Quantum Imaging

Quantum Radiometry and Quantum Aberration Correction

Robert W. Boyd

Department of Physics and
School of Electrical Engineering and Computer Science
University of Ottawa

The Institute of Optics and
Department of Physics and Astronomy
University of Rochester

The visuals of this talk will be posted at boydnlo.ca/presentations

Presented at the workshop on Advances in Computational and Quantum Imaging (ACQI), Purdue University, West Lafayette, Indiana, USA September 11, 2019

Quantum Imaging Outline

Introduction to Quantum Imaging

Examples of Quantum Imaging
- Two-color ghost imaging
- Interaction-free ghost imagin
- Imaging with “undetected photons”

Structured Light Fields for Quantum Information
- Dense coding of information using orbital angular momentum of light
- Secure Communication transmitting more than one bit per photon

Quantum, Nonlocal Aberration Correction

Quantum Radiometry

Quantum Imaging

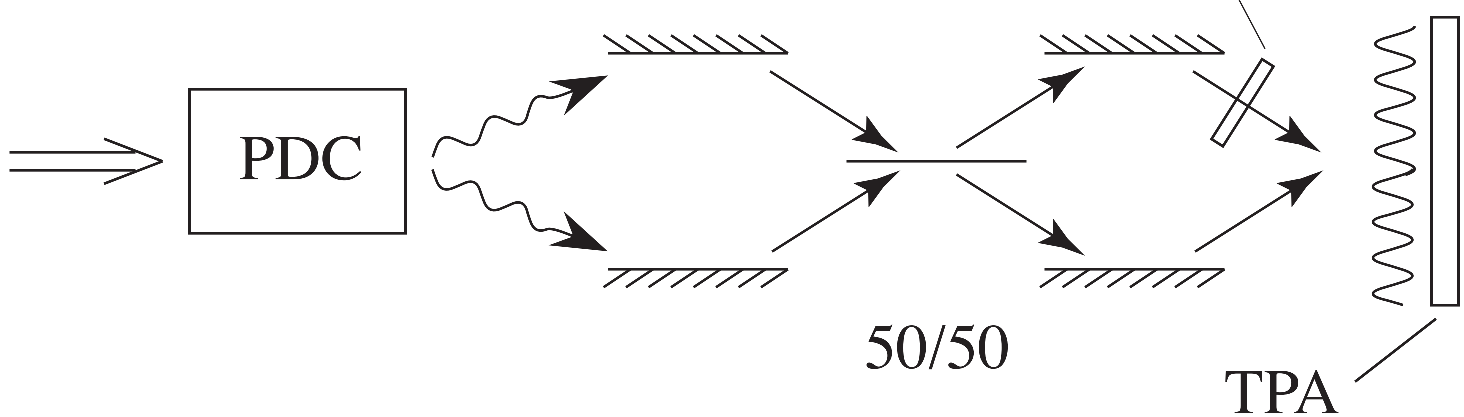
- Goal of quantum imaging is to produce "better" images using quantum methods
  - image with a smaller number of photons
  - achieve better spatial resolution
  - achieve better signal-to-noise ratio
- Alternatively, quantum imaging exploits the quantum properties of the transverse structure of light fields

SHARPER IMAGE®

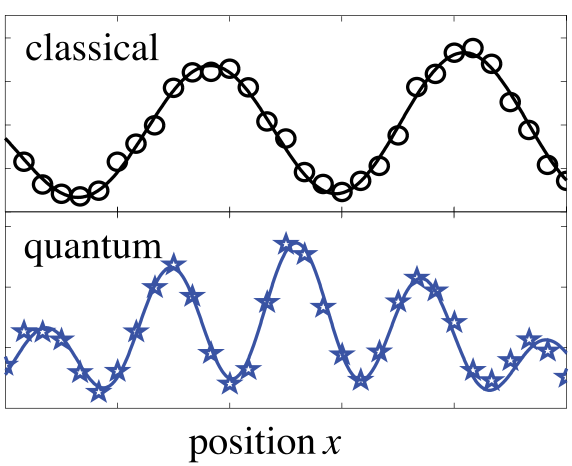
Quantum Lithography: Concept of Jonathan Dowling

- Entangled photons can be used to form an interference pattern with detail finer than the Rayleigh limit
- Resolution ≈ $\lambda/2N$, where N = number of entangled photons

Boto et al., Phys. Rev. Lett. 85, 2733, 2000.



- No practical implementation to date, but some laboratory results

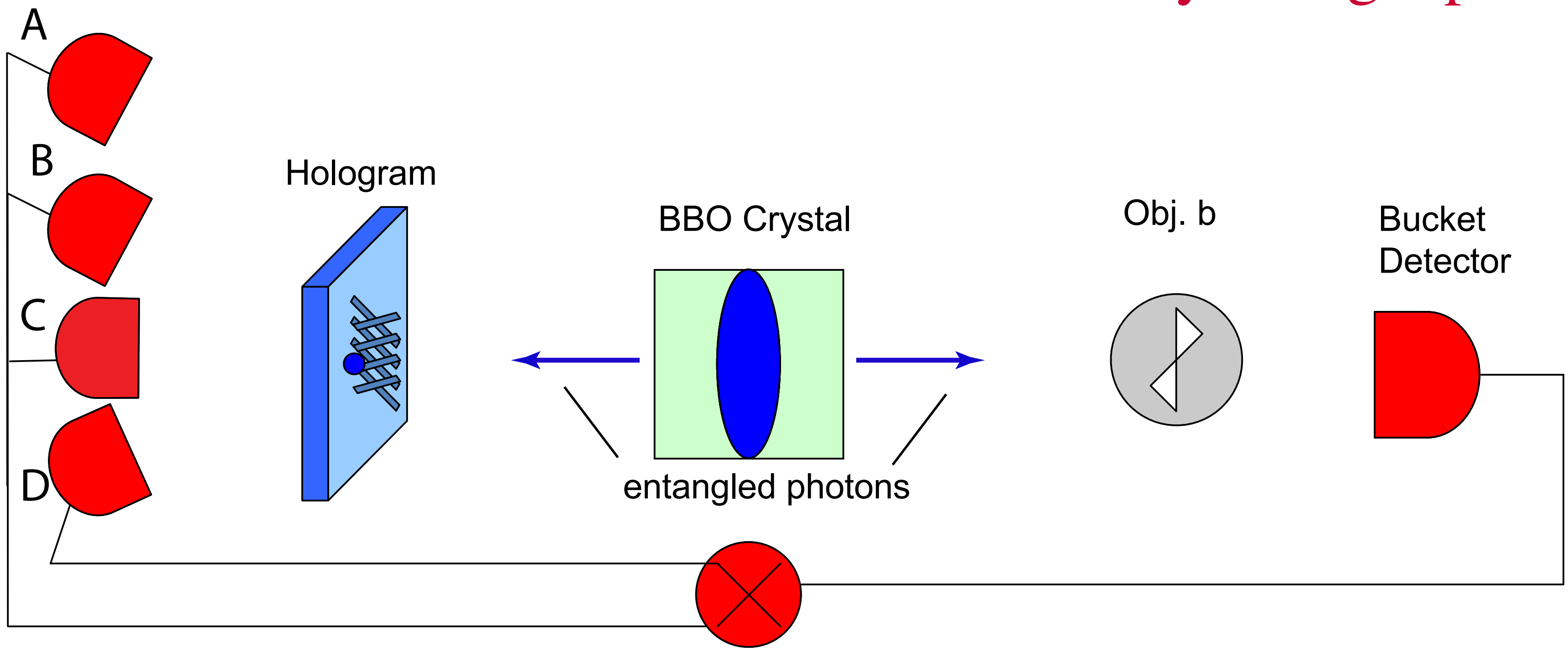


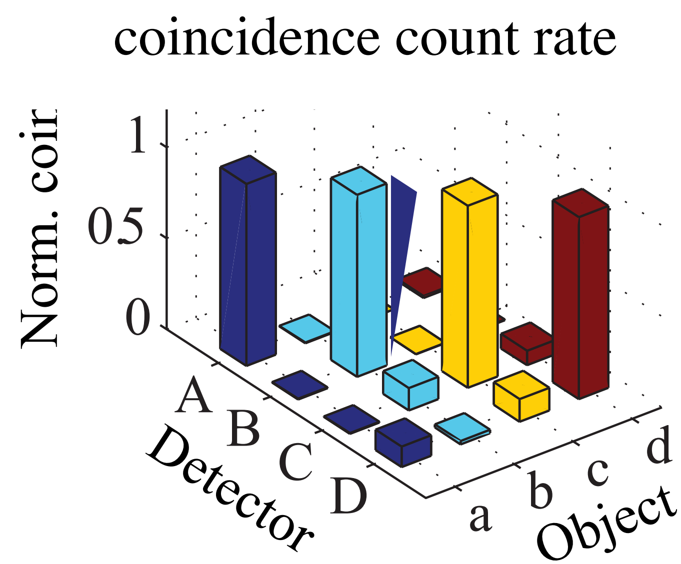
Quantum spatial superresolution by optical centroid measurements, Shin, Chan, Chang, and Boyd, Phys. Rev. Lett. 107, 083603 (2011).

See also, Quantum Lithography: Status of the Field, R.W. Boyd and J.P. Dowling, Quantum Information Processing, 11:891–901 (2012).

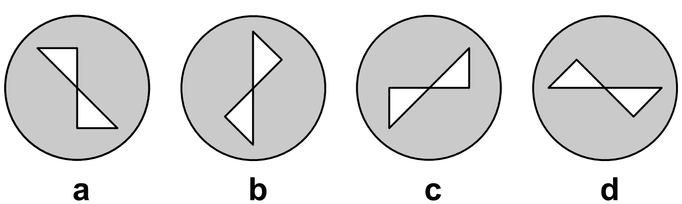
Single-Photon Coincidence Imaging

How much information can be carried by a single photon?





We discriminate among four orthogonal images using single-photon interrogation in a coincidence imaging configuration.



Malik, Shin, O'Sullivan. Zerom, and Boyd, Phys. Rev. Lett. 104, 163602 (2010).

Quantum Imaging Outline

Introduction to Quantum Imaging

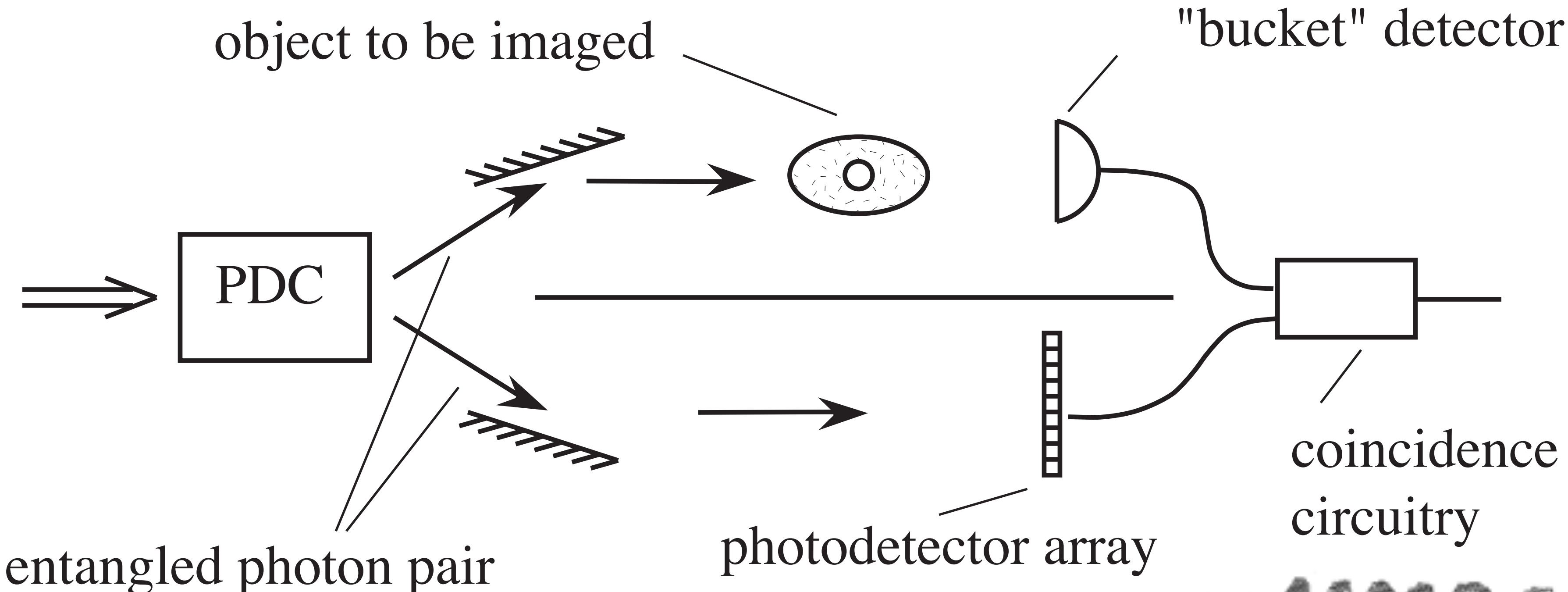
Examples of Quantum Imaging
- Two-color ghost imaging
- Interaction-free ghost imaging
- Imaging with “undetected photons”

Structured Light Fields for Quantum Information
- Dense coding of information using orbital angular momentum of light
- Secure Communication transmitting more than one bit per photon

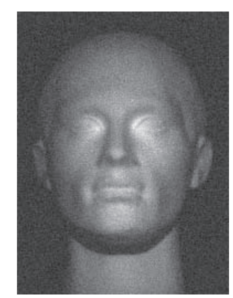
Quantum, Nonlocal Aberration Correction

Quantum Radiometry

Ghost (Coincidence) Imaging



- Obvious applicability to remote sensing!
  (imaging under adverse situations, bio, two-color, etc.)
- Is this a purely quantum mechanical process? (No)
- Can Brown-Twiss intensity correlations lead to ghost imaging? (Yes)



Padgett Group

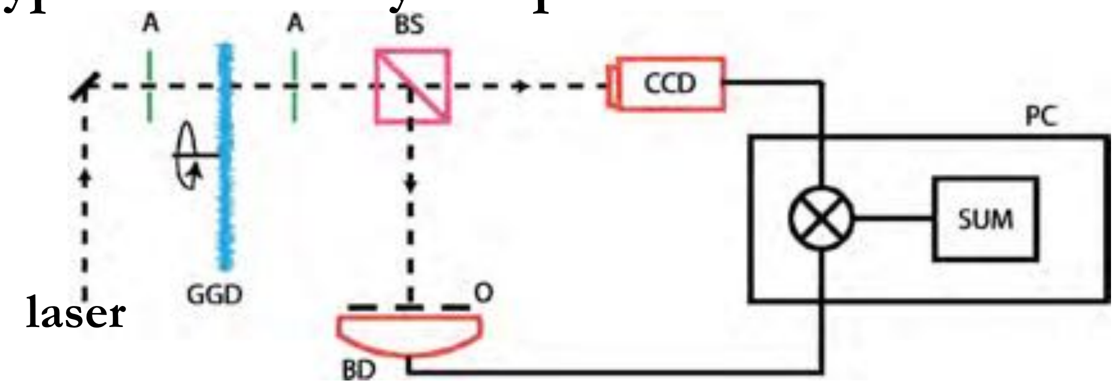
Strekalov et al., Phys. Rev. Lett. 74, 3600 (1995).
Pittman et al., Phys. Rev. A 52 R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. 87, 123602 (2001).
Bennink, Bentley, and Boyd, Phys. Rev. Lett. 89 113601 (2002).
Bennink, Bentley, Boyd, and Howell, PRL 92 033601 (2004)
Gatti, Brambilla, and Lugiato, PRL 90 133603 (2003)
Gatti, Brambilla, Bache, and Lugiato, PRL 93 093602 (2003)

Thermal Ghost Imaging

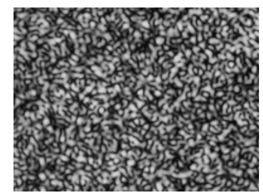
Instead of using entangled photons, one can perform ghost imaging using the (HBT) correlations of thermal (or quasithermal) light.

(Gatti et al., Phys. Rev. Lett. 93, 093602, 2004).

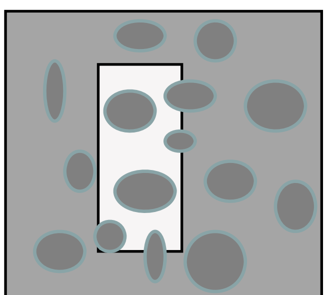
- **Typical laboratory setup**



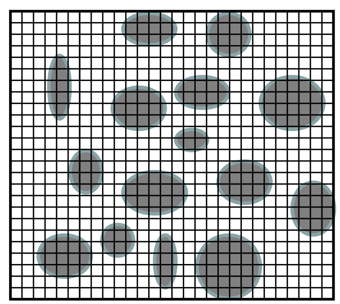
identical speckle patterns in each arm



- **How does this work? (Consider the image of a slit.)**



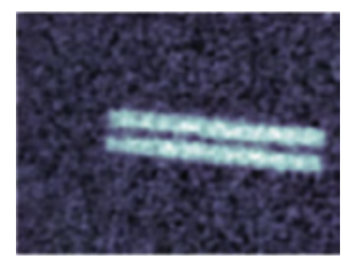
Object arm, bucket detector



Reference arm, CCD

Calculate (total transmitted power) x (intensity at each pixel) and average over many speckle patterns.

Example ghost image

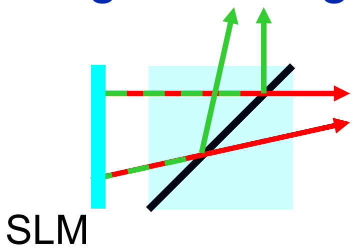


Zerom et al., A 86, 063817 (2012)

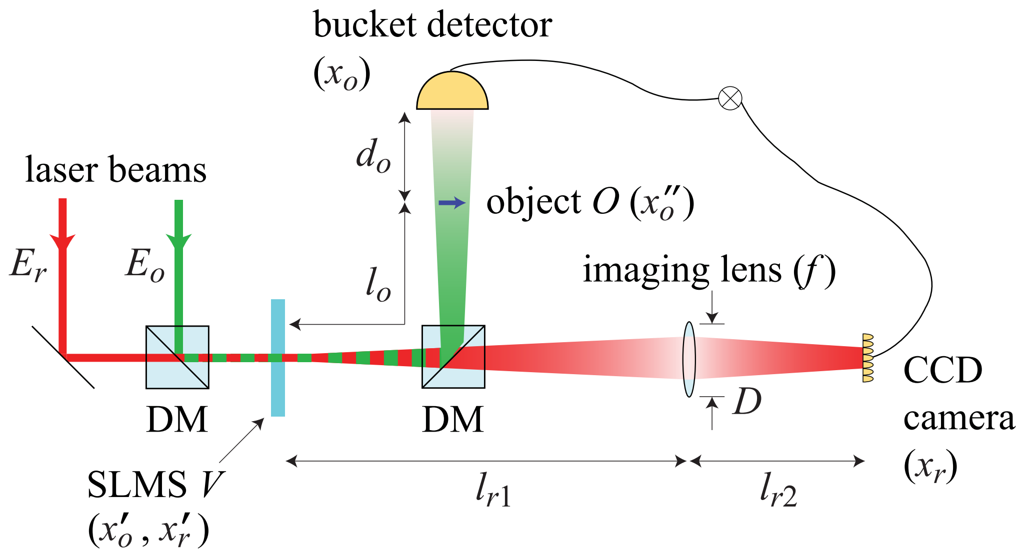
Two-Color Ghost Imaging

New possibilities afforded by using different colors in object and reference arms

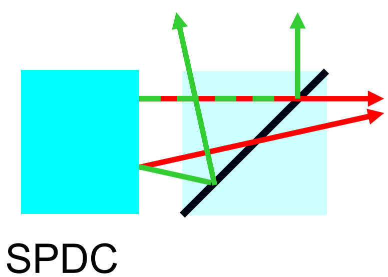
Thermal ghost imaging

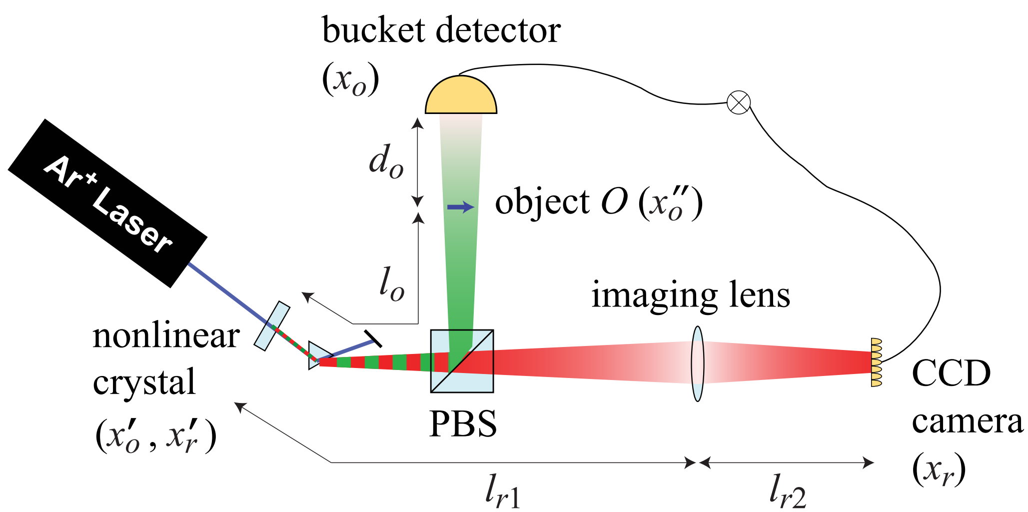


But no obvious way to make identical speckle patterns at two wavelengths



Quantum ghost imaging





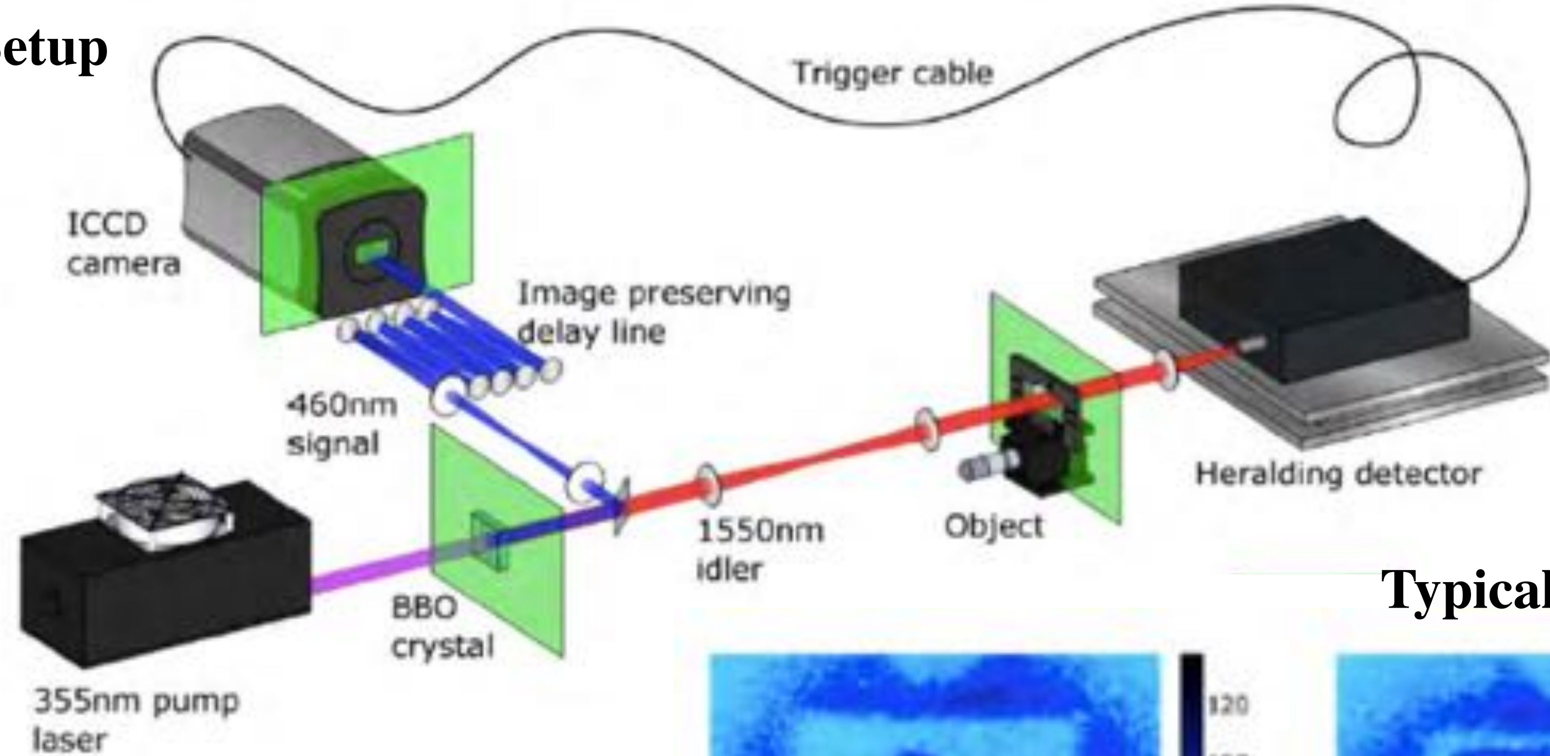
Spatial resolution depends on wavelength used to illuminate object.

Two-Color Ghost Imaging, K.W.C. Chan, M.N. O'Sullivan, and R.W. Boyd, Phys. Rev. A 79, 033808 (2009).

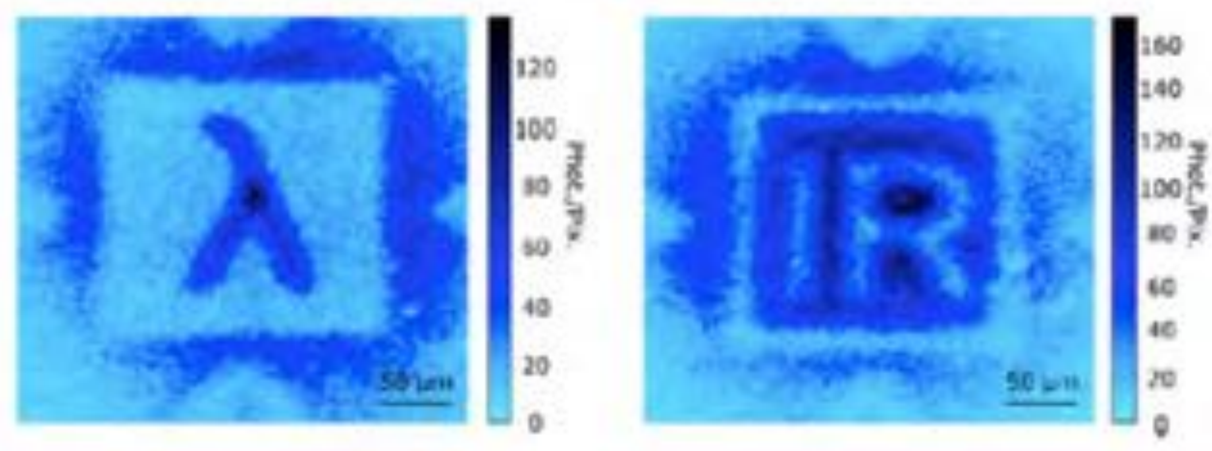
Wavelength-Shifted (Two-Color) Ghost Microscopy

- Pump at 355 nm produces signal at 460 nm and idler at 1550 nm
- Object is illuminated at 1550 nm, but image is formed (in coincidence) at 460 nm
- Wavelength ratio of 3.4 is the largest yet reported.

Setup



Typical images



Photon-sparse microscopy: visible light imaging using infrared illumination, R.S. Aspden, N. R. Gemmell, P.A. Morris, D.S. Tasca, L. Mertens, M.G. Tanner, R. A. Kirkwood, A. Ruggeri, A. Tosi, R. W. Boyd, G.S. Buller, R.H. Hadfield, and M.J. Padgett, Optica 2, 1049 (2015).

Quantum Imaging Outline

Introduction to Quantum Imaging

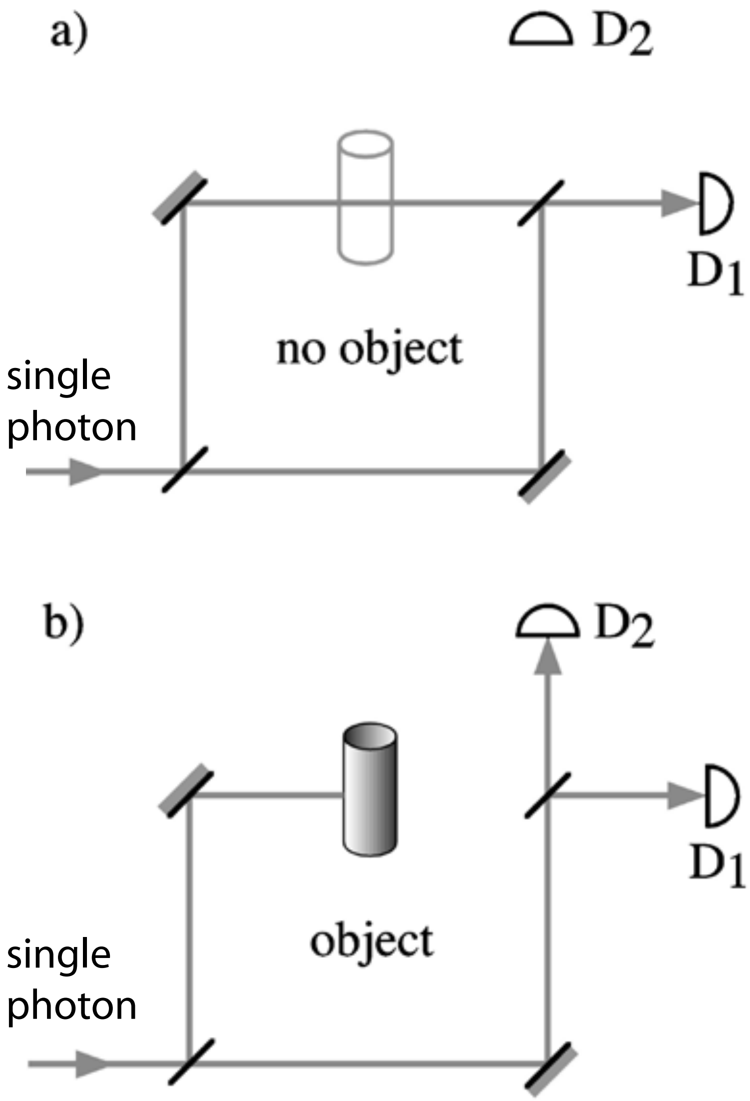
Examples of Quantum Imaging
- Two-color ghost imaging
- Interaction-free ghost imaging
- Imaging with “undetected photons”

Structured Light Fields for Quantum Information
- Dense coding of information using orbital angular momentum of light
- Secure Communication transmitting more than one bit per photon

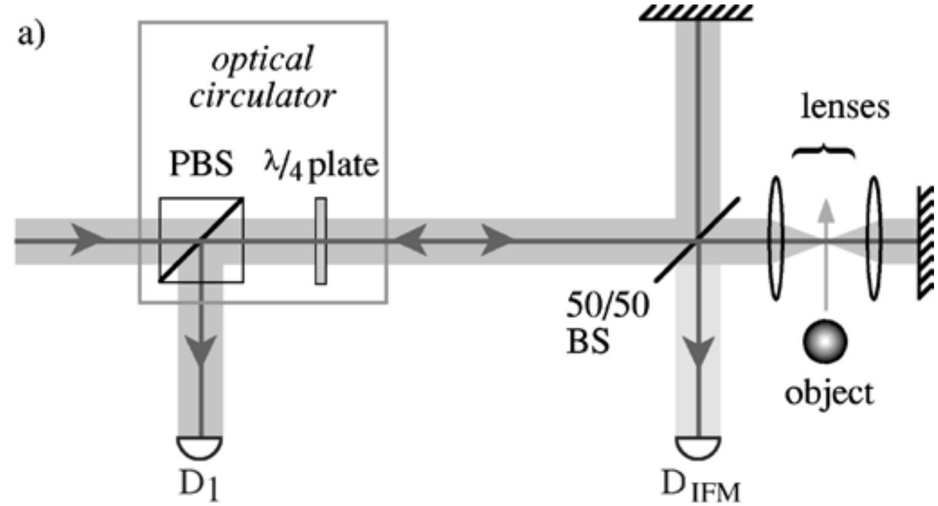
Quantum, Nonlocal Aberration Correction

Quantum Radiometry

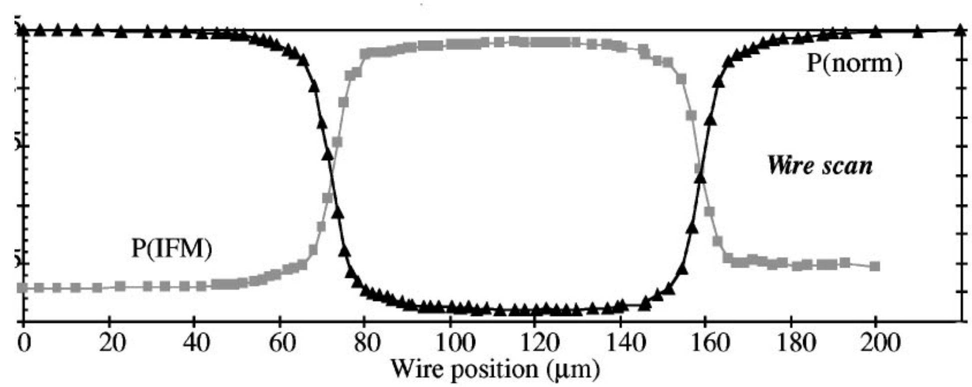
Quantum Imaging by Interaction-Free Measurement



imaging setup

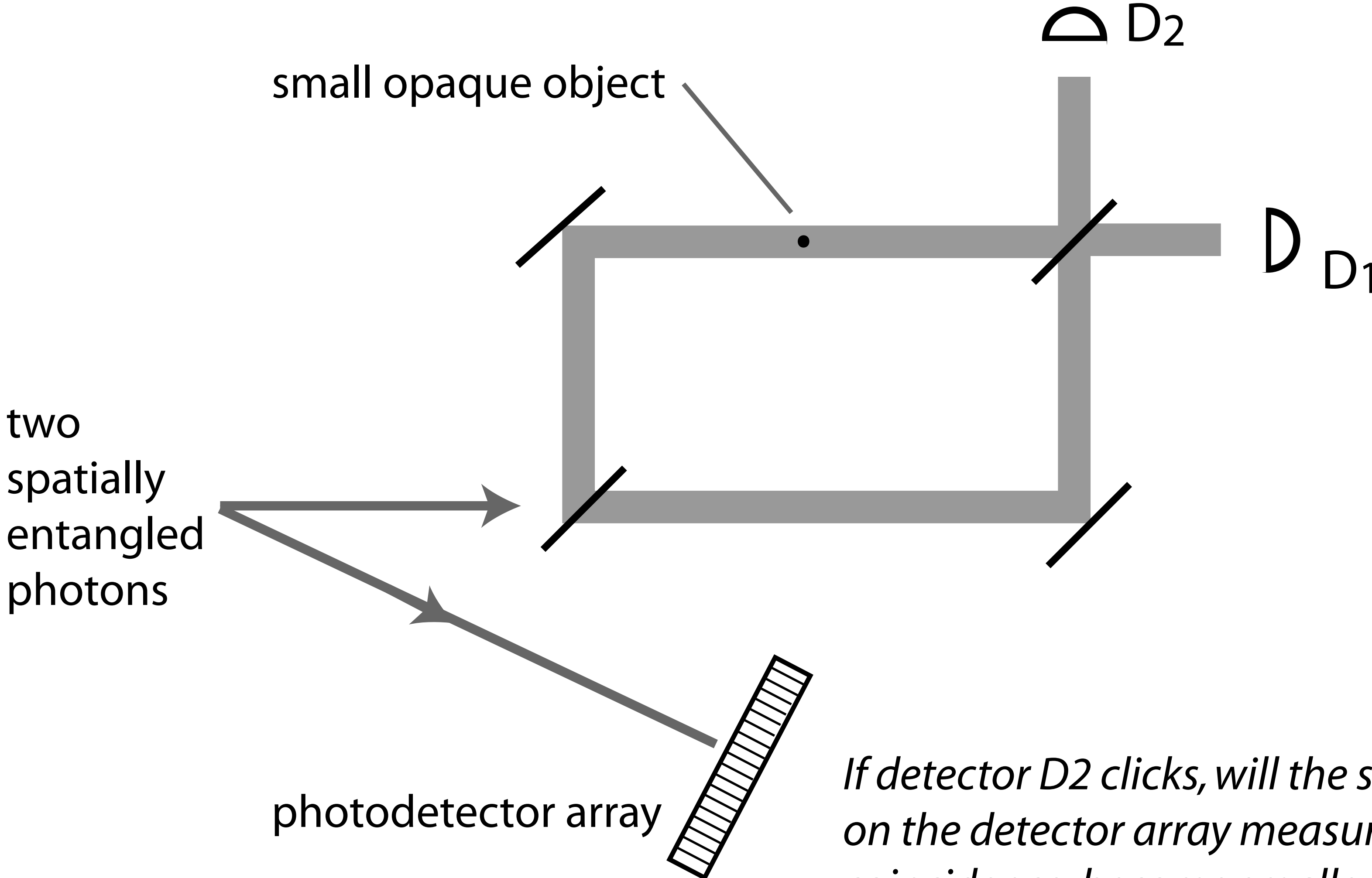


results



M. Renninger, Z. Phys. 15S, 417 (1960).
R. H. Dicke, Am. J. Phys. 49, 925 (1981).
A. Elitzur and L. Vaidman, Found. Phys. 23, 987 (1993).
L. Vaidman, Quant. Opt. 6, 119 (1994).
P. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger, and M. A. Kasevich, Phys. Rev. Lett. 74, 4763 (1995)
A. G. White, J. R. Mitchell, O. Nairz, and P. G. Kwiat, Phys. Rev. A 58, 605 (1998).

Interaction-Free Measurements and Entangled Photons

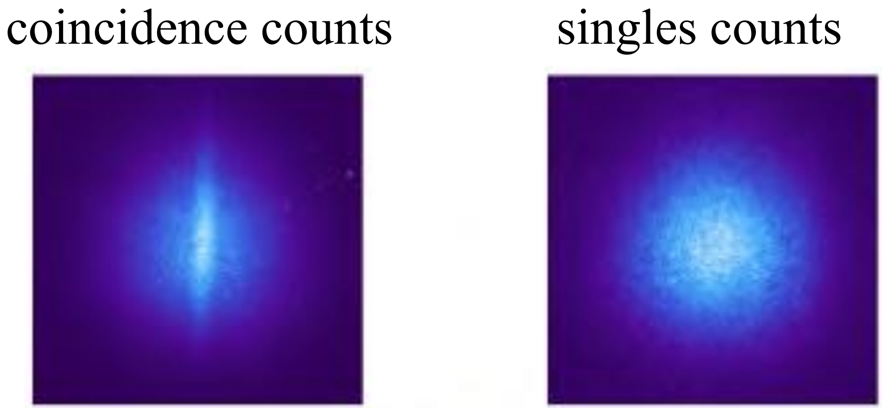


If detector D2 clicks, will the spot size on the detector array measured in coincidence become smaller?

- Does an interaction-free measurement constitute a “real” measurement?
- Does it lead to the collapse of the wavefunction of its entangled partner?
- More precisely, does the entire two-photon wavefunction collapse?

Experimental Results

Interaction-free ghost image of a straight wire



- Note that the interaction-free ghost image is about five times narrower than full spot size on the ICCD camera

- This result shows that interaction-free measurements lead to wavefunction collapse, just like standard measurements.

Zhang, Sit, Bouchard, Larocque, Grenapin, Cohen, Elitzur, Harden, Boyd, and Karimi, Optics Express 27, 2212-2224 (2019).

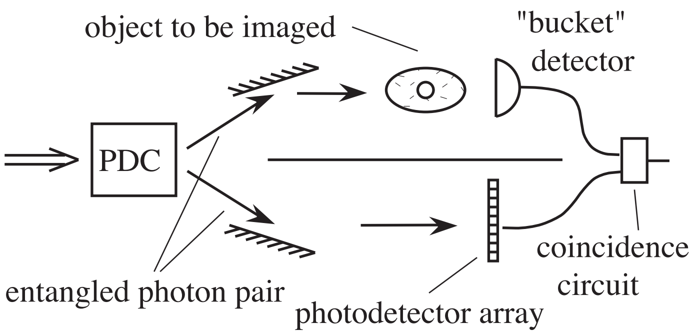
Is interaction-free imaging useful?

Interaction-free imaging allows us to see what something looks like *in the dark*!

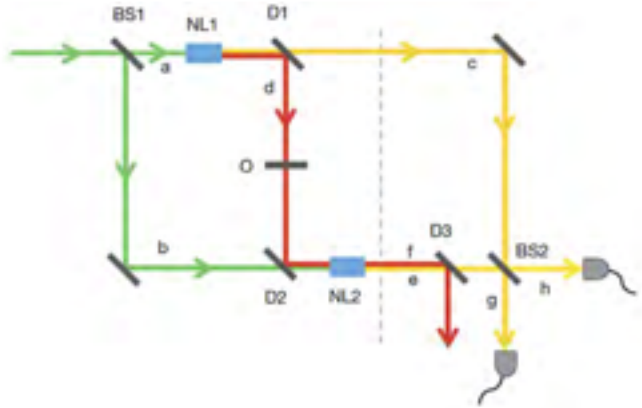
Could be extremely useful for biophysics. What does the retina look like when light does not hit it?

Quantum Imaging Overview

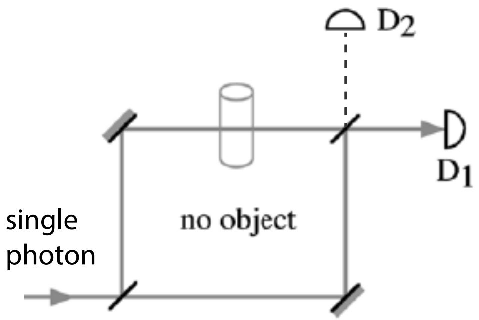
Ghost Imaging (Shih)



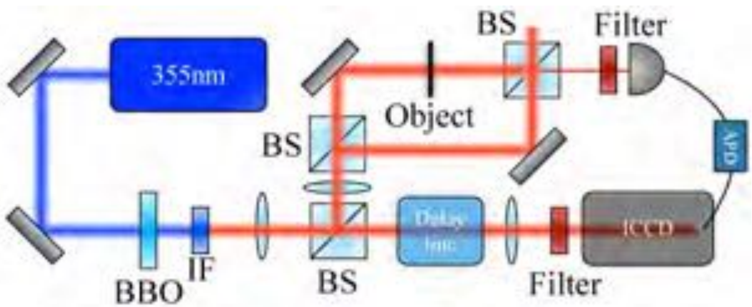
Imaging with Undetected Photons (Zeilinger)



Interaction-Free Imaging (White)



Interaction-Free Ghost Imaging (this talk)



Do We Study Quantum Imaging or Quantum Imogene?

Sid Caesar and Imogene Coca in 1953

Quantum Imaging Outline

Introduction to Quantum Imaging

Examples of Quantum Imaging
- Two-color ghost imaging
- Interaction-free ghost imaging
- Imaging with “undetected photons”

Structured Light Fields for Quantum Information
- Dense coding of information using orbital angular momentum of light
- Secure Communication transmitting more than one bit per photon

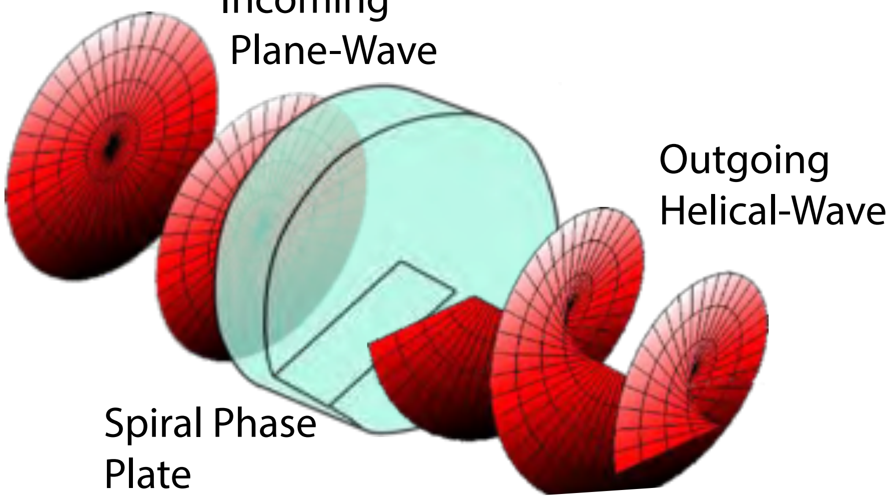
Quantum, Nonlocal Aberration Correction

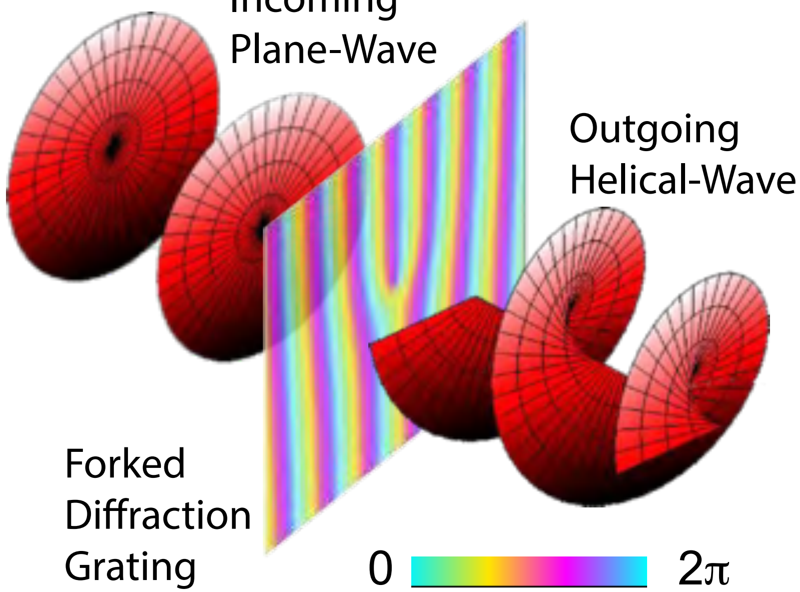
Quantum Radiometry

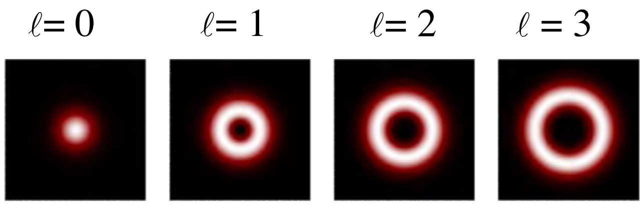
How to create a beam carrying orbital angular momentum?

- Pass beam through a spiral phase plate

- Use a spatial light modulator acting as a computer generated hologram (more versatile)







Exact solution to simultaneous intensity and phase masking with a single phase-only hologram, E. Bolduc, N. Bent, E. Santamato, E. Karimi, and R. W. Boyd, Optics Letters 38, 3546 (2013).

QKD System Carrying Many Bits Per Photon

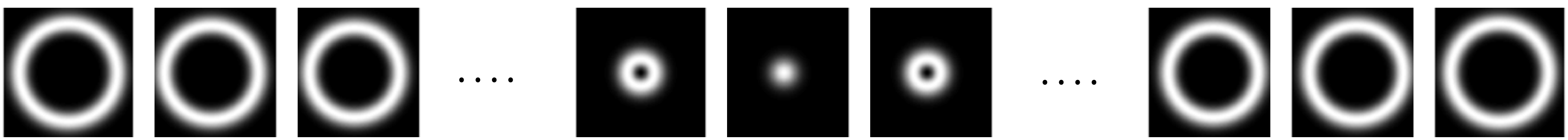
We are constructing a QKD system in which each photon carries many bits of information

We encode in states that carry OAM such as the Laguerre-Gauss states

We also need a second basis composed of linear combinations of these states

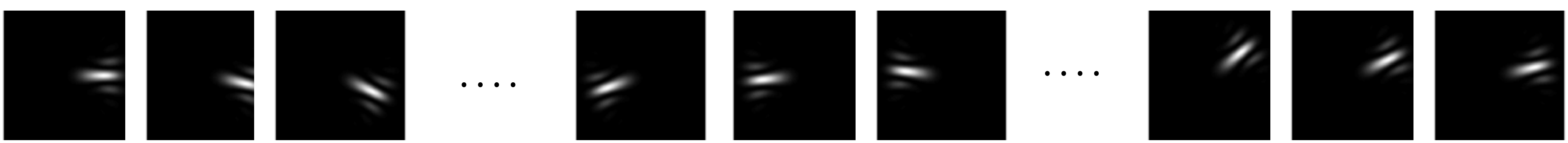
Single Photon States

Laguerre-Gaussian Basis $\ell = -13, \ldots, 13$



-13 -12 -11 .... -1 0 1 .... 11 12 13

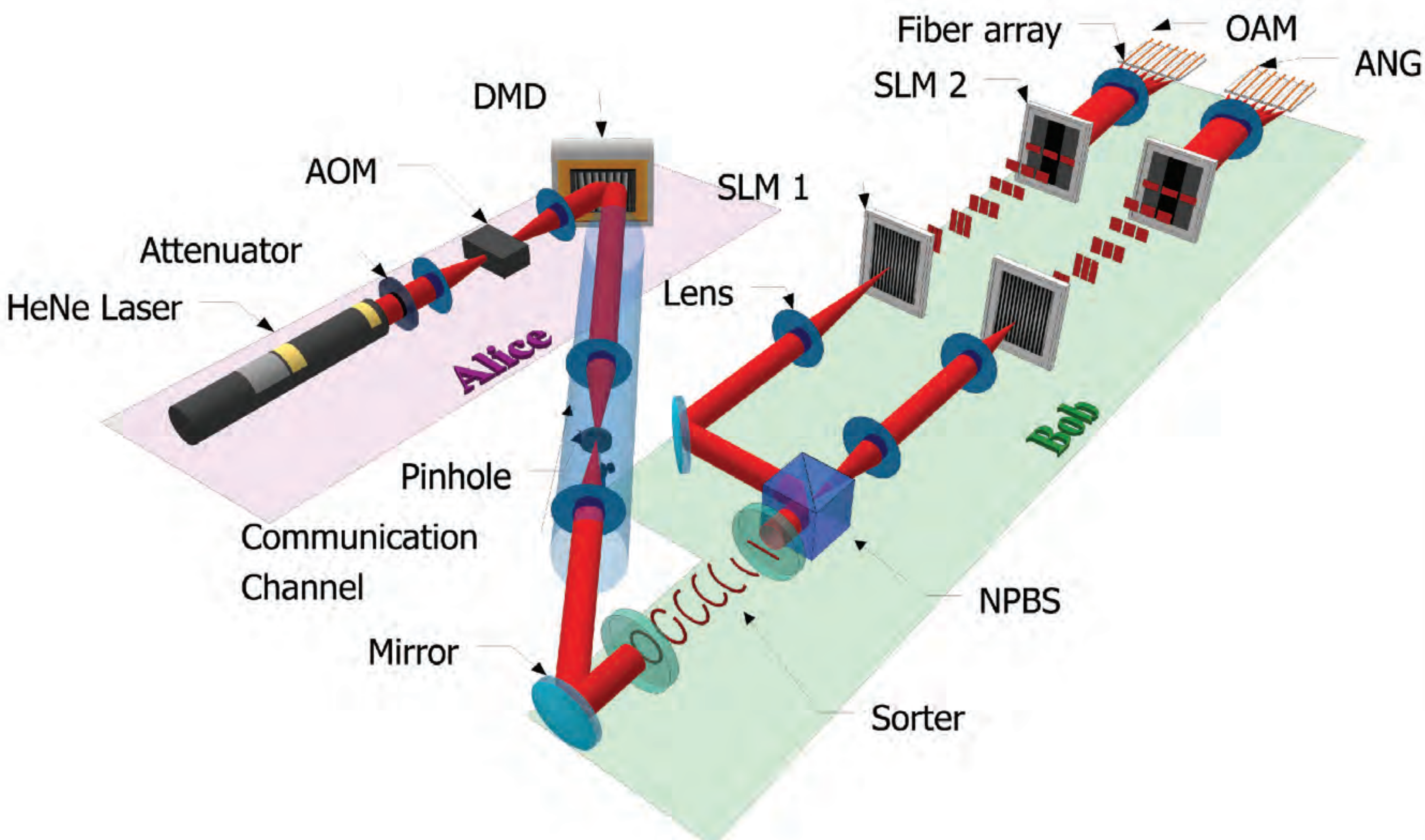
"Angular" Basis (mutually unbiased with respect to LG)

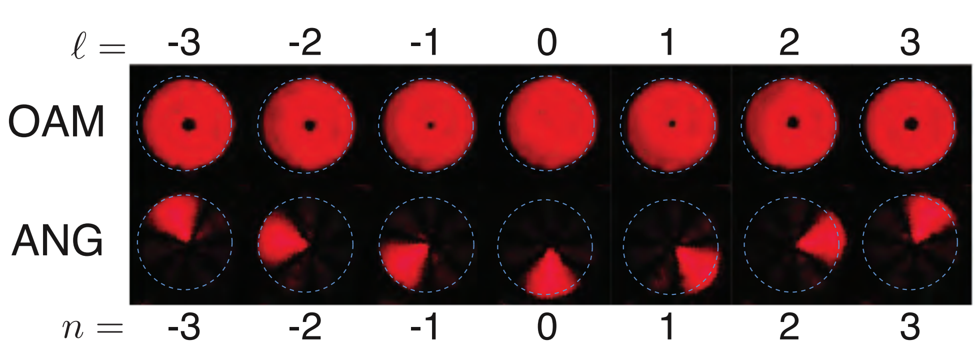


0 1 2 .... 12 13 14 .... 25 26 27

$$\Psi_{\mathrm{AB}}^{N} = \frac{1}{\sqrt{27}} \sum_{l=-13}^{13} \mathrm{LG}_{l,0} \exp\left(i 2\pi N l / 27\right)$$

Laboratory Demonstration of OAM-Based Secure Communication





We use a seven-dimensional state space.

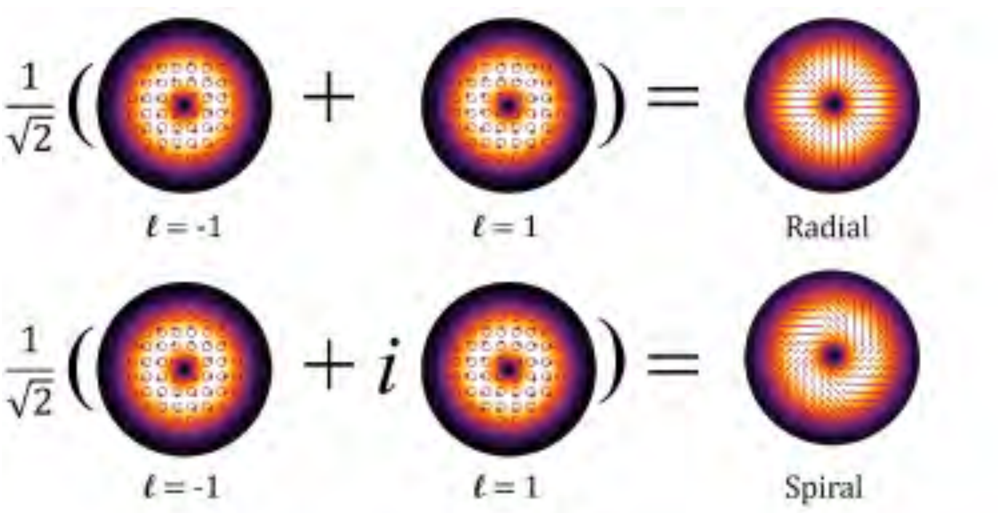
We transfer 2.1 bits per detected photon

Mirhosseini et al., New Journal of Physics 17, 033033 (2015).

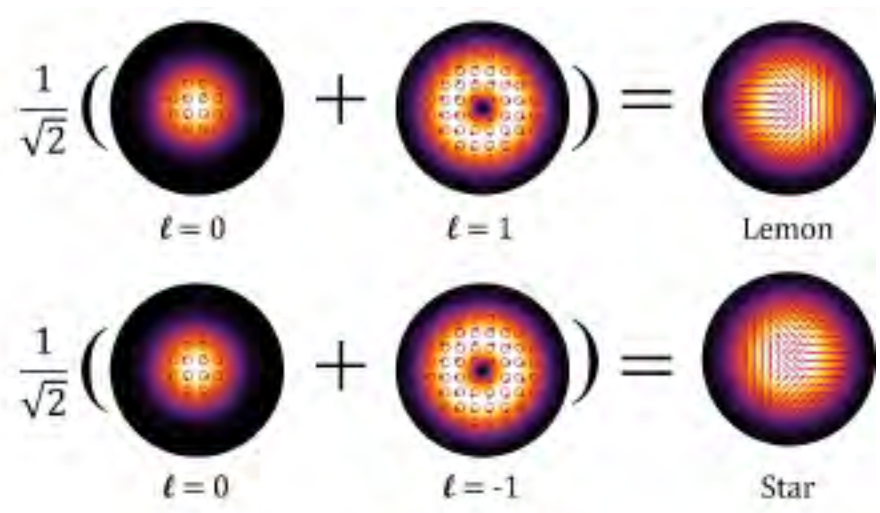
Structured Light Beams

- One can use the transverse degree of freedom of the light field to encode information.
- Not all light waves are infinite plane waves!
- Even a single photon in such a structured field can carry many bits of information
- Example: Space-Varying Polarized Light Beams

Vector Vortex Beams



Poincaré Beams



Larocque et al, PRL 2016 (in press)

Quantum Imaging Outline

Introduction to Quantum Imaging

Examples of Quantum Imaging
- Two-color ghost imaging
- Interaction-free ghost imaging
- Imaging with "undetected photons"

Structured Light Fields for Quantum Information
- Dense coding of information using orbital angular momentum of light
- Secure Communication transmitting more than one bit per photon

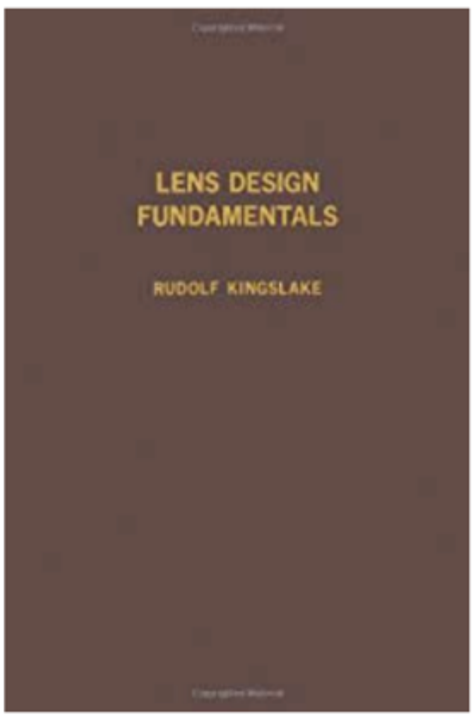
Quantum, Nonlocal Aberration Correction

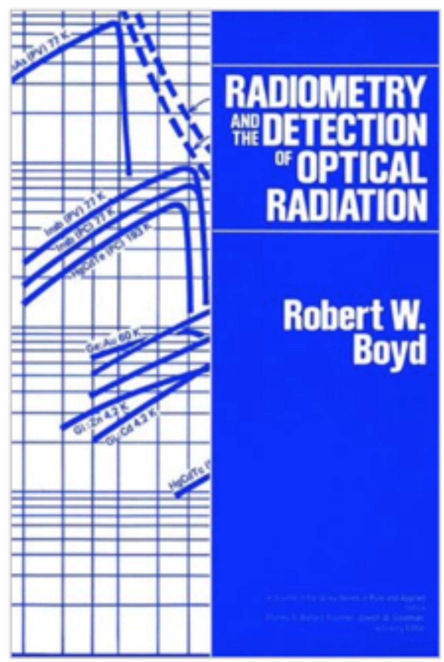
Quantum Radiometry

Quantum Technologies for Realistic Optical Engineering

- Quantum technologies are by now sufficiently advanced to be used for realistic applications in optical engineering.

- In this talk we provide two examples
  -- Quantum, nonlocal aberration correction
  -- Absolute calibration of a spectrophotometer (quantum radiometry)

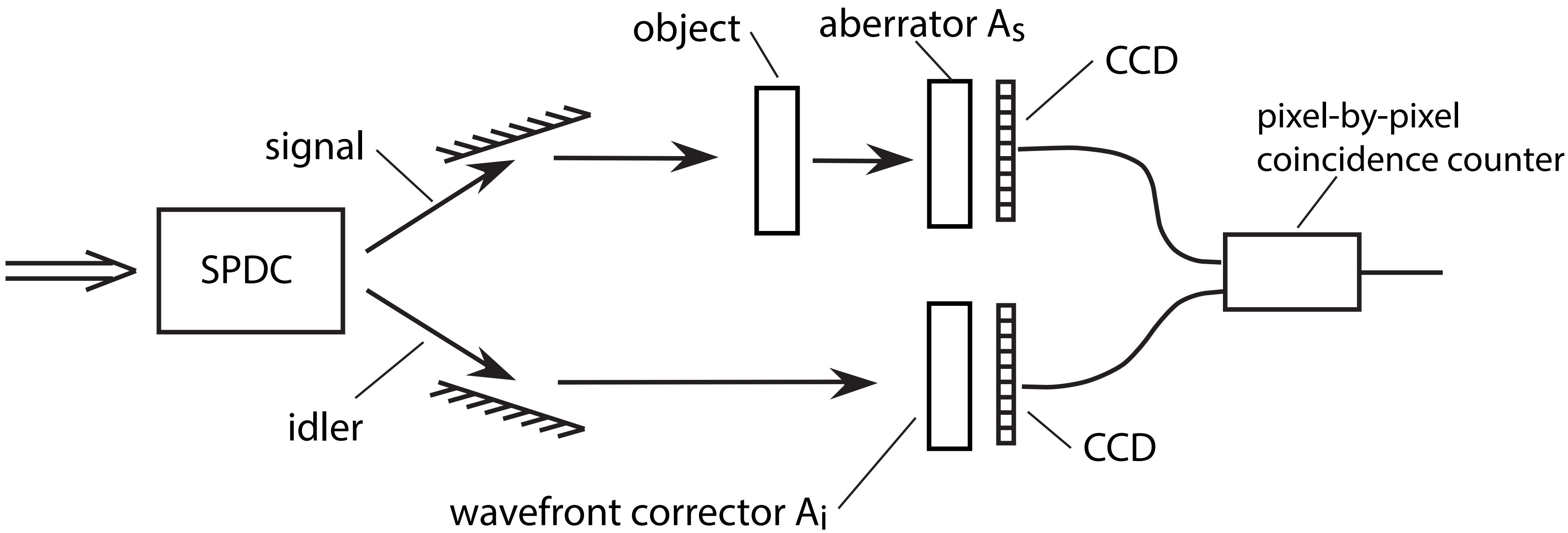




Nonlocal Quantum Aberration Correction

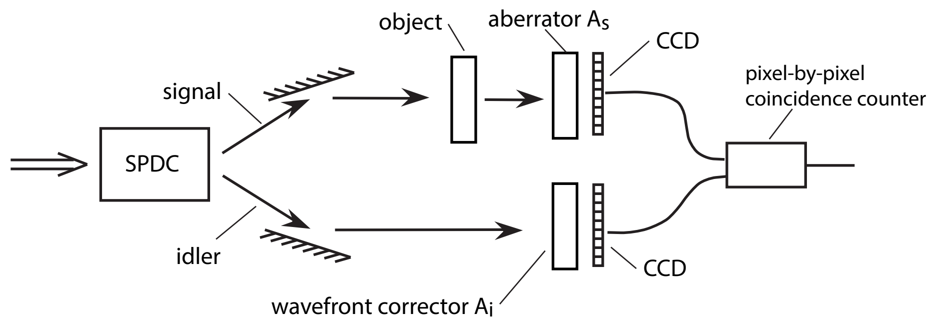
- Can a wavefront corrector in the idler path correct for aberrations in the signal path? (When measured in coincidence.)

(This is what we mean by "nonlocal" in the present context.)



Nonlocal Quantum Aberration Correction

- Can a wavefront corrector in the idler path correct for aberrations in the signal path? (When measured in coincidence.)



- This situation is reminiscent of Franson's dispersion cancellation, in the time domain.

- Recall strong similarity between time and spatial domains

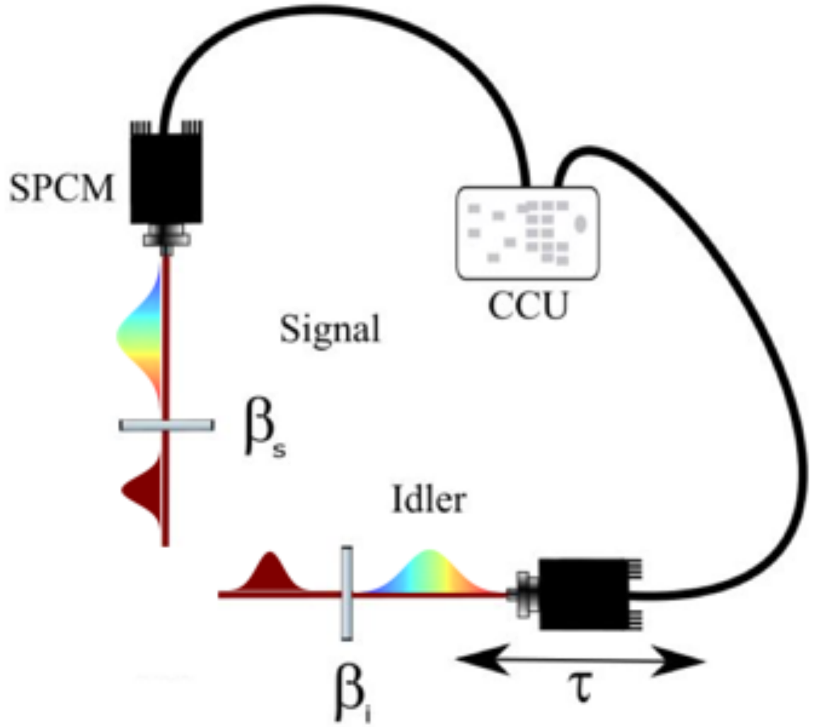
time domain: $$\frac{\partial \tilde{A}_s}{\partial z} + \frac{1}{2} i k_2 \frac{\partial^2 \tilde{A}_s}{\partial \tau^2} = i\gamma |\tilde{A}_s|^2 \tilde{A}_s.$$

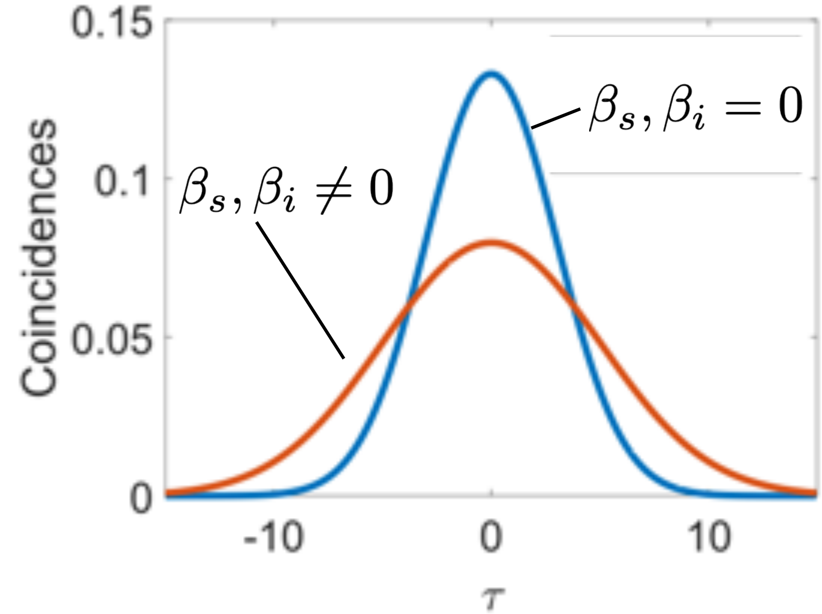
spatial domain: $$2ik_0 \frac{\partial A}{\partial z} + \frac{\partial^2 A}{\partial x^2} = -3\chi^{(3)} \frac{\omega^2}{c^2} |A|^2 A$$

- Let's remind ourselves about Franson's dispersion cancellation.

Nonlocal Dispersion Cancellation

Laboratory setup





$$k_j(\omega) = k_{j,0} + \alpha_j(\omega_j - \omega_0) + \beta_j(\omega_j - \omega_0)^2 + \cdots$$

α_j: $1/v_g(\omega_0)$

β_j: GVD parameter, $d/d\omega[1/v_g(\omega)]$

classical result

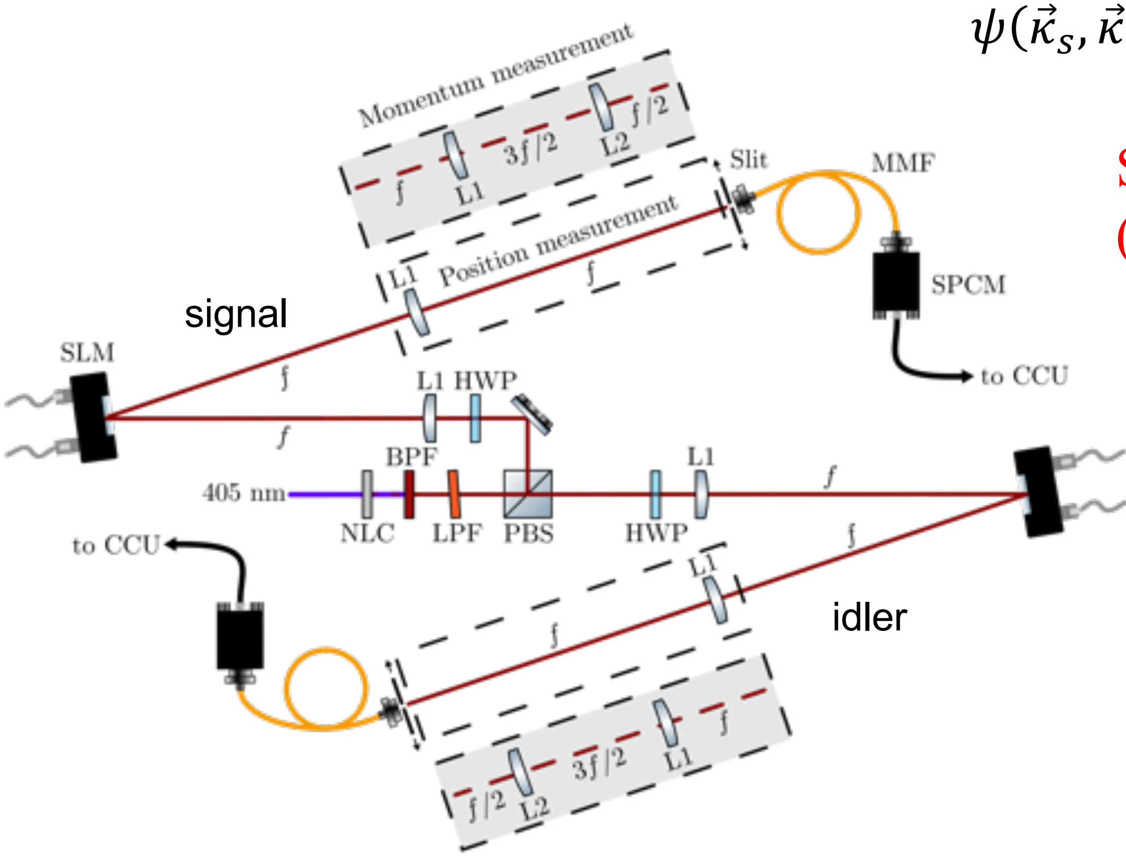
$$\sigma_\tau^2 = \frac{2\,\sigma_0^4 + \left(\beta_s^2 + \beta_i^2\right) x^2}{\sigma_0^2}$$

quantum result

$$\sigma_T^2 = \frac{4\,\sigma_0^4 + (\beta_s + \beta_i)^2\, x^2}{2\,\sigma_0^2}$$

J. D. Franson, Phys. Rev. A 45, 3126 (1992).

Nonlocal Aberration Cancellation



Scan slits to obtain one-dimensional images

Two-photon wavefunction

$$\psi(\vec{\kappa}_s,\vec{\kappa}_i) \approx A\,\nu(\vec{\kappa}_s+\vec{\kappa}_i)\zeta(\vec{\kappa}_s-\vec{\kappa}_i)H_s(\vec{\kappa}_s)H_i(\vec{\kappa}_i)$$

Signal-idler correlation function (in plane-wave-pump approximation)

$$\nu(\vec{\kappa}_s+\vec{\kappa}_i) \approx \delta(\vec{\kappa}_s+\vec{\kappa}_i)$$

Phase-matching function

$$\zeta(\vec{\kappa}_s-\vec{\kappa}_i) = \mathrm{sinc}\left(\frac{\mathrm{l_c}|\vec{\kappa}_s-\vec{\kappa}_i|^2}{4k_p}\right) e^{-i\frac{\mathrm{l_c}|\vec{\kappa}_s-\vec{\kappa}_i|^2}{4k_p}}$$

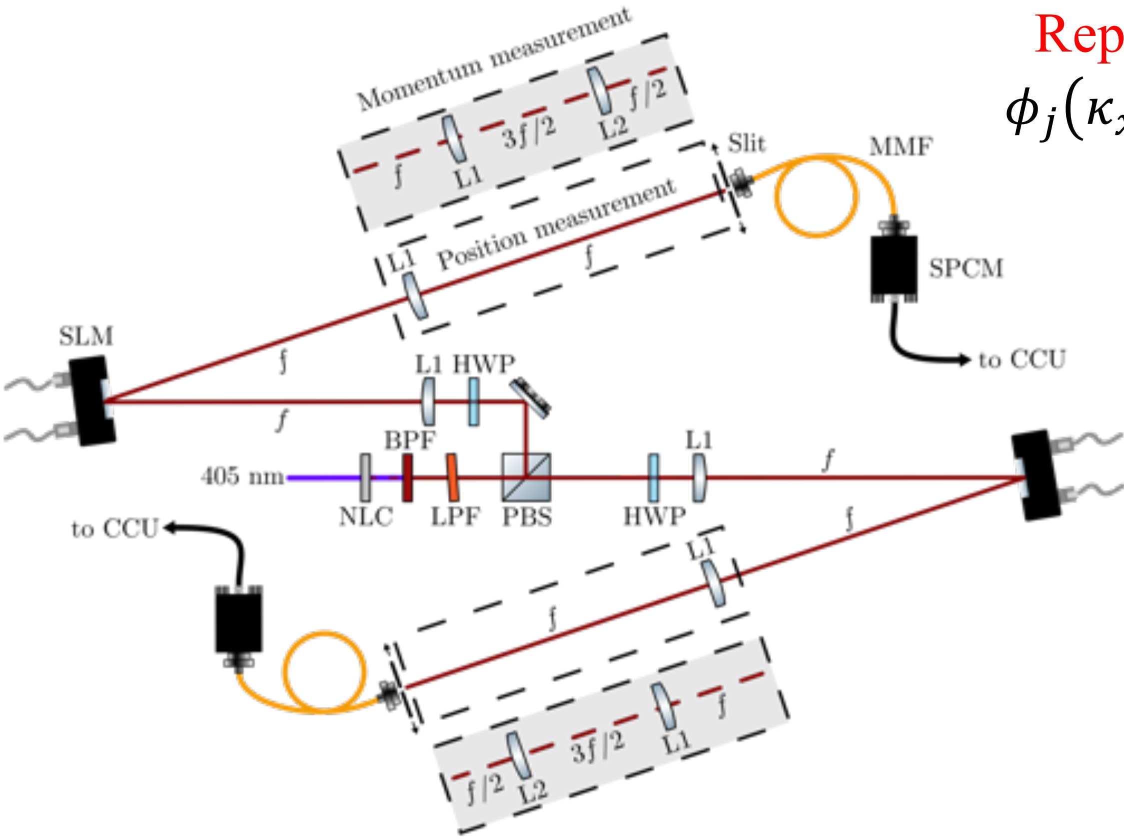
$$\mathrm{sinc}\left(\frac{\mathrm{l_c}|\vec{\kappa}_s-\vec{\kappa}_i|^2}{4k_p}\right) \approx \exp\left(-\frac{L_c|\vec{\kappa}_s-\vec{\kappa}_i|^2}{4}\right)$$

$$L_c = 0.455\,\frac{\mathrm{l_c}}{k_p}$$

Aberration transfer function

$$H_s(\vec{\kappa}_s)H_i(\vec{\kappa}_i) = \exp\big(\mathrm{i}\,\phi_s(\vec{\kappa}_s)\big)\exp\big(\mathrm{i}\,\phi_i(\vec{\kappa}_i)\big)$$

Nonlocal Aberration Cancellation



Represent aberration as a phase variation

$$\phi_j(\kappa_{x,j}) = +\phi_j'(0)\,\kappa_{x,j} + \phi_j''(0)\kappa_{x,j}^2/2 + \ldots$$

$$j = s, i$$

All-order aberration cancellation

$$\phi_s(\kappa_x) = -\phi_i(-\kappa_x)$$

Second-order aberration cancellation

$$\phi_s''(0) = -\phi_i''(0)$$

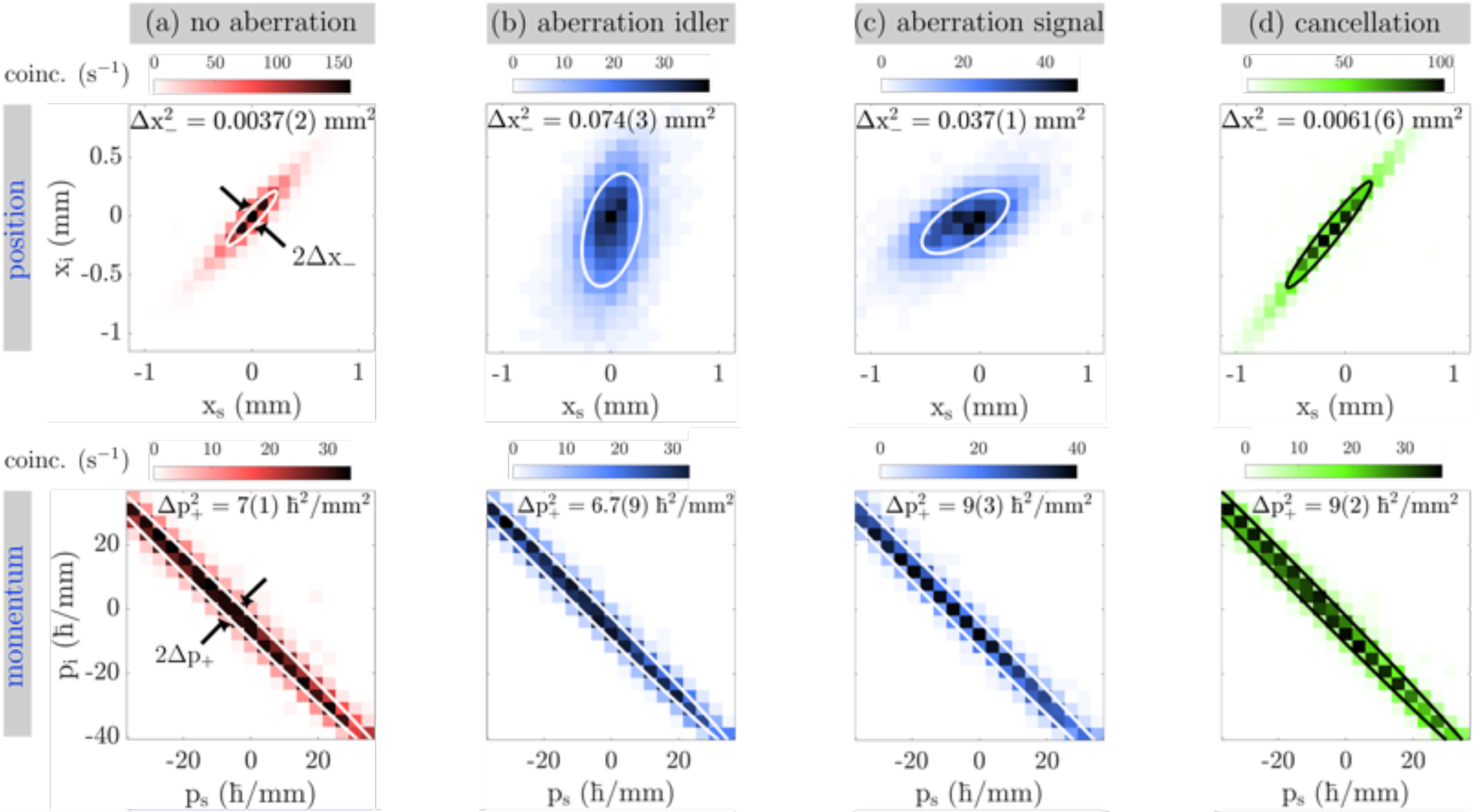
Coincidence count rate

$$P_{\text{coinc}}(x_s, x_i) \propto \exp\left[-\frac{L_c(x_- + \phi_-'(0))^2}{\frac{1}{2}\left(L_c^2 + \left(\frac{l_c}{k_p} - \frac{1}{2}\left(\phi_s''(0) + \phi_i''(0)\right)\right)^2\right)}\right],$$

$$x_- = \frac{1}{\sqrt{2}}(x_s - x_i)$$

$$x_+ = \frac{1}{\sqrt{2}}(x_s + x_i)$$

Laboratory Results

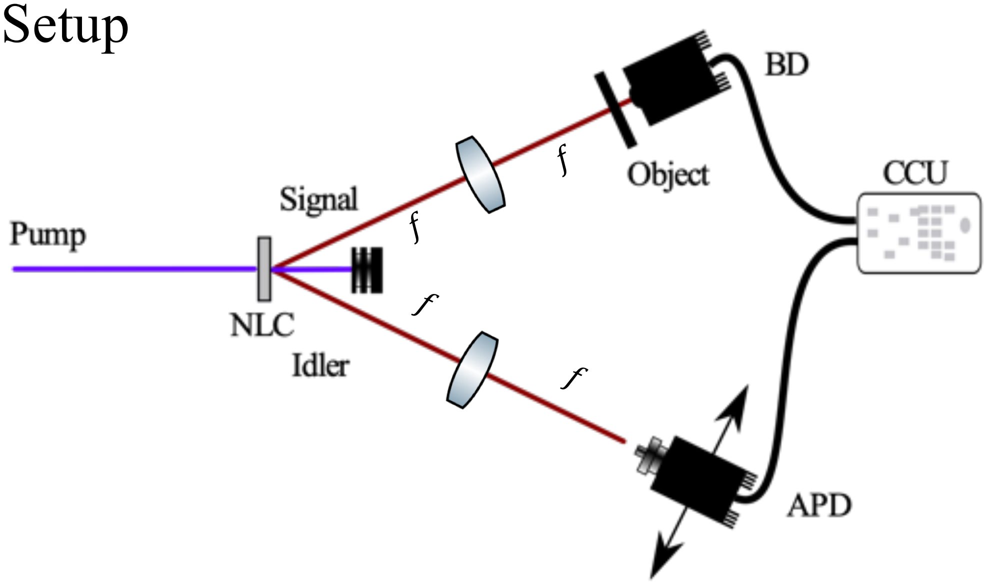


	(a)	(b)	(c)	(d)
$\phi_s''(0)$	0	0	0.0104 mm²	0.0104 mm²
$\phi_i''(0)$	0	−0.0104 mm²	0	−0.0104 mm²
$\Delta x_-^2 \Delta p_+^2$	0.026(4) $\hbar^2$	0.50(7) $\hbar^2$	0.3(1) $\hbar^2$	0.05(1) $\hbar^2$

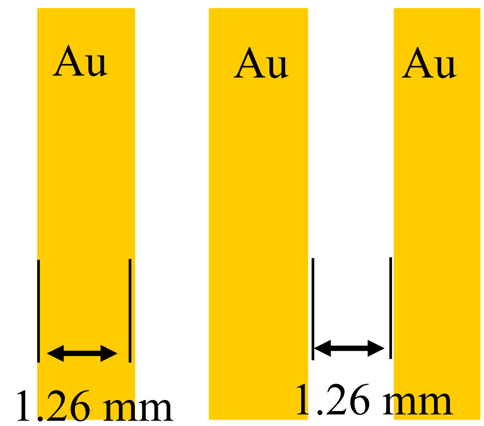
$(\Delta x_-)^2(\Delta p_+)^2 < \hbar^2/4$ Mancini criterion for entanglement (PRL 88, 120401 (2002).

Nonlocal Aberration Cancellation for a Real Object

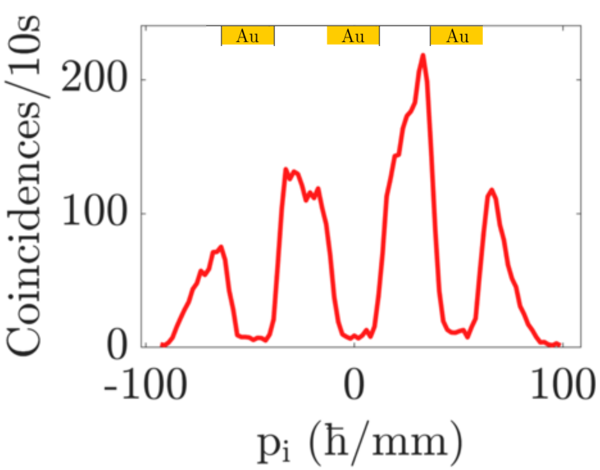
Setup



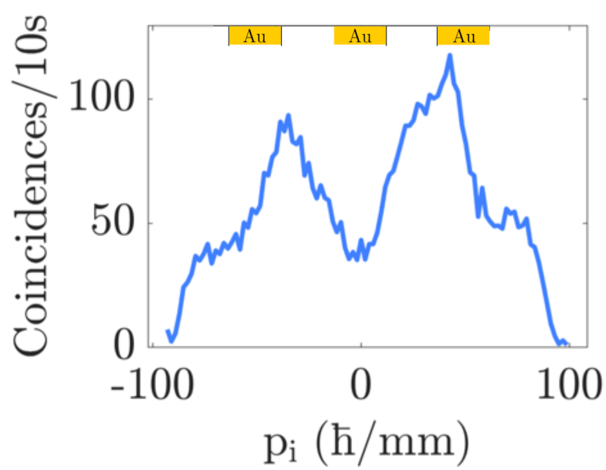
Object:



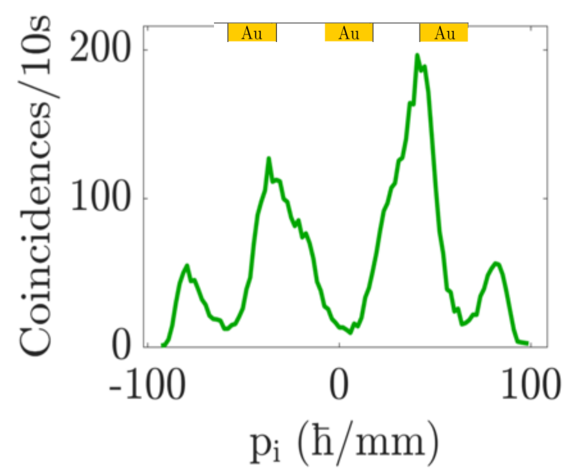
No aberrations



Aberrations in signal beam only



Aberrations compensated by idler beam



Earlier Work on Aberration Correction

PRL **101**, 233603 (2008) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2008

Even-Order Aberration Cancellation in Quantum Interferometry

Cristian Bonato,[1,2] Alexander V. Sergienko,[1,3] Bahaa E. A. Saleh,[1] Stefano Bonora,[2] and Paolo Villoresi[2]
[1]*Department of Electrical & Computer Engineering, Boston University, Boston, Massachusetts 02215, USA*
[2]*CNR-INFM LUXOR, Department of Information Engineering, University of Padova, Padova, Italy*
[3]*Department of Physics, Boston University, Boston, Massachusetts 02215, USA*
(Received 18 July 2008; published 2 December 2008)

→ Local, even-order only

PHYSICAL REVIEW A **84**, 043817 (2011)

Nonlocal compensation of pure phase objects with entangled photons

Simone Cialdi*
Dipartimento di Fisica dell'Università degli Studi di Milano, I-20133 Milano, Italy and INFN, Sezione di Milano, I-20133 Milano, Italy

→ Explored polarization entanglement

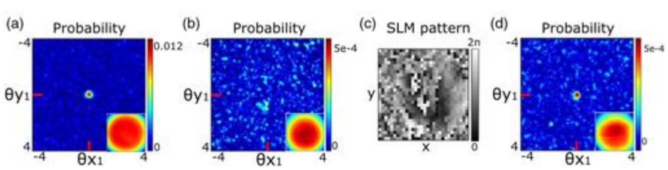
Experimental observation of aberration cancellation in entangled two-photon beams

L. A. P. Filpi, M. V. da Cunha Pereira, and C. H. Monken*
Departamento de Física, Universidade Federal de Minas Gerais, Caixa Postal 702, Belo Horizonte, MG 30123-970, Brazil

Received 5 Nov 2014; revised 18 Jan 2015; accepted 23 Jan 2015; published 9 Feb 2015
23 Feb 2015 | Vol. 23, No. 4 | DOI:10.1364/OE.23.003841 | OPTICS EXPRESS 3841

→ Local, odd-order only

H. Defienne et al., PRL, **121**, 233601 (2018)



→ Local, all orders

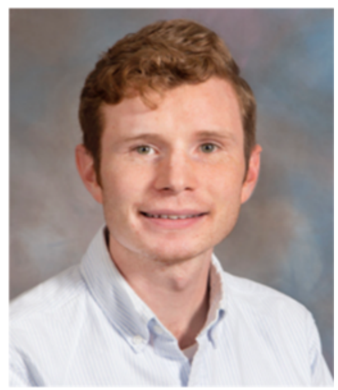
Conclusions

- Demonstrated effect of aberrations on transverse entanglementof photons.
- Observed simultaneous even- and odd-order nonlocal aberration cancellation.
- Observed nonlocal cancellation of defocus in quantum ghost imaging.
- Manuscript describing these results is presently in review

My coauthors

Enno Giese

Boris Braverman



Nick Black

Stephen Barnett

Nicholas Zollo (not pictured)

Quantum Imaging Outline

Introduction to Quantum Imaging

Examples of Quantum Imaging
- Two-color ghost imaging
- Interaction-free ghost imaging
- Imaging with “undetected photons”

Structured Light Fields for Quantum Information
- Dense coding of information using orbital angular momentum of light
- Secure Communication transmitting more than one bit per photon

Quantum, Nonlocal Aberration Correction

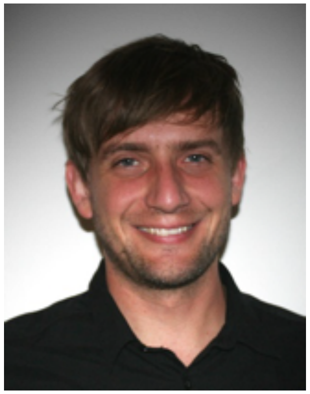
Quantum Radiometry

Quantum Radiometry

- Quantum method to provide absolute calibration of a spectrophotometer
- We exploit vacuum fluctuations as a primary standard for radiometry

Samuel Lemieux

Enno Giese



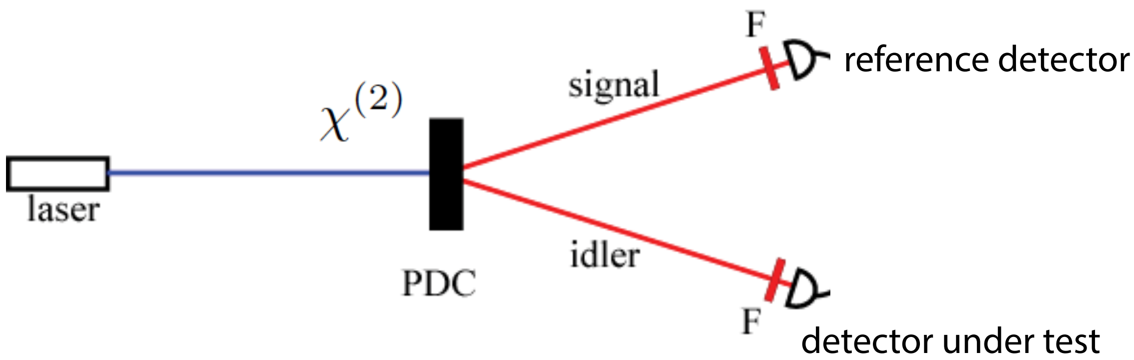
Robert Fickler

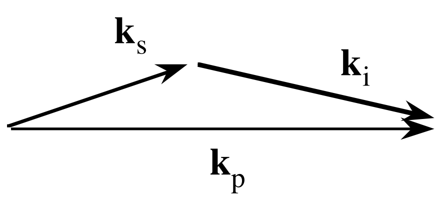
Maria V. Chekhova

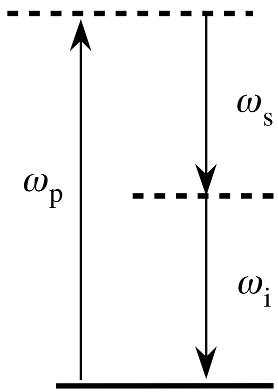
Samuel Lemieux, Enno Giese, Robert Fickler, Maria V. Chekhova, and R.W. Boyd, A primary radiation standard based on quantum nonlinear optics, Nature Physics 15, 529 (2019).

Earlier Work on Quantum Radiometry

- Absolute measurement of detector quantum efficiency (Klyshko, Sergienko, Migdall, Polyakov, etc.)



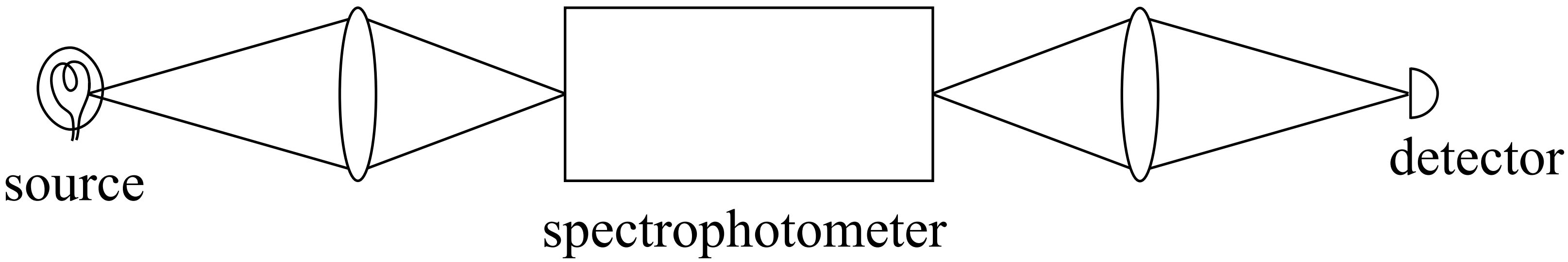


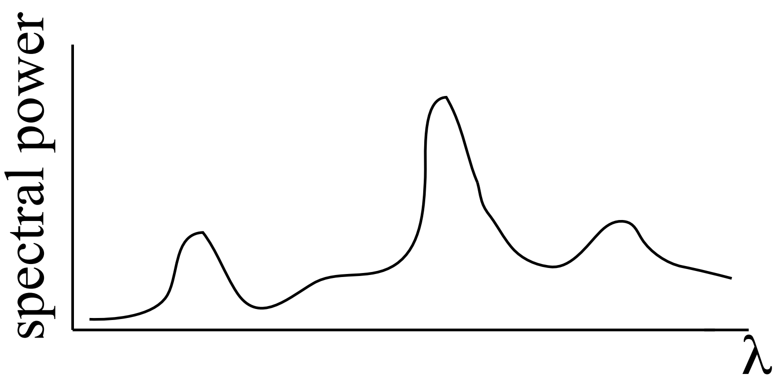


- Earlier work (Klyshko) established that the light produced by spontaneous parametric downconversion (SPDC) can be characterized in terms of the radiometric property known as brightness (or radiance).

Goal of Our Research

- Use quantum methods to perform absolute calibration of a spectrophotometer.





- How do we perform an absolute calibration of the vertical axis in units of watts per nm of spectral bandwidth?

S. Lemieux et al., Nature Physics 15, 529 (2019).

Traditional Approach to Calibration

- Use a black body source, or a lamp calibrated to a black body source
- Theory of black body radiation is very well understood

(1) Density of field modes (number of modes per unit volume per unit frequency interval) is given by

$$\rho_\nu = \frac{8\pi\nu^2}{(c/n)^3}$$

(2) Energy per field mode is $h\nu\bar{n}$ where $\bar{n}$ is the mean number of photons per mode:

$$\bar{n} = \frac{1}{e^{(h\nu/k_B T)} - 1}$$ Planck distribution

(3) Energy density of black body radiation (energy per unit volume) give by

$$u_\nu = 2\rho_\nu h\nu\,\bar{n} = \frac{8\pi h\nu^3}{(c/n)^3(e^{h\nu/k_B T} - 1)}$$ Planck radiation law

(4) Brightness (radiance) of black body radiation (power per unit area per unit solid angle) is given by

$$B_\nu = \frac{(c/n)}{4\pi}u_\nu = \frac{2h\nu^3}{(c/n)^2(e^{h\nu/k_B T} - 1)}$$ Planck radiation law

Problem with Traditional Approach to Calibration

Need to use a non-optical means to determine the temperature of a black body source

This step is not easy and is prone to error.

Our New Approach to Absolute Calibration

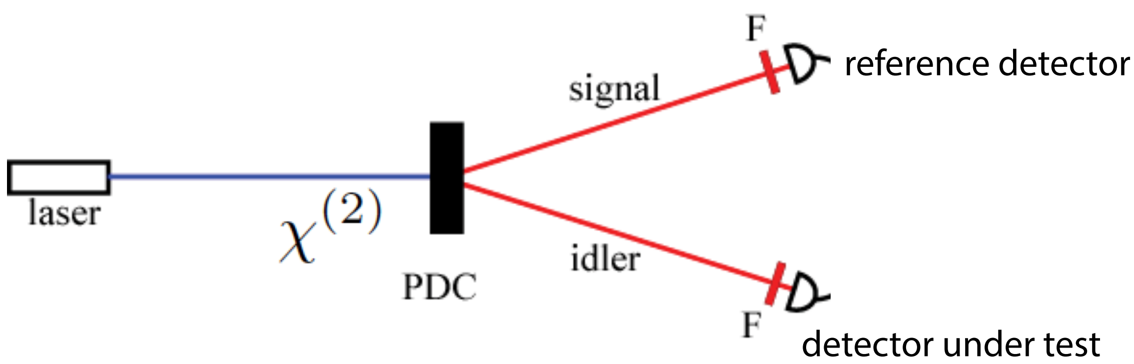
We make use of black body radiation, but at very low temperature.

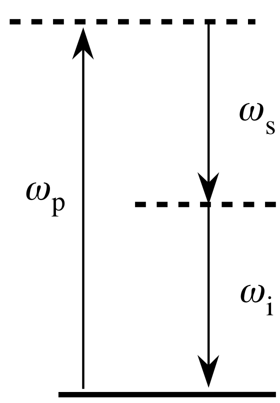
At low temperature the emission vanishes, but quantum field fluctuations remain.

We use these fluctuations to seed the process of spontaneous parametric down conversion (SPDC).

We calibrate our spectrophotometer with this radiation, whose strength can be traced back to Planck's constant *h*.

Our approach builds upon the work of Klyshko, Sergienko, Migdall, Polyakov, etc., but is distinct from it





Theory of Spontaneous Parametric Down Conversion (SPDC)

The theory of SPDC is very well developed (see, for instance, D. N. Klyshko, *Photons and Nonlinear Optics,* Gordon and Breach, 1989). Here we convey only a few key elements.

- Macroscopic Hamiltonian

$$\hat{H} \sim E_p \chi^{(2)} \hat{E}_s^\dagger \hat{E}_i^\dagger + \text{h.c.}$$

- Quantization

$$\hat{E}_j \sim \int \mathrm{d}^3 k_j \sqrt{\frac{\omega_j}{n_j}}\, \hat{a}_j\, \mathrm{e}^{i(\boldsymbol{k}_j \boldsymbol{r} - \omega_j t)}$$

↑ Vacuum amplitude

with

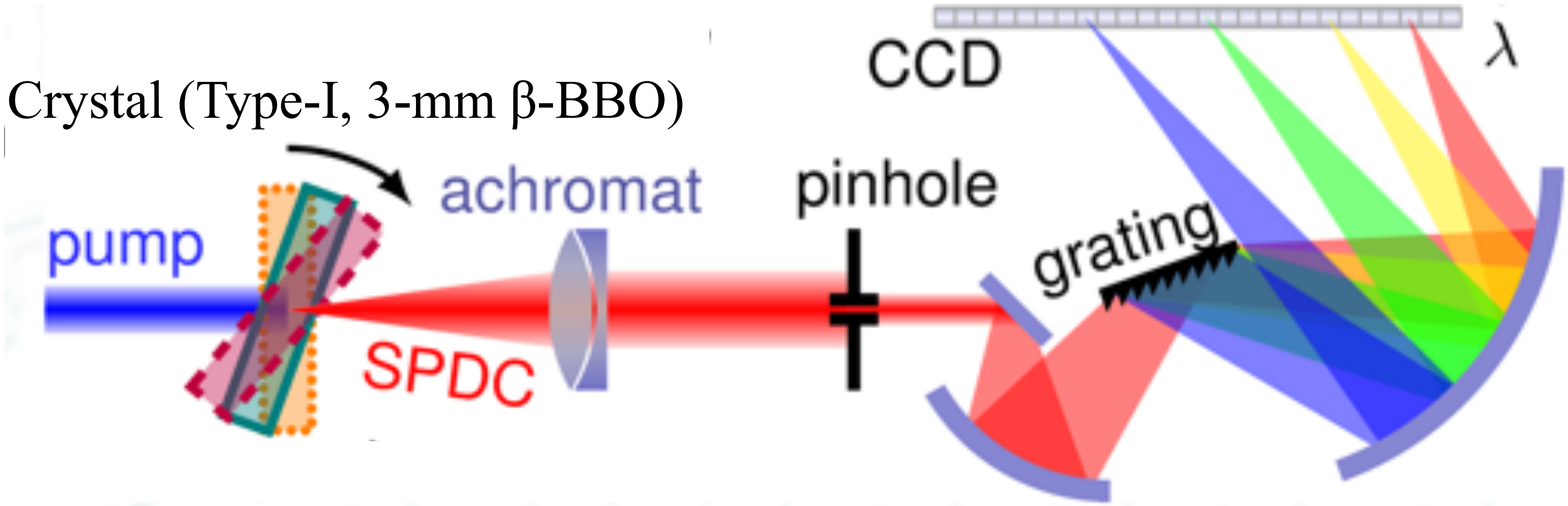
$$\boldsymbol{k}_j = (\boldsymbol{q}_j, \kappa_j)$$

We then determine the number of downconverted signal photons per mode

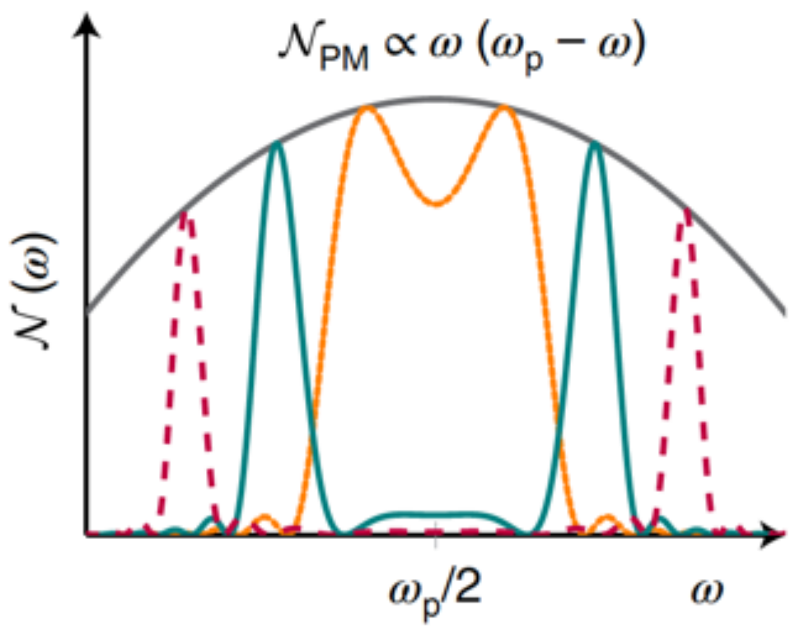
$$N(\boldsymbol{k}_s) \sim \underbrace{\left(\frac{\mathcal{E}_p \chi^{(2)} L}{\sqrt{n_s n_i}}\right)^2}_{\mathcal{G}(\lambda_s)} \underbrace{\omega_s \omega_i}_{Q(\lambda_s)} \underbrace{\operatorname{sinc}^2 \frac{\Delta\kappa L}{2}}_{\mathcal{S}(\lambda_s)}$$

S. Lemieux et al., Nature Physics 15, 529 (2019).

Our Experimental Setup



- We rotate the crystal to vary the phase matched wavelength. We end up with data that look like this.



Note that

$$\omega_s \omega_i = \omega_s(\omega_p - \omega_s)$$

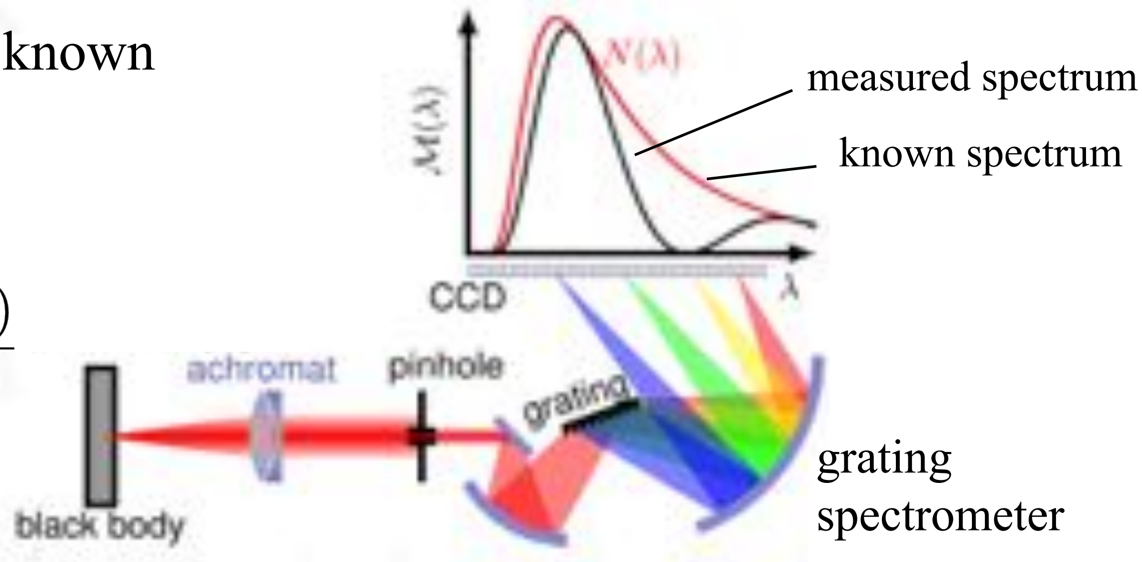
which give the form of the parabola shown in the figure.

- Intuition: For every photon emitted at the signal frequency, exactly one photon is emitted at the idler frequency.

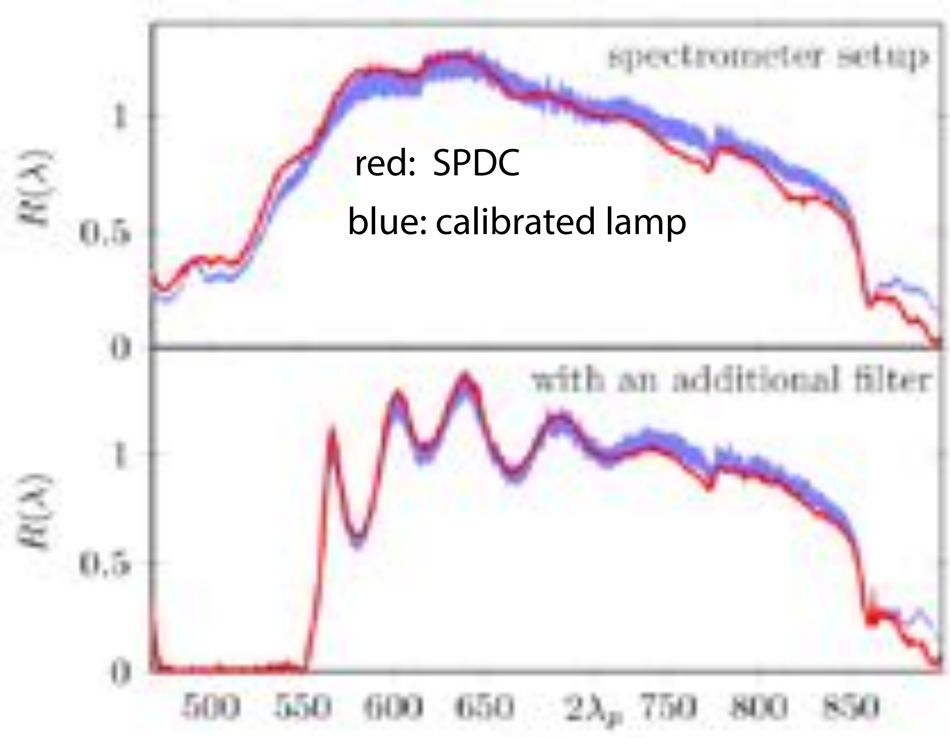
Determining the Response Function

- Spectrometer might not dispay the known spectrum of the calibrated source.
- Define response function

$$\mathcal{R}(\lambda) = \frac{\text{measured spectrum } \mathcal{M}(\lambda)}{\text{known spectrum } N(\lambda)}$$



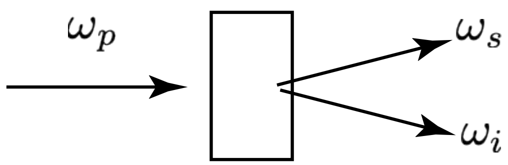
- Laboratory measurements of the response function



How the new calibration method works

Relative calibration

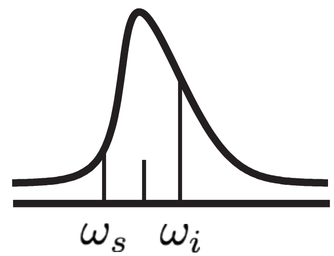
- Parametric downconversion (PDC)



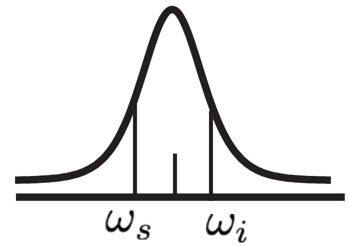
- For every signal photon, there is exactly one idler photon

- If the measured spectrum looks like the “before,” we know that the spectrometer is out of calibration

– before calibration



– after calibration



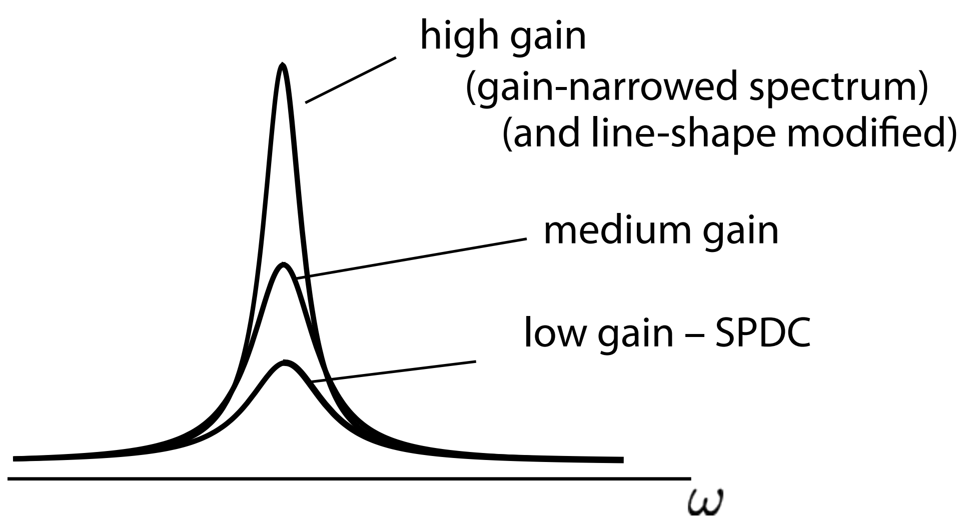
Absolute calibration

- The PRC emission spectrum becomes distorted in the high gain limit.

- Through careful measurements of the emission line shape, we can deduce the value of the gain.

- PDC is initiated by quantum noise. We thus know the actual number of photons in each of the signal and idler modes.

- Parametric downconversion emission spectra



Absolute Calibration: Use Strong Pump for Stimulated PDC

- The theory for absolute calibration is formulated as follows. We define the efficiency $\eta(\lambda)$ of the downconversion process through

$$M(\lambda) = \eta(\lambda)\, N(\lambda)$$

where $M(\lambda)$ is the measured signal and $N(\lambda)$ is the known signal.

- We express efficiency as $\eta(\lambda) = \alpha R(\lambda)$ where α is a wavelength-independent scaling.

- The predicted signal under phase-matched conditions is $\mathcal{N}_{\mathrm{PM}}$

$$\mathcal{N}_{\mathrm{PM}} = \sinh^2\left(\mathcal{G}\sqrt{\omega(\omega_p - \omega)}\right)$$

where we have introduced the gain parameter $\mathcal{G} = c^{-1}\, L\, \chi^{(2)} E_p / \sqrt{n\, n_i}$,

- Finally, we deduce the result

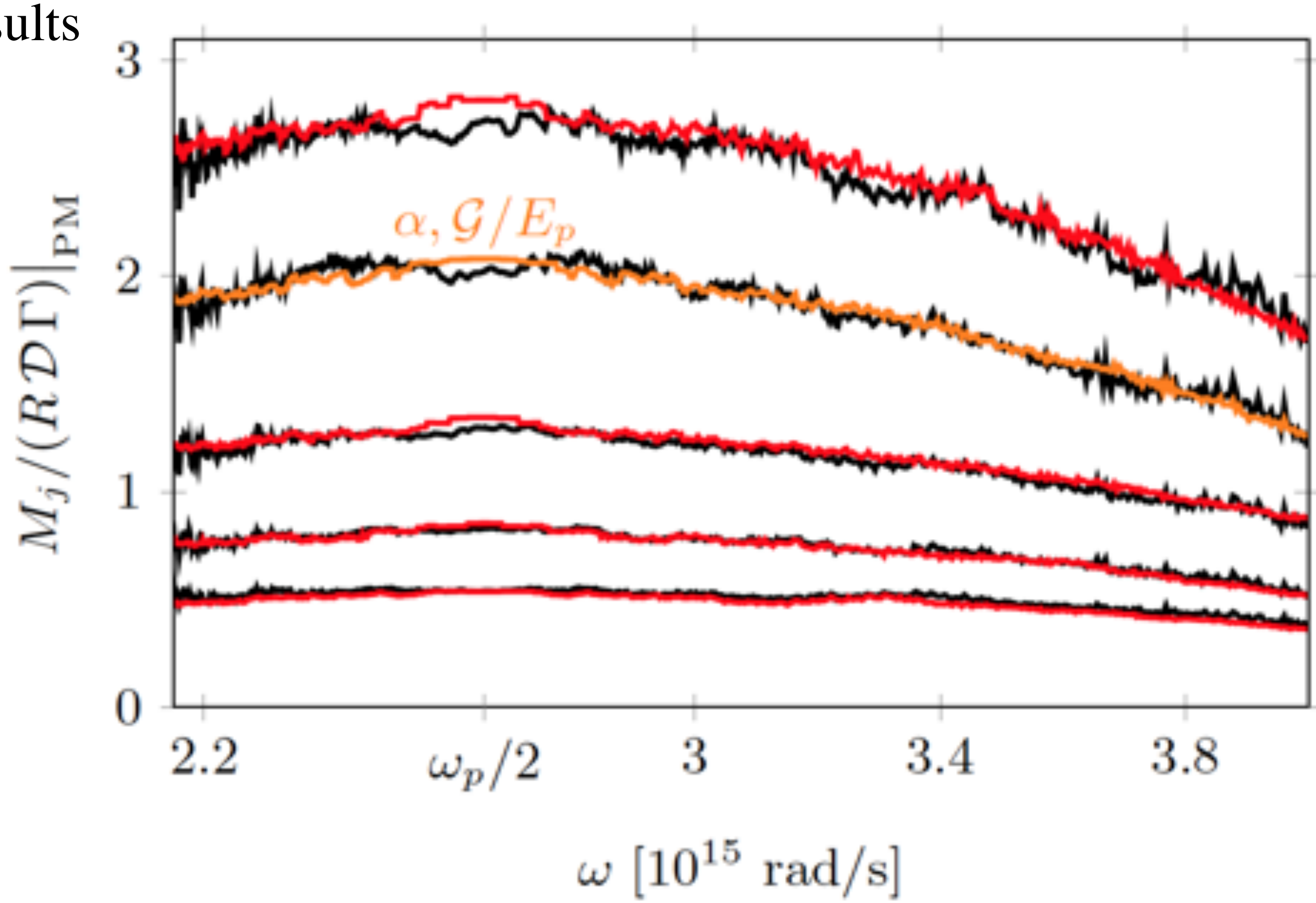
$$\alpha \sinh^2\left(\mathcal{G}\sqrt{\omega(\omega_p - \omega)}\right) = \left.\frac{M(\lambda)}{R(\lambda)\mathcal{D}(\lambda)\,\Gamma}\right|_{\mathrm{PM}} \quad \text{where} \quad \Gamma = \Delta\Omega\Delta\lambda\, A_s c \tau_s$$

In this equation, everything is known or directly measurbable except for α, which can thereby be determine.

- Intuition: As we increase the pump intensity, we increase the gain and thus the emission spectrum measures through gain narrowing. By measuring the line width of the emission, we can deduce the value of the gain parameter and thus $\mathcal{N}_{\mathrm{PM}}$

Absolute Calibration

Laboratory results



Black curve: right-hand side of displayed equation

Red and orange curves: fit to the left-hand side of the equation. The deduced value of α is 0.38.

$$\alpha \sinh^2\left(\mathcal{G}\sqrt{\omega(\omega_p - \omega)}\right) = \left.\frac{M(\lambda)}{R(\lambda)\mathcal{D}(\lambda)\,\Gamma}\right|_{\rm PM}$$

Conclusions

- We have proposed and demonstrated a new protocol for calibrating a spectrophometer.

- The method is based on the process parametric downconversion (PDC).

- For a weak pump beam, the emission is induced by vacuum fluctuation and is known as spontaneous PDC. This emission can provide a relative calibration of a spectrophometer

- For a strong pump beam, the emission is still initiated by vacuum fluctuations, but it is then amplified by parametric gain processes. The process is then one of stimulated PDC, and when combined with spontaneous PDC can provide an absolute calibration of the spectrophometer.

- The advantage of this method is that it relies only on basic quantum physics to provide the calibration

Special Thanks To My Students and Postdocs!

Ottawa Group

Rochester Group