Laboratoire Kastler Brossel
Physique quantique et applications

ENS
SORBONNE UNIVERSITÉ
COLLÈGE DE FRANCE
CNRS

Analogue gravity with waves in nonlinear media

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Laboratoire Kastler Brossel, CNRS and Sorbonne University, Paris

GDR Complexe 8/12/2022

PhoQuS
Photons for Quantum Simulation

Today’s talk

The propagation of waves in nonlinear media may be controlled to engineer situations where the waves propagate as though they were on a curved spacetime, like around a black hole or in an inflating universe. This enables the experimental simulation of field theories on curved spacetime.

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The propagation of waves in nonlinear media may be controlled to engineer situations where the waves propagate as though they were on an effectively curved geometry, like around a black hole or in an inflating universe. This enables the experimental study of field theories on curved geometries.

Controlled propagation of waves → effective geometry → linearised excitations

Controlled propagation of waves	effective geometry	linearised excitations
(engineered nonlinearity)	(curvature)	(quantum field)

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Controlled propagation of waves → effective geometry → linearised excitations
(engineered nonlinearity) (curvature) (quantum field)

Spatial change in geometry: black hole

Temporal change in geometry: cosmology

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Temporal change in geometry: cosmology

Spontaneous emission from the vacuum

Correlated/entangled waves

Dynamical instabilities

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How to create the spacetime of a Schwarzschild black hole in the laboratory?

curvature

How to observe the Hawking effect in the laboratory?

quantum field

Our experiment with a quantum fluid of microcavity polaritons

engineered nonlinearity

correlated waves

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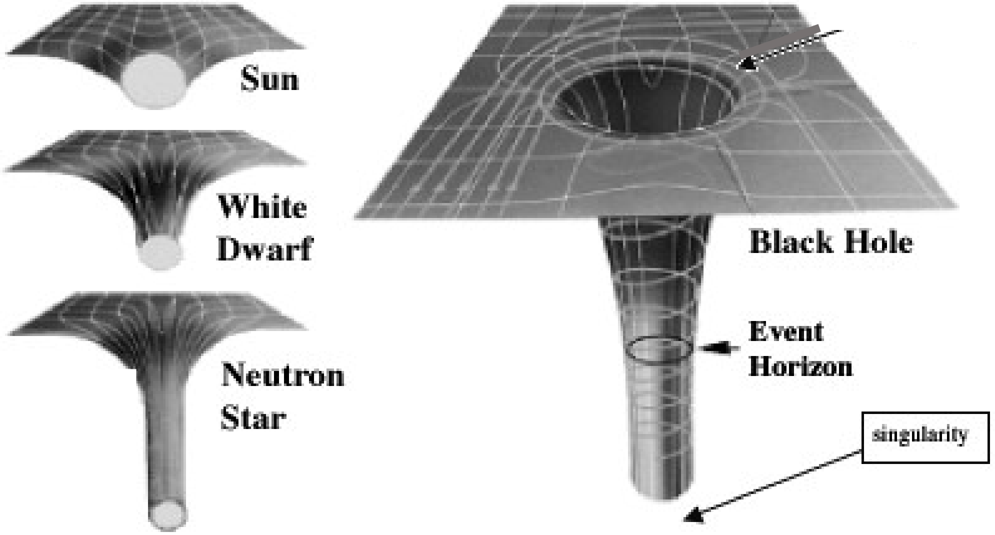


Nasa website

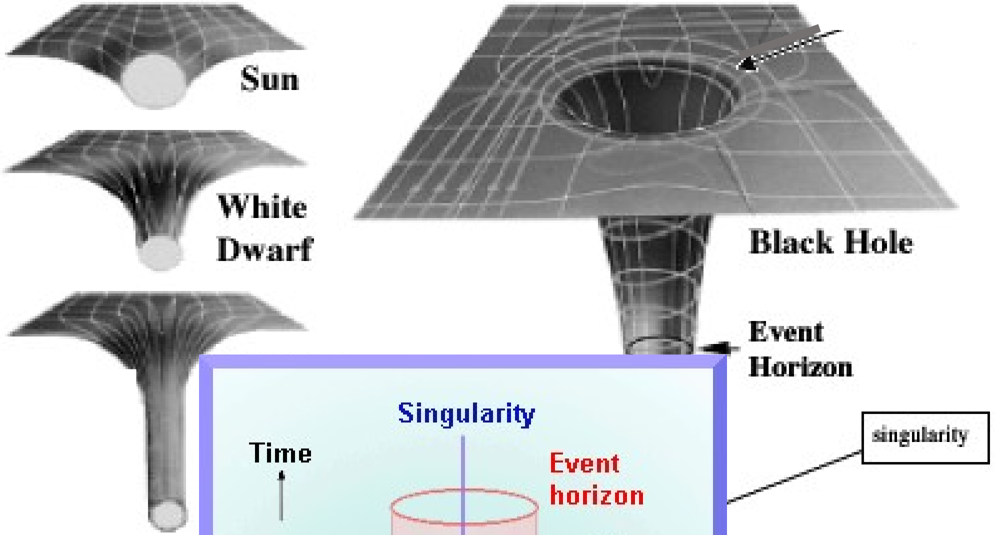
Penrose, 1972

General Relativity identifies gravity with curvature of spacetime

Point of no return: event horizon

General Relativity: nothing can escape a black hole

Black holes



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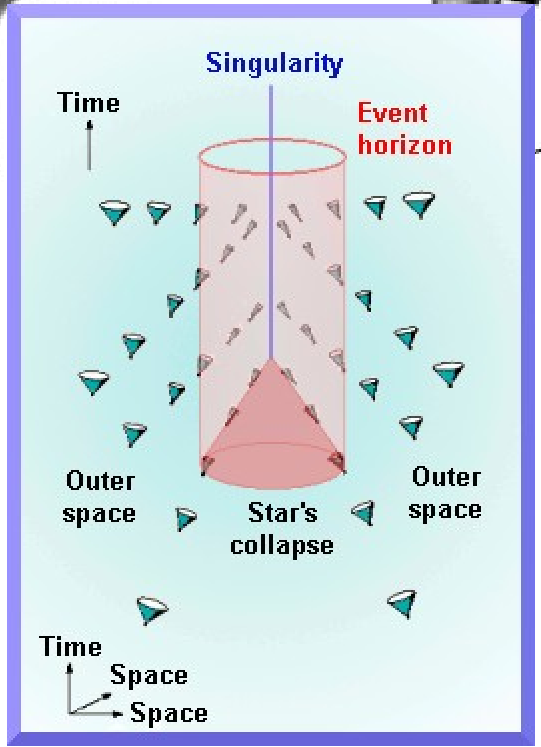

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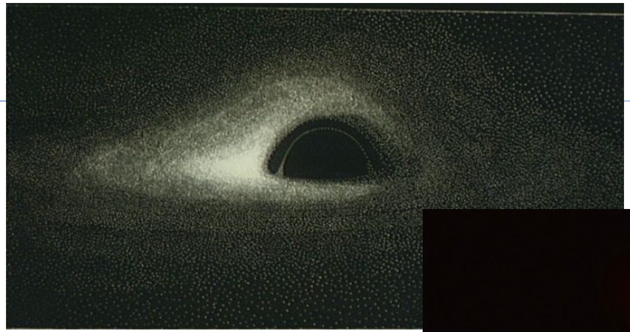
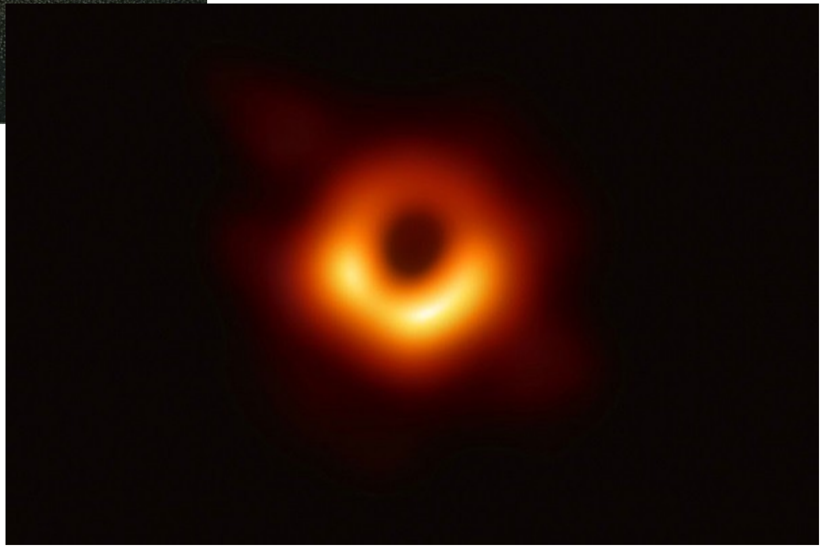
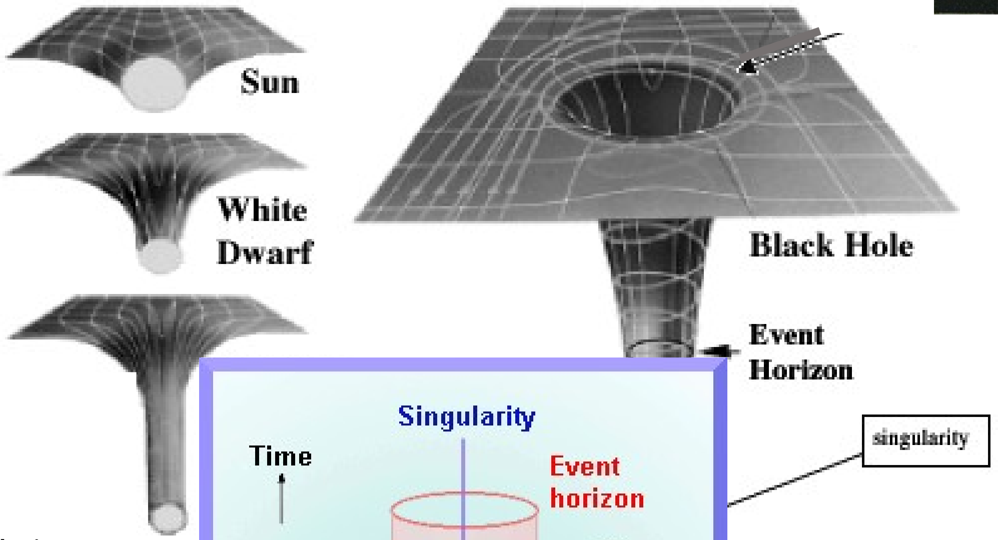


Luminet, 1979

EHT, 2019





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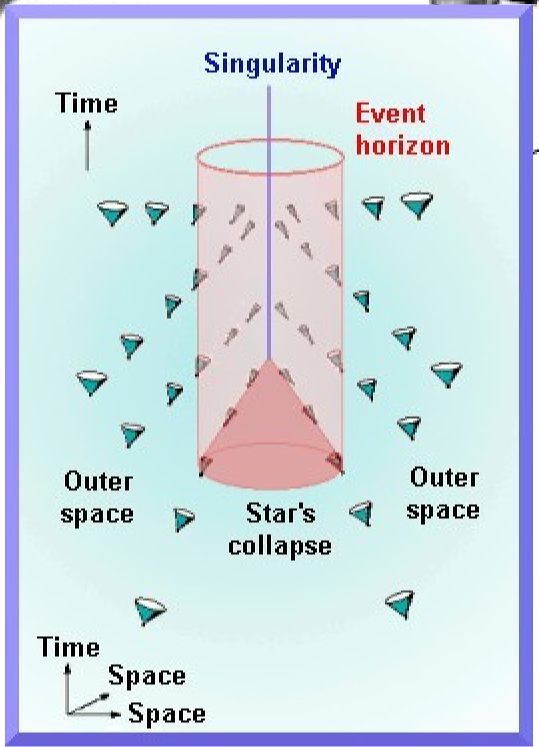

Penrose, 1972

General Relativity identifies gravity with curvature of spacetime

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General Relativity: nothing can escape a black hole

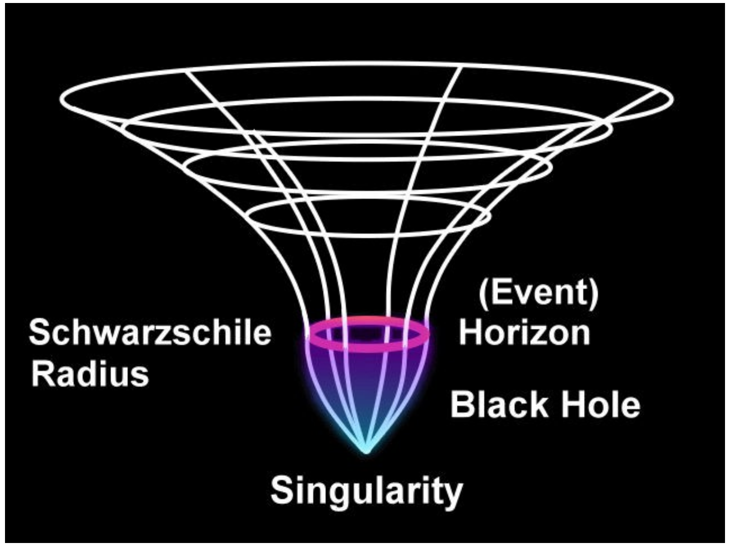
Black holes are characterised by their mass, their momentum and their charge

Non-rotating black hole : Schwarzschild

Schwarzschild black holes are characterised solely by their mass → Schwarzschild black hole = 4-sphere

Rotational spatial symmetry

→ full description in 1+1D

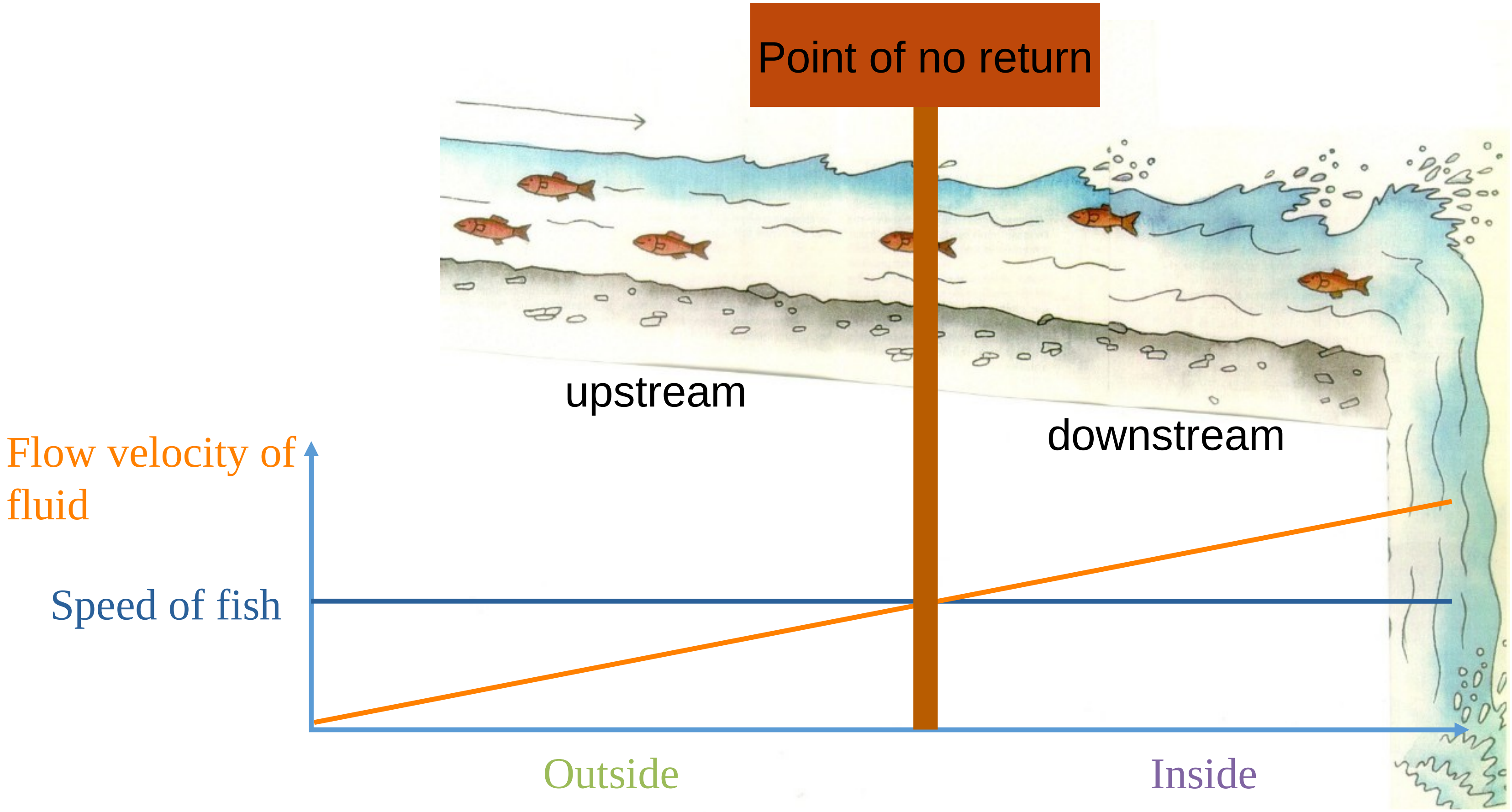


https://universe-review.ca/F05-galaxy02.htm

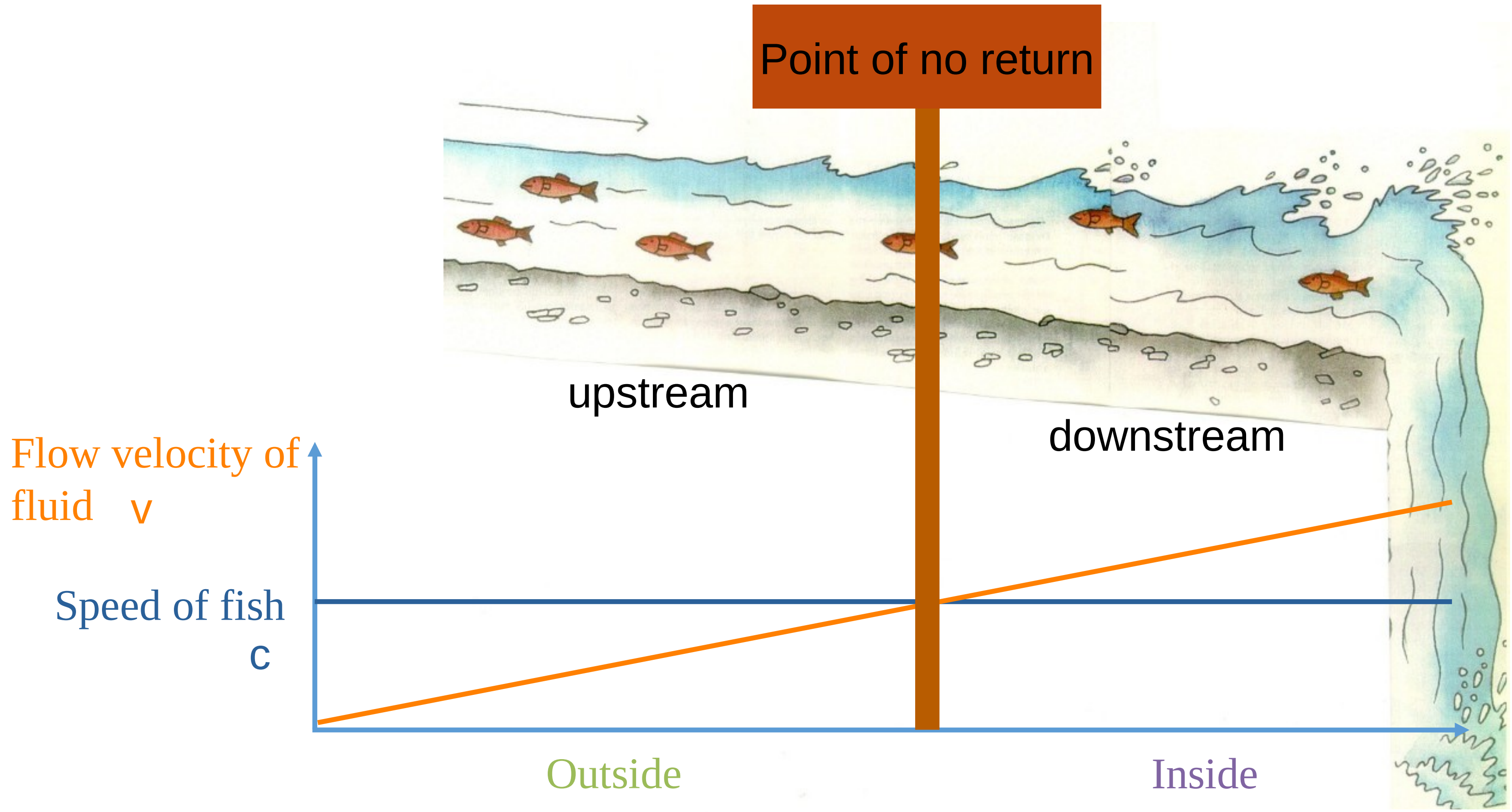
Event horizon = point of no return

Schwarzschild black holes are characterised solely by their mass → Schwarzschild black hole = 4-sphere

Rotational spatial symmetry → full description in 1+1D



Schwarzschild geometry ↔ waterfall geometry

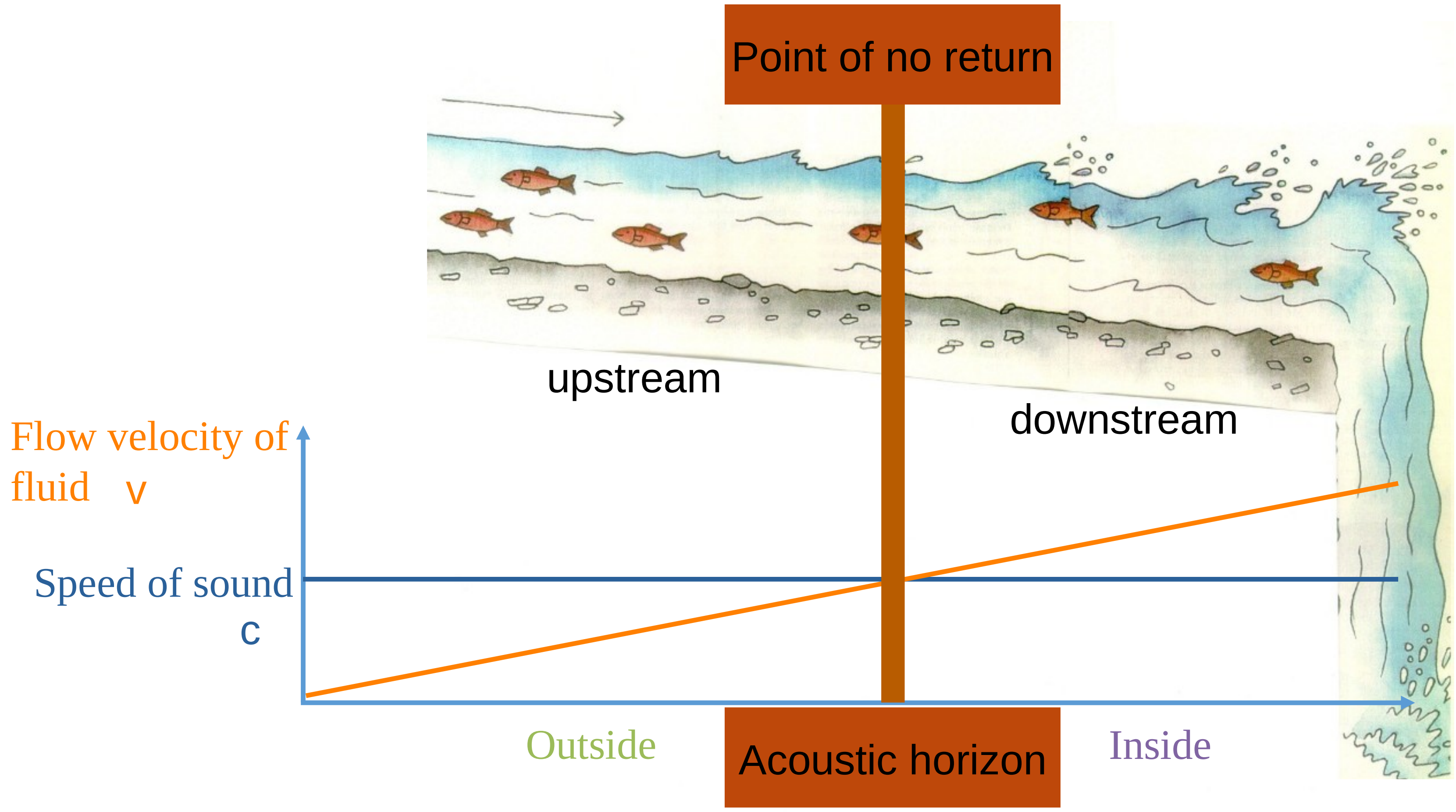


Wave equation for scalar field on Schwarzschild geometry:

$$g^{\mu\nu}_{schw} = \begin{pmatrix} -1 & -v \\ -v & (c^2 - v^2) \end{pmatrix}$$

Inverse metric tensor of Painlevé-Gullstrand metric in 1+1D

Schwarzschild geometry ↔ waterfall geometry



Wave equation for scalar field on Schwarzschild geometry:

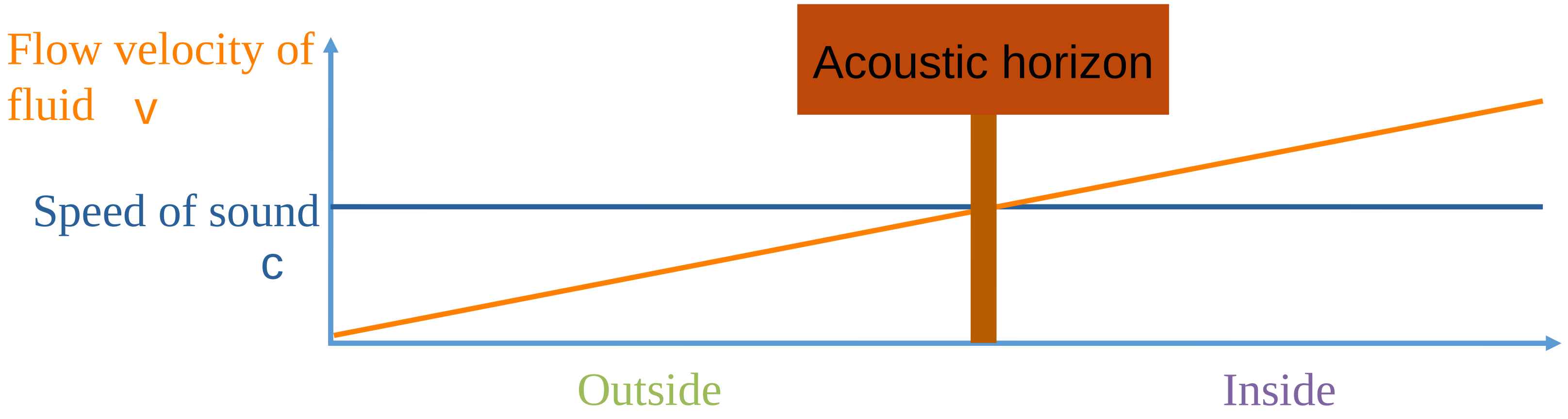
$$g^{\mu\nu}_{schw} = \begin{pmatrix} -1 & -v \\ -v & (c^2 - v^2) \end{pmatrix}$$

$$g^{\mu\nu}_{Unruh} = \begin{pmatrix} -1 & -v \\ -v & (c^2 - v^2) \end{pmatrix}$$

Unruh *PRL* **46** 1351 (1981): wave equations are

Quantised acoustic field in waterfall geometry

Schwarzschild geometry ↔ waterfall geometry

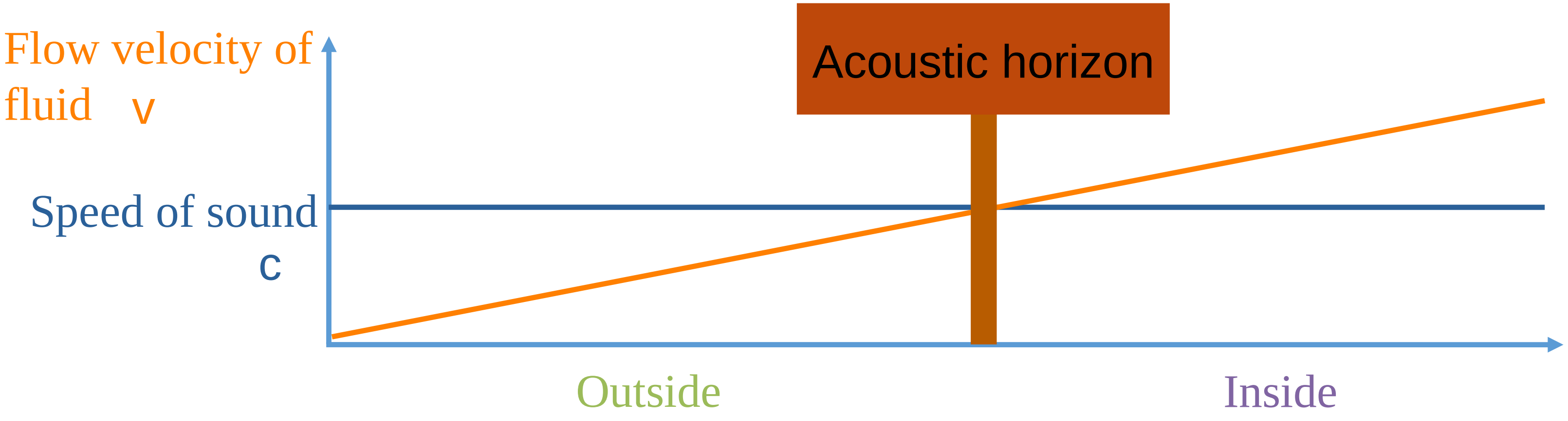


Wave equation of quantised acoustic field:

$$g^{\mu\nu}_{Unruh} = \begin{pmatrix} -1 & -v \\ -v & (c^2 - v^2) \end{pmatrix}$$

Unruh *PRL* **46** 1351 (1981): wave equations are

Schwarzschild geometry ↔ waterfall geometry



Quantised acoustic field:

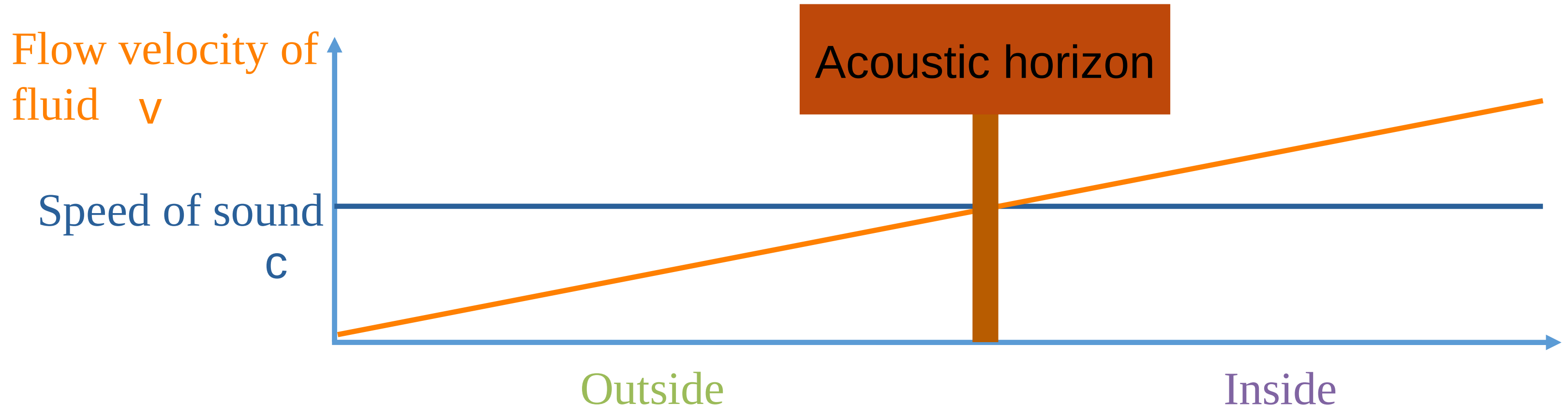
in: $\phi = \int d\omega \left(a_\omega f_\omega + a^\dagger_\omega f^*_\omega\right) \quad a\left|0\right\rangle = 0$

out: $\phi = \int d\omega \left(\bar{a}_\omega F_\omega + \bar{a}^\dagger_\omega F^*_\omega\right) \quad \bar{a}\left|\bar{0}\right\rangle = 0$

Express out modes in terms of in modes:

$$F_\omega = \int d\omega' \left(\alpha_{\omega\omega'} f_{\omega'} + \beta_{\omega\omega'} f^*_{\omega'}\right)$$

Schwarzschild geometry ↔ waterfall geometry



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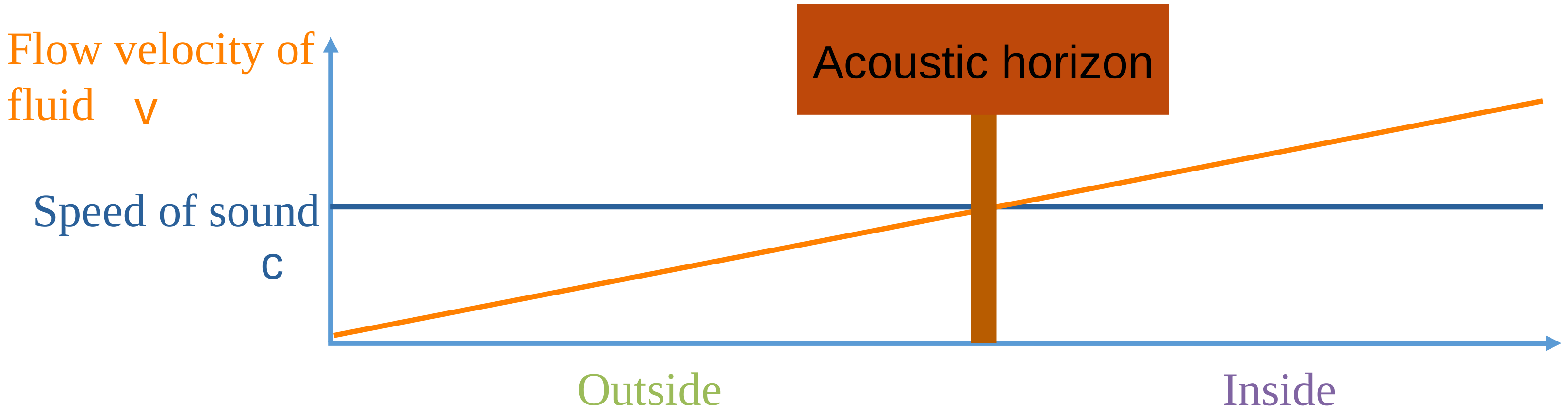
Different speed on either side of the horizon $\Rightarrow |\bar{0}\rangle \neq |0\rangle \Rightarrow \beta_{\omega\omega'} \neq 0$

Quantised acoustic field in waterfall geometry

Schwarzschild geometry ↔ waterfall geometry



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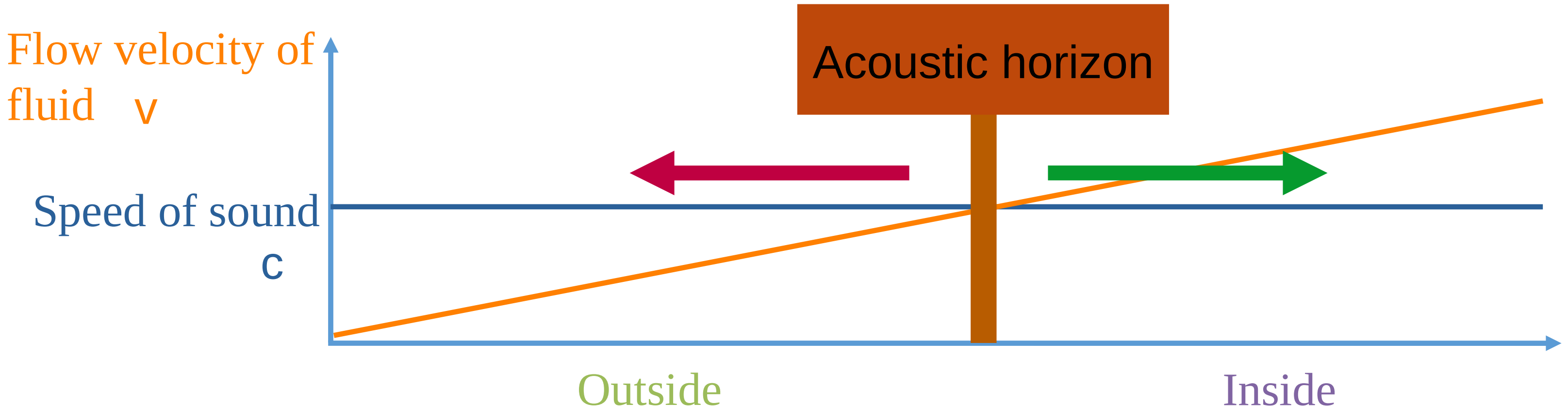
mixing of positive and negative frequency waves
⇒ mixing of creation and annihilation operators

$$\mathrm{a}\left|\bar{0}\right\rangle = \sum_{\omega'} \beta_{\omega\omega'} \left|\bar{1}\right\rangle > 0$$

Schwarzschild geometry ↔ waterfall geometry



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Different speed on either side of the horizon

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mixing of positive and negative frequency waves
⇒ mixing of creation and annihilation operators

Spontaneous emission from the vacuum!

Hawking effect

Unruh *PRL* **46** 1351

Today's talk

How to create the spacetime of a Schwarzschild black hole in the laboratory?
curvature

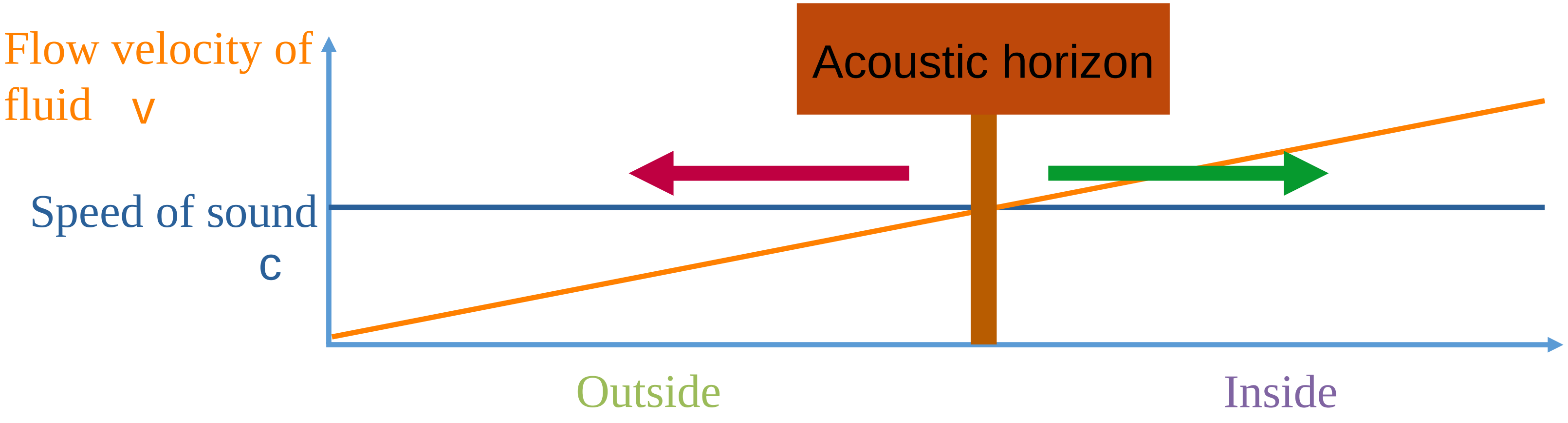
How to observe the Hawking effect in the laboratory?
quantum field

Our experiment with a quantum fluid of microcavity polaritons
engineered nonlinearity
correlated waves

1) create a transsonic fluid → acoustic horizon where v=c
different speed on either side of acoustic horizon → mixing of positive and negative frequency waves
→ spontaneous emission of phonon pairs from the vacuum
Unruh *PRL* **46** 1351 (1981)

2) observe Hawking spectrum

3) observe correlations across the horizon



‘Black hole’ experiments in analogue gravity

Sound waves

In BEC

Hawking correlations
Steinhauer 2019

Black hole laser?
Steinhauer 2014

In fluid of light
(microcavity polaritons)
Proof of principle by Amo and Bloch 2015
New experiments in Paris 2022

Gravity/Capilary waves

Scattering at the white hole
Rousseaux and Leonhardt 2008
Weinfurtner and Unruh 2010
Correlations across the WH horizon
Rousseaux and Parentani 2016
Correlations across the BH horizon
Rousseaux 2020

Rotating black hole - superradiance
Weinfurtner 2016
Rotating black hole – oscillation of light rings (QNMs)
Weinfurtner 2020

Light waves

Scatteringt at the BH/WH horizon
König and Leonhardt (Fibre) 2008
Faccio (Bulk) 2010
König (Fibre) 2012
Wang (Fibre) 2013
Murdoch (Fibre) 2015?
Bose (Fibre) 2015
Ciret (waveguide) 2016
Kanakis (Fibre) 2016
Gaafar (waveguide) 2017
König and Jacquet (Fibre) 2018
Leonhardt (Fibre) 2019

Negative frequency waves
König and Faccio 2012
König 2014, 2015

Universality of the Hawking effect, Unruh and Schützhold PRD **71** 024028 (2005)?

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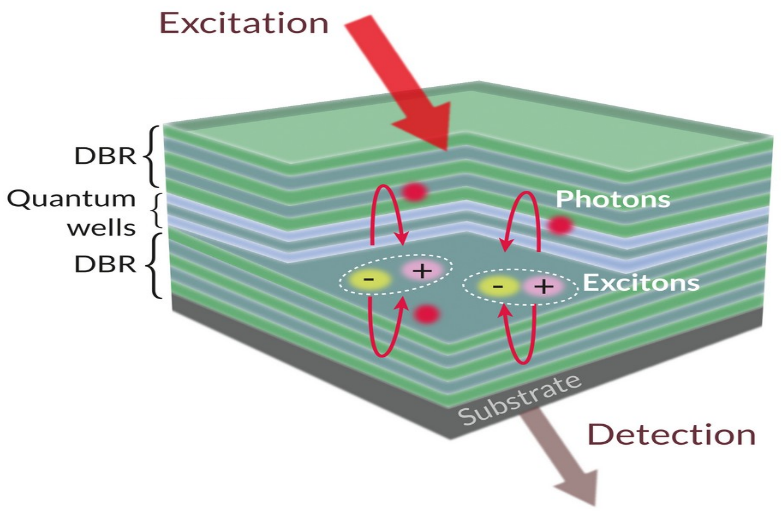
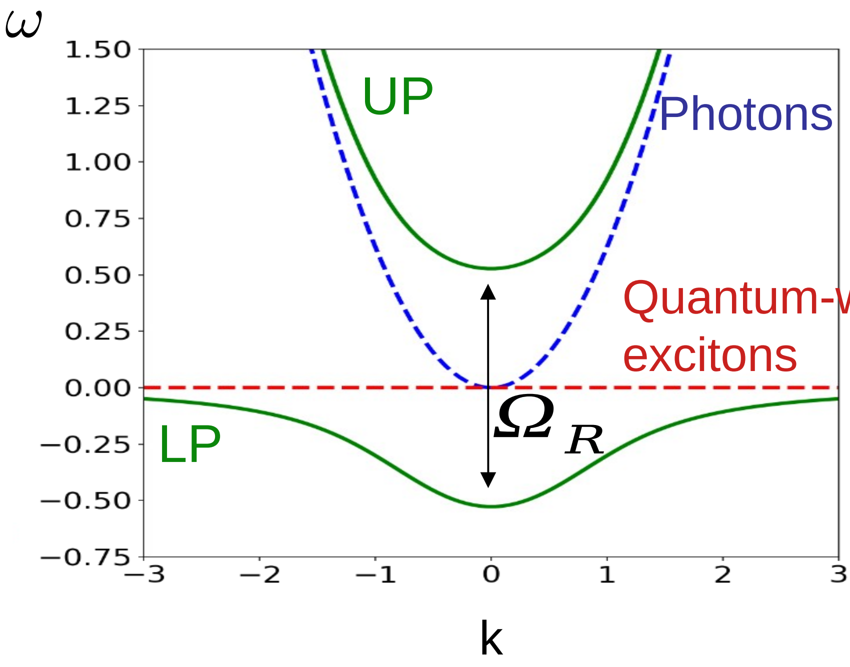
Carusotto and Ciutti RMP **85** 299 (2013)

Polaritons= photons dressed with material excitations that live in the cavity plane





effective mass from confinement

interactions

Dynamics in the cavity plane described by Gross-Pitaevskii (Nonlinear Schrödinger) equation:

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

($n = |\psi|^2$)

g polariton-polariton interaction constant

γ losses

P pump

Driven-dissipative dynamics $\rightarrow$ **Out-of-equilibrium system**

Resonantly excited microcavity polaritons

Maître *et al* PRX **10** 041028 (2020)

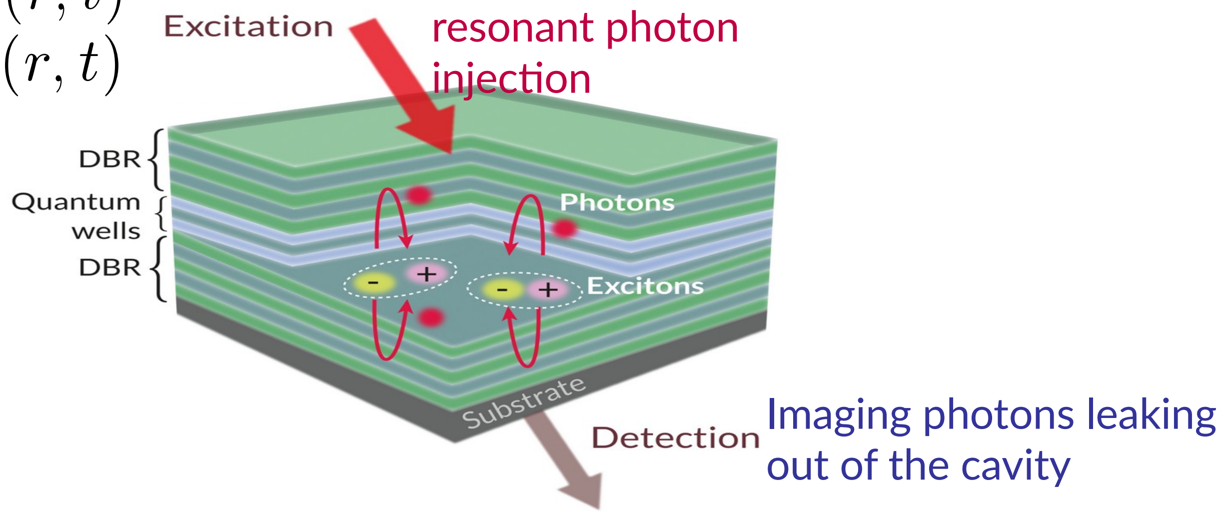
Polaritons= photons dressed with material excitations that live in the cavity plane

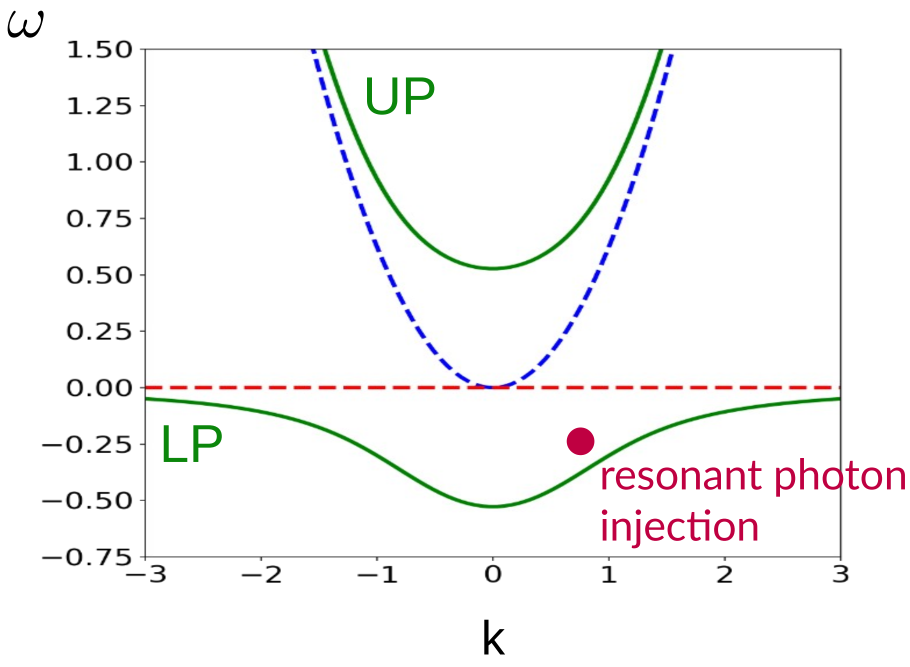
$\mathrm{I(r,t)} \rightarrow n(r,t)$

$\phi(r,t) \rightarrow v(r,t)$

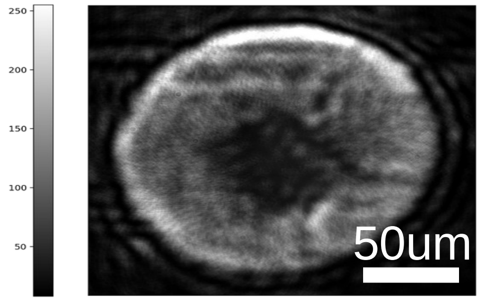
Phase + intensity profile of driving field

→ Spatial Light Modulator (SLM)





$\mathrm{n(r,t)} \rightarrow I(r,t)$



$\mathrm{v(r,t)} \rightarrow \phi(r,t)$

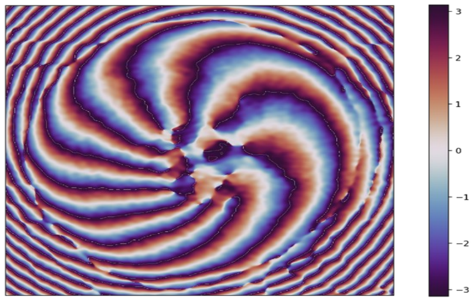


Image of the **cavity plane**

→ density map: $\mathrm{c} \propto \sqrt{n}$

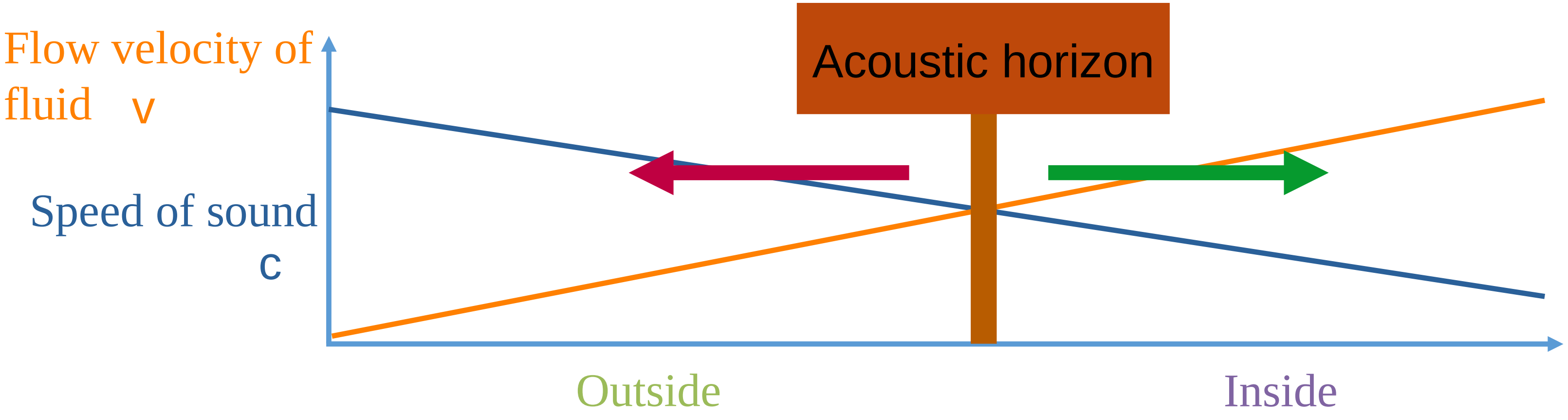
→ velocity map: $\mathrm{v} \propto \nabla\phi$

Full optical experiment

(2D planar sample, no microstructure)

1) create a transsonic fluid → acoustic horizon where v=c
2) observe Hawking spectrum
3) observe correlations across the horizon

Unruh *PRL* **46** 1351 (1981)
Visser *Class Quant Grav* **15** 1767 (1998)

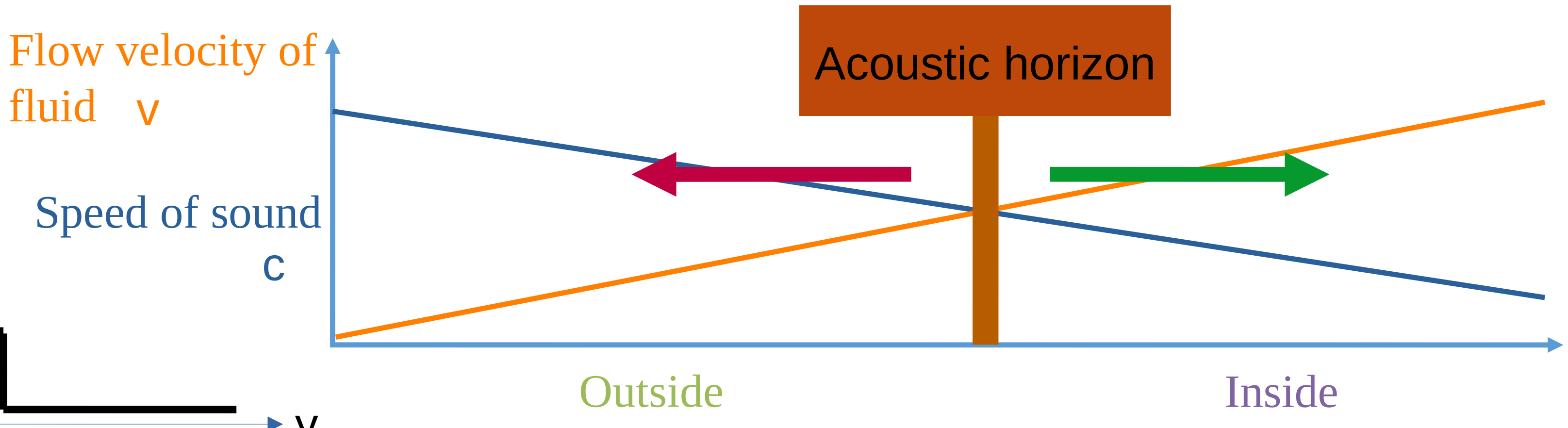


First proposal by Solnyshkov *et al. PRB* **84** 233405 (2011)
Numerical studies in Gerace and Carusotto *PRB* **86** 144505 (2012)
Grisins *et al*. *PRB* **94** 144518 (2016)
Jacquet *et al*. *EPJD* **76** 152 (2022)
Proof of principle experiments for acoustic horizon by Nguyen *et al. PRL* **114** 036402 (2015)
Jacquet *et al.* PTRSA **378** 201190225 (2020)

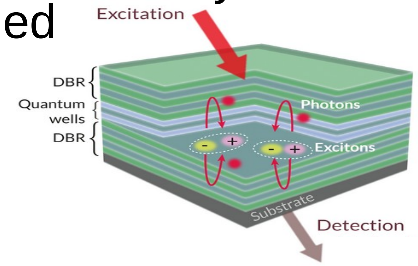
Hawking effect has not been seen in polaritons to date

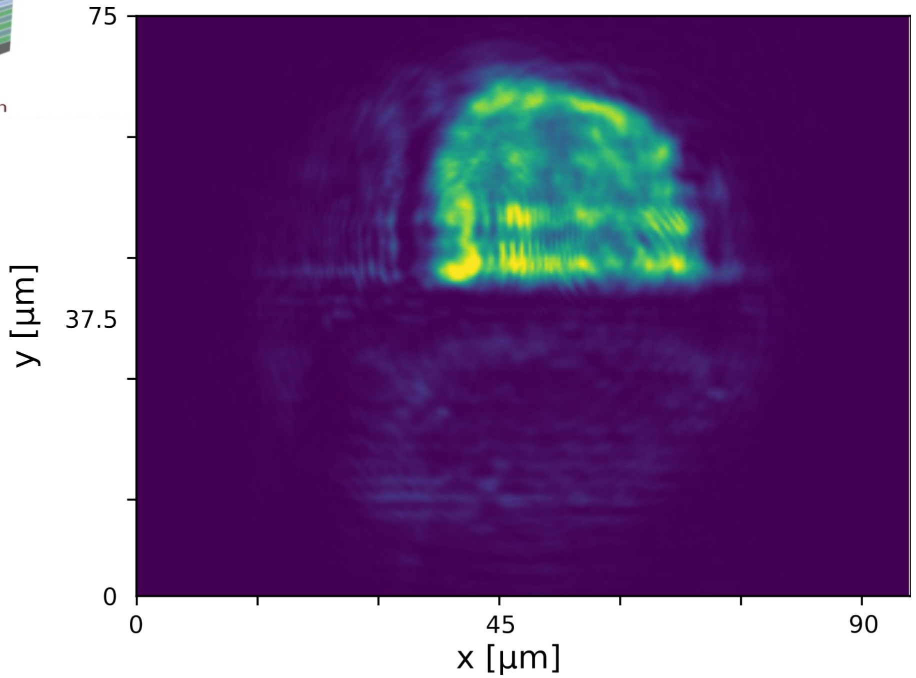
Acoustic horizon

New data by PhD student Kévin Falque

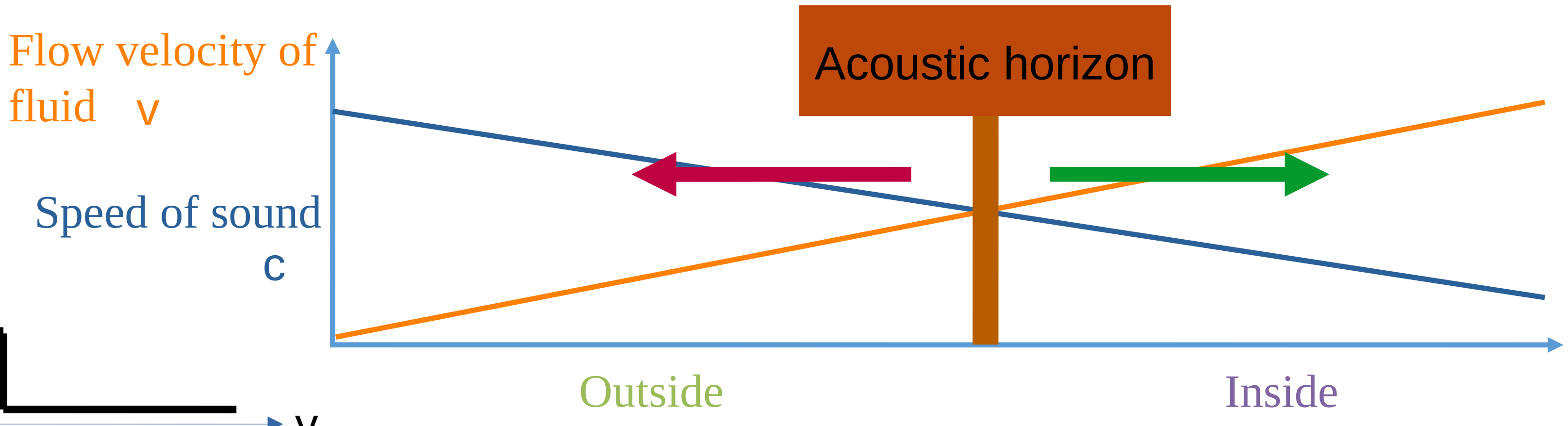


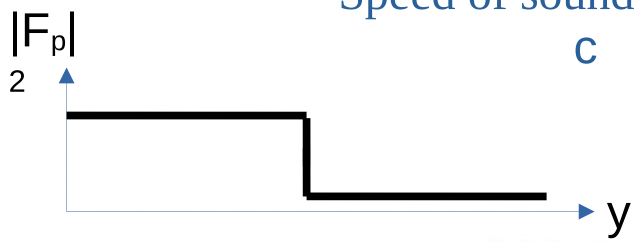
+ phase controlled with SLM

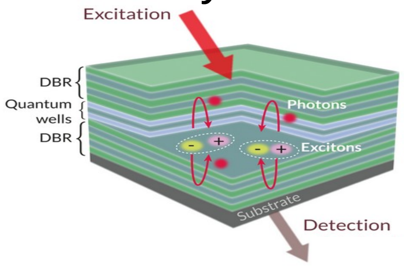


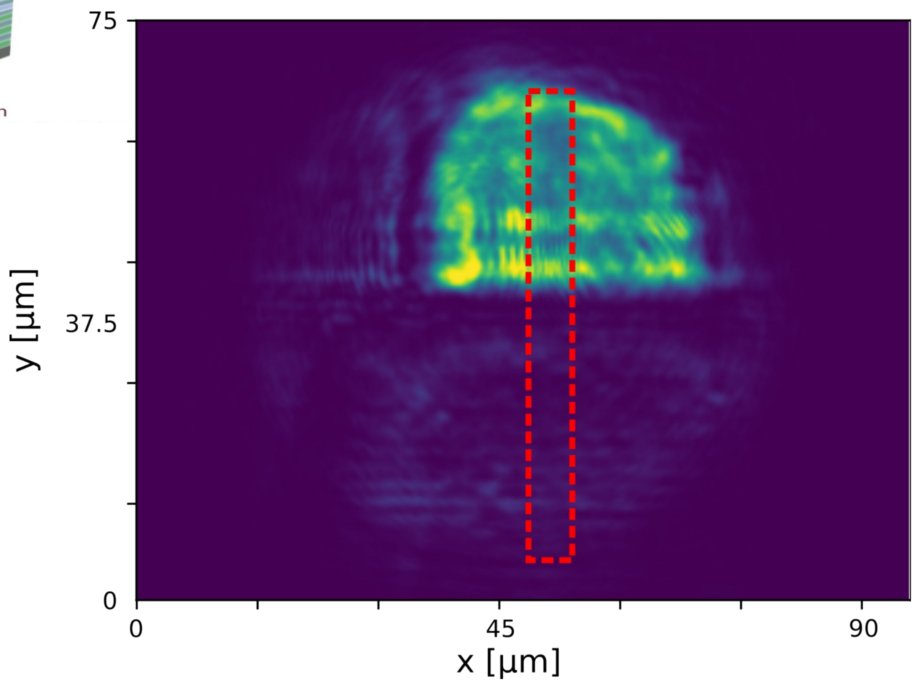


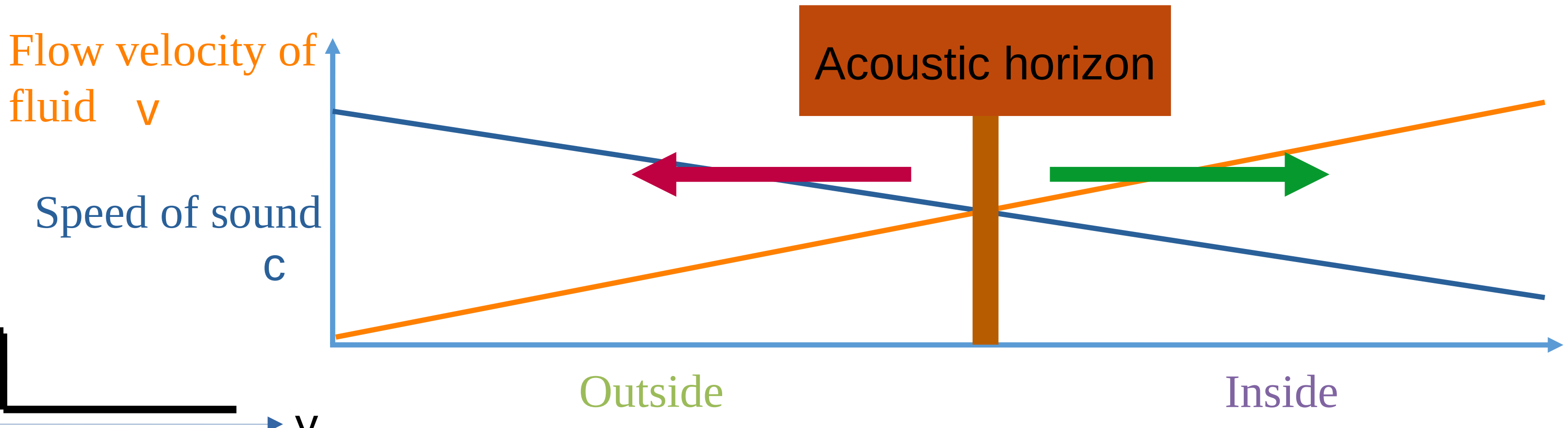
Acoustic horizon

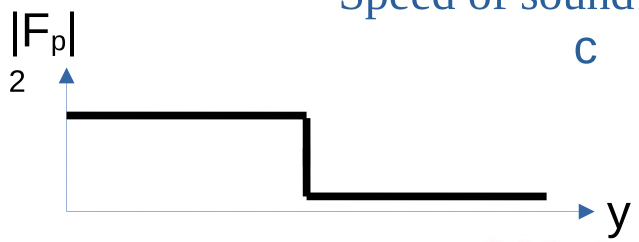


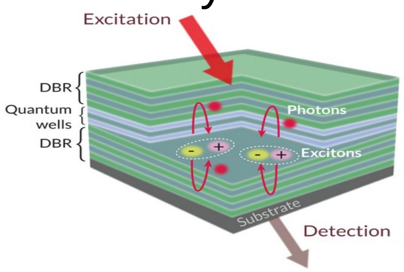


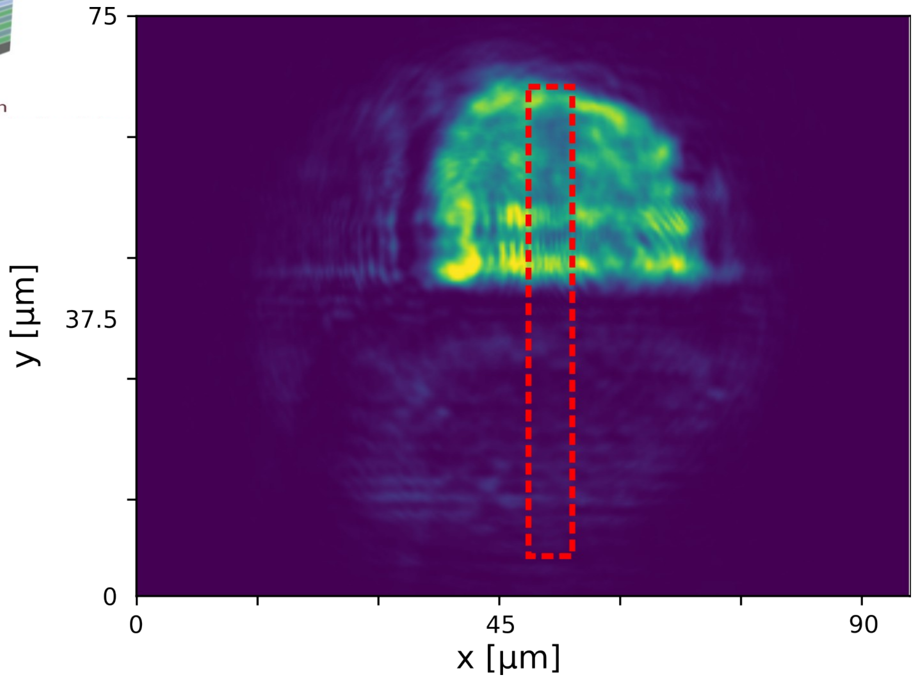


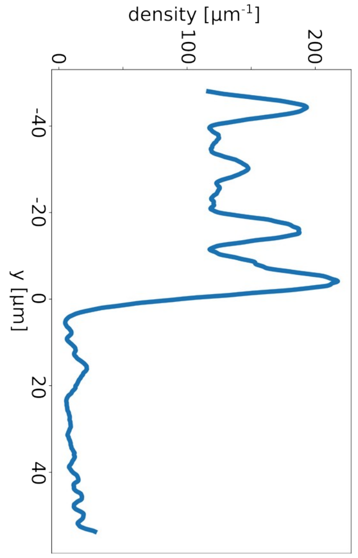


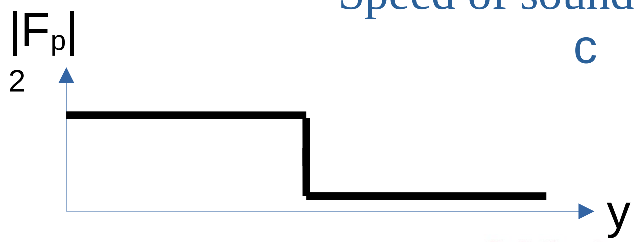

Flow velocity of fluid v
Speed of sound c
Acoustic horizon
Outside
Inside

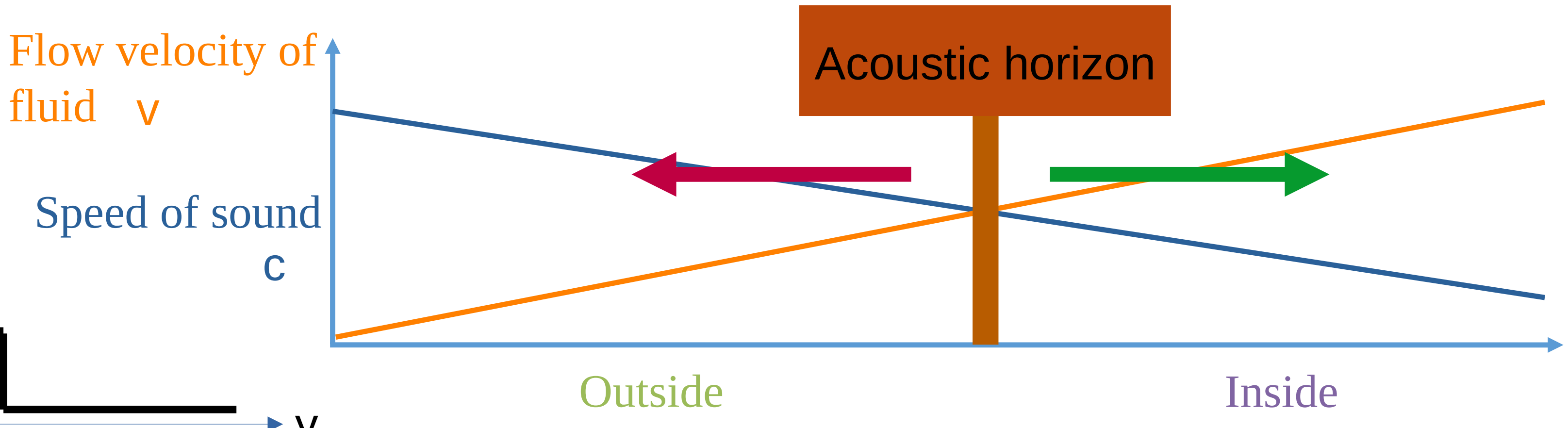

|Fp|
2
y

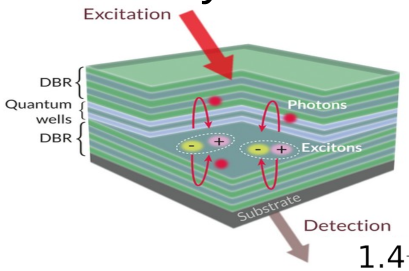

Excitation
DBR
Quantum wells
DBR
Photons
Excitons
Substrate
Detection


75
37.5
0
y [µm]
0
45
90
x [µm]

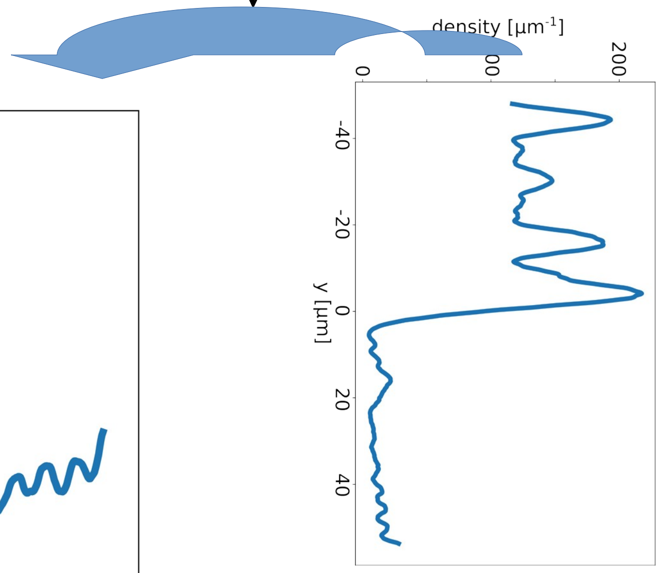

density [µm-1]
0
100
200
-40
-20
0
20
40
y [µm]

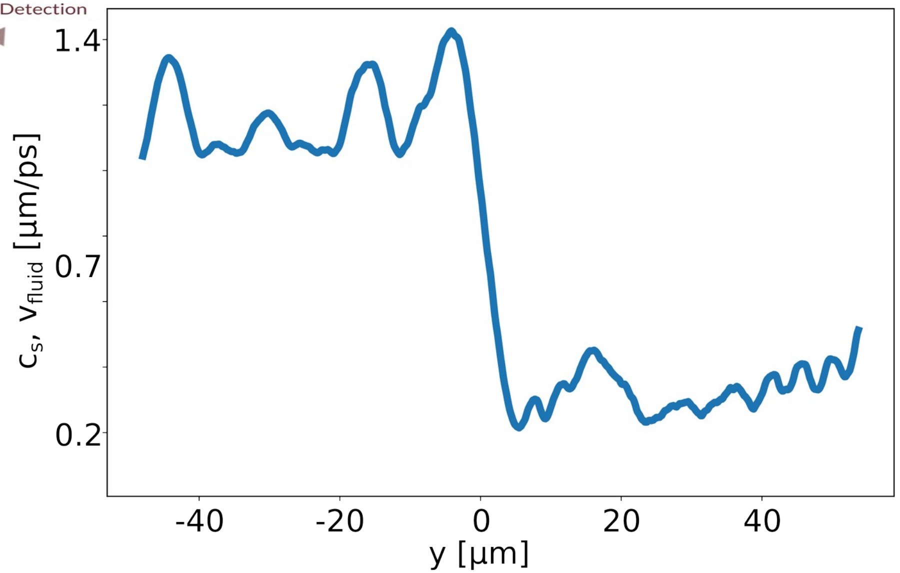






$$c \propto \sqrt{n}$$





Acoustic horizon

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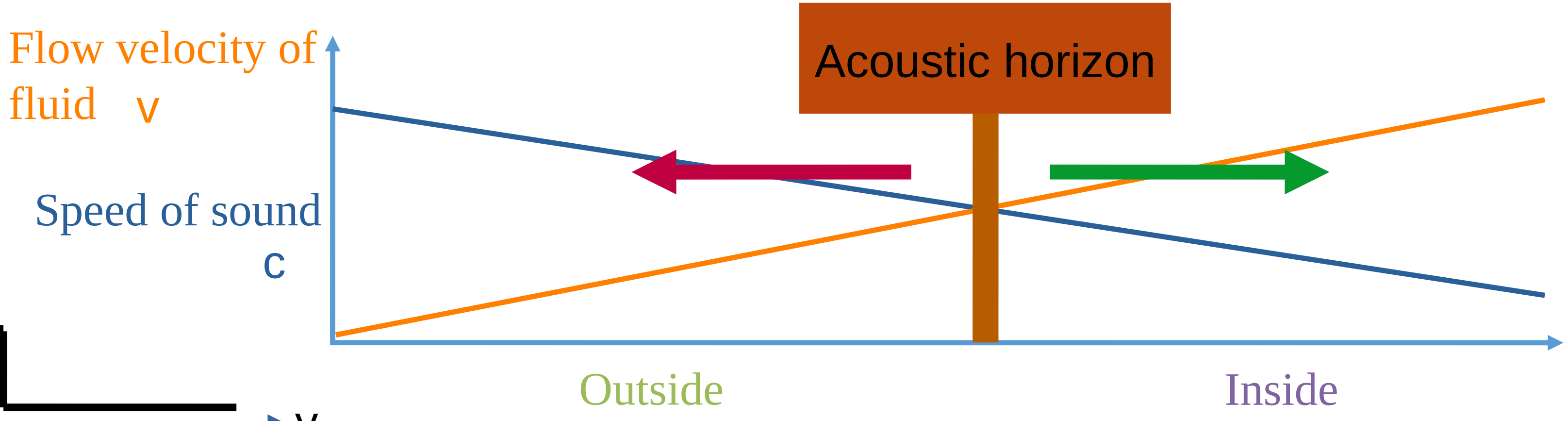
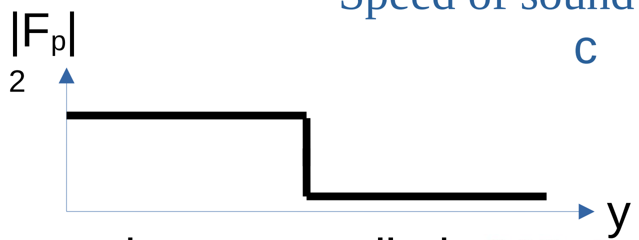
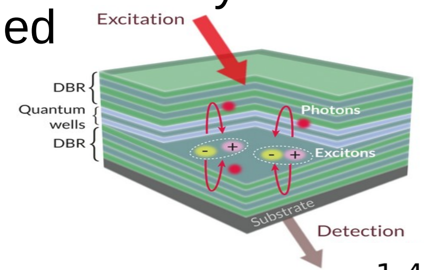


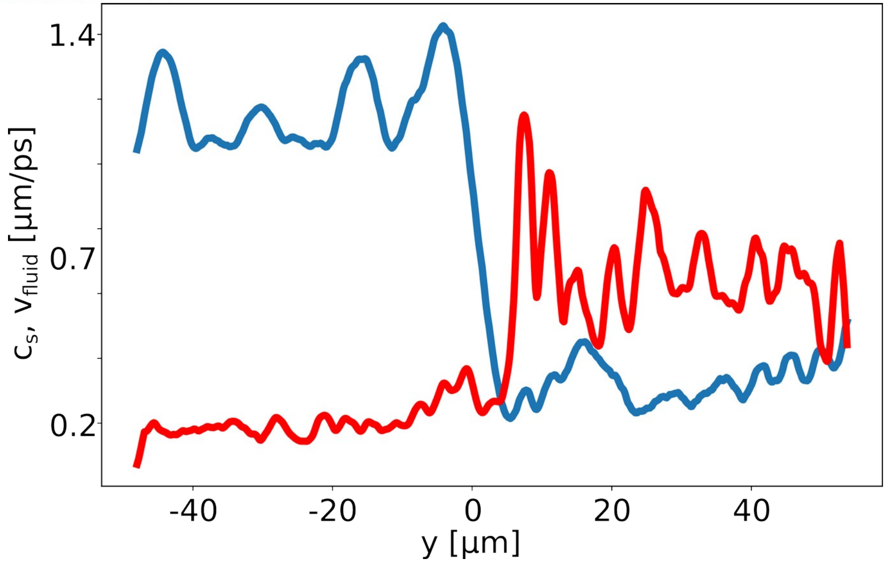


+ phase controlled with SLM

$v \propto \nabla \phi$



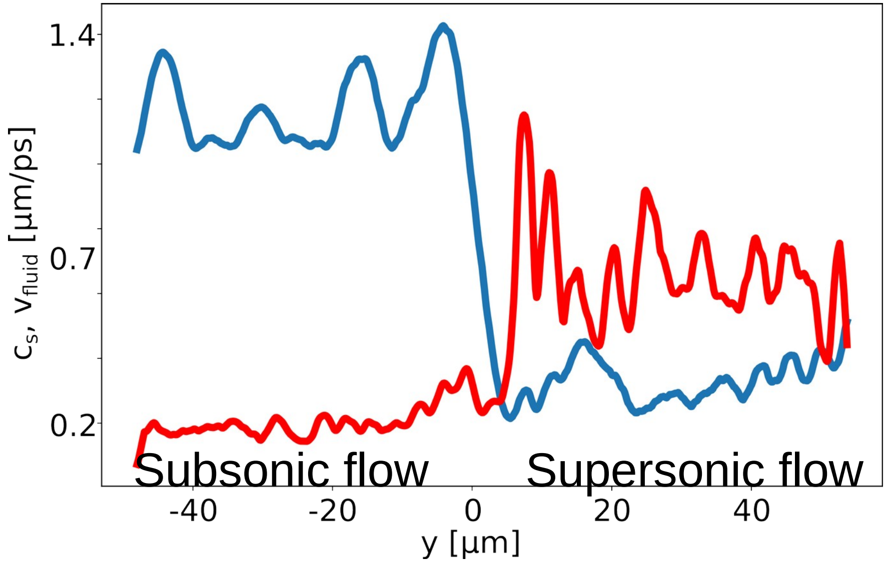
$c \propto \sqrt{n}$



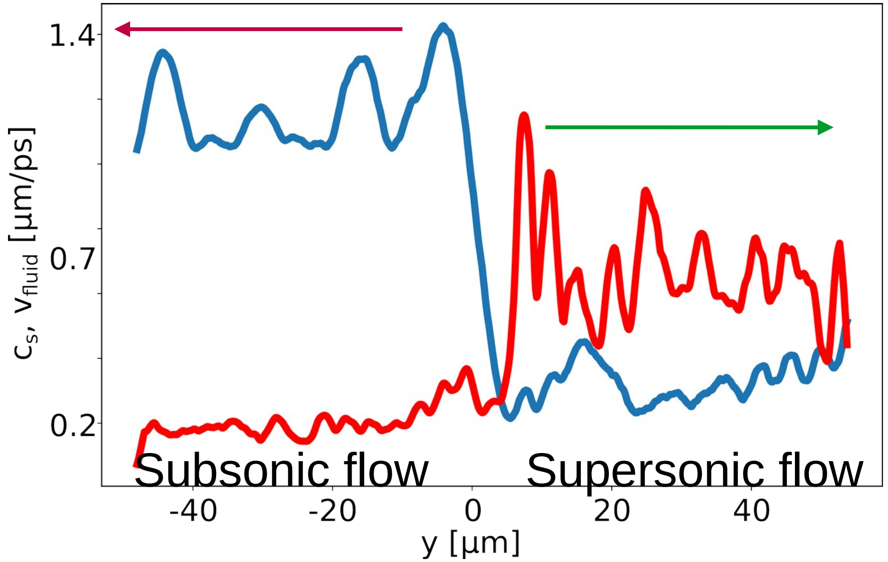
1) create a transsonic fluid → acoustic horizon where v=c

2) observe Hawking spectrum

3) observe correlations across the horizon

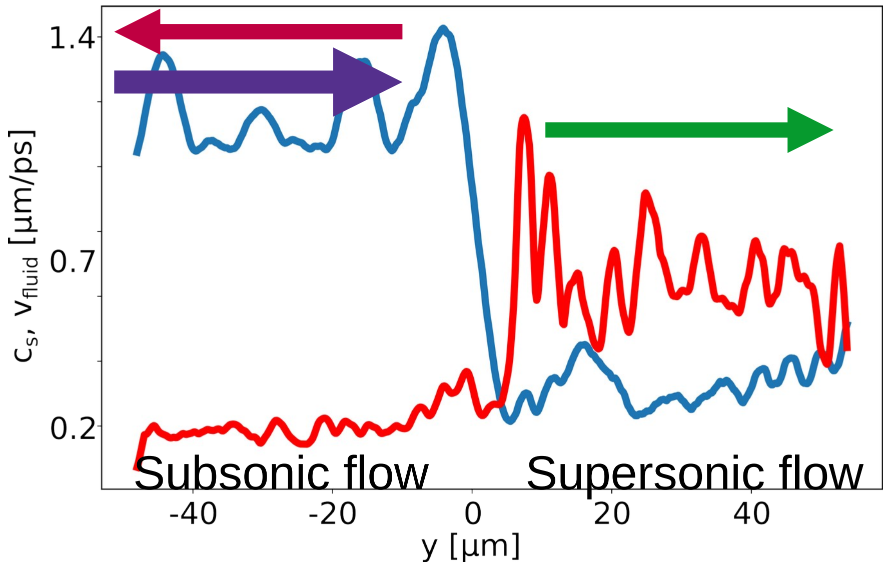


Hawking effect at the horizon: emission of acoustic waves on either side of the horizon



Hawking effect at the horizon: emission of acoustic waves on either side of the horizon

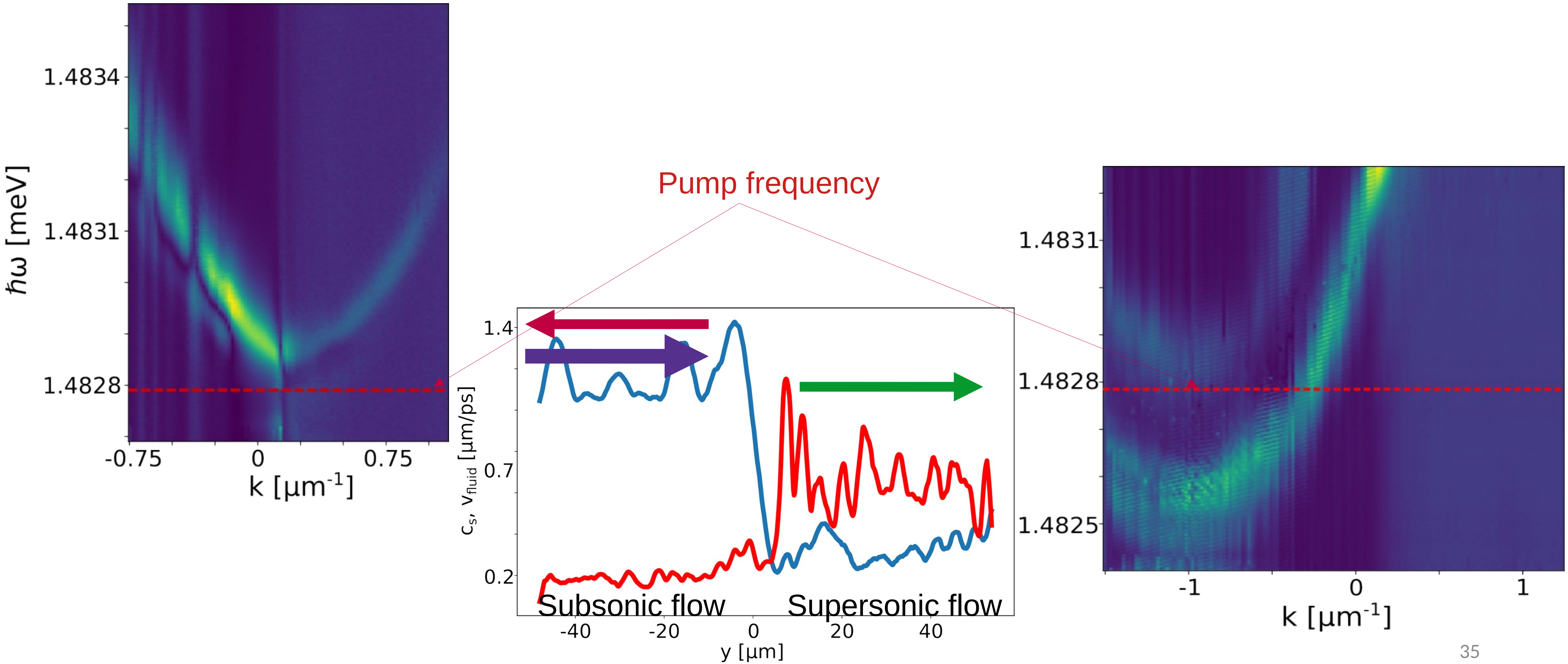
Stimulate emission with **coherent probe at input** → create acoustic wave that impinges on horizon and scatters
→ reflection = Hawking radiation
transmission = partner



Sound waves on either side of the horizon: Bogoliubov dispersion relation

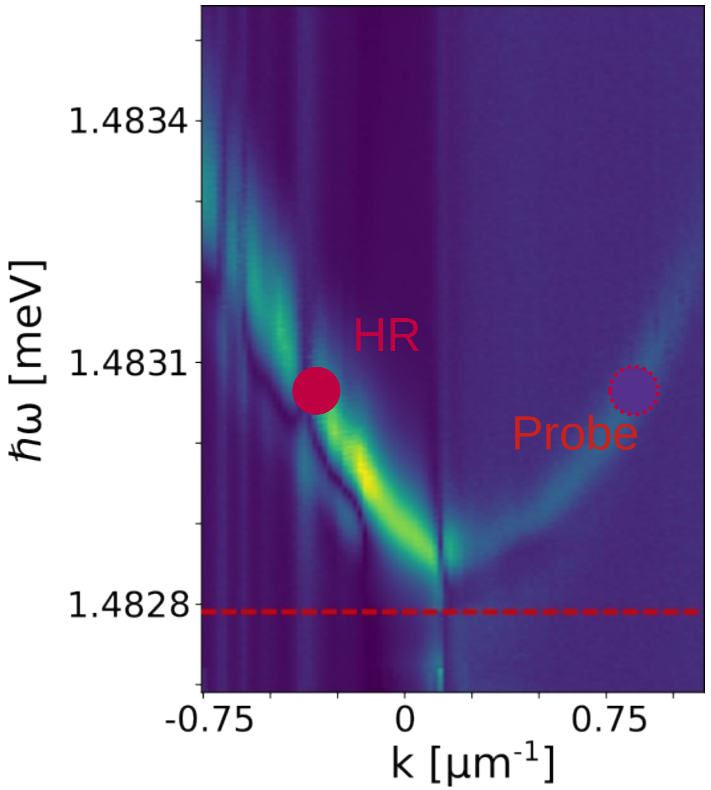
measured with coherent probe spectroscopy

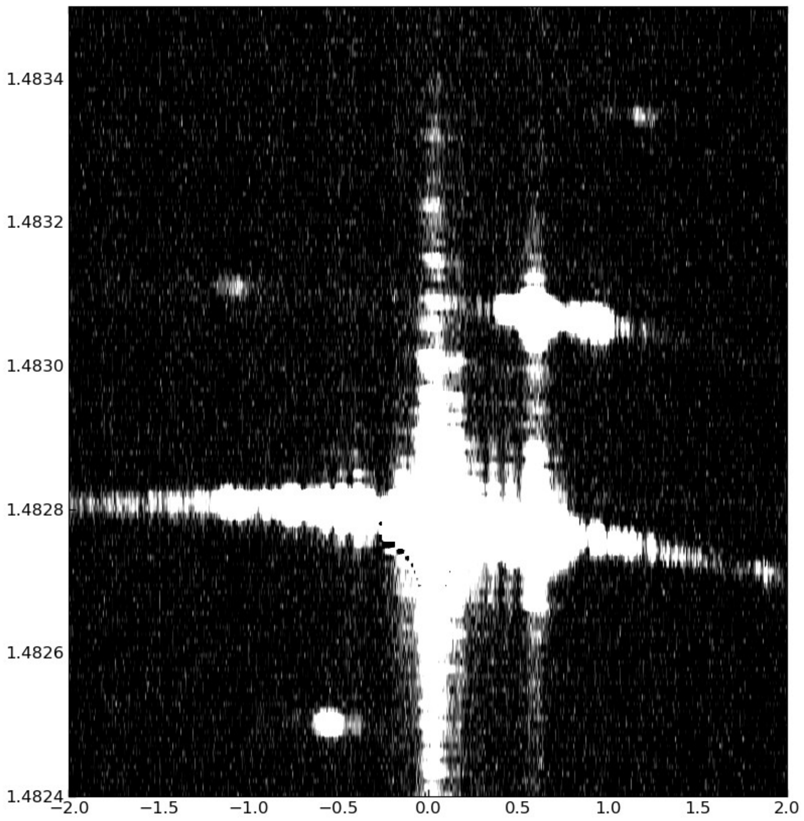
F Claude, M Jacquet *et al* PRL **129** 103601 (2022)

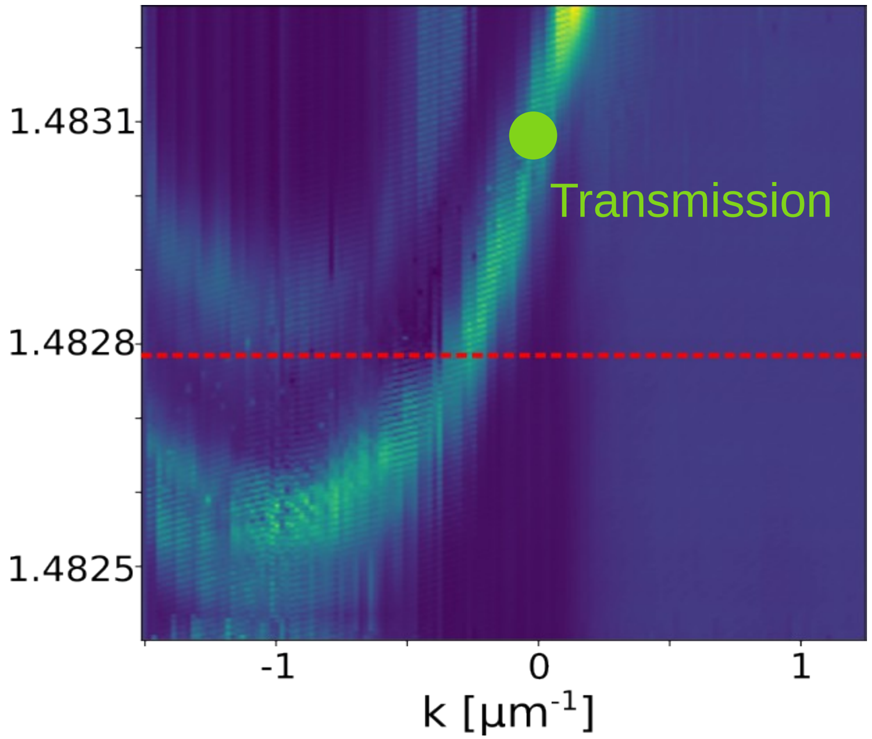


New data by PhD student Kévin Falque

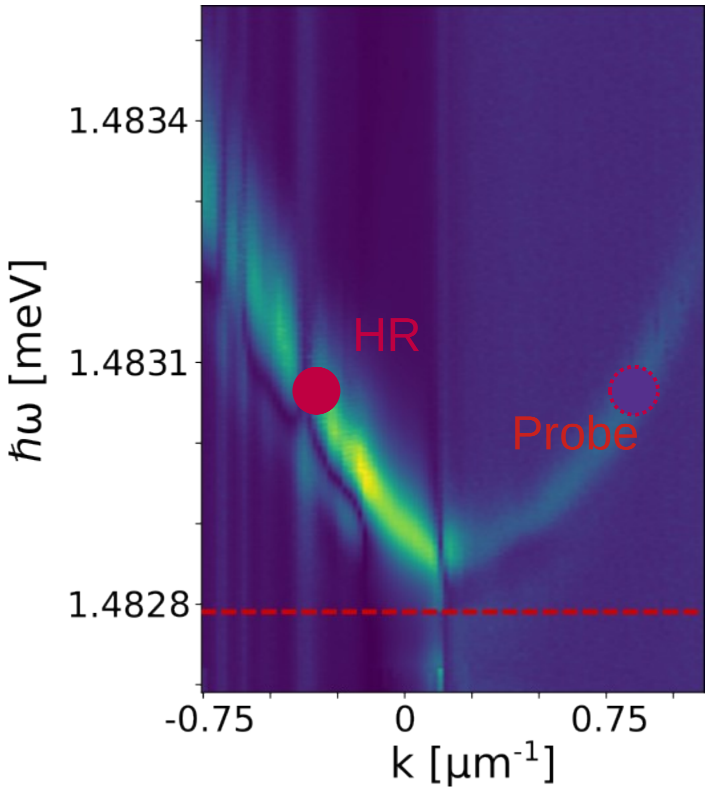
Stimulate emission with **coherent probe at input** → create acoustic wave that impinges on horizon and scatters
→ reflection = Hawking radiation
transmission = partner

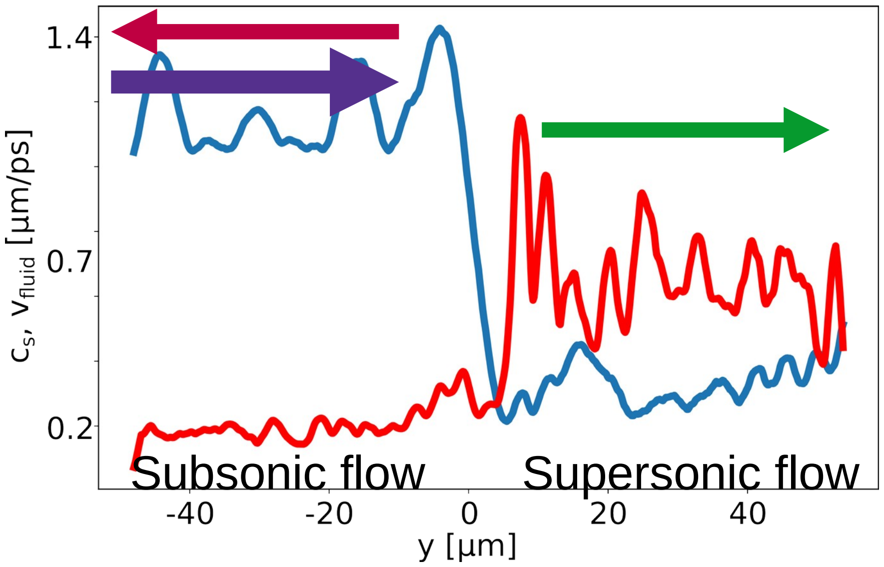


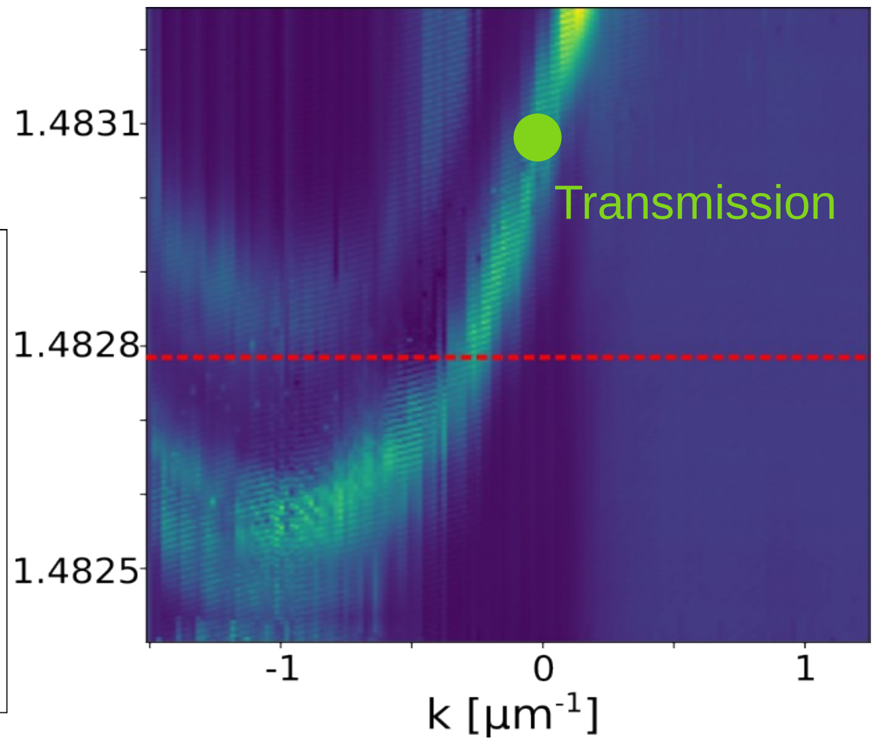




Scattering of probe at acoustic horizon = observation of Hawking effect





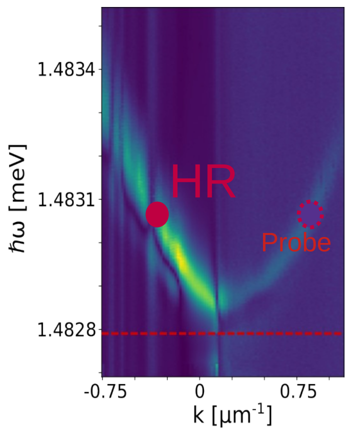


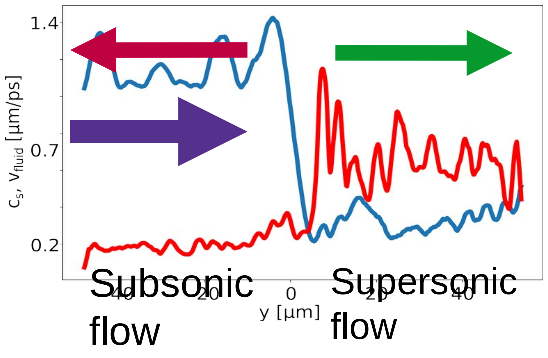
Today's talk

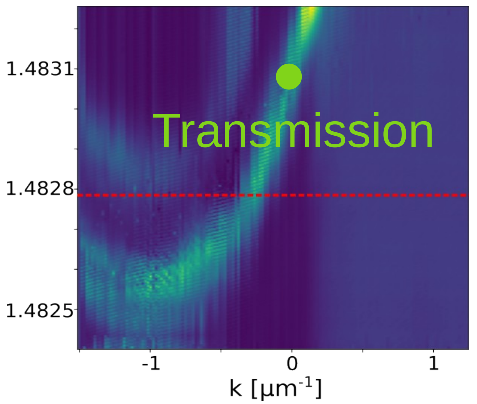
The propagation of waves in nonlinear media may be controlled to engineer situations where the waves propagate as though they were on an effectively curved geometry, like around a black hole or in an inflating universe. This enables the experimental study of field theories on curved geometries.

A transsonic fluid creates an acoustic horizon

Our experiment with a quantum fluid of microcavity polaritons: Hawking effect







New data by PhD student Kévin Falque

Next: - observe full spectrum of Hawking radiation, including negative frequencies
- measure correlations across the horizon
- simulate rotating geometry?

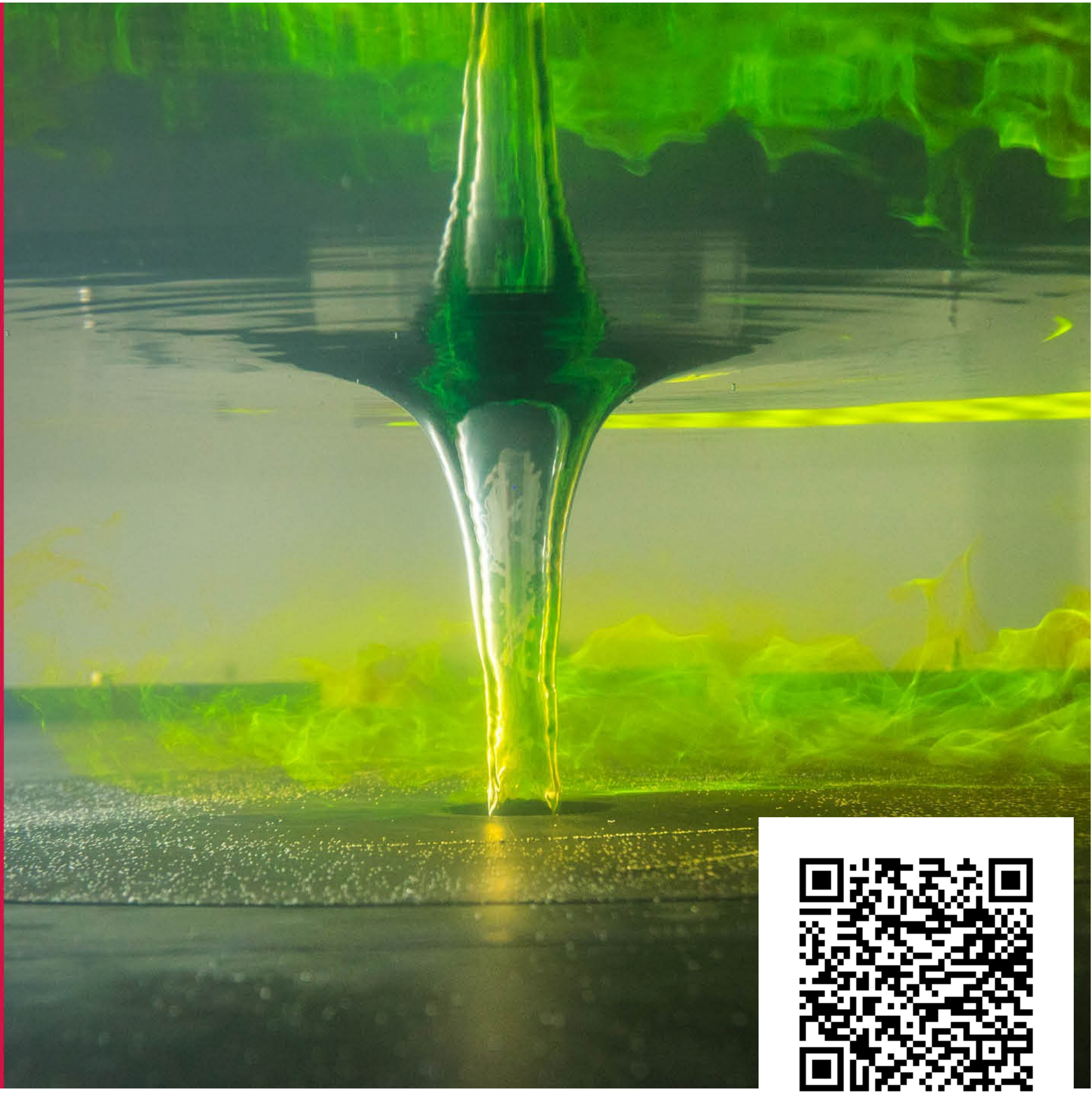
The next generation of analogue gravity experiments

9 – 10 December 2019

Organised by Dr Maxime Jacquet, Dr Silke Weinfurtner and Dr Friedrich König.

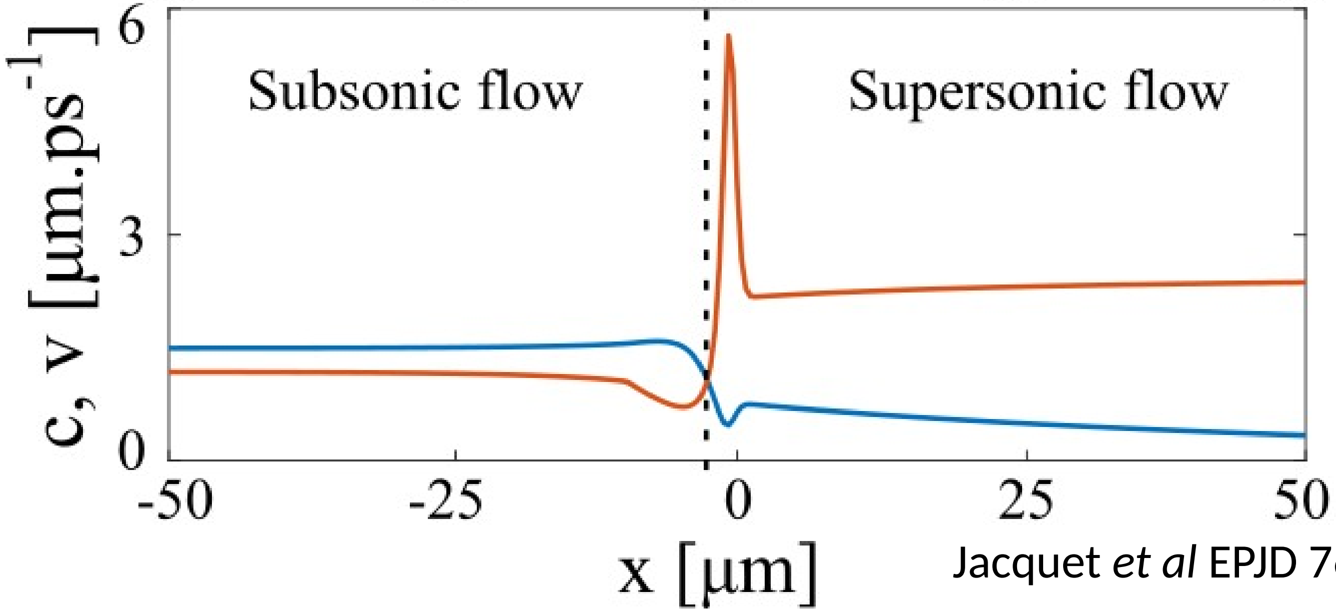
THE ROYAL SOCIETY

Image: © Alex Wilkinson Media.



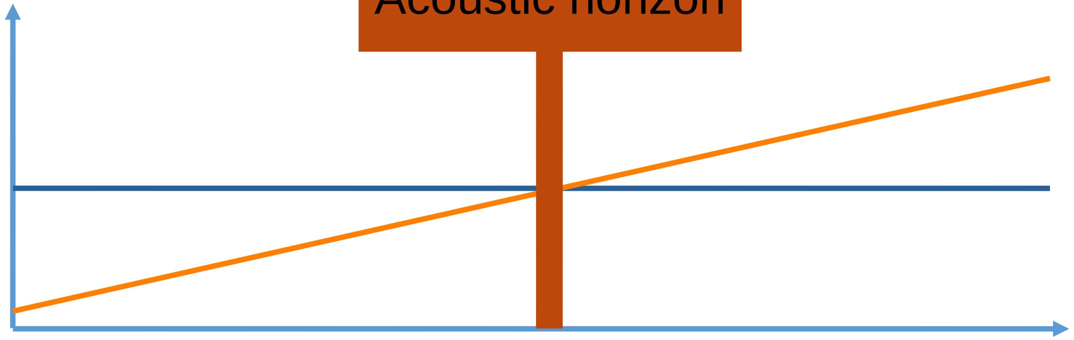
Modelling a BH spacetime with a fluid of microcavity polaritons

Acoustic horizon

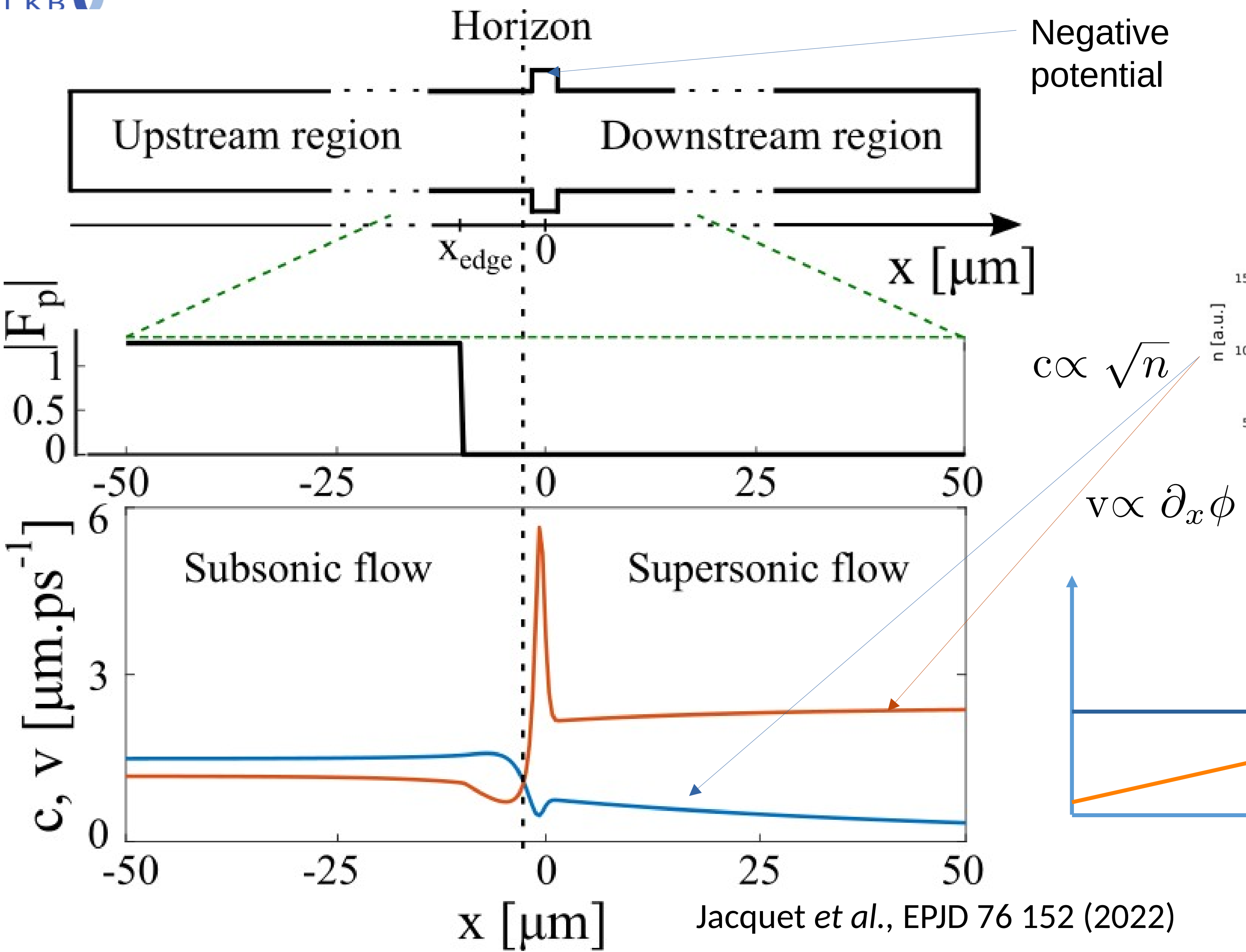


Jacquet *et al* EPJD 76 152 (2022)

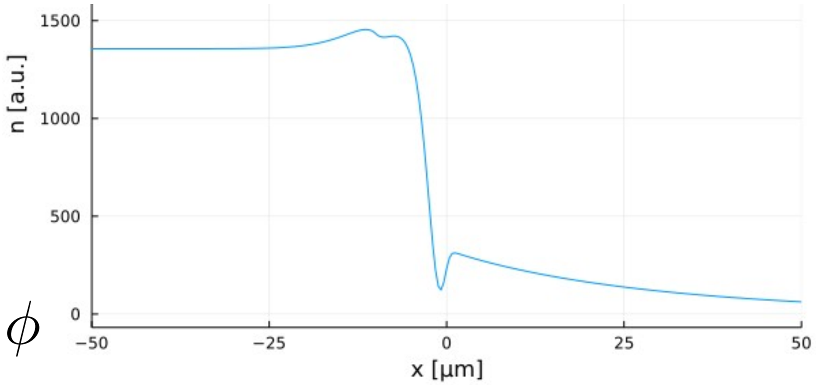
Acoustic horizon

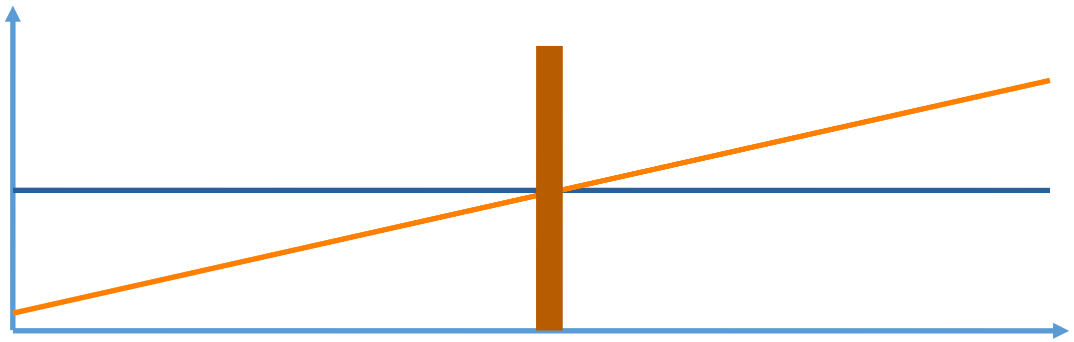


Acoustic horizon in polaritons



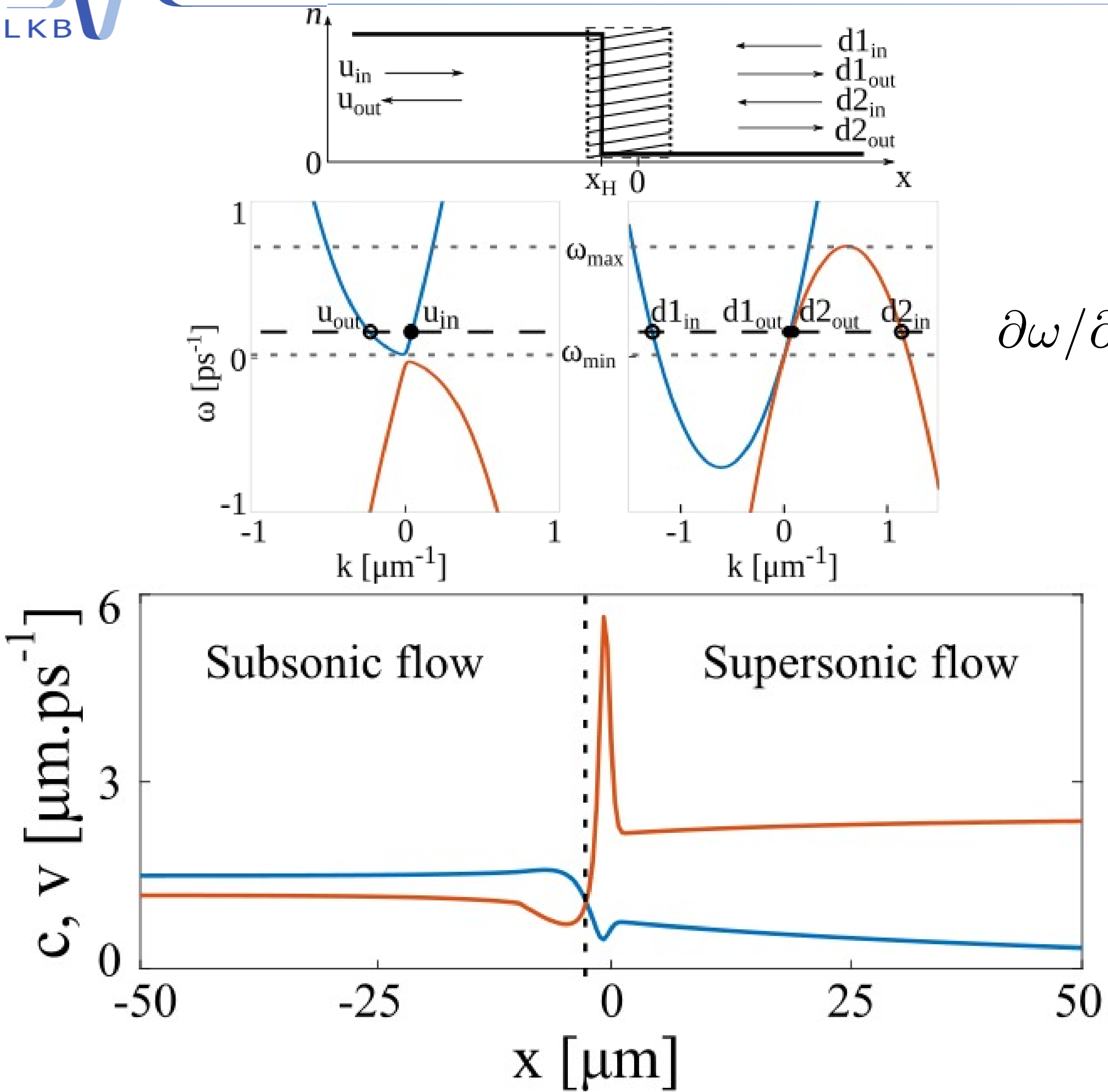
Simulate sample of Nguyen HS *et al.*, PRL 114 036402 (2015)





Jacquet *et al.*, EPJD 76 152 (2022)

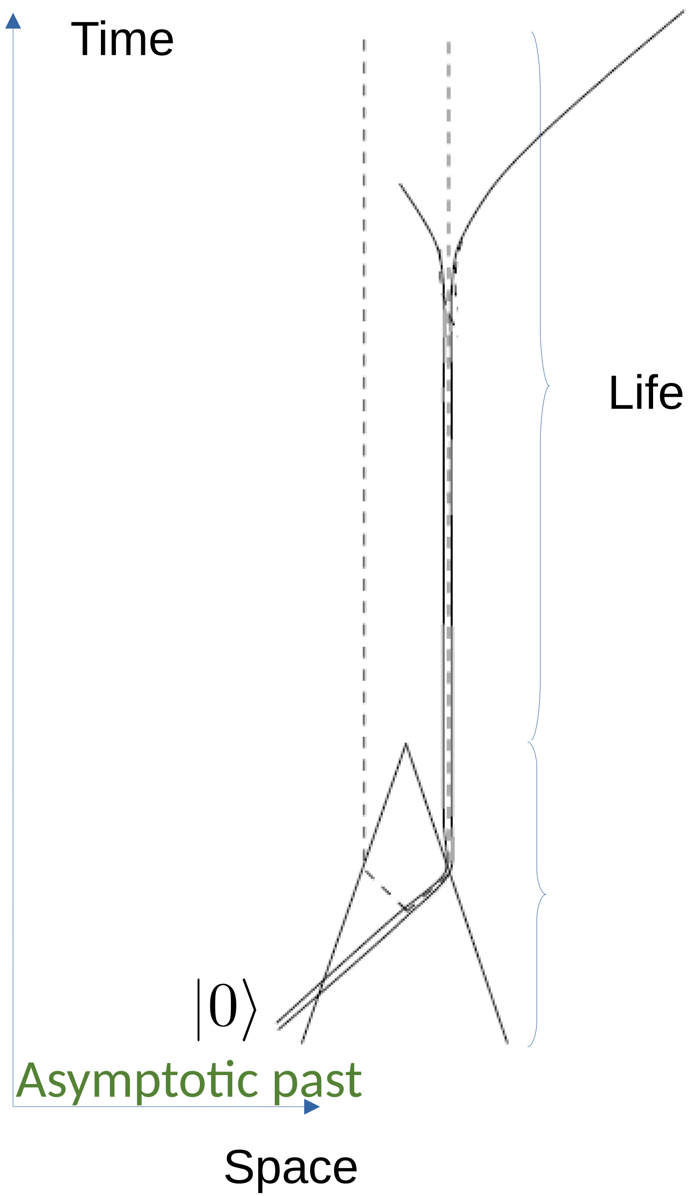
Acoustic horizon in polaritons: the modes



$\partial\omega/\partial k$ Group velocity of modes → propagation w.r.t horizon

Perturbation of black hole

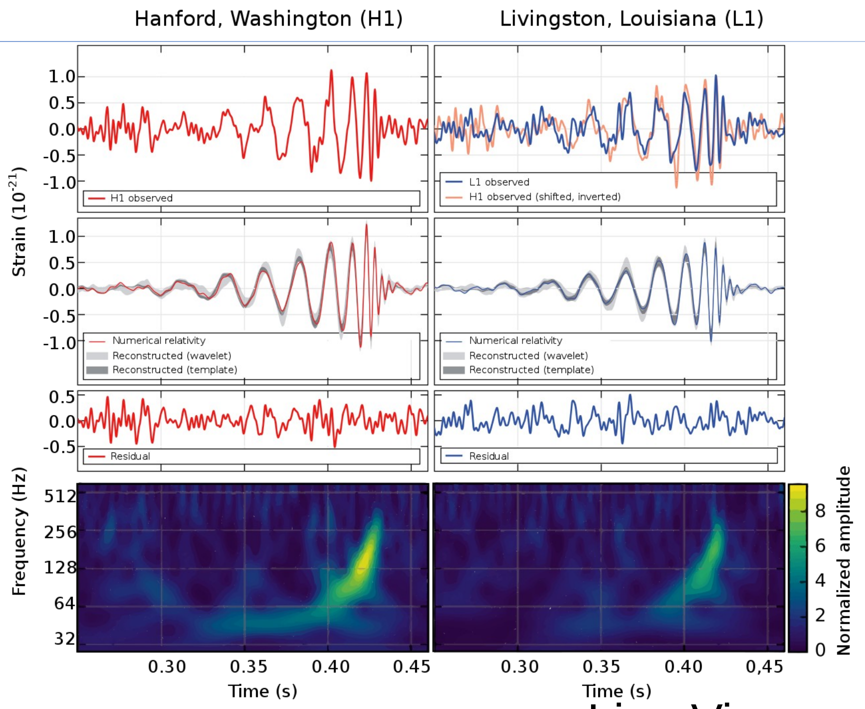
To asymptotic observer



Life of a Schwarzschild black hole

if perturbed by large amplitude object, relaxation by gravitational waves

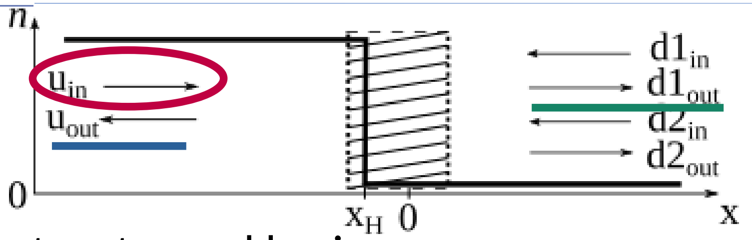
Quasi-normal mode of the gravitational field



Ligo Virgo 2016

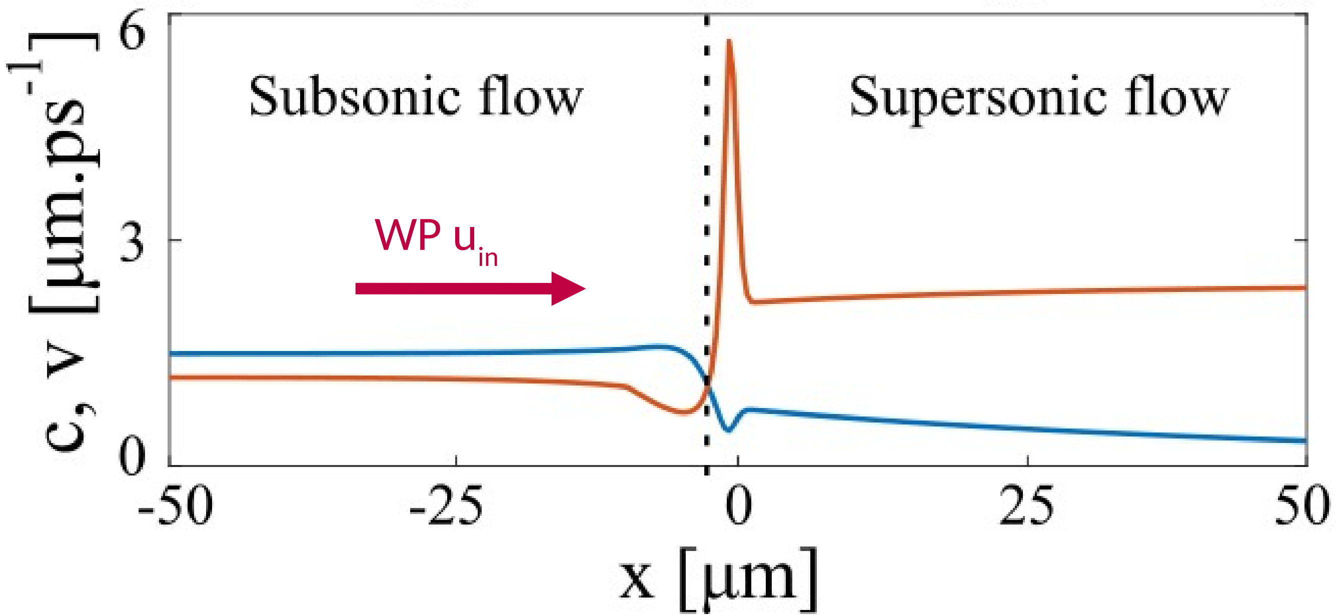
Jacquet *et al.*, arxiv:2110.14452

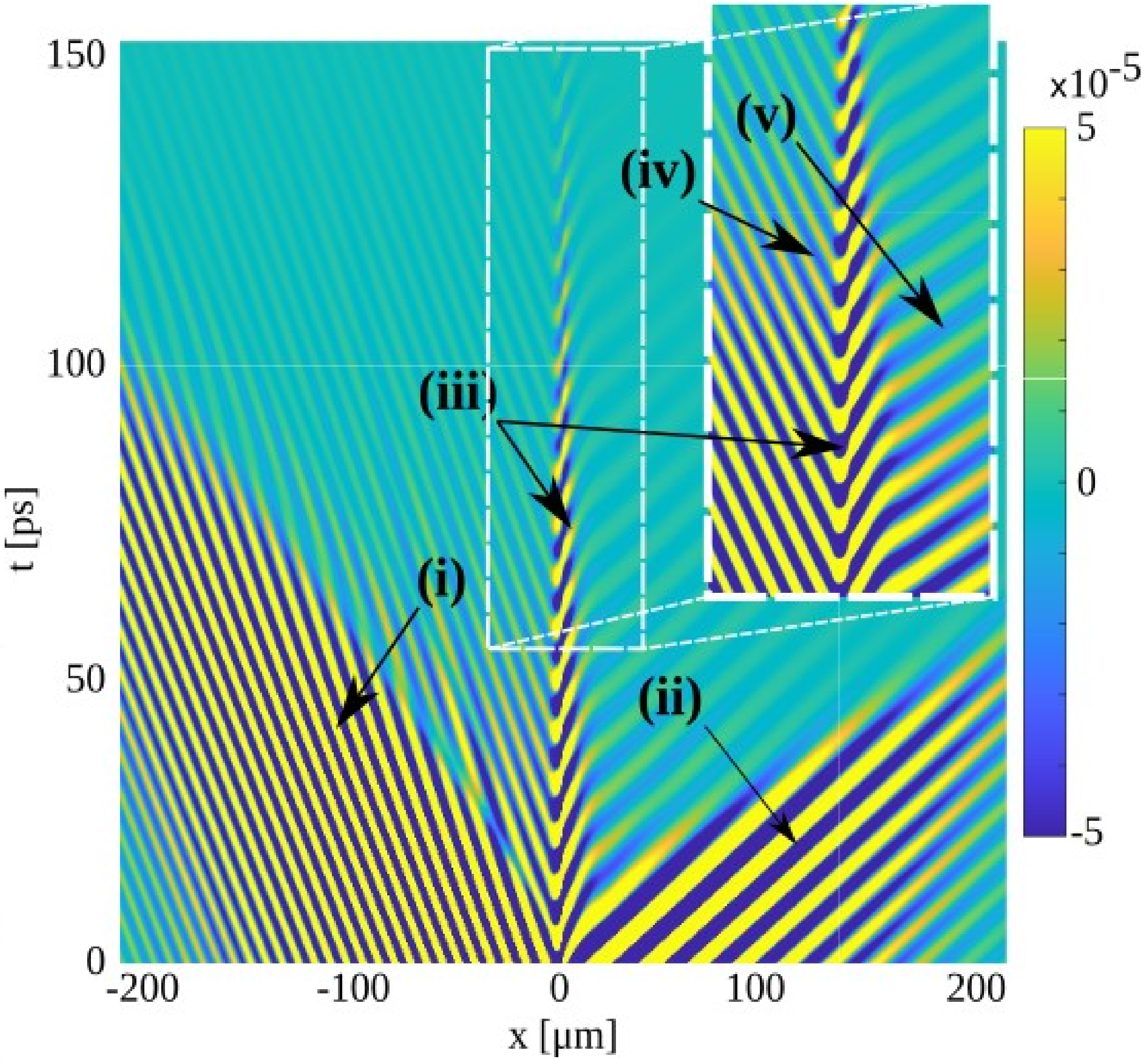
Perturb horizon with classical wavepacket



Send wavepacket u_{in} toward horizon:

(i) reflection
(ii) transmission
(iii) density @horizon oscillates and dampens
(iv) density @horizon couples with mode propagating outward
(v) density @horizon couples with mode propagating inward





Ringdown upon perturbation!

Send wavepacket u_{in} toward horizon:

(i) reflection
(ii) transmission
(iii) density @horizon oscillates and dampens
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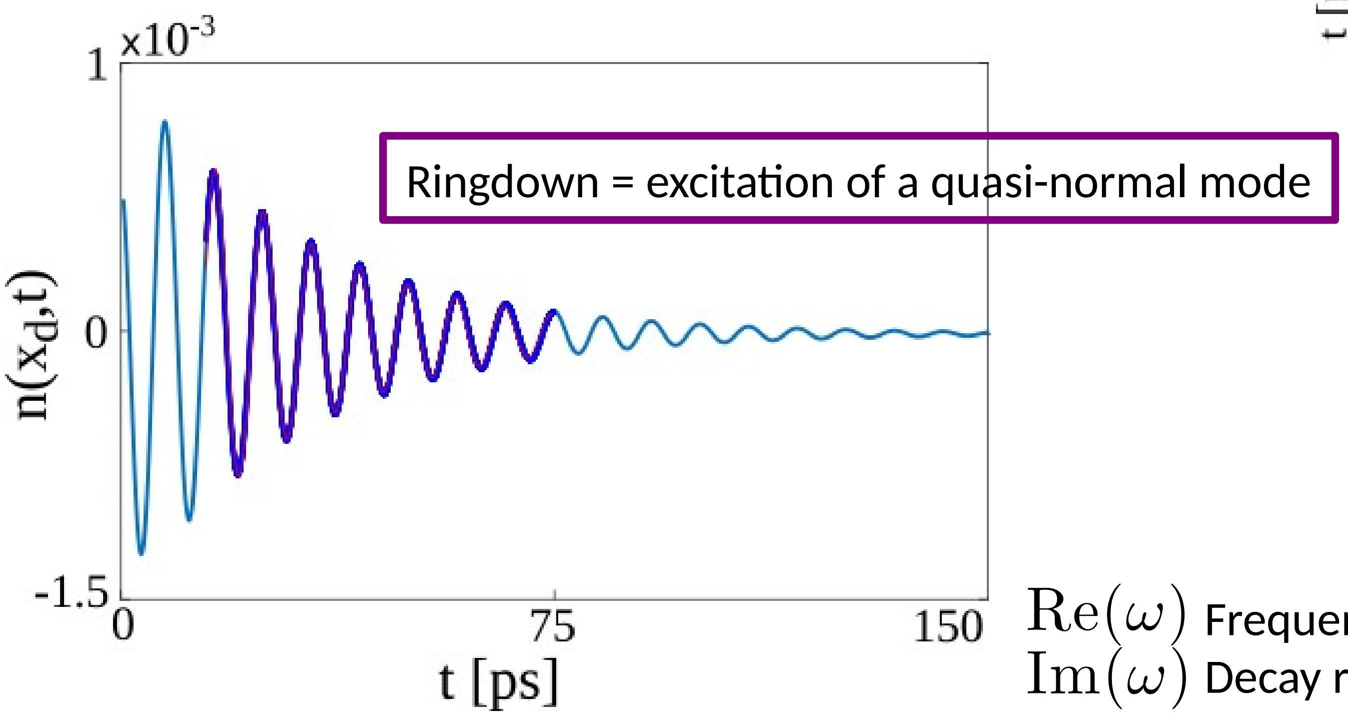
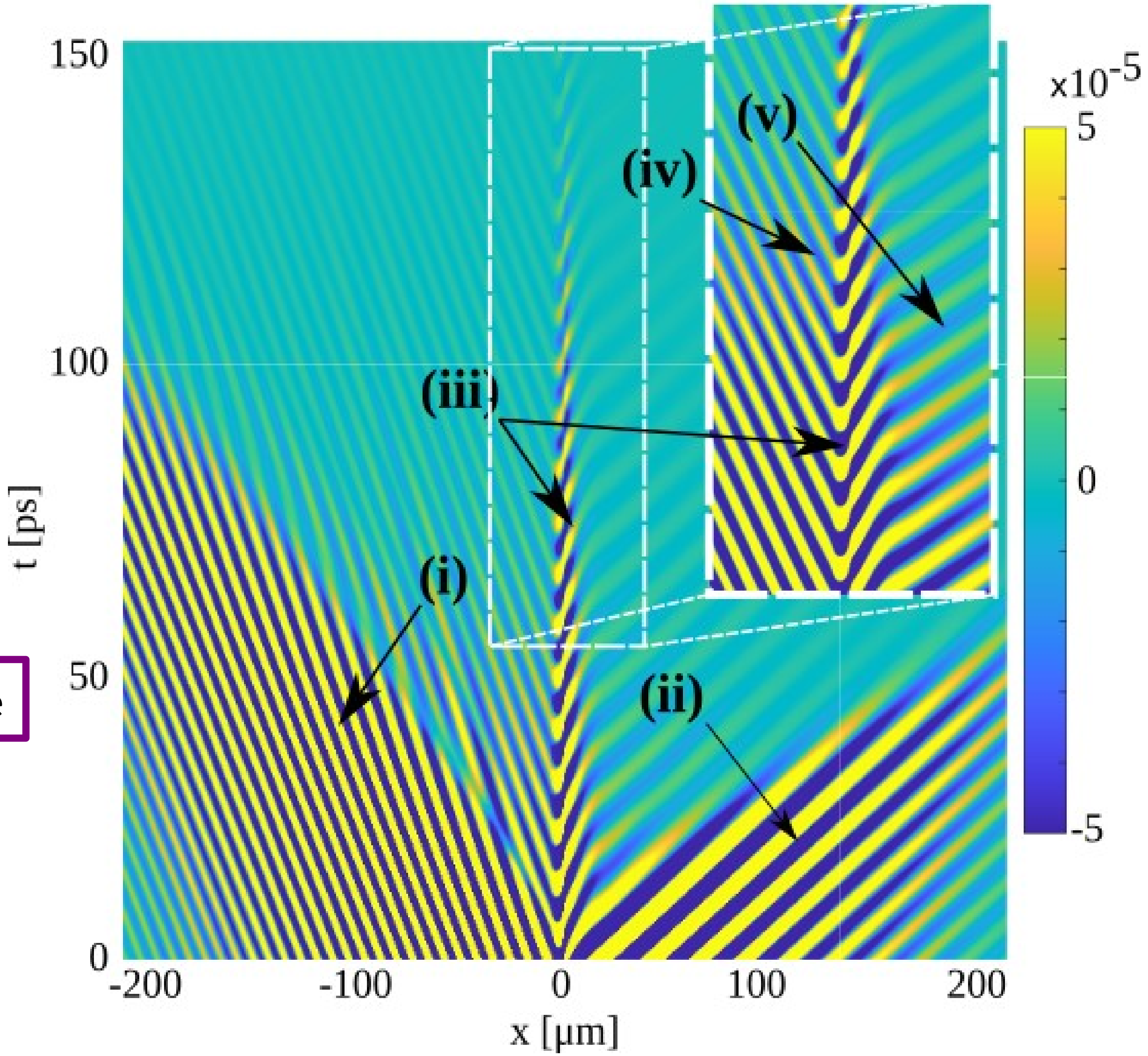




$\mathrm{Re}(\omega)$ Frequency of oscillation
$\mathrm{Im}(\omega)$ Decay rate < γ (bare polariton lifetime)

Scattering of vacuum fluctuations: long and strong Hawking correlations

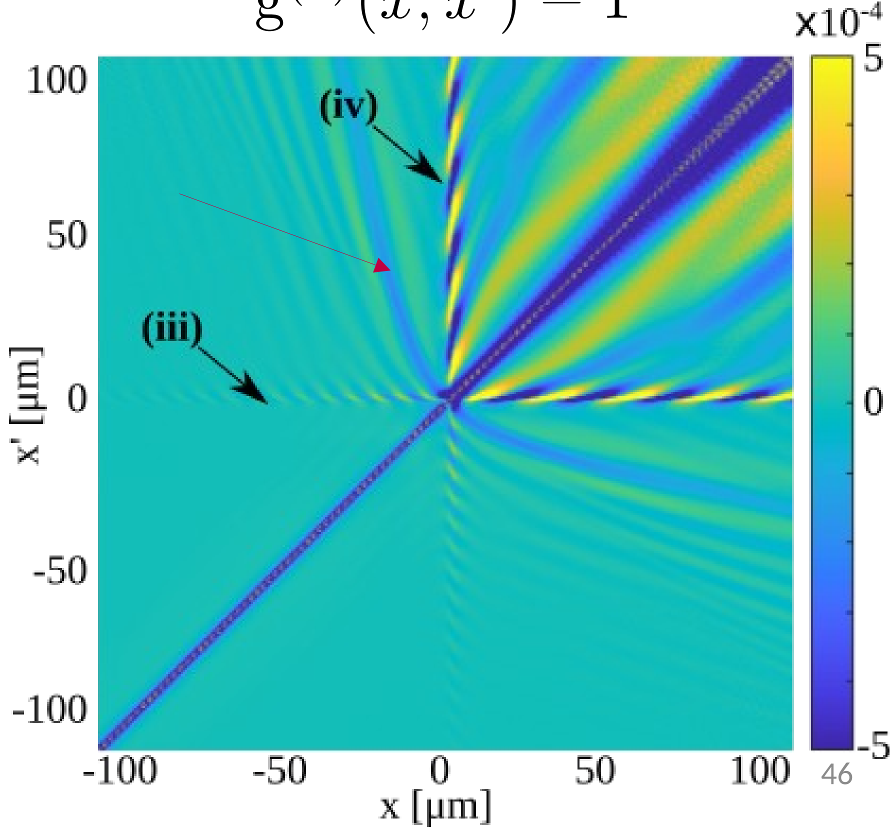
Numerical simulation: Truncated Wigner Approximation
(1 billion realisations)

Measure equal time correlations

$$g^{(2)}(x,x') = \frac{\left\langle \Psi(x)^\dagger \Psi(x')^\dagger \Psi(x)\Psi(x')\right\rangle}{\langle \Psi(x)^\dagger \Psi(x)\rangle \langle \Psi(x')^\dagger \Psi(x')\rangle}$$

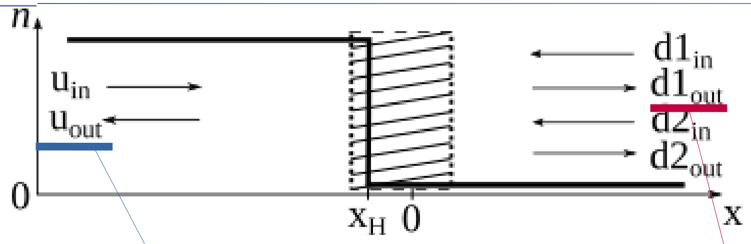
$$g^{(2)}(x,x') - 1$$

Hawking correlations



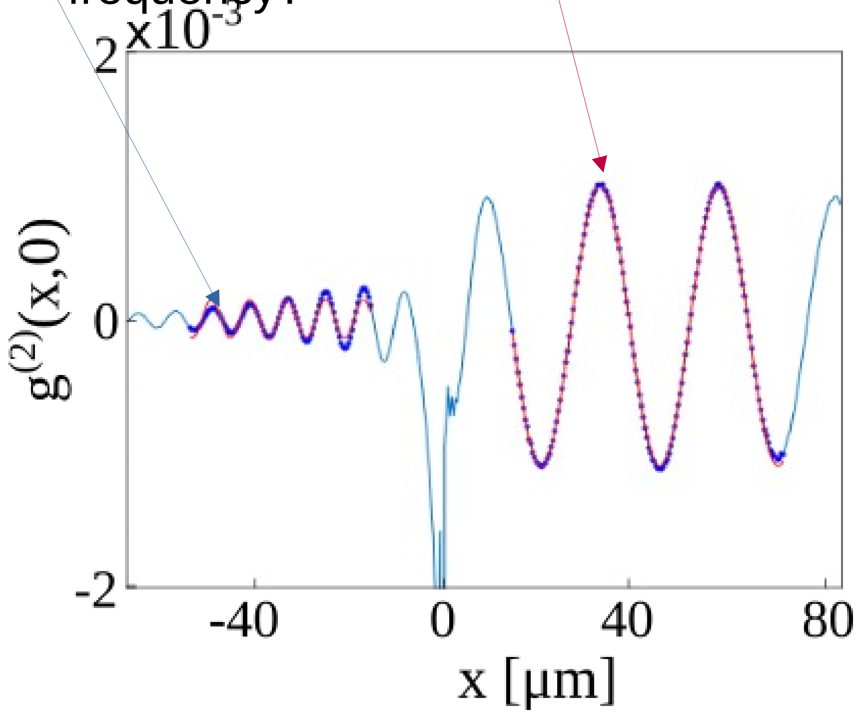
(iii) horizon - outside
(iv) horizon - inside

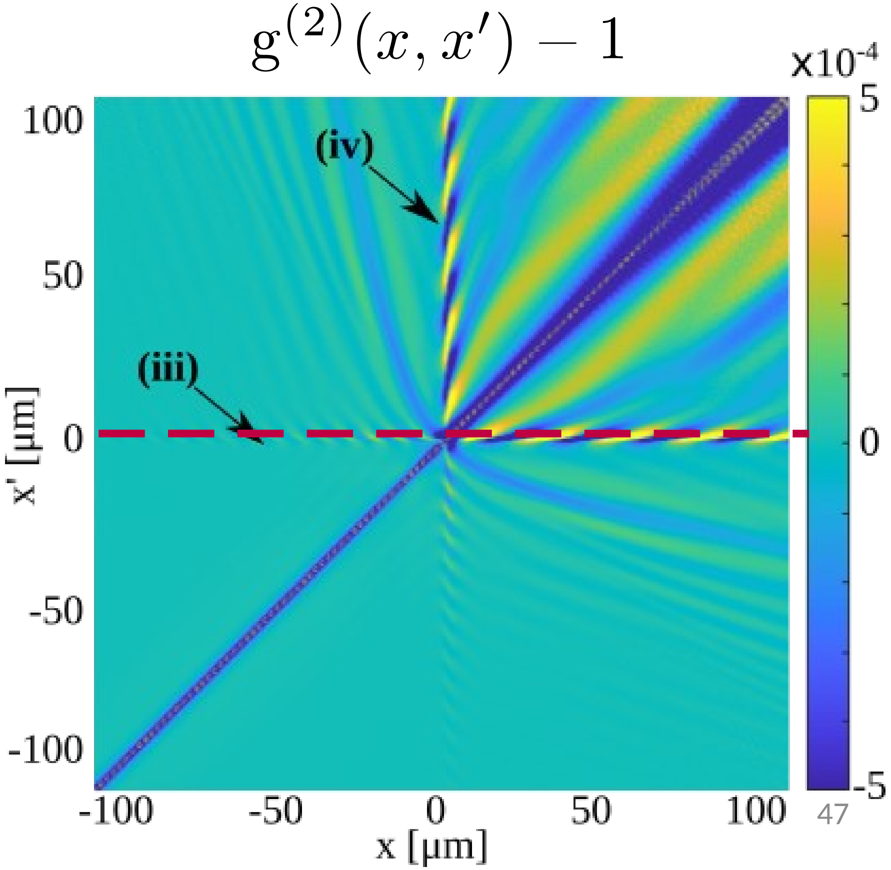
Scattering of vacuum fluctuations: horizon correlations



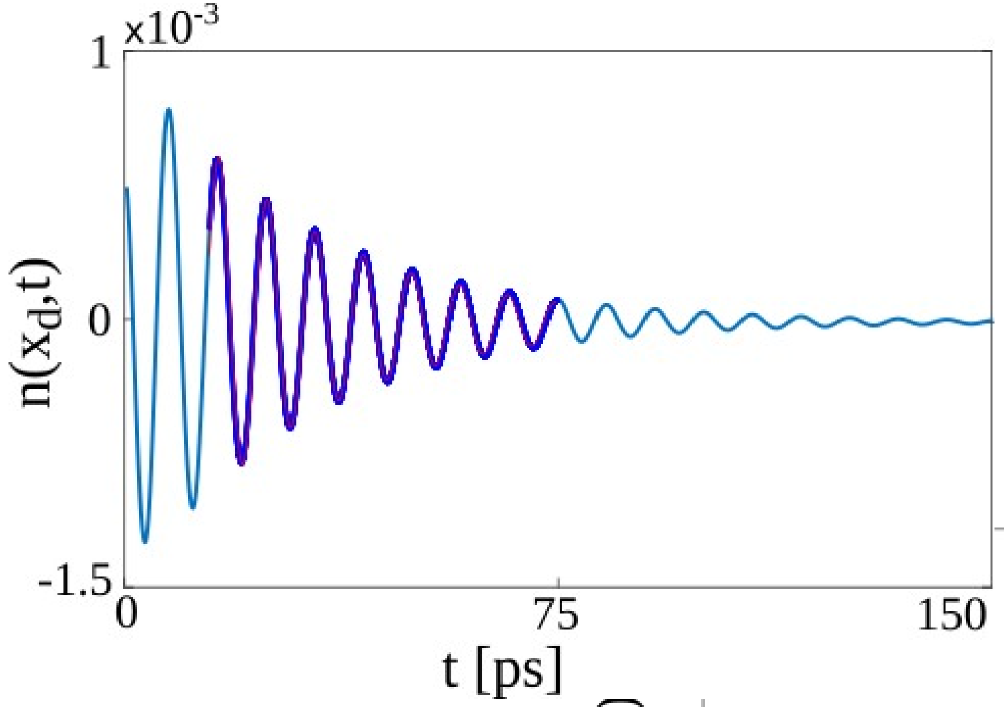
(iii) horizon - outside
(iv) horizon - inside

Spatial frequency?





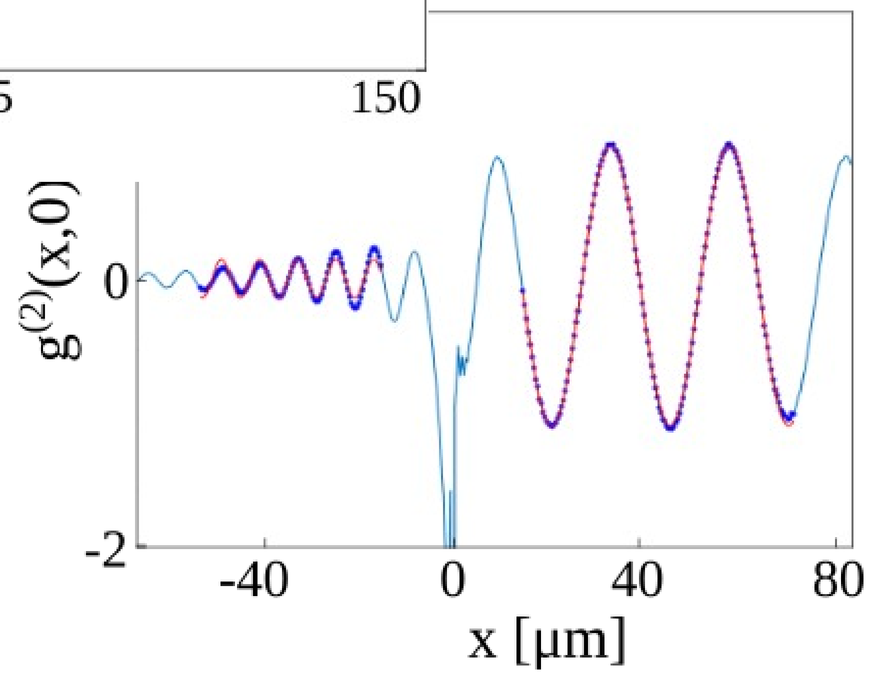
Scattering of vacuum fluctuations: excitation of a quasi normal mode



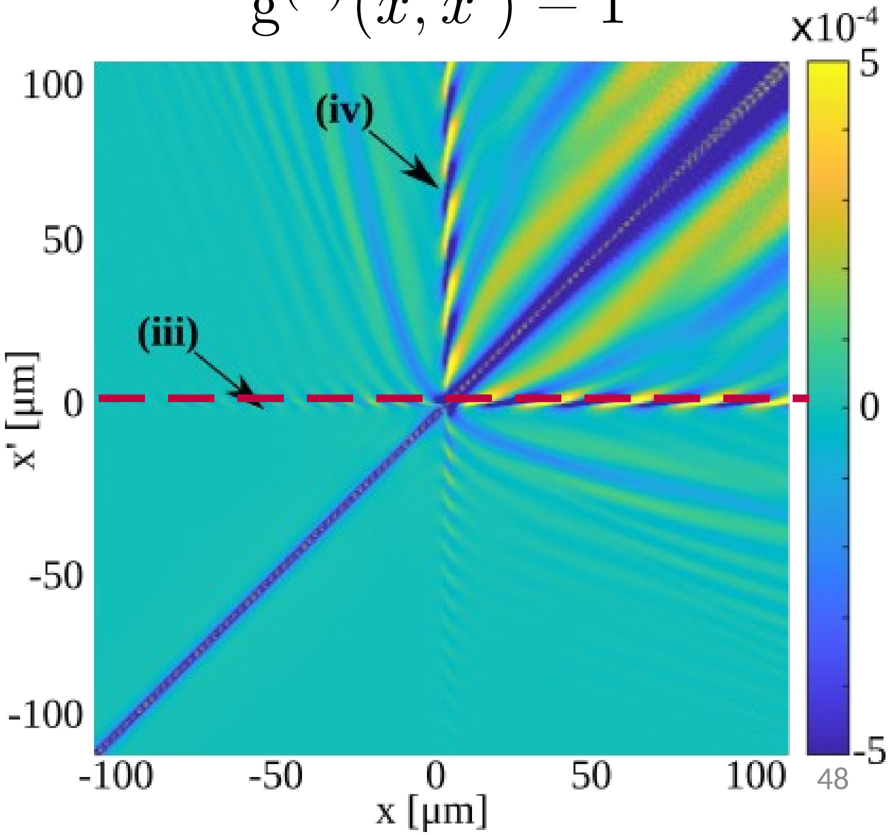
$\mathrm{Re}(\omega)$ Frequency of oscillation
$\mathrm{Im}(\omega)$ Decay rate < γ

(iii) horizon - outside
(iv) horizon - inside

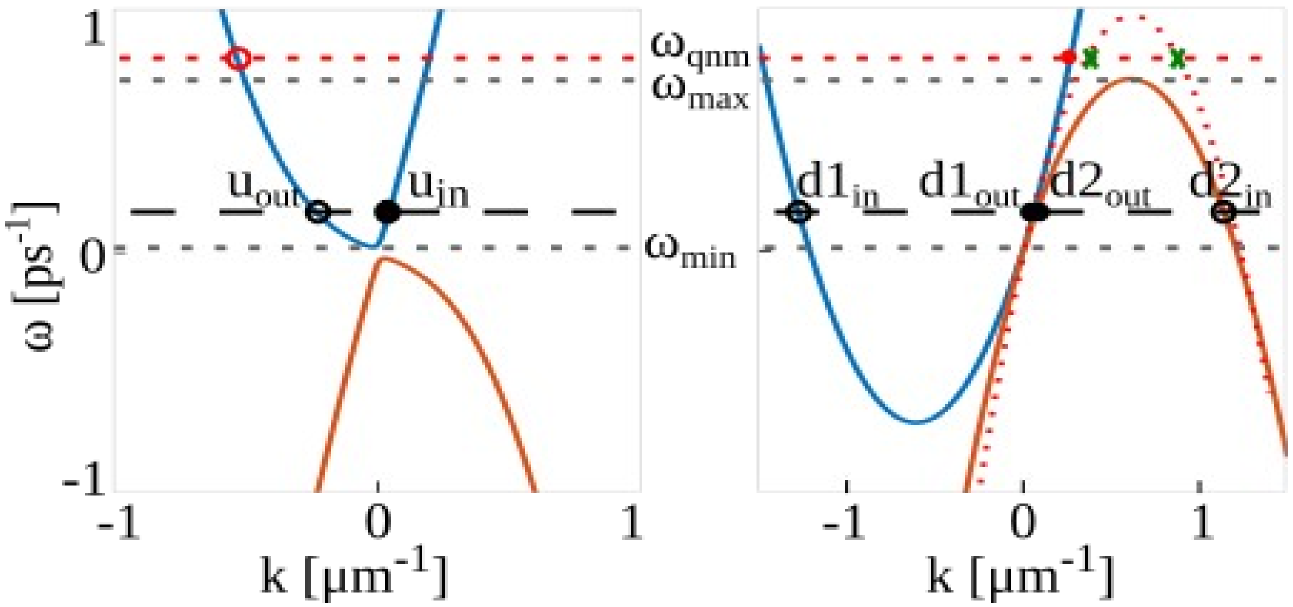
→ excitation of a quasi-normal mode

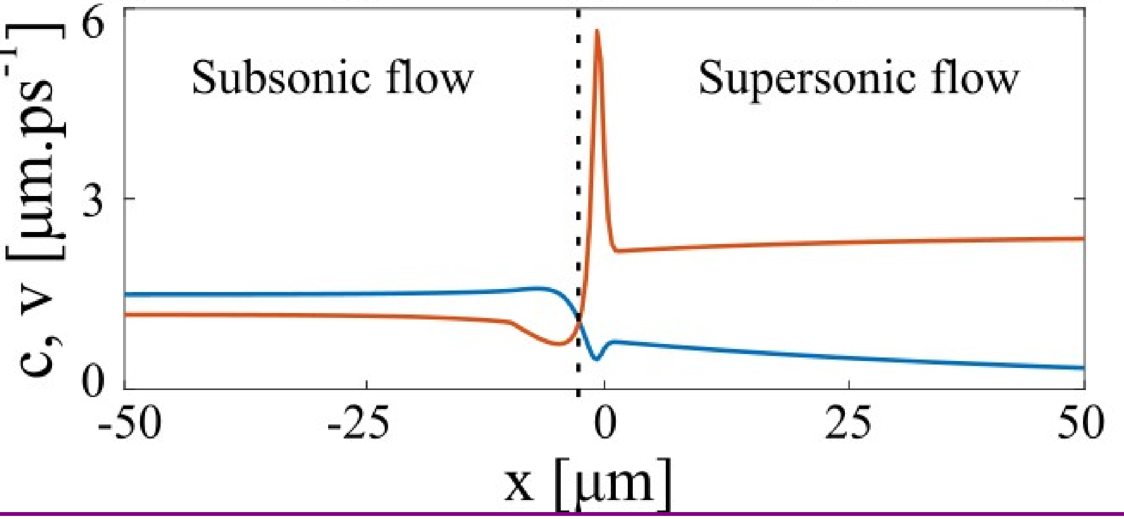


$g^{(2)}(x, x') - 1$

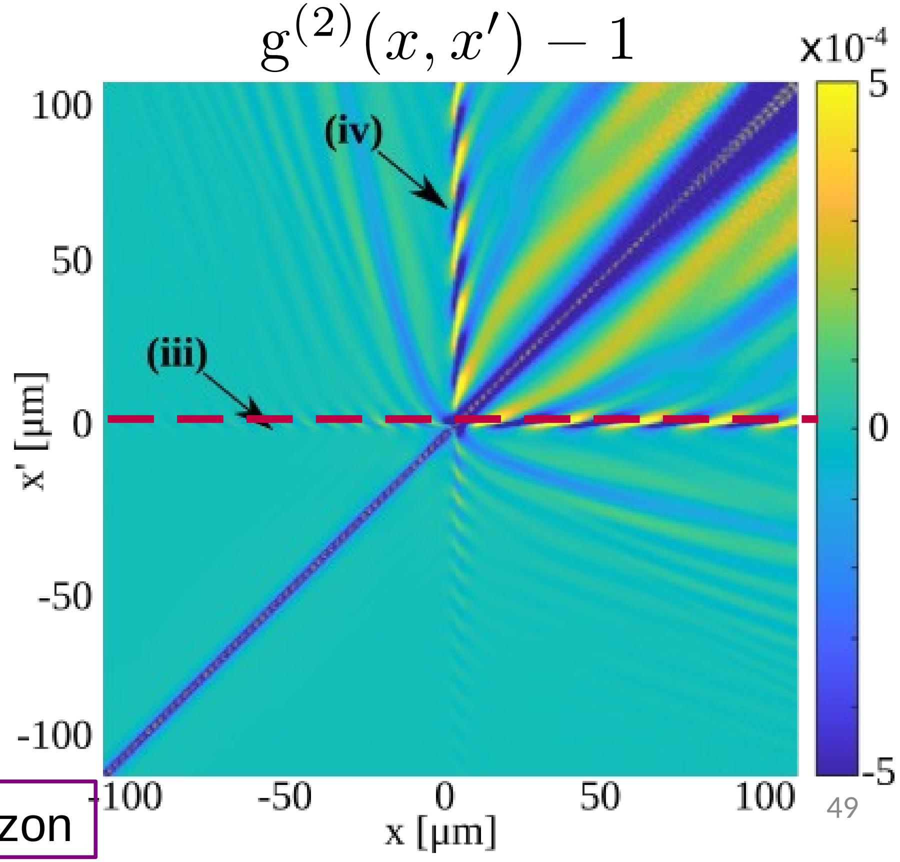


Scattering of vacuum fluctuations: effective potential





(iii) horizon - outside
(iv) horizon - inside



Velocity spike creates negative potential for negative modes near horizon

Spectral modulation