Using Entangled Photons to Enhance Tomography, Photoemission, Microscopy, and Lithography

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Quantum-Imaging MURI Annual Review
UMBC, 17 November 2008

EXAMPLES

Multiphoton

- Absorption

T: Göppert-Mayer (1931)

E: Franken *et al*. (1961)

- Photoemission

T: Bloch (1964)

E: Teich & Wolga (1964)

- Microscopy

T: Sheppard & Kompfner (1978)

E: Denk *et al.* (1990)

- Lithography

T: ancient

E: 3D..Maruo & Kawata (1997)

- OCT (Optical Coherence Tomography – Single Photon)

T: Youngquist *et al*. (1987)

E: Huang *et al*. (1991)

Entangled-Photon

- Absorption

T: Fei *et al.* (1997)

E: Dayan *et al.* (2004)

- Photoemission

T: Lissandrin *et al.* (2004)

E:

- Microscopy

T: Teich & Saleh (1997)

E:

- Lithography

T: Boto *et al.* (2000)

E:

- QOCT (Quantum Optical Coherence Tomography – 2-Photon)

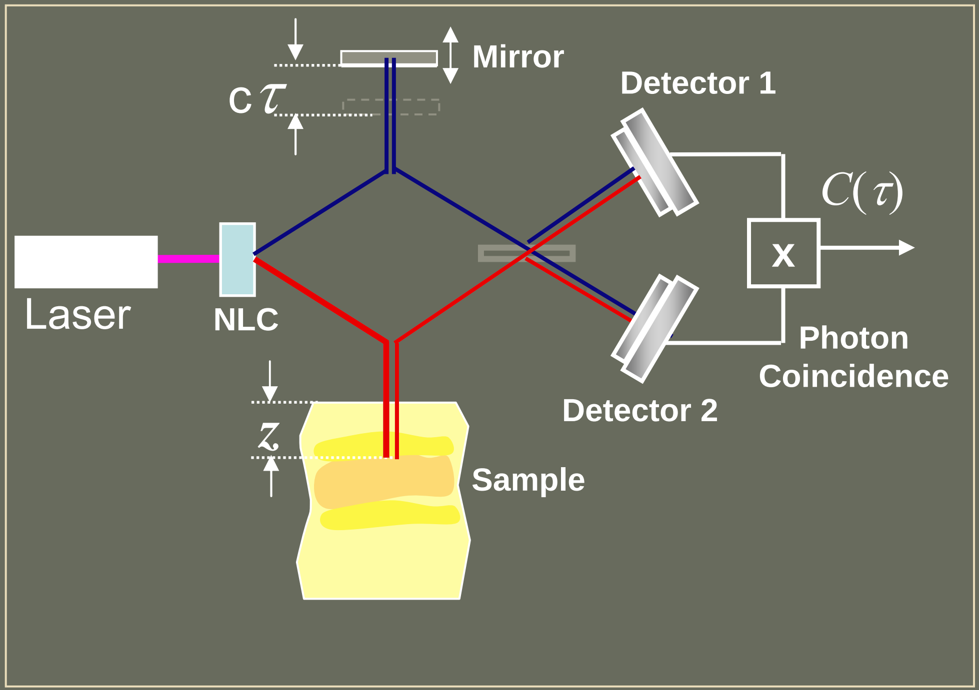
T: Abouraddy *et al.* (2002)

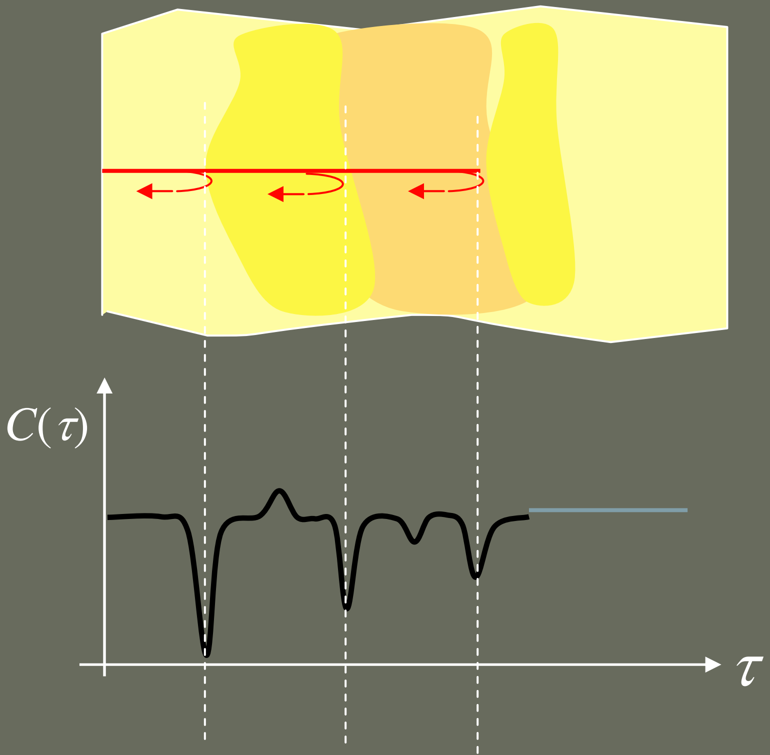
E: Nasr *et al.* (2003)

[Other applications include distributed imaging and holography, quantum metrology and ellipsometry, quantum information and communications]

Quantum Optical Coherence Tomography (QOCT)

= OCT based on quantum interferometry of spectrally-entangled photons generated by downconverted light from a nonlinear crystal

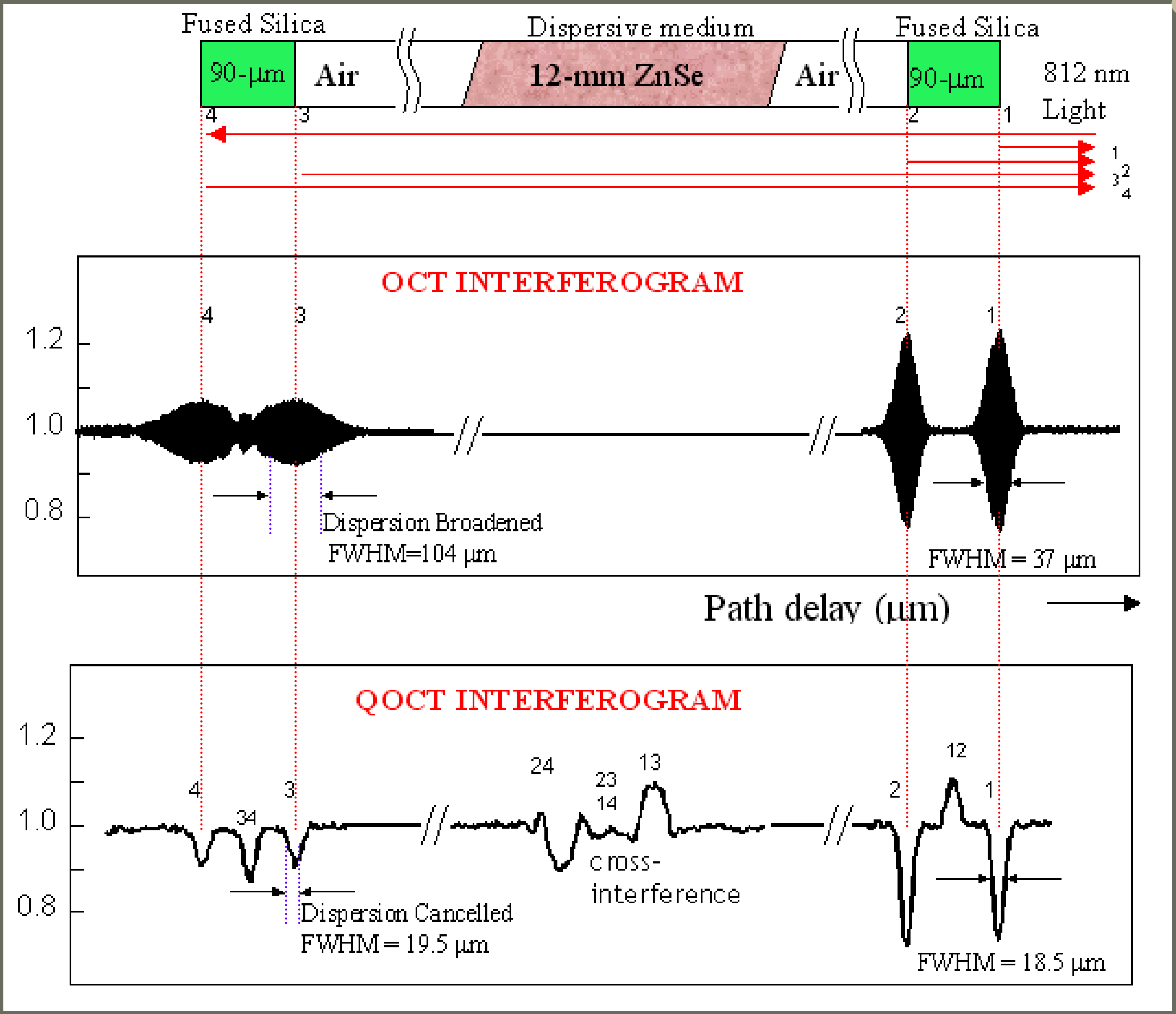




Advantages of QOCT

- ❑ Factor of 2 improvement in axial resolution for same spectral width
- ❑ Insensitivity to group-velocity dispersion with concomitant improvement in axial resolution

Dispersion-Free QOCT (Experiment)



After Nasr *et al.*, *Opt. Exp. 12*, 1353-1362 (2004)

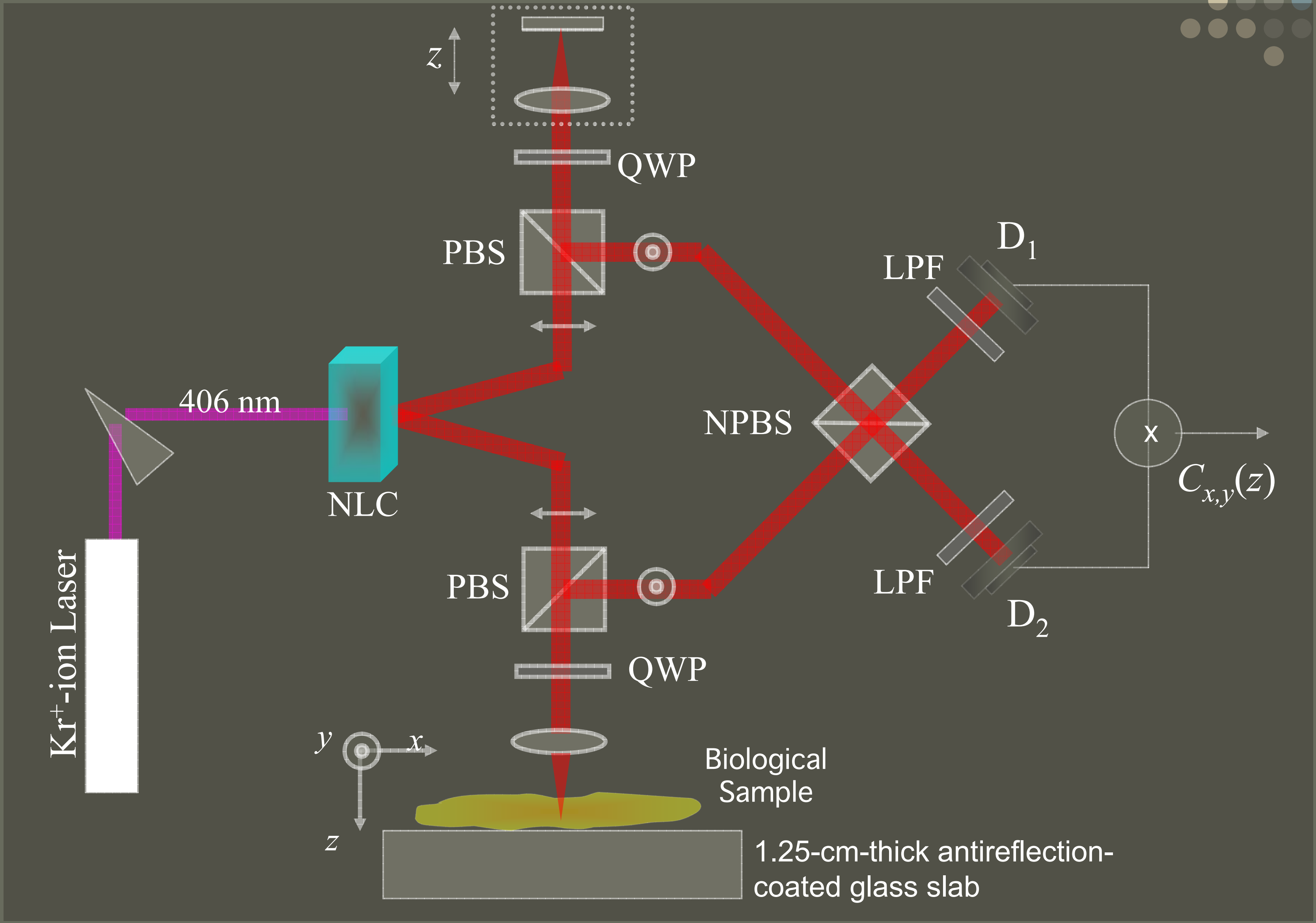
Challenges

- Not enough photons (long run time). 3D imaging is not viable
- Poor axial resolution (19 μm). Source bandwidth too narrow
- Not certain about quantum entanglement in the nonplanar scattering/diffusive media such as biological samples

Improvements Enabling Biological QOCT

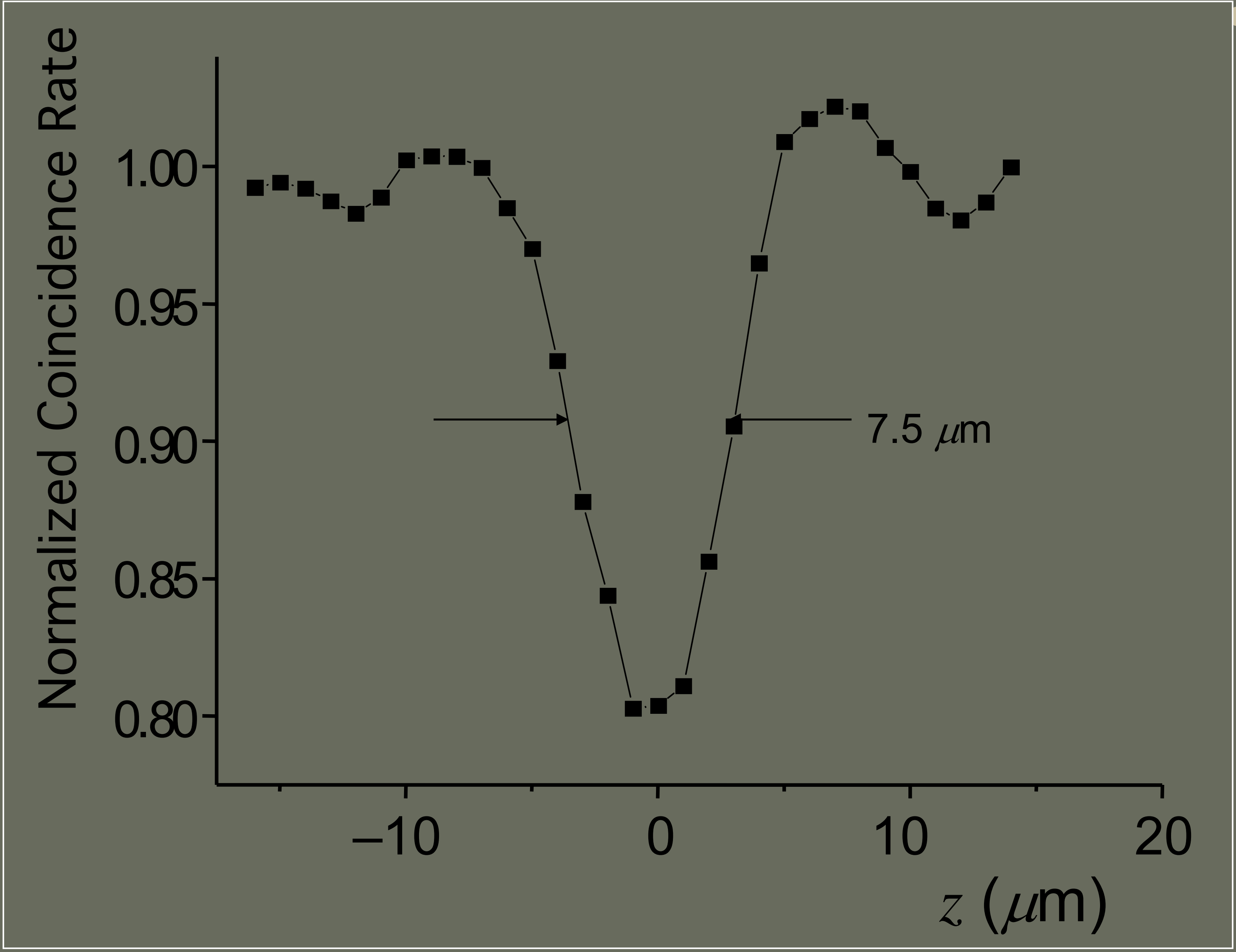
- Compact optical configuration
- Use of lenses to enhance spatial resolution
- Use of PBS/QWPs to increase photon flux (factor of 4)
- Enhanced sample preparation using gold nanoparticles

QOCT of Onion-Skin Cells in 3D (Experiment)



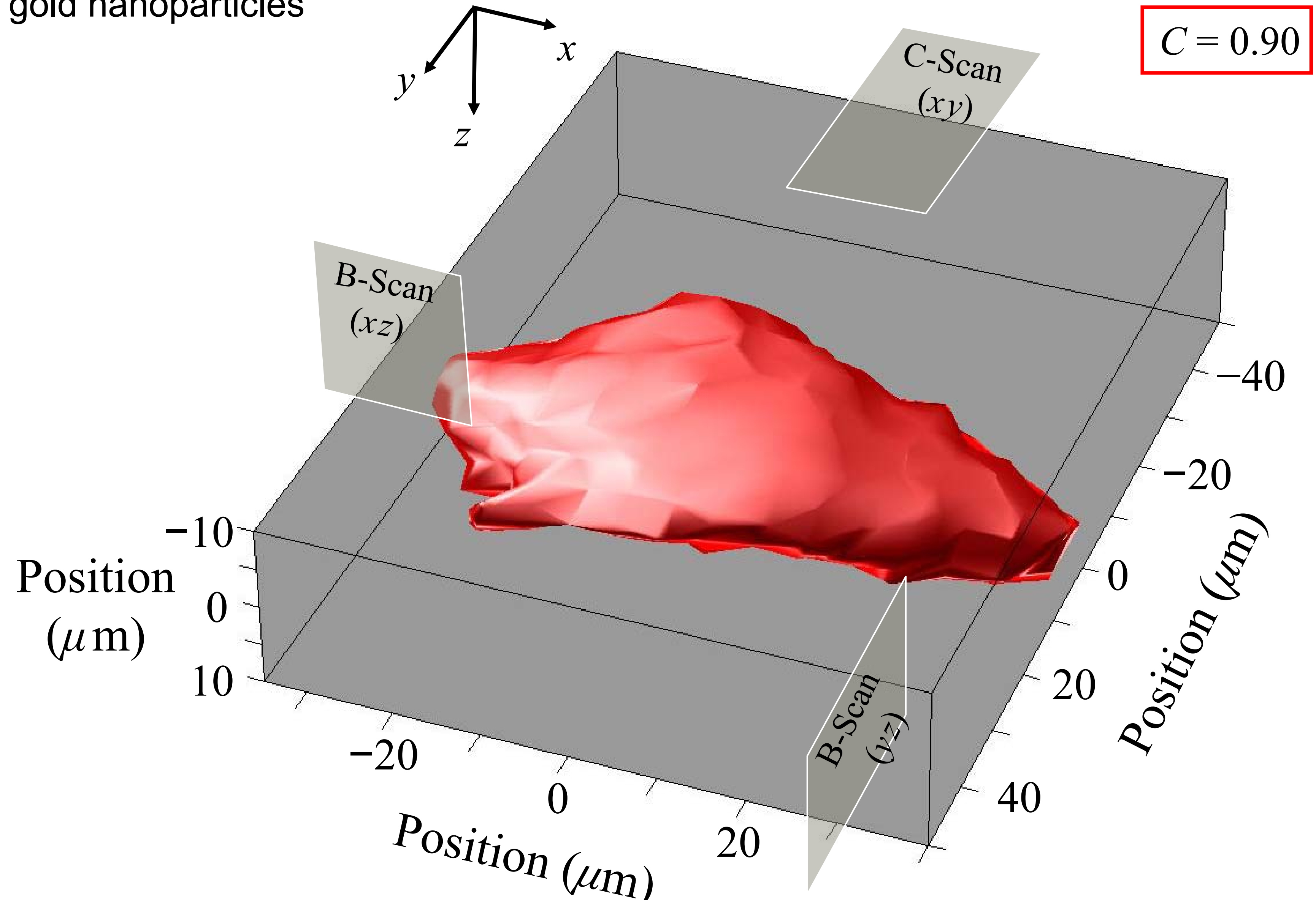
After M. B. Nasr, D. P. Goode, N. Nguyen, G. Rong, L. Yang, B. M. Reinhard, B. E. A. Saleh, and M. C. Teich, “Quantum Optical Coherence Tomography of a Biological Sample,” *Optics Communications* (2008, in press) [http://xxx.lanl.gov/abs/0809.4721]

A-Scan

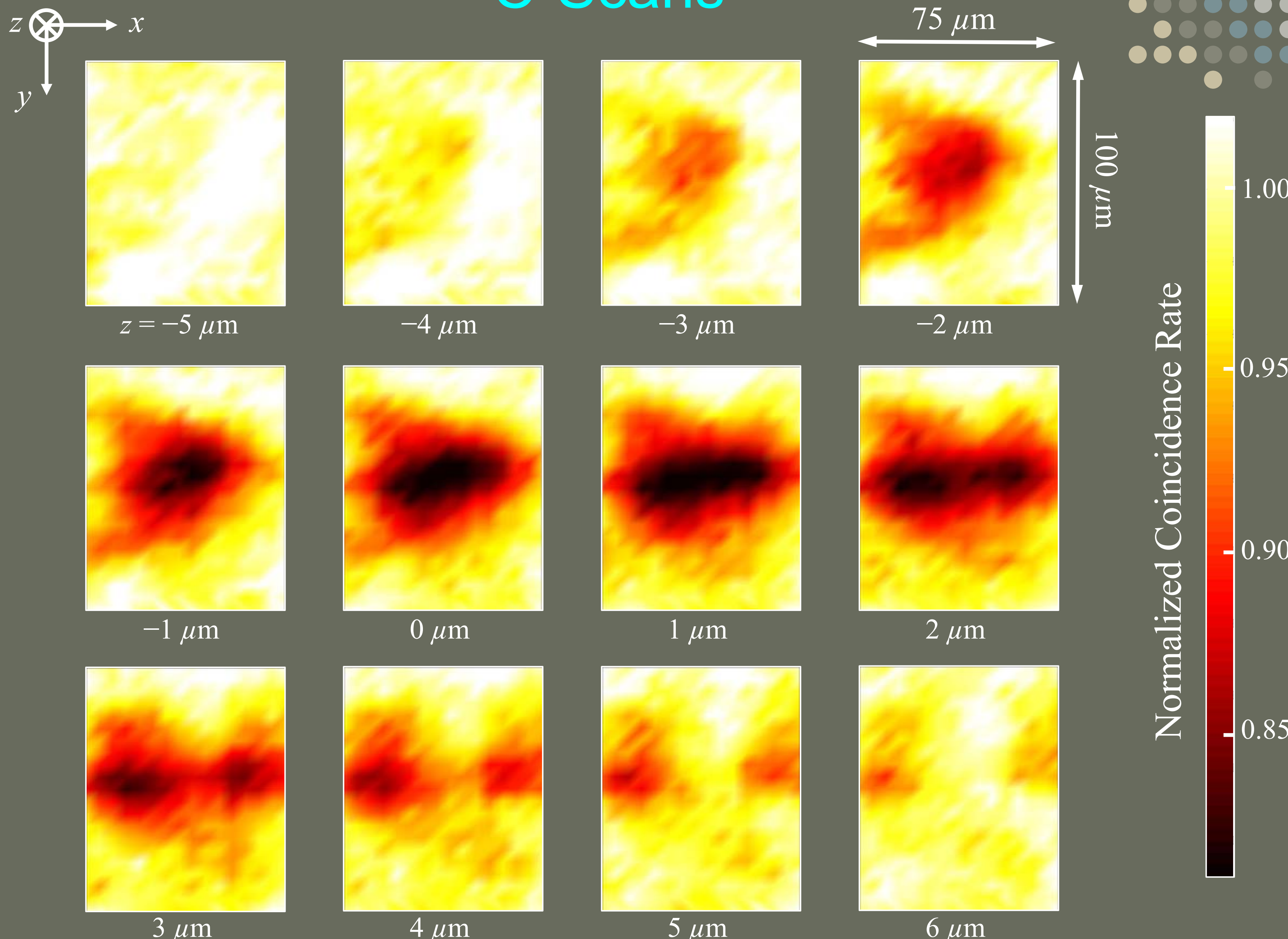

Normalized Coincidence Rate
1.00
0.95
0.90
0.85
0.80
7.5 μm
–10
0
10
20
z (μm)

3D contours of constant coincidence

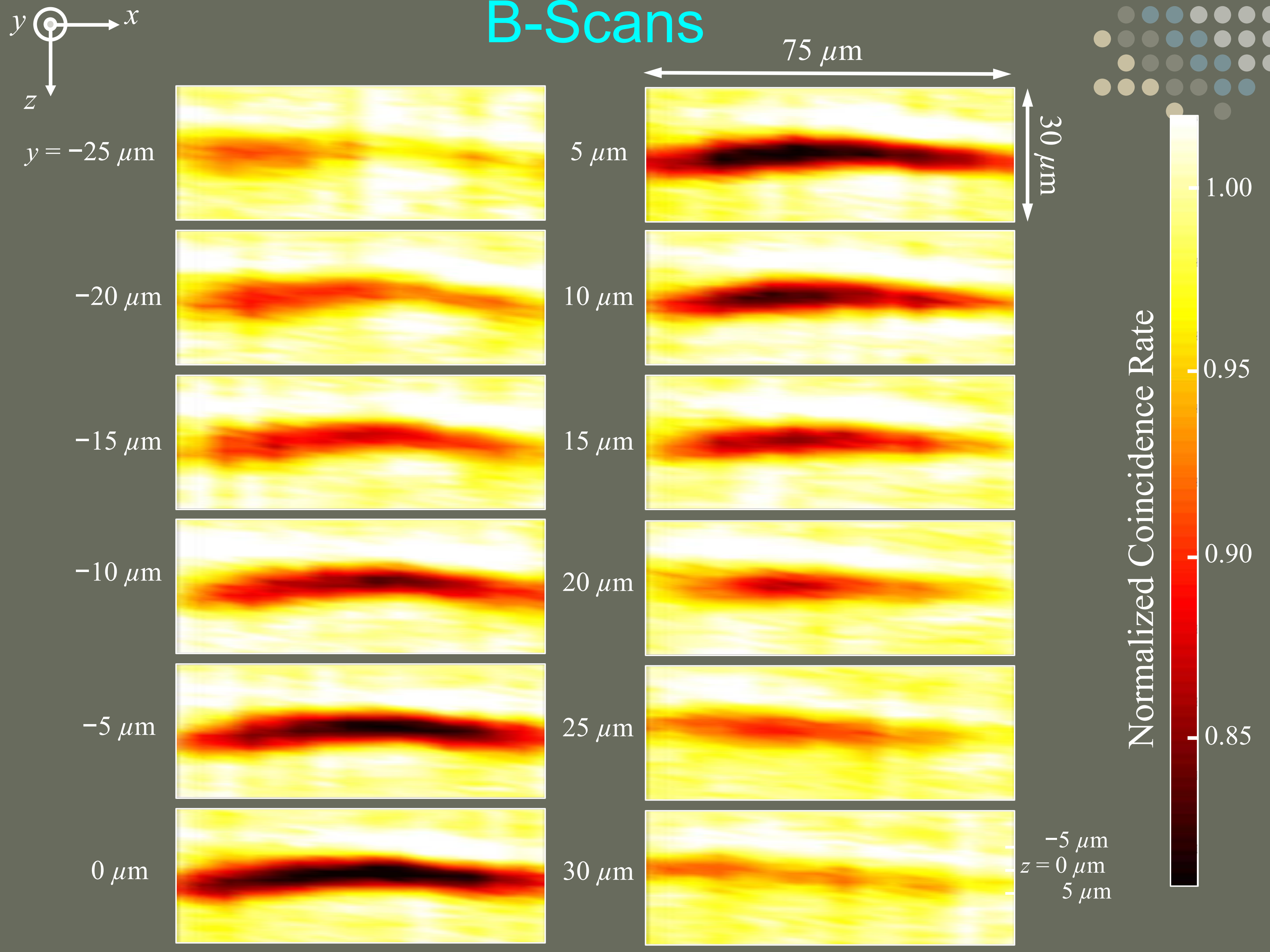
Sample coated with BSA-functionalized gold nanoparticles

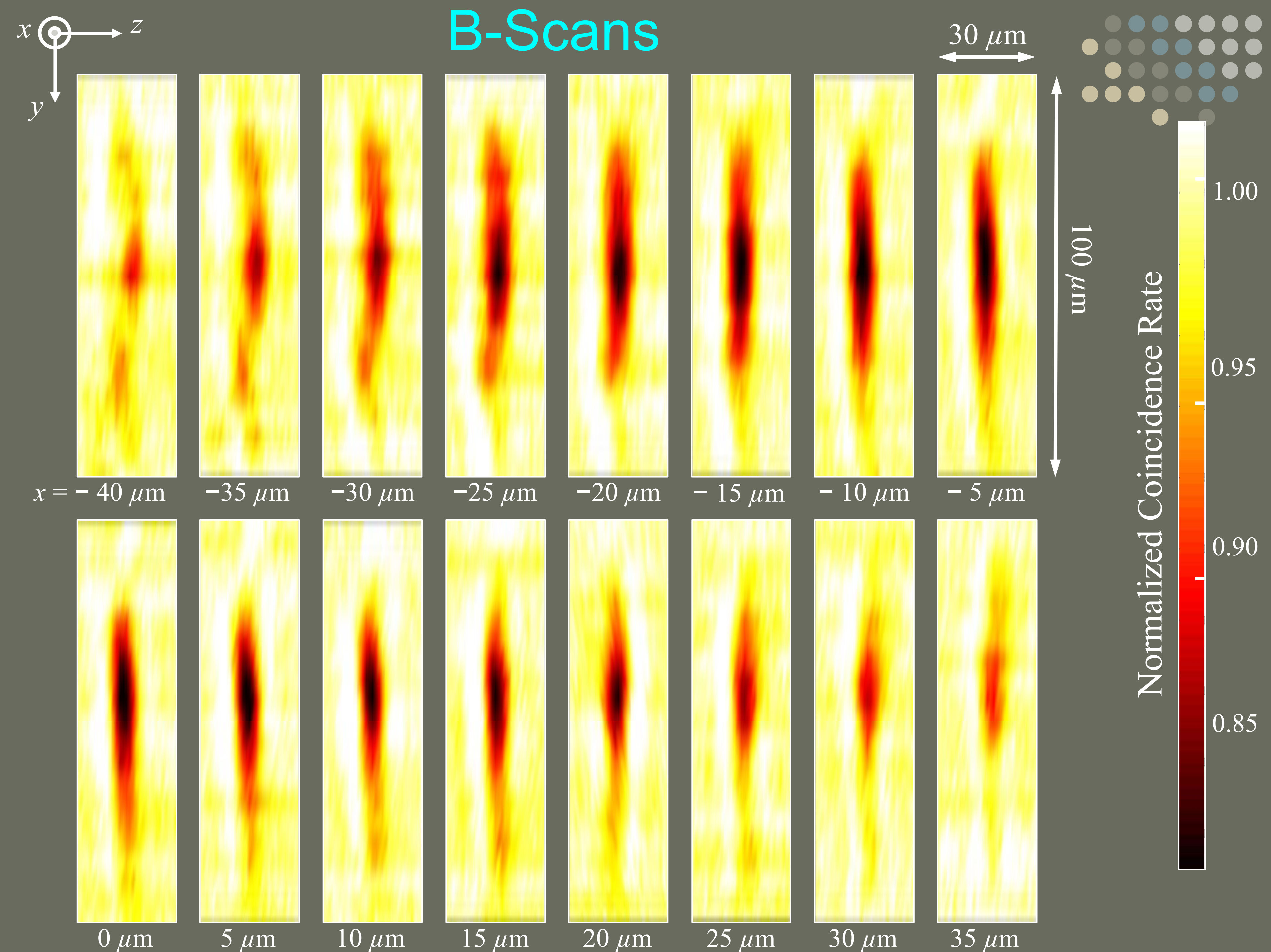


C-Scans


z
x
y
75 μm
100 μm
z = −5 μm
−4 μm
−3 μm
−2 μm
−1 μm
0 μm
1 μm
2 μm
3 μm
4 μm
5 μm
6 μm
Normalized Coincidence Rate
1.00
0.95
0.90
0.85

B-Scans


y
x
z
75 μm
30 μm
y = −25 μm
−20 μm
−15 μm
−10 μm
−5 μm
0 μm
5 μm
10 μm
15 μm
20 μm
25 μm
30 μm
−5 μm
z = 0 μm
5 μm
Normalized Coincidence Rate
1.00
0.95
0.90
0.85



B-Scans
x
z
y
30 μm
100 μm
x = − 40 μm
−35 μm
−30 μm
−25 μm
−20 μm
− 15 μm
− 10 μm
− 5 μm
0 μm
5 μm
10 μm
15 μm
20 μm
25 μm
30 μm
35 μm
Normalized Coincidence Rate
1.00
0.95
0.90
0.85

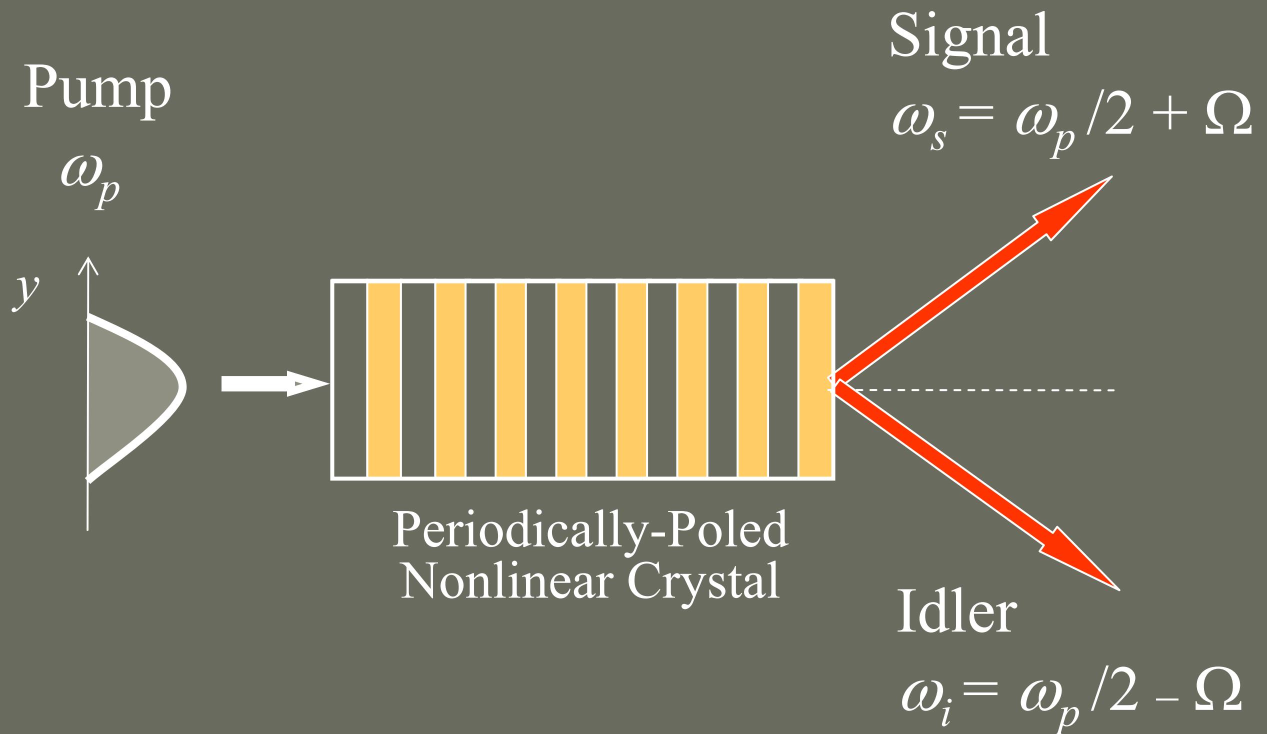
Biological QOCT: Summary

- First demonstration of the interaction of a quantum-entangled entity and a biological system (nonplanar, scattering, diffusive medium) — entanglement survived the interaction to create an image
- Demonstration of the viability of quantum 3D imaging of a biological sample
- Gold nanoparticles were used to enhance the sample reflectance — a new paradigm for quantum imaging
- Axial resolution (7.5 μm) can be improved to 1μm. Transverse resolution (12 μm) can also be improved
- Scan time remains too long (but pump power was only 2 mW, corresponding to 0.5 pW of downconverted photons or 10^6 photon pairs/sec)

Further Improvements

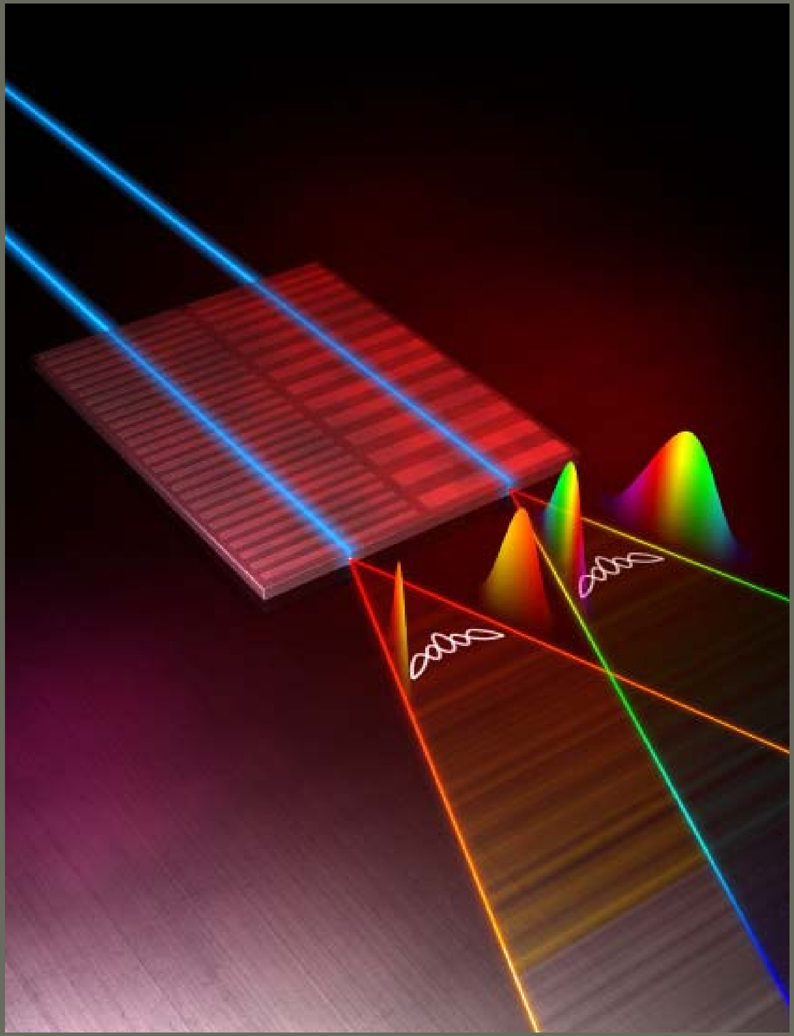
- Quasi-phase matching (increased source flux)
- Chirped quasi-phase matching (increased source bandwidth)
- SSPDs (increased detector bandwidth)
- Odd-order, as well as even-order, dispersion cancelation
- Use of ultrafast compression techniques for biphotons

Quasi-Phase-Matched Downconversion



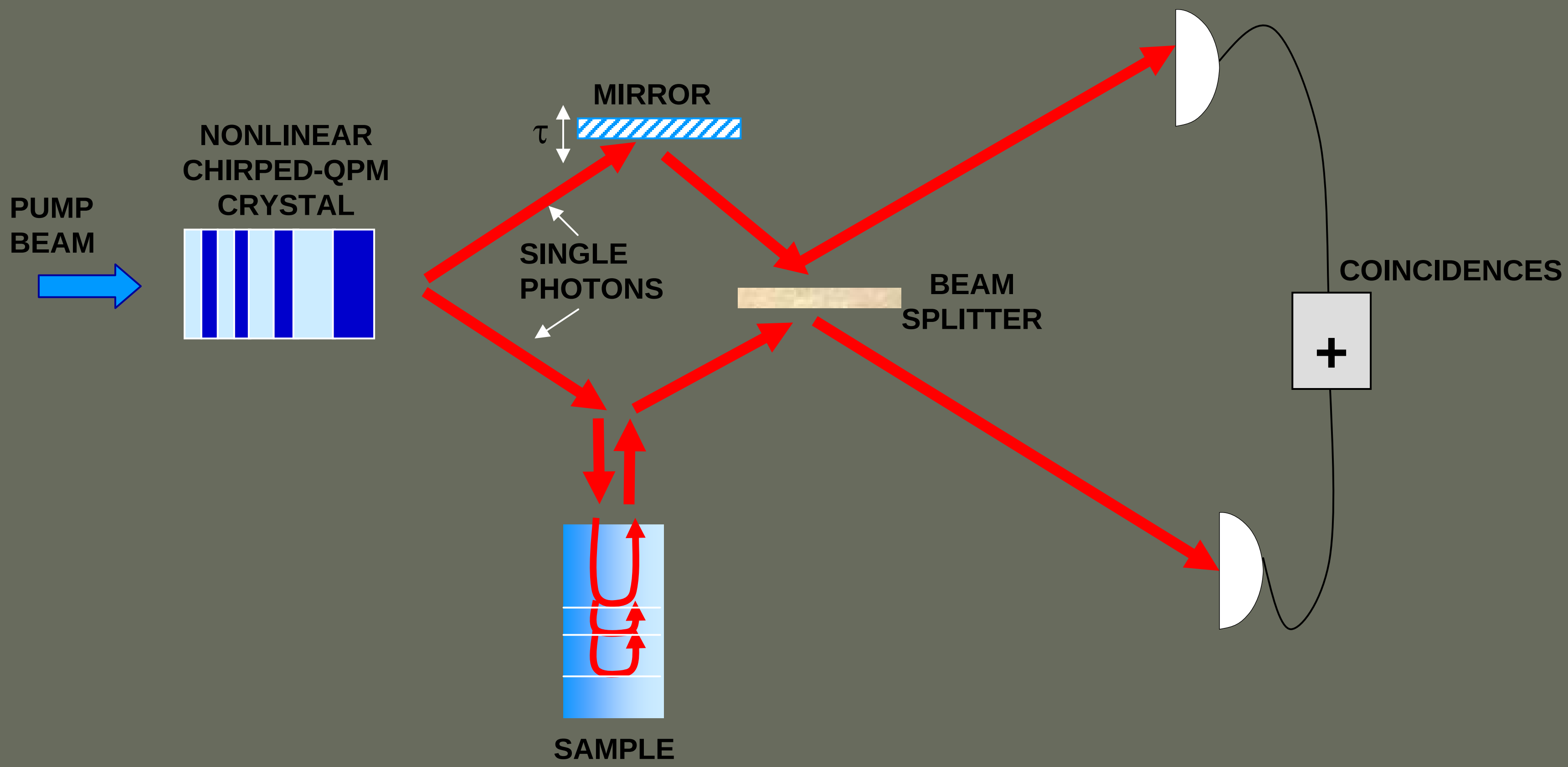
Yields: Increased photon flux

Chirped Quasi-Phase-Matched Downconversion



Yields: Increased spectral bandwidth

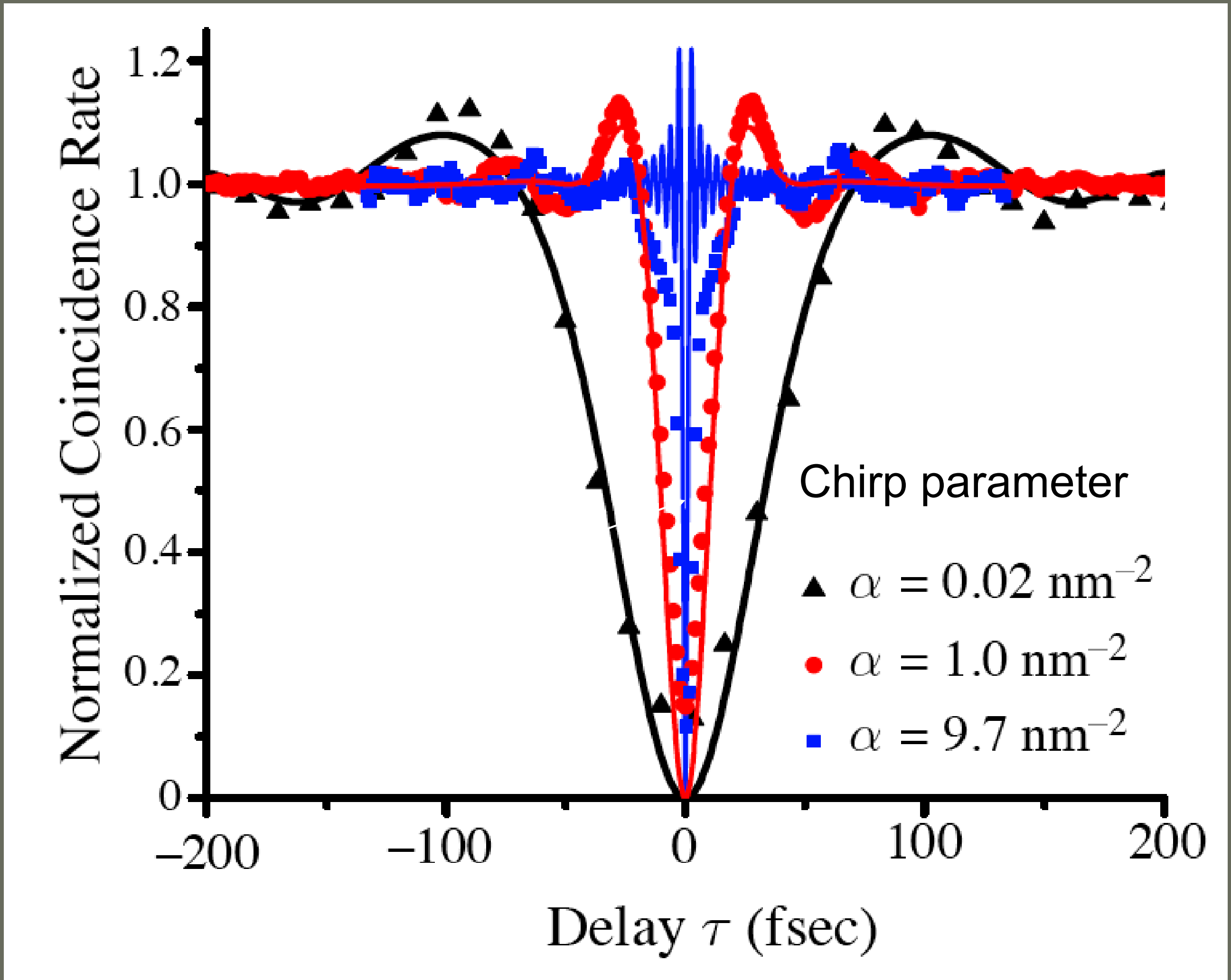
QOCT with Chirped-QPM Downconversion



Increased spectral bandwidth yields enhanced resolution

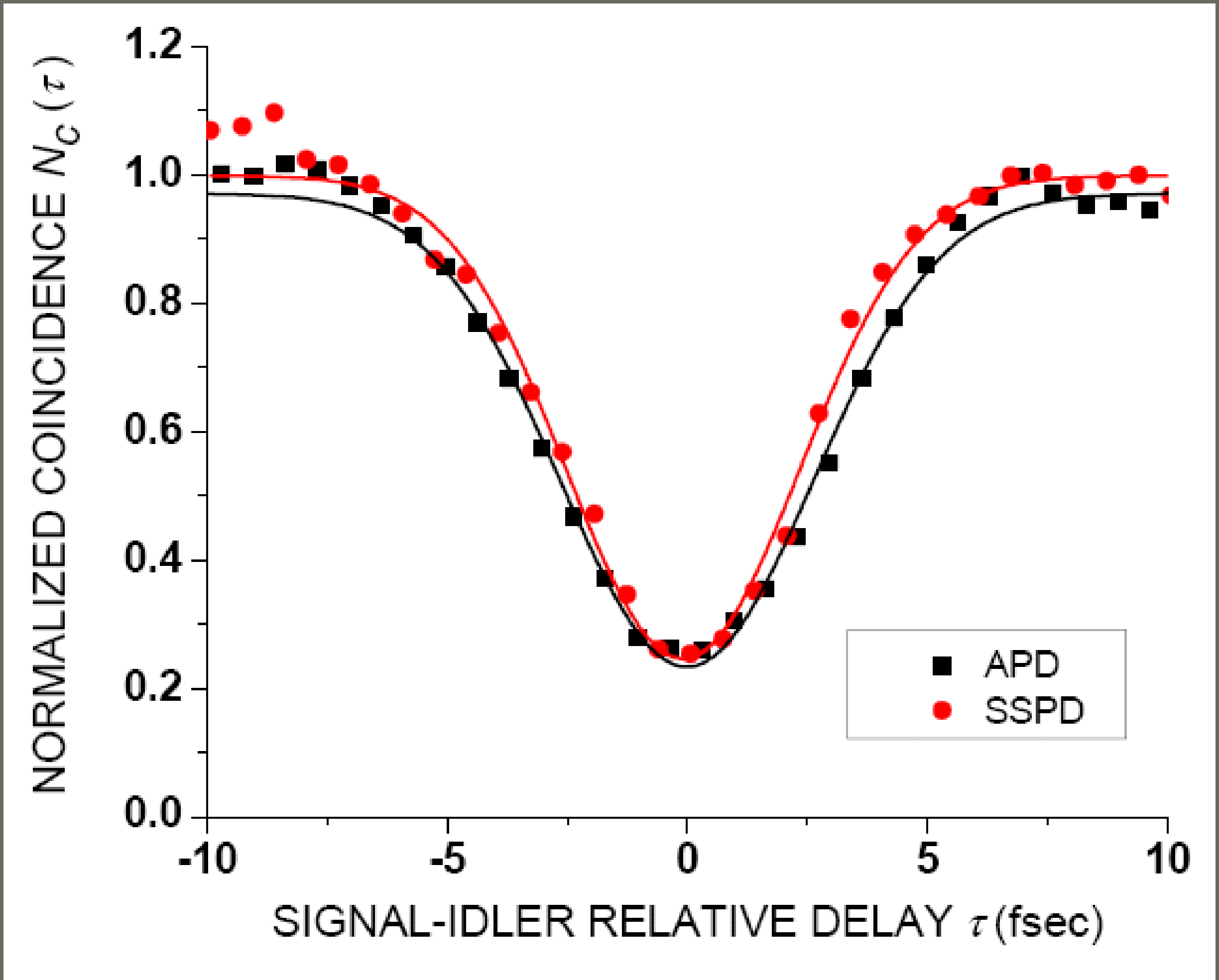
After Carrasco *et al.*, *Opt. Lett.* **29**, 2429-2431 (2004)

Enhancement of QOCT Resolution via Chirped QPM: 19 μm to 1 μm



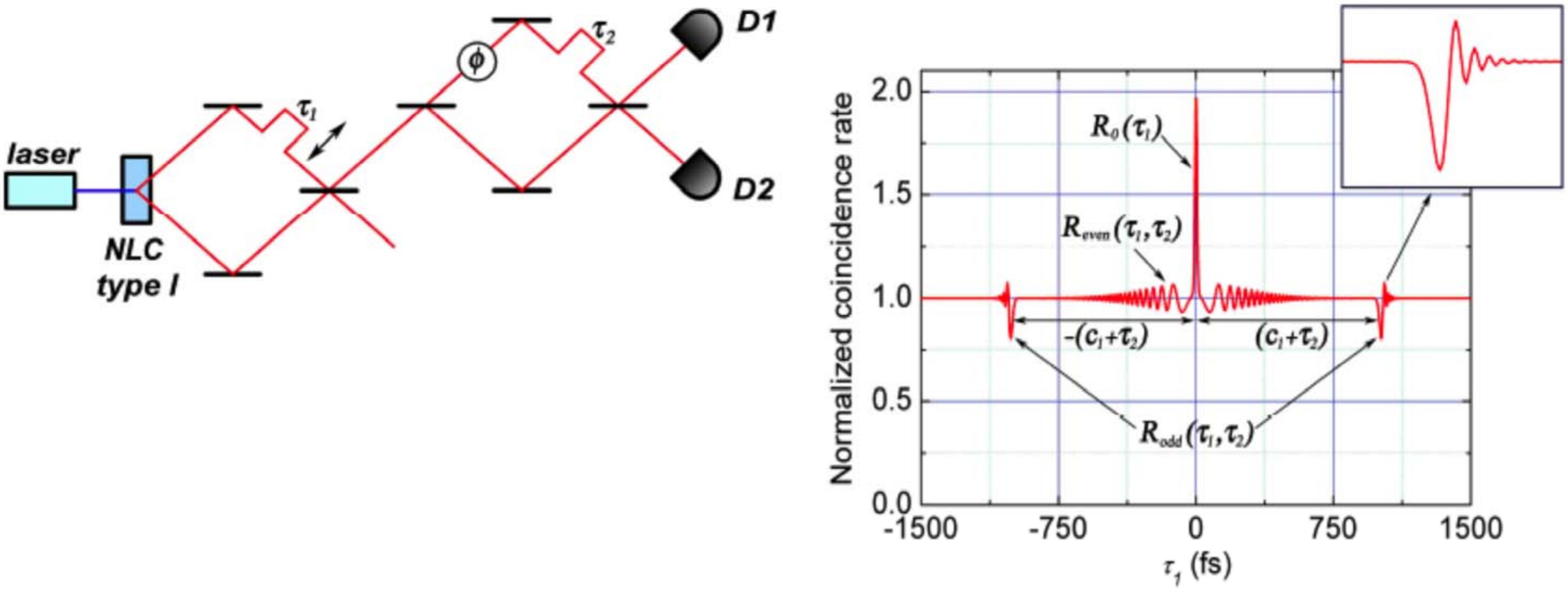
After M. B. Nasr, S. Carrasco, B. E. A. Saleh, A. V. Sergienko, M. C. Teich, J. P. Torres, L. Torner, D. S. Hum, and M. M. Fejer, "Ultrabroadband Biphotons Generated via Chirped Quasi-Phase-Matched Optical Parametric Down-Conversion," *Phys. Rev. Lett.* **100**, 183601 (2008).

Enhancement of QOCT Resolution via Increase in Detector Bandwidth



After M. B. Nasr, O. Minaeva, G. N. Goltsman, A. V. Sergienko, B. E. A. Saleh, and M. C. Teich, "Submicron Axial Resolution in an Ultrabroadband Two-Photon Interferometer Using Superconducting Single-Photon Detectors," *Opt. Express* **16**, 15104 (2008), co-published in *Virtual Journal of Biomedical Optics.*

Odd-Order and Even-Order Dispersion Cancelation

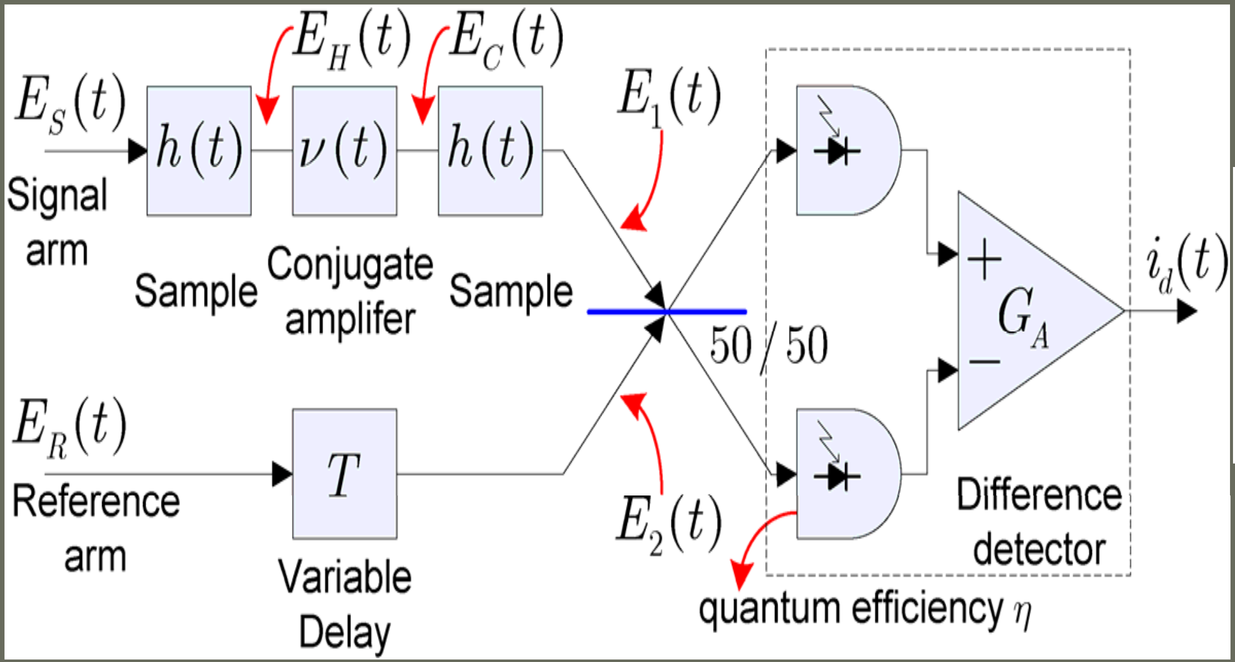


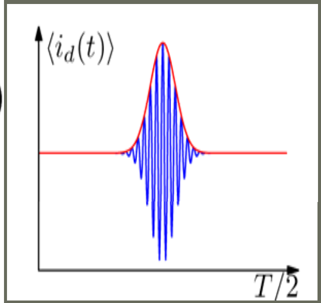
Simultaneous odd- and even-order dispersion cancellation in quantum interferometry

Olga Minaeva,[1,2] Cristian Bonato,[1,3] Bahaa E.A. Saleh,[1] David S. Simon,[1] and Alexander V. Sergienko[1,4]

Quantum-Mimetics

Phase-Sensitive Optical Coherence Tomography

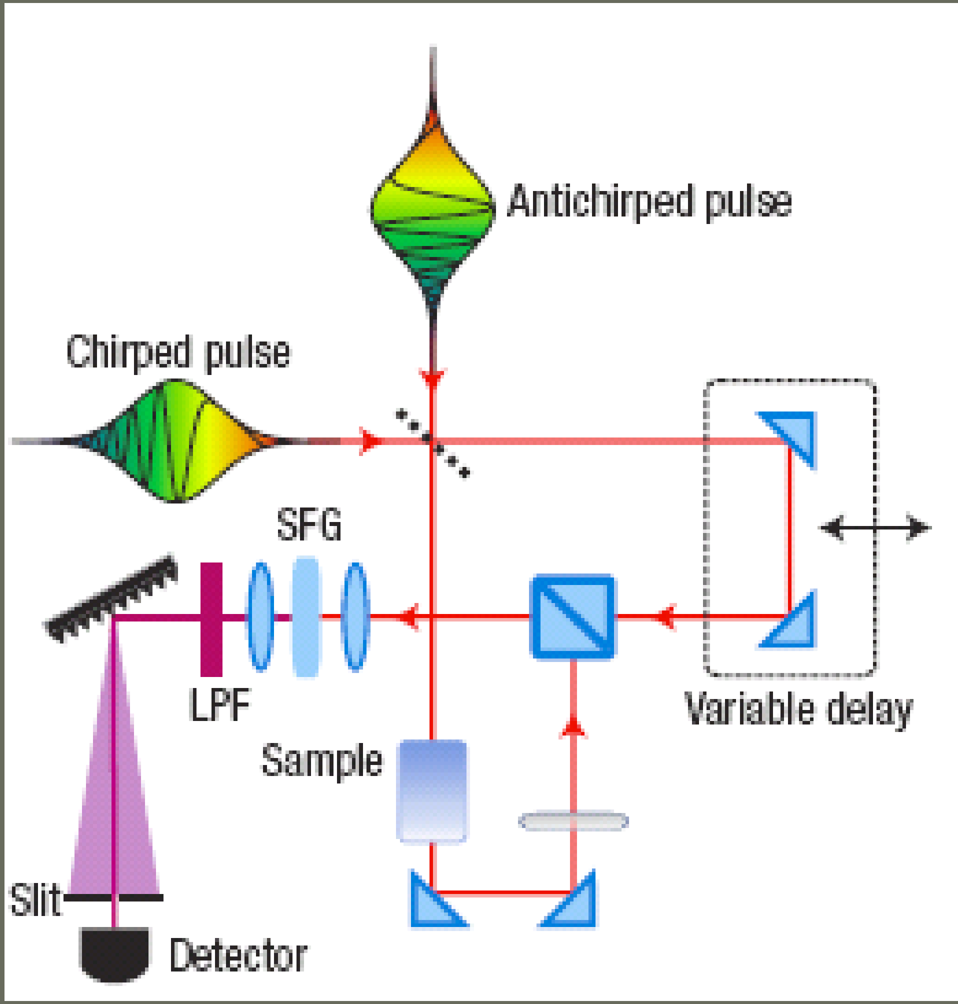




B. I. Erkmen and J. H. Shapiro, "Phase-Conjugate Optical Coherence Tomography," *Phys. Rev. A* **74**, 041601 (2006).

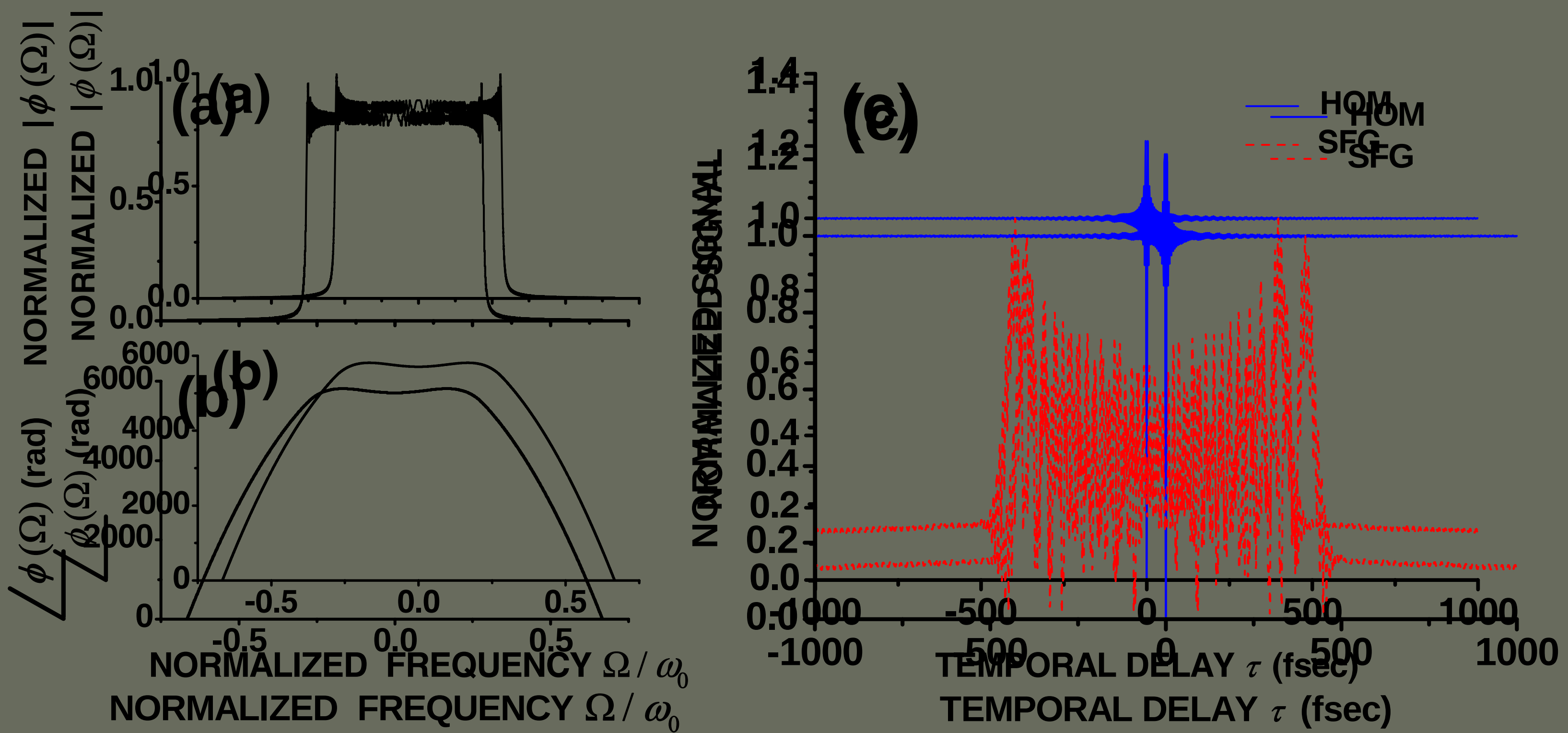
Quantum-Mimetics

Chirped-Pulse Interferometry Using SFG (Time-Reversed HOM)



R. Kaltenbaek, J. Lavoie, D. N. Biggerstaff, and K. J. Resch, “Quantum-Inspired Interferometry with Chirped Laser Pulses,” *Nature Physics*, in press (2008).

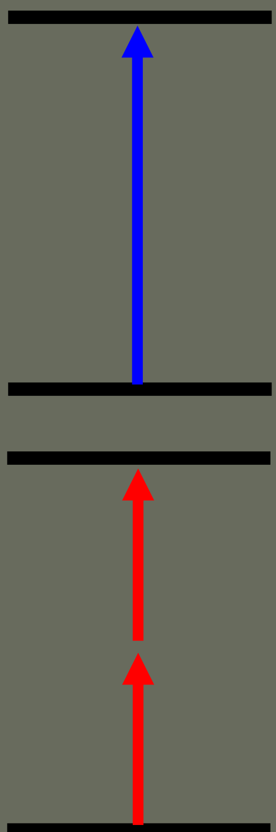
Biphoton Compression Makes Entangled-Photon Photoemission, Microscopy, and Lithography Work



After M. B. Nasr, S. Carrasco, B. E. A. Saleh, A. V. Sergienko, M. C. Teich, J. P. Torres, L. Torner, D. S. Hum, and M. M. Fejer, “Ultrabroadband Biphotons Generated via Chirped Quasi-Phase-Matched Optical Parametric Down-Conversion,” *Phys. Rev. Lett.* **100**, 183601 (2008).

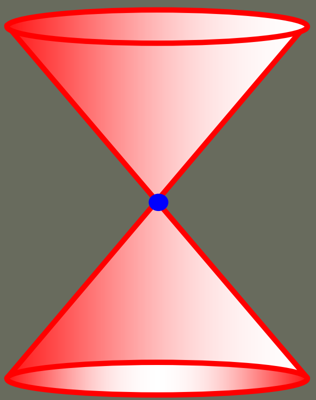
Multiphoton Excitation
vs
Entangled-Photon Excitation

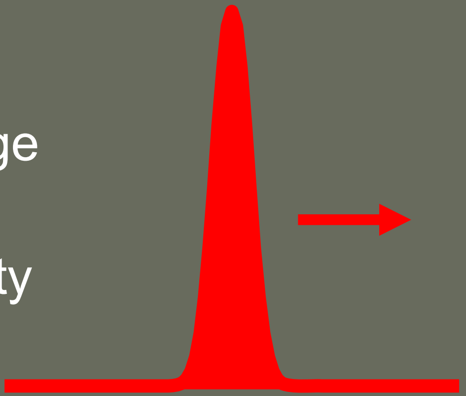
Optics & Photonics News **11**, 40 (2000)



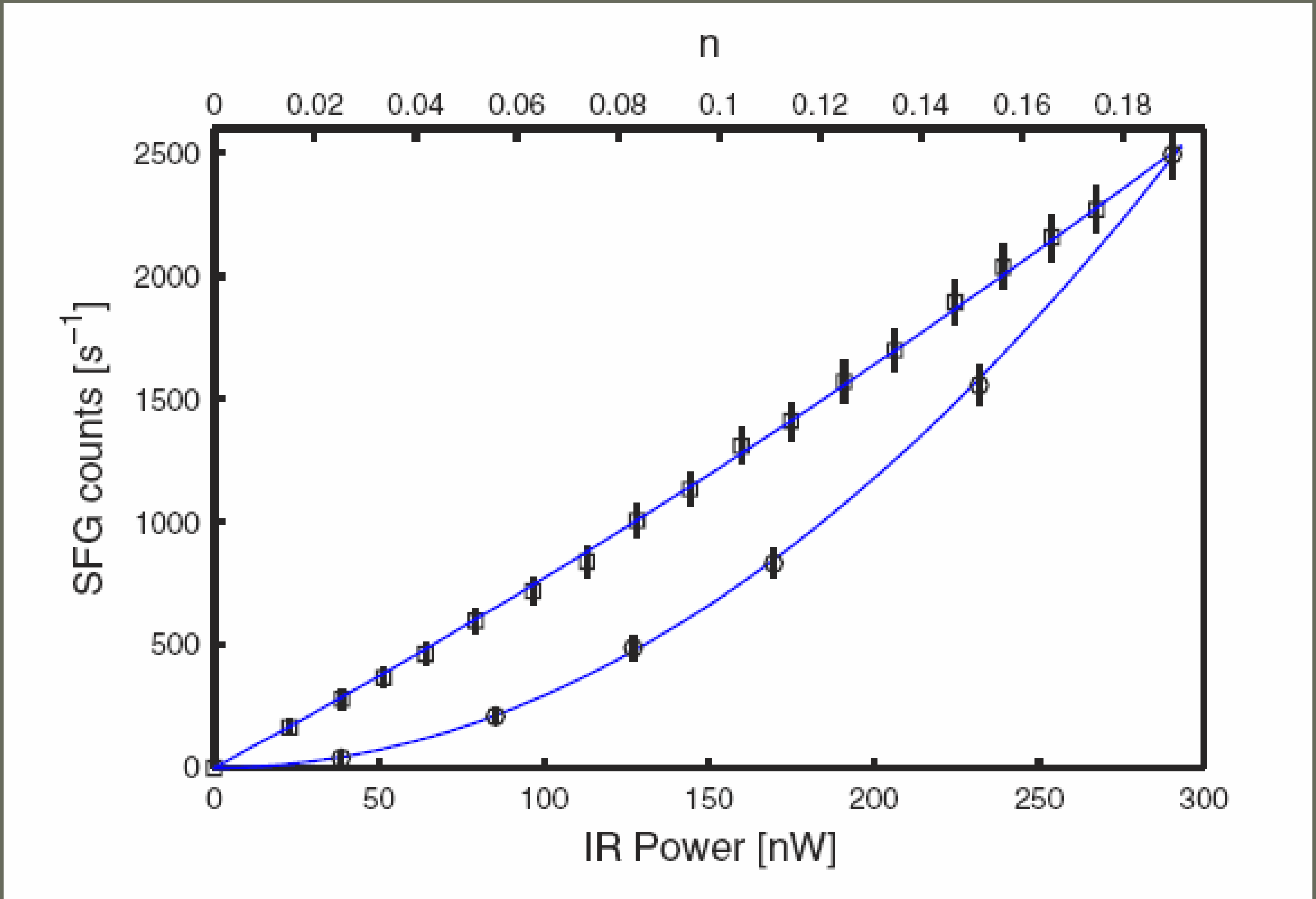
- For classical light, probability of simultaneous absorption of

  n photons $\propto I^{n}$
- Multiphoton absorption more likely in regions of high light intensity
- Excitation (photoemission, fluorescence, lithography, photochemistry, n photons can be localized
- Ultrafast light pulses have high peak intensities, allowing MPE at low average power
- For entangled-n-photon light, probability of simultaneous absorption of n photons $\propto I$





Entangled-Photon SFG (Experiment)



After Dayan, Pe'er, Friesem, and Silberberg, *Phys. Rev. Lett.* **94**, 043602 (2005)

EXAMPLES

Multiphoton

- Absorption

T: Göppert-Mayer (1931)

E: Franken *et al.* (1961)

- Photoemission

T: Bloch (1964)

E: Teich & Wolga (1964)

- Microscopy

T: Sheppard & Kompfner (1978)

E: Denk *et al.* (1990)

- Lithography

T: ancient

E: 3D..Maruo & Kawata (1997)

- OCT (Optical Coherence Tomography – Single Photon)

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T: Fei *et al.* (1997)

E: Dayan *et al.* (2004)

- Photoemission

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E:

- Microscopy

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E:

- Lithography

T: Boto *et al.* (2000)

E:

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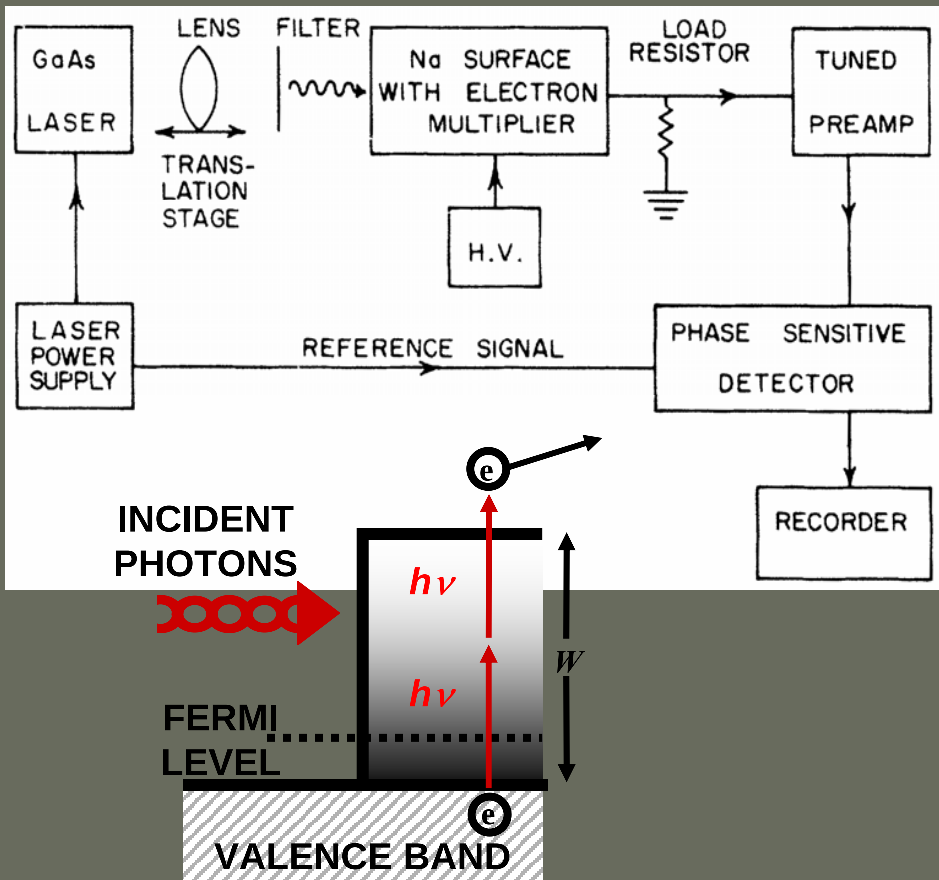
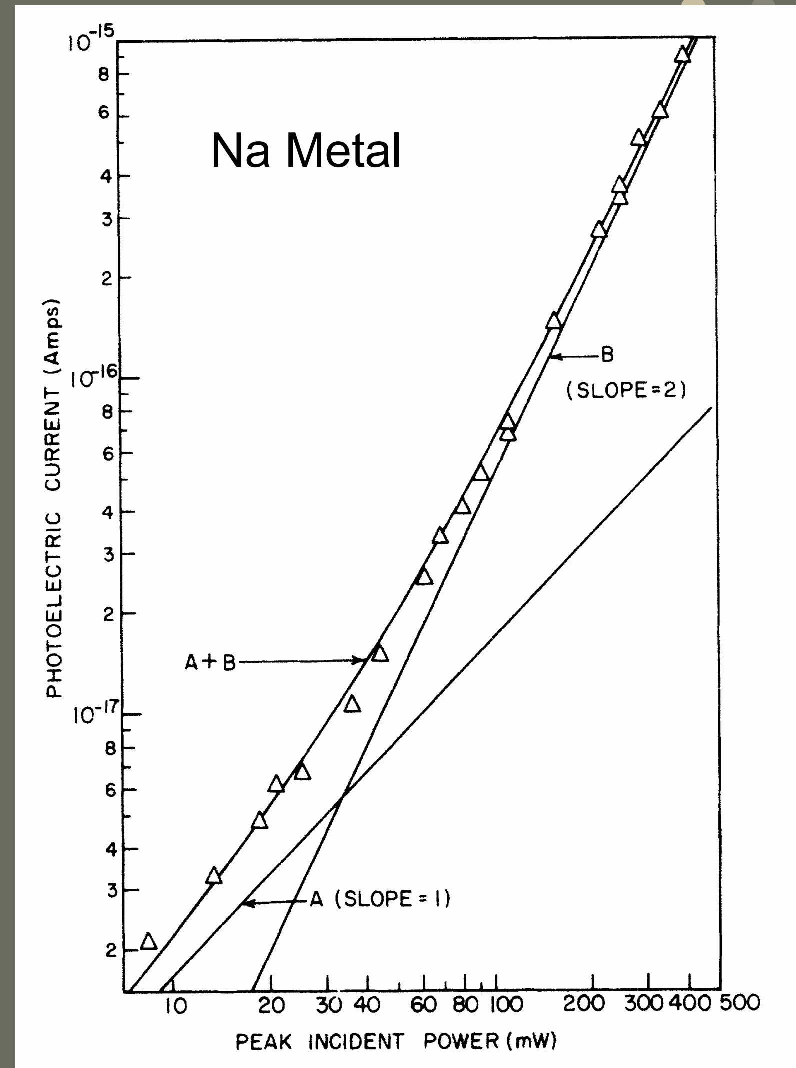
T: Abouraddy *et al.* (2002)

E: Nasr *et al.* (2003)

Two-Photon Photoemission



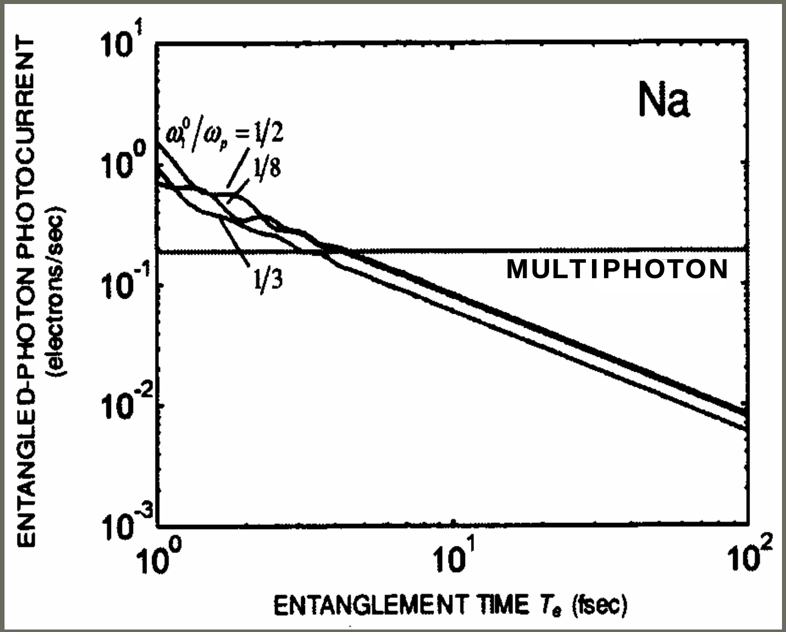


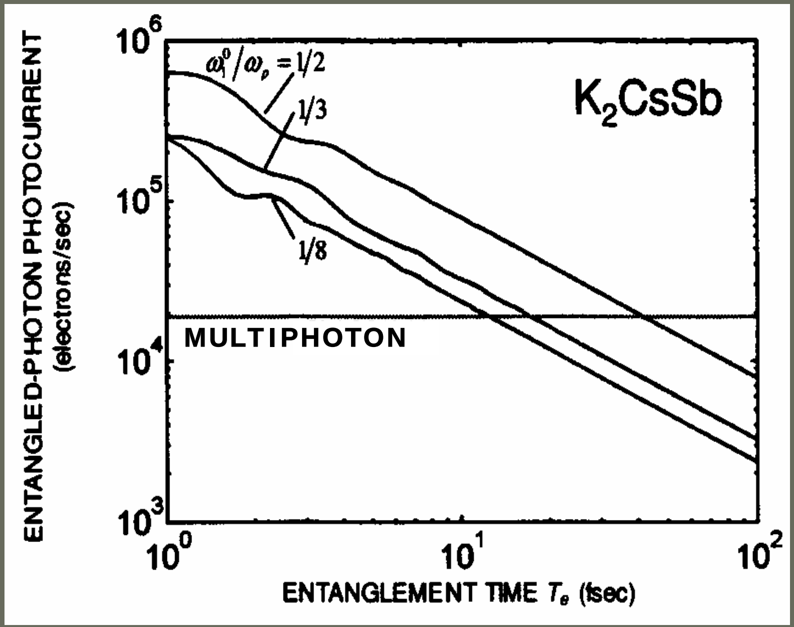
$E_{max} = h\nu - W$ (Einstein)

$E_{max} = 2h\nu - W$ (2QPE)

After Teich, Schroeer, & Wolga, *Phys. Rev. Lett.* **13**, 611-614 (1964)

Entangled-Photon Photoemission (Theory)





After Lissandrin, Saleh, Sergienko, & Teich, *Phys. Rev. B* **69**, 165317 (2004)

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E:

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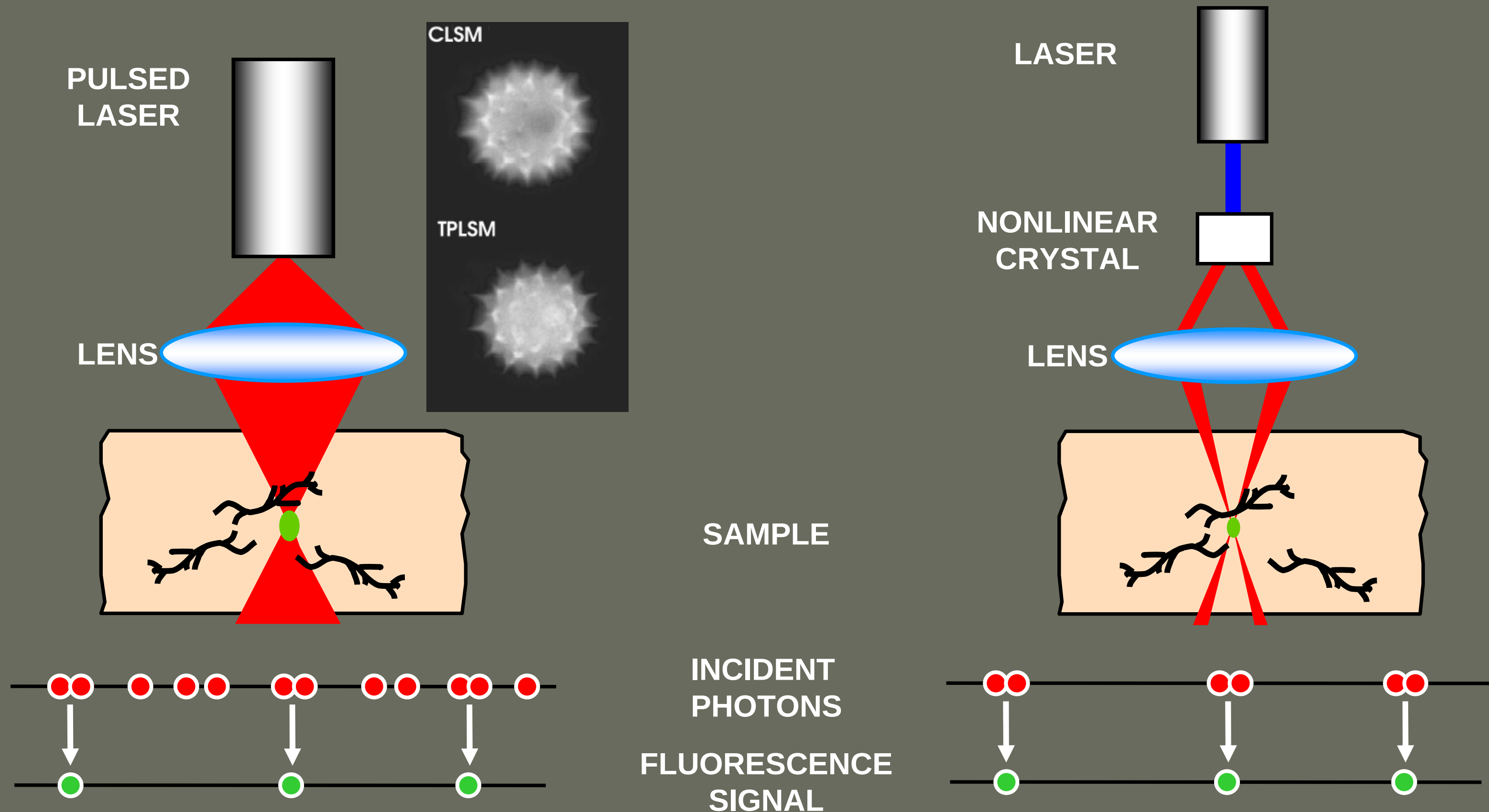
Multiphoton Microscopy

Entangled-Photon Microscopy



ADVANTANGES: Longer wavelength source penetrates more deeply into tissue. Excitation only occurs only at focal region – eliminates pinhole detectors, increases SNR, and provides optical sectioning capabilities.

DISADVANTAGES: Large photon flux is required. Samples must have broad upper-energy levels. Expensive titanium:sapphire laser system. Sample photodamage.

ADVANTANGES: Guaranteed photon pairs create comparable depth penetration but at substantially reduced light levels. Samples do not require broad upper-energy levels. Pump laser can be continuous wave or pulsed.

DISADVANTAGES: Overall photon flux is low. Entangled-photon absorption cross-section and focusing optics are unknown.

After Teich & Saleh, *Československý časopis pro fyziku* **47**, 3-8 (1997); U.S. Patent 5,796,477 (issued August 18, 1998)

EXAMPLES

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E:

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[***Other applications include distributed imaging and holography, quantum metrology and ellipsometry, quantum information and communications***]

BOSTON UNIVERSITY
Statement of Work
May 1, 2008 – April 30, 2010

1. **QUANTUM-OPTICAL COHERENCE TOMOGRAPHY (QOCT) USING PARAMETRIC DOWNCONVERSION IN CHIRPED NONLINEAR CRYSTALS**

2. **THERMAL VS. TWO-PHOTON IMAGING**

3. **ENTANGLED-PHOTONIC QUBITS IN SPATIAL-PARITY SPACE FOR DIGITAL QUANTUM IMAGING**

1. QUANTUM-OPTICAL COHERENCE TOMOGRAPHY (QOCT) USING PARAMETRIC DOWNCONVERSION IN CHIRPED NONLINEAR CRYSTALS

M. B. Nasr, S. Carrasco, B. E. A. Saleh, A. V. Sergienko, M. C. Teich, J. P. Torres, L. Torner, D. S. Hum, and M. M. Fejer, “Ultrabroadband Biphotons Generated via Chirped Quasi-Phase-Matched Optical Parametric Down-Conversion,” *Phys. Rev. Lett.* **100**, 183601 (2008), highlighted in *Optics in 2008*, *OPN* (December 2008).

M. B. Nasr, O. Minaeva, G. N. Goltsman, A. V. Sergienko, B. E. A. Saleh, and M. C. Teich, “Submicron Axial Resolution in an Ultrabroadband Two-Photon Interferometer Using Superconducting Single-Photon Detectors,” *Opt. Express* **16**, 15104 (2008), co-published in *Virtual Journal of Biomedical Optics.*

N. Mohan, O. Minaeva, G. N. Gol’tsman, M. B. Nasr, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich, “Photon-Counting Optical Coherence-Domain Reflectometry Using Superconducting Single-Photon Detectors,” *Opt. Express* **16**, 18118-18130 (2008).

M. B. Nasr, D. P. Goode, N. Nguyen, G. Rong, L. Yang, B. M. Reinhard, B. E. A. Saleh, and M. C. Teich, “Quantum Optical Coherence Tomography of a Biological Sample,” *Opt. Commun.* (2008, in press), quantum physics eprint on Los Alamos National Laboratory server (2008) [http://xxx.lanl.gov/abs/0809.4721].

2. THERMAL VS. TWO-PHOTON IMAGING

B. E. A. Saleh and M. C. Teich, "Noise in Classical and Quantum Photon-Correlation Imaging," in *Advances in Information Optics and Photonics*, Vol. PM183, edited by A. T. Friberg and R. Dändliker (SPIE Press, Bellingham, WA, 2008), ch. 21, pp. 423-435.

- Two-photon imaging has higher SNR for same photon flux.
- However, since thermal light may have much greater photon flux, it can be superior.
- Detailed calculations are provided in book chapter cited above.

3. ENTANGLED-PHOTONIC QUBITS IN SPATIAL-PARITY SPACE FOR DIGITAL QUANTUM IMAGING

A. F. Abouraddy, T. Yarnall, B. E. A. Saleh, and M. C. Teich, "Violation of Bell's Inequality with Continuous Spatial Variables," *Phys. Rev. A* 75, 052114 (May 2007).

T. Yarnall, A. F. Abouraddy, B. E. A. Saleh, and M. C. Teich, "Experimental Violation of Bell's Inequality in Spatial-Parity Space," *Phys. Rev. Lett.* 99, 170408 (November 2007), co-published in *Virtual Journal of Quantum Information*.

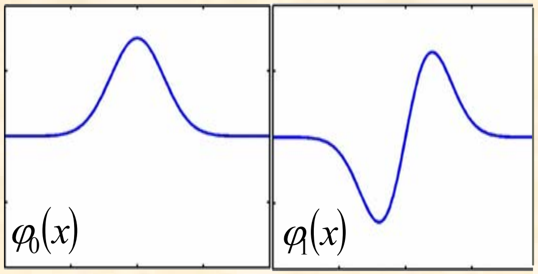
T. Yarnall, A. F. Abouraddy, B. E. A. Saleh, and M. C. Teich, "Synthesis and Analysis of Entangled Photonic Qubits in Spatial-Parity Space," *Phys. Rev. Lett.* 99, 250502 (December 2007), co-published in *Virtual Journal of Quantum Information*.

T. Yarnall, A. F. Abouraddy, B. E. A. Saleh, and M. C. Teich, "Spatial Coherence Effects in Second- and Fourth-Order Temporal Interference," *Opt. Express* 16, 7634-7640 (May 2008).

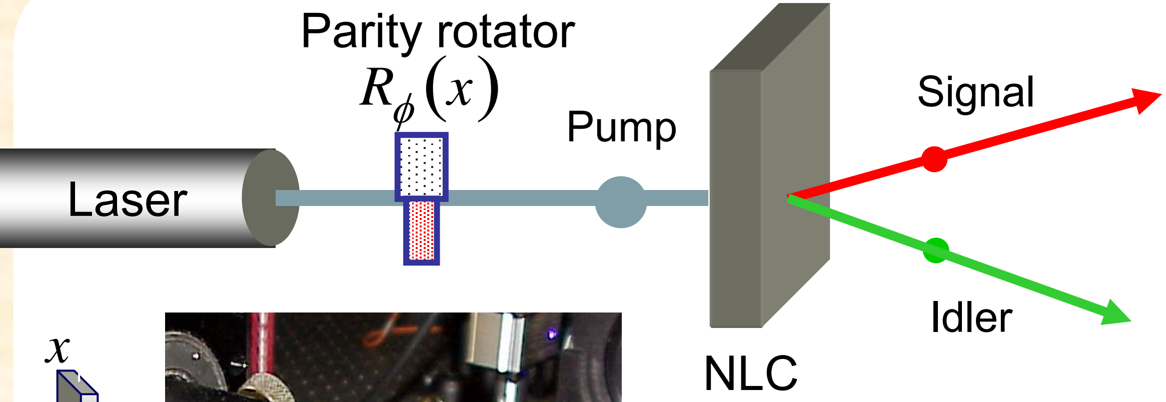
Digital Quantum Imaging

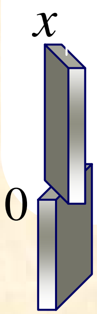
- Image acquisition (metrology, microscopy)
- Image synthesis (lithography)
- Image processing (enhancement, restoration)
- Image recognition & classification
- Image coding

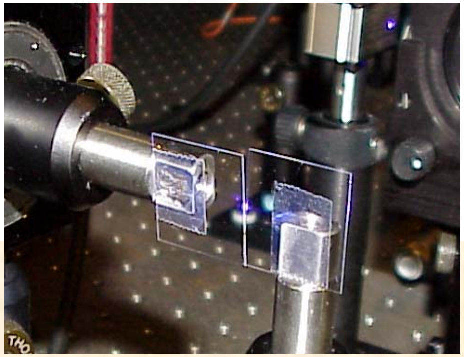
Spatial Parity Qubits



We demonstrated that entangled spatial-parity qubits can be generated by SPDC controlled by a classical pump parameter







Photon-Pair State

$$\left|\Phi^+\right\rangle + e^{i\phi}\left|\Psi^+\right\rangle$$

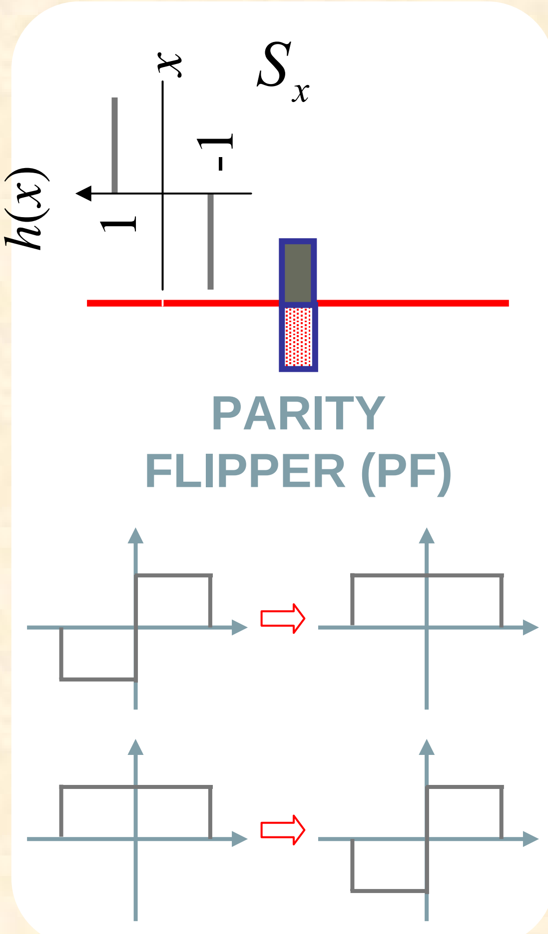
$$\left|\Phi^\pm\right\rangle = \frac{1}{\sqrt{2}}\left[\left|e\right\rangle\left|e\right\rangle \pm \left|o\right\rangle\left|o\right\rangle\right]$$

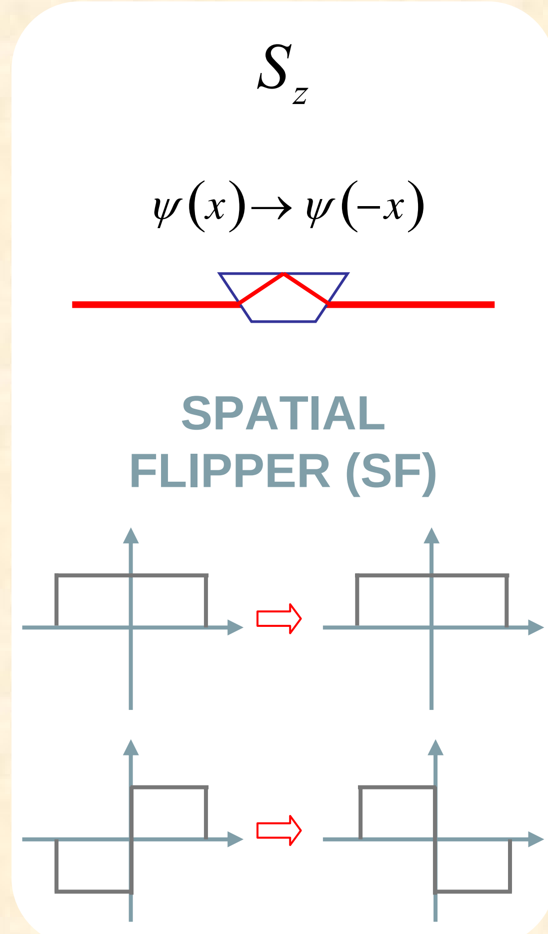
$$\left|\Psi^\pm\right\rangle = \frac{1}{\sqrt{2}}\left[\left|e\right\rangle\left|o\right\rangle \pm \left|o\right\rangle\left|e\right\rangle\right]$$

By manipulating the pump spatial parity, a CLASSICAL parameter, we can dial in superpositions of the two Bell states $\left|\Psi^+\right\rangle, \left|\Phi^+\right\rangle$

We tested the entanglement of the generated state via measurement of quantum interferograms and a Bell-inequality test

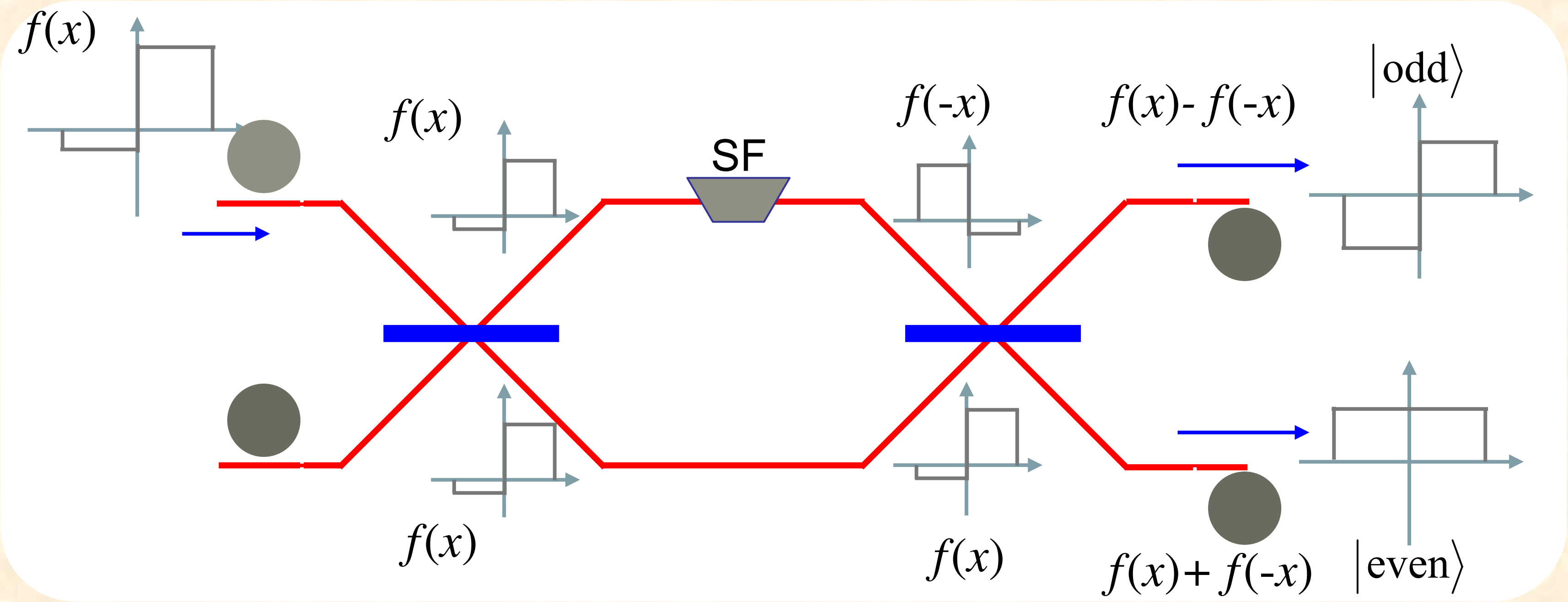
Quantum operators, such as rotation in the Poincaré sphere, can be implemented with simple optical elements (phase modulators)





QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

A parity Analyzer (PA) is implemented by a MZI with an additional mirror in one arm



Future work: Generalization to multiple pixels

Digital Quantum Imaging