고려대학교
KOREA UNIVERSITY

2016.7.20

Image Reconstruction from the Spatial Correlation of Speckle Illumination

Quantum Optics & Quantum Information Laboratory

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Joo-Eon Oh

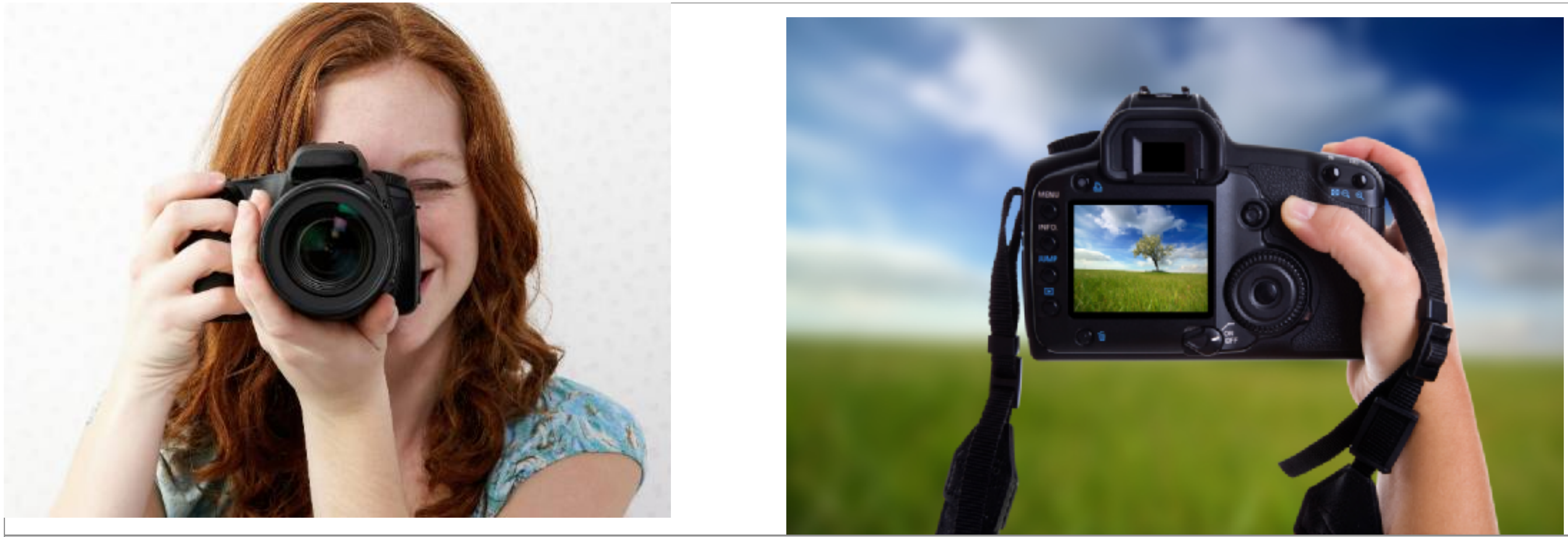
POSTECH

Imaging?

Image?


XPERIA
Sony Ericsson

Imaging in Daily Life



How to be a good photographer?

- Imaging by classical techniques

other than nonlinearity or non-classicality ?

Imaging

$$E(x)=A(x)\bullet e^{-\Delta\varphi}$$

Amplitude Phase

How to Image

Intensity

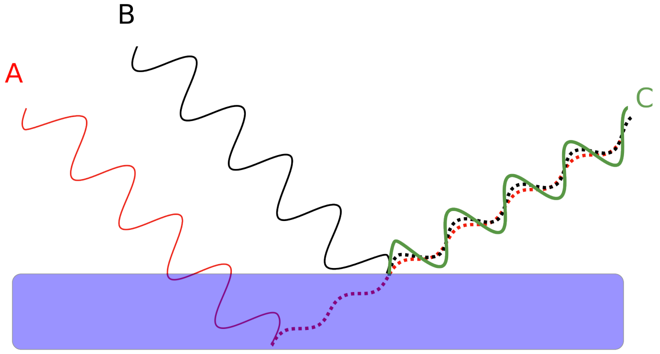
amplitude

$$E(x)=A(x)\bullet e^{-\Delta\varphi}$$

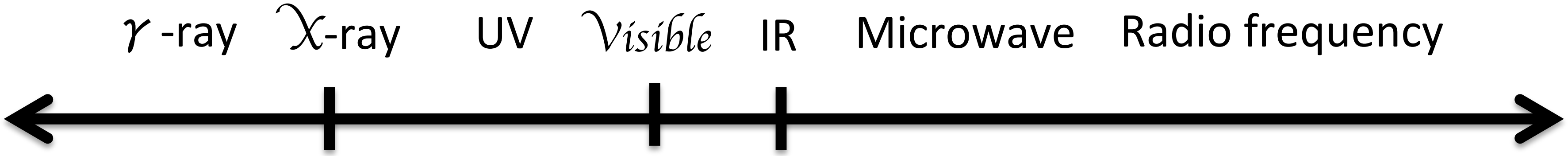
e. field

phase

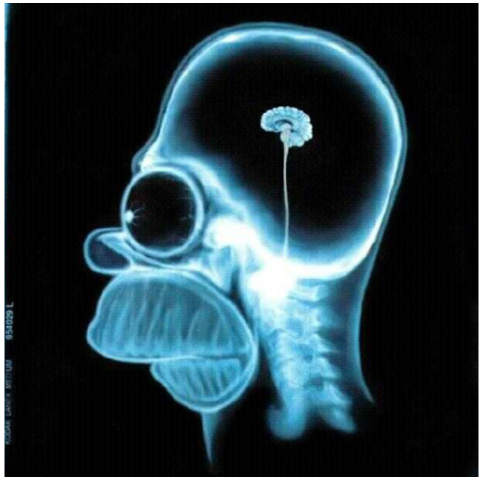
Interference

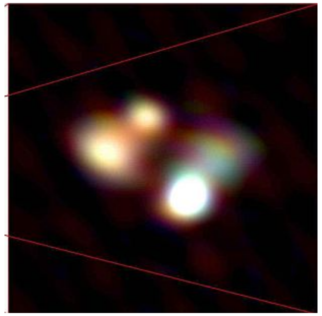


The Light

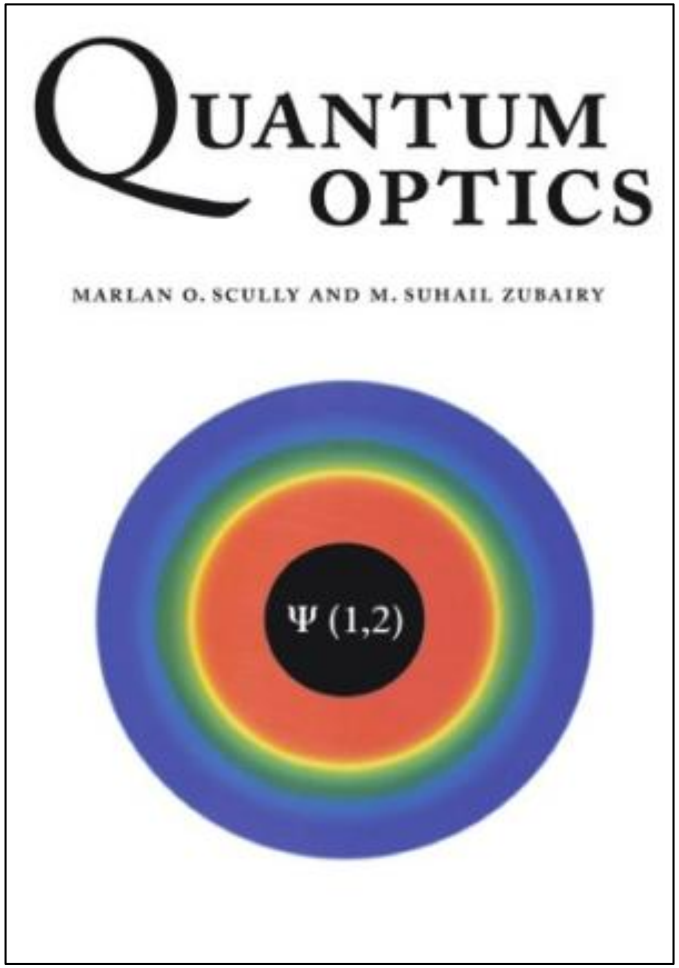


γ-ray X-ray UV Visible IR Microwave Radio frequency





The Lights in Quantum Optics

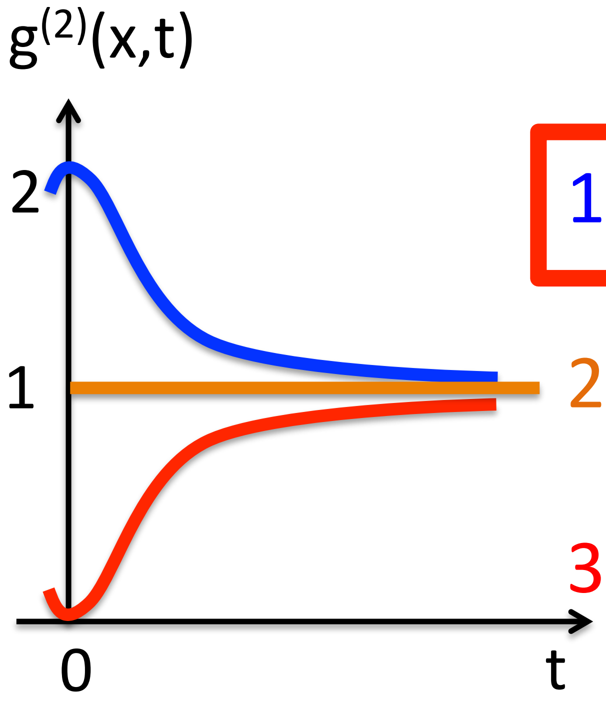


☐Non-classical light

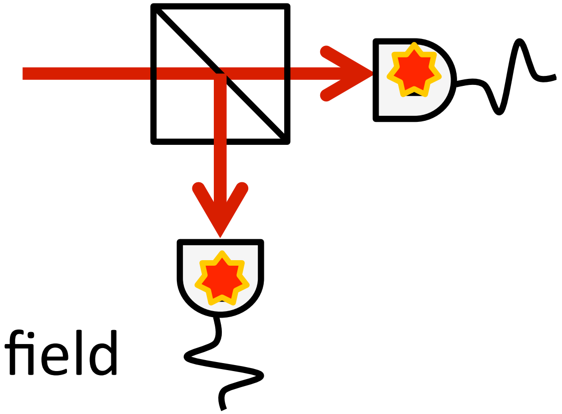
☐Coherent light

☐Incoherent light

The Lights in Quantum Optics



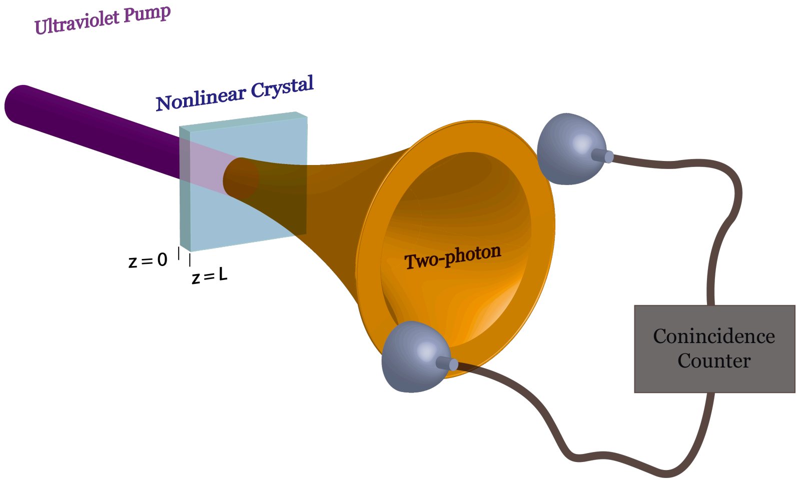
1. Incoherent Light (e.g. LED, sun light)
2. Coherent Light (e.g. the laser)
3. Non-classical Light (e.g. single photon)

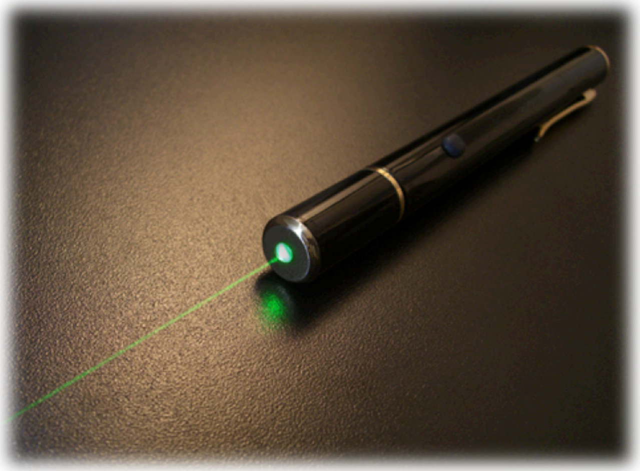


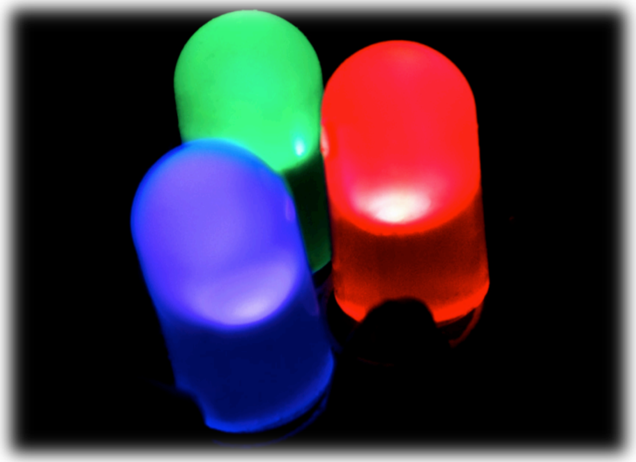
The Correlation Function

- $g^{(1)}(x,t)$; a coherent effect of the electromagnetic field
- $g^{(2)}(x,t)$; Classical statistical correlation of intensity fluctuation.

The Light


Ultraviolet Pump
Nonlinear Crystal
z = 0
z = L
Two-photon
Conincidence Counter





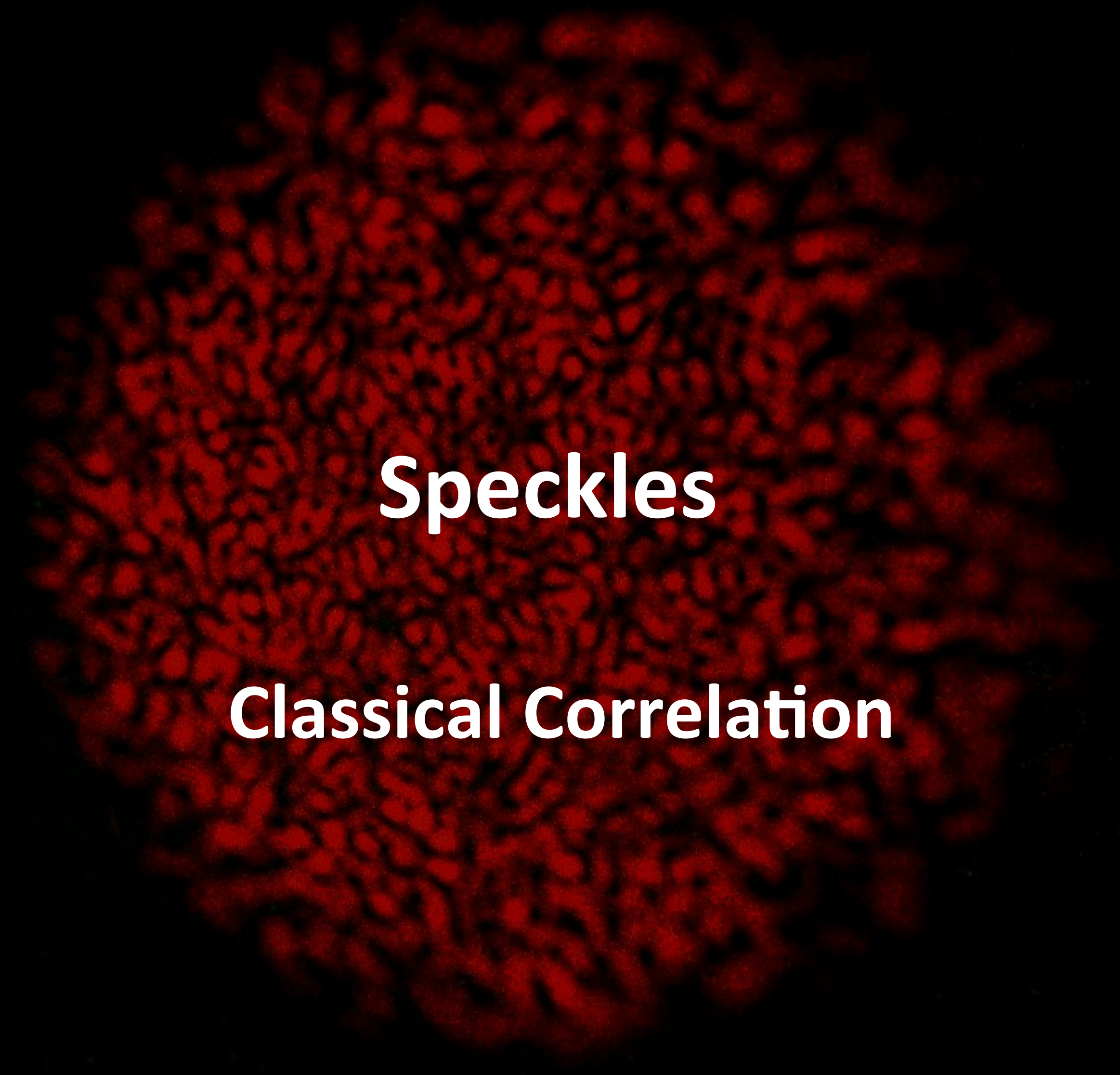
The Light

Non-classical
Light

Coherent
Light

Incoherent
Light

New Imaging Modality



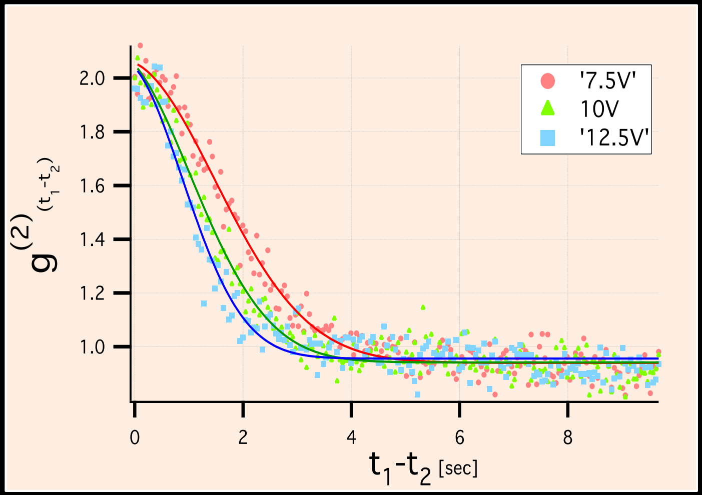
Speckles

Classical Correlation

Classical Correlation

Observe the statistical properties of photons

Temporal Correlation



- The Correlation Function $G^{(2)}$

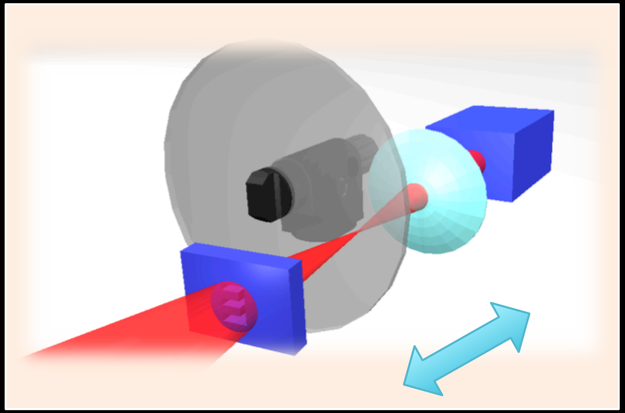
$G^{(2)}$; Statistical correlations of intensity fluctuations

$$G^{(2)}(x_1,t_1;x_2,t_2)=\left\langle E^*(x_1,t_1)E(x_1,t_1)E^*(x_2,t_2)E(x_2,t_2)\right\rangle$$
$$=\left\langle I(x_1,t_1)I(x_2,t_2)\right\rangle$$

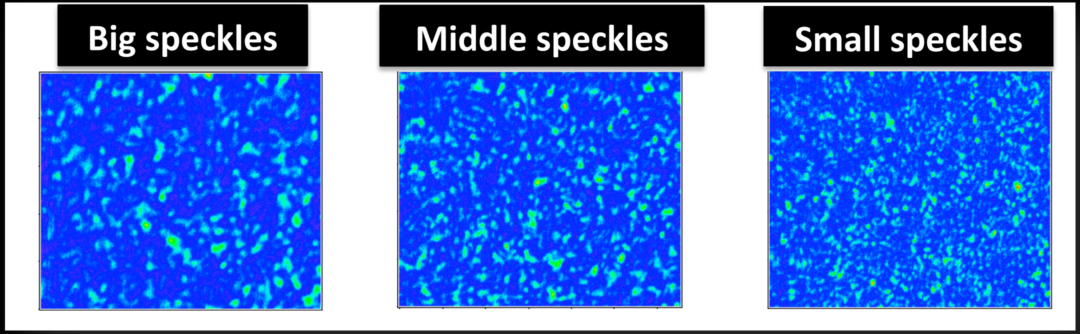
$g^{(2)}$; Normalized $G^{(2)}$

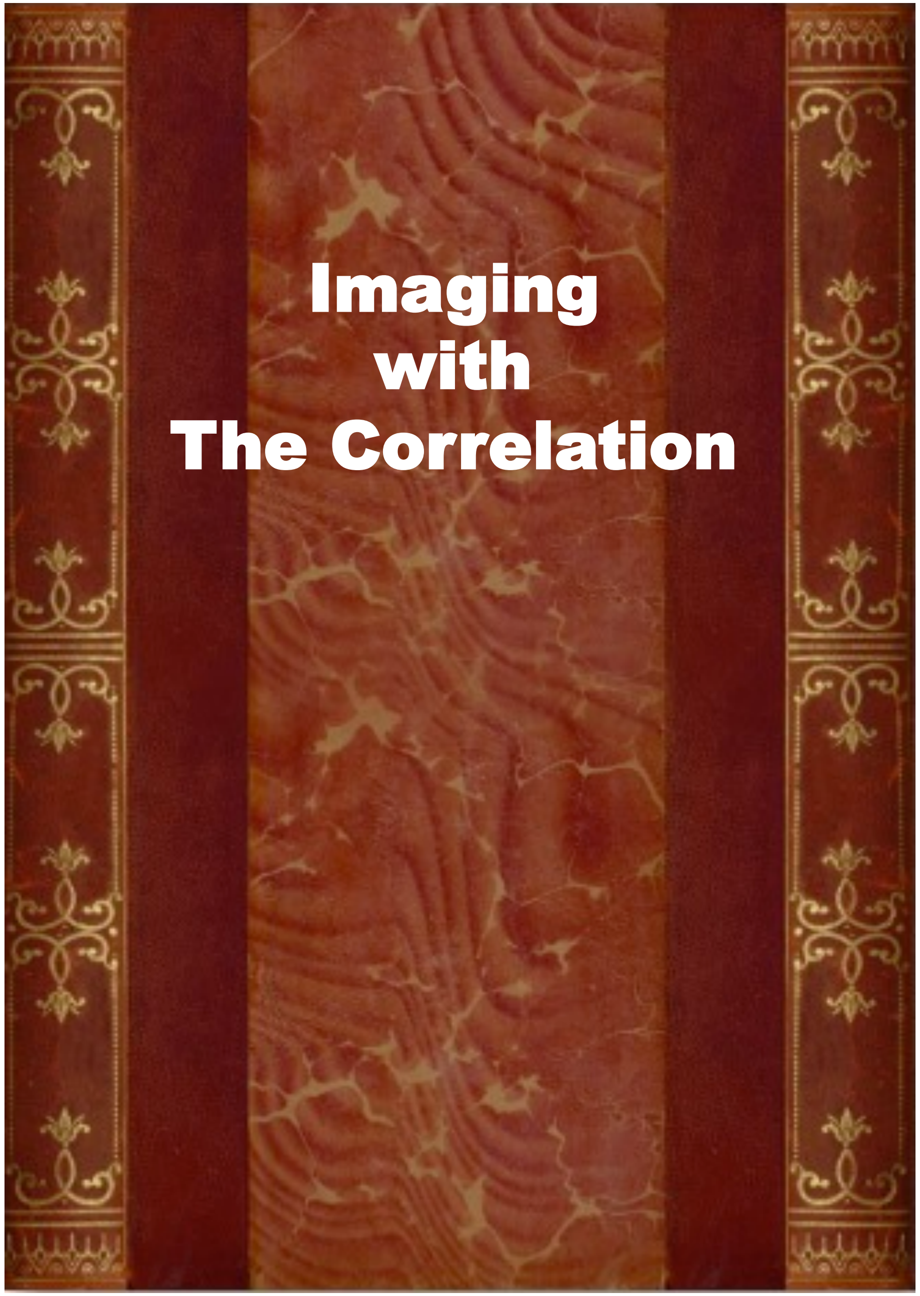
$$g^{(2)}(\tau)=\frac{<I(t)I(t+\tau)>}{<I(t)><I(t+\tau)>}$$

Spatial Correlation



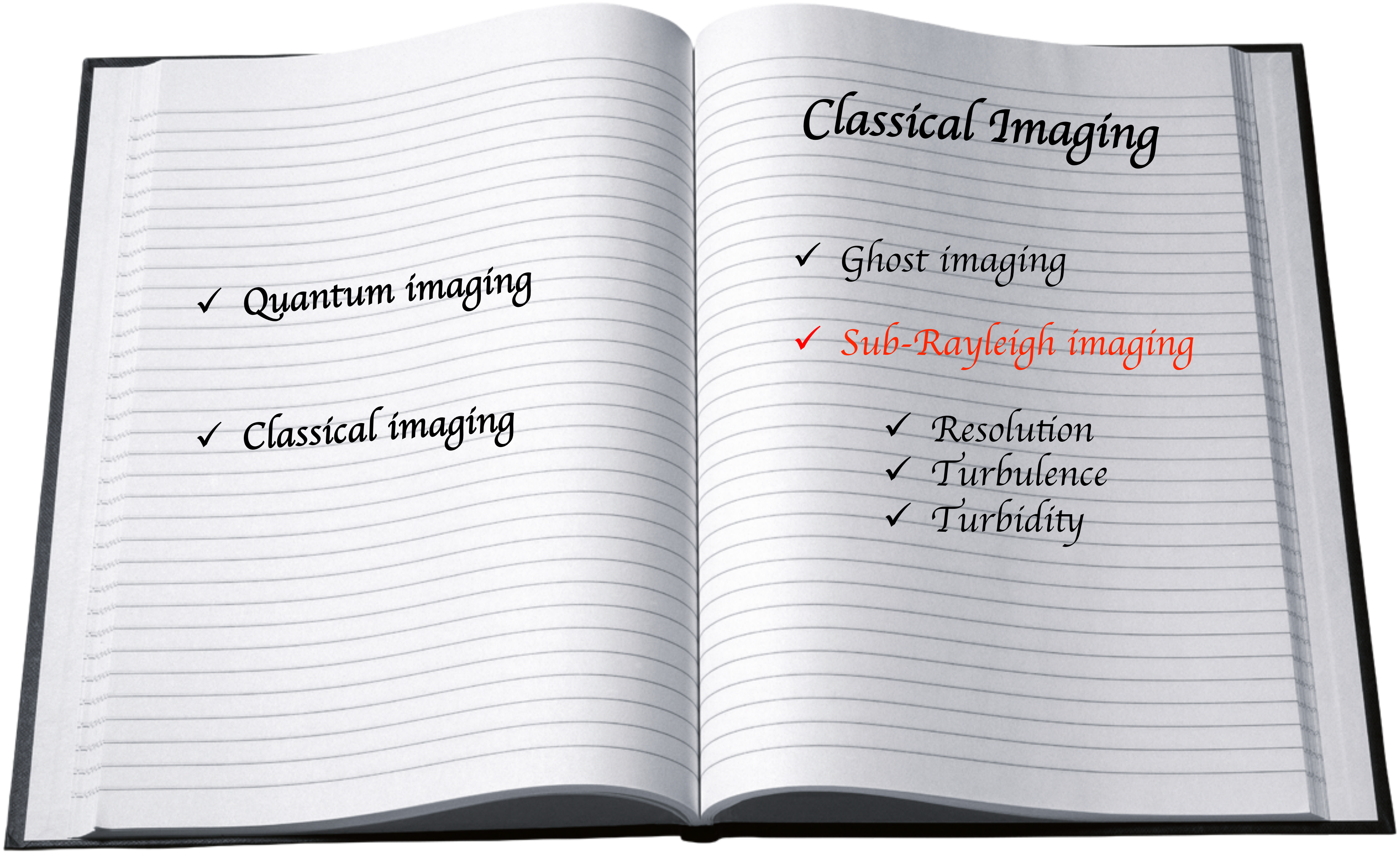
- Transverse coherence length





Imaging with The Correlation

Imaging with the Correlation



- ✓ Quantum imaging
- ✓ Classical imaging

Classical Imaging

- ✓ Ghost imaging
- ✓ Sub-Rayleigh imaging
  - ✓ Resolution
  - ✓ Turbulence
  - ✓ Turbidity

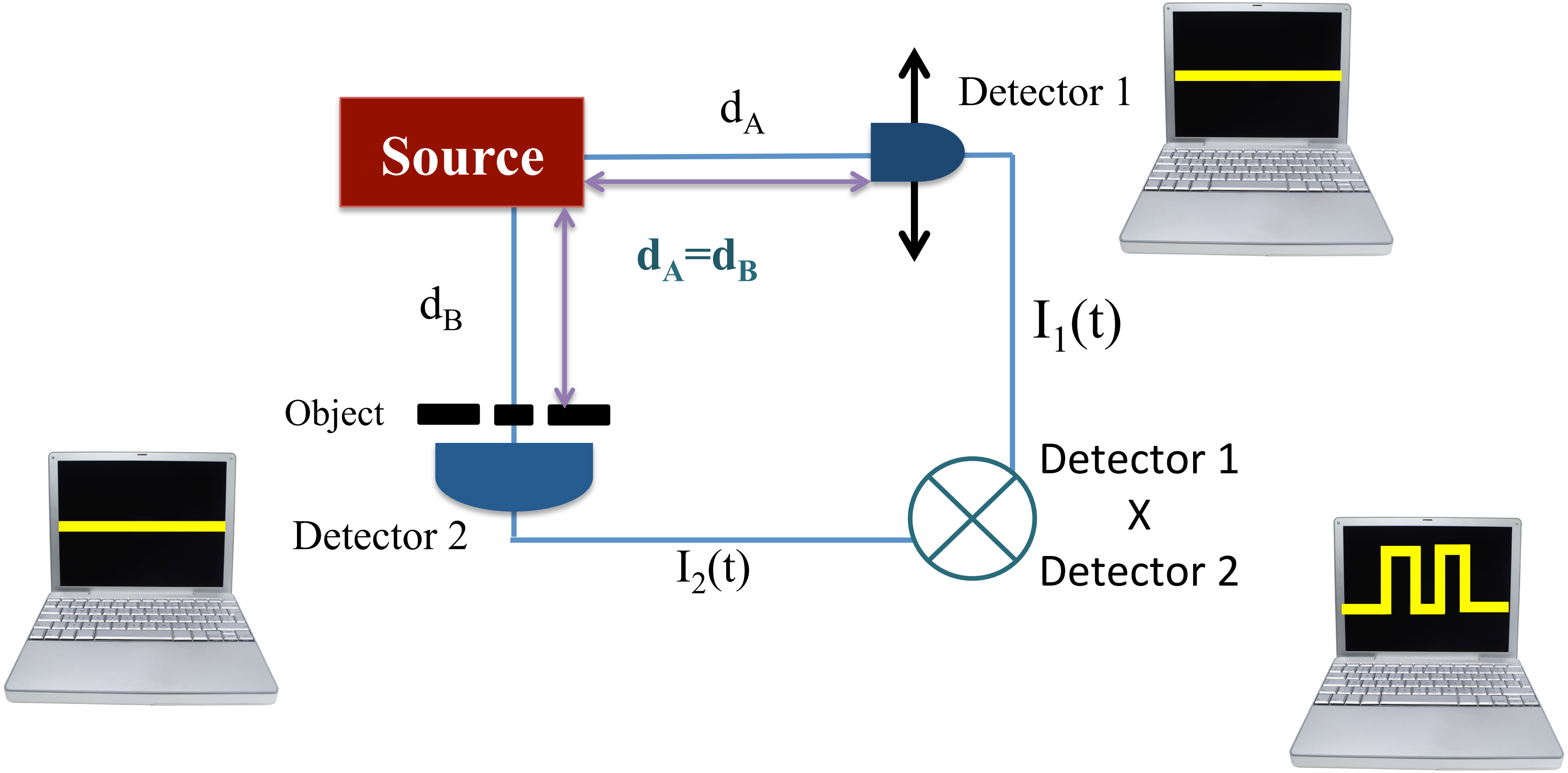
Ghost Imaging

THE CORRELATION IMAGING

Ghost Imaging principle

Ghost Imaging (GI)

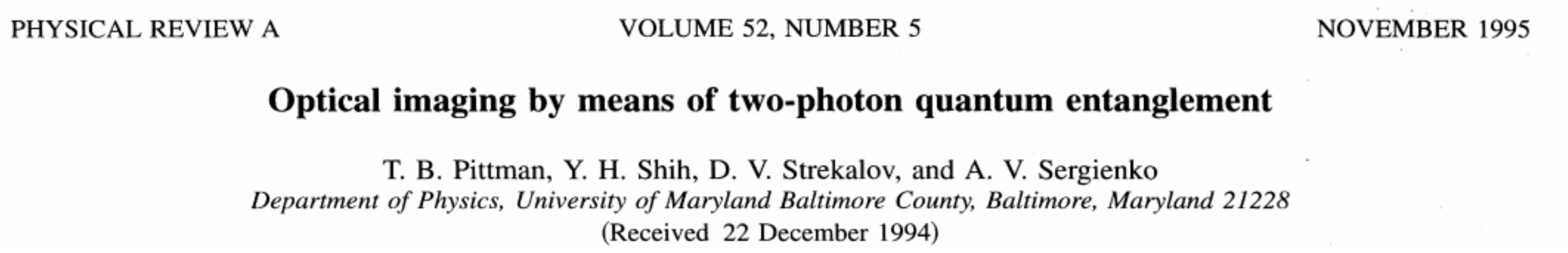
Reconstruct the ghost image from the correlation of two detector signals



SPDC Ghost Imaging

Pittman, PRA **52** R3429 (1995)

The Ghost Imaging is **a quantum effect** because of an entangled-state light source



PHYSICAL REVIEW A VOLUME 52, NUMBER 5 NOVEMBER 1995

Optical imaging by means of two-photon quantum entanglement

T. B. Pittman, Y. H. Shih, D. V. Strekalov, and A. V. Sergienko
Department of Physics, University of Maryland Baltimore County, Baltimore, Maryland 21228
(Received 22 December 1994)

…."The entanglement of this two-photon state can be used to demonstrate high-resolution imaging"…..

History of Ghost Imaging

The Ghost Imaging is **a quantum effect** because of an entangled source

No!
The Ghost Imaging do not rely on entanglement.

Thermal Light Ghost Imaging

Bennink, PRL **89** 113601(2002)

No!
The Ghost Imaging do not
rely on entanglement.


VOLUME 89, NUMBER 11 PHYSICAL REVIEW LETTERS 9 SEPTEMBER 2002

“Two-Photon” Coincidence Imaging with a Classical Source

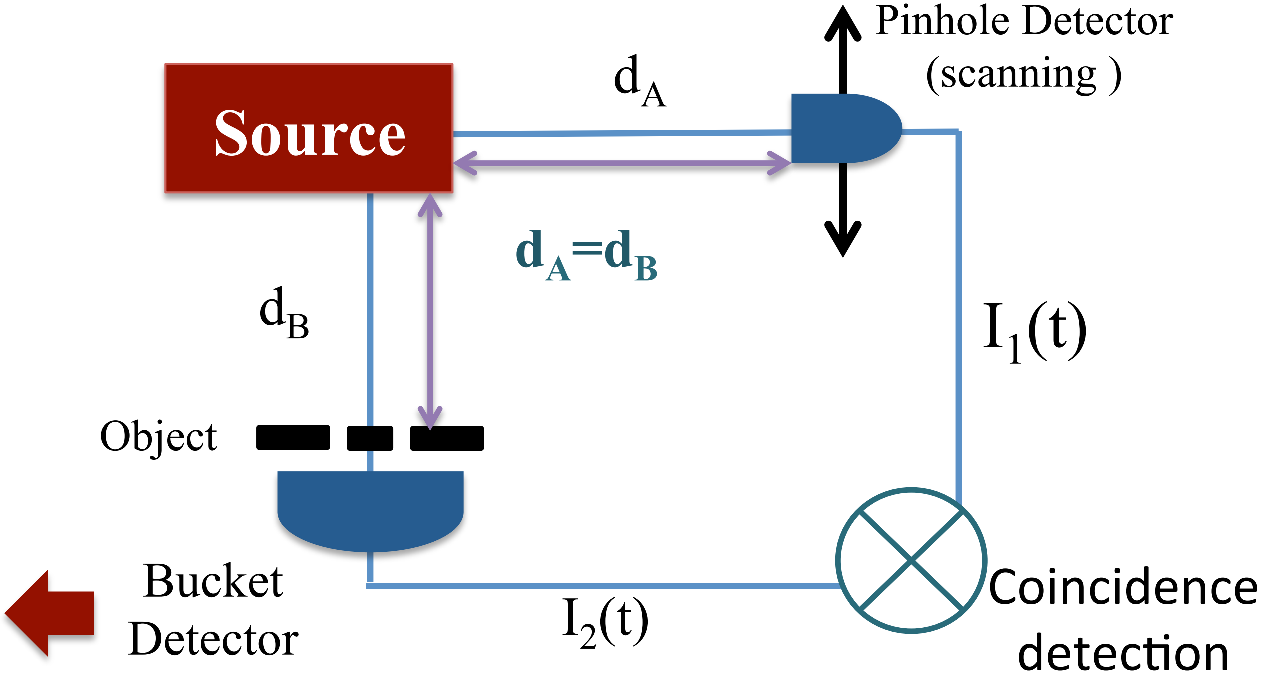
Ryan S. Bennink,* Sean J. Bentley, and Robert W. Boyd
The Institute of Optics, University of Rochester, Rochester, New York 14627
(Received 15 March 2002; published 26 August 2002)

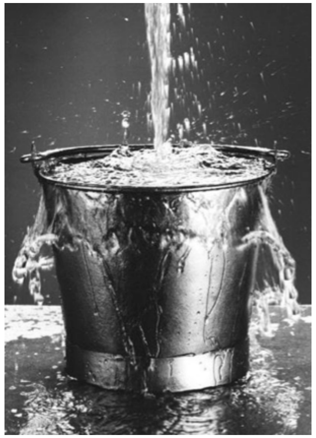
…”Ghost imaging technique could also be implemented using a classical source with the proper statistical properties. The entanglement is not necessary for this”….

Ghost Imaging principle

Ghost Imaging (GI)

Reconstruct the ghost image from the correlation of two detector signal

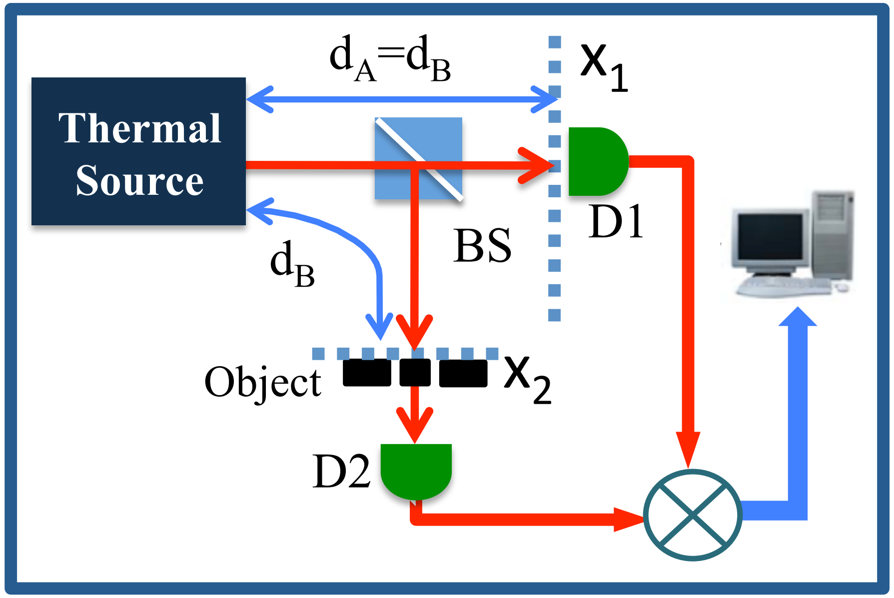




Detector : Bucket detector + single/multi-pixelized detector
(spatially non-resolving) (spatially resolving)

Correlation from Ghost Imaging

Second-Order Correlation Function of the Intensity



Transverse Coherence

$$G^{(2)}(|x_1 - x_2|, t) = < I_1(x_1, t) I_2(x_2, t) >$$

Second-order Correlation of the Intensity Fluctuation

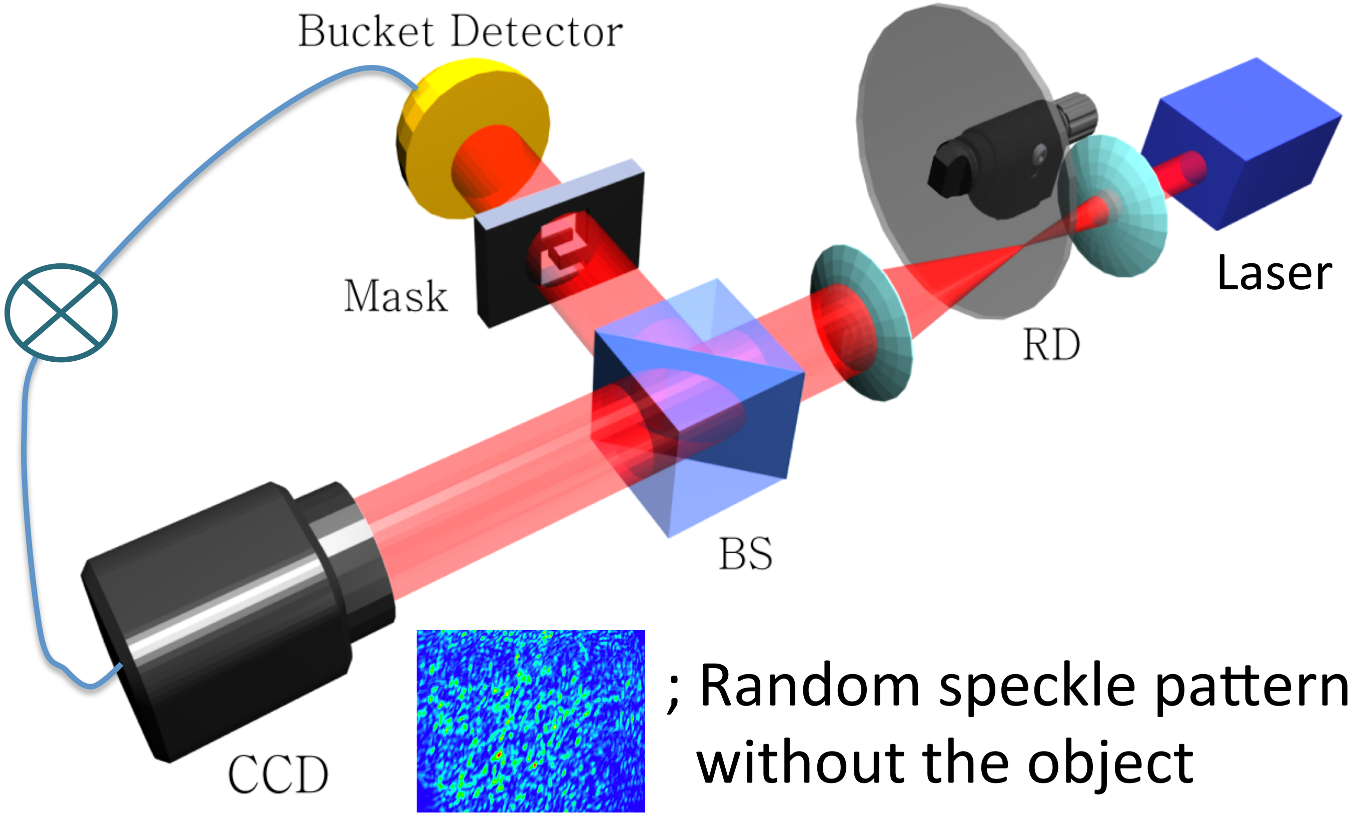
$$< \Delta I_1(x_1) \Delta I_2(x_2) > = < I_1(x_1) I_2(x_2) > - < I_1(x_1) > < I_2(x_2) >$$

Incoherent Light Ghost Imaging (GI)

Ghost images= Bucket signal X CCD

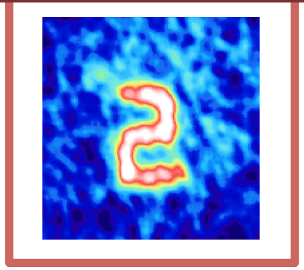
Constant

Random speckle patterns



; Random speckle patterns without the object

Ghost Image



Incoherent Light Ghost Imaging

- An incoherent light source is able to simulate one of the main features of entangled ghost imaging.
  - Bennink et al, Phys. Rev. Lett 89 113601 (2002)
  - Abouraddy, Phys. Rev. Lett. 87 123602 (2001)
  - Gatti, Phys. Rev. A 70 013802 (2004)

- Based on the 2nd-order spatial correlation $g^{(2)}$

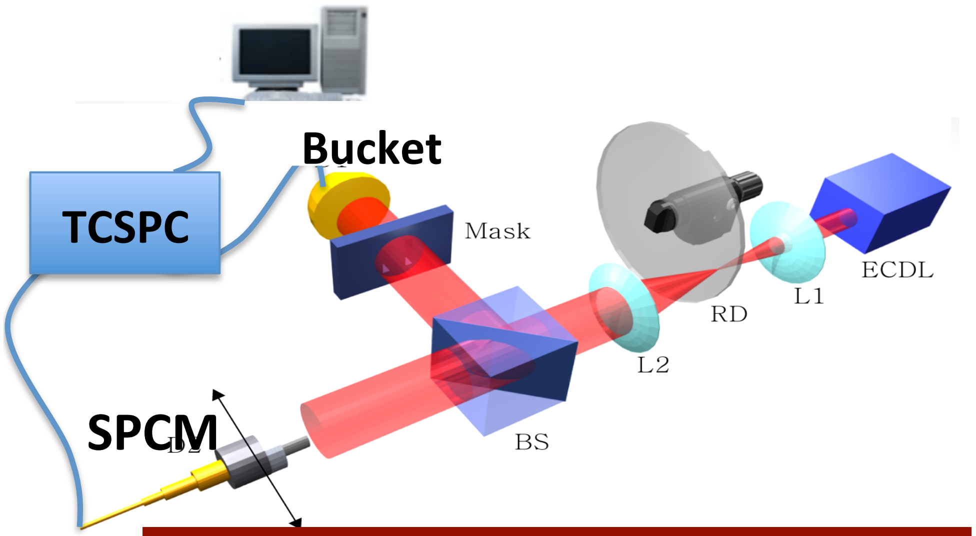
It's not surprising or new observation !

Hanbury Brown Twiss Experiment (HBT) [2]

- Measures the classical correlation of the intensity
- Applied in astronomy for measuring the angular size of stars

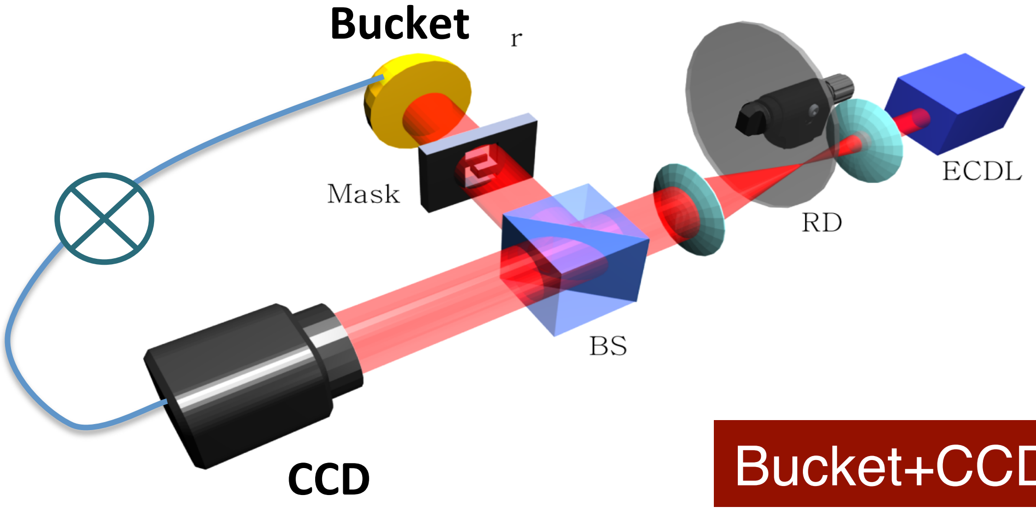
[2] Hanbury-Brown *et al.* [Nature **178** 1046 (1956)]

Detection of GI



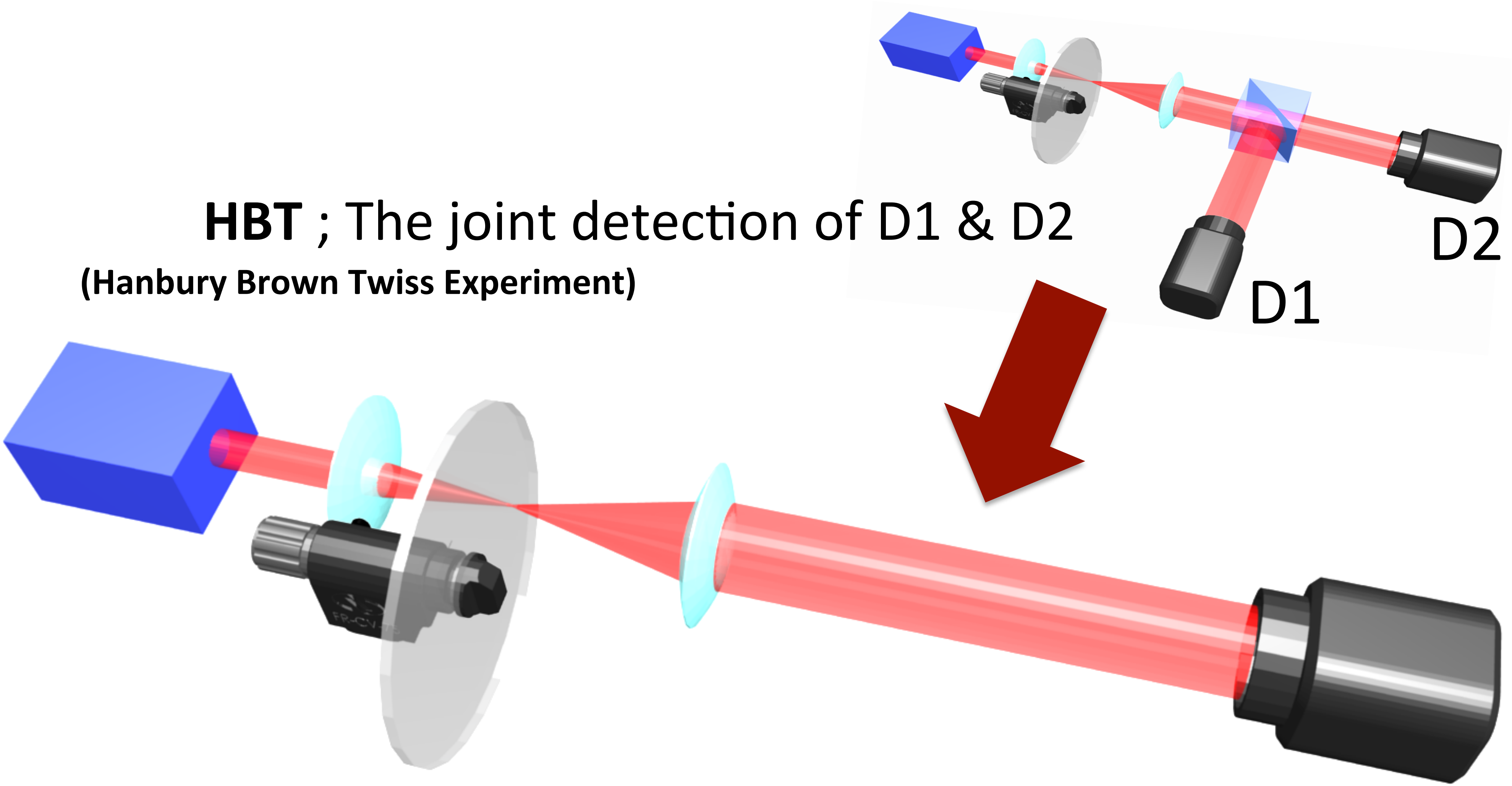
Bucket+Scanning point detector

$$\begin{aligned} < I_i(\vec{x}_i) > \quad & \sim < n_i(t) > (\mathit{photon\ number})\ ; \mathit{SPCM} \\ & \sim < i_i(t) > (\mathit{photocurrent})\ ; \mathit{PD}, \mathit{a\ pixel\ of\ CCD} \end{aligned}$$



Bucket+CCD

The Auto-correlation Measurement



HBT ; The joint detection of D1 & D2

(Hanbury Brown Twiss Experiment)

Our Experiment ; $G^{(2)}$ from the auto-correlation measurement

- Three problems are solved
in the experiment of correlation imaging.

The Fundamental Problems in Imaging

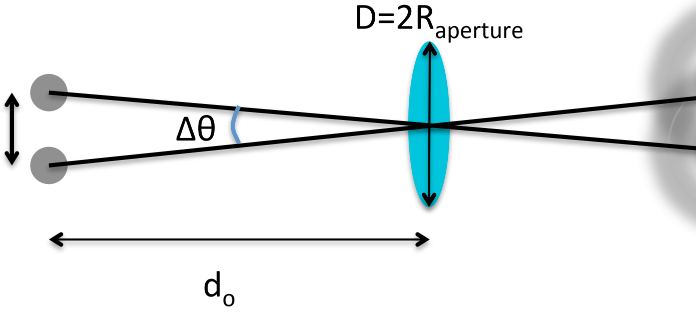
Resolution

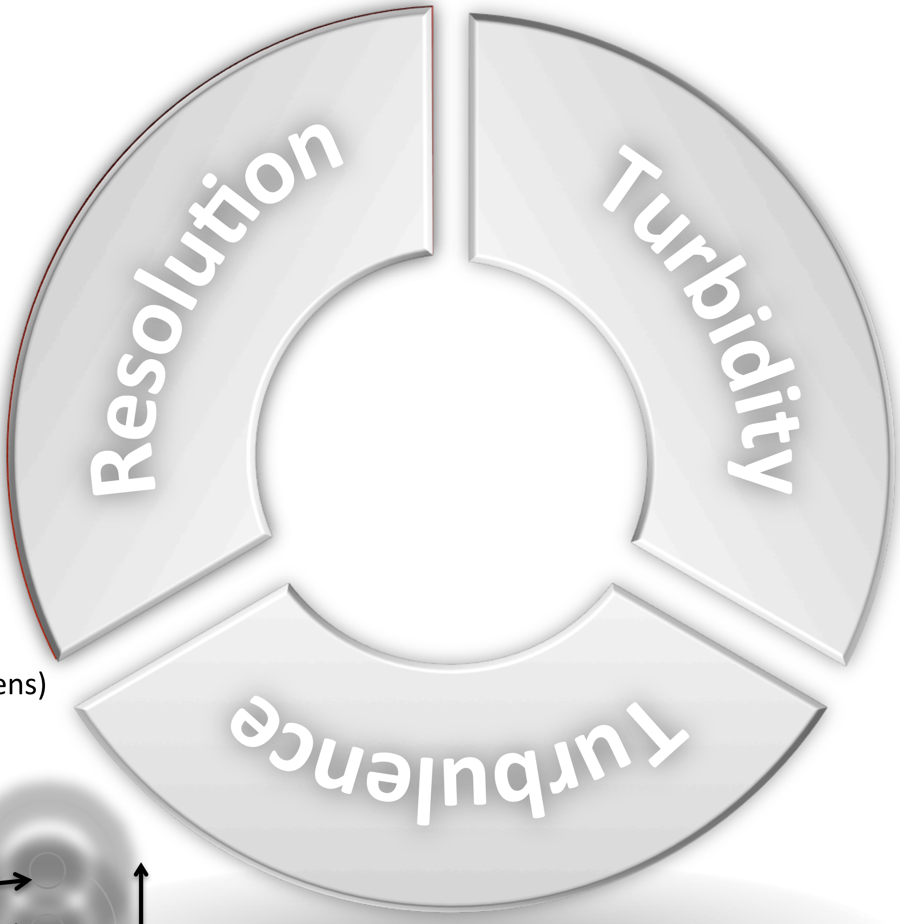
Classical: Rayleigh Limit

$$\Delta\theta = 1.22\frac{\lambda}{D}$$

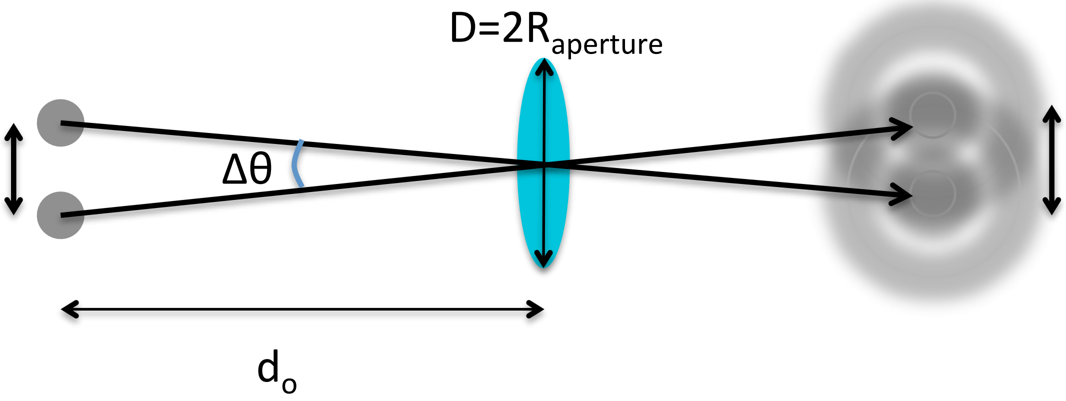
where

λ ; the wavelength of the source
d_o ; the distance from the source to the aperture(lens)
D ; the diameter of the aperture(lens)




Resolution
Turbidity
Turbulence

The Rayleigh Limit



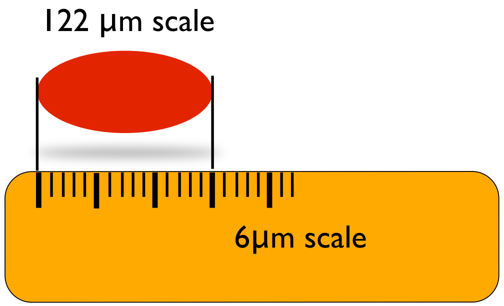
Angular Resolution

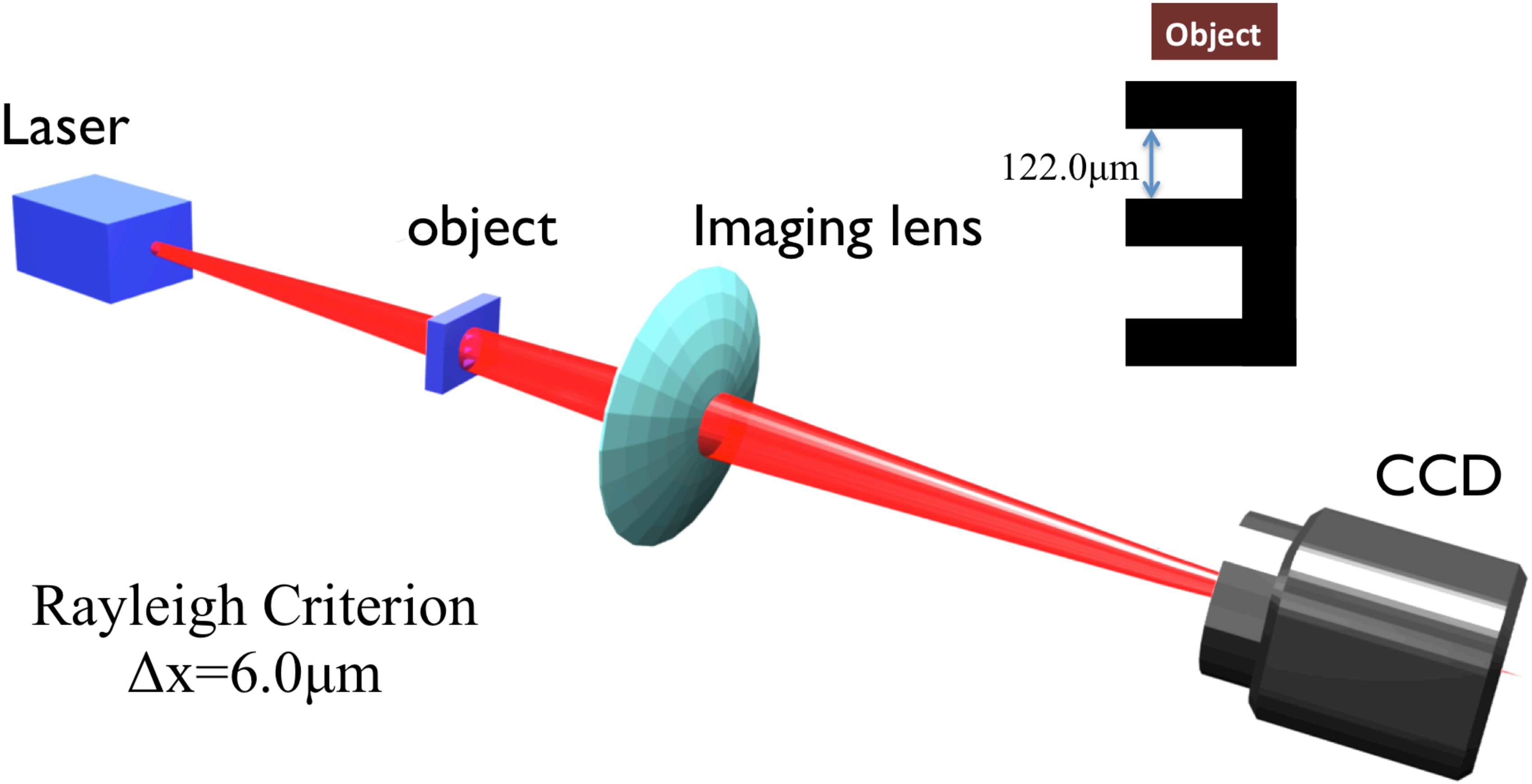
$$\Delta\theta = 1.22\frac{\lambda}{D}$$

Minimum Resolvable Length

$$\Delta x = 0.61\frac{\lambda \cdot d_o}{R_{aperture}} \cdot M$$

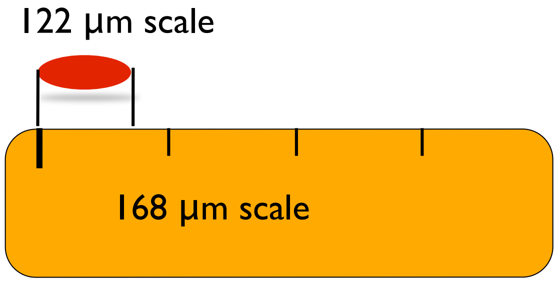
where λ ; the wavelength of the source
d$_o$; the distance from the source to the aperture(lens)
D ; the diameter of the aperture(lens)

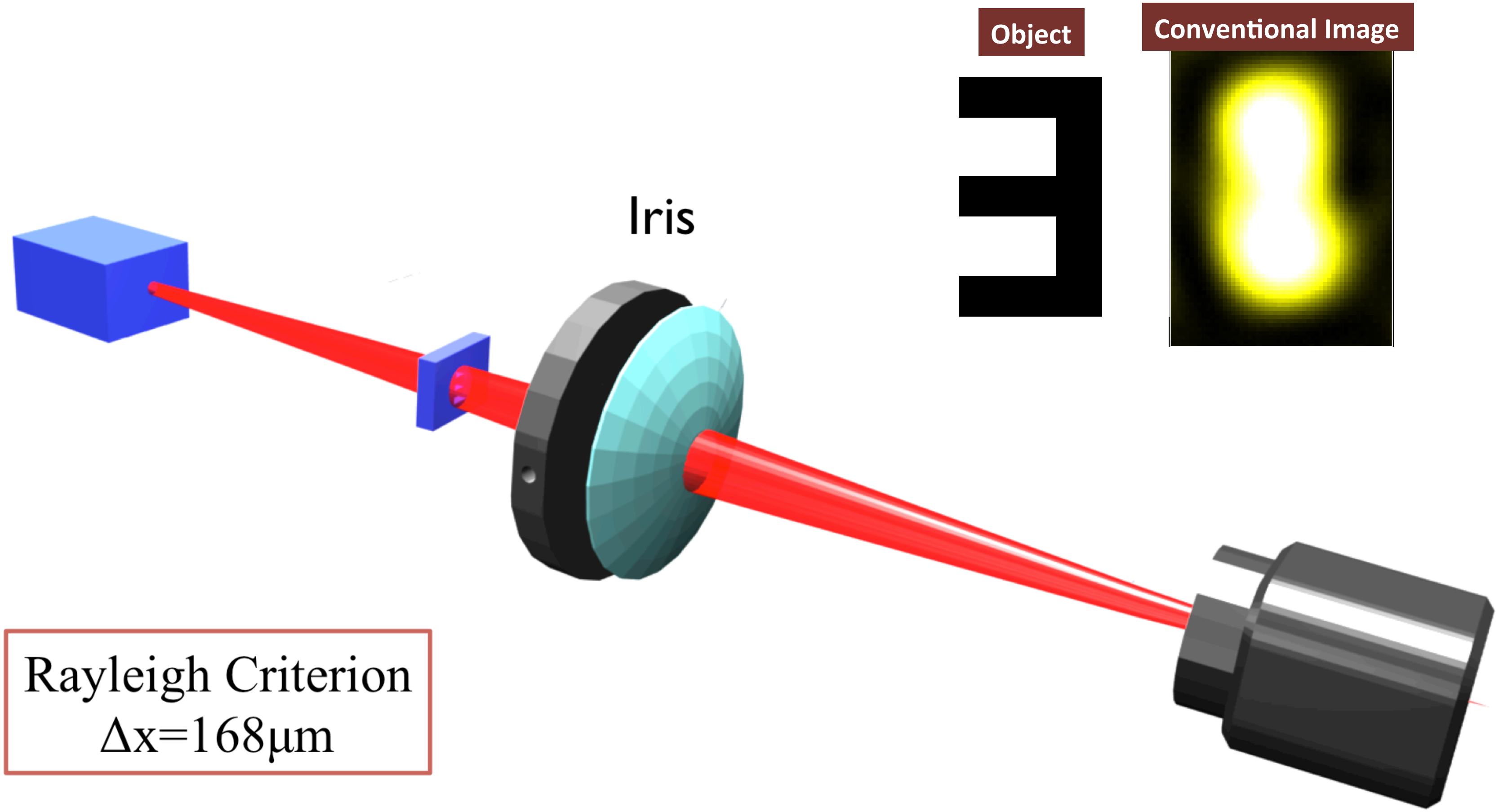




Rayleigh Criterion

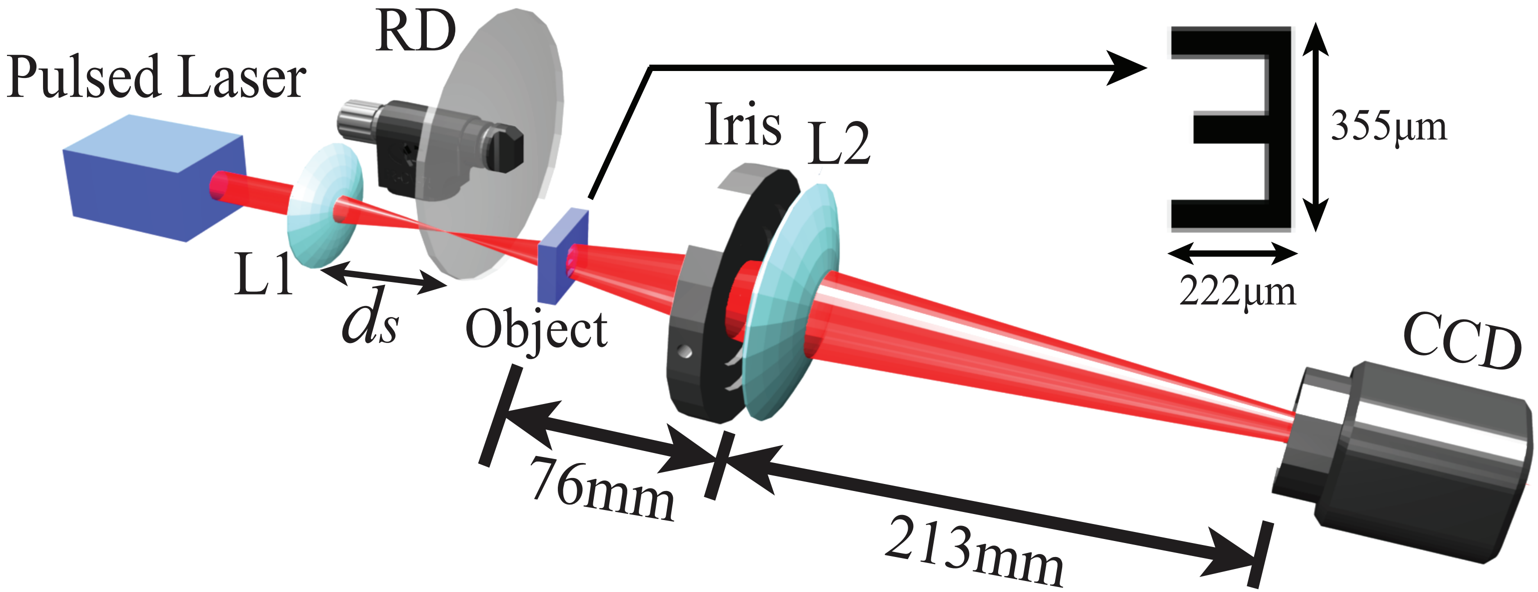
$\Delta x = 6.0\mu m$

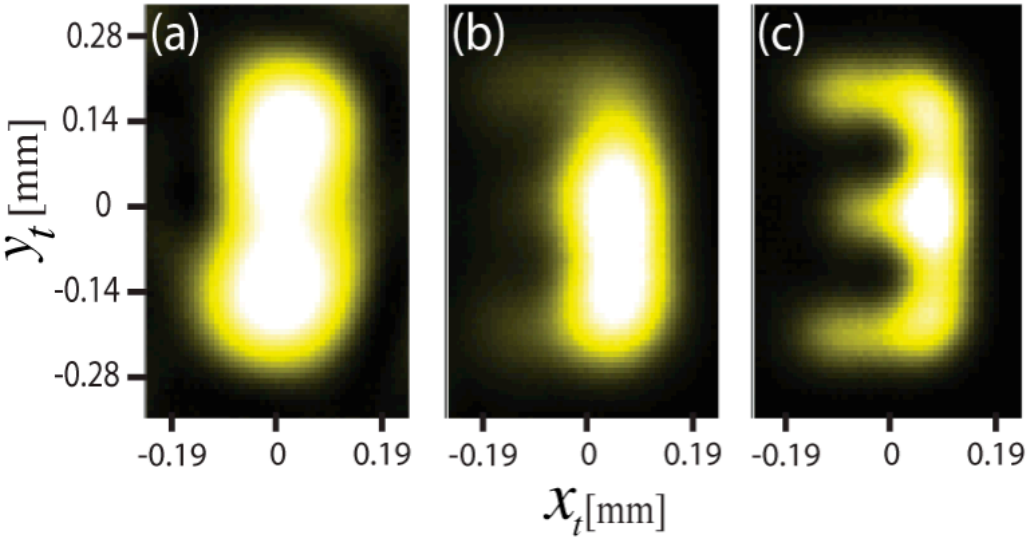




Rayleigh Criterion
Δx=168μm

[J.-E. Oh *et al.*, Opt. Lett. **38** 682 (2013)]

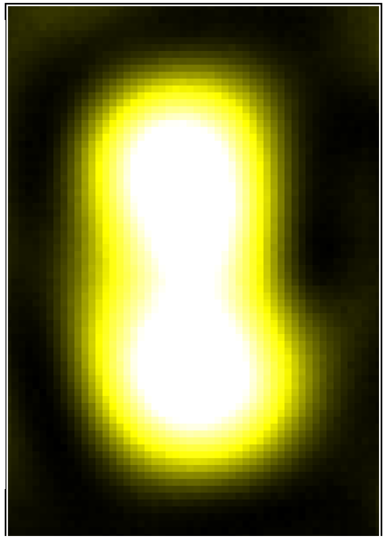




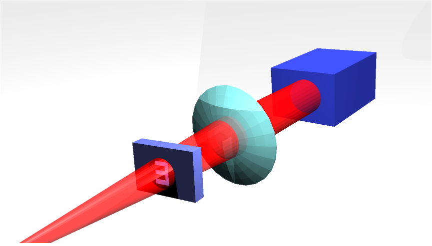
(a) Conventional imaging.
(b) Speckle illumination with big speckles
(c) Speckle illumination using small speckles

Sub-Rayleigh Imaging via Speckle Illumination

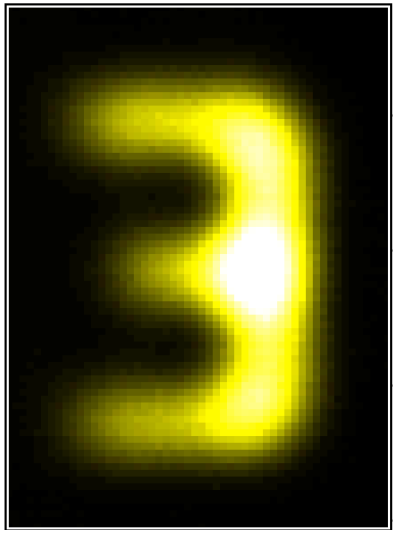
Intensity images



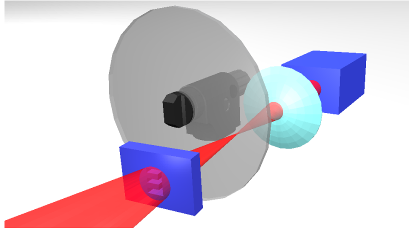
Coherent Illumination



Correlation images



Speckle Illumination



- What happened in the Correlation imaging with the turbidity or turbulence?

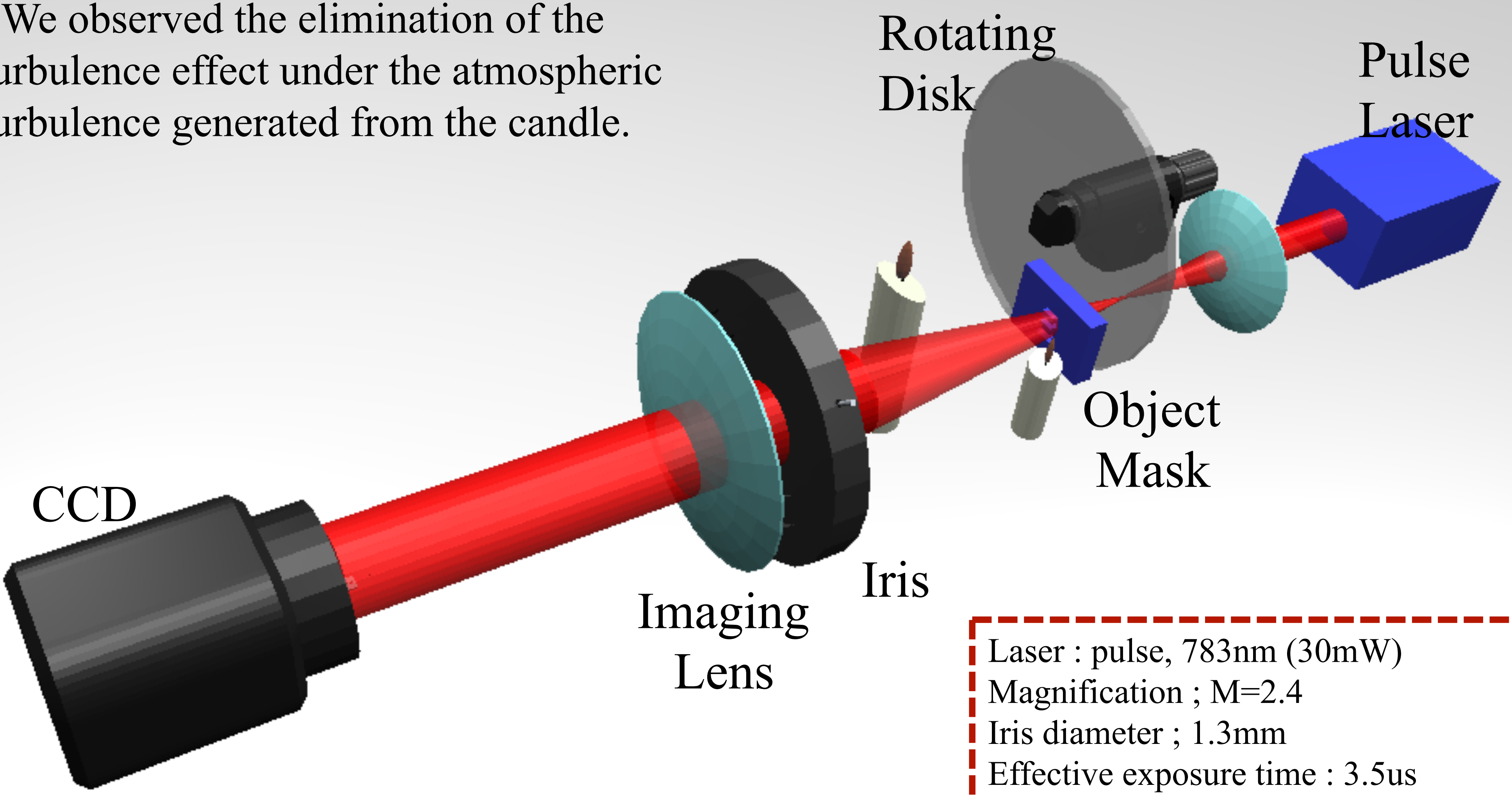
The Fundamental Problems in Imaging

Turbulence

Turbulence Coefficeint (C_n)

Experimental Setup I

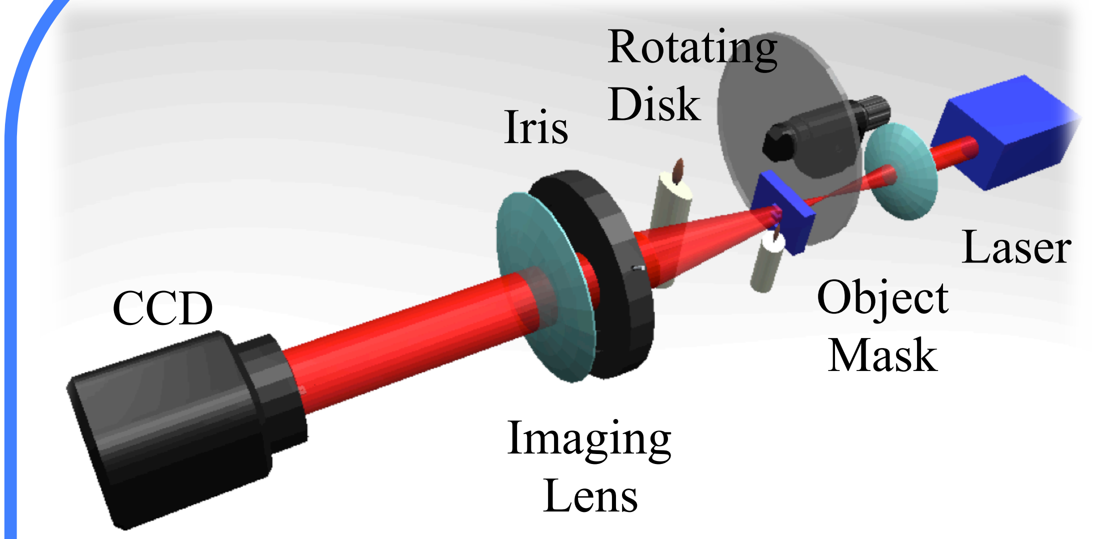
The test with the candles
: We observed the elimination of the turbulence effect under the atmospheric turbulence generated from the candle.



Laser : pulse, 783nm (30mW)
Magnification ; M=2.4
Iris diameter ; 1.3mm
Effective exposure time : 3.5us
Rayleigh limit ; 118.2um

Classical Correlation

[J.-E. Oh *et al.*, *in preparation*]

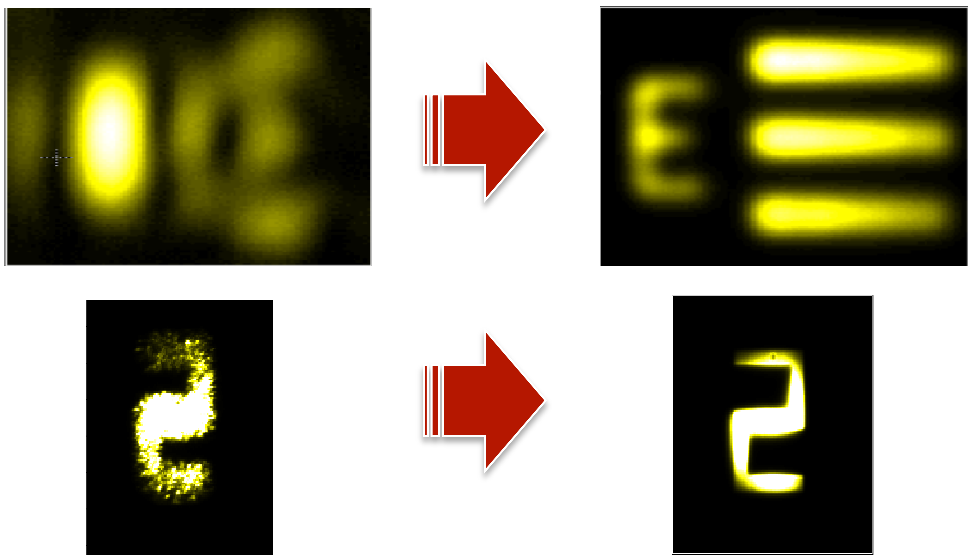


Imaging thru the Turbulence

Intensity images | **Correlation images**

Single-lens system

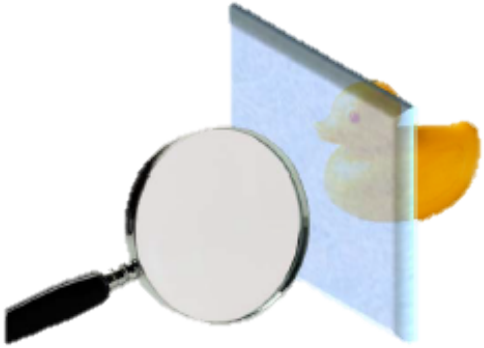
4f-imaging system



The Fundamental Problems in Imaging

Turbidity

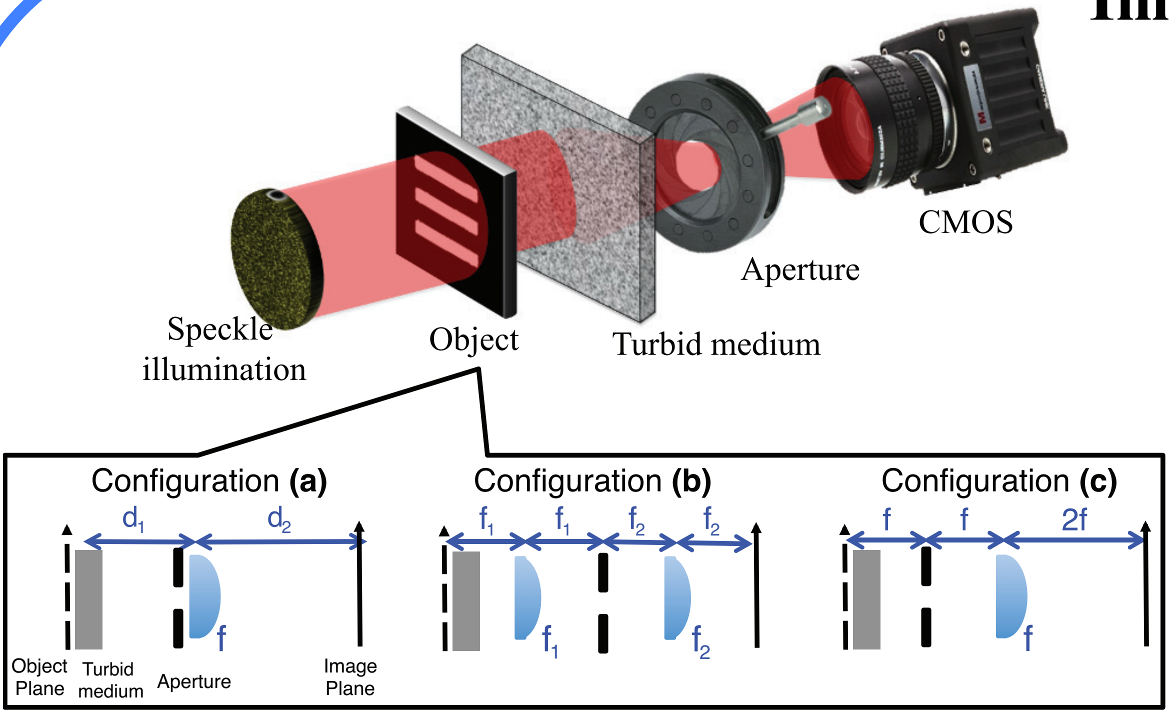
Scattering Coefficeint (μ_s)
Mean free path ($l_S=1/\mu_s$)



Classical Correlation

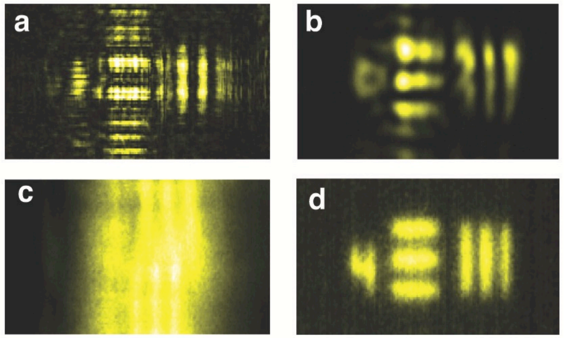
[J.-E. Oh *et al.*, *in preparation*]

Imaging thru the Turbidity

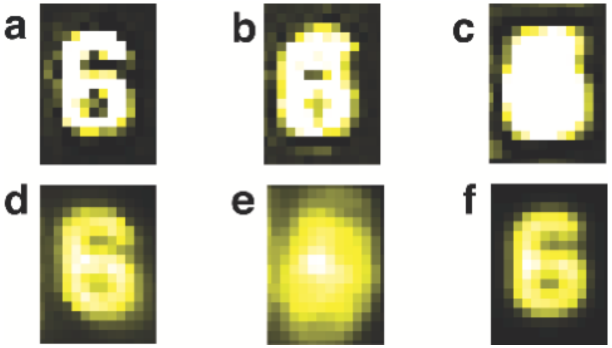


The diluted intralipid solution

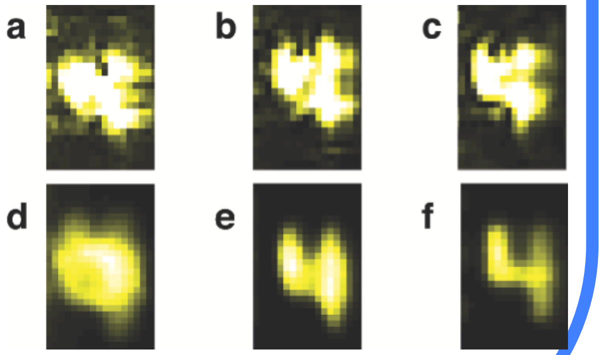
I. Single-lens imaging system



II. 4f imaging system



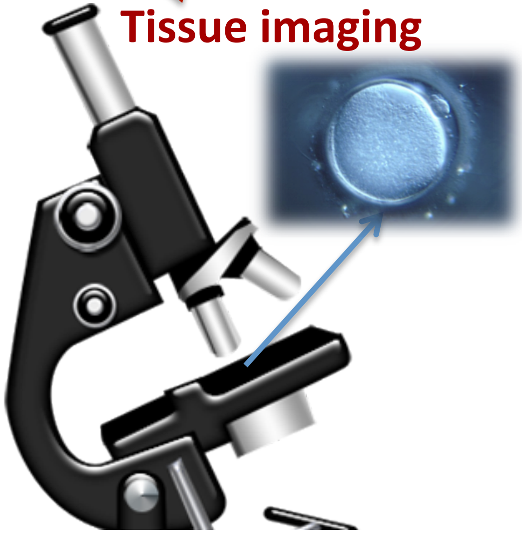
II. 2f-2f imaging system



Future Applications

Atmostpheric turbulence

Tissue imaging



Resolution improvement

Thank You!