Skipper-CCD for quantum microscopy: status and plan

Agustina G. Magnoni

March 19th, 2021

Collaboration between the Fermi Accelerator National Laboratory (**Fermilab**) the Physics Department at Universidad de Buenos Aires (**UBA**)

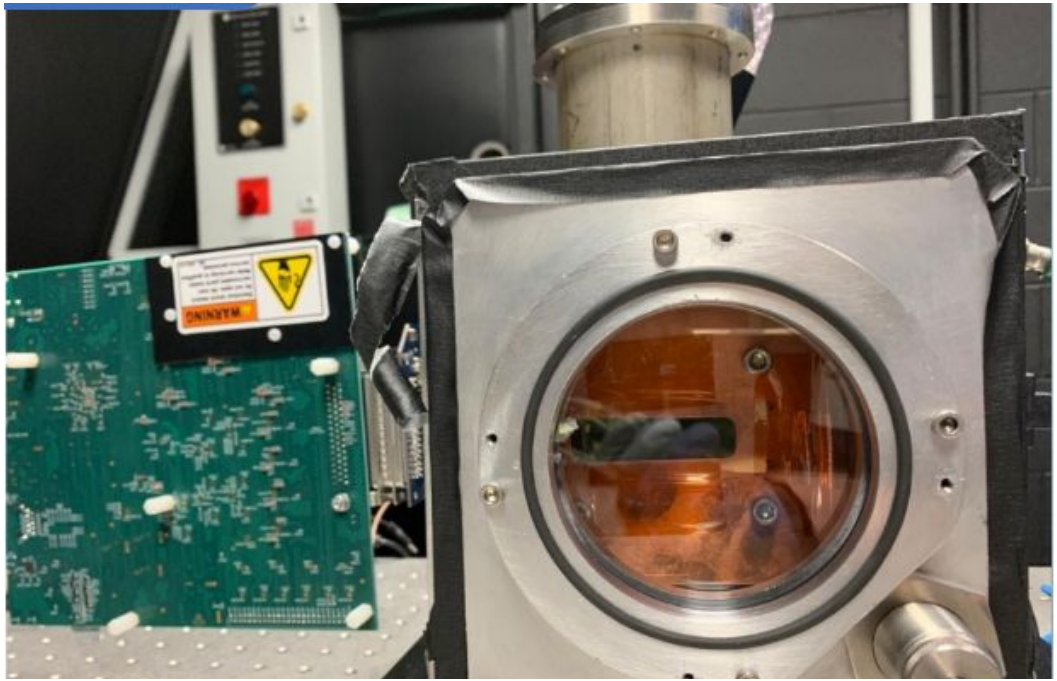
Fermilab

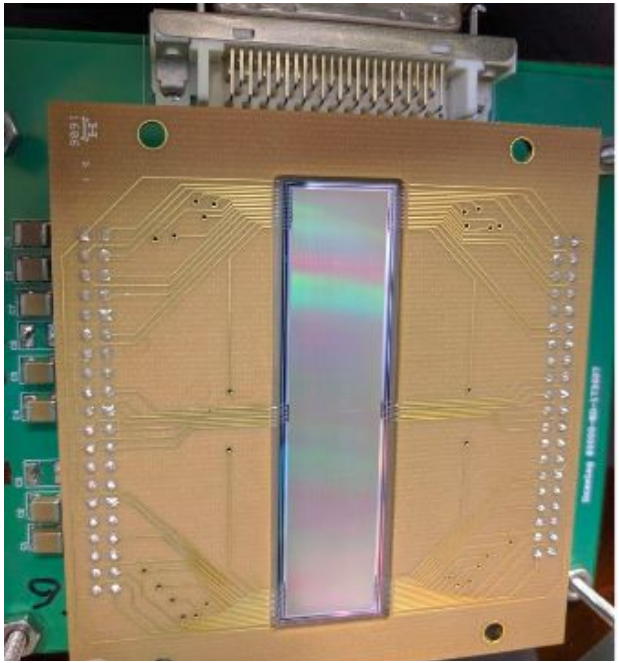
universidad de buenos aires - exactas
departamento de física

CITEDEF

Skipper CCD

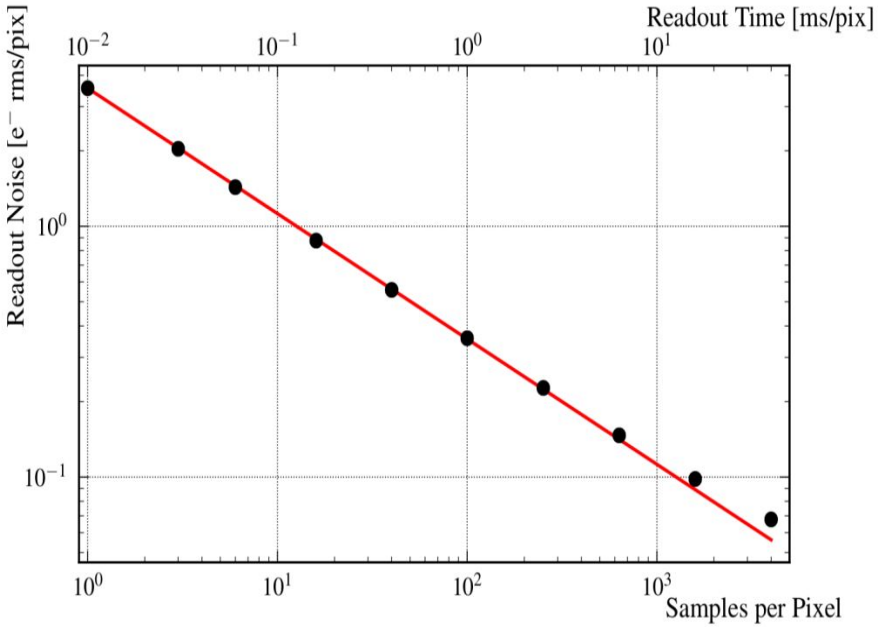
Skipper CCD



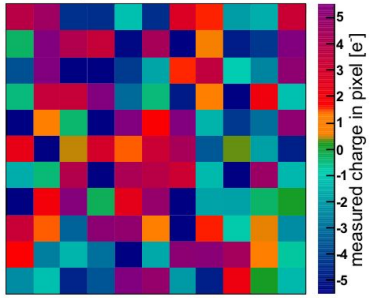


Technology developed for Dark Matter Searches (SENSEI)
in collaboration with Berkeley Lab

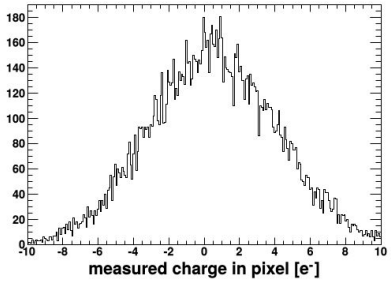
Skipper CCD - readout noise



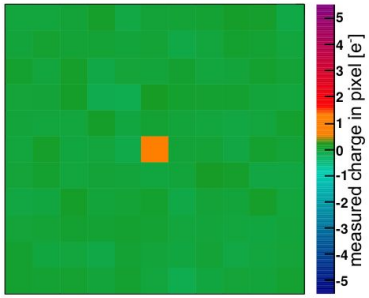
Standard CCD mode: charge in each pixel is measured once



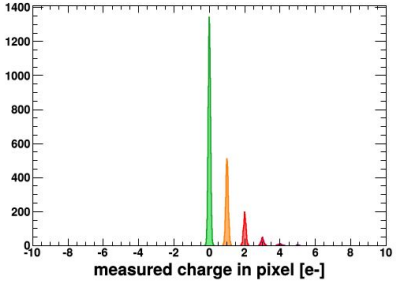
Readout-noise: 3.5 e RMS



New Skipper CCD: charge in each pixel is measured multiple times



Readout-noise: 0.06 e RMS



Skipper CCD - specifications

Characteristics	Value	Unit
Format	4126 x 886	pixels
Pixel Scale	15	um
Thickness	200	um
Silicon Resistivity	10	kΩ
Dark current	<<1	e^-/pix/day
Operating Temperature	120 - 160	K
Readout noise (1 sample)	2	e^- rms/pix
Readout noise (150 samples)	0.16	e^- rms/pix
Readout time (/pix/sample)	10 - 40	μs

$$Detection\ efficiency\ @810nm \geq 0.9$$

Applications in Quantum Microscopy

Sub-shot-noise imaging

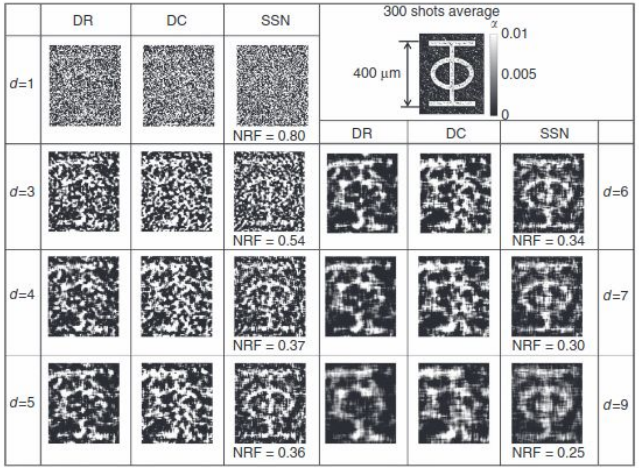
OPEN

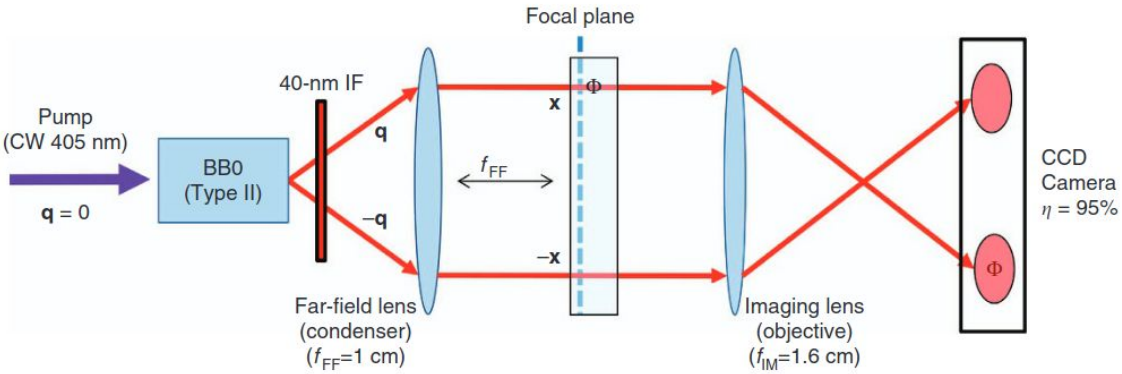
Light: Science & Applications (2017) 6, e17005; doi:10.1038/lsa.2017.5
Official journal of the CIOMP 2047-7538/17
www.nature.com/lsa

ORIGINAL ARTICLE

Realization of the first sub-shot-noise wide field microscope

Nigam Samantaray[1,2], Ivano Ruo-Berchera[1], Alice Meda[1] and Marco Genovese[1,3]





Samantaray, N., Ruo-Berchera, I., Meda, A. *et al.* Realization of the first sub-shot-noise wide field microscope. *Light Sci Appl* **6,** e17005 (2017)

Sub-shot-noise imaging

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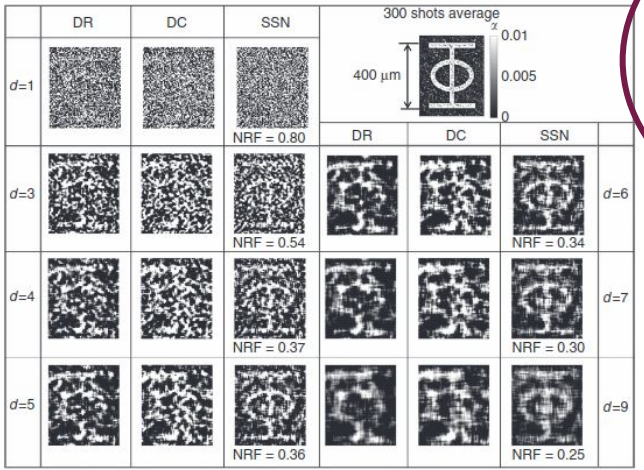
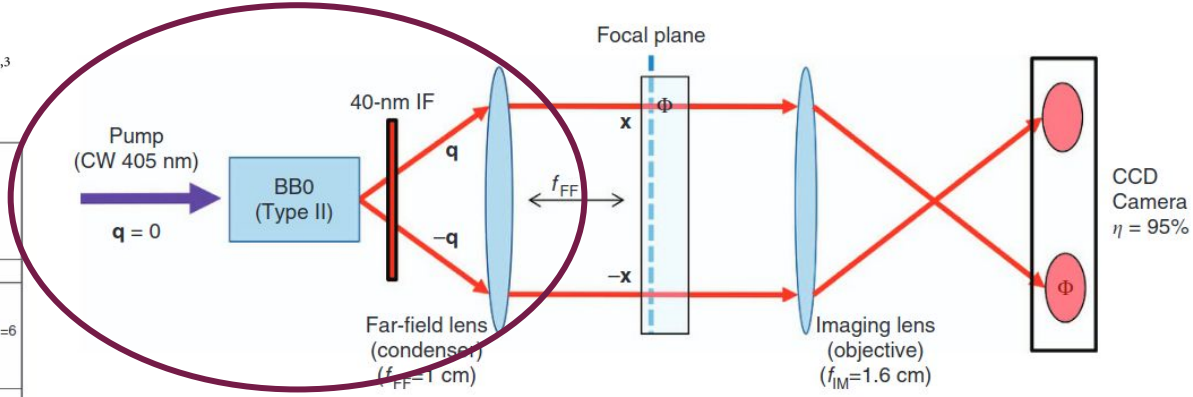


Best possible photon pair generation



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Sub-shot-noise imaging

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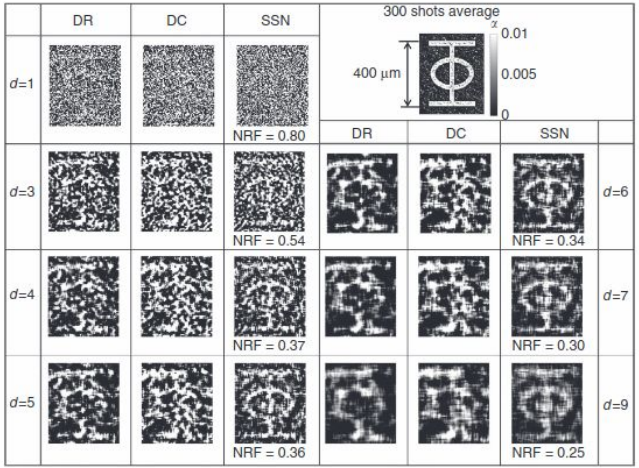
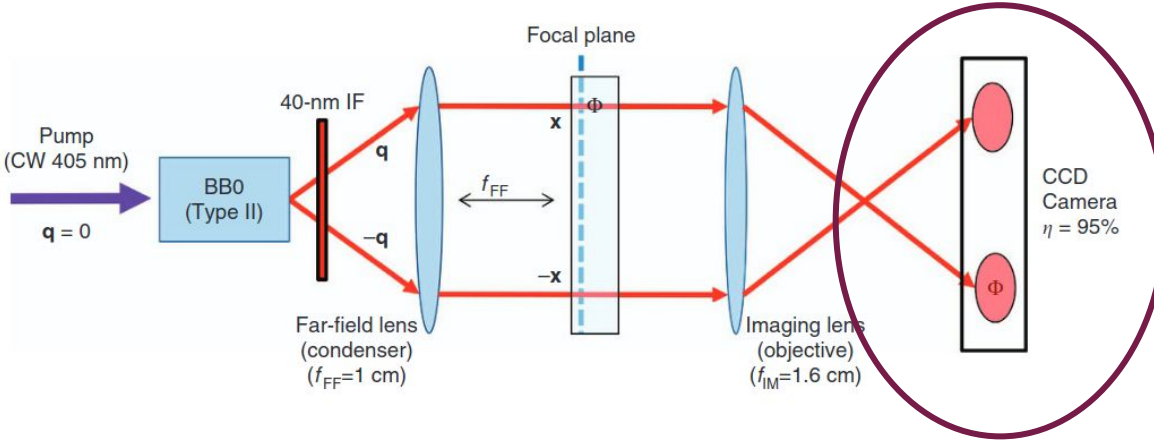


Spatially-resolved, photon number detection with lowest possible noise



Samantaray, N., Ruo-Berchera, I., Meda, A. *et al.* Realization of the first sub-shot-noise wide field microscope. *Light Sci Appl* **6,** e17005 (2017)

Noise reduction factor

from Samantaray et al. 2017, supplementary material

$$\sigma = \frac{<\Delta^2(N_1 - N_2)>}{<N_1> + <N_2>}$$

$$\sigma_{eff} = \sigma f^{(TWB)} + f^{(noise)}$$

Noise reduction factor

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$$f^{(noise)} = \frac{\Delta^{(el)^2}}{N^{(tot)}} + \frac{N^{(st)}}{N^{(tot)}}$$

Normal CCD

$$\Delta^{(el)} \sim 5e^- / pix / frame$$

PIXIS: 400B Teledyne, Princeton Instrument

Skipper-CCD

$$\Delta^{(el)} \sim 0.16$$

*Sub-shot-noise wide field microscope - **Skipper vs CCD***

First strategy: **Increase number of photons per pixel**
Same binning and Noise Reduction Factor condition

$$\left(\frac{CCD\ noise}{Skipper\ Noise}\right)^2 \sim \frac{photons\ per\ pixel\ on\ CCD}{photons\ per\ pixel\ on\ Skipper}$$

$$\left(\frac{\sim 5\ e^-}{\sim 0.16\ e^-}\right)^2 \sim 1000$$

Starting with $2e^-$ of readout noise, 0.16 e^- is reached after taking 156 samples per pixel

Increasing the number of photons per pixel is an undesirable condition because the sample could be damaged.

*Sub-shot-noise wide field microscope - **Skipper vs CCD***

Second strategy: **Binning (worse resolution)**
Same number of photons per pixel and Noise Reduction Factor *condition*

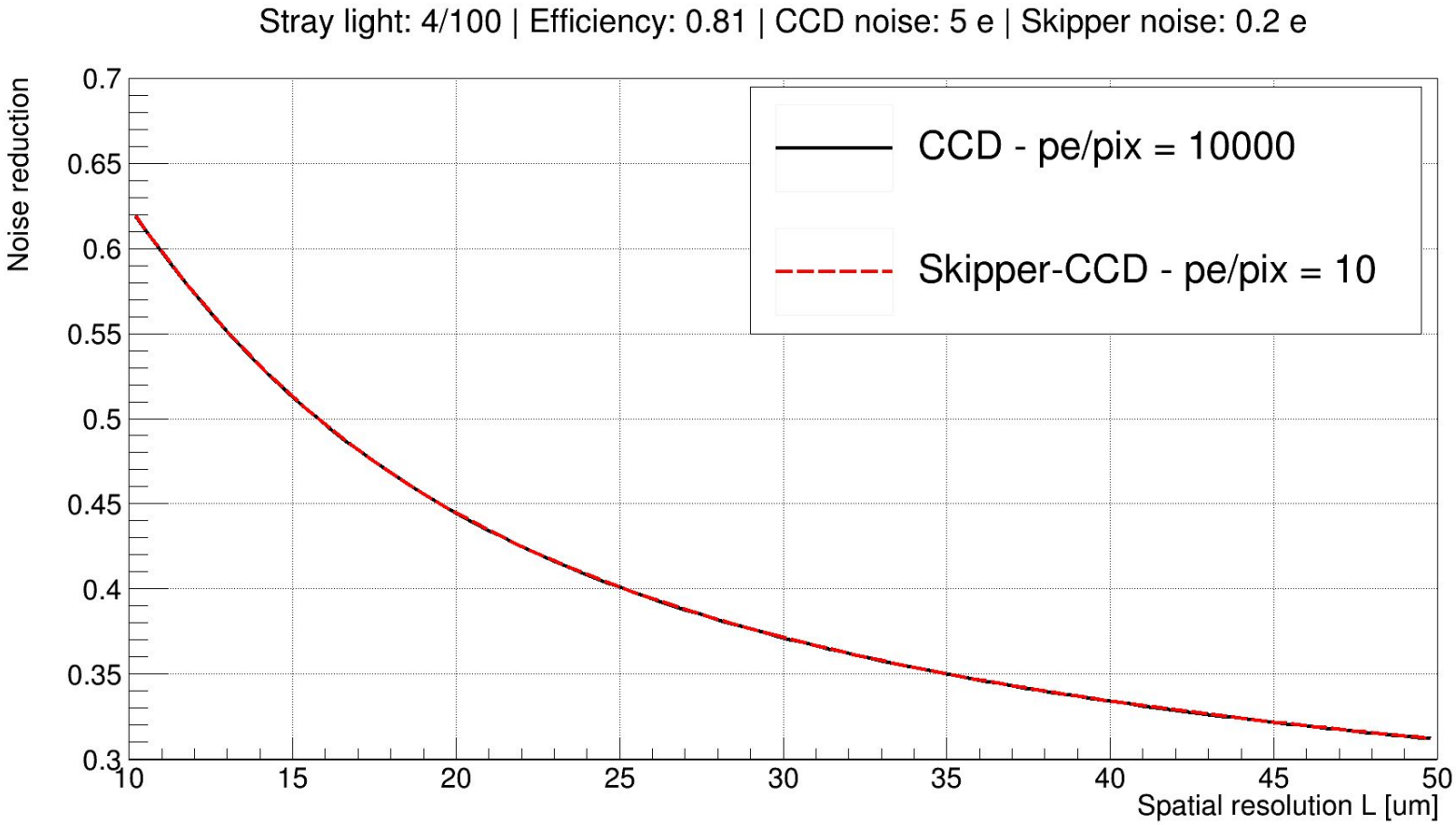
$$\left(\frac{CCD\ noise}{Skipper\ Noise}\right)^2 \sim \frac{photons\ per\ pixel\ on\ CCD}{photons\ per\ pixel\ on\ Skipper} \sim \left(\frac{CCD\ Super\ bin}{Skipper\ pixel\ size}\right)^2$$

$$\frac{\sim 5\ e^-}{\sim 0.16\ e^-} \sim 31.6$$

Skipper-CCD Pixel size $15\mu m$

Required CCD Super binned Pixel size $474\mu m$

*Sub-shot-noise wide field microscope - **Skipper vs CCD***



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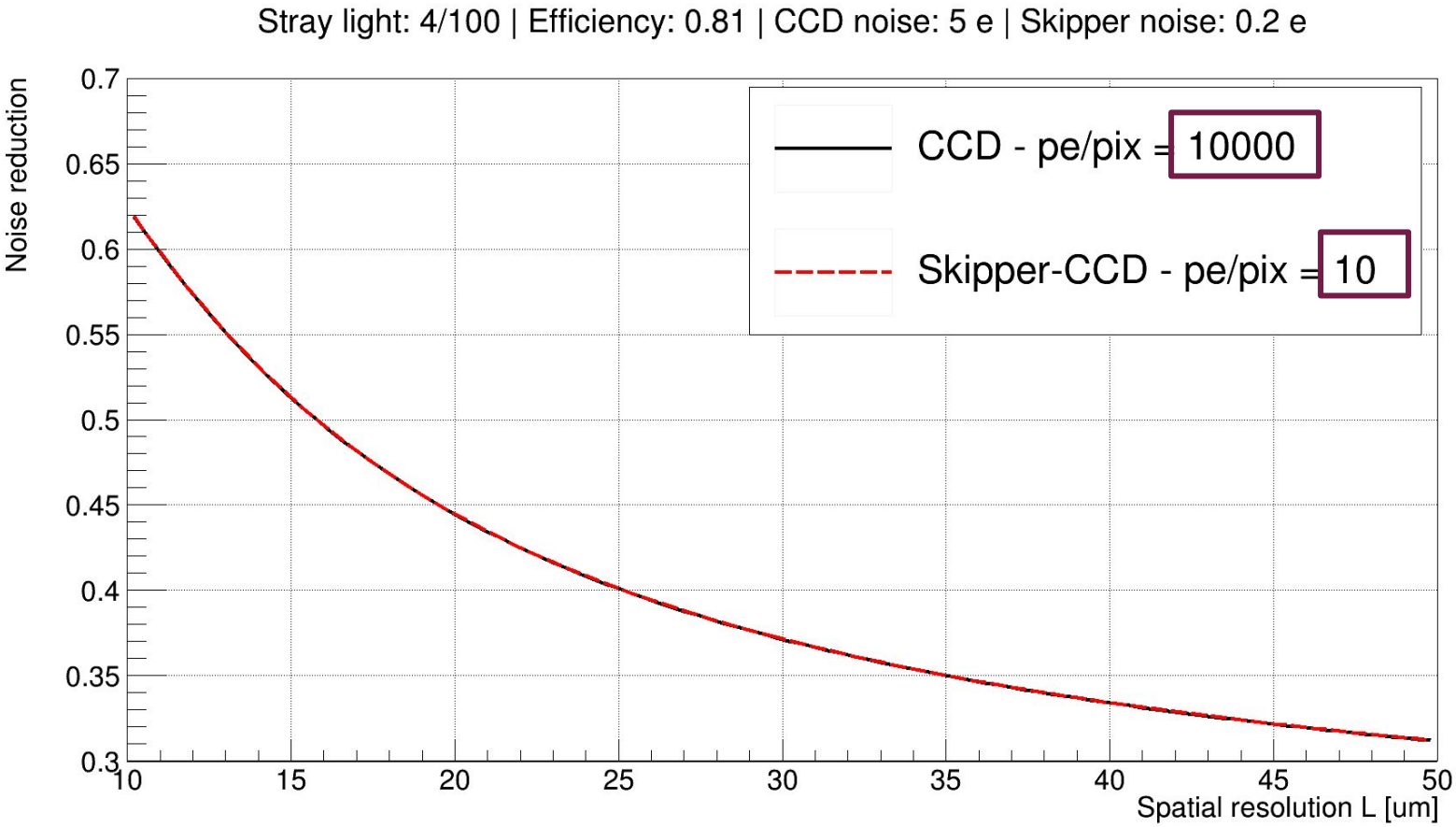

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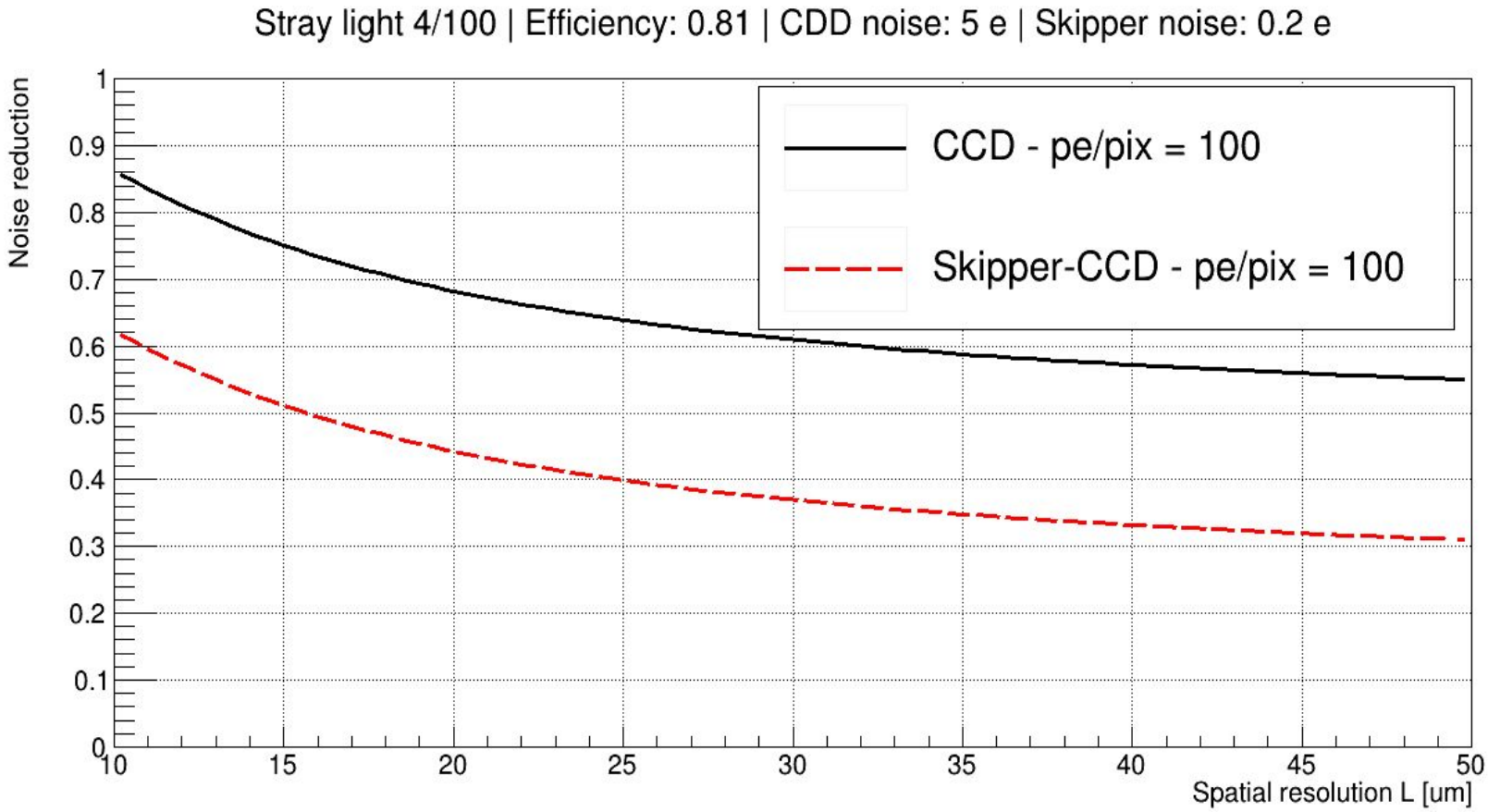
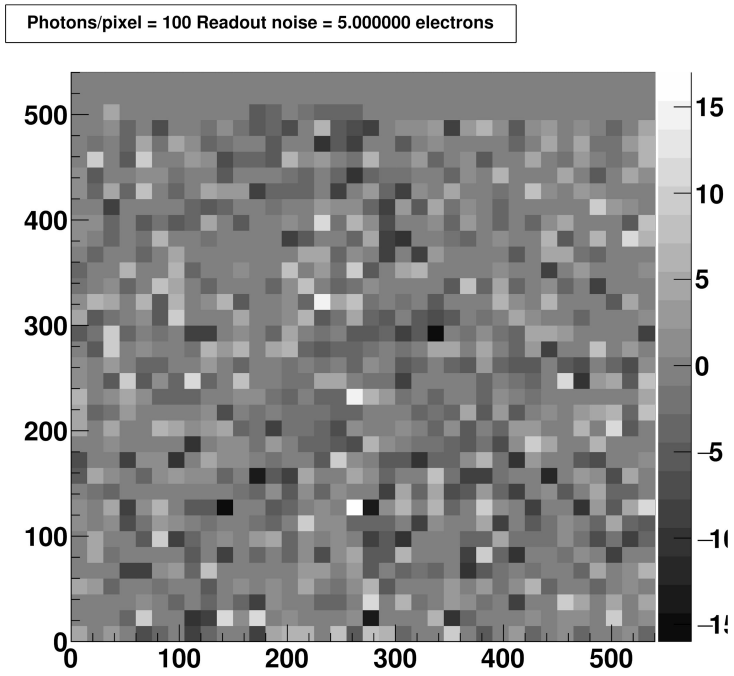
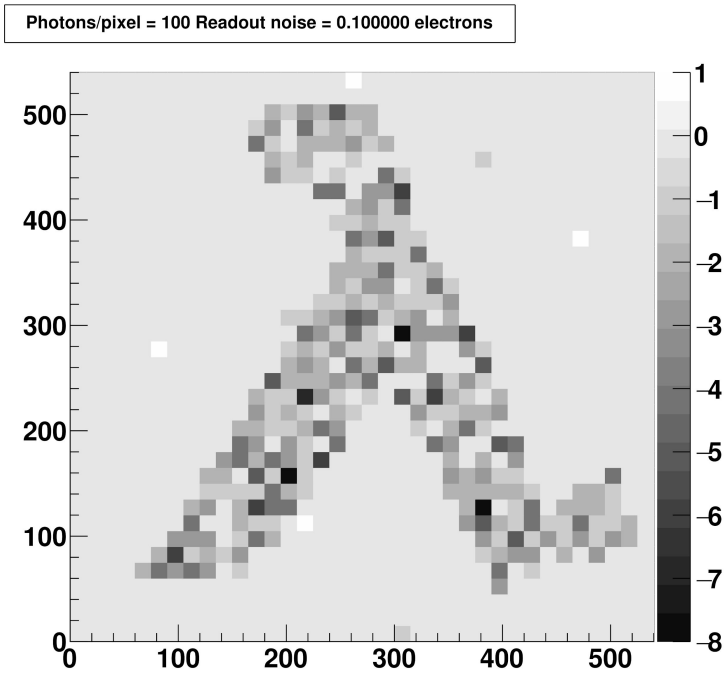


Simulation for a sample with an absorbance of 1%





- A Skipper CCD is a very promising detector for Quantum Optics (specially Quantum Metrology) applications.

- In Quantum Microscopy is particularly useful in the low light regime, where it makes a difference in the information of the absorbance obtained per sent photon.

nature photonics

ARTICLES

PUBLISHED ONLINE: 3 FEBRUARY 2013 | DOI: 10.1038/NPHOTON.2012.346

Biological measurement beyond the quantum limit

Michael A. Taylor[1,2], Jiri Janousek[3], Vincent Daria[3], Joachim Knittel[1], Boris Hage[3], Hans-A. Bachor[3] and Warwick P. Bowen[2]*

¡Thank you!

¿Questions?

extra slides

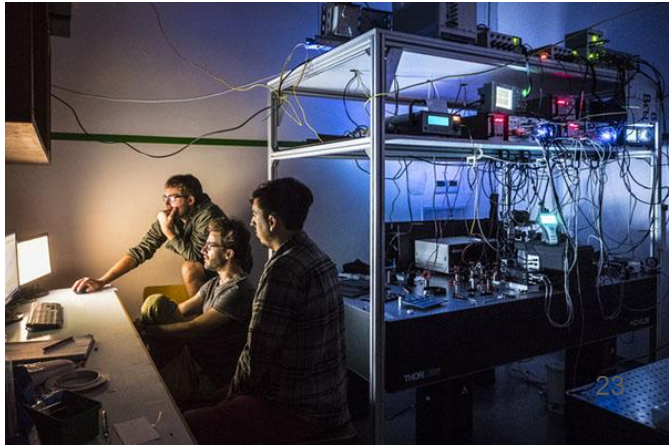
Refurbish work: Starting on April 2021.

Importation: We started to import the required equipment.

Physical work: Nowadays it is allow to make experimental research at the Physical Department Laboratories.

Immediate UBA Resources

Dark Room and Instrumentation for a first QIS experiments.
LIAF: Laboratorio de Iones y átomos fríos

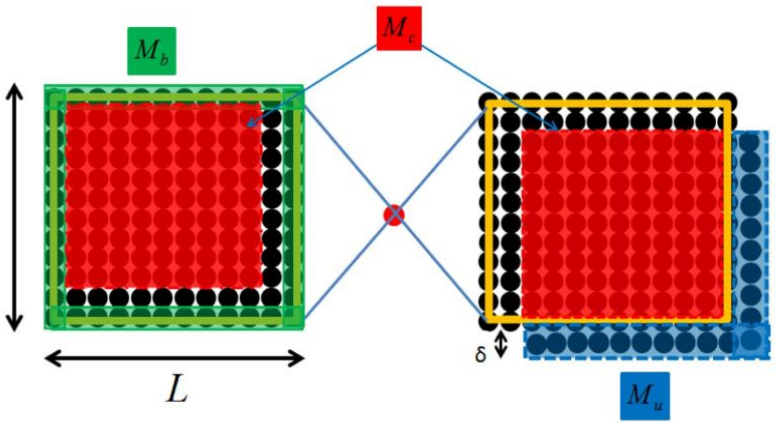


Noise reduction factor: correlation quantifier

$$\sigma = \frac{<\Delta^2(N_1 - N_2)>}{<N_1> + <N_2>}$$

$$\sigma = \frac{\gamma+1}{2} - \eta_0 \eta_{coll}$$

$$\eta_{coll} = \frac{X(\pi\beta^2 - 2D(\mu+1) - 2) + X^2 + 1)}{X^2 + (\pi\beta - 2)X + 1}$$



$$D = \delta/2r \qquad X = L/2r$$

r is the coherence radius at the detection plane.

from Samantaray et al. 2017, supplementary material

Why low illumination level is so important? from Brida et al, 2009, PRL

Low illumination levels are needed in the presence of pigments or other photo-sensible molecules (see, e.g., Y. Fu et al., Opt. Express 14, 3942 (2006), and references therein.). The sub-shot-noise imaging requires a photon flux roughly times smaller than an equivalent classical one, in order to achieve the same signal-to-noise ratio.

In order to achieve a sensitivity superior to that available with classical techniques, one should be able to reach a sub-shot-noise (SSN) regime in spatial correlations even in the presence of the unavoidable background noise (electronic noise, scattered light). Demonstration with low photon number were done subtracting the dominant background noise. Clearly, such a regime cannot be used for concrete imaging schemes, as the image distribution would remain hidden in the background noise.

Similarly, a single-mode sub-shot-noise intensity correlation cannot be used to retrieve high-sensitivity information on the spatial distribution of an object, since the quantum character of the correlation vanishes when one detects small portions of the beams instead of the whole beams

They conclude: Thus, high-sensitivity imaging requires spatial quantum correlations in a regime where the photon flux is high enough to make the background noise negligible.

But, *Skipper-CCD enables the low photon counting regime making the readout electronic negligible* *(even if the scattered light can not be suppressed).*

Brief chronology of the evolution of Quantum Imaging and where the Skipper-CCD can make the difference

*Absolute calibration of CCD cameras (Brida et al, **2010**)*

$$\sigma = \frac{\gamma+1}{2} - \eta_0 * \eta_{coll},$$

$$\eta_{coll} = \frac{X(\pi\beta^2 - 2D(\mu+1) - 2) + X^2 + 1}{X^2 + (\pi\beta - 2)X + 1}$$

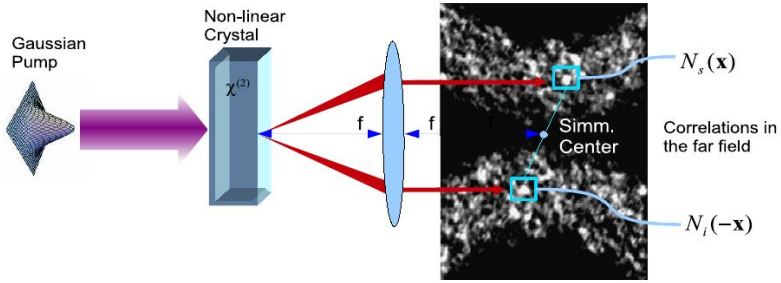


Fig. 1. Scheme for spatial correlations detection in PDC. The PDC emission from the non-linear crystal is detected in the far field, reached by a optical $f-f$ configuration. The pump transverse size determines an uncertainty in the photon propagation direction. The speckled image showed, has been obtained experimentally in very high gain regime. For this reason, the spatial fluctuations are very strong, and the coherence area is roughly represented by the typical size of the speckles.

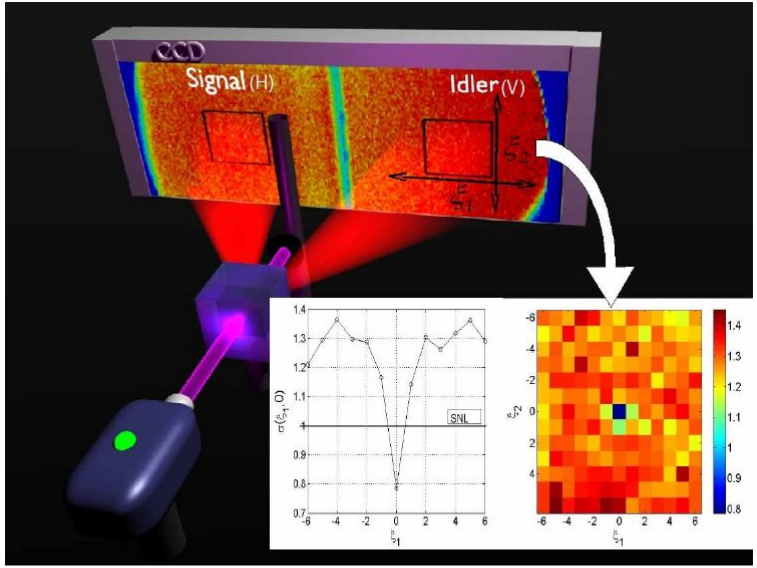


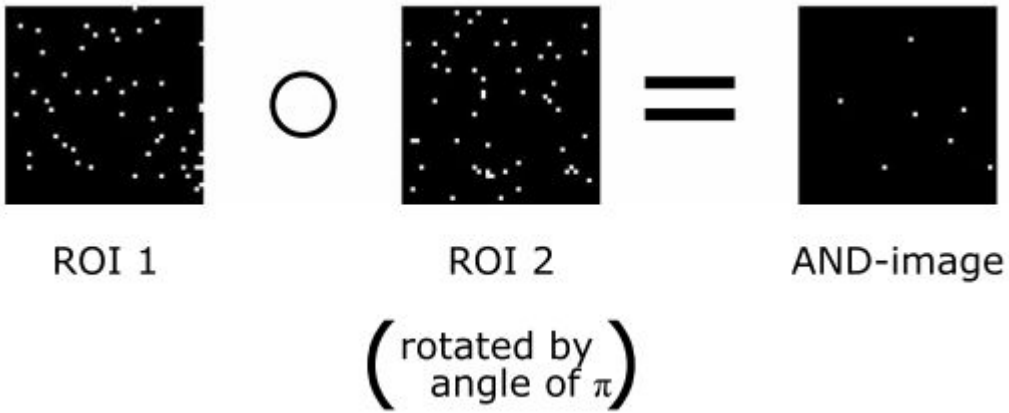
Fig. 2. Determination of center of symmetry. The right hand side presents a typical image obtained by the CCD in the working condition. The images is separated in two portions, one collecting the light from the signal beam (H-polarized) and the other the light of the idler beam (V-polarized). Two regions R_s and R_i (squares) are selected, and subtracted pixel by pixel. The spatial noise of the difference σ is reported in the inserts (right-bottom) in function of the position $\xi = (\xi_1, \xi_2)$ of the idler region in the discrete pixel grid, both in a 1-dimensional graphic in function of ξ_1 having fixed $\xi_2 = 0$ and in a contour plot.

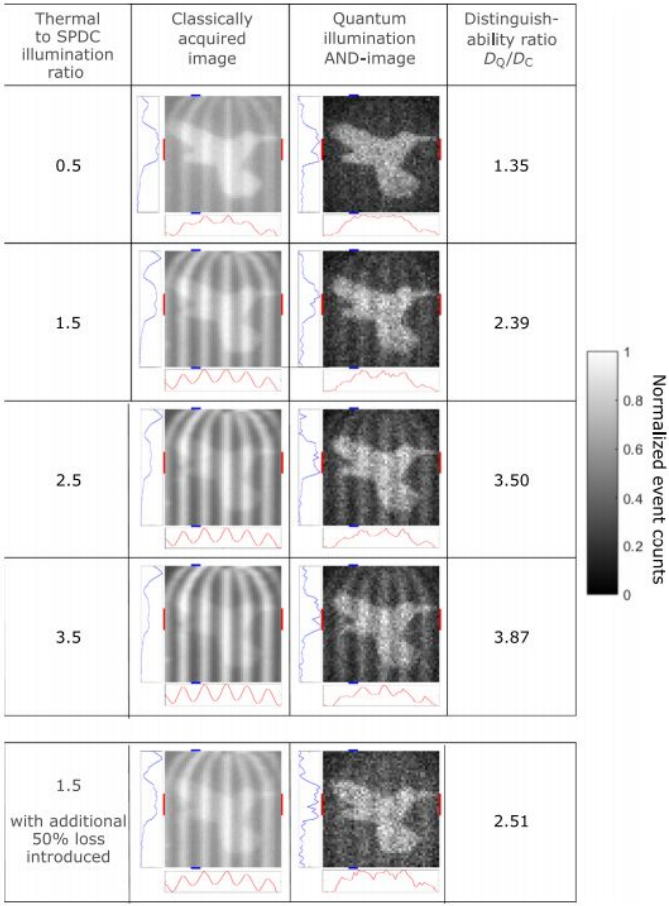
OPTICS

Imaging through noise with quantum illumination

T. Gregory, P.-A. Moreau, E. Toninelli, M. J. Padgett*

The contrast of an image can be degraded by the presence of background light and sensor noise. To overcome this degradation, quantum illumination protocols have been theorized that exploit the spatial correlations between photon pairs. Here, we demonstrate the first full-field imaging system using quantum illumination by an enhanced detection protocol. With our current technology, we achieve a rejection of background and stray light of up to 5.8 and also report an image contrast improvement up to a factor of 11, which is resilient to both environmental noise and transmission losses. The quantum illumination protocol differs from usual quantum schemes in that the advantage is maintained even in the presence of noise and loss. Our approach may enable laboratory-based quantum imaging to be applied to real-world applications where the suppression of background light and noise is important, such as imaging under low photon flux and quantum LIDAR.





LETTER

doi:10.1038/nature13586

Quantum imaging with undetected photons

Gabriela Barreto Lemos[1,2], Victoria Borish[1,3], Garrett D. Cole[2,3], Sven Ramelow[1,3]†, Radek Lapkiewicz[1,3] & Anton Zeilinger[1,2,3]

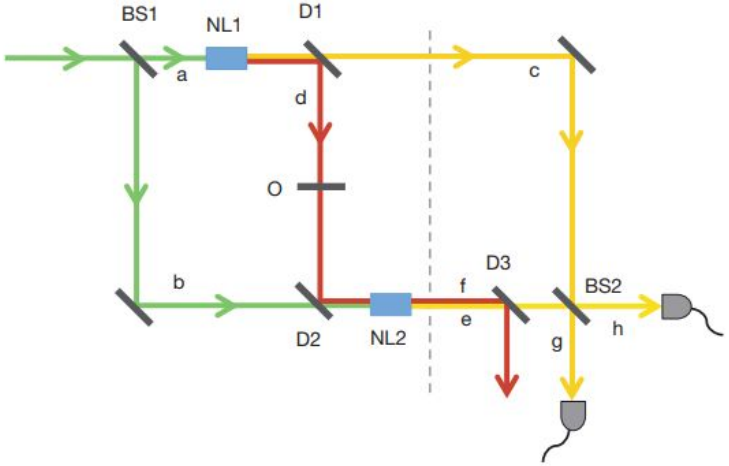


Figure 1 | Schematic of the experiment. Laser light (green) splits at beam splitter BS1 into modes a and b. Beam *a* pumps nonlinear crystal NL1, where collinear down-conversion may produce a pair of photons of different wavelengths called signal (yellow) and idler (red). After passing through the object O, the idler reflects at dichroic mirror D2 to align with the idler produced in NL2, such that the final emerging idler $|f\rangle_i$ does not contain any information about which crystal produced the photon pair. Therefore, signals $|c\rangle_s$ and $|e\rangle_s$ combined at beam splitter BS2 interfere. Consequently, signal beams $|g\rangle_s$ and $|h\rangle_s$ reveal idler transmission properties of object O.

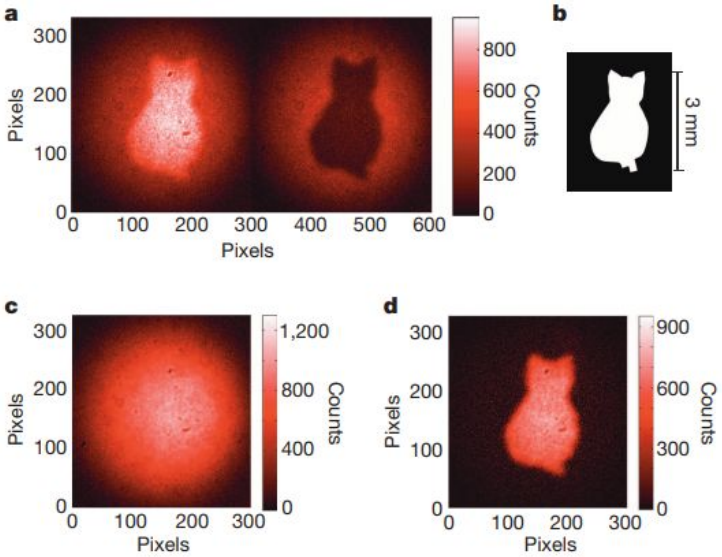


Figure 3 | Intensity imaging. **a**, Inside the cat, constructive and destructive interference are observed at the outputs of BS when we placed the cardboard cut-out shown in **b** in the path D1–D2. Outside the cat, idler photons from NL1 are blocked and therefore the signals do not interfere. **c**, The sum of the outputs gives the intensity profile of the signal beams. **d**, The subtraction of the outputs leads to an enhancement of the interference contrast, as it highlights the difference between constructive and destructive interference.

Version October 28, 2018

High-sensitivity imaging with multi-mode twin beams

E. Brambilla, L. Caspani, O. Jedrkiewicz, L. A. Lugiato and A. Gatti
INFM-CNR-CNISM, Dipartimento di Scienze Fisiche e Matematiche, Università dell'Insubria, Via Valleggio 11, 22100 Como, Italy

Twin entangled beams produced by single-pass parametric down-conversion (PDC) offer the opportunity to detect weak amount of absorption with an improved sensitivity with respect to standard techniques which make use of classical light sources. We propose a differential measurement scheme which exploits the spatial quantum correlation of type II PDC to image a weak amplitude object with a sensitivity beyond the standard quantum limit imposed by shot-noise.

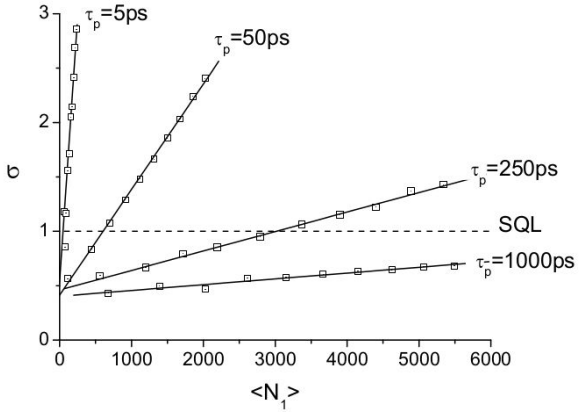
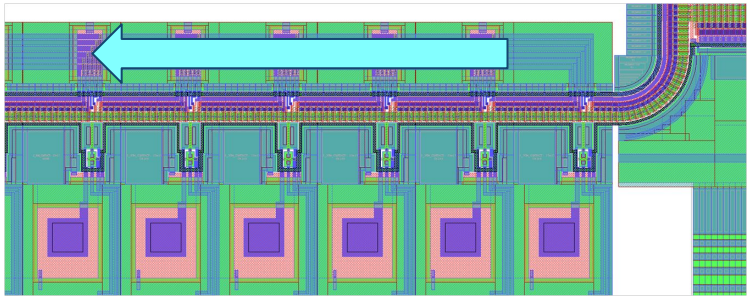


FIG. 5: Plot of the correlation factor σ as a function of $\langle N_1 \rangle$ for different values of the pump pulse duration τ_p (see legend). The error in the symmetry center is $x_{shift} = 4\,\mu$m. $\langle N_1 \rangle$ is increased by varying the parametric gain g. The pixel detector size is 20μm. The other parameters are the same as in Fig. 4

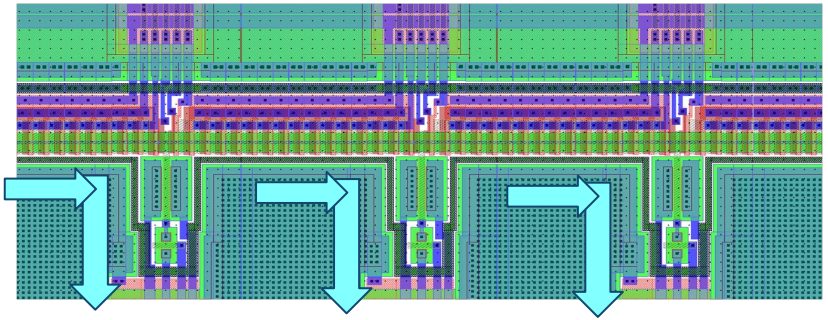
New QIS sensors testing

After having the first setup working at LAMBDA

Schedule: second semester of 2021

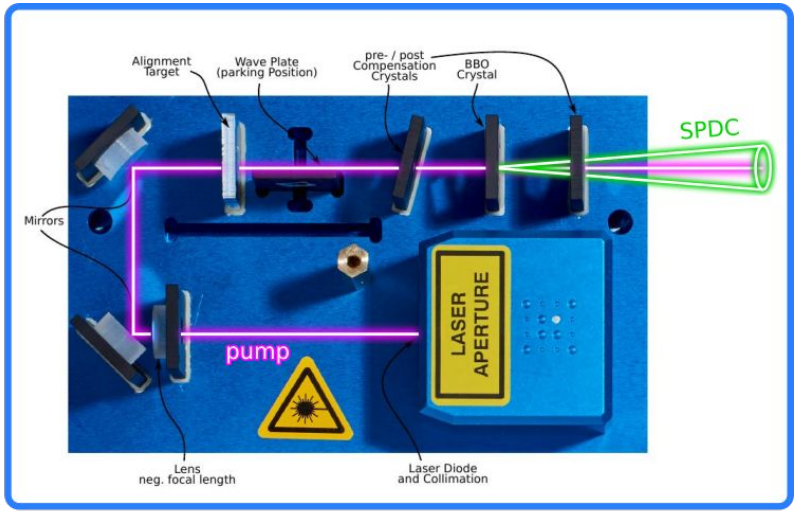


One serial register with many sense nodes.

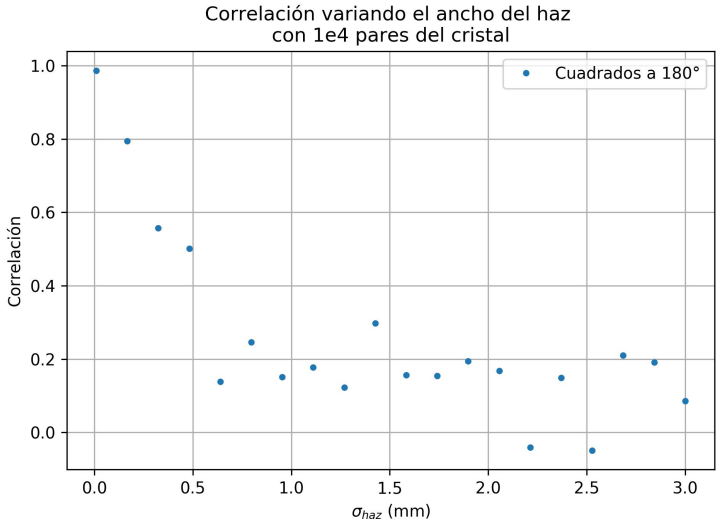


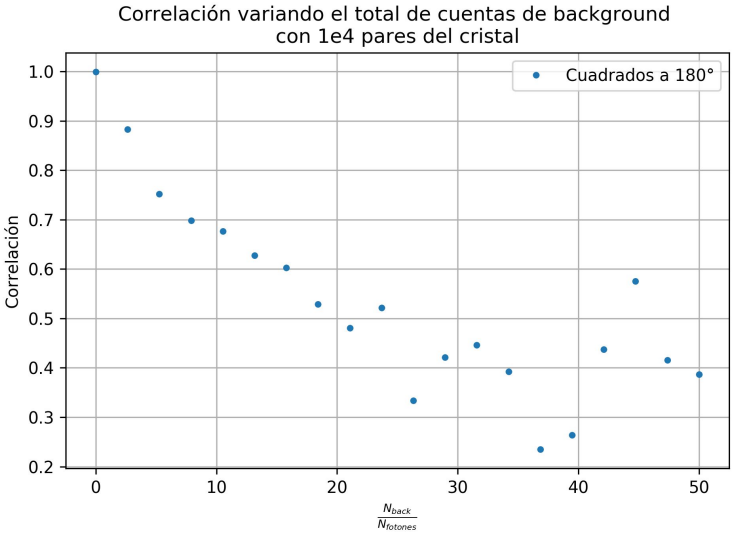
16 independent serial registers, one amp on each.

Planned to be performed at LAMBDA

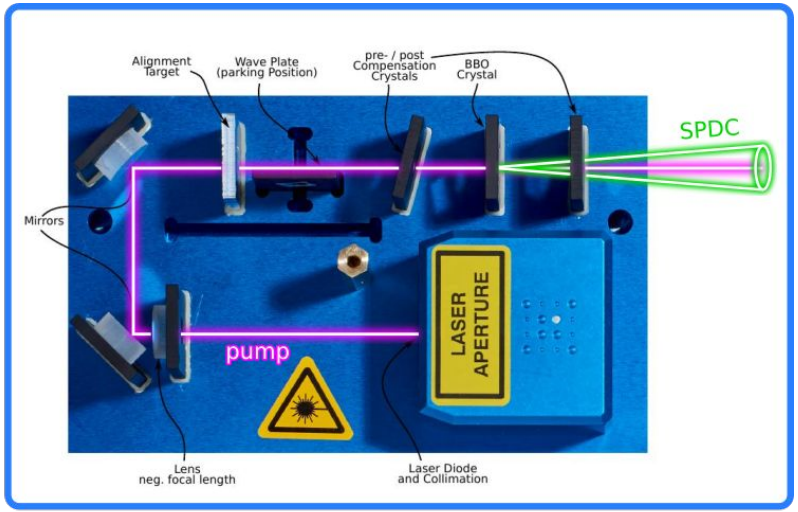


- Many stages losing photons by reflection
- Type I BBO
- No spatial filtering
- Very unstable laser beam
- Bandwidth pass filters emits fluorescence



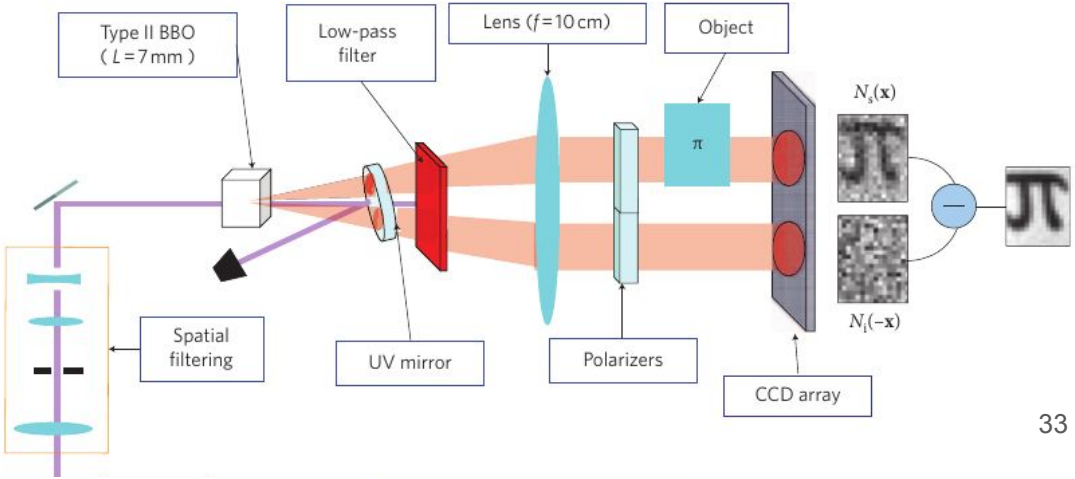


plots from Muriel Bonetto

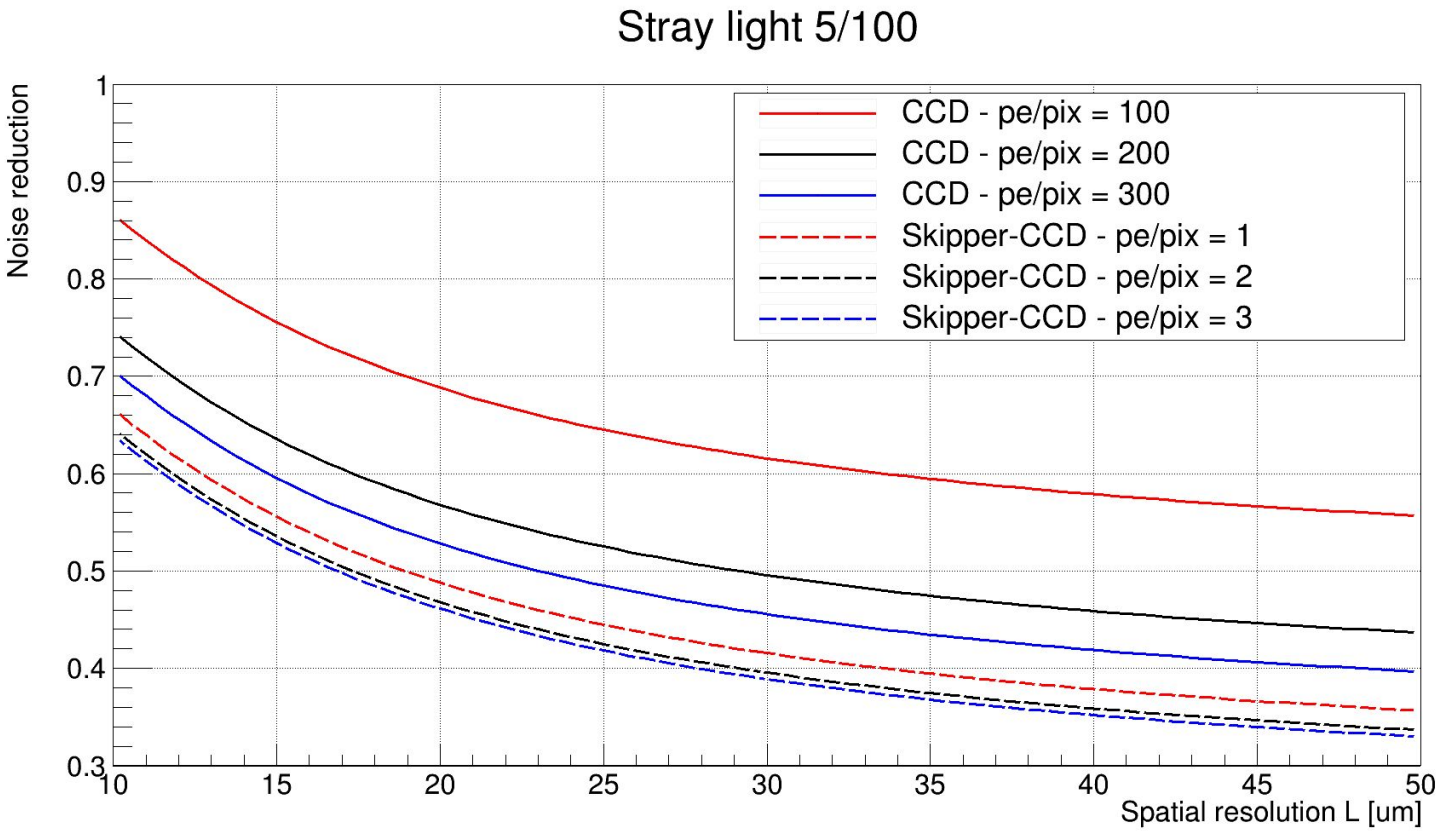


- Many stages losing photons by reflection
- Type I BBO
- No spatial filtering
- Very unstable laser beam
- Bandwidth pass filters emits fluorescence

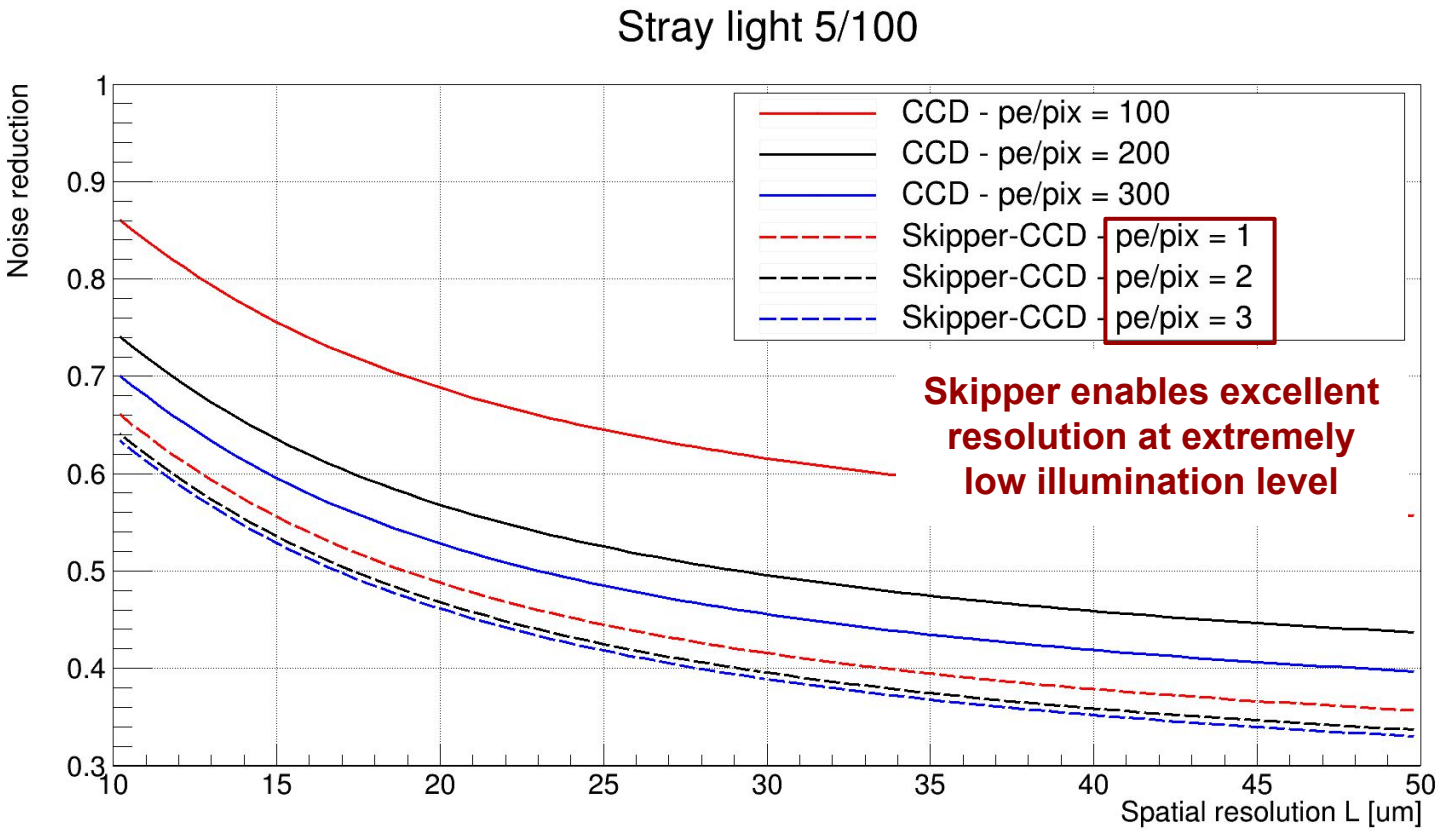
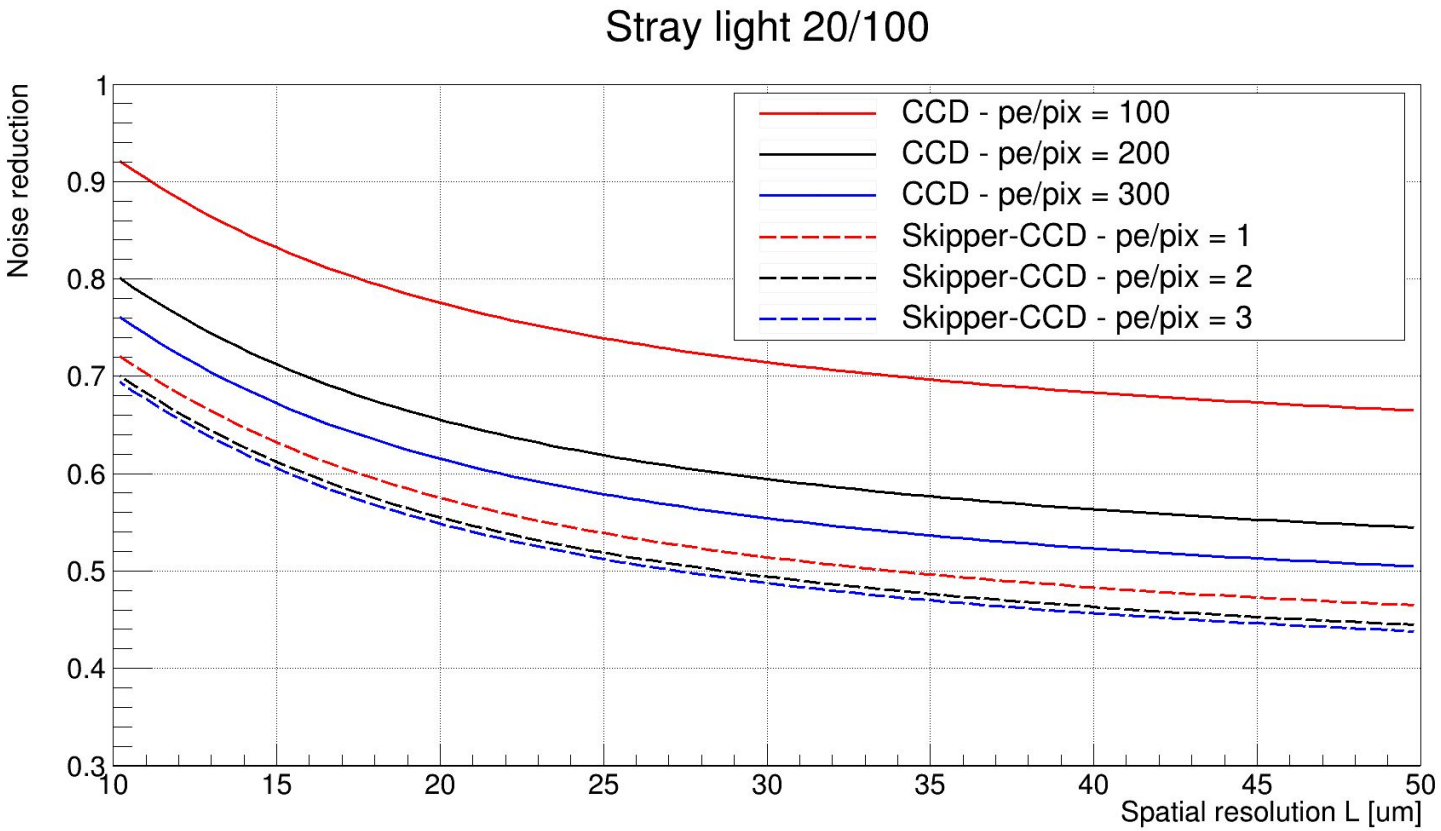
- Anti Reflective coat
- Type II BBO and polarizers
- Spatial filtering
- Very stable laser beam
- Dichroic filters



*Sub-shot-noise wide field microscope - **Skipper vs CCD***



*Sub-shot-noise wide field microscope - **Skipper vs CCD***



*Sub-shot-noise wide field microscope - **Skipper vs CCD***