Title: Black hole experiments: Testing effective field theories in curved spacetimes

Date: Nov 11, 2009 02:00 PM

URL: http://pirsa.org/09110038

Abstract: In 1981 Bill Unruh showed that the equation of motion for sound waves in a convergent fluid flows is given by a wave equation in an acoustic metric geometry. More importantly it is possible to set up sonic horizons in transsonic flows, and thus in principle to mimic experimentally the black-hole evaporation process. Almost 30 years later we have set up an experiment at the University of British Columbia to find out if indeed it is possible to detect (traces of) black hole radiation. We will discuss the necessary theoretical milestones, such as the effective field theory description for water to explore the robustness of Hawking radiation, and the avoidance of shock waves using surface waves rather then sound waves. In theory we should be able to detect the classical component of the thermal emission of black holes in our system and answer the ultimate question: How much do we trust our effective quantum field theory in curved spacetimes?

Testing effective field theories in

BLACK HOLE EXPERIMENTS

curved spacetimes

by

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- Matt Penrice
- Ted Tedford
- Mauricio Richartz
- Bill Unruh

Silke Weinfurtner

Outlook - Can we do BH-physics in the lab?

There exists an **effective field theory**, such that:

- has an **emergent lorentz symmetry** (with respect to the maximum propagation speed) in the *IR*;
- is capable of exhibiting effective **black and white hole horizons**;
- can be realised in a **undergraduate Civil Engineering laboratory**;
- offers the possibility to experimentally put our **trust in effective field theories in curved spacetimes** to the test!!?

Spacetime geometry without Einstein field equations

1915 Albert Einstein:

Gravity is a **consequence** of dynamical space+time **geometry**!

Gravitational field is a symmetric rank two tensor:

$$g_{ab} = \begin{bmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{01} & g_{11} & g_{12} & g_{13} \\ g_{02} & g_{12} & g_{22} & g_{23} \\ g_{03} & g_{13} & g_{23} & g_{33} \end{bmatrix}$$

+

Dynamical equations
(Einstein Field equations)

$$G_{ab}(g_{ab}, \Lambda) = 8\pi G_{\mathrm{N}}\, T_{ab}$$

Emergent spacetime geometry

Dynamical equations
(Various systems)

Some notion of...

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Dynamical equations
(Various systems)

Broad class of systems with ***completely*** different dynamics:

electromagnetic waveguide, **fluids**,

ultra-cold gas of Bosons and Fermions;

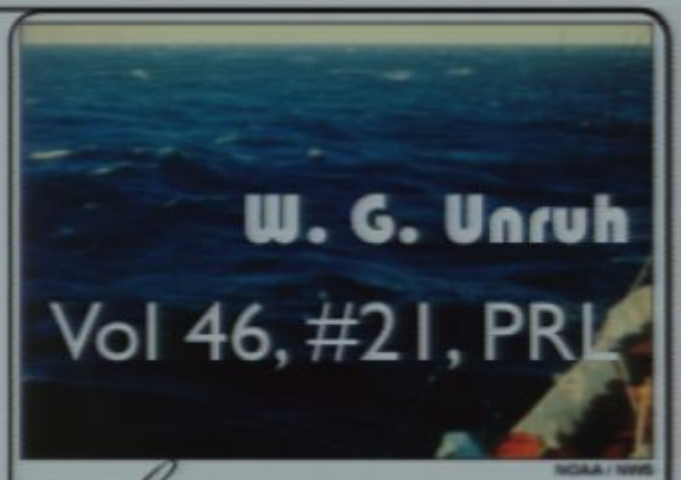
25 May 1982 - Experimental Black-Hole Evaporation?

Convergent fluid flow

- vorticity free (locally irrotational)

$$\vec{\nabla} \times \vec{v} = 0 \qquad \rightarrow \quad \vec{v} = -\vec{\nabla}\phi$$

- incompressible $\quad \dfrac{D\rho}{Dt} = 0$
- inviscid (high Reynolds number)



where

$$D = \partial_t + \vec{v} \cdot \vec{\nabla}$$

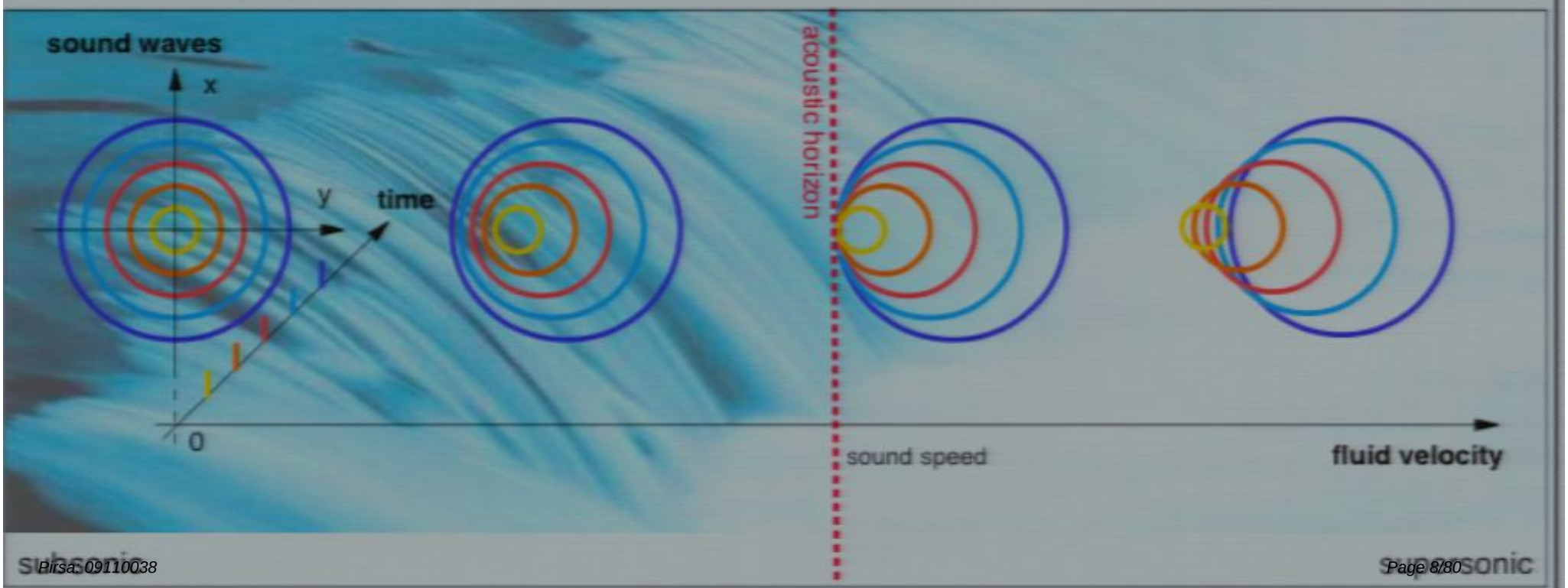
Equations of motion

- Continuity equation $\quad \partial_t \rho + \vec{\nabla} \cdot (\rho \vec{v}) = 0$
- Euler Equation $\quad \rho \dfrac{D\vec{v}}{Dt} = \vec{f} \quad$ *here* $\quad \vec{f} = -\vec{\nabla} p$
- Equation of state $\quad p = p(\rho)$

Perturbation around background flow

Sound waves

$$\rho = \rho_0 + \epsilon\,\rho_1 + \mathcal{O}(\epsilon^2)$$
$$p = p_0 + \epsilon\,p_1 + \mathcal{O}(\epsilon^2)$$
$$\phi = \phi_0 + \epsilon\,\phi_1 + \mathcal{O}(\epsilon^2)$$

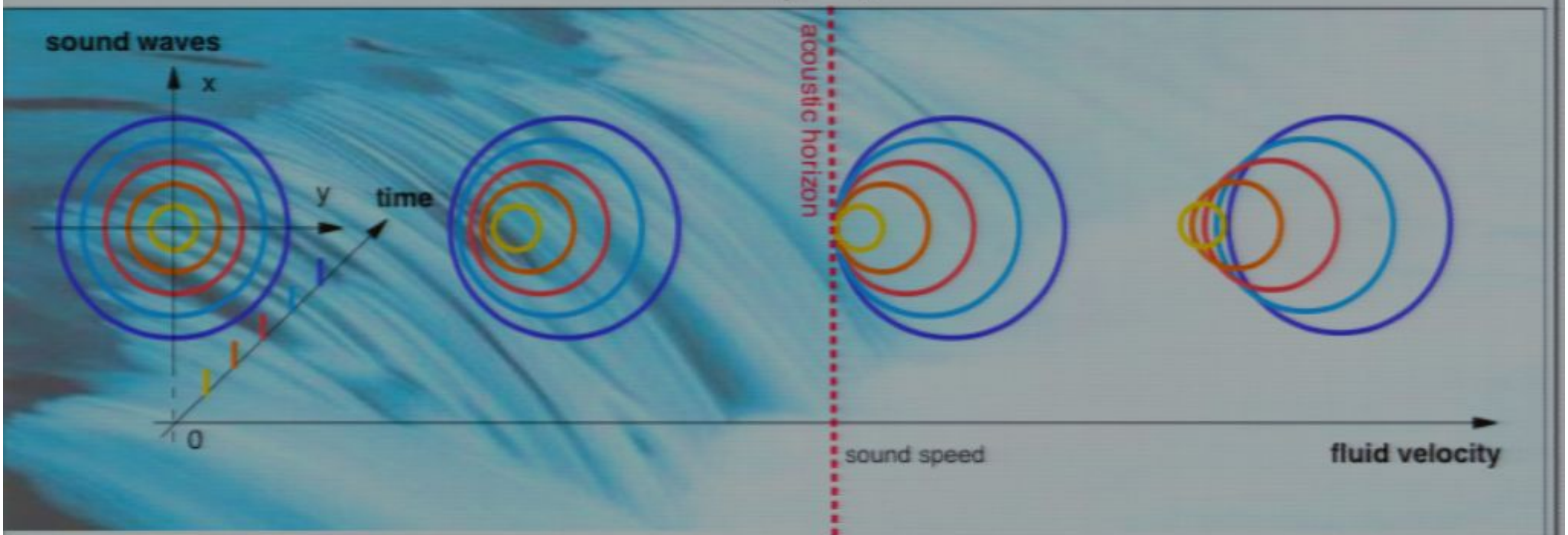


Acoustic metric

flow velocity: $\vec{v} = \vec{\nabla}\phi_0$

sound speed: $c^2 = \dfrac{\partial \rho}{\partial p}$

Excitation spectrum: $\dfrac{1}{\sqrt{-g}}\partial_a\left(\sqrt{-g}g^{ab}\partial_b\phi_1\right) = 0$



subsonic

supersonic

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

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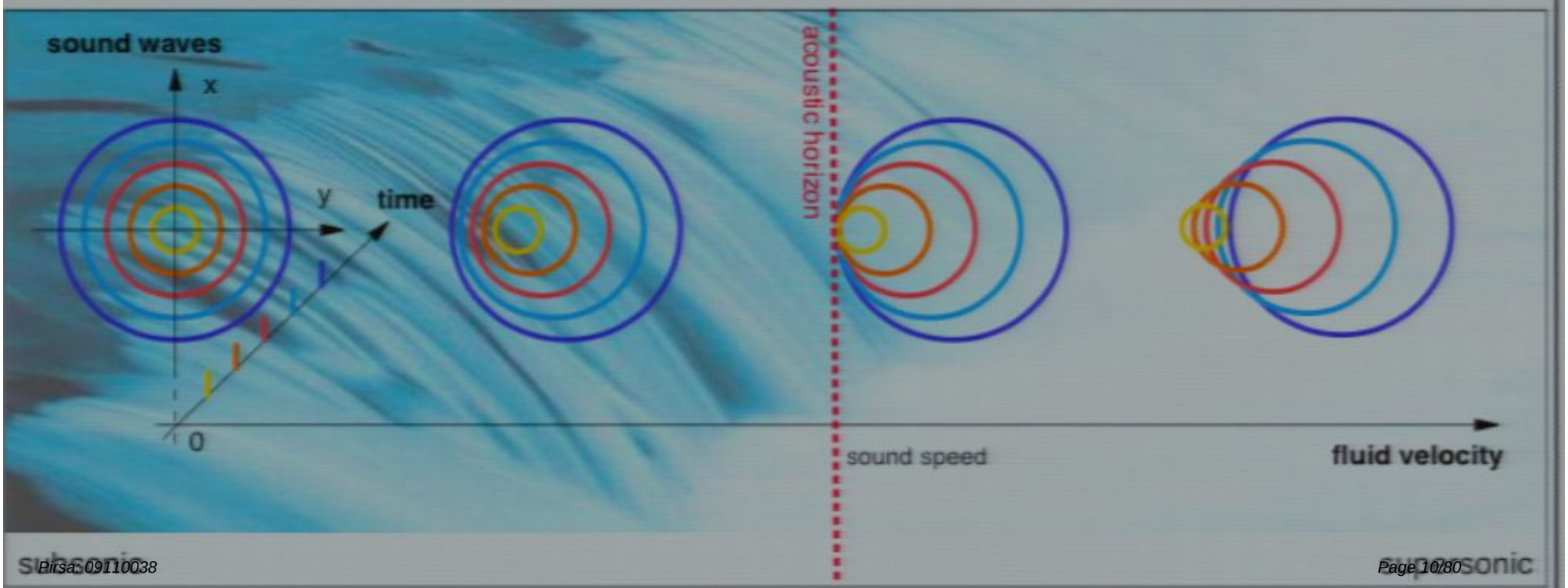

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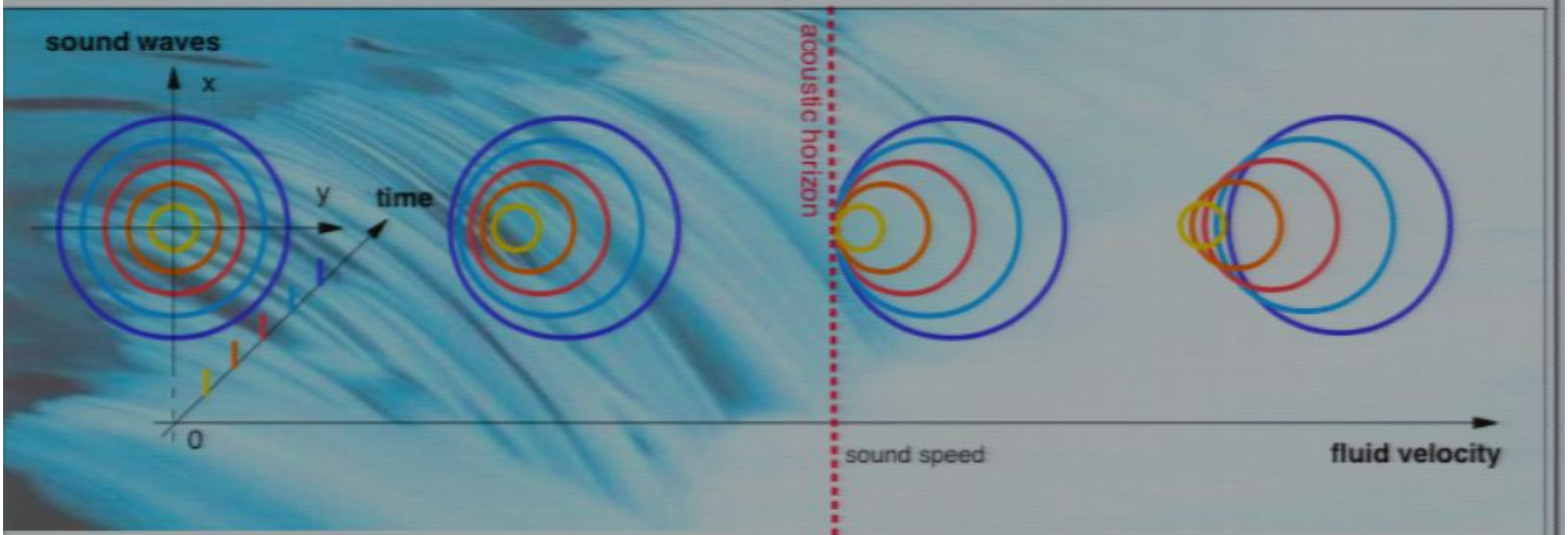

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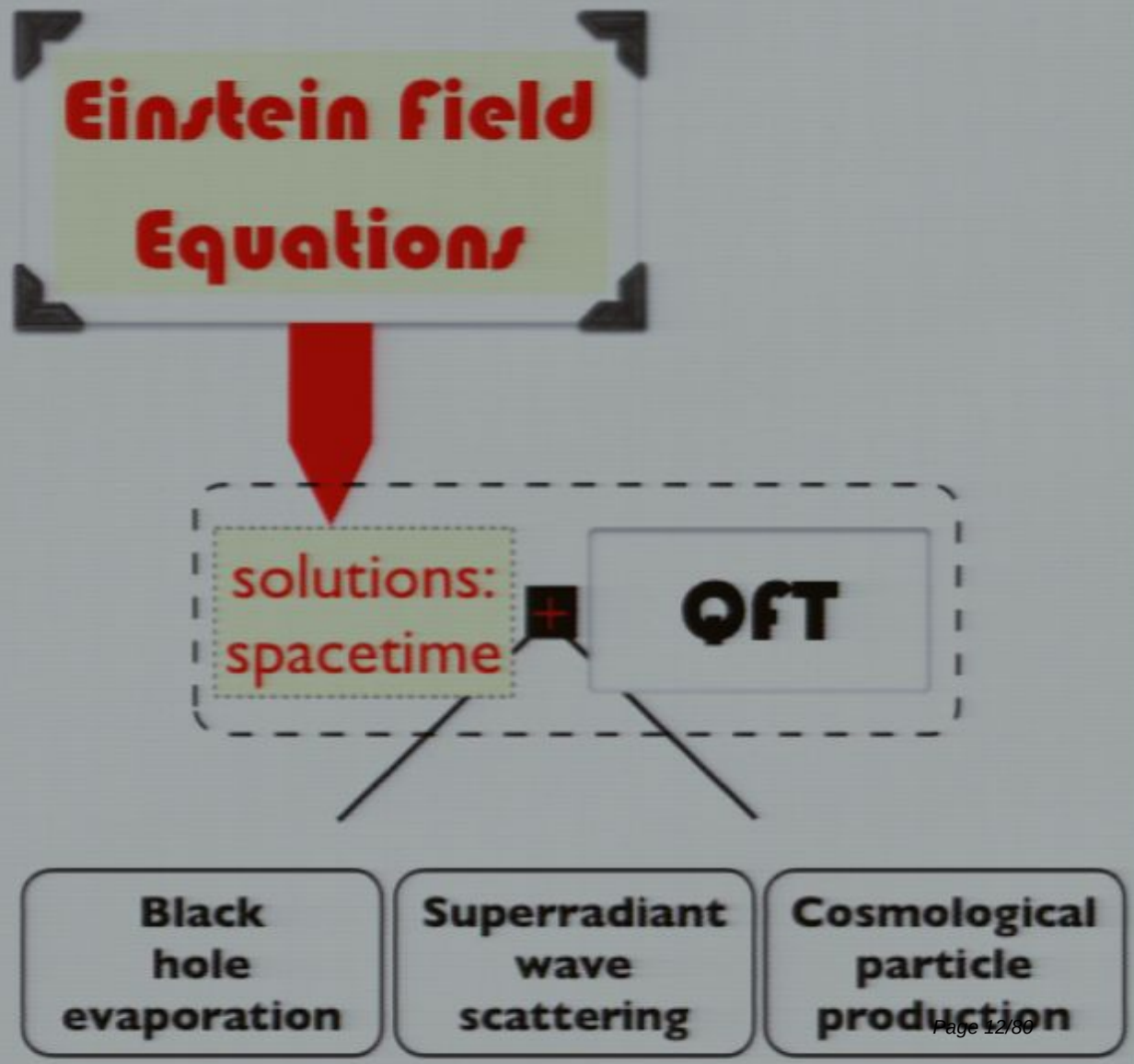
Validity of analogy: Effective field theory in CST



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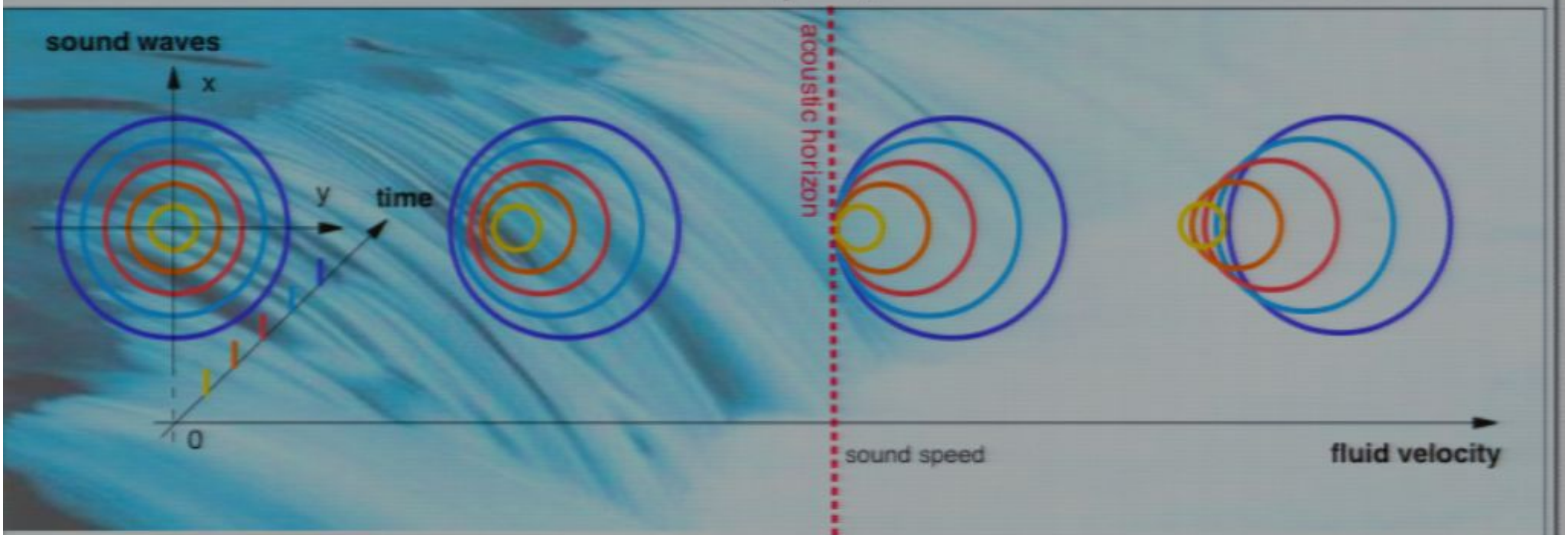

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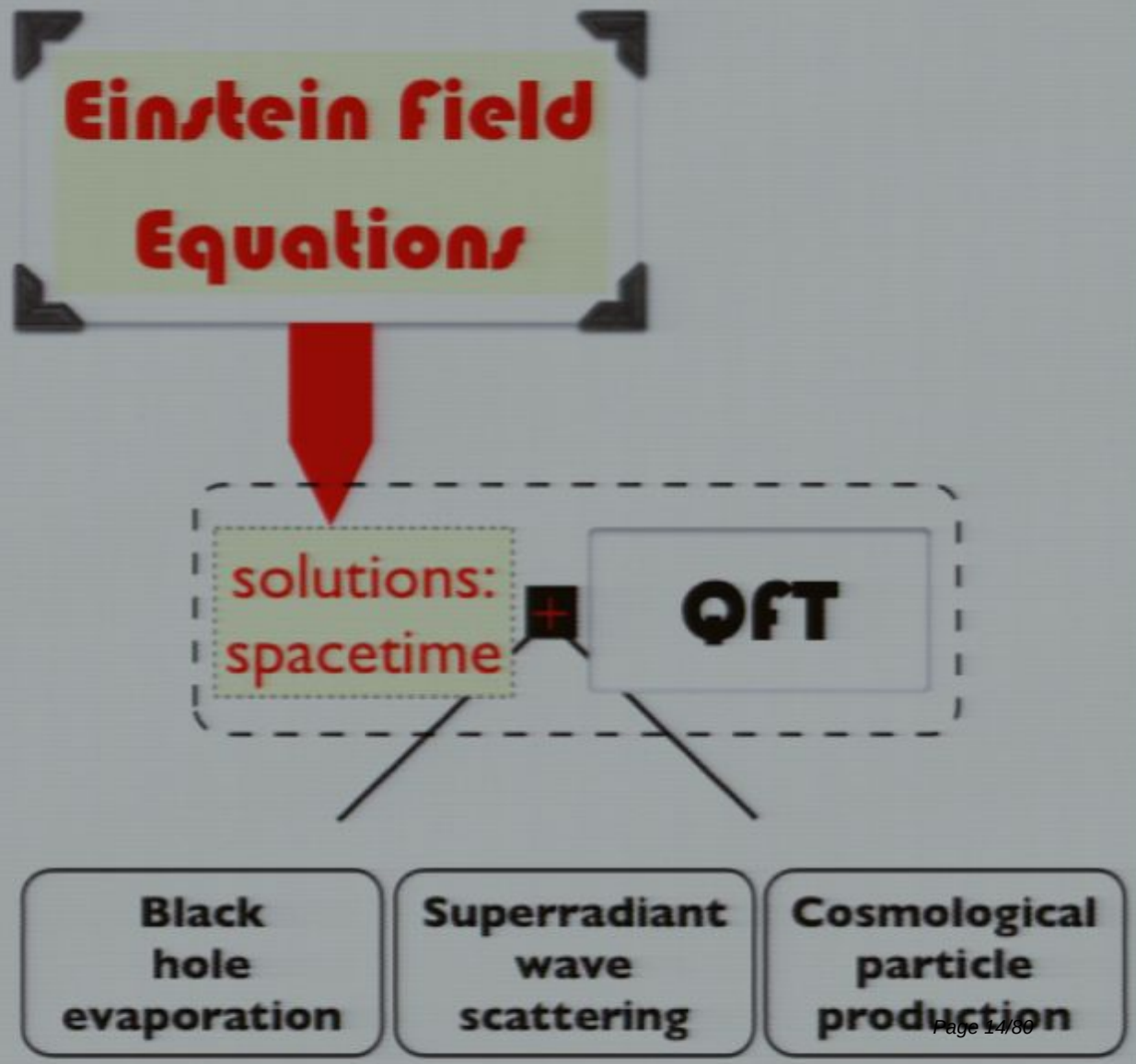

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Hydrodynamic Equations

emergent spacetime
+
effective field theory

Einstein Field Equations

solutions: spacetime + QFT

Black hole evaporation

Superradiant wave scattering

Cosmological particle production

Validity of analogy: Effective field theory in GST

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+ validity of effective description..?

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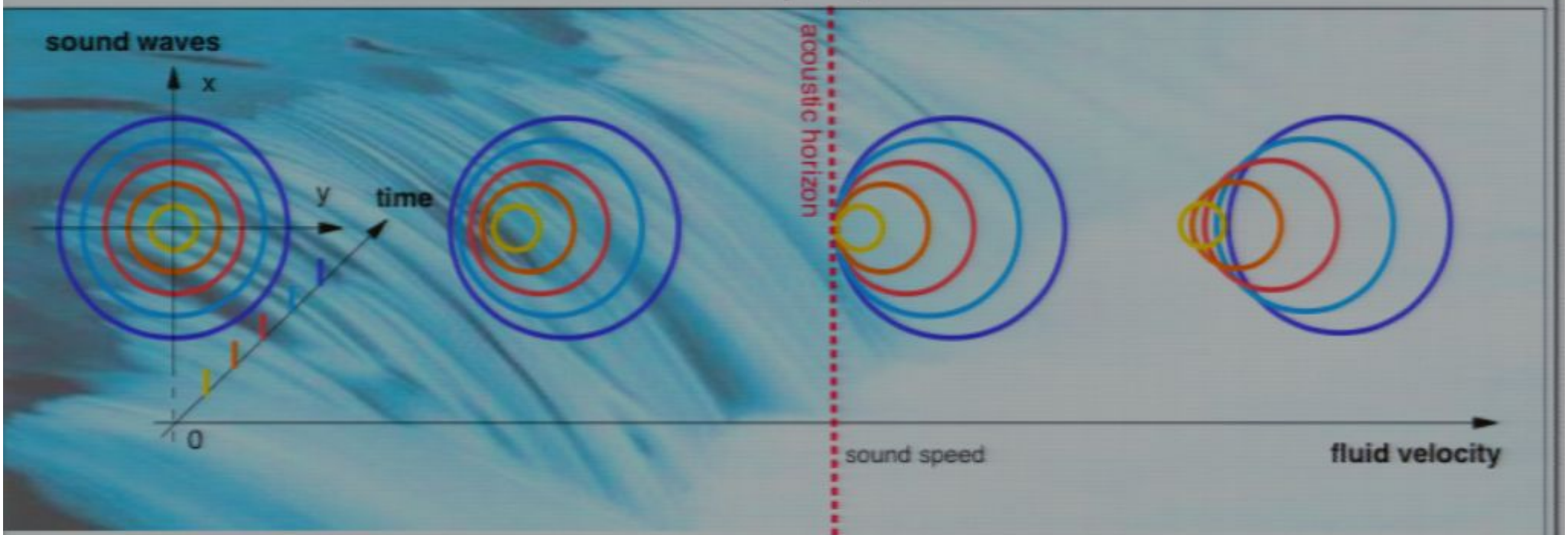

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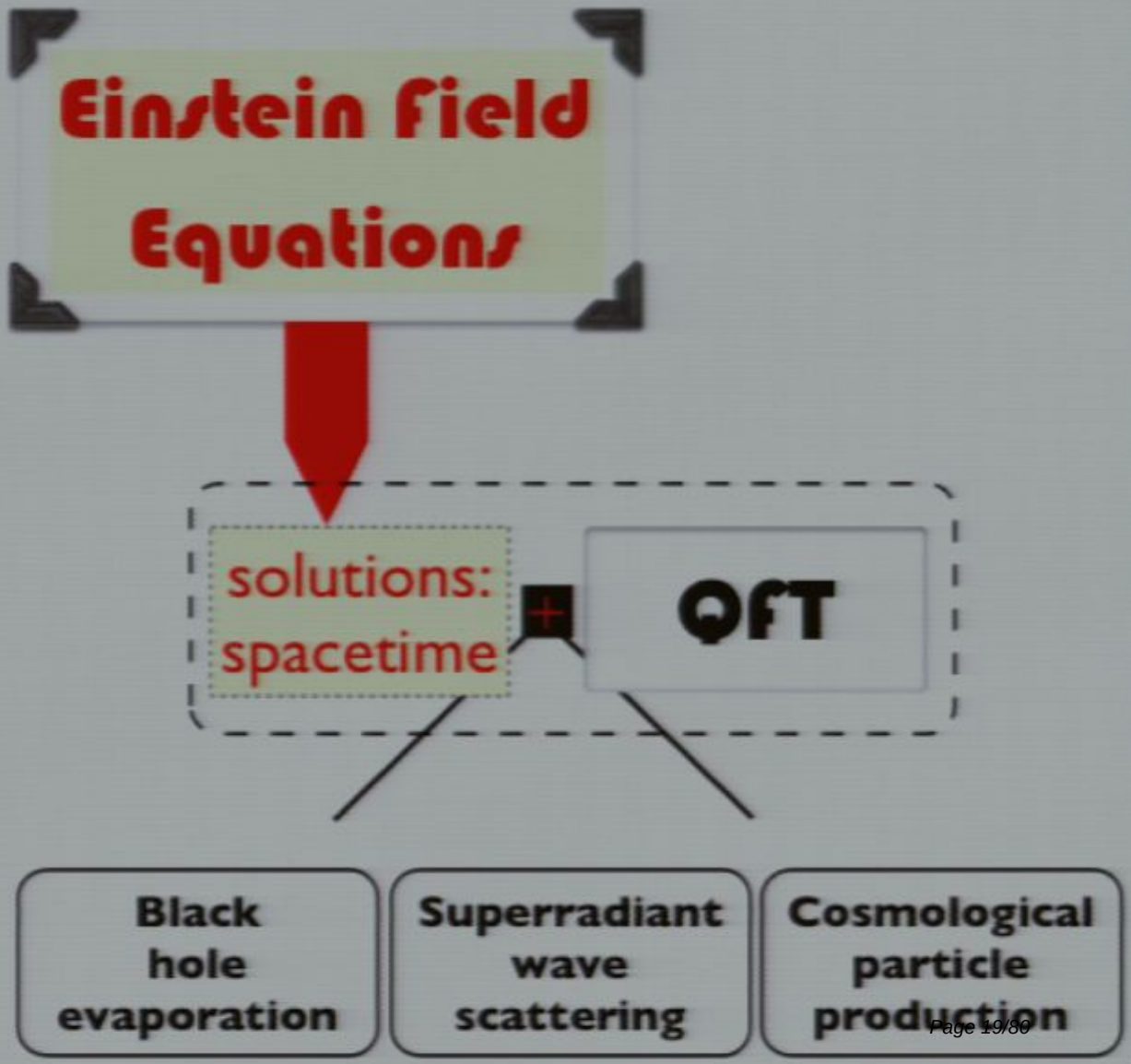

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semi-classical quantum gravity w/o b.r.

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Quantum gravity versus QFT in CST

Assumptions:

$$T = \frac{\hbar c^3}{8\pi k G M_{BH}}$$

(a) gravitational field is semi-classical

(b) effective field theory holds on all scales

Breakdown:

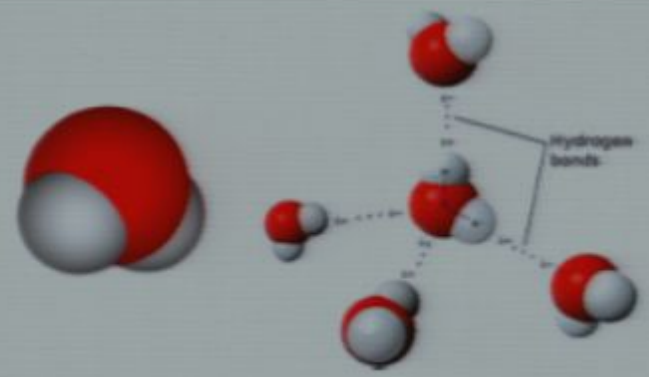
Breakdown of evaporation process:
blue-shift of quantum field modes to

$$\frac{k_{\rm H}}{k_0} \approx \exp(10^4)$$

Problem:

Experimental investigation
IMPOSSIBLE!!?... unless...

Effective field theory in our toy model



Fluid equation does not take **atomic nature of fluid** into account, but the effective field theory changes dispersion relation for sound waves!!!

$$\omega^2 = F^2(k)$$

Hydrodynamic Equations

emergent spacetime
+
effective field theory

Emergent Lorentz symmetry (with respect to the sound waves) in the *IR*: Anisotropic scaling with higher spatial derivatives...

Shock waves at Acoustic Horizon

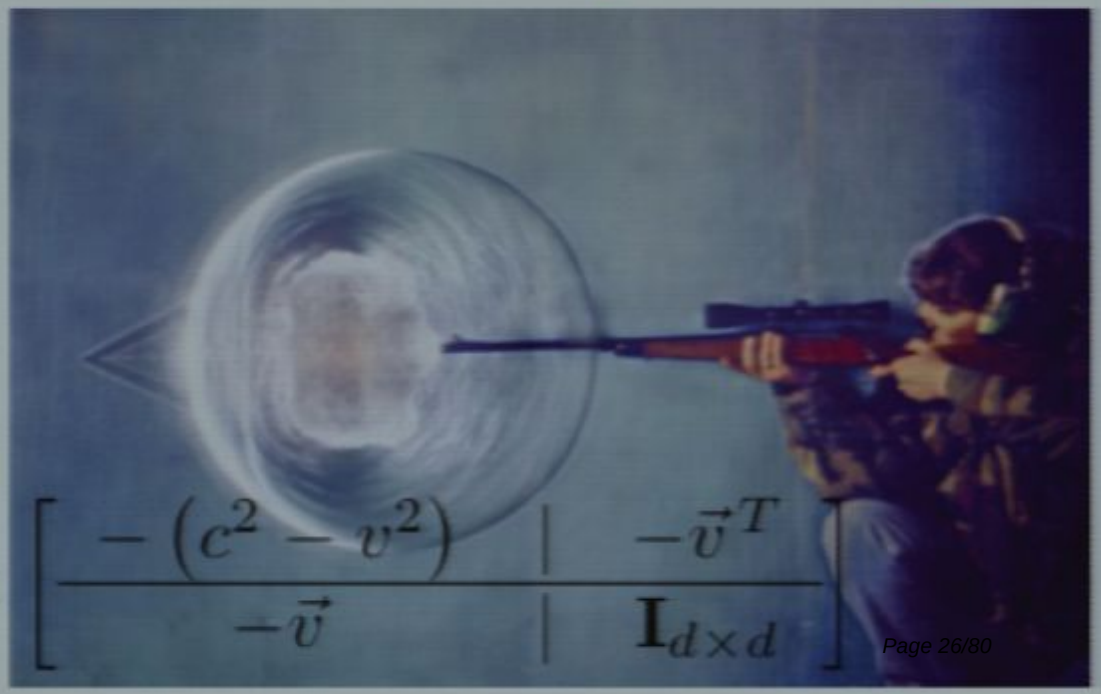
(a) ~~gravitational field is semi-classical~~

setup is within the validity of the linearisation scheme

(b) effective field theory ~~holds on all scales~~

with anisotropic scaling

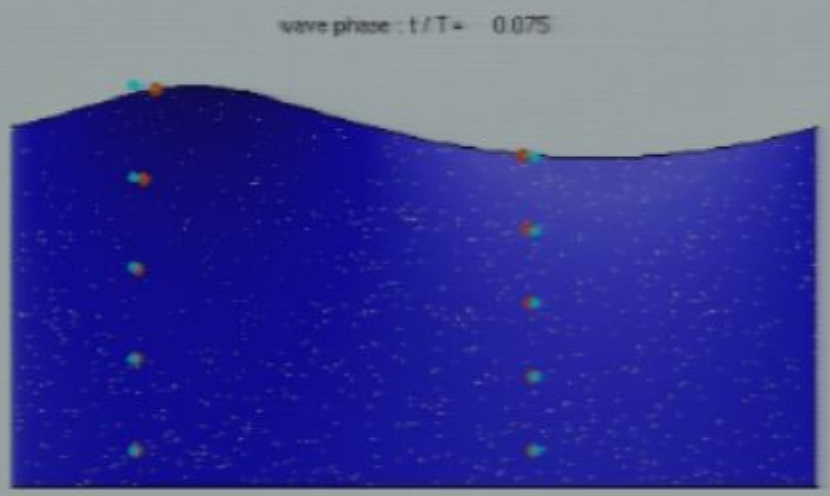
Wikipedia. When an object (or disturbance) moves faster than the information about it can be propagated into the surrounding fluid, fluid near the disturbance cannot react or "get out of the way" before the disturbance arrives. In a shock wave the properties of the fluid (density, pressure, temperature, velocity, Mach number) change almost instantaneously.



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

Solution: Surface waves instead of sound waves!

excitations creaed at interface between two media



Incompressible, inviscid and irrotational fluid

$$\mathbf{v} = \nabla\psi + \partial_z\psi$$

(CE) $$\nabla^2\psi + \partial_z^2\psi = 0$$

Taylor expansion around $z = 0$

$$\psi(t,x,y,z) = \sum_{n=0}^{\infty} \frac{z^n}{n!}\psi_{(n)}(t,x,y)$$

$$\psi_{(n+2)} + \nabla^2\psi_{(n)} = 0, \quad \forall n$$

Gravity wave can adjusted and driven supercritical w/o forming shock waves!!!

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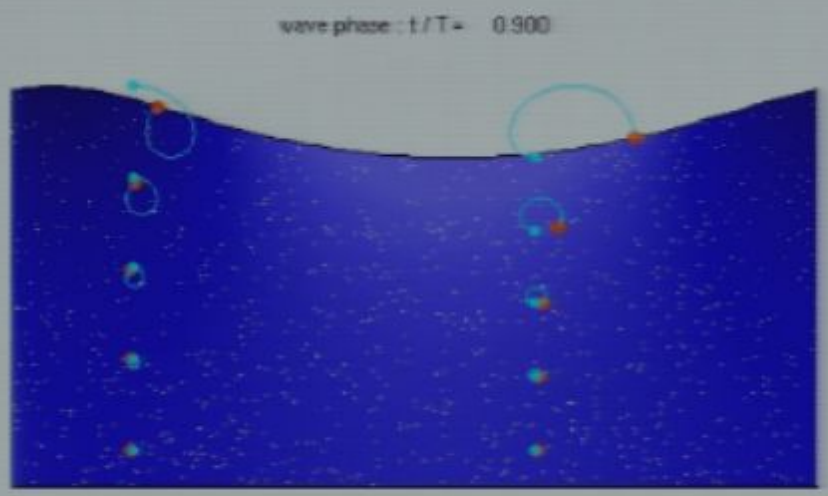

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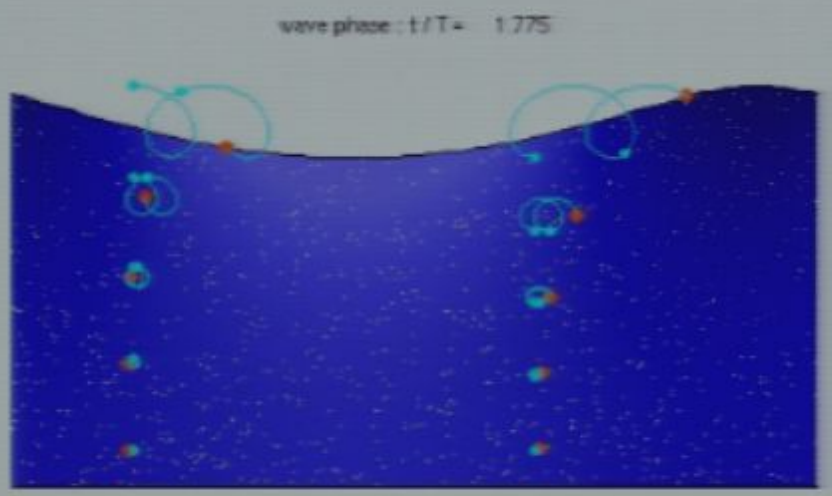

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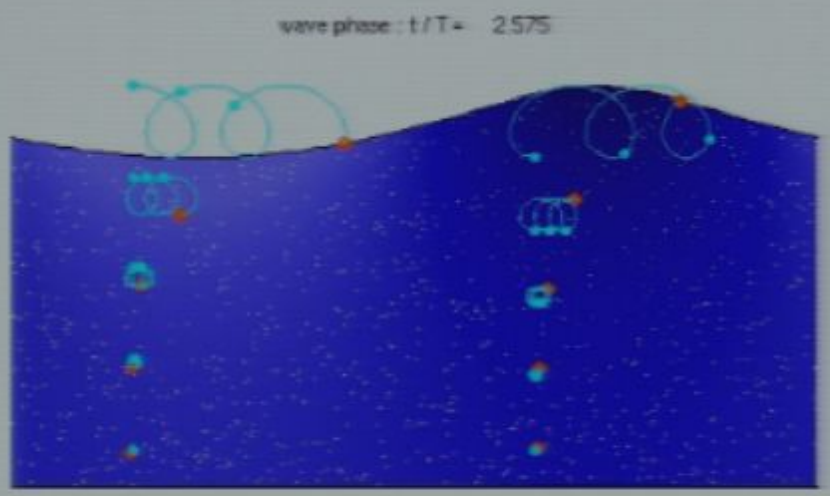

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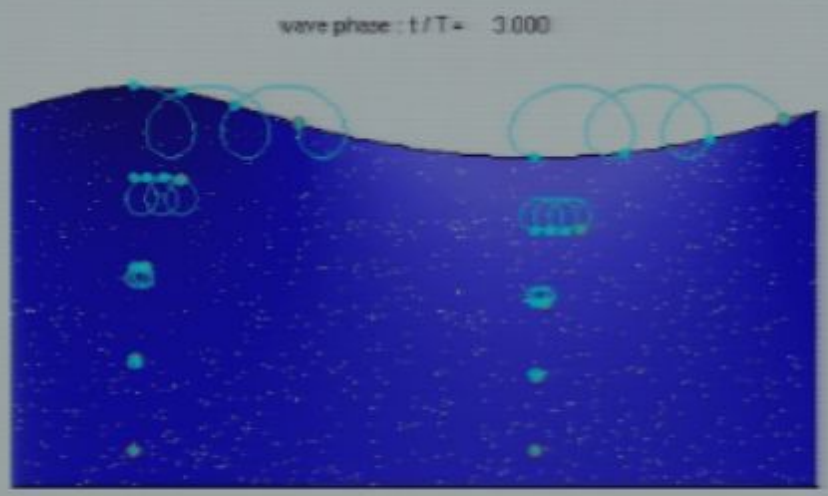

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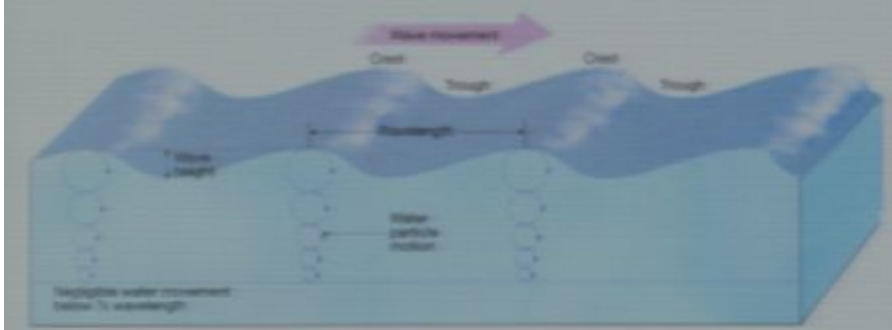
Open channel flows

$$\mathbf{v} = \nabla\psi + \partial_z\psi$$

$$\psi(t,x,y,z) = \sum_{n=0}^{\infty}(-1)^n \frac{z^{2n}}{(2n)!}\nabla^{2n}\psi_{(0)} + \sum_{n=0}^{\infty}(-1)^n \frac{z^{2n+1}}{(2n+1)!}\nabla^{2n}\psi_{(1)}$$

+ Euler equation... dynamical equations for the surface waves...

Boundary conditions



$$\left.\frac{\partial\psi}{\partial z}\right|_{z=h} = \frac{\partial h}{\partial t} + \nabla h \cdot (\nabla\psi)|_{z=h}$$

$$\left.\frac{\partial\psi}{\partial z}\right|_{z=0} = \psi_{(1)} = 0$$

Only for constant height

Effective field theory for surface waves

$$\left(\frac{\partial}{\partial t}+\nabla\cdot\mathbf{u}_h\right)\frac{1}{\tilde{g}}\left(\frac{\partial}{\partial t}+\mathbf{u}_h\cdot\nabla\right)\left((1-D_1)\delta\psi_{(0)}\right)-\nabla\cdot\left(\mathbf{D_2}\delta\psi_{(0)}\right)=0$$

$$\partial_a\left(\left\{f^{ab}+\tilde{f}^{ab}\right\}\partial_b f\right)=0$$

Anisotropic scaling

$$f^{ab}=\left(\frac{1}{\bar{g}}\right)\begin{pmatrix}-1 & -(u_h)_x & -(u_h)_y\\ -(u_h)_x & -(u_h)_x^2+\bar{g}h & -(u_h)_x(u_h)_y\\ -(u_h)_y & -(u_h)_x(u_h)_y & -(u_h)_y^2+\bar{g}h\end{pmatrix}$$

$$\tilde{f}^{\mu\nu}=\left(\frac{1}{\bar{g}}\right)\begin{pmatrix}0 & 0 & 0\\ 0 & \bar{g}h\left(\frac{1}{2!}\partial_x h^2\partial_x-\frac{1}{3!}h^2\partial_x^2\right) & \bar{g}h\left(\frac{1}{2!}\partial_x h^2\partial_y-\frac{1}{3!}h^2\partial_x\partial_y\right)\\ 0 & \bar{g}h\left(\frac{1}{2!}\partial_y h^2\partial_x-\frac{1}{3!}h^2\partial_y\partial_x\right) & \bar{g}h\left(\frac{1}{2!}\partial_y h^2\partial_y-\frac{1}{3!}h^2\partial_y^2\right)\end{pmatrix}$$

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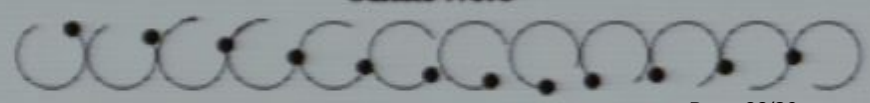
Surface Wave



A surface wave is sometimes referred to as a circular wave because particles of the medium undergo a motion in a complete circle.

Open channel flows

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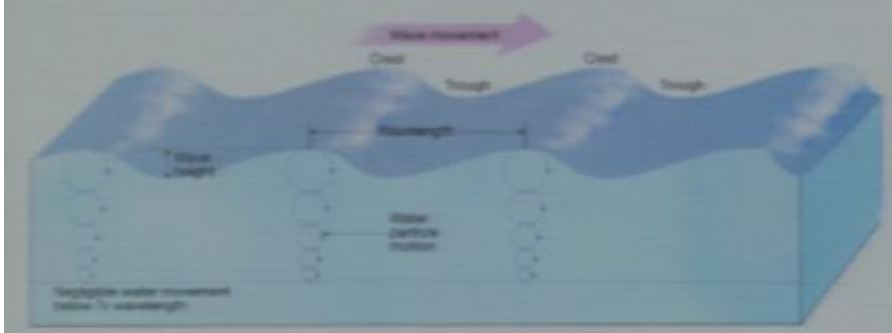
$$\psi(t,x,y,z) = \sum_{n=0}^{\infty}(-1)^n \frac{z^{2n}}{(2n)!}\nabla^{2n}\psi_{(0)} + \sum_{n=0}^{\infty}(-1)^n \frac{z^{2n+1}}{(2n+1)!}\nabla^{2n}\psi_{(1)}$$

+ Euler equation... dynamical equations for the surface waves...

Boundary conditions



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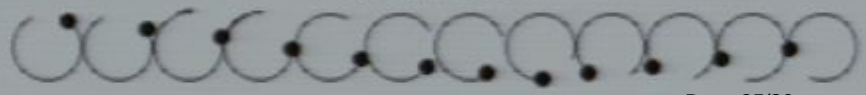
Anisotropic scaling

$$f^{ab}=\left(\frac{1}{\tilde{g}}\right)\begin{pmatrix}-1 & -(u_h)_x & -(u_h)_y\\ -(u_h)_x & -(u_h)_x^2+\tilde{g}h & -(u_h)_x(u_h)_y\\ -(u_h)_y & -(u_h)_x(u_h)_y & -(u_h)_y^2+\tilde{g}h\end{pmatrix}$$

$$\tilde{f}^{\mu\nu}=\left(\frac{1}{\tilde{g}}\right)\begin{pmatrix}0 & 0 & 0\\ 0 & \tilde{g}h\left(\frac{1}{2!}\partial_x h^2\partial_x-\frac{1}{3!}h^2\partial_x^2\right) & \tilde{g}h\left(\frac{1}{2!}\partial_x h^2\partial_y-\frac{1}{3!}h^2\partial_x\partial_y\right)\\ 0 & \tilde{g}h\left(\frac{1}{2!}\partial_y h^2\partial_x-\frac{1}{3!}h^2\partial_y\partial_x\right) & \tilde{g}h\left(\frac{1}{2!}\partial_y h^2\partial_y-\frac{1}{3!}h^2\partial_y^2\right)\end{pmatrix}$$

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

Surface Wave



A surface wave is sometimes referred to as a circular wave because particles of the medium undergo a motion in a complete circle.

Dispersion relation (eikonal approximation)

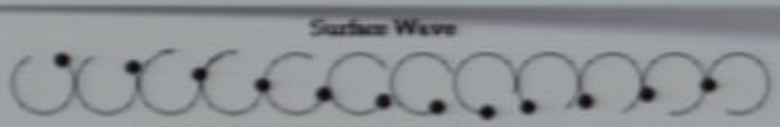
For constant, or slowly varying bottom we get:

$$\left(\frac{\partial}{\partial t} + \nabla \cdot \mathbf{u}_h\right)\left(\frac{\partial}{\partial t} + \mathbf{u}_h \cdot \nabla\right)\delta\psi_h - \nabla \cdot \left(\frac{g}{k}\tanh(kh)\,\nabla\delta\psi_h\right) = 0$$

Momentum dependent speed of sound $c^2 = \frac{g}{k}\tanh(kh)$

Full dispersion relation including surface tension:

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

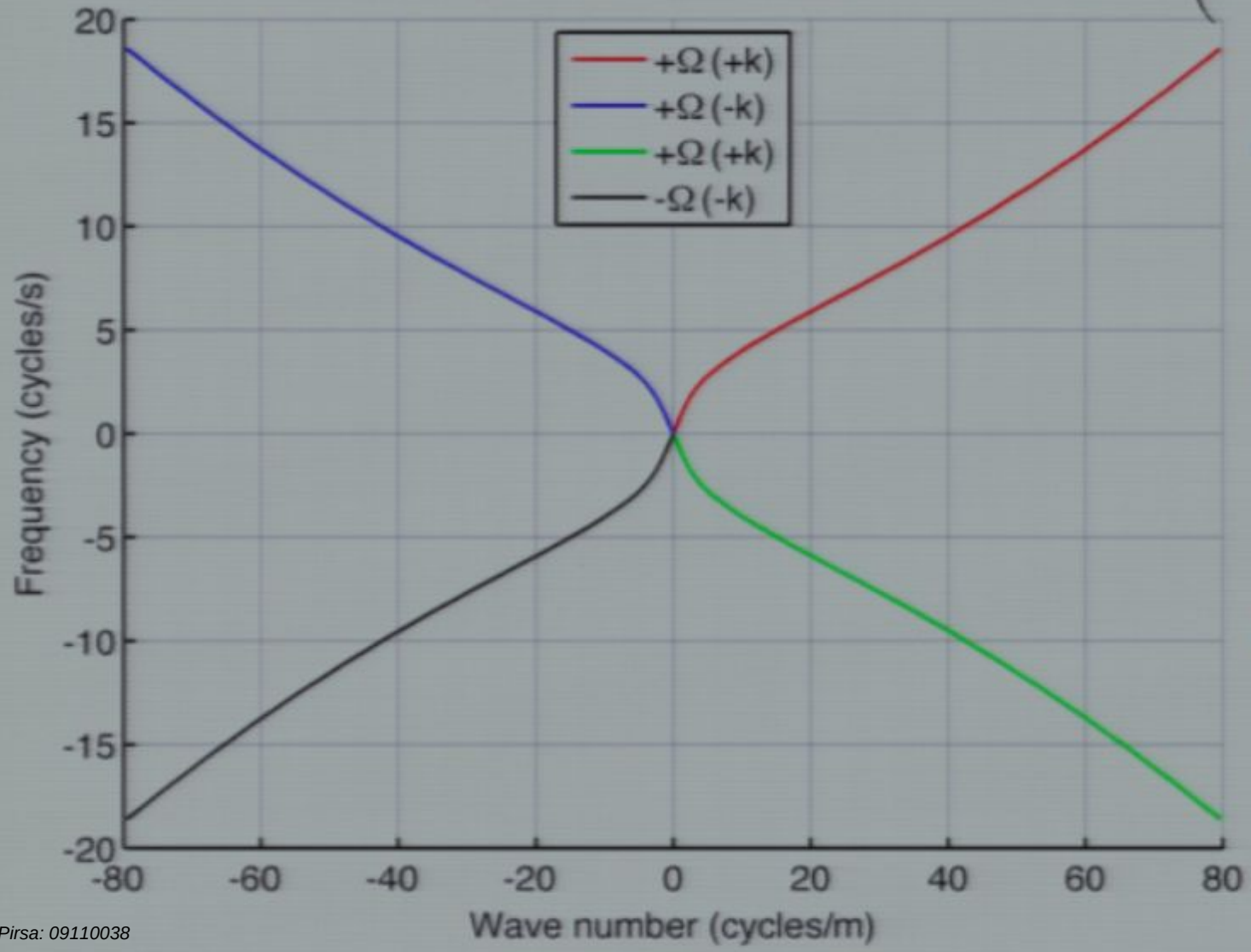


A surface wave is sometimes referred to as a circular wave because particles of the medium undergo a motion in a complete circle.

Dispersion Relation for Surface Waves (fluid at rest)

$\omega_0 = \pm\Omega_x(\pm k)$, where $v_0 = 0$

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



shallow:

$$\Omega^2 = (g\,h)\,k^2$$

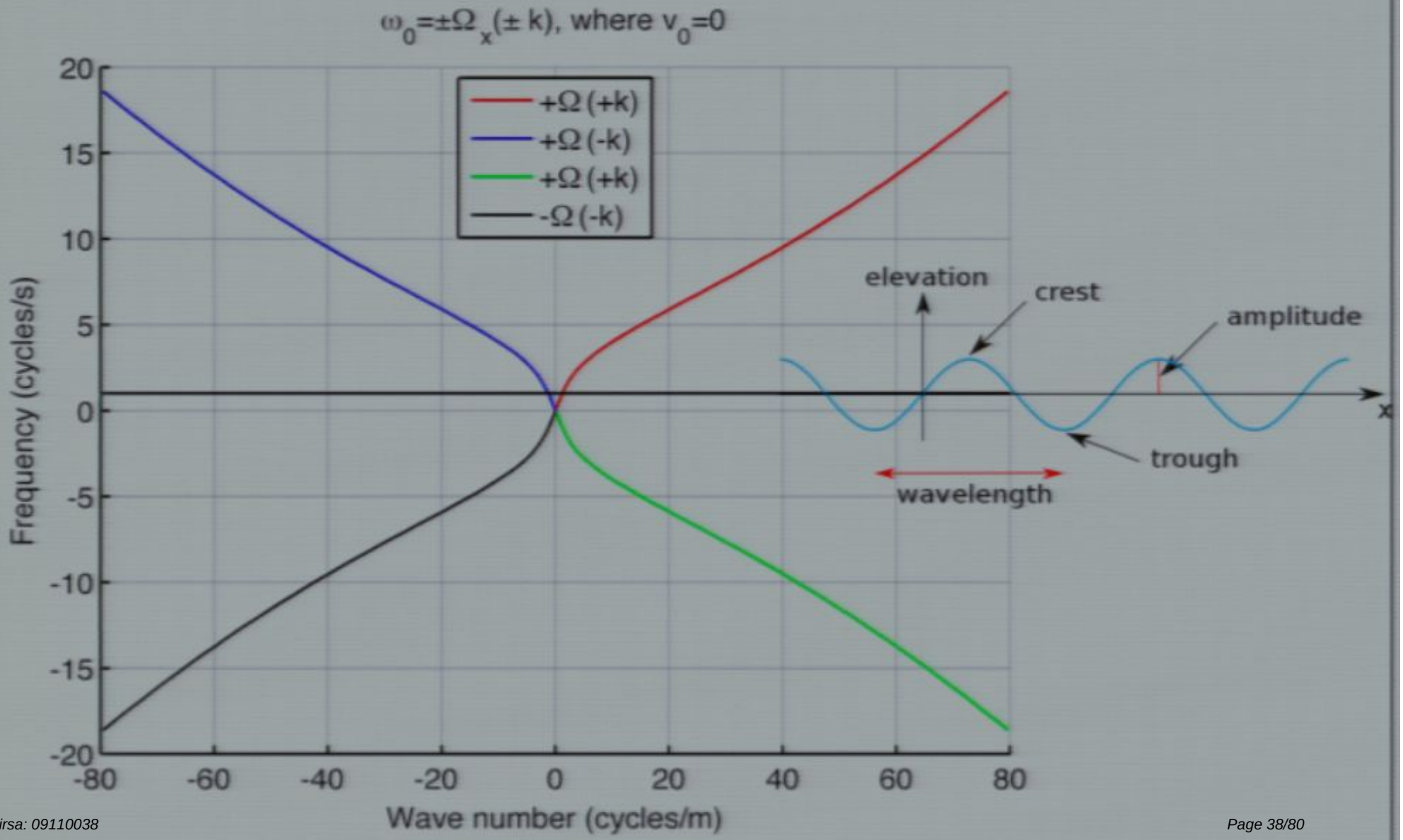
deep:

$$\Omega^2 \propto \tanh(h\,k)$$

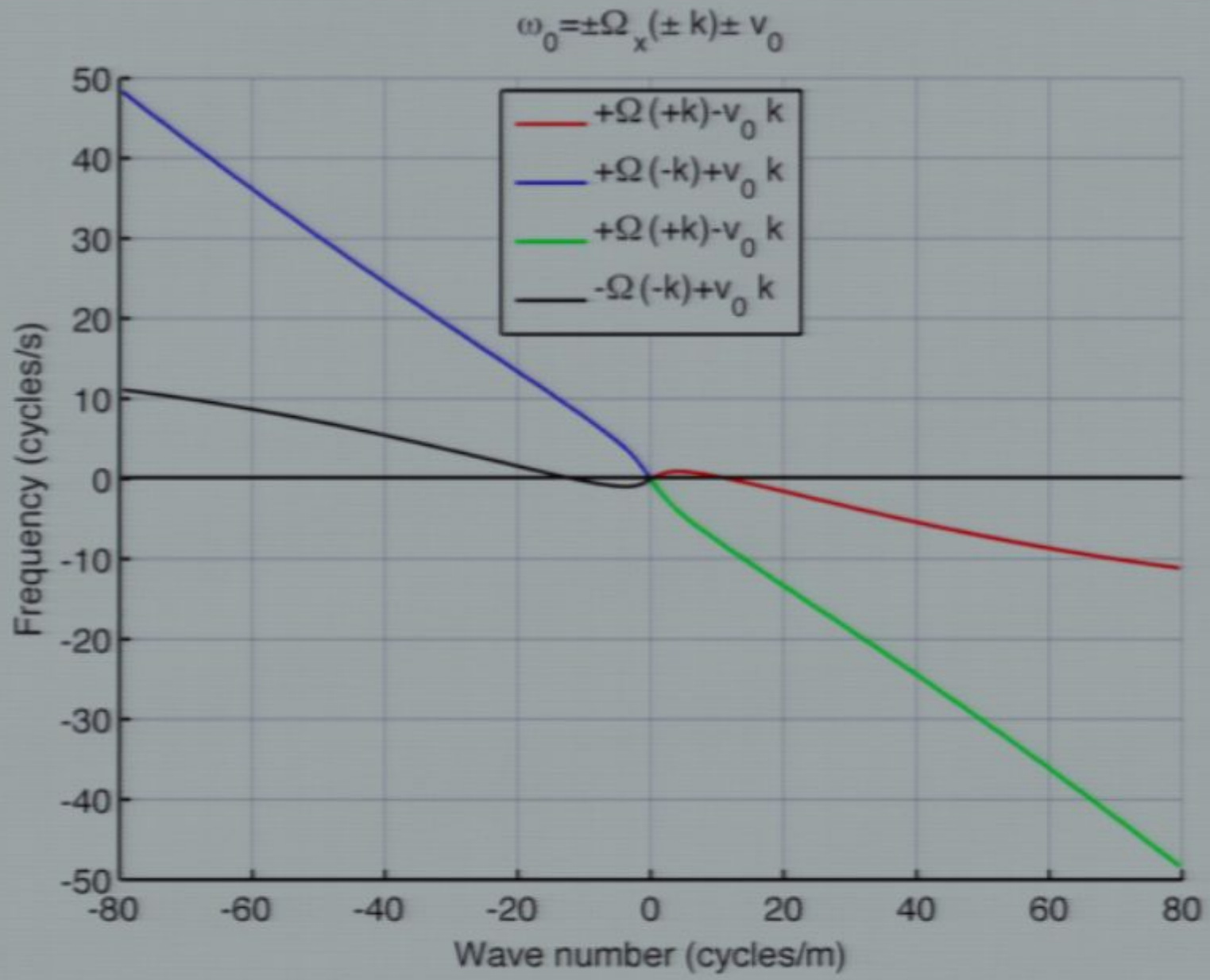
capillary:

$$\Omega^2 \propto \frac{\sigma}{\rho}\,k^3$$

Dispersion Relation for Surface Waves (fluid at rest)



Dispersion Relation for Surface Waves (moving fluid)



Ready for the experiment - almost!

New Journal of Physics **10** (2008) 053015 (12pp)
Received 24 December 2007
Published 13 May 2008
Online at http://www.njp.org/
doi:10.1088/1367-2630/10/5/053015

Notice: We do NOT look at quantum effects, those would be too small to detect:

$$T = \frac{\hbar}{2\pi k}\frac{\partial v_r}{\partial r}\bigg|_{\text{Horizon}}$$

Observation of negative-frequency waves in a water tank: a classical analogue to the Hawking effect?

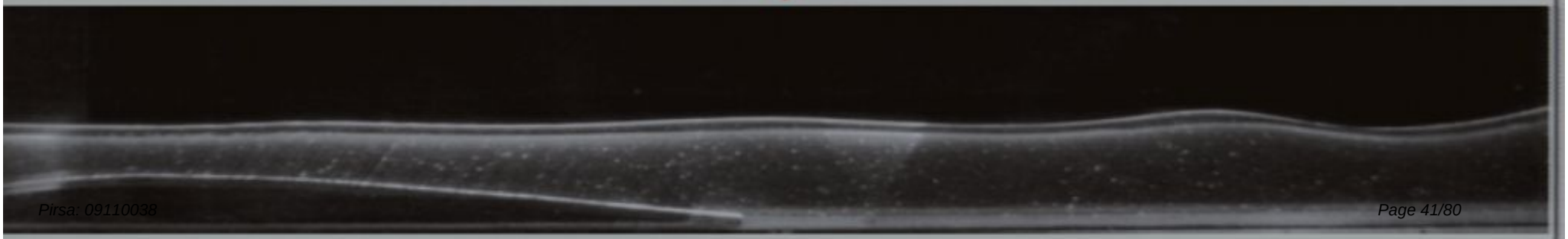
Germain Rousseaux[1,2], Christian Mathis[2], Philippe Maïssa[2], Thomas G Philbin[3,4] and Ulf Leonhardt[3,5]

Problems:

- negative frequency waves with wrong frequency (indicating non-linear effects)
- negative frequency modes with and without acoustic horizons
- separation of flow

Effective field theory laboratory

Our flume tank (7.47m long and 5.4m wide):

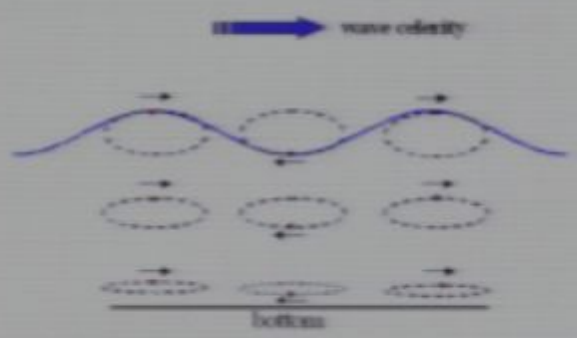


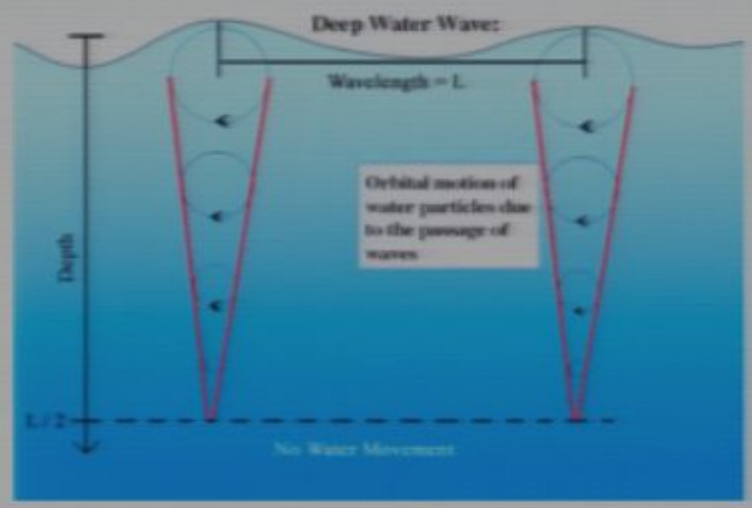
Obstacles

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

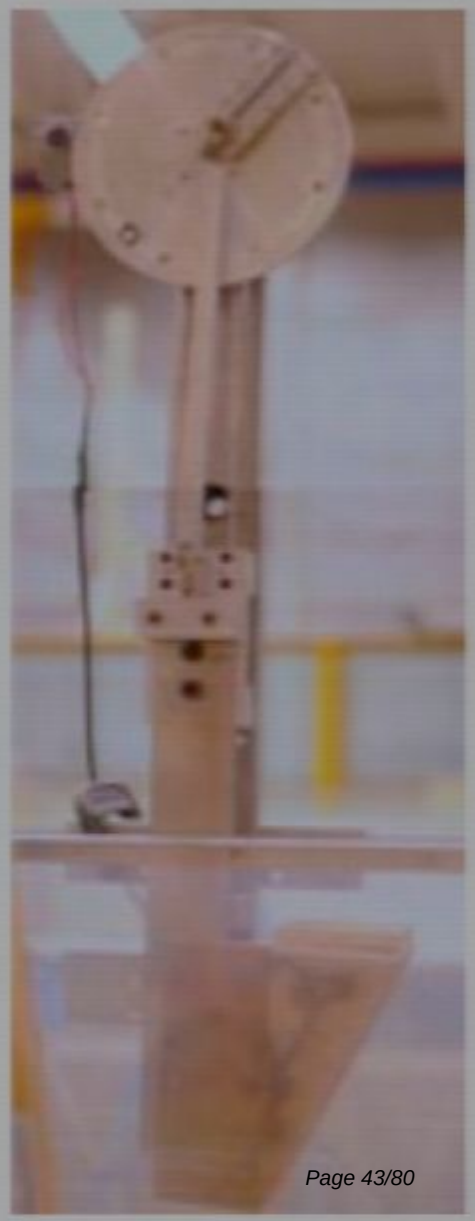
Wave generator: How to generate waves..?

Shallow water waves

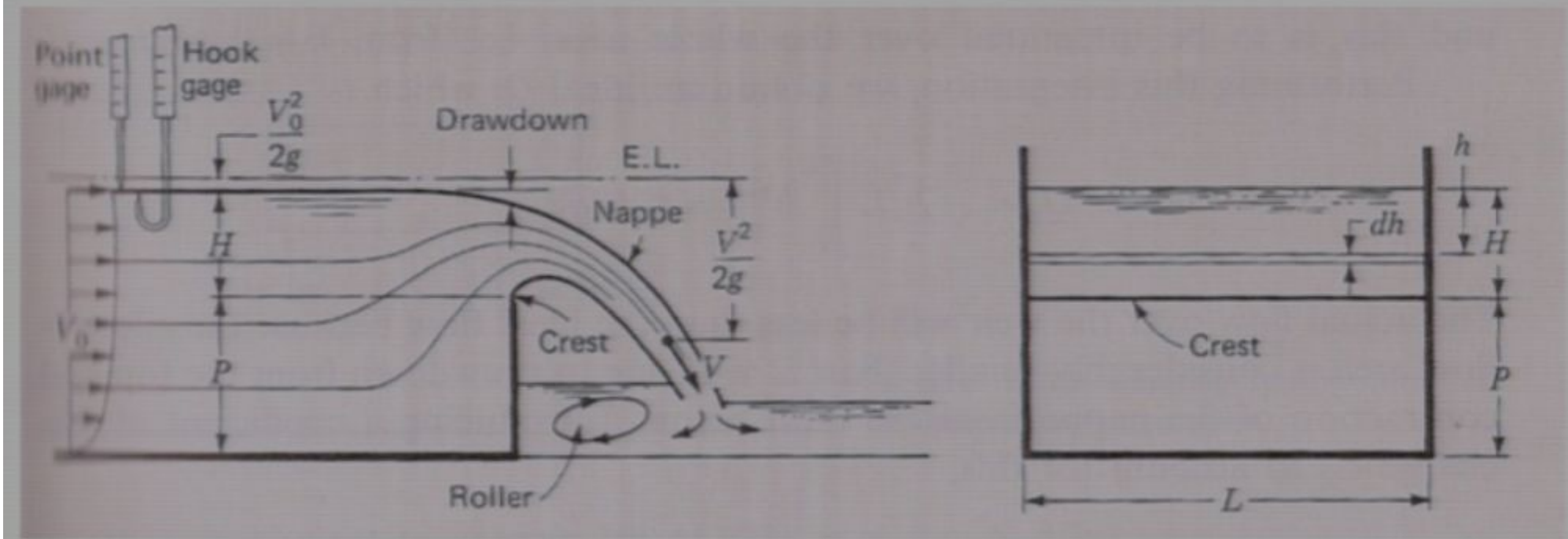




Deep water waves

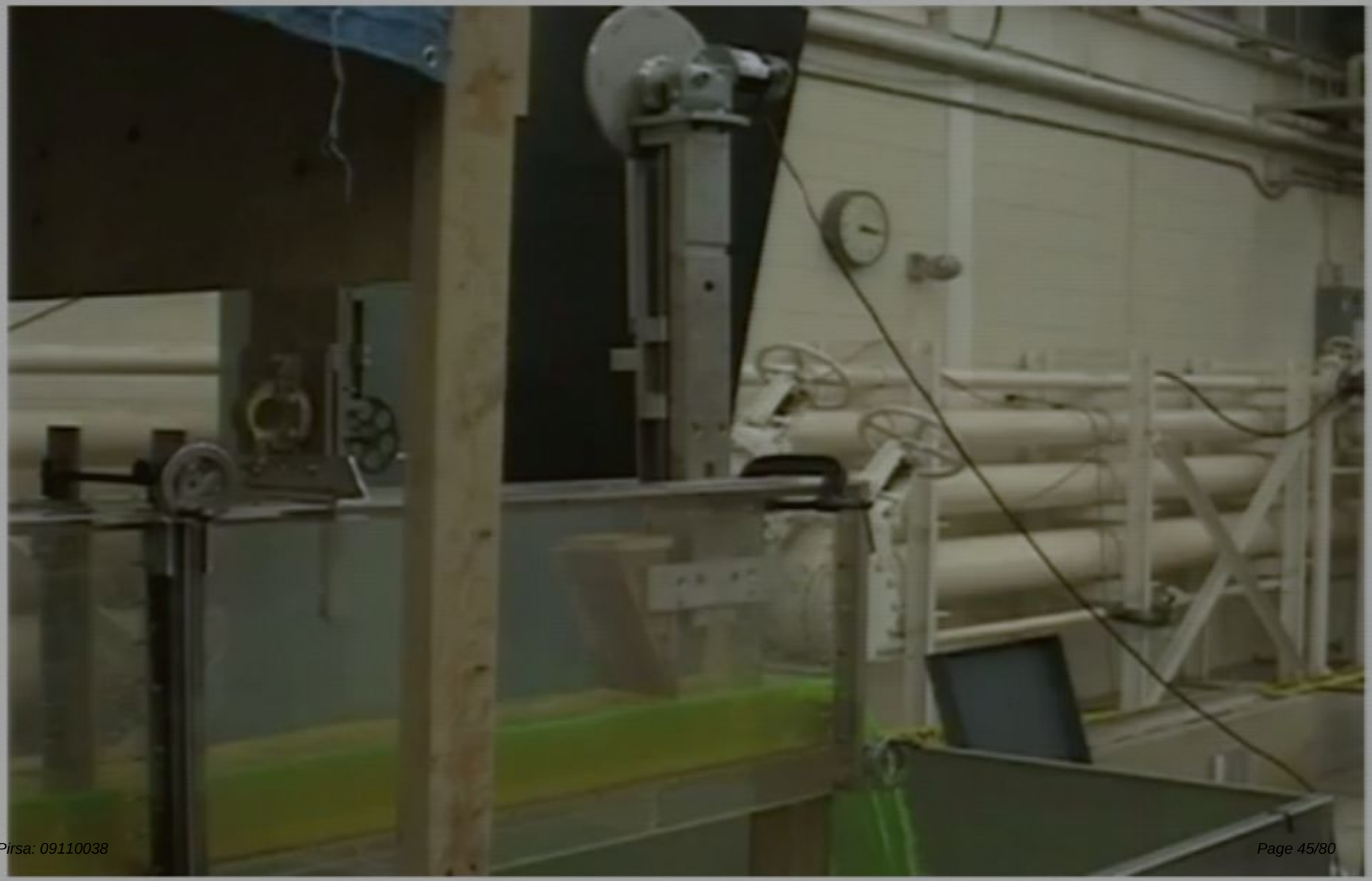


Some nice physics at the end (of our flume tank)



Claim: At the end of the flume tank, for a stationary flow, there sits a black hole horizon.

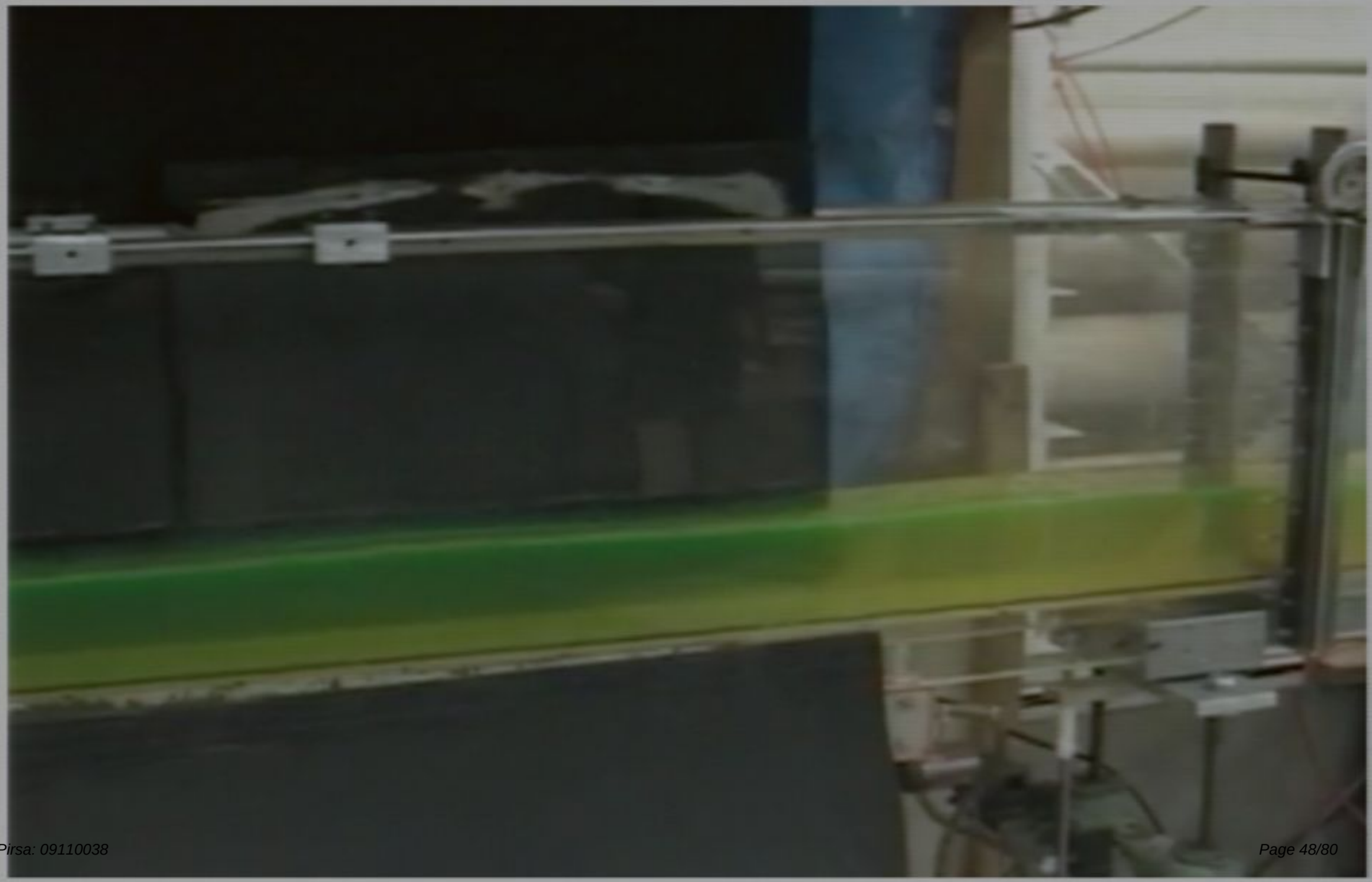
The experiment



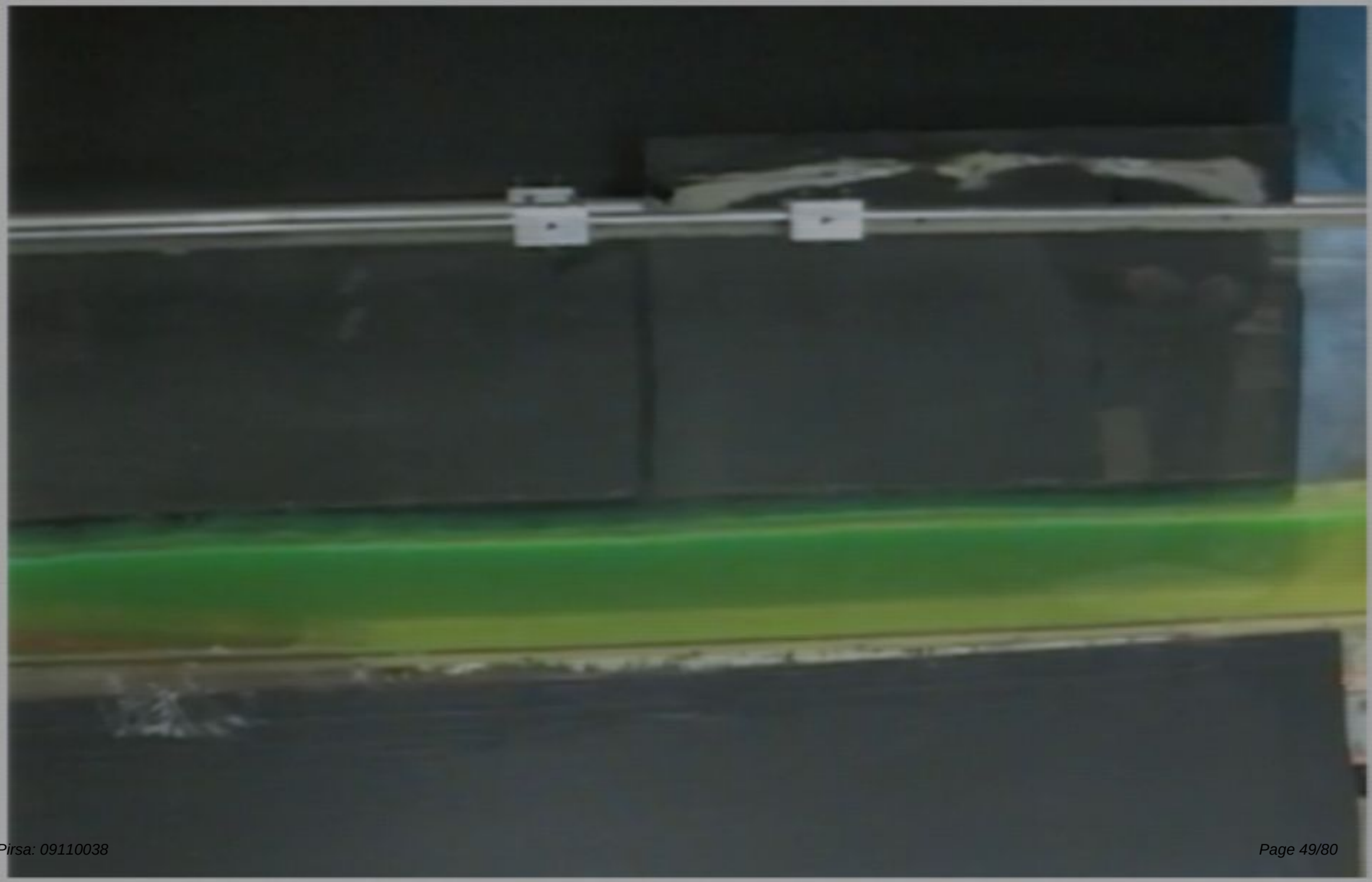
The experiment

The experiment

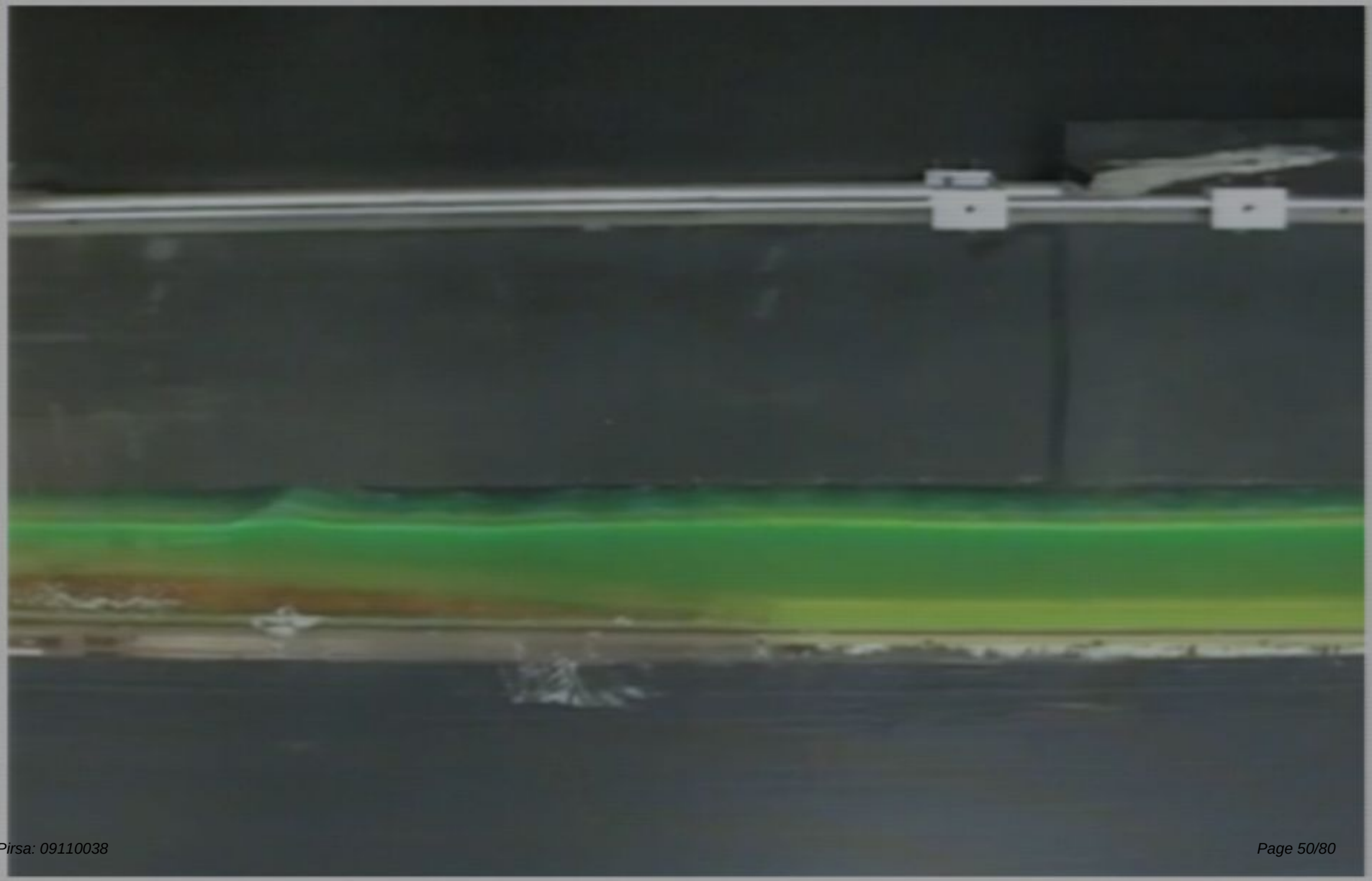
The experiment



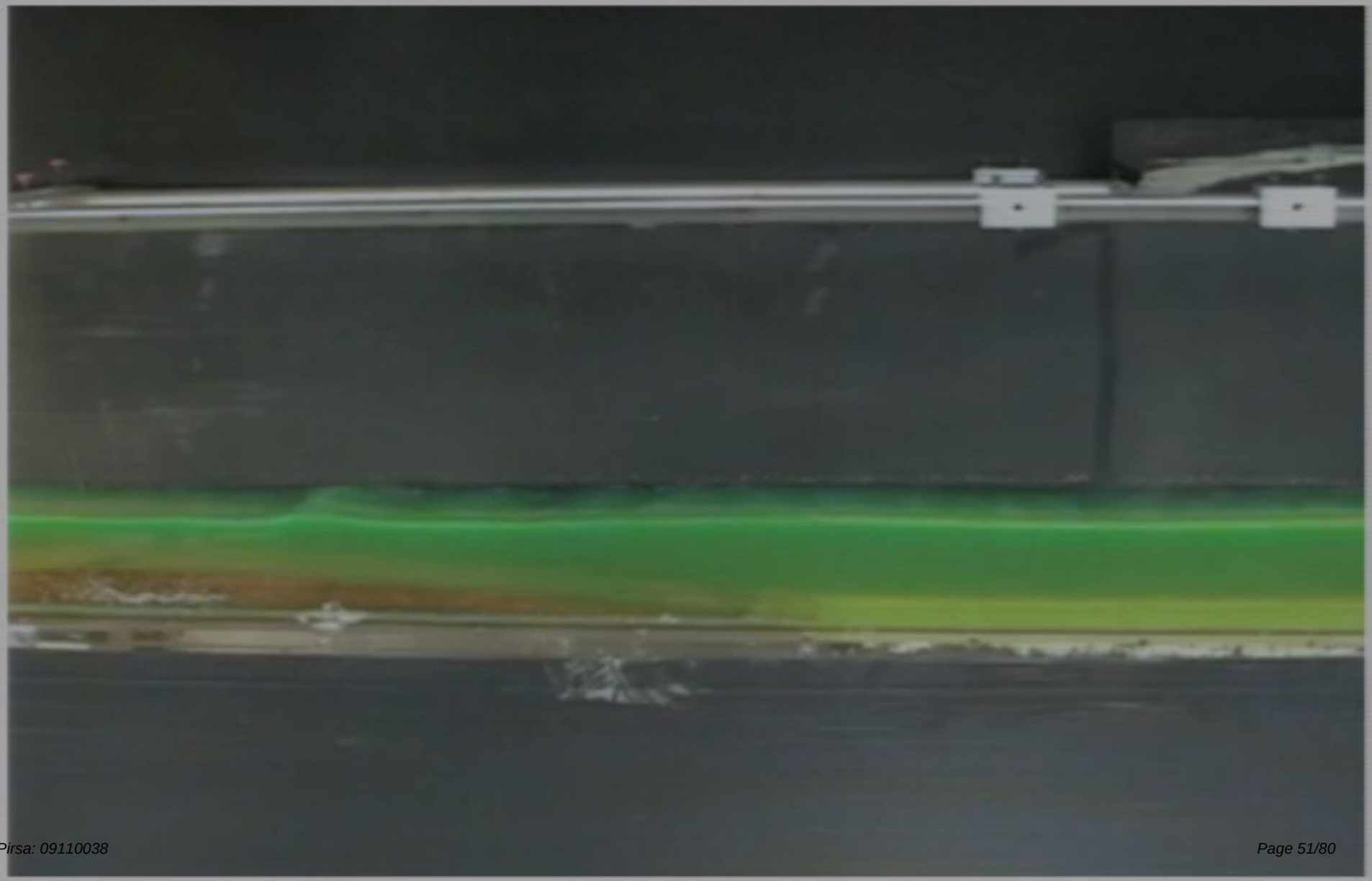
The experiment



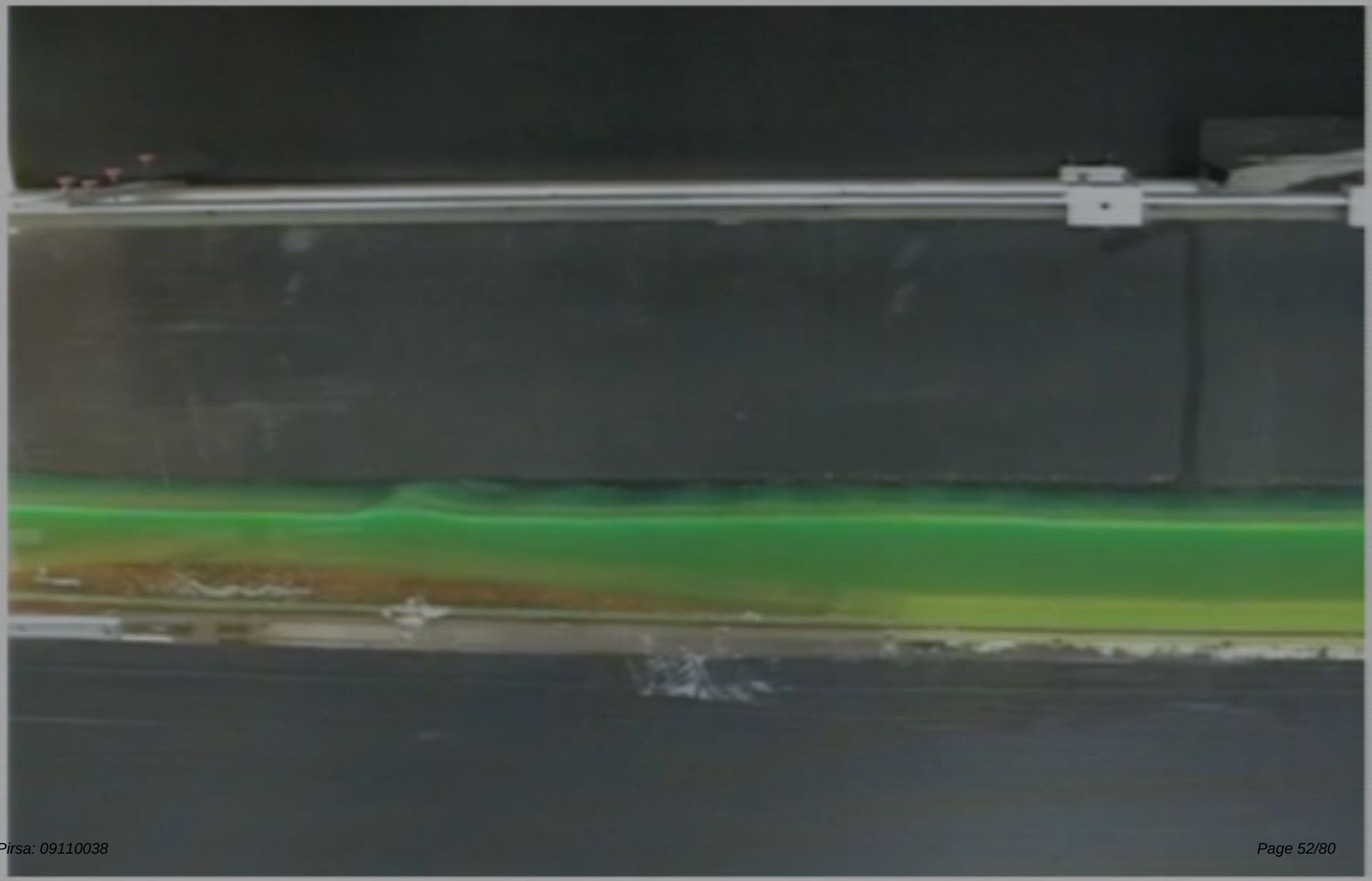
The experiment



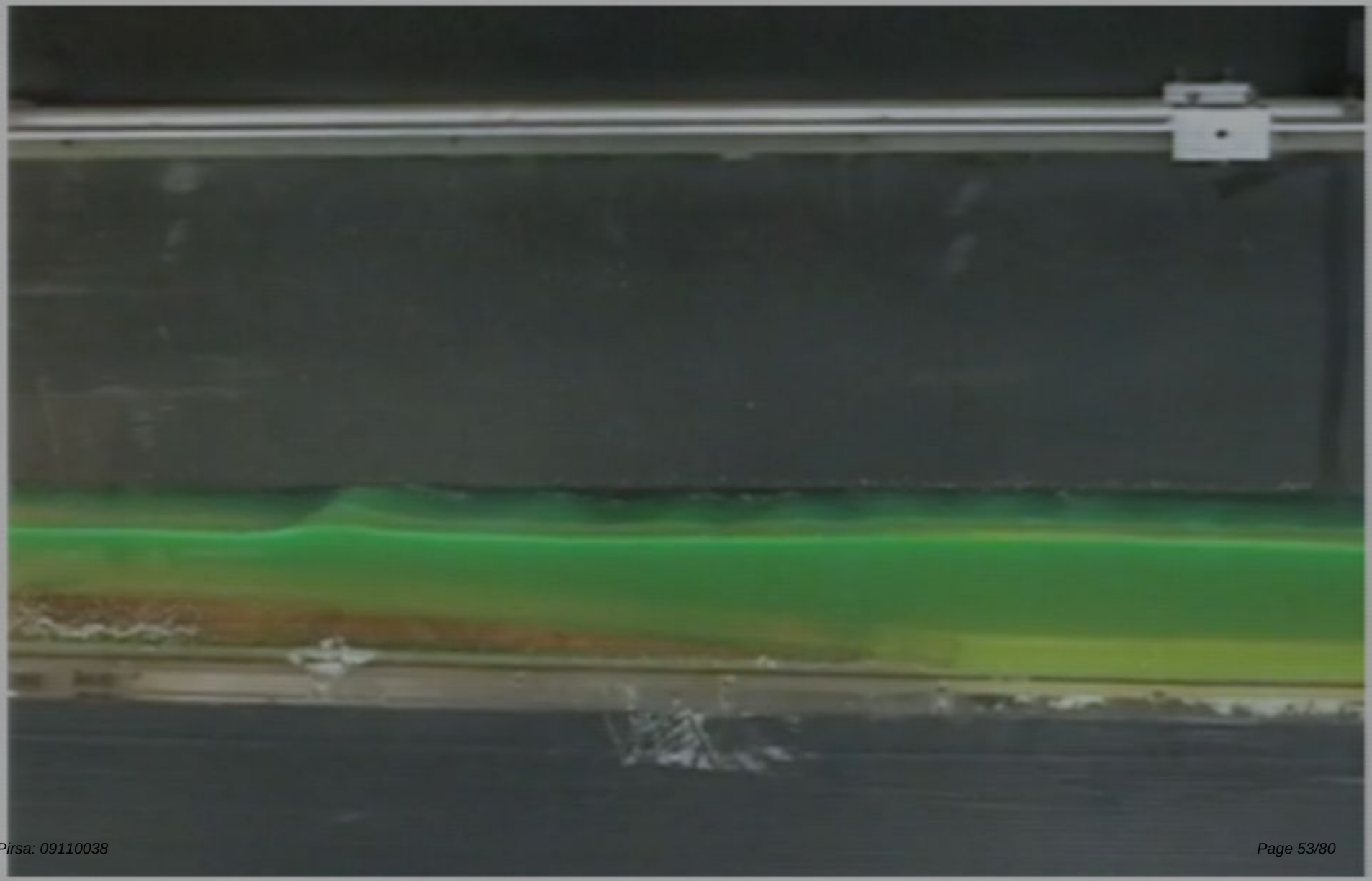
The experiment



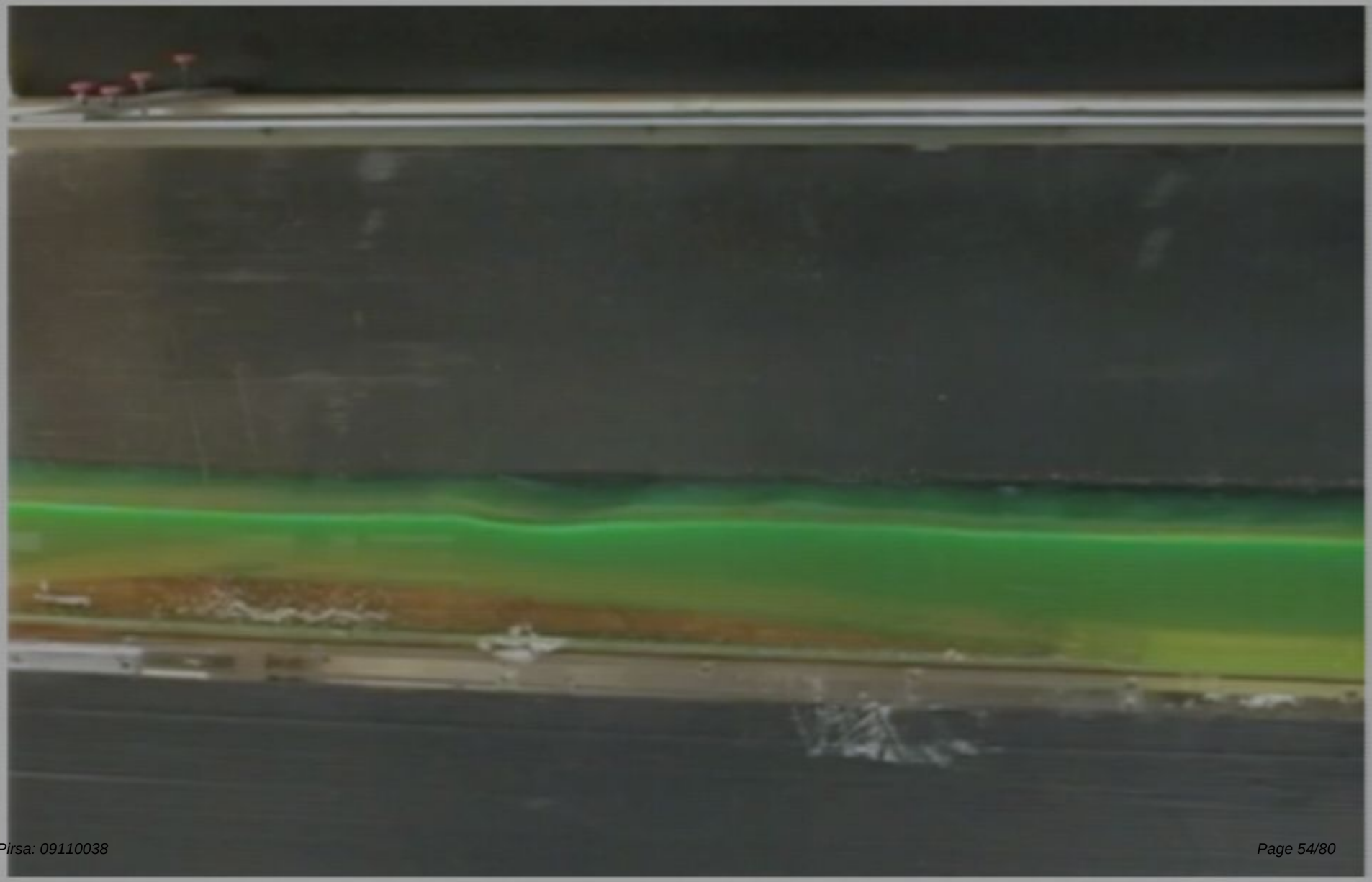
The experiment



The experiment



The experiment



What can we detect?

Adiabatic and non-adiabatic conversions effects:

- **shallow-deep(-capillary)** at White Hole
- negative frequency (non-adiabatic); or classical equivalent of black hole evaporation process
- deep-shallow at Black Hole horizon

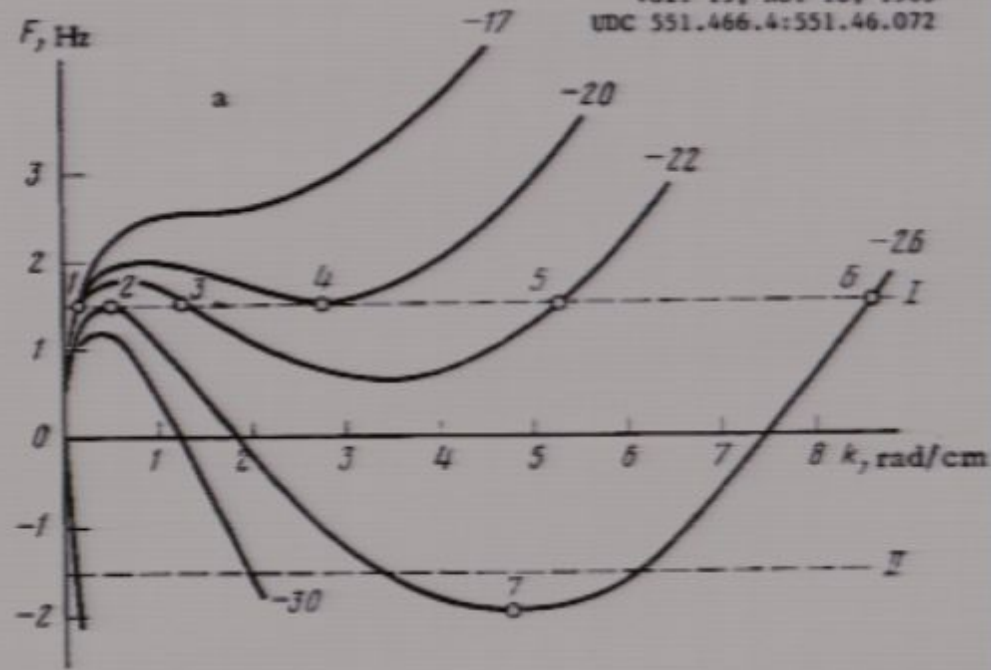
Dispersion Relation (adiabatic conversion)

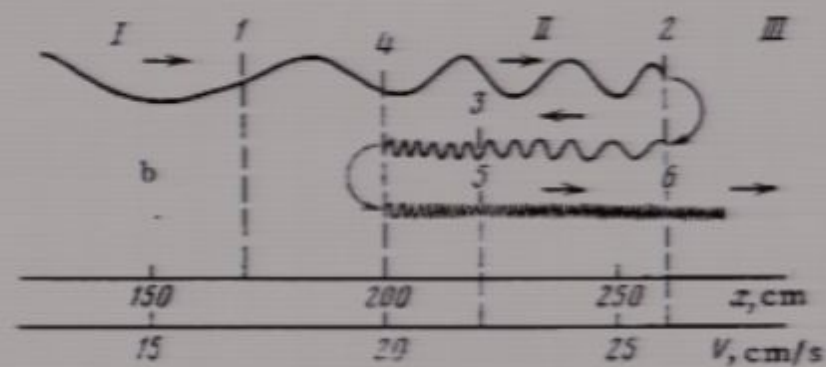
A Laboratory Study of the Transformation of Regular Gravity–Capillary Waves on Inhomogeneous Flows

Vol. 19, No. 10, 1983
UDC 551.466.4:551.46.072

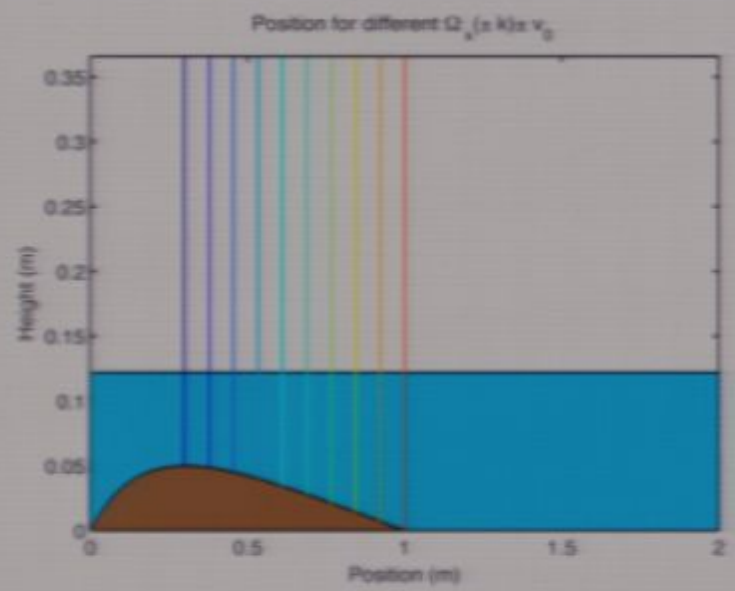
S. I. BADULIN, K. V. POKAZEYEV AND A. D. ROZENBERG

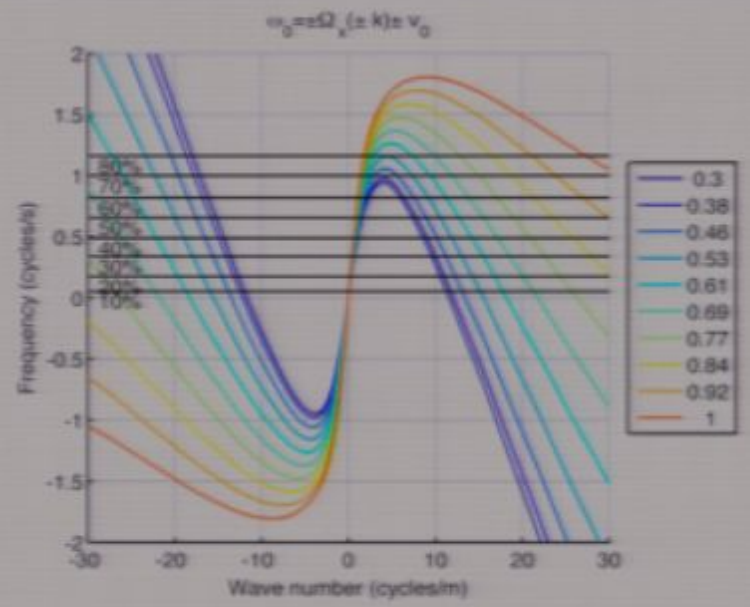
Moscow State University;
Institute of Oceanology, USSR Academy of Sciences

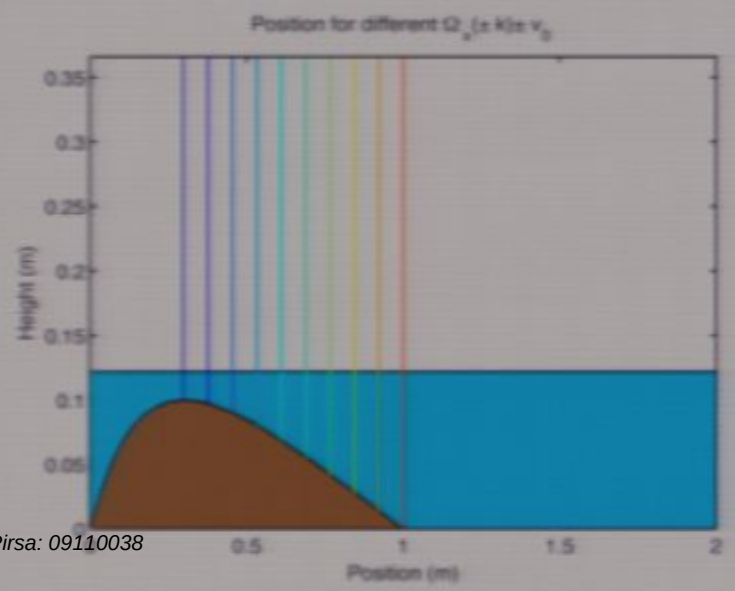


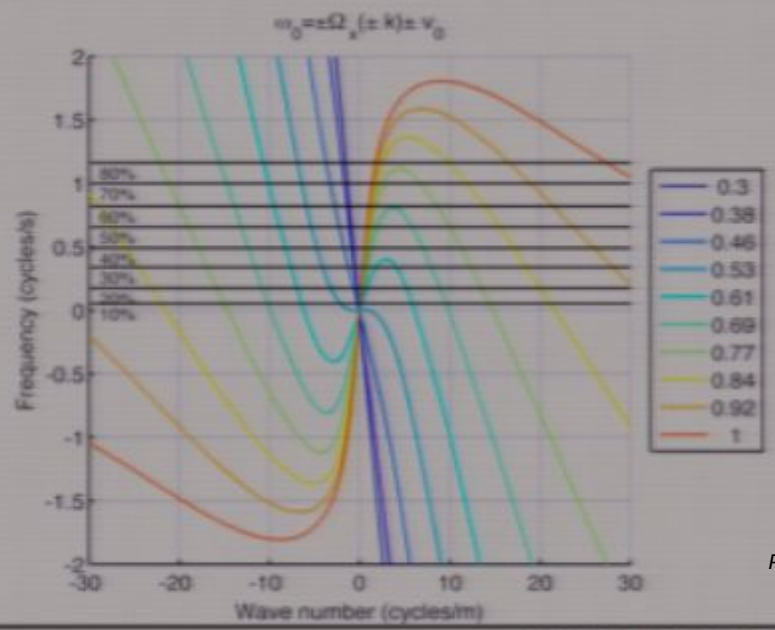


How to design our experiments!

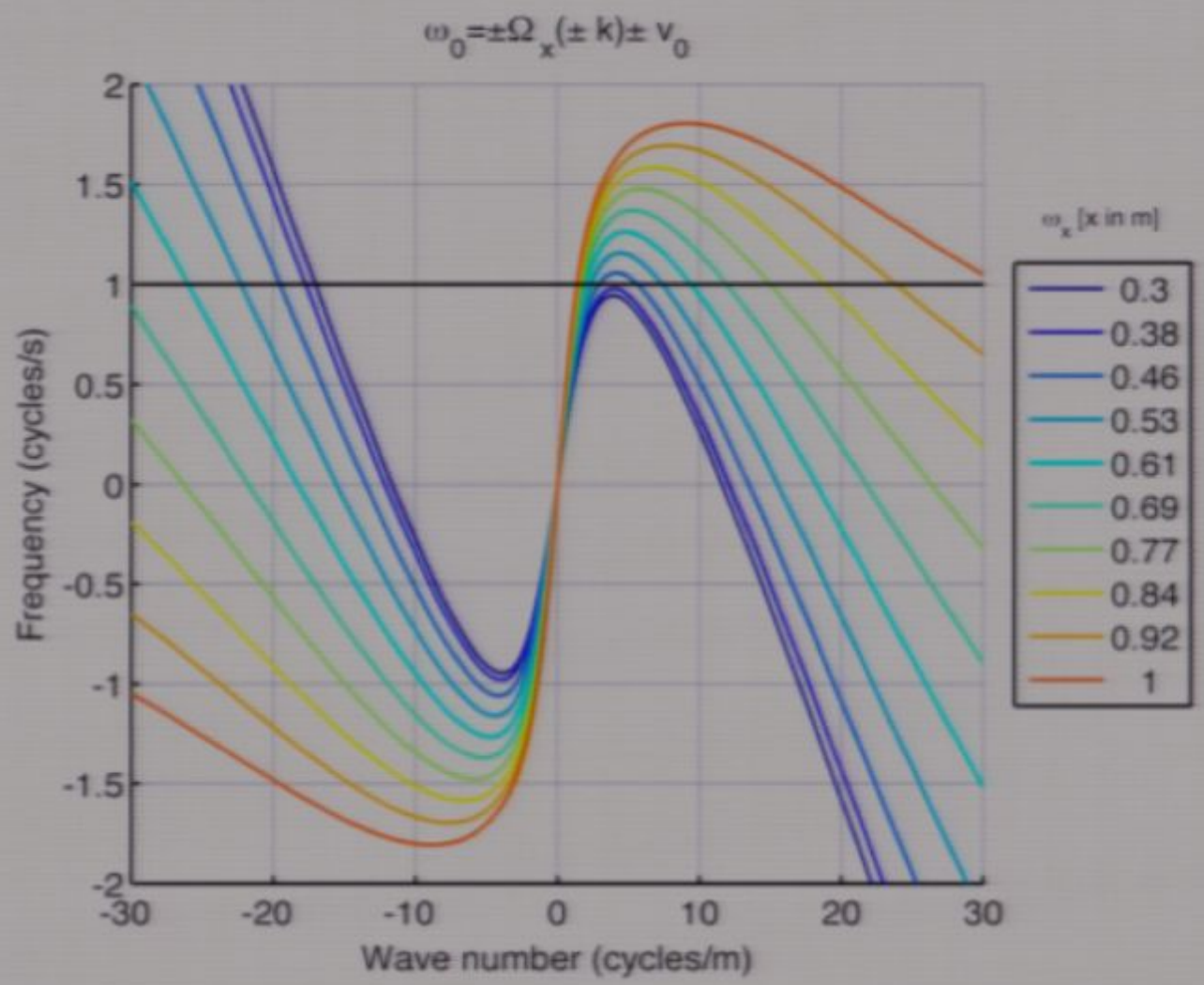


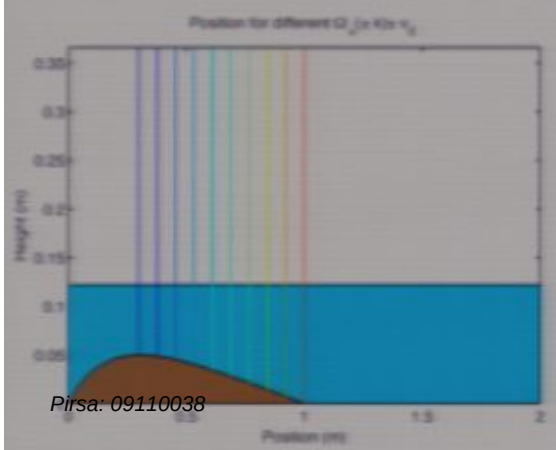




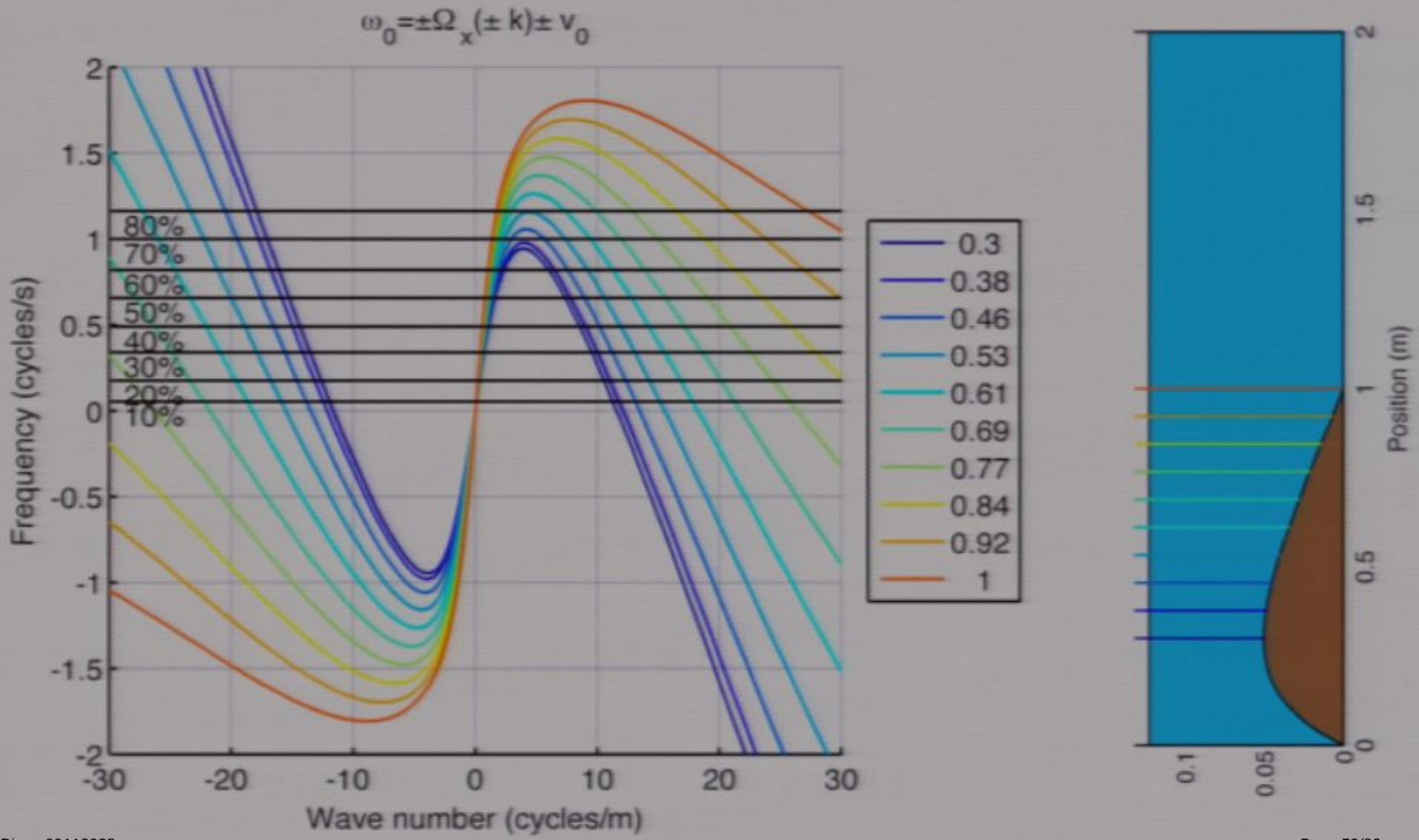


Dispersion Relation for Surface Waves (flume tank)

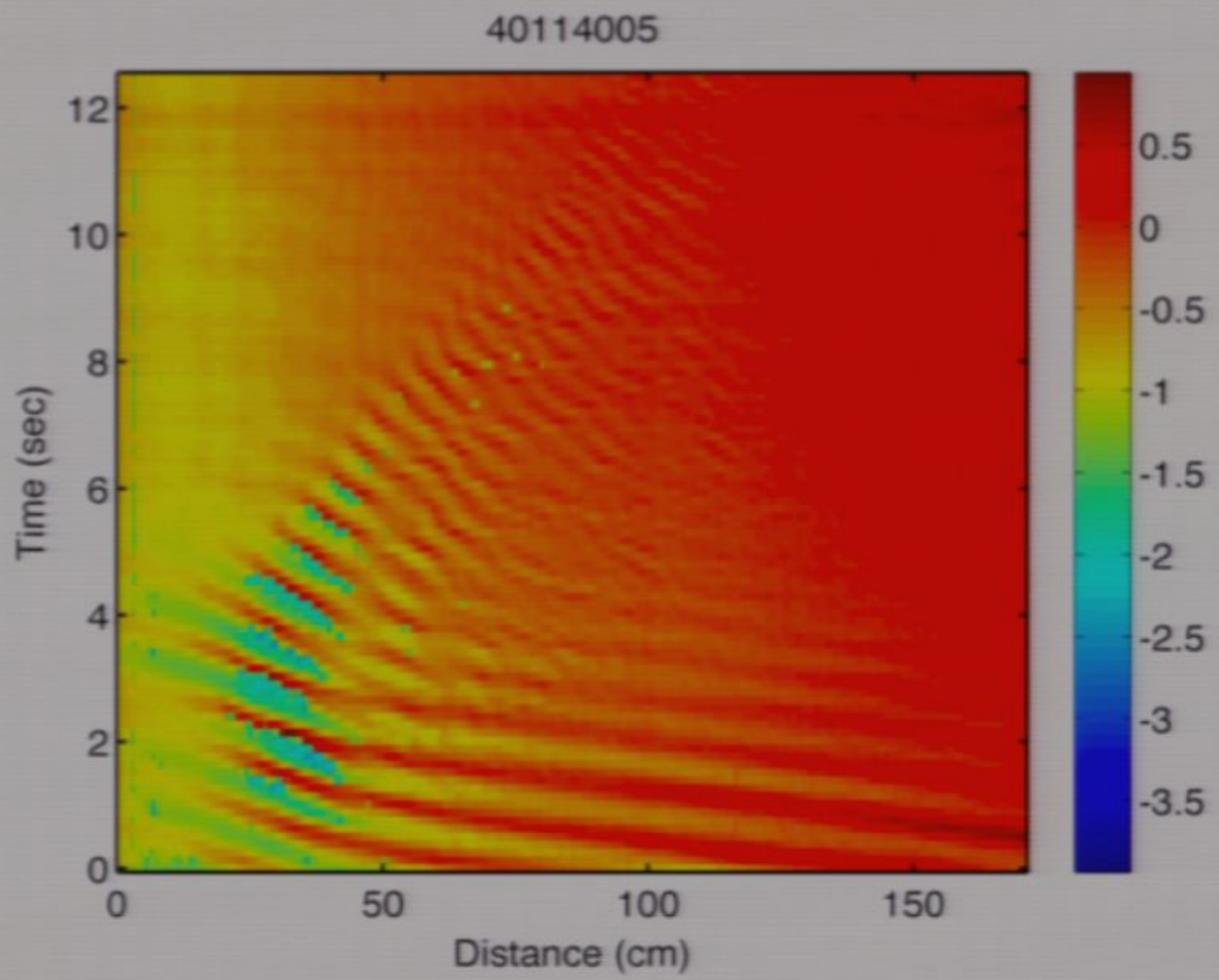




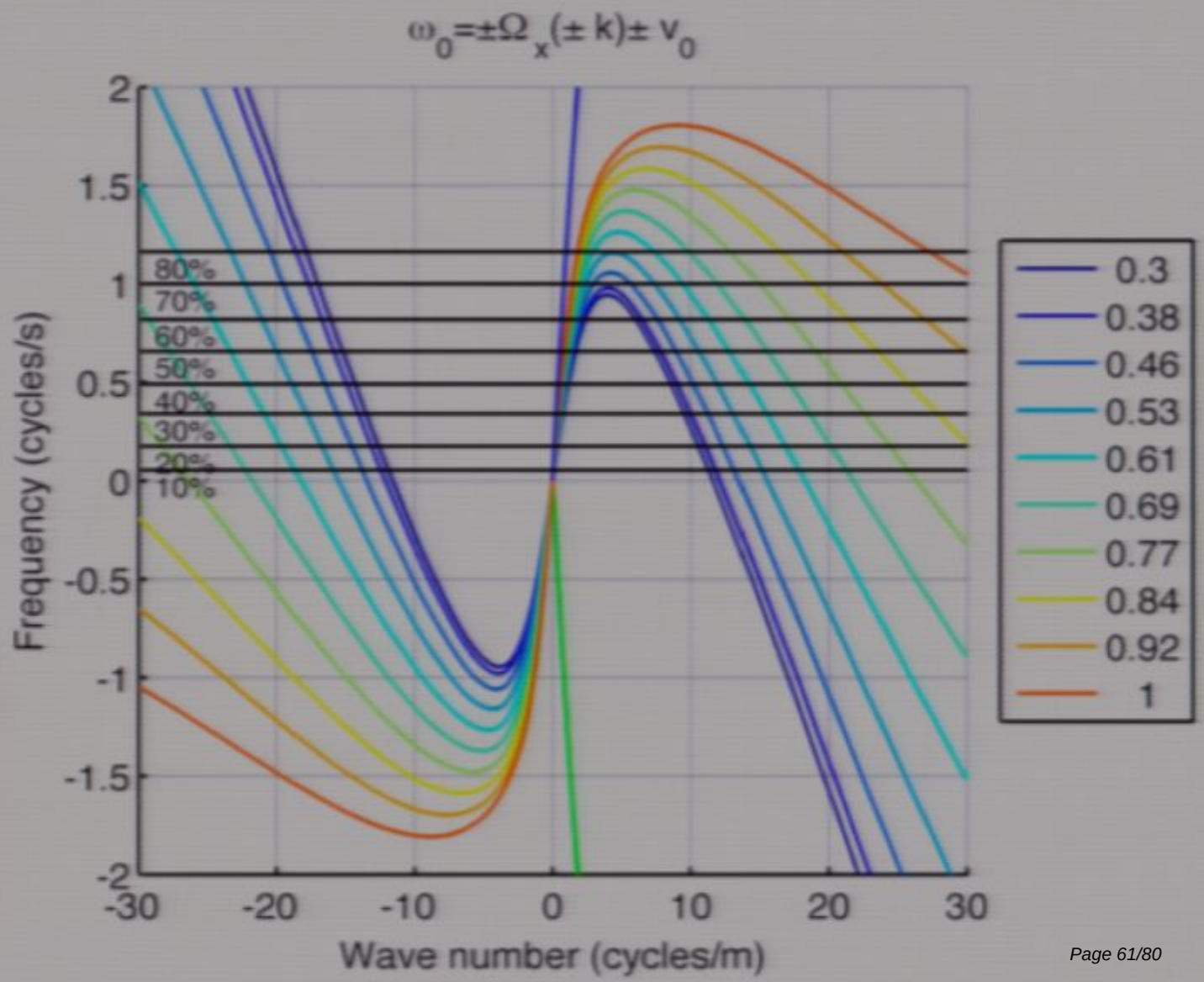
Adiabatic processes ✔

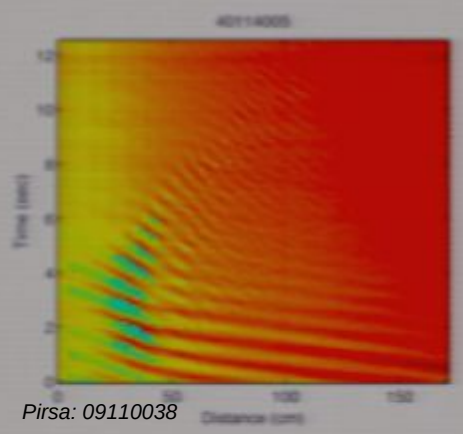


Wave generator on 70% - 5 bursts

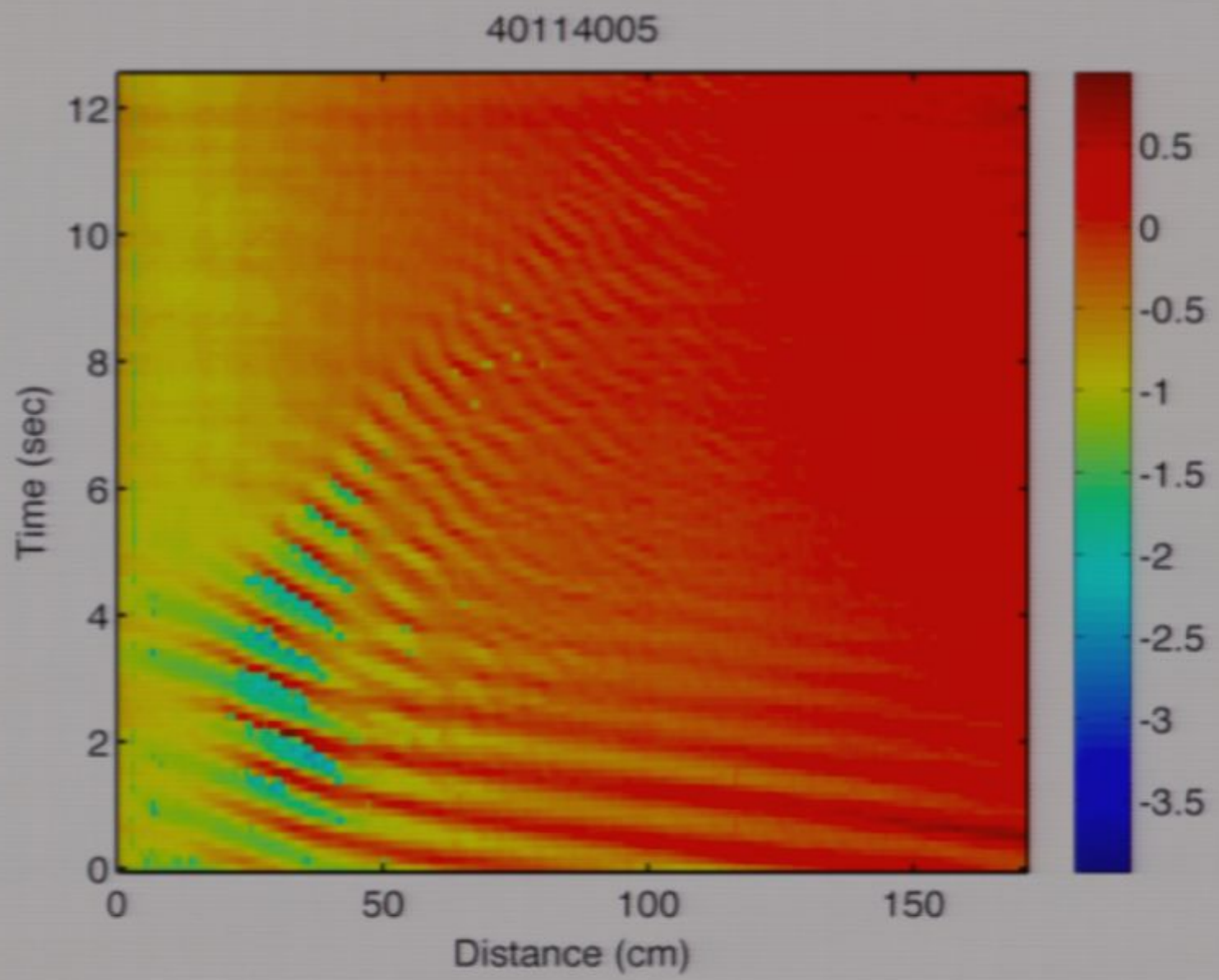


Wave generator on 70% - 5 bursts

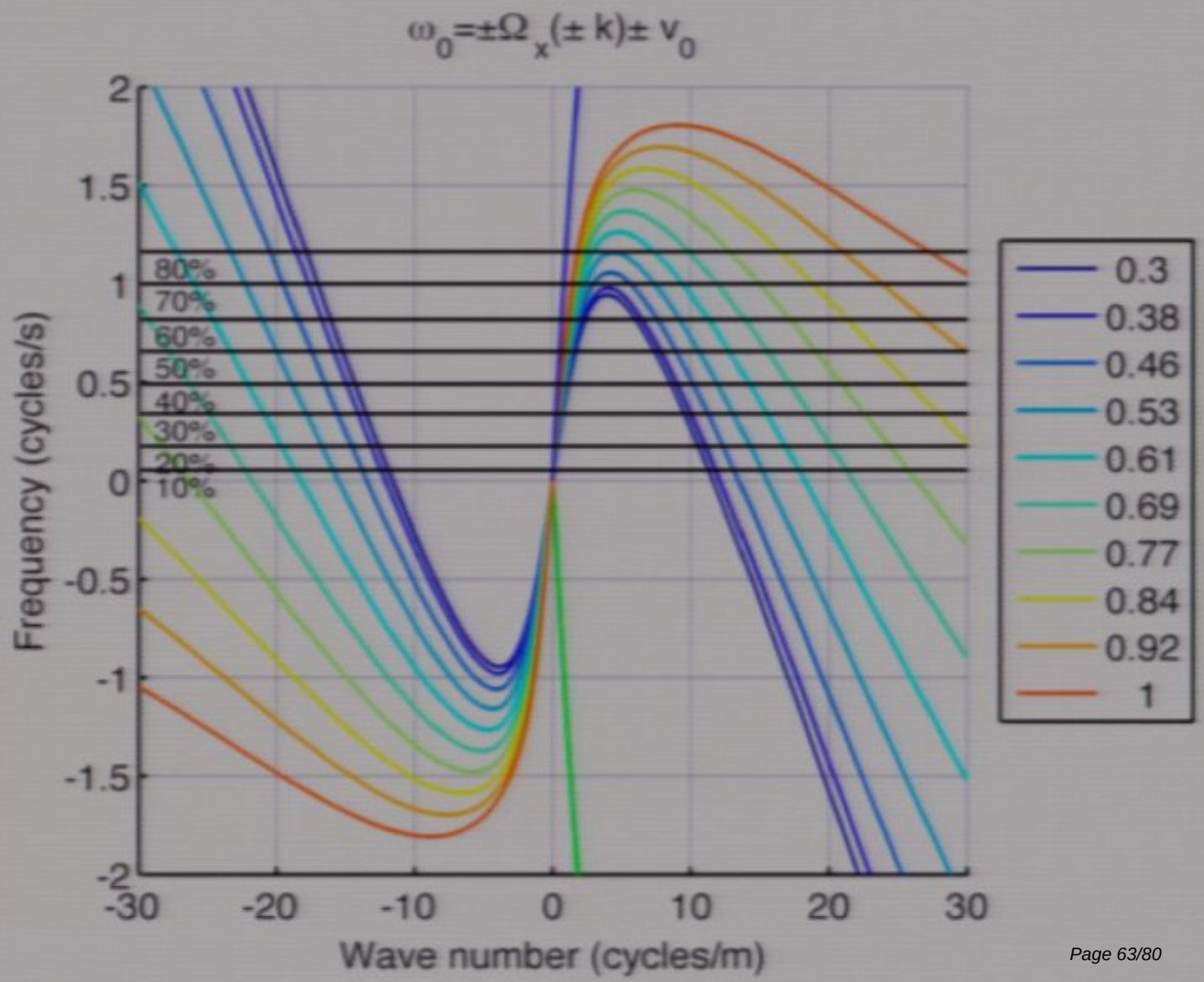


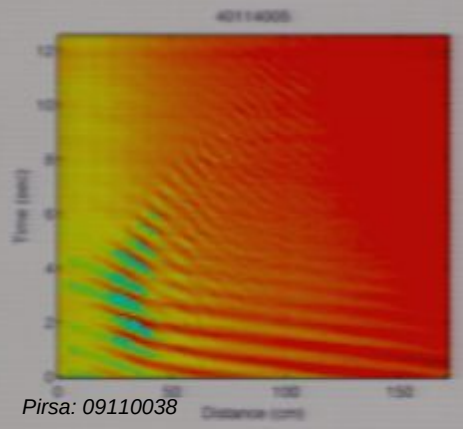


Wave generator on 70% - 5 bursts

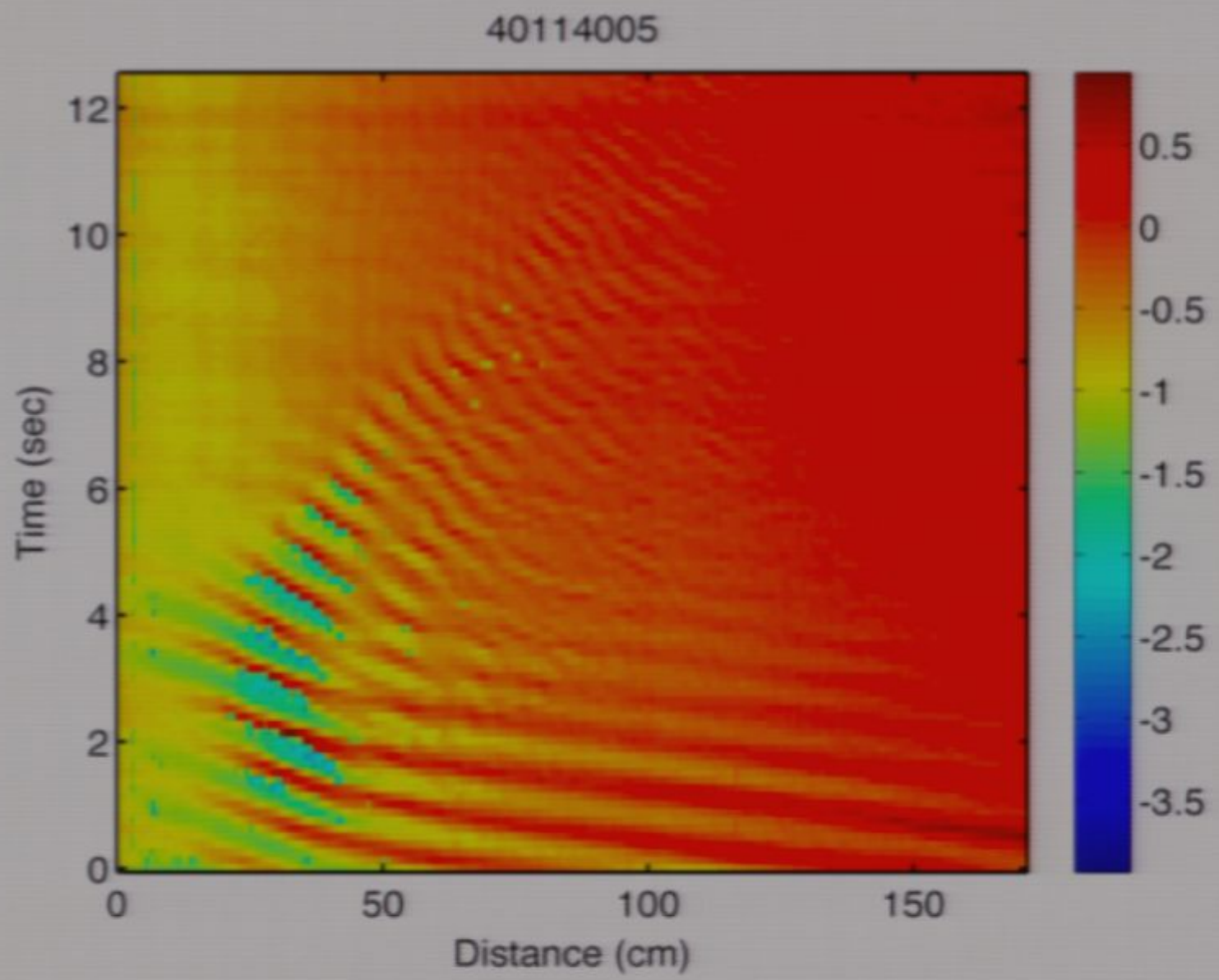


Wave generator on 70% - 5 bursts

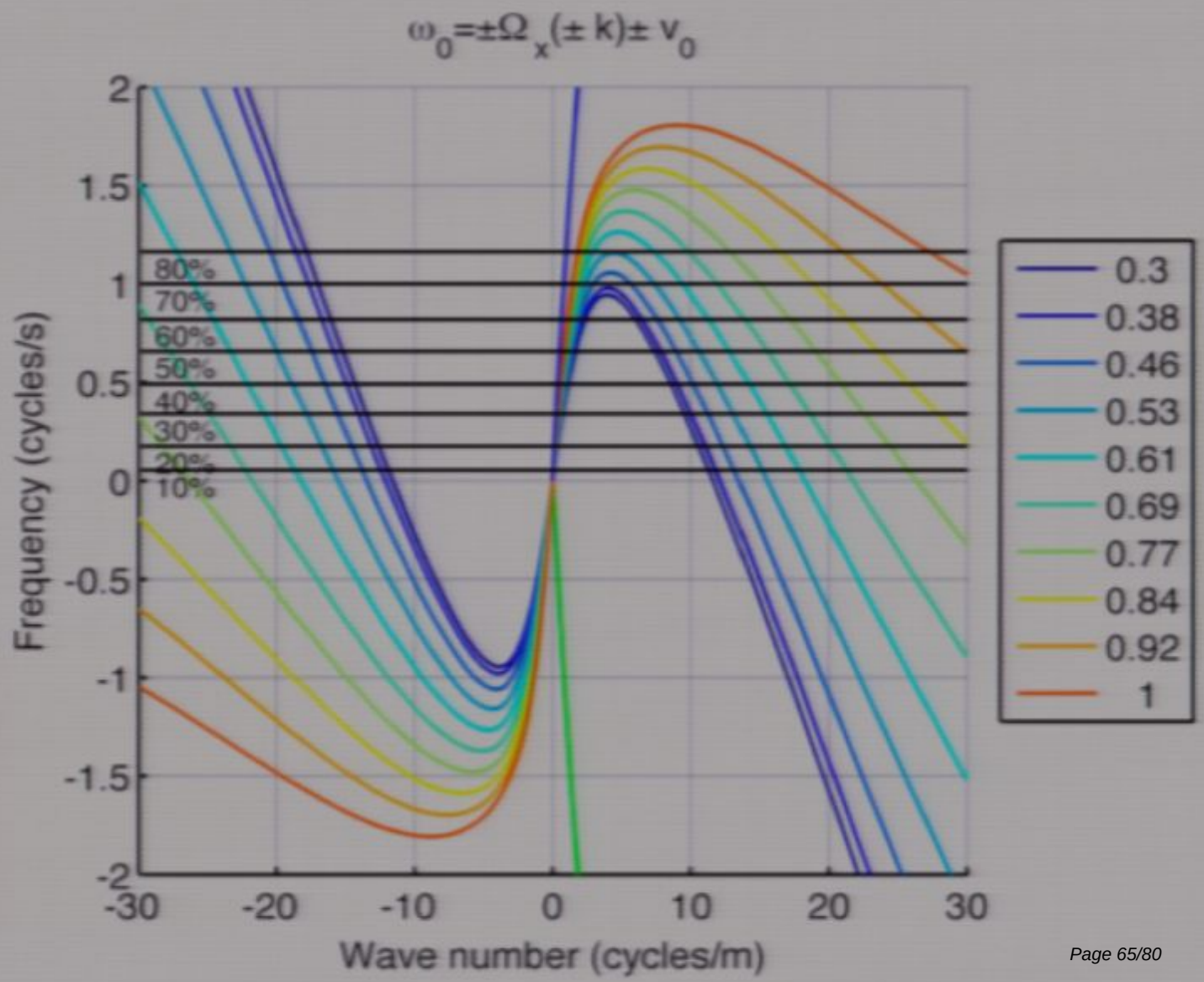


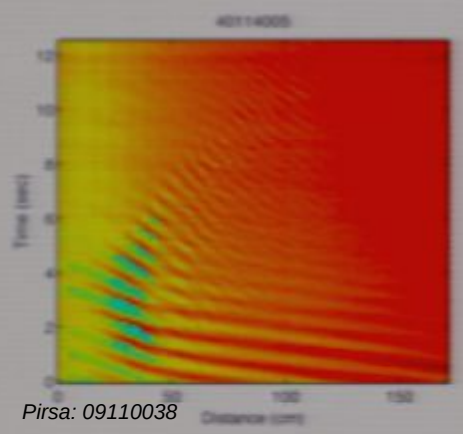


Wave generator on 70% - 5 bursts

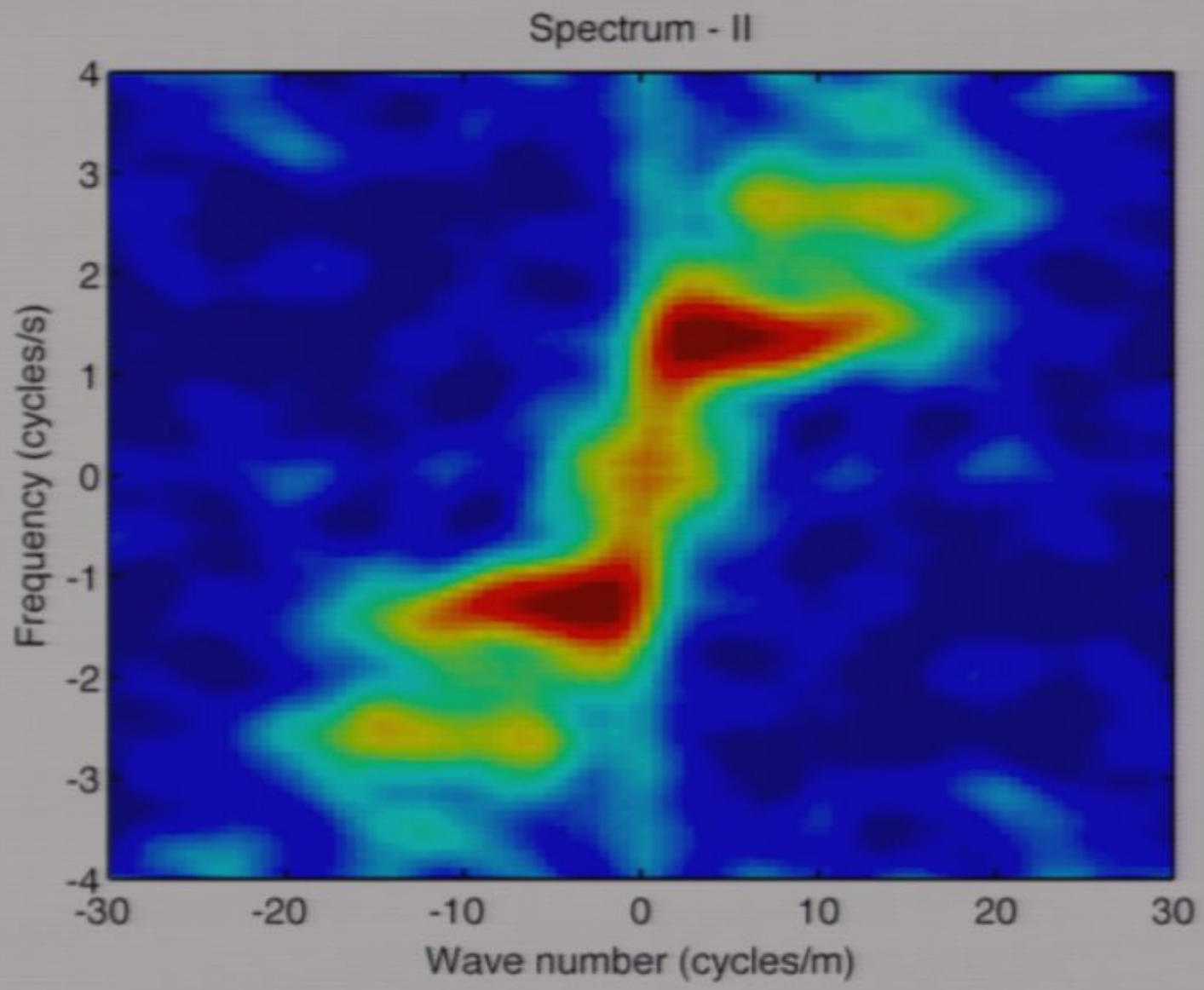


Wave generator on 70% - 5 bursts

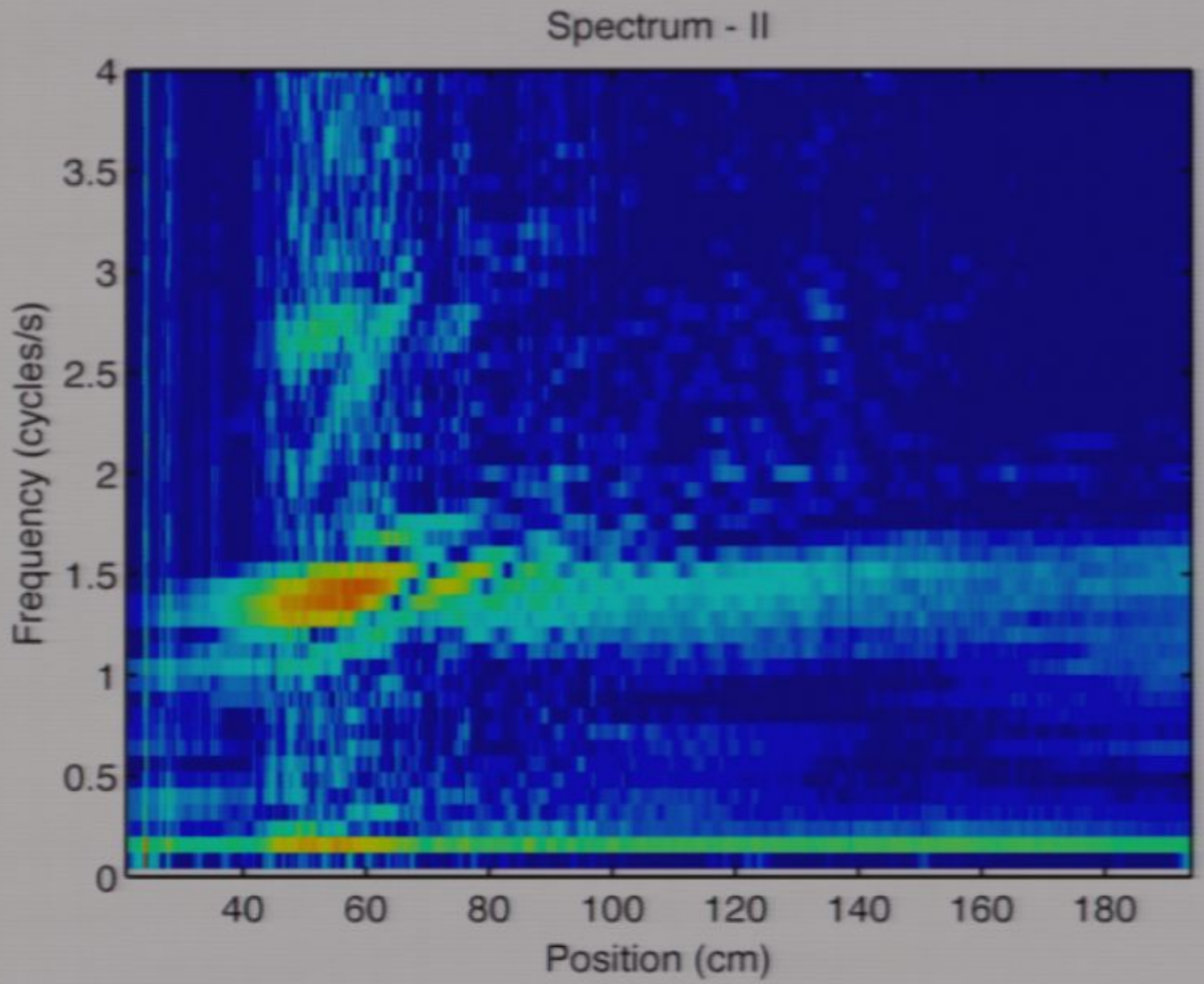




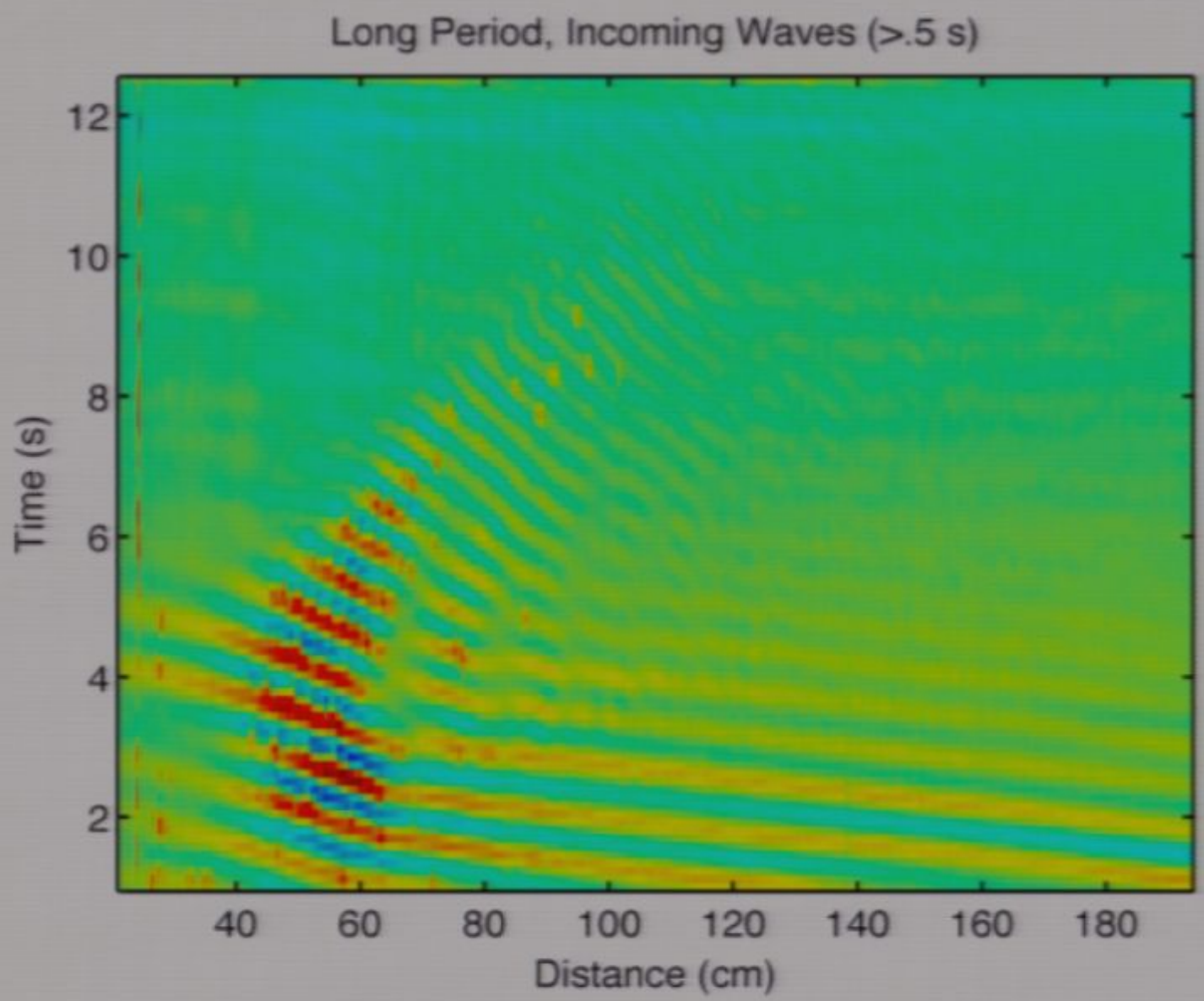
Wave generator on 70% - 5 bursts



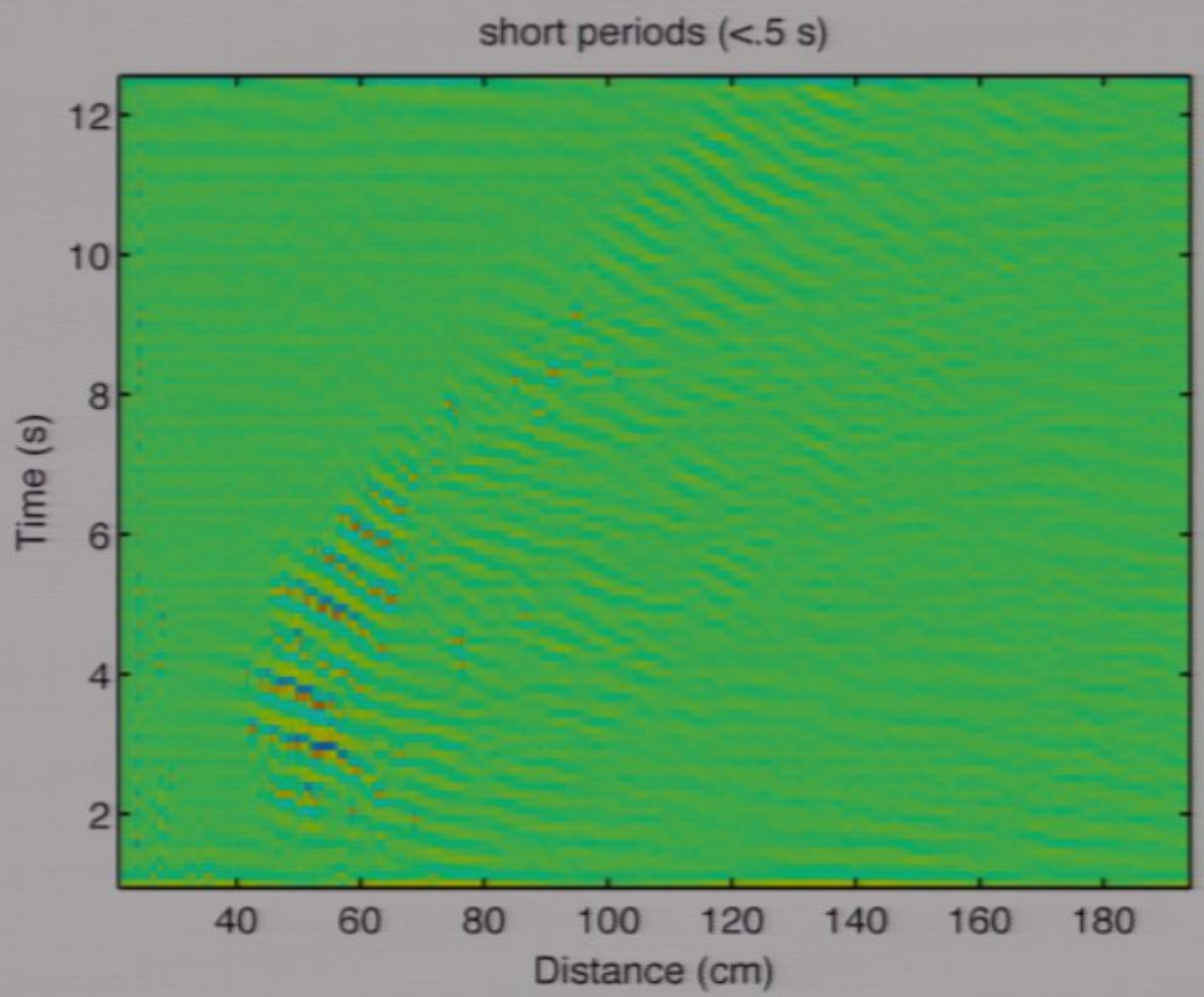
Wave generator on 70% - 5 bursts



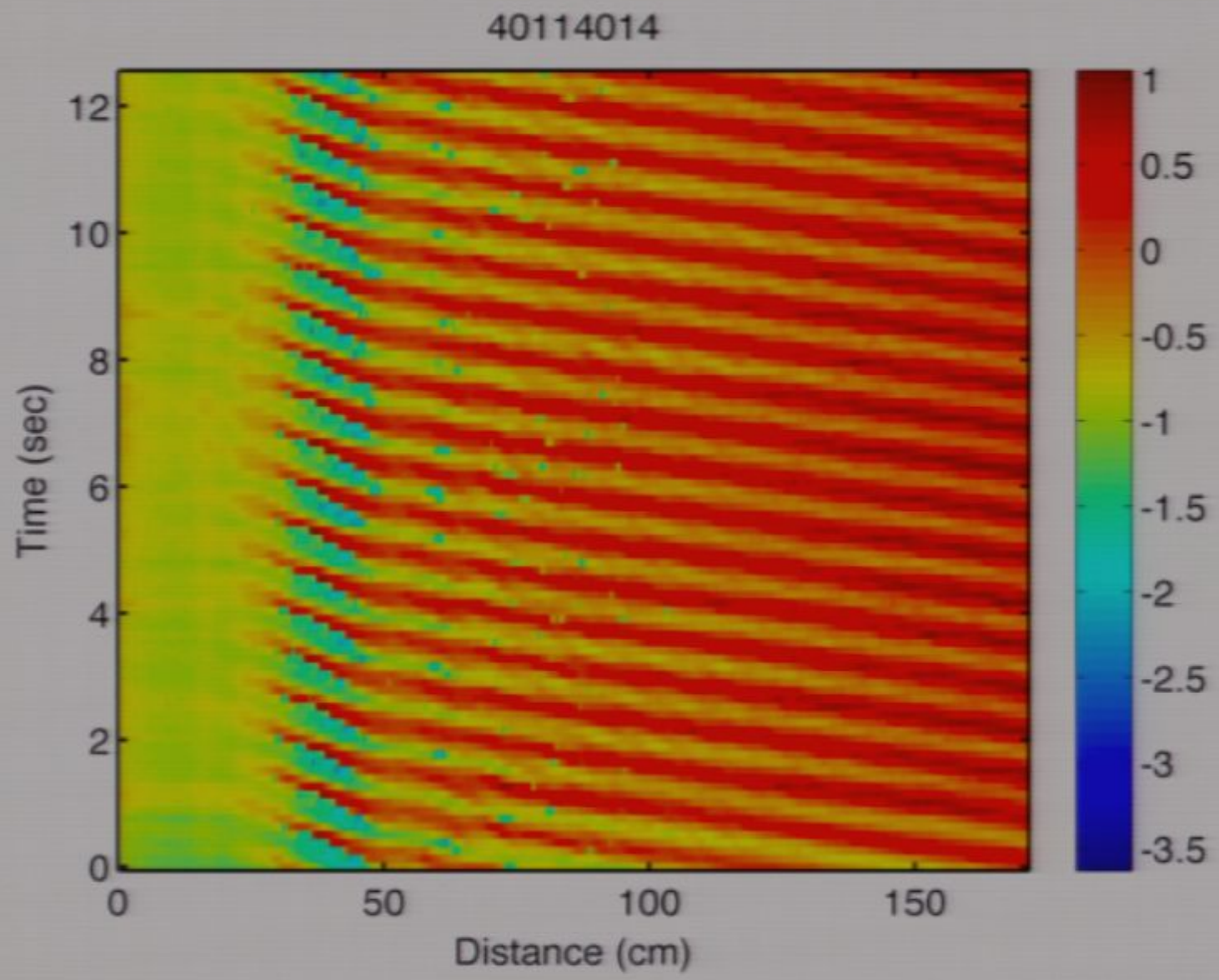
Wave generator on 70% - 5 bursts



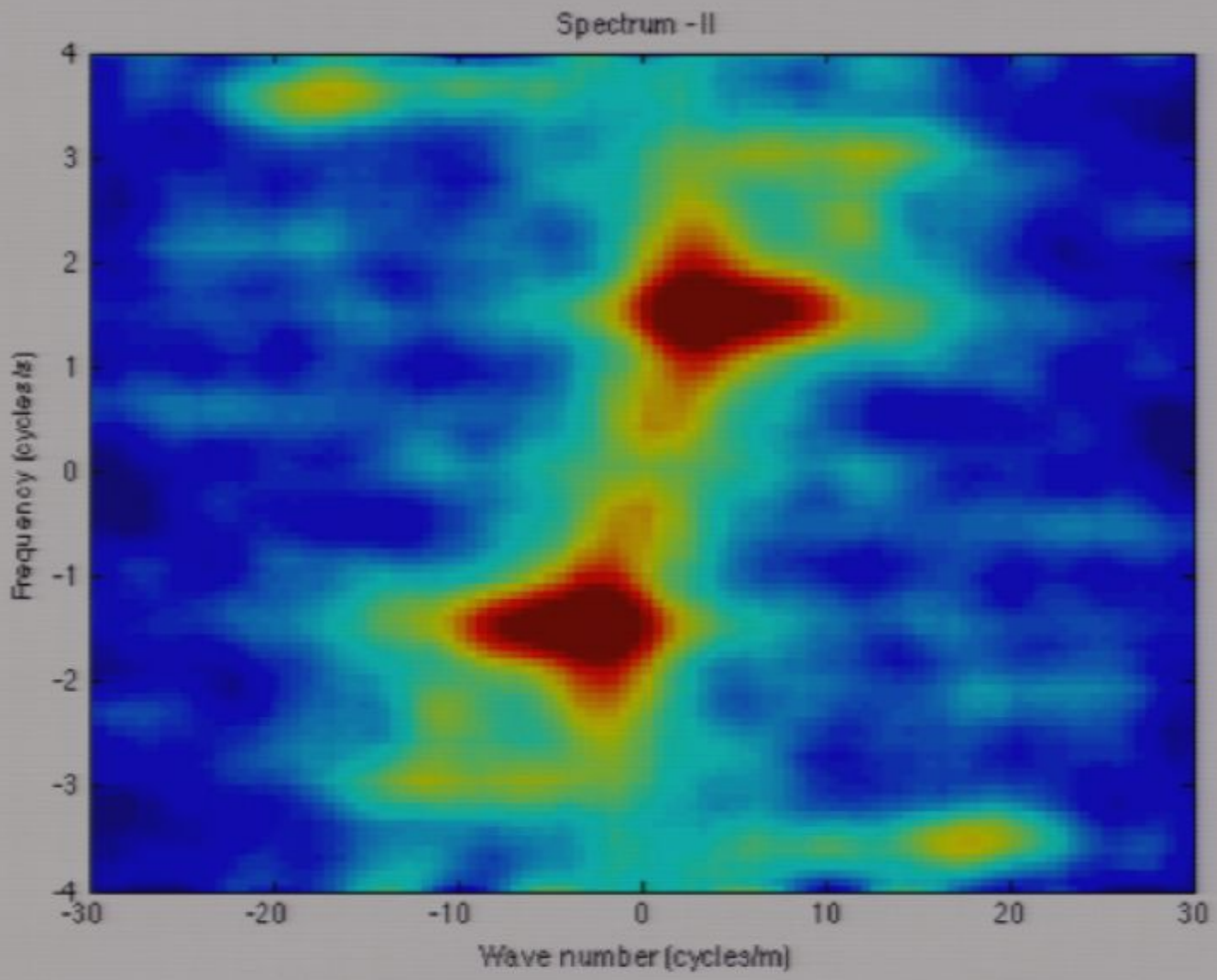
Wave generator on 70% - 5 bursts



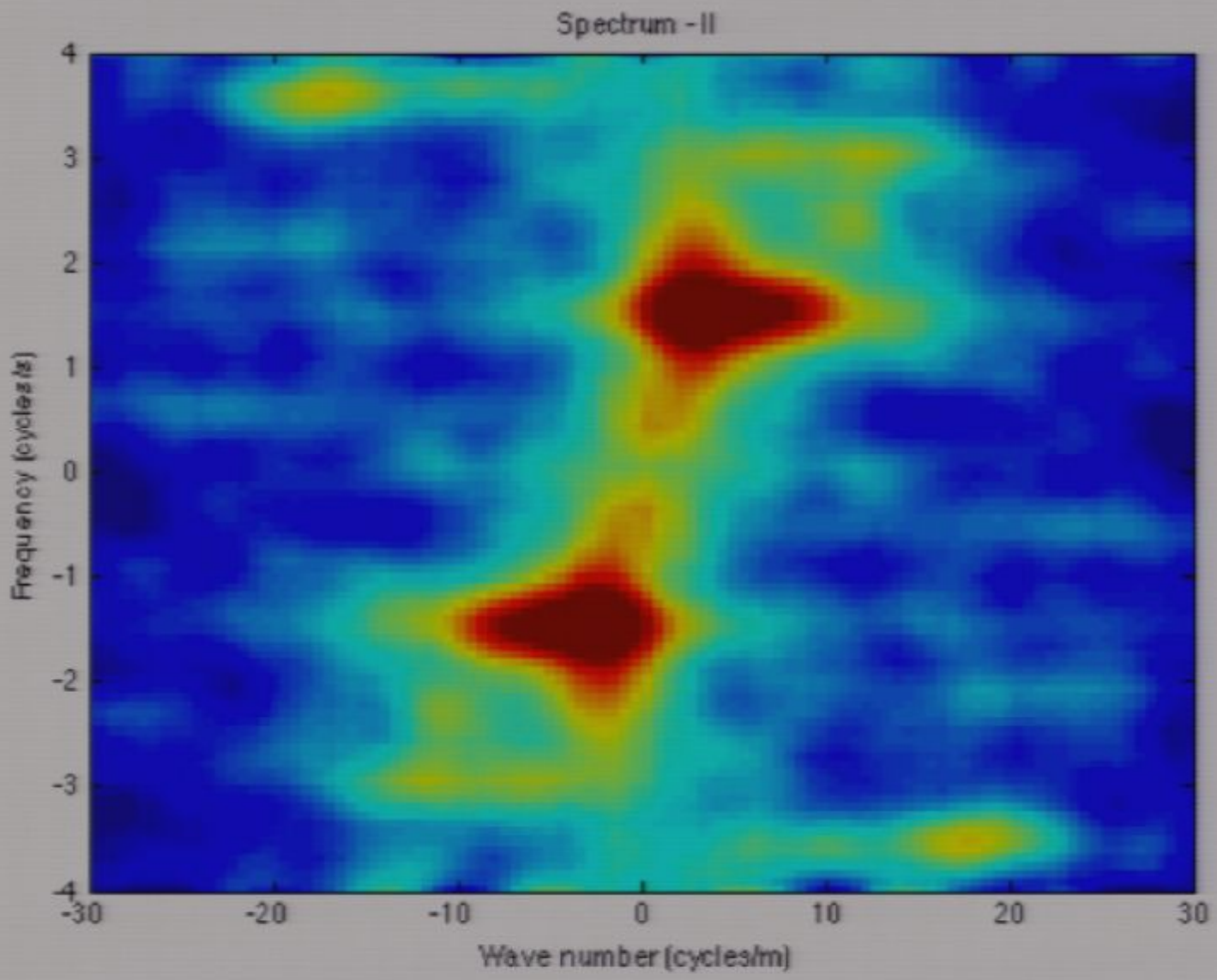
Wave generator on 80% - continuos bursts



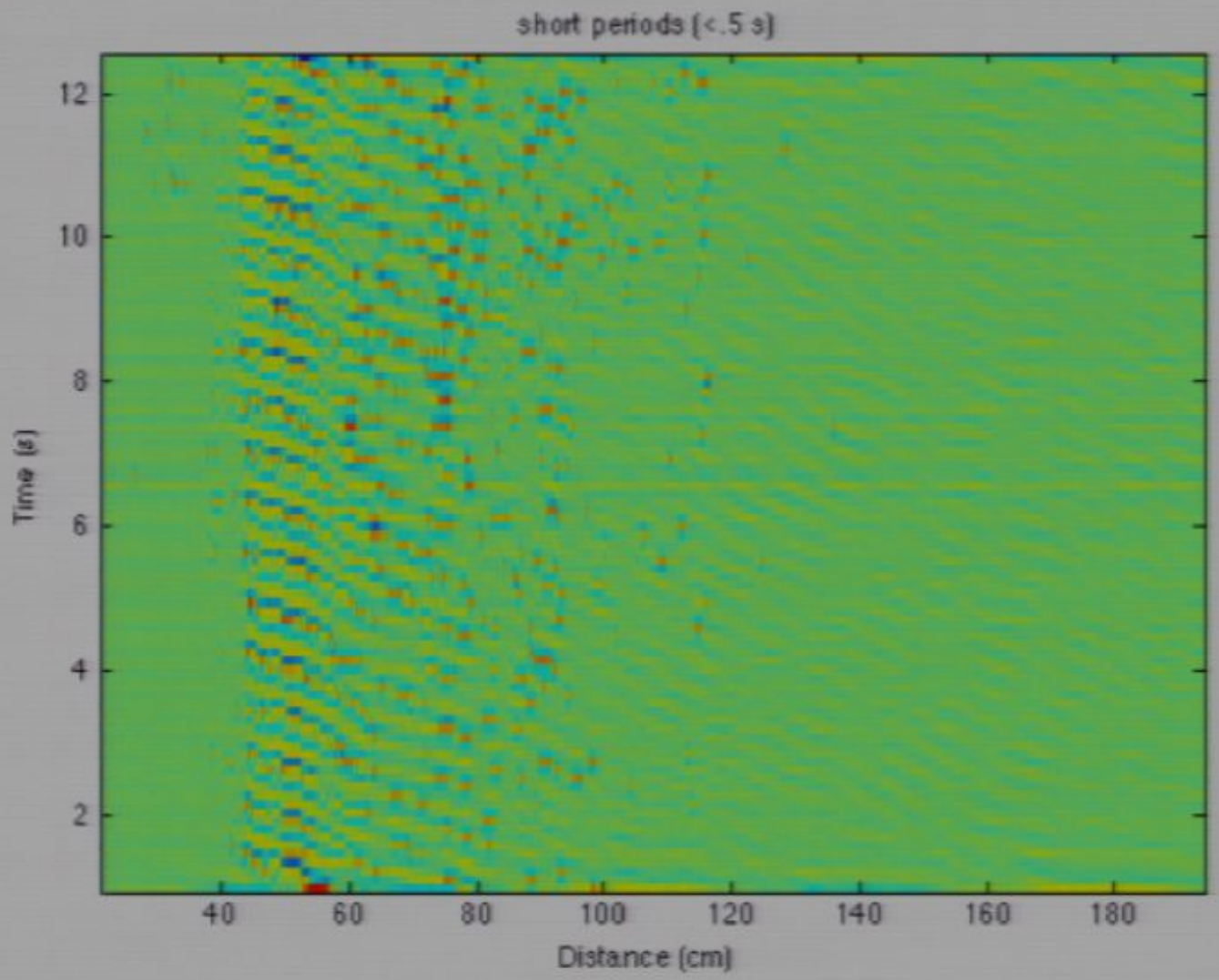
Wave generator on 80% - continuos bursts



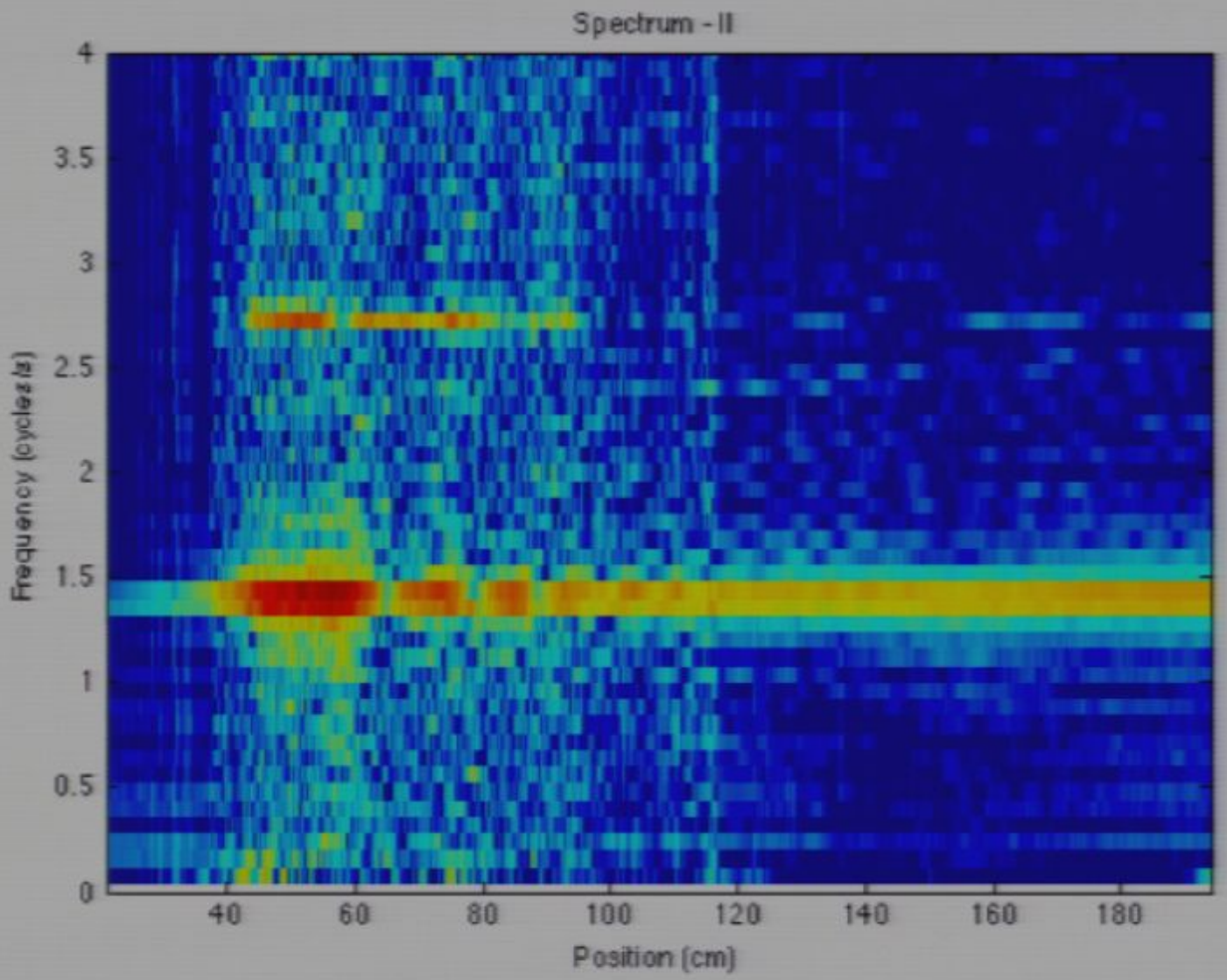
Wave generator on 80% - continuos bursts



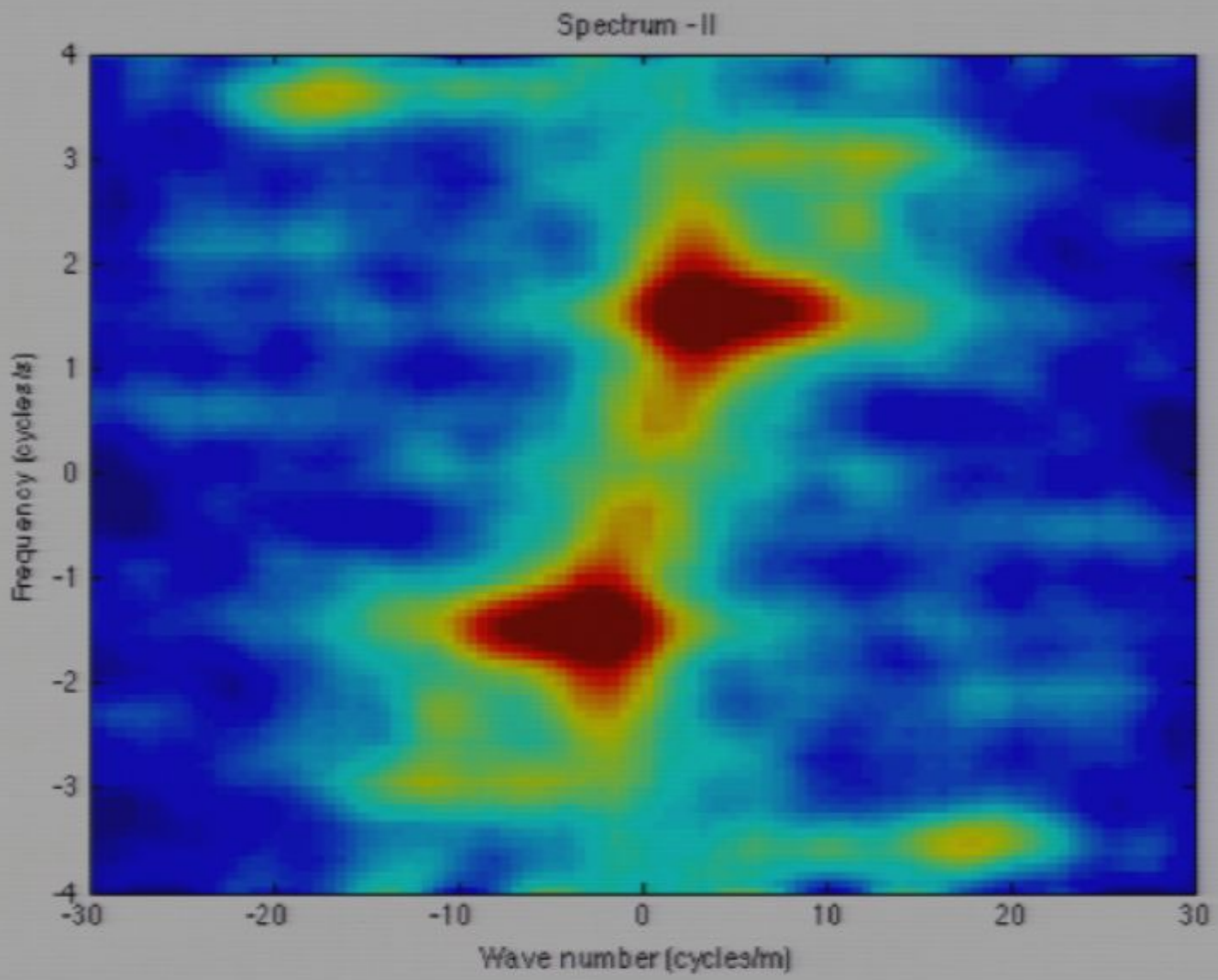
Wave generator on 80% - continuos bursts



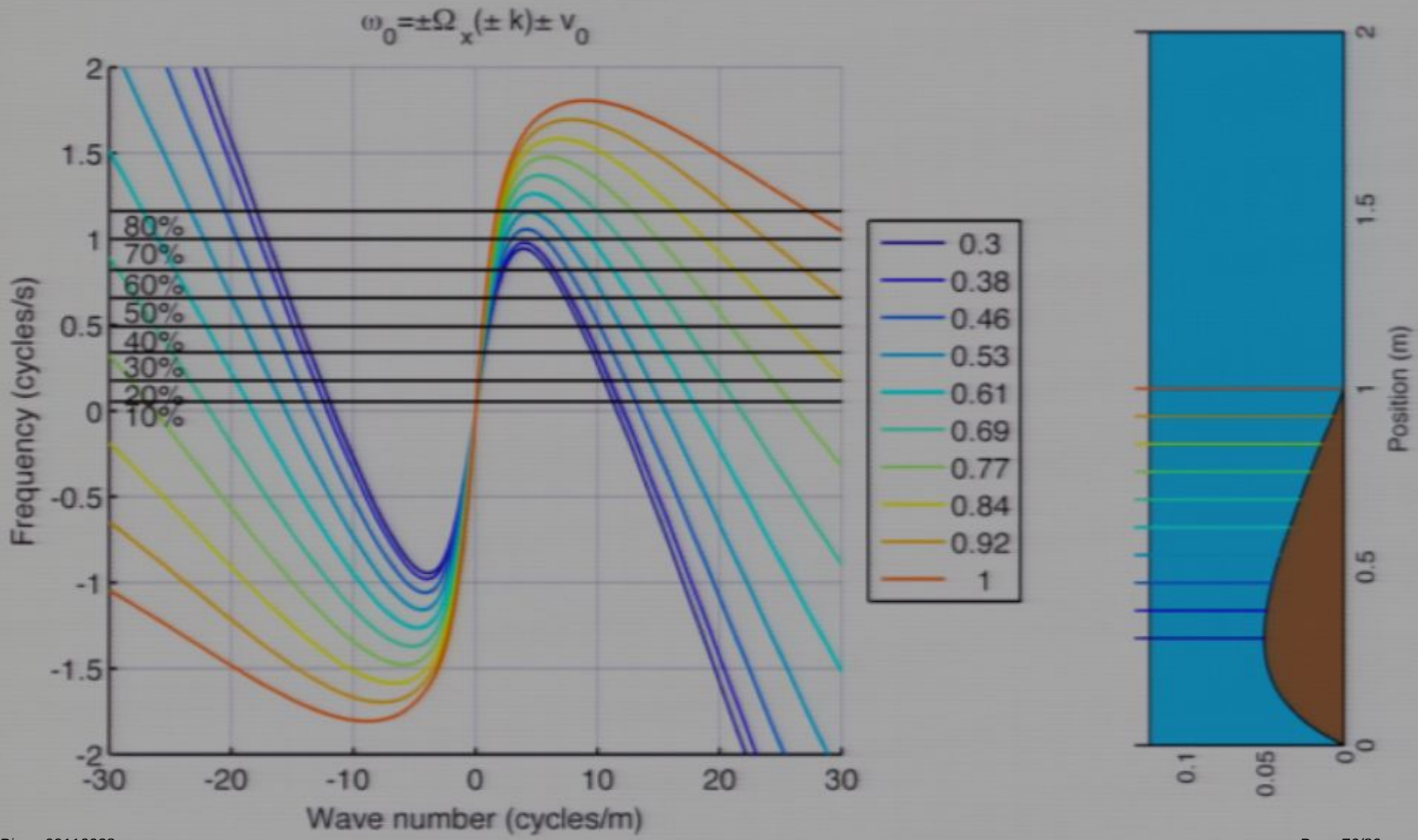
Wave generator on 80% - continuos bursts



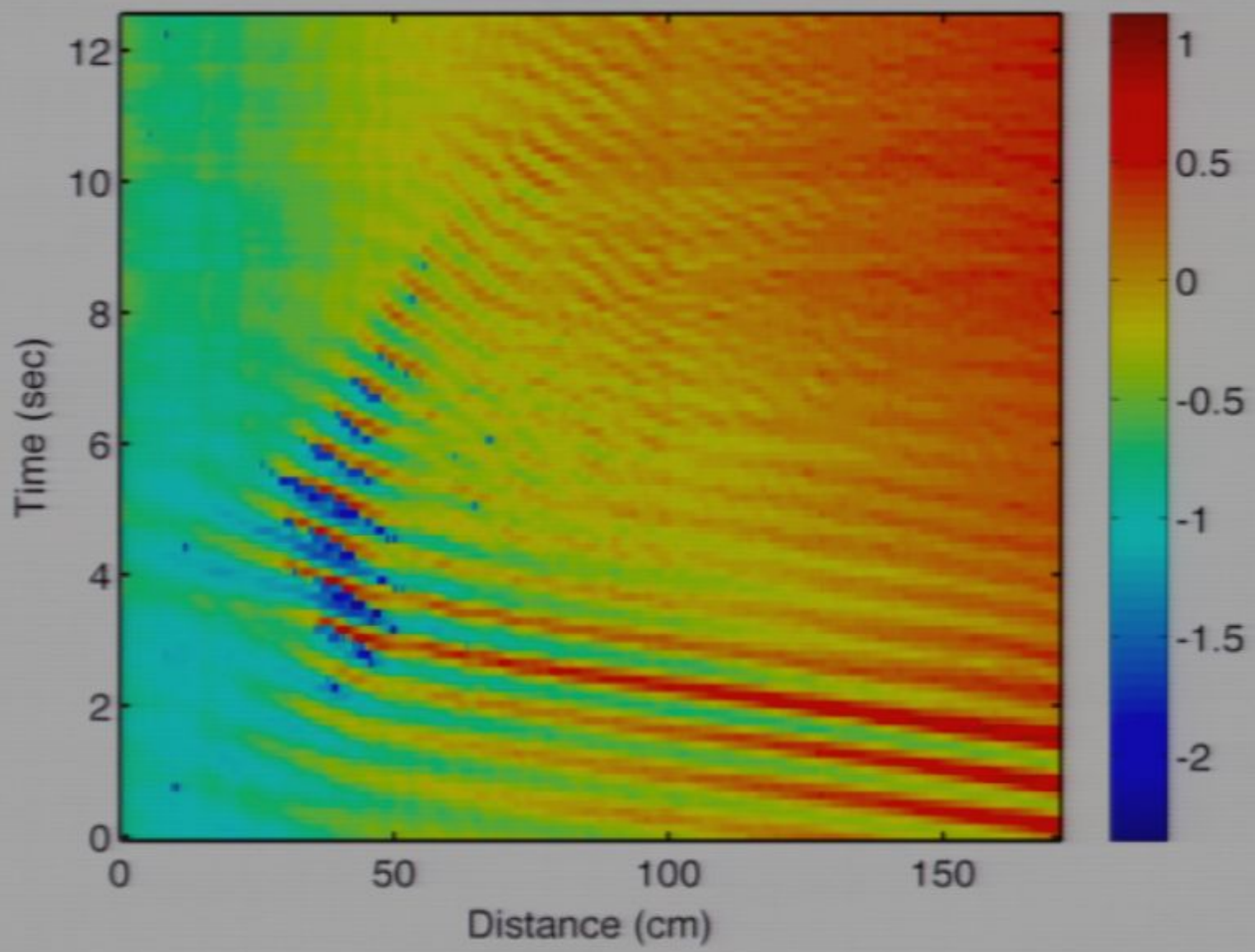
Wave generator on 80% - continuos bursts



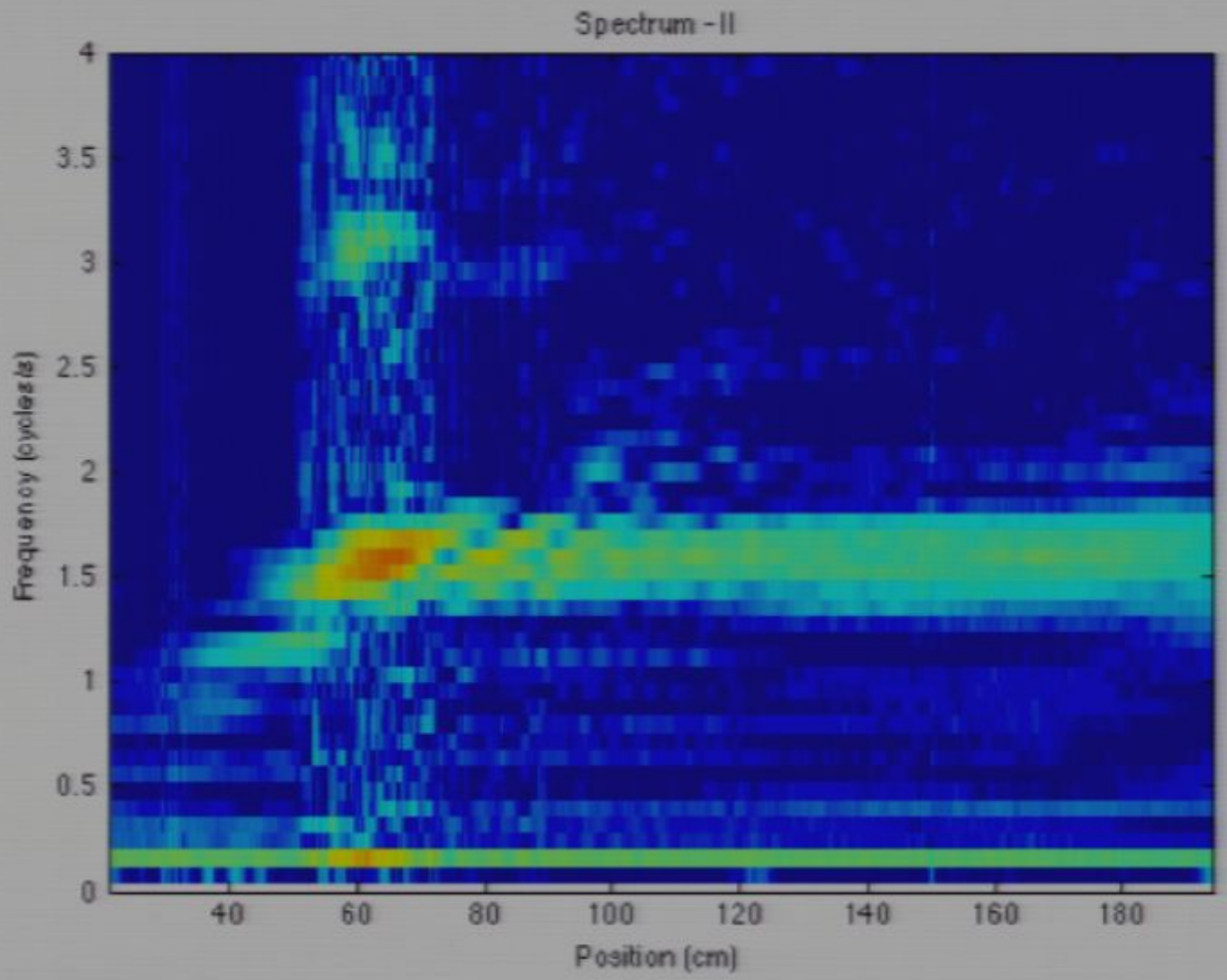
Adiabatic processes ✔



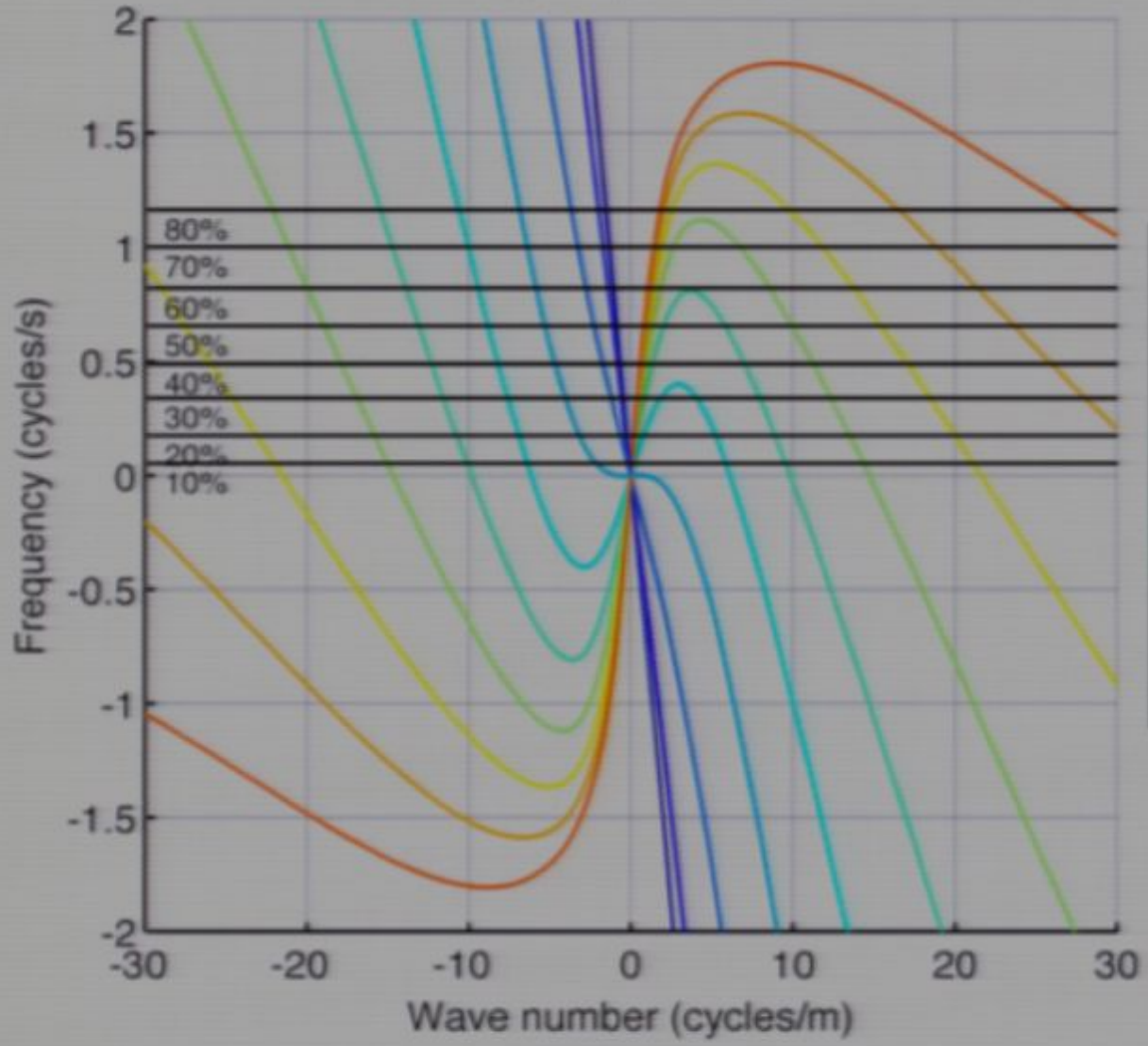
Wave generator on 80% - 5 bursts

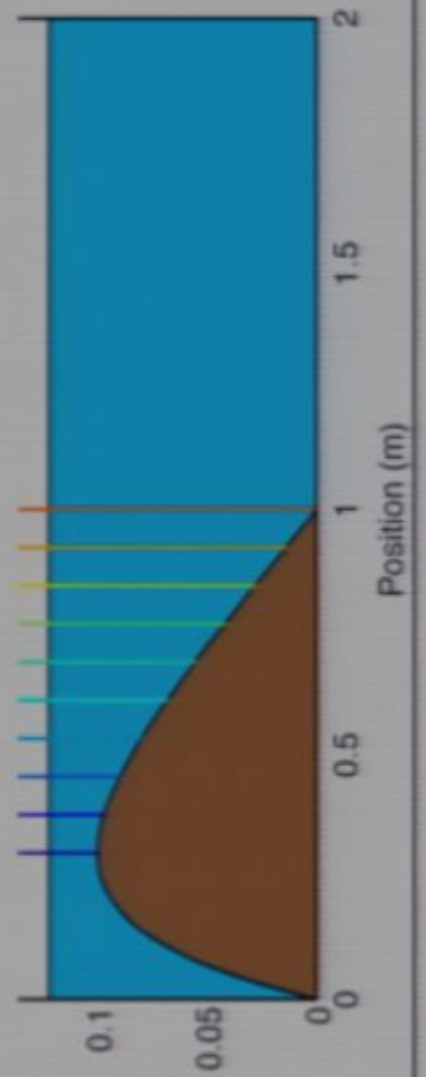


Wave generator on 80% - 5 bursts



Classical equivalent of BH evaporation (non-adiabatic)





Conclusions and outlook

Experiment

Consequences for environmental physics, e.g. Tsunami waves (Berry 2007)

More experiments, e.g. superradiant wave scattering...

Theory

What if we do/don't see the negative frequency modes..?!

Ad-hoc effective field theories versus emergent field theories...