# Quantum Imaging: Q-OCT

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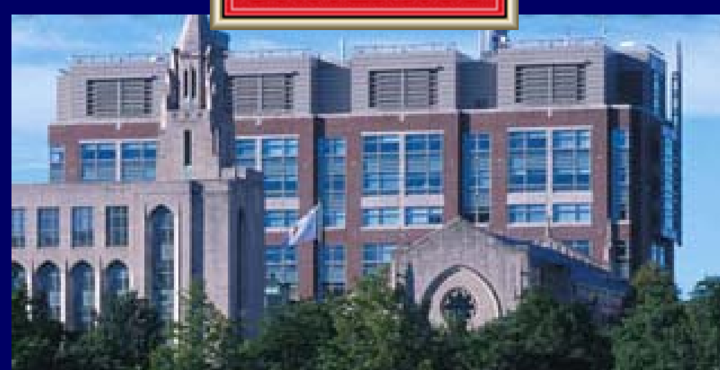

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are needed to see this picture.

# Outline

1. Quantum Imaging
2. Two-Photon Imaging
3. Quantum OCT

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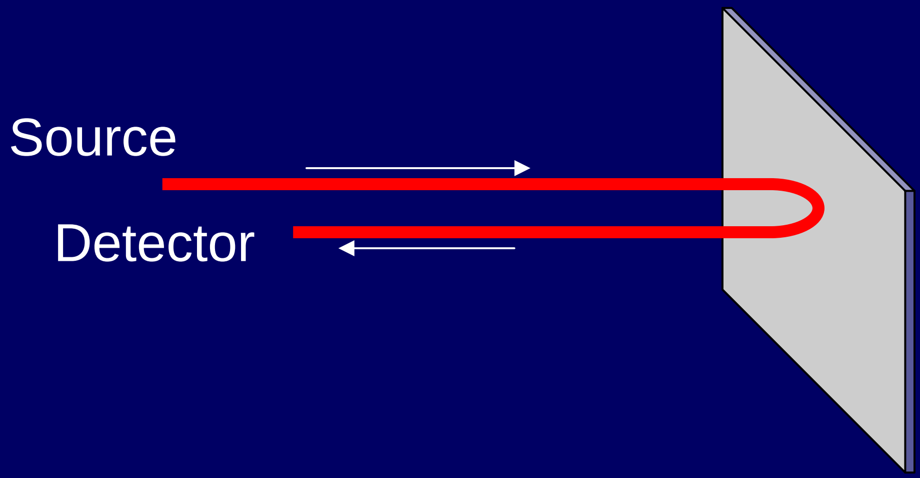
# Optical Imaging

= Estimation of the spatial distribution (2D, 3D, 4D) of a physical object by use of optical measurement (direct or interferometric)




Reflectance $R(x,y)$

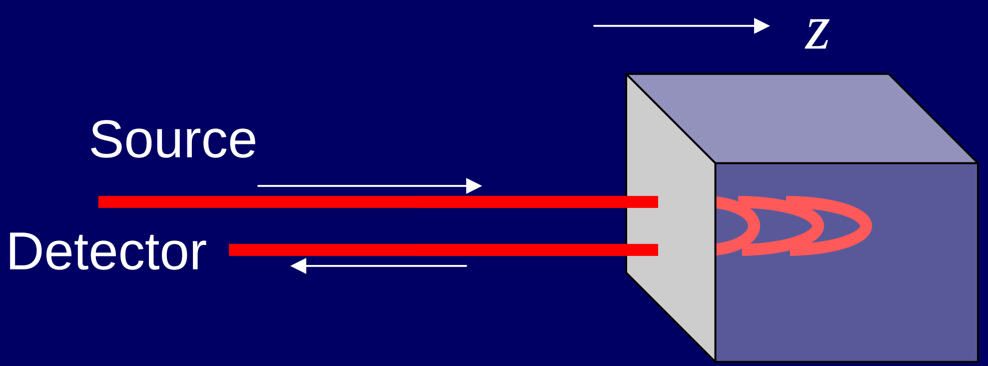
**Conventional Imaging**
**Metrology**

or $R(x,y,\lambda\ )$

**Spectral or**
**Hyperspectral Imaging**

or Jones matrix $\mathrm{J(x,y)}$

**Polarization-sensitive**
**Imaging (Ellipsometry)**




or $R(z)$ **Ranging**

**Axial imaging**

or $\alpha(x,y,z)$

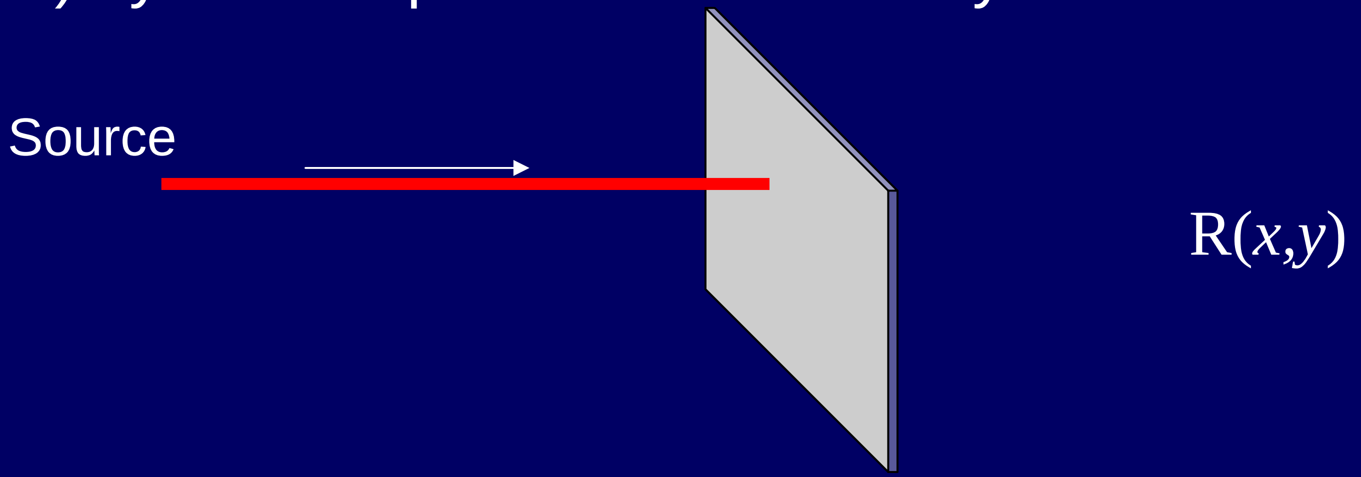
**3D Imaging**

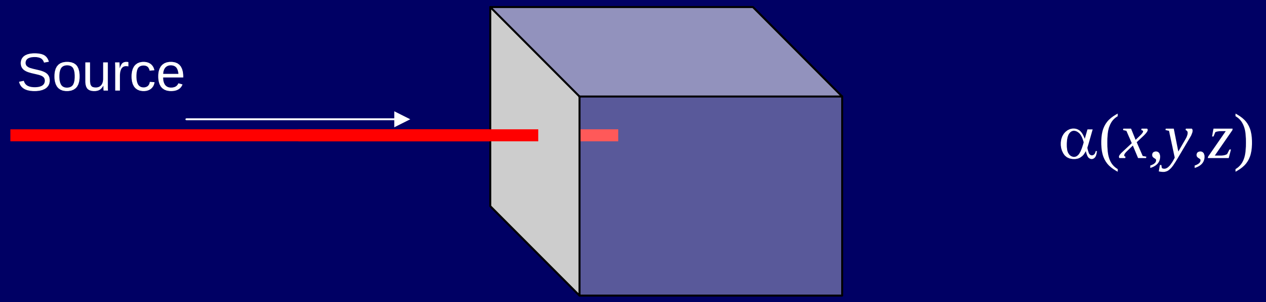
**Subsurface imaging**

Imaging may involve spatial, spectral, and/or polarization effects

# Optical Lithography

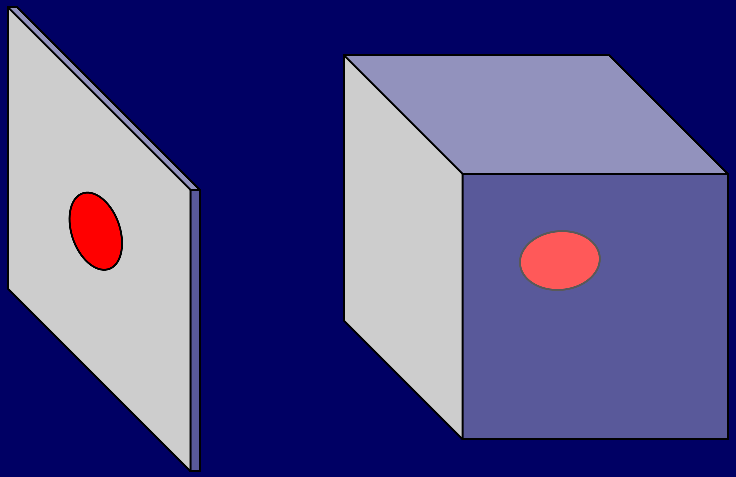
= Fabrication of objects with specified spatial distributions (2D, 3D) by use of optical sources and systems



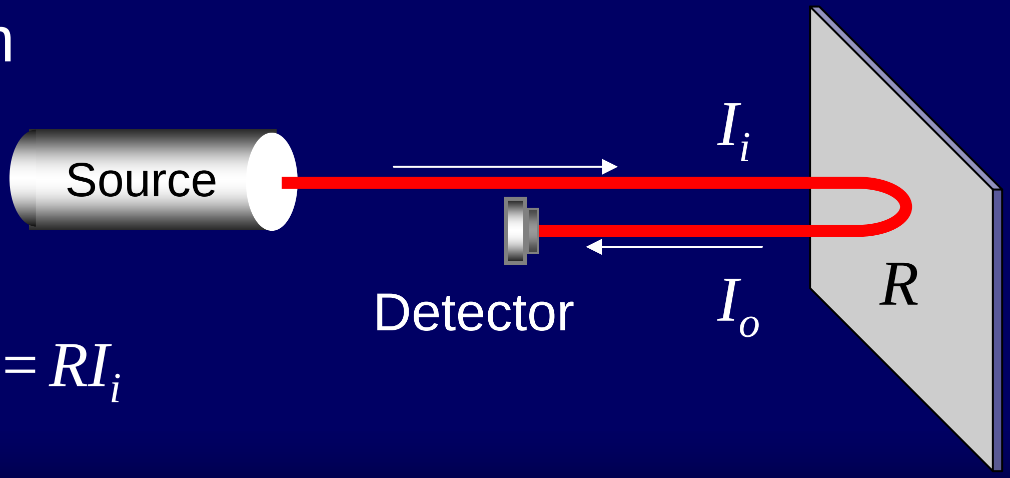
# Limitations of Optical Imaging & Lithography

- Resolution (transverse & axial)



- Noise —— Classical

  Quantum




$$I_o = RI_i$$

# Quantum Imaging

= Estimation of the spatial distribution of a physical object by use of light field in a nonclassical state & direct or Interferometric measurement

# Quantum Lithography

= Fabrication of objects with specified spatial distribution by use of light field in a nonclassical state

# States of Light

Coherent (laser imaging)

Thermal (conventional, photon-correlation imaging)

...

## Nonclassical States

Quadrature-Squeezed

Photon-Number Squeezed

Two-Photon

Gaussian

NOON ...

Saleh et al. PRA 2000

Saleh et al. PRL 2005

PRL **94,** 223601 (2005) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2005

**Wolf Equations for Two-Photon Light**

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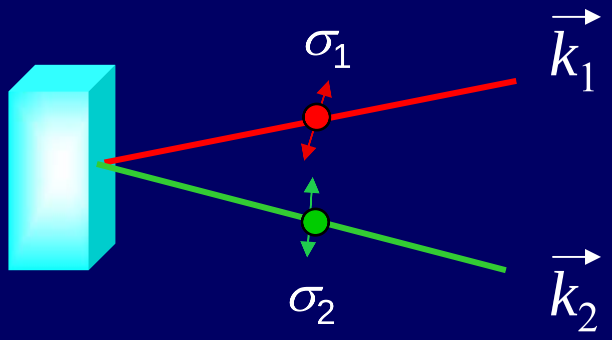
# Two-Photon light




= a state of exactly two photons in multimodes (spatial/spectral/polarization)

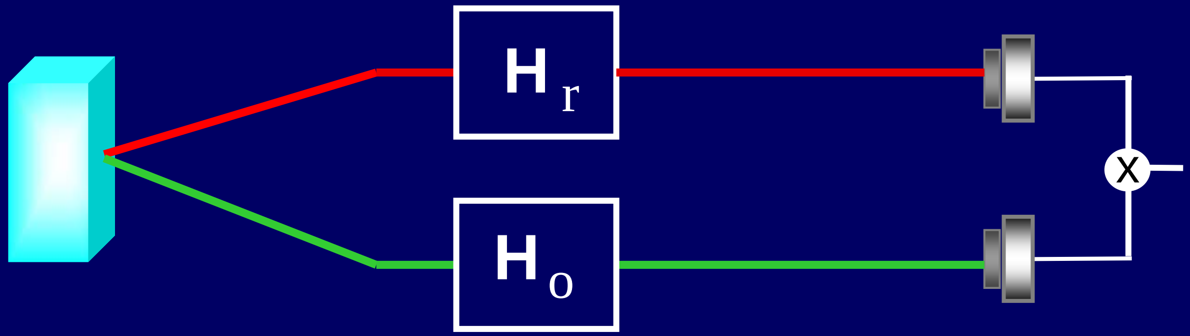
$$|\Psi\rangle = \sum_{\sigma_1}\sum_{\sigma_2} \iint dq_1 dq_2 \iint d\omega_1 d\omega_2 \; \underbrace{\varphi(q_1,\omega_1,\sigma_1;\, q_2,\omega_2,\sigma_2)}_{\text{non-separable function} \,\equiv\, \text{entangled state}} \left|1_{q_1,\omega_1,\sigma_1}, 1_{q_2,\omega_2,\sigma_2}\right\rangle$$

non-separable function ≡ entangled state

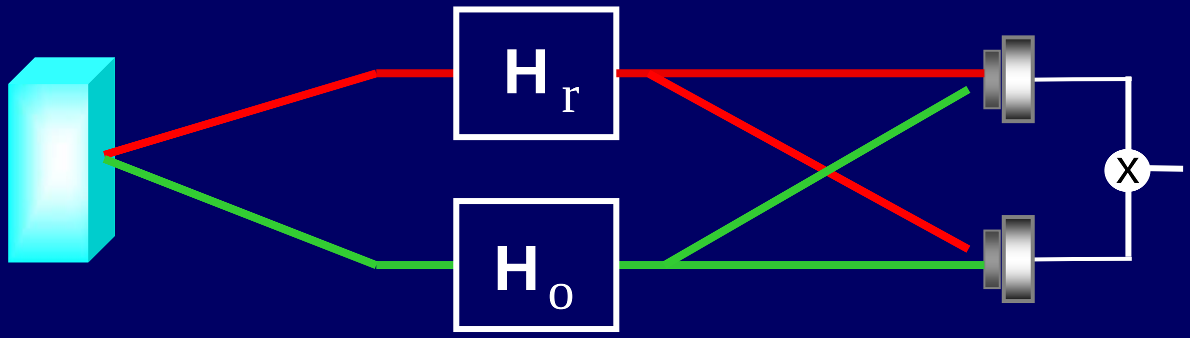
Entanglement: Spatial (momentum)
Spectral
Polarization

# Two Configurations

A. Direct

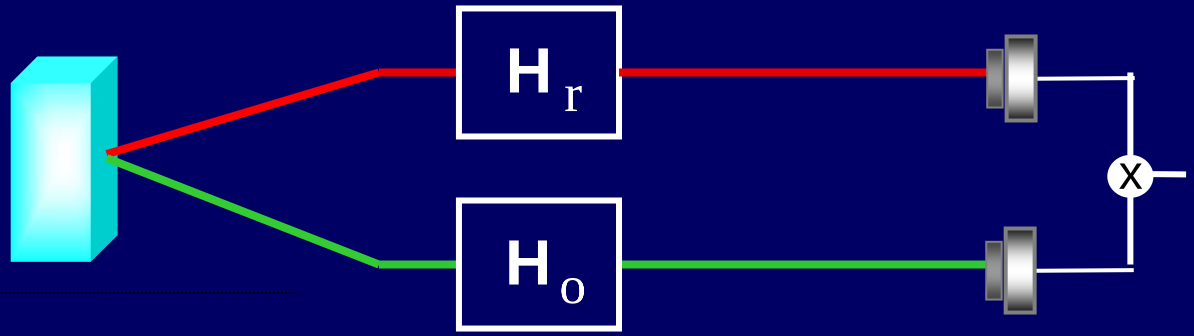



B. Interferometric



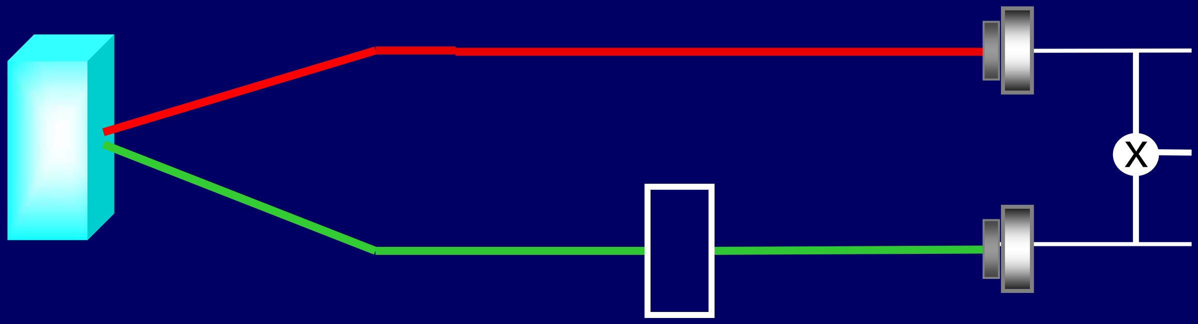

**H** = Spatial, spectral, or polarization system

# A. Applications of Direct 2-Photon Imaging



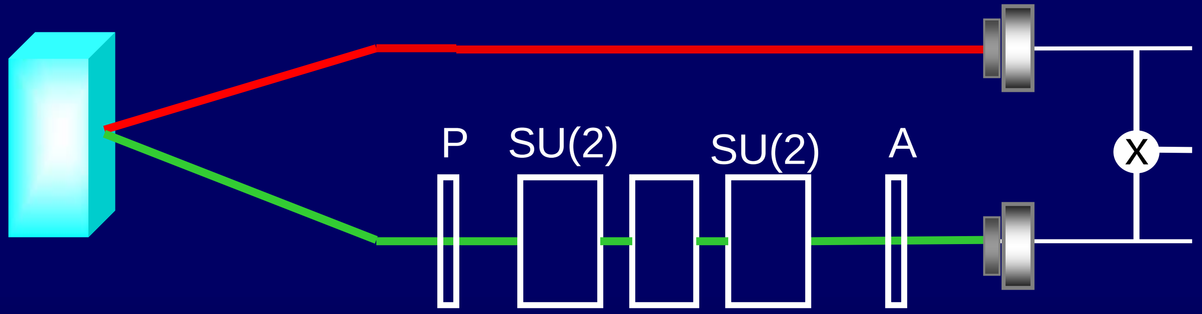
# 1. Correlated-Photon Absolute Measurement

Measurement of reflectance/ Transmittance/ Quantum Efficiency



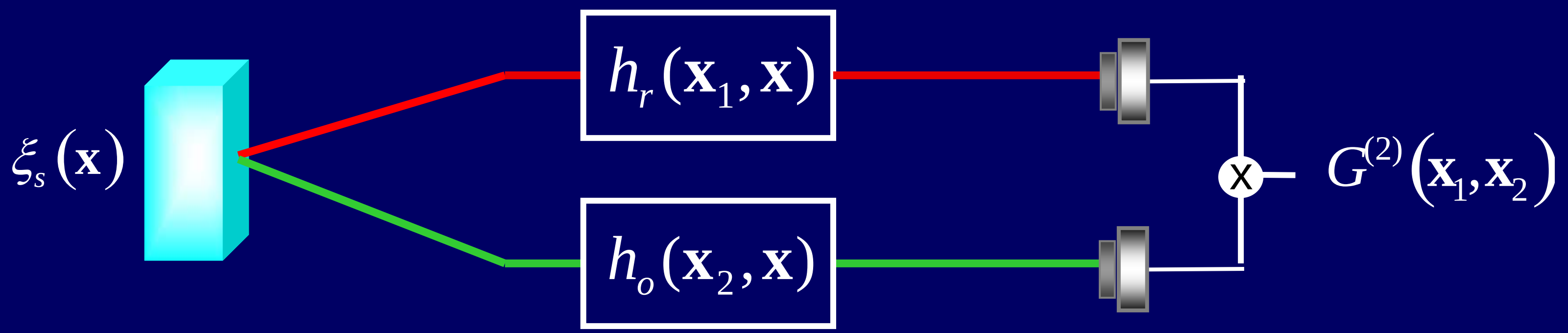

Klyshko, SJQE 77
Branning *et al*. PRA 00

Ellipsometry




Toussaint et al. PRA 04

# 2. Imaging (transverse) - Spatial modes



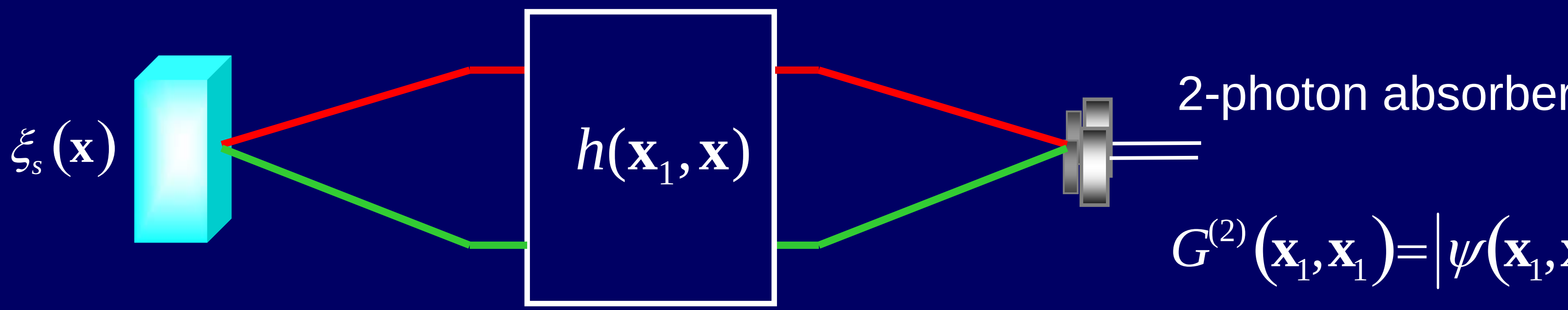

$$G^{(2)}(\mathbf{x}_1,\mathbf{x}_2)=\left|\psi(\mathbf{x}_1,\mathbf{x}_2)\right|^2$$

$$\psi(\mathbf{x}_1,\mathbf{x}_2)\propto\int\xi_s(\mathbf{x})h_r(\mathbf{x}_1,\mathbf{x})h_o(\mathbf{x}_2,\mathbf{x})d\mathbf{x}$$

Belinskii & Klyshko, Zh. Eksp. Teor. Fiz. 94

Pittman *et al*., PRA 95

# 3. Two-Photon Microscopy / Lithography




$$G^{(2)}(\mathbf{x}_1,\mathbf{x}_1) = \left|\psi(\mathbf{x}_1,\mathbf{x}_1)\right|^2$$

$$\psi(\mathbf{x}_1,\mathbf{x}_1) \propto \int \xi_s(\mathbf{x}) h^2(\mathbf{x}_1,\mathbf{x}) d\mathbf{x}$$

Example: Optical Fourier transform $h = \exp(jkx_1x/2)$

$$\psi(\mathbf{x}_1,\mathbf{x}_1) \propto \int \xi_s(\mathbf{x}) \exp[j2\frac{k}{2f}\mathbf{x}_1.\mathbf{x}] d\mathbf{x}$$

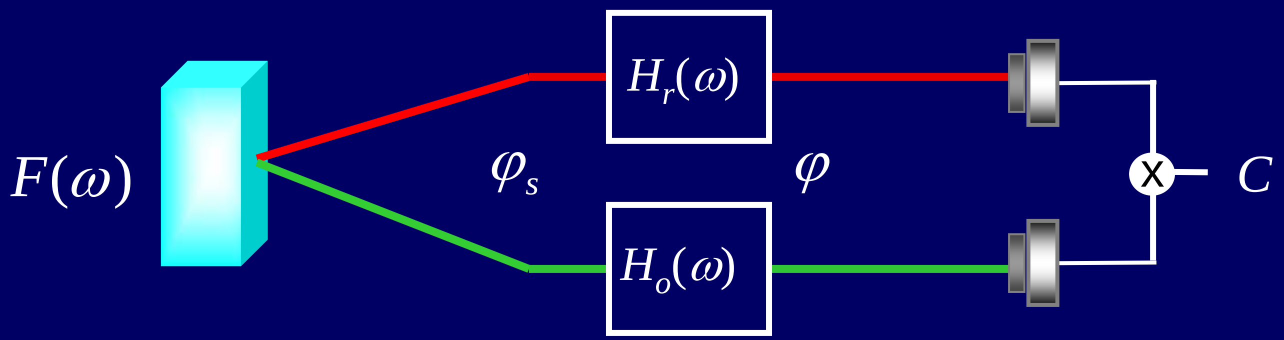
Factor of 2 enhancement

Teich & Saleh, Cesk. Cas. Fyz. 97

Boto *et al*., PRL 00

Abouraddy *et al*., JOSA-B 02

# 4. Dispersion Compensation



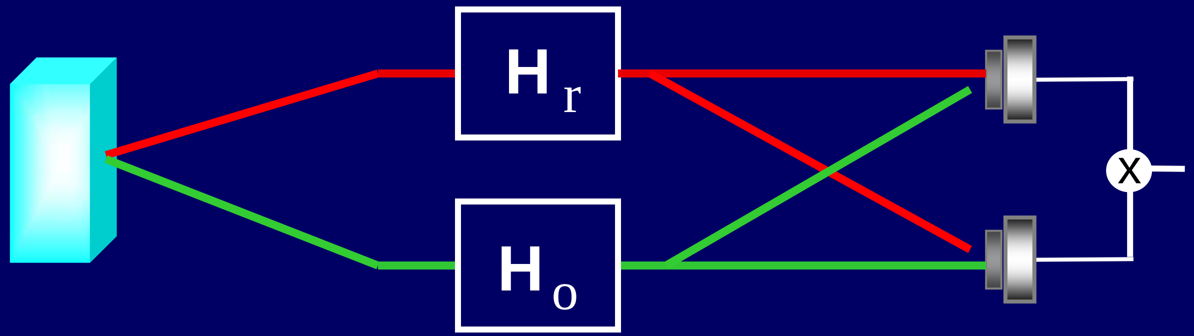

$$\varphi_s(\omega_1,\omega_2) = F(\omega_1)\delta(\omega_1+\omega_2-\omega_p)$$

$$\varphi(\omega_1,\omega_2) = H_r(\omega_1)H_o(\omega_2)F(\omega_1)\delta(\omega_1+\omega_2-\omega_p)$$

GVD's of opposite signs cancel

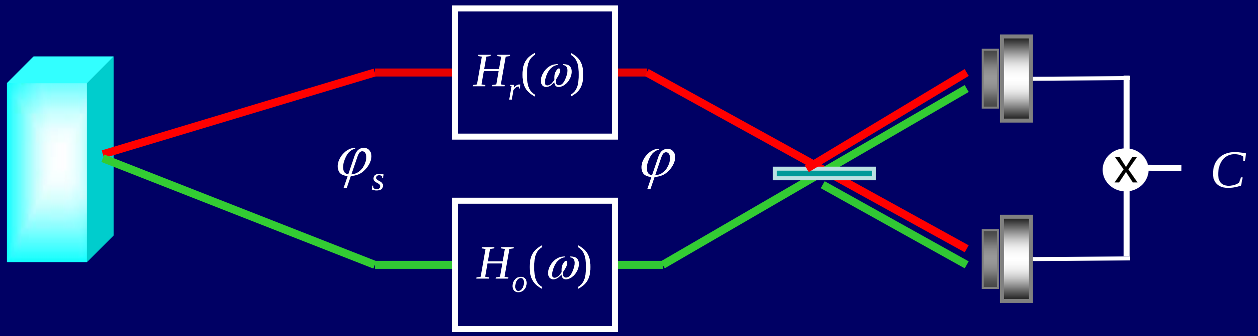
**Franson PRA 1992**

# B. Applications of Interferometric 2-Photon Imaging



# Axial Imaging/Ranging

## Spectral Modes




$$\varphi(\omega_1,\omega_2) = H_r(\omega_1)H_o(\omega_2)F(\omega_1)\delta(\omega_1+\omega_2-\omega_p)$$

$$C = \frac{1}{4}\iint \left|\ \varphi(\omega_1,\omega_2) - \varphi(\omega_2,\omega_1)\ \right|^2 d\omega_1 d\omega_2$$

Interference term in $C \propto H_o(\omega_1)H_o^*(\omega_2)H_r(\omega_1)H_r^*(\omega_2)\delta(\omega_1+\omega_2-\omega_p)$

*i.e.*, insensitive to even-order dispersion (GVD) in $H_o$,

Nonlocal Dispersion Cancellation

Steinberg, Kwiat, Chiao, PRL 92; PRA 92
Shapiro, Sun, JOSA-B 94
Larchuk, Teich, Saleh, PRA 95

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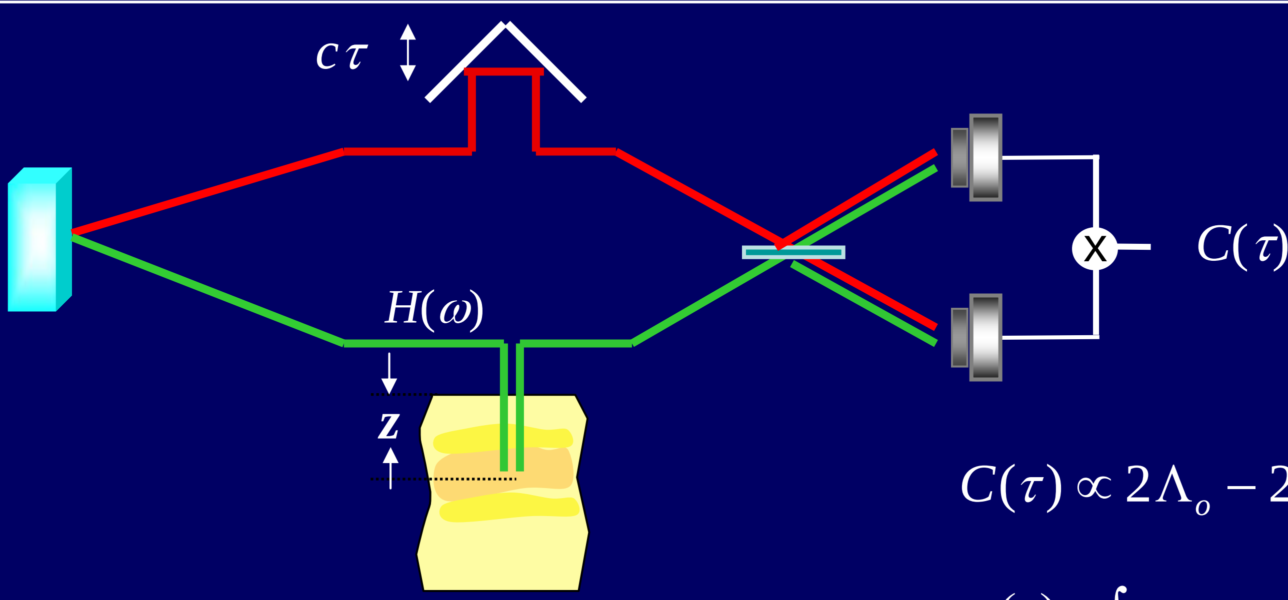
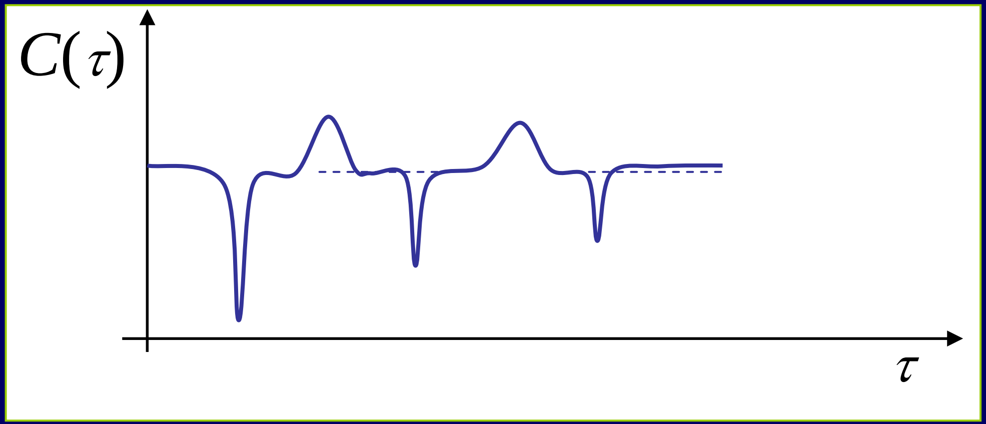
# Q-OCT = Two-Photon Axial Imaging




$$C(\tau) \propto 2\Lambda_o - 2\,\mathrm{Re}\left\{\Lambda(2\tau)\right\}$$

$$\Lambda(\tau) = \int d\Omega\, H(\omega_o + \Omega) H^*(\omega_o - \Omega) S(\Omega) e^{-i\Omega\tau}$$

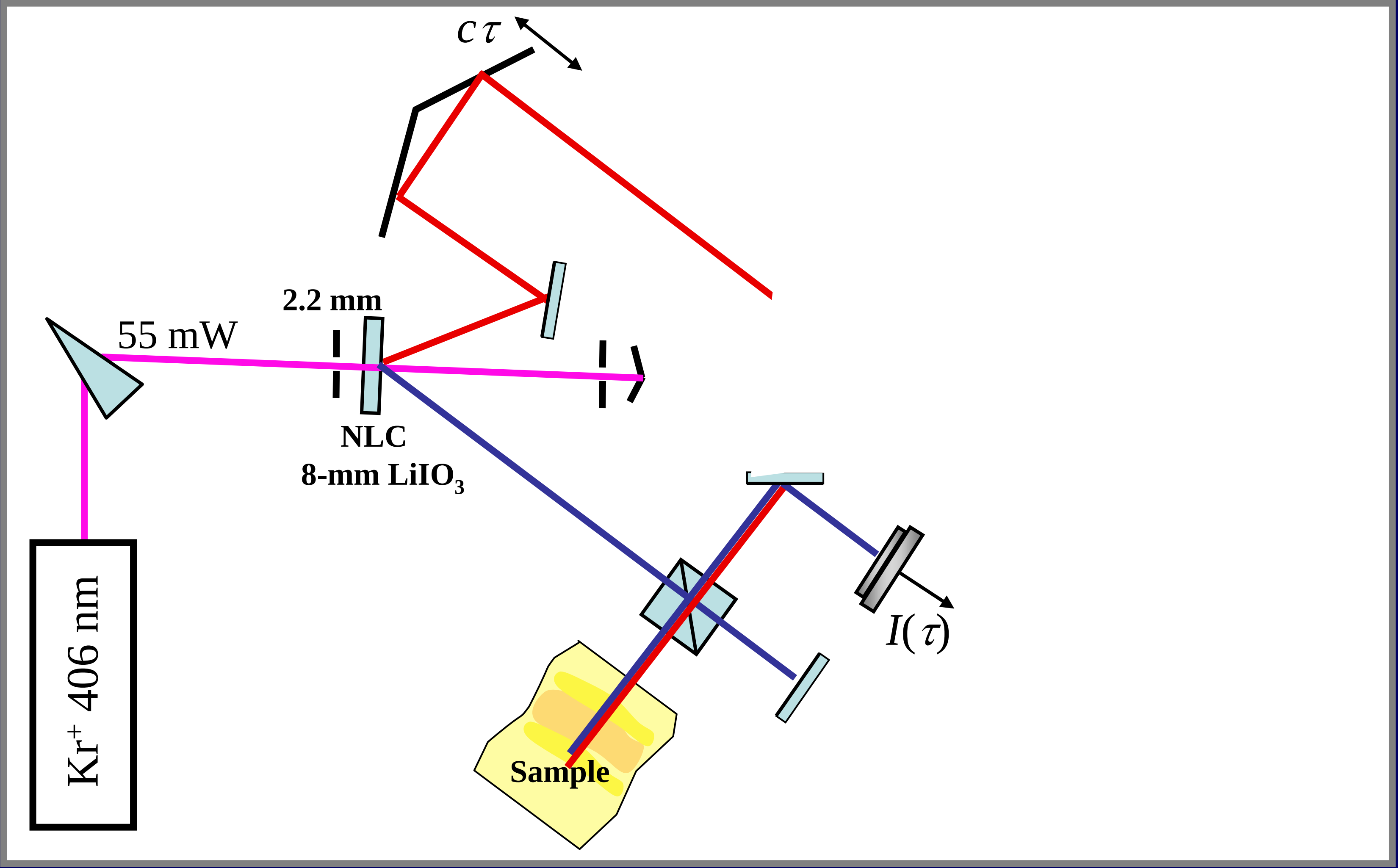
Dispersion-Cancellation




Hong-Ou-Mandel Interferometer

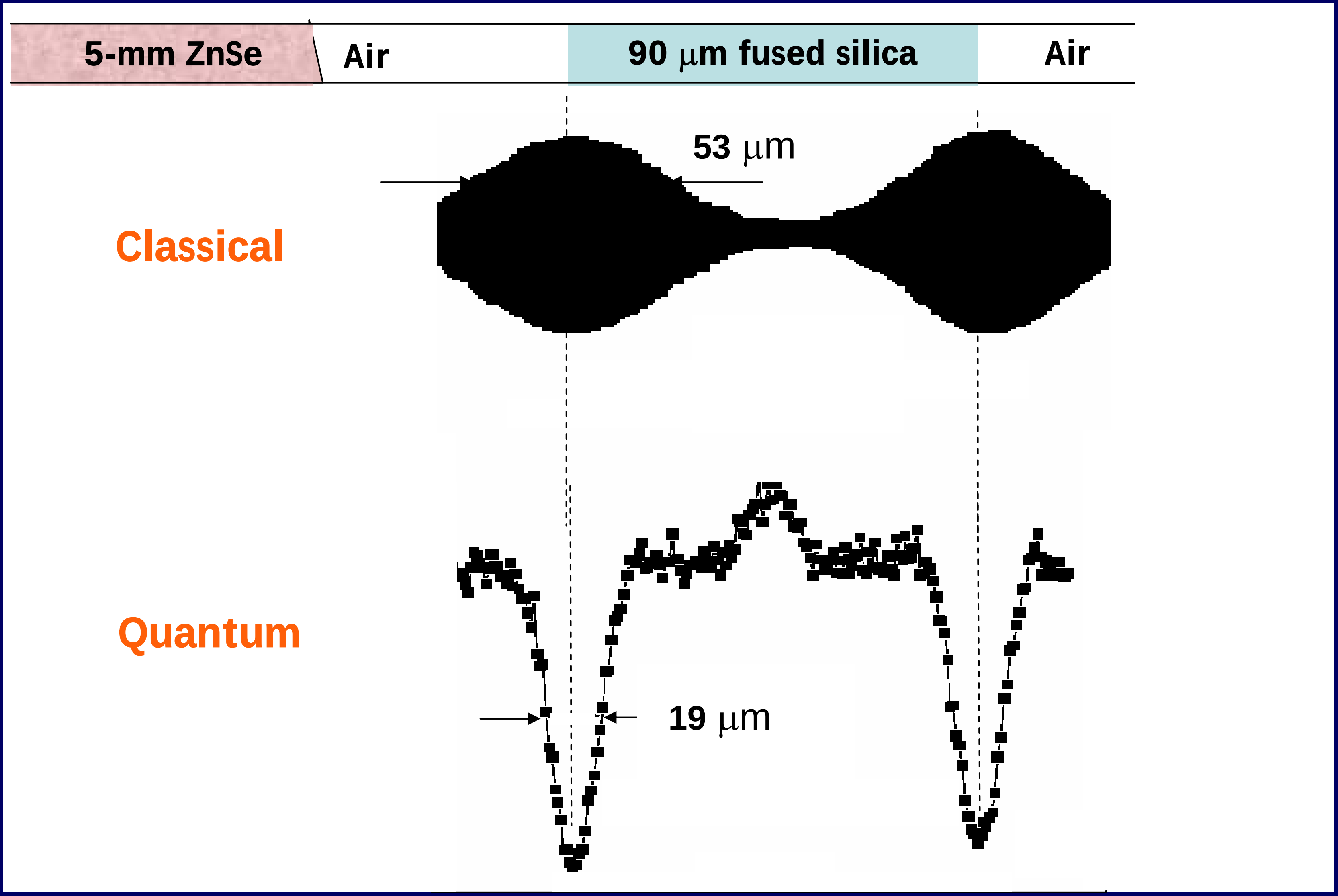
Abouraddy et al. PRA, 053817, 2002

# Experiment

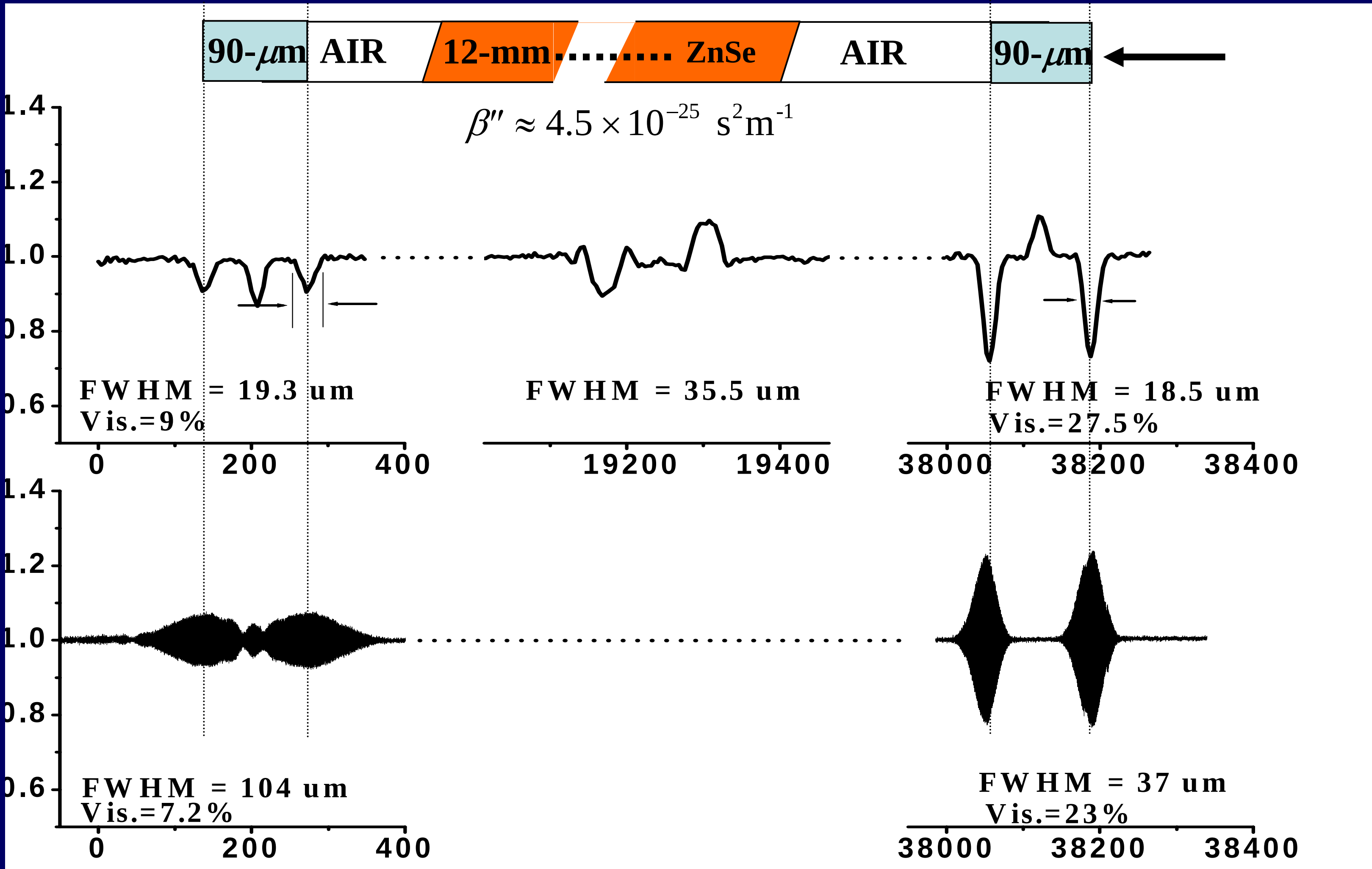



Nasr et al. PRL, 91, August 2003

# Two Boundaries + dispersive layer



# Four Boundaries + dispersive medium in-between




M. B. Nasr *et al.*, Opt. Express **12,** 1353-1362 (2004)

# The Promise of Q-OCT

- Q-OCT promises x2 improved axial resolution in comparison with conventional OCT for sources of same spectral bandwidth
- Self-interference at each boundary is immune to GVD introduced by upper layers
- Inter-boundary interference is sensitive to dispersion of inter-boundary layers; dispersion parameters can thus be estimated
- Preliminary experiments demonstrated viability of technique
- Technique can be extended to transverse imaging (Q-OCM)
- Technique can be extended to polarization-sensitive Q-OCT

# Q-OCT: Challenges & Plans

- State-of-the-art linewidth is not sufficiently large (Axial resolution is only 19 μm).
- Two-photon flux is low. Duration of experiment is too long.

A better 2-photon source is needed!

Faster broadband single-photon detector is needed!

- Applications to scattering media (e.g., tissue). Theoretical & experimental research is necessary.
- Algorithms for data processing need to be developed.

# Reprints

http://www.bu.edu/qil/

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TIFF (Uncompressed) decompressor
are needed to see this picture.

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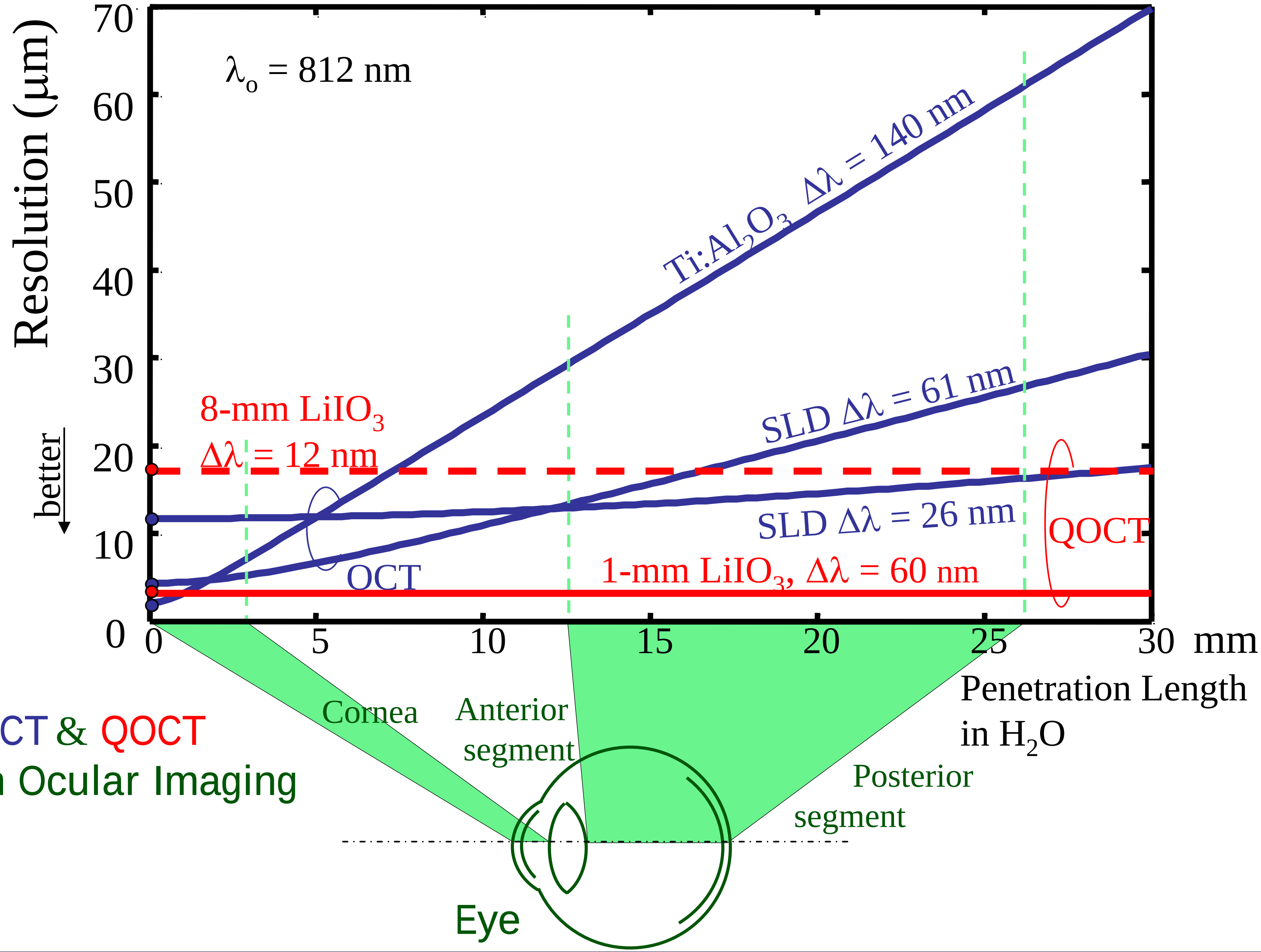
# Comparison of OCT & QOCT




OCT & QOCT
in Ocular Imaging