Observing superradiance in a vortex flow

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UNITED KINGDOM · CHINA · MALAYSIA

Quantum Gravity
LABORATORY

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Rotational superradiant scattering in a vortex flow, T.T. *et al*
Nature Physics (June 2017), doi : 10.1038/nphys4151

Introduction

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Use a hydrodynamic system to mimic gravity effect

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↓

Analogue gravity

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Analogue gravity

Good review
Barcelo *et al*, arXiv : gr-qc 0505065

- BEC
- Fluids of Light
- Water

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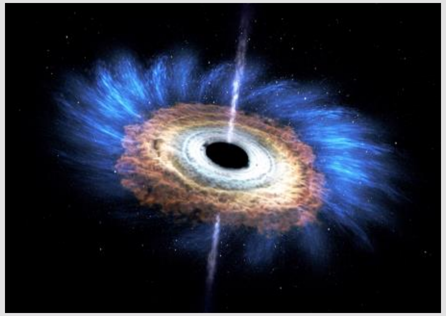
Black holes



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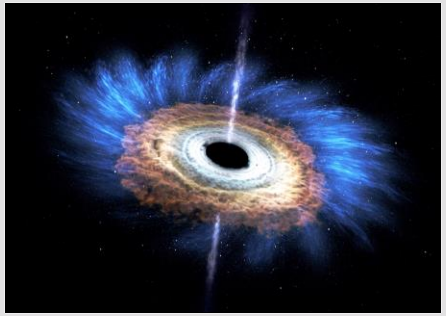

How do black holes loose their energy ?

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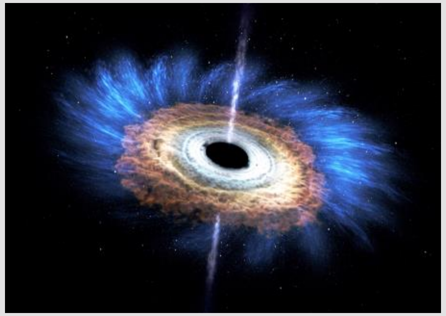

How do black holes loose their energy ?

Hawking Radiation

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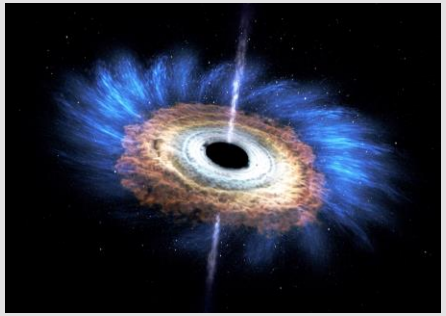


How do black holes loose their energy ?

Superradiance

Hawking Radiation

Superradiance

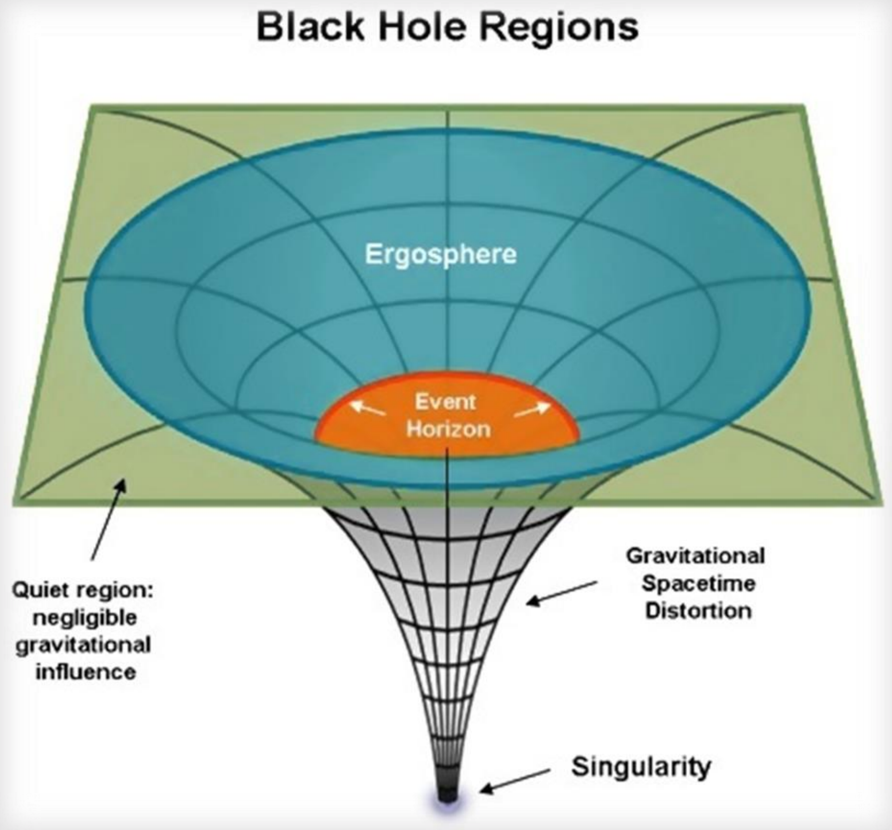
Superradiance

- Zel'Dovich (1971)
- Rotating Black Holes
- Many other systems

<u>Review :</u> Brito *et al,*
Superradiance. Lect. Notes Phys.,
906:pp.1-237,2015.

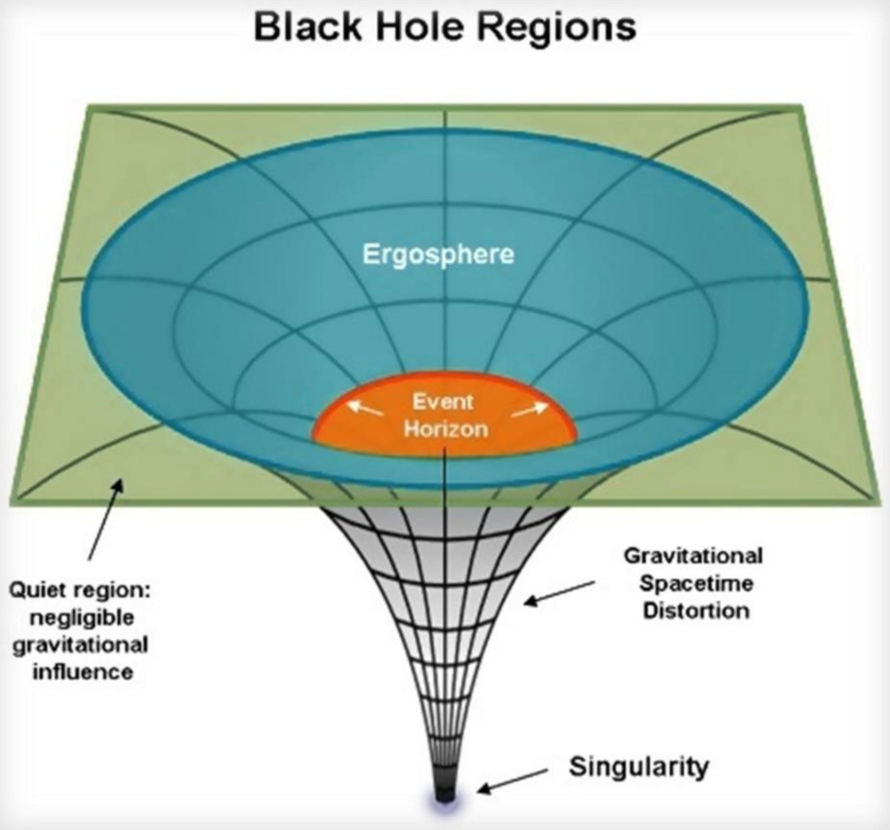
Superradiance

Rotating Black Holes



Superradiance

Rotating Black Holes



During 70's : Bekenstein and Hawking
Black Hole Thermodynamics

Superradiance

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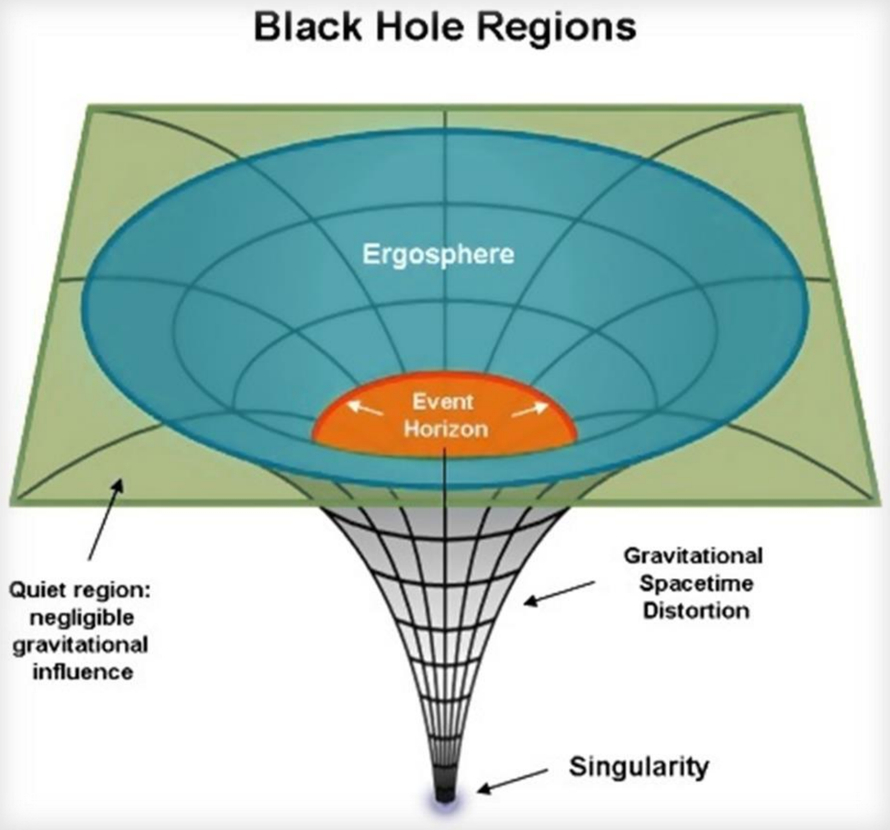

During 70's : Bekenstein and Hawking
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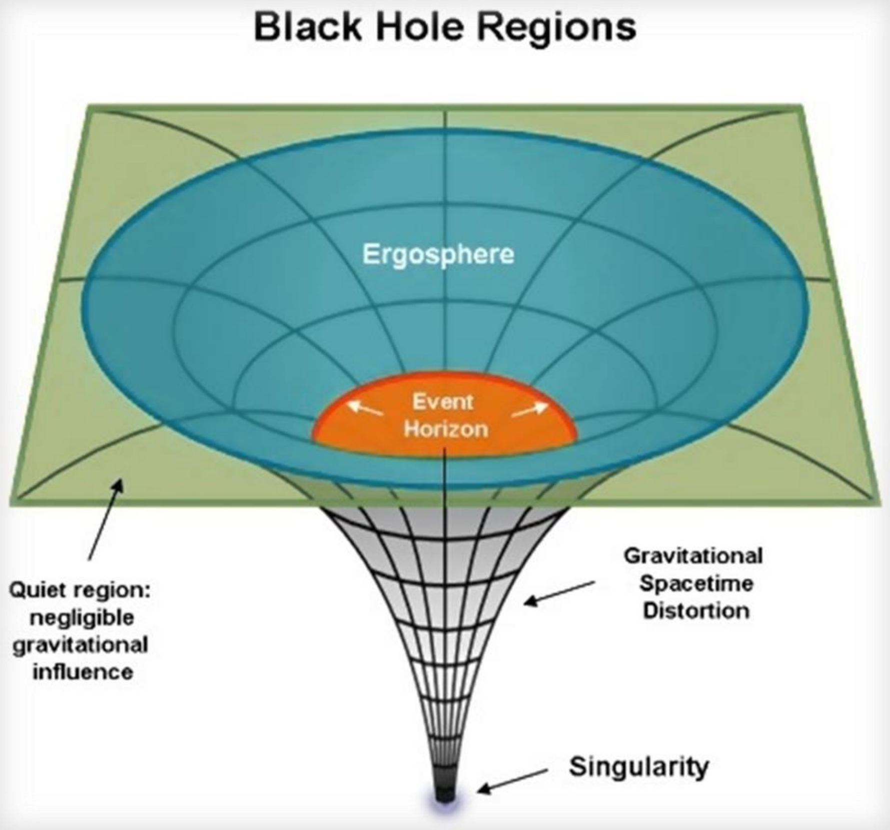
$$S_{BH} = \frac{k_B A}{4{l_P}^2}$$

First law : $\delta M = \frac{\kappa}{8\pi}\delta A + \Omega_H \delta J$

Second law : $\delta A \geq 0$

Superradiance

Rotating Black Holes



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Superradiance : Radiance enhancement process

Superradiance

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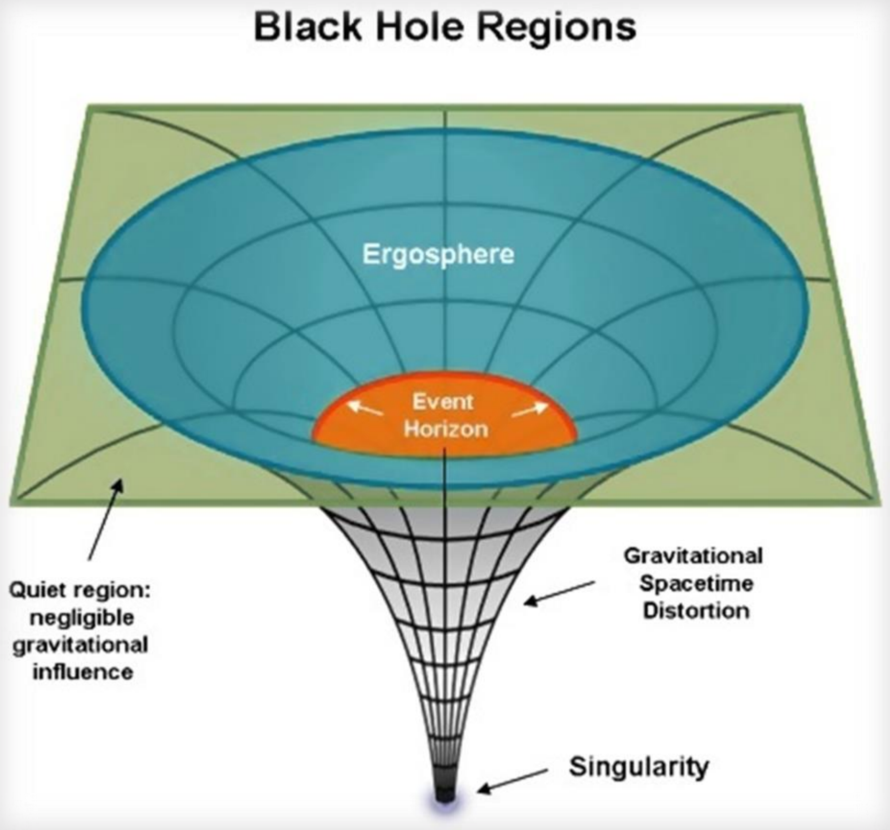

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Wave scattering : m, ω

Superradiance

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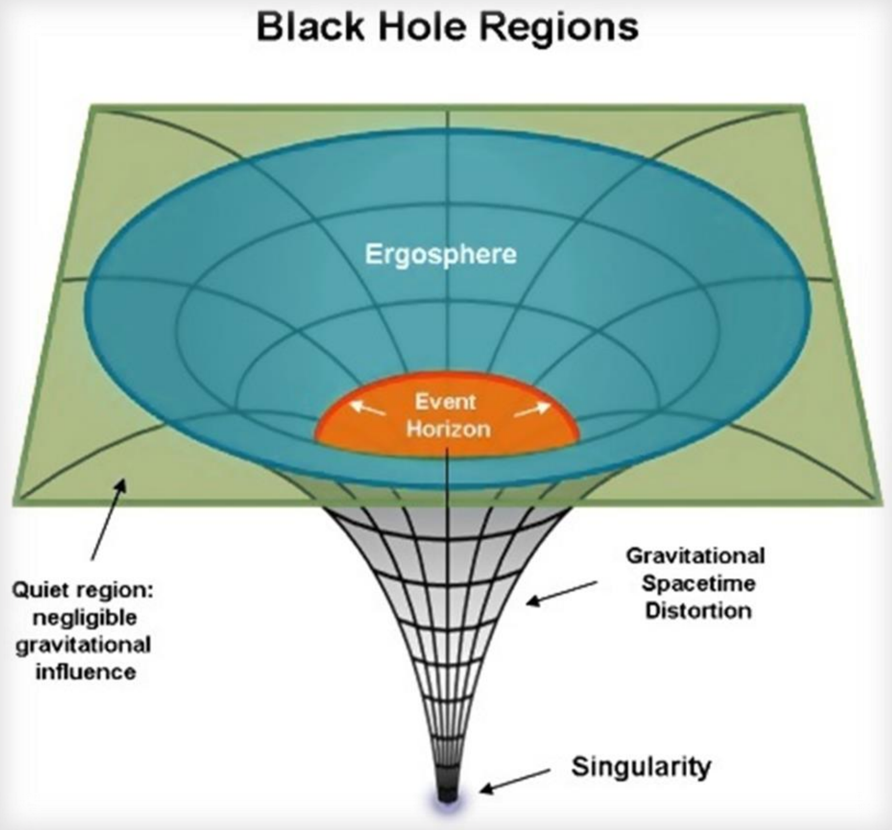

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Superradiance

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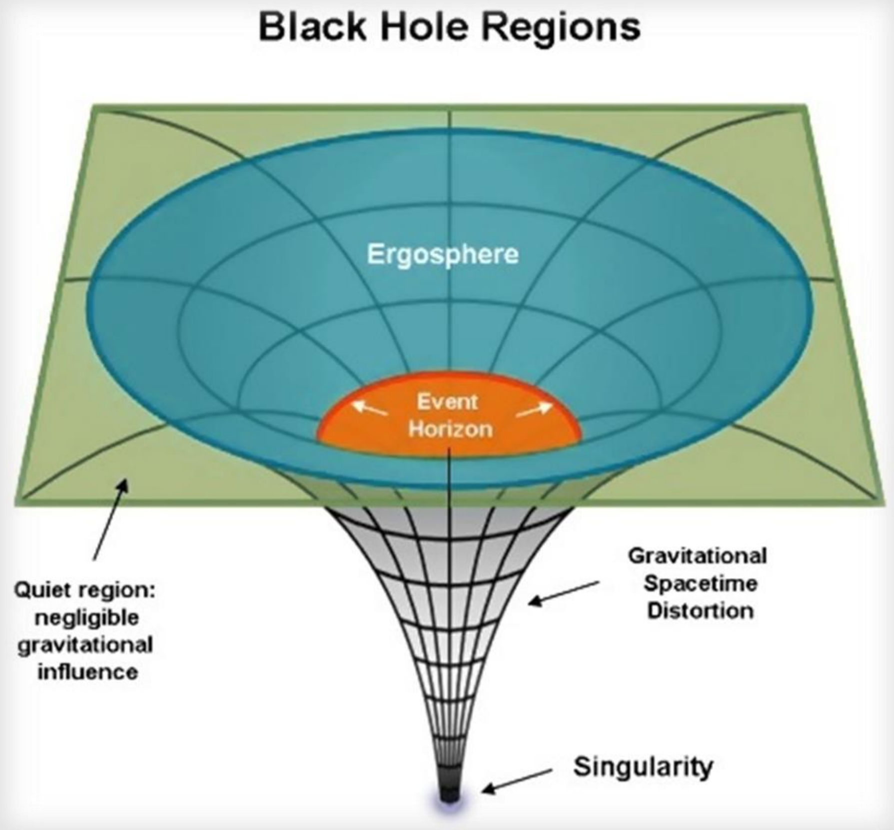

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$$\delta M \left(\frac{\omega - m\Omega_H}{\omega}\right) = \frac{\kappa}{8\pi}\delta A$$

Superradiance

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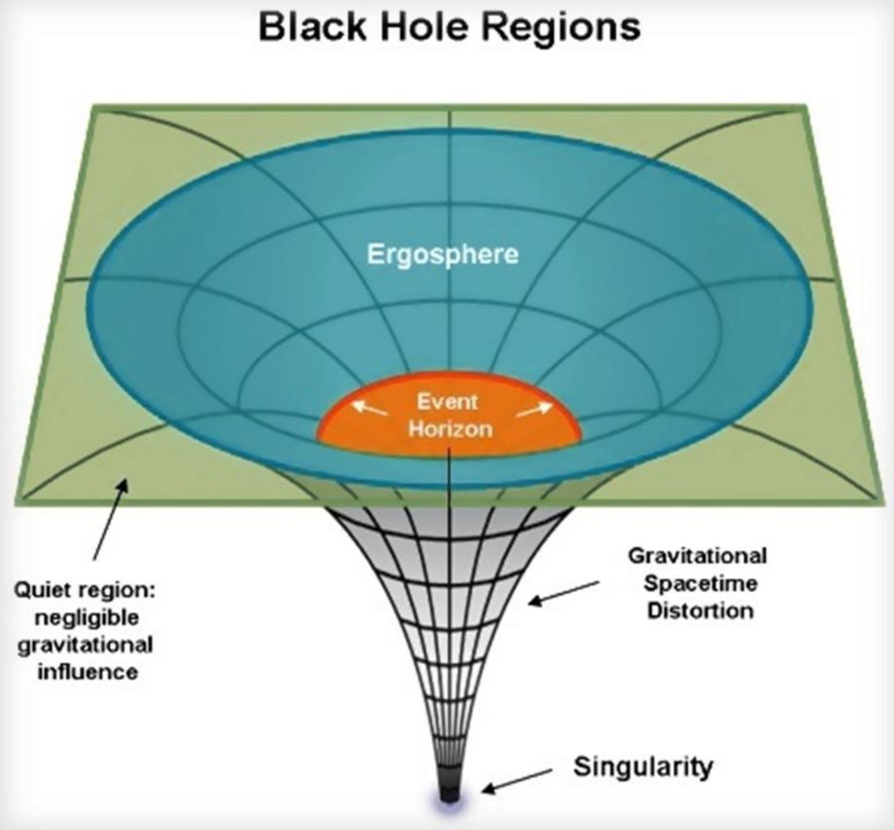

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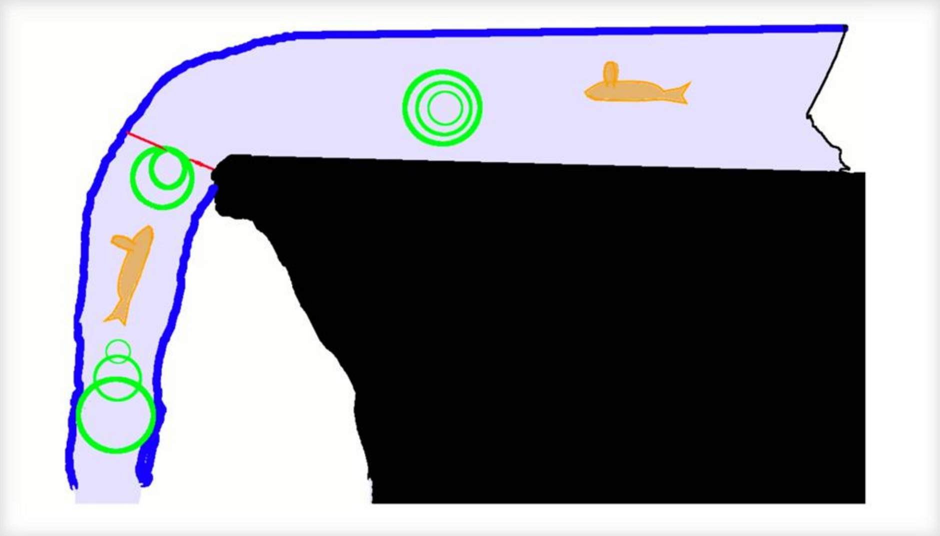
Analogue gravity

Analogue gravity



Credits : W. Unruh

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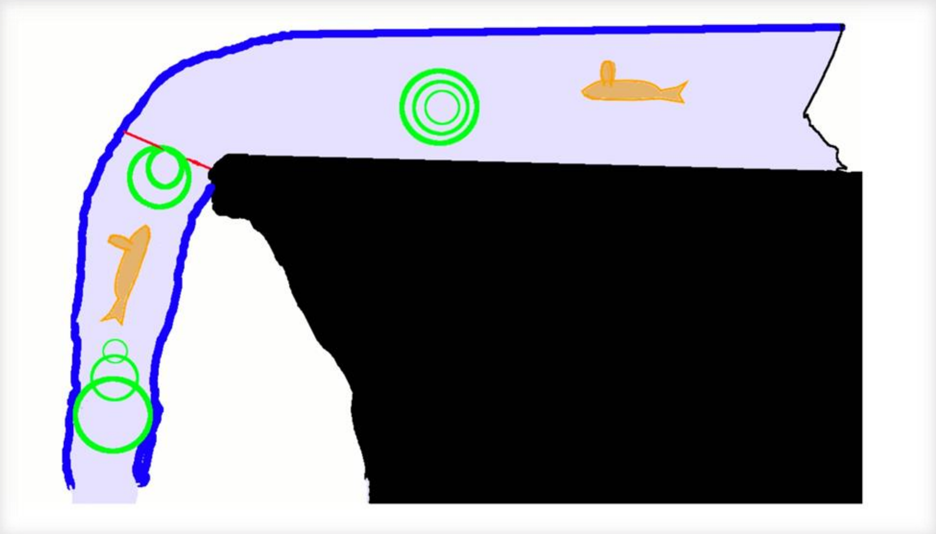

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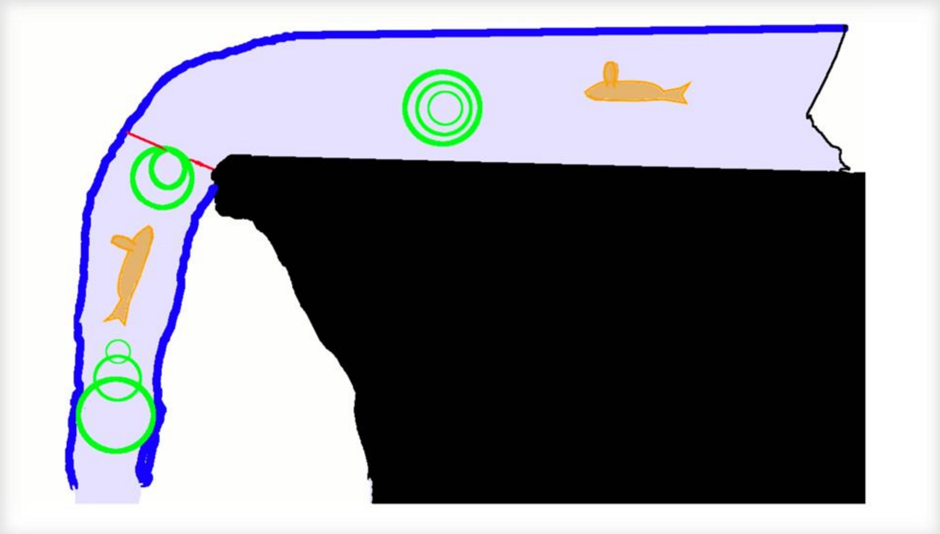
When $c_{Flow} < c_{wave}$: can propagate in all direction

Analogue gravity



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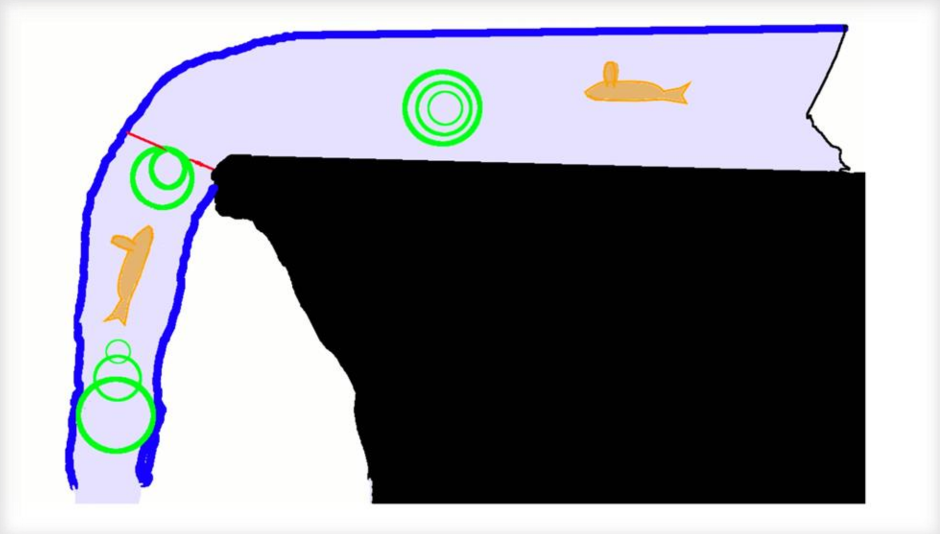

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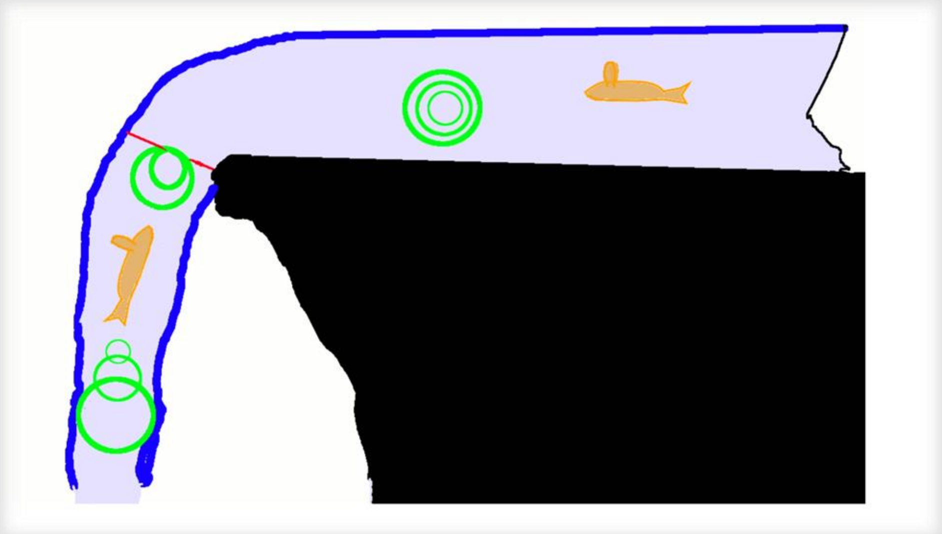
Analogue horizon

Analogue gravity



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Mathematically equivalent !

R.Schützhold and W.G. Unruh.
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PRD, 66:044019, Aug. 2012

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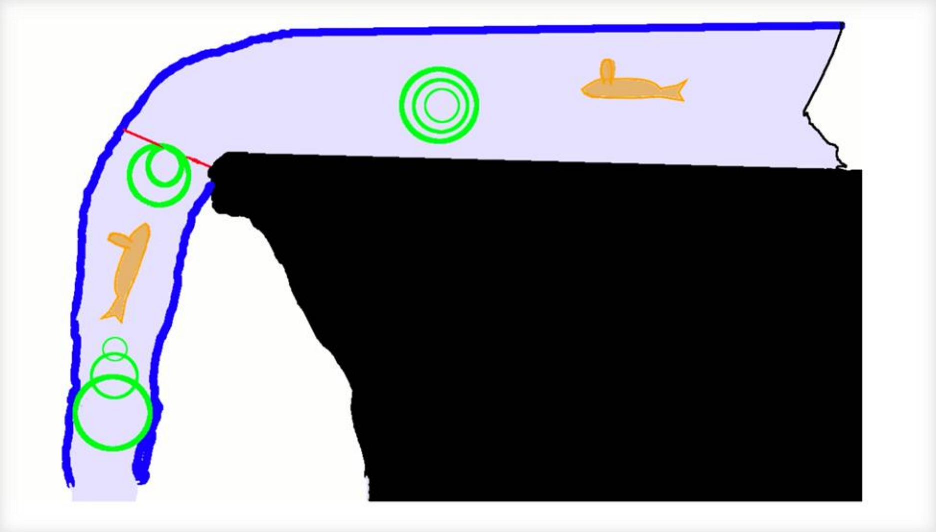

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Navier-Stokes + Continuity + Boundary conditions

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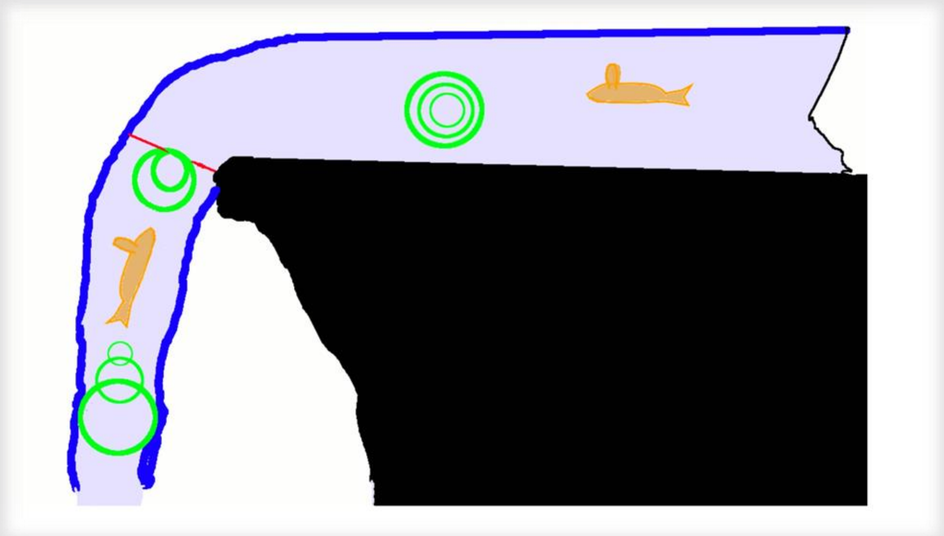

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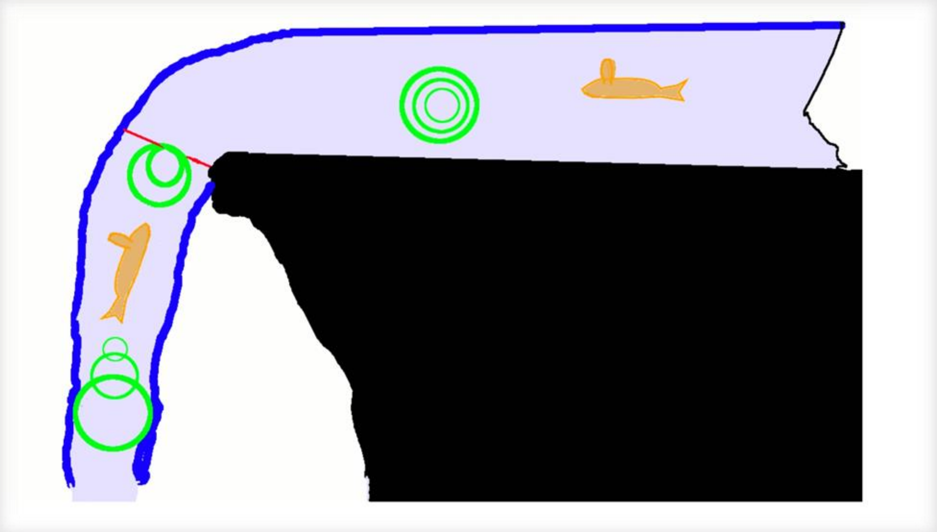
Flow : Inviscid fluid, Incompressible, Irrotational
Waves : Small amplitude, Shallow water waves

Analogue gravity



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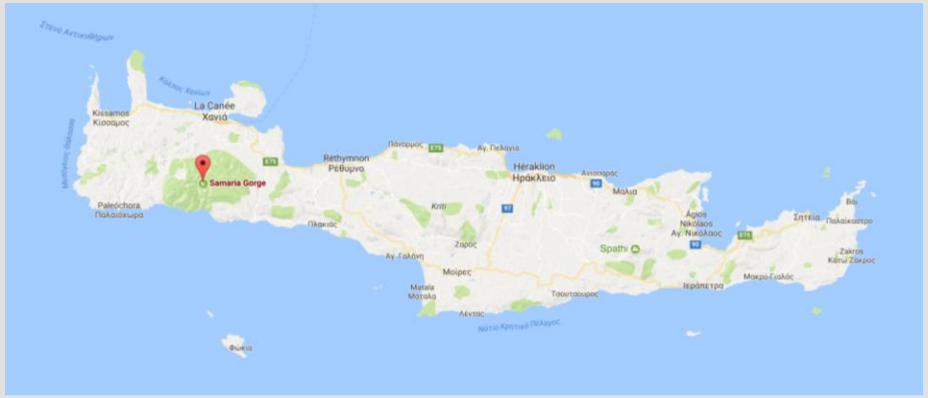
Scalar field propagating on an effective metric

$$g^{\mu\nu} = \begin{pmatrix} 1 & \overrightarrow{v_B} \\ \overrightarrow{v_B}^T & \overrightarrow{v_B} \times \overrightarrow{v_B} - gh_B.Id \end{pmatrix}$$

Analogue gravity

Example in Samaria Gorges



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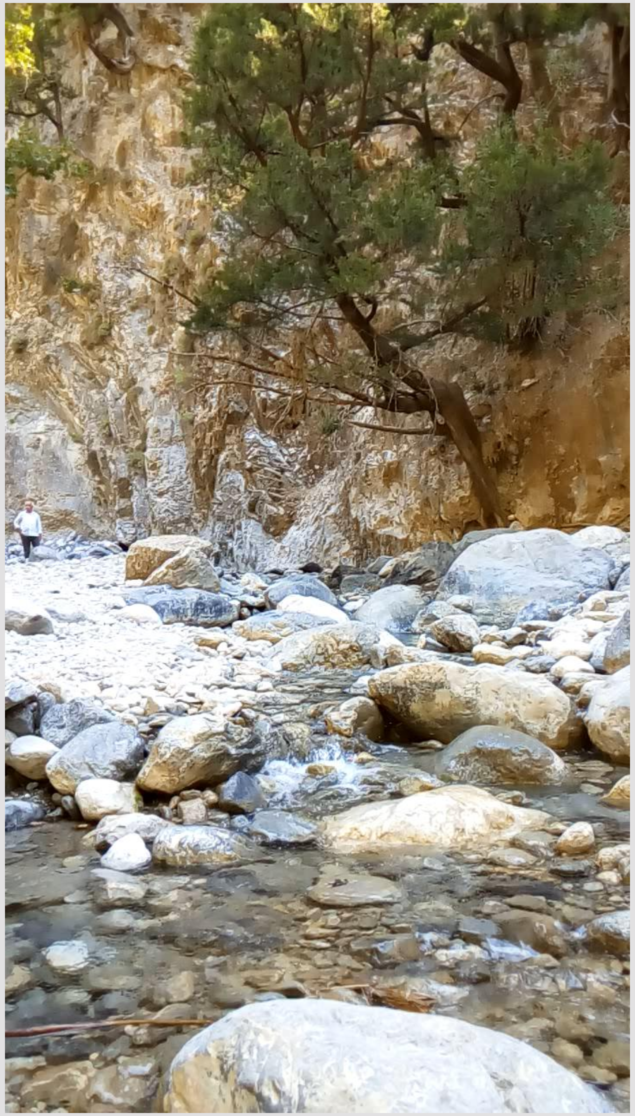

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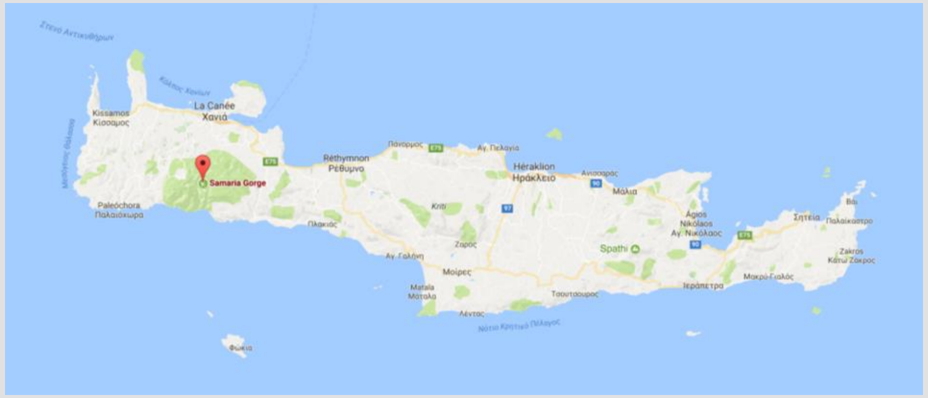

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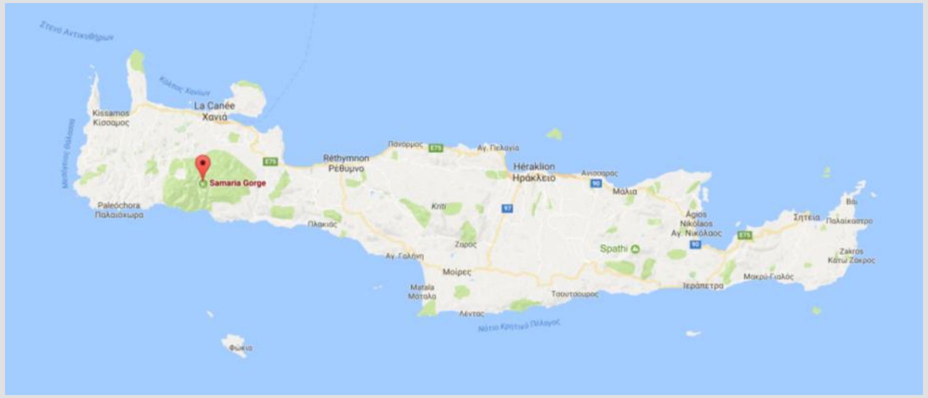

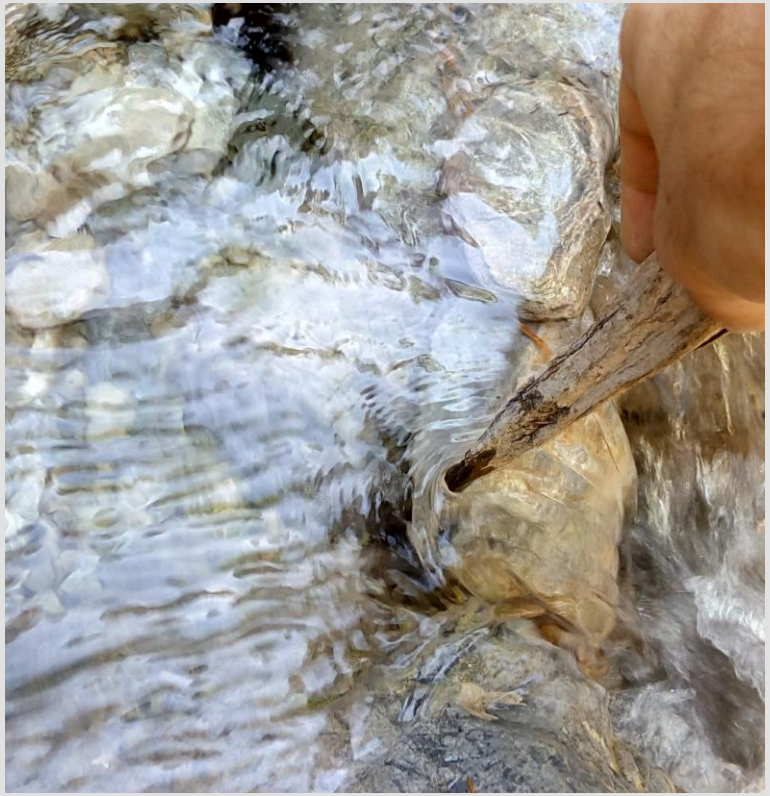

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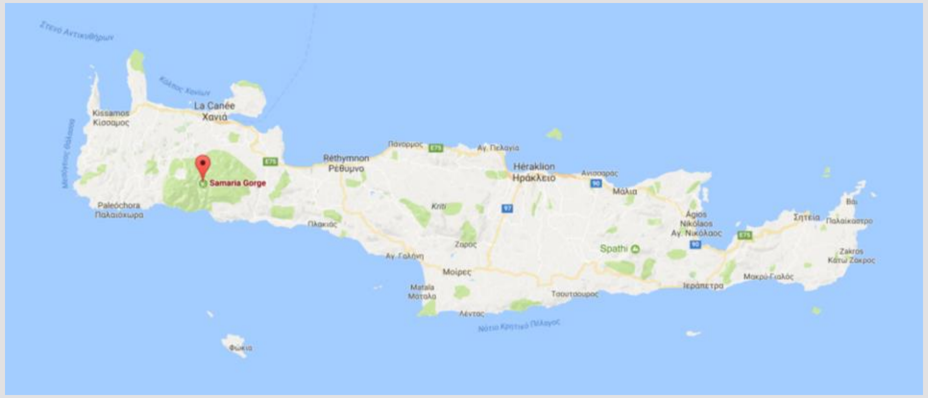

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Try to propagate
against the flow
(blue shift)

↓

Analogue horizon

Creating the analogue BH

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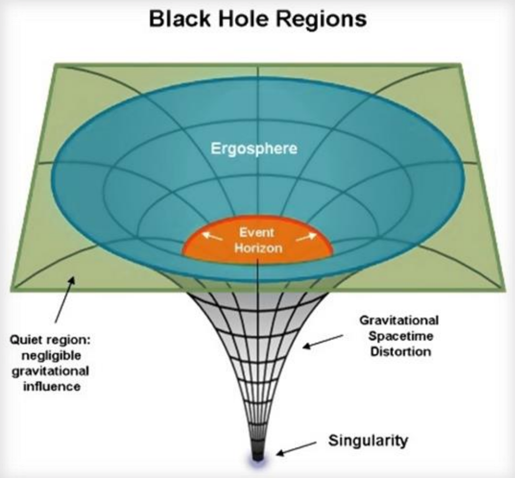

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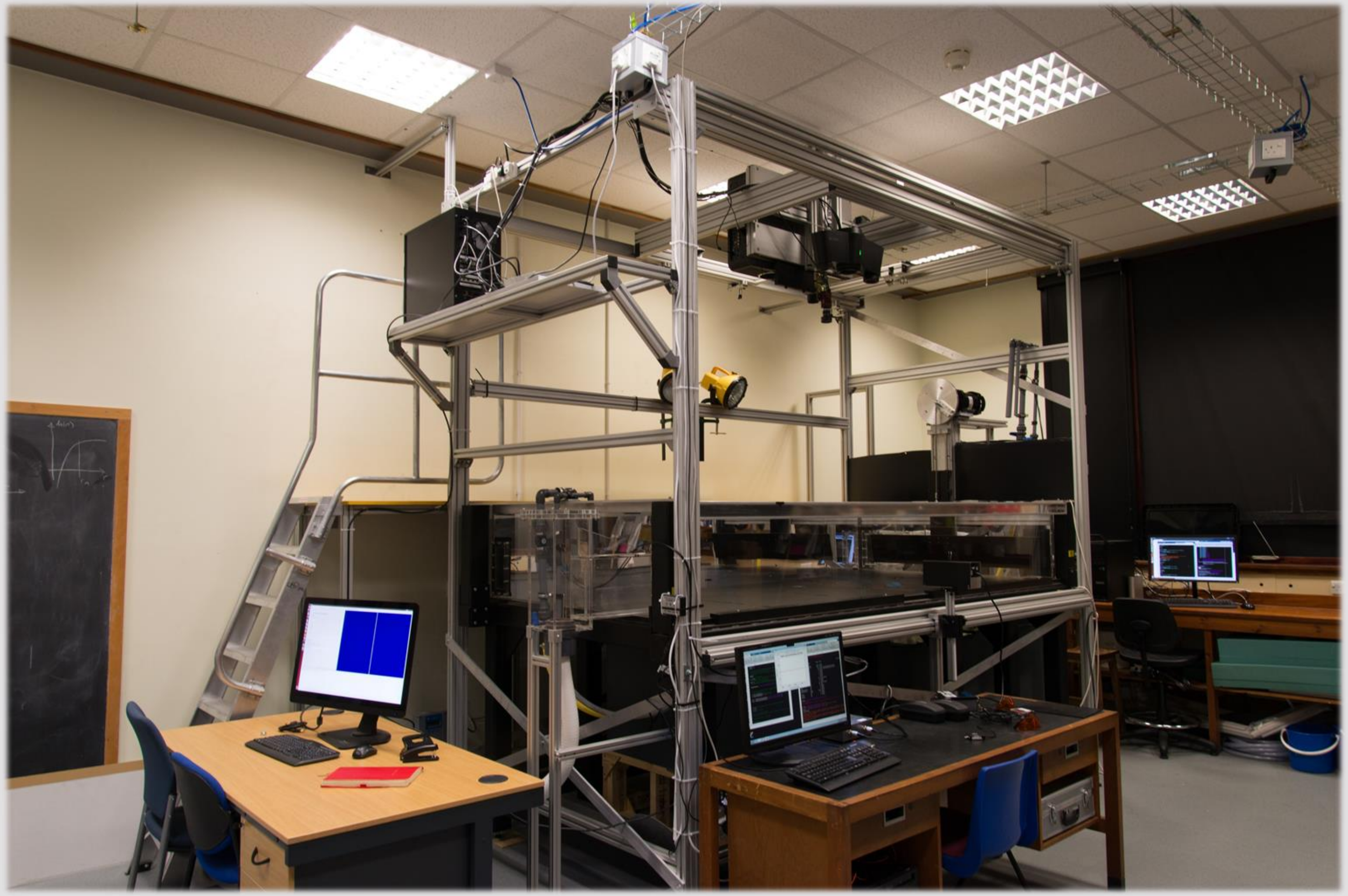

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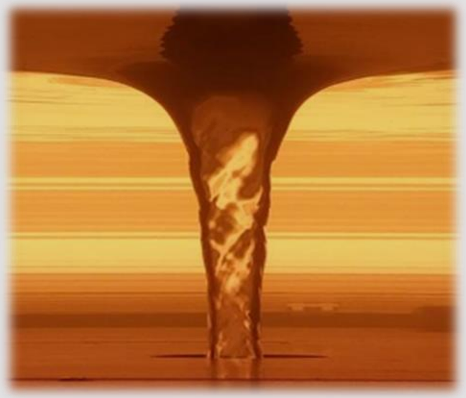

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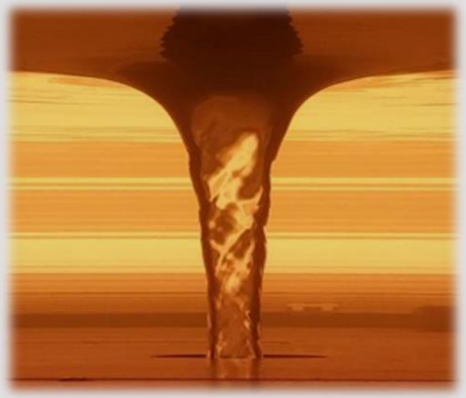

Irrotational

Axisymmetric

Stationary

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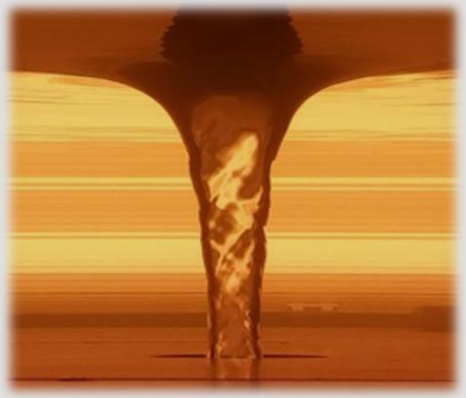

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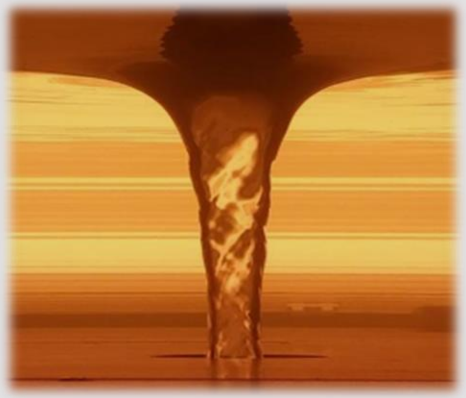

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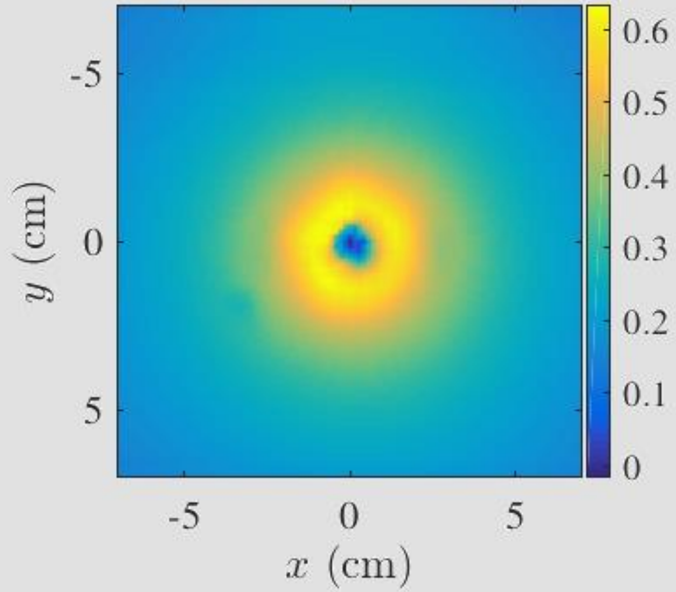

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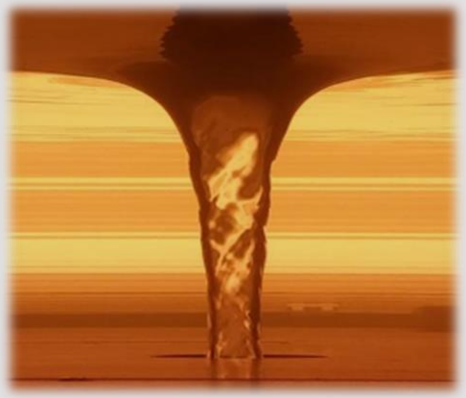
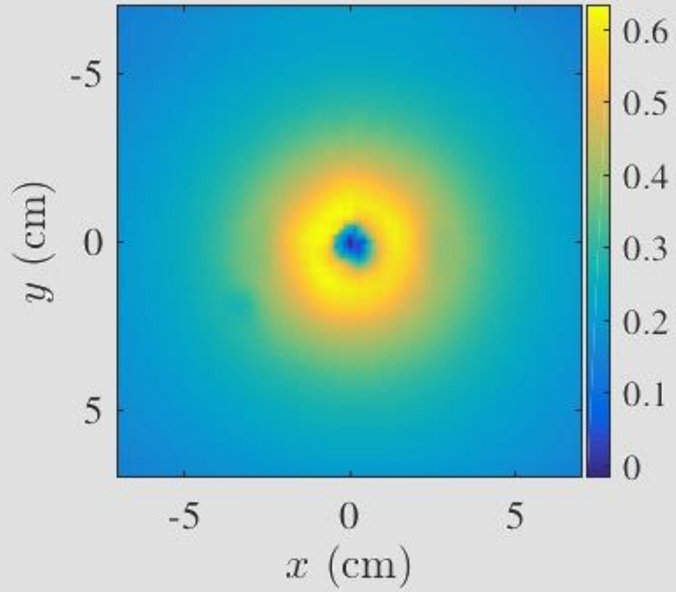
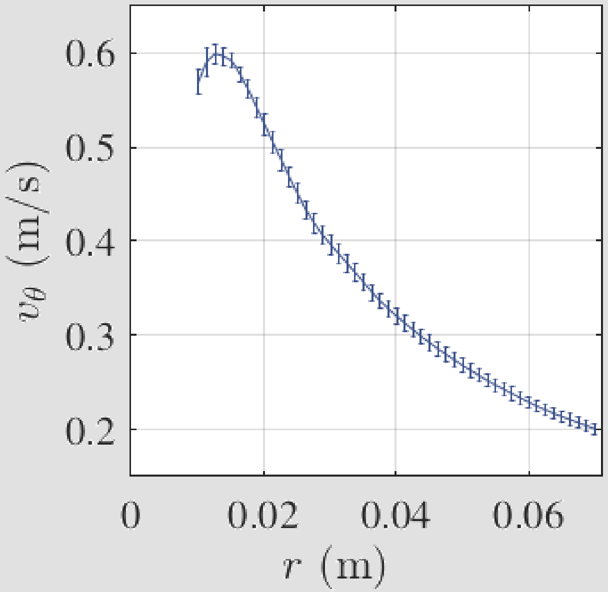


Irrotational Axisymmetric Stationary





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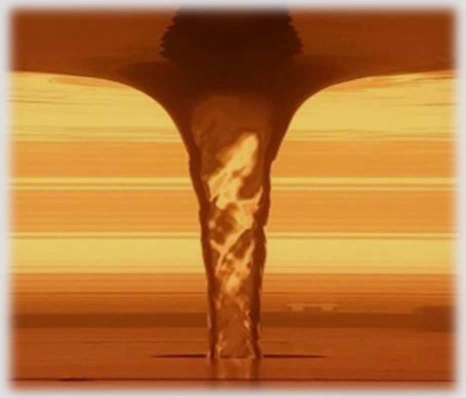

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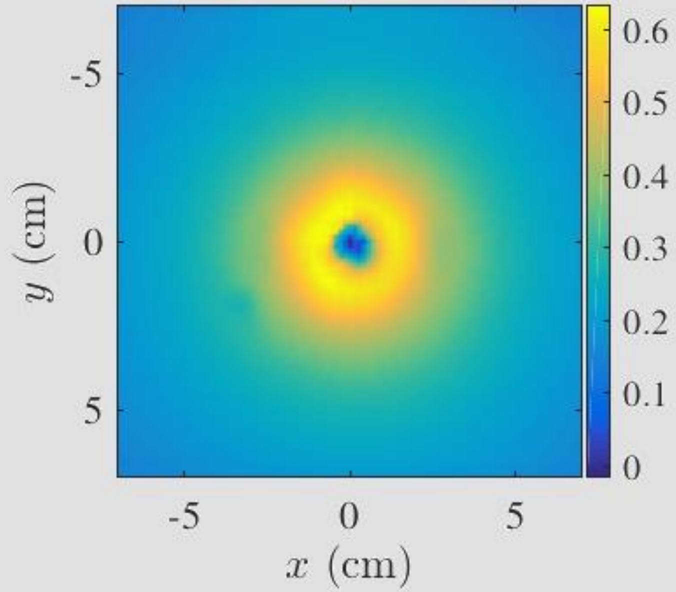

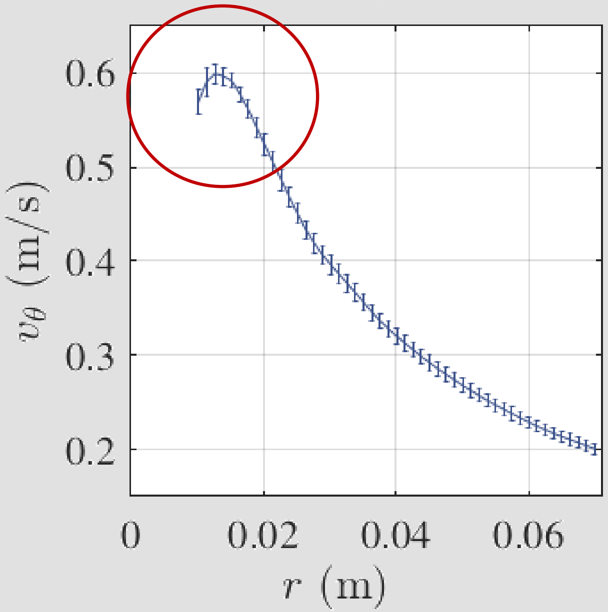

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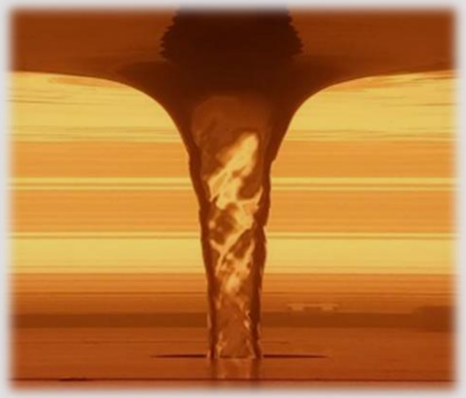

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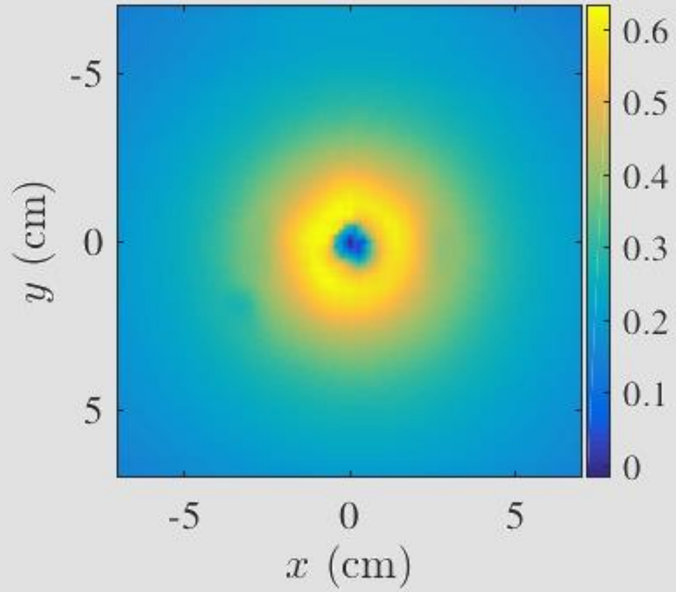

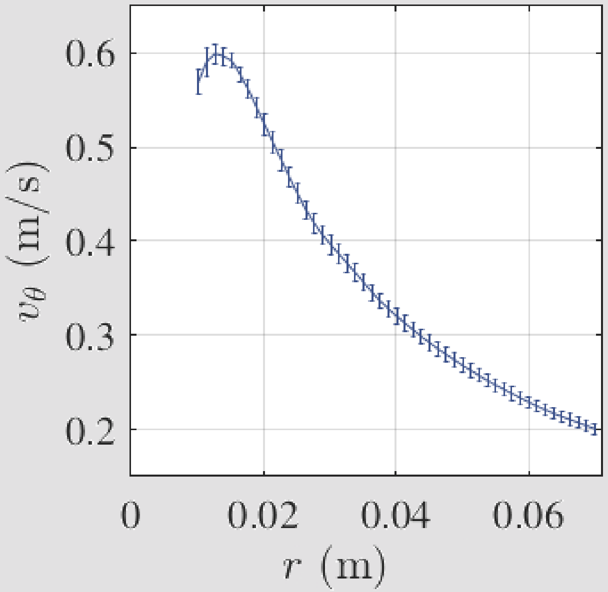

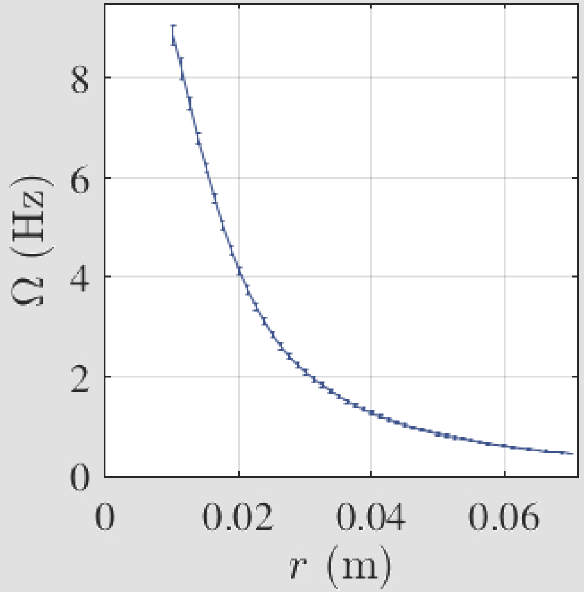

Excitation of waves

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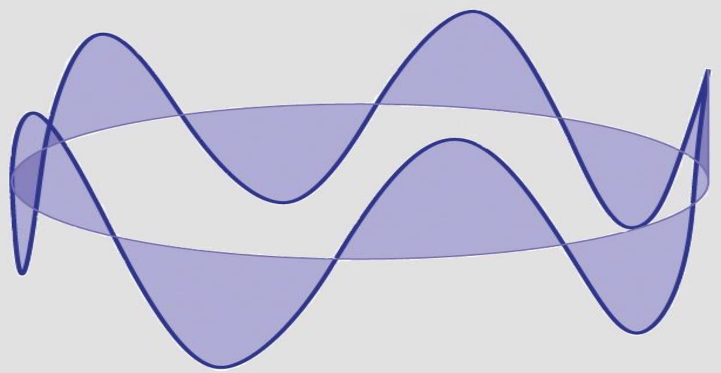
Condition of superradiance : $\omega - m\Omega < 0$

Azimuthal number

Excitation of waves

Condition of superradiance : $\omega \ - m\Omega < 0$

We want to excite azimuthal waves



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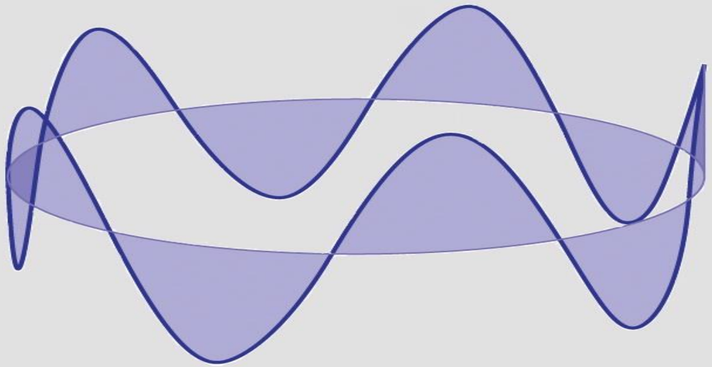
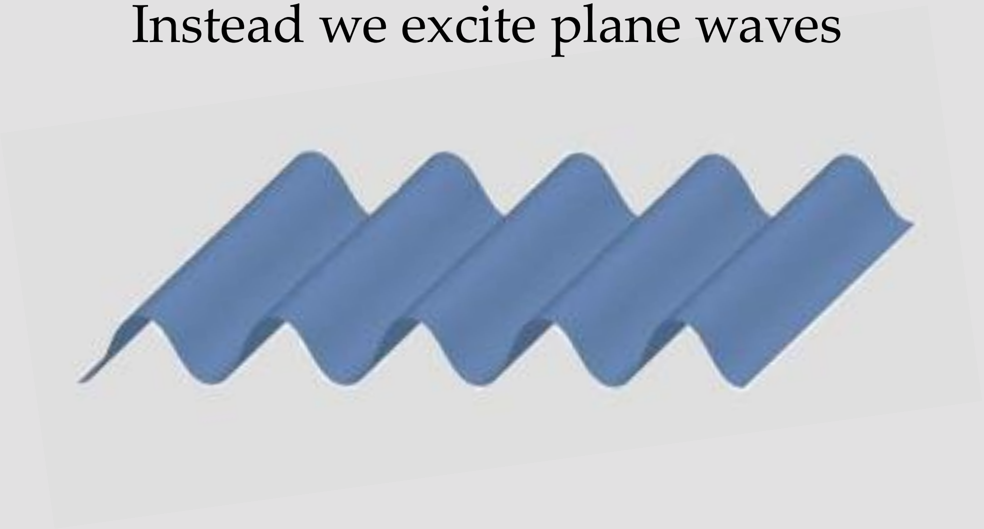


Instead we excite plane waves



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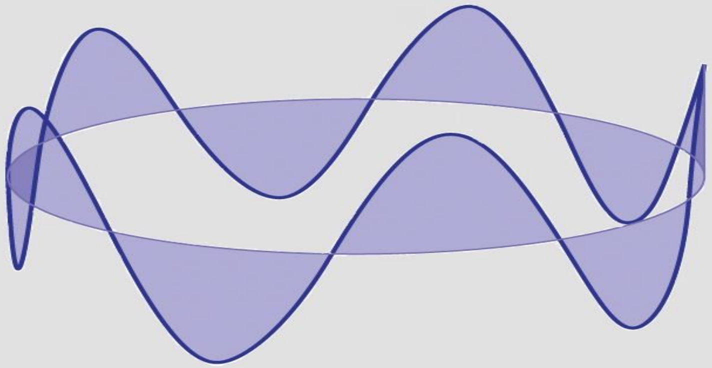

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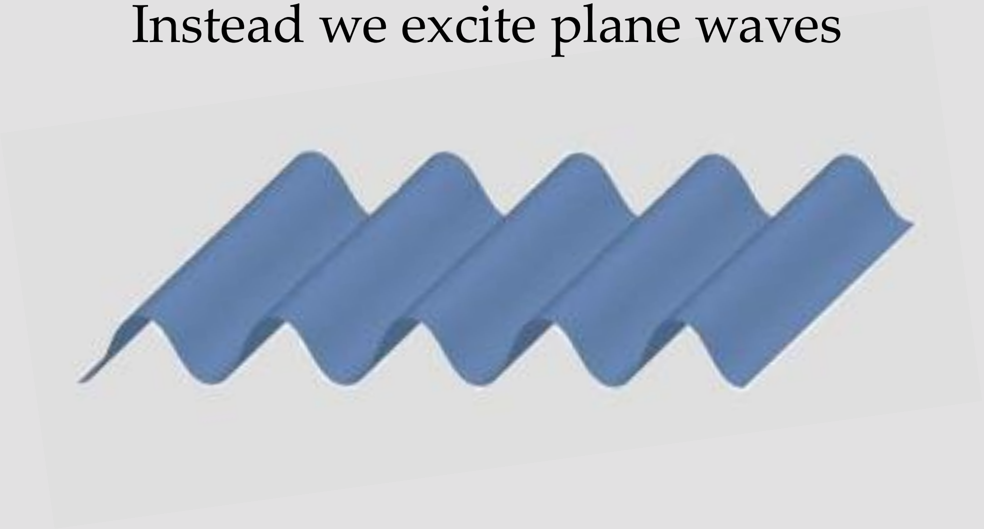

$$e^{i\vec{k}.\vec{r}} = \sum_{m=-\infty}^{\infty} i^m J_m(kr) e^{im\theta}$$

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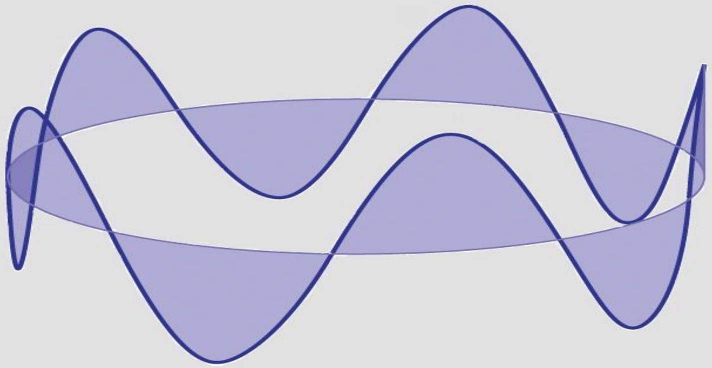

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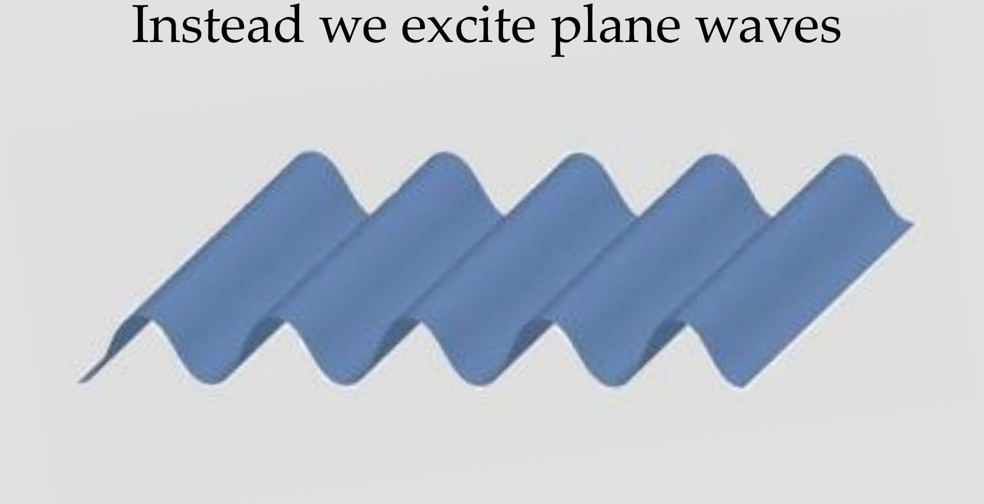

$$e^{i\vec{k}.\vec{r}} = \sum_{m=-\infty}^{\infty} i^m J_m(kr) e^{im\theta}$$

<u>Data analysis procedure :</u>

- Excite plane waves
- Extract different azimuthal component
- Compare in/out part of the different m's

Detection method

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Shallow water regime : $\lambda \gg h_B$

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Small amplitude : $A \ll h_B$

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Pattern projector

Detection method

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Pattern projector

Two cameras

Stereo-photogrammetry

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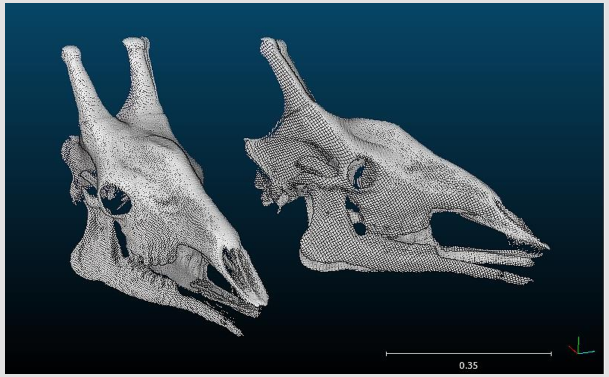

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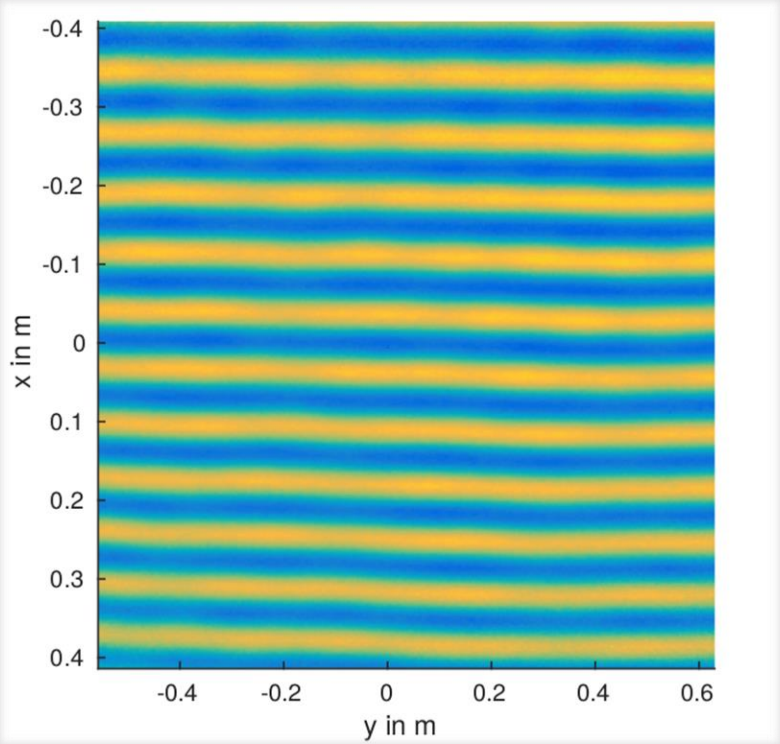

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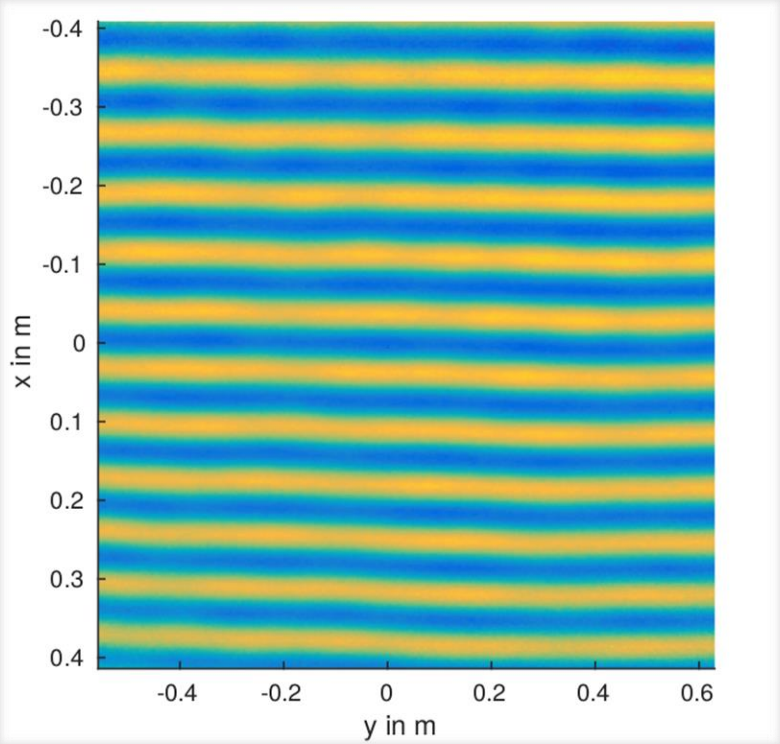

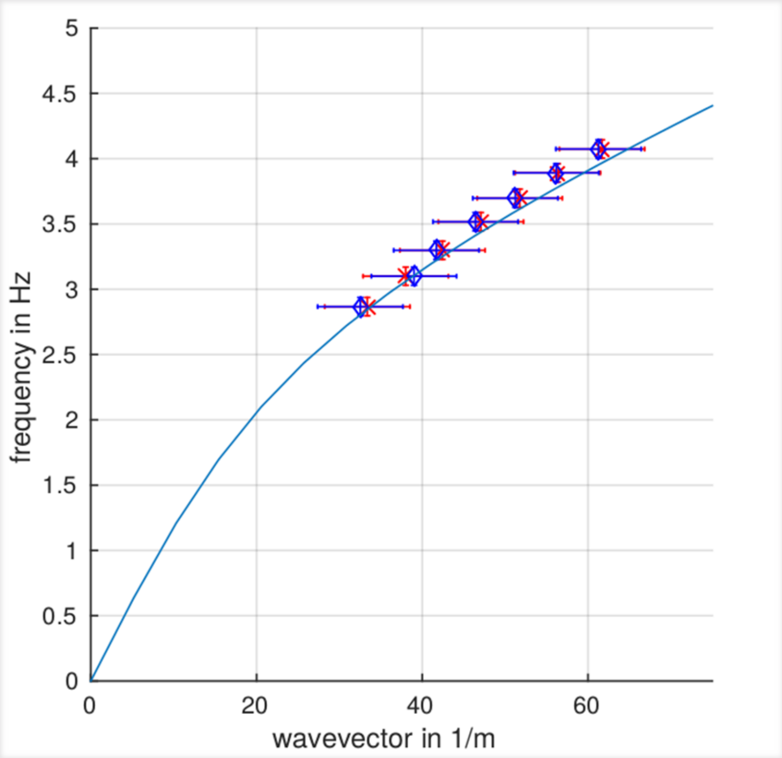

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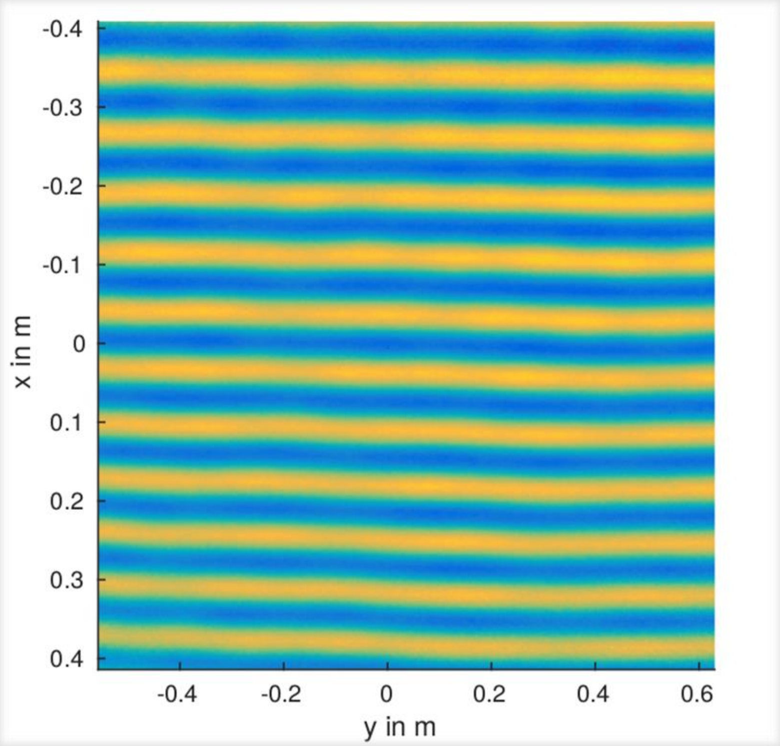
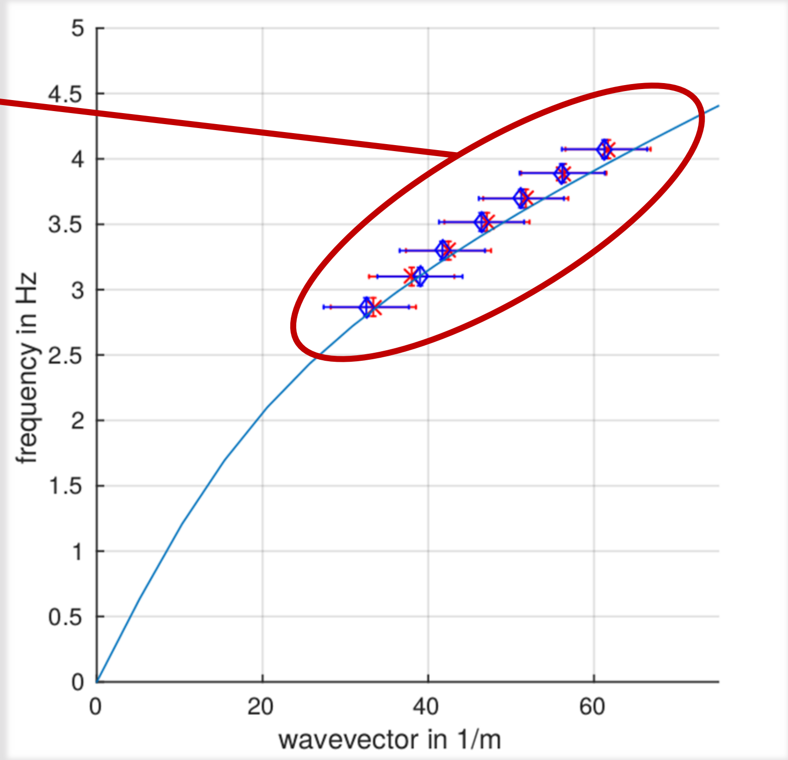


Dispersion – $c(\lambda)$



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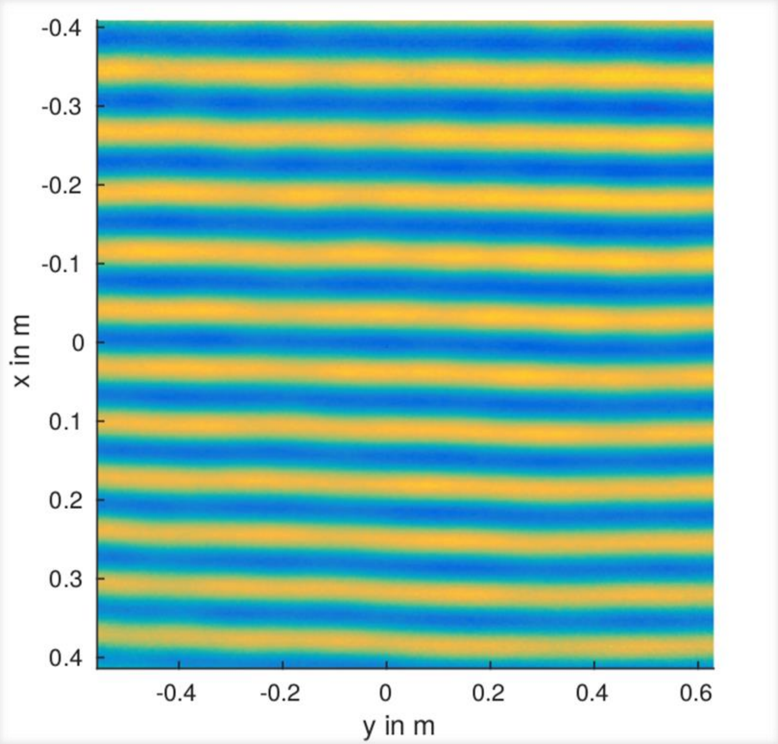

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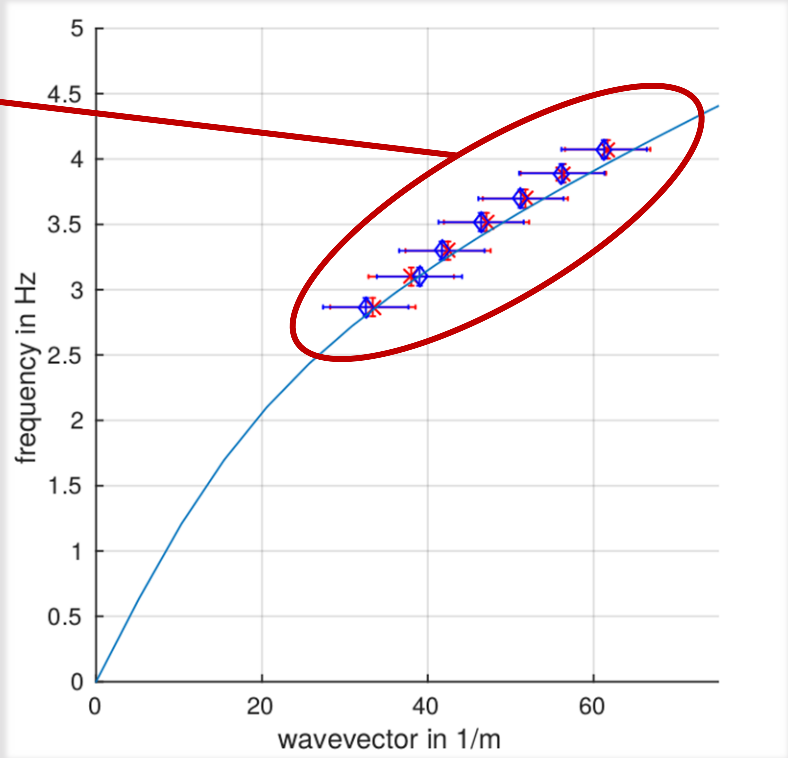

Experimental realisation

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<u>Analogue Black Hole :</u>

- Irrotational
- Stationary
- Axisymmetric

<u>Waves :</u>

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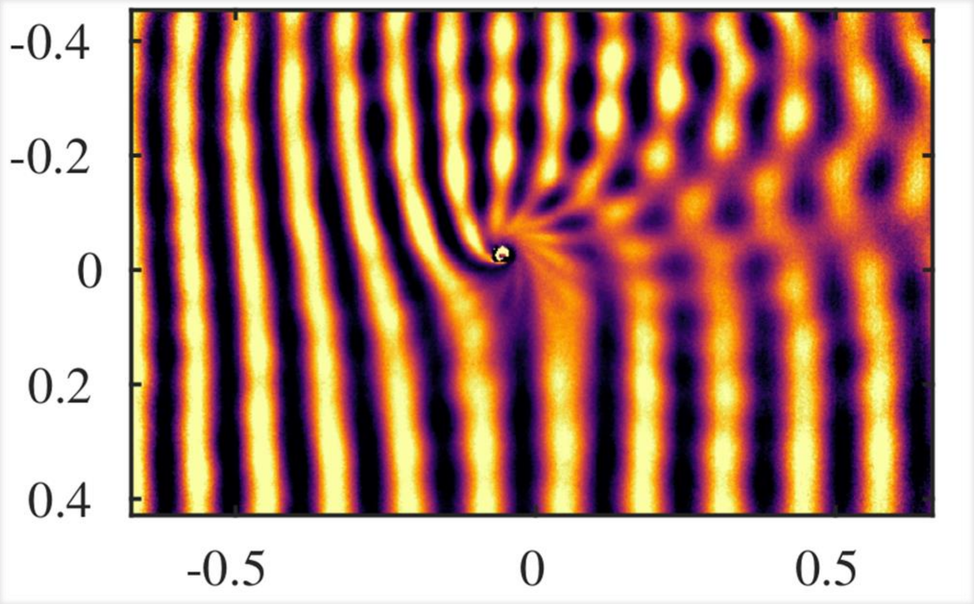

Free surface at 3.70 Hz

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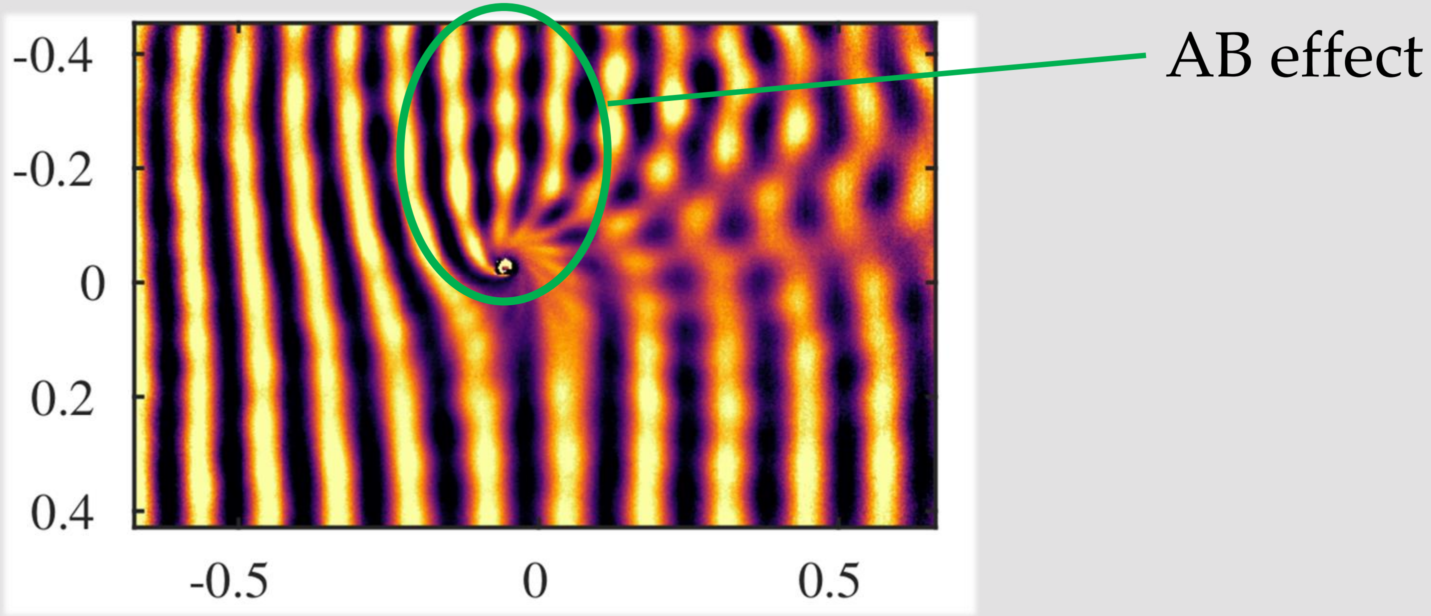

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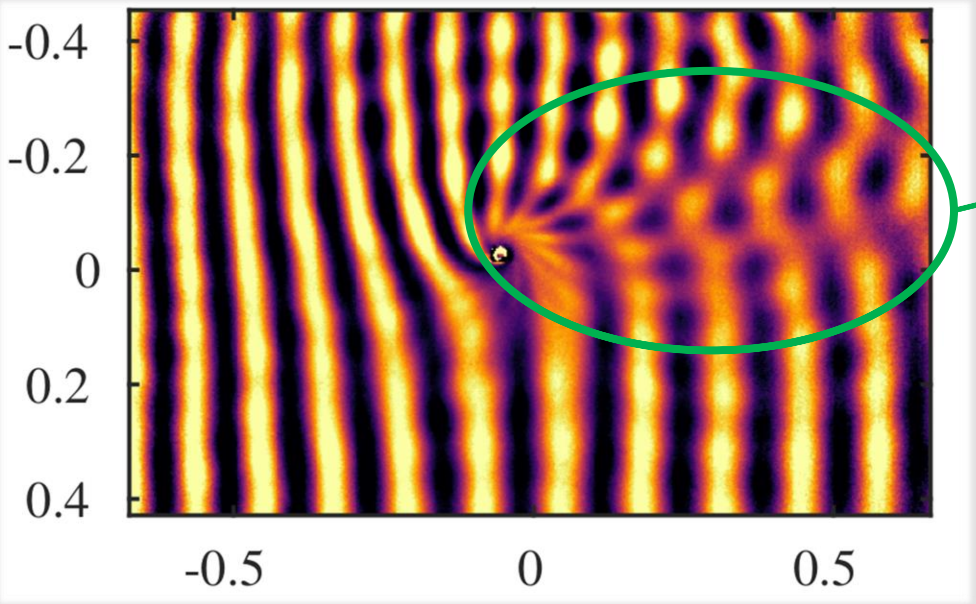

Free surface at 3.70 Hz

AB effect

Scattering

Experimental realisation

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<u>Waves :</u>
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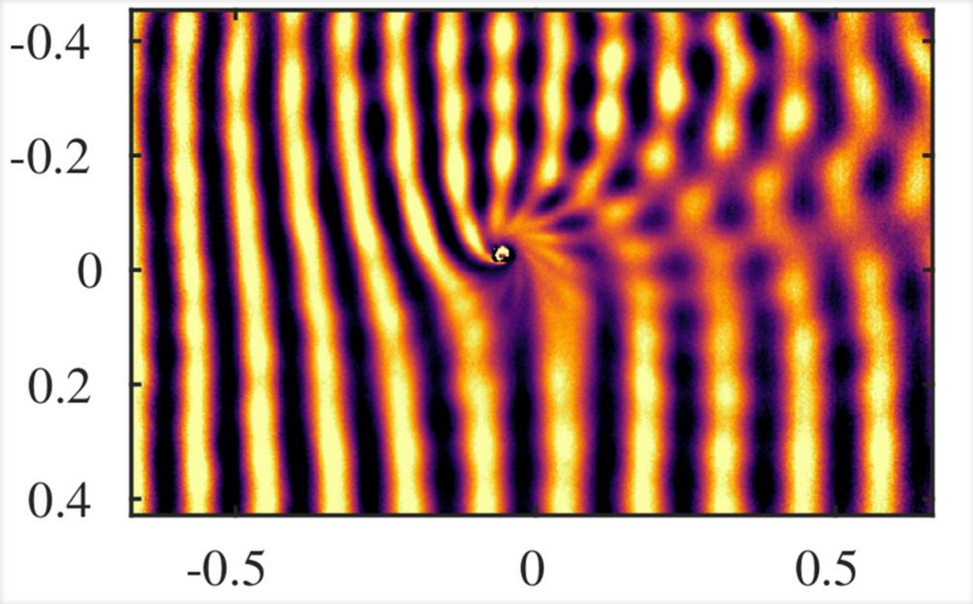
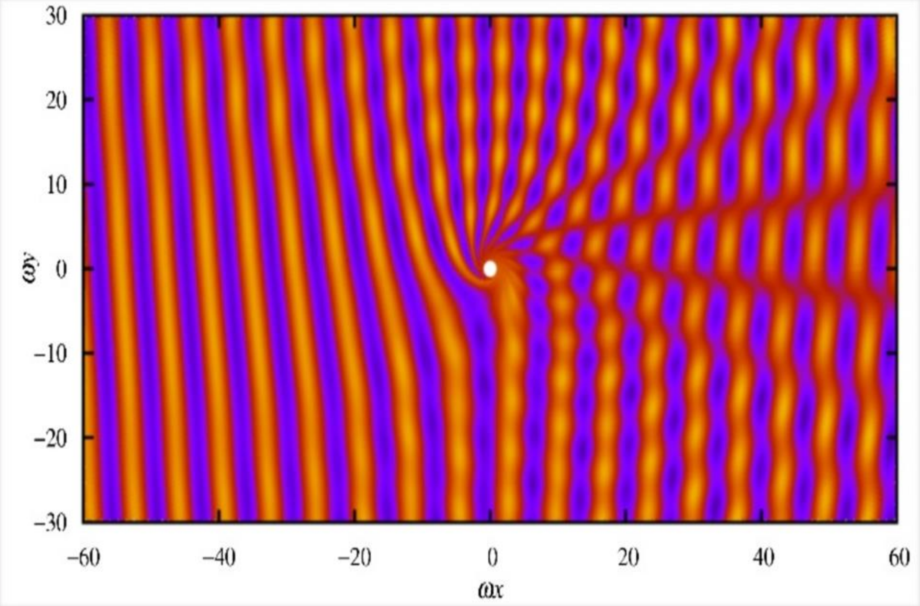
- Small Amplitude

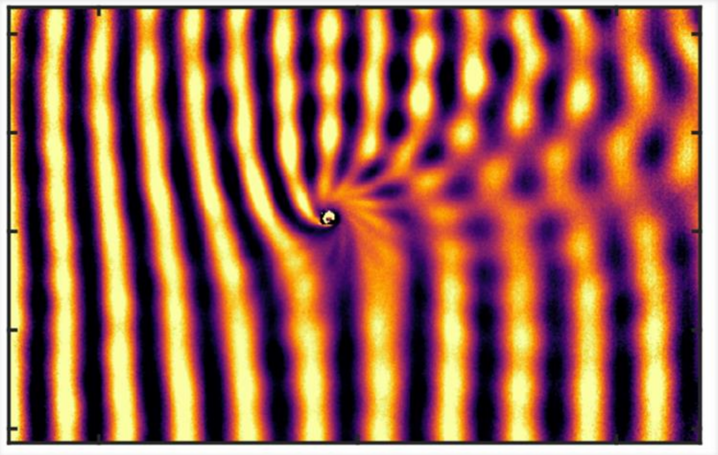


Free surface at 3.70 Hz



Numerical simulation by Dolan, S. & Oliveira, E. PRD87, 124038 (2013).

Experimental realisation



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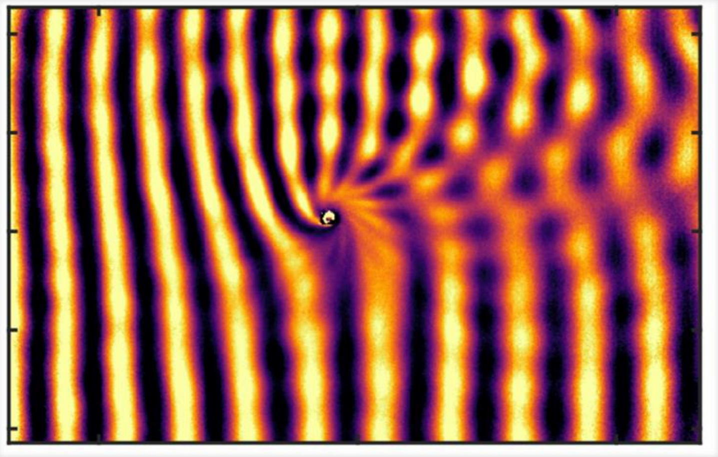
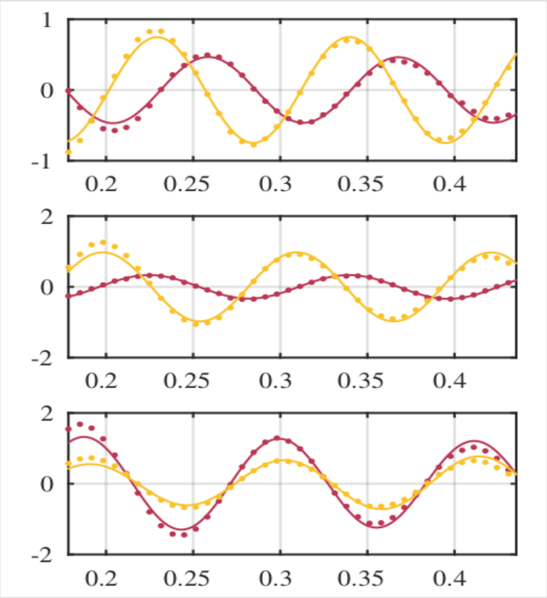


m = -1

m = 0

m = 1



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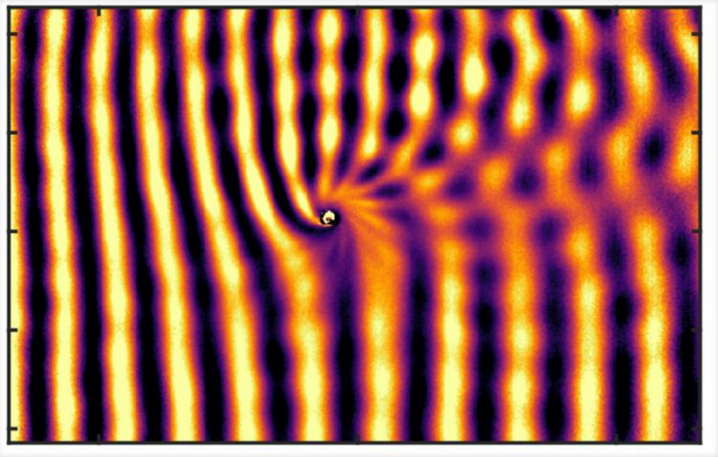

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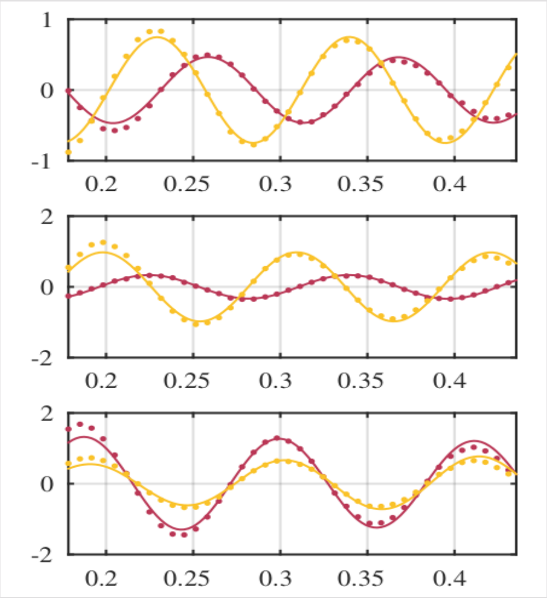
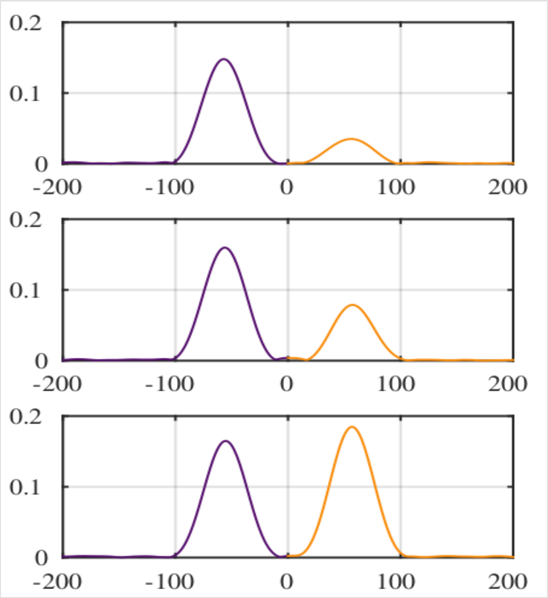


IN OUT



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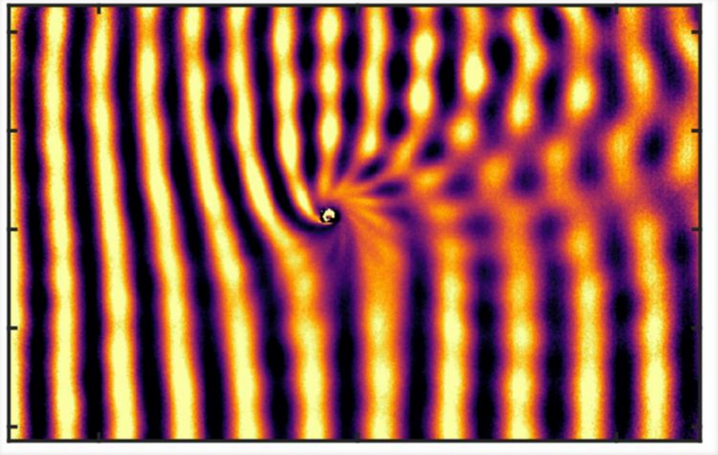

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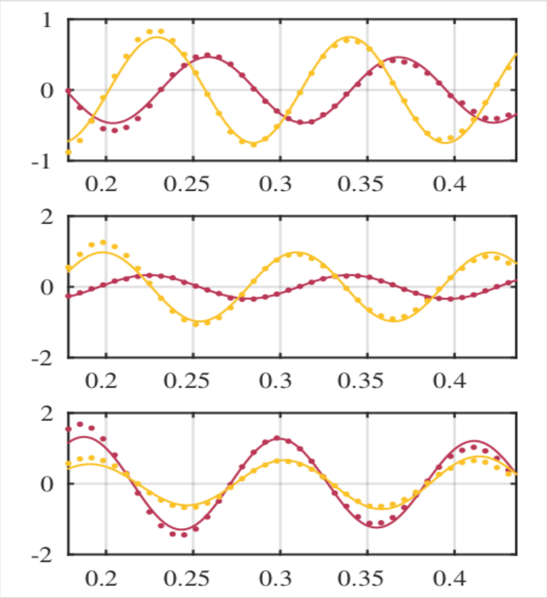

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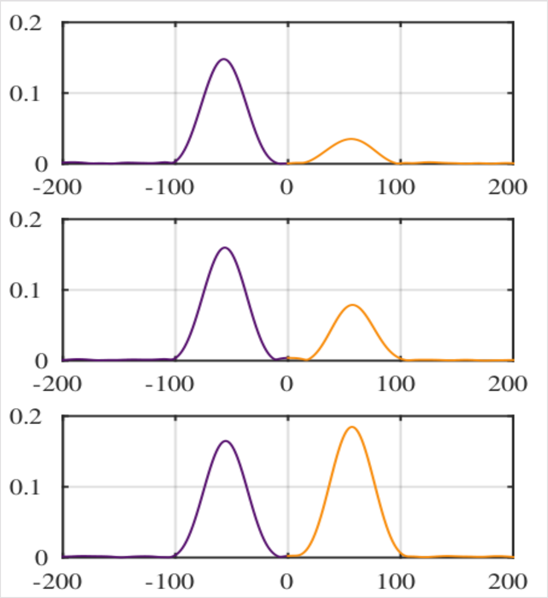
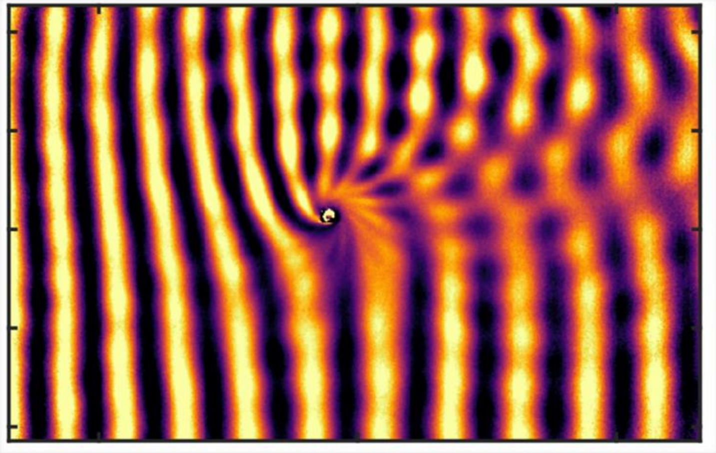


Absorption

Experimental realisation



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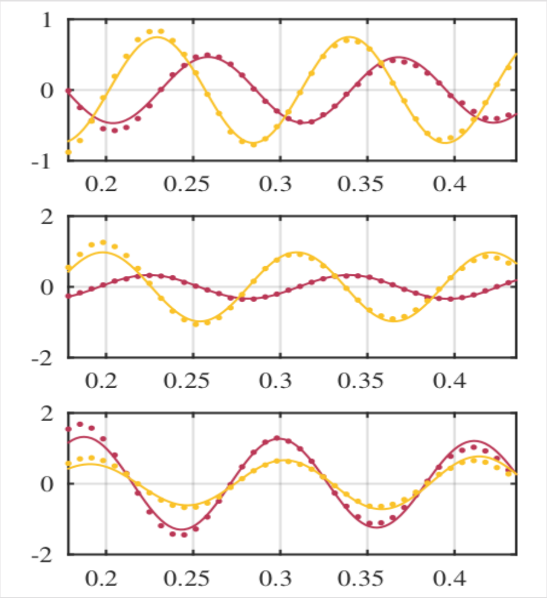

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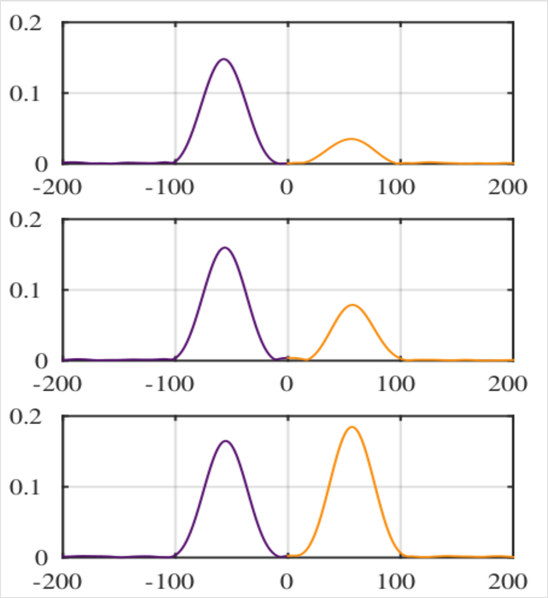
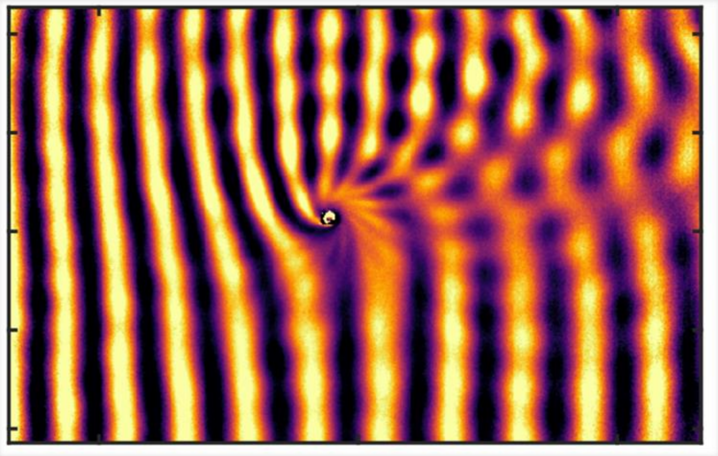
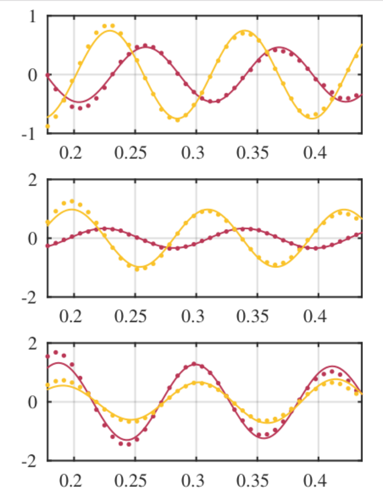


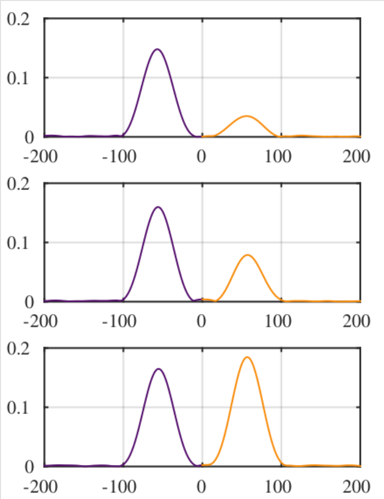
Absorption

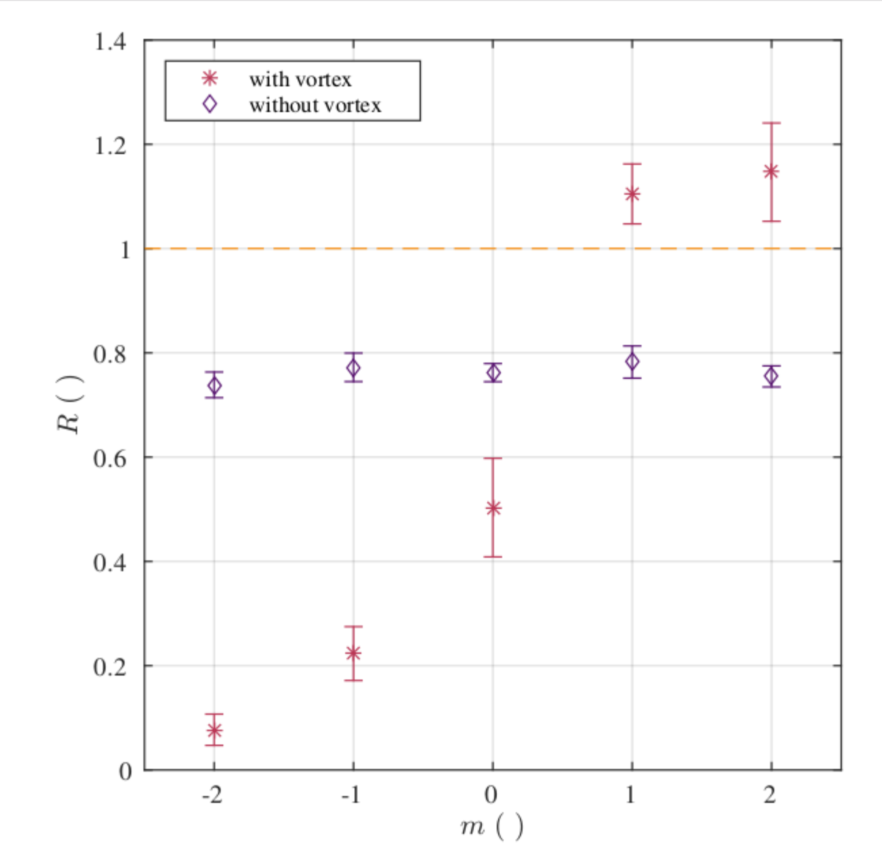
→ Amplification !

Experimental realisation









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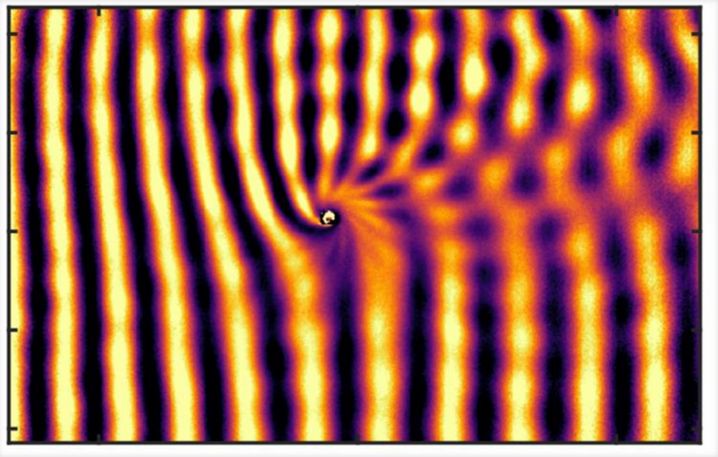
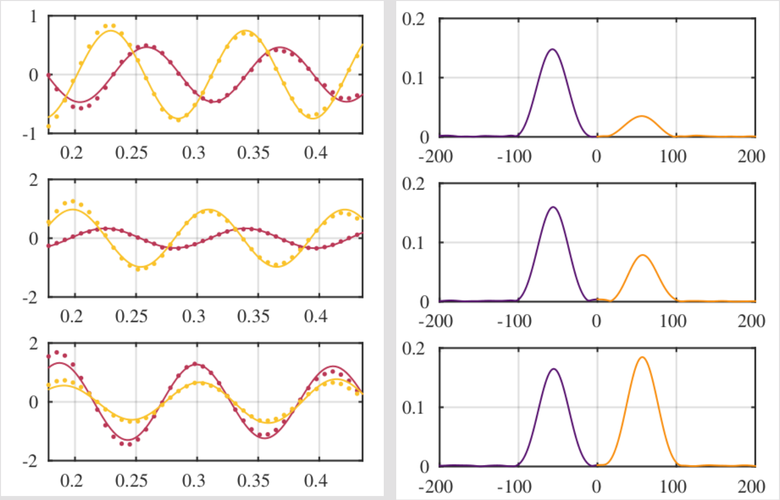
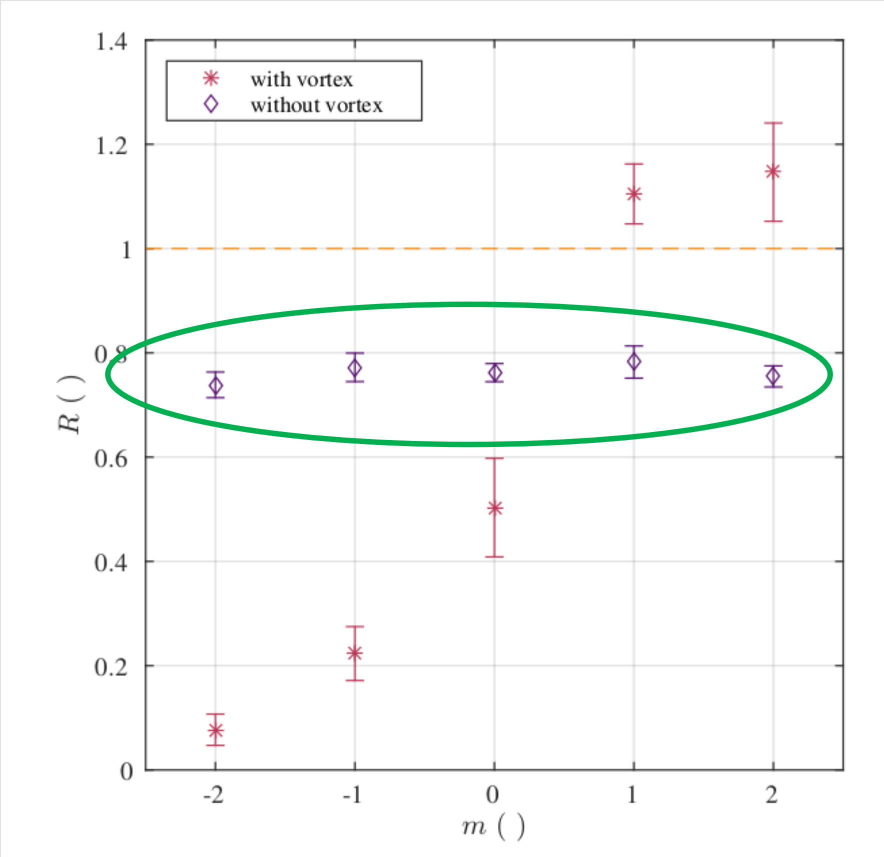
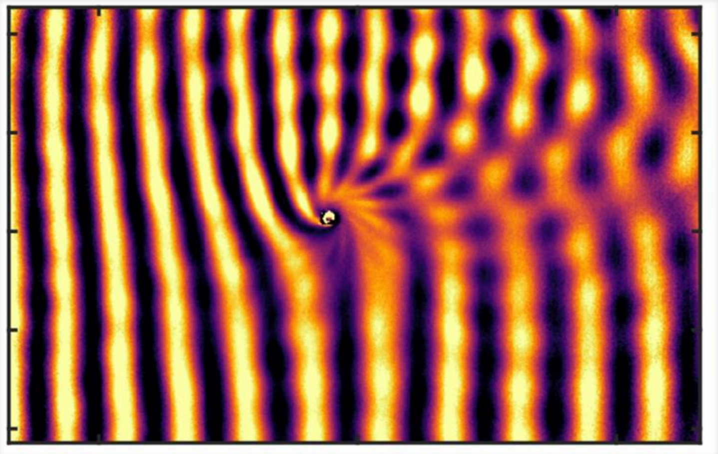


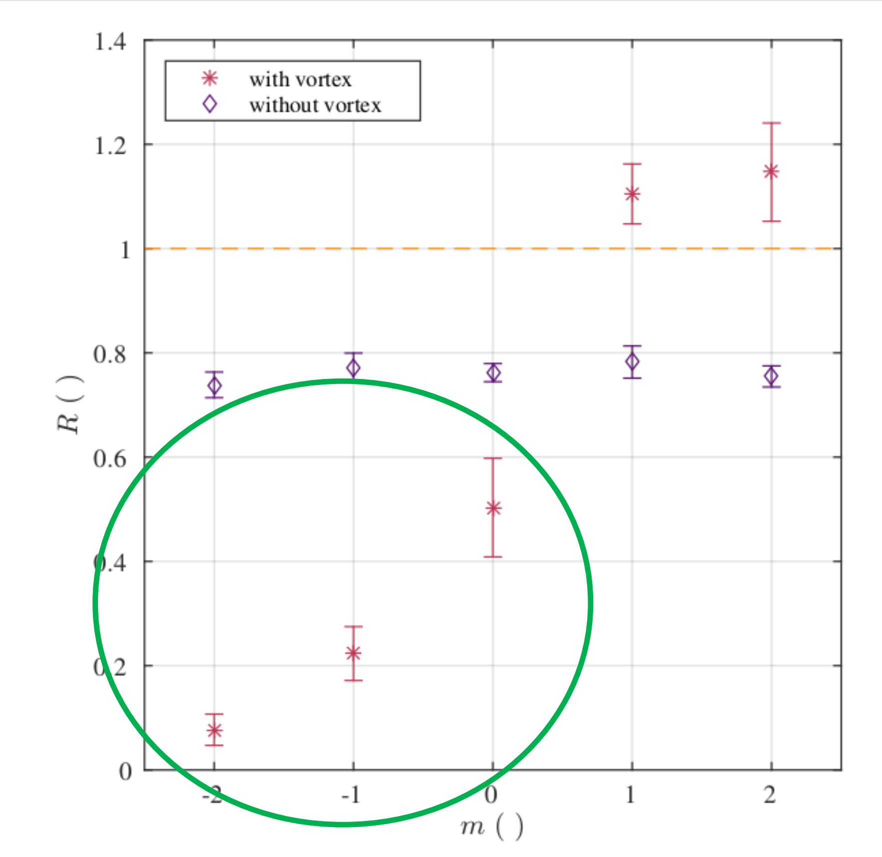




Plane wave absorbed symmetrically

Experimental realisation

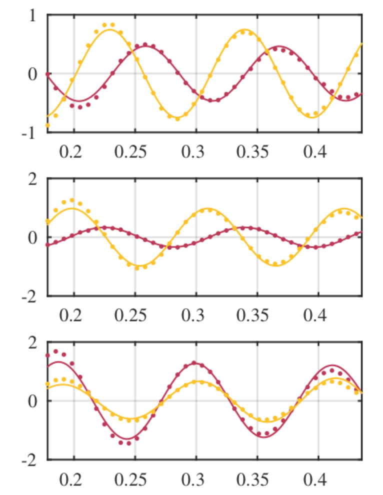


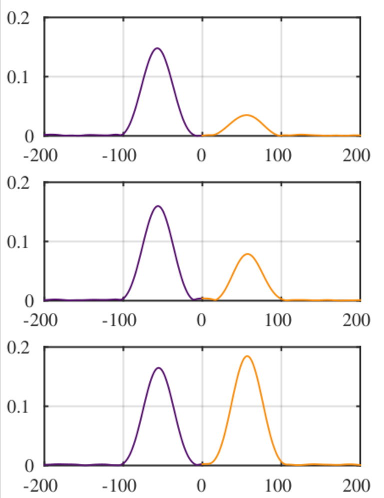


Plane wave absorbed symmetrically

VORTEX

Negative m's are absorbed





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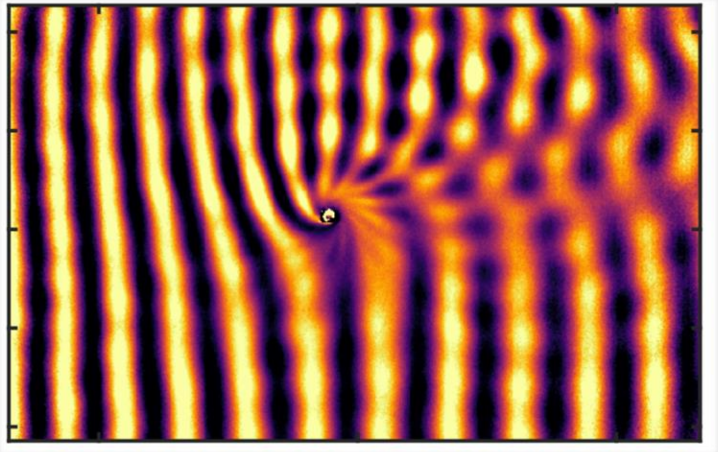

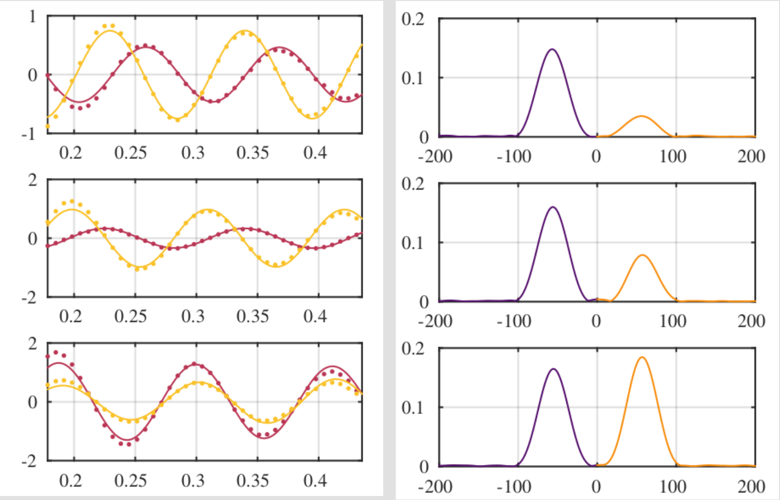

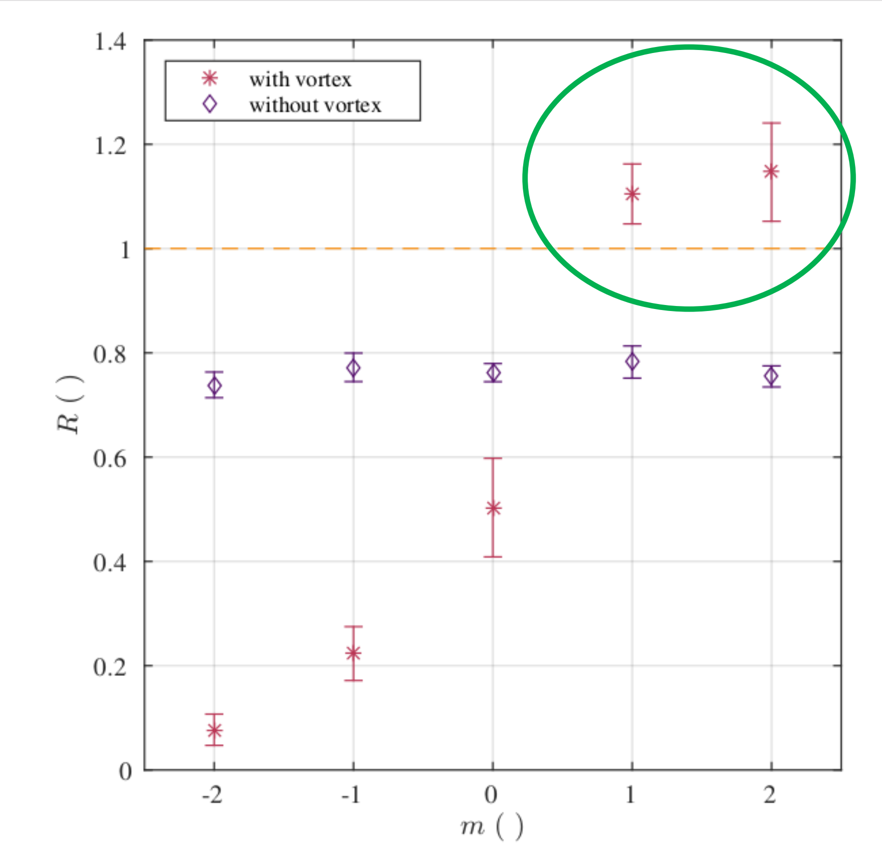

Plane wave absorbed symmetrically

VORTEX

Negative m's are absorbed

Positive m's are <u>amplified</u> ~ 10 - 15%

Results

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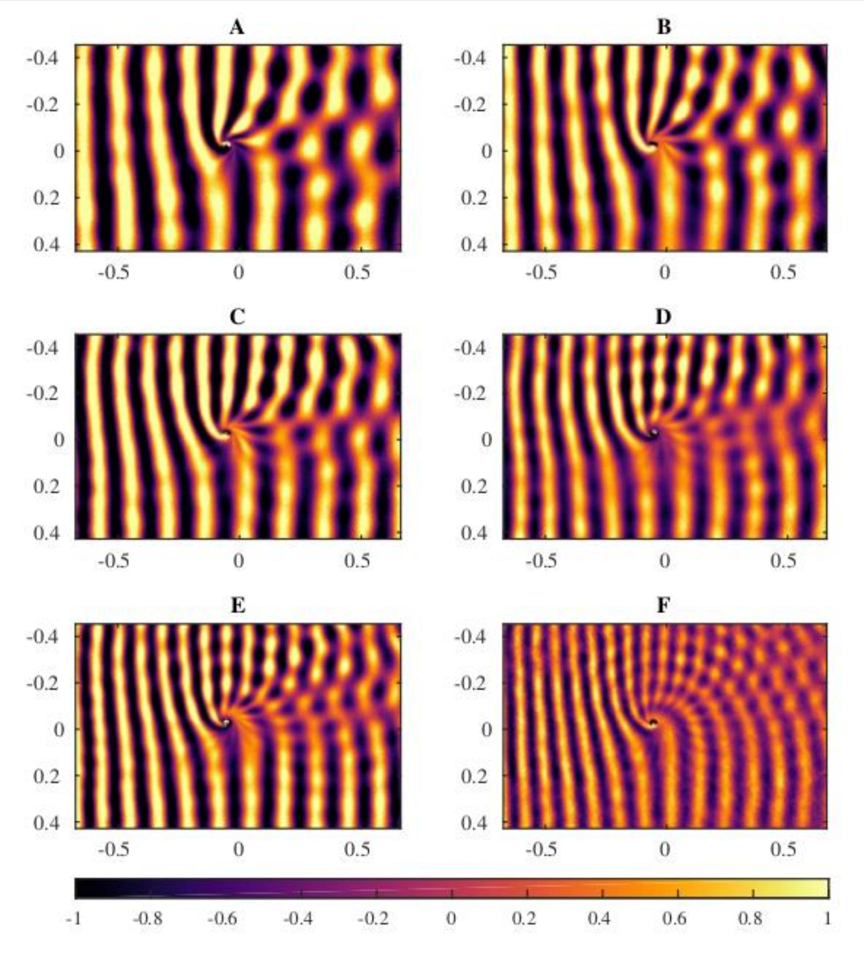

Free surface at various frequency ω
(2.87, 3.04, 3.27, 3.45, 3.70, 4.11 Hz)

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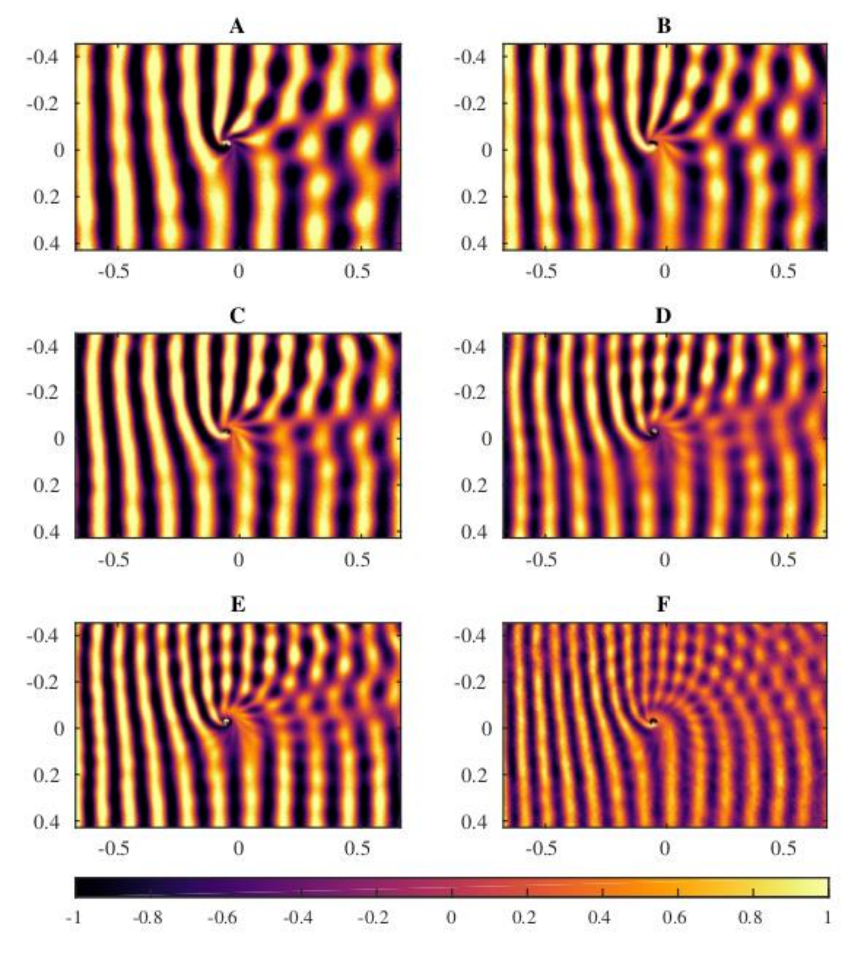

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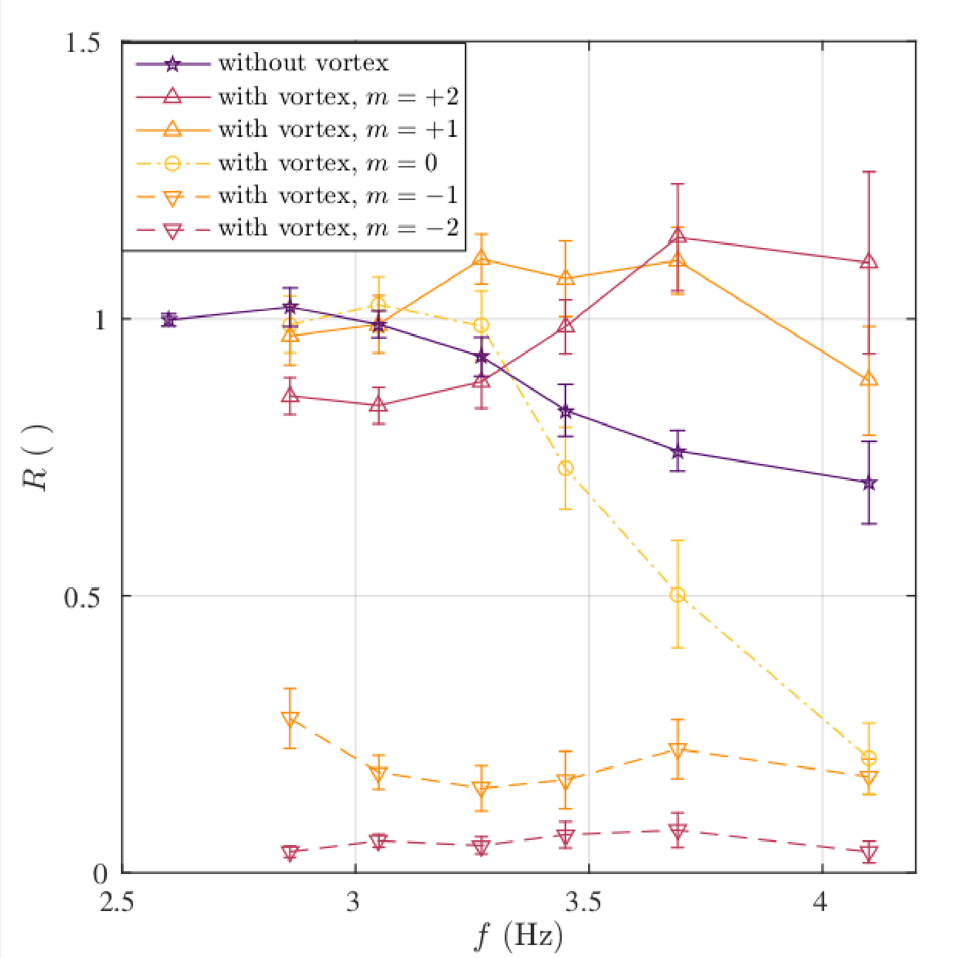

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The superradiance conditions are fulfilled and we were able to make the first detection of this effect in this system !

→ *Rotational superradiant scattering in a vortex flow*, Nature Physics (June 2017), doi : 10.1038/nphys4151

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Theoretical work :

Dispersion (T.T. in preparation)

Rotationnal flow (S. Patrick in preparation)

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→ New ideas on gravity… ?

Thank you !