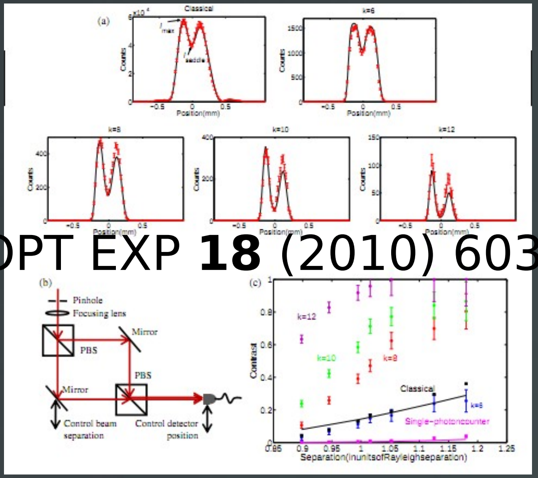
Transition-Edge Sensor in Quantum Land

Emanuele Taralli

iNRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Why TESs?



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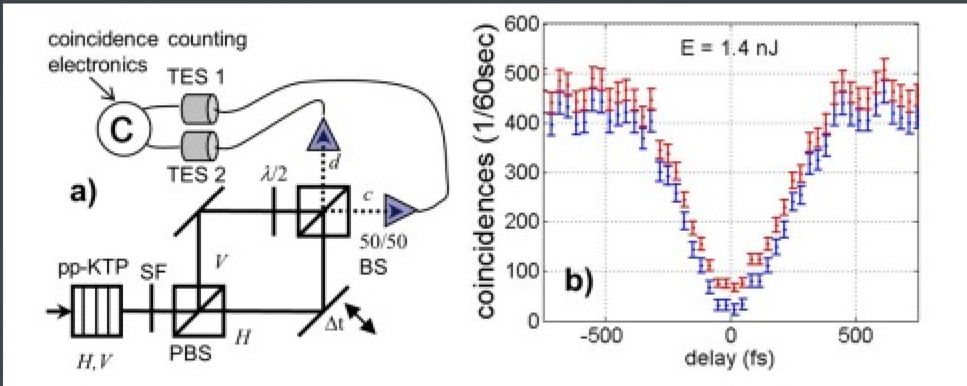

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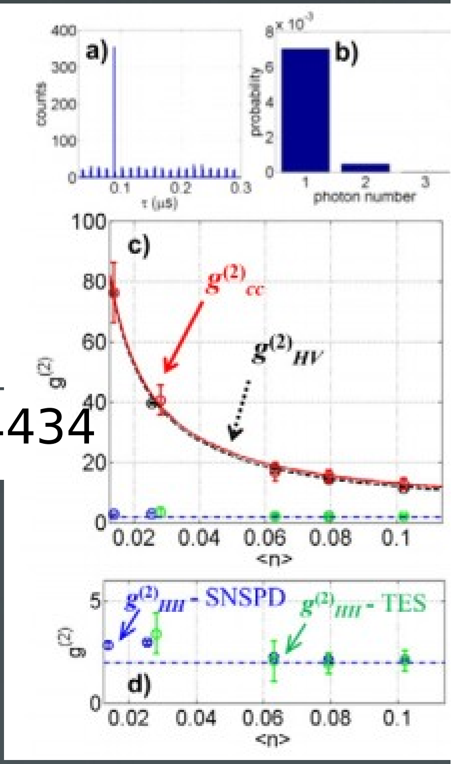
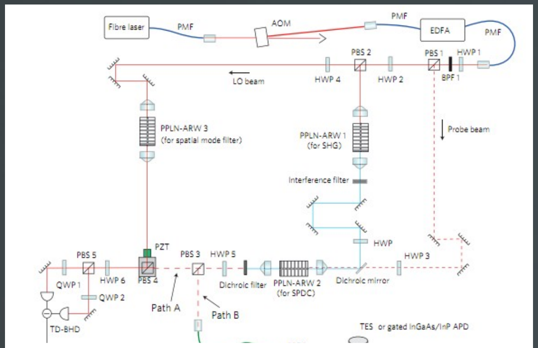
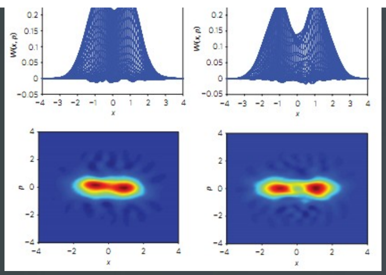
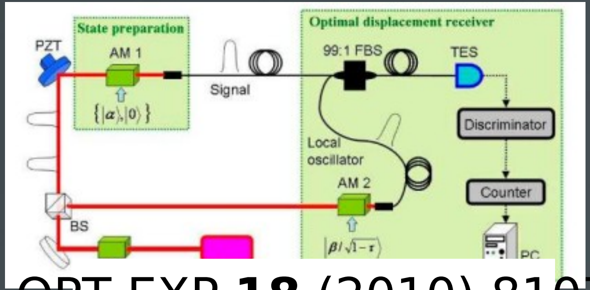




NAT PHOT **4** (2010) 655





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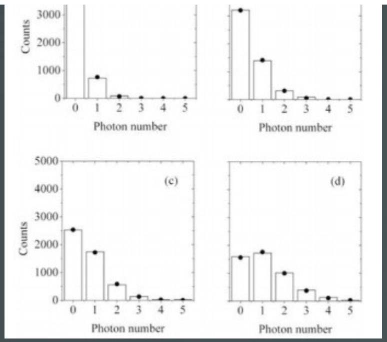
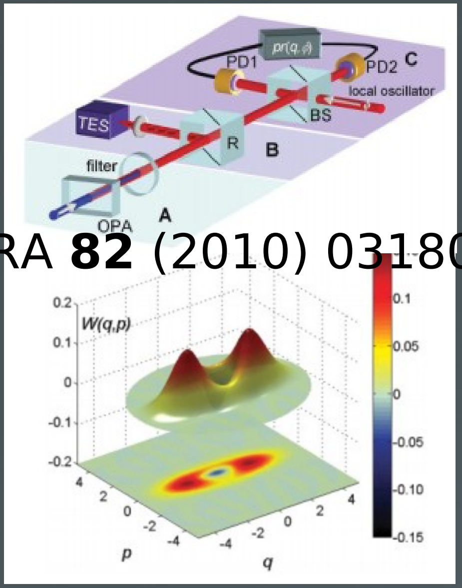
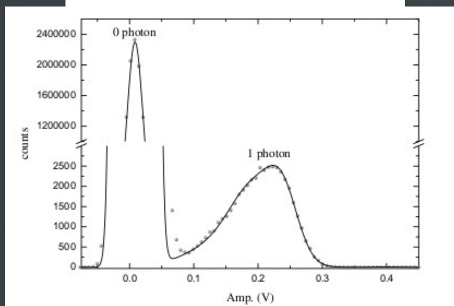




PRA **82** (2010) 031802

Why TESs?

IJQI **9** (2011) 405



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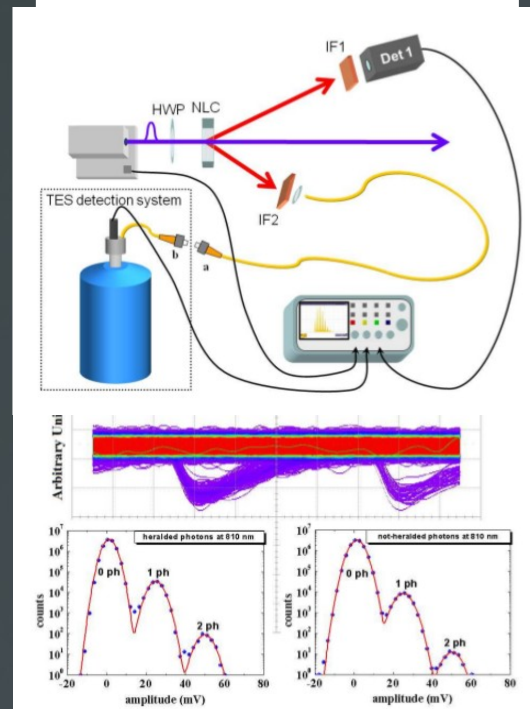
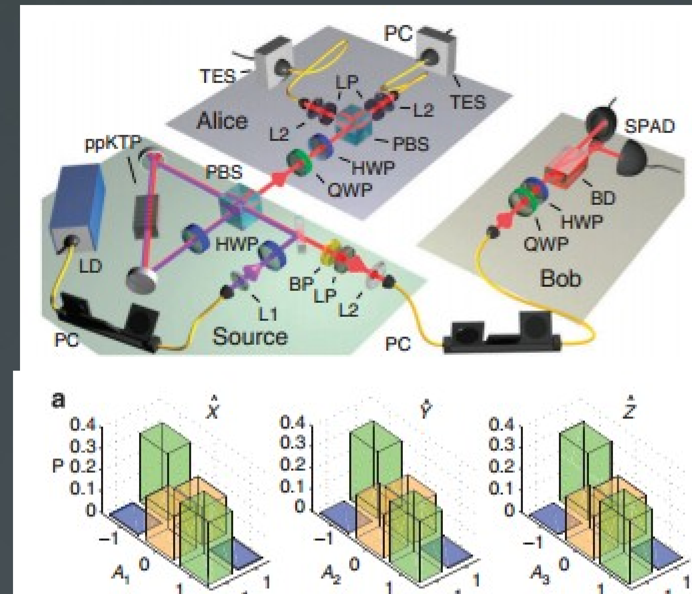
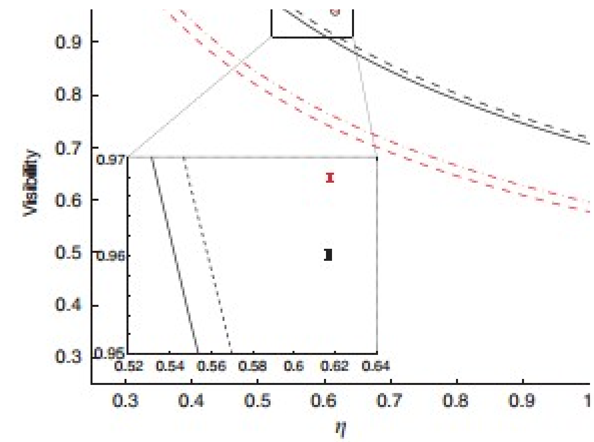
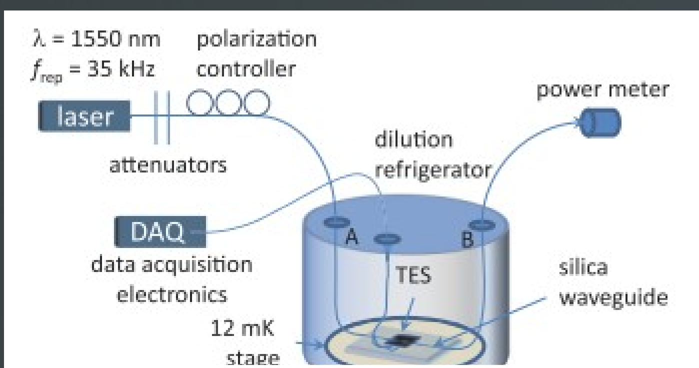


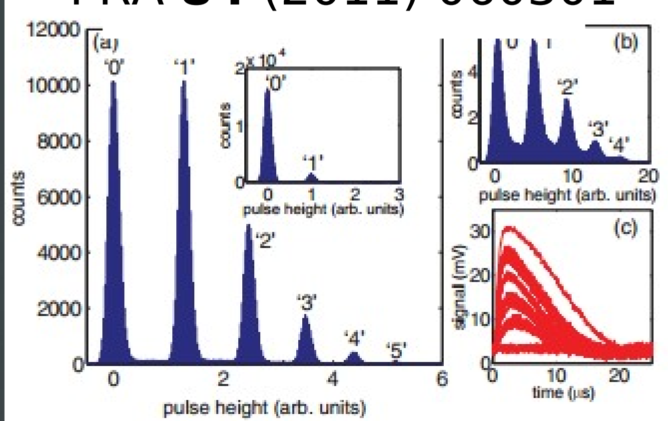


NAT COM **3** (2012) 625

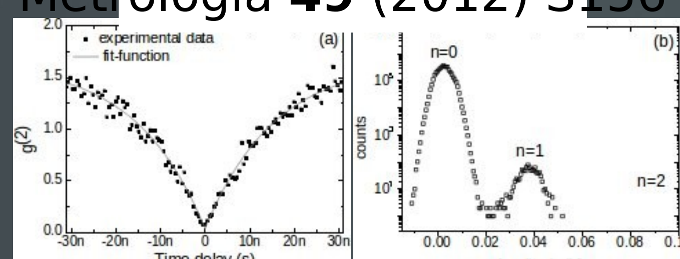




PRA **84** (2011) 060301



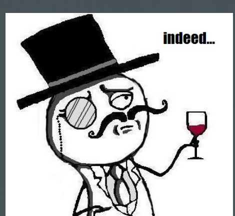
Metrologia **49** (2012) S156



Quantum Land : Visitors and Inhabitant

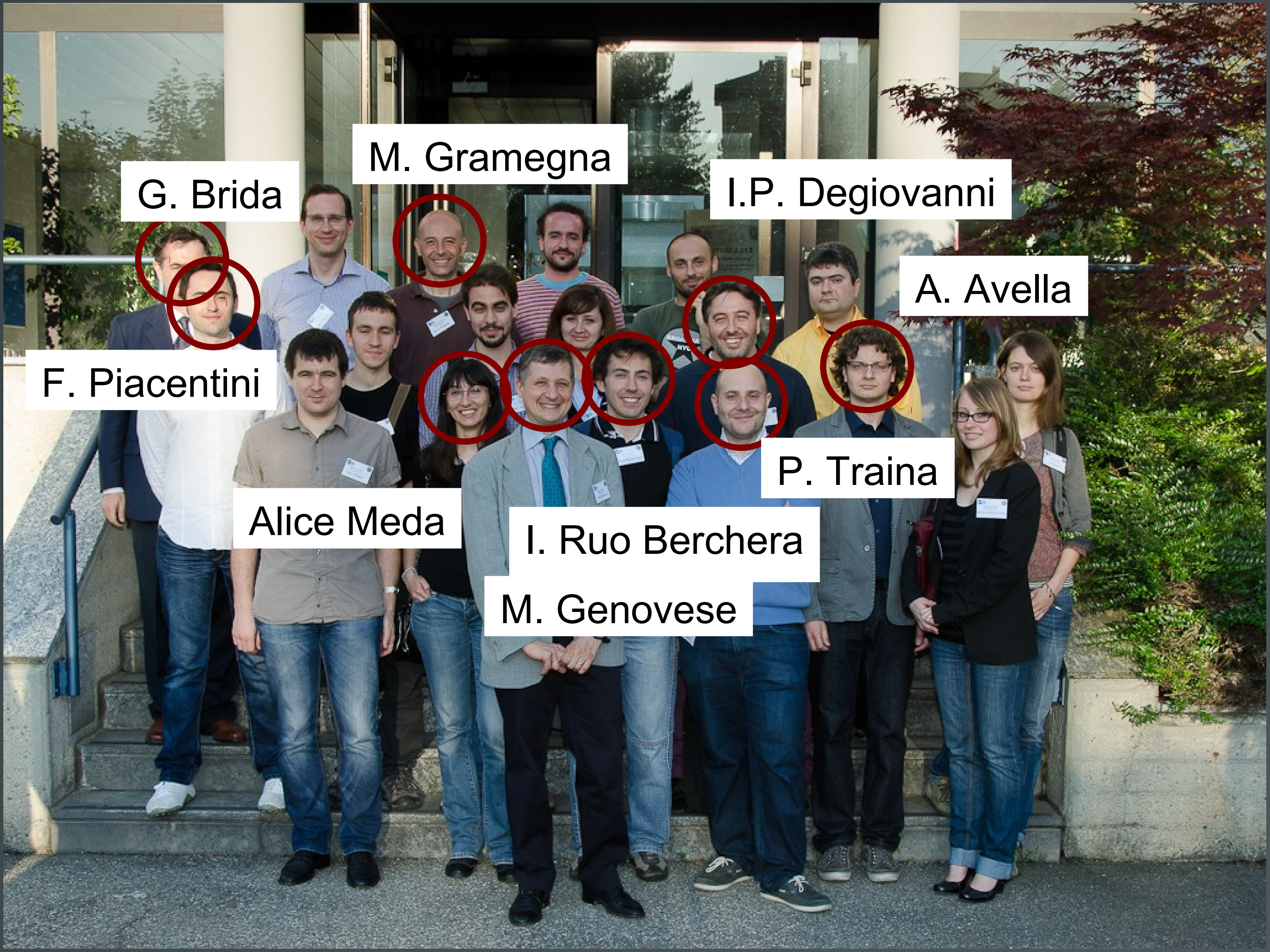
Chiara Portesi

Eugenio Monticone



TES group: Visitors of Quantum Land

Quantum Land : Visitors and Inhabitant



Quantum Optics group: Inhabitant of Quantum Land

What Quantum Inhabitants want

The most important TES characteristics for the quantum land's inhabitant are:

- negligible numbers of dark-counts;
- discrimination of the number of impinging photons;
- high energy resolution;
- very fast response;
- devices with a very high quantum efficiency.

In particular, has been already demonstrate that is possible to fabricate devices with quantum efficiency (QE) over 90%

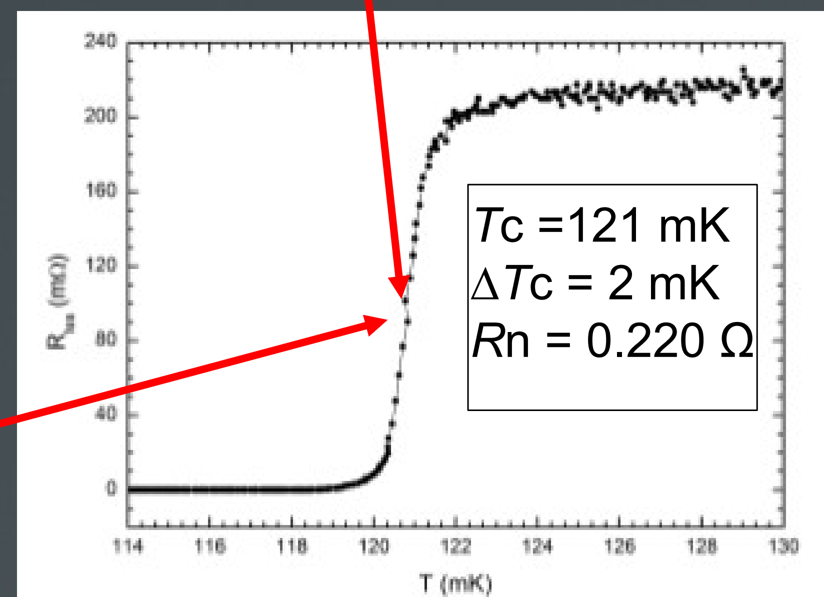
very attractive for performing detection loophole free tests of contextuality, steering and eventually, Bell's inequalities.

What Quantum Visitors offer

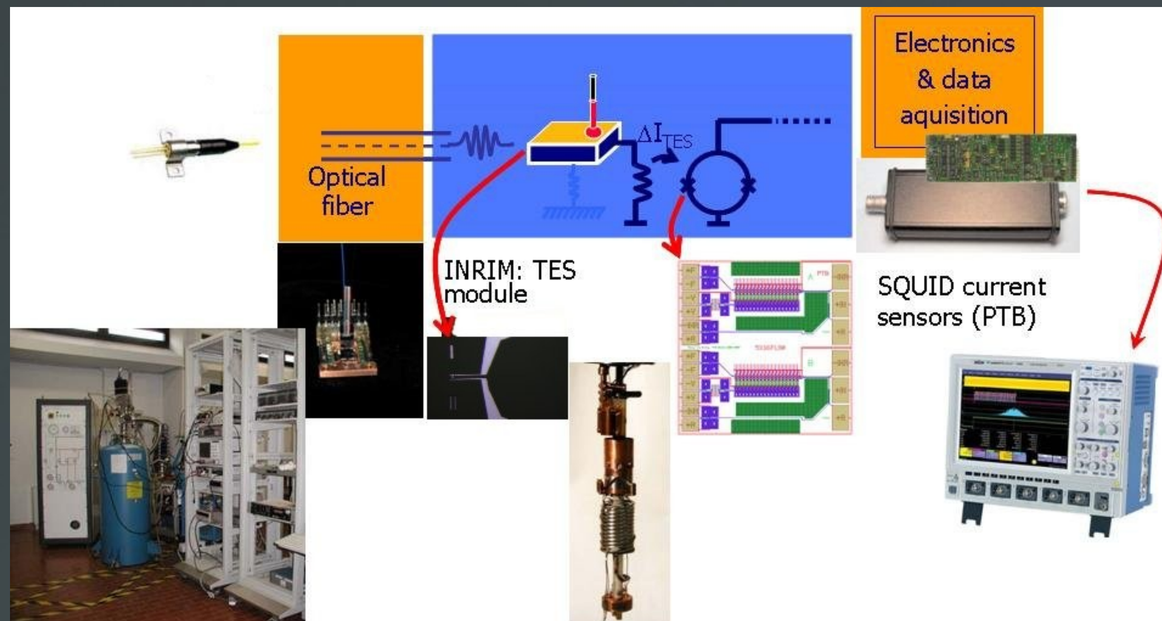
Bilayer – proximity effect

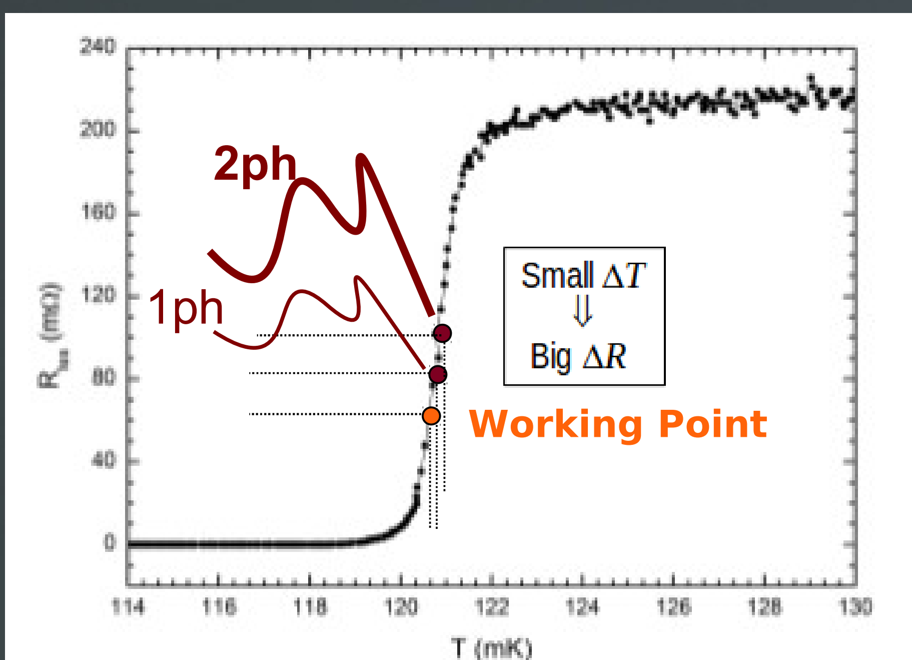
Ti=24 nm, Au=54 nm

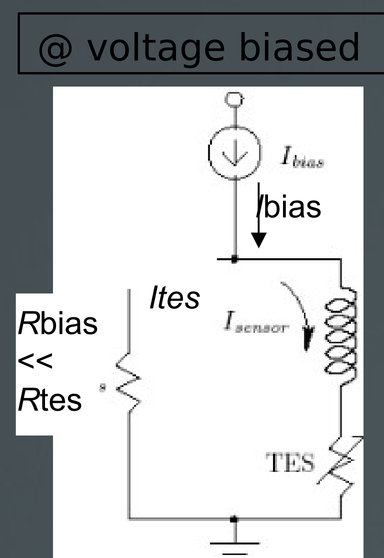
Microcalorimeter based on superconducting thin film working as very sensitive thermometer

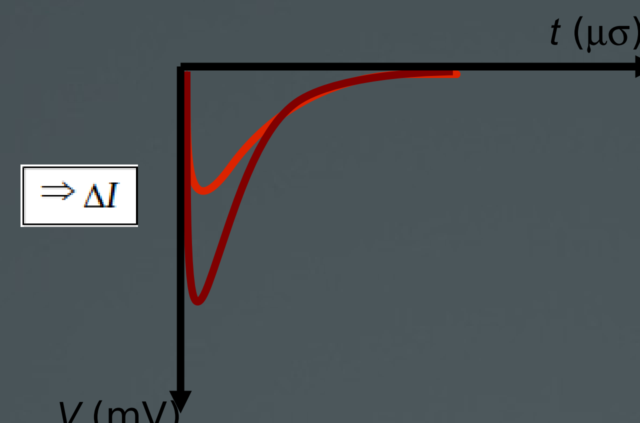


What Quantum Visitors offer

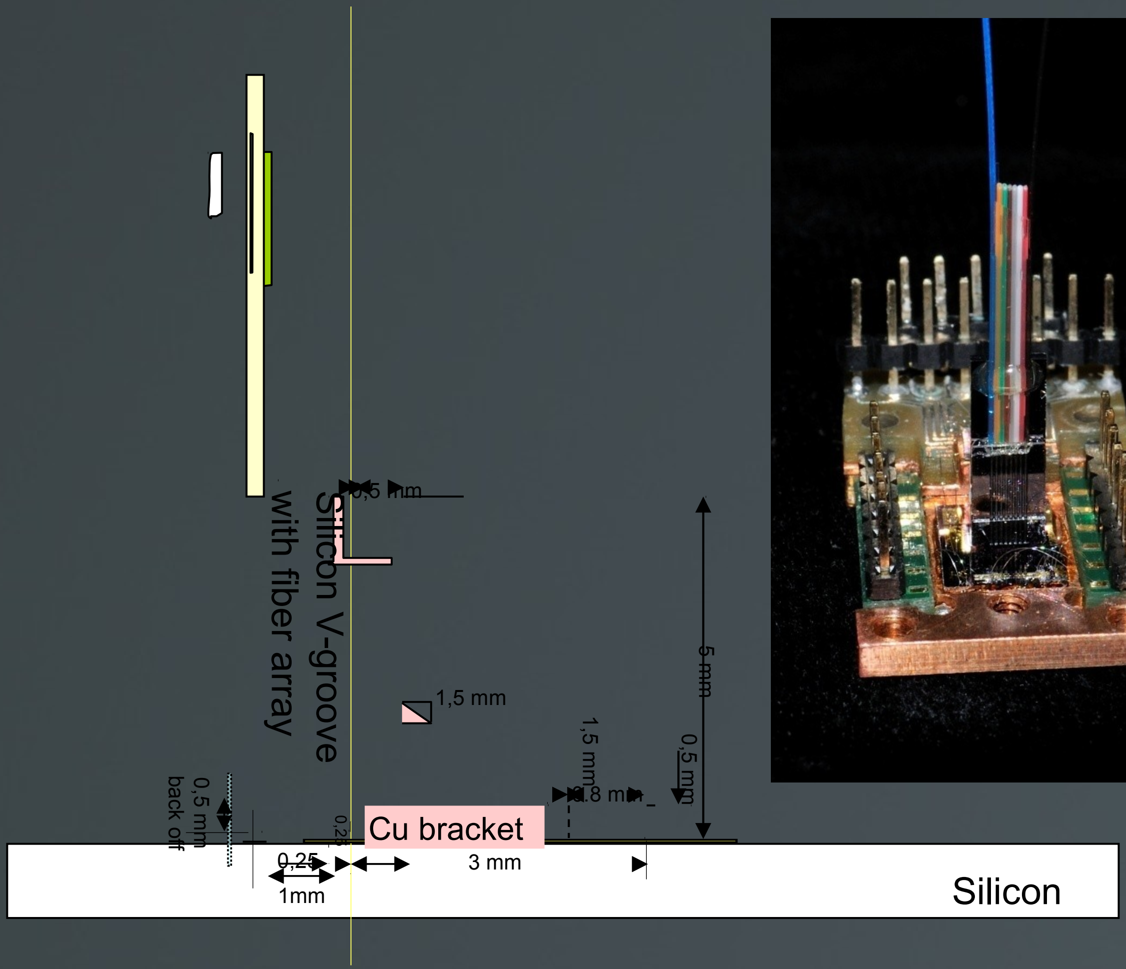


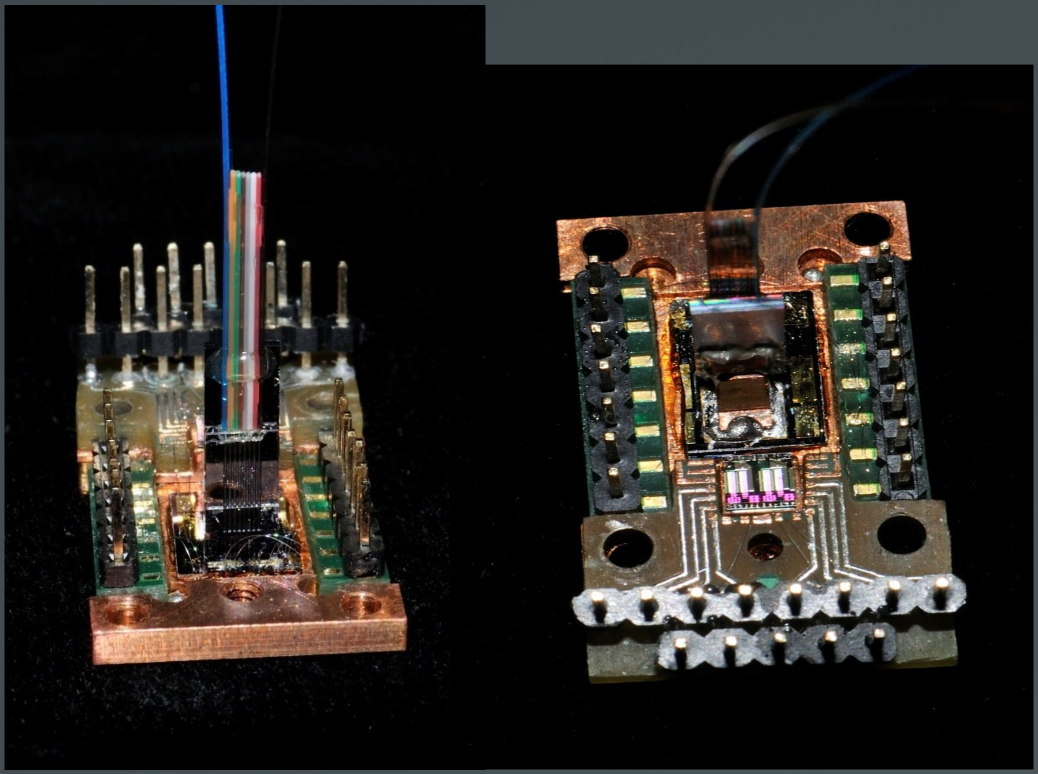




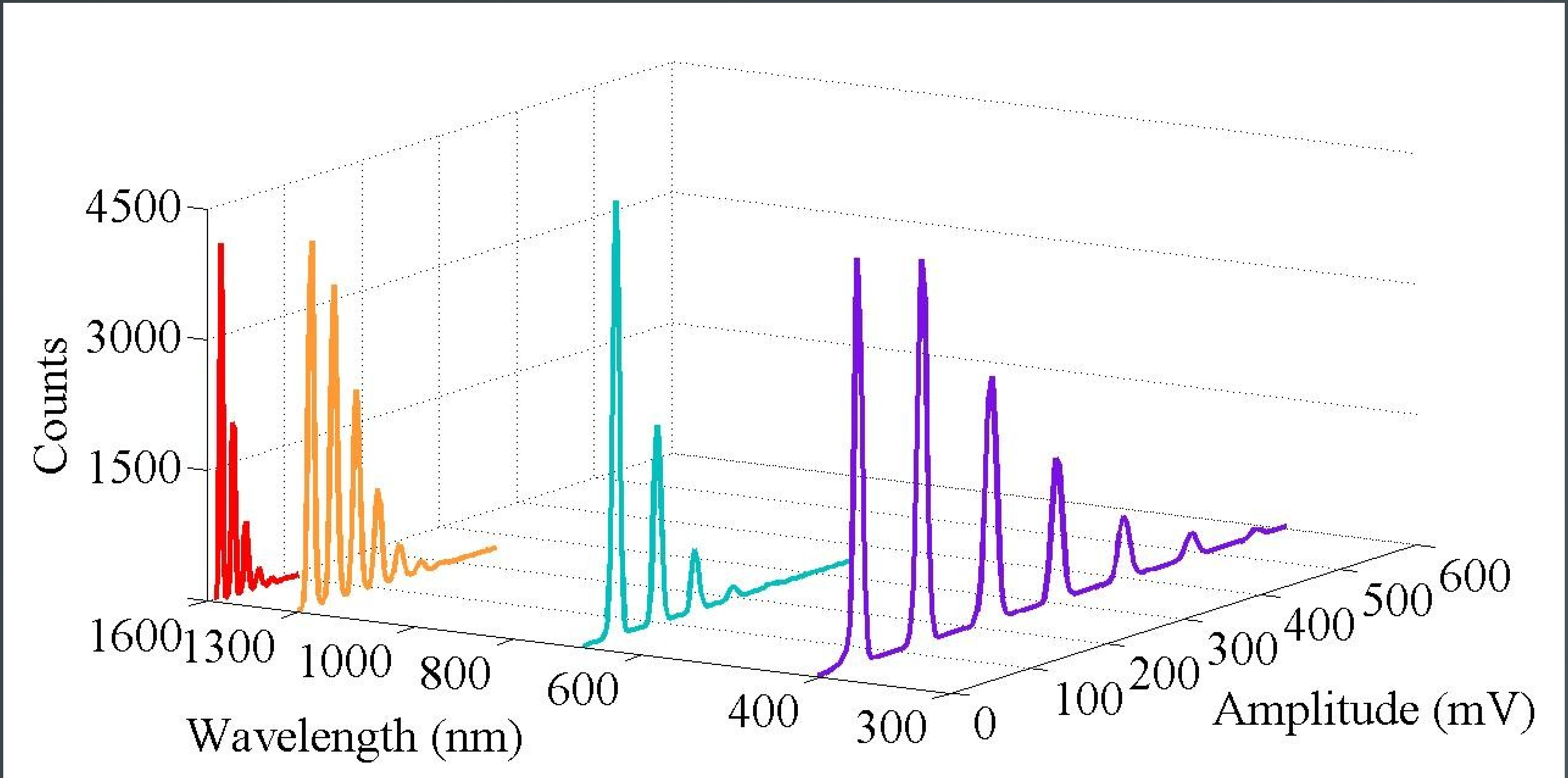


What Quantum Visitors offer

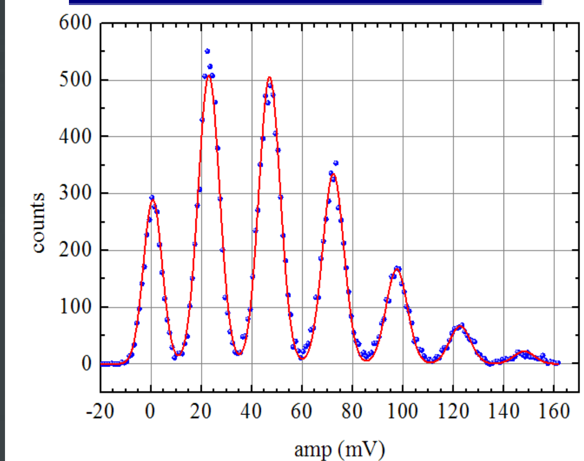




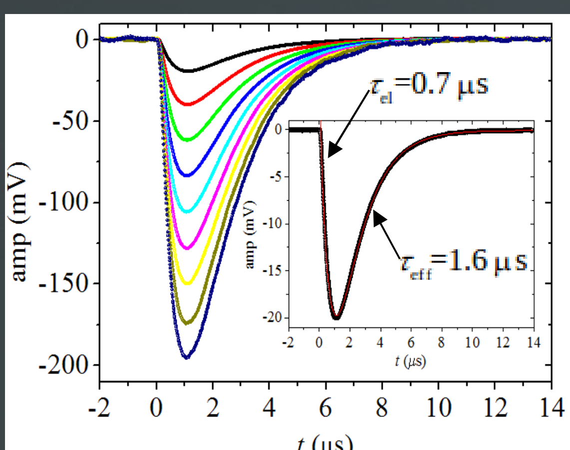
What Quantum Visitors offer



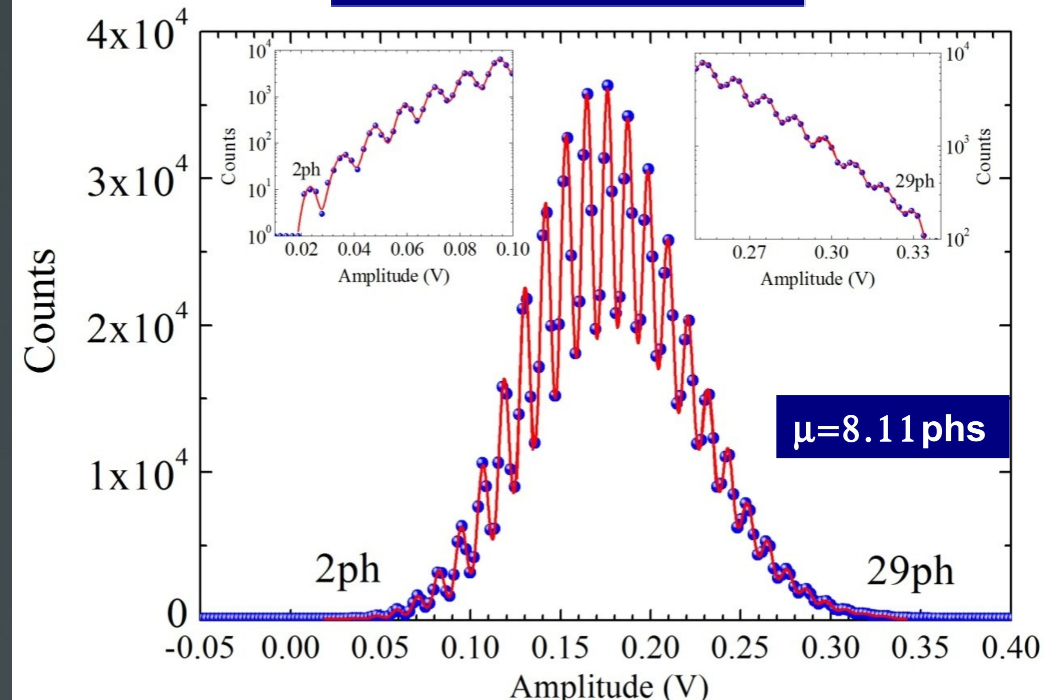
λ=1310 nm, ΔE=0.39 eV

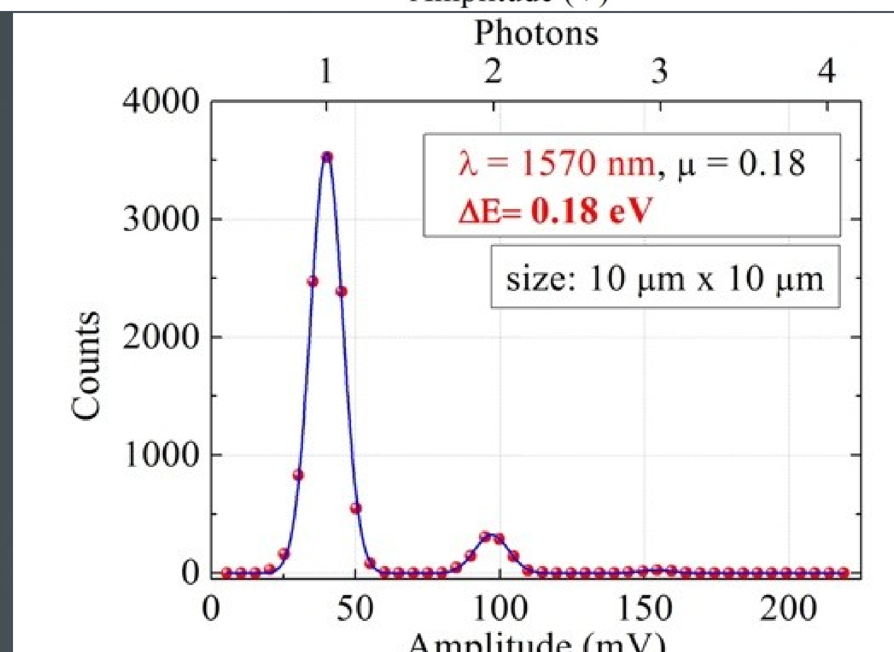


λ=1310 nm
averaged single photon pulses



λ=1570 nm, ΔE=0.51 eV





First steps in Quantum land

TES ABSOLUTE CALIBRATION

A. Avella et al, OPTICS EXPRESS 2011 **19** p. 23249-23257

TES TOMOGRAPHY

G. Brida et al, NEW JOURNAL OF PHYSICS, in Press

g(2) MEASUREMENT

W. Schmunk et al, METROLOGIA 2012 **49** p156-160

TES Absolute Calibration

Klyshko's Absolute Technique for QE Measurement
[Exploiting heralded single photon source based on PDC]

- **Provide an efficient measurement solution in photon counting regime**
- **Well developed for "click/non-click" detector**
- **Extension to the calibration of PNR detector straightforward**

Drawback: Klyshko's technique is not able to exploit the PNR ability of the detector

Proposal and demonstration of an absolute technique for measuring quantum efficiency, based on an heralded single photon source, but exploiting the PNR ability of the detector

A. Avella et al OPTICS EXPRESS 2011 **19** p. 23249-23257

Theory - 1

$P_H(i)$ **Probability of observing i photons per heralding count in the presence of the heralded photon**

$P_A(i)$ **Probability of observing i photons per heralding count in the absence of the heralded photon (i.e. of observing *i* "accidental" counts)**

The probability of observing 0 photons per heralding count :

$$P_H(0) = \xi(1-\gamma)P_A(0) + (1-\xi)P_A(0)$$

Non detection & No accidental   False her.& No accidental

$\gamma = \tau\eta$ **"Total" Quantum Efficiency of the PNR detector**
τ ***optical and coupling losses***
η **detector proper Quantum Efficiency**

ξ **Probability of having a True Heralding Count (not due to stray-light or dark counts)**

Theory - 2

The probability of observing i photons per heralding count

$$P_H(i) = \xi\left[(1-\gamma)P_A(i) + \gamma P_A(i-1)\right] + (1-\xi)P_A(i)$$

From each $P_H(i)$ a value of "Total" Quantum Efficiency can be estimated *Consistency Test*

From the probability of *0* →

$$\gamma_0 = \frac{P_A(0) - P_H(0)}{\xi P_A(0)}$$

From the probability of *i* →

$$\gamma_i = \frac{P_H(i) - P_A(i)}{\xi\left[P_A(i-1) - P_A(i)\right]}$$

Hp of the Klyshko's Technique: multiphoton PDC events negligible

Experimental Setup - 1

Heralded Single-Photon Source

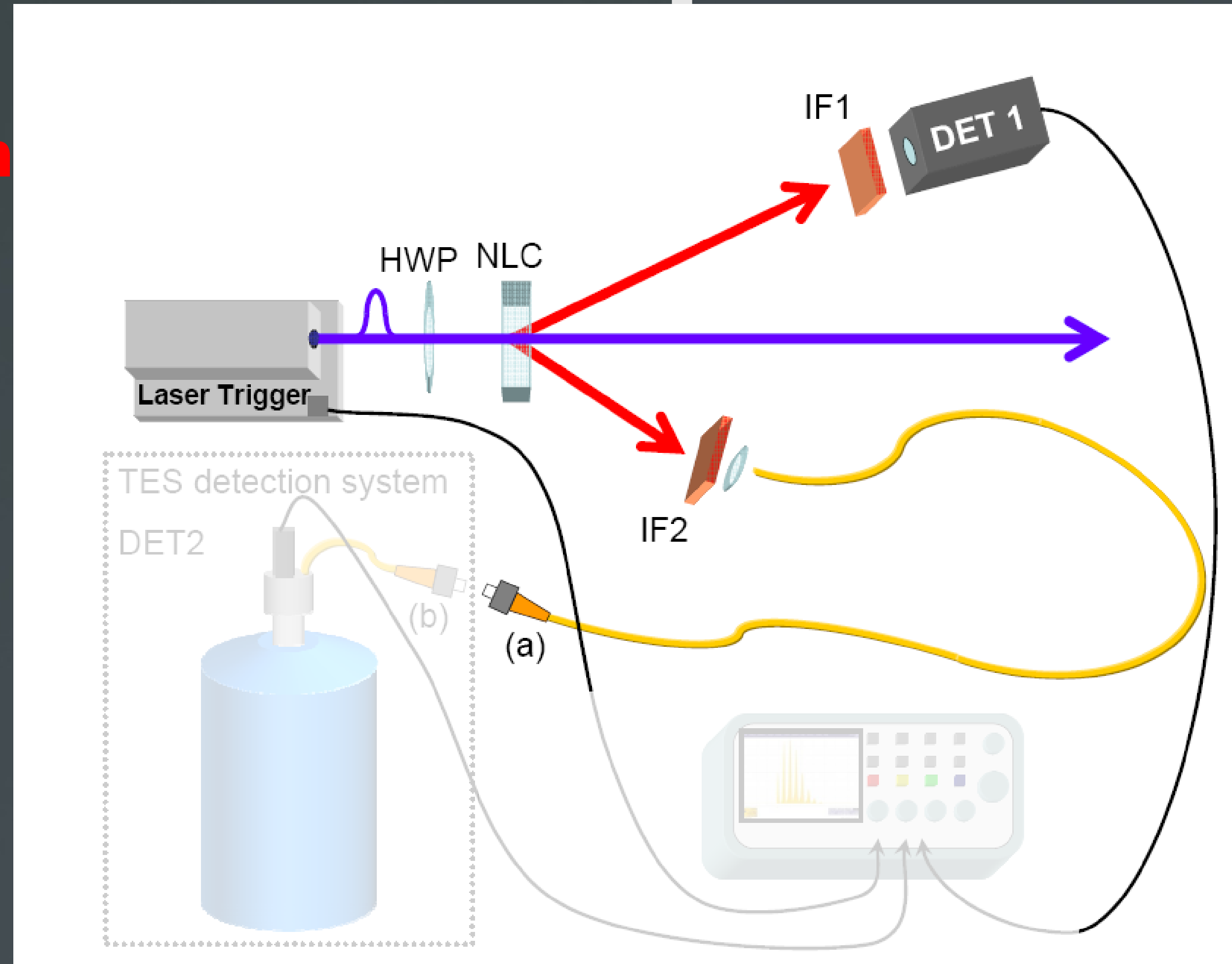
Pulsed Pump @ 406 nm
40 KHz, pulse 80 ns long
(<*TES Deadtime and Jitter*)

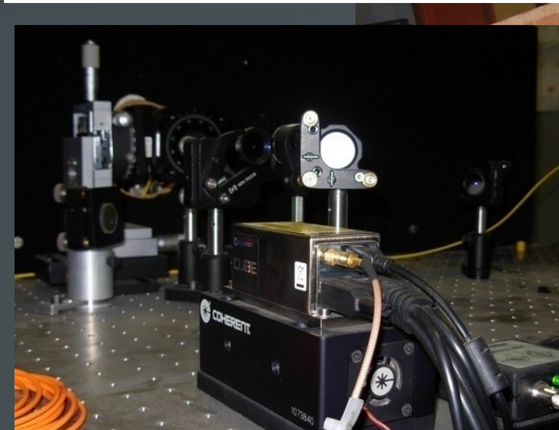
Non-collinear Degenerate PDC (@ 812 nm)

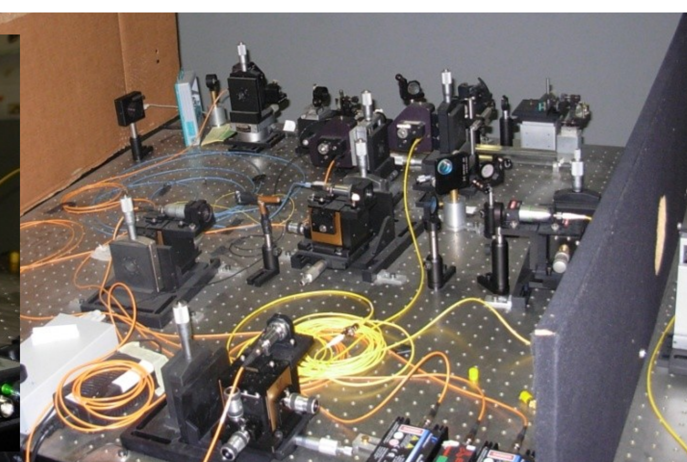
Heralding Ch.:
IF1 FWHM= 1nm
Det1: SPCM-AQR-14
True HC

Heralded Ch.:
IF2 FWHM=10nm
Optical and Coupling losses: τ

$\xi=0.98793\pm0.00007$

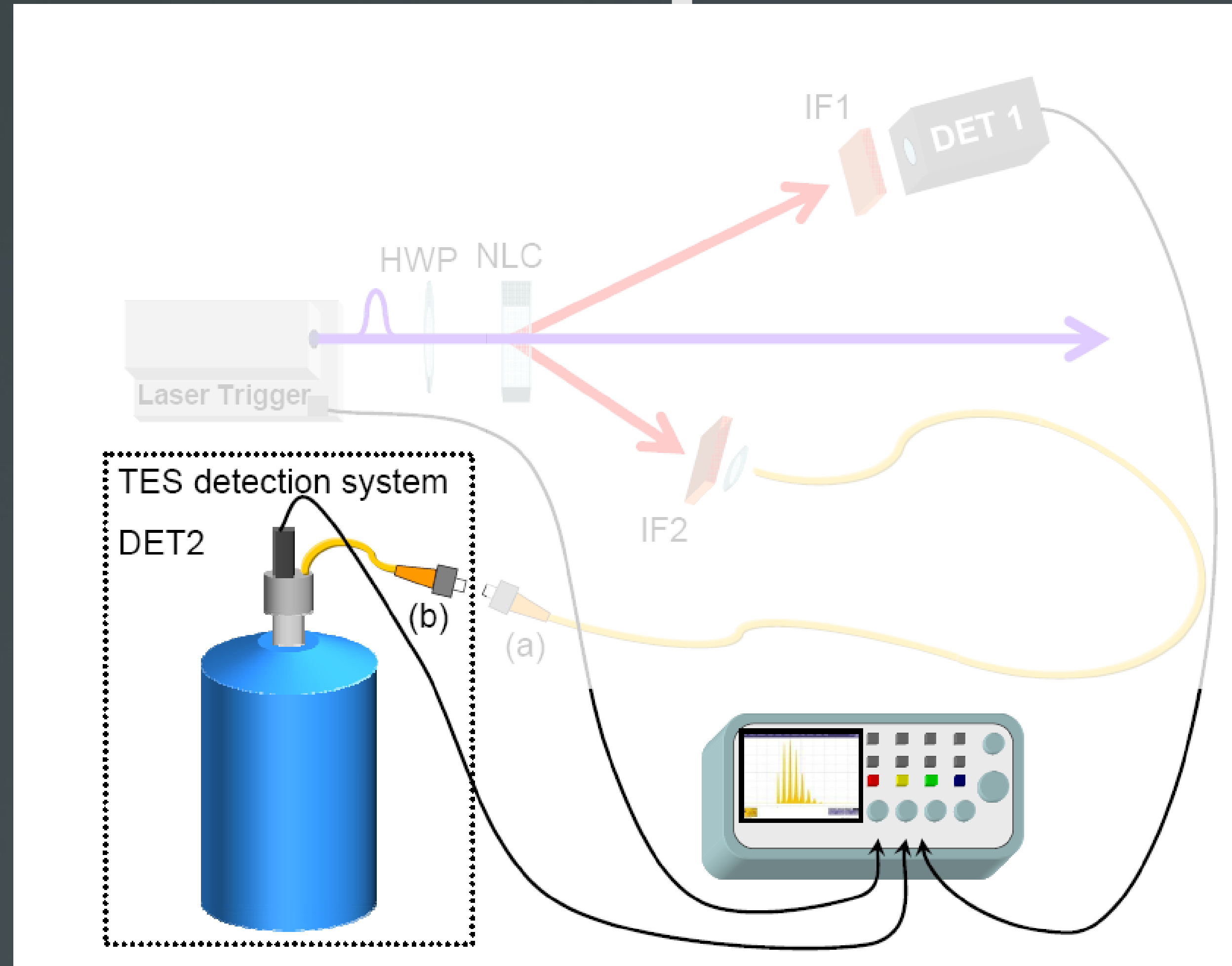




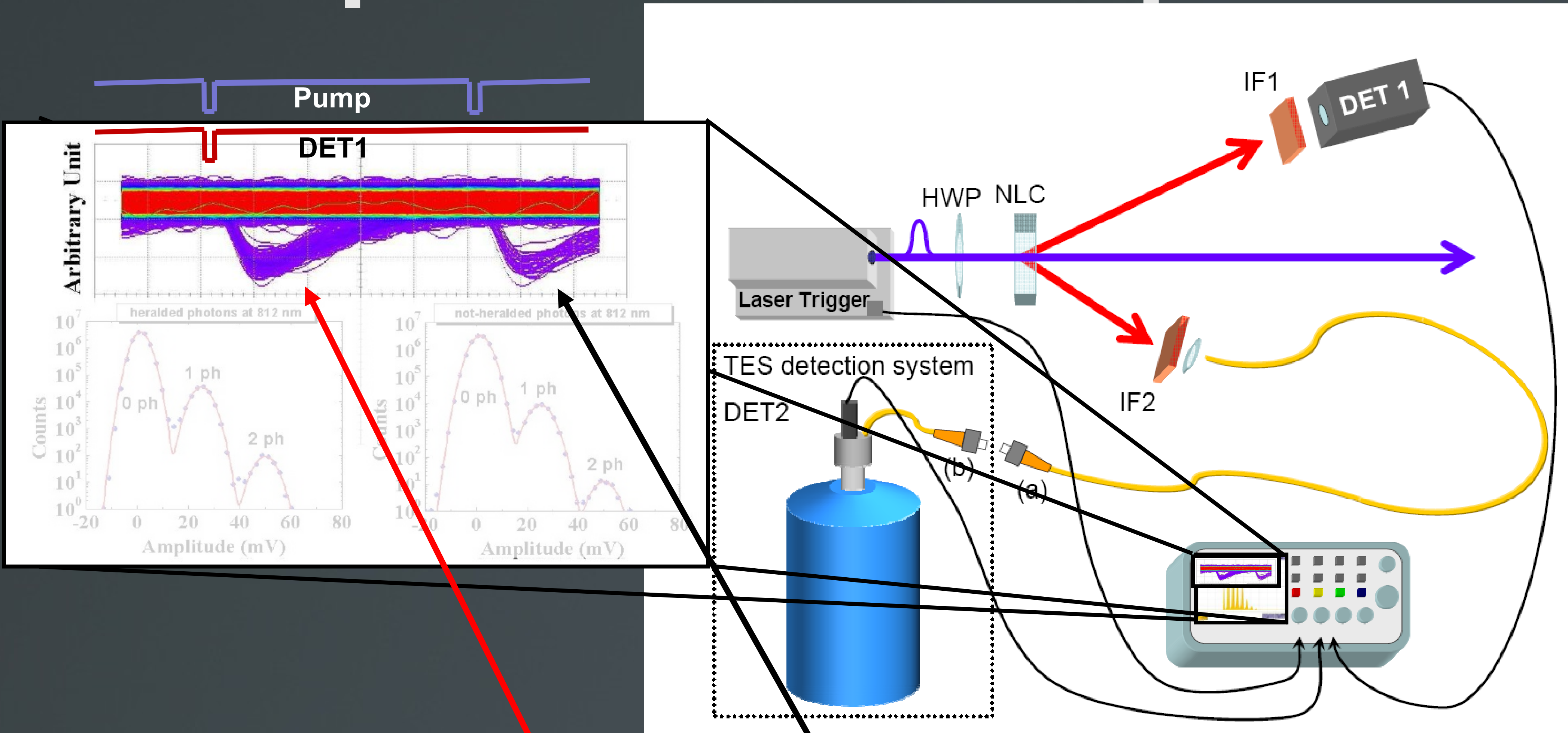


Experimental Setup - 2

η **Quantum Efficiency of the TES detector:** **TES detector is the system from the fibre end (b) to the sensitive area** (*as this represents the real detector for applications*)



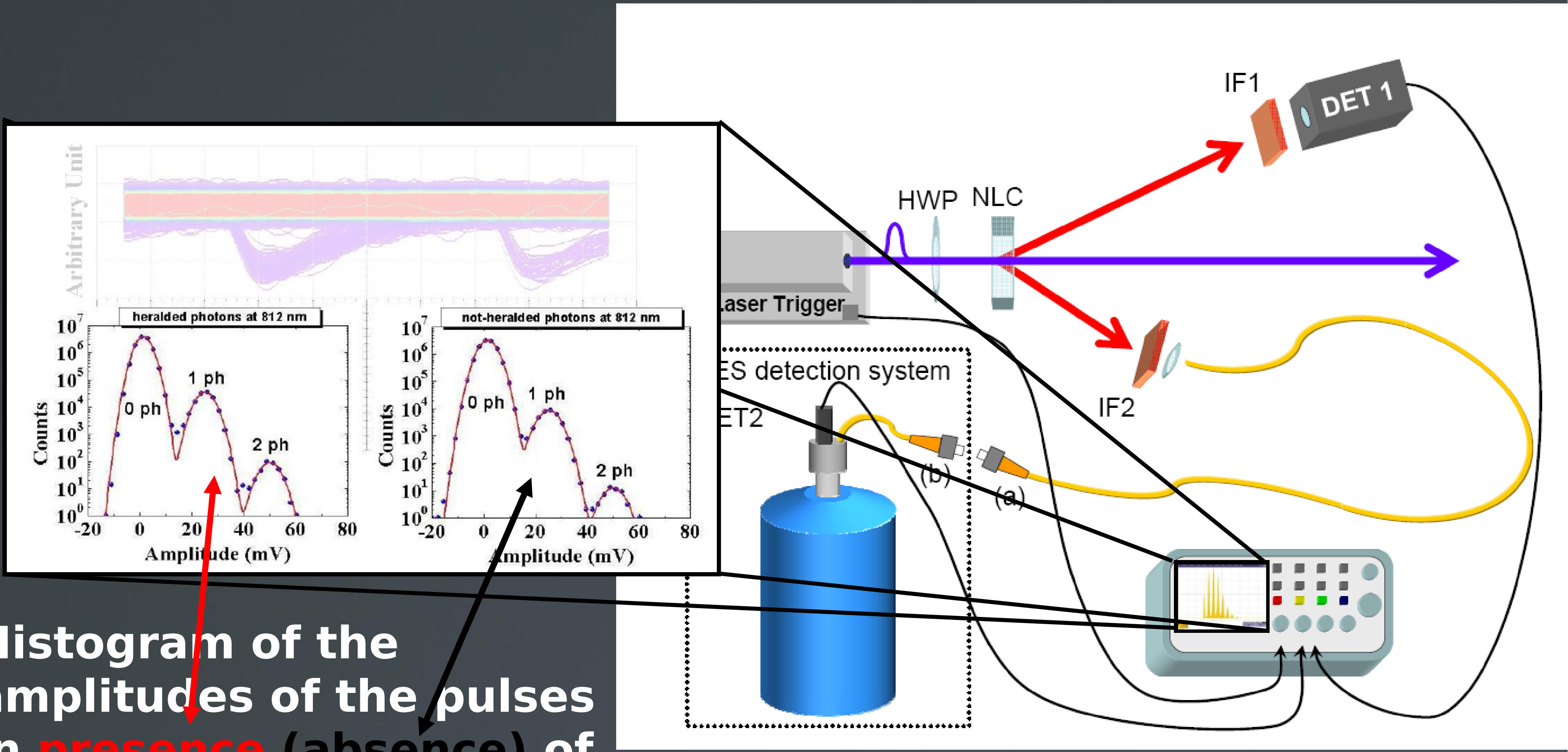
Experimental Setup - 3



Oscilloscope Triggered by DET1 Heralding signal & Pump trigger

Oscilloscope Screen-shot with traces of the TES detected events in the presence (absence) of heralded photon

Results - 1



Histogram of the amplitudes of the pulses in presence (absence) of heralding signals. (Gaussian fit)

Number of counted events corresponding to i detected photons in the presence $C(i)$ (absence $\mathcal{C}(i)$)

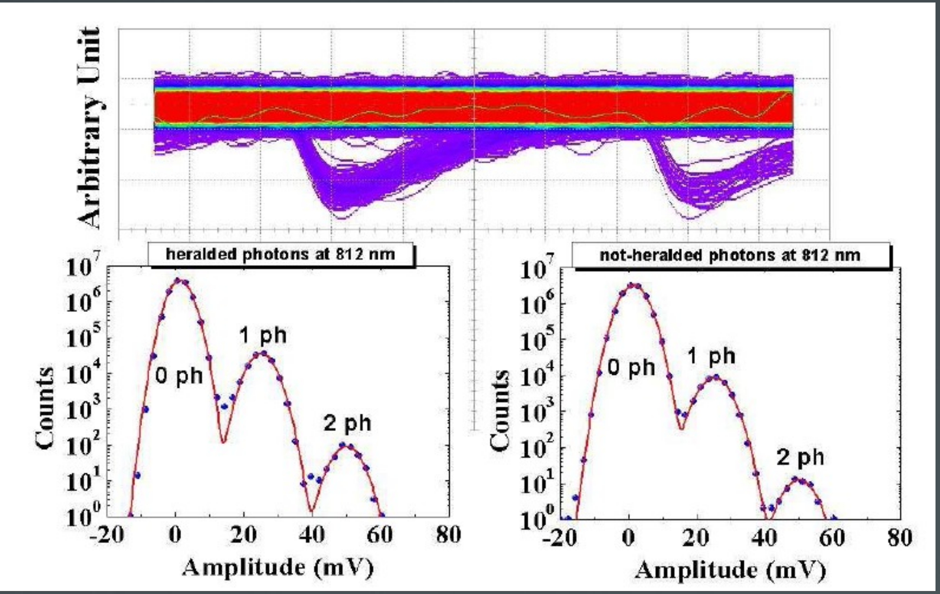
$$P(i) = C(i)/\sum_i C(i)$$
$$\mathcal{P}(i) = \mathcal{C}(i)/\sum_i \mathcal{C}(i)$$

Results - 2

Measured "Total" Quantum Efficiency

γ_0=(0.709±0.003)%
γ_1=(0.709±0.003)%
γ_2=(0.65±0.05)%

6 Repeated meas each 5 hr. long >5 106 counts



High uncertainty in γ_2 due to poor statistics

All the values are in agreement within the uncertainty (k=1)

The material of the TES surface suggest a ≈49% Quantum Effciency, while the optical losses are estimated to be 10%.
Thus, the geometrical and optical losses inside the refrigerator contribute to lower the value of the Quantum Efficiency to 7%.

A. Avella et al, OPTICS EXPRESS 2011 **19** p. 23249-23257

TES Tomography

General assumptions for TESs:
- linear photon counters
- detection process correspond to a binomial convolution
- dark counts are not present

It is possible to characterize TES by a single number: quantum efficiency η

We need the first demonstration of these assumptions with experimental verification

For this we perform a tomographic reconstruction of the **positive operator valued measure (POVM)** corresponding to our device.

This technique is based on recording the detector response for a known and suitably chosen quorum of input states, e.g. an ensemble of coherent signals providing a sample of the Q-function $\Pi_{nm}=\langle\alpha_j|\Pi_n|\alpha_j\rangle$ of the POVM describing the detector response to m incident phs.

k=n° coherent states
$|\alpha_j\rangle$=amplitude

$$p_{nj} = \mathrm{Tr}[|\alpha_j\rangle\langle\alpha_j|\Pi_n] = \sum_m \Pi_{nm}\, q_{mj}$$

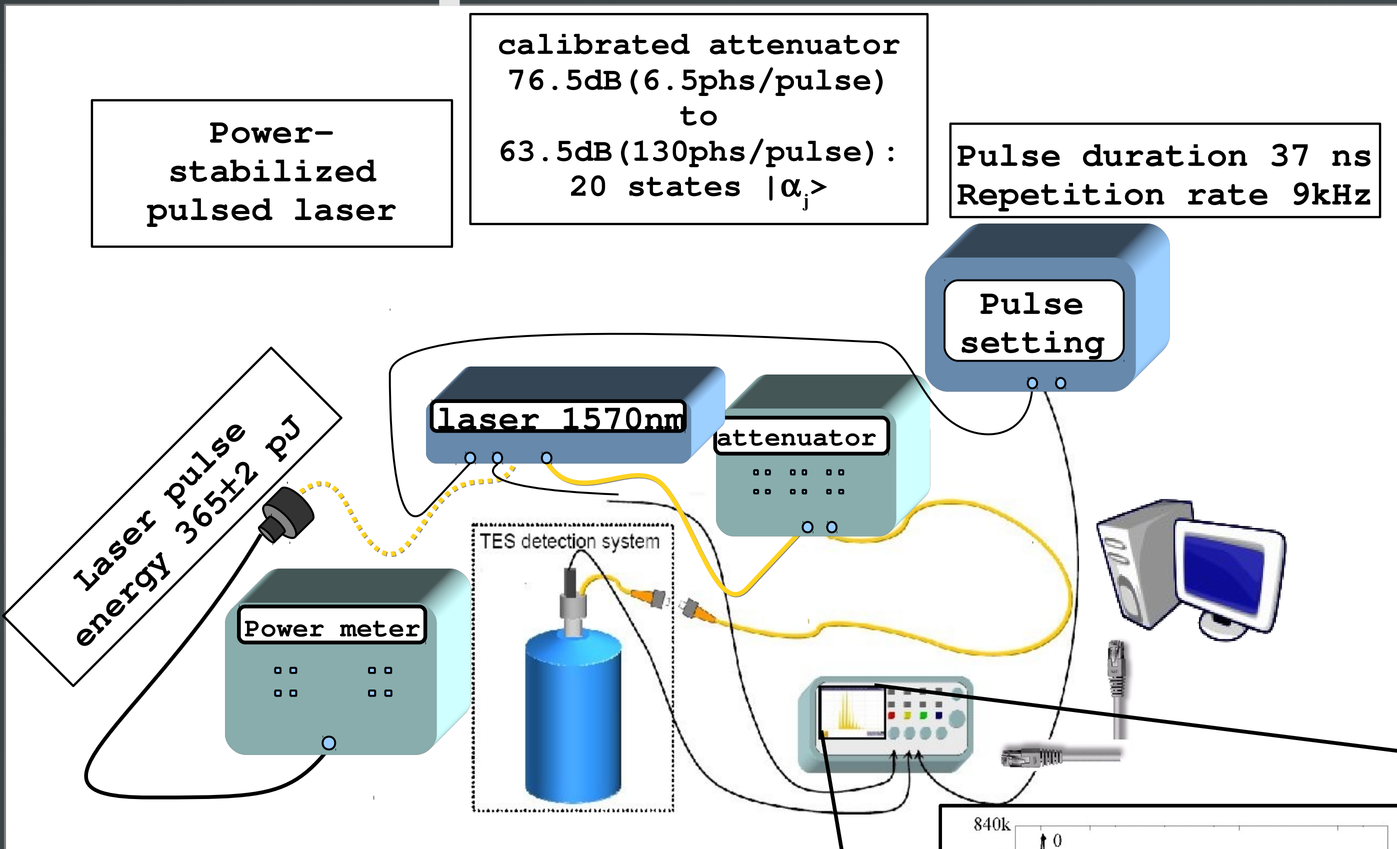
Ideal photons statistics of the coherent states

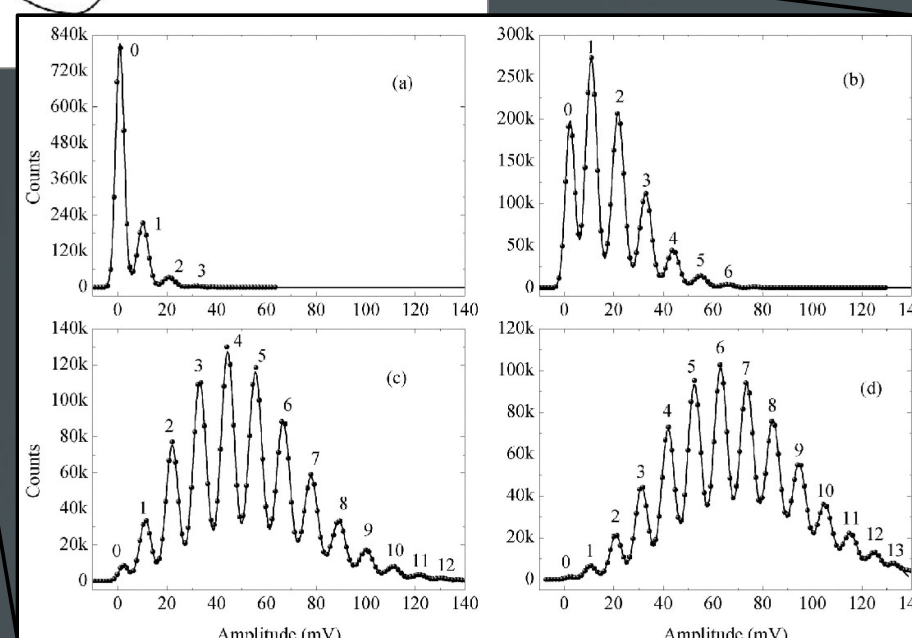
what we measure: probability of detecting n phs with j-th states as input with m incident phs

Estimated minimizing with least square

$$\sum_{nj}\left(\sum_{m=0}^{M-1} q_{mj}\,\Pi_{nm} - p_{nj}\right)^2$$

Experimental Setup





In order to obtain the number of events of the n-th peak, one integrates the corresponding independent Gaussian.

The distributions p_{nj} are finally evaluated upon normalizing the histograms

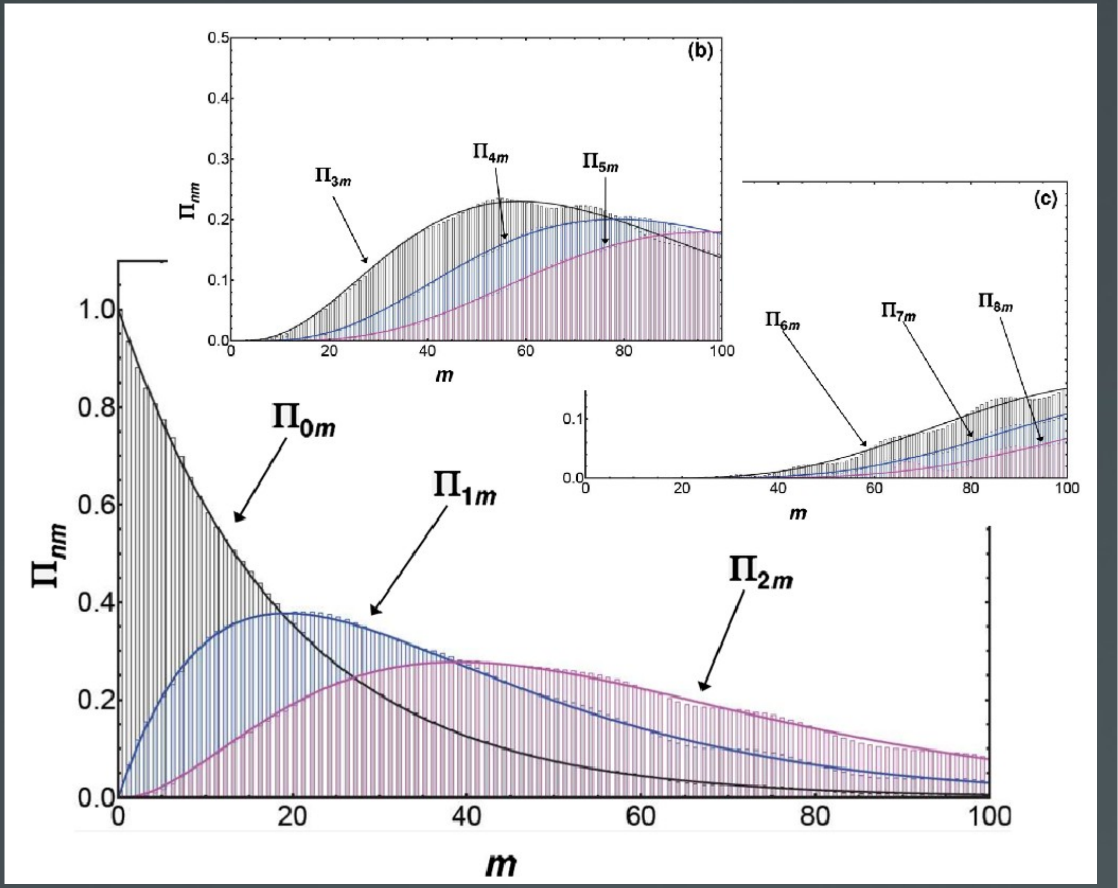
Results - 1

Matrix elements Π_{nm} of the first 9 POVM operators for $0 \le m \le 100$

Analysis made for:
Incoming phs $m \le M = 140$
Detected phs n from 1 to N
N=12 POVM elements Π_n

Histogram bars=reconstructed Π_n $\quad \Pi_n = \sum_{m=n}^{\infty} B_{nm} |m\rangle\langle m|$

Lines denote the matrix element of linear detector following binomial distributions of the ideal photon number spectral measure with $B_{nm} = \binom{m}{n} \eta^n (1-\eta)^{m-n}$

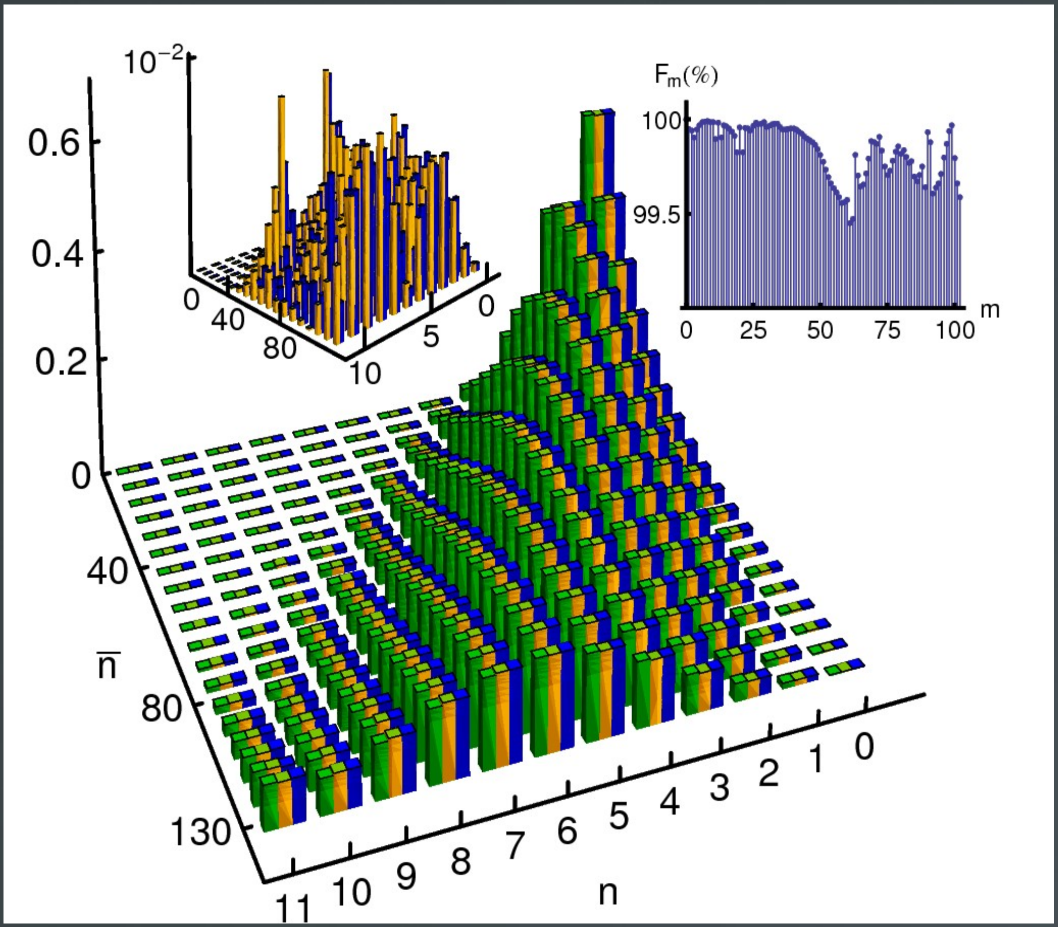


To compare POVM elements of linear det. with POVM of reconstructed elements we needed quantum efficiency $\eta = (5.08 \pm 0.04) \times 10^{-2}$, estimated by log-likelihood function

$$L_j = \sum_n N_{nj} \log \left(\sum_m B_{nm} q_{mj} \right)$$

Results - 2

$|p_{nj}-l_{nj}|$ yellow bars
$|p_{nj}-r_{nj}|$ blue bars



excellent agreement with η estimated
Fidelity>99% for 0<m<100
Fidelity >95% for 100<m<140

$$F_m = \sum_n \sqrt{\Pi_{nm} B_{nm}}$$

To confirm linearity hyp and reconstruction reliability we compare measured p_{nj} (green bars) with:

- that obtained under linear hyp $l_{nj} = \eta^n \exp(-\eta \bar{n}_j) \bar{n}_j^n / n!$ (blue bars)
- that obtained using POVM elements $r_{nj} = \sum_{m=n}^{M} \Pi_{nm} q_{mj}$ (yellow bars)

We introduce the possibility of dark-count (γ) so POVM are given by $\Pi_{nm} = \exp(-\gamma) \sum_j \gamma^j / j! \, B_{(n-j)m}$ and with ML we estimate the same value for η and γ=(-0.03±0.04)

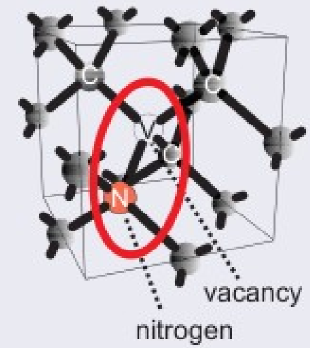
As shown from the plot, we have an excellent agreement between the different determinations of the distribution

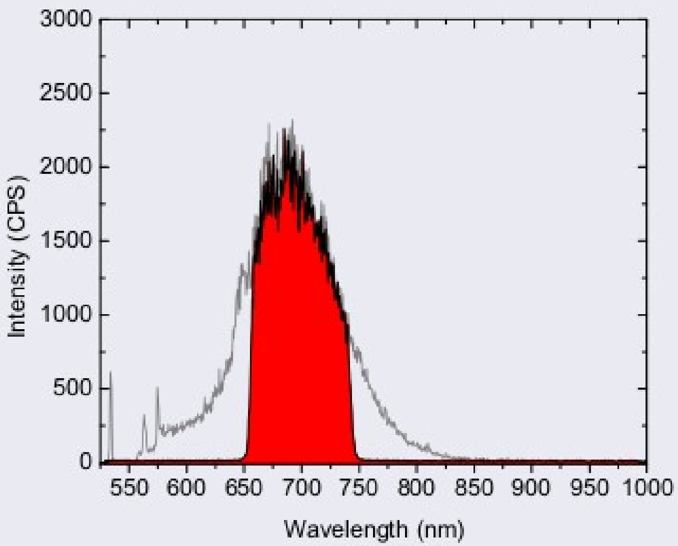
G. Brida et al, NEW JOURNAL OF PHYSICS, in Press

g(2) measurements

Basic properties of nitrogen-vacancy (N-V) centers

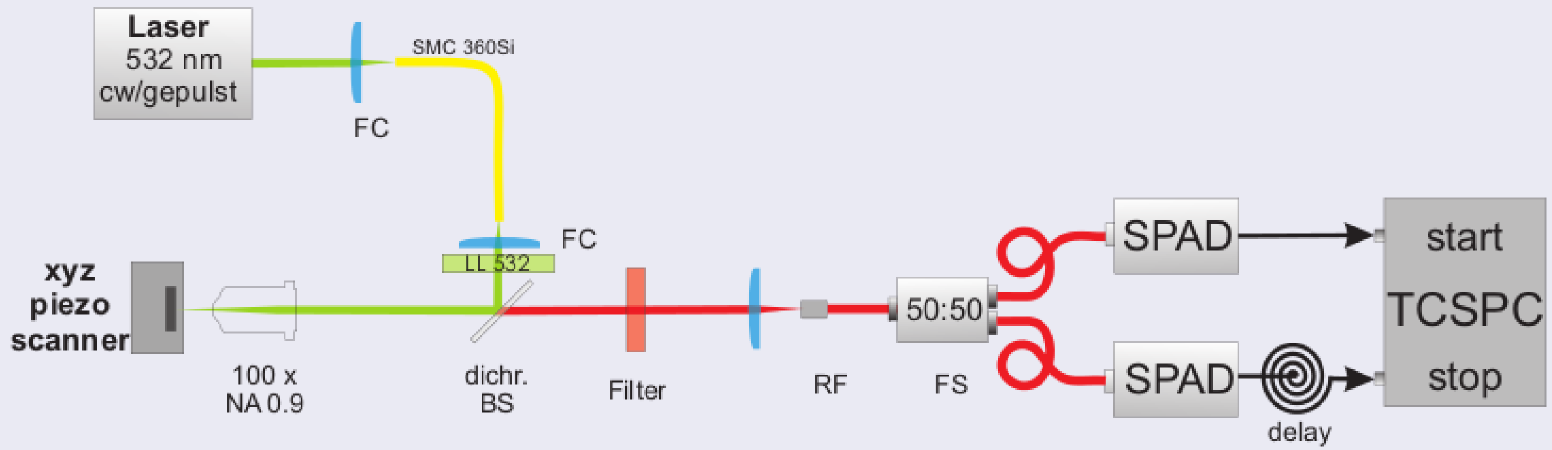
- Simple setup
- Room temperature handling
- Extreme photo stability
- Bright single photon emission
  today up to $\sim 10^6$ photons per second
- Short decay time $\tau \sim 8 - 30$ ns
- Broad luminescence spectrum
- N-V defects in nano diamonds:
  minimization of limitations due the high refractive index of diamond





g(2) measurements

Confocal setup with Hanbury Brown-Twiss interferometer



- $g^{(2)}(t) = \frac{\langle I(\tau)I(\tau+t)\rangle}{\langle I(\tau)\rangle^2} = \frac{N_c}{N_1 \cdot N_2 \cdot T \cdot \Delta\tau}$

  N_c - number of coincidence events, $N_{1/2}$ - count rate of each detector, T - measurement time and $\Delta\tau$ - time bin of coincidence electronic
- $g^{(2)}(0) = 1 - \frac{1}{n}$

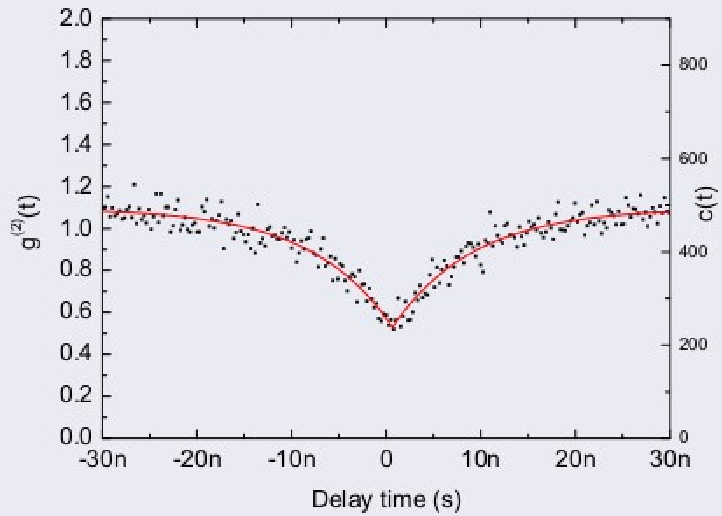
  n - number of single emitters

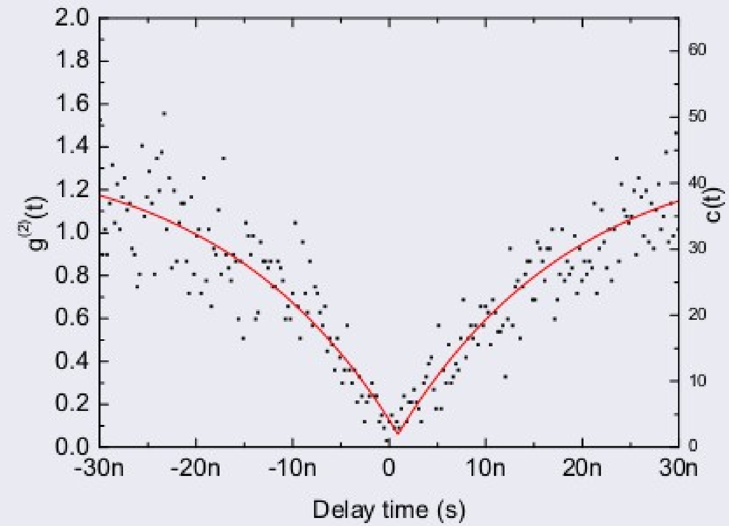
g(2) measurements

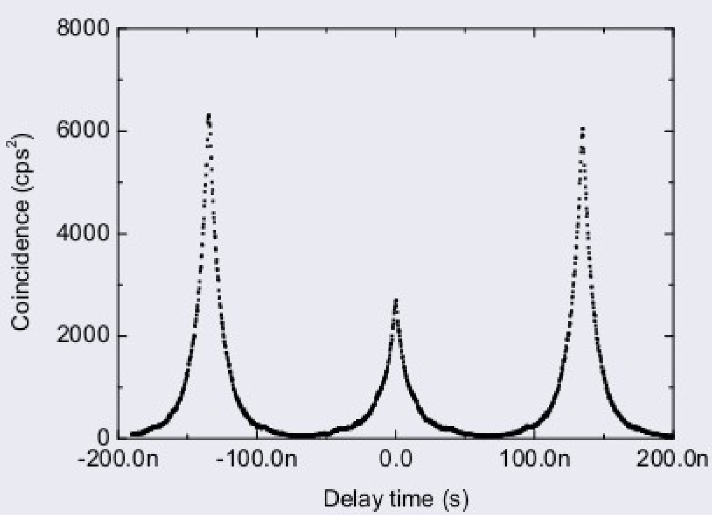
HBT interferometer measurements

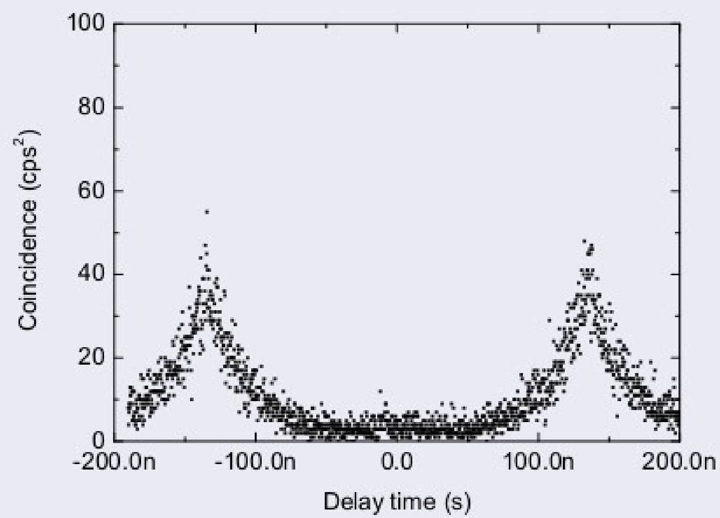
Center 1: $g^{(2)}(0) = 0.53 \pm 0.02$

Center 2: $g^{(2)}(0) = 0.06 \pm 0.03$





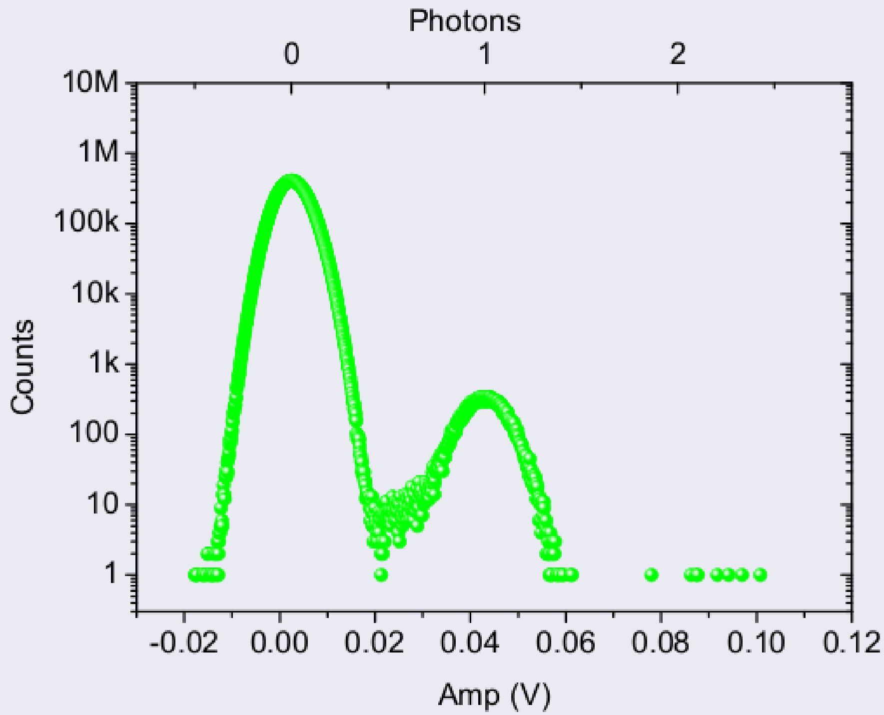




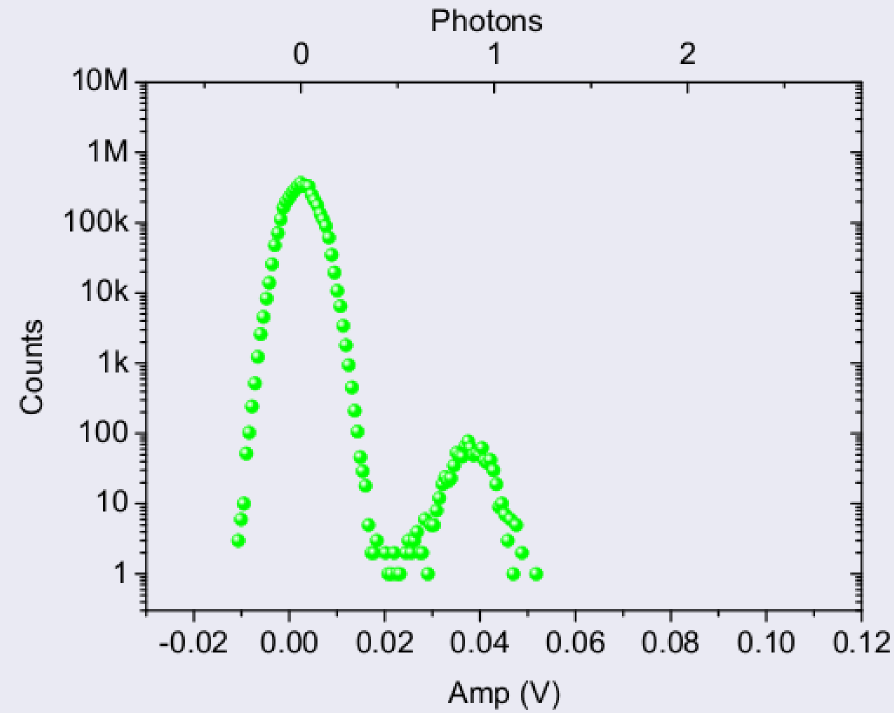
g(2) measurements

Photon number distribution of the N-V centers

Center 1: $g^{(2)}(0) = 0.5 \pm 0.1$



Center 2: $g^{(2)}(0) = 0 + 0.1$



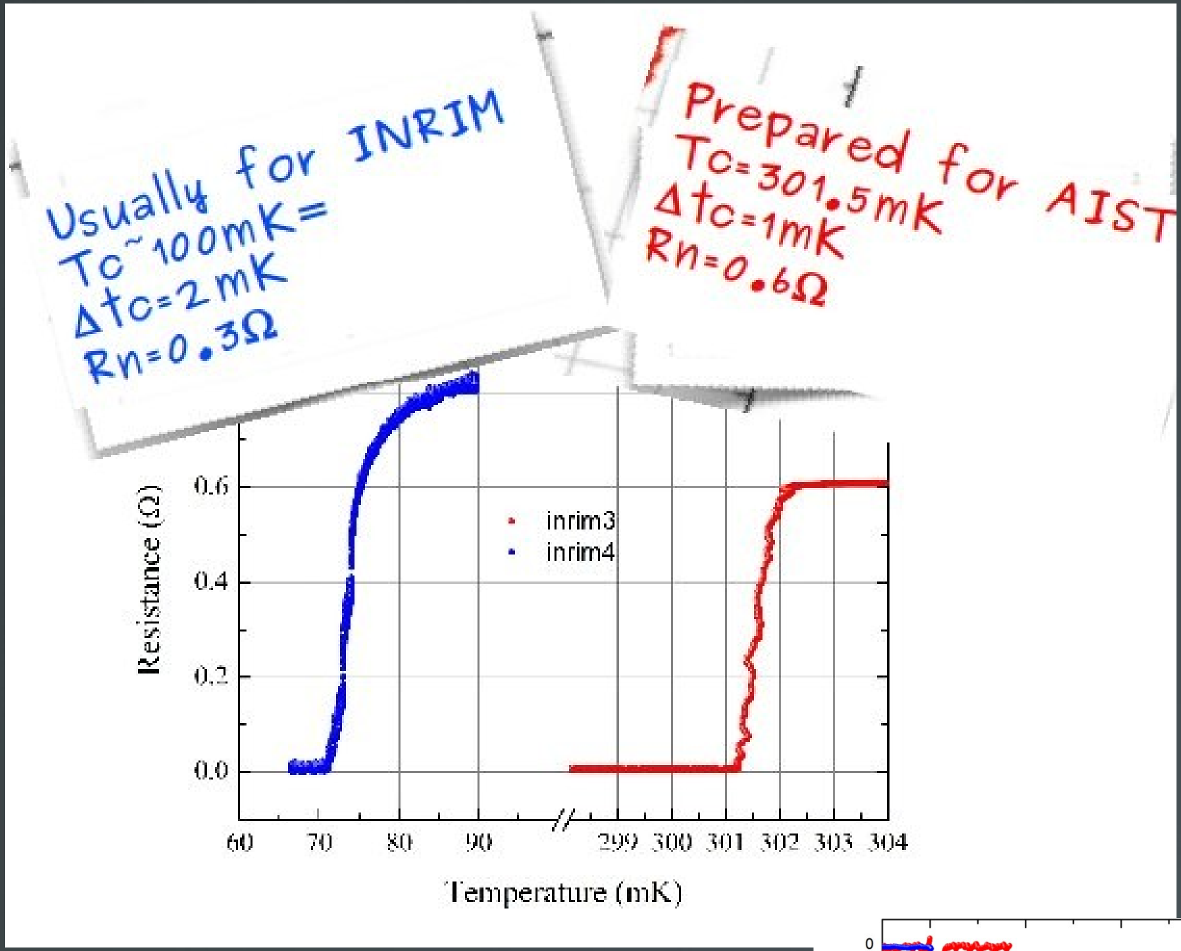
$$g^{(2)}(0) = \frac{\sum_n (n^2 P_n - n P_n)}{(\sum_n n P_n)^2}$$

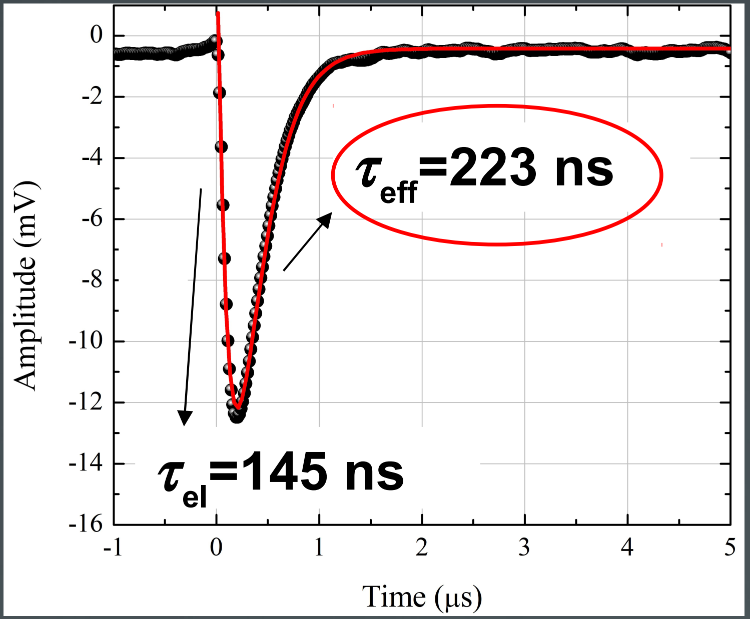
W. Schmunk et al, METROLOGIA 2012 **49** p156-160

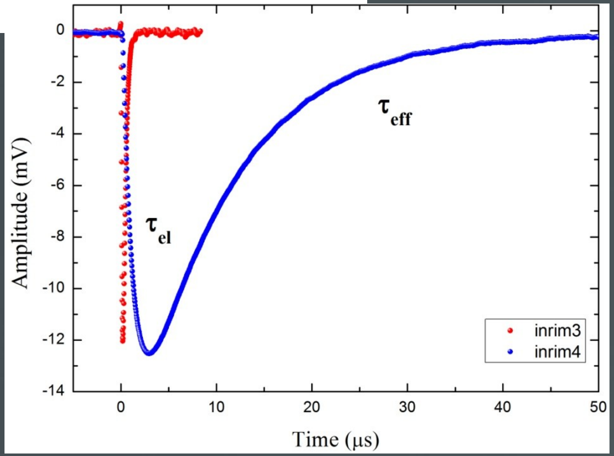
Someone wants more

Quantum land inhabitants are never satisfied

Faster, efficient and resolving

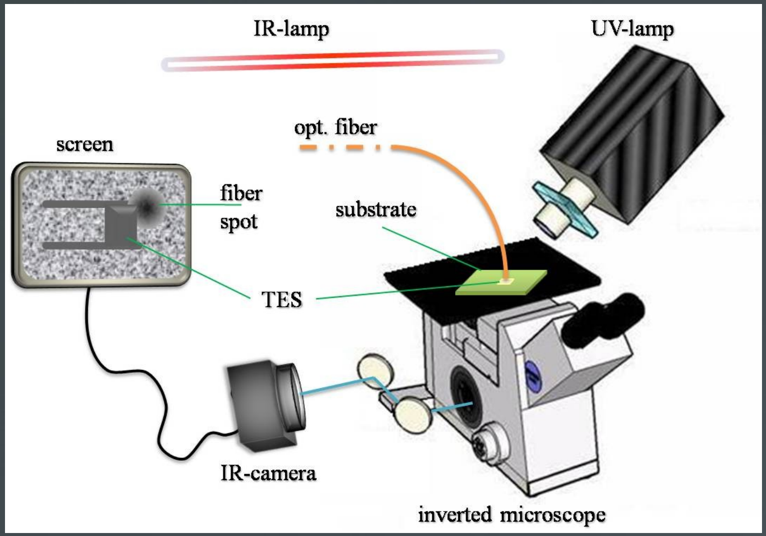


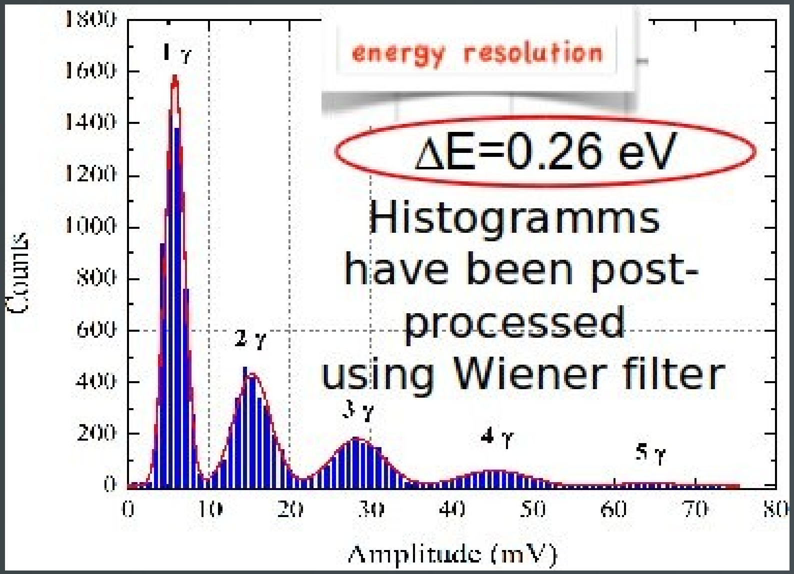


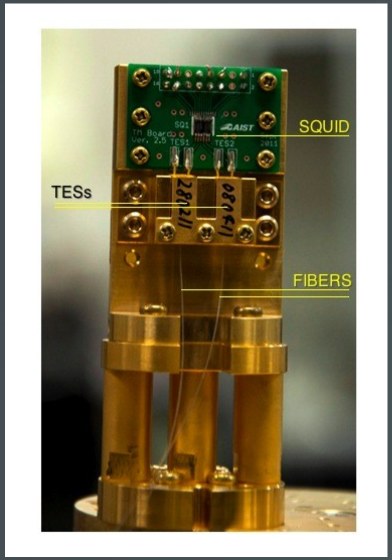


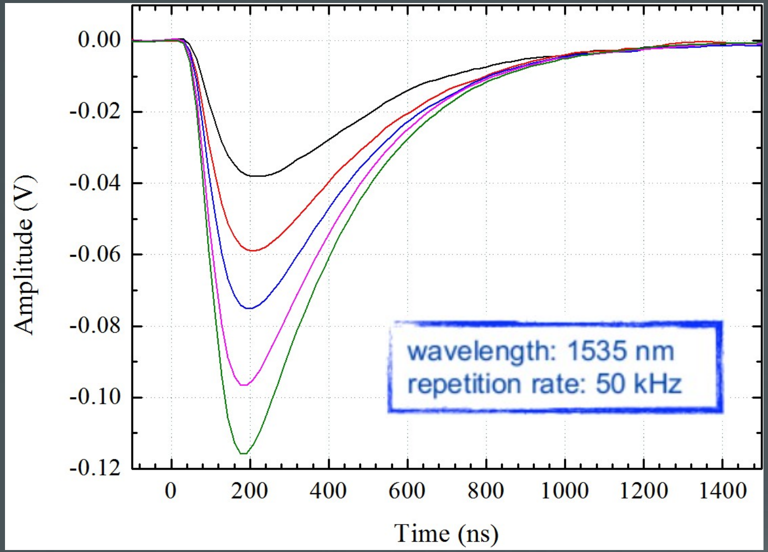
Faster, efficient and resolving

We flew to Japan for fiber allignement





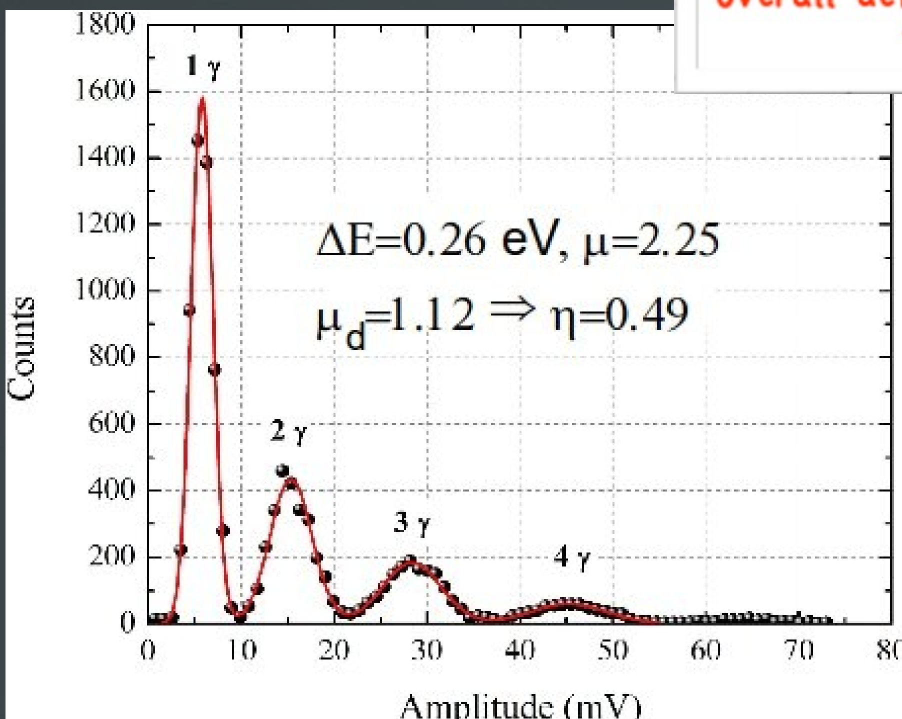


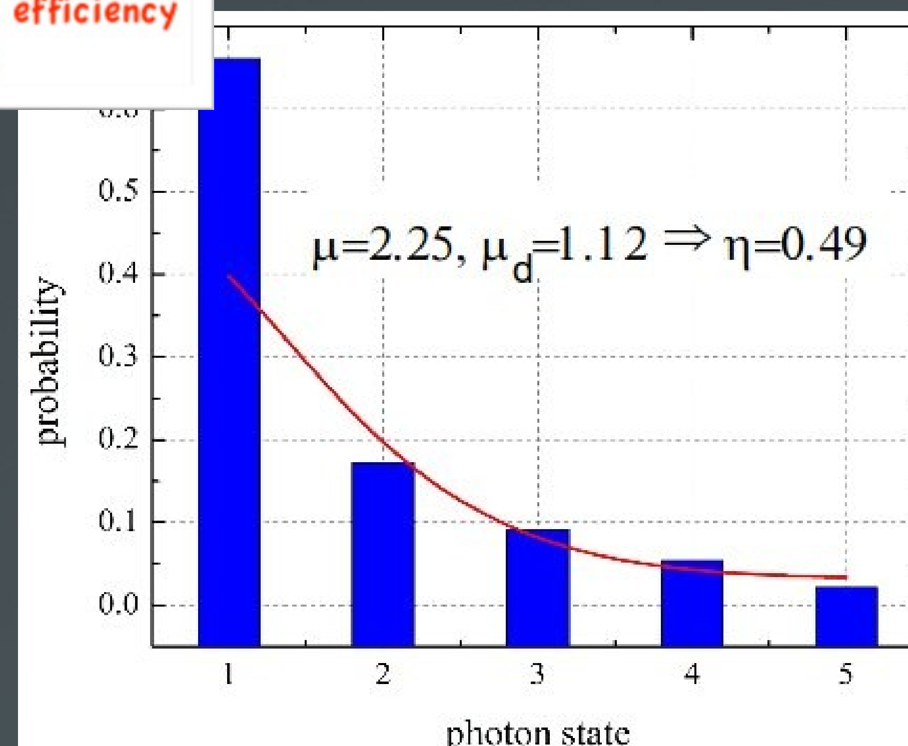


Faster, efficient and resolving

Due to the Poissonian emission distribution of laser, we can estimate the discriminated mean photon number by fitting the probability μ_d photon state histogram, $\mu_d = \eta\mu = 1.12$: where μ is the mean photon number emitted by the source and η is the TES detection efficiency we want to estimate. The laser source was optical attenuated to the single photon counting regime $\mu \sim 5$.

Overall detection efficiency ~ 50%





A rough estimate of the detection efficiency over several optical attenuations ***QE*** **~ 50%±5%**.

This result has been obtained without any antireflaction coating or optical cavity .

Conclusion

First steps of single photons resolving detector TES in quantum land have been shown

Quantum efficiency of our TESs can be further improved and we are working for that

We like very much the quantum land and its inhabitants so others steps in this land will be in progress

Thank you very much for your attention