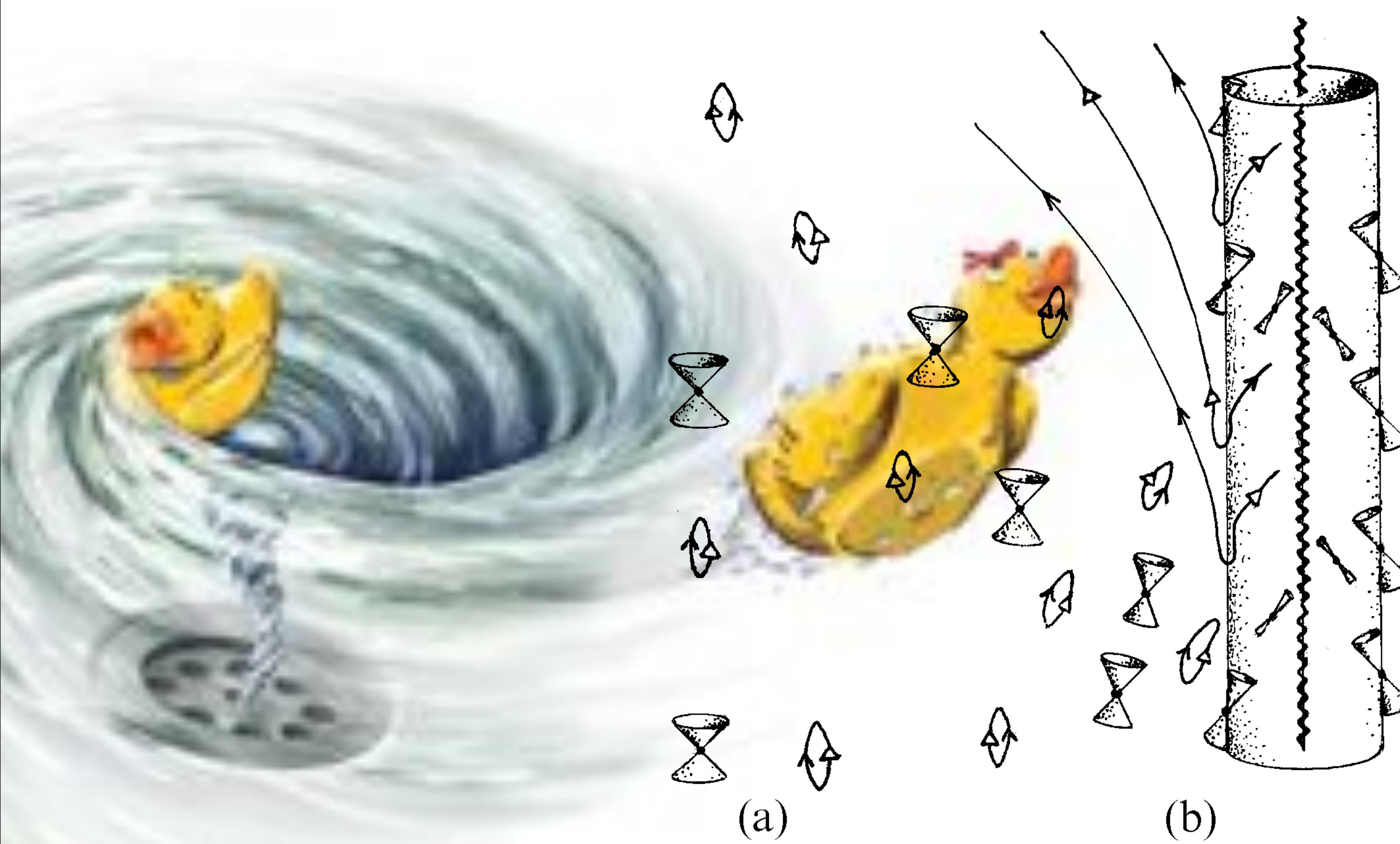
Analogue Gravity: theory & experiment

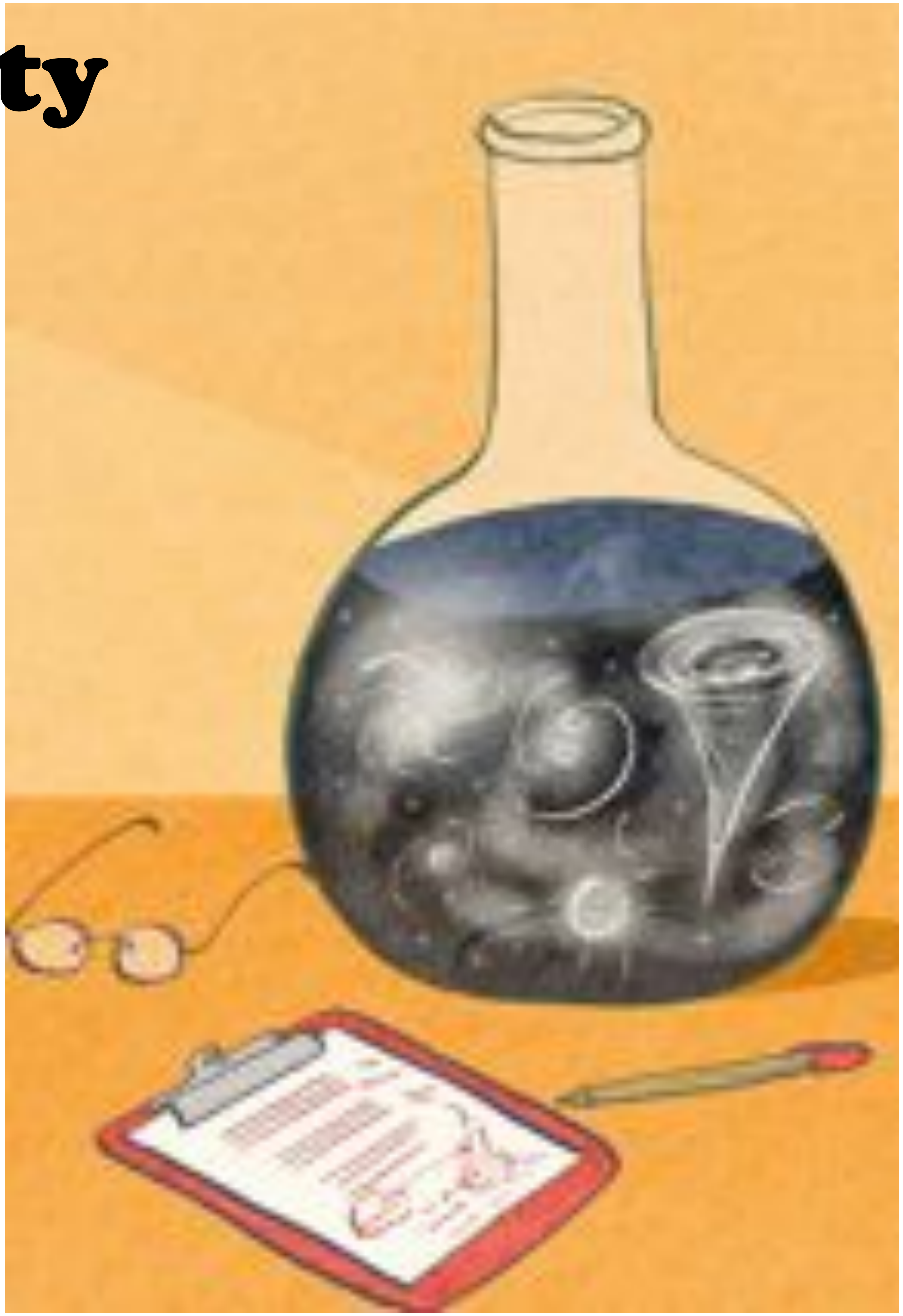
THE ROYAL SOCIETY



http://www.gravitylaboratory.com

Analogue Gravity in a nutshell

analogue simulations of classical and quantum field theory in curved spacetimes



The Big Bang Theory

The Big Bang Theory

Black hole horizons *in gravity*

A **black hole** is a region of spacetime from which **gravity prevents** <u>**anything**</u>**, including light, from escaping.**

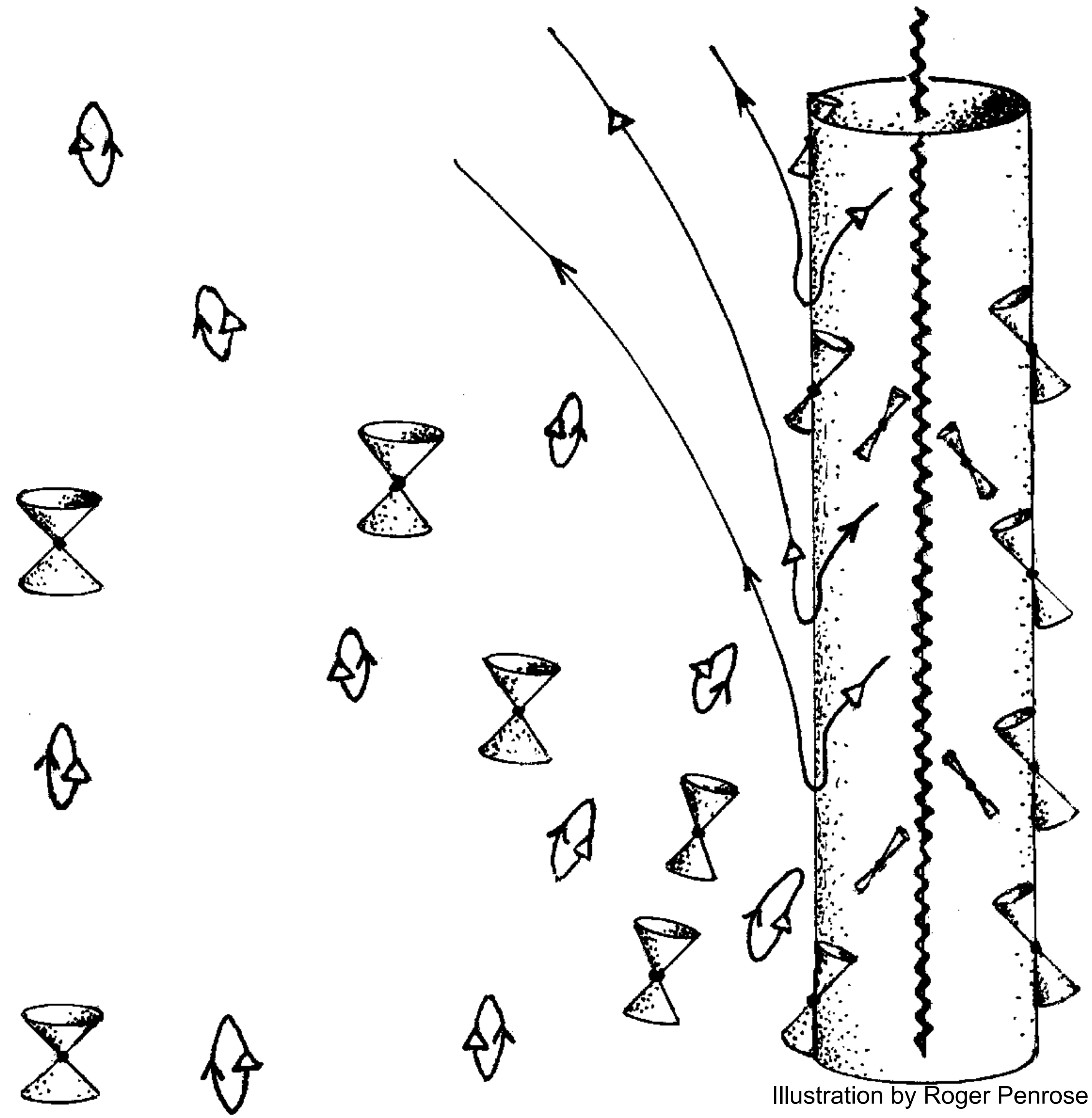


Illustration by Roger Penrose

Black hole horizons *in gravity*

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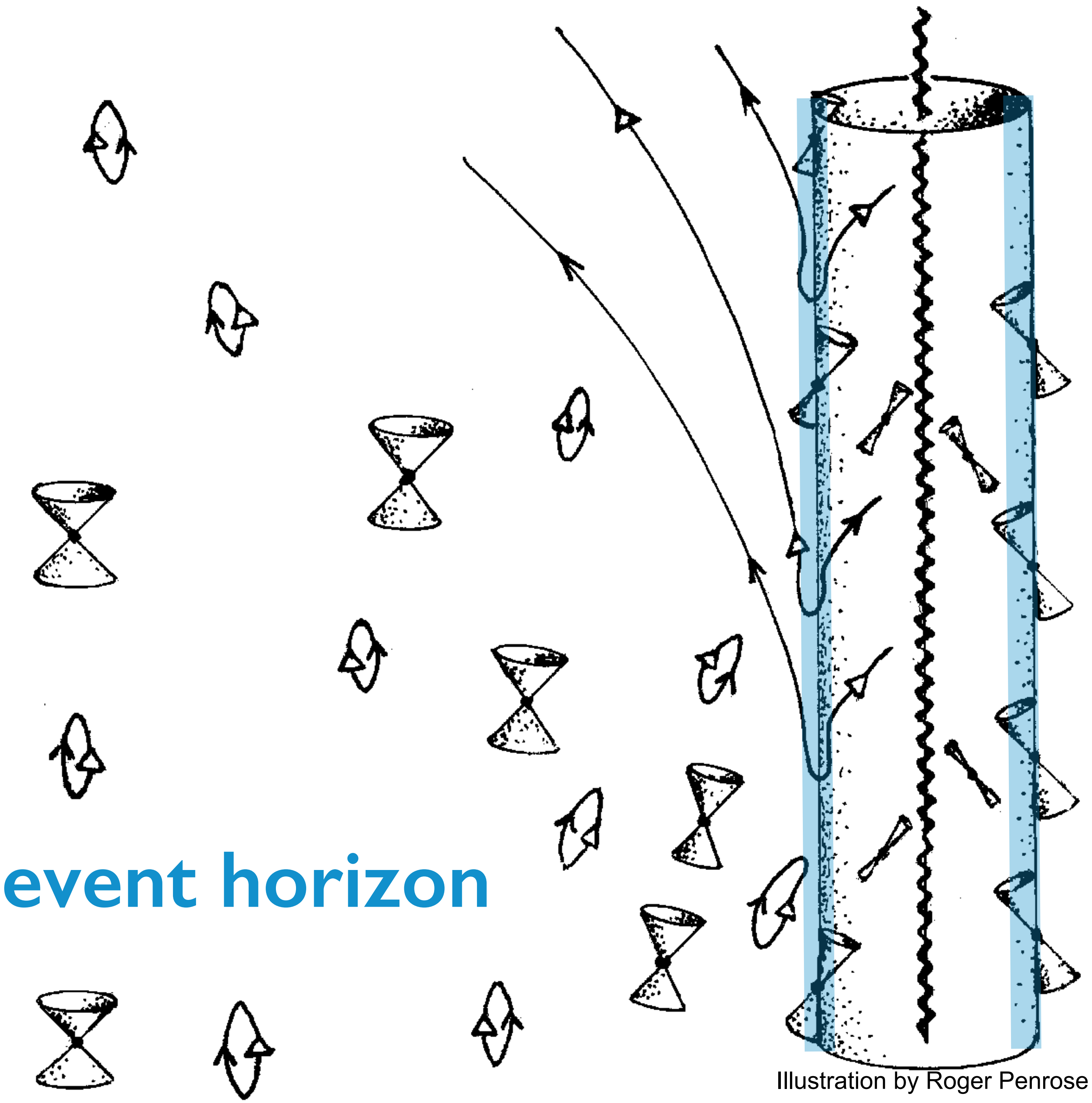

Illustration by Roger Penrose

point of no return = event horizon

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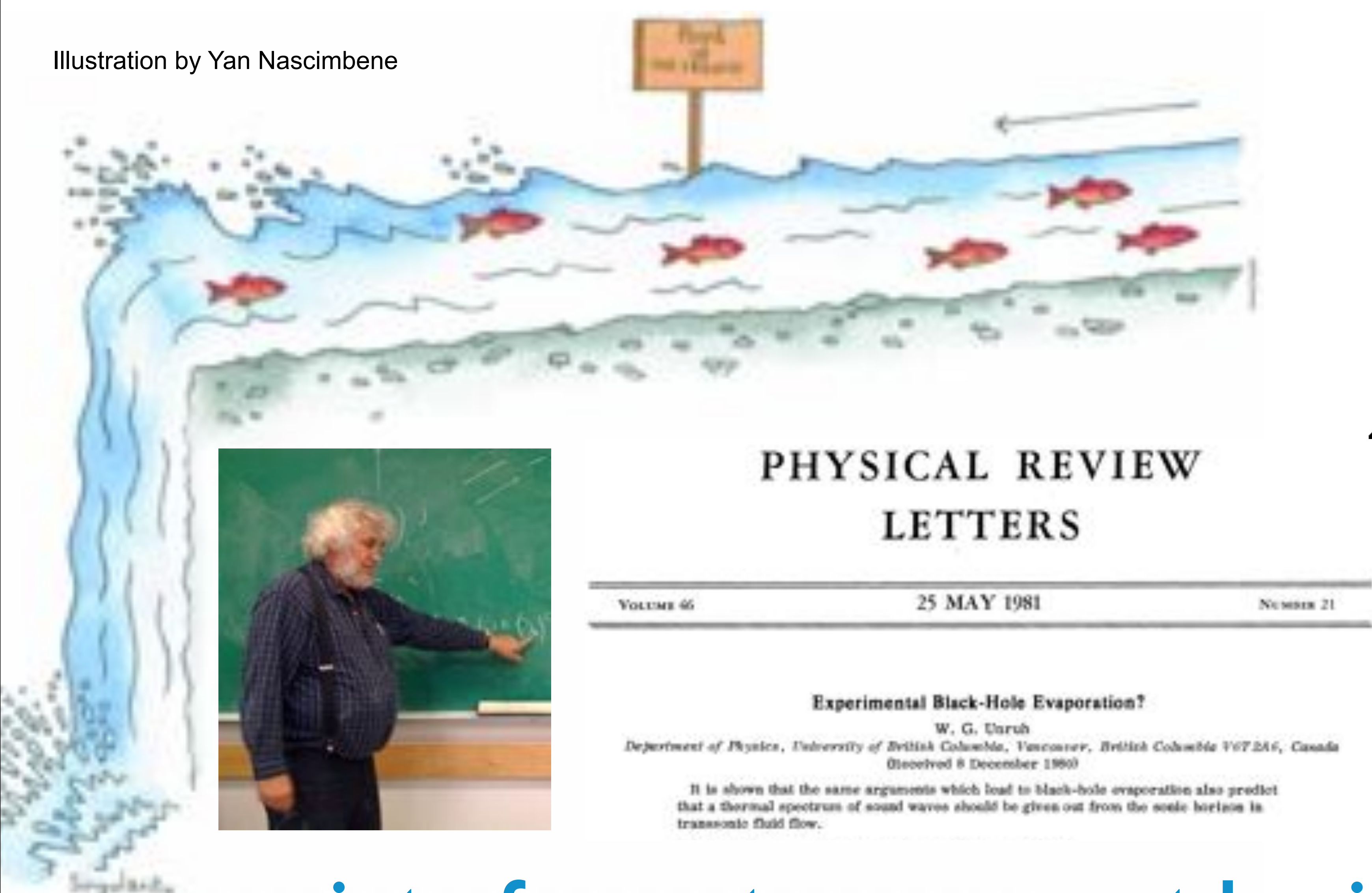
Black hole horizons *in gravity*

Illustration by Yan Nascimbene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Experimental Black-Hole Evaporation?

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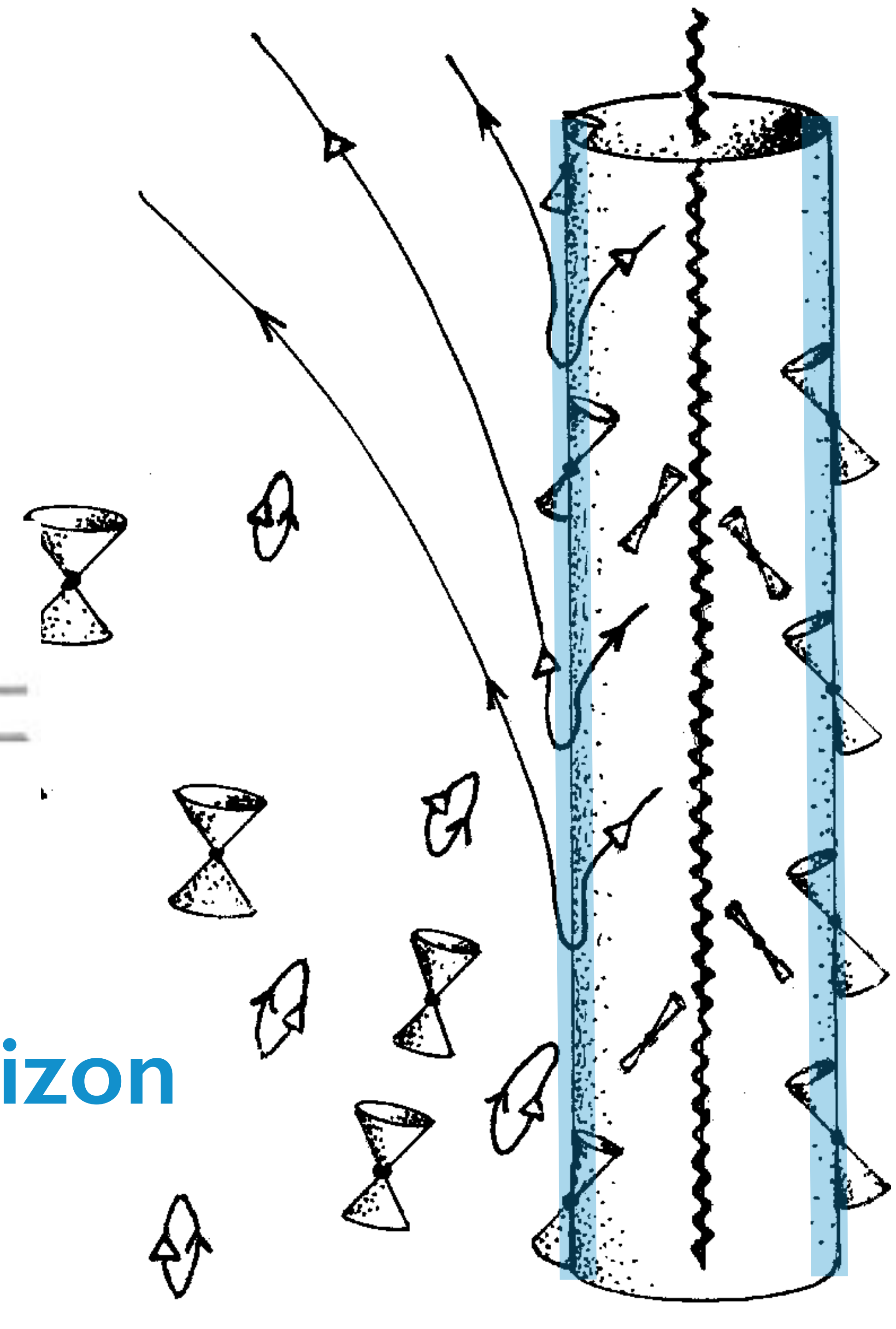
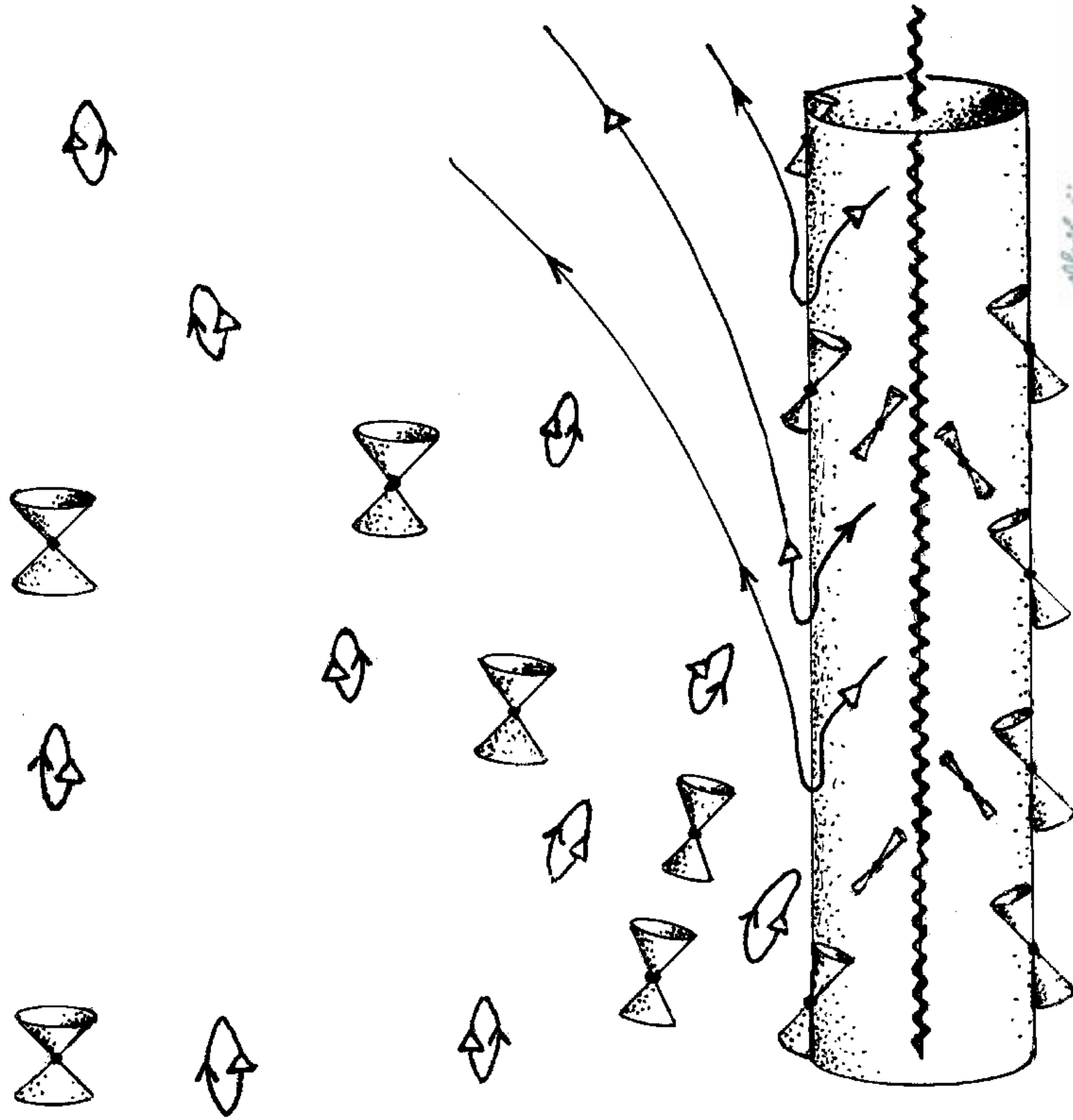
(Received 8 December 1980)

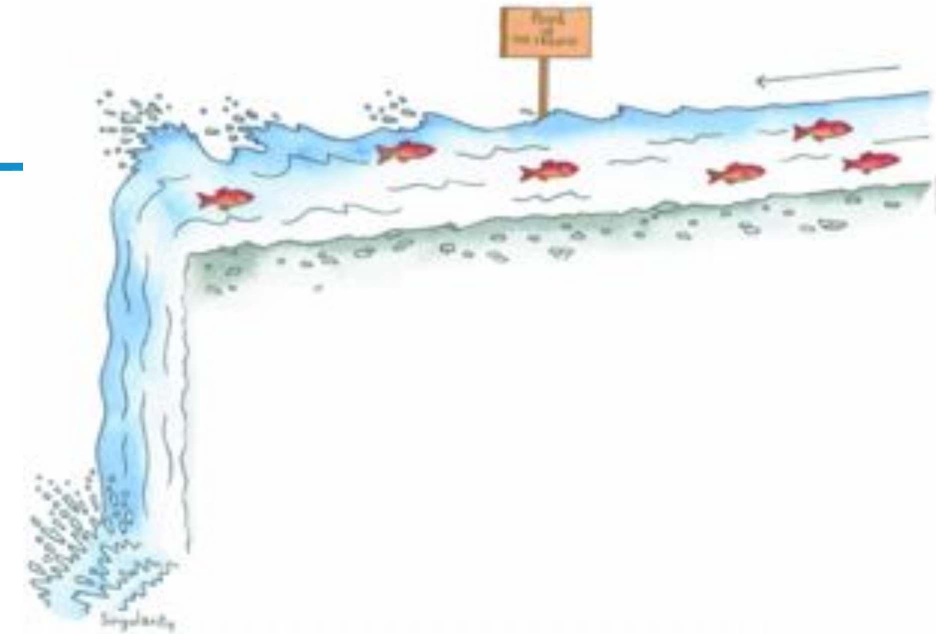
It is shown that the same arguments which lead to black-hole evaporation also predict that a thermal spectrum of sound waves should be given out from the sonic horizon in transonic fluid flow.



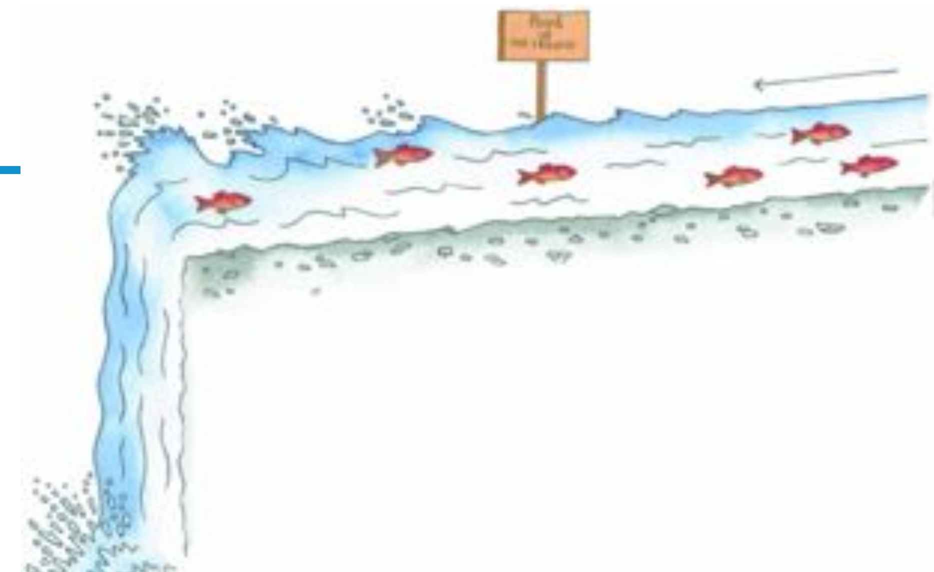
point of no return = event horizon

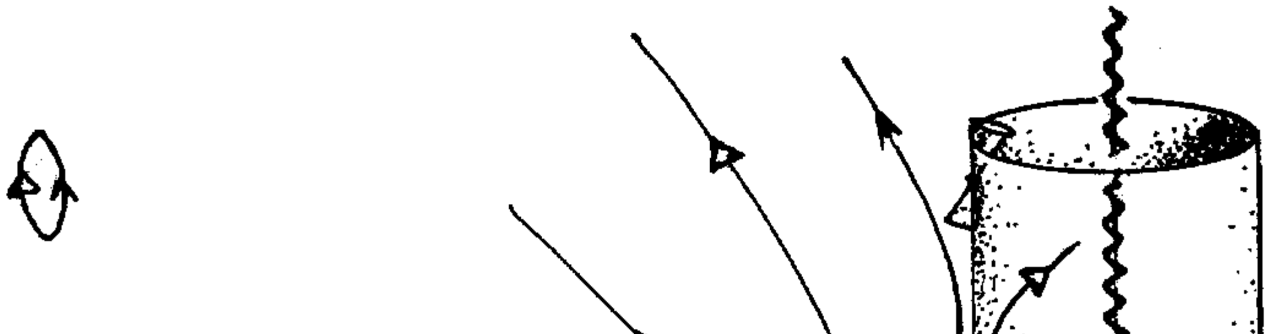
Black hole horizons *in fluids*

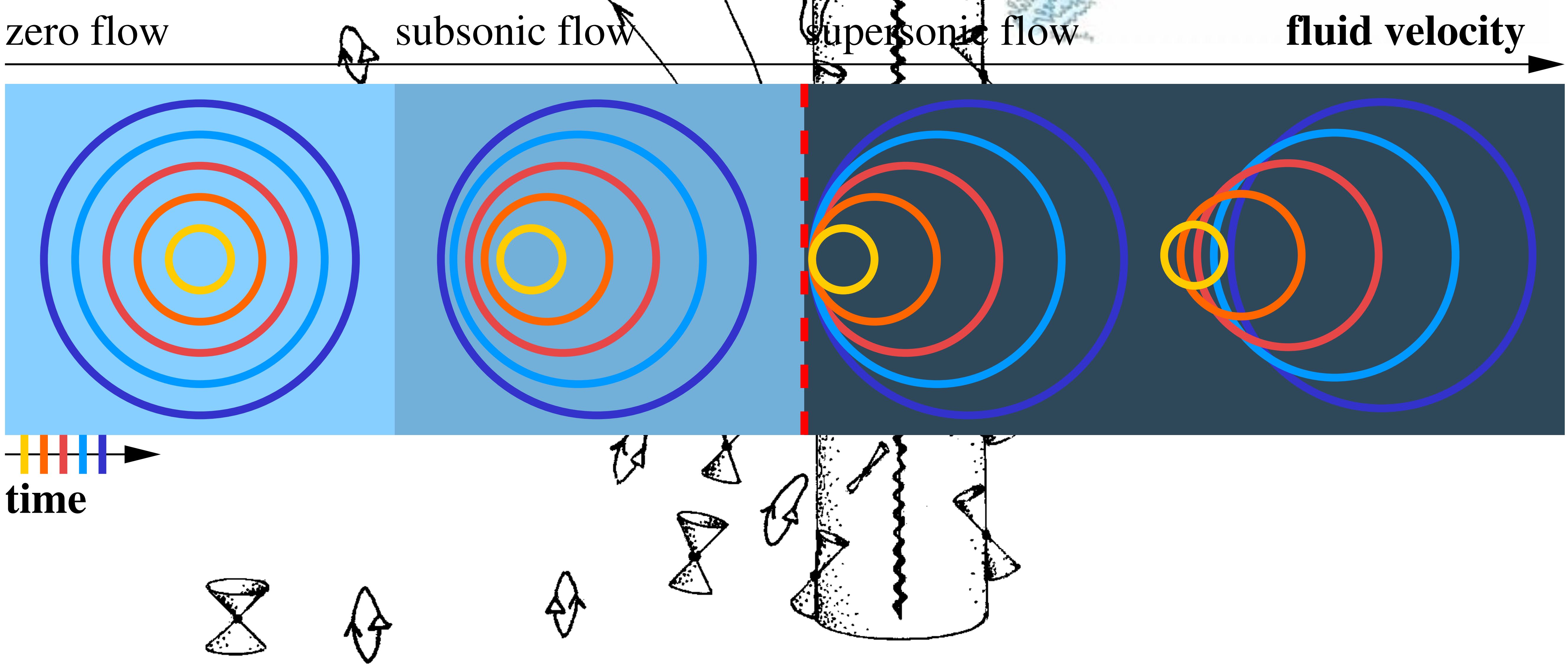




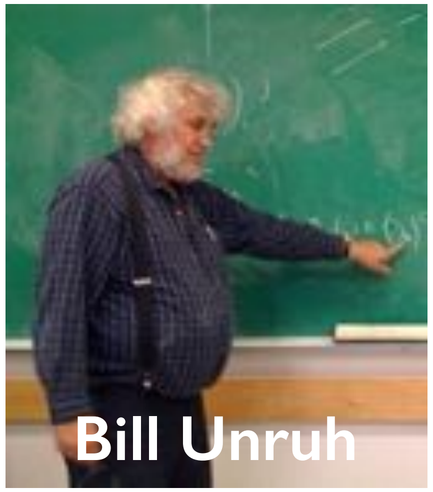
Black hole horizons *in fluids*



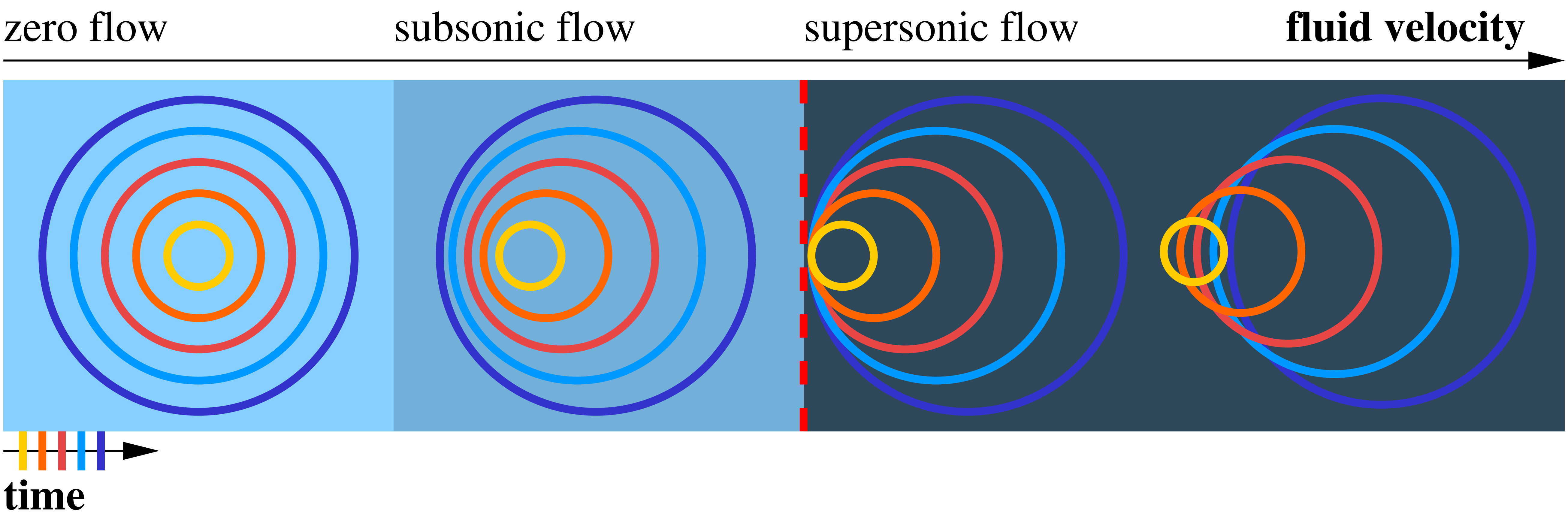




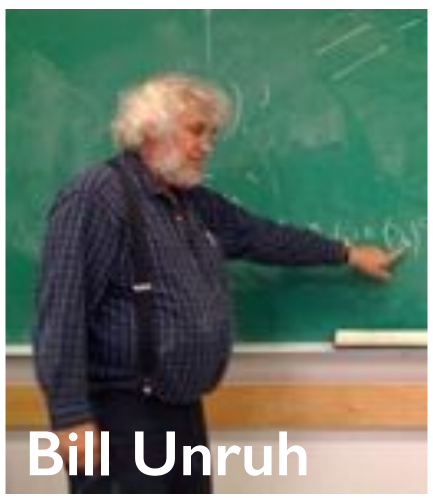
Analogue gravity



fluids can exhibit effective horizons
as seen by small fluctuations
(e.g. sound waves and surface waves)



Analogue gravity *a strong analogy*



The **equations of motion for linear perturbations** in an analogue/effective/emergent gravity system experience an effective/acoustic/emergent metric tensor (an effective gravitational field).

Simple example:

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

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

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

Simple example:

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

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

↓

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

$$\partial_a\left(\sqrt{-g}\,g^{ab}\partial_b\,\psi\right) = 0 \quad \text{where} \quad g_{ab} = \begin{bmatrix} g_{00}(\mathbf{x},t) & g_{01}(\mathbf{x},t) & g_{02}(\mathbf{x},t) & g_{03}(\mathbf{x},t) \\ g_{01}(\mathbf{x},t) & g_{11}(\mathbf{x},t) & g_{12}(\mathbf{x},t) & g_{13}(\mathbf{x},t) \\ g_{02}(\mathbf{x},t) & g_{12}(\mathbf{x},t) & g_{22}(\mathbf{x},t) & g_{23}(\mathbf{x},t) \\ g_{03}(\mathbf{x},t) & g_{13}(\mathbf{x},t) & g_{23}(\mathbf{x},t) & g_{33}(\mathbf{x},t) \end{bmatrix}$$

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.

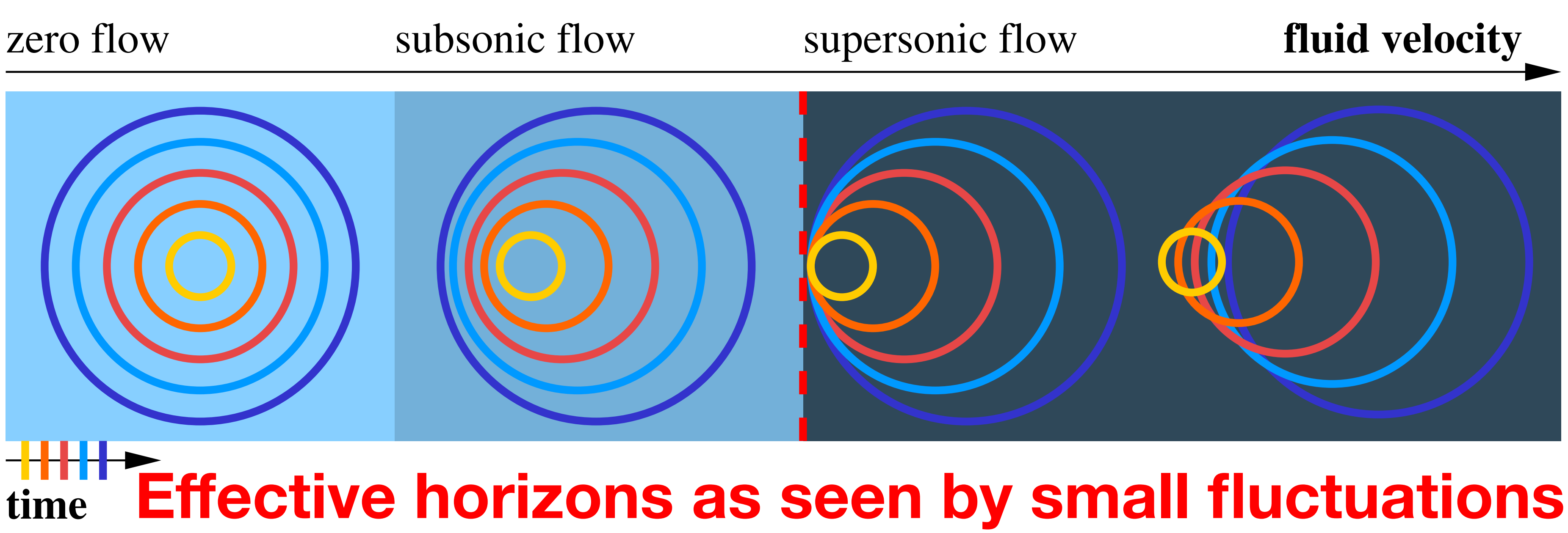
In example below: Fluid dynamics derived from conservation laws:

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

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

Simple example:

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

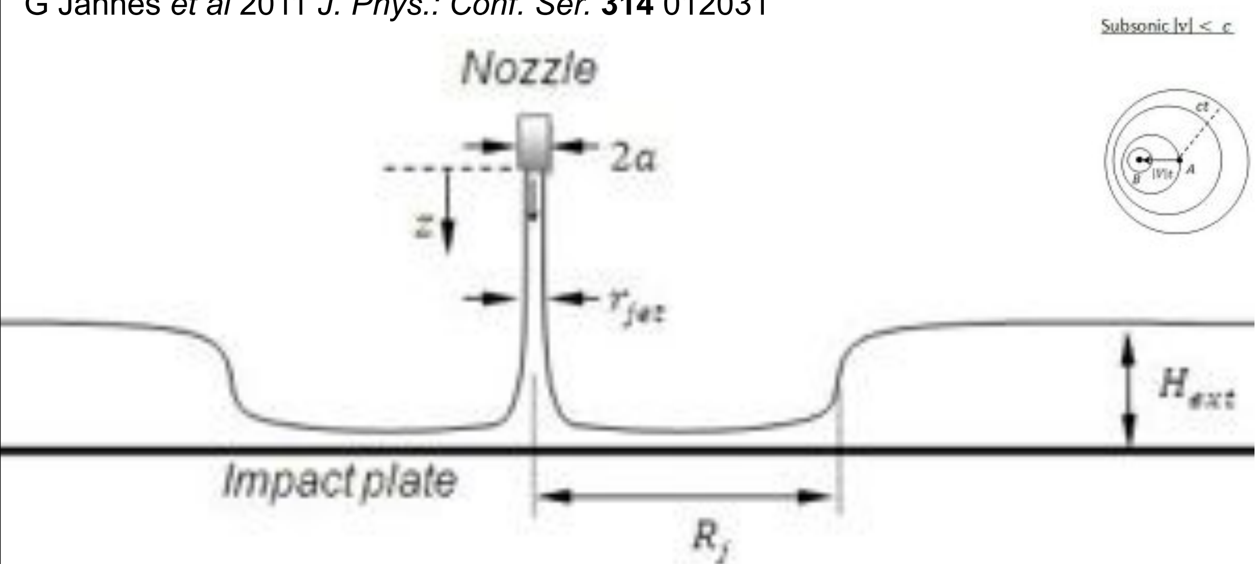


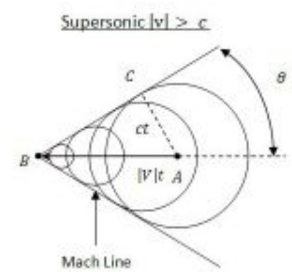
Effective horizons as seen by small fluctuations

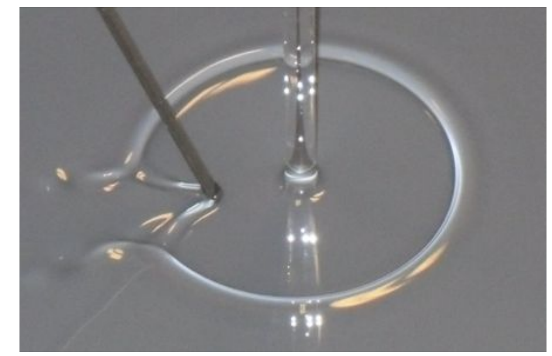
1981: W.G. Unruh

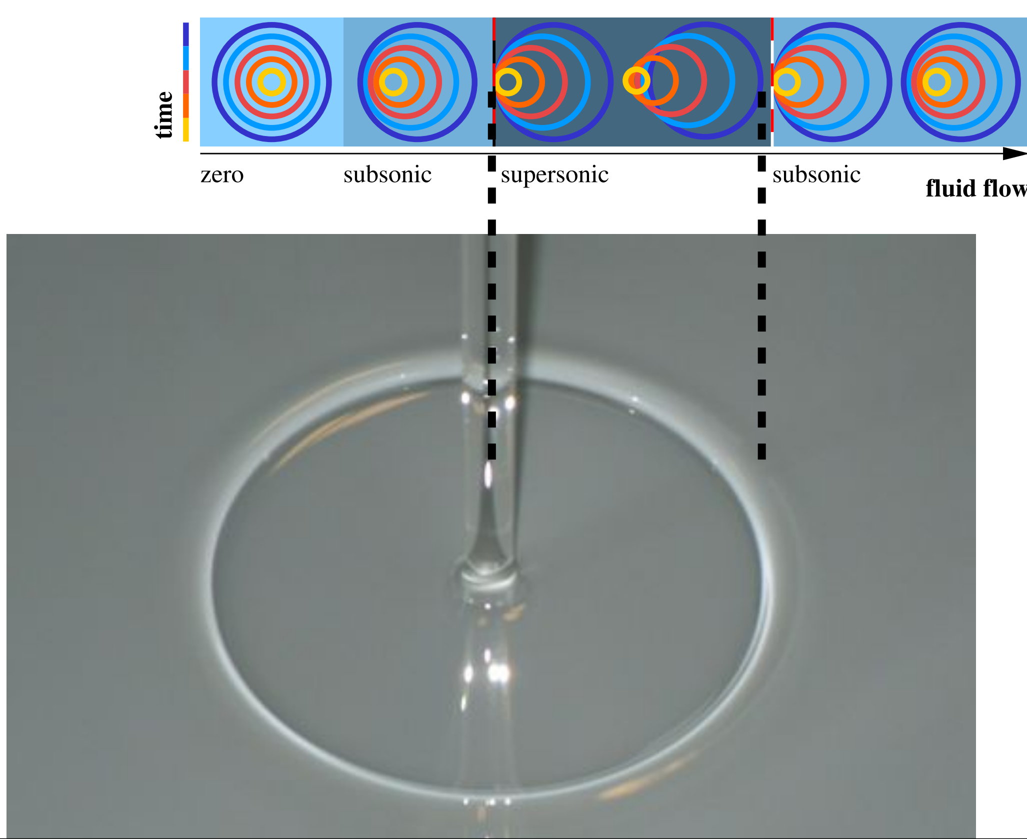
Analogue spacetimes *do they exist in nature?*

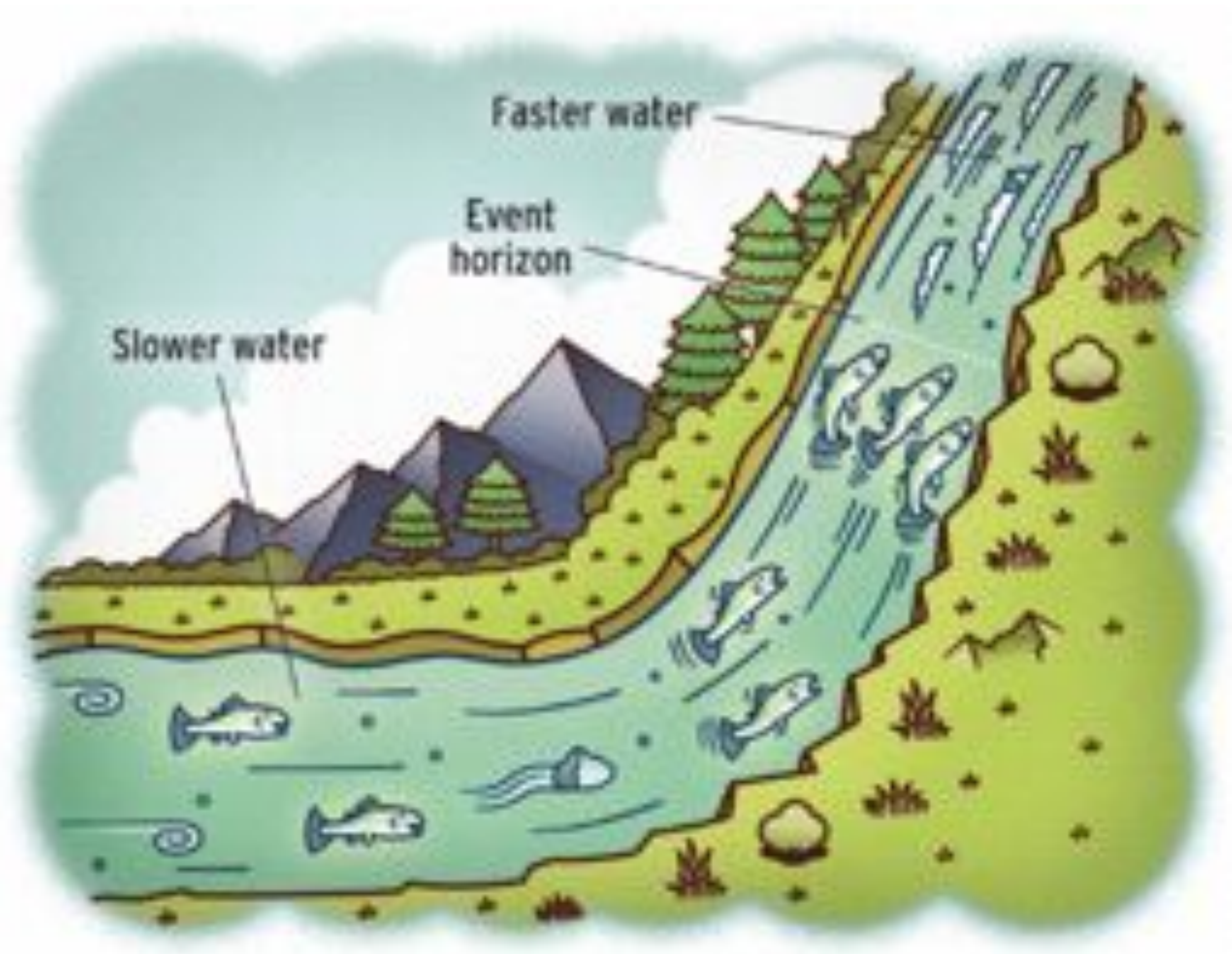
G Jannes *et al* 2011 *J. Phys.: Conf. Ser.* **314** 012031











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Analogue spacetimes *do they exist in nature?*

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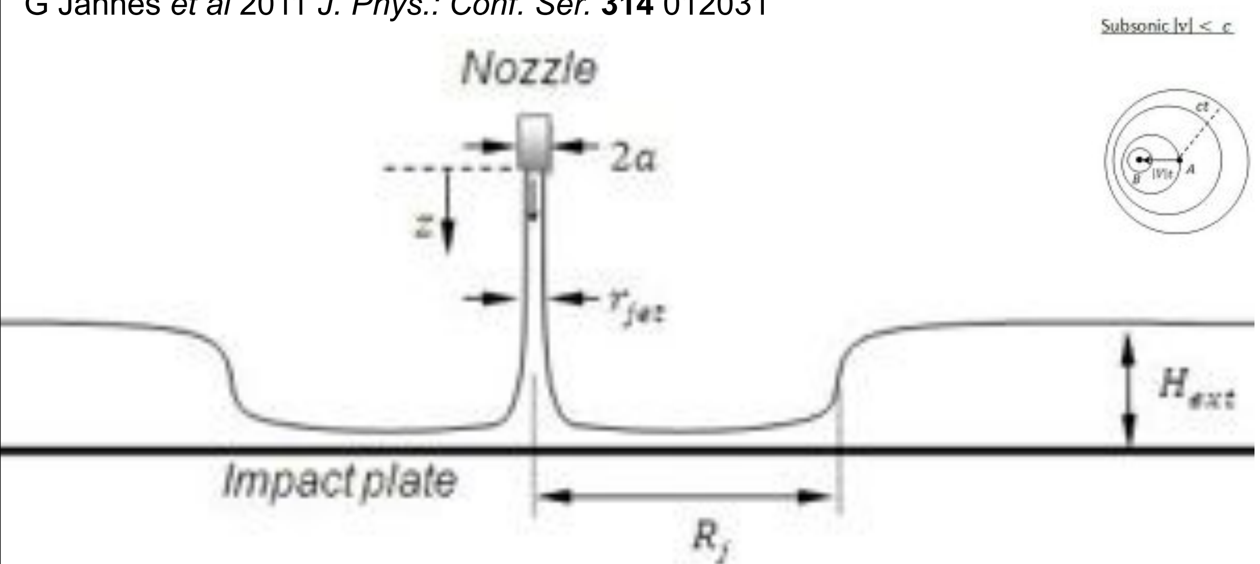

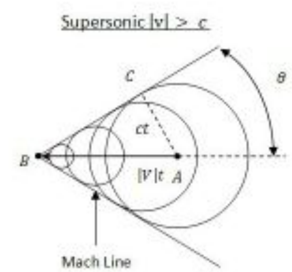

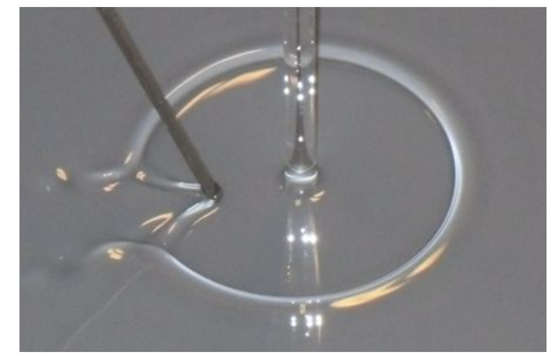

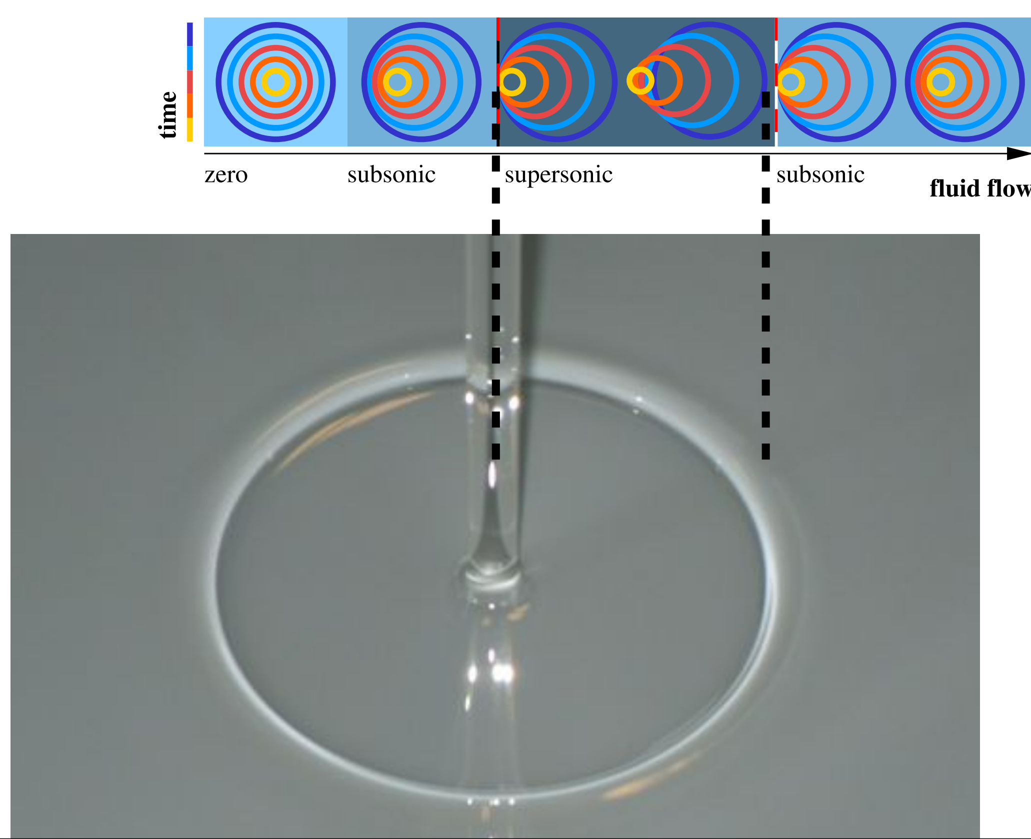

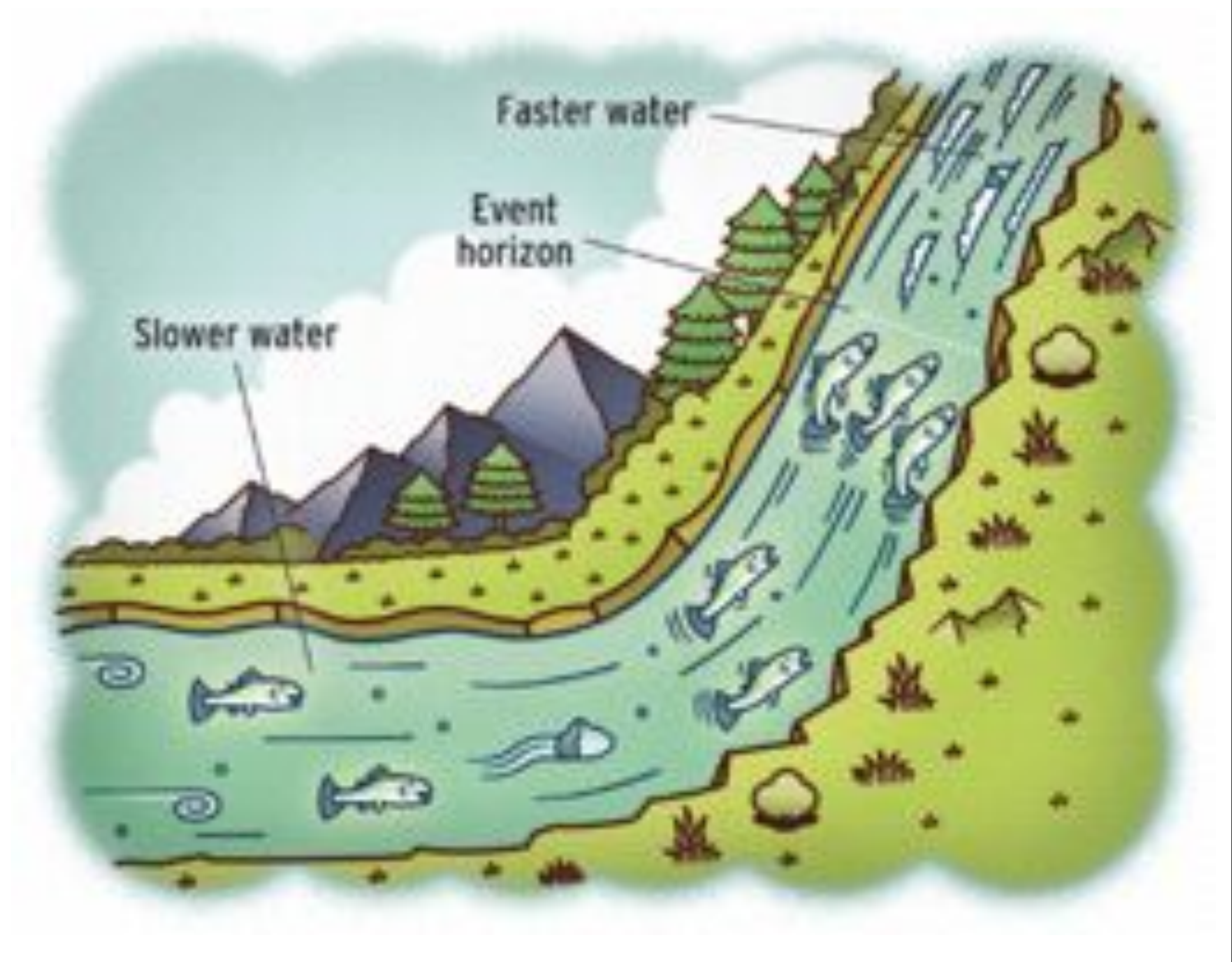

Analogue spacetimes *do they exist in nature?*

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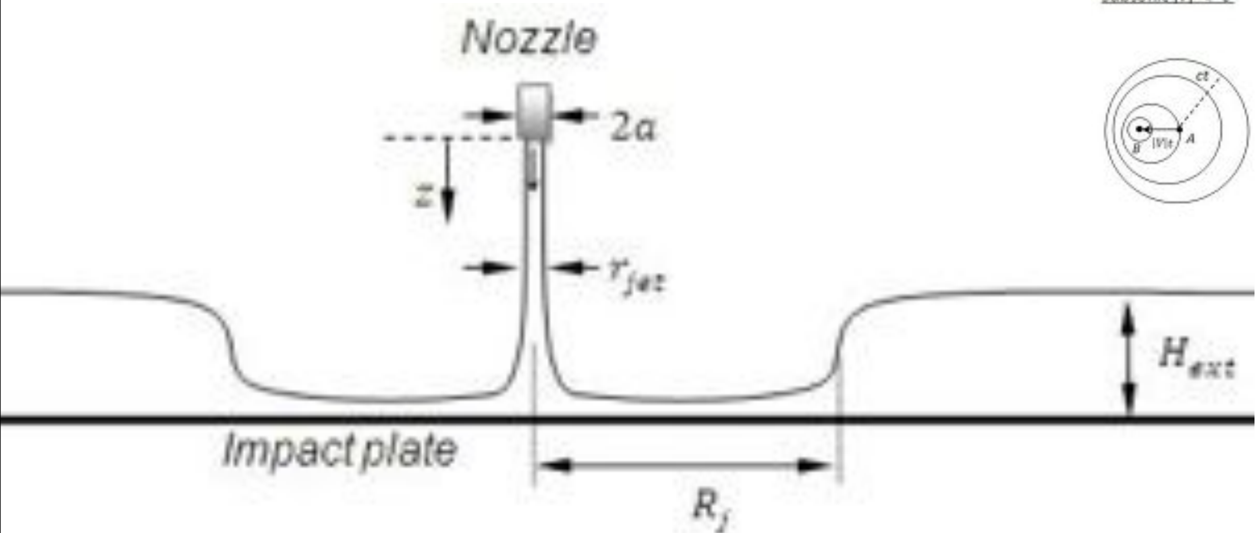
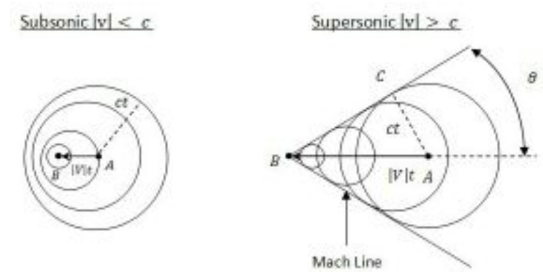
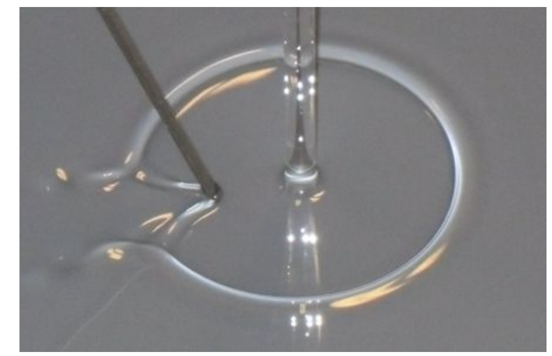
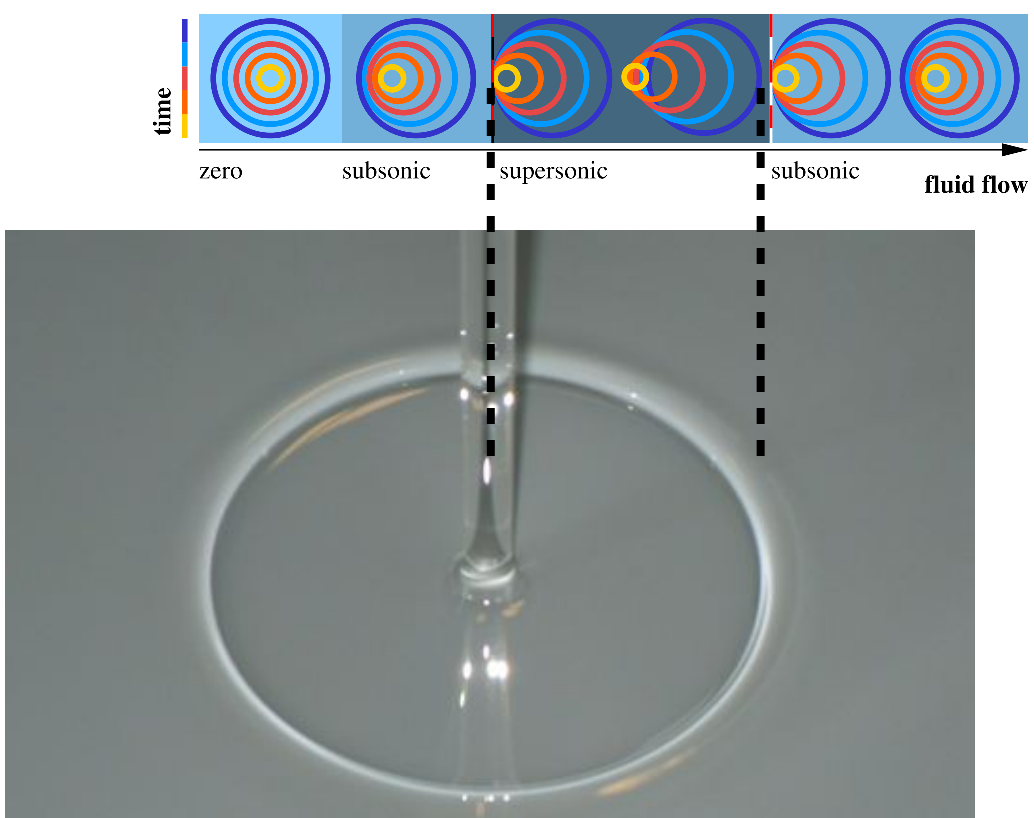


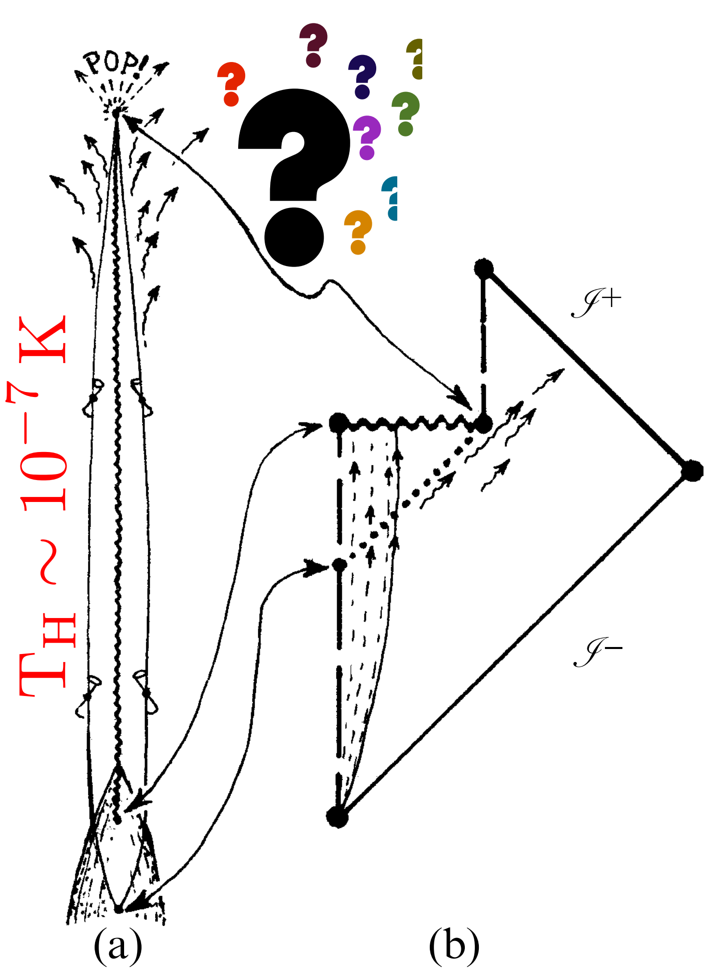




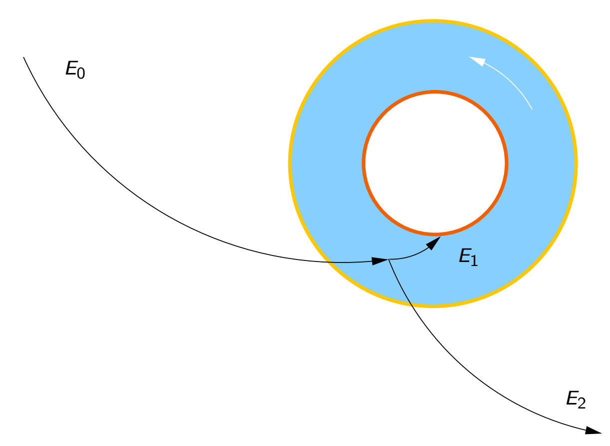


Analogue gravity *applications*

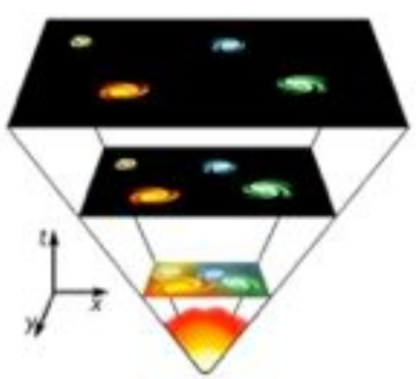
1981: **Experimental black hole evaporation?**



Experimental Black Hole Evaporation



Superradiant scattering from rotating black holes



Cosmological particle production

Possibility for experimental verification of some of the exotic effects predicted to occur in our universe!

Big Bang Theory *small corrections...*

Hawking
wants to detect
Unruh radiation

→

Unruh
wants to detect
Hawking radiation

in a hydrodynamic system

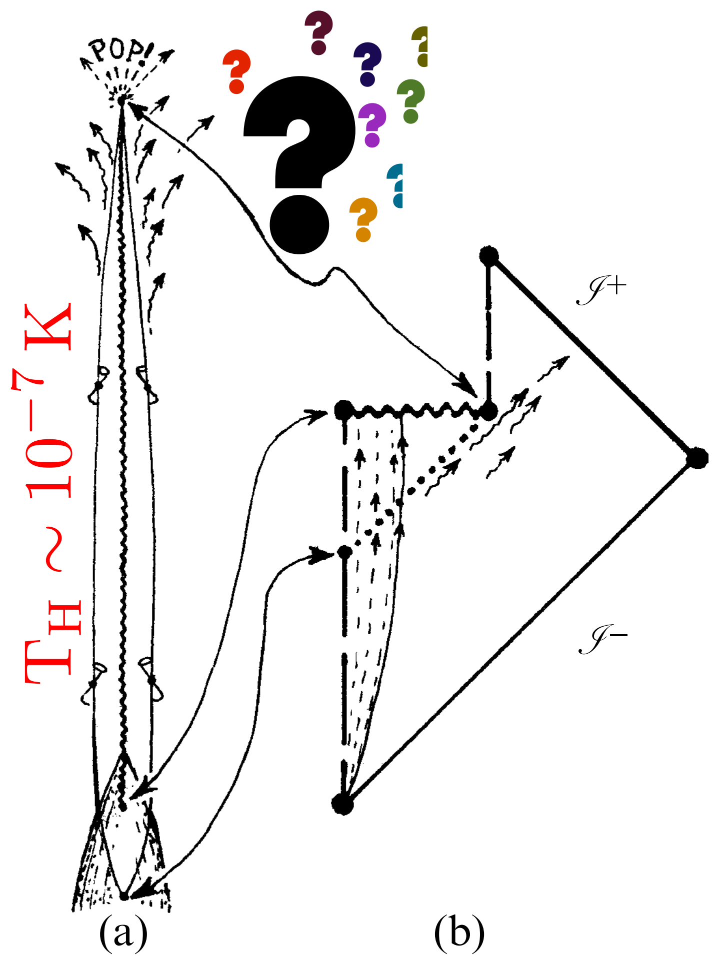
at the North Pole

→

in an **undergraduate laboratory** in Canada

Black hole evaporation *in the laboratory*

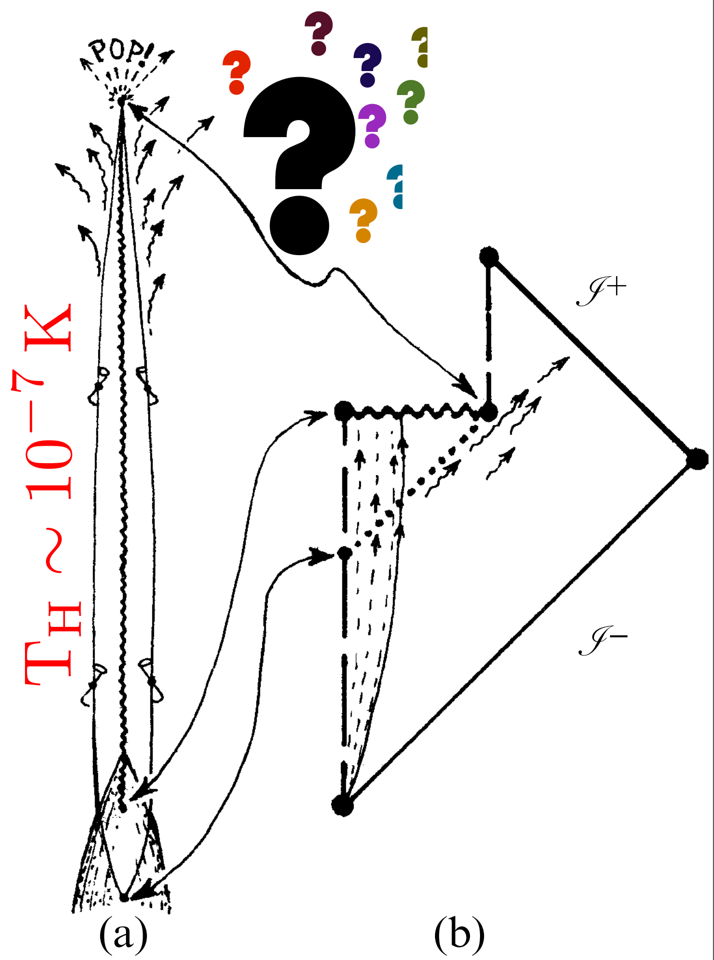
1981: **Experimental black hole evaporation?**



Experimental Black Hole Evaporation

Illustration by David Simonds
The Economist, **Dumb insolence**

Black hole evaporation *in a nutshell*



Example 1:

Experimental Black Hole Evaporation

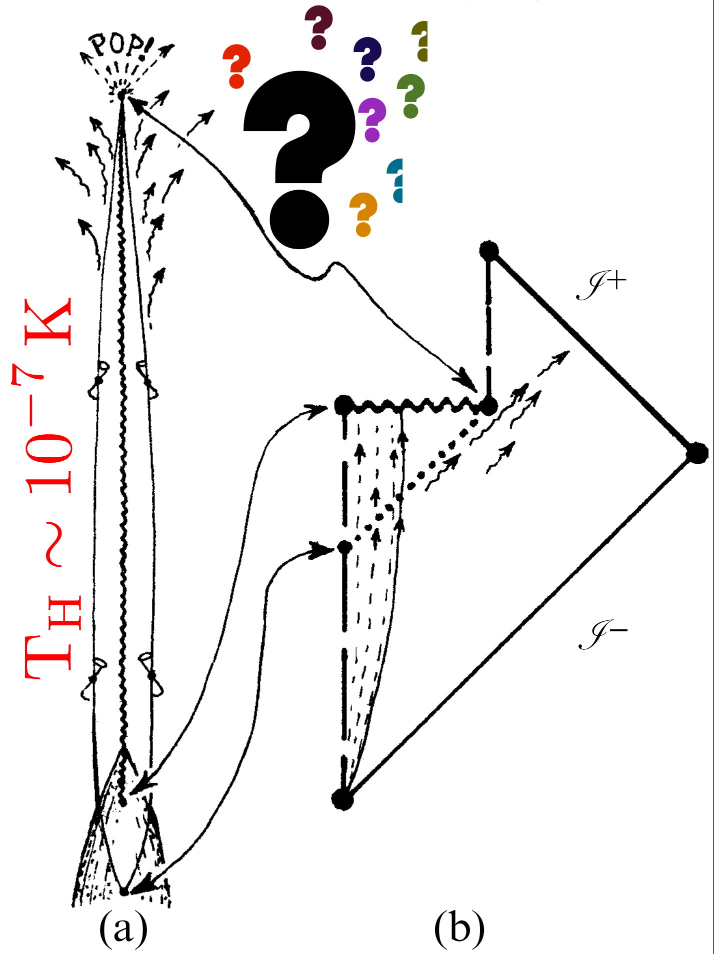
(**1**) What is Hawking radiation?

(**2**) How can we set up a table-top experiments to "conclusively" test Hawking/Unruh's prediction?

(**3**) Why is of scientific interest to carry out analogue simulations of Hawking radiation?

Black hole evaporation *in a nutshell*

Illustration by Roger Penrose



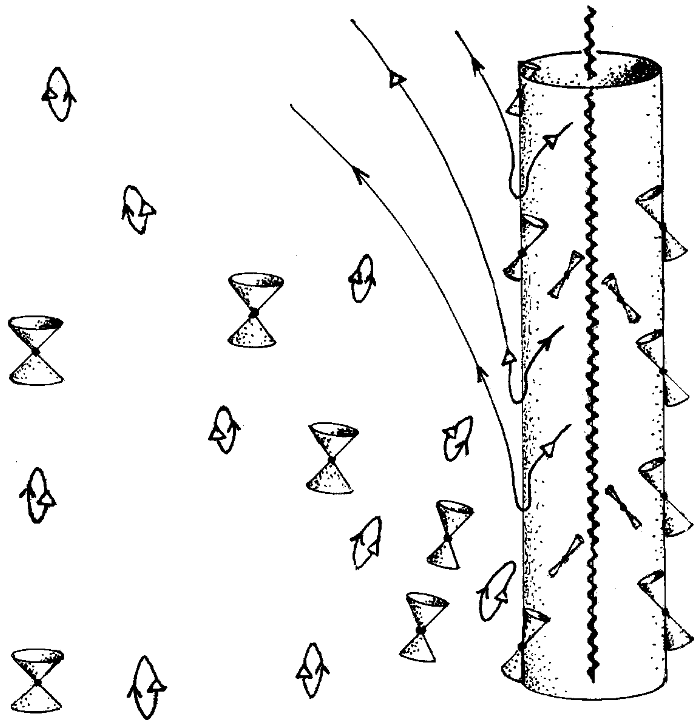
Example 1:

Experimental Black Hole Evaporation

Classically NOTHING can escape a black hole, but **including quantum effects it can evaporate away!**

Hawking radiation: how black holes lose their mass

Black hole evaporation *how does it work*



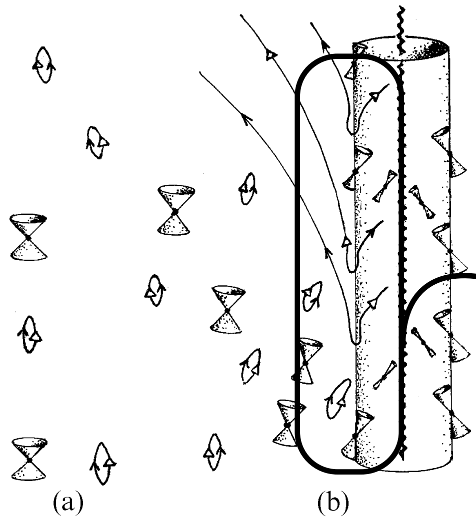
Pair-creation:

Separation of particle-anti-particle pairs from the quantum vacuum;
Negative norm modes absorbed by black hole;

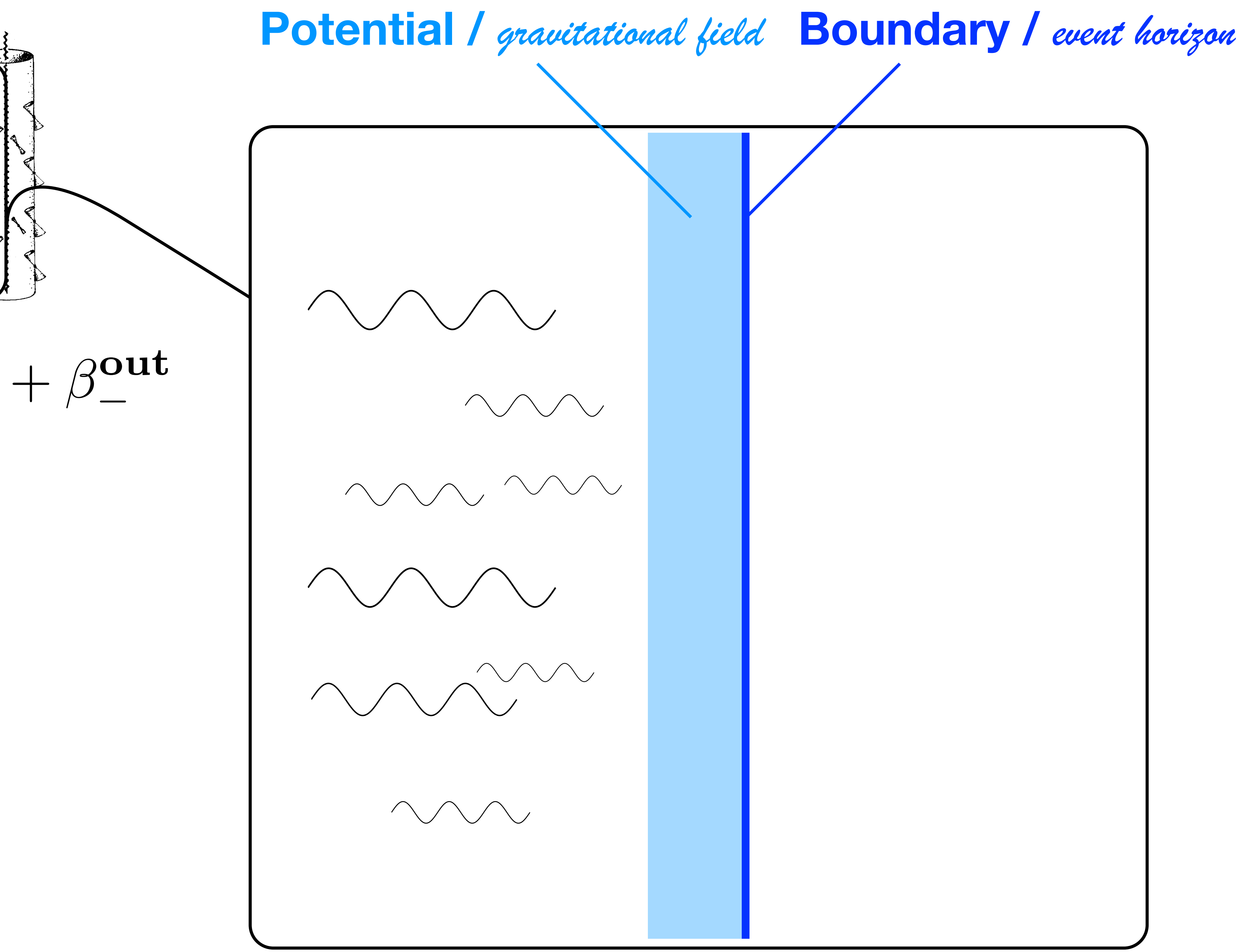
[Particle Creation by Black Holes, by Stephen Hawking, in 1974]

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

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



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



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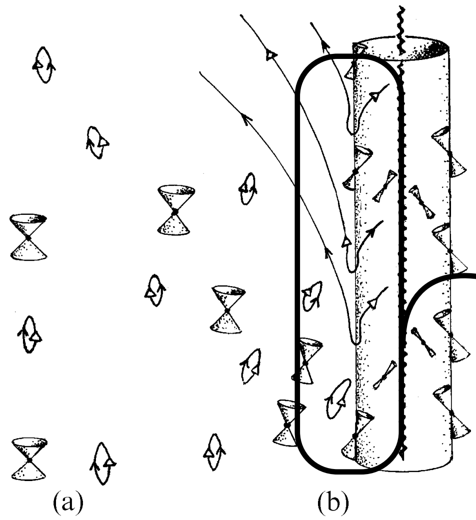

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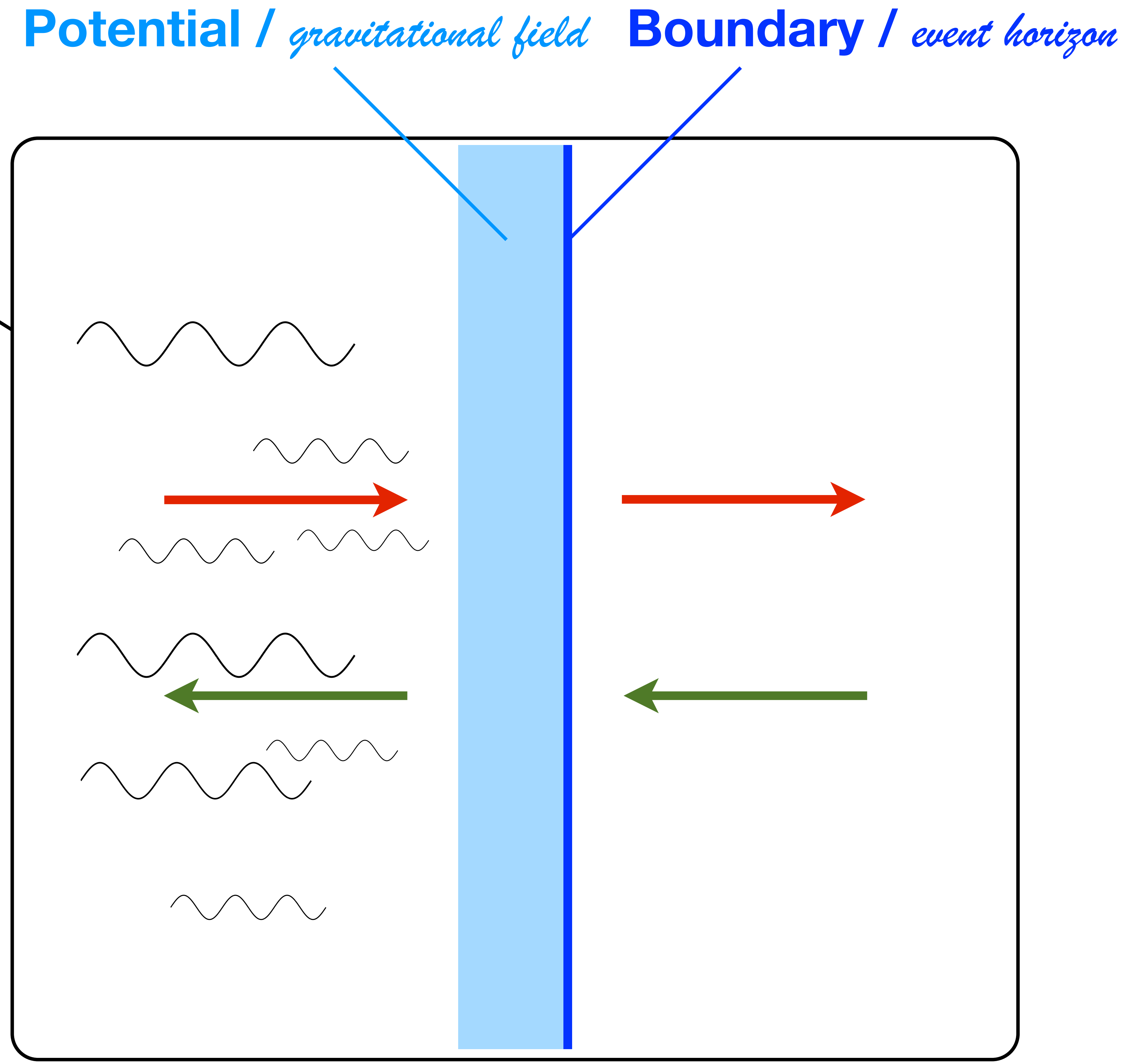
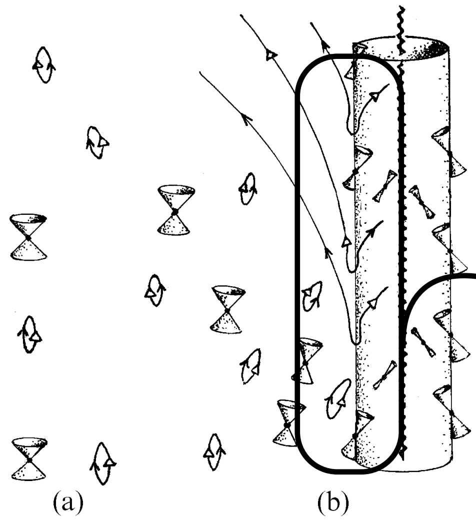


Right moving modes

Left moving modes



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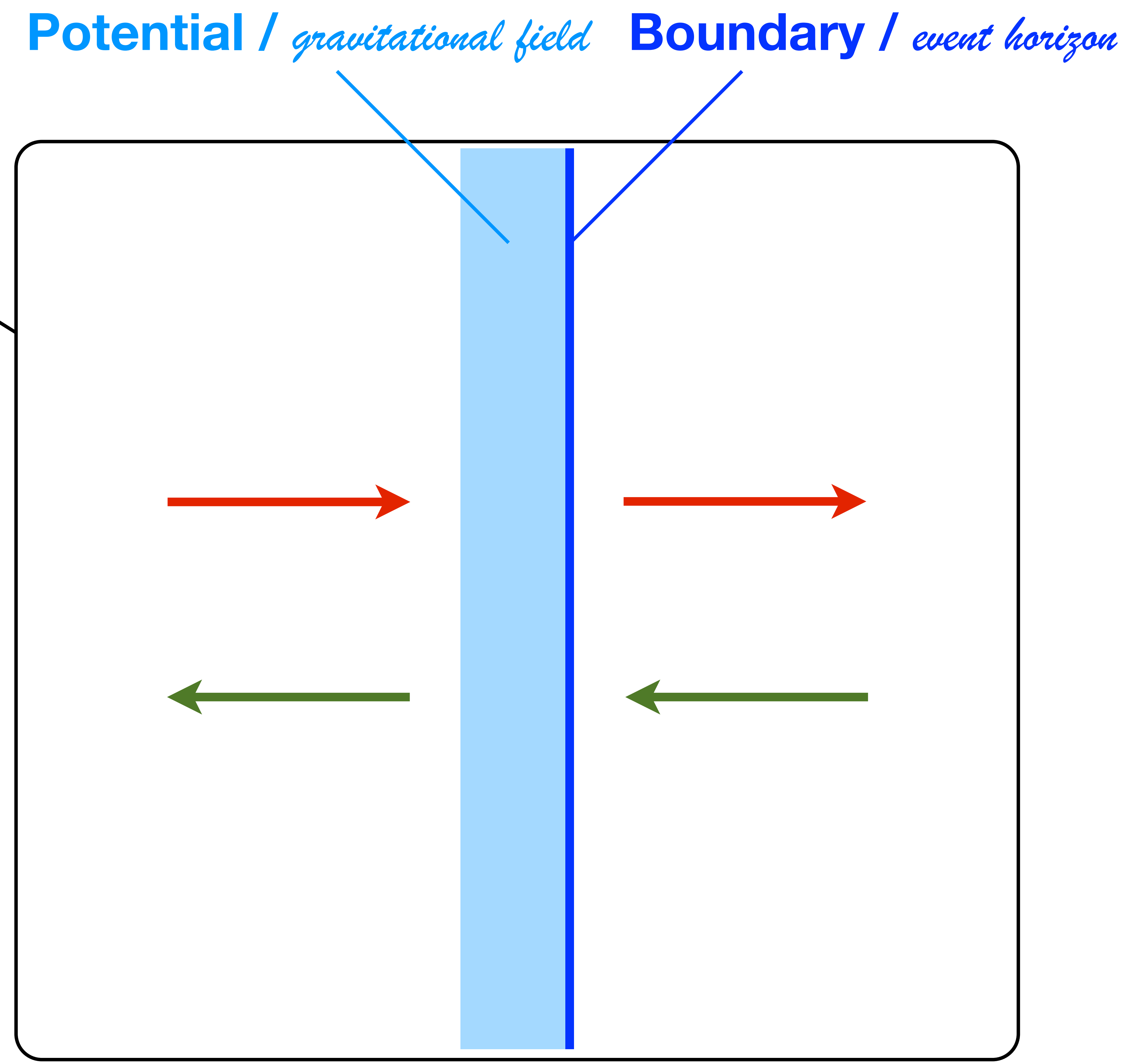
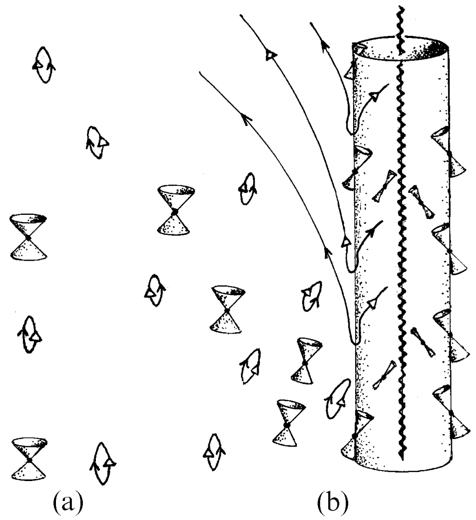


Right moving modes

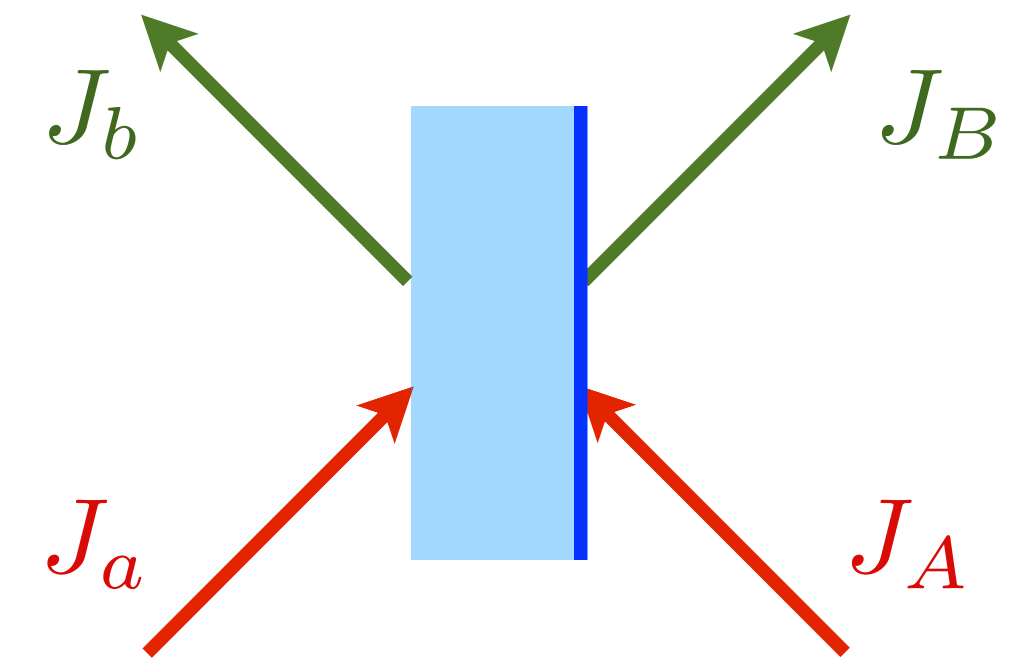
Left moving modes



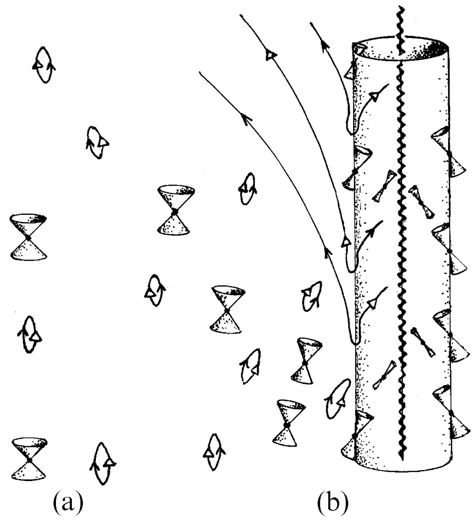
$$\phi_\omega^{\mathbf{in}} = \alpha_+^{\mathbf{out}} + \beta_-^{\mathbf{out}}$$

Modes moving into potential

Modes moving out of potential

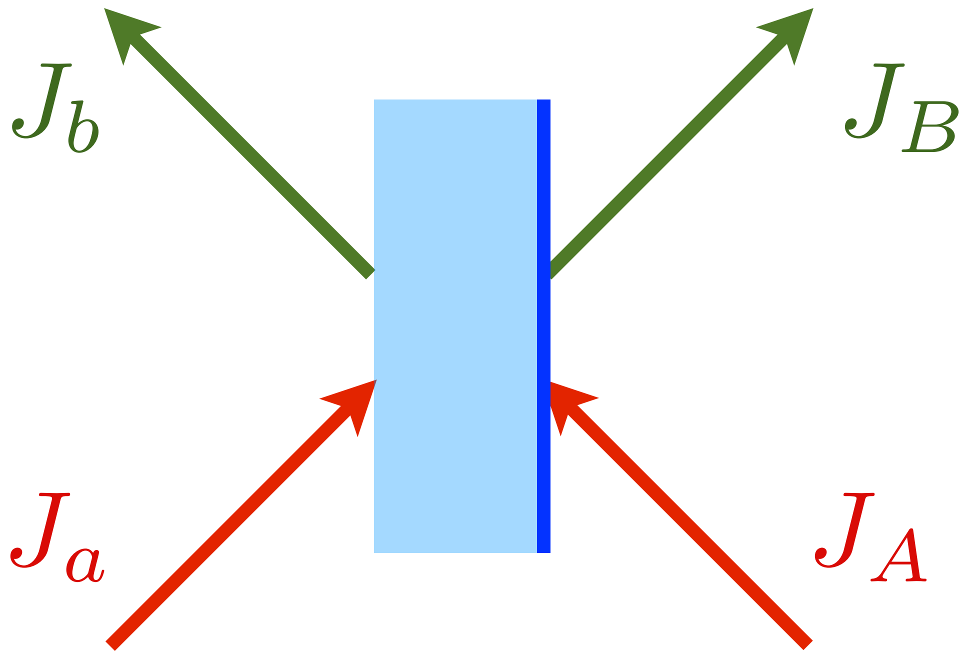


$$J_a + J_A = J_b + J_B$$



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

Conserved quantity: energy/norm/ particle current



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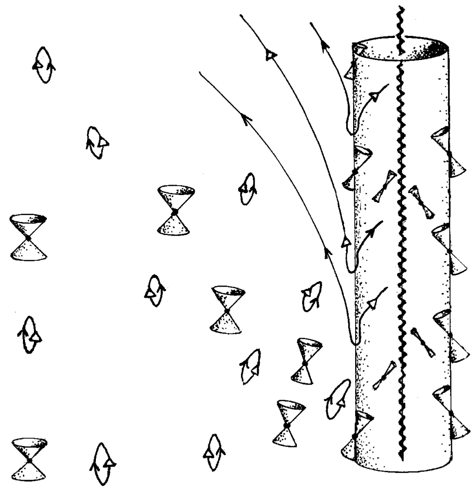
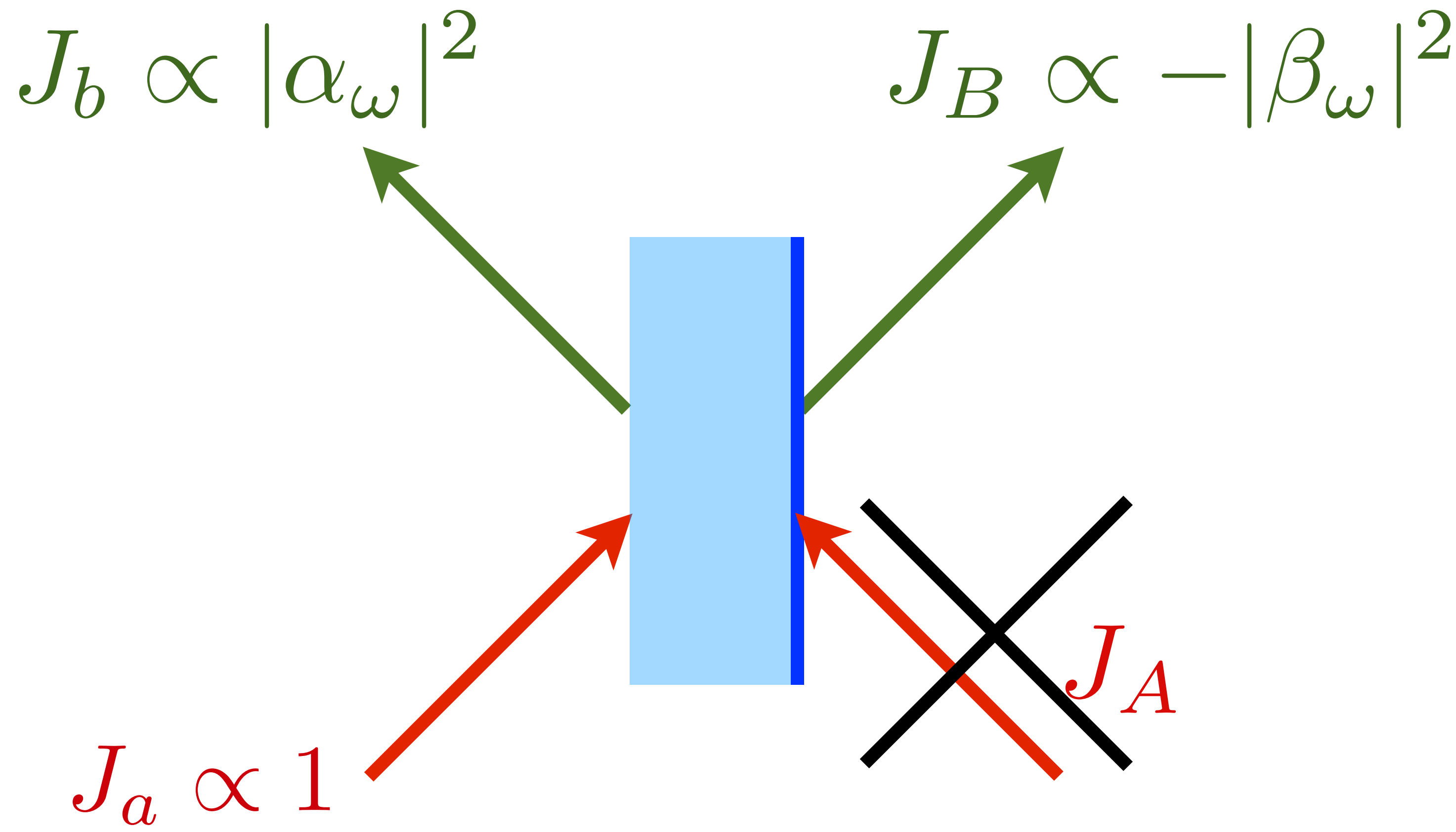
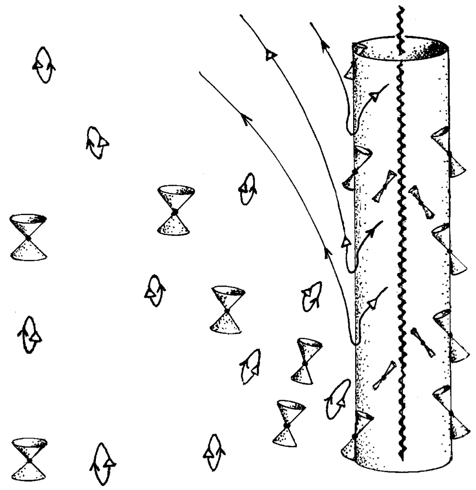

(a) (b)

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

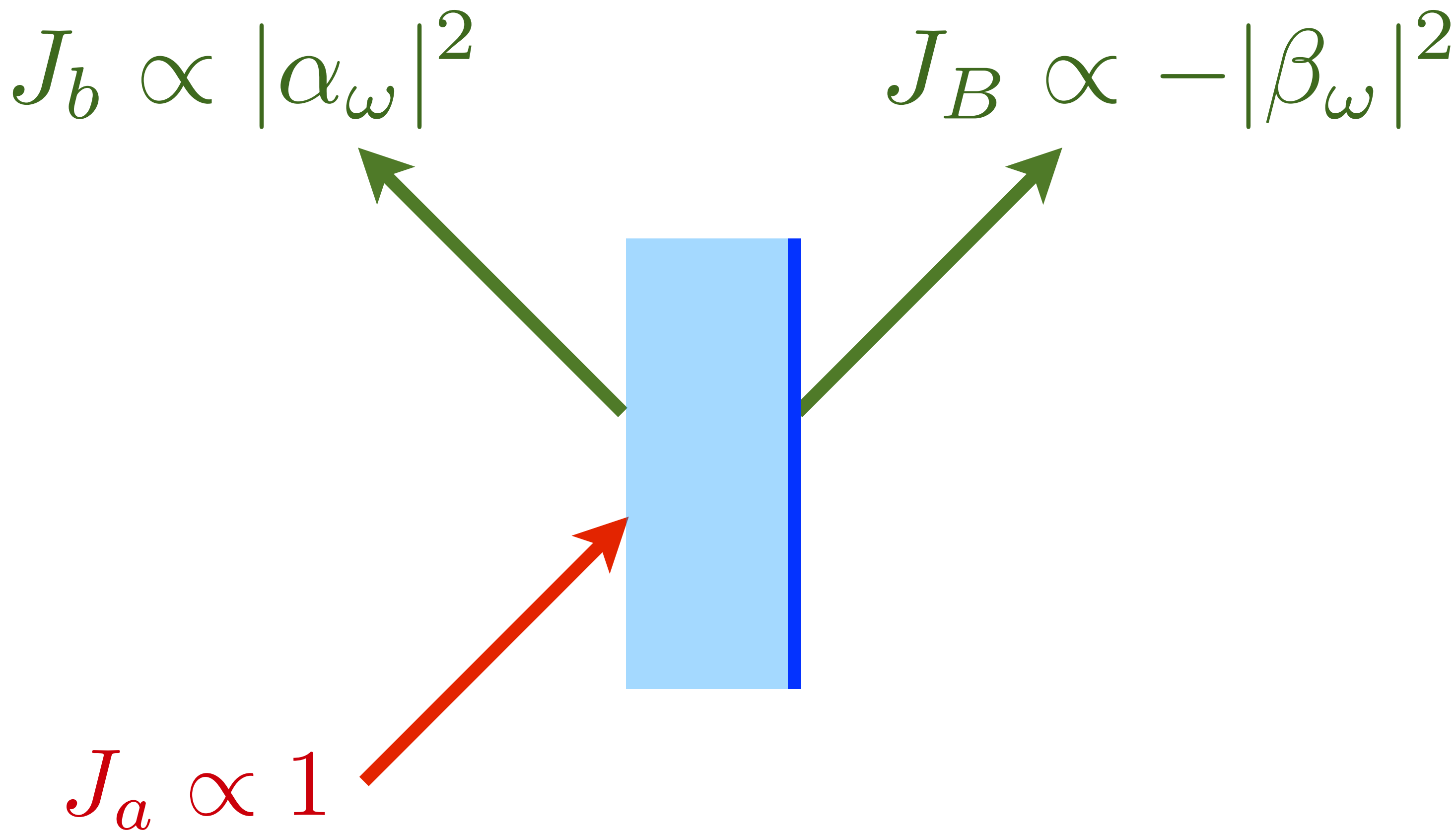


$$1 + 0 = |\alpha_\omega|^2 + -|\beta_\omega|^2$$

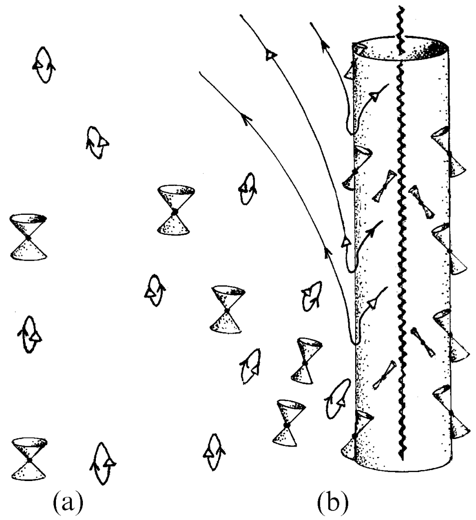


(a) (b)

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



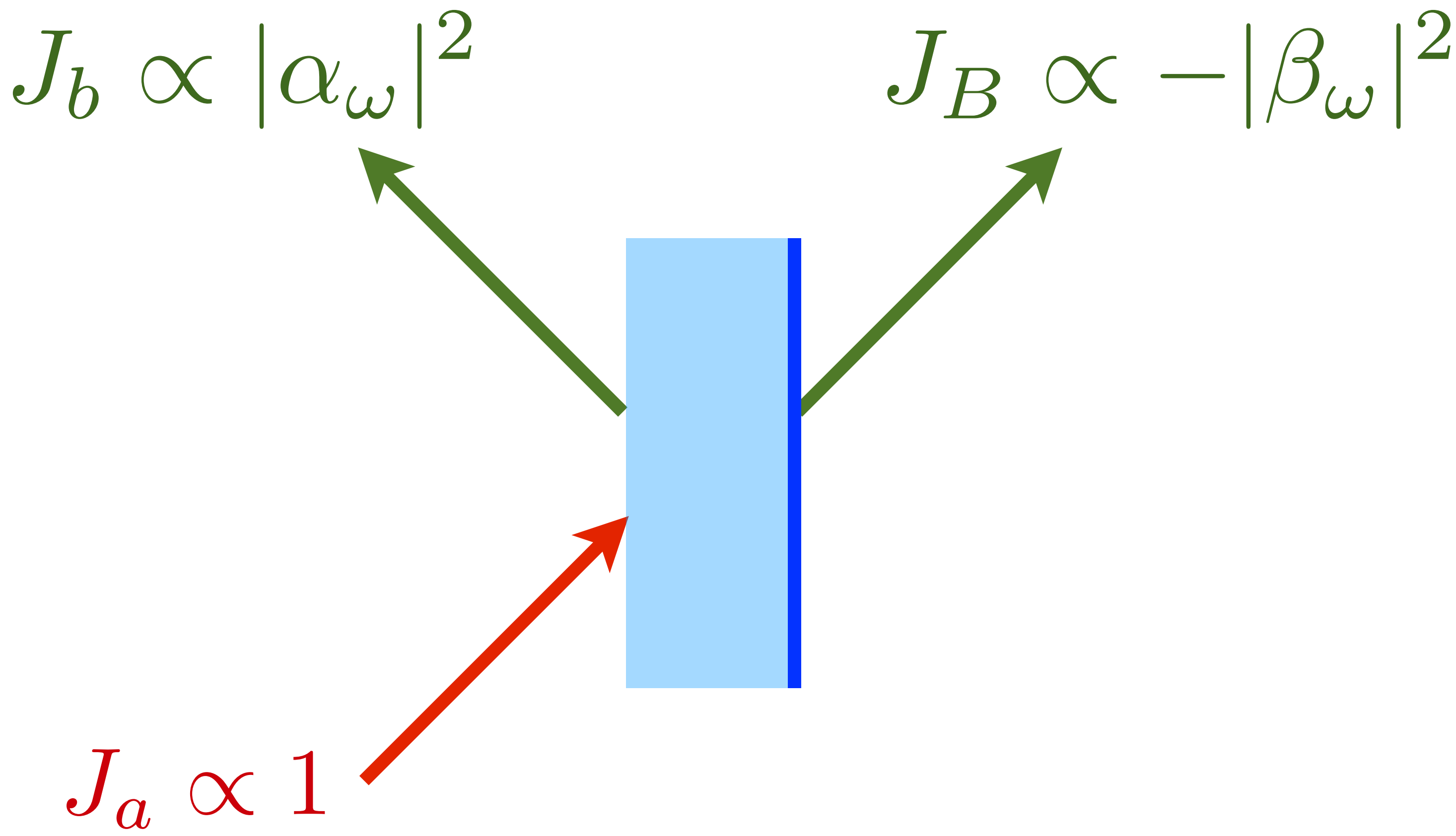
$$1 + 0 = |\alpha_\omega|^2 + -|\beta_\omega|^2$$



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

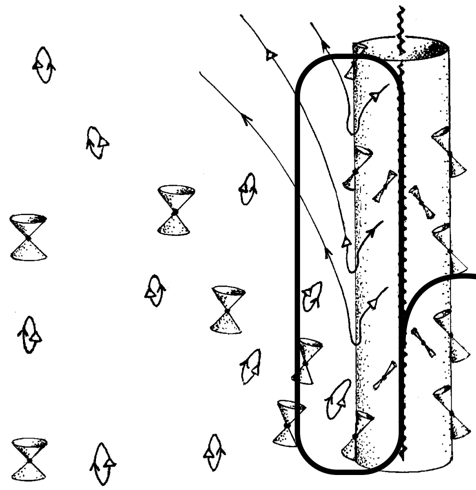
$$\frac{|\beta_\omega|^2}{|\alpha_\omega|^2} = e^{-\frac{2\pi\omega}{g_\mathrm{H}}} = e^{-\frac{\hbar\,\omega}{k_B \mathbf{T}}}$$

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



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

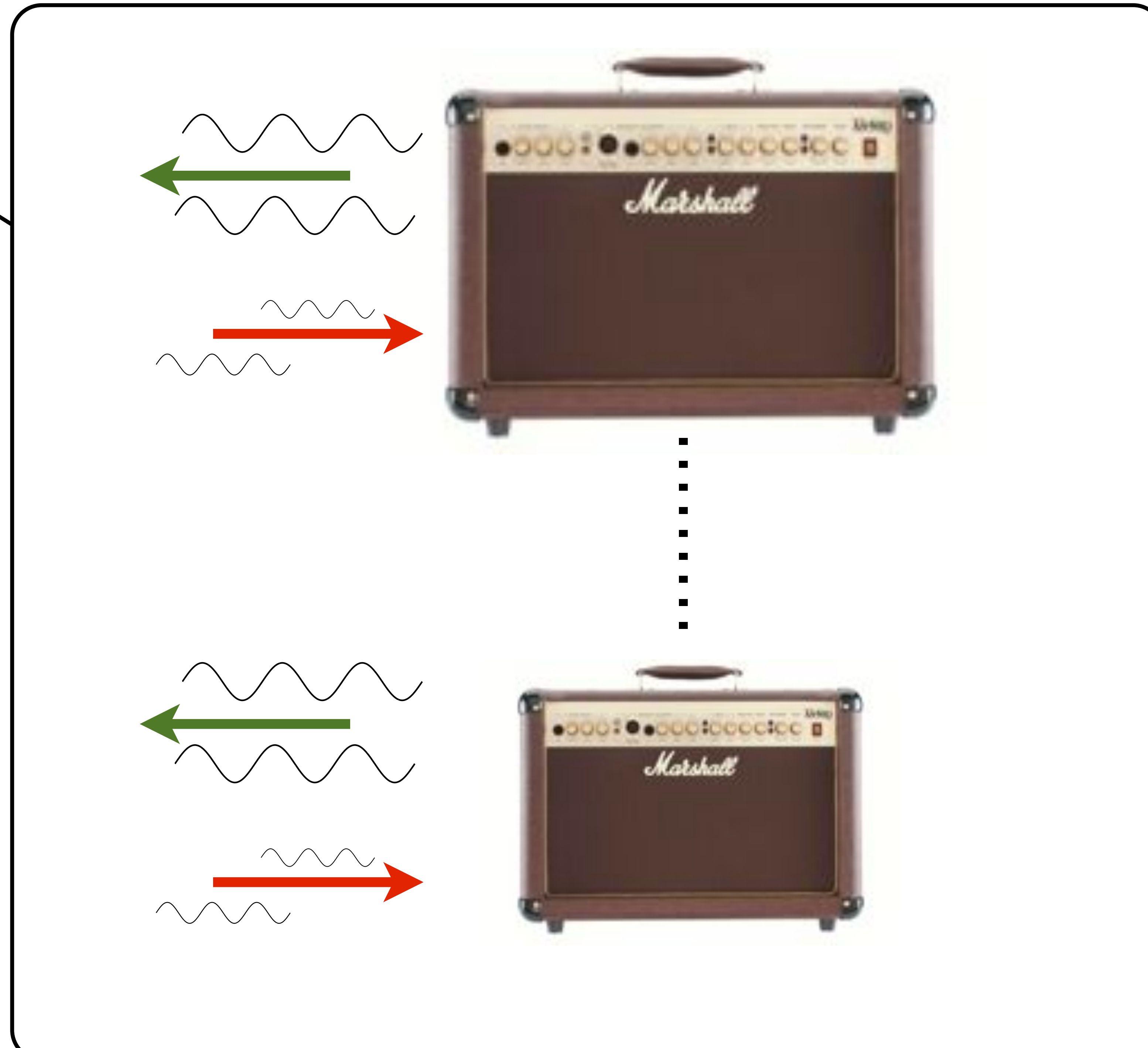
Black holes: Linear Classical and Quantum Field Amplifier!



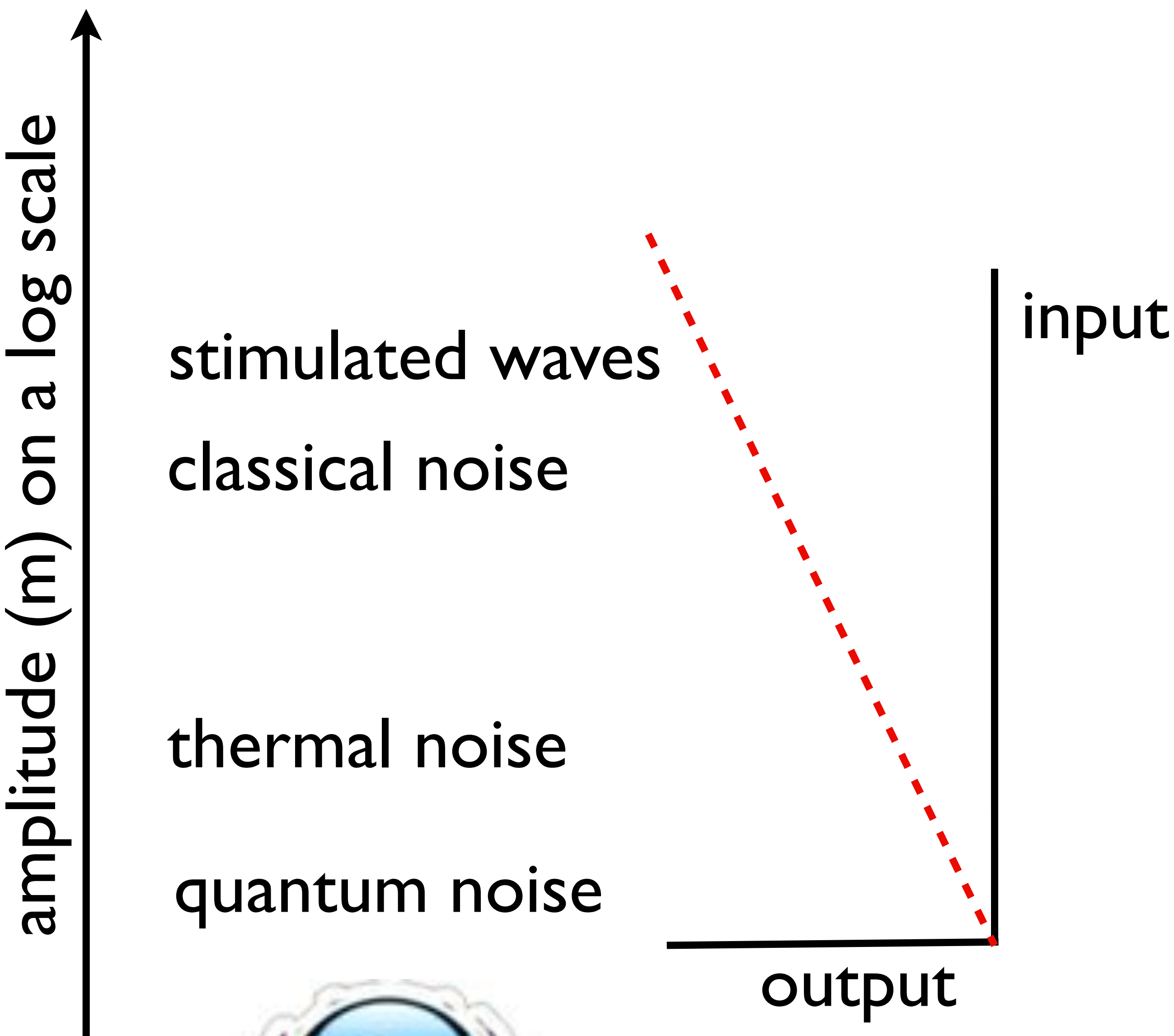
$$\phi_\omega^{\mathbf{in}} = \alpha_+^{\mathbf{out}} + \beta_-^{\mathbf{out}}$$

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

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



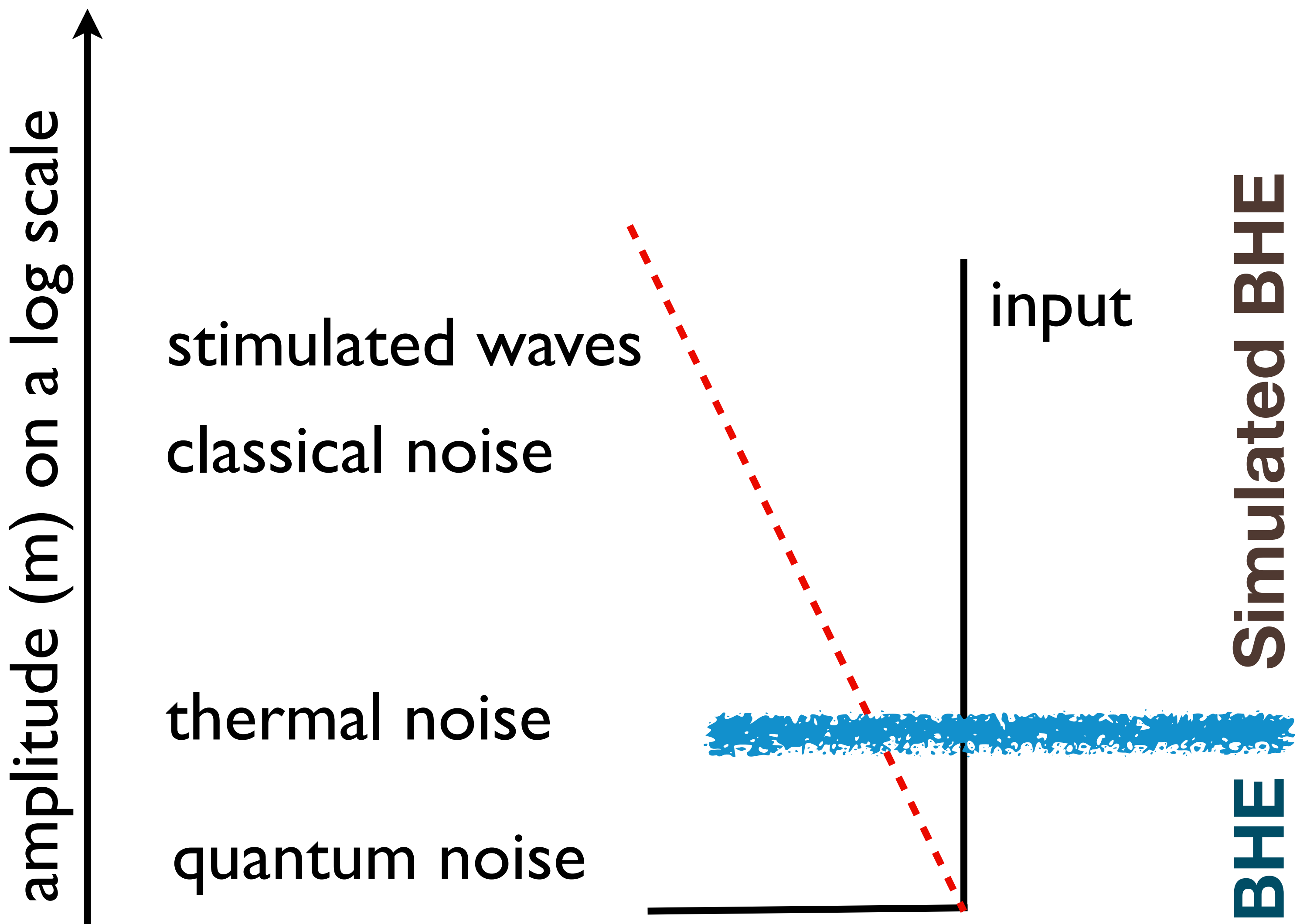
Hawking radiation *classical or quantum?*



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

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

Hawking radiation *classical or quantum?*



<u>Assumption:</u>

Linear amplifier over a huge range!

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

- ✔ quantum correlations

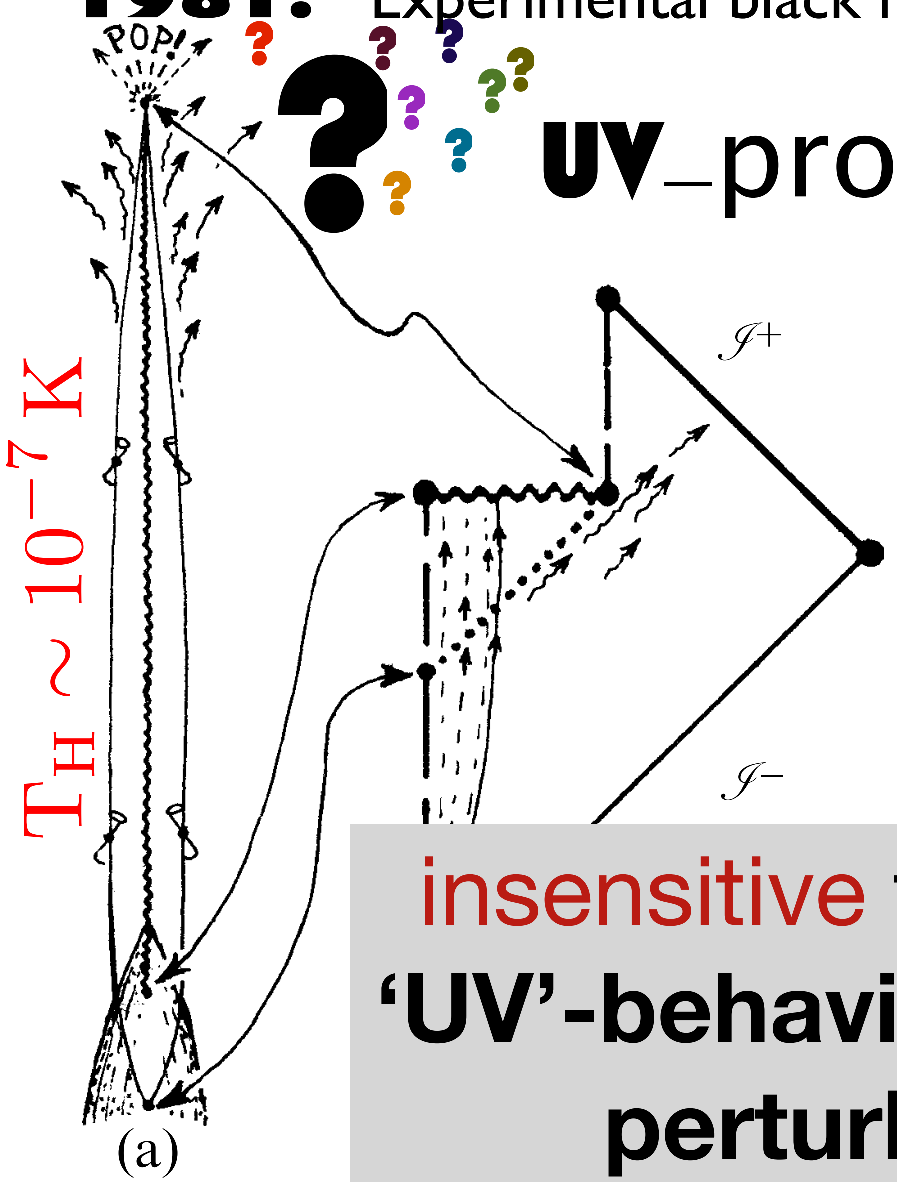
BHE process ➤ the UV-**problem**

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**

EXP. #1 *surface waves on open channel flows*

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

Measurement of Stimulated Hawking Emission in an Analogue System

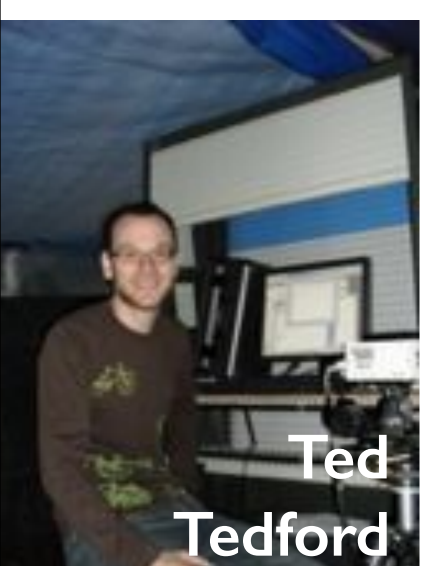
Silke Weinfurtner,[1] Edmund W. Tedford,[2] Matthew C. J. Penrice,[1] William G. Unruh,[1] and Gregory A. Lawrence[2]

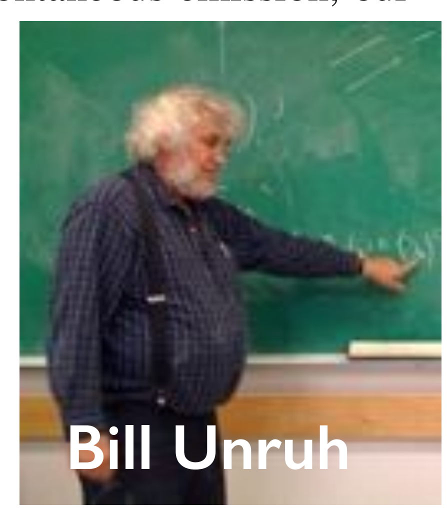
[1]*Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada V6T 1Z1*

[2]*Department of Civil Engineering, University of British Columbia, 6250 Applied Science Lane, Vancouver, Canada V6T 1Z4*

(Received 30 August 2010; published 10 January 2011)

Hawking argued that black holes emit thermal radiation via a quantum spontaneous emission. To address this issue experimentally, we utilize the analogy between the propagation of fields around black holes and surface waves on moving water. By placing a streamlined obstacle into an open channel flow we create a region of high velocity over the obstacle that can include surface wave horizons. Long waves propagating upstream towards this region are blocked and converted into short (deep-water) waves. This is the analogue of the stimulated emission by a white hole (the time inverse of a black hole), and our measurements of the amplitudes of the converted waves demonstrate the thermal nature of the conversion process for this system. Given the close relationship between stimulated and spontaneous emission, our findings attest to the generality of the Hawking process.

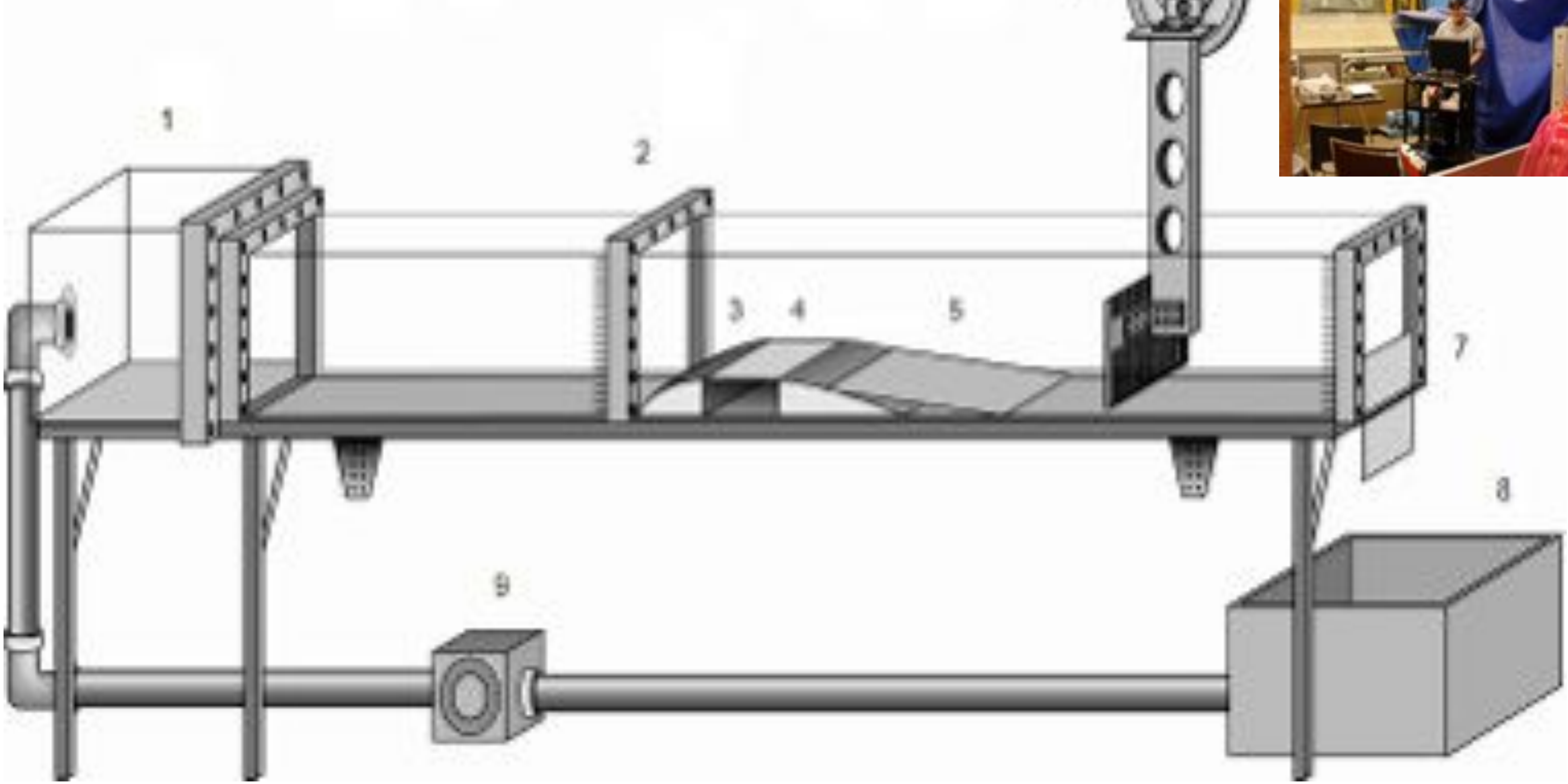




THE ROYAL SOCIETY

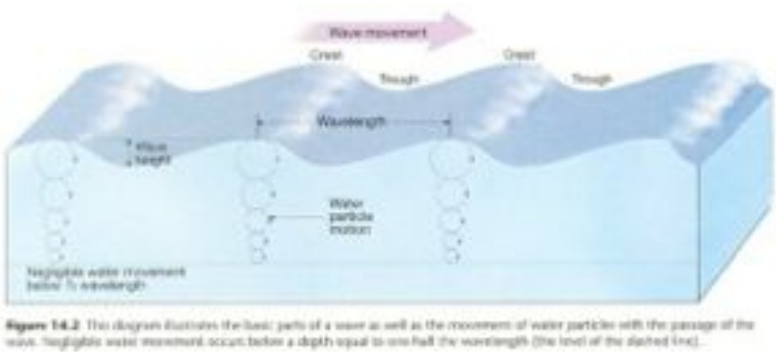
Our experiment *setup*

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



Basic Idea

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



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

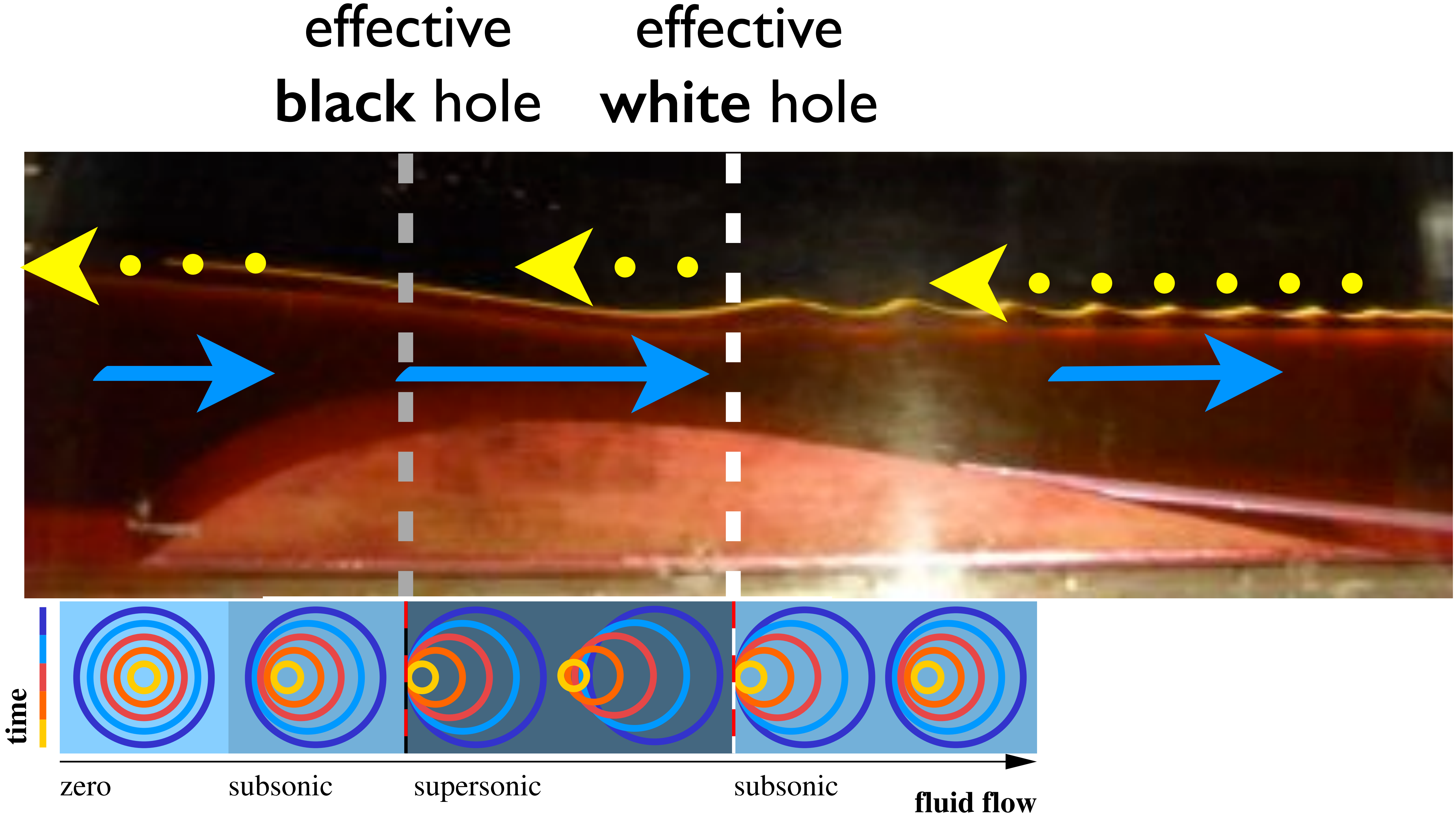
$$c = c(x) \approx \sqrt{g h(x)} \propto \sqrt{h(x)}$$

Let's recall the acoustic line-element:

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

THE ROYAL SOCIETY

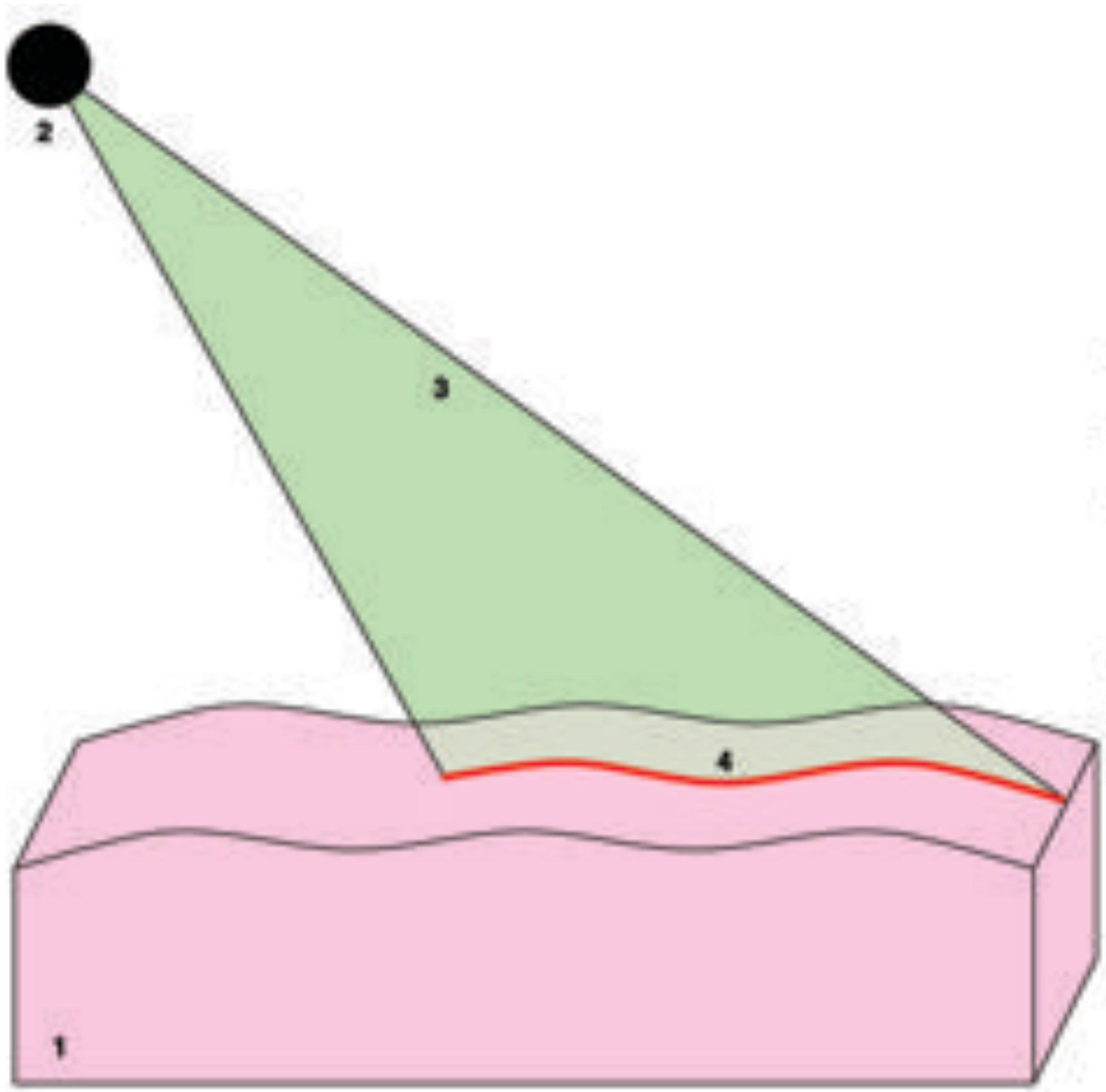
Our experiment *black and white hole horizons*



Our experiment *in motion*

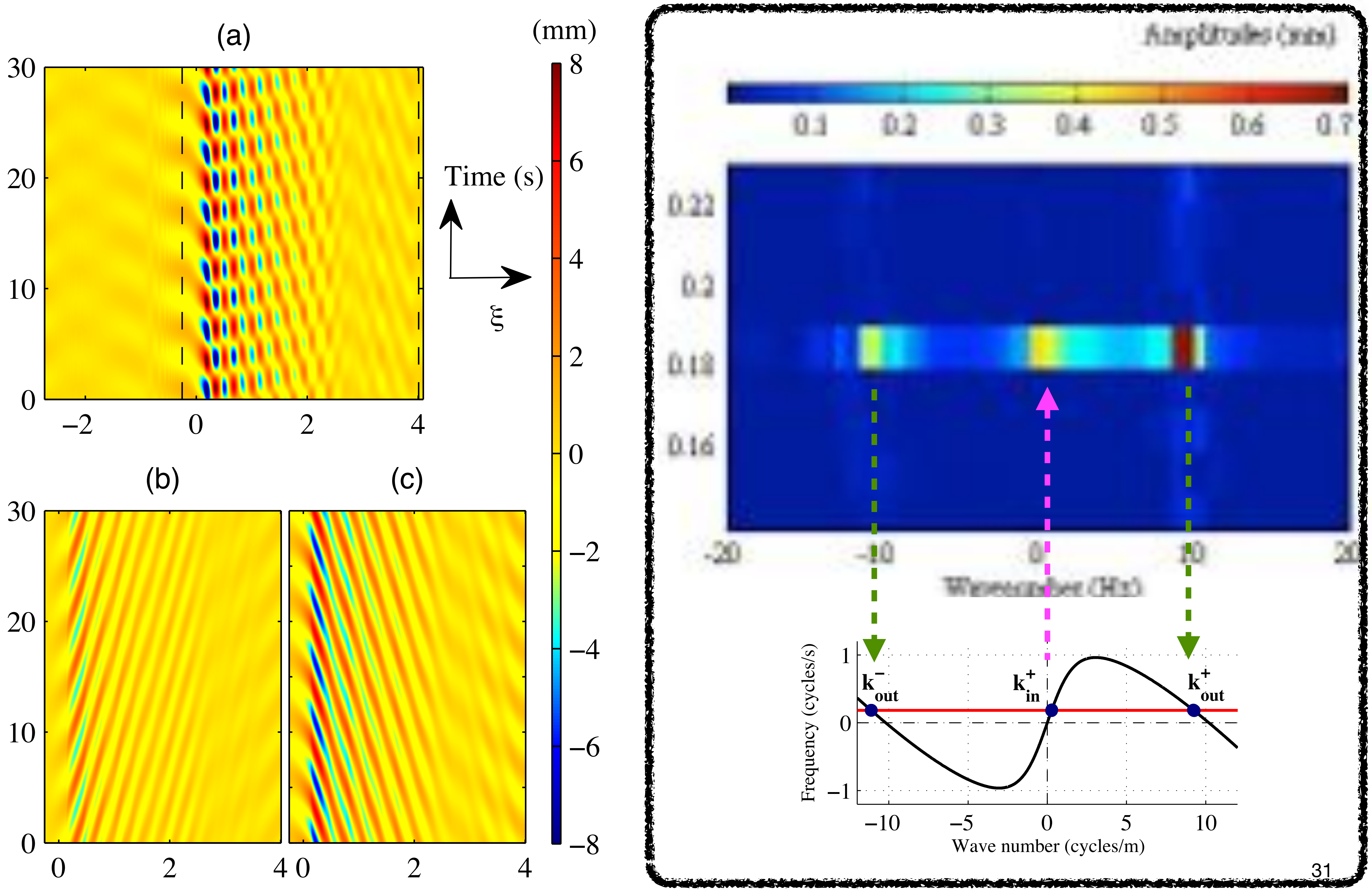
Our experiment *in motion*

Our experiment *how we did it*



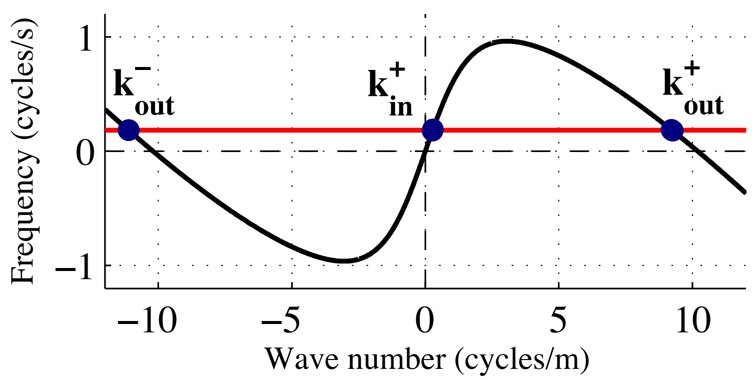
Observable: free surface

✔ pair-creation process (classical correlations)

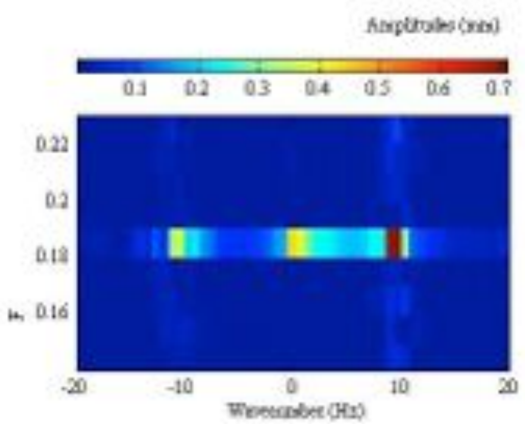


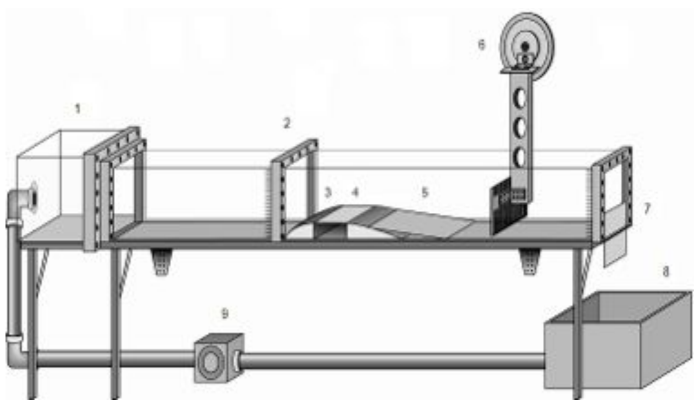
✔ Boltzmann distribution

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



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

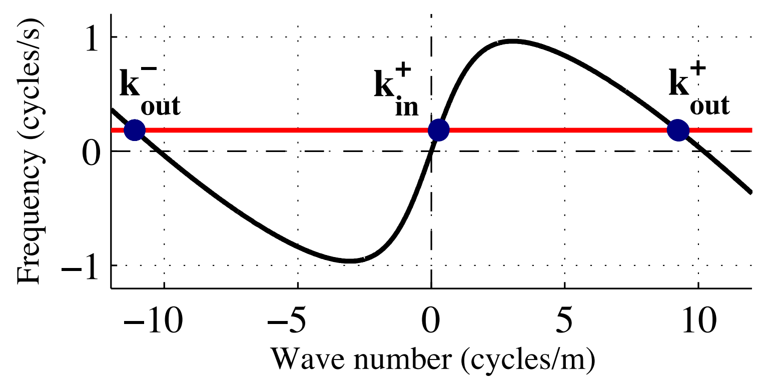


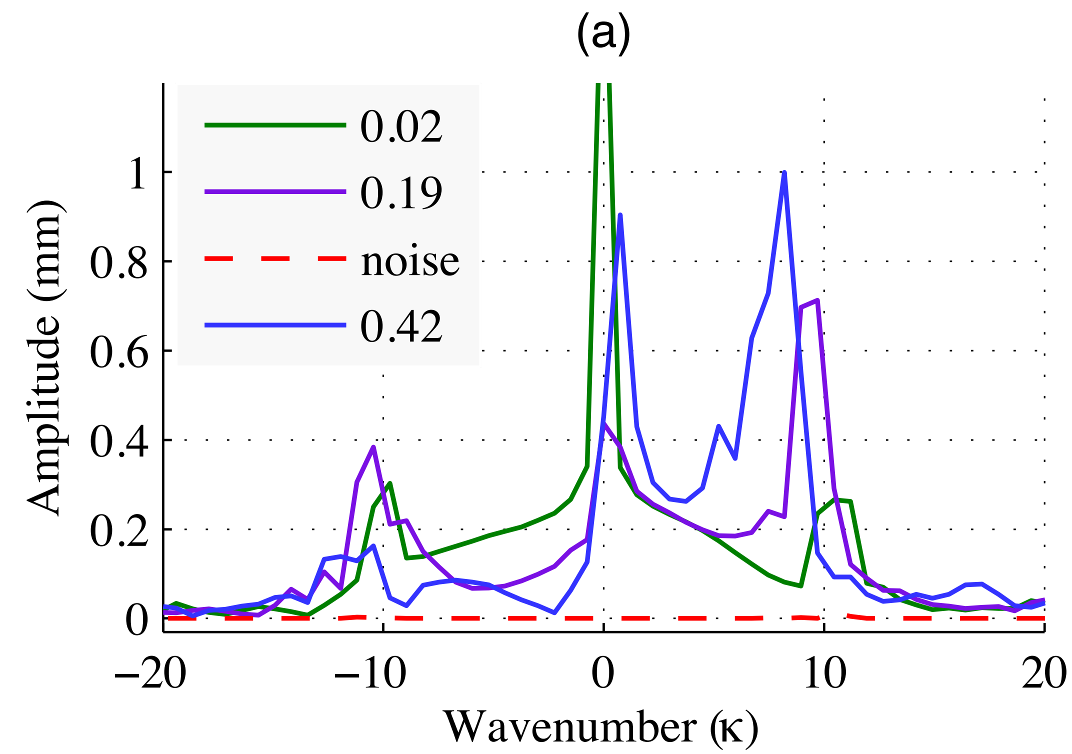


(ii) Norm is conserved: $\int \frac{|A(f,\kappa)|^2}{f+\kappa} d\kappa$

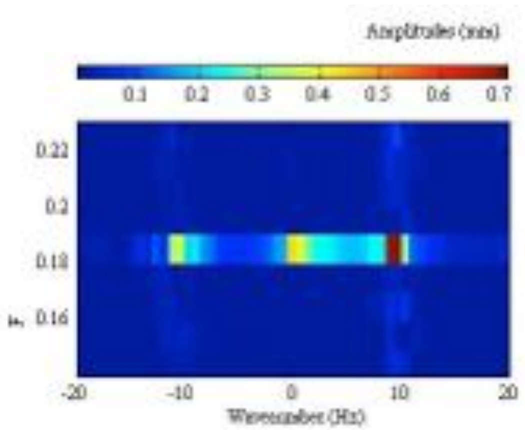
✔ Boltzmann distribution

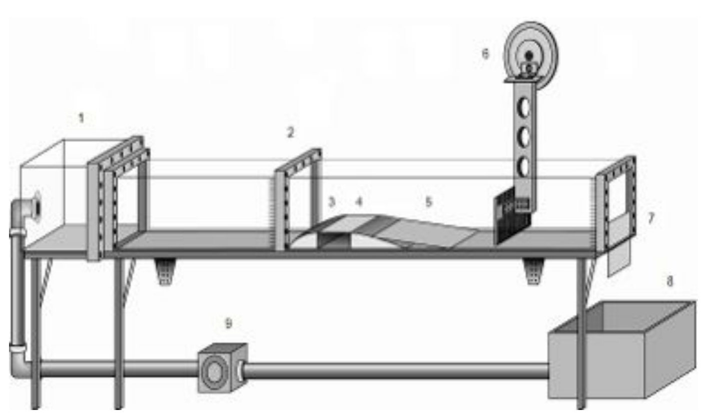
(i) Amplitudes of converted waves depending on ingoing frequency:





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



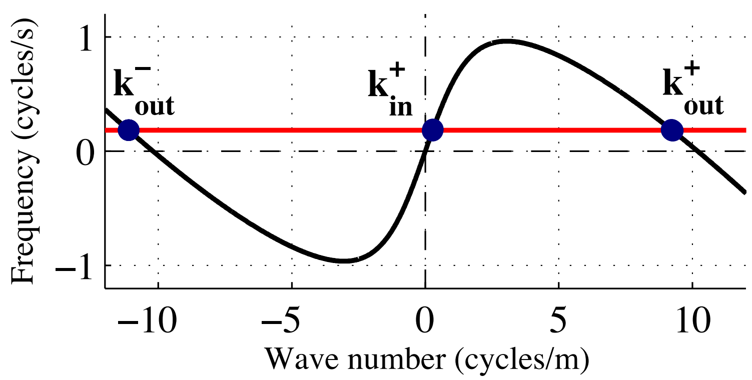


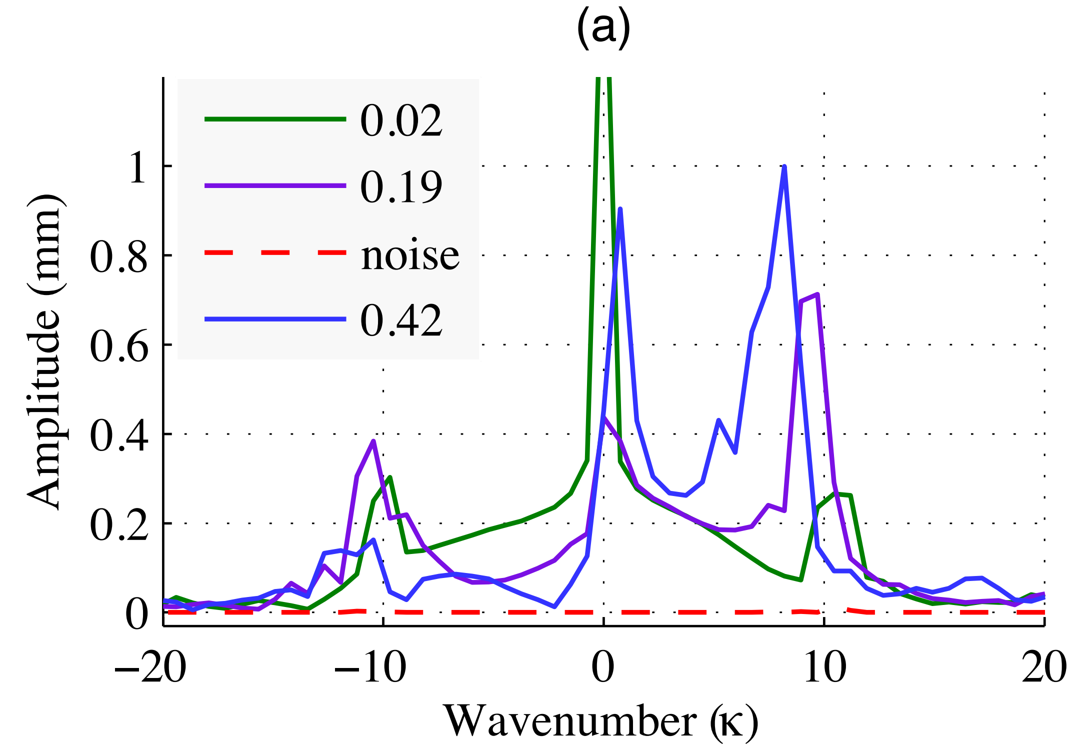
(ii) Norm is conserved:

$$\int \frac{|A(f,\kappa)|^2}{f+\kappa}\, d\kappa$$

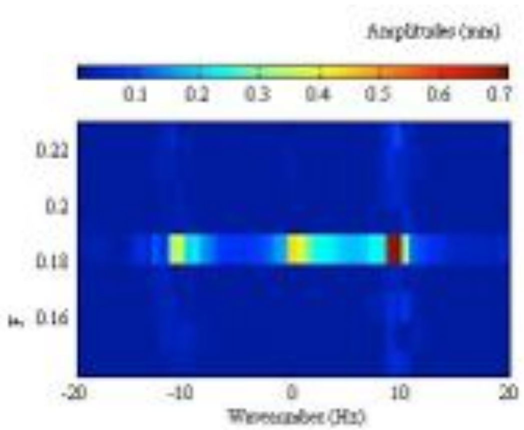
✔ Boltzmann distribution

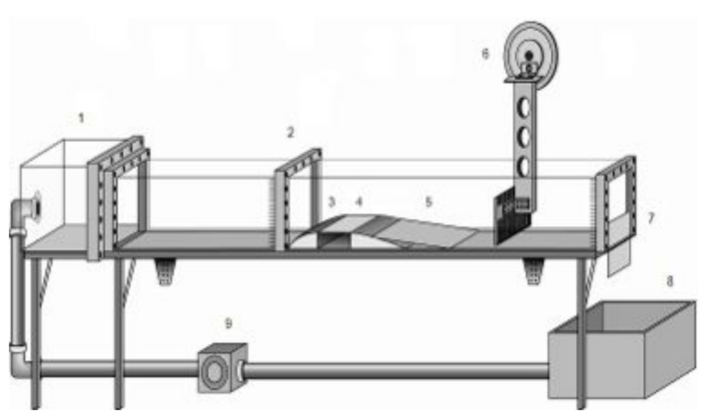
(i) Amplitudes of converted waves depending on ingoing frequency:

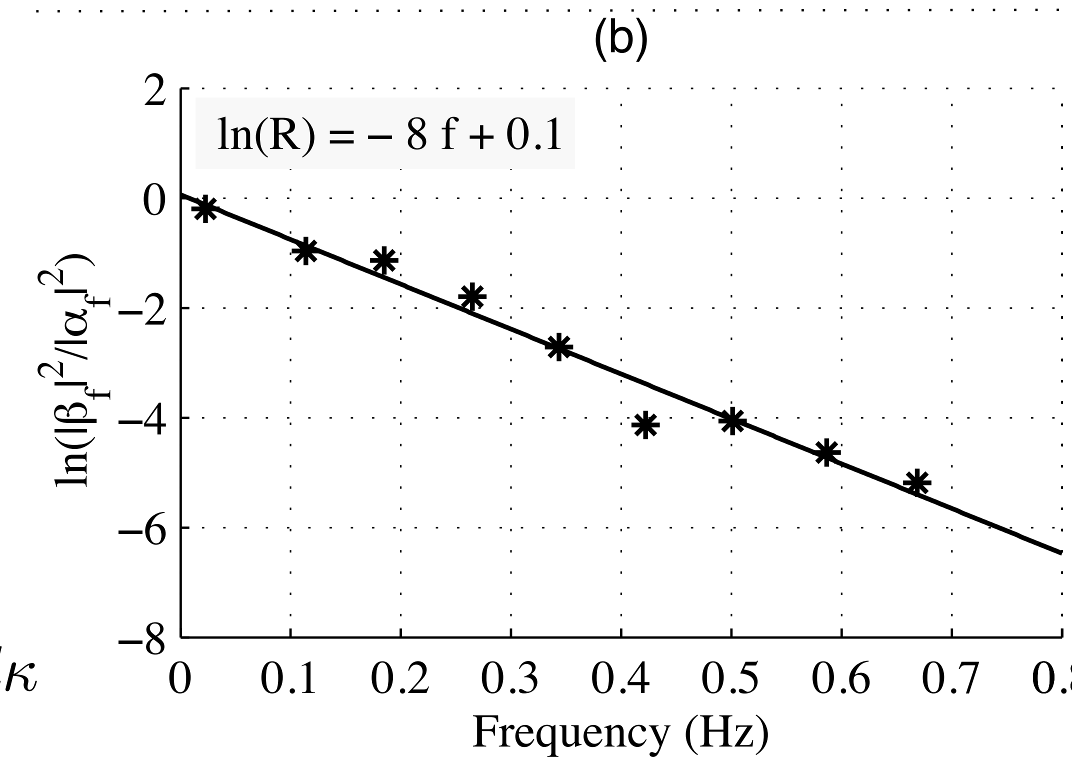




(ii) what is a wave (particle) nearbythe white hole horizon..?







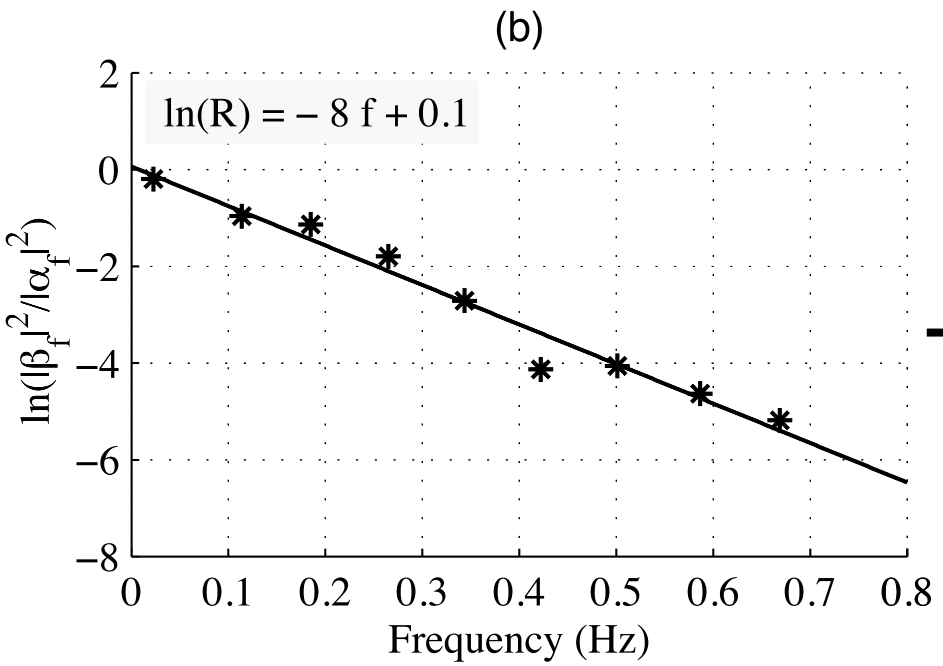
(ii) Norm is conserved:

$$\int \frac{|A(f,\kappa)|^2}{f+\kappa} d\kappa$$

✔ Boltzmann distribution depends on surface gravity

Our experiment *surface gravity*

Excitations on free surface:



$$\frac{|\beta_\omega|^2}{|\alpha_\omega|^2} = e^{-\frac{2\pi\omega}{g_H}}$$

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

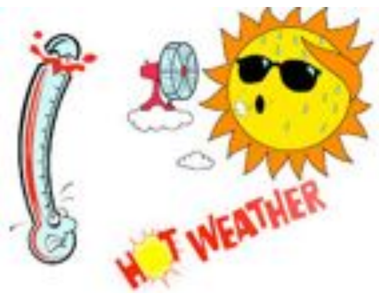
surface gravity (Hz) via **background: 0.08-0.18 Hz**

Our experiment *surface gravity*

Assumption:
Linear amplifier over a huge range!

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

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!!!



THE ROYAL SOCIETY

Our experiment *surface gravity*

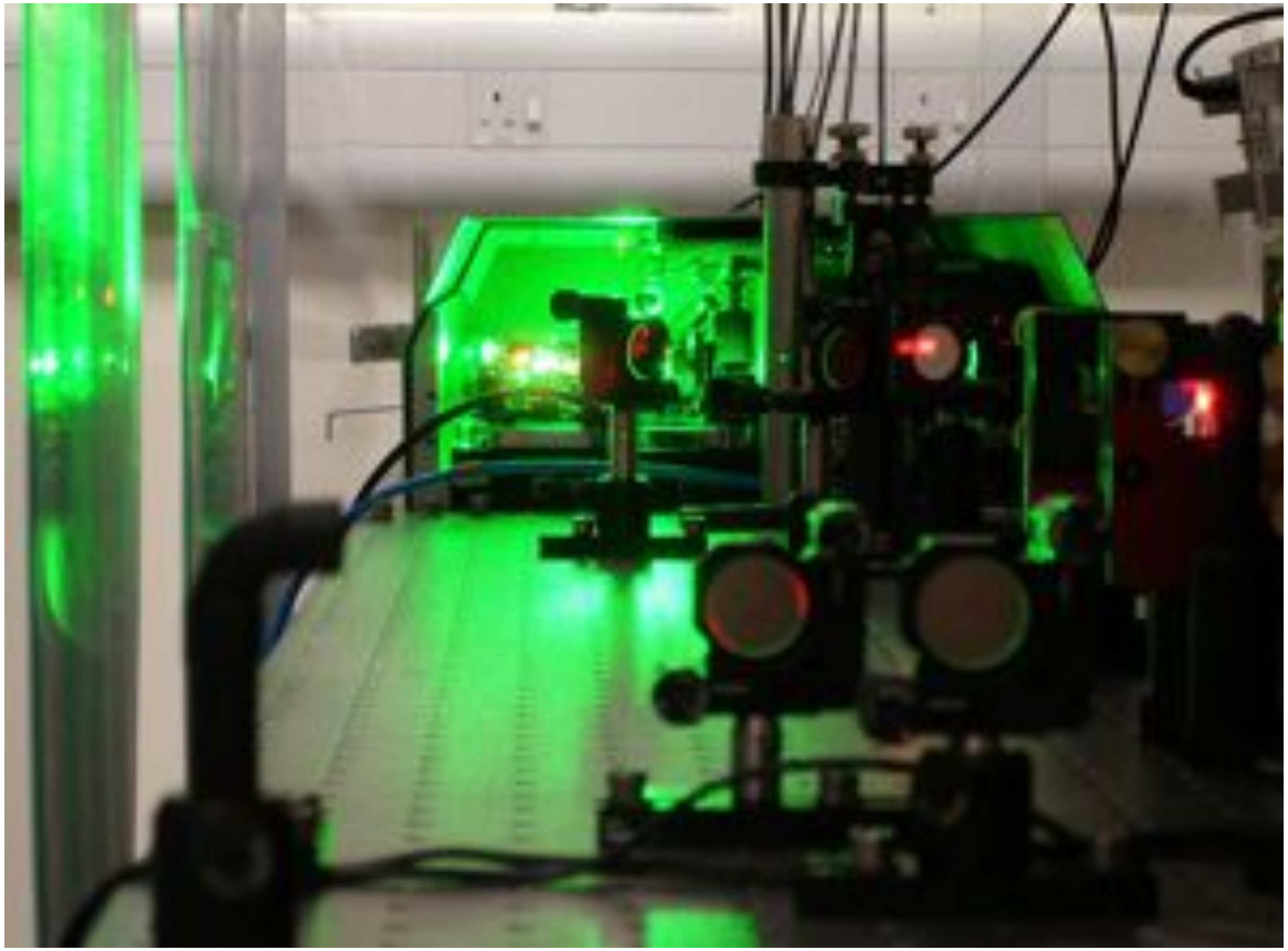
Assumption:
Linear amplifier over a huge range!

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

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!!!

However: Spontaneous emission straightforward, but undetectable (**6x10^-12 K**);
NO QUANTUM EFFECT
superfluid experiments necessary...

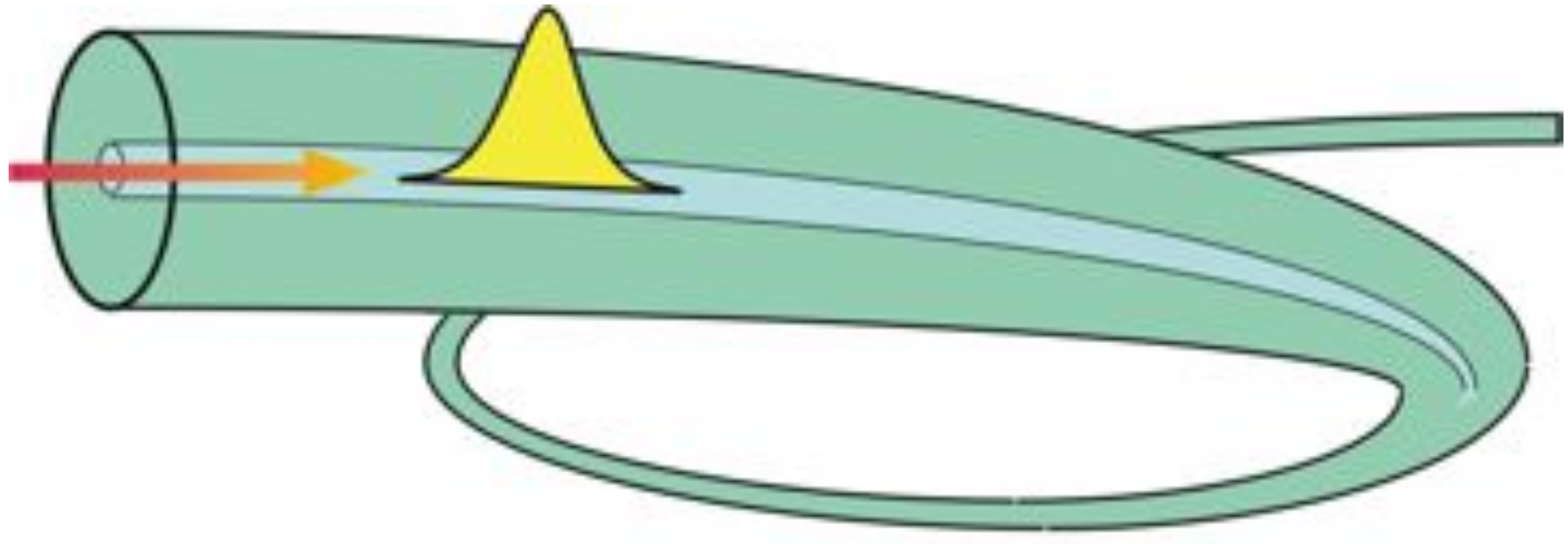
EXP. #2 *optical analogues of the event horizon*



Analogue gravity *from optical media*

Sound waves/surface wave → light

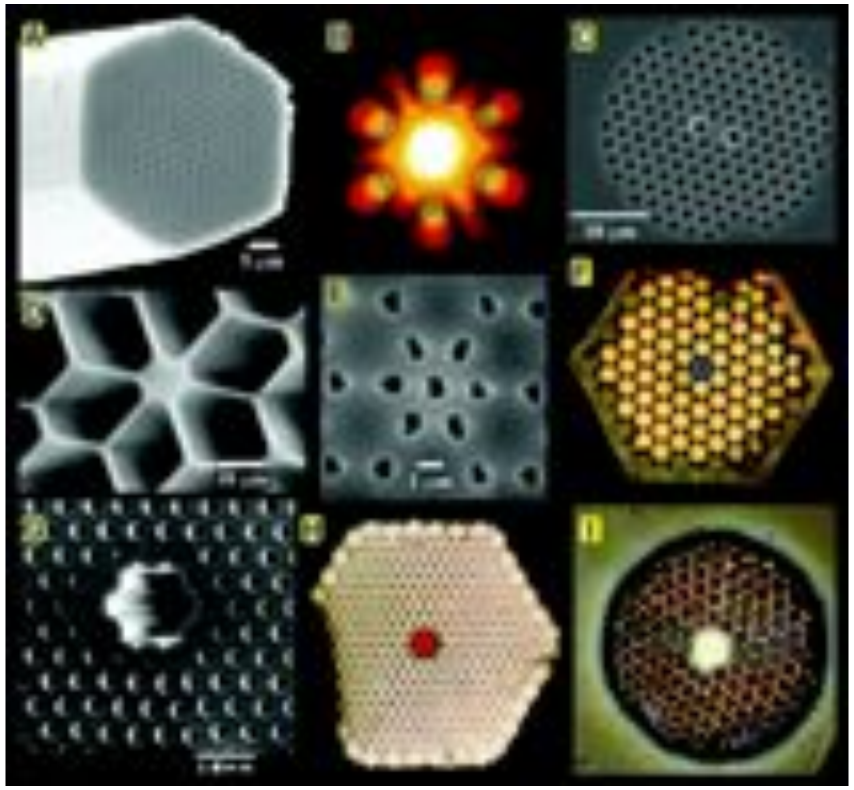
the equivalent of the river flow needs to exceed the speed of light in medium!!



→ medium with refractive index to reduce the speed of light in vacuum drastically…

Analogue gravity *from optical media*

Sound waves/surface wave → light



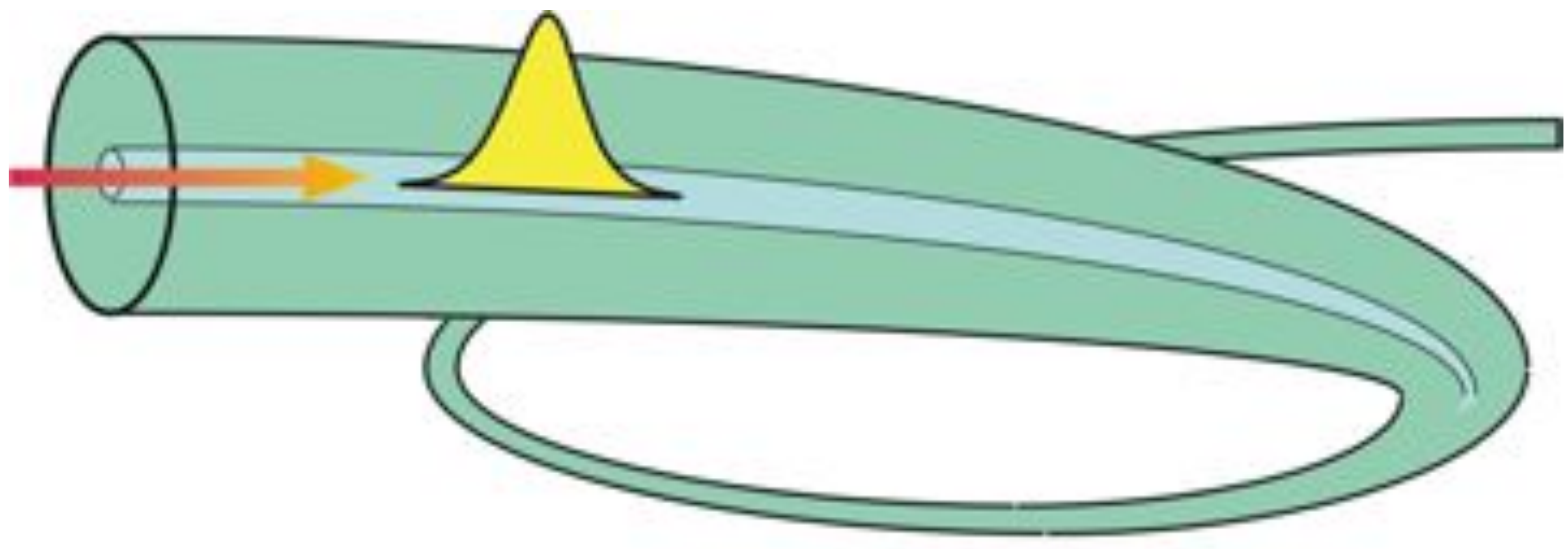
the equivalent of the river flow needs to exceed the speed of light in medium!!

→ optical (fibre-optic) telecommunication: information care light pulses confined to the core of optical fibres.

Analogue gravity *from optical media*

Sound waves/surface wave → light

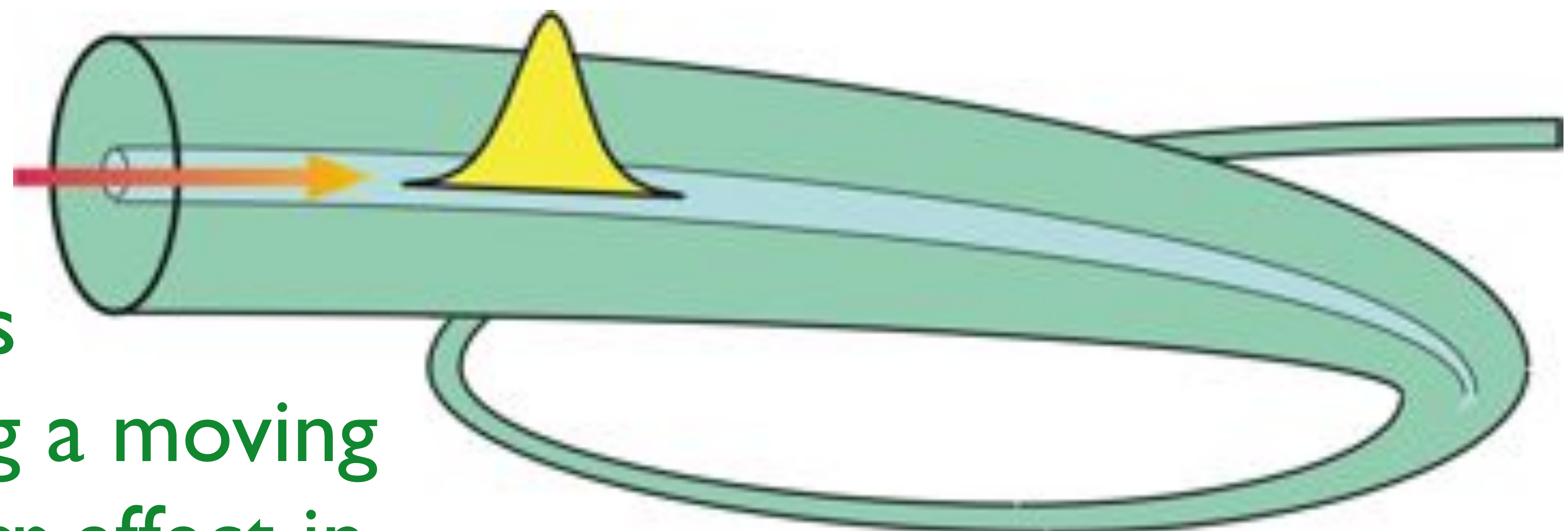
the equivalent of the river flow needs to exceed the speed of light in medium!!



→ every pulse adds a slight contribution to the refractive index of the fibre (prop. to the refractive index of intensity profile)

Analogue gravity *from optical media*

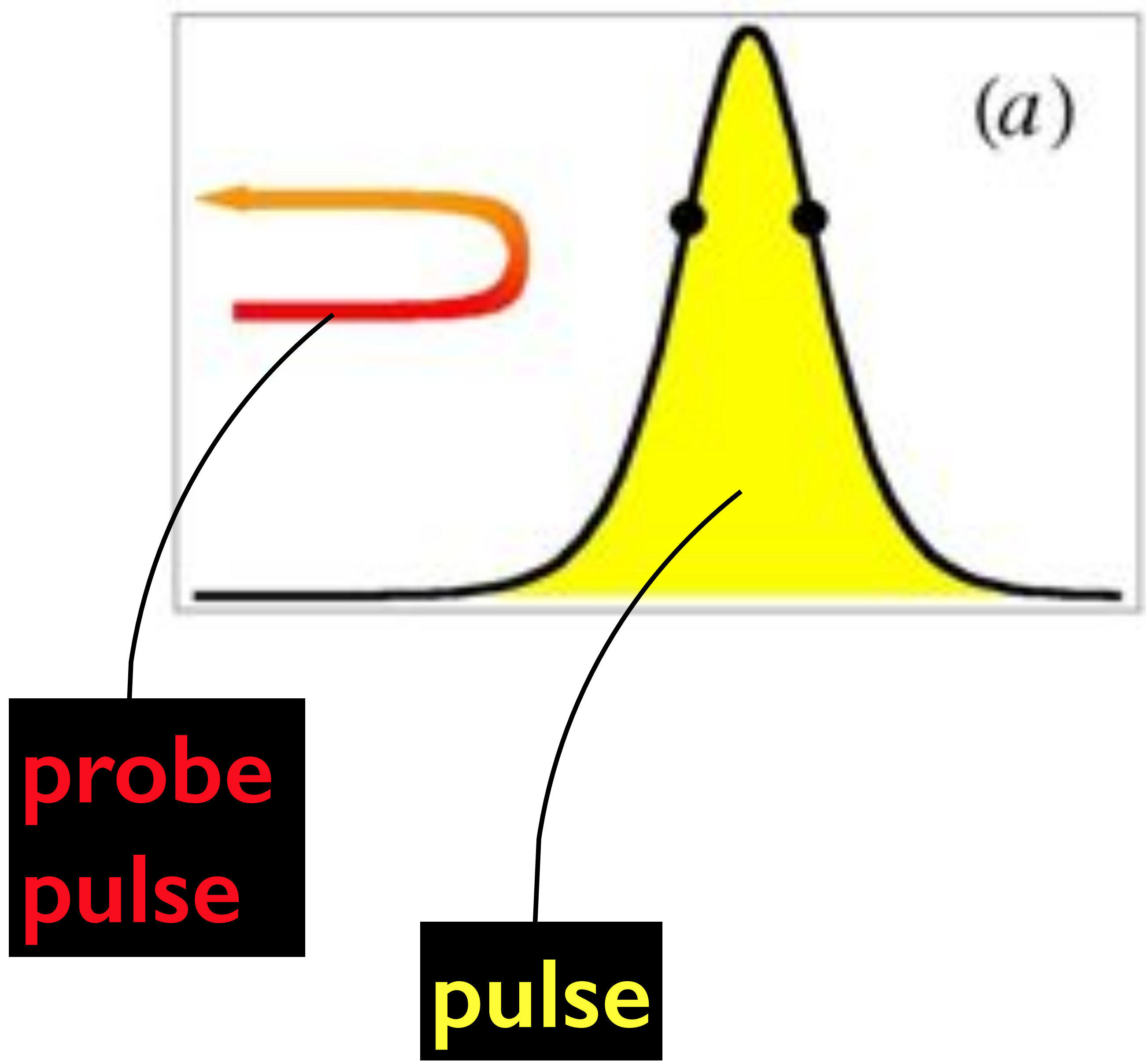
Sound waves/surface wave → light



→ the pulse is establishing a moving media (Kerr effect in ninliear fibre optics)

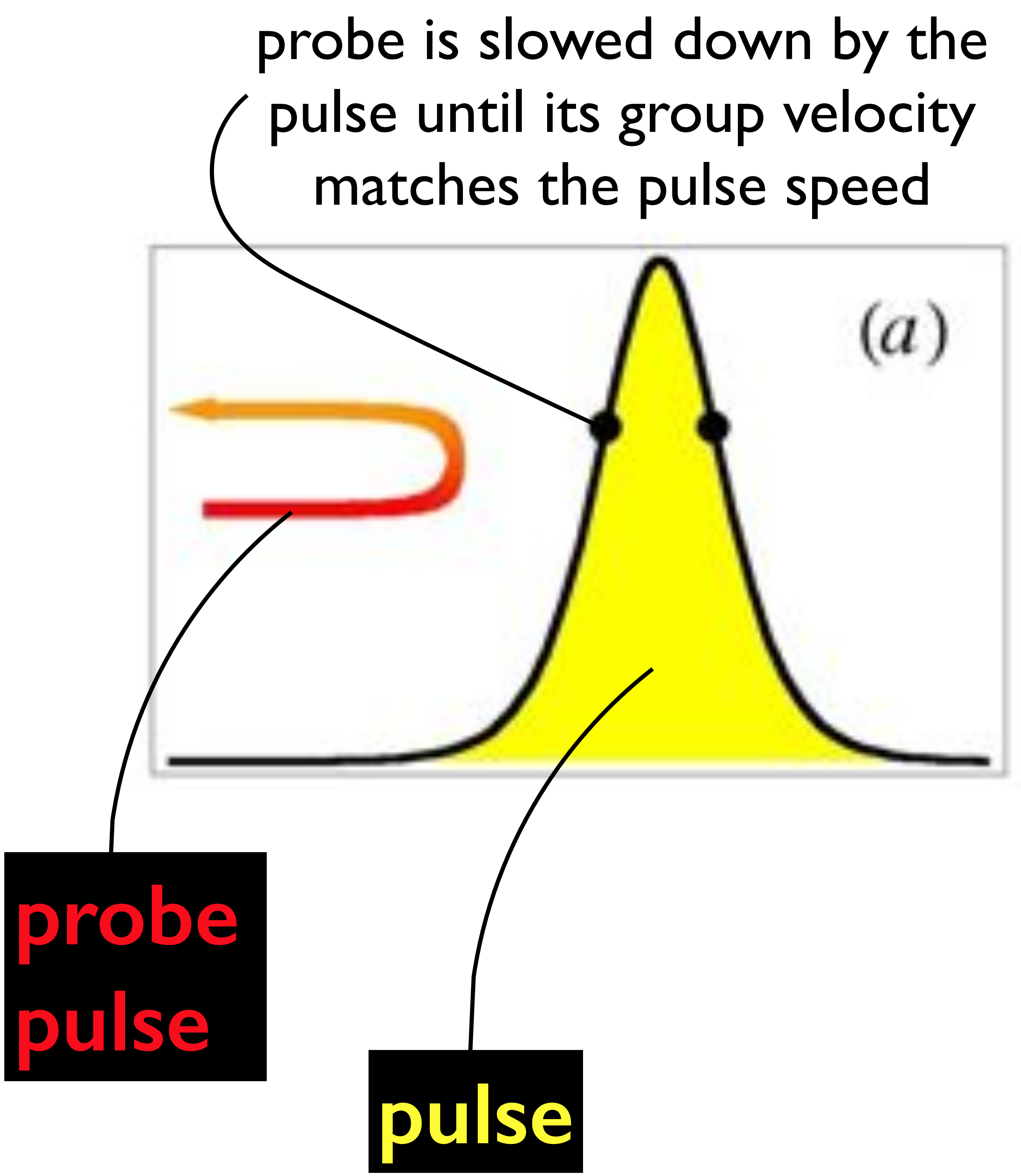
→ medium naturally moves with the speed of sound

Analogue black hole *from optical media*



Probing the effective geometry with a probe pulse

Analogue black hole *from optical media*



Probing the effective geometry with a probe pulse

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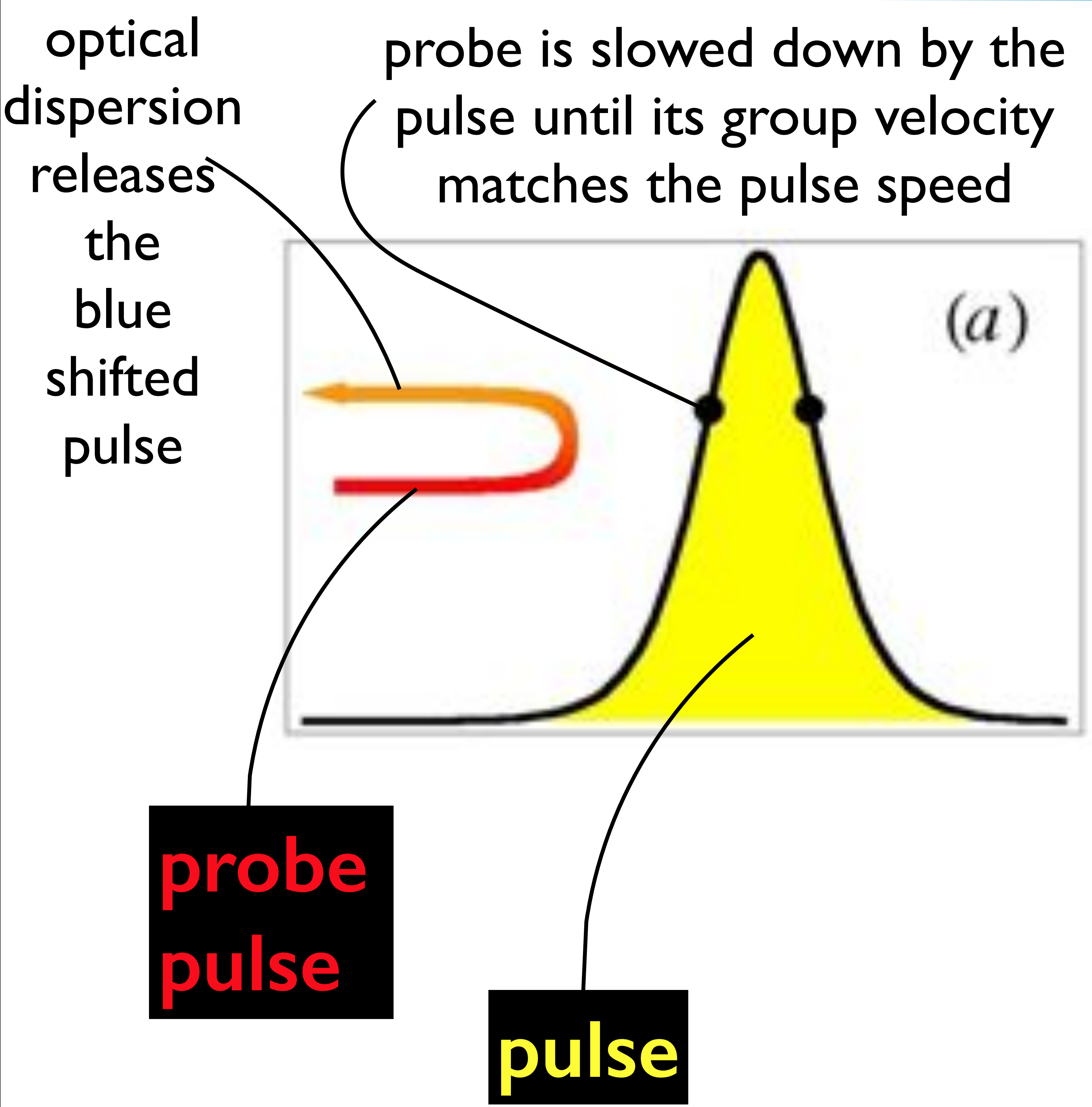
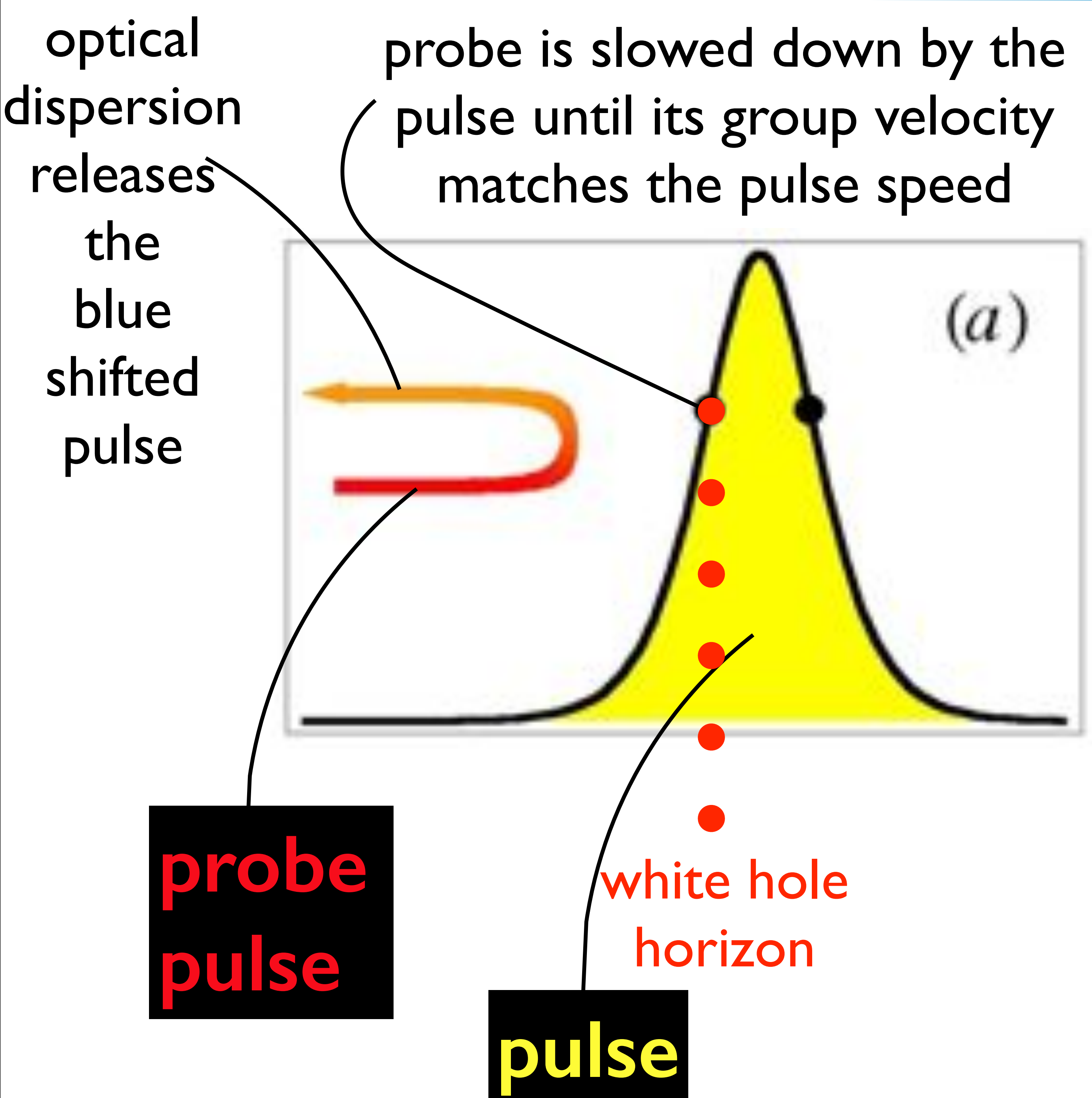
Analogue black hole *from optical media*



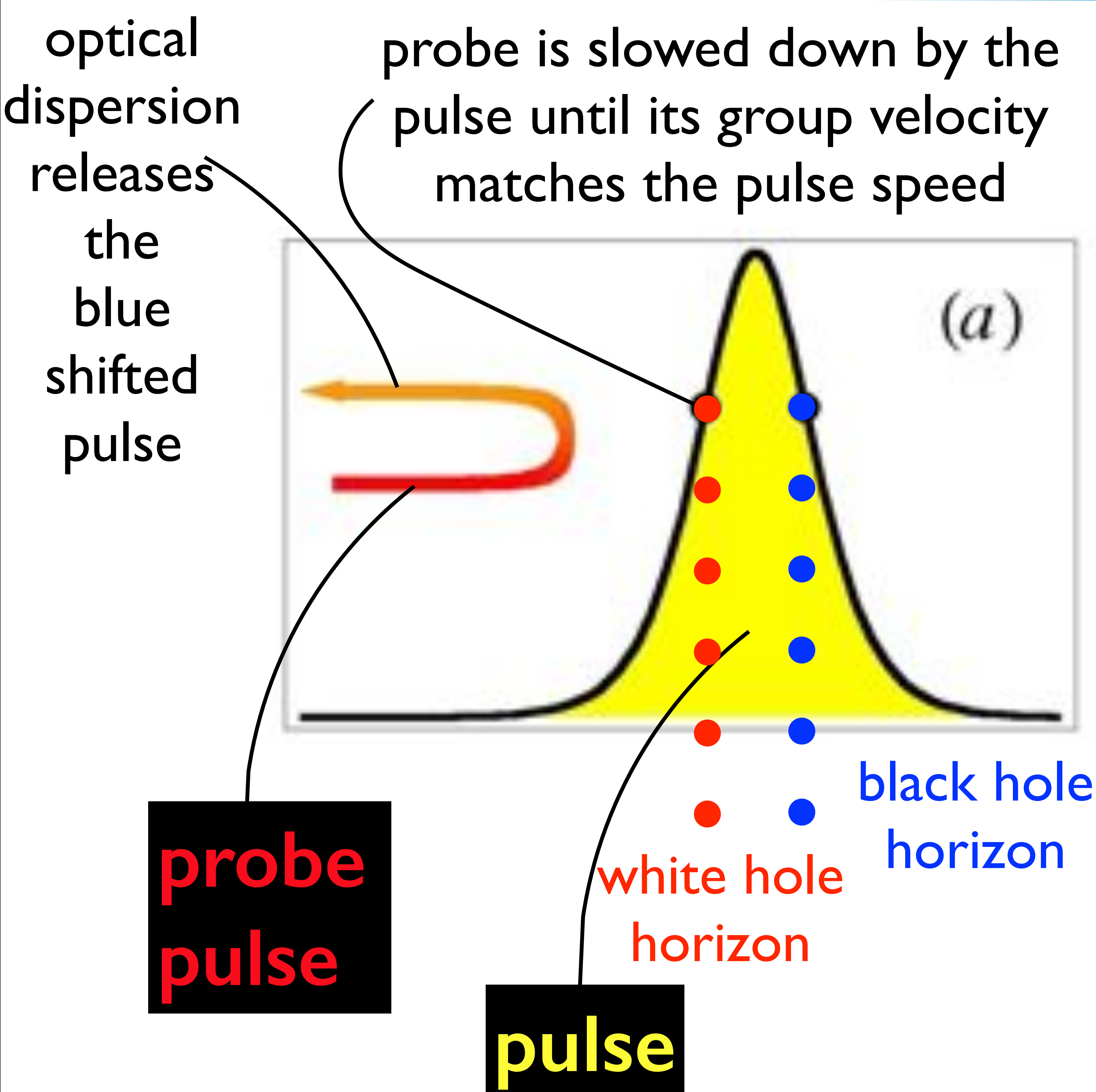
Probing the effective geometry with a probe pulse

Analogue black hole *from optical media*



Probing the effective geometry with a probe pulse

Analogue black hole *from optical media*

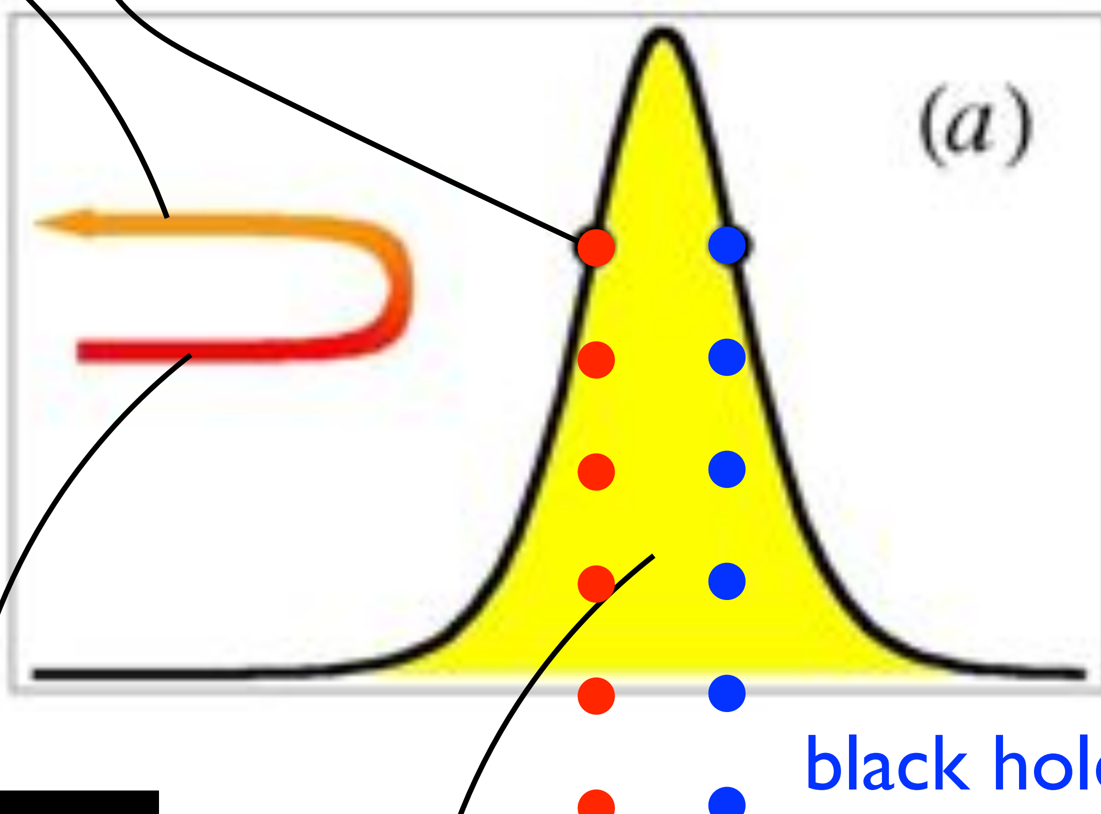


Probing the effective geometry with a probe pulse

Analogue black hole *from optical media*

optical dispersion releases the blue shifted pulse

probe is slowed down by the pulse until its group velocity matches the pulse speed



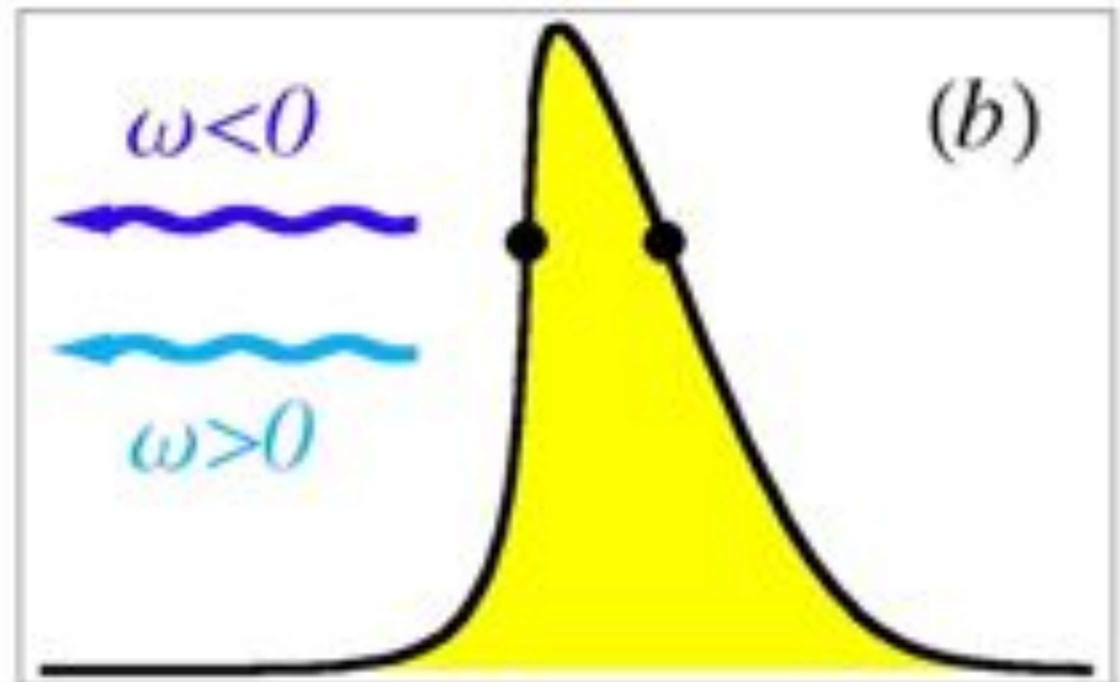
probe pulse

pulse

white hole horizon

black hole horizon

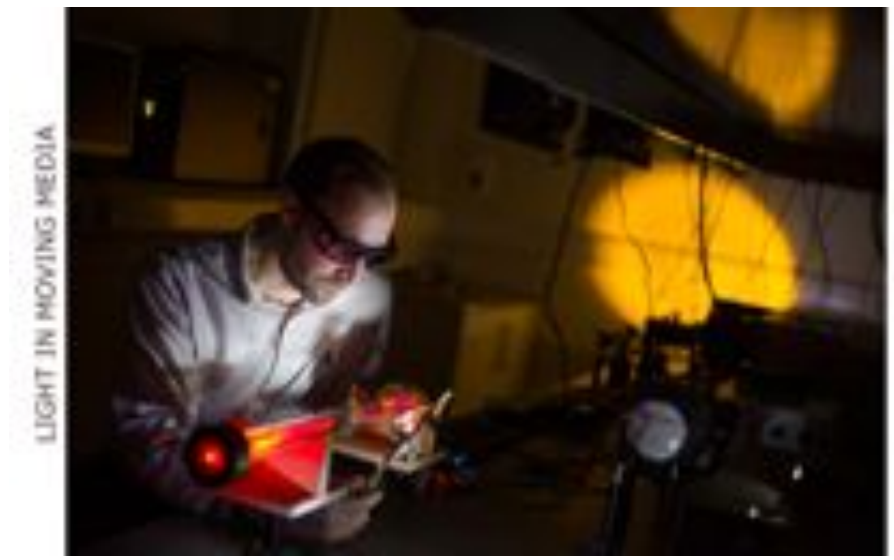
Without probing pulse:

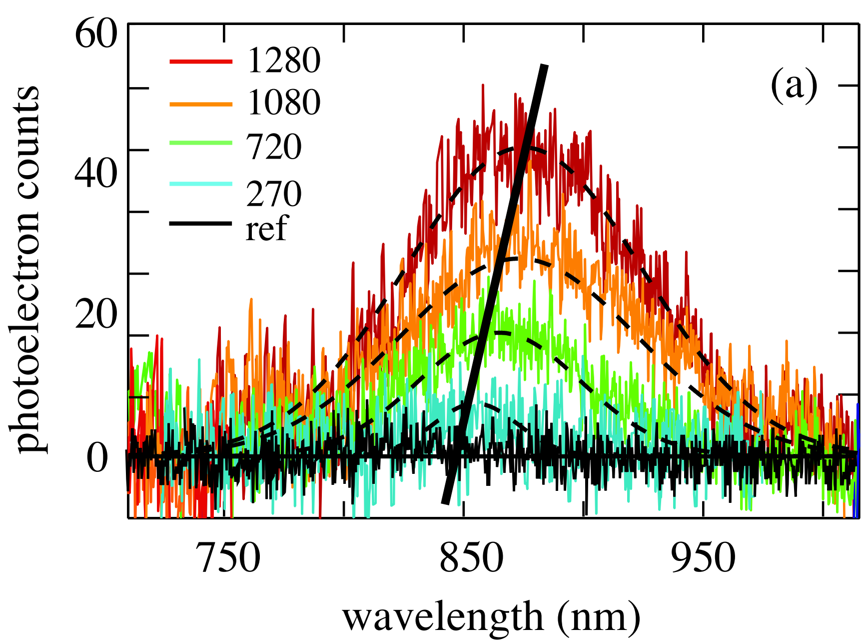


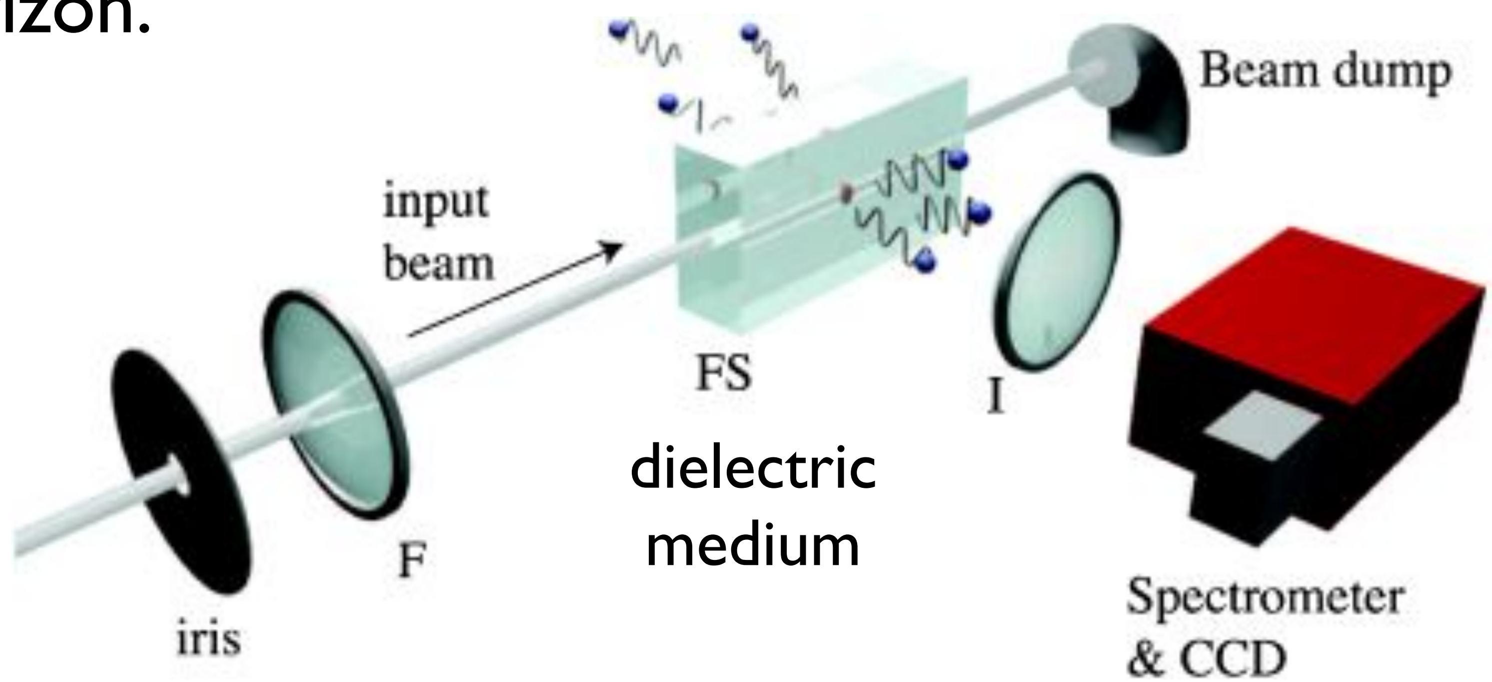
White hole emits photon pairs; Note: optical shock has steepened the pulse edge (increasing the surface gravity at the effective white hole horizon)

Hawking radiation *subtitle*

"we report experimental evidence of photon emission that on the one hand bears the characteristics of Hawking radiation and on the other is distinguishable and thus separate from other known photon emission mechanisms. We therefore interpret the observed photon emission as an indication of Hawking radiation induced by the analogue event horizon."







(i) in a bulk medium and
(ii) in a few-millimeter-long photonic-crystal fiber

THE ROYAL SOCIETY

Negative-Frequency Radiation *or HR?*

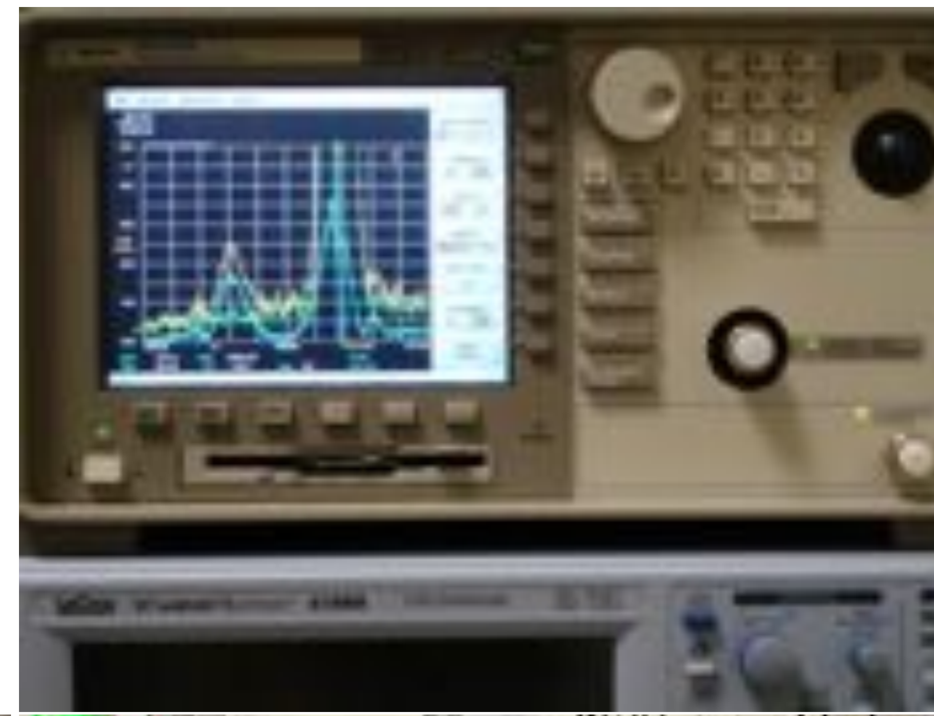
Selected for a Viewpoint in *Physics*
PRL **108,** 253901 (2012) PHYSICAL REVIEW LETTERS week ending 22 JUNE 2012

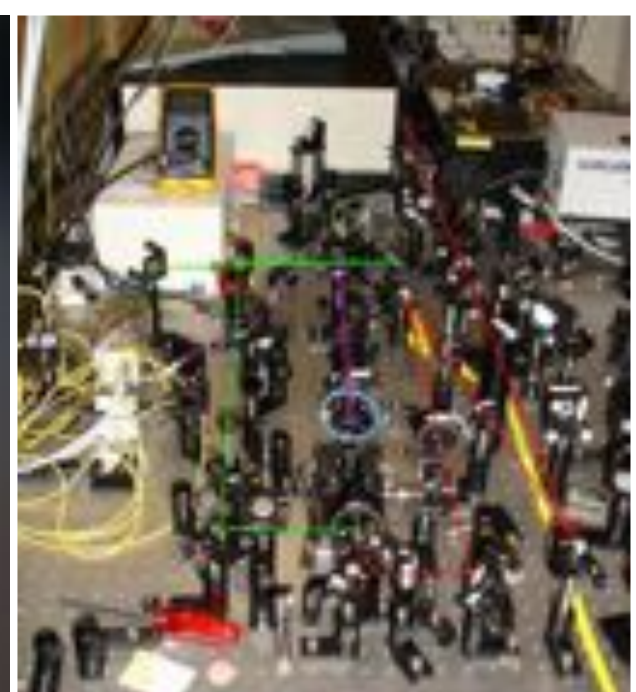
Negative-Frequency Resonant Radiation

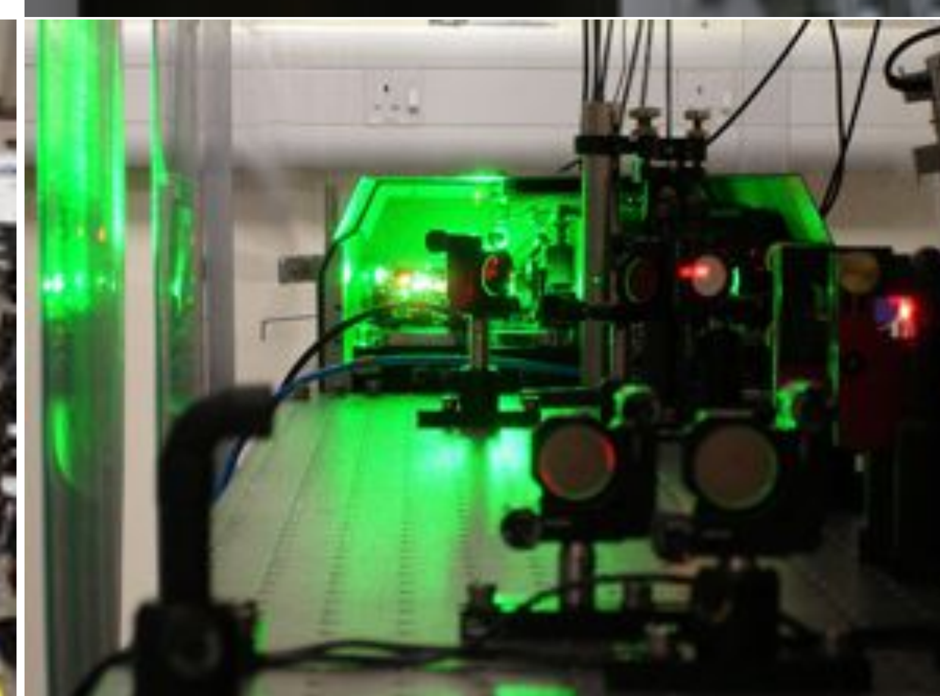
E. Rubino,[1] J. McLenaghan,[2] S. C. Kehr,[2] F. Belgiorno,[3] D. Townsend,[4] S. Rohr,[2] C. E. Kuklewicz,[4] U. Leonhardt,[2] F. König,[2,†] and D. Faccio[4,*]

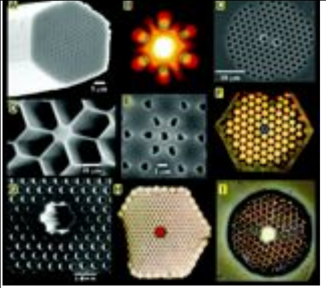
[1]*Dipartimento di Scienza e Alta Tecnologia, Università dell'Insubria, Via Valleggio 11, IT-22100 Como, Italy*
[2]*School of Physics and Astronomy, SUPA, University of St Andrews, North Haugh, St Andrews, KY16 9SS, United Kingdom*
[3]*Dipartimento di Matematica, Politecnico di Milano, Piazza Leonardo 32,20133 Milano, Italy*
[4]*School of Engineering and Physical Sciences, SUPA, Heriot-Watt University, Edinburgh EH14 4AS, United Kingdom*
(Received 16 December 2011; published 18 June 2012)

Optical solitons or solitonlike states shed light to blueshifted frequencies through a resonant emission process. We predict a mechanism by which a second propagating mode is generated. This mode, called negative resonant radiation, originates from the coupling of the soliton mode to the negative-frequency branch of the dispersion relation. Measurements in both bulk media and photonic-crystal fibers confirm our predictions.





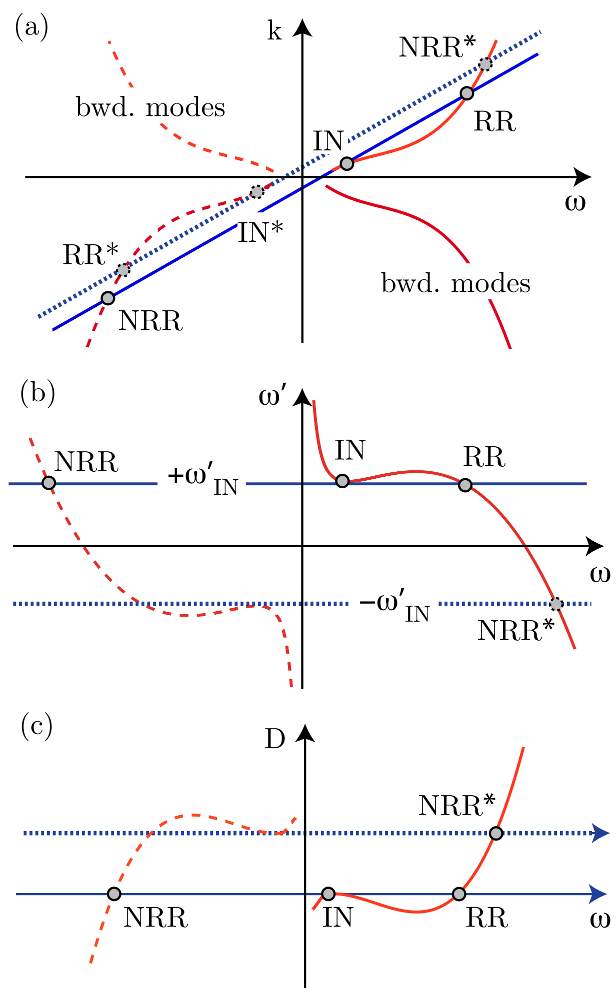


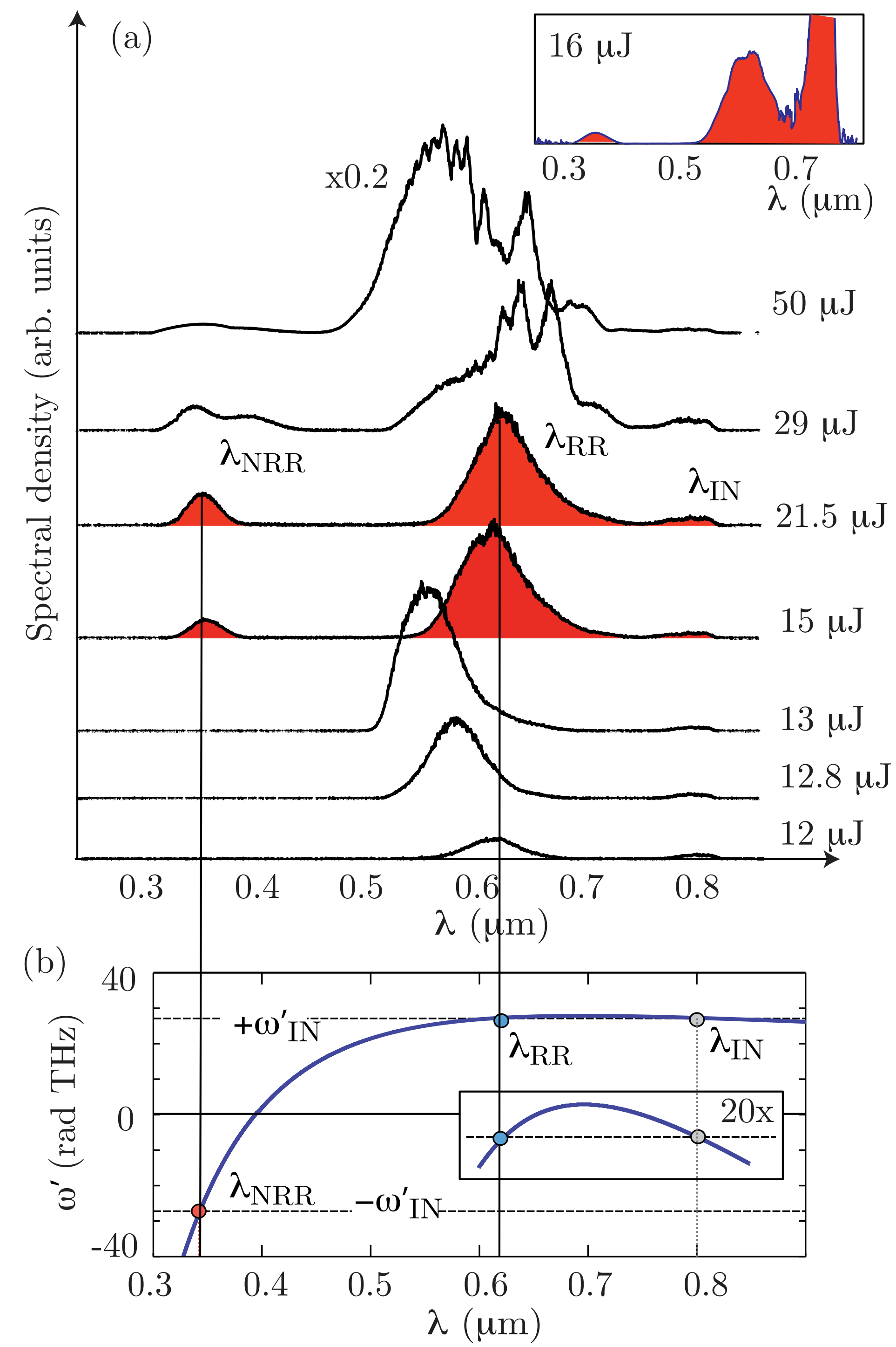


Negative resonant radiation *pair-creation*

Introduction.—Resonant radiation (RR), often also referred to as dispersive-wave or Cherenkov radiation, is a nonlinear optical process by which a soliton propagating in an optical fiber in the presence of higher-order dispersion sheds light through a resonantlike process to a shifted frequency [1–5]. This process and the precise frequency

Analogue gravity studies predicted the existence of Negative resonant radiation (NRR)





EXP. #3 *superfluid analogues of black holes*

PRL **105,** 240401 (2010) PHYSICAL REVIEW LETTERS week ending 10 DECEMBER 2010

Realization of a Sonic Black Hole Analog in a Bose-Einstein Condensate

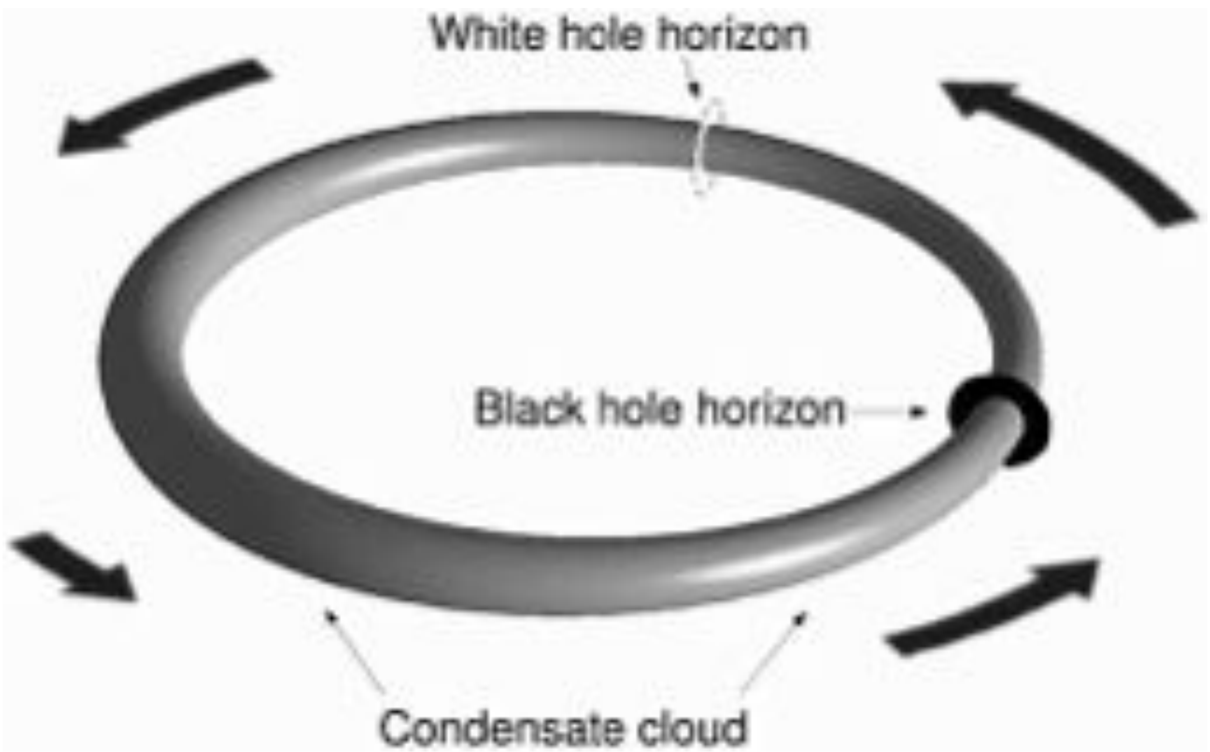
Oren Lahav, Amir Itah, Alex Blumkin, Carmit Gordon, Shahar Rinott, Alona Zayats, and Jeff Steinhauer

Technion—Israel Institute of Technology, Haifa, Israel

(Received 21 June 2009; revised manuscript received 21 October 2010; published 7 December 2010)

We have created an analog of a black hole in a Bose-Einstein condensate. In this sonic black hole, sound waves, rather than light waves, cannot escape the event horizon. A steplike potential accelerates the flow of the condensate to velocities which cross and exceed the speed of sound by an order of magnitude. The Landau critical velocity is therefore surpassed. The point where the flow velocity equals the speed of sound is the sonic event horizon. The effective gravity is determined from the profiles of the velocity and speed of sound. A simulation finds negative energy excitations, by means of Bragg spectroscopy.

Alternative proposals *ring geometry*



Quantum de Laval nozzle: Stability and quantum dynamics of sonic horizons in a toroidally trapped Bose gas containing a superflow

Phys. Rev. A 76, 023617 – Published 31 August 2007

P. Jain, A. S. Bradley, and C. W. Gardiner

Sonic black holes in dilute Bose-Einstein condensates

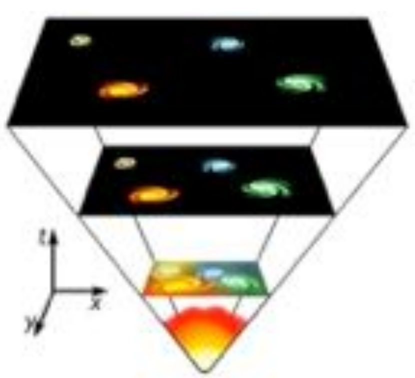
L.J. Garay[1,2], J.R. Anglin[1,3], J.I. Cirac[1], and P. Zoller[1]

Boundaries (open versus closed flow) do matter!

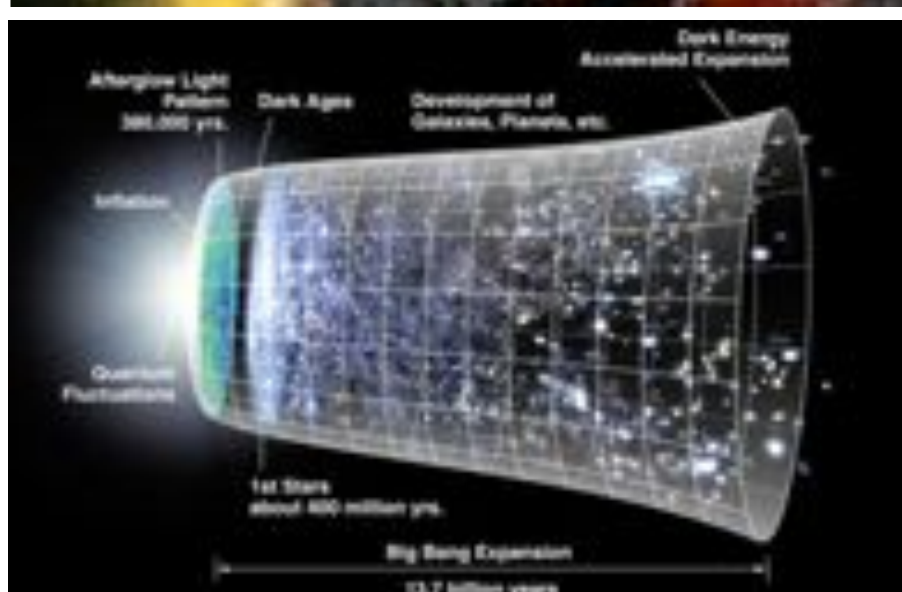
THE ROYAL SOCIETY

The University of Nottingham

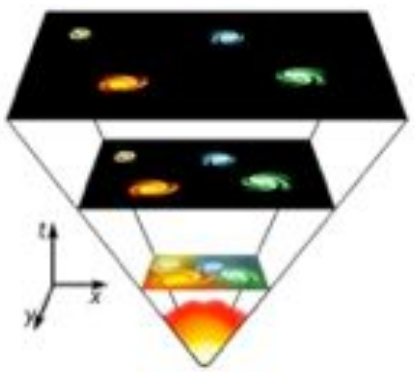
Cosmological particle production *in the laboratory*



Cosmological particle production



Cosmological particle production *in a nutshell*



Cosmological particle production

(**1**) How does it work?

(**2**) How can we set up a table-top experiments to mimic the mechanism that created particles in our universe?

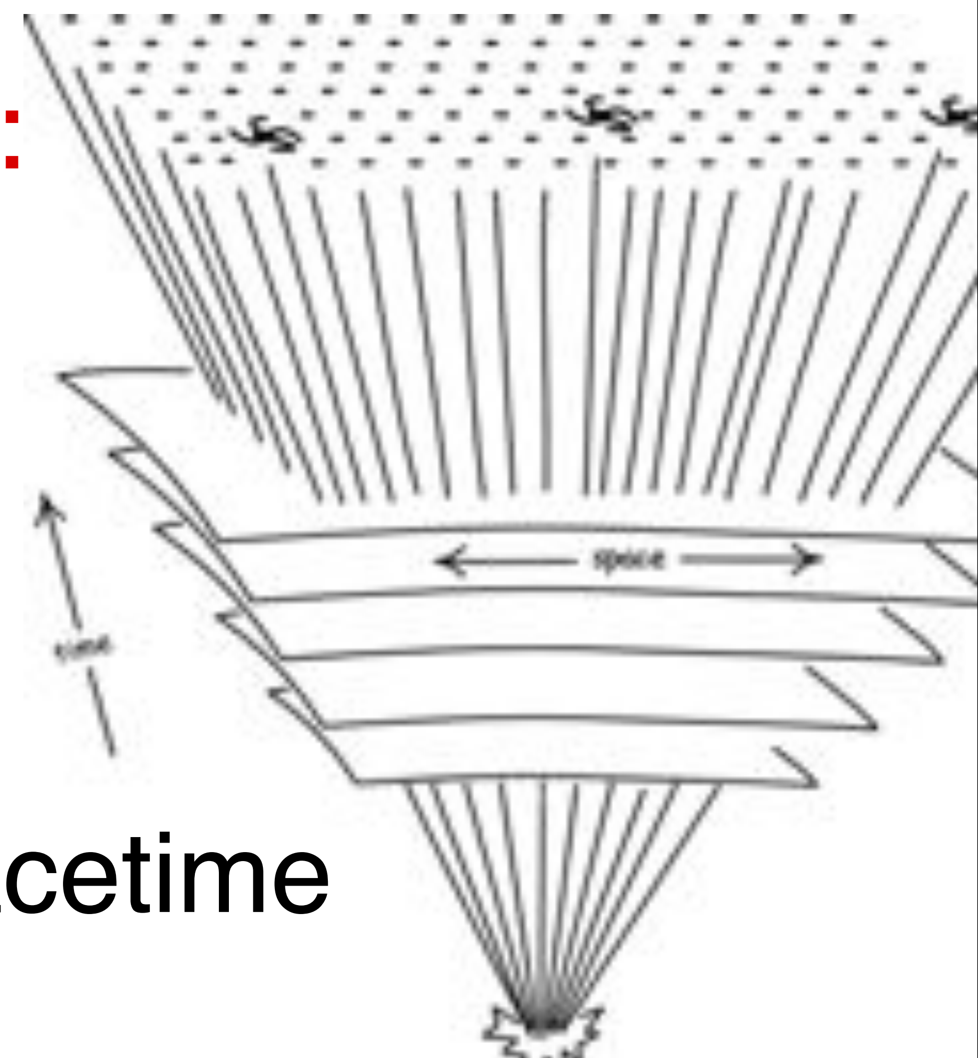
(**3**) Why is of scientific interest to carry out analogue simulations of cosmological particle production?

FRW spacetime *evolution of the universe as a whole*

Gravitational field matching our observations

our universe on cosmic scales is:

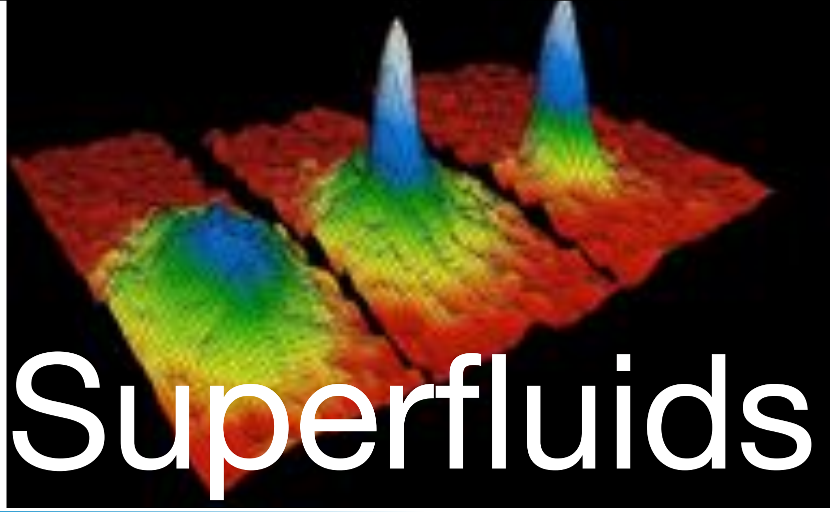
- expanding (redshift of spectra of distance galaxies)
- isotropic (uniform in all directions)
- homogeny (no large scale formation)



Friedmann-Robertson-Walker spacetime

only maximally symmetric three-dimensional subspace with pos. eigenvalues

$$\mathrm{d}s^2 = g^{ab}\,\mathrm{d}x^a\,\mathrm{d}x^b = -\mathrm{d}t^2 + a(t)^2\,\mathrm{d}\mathcal{L}^2$$



Superfluids *with a time-dependent speed of sound*

✻ Low temperature phase: microscopic degrees give way to macroscopic variables: $\hat{\psi} \rightarrow \langle \hat{\psi} \rangle \equiv \psi$

Ultra-cold weakly interacting gas of bosons

external trapping potential

density

$$\psi(t, \mathbf{x}) = \sqrt{n(t, \mathbf{x})}\, \exp(i\theta(t, \mathbf{x}))$$

phase

time-dependent condensate density

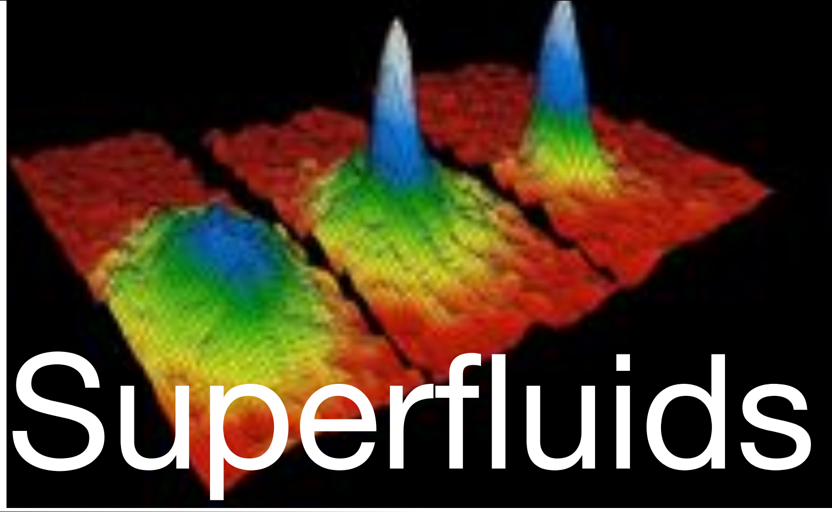
cold-collision regime

$$U = \frac{4\pi\hbar^2 a_{\mathrm{scatt}}(t)}{m}$$

inter atomic potential

Small excitations around the ground state see a superfluid and their propagation speed proportional to the condensate density and interaction strength:

$$c^2 = \frac{n(t)\, U(t)}{m}$$



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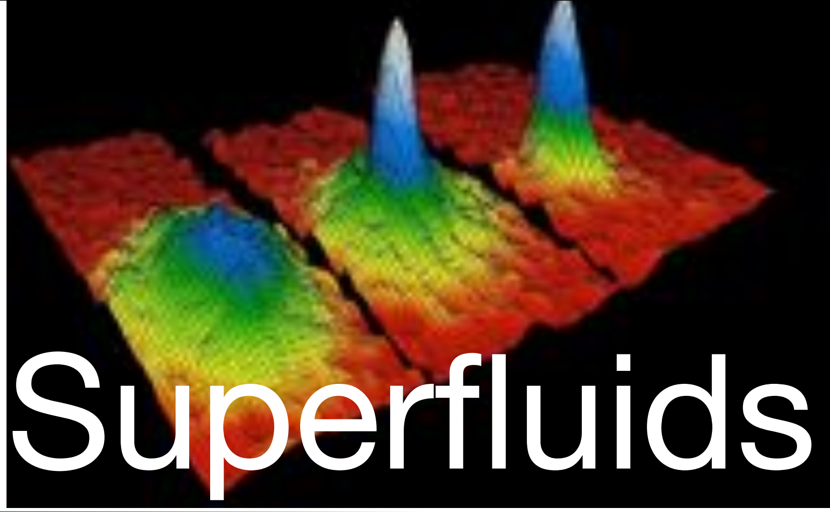


Superfluids *as an effective expanding universe*

Scale factor for Boson interactions

$$b(t) = \begin{cases} \exp(-t/t_s) & \text{for} \quad d = 2; \\ t_s/(t+t_s) & \text{for} \quad d = 3; \end{cases}$$

A specific time-dependent change in the interaction strength/ condensate density results in an effective de-Sitter universe.

Hubble parameter

Rate of change

$$H = \frac{1}{2\,t_s}$$

FRW-scale factor

$$a(\tau) = \exp(H\,\tau)$$

THE ROYAL SOCIETY

Cosmological particle production

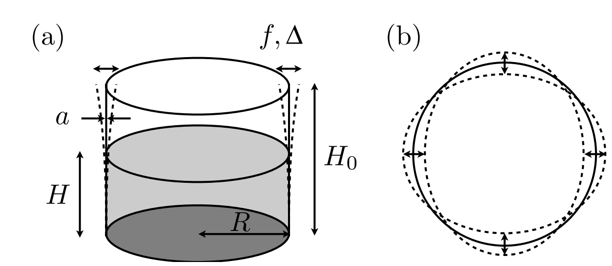
Simple example: assume cyclic universe, that is a cyclic scale factor (cyclic variations in the speed of sound in our analogue), this leads to parametric resonance.

Tibetan singing bowls

Denis Terwagne[1] **and John W M Bush**[2]

[1] GRASP, Département de Physique, Université de Liège, B-4000 Liège, Belgium
[2] Department of Mathematics, Massachusetts Institute of Technology, 02139 Cambridge, MA, USA

Received 8 April 2010
Published 1 July 2011



$$\mathrm{d}s^2 = g^{ab}\,\mathrm{d}x^a\,\mathrm{d}x^b = -\mathrm{d}t^2 + a(t)^2\,\mathrm{d}\mathcal{L}^2$$

THE ROYAL SOCIETY

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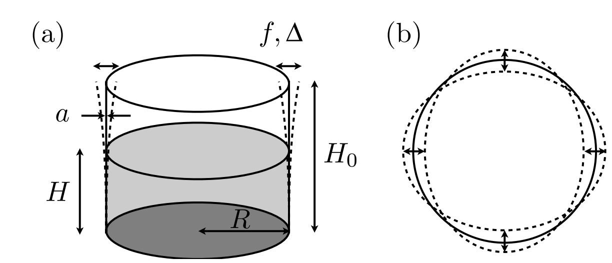
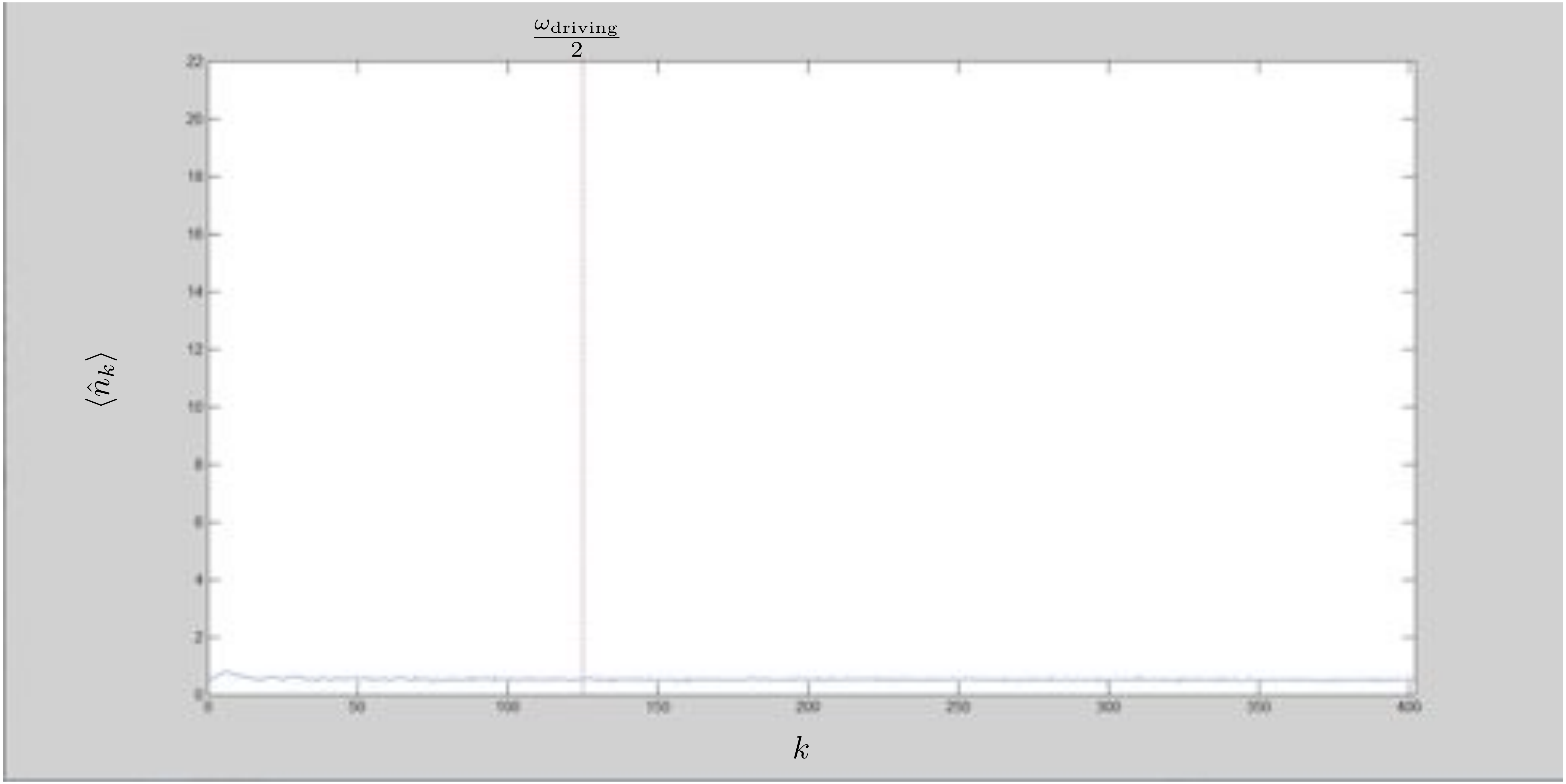


$$\mathrm{d}s^2 = g^{ab}\,\mathrm{d}x^a\,\mathrm{d}x^b = -\mathrm{d}t^2 + a(t)^2\,\mathrm{d}\mathcal{L}^2$$

Cosmo. particle production *in BEC*



Parametric resonance in BEC simulation

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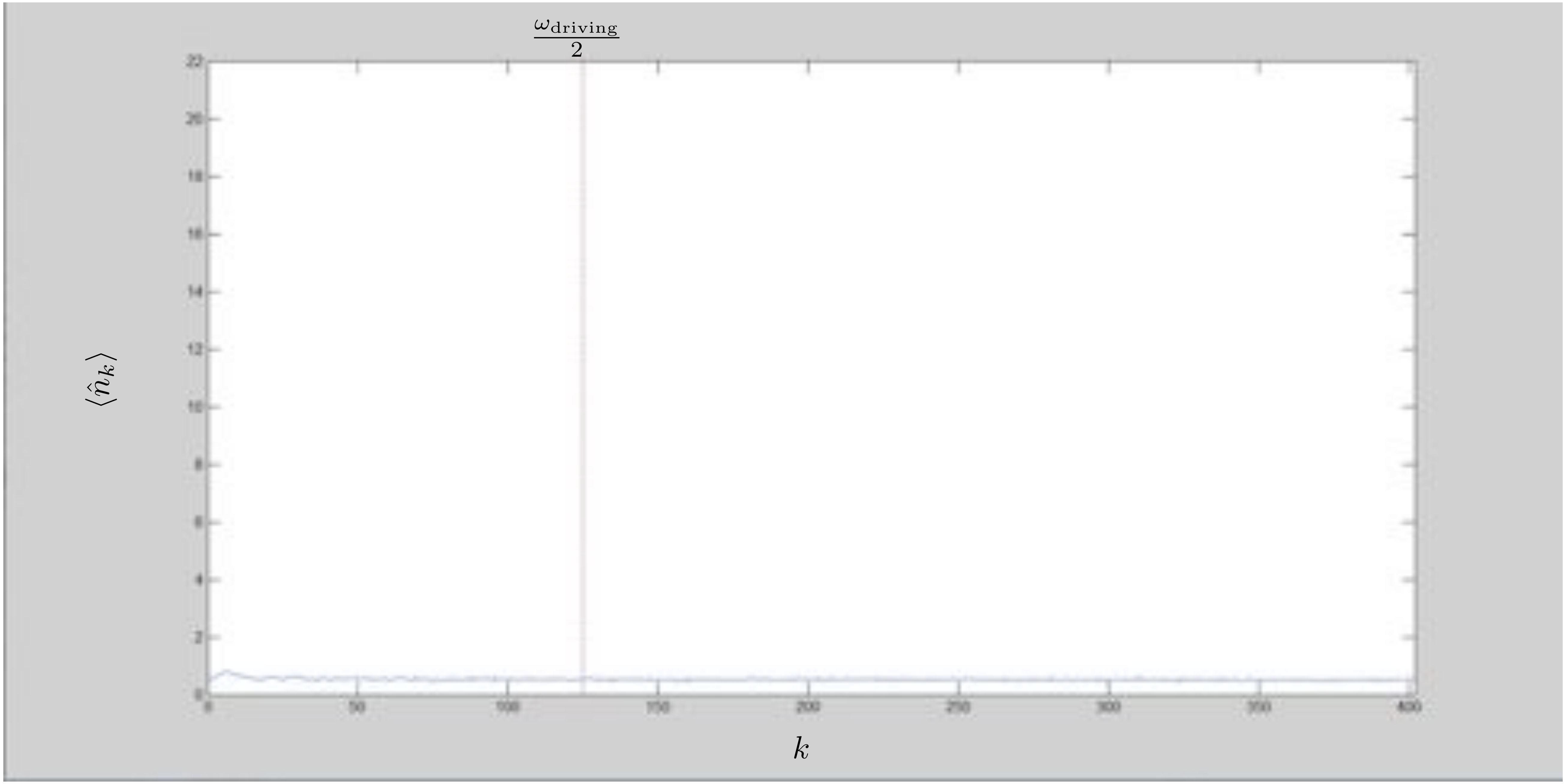
Cosmo. particle production *in BEC*



Parametric resonance in BEC simulation

Inflation *and particle production (in qft as well as bec's)*

$$\ddot{\hat{\chi}}_k(t) + \left(\omega_k(t)^2 - H^2\right)\hat{\chi}_k(t) = 0$$

$$\mathcal{R}_k = \frac{\omega_k(t)^2}{H^2}$$

$$H = \frac{1}{2\,t_s}$$

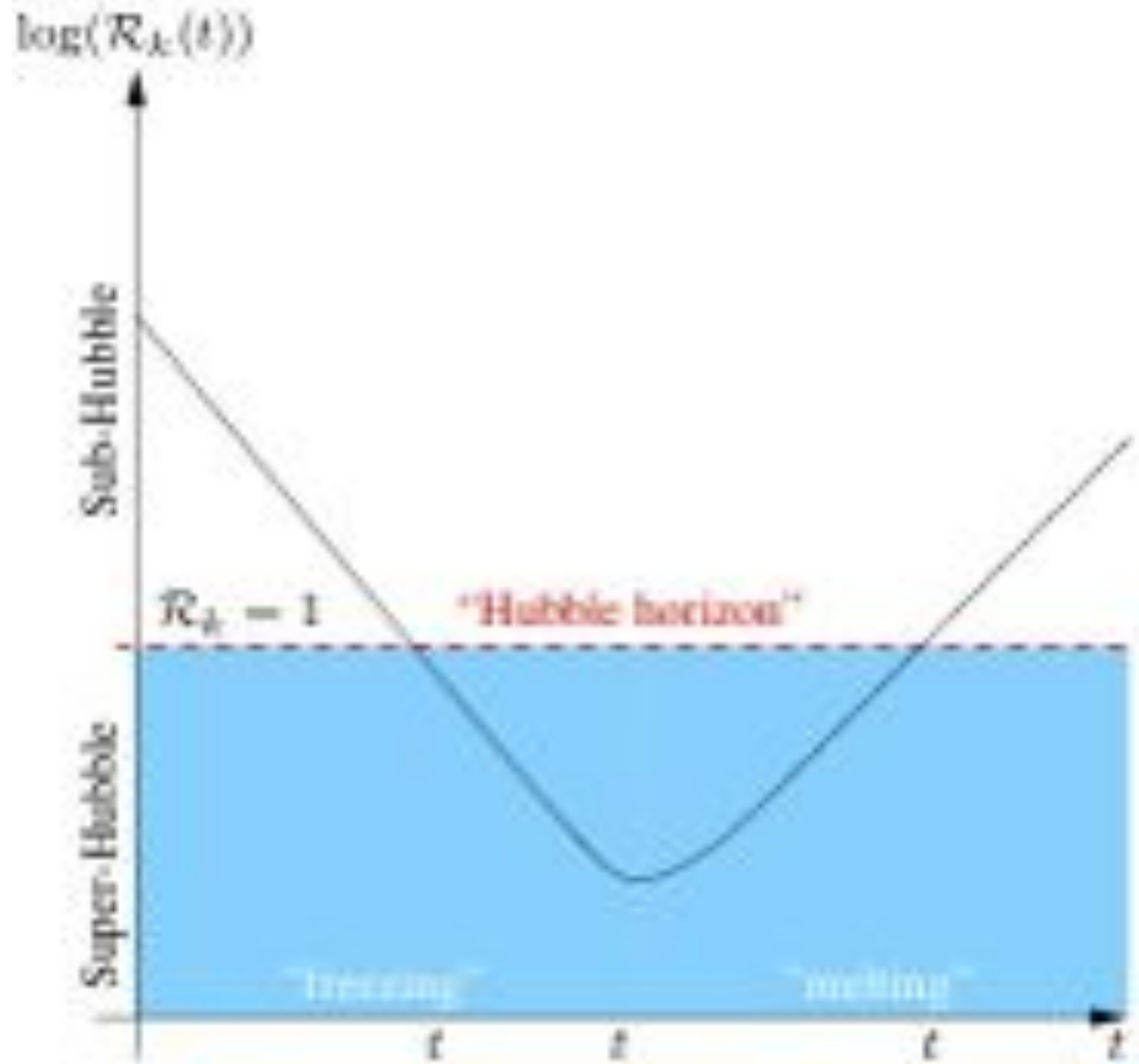


FIG. 8: Schematic description of the freezing and melting of quantum modes.

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Exp. #4 *particle creation in an effective cyclic universe*

Selected for a Viewpoint in *Physics*

PRL **109,** 220401 (2012) PHYSICAL REVIEW LETTERS week ending 30 NOVEMBER 2012

Acoustic Analog to the Dynamical Casimir Effect in a Bose-Einstein Condensate

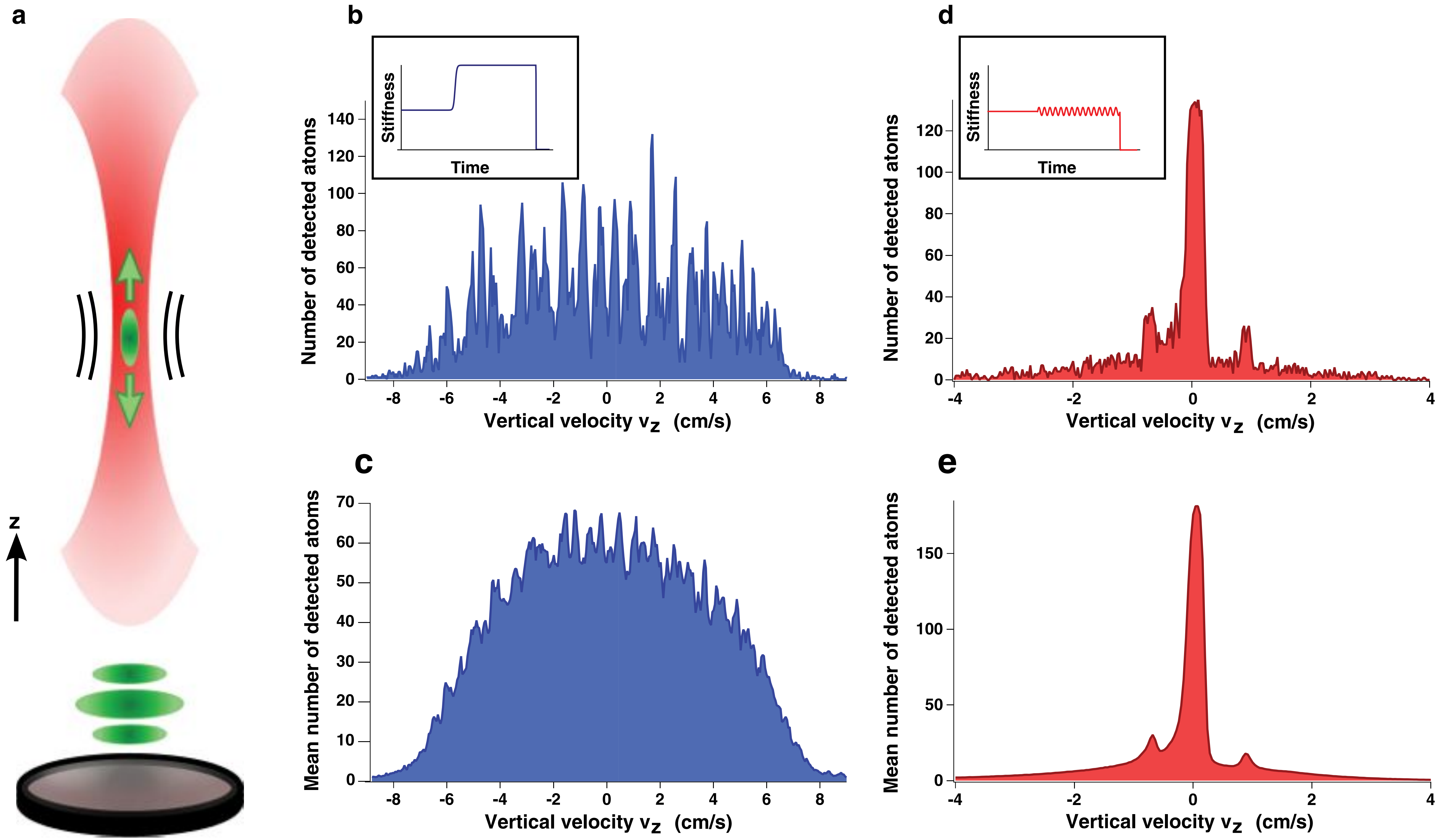
J.-C. Jaskula,[*] G. B. Partridge,[†] M. Bonneau, R. Lopes, J. Ruaudel, D. Boiron, and C. I. Westbrook

Laboratoire Charles Fabry, Institut d'Optique, CNRS, Université Paris-Sud, 2 avenue Augustin Fresnel, 91127 Palaiseau, France

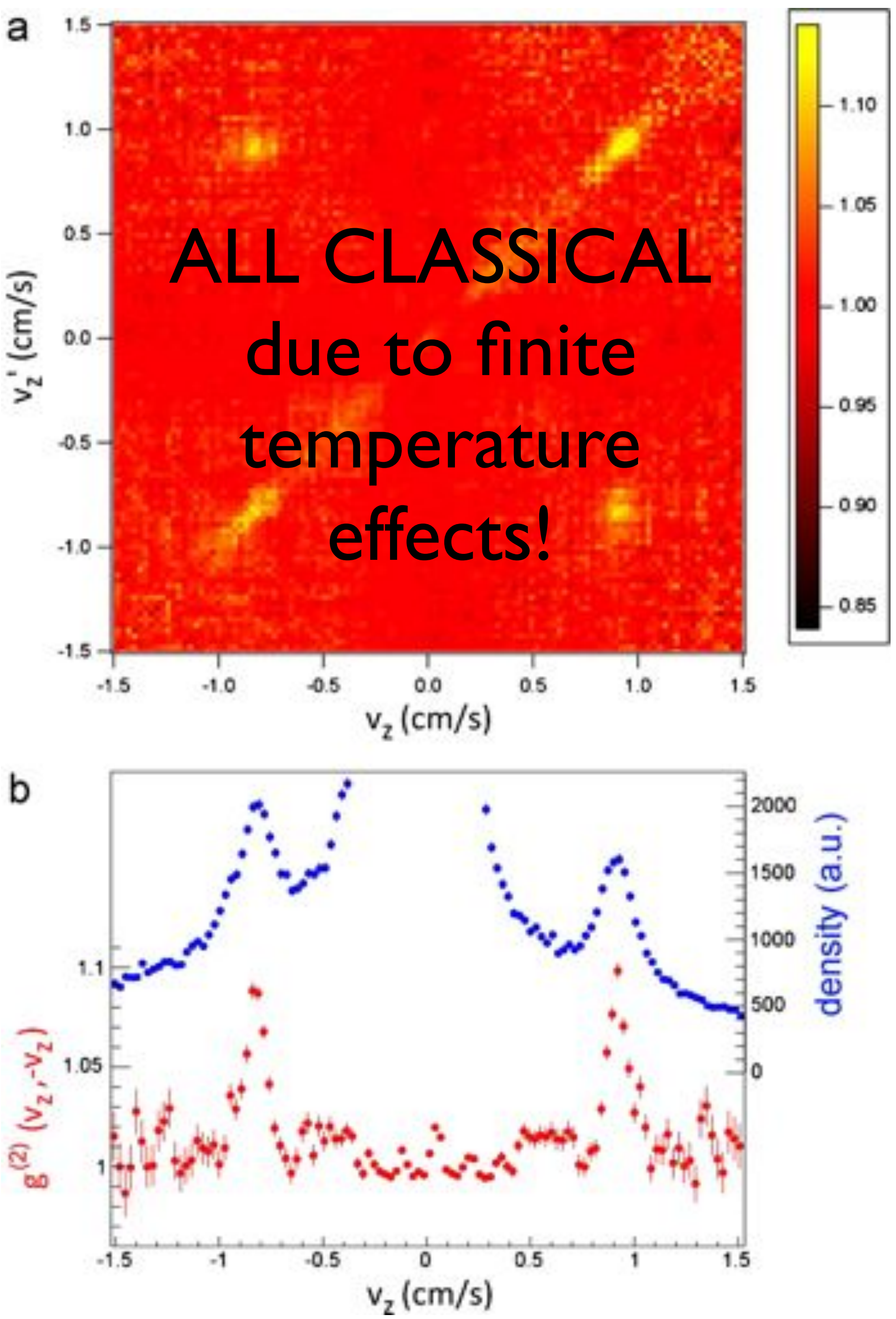
(Received 5 July 2012; published 26 November 2012)

We have modulated the density of a trapped Bose-Einstein condensate by changing the trap stiffness, thereby modulating the speed of sound. We observe the creation of correlated excitations with equal and opposite momenta, and show that for a well-defined modulation frequency, the frequency of the excitations is half that of the trap modulation frequency.

Pair-particle process *at half of the driving freq.*



Correlations *classical or quantum?*



Are these fluctuations described by classical or quantum statistics..?

One indicator of non-classical statistics is the 2-mode variance / strength of correlations

$$V(\mathbf{k},\mathbf{k}'=-\mathbf{k},t) \;=\; 1+\frac{G^{(2)}_{\mathbf{k},\mathbf{k}}-G^{(2)}_{\mathbf{k},-\mathbf{k}}}{\langle\hat{n}_{\mathbf{k}}\rangle}$$

auto-correlations versus cross-correlations

$$V(\mathbf{k},\mathbf{k}',t)\begin{cases} >1 & \text{super-Poissonian} \\ =1 & \text{Poissonian} \\ <1 & \text{sub-Poissonian}\end{cases}$$

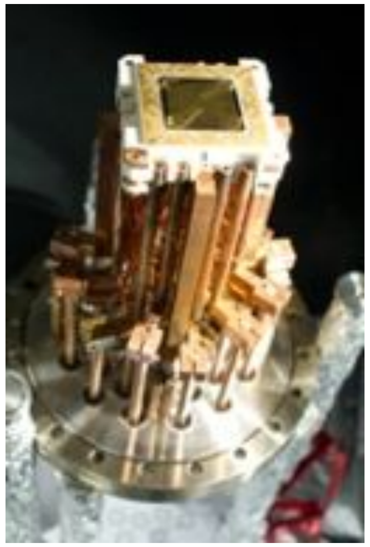
Why is it useful..? *quantum versus classical*

Up until now:
we have **<u>not</u>** managed to mimic any quantum aspect of field theory in curved spacetimes!!!

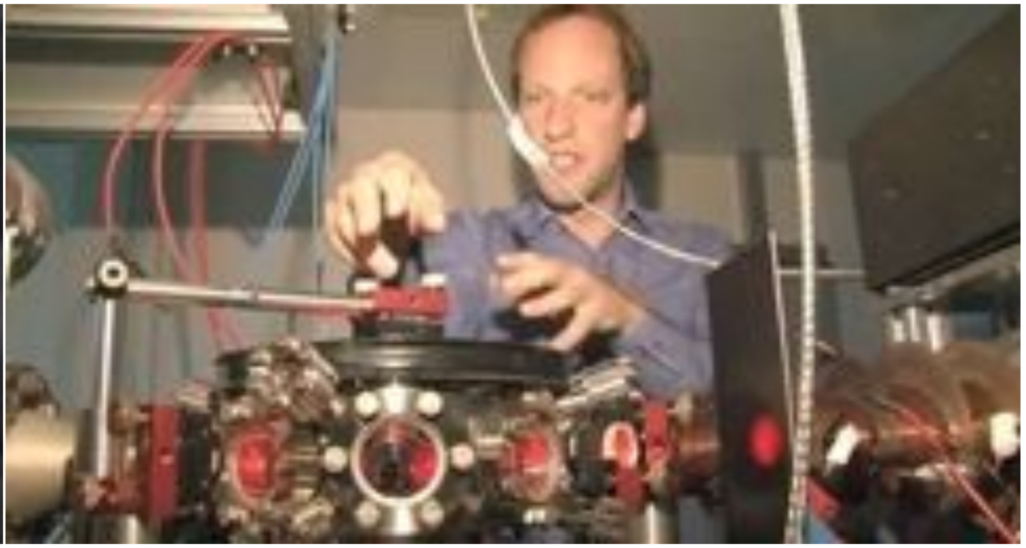
(i) we need to gain more insights into the difficulties in generating quantum-correlated (entangled) pairs of phonons in such a controllable setting, and then try to apply our findings to cosmology;
(ii) we should be able to apply the mechanisms behind cosmological particle production for quantum information purposes, or at least to enhance our understanding of entanglement in weakly interaction systems (e.g. thermalization versus loss of non-classical behavior due to interaction);

Cosmology inspired *ultra-cold atom experiments*

Atom-chips: Prof. Joerg Schmiedmayer and Prof. Peter Kruger

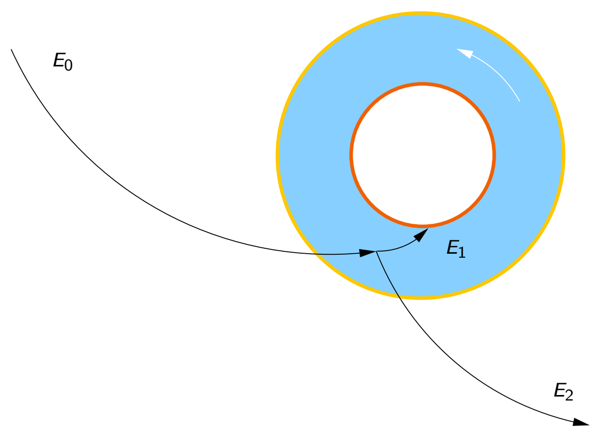


highly controllable atom traps

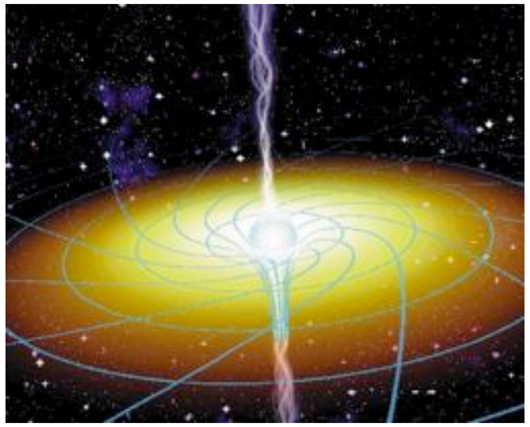


More experiments planned: Chris Westbrook (e.g. repeat the experiment looking for non-classical correlations...)

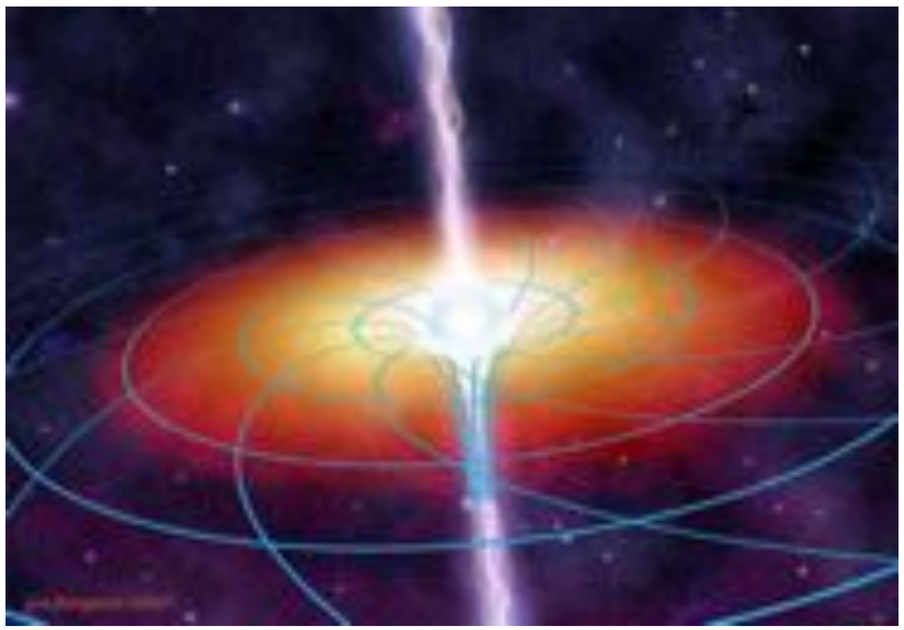
Superradiant scattering *in the laboratory*

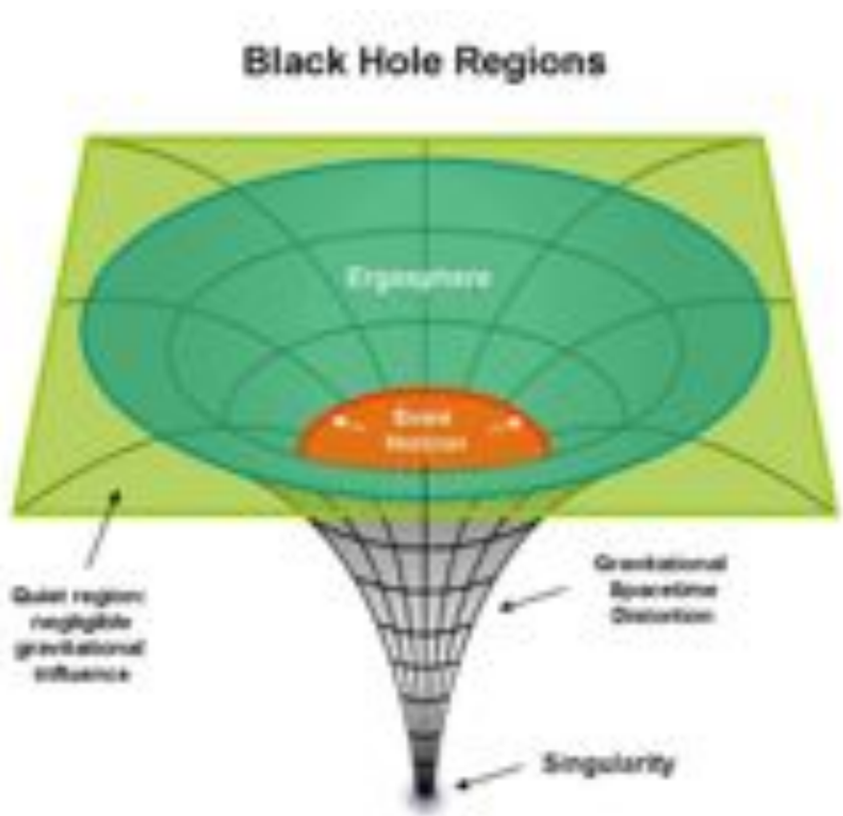


Superradiant scattering from rotating black holes



Superradiant scattering *in a nutshell*

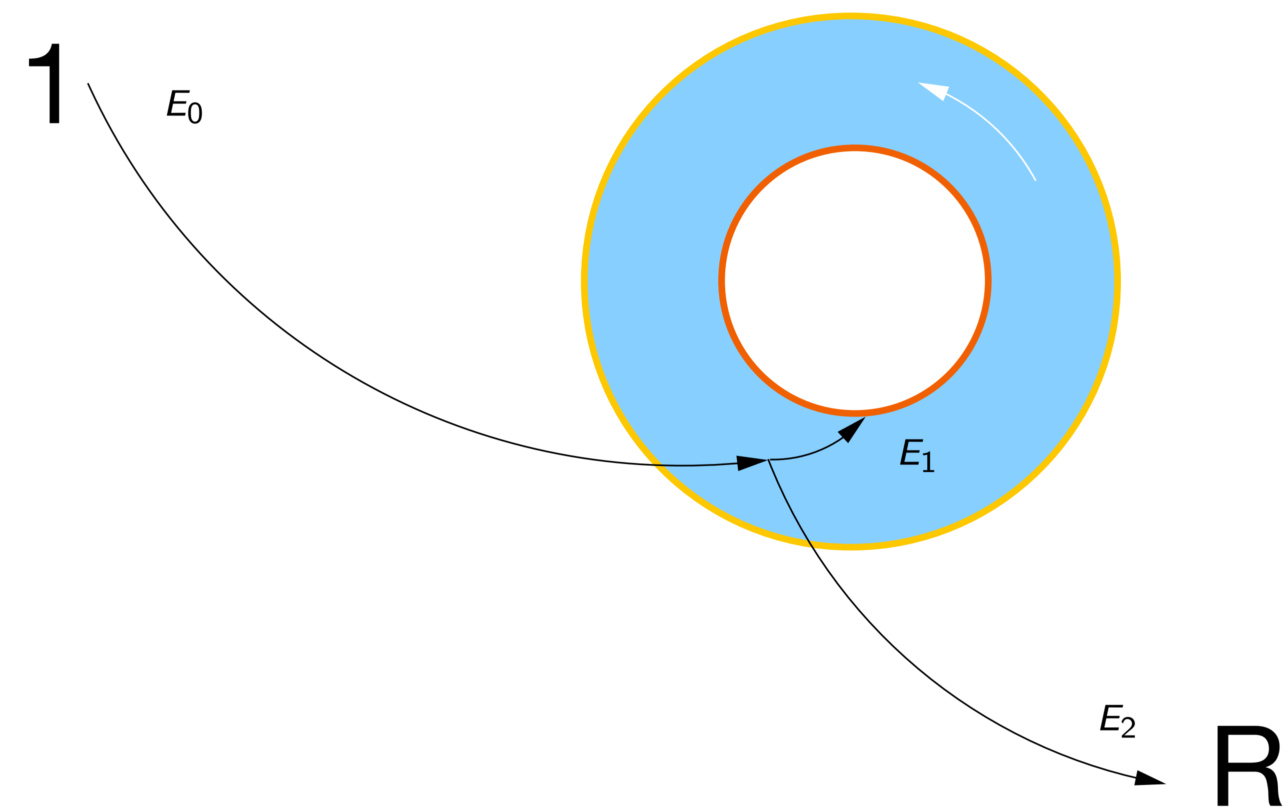




angular velocity and electric potential

at the event horizon

$$|\mathcal{R}|^2 = 1 - \frac{\omega - m\Omega_h - e\Phi_h}{\omega}|\mathcal{T}|^2$$



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

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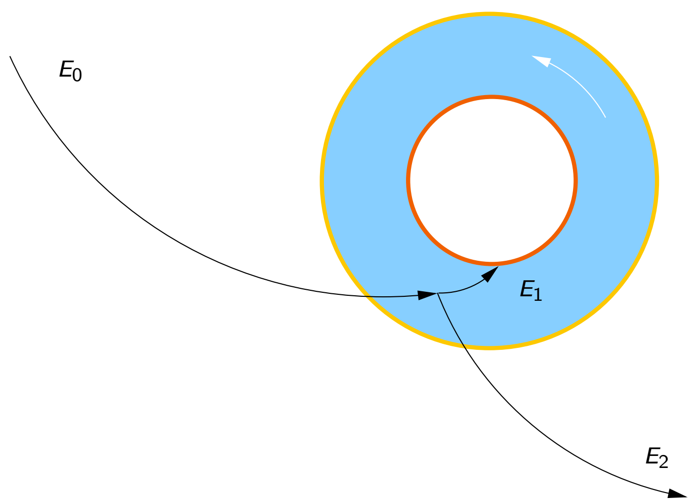
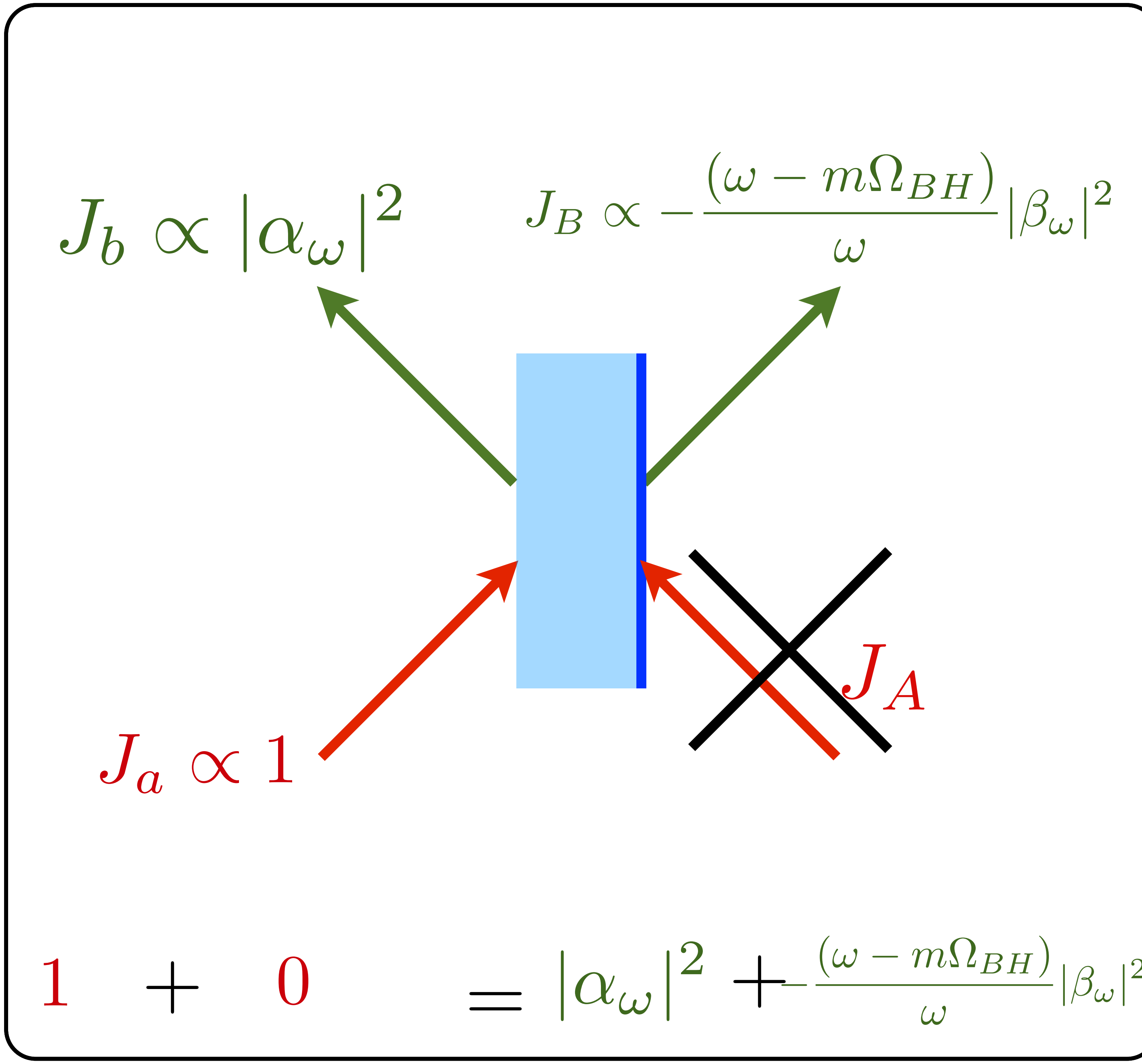
Superradiant scattering *compared to HR*



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

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



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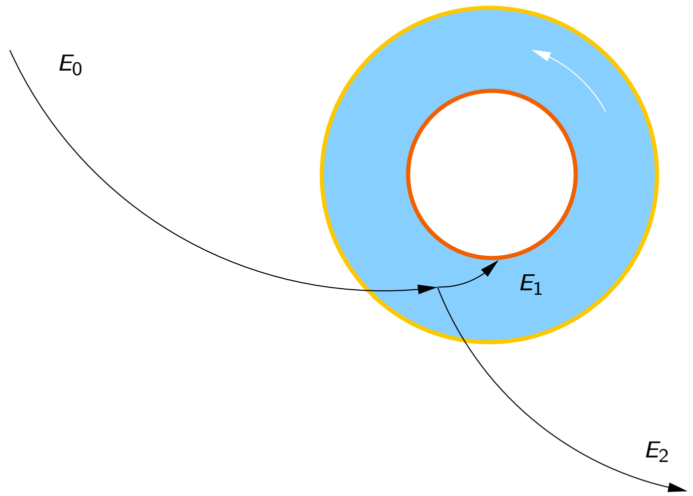

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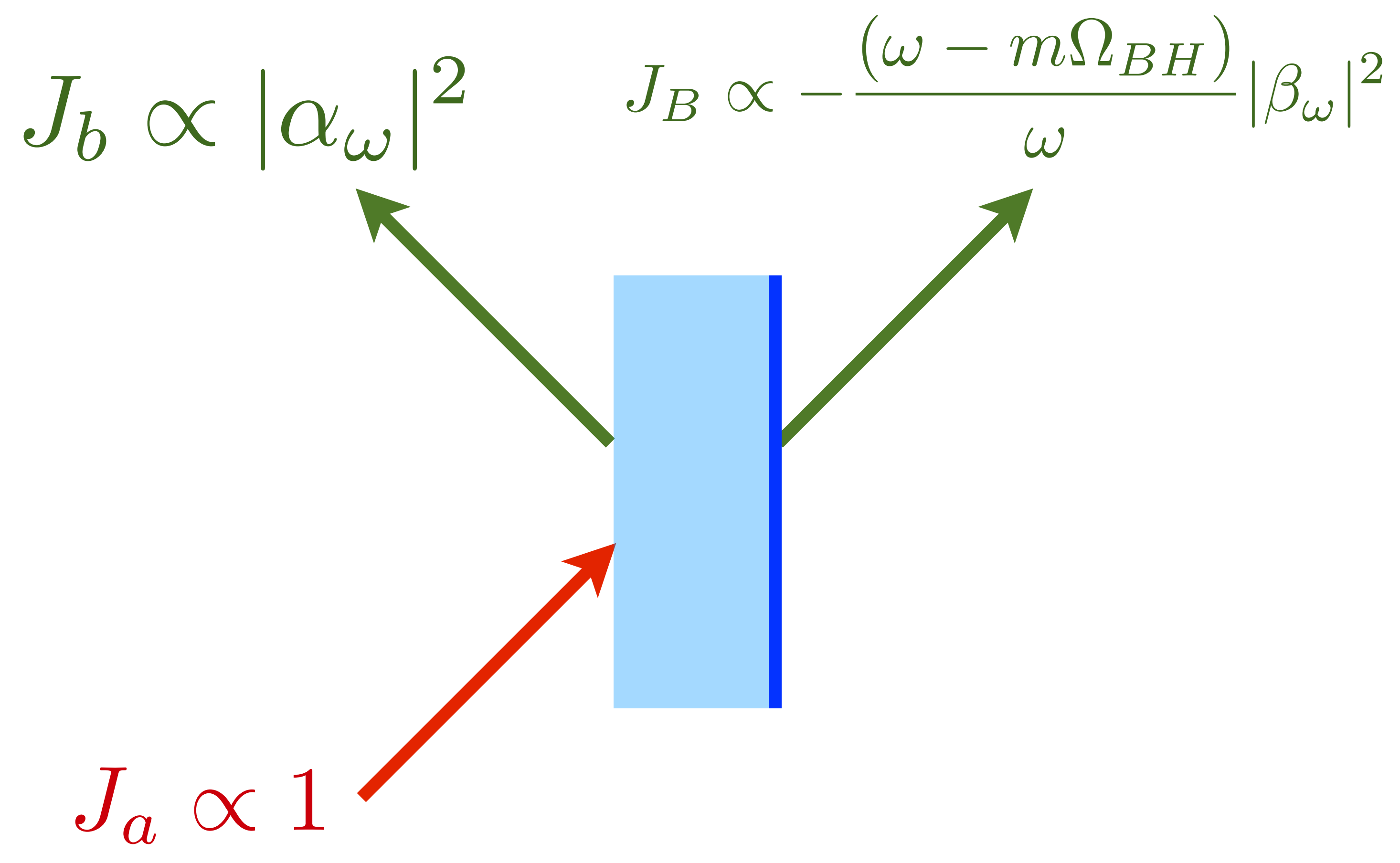
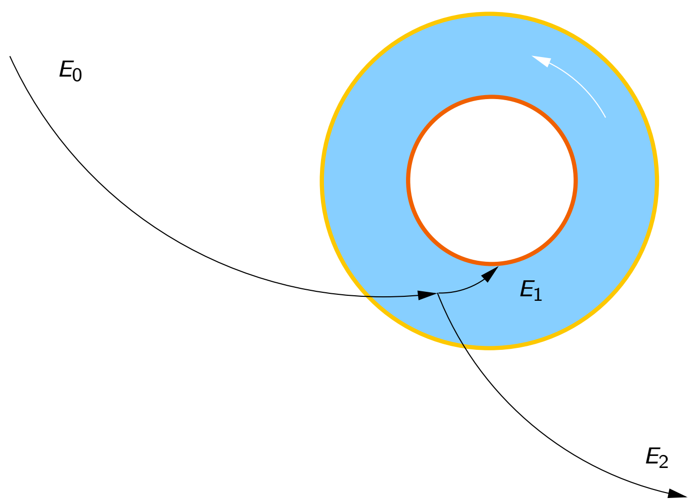


$$1 + 0 = |\alpha_\omega|^2 + -\frac{(\omega - m\Omega_{BH})}{\omega}|\beta_\omega|^2$$

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

Superradiant scattering *compared to HR*



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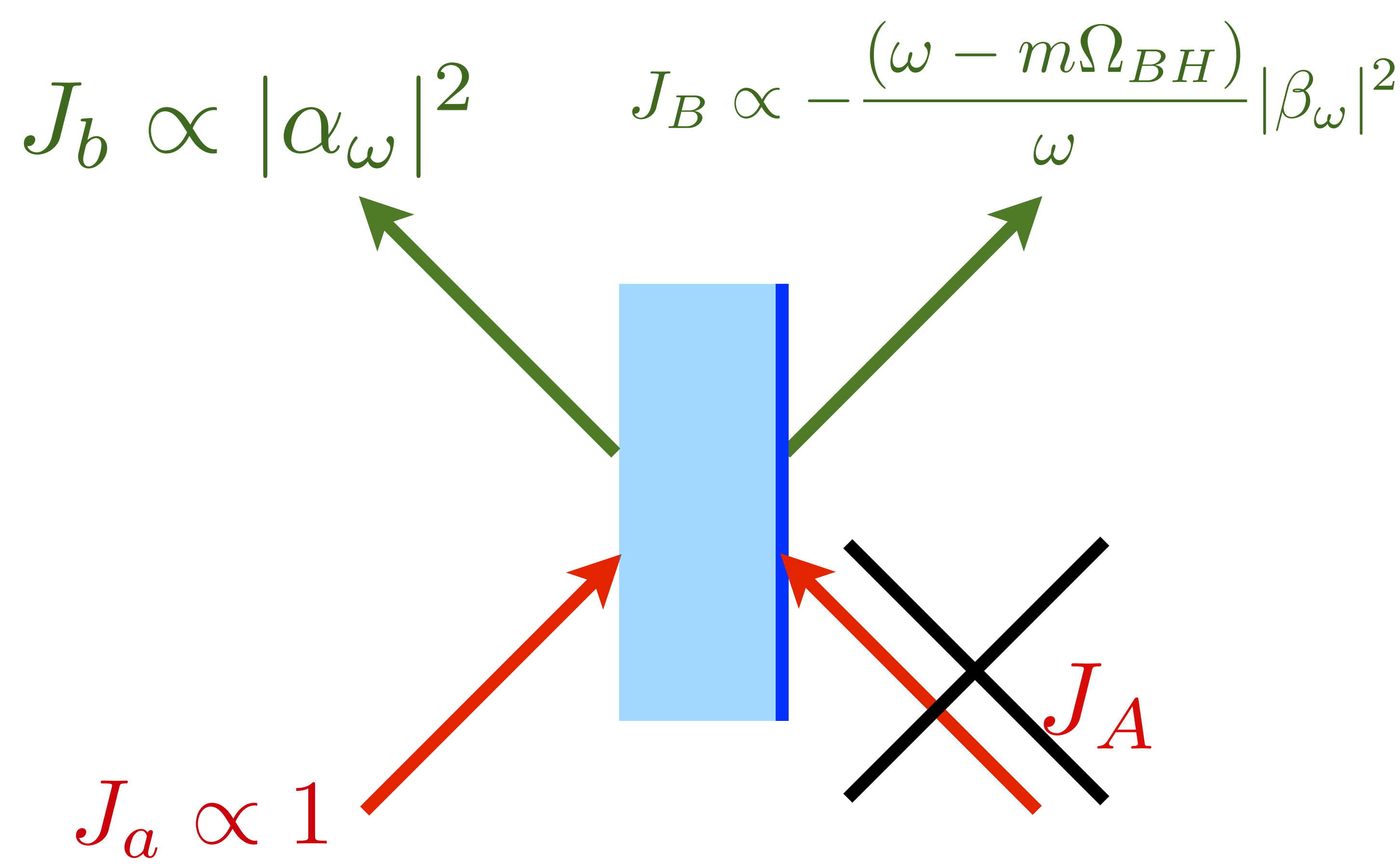
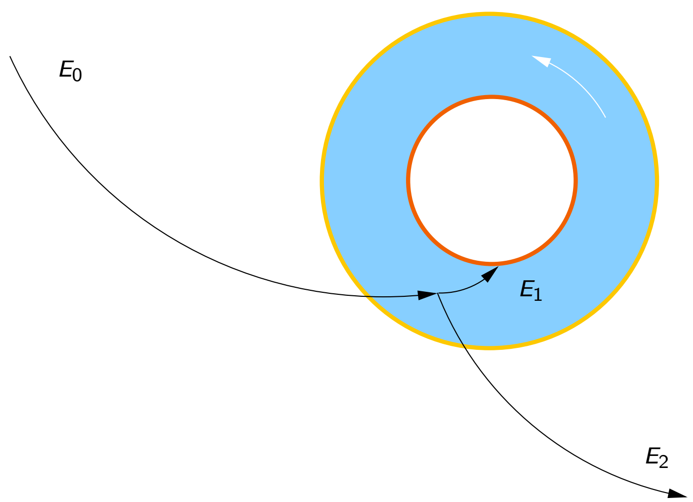


$$1 \quad + \quad 0 \qquad = |\alpha_\omega|^2 + - \frac{(\omega - m\Omega_{BH})}{\omega} |\beta_\omega|^2$$

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

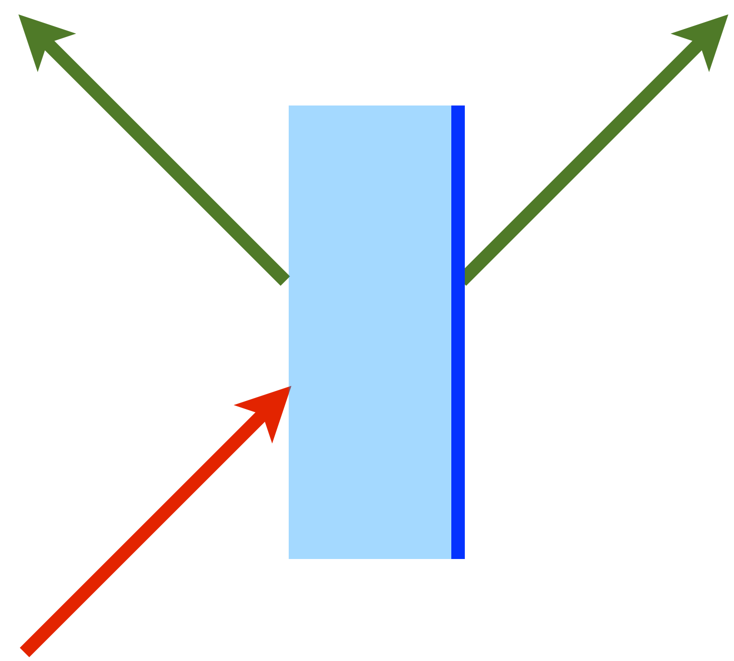
Superradiant scattering *compared to HR*



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

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

$$J_b \propto |\alpha_\omega|^2 \qquad J_B \propto -\frac{(\omega - m\Omega_{BH})}{\omega} |\beta_\omega|^2$$

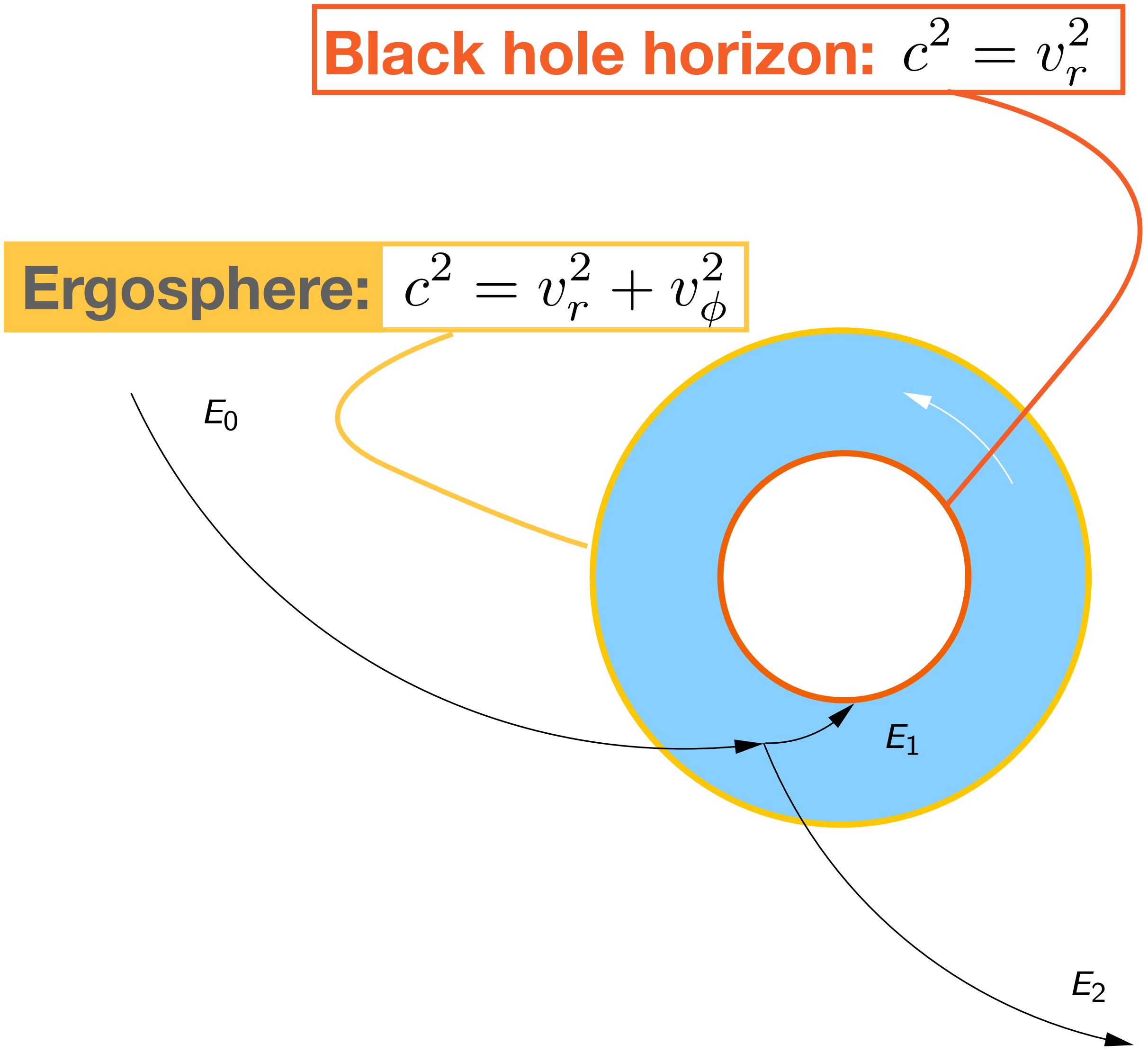


$$J_a \propto 1$$

$$1 \quad + \quad 0 \qquad = |\alpha_\omega|^2 + -\frac{(\omega - m\Omega_{BH})}{\omega} |\beta_\omega|^2$$

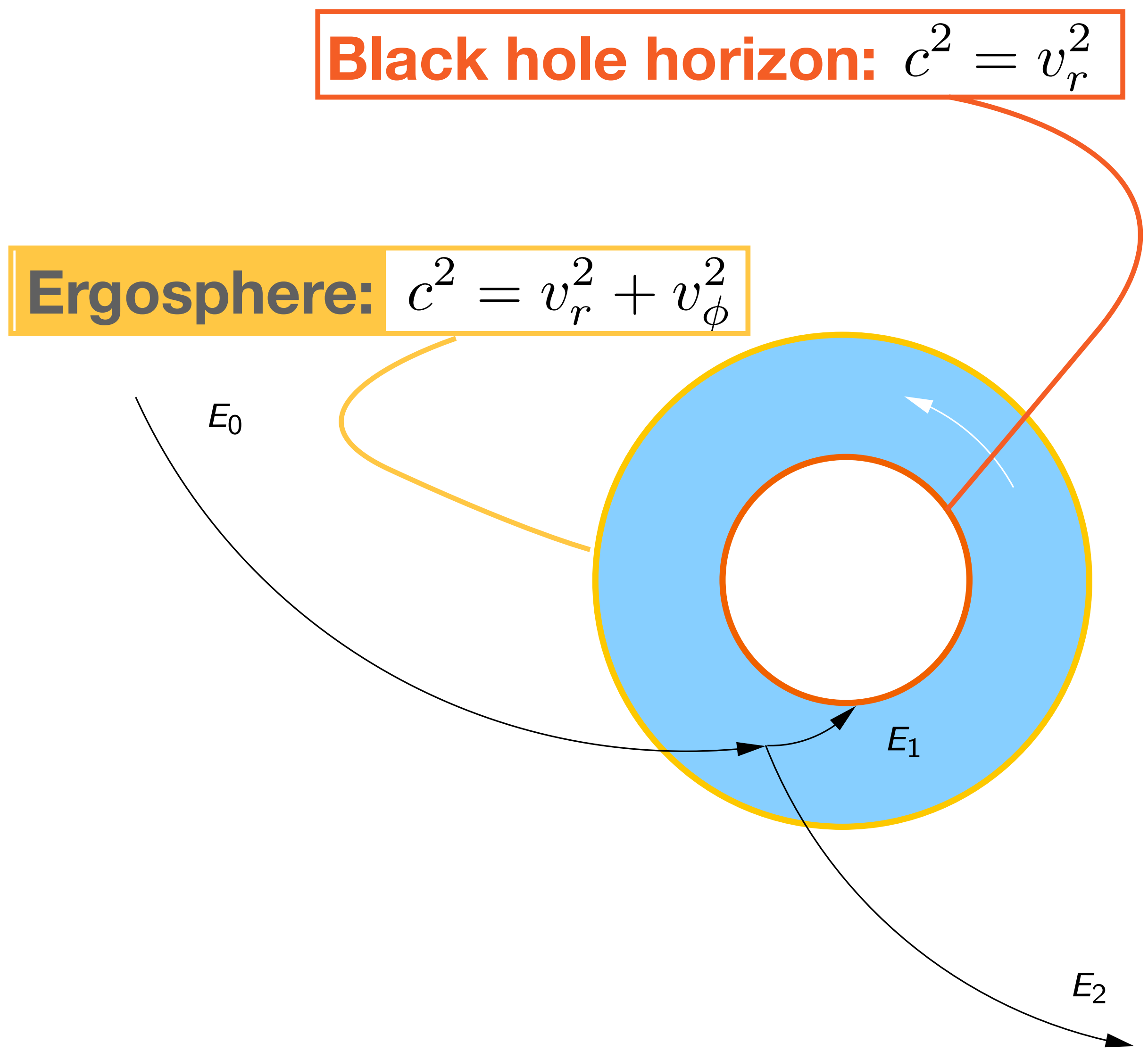
‘Black Holes in the Bathtub’ by MARISSA CEVALLOS (ScienceNews)

Exp. #5 *surface waves on draining fluid-work in progress*



Bathtub vortex flow: stationary draining flow with non-zero angular momentum

Rotating black hole *or bathtub vortex flow*

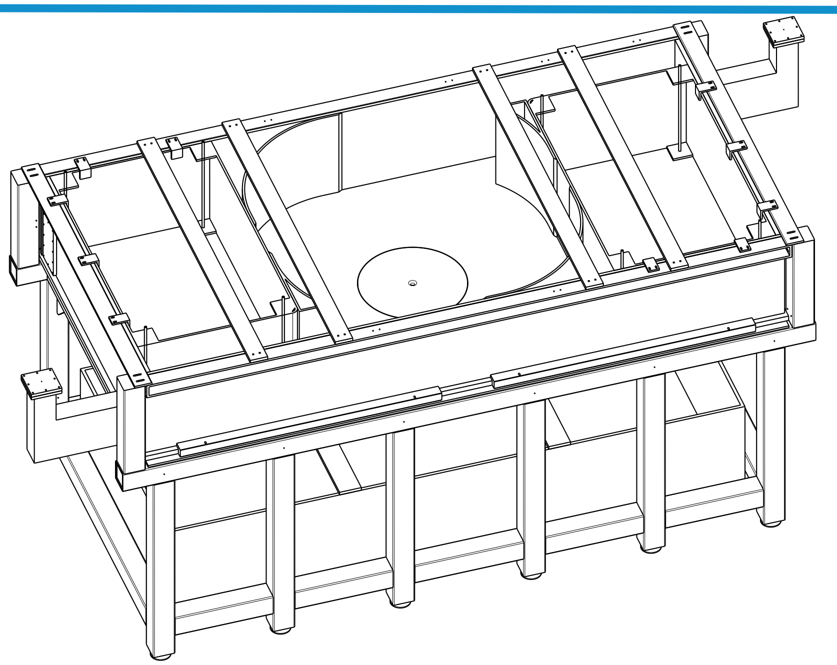
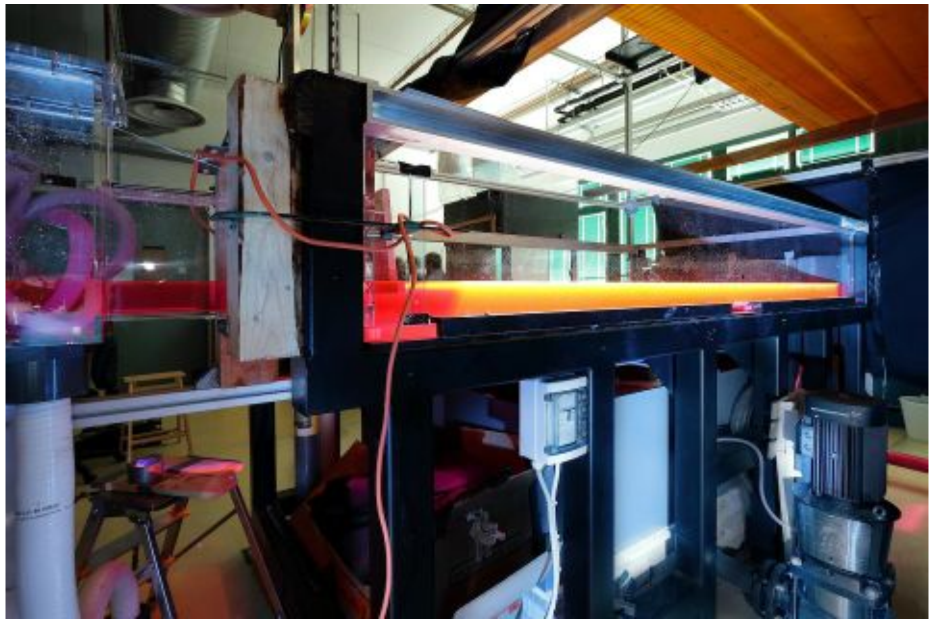
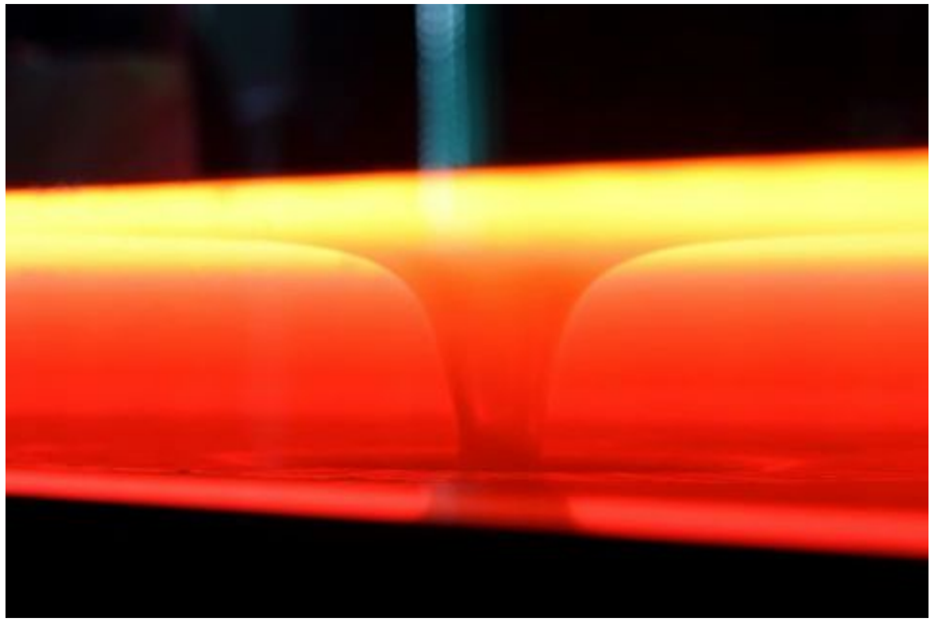
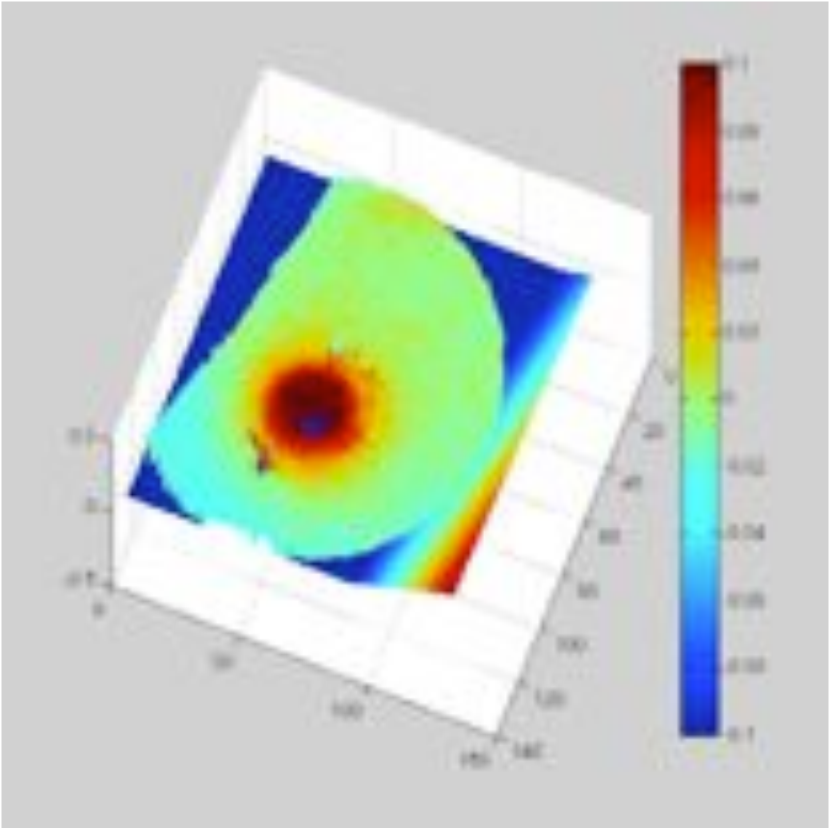


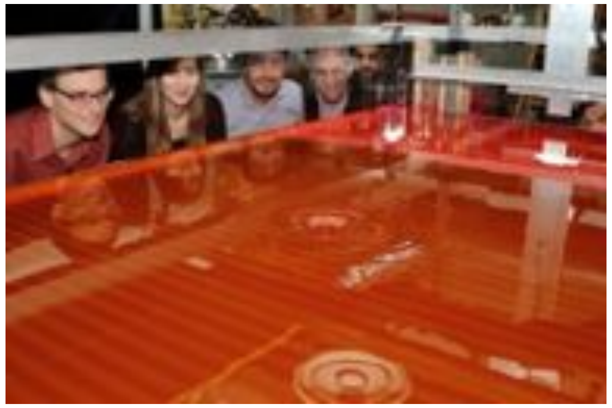
Bathtub vortex flow: stationary draining flow with non-zero angular momentum

Superradiant scattering process: ingoing transmitted

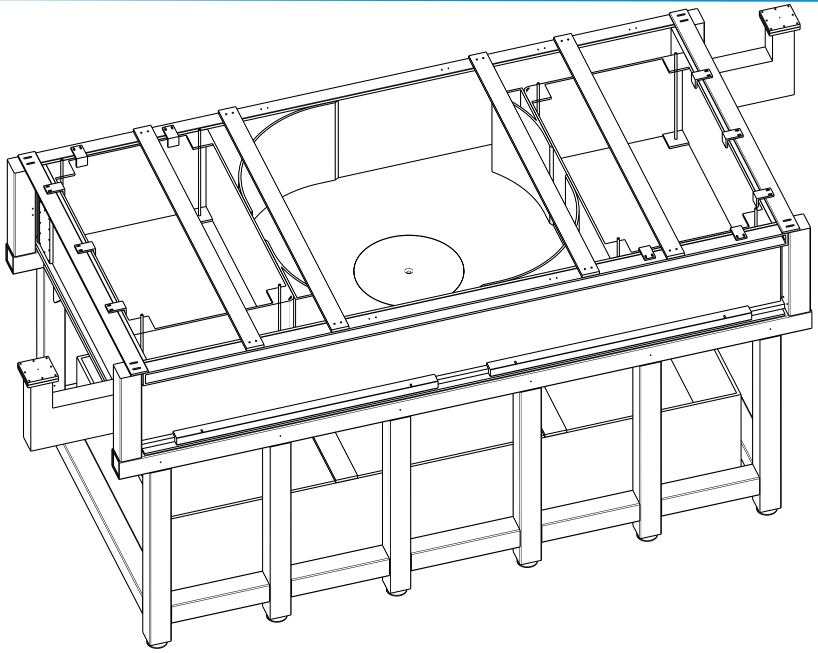
$$|\mathcal{R}|^2 = 1 - \frac{\omega - m\,\Omega_\mathrm{h}}{\omega}|\mathcal{T}|^2$$

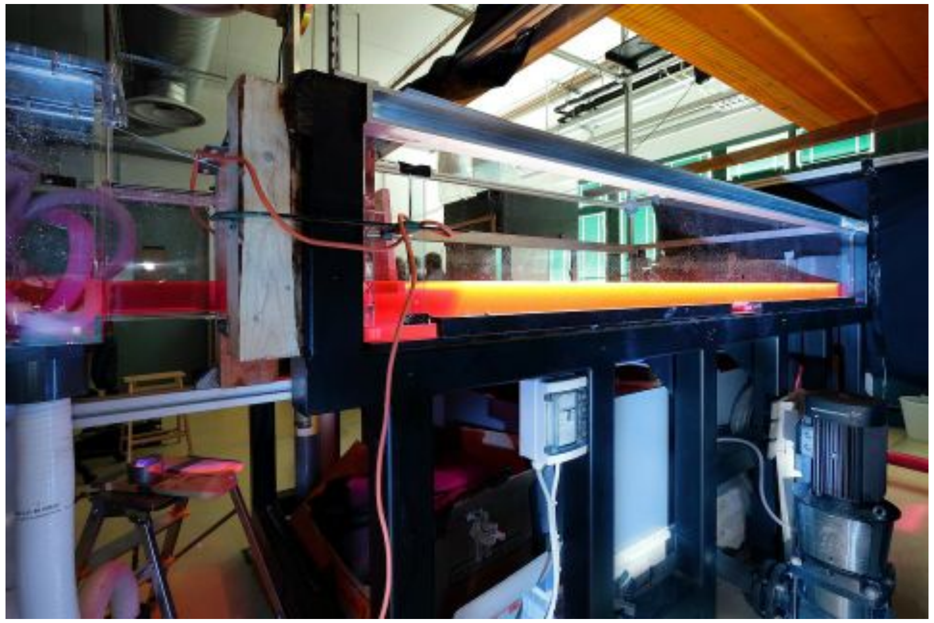
Exp. #5 *surface waves on draining fluid-work in progress*

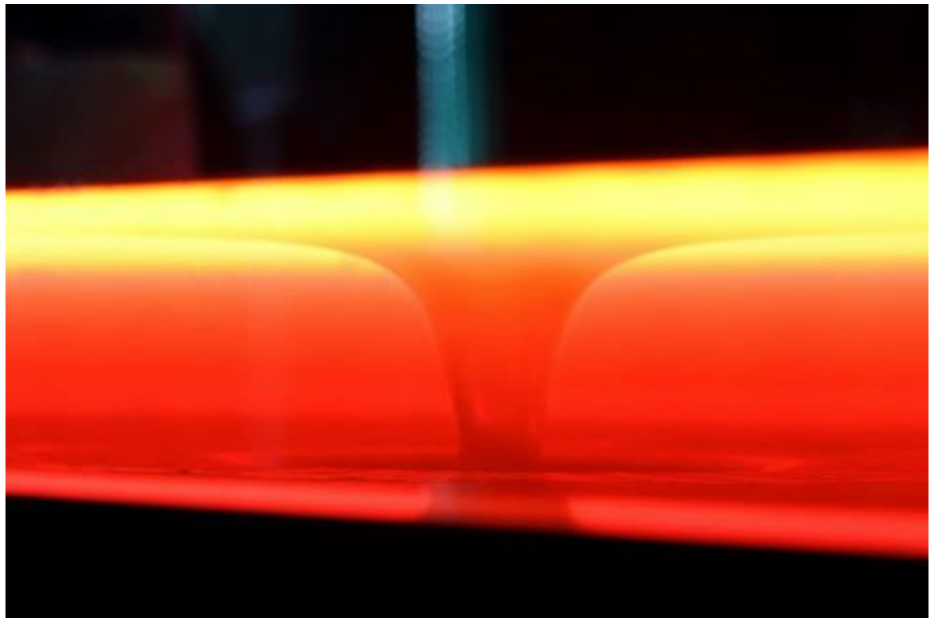





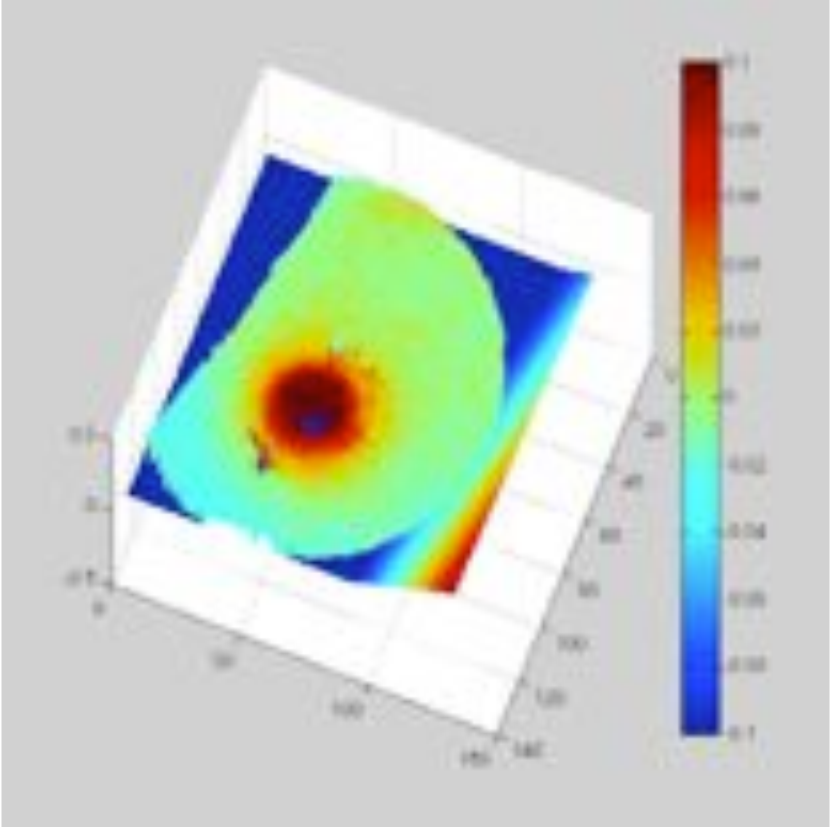


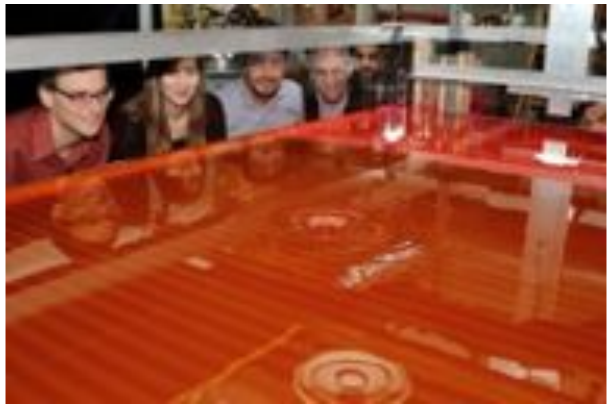

Exp. #5 *surface waves on draining fluid-work in progress*











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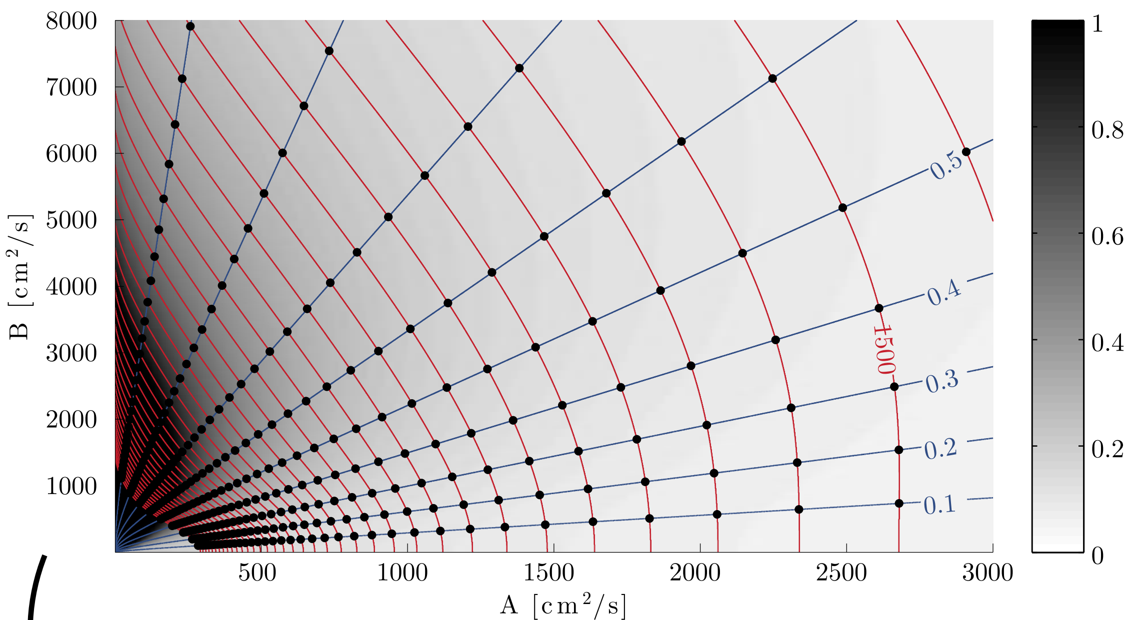
Exp. #5 *surface waves on draining fluid-work in progress*

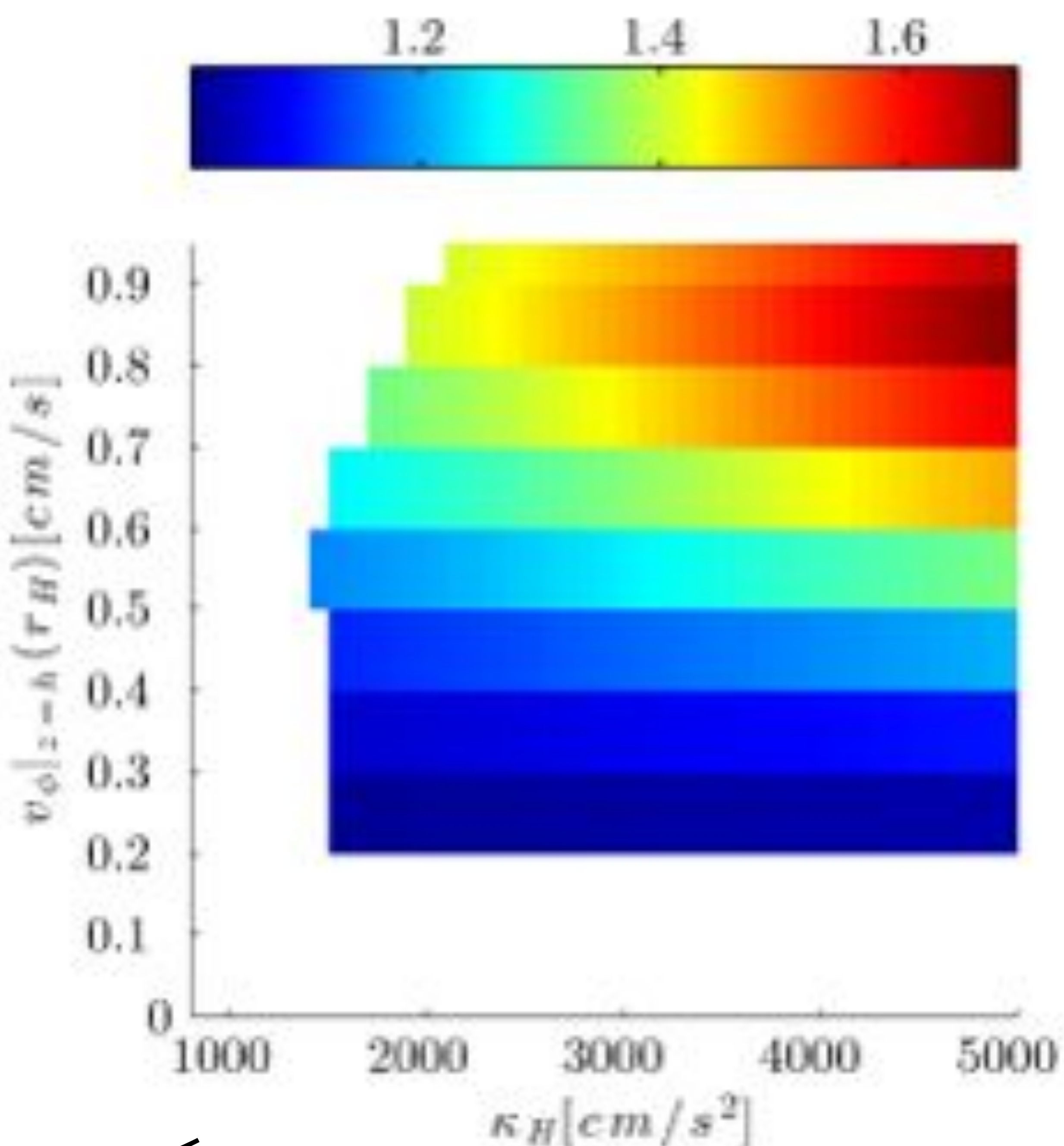
Exp. #5 *surface waves on draining fluid-work in progress*

Superradiant scattering *water equivalent*

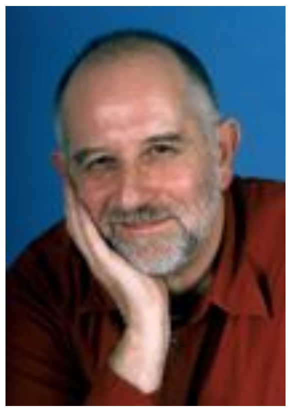
$h_{\rm inf} = 10\,{\rm cm}$



to understand the scattering process it is essential to change from fluid parameter to effective spacetime parameters…



Aharonov-Bohm-effect *water equivalent*



Wavefront dislocations in the Aharonov–Bohm effect and its wat wave analogue

M V Berry, R G Chambers, M D Large, C Upstill and J C Walmsley

H H Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, England

Received 20 June 1980

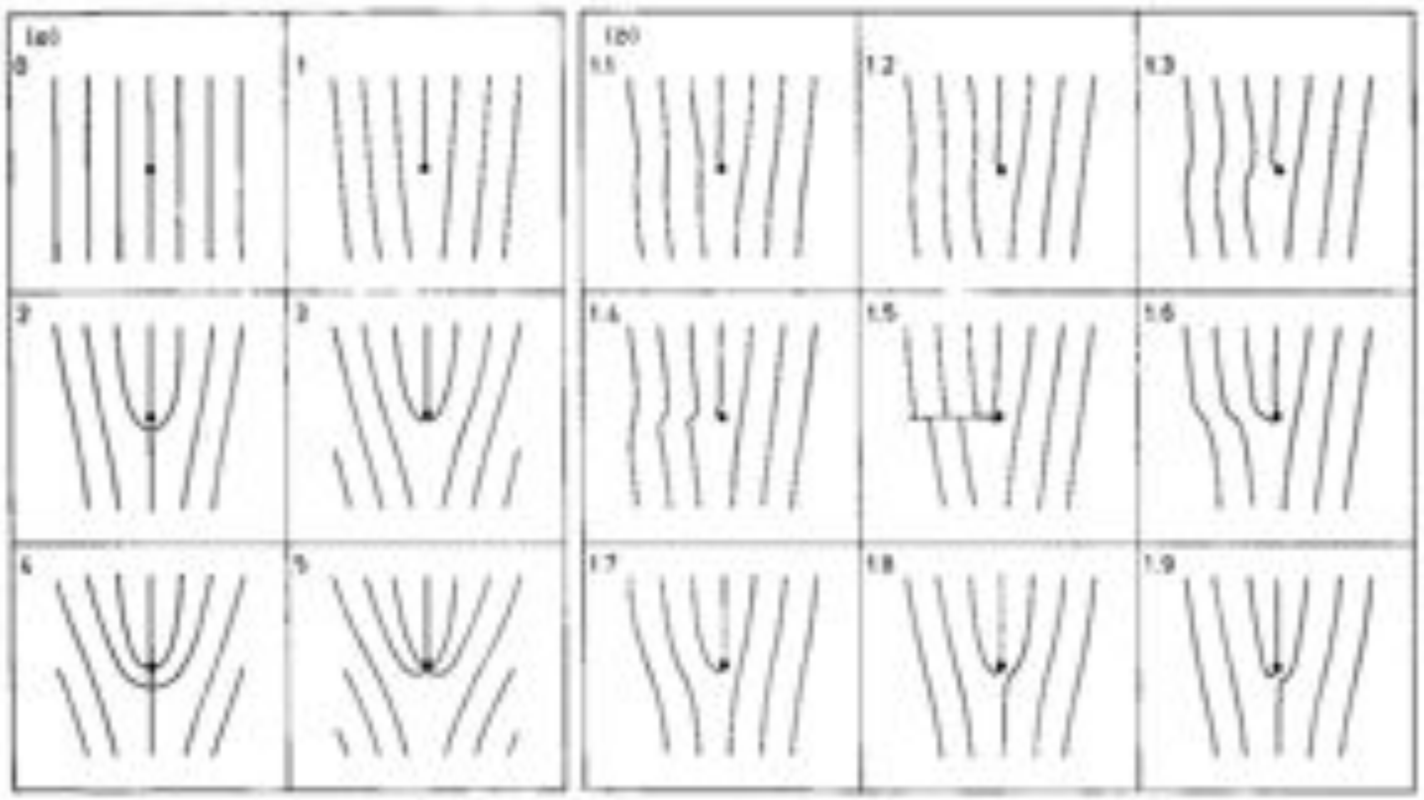
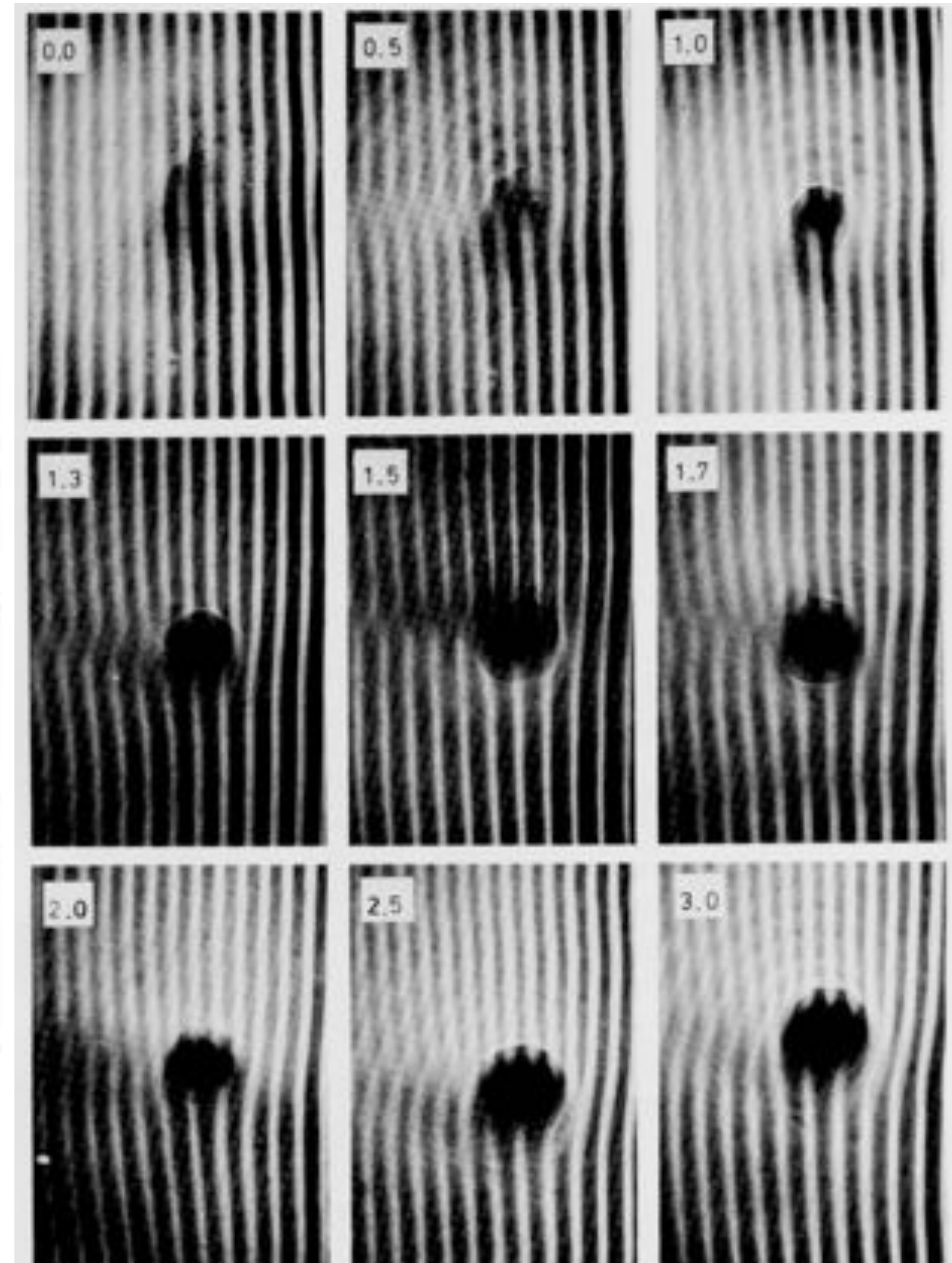
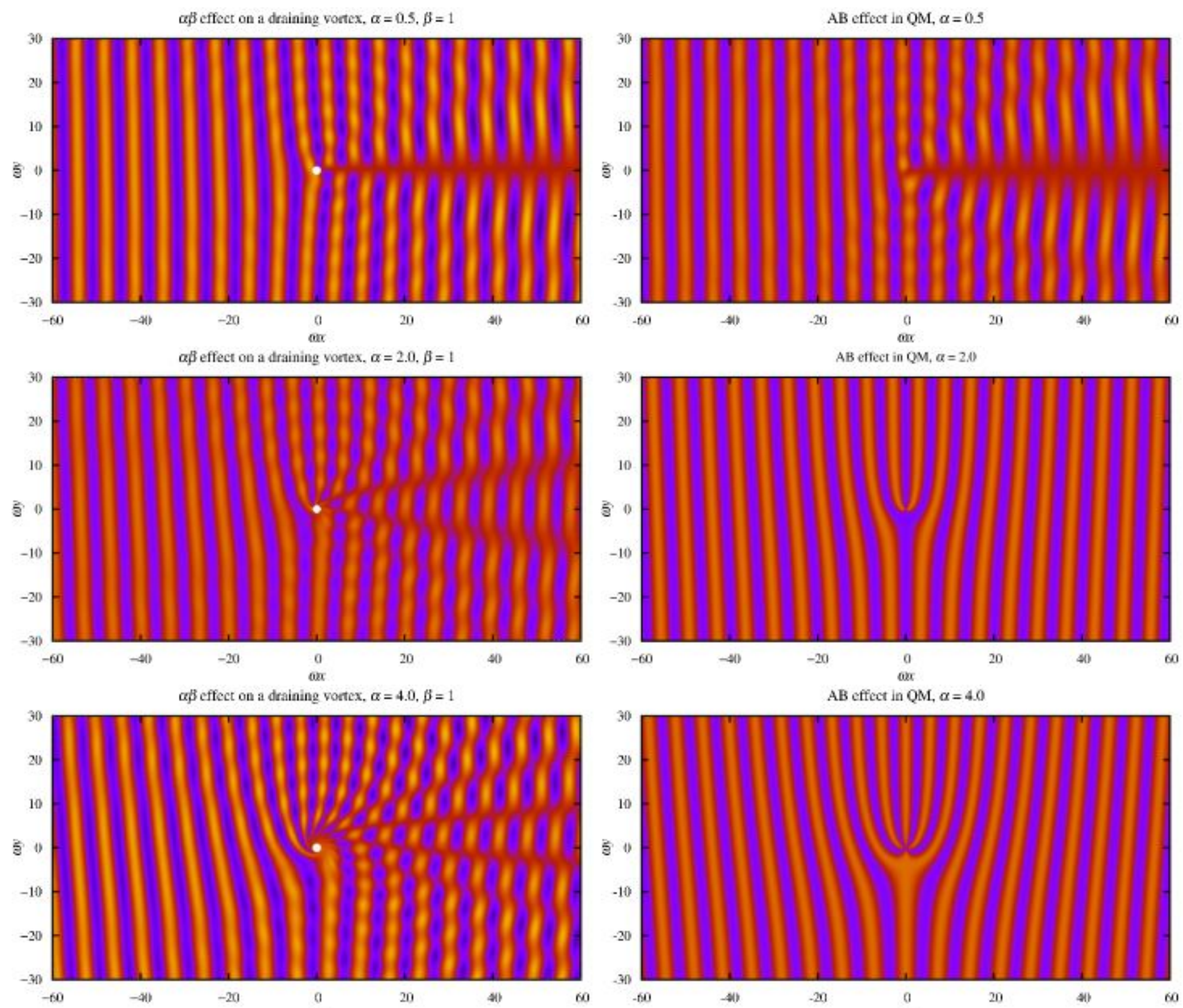


Figure 3 Wave crests of exp[$-i\alpha(2)\phi_{AB}$]. (*a*) Integer values of α from 0 to 5. (*b*) Values of α between 1 and 2, showing unlinking and reconnection as α passes through $1\frac{1}{2}$. In all cases the waves are incident from the right, and the flux parameter corresponds to a magnetic field at the origin and pointing out of the paper. The wave crests were drawn by interpolating between calculated positions for ($r \to \infty$, $\theta = \pm\pi/2$) and on the x axis, taking account of the calculated directions of the wave crests at $r = 0$.



Aharonov-Bohm-effect *and beyond*

Scattering by a draining bathtub vortex, Sam R. Dolan and Ednilton S. Oliveira



fluid of light: graphene dissolved in methanol

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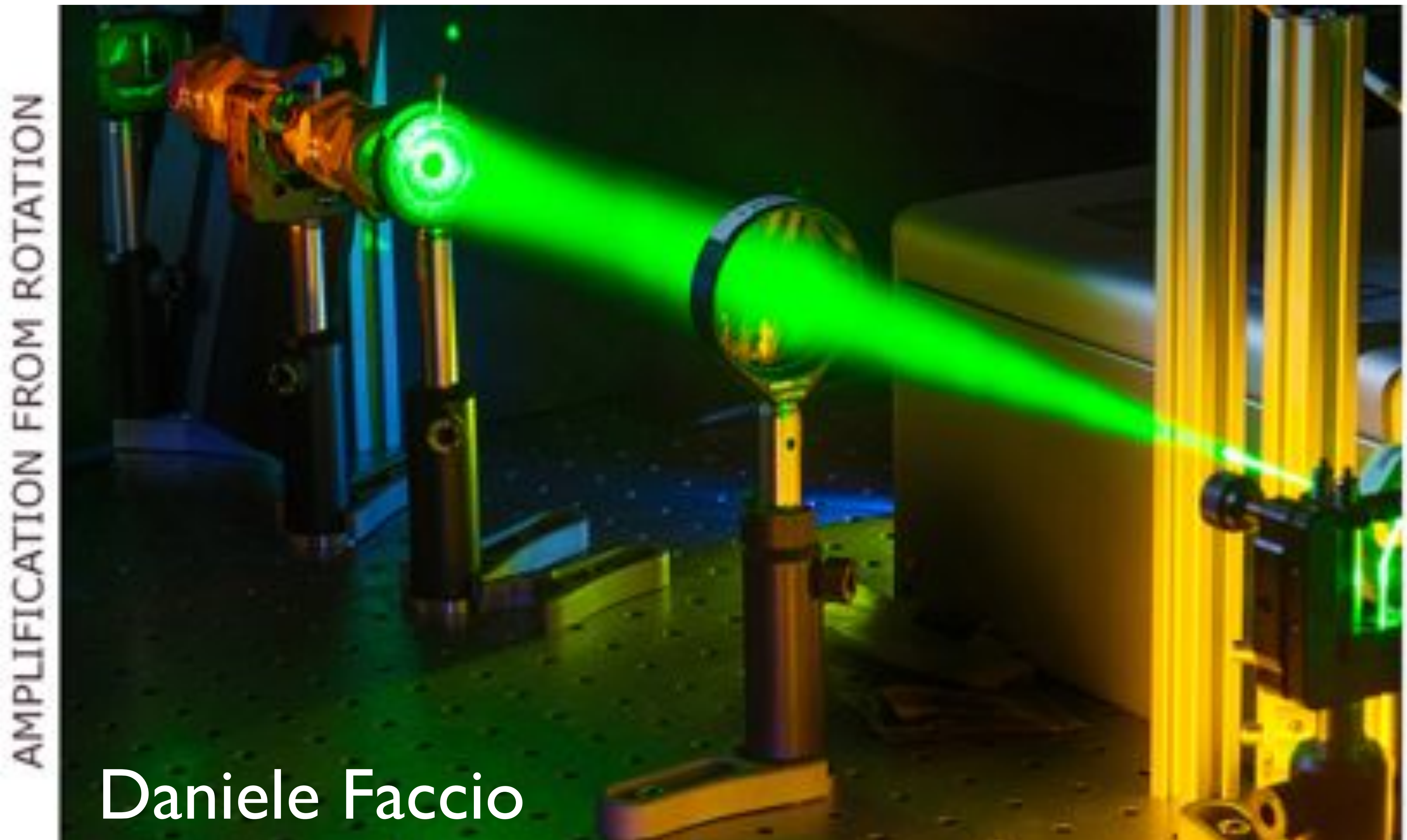
Exp. #6 *rotating black holes in a fluid of light*



Summary & outlook

analogue gravity and beyond

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General idea is...

to test various aspects of quantum gravity in table-top experiments

some aspects/ideas of/for quantum gravity that are otherwise hard to impossible to access observationally/experimentally

...using
- fluids and superfluids
- condensed matter systems
- quantum information

in **theoretical**, NUMERICAL & **experimental** studies.

semi-classical & quantum gravity

classical and quantum field theory in curved spacetimes

- super-radiant scattering from rotating black holes

  ongoing experiments

- black-hole radiation

  first results from fluids, superfluids, and optical systems

- cosmological particle production

  first results from superfluids

discrete gravity & effective field theories

- emergence of spacetimes
- Horava-Lifshitz gravity

...and to apply quantum gravity studies to other branches of physics

Summary & outlook

analogue gravity and beyond

General idea is...

to test various aspects of qu ... **experiments**

some aspects/ideas of/for quantum gravity that are otherwise hard to impossible to access observationally/experimentally

...using
- fluids and superfluids
- condensed matter systems
- quantum information

in **theoretical**, NUMERICAL & **experimental** studies.

how robust are effects predicted within classical and quantum field theory in curved spacetimes?

classical and quantum

classica... theory in cu...

...uantum gravity

...iscrete gravity & effective field theories

- super-radiant scattering from rotating black holes

  ongoing experiments

- black-hole radiation

  first results from fluids, superfluids, and optical systems

- cosmological particle production

  first results from superfluids

- emergence of spacetimes
- Horava-Lifshitz gravity

...and to apply quantum gravity studies to other branches of physics

Summary & outlook

analogue ... d beyond

Gener

how much can we control those analogue systems?

classical versus quantum

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can we apply the acquired experimental expertise to real **QFT in CS** and/or **quantum gravity** experiments

...antum gravity

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can we apply our insights gained from analogue gravity to?

QFT in CS and/or quantum gravity

can we apply the acquired experimental expertise to real

QFT in CS and/or quantum gravity experiments

...rom superfluids

...and to apply quantum gravity studies to other branches of physics