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Abstract:

uOttawa University of Glasgow UNIVERSITY of ROCHESTER

Some Topics in Quantum Photonics

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Some Topics in Quantum Photonics

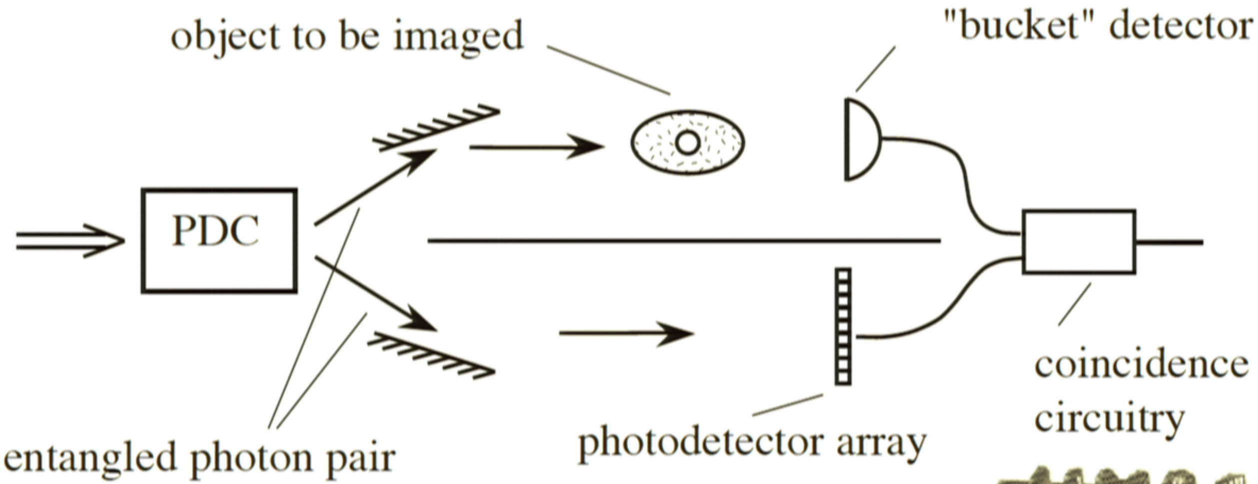
1. Overview of “Ghost Imaging”

2. “Interaction-Free” Ghost Imaging

3. New Photonic Material for Quantum Information

4. Quantum Key Distribution with Many Bits per Photon

Ghost (Coincidence) Imaging



object to be imaged

"bucket" detector

PDC

entangled photon pair

photodetector array

coincidence circuitry

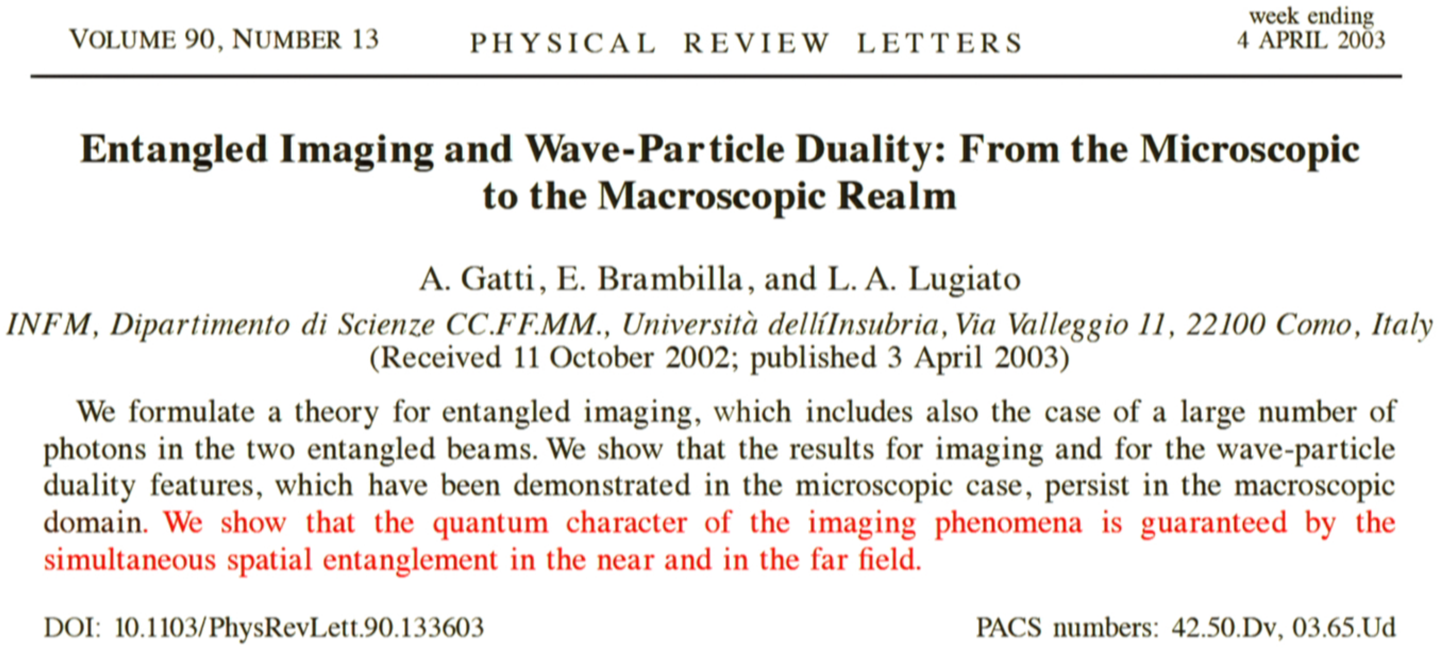
- Obvious applicability to remote sensing!
  (imaging under adverse situations, bio, two-color, etc.)
- Is this a purely quantum mechanical process? (No)
- Can Brown-Twiss intensity correlations lead to ghost imaging? (Yes)

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)

Is Ghost Imaging a Quantum Phenomenon?



VOLUME 90, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 4 APRIL 2003

Entangled Imaging and Wave-Particle Duality: From the Microscopic to the Macroscopic Realm

A. Gatti, E. Brambilla, and L. A. Lugiato
INFM, Dipartimento di Scienze CC.FF.MM., Università dellíInsubria, Via Valleggio 11, 22100 Como, Italy

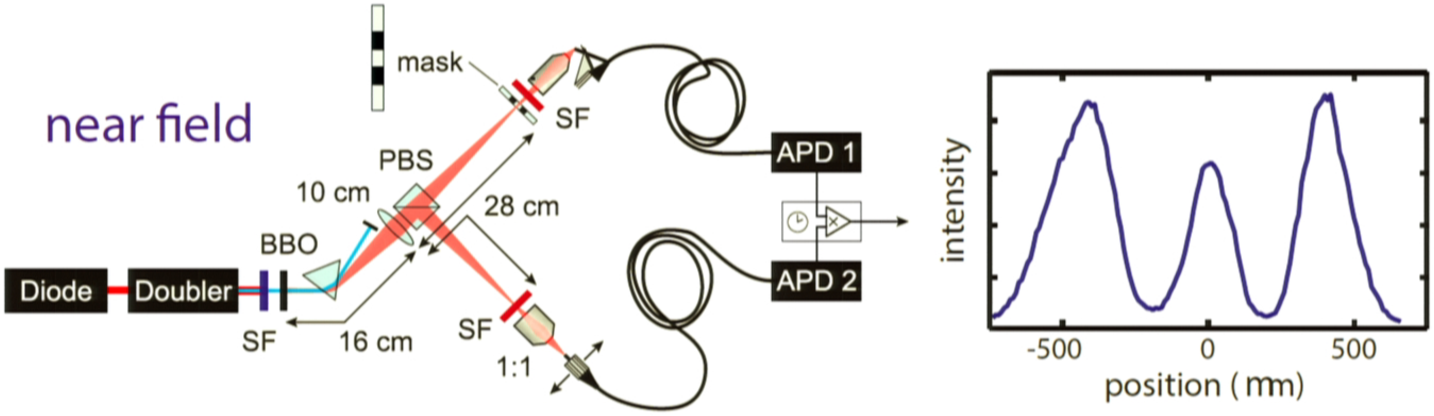
(Received 11 October 2002; published 3 April 2003)

We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain. We show that the quantum character of the imaging phenomena is guaranteed by the simultaneous spatial entanglement in the near and in the far field.

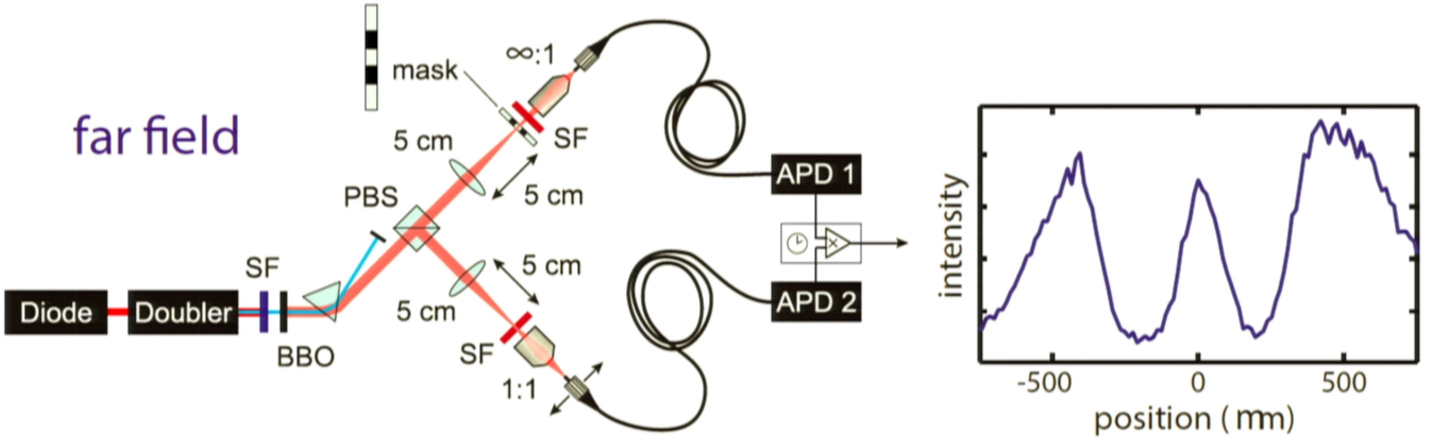
DOI: 10.1103/PhysRevLett.90.133603 PACS numbers: 42.50.Dv, 03.65.Ud

Near- and Far-Field Ghost Imaging Using Quantum Entanglement

near field



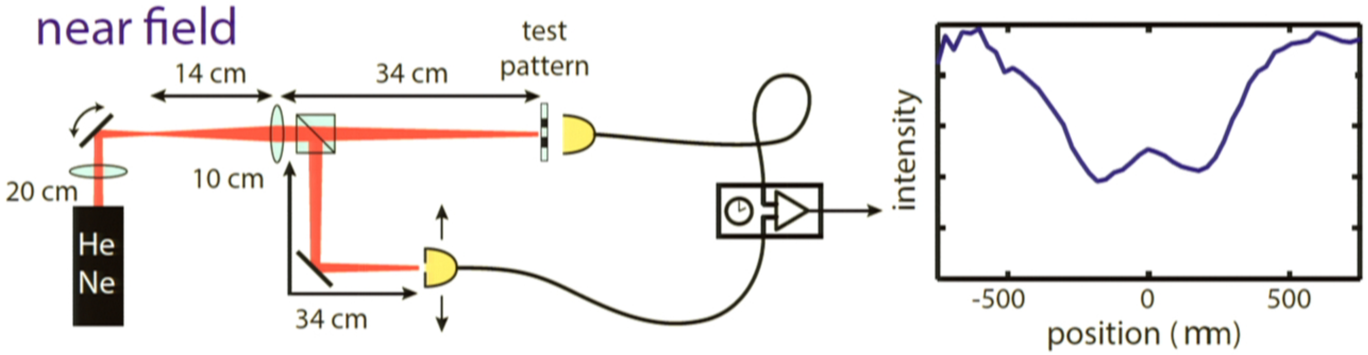
far field

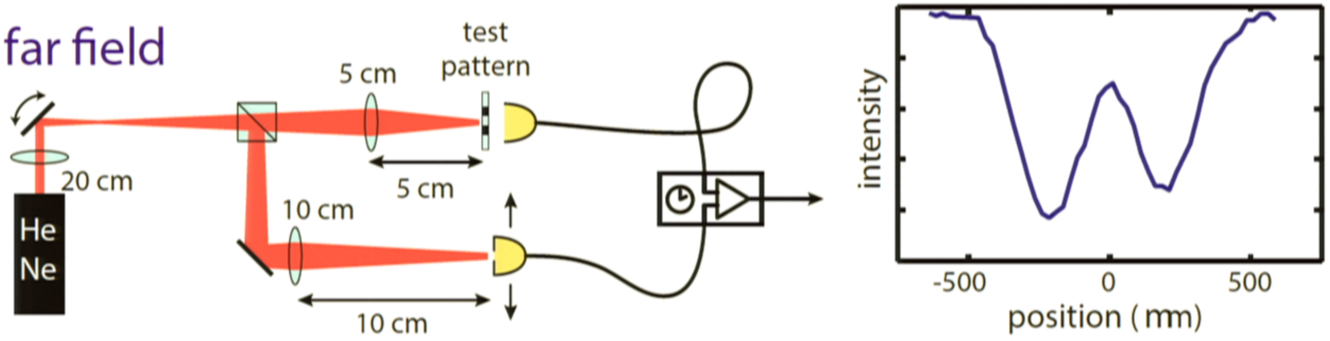


Good imaging observed in both the near and far field

Bennink, Bentley, Boyd, and Howell, Phys. Rev. Lett., 92, 033601, 2004.

Near- and Far-Field Ghost Imaging With a Classical Source



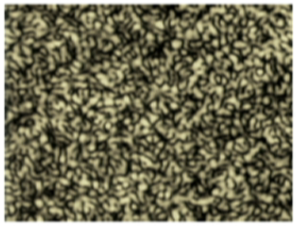


- Good imaging can be obtained only in near field or far field.
- Detailed analysis shows that in the quantum case the space-bandwidth exceeded the classical limit by a factor of three.

Thermal Ghost Imaging

Instead of using quantum-entangled photons, one can perform ghost imaging using the correlations of a thermal light source, as predicted by Gatti et al. 2004.

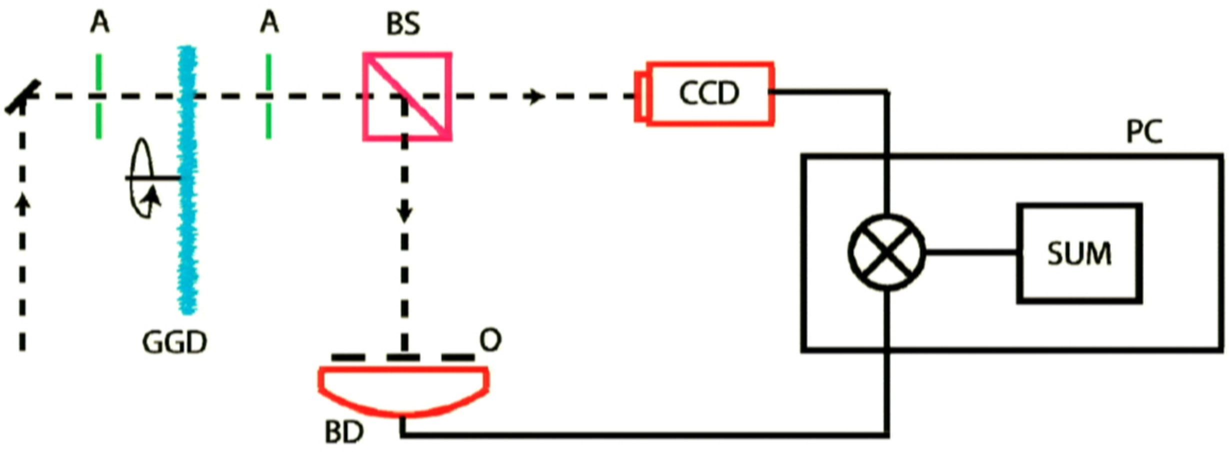
Recall that the intensity distribution of thermal light looks like a speckle pattern.



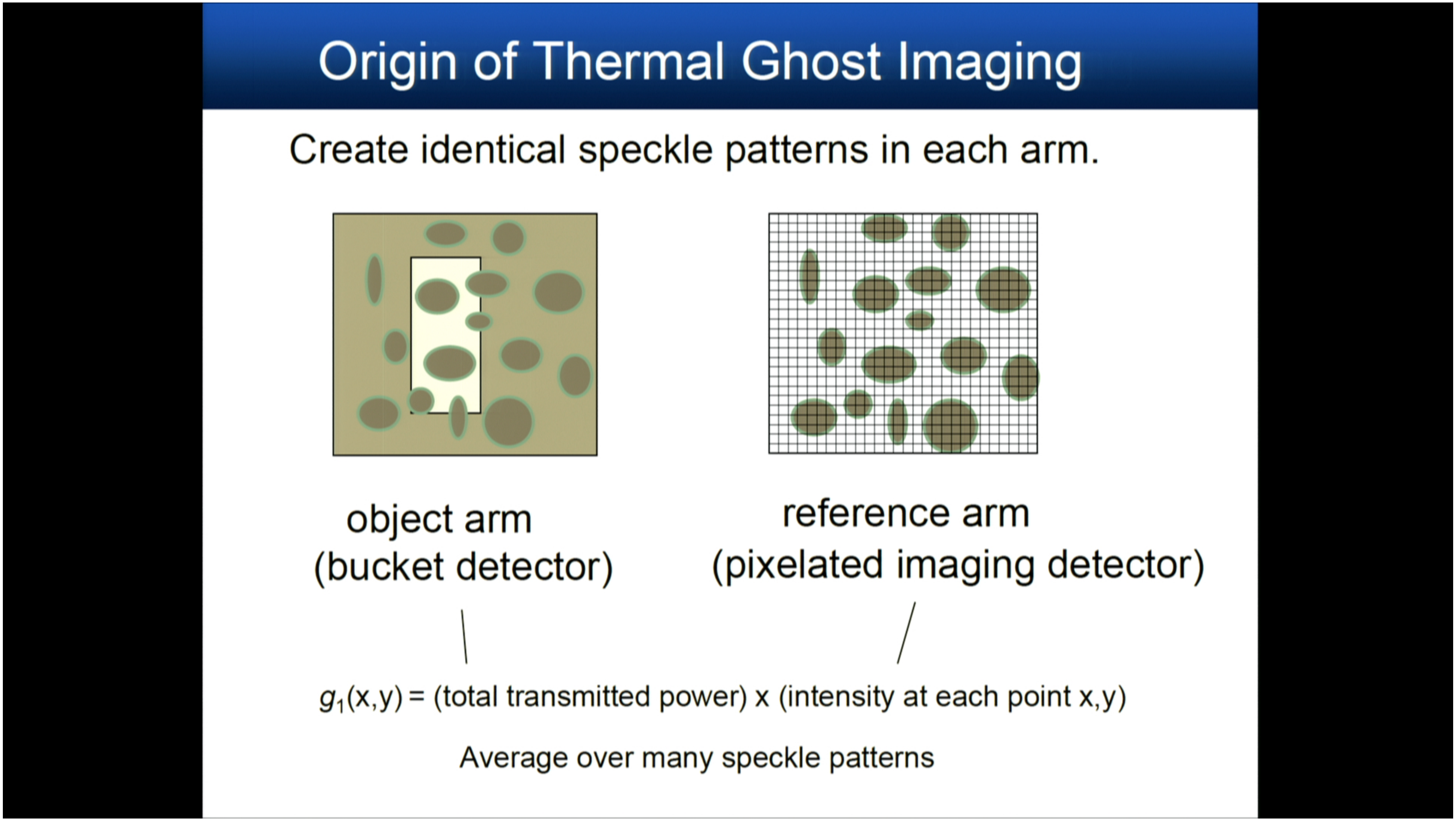
We use pseudothermal light in our studies: we create a speckle pattern with the same statistical properties as thermal light by scattering a laser beam off a rotating ground glass plate.

A. Gatti, E. Brambilla, M. Bache, and L. A. Lugiato, Phys. Rev. Lett. 93, 093602 (2004).

How does thermal ghost imaging work?



- Ground glass disk (GGD) and beam splitter (BS) create two identical speckle patterns
- Many speckles are blocked by the opaque part of object (O), but some are transmitted, and their intensities are summed by bucket detector (BD)
- CCD camera measures intensity distribution of speckle pattern
- Each speckle pattern is multiplied by the output of the BD
- Results are averaged over a large number of frames.



Origin of Thermal Ghost Imaging

Create identical speckle patterns in each arm.

object arm
(bucket detector)

reference arm
(pixelated imaging detector)

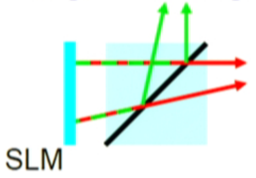
$g_1(x,y)$ = (total transmitted power) x (intensity at each point x,y)

Average over many speckle patterns

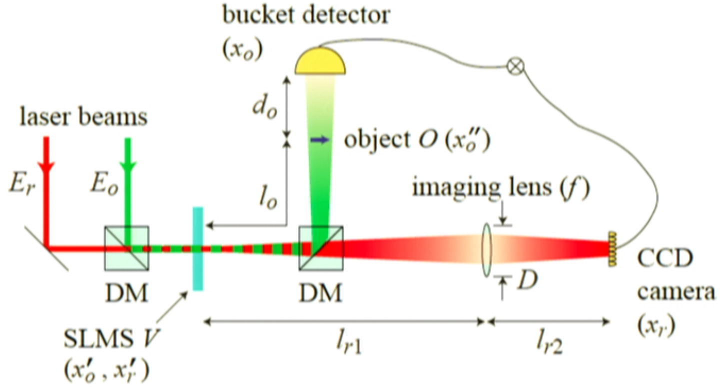
Two-Color Ghost Imaging

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

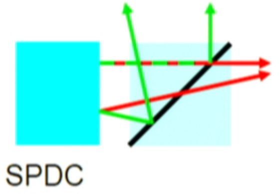
Thermal ghost imaging

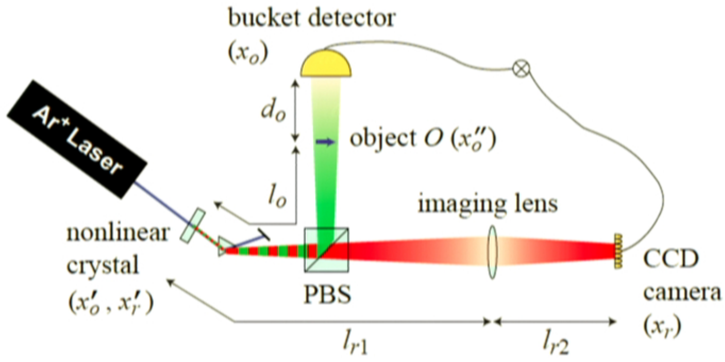


But no obvious way to make identical speckle patterns at two wavelengths



Quantum ghost imaging





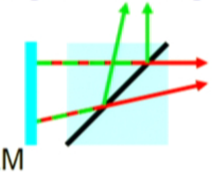
Spatial resolution depends on wavelength used to illuminate object.

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

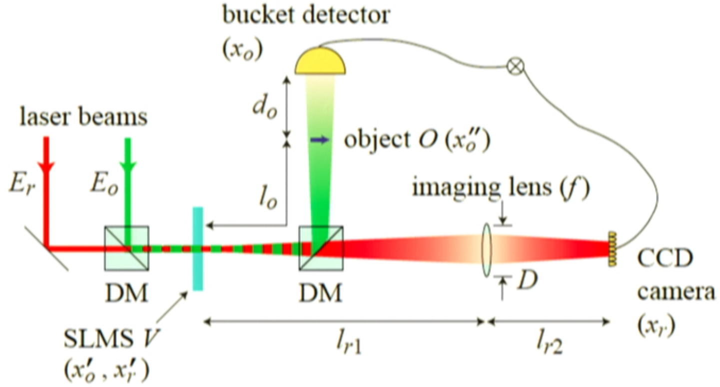
Two-Color Ghost Imaging

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

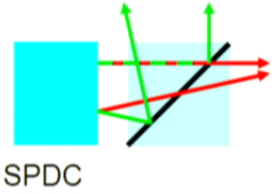
Thermal ghost imaging

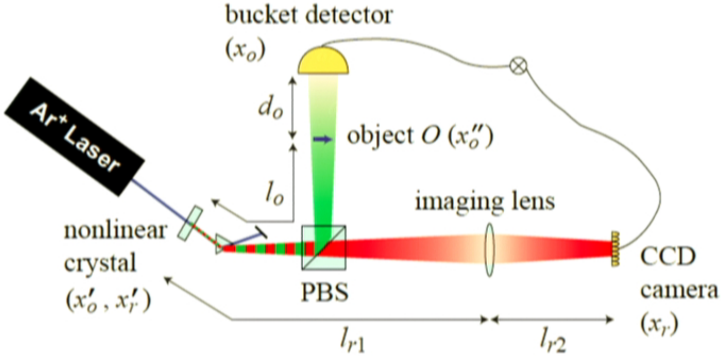


But no obvious way to make identical speckle patterns at two wavelengths



Quantum ghost imaging





Spatial resolution depends on wavelength used to illuminate object.

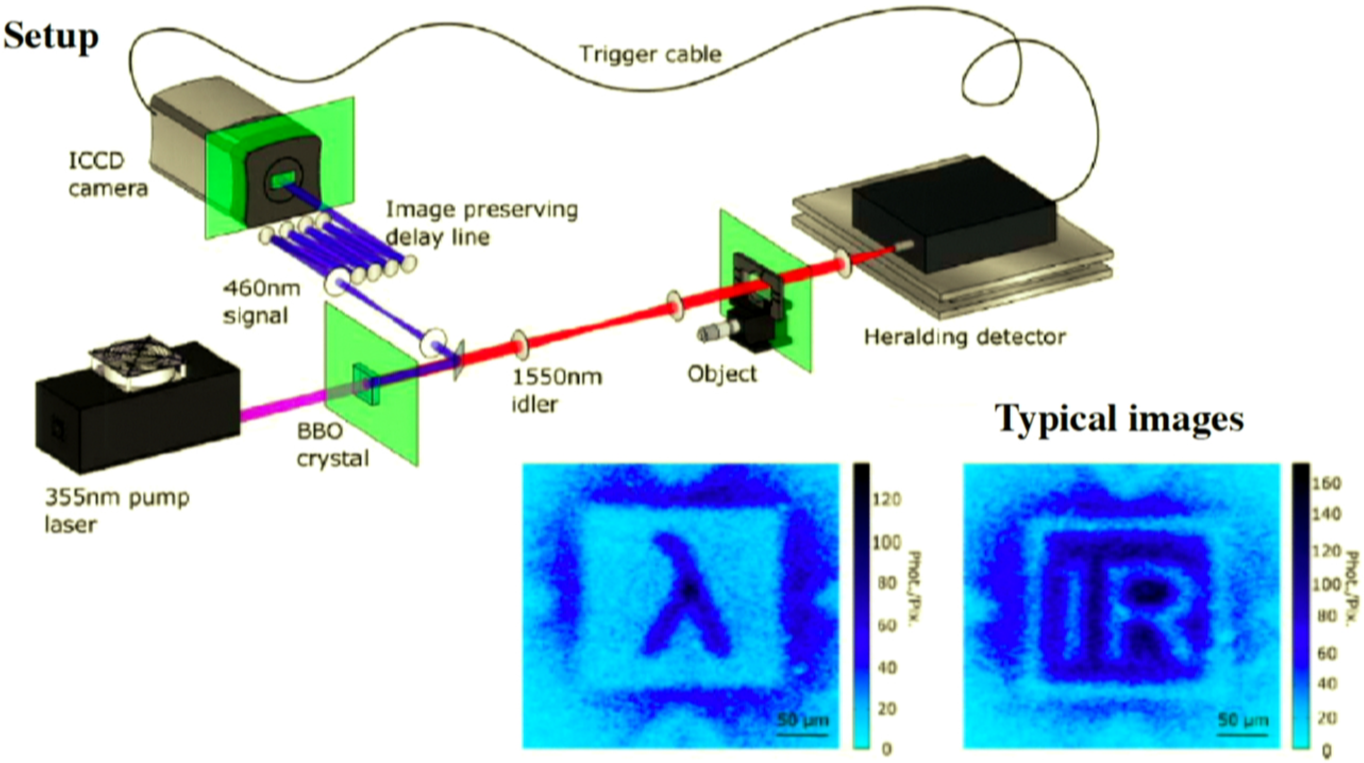
Two-Color Ghost Imaging, K.W.C. Chan, M.N. O'Sullivan, and R.W. Boyd, Phys. Rev. A 79, 033808 (2009).

Wavelength-Shifted (Two-Color Ghost) Microscopy

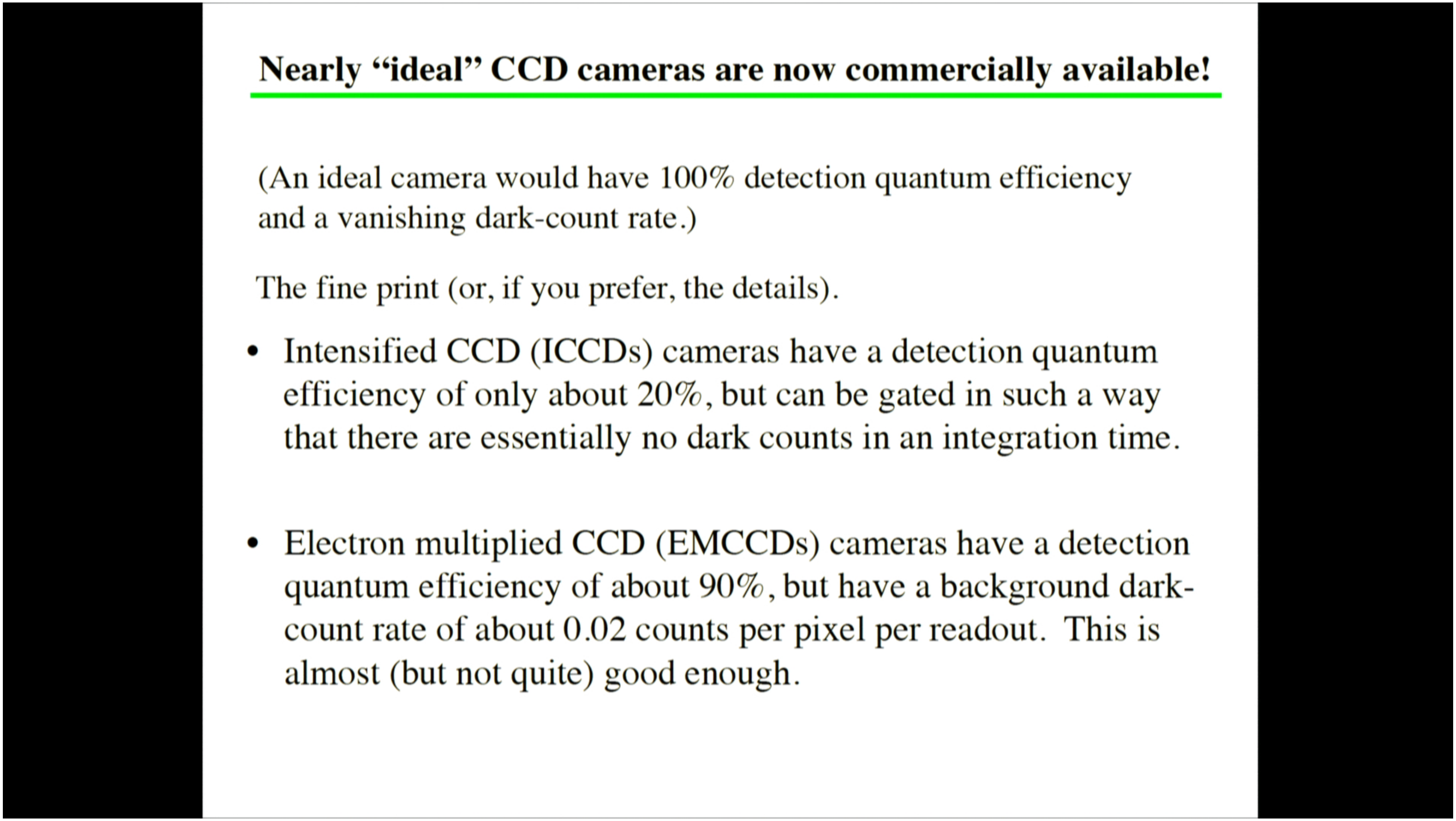
- Pump at 355 nm produces signal at 460 nm and idler at 1550 nm
- Object is illuminated at 1550 nm, but image is formed (in coincidence) at 460 nm
- Wavelength ratio of 3.4 is the largest yet reported.

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).



Nearly “ideal” CCD cameras are now commercially available!

(An ideal camera would have 100% detection quantum efficiency and a vanishing dark-count rate.)

The fine print (or, if you prefer, the details).

- Intensified CCD (ICCDs) cameras have a detection quantum efficiency of only about 20%, but can be gated in such a way that there are essentially no dark counts in an integration time.
- Electron multiplied CCD (EMCCDs) cameras have a detection quantum efficiency of about 90%, but have a background dark-count rate of about 0.02 counts per pixel per readout. This is almost (but not quite) good enough.

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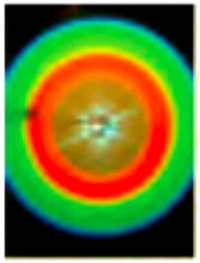
Imaging high-dimensional spatial entanglement with a camera

M.P. Edgar, D. S. Tasca, F. Izdebski, R.E. Warburton, J. Leach, M. Agnew, G. S. Buller, R.W. Boyd & M.J. Padgett



Large number of entangled modes in PDC field

But we can access them only one mode at a time using APDs

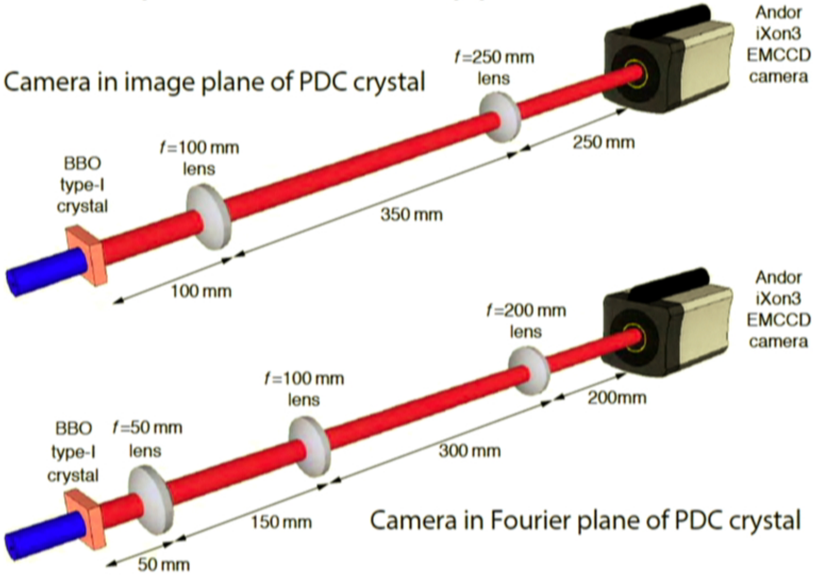
Need a camera with unit quantum efficieny and no dark signal

Modern EMCCD cameras provide a close approximation

Andor iXon3:
90% quantum efficiency
dark signal of 0.02 events per pixel per readout

This performance is adequate for studies in quantum information.

See also, e.g., Zhang, L., Neves, L., Lundeen, J. S. & Walmsley, I. A. J. Phys. B 42, 114011 (2009).



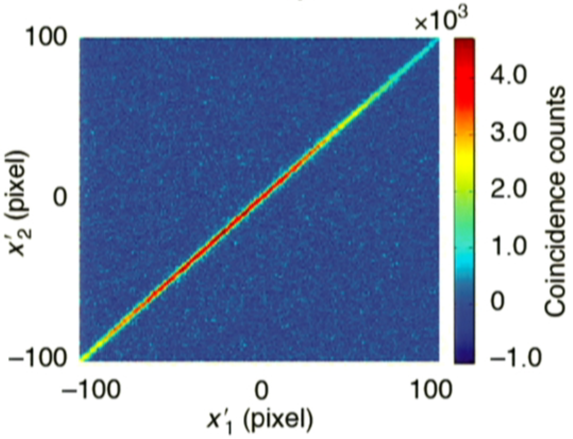
Camera in image plane of PDC crystal

Camera in Fourier plane of PDC crystal

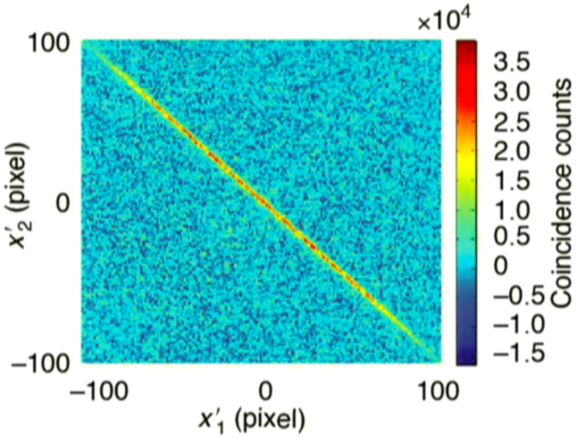
Imaging high-dimensional spatial entanglement with a camera

- Correlations:

near-field (position)



far-field (momentum)



2500 spatial modes are entangled!

- Our data shows violations of the Reid EPR criterion

$$\Delta^2_{\min}(x_1 \mid x_2)\Delta^2_{\min}(p_{x_1} \mid p_{x_2}) = (6.6 \pm 1.0) \times 10^{-4}\hbar^2,$$

$$\Delta^2_{\min}(x_2 \mid x_1)\Delta^2_{\min}(p_{x_2} \mid p_{x_1}) = (6.2 \pm 0.9) \times 10^{-4}\hbar^2,$$

New Journal of Physics
The open access journal for physics

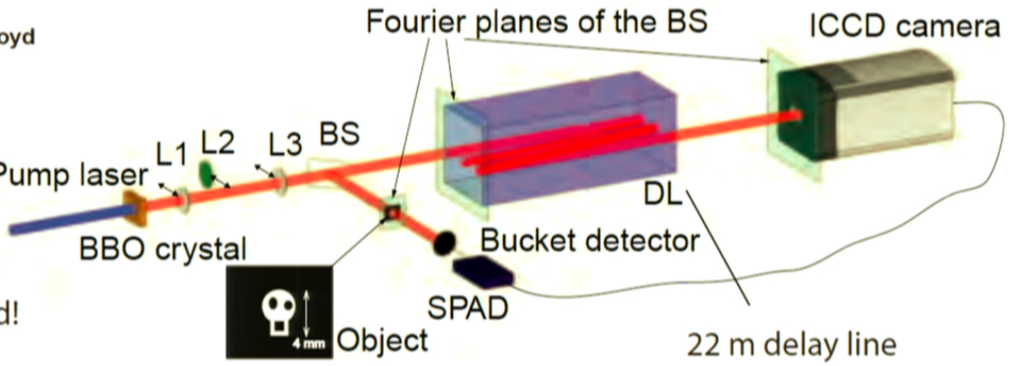
EPR-based ghost imaging using a single-photon-sensitive camera

Reuben S Aspden, Daniel S Tasca, Robert W Boyd and Miles J Padgett

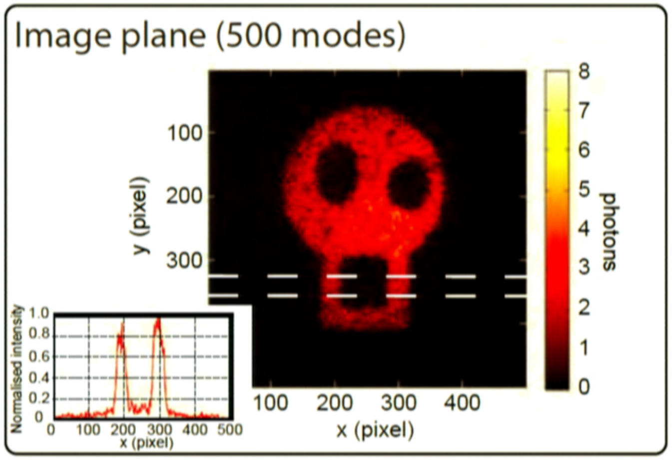
New Journal of Physics **15** (2013) 073032 (11pp)

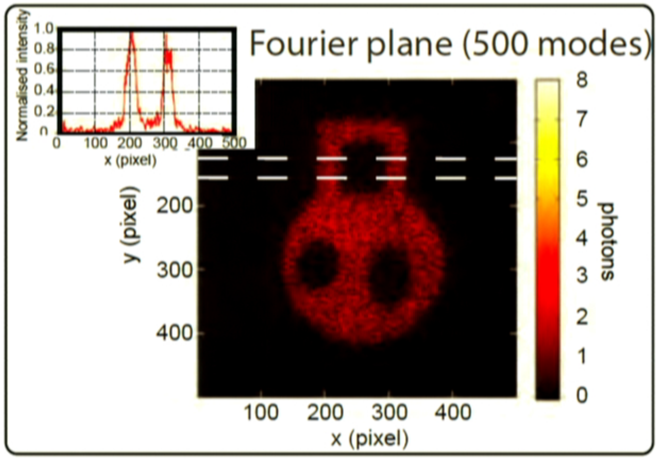
Essentially "ideal" cameras now are available!

When time gated, essentially all background noise is eliminated!



Edgar M P, Tasca D S, Izdebski F, Warburton R E, Leach J, Agnew M, Buller G S, Boyd R W and Padgett M J 2012 Imaging high-dimensional spatial entanglement with a camera Nature Commun. 3 984





Trying to Give Credit

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Some Topics in Quantum Photonics

1. Overview of “Ghost Imaging”
2. “Interaction-Free” Ghost Imaging
3. New Photonic Material for Quantum Information
4. Quantum Key Distribution with Many Bits per Photon

Interaction-Free Ghost Imaging

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and Robert W. Boyd*
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University of Ottwa

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

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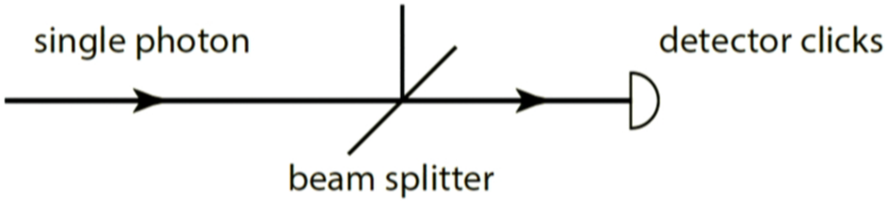
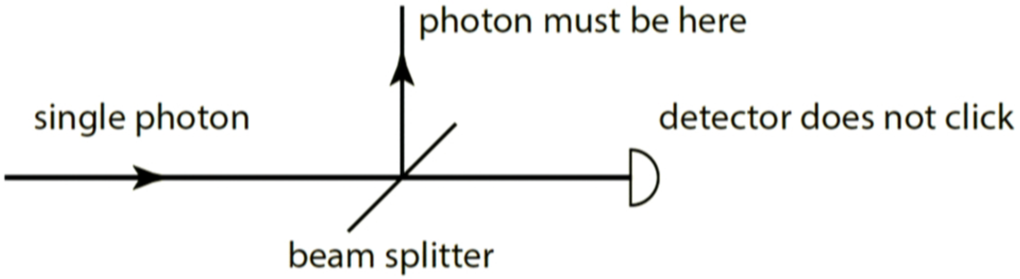
University of Glasgow

What Constitutes a Quantum Measurement?

- Situation 1

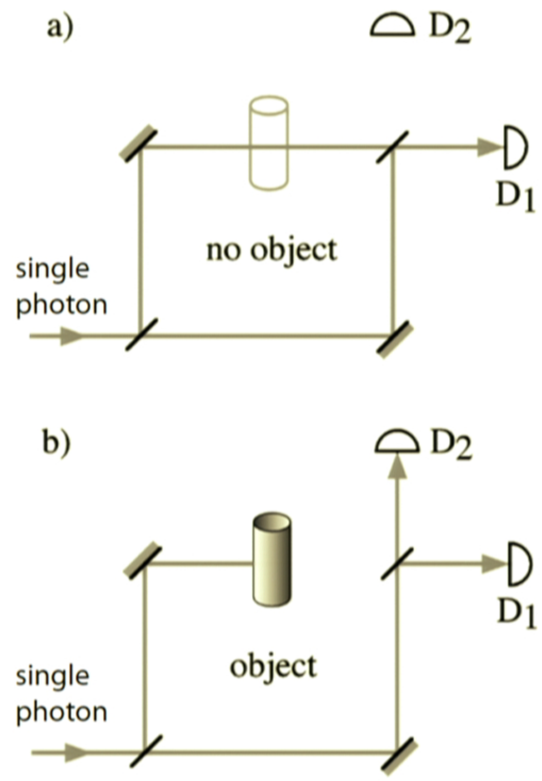


- Situation 2

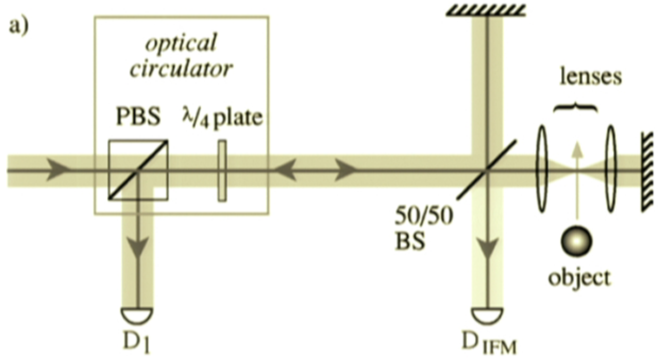


M. Renninger, Z. Phys. 15S, 417 (1960).
R. H. Dicke, Am. J. Phys. 49, 925 (1981).

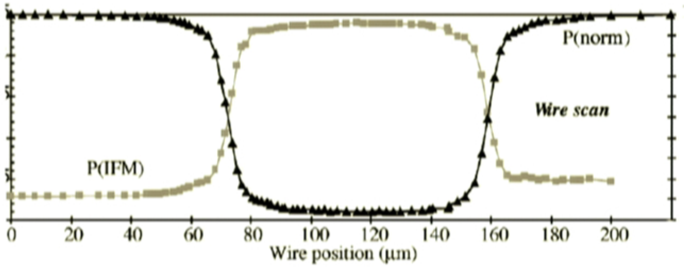
Quantum Imaging by Interaction-Free Measurement



imaging setup



results



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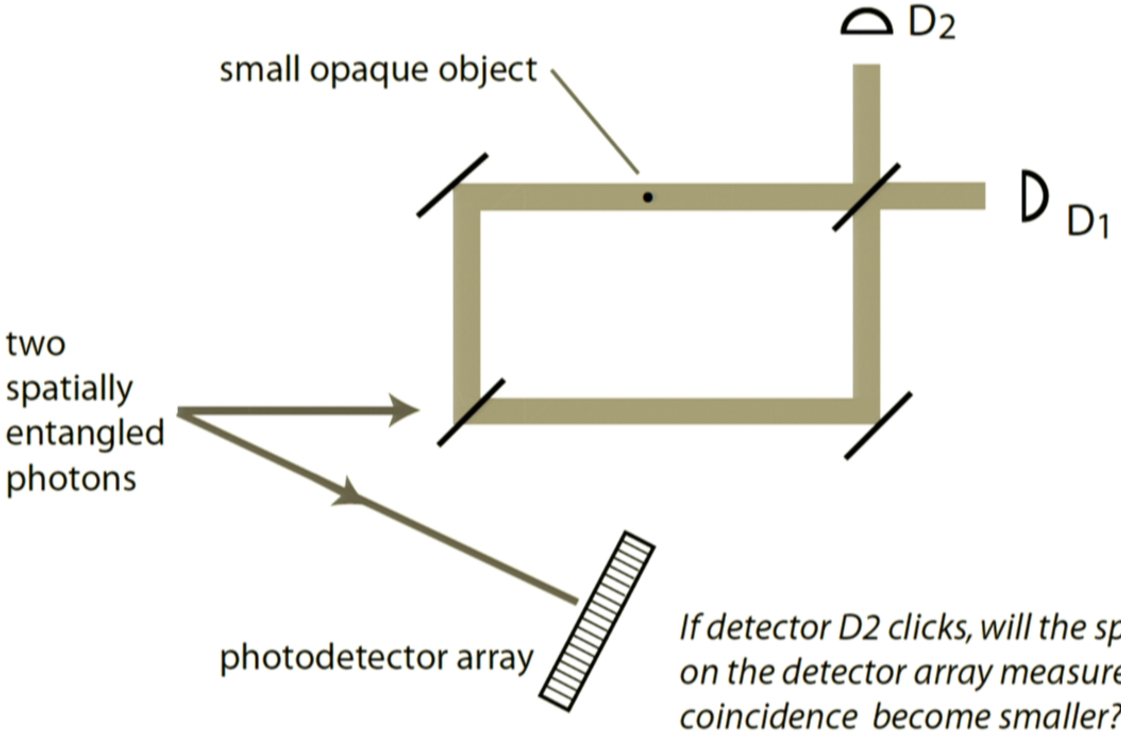
Interaction-Free Measurements and Entangled Photons



D2

small opaque object

D1

two spatially entangled photons

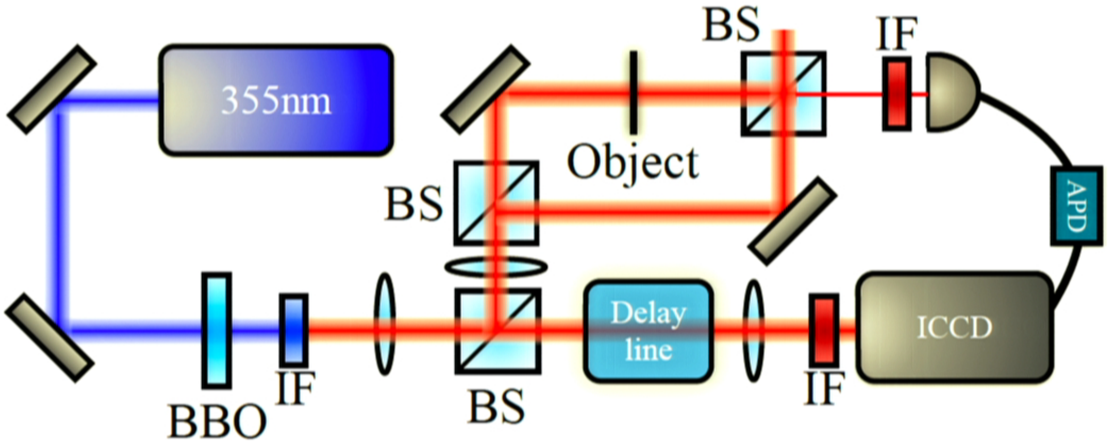
photodetector array

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?

Interaction-Free Ghost Imaging

Experimental Setup

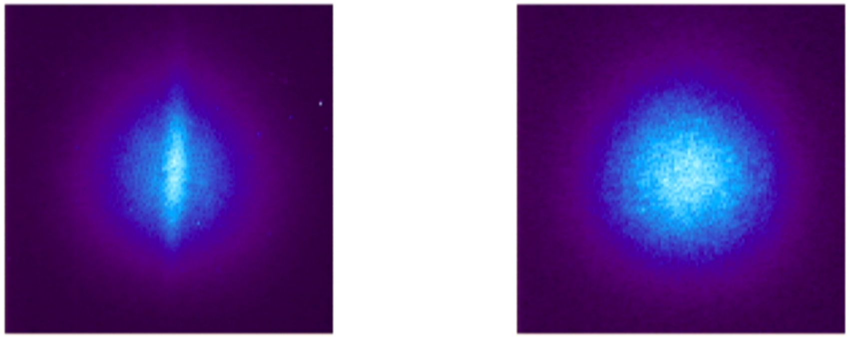


IF = interference filter

BS = beam splitter
ICCD = intensified CCD camera

Experimental Results

Interaction-free ghost image of a straight wire



coincidence counts

singles counts

- 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.

Was this experiment even worth doing?

We could instead have simply answered the question theoretically (of whether interaction-free measurements lead to wavefunction collapse).

My response: Physics is an experimental science. Theoretical models are developed to explain the results of experiment, and not vice versa.

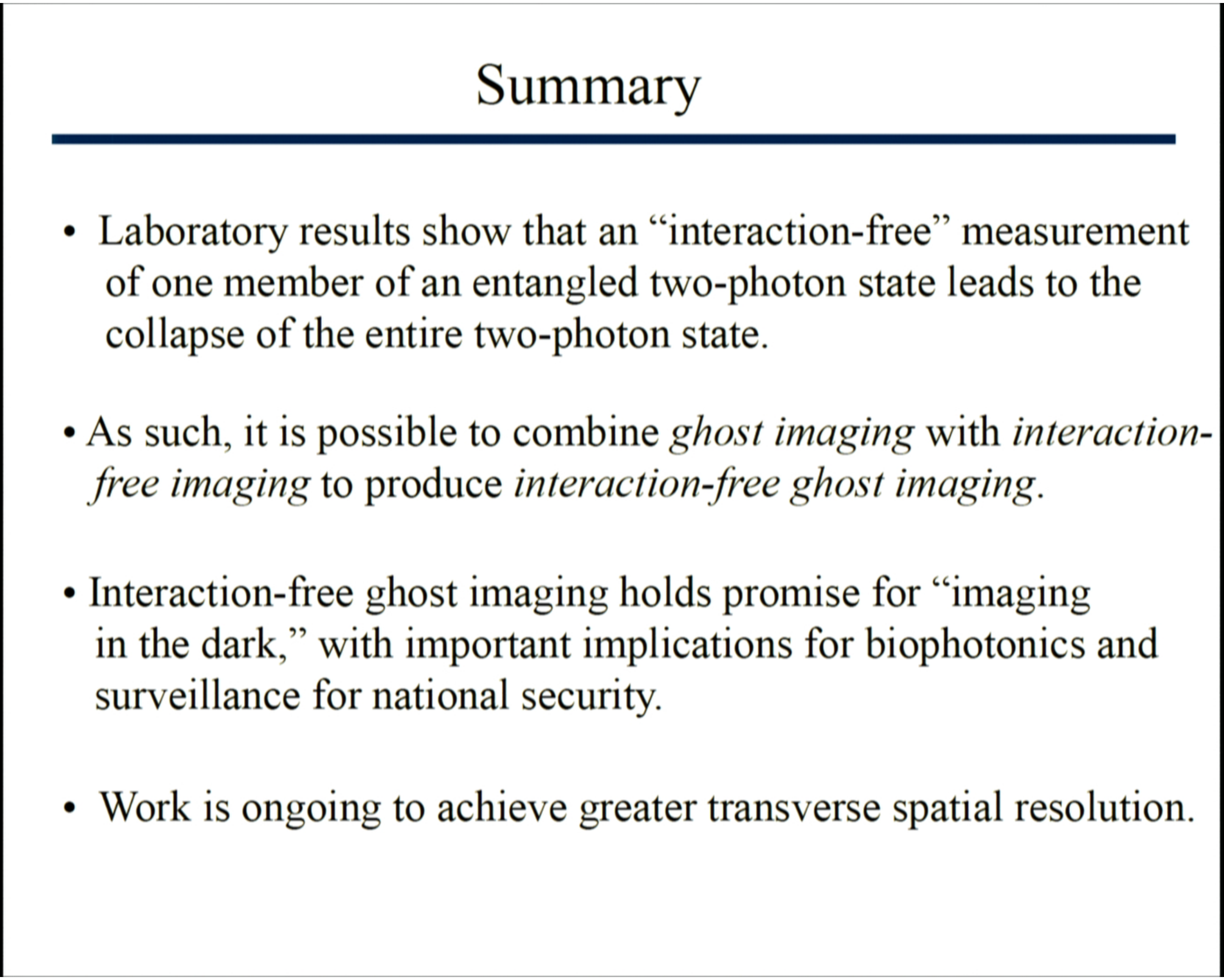
In their mathematical treatment of interaction-free measurements, Elitzur and Vaidman state: "*Assuming* that detectors cause the collapse of the quantum state . . ." (Emphasis mine.)

Foundations of Physics 23, 987 (1993).

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?

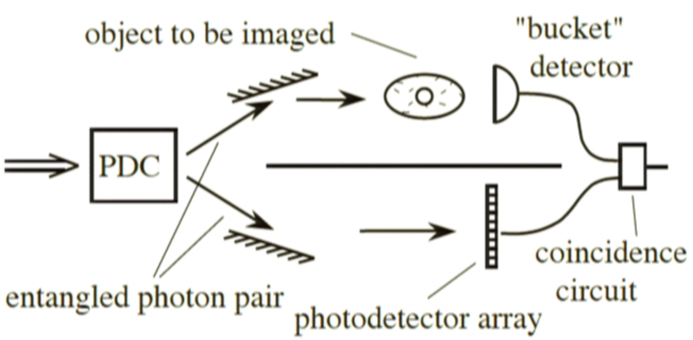


Summary

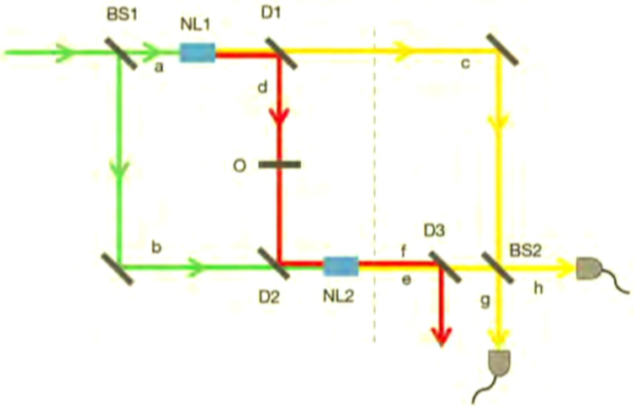
- Laboratory results show that an “interaction-free” measurement of one member of an entangled two-photon state leads to the collapse of the entire two-photon state.
- As such, it is possible to combine *ghost imaging* with *interaction-free imaging* to produce *interaction-free ghost imaging*.
- Interaction-free ghost imaging holds promise for “imaging in the dark,” with important implications for biophotonics and surveillance for national security.
- Work is ongoing to achieve greater transverse spatial resolution.

Quantum Imaging Overview

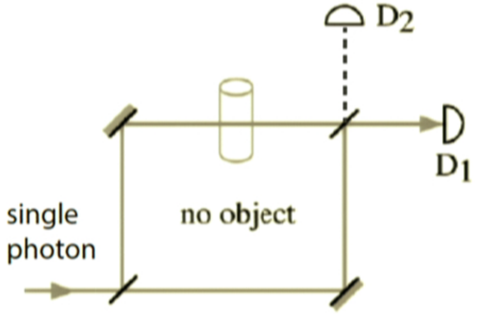
Ghost Imaging (Shih)



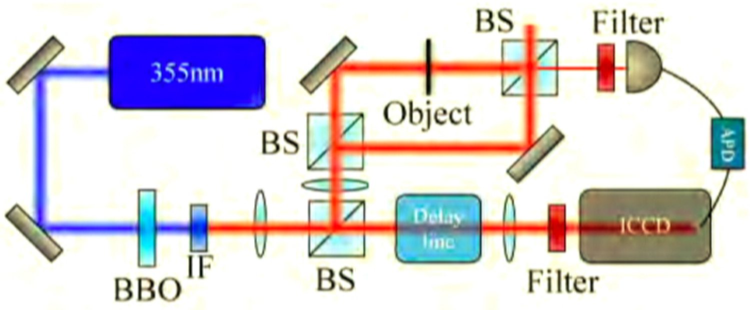
Imaging with Undetected Photons (Zeilinger)

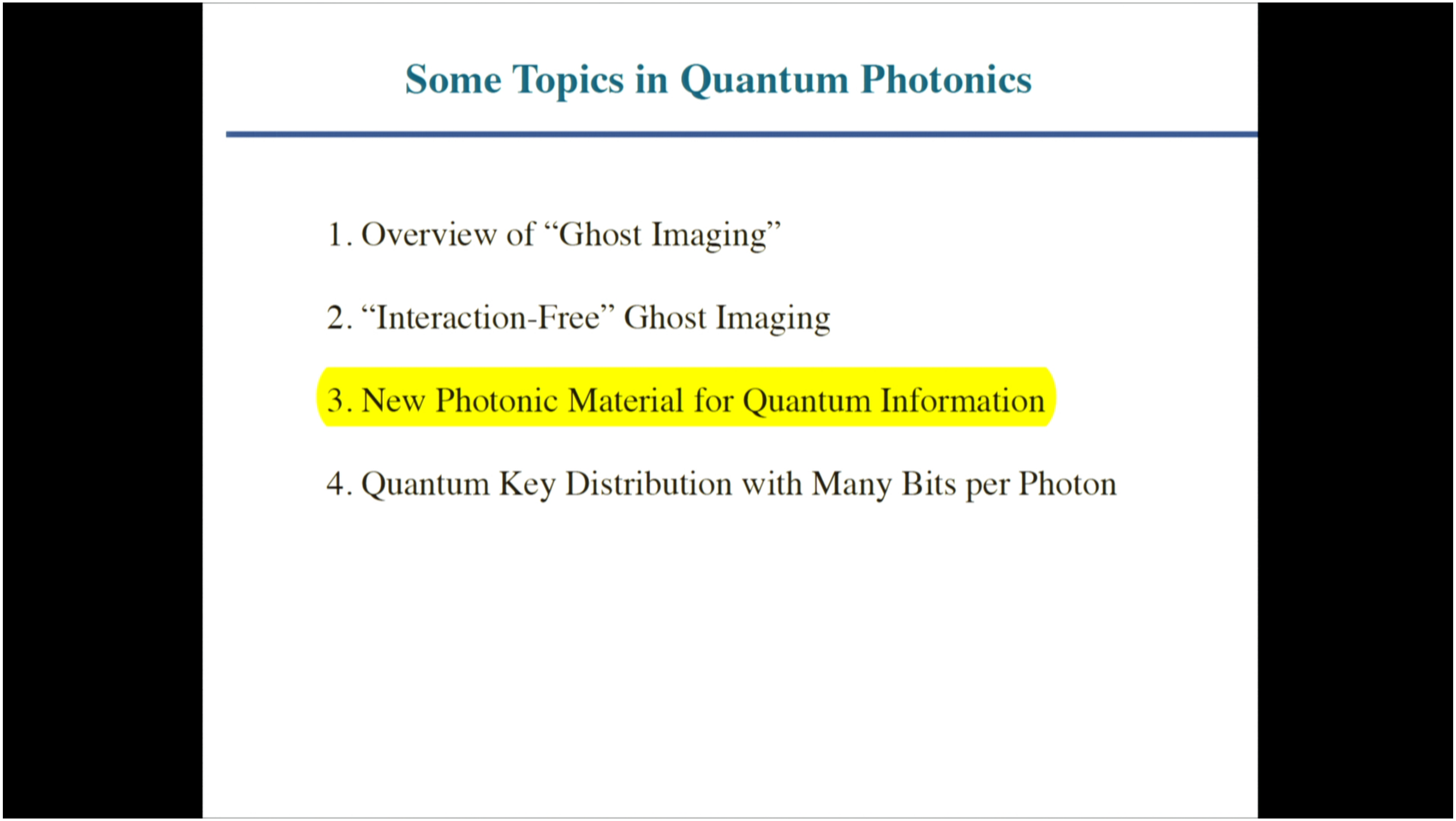


Interaction-Free Imaging (White)



Interaction-Free Ghost Imaging (this talk)





Some Topics in Quantum Photonics

1. Overview of “Ghost Imaging”
2. “Interaction-Free” Ghost Imaging
3. New Photonic Material for Quantum Information
4. Quantum Key Distribution with Many Bits per Photon

2. New Nonlinear Optical Material for Quantum Information Processing

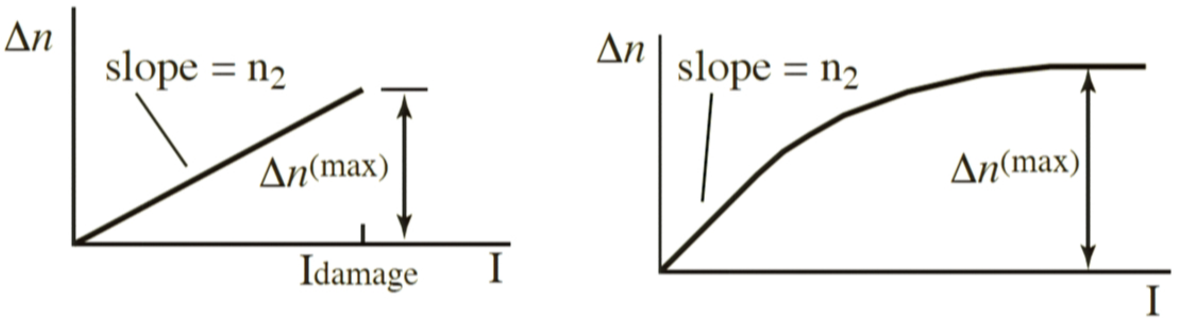
- We want all-optical switches that work at the single-photon level
- We need photonic materials with a much larger NLO response
- I report a new NLO material with an n_2 value 100 times larger than any previously reported results (but with background absorption).

(First release: M. Z. Alam et al., Science 10.1126/science.aae0330 2016.)

What Makes a Good (Kerr-Effect) Nonlinear Optical Material?

Want n_2 large ($\Delta n = n_2 I$). We also want $\Delta n^{(\max)}$ large.

These are distinct concepts! Damage and saturation can limit $\Delta n^{(\max)}$



We report a material for which both n_2 and $\Delta n^{(\max)}$ are extremely large!
(M. Z. Alam et al., Science 10.1126/science.aae0330 2016.)

For ITO at ENZ wavelength, $n_2 = 1.1 \times 10^{-10}$ cm^2/W and $\Delta n^{(\max)} = 0.8$

(For silica glass $n_2 = 3.2 \times 10^{-16}$ cm^2/W, $I_{\text{damage}} = 1$ TW/cm^2, and thus $\Delta n^{(\max)} = 3 \times 10^{-4}$)

Nonlinear Optical Properties of Indium Tin Oxide (ITO)

ITO is a degenerate semiconductor (so highly doped as to be metal-like).

It has a very large density of free electrons, and a bulk plasma frequency corresponding to a wavelength of approximately 1.24 μm.

Recall the Drude formula

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}$$

Note that $\mathrm{Re}\,\epsilon = 0$ for $\omega = \omega_p/\sqrt{\epsilon_\infty} \equiv \omega_0$.

The region near ω_0 is known as the epsilon-near-zero (ENZ) region.

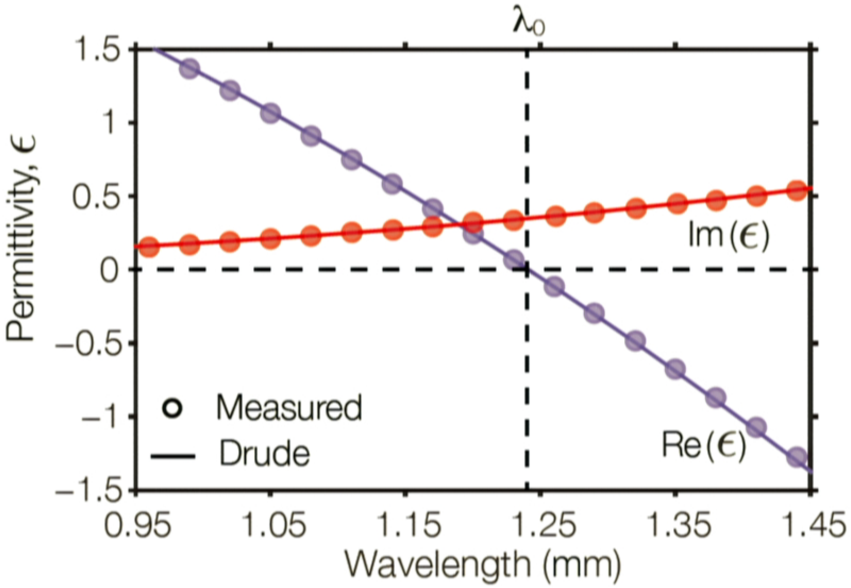
There has been great recent interest in studies of ENZ phenomena:

H. Suchowski, K. O'Brien, Z. J. Wong, A. Salandrino, X. Yin, and X. Zhang, Science 342, 1223 (2013).
C. Argyropoulos, P.-Y. Chen, G. D'Aguanno, N. Engheta, and A. Alu, Phys. Rev. B 85, 045129 (2012).
S. Campione, D. de Ceglia, M. A. Vincenti, M. Scalora, and F. Capolino, Phys. Rev. B 87, 035120 (2013).
A. Ciattoni, C. Rizza, and E. Palange, Phys. Rev. A 81,043839 (2010).

The Epsilon-Near-Zero (ENZ) region of Indium Tin Oxide (ITO)

Measured real and imaginary parts of the dielectric permittivity.

Commercial ITO sample, 310 nm thick on a glass substrate



Drude fit

$\epsilon_\infty = 3.77$

$\gamma = 0.0468\ \omega_p$

$\omega_p/2\pi = 473\ \text{THz}$

Note that Re(ϵ) vanishes at 1.24 mm, but that the loss-part Im(ϵ) is non-zero.

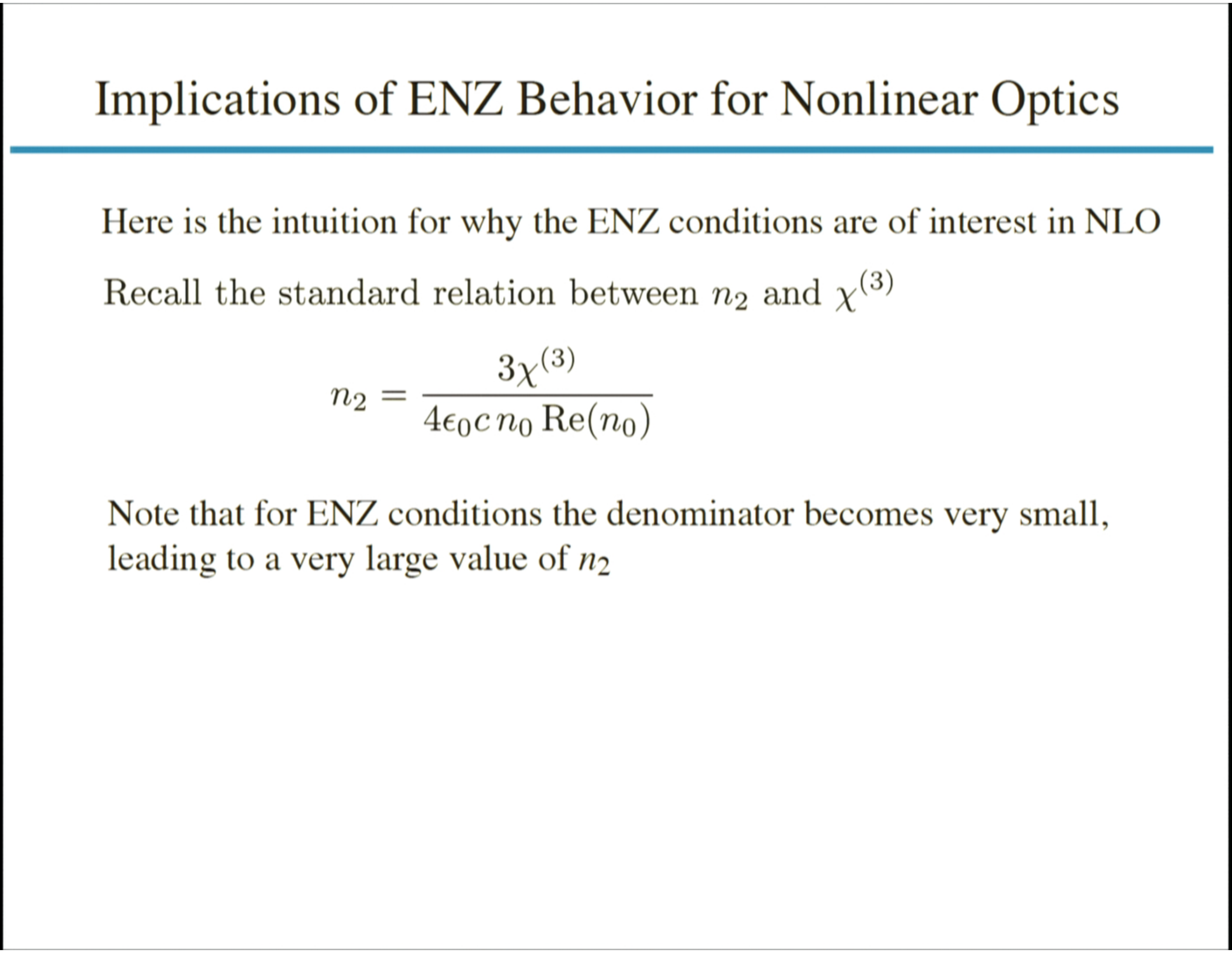
Implications of ENZ Behavior for Nonlinear Optics

Here is the intuition for why the ENZ conditions are of interest in NLO

Recall the standard relation between n_2 and $\chi^{(3)}$

$$n_2 = \frac{3\chi^{(3)}}{4\epsilon_0 c\, n_0\, \mathrm{Re}(n_0)}$$

Note that for ENZ conditions the denominator becomes very small, leading to a very large value of n_2



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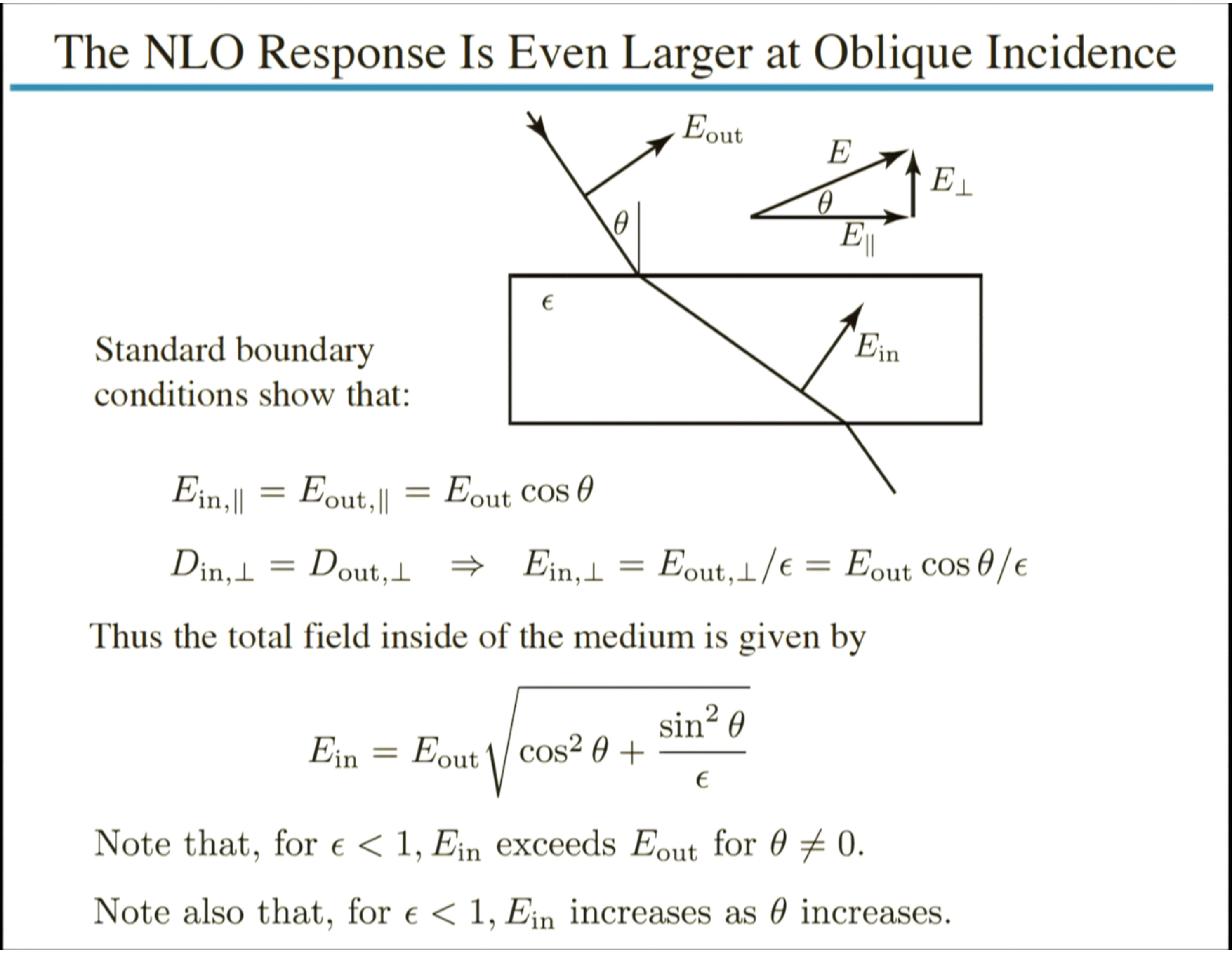


The NLO Response Is Even Larger at Oblique Incidence

Standard boundary
conditions show that:

$$E_{\text{in},\parallel} = E_{\text{out},\parallel} = E_{\text{out}} \cos\theta$$

$$D_{\text{in},\perp} = D_{\text{out},\perp} \quad \Rightarrow \quad E_{\text{in},\perp} = E_{\text{out},\perp}/\epsilon = E_{\text{out}} \cos\theta/\epsilon$$

Thus the total field inside of the medium is given by

$$E_{\text{in}} = E_{\text{out}} \sqrt{\cos^2\theta + \frac{\sin^2\theta}{\epsilon}}$$

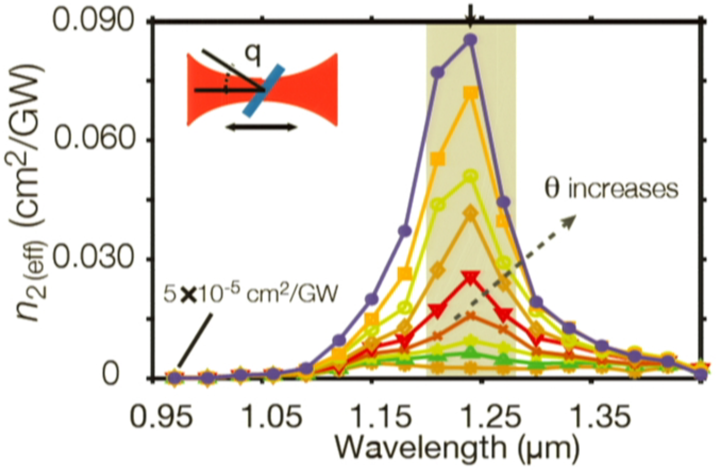
Note that, for $\epsilon < 1$, E_{in} exceeds E_{out} for $\theta \neq 0$.

Note also that, for $\epsilon < 1$, E_{in} increases as θ increases.

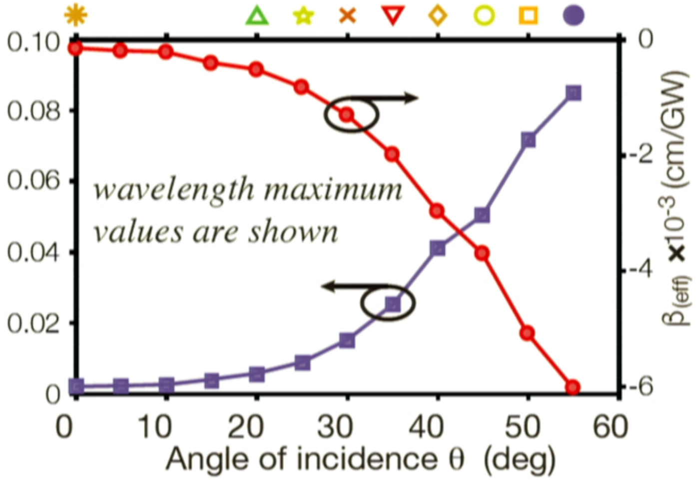
Huge Nonlinear Optical Response of ITO

Z-scan measurements for various angles of incidence

Wavelength dependence of n_2

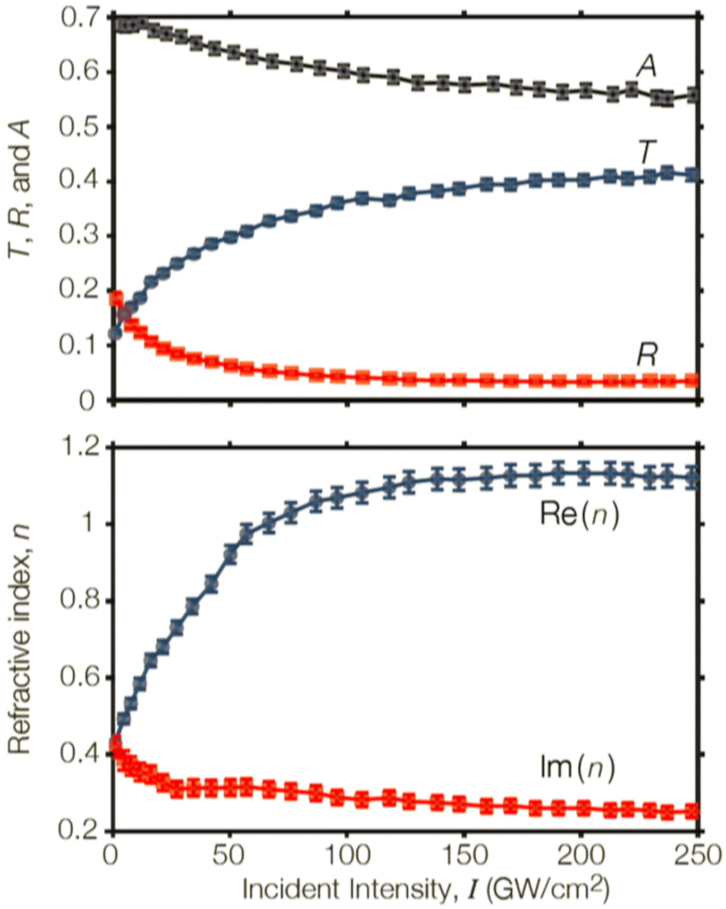


Variation with incidence angle



- Note that n_2 is positive (self focusing) and β is negative (saturable absorption).
- Both n_2 and nonlinear absorption increase with angle of incidence
- n_2 shows a maximum value of 0.11 cm^2/GW = 1.1 x 10^{-10} cm^2/W at 1.25 μm and 60 deg.

Beyond the $\chi^{(3)}$ limit



The nonlinear change in refractive index is so large as to change the transmission, absorption, and reflection!

Note that transmission is increased at high intensity.

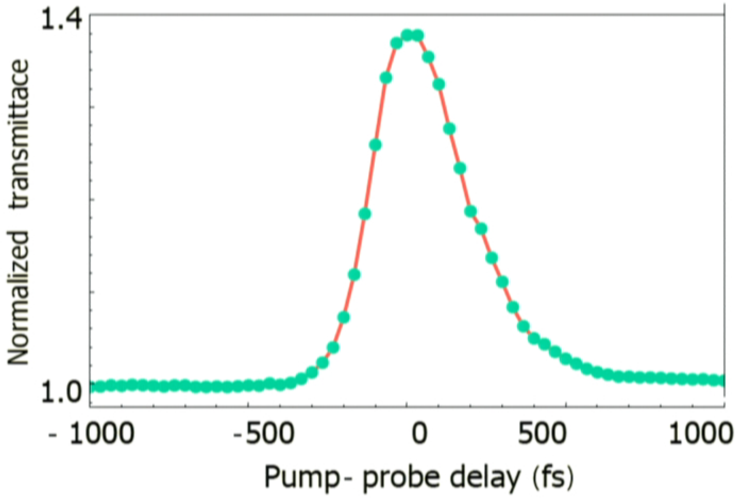
Here is the refractive index extracted from the above data.

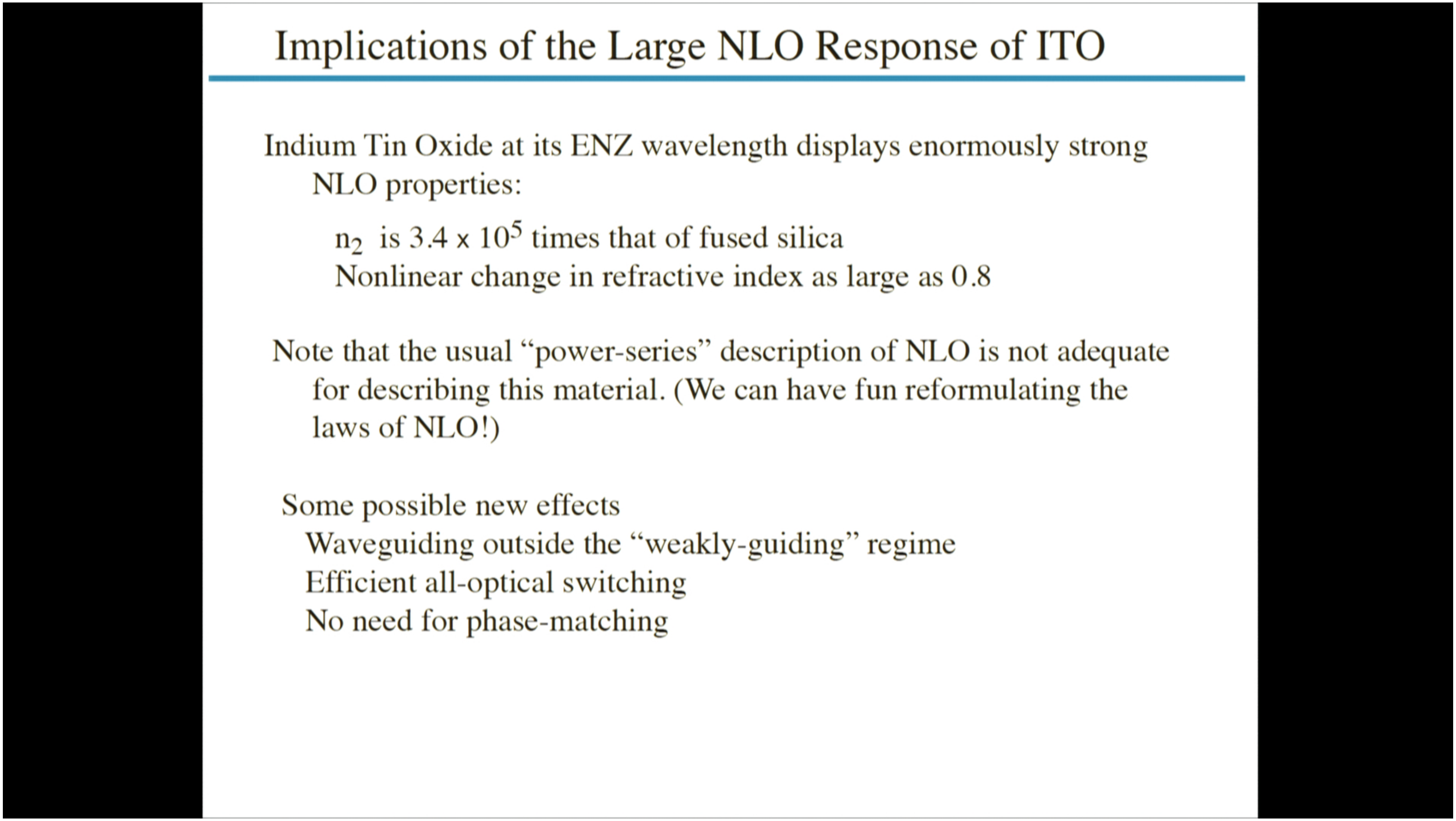
Note that the total nonlinear change in refractive index is $\Delta n = 0.8$.

The absorption decreases at high intensity, allowing a predicted NL phase shift of 0.5 radians.

Measurement of Response Time of ITO

- We have performed a pump-probe measurement of the response time. Both pump and probe are 100 fs pulses at 1.2 μm.
- Data shows a rise time of no longer than 200 fs and a recover time of of 360 fs.
- Results suggest a hot-electron origin of the nonlinear response
- ITO will support switching speeds as large as 1.5 THz





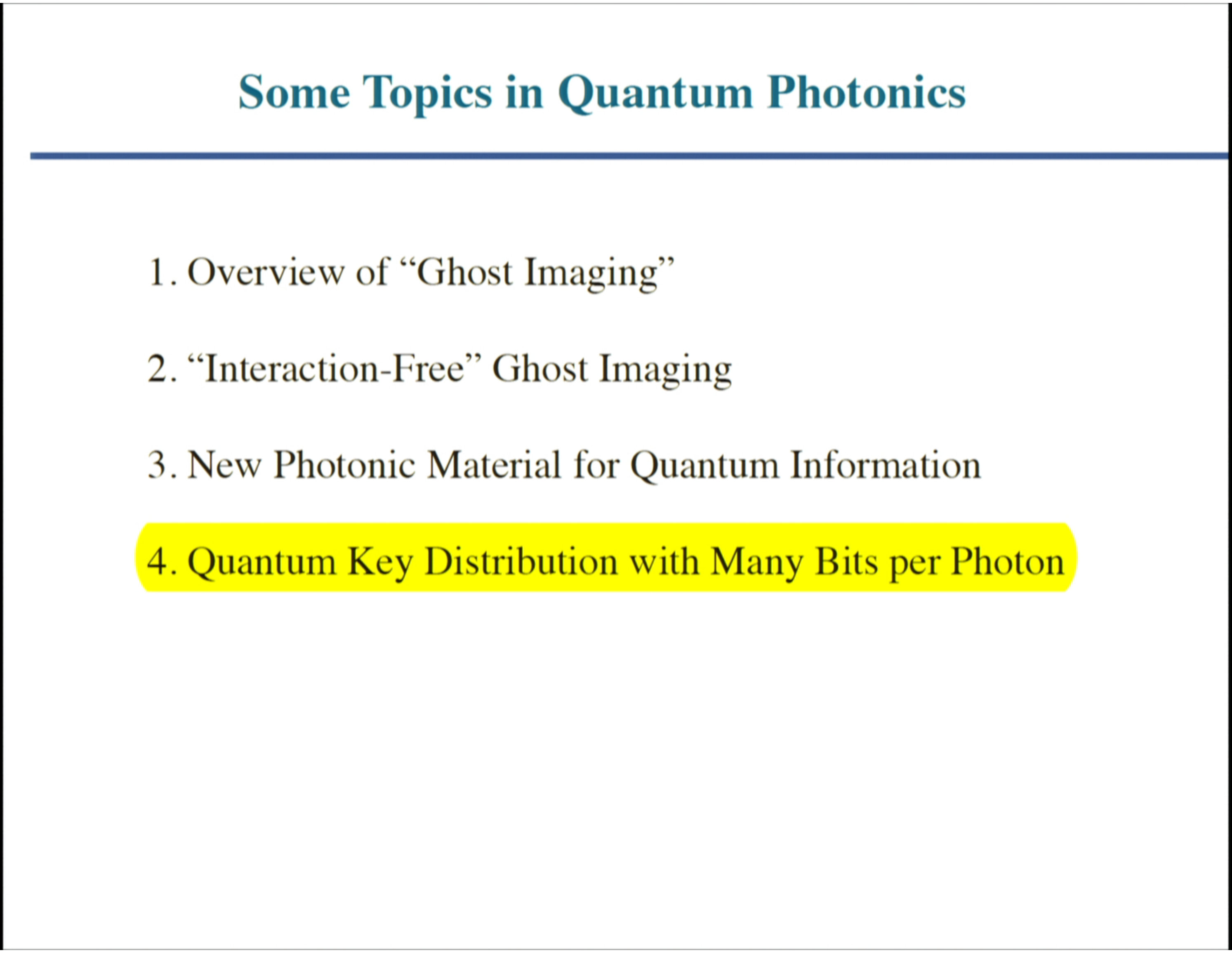
Implications of the Large NLO Response of ITO

Indium Tin Oxide at its ENZ wavelength displays enormously strong NLO properties:

n_2 is 3.4×10^5 times that of fused silica
Nonlinear change in refractive index as large as 0.8

Note that the usual "power-series" description of NLO is not adequate for describing this material. (We can have fun reformulating the laws of NLO!)

Some possible new effects
Waveguiding outside the "weakly-guiding" regime
Efficient all-optical switching
No need for phase-matching



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We’re bringing oil to American shores.