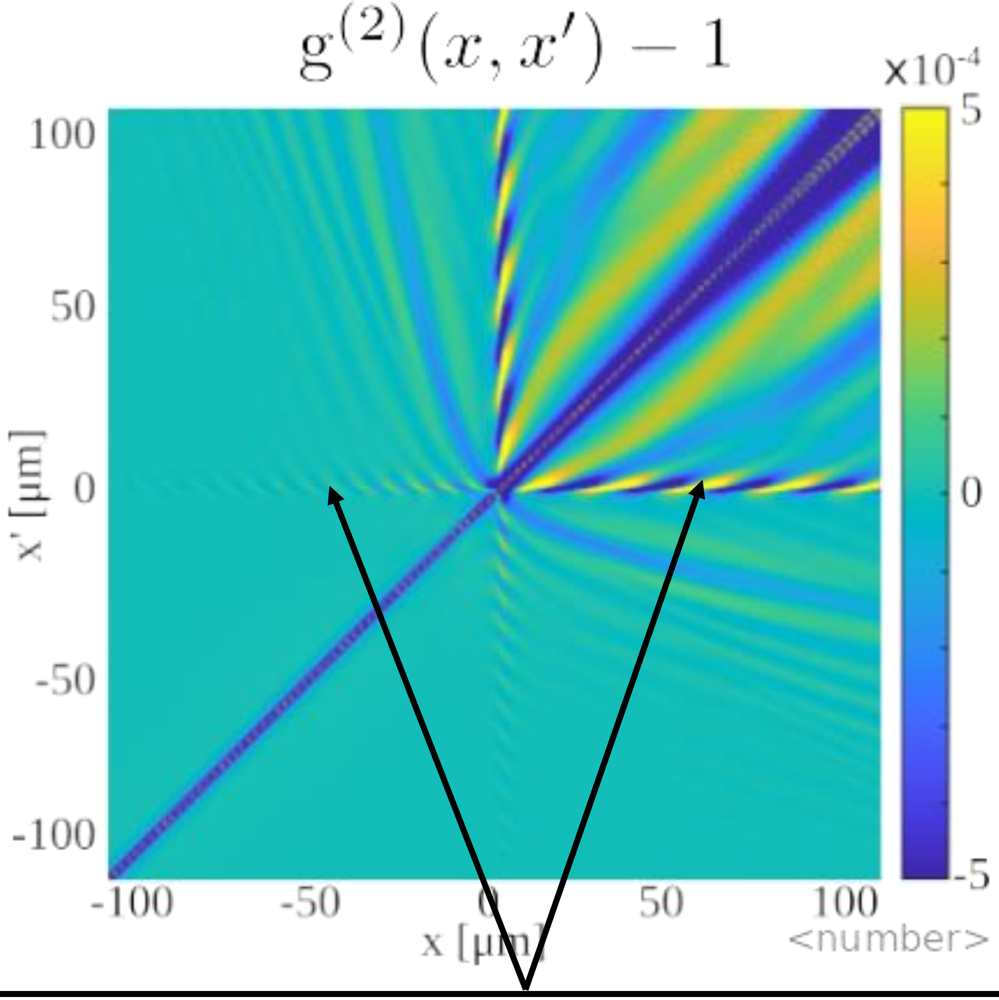
- **Ecole d'été de Varenne Quantum Fluid of light**- Société Italienne de Physique, Varenna ,Italie 1 au 7 Juillet 2022. -30h

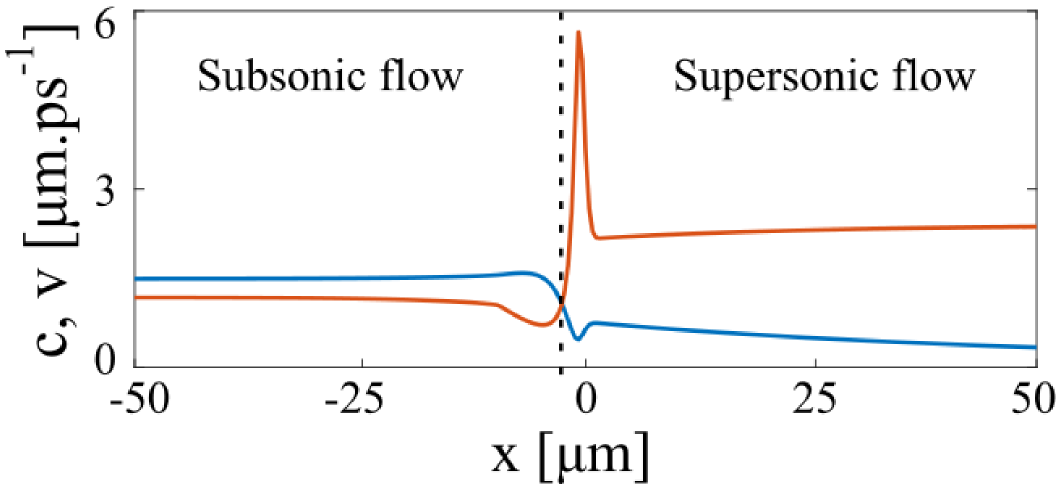
- Stage de formation sur les risques liés aux liquides cryogéniques, Septembre 2022– **3h30**

- 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**

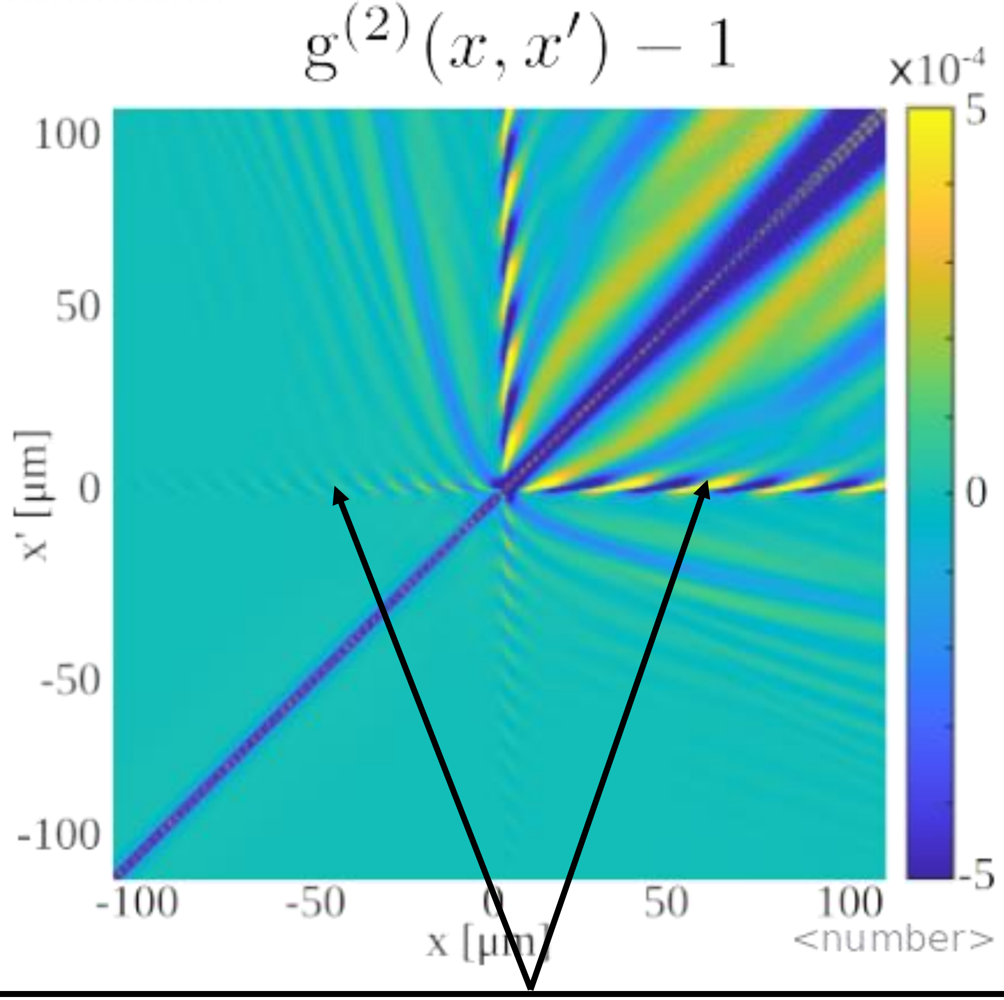
A new feature : Quasi Normal Mode of the black hole





The horizon (x=0) is correlated to the whole spacetime : upstream (x<0) and downsream (x>0).

A new feature : Quasi Normal Mode of the black hole

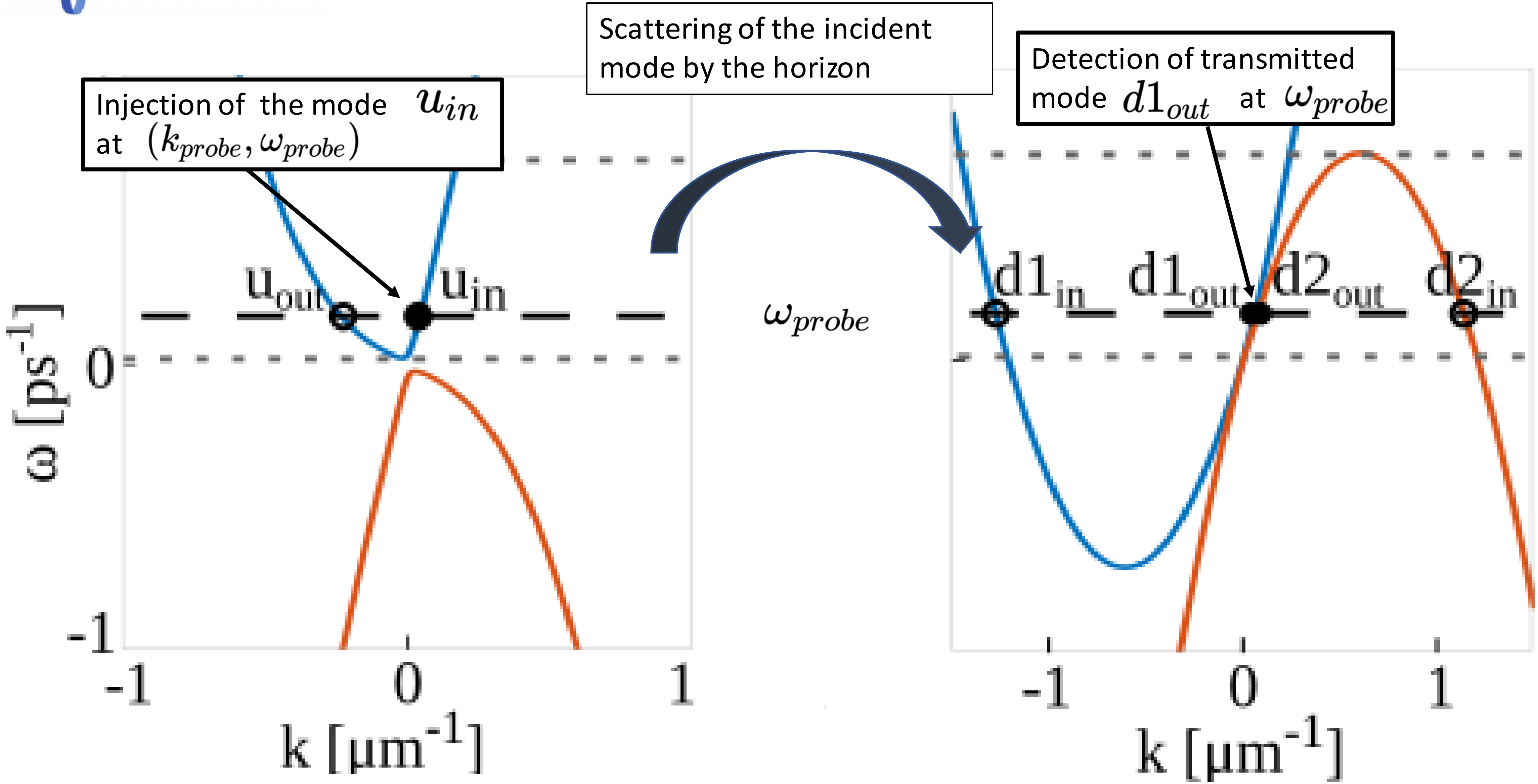


<number>

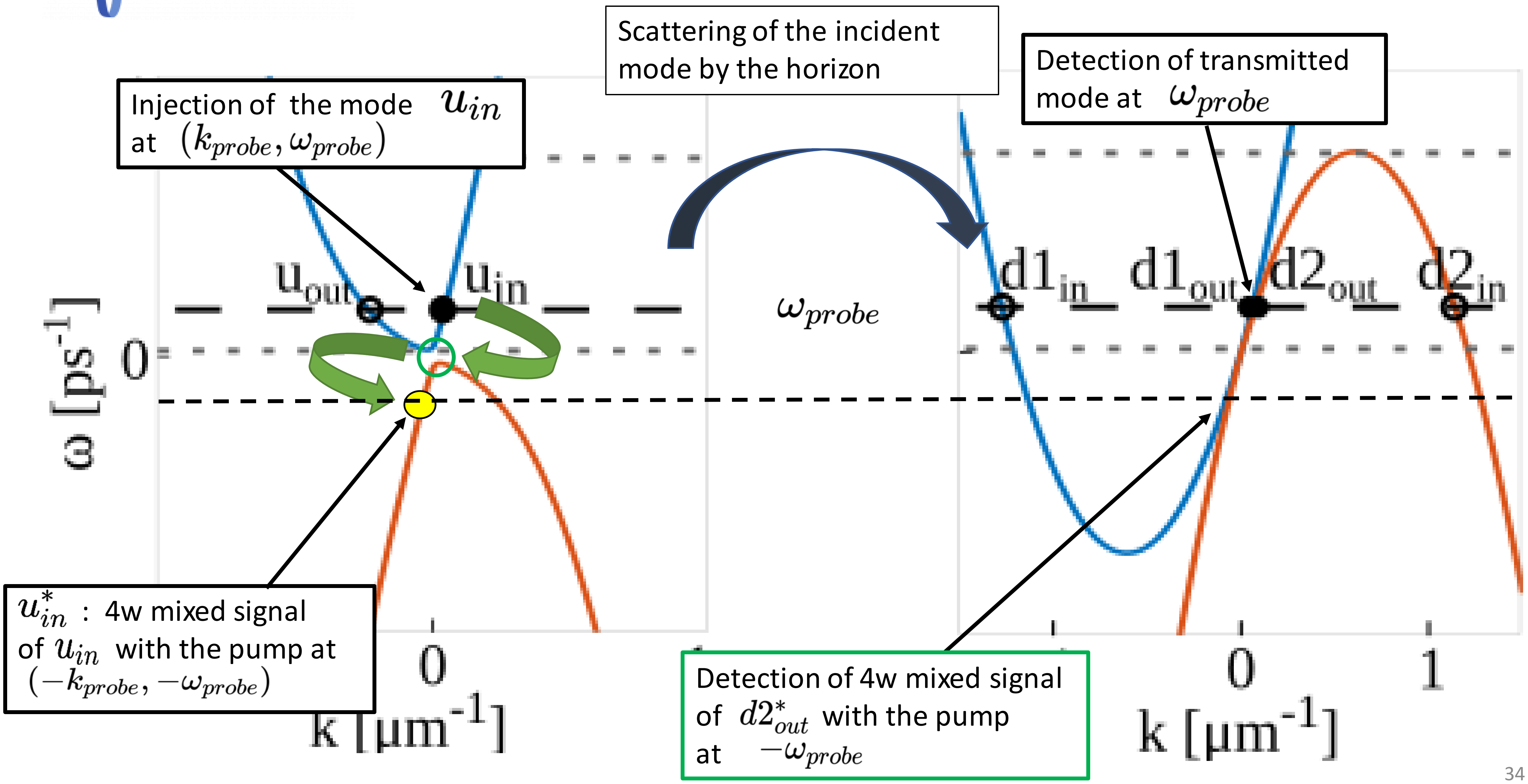
Signature of the black hole **ring down,** intrinsic to the BH.

The horizon (x=0) is correlated to the whole spacetime : upstream (x<0) and downsream (x>0).

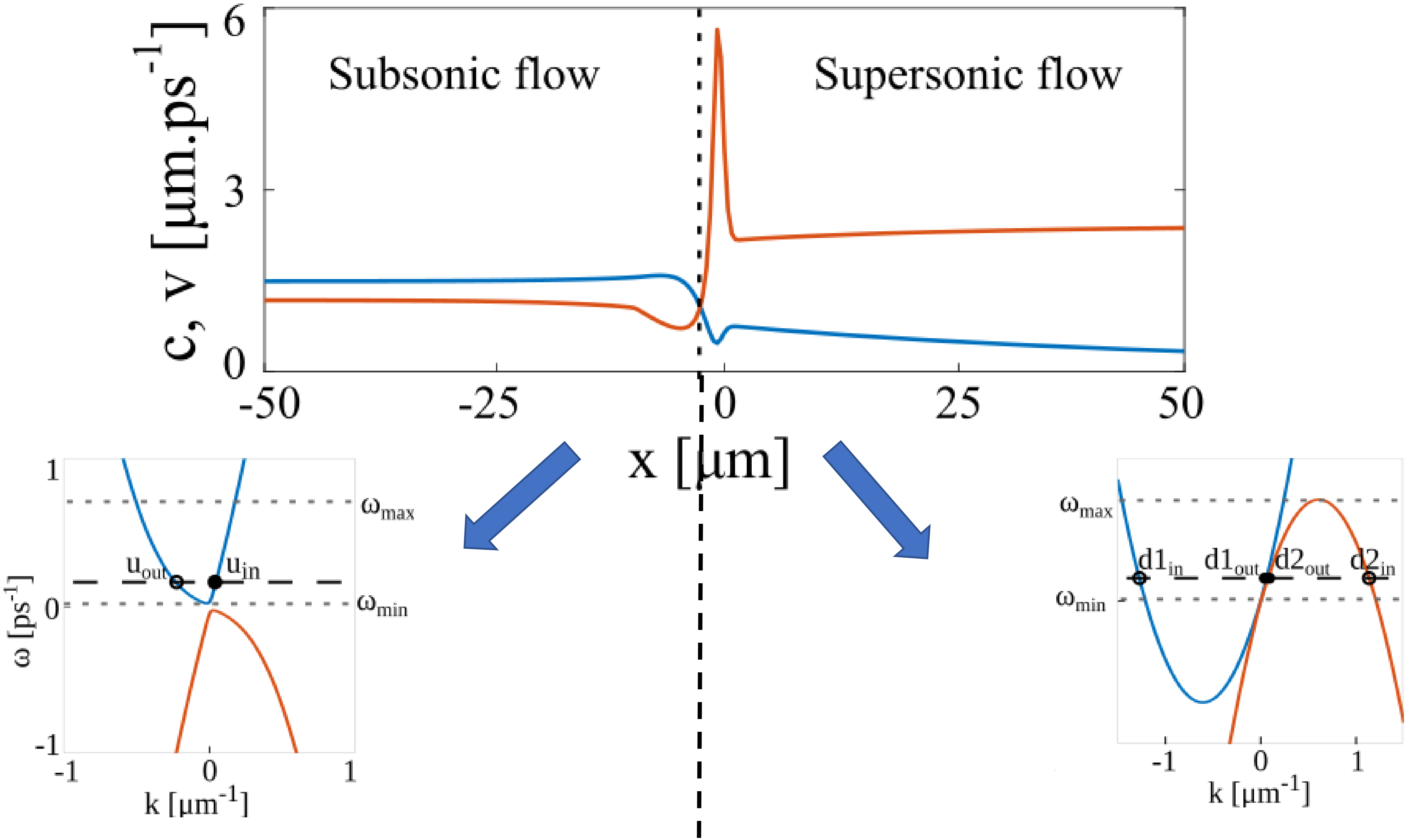
Towards the observation of a stimulated Hawking effect



Towards the observation of a stimulated Hawking effect



Bogoliubov dispersion to probe the "space-time"



Experimental Set up