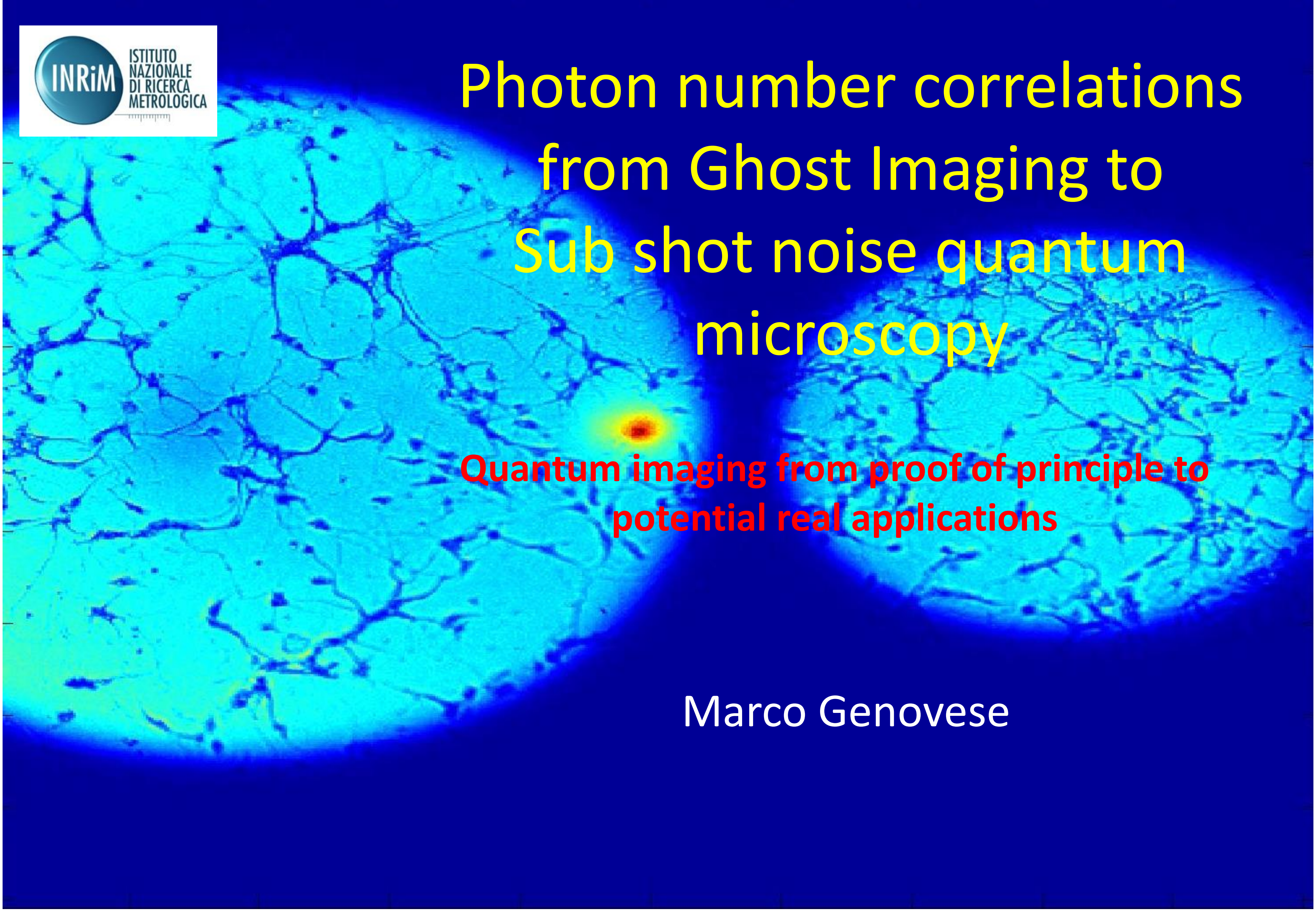
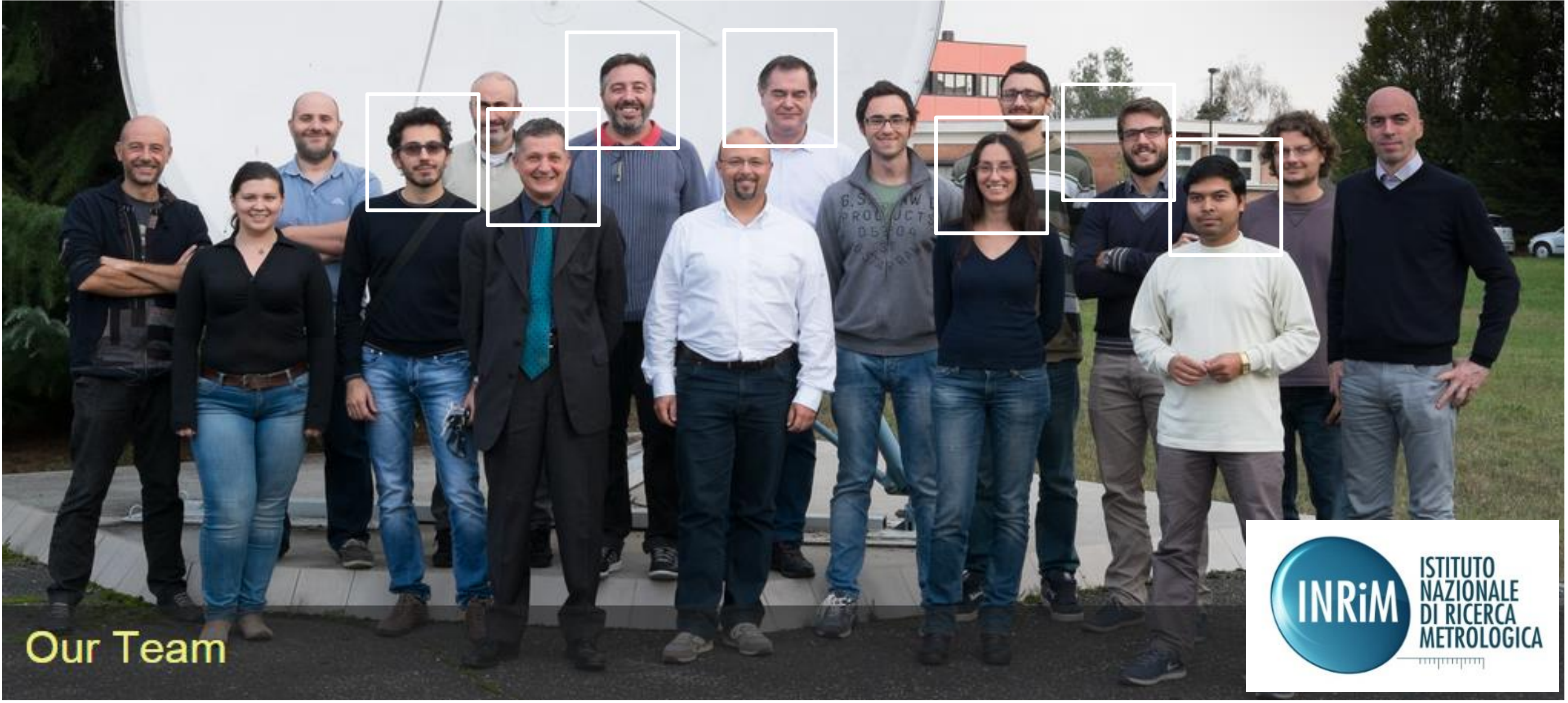


Photon number correlations from Ghost Imaging to Sub shot noise quantum microscopy

Quantum imaging from proof of principle to potential real applications

Marco Genovese



I Ruo Berchera,
Alice Meda
Ivo Degiovanni
Giorgio Brida
Marco Genovese

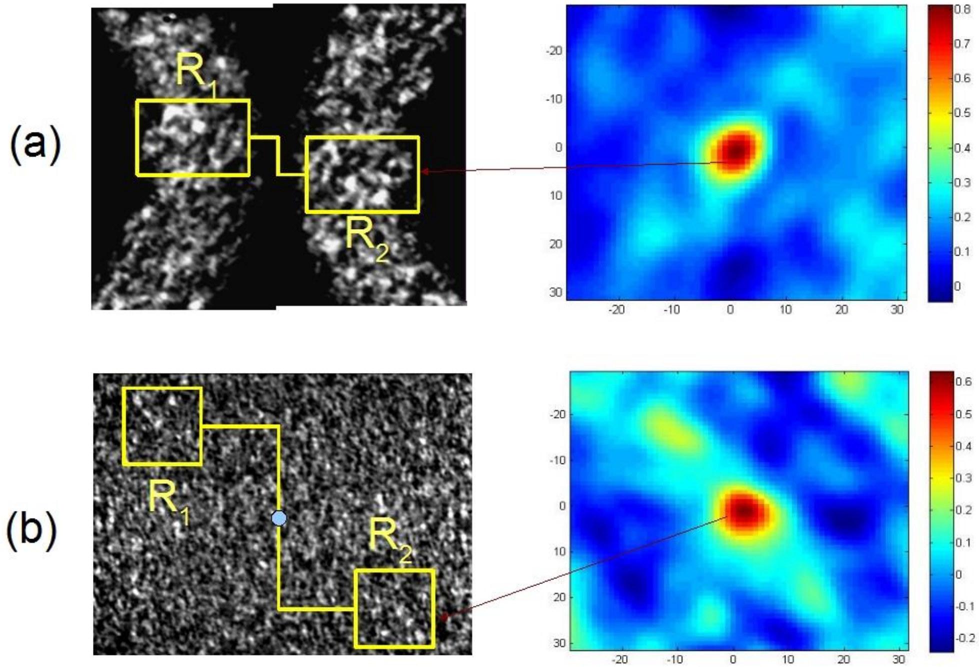
Nigam Samataray (PhD)
Elena Losero (PhD)
Fabio Scafirimuto(M Th)

Photon number correlations and twin beams: a tool for quantum imaging & sensing

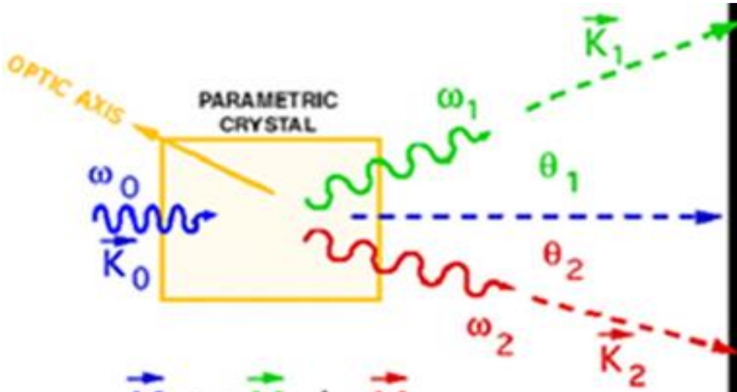
Photon number correlations represent a fundamental tool for
Quantum imaging metrology & sensing

"Real applications of quantum imaging", M.Genovese, Journal of Optics, 18 (2016) 073002

“Photon number correlation for quantum enhanced imaging and sensing», A.Meda et al. arXiv:1612.08103

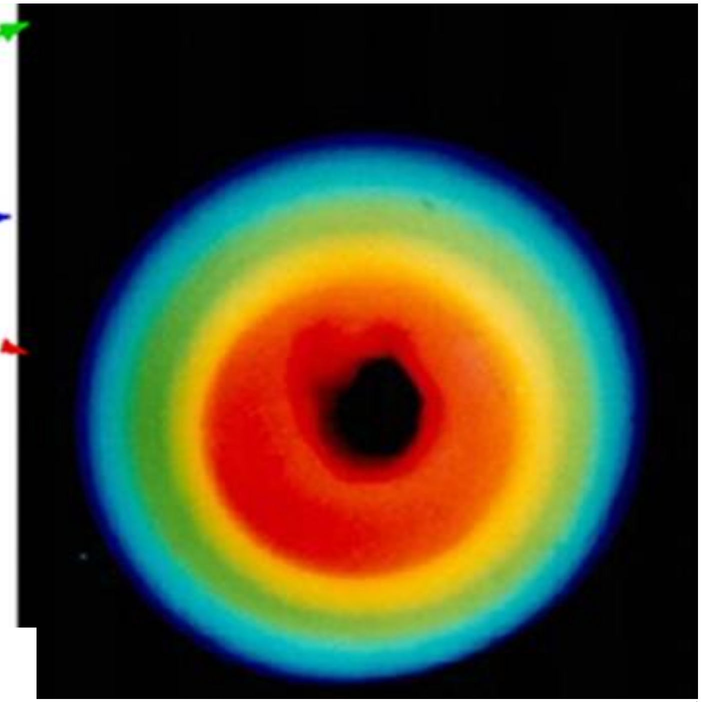


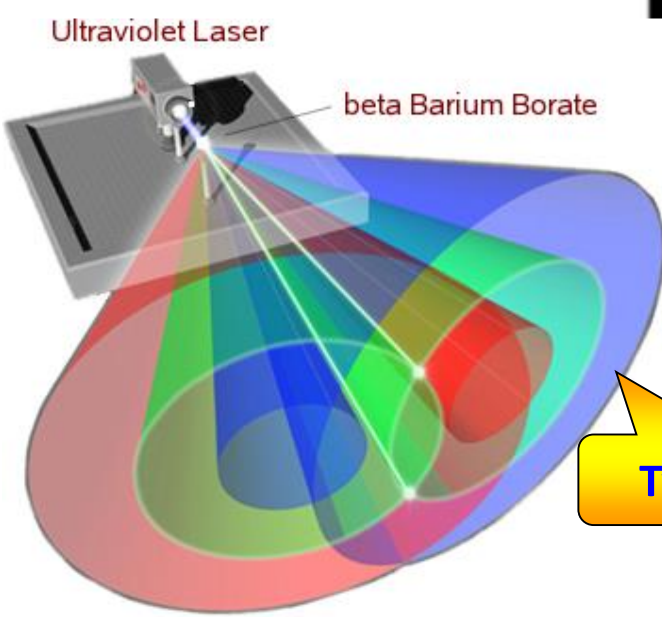
PDC: a brief summary



$$\vec{K}_0 = \vec{K}_1 + \vec{K}_2$$

$$\omega_0 = \omega_1 + \omega_2$$

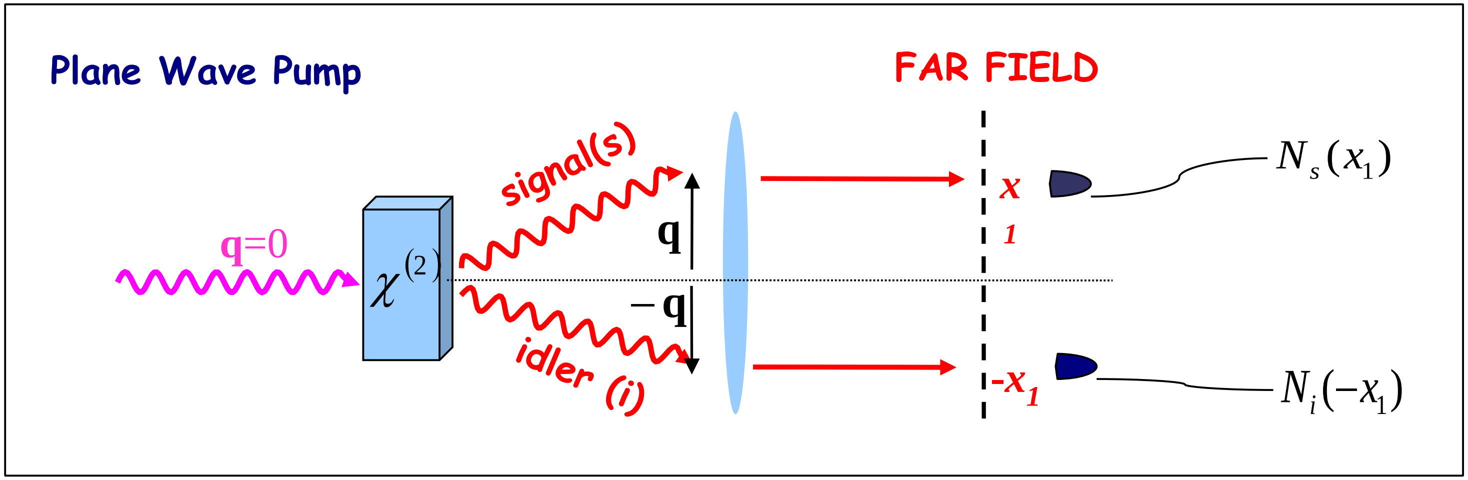




Type-II PDC

Type-I PDC

Photon number correlations in twin beams/ideal case



Two-Mode Entangled State
(squeezed vacuum)

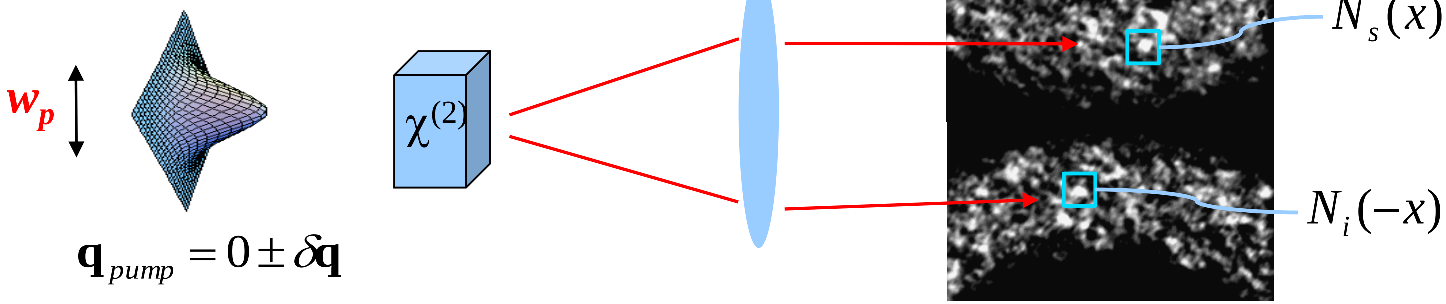
Two-Mode Photon
number correlation

$$\left|\psi_{\mathbf{q}}\right\rangle = \exp(-z a_1 a_2 + h.c)\left|0\right\rangle = \sum_{n=0}^{\infty} c_n(\mathbf{q})\left|n_{\mathbf{q}}\right\rangle\left|n_{-\mathbf{q}}\right\rangle \Longrightarrow N_s(\mathbf{x}_1) = N_i(-\mathbf{x}_1)$$

Photon number correlations in twin beams/gaussian pump

Noisy Intensity Pattern, where the typical scale is the Coherence Area

Gaussian Pump



$$\mathbf{q}_{pump} = 0 \pm \delta\mathbf{q}$$

Relaxation of the phase matching condition

$$\mathbf{q}_1 + \mathbf{q}_2 = 0 \pm \delta\mathbf{q}$$

⇒

uncertainty in the propagation directions of twin photons

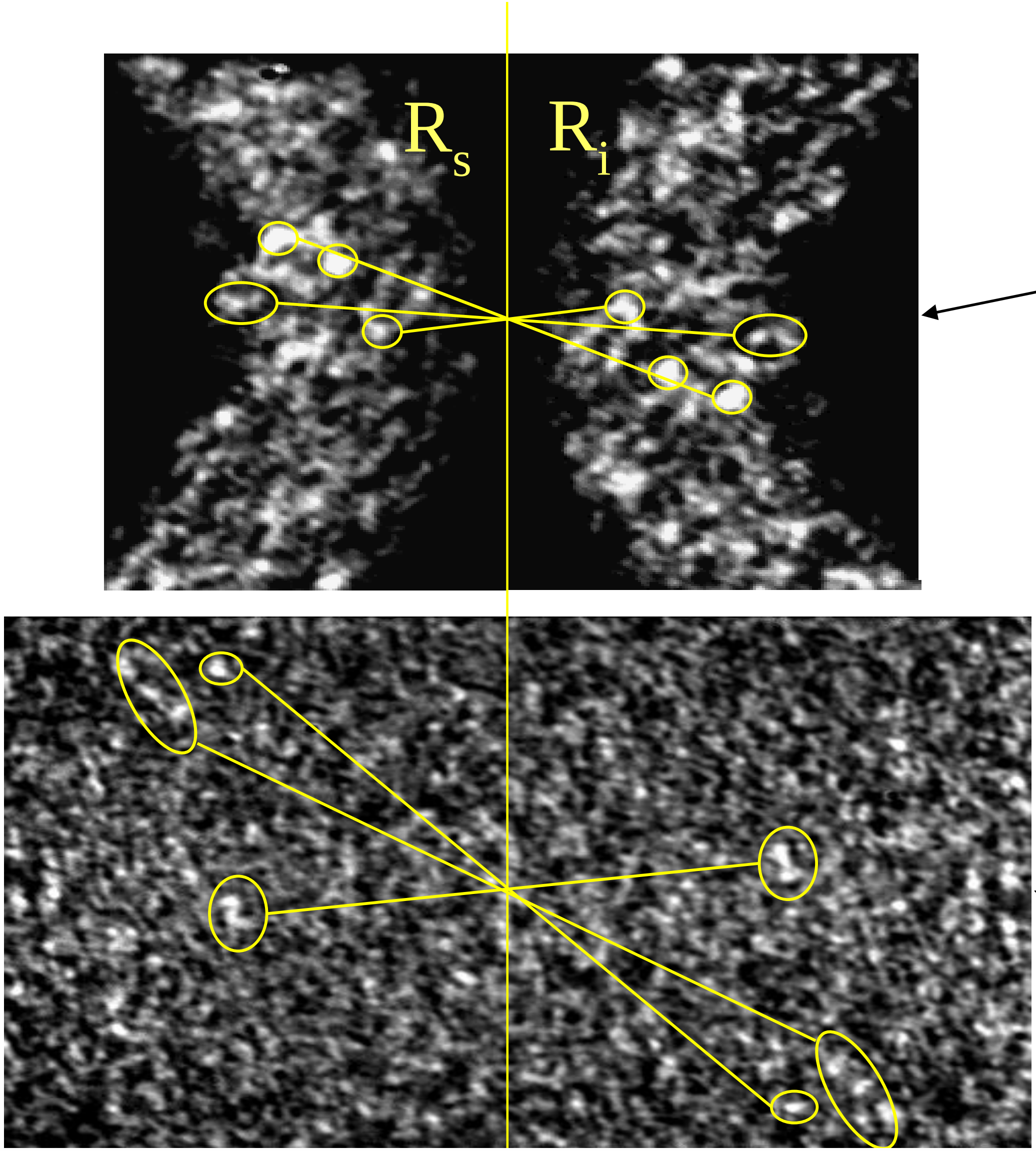
$$\mathbf{x}_1 + \mathbf{x}_2 = 0 \pm \delta\mathbf{x} \qquad (\delta\mathbf{x})^2 \propto \left(\frac{\lambda f}{2\pi}\right)^2 \cdot \frac{1}{w_p^{\,2}}$$

To detect quantum correlation, the detector size must be larger than the single spatial mode

$$A_{detection} / A_{coherence} >> 1$$

[Brambilla *et al*. Phys Rev A 69, 023802 (2004)].

Spatial entanglement in PDC/Single Shot Images by CCD



With interference filter (10nm bandwidth) in front of the CCD camera

Parametric gain>1, the thermal fluctuation are dominant, and the correlations are clearly visible

Without narrow frequency selection

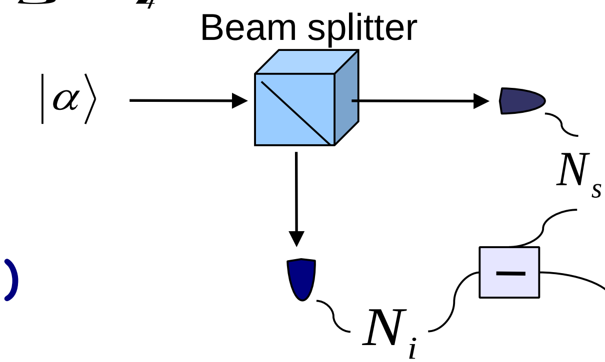
Spatial entanglement in PDC\NRF

[G.Brida, L. Caspani, A. Gatti,M.G., A.Meda, I.Ruo-Berchera, PRL 102, 213602 (09).]

For quantifying the level of correlation we use the Noise Reduction Factor, defined as the fluctuation of the difference N_s-N_i normalized to the Shot Noise Level (Standard Quantum Limit).

$$NRF = \frac{\langle \delta^2 (N_s - N_i) \rangle}{\langle N_s + N_i \rangle}$$

$NRF = 1$ for coherent states

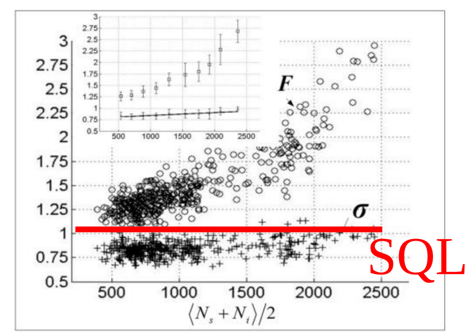


$\langle \delta^2 (N_s - N_i) \rangle_{coh} = \langle N_s + N_i \rangle$

$NRF \geq 1$ for classical light (e.g. thermal)

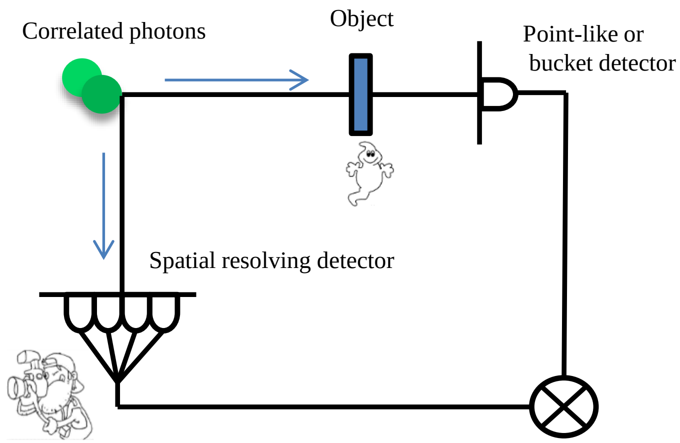
$NRF = 1 - \eta$ For PDC→sub shot noise regime

$(A_{det} >> A_{coh})$ η is the overall transmission of the optical channel

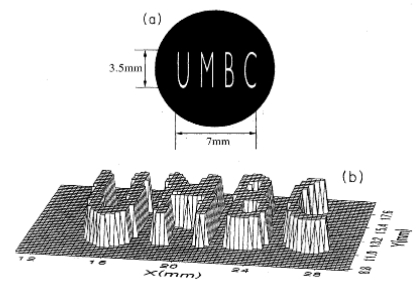


see also: Agafonov, Chekhova,Leuchs,arXiv:0910.4831; Bondani et al., Phys. Rev. A 76, 013833(2007); O. Jedrkievicz *et al.*, Phys. Rev. Lett. 93, 243601 (2004); J. Blanchet *el al.* Phys Rev. Lett. 101, 233604 (2008), J.Perina et al., Phys. Rev. A 85(2012) 023816.

Ghost Imaging

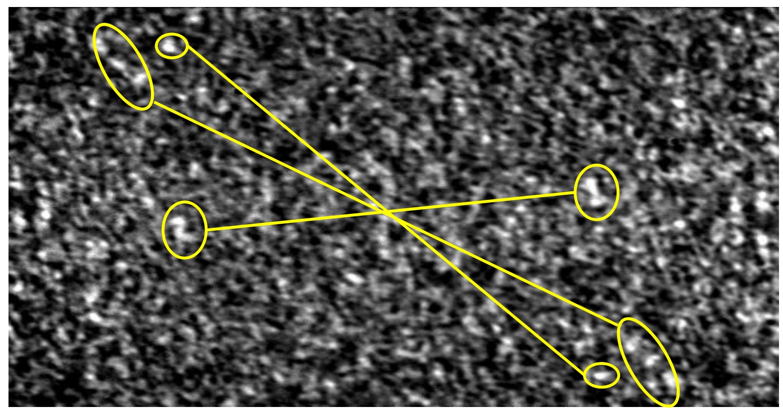


intensity fluctuations correlation



Pittman et al., Phys. Rev. A 52, 5 (1995).

Correlated Speckles



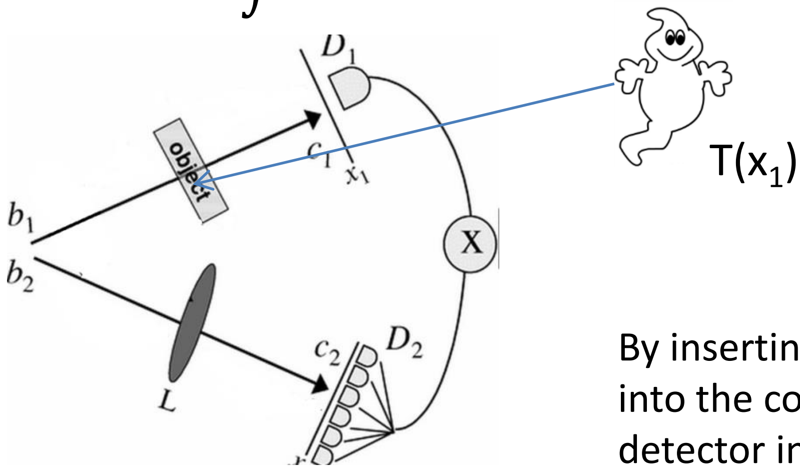
Ghost Imaging: theory

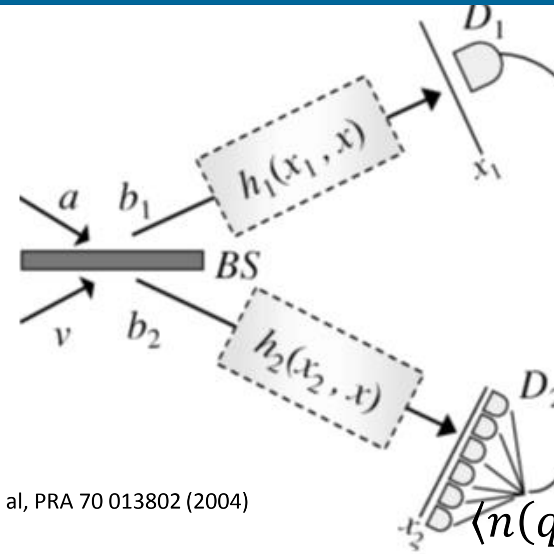
G.Brida, M.V.Chekhova, G.A. Fornaro, M.Genovese, L.Lopaeva, I. Ruo Berchera; Phys Rev. A 83, 063807 (2011)

Imaging system

The fields at the detection planes are given by

$$c_i(x_i) = \int dx_i'\, h_i(x_i, x_i')\, b_i(x_i')$$





Gatti et al, PRA 70 013802 (2004)

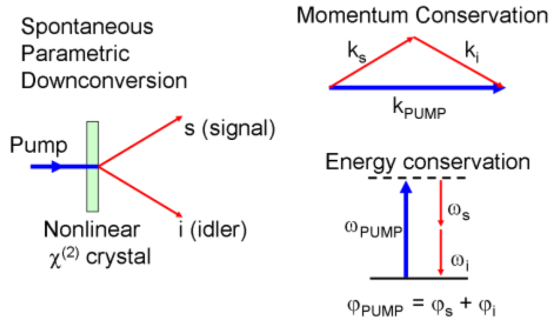
$$\langle n(q) \rangle \cong \mu$$

By inserting these propagators related to the imaging system into the correlation function and taking into account a bucket detector in path 1:

$$G(x_2) = \int dx_1 G(x_1, x_2) \propto \boxed{T\left(\frac{x_2}{M}\right)} (rt)^2 \mu^2$$

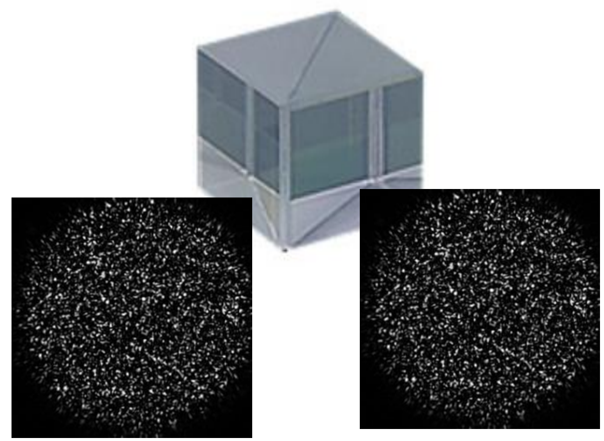
It is like a ghost object has appeared in arm 2 of our imaging system!

Ghost Imaging: theory



"It is possible to imagine some type of classical source that could partially emulate this behavior".

Thermal ligth beam



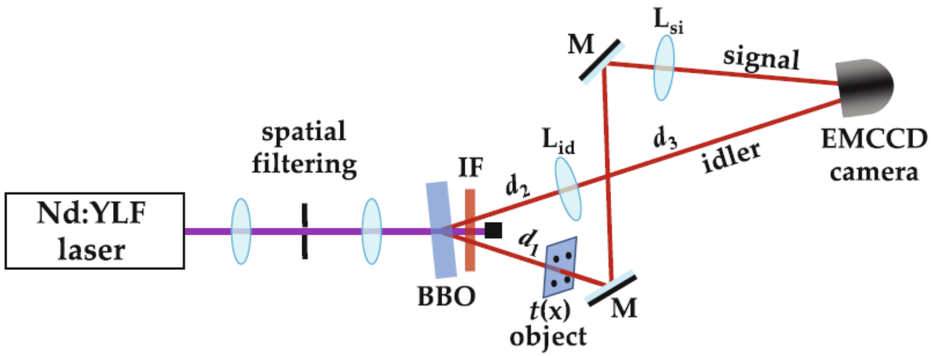
It was successfully interpreted as a statistical correlation of intensity fluctuations of the classical correlated beams.

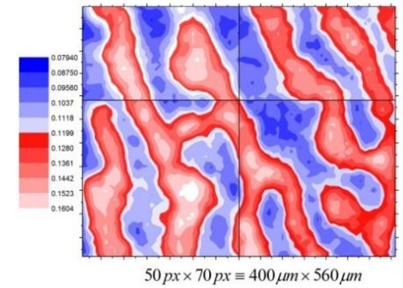
Bennik et al., PRL 89, 11 (2002), Gatti et al., PRL **94,** 183602 (2005),

Speckle –speckle correlation in pseudothermal beam

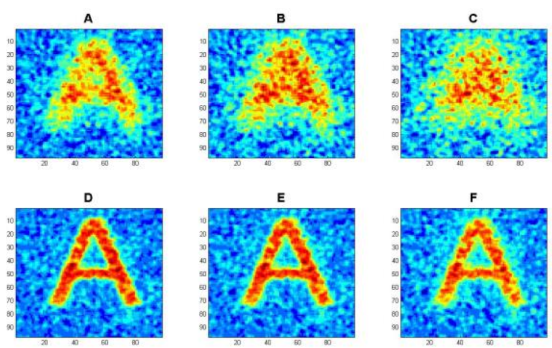
Photon counting regime!

applications





Magentic domains [INRIM]

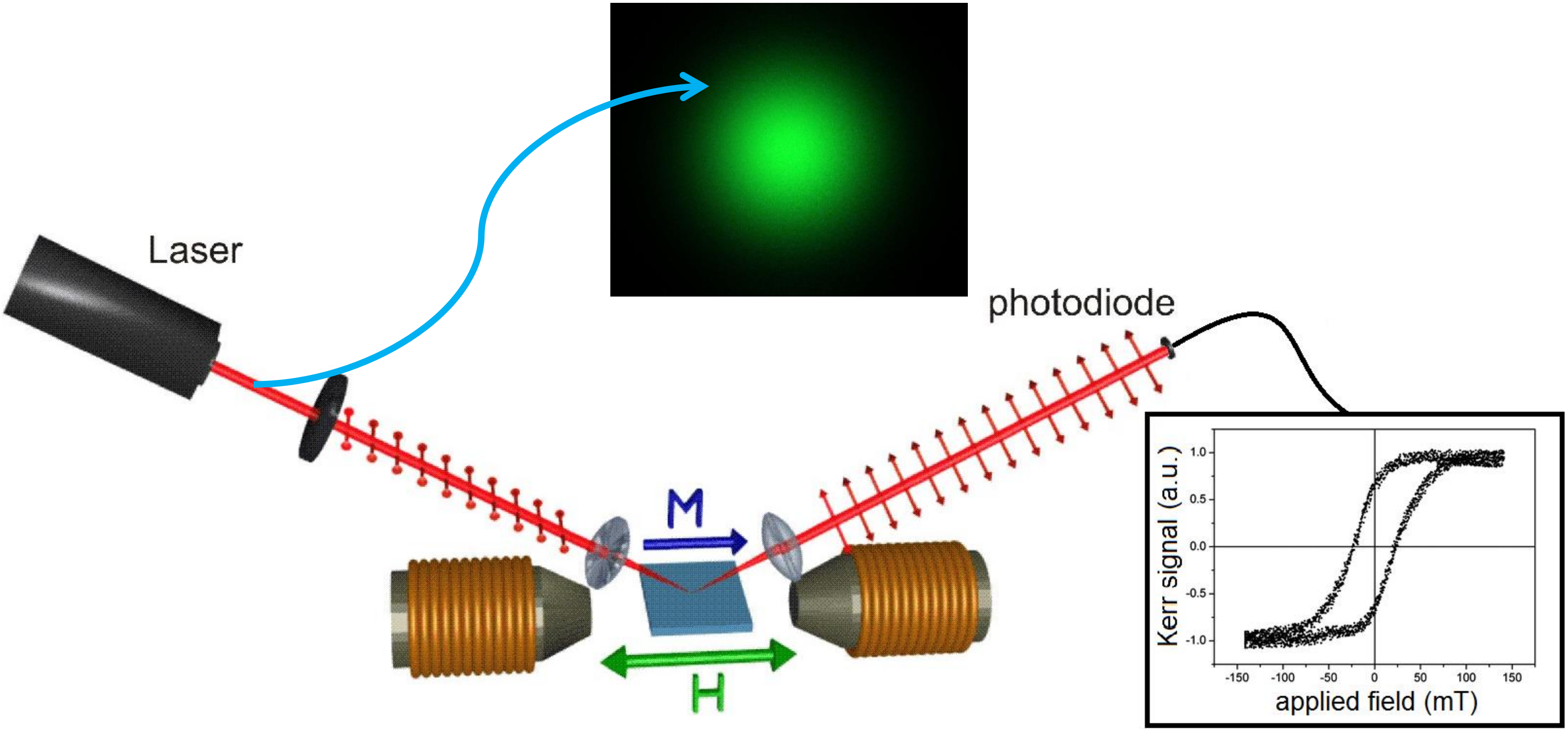


Imaging through turbolent atmosphere [D.Shi et al.]

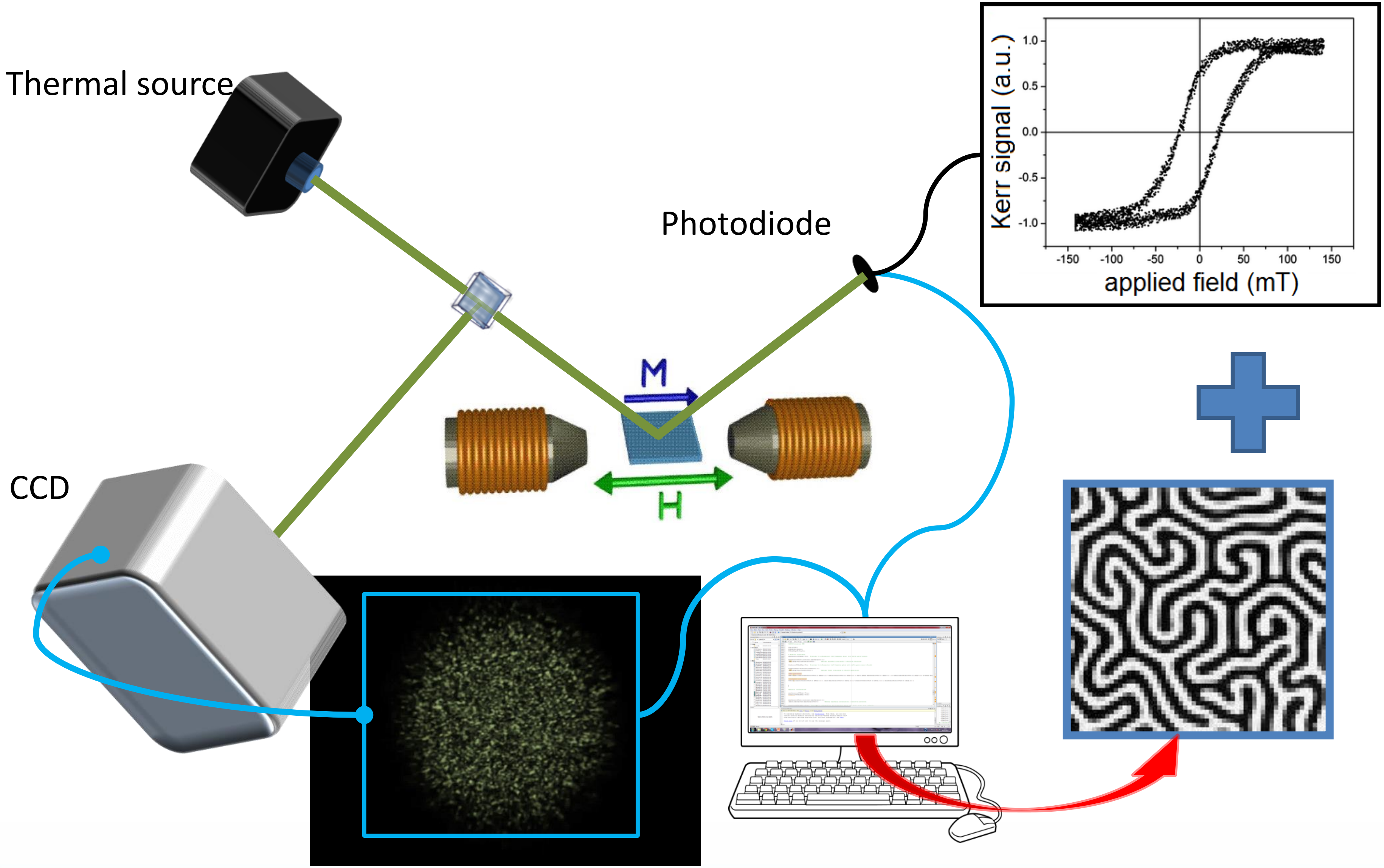
Imaging through diffusive media…[R.Meyers et al., M.Bondani et al.…]

Magneto optics application

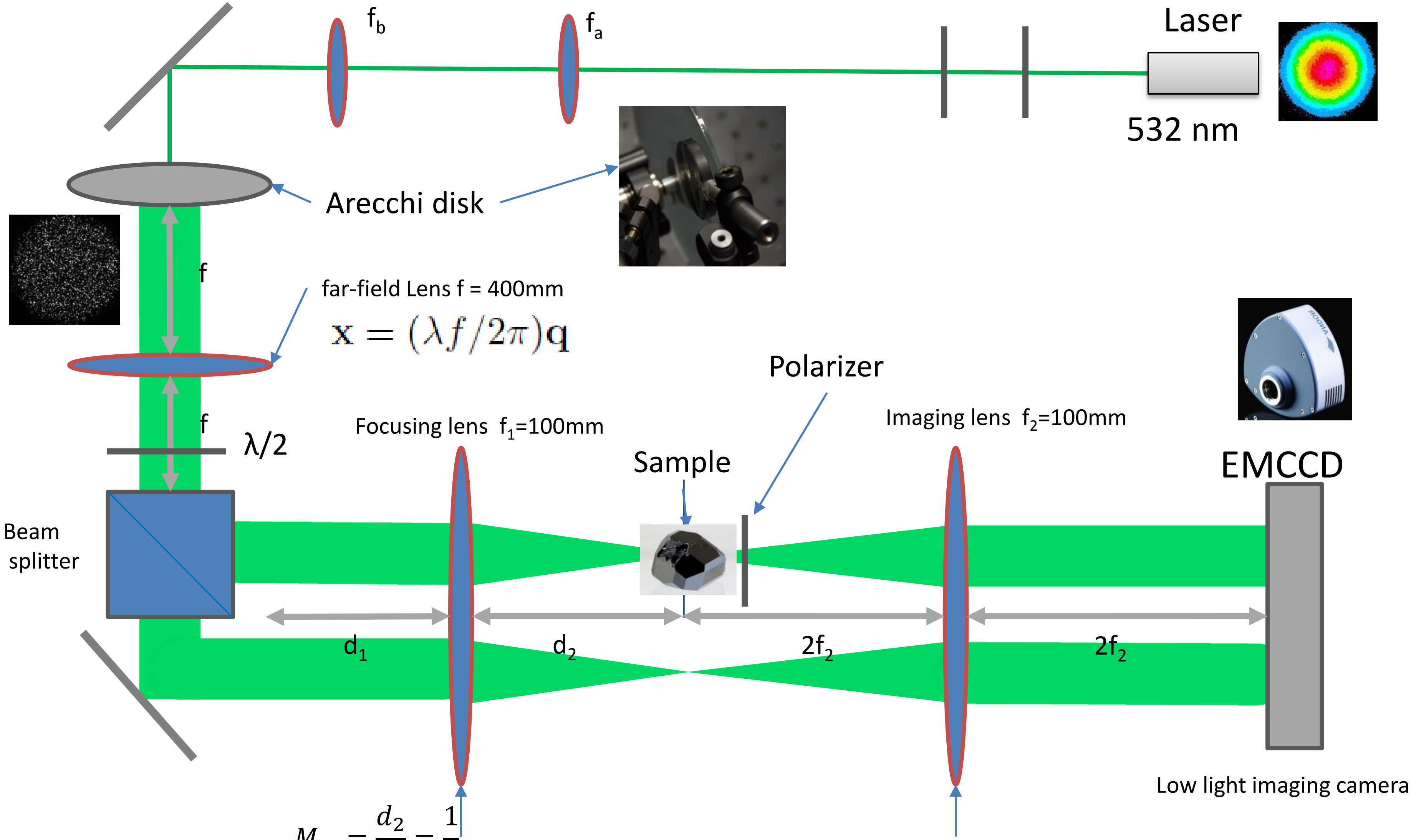
A. Meda, A. Caprile, A. Avella, I. Ruo Berchera, I. P. Degiovanni, A. Magni, and M. Genovese; Appl. Phys. Lett. 106, 262405 (2015);



Magneto optics application



GI: the experiment

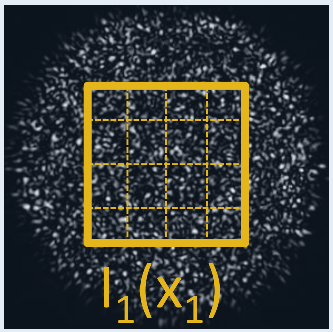


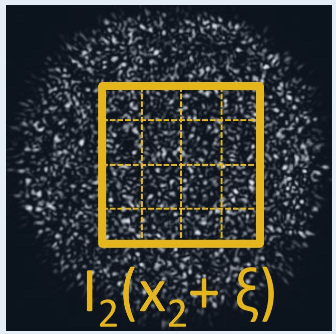
$$M = \frac{d_2}{d_1} = \frac{1}{5}$$

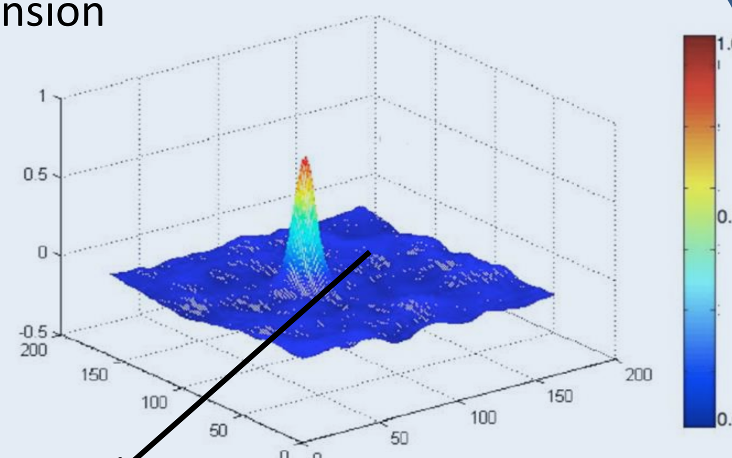
GI: the experiment

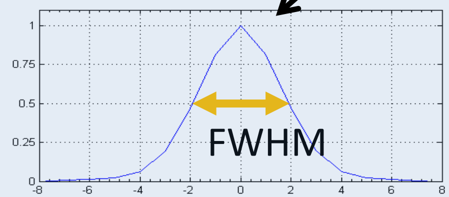
Coherence area and speckle dimension

$$Corr(x_1, x_2, \xi) = \frac{\langle I_1(x_1) I_2(x_2+\xi)\rangle - \langle I_1(x_1)\rangle\langle I_2(x_2+\xi)\rangle}{\sqrt{v(I_1(x_1))}\sqrt{v(I_2(x_2+\xi))}}$$



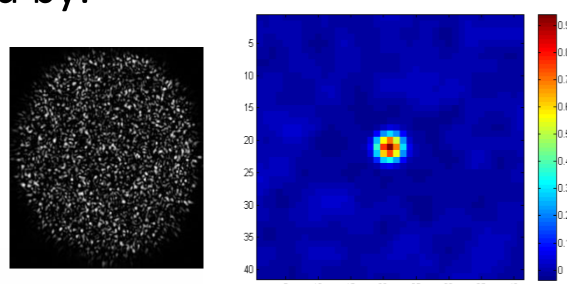


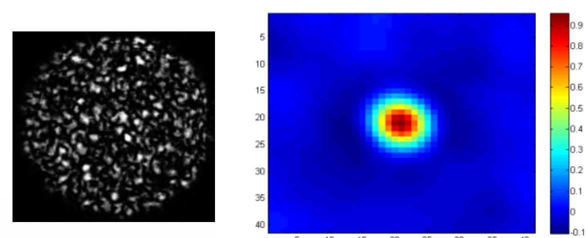




Dimension of speckle determined by:

- Pump diameter
- Far field lens LF
- Focusing lens LC



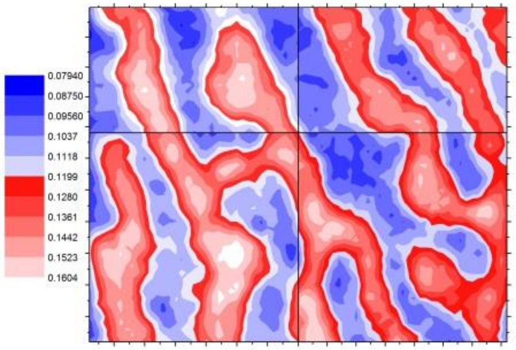


Results

The objects image is reconstructed evaluating the second-order correlation coefficient

$$c2_i = \frac{\langle I_1 I_{2,i}\rangle - \langle I_1\rangle\langle I_{2,i}\rangle}{\sqrt{\left\langle (I_1 - \langle I_1\rangle)^2\right\rangle}\sqrt{\left\langle (I_{2,i} - \langle I_{2,i}\rangle)^2\right\rangle}}$$

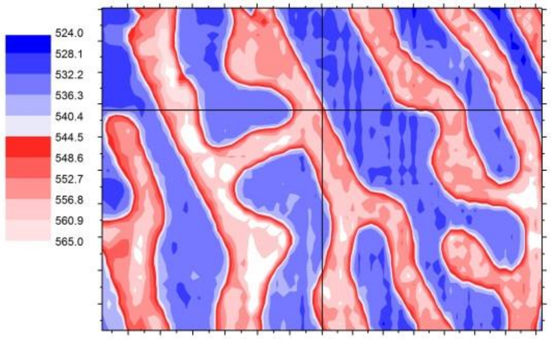
Faraday ghost imaging



$50\,px \times 70\,px \equiv 400\,\mu m \times 560\,\mu m$

Resolution: 3 px = 24 μm

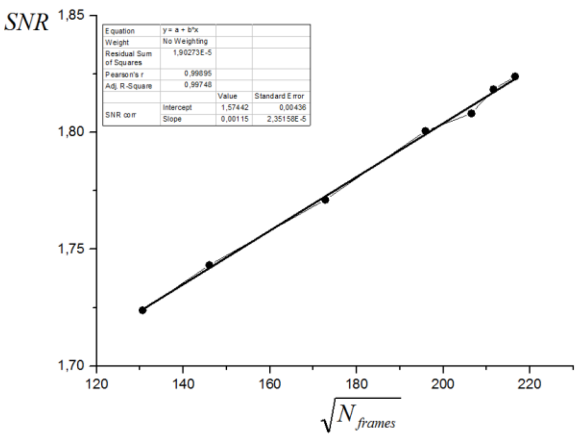
N_{frames} = 40000



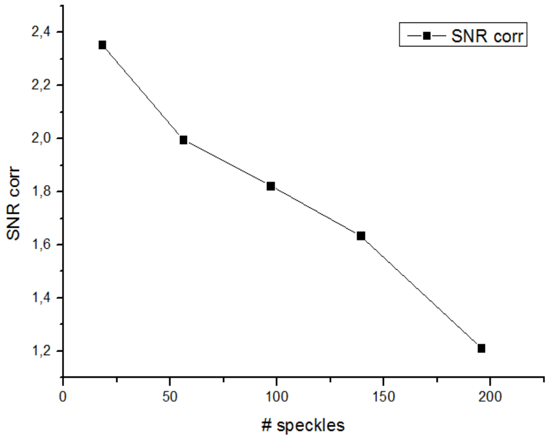
$50\,px \times 70\,px \equiv 400\,\mu m \times 560\,\mu m$

Faraday direct imaging

Resolution: 1 px = 8 μm

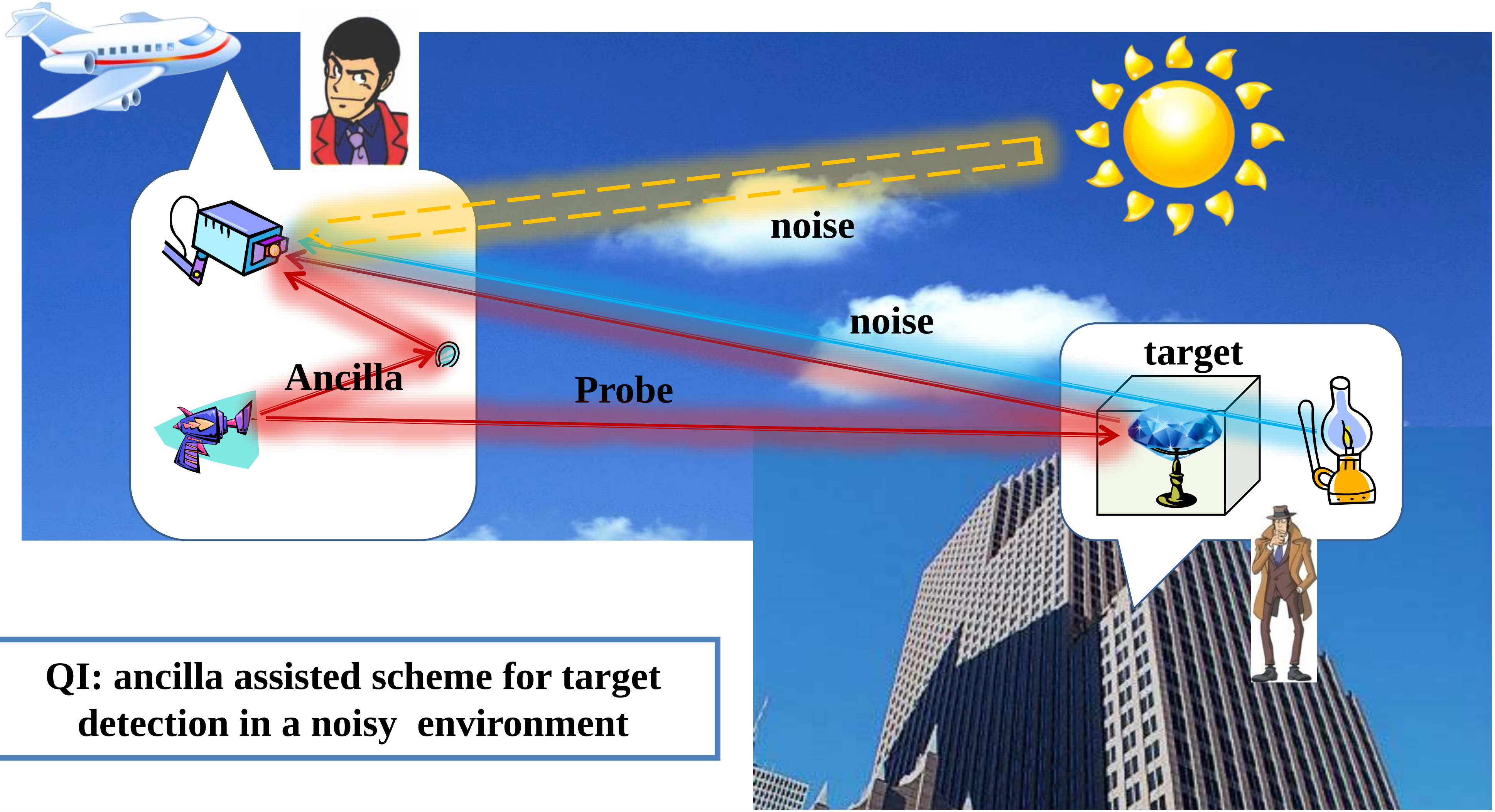


Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	1,90273E-5		
Pearson's r	0,99895		
Adj. R-Square	0,99748		
		Value	Standard Error
SNR corr	Intercept	1,57442	0,00436
SNR corr	Slope	0,00115	2,35158E-5



Quantum Illumination

E.Lopaeva, I.Ruo Berchera, I.Degiovanni, S.Olivares, G. Brida, M. Genovese
Phys. Rev. Lett. 110, 153603 (2013)



QI: ancilla assisted scheme for target detection in a noisy environment

First QI Proposal

Enhanced Sensitivity of Photodetection via Quantum Illumination
Seth Lloyd
Science **321**, 1463 (2008);
DOI: 10.1126/science.1160627

unentangled signal photon. The enhancement of sensitivity and effective signal-to-noise ratio that quantum illumination provides is exponential in the number of bits of initial entanglement and persists even in the presence of large amounts of noise and loss, when no entanglement survives at the receiver. This entanglement-induced enhance-

- **Source:** signal and ancilla beams contain one photon $n = 1$ in a d-mode entangled state.

$$|\psi\rangle_{SA} = (1/\sqrt{d})\sum_k |k\rangle_S |k\rangle_A$$

- **Noise:** thermal noise bath with small number of photons $n_b \ll 1$
- **Strategy**: optimal state discrimination theory
- **Object:** reflection $r \ll 1$

✓ Exponential enhancement! ☺
✓ Extremely robust against noise and losses!☺
✓ Entanglement do not survive!☺

to image features of the object. Many practical questions remain; notably, can the requisite entangled measurements be performed efficiently?

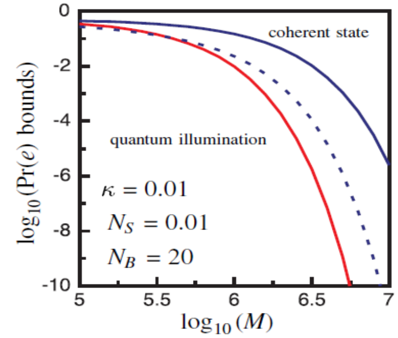
sion of detection issues see (*11*)]. Does the enhancement persist at higher noise temperatures and for larger numbers of photons in the signal? What are the maximum enhancements obtainable via quantum illumination over multiphoton input states, including Gaussian states? These questions and many others must be answered before quantum illumination can prove itself useful in practice.

✓ **No practical scheme how to do it in practice!☹**

PRL **101,** 253601 (2008) PHYSICAL REVIEW LETTERS week (19 DECEM

Quantum Illumination with Gaussian States

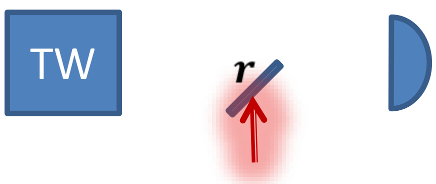
Si-Hui Tan,[1] Baris I. Erkmen,[2,*] Vittorio Giovannetti,[3] Saikat Guha,[2,†] Seth Lloyd,[2] Lorenzo Maccone, Stefano Pirandola,[2] and Jeffrey H. Shapiro[2,‡]



- ❑ **Source: Gaussian twin beams (PDC)**

$$|\psi\rangle_{SI} = \sum_{n=0}^{\infty} \sqrt{\frac{N_S^n}{(N_S+1)^{n+1}}}\,|n\rangle_S|n\rangle_I$$

- ❑ **Noise:** thermal noise bath with large number of photons $n_b \gg 1$ mixed at the objet with the probe



- ❑ **Strategy**: optimal state discrimination strategies (chernoff bound etc..)
- ❑ **Object:** reflection $\boldsymbol{r} \ll 1$.

- ✓ Exponential enhancement! ☺...
- ✓ ….Even if entanglement do not survive!
- ✓ Extremely robust against noise and losses!☺
- ✓ The source is experimentally trivial !☺ ☺

But challenging receiver in practice!☹

S. Guha, B. I. Erkmen, Phys. Rev. A 80, 052310 (2009).

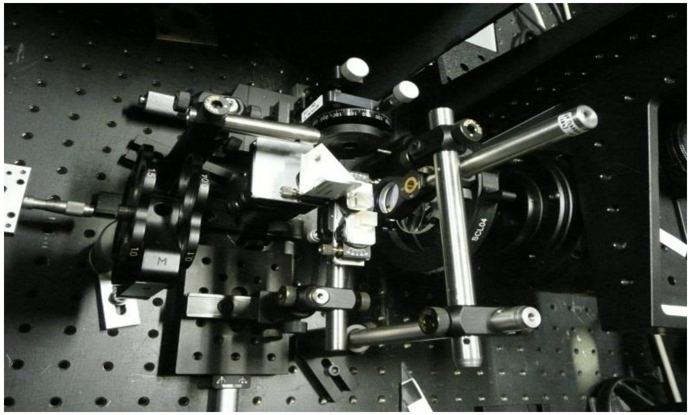
Photon counting based QI

A probe beam of a bipartite correlated state may be partially reflected by an object towards a camera, which is also illuminated by a thermal field acting as noisy, and a priori unknown, background (thermal bath)

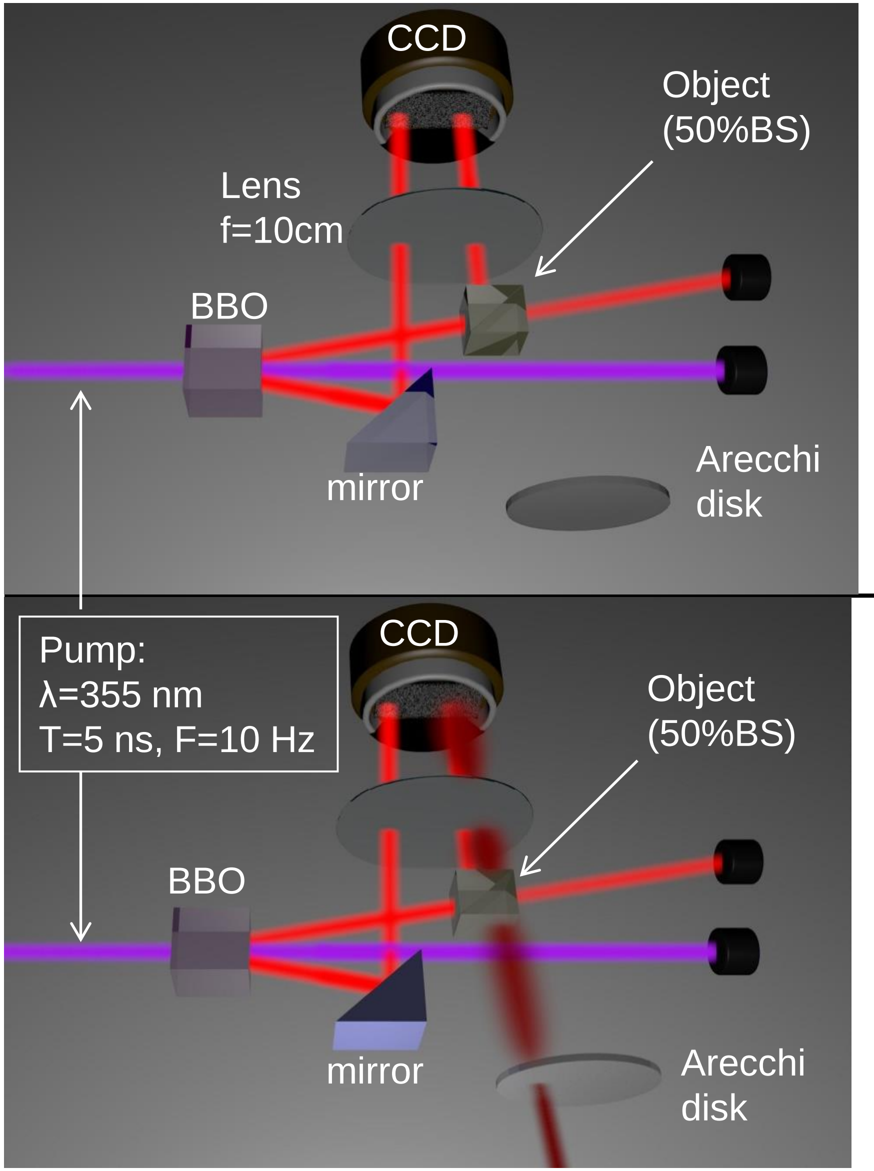
- ❑ **Source:** multimode parametric down conversion, number of photon per mode $\mu \ll 1$
- ❑ **Noise:** the most general multi-thermal bath
- ❑ **Receiver: is a CCD camera used as a photon number counter.**
- ❑ **Strategy: measuring the correlation between the photon numbers distribution N_1 , N_2 of the two beams.**
- ❑ **Hypothesis:** no a priori information on the thermal bath-> the first order momenta of the distribution (mean values $\langle N_1 \rangle$, $\langle N_2 \rangle$) are not informative
- ❑ **Object:** neither information on the reflectivity of the object nor on the position.

- ✓ Exponential enhancement! ☺
- ✓ Extremely robust against noise and losses!☺
- ✓ Quantum correlations “hidden” (above the standard quantum limit)!☺

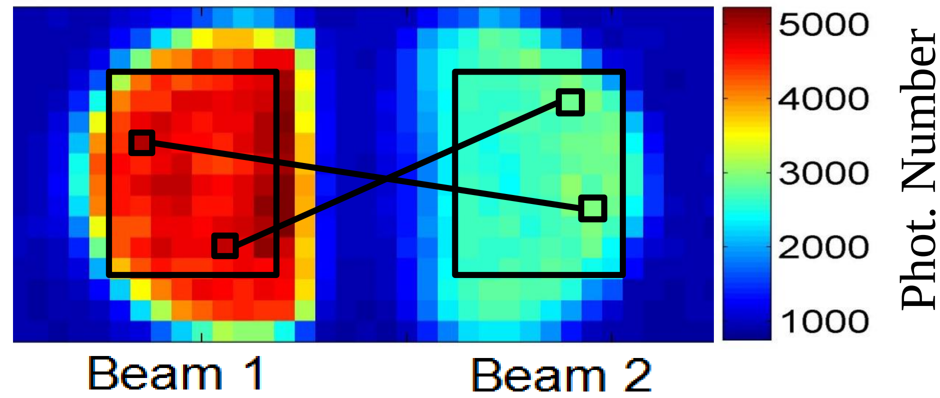
Go To Experiment!



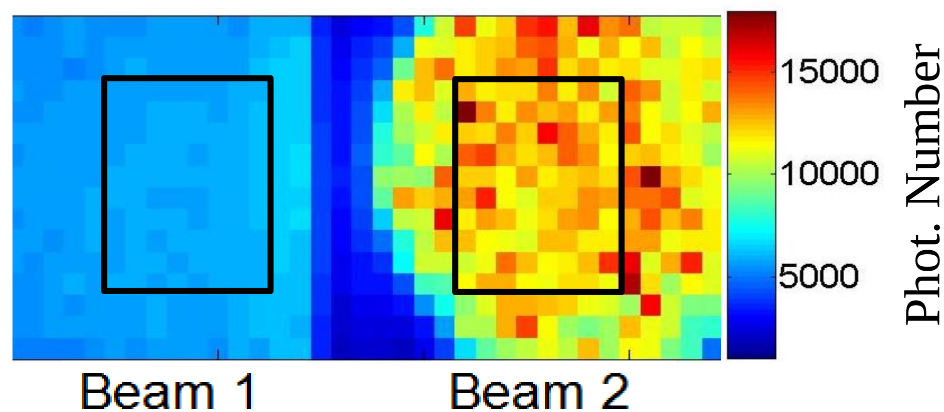
Experimental set up: Quantum



Interf. Filter **λ=710±5 nm**; thermal bath **off**

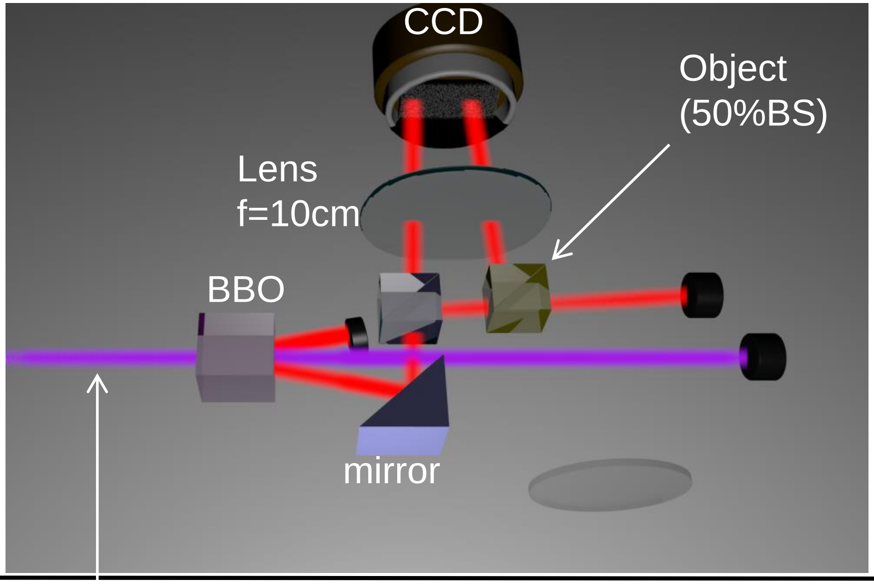


No narrow filtering; thermal bath **on** --> **measurement condition**

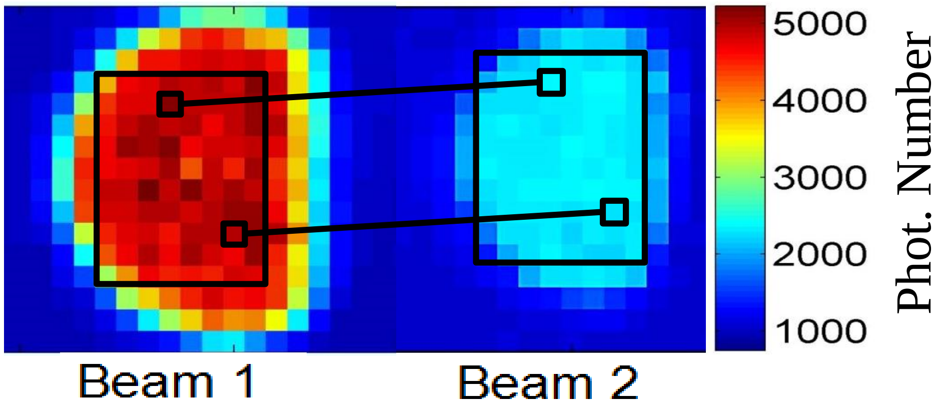


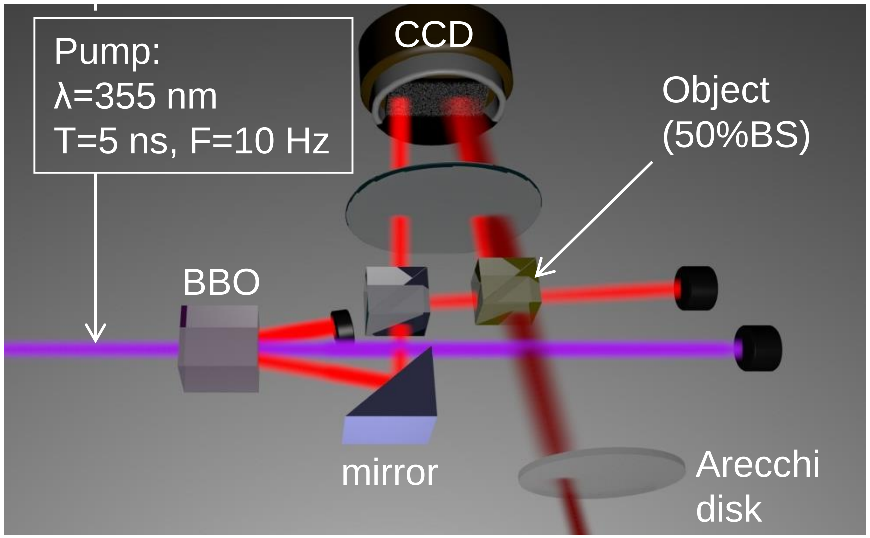
Brida, Genovese, Ruo Berchera, Nat. Phot. 4, 227 (2010)
G.Brida *et al.*, Phys. Rev. A 83, 063807 (2011).

Experimental set up: Classical

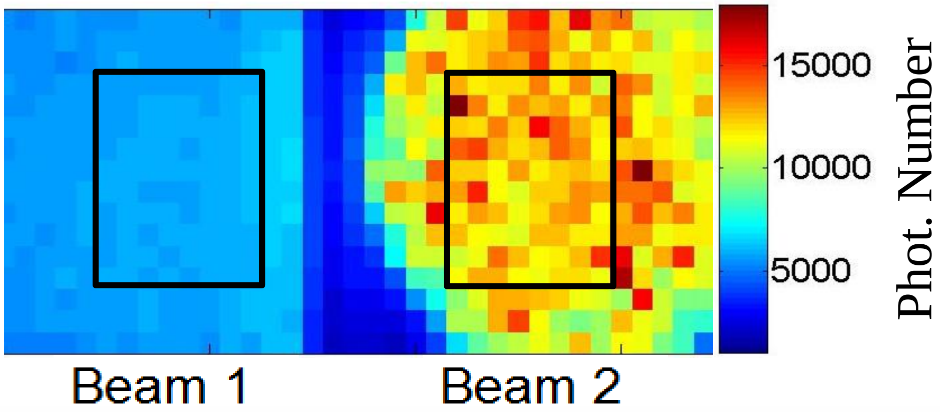


Interf. Filter **λ=710±5 nm**; thermal bath **off**



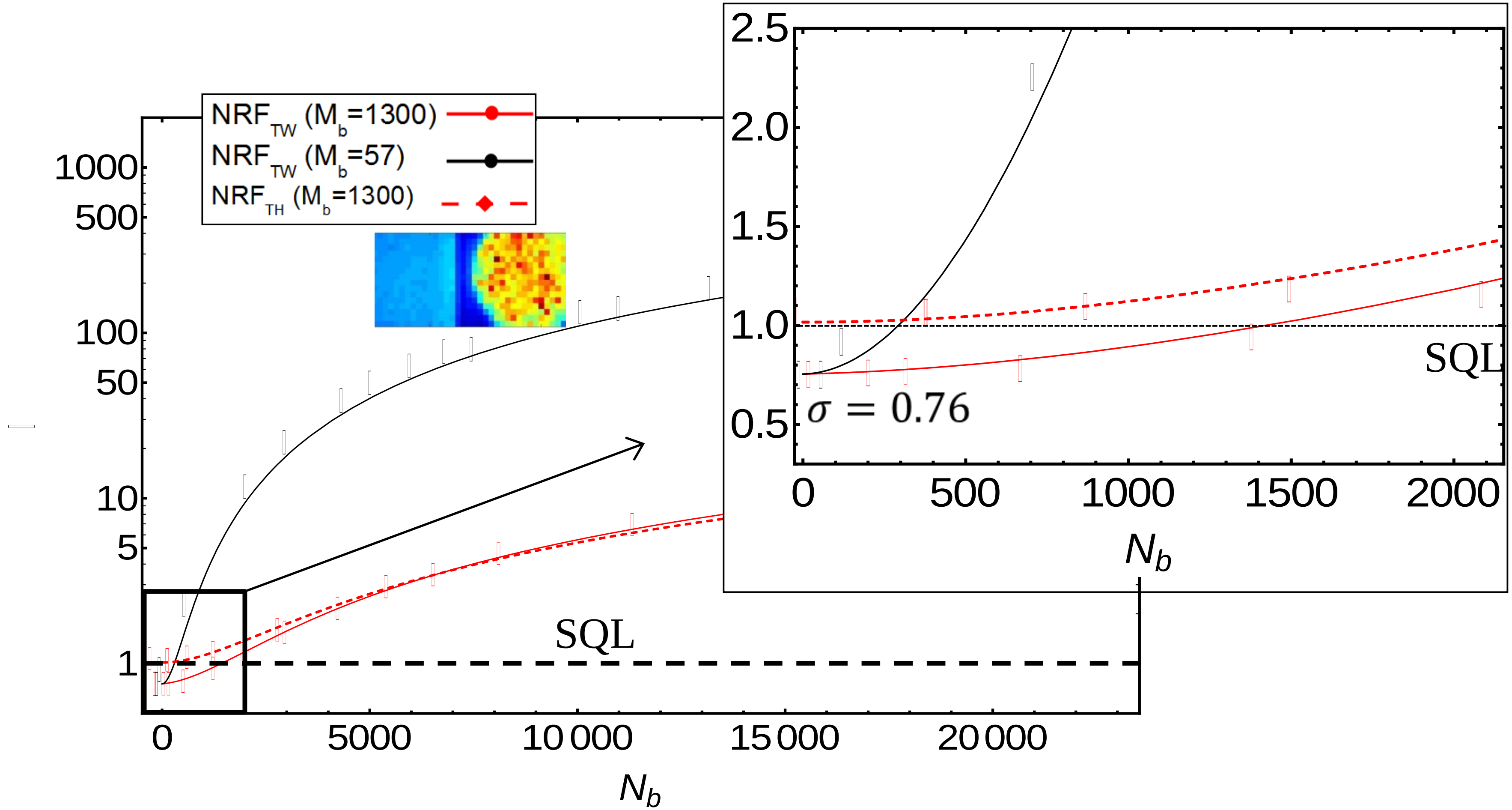


No narrow filtering; thermal bath **on** -->
measurement condition

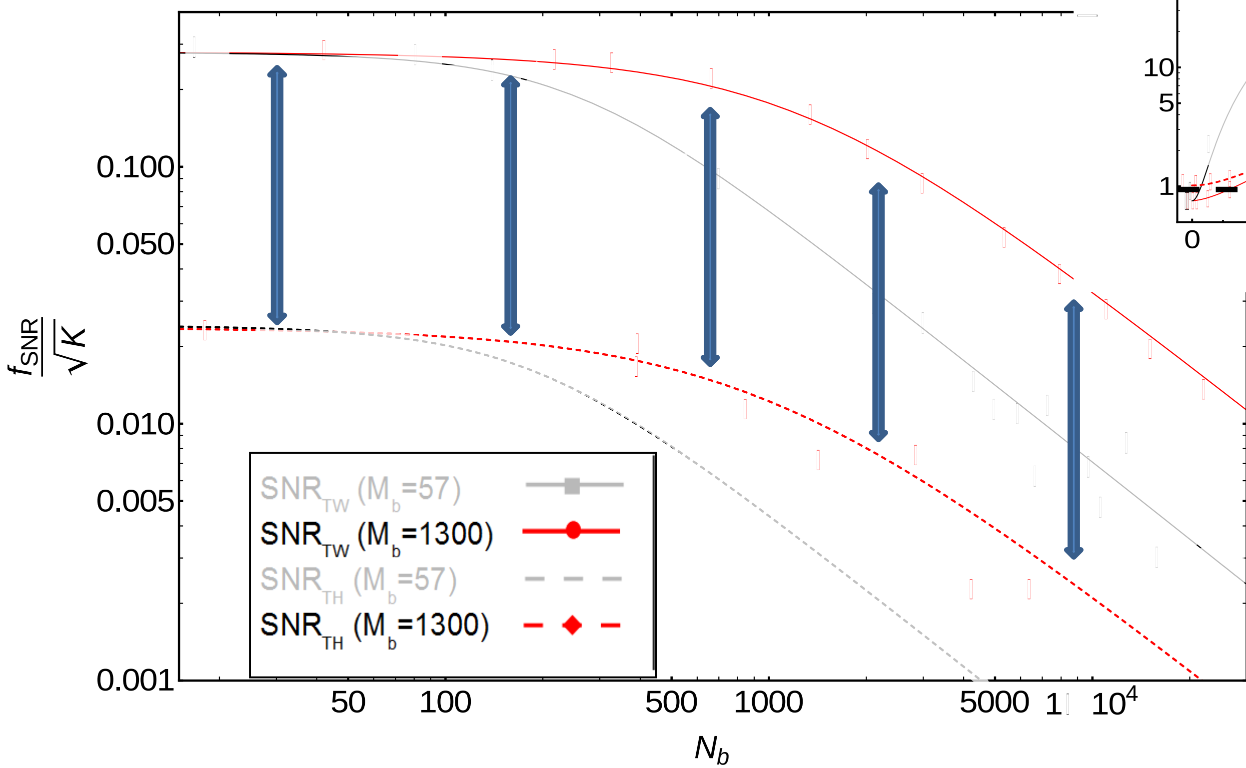


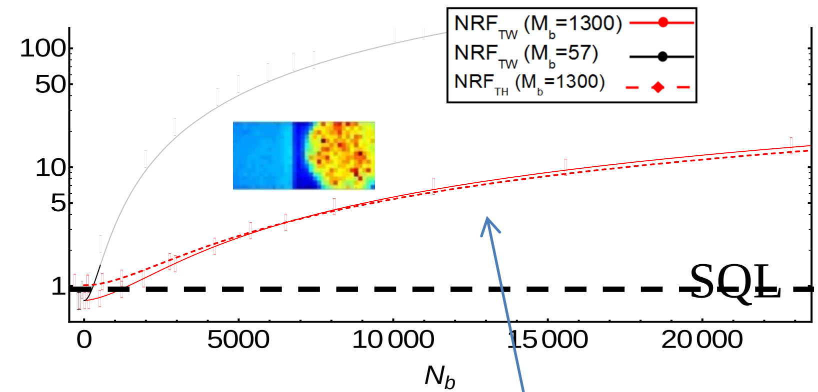
Sub-shot-noise correlations

$M = 9 * 10^4$ number of modes per pixel	$\eta_a = \eta = 0.4$ ancilla detection probability
$\mu = 0.075$ number of photons per mode	$\eta_2 = \eta\, \boldsymbol{r} = 0.4 \cdot 0.5 = 0.2$



Experimental results: signal-noise ratio



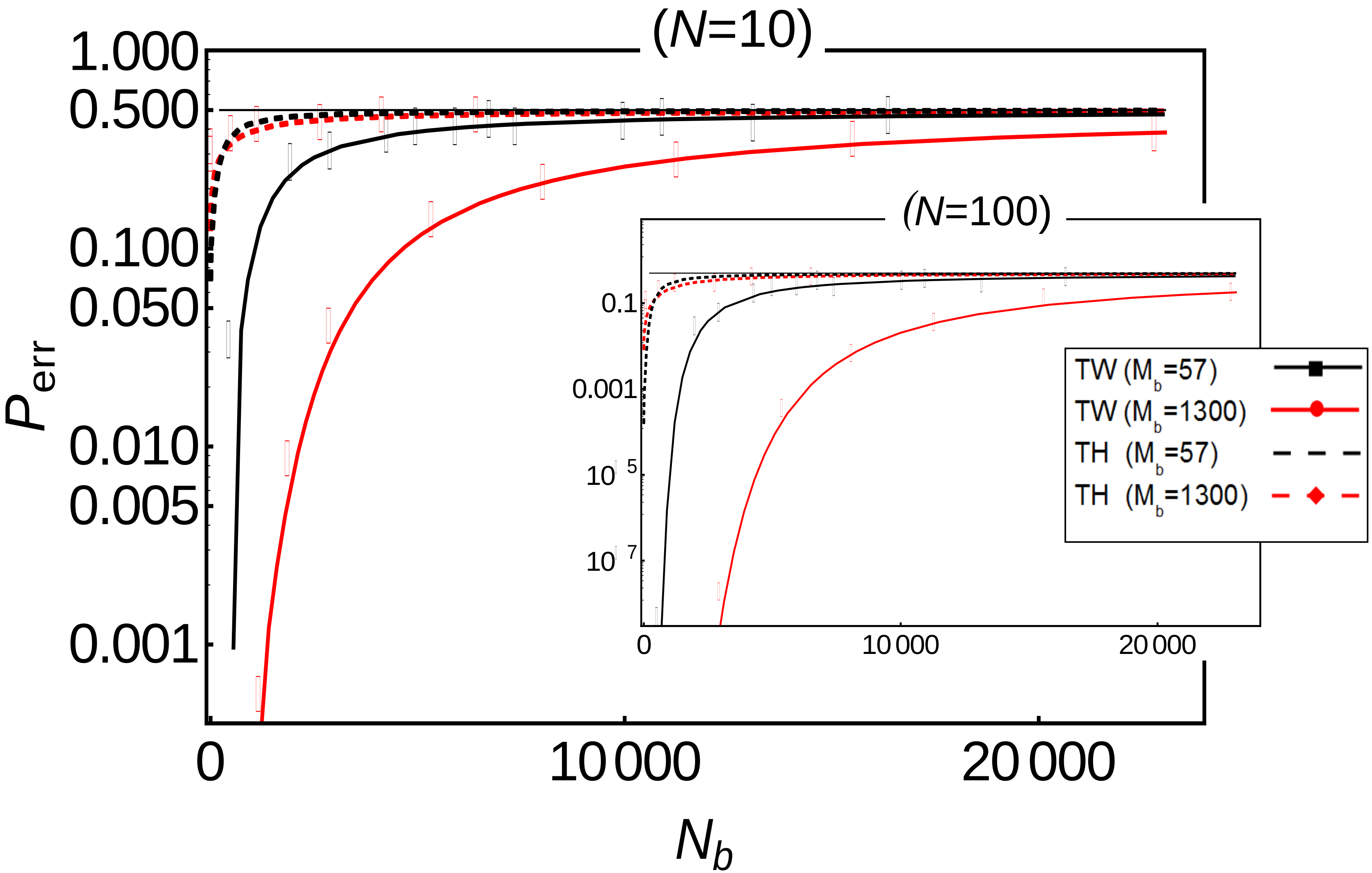


Even if the correlation are above the standard quantum limit...

$$\frac{f_{\rm SNR}^{(Tw)}}{f_{\rm SNR}^{(Th)}} \longmapsto \frac{(1+\mu)}{\mu} = \frac{(1+0.075)}{0.75} = 14$$

....more than one order of magnitude of quantum enhancement!!

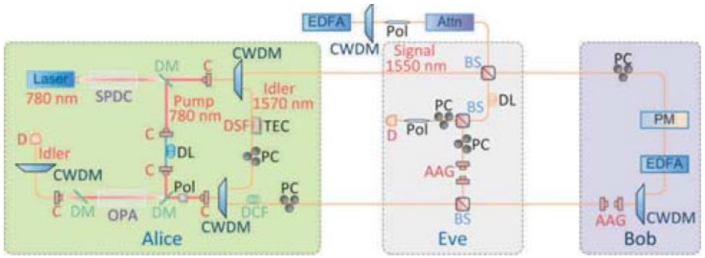
Experimental results: error probability



Further progresses:

- Which resource is really needed for this specific protocol ?
  [Ragy S 2014 JOSA B31 2045] improvement in the signal-to-noise ratio achieved by the quantum sources over the classically correlated thermal ones closely related to the respective **ratio of mutual informations of return and idler beams**

- Improved detection, albeit sub-optimal, combining the return and idler modes in a OPA. The method was applied to secure quantum communication [Z. Zhang et al., Phys. Rev. Lett. 111, 010501]



- Theoretical idea for an extension to microwave region [Barzanjeh S et al 2015 PRL 114 080503]

- ...

PRL **110,** 213601 (2013) PHYSICAL REVIEW LETTERS week ending 24 MAY 2013

Quantum Light in Coupled Interferometers for Quantum Gravity Tests

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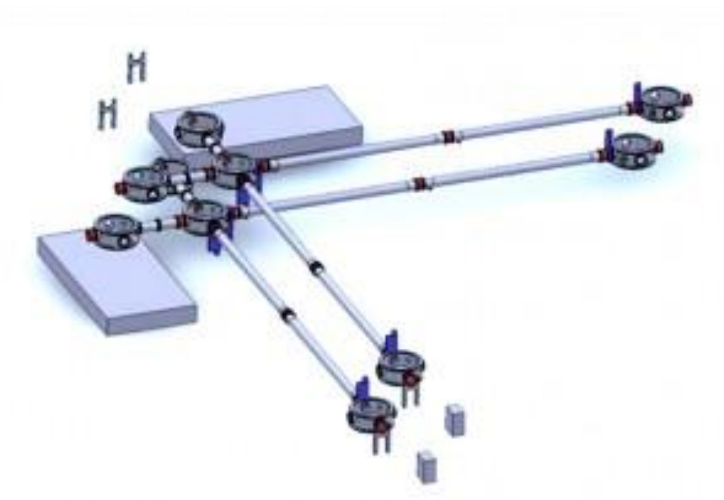
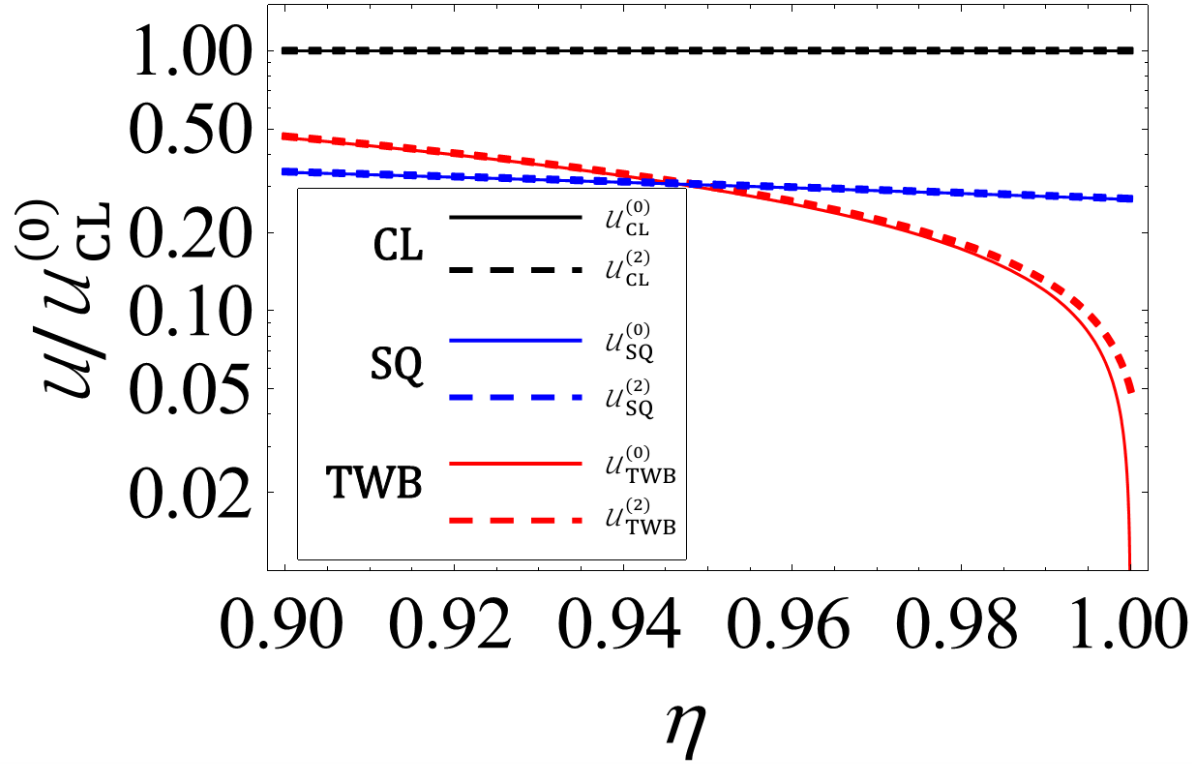
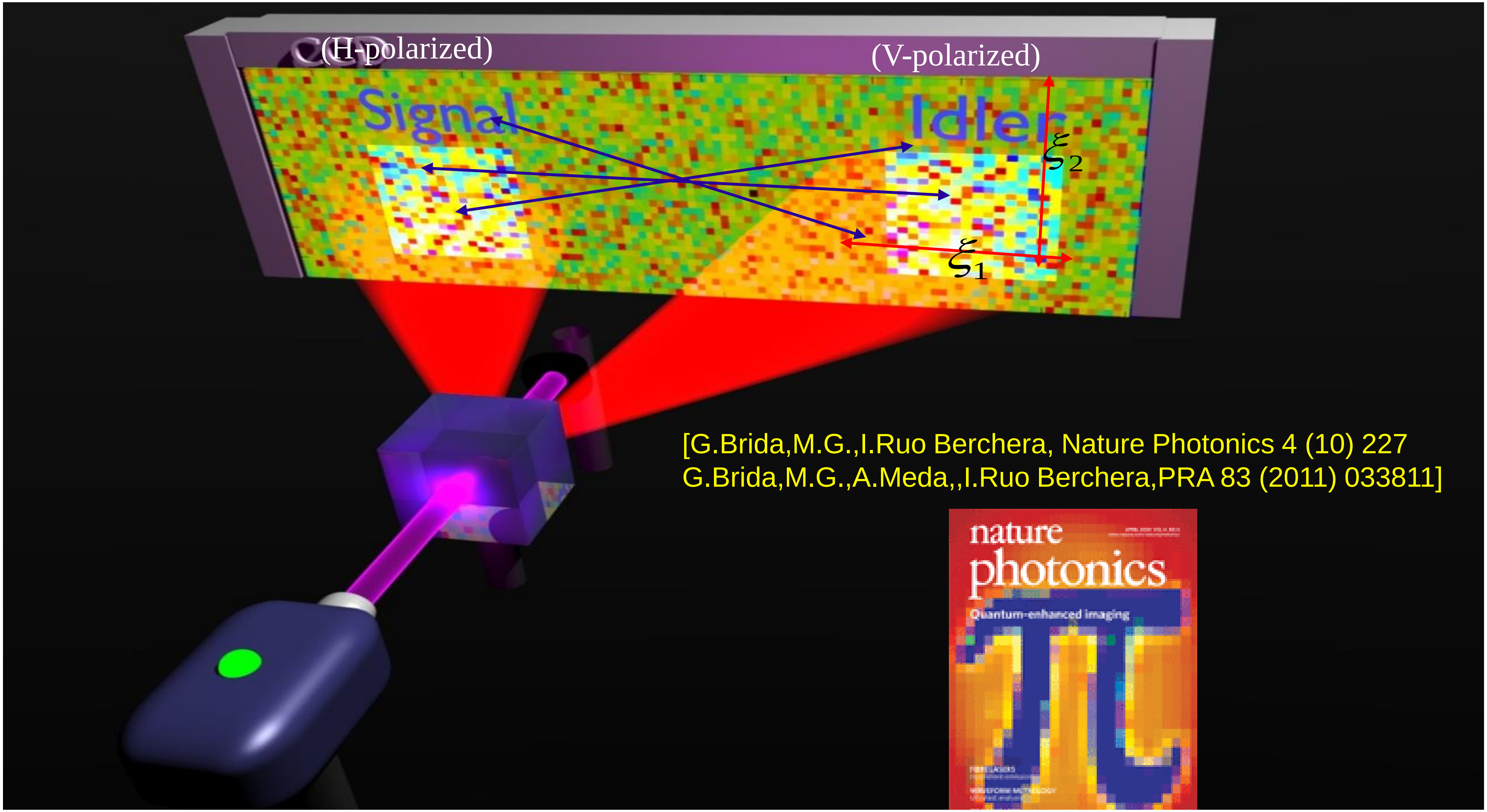


The holometer



Sub shot noise quantum imaging

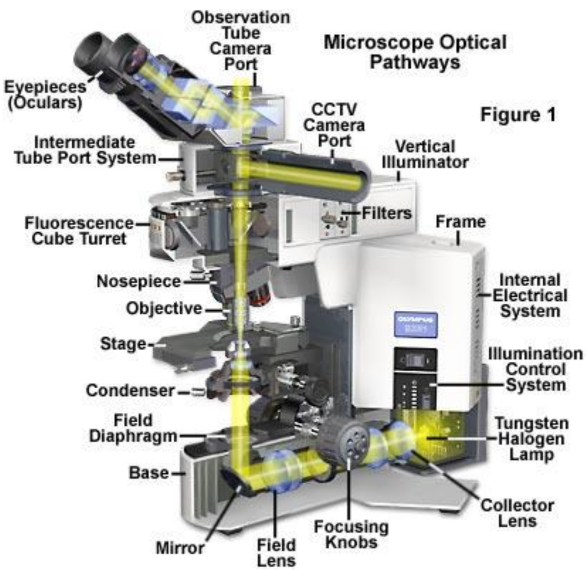


[G.Brida,M.G.,I.Ruo Berchera, Nature Photonics 4 (10) 227
G.Brida,M.G.,A.Meda,,I.Ruo Berchera,PRA 83 (2011) 033811]

Sub Shot Noise Wide Filed Microscope

What biologists say about Live-cell imaging?

“The wavelength of illuminating light, and the total photon dose that the cells are exposed to, comprise two of the most important and controllable parameters of live-cell imaging. **The lowest photon dose that achieves a measureable metric for the experimental question should be used**, not the dose that produces cover photo quality images. This is paramount to ensure that the cellular processes being investigated are in their in vitro state and not shifted to an alternate pathway due to environmental stress.”



What biologists say about wide-field imaging?

“If the specimen is a monolayer then wide-field microscopy **(WFM) is almost always a better choice than a confocal laser scanning microscope** (CLSM).”

“This is the simplest, least expensive, and oldest imaging modality used for live-cell imaging. **It has the advantage of requiring the lowest photon dose, especially for transmitted light imaging”**…

(and is fast → dynamic imaging)

[R. Cole, Live-cell imaging: The cell’s perspective, Cell Adh. Migr. 8 (5) (2015) 452–459]

SSN WFM- quantum enhanced WFM requirements

Quantum enhanced imaging can improve the sensitivity /photon
→ more information at the same photon flux, but….

Thousands pixels involved

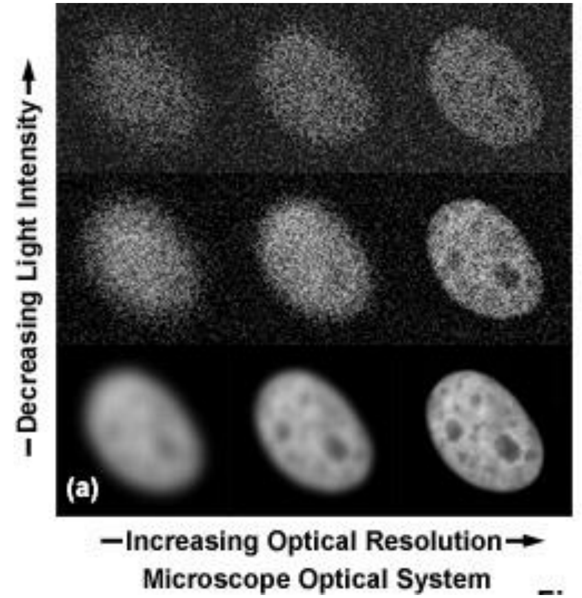
Thousands of spatial modes with non-classical features

Enhanced Signal-to-noise ratio (SNR) for each pixel

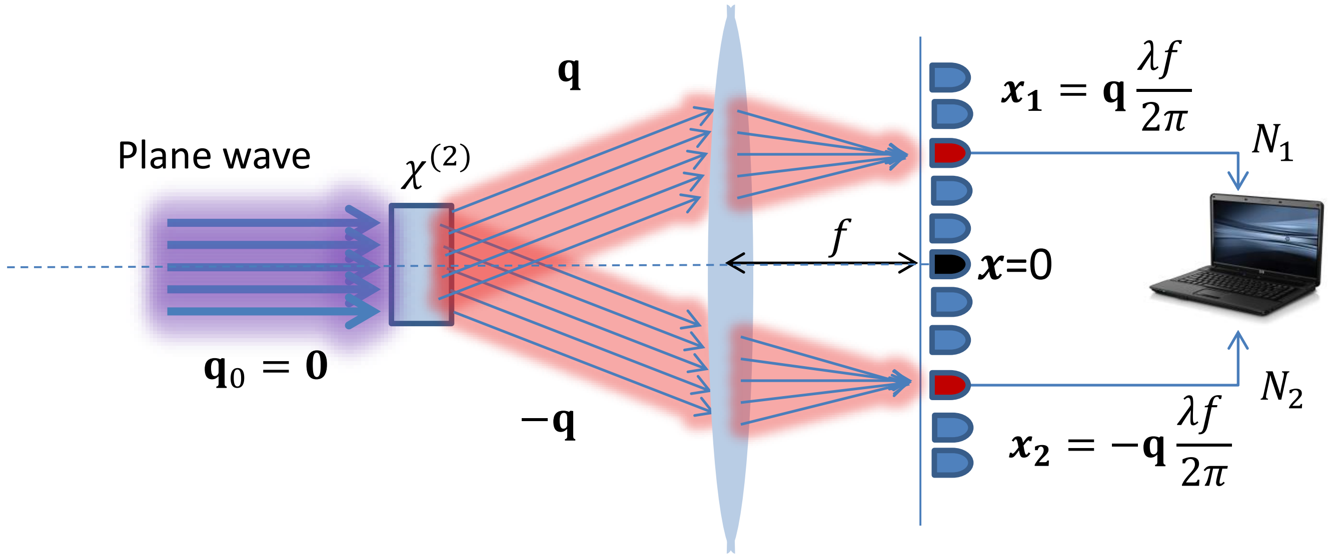
Each pixel detecting efficiently n>1 modes

Microscopic spatial resolution: $(\sim 1\mu m)$

Mode size of the order of $1\mu m$ in the object plane



SSN WFM- Spatial multi-mode correlations



Degenerate λ

$$\boldsymbol{x}_{CS} = \frac{\boldsymbol{x}_1 + \boldsymbol{x}_2}{\mathbf{2}} = \mathbf{0}$$

- Travelling wave PDC is broadband both in time frequency (λ) and spatial frequency ($\mathbf{q}$)
- Transverse momentum conservation $\mathbf{q}_0 = \mathbf{q}_1 + \mathbf{q}_2$ implies photon pairs propagate along correlated directions.
- In the Far Field plane waves are focused in points → Two point-like detectors would detect perfect two-modes quantum correlation (both in low and high gain regime)

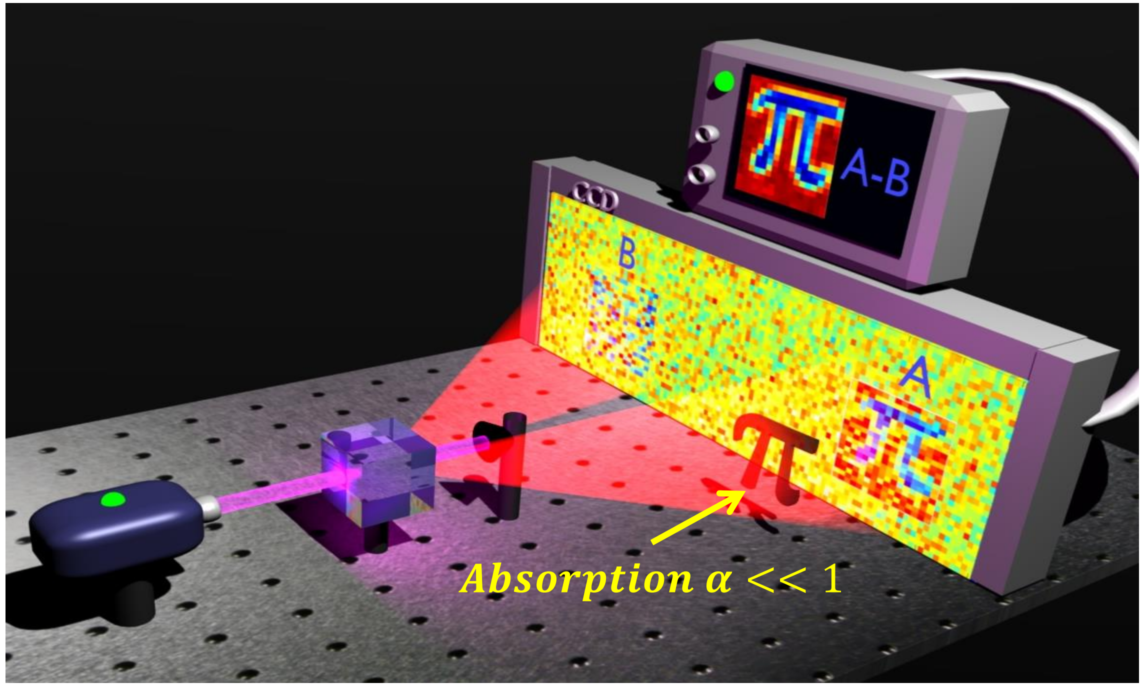
$$\sigma = \frac{Var(N_1 - N_2)}{\langle N_1 + N_2 \rangle} = 1 - \eta < 1$$

NON-CLASSICAL

SSN WFM- the scheme

The number of photon detected by each pixel in «A» equals the number of photon measured in its symmetric pixel in «B»
Placing an object in one branch, the noise on the image can be removed by subtracting the noise pattern on the other branch

E. Brambilla, L. Caspani, O. Jedrkiewicz, L. A. Lugiato, and A. Gatti, PRA 77, 053807 (2008)



$\alpha << 1$

$$\delta\alpha = \frac{\sqrt{\langle \delta^2 N_- \rangle}}{|\partial_\alpha \langle N_- \rangle|} \approx \sqrt{\frac{1}{\eta \langle n \rangle}}\sqrt{2\sigma}$$

Sensitivity in absorption measurement

$$\sigma = \frac{Var(N_1 - N_2)}{\langle N_1 + N_2 \rangle} = 1 - \eta < 1$$

Noise reduction factor

- $\sigma < 0.5$ allows beating shot noise limited direct (one path) classical imaging

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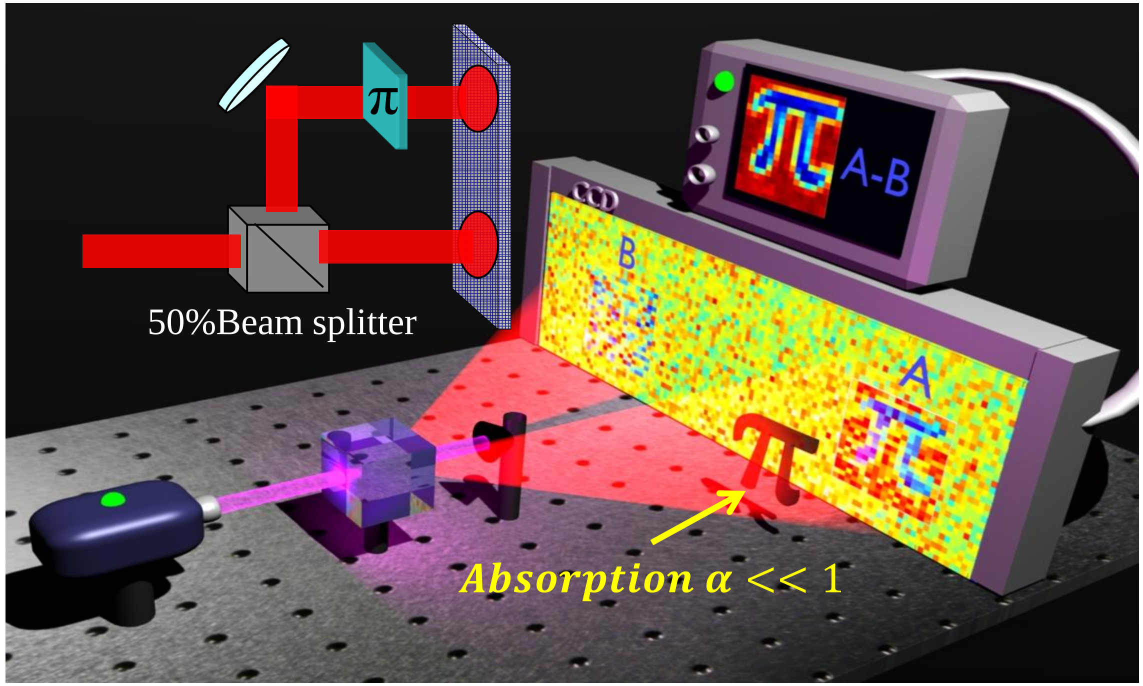


$F = 1, \alpha << 1$

$$\delta\alpha = \frac{\sqrt{\langle \delta^2 N_- \rangle}}{|\partial_\alpha \langle N_- \rangle|} \approx \sqrt{\frac{1}{2\,\eta\langle n\rangle}}\sqrt{2\sigma}$$

Sensitivity in absorption measurement

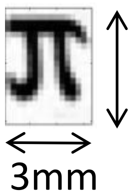
$$\sigma = \frac{Var(N_1 - N_2)}{\langle N_1 + N_2 \rangle} = 1 - \eta < 1$$

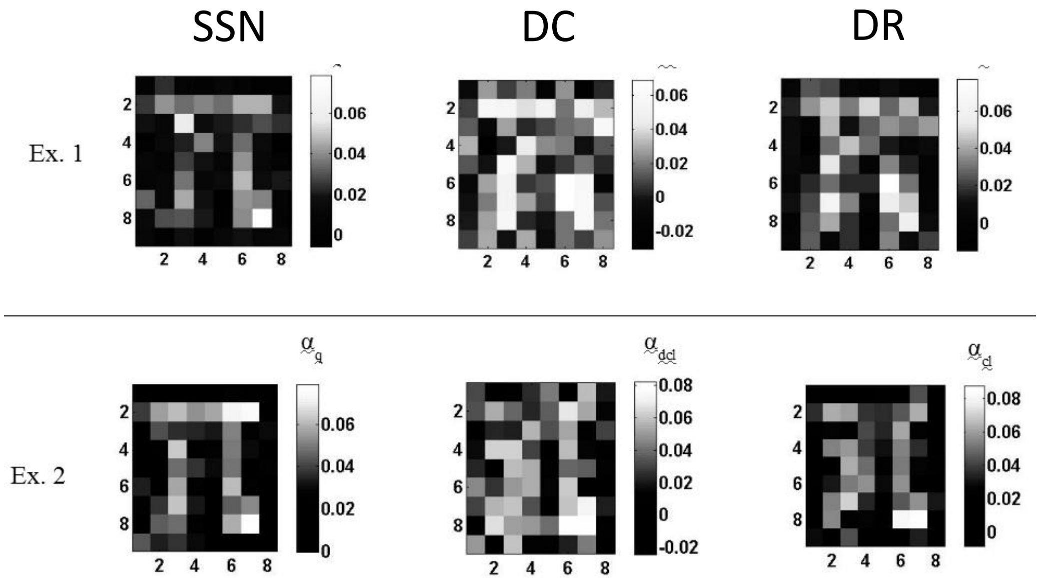
Noise reduction factor

- $\sigma < 0.5$ allows beating shot noise limited direct (one path) classical imaging
- $\sigma < 1$ allows beating differential classical imaging (always)

SSN WFM - First proof of principle in 2010

G. Brida *et al*, Nat. Phot. **4**, 227 (2010). PRA **83**, 033811 (2011)

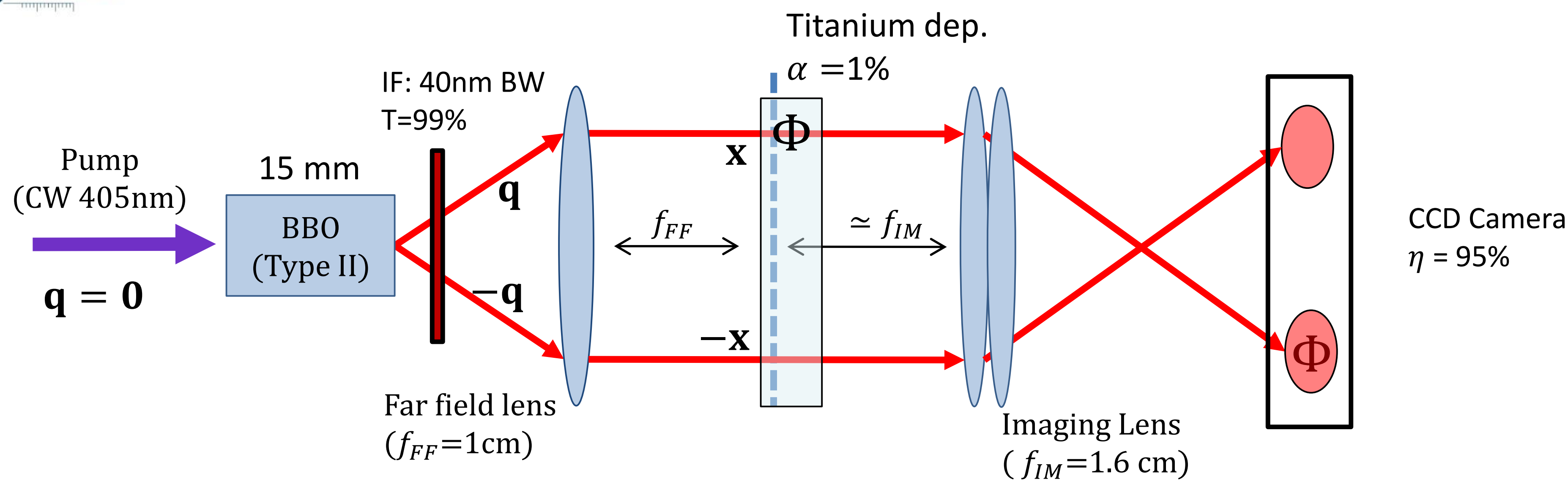


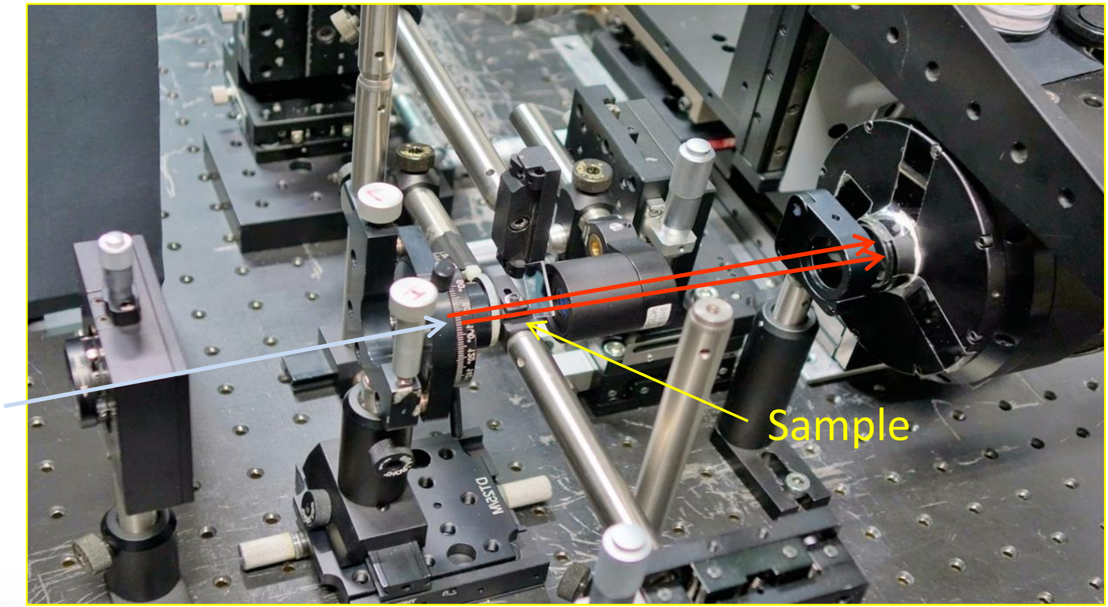


- Number of pixels 9 x 8 = 72 pixels
- Resolution 480 μm
- Noise reduction Factor for each pixel $\sigma \lesssim 0.5$

Not so exciting for real world applications…

SSN WFM - NEW experimental Setup

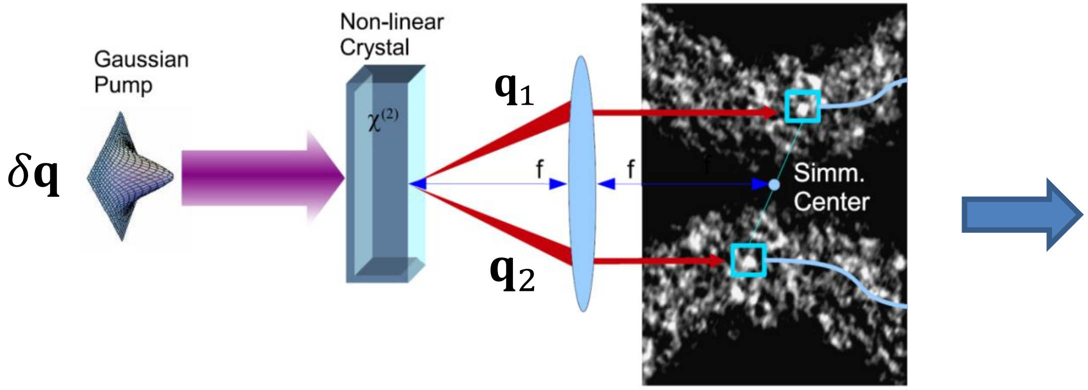




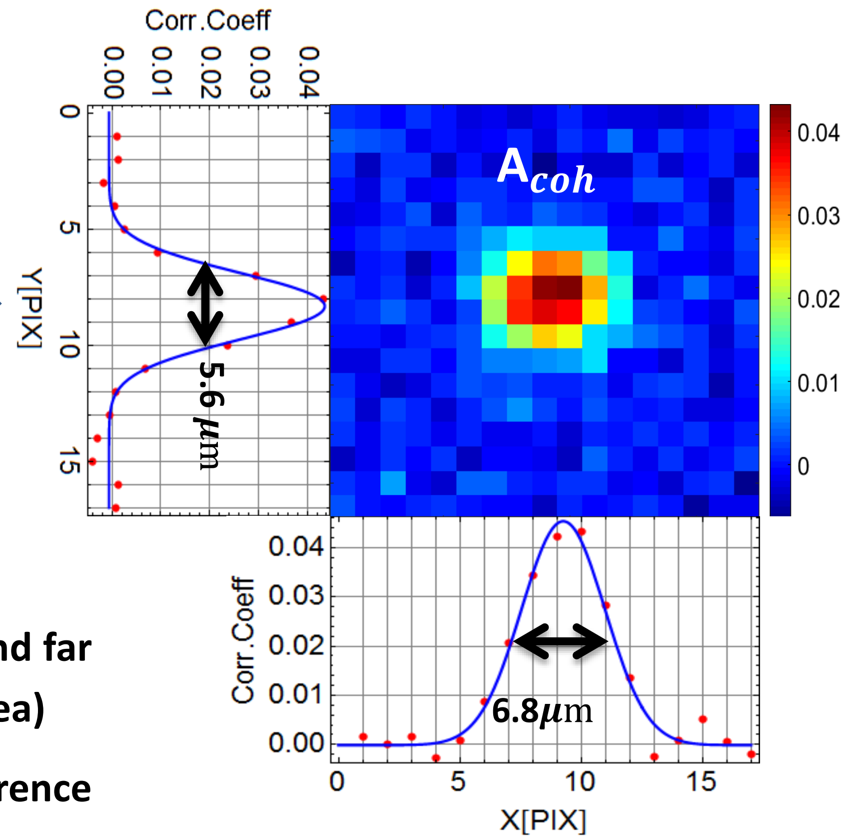
"Realization of the first sub-shot-noise wide field microscope",N. Samantaray, I.Ruo-Berchera, A.Meda, M,Genovese; Light: Science & Applications-Nature group (2017) 6, e17005; doi: 10.1038/lsa.2017.5.

SSN WFM - Resolution

Spatial coherence of the correlations = RESOLUTION



$$\mathbf{q}_1+\mathbf{q}_2 = \mathbf{0} \pm \delta\mathbf{q}$$

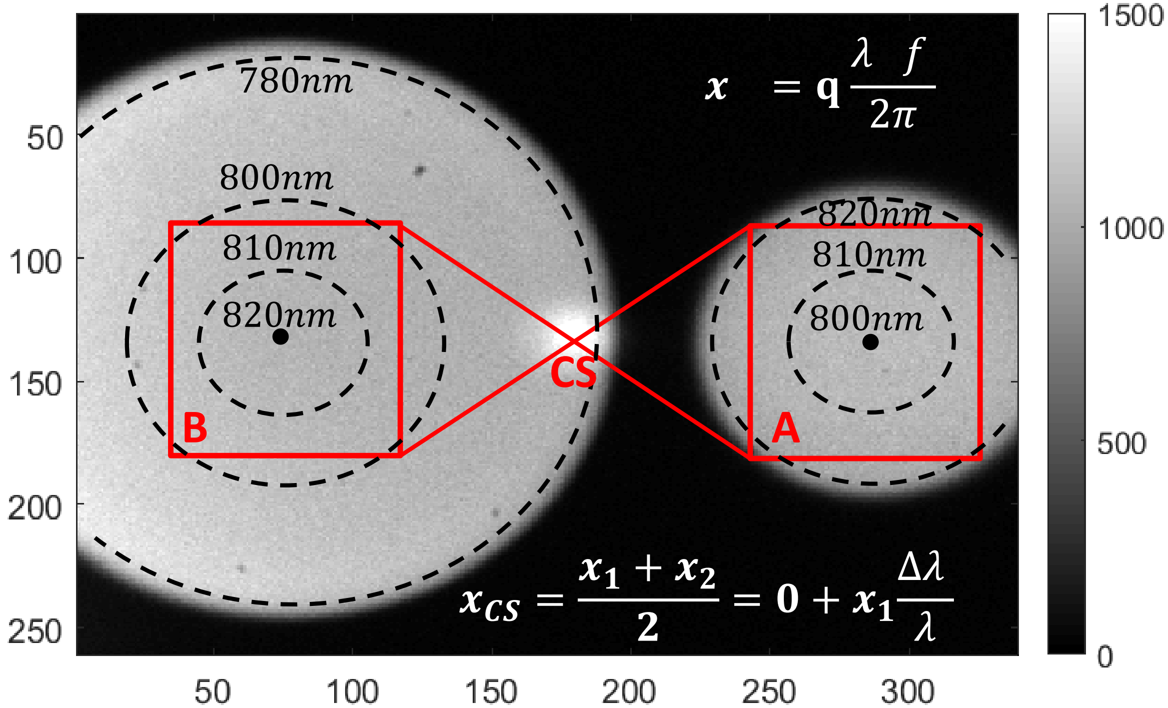


Uncertainty in the relative propagation direction and far field positions of correlated photons (coherence area)

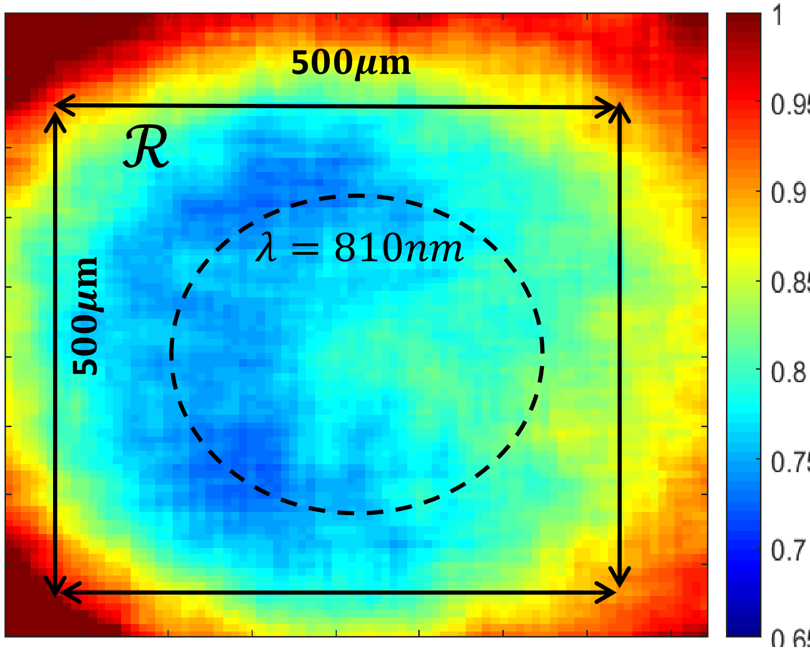
Pixels must be larger than the correlation coherence area $\mathbf{A}_{coh}$

Spatial resolution around 5 μm

Camera view of PDC emission (40nm spectral BW)



NRF 2-D map

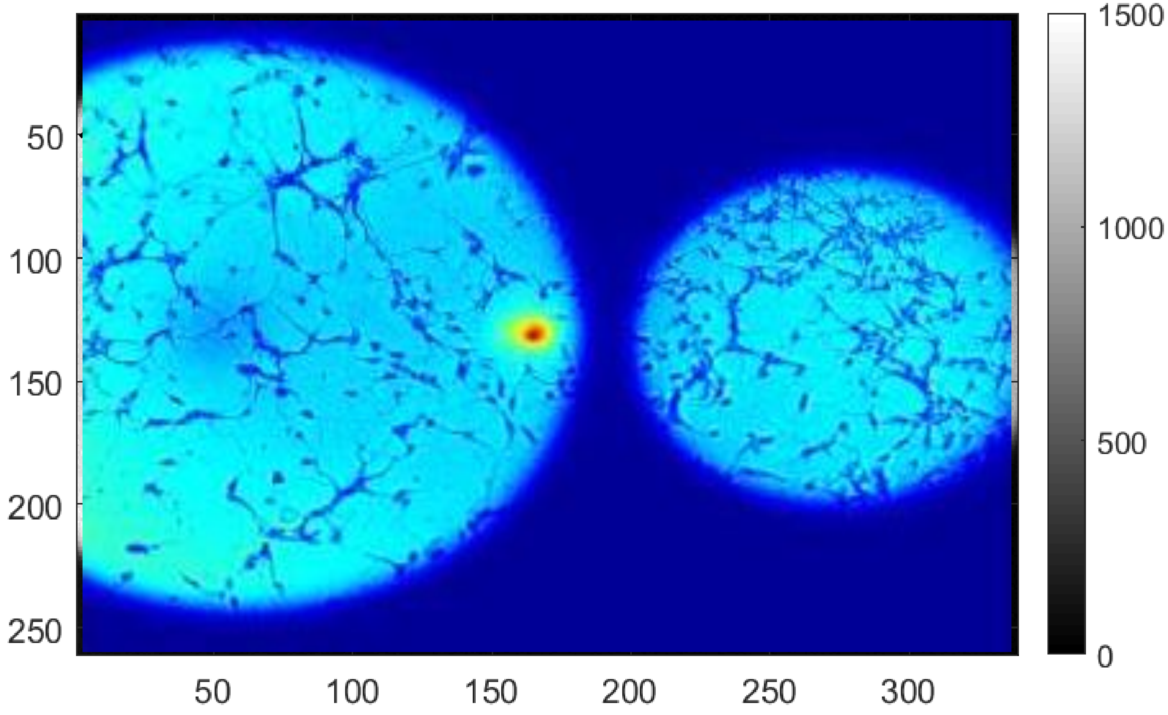


Field of view limited by the necessity to stay close to degenerate λ, in a range of $\Delta\lambda$ <40 nm → $\mathcal{R} = (500\mu\mathrm{m})^2$. Misalignment of pixel far from degeneracy deteriorate the NRF

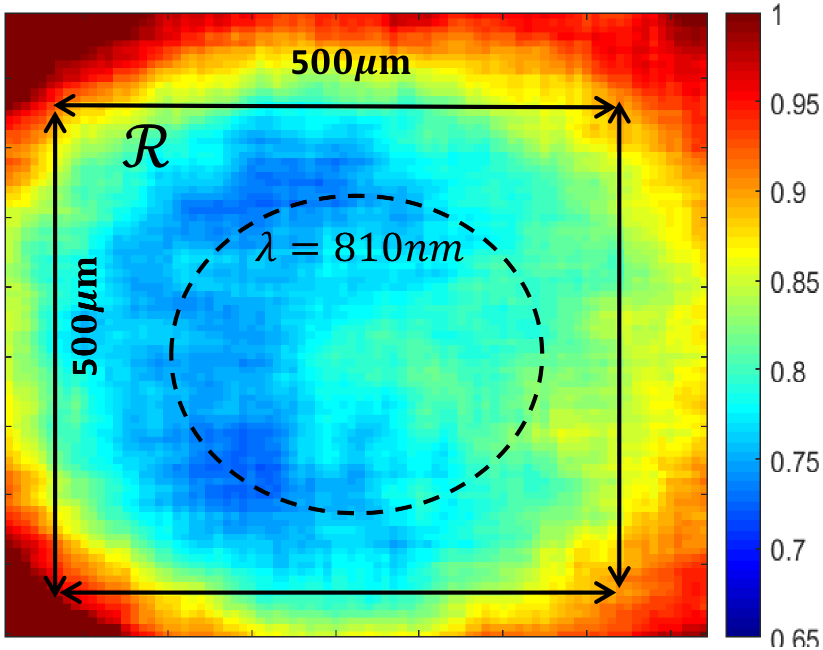
NUMBER of SPATIAL MODE AVAILABLE IS $\mathcal{R}$ / A_{coh}~8000 !!

SSN WFM - Number of spatial modes

Camera view of PDC emission (40nm spectrlal BW)



NRF 2-D map



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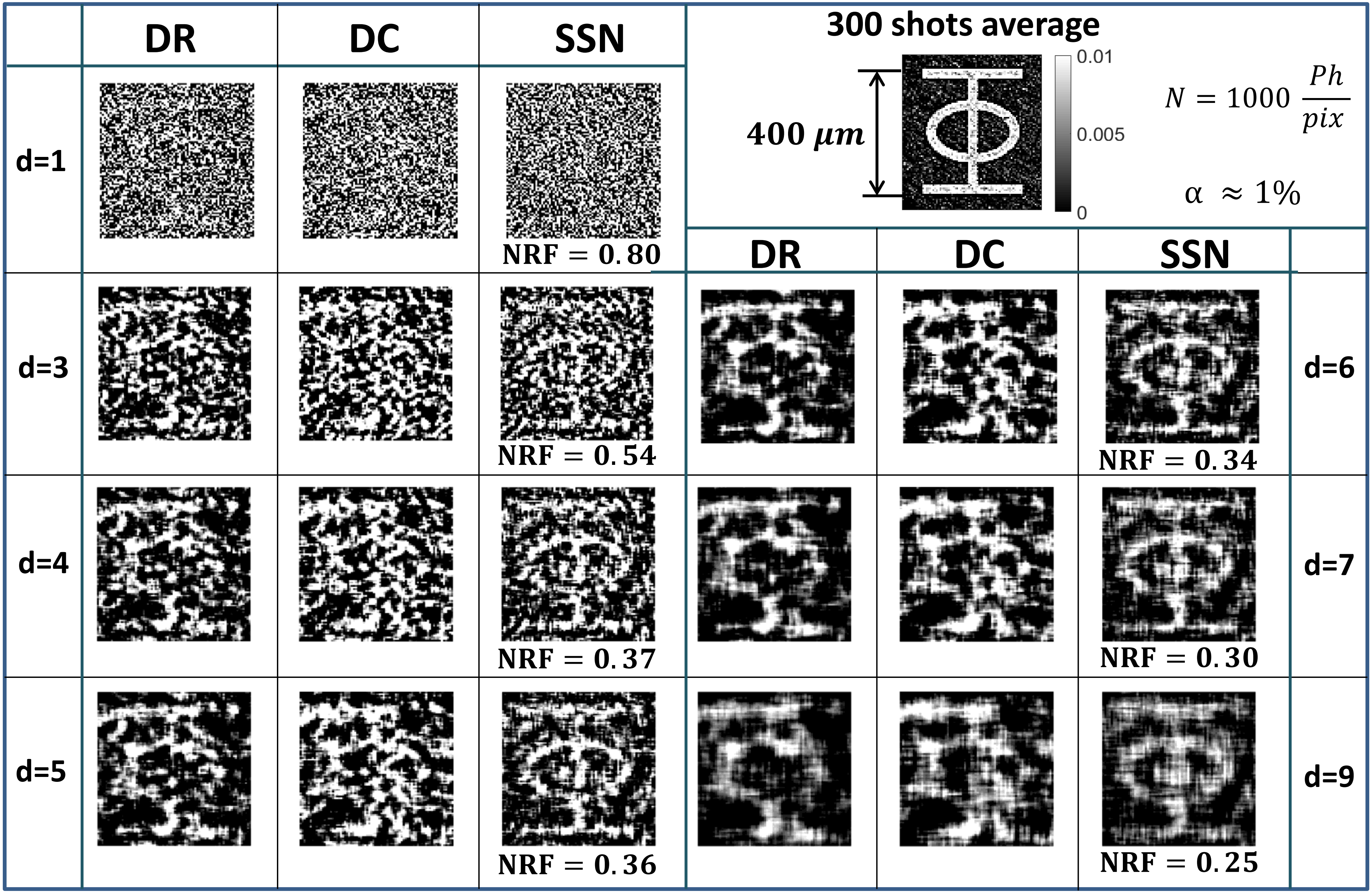
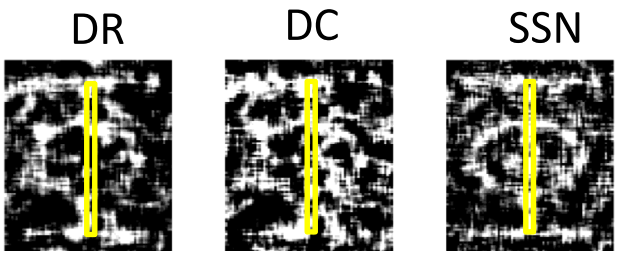


DR
DC
SSN
300 shots average
400 μm
0.01
0.005
0
N = 1000 Ph/pix
α ≈ 1%
d=1
NRF = 0.80
DR
DC
SSN
d=3
NRF = 0.54
d=6
NRF = 0.34
d=4
NRF = 0.37
d=7
NRF = 0.30
d=5
NRF = 0.36
d=9
NRF = 0.25

SSN WFM - Results - Signal-to-Noise Ratio (SNR)

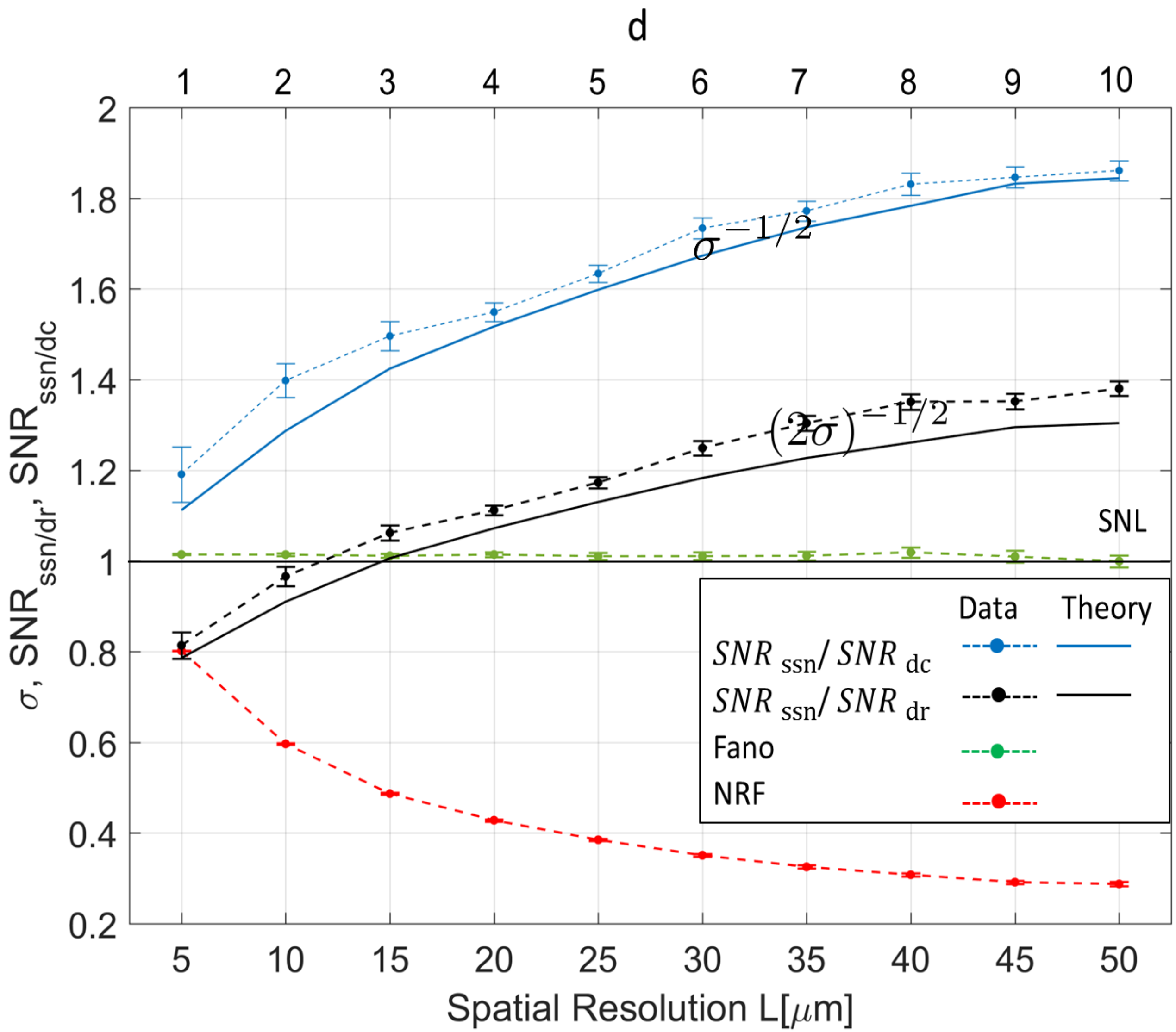


Theoretical expectation:

$$\frac{SNR_{ssn}}{SNR_{dr}} = (2\sigma)^{-1/2}$$

$$\frac{SNR_{ssn}}{SNR_{dc}} = \sigma^{-1/2}$$

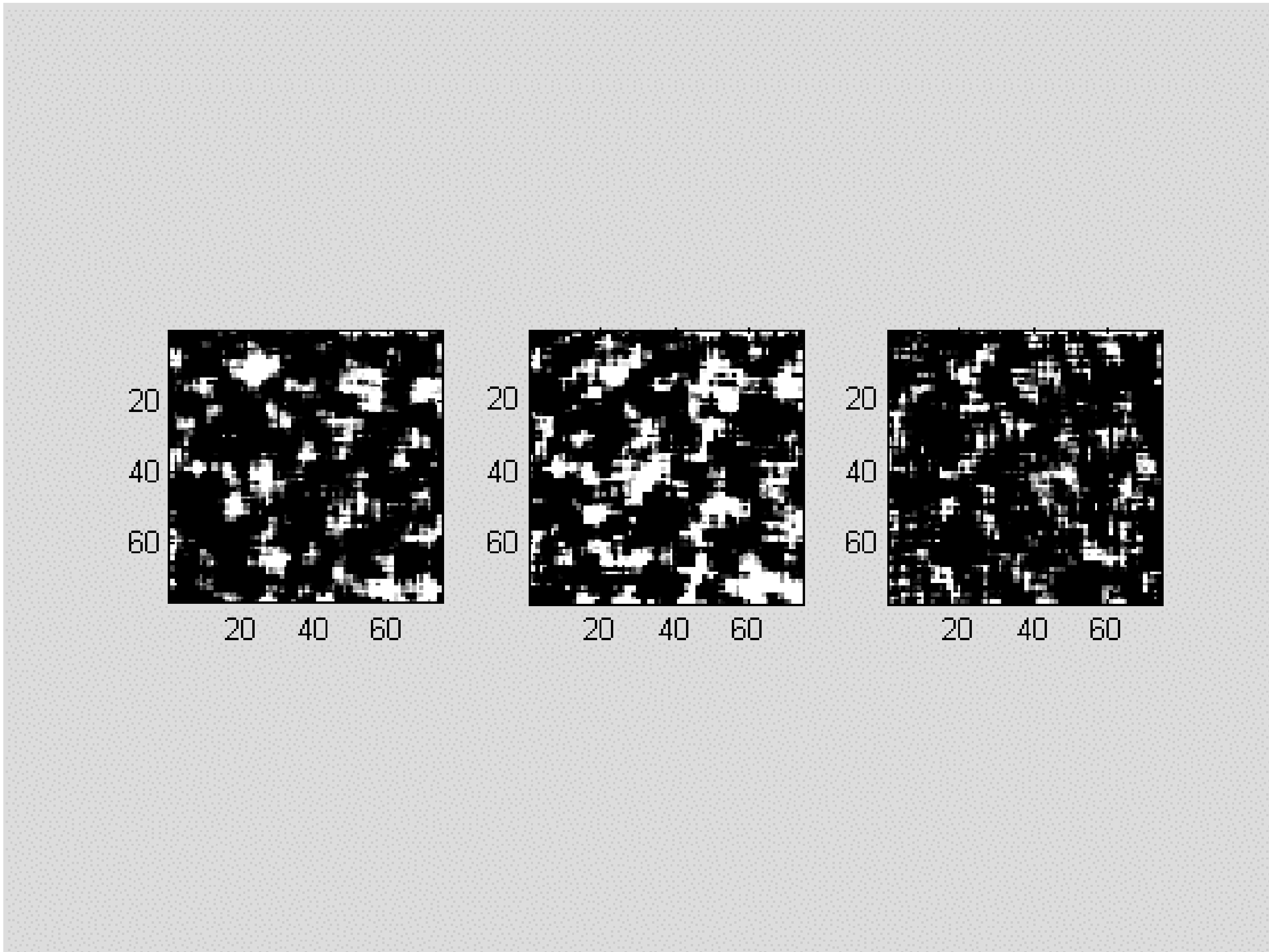
Noise reduction reaches less than 30% of the SN and the SNR enhancement reaches 80% more than DC imaging and 40% more than DR imaging



- With present camera settings and photon flux available in our experiment:

single frame exposure time is 100 ms and read-out time is few hundreds ms

- Up to $10^2 frames/sec$ is possible improving photon flux and camera read-out speed (controlling electronic read noise) ***The first sub-shot noise movie!***



Dynamic, real time imaging of complex structures is possible

REMARKS

- ✓ Wide-field microscopy (WFM) , especially at low illumination, is important.
- ✓ Sub-shot- noise WFM in a matrix of 8000 pixels and resolution of 5μm has been realized (sufficient for imaging of complex structures)
- ✓ Quantum enhanced median filter has been introduces with improves the standard post processing noise rejection capabilities
- ✓ SNR exceeding classical one by 40% (respect to DR) and 80% (respect to DC)

PERSPECTIVES

- ➢ To reduce the coherence area to 1μm
- ➢ Use the microscope in biological or applicative context
- ➢ Increase the photon flux (pulsed, middle/high gain regime)
- ➢ Application of the technique to other protocols:
- • Enhanced ghost imaging [Brida *et al.* PRA, 83, 063807 (2011)
- • Environmental noise rejection [Lopaeva *et al.* PRL 110 (2013) 153603, Morris *et al.* Nat. Comm. 6 (2015)].
- • Few photon stimulation (retina response characterization, [Phan *et al.* PRL, 112 (2014)] Absolute calibration of spatially resolving detector [Meda *et al.* APL (2014)]

Conclusions

Quantum photon number correlations: a fundamental tool for quantum imaging & sensing