Quantum vacuum excitation of a quasi-normal mode in an analogue model of black hole spacetime

Work done with Iacopo Carusotto and Luca Giacomelli, Trento

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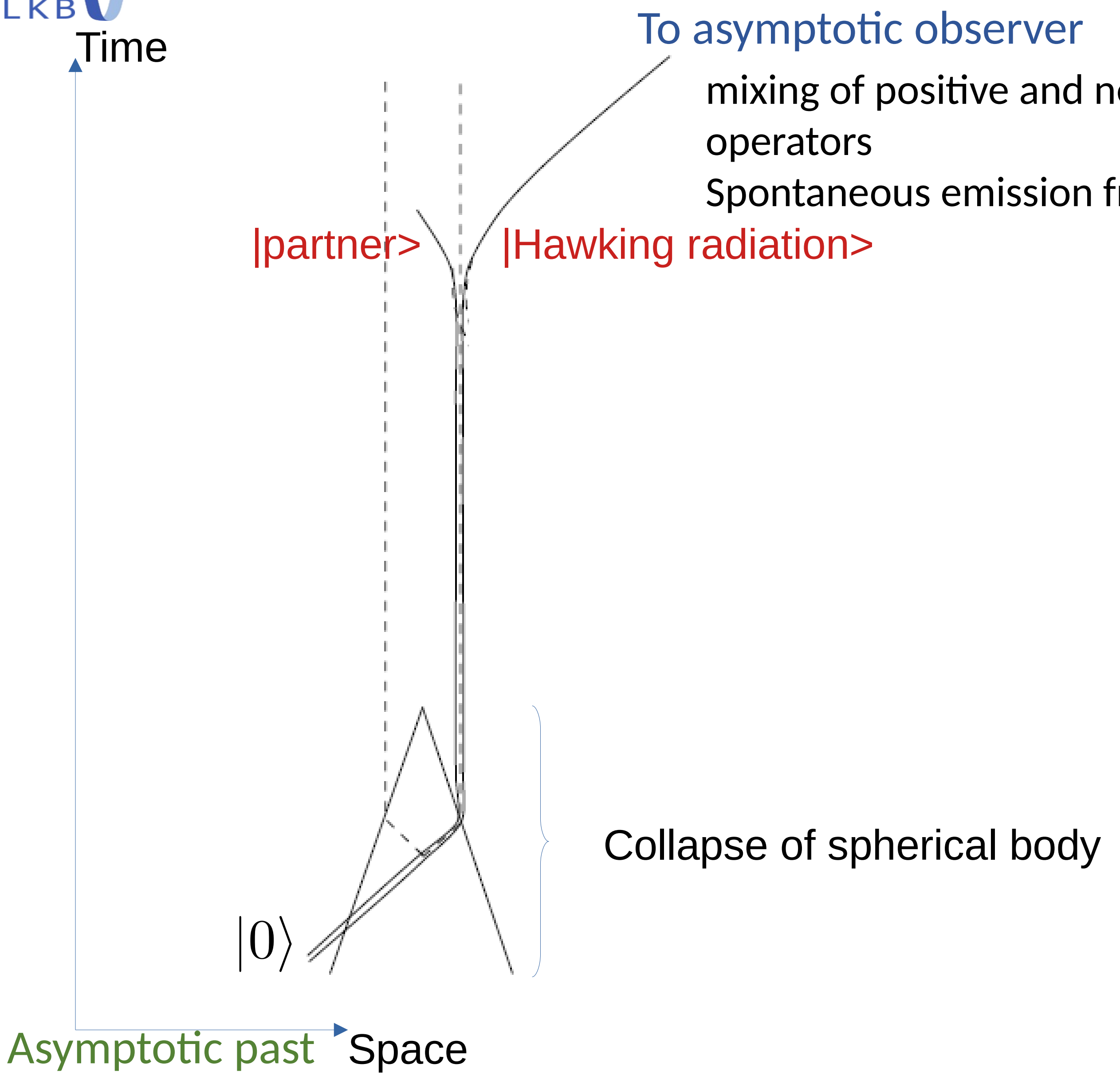
Laboratoire Kastler Brossel, CNRS and Sorbonne University, Paris

TUG Montpellier 04/10/2022

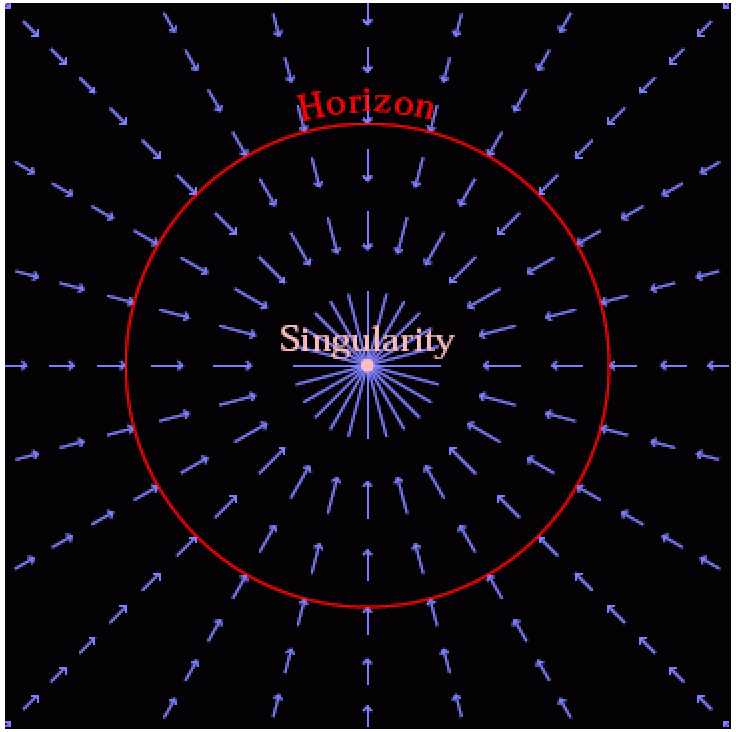
The Hawking effect



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

Spontaneous emission from the vacuum. Black hole ⇒ Hawking effect

$$k_B T = \frac{\hbar\alpha}{2\pi c} = \frac{\hbar c^3}{8\pi G M}$$

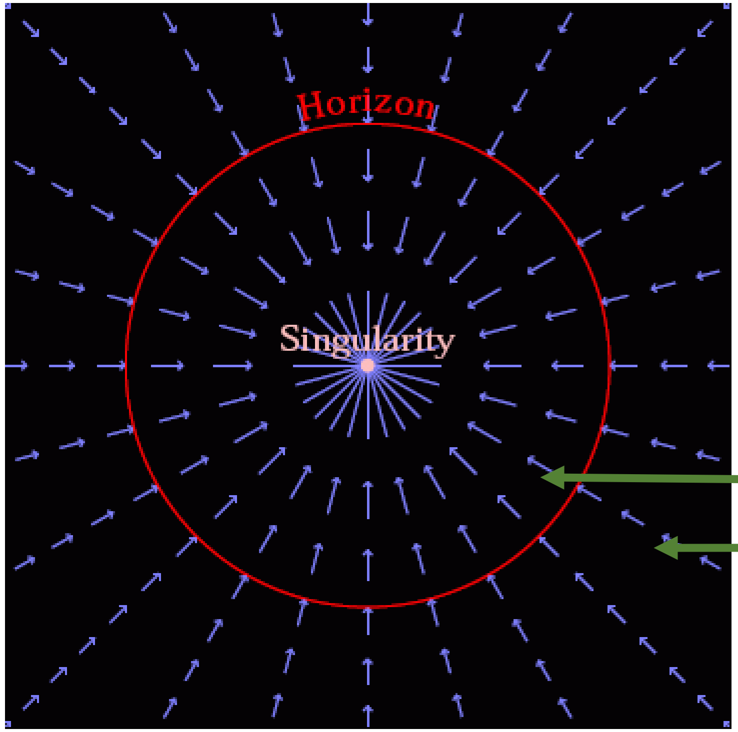


Inverse metric tensor of Painlevé-Gullstrand metric in 1+1D

$$g_{PG}^{\mu\nu} = \begin{pmatrix} -1 & -\beta \\ -\beta & \left(c^2 - \beta^2\right) \end{pmatrix}$$

Space flows radially inwards at velocity .
At the horizon, : nothing can escape from the inside of a black hole.
t ever increases towards the horizon -> light from infalling objects redshifts

Metaphor: the event horizon and the flow of spacetime



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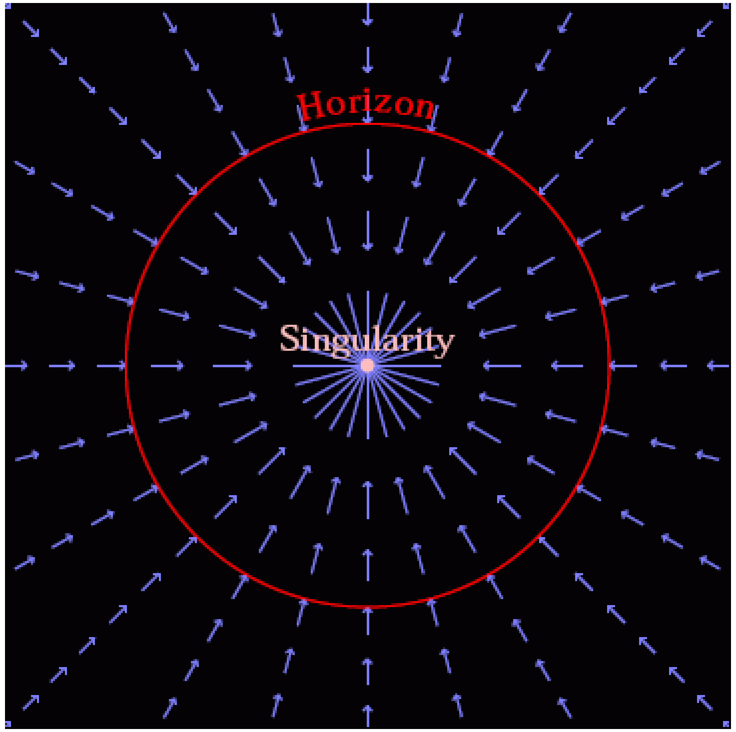
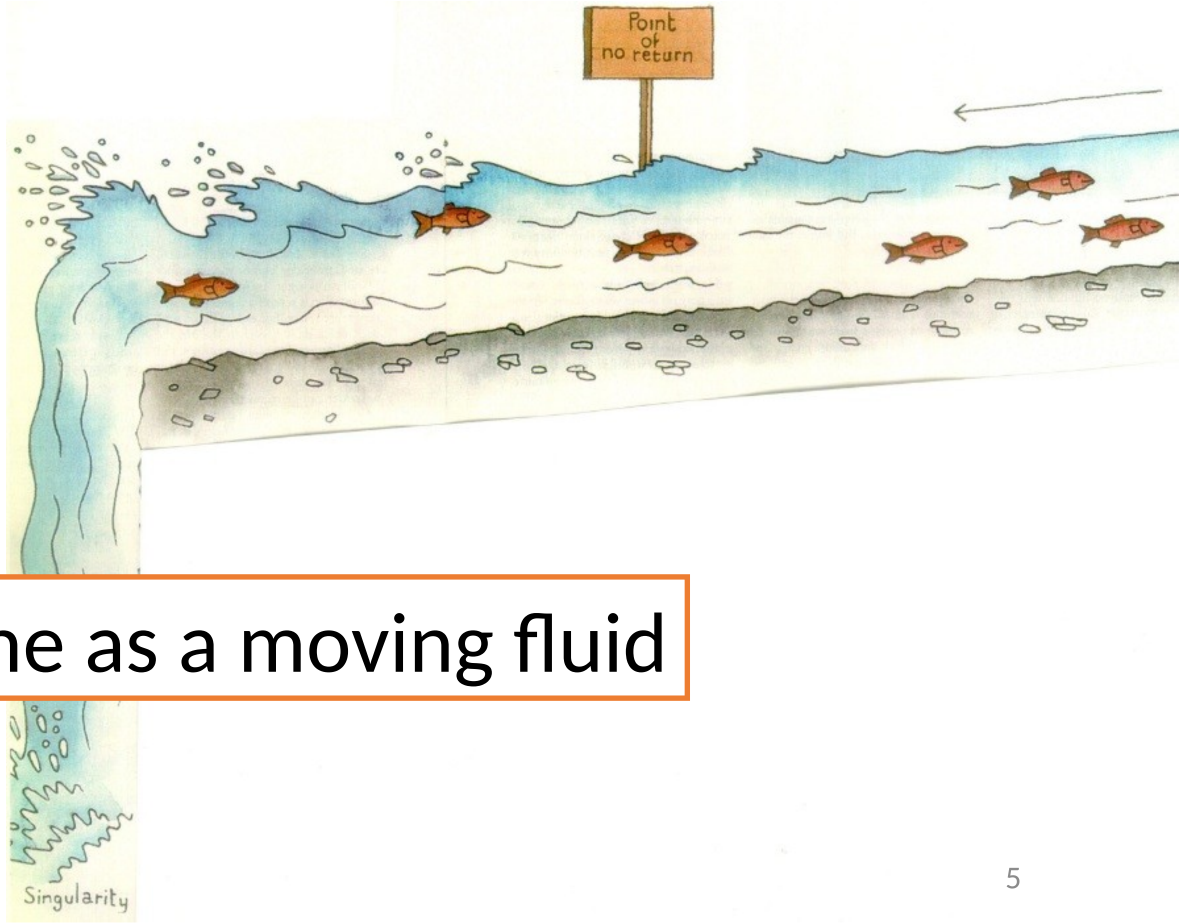
Superluminal flow of spacetime
Subluminal flow of spacetime

Event horizon separates region of sub from superluminal flow

See eg. Hamilton and Lisle Amer Jour Phys **76** 519 (2008) or Jacobson PTPS **136** 1 (1999)

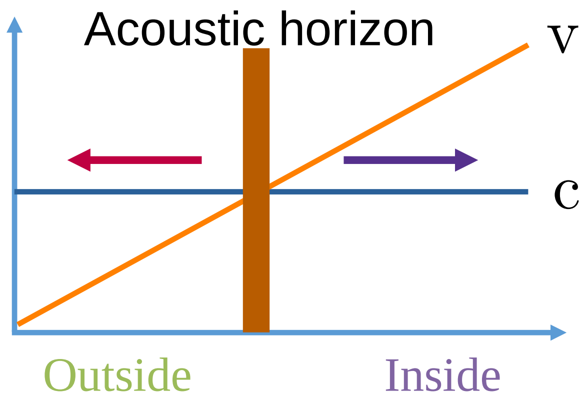
Metaphor: the event horizon and the flow of spacetime





Unruh (1974): spacetime as a moving fluid

Analogy: Isomorphism and ‘dumb’ holes



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

$$g^{\mu\nu}_{PG} = \begin{pmatrix} -1 & -\beta \\ -\beta & \left(c^2 - \beta^2\right) \end{pmatrix}$$

c – speed of light
β – flow velocity of space

Wave equation of sound in fluid 1+1D flow

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

c – speed of sound in fluid
v – flow velocity of fluid

Unruh, PRL **46** 1351 (1981):

acoustic field = Klein-Gordon field on effectively curved spacetime
+ quantised acoustic field gives Hawking effect

Visser, Class Quant Grav **15** 1767 (1998): speed of sound may vary spatially+canonical black hole (3+1D)

Experimental observations with dumb holes

Sound waves

In BEC

Hawking correlations
Steinhauer 2019

Black hole laser?
Steinhauer 2014

In fluid of light
(Polariton microcavity)
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

Frequency shift 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)?

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

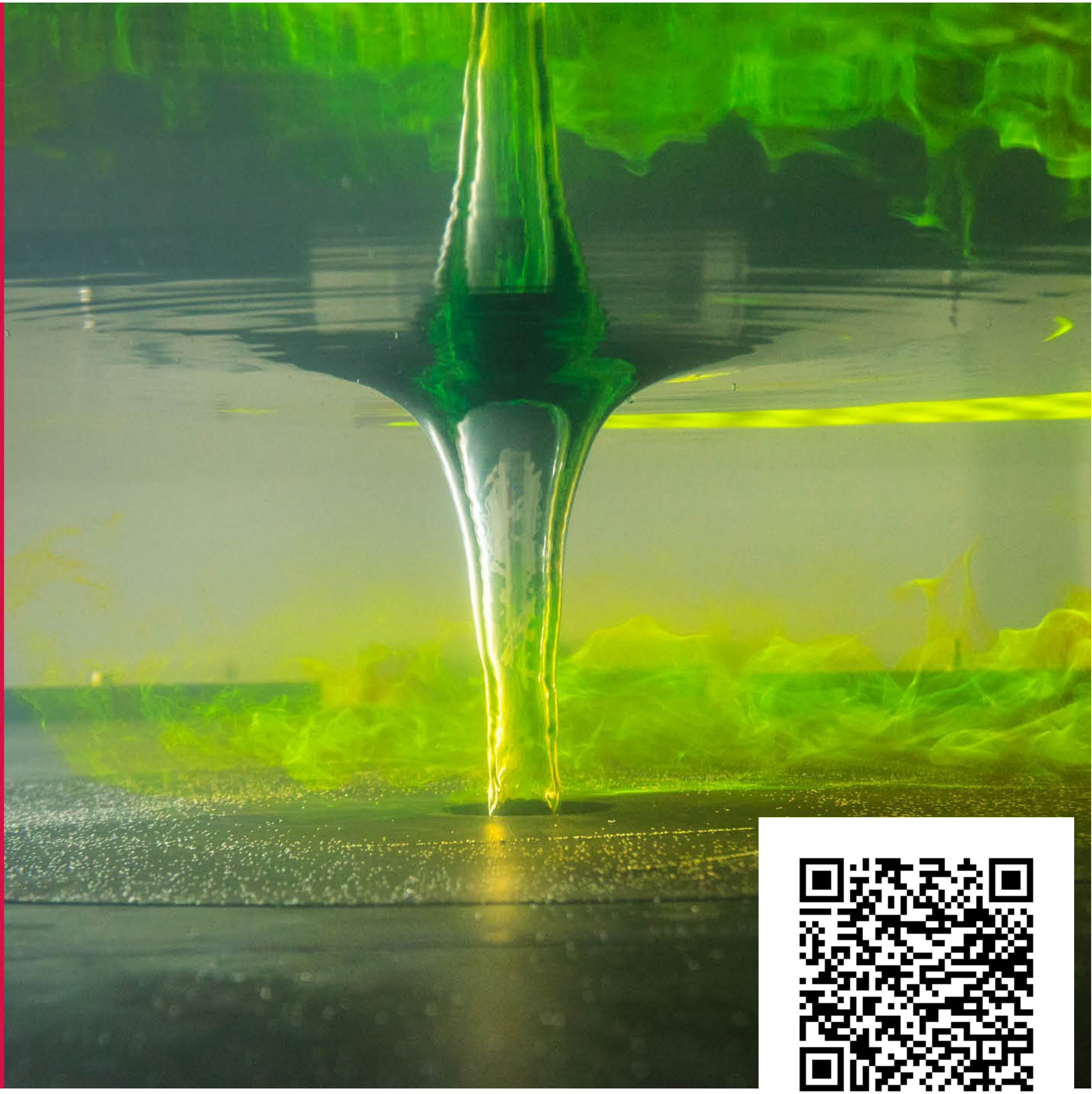
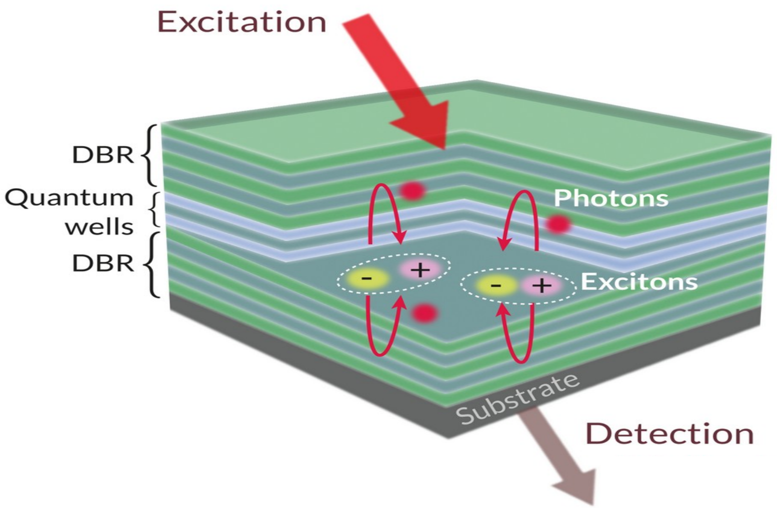
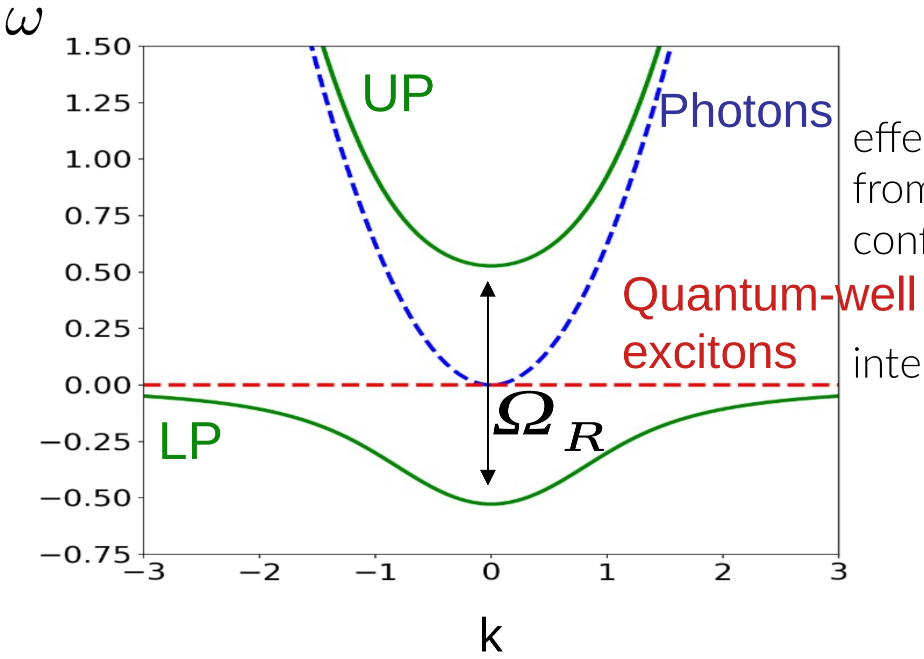


Image: © Alex Wilkinson Media.

Microcavity polaritons

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





effective mass from confinement

interactions

Strong coupling regime: $\gamma_X, \gamma_\phi < \Omega_R$

→ Photons/Excitons energies anticrossing

New eigenstates: upper & lower polaritons

= Half-matter, half-light particules

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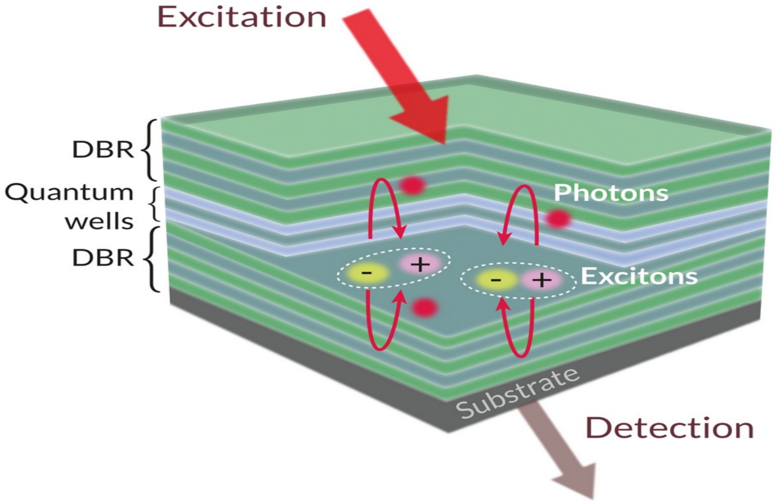

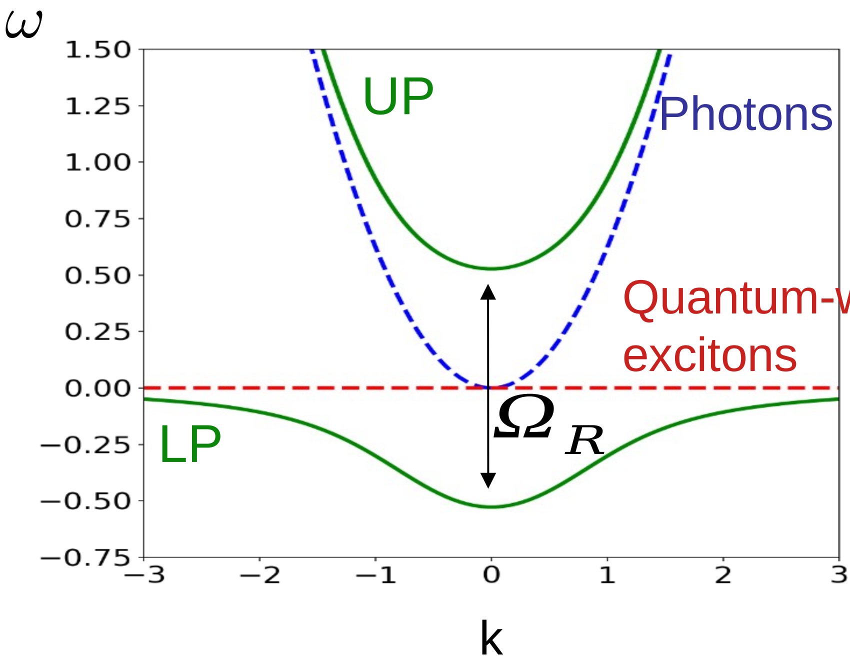

effective mass from confinement

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

$$|\psi|^2$$

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

g polariton-polariton interaction constant

γ losses

P pump

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

See also work on spectrum and entanglement in Parentani PRA **89** 043819 (2014)

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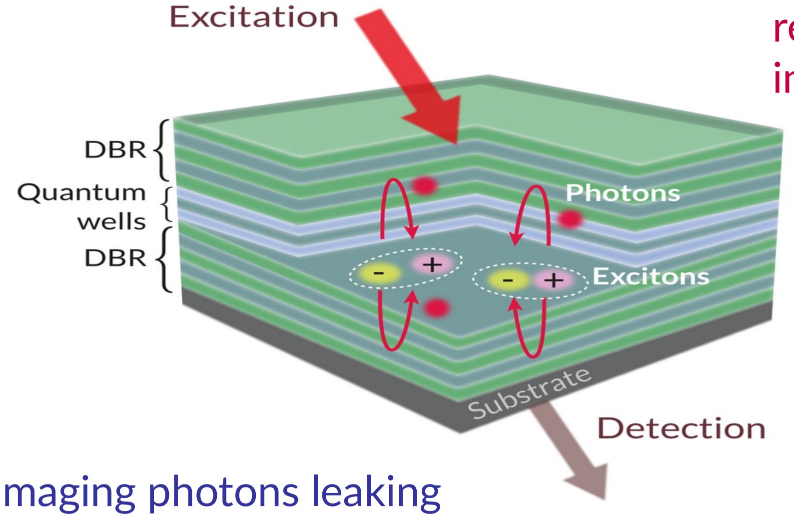
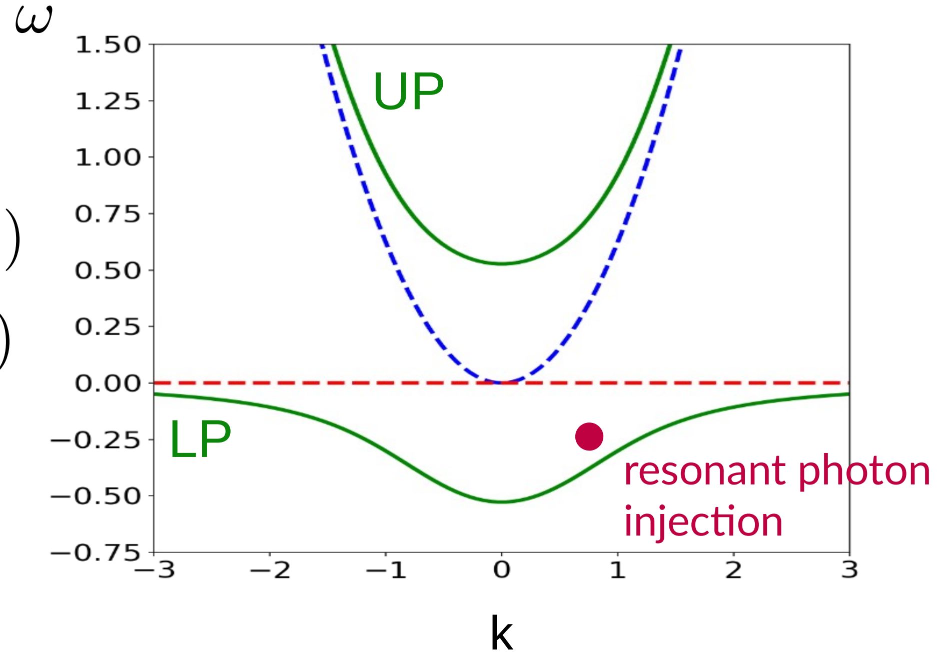


resonant photon injection

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

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



Imaging photons leaking out of the cavity

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

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

Phase profile of the driving field → Spatial Light Modulator (SLM)

Image of the **cavity plane**

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

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

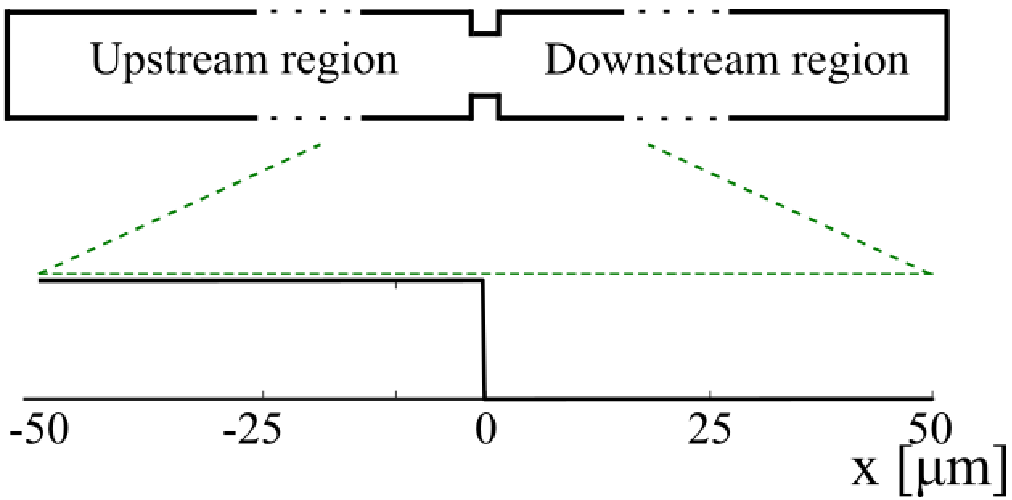
Full optical experiment

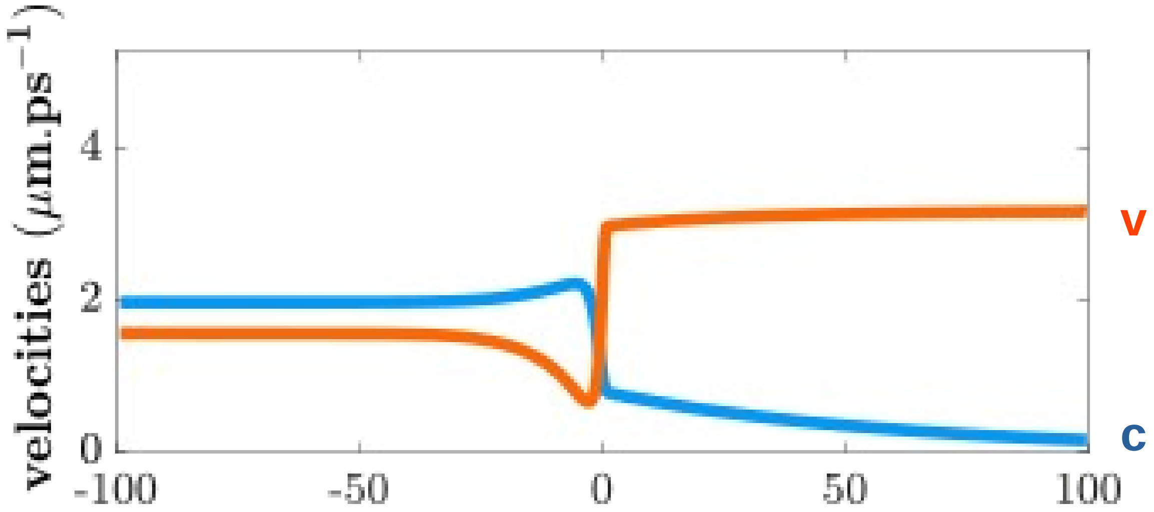
Carusotto and Ciutti RMP **85** 299 (2013)

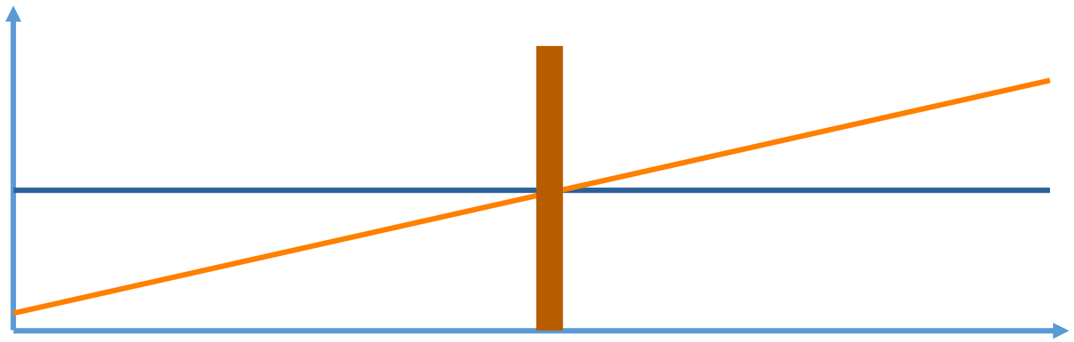
Acoustic horizon in polaritons

$c \propto \sqrt{n}$ $\qquad$ $v \propto \partial_x \phi$

Simulate sample of Nguyen PRL 114 036402 (2015)







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

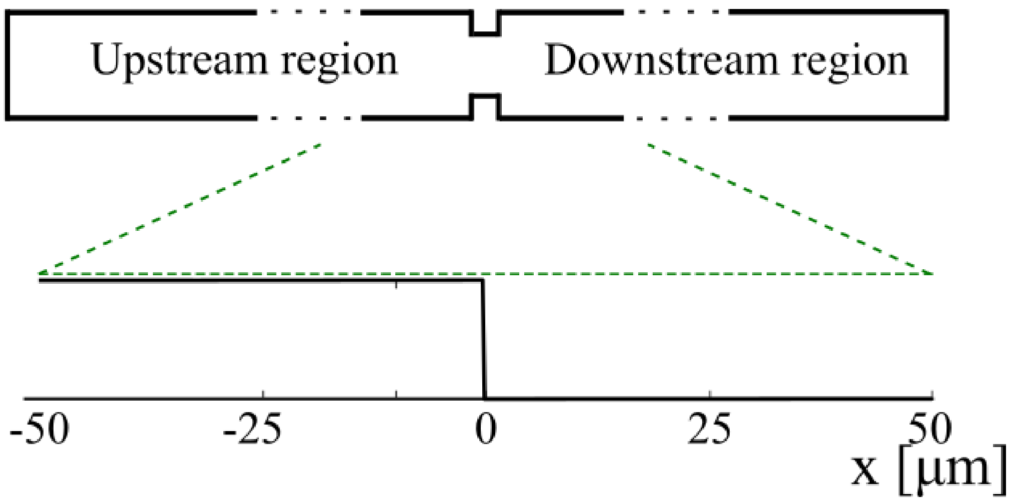
Hawking effect in polaritons

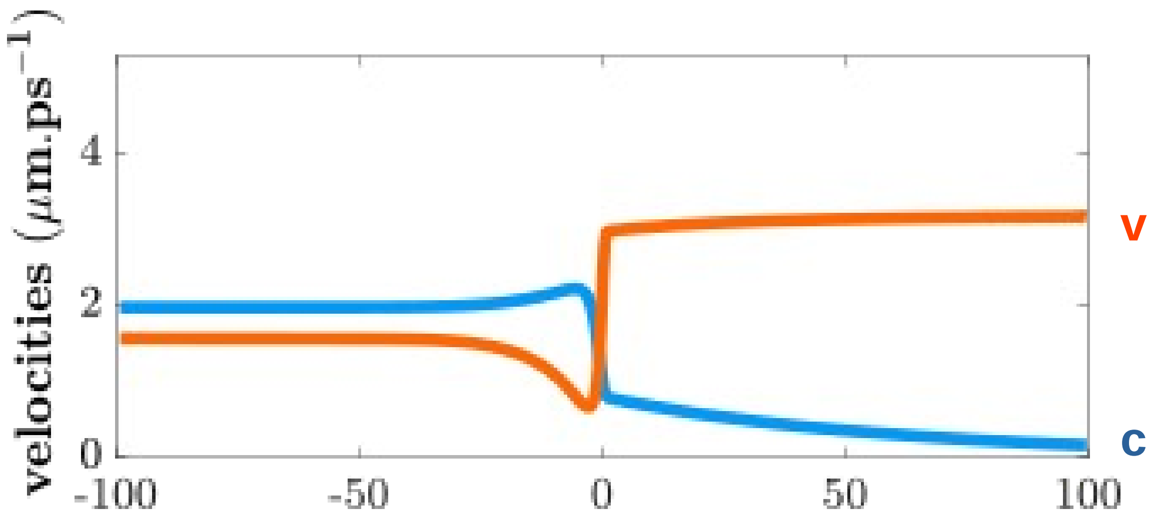
$c \propto \sqrt{n}$ $\qquad$ $v \propto \partial_x \phi$

Numerical simulation: Truncated Wigner Approximation (1 million realisations) ONLY $|0\rangle$ at input

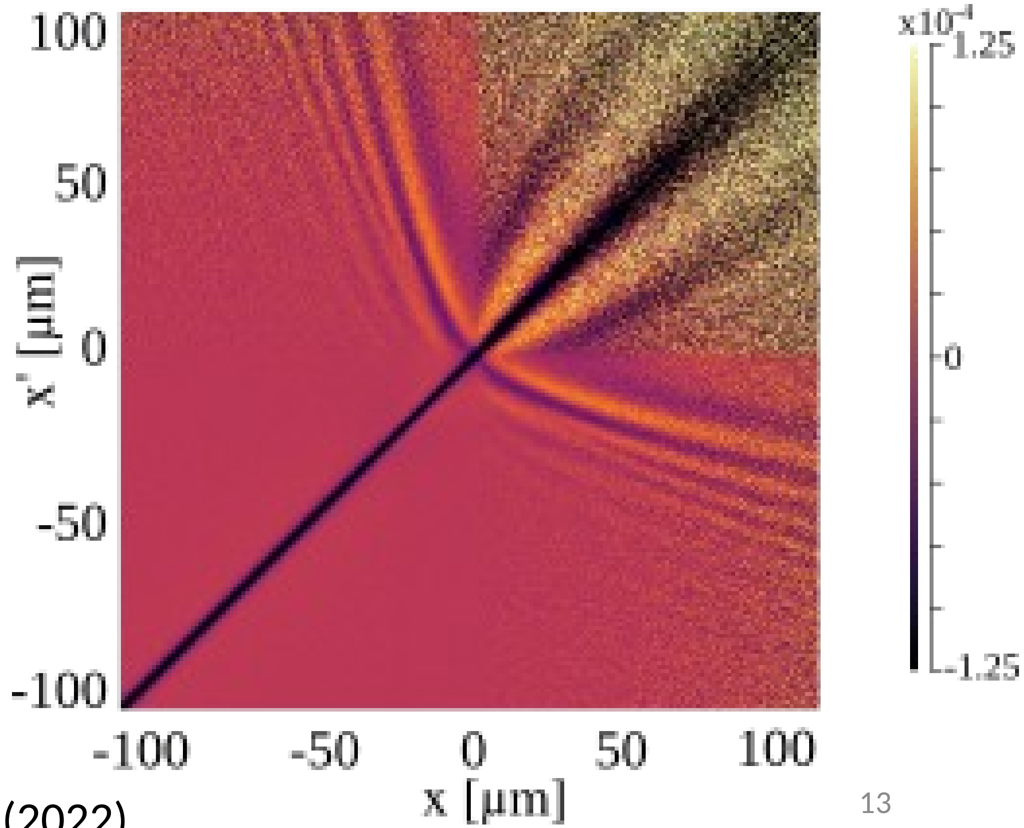
Measure equal time correlations

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





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



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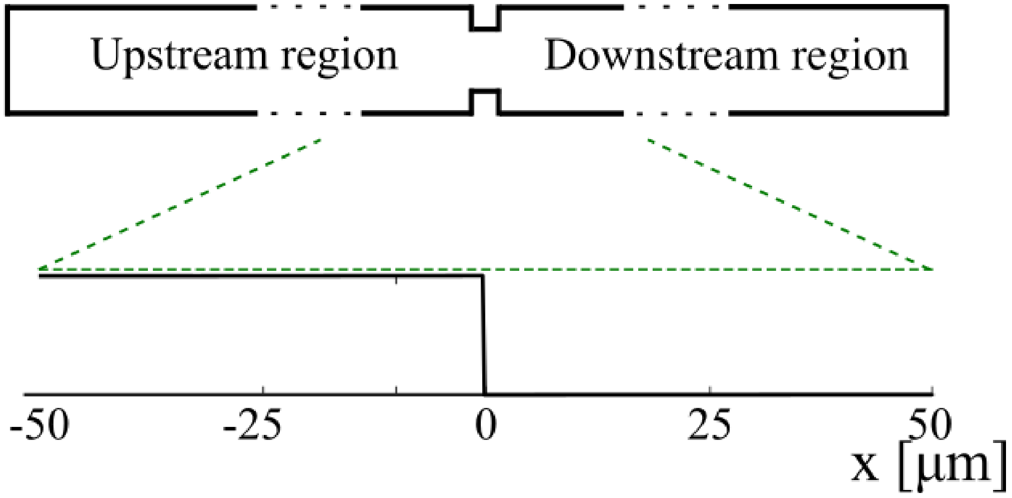
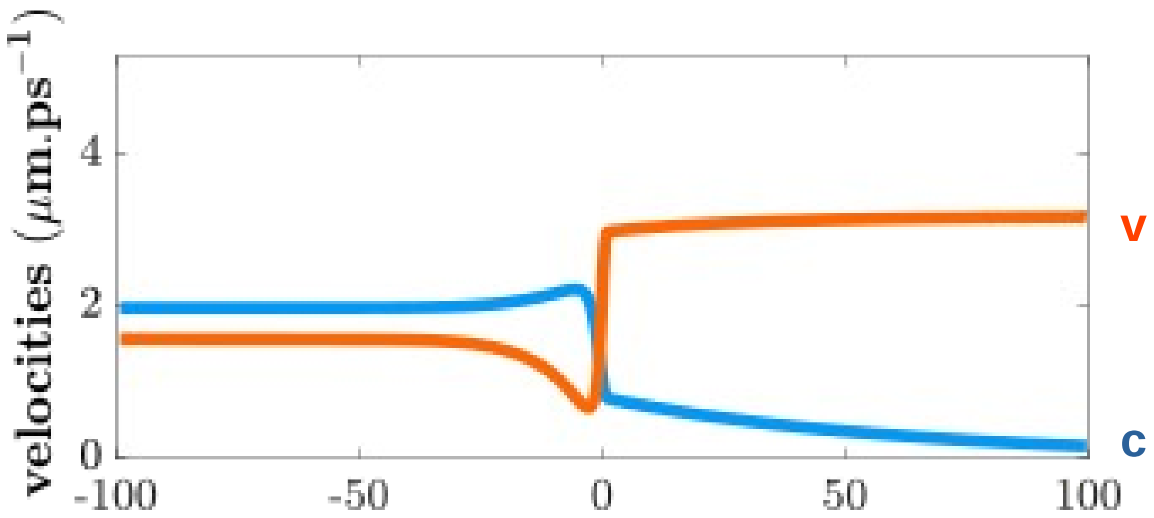
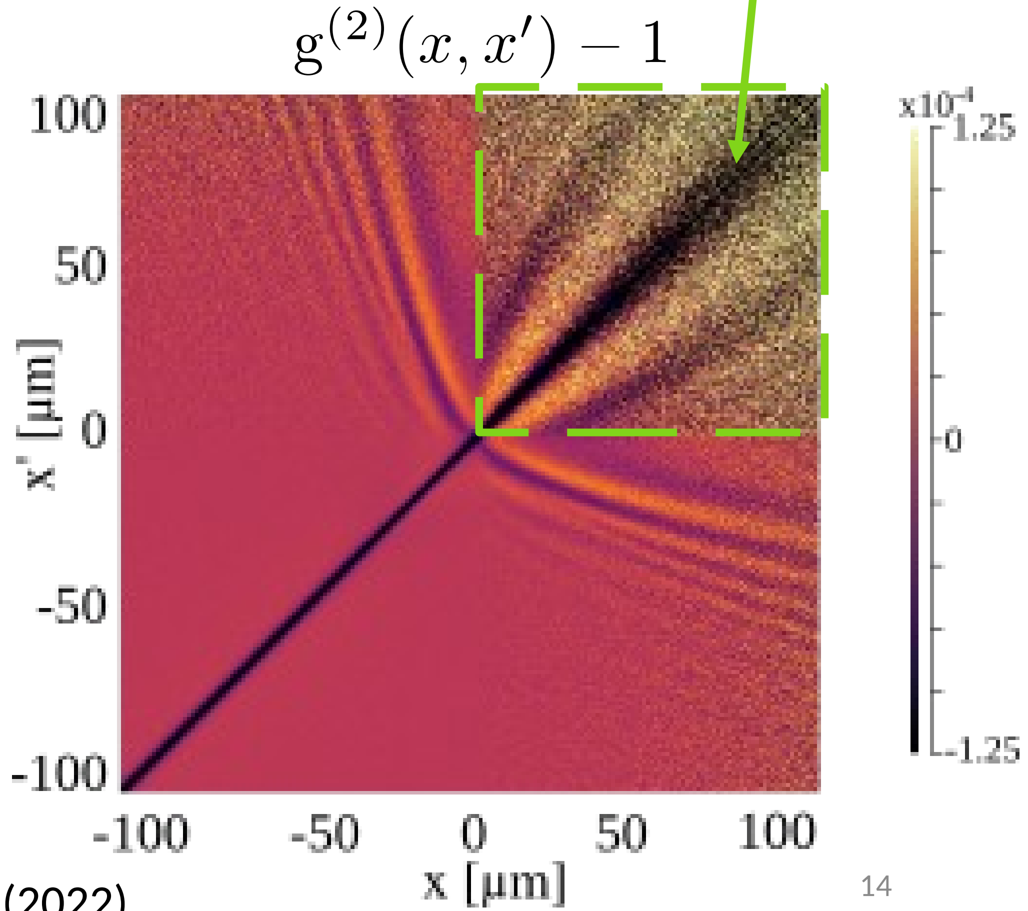




Correlations inside the horizon



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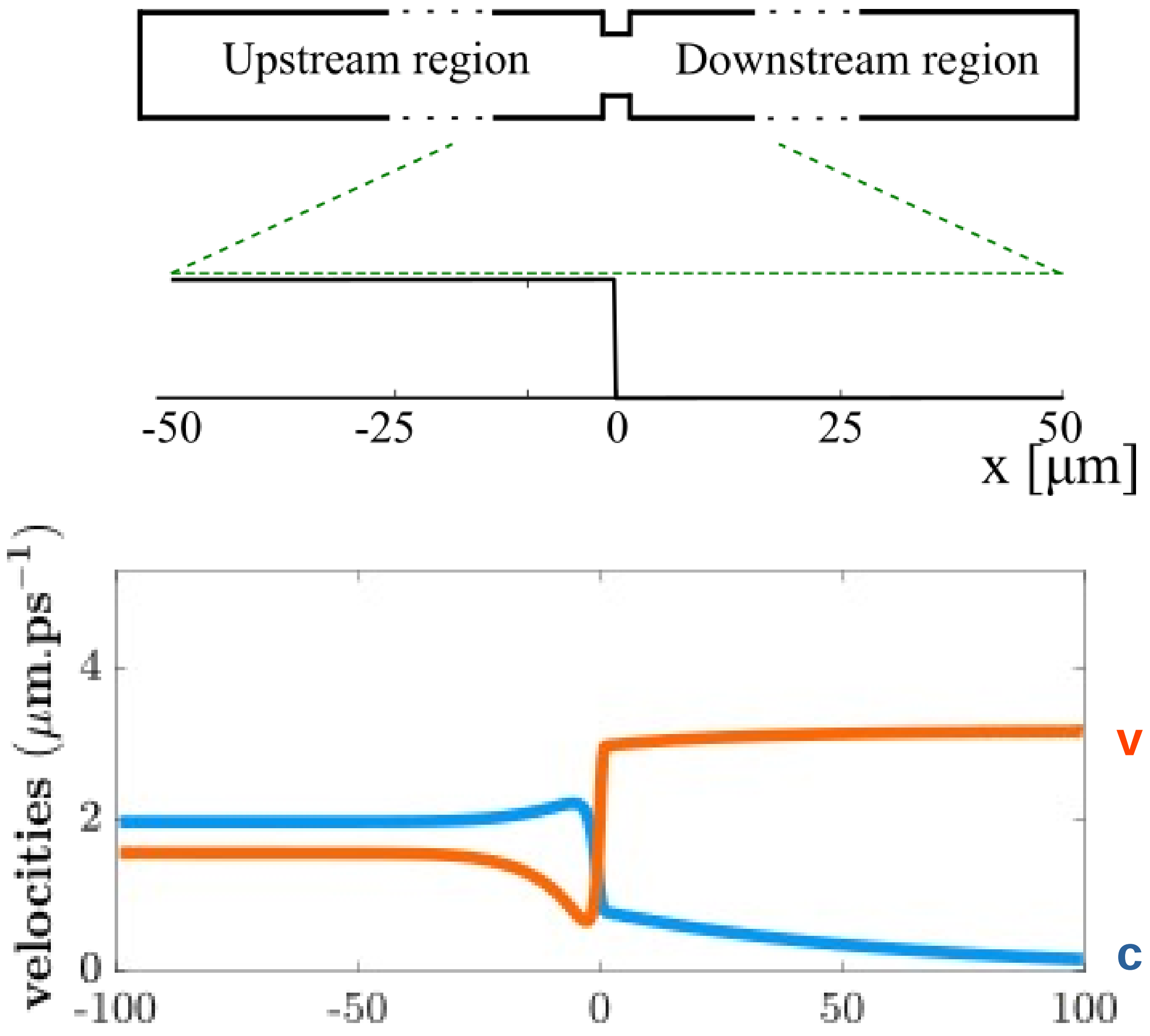

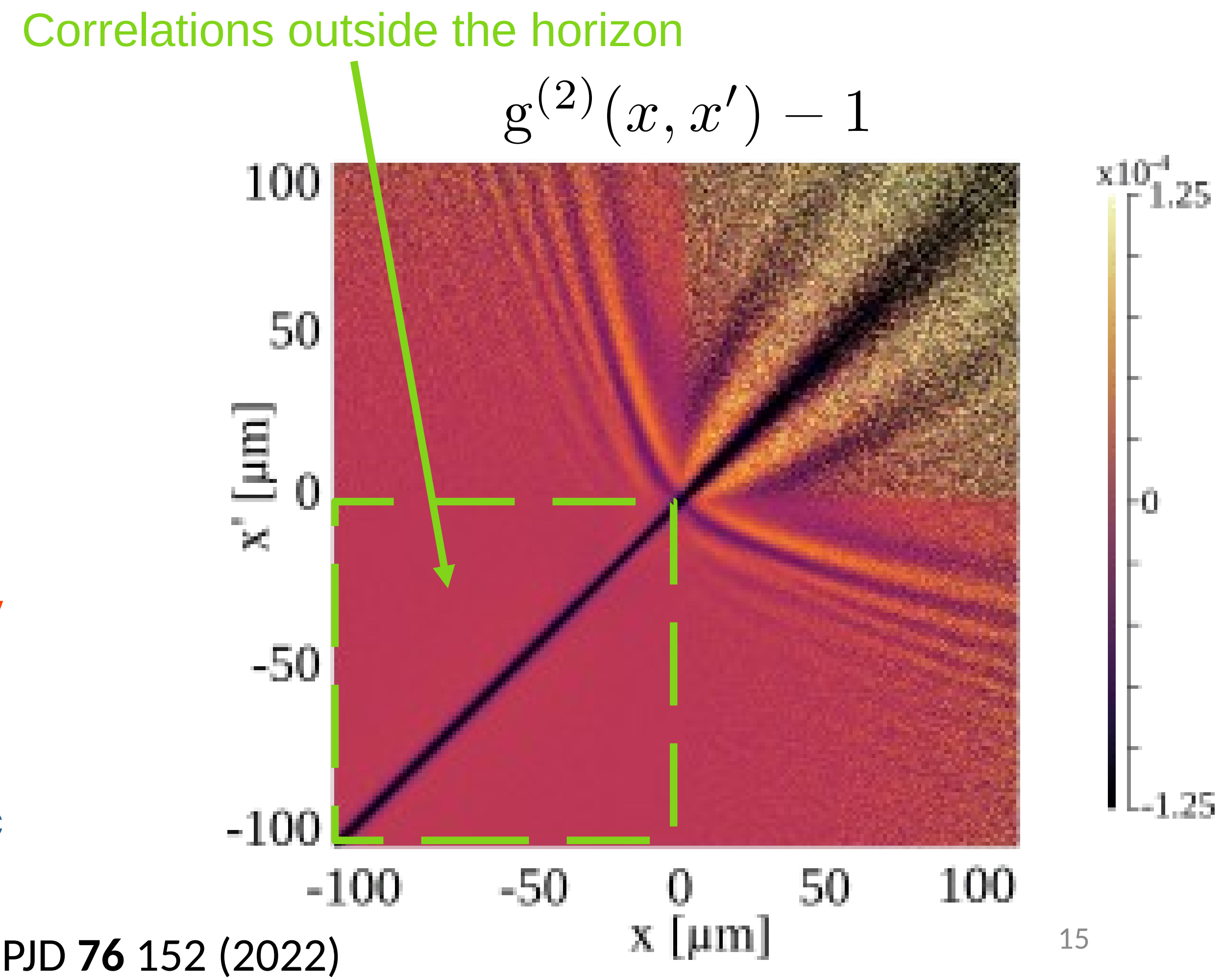

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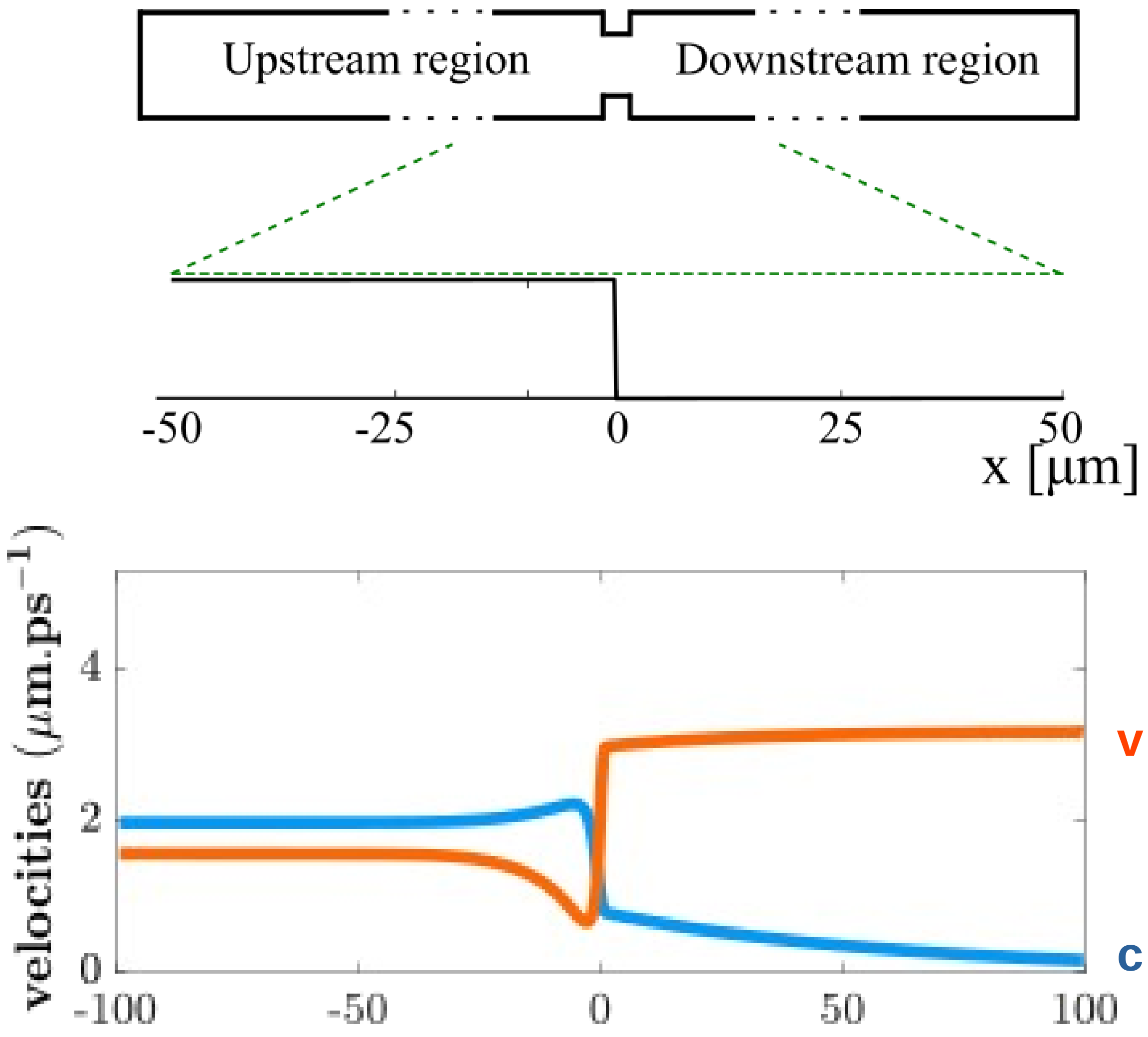
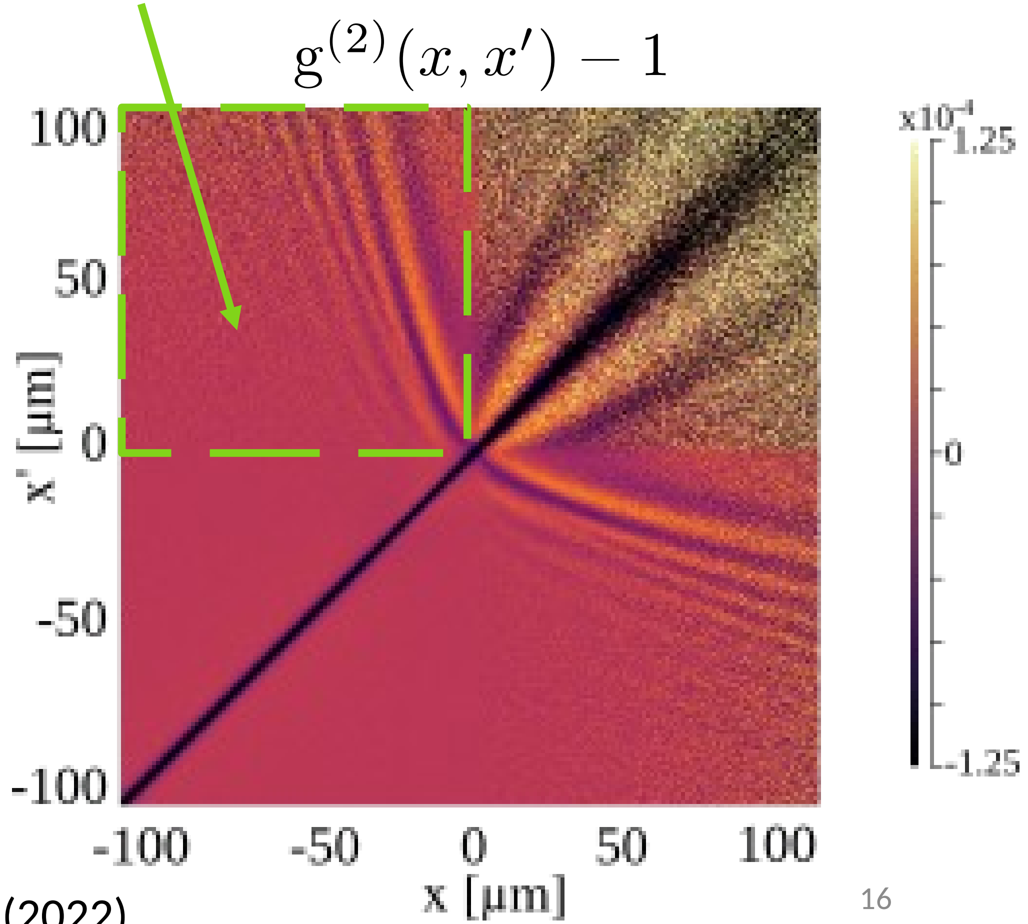


Correlations across the horizon



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Hawking effect in polaritons

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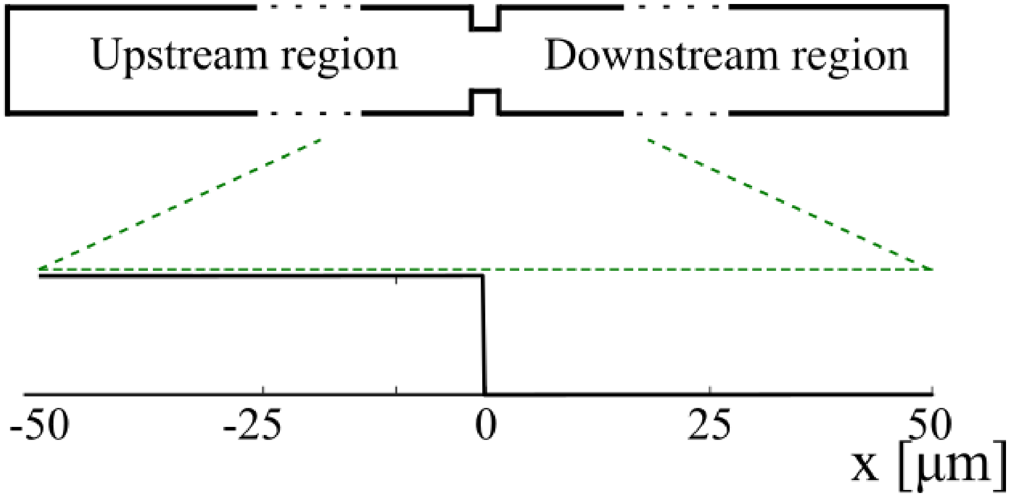

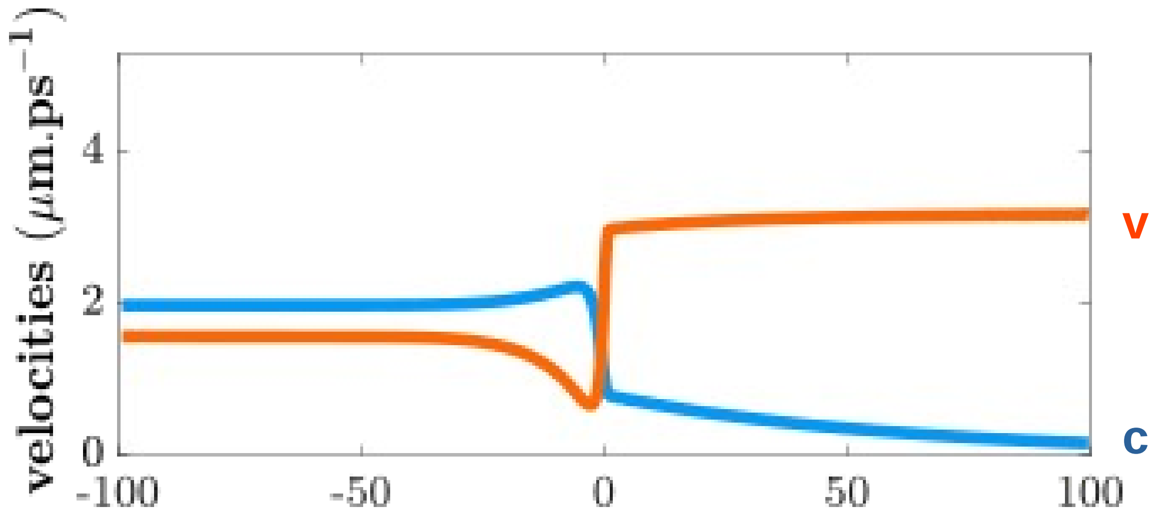

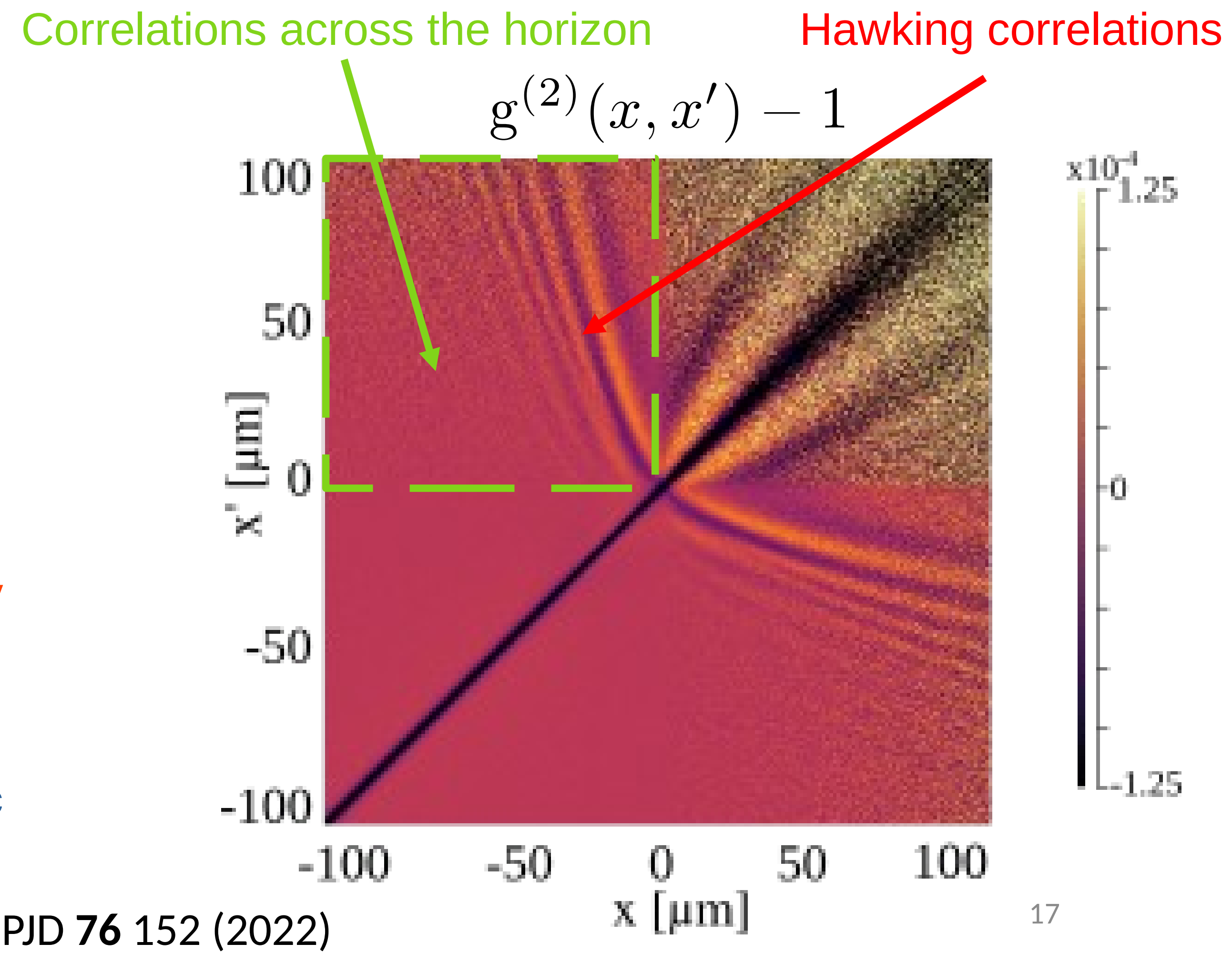

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Numerical simulation: Truncated Wigner Approximation
(1 billion realisations) ONLY $|0\rangle$ at input

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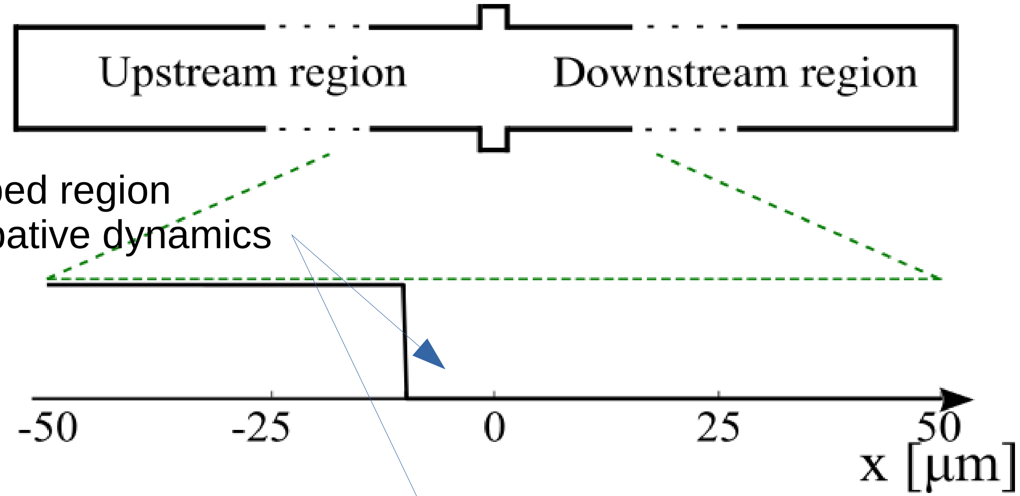
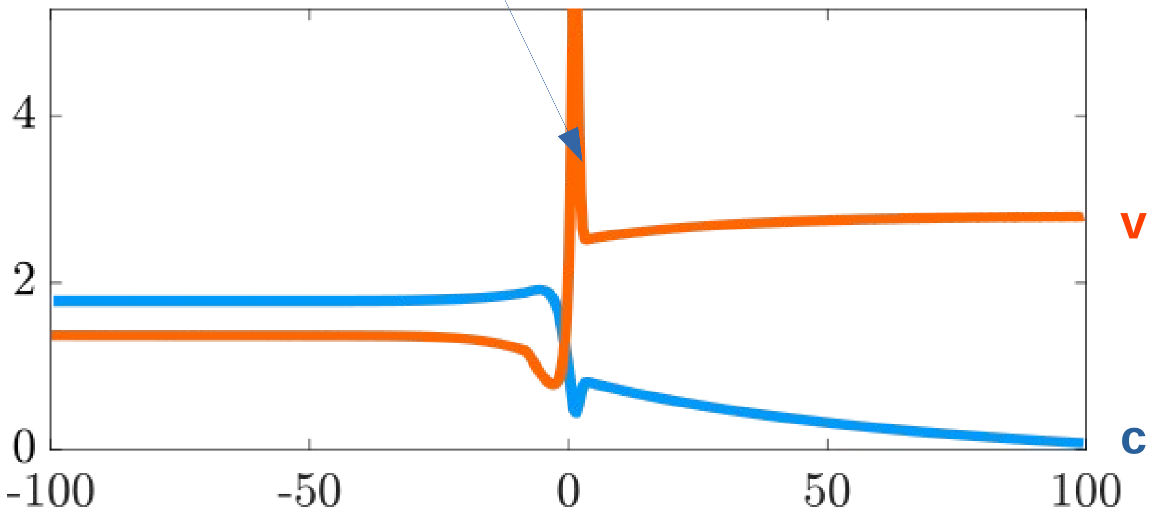
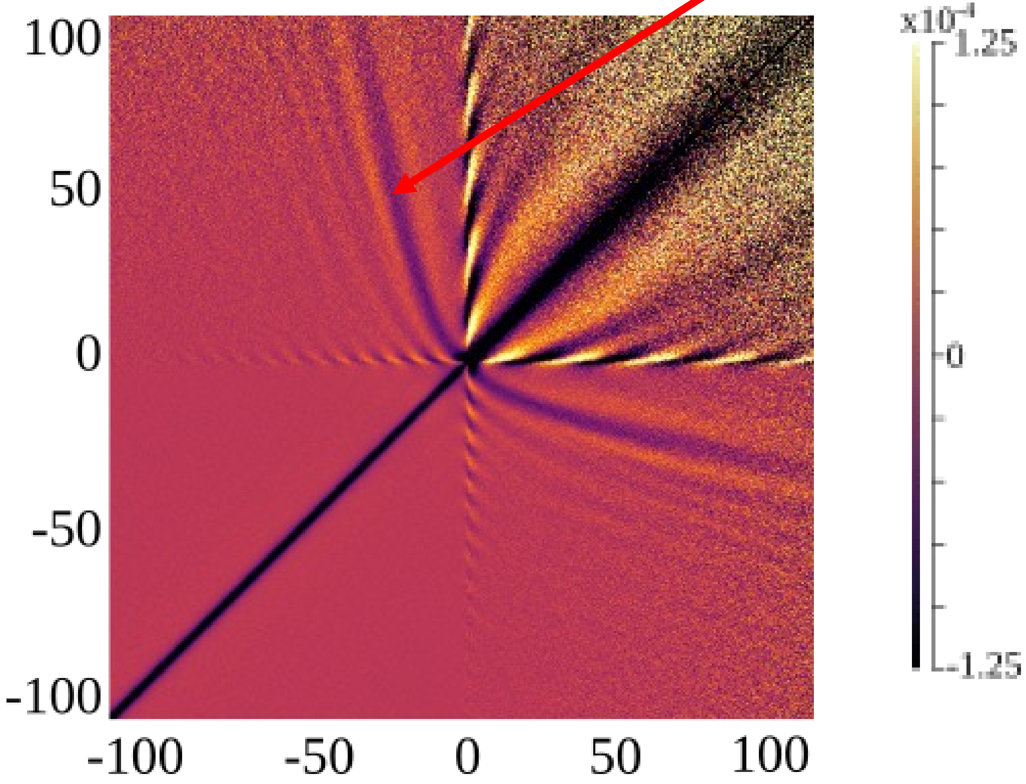


Unpumped region
→ dissipative dynamics



Hawking correlations

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



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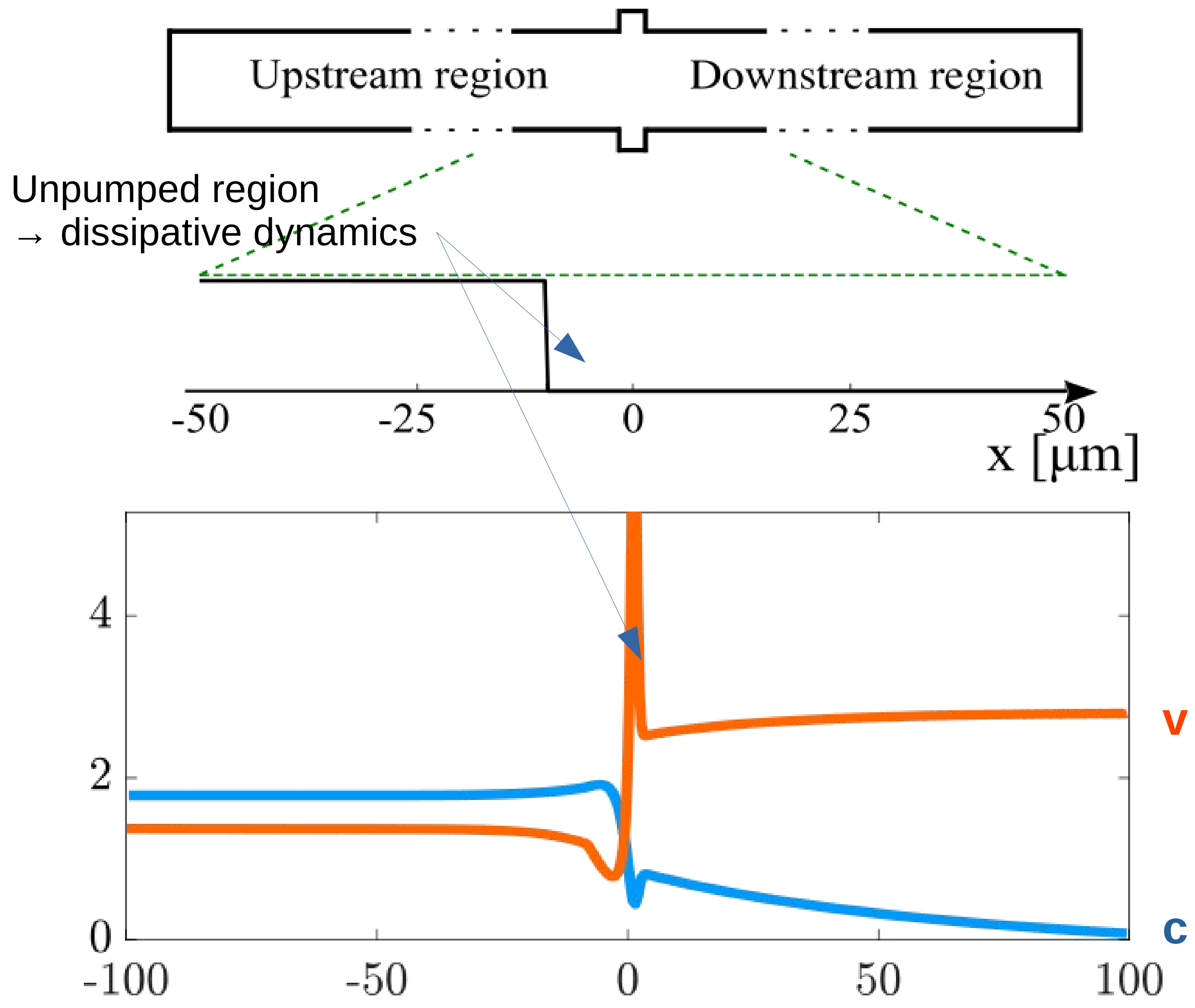
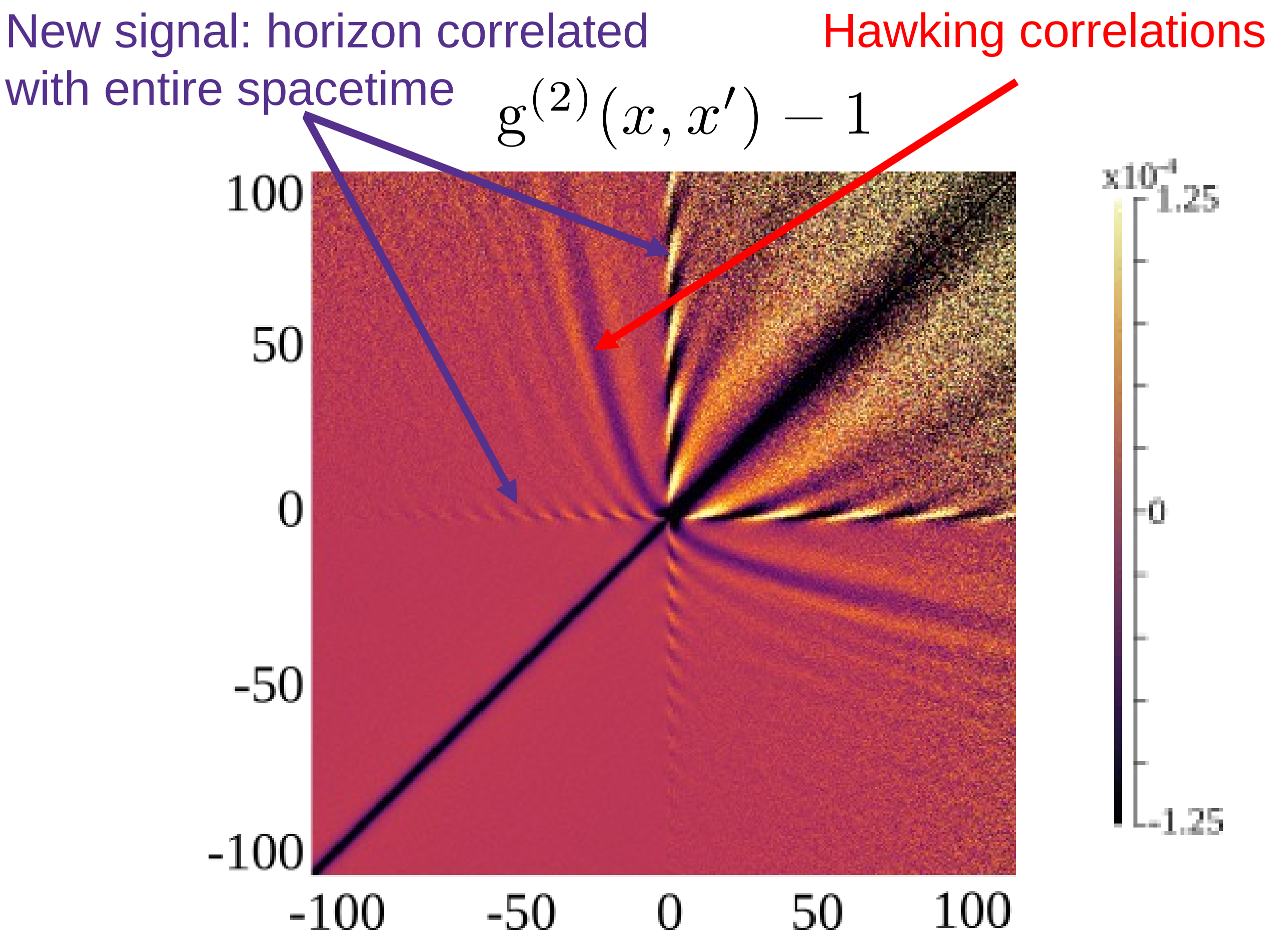




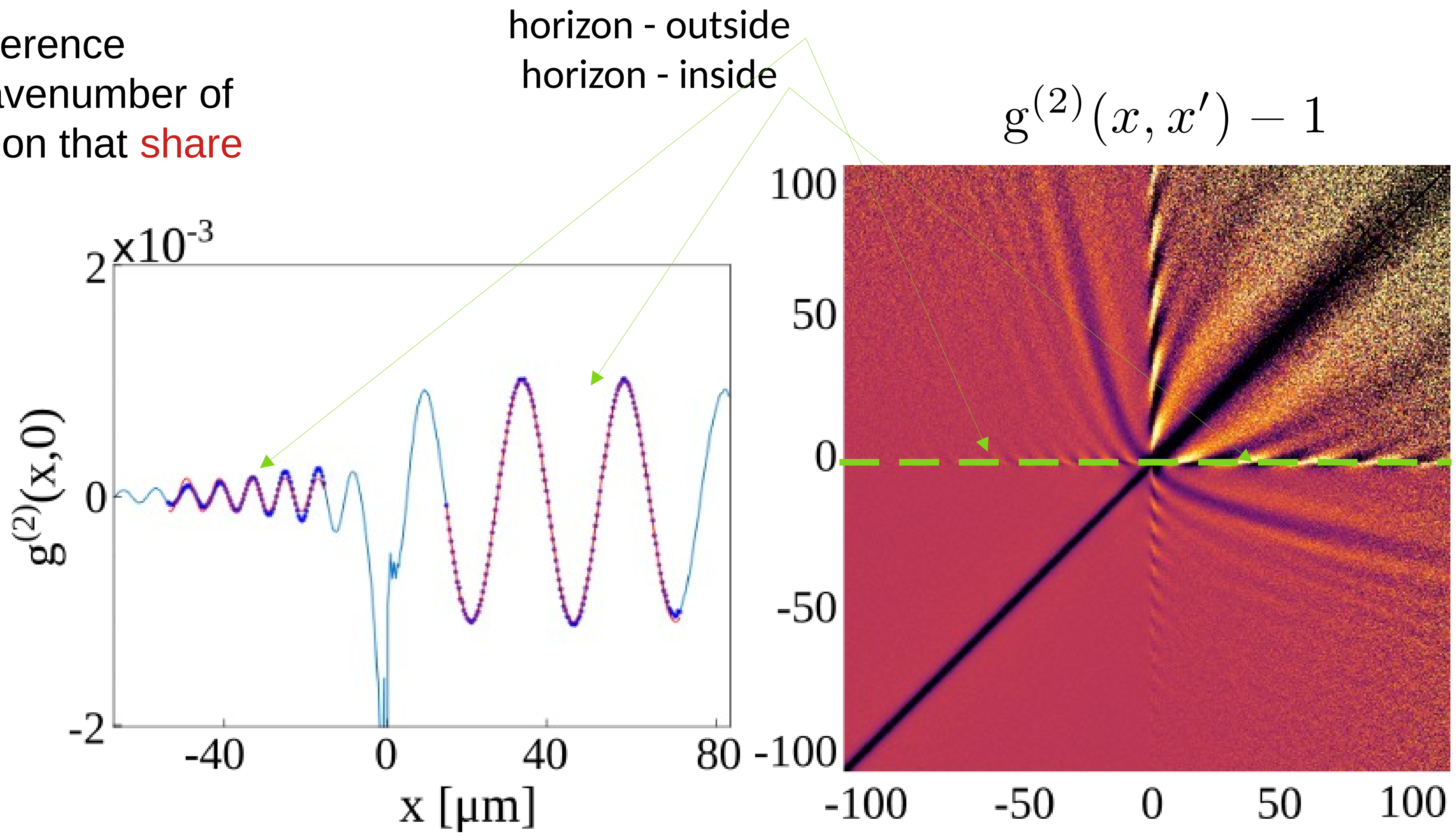
Jacquet *et al.*, EPJD **76** 152 (2022)

Scattering of vacuum fluctuations: horizon correlations

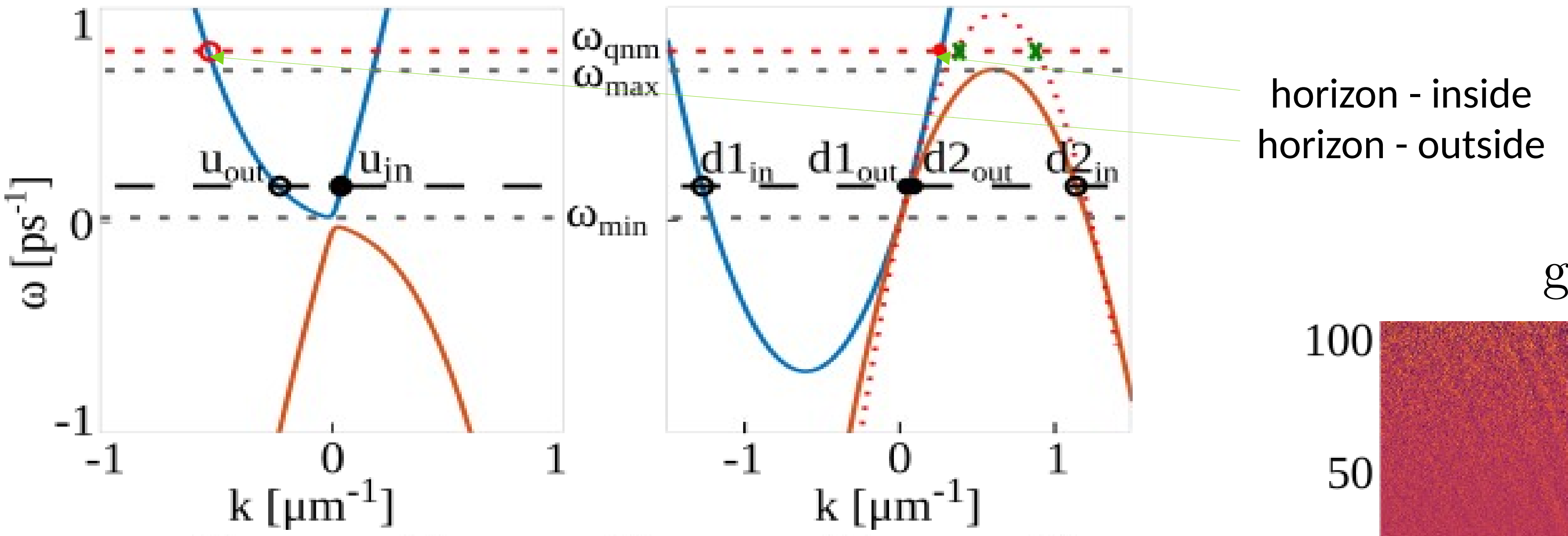
ONLY $|0\rangle$ at input

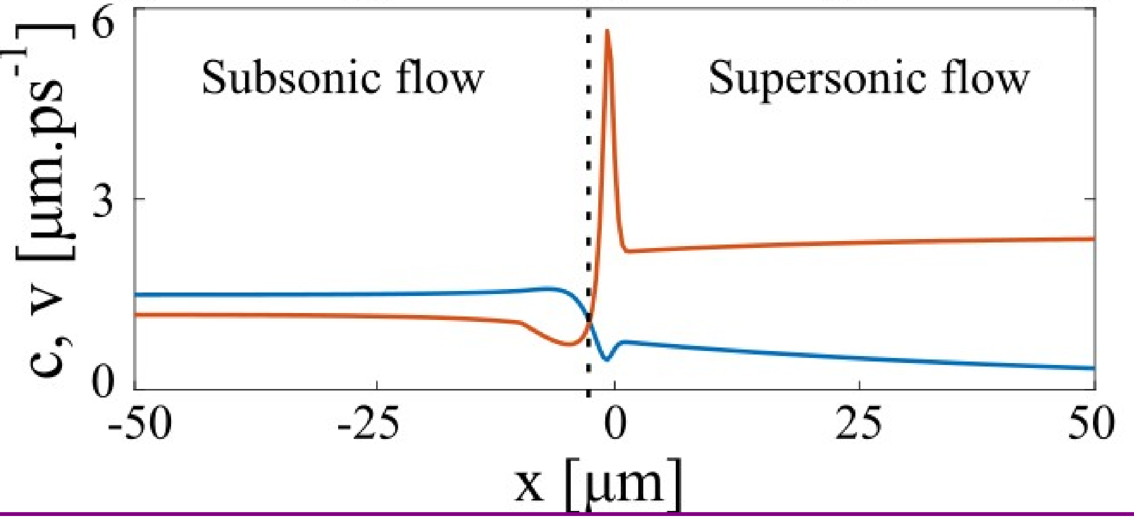
Spatial frequency of interference fringes corresponds to wavenumber of field modes in/out of horizon that share the same frequency

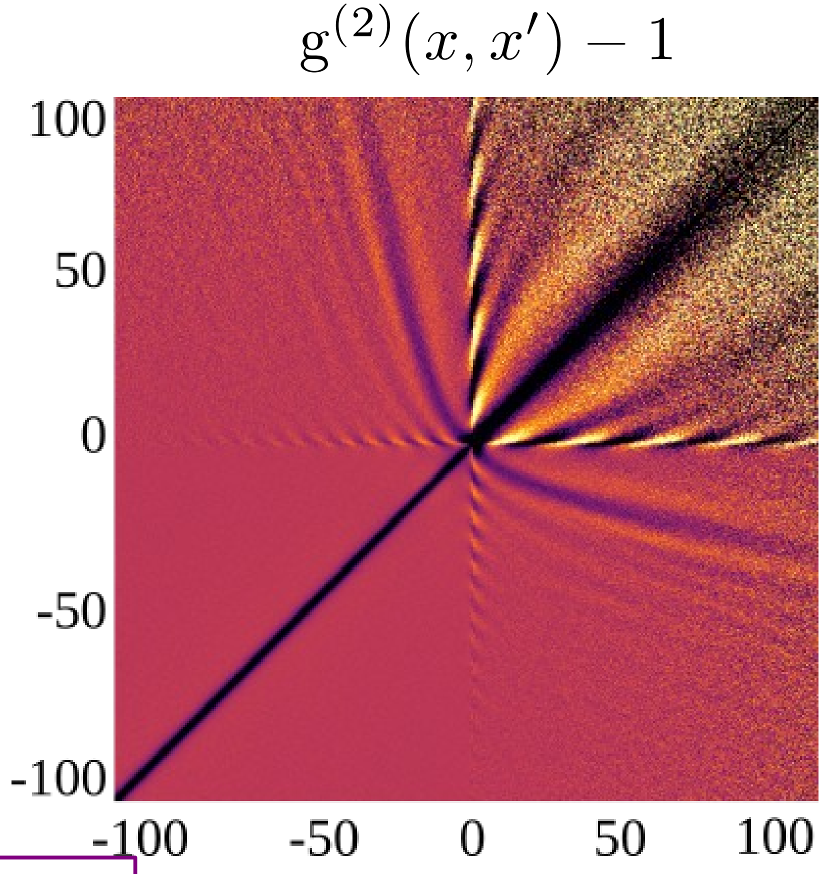
(cf dispersion relation)



Scattering of vacuum fluctuations: effective potential



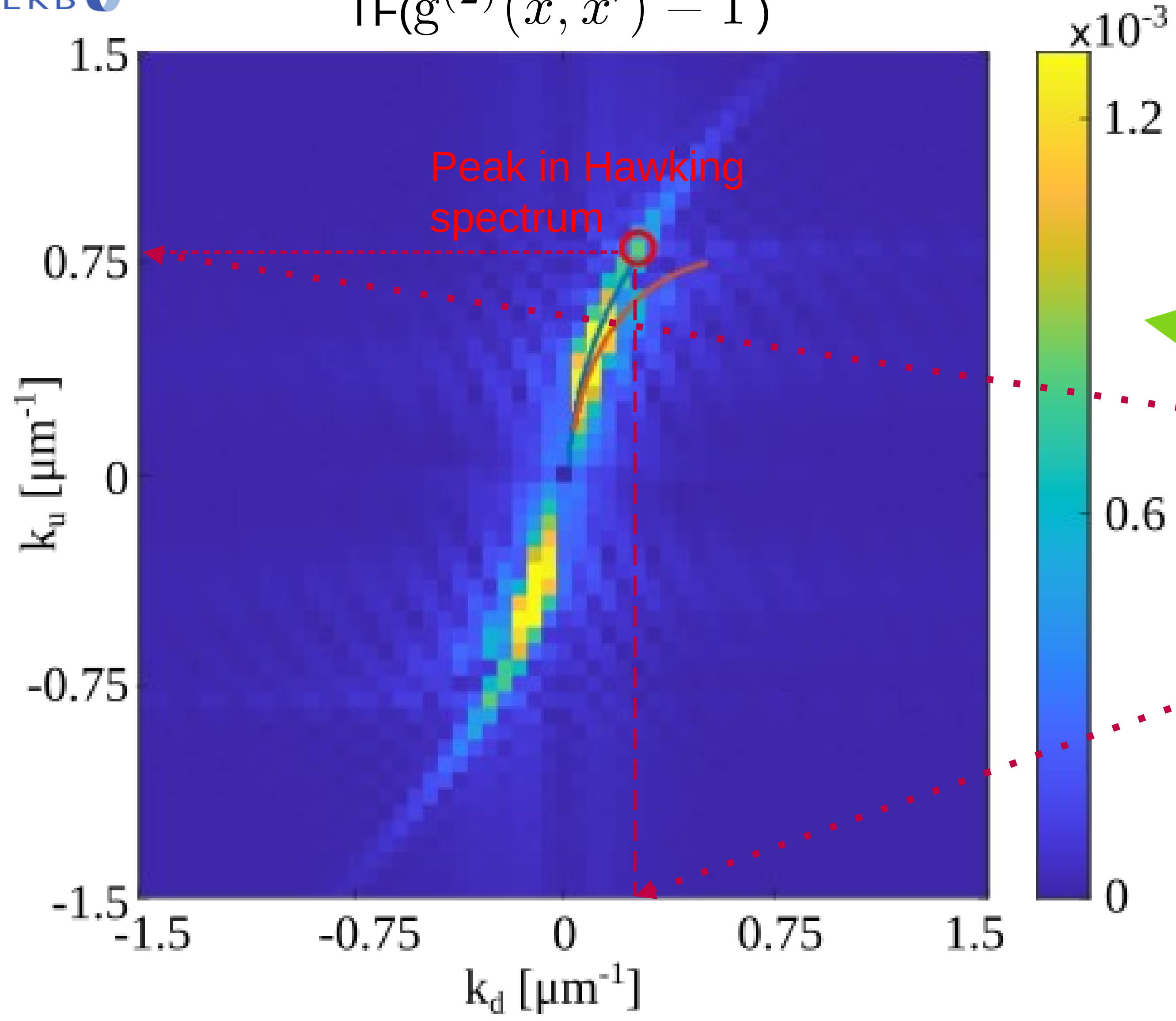




Velocity spike creates negative potential for negative modes near horizon

Spectral modulation

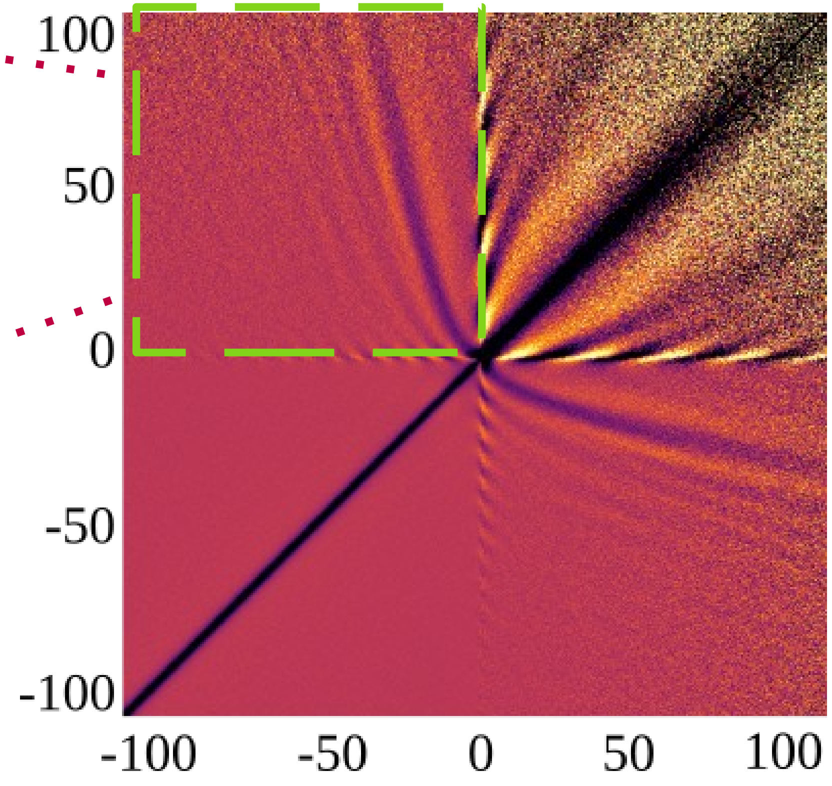
TF($g^{(2)}(x,x') - 1$)



ONLY $|0\rangle$ at input

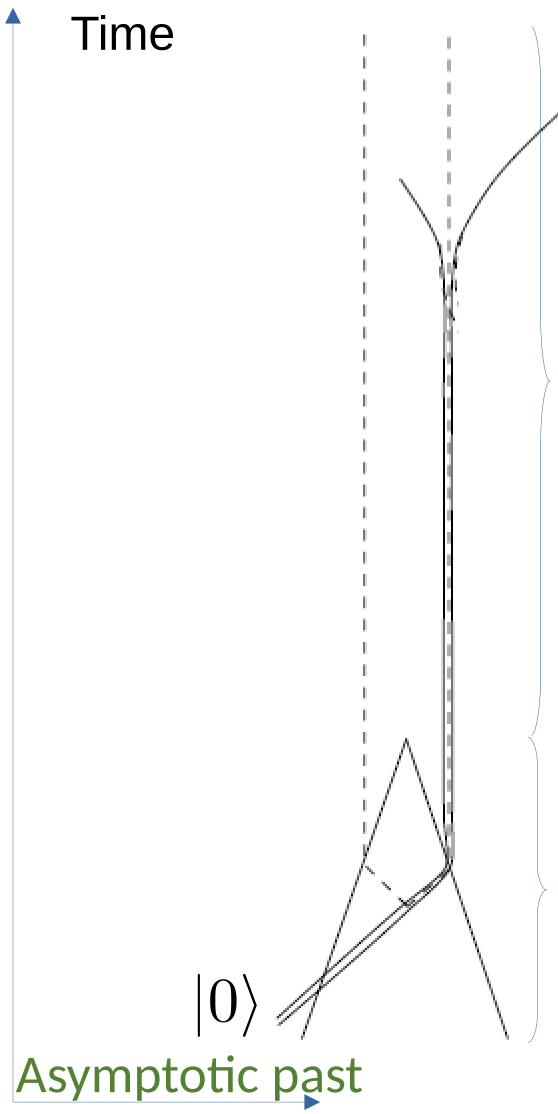
2D Fourier Transform of data

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



Jacquet *et al.*, arxiv:2110.14452

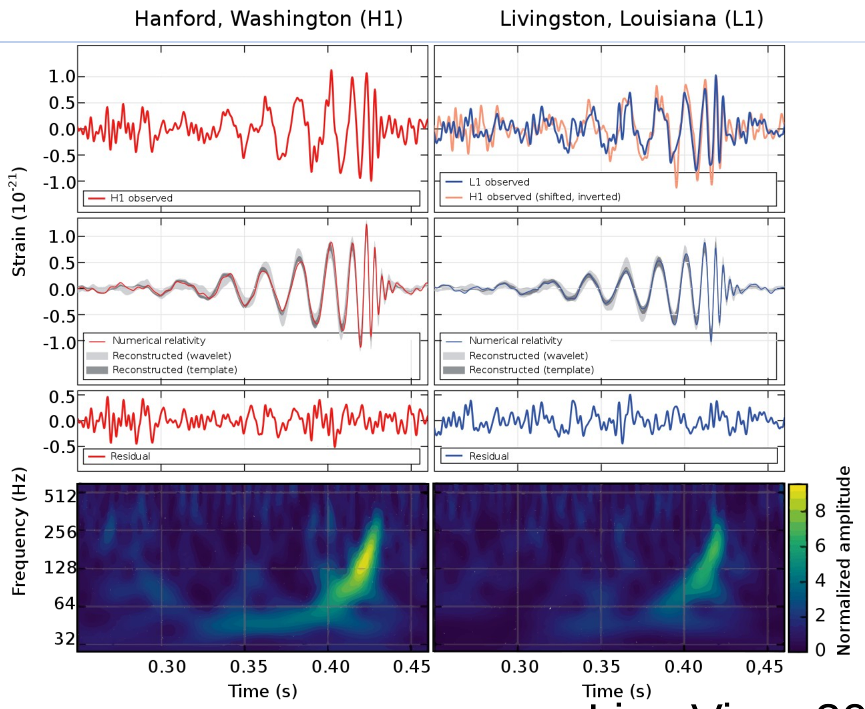
Perturbation of black hole?



Life of a Schwarzschild black hole

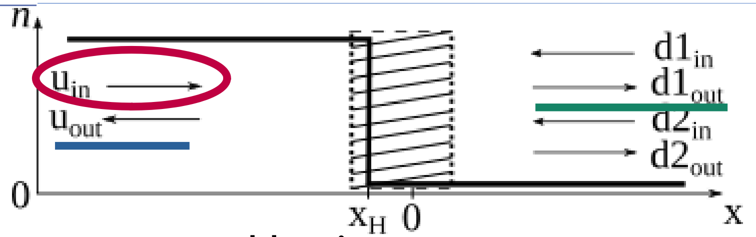
if perturbed by large amplitude object, relaxation by gravitational waves

Quasi-normal mode of the gravitational field



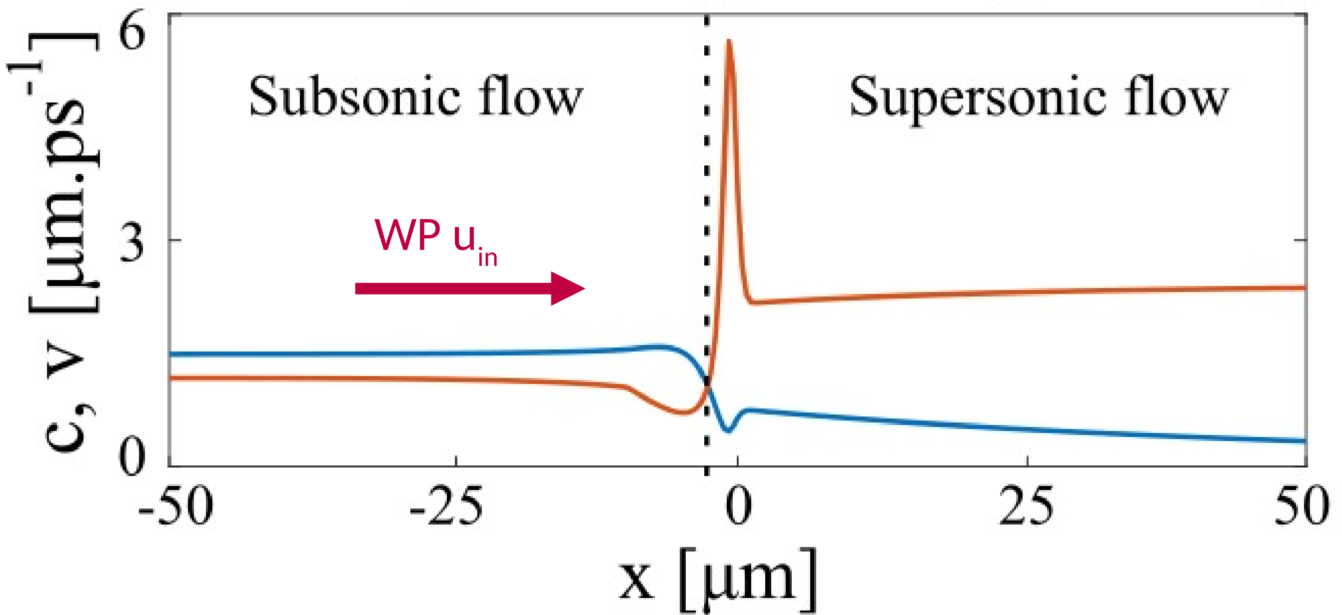
Ligo Virgo 2016

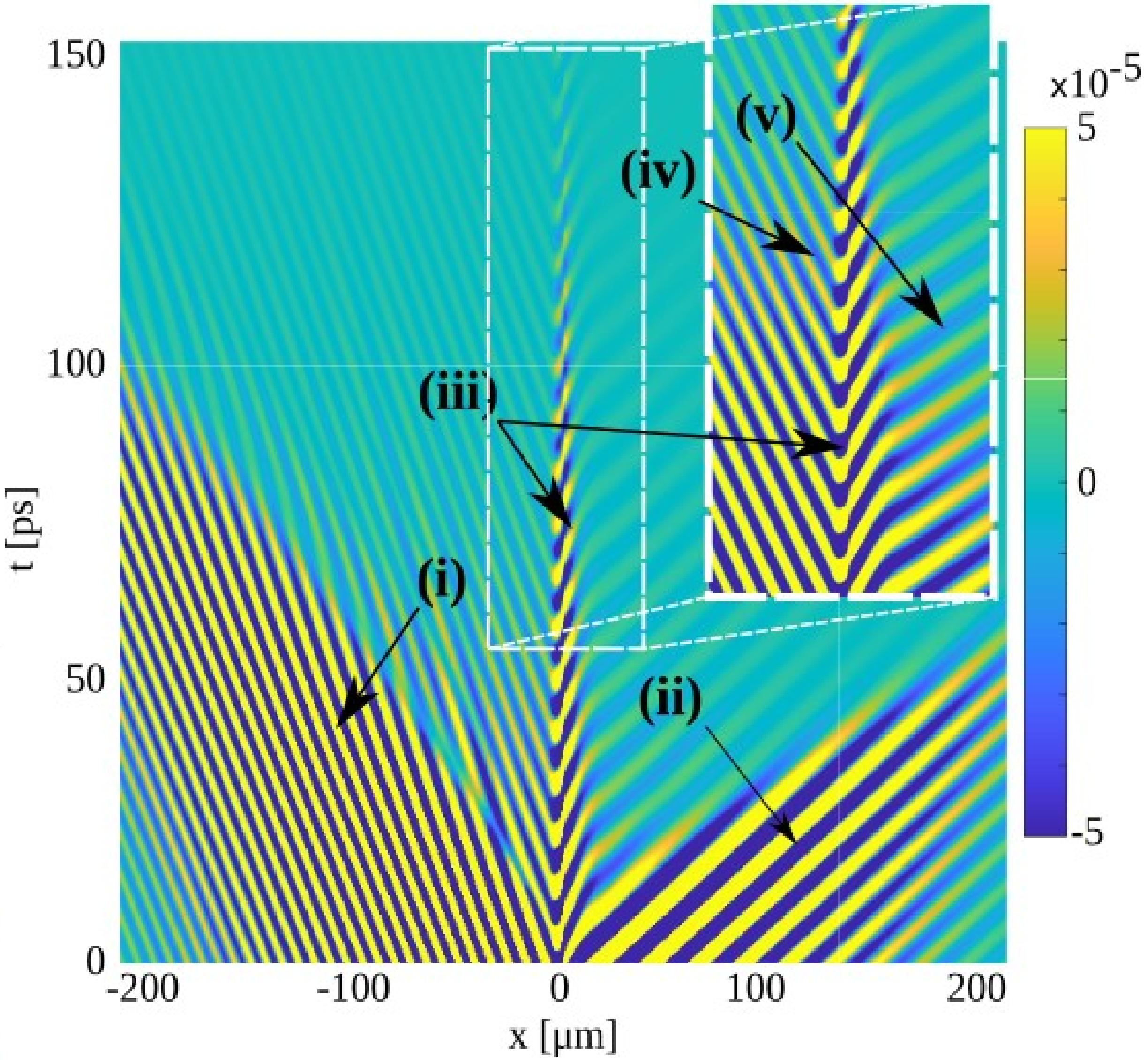
Perturb horizon with classical wavepacket



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:

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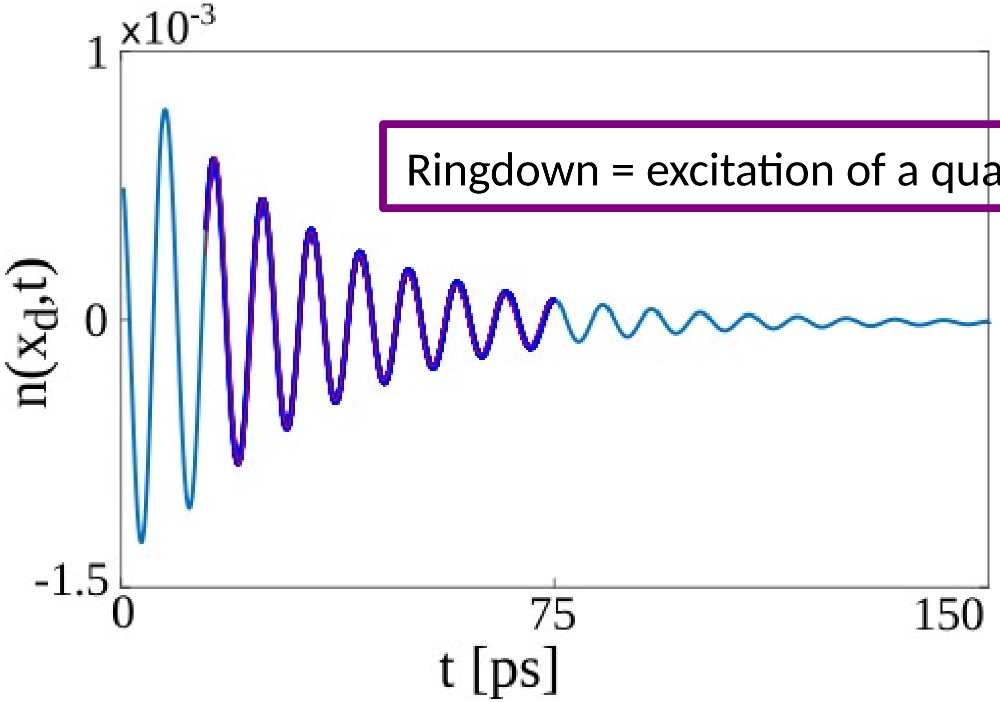
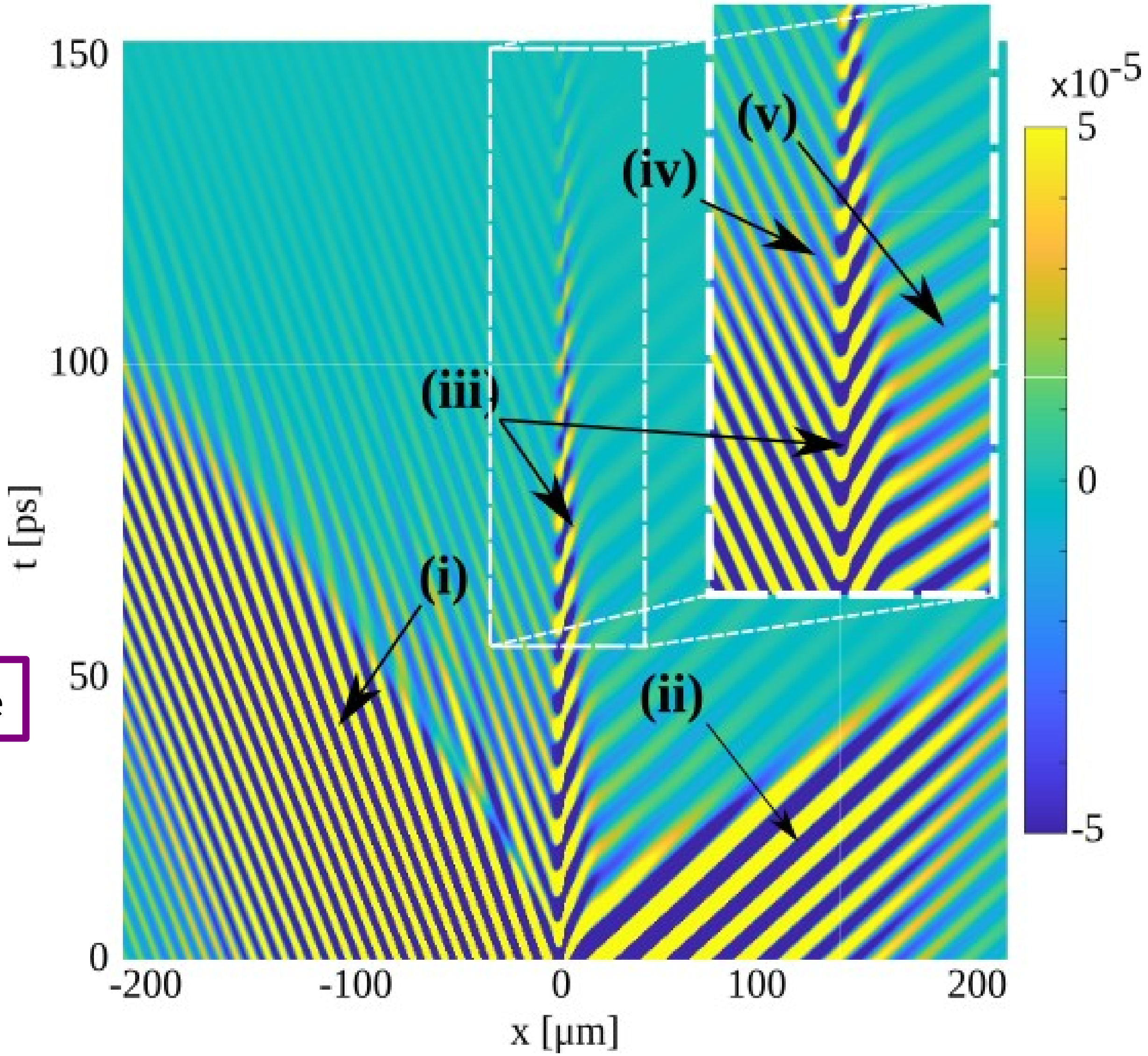
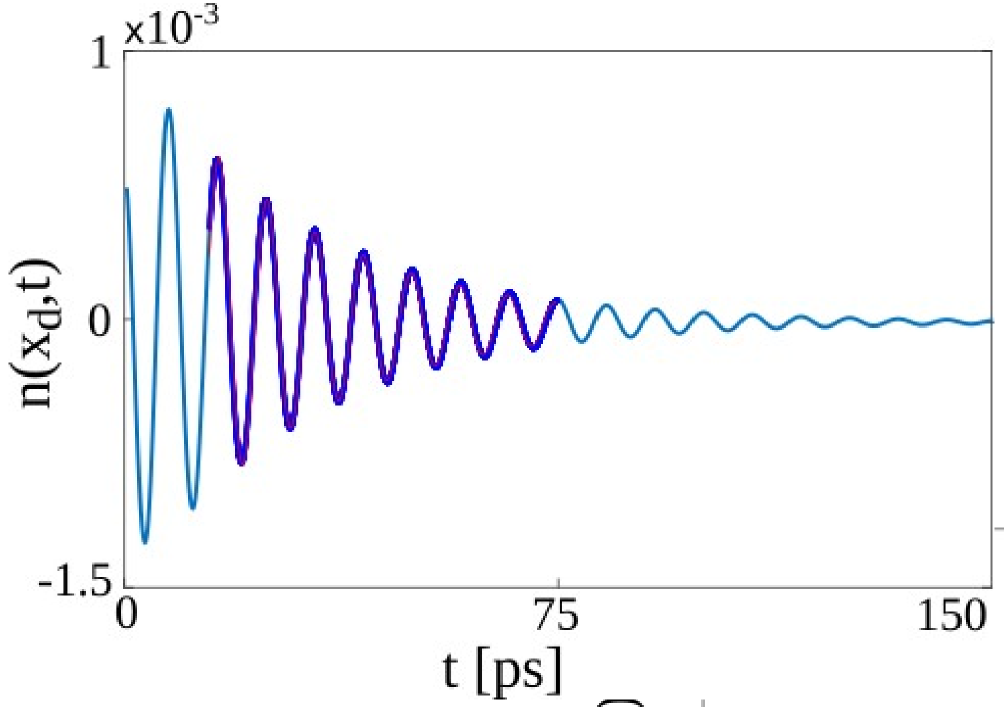


Ringdown = excitation of a quasi-normal mode



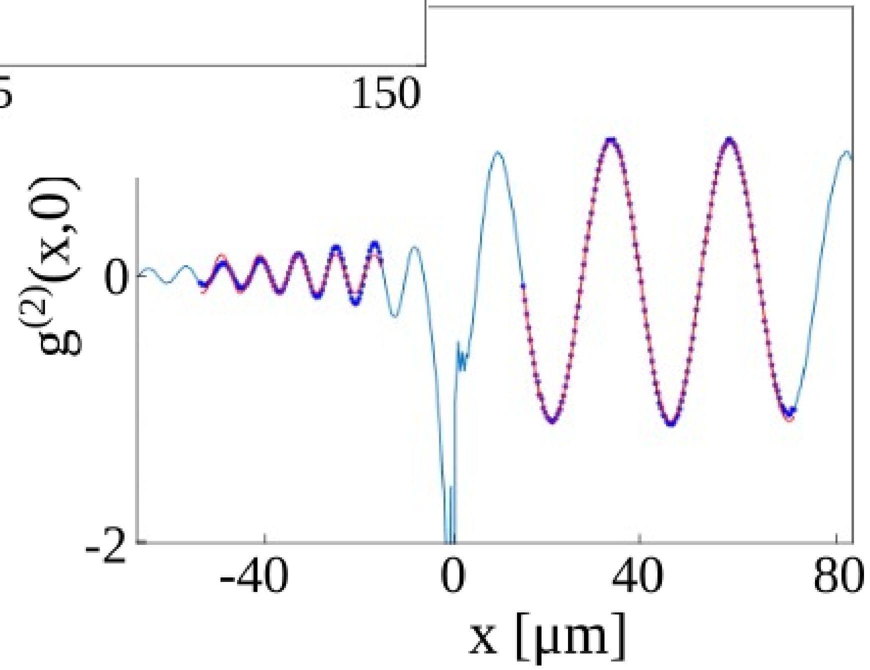
$\mathrm{Re}(\omega)$ Frequency of oscillation
$\mathrm{Im}(\omega)$ Decay rate approx γ (bare polariton lifetime)

Scattering of vacuum fluctuations: excitation of a quasi normal mode



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

→ excitation of a quasi-normal mode



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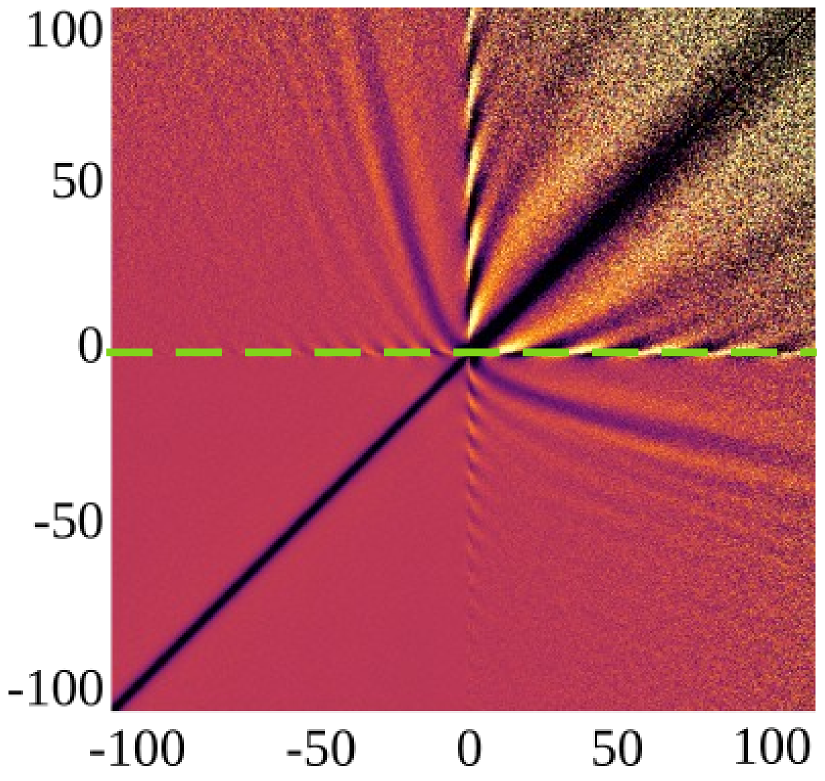


The story is not finished

Modulation of Hawking spectrum? Yes: greybody factor

(effect of local gravitational field)

But quantum fluctuations of QNMs?

Classical aspects (related to area quantisation): Hod PRL **81** 4293 (1998) and Maggiore PRL **100** 141301 (2008)

Generic effect of fields on curved geometries

→ black holes?

→ entropy?

→ gravity?

i.e. beyond Klein-Gordon fields/linearised excitations-perturbations

What can we learn from analogue quantum simulation of field phenomena?

The story is not finished

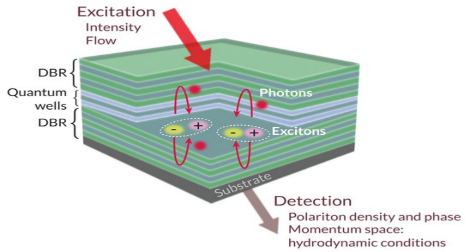
Get in touch: maxime.jacquet@lkb.upmc.fr

Analogue gravity: study of Klein-Gordon fields on effectively curved spacetimes

Foundational papers: Unruh PRL **46** 1351 (1981) and Visser Class Quant Grav **15** 1767 (1998)

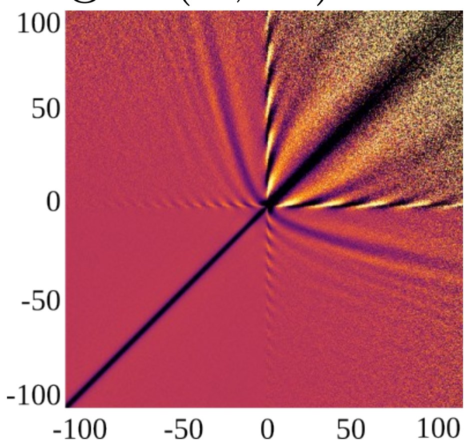
Recent paper on observation of light ring oscillations: Torres PRL **125** 011301 (2020)

Hawking effect in driven-dissipative quantum fluid of polaritons



Nguyen HS *et al.*, PRL **114** 036402 (2015)
Jacquet *et al.*, EPJD **76** 152 (2022)

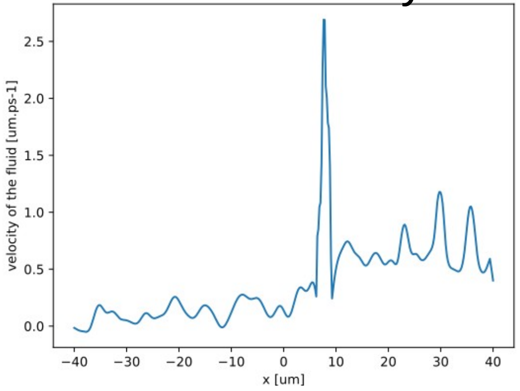
$g^{(2)}(x,x')-1$



New effects: quantum vacuum excitation of quasi-normal mode of the field
→ modulation of Hawking effect

Jacquet *et al.*, arxiv:2110.14452

Fluid velocity

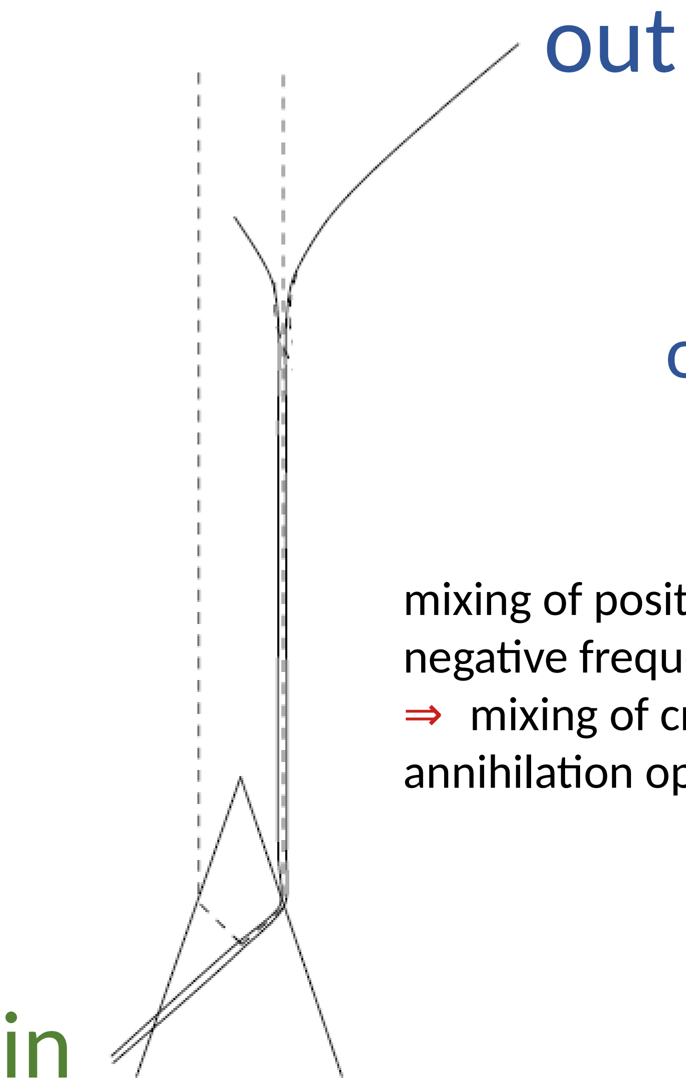


System configuration controlled optically, detection of photons at the output

Jacquet *et al.*, Phil Trans Roy Soc A **378** 20190225 (2020)
Carusotto and Ciuti RMP **85** 299 (2013)

Preliminary experimental data

Quantum field theory near black holes



positive frequency wave

negative frequency wave

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

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

Express out modes in terms of in modes: $F_\omega = \int d\omega' \left(\alpha_{\omega\omega'} f_{\omega'} + \beta_{\omega\omega'} f_{\omega'}^*\right)$

$\Rightarrow |\bar{0}\rangle \neq |0\rangle$

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

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

Spontaneous emission from the vacuum!

Black hole ⇒ Hawking radiation

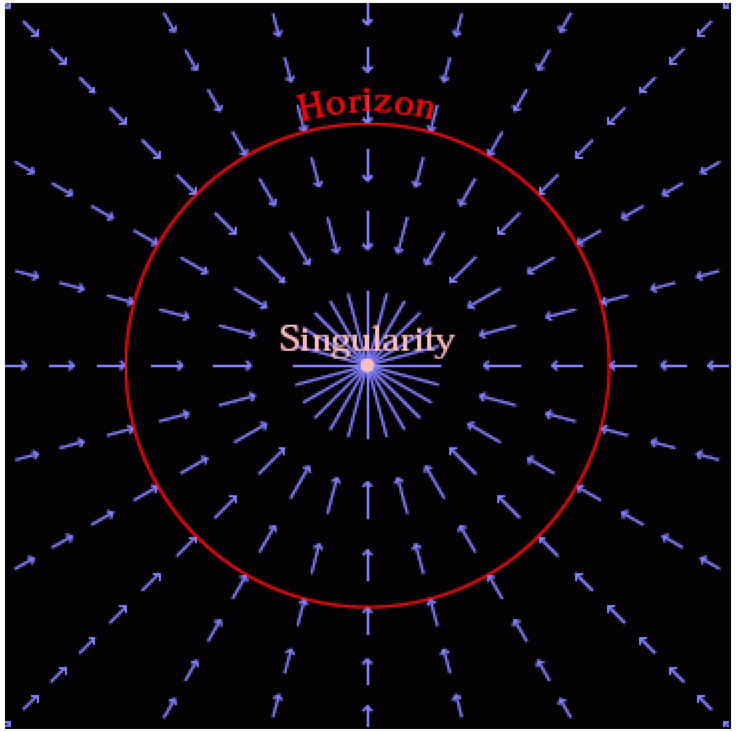
$\omega_{in} \approx e^{\kappa t} \omega_{out}$

surface gravity of the black hole

There exist other regimes of spacetime curvature, *eg*, in analogue gravity!

Universality of the Hawking effect, Unruh and Schützhold (2005)?

Analogy: the questions it raises



- Lorentzian manifolds without gravity
- Kinematics and dynamics in GR? (*eg* connection to Einstein's equations)
- Connections and differences between Lorentzian geometry, equivalence principle and GR
- What has to do with gravity *per se*?
  - Classical features (space-time curvature, horizons)
  - Semiclassical features (spontaneous emission from the vacuum)

$$g^{\mu\nu}_{PG} = \begin{pmatrix} -1 & -\beta \\ -\beta & \left(c^2 - \beta^2\right) \end{pmatrix}$$

– speed of light
– flow velocity of space

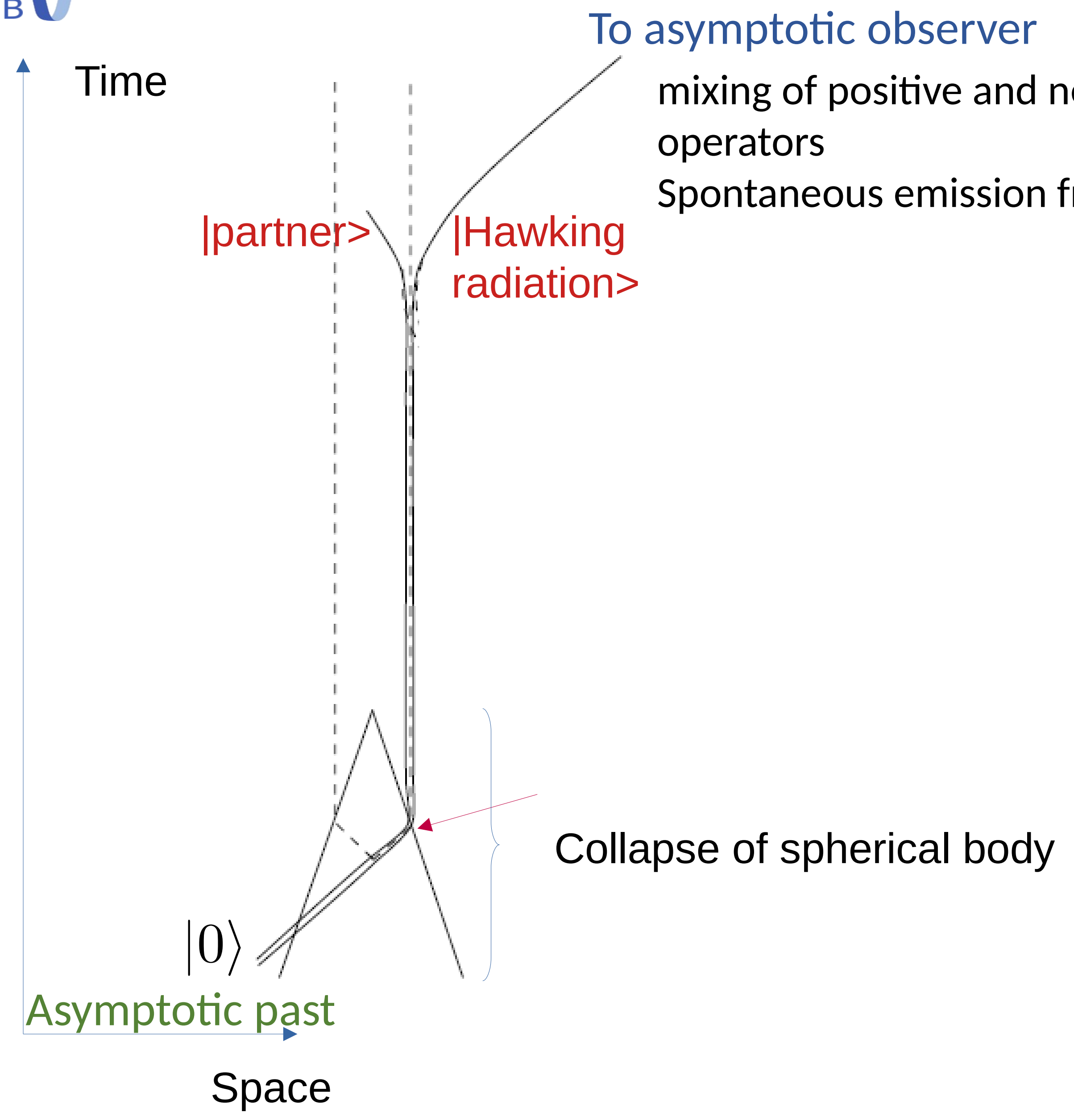
$$g^{\mu\nu}_{Unruh} = \begin{pmatrix} -1 & -v \\ -v & \left(c^2 - v^2\right) \end{pmatrix}$$

– speed of sound in fluid
– flow velocity of fluid

Can we simulate the Hawking effect? Can this confirm Hawking's theory?

Visser *et al* (2002), Barceló *et* al (2004), Dardashi *et al* (2017)

The Hawking effect

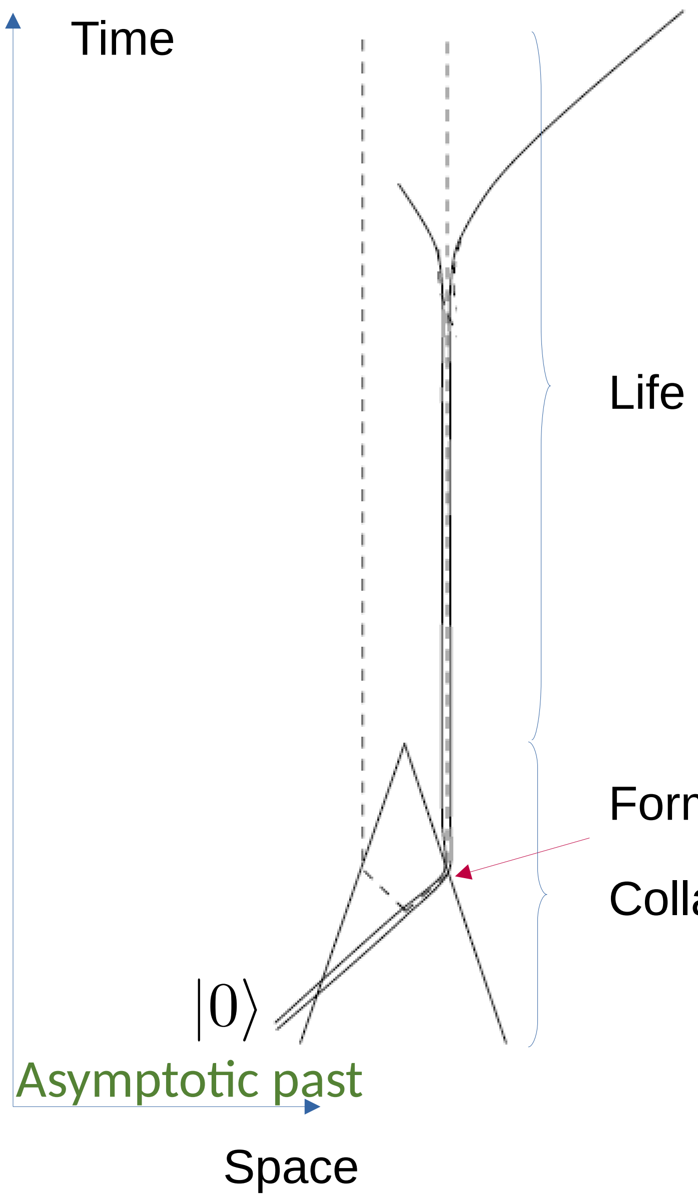


mixing of positive and negative frequency waves ⇒ mixing of creation and annihilation operators

Spontaneous emission from the vacuum. Black hole ⇒ Hawking effect

$$k_B T = \frac{\hbar \alpha}{2\pi c} = \frac{\hbar c^3}{8\pi G M}$$

Perturbation of black hole



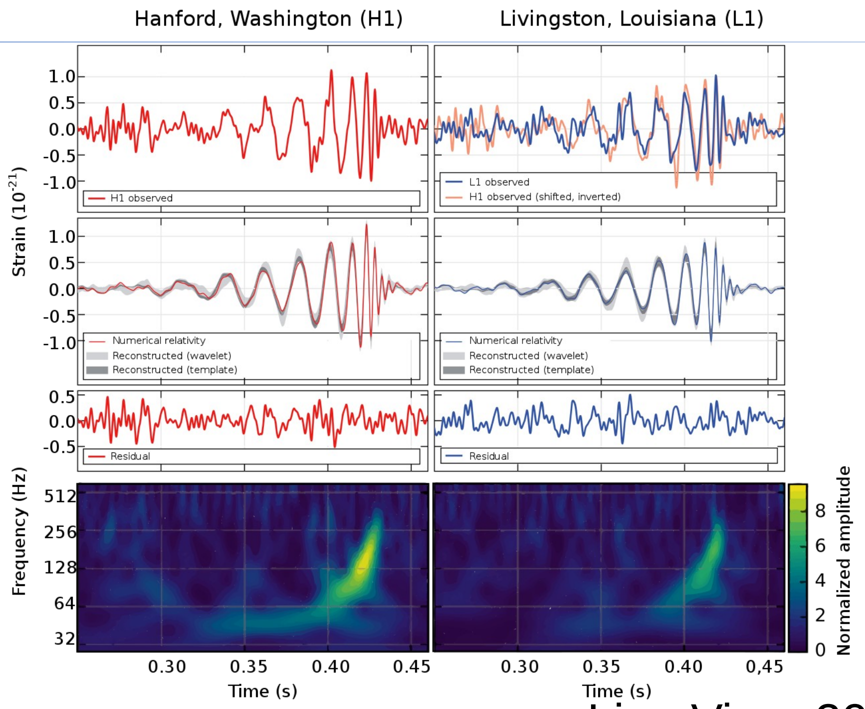
Life of a Schwarzschild black hole

if perturbed by large amplitude object, relaxation by gravitational waves

Quasi-normal mode of the gravitational field

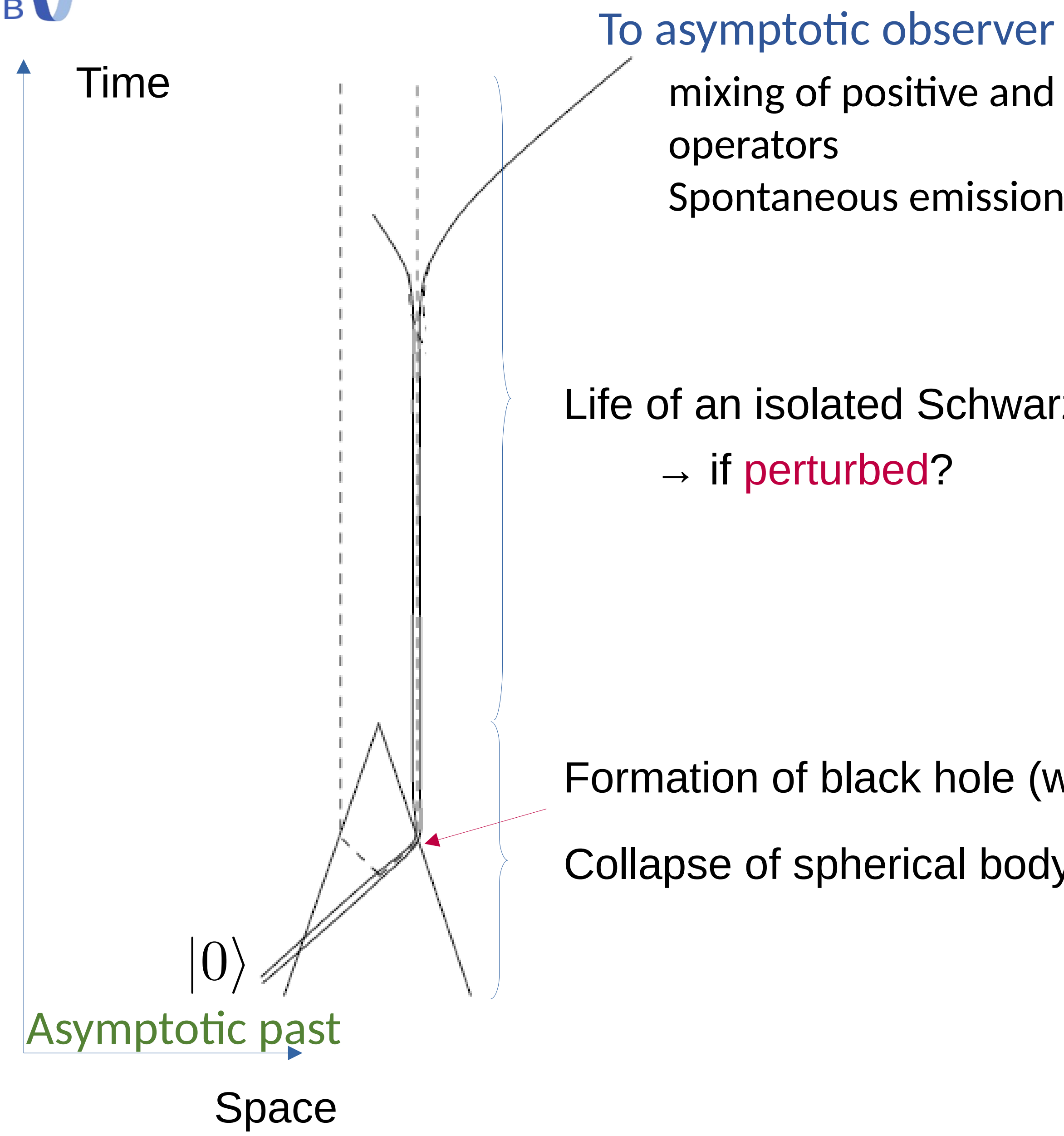
Formation of black hole (wobble, relaxation by gravitational waves)

Collapse of spherical body



Ligo Virgo 2016

Perturbation of black hole



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

Spontaneous emission from the vacuum. Black hole ⇒ Hawking radiation

Life of an isolated Schwarzschild black hole

→ if perturbed?

Effect of local gravitational field on HR

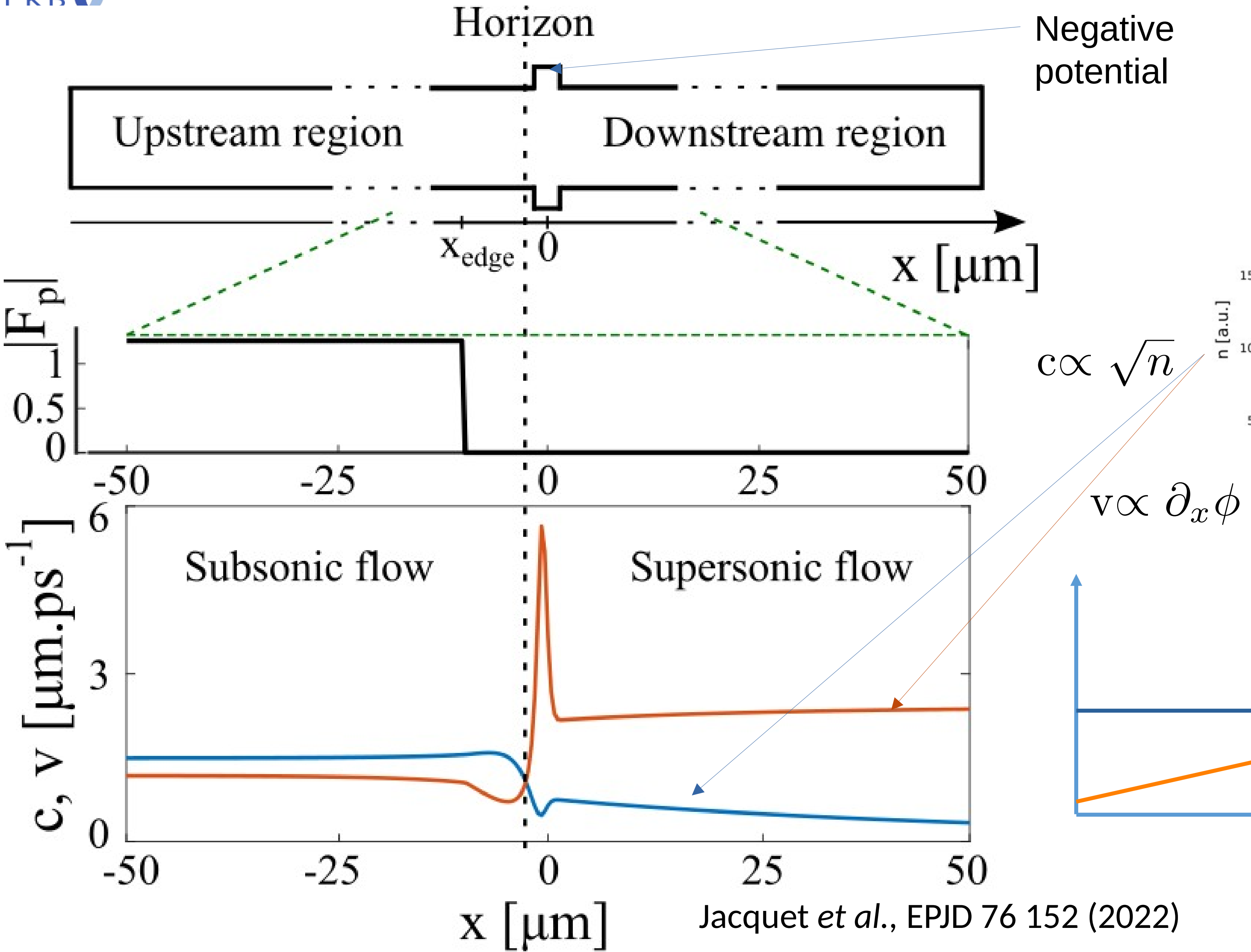
York PRD **28** 2929 1983

Hod PRL **81** 4293 1998

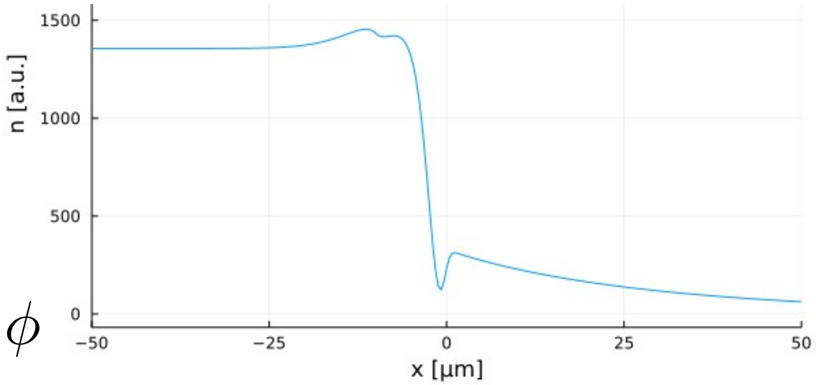
Formation of black hole (wobble, relaxation by gravitational waves)

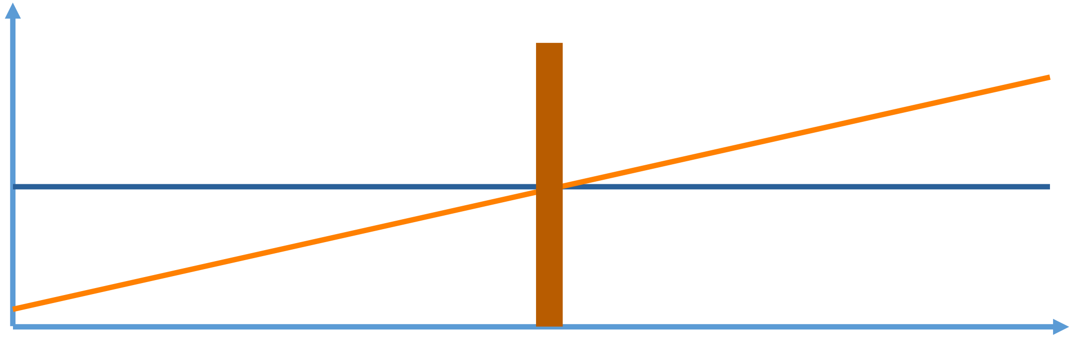
Collapse of spherical body

Acoustic horizon in polaritons



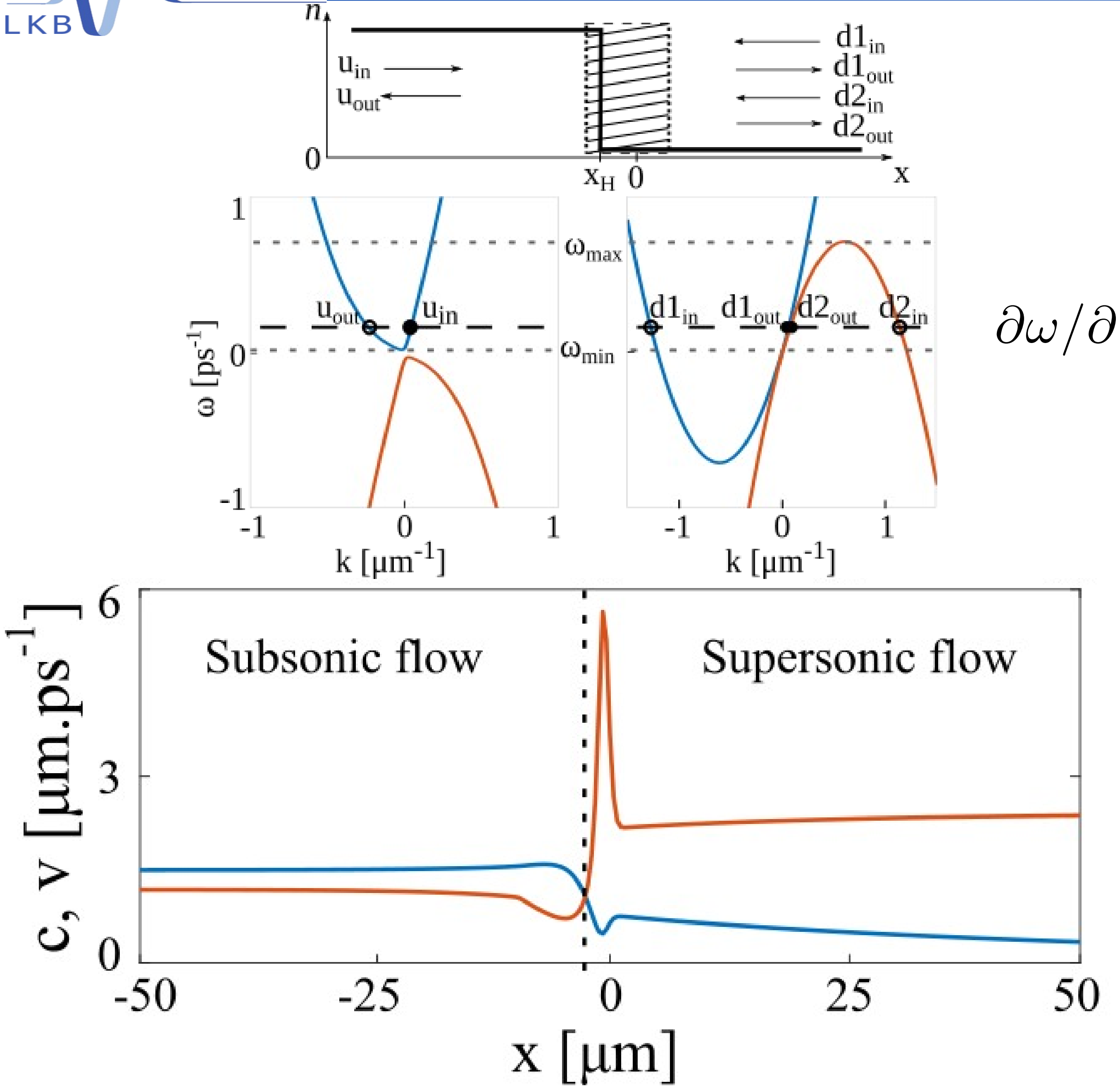
Simulate sample of Nguyen HS *et al.*, PRL 114 036402 (2015)





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