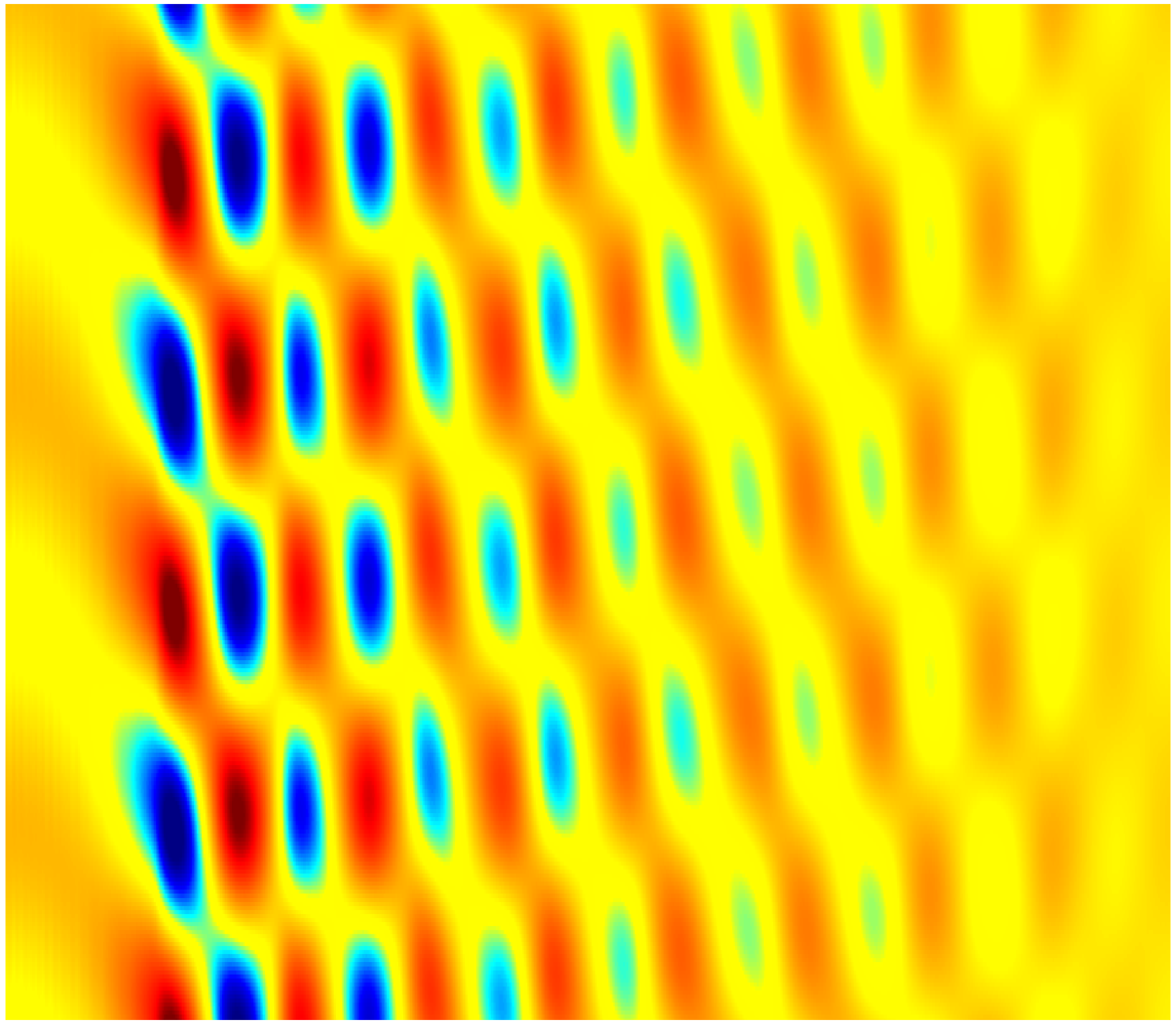
Phys. Rev. Lett. 106, 021302 (2011)

Measurement of *stimulated* Hawking emission in an analogue system

- Greg Lawrence
- Matt Penrice
- Ted Tedford
- Bill Unruh

Silke Weinfurtner



Semi-classical gravity ➤ (Q)FT in curved spaces

Gravitational field is classical and **back-reaction** of the quantum processes onto the classical gravitational field are **negligible**.

Simple example:

(i) waves propagating on **flat** spacetime (massless minimally coupled Klein-Gordon scalar field):

$$\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\psi = \nabla^2\psi \quad \text{equivalently to} \quad \partial_a\left(\sqrt{-\eta}\,\eta^{ab}\partial_b\,\psi\right) = 0 \quad \text{where} \quad \eta_{ab} = \begin{bmatrix} -c^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

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↓

(ii) "minimal substitution" **curved** spacetime :

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(iii) quantized Klein-Gordon scalar on generally curved-spacetime:

$$\partial_a\left(\sqrt{-g}\,g^{ab}\partial_b\,\hat{\psi}\right) = 0 \quad \text{where} \quad G_{ab}(g_{ab},\Lambda) \not= 8\pi G_{\mathrm{N}}\,\langle \hat{T}_{ab}\rangle$$

QFT in CS ➤ Analogue/Effective Gravity

Analogue gravity systems:

The equations of motion for linear perturbations in an analogue/effective/emergent gravity system can be simplified to

$$\frac{1}{\sqrt{-g}}\partial_a\left(\sqrt{-g}g^{ab}\partial_b\psi\right) = 0$$

defining an effective/acoustic/emergent metric tensor:

$$g_{ab} \propto \begin{bmatrix} -\left(c^2(\mathbf{x},t) - v^2(\mathbf{x},t)\right) & -\vec{v}^T(\mathbf{x},t) \\ -\vec{v}(\mathbf{x},t) & \mathbf{I}_{d\times d} \end{bmatrix}$$

Where do we expect such a behavior?

Broad class of systems with various dynamical equations, e.g. electromagnetic waveguide, fluids, ulatra-cold gas of Bosons and Fermions.

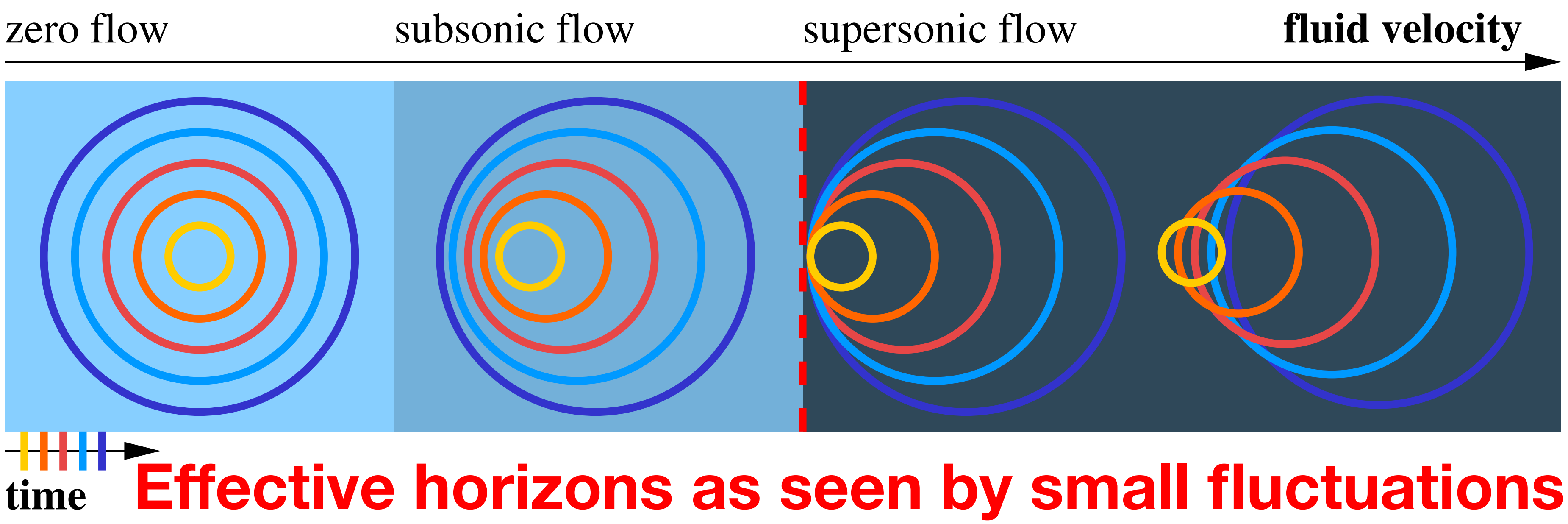
In example below: Fluid dynamics derived from conservation laws:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\,\mathbf{v}) = 0 \quad \textit{Continuity equation}$$

$$\rho\frac{D\mathbf{v}}{Dt} = -\nabla p \quad \textit{Euler equation}$$

Simple example:

Small fluctuations in **inviscid**, **irrotational**, **incompressible** fluid flow



Effective horizons as seen by small fluctuations

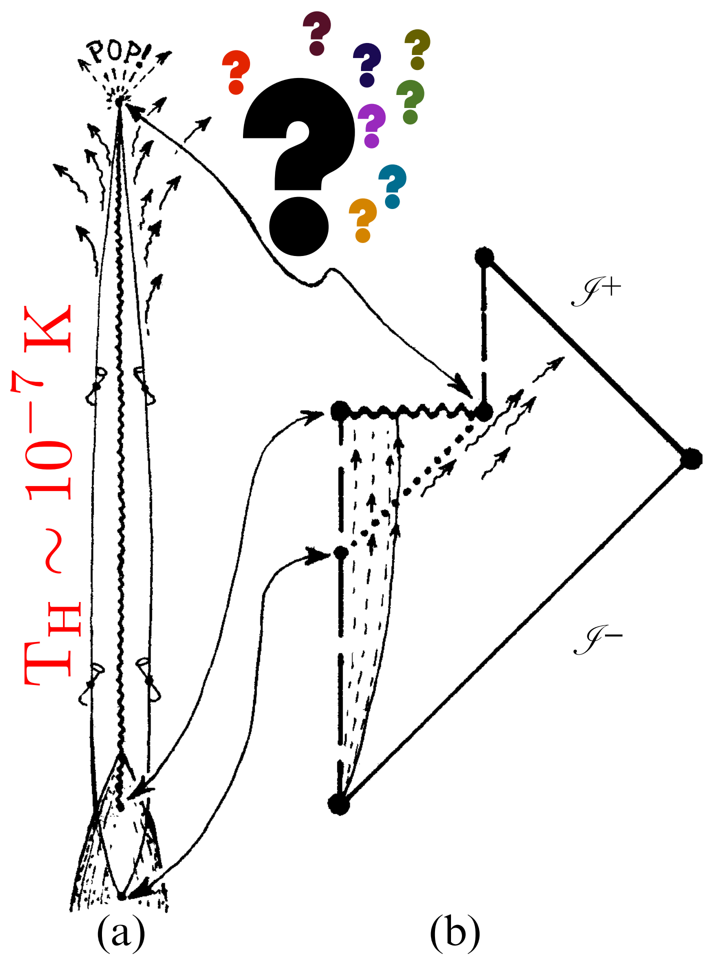
Analogue Gravity ➤ Applications

Let us first put aside the issue of classical versus quantum field theory in curved spacetimes...

1981: **Experimental black hole evaporation?** W.G. Unruh

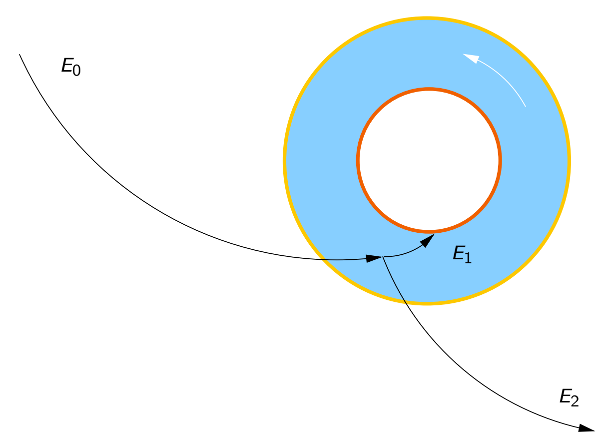
Possibility for experimental verification of the generality (UV-independence) of effects predicted within quantum field theory in curved spacetimes!

Analogy Gravity: Strong model dependent deviations and eventual break-down at 'small' scales expected!



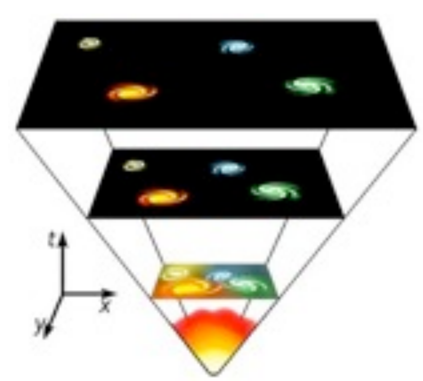
Example 1:

Experimental Black Hole Evaporation



Example 2:

Superradiant scattering from rotating black holes

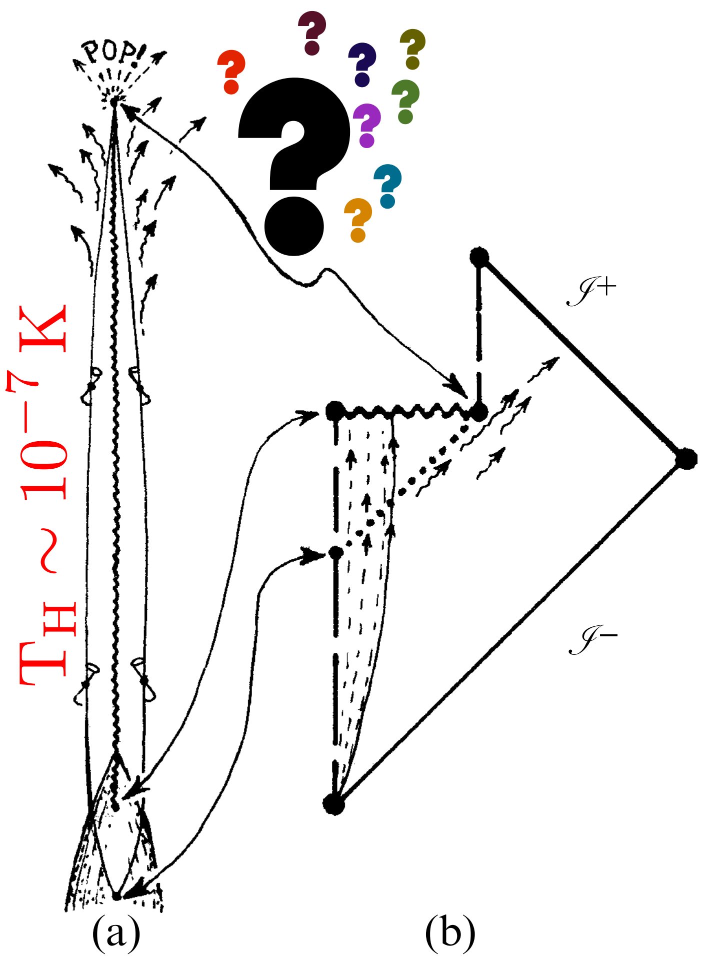


Example 3:

Cosmological particle production

Experimental Black Hole Evaporation [**Example 1**]

How do black holes lose their mass..?



Example 1:

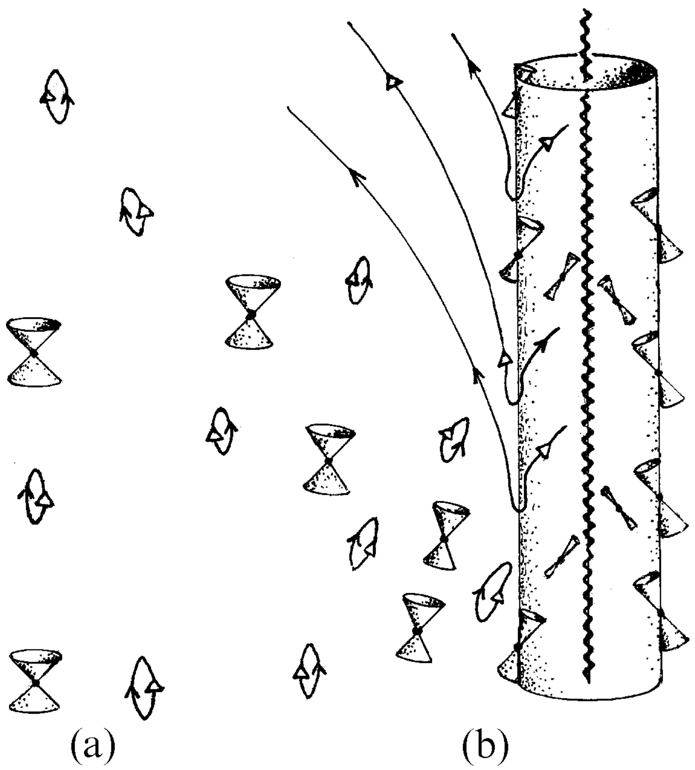
Experimental Black Hole Evaporation

(1) What is Hawking radiation?

(2) Is there a reason why we should at all doubt that black holes evaporate..?

(3) How can we set up a table-top experiment that "conclusively" tests Hawking/Unruh's prediction?

BHE process ➤ What is Hawking radiation?

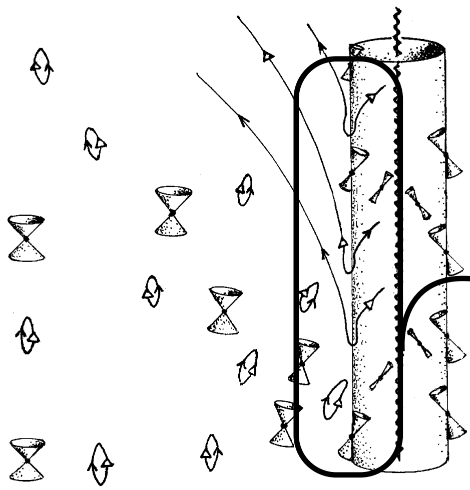


<u>Pair-creation:</u>
Separation of particle-anti-particle pairs from the quantum vacuum;
Negative norm modes absorbed by black hole;
[Particle Creation by Black Holes, by Stephen Hawking, in 1974]

$$\phi_{\omega}^{\mathbf{in}} = \alpha_{+}^{\mathbf{out}} + \beta_{-}^{\mathbf{out}}$$

Let's try to understand Hawking radiation as a simple scattering process...

BHE process ➤ What is Hawking radiation?



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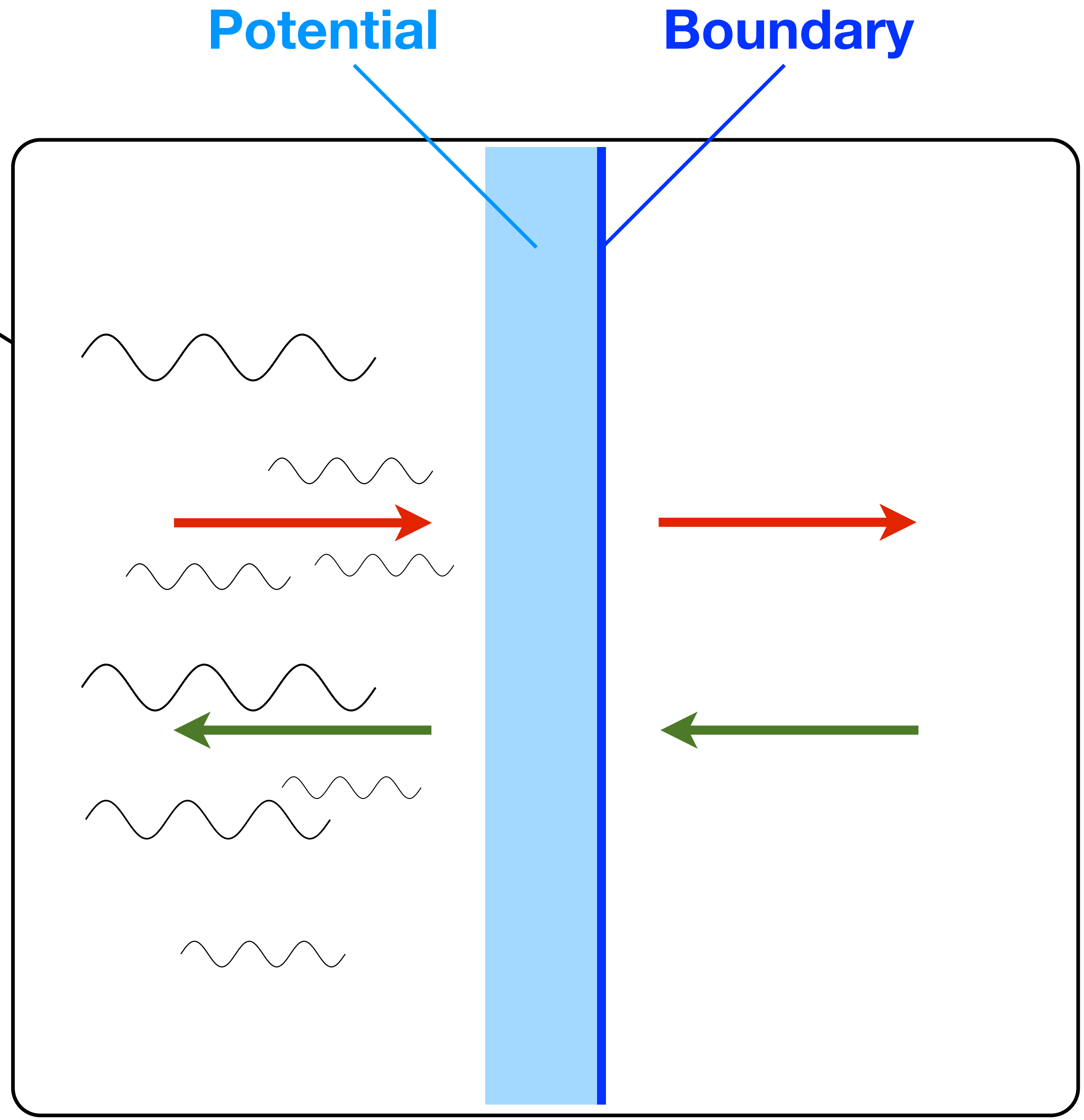
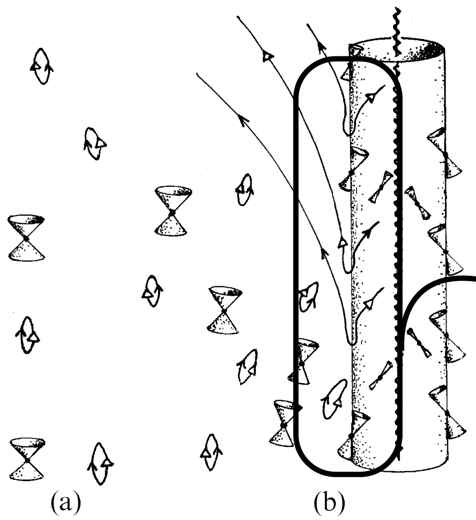


Right moving modes

Left moving modes

BHE process ➤ What is Hawking radiation?



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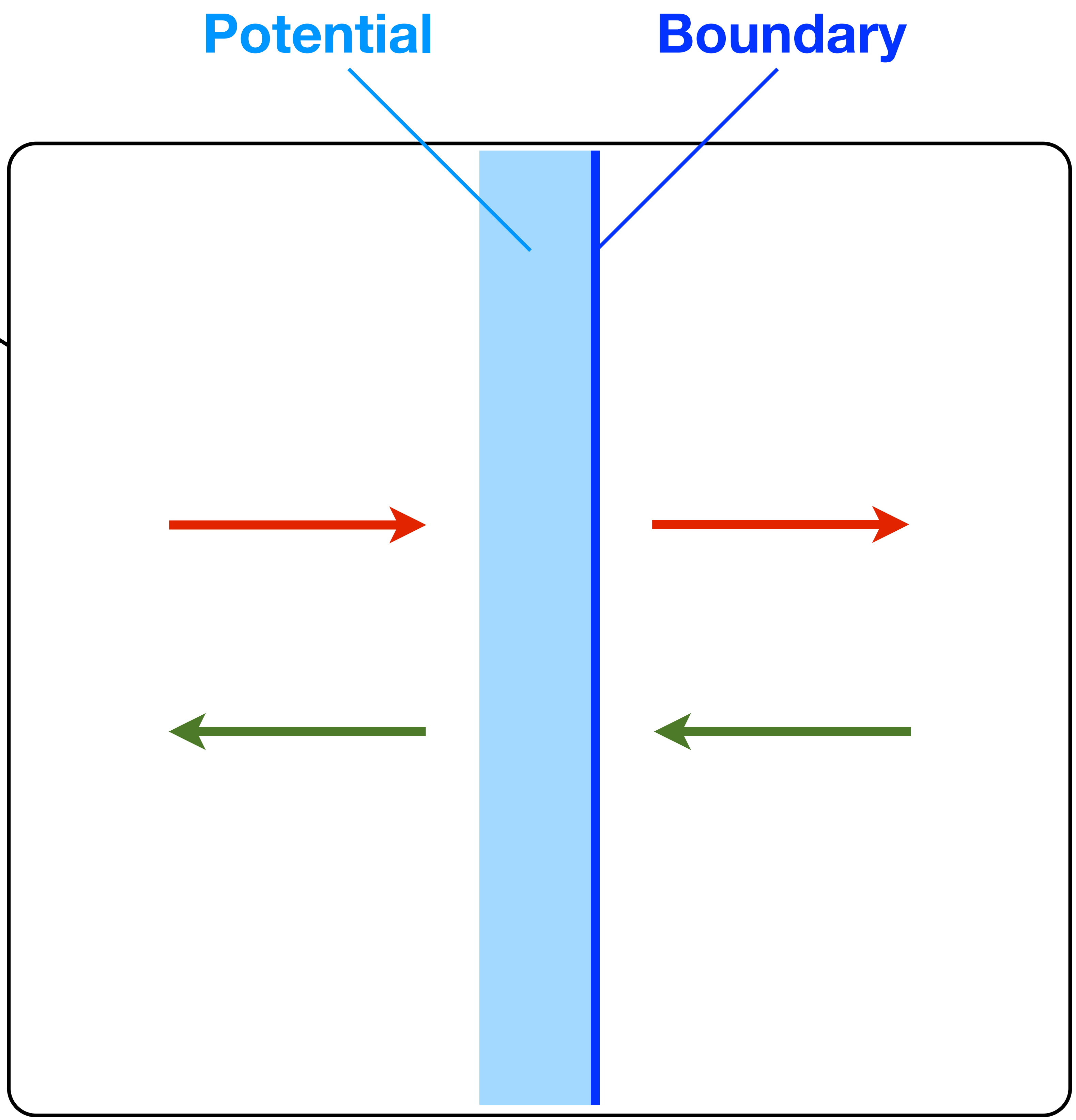

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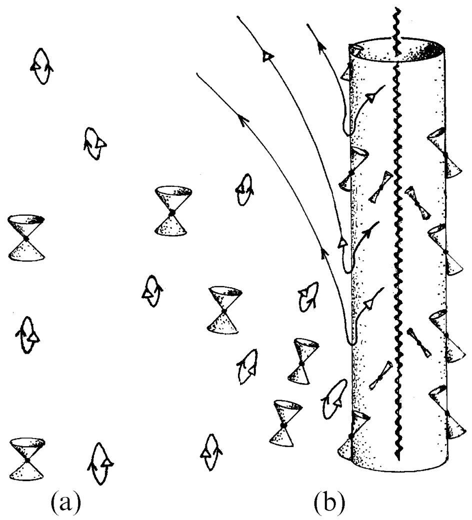

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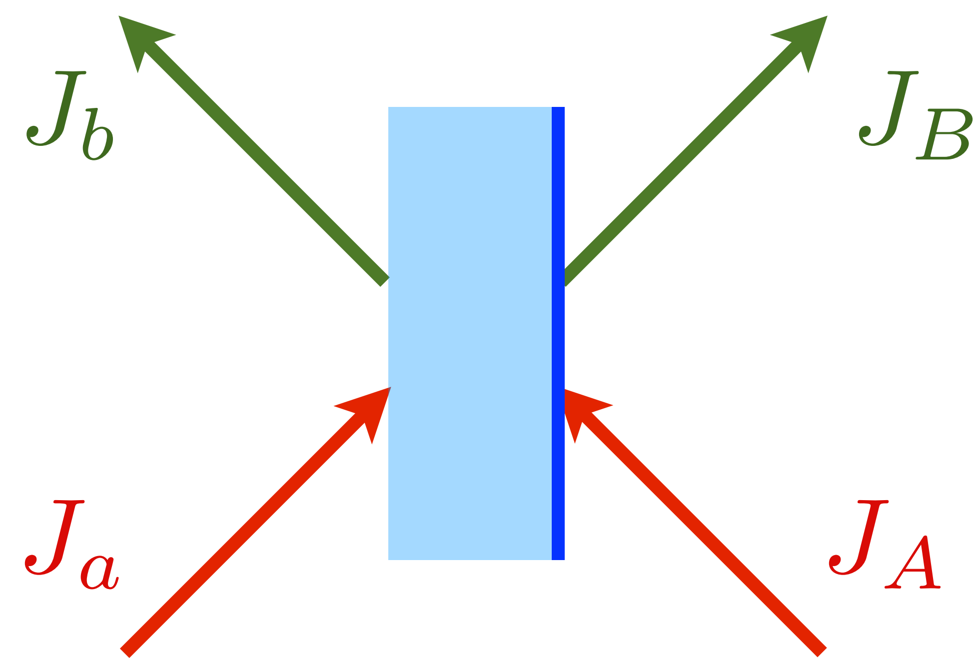
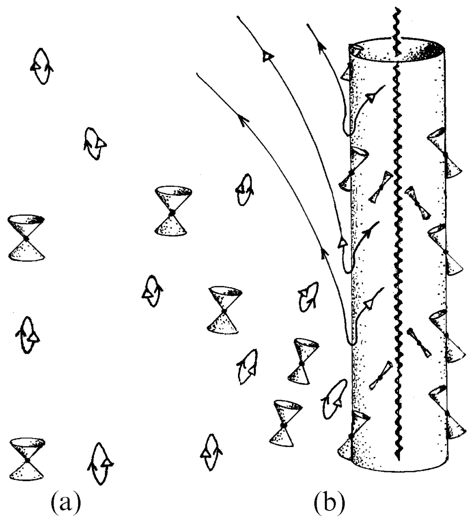
Modes moving into potential

Modes moving out of potential



$$J_a + J_A = J_b + J_B$$

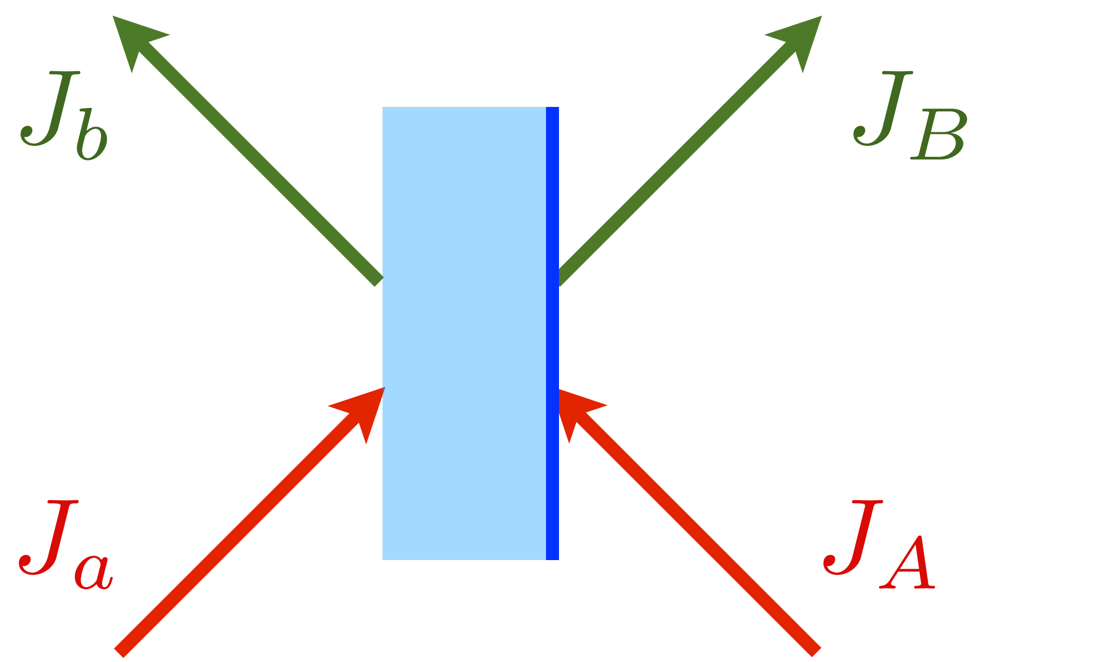
BHE process ➤ What is Hawking radiation?



$$\phi_\omega^{\mathbf{in}} = \alpha_+^{\mathbf{out}} + \beta_-^{\mathbf{out}}$$

Conserved quantity: Particle current:

$$J_n := |A_n|^2 \, \Omega|_{\pm\infty} \, \frac{d\omega}{dk}\bigg|_{k_n}$$



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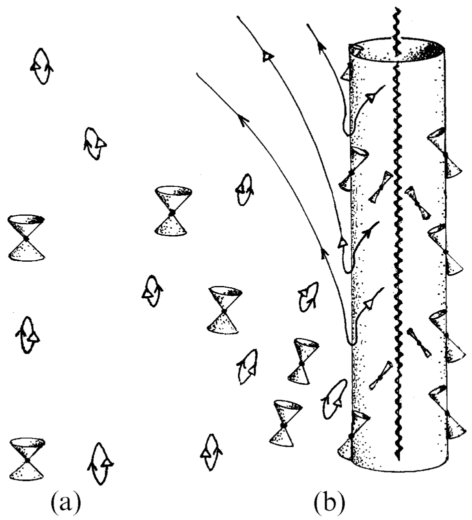

$$\phi_\omega^{\mathbf{in}} = \alpha_+^{\mathbf{out}} + \beta_-^{\mathbf{out}}$$

$$\frac{|\beta_\omega|^2}{|\alpha_\omega|^2} = e^{-\frac{2\pi\omega}{g_{\mathrm{H}}}} = e^{-\frac{\hbar\,\omega}{k_B \mathbf{T}}}$$

$$|\alpha_\omega|^2 - |\beta_\omega|^2 = 1$$

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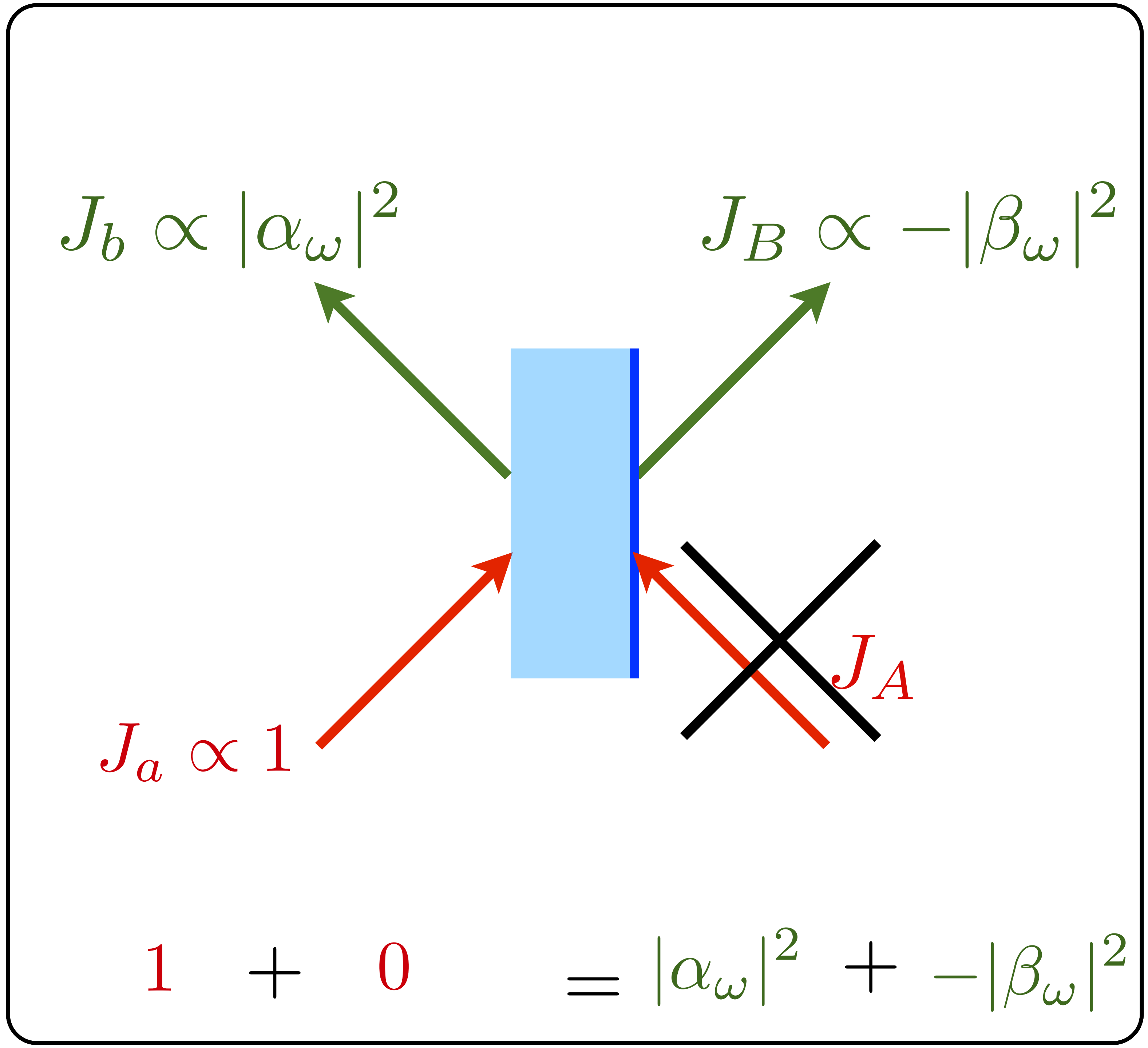
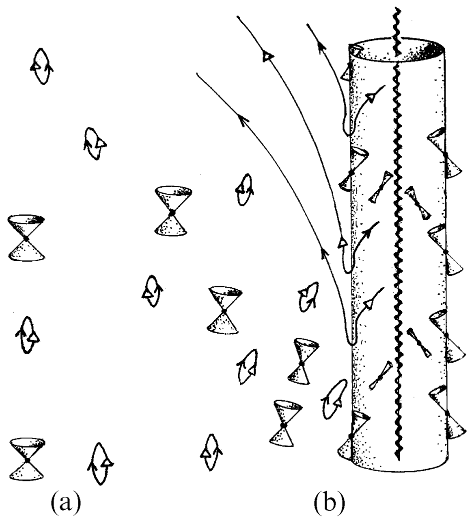


Black holes: Linear Classical and Quantum Field Amplifier!

BHE process ➤ What is Hawking radiation?



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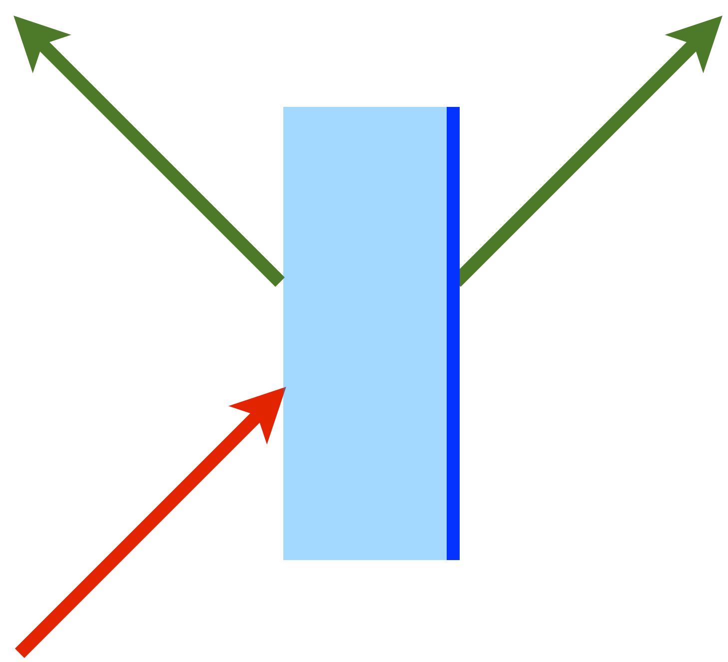
$$\phi_\omega^{\mathbf{in}} = \alpha_+^{\mathbf{out}} + \beta_-^{\mathbf{out}}$$

$J_b \propto |\alpha_\omega|^2$ $J_B \propto -|\beta_\omega|^2$



$J_a \propto 1$

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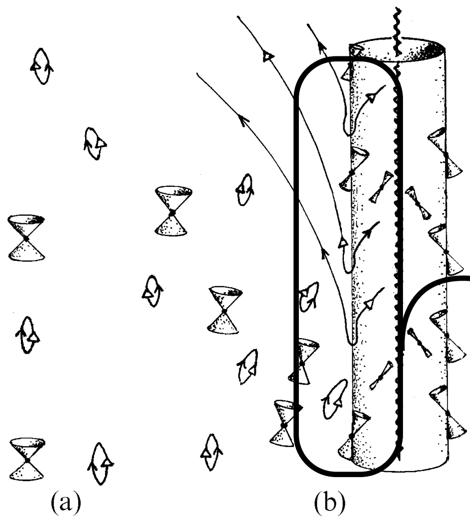
$$|\alpha_\omega|^2 - |\beta_\omega|^2 = 1$$

$$1 + 0 = |\alpha_\omega|^2 + -|\beta_\omega|^2$$

Black holes: Linear Classical and Quantum Field Amplifier!

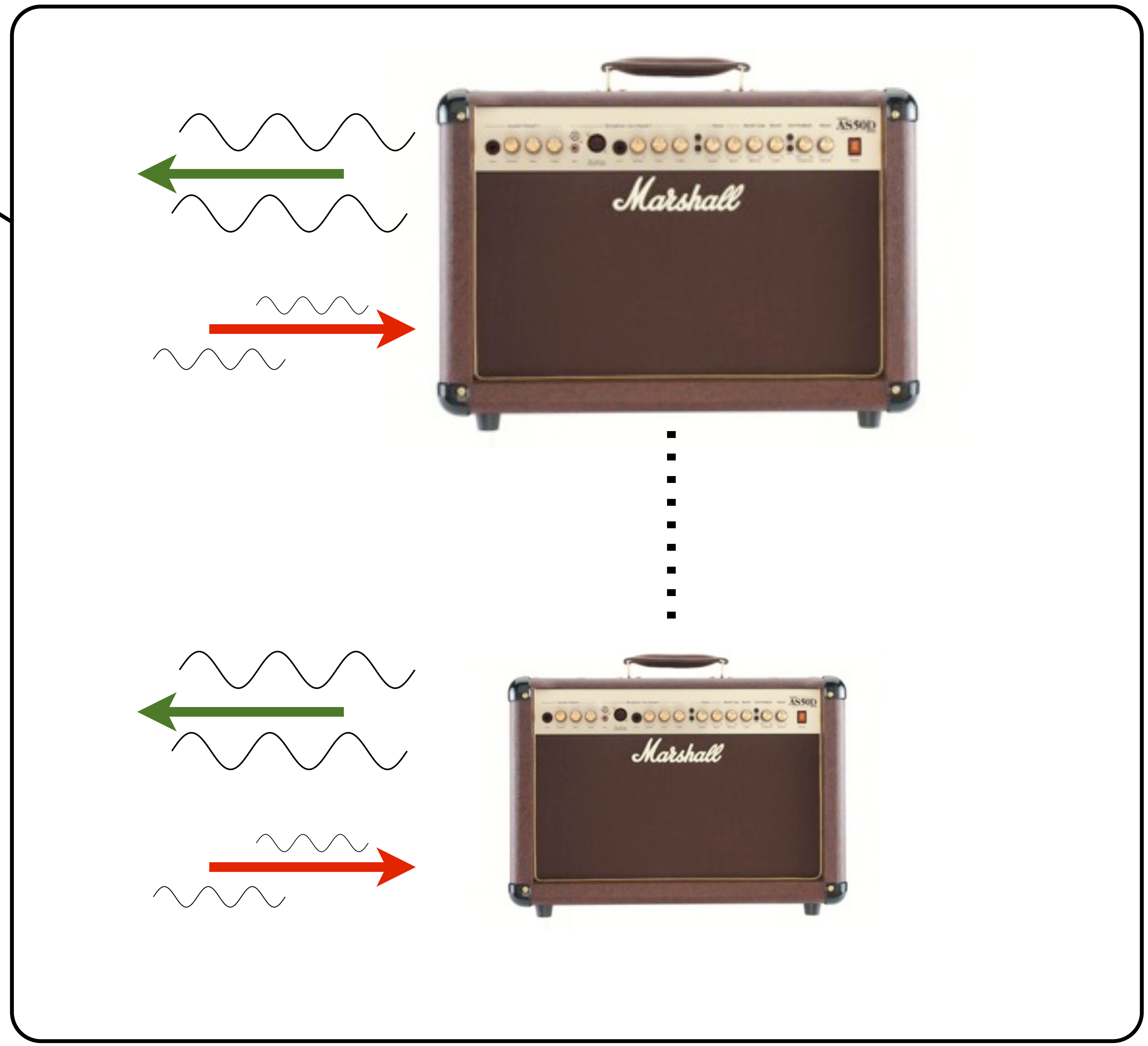
BHE process ➤ What is Hawking radiation?



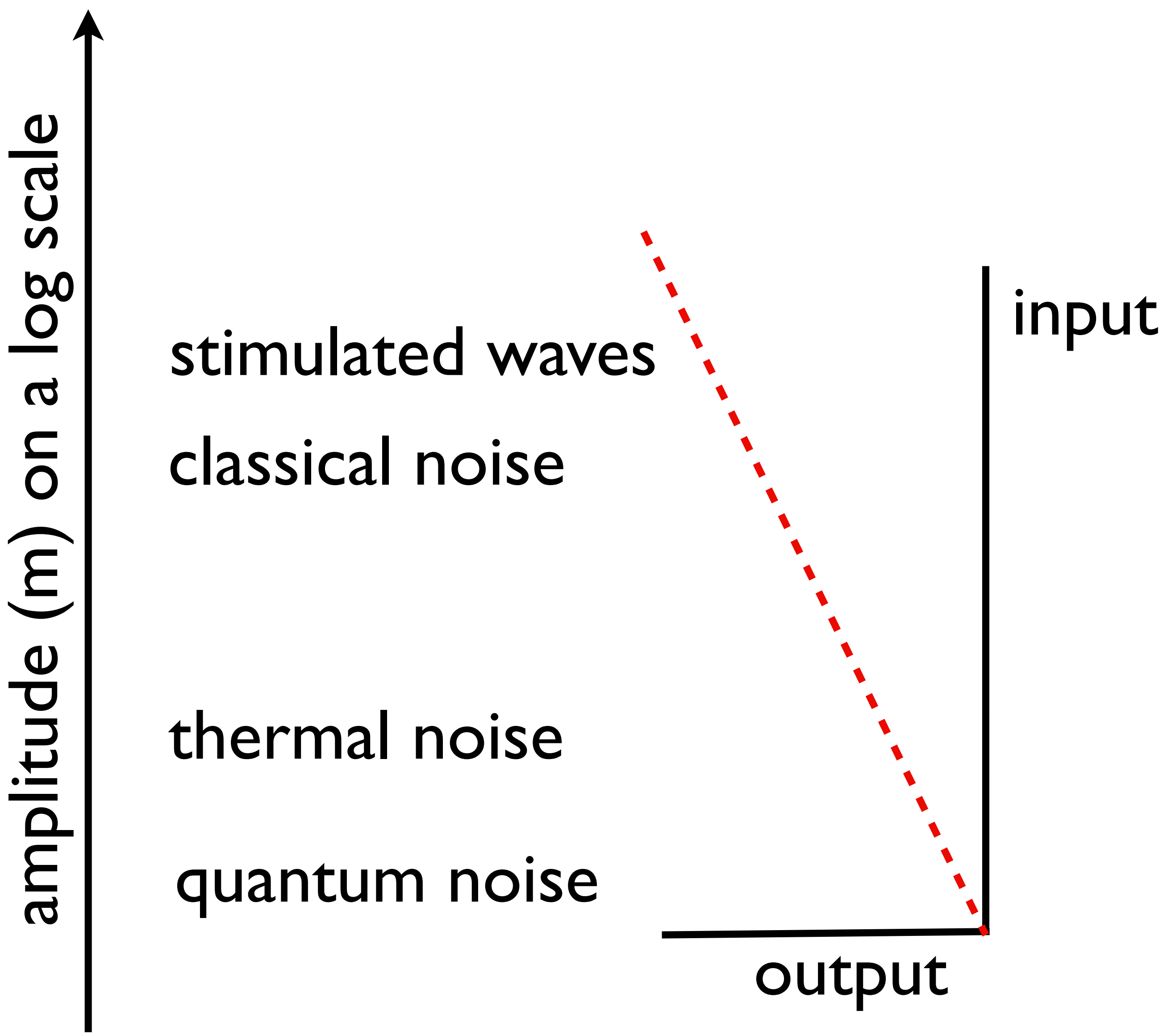
$$\phi^{\mathbf{in}}_{\omega} = \alpha^{\mathbf{out}}_{+} + \beta^{\mathbf{out}}_{-}$$

$$\frac{|\beta_\omega|^2}{|\alpha_\omega|^2} = e^{-\frac{2\pi\omega}{g_{\mathrm{H}}}}$$

- ✔ pair-creation process
- ✔ Boltzmann distribution
- ✔ surface gravity



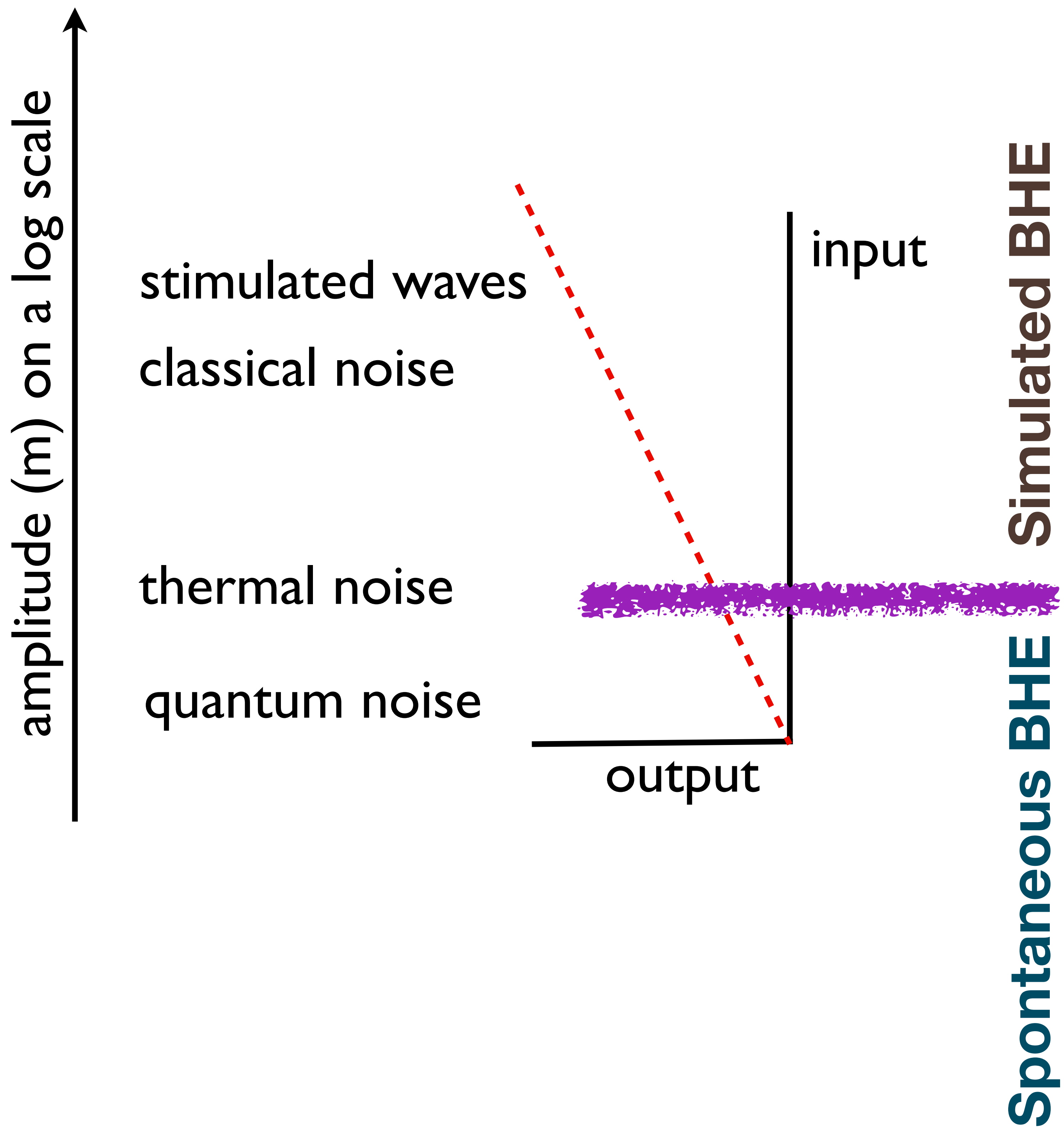
BHE process ➤ What is being amplified?



Assumption:
Linear amplifier over a huge range!

✔ pair-creation process (classical correlations)
✔ Boltzmann distribution
✔ surface gravity

BHE process ➤ What is being amplified?



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✔ Boltzmann distribution

✔ surface gravity

✔ quantum correlations

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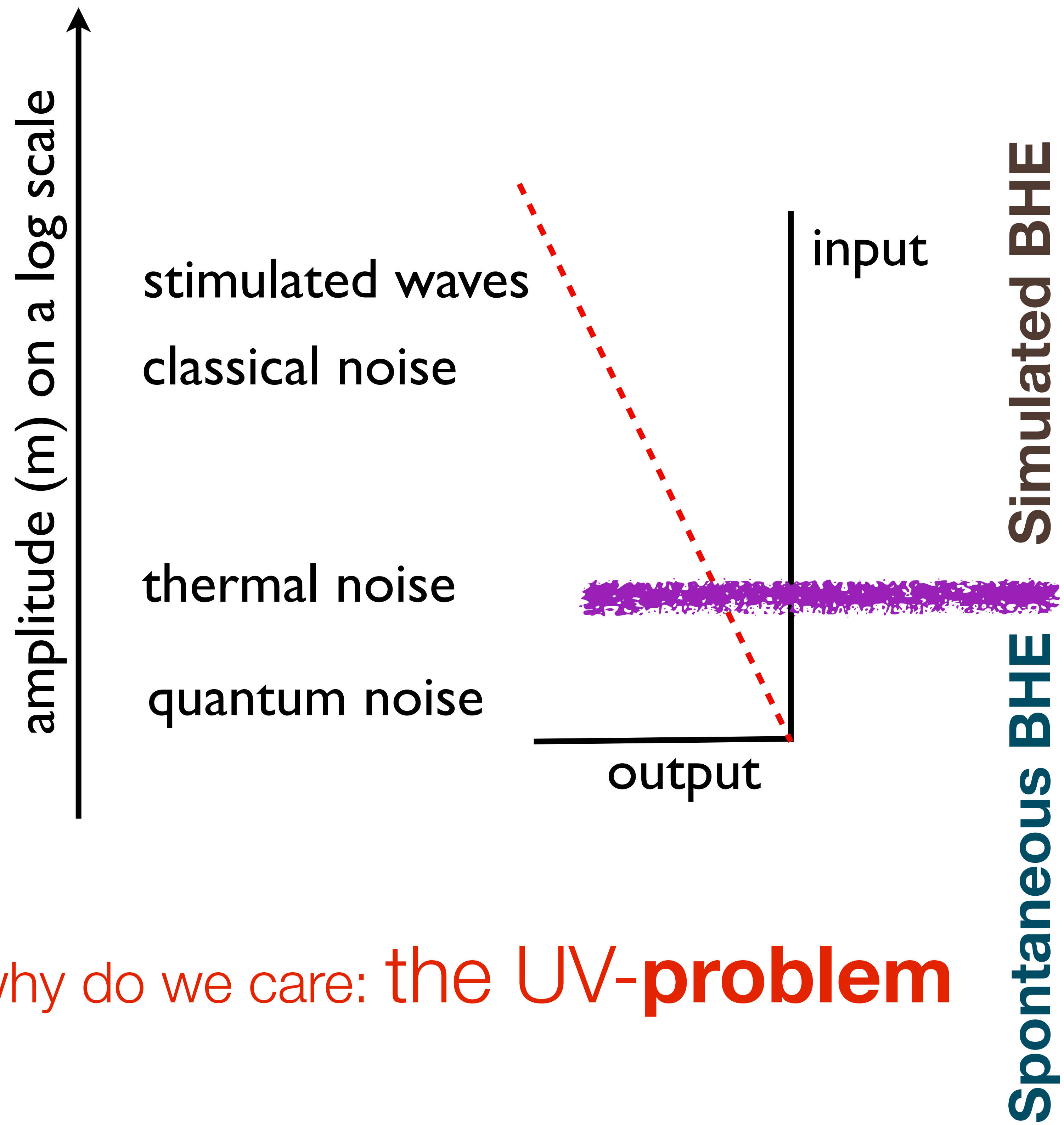

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✔ surface gravity

why do we care: the UV-**problem**

✔ quantum correlations

BHE process ➤ the UV-**problem**

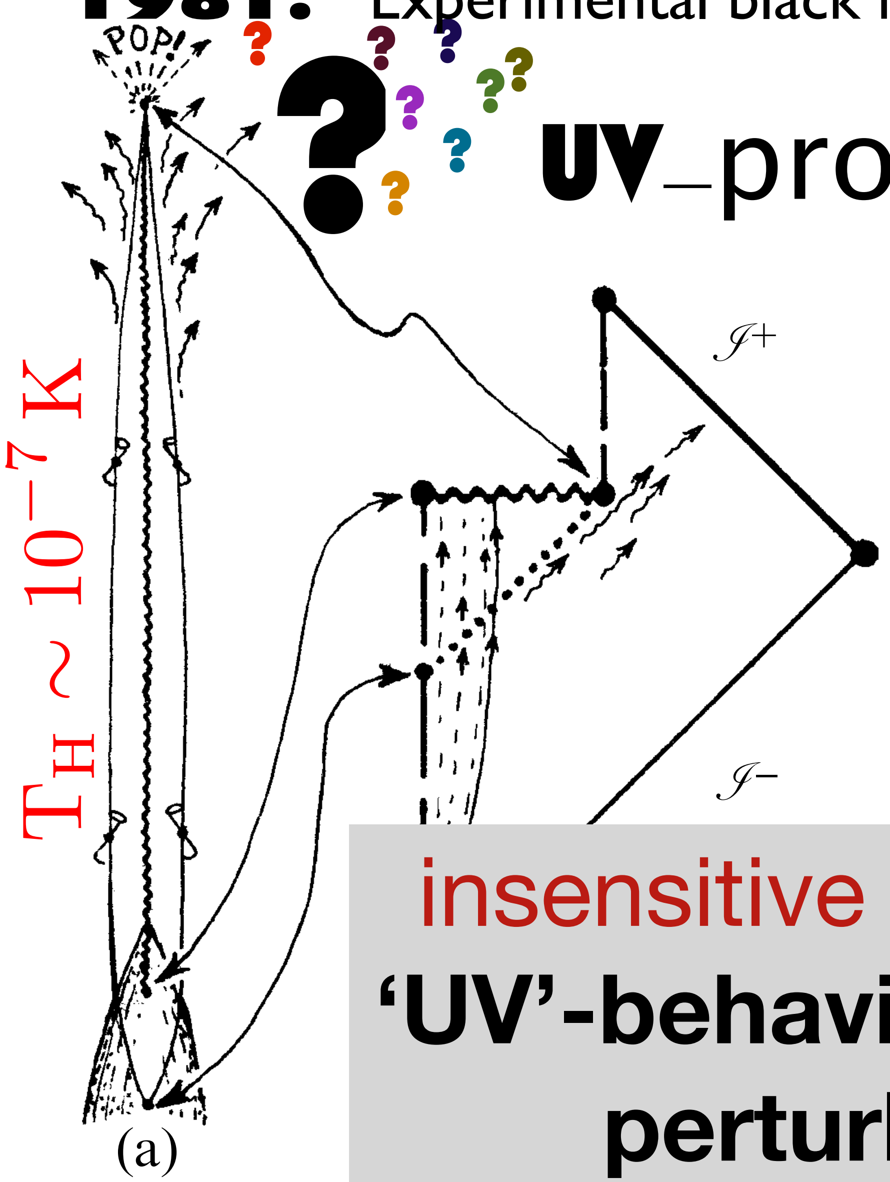
Equation of motion for **linear** perturbations in analogue gravity systems:

[Wave equation on effective curved spacetime]

$$\frac{1}{\sqrt{-g}}\,\partial_a\left(\sqrt{-g}g^{ab}\partial_b\phi_1\right)=0$$

1981: Experimental black hole evaporation?, by Bill Unruh; Vol 46, #21, PRL.

UV_problem?



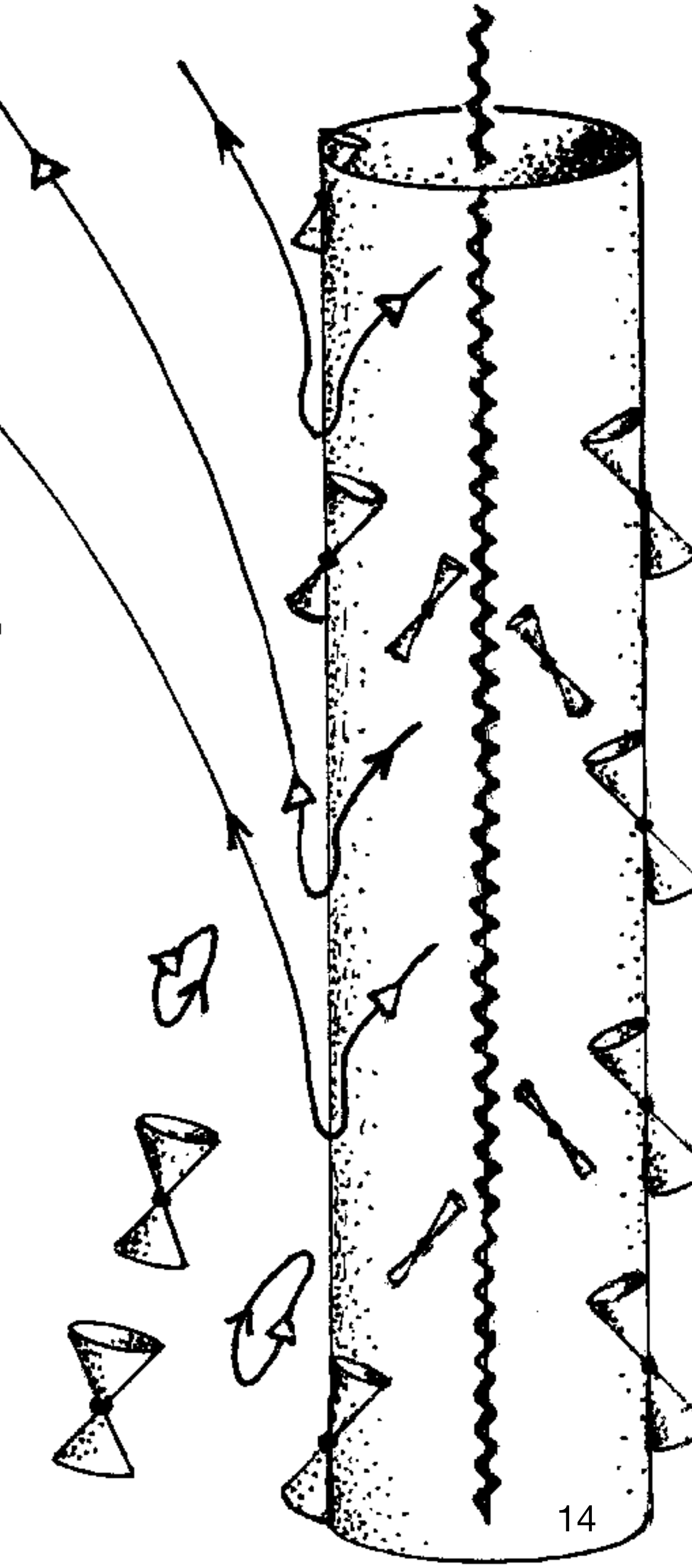
Possibility to test **experimentally** the ***generality*** of the **Hawking process**!

insensitive to particular **'UV'-behaviour of linear perturbations**

robust against model-specific **dynamics**

Scientific goal ➤ conclusive detection of BHE

- Spontaneous versus stimulated emission: Black holes are phase insensitive linear amplifiers...
- Nature of Hawking process: Semi-classical quantum gravity effect, where the Einstein dynamics is not taken into consideration.
- Black versus white hole emission: White holes are the time-reversal of black holes, and the Hawking process applies to both.



Our experiment ➤ Principle idea

2002: Schutzhold & Unruh: Gravity wave analogs of black holes (Phys. Rev. D66 044019)

Our experiment in a nutshell

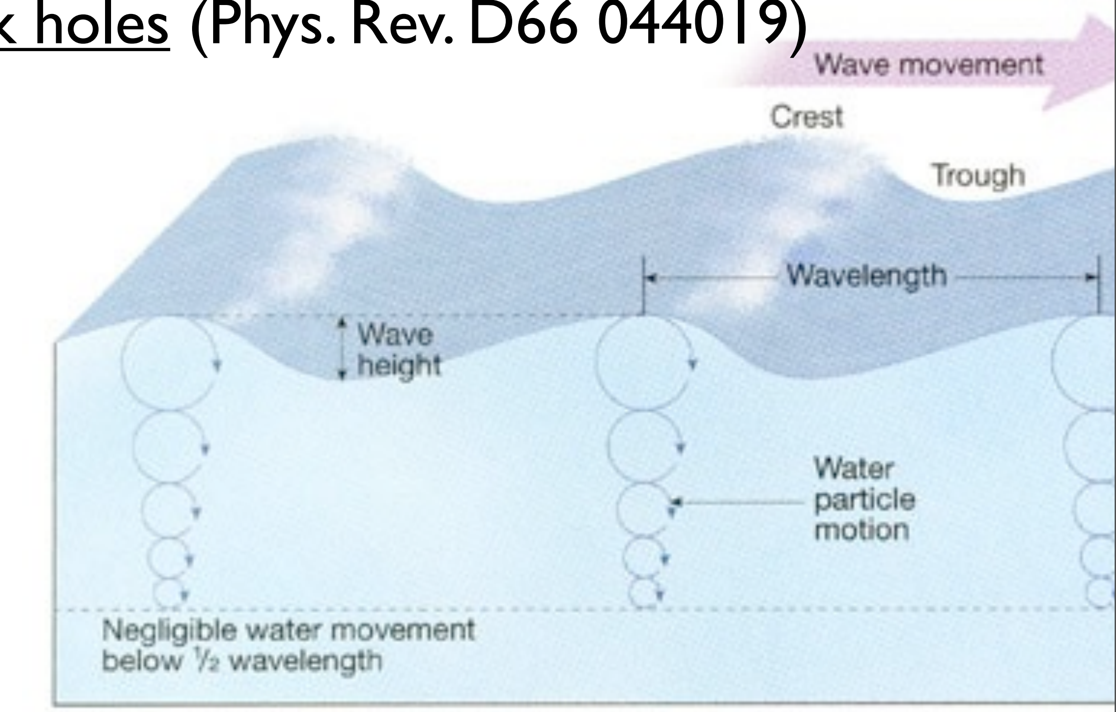


Figure 14.2 This diagram illustrates the basic parts of a wave as well as the m
wave. Negligible water movement occurs below a depth equal to one-half the

Set-up: Surface waves on open channel flow with varying depth.

- stationary
- irrotational
- *incompressible*
- *inviscid*

$$v = v(x) = \frac{q}{h(x)} \propto \frac{1}{h(x)}$$

$$c = c(x) \approx \sqrt{g h(x)} \propto \sqrt{h(x)}$$

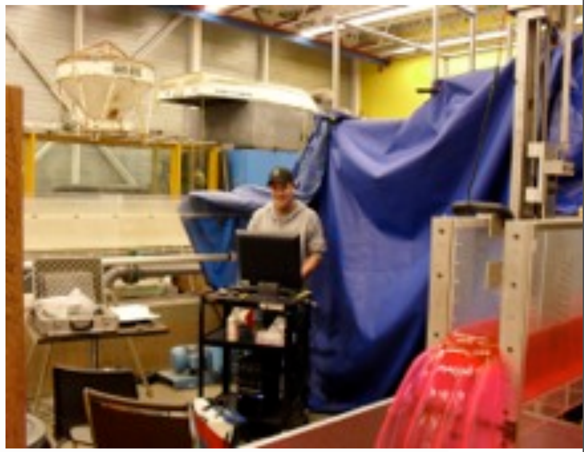
Let's recall the acoustic line-element:

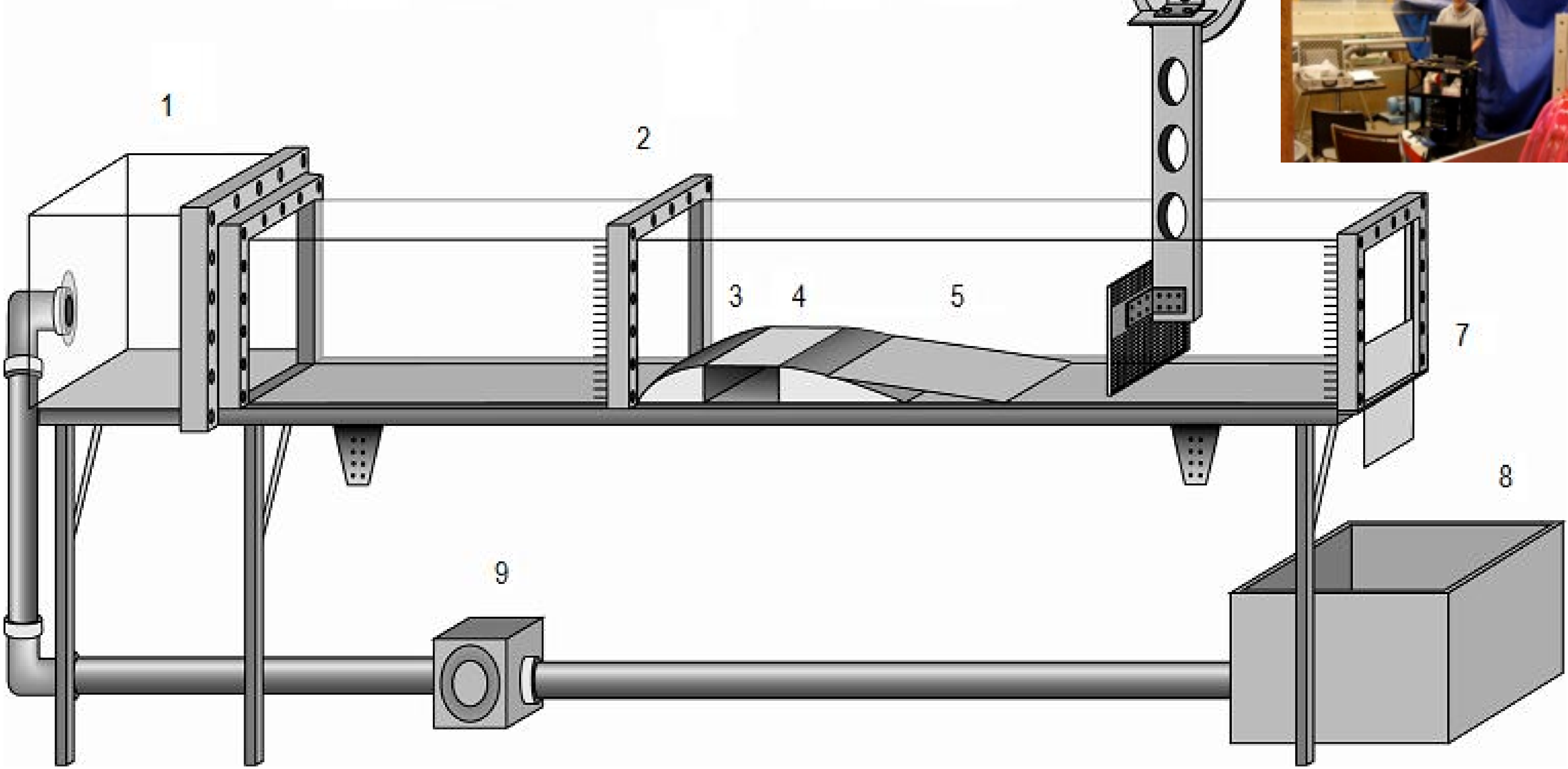
$$g_{ab} \propto \begin{bmatrix} -\left(c^2 - v^2\right) & -\vec{v}^T \\ -\vec{v} & \mathbf{I}_{d\times d} \end{bmatrix}$$

Goal: Set up black and white horizon & detect stimulated conversion to pos. & neg. waves who's relative amplitudes obey HS.

Our experiment ➤ Setup

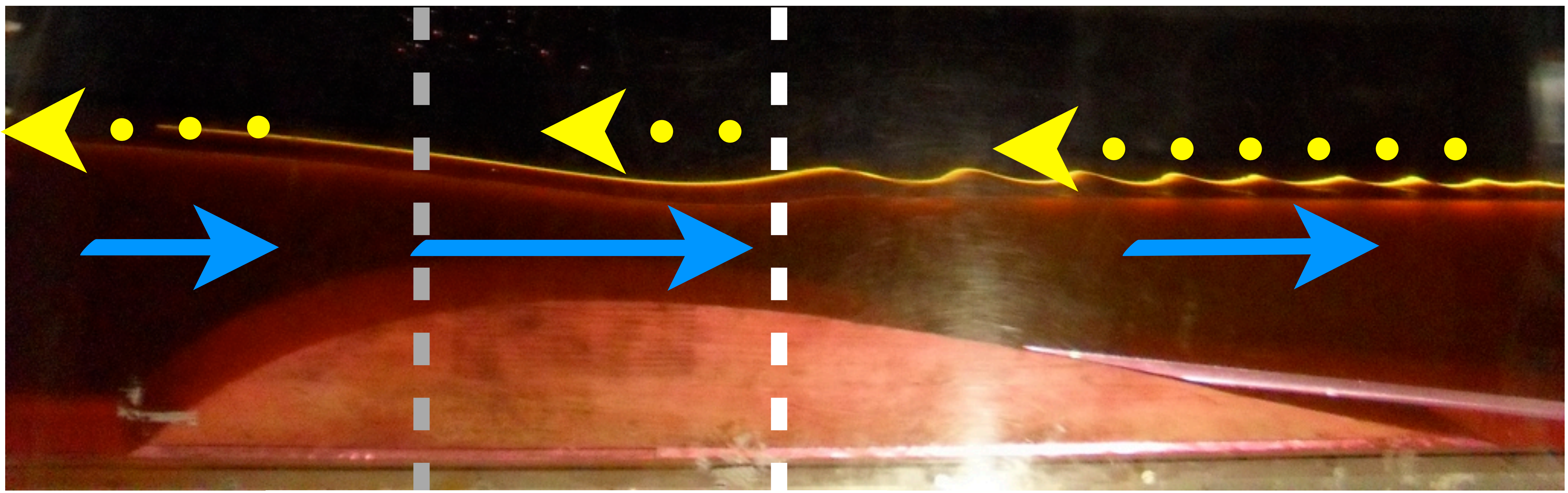
Our flume tank (7.47m long and 15.4cm wide):





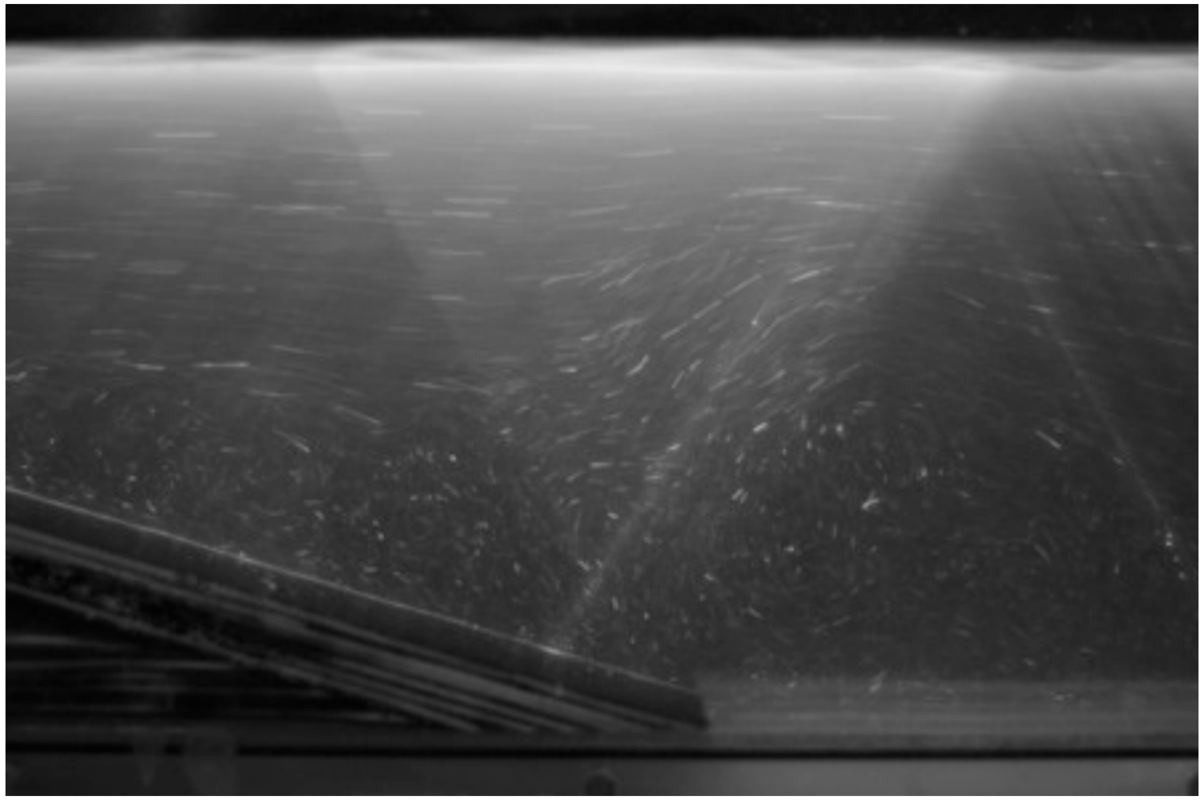
Our experiment ➤ Black & White hole horizons

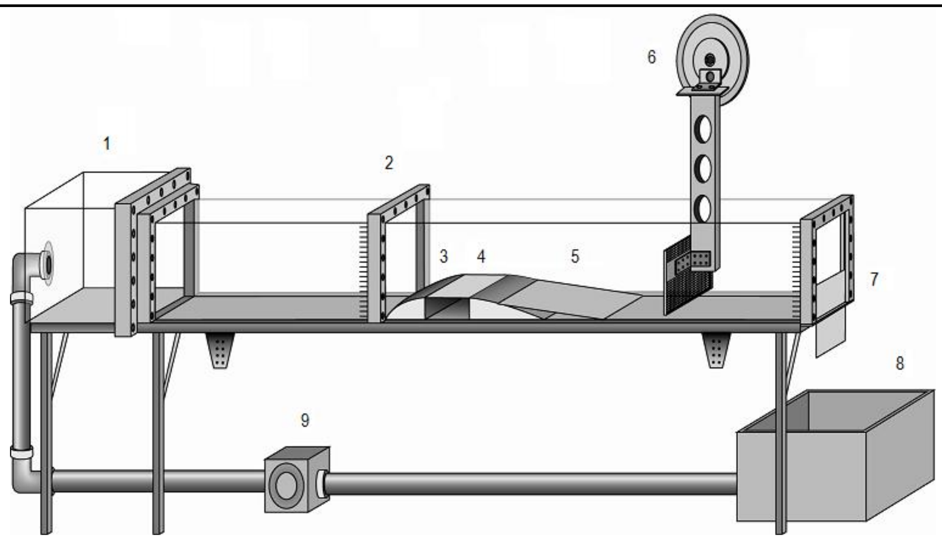
effective
white hole



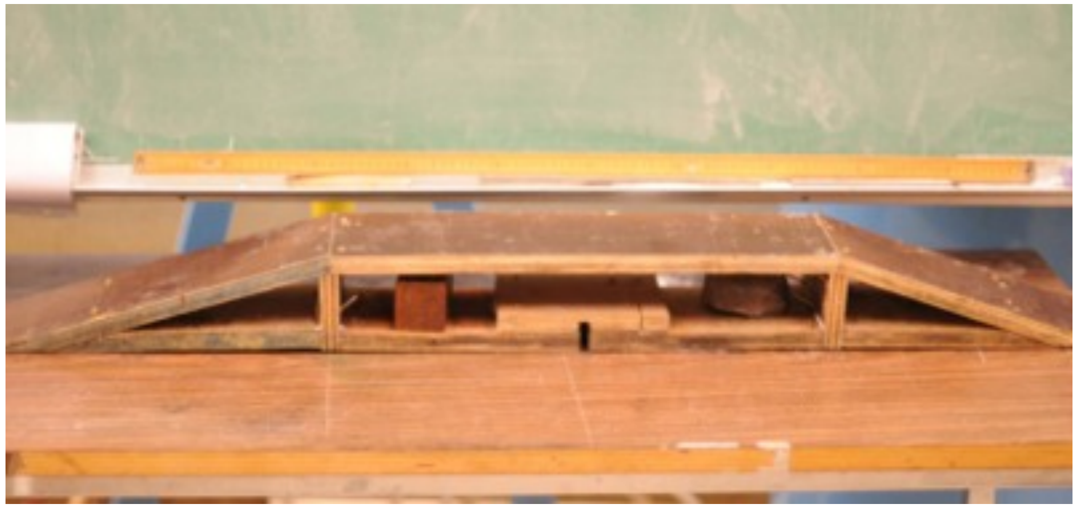
effective
black hole

Our experiment ➤ The design of our obstacle



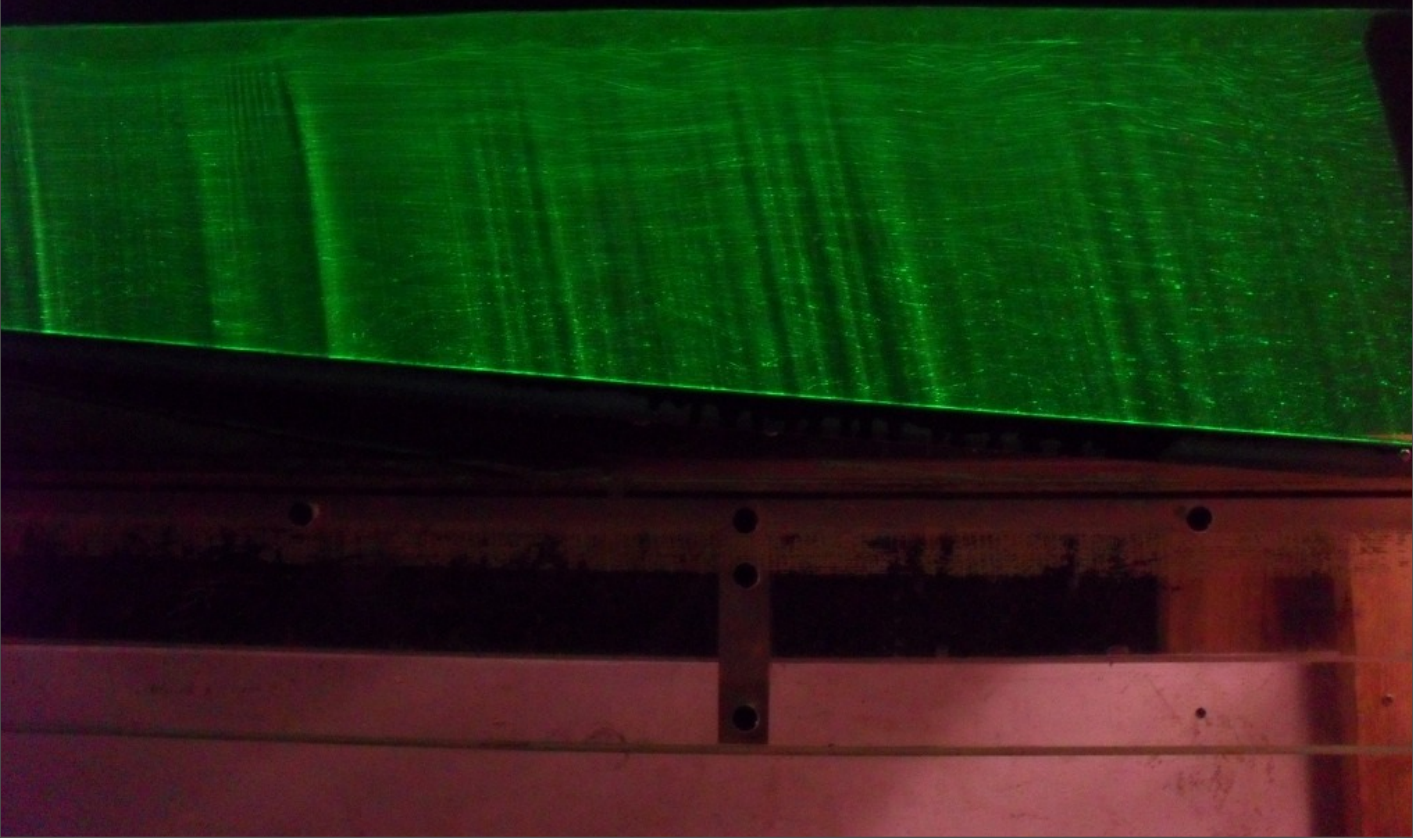


Initial design for our experiment

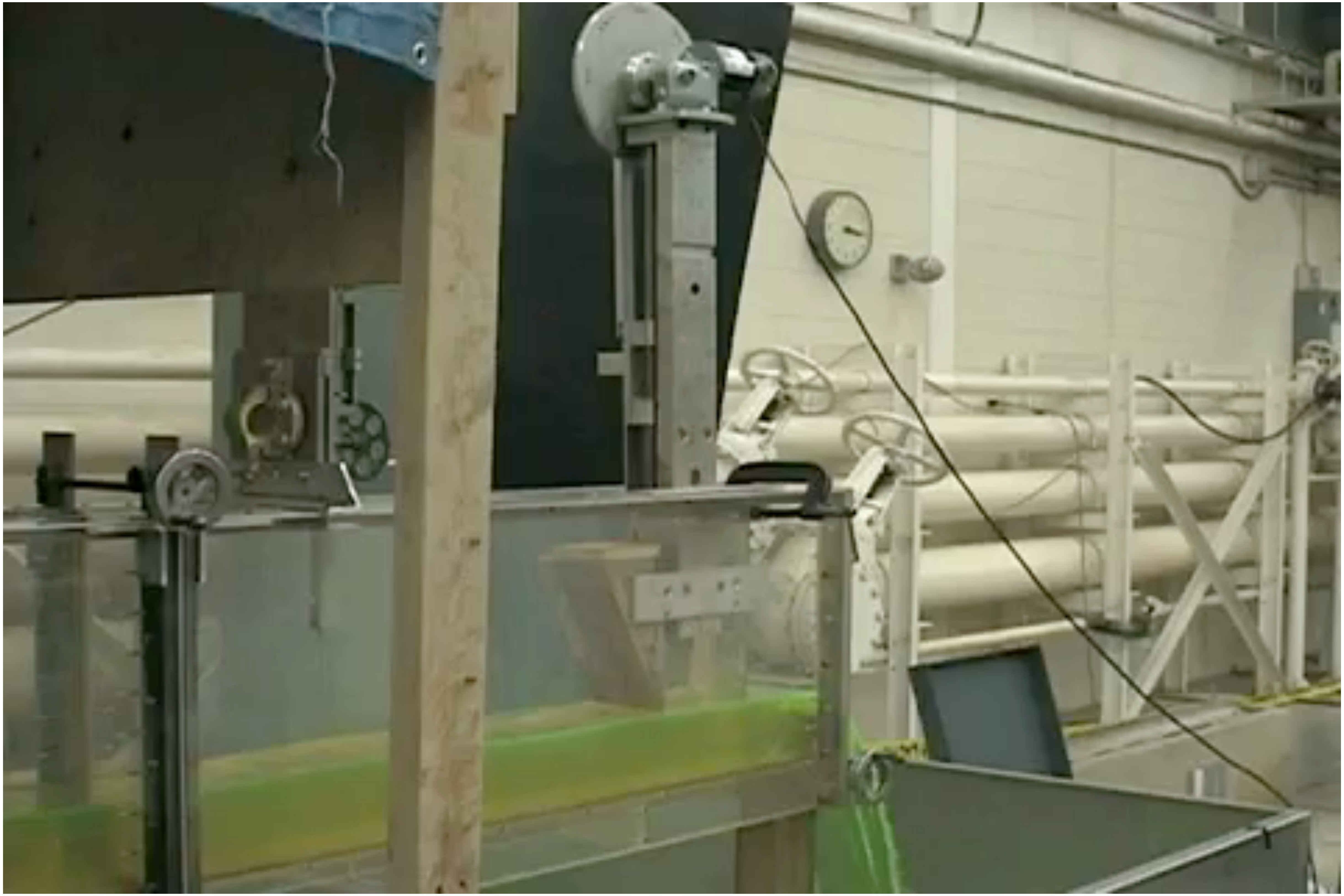


Down-scaled version of Germain Rousseaux et al. obstacle.
[length: 14m to 1m]

Our experiment ➤ The design of our obstacle



Our experiment ➤ early experiment with bigger waves



Field theory ➤ physics of surface waves

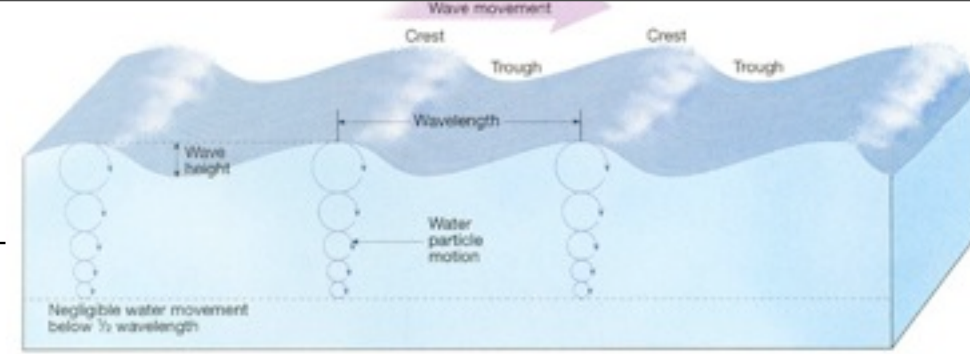
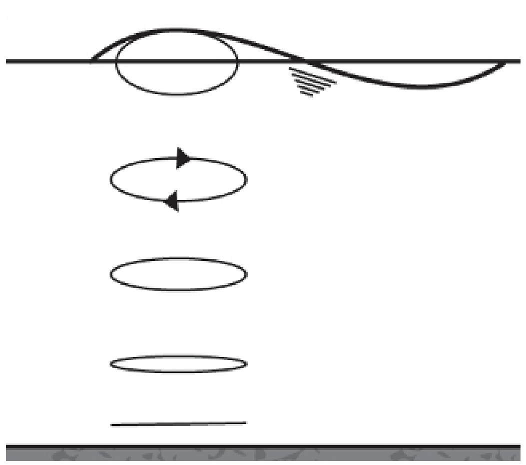
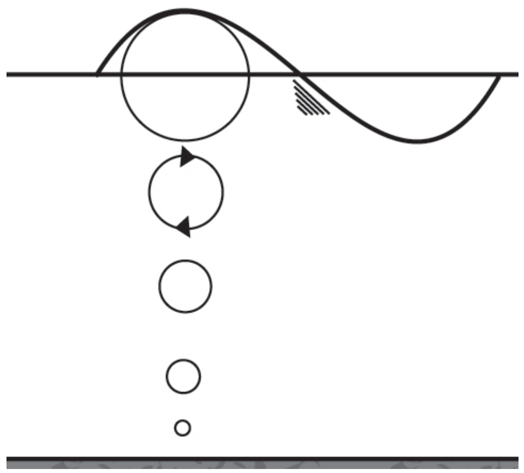


Figure 14.2 This diagram illustrates the basic parts of a wave as well as the movement of water particles with the passage of the wave. Negligible water movement occurs below a depth equal to one-half the wavelength (the level of the dashed line).





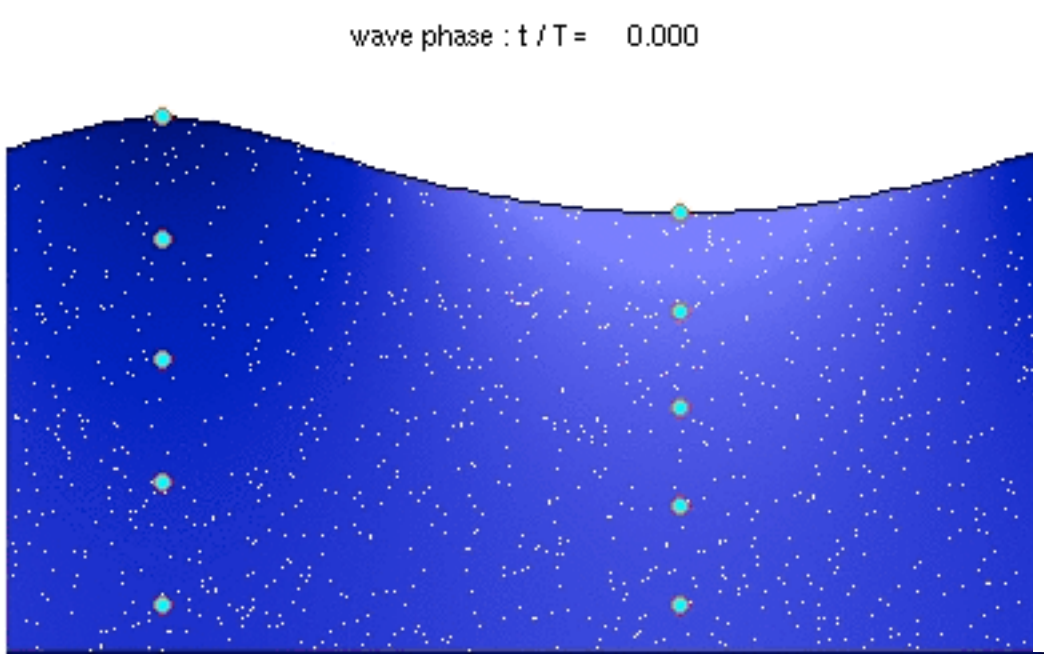
$$\Omega^2 = \left(g\,k + \frac{\sigma}{\rho} k^3 \right) \tanh(k\,h)$$

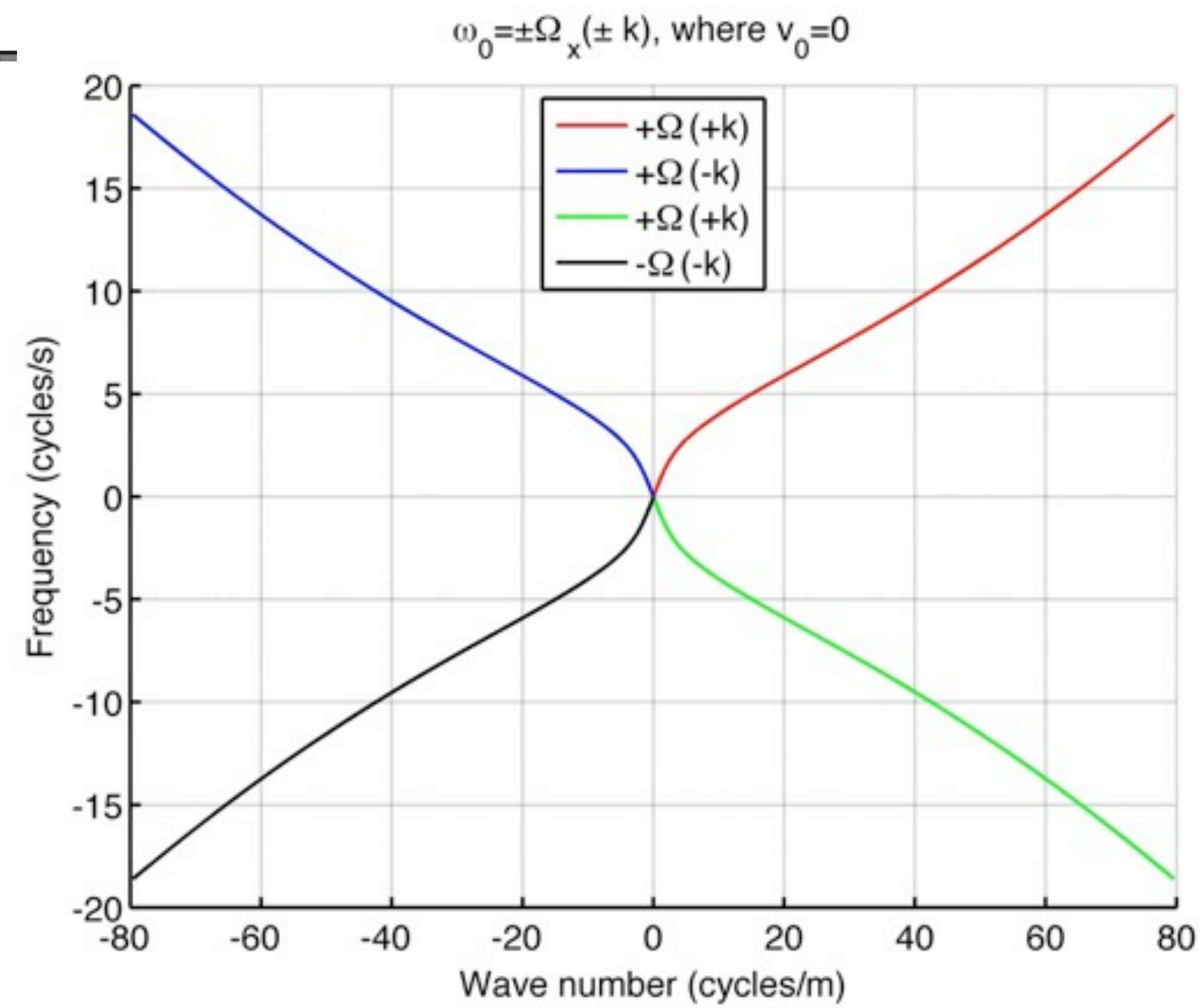
shallow:

$$\Omega = \sqrt{gh}\,k$$

deep:

$$\Omega = \sqrt{gk}$$





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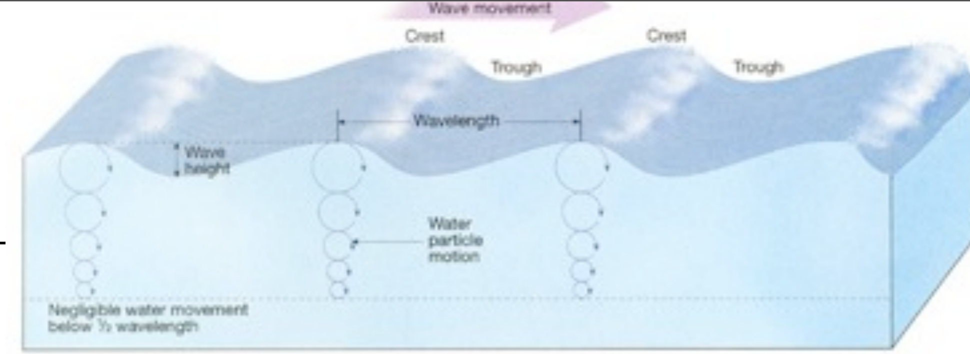
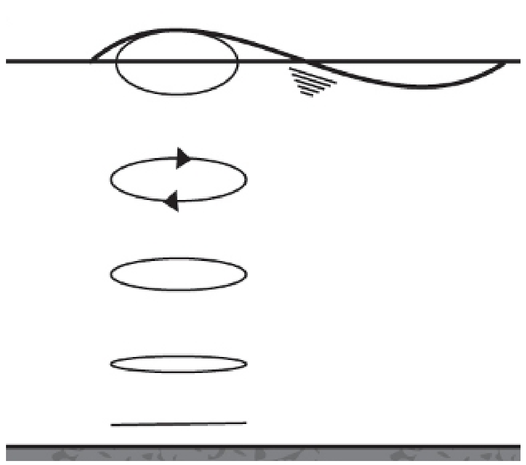
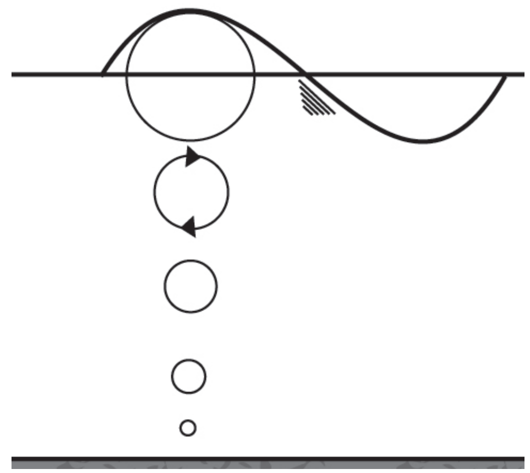


Figure 14.2 This diagram illustrates the basic parts of a wave as well as the movement of water particles with the passage of the wave. Negligible water movement occurs below a depth equal to one-half the wavelength (the level of the dashed line).





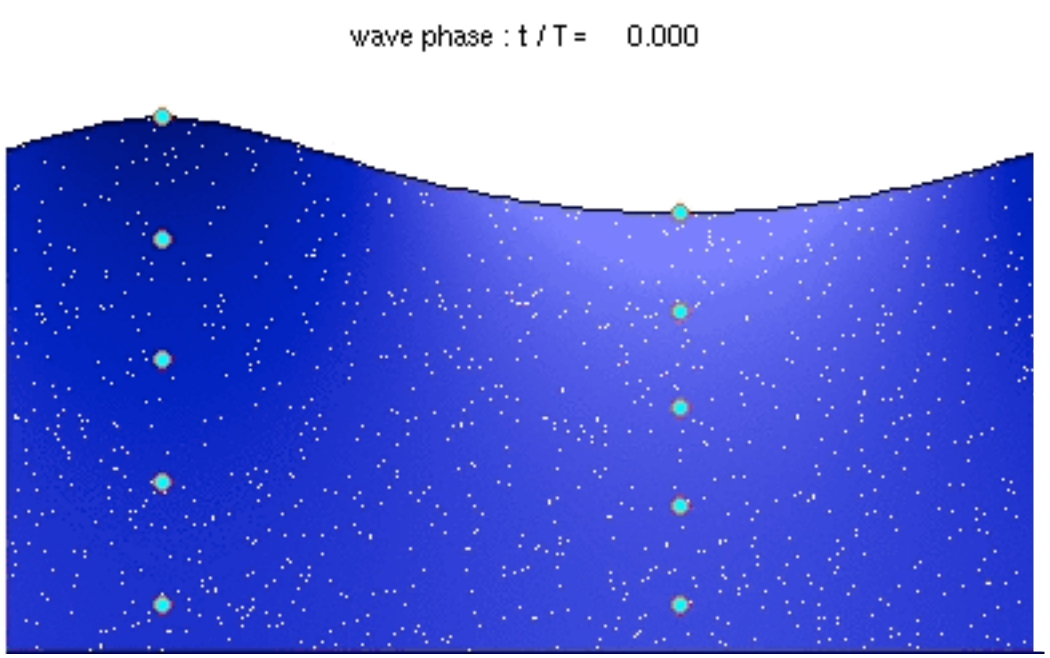
$$\Omega^2 = \left(g\,k + \frac{\sigma}{\rho}\,k^3\right)\,\tanh(k\,h)$$

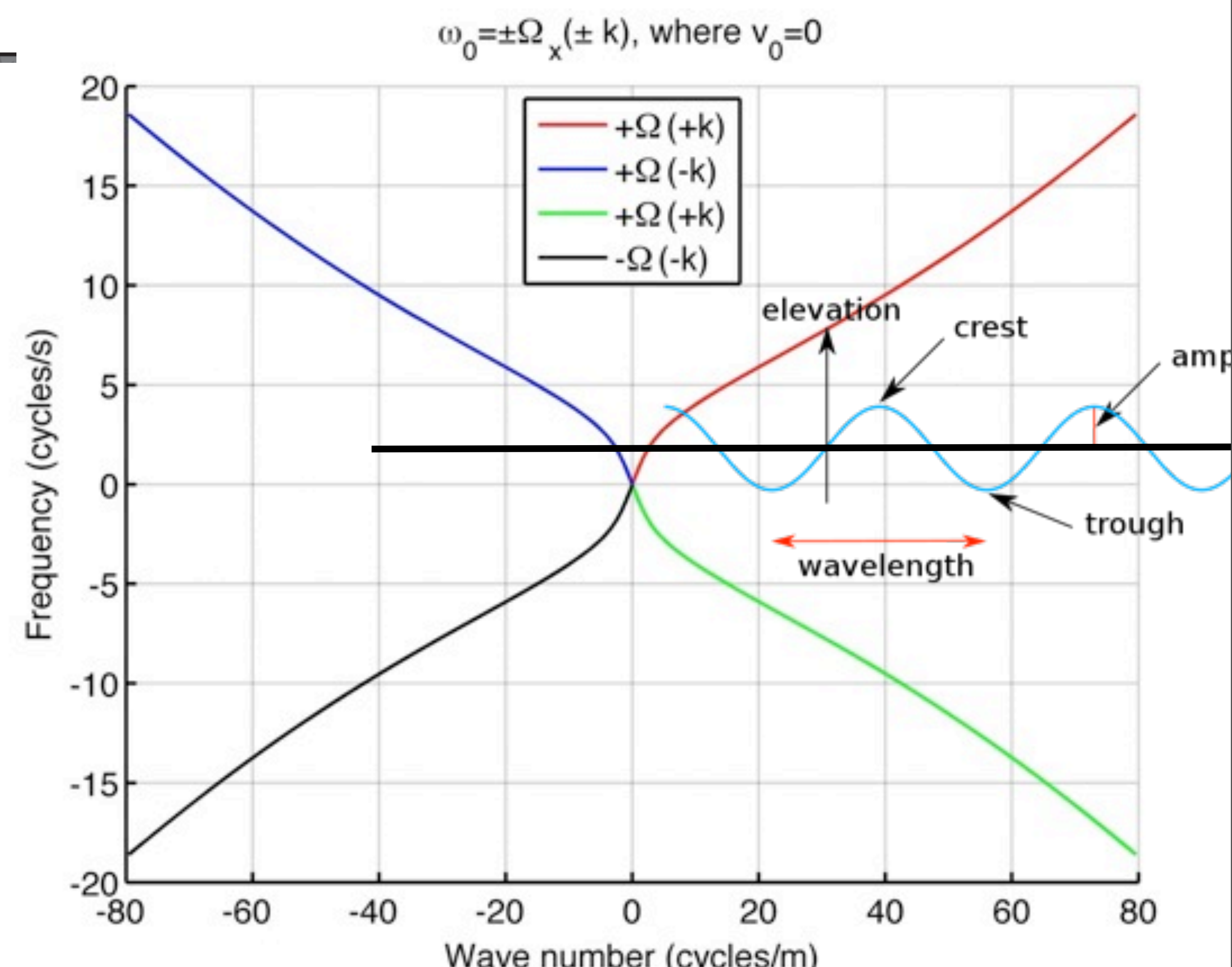
shallow:

$$\Omega = \sqrt{gh}\,k$$

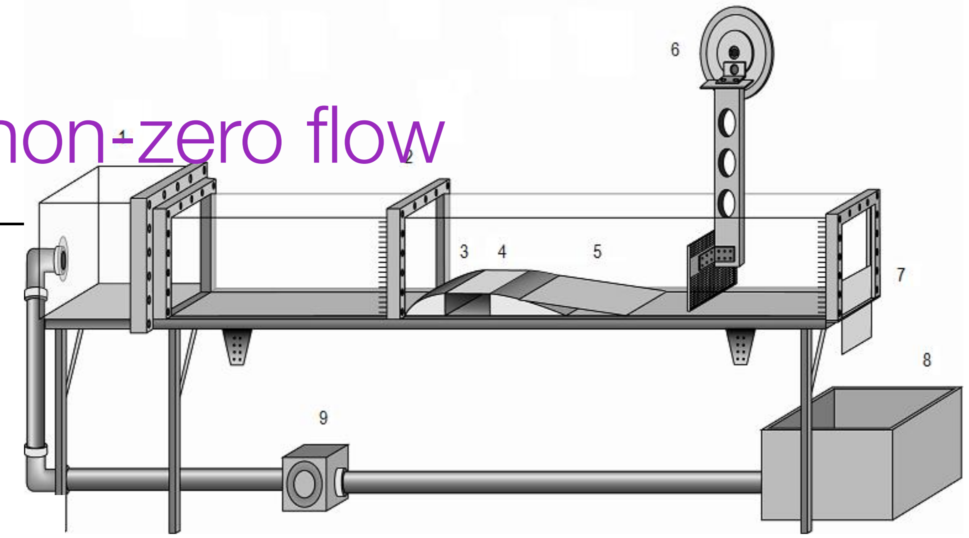
deep:

$$\Omega = \sqrt{gk}$$

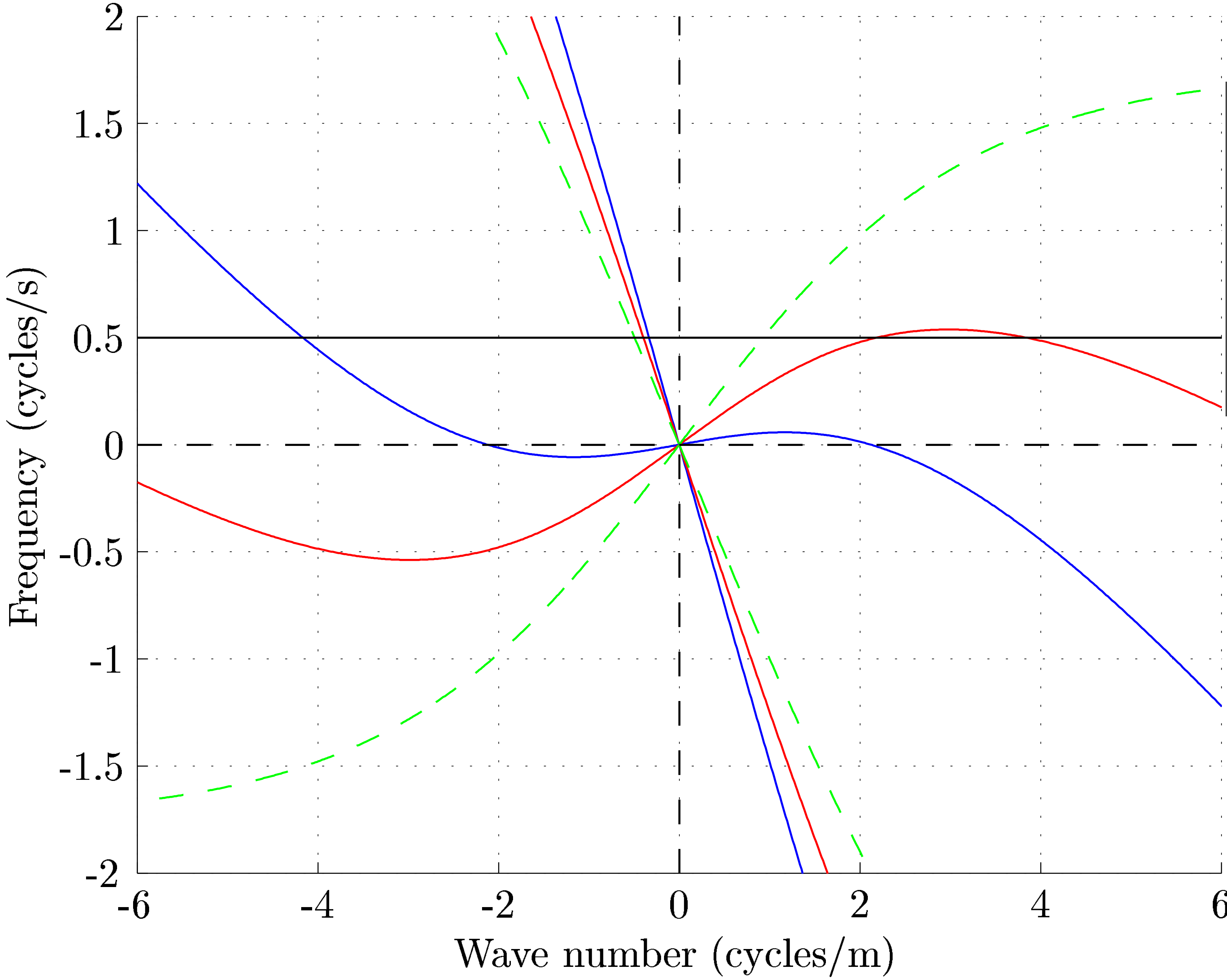




Field theory ➤ physics of surface waves non-zero flow



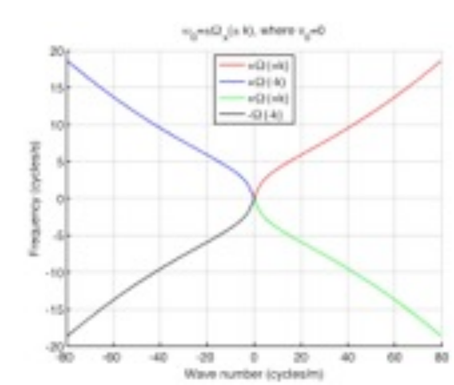
$$\Omega_{\mathrm{LAB}} = \Omega_{\mathrm{WATER}} \pm v\,k$$



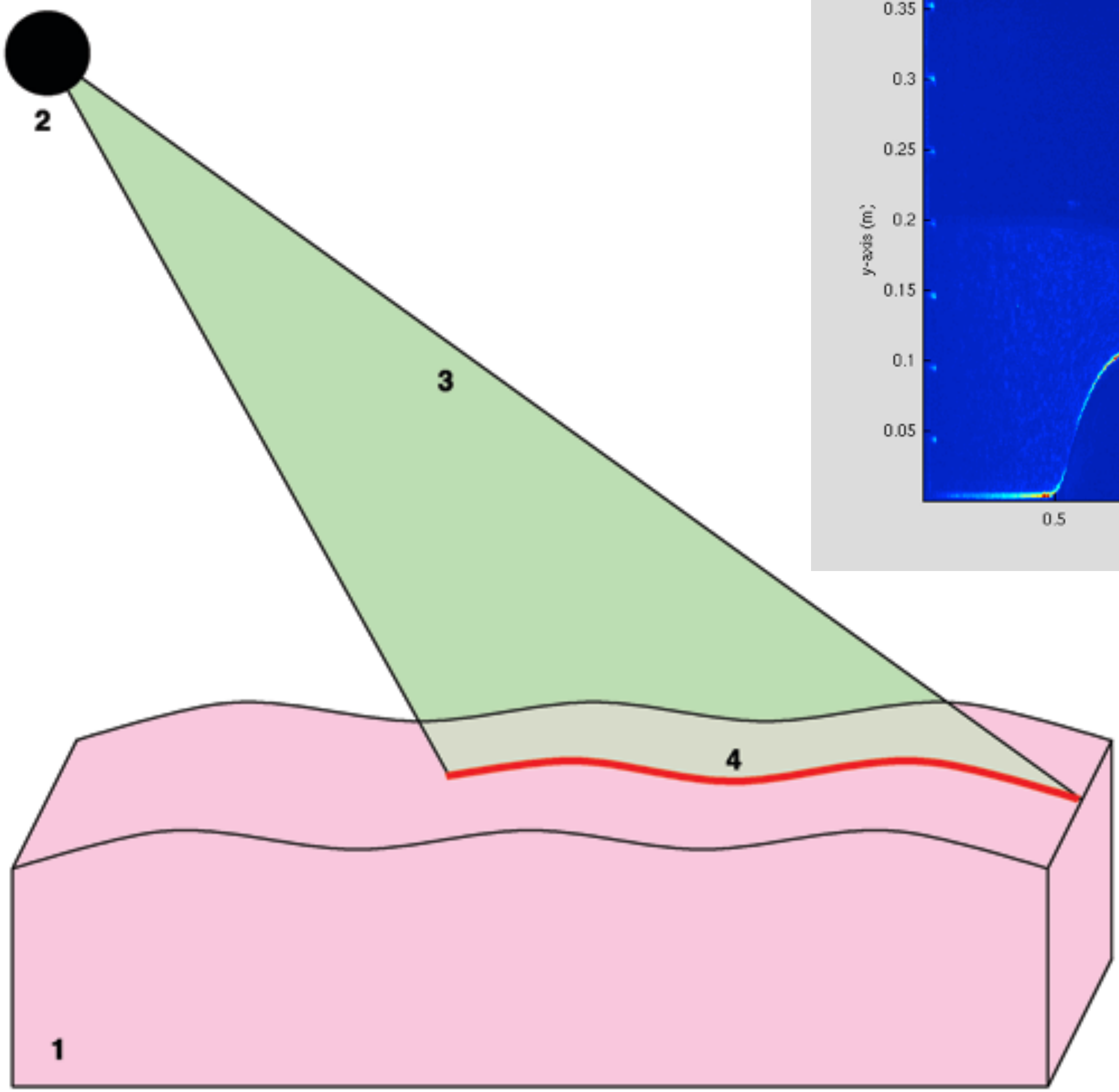
Dispersion relation for
maximum height
conversion point
minimum height

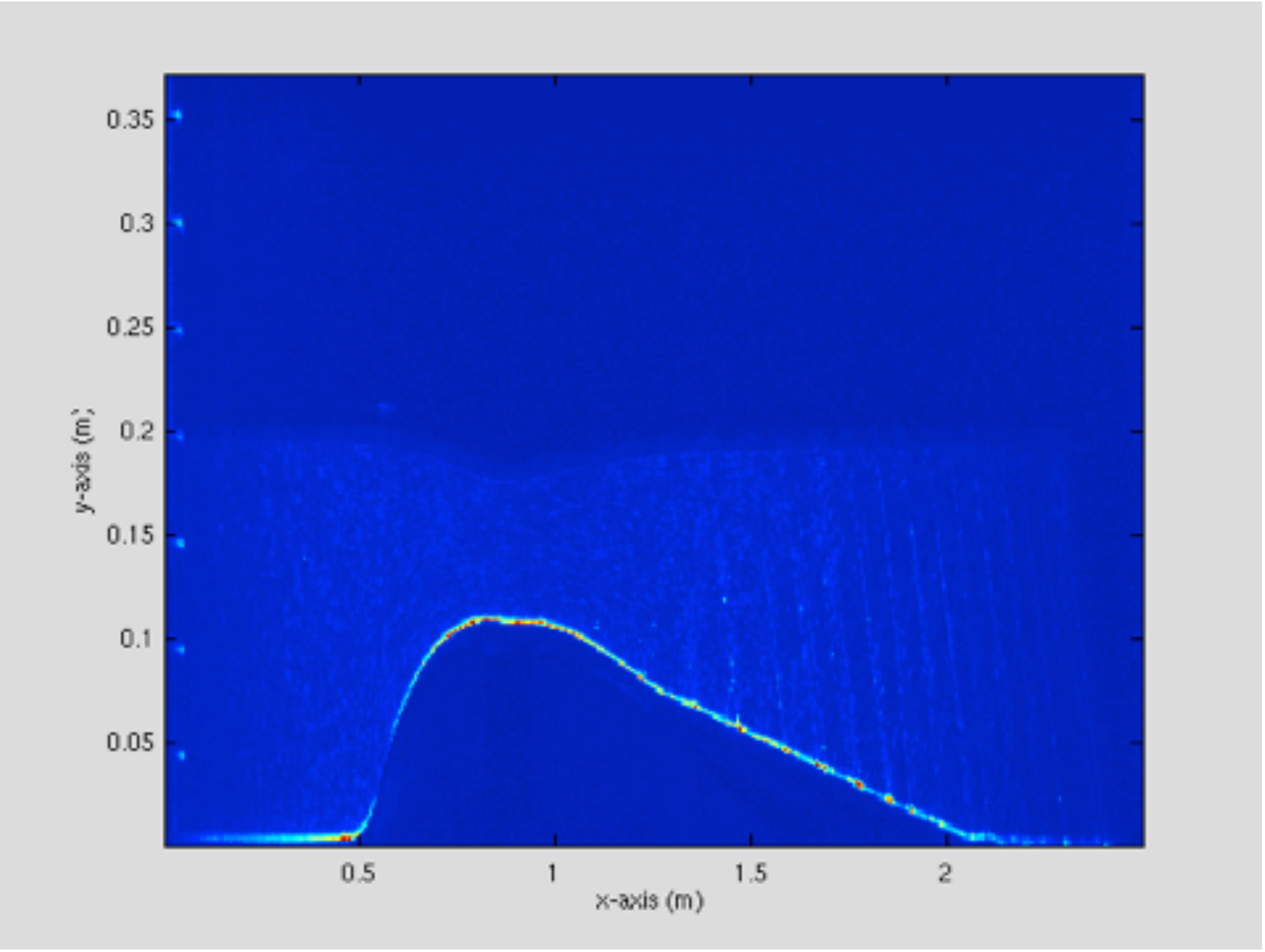
shallow: $\Omega = \sqrt{gh}\,k$

deep: $\Omega = \sqrt{gk}$

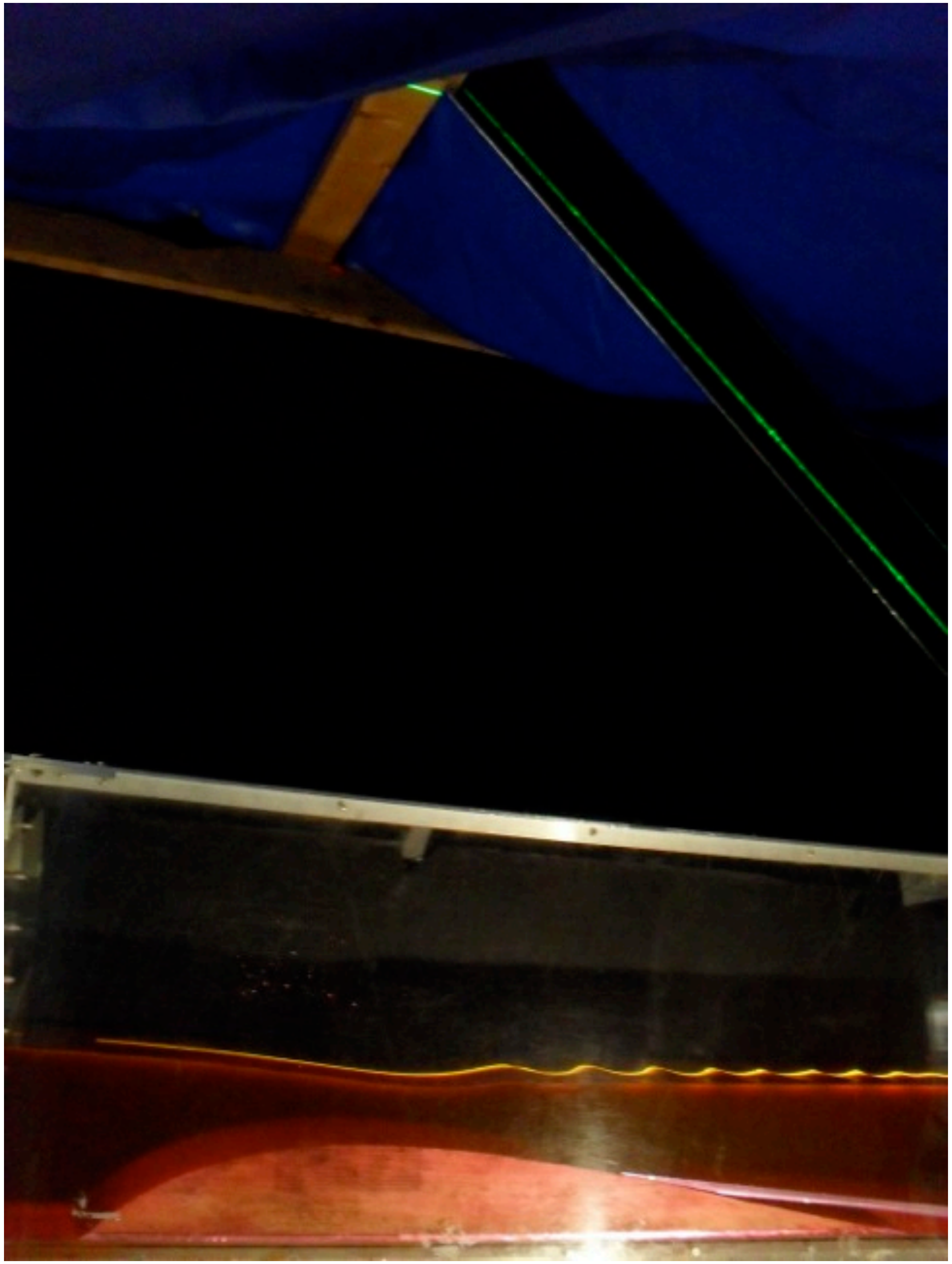


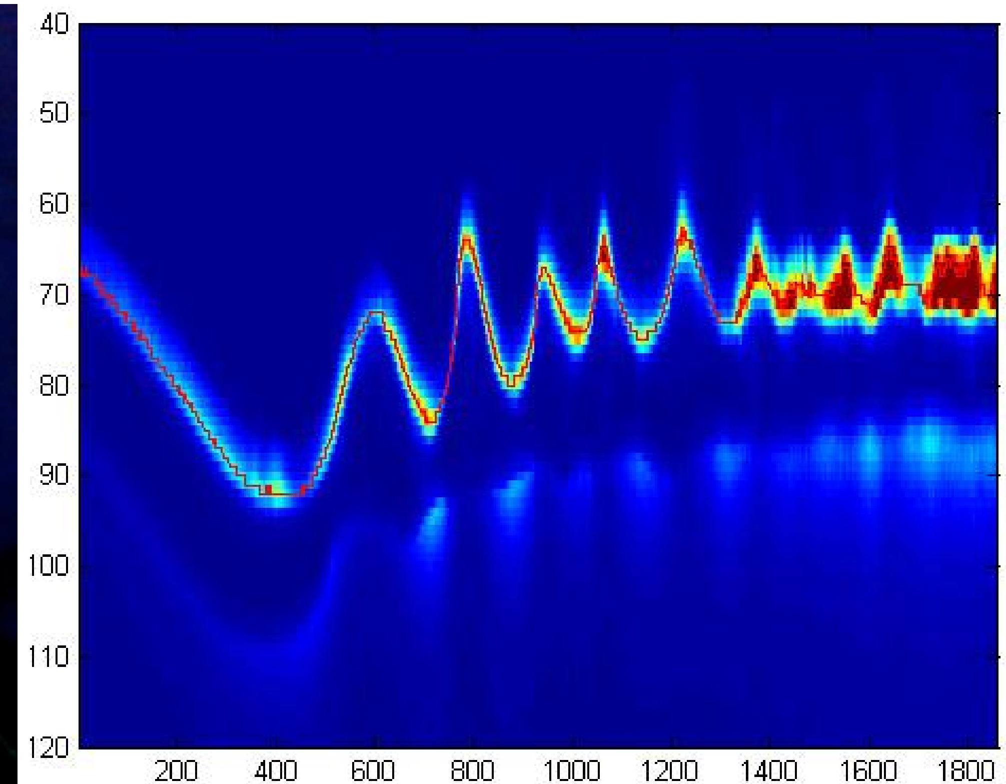
Our experiment ➤ Observable

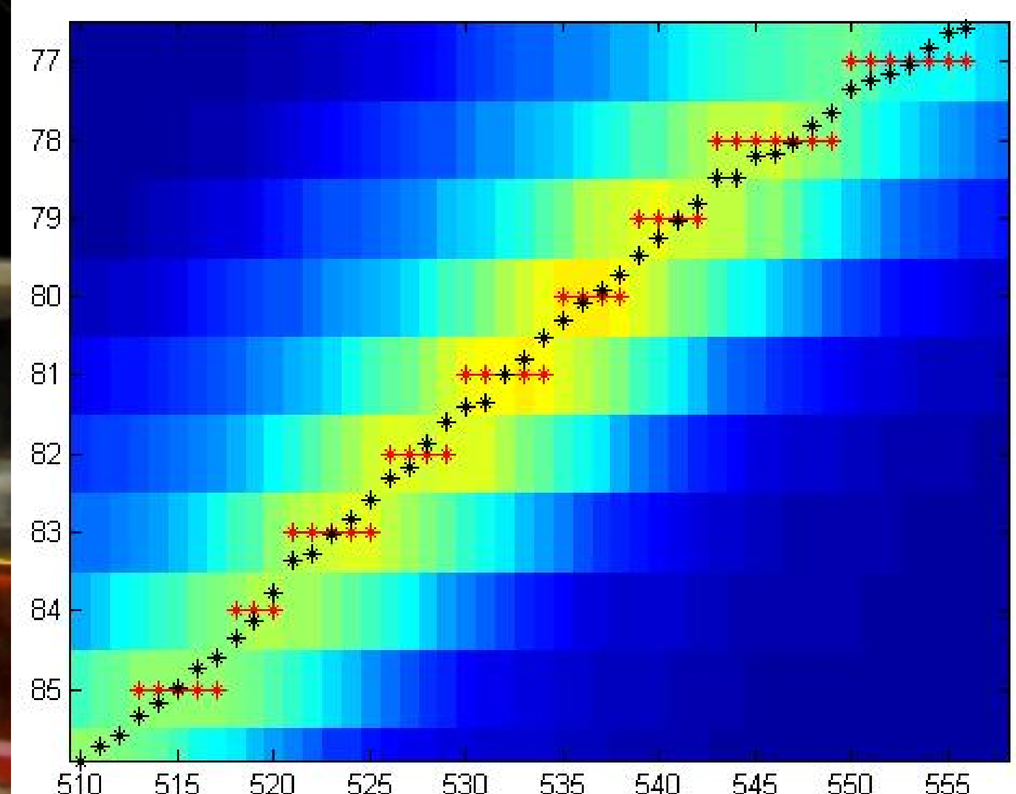


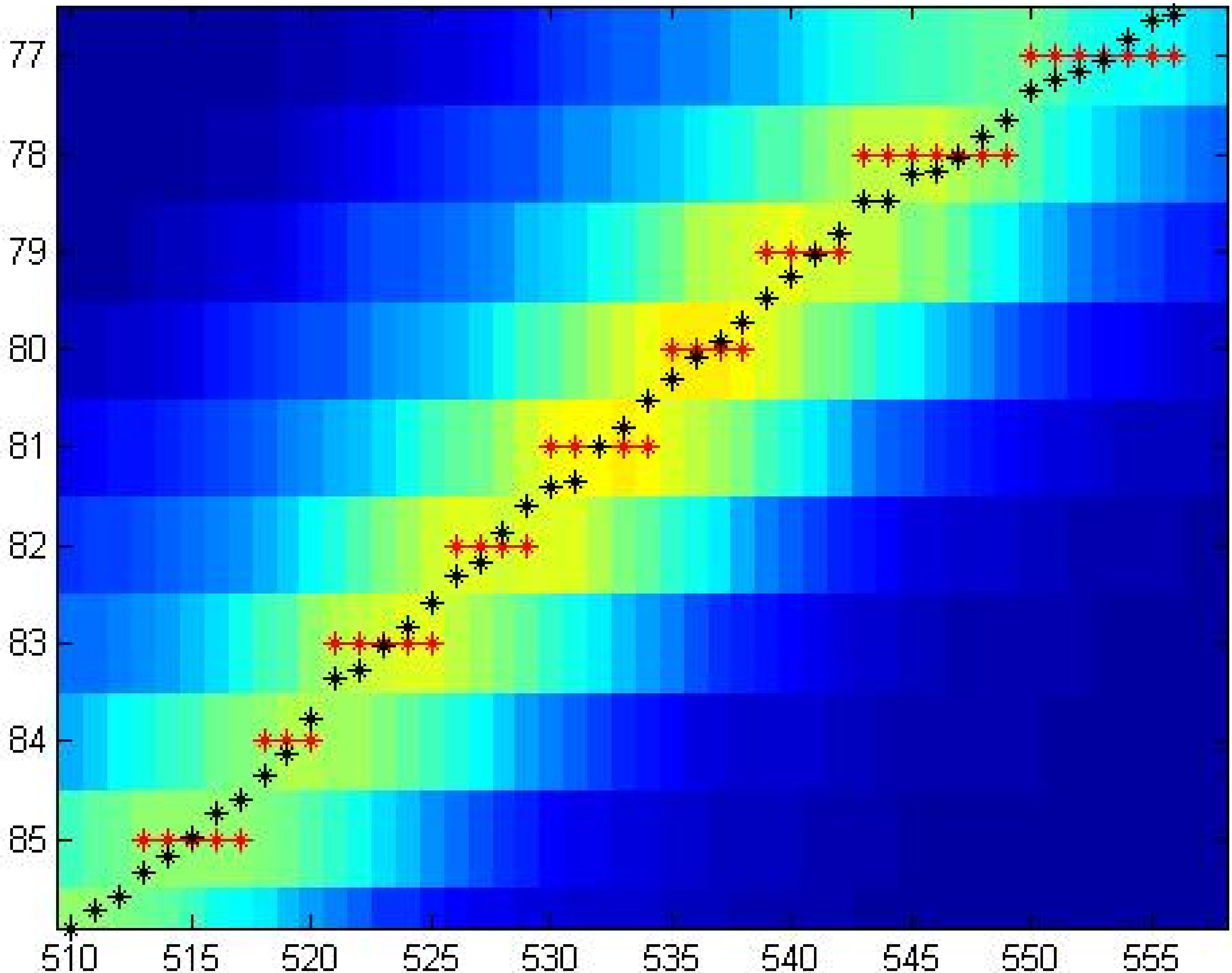


Our experiment ➤ Data analysis









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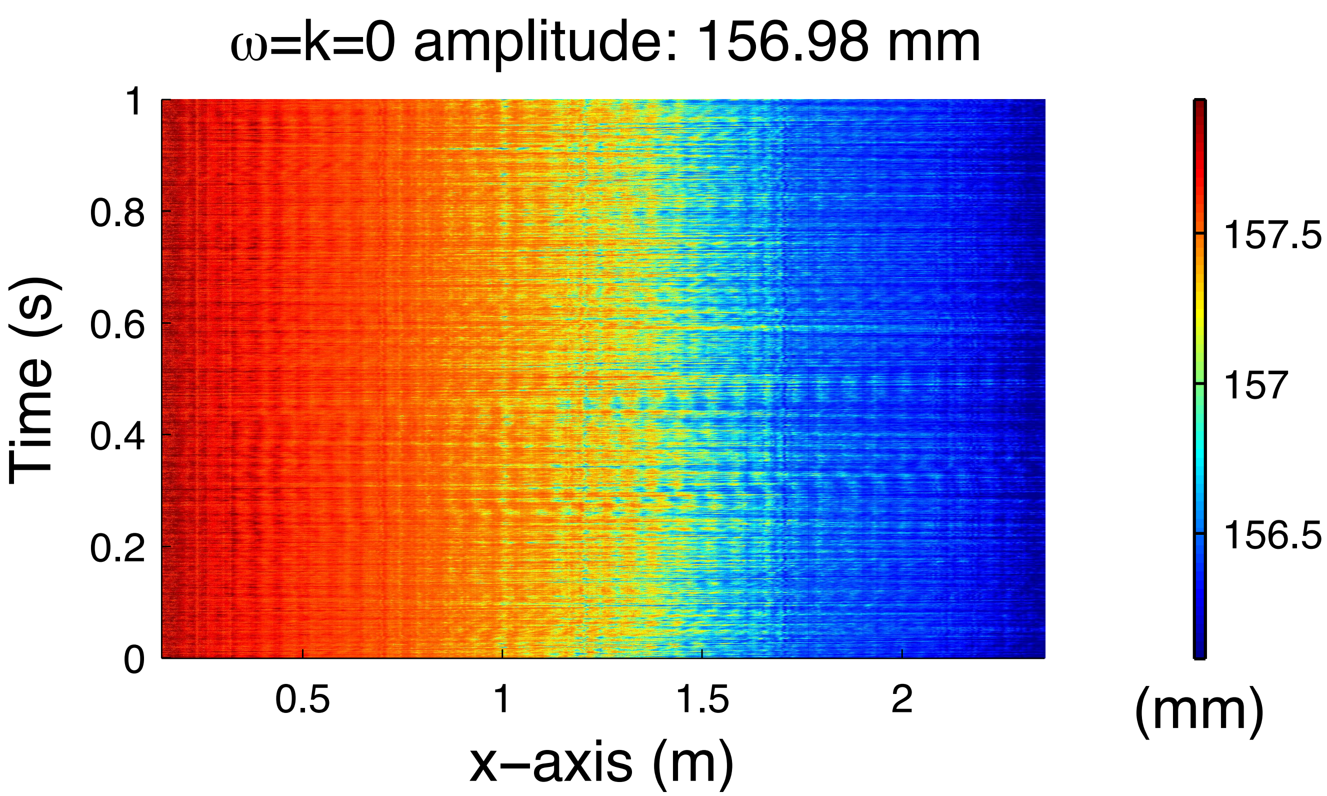
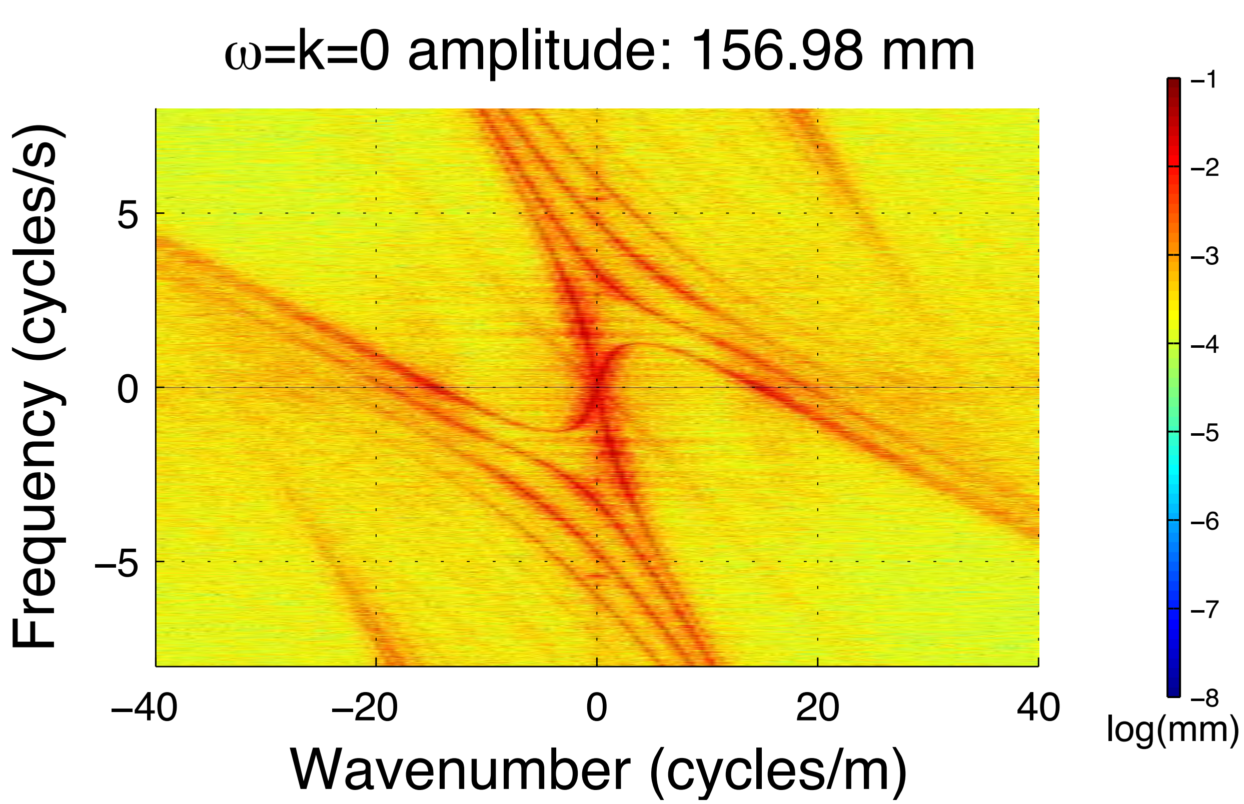
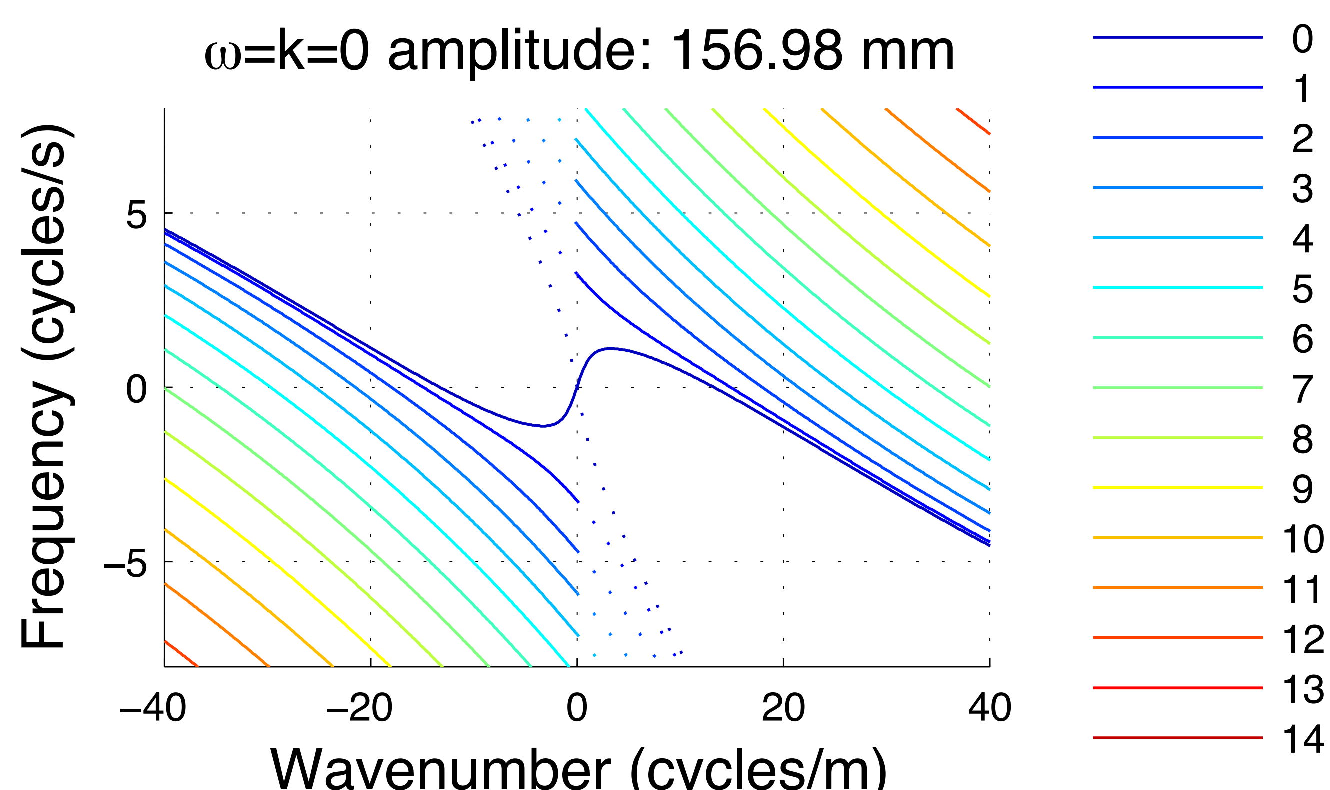
Data analysis ➤ from wave characteristic to dispersion rel.



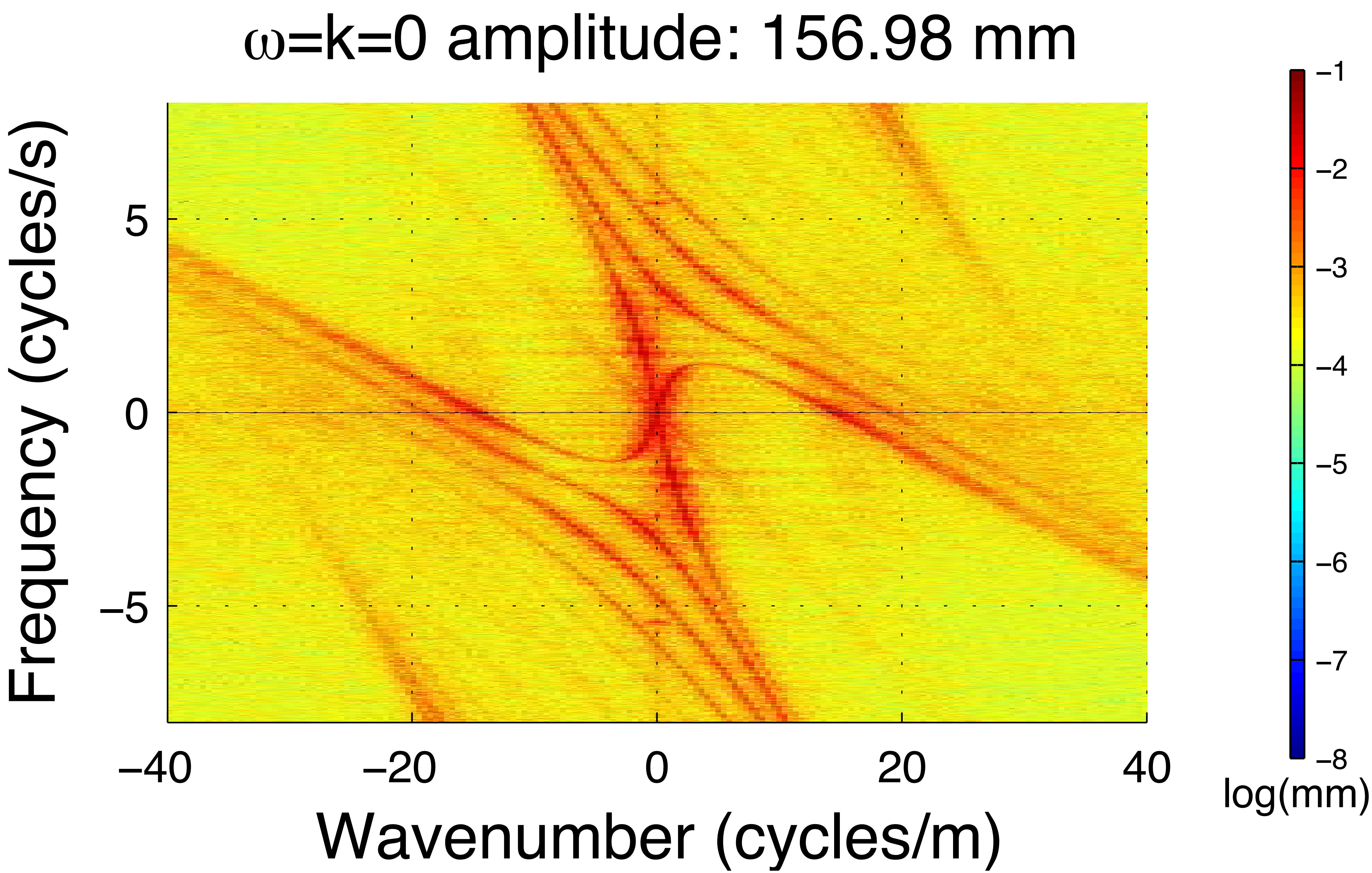
$$(f + \tilde{v}\,k)^2 = \left(\frac{g\,k}{2\,\pi}\right)\cdot\tanh(2\,\pi\,k\,h)$$

$$k = \sqrt{k_{||}^2 + k_{\perp}^2} = \sqrt{(1/\lambda)^2 + (n/l_w).^2},$$

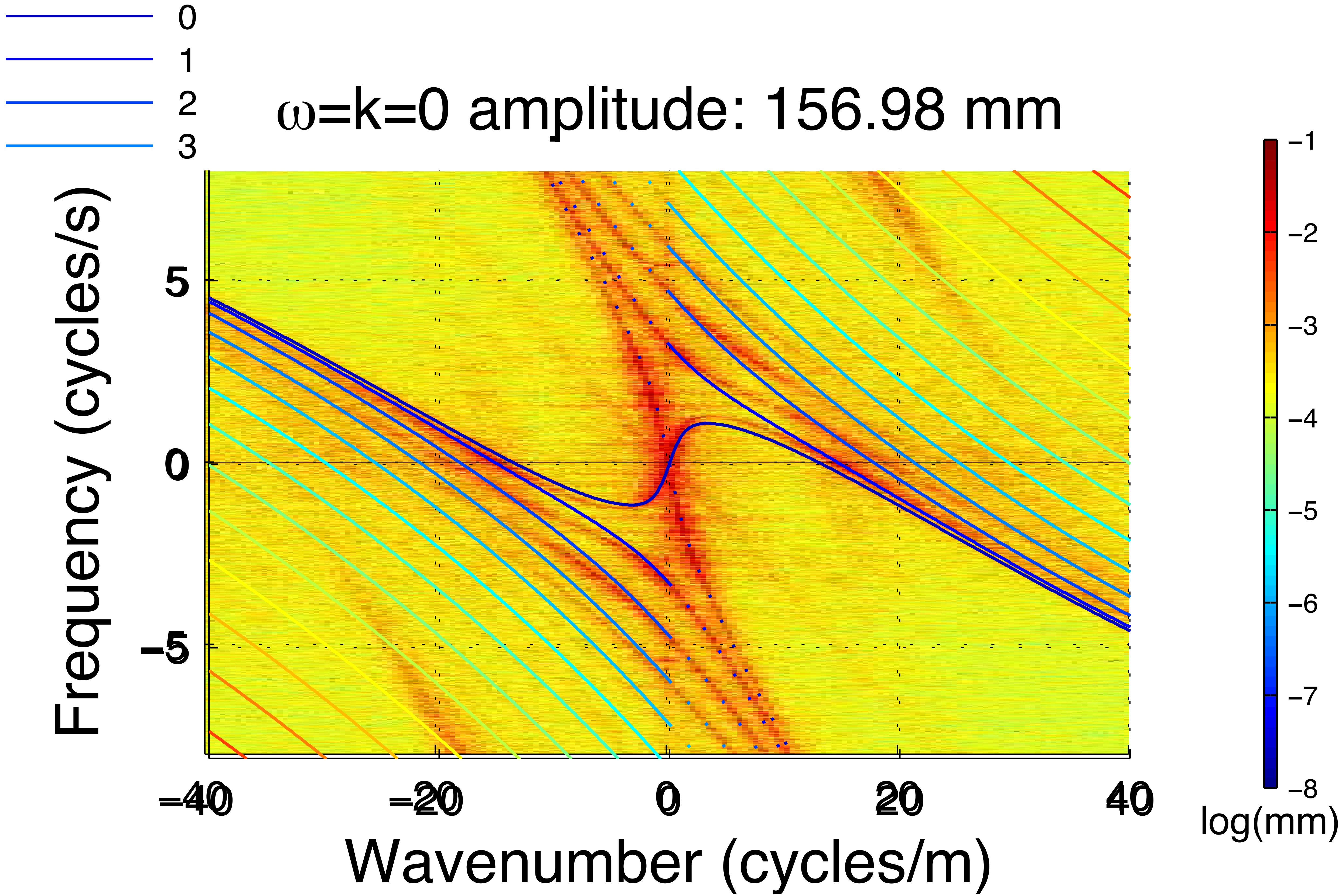




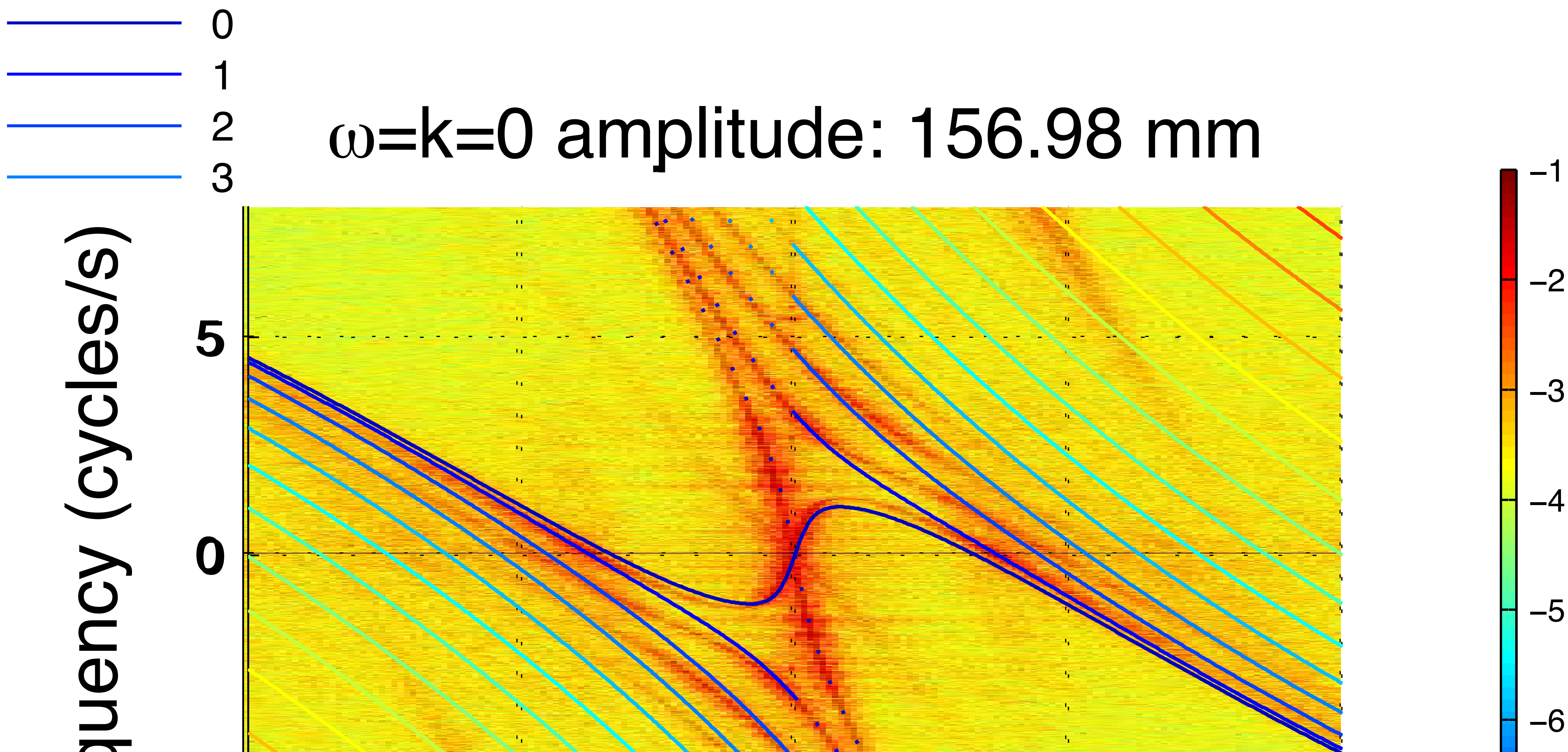
Data analysis ➤ from wave characteristic to dispersion rel.



Data analysis ➤ from wave characteristic to dispersion rel.



Data analysis ➤ from wave characteristic to dispersion rel.



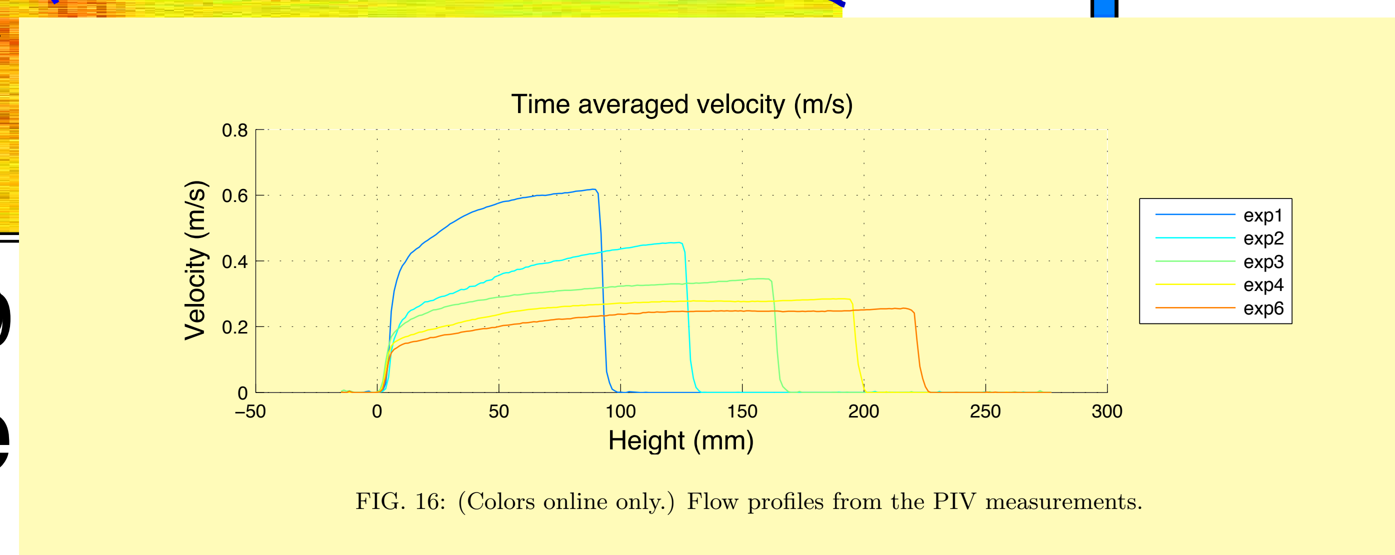
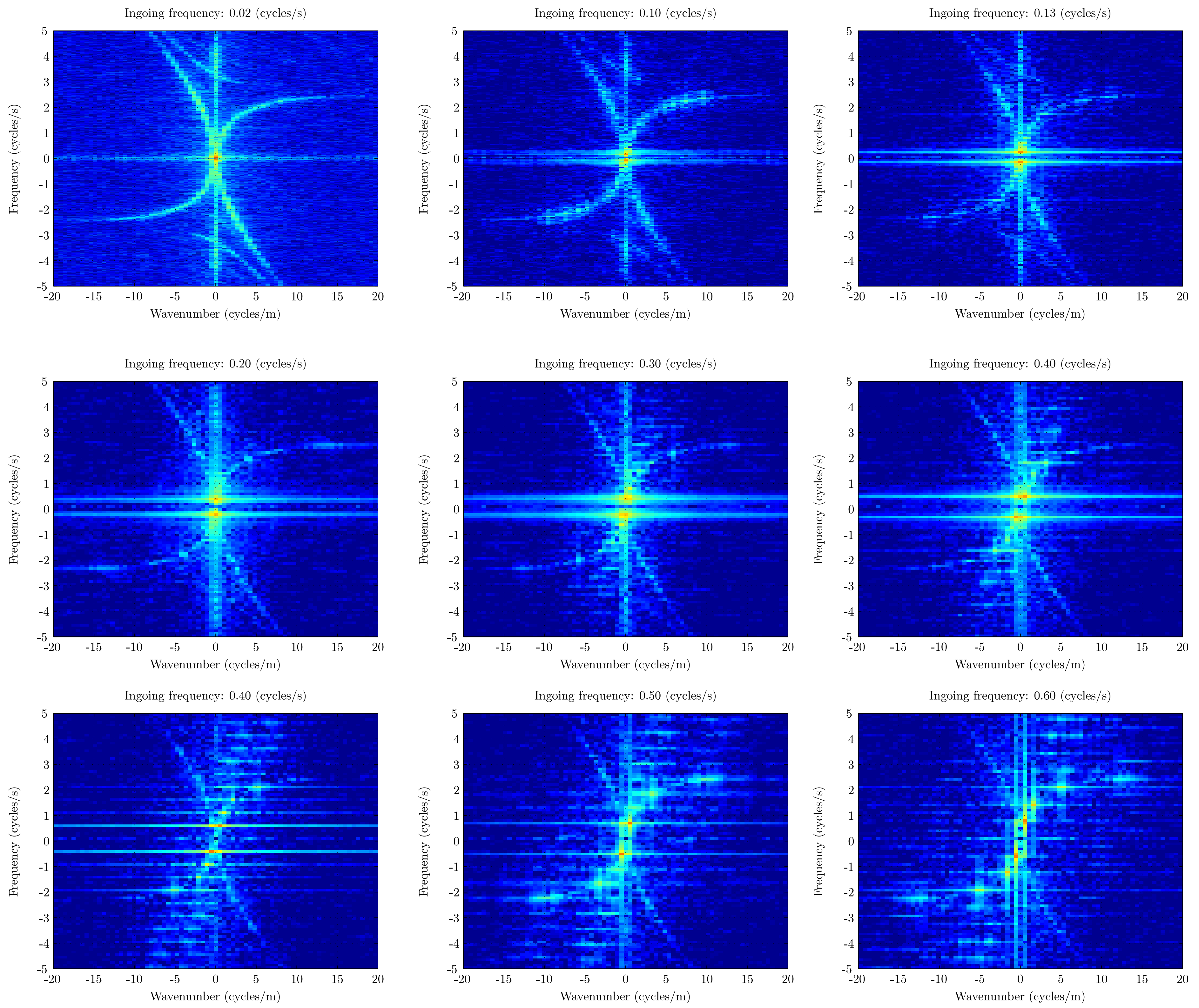
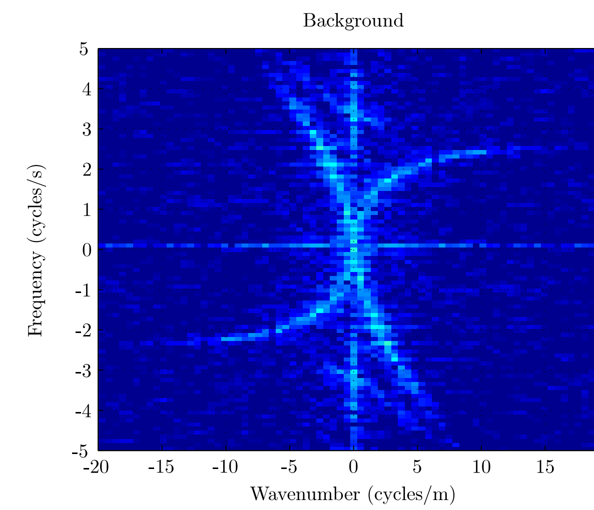


FIG. 16: (Colors online only.) Flow profiles from the PIV measurements.

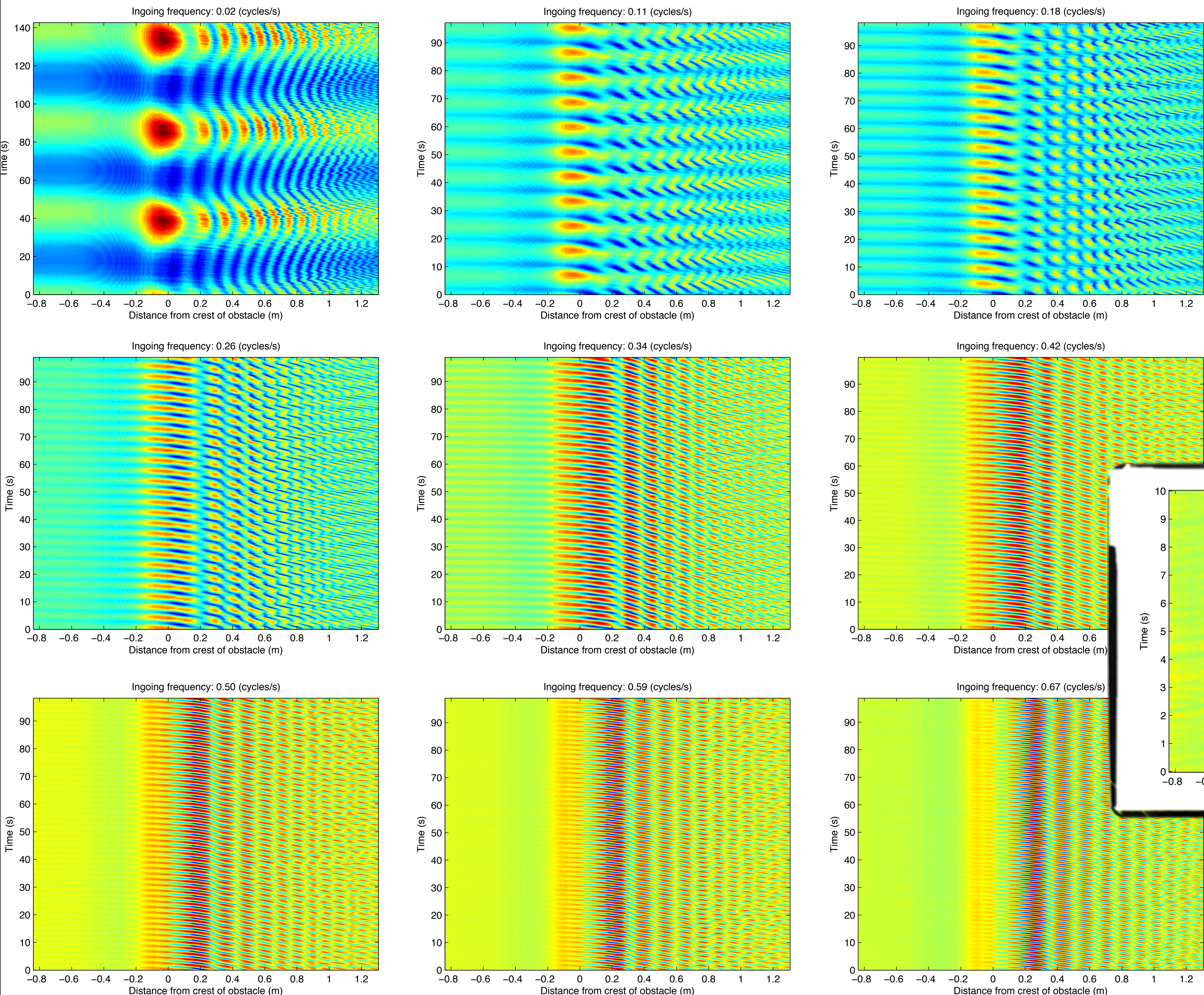
Our experiment ➤ Exciting classical field modes

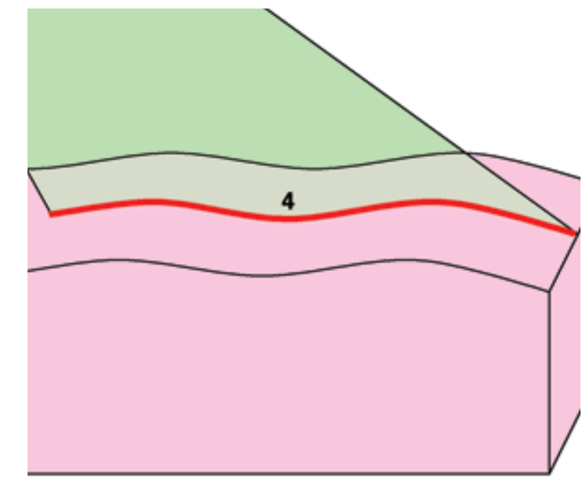


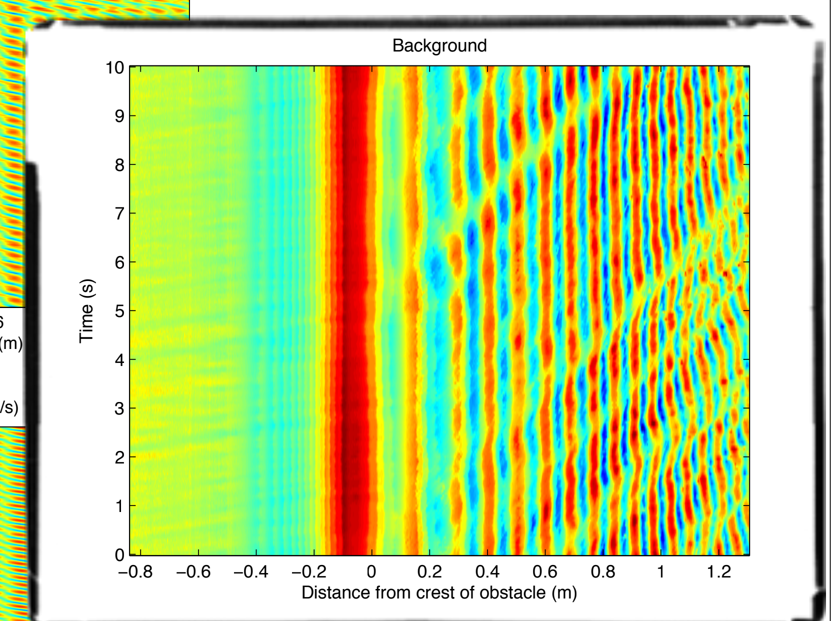


+

Our experiment ➤ Experimental procedure

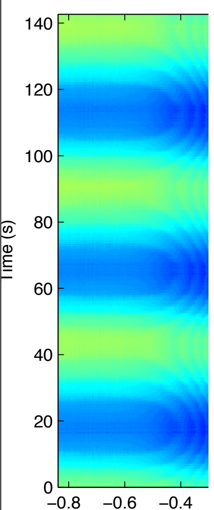


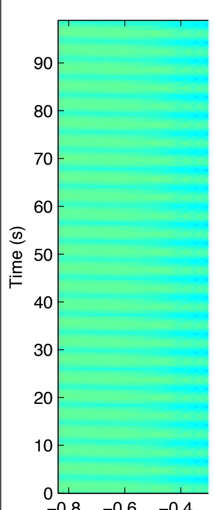


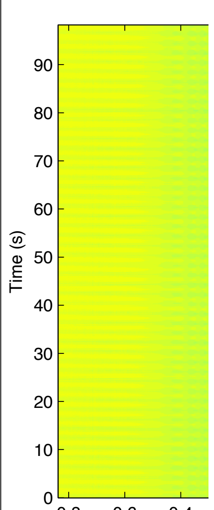


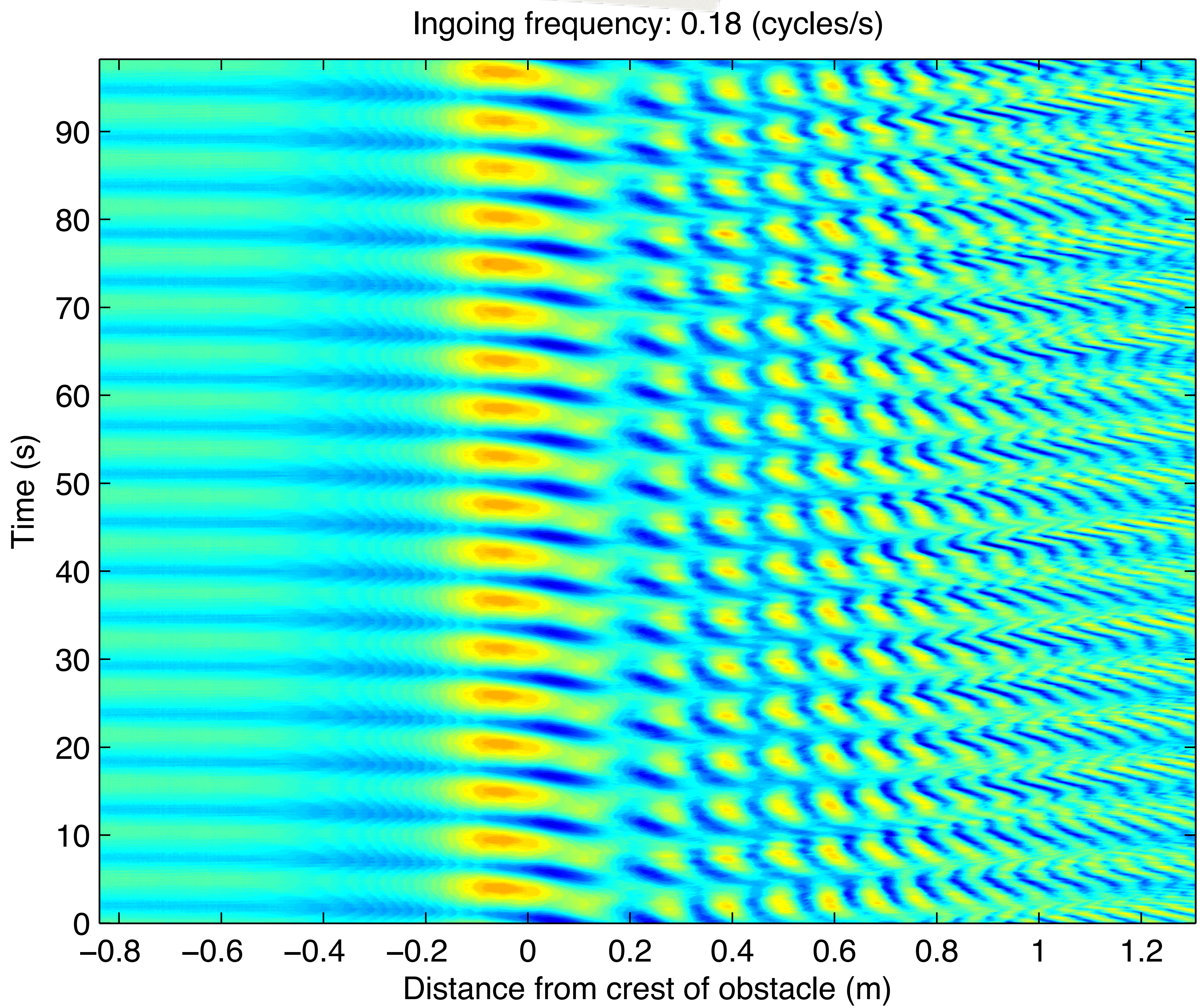
Standing wave: the undulation?

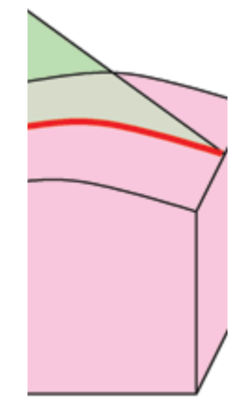
Our experiment ➤ Experimental procedure

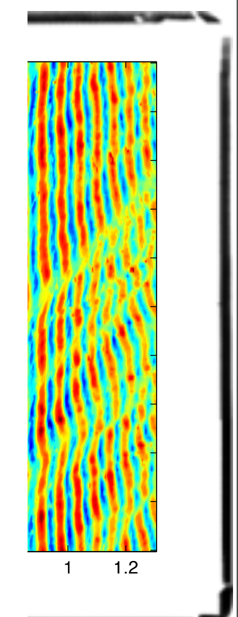








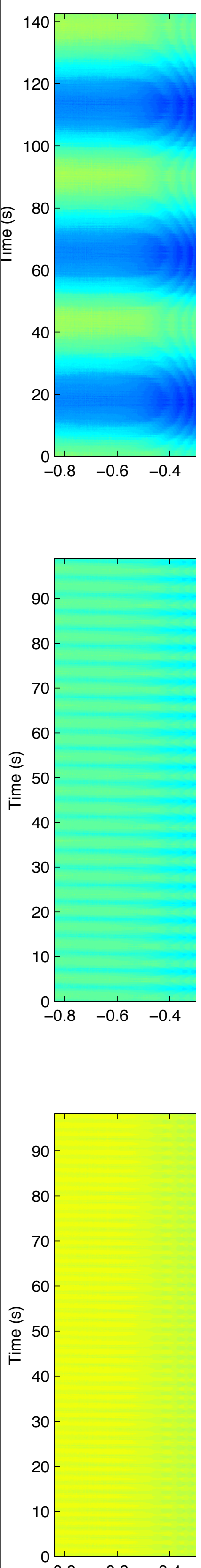


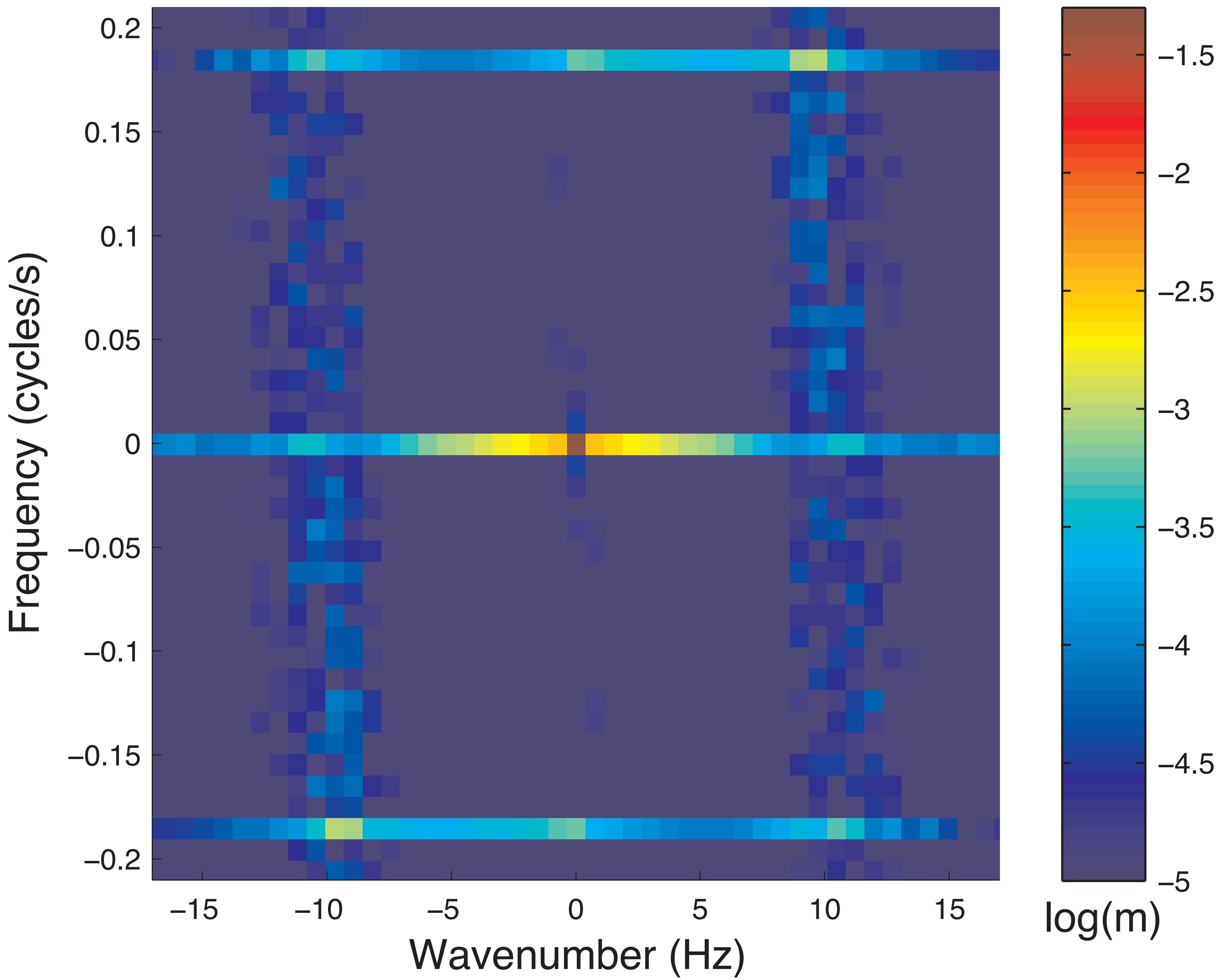


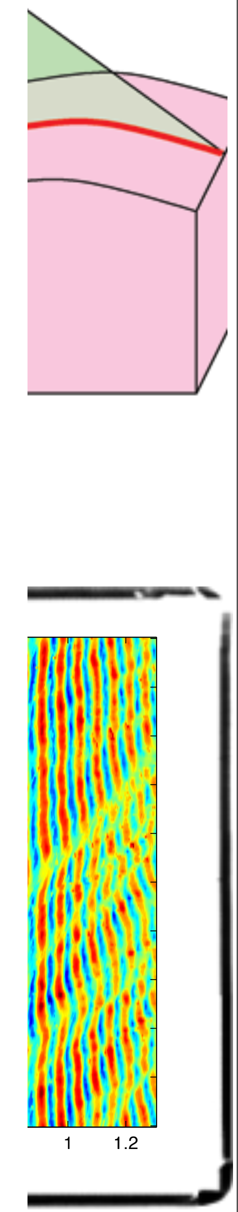
vave:

tion?

Our experiment ➤ Experimental procedure

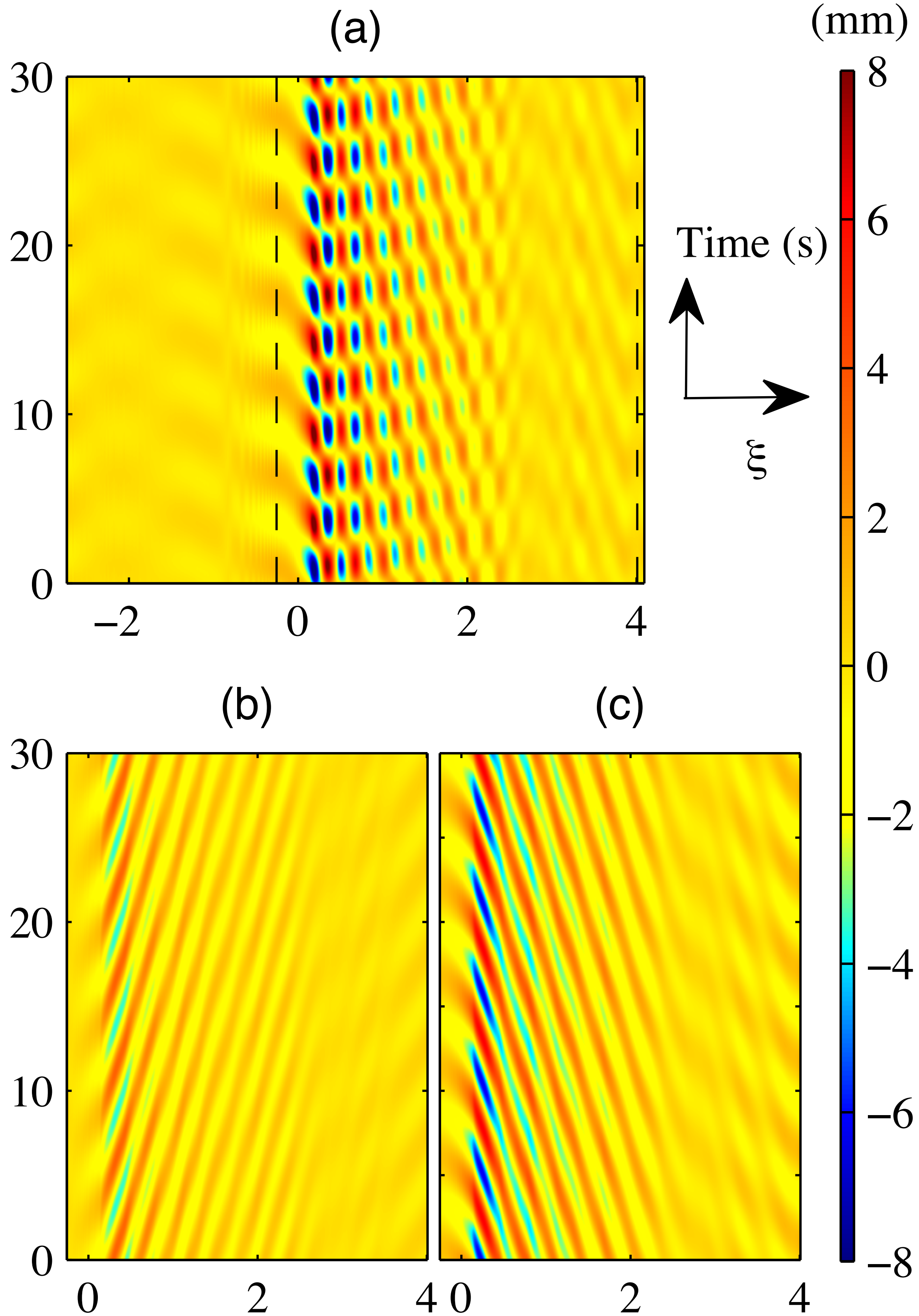


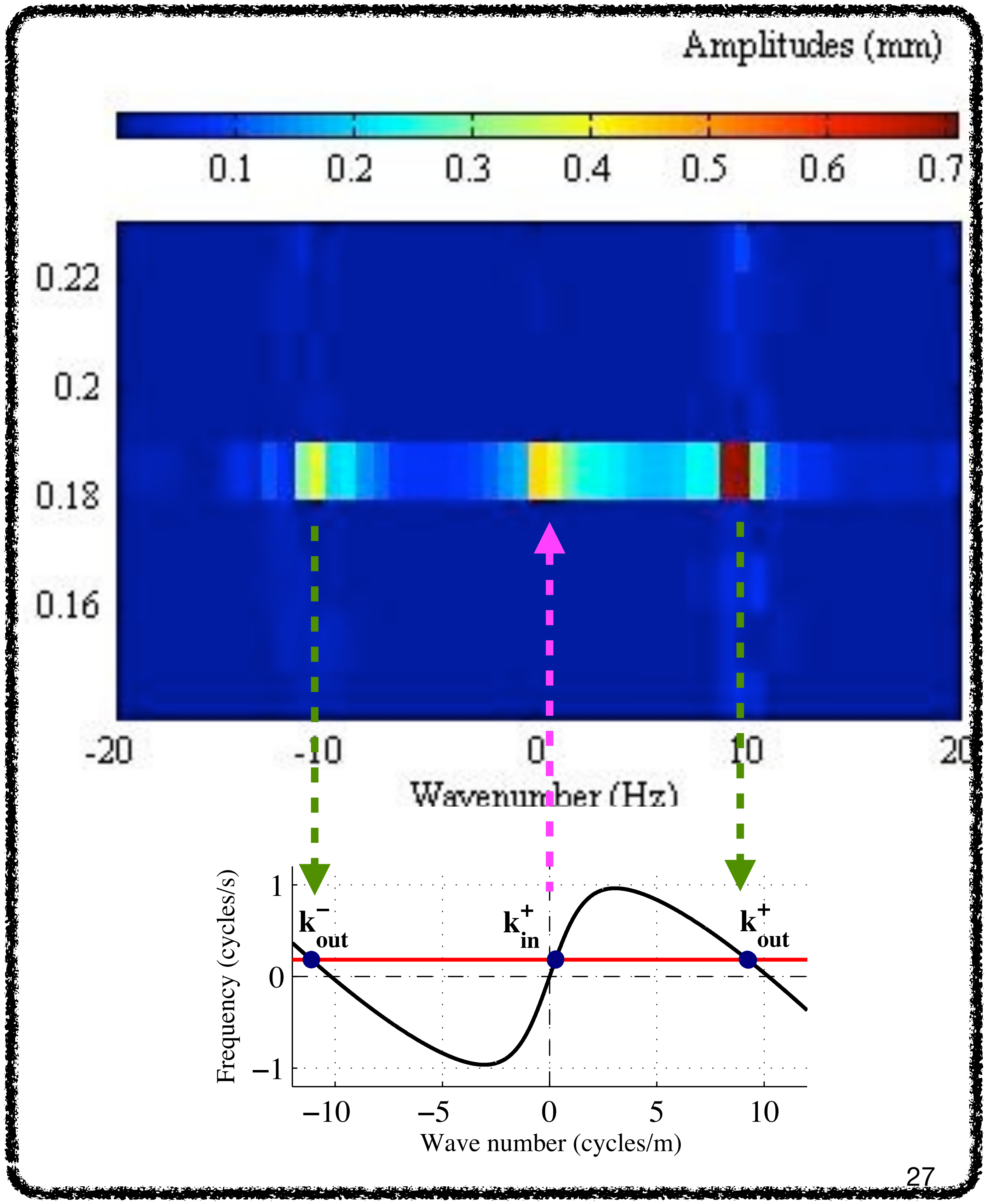




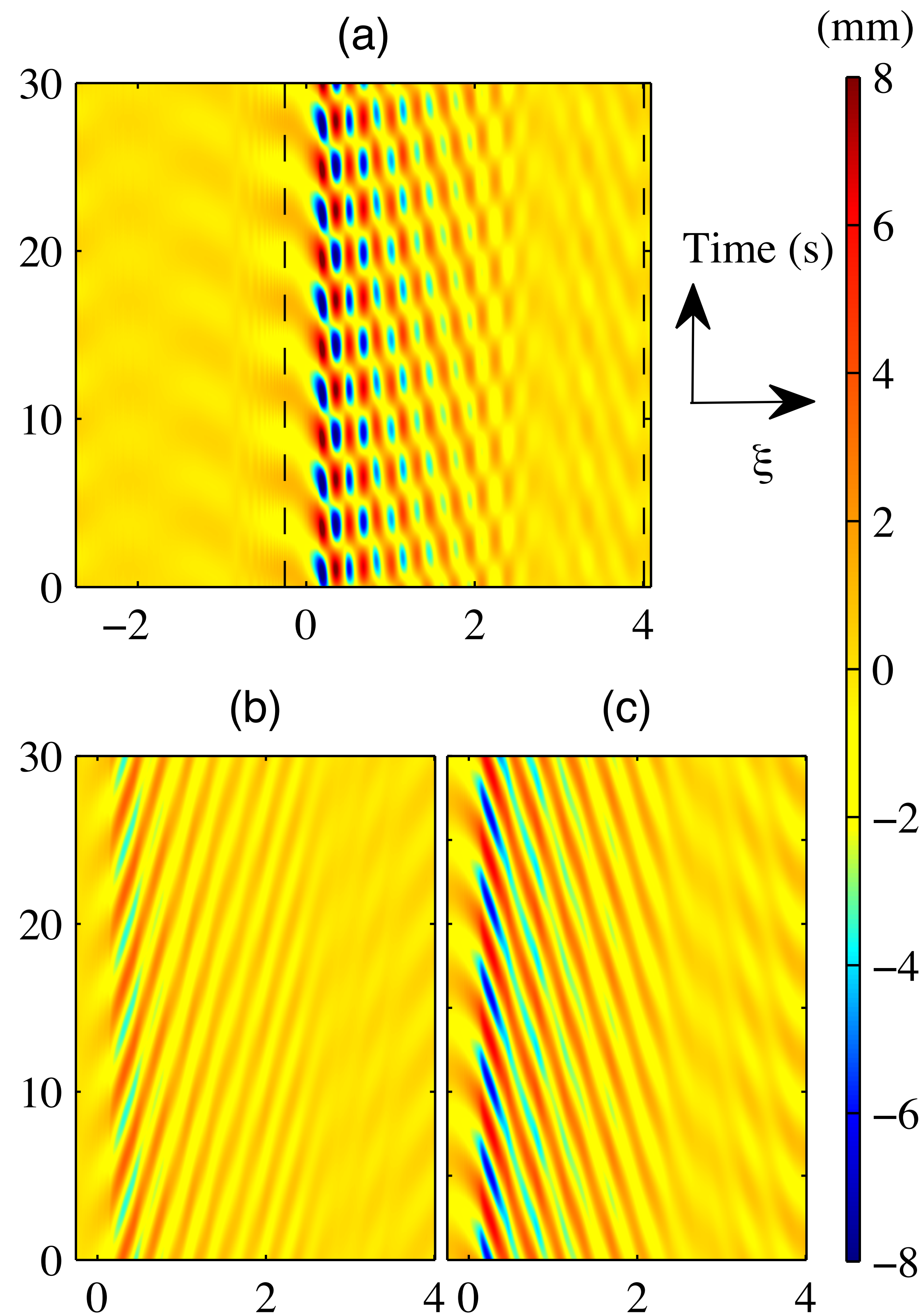
vave:
tion?

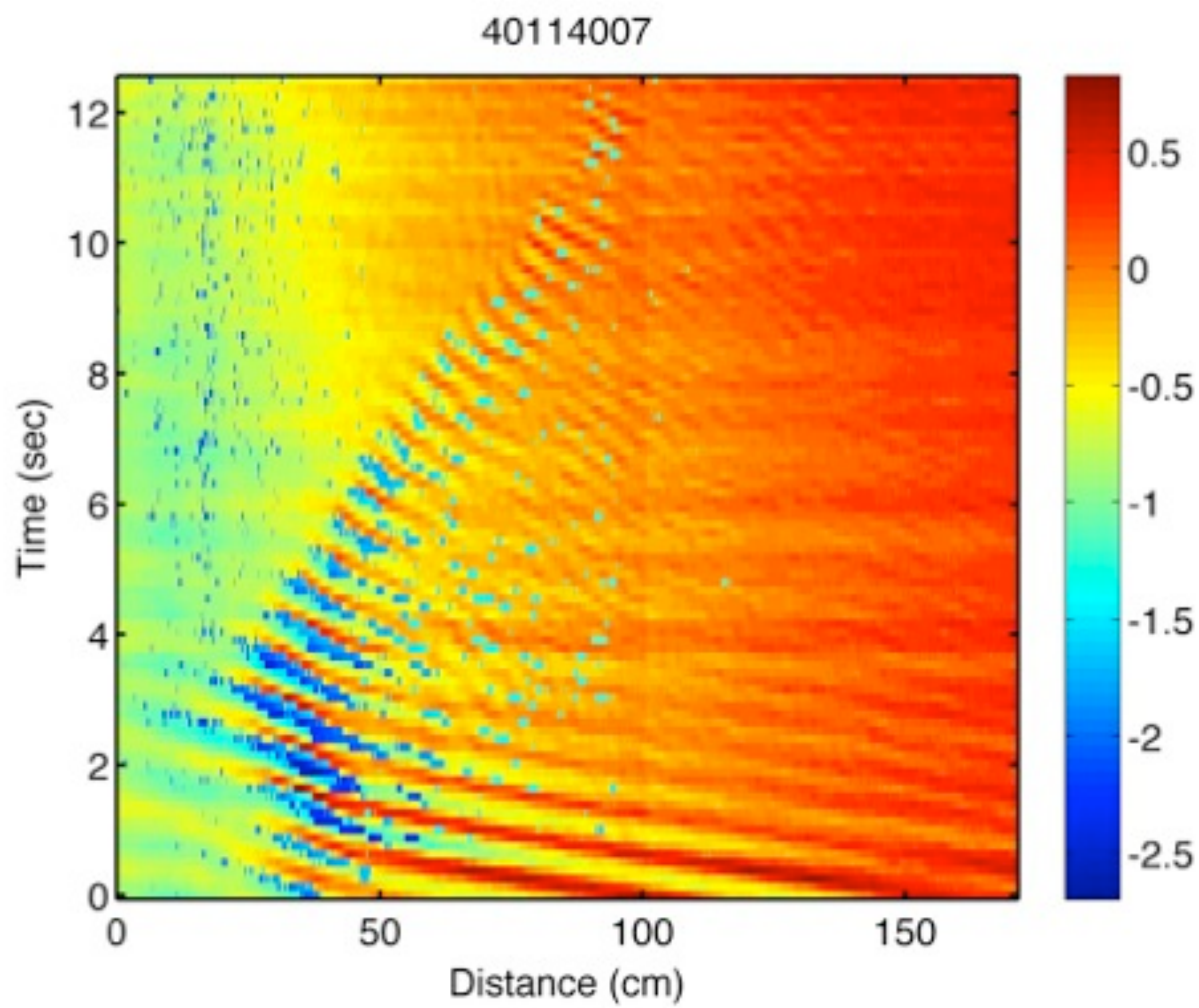
Our experiment ➤ Pair-creation process





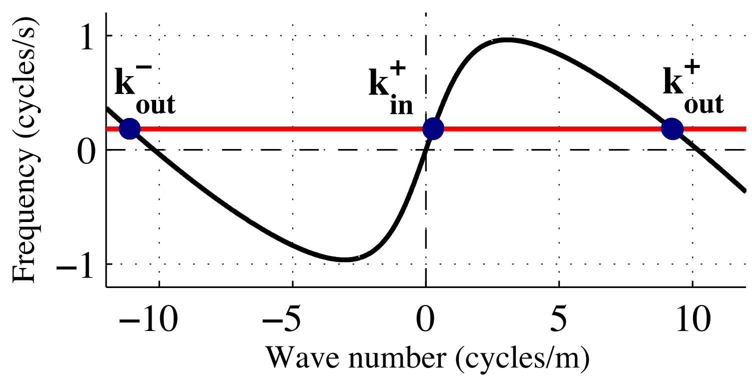
Our experiment ➤ Group versus phase velocity horizon



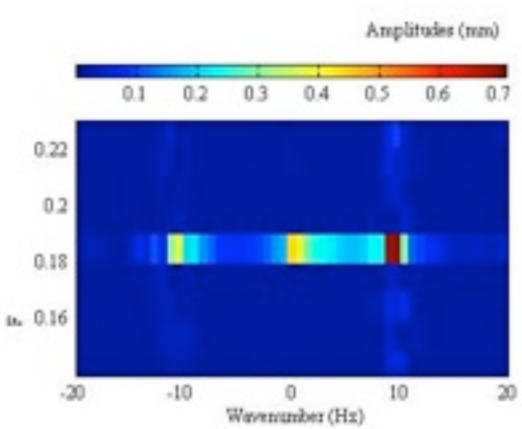


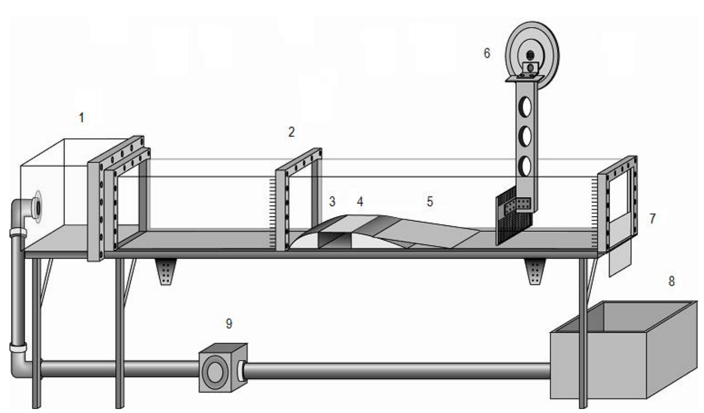
Our experiment ➤ Boltzmann distribution

(i) Amplitudes of converted waves depending on ingoing frequency:



(ii) what is a wave (particle) nearbythe white hole horizon..?

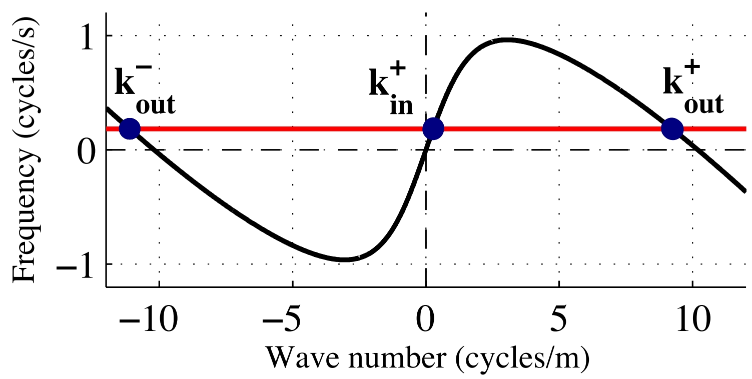


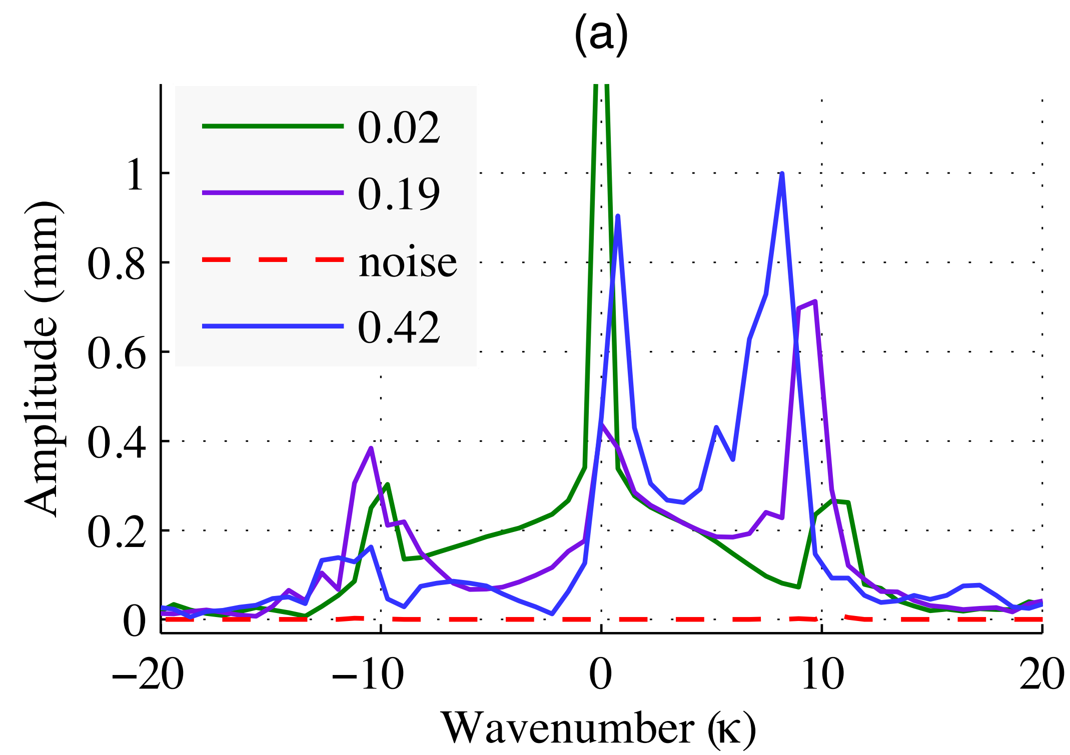


(ii) Norm is conserved: $$\int \frac{|A(f,\kappa)|^2}{f+\kappa} d\kappa$$

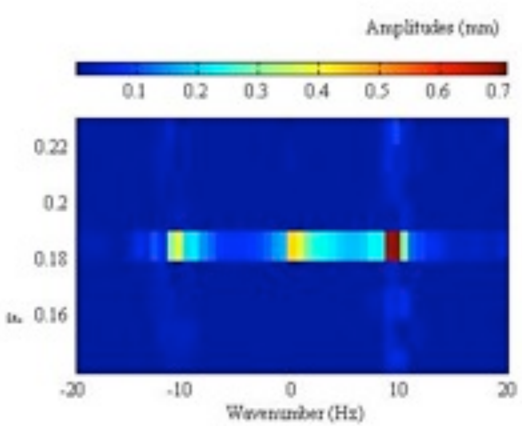
Our experiment ➤ Boltzmann distribution

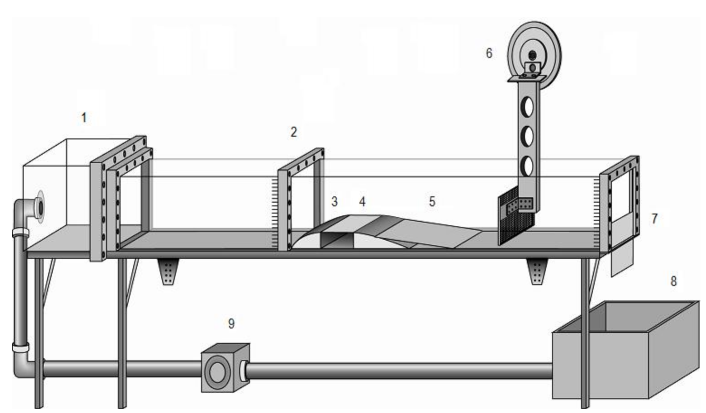
(i) Amplitudes of converted waves depending on ingoing frequency:





(ii) what is a wave (particle) nearbythe white hole horizon..?

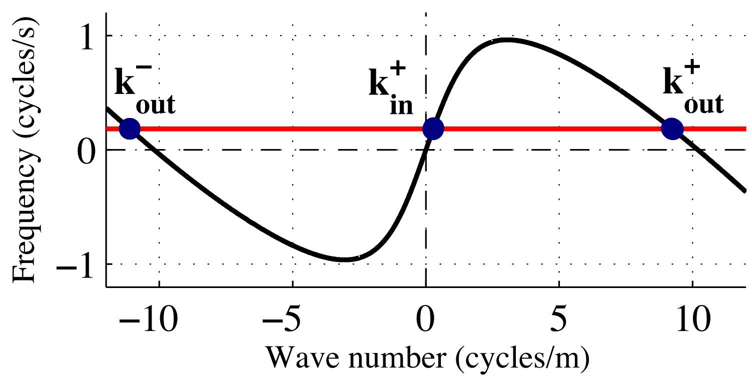




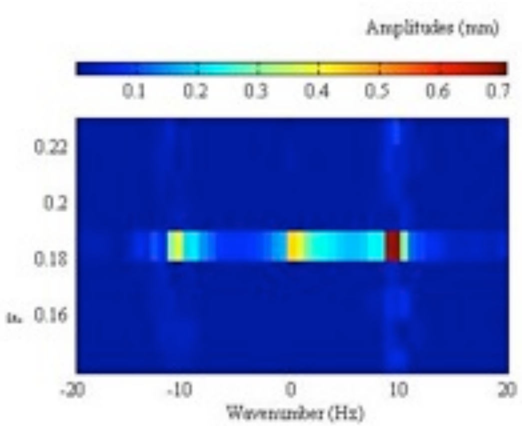
(ii) Norm is conserved: $\int \frac{|A(f,\kappa)|^2}{f+\kappa} d\kappa$

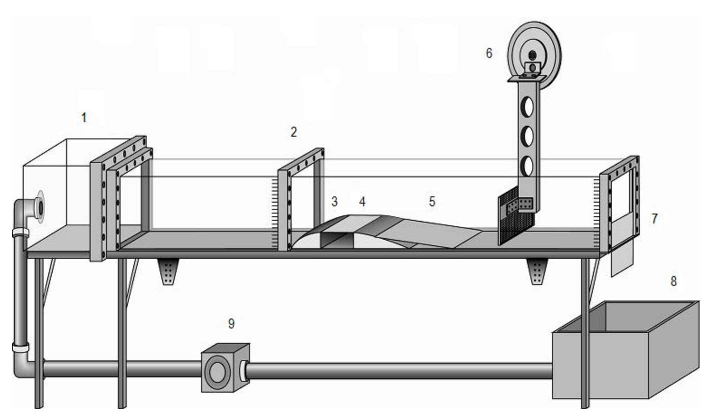
Our experiment ➤ Boltzmann distribution

(i) Amplitudes of converted waves depending on ingoing frequency:

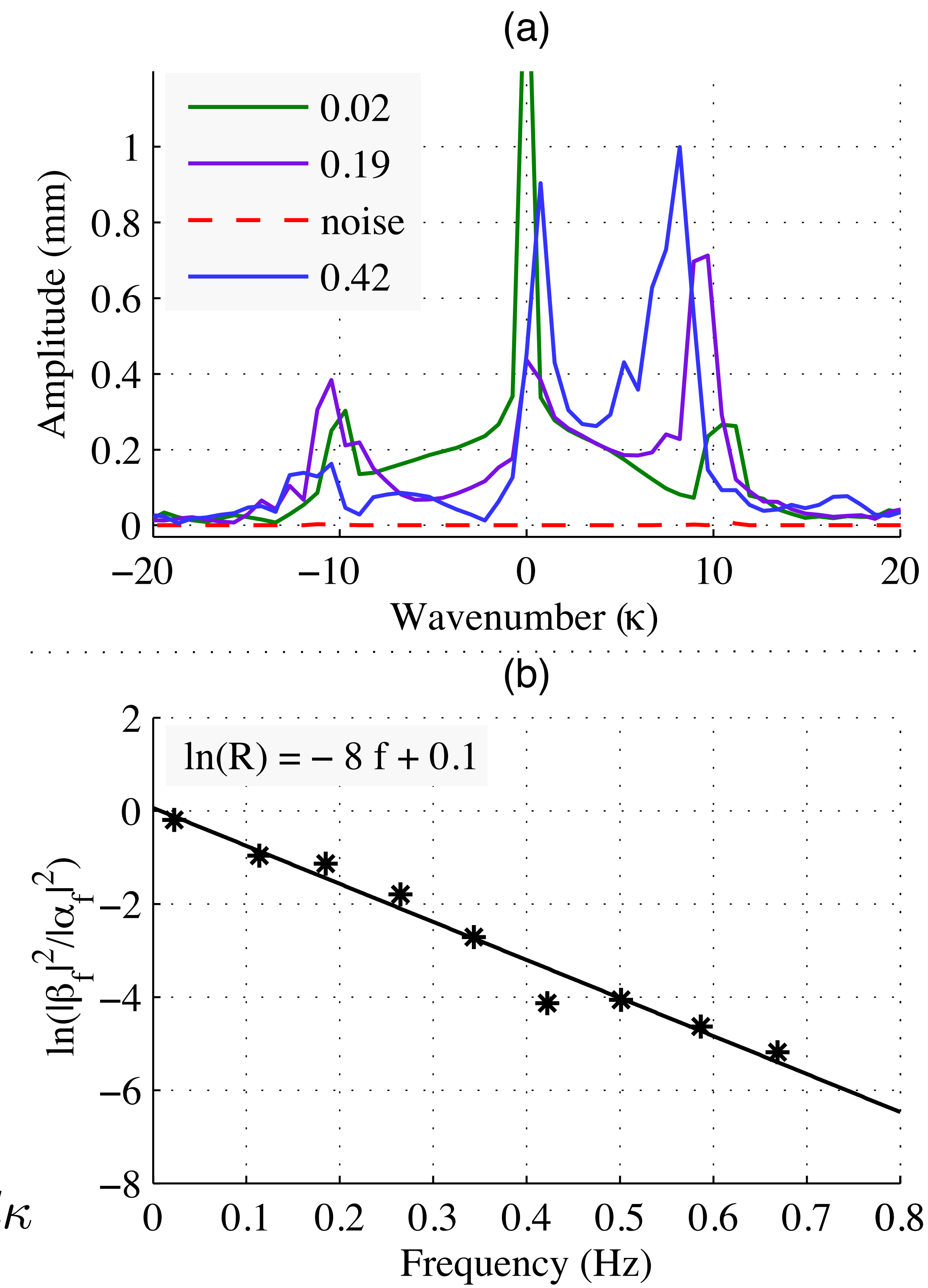


(ii) what is a wave (particle) nearbythe white hole horizon..?





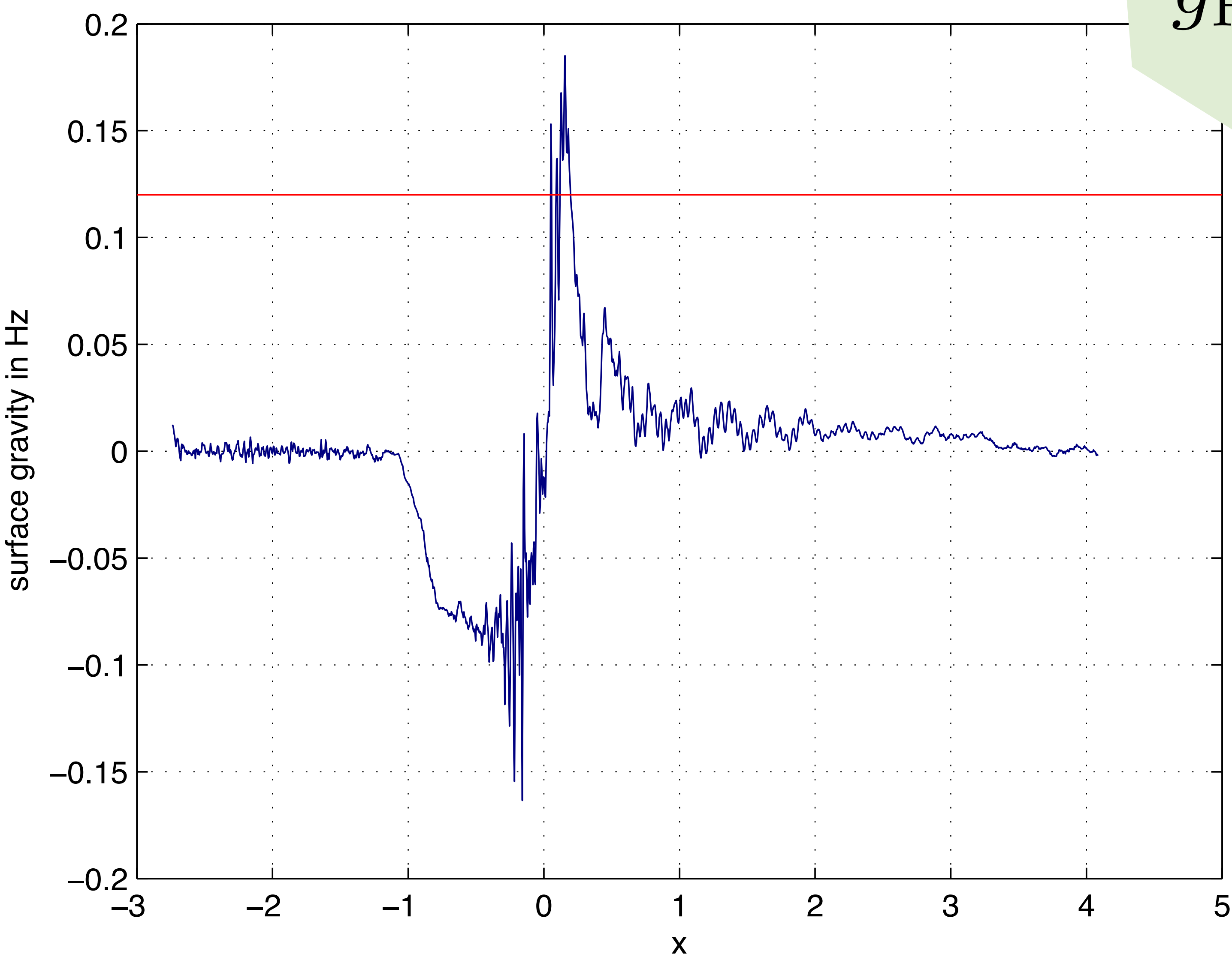
(ii) Norm is conserved: $$\int \frac{|A(f,\kappa)|^2}{f+\kappa} d\kappa$$



Our experiment ➤ Surface gravity

- BH evaporation: $$|\beta_\omega|^2 = e^{-\frac{2\pi\omega}{g_{\mathbf{H}}}} |\alpha_\omega|^2$$

$$g_{\mathrm{H}} = \frac{1}{2}\frac{\partial(c^2 - v^2)}{\partial n}$$

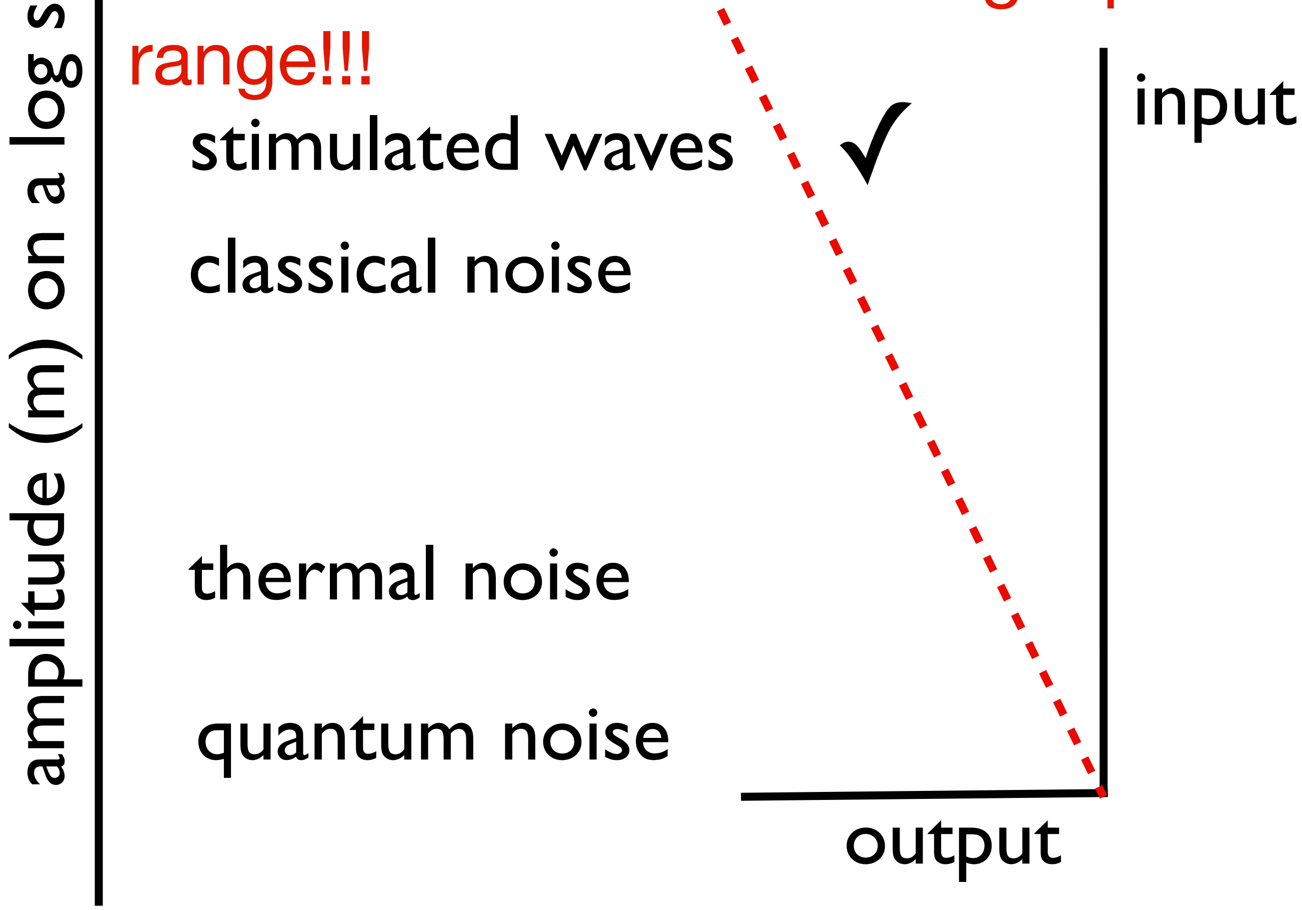


surface gravity (Hz) via **excitations:** **0.12 HZ**

surface gravity (Hz) via **background:** **0.08-0.18 Hz**

Our experiment ➤ Summary

Lesson: The thermal emission is a universal phenomenon, surviving fluid-dynamic deviations (viscosity, vorticity) and vastly altered dispersion relations, and linear over an amazing input range!!!

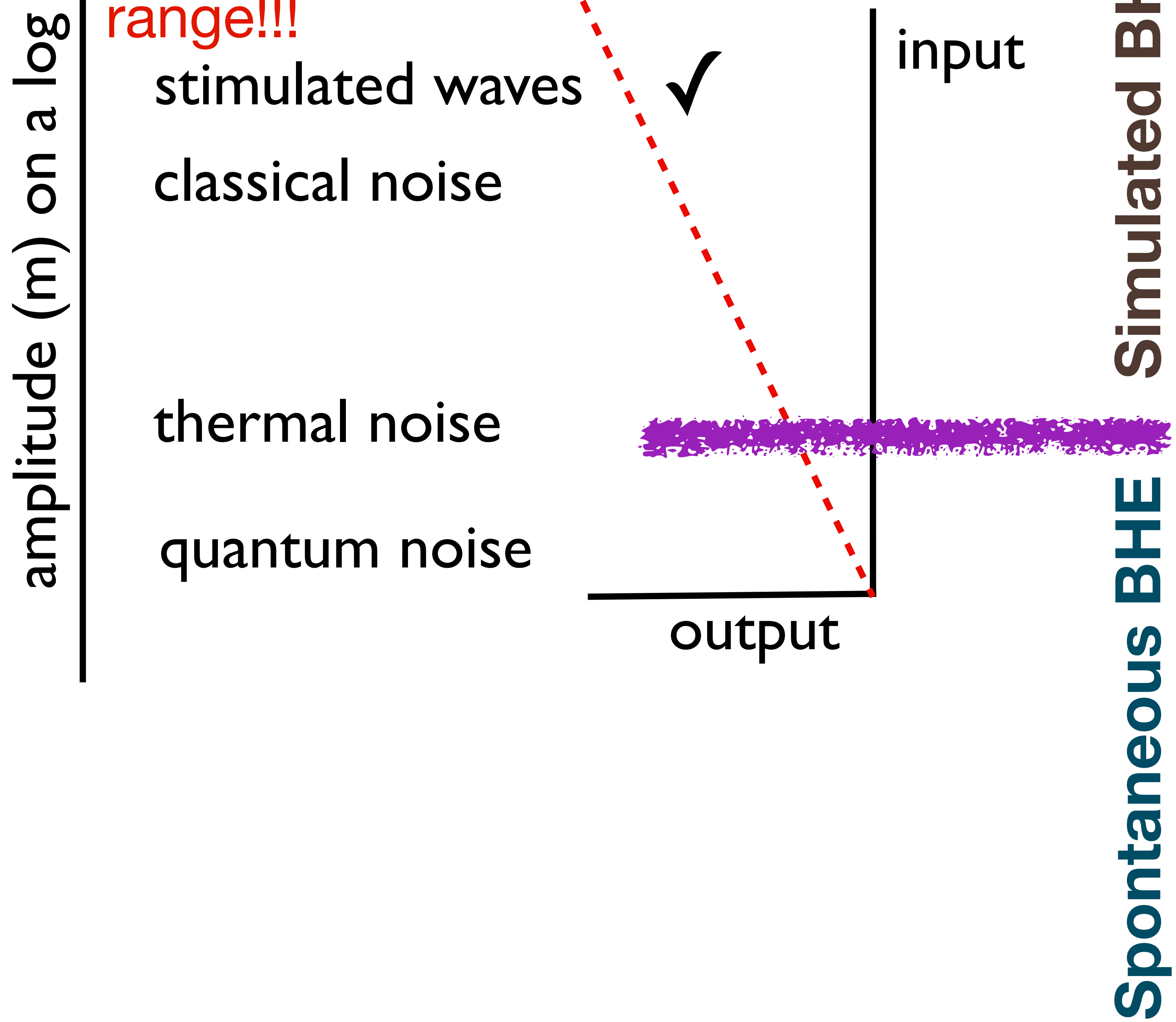


Assumption:
Linear amplifier over a huge range!

✔ pair-creation process (classical correlations)
✔ Boltzmann distribution
✔ surface gravity

Our experiment ➤ Summary

Lesson: The thermal emission is a universal phenomenon, surviving fluid-dynamic deviations (viscosity, vorticity) and vastly altered dispersion relations, and linear over an amazing input range!!!



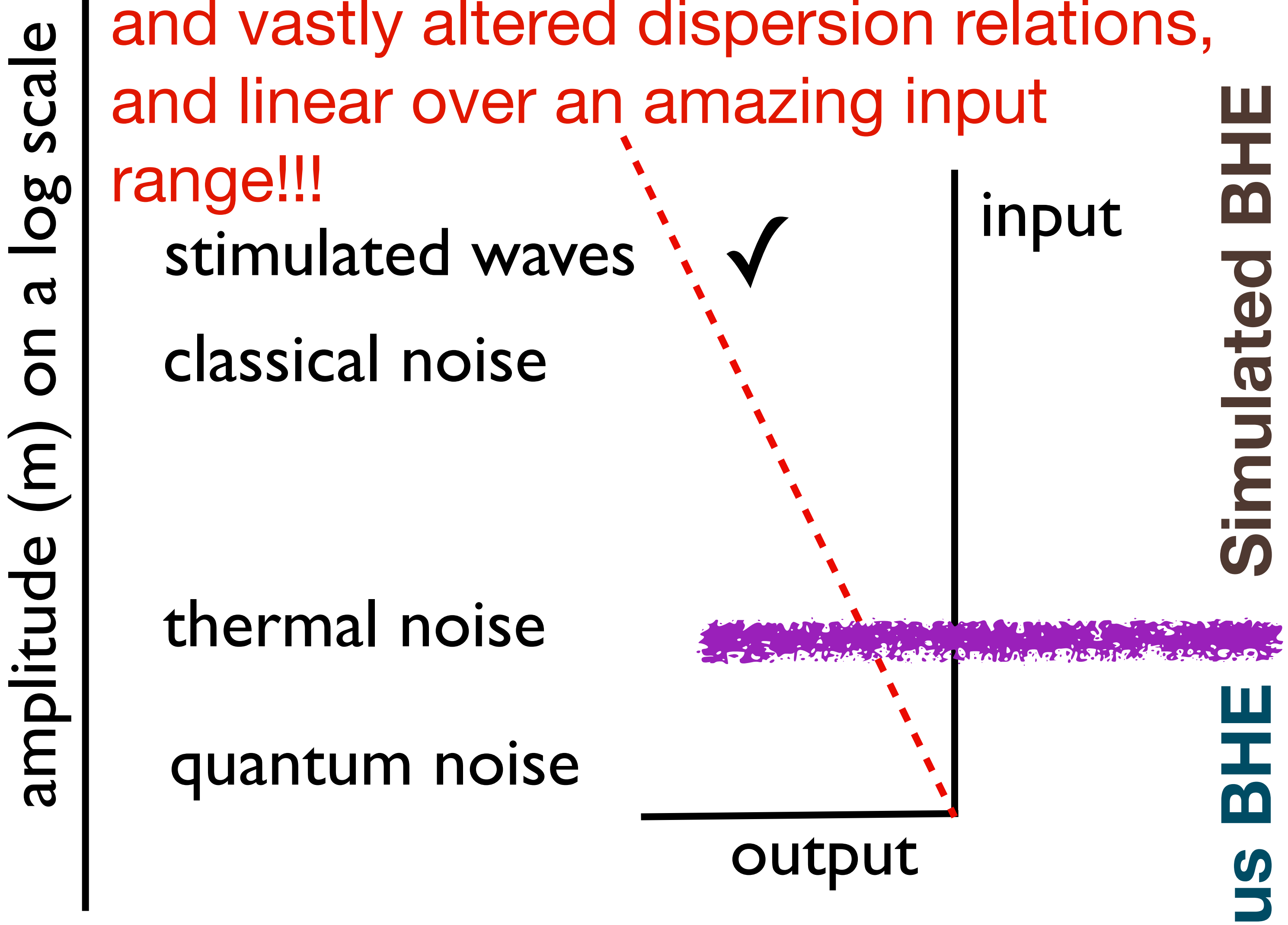
<u>Assumption:</u>
Linear amplifier over a huge range!

- ✔ pair-creation process (classical correlations)
- ✔ Boltzmann distribution
- ✔ surface gravity

- ✔ quantum correlations

Our experiment ➤ Summary

Lesson: The thermal emission is a universal phenomenon, surviving fluid-dynamic deviations (viscosity, vorticity) and vastly altered dispersion relations, and linear over an amazing input range!!!



there is **NO** UV-**problem in our system...**

Assumption:

Linear amplifier over a huge range!

✔ pair-creation process (classical correlations)

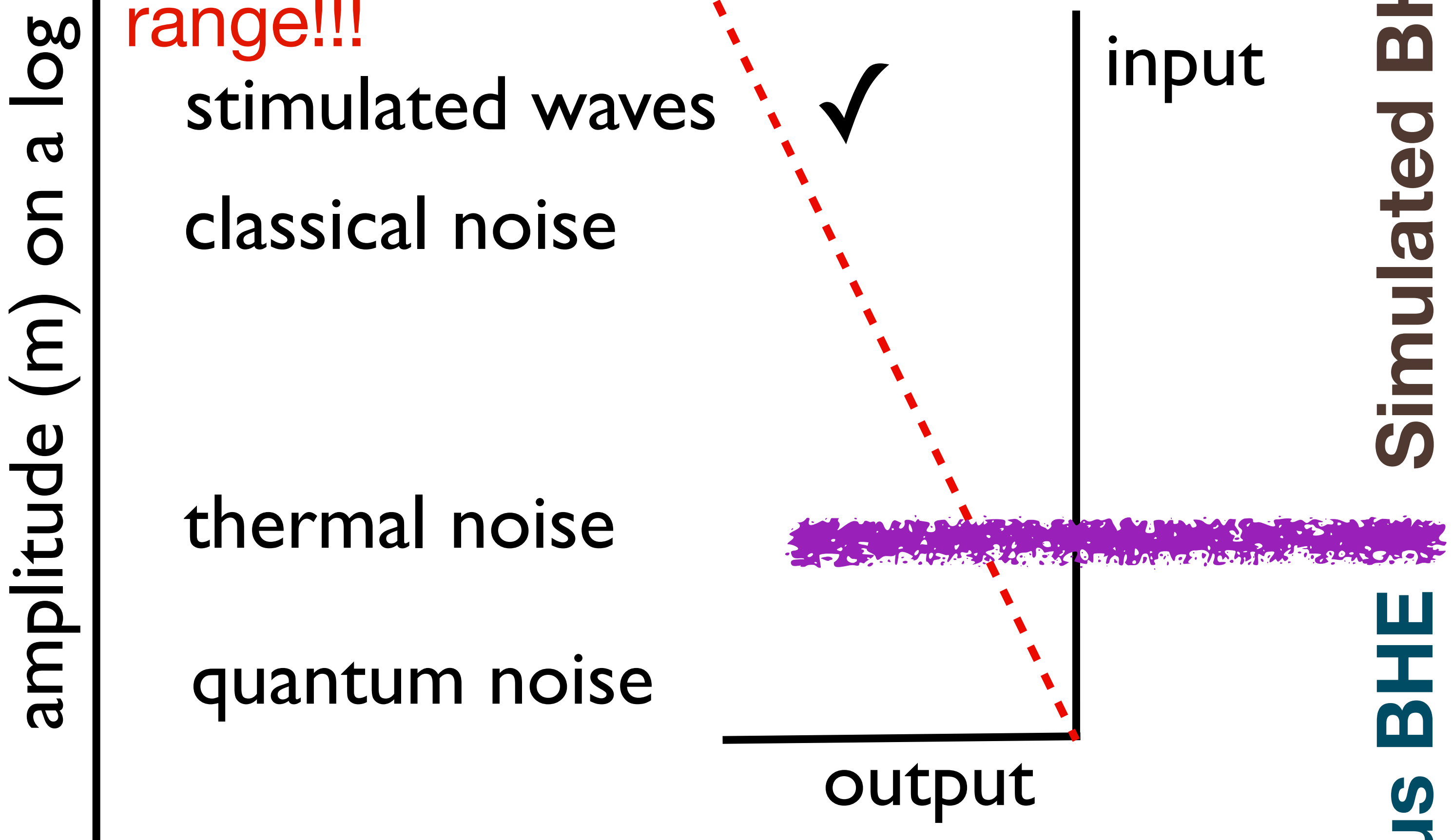
✔ Boltzmann distribution

✔ surface gravity

✔ quantum correlations

Our experiment ➤ Summary

Lesson: The thermal emission is a universal phenomenon, surviving fluid-dynamic deviations (viscosity, vorticity) and vastly altered dispersion relations, and linear over an amazing input range!!!



there is **NO** UV-**problem in our system...**

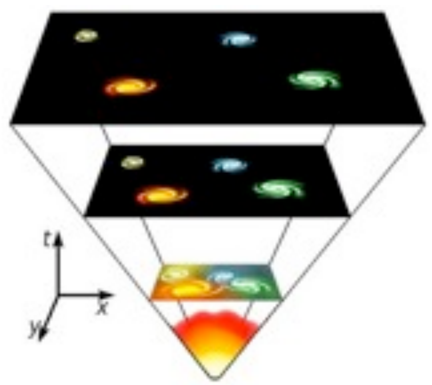
Assumption:
Linear amplifier over a huge range!

- ✔ pair-creation process (classical correlations)
- ✔ Boltzmann distribution
- ✔ surface gravity

However: Spontaneous emission straightforward, but un- detectable (**6x10^-12 K**); superfluid experiments necessary...

- ✔ quantum correlations

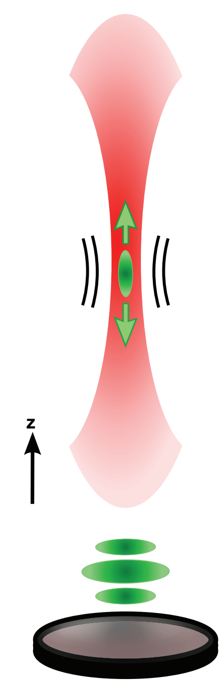
Other experiment(s)➤ Classical versus quantum?



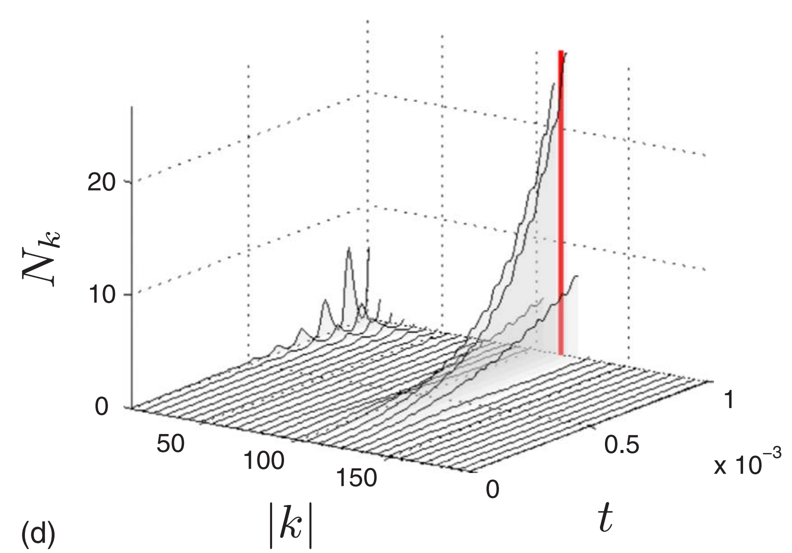
Example 3:

Cosmological particle production

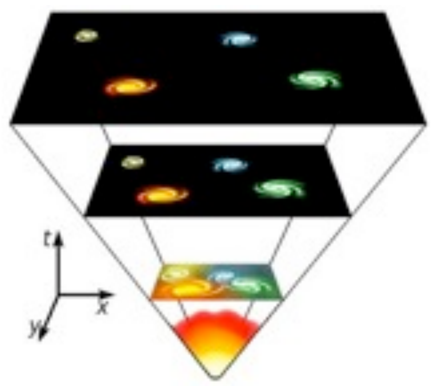
Cyclic universe:



‘**Analogue model of a FRW universe in Bose-Einstein condensates: Application of the classical field method**’, Phys. Rev. A 76, 033616 (2007), P. Jain, S.W., M. Visser and C. W. Gardiner.



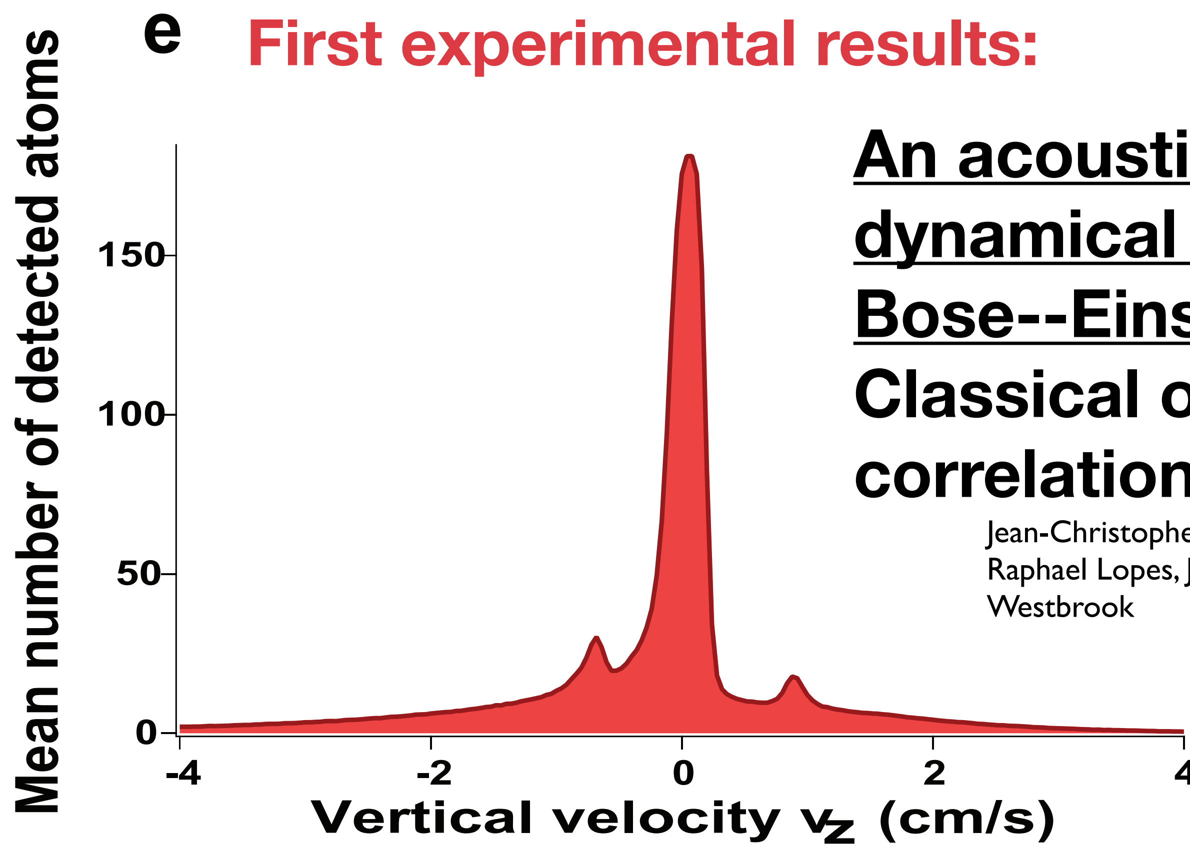
Other experiment(s)➤ Classical versus quantum?



Example 3:

Cosmological particle production

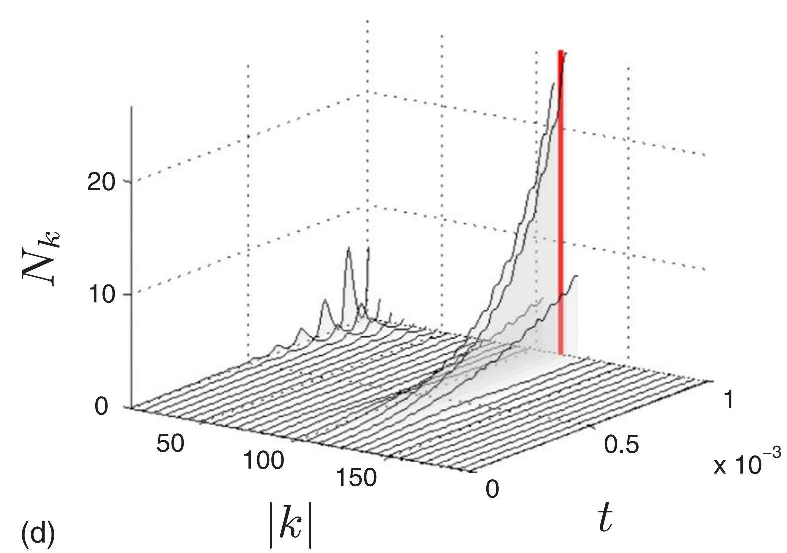
Cyclic universe:



An acoustic analog to the dynamical Casimir effect in a Bose--Einstein condensate: Classical or quantum correlations?

Jean-Christophe Jaskula, Guthrie B. Partridge, Marie Bonneau, Raphael Lopes, Josselin Ruaudel, Denis Boiron, Christoph I Westbrook

'Analogue model of a FRW universe in Bose-Einstein condensates: Application of the classical field method', Phys. Rev. A 76, 033616 (2007), P. Jain, S.W., M. Visser and C. W. Gardiner.



(d)

Phys. Rev. Lett. 108, 260401 (2012) [5 pages]

Violation of the Cauchy-Schwarz Inequality with Matter Waves

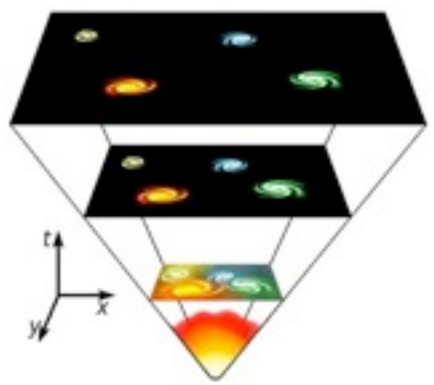
K. V. Kheruntsyan[1], J.-C. Jaskula[2,*], P. Deuar[3], M. Bonneau[2], G. B. Partridge[2,†], J. Ruaudel[2], R. Lopes[2], D. Boiron[2], and C. I. Westbrook[2]

[1]*The University of Queensland, School of Mathematics and Physics, Brisbane, Queensland 4072, Australia*

[2]*Laboratoire Charles Fabry de l'Institut d'Optique, CNRS, Université Paris-Sud, Campus Polytechnique RD128, 91127 Palaiseau, France*

[3]*Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warsaw, Poland*

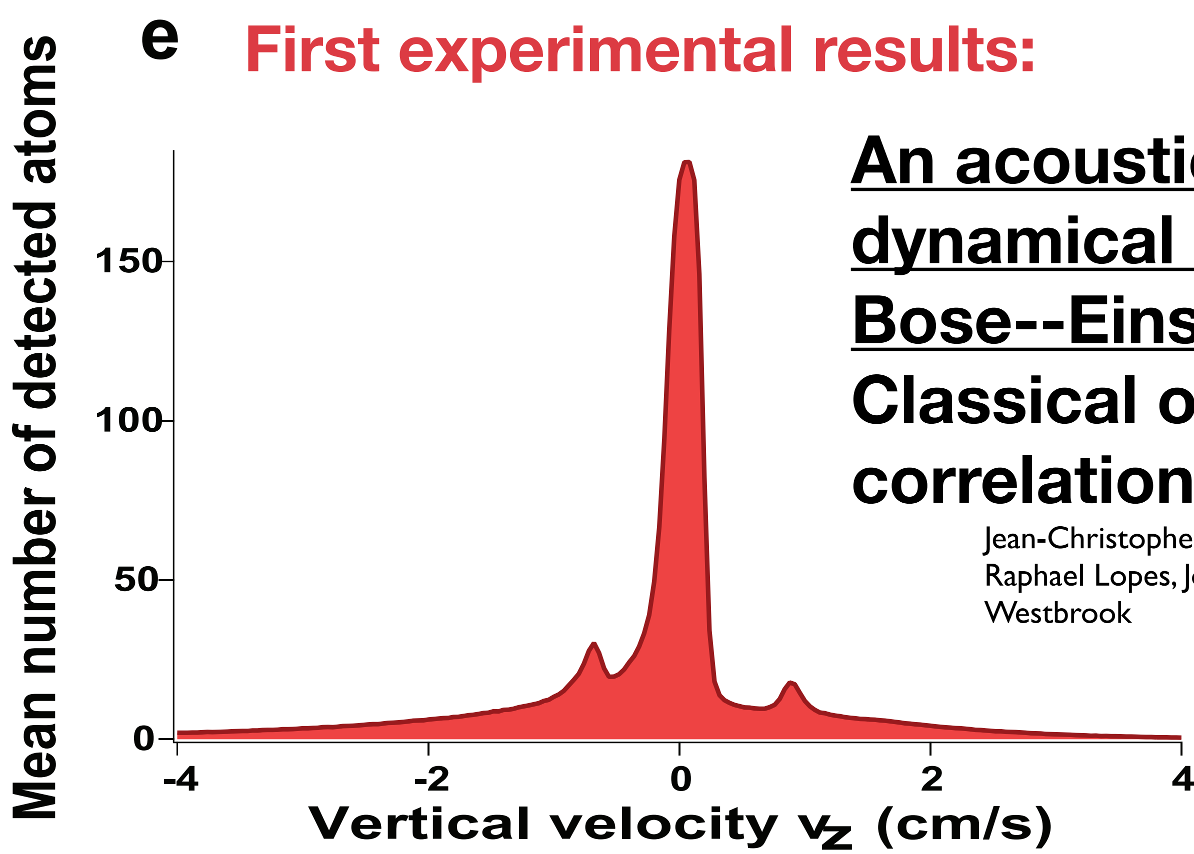
Other experiment(s)➤ Classical versus quantum?



Example 3:

Cosmological particle production

Cyclic universe:



An acoustic analog to the dynamical Casimir effect in a Bose--Einstein condensate: Classical or quantum correlations?

Jean-Christophe Jaskula, Guthrie B. Partridge, Marie Bonneau, Raphael Lopes, Josselin Ruaudel, Denis Boiron, Christoph I Westbrook

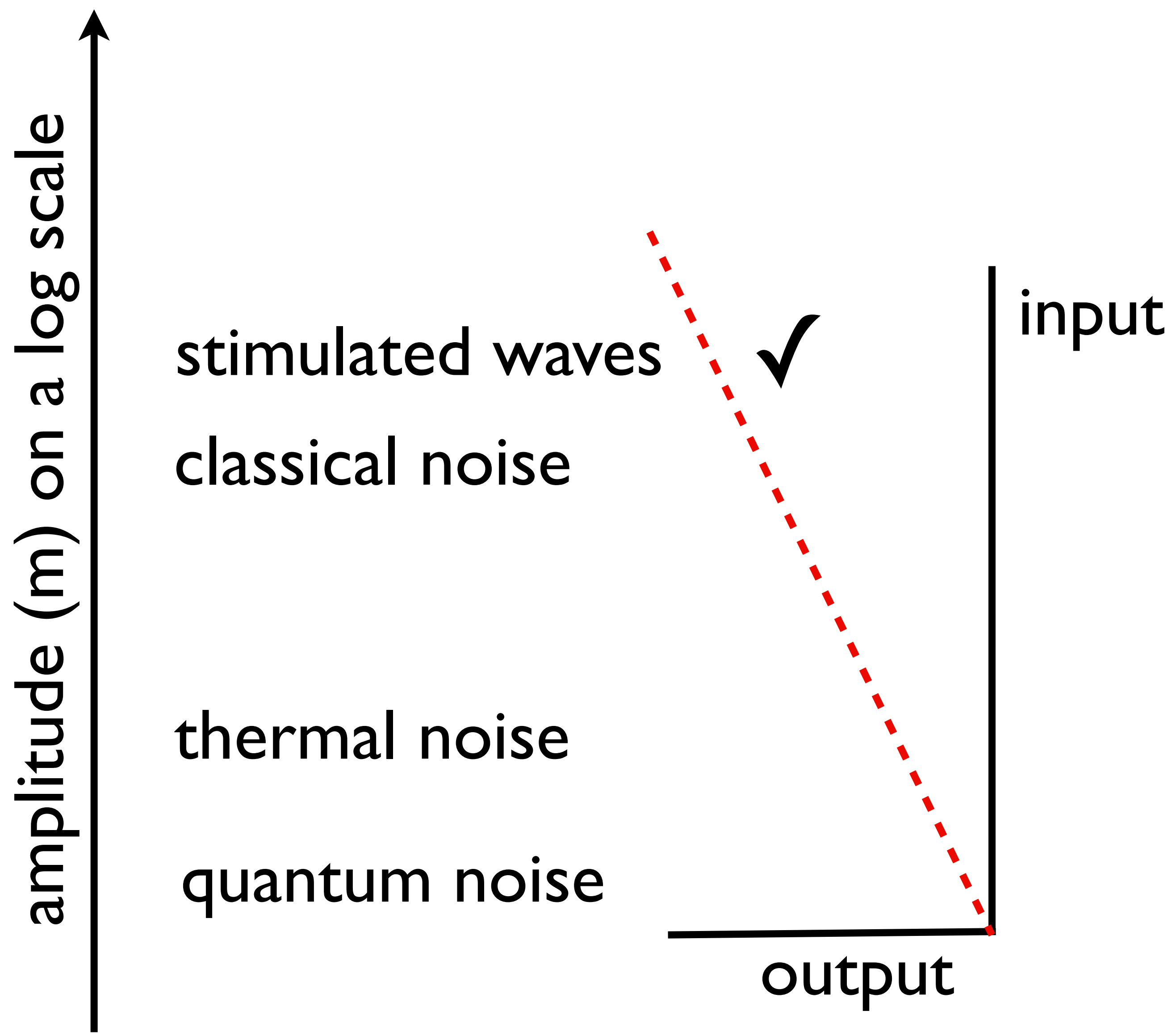
No stronger-than-classical correlations detected...

Phys. Rev. Lett. 108, 260401 (2012) [5 pages]

Violation of the Cauchy-Schwarz Inequality with Matter Waves

K. V. Kheruntsyan[1], J.-C. Jaskula[2,*], P. Deuar[3], M. Bonneau[2], G. B. Partridge[2,†], J. Ruaudel[2], R. Lopes[2], D. Boiron[2], and C. I. Westbrook[2]
[1]*The University of Queensland, School of Mathematics and Physics, Brisbane, Queensland 4072, Australia*
[2]*Laboratoire Charles Fabry de l'Institut d'Optique, CNRS, Université Paris-Sud, Campus Polytechnique RD128, 91127 Palaiseau, France*
[3]*Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warsaw, Poland*

Our experiment ➤ "Quantum" field theory in CS..?



<u>Assumption:</u>
Linear amplifier over a huge range!

✔ pair-creation process (classical correlations)
✔ Boltzmann distribution
✔ surface gravity

"<u>Quantum</u>" Field Theory in curved spacetimes...?

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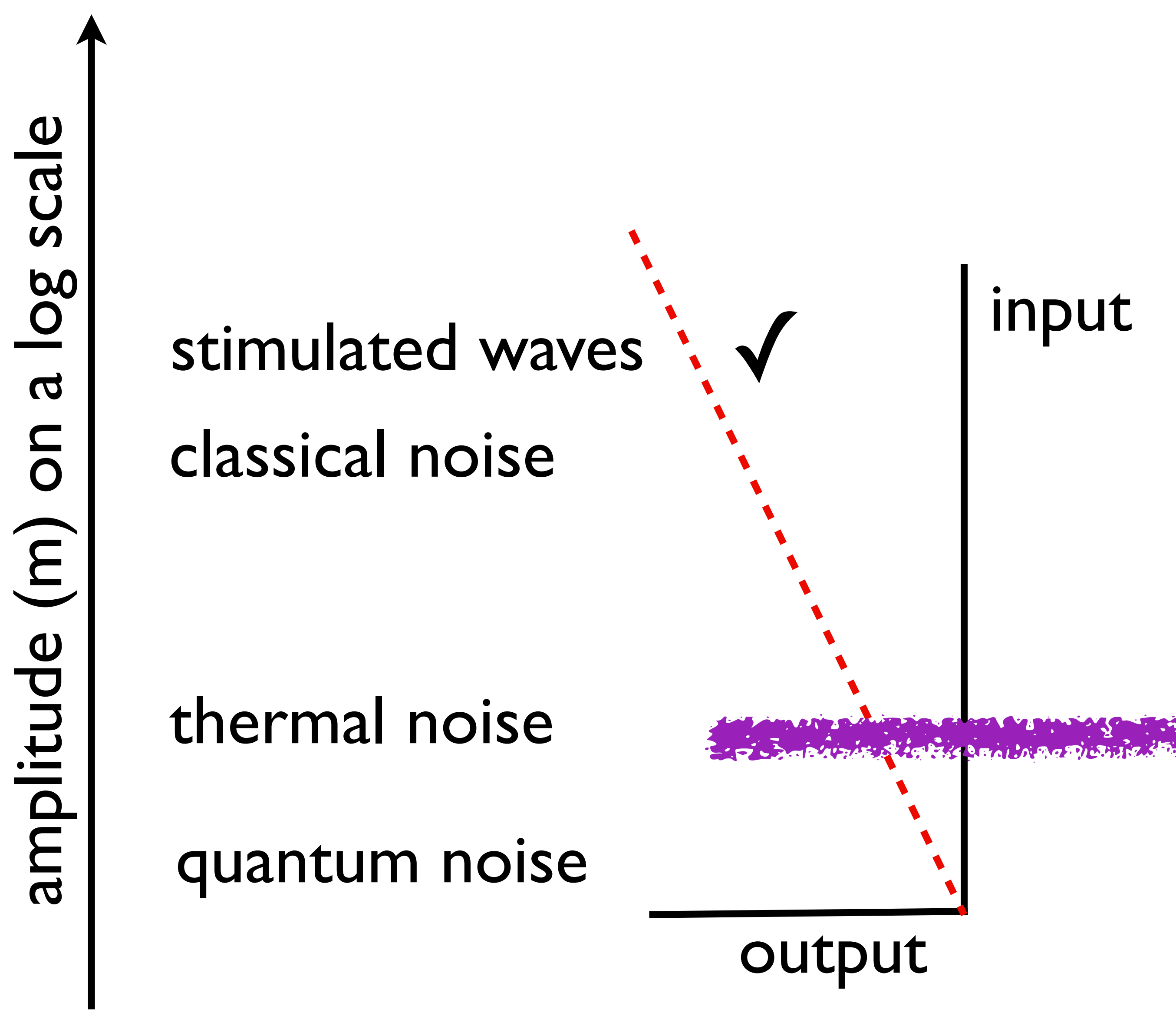

Simulated BHE

Spontaneous BHE

“<u>Quantum</u>” Field Theory in curved spacetimes...?

<u>Assumption:</u>
Linear amplifier over a huge range!

- ✔ pair-creation process (classical correlations)
- ✔ Boltzmann distribution
- ✔ surface gravity

- ✔ quantum correlations

Summary ➤ Results from AM experiments

Analogue Gravity experiments	Vancouver: stimulated **white hole** emission	Daniele Faccio: spontaneous **white hole** emission	Westbrook: **cosmological** particle production
Pair-creation (classical correlations)	✓	?	✓
Boltzmann distribution	✓	? (impossible)	irrelevant
Effective gravity (determines physics)	✓	unclear	✓
Quantum correlations	impossible	?	tested, outcome so far negative ✓

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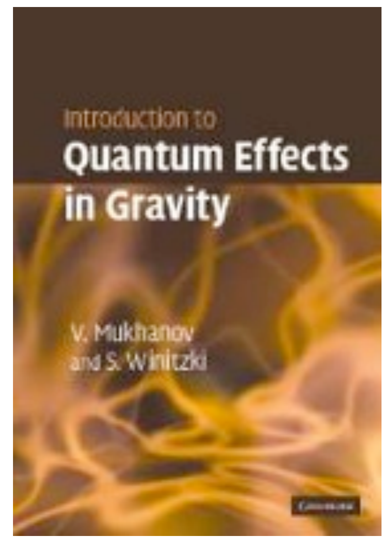
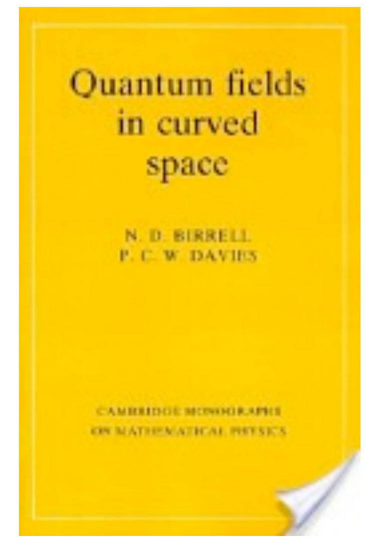
Summary ➤ Results from AM experiments

(Q)FT in curved spacetimes



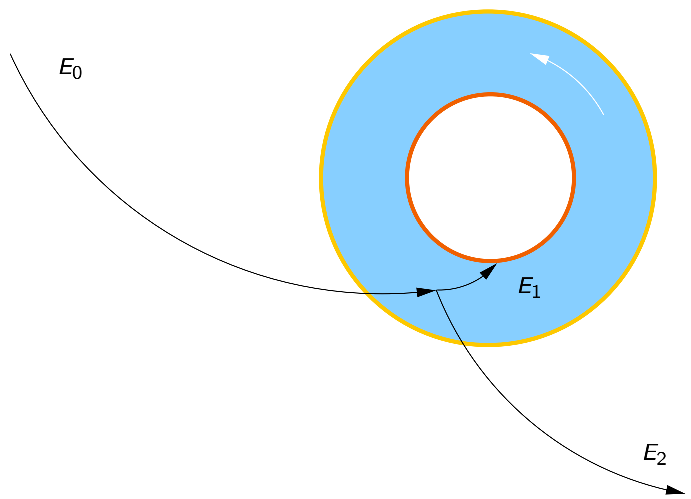


	Fluid dynamics	**Optical systems**	**Ultra-cold atoms**
Interesting Physics	✓	✓	✓

New experiment - ongoing experiments at SISSA

Description: Experimental studies of effective rotating black holes, to detect:

- superradiant wave-scattering
- stimulated black-hole emission



Surface waves on stationary draining water / bathtub vortex / analogue rotating black hole...

...superfluid bathtub vortex flows

Theoretical studies:

✻ Vortex geometry for the equatorial slice of the Kerr black hole (M. Visser, S.W.);

✻ **In preparation:** Generalized superradiant scattering (M. Richartz, S.W., A.J. Penner, W.G. Unruh);

✻ **ArXiv:** Dispersive superradiant scattering (A. Prain, M. Richartz, S.W., S. Liberati)

Numerical studies:

✻ In preparation: Experimental superradiant scattering (M. Richartz, J. Penner, A. Prain, J. Niemela, S.W.)

Experiment studies:

✻ surface wave detection

✻ design for water flume

✻ prototype ready for experiments

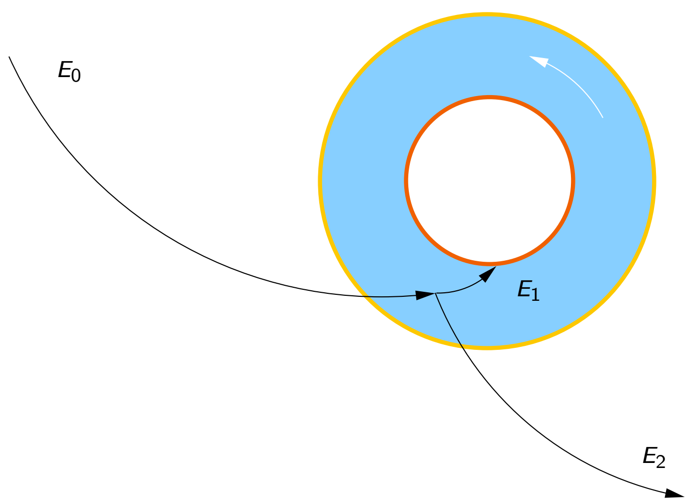
✻ big water flume (3 x 1.5 x 0.5 meter) under construction

The team:

✻ *Prof. J. Niemela* (ICTP), Prof. S. Liberati (SISSA), Dr. M. Richartz (Brasil), Dr. J. Penner (France), Dr. M. Danailov, A. Prain, M. Penrice

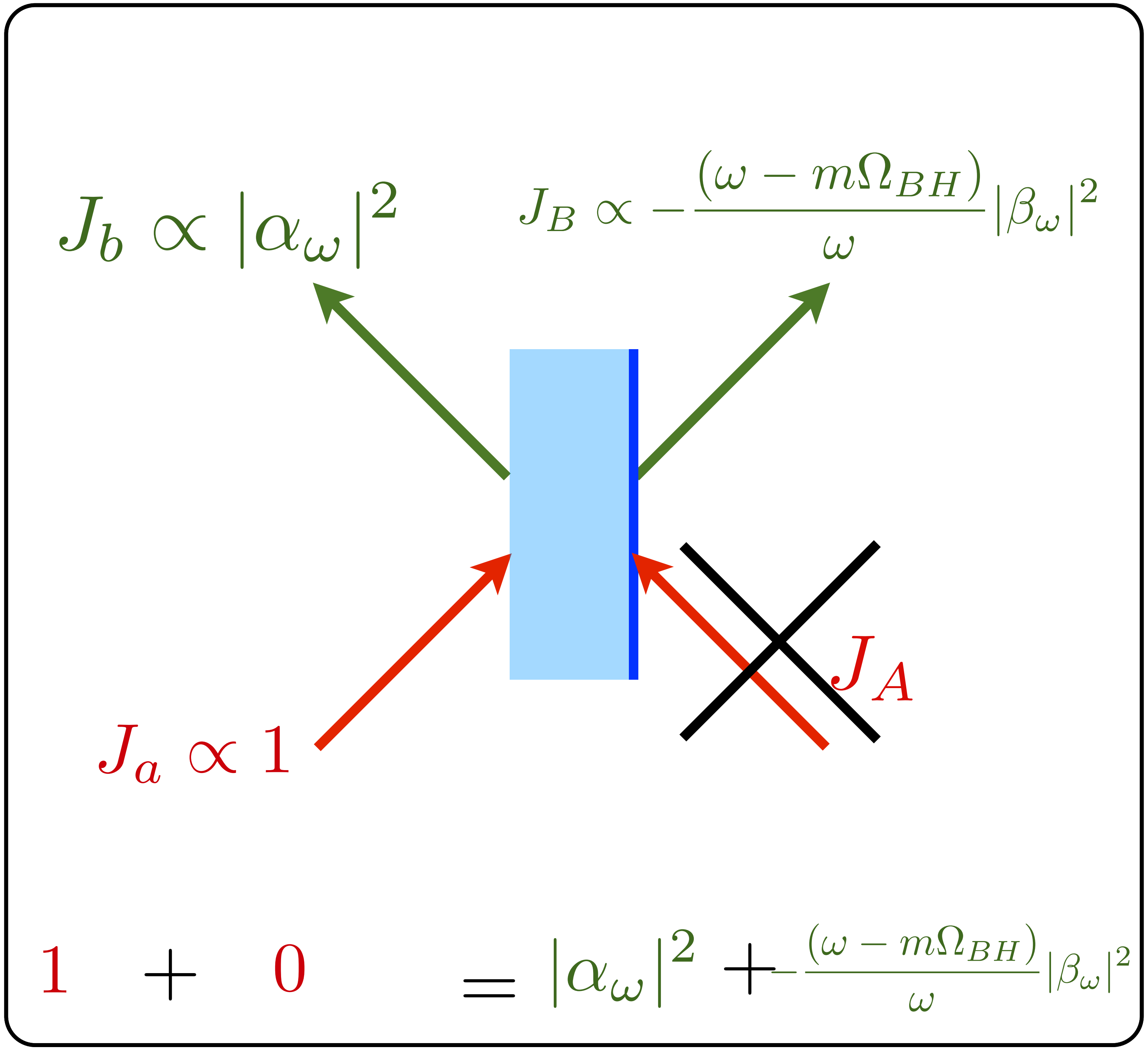
New experiment ➤ Superradiant wave scattering

Particle current: $J_n := |A_n|^2 \, \Omega|_{\pm\infty} \left.\frac{d\omega}{dk}\right|_{k_n}$



$$|R|^2 = 1 - \frac{(\omega - m\Omega_{BH})}{\omega}|T|^2$$

Dispersive superradiant scattering (A. Prain, M. Richartz, S.W., S. Liberati)



Rotating Black holes: Linear Classical and Quantum Field Amplifier!

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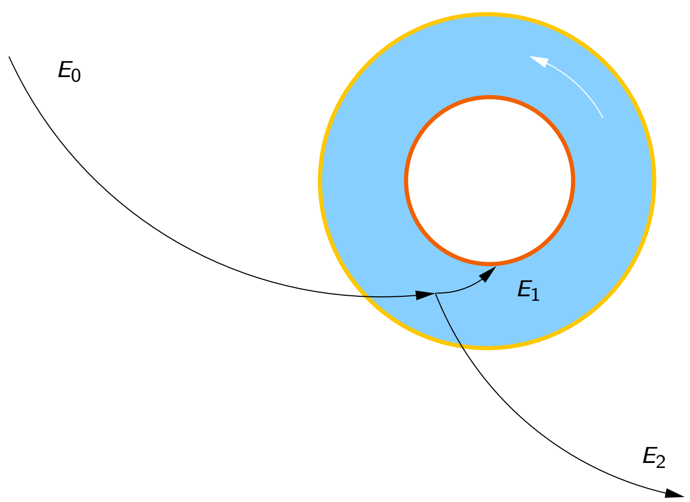

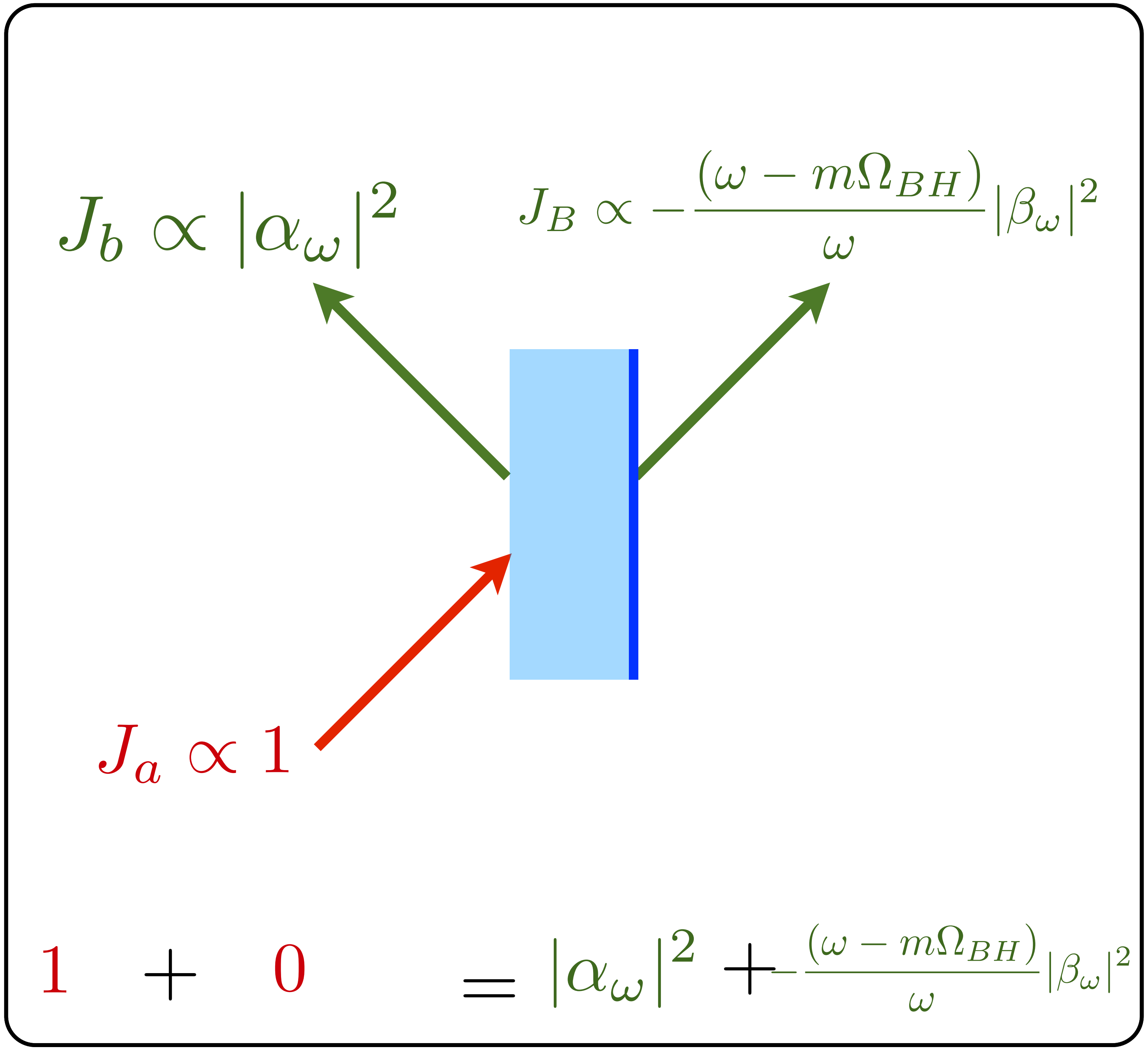

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