Putting Quantum Optics to Work: Quantum Radiometry and Quantum Aberration Correction

Robert W. Boyd

Department of Physics and
Max-Planck Centre for Extreme and Quantum Photonics
University of Ottawa

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

with:

Samuel Lemieux, Enno Giese, Robert Fickler, Maria V. Chekhova, A. Nicholas Black, Enno Giese, Boris Braverman, Nicholas Zollo, and Stephen M. Barnett

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

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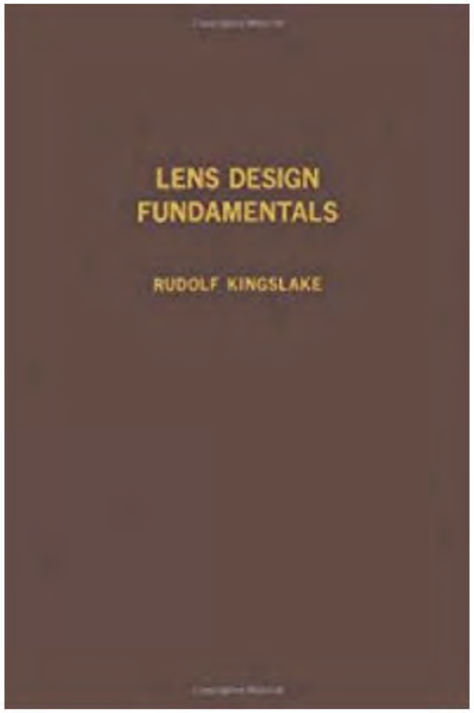
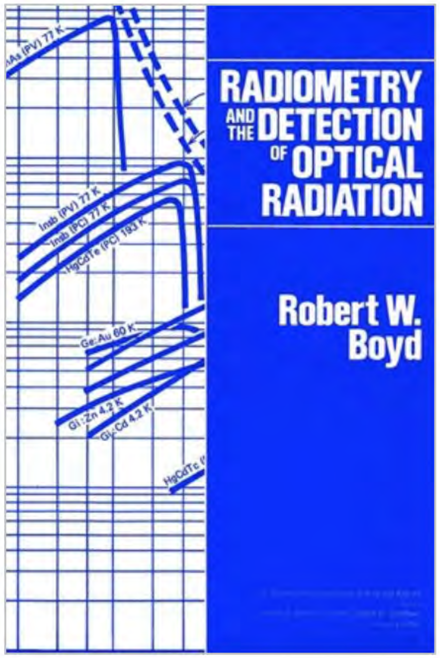
Quantum Technologies for Realistic Optical Engineering

- 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)

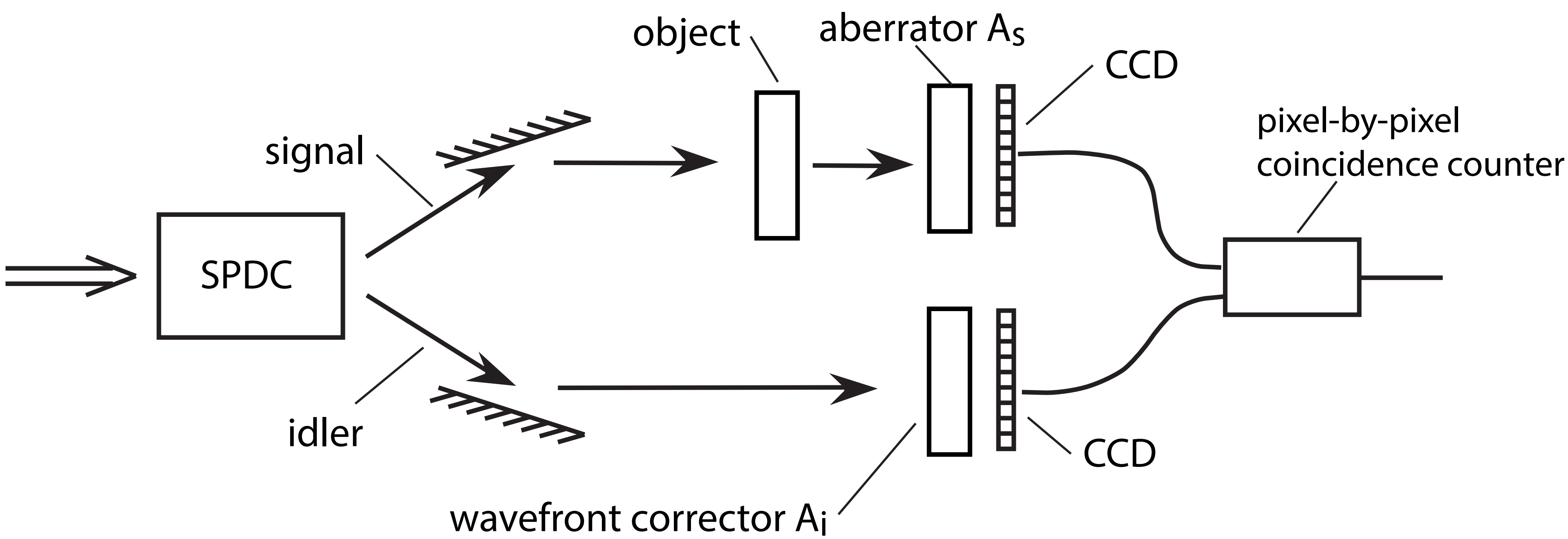




Nonlocal Quantum Aberration Correction

- 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

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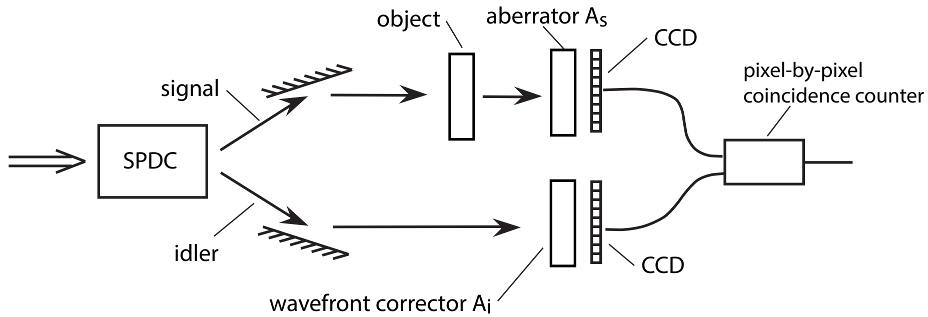


- This situation is reminiscent of Franson's dispersion cancellation, in the time domain.

- Recall strong similarity between time and spatial domains

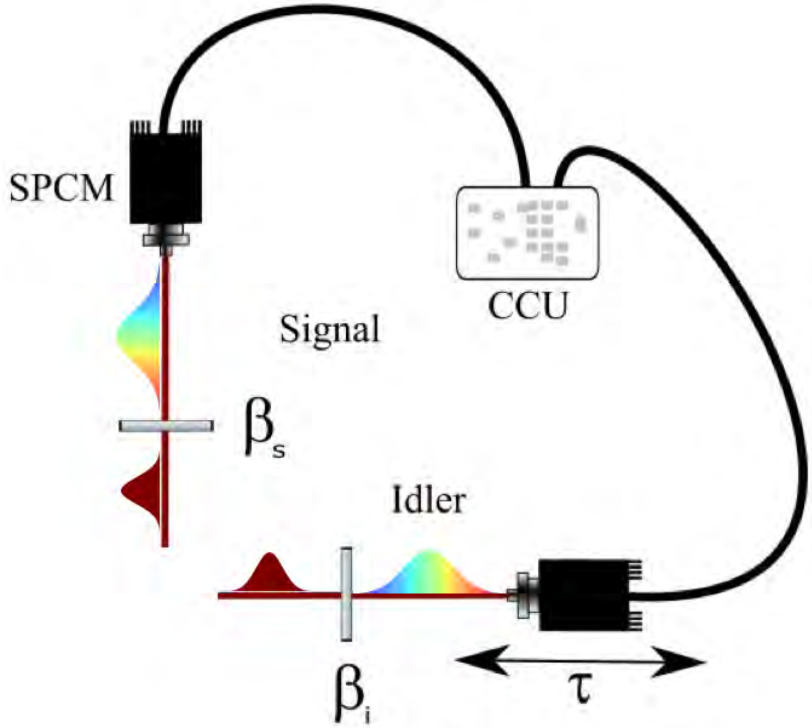
time domain: $$\frac{\partial \tilde{A}_s}{\partial z} + \frac{1}{2} i k_2 \frac{\partial^2 \tilde{A}_s}{\partial \tau^2} = i\gamma |\tilde{A}_s|^2 \tilde{A}_s.$$

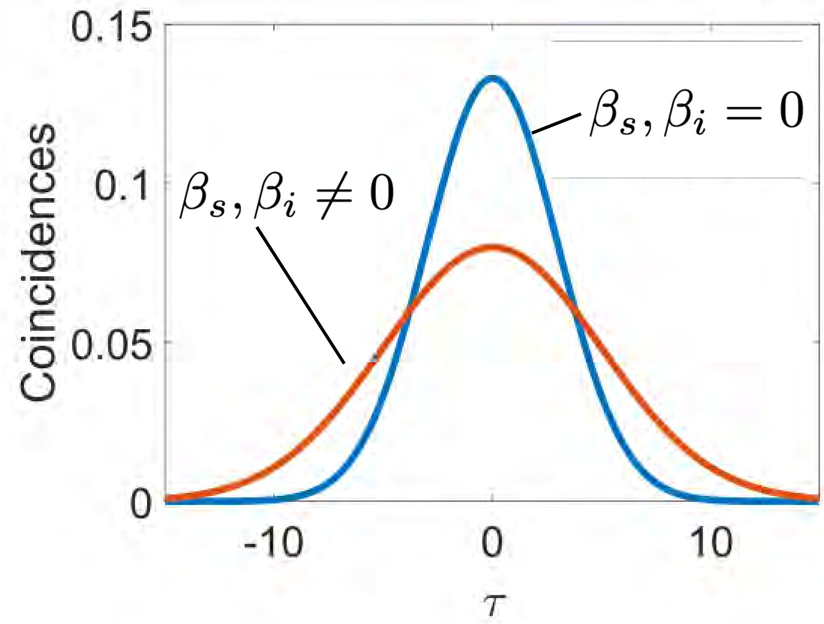
spatial domain: $$2ik_0 \frac{\partial A}{\partial z} + \frac{\partial^2 A}{\partial x^2} = -3\chi^{(3)} \frac{\omega^2}{c^2} |A|^2 A$$

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

Nonlocal Dispersion Cancellation

Laboratory setup





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

$1/v_g(\omega_0)$

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

classical result

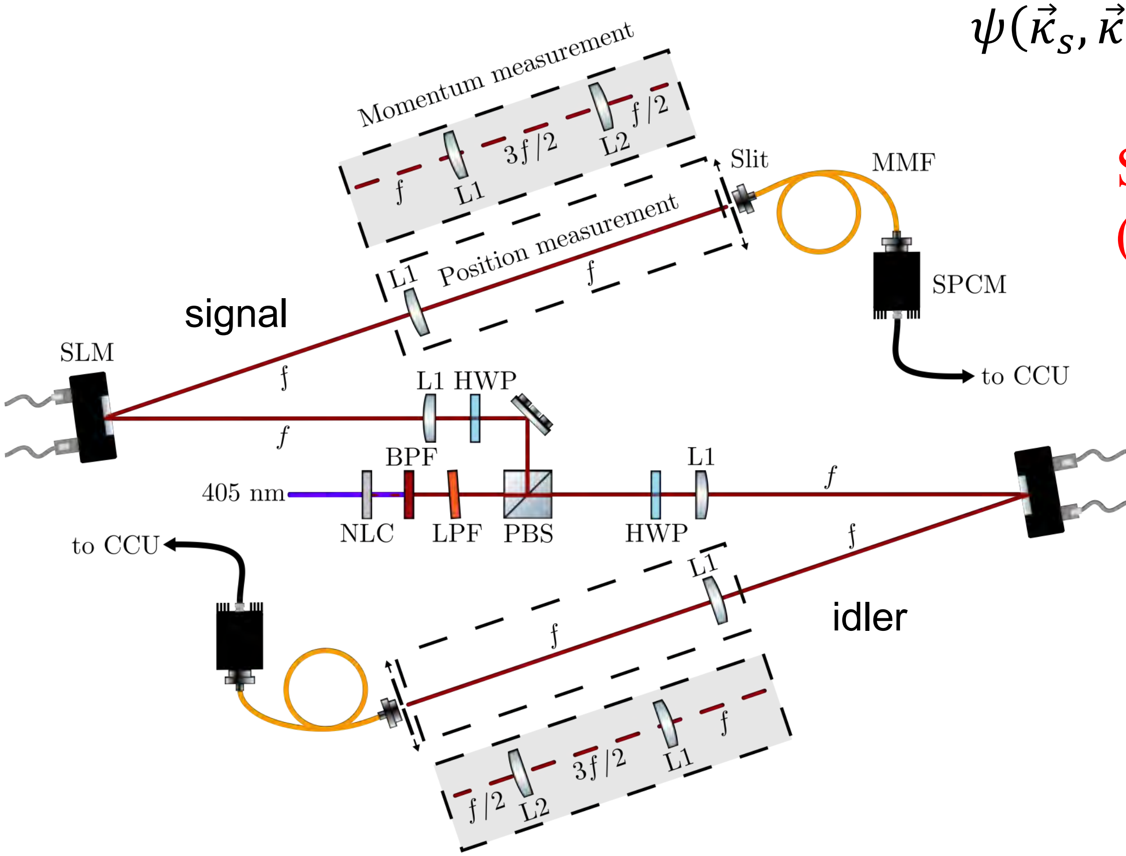
$$\boxed{\sigma_\tau^2 = \frac{2\,\sigma_0^4 + (\beta_s^2 + \beta_i^2)\,x^2}{\sigma_0^2}}$$

quantum result

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

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

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

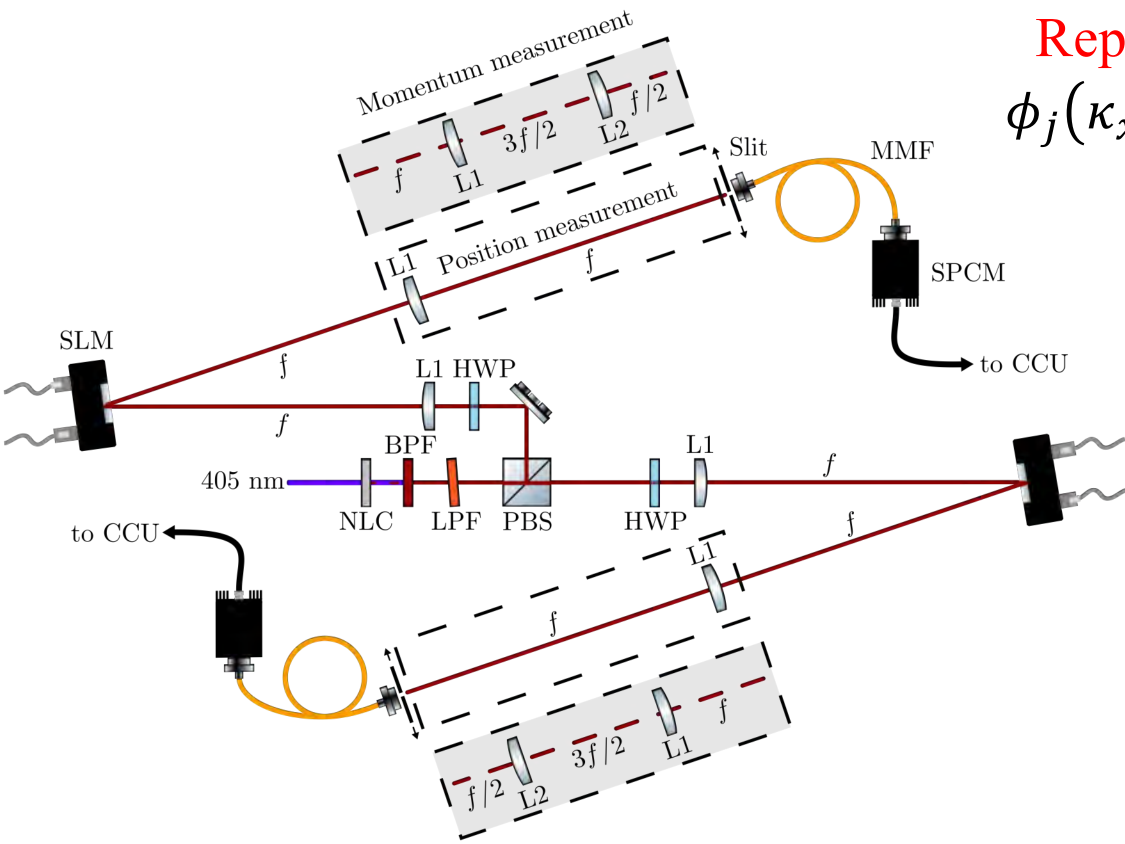
$$\mathrm{sinc}\left(\frac{\mathrm{l_c}|\vec{\kappa}_s-\vec{\kappa}_\mathrm{i}|^2}{4k_p}\right) \approx \exp\left(-\frac{L_c|\vec{\kappa}_s-\vec{\kappa}_i|^2}{4}\right)$$

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

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

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

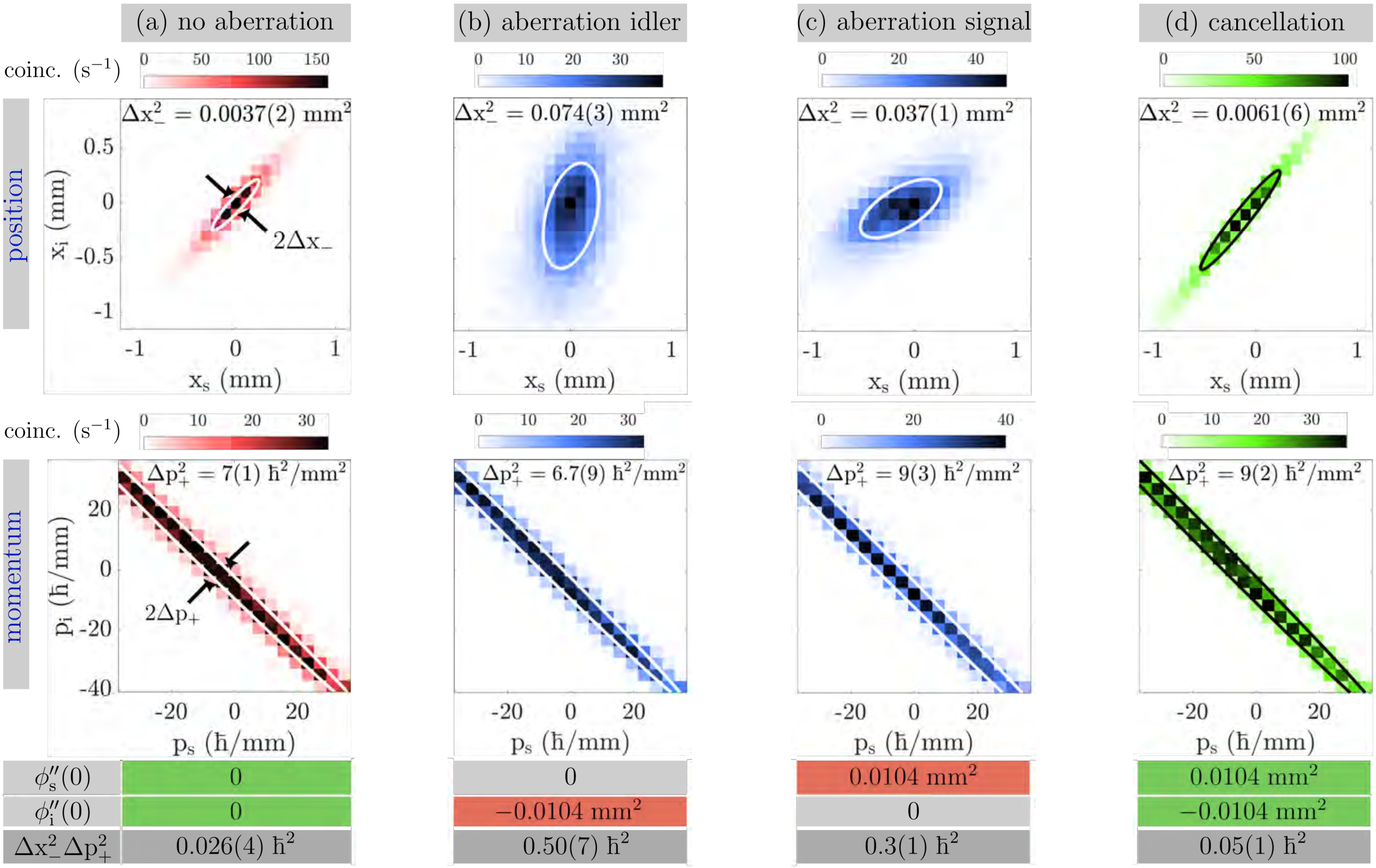
Coincidence count rate

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

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

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

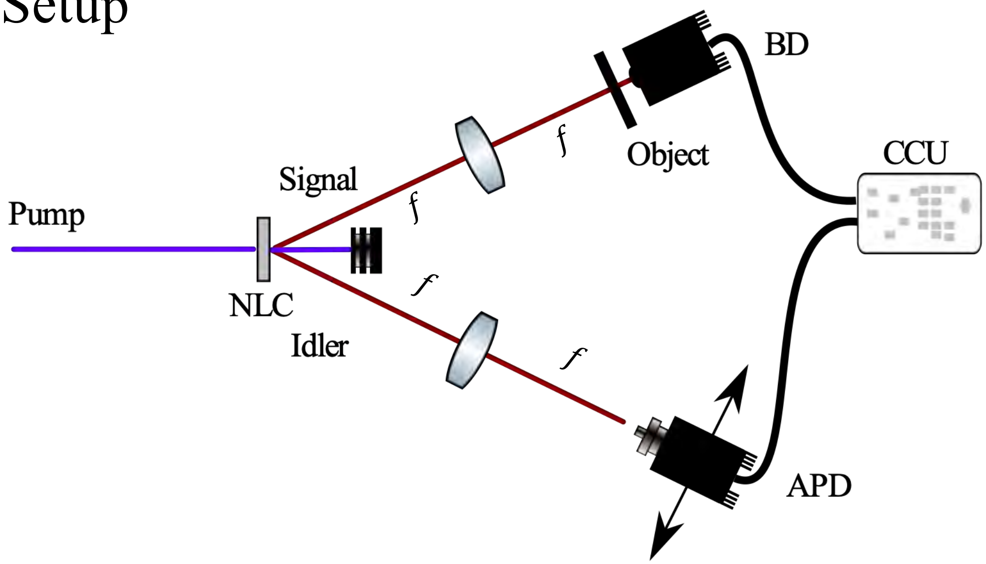
Laboratory Results



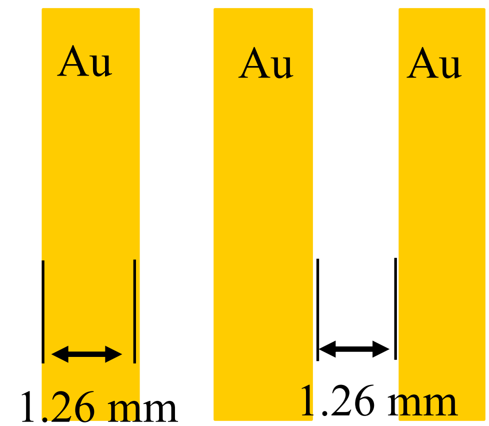
$(\Delta x_-)^2(\Delta p_+)^2 < \hbar^2/4$ Mancini criterion for entanglement (PRL 88, 120401 (2002).

Nonlocal Aberration Cancellation for a Real Object

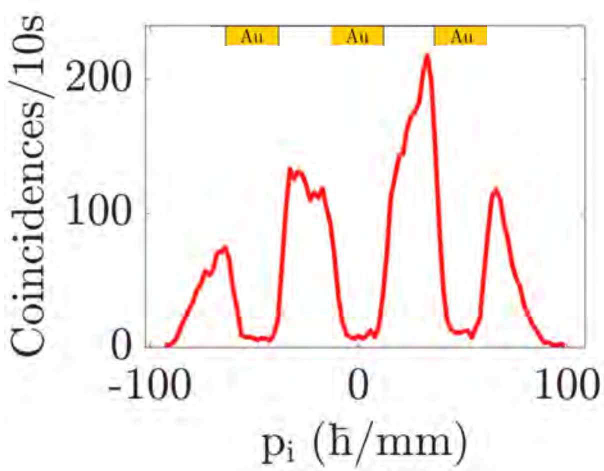
Setup



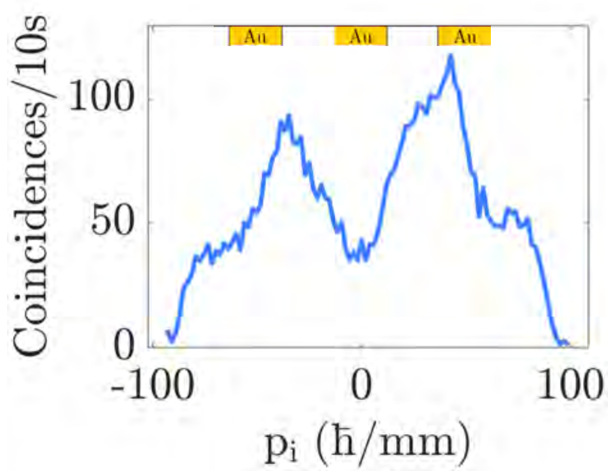
Object:



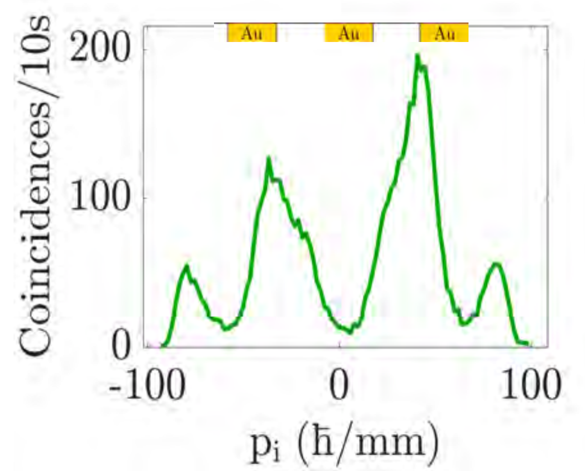
No aberrations



Aberrations in signal beam only



Aberrations compen-sated 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

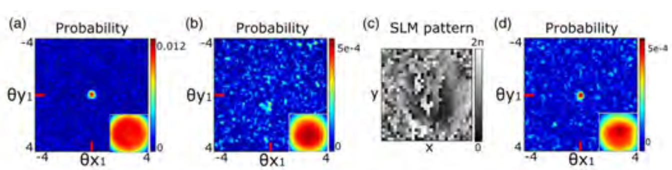
Experimental observation of aberration cancellation in entangled two-photon beams

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

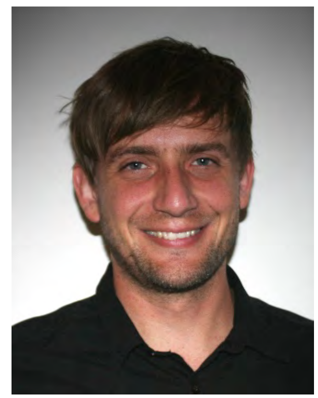
Nicholas Zollo (not pictured)

Quantum Radiometry

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

Samuel Lemieux

Enno Giese



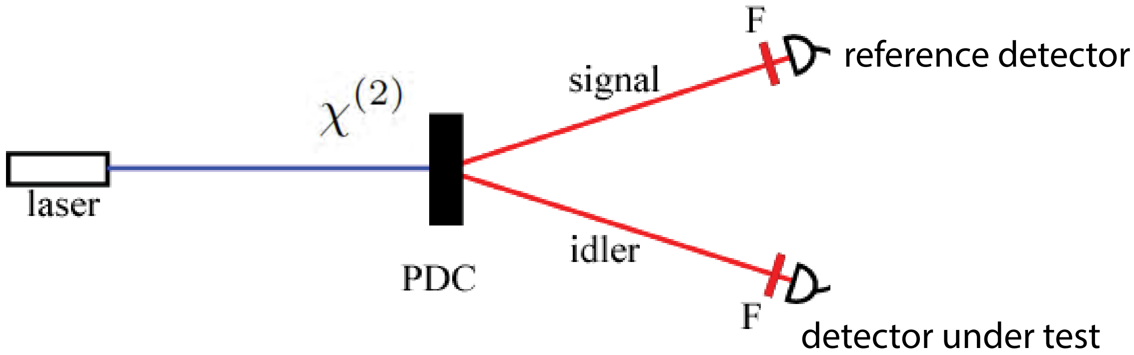
Robert Fickler

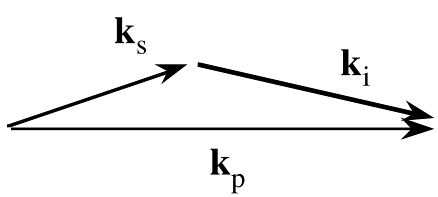
Maria V. Chekhova

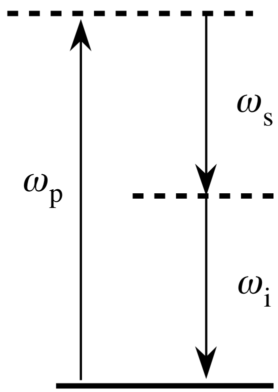
Samuel Lemieux, Enno Giese, Robert Fickler, Maria V. Chekhova, and R.W. Boyd, A primary radiation standard based on quantum nonlinear optics, Nature Physics 15, 529 (2019).

Earlier Work on Quantum Radiometry

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



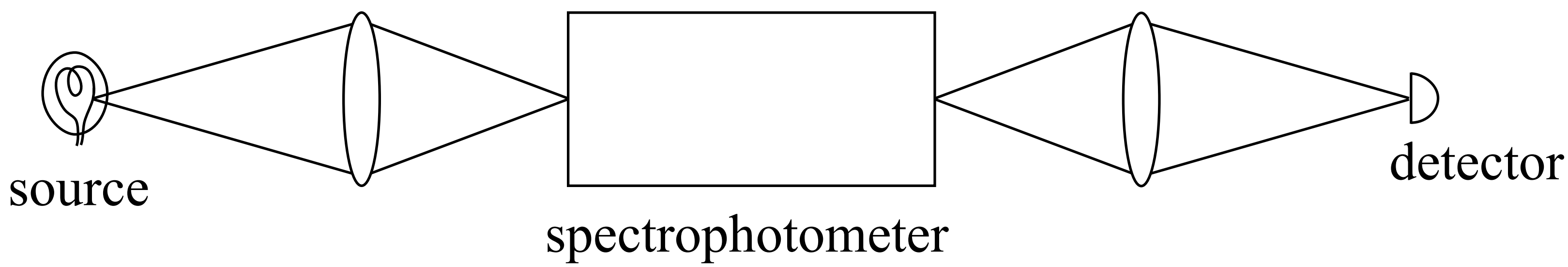


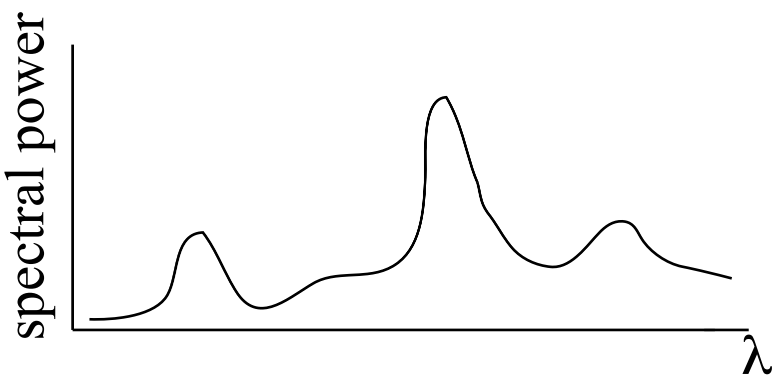


- Earlier work (Klyshko) established that the light produced by spontaneous parametric downconversion (SPDC) can be characterized in terms of the radiometric property known as brightness (or radiance).

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

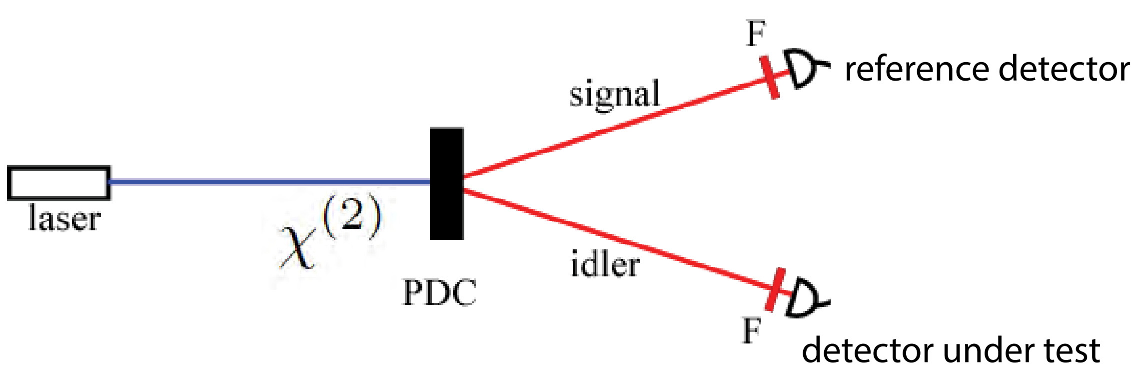
We make use of black body radiation, but at very low temperature.

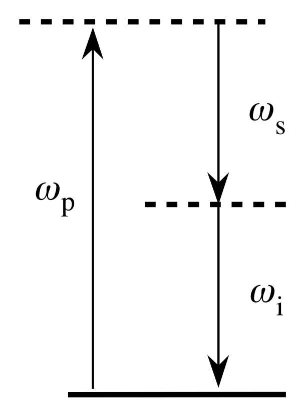
At low temperature the emission vanishes, but quantum field fluctuations remain.

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

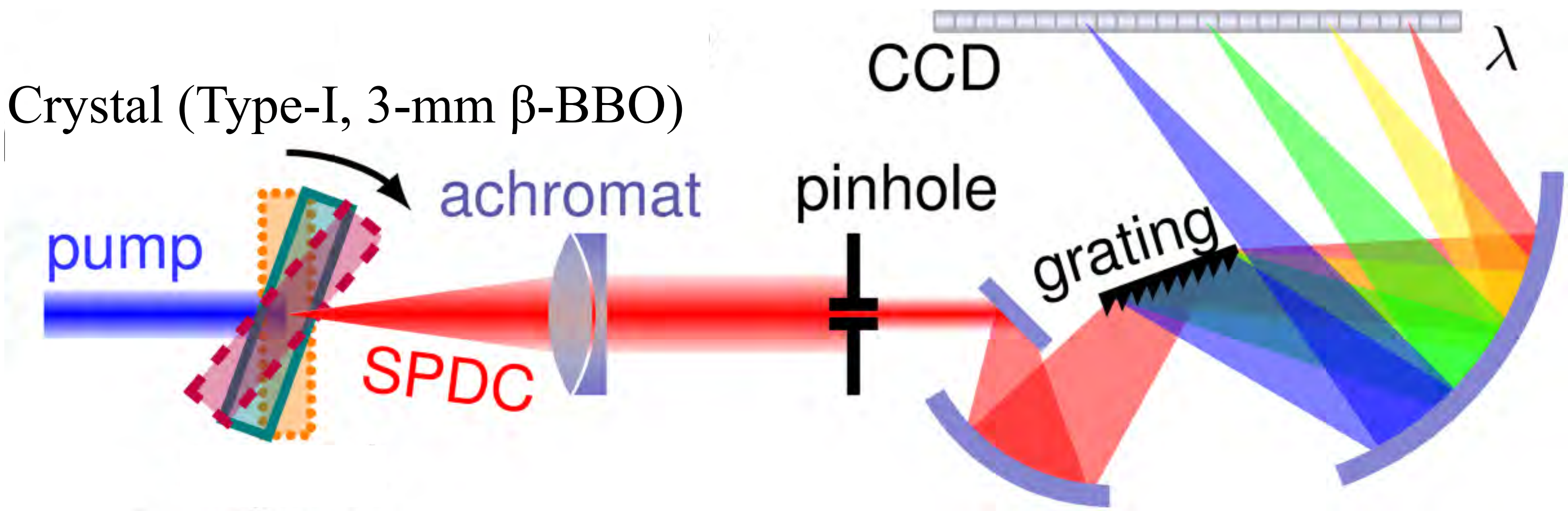
$$\boldsymbol{k}_j = (\boldsymbol{q}_j, \kappa_j)$$

We then determine the number of downconverted signal photons per mode

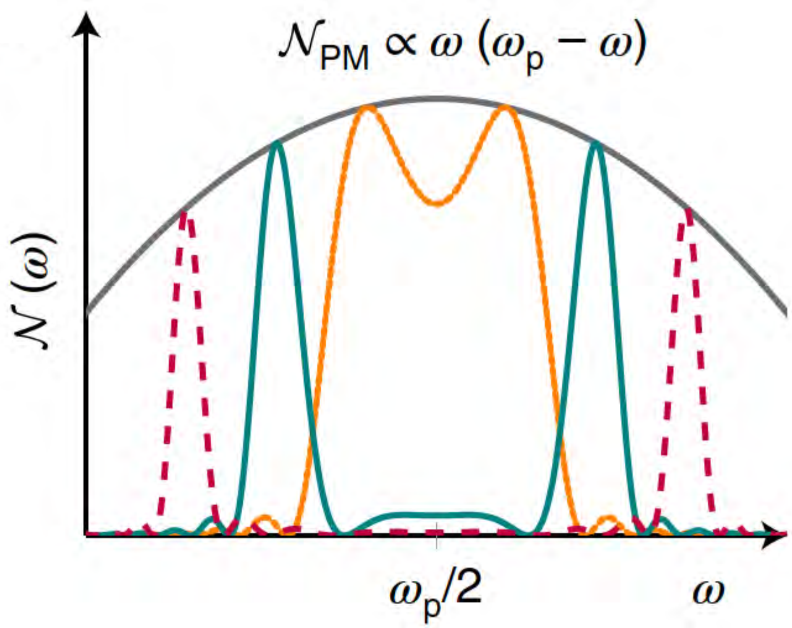
$$N(\boldsymbol{k}_s) \sim \underbrace{\left(\frac{\mathcal{E}_p \chi^{(2)} L}{\sqrt{n_s n_i}}\right)^2}_{\mathcal{G}(\lambda_s)} \underbrace{\omega_s \omega_i}_{Q(\lambda_s)} \underbrace{\operatorname{sinc}^2 \frac{\Delta \kappa L}{2}}_{\mathcal{S}(\lambda_s)}$$

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.

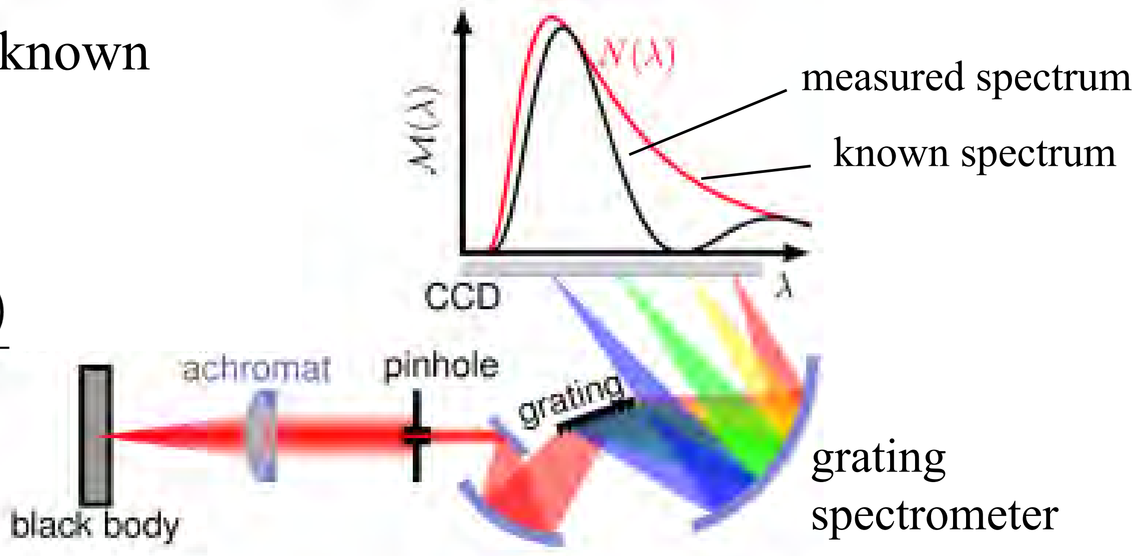
- Intuition: For every photon emitted at the signal frequency, exactly one photon is emitted at the idler frequency.

Determining the Response Function

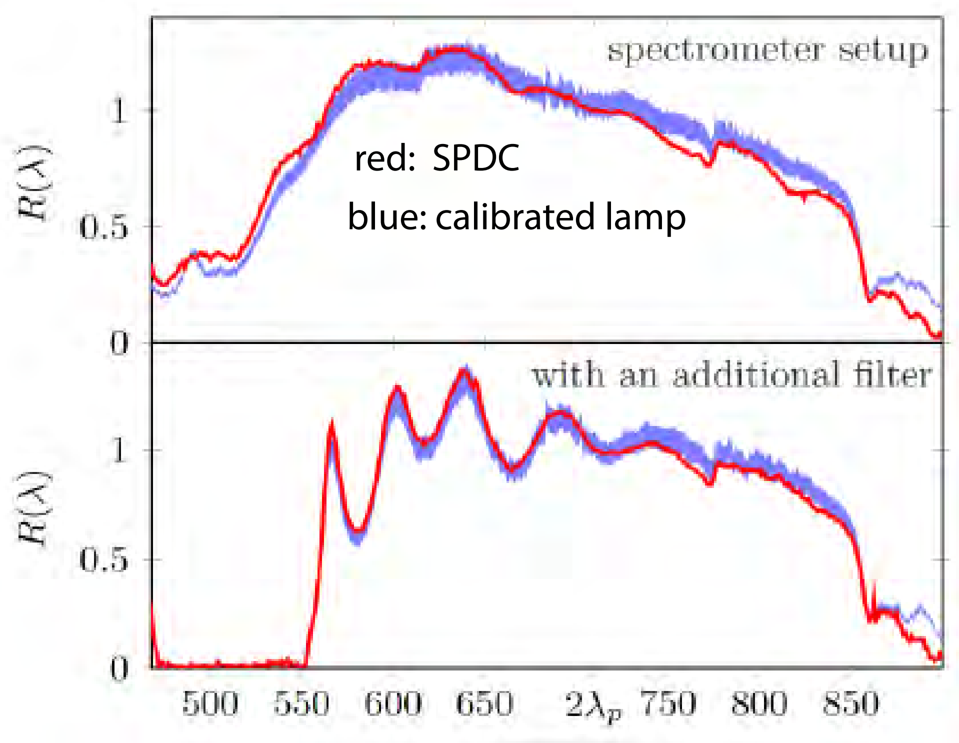
- Spectrometer might not dispay the known spectrum of the calibrated source.

- Define response function

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



- Laboratory measurements of the response function



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

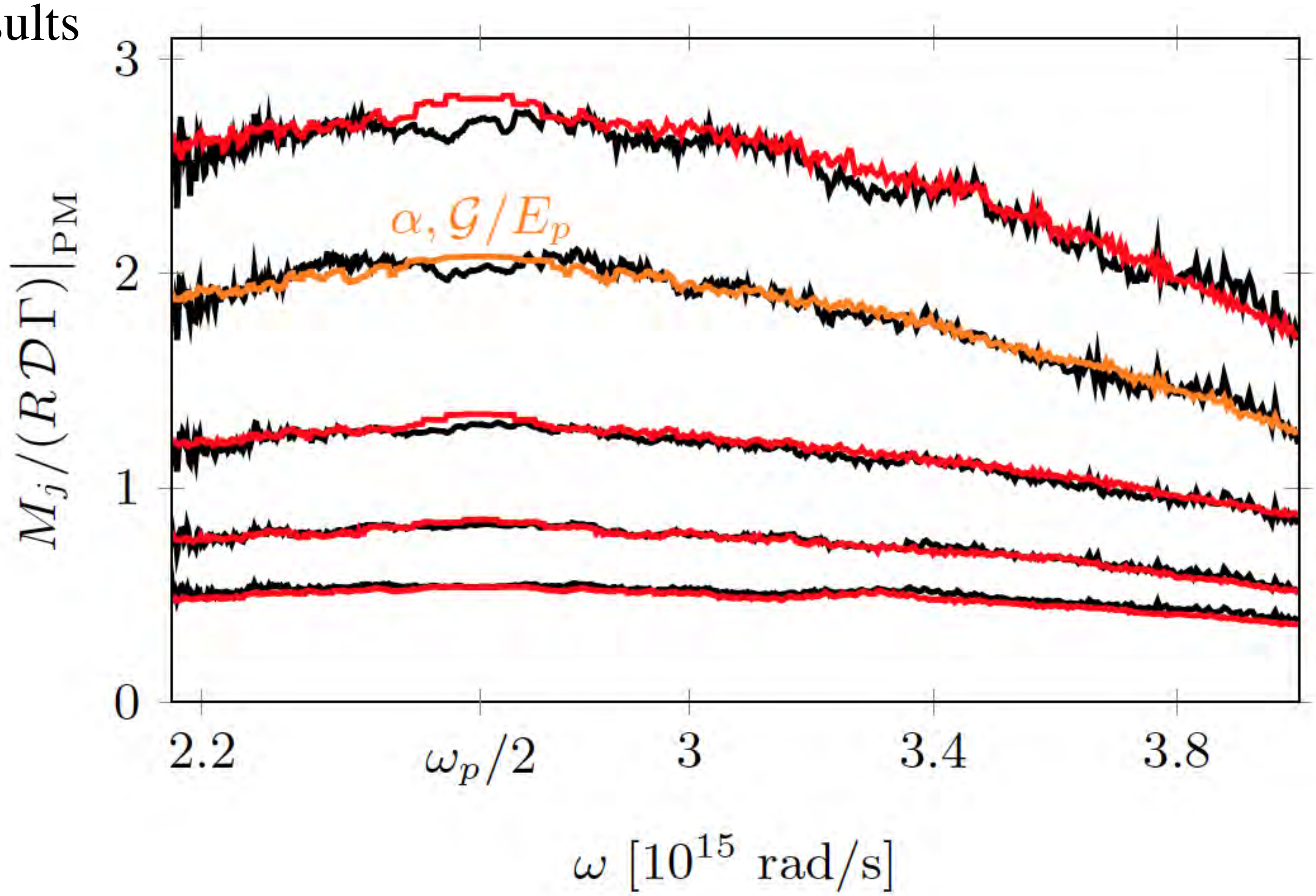
$$\alpha \sinh^2\left(\mathcal{G}\sqrt{\omega(\omega_p - \omega)}\right) = \left.\frac{M(\lambda)}{R(\lambda)\mathcal{D}(\lambda)\,\Gamma}\right|_{\mathrm{PM}} \quad \text{where} \quad \Gamma = \Delta\Omega\Delta\lambda\, A_s c\tau_s$$

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.

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

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

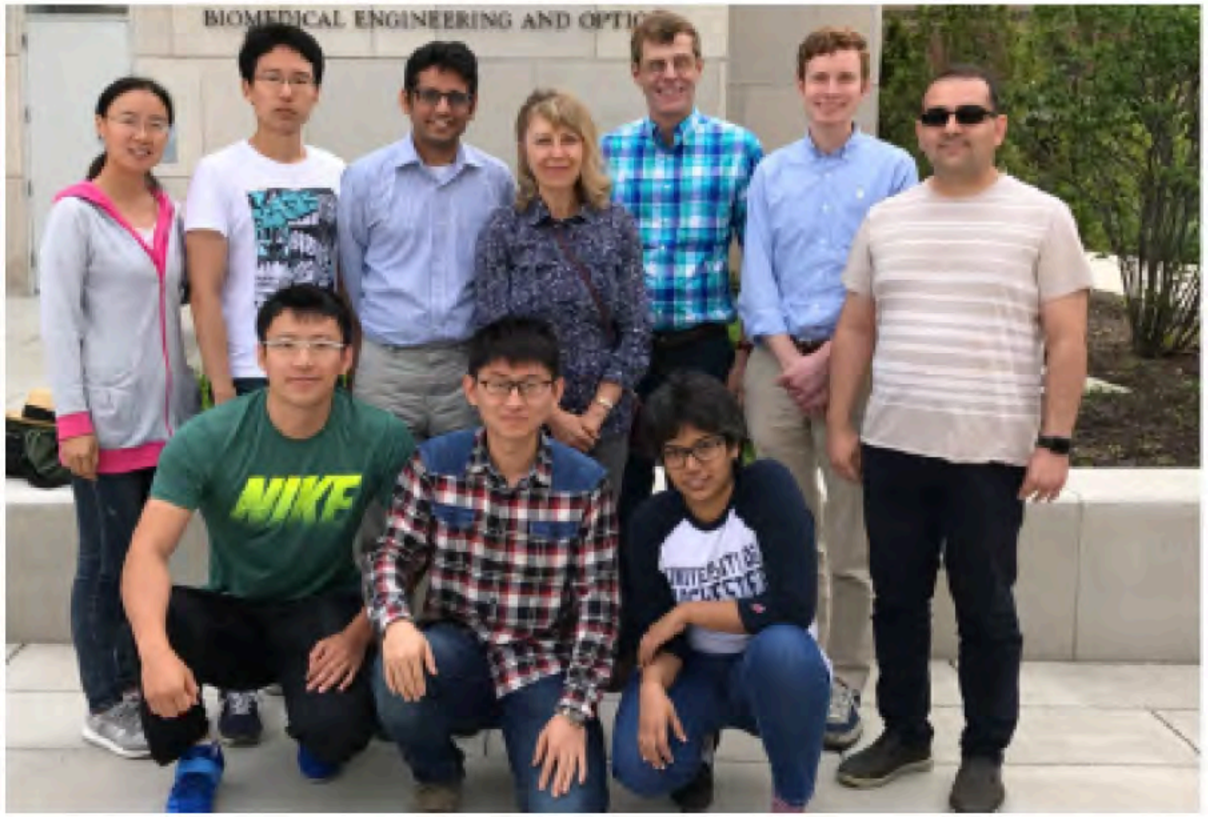
- For a strong pump beam, the emission is still initiated by vacuum fluctuations, but it is then amplified by parametric gain processes. The process is then one of stimulated PDC, and when combined with spontaneous PDC can provide an absolute calibration of the spectrophometer.

- 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



Relative and Absolute Calibration

The results from the last slide demonstrated that SPDC can provide good ***relative*** calibration.

Specifically, we presented a protocol for determining the relative response $R(\lambda)$. Through knowledge of $R(\lambda)$ one can correct for any wavelength-dependent inefficiencies of a spectrophometer.

A more challenging task is to determine the absolute calibration, that is, to determine exactly how many watts (or watts per spectral bandwidth) are leaving the spectrophotometer.

The theory and data presented up till now have been taken in the limit of a weak pump wave, that is for ***spontaneous*** parametric downconversion. As we will show next, when this procedure is repeated for a strong pump wave, the process is one of ***stimulated*** parametric down conversion. For this situation, additional information becomes available and it is possible to perform an absolute calibration.