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Quantum sensing using squeezed light

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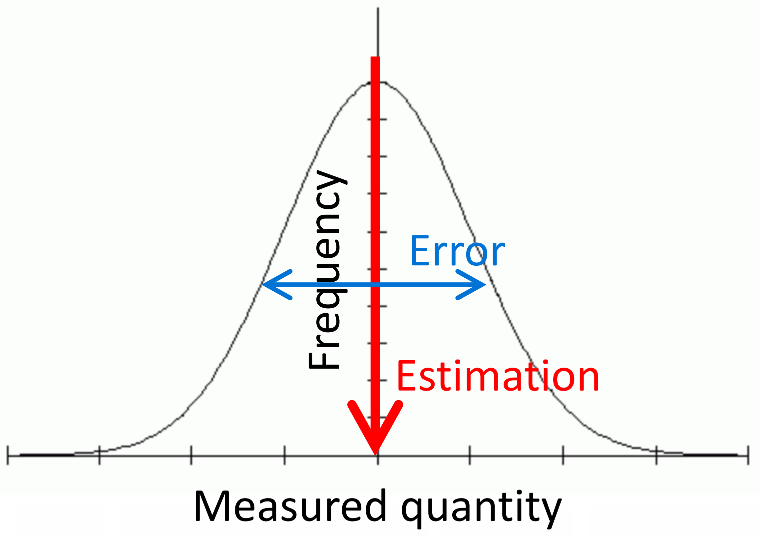
Sensing is a parameter estimation

- Error sources
  - Various *classical* errors (1/f, thermal/mechanical noises, etc.)
  - Measurement back-action
    - The interaction incurs some changes to the physical object/property.
  - Tool's precision limits the accuracy of detection.

- One (typical) mitigation
  - Parameter estimation based on ensemble measurement



Reducing sensing errors via averaging

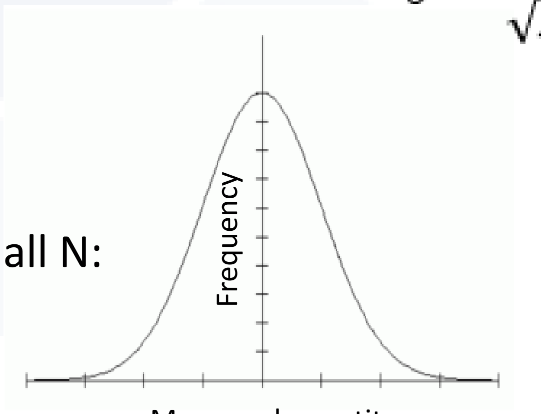
- "Standard limit" of sensing error
  - The variance of measurement error reduces as $1/\sqrt{N}$ where N is the number of trials.
  - For independent and identically distributed (i.i.d.) trials:

$$Var\left(\frac{1}{N}\sum_{i=1}^{N} X_i\right) = \frac{1}{N^2}\sum_{i=1}^{N} Var(X_i) = \frac{1}{N^2}N\sigma^2 = \frac{\sigma^2}{N}$$

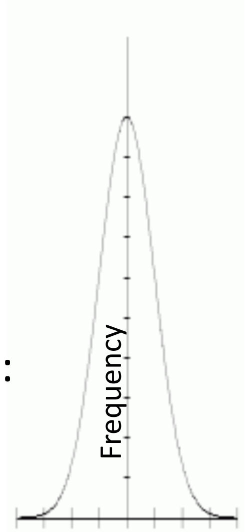
  - So, the error (standard deviation) scales as

$$\sigma' = \frac{\sigma}{\sqrt{N}}$$

Small N:

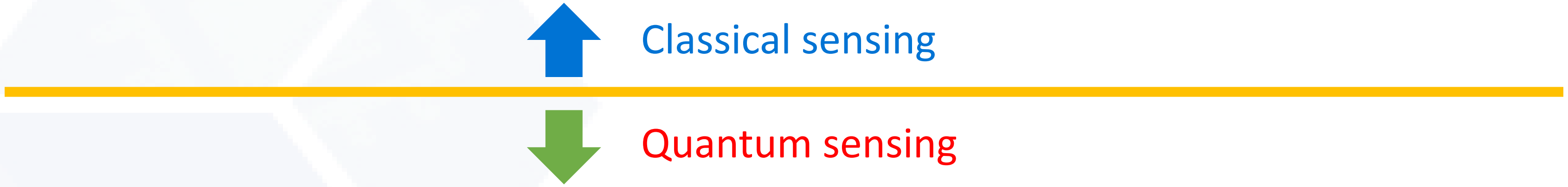


Large N:



Paradigm of quantum sensing

- First, remove (reduce significantly) all reducible errors.
  - Even if all classical error sources are suppressed, quantum errors stay.



- Implement an appropriate sensing interaction scheme.
  - Reduce the interaction-induced back action
    - Check if the interaction is compatible (commuting) with Hamiltonian
  - Search for best measurement scheme
    - To maximize obtainable information amount

- Fight to reduce the remaining quantum errors

Be careful when claiming advantage of quantum sensing

- We learned that the estimate error can be arbitrarily small via increasing the resources (N: number of photons).

- Quantum sensing claims a favorable scaling rule between accuracy and number of resources.
  - Quantum sensing must answer why one cannot simply increase N to reduce the error.

- Typical situations where increasing N is not plausible:
  - Worried about the back action from large optical powers.
  - Higher optical power may saturate the optical detector.
  - Intense light may harm photosensitive ligands.
  - High power probe light may damage benign (bio) samples.
  - Driving lasers for high powers may increase classical noises (1/f, thermal).

Light is a harmonic oscillator

- Hamiltonian

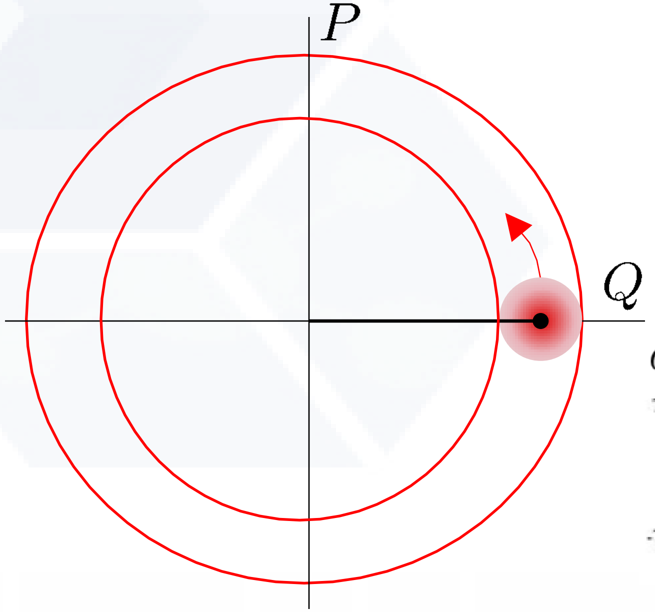
$$H = \hbar\omega a^\dagger a = \frac{1}{2}\left(P^2 + Q^2\right)$$

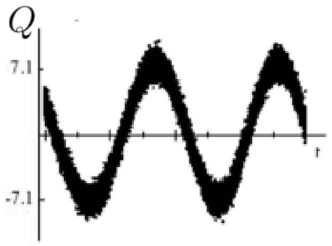
- Coherent state

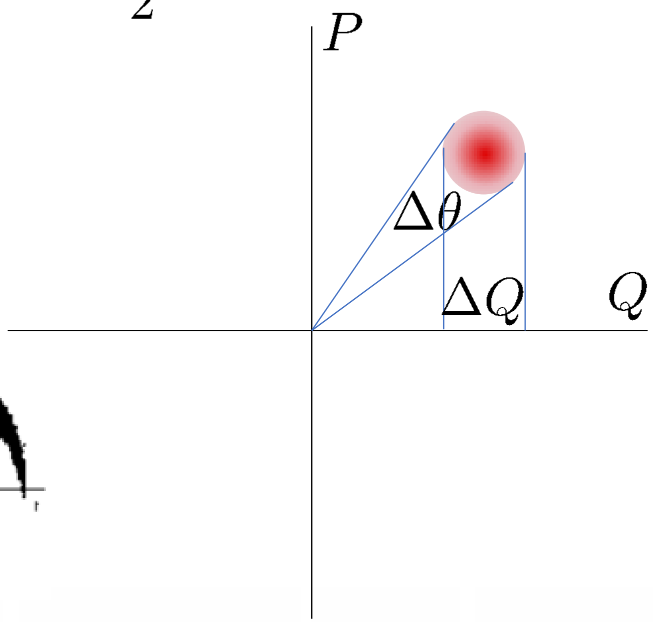
$$a|\alpha\rangle = \alpha|\alpha\rangle$$

- Uncertainty principle

$$[Q, P] = i, \quad \Delta P \Delta Q \geq \frac{\hbar}{2}$$



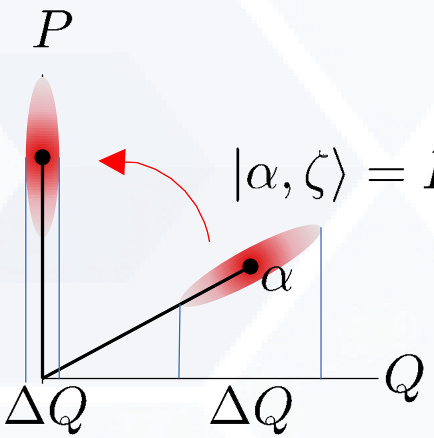




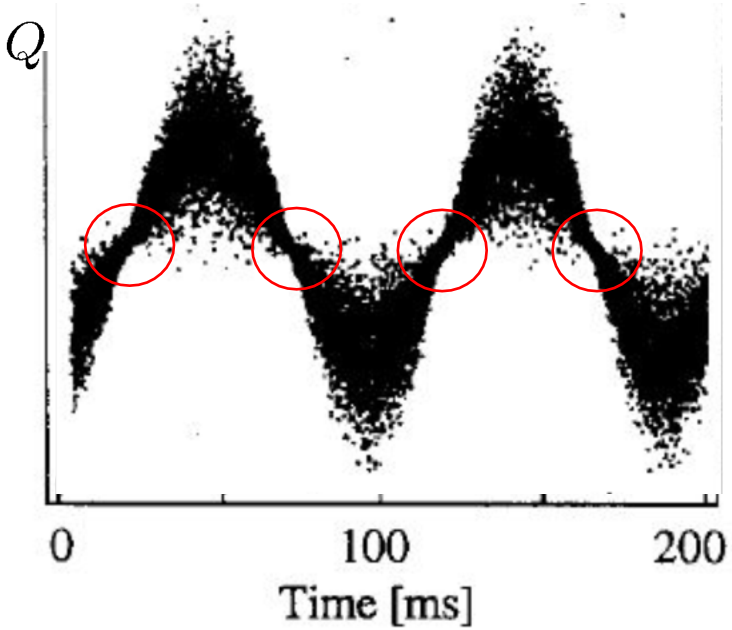
Squeezed light

- Squeezing operator

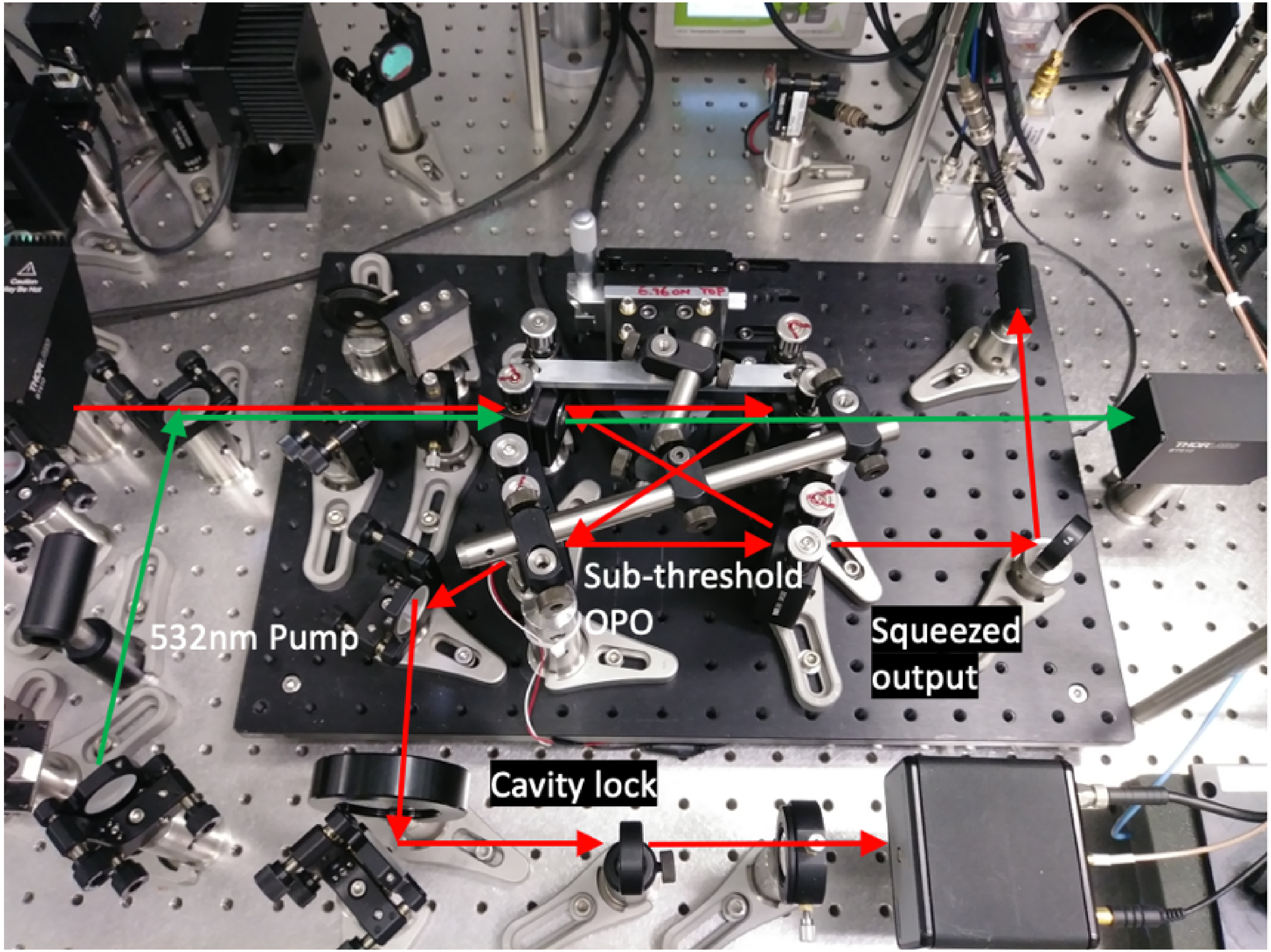
$$S(\zeta) = \exp\left[\frac{1}{2}\left(\zeta^* a^2 - \zeta a^{\dagger 2}\right)\right]$$



$$|\alpha, \zeta\rangle = D(\alpha) S(\zeta) |0\rangle$$

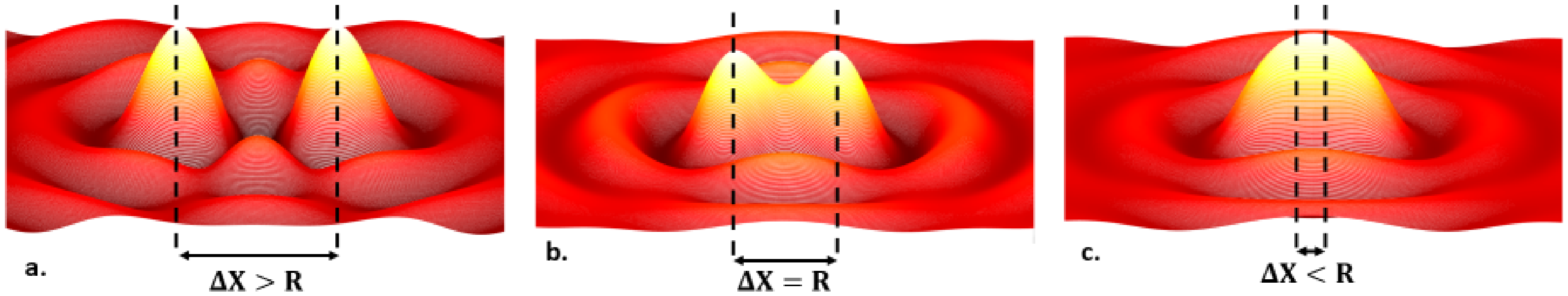


Experimental setup for squeezed light production



Limitations in classical imaging

- Rayleigh



$$\text{Rayleigh diffraction limit R} \simeq \frac{\text{Light wavelength} \times \text{Lens focal length}}{\text{Lens diameter}}$$

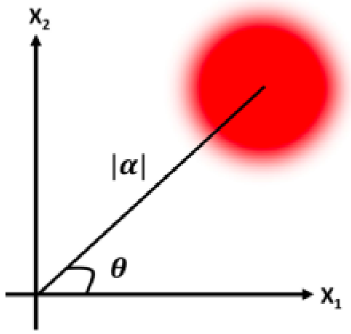
- Various methods to improve the classical imaging resolution
  - Best-form lenses
  - Immersive optics
  - Current practical limit of imaging resolution > 200 nm if 1 μm light wavelength is used.

Super-resolution imaging

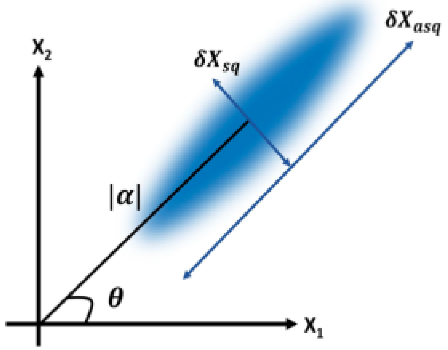
[Kolobov & Fabre, PRL 85, 3789 (2000)]

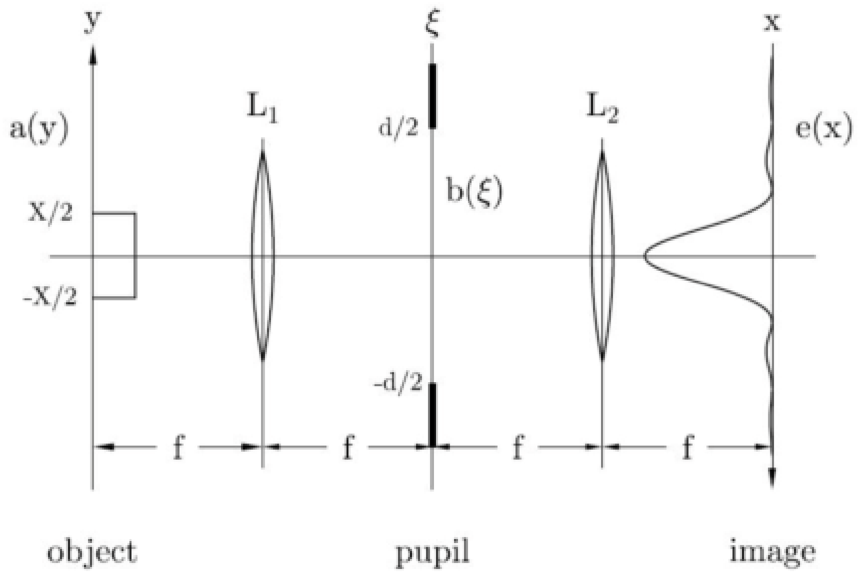
- Light is noisy

Coherent-state



Squeezed-state

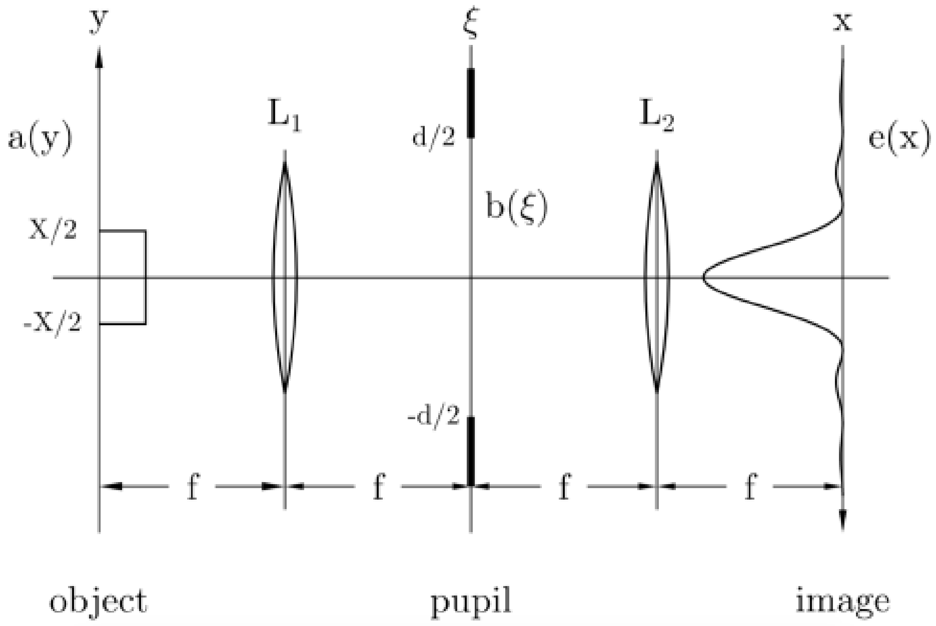




- Reconstructing imaging
  - Due to limited lens aperture sizes, high-order Fourier components are lost (Rayleigh diffraction limit).
  - It is in principle possible to retrieve the lost information using accurate information within pupil and extrapolate it (c.f. analytical).
  - It takes long time (or large number of photons) to obtain sufficiently accurate information within pupil after averaging.
  - Squeezed-state of light reduces the time/number-of-photons.

Formalism of super-resolution imaging

- Goal: reconstruct the original object after retrieving the *missing* information.



$$(c = \pi d X / 2\lambda f)$$

Image

$$e(s) = (La)(s) = \int_{-1}^{1} ds' \frac{\sin[c(s-s')]}{\pi(s-s')} a(s'), \quad -\infty < s < \infty.$$

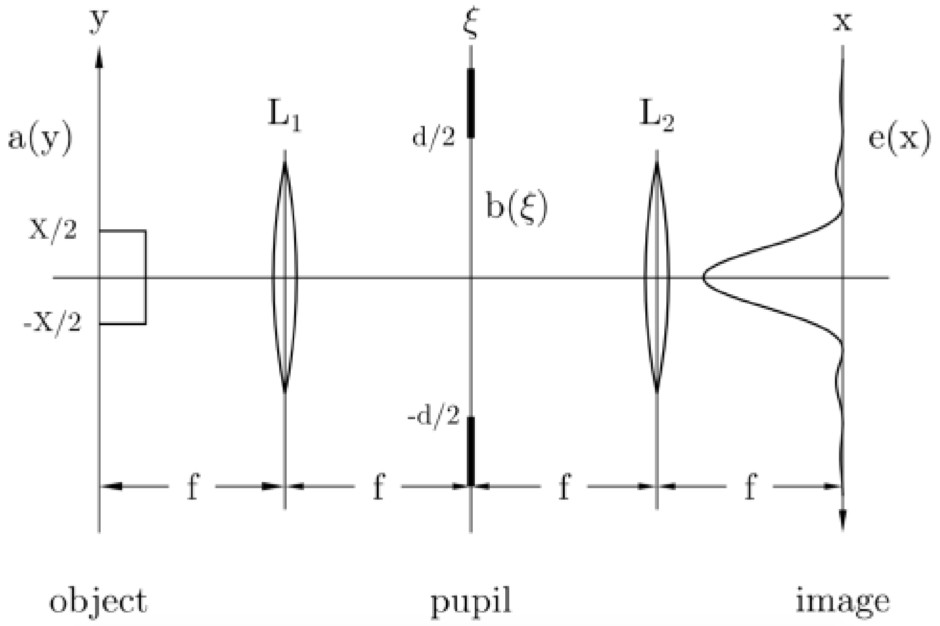
Reconstructed object

$$\tilde{a}(s') = (L^{\star}e)(s') = \int_{-\infty}^{\infty} ds \frac{\sin[c(s'-s)]}{\pi(s'-s)} e(s), \quad -1 \leq s' \leq 1.$$

[Kolobov & Fabre, PRL 85, 2000]

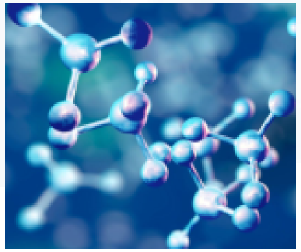
Formalism of super-resolution imaging

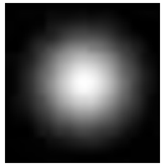
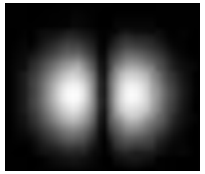
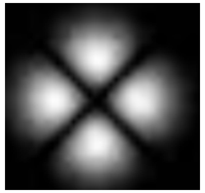
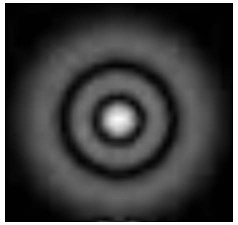
- Goal: reconstruct the original object after retrieving the *missing* information.



- Reconstruction of object from image measurements:

$$a(y) = \sum_{n=0}^{Q} a_n \phi_n(y)$$

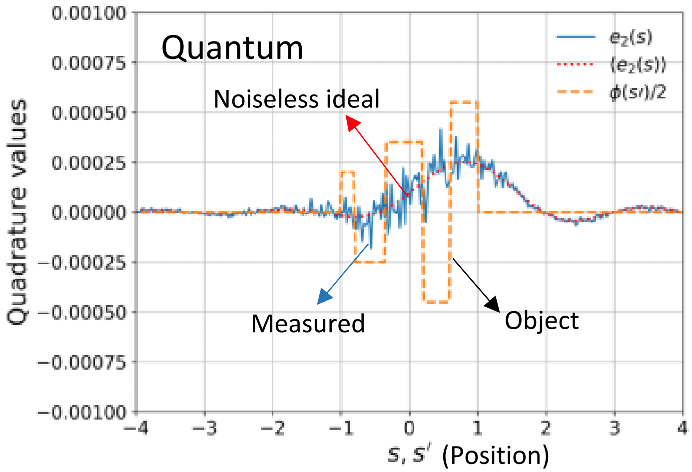


$= a_0$  $+ a_1$  $+ a_2$  $+ a_3$  $\cdots$

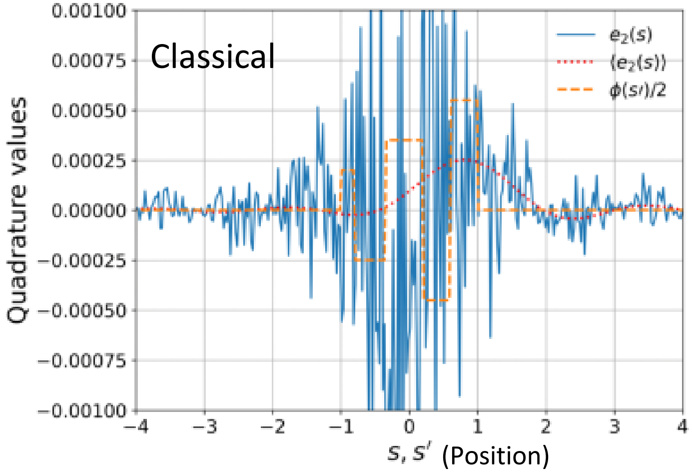
Result: Quantum vs. Classical super-resolution imaging

- Comparison of quantum and classical imaging on a fictitious 1D sample with varying optical phase (same number of photons)

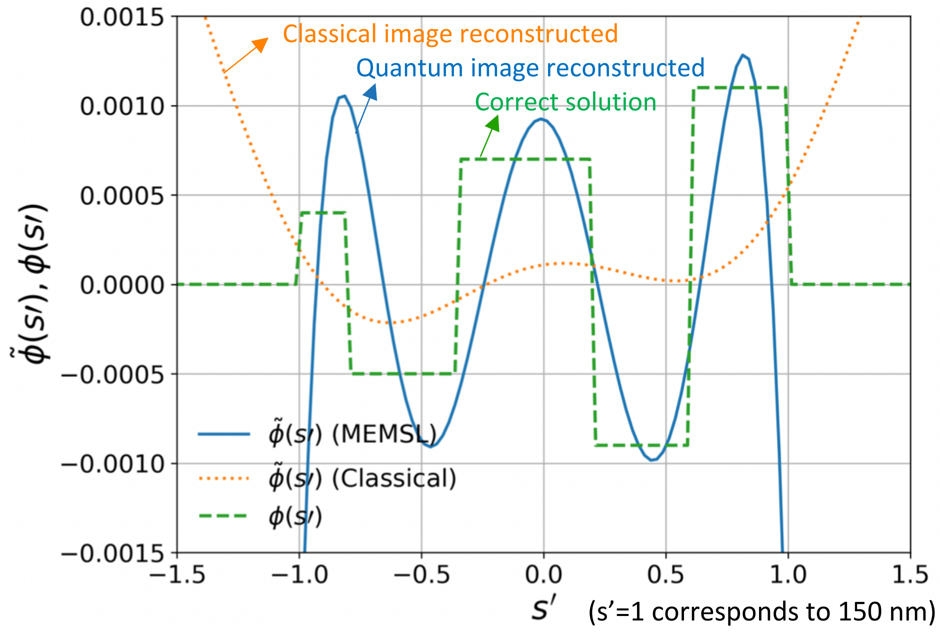
[Soh, “Label-free quantum super-resolution imaging…”, arXiv 2207.10826 (2022)]



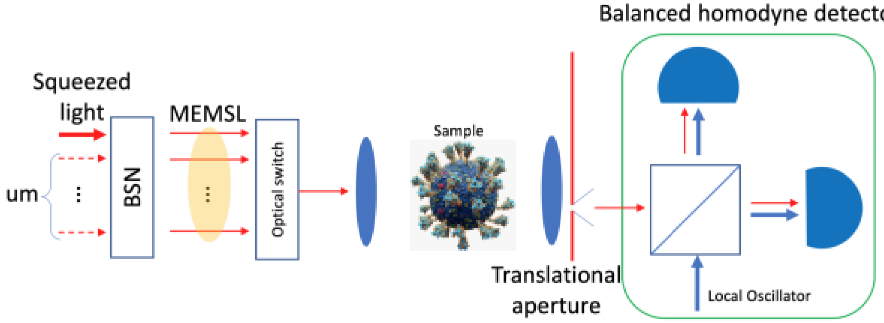
(a)



(b)

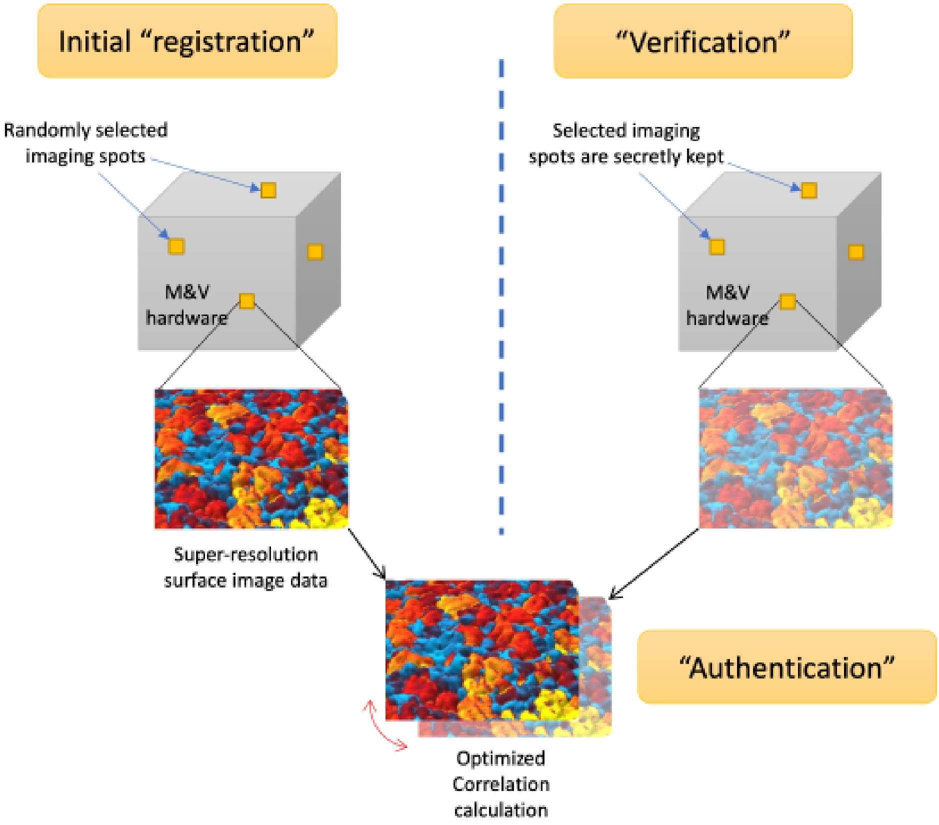


- # of photons used:50x50000
- Wavelength: 780nm
- Quantum img resol: 40 nm
- Classical img resol: ~200 nm



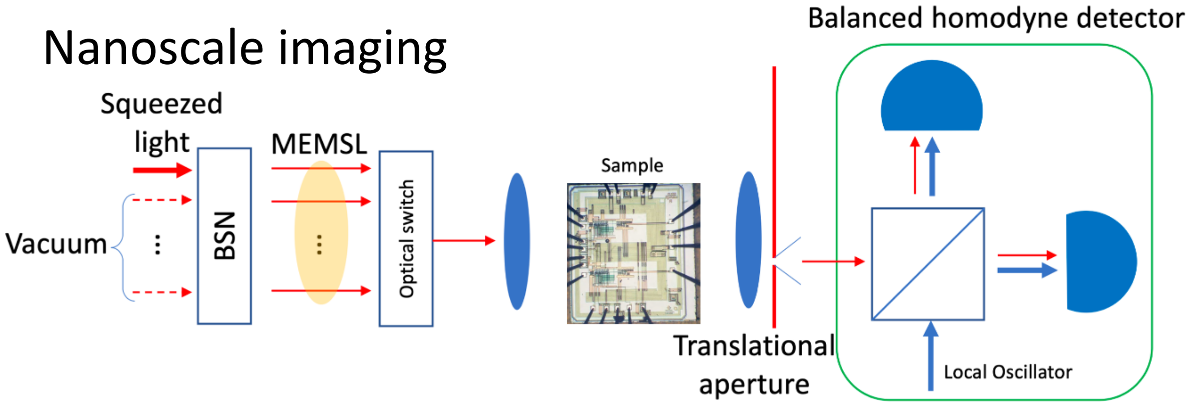
Applications of super-resolution imaging

Authentication



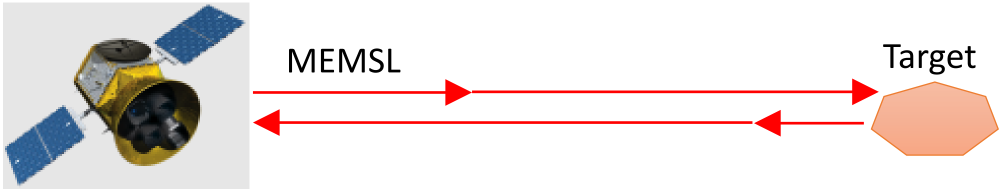
- Requirements: 780 nm, ~ 20 nm resolution, 5×10^9 photons (1 nJ), limited by operating time.
- Squeezing level: 10 dB, expected optical loss: 3 dB

Nanoscale imaging



- Requirements: 1064 nm, ~ 40 nm resolution, 5×10^6 photons (1 pJ), limited by protection need for chip function
- Squeezing level: 10 dB, expected optical loss: 1 dB

Remote sensing



- Requirements: 1064 nm, XX photons, limited by operating power
- Squeezing level: 10 dB, expected optical loss: ~ 10 dB