Universal Long Range Nanometric Bending of Water by Light

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IN PURSUIT OF KNOWLEDGE

Maxwell's great unification: Light is an ElectroMagnetic wave

James Clerk Maxwell (1831–1879)

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

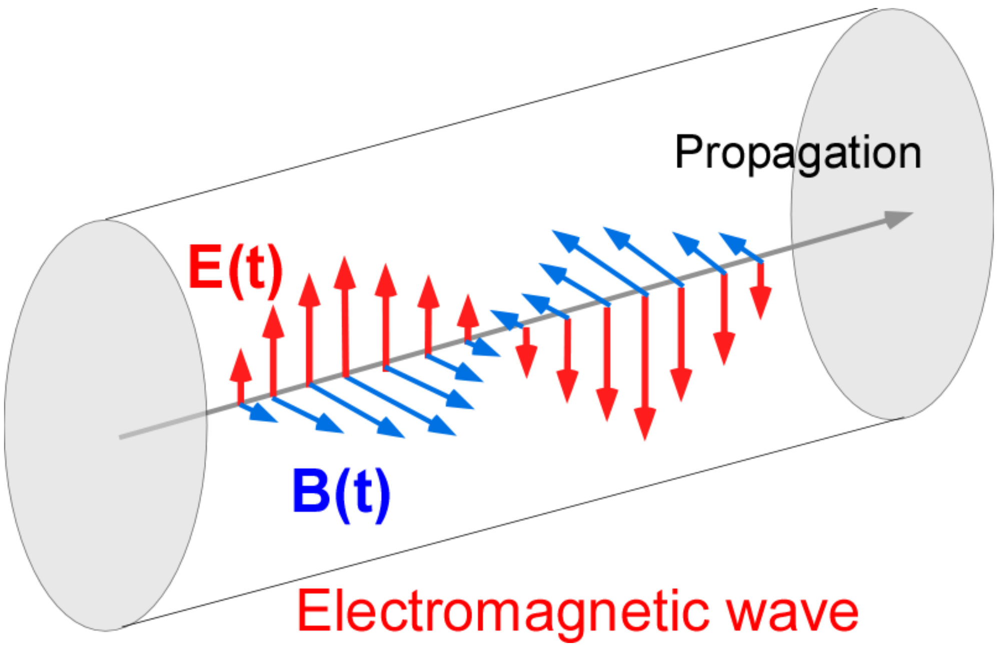
- Explained **speed of light 'c'** in vacuum
- **c/n** in transparent medium

ElectroMagnetic waves carry Energy & Momentum

- **Energy density:**

$$u = \epsilon E^2$$

(J/m3)



- **Energy flux:** (flow per unit area)

$$<S> = \frac{1}{2} c \ \epsilon E^2$$

- **Radiation pressure: (N/m2)**

$$<P> = \frac{<S>}{c}$$

(N/m2 or J/m3)

Light (photons) exert pressure on a surface upon reflection, absorption.

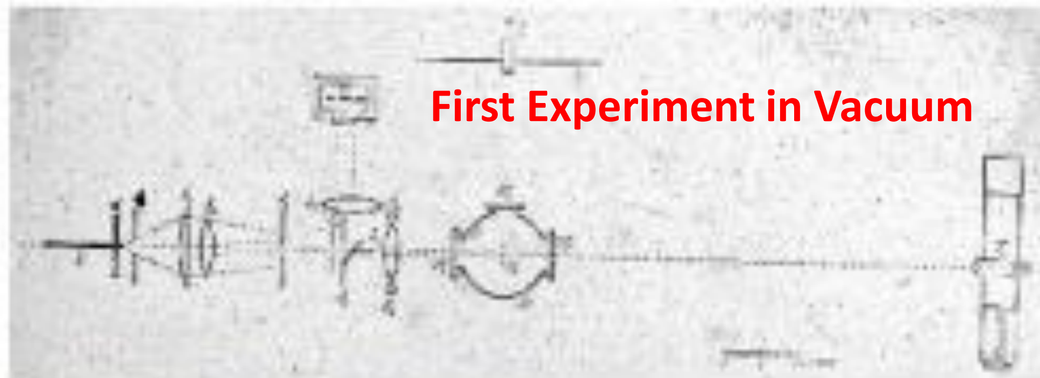
Radiation Pressure force is very small

1 Watt on perfectly reflecting mirror = 6 nN

A torsion pendulum setup with mirrors produced
Deflection that confirmed the light force in vacuum.

Challenging experiment:
(No lasers, poor vacuum, sensitive detection etc)

Nichols and G. F. Hull,
Phys. Rev. 13, 307-320 (1901).



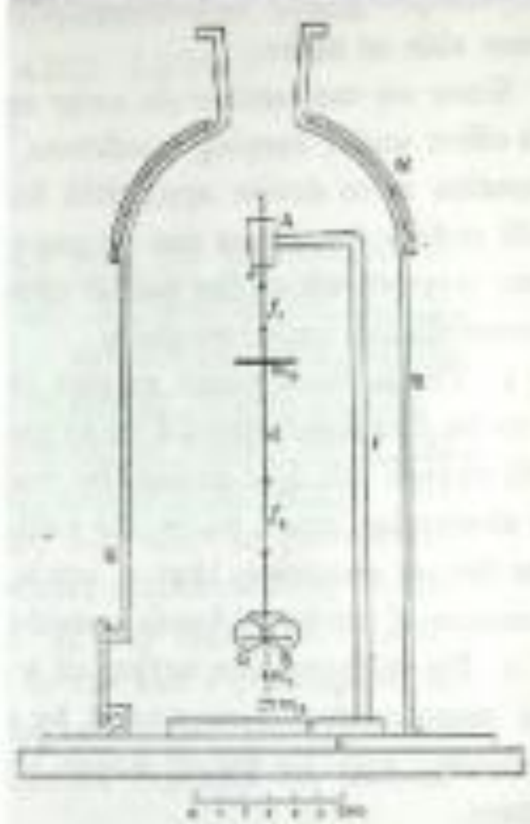
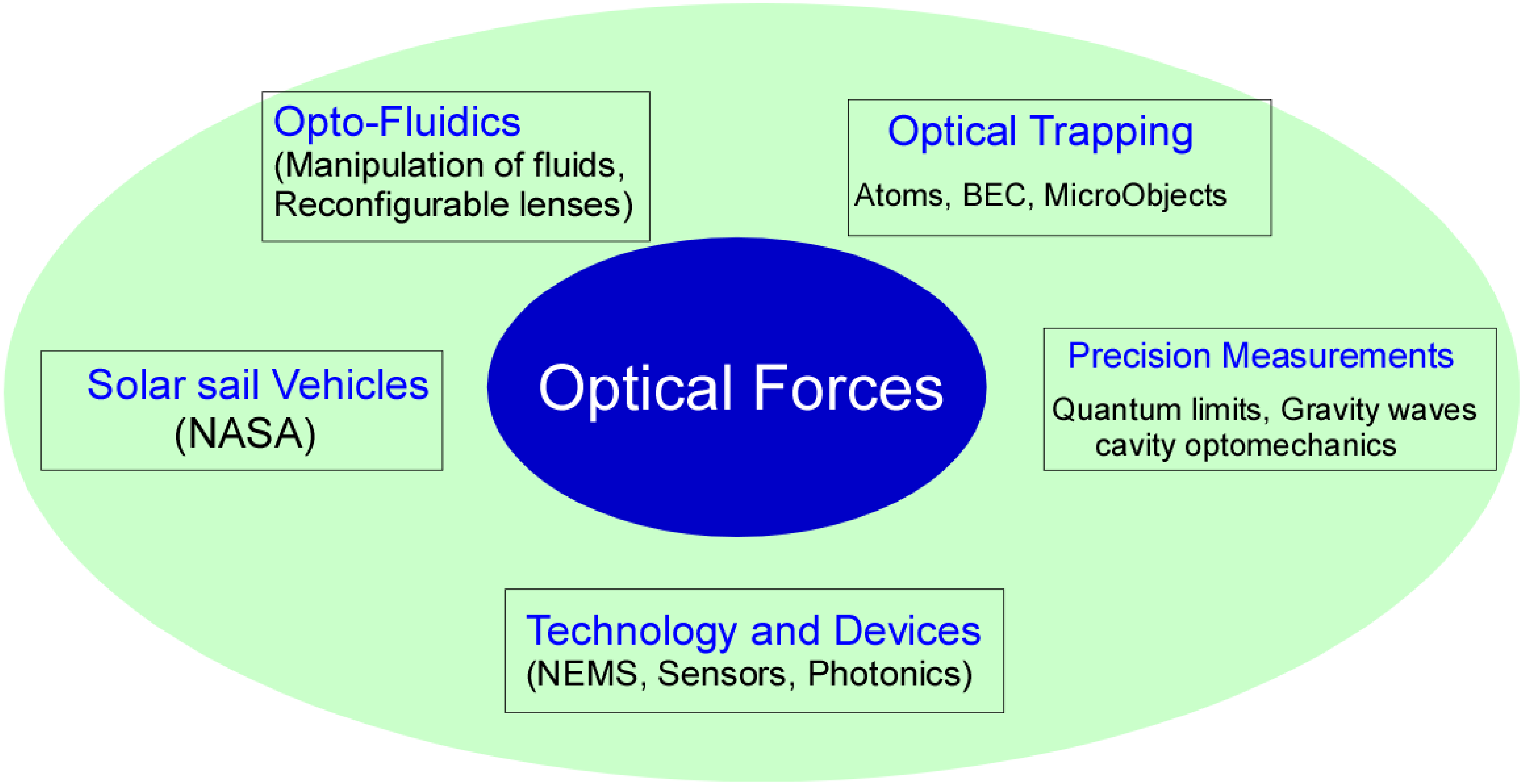


Figure 1 (Top), showing the apparatus used by Nichols and Hull in the light pressure experiment. Figure 2 (Left), showing the Nichols radiometer.

Image courtesy of the Rauner Special Collections Library.

In vacuum, momentum carried by photons was confirmed !

Diverse Applications of Radiation Pressure



Non-contact, High Precision, Reconfigurable

HOW much momentum light carries in a medium?

When light travels through a medium (water), does it Pull or Push on the medium?

Two propositions for principal momenta of light

1-Hermann Minkowski (1908) predict light momentum increase ("n" times of refractive index of medium) in dielectric medium (water, glass, etc.).

$$P_{Minko} = n\frac{I}{c}$$

2-Max Abraham (1909) predict exact opposite result in which momentum is decrease in dielectric medium.

$$P_{Abr} = \frac{1}{n}\frac{I}{c}$$

Where, I is intensity of light and c is speed of light

Abraham Minkowski momenta & Wave Particle duality

*Ulf Leonhardt, "Momentum in an uncertain light" Nature **444**, 823 (2006).*

Wave nature of light

- De Broglie relation: $\mathbf{p = h/\lambda}$
- In dielectric medium:

  λ reduces by refractive index $\boldsymbol{\lambda/n}$

  (Single-double slit exp. proves this)
- Hence $\mathbf{P_M = n\ h}/\lambda = \mathbf{n\ p}$

Minkowski: Photons Gain momentum

Particle nature of light

- Mass–energy equivalence in relativity, $\mathbf{p=E/c}$ where $\mathbf{E= mc^2}$
- In a dielectric medium of index (n):

  speed c is reduced by $\mathbf{c/n}$
- Hence, $\mathbf{P_M = (E/c)/n = p/n}$

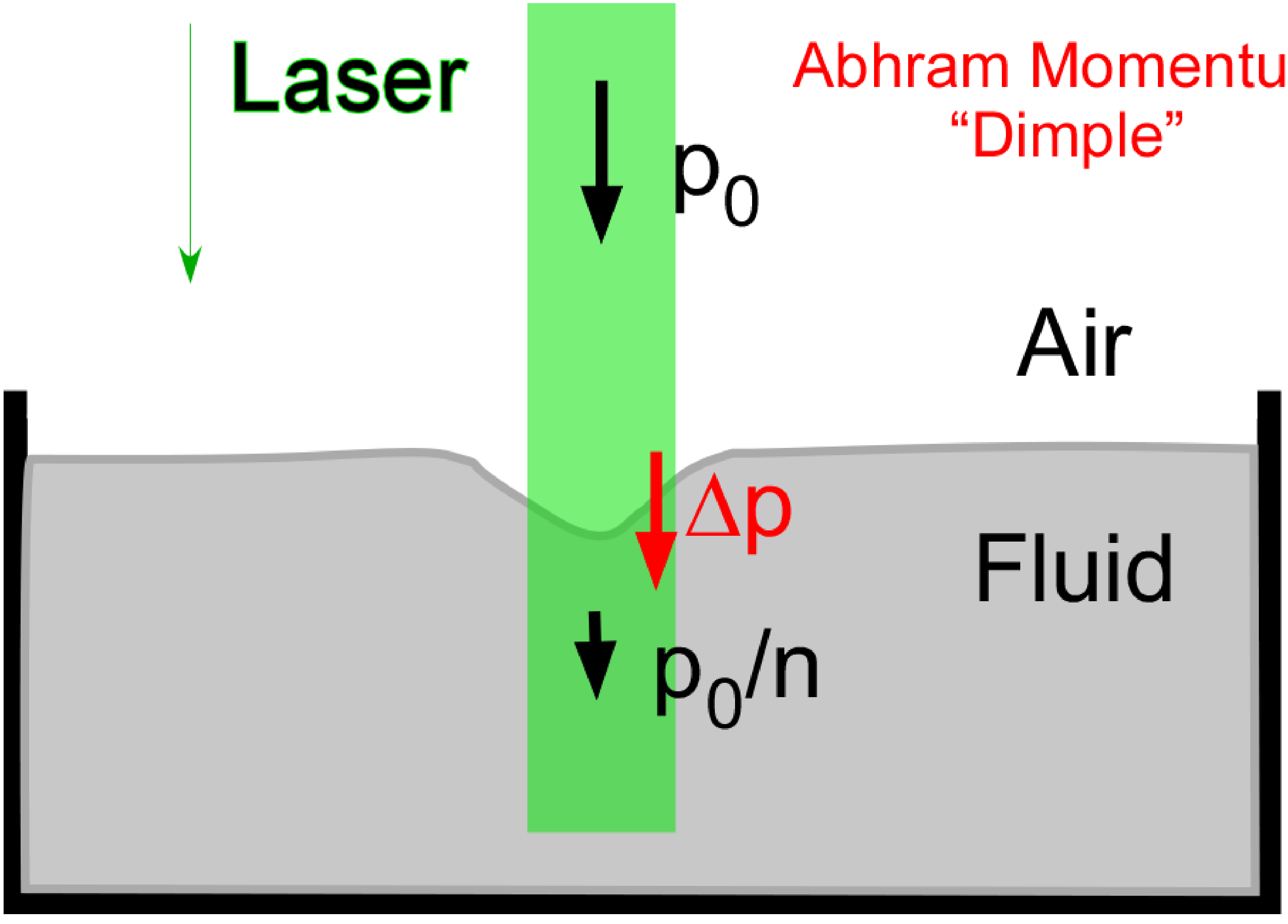
Abraham: Photons loose momentum

How to experimentally test these predictions ?

Deformability of fluids as a test bed for photons momentum

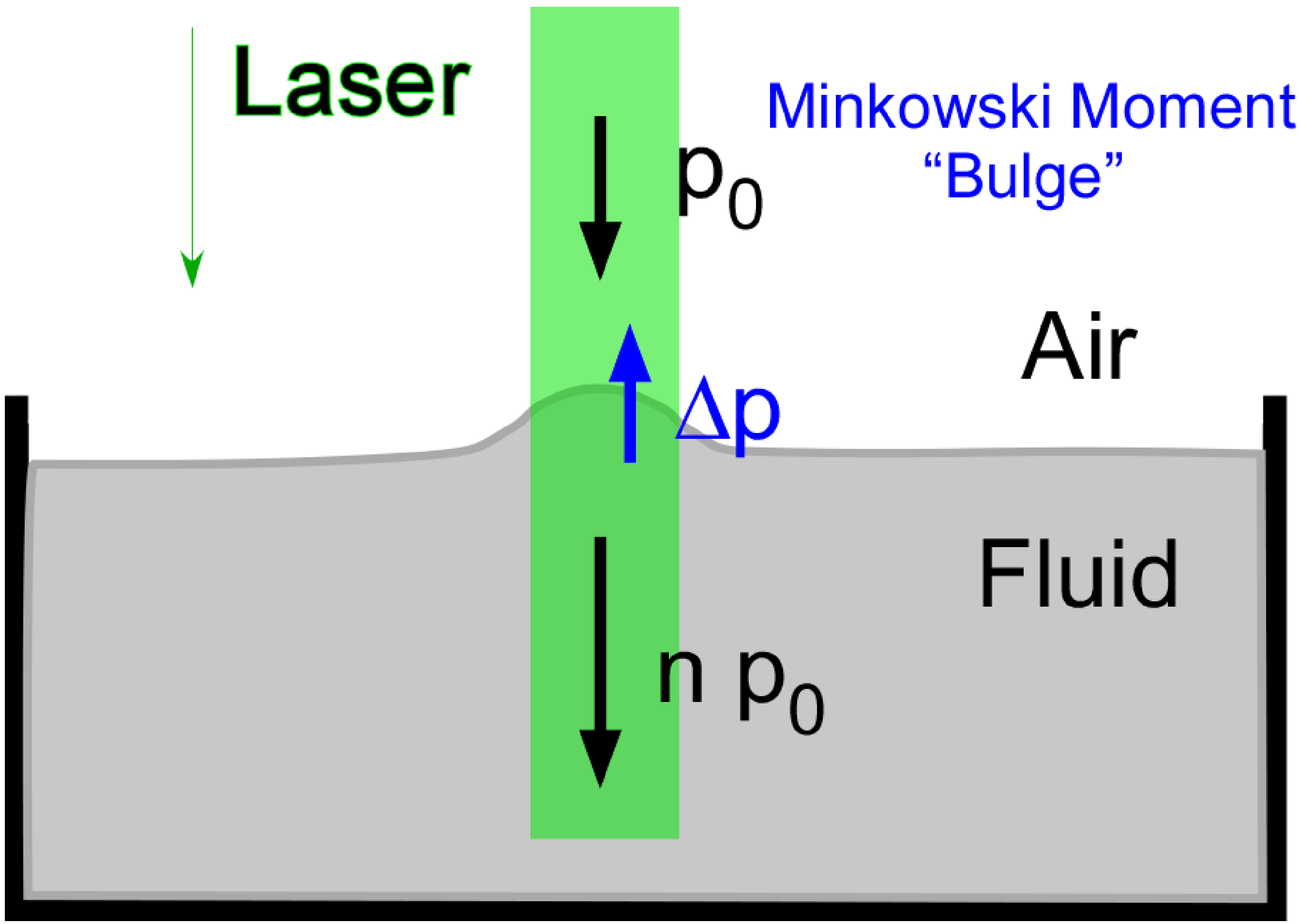
Change in photons momentum causes deformation:

Abraham $$\Delta p_m = -\frac{(n+1)}{(n-1)}\frac{2I}{c}$$



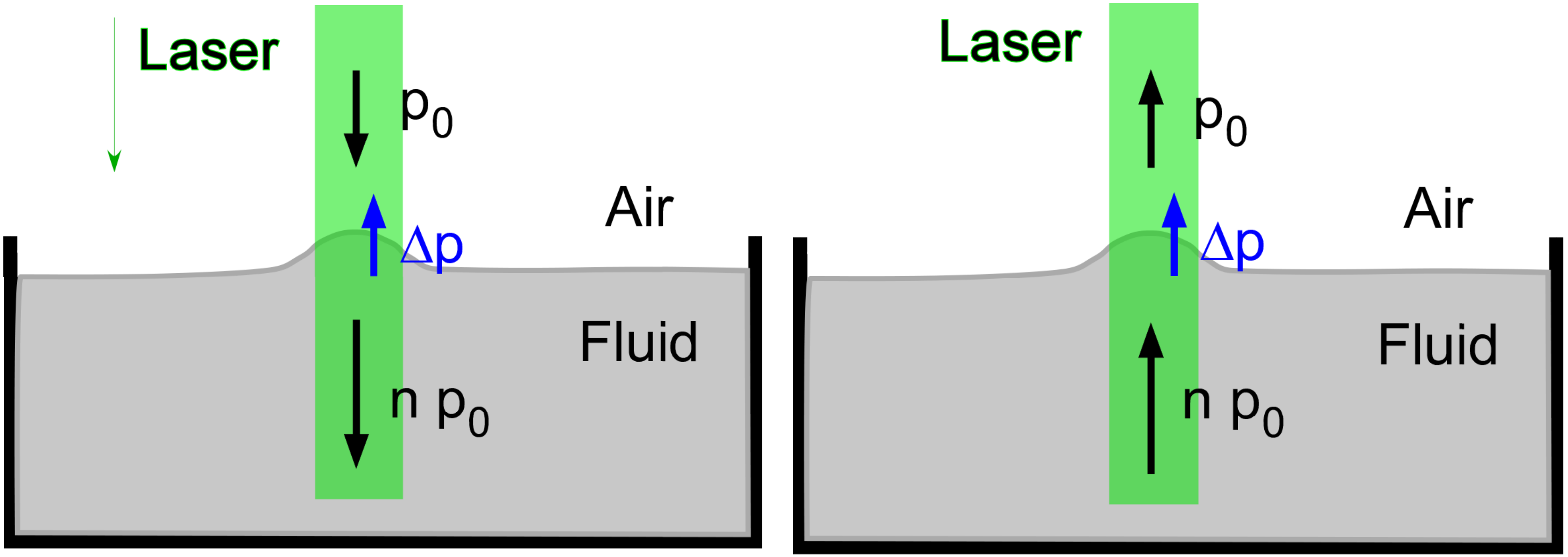
Both are equal in magnitude but exact oppsite in direction .

Minkowski $$\Delta p_m = +\frac{(n+1)}{(n-1)}\frac{2I}{c}$$



Surprising properties of radiation pressure force:

Independent of beam propagation direction
(upward or downward)



Experimental Detection of Radiation Pressure effect on Fluids

First Experimental Observation by Ashkin: A micro-Bulge on water

VOLUME 30, NUMBER 4 PHYSICAL REVIEW LETTERS 22 JANUARY 1973

Radiation Pressure on a Free Liquid Surface

Father of Optical Tweezers

A. Ashkin and J. M. Dziedzic
Bell Telephone Laboratories, Holmdel, New Jersey 07733
(Received 10 November 1972)

The force of radiation pressure on the free surface of a transparent liquid dielectric has been observed using focused pulsed laser light. It is shown that light on either entering or leaving the liquid exerts a net outward force at the liquid surface. This force causes strong surface lens effects, surface scattering, and nonlinear absorption. The data relate to the understanding of the momentum of light in dielectrics.

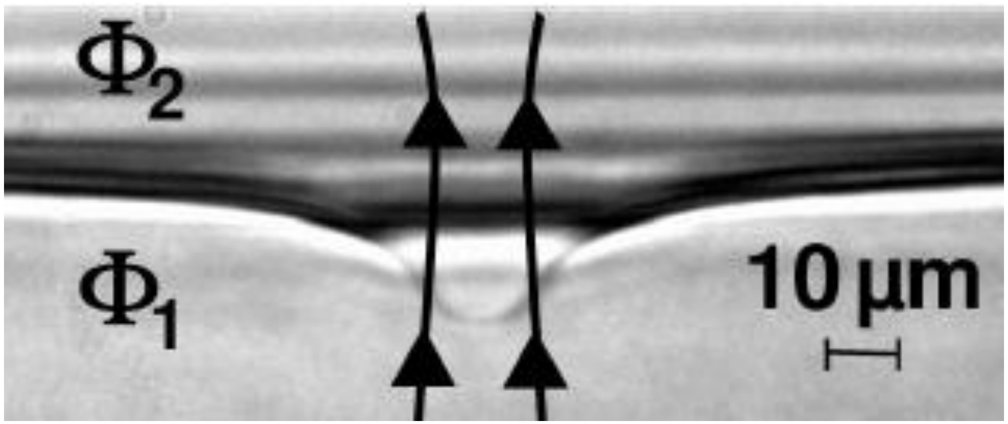
- *Due to small momentum of photons intense field are required (ns pulses @ kW peak powers)*
- *Heating effect competed with radiation pressure effects*
- *Measurements was qualitative and lacked nanoscale precision*

Complimentary Approach: Soft Liquid-liquid interfaces

VOLUME 87, NUMBER 5 PHYSICAL REVIEW LETTERS 30 JULY 2001

Giant Deformations of a Liquid-Liquid Interface Induced by the Optical Radiation Pressure

Alexis Casner* and Jean-Pierre Delville†
Centre de Physique Moleculaire Optique et Hertzienne, UMR CNRS/Universit 5798, Universit Bordeaux I, 351 Cours de la Libration, F-33405 Talence cedex, France
(Received 9 April 2001; published 16 July 2001)



Phase separated liquid mixtures
tunable surface tension
around micro Nm

- Low power cw laser were sufficient to create huge stationary bulges, in agreement with Minkowski's predictions.

However, these are not suitable to any angle of incidence and no polarization sensitivity

Universal Long-Range Nanometric Bending of Water by Light

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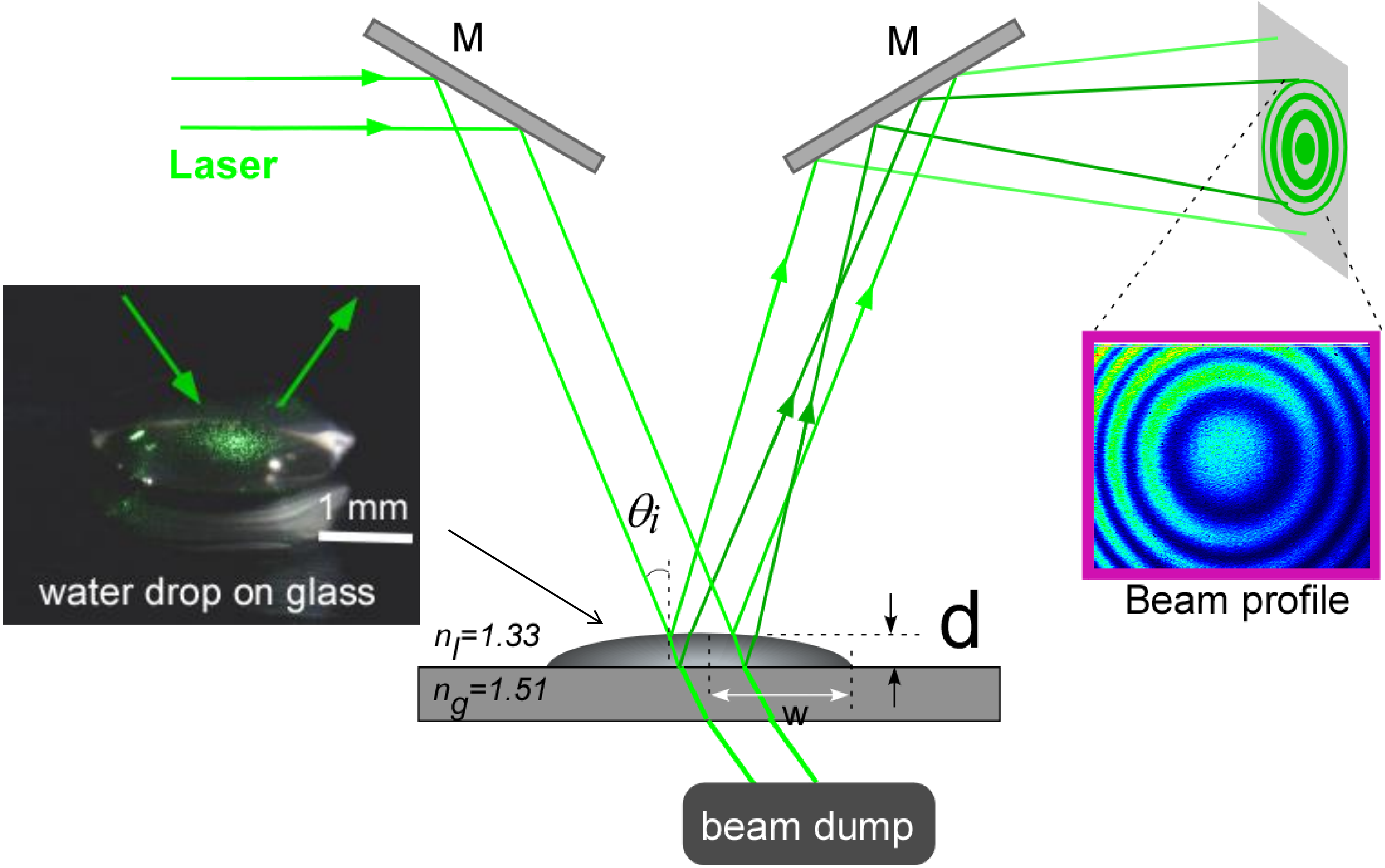
(Received 19 May 2015)

Resolving mechanical effects of light on fluids has fundamental importance with wide applications. Most experiments to date on optofluidic interface deformation exploited radiation forces exerted by normally incident lasers. However, the intriguing effects of photon momentum for any configuration, including the unique total internal reflection regime, where an evanescent wave leaks above the interface, remain largely unexplored. A major difficulty in resolving nanomechanical effects has been the lack of a sensitive detection technique. Here, we devise a simple setup whereby a probe laser produces high-contrast Newton-ring-like fringes from a sessile water drop. The mechanical action of the photon momentum of a pump beam modulates the fringes, thus allowing us to perform a direct noninvasive measurement of a nanometric bulge with sub-5-nm precision. Remarkably, a < 10 nm difference in the height of the bulge due to different laser polarizations and nonlinear enhancement in the bulge near total internal reflection is isolated. In addition, the nanometric bulge is shown to extend far longer, 100 times beyond the pump spot. Our high precision data validate the century-old Minkowski theory for a general angle and offer potential for novel optofluidic devices and noncontact nanomanipulation strategies.

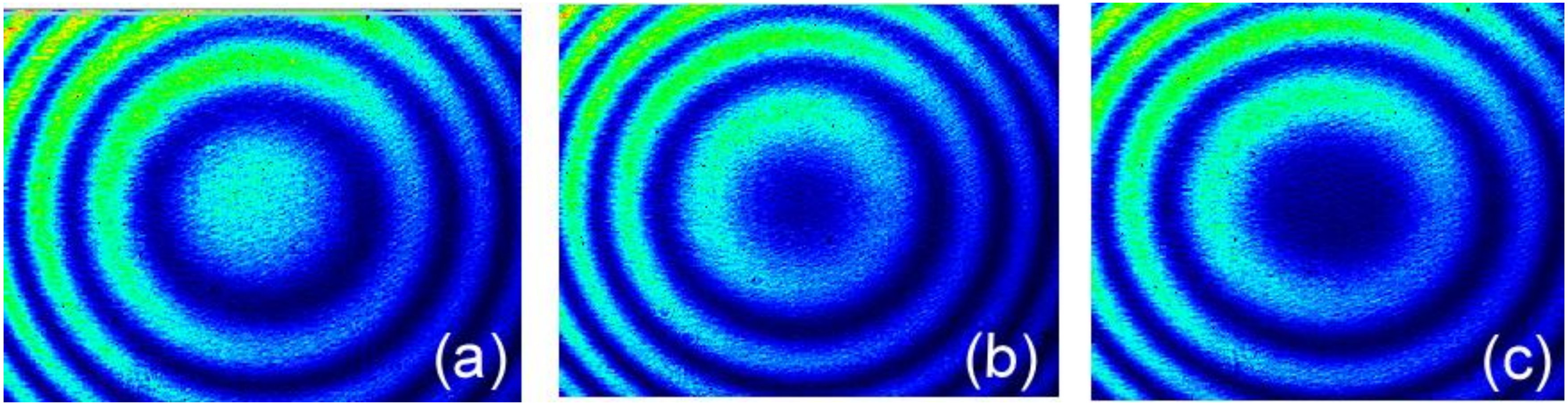
DOI: 10.1103/PhysRevLett.115.143902 PACS numbers: 42.25.Gy, 42.50.Wk, 68.03.-g, 83.85.Ei

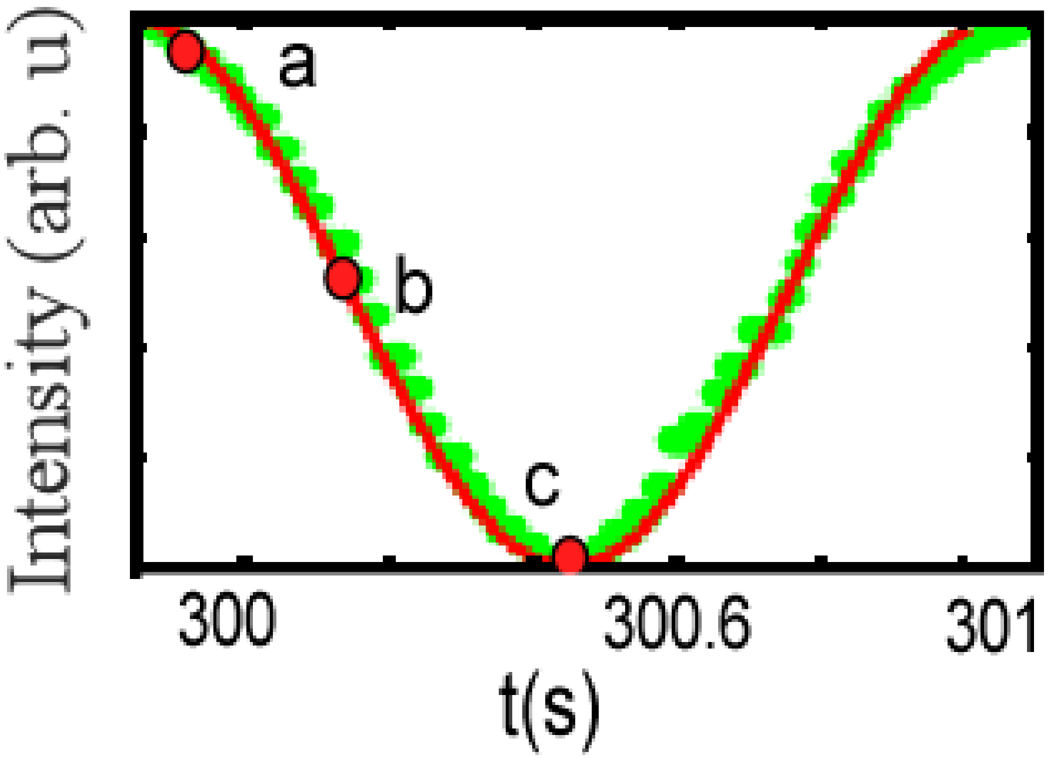
Time-resolved Interference from a Water Drop



G. Verma & K. P. Singh, Appl. Phys. Lett. 104, 244106 (2014)

High-contrast Newton-ring like dynamical fringes





- **Self-calibration:**

$$\frac{\lambda}{4n} \cong 100\, nm$$

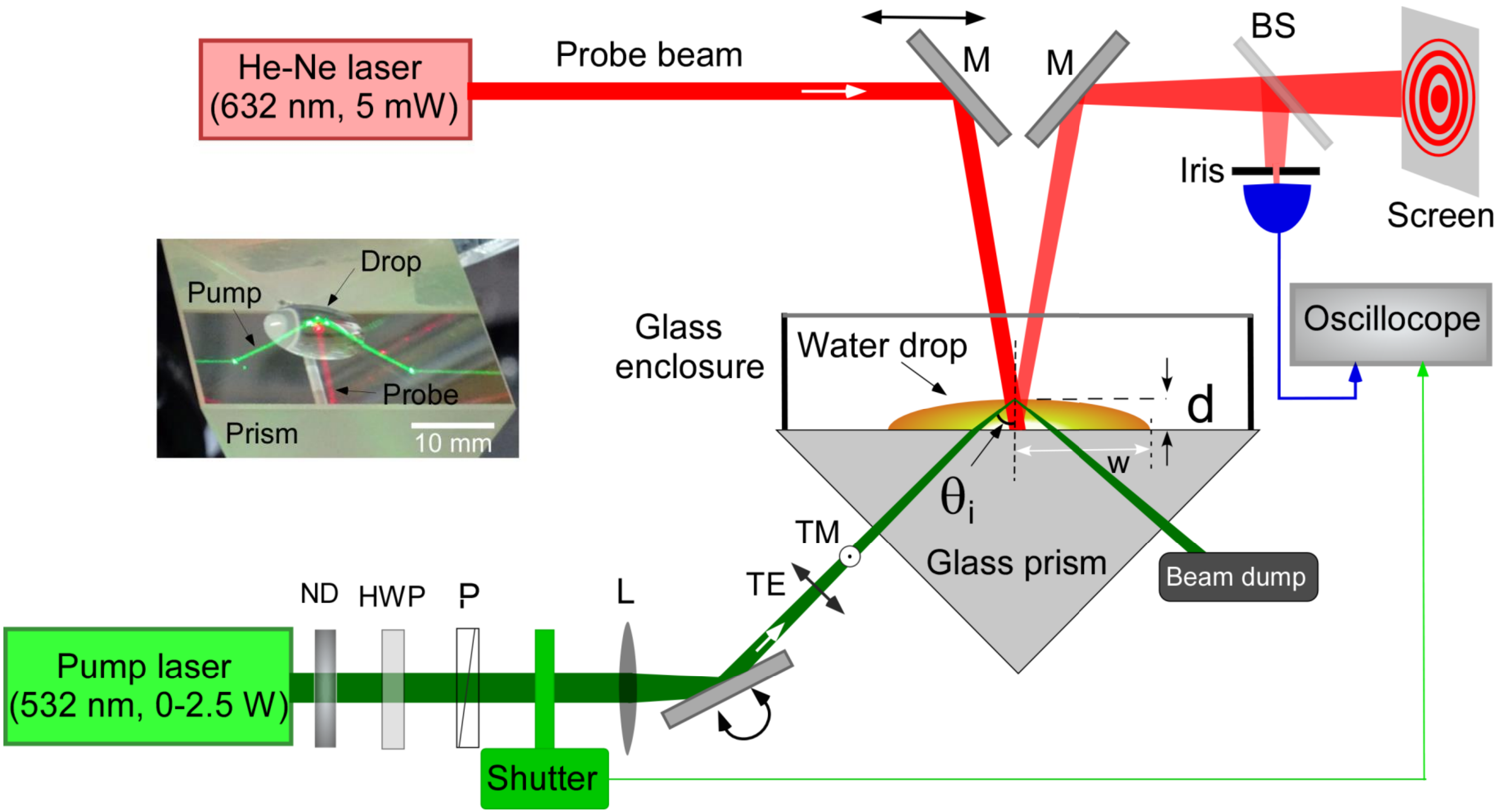
- **High precision:**

λ/100 ~ 5 nm

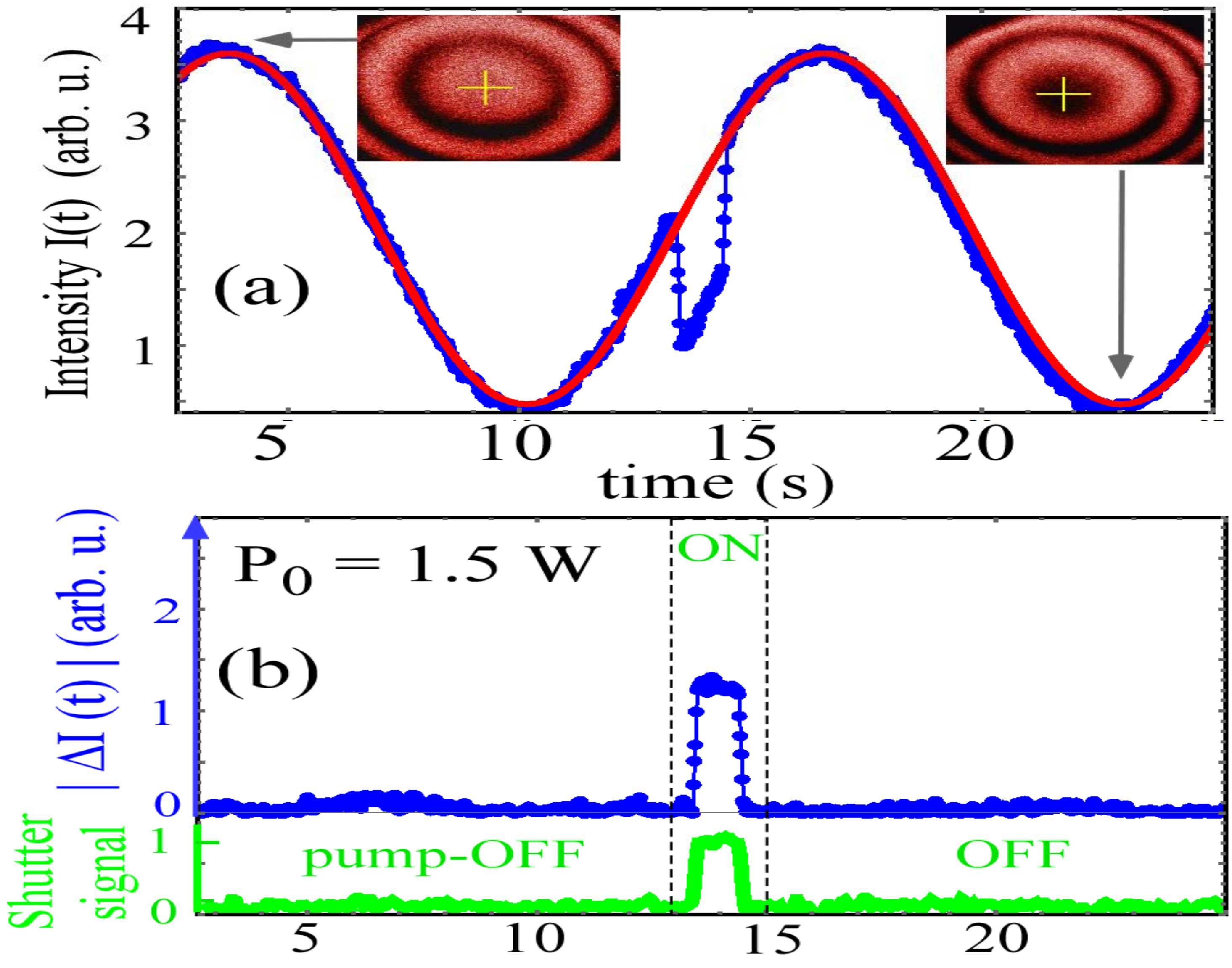
(Δm ~ 19 pico gm)

- **Non-invasive**

❑ Nanomechanical effects of photons momentum: setup

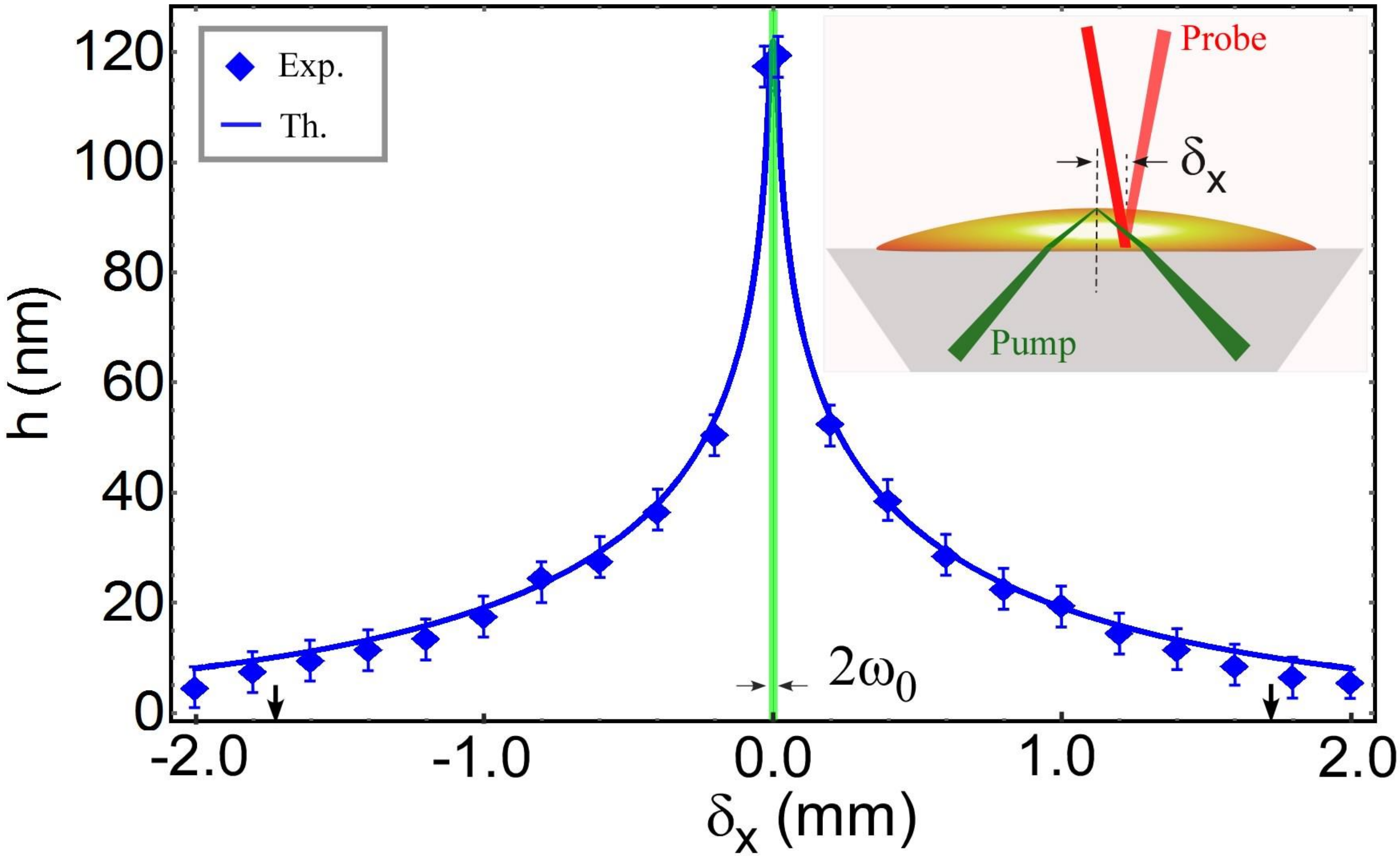


Determining the direction and magnitude of the deformation



Deformation is a bulge towards air & there is no heating effect

Long range nature of the bulge on the water



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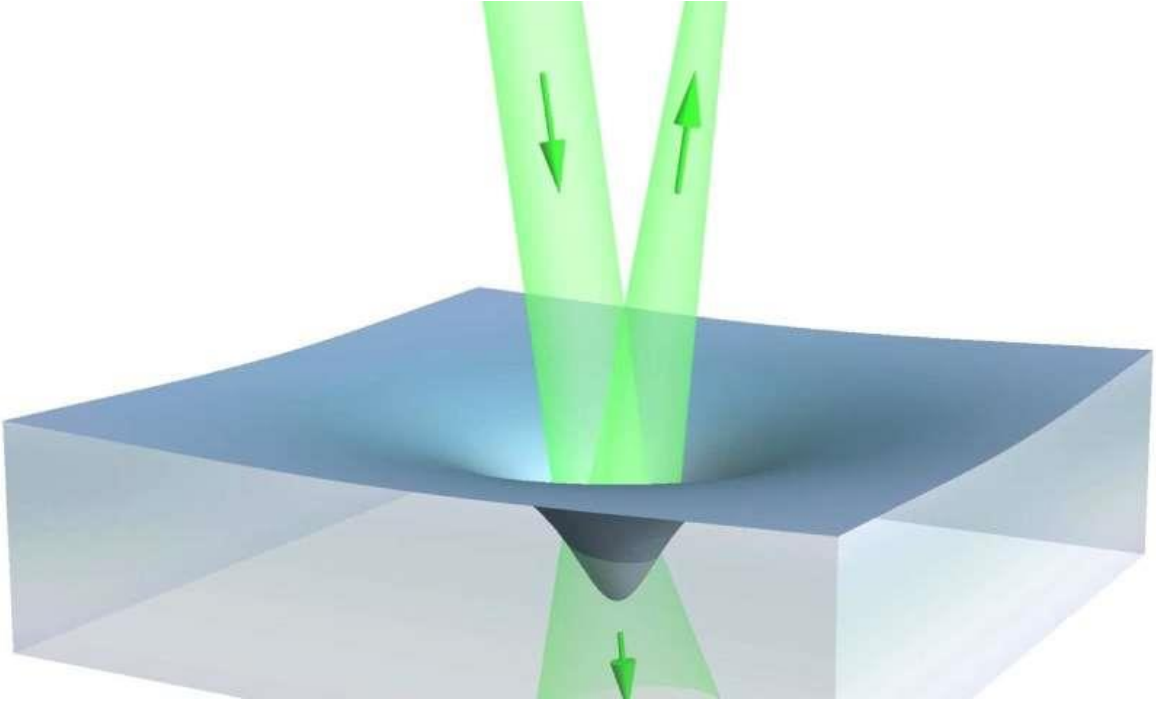
(Received 19 May 2015)

Can we observe Abraham momentum on water surface?

Physicists make first observation of the pushing pressure of light



- Li Zhang, et al. "Experimental evidence for Abraham pressure of light." *New Journal of Physics*. 2015.

Quantitative measurement of radiation pressure effects, Scientific Reports (2015)

Moral: The quest for understanding light in medium continues …..