Title: Bright nanoscale source of highly entangled photon pairs

Date: Nov 22, 2016 02:30 PM

URL: http://pirsa.org/16110086

Abstract: <p>The on-demand generation of bright entangled photon pairs is highly needed in quantum optics and emerging quantum information applications. However, a quantum light source combining both high fidelity and on-demand bright emission has proven elusive with current leading photon technologies. In this work we present a new bright nanoscale source of strongly entangled photon pairs generated with a position controlled nanowire quantum dot. The major breakthrough in the nanowire growth to achieve both bright photon emission and highly entangled photon pairs will be discussed [2, 3]. Recent experiments show the entanglement fidelity approaching unity, while enhancing the photon pair efficiency beyond state-of-the-art. We further demonstrate violation of the famous Clauser-Horne-Shimony-Holt inequality in the traditional linear basis [4]. This is the first bright nanoscale source of entangled photon pairs capable of violating Bell`s inequalities, opening up future experiments in quantum optics and developments in quantum information applications.</p>

<p>For long-distance quantum communication we convert polarization entangled photons generated by a single quantum dot into time-bin entangled photons by sending them through a polarization-time-bin interface [5]. Importantly, this conversion is performed without loss of entanglement strength. Time-bin entanglement is more robust for long-distance quantum communication than polarization entanglement, since time-bin entangled photons are insensitive to thermal and mechanical disturbances in optical fibers.</p>

<p> </p>

<p>References</p>

<p>[1] M. A. M. Versteegh, M. E Reimer, K. D JÃ¶ns, D. Dalacu, P. J. Poole, A. Gulinatti, A. Giudice, and V. Zwiller, Nature Commun. 5, 5298 (2014).</p>

<p>[2] D. Dalacu, K. Mnaymneh, J. Lapointe, X. Wu, P. J. Poole, G. Bulgarini, V. Zwiller, and M. E. Reimer, Nano Lett. 12 (11), 5919-5923 (2012).</p>

<p>[3] M. E. Reimer et al., Phys. Rev. B 93, 195316 (2016).</p>

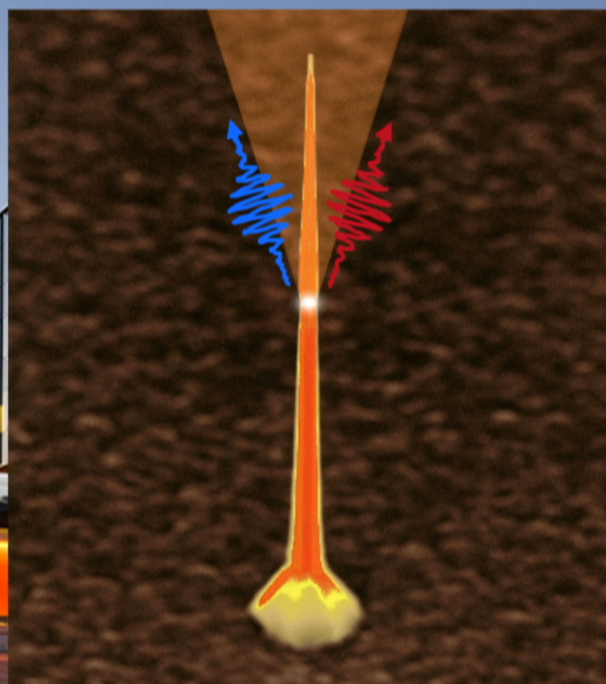
<p>[4] K. D. JÃ¶ns et al., arXiv:1510.03897 (2015).</p>

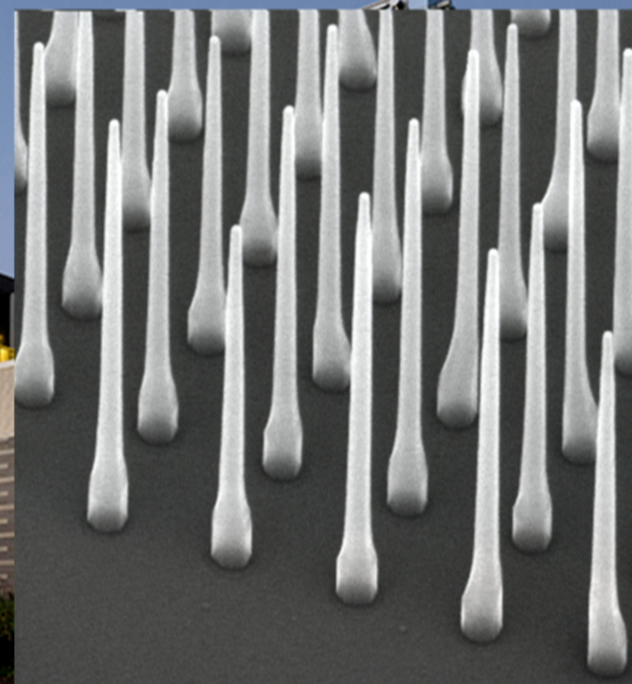
<p>[5] M. A. M. Versteegh, M. E. Reimer, A. A. van den Berg, G. Juska, V. Dimastrodonato, A. Gocalinska, E. Pelucchi, and V. Zwiller, Phys. Rev. A 92, 033802 (2015).</p>

Bright nanoscale source of highly entangled photon pairs

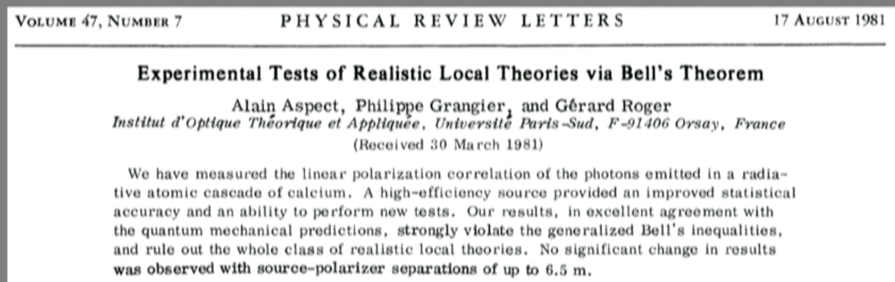
Michael E. Reimer

Institute for Quantum Computing, Waterloo, Canada





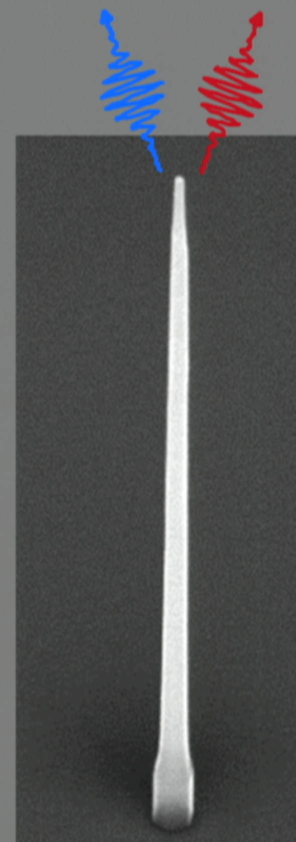
From the optics lab to the nanoscale


VOLUME 47, NUMBER 7 PHYSICAL REVIEW LETTERS 17 AUGUST 1981

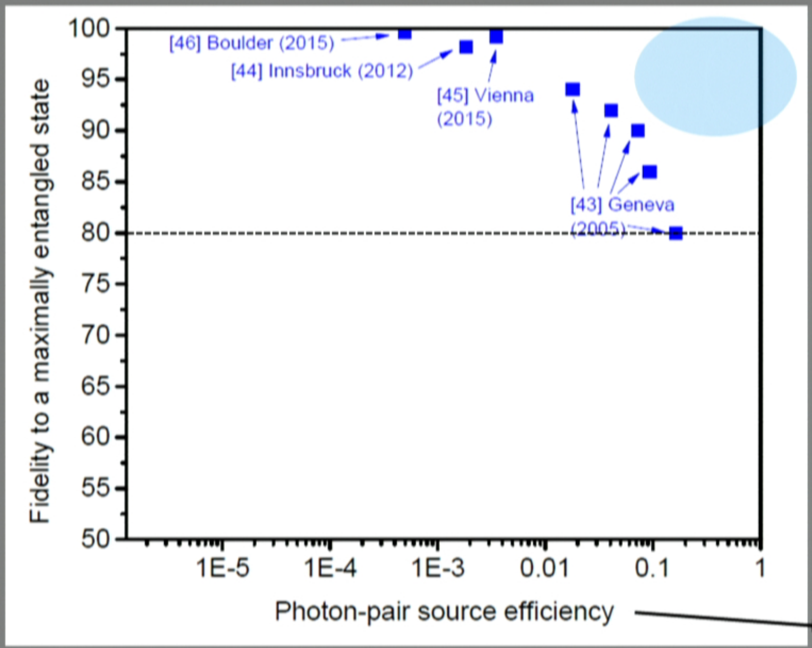
Experimental Tests of Realistic Local Theories via Bell's Theorem

Alain Aspect, Philippe Grangier, and Gérard Roger
Institut d'Optique Théorique et Appliquée, Université Paris-Sud, F-91406 Orsay, France
(Received 30 March 1981)

We have measured the linear polarization correlation of the photons emitted in a radiative atomic cascade of calcium. A high-efficiency source provided an improved statistical accuracy and an ability to perform new tests. Our results, in excellent agreement with the quantum mechanical predictions, strongly violate the generalized Bell's inequalities, and rule out the whole class of realistic local theories. No significant change in results was observed with source-polarizer separations of up to 6.5 m.

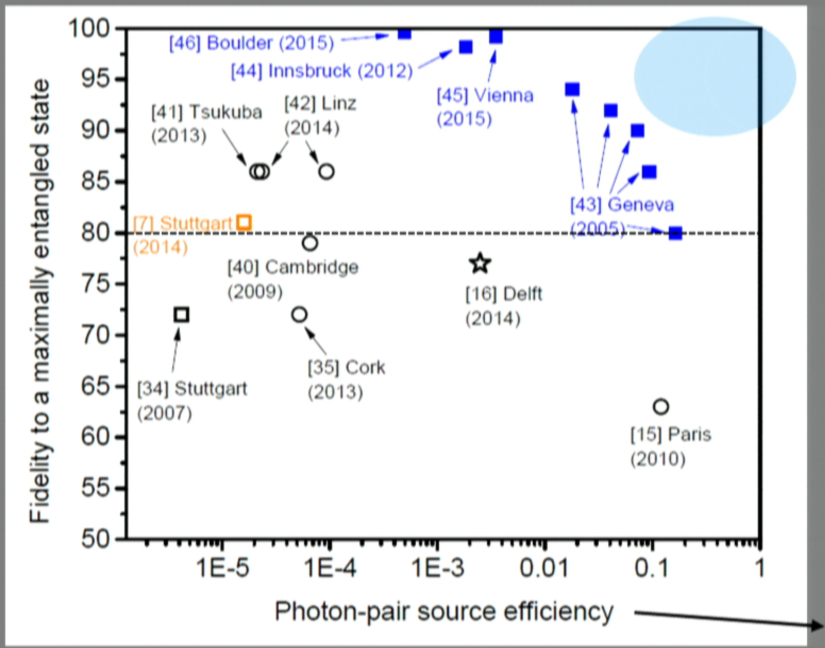


Comparison of pulsed entangled photon sources



Probability of collecting a photon pair per excitation pulse at the first lens or fiber

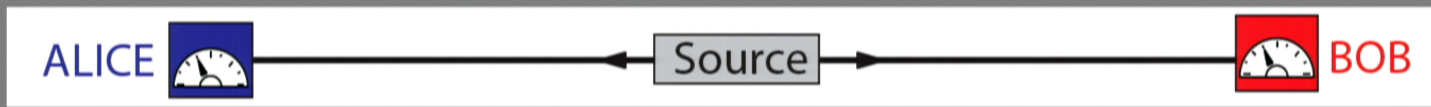
Comparison of pulsed entangled photon sources



Probability of collecting a photon pair per excitation pulse at the first lens or fiber

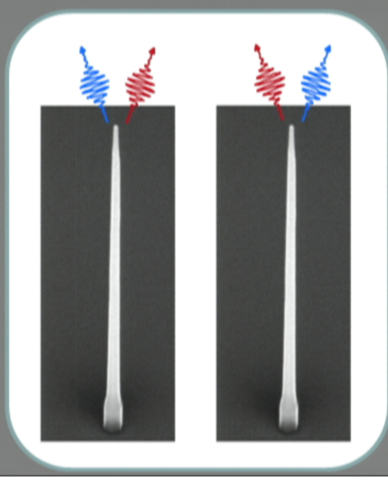
Motivation: quantum information

Long distance quantum communication (E91 protocol)



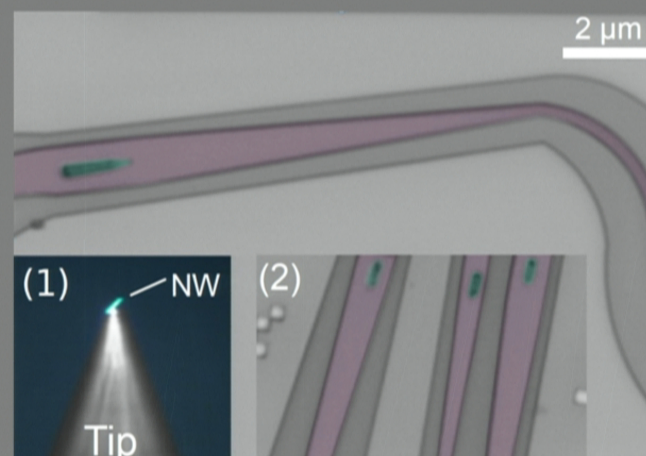
Quantum repeater

- Extend distance of quantum communication



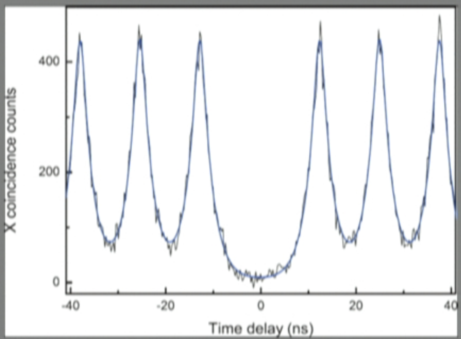
Quantum photonic circuits

- New on-chip source of single and entangled photon pairs



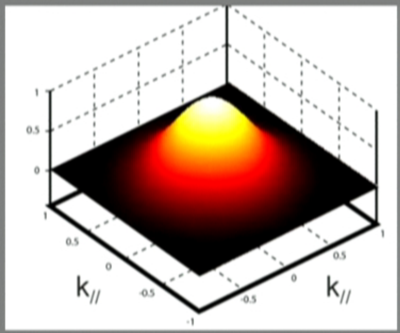
Advantages of quantum dots in nanowires

Bright and pure



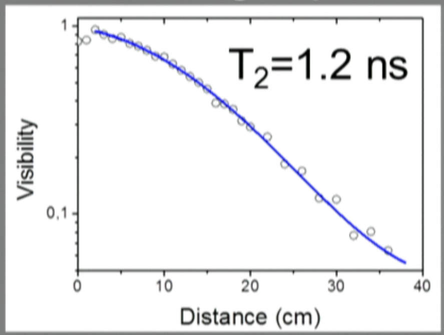
M.E. Reimer et al., Nature Commun. 3, 737 (2012)
J. Claudon et al., Nature Photon. 4, 174 (2010)

Gaussian emission profile



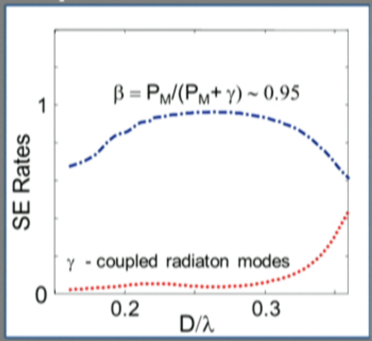
G. Bulgarini, Nano Lett. 14, 4102 (2014)

Coherent single photons



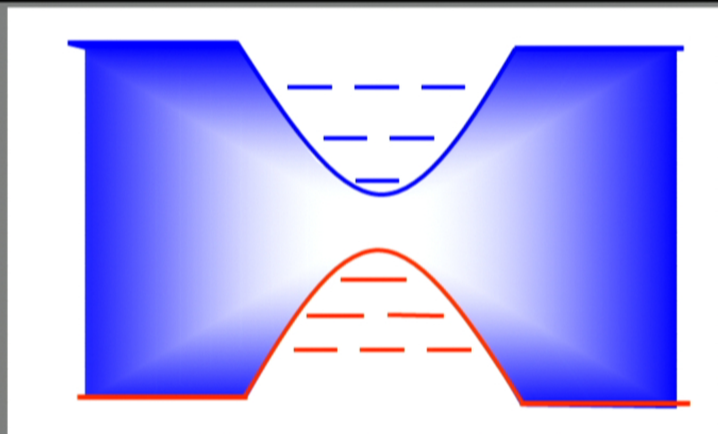
M.E. Reimer et al., Phys. Rev. B (2016)

Broad operation bandwidth



See I. Friedler, Opt. Express (2009) for details

On-demand quantum light source



- Quantum dots have near unity quantum efficiency at low temperatures
- Deterministic source of single-photon or entangled photon pairs

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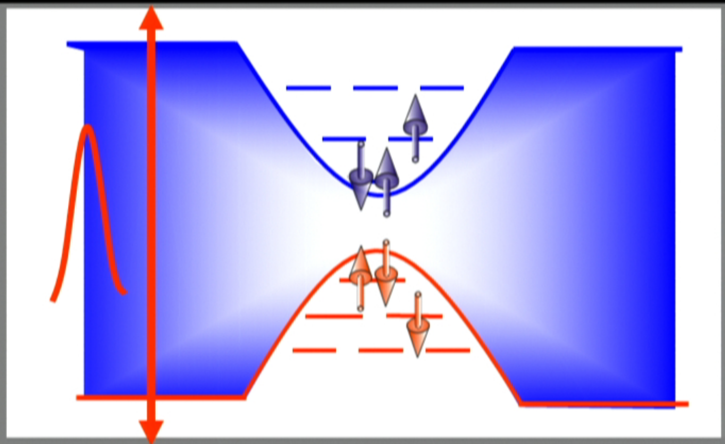

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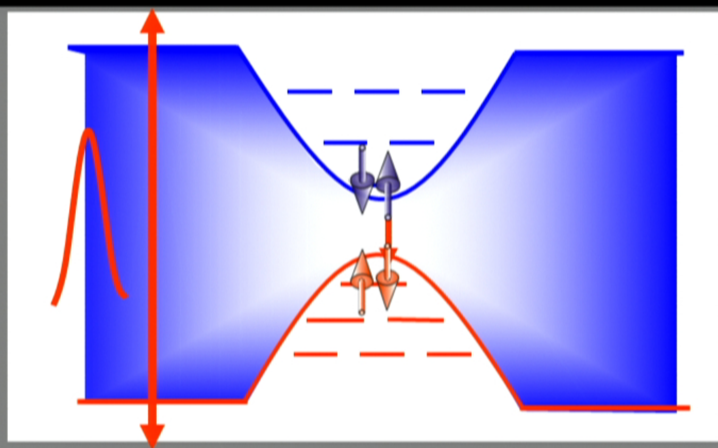

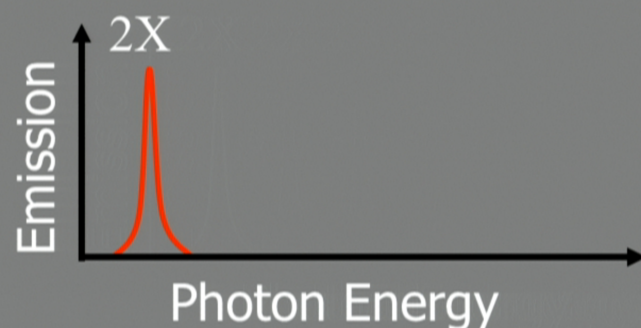

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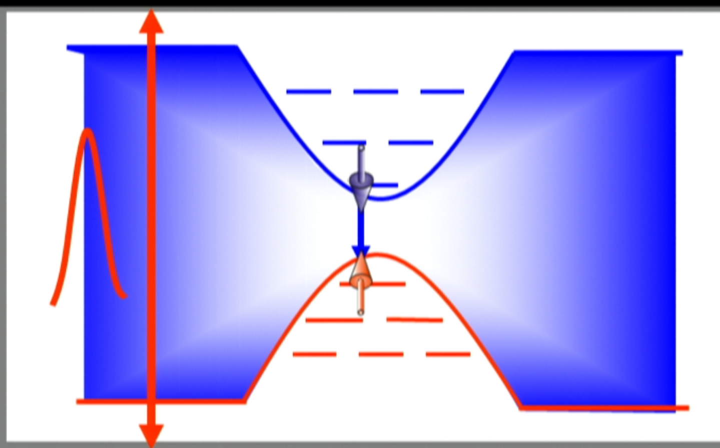

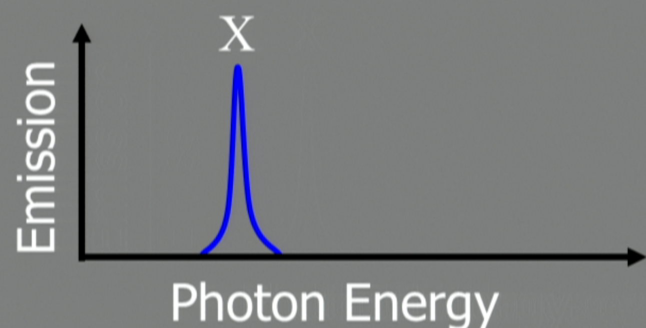

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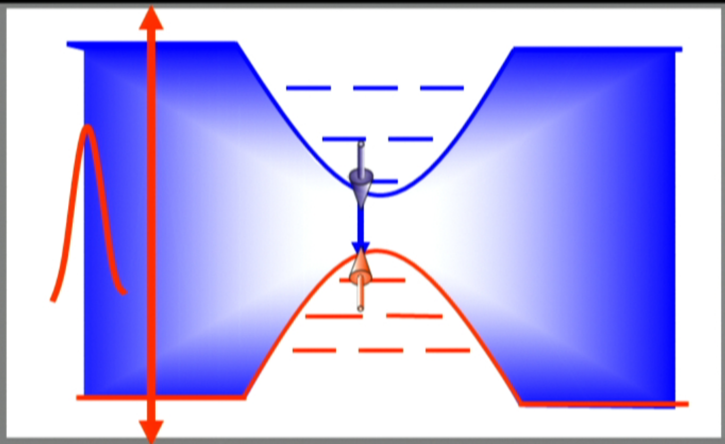

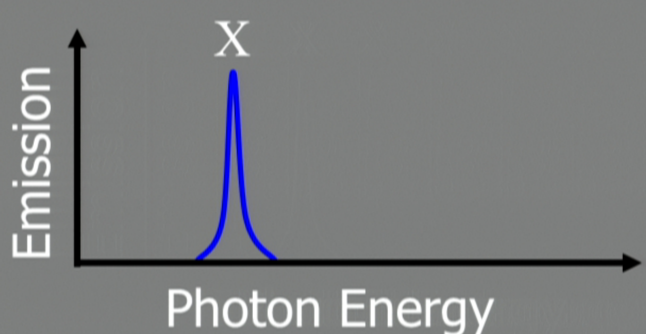

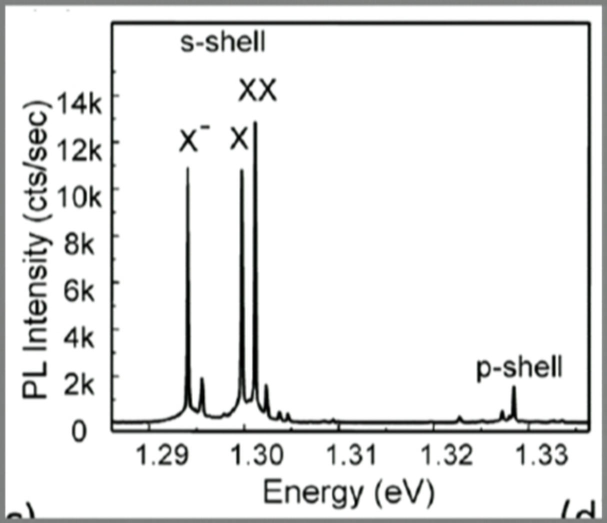

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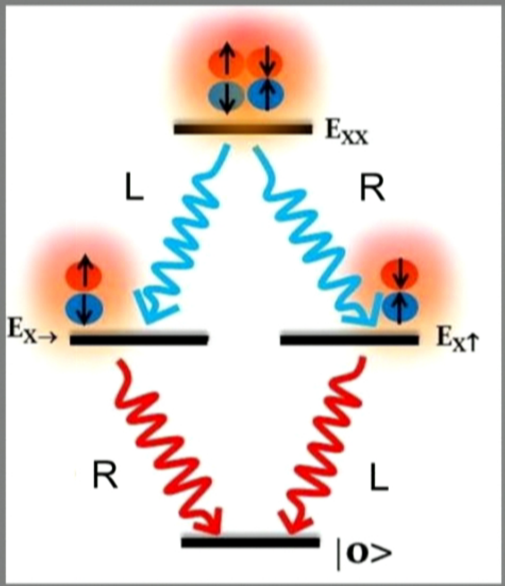
How is the entanglement generated?

Symmetric confining potential



Akopian et al., PRL 96, 130501 (2006)

$$|\Phi^+\rangle = (|R\rangle|L\rangle + |L\rangle|R\rangle)/\sqrt{2}$$

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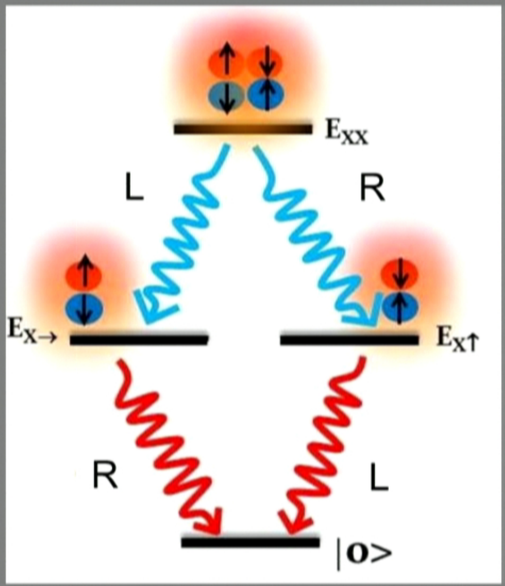
Symmetric confining potential



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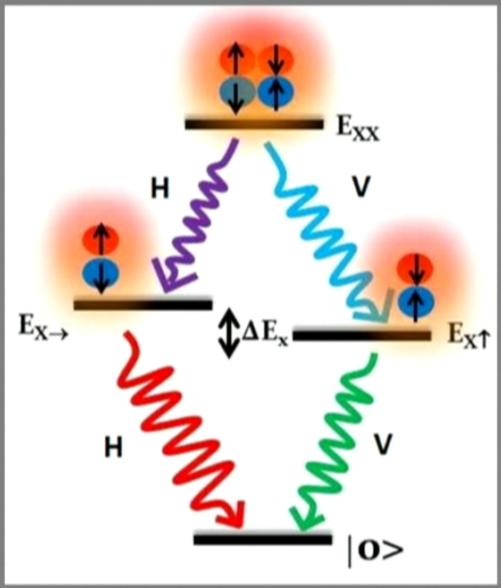
$$|\Phi^+\rangle = (|R\rangle|L\rangle + |L\rangle|R\rangle)/\sqrt{2}$$

$$|\Phi^+\rangle = (|H\rangle|H\rangle + |V\rangle|V\rangle)/\sqrt{2}$$

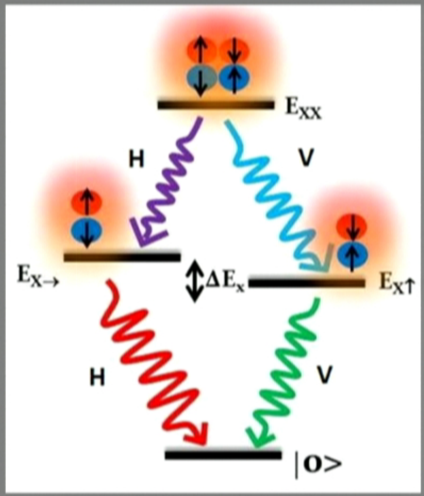
Asymmetric confining potential



Hafenbrak et al., NJP 9, 315 (2007)

$$(|H\rangle|H\rangle + e^{i\tau\Delta E_X/\hbar}|V\rangle|V\rangle)/\sqrt{2}$$

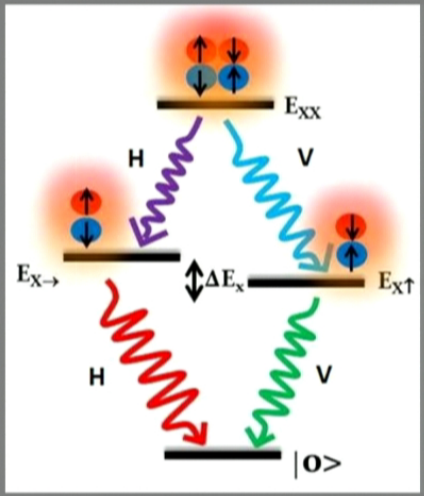
The problem



Asymmetric confining potential destroys the entanglement

- Caused by strain, dot shape, and dot composition

The problem



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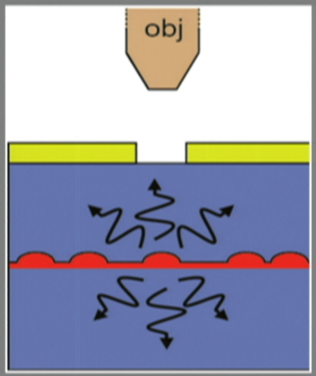
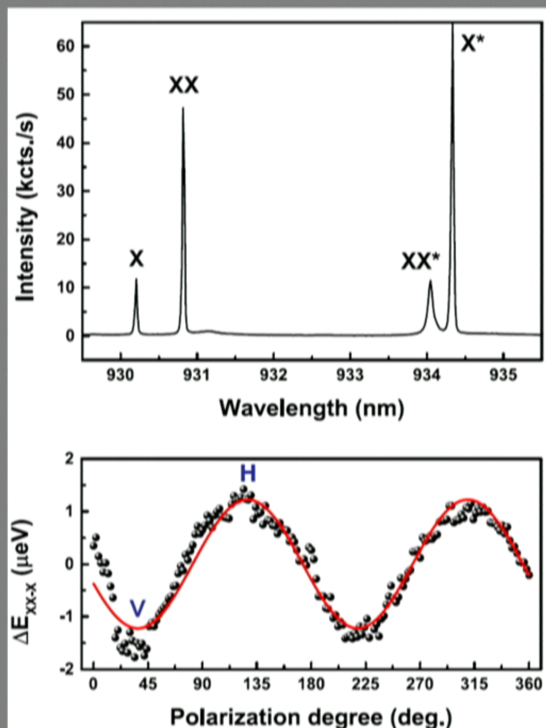


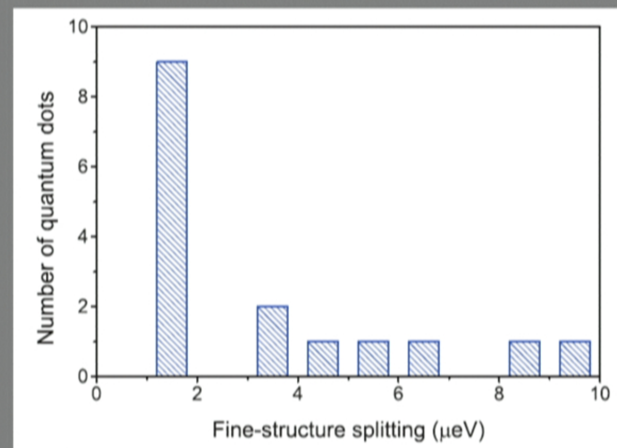
- Total internal reflection
- 'Zero' photon sources
- Efficiency limited to 1% per photon
- ~ 0.01% efficiency for the entangled pair

Nanowire Quantum Dots as an Ideal Source of Entangled Photon Pairs

Ranber Singh and Gabriel Bester
Max Planck Institute for Solid State Research, D-70569 Stuttgart, Germany
(Received 10 March 2009; published 3 August 2009)

We predict that heterostructure quantum wires and [111] grown quantum dots have a vanishing fine-structure splitting on the grounds of their symmetry, and are therefore ideal candidates to generate entangled photon pairs. We underpin this proposal by atomistic million-atom many-body pseudopotential calculations of realistic structures and find that the vanishing fine-structure splitting is robust against possible variations in morphology.

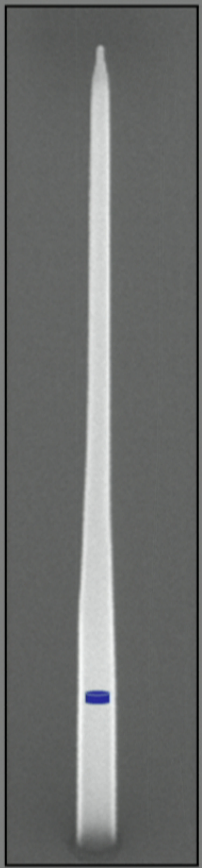




> 50 % of quantum dots show FSS < 2 µeV

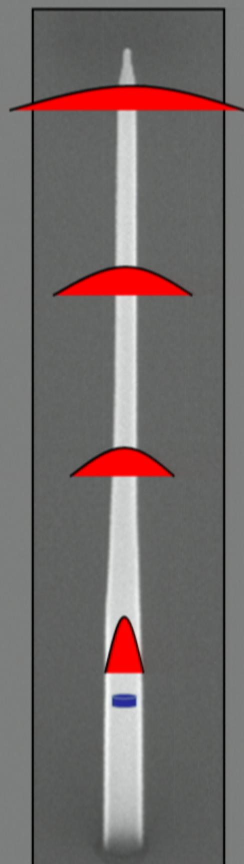
Measured fine-structure splitting of 1 µeV

Bright and directional photon emission



M.E. Reimer et al., Nature Commun. (2012)

Bright and directional photon emission



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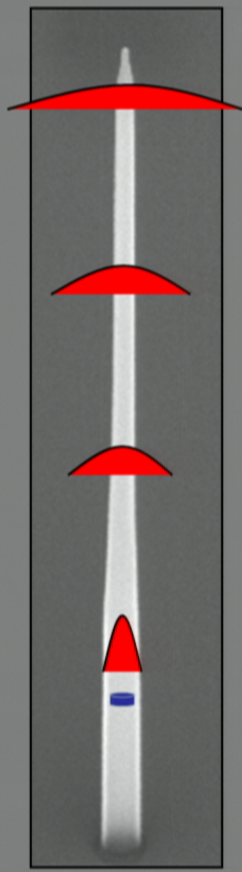

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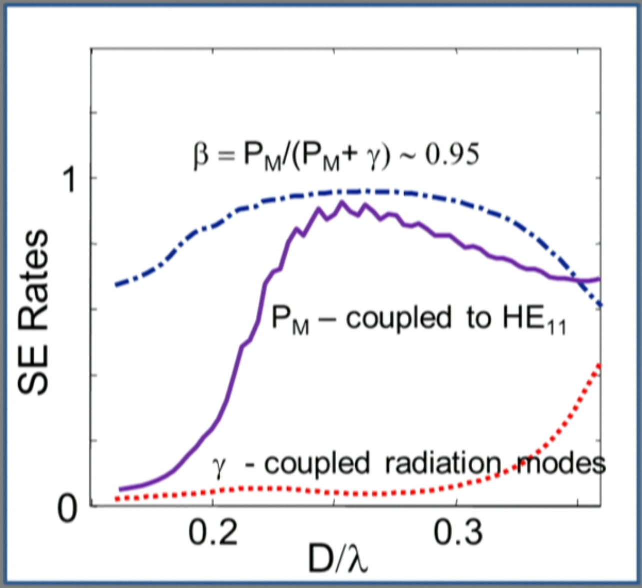
Broad operation bandwidth

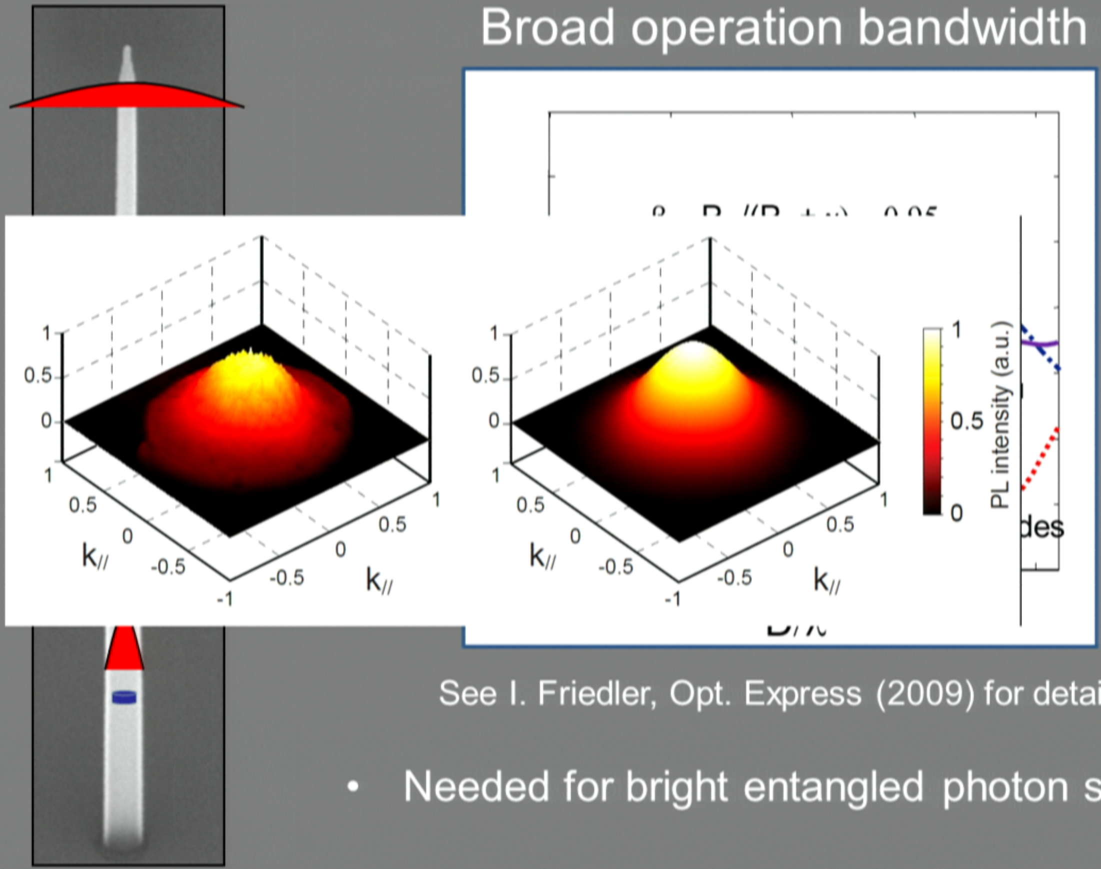


See I. Friedler, Opt. Express (2009) for details

- Needed for bright entangled photon source!

Bright and directional photon emission

Broad operation bandwidth



See I. Friedler, Opt. Express (2009) for details

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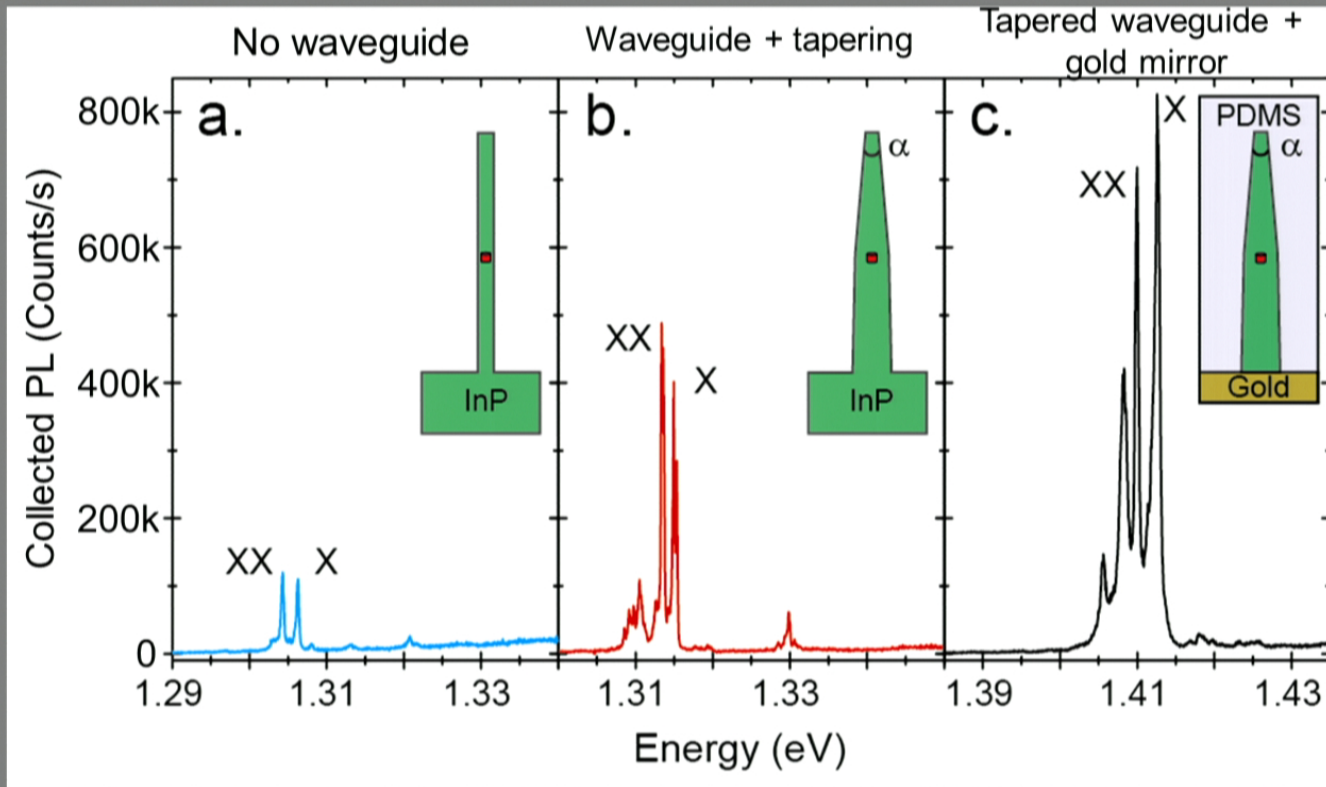
M.E. Reimer et al., Nature Commun. (2012)

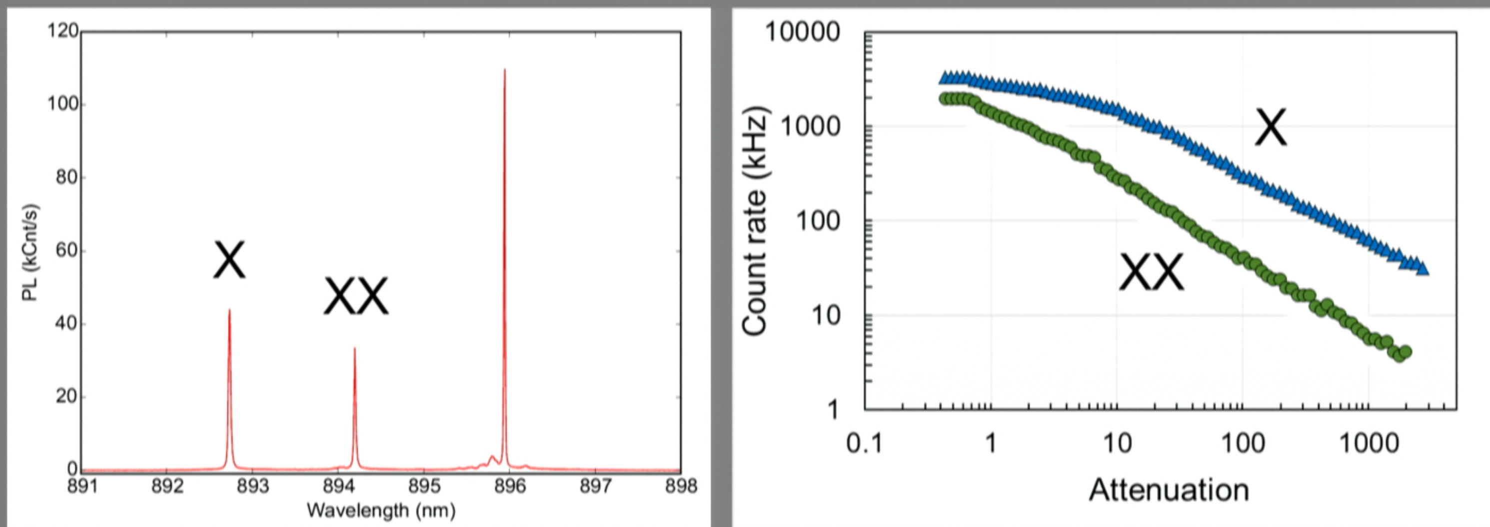
Collection efficiency enhancement



- x10 enhancement compared to previous work without waveguide

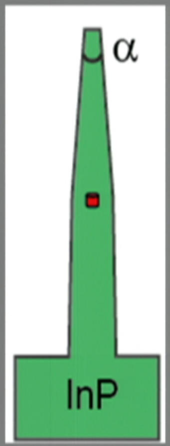
M.E. Reimer et al., *Nature Communications* **3**, 737 (2012)

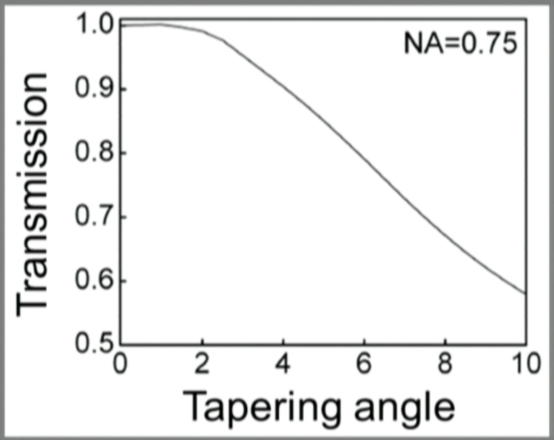
Bright entangled photon emission



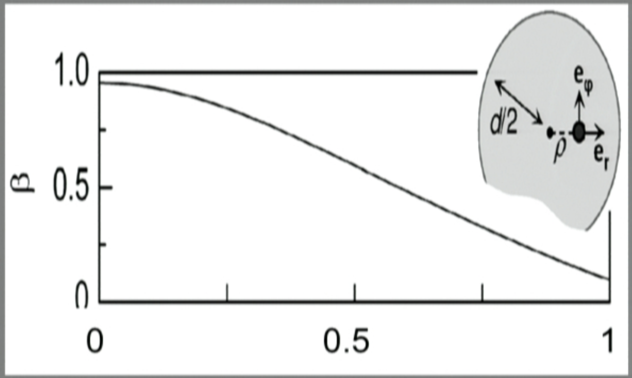
Theoretical maximum

- 97% light extraction efficiency (theoretical maximum)
  - 1 degree nanowire taper (near-unity transmission)
  - on-axis quantum dot (~95% coupling efficiency)
  - perfect mirror



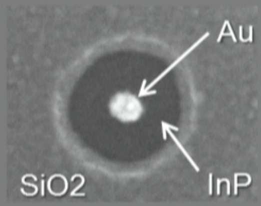


J. Claudon et al., ChemPhysChem, 14: 2393 – 2402 (2013)



- J. Claudon et al., ChemPhysChem (2013)
- J. Bleuse et al., PRL 106, 103601 (2010)

Position controlled nanowires



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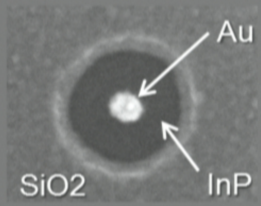

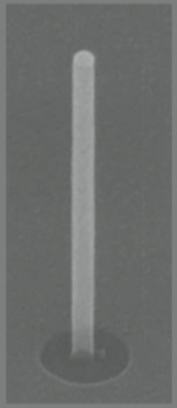

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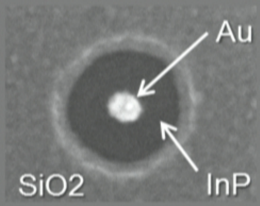

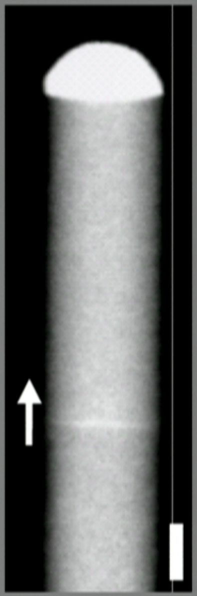

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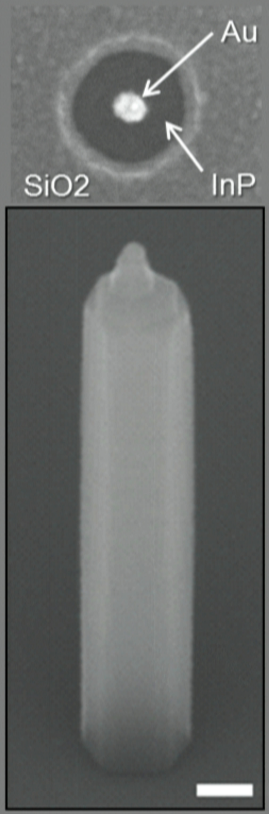

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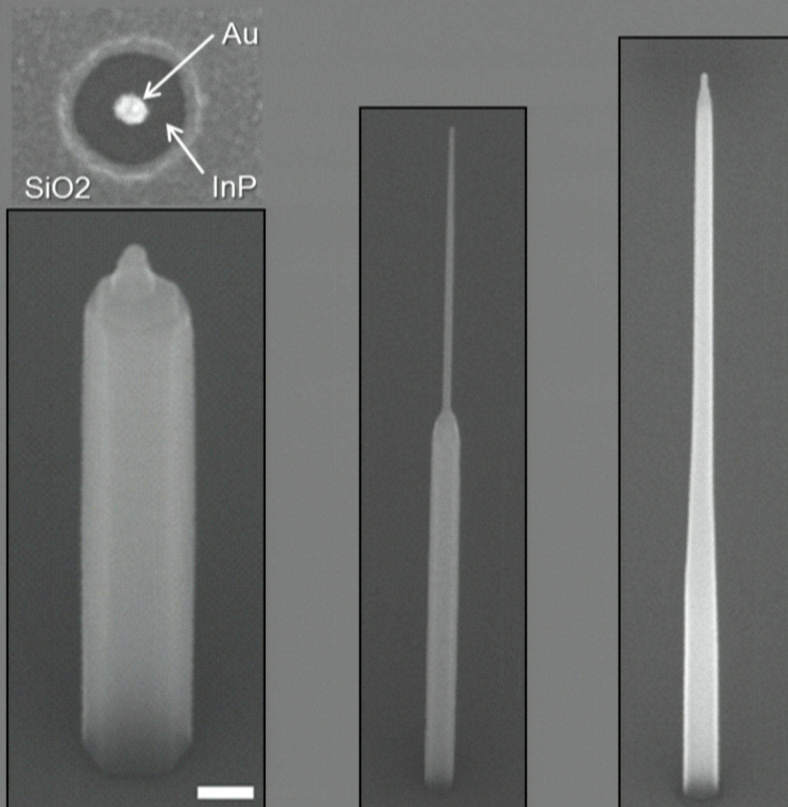

- Independently control dot size and location, as well as waveguide shell around it
- D. Dalacu et al., APL, 251101 (2011)
- D. Dalacu et al., Nano Lett. 5919 (2012)

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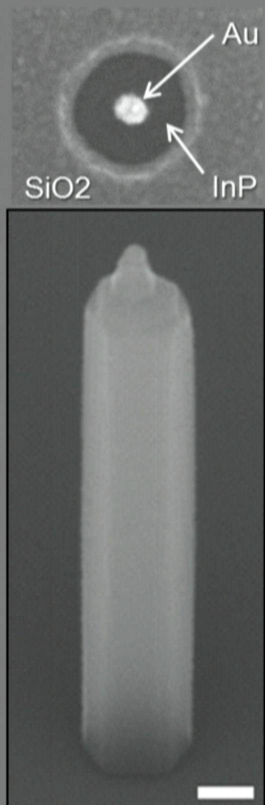

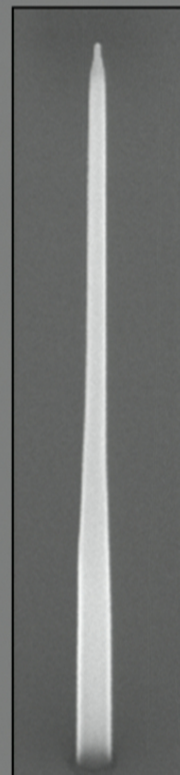

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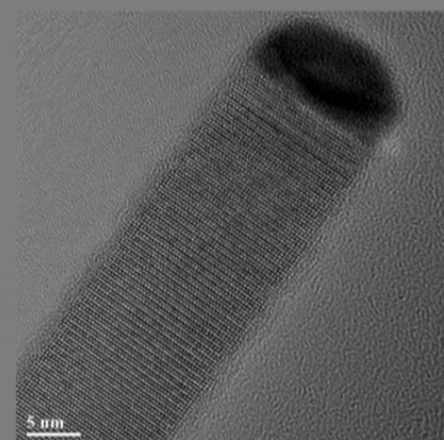
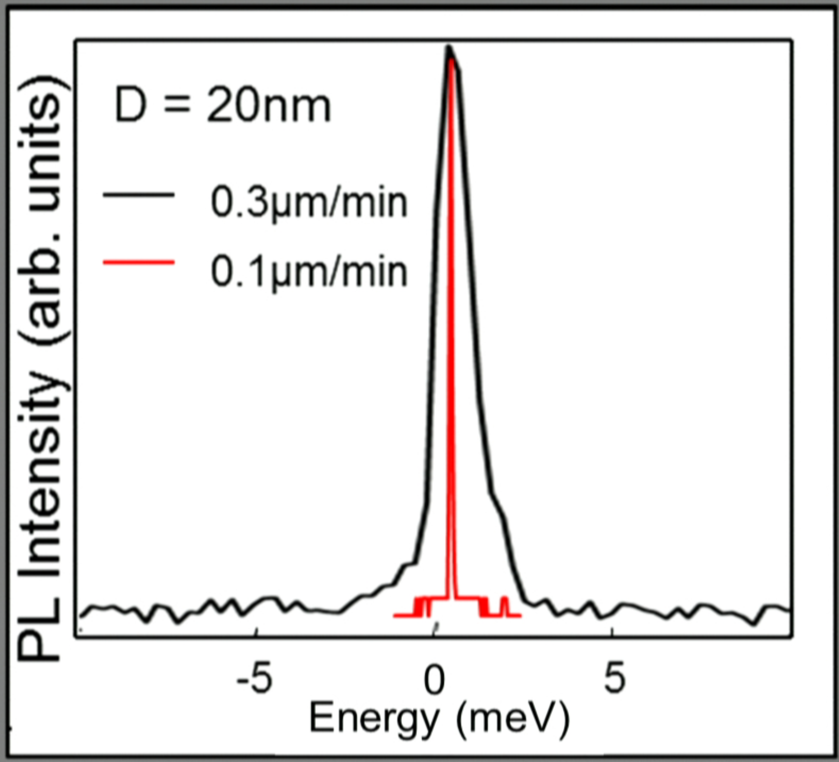
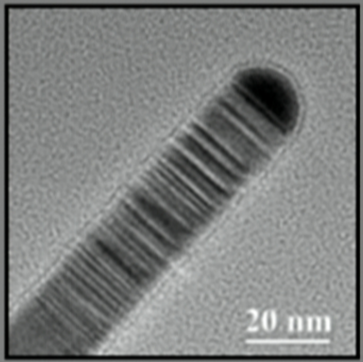
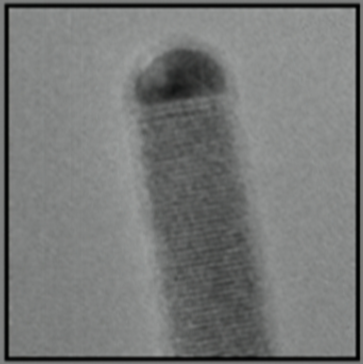


Role of crystal phase purity







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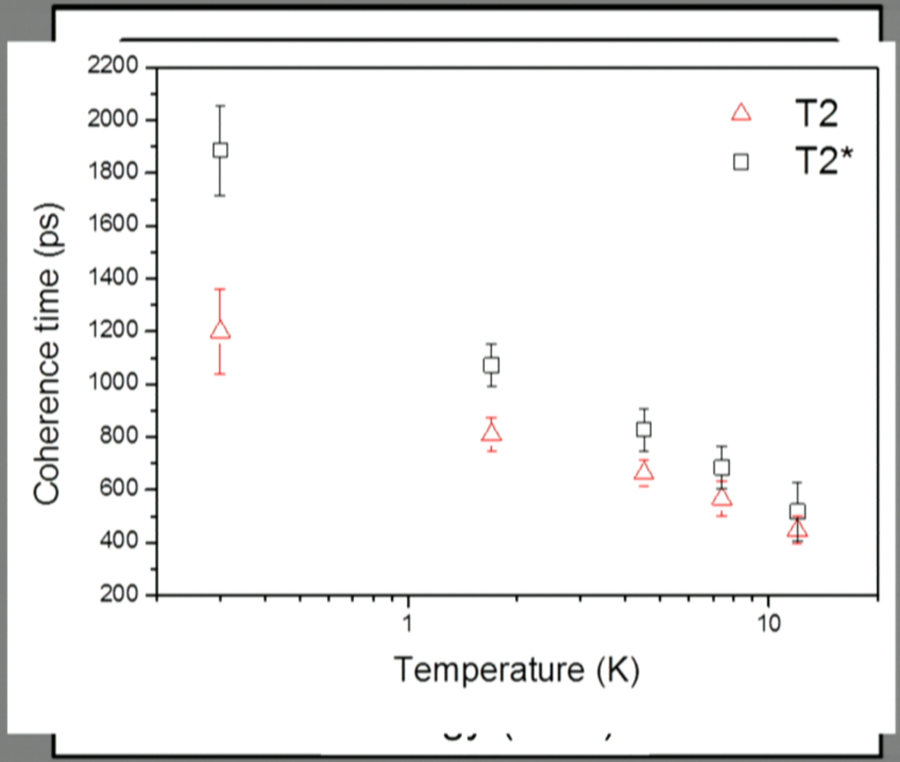
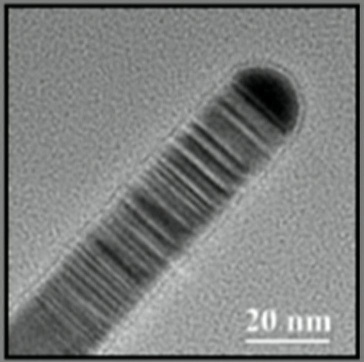
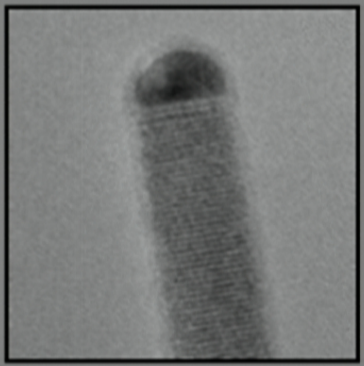
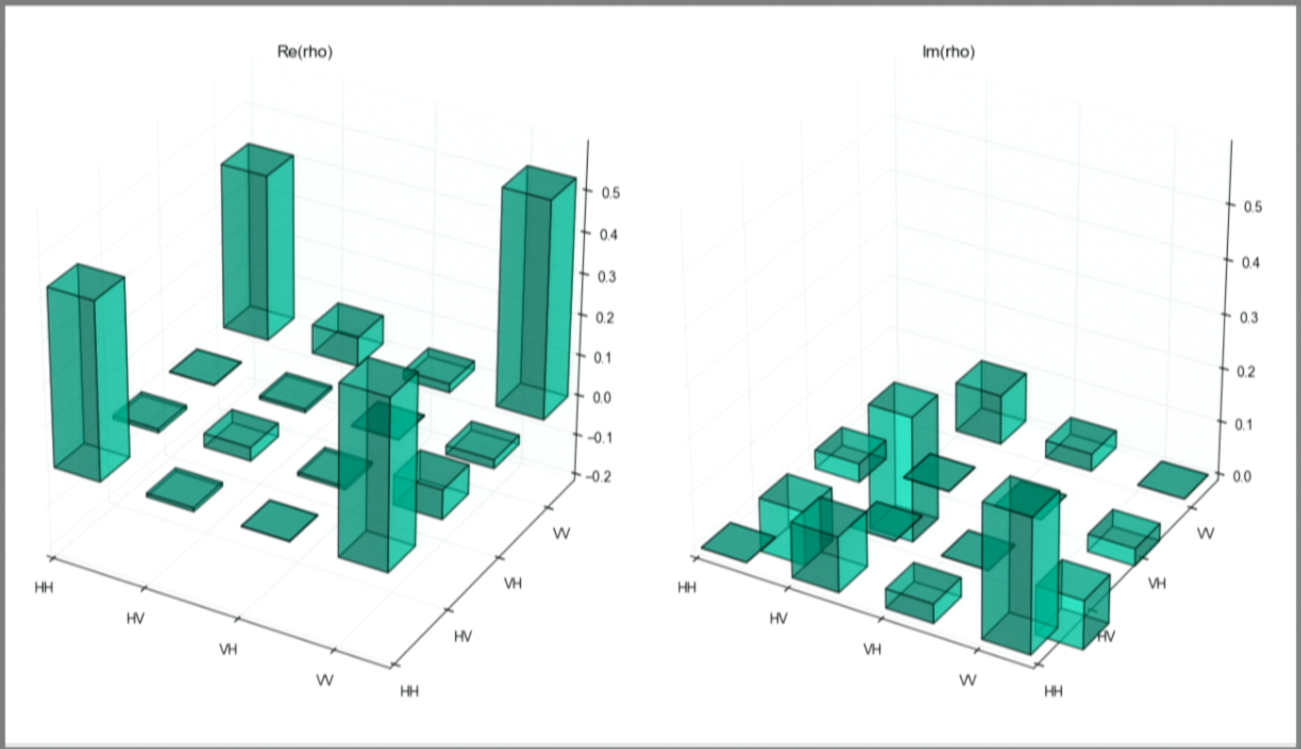




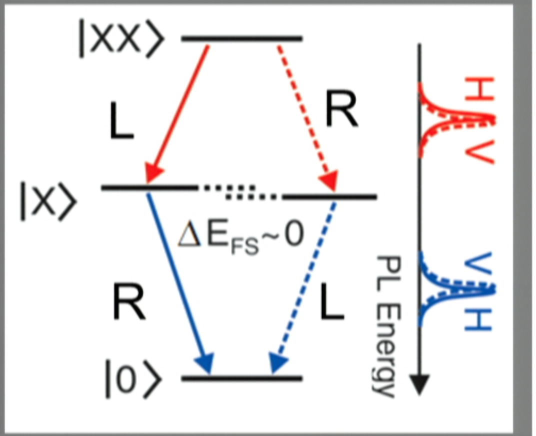


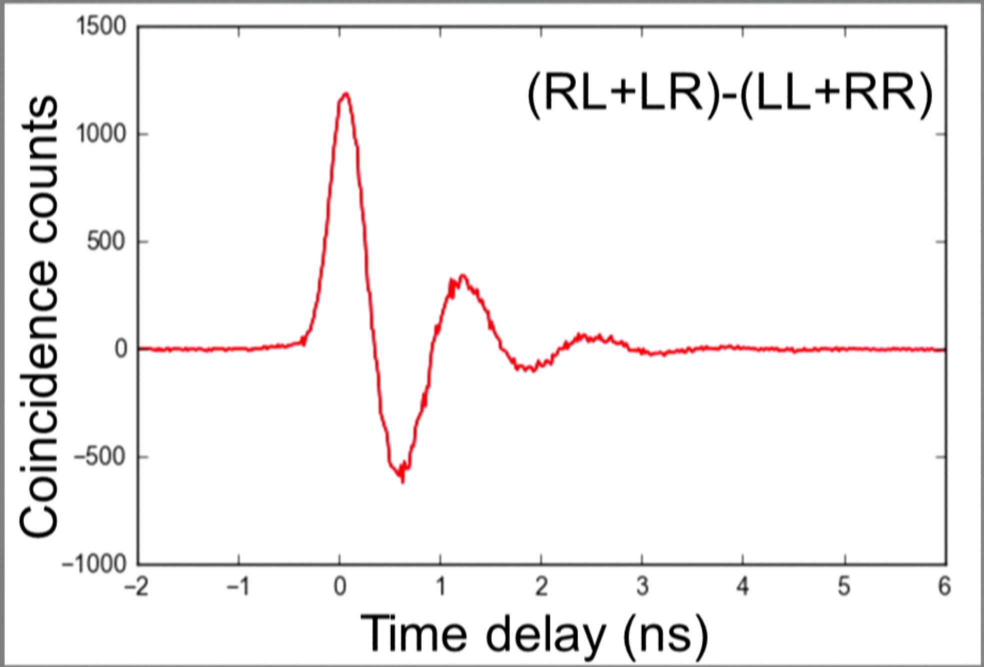
What about the entanglement fidelity?



- Entanglement fidelity of 98% for 500 ps time window
- Concurrence ~ 95%

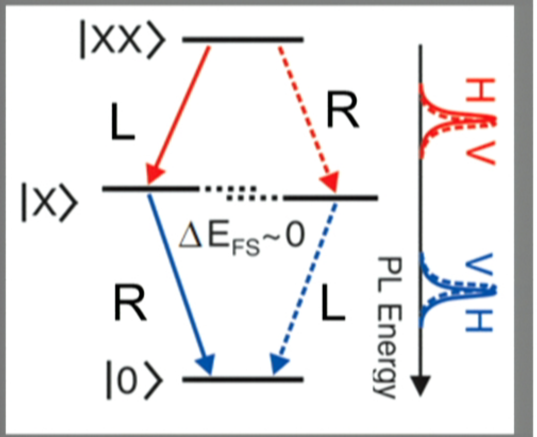
Quantum Oscillations

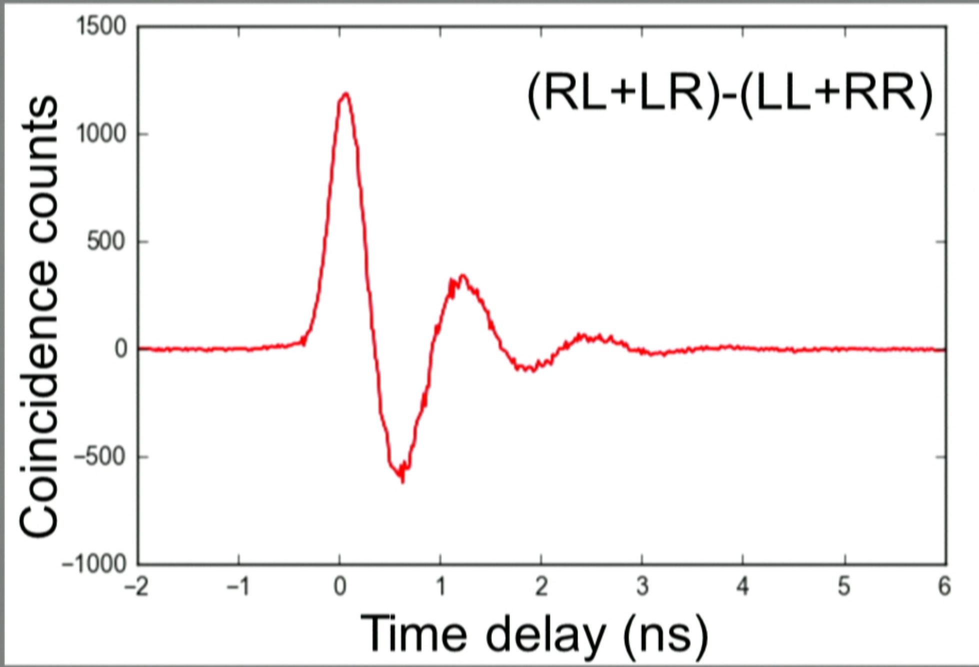




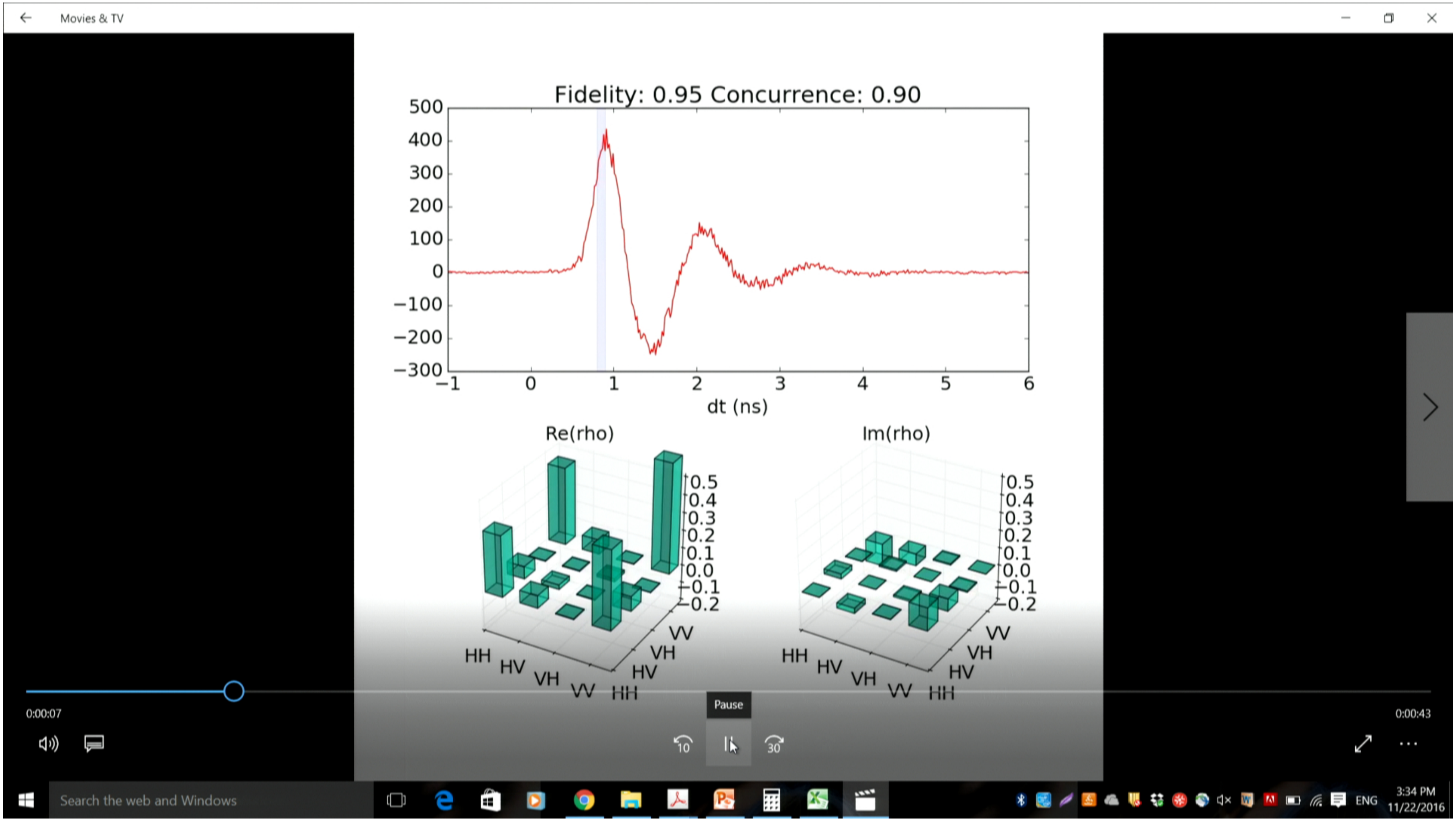
- Entanglement fidelity preserved during exciton precession

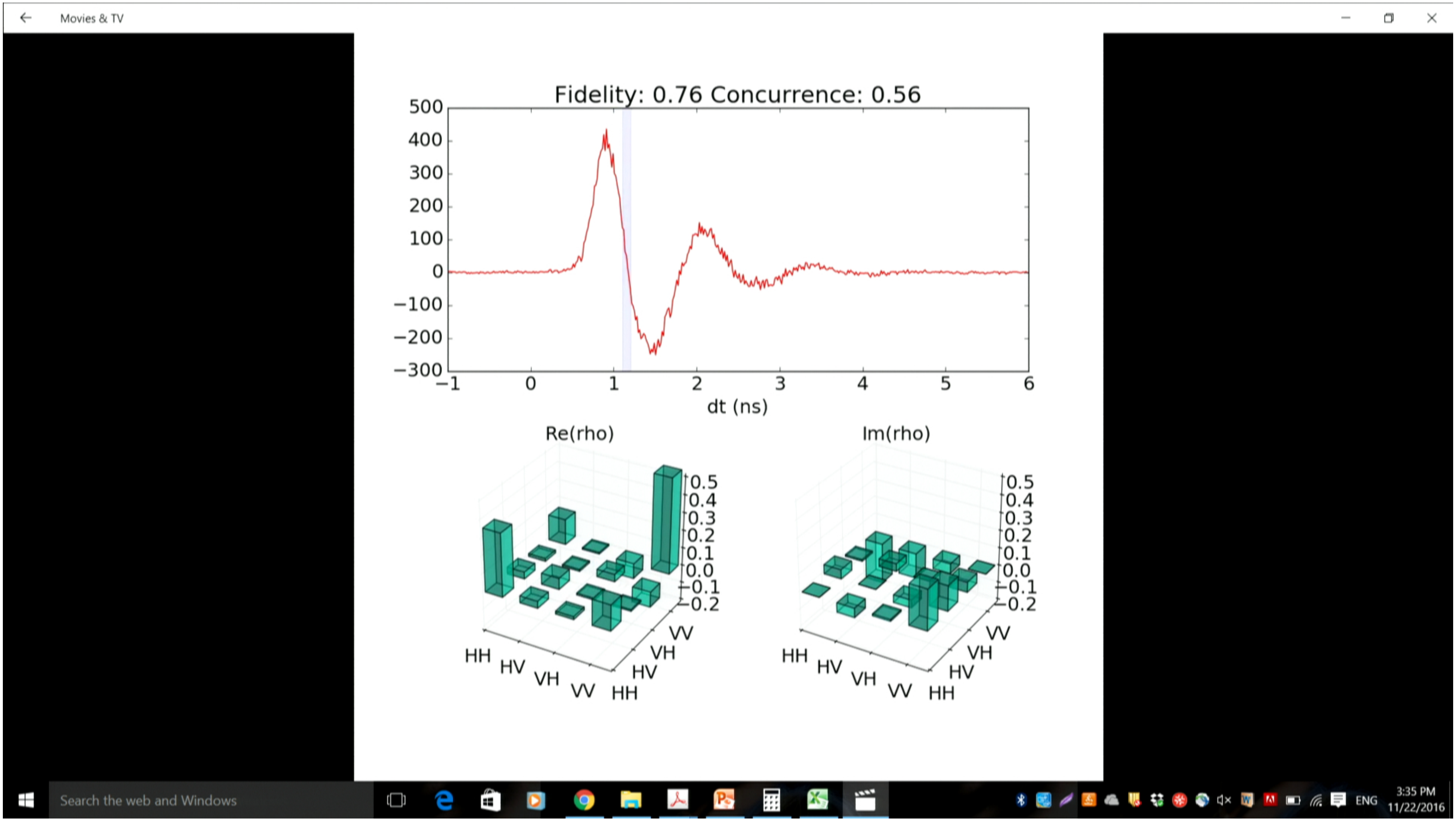
Quantum Oscillations

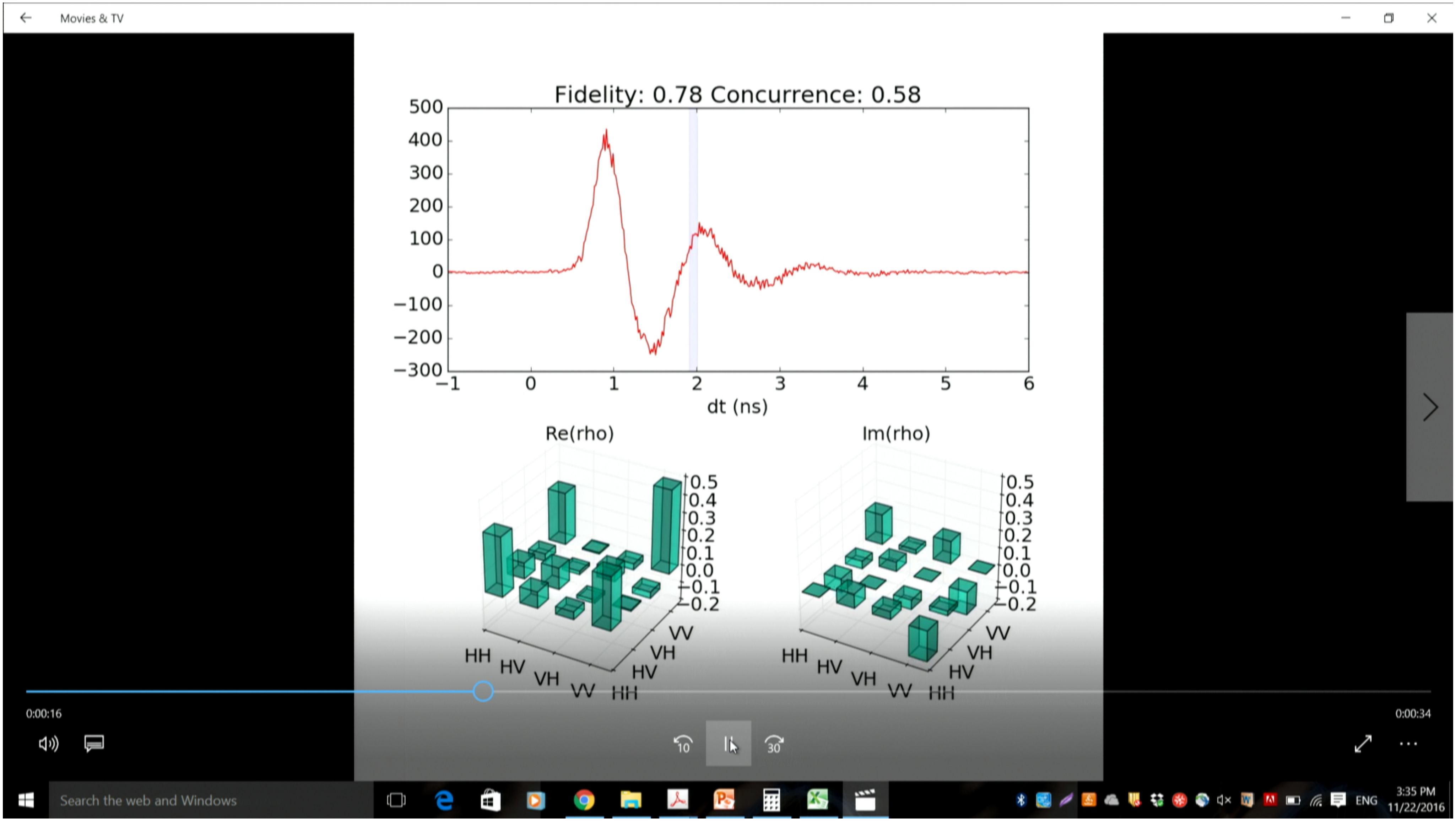


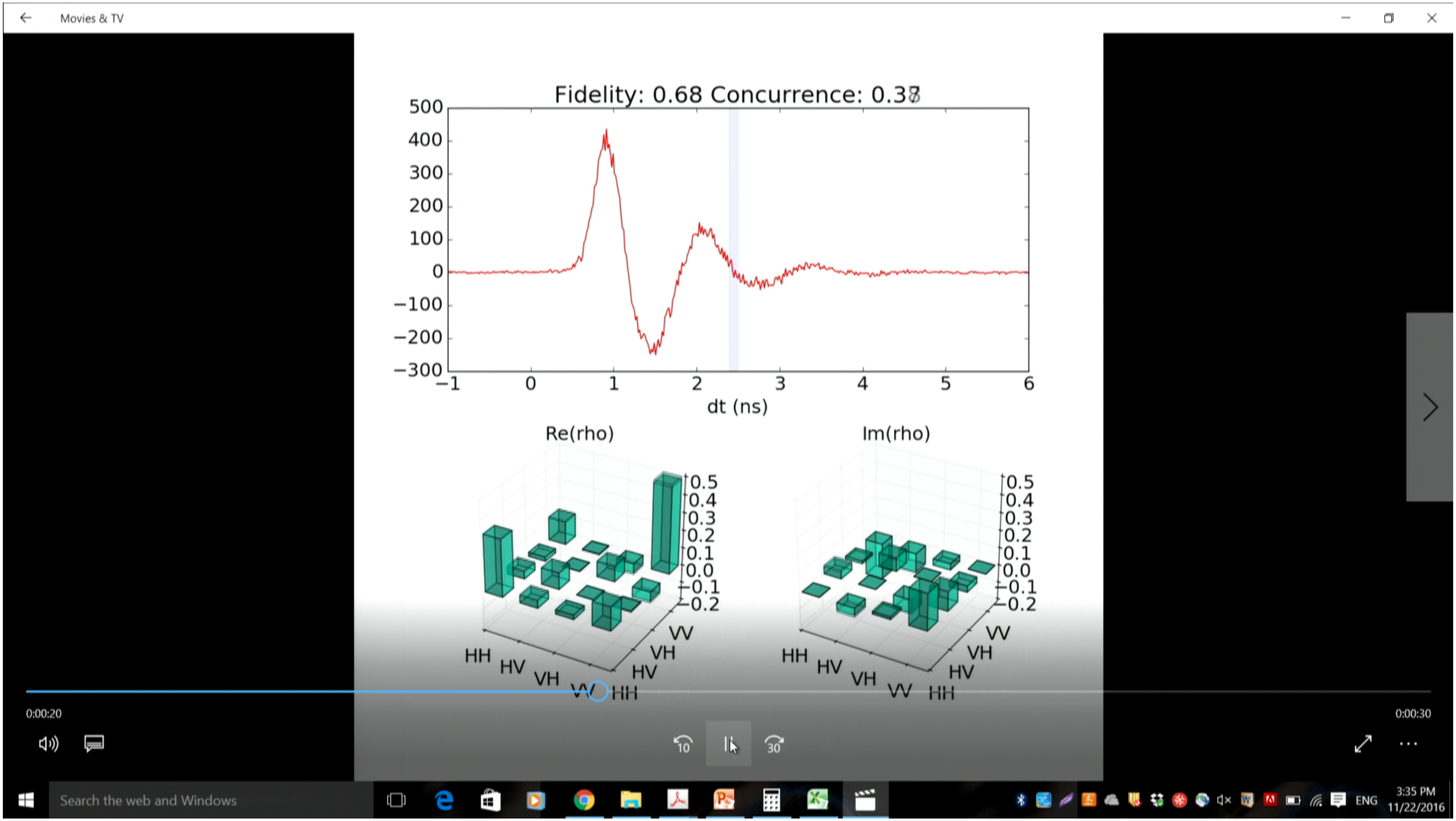


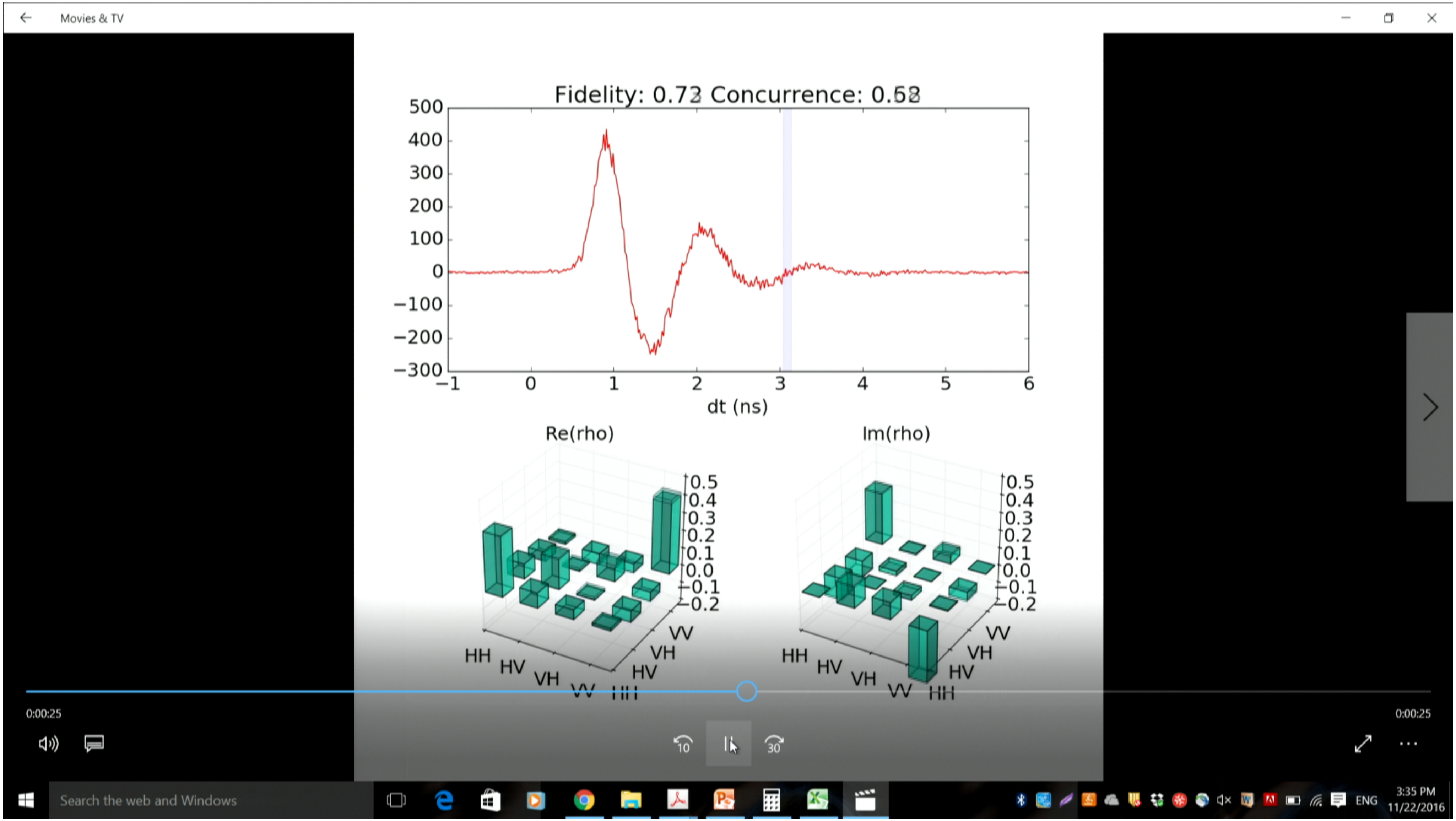
- Entanglement fidelity preserved during exciton precession


Movies & TV
Fidelity: 0.95 Concurrence: 0.90
dt (ns)
Re(rho)
Im(rho)
HH
HV
VH
VV
Pause
0:00:07
0:00:43
Search the web and Windows
ENG
3:34 PM
11/22/2016

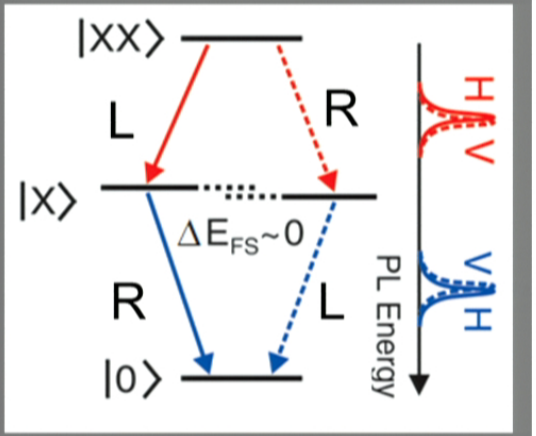

Movies & TV
Fidelity: 0.76 Concurrence: 0.56
500
400
300
200
100
0
−100
−200
−300
−1
0
1
2
3
4
5
6
dt (ns)
Re(rho)
Im(rho)
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
HH
HV
VH
VV
Search the web and Windows
ENG
3:35 PM
11/22/2016

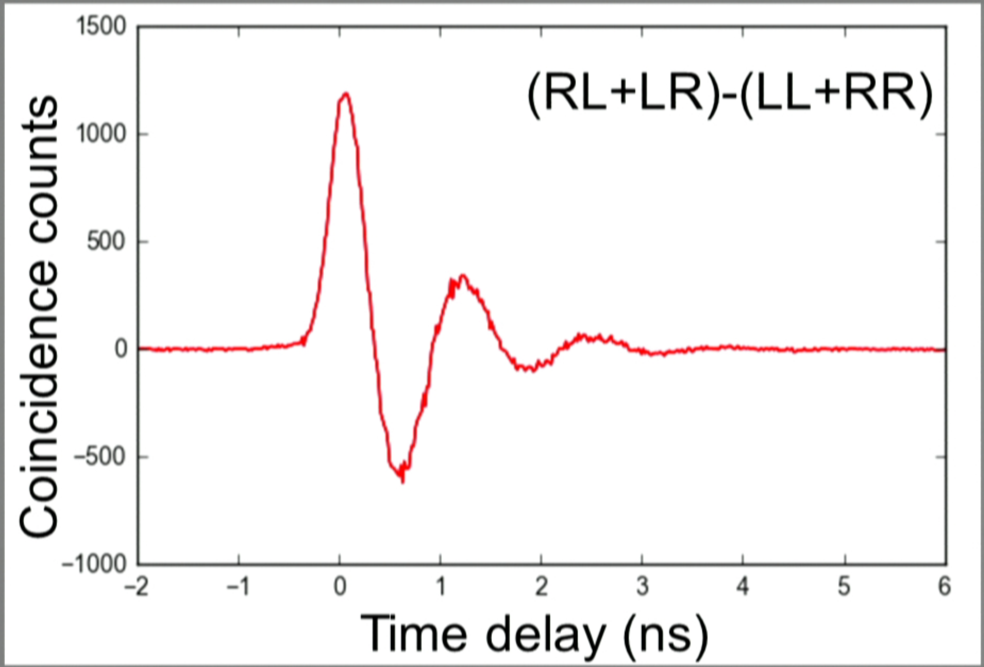

Movies & TV
Fidelity: 0.78 Concurrence: 0.58
500
400
300
200
100
0
−100
−200
−300
−1
0
1
2
3
4
5
6
dt (ns)
Re(rho)
Im(rho)
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
HH
HV
VH
VV
0:00:16
0:00:34
Search the web and Windows
ENG
3:35 PM
11/22/2016


Movies & TV
Fidelity: 0.68 Concurrence: 0.37
dt (ns)
Re(rho)
Im(rho)
HH
HV
VH
VV
0:00:20
0:00:30
Search the web and Windows
ENG
3:35 PM
11/22/2016


Movies & TV
Fidelity: 0.72 Concurrence: 0.58
dt (ns)
Re(rho)
Im(rho)
HH
HV
VH
VV
0:00:25
0:00:25
Search the web and Windows
ENG
3:35 PM
11/22/2016

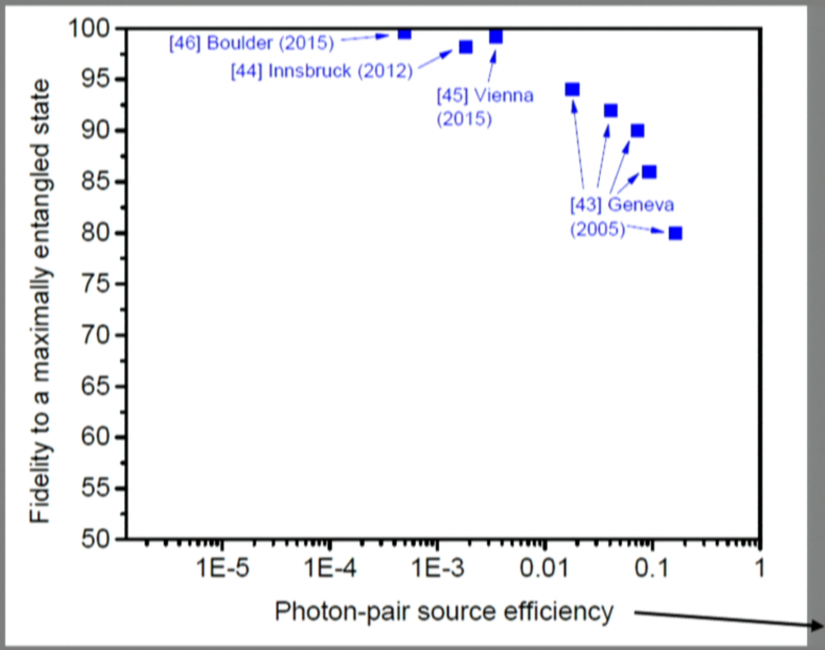
Quantum Oscillations





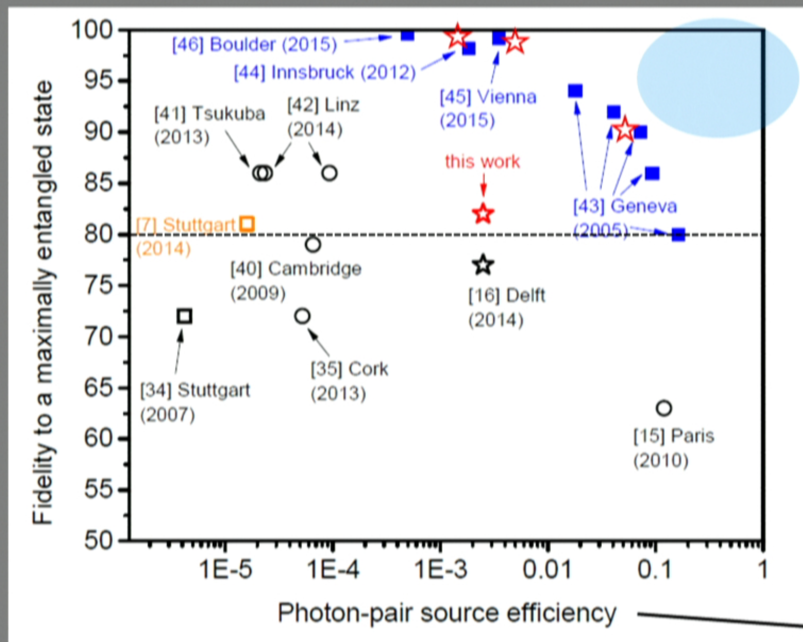
- Entanglement fidelity preserved during exciton precession

Comparison of pulsed entangled photon sources



Probability of collecting a photon pair per excitation pulse at the first lens or fiber

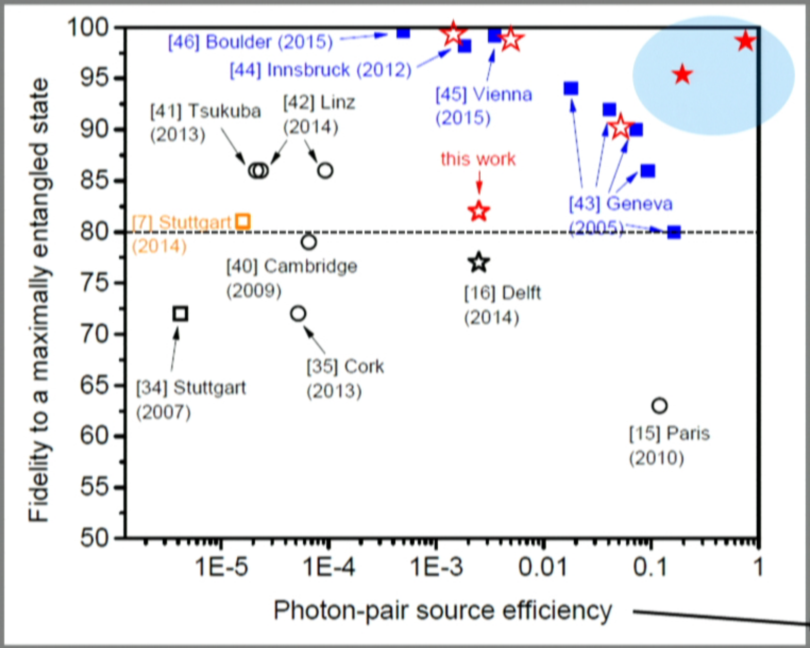
Comparison of pulsed entangled photon sources



Probability of collecting a photon pair per excitation pulse at the first lens or fiber

- Control charge state

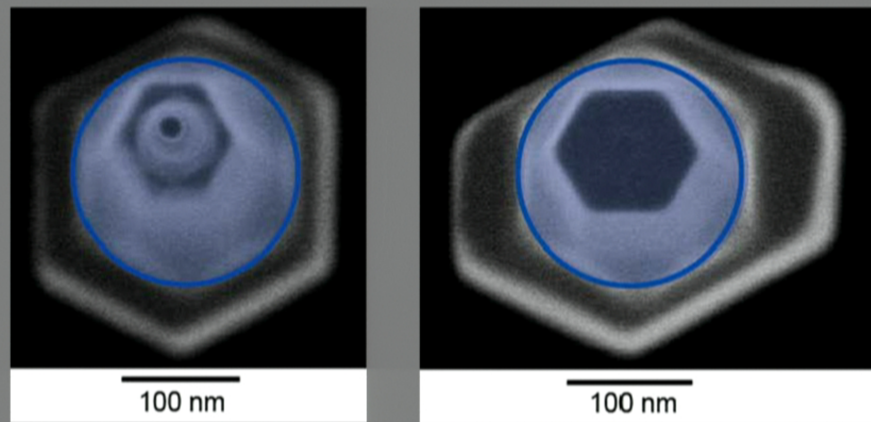
Comparison of pulsed entangled photon sources



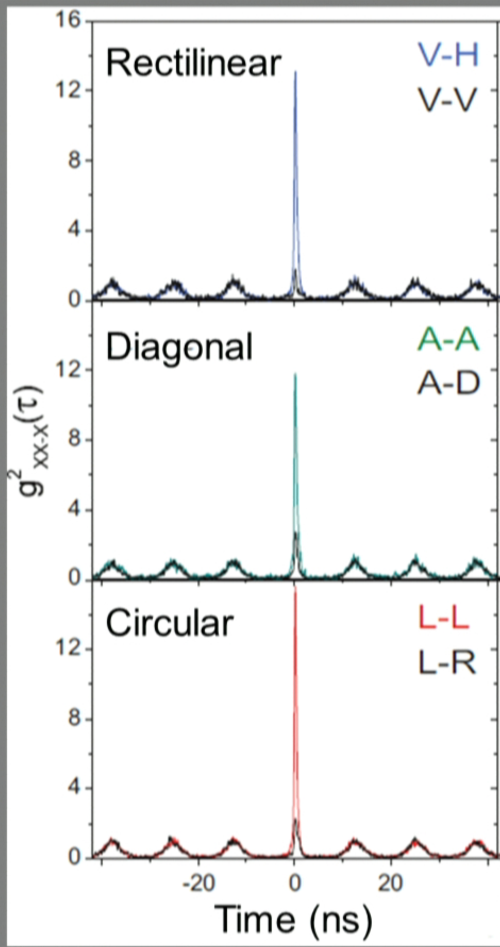
Probability of collecting a photon pair per excitation pulse at the first lens or fiber

- Control charge state
- Electric field tuning of fine-structure splitting to zero
- Two-photon resonant excitation

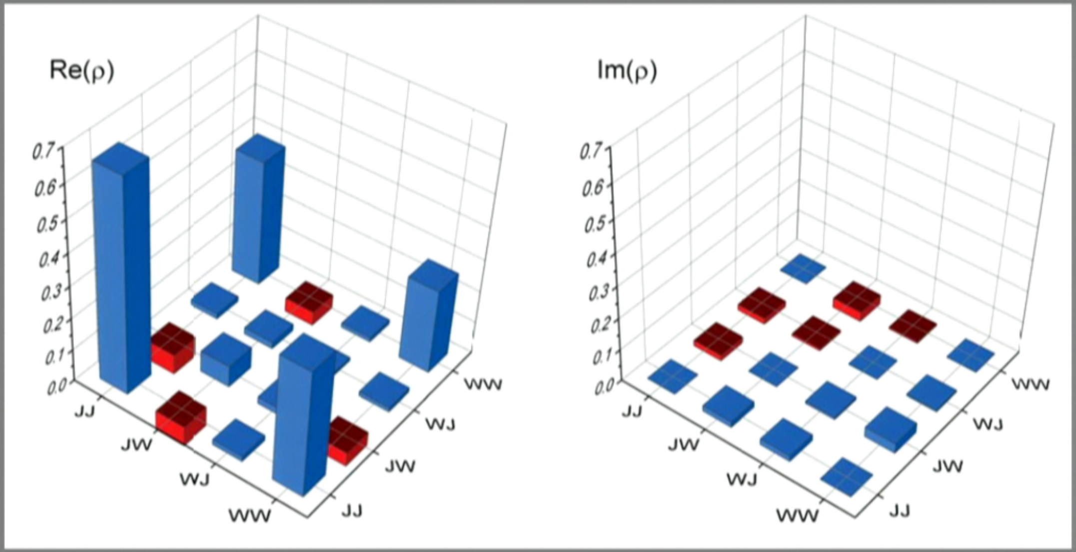
Role of NW waveguide symmetry



Entangled photon generation



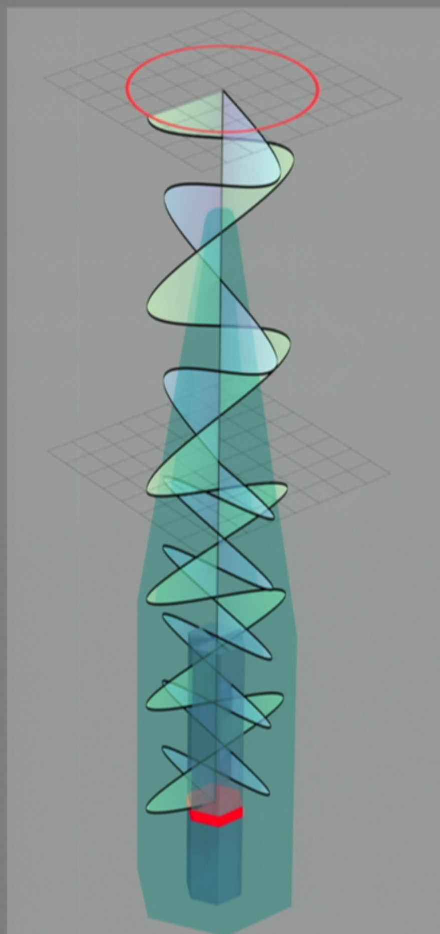
Strong entanglement



- Fidelity of 0.82 (for full time window)
- Fidelity of 0.86 and concurrence of 0.8 (130 ps time window)

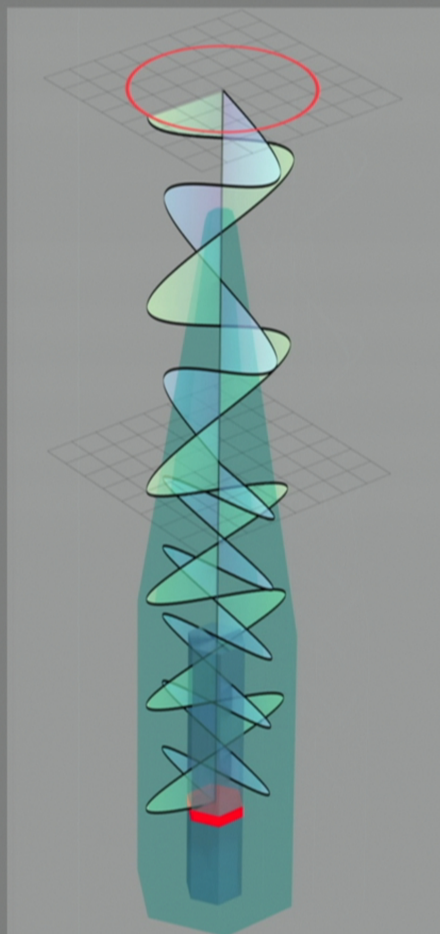
Versteegh, Reimer, Jöns et al., Nature Commun. 5, 5298 (2014)

Why do we observe a different quantum state?



- Birefringence due to nanowire asymmetries of the waveguide shell
- Propagation along an asymmetric nanowire waveguide could lead to the observed phase difference
  - i.e., HH+VV is transformed to RR+LL
  - And RL+LR is transformed to HV+VH

Why do we observe a different quantum state?



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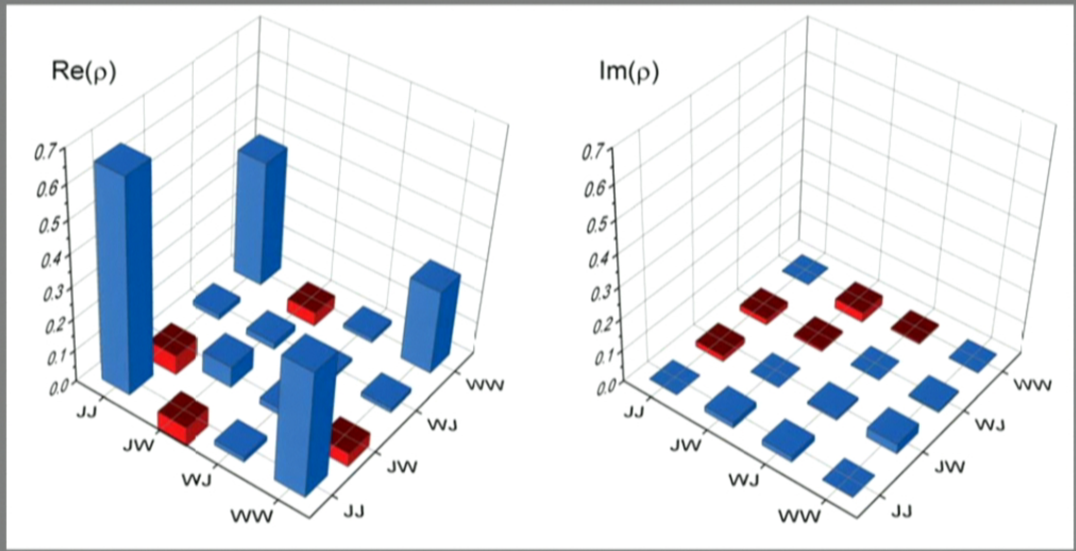
Different quantum state

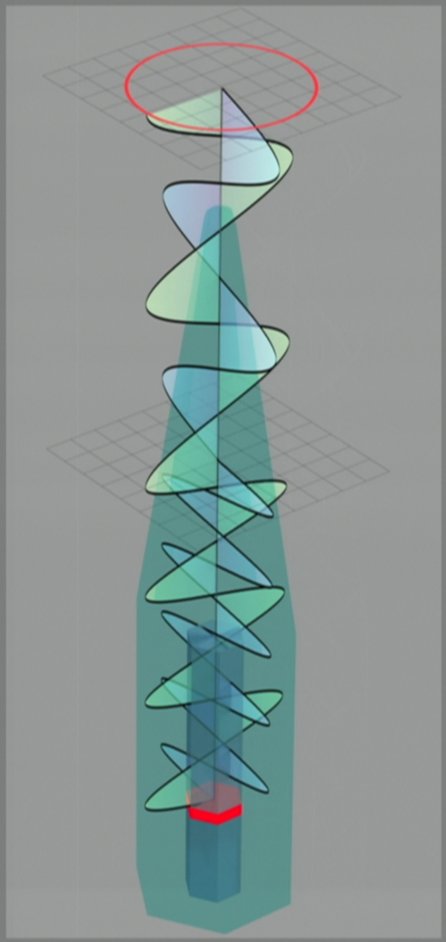


$$|\Psi\rangle = |JJ\rangle + |WW\rangle$$

$$J = He^{-i\beta}\cos\alpha + Ve^{-i\beta}\sin\alpha \text{ and } W = -He^{i\beta}\sin\alpha + Ve^{i\beta}\cos\alpha$$

Versteegh, Reimer, Jöns et al., Nature Commun. 5, 5298 (2014)

Why do we observe a different quantum state?



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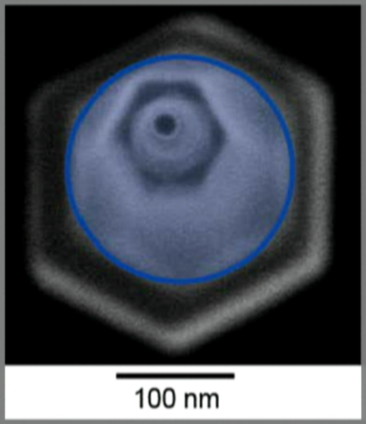
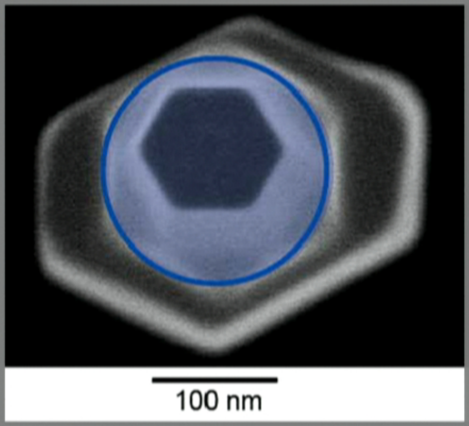
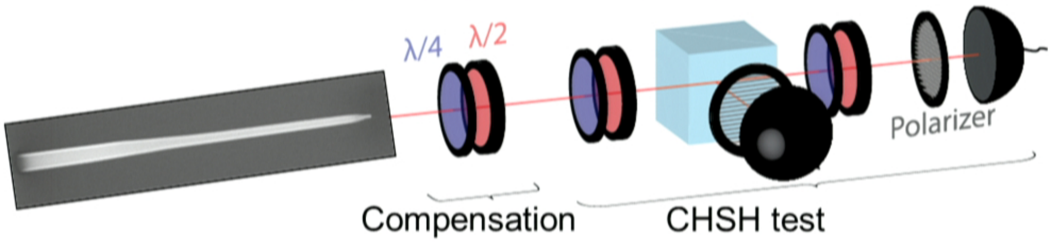
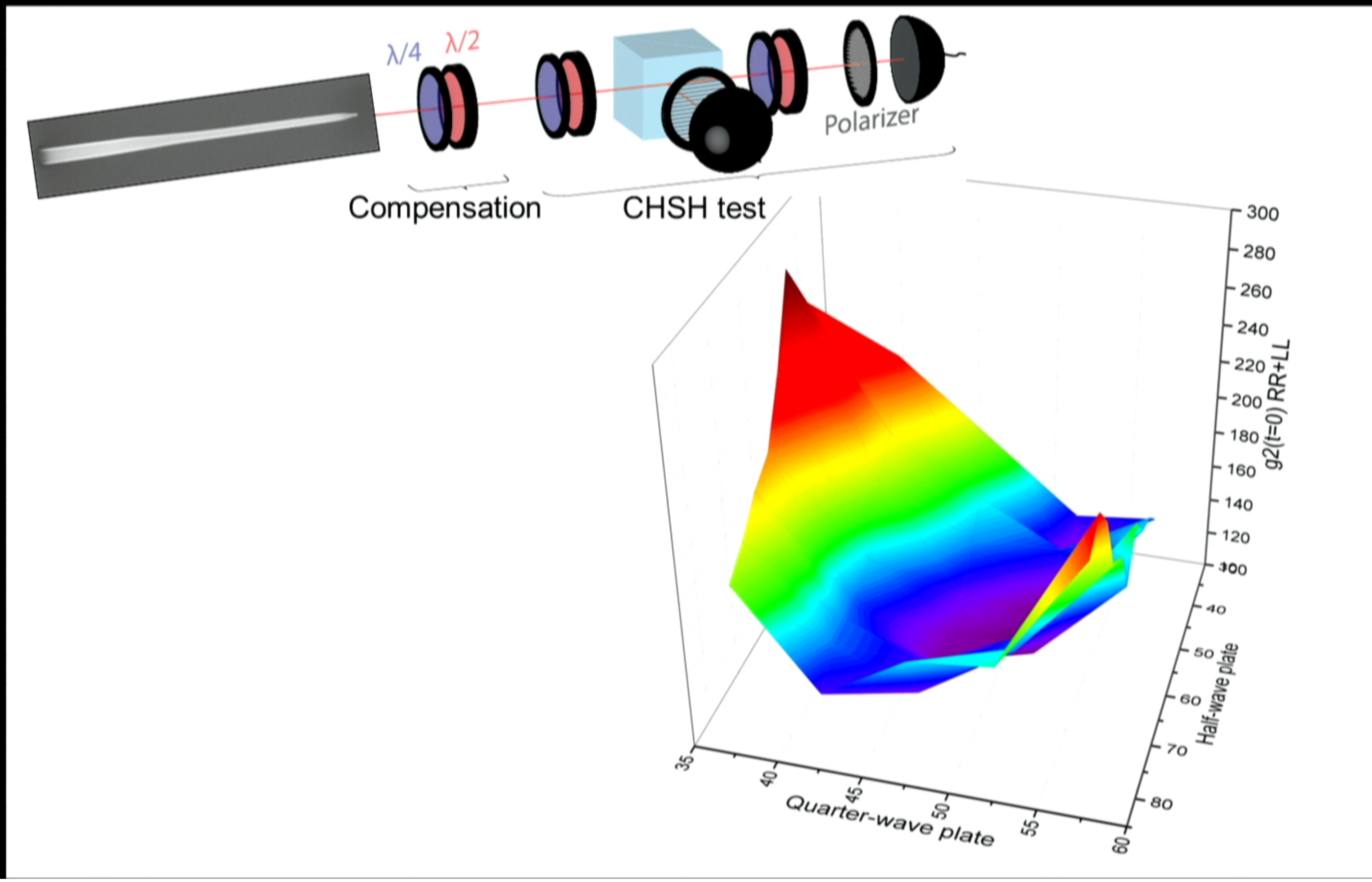




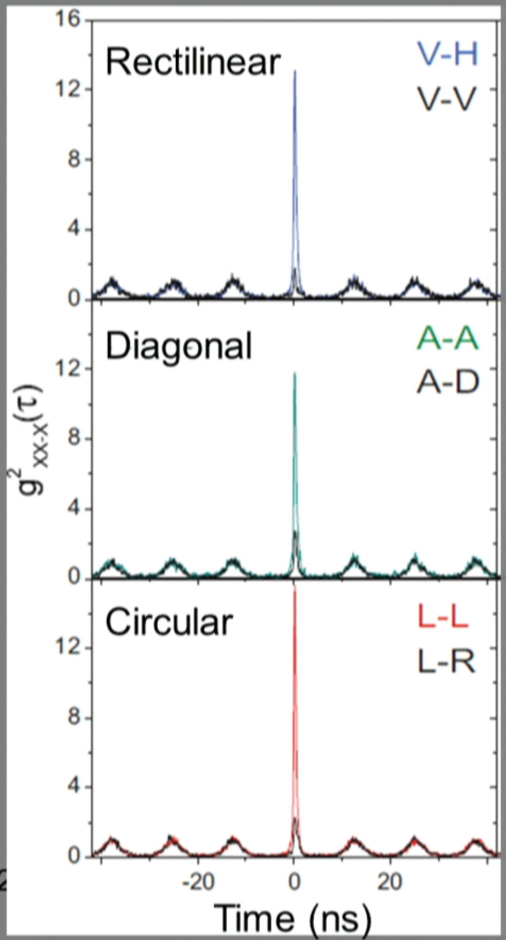
Compensating for the NW birefringence



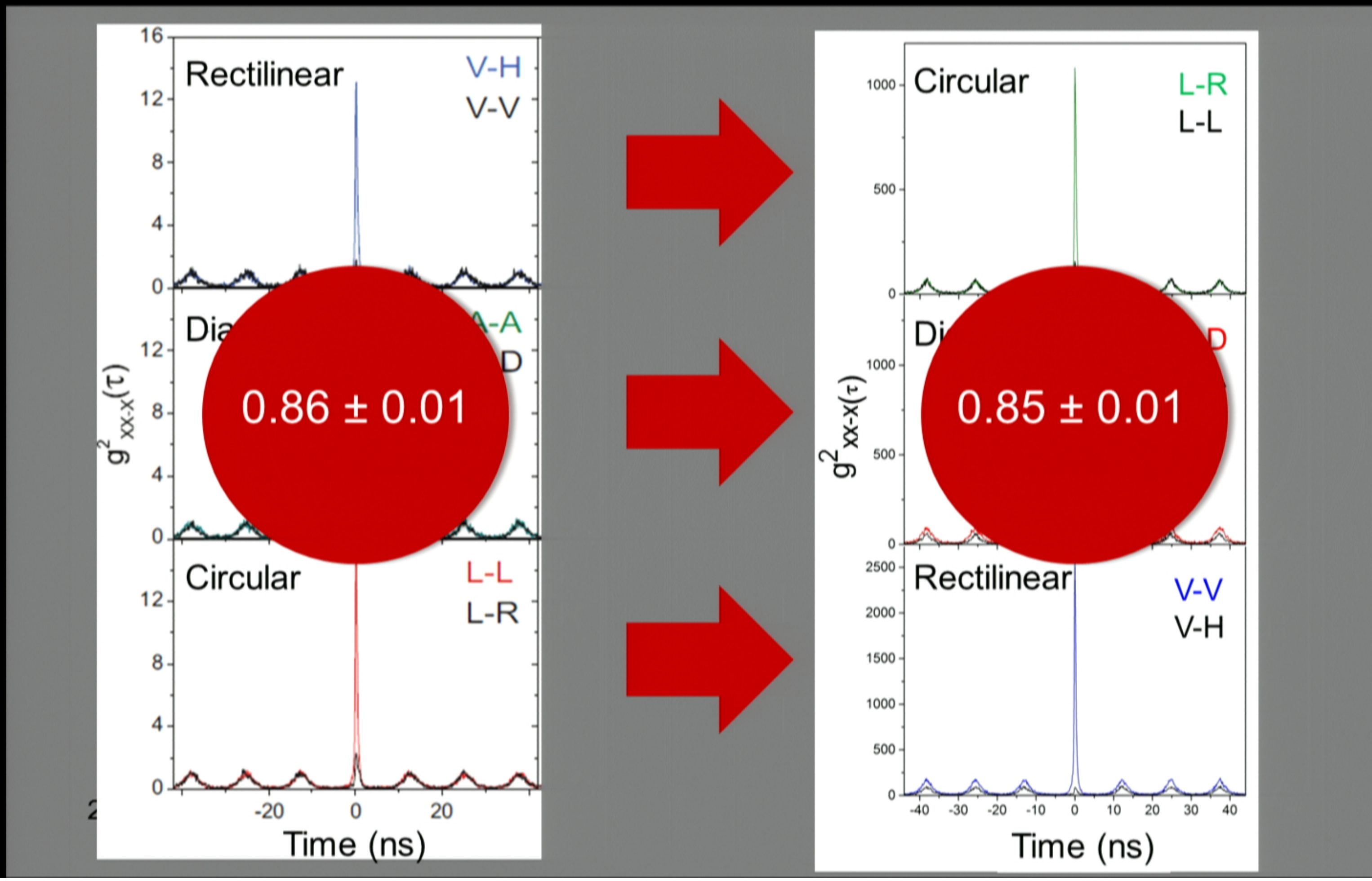
Compensating for the NW birefringence



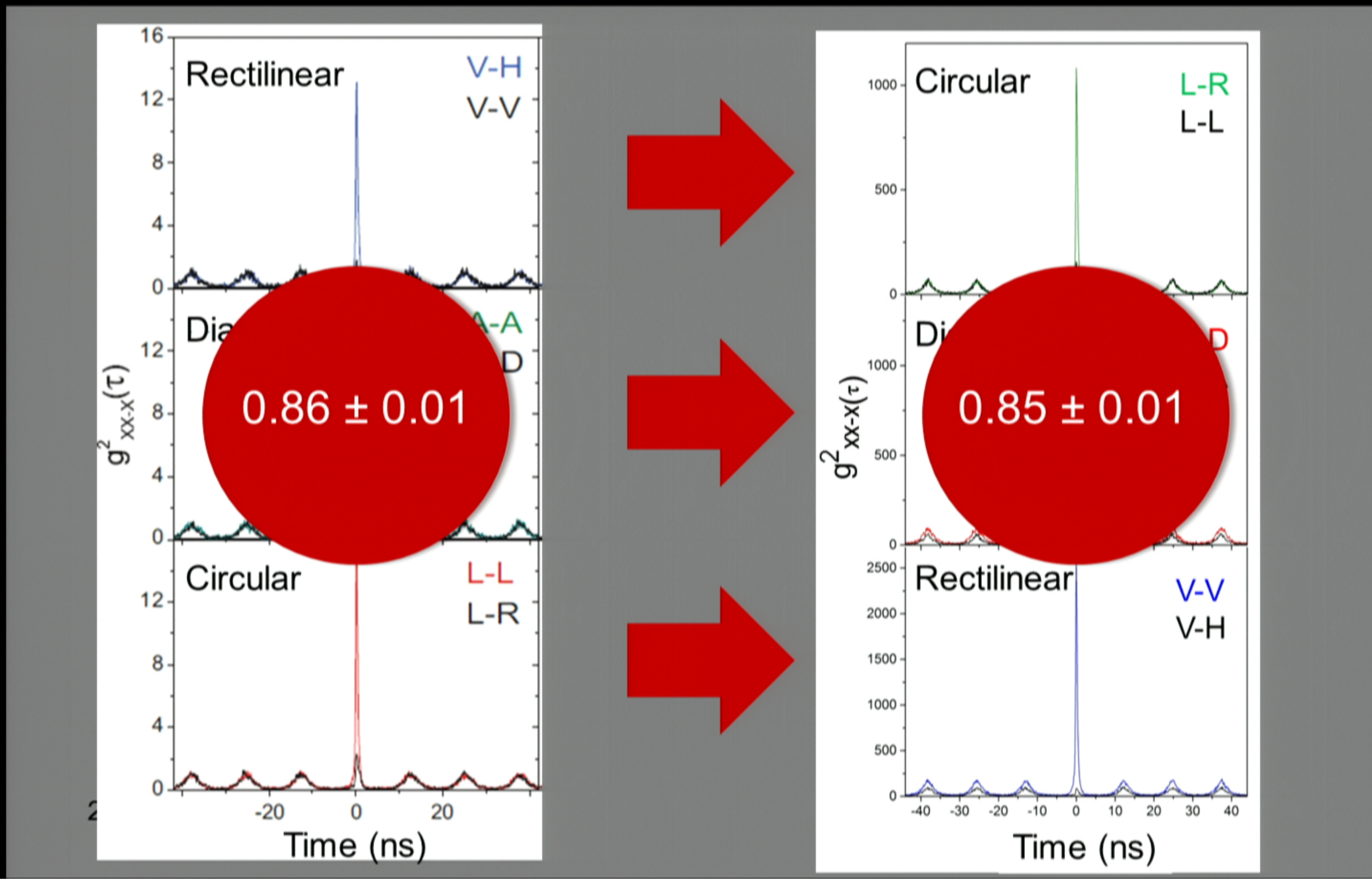
Compensating for the NW birefringence



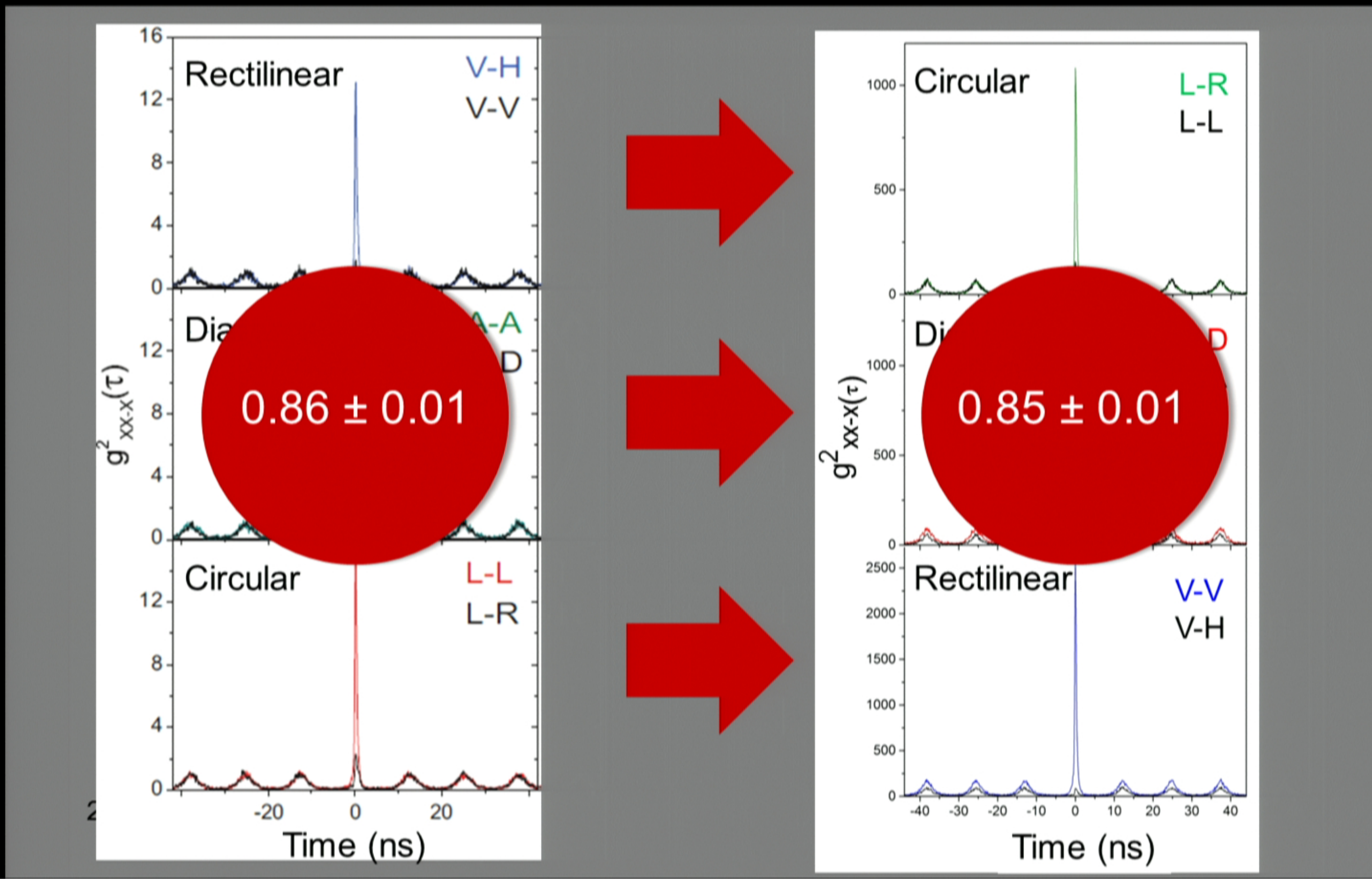
Compensating for the NW birefringence



Compensating for the NW birefringence



Compensating for the NW birefringence

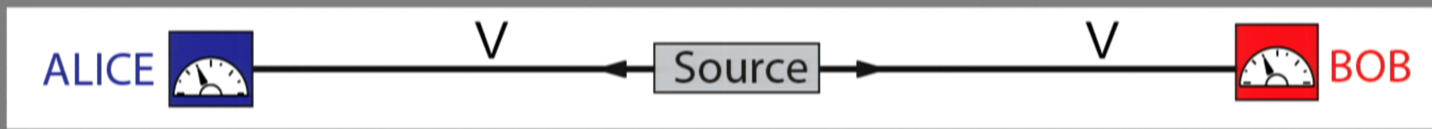


CHSH inequality

J.F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, Phys. Rev. Lett. **23**, 880 (1969).

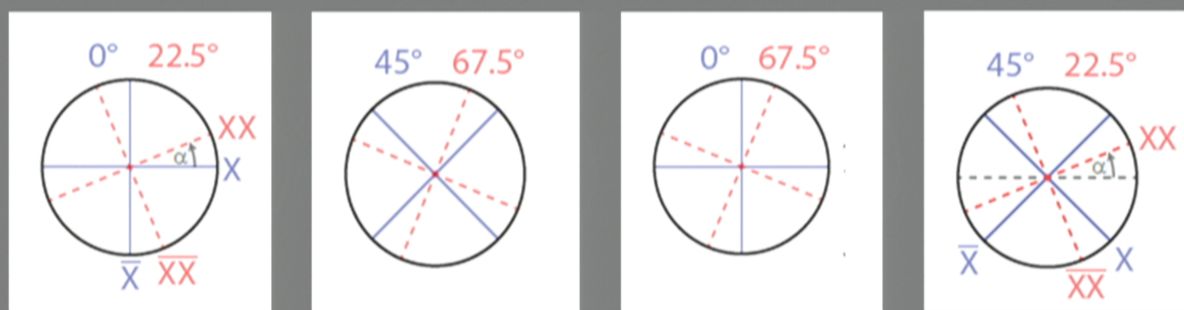
- More strict test of quantum entanglement → shows source is useful for quantum key distribution
- Local realism test
  - Demonstrates incompatibility of local realism and quantum mechanics

Violation of CHSH inequality



$$|\Psi\rangle = (|H\rangle|H\rangle + |V\rangle|V\rangle)/\sqrt{2}$$

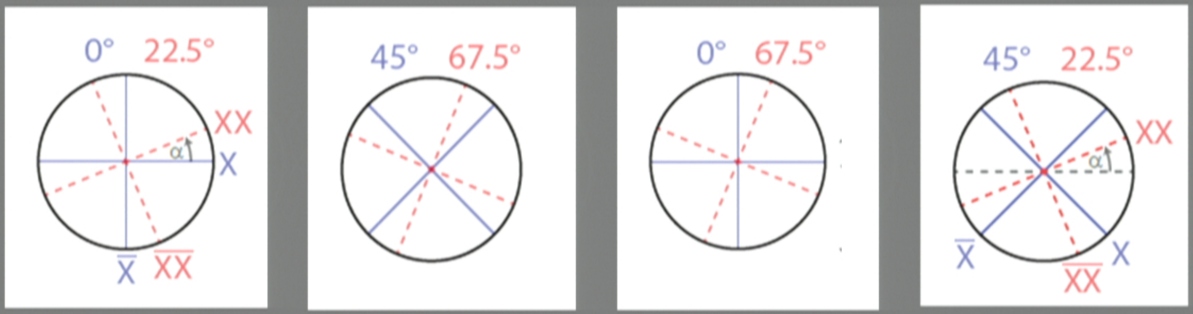
$$S = E(\alpha, \beta) - E(\alpha', \beta) + E(\alpha, \beta') + E(\alpha', \beta') \leq 2.$$



arXiv:1510.03897

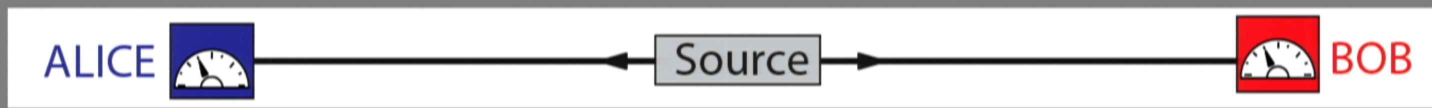
What do we measure?

$$S = E(\alpha, \beta) - E(\alpha', \beta) + E(\alpha, \beta') + E(\alpha', \beta') \leq 2.$$

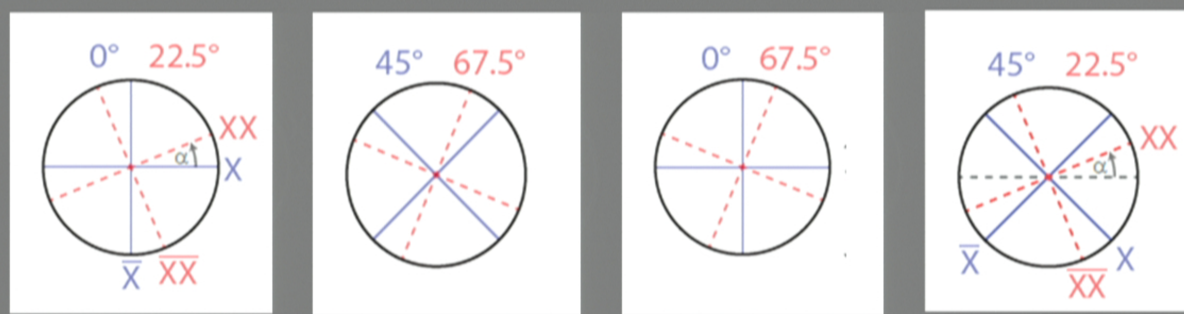


- Quantum mechanics predicts a maximum violation of $2\sqrt{2}$

What do we measure?



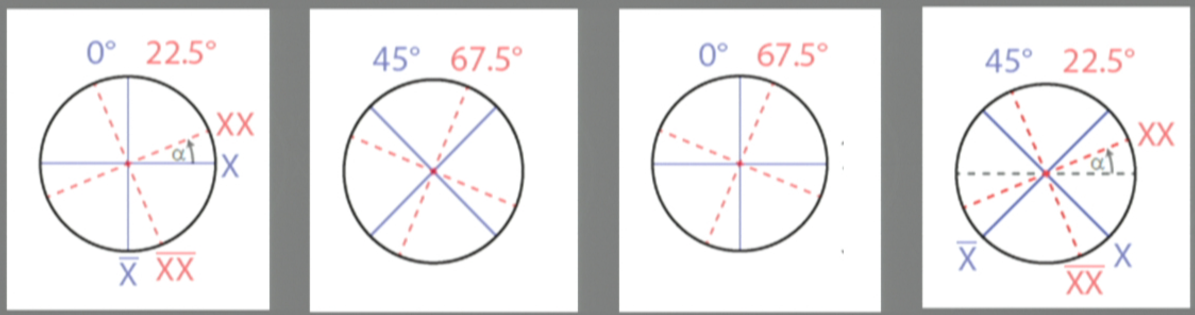
$$S = E(\alpha, \beta) - E(\alpha', \beta) + E(\alpha, \beta') + E(\alpha', \beta') \leq 2.$$



- Quantum mechanics predicts a maximum violation of $2\sqrt{2}$
- We measure S = 2.16 ± 0.01 in the traditional rectilinear-diagonal basis

What do we measure?

$$S = E(\alpha, \beta) - E(\alpha', \beta) + E(\alpha, \beta') + E(\alpha', \beta') \leq 2.$$

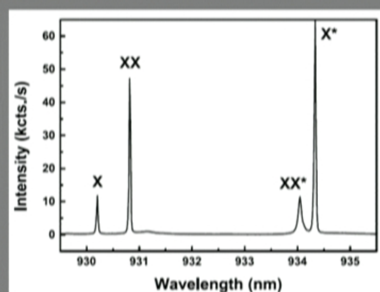


- Quantum mechanics predicts a maximum violation of $2\sqrt{2}$
- We measure S = 2.16 ± 0.01 in the traditional rectilinear-diagonal basis
- S = 2.25 ± 0.01 in the rectilinear-circular basis

NW entanglement summary

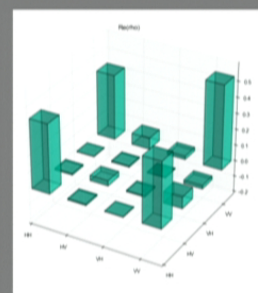
New bright source of strongly entangled photon pairs for quantum information applications

Bright photon emission



State-of-the-art photon pair efficiency ~17%

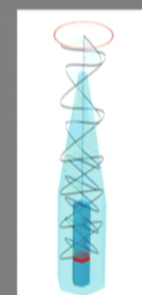
Strong entanglement



Near-unity fidelity

Concurrence of 0.95

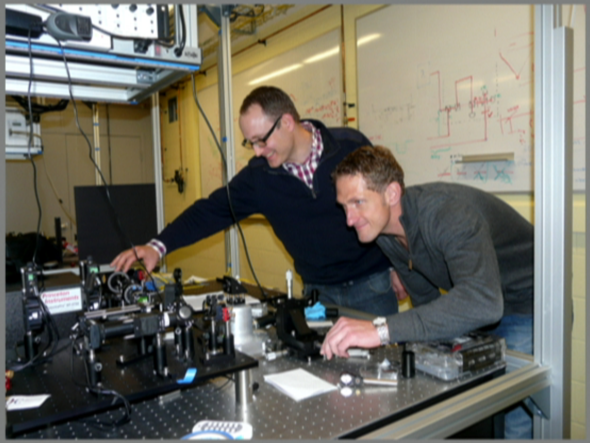
CHSH Violation

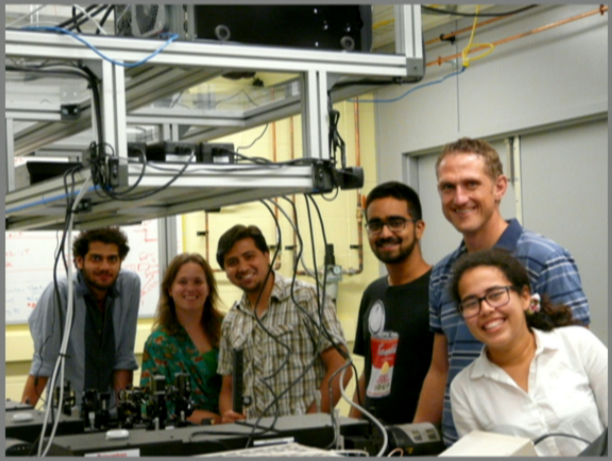


$S = 2.25 \pm 0.01$

arXiv:1510.03897

Thanks for your attention!






Thanks for your attention!