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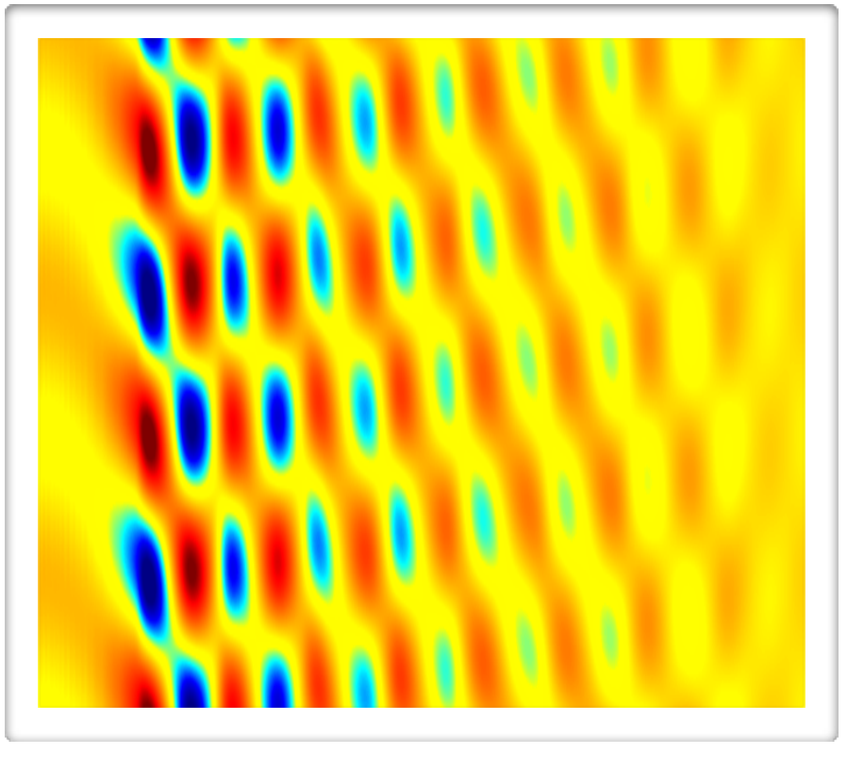
Experimental verification of the stimulated Hawking process

by

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

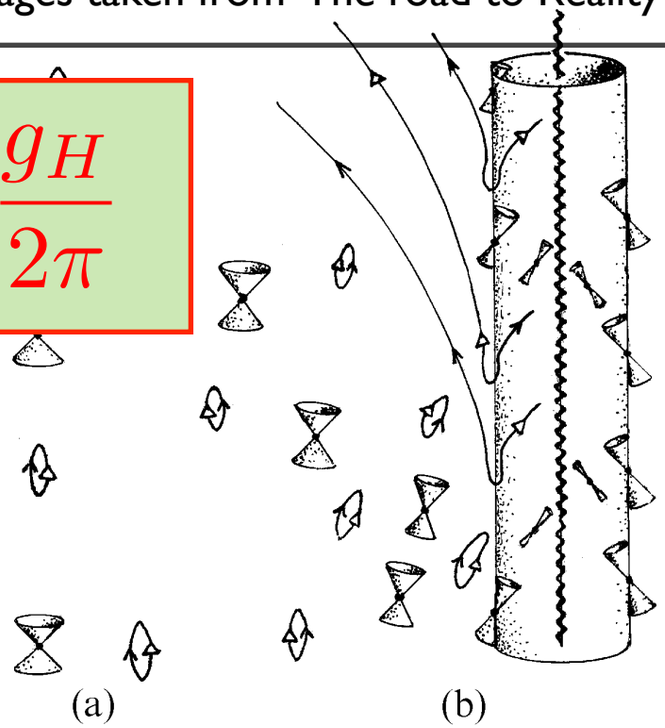
Silke Weinfurtner



Introduction - The black hole evaporation process

[Images taken from 'The road to Reality', by Roger Penrose.]

$$T = \frac{g_H}{2\pi}$$



Pair-creation:

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]

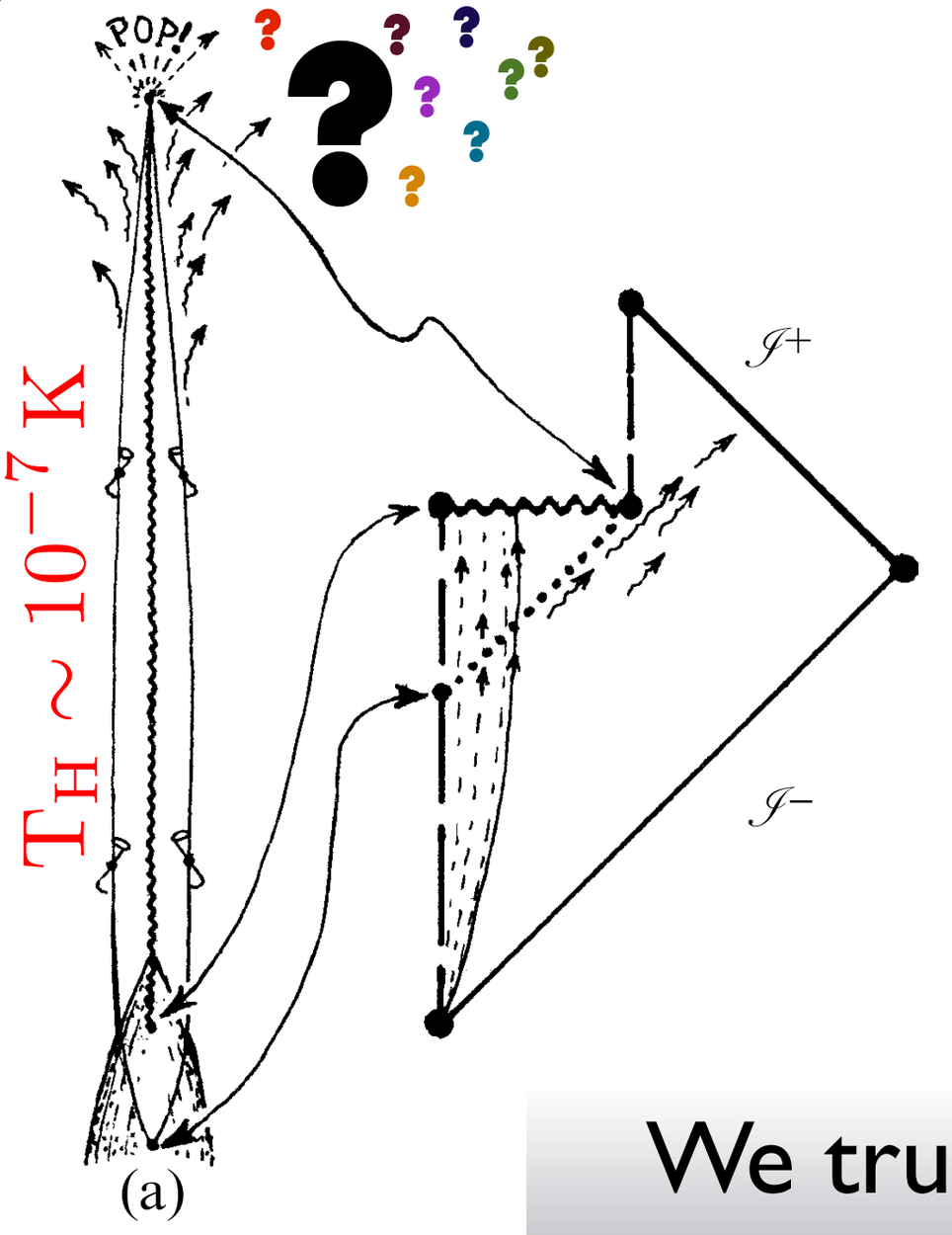
$$\phi_\omega^{\mathbf{in}} = \alpha_+^{\mathbf{out}} + \beta_-^{\mathbf{out}}$$

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

- Nature of Hawking process: Semi-classical quantum gravity effect, where the Einstein dynamics is not taken into consideration.
- Spontaneous versus stimulated emission: If the stimulated emission is there, the quantum will follow (Einstein).
- Black versus white hole emission: White holes are the time-reversal of black holes, and the Hawking process applies to both.

Motivation - The importance of Hawking radiation..?

[Images taken from 'The road to Reality', by Roger Penrose.]



- (indirect) observations of the existence of black holes;
- NO (indirect or direct) observation of the black hole evaporation process;

WE THINK BUT WE DON'T KNOW THAT BLACK HOLES EVAPORATE!

We trust in quantum field theory, BUT:

- blue-shift of the modes at horizon
- robustness of HR to modification at UV

Our experiment and goals

Our experiment in a nutshell

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

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

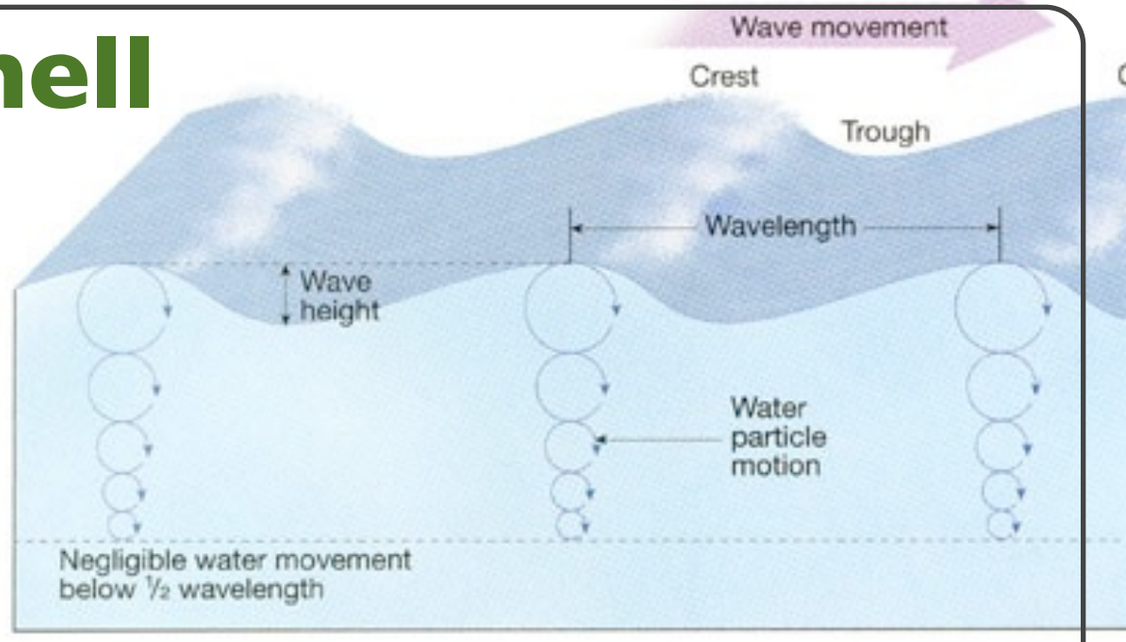


Figure 14.2 This diagram illustrates the basic parts of a wave as well as the movemen wave. Negligible water movement occurs below a depth equal to one-half the wavelen

$$v = v(x) = \frac{q}{h(x)} \propto \frac{1}{h(x)} \qquad c = c(x) \approx \sqrt{g h(x)} \propto \sqrt{h(x)}$$

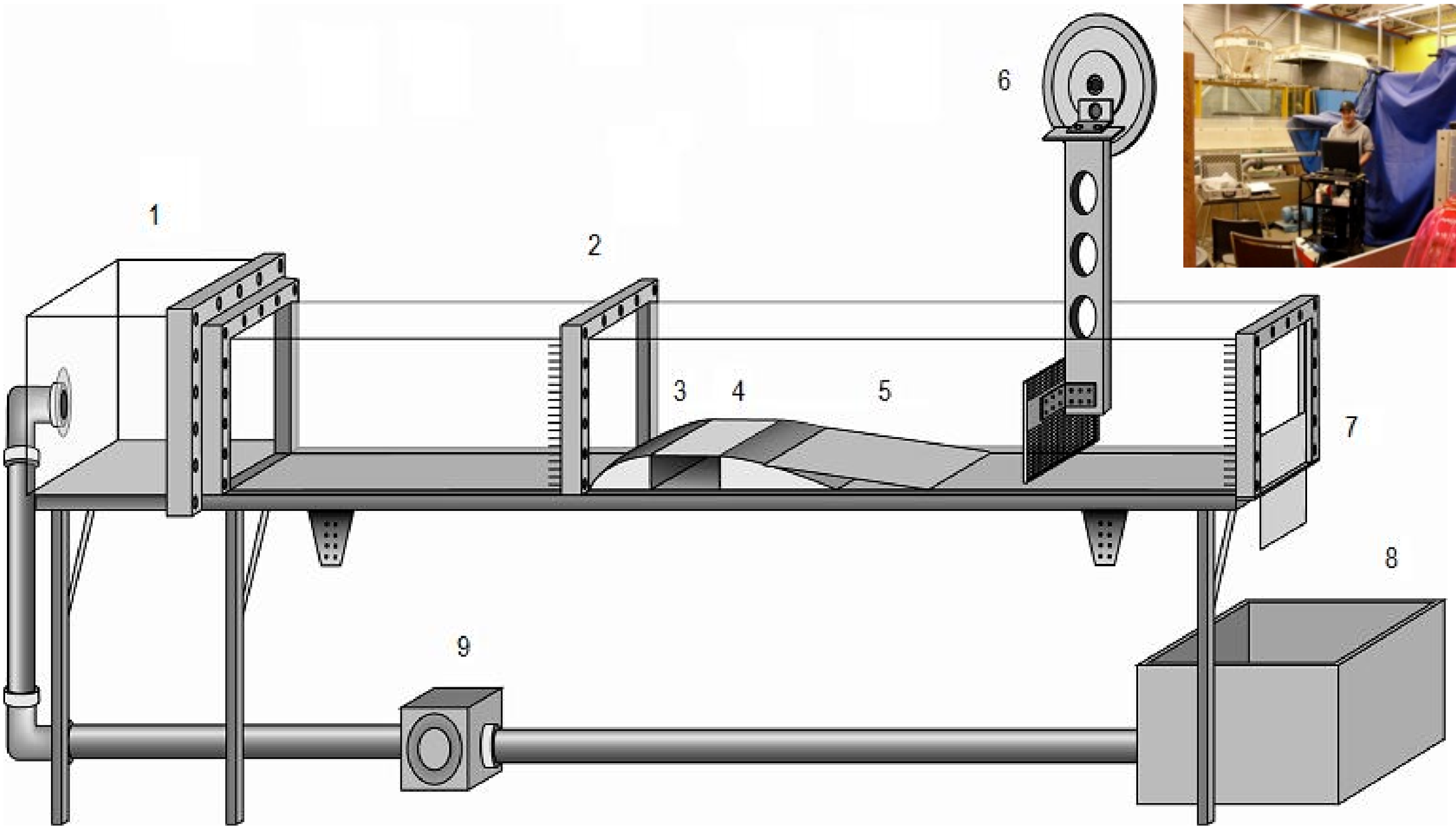
Let's recall the acoustic line-element:

$$g_{ab} = \left(\frac{\rho}{c}\right)^{2/(d-1)} \begin{bmatrix} -\left(c^2 - v^2\right) & -\vec{v}^{\,T} \\ -\vec{v} & \mathbf{I}_{d\times d} \end{bmatrix}$$

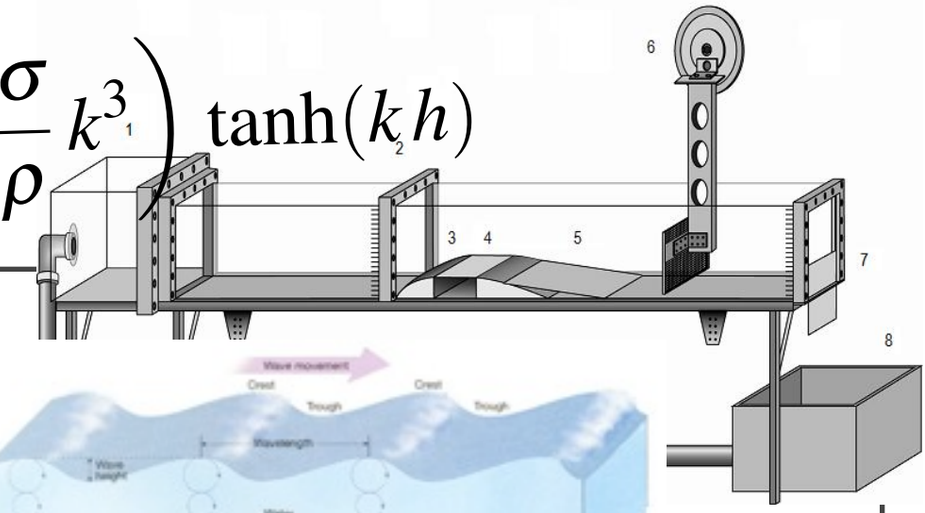
Goal: Set up black and white horizon & detect stimulated conversion to pos. & neg. waves who's relative amplitudes obey HS.

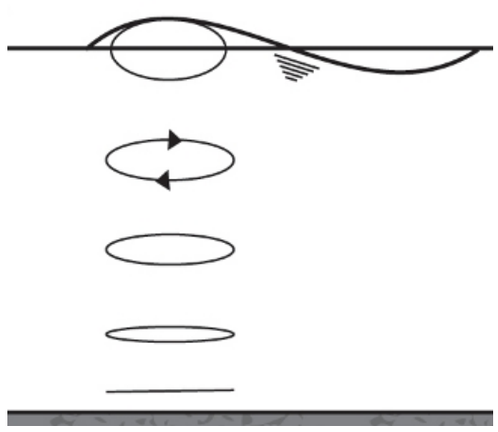
Experimental apparatus

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



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





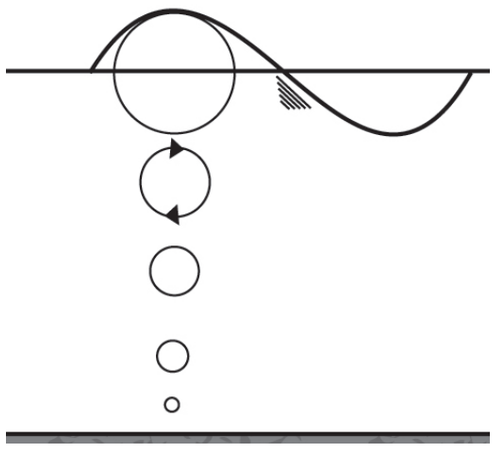


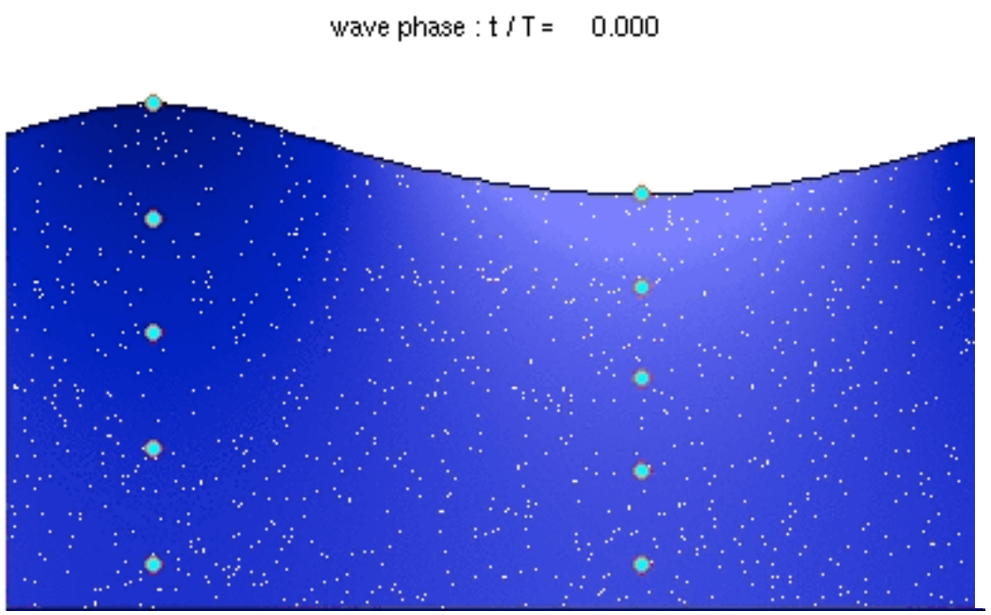
Figure 14.2 This diagram illustrates the basic parts of a wave as well as the movement of water particles with the passage of the wave. Negligible water movement occurs below a depth equal to one-half the wavelength (the level of the dashed line).

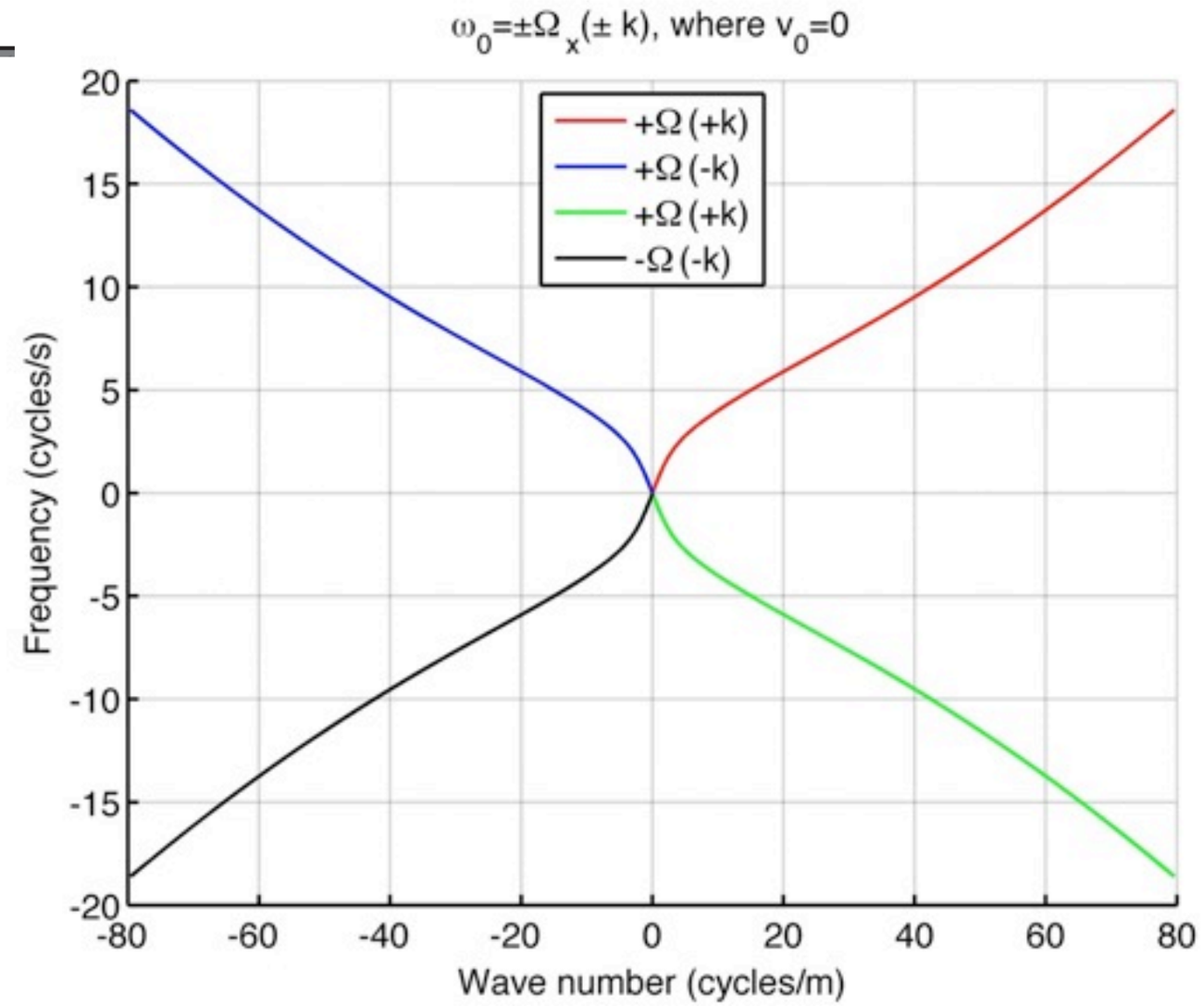
shallow:

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

deep:

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





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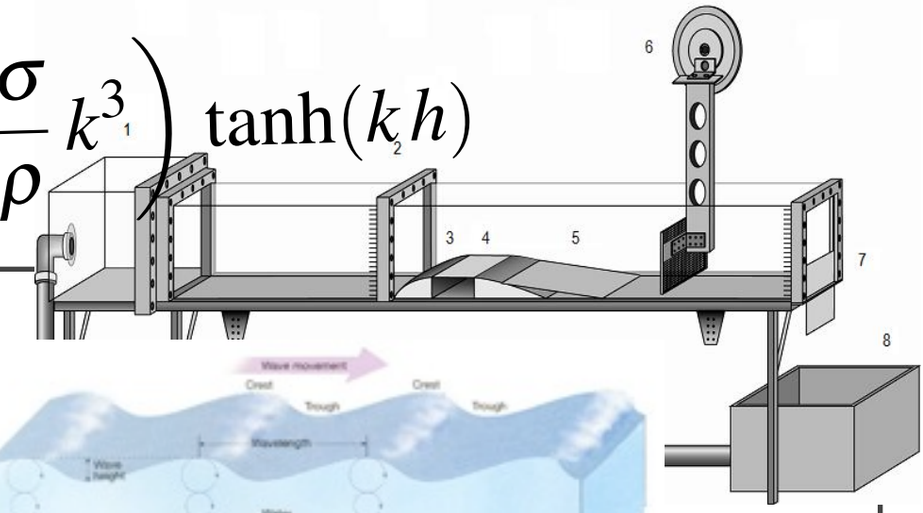

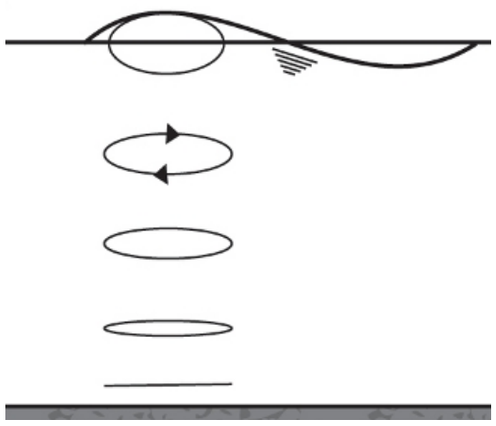

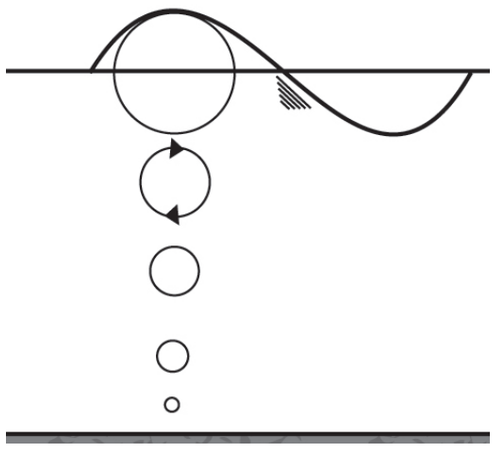

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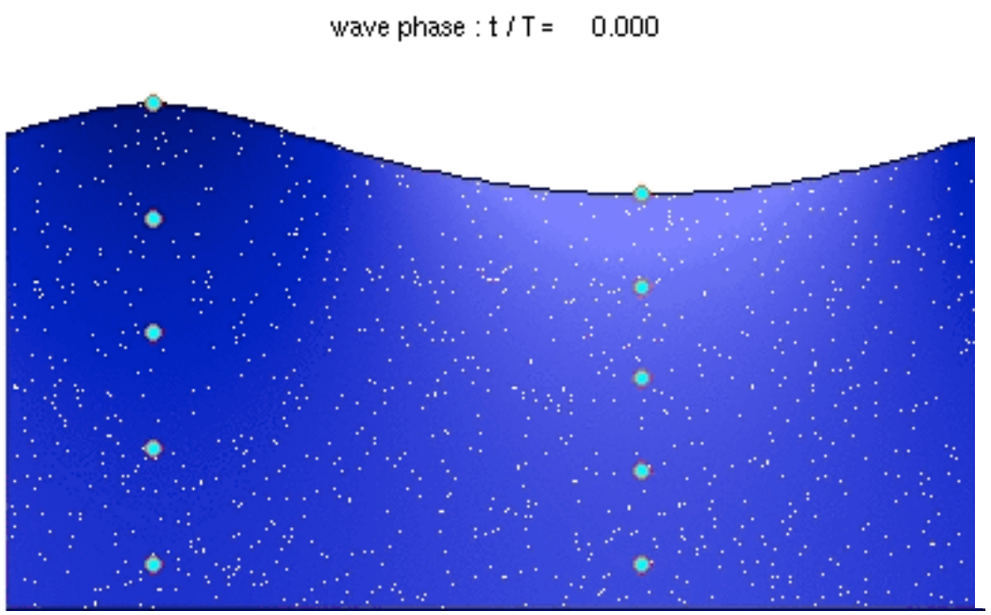

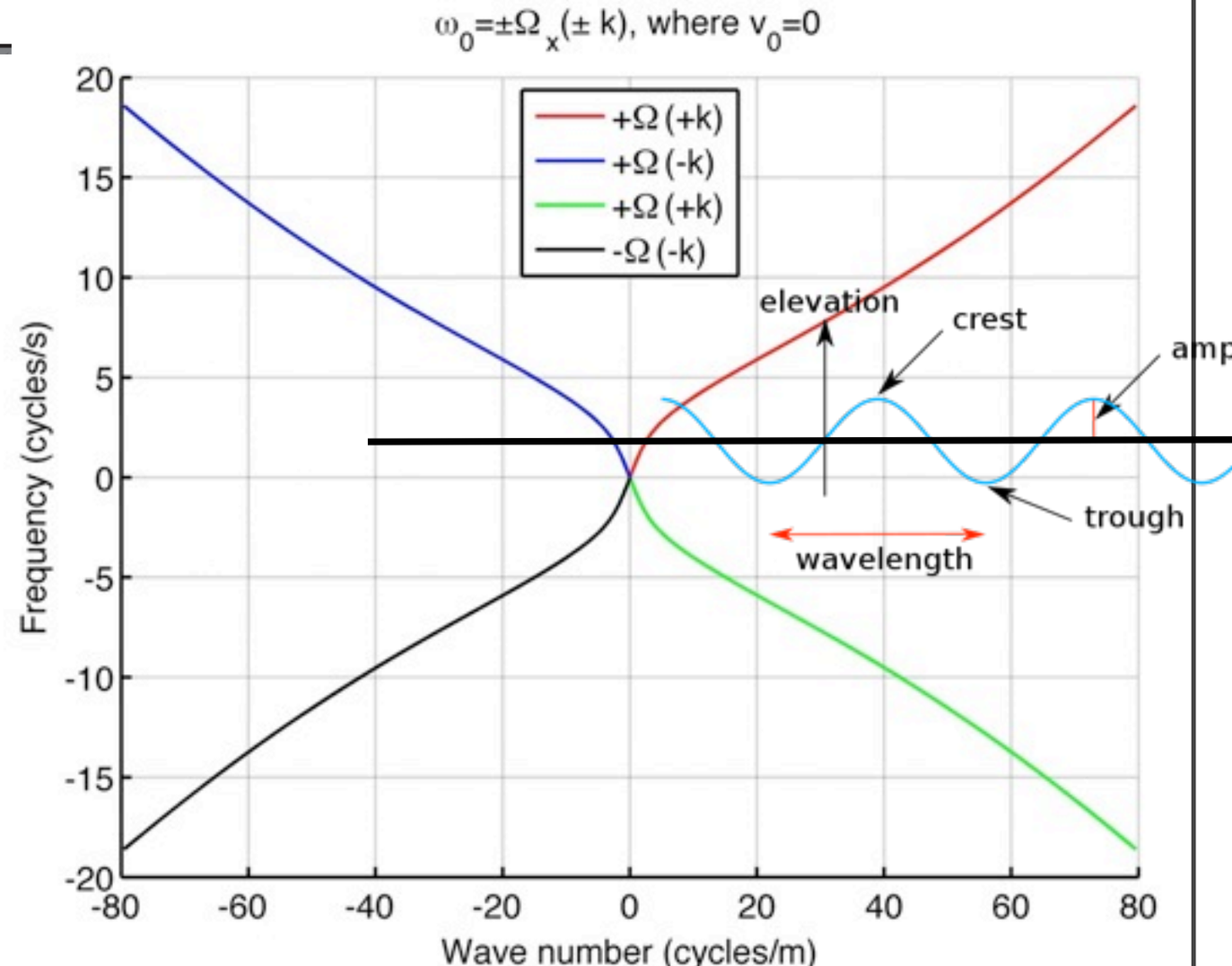

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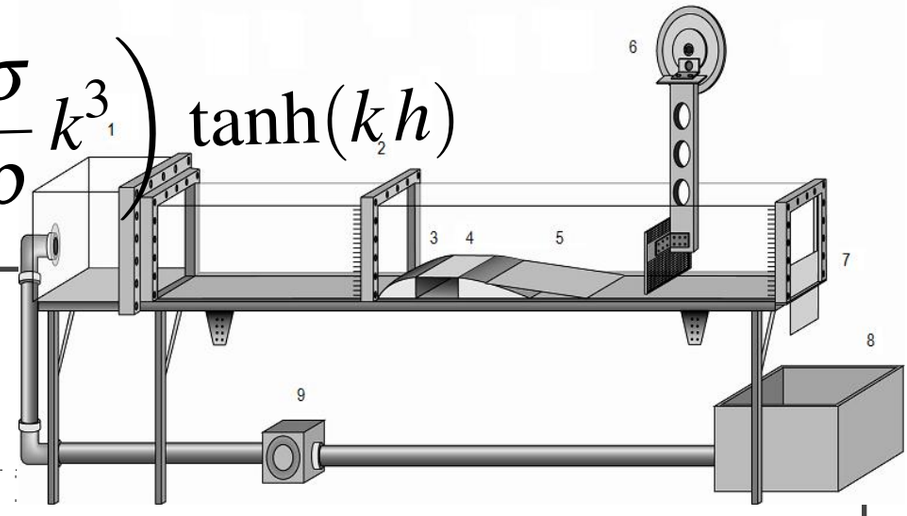
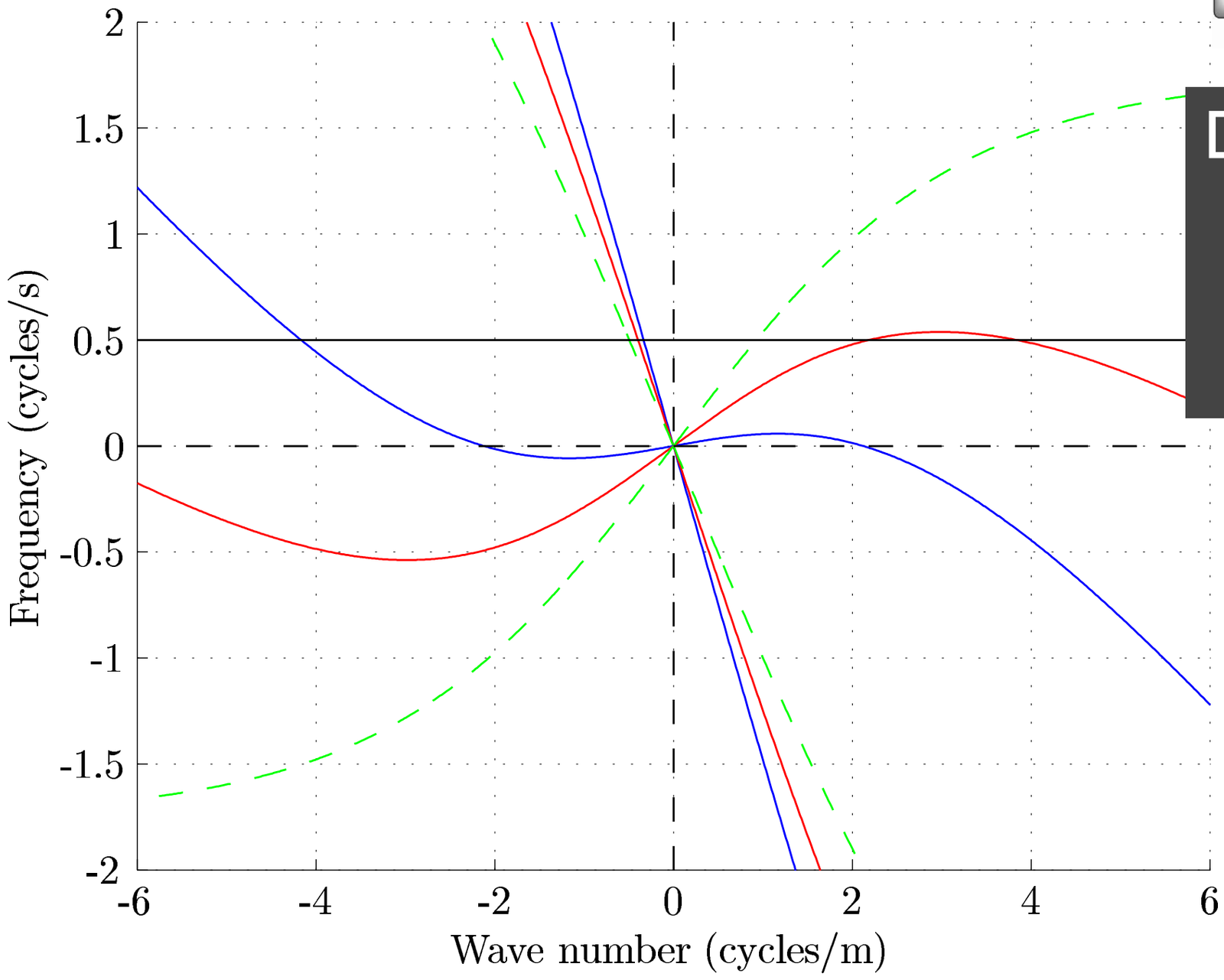


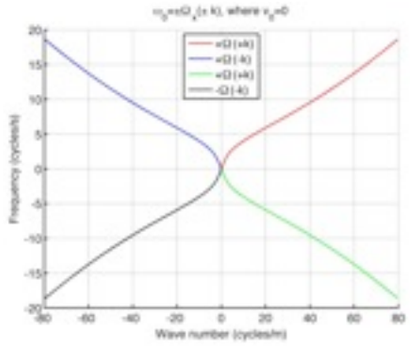
$$\Omega_{\mathrm{LAB}} = \Omega_{\mathrm{WATER}} \pm v\,k$$



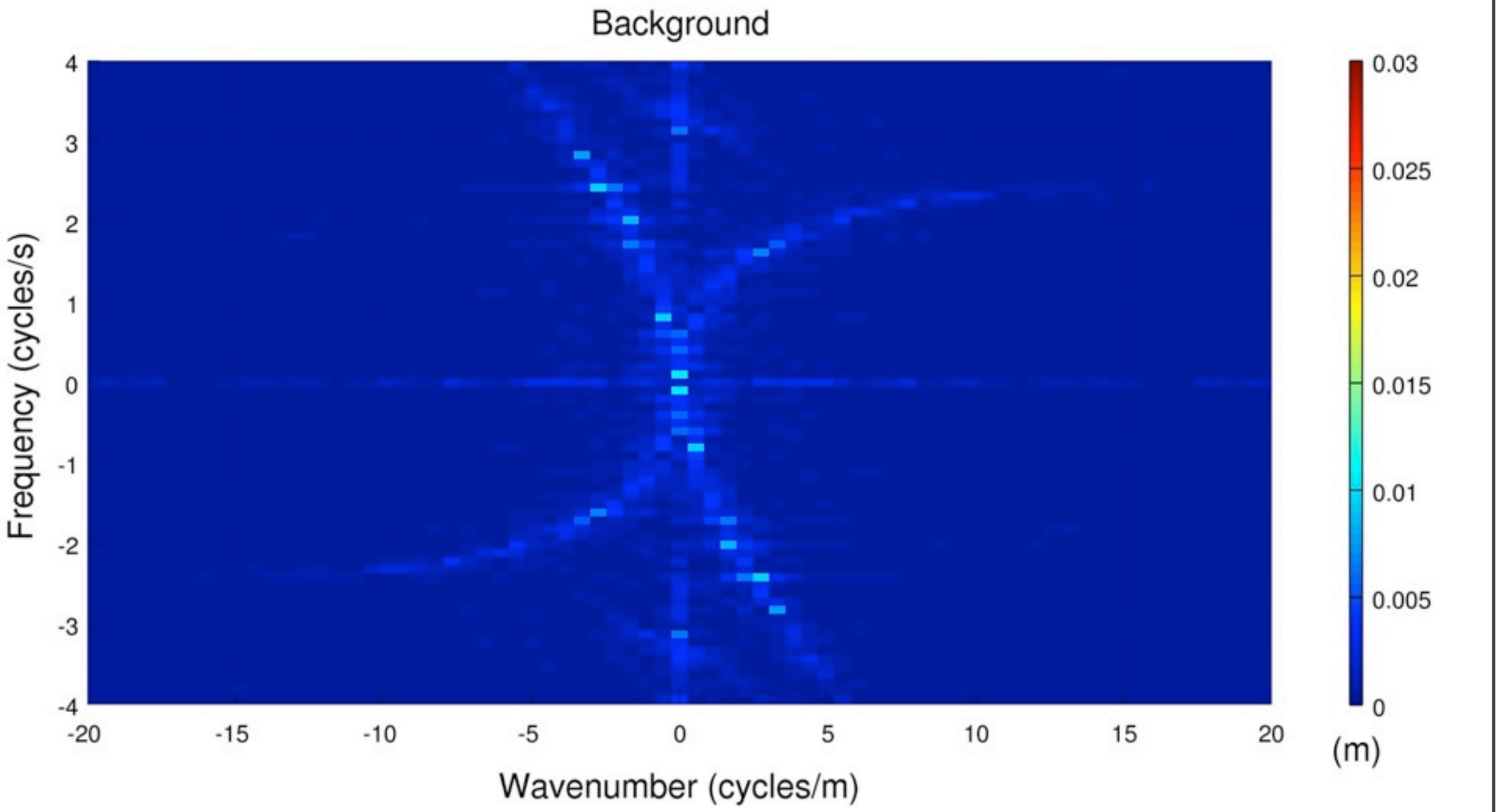
Dispersion relation for
maximum height
conversion point
minimum height

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

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



1st experimental result: Flume without the obstacle



Application: Indirect way to measure the flow rate...

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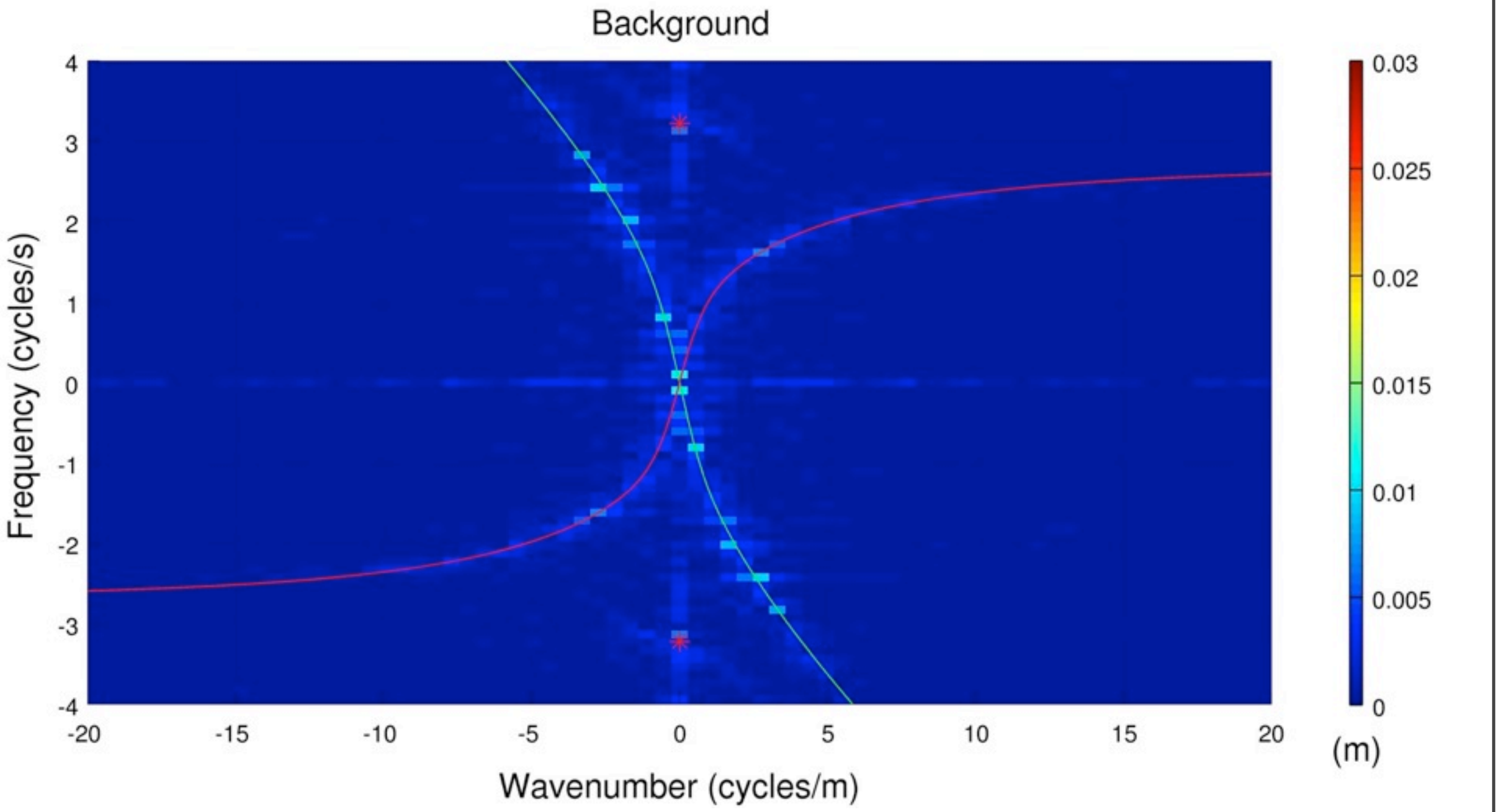
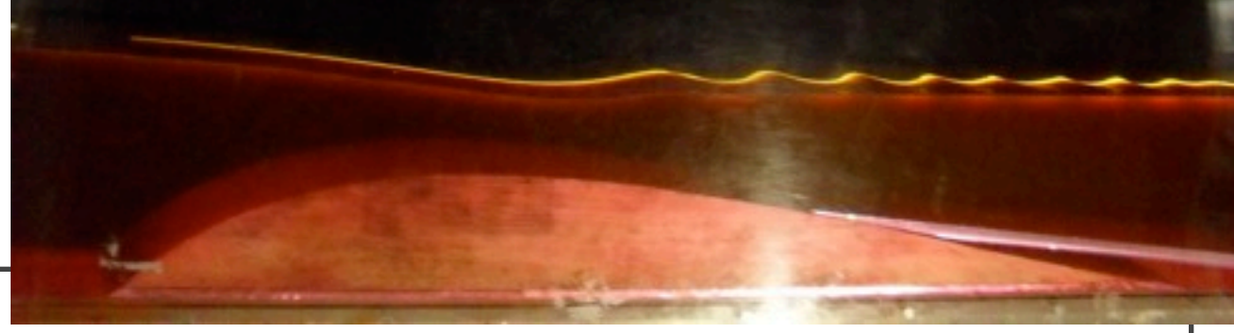
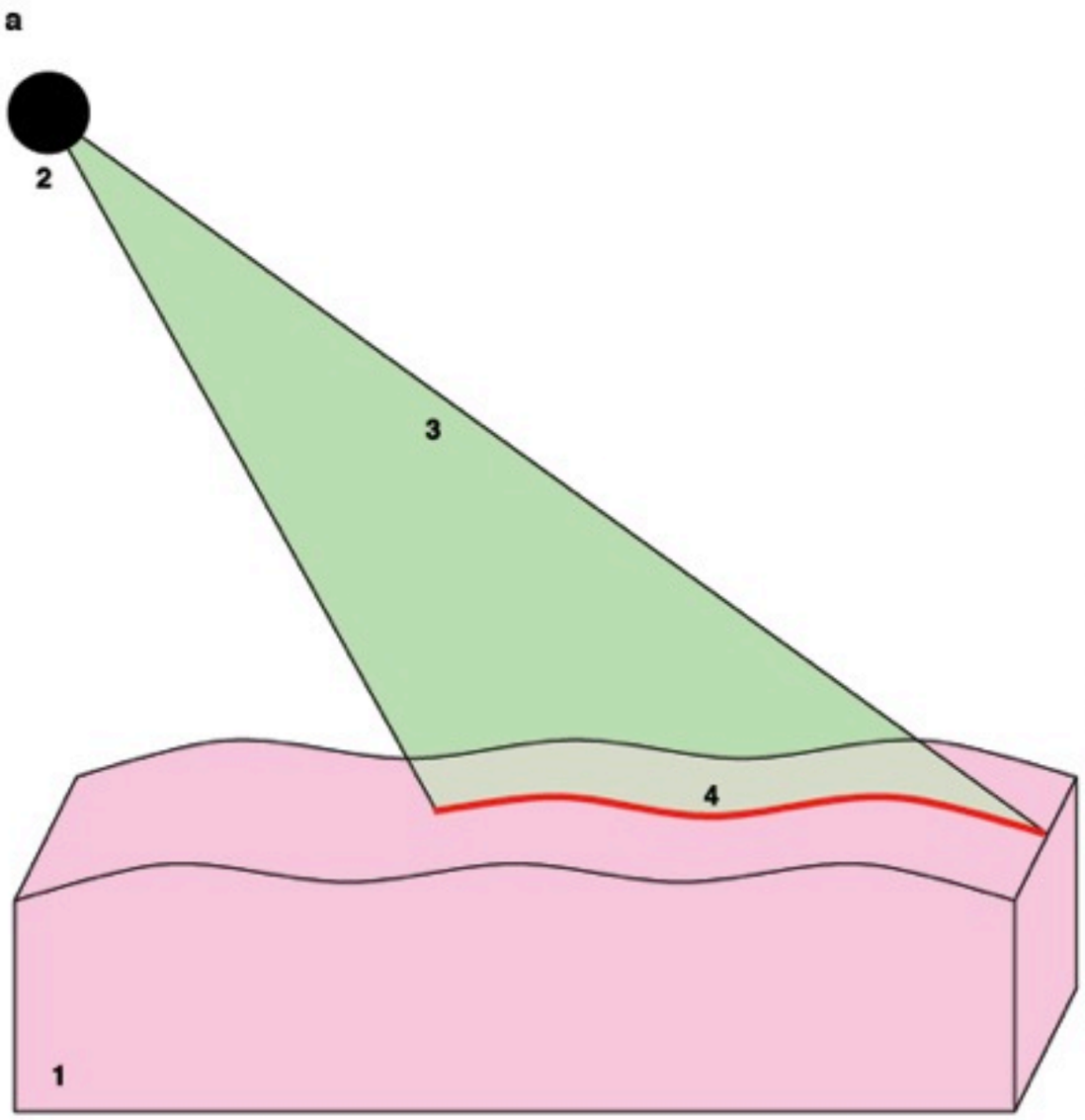
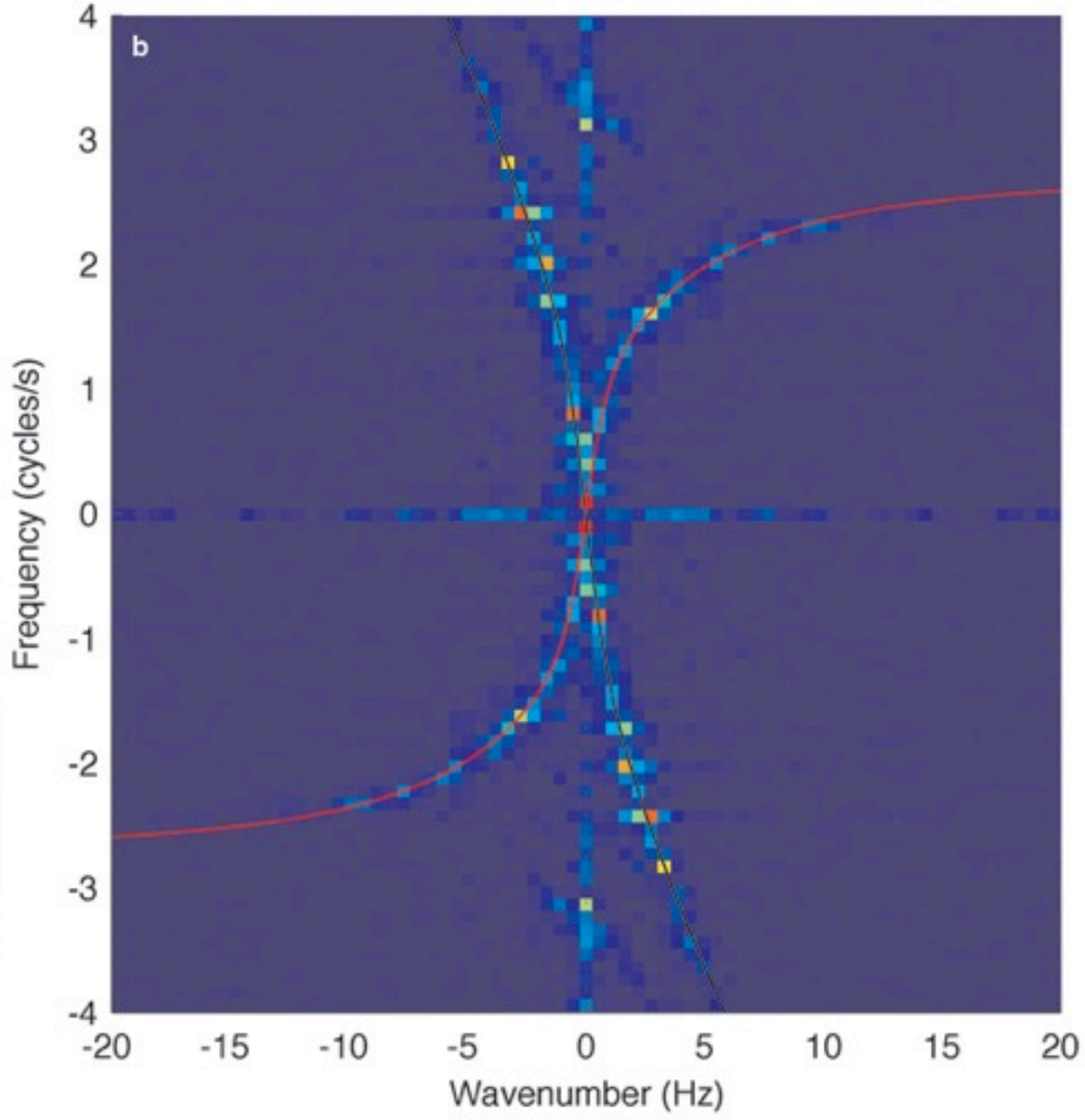


Application: Indirect way to measure the flow rate...

Free surface: our observable







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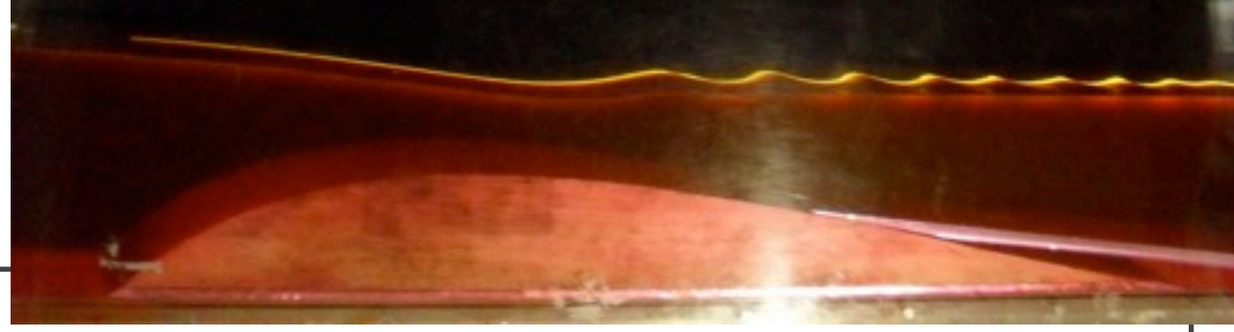

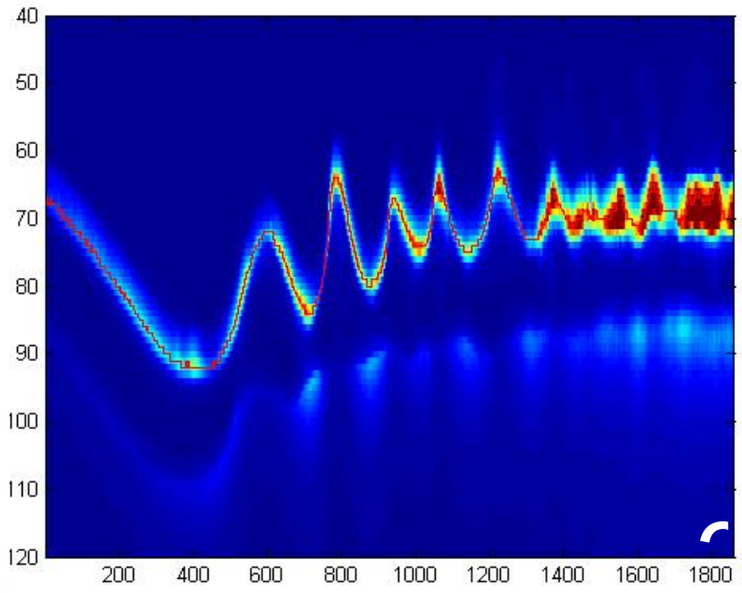

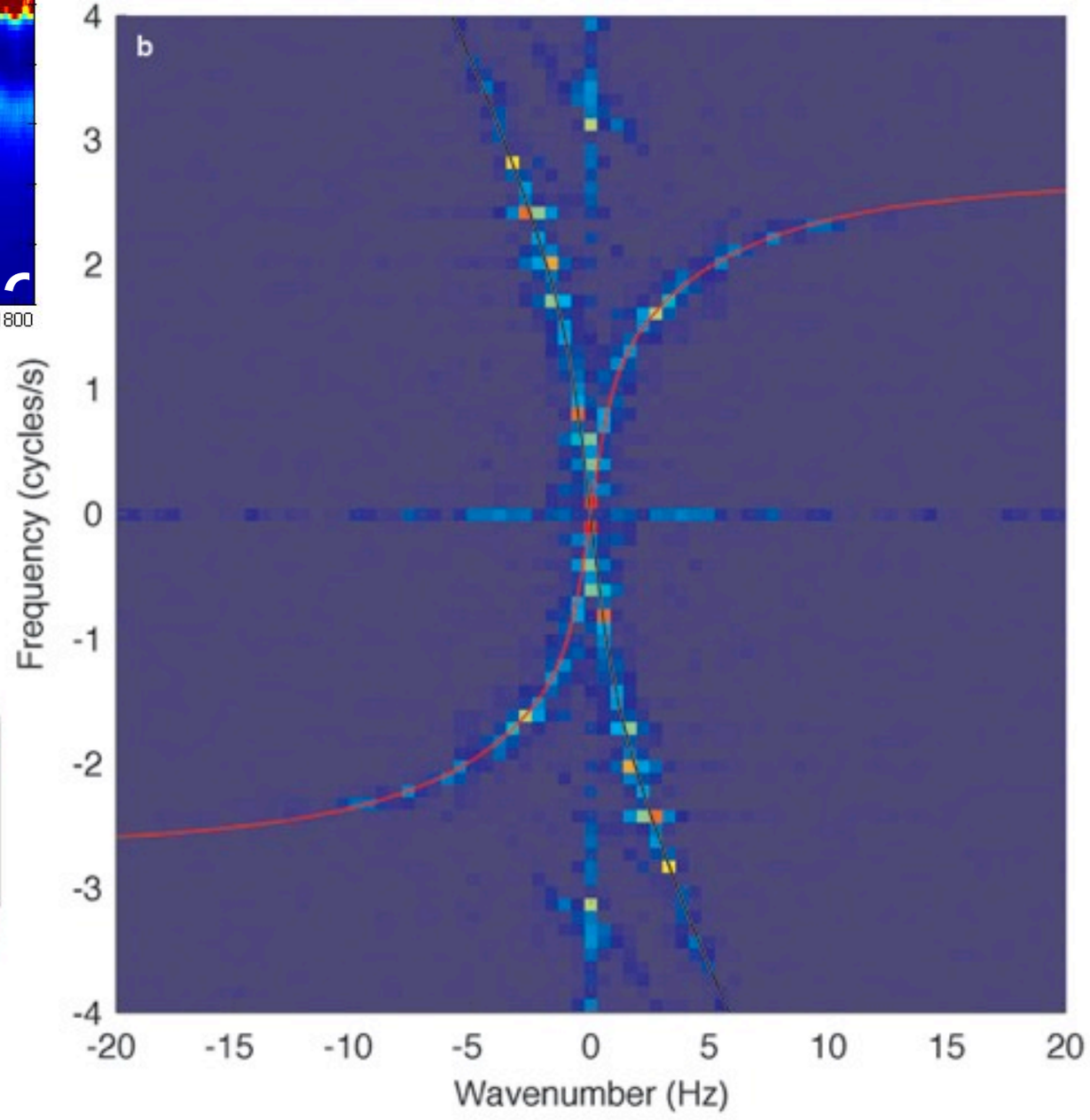

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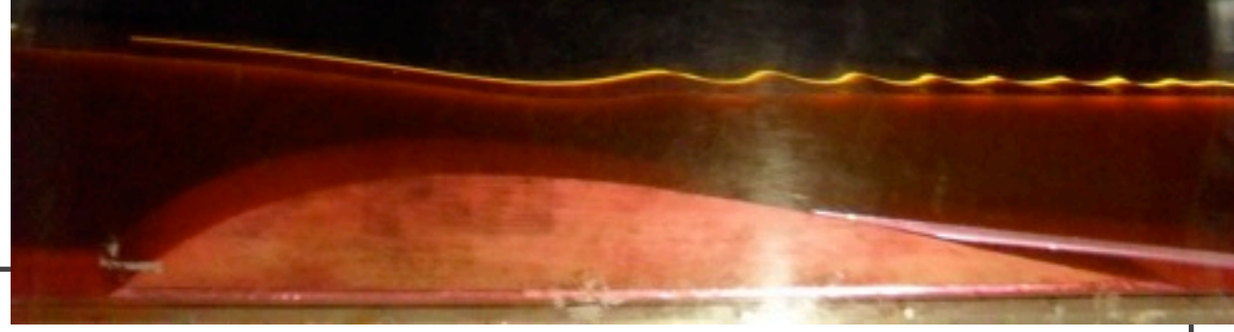
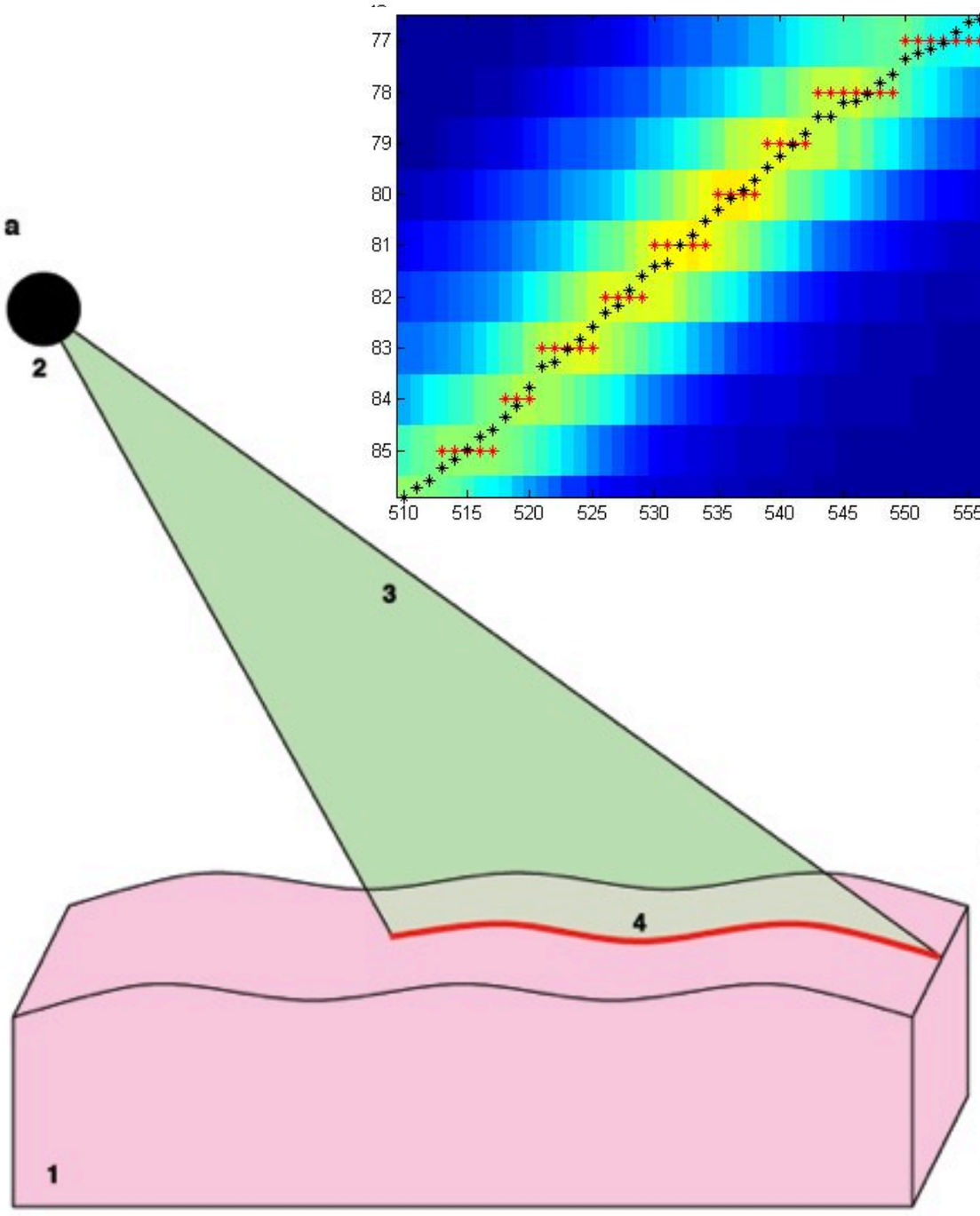
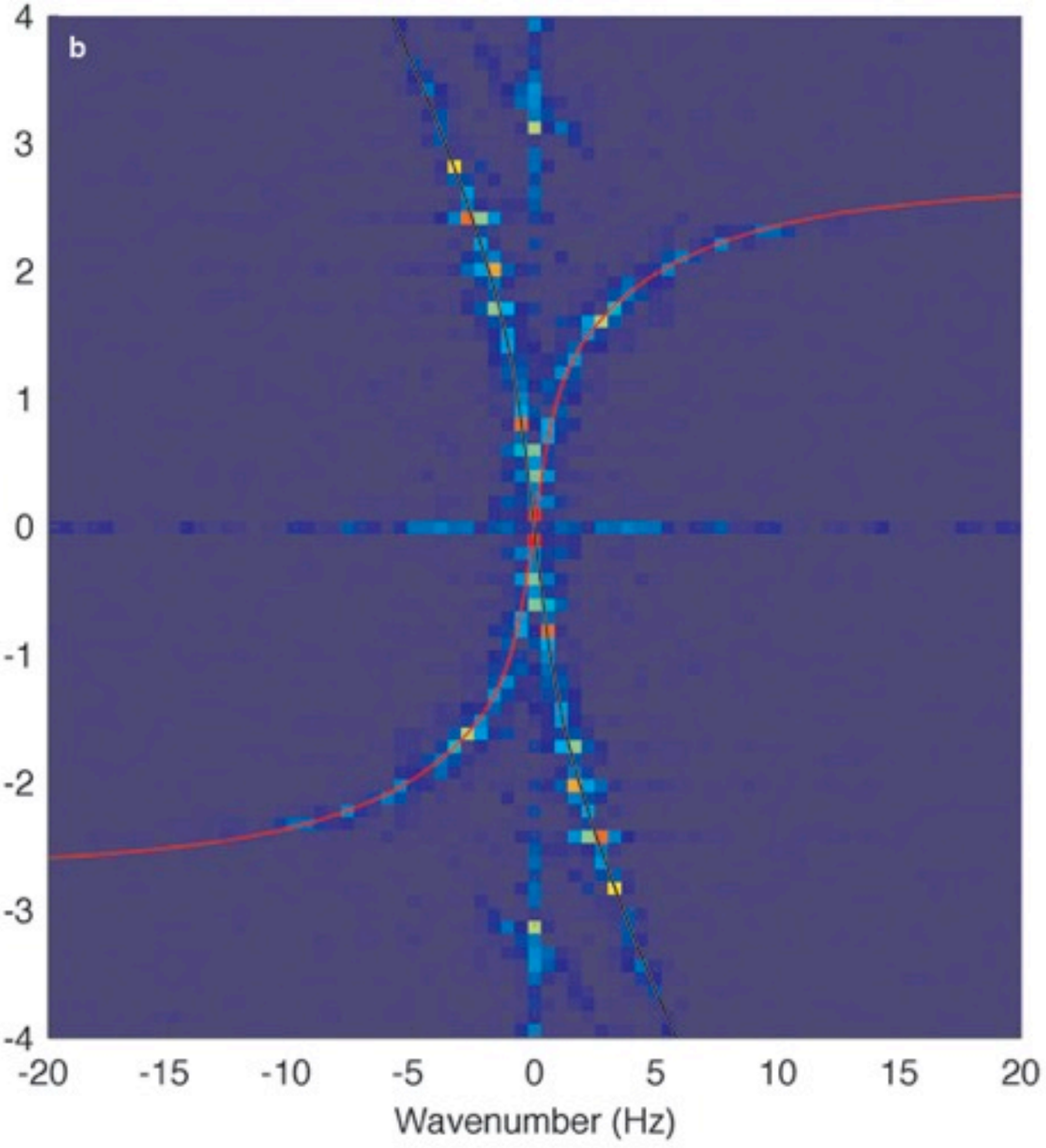
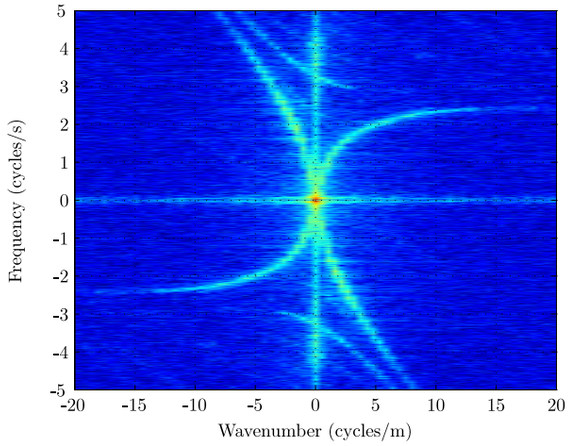
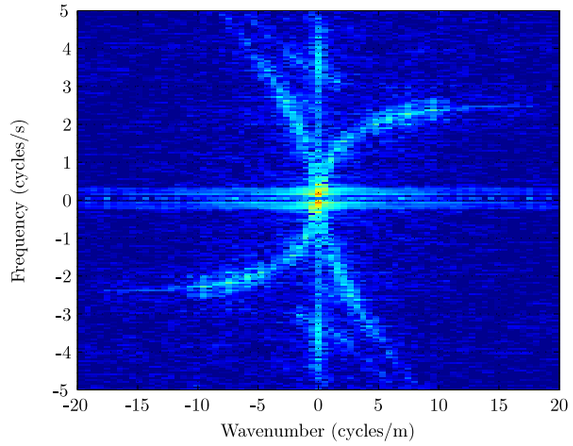


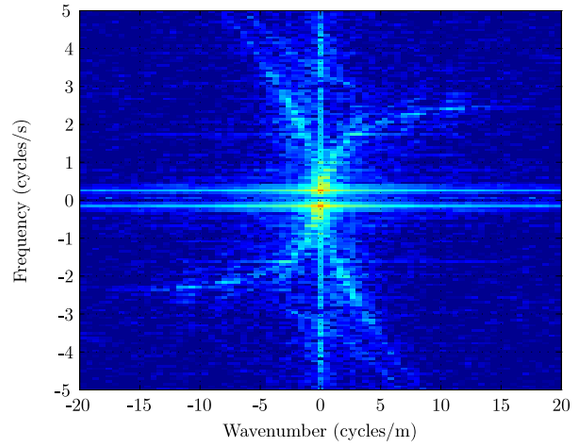


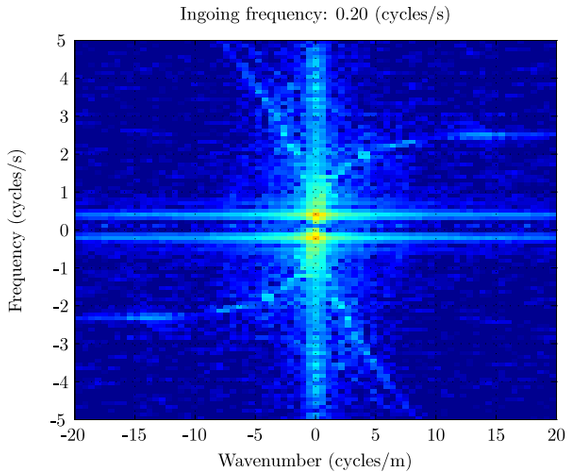


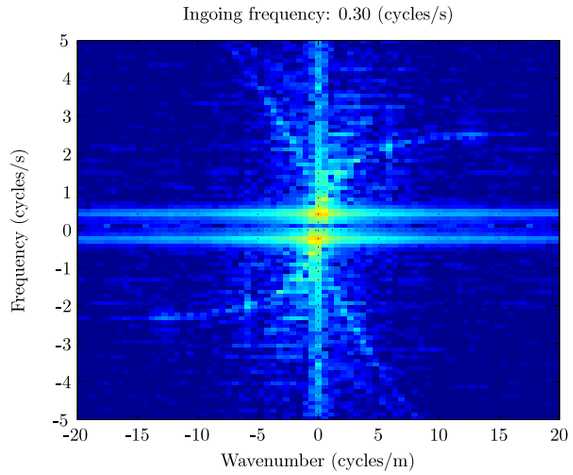
Stimulated system - generated ingoing waves

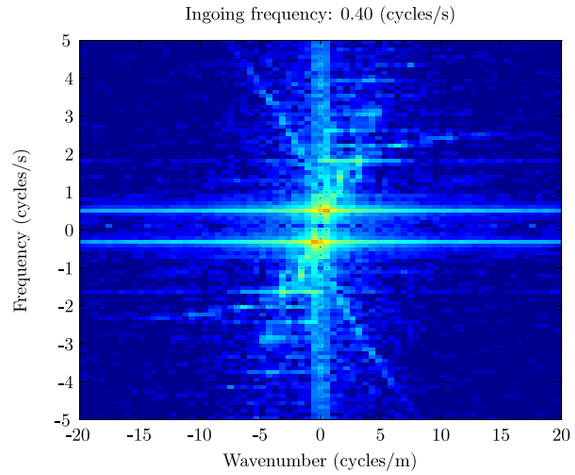


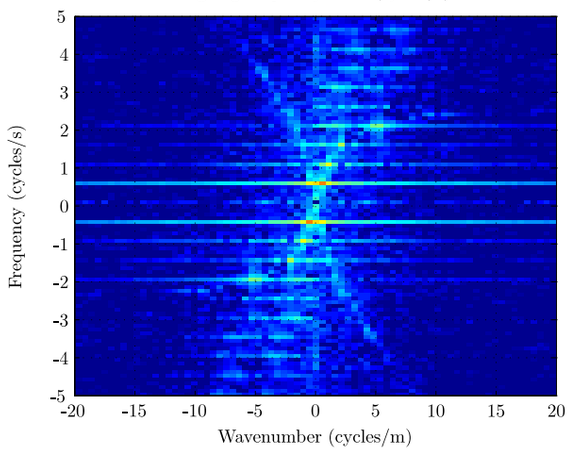


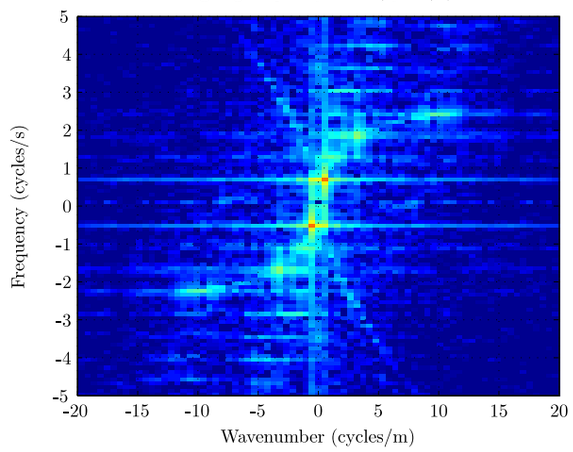


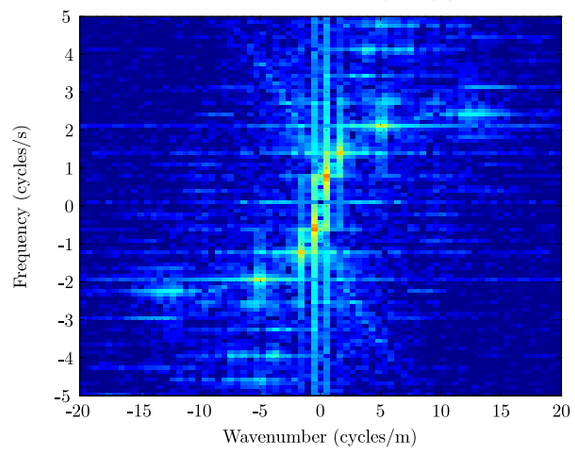


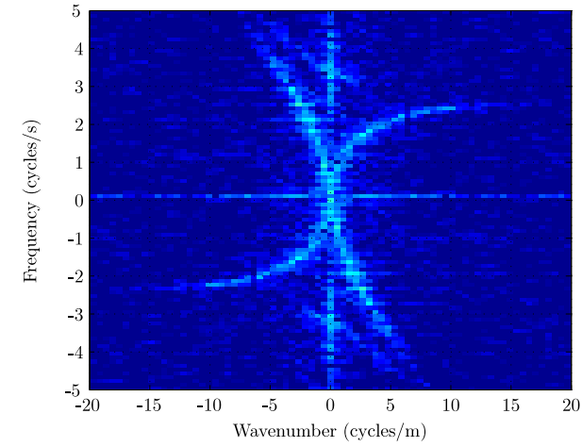




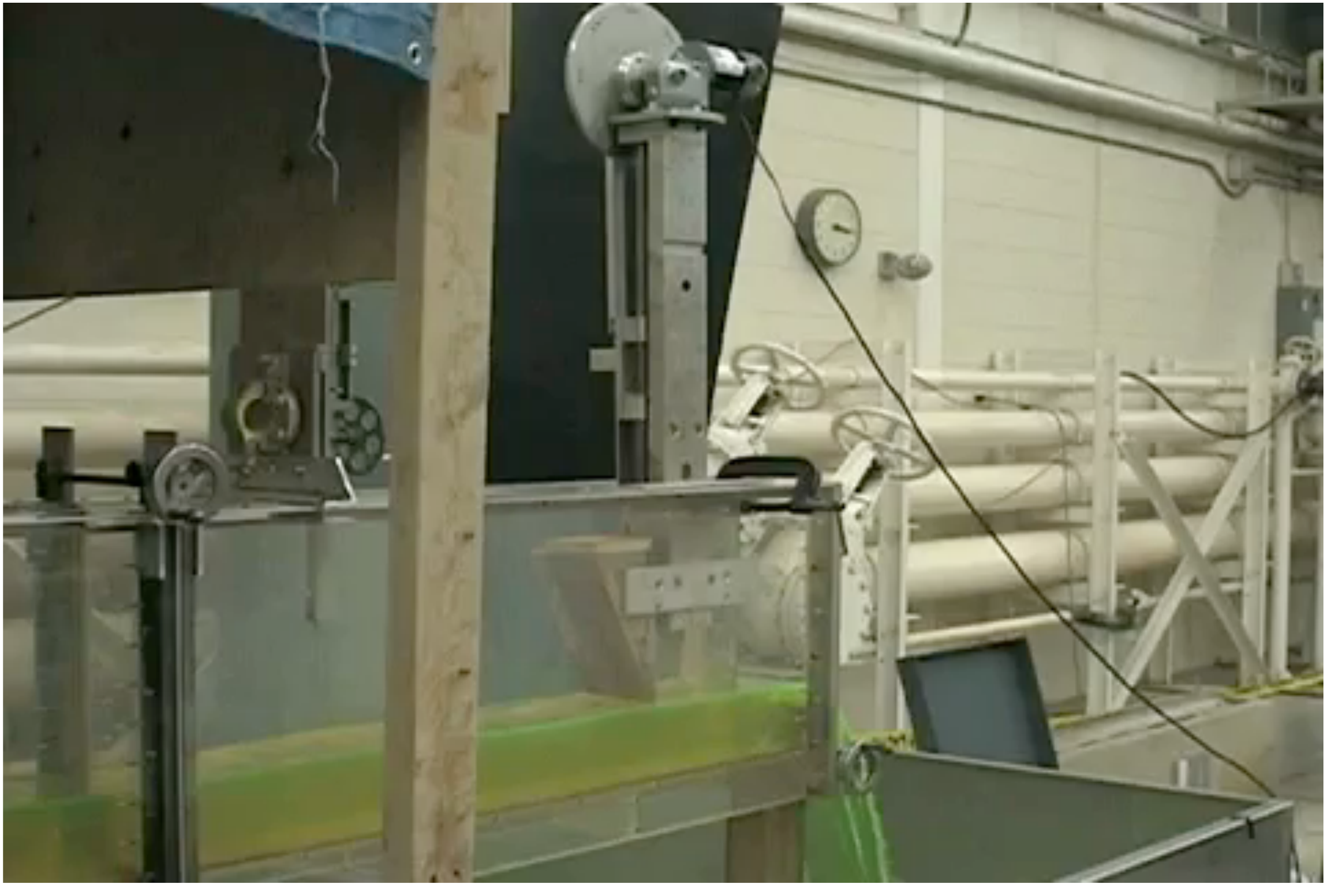




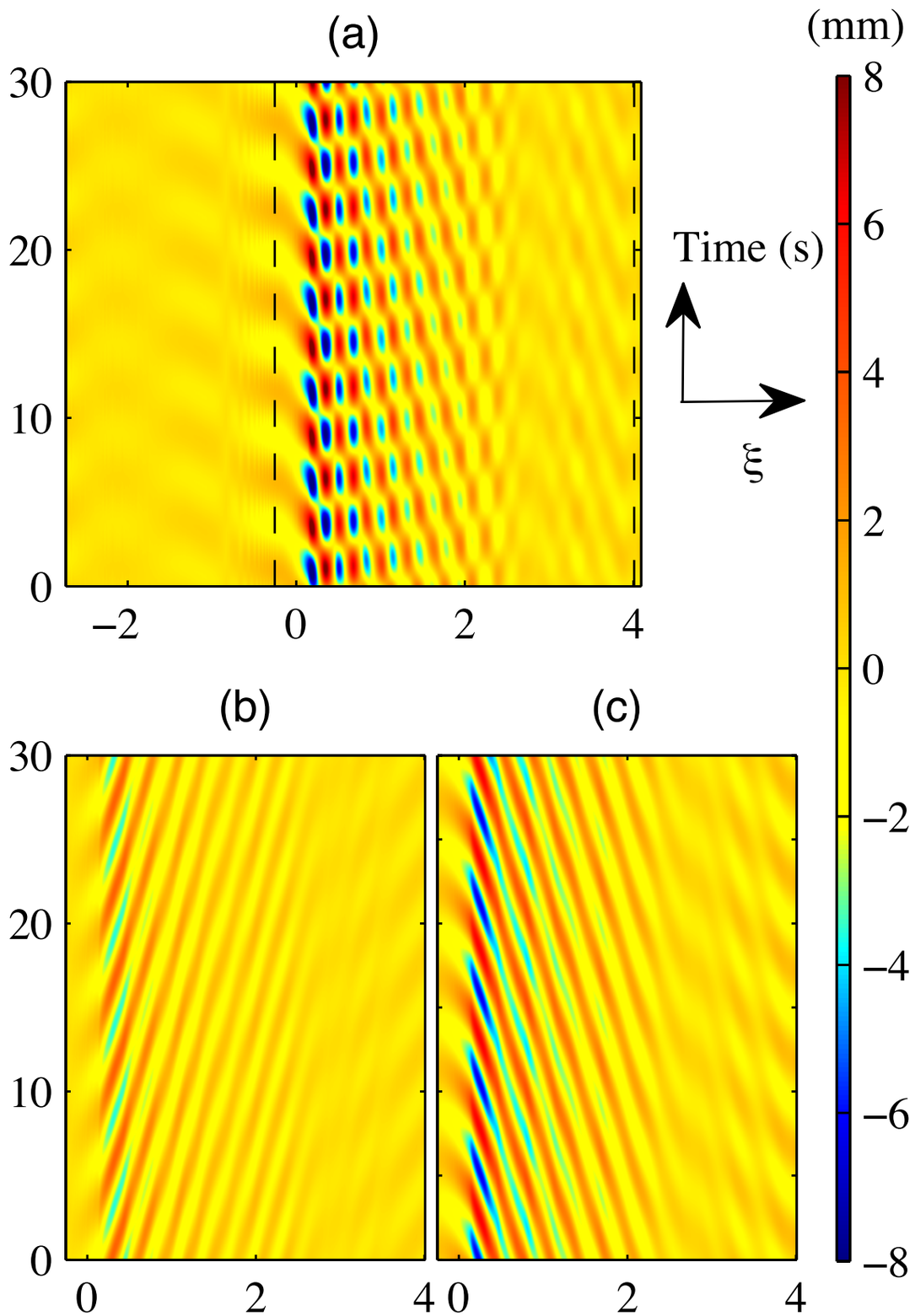


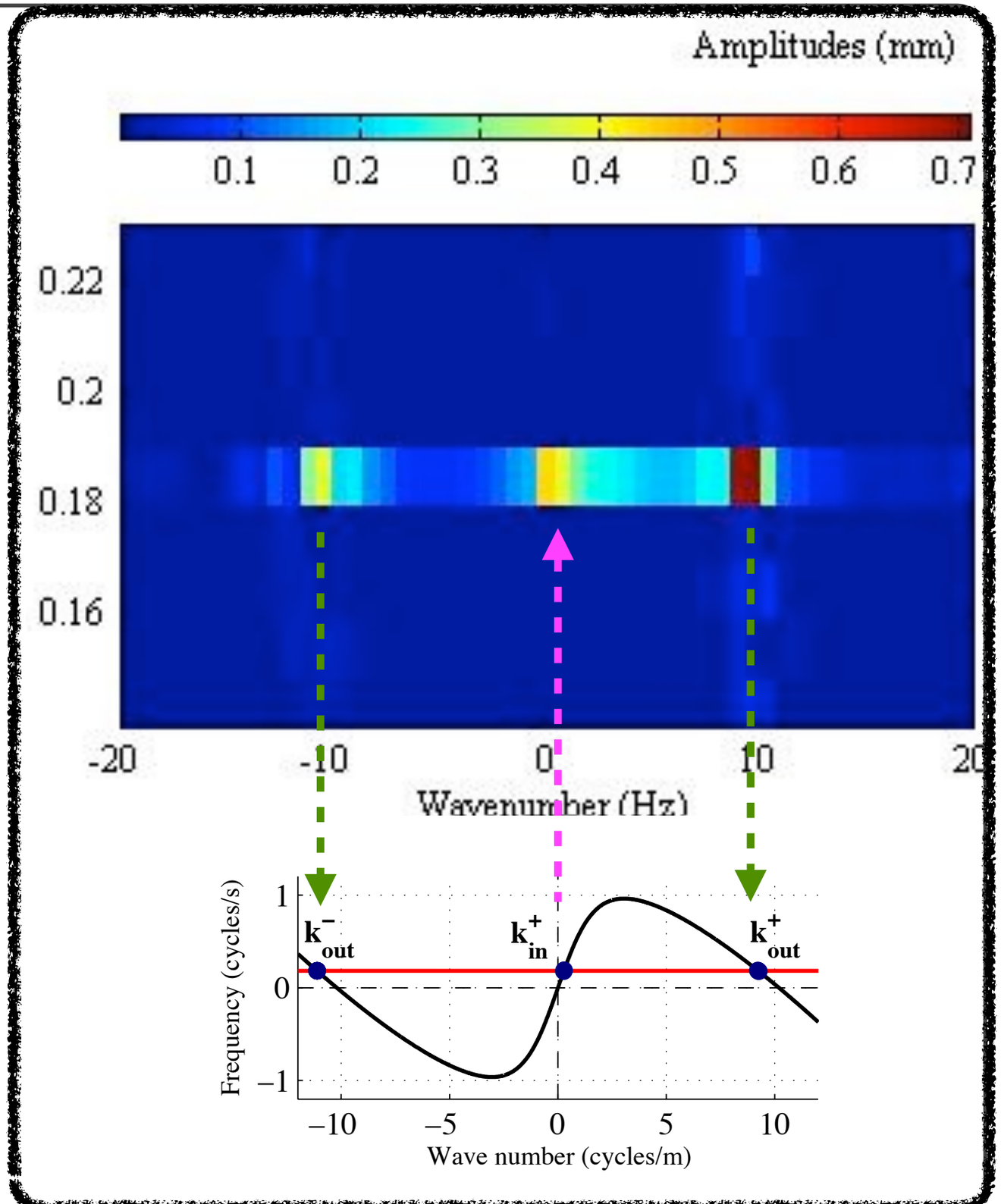


The experiment (early experiment with bigger waves)



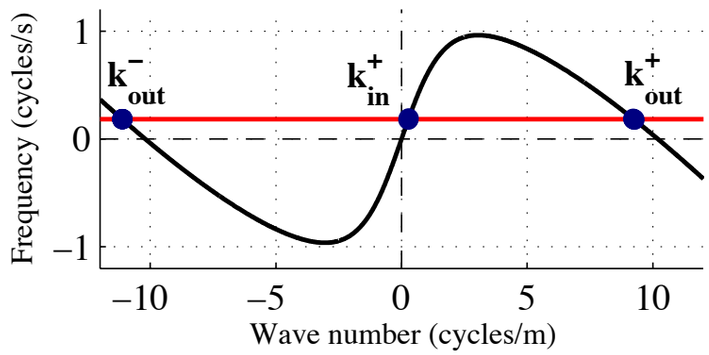
Right and left moving waves: Pair-creation process



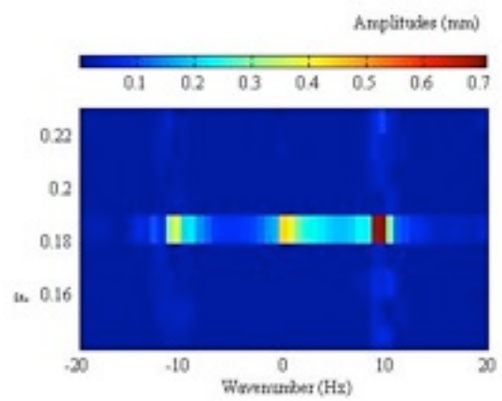


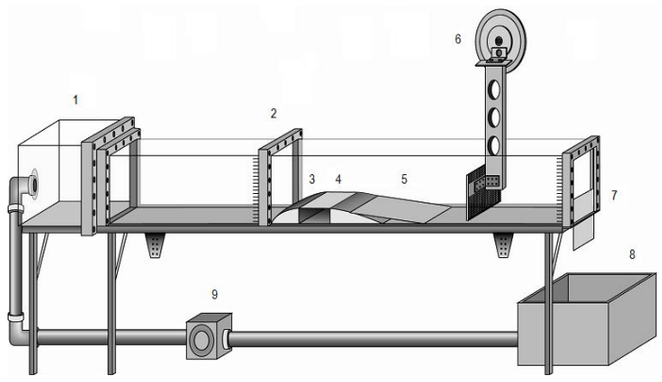
From amplitudes to Hawking spectra

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



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





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

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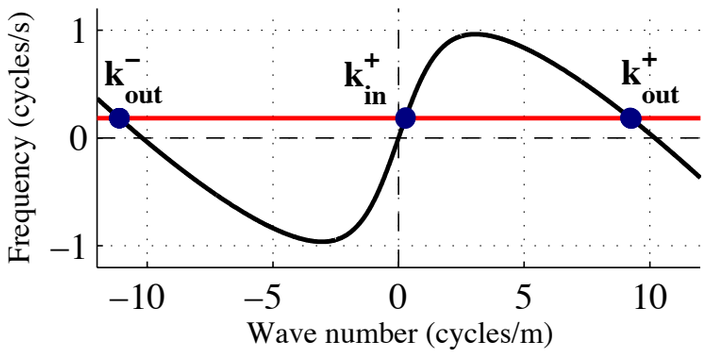

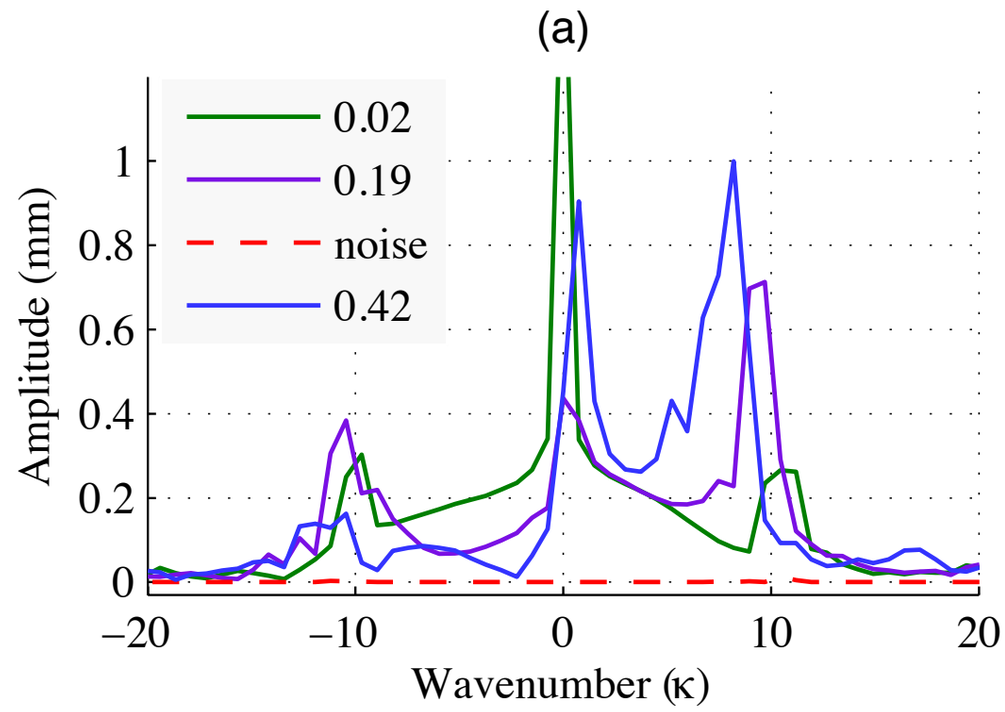

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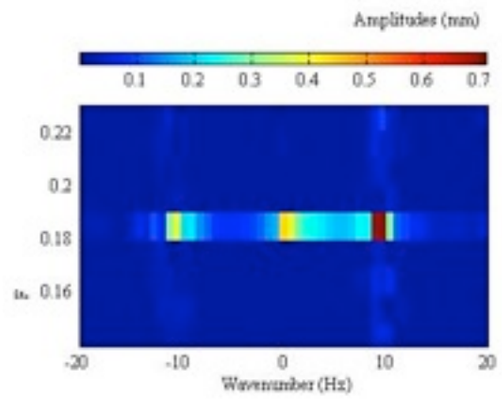

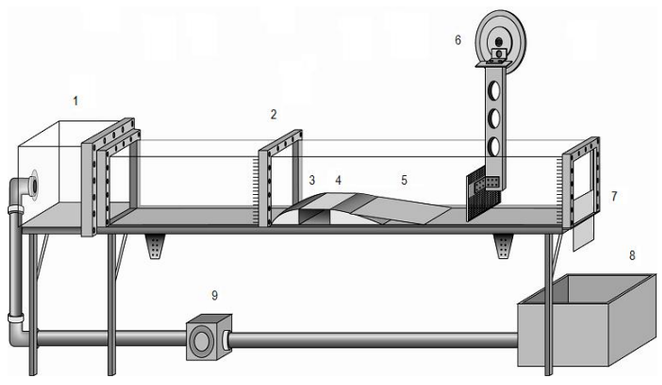

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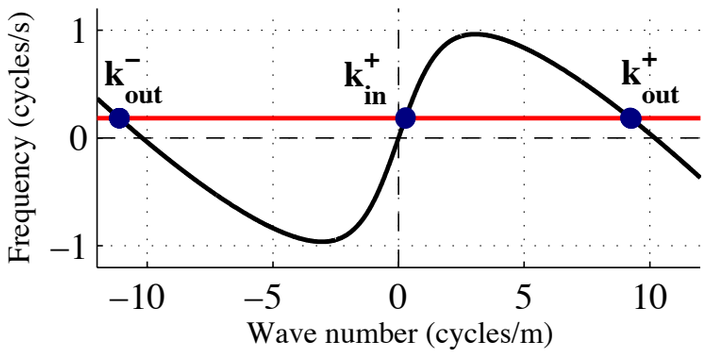
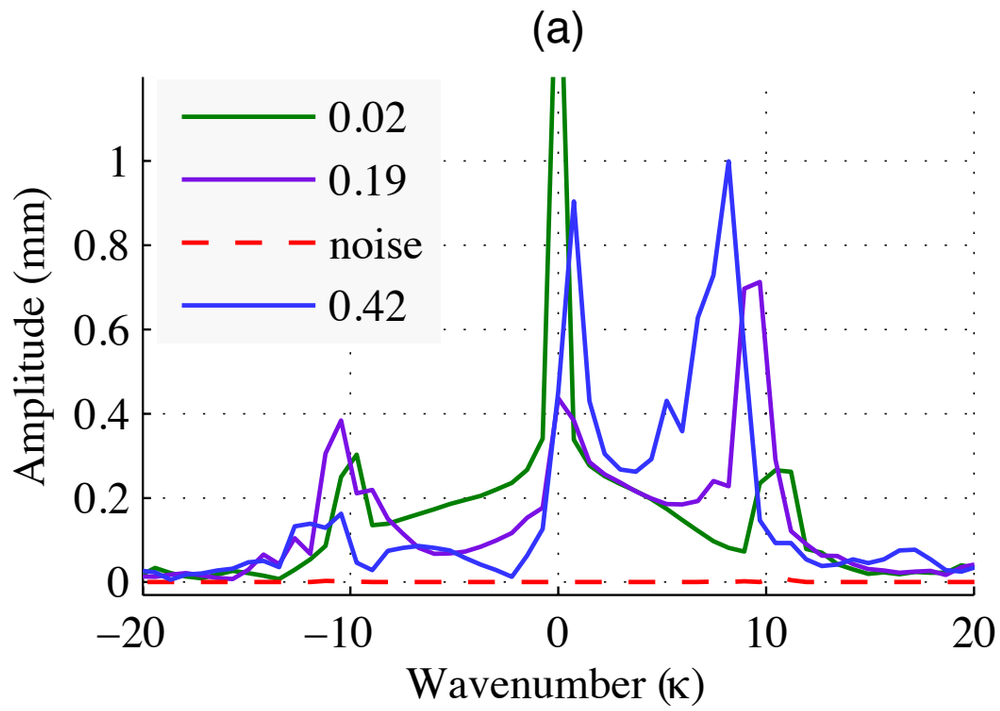
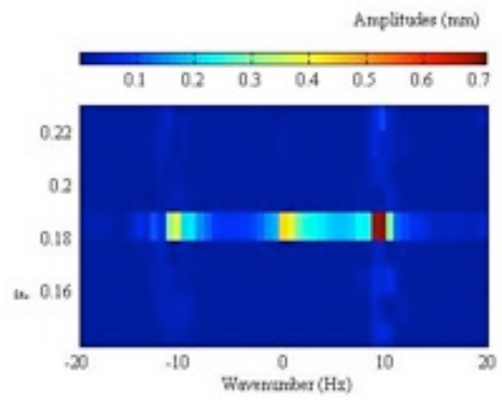
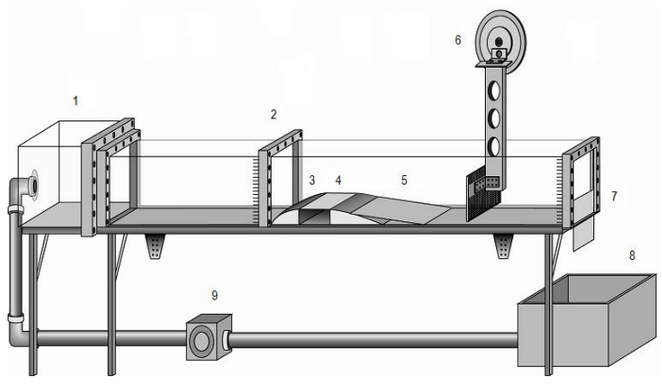
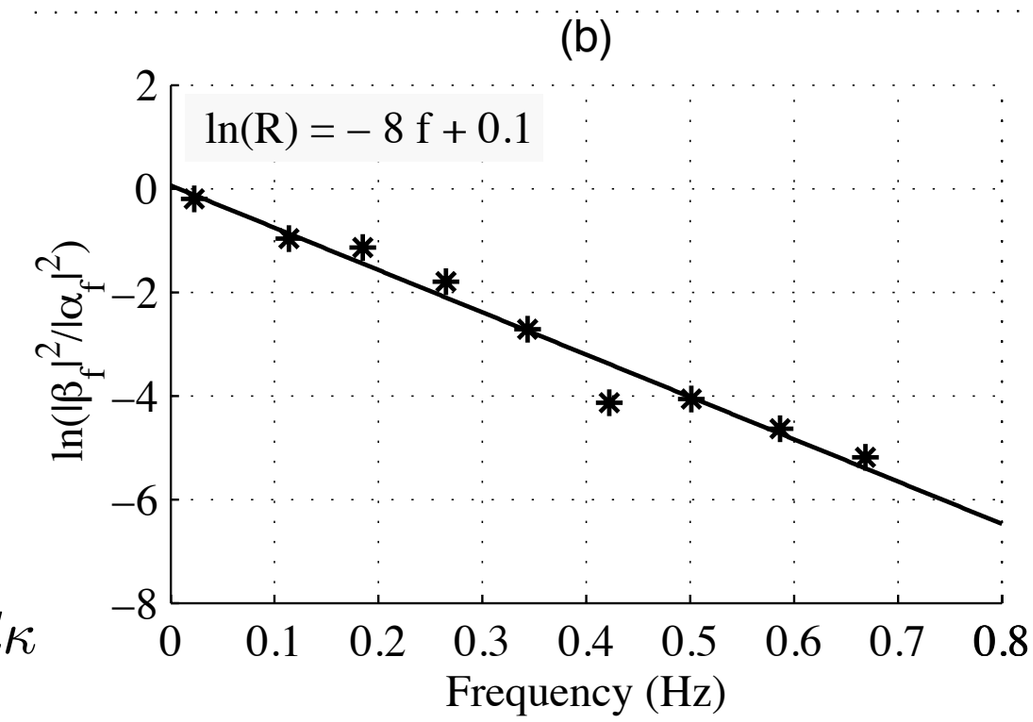




(ii) what is a wave (particle) nearbythe white hole horizon..?







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

Summary & Outlook

– Preliminary work, however a first check confirmed that $|\beta_\omega|^2 = e^{-\frac{2\pi\omega}{g_{\mathbf{H}}}}|\alpha_\omega|^2$

Order of magnitude is right at the place where the waves get blocked!

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

✓ Stimulated Hawking process [pair-creation with a thermal spectra] is confirmed at white hole in analogue gravity system.

– The thermal emission is a universal phenomenon, surviving fluid-dynamic deviations (viscosity, vorticity) and vastly altered dispersion relations.

Spontaneous emission straightforward, but undetectable; superfluid experiments necessary...

Creating the lightsheet: Adding dye to the water