Centre for Quantum Engineering and Space-Time Research
Deutsche Forschungsgemeinschaft
Leibniz Universität Hannover

Frequency Up-Conversion of Gaussian and Non-Gaussian States

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Albert Einstein Institute Hannover

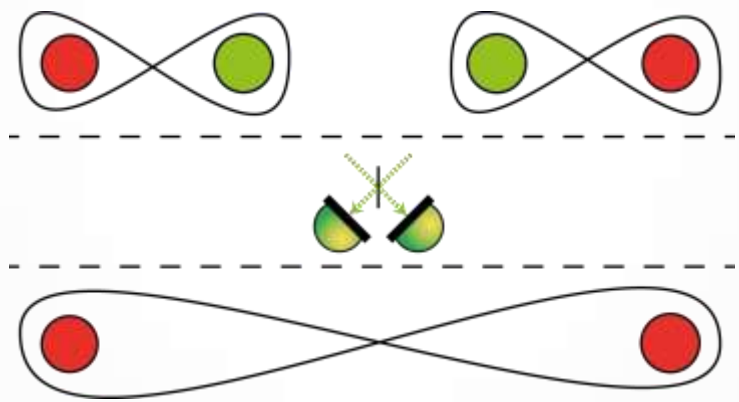
Outline

- Introduction and Motivation
  - Quantum memories
  - Frequency up-conversion
  - Up-conversion of squeezed vacuum states

- Up-conversion of single photons
  - Non-classicality
  - Quantum Non-Gaussianity
  - Outlook

Quantum Repeater

- **Quantum communication fails when channels are long**
- **Solution: Quantum repater**
  - **Divide channel into segments**
  - **Prepare locally entangled states**
  - **Distribute to neighbouring segments**
  - **Swap entanglement**
  - **Iterate until full channel length is connected**



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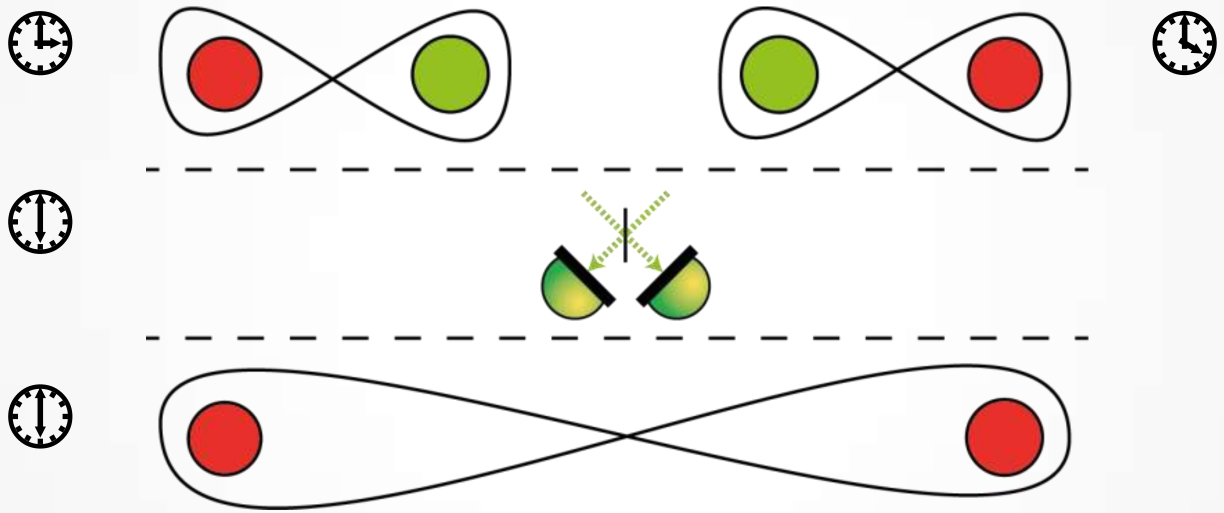
Quantum Repeaters: The Role of Imperfect Local Operations in Quantum Communication

H.-J. Briegel,[1,2,*] W. Dür,[1] J. I. Cirac,[1,2] and P. Zoller[1]

Quantum Memory

- **Need synchronisation of segments**
- **Storage of states and on demand release**

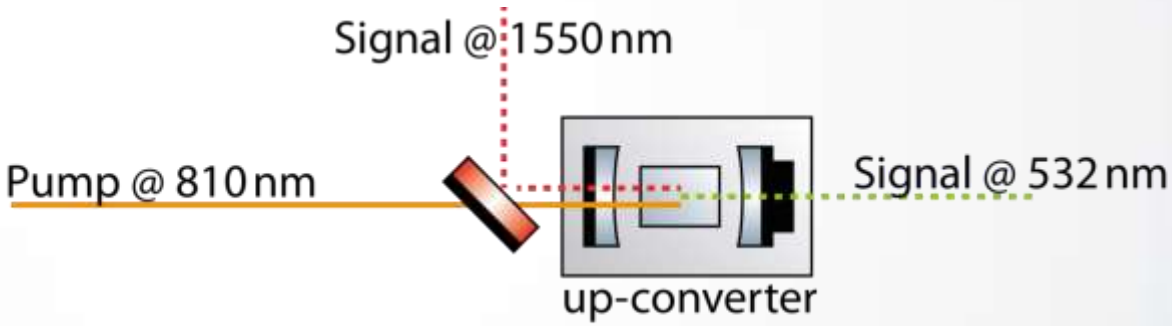


The `Wavelength Problem´

- **Very efficient generation of entangled states at 1550 nm**
- **Distribution: Lowest losses in optical fibers at 1550 nm**
- **Optical transitions of quantum memories: 500-900 nm**
- **Solution: Quantum Up-Conversion**
  - **Quantum states converted from 1550 nm to 532 nm**
  - **Use low noise, commercially available, and easy-to-handle single photon detectors at visible wavelengths**

Quantum Up-Conversion

- **Sum-frequency generation with a strong pump in PPKTP**
- **Pump and signal frequency add up:**
  signal converted to 532 nm!
- **More efficient in a cavity**
- **Well defined input and output modes**



Quantum Up-Conversion

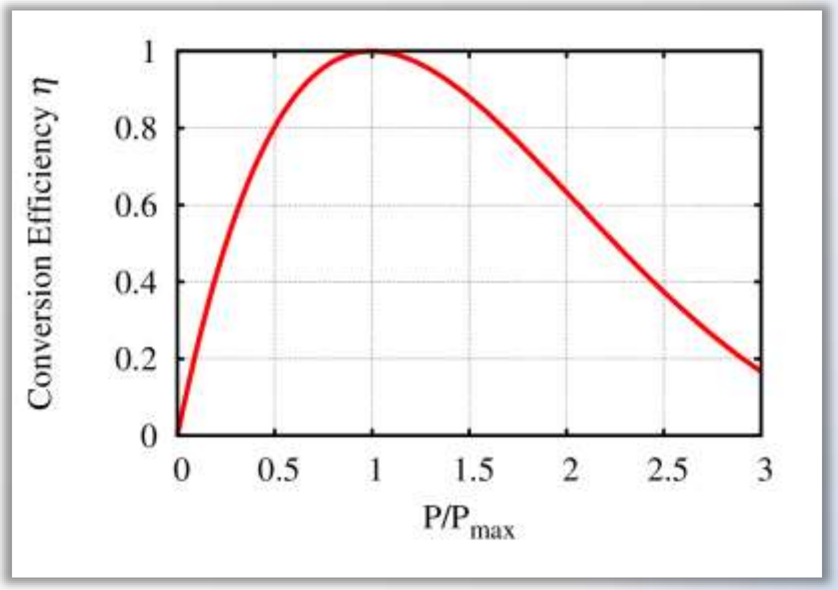
- **Strong pump, treated classically** $\frac{d\hat{a}_{810}}{dt} \approx 0$

- **Hamiltonian of quantum up-conversion**
  $$\hat{H} = i\hbar\langle\hat{a}_{810}\rangle\zeta(\hat{a}_{1550}\hat{a}^{\dagger}_{532} - h.c.)$$

- ζ **: nonlinear coupling parameter**

- **Time evolution**
  $$\hat{a}_{532}(t) = \sin\left(\langle\hat{a}_{810}\rangle\zeta t\right)\ \hat{a}_{1550}(0)$$

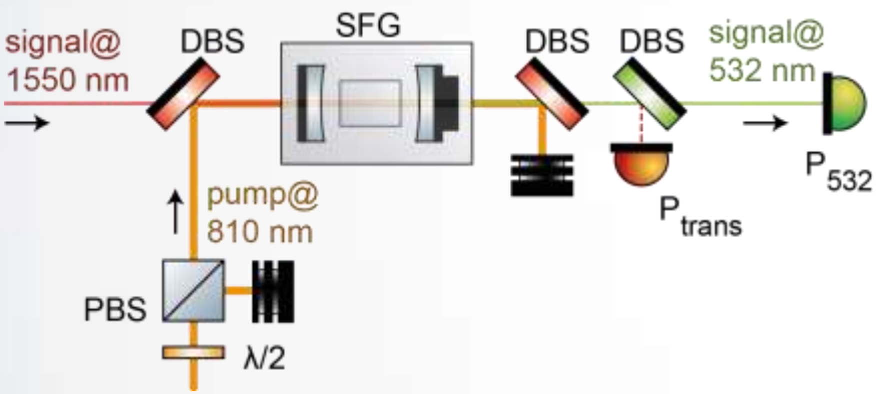
- **Conversion efficiency**
  $$\eta = \frac{n_{532}}{n_{1550}}$$

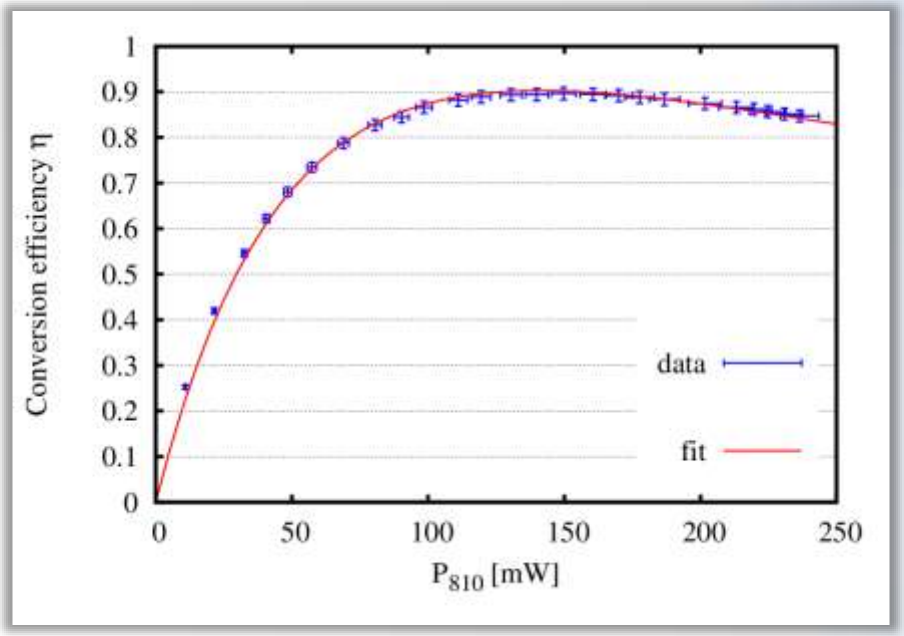


Conversion Efficiency

- **Determined with dim classical fields**
- **90.2 ± 1.5 %**

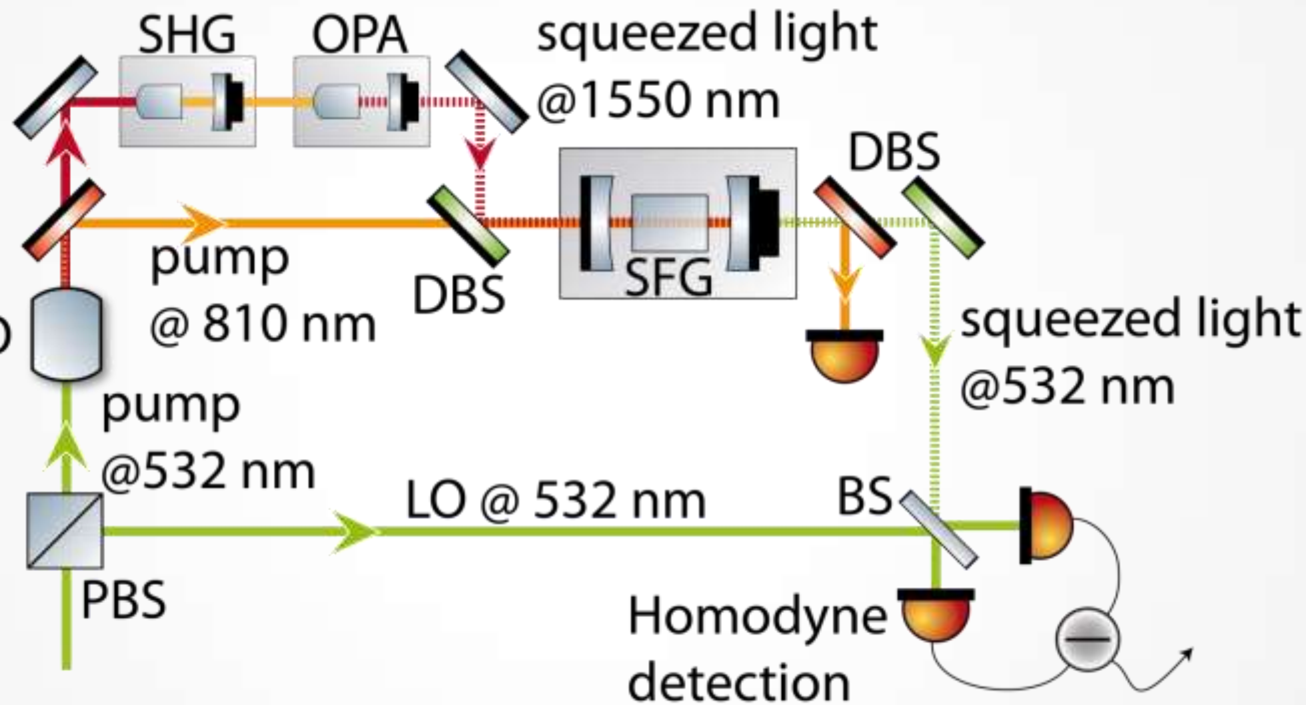
$$\eta = \frac{n_{532}}{n_{1550}}$$





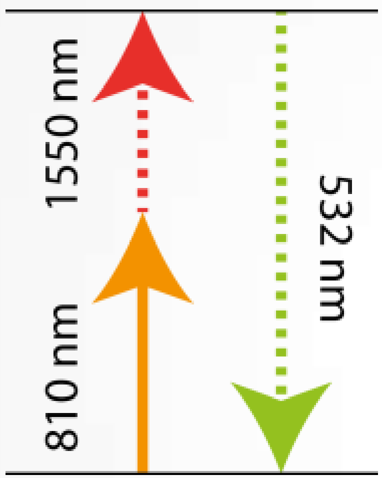
Squeezed States at 532 nm

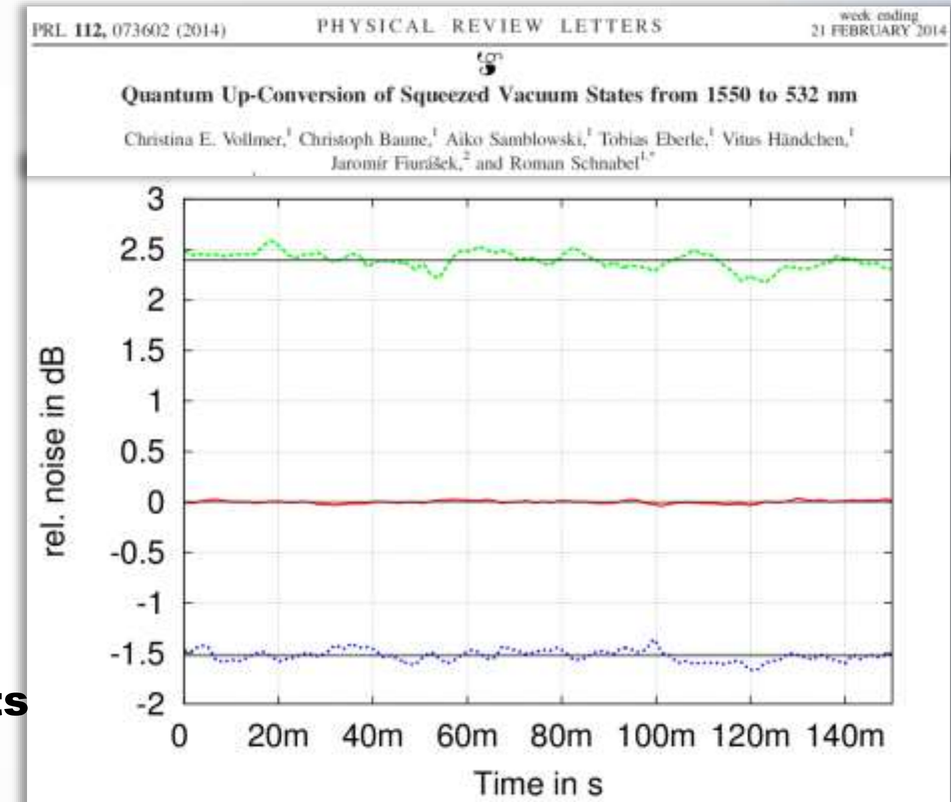
- **Quantum state up-conversion of squeezed light**



Squeezed States at 532 nm

- Quantum state up-conversion with squeezed light
  - 4 dB @ 1550 nm converted to 1.5 dB at 532 nm





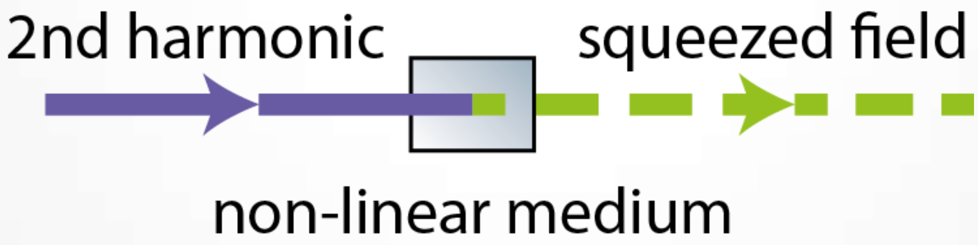
Further possible applications:

- High precision phase measurements (e.g. gravitational wave detectors)
- Quantum enhanced imaging
- Quantum enhanced spectroscopy

`Direct´ Squeezing?

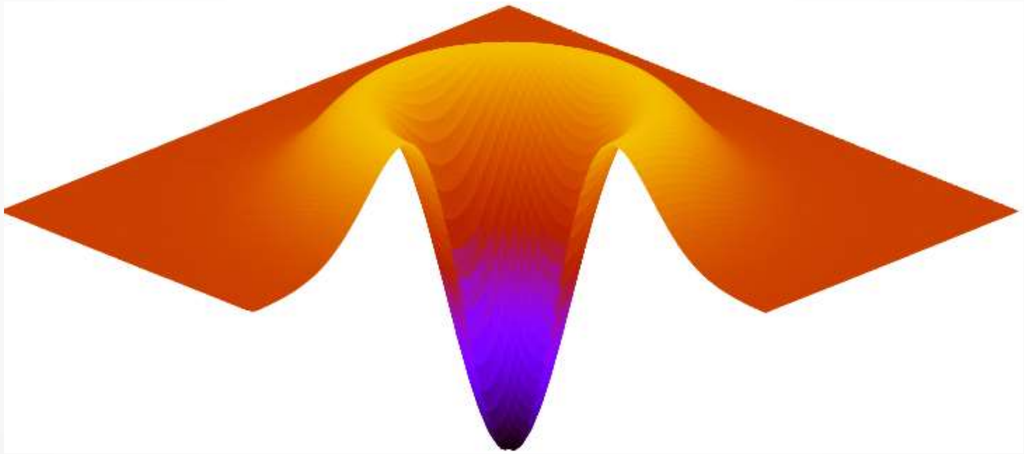
- Common method to generate squeezed vacuum states: Parametric down-conversion
- Requires second harmonic as pump: ultra violet light

- PDC not applicable to produce high-quality squeezed states at 532 nm
- Quantum up-conversion promises up to 6 dB squeezing!



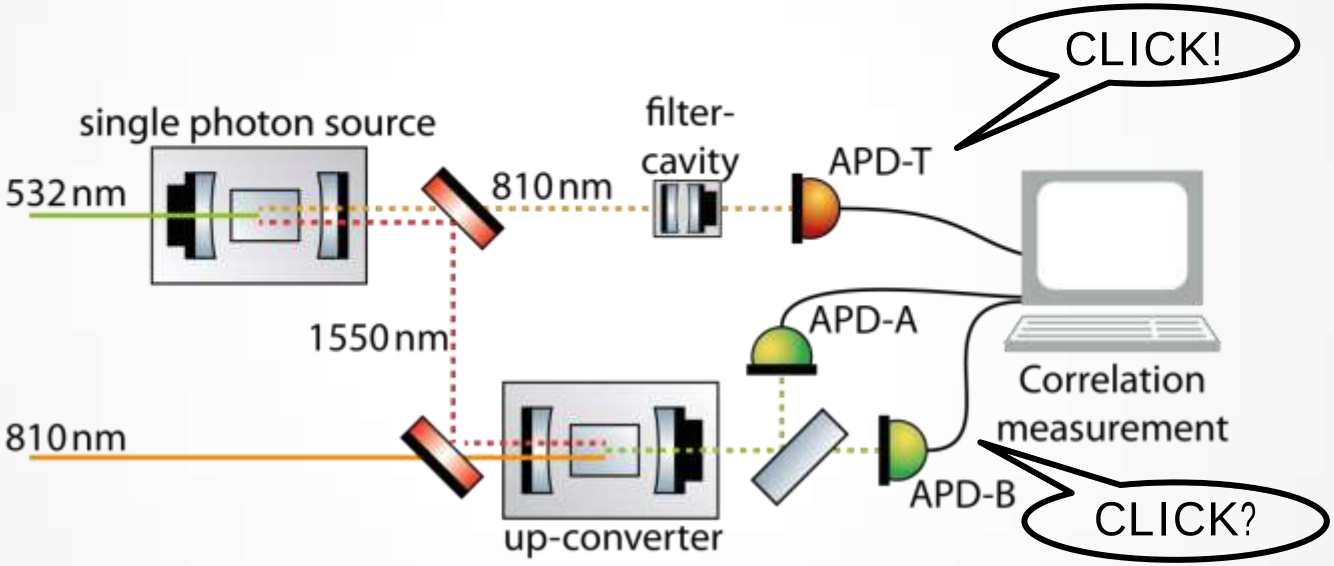
Gaussian vs. Non-Gaussian

- **Squeezed states are Gaussian states**
- **No-go theorems for Gaussian states**
- **Many quantum information protocols require non-Gaussian states**
  - **Entanglement distillation**
  - **Quantum state teleportation**
- **Non-Gaussian state: Single photon!**



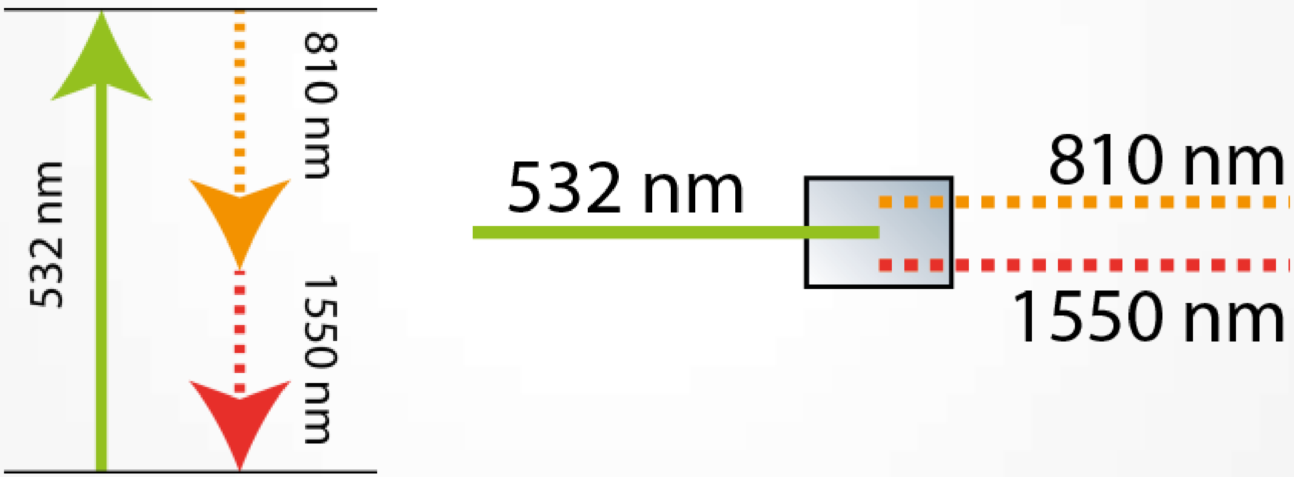
Single Photon Up-Conversion

- **Produce correlated photon pairs at 1550 and 810 nm**
- **Up-convert 1550 nm photons to 532 nm**
- **Perform correlation measurement with 810 nm photons**



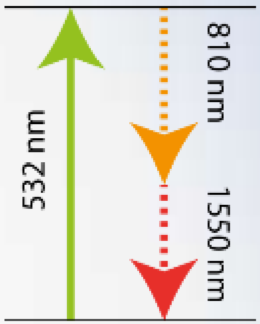
Generation of Single Photons

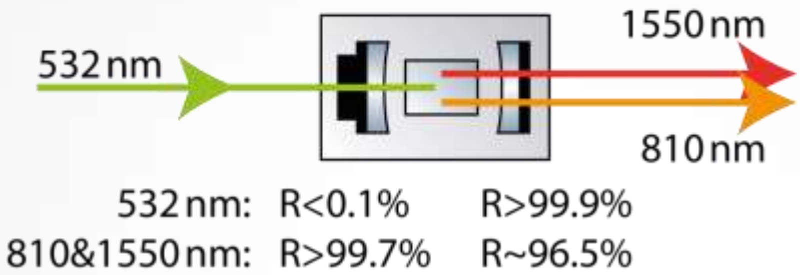
- **Use spontaneous parametric down-conversion in non-linear medium (PPKTP)**
- **By detecting one single photon at 810 nm we project the 1550 nm mode onto a single photon state**



Generation of Single Photons II

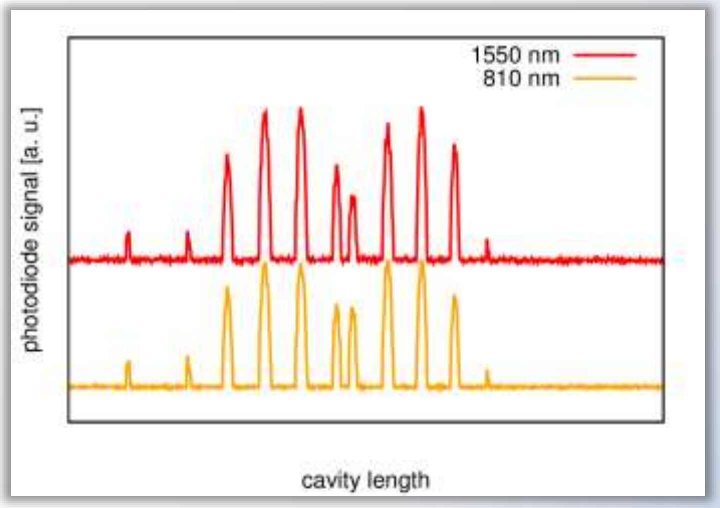
- **More efficient in a cavity; well defined output modes**
- **Cavity doubly resonant for 810 & 1550 nm**



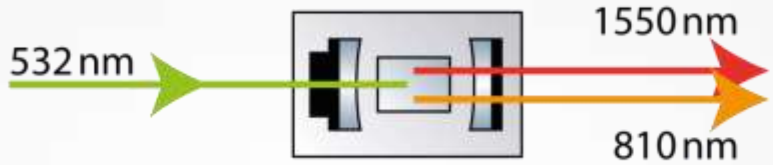


- **Tuning of cavity length makes small wavelength changes (<1nm)**
  - **Find optimal mode for up-conversion**

- **Pump exceeds threshold: oscillation**
  - **Optical parametric oscillator (OPO)**
  - **Nice for alignment purposes!**



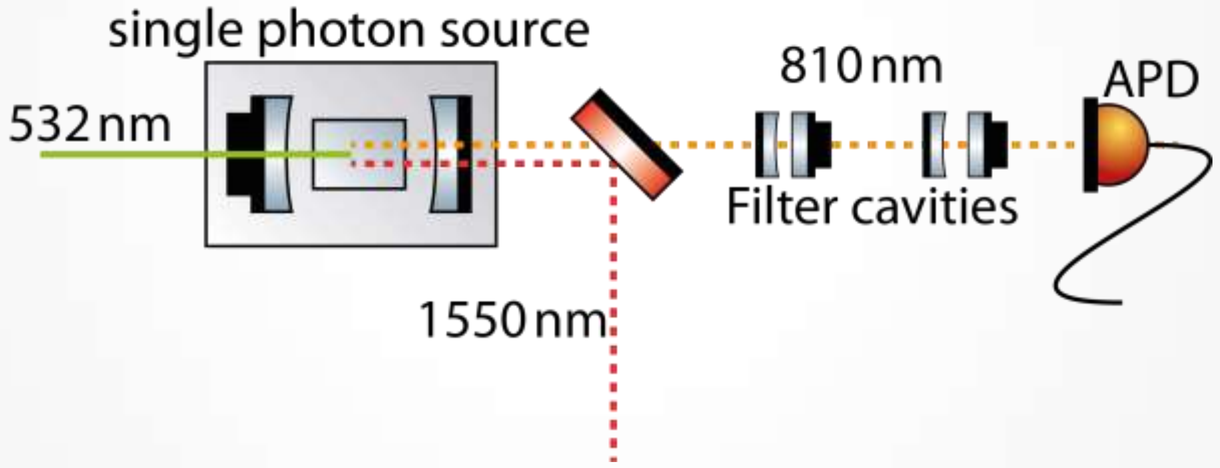
Single Photon Source



532 nm:	R<0.1%	R>99.9%
810&1550 nm:	R>99.7%	R~96.5%

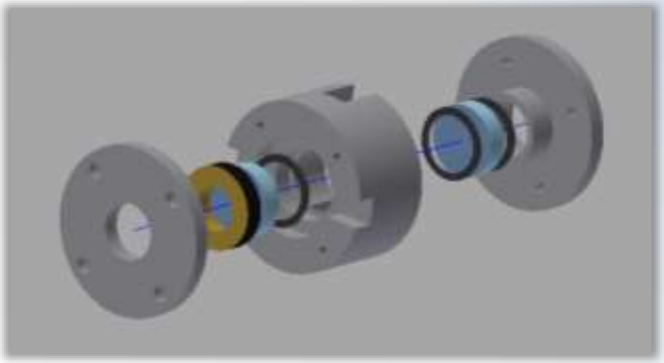
Trigger Mode Filtering

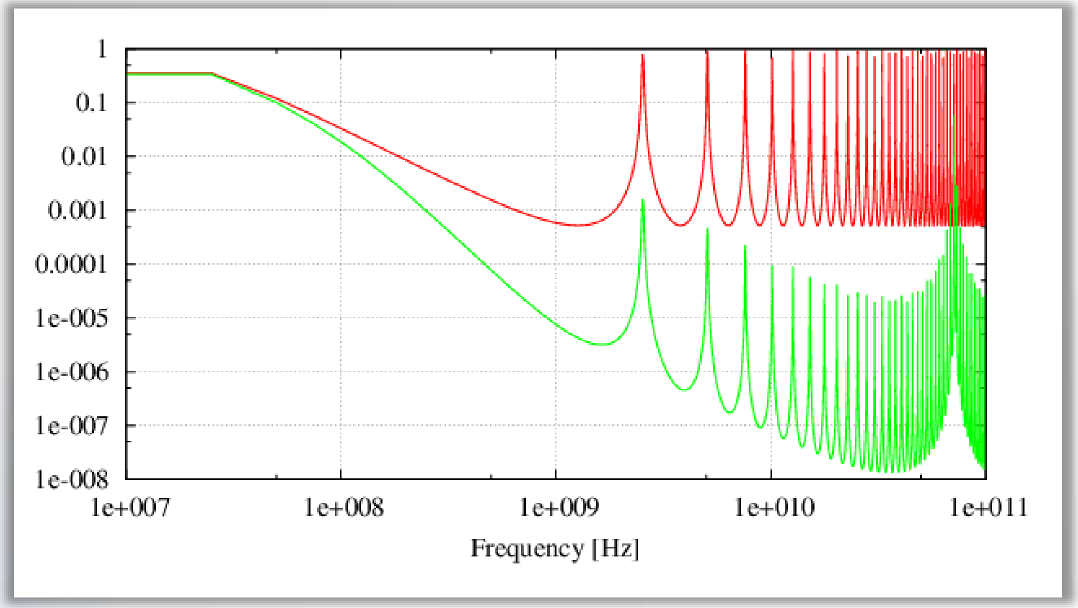
- **Photons are generated in many free spectral ranges (FSR)**
- **Need for efficient filtering in heralding path to suppress uncorrelated modes**



Filter Cavity

- **Two mirrors, R=99%**
- **Spacing 2.5 mm**
- **Suppression of ~20 FSRs by -30 dB**



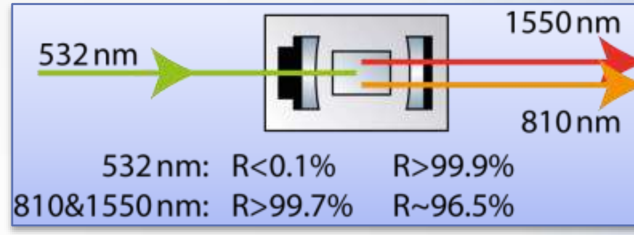


Photon source transmission

Filter cavity transmission

PDC - Linewidths

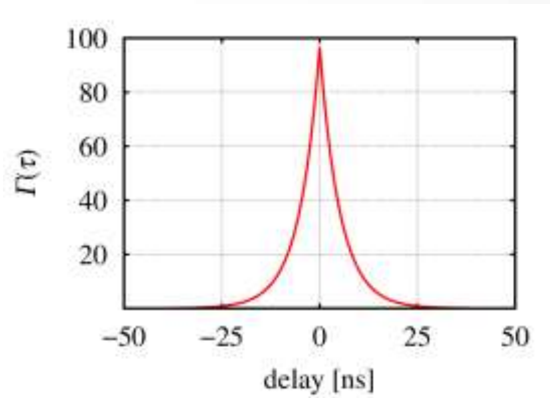
Two-fold coincidences between 810 nm (trigger) and 1550 nm (signal) defined as:



$$\Gamma(\tau) = \langle E^{-}_{\text{trigger}}(t) E^{-}_{\text{signal}}(t+\tau) E^{+}_{\text{signal}}(t+\tau) E^{+}_{\text{trigger}}(t) \rangle$$

Symmetric decay rates $\gamma_{810} = \gamma_{1550} = \gamma$

$$\Gamma(\tau) = \left[\frac{\varepsilon\gamma}{2} \left(\frac{1}{\lambda} \mathrm{e}^{-\lambda|\tau|} + \frac{1}{\mu} \mathrm{e}^{-\mu|\tau|} \right) \right]^2$$

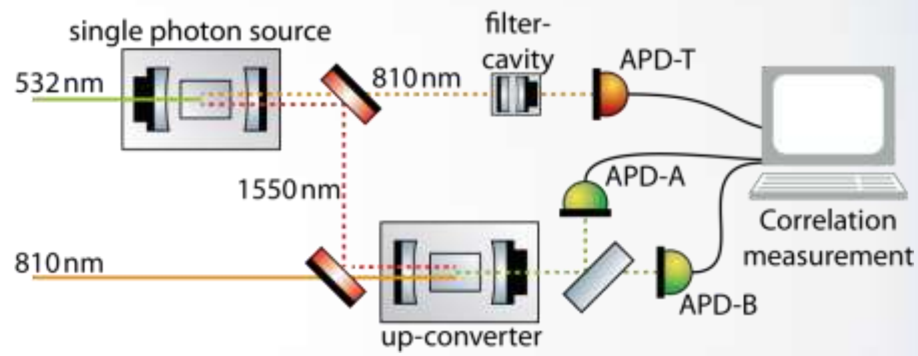


γ : cavity decay rate
ϵ : gain parameter
$\lambda = \gamma - |\epsilon|$
$\mu = \gamma + |\epsilon|$
κ : extra filter decay rate

Extra filtering effect: $\gamma_{810} > \gamma_{1550}$ **and up-conversion cavity:** κ

Extra Filtering Effect

…due to asymmetric cavity decay rates and up-conversion cavity

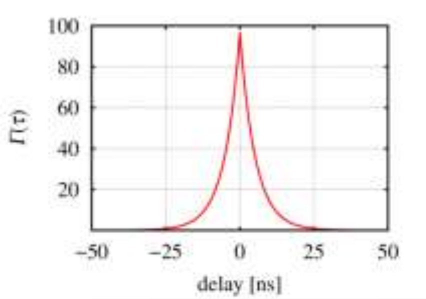


κ : linewidth of extra filter

Gain Parameter ϵ

- **Two-fold coincidences:**

$$\Gamma(\tau) = \left[\frac{\varepsilon\gamma}{2}\left(\frac{1}{\lambda}\mathrm{e}^{-\lambda|\tau|} + \frac{1}{\mu}\mathrm{e}^{-\mu|\tau|}\right)\right]^2$$



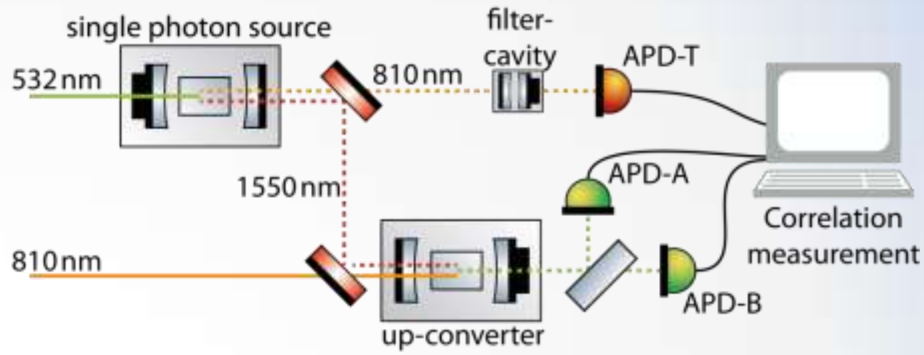
- ϵ **is proportional to pump amplitude**

- **Larger** ϵ **:**
  - **Larger photon production rate**
  - **Higher multiphoton contribution |n=2> , ...**
  - **Lower single photon purity**

$$\mathrm{e}^{i(\varepsilon\hat{a}_s^\dagger\hat{a}_i^\dagger + \varepsilon^*\hat{a}_s\hat{a}_i)}|0,0\rangle = (1 - \tfrac{1}{2}|\varepsilon|^2)|0,0\rangle + \varepsilon|1,1\rangle + \varepsilon^2|2,2\rangle + \ldots$$

Data Acquisition

- **APD signals recorded with oscilloscope**
  - **Triggered on 810 nm photons**
  - **Stored and processed on PC**

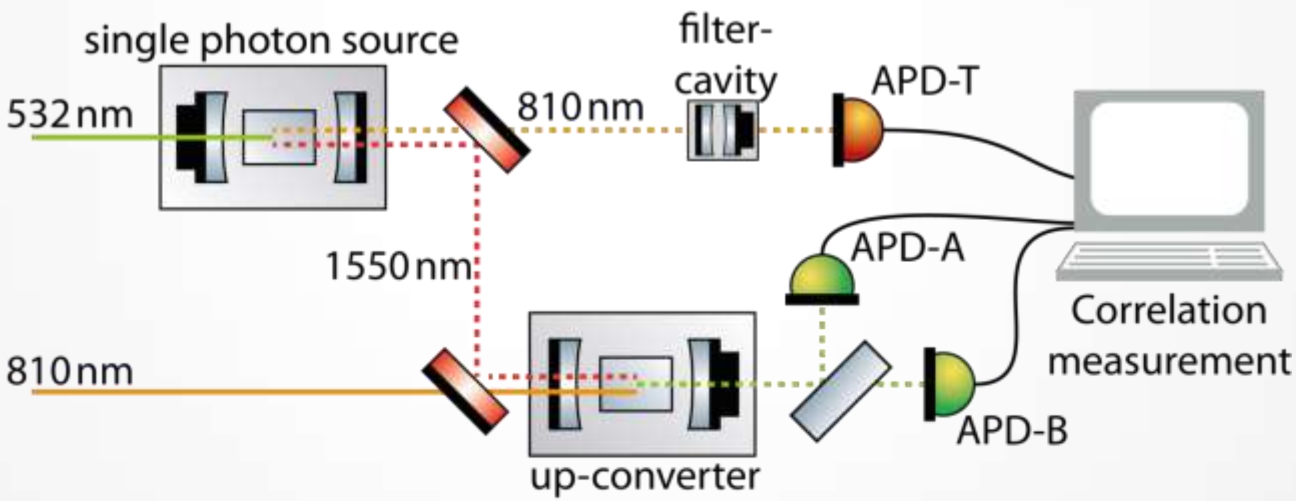


- **Disadvantages**
  - **Slow and inefficient (4h measurement time for 4s data)**

- **Advantages**
  - **Access to full time series in post-processing, 0.5 ns resolution**
  - **Easy, inexpensive, available**

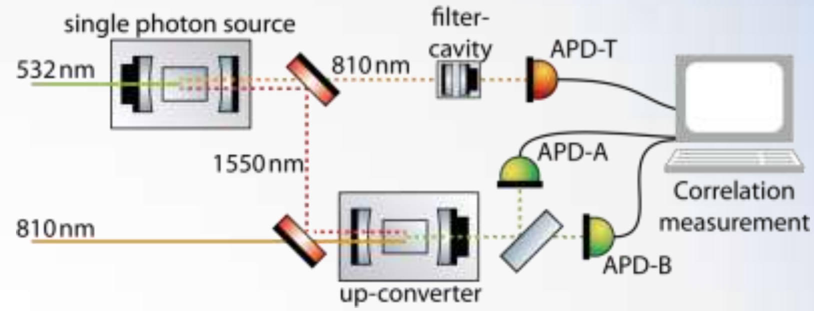
Coincidences

- **Analyse time series according to:**
  - **Two-fold coincidences**
    - **APD-T and APD-A**
    - **APD-T and APD-B**
  - **Three-fold coincidences**
    - **APD-T and APD-A and APD-B**



Photon Statistics

- **Low gain** $\epsilon = 0.10\,\gamma$
  - **Very low three-fold coincidence rate**

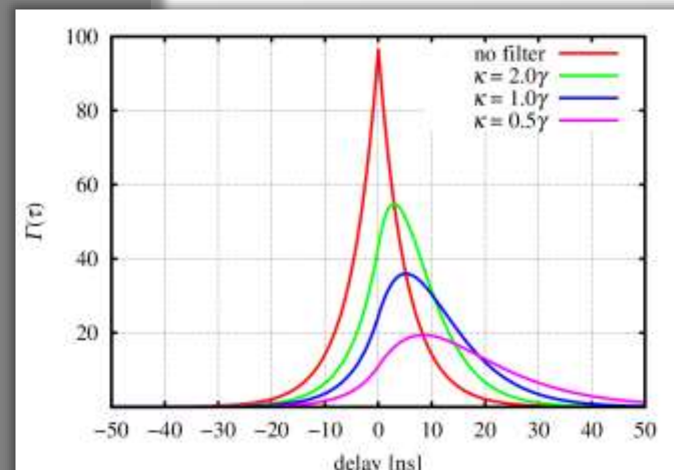


$\epsilon = 0.10\,\gamma$

← T+A

← T+B

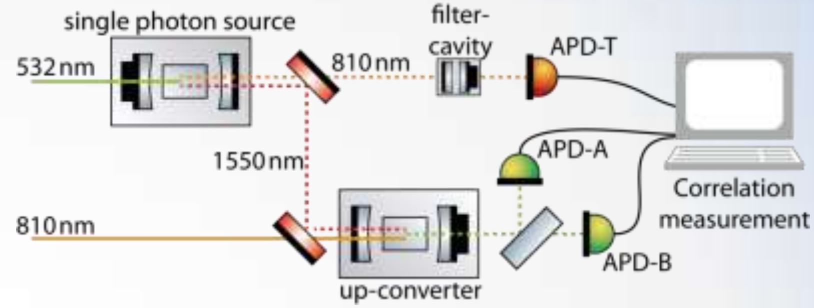
T+A+B →

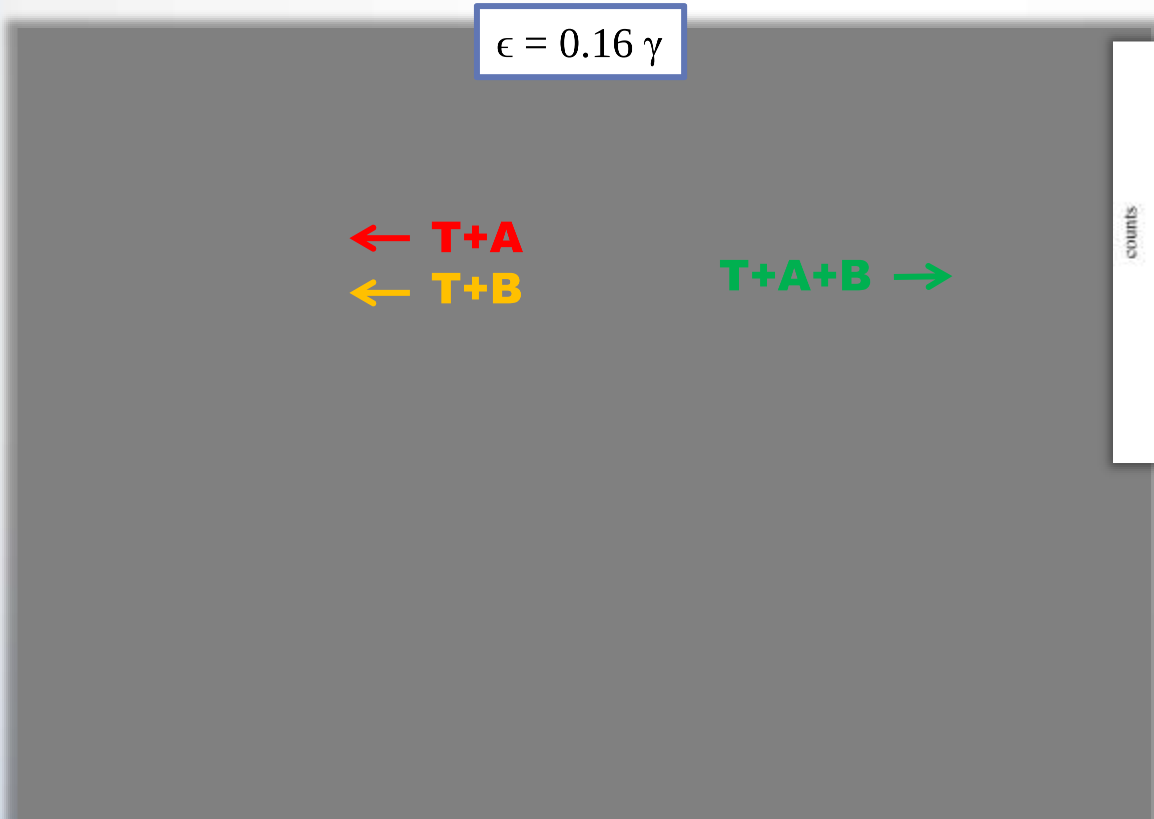


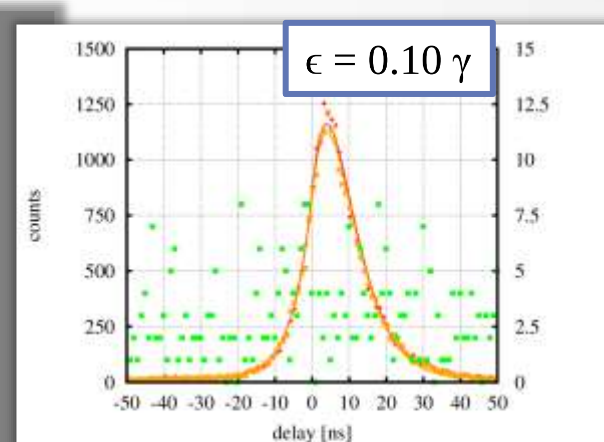
Shape of two-fold coincidence curve fits the theoretically expected shape!

Photon Statistics

- **Medium gain** $\epsilon = 0.16\,\gamma$
  - **moderate three-fold coincidence rate**

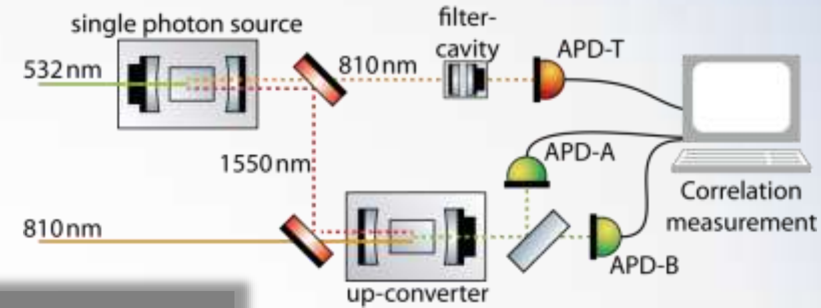






Photon Statistics

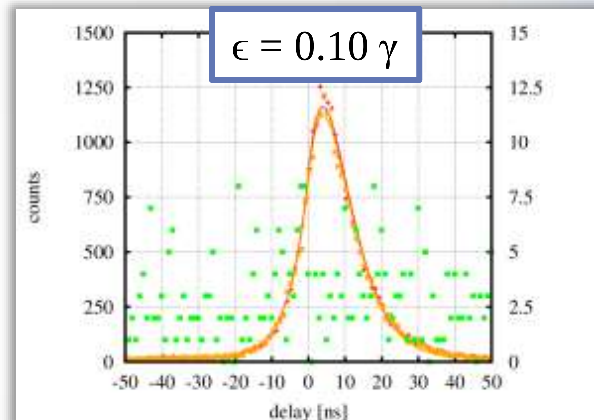
- **High gain** $\epsilon = 0.28\,\gamma$
  - **high three-fold coincidence rate**



$\epsilon = 0.28\,\gamma$

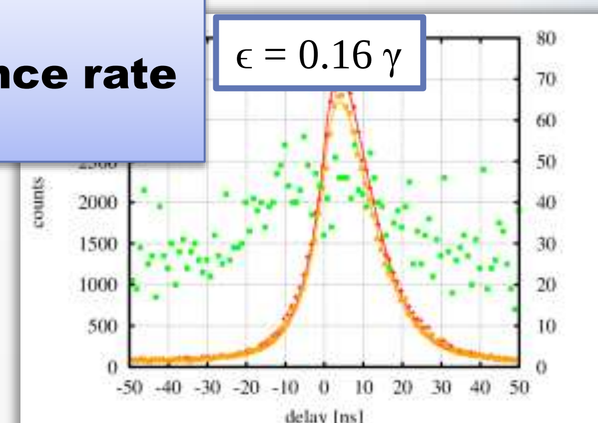
← **T+A**
← **T+B**
T+A+B →

$\epsilon = 0.10\,\gamma$



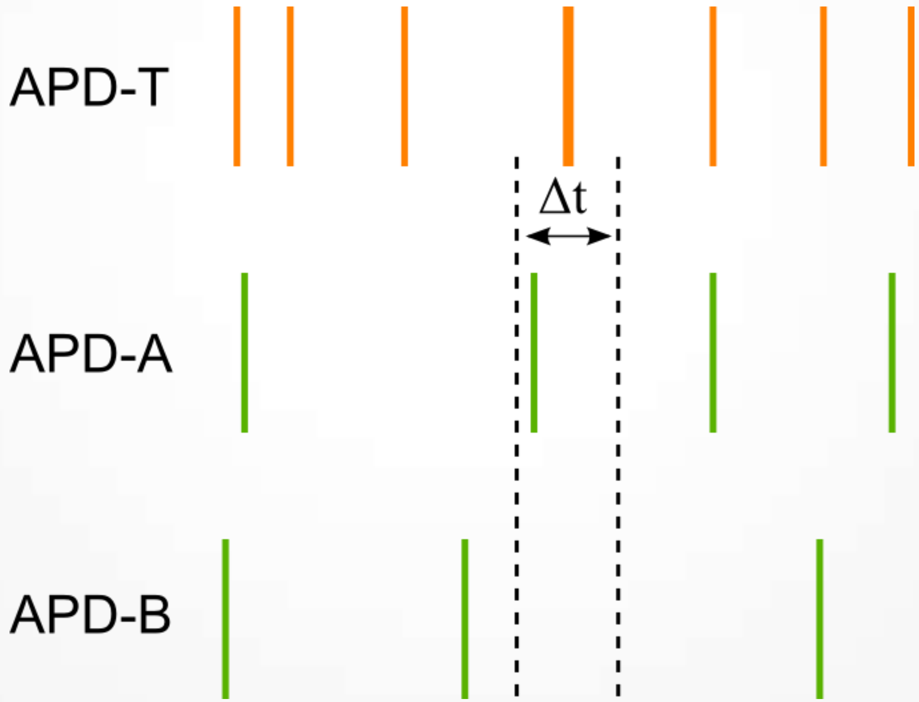
Higher gain
- **Higher three-fold coincidence rate**
- **Lower single photon purity**

$\epsilon = 0.16\,\gamma$



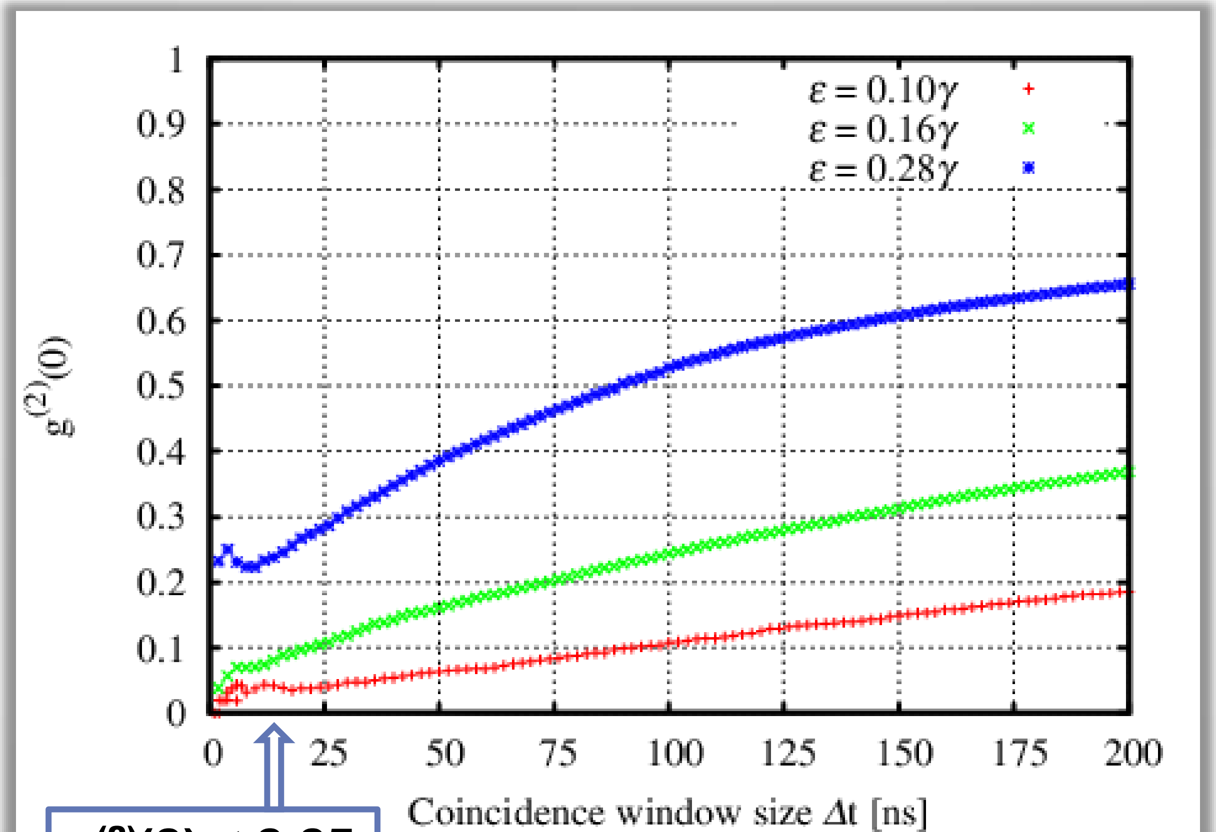
Coincidence Window

- Time window around the trigger of detecting a signal photon
  - Small window: few two-fold coincidence events, low noise
  - Large window: more two-fold coincidence events, higher noise
- Can be set in post-processsing
- Determine p_0, p_1



$g^{(2)}(0)$ Values

- All states show $g^{(2)}(0)<1$: Evidence for non-classicality
- Larger coincidence window:
  more three-fold coincidences, either true or noise

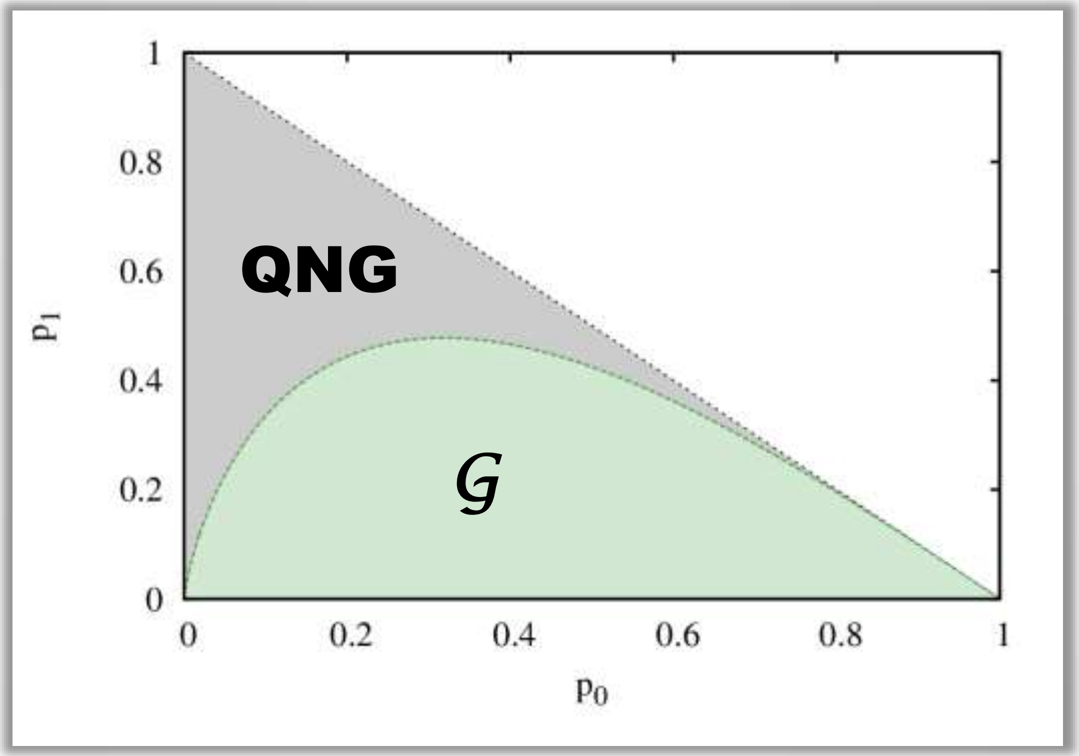


$g^{(2)}(0) < 0.05$

Quantum Non-Gaussianity (QNG)

Can the up-converted state be expressed as a convex mixture of Gaussian states?

- **Strong and robust measure on non-classicality**
- **Does not require full state tomography**
- **Only p_0 and p_1 to be determined**



Witness of QNG

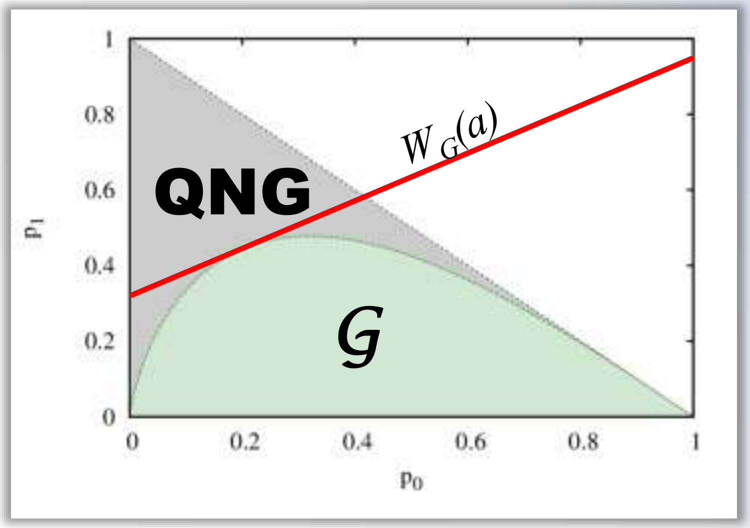
- **Difference of witness from Gaussian states**
  $W = p_1 + a\, p_0 - W_G(a)$

- **If $W>0$, then QNG**

- **$W_G(a)$ is the maximum of $p_1 + a\, p_0$ achievable with Gaussian states, tangent to $\mathcal{G}$**

- **$a<1$ specifies the witness, used to maximise W**

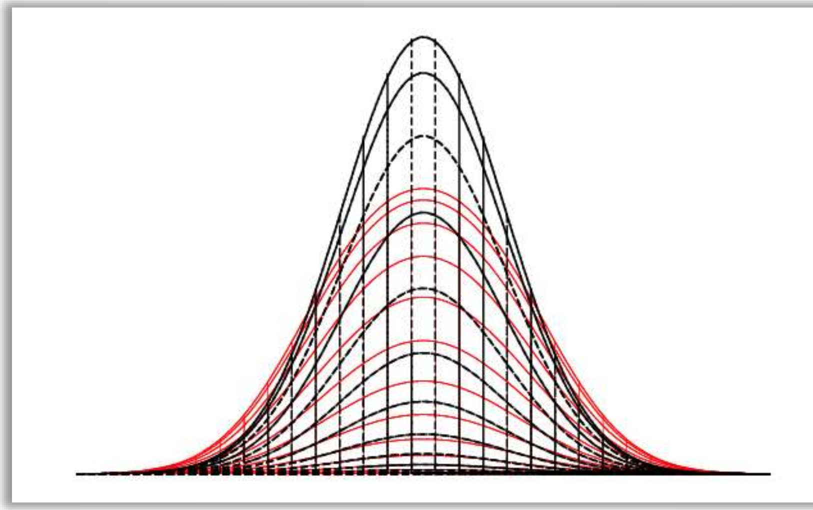
- **Poissonian statistics of the coincidence rates:**
  - **Statistical error of the witness can be expressed in standard deviations**
    $W / \Delta W$



Quantum Non-Gaussianity (QNG)

- **Verification of QNG with up to 16 standard deviations** ΔW
- **QNG destroyed if coincidence window too large or gain too high**

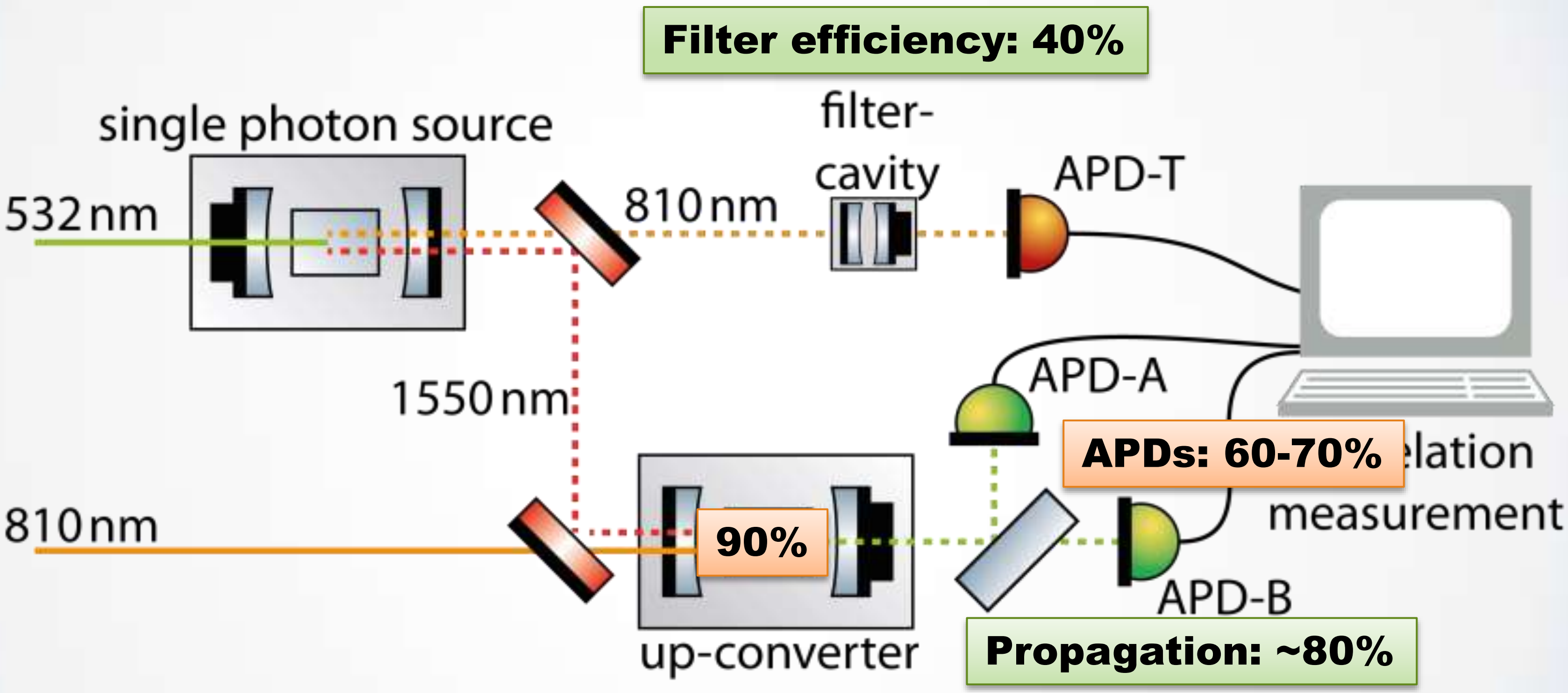
Reconstructed Wigner Function



Wigner function compared to coherent/vacuum wigner function

Reduce Losses

Total detection efficiency: 20%

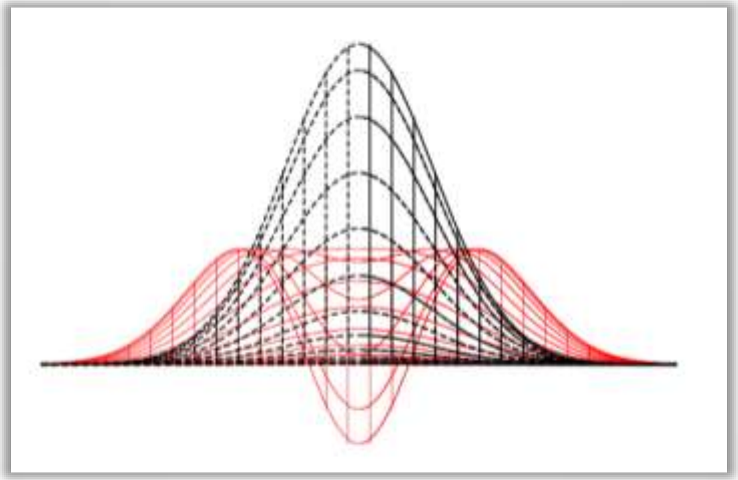


Additional filtering and new components would increase the detection efficiency to about 60%!

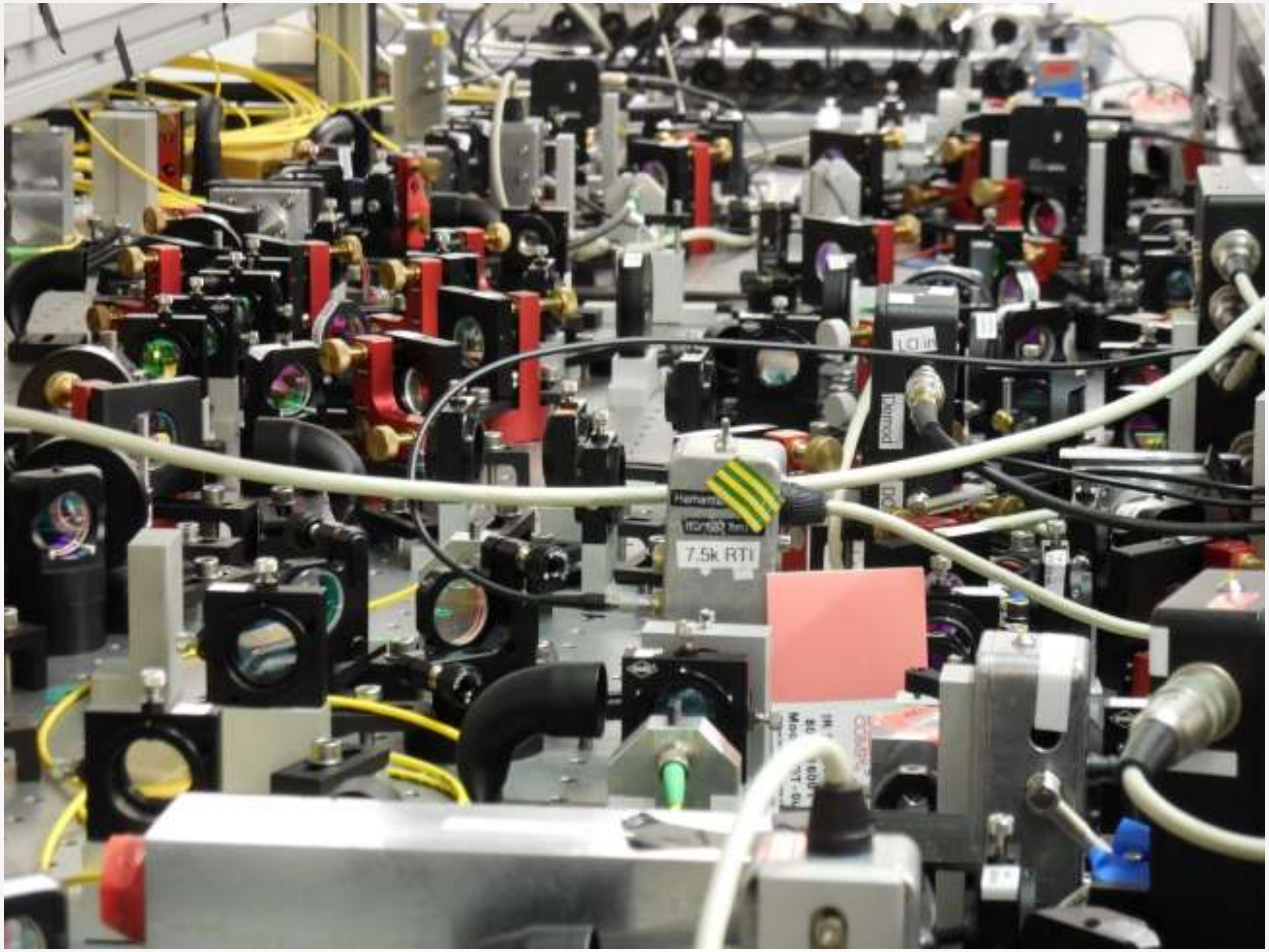
Optimized Detection Efficiency

- **Additional filter cavities (requires locking schemes)**
- **AR-coated fibers**

Improved detection efficiency: 60%



In The Lab



Single Photon Up-Conversion

Who?	Efficiency	
Albota, Wong Opt. Lett.29 (2004)	90% conversion 33% detection (?)	Dim coherent field 1550 to 633 nm
Langrock et al. Opt. Lett. 30 (2005)	46% detection	Dim coherent field 1550 to 700 nm
Pan, Dong, Zeng Appl. Phys. Lett. 89 (2006)	96% conversion 40% detection	Dim coherent field 1550 to 630 nm
Rakher et al. Nat. Photonics 4 (2010)	75% conversion 21% detection	Single photons from quantum dots 1300 to 700 nm, $g^{(2)}(0)<0.165$
This work	90% conversion 20% detection	Heralded single photons from SPDC 1550 to 532 nm, $g^{(2)}(0)<0.05$ Quantum Non-Gaussianity

Thanks to:

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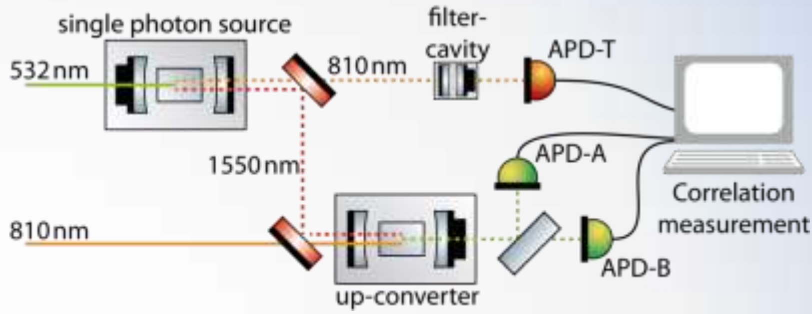
Int. Max Planck Research School (IMPRS) on Gravitational Wave Astronomy

Albert Einstein Institute Hannover

Summary



- **Single photons are non-Gaussian states**
  - **Non-Gaussian operations are very interesting for quantum information**
- **Up-conversion of single photons**
  - **Proof of signal photon at telecom wavelength of 1550 nm by efficient detection at 532 nm**
  - **Possible resource for quantum memories**
- **Verified Quantum Non-Gaussianity of up-converted signal**
  - **Up to 16 standard deviations**

Thank you for your attention!
Děkuji!