MURI
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Quantum Ghost Imaging

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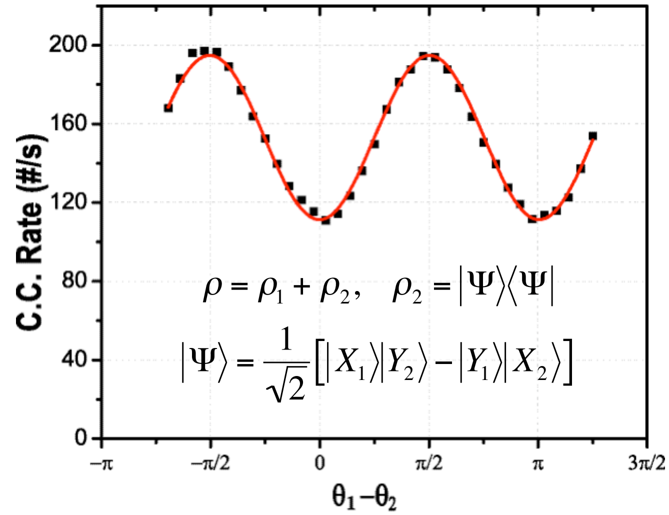
Quantum Imaging - UMBC

Objective

• Study the physics of multi-photon imaging for entangled state, coherent state and chaotic thermal state: distinguish their quantum and classical nature, in particular, the necessary or unnecessary role of quantum mechanics in ghost imaging and lithography;

•Investigate a practical ghost imaging system with Sun light (the best available thermal source).



Bell-type two-photon polarization correlation with thermal light.

Approach

• Using entangled photon source, chaotic light source, coherent light source for two-photon spatial correlation study and ghost imaging at quantum level and at classical level;

• Using a new-type of two-photon interferometer with thermal light source for the study of two-photon interferometry in space-time variable and in polarization;

• Using two-photon phenomena of thermal light to distinguish the quantum theory of second-order coherence from classical statistical correlation of intensity fluctuations.

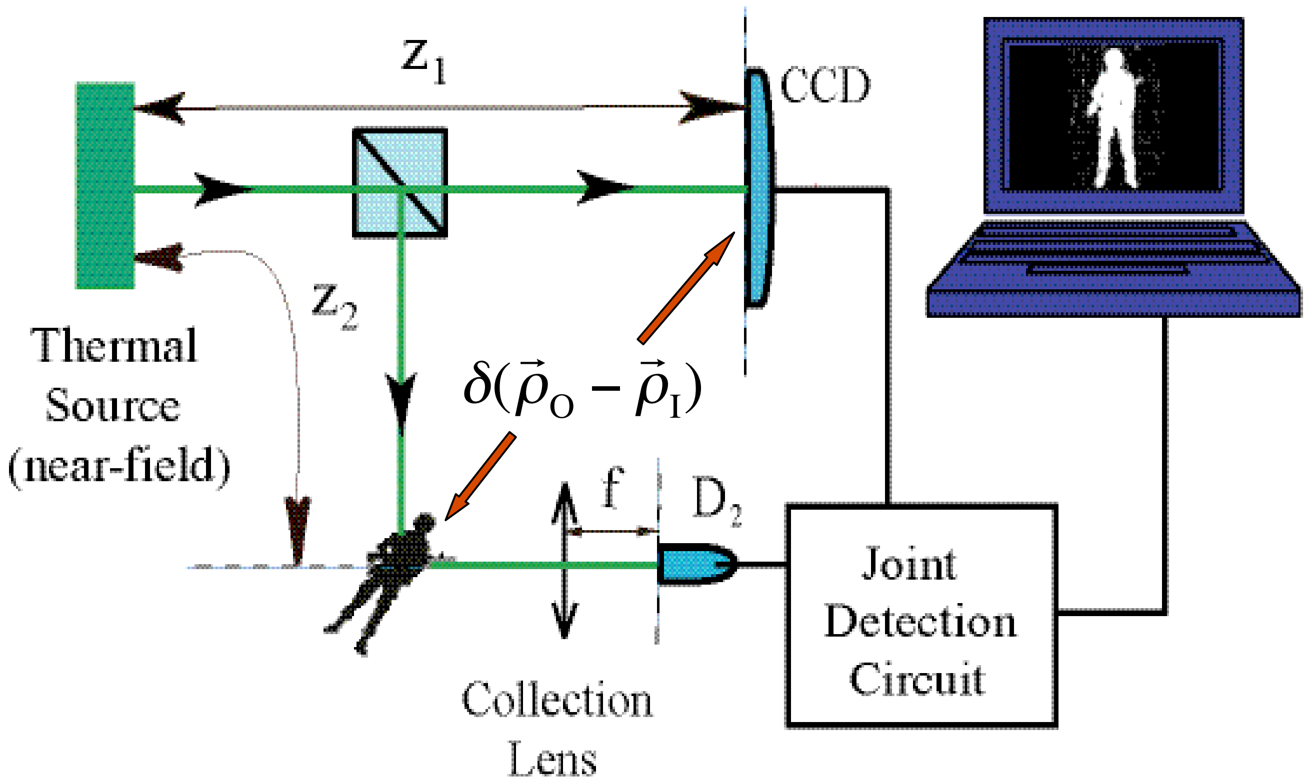
Accomplishments

• The nonlocal quantum interference nature of thermal light ghost imaging has been successfully distinguished from its classical simulations theoretically and experimentally;
• Observations of anti-correlation “dip”, correlation “peak” and Bell-type polarization correlation of thermal light;
• Observation of three-photon coherence of thermal light for higher contrast and higher spatial resolution ghost imaging;
• Observation of second-order temporal and spatial correlation of Sun light (first step toward a practical ghost imaging system with Sun light for space and field applications);
• Observation of “turbulence-free” ghost imaging of thermal light (in collaboration with ARL);
• Observation of classically simulated “ghost” imaging in an one detector scheme (an important step in distinguish quantum imaging with its classical simulations) (in collaboration with ARL).

Part-I

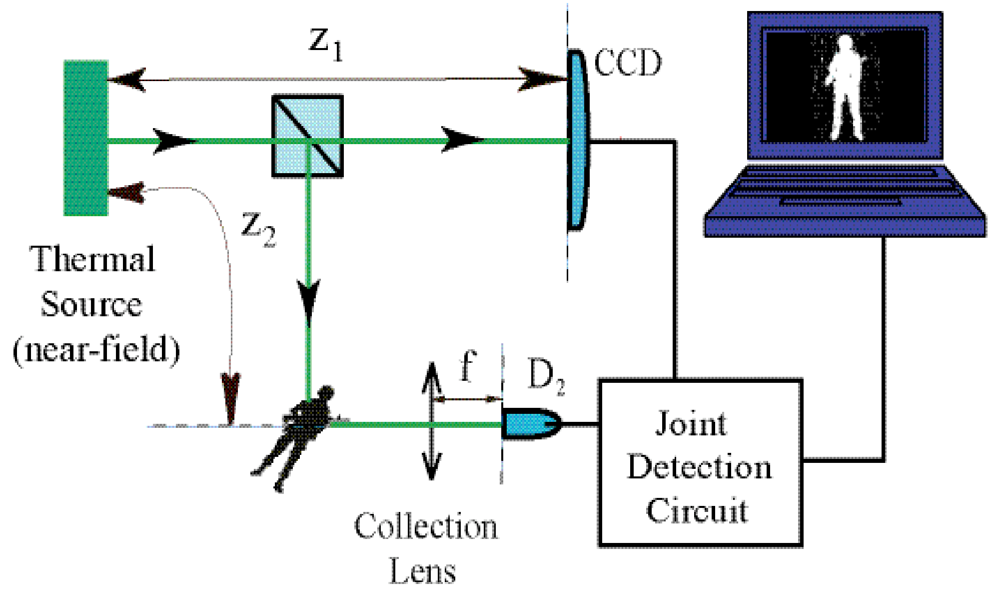
Quantum ghost imaging with thermal light
and its classical simulations

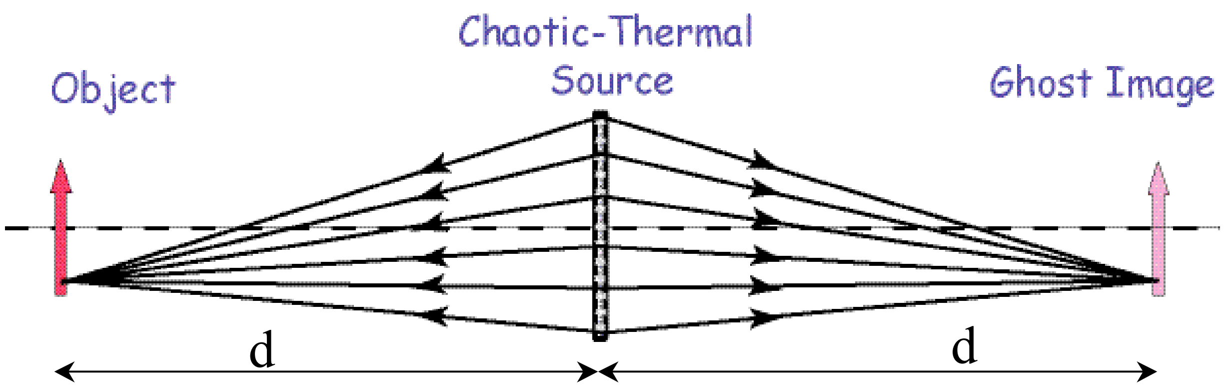
The concept of ghost imaging with thermal light



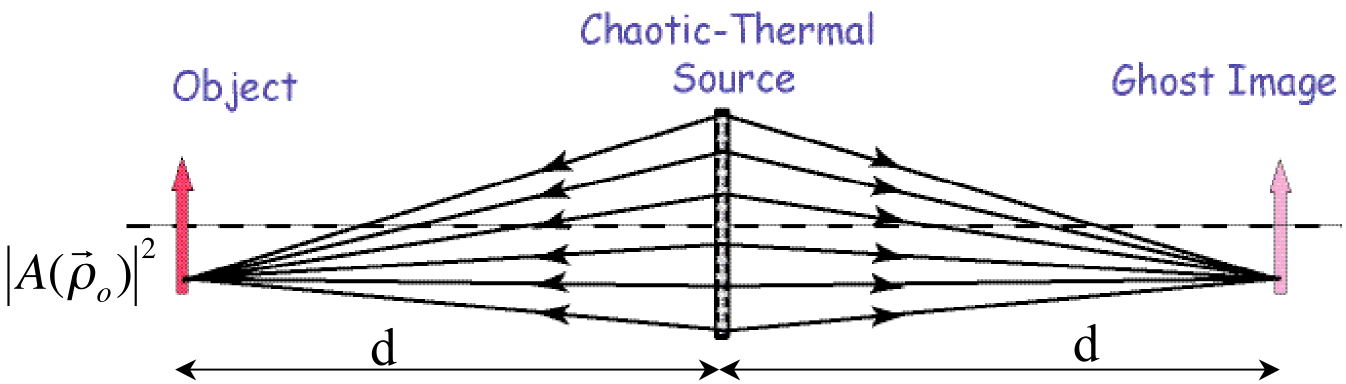
A successful collaboration with ARL

A photon counting detector, D_1, is used to collect and to count all the photons that are randomly scattered-reflected from the toy soldier. A CCD array (2D) was facing the light source instead of the object. An image of the soldier was observed in the joint-detection of D_1 and the CCD. (Near-field lensless ghost imaging.)





Klyshko's picture of the near-field lensless ghost imaging - easier to see the physics.



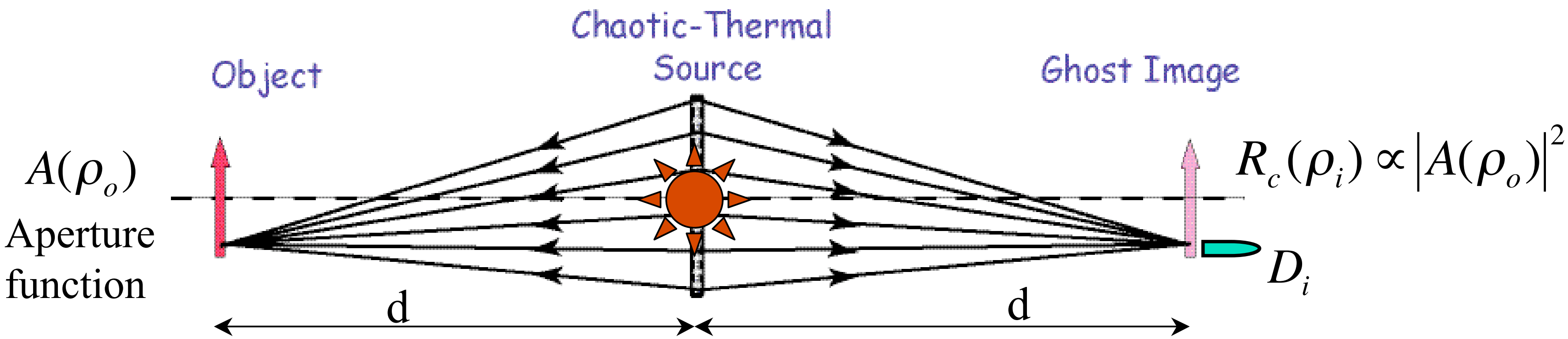
$$g^{(2)}(\vec{\rho}_{\rm o},\vec{\rho}_{\rm i}) = 1 + somb^2[\frac{D}{d}\frac{\pi}{\lambda}|\vec{\rho}_{\rm o} - \vec{\rho}_{\rm i}|]$$

Natural, non-factorizable,
"point-to-point" correlation.

$$R_c(\vec{\rho}_i) = \int_{obj} d\vec{\rho}_o |A(\vec{\rho}_o)|^2 g^{(2)}(\vec{\rho}_o,\vec{\rho}_i)$$

Ghost imaging is the result of a convolution between the aperture function $|A(\vec{\rho}_o)|^2$ of the object and the non-factorizable correlation function $g^{(2)}(\vec{\rho}_{\rm o},\vec{\rho}_{\rm i})$.

Why Quantum?

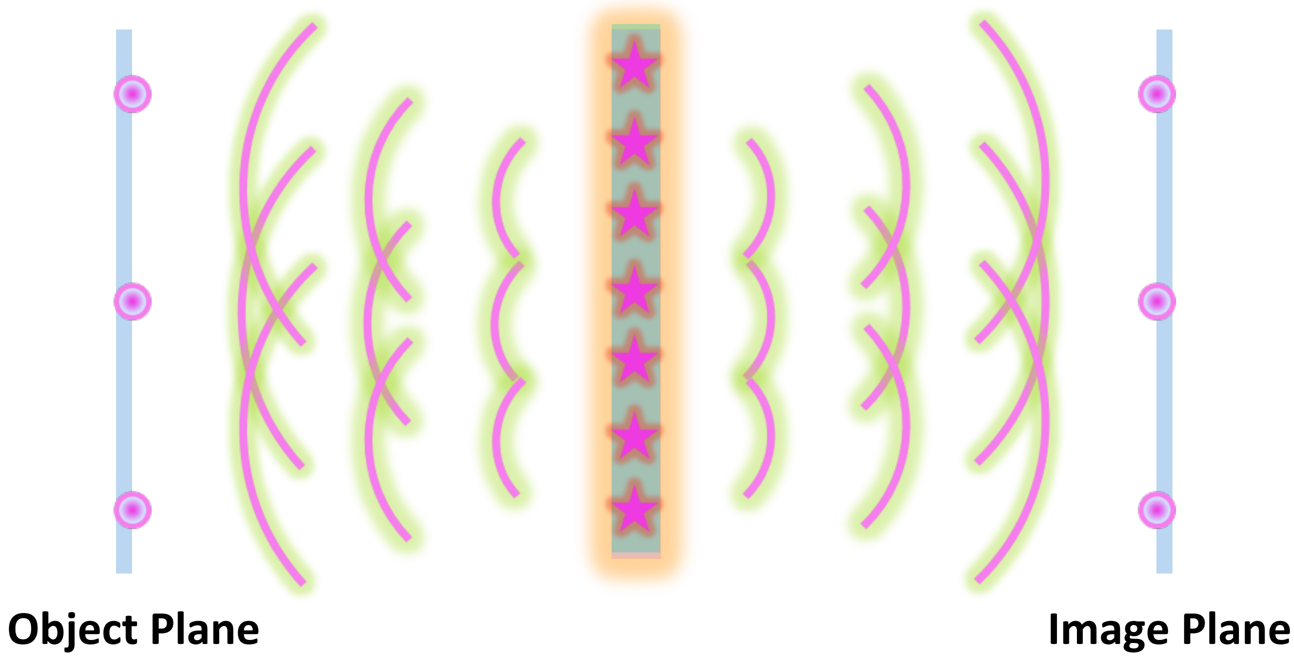


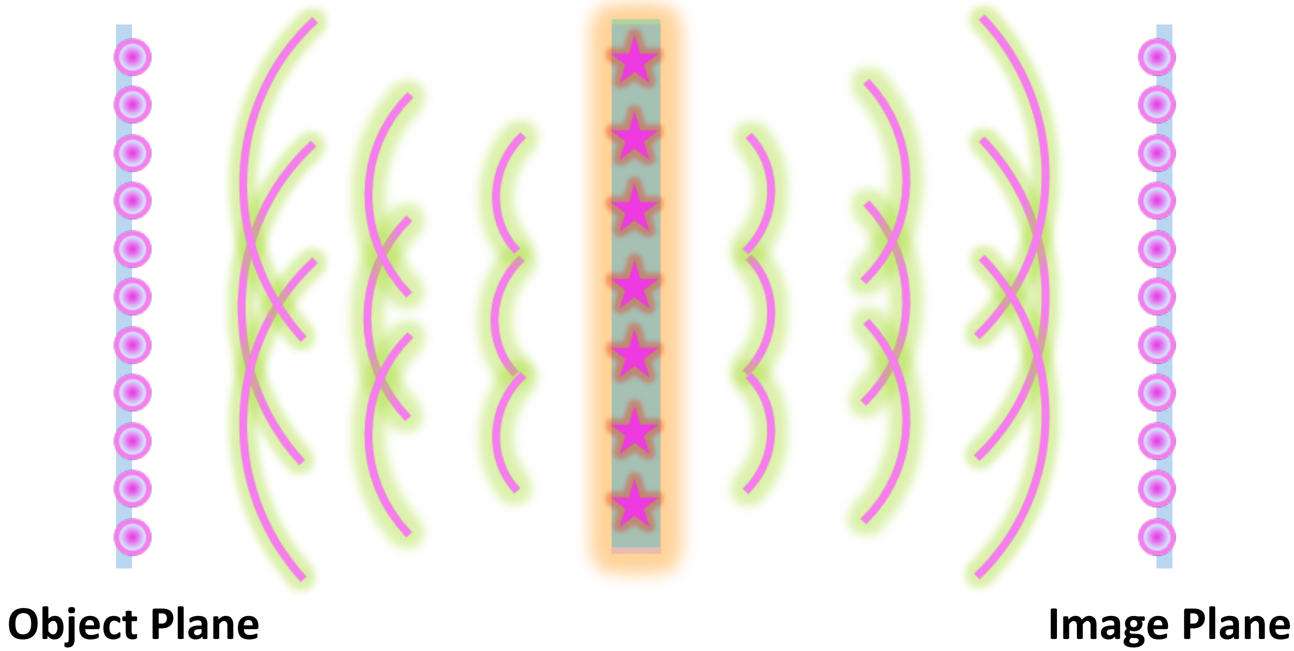
Suppose the point detector D_i or a CCD element is triggered by a photon at a transverse position of ρ_i in a joint-detection event with the bucket detector which is triggered by another photon that is either transmitted or reflected from the object. The photon from the object would have twice greater chance to be found at $\rho_o = \rho_i$. If we move D_i to another transverse position ρ'_i, or locate another CCD element at the imaging plan for joint-detection. The photon that triggers the bucket detector would have twice greater chance of been located at $\rho'_o = \rho'_i$. The probabilities of receiving a joint detection event at $\rho_o = \rho_i$ and at $\rho'_o = \rho'_i$ would be modulated by the values of the aperture function $A(\rho_o)$ and $A(\rho'_o)$, respectively. Accumulating a large number of joint-detection events for each transverse coordinates on the image plane, or for each CCD element in the image plane, a 50% contrast aperture function $A(\rho_o)$ is thus reproduced in the joint-detection as a function of ρ_i.

Having more than one coincidences within the coincidence time window would mix up the values of $A(\rho_o)$, $A(\rho'_o)$, … and average out the ghost image.

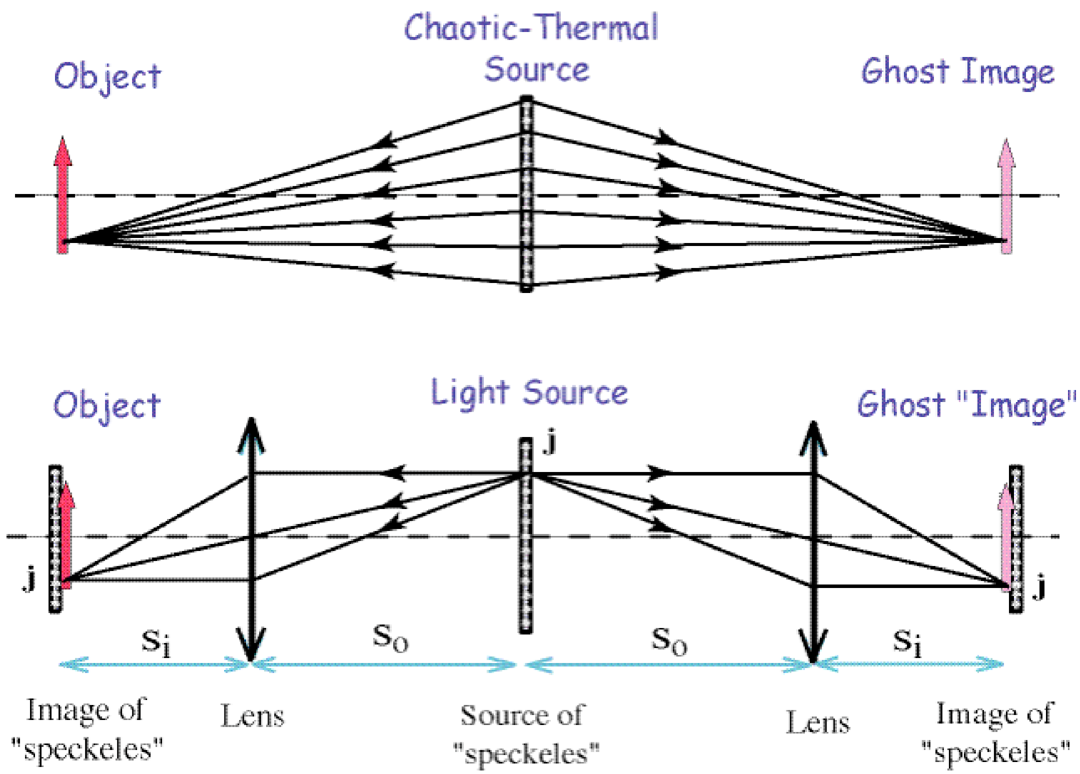
Why Quantum?

Slide Show


Object Plane
Image Plane


Object Plane
Image Plane

Is classical simulation possible?



Nondeterministic photon source

Simulation?

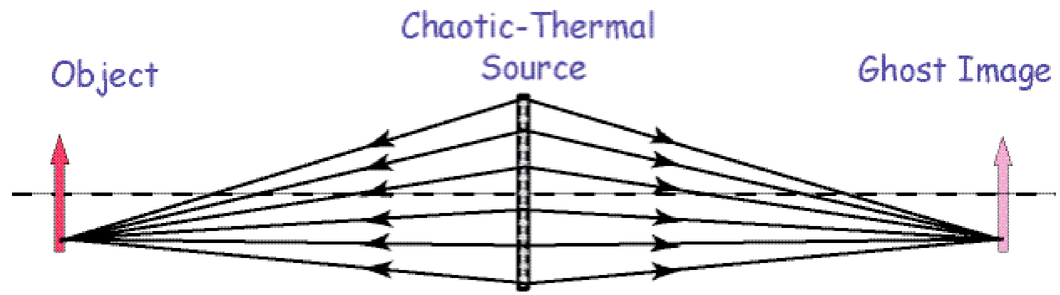
“Deterministic”source of classical “speckles”

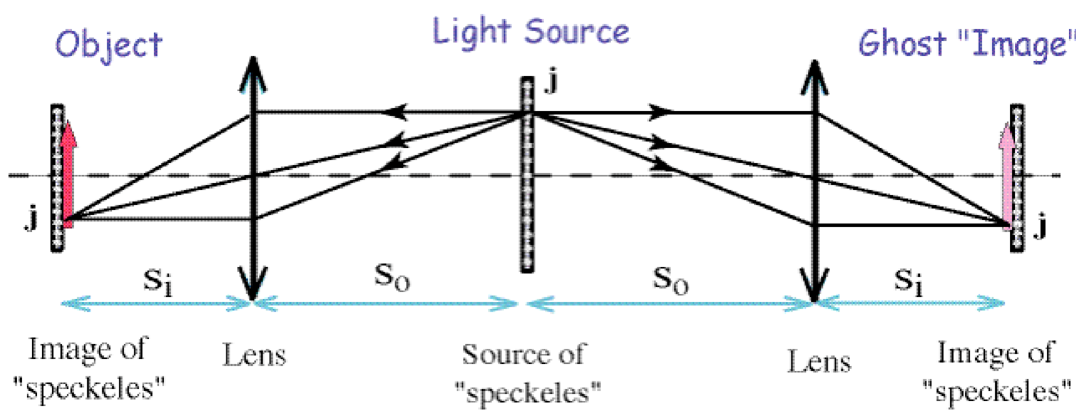
$$g^{(2)}(\vec{\rho}_o,\vec{\rho}_i) = \left\{ somb^2[\frac{D}{s_o}\frac{\pi}{\lambda}|\vec{\rho}_s - \vec{\rho}_o/m|] \right\} \times \left\{ somb^2[\frac{D}{s_o}\frac{\pi}{\lambda}|\vec{\rho}_s - \vec{\rho}_i/m|] \right\}$$

A man-made factorizable intensity-intensity correlation is achievable by two sets of classical images of the speckles of the light source. Basically, the light has to know where to go (deterministic)! In fact, it is unnecessary to use joint detection at all for such kind deterministic light source!

Quantum is quantum!

$$g^{(2)}(\vec{\rho}_o,\vec{\rho}_i) = 1 + somb^2[\frac{D}{d}\frac{\pi}{\lambda}|\vec{\rho}_o - \vec{\rho}_i|]$$ (nonlocal)

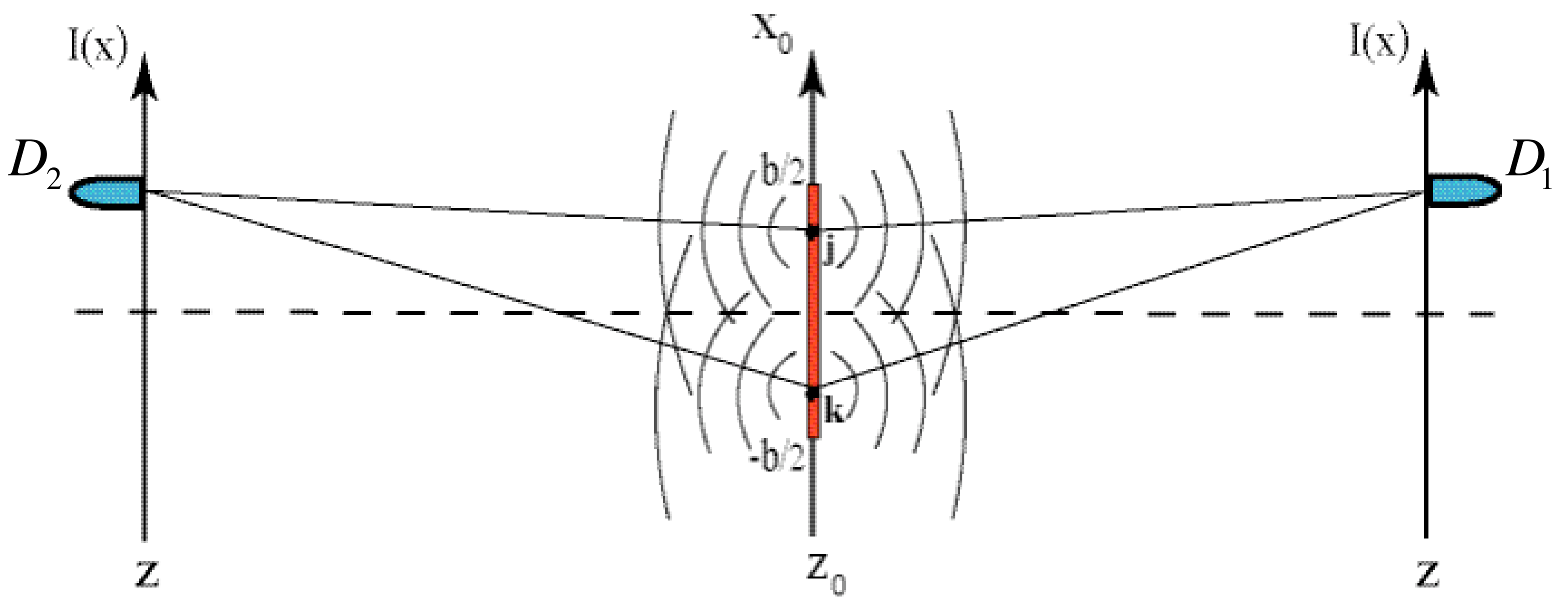




$$g^{(2)}(\vec{\rho}_o,\vec{\rho}_i) = \left\{somb^2[\frac{D}{s_o}\frac{\pi}{\lambda}|\vec{\rho}_s - \vec{\rho}_o/m|]\right\} \times \left\{somb^2[\frac{D}{s_o}\frac{\pi}{\lambda}|\vec{\rho}_s - \vec{\rho}_i/m|]\right\}$$ (local)

Classical is classical!

(An interesting story…)



$$\left|A(r_{j1},r_{k2}) + A(r_{k1},r_{j2})\right|^2 \quad \Longrightarrow \quad g^{(2)}(\vec{\rho}_1,\vec{\rho}_2) = 1 + somb^2[\frac{D}{d}\frac{\pi}{\lambda}|\vec{\rho}_1 - \vec{\rho}_2|]$$

Symmetried effective wavefunction

The natural, nonfactorizable, point-to-point, image-forming correlation between the object and image planes in ghost imaging is the result of a constructive-destructive interference which involves the nonlocal superposition of two-photon amplitudes, a nonclassical entity corresponding to different yet indistinguishable alternative ways of triggering a joint-detection event. It is “turbulence-free”! It can be done in strong light condition by using ND filters.

Due to its nonlocal quantum interference nature:

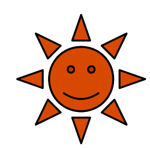
(1) Nonlocal imaging (useful for certain applications).
(2) Enhanced spatial resolution (useful for all applications).
(3) Turbulence-free (useful for all applications).

Sun light quantum ghost imaging system (color image)
- for space and field applications

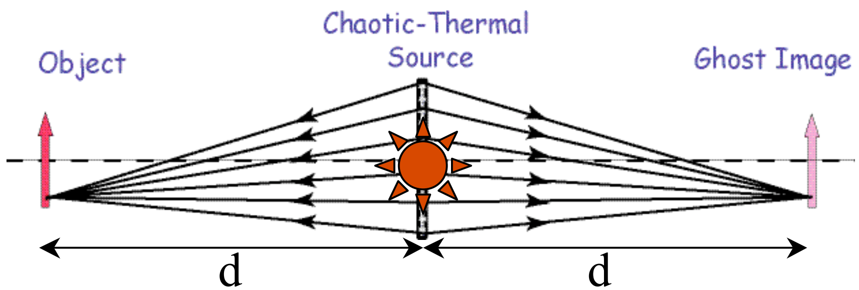
* A natural thermal source with high resolution;

$$somb^2\left\{\frac{D}{d}\frac{\pi}{\lambda}\left|\vec{\rho}_o-\vec{\rho}_i\right|\right\}$$

Sun: D/d~0.53^o…



* Any index-fluctuation type "turbulence" has no effect on the ghost imaging.



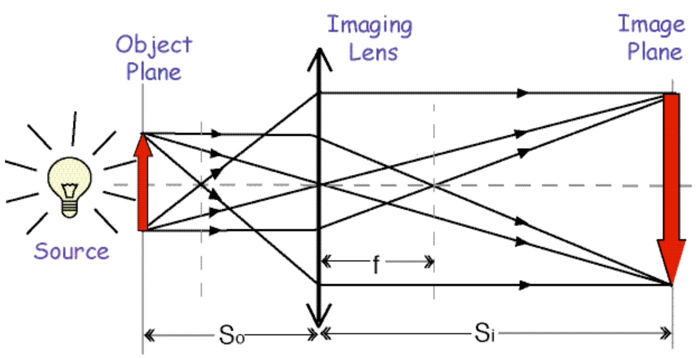
Sun: $\frac{D}{d} \cong \Delta\theta \cong 0.53^{\circ}$

$$R_C(\vec{\rho}_i) \propto \int d\vec{\rho}_o \, A^2(\vec{\rho}_o)\,[1 + somb^2[\frac{D}{d}\frac{\pi}{\lambda}|\vec{\rho}_o - \vec{\rho}_i|]]$$

Lensless ghost imaging: Spatial Resolution

$somb(x) = \frac{2J_1(x)}{x}$

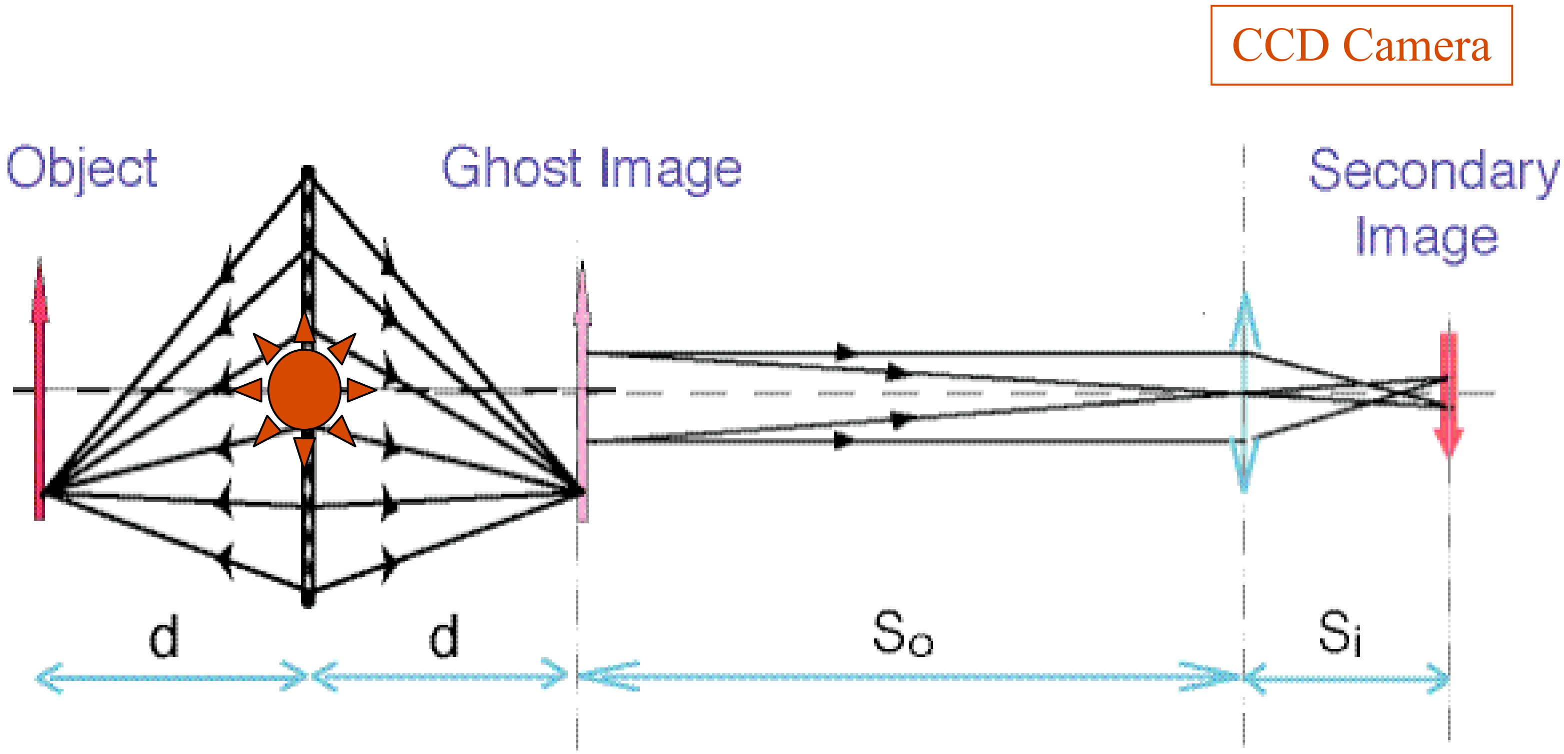
Equivalent: a classical camera with 92 meter lens taking pictures at 10 kilometers.



$$\frac{92\,\text{meters}}{10k\,\text{meters}} = \frac{D}{S_o} \cong \Delta\theta \cong 0.53^{\circ}$$

Classical imaging: $I(\vec{\rho}_i) = \int d\vec{\rho}_o \, A^2(\vec{\rho}_o)\, somb^2 \frac{D}{S_o}\frac{\pi}{\lambda}(\vec{\rho}_o - \vec{\rho}_i / m)$

A Conceptual Sun Light Ghost Imaging System

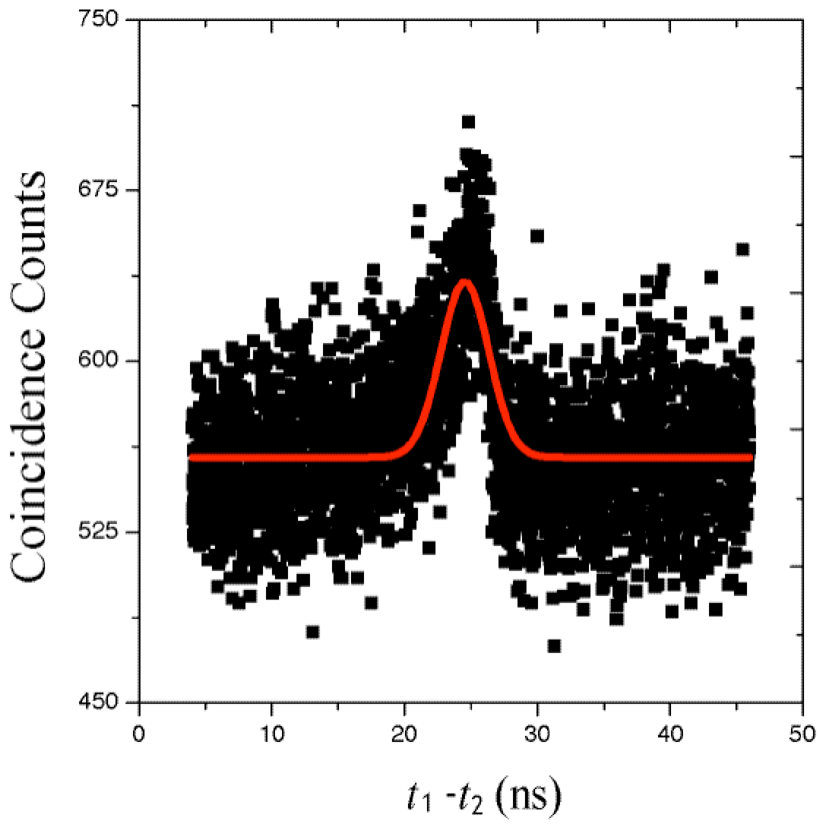


* Enhanced spatial resolution of the ghost image.

* Enhanced controllable field of view.

* Turbulence-free imaging.

Temporal Correlation of Sun light

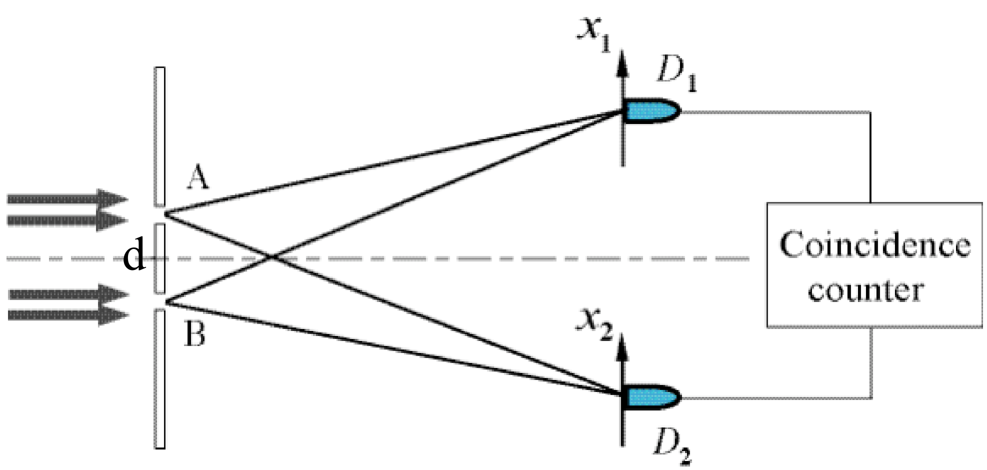


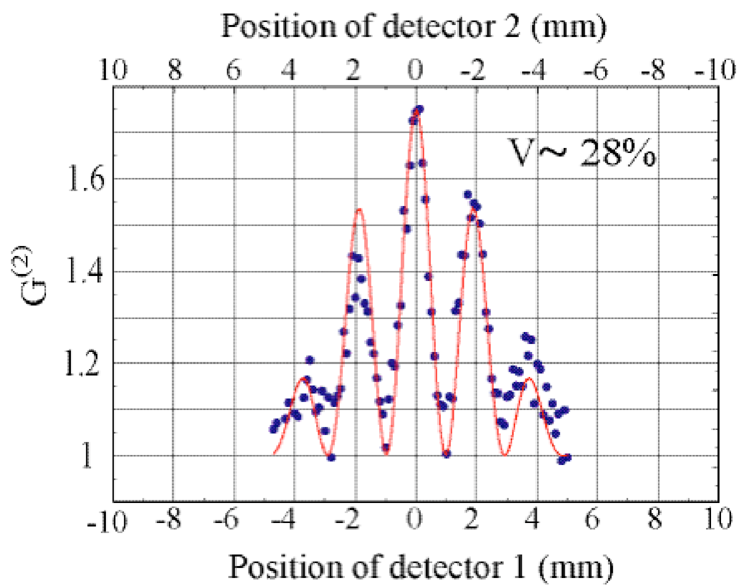
Sanjit with his “magic black box”

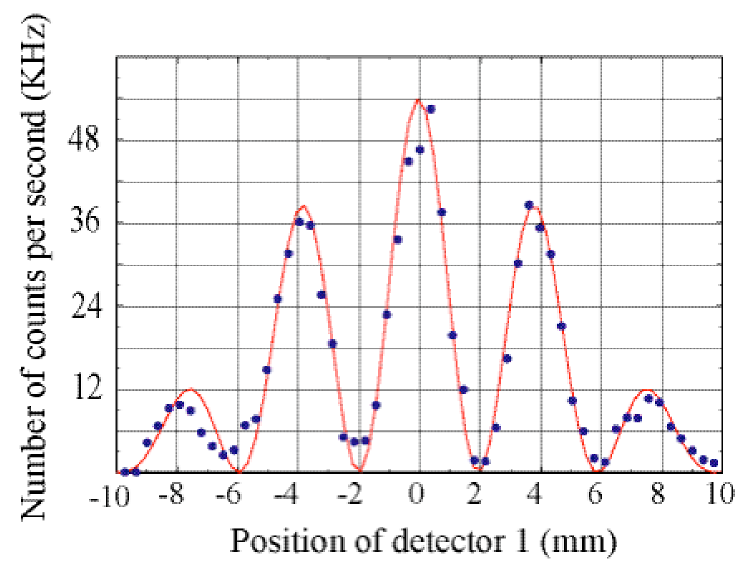
Part-II

Multi-photon interferometry with thermal light

Experiment 1: Young's interference with incoherent thermal light



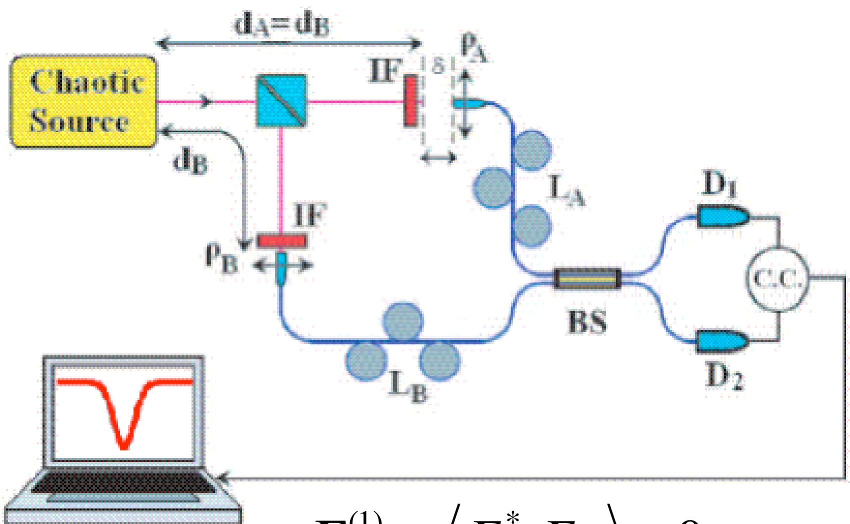




$$d >> \frac{\lambda}{\Delta\theta} \qquad \Gamma_{AB}^{(1)} = \langle E_A^* E_B \rangle = 0$$

Can we observe interference between incoherent thermal light?

Experiment 2: Two-photon anti-correlation with incoherent thermal light

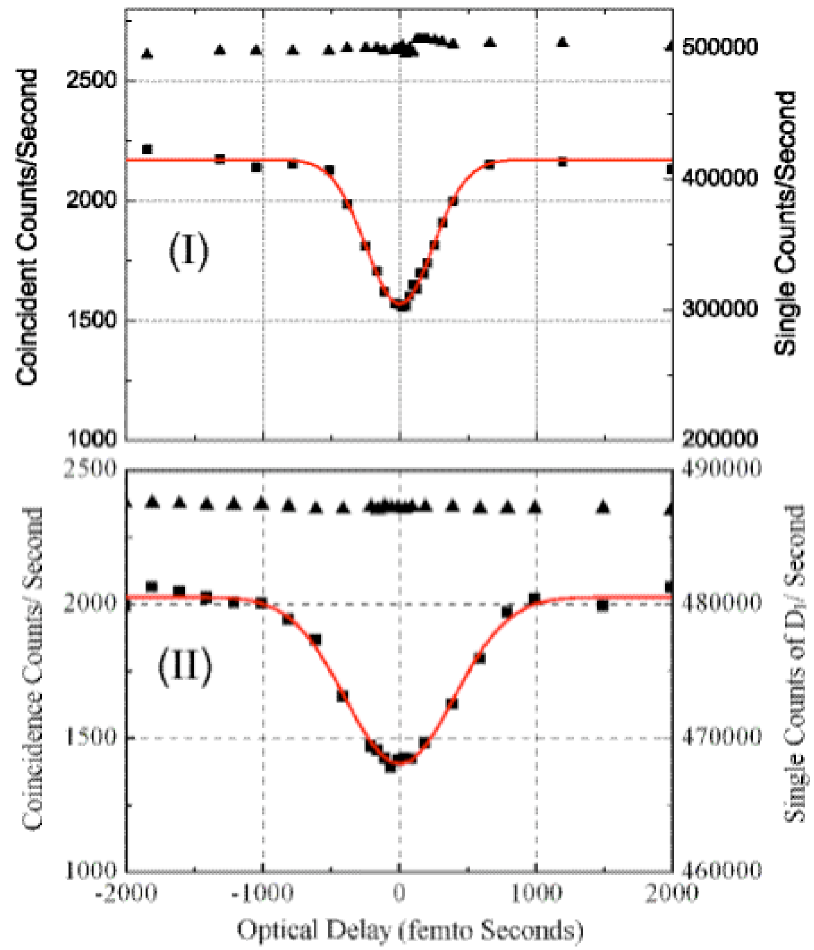


$$\Gamma^{(1)}_{AB} = \langle E^*_A \, E_B \rangle = 0$$

$$\Gamma^{(2)} = \langle I_1 I_2 \rangle = \langle |E_A + E_B|^2 |E_A - E_B|^2 \rangle$$

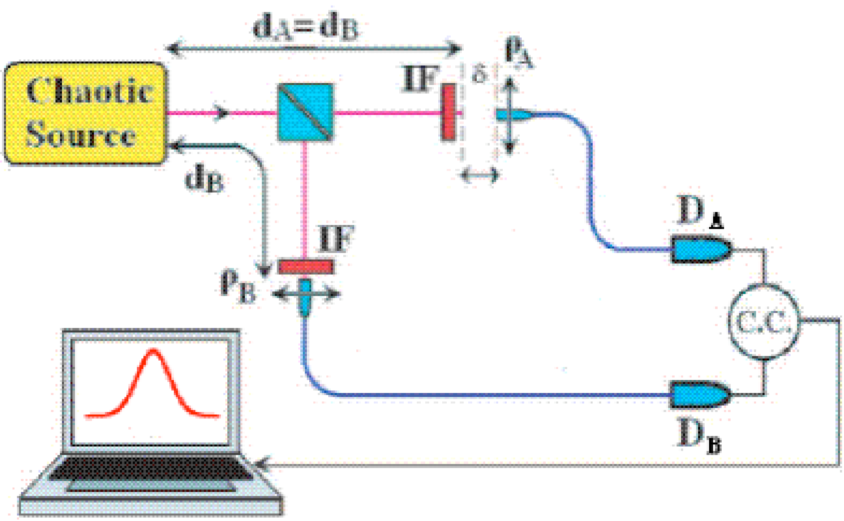
Classical statistical intensity correlation: independent of δ

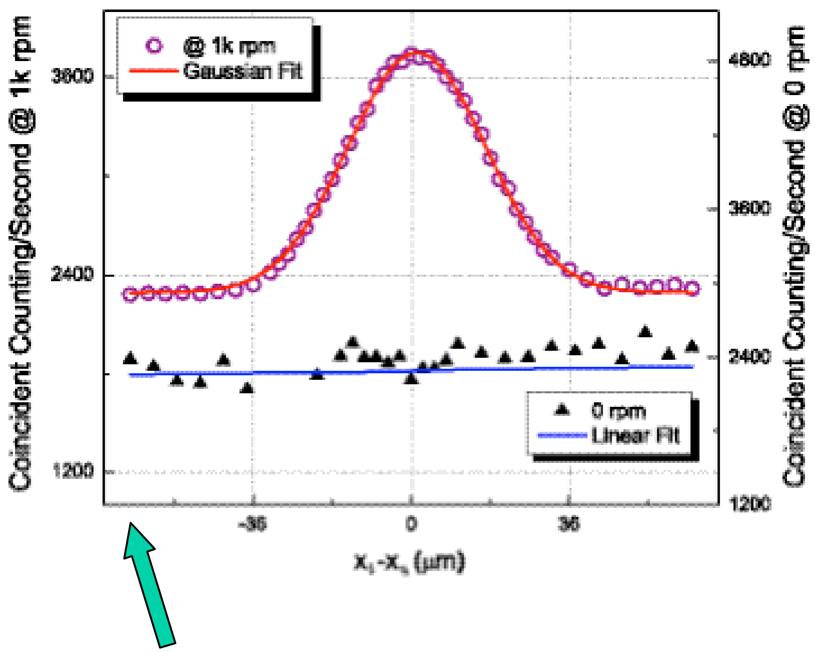
$$|\vec{\rho}_A - \vec{\rho}_B| \approx 40 \, \lambda / \Delta\theta$$



Two-photon anti-correlation with incoherent thermal light

Chaotic nature of the light source



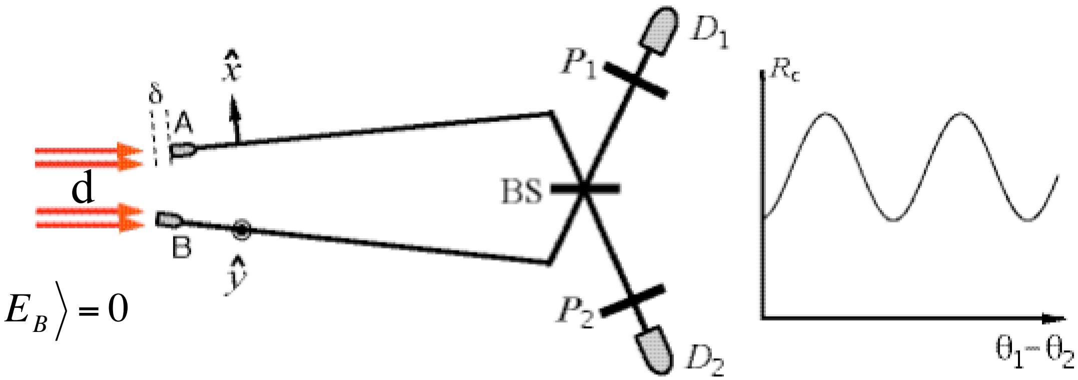


Experimental condition: $\left|\vec{\rho}_A - \vec{\rho}_B\right| \approx 40\ \lambda/\Delta\theta$

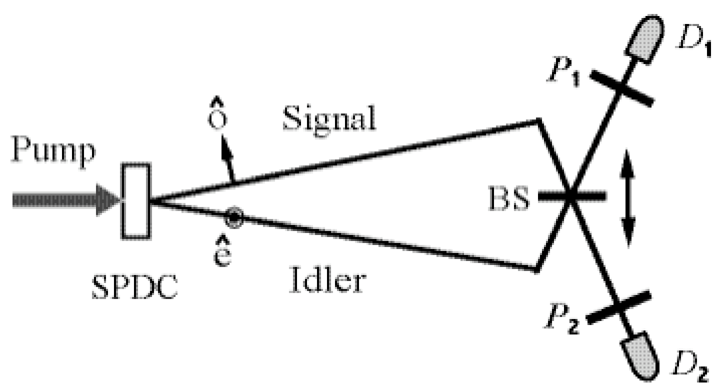
Experiment 3: Two-photon anti-correlation, correlation in space-time and in polarization with incoherent and orthogonal polarized thermal light

$$d >> \frac{\lambda}{\Delta\theta}$$

$$\Gamma_{AB}^{(1)} = \langle E_A^* E_B \rangle = 0$$

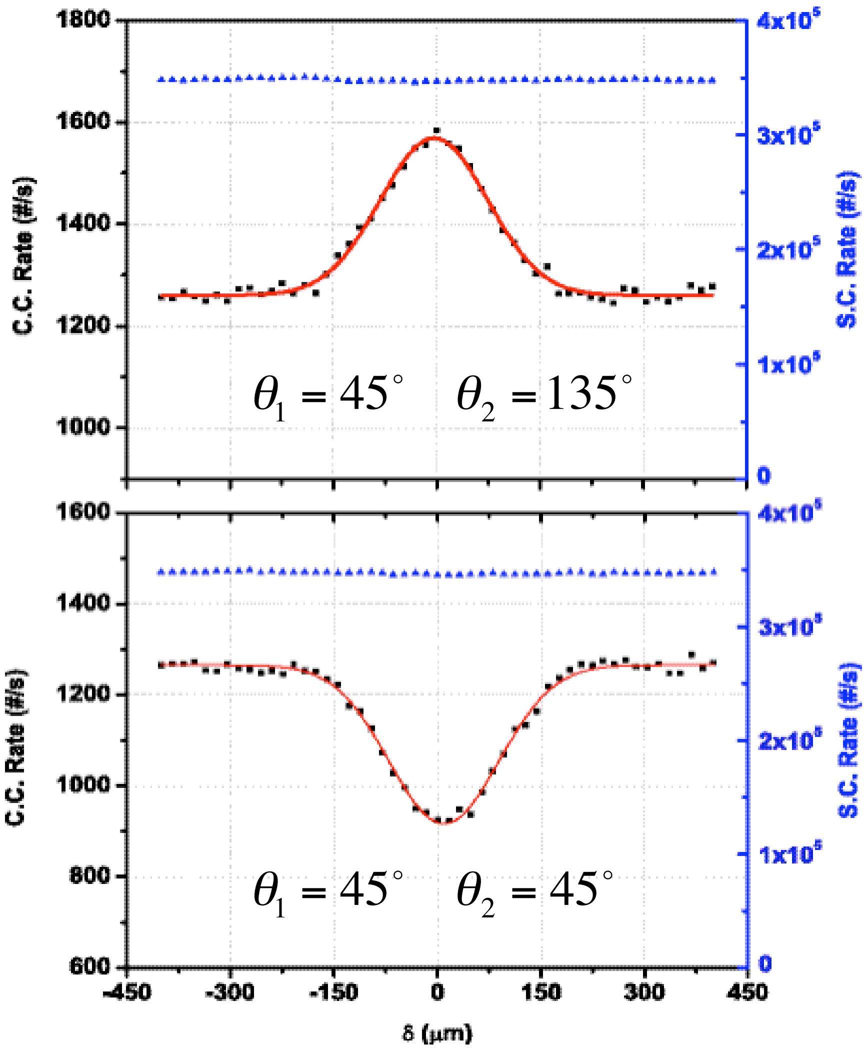


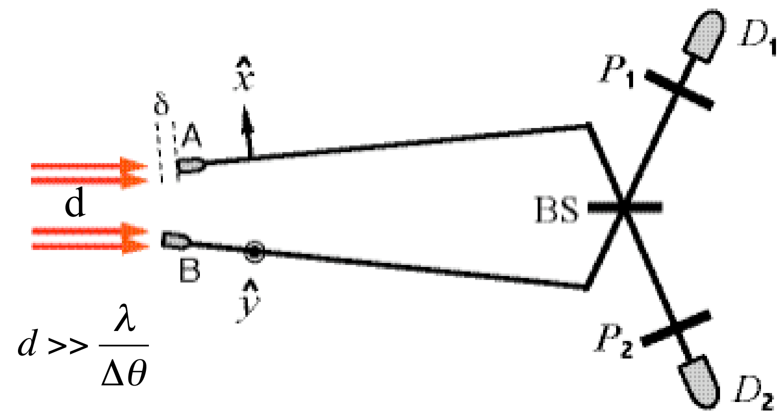
$$G^{(2)} = \left| (\theta_1 \cdot \vec{y})(\theta_2 \cdot \vec{x}) A(\boldsymbol{\tau}_{A2}^{T}, \boldsymbol{\tau}_{B1}^{T}) - (\theta_1 \cdot \vec{x})(\theta_2 \cdot \vec{y}) A(\boldsymbol{\tau}_{B2}^{R}, \boldsymbol{\tau}_{A1}^{R}) \right|^2$$

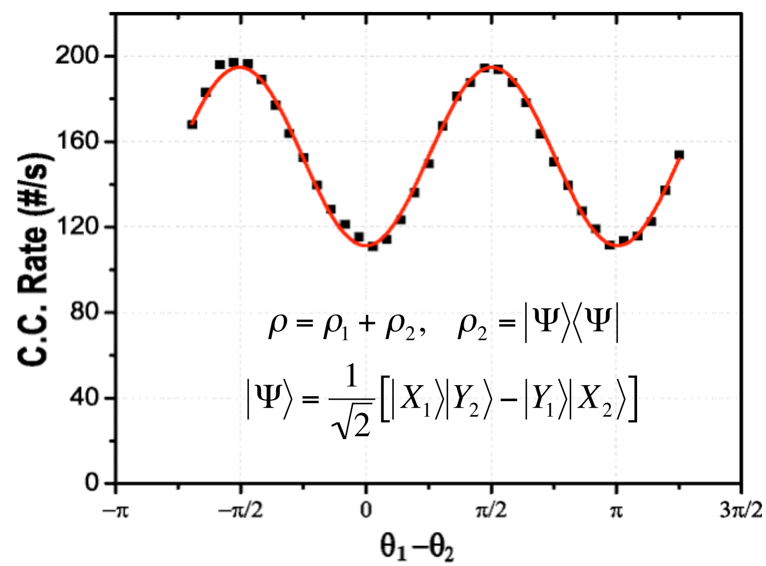


Historical experiment with entangled photon pairs.

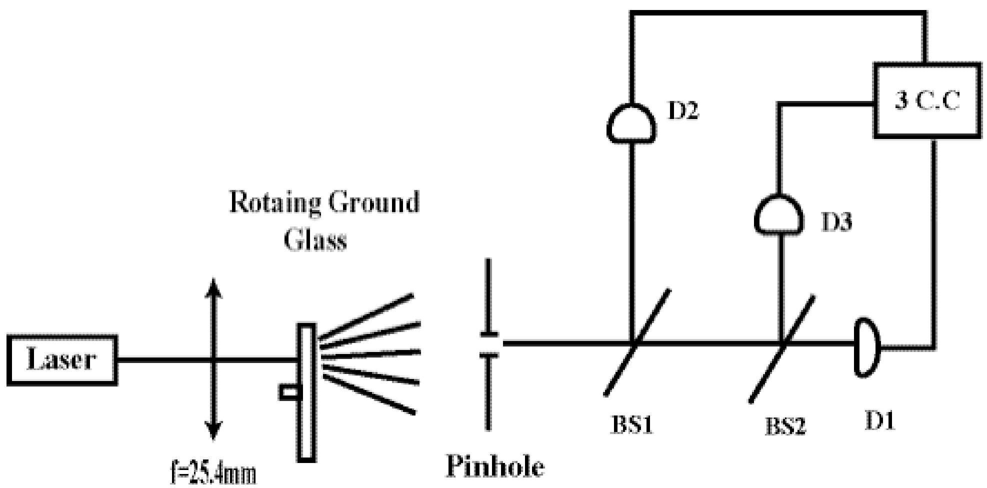
Two-photon anti-correlation, correlation in space-time and in polarization with incoherent and orthogonal polarized thermal light

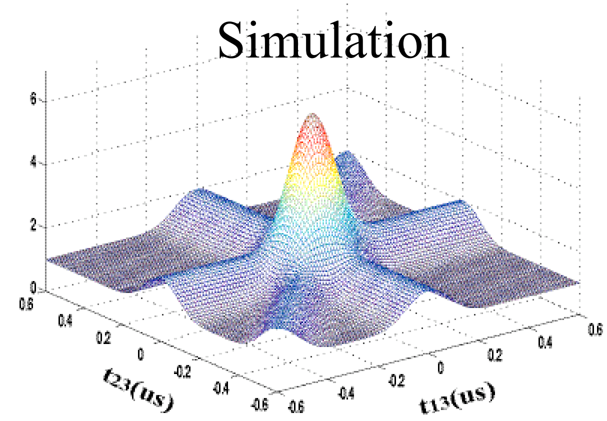






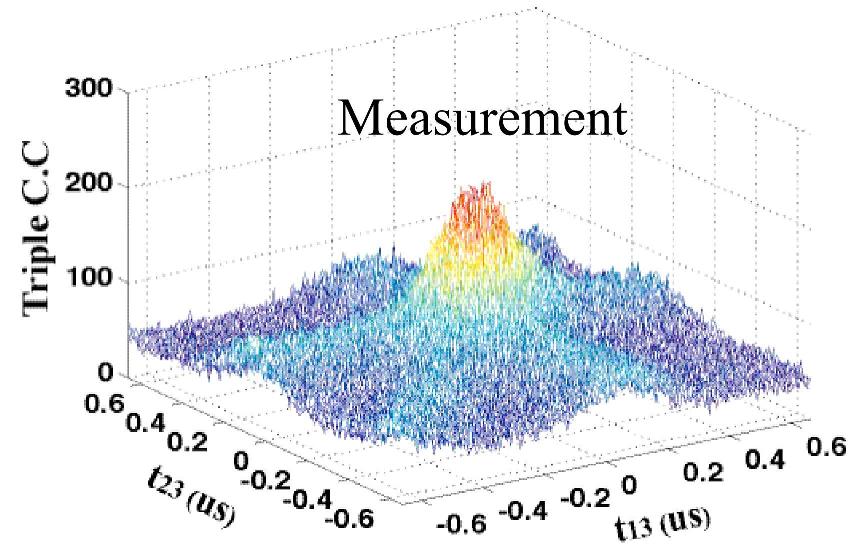
Experiment 4: Thermal light three-photon temporal correlation





$$G^{(3)}(t_1,t_2,t_3)$$

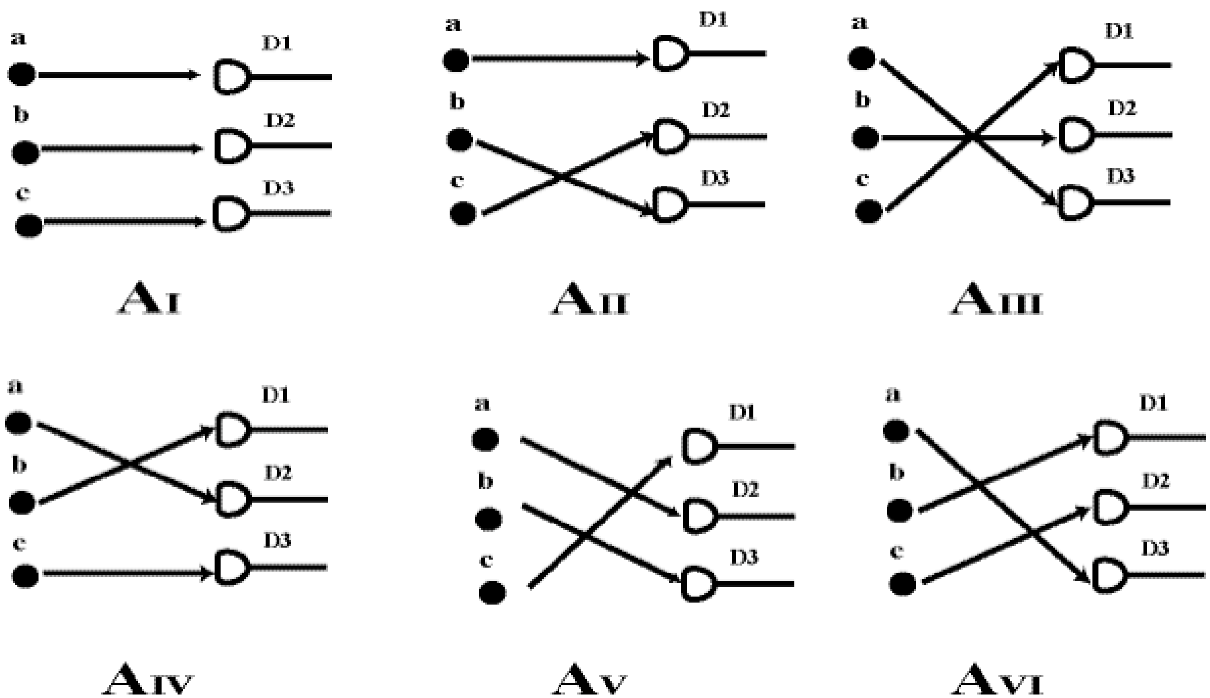
$$= \sum_{\substack{Sub- \\ Source}} \left| \frac{1}{\sqrt{6}} (A_I^{(3)} + A_{II}^{(3)} + A_{III}^{(3)} + A_{IV}^{(3)} + A_V^{(3)} + A_{VI}^{(3)}) \right|^2$$



Can N-photon correlation be considered as photon bunching?

Superposition of three-photon amplitudes

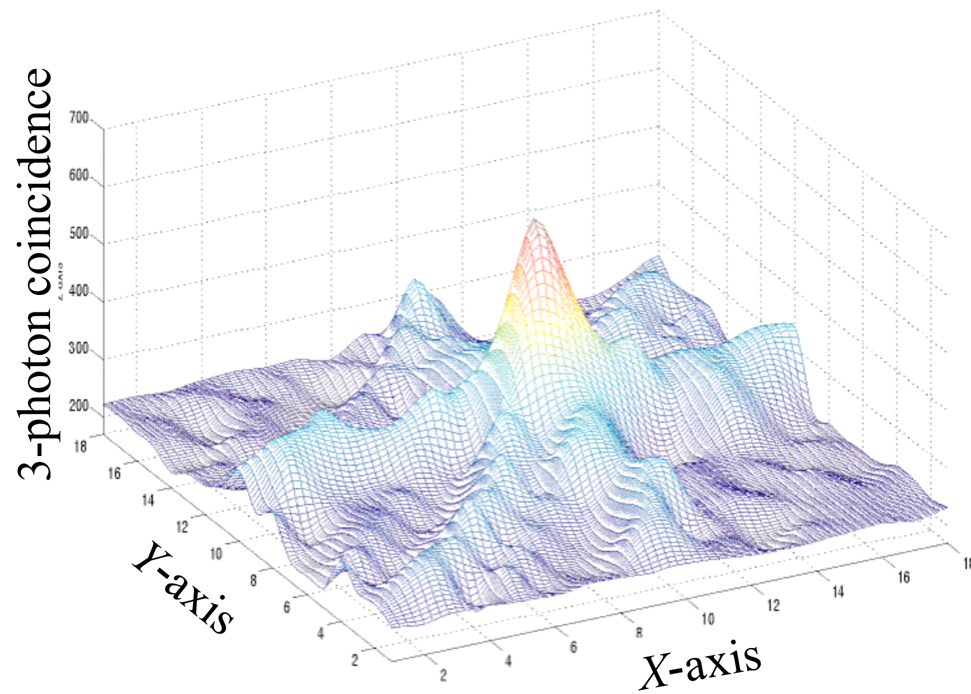
$$G^{(3)}(t_1,t_2,t_3) = \sum_{a,b,c} \left| \frac{1}{\sqrt{6}} (A_I^{(3)} + A_{II}^{(3)} + A_{III}^{(3)} + A_{IV}^{(3)} + A_V^{(3)} + A_{VI}^{(3)}) \right|^2$$



$$G^{(N)}(t_1,\ldots,t_N) = \sum_{\substack{Sub- \\ Source}} \left| \frac{1}{\sqrt{N!}} (A_I^{(N)} + \ldots + A_{N!}^{(N)}) \right|^2$$

Superposition of
N-photon amplitudes

Experiment 5: Thermal light three-photon spatial correlation



$$G^{(3)}(\vec{\rho}_1,\vec{\rho}_2,\vec{\rho}_3) = \sum_{\substack{Sub- \\ Source}} \left| \frac{1}{\sqrt{6}} (A_I^{(3)} + A_{II}^{(3)} + A_{III}^{(3)} + A_{IV}^{(3)} + A_V^{(3)} + A_{VI}^{(3)}) \right|^2$$

Experiment 6: 3-D ghost imaging for medical applications

Experiments in progress, observed "two-color" ghost imaging, in collaboration with Harvard Medical School.

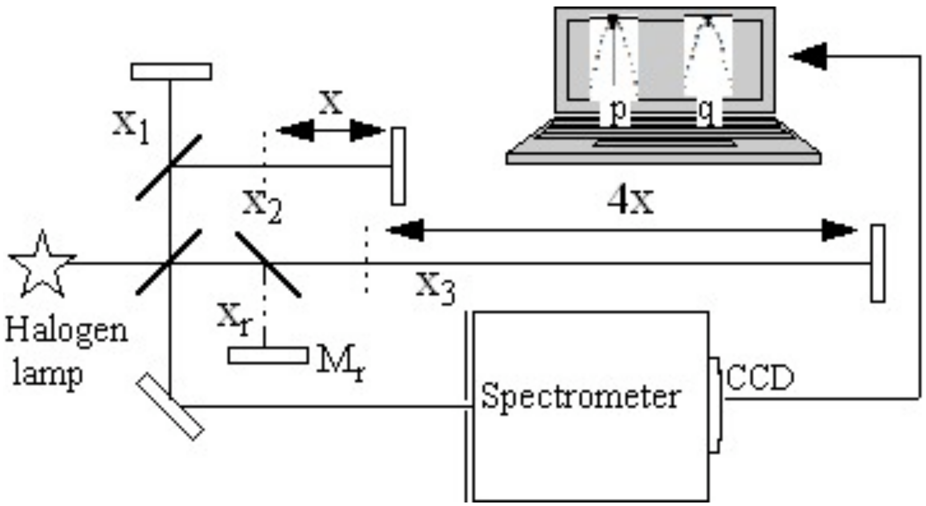
Experiment 7: Sun light ghost imaging

Experiments in progress, observed Sun light correlation, in collaboration with ARL and NGC.

Experiment 8: Ghost imaging of the Moon

Experiment in planning, in collaboration with ARL and NGC.

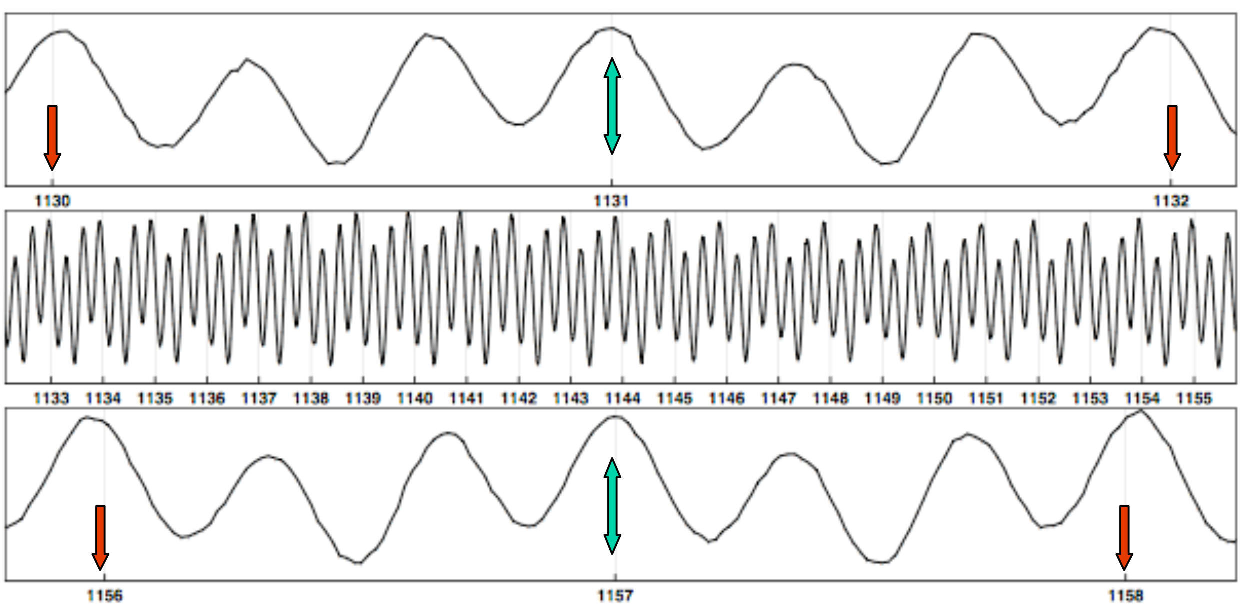
Experiment extra: A new algorithm and its interferogram approach for factoring arbitrary numbers



$$A_N^M(l) = \frac{1}{M+1}\sum_{m=0}^{M} \exp\left[-2\pi i m^2 \frac{N}{l}\right]$$

$N = 1131 \times 1157$

$N' = 1133 \times 1153$



Thanks MURI!

Thanks all the team members, especially these who have been on the other side of the debate!