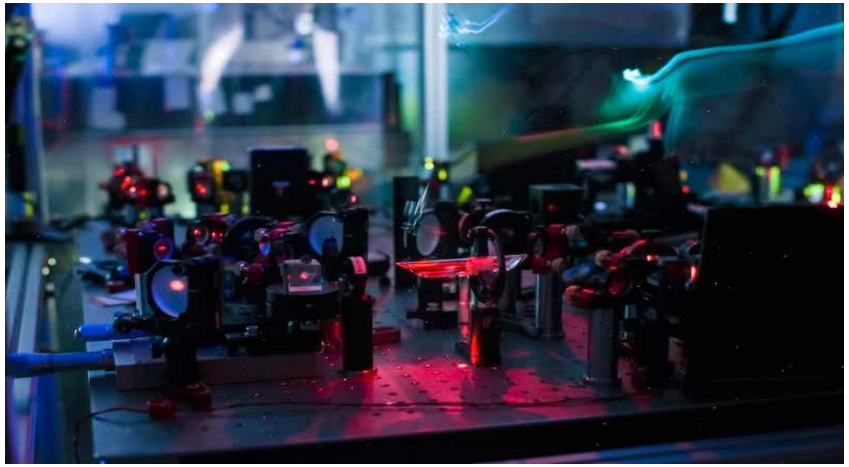
# The analogy between matter waves and nonlinear optics: insights into Quantum Fluids of Light



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**6th Physics Erasmus Summer School**

# Analogies in Physics

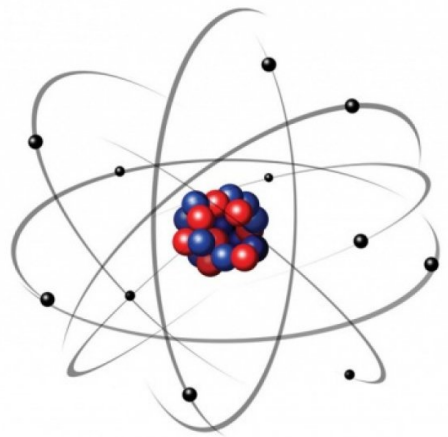
## What is an analogy?

Oxford dictionary: a comparison made between one thing and another for the purpose of explanation or clarification

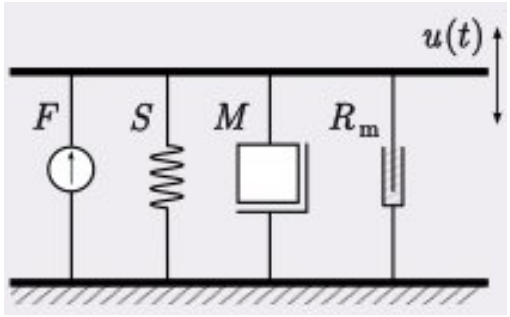
Wikipedia: Analogy […] cognitive process of transferring some information or meaning of a particular subject (the analog, or source) onto another (the target).

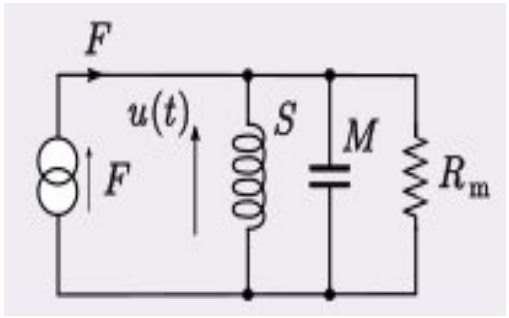
# Analogies in Physics

- Bohr’s atomic model and the solar system



- Mechanical–electrical analogies




... among many others

# Analogies in Physics

Do analogies always work? Of course, they do not!

When do they fail?

... when the analog is too complex or is not understood either

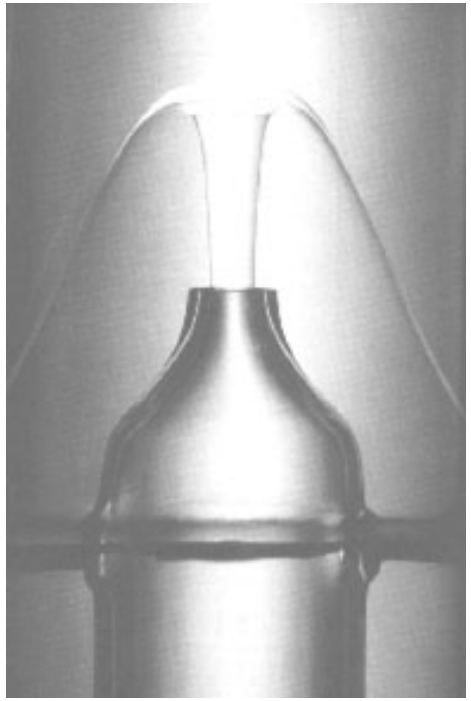
... wrong (embeds a misconception)

... taken too far (analog ceases to be true)

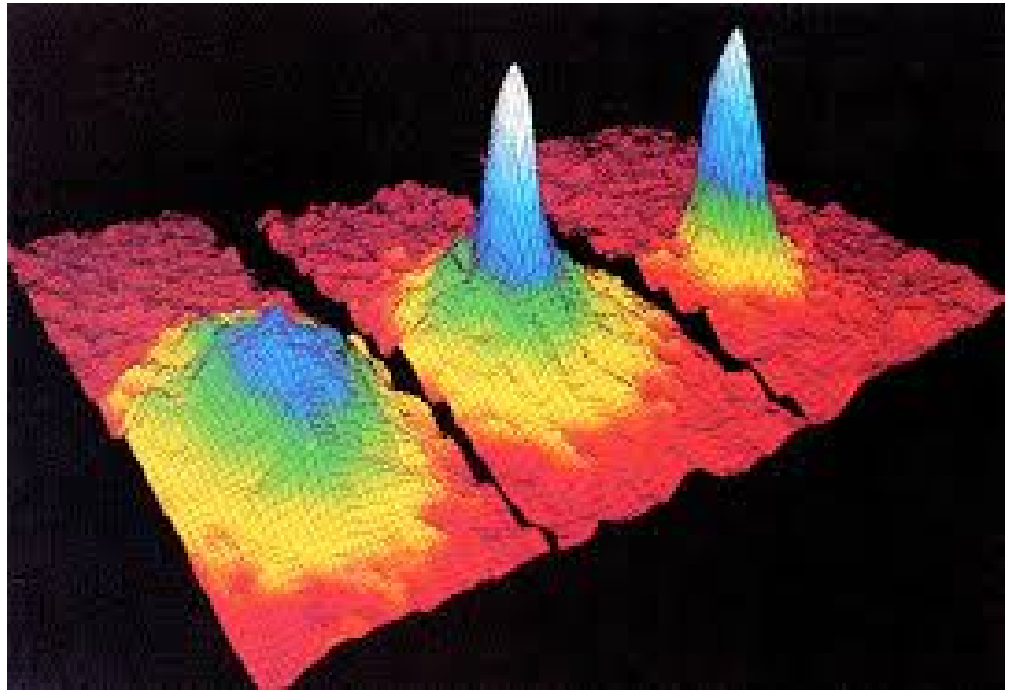
Prior and SOLID knowledge is crucial!

# Setting up the figure of a quantum fluid of light (QFoL)

## Connecting matter waves and nonlinear optics



Liquid Helium



Bose-Einstein condensate (BEC)

# Setting up the figure of a quantum fluid of light (QFoL)

## Connecting matter waves and nonlinear optics

### Gross-Pitaevskii equation (GPE)

$$i\hbar\frac{\partial\psi\left(\mathbf{r},t\right)}{\partial t}=\left(-\frac{\hbar^{2}}{2m}\nabla^{2}+V\left(\mathbf{r}\right)+g\left|\psi\left(\mathbf{r},t\right)\right|^{2}\right)\psi\left(\mathbf{r},t\right)$$

### Nonlinear Schrödinger equation (NLSE)

$$i\frac{\partial\Omega\left(\mathbf{r}_{\perp},z\right)}{\partial z}=\left(-\frac{1}{2k_{0}}\nabla_{\perp}^{2}-\frac{\delta n\left(\mathbf{r}_{\perp}\right)k_{0}}{n_{0}}-k_{0}\alpha\left|\Omega\left(\mathbf{r}_{\perp},z\right)\right|^{2}\right)\Omega\left(\mathbf{r}_{\perp},z\right)$$

**Madelung transformation** converts the Gross-Pitaevskii equation into a hydrodynamic form, describing the BEC (or the NLSE) as a **quantum fluid**.

# Setting up the figure of a quantum fluid of light (QFoL)

How do these two descriptions connect to each other?

$$
\begin{array}{ccc}
GPE & \longleftrightarrow & NLSE \\
\psi(\mathbf{r},t) & \longleftrightarrow & \Omega(\mathbf{r}_\perp,z) \\
\frac{m}{\hbar} & \longleftrightarrow & k_o \\
\frac{V(\mathbf{r})}{\hbar} & \longleftrightarrow & -\frac{\delta n(\mathbf{r}_\perp)k_0}{n_0} \\
\frac{g}{\hbar} & \longleftrightarrow & -k_0\alpha
\end{array}
$$

# Setting up the figure of a quantum fluid of light (QFoL)

- Light field is composed by a large number of photons but in the vacuum photons do not interact.

- Optics is usually controlled by single-particle behaviour, however...

  Can we give photons a mass ?

  Can photon-photon interactions make light behave as a fluid ?

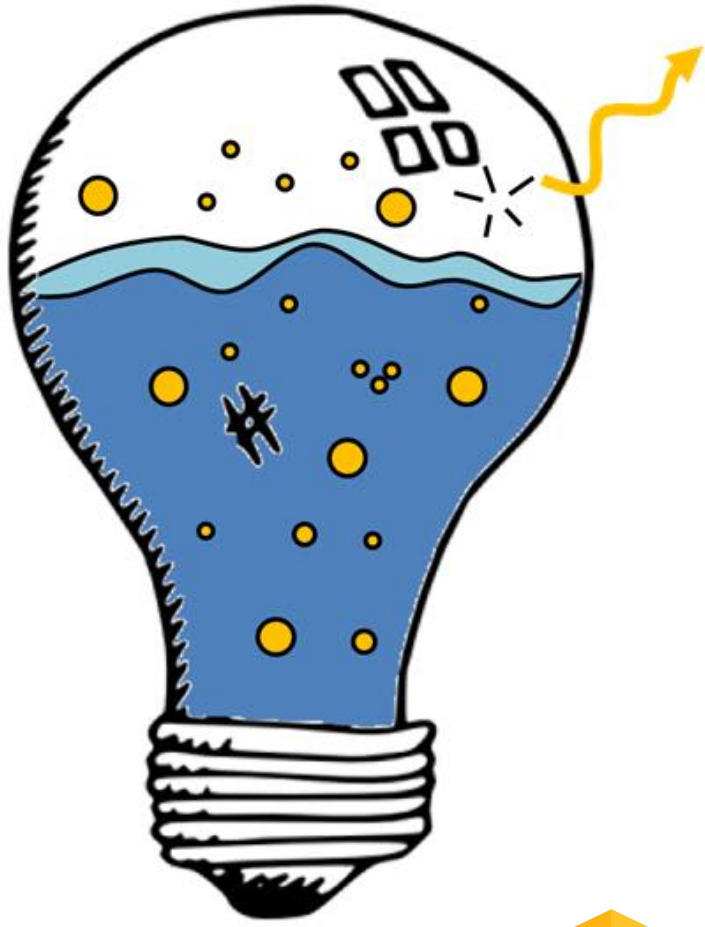
# Setting up the figure of a quantum fluid of light (QFoL)

## Main ingredients

- Optical nonlinearities ➡ effective photon-photon interactions.

- Spatial confinement ➡ effective photon mass

Collective behaviour of a photonic quantum fluid.



# Applications: the use of QFoL to investigate astrophysical phenomena

## Problem

Some experiments are too hard to study (with current technology)

## A way out

Create analog experimental systems that reproduce underlying (simplified) equations and verify predictions

## Implicit, nontrivial assumption:

equations describing one system can be used to describe a completely different system.


**1981 Bill Unruh: dumb hole with a sonic horizon**

# Applications: the use of QFoL to investigate astrophysical phenomena

Penrose process: energy extraction from a rotating black hole.

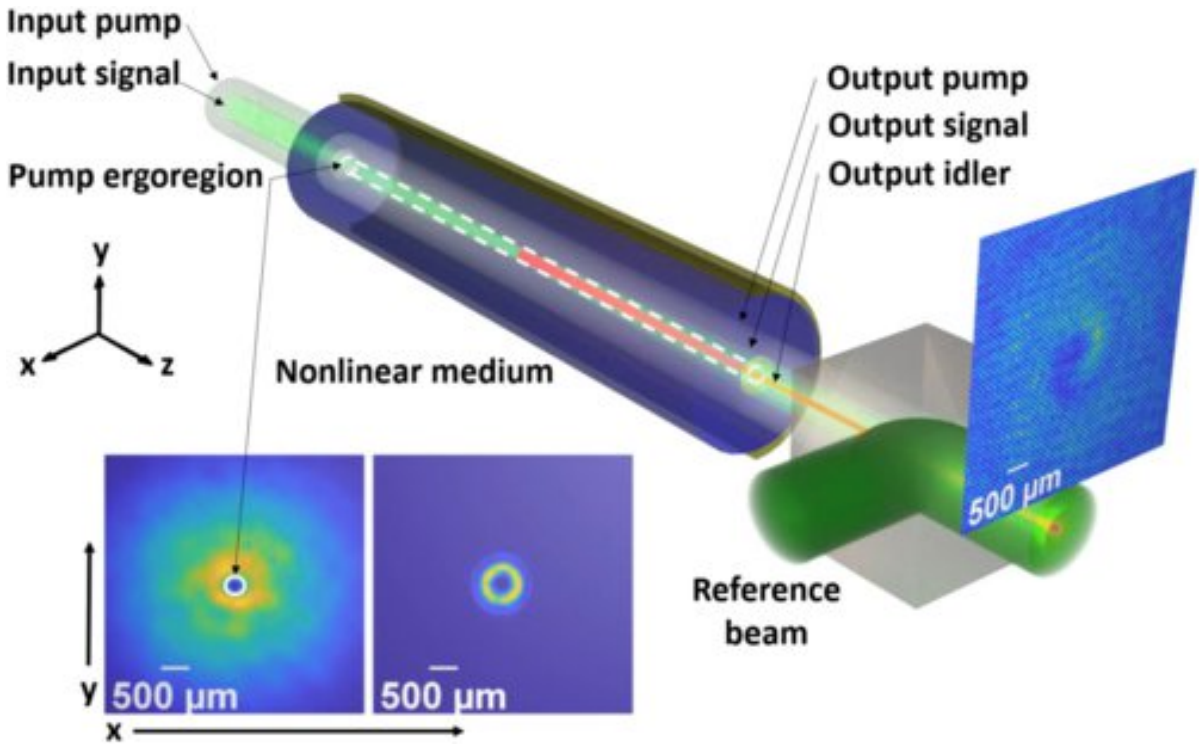
Superradiance is a scattering effect whereby waves reflected from a moving medium are amplified, extracting energy and momentum in the process.

## Zel'dovich – Misner condition

Negative doppler shifted frequency.

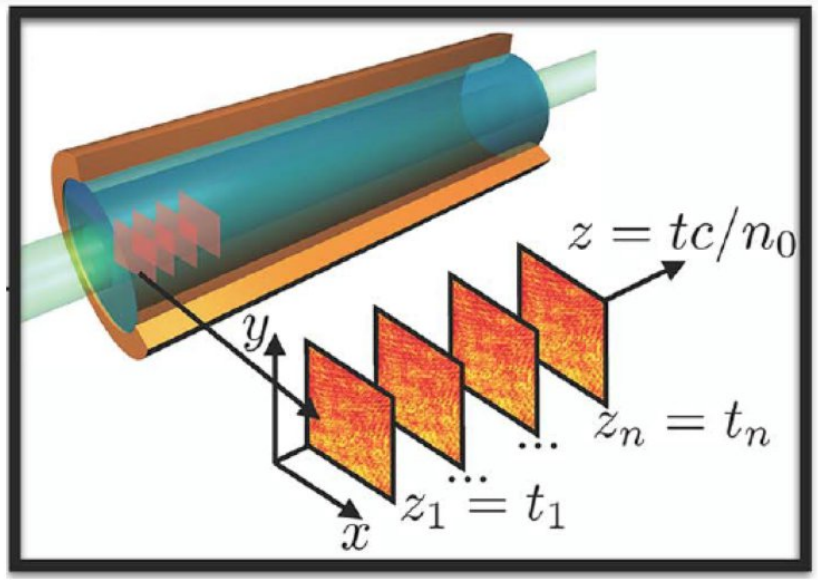
$$\omega - m\Omega < 0$$

# Applications: the use of QFoL to investigate astrophysical phenomena




**PRL 128, 013901 (2022)**

Thermo-optic liquid setting




*Optica*, *2*(5), 484-490

# Applications: the use of QFoL to investigate astrophysical phenomena

Theoretical description

$$E = E_0 + E_s + E_i$$

$$i\frac{\partial E}{\partial z} + \frac{1}{2k}\nabla_{\perp}^2 E + \frac{k}{n_0}\Delta n(|E|^2)E = 0$$

$$\Delta n(\mathbf{r}) = n_2 \int R(\mathbf{r}-\mathbf{r}')|E(\mathbf{r}')|^2 d\mathbf{r}'$$

$$R(\mathbf{r}) = [1/(2\pi\sigma^2)]K_0(|\mathbf{r}|/\sigma)$$

Zel'dovich Misner condition

$$\mathrm{m} = (n-l) > 0$$

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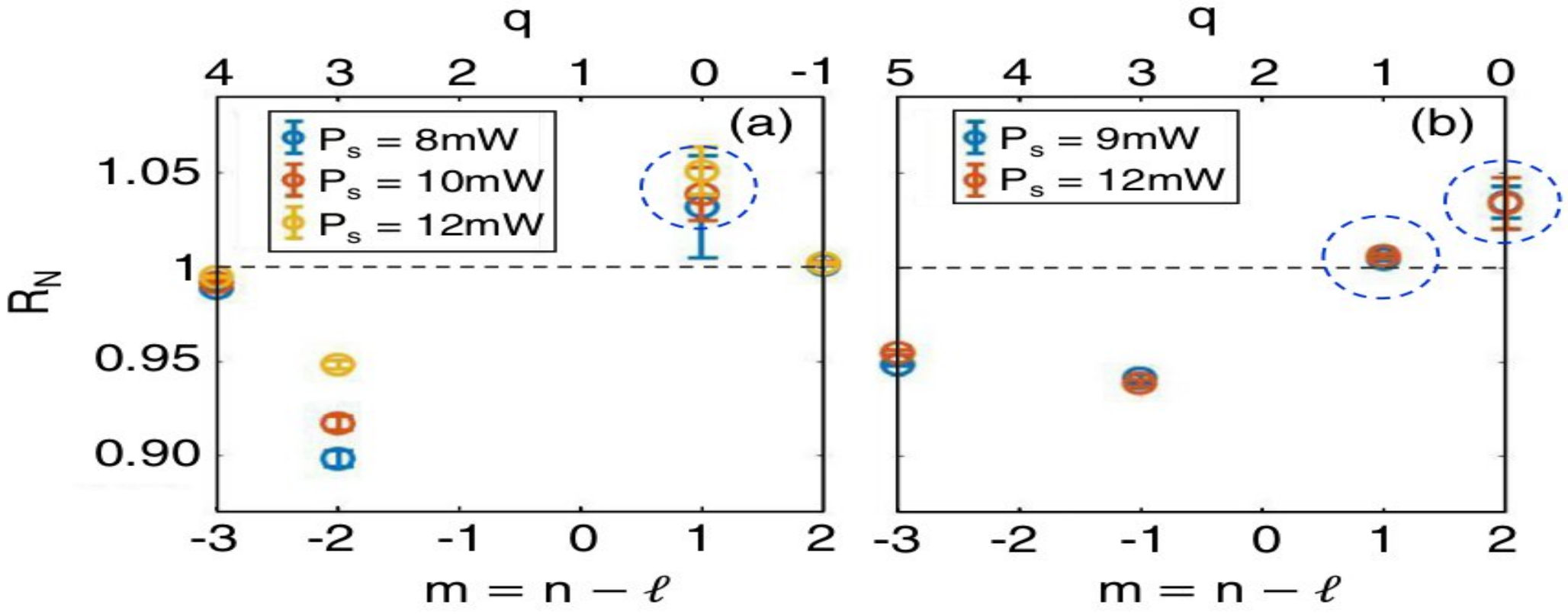
# Applications: the use of QFoL to investigate astrophysical phenomena




**PRL 128, 013901 (2022)**

# Take home messages

- Analogies are important, however, they must be used with care.
- Previous and solid knowledge of the mathematical formalism and the physics are essential to set up good analogies.
- QFoL can be used as a simulation platform for analog gravity experiments.
- Other physics phenomena can be investigated as well using QFoL, such as quantum droplets, vortices, turbulence, etc.

Thank you!