Title: Photon-bubble turbulence in cold atomic gases

Speakers: Hugo TerÃ§as

Collection: Cold Atom Molecule Interactions (CATMIN)

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Abstract: Turbulent radiation flow is ubiquitous in many physical systems where light-matter interaction becomes relevant. Photon bubble instabilities, in particular, have been identified as a possible source of turbulent radiation transport in astrophysical objects such as massive stars and black hole accretion disks. Here, we report on the experimental observation of a photon bubble instability in cold atomic gases, in the presence of multiple scattering of light. A two-fluid theory is developed to model the coupled atom-photon gas and to describe both the saturation of the instability in the regime of quasi-static bubbles and the low-frequency turbulent phase associated with the growth and collapse of photon bubbles inside the atomic sample. We also employ statistical dimensionality reduction techniques to describe the low-dimensional nature of the turbulent regime. The experimental results reported here, along with the theoretical model we have developed, may shed light on analogue photon bubble instabilities in astrophysical scenarios. Our findings are consistent with recent analyses based on spatially resolved pump-probe measurements.

# Photon-bubble turbulence in cold atomic traps

**Hugo Terças**

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ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

**CATMIN 2022 | Perimeter Institute**

# Our team @ IST (Lisbon)



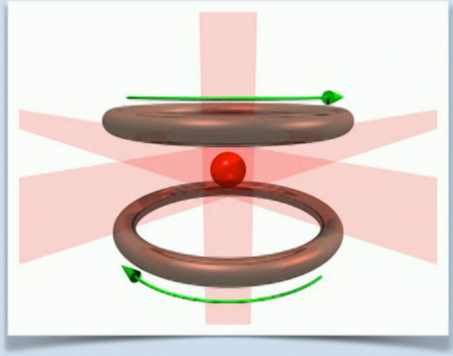

# Cold atoms as astrophysics simulators

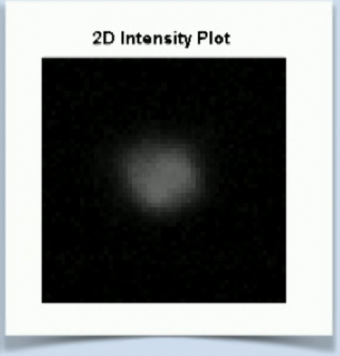
Cold atoms in MOTs = effective plasmas

$$\frac{\partial n}{\partial t} + \boldsymbol{\nabla} \cdot (n\mathbf{v}) = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \boldsymbol{\nabla})\,\mathbf{v} = \frac{\mathbf{F} + \mathbf{F}_T}{m} - \frac{\boldsymbol{\nabla} P}{mn}$$

$$\boldsymbol{\nabla} \cdot \mathbf{F} = Qn$$






Effective charge

$$Q = \sigma_L\,(\sigma_R - \sigma_L)\,I_0/c$$

Gapped dispersion relation

$$\omega^2 = \omega_p^2 + u_s^2 k^2$$

J. T. Mendonça et al, PRA 78, 013408 (2008)

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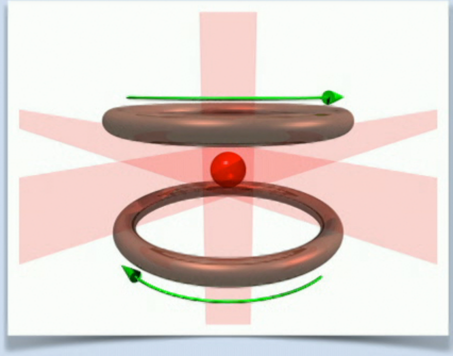

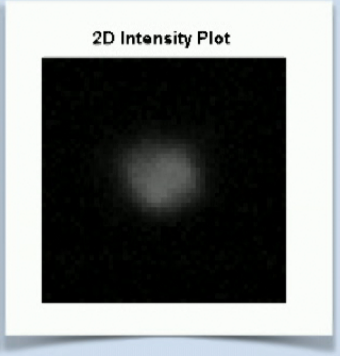


Effective charge

$$Q = \sigma_L \left(\sigma_R - \sigma_L\right) I_0 / c$$

"Plasma" frequency

$$\omega_p = \sqrt{\frac{Q n_0}{m}} \sim 2\pi \times 100 \text{ Hz}$$

J. T. Mendonça et al, PRA 78, 013408 (2008)

# Cold atoms as astrophysics simulators

**Astrophysics:** we assume a polytropic equation of state

$$P \sim n^\gamma$$

"Star" equilibrium: Generalized **Lane-Emden equation** $\theta = n/n_0$

$$\Omega = \frac{\omega_p}{3\omega_0}$$

$$\xi = r/a_\gamma$$

$$\gamma \frac{1}{\zeta^2}\frac{d}{d\zeta}\left(\zeta^2\theta^{\gamma-2}\frac{d\theta}{d\zeta}\right) - \Omega\theta + 1 = 0$$

H. Terças and J.T. Mendonça, PRA 88, 023412 (2013)

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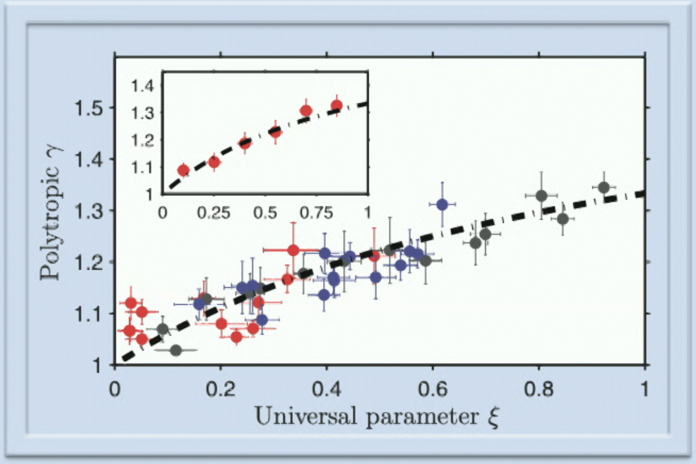
Pressure

H. Terças and J.T. Mendonça, PRA 88, 023412 (2013)

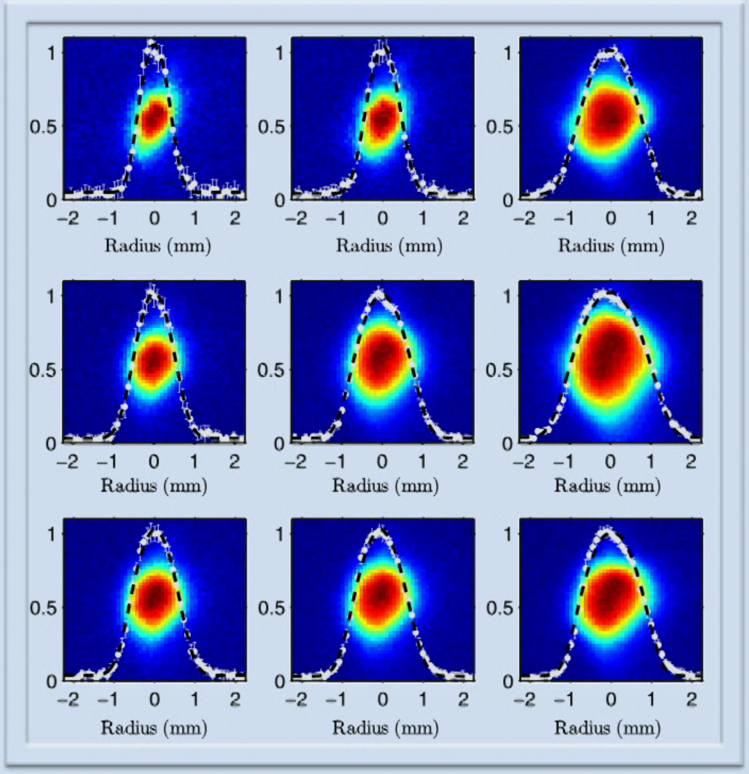
# Cold atoms as astrophysics simulators

## Theory

$$\gamma \frac{1}{\zeta^2}\frac{d}{d\zeta}\left(\zeta^2\theta^{\gamma-2}\frac{d\theta}{d\zeta}\right) - \Omega\theta + 1 = 0$$




## Experiments

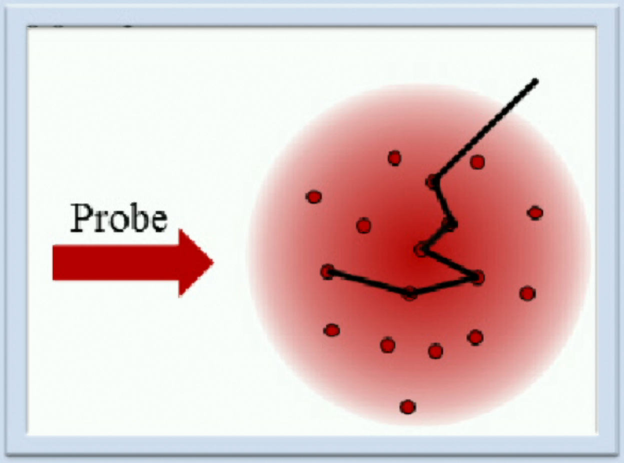



J. D. Rodrigues et al, PRA 93, 023404 (2016)

# Photon bubbles

**Astrophysics**: Radiation trapping leads to slow diffusion of light inside massive stars

Scape time: $\tau \sim 1000$ years




**Cold atoms**: Radiation trapping due to multiple scattering of photons (near resonance)

$$v_{\text{diffusion}} \sim 10^{-5}c$$

G. Labeyrie et al, PRL 91, 223904 (2003)
G. Labeyrie et al, Ap.P.B 81,1001 (2005)

# Photon bubble instability

**Mendonça—Kaiser instability:** radiation diffusion near resonance causes density instabilities in the atoms

Atoms

$$\frac{\partial n}{\partial t} + \boldsymbol{\nabla} \cdot (n\mathbf{v}) = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \boldsymbol{\nabla})\, \mathbf{v} = \frac{\mathbf{F} + \mathbf{F}_T}{m} - \frac{\boldsymbol{\nabla} P}{mn} - \nu \mathbf{v}$$

$$\boldsymbol{\nabla} \cdot \mathbf{F} = Qn$$

Radiation

$$\frac{\partial I}{\partial t} - D\nabla^2 I = -\gamma_{\text{abs}} I$$

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Radiation

$$\frac{\partial I}{\partial t} - D\nabla^2 I = -\gamma_{\text{abs}} I$$

Diffusion coefficient

$$D = \frac{1}{\tau \sigma_L^2 n^2} = \frac{\ell^2}{\tau}$$

Effective charge

$$Q = \sigma_L(\sigma_R - \sigma_L) I/c$$

# Photon bubble instability

**Mendonça—Kaiser instability:** radiation diffusion near resonance causes density instabilities in the atoms

$n, I \sim e^{i\mathbf{q}\cdot\mathbf{r} - i\omega t}$

Secular equation:

$$\boxed{\left(-i\omega + D_0 q^2 + \gamma_0\right)\left(\omega^2 + i\omega\nu - \omega_s^2\right) = -\beta\left(\epsilon + ia\right)\omega}$$

$$\omega_s^2 = \omega_p^2 + u_s^2 q^2$$

$$\beta = \omega_p^2 n_0 / I_0$$

Isotropic coupling

$$\epsilon = 2\frac{D_0}{n_0}\nabla^2 I_0$$

Anisotropic coupling

$$a = 2\frac{D_0}{n_0}\left(\mathbf{q}\cdot\boldsymbol{\nabla} I_0\right)$$

# Oscillating bubbles, $\mathrm{Re}(\omega) \neq 0$

Looking for instabilities near the plasma mode: $\omega \simeq \omega_s + \delta$, with $\delta \ll \omega_s$

$$\delta \simeq -i\frac{\nu}{2} - i\frac{\beta\epsilon}{2\omega_s^2}\left(i + \frac{D_0 q^2}{\omega_s^2} + \frac{\gamma_0}{\omega_s}\right)$$

Instability conditions

$$\beta\epsilon < 0, \quad |\beta\epsilon| > \nu\omega_s^2$$

$$\sigma_R > \sigma_L \Rightarrow \nabla^2 I_0 < 0$$

# Static bubbles, $\mathrm{Re}(\omega) = 0$

Purely growing modes, $|\mathrm{Im}(\omega)| \ll \omega_s$

$$\mathrm{Im}(\omega) = \frac{\beta\epsilon}{\omega_s^2} - \left(D_0 q^2 + \gamma_0\right)$$

Instability condition

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# Photon bubble instability threshold

The threshold for the **MK instability** can be described in terms of the local "intensity curvature"

$$L^2 = \frac{I_0}{|\nabla^2 I_0|}$$

Oscillating bubbles

$$L_o \lesssim \frac{2\ell}{\sqrt{2\tau\nu}}, \quad \Gamma_o \simeq \frac{1}{\tau}\frac{\ell^2}{L_o^2}$$

Static bubbles

$$L_s \lesssim \frac{\sqrt{2}\ell}{\sqrt{q^2 + \gamma_0/D_0}}, \quad \Gamma_s \simeq \frac{2}{\tau}\frac{\ell^2}{L_s^2}$$

$$\Gamma_{o,s} \gtrsim 10 \text{ ms}^{-1}$$

J. T. Mendonça and R. Kaiser, PRL 108, 033001 (2012)

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Typical experimental conditions:

$$D_0 \simeq 0.6 \text{ m/s}^2$$
$$\ell \simeq 300\ \mu\text{m}$$
$$\tau \simeq 0.1\ \mu\text{s}$$

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$\longrightarrow$

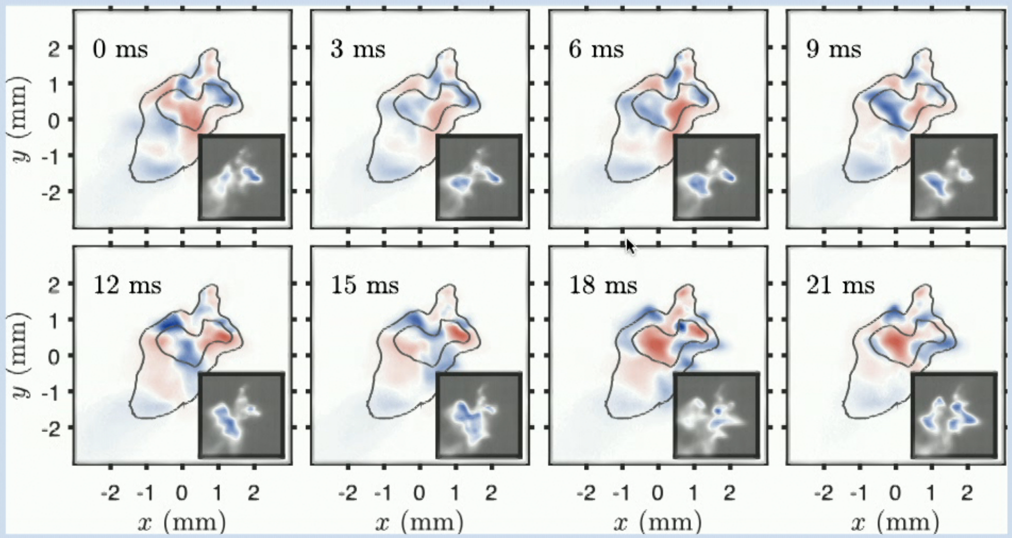
**Reasonable growth rates!**

$$\Gamma_{o,s} \gtrsim 10 \text{ ms}^{-1}$$

J. T. Mendonça and R. Kaiser, PRL 108, 033001 (2012)

# Experimental evidence I

Our first attempt to observe photon bubble turbulence (3D case)



# Experimental evidence I

Our first attempt to observe photon bubble turbulence (3D case)

## Photon Bubble Turbulence in Cold Atomic Gases

João D. Rodrigues [1], José A. Rodrigues [2], António V. Ferreira [1], Hugo Terças [3], Robin Kaiser [4], José T. Mendonça [1]

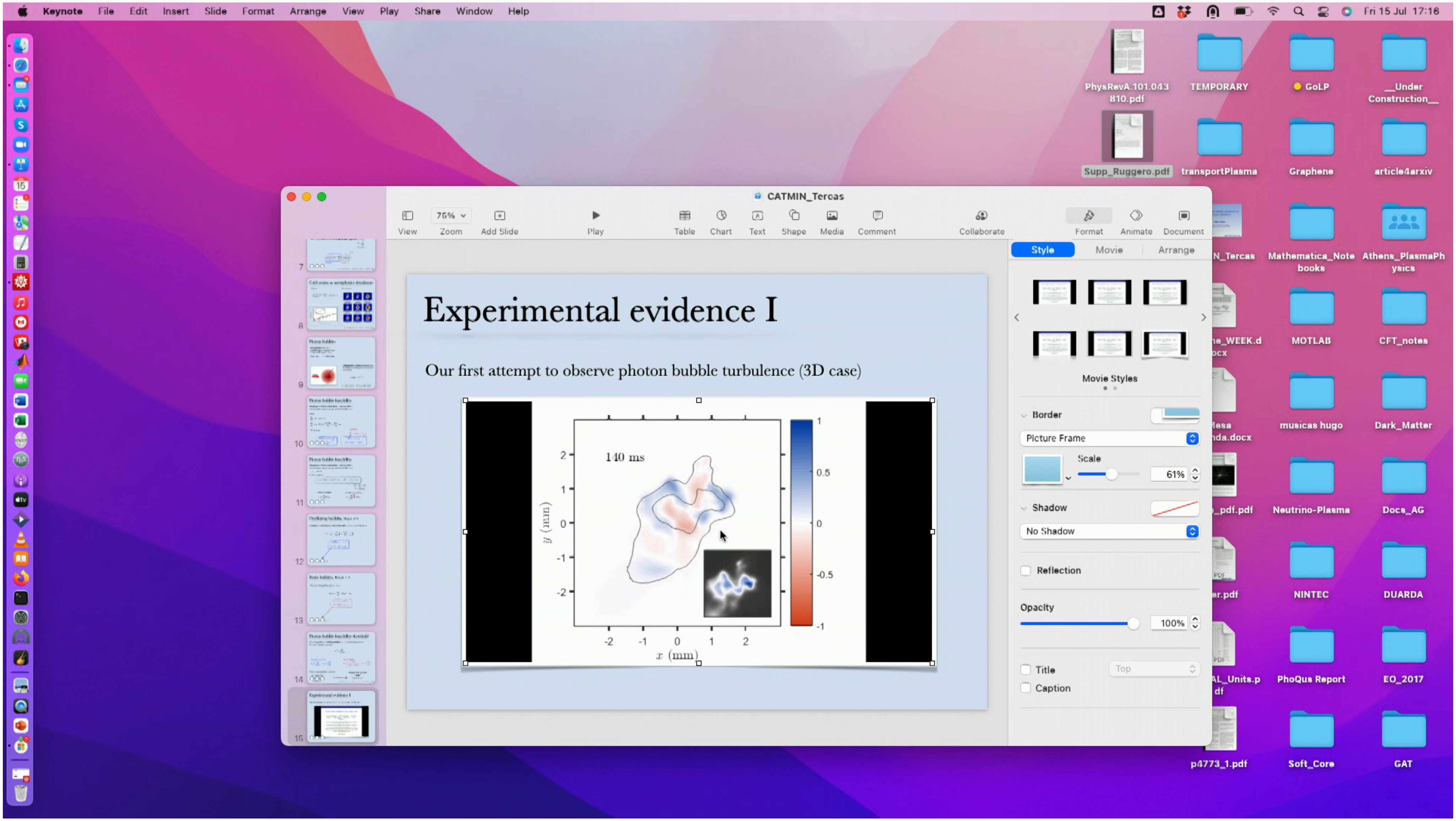
[1]Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisbon, Portugal

[2]Departamento de Física, Faculdade de Ciências e Tecnologia, Universidade do Algarve, 8005-139 Faro, Portugal

[3]Physics of Information Group, Instituto de Telecomunicações, Lisbon, Portugal

[4]Institut Non Linéaire de Nice, CNRS and Université Nice Sophia Antipolis, 1361 route des Lucioles, 06560 Volbonne, France

April 15, 2016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Fri 15 Jul 17:16
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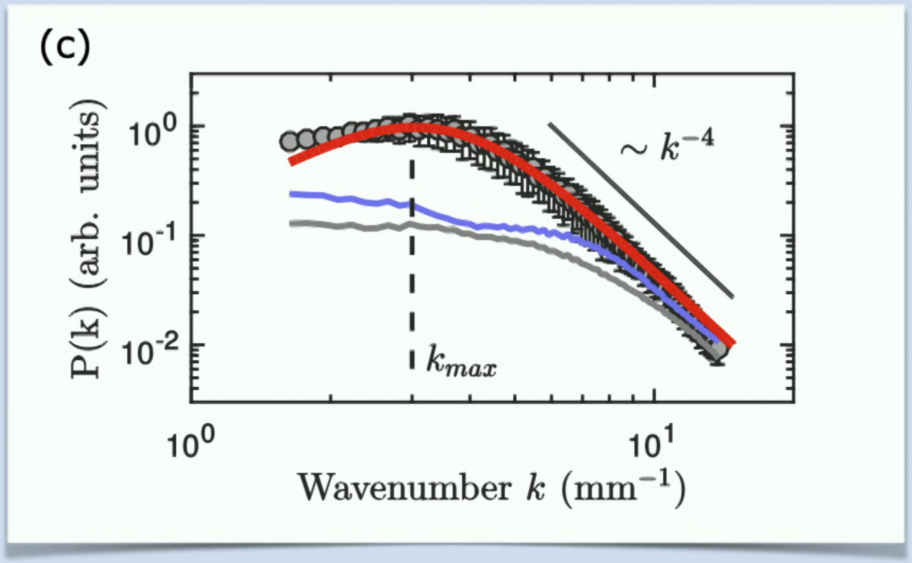
Experimental evidence I
Our first attempt to observe photon bubble turbulence (3D case)
140 ms
$x$ (mm)
$y$ (mm)
Style
Movie
Arrange
Movie Styles
Border
Picture Frame
Scale
61%
Shadow
No Shadow
Reflection
Opacity
100%
Title
Caption

# Experimental evidence I

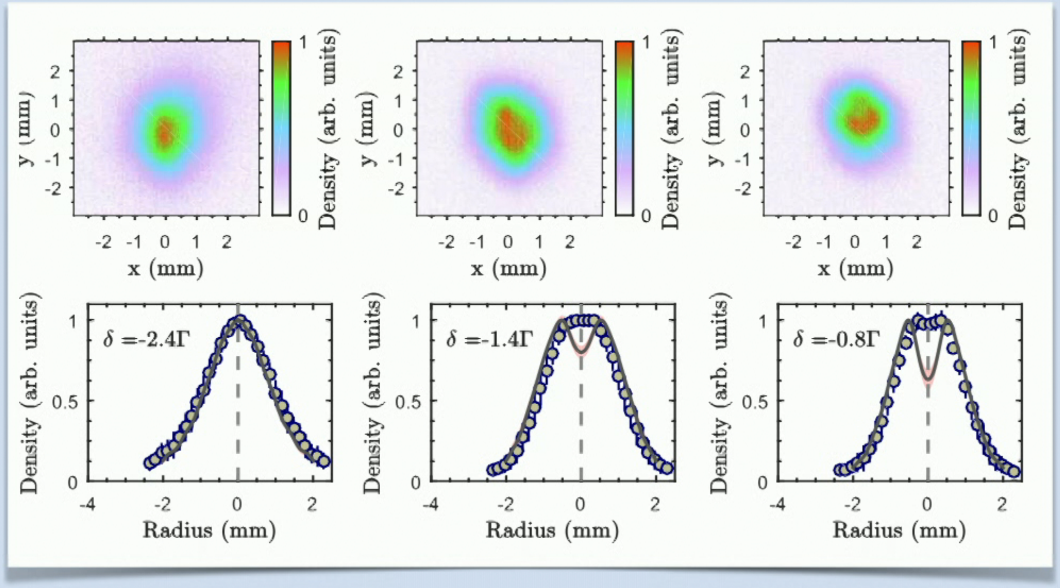
First attempt to observe photon bubble turbulence: integrated (3D case)




"non Kolmogorov" cascade!

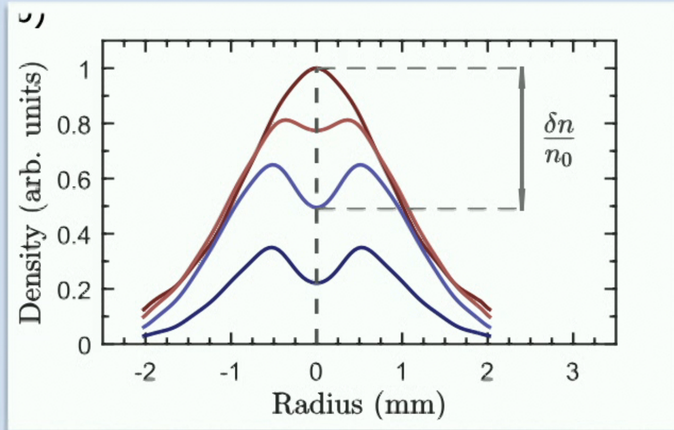
# Experimental evidence I

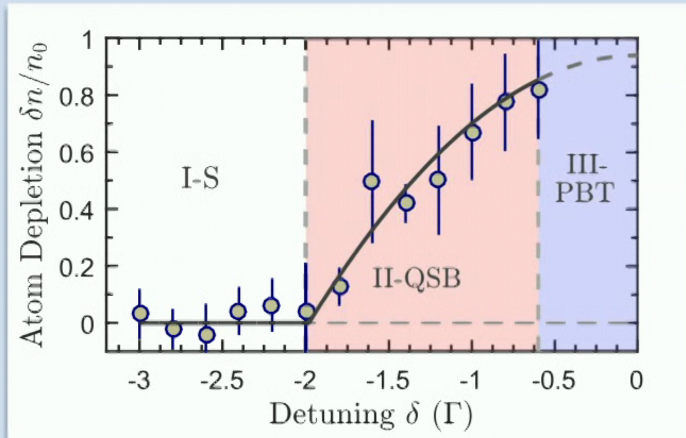
We could observe three different regimes



# Experimental evidence I: 3D imaging

Transition from static to oscillating bubbles (turbulence)

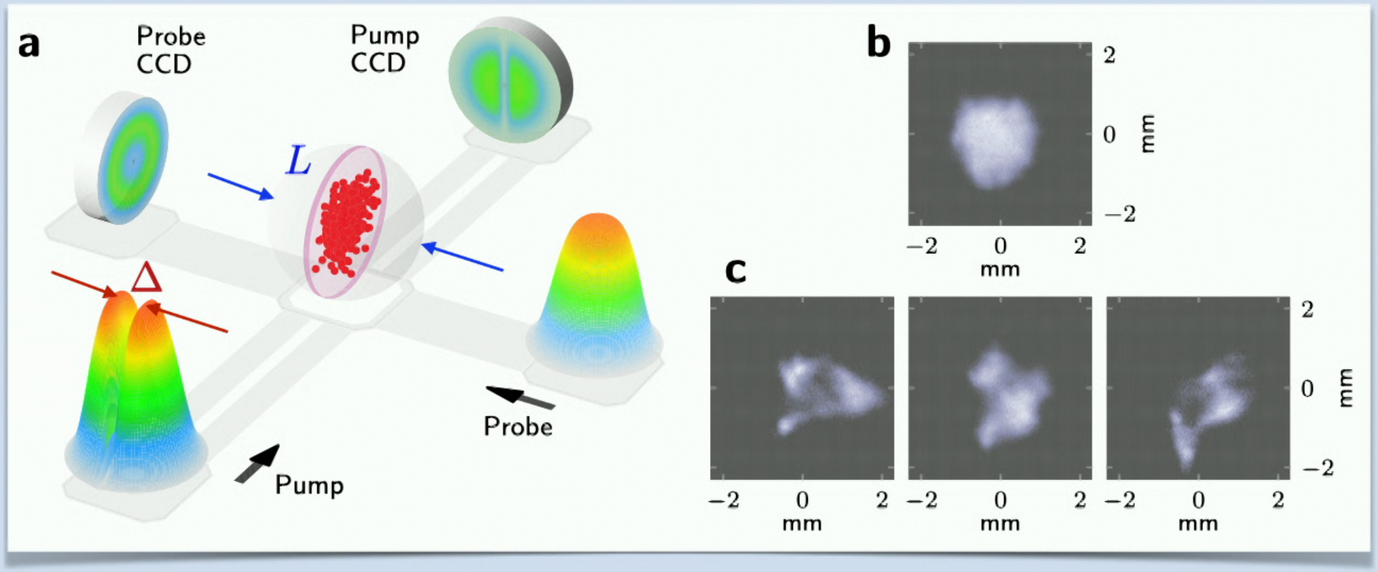



J.D. Rodrigues et al, Atoms 10, 45 (2022)

# Experimental evidence II: 2D imaging

Second attempt: a direct (2D) observation of the bubbles

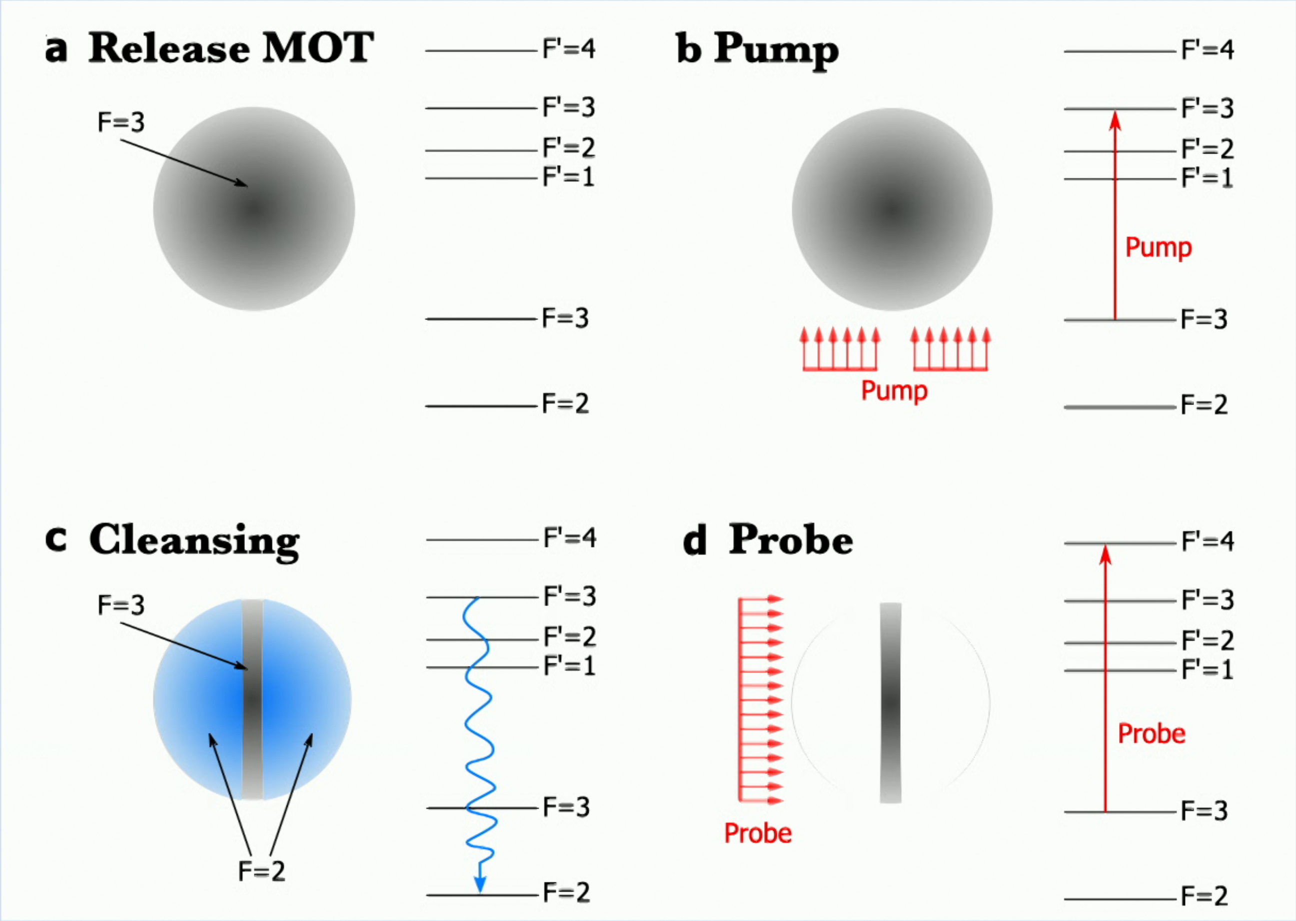



$\Delta \simeq 70\ \mu\mathrm{m}$

$L \simeq 4\ \mathrm{mm}$

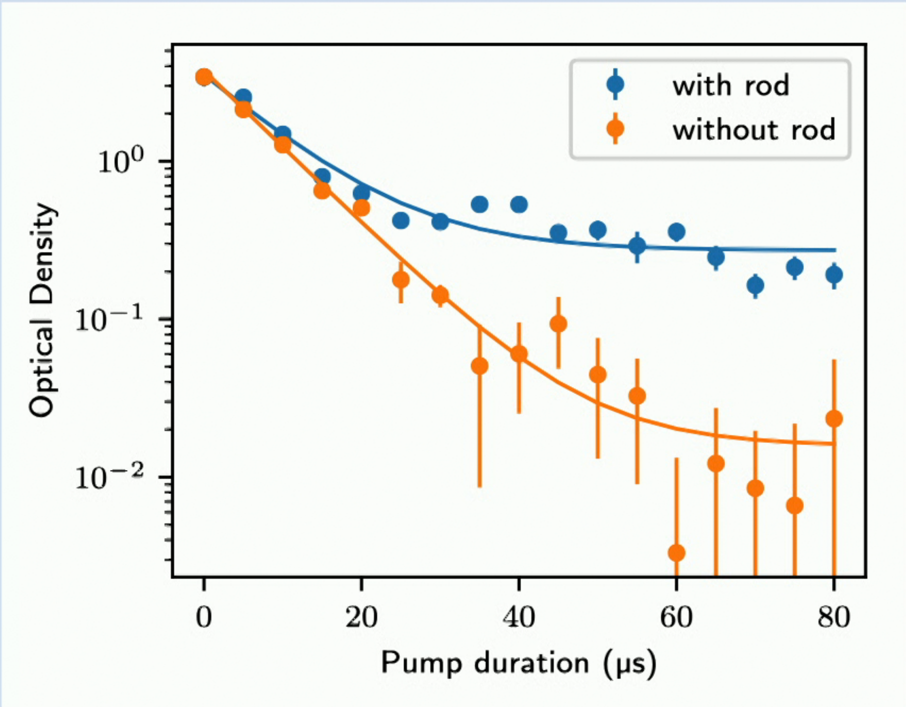
R. Giampaoli et al, Nat. Comm. 12, 3240 (2021)

# Experimental evidence II: 2D imaging



# Experimental evidence II: 2D imaging

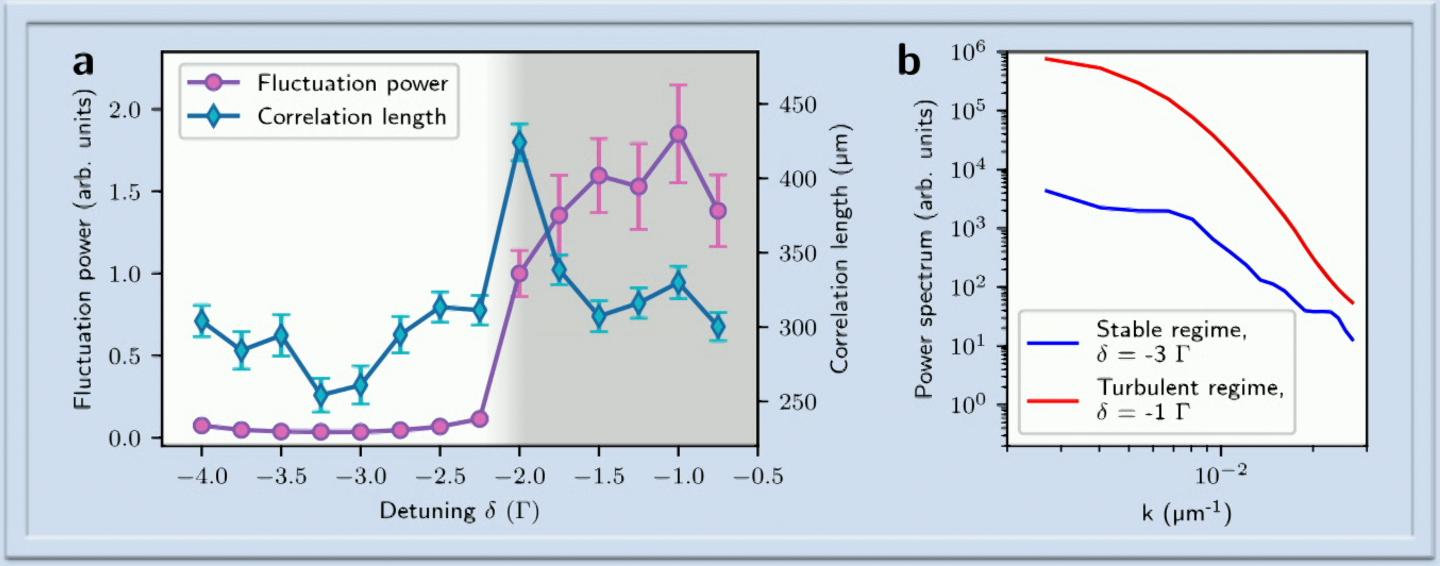
Calibration of the pump time: outer atoms are pumped away and OD saturates.




$\tau_{\mathrm{pump}} = 75\ \mu s$

# Experimental evidence II

**Turbulence signature 1:** fluctuations become stronger near resonance

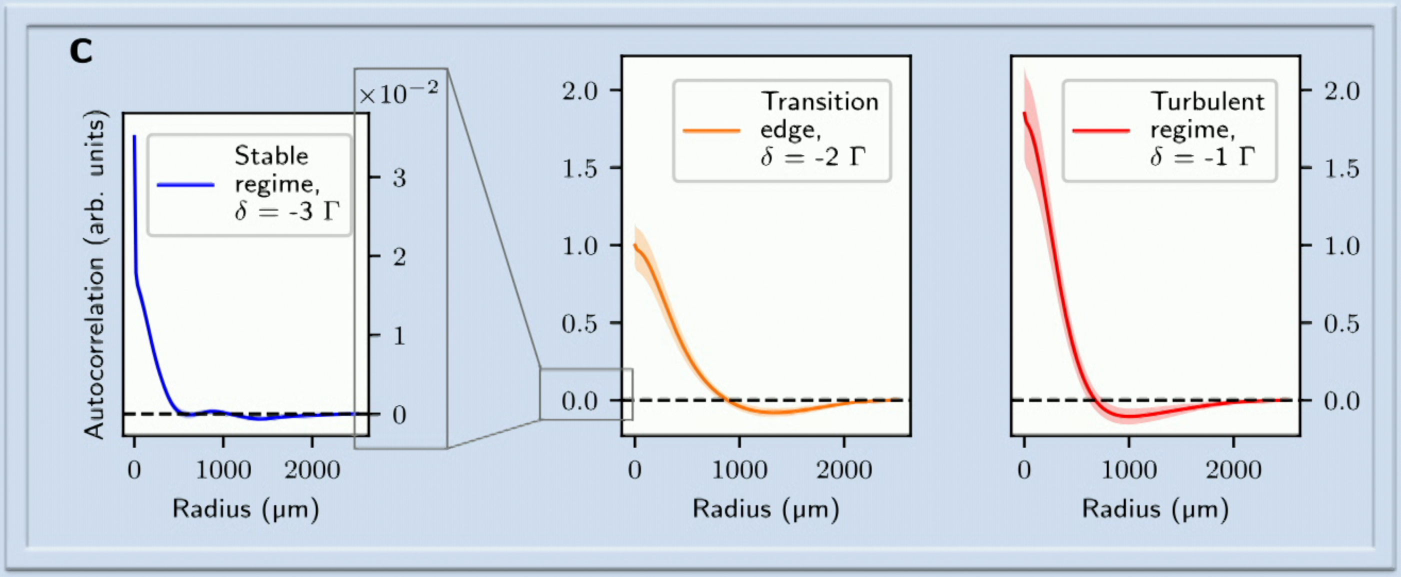



R. Giampaoli et al, Nat. Comm. 12, 3240 (2021)

# Experimental evidence II

Second attempt: a direct (2D) observation of the bubbles

**Turbulence signature 2:** spatial auto-correlation emerges

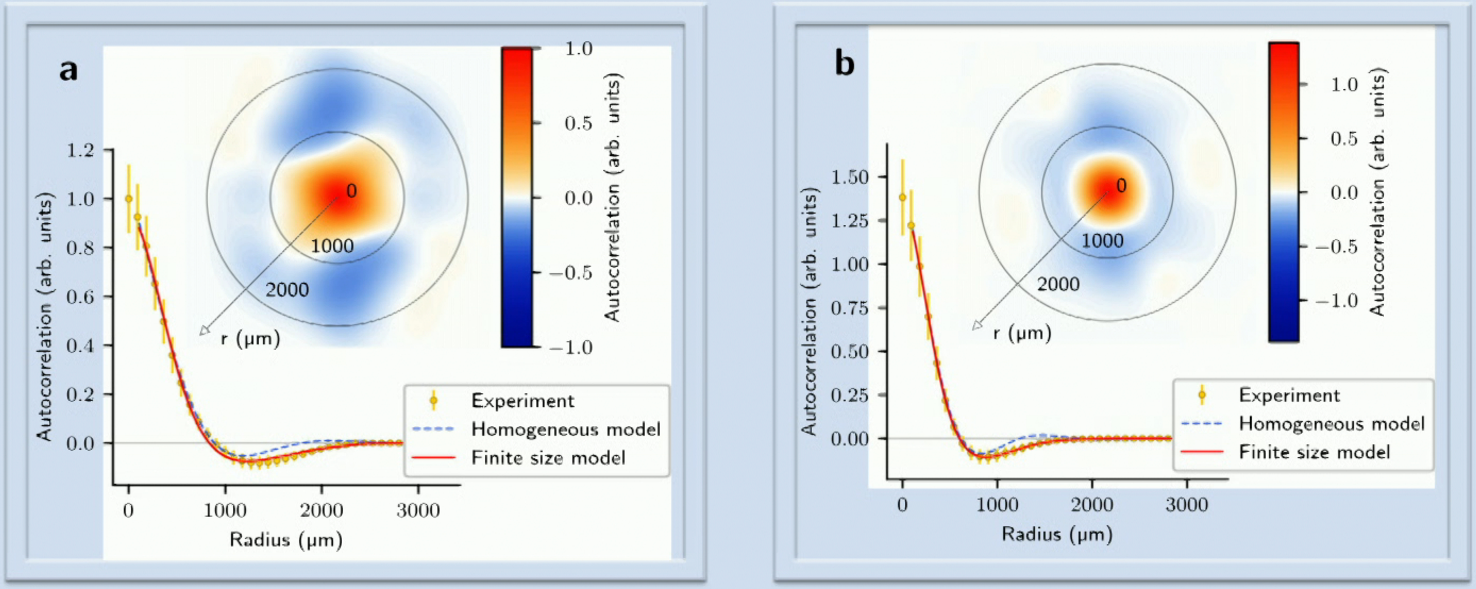



R. Giampaoli et al, Nat. Comm. 12, 3240 (2021)

# Experimental evidence II

**Auto-correlation:** comparison with the photon bubbling theory

$$F(r) = j_0(qr)e^{-\gamma r}$$




$\delta = -2\Gamma$ $\qquad$ $\delta = -0.75\Gamma$

R. Giampaoli et al, Nat. Comm. 12, 3240 (2021)


Thank you!