Hydrodynamical black holes
in theory and in practice

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Analogue Gravity in 2026
Centro de Ciencias Pedro Pascuale, Benasque

13 January 2026

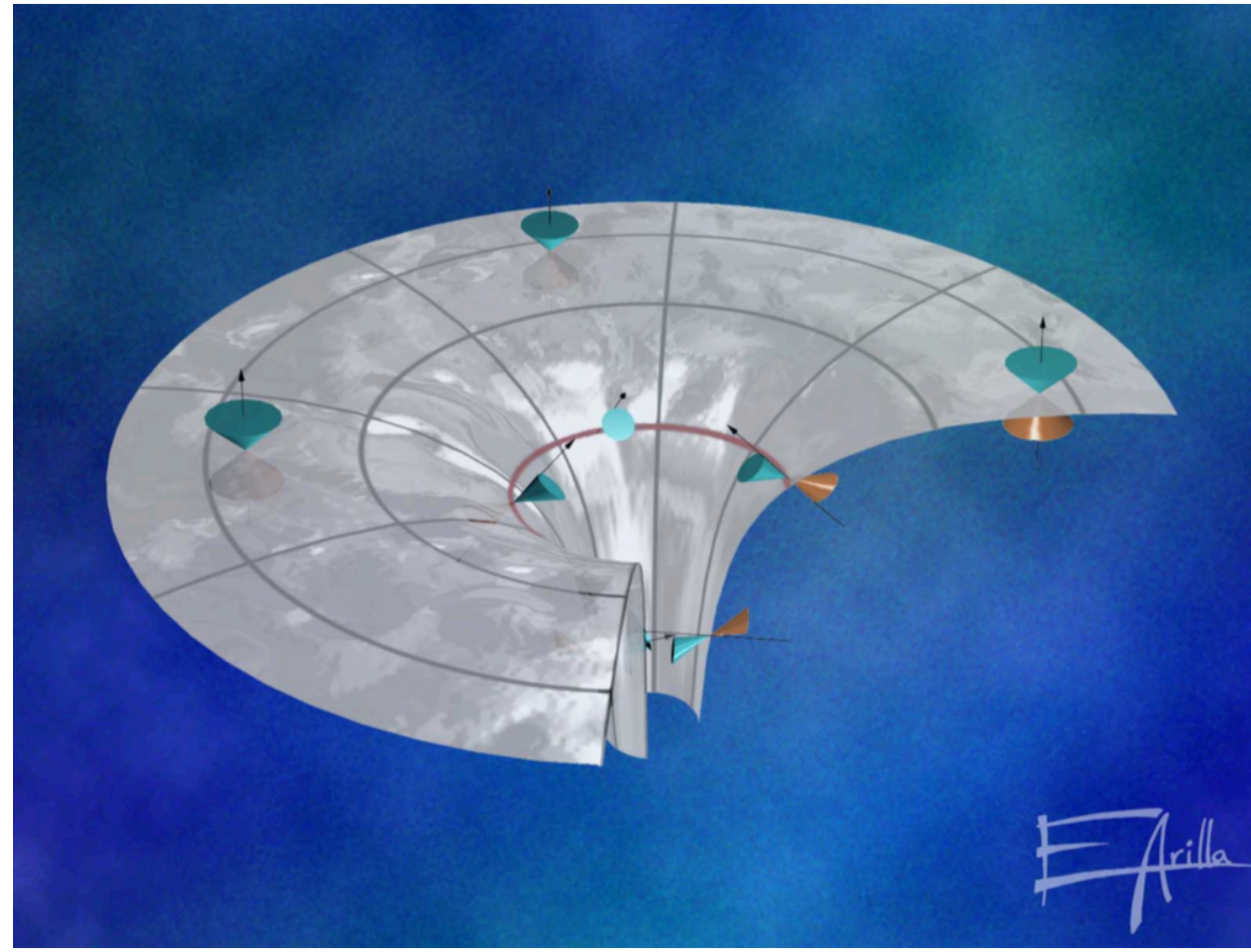
Outline

- Introduction
- Theoretical overview of Analogue Gravity (**much** revision!)
- Water wave analogy
- Experiments with water waves (in **1D transcritical flows**)
- Conclusions

Context and motivations

Black holes
- gravitational fields of very dense objects
- nothing can escape from beneath the event horizon

Fields in BH spacetime
- ***negative-energy states*** around BH
- allows e.g. Penrose process (Penrose, 1971)



Picture courtesy of Enrique Arilla

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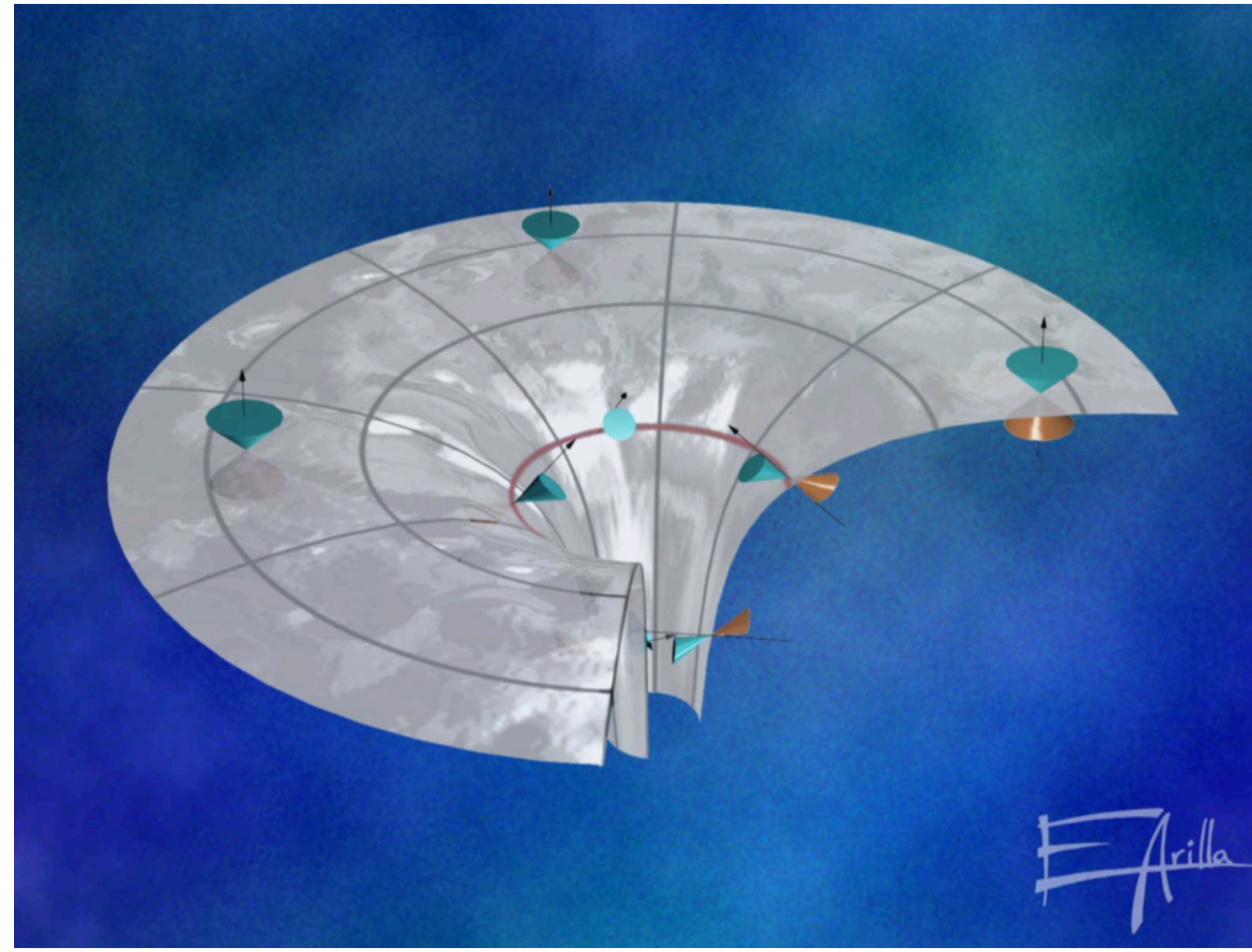
Black hole thermodynamics
- obey analogues of thermodynamical laws, with temp. prop. to surface gravity (Bekenstein, 1972)
- QFT in BH spacetime gives thermal emission with correct temp. dependence (Hawking, 1974)



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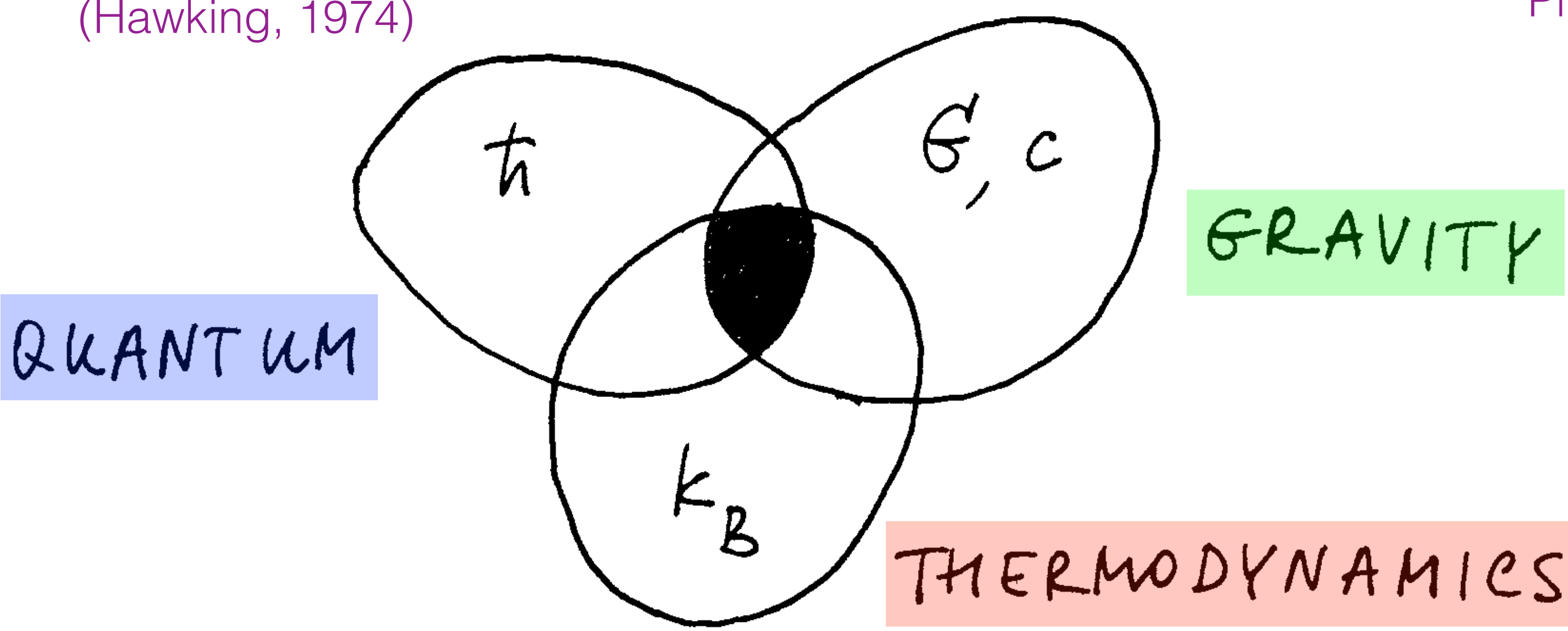


Picture courtesy of Ulf Leonhardt

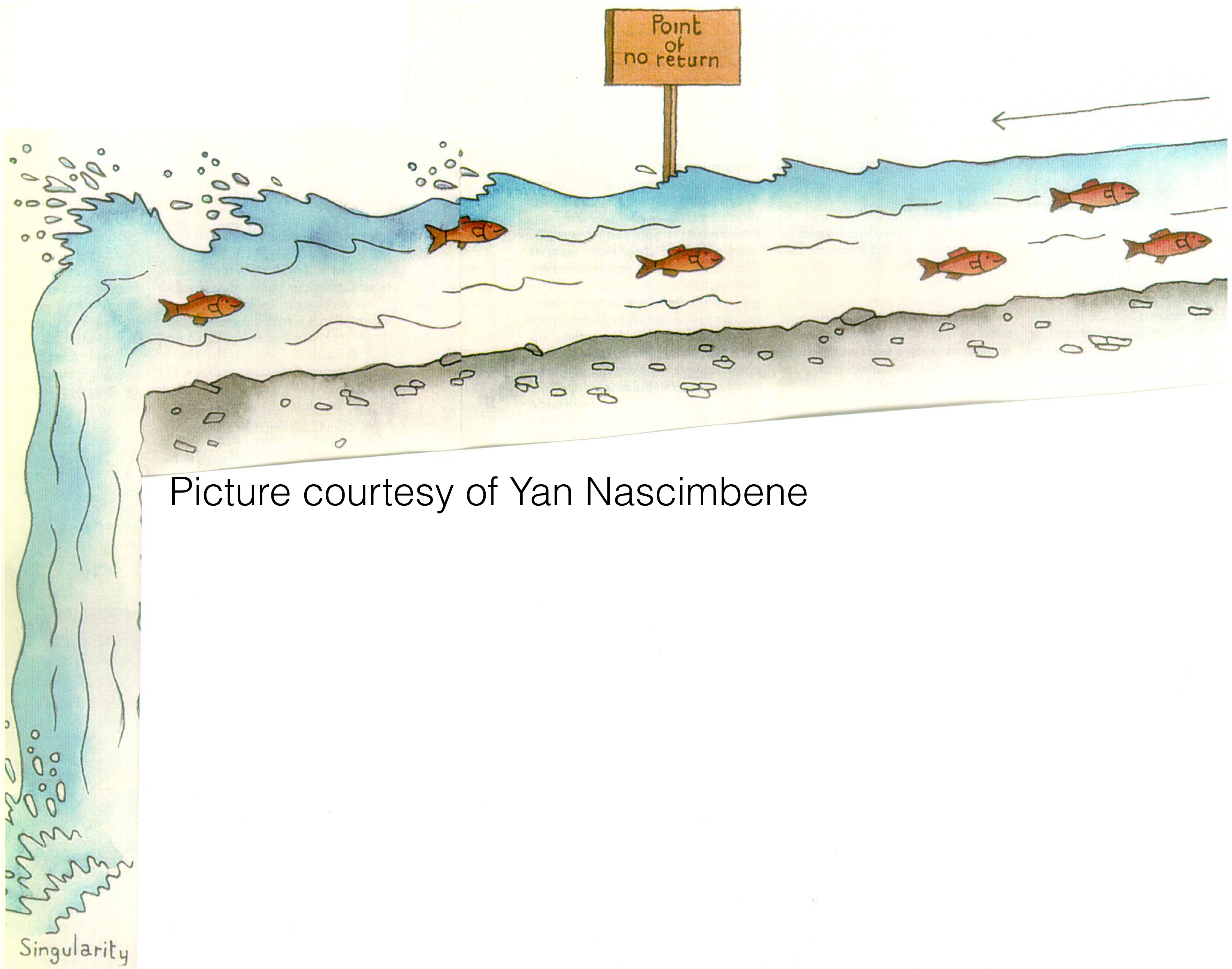
$$k_B T = \frac{\hbar \kappa}{2\pi}$$

where

$$\kappa = \frac{g}{c} = \frac{c^3}{4GM} = \frac{c}{2r_S}$$

Analogue black holes

Unruh (1981): • **waves in moving media** behave as if in curved spacetime



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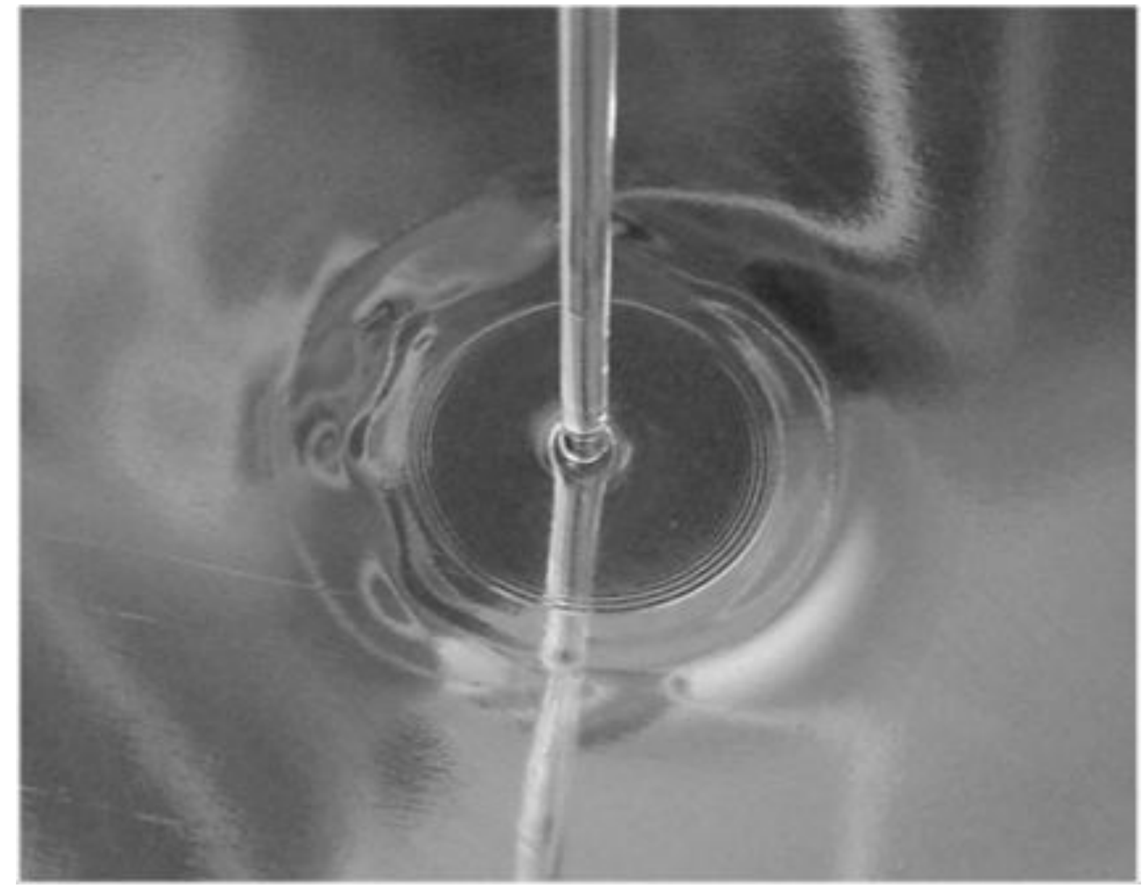

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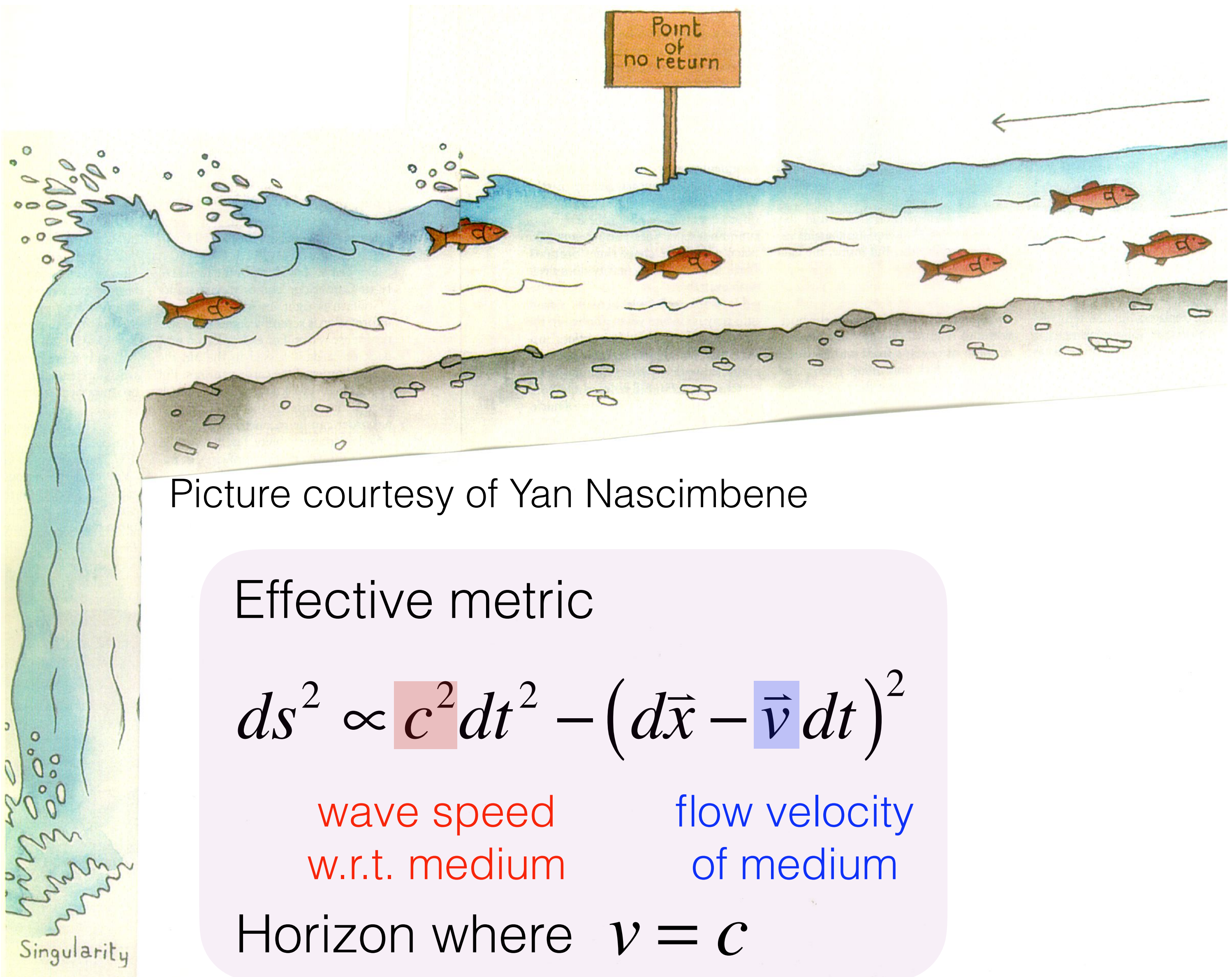


Picture courtesy of Yan Nascimbene

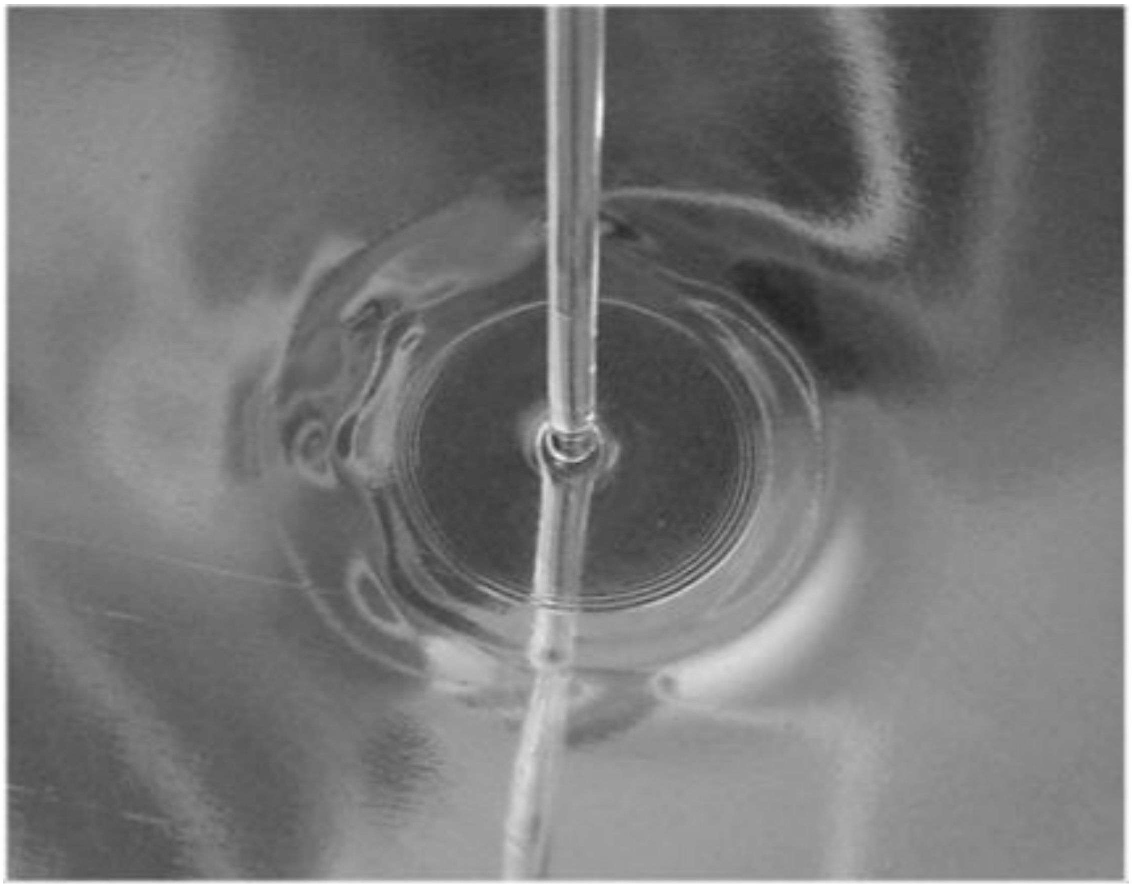
Effective metric

$$ds^2 \propto c^2 dt^2 - \left(d\vec{x} - \vec{v}\,dt\right)^2$$

wave speed w.r.t. medium

flow velocity of medium

Horizon where $v = c$



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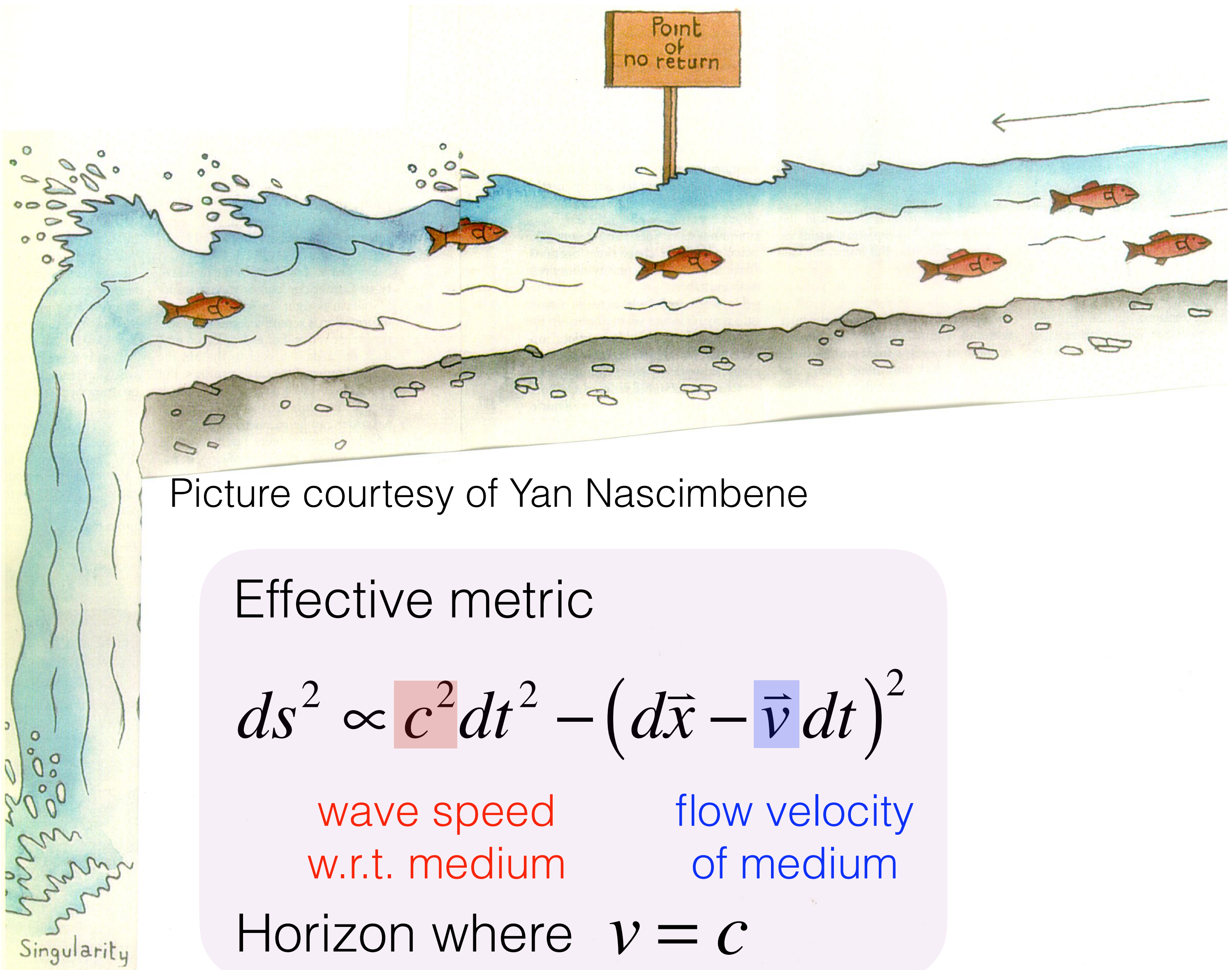

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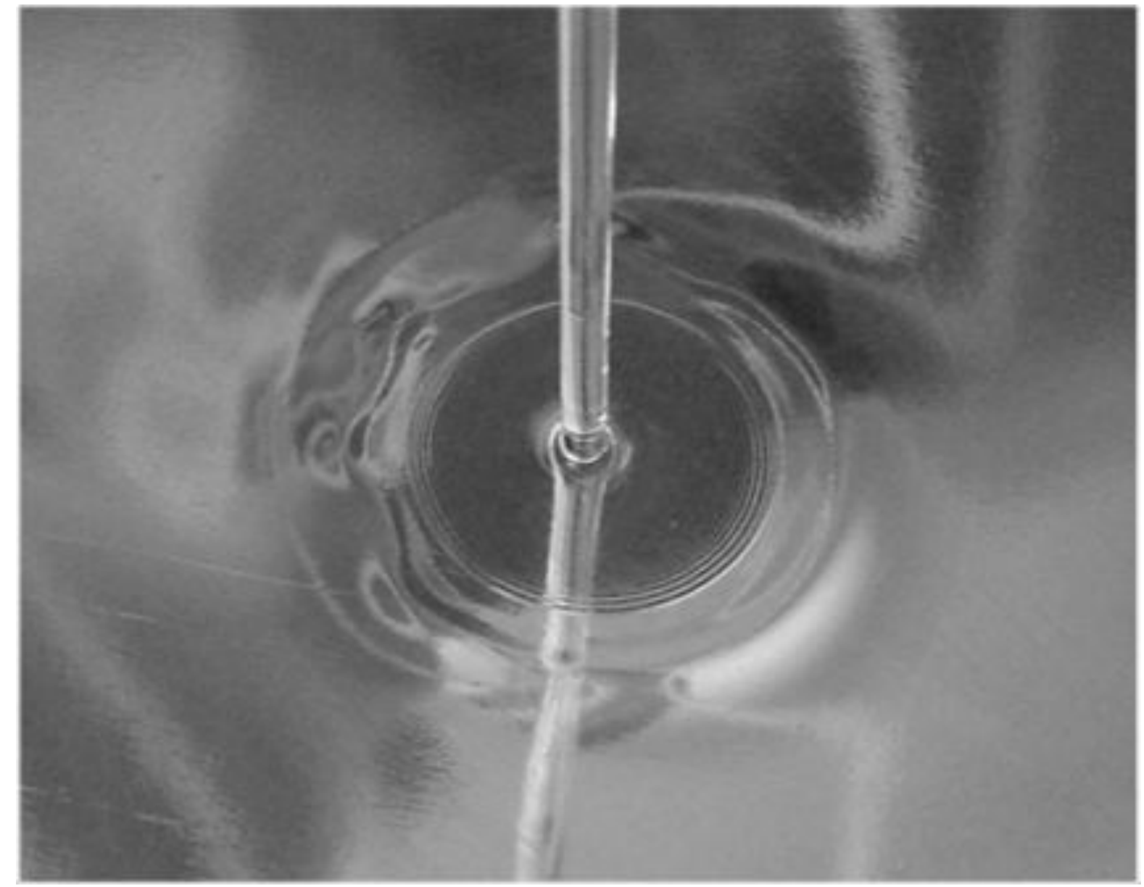
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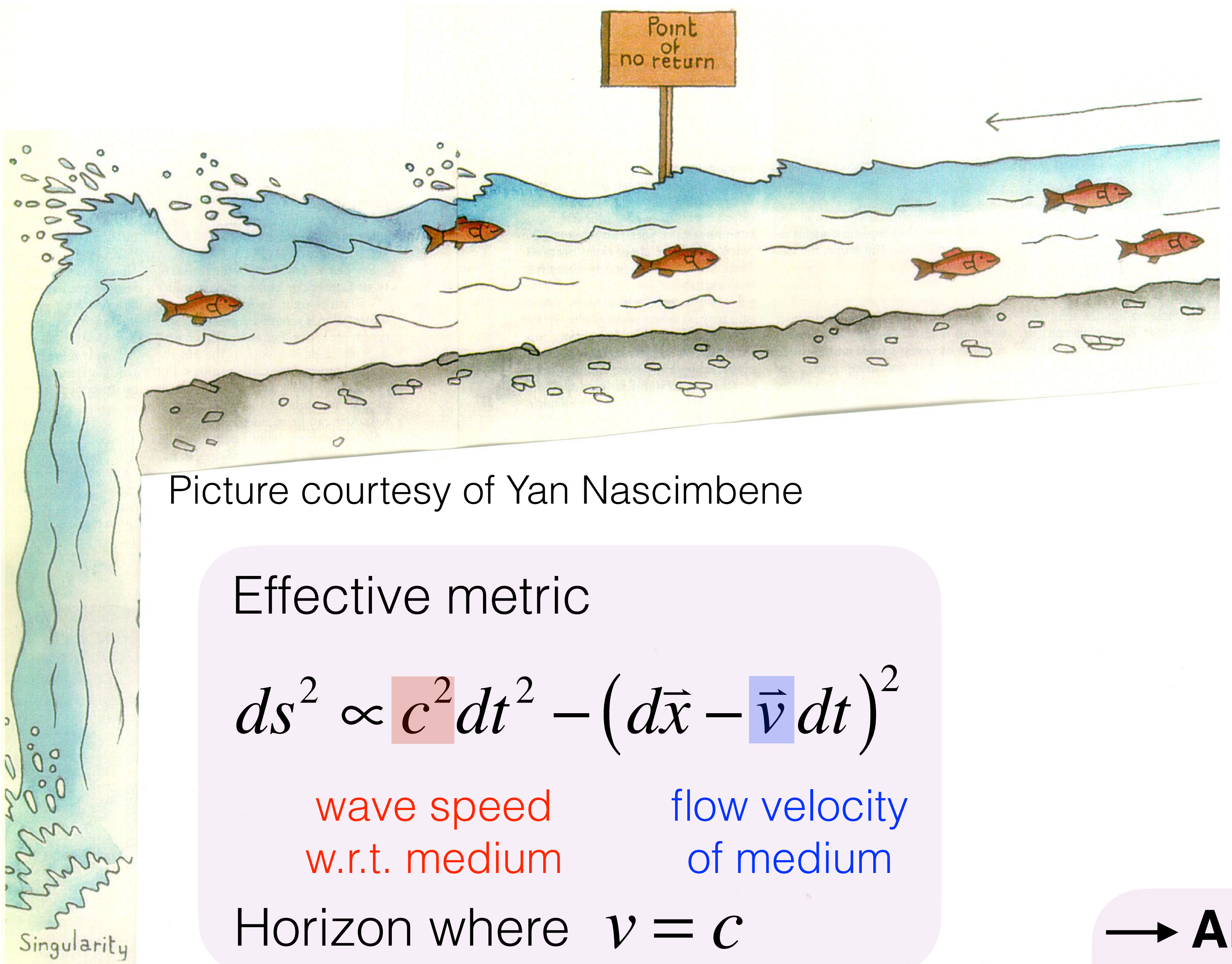
Horizon where $v = c$

Schwarzschild in Painlevé-Gullstrand coords:

$$ds^2 = c^2 dt^2 - \left(dr + \sqrt{\frac{r_S}{r}}\,c\,dt\right)^2 - r^2 d\Omega^2$$

Analogue black holes

Unruh (1981):
- **waves in moving media** behave as if in curved spacetime
- **Hawking's prediction of thermal emission** should apply



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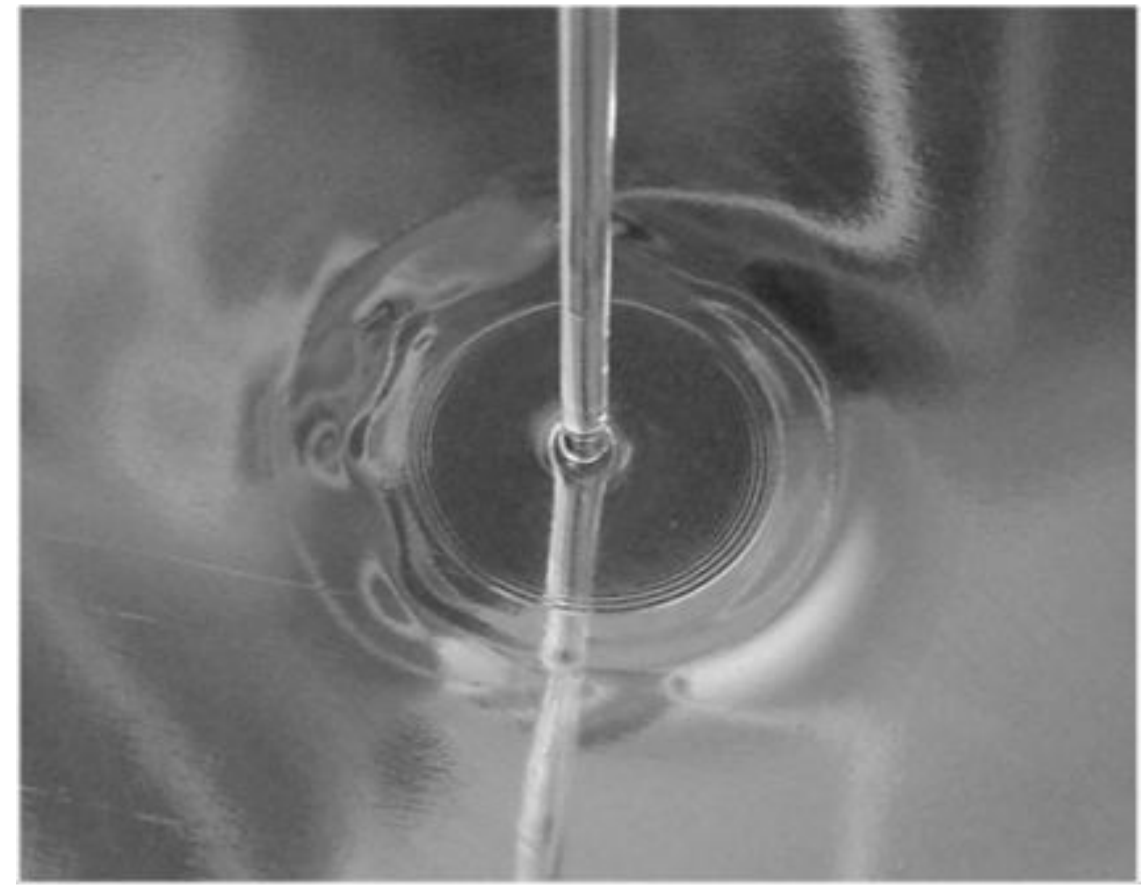
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⟶ **Analogue Hawking effect**
waves emitted as thermal spectrum

$$k_B T = \frac{\hbar\kappa}{2\pi} \quad \text{where} \quad \kappa = \left.\frac{d(v-c)}{dx}\right|_{\text{hor.}}$$

Wave scattering at a black hole

Waves are solutions of dispersion relation: $\omega - vk = \pm ck$ (Doppler shift)

co-moving frequency $\longrightarrow$ **sign of norm**

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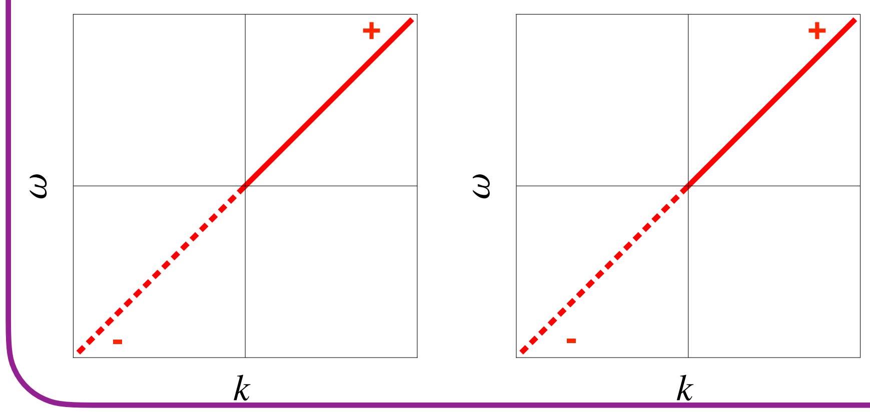

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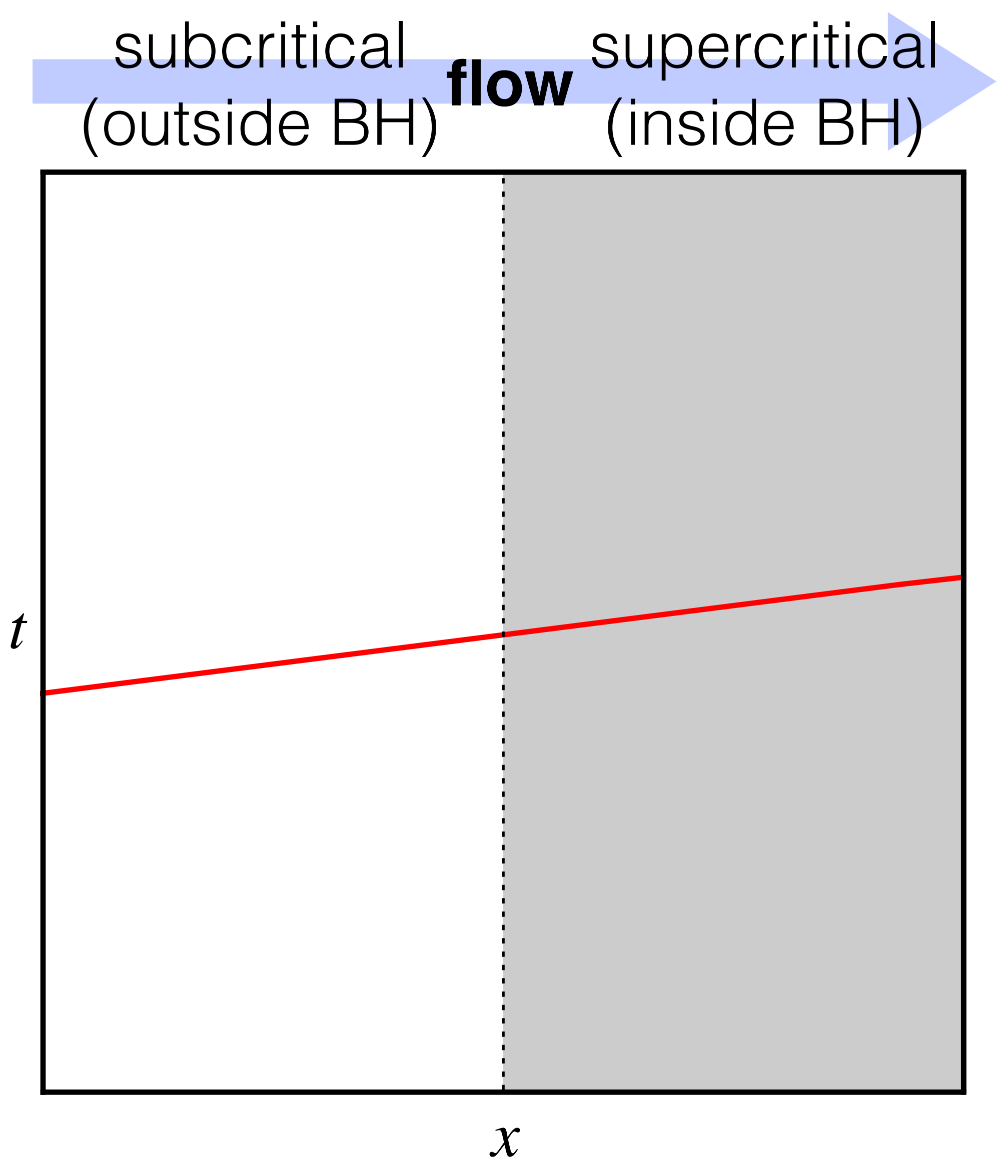
  — experience nothing special at horizon



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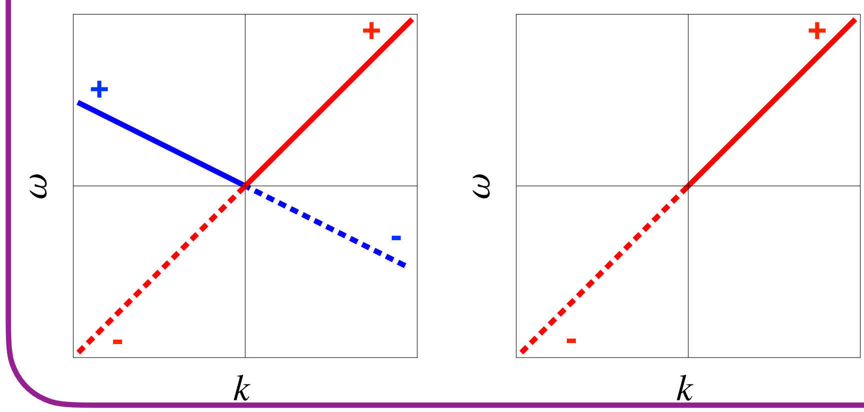

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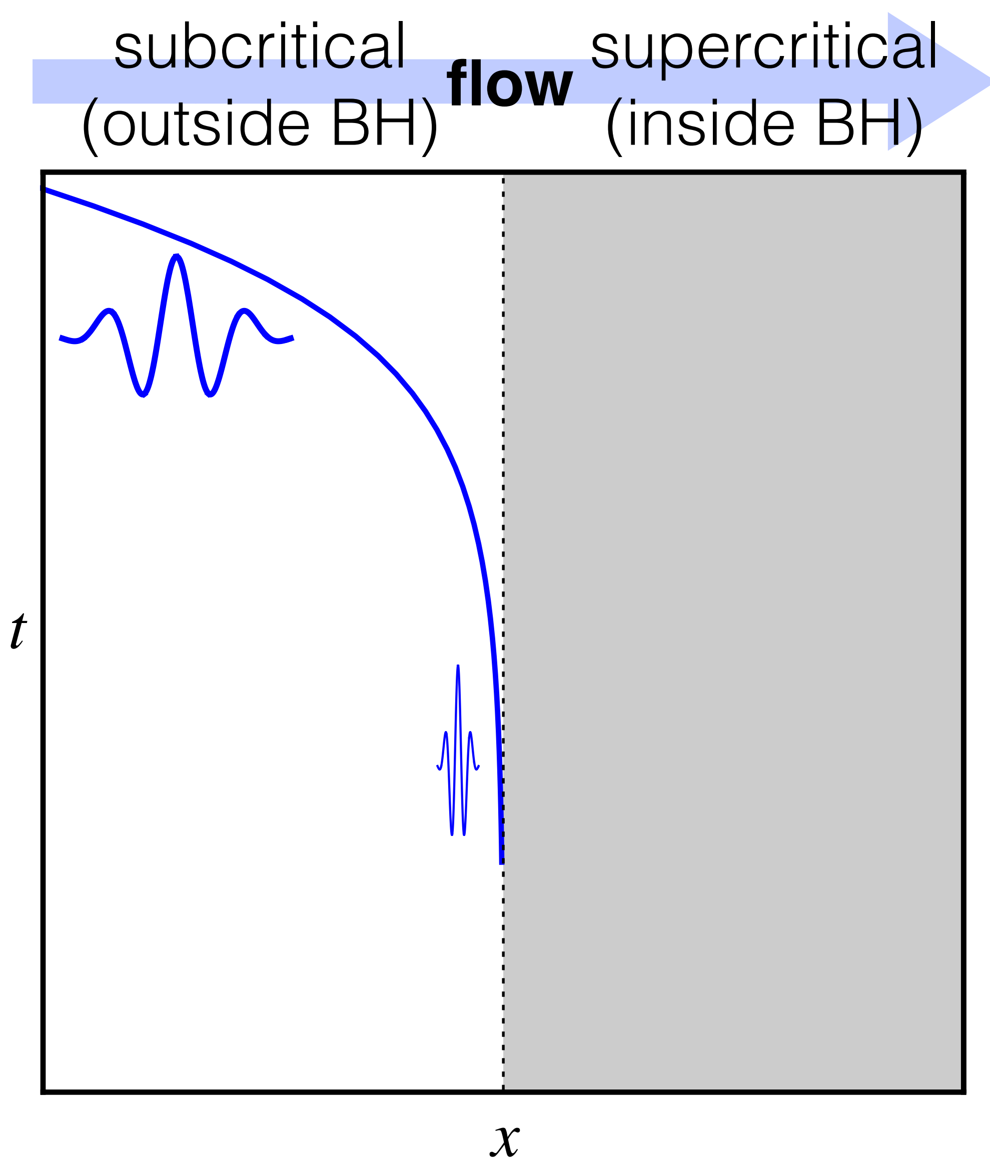
- counter-propagating waves



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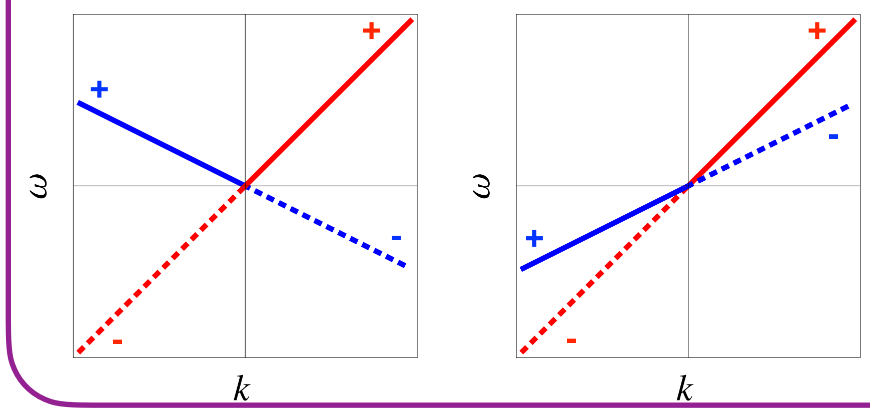

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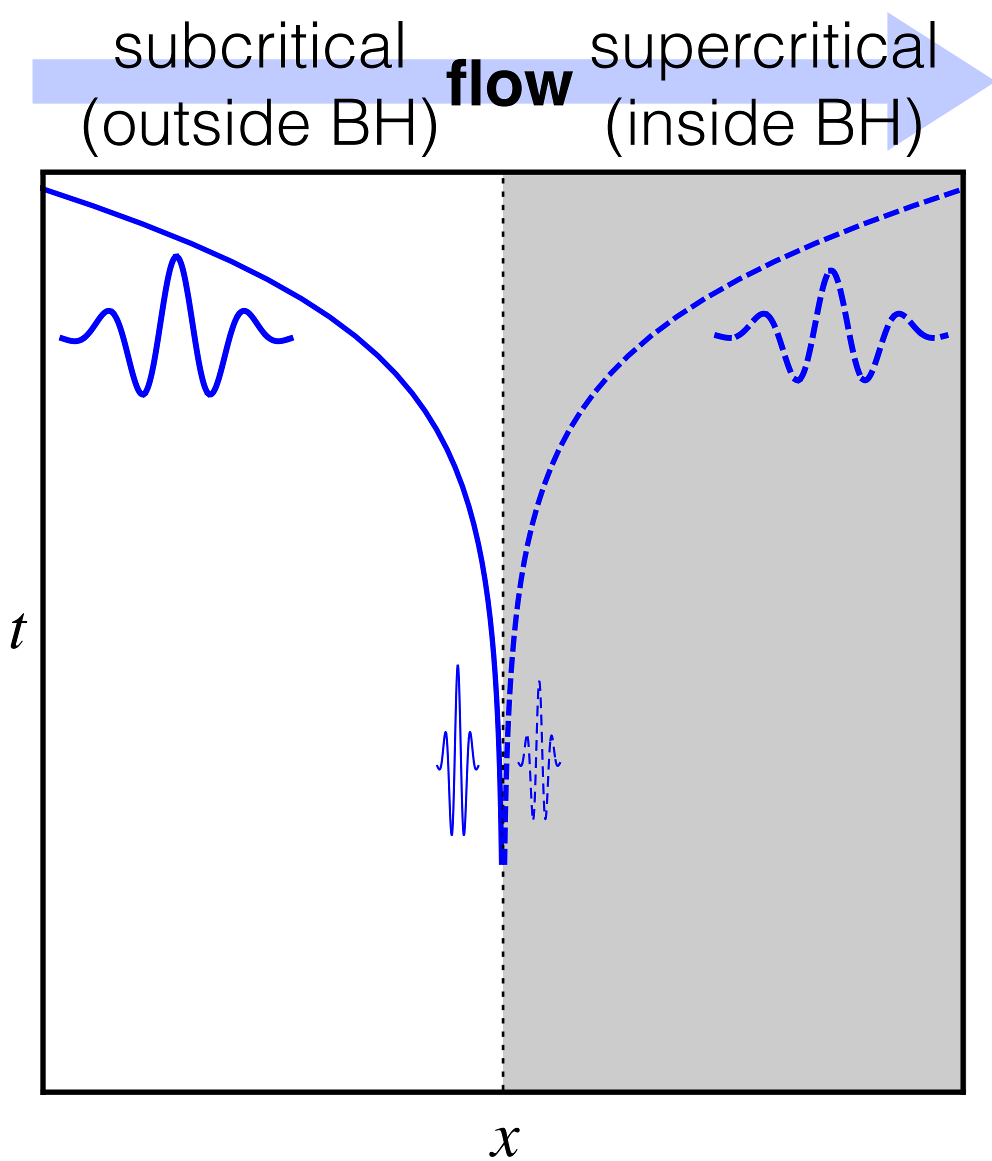
- counter-propagating waves
  — "split" into **two** separate modes of **opposite norm**



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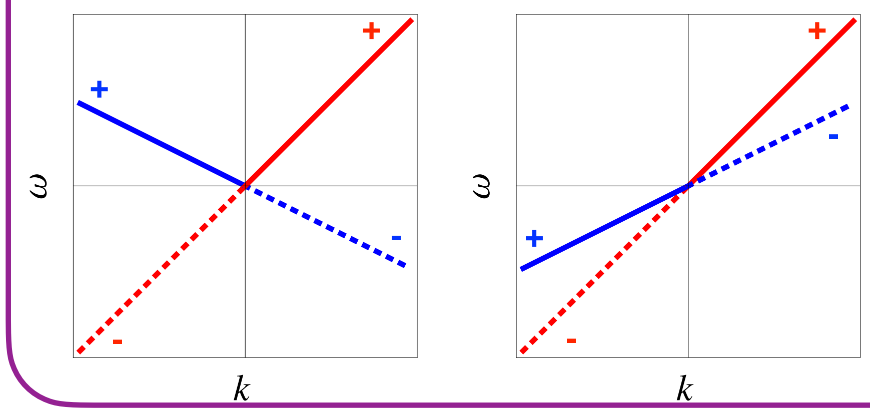

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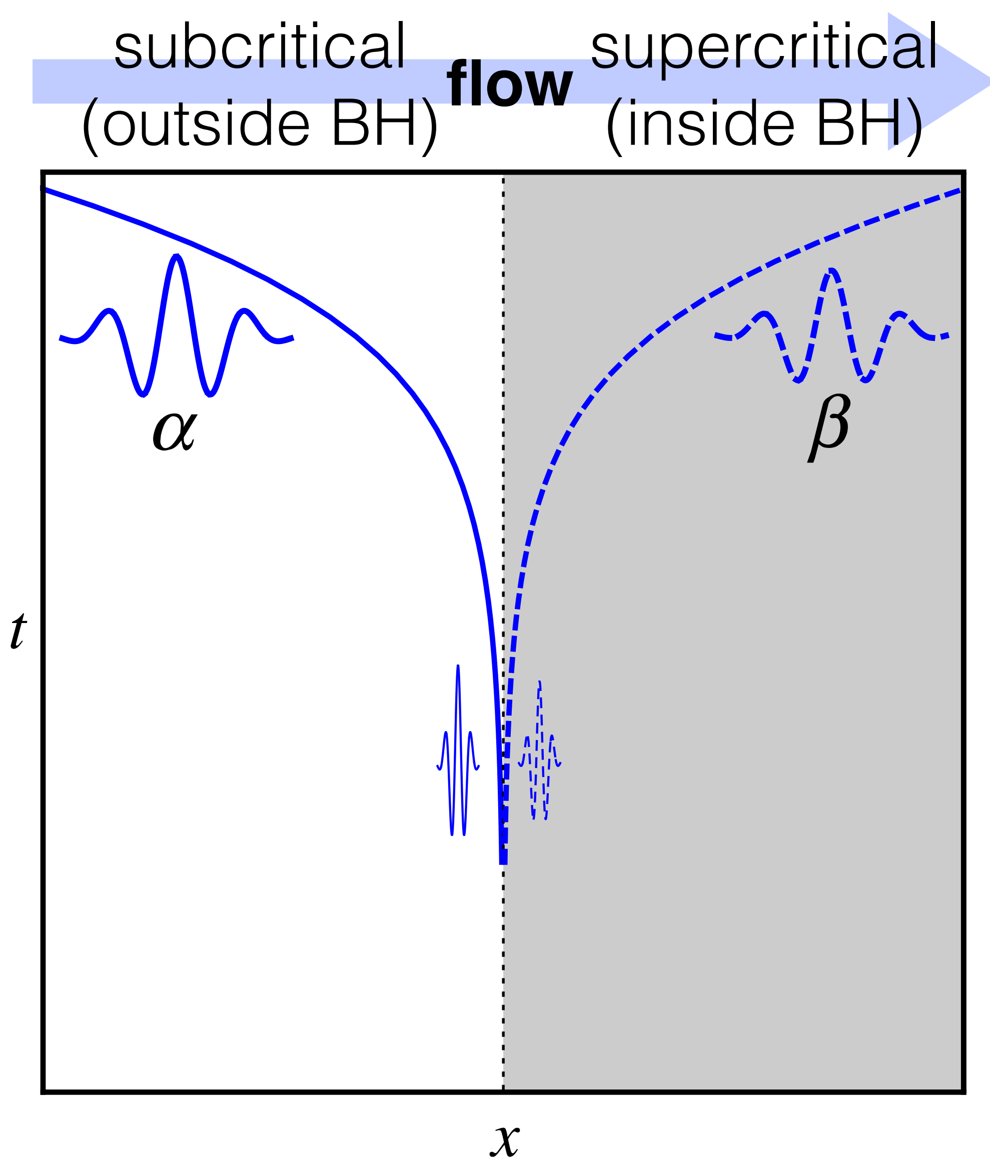

Allows **anomalous scattering**:

Incident mode of **positive norm** partially scatters into outgoing mode of **negative norm**

Must satisfy $\boxed{|\alpha|^2 - |\beta|^2 = 1}$ (unitarity relation)

But what is the initial or "ingoing" state?

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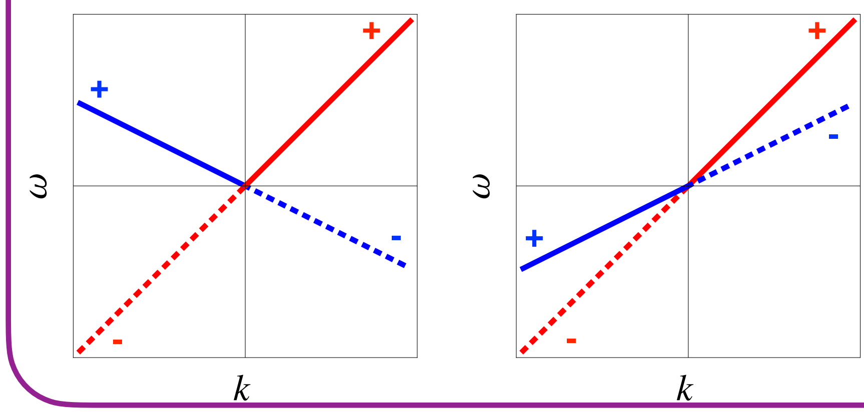

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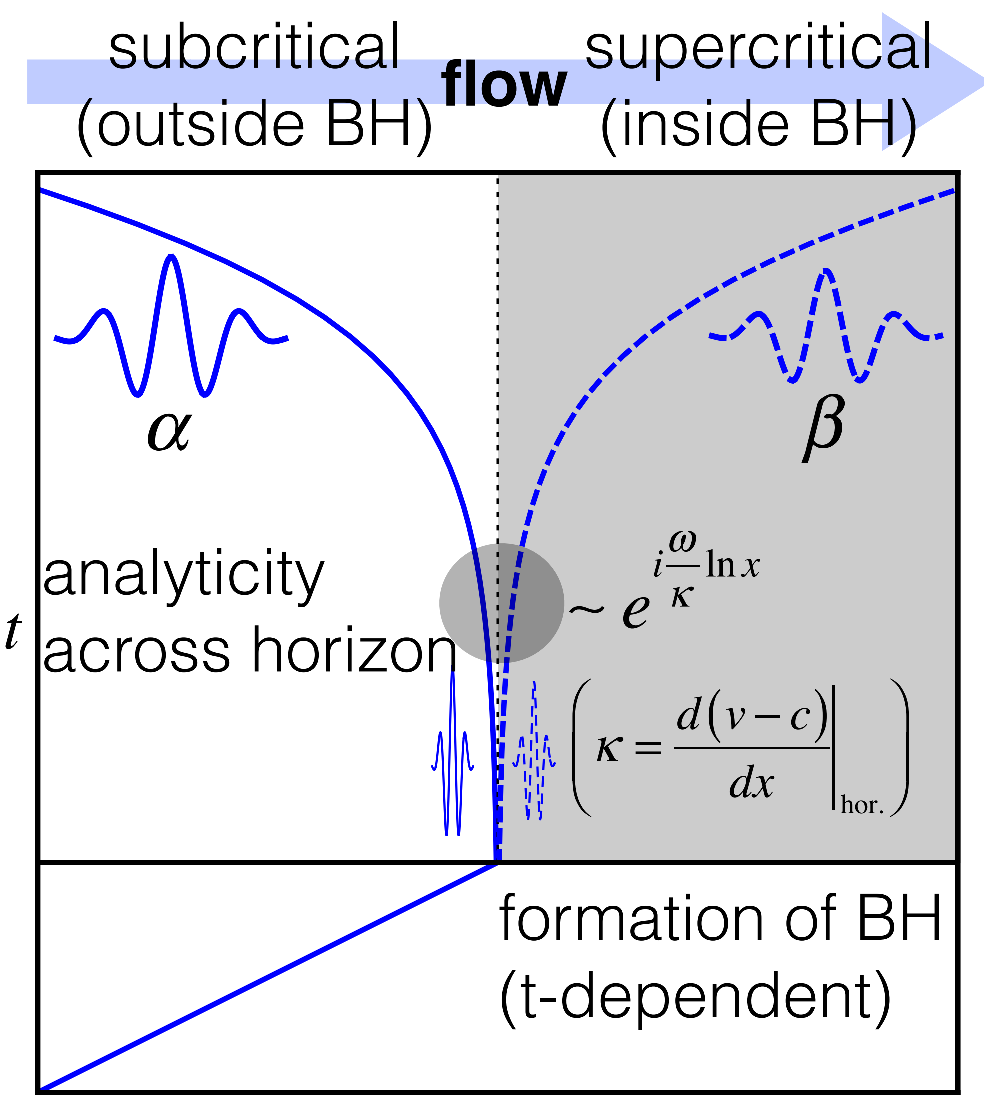

(Hawking '74)

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$$\left|\frac{\beta}{\alpha}\right|^2 = e^{-2\pi\frac{\omega}{\kappa}} \longrightarrow |\beta|^2 = \frac{1}{e^{2\pi\omega/\kappa} - 1}$$

Planck spectrum!

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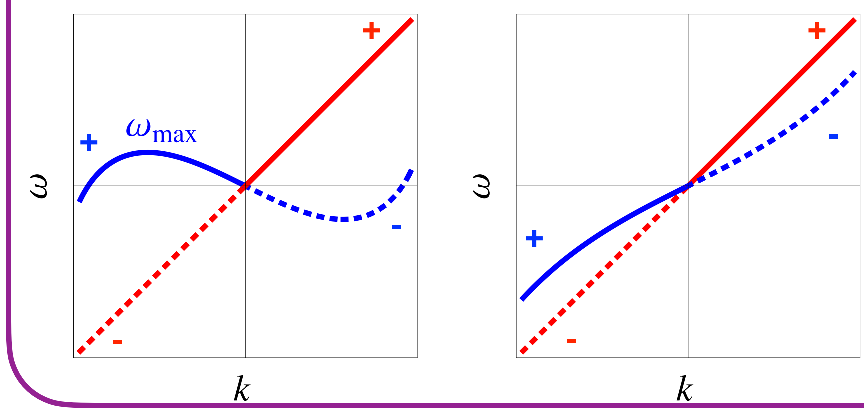

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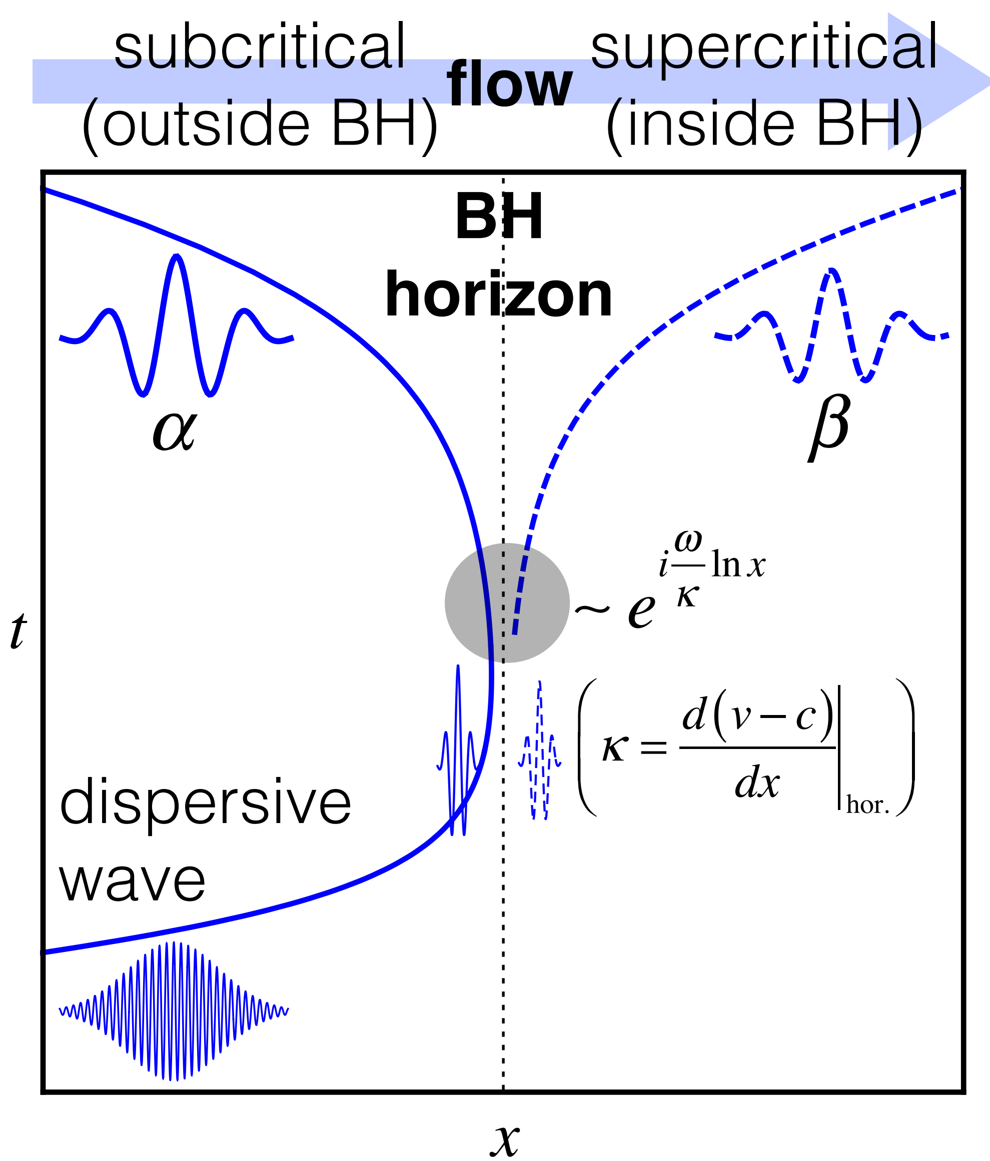

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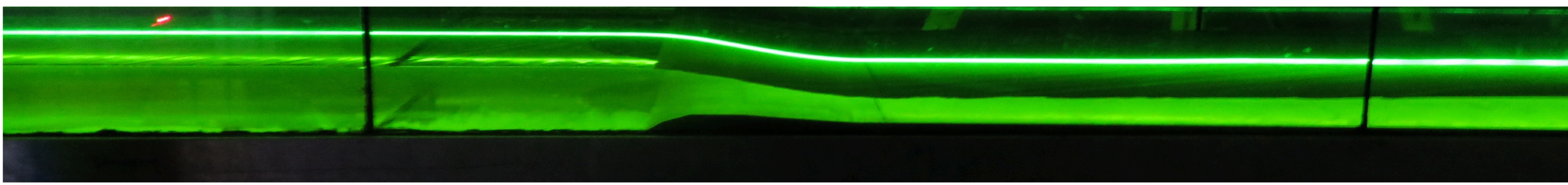
Planck spectrum!

Remains a good approximation when $\kappa \ll \omega_{\max}$

(Unruh '95, Brout *et al.* '95)

The water wave analogy

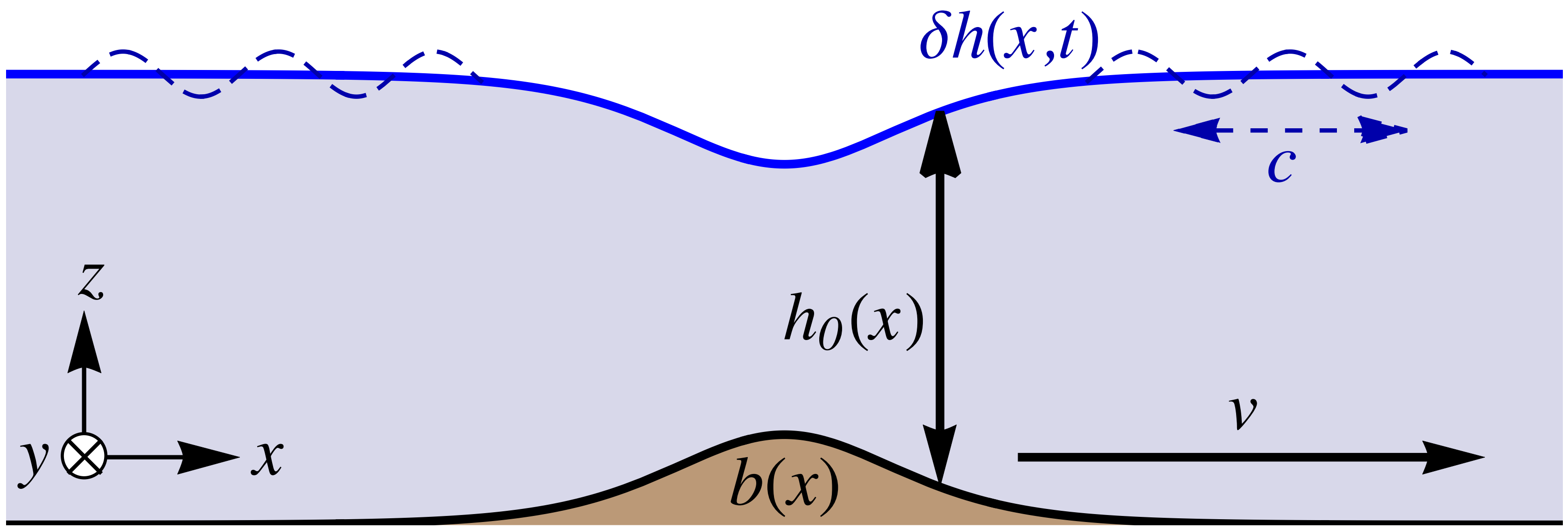


See, e.g.,

- R. Schützhold and W. G. Unruh, **'Gravity wave analogues of black holes'**, *Phys. Rev. D* **66**, 044019 (2002)
- **"Analogue Gravity Phenomenology: Analogue Spacetimes and Horizons, from Theory to Experiment"** (Springer International Publishing, Cham, 2013)

The water wave analogy

(Unruh and Schützhold, 2002)



Assumptions on flow:

- inviscid
- irrotational $\vec{v} = -\nabla\phi$
- surface close to flat
- no dependence on y
- ∂_z much larger than ∂_x

Mass conservation

$$\partial_t h + \partial_x \left(h\, v\right) = 0$$

Acceleration of fluid parcel (at free surface)

$$\partial_t v + \partial_x \left(\frac{1}{2} v^2 + g\, \left(h + b\right) \right) = 0$$

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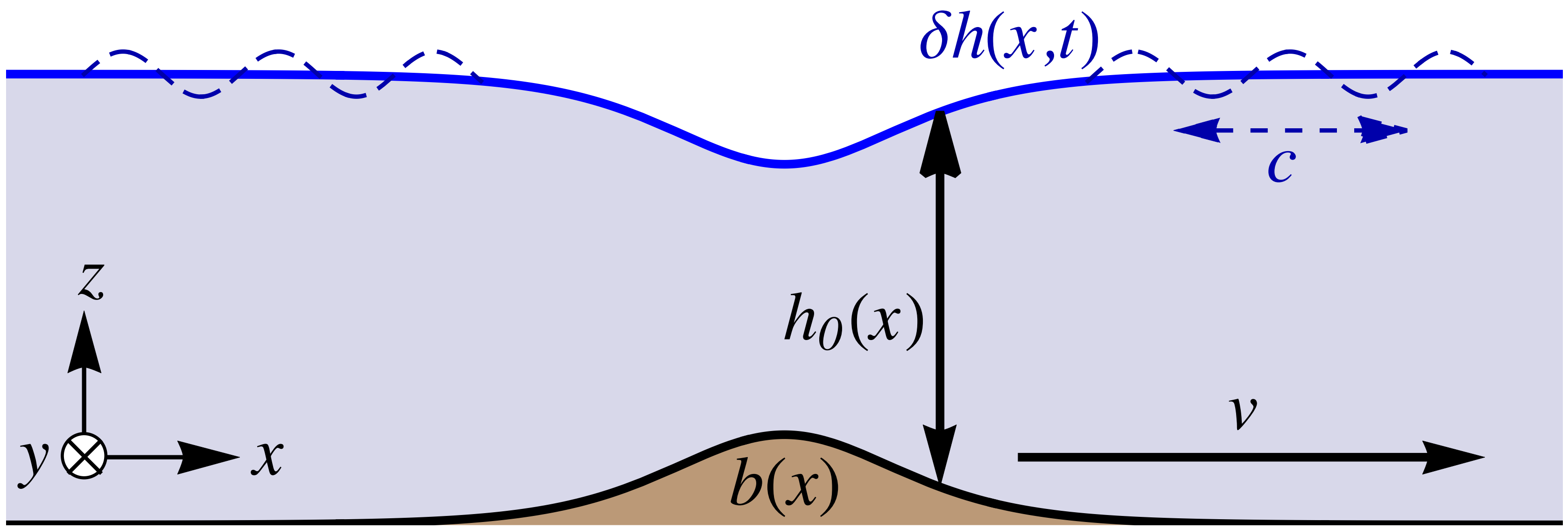

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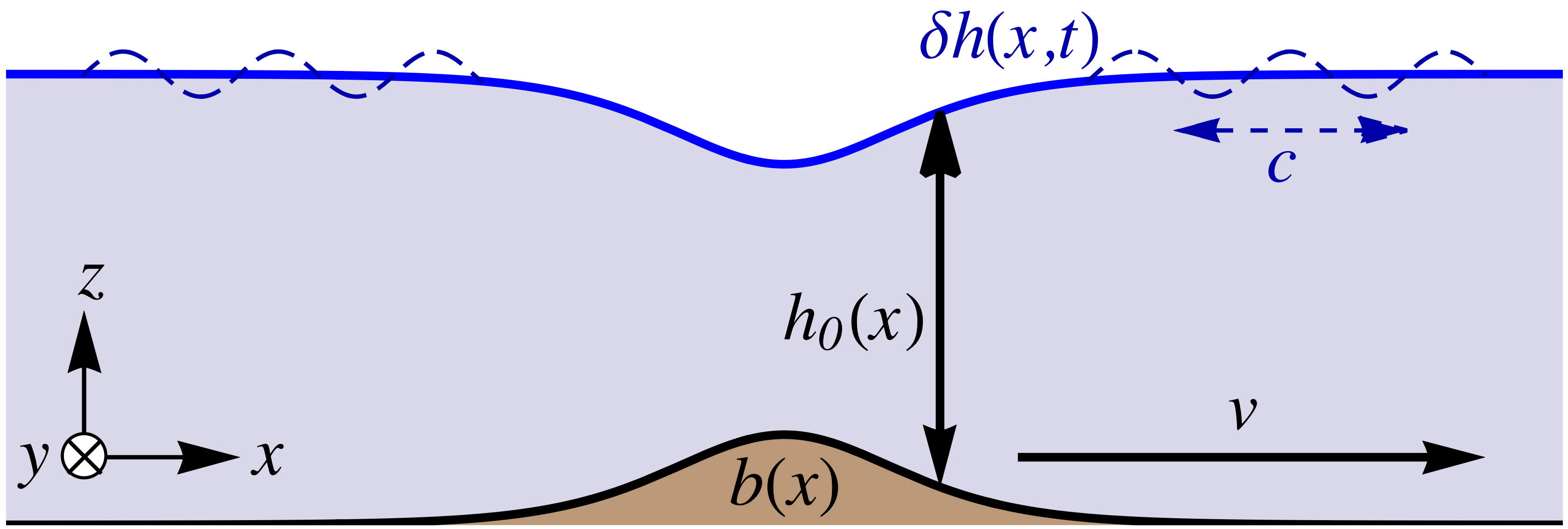

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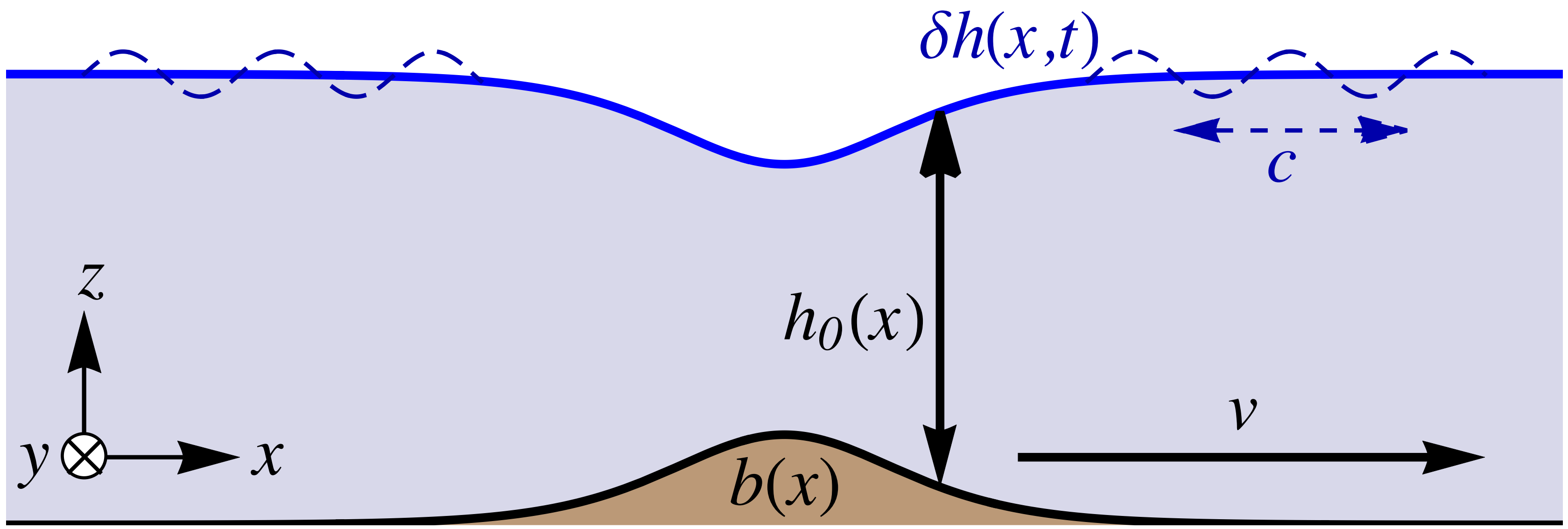

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Massless scalar field in metric $\mathrm{d}s^2 = \dfrac{h_0}{L}\left[g h_0(x)\,\mathrm{d}t^2 - \left(\mathrm{d}x - v_0(x)\,\mathrm{d}t\right)^2 - \mathrm{d}y^2\right]$

The stationary background

Mass conservation

$$\partial_x \left(h_0 v_0\right) = 0 \longrightarrow h_0 v_0 = q$$

Acceleration of fluid parcel (at free surface)

$$\partial_x \left(\frac{1}{2} v_0^2 + g\left(h_0 + b\right) \right) = 0$$

$$\frac{q^2}{2 g h_0^2} + h_0 + b = e(h_0) + b = C$$

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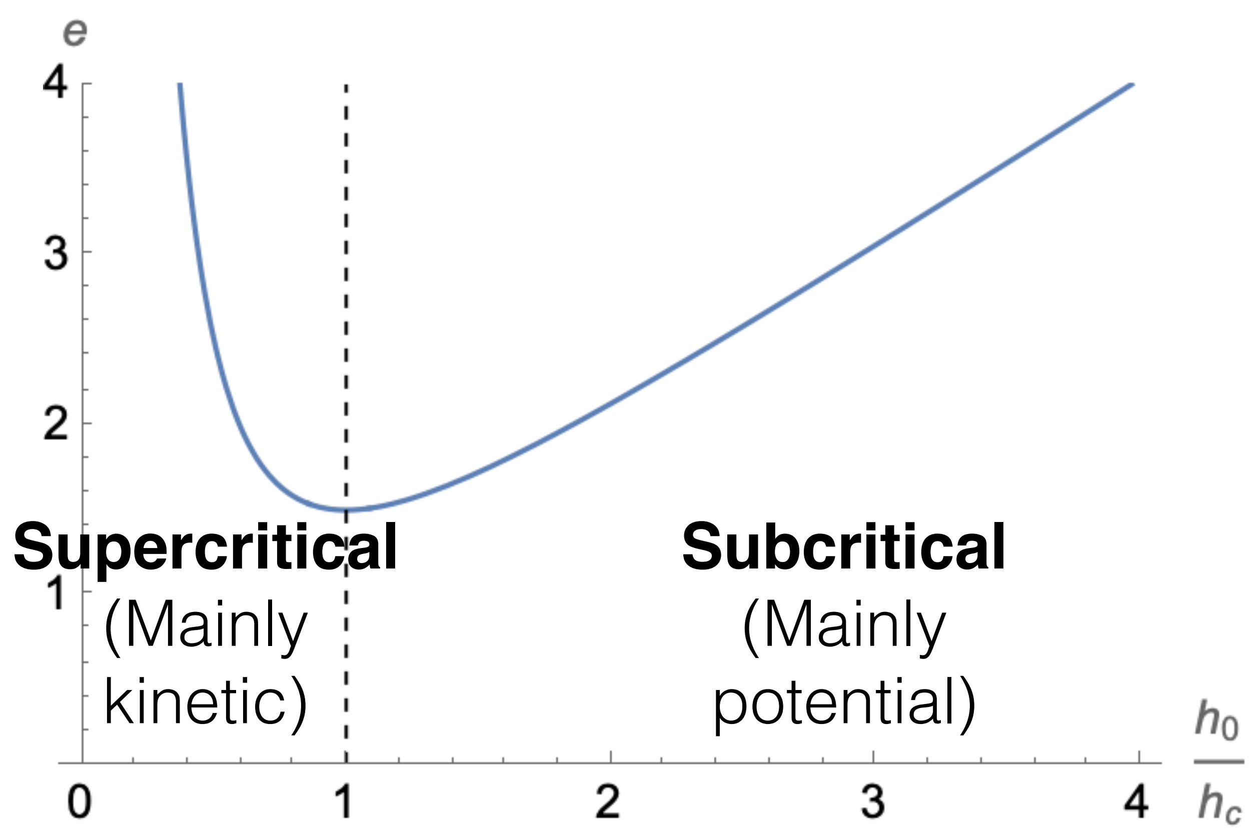
Minimize $\dfrac{q^2}{g h_c^3} = \dfrac{\left(q/h_c \right)^2}{g h_c} = \dfrac{v^2}{c^2} = 1 \longrightarrow \underbrace{\left(\dfrac{h_0}{h_c} \right)^{-2}}_{\text{Kinetic energy}} + \underbrace{\dfrac{h_0}{h_c} + \dfrac{b}{h_c}}_{\text{Potential energy}} = C'$



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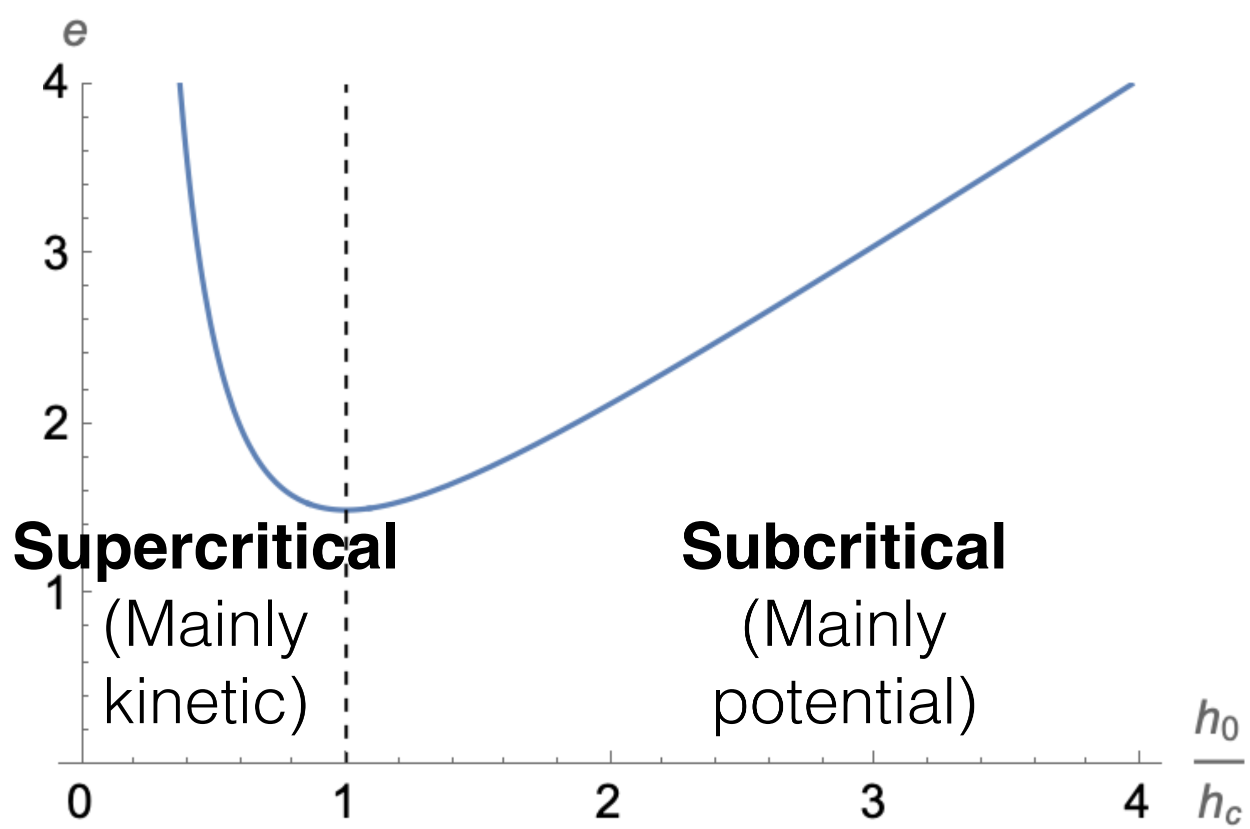


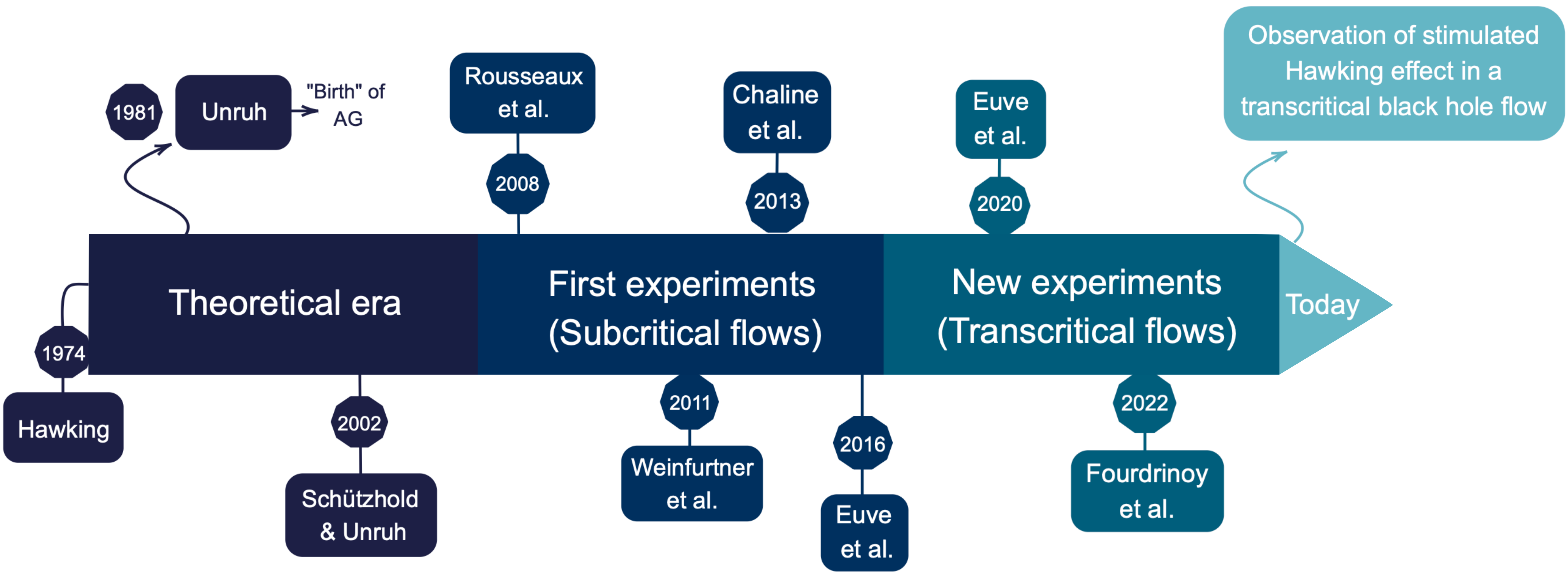
In supercritical region, counter-propagating wave reduces total kinetic energy of system

$\longrightarrow$ Effectively **negative energy**

(Related to negative KG norm)

Water wave experiments
(in 1D)

Timeline of water wave experiments (in 1D)



(courtesy of Ludivine Goncalves)

Water wave experiments in subcritical flows

All previous experiments (in 1 dimension) were in **purely subcritical flows**

Rousseaux et al., New J. Phys. 10, 053015 (2008)
Weinfurtner et al., Phys. Rev. Lett. 106, 021302 (2011)
Euvé et al., Phys. Rev. Lett. 117, 121301 (2016)

⟶ **No horizon** in the effective metric

⟶ **No thermality** in the sense of Hawking/Unruh

(Nontrivial scattering allowed thanks to **dispersion**)

(Michel and Parentani, Phys. Rev. D 90, 044033 (2014))
(Robertson, Michel and Parentani, Phys. Rev. D 93, 124060 (2016))

Water wave experiments in transcritical flows

I. 'Grey-body' scattering at transcritical black hole

L.-P. Euvé *et al.*, *Phys. Rev. Lett.* **124**, 141101 (2020)

- scattering of co-propagating wave off effective potential ("grey-body")

II. Hawking effect at transcritical white hole?

J. Fourdrinoy *et al.*, Phys. Rev. D 105, 085022 (2022)

- counter-propagating waves incident on WH horizon

III. Hawking effect at transcritical black hole?

A. Bossard *et al.*, **work in progress**

- attempted stimulation of Hawking effect at BH horizon

Water wave experiments in transcritical flows

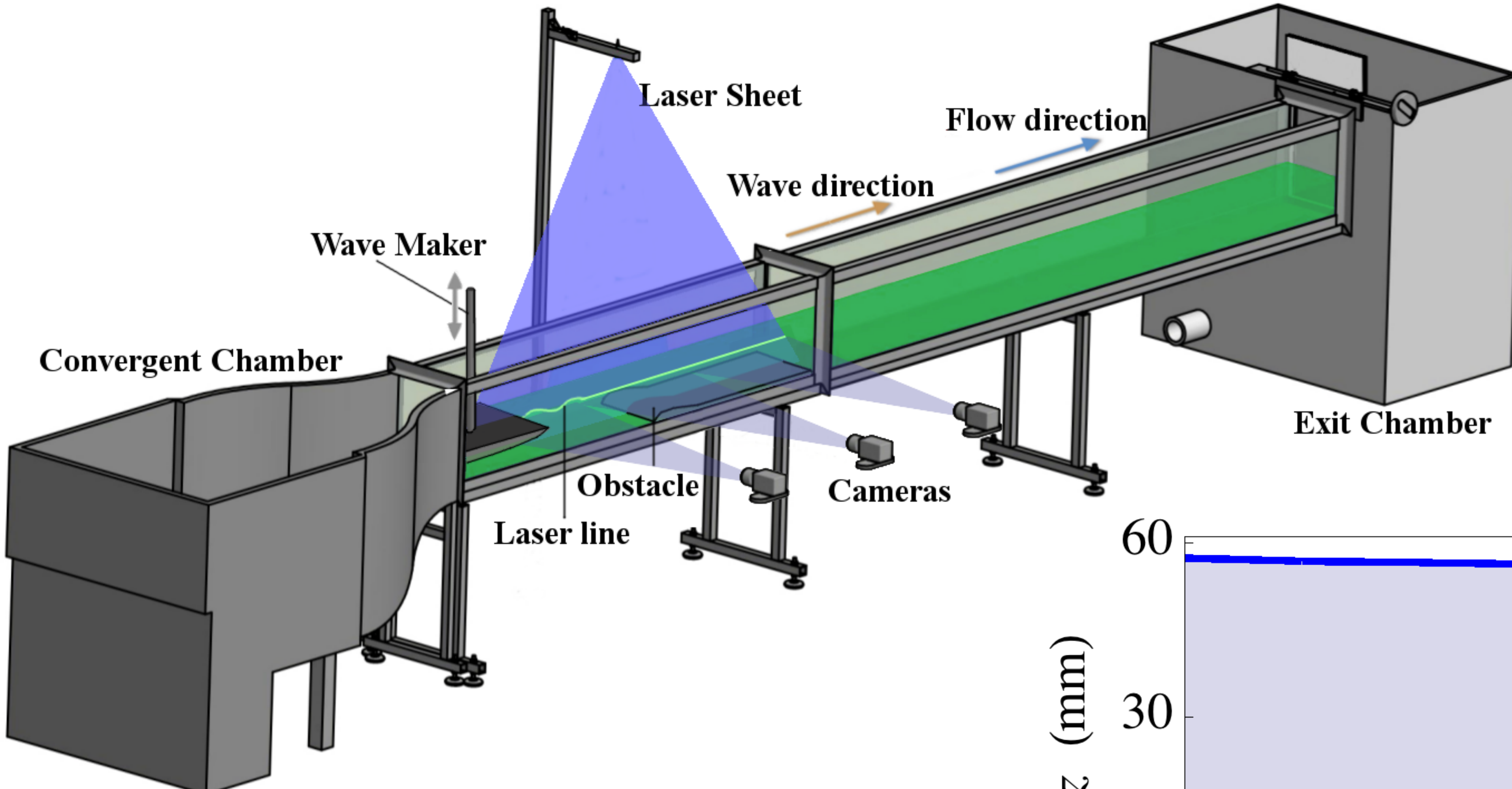
I. ‘Grey-body’ scattering

L.-P. Euvé *et al.*, PRL 124, 141101 (2020)

PHYSICAL REVIEW LETTERS **124**, 141101 (2020)

Scattering of Co-Current Surface Waves on an Analogue Black Hole

Léo-Paul Euvé,[1] Scott Robertson,[2] Nicolas James,[3] Alessandro Fabbri,[4,5,2] and Germain Rousseaux[6]



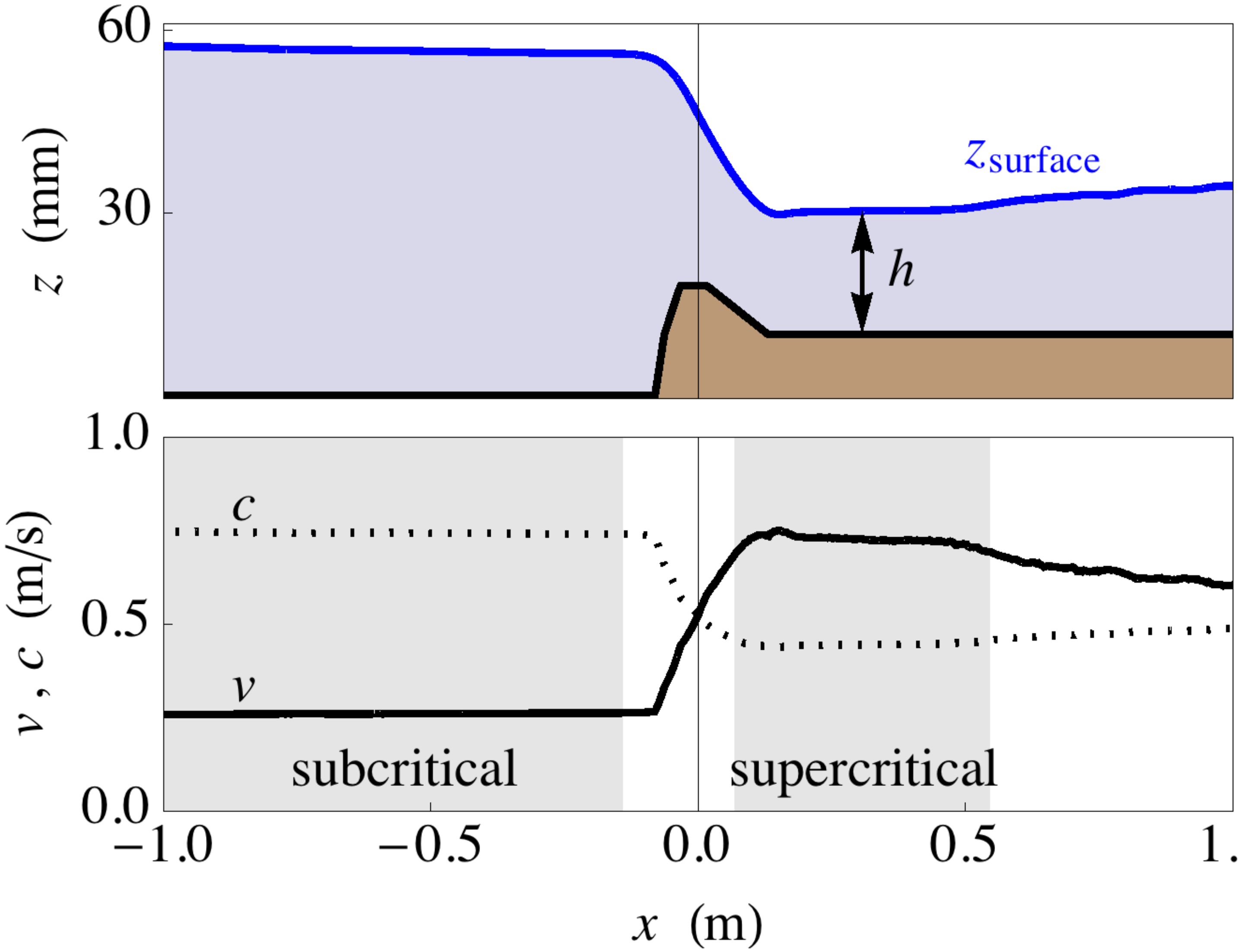
$$v = \frac{q}{h} \qquad c = \sqrt{gh}$$

Transcritical: Horizon where $v = c$

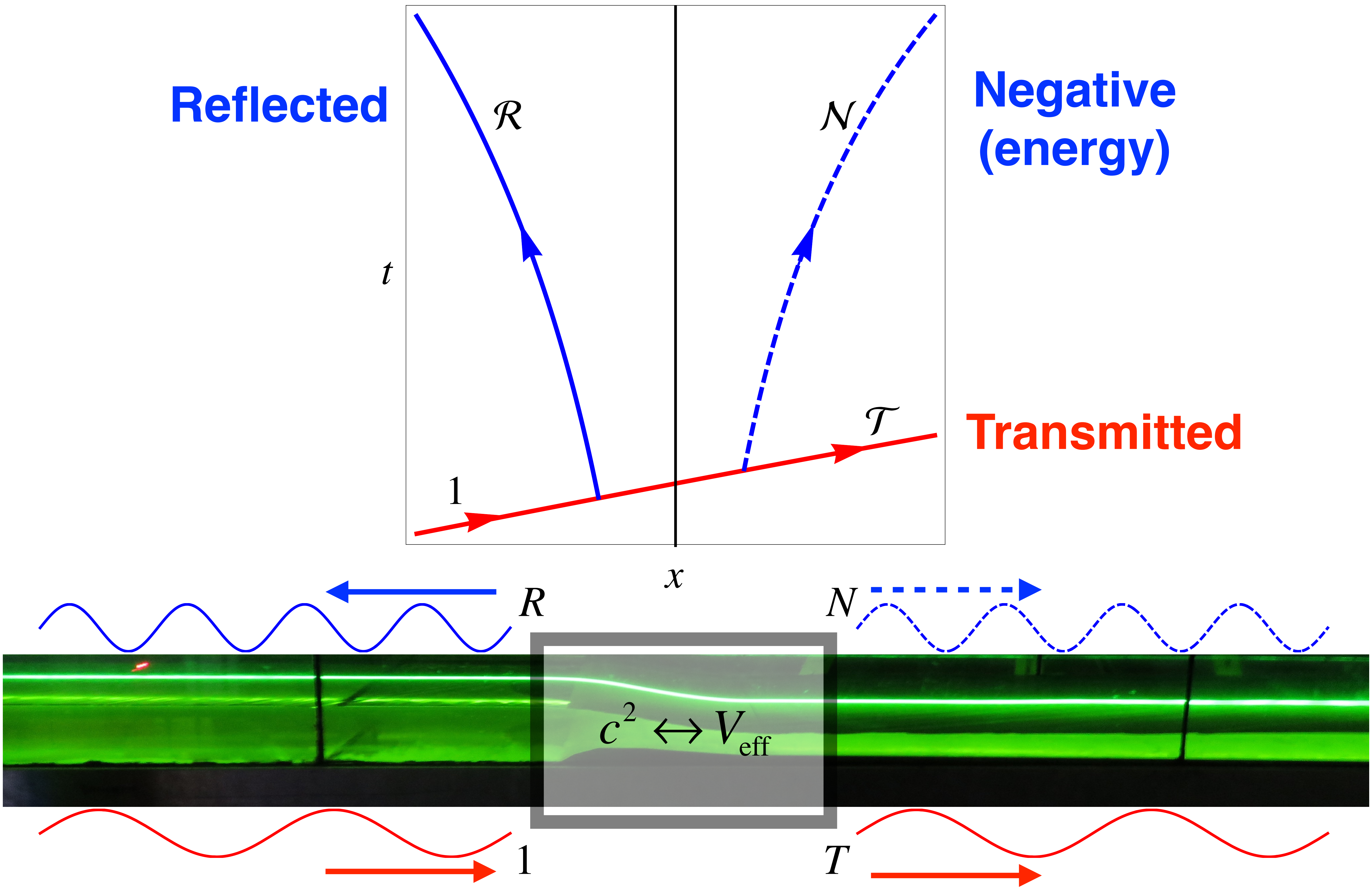
Hawking prediction

"Surface gravity" $\kappa = \partial_x (v - c) = 4.56\ \text{Hz}$

BH temperature $T = \frac{\hbar\kappa}{2\pi k_B} = 5.55\ \text{pK}$



Scattering of incident probe



Dispersion relation

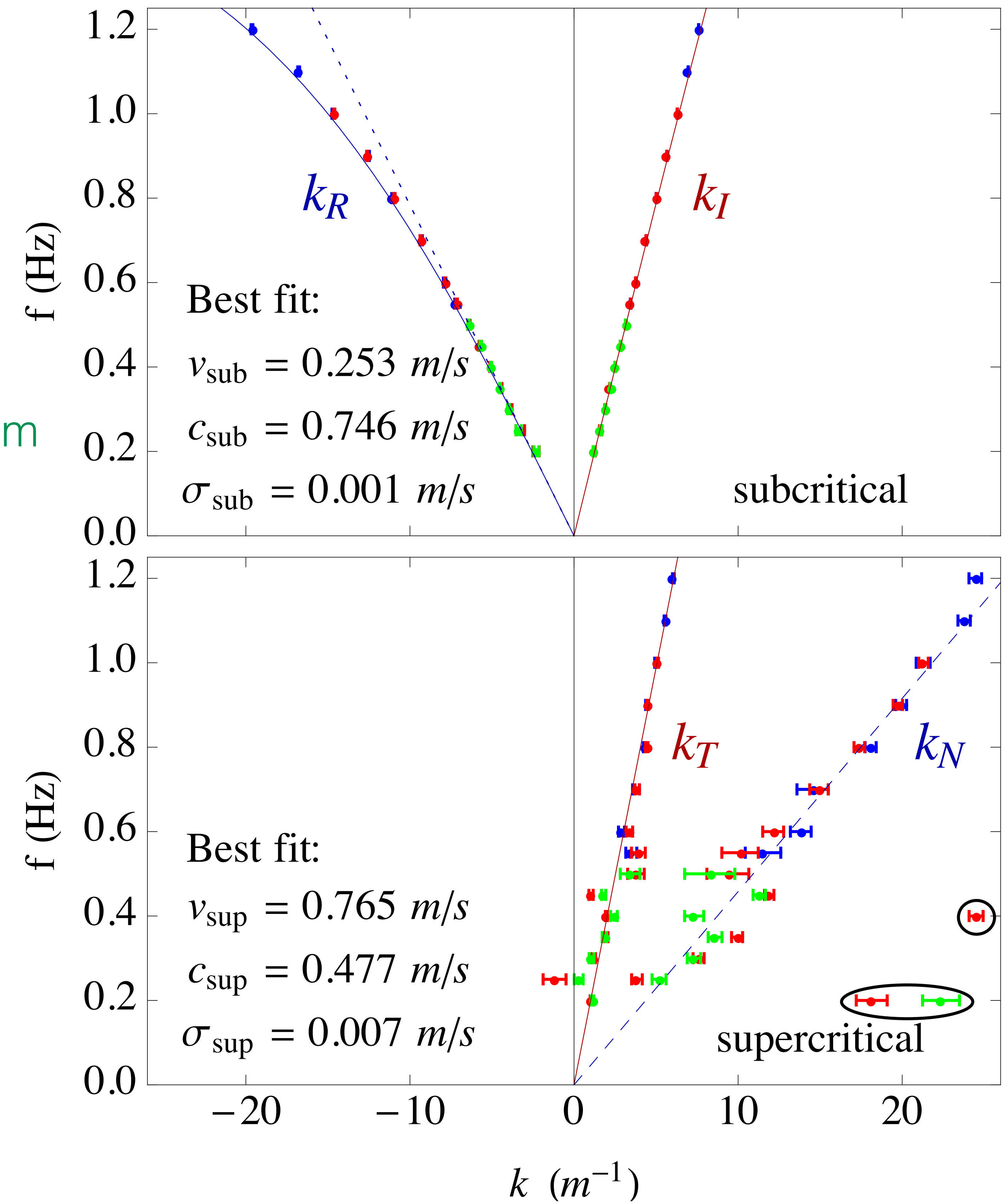
Latest results

Found by FT'ing in time
then fitting to sum of two plane waves

Different colours represent different wave maker amplitudes: 0.25 mm, 0.5 mm, 1 mm

Allows fitting of *v* and *c*

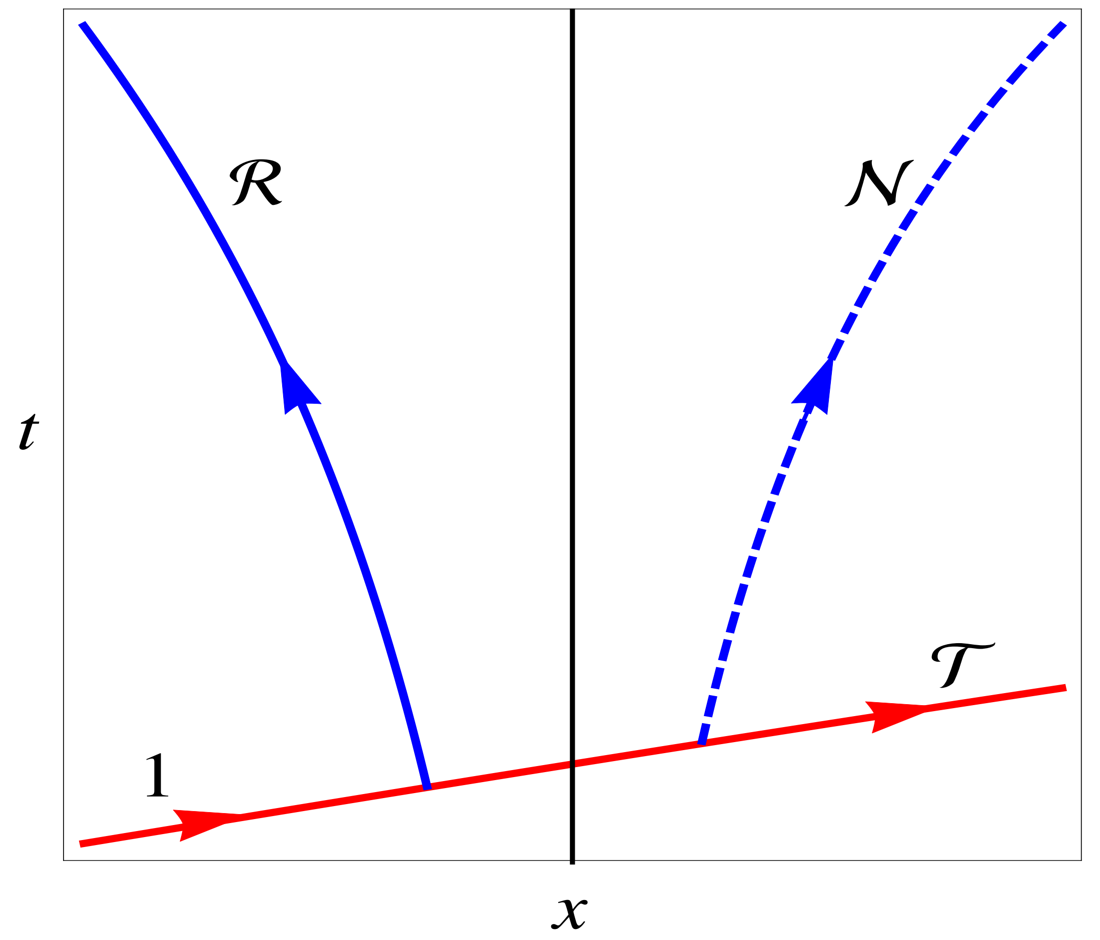
- very close to values inferred from depth in subcritical region
- small difference in supercritical region (likely due to presence of vorticity)



"Grey-body" scattering

Wave maker amplitudes: 0.25 mm, 0.5 mm, 1 mm

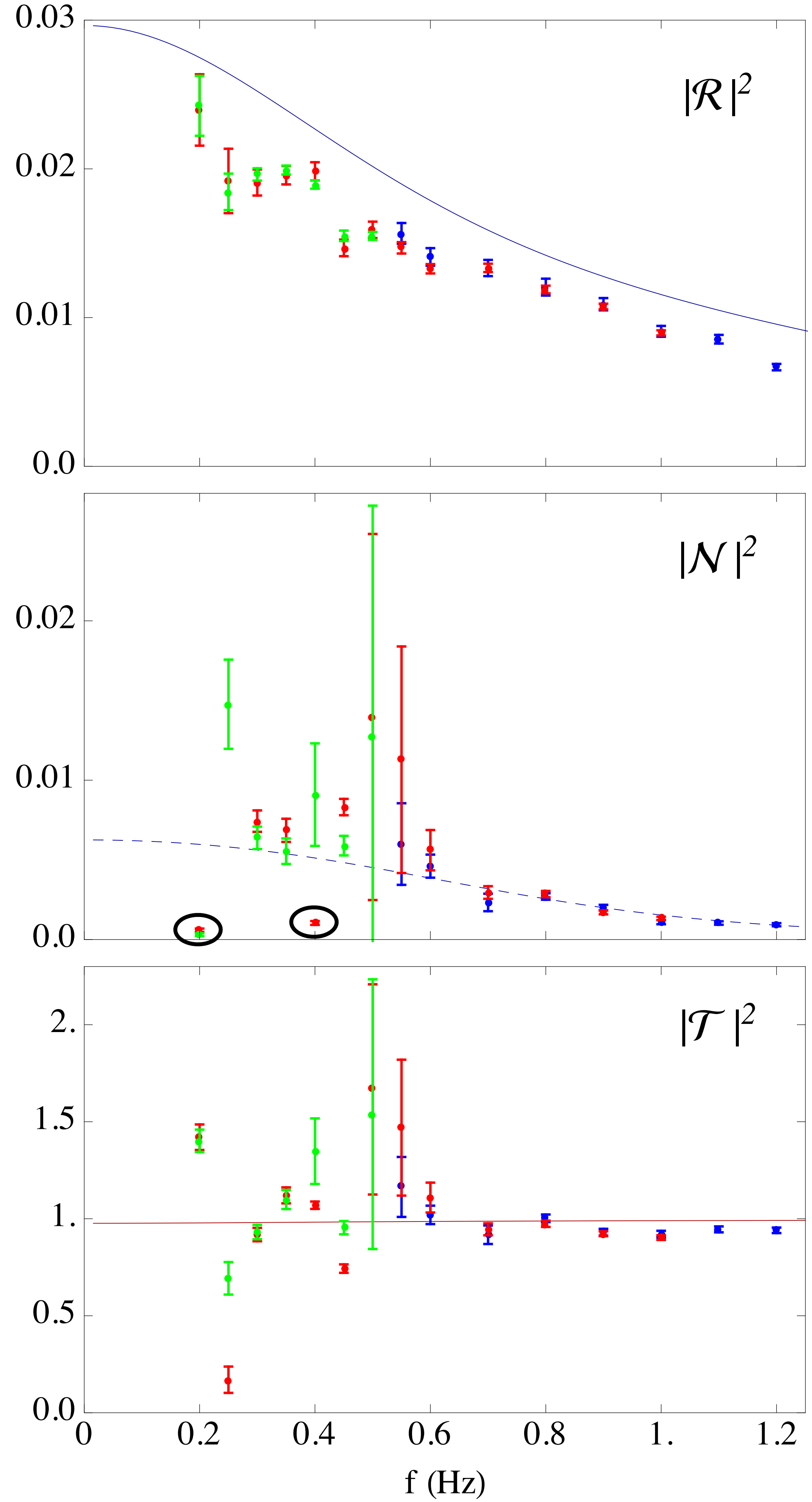
Scattering off V_{eff} engendered
by variation of conformal factor c^2



- Unitarity relation:

$$|\mathscr{R}|^2 - |\mathscr{N}|^2 + |\mathscr{T}|^2 = 1$$

(Unable to verify)



Water wave experiments in transcritical flows

II. Hawking effect at a white hole?

J. Fourdrinoy *et al.*, PRD 105, 085022 (2022)

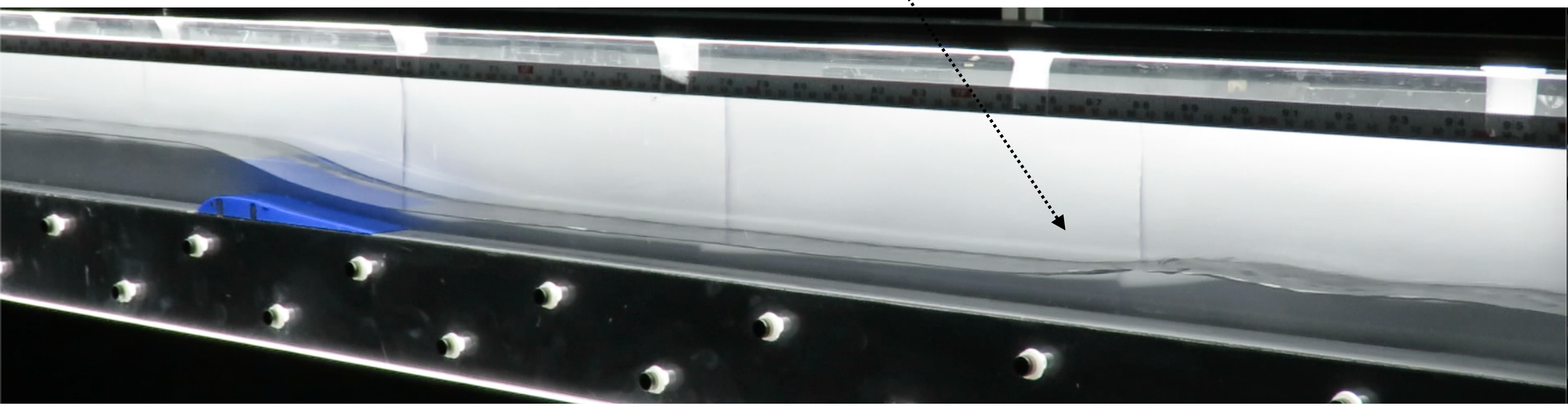
PHYSICAL REVIEW D **105,** 085022 (2022)

Correlations on weakly time-dependent transcritical white-hole flows

Johan Fourdrinoy,[1] Scott Robertson,[2,3] Nicolas James,[4] Alessandro Fabbri,[5,3] and Germain Rousseaux[1]

Hydraulic jump: Sudden deceleration

→ **White-hole horizon**

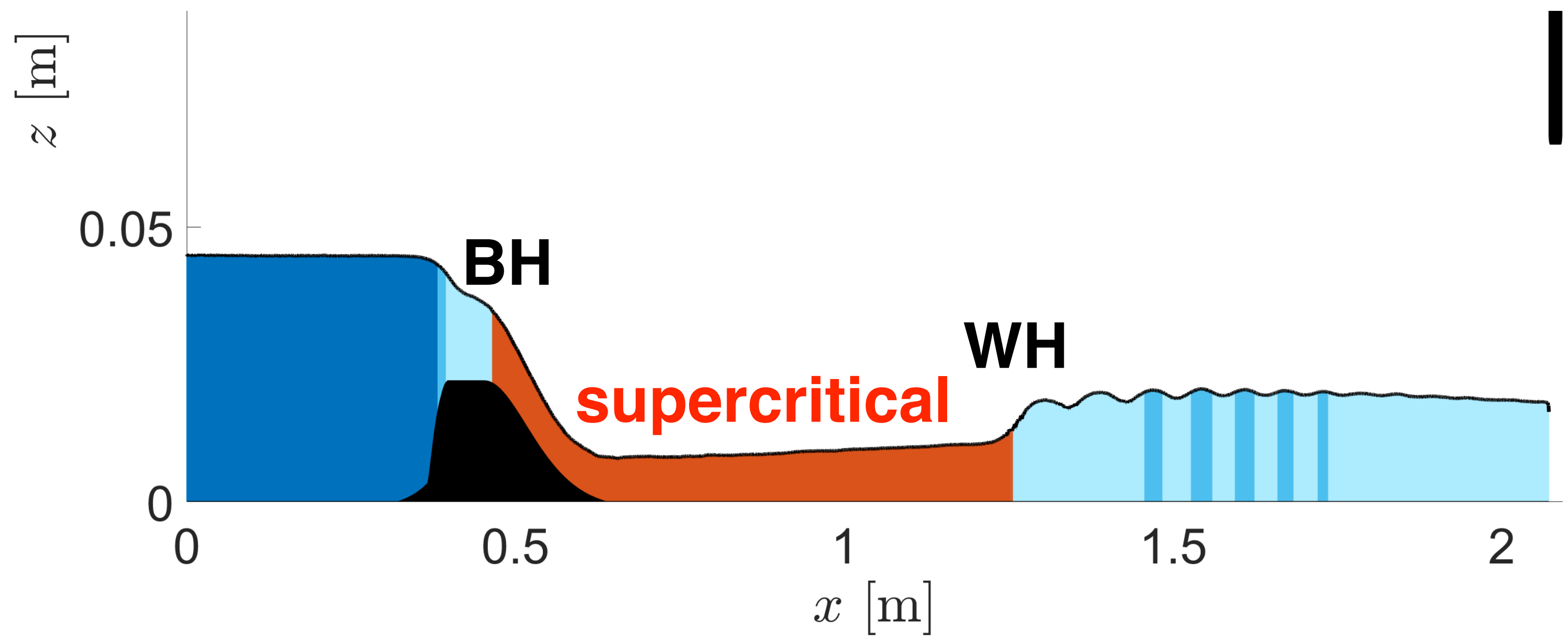


- Narrow channel (~ 5 cm wide, ~ 2 m long)
- Cameras record height of side meniscus
- **No wave maker**: waves induced by intrinsic noise
  - Relevant observable is two-point correlation function:

$$\langle \delta h(x,t)\, \delta h(x',t) \rangle_t \quad \text{or} \quad \left\langle \widetilde{\delta h}(k,t)\, \widetilde{\delta h}^{\star}(k',t) \right\rangle_t$$

Two types of (transcritical) white hole

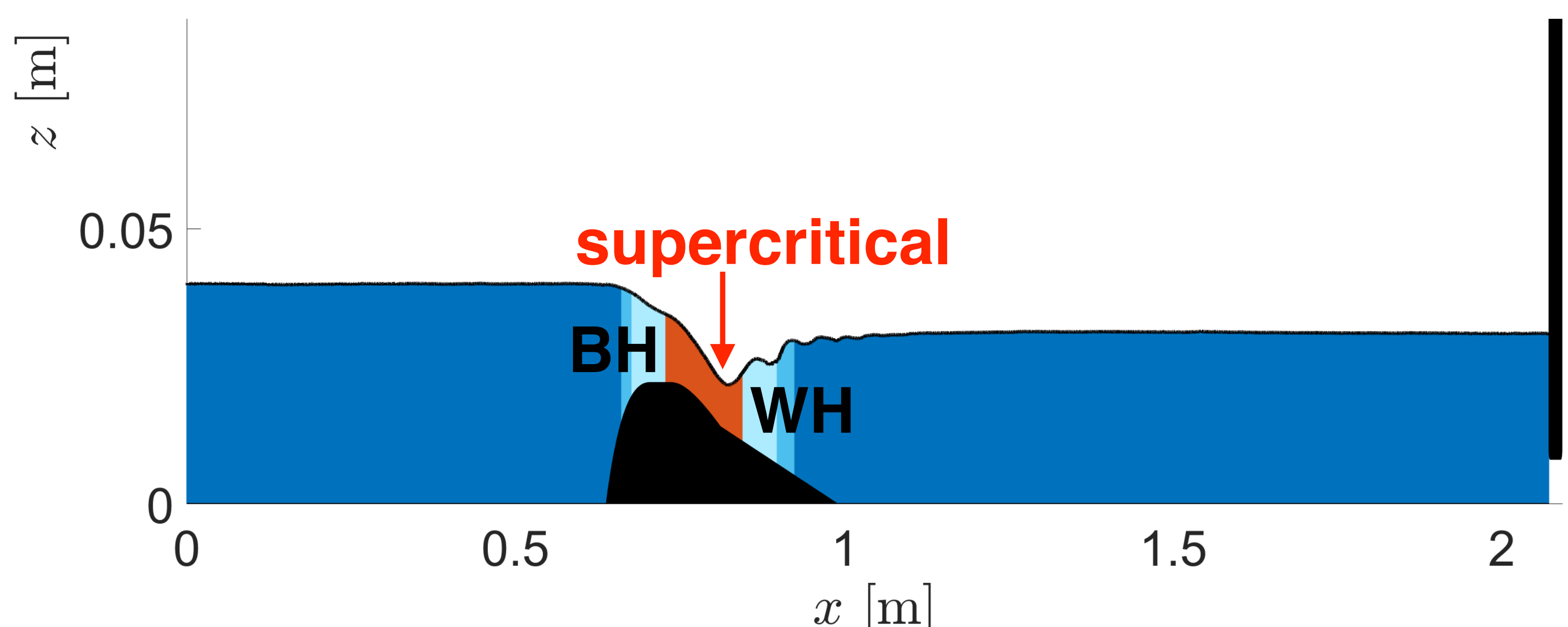
Type 1: Free flows



Gate open

- long supercritical region
- undular hydraulic jump far from obstacle (governed by **dissipation**)

Type 2: Gated flows

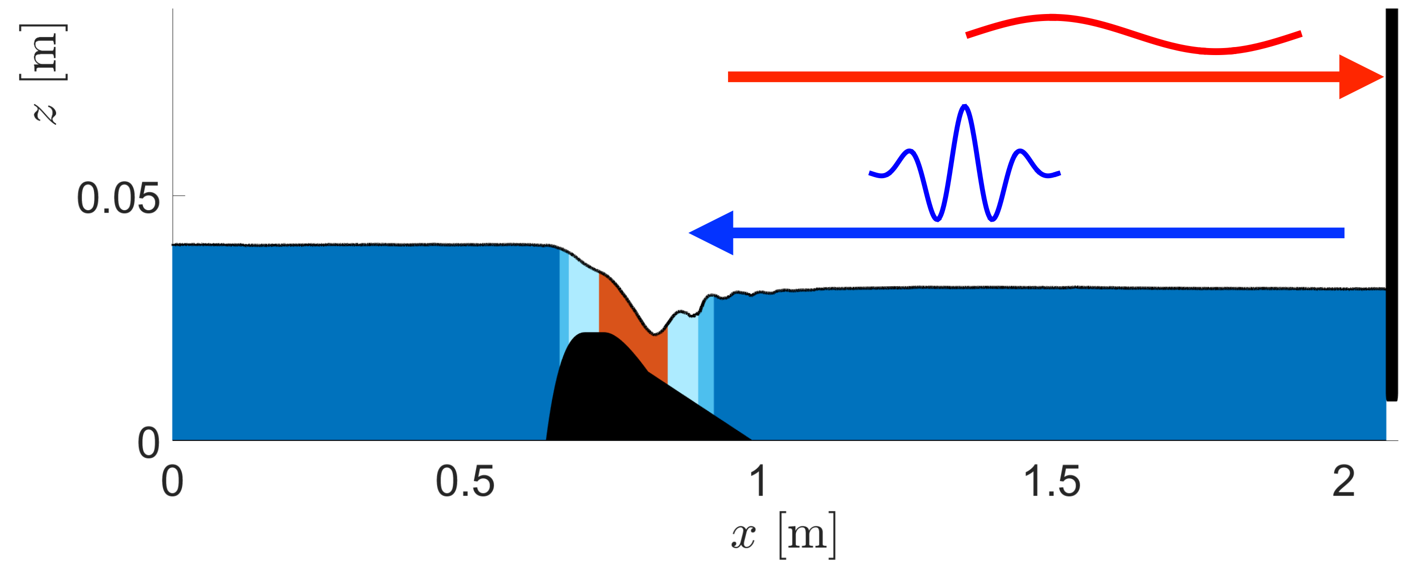


Gate partially closed

- short supercritical region
- undulation "attached" to obstacle (governed by **boundary conditions**)

Gated flows: Is there a Hawking effect?

Hawking effect **expected** since hydrodynamical waves reflected by gate and incident on WH horizon:



Gated flows: Is there a Hawking effect?

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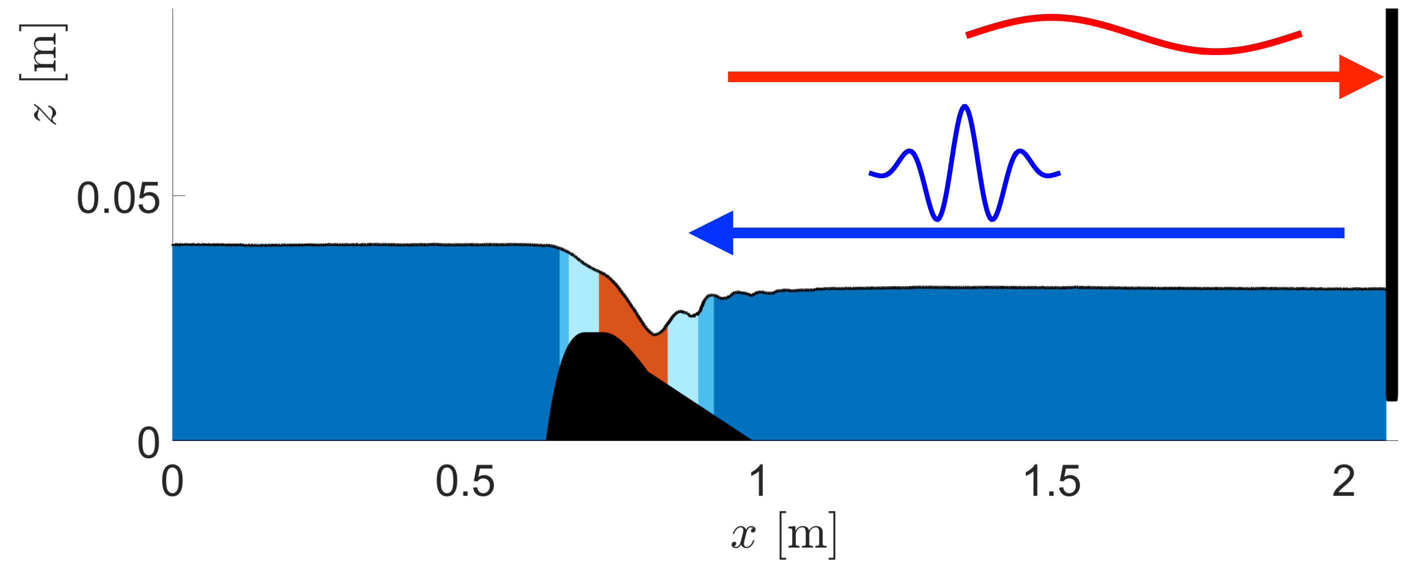
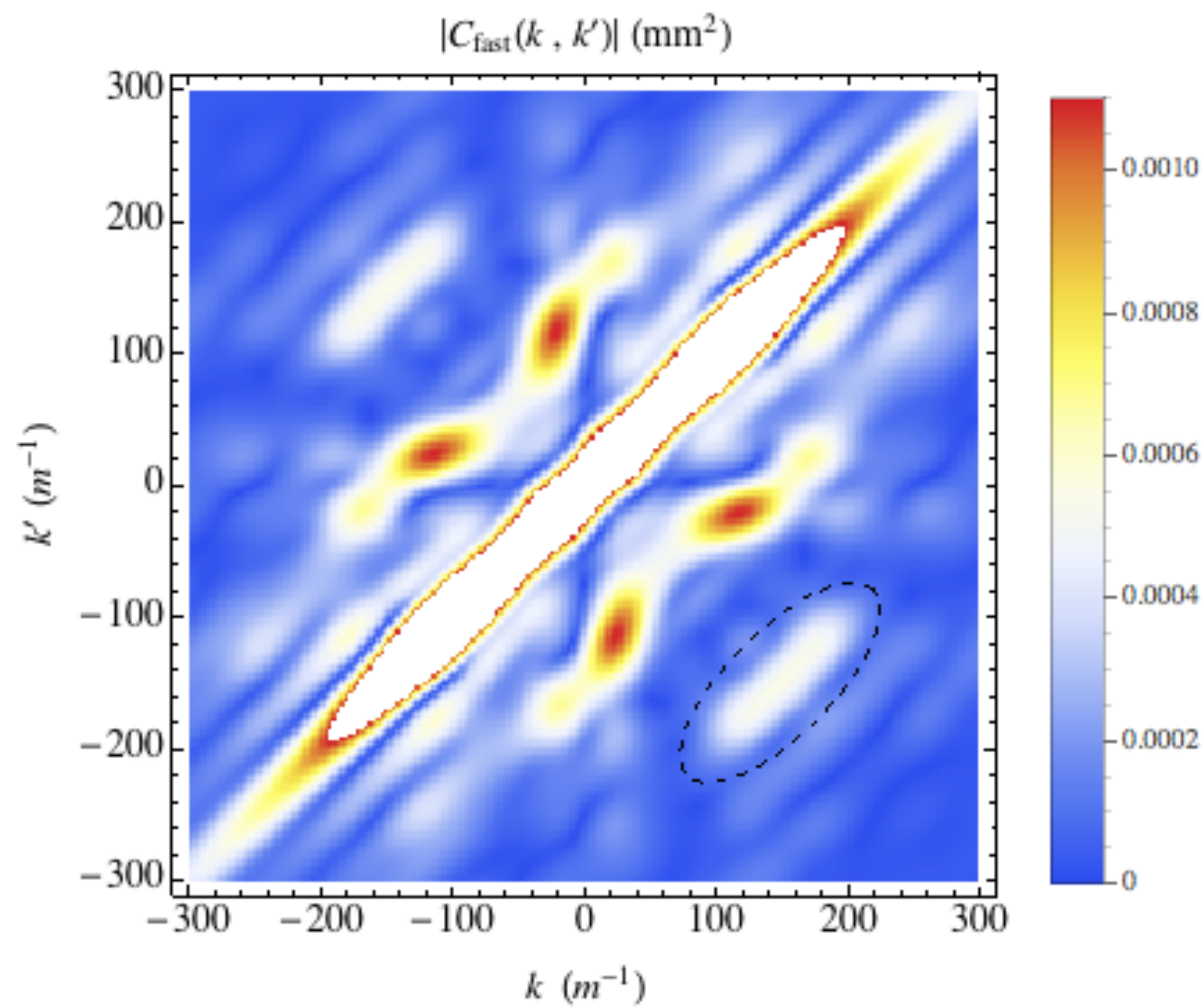


Consider k-space correlations (in vicinity of undulation):

$$C(k,k') = \left\langle \delta\widetilde{h}(k,t)\,\delta\widetilde{h}^{\star}(k',t) \right\rangle_t$$



Water wave experiments in transcritical flows

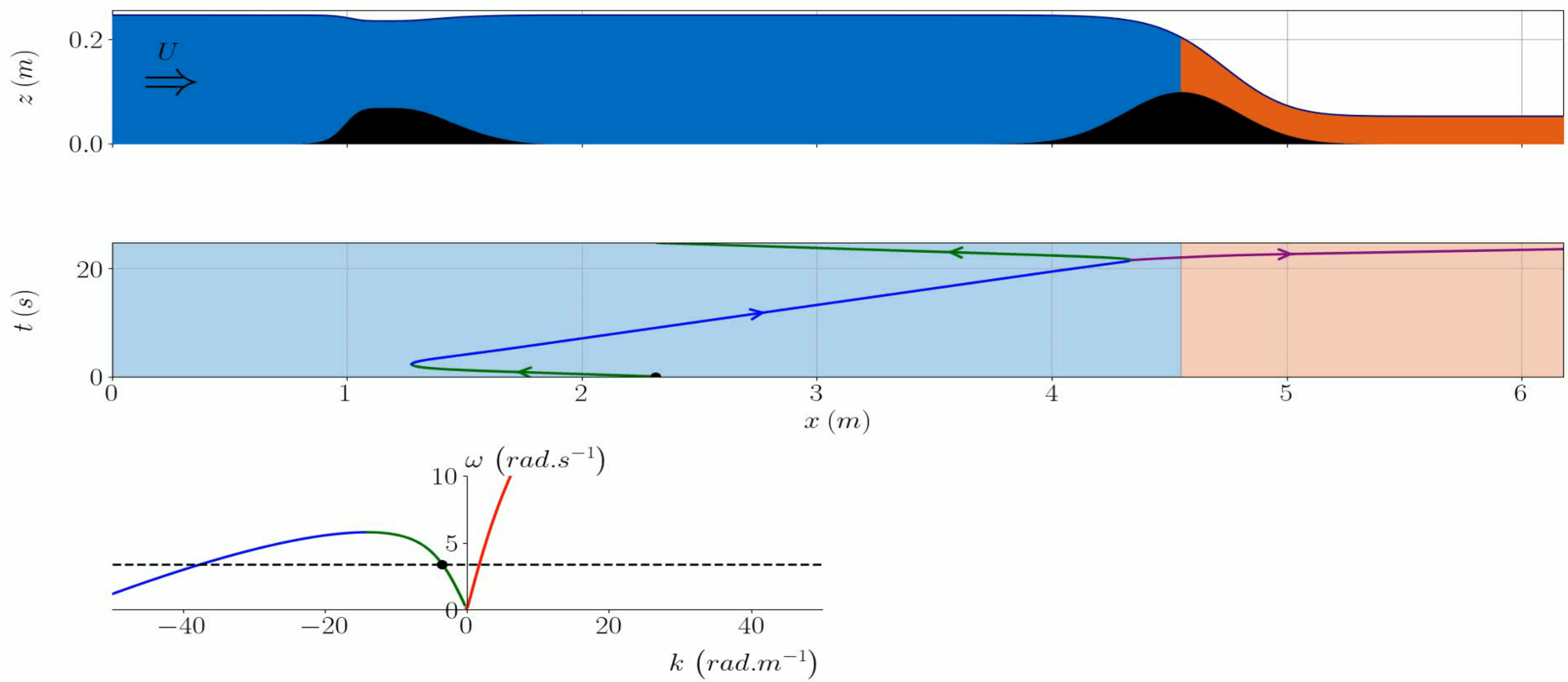
III. Hawking effect at a black hole?

with A. Bossard, L. Goncalves, G. Rousseaux

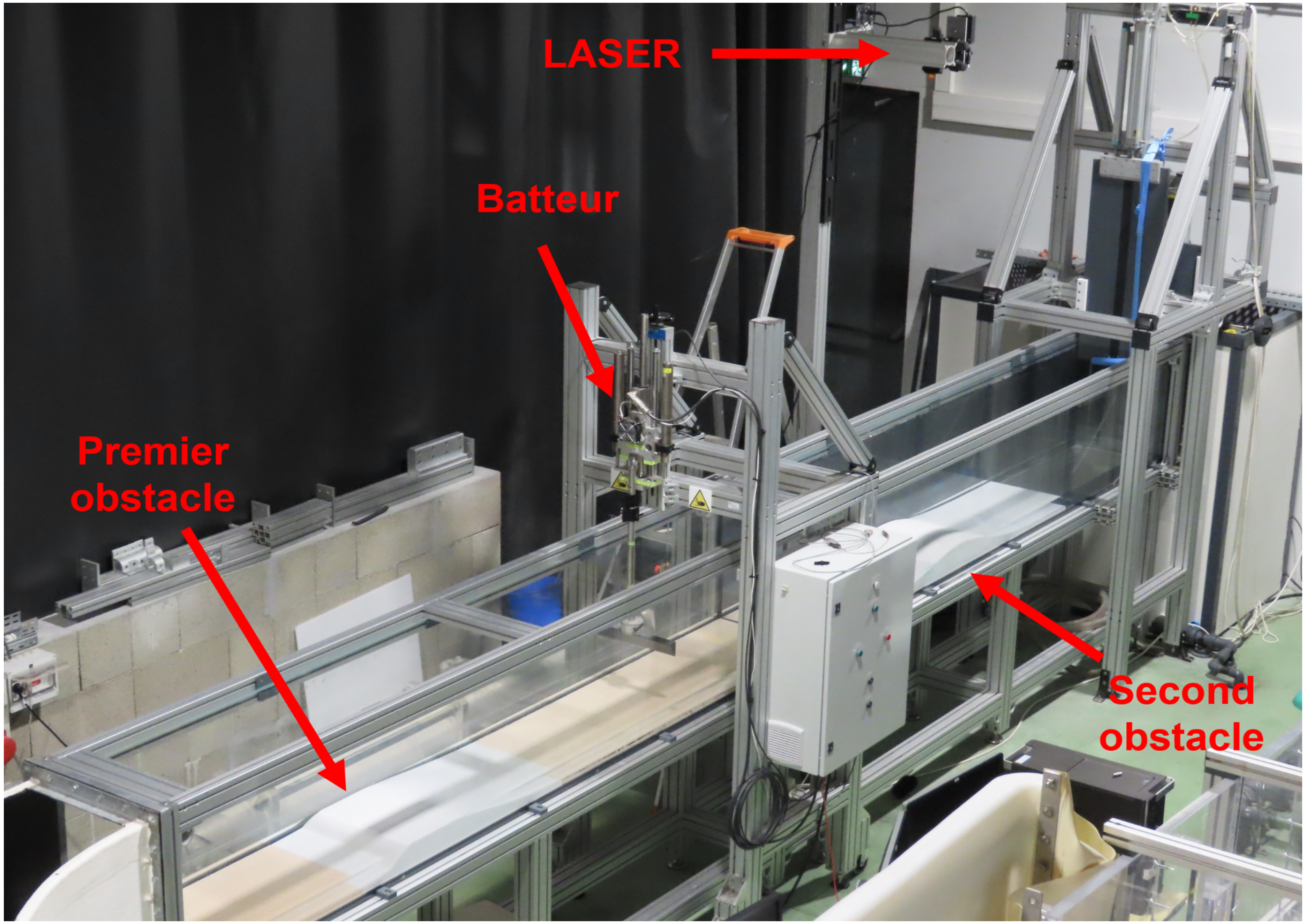
(Not published, work in progress)

How to stimulate the Hawking effect?

- **Black hole horizon**: Need to send in dispersive waves
    - **Wave maker design** : Work in progress (with Ludivine GONCALVES)
    - **Use WH horizon** to convert *hydrodynamical waves* ⟶ *dispersive waves*



Experiment (performed by Alexis Bossard)



Channel characteristics:

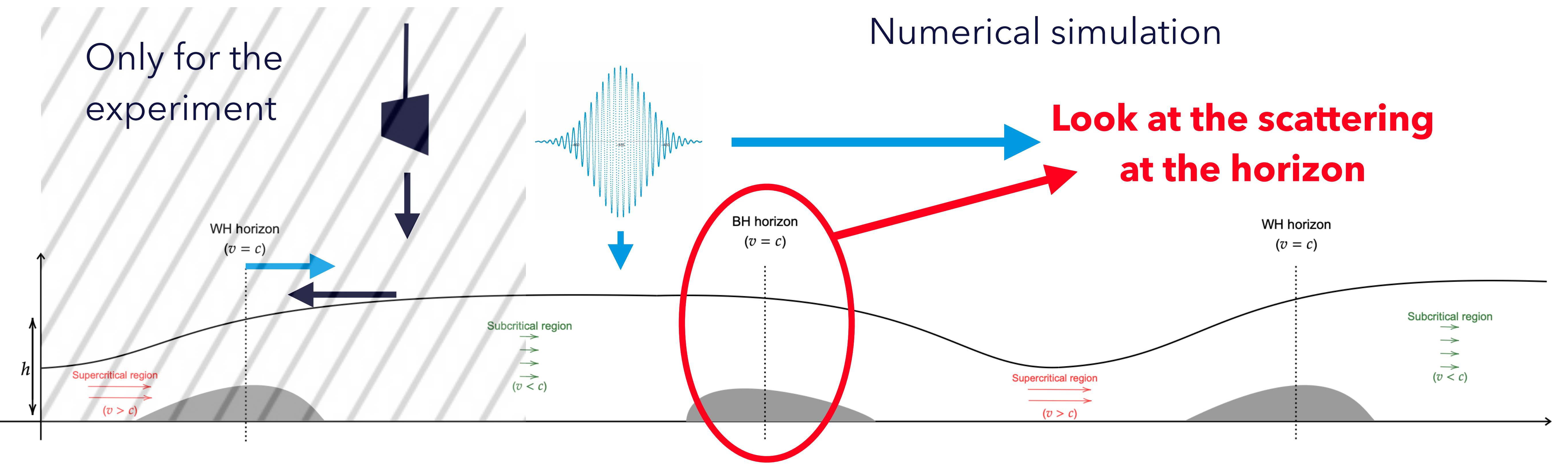
- Length: L=7 m
- Width: W=0,385 m
- Height: H=0,6 m
- Flow rate: 2 to 60 L/s

Main idea :

Use dispersive modes produced at first obstacle to send them back to the analogue black hole.

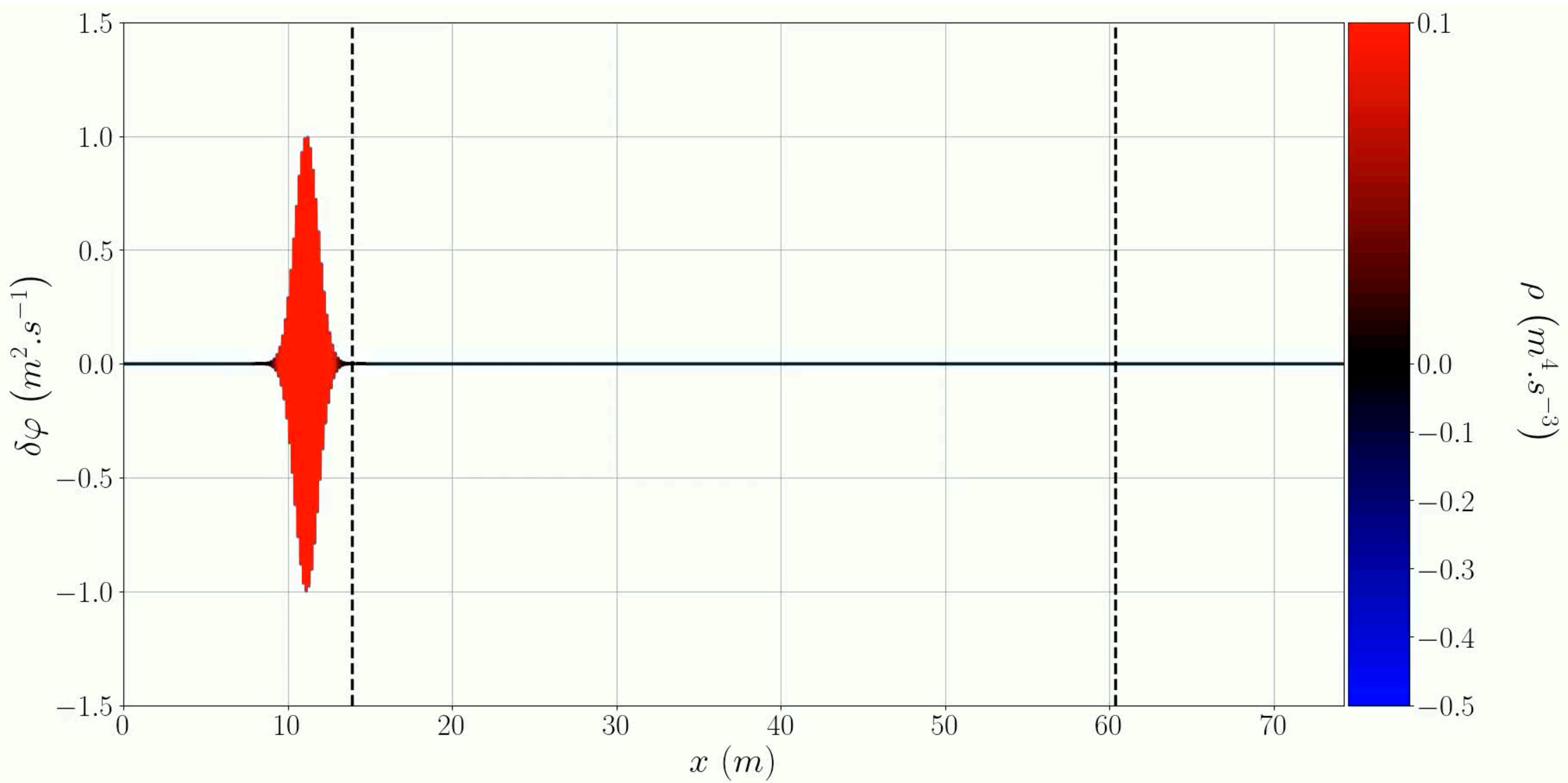
Numerical simulation

- Scheme of the numerical simulation flow profile :



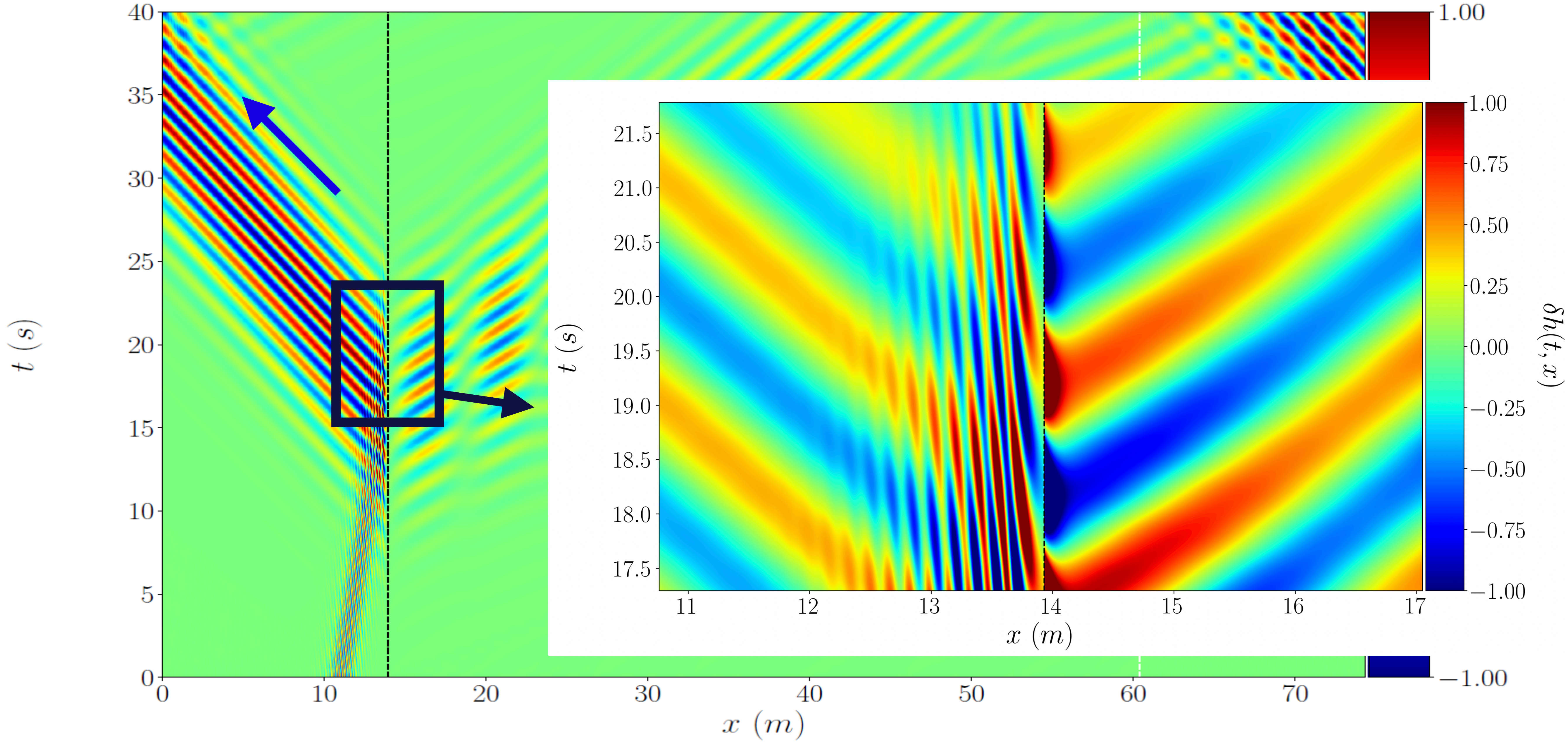
Numerical simulation

$$\rho = i\left(\delta\phi^\star\left(\partial_t + v\partial_x\right)\delta\phi - \delta\phi\left(\partial_t + v\partial_x\right)\delta\phi^\star\right)$$ (norm density)



Results comparison: Numerical vs Experimental

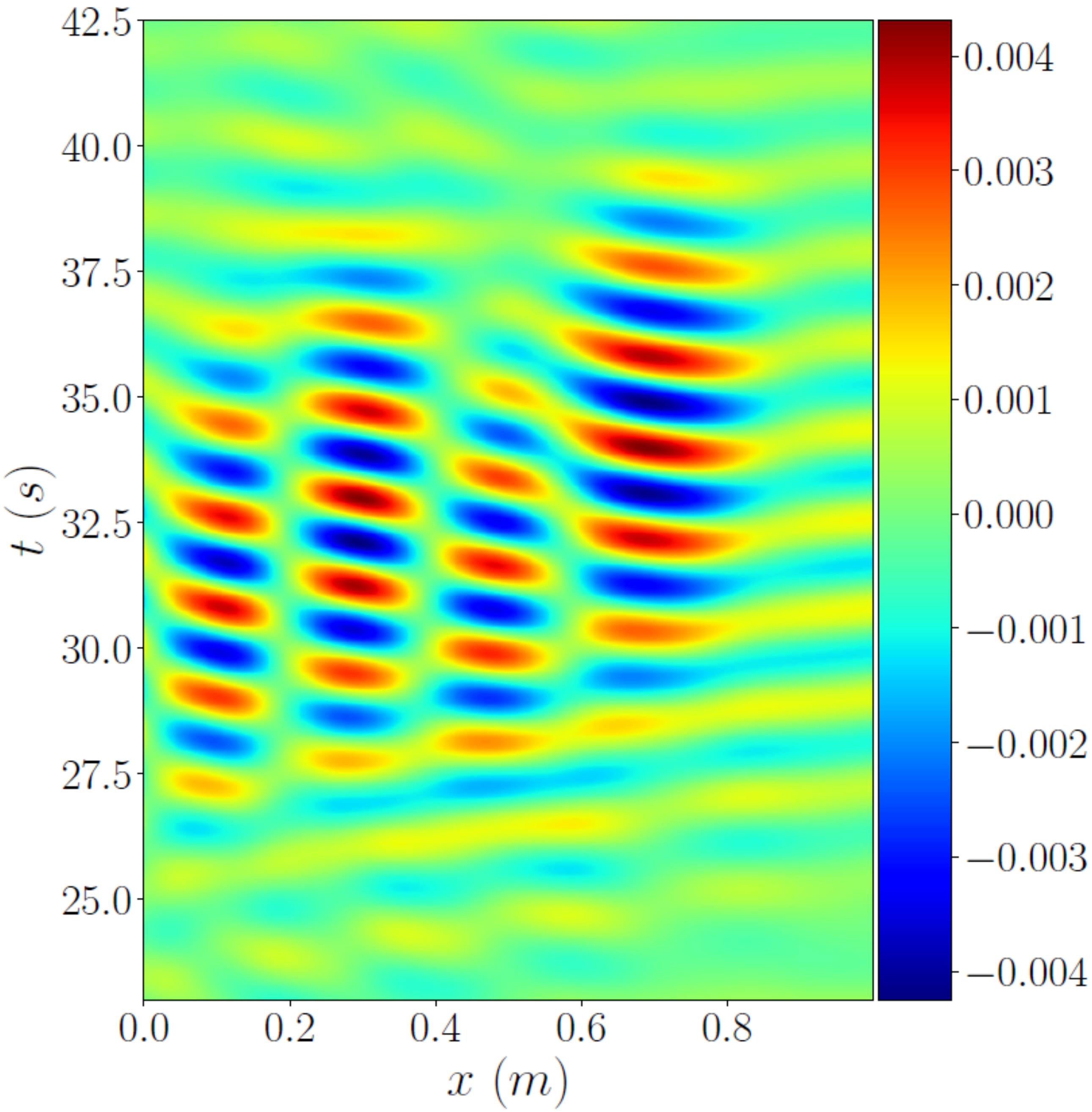
- Numerical space-time diagram of the propagation of $\delta\varphi$



Results comparison:
Numerical vs Experimental

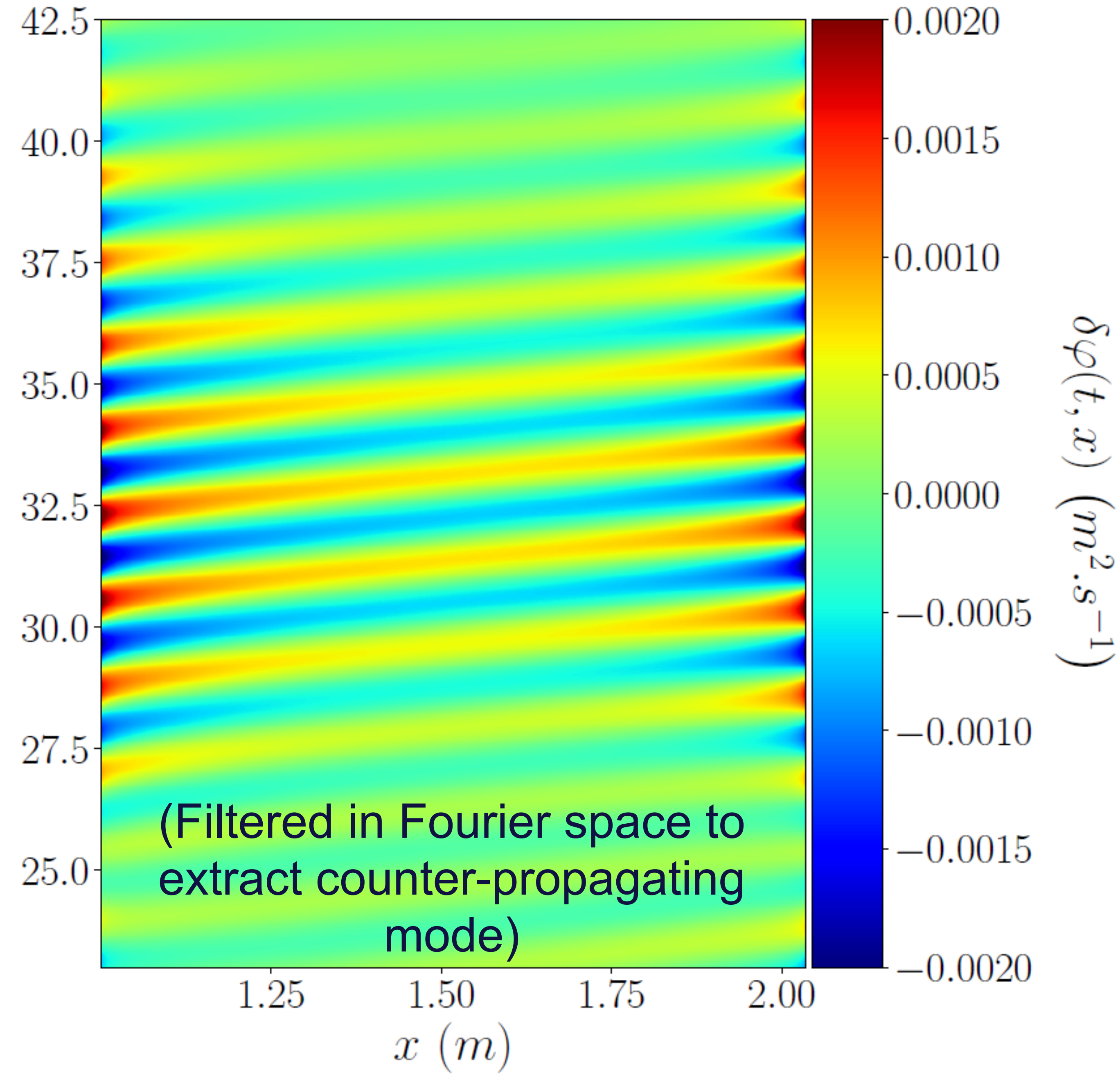
Subcritical

$U(x) < c(x) = \sqrt{gh(x)}$



Supercritical region

$U(x) > c(x) = \sqrt{gh(x)}$

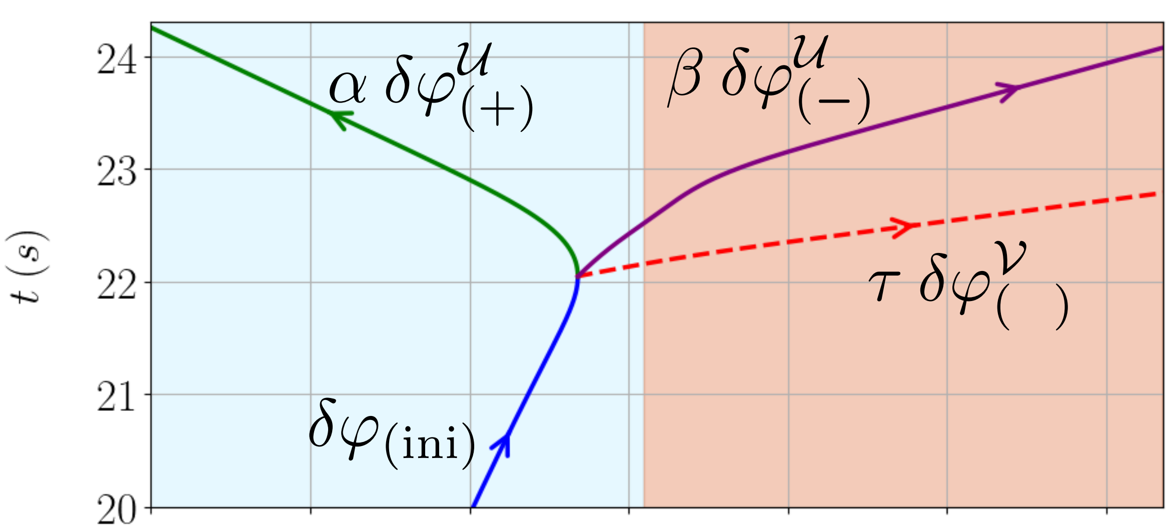


Results comparison: Numerical vs Experimental

- Scattering coefficients of each mode

Scalar product $$(\delta\varphi_1, \delta\varphi_2) = i \int_{\mathbb{R}} \delta\varphi_1^* \left(\partial_t + U(x)\partial_x\right) \delta\varphi_2 - \delta\varphi_2 \left(\partial_t + U(x)\partial_x\right) \delta\varphi_1^* \, \mathrm{d}x$$

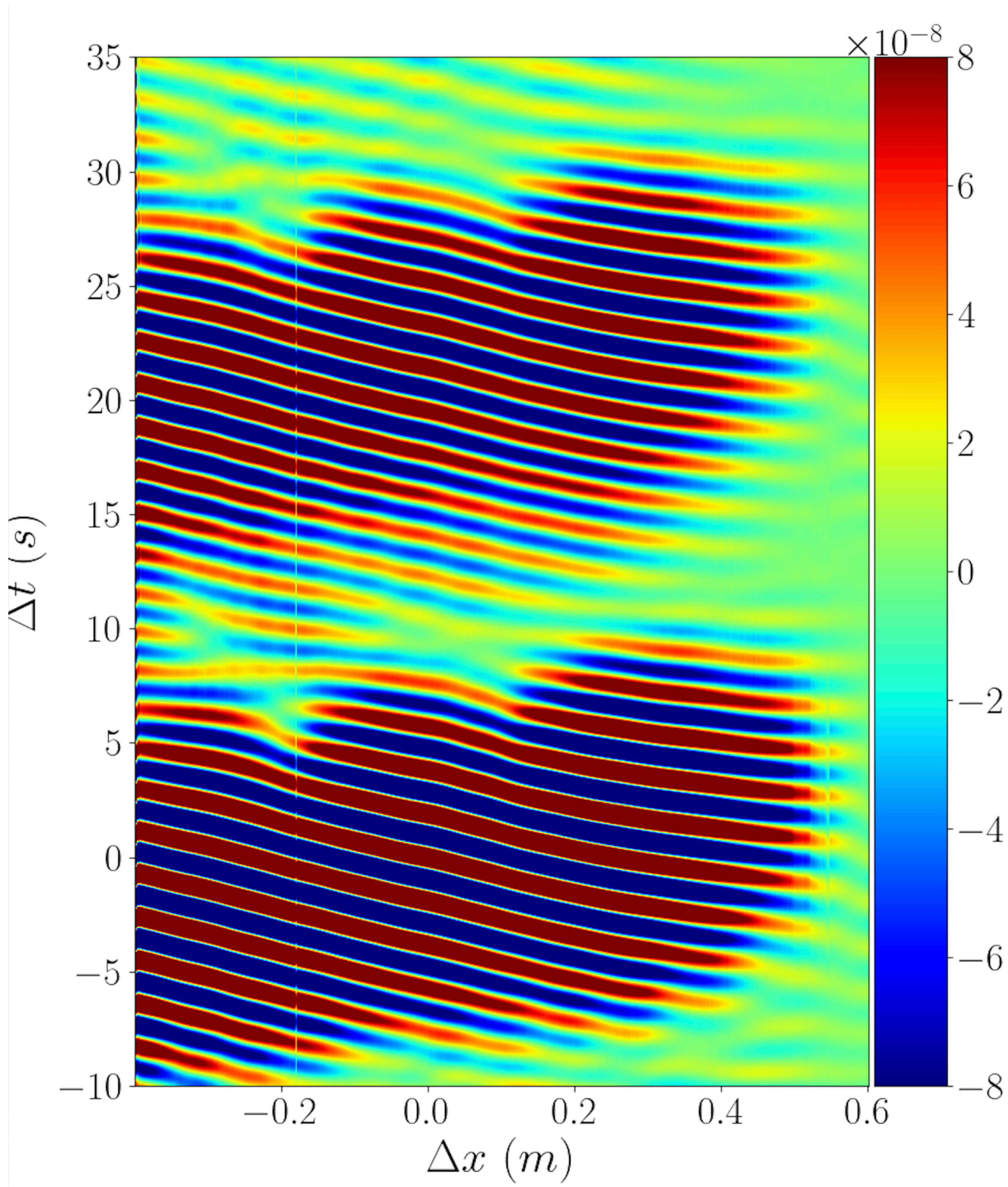
$$|\alpha|^2 = \frac{\left(\delta\varphi^{\mathcal{U}}_{(+)}, \delta\varphi^{\mathcal{U}}_{(+)}\right)}{\left(\delta\varphi_{(\mathrm{ini})}, \delta\varphi_{(\mathrm{ini})}\right)} \quad , \quad |\tau|^2 = \frac{\left(\delta\varphi^{\mathcal{V}}_{(+)}, \delta\varphi^{\mathcal{V}}_{(+)}\right)}{\left(\delta\varphi_{(\mathrm{ini})}, \delta\varphi_{(\mathrm{ini})}\right)} \quad , \quad |\beta|^2 = -\frac{\left(\delta\varphi^{\mathcal{U}}_{(-)}, \delta\varphi^{\mathcal{U}}_{(-)}\right)}{\left(\delta\varphi_{(\mathrm{ini})}, \delta\varphi_{(\mathrm{ini})}\right)}$$

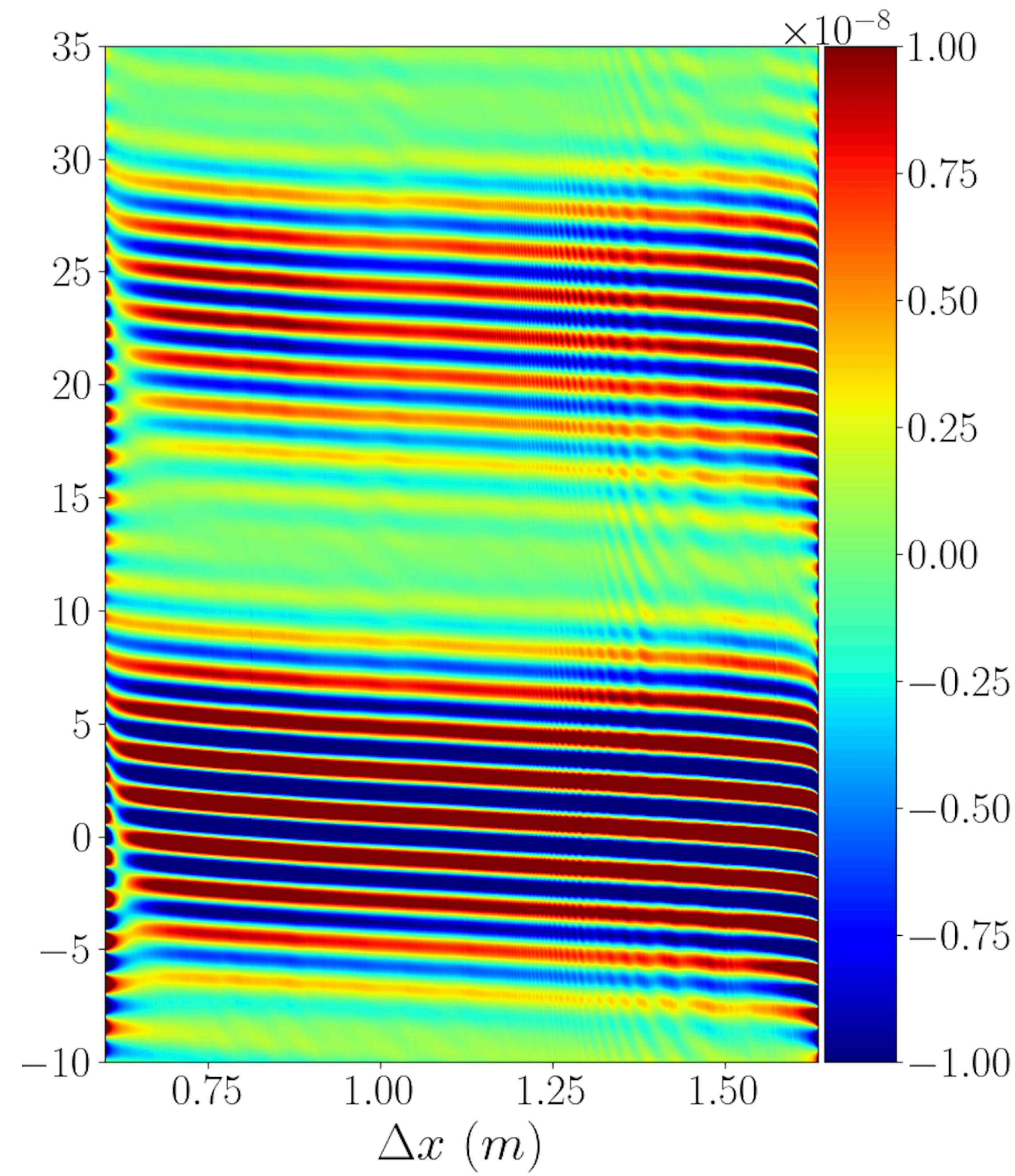


	Experimental	Numerical
$\|\alpha\|^2$		1.031
$\|\beta\|^2$		0.085
$\|\tau\|^2$		0.046
$\|\alpha\|^2 - \|\beta\|^2 + \|\tau\|^2$		0.992

A further mystery…

The main contribution on the supercritical side is…
a backwards-propagating wave?!





Summary and outlook

- We are able to realize **transcritical black-hole flows**
- Can probe with co-current waves
  - scattering **compatible with metric description**
- Can now excite dispersive waves, which may trigger **Hawking effect**
  - **negative-energy wave** appears to be produced
  - unknown reflected wave seen in supercritical region

Outlook:

- Provide a more **quantitative** analysis of Hawking, check against theory
- Explain unexpected phenomena
  - **Backwards-propagating mode** in supercritical region — a vorticity mode? (Biondi *et al.*, arXiv:2409.16864)
- Head towards controlled, systematic stimulation by dispersive waves using dedicated **wave maker**

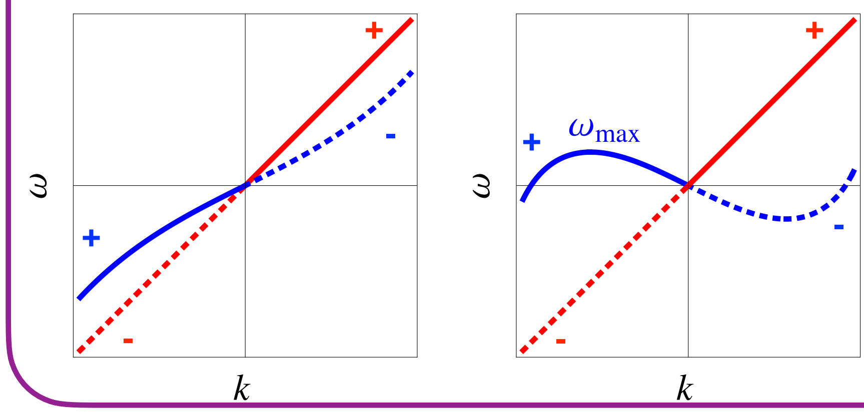
Backup slides

Introducing Vancouver…

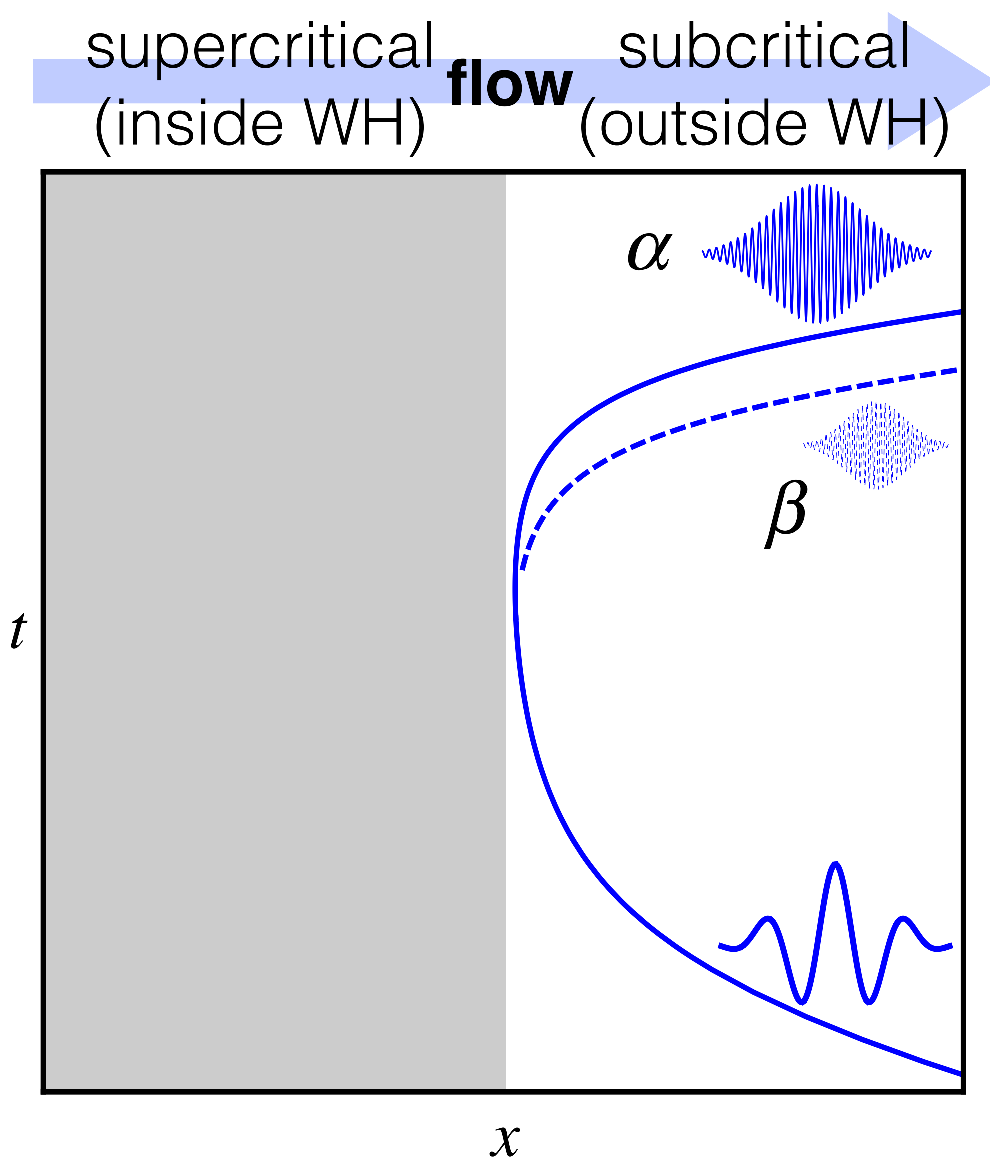
Wave scattering at a white hole

Waves are solutions of dispersion relation: $\omega - vk = \pm ck$ (Doppler shift)

co-moving frequency ⟶ **sign of norm**



- co-propagating waves
  — experience nothing special at horizon
- counter-propagating waves
  — “split” into **two** separate modes of **opposite energy**



$$|\alpha|^2 - |\beta|^2 = 1$$

$$|\beta|^2 = \frac{1}{e^{2\pi\omega/\kappa} - 1}$$

as before

(Inversion of 2x2 *S*-matrix)

Advantageous for experiment

- Long wavelengths ingoing (easily excited)
- Short wavelengths outgoing (easily measured)

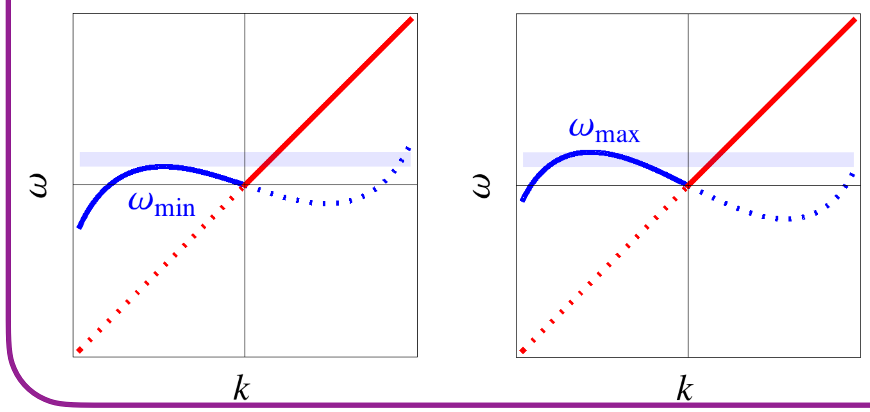
But: susceptible to breaking when transcritical

Consider instead purely **subcritical** flow…

Wave scattering at a "white hole"

Waves are solutions of dispersion relation: $\omega - vk = \pm ck$ (Doppler shift)

co-moving frequency ⟶ **sign of norm**



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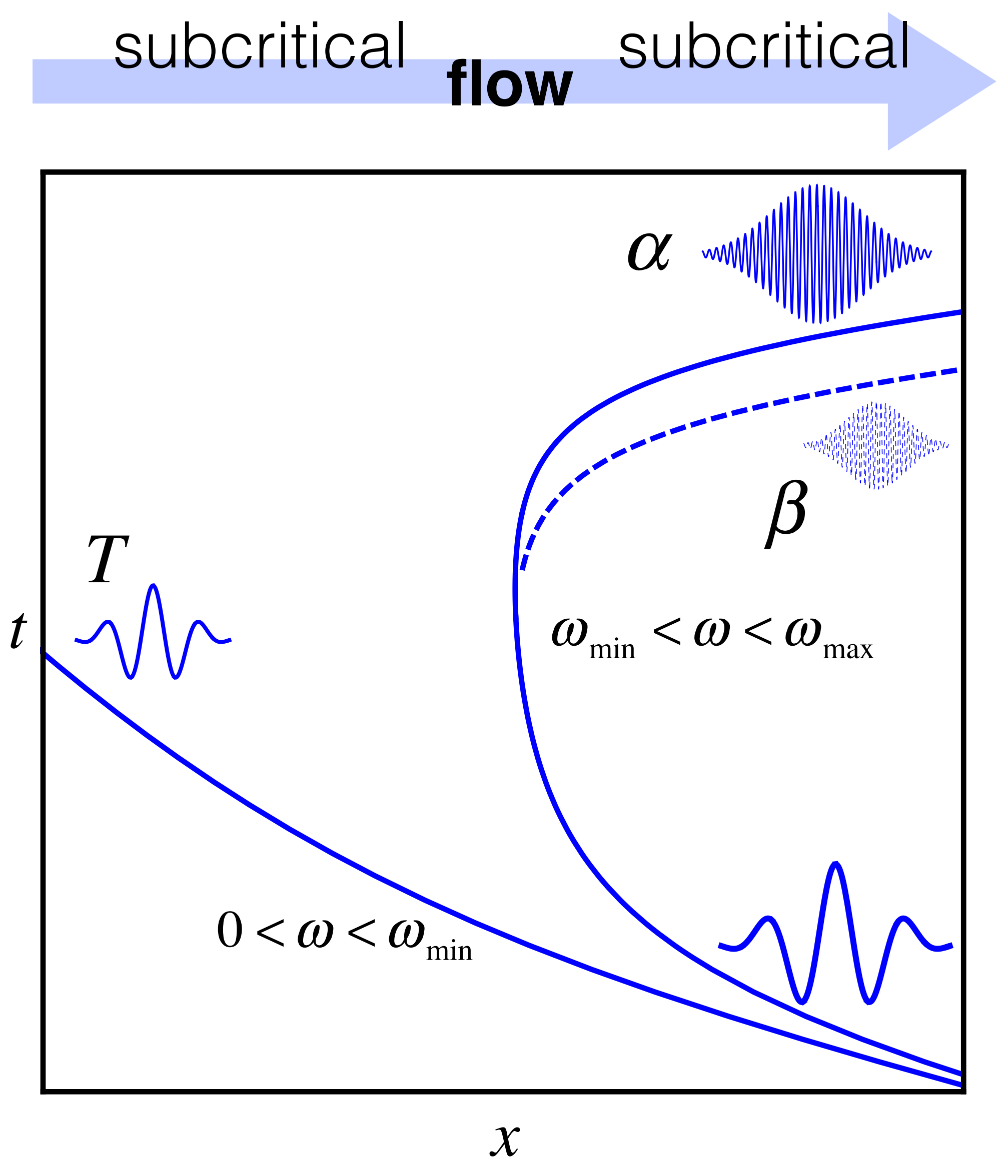

$$|\alpha|^2 - |\beta|^2 + |T|^2 = 1$$

transmission
(esp. at low frequency)

F Michel and R Parentani, PRD 90, 044033 (2014)

Wave scattering at a "white hole"

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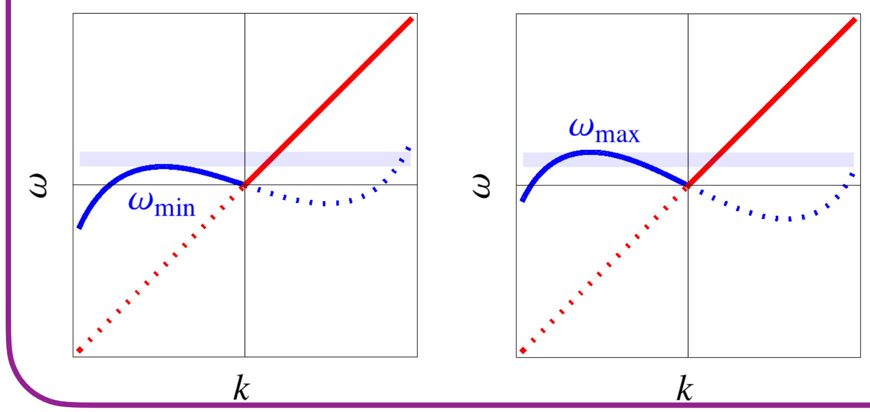

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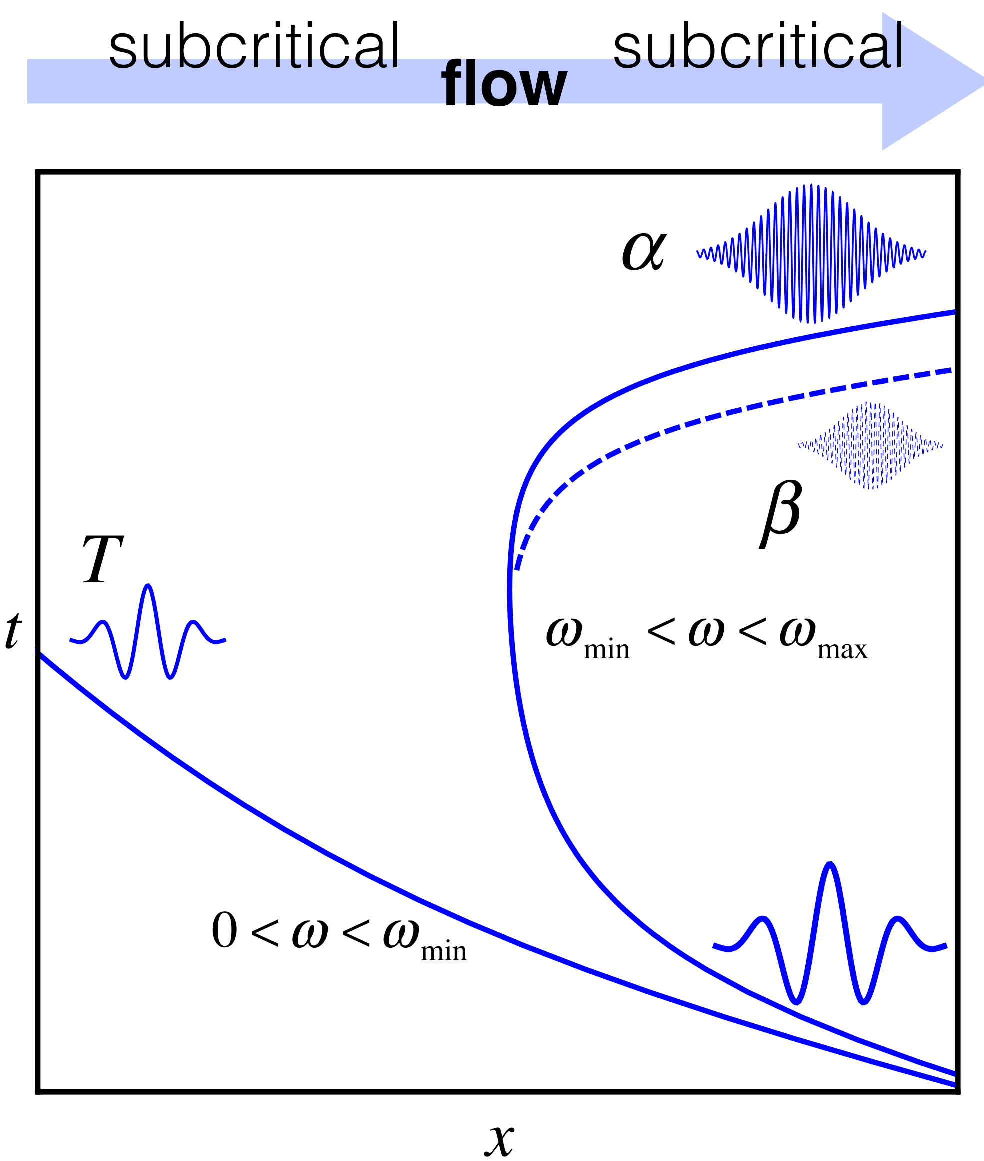

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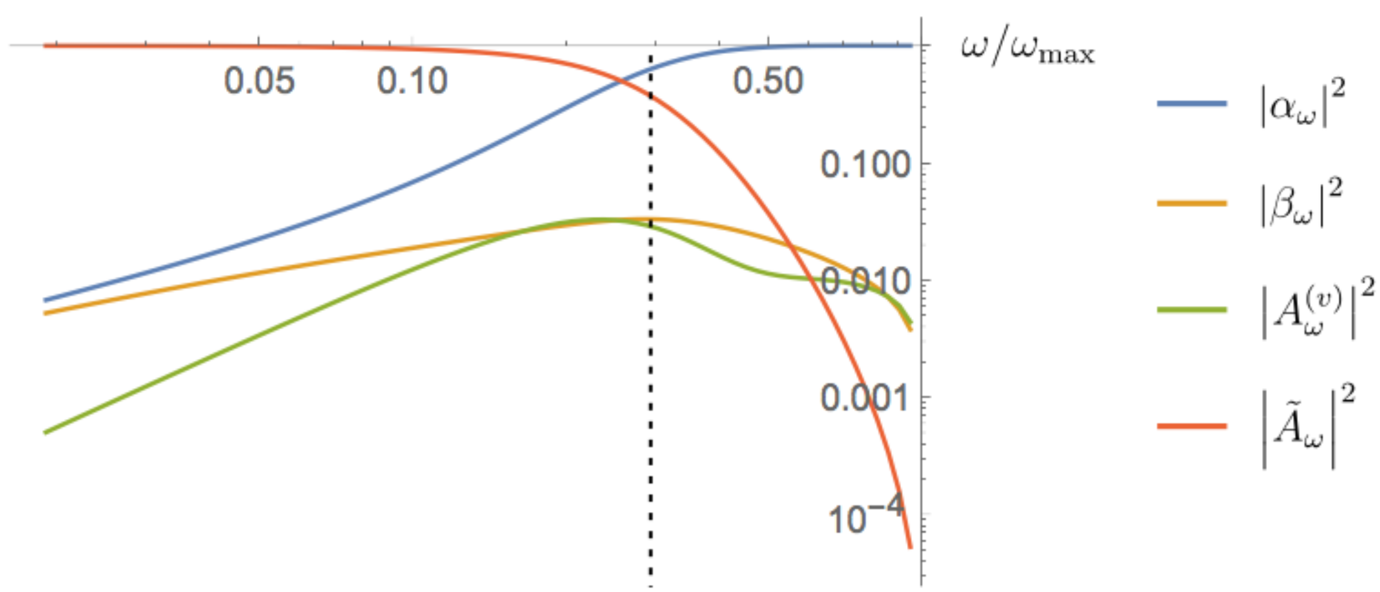
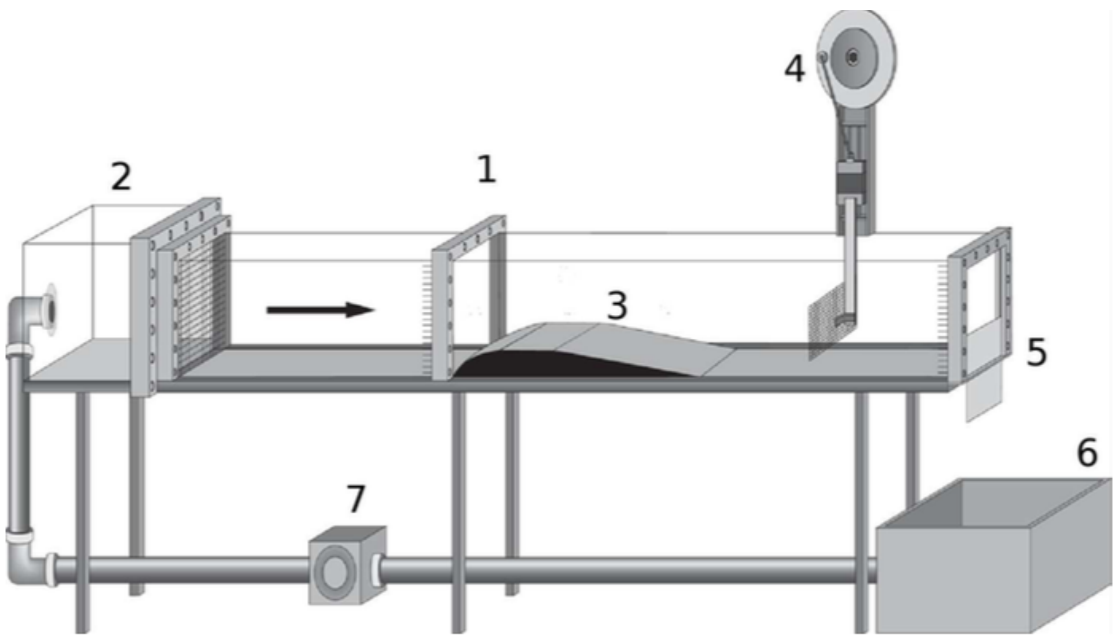


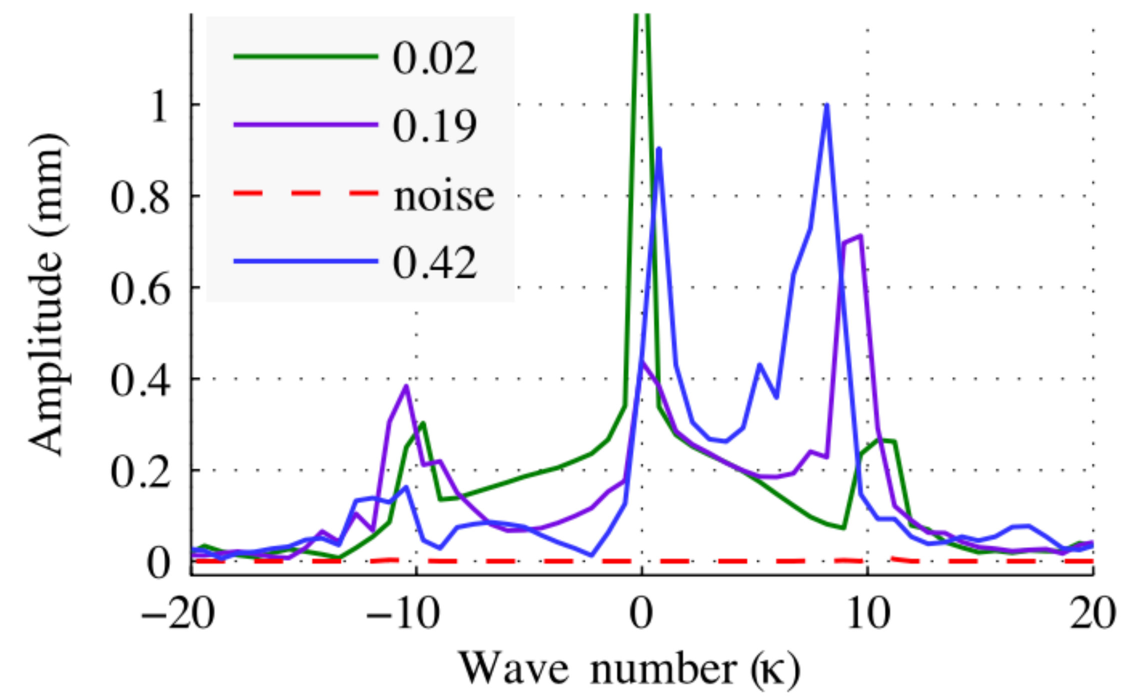
SR, F Michel and R Parentani, PRD 93, 124060 (2016)

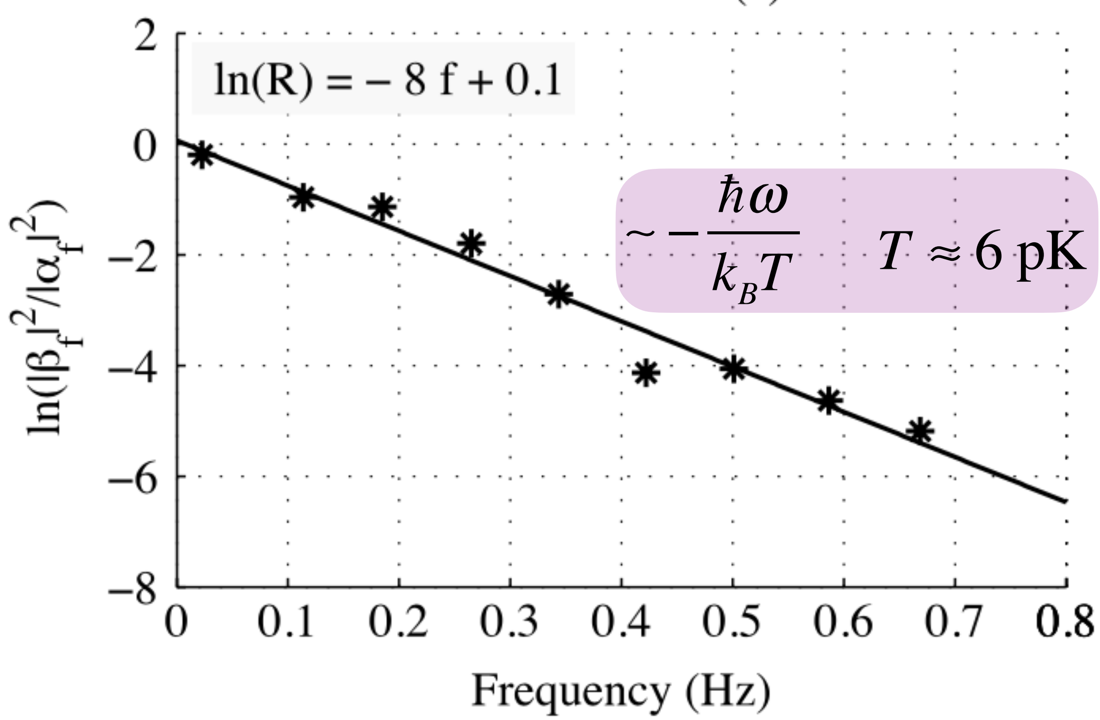
PRL **106,** 021302 (2011) PHYSICAL REVIEW LETTERS week ending 14 JANUARY 2011

Measurement of Stimulated Hawking Emission in an Analogue System

Silke Weinfurtner,[1] Edmund W. Tedford,[2] Matthew C. J. Penrice,[1] William G. Unruh,[1] and Gregory A. Lawrence[2]
[1]*Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada V6T 1Z1*
[2]*Department of Civil Engineering, University of British Columbia, 6250 Applied Science Lane, Vancouver, Canada V6T 1Z4*
(Received 30 August 2010; published 10 January 2011)







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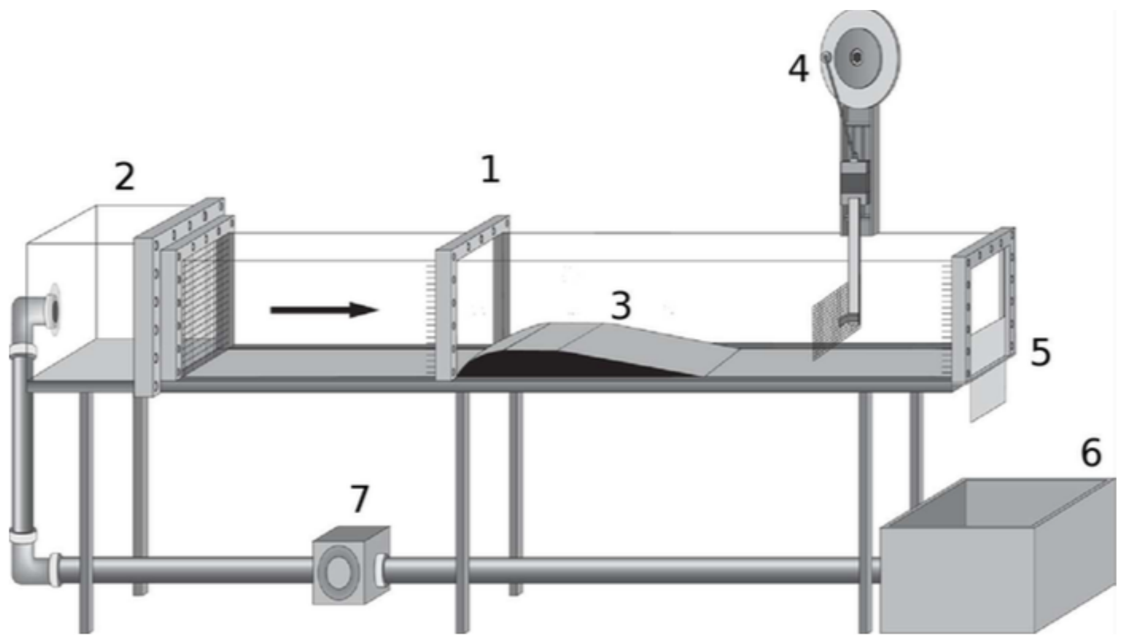
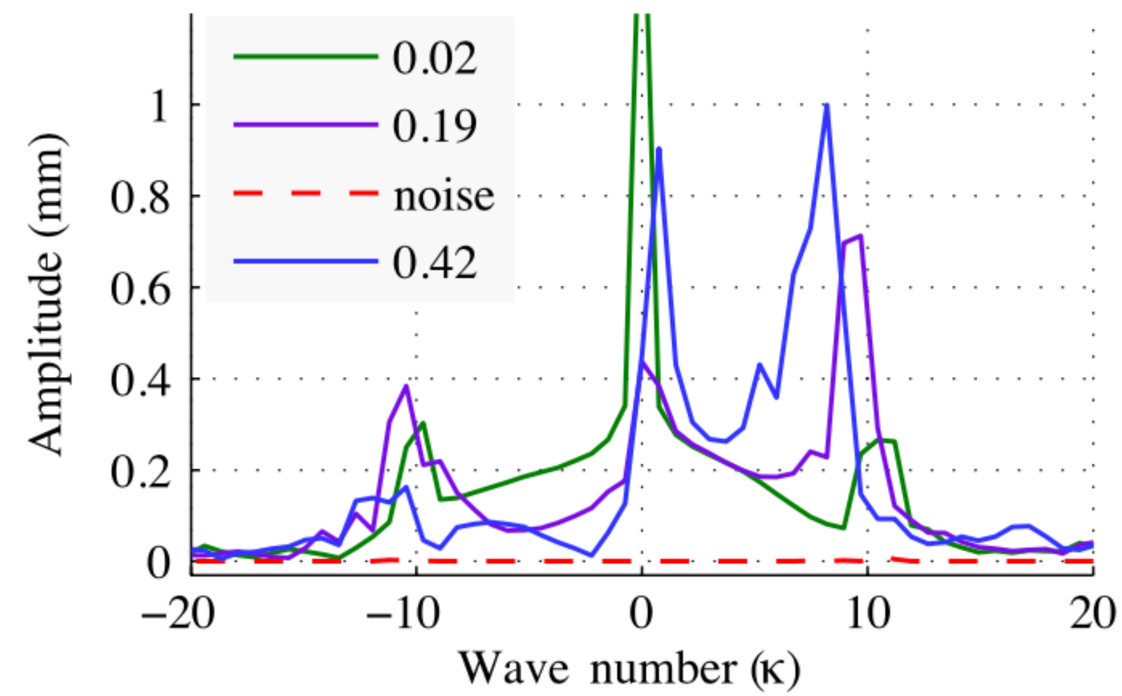




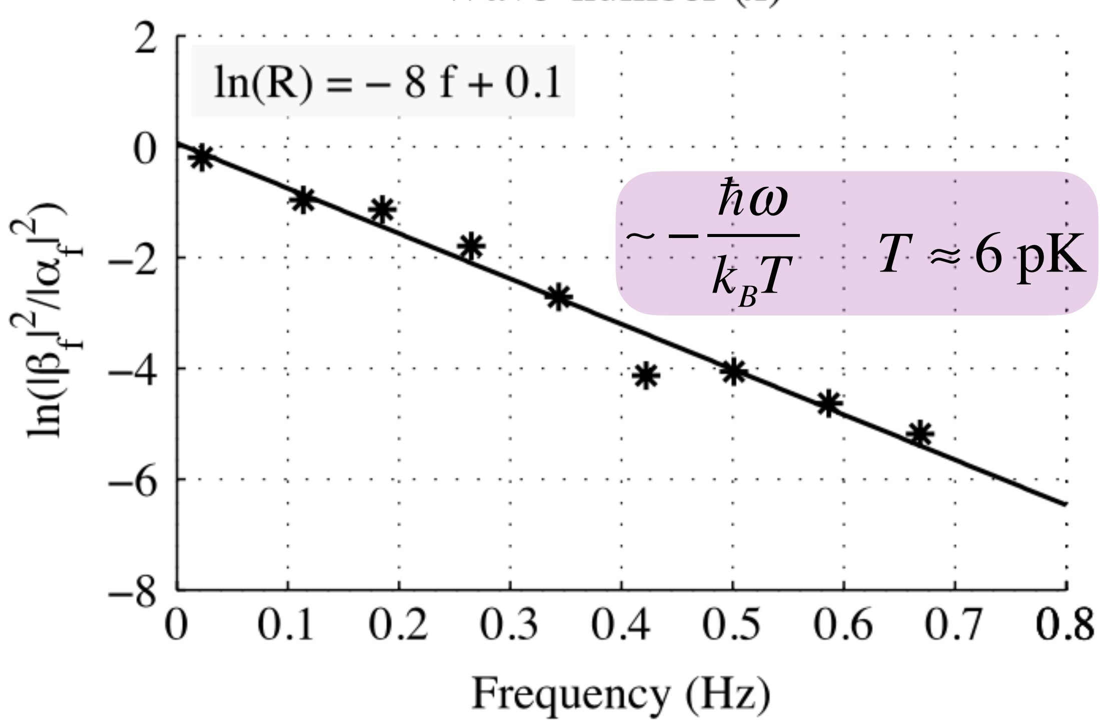
Purely subcritical flow

Anomalous scattering allowed by dispersion

$$|\alpha|^2 - |\beta|^2 + |T|^2 = 1$$

No horizon in effective metric

No thermal prediction in Hawking/Unruh sense



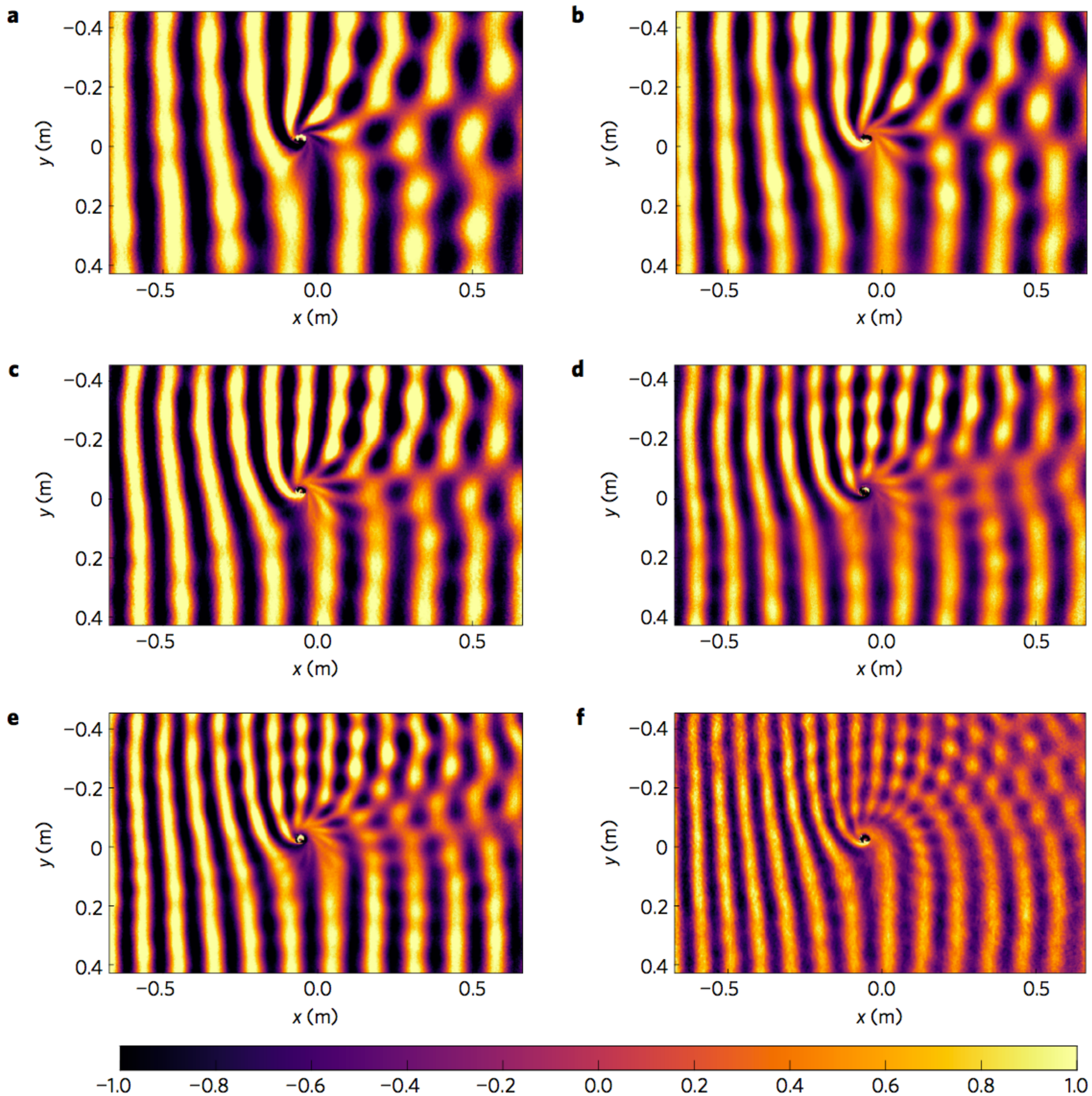
nature physics

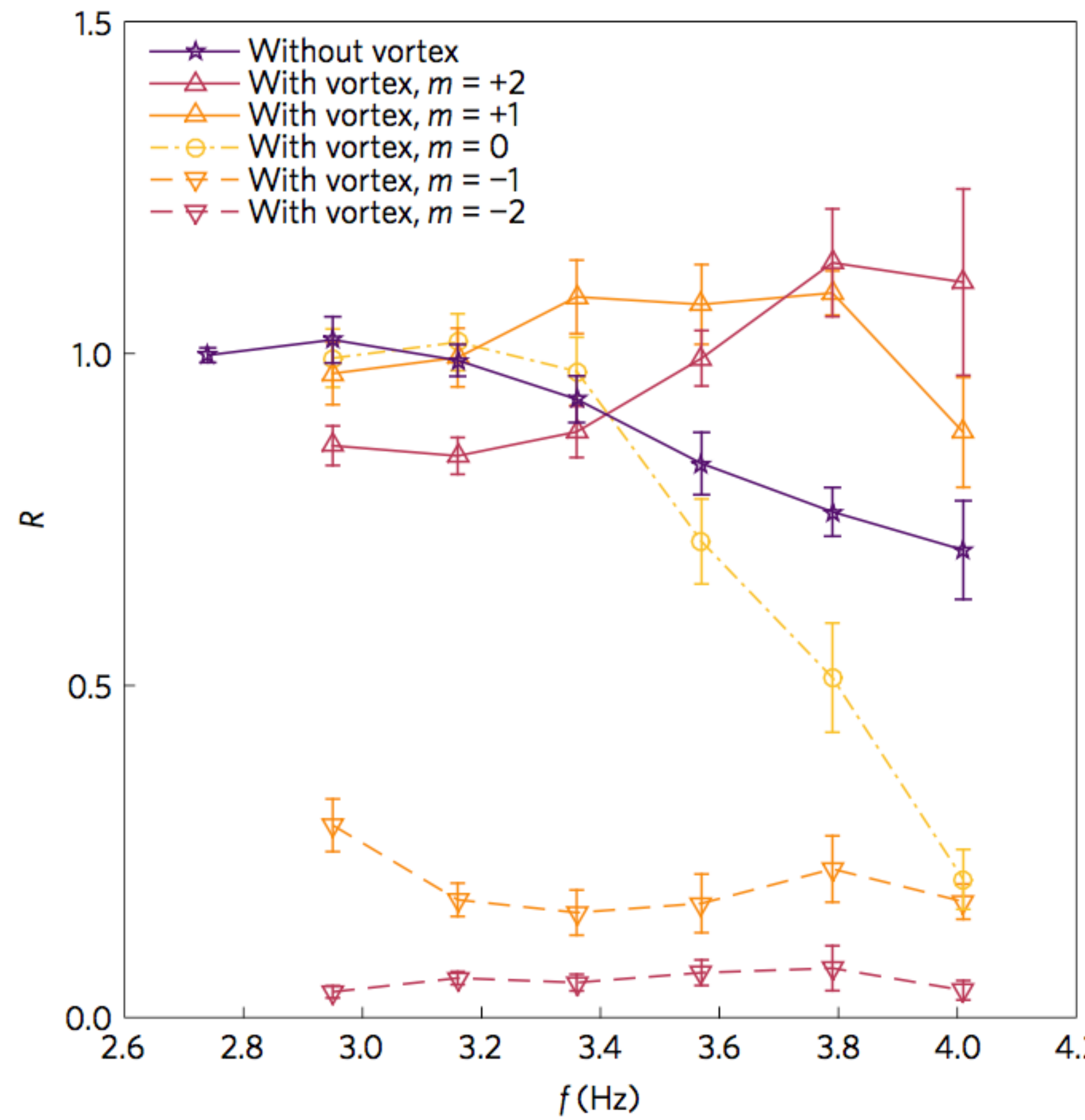
LETTERS

PUBLISHED ONLINE: 12 JUNE 2017 | DOI: 10.1038/NPHYS4151

Rotational superradiant scattering in a vortex flow

Theo Torres[1], Sam Patrick[1], Antonin Coutant[1], Maurício Richartz[2], Edmund W. Tedford[3] and Silke Weinfurtner[1,4,5]*

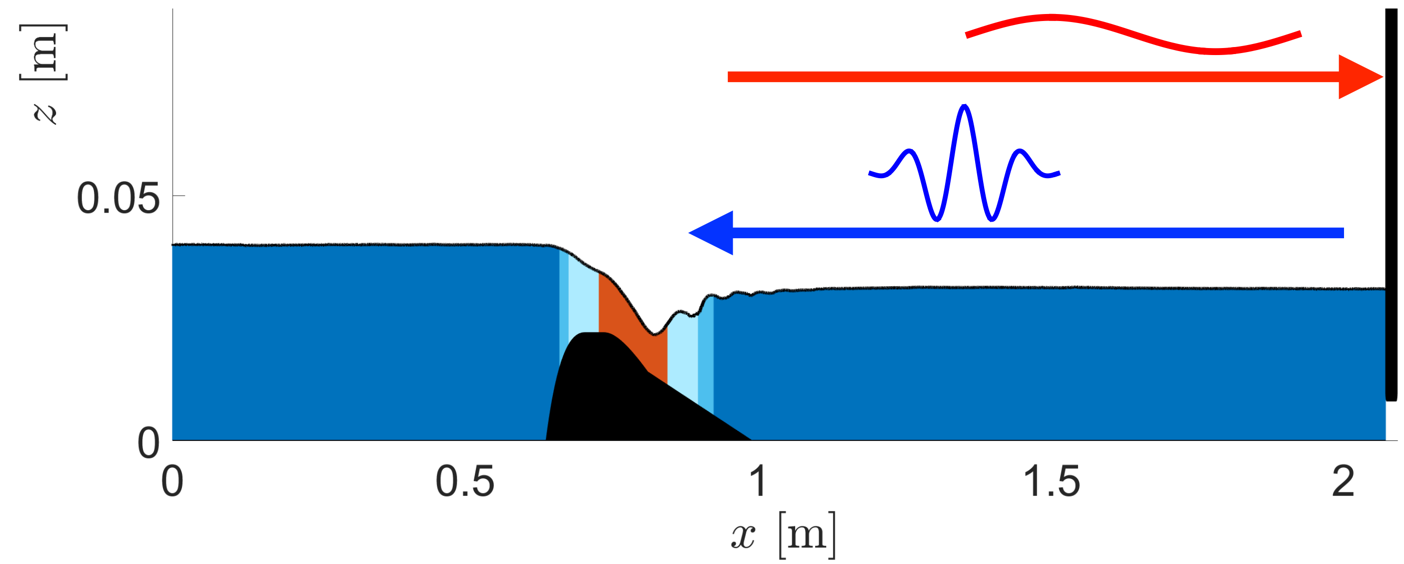




Gated flows: Is there a WH Hawking effect?

J. Fourdrinoy *et al.*, *Phys. Rev. D* **105**, 085022 (2022)

Hawking effect **expected** since hydrodynamical waves reflected by gate and incident on WH horizon:



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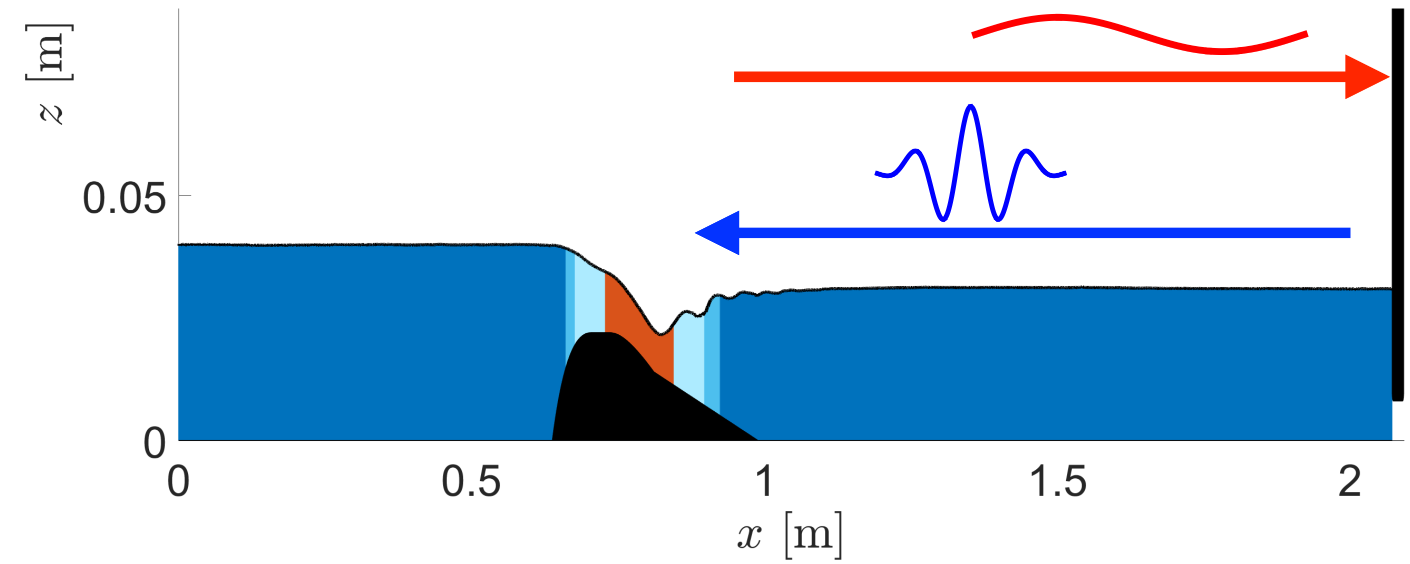
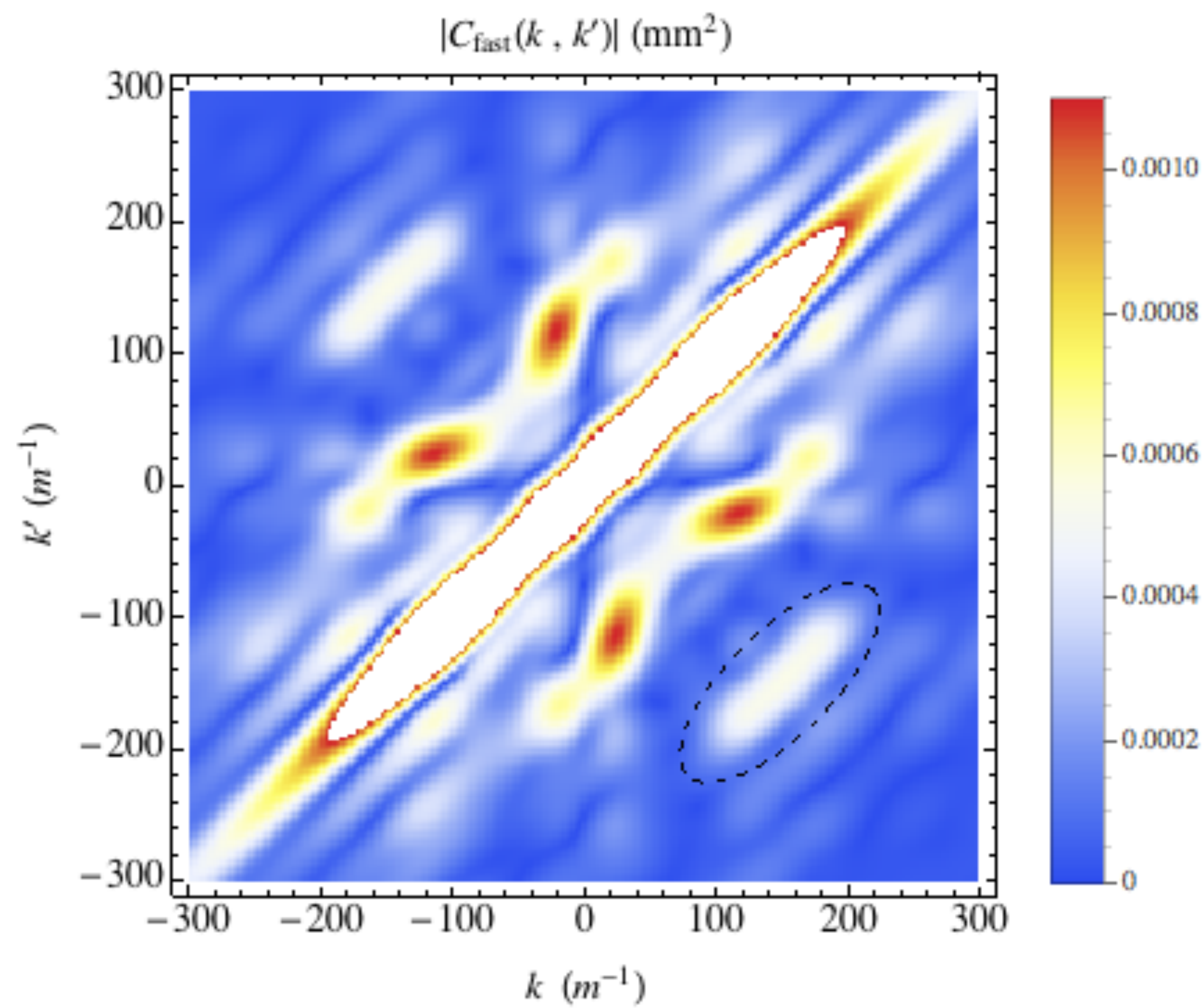


Consider k-space correlations:

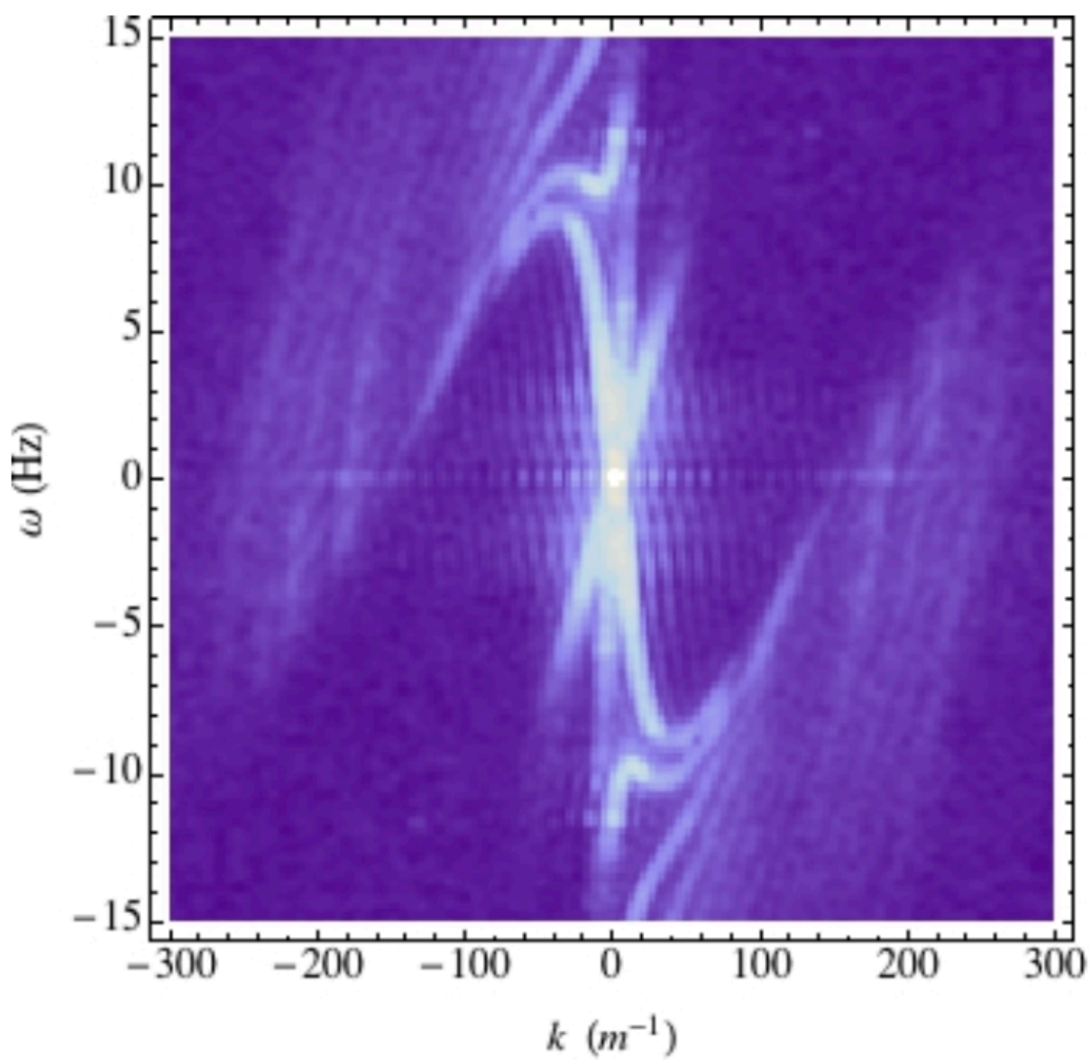
$$C(k,k') = \left\langle \delta\widetilde{h}(k,t)\, \delta\widetilde{h}^{\star}(k',t) \right\rangle_t$$



1-slide Interlude: Scattering of additional mode?

Dispersion relation

(in upstream region)



Fixed-point correlation

$$\left\langle \delta h(t+\Delta t, x)\, \delta h(t, x_0) \right\rangle_t$$