Single Photon Imaging and Two-Photon Absorption

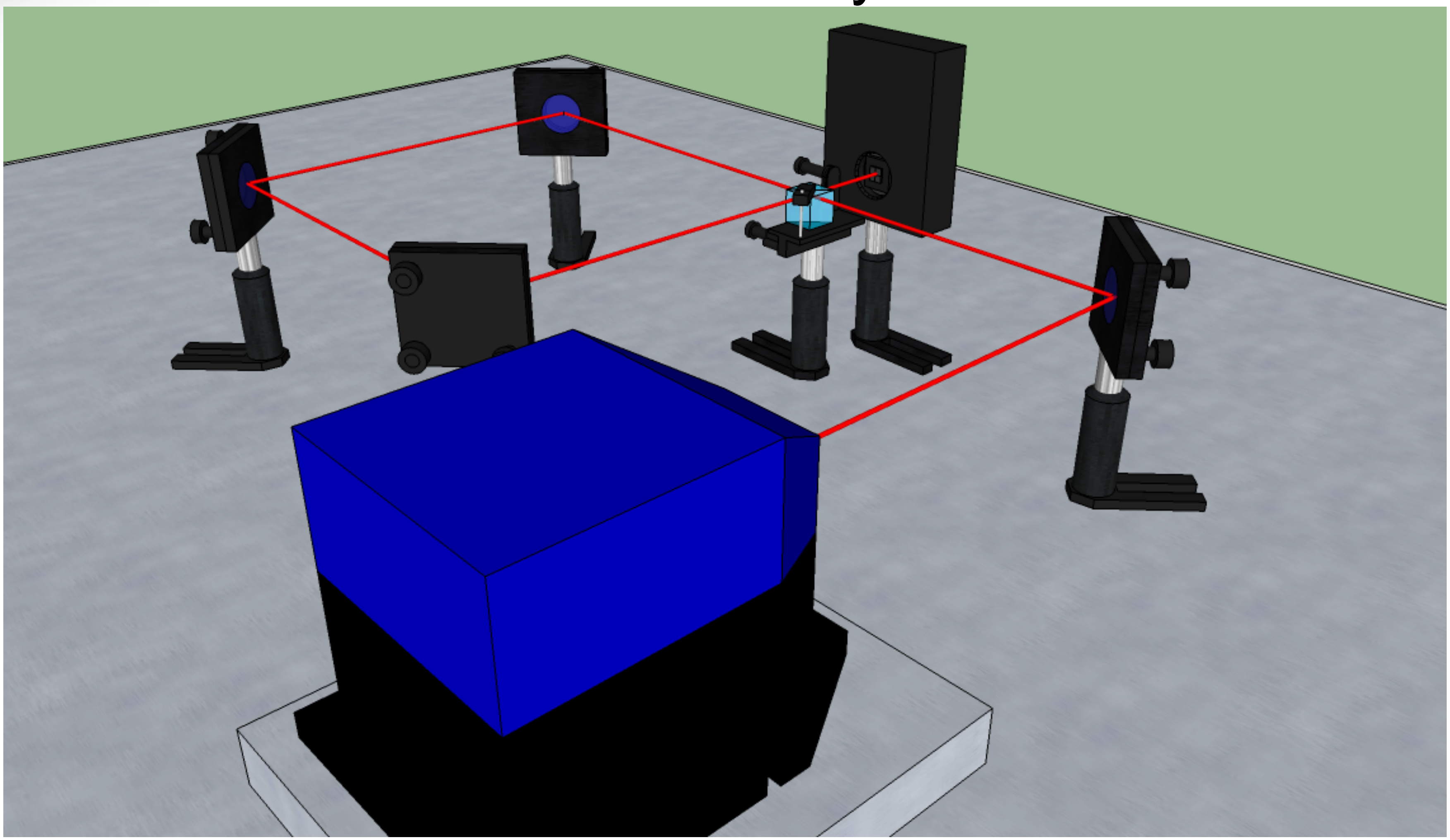
Howell, Boyd, Saleh and Teich
Quantum Imaging MURI

Overview

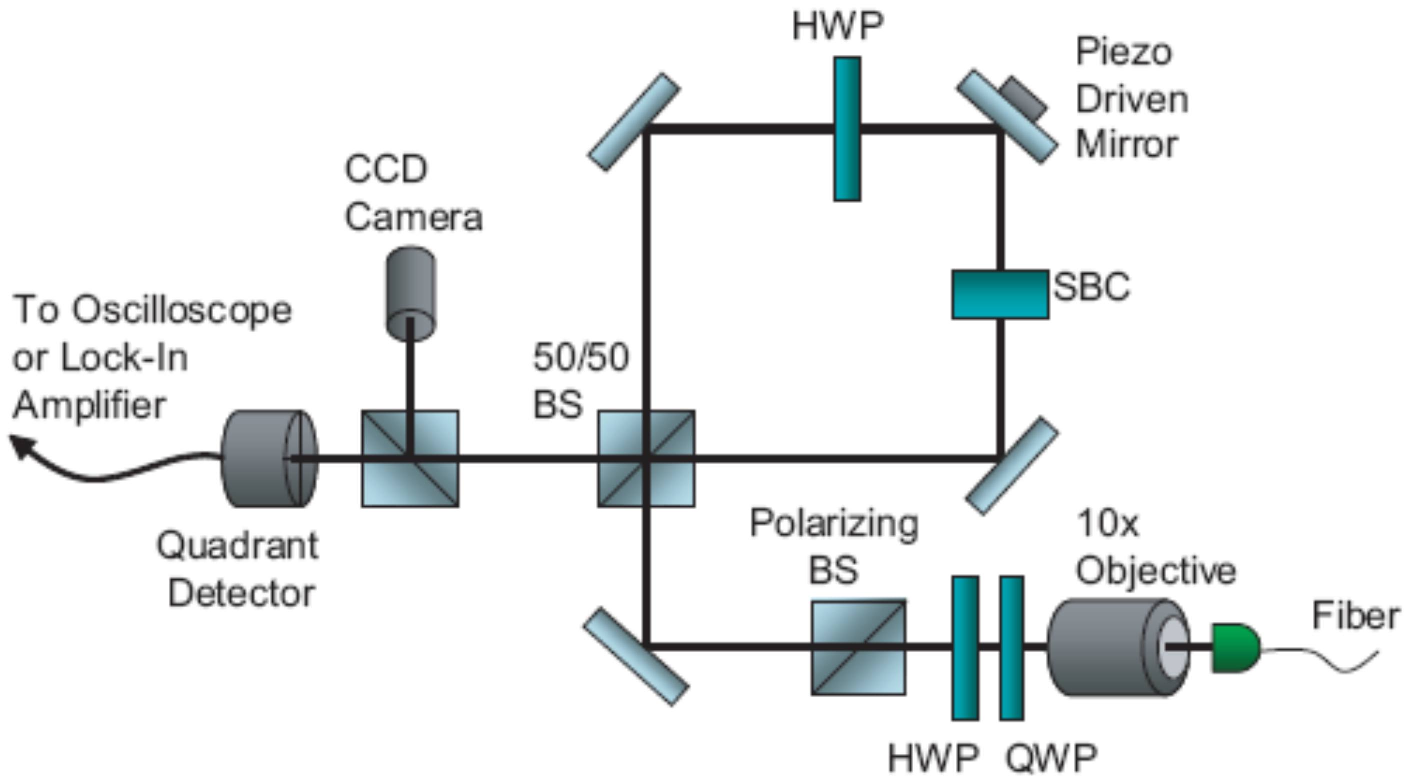
- Recent Achievements
  - Beam Deflection Measurements
  - Partial Coherence
- Current Work
  - 4^{th} order diffractionless propagation
  - Two-Photon Absorption (in Rb and QDots)
- Future
  - Steganography

UNIVERSITY of ROCHESTER

Weak Value Deflection
Interferometrically enhanced defelction

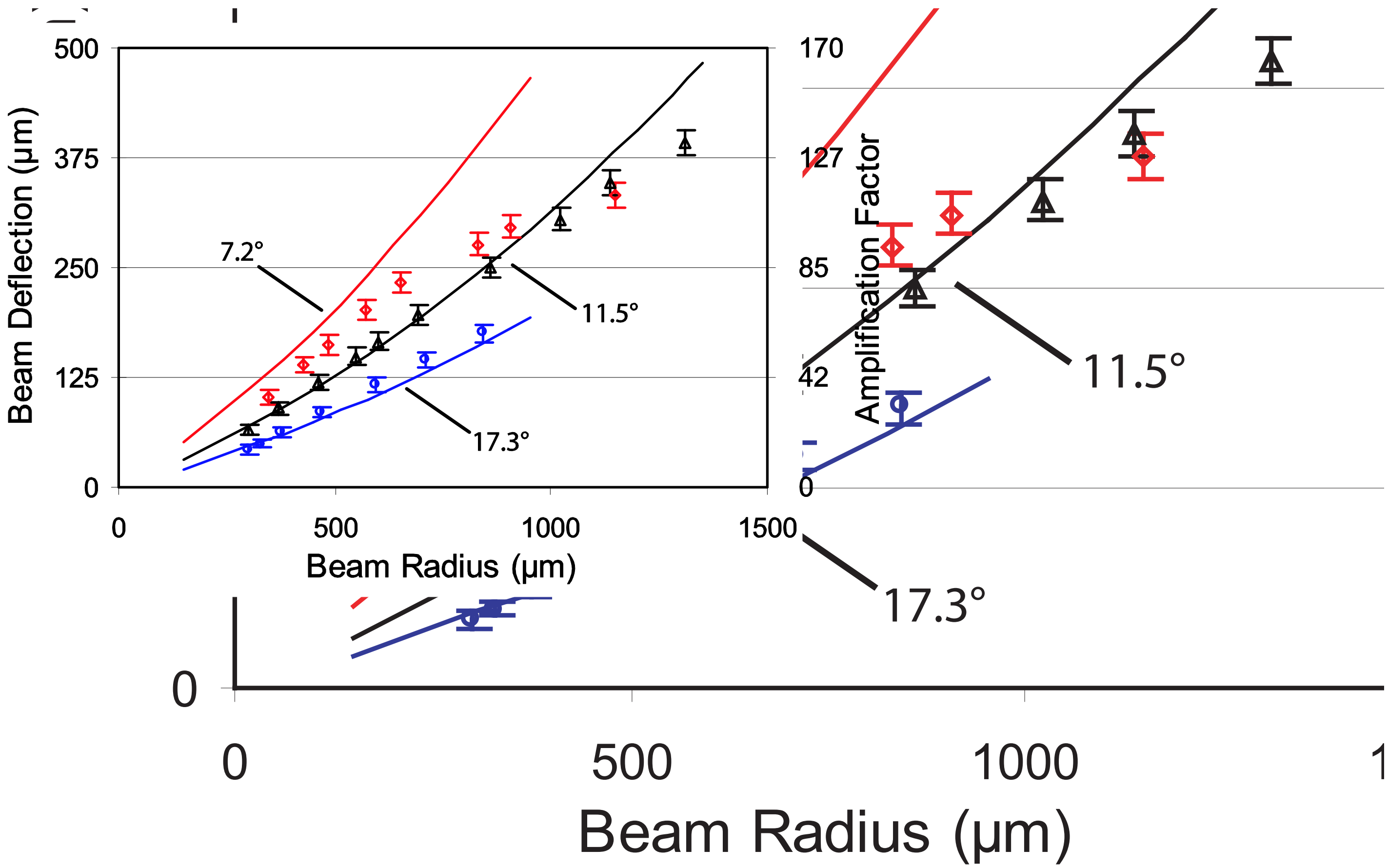


Experiment

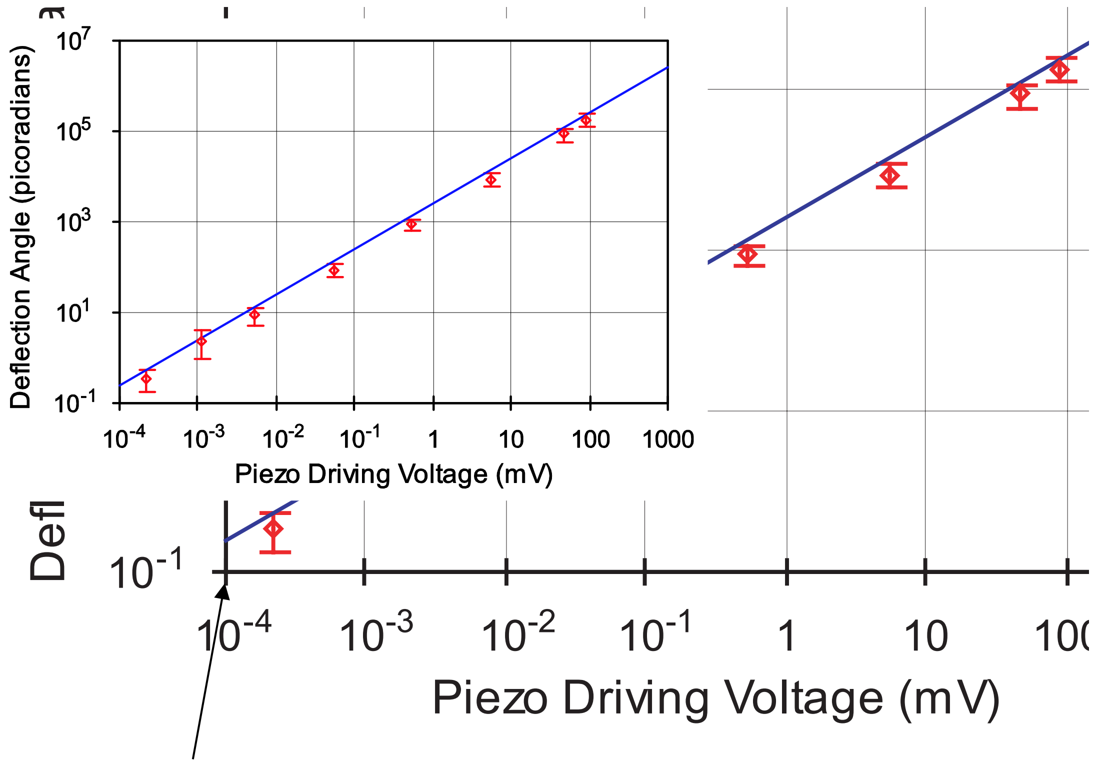


Phys. Rev. Lett. **102**, 173601 (2009)

Results


Beam Deflection (µm)
500
375
250
125
0
0
500
1000
1500
Beam Radius (µm)
7.2°
11.5°
17.3°
Amplification Factor
170
127
85
42
0
11.5°
17.3°
0
0
500
1000
Beam Radius (µm)

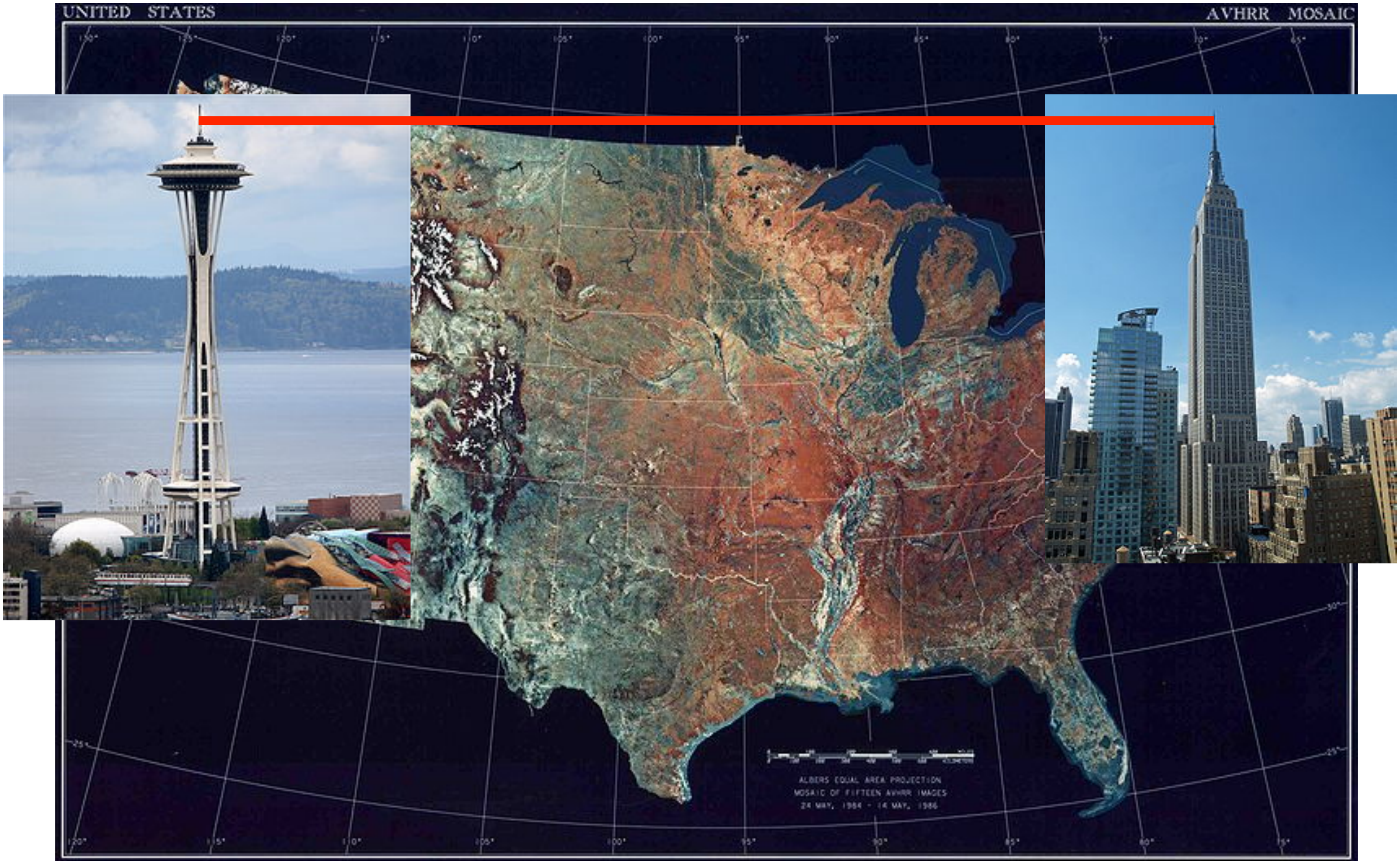
Precision Beam Deflection



560 femto radians

Phys. Rev. Lett. **102**, 173601 (2009)

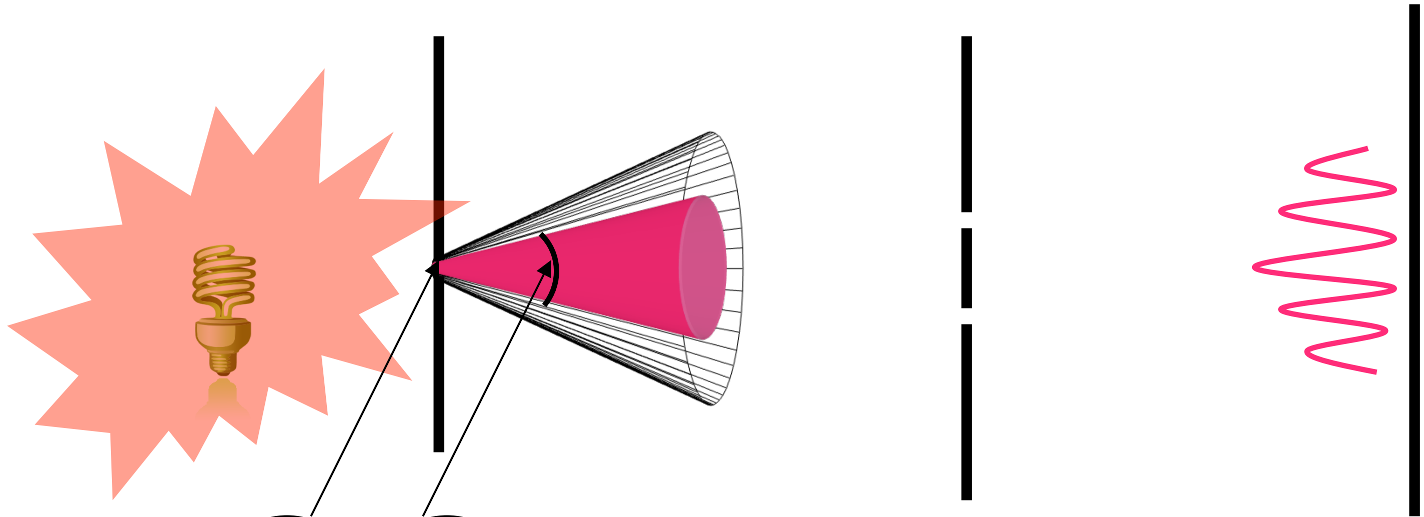
Deflection


UNITED STATES
AVHRR MOSAIC
ALBERS EQUAL AREA PROJECTION
MOSAIC OF FIFTEEN AVHRR IMAGES
24 MAY, 1984 - 14 MAY, 1986

Possibilities

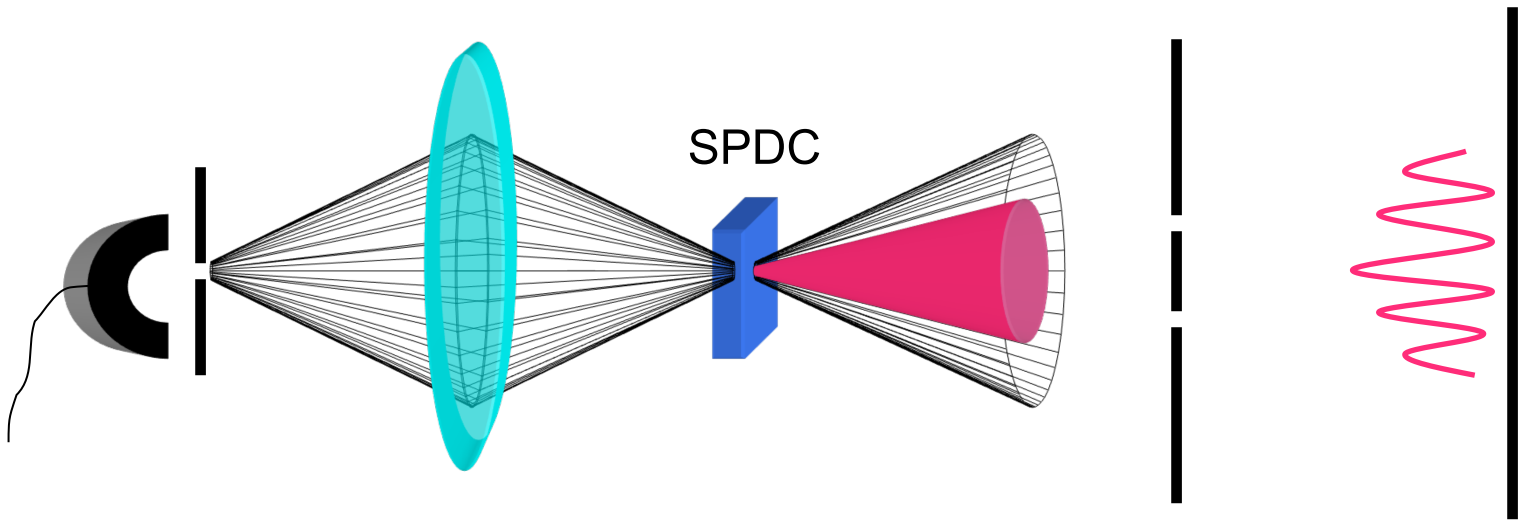
- Standard Quantum Limit
  - Squeezed and other quantum beams can increase the SNR
- Phase Amplification with low light levels on detector to SQL
- Position measurements to attometer sensitivity
- Kasevich’s group and Gravity group at Washington building setups

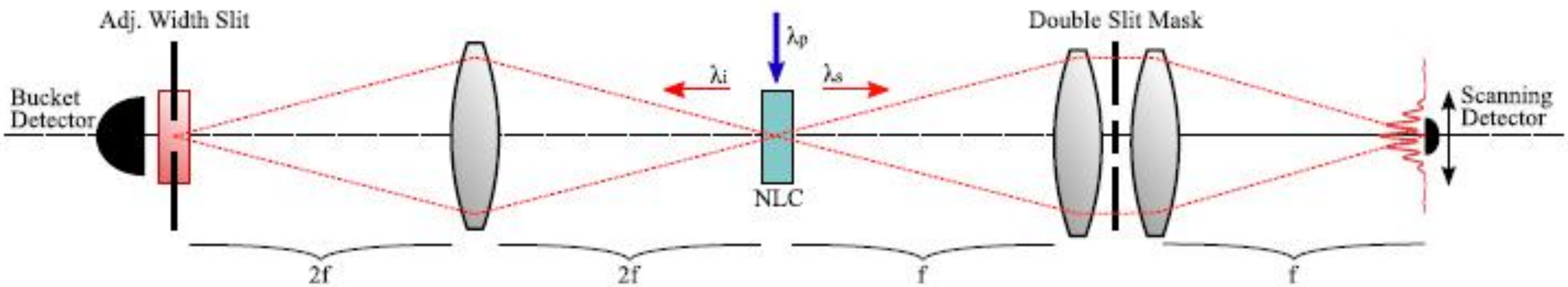
Partial Coherence with Bob Boyd



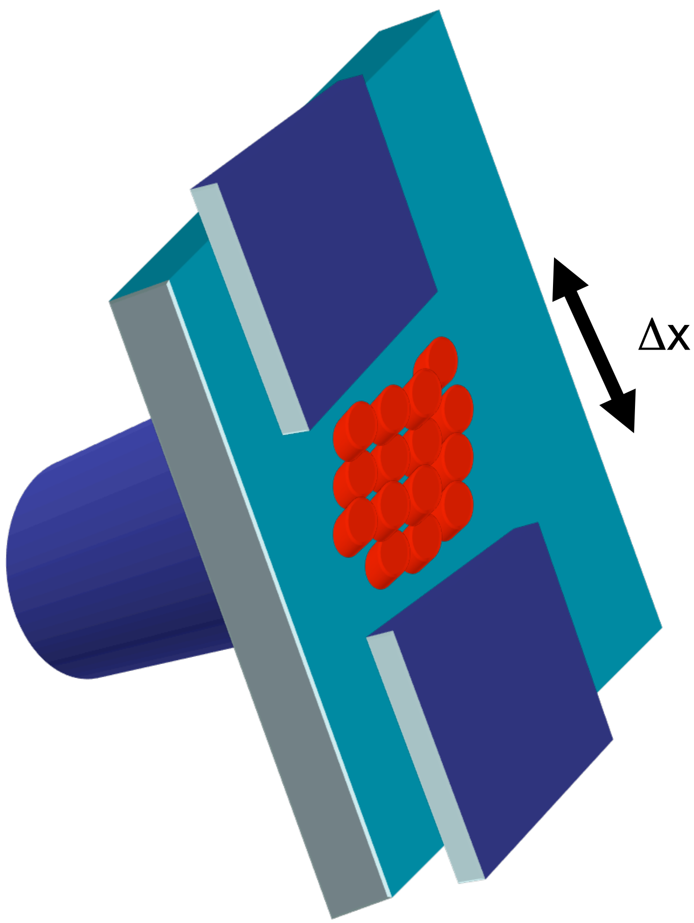
$$\Delta x \Delta \theta \geq 2\lambda$$

Single Photon Partial Coherence with Bob Boyd



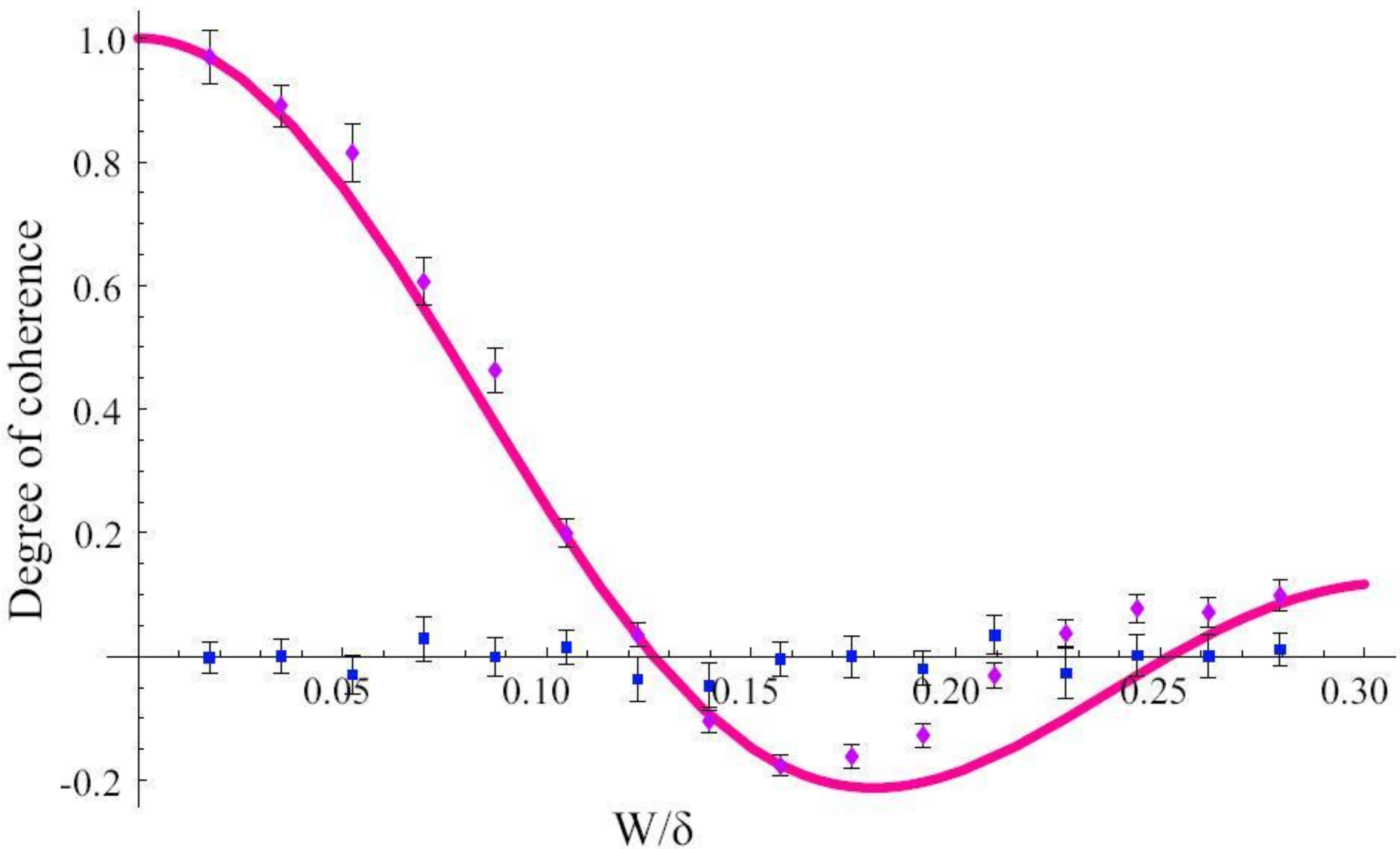


Biphoton Birthplace and Partial Coherence



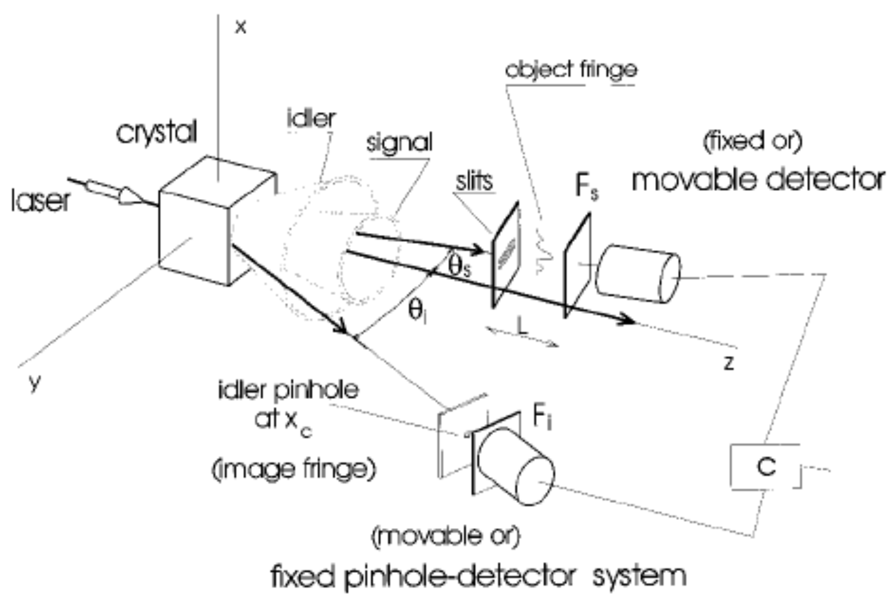
- Transverse Δx modified projectively by measuring the twin
- Slit width constrained by twin

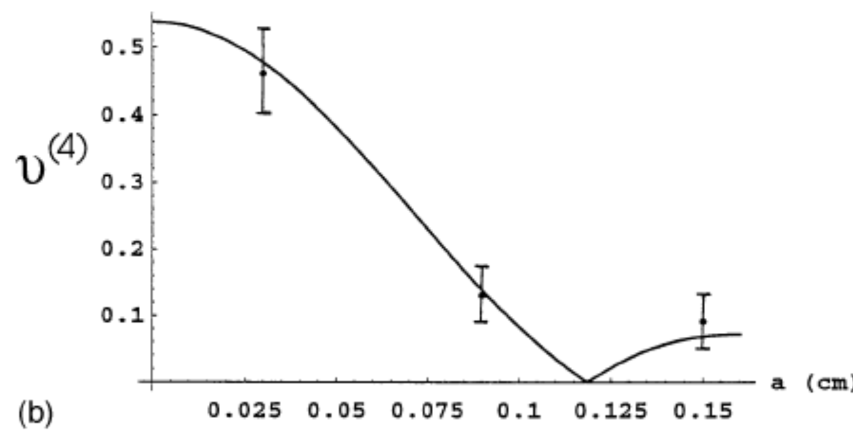
Heralded Single Photon Partial Coherence



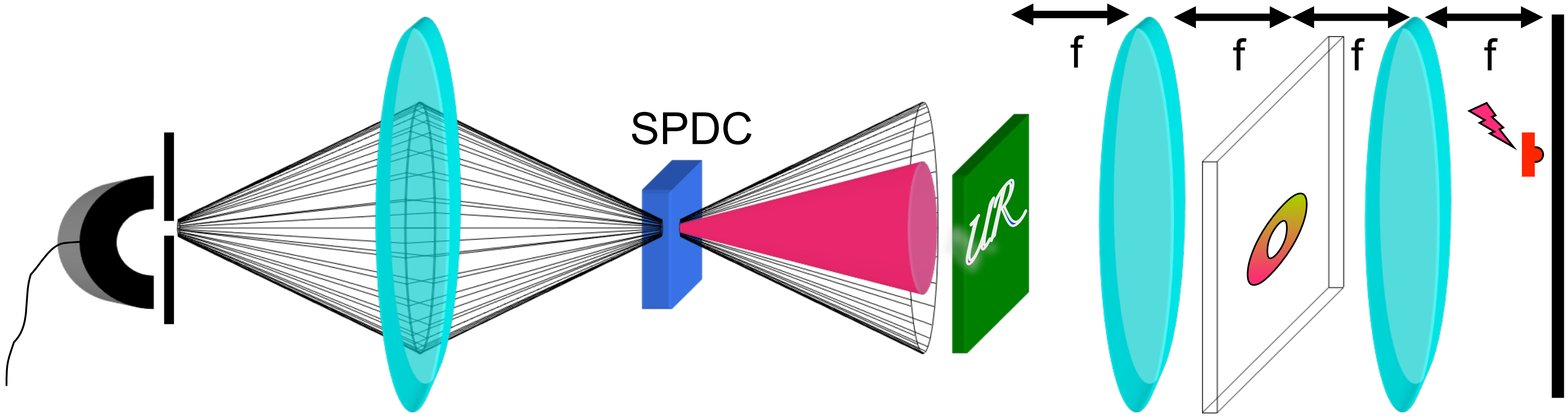
Related Work

- Geraldo Barbosa
  - "Quantum images in double-slit experiments with Spontaneous down-conversion light" PRA **54**, 4473 (1996)



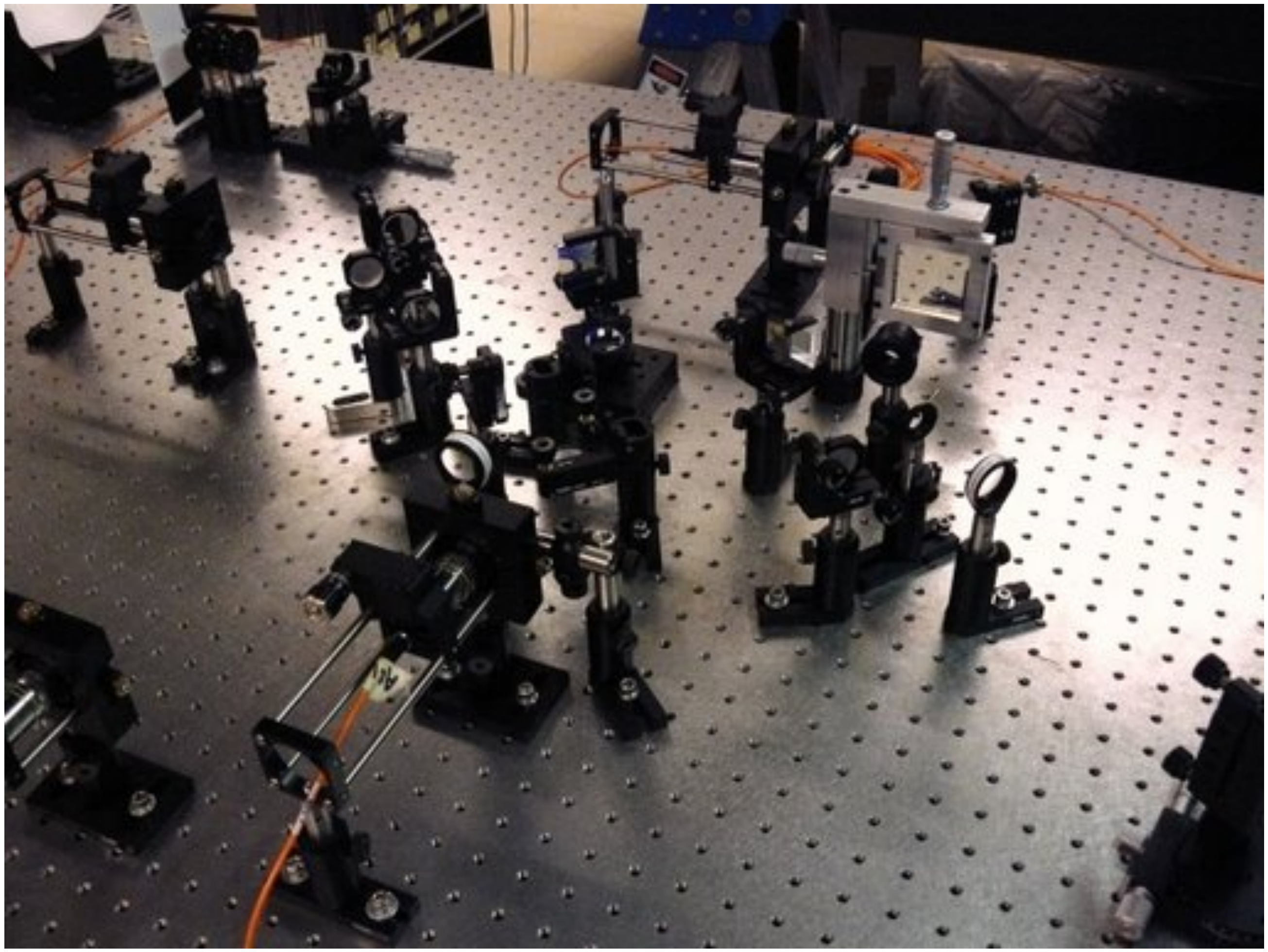


Quantum Steganography Setup



- High Pass Vanderlugt Filter (Nonorthogonal Images)
- 2nd Order Low Coherence (Trace over transverse momentum)
- 4th order High Coherence
- Multiplexed Holograms

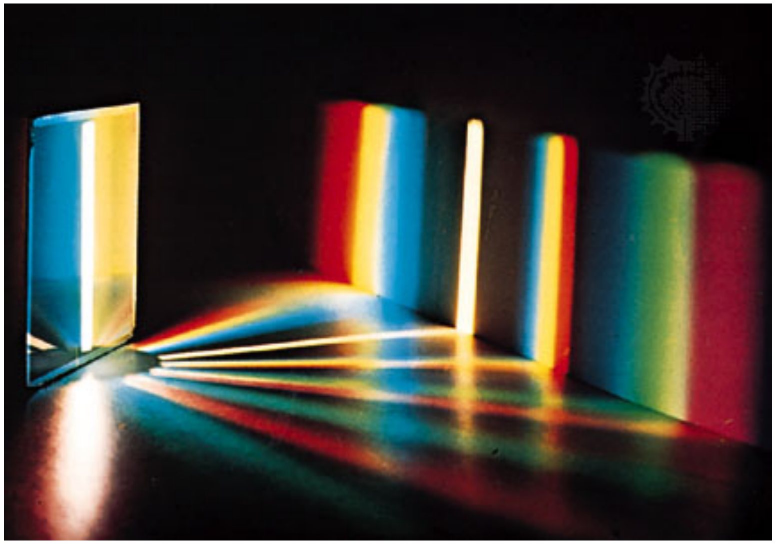
Apparatus



Steganography Agenda

- Tried 9 months unsuccessfully
- Shelved until we obtain spatial light modulators

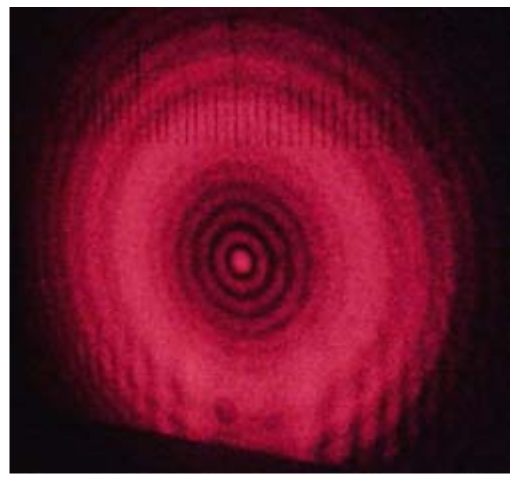
Diffractionless Propagation: Examples of Diffraction



Diffraction Grating

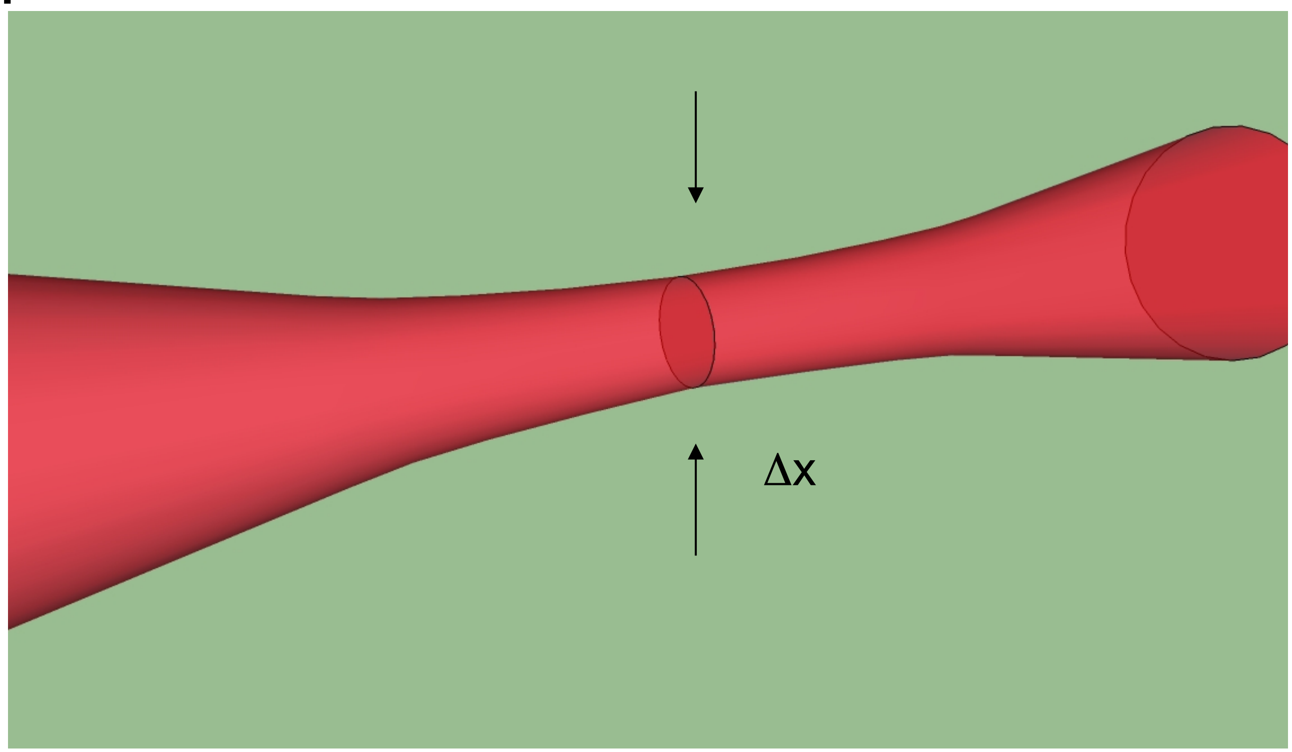
Solar Glory

Poisson's (Arago's or Maraldi's) Spot



4^{th} order Diffractionless Propagation

- Diffraction reveals wavenature of light
- Gaussian Beams have Fourier Transform related properties $\Delta x \Delta k=1$



4th order Diffractionless Propagation

Heisenberg Uncertainty Relation

$$\Delta x \Delta p \geq \frac{1}{2}\left|\langle [x, p] \rangle\right|$$

Einstein Podolsky Rosen Observables

$$x_{12} = x_1 - x_2 \quad p_{12} = p_1 + p_2$$

EPR Uncertainty Relation

$$\Delta x_{12} \Delta p_{12} \geq 0$$

Does this hint at 4^{th} order diffractionless propagation of a beam?

Related Work

- BU Group
  - “Odd- and Even-Order Dispersion Cancellation in Quantum Interferometry” Phys. Rev. Lett. 102, 100504 (2009)
  - “Even-Order Aberration Cancellation in Quantum Interferometry”, Cristian Bonato, Alexander V. Sergienko, Bahaa E. Saleh, Stefano Bonora, and Paolo Villoresi, Phys. Rev. Lett. 101, 233603 (2008)

4th order Diffractionless Propagation

Start off with a state vector

$$|\psi\rangle = A \int dk_i \int dk_s f(k_i, k_s) g(k_i, k_s) a^\dagger_{k_i} a^\dagger_{k_s} |0\rangle,$$

where

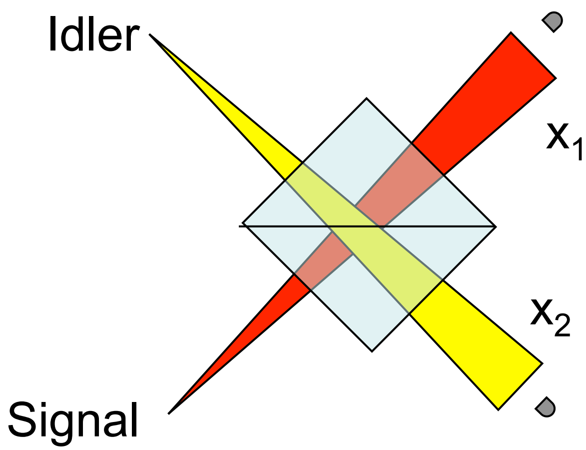
$$f(k_i, k_s) = e^{-(k_i + k_s)^2 \frac{\sigma^2}{8}} \qquad g(k_i, k_s) = \sin\left[\frac{k_i^2 L}{4k_0} + \frac{k_s^2 L}{4k_0}\right] / (k_i^2 + k_s^2)$$

After propagation the positive frequency field operators are given by

$$E_s^+(x_1) = \int dk_s^+ e^{-ik_s^+ x_1} e^{\frac{i(k_s^+)^2 z_s}{2k_0}} e^{-ik_s^+ d} e^{-\frac{i2\pi l_s}{\lambda}}$$

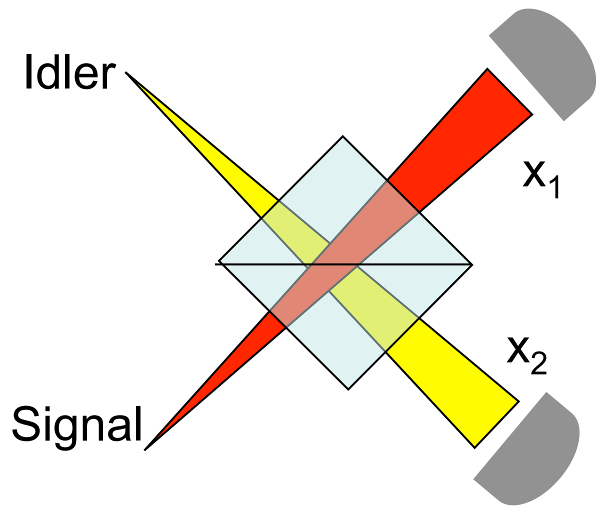
$$E_i^+(x_2) = \int dk_i^+ e^{-ik_s^+ x_2} e^{\frac{i(k_i^+)^2 z_i}{2k_0}} e^{-\frac{i2\pi l_i}{\lambda}}$$

4th order Diffractionless Propagation

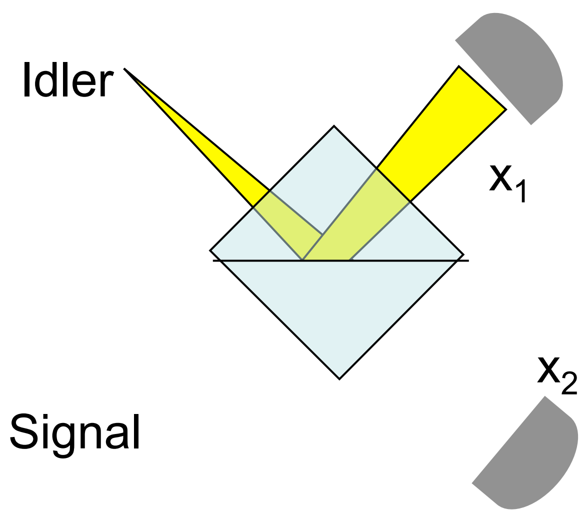


$$A_1(x_1, x_2) = \langle 0|E_s^+(x_1)E_i^+(x_2)|\psi\rangle$$

4th order Diffractionless Propagation



$$A_1(x_1, x_2) = \langle 0|E_s^+(x_1)E_i^+(x_2)|\psi\rangle$$



$$A_2(x_1, x_2) = \langle 0|E_s^+(x_2)E_i^+(x_1)|\psi\rangle$$

•Detectors become infinite in transverse dimension

4th order diffractionless propagation

The destructive interference rate function is then given by

$$R \propto \int_{-\infty}^{\infty} dx_1 \int_{-\infty}^{\infty} dx_2 \left| A_2(x_1, x_2) - A_1(x_1, x_2) \right|^2$$

The “infinite” bucket detectors and the momentum correlation imply

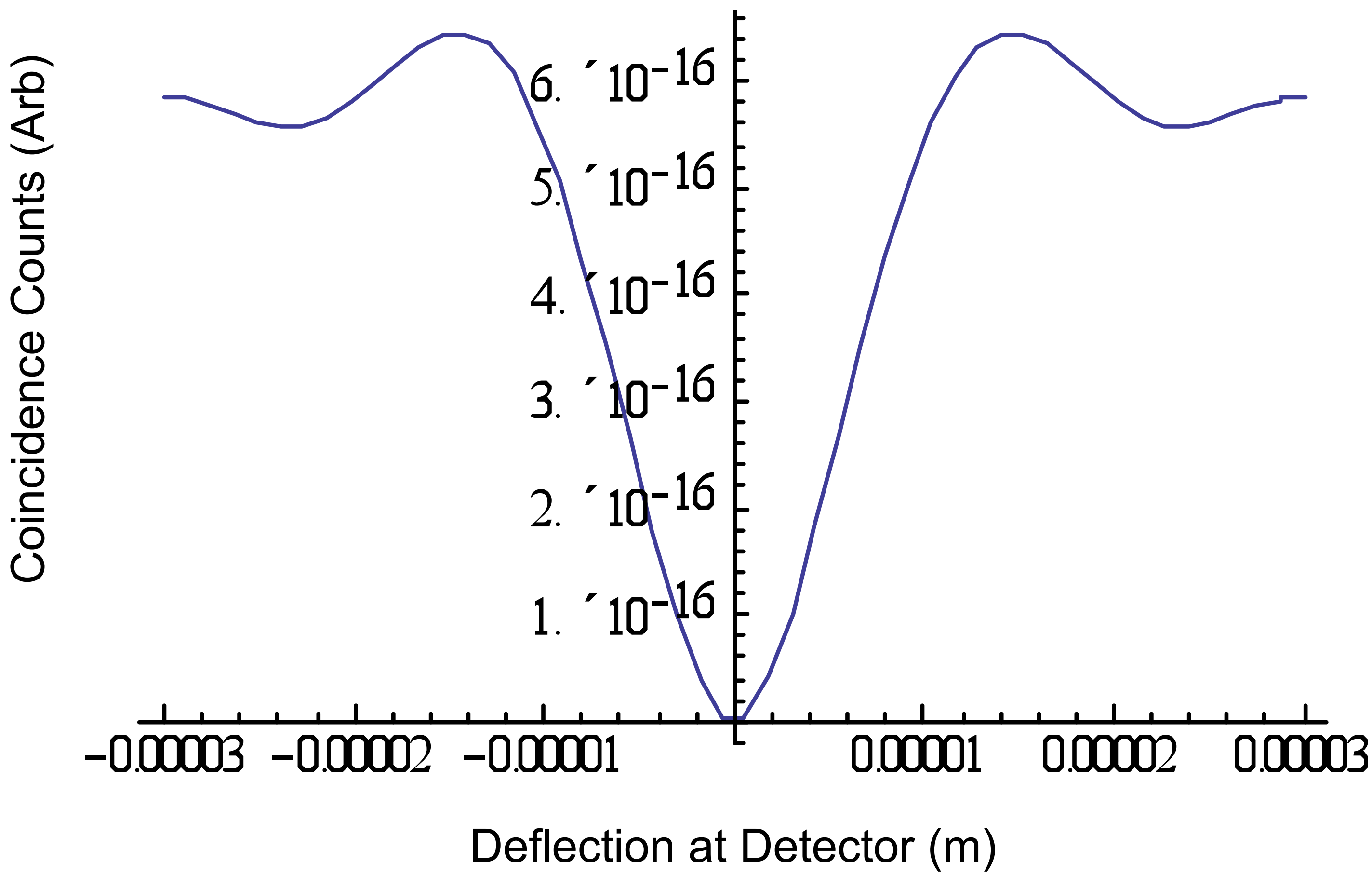
$$\int_{-\infty}^{\infty} dx_1 \int_{-\infty}^{\infty} dx_2 e^{i(k_s^- - k_s^+)} e^{i(k_i^- - k_i^+)} \propto \delta(k_s^- - k_s^+)\delta(k_i^- - k_i^+)$$

$$f(k_s, k_i) \propto \delta(k_s + k_i)$$

Leading to a rate function independent of propagation length

$$R \propto \int dk \sin^2(kd) \frac{\sin^2\left[\frac{k^2 L}{2k_0}\right]}{k^2}$$

Predicted Rate Function



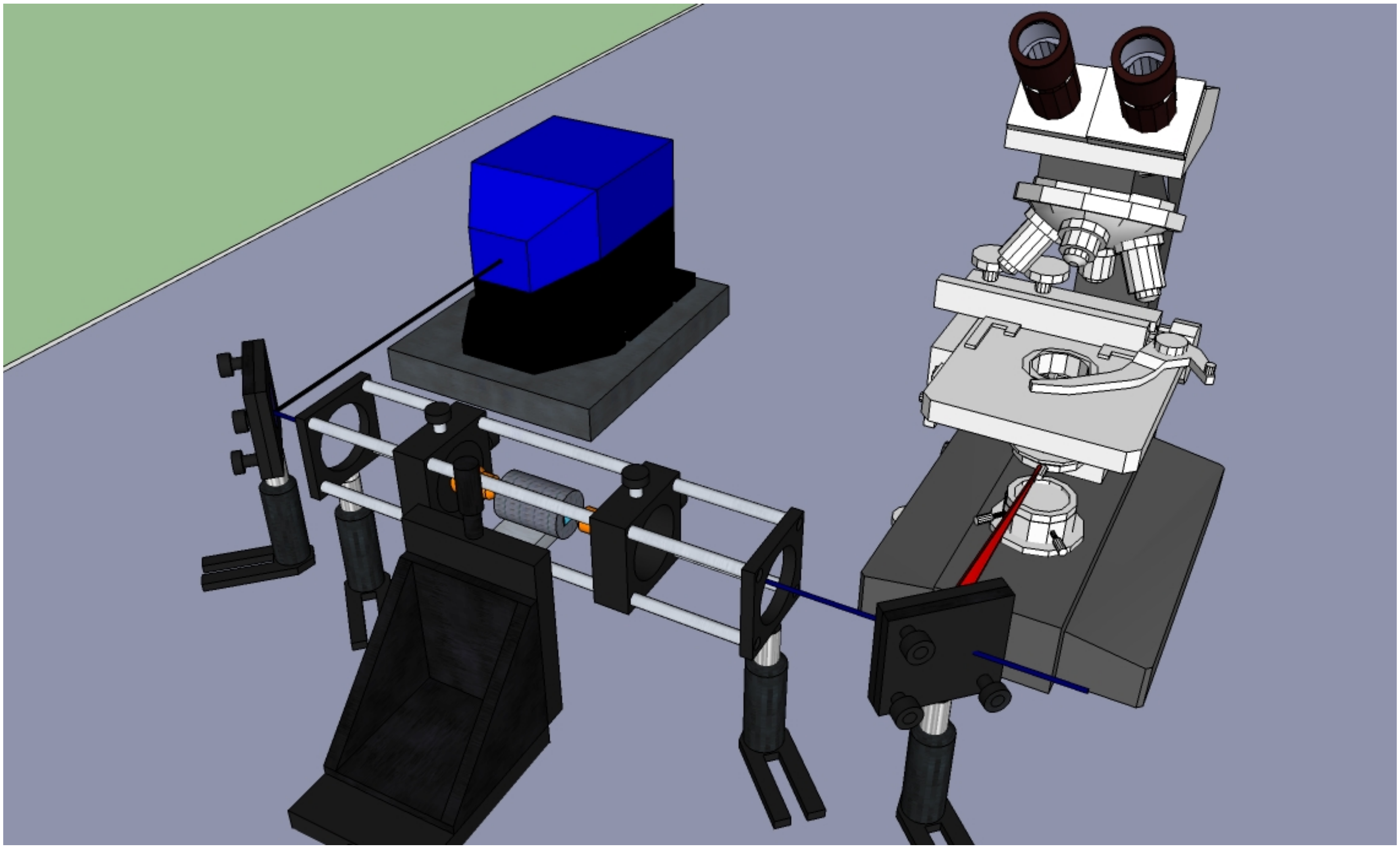
Diffraction Cancellation Spatial Analog of GVD compensation in HOM interferometer

Diffractionless Propagation		Dispersion Compensation
• Infinite transverse detector • Diffraction even order-paraxial • Vary transverse deflection to observe dip • Momentum Correlation (limited by pump angular bandwidth)	$\longleftrightarrow$	• Infinite detector response time • Even order dispersion cancellation • Vary path length to observe dip • Spectral Correlation (limited by pump spectral bandwidth)

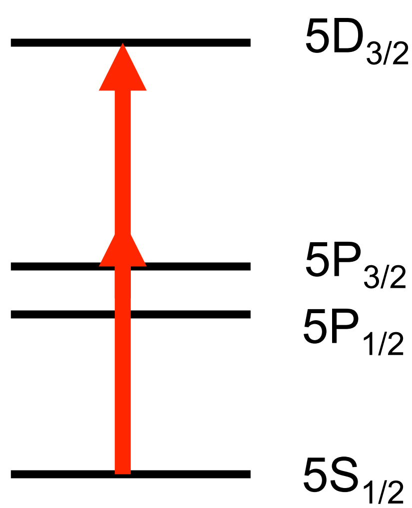
Now What?

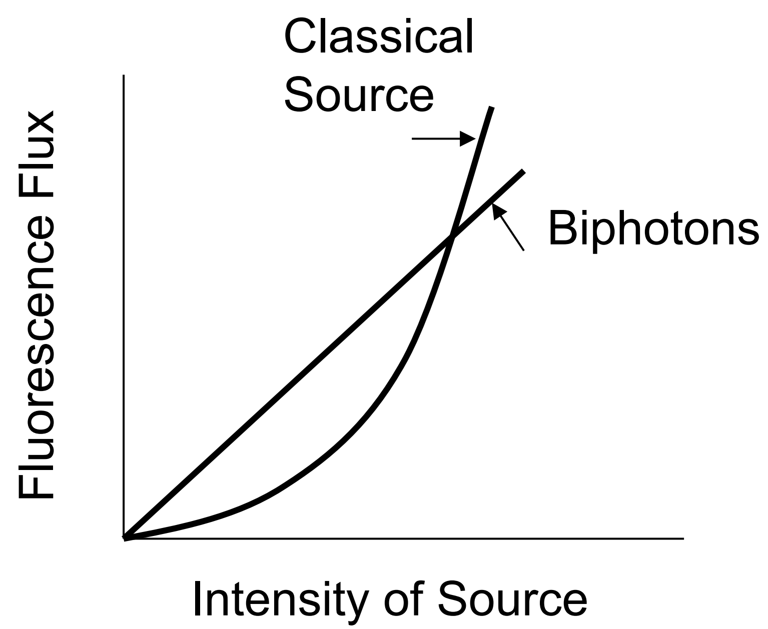
- Possibilities
  - Franson nonlocal dispersion cancellation → nonlocal diffraction cancellation
- Speculation
  - Propagation of images without diffraction?
  - Fourier transform in 2nd order, but image in 4th order?

Two Photon Absorption with Saleh and Teich, SRI and CVS



Two-Photon Absorption in Alkalis





Two-Photon Calculation

Time-frequency entangled biphoton

$$|\psi\rangle = \int d\omega_s \int d\omega_i f(\omega_s)\delta(\omega_p - \omega_s - \omega_i)\hat{a}_s^\dagger(\omega_s)\hat{a}_i^\dagger(\omega_i)|0\rangle$$

Second order perturbation theory in interaction picture

$$\langle 3|\langle 0|U^{(2)}(t_1,t_0)|\psi\rangle|1\rangle = \langle 3|\langle 0|\frac{1}{(i\hbar)^2}\int_{t_0}^{t} dt_1 \int_{t_0}^{t_1} dt_2 e^{-\frac{i\hat{H}_0}{\hbar}(t-t_1)}(\hat{\mathbf{d}}\cdot\hat{\mathbf{E}}(\mathbf{t_1}))e^{-\frac{i\hat{H}_0}{\hbar}(t_1-t_2)}(\hat{\mathbf{d}}\cdot\hat{\mathbf{E}}(\mathbf{t_2}))e^{-\frac{i\hat{H}_0}{\hbar}(t_2-t_0)}|\psi\rangle|1\rangle$$

Atom-field state after interaction

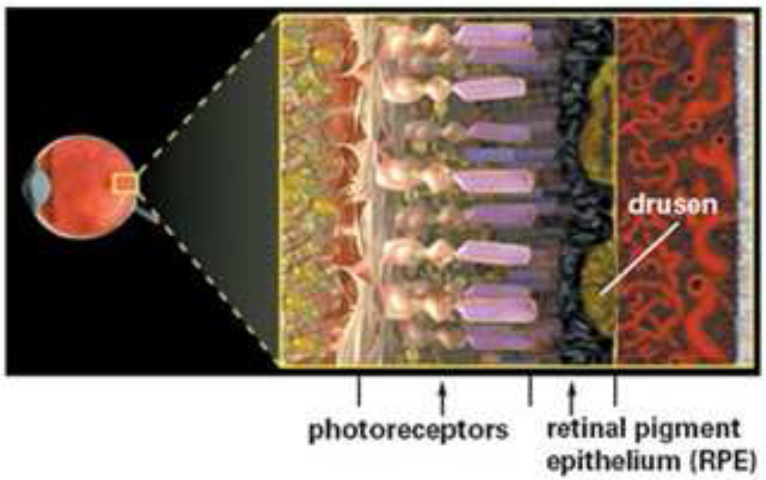
$$= -\sum_n d_{1n}d_{n3}\frac{\hbar\sqrt{\omega_0(\omega_p-\omega_0)}}{2\epsilon_0 cA}e^{-i\omega_{31}(t-t_1)}e^{-i\omega_p t_2}e^{-i(\omega_p-\omega_0+\omega_{n1})(t_1-t_2)}e^{-i\omega_0 t_2}e^{-i(\omega_p-\omega_0)t_1}g(t_2-t_1)|0\rangle|3\rangle$$

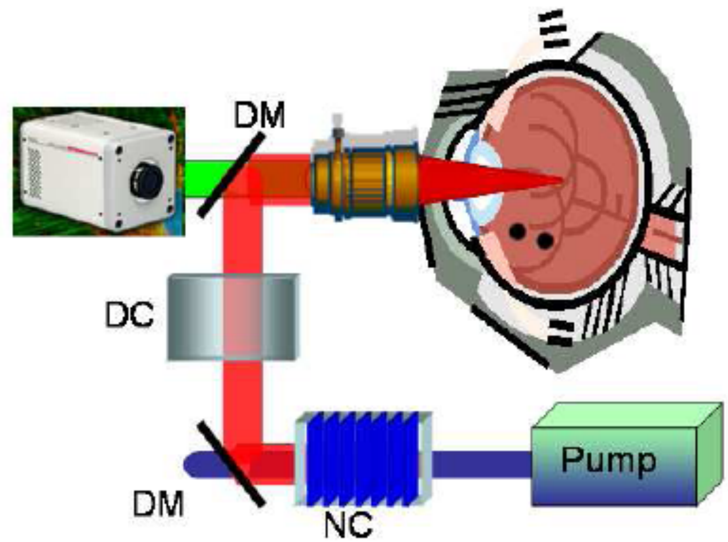
$$- \sum d_{1n}d_{n3}\frac{\hbar\sqrt{\omega_0(\omega_p-\omega_0)}}{2\epsilon_0 cA}e^{-i\omega_{31}(t-t_1)}e^{-i\omega_p t_2}e^{-i(\omega_0+\omega_{n1})(t_1-t_2)}e^{-i\omega_0 t_1}e^{-i(\omega_p-\omega_0)t_2}g(t_1-t_2)|0\rangle|3\rangle$$

Excited state probability for single intermediate excited state

$$|b_f(t)|^2 = \left|d_{23}d_{12}\frac{\omega_0}{\hbar\epsilon_0 cA}\right|^2 \frac{1}{\delta^2+(\gamma/2)^2}$$

Biphoton Bioimaging





- RPE cleans photoxins in eye (macular degeneration)
- Image Lipofuscin (fluorophor) between photoreceptors

- Future Work
  - Biological Quantum Imaging
  - Unsaturable Bell Inequality-like Weak Value experiment
  - Explore Transverse Properties of Propagation